Flavour Physics at Hadron Colliders

Guy Wilkinson
University of Oxford and CERN

Flavour physics at LHC
CERN, 26 & 27 May 2025

Lecture plan

Today

1) Why study flavour at hadron machines, and how to do it.

2) Unitarity Triangle metrology and CPV measurements

Tomorrow

3) New Physics searches through studies of Flavour-Changing Neutral Currents (with digression on tree-level anomalies)

4) Charm physics at the LHC

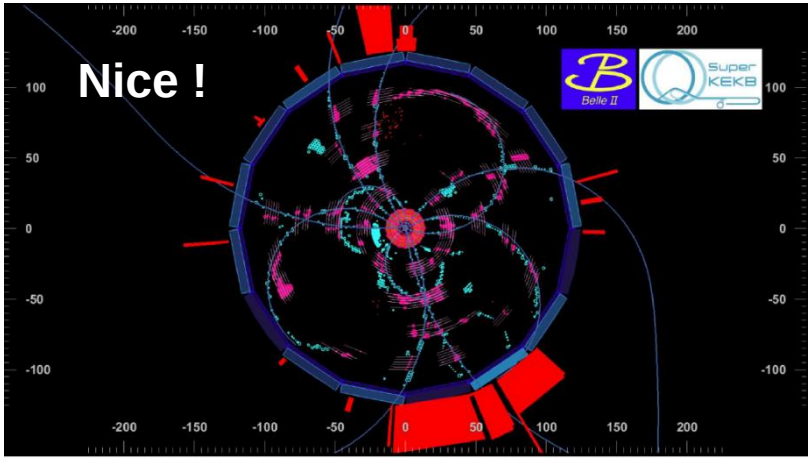
5) Future prospects for hadron-collider flavour studies

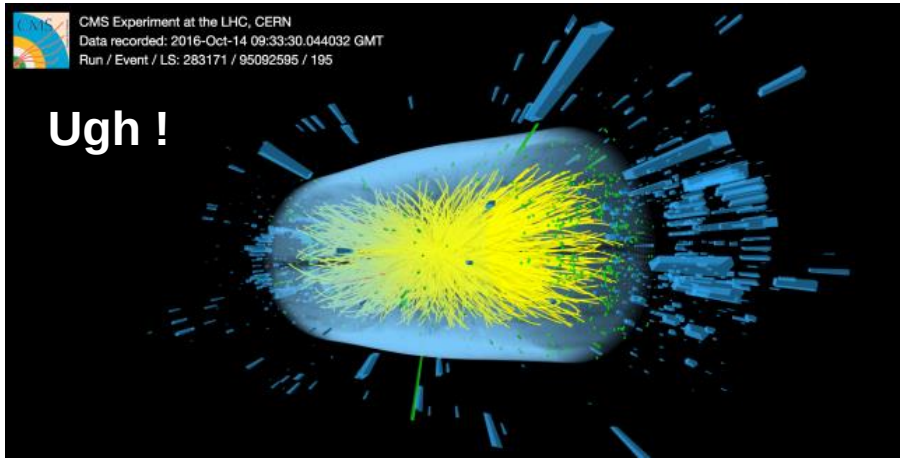
Flavour Physics at Hadron Colliders

1) Why study flavour at hadron machines, and how to do it

Why flavour physics at a hadron machine ?

Flavour-physics studies often consist of precise measurements of delicate and rare processes. Therefore, the choice of environment is surely a no brainer ?





Related to this event complexity / furthermore:

- (Initial) backgrounds much higher, particularly for studies with neutrals;
- Much more severe trigger challenge;
- Initial-state flavour tagging much less performant.

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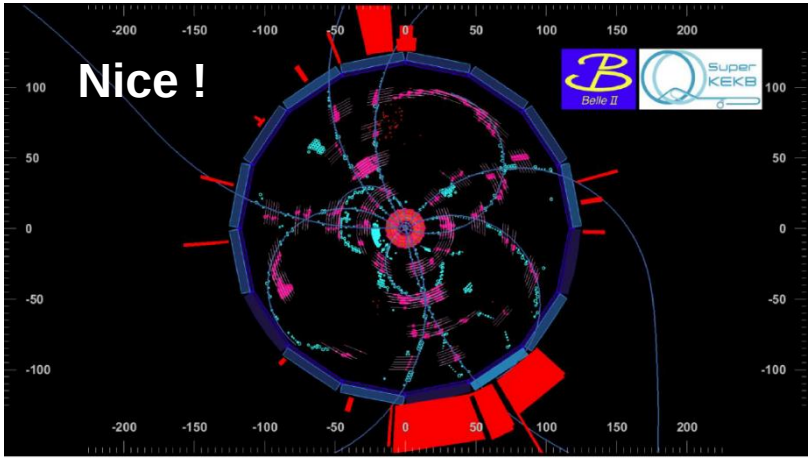

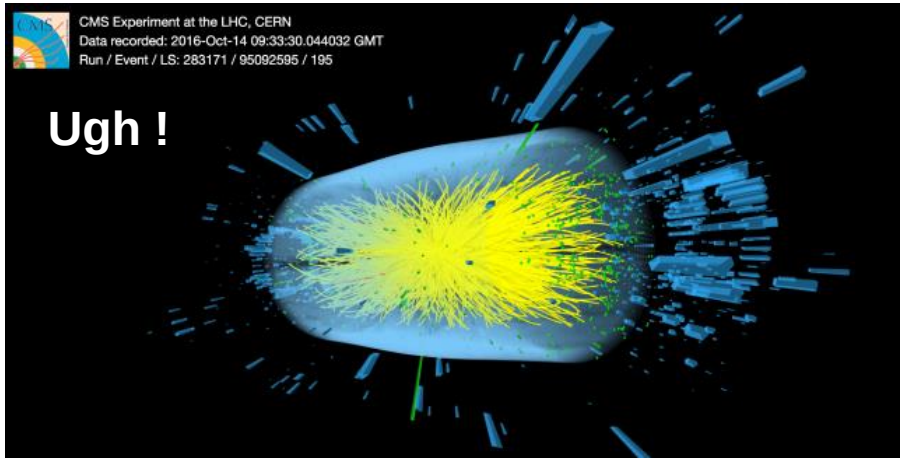

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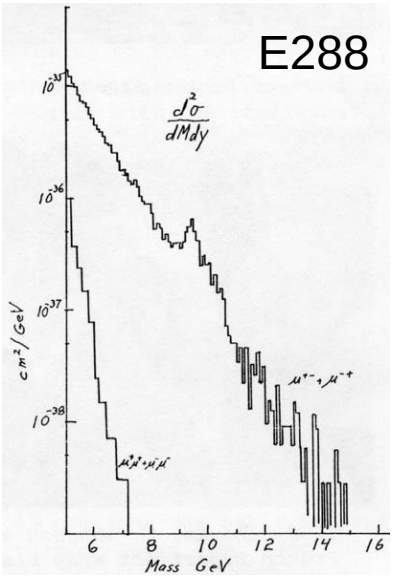
Nonetheless:

- *Much* higher cross section: $\sigma_{b\bar{b}}[\Upsilon(4S)] \approx 1$ nb $\sigma_{b\bar{b}}[\mathrm{LHC@14\ TeV}] \approx$ 600 μb ;
- In contrast to the Υ(4S), all b-hadron species are produced ;
- High boost.

Hadron beams and colliders have a strong tradition in b-physics

[E288, PRL 35 (1977) 252]

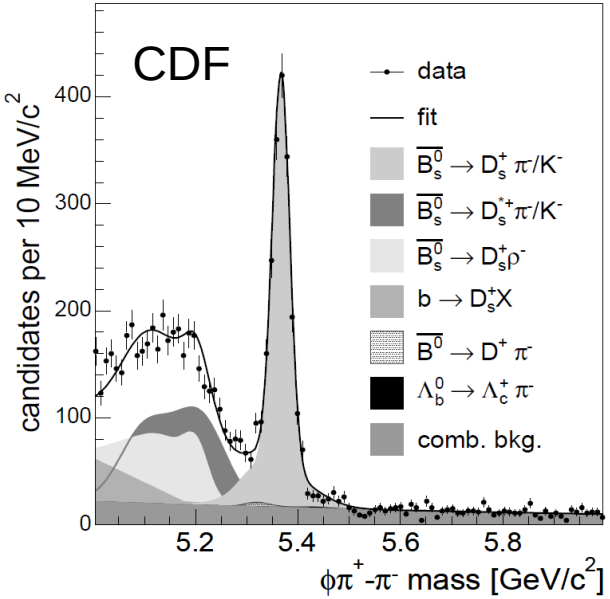


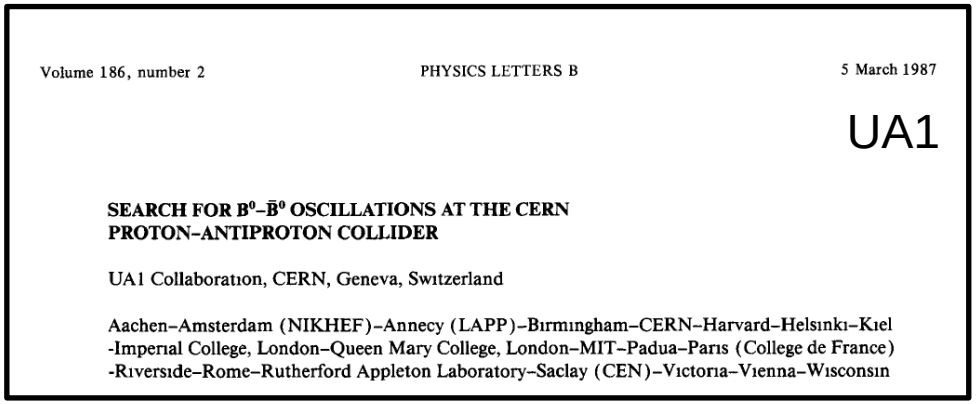
Discovery of b quark (ϒ) by Lederman and E288 in 1977.

Discovery of neutral B oscillations by UA1 in 1987.

Discovery of resolved B_s oscillations by CDF in 2006.

[CDF, PRL 97 (2006) 242003]





Volume 186, number 2 PHYSICS LETTERS B 5 March 1987

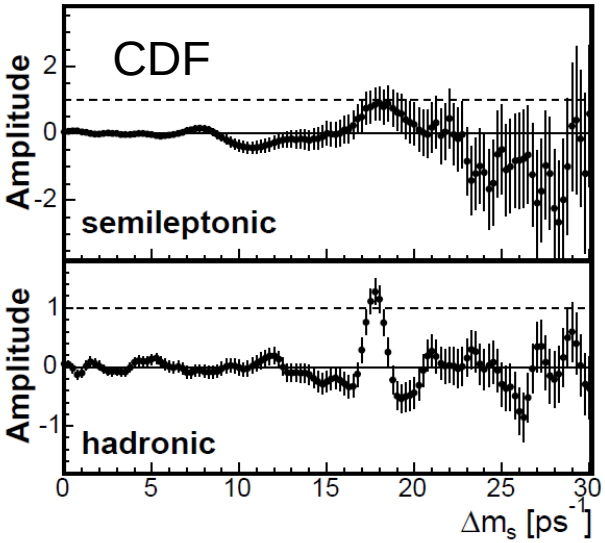
UA1

SEARCH FOR B^0–$\bar{B}^0$ OSCILLATIONS AT THE CERN PROTON–ANTIPROTON COLLIDER

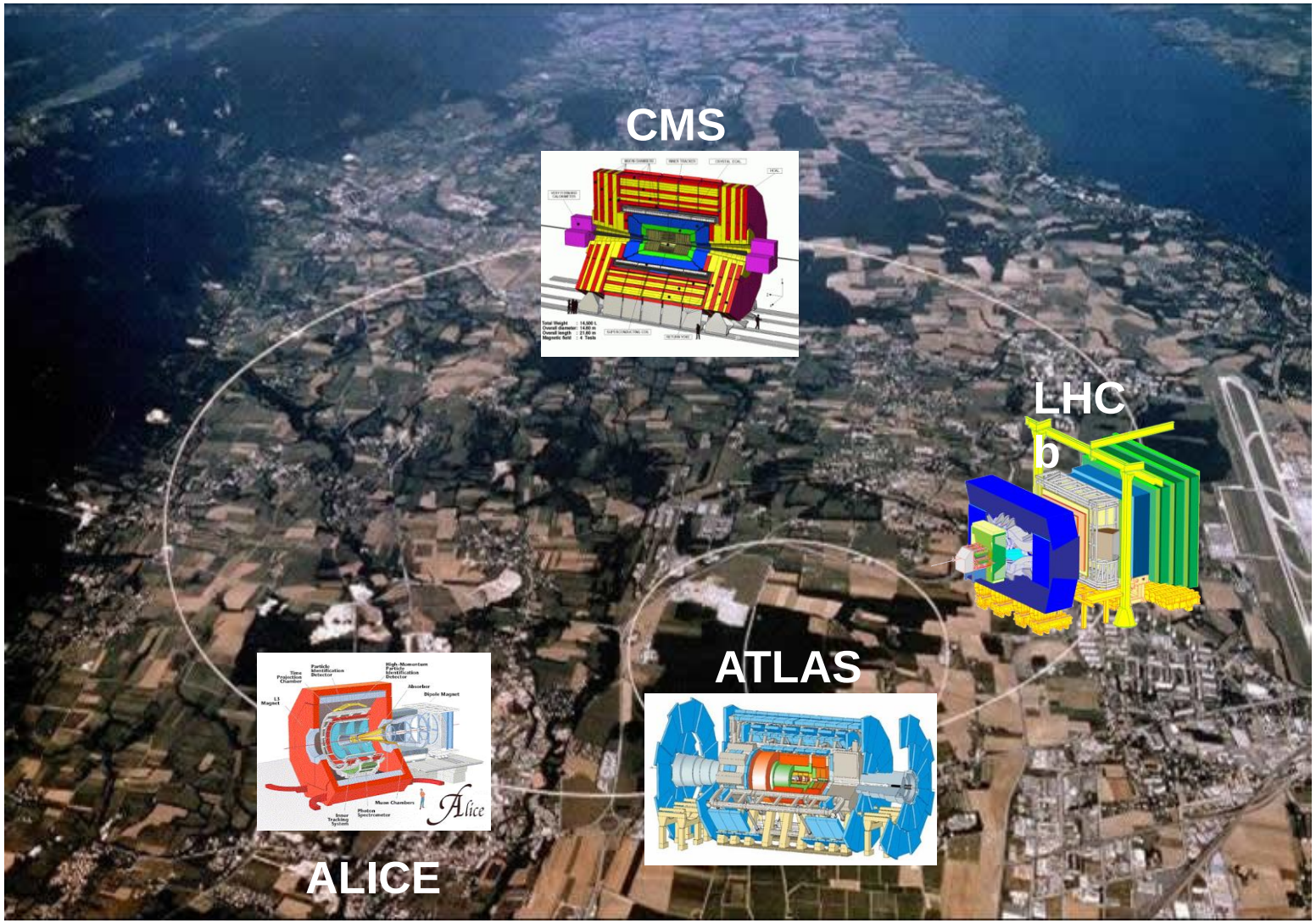
UA1 Collaboration, CERN, Geneva, Switzerland

Aachen–Amsterdam (NIKHEF)–Annecy (LAPP)–Birmingham–CERN–Harvard–Helsinki–Kiel –Imperial College, London–Queen Mary College, London–MIT–Padua–Paris (College de France) –Riverside–Rome–Rutherford Appleton Laboratory–Saclay (CEN)–Victoria–Vienna–Wisconsin

[UA1, PLB 186 (1987) 247]



The LHC: a multipurpose machine



Why do we need a 'dedicated' flavour physics experiment at the LHC ?

CMS and ATLAS can! They are exceptionally versatile detectors that have produced high quality results in flavour physics. However their studies are (mostly) restricted to final states involving di-muons (I will qualify this statement soon…), and they have no hadron PID capabilities. This puts many measurements out of reach.

Towards a dedicated b-physics experiment at the LHC

In early 1990s three ideas took shape for dedicated b-physics experiment at LHC.

GAJET	Fixed target – LHC protons impinging on gas jet. Calorimeter trigger, giving efficiency for hadron final states.
LHB	Fixed target – extracting LHC beam halo with bending crystal.
COBEX	Forward collider experiment, benefitting from full $\sqrt{s}$ =14 TeV cross section. Equipped with vertex detector sitting inside secondary vacuum. Muon trigger, followed by vertex trigger.

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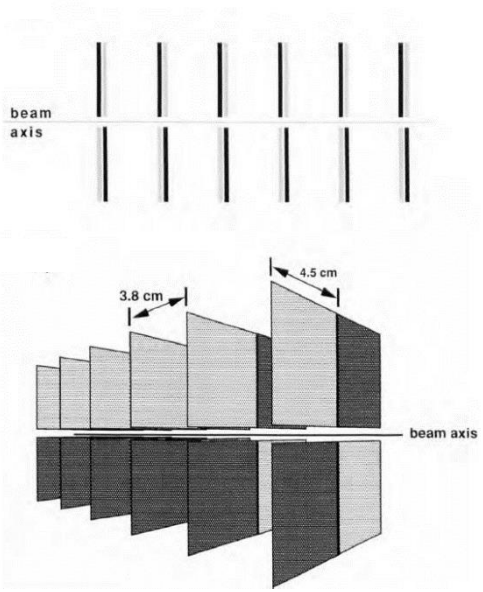
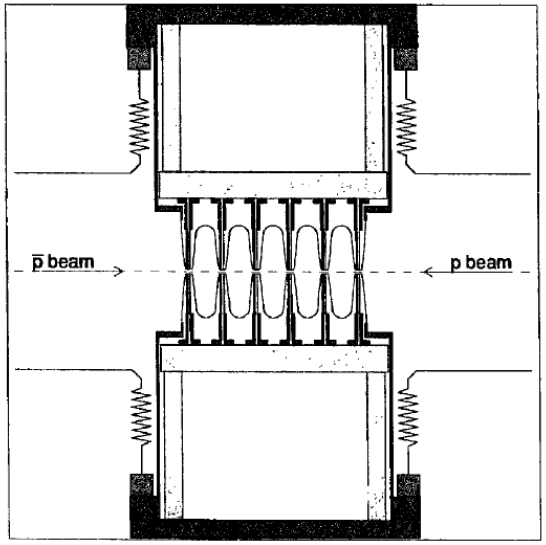
These aspects of proposal had a compelling proof-of-principle coming from P238 project at SPS.

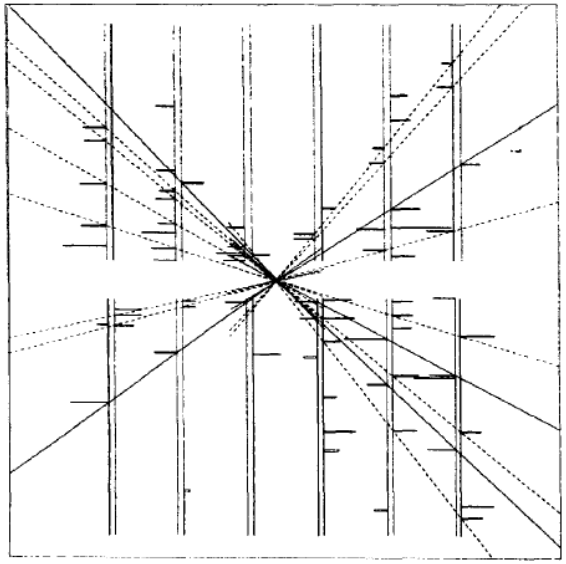
P238 – towards the LHCb VELO

'Development and test of a large silicon strip system for a hadron collider beauty Trigger' [P. Schlein *et al.*, NIM A 317 (1992) 28]

Large aperture forward spectrometers with planar geometry perpendicular to the beam line are the natural detectors to accomodate the expected forward peaking of Beauty particle production at high energy hadron colliders. We have designed, built and tested a prototype planar silicon strip vertex detector for triggering such a spectrometer system. The test system consisted of 43000 channels, configured in six planes, each with four quadrants, perpendicular to the beam line and installed inside the SPS-collider vacuum pipe at the center of an interaction region. Events recorded with the rf shield of the silicon system 1.5 mm from the circulating beams show negligible event-unrelated background.







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These proto-collaborations were encouraged to join forces and develop a detector concept that merged the best features of each, in particular collider operation and good trigger efficiency across a wide range of b-hadron decays.

Towards a dedicated b-physics experiment at the LHC

In early 1990s three ... s experiment at LHC.

GAJET

Fix ... as jet.

Ca ... ron final states.

LHB

Fix ... th bending crystal.

COBEX

Fo ... fro ...

Ec ... secondary vacuum.

Mu ...

These proto-collabo ... nd develop a detector concept that merge ... collider operation and good trigger eff ... decays.

CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

Meanwhile, at DESY, Hamburg…

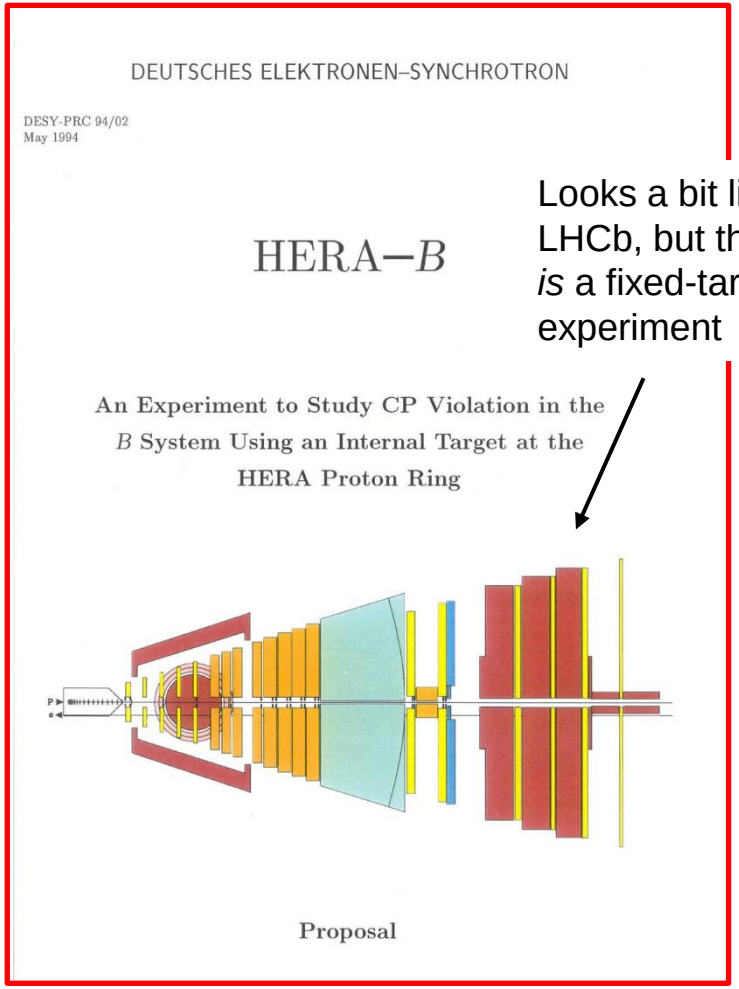
HERA-B, first proposed in 1992, starting ~2000, operated with HERA proton beam on fixed-wire target.

Principal goal was to be first experiment to see CP violation in $B^0 \to J/\psi K_S^0$.

Hugely demanding (harder than LHCb !), as $b\bar{b}$ / minimum bias cross-section ratio at $\sqrt{s}$ = 920 GeV is 10^{-6} , and interaction rate, with pileup, was 10s of MHz.

Much was learned, concerning:

- triggering;
- vertex detectors and RICHes;
- challenges of operating MSGCs in high radiation environments;
- why too much material is bad.


DEUTSCHES ELEKTRONEN–SYNCHROTRON

DESY-PRC 94/02
May 1994

HERA–B

An Experiment to Study CP Violation in the B System Using an Internal Target at the HERA Proton Ring

Proposal

Looks a bit like LHCb, but this *is* a fixed-target experiment

Many of these lessons were very valuable for LHCb. But for HERA-B it was too late. The B factories started too well and quickly, and HERA-B data taking ceased in 2003.

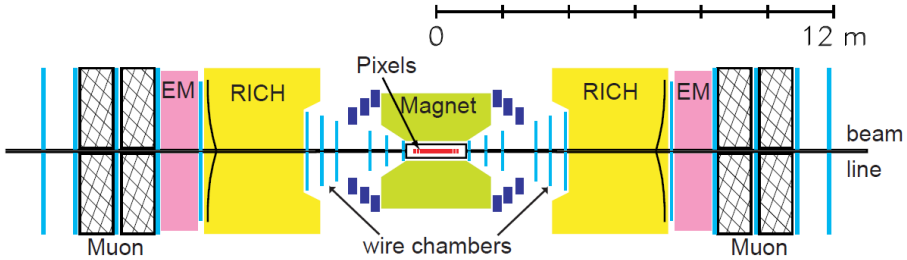
…and at FNAL, Illinois

BTeV was proposed as a dedicated B physics experiment at the Tevatron.

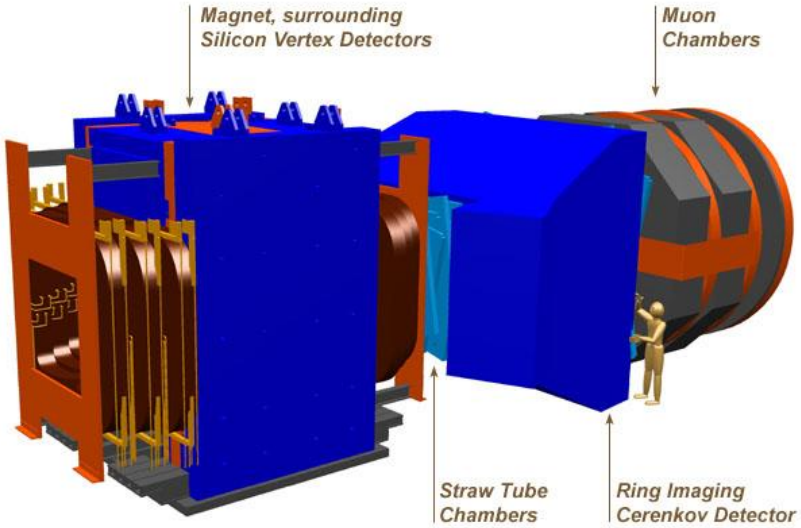
Differences w.r.t. LHCb:

- Two-arm spectrometer;
- Pixel, not strip, vertex detector and intention to use vertex signatures at earliest trigger stage;
- Higher emphasis on ECAL physics.

Given first-stage approval in 2004, but cancelled soon after. Some aspects of BTeV are central to LHCb Upgrades.



One arm of BTeV

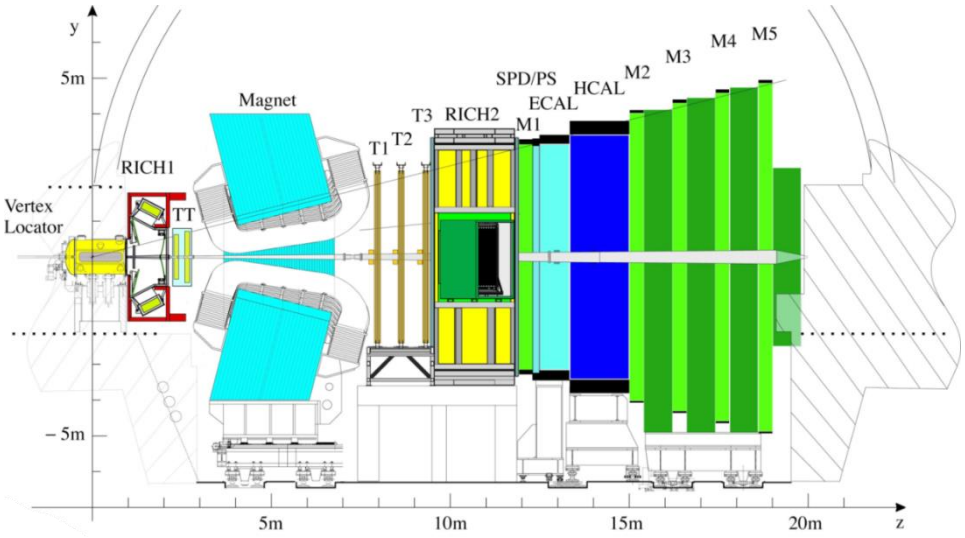


LHCb: a dedicated experiment for flavour physics at the LHC

Designed to be a *dedicated* experiment for b- and c-physics at the LHC.

Dedicated in the sense of the following attributes:

- Acceptance
- Operating luminosity
- Instrumentation
- Trigger

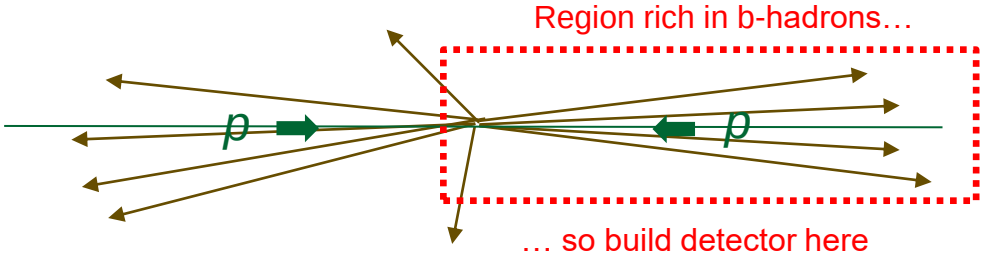


These capabilities give the experiment high sensitivity in other studies apart from flavour, but describing these goes beyond the scope of these lectures.

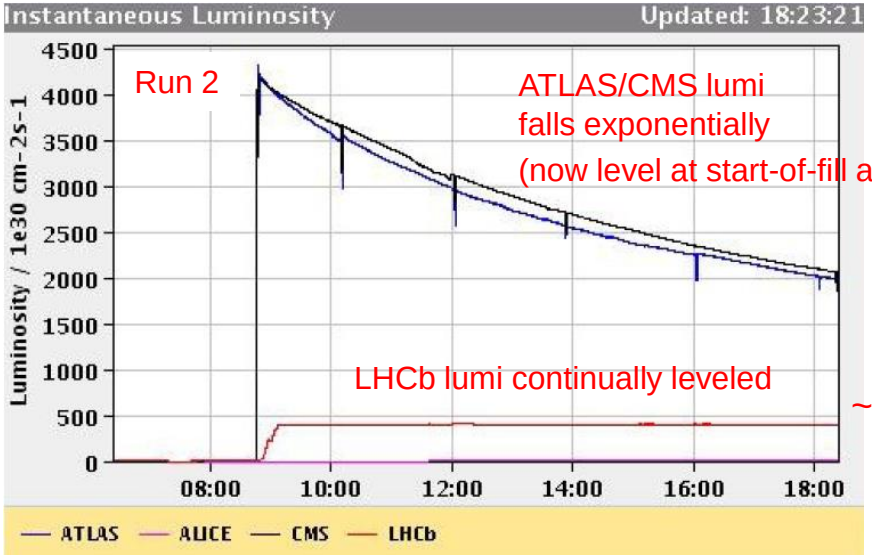
A dedicated experiment for flavour physics at the LHC – general considerations

Go forward ! This collects a large fraction of the $b\bar{b}$ pairs, which are predominantly produced by gluon fusion at low angles. This choice of geometry brings other benefits:

- Vertex detector can get *really* close to beamline;
- High boost;
- Lots of space (very helpful for RICH detectors);
- 'High p_T' can be redefined to mean a few GeV, which is typical p_T of b-decay products.

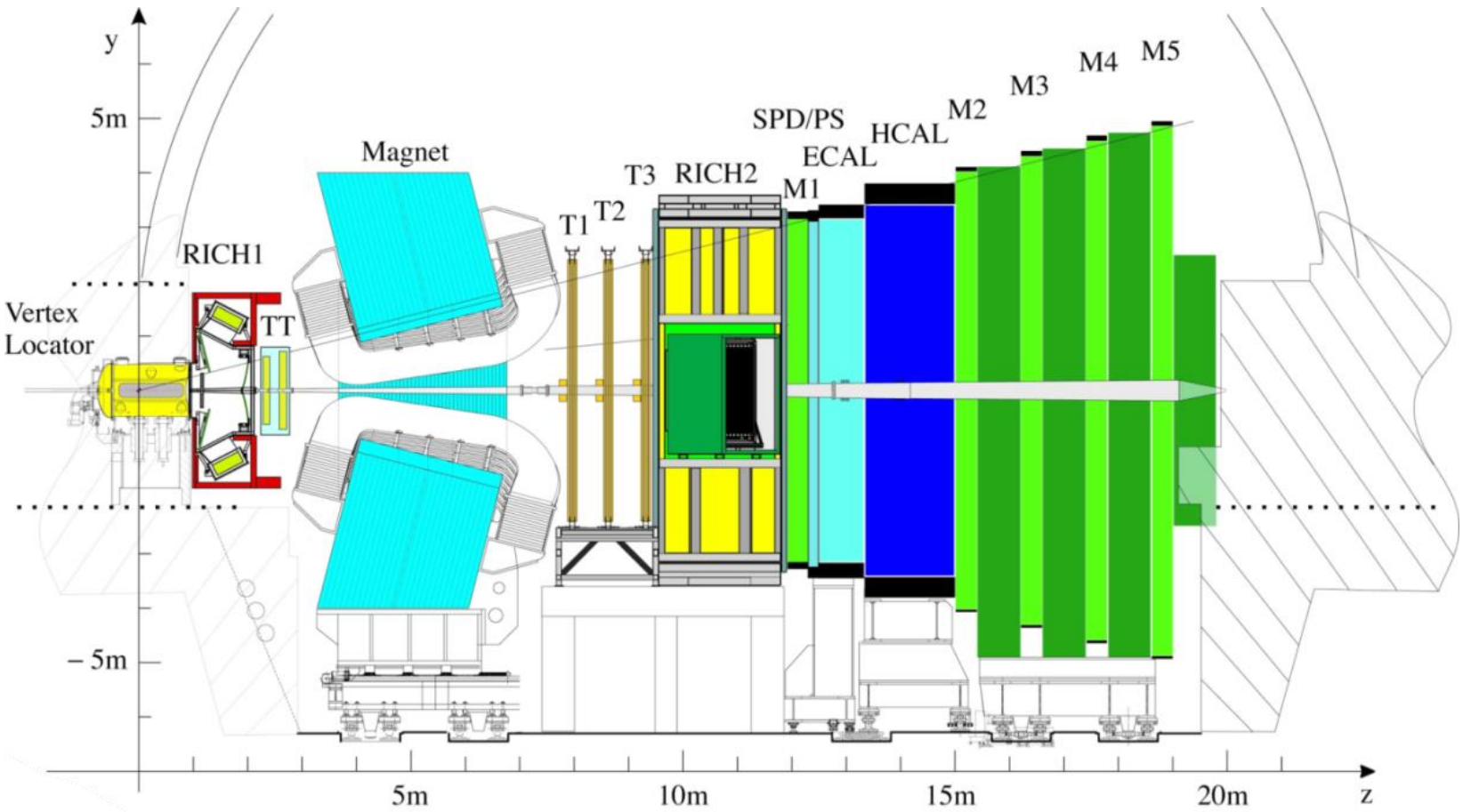


This necessitates operating at lower luminosity than ATLAS / CMS (also needed for trigger – see later).

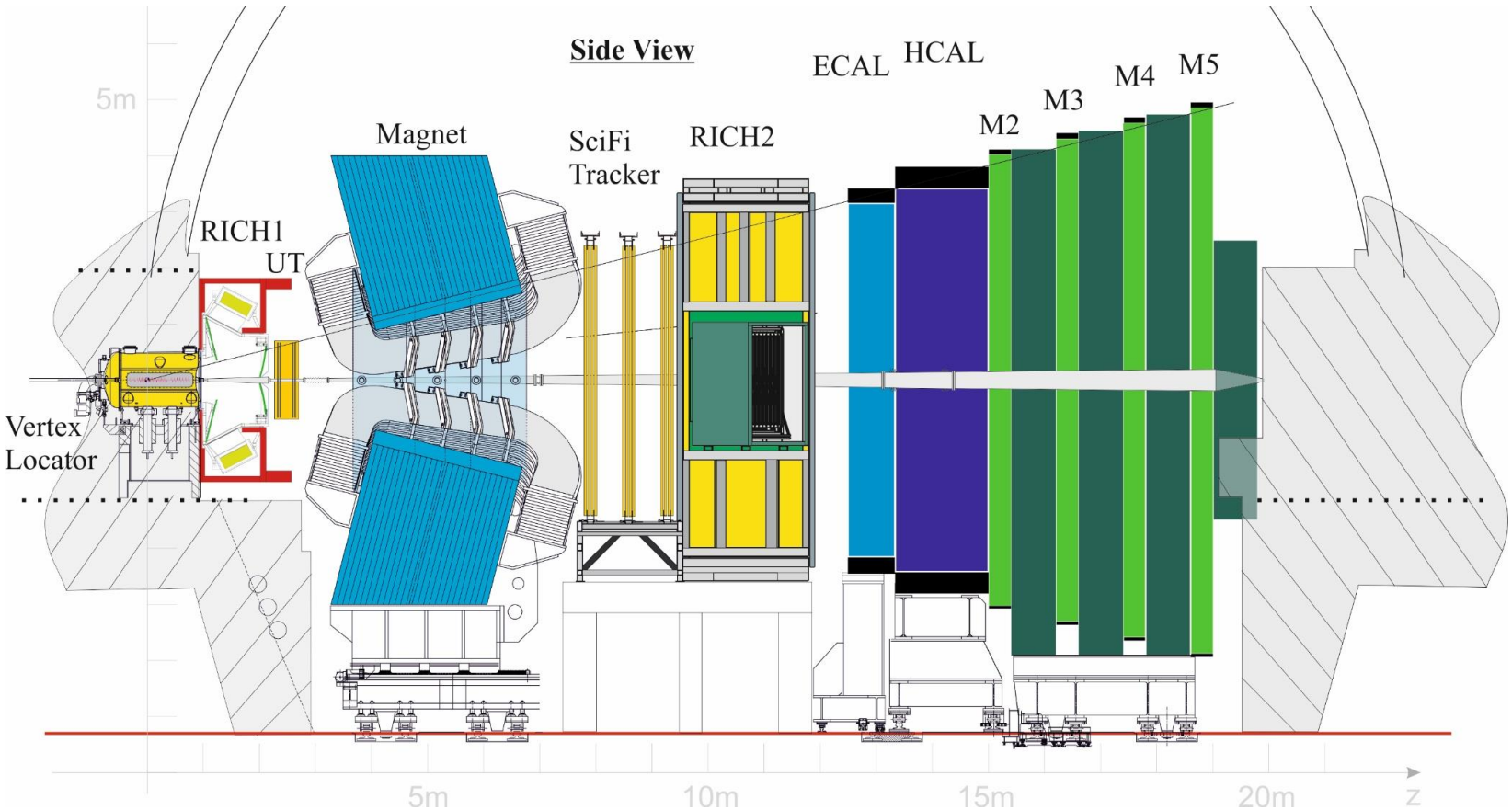


~4 x 10^{32} $cm^{-2}s^{-1}$

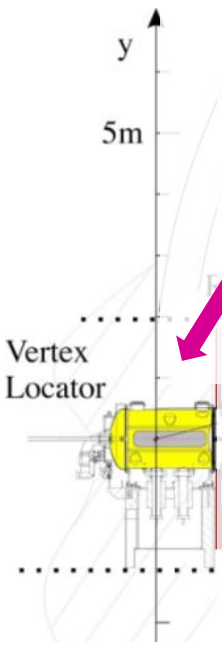
LHCb – a forward spectrometer for flavour physics: Runs 1 and 2 ('the OG')



LHCb – a forward spectrometer for flavour physics: Runs 3 and 4 (Upgrade 1)



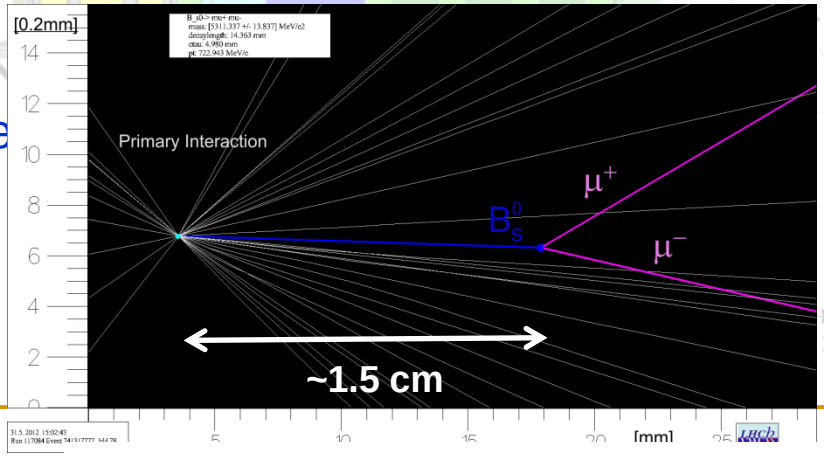
LHCb – vertex locator (VELO)



The VELO is a silicon strip detector around the interaction point.

One-half of the VELO under construction

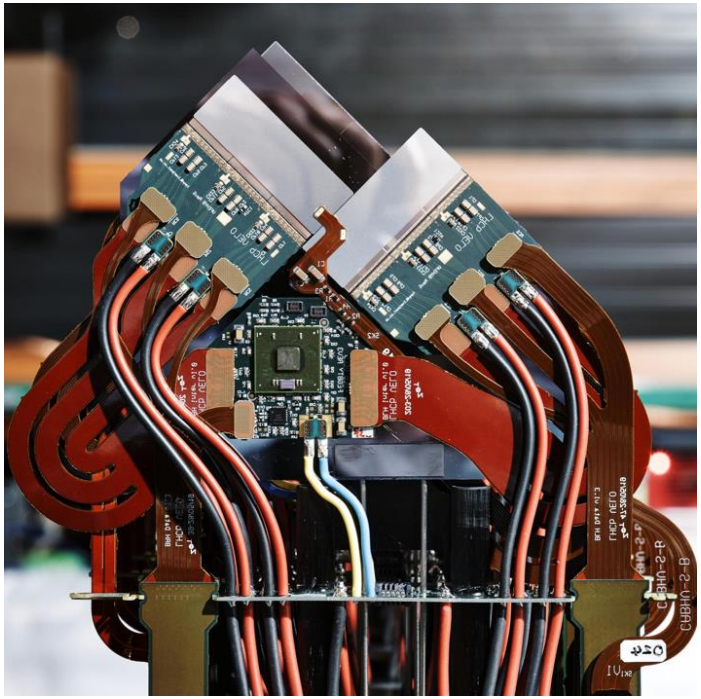
It approaches within 5.1 mm of the beamline, sits in a secondary vacuum, and reconstructs the *b*-hadron decay vertex precisely.

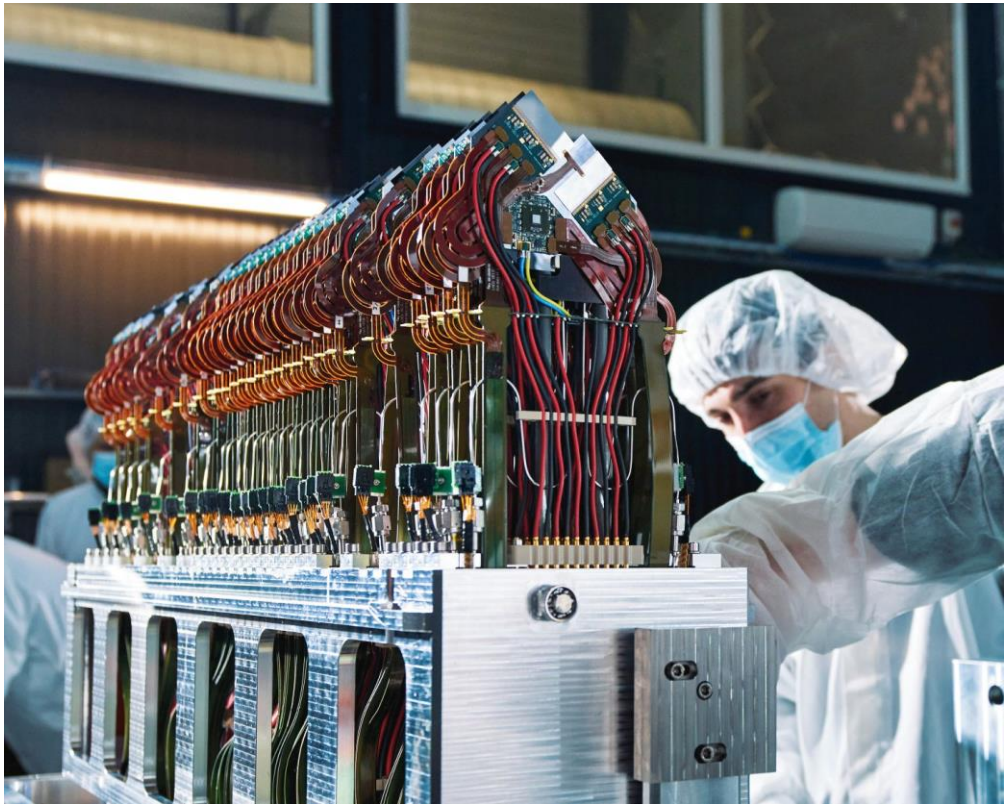


A reconstructed *b*-hadron decay vertex

VELO – built for precision

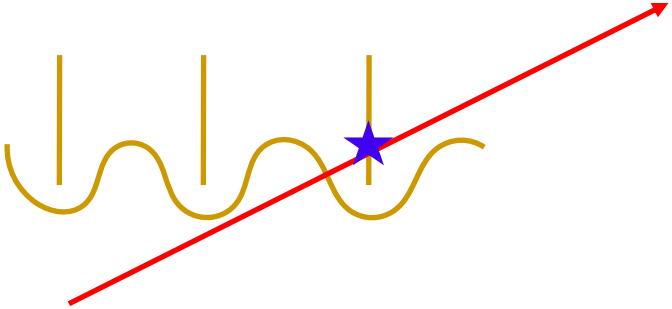
Closest measurement point has down to 4 μm precision and is 5.1 mm from beam. There material is minimal – only the sensor, no electronics or cooling.



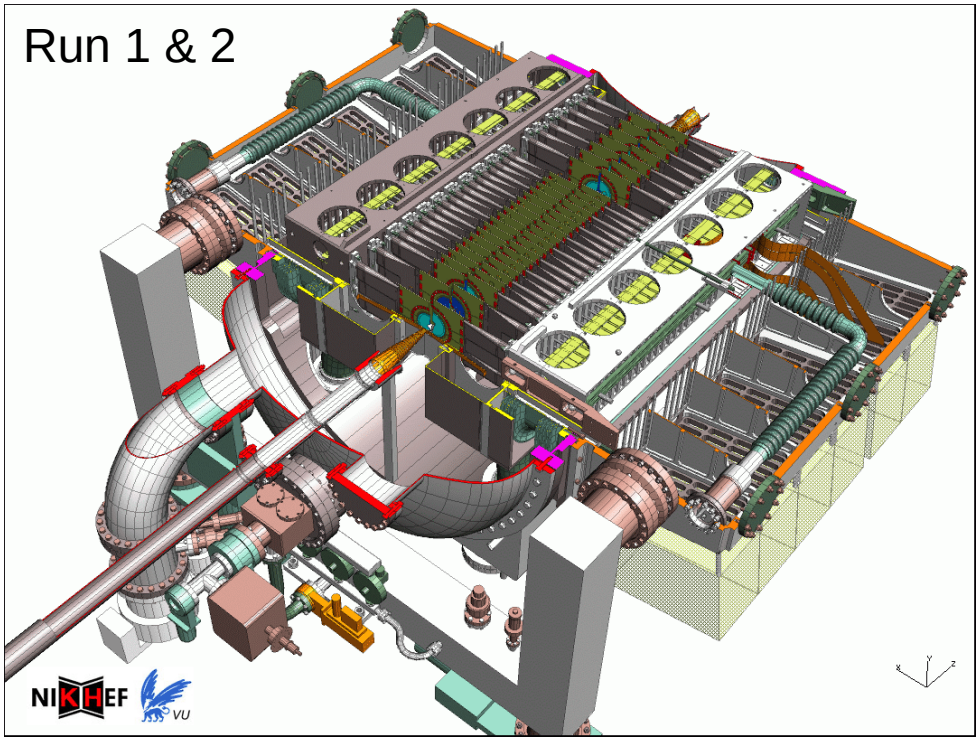


VELO – close to beam

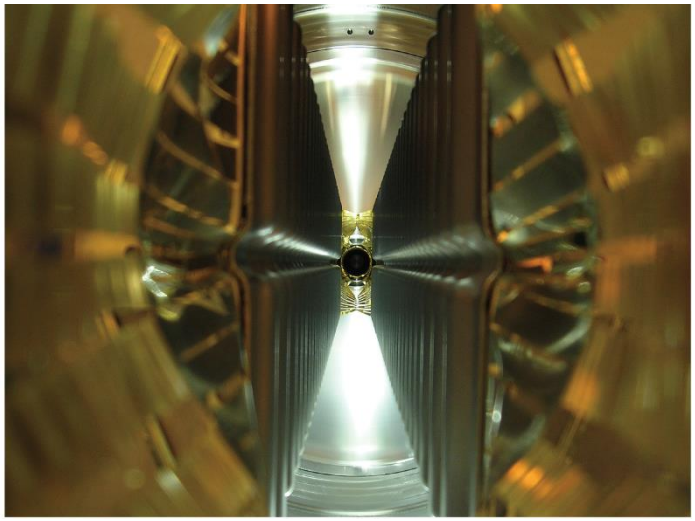
VELO is moveable and operates in vacuum.
The RF foil “beampipe” surrounding it
is ultra-thin, and corrugated.



Track passes through RF foil perpendicularly – good for multiple coulomb scattering.



What the protons see in injection



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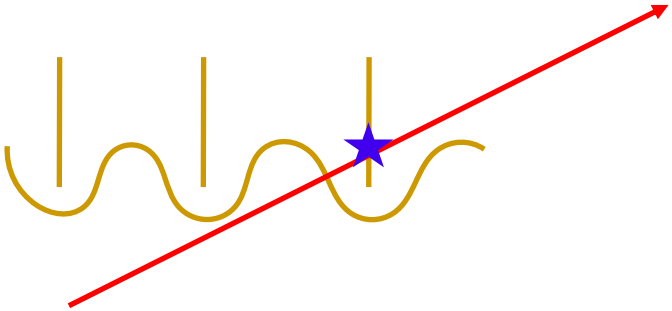

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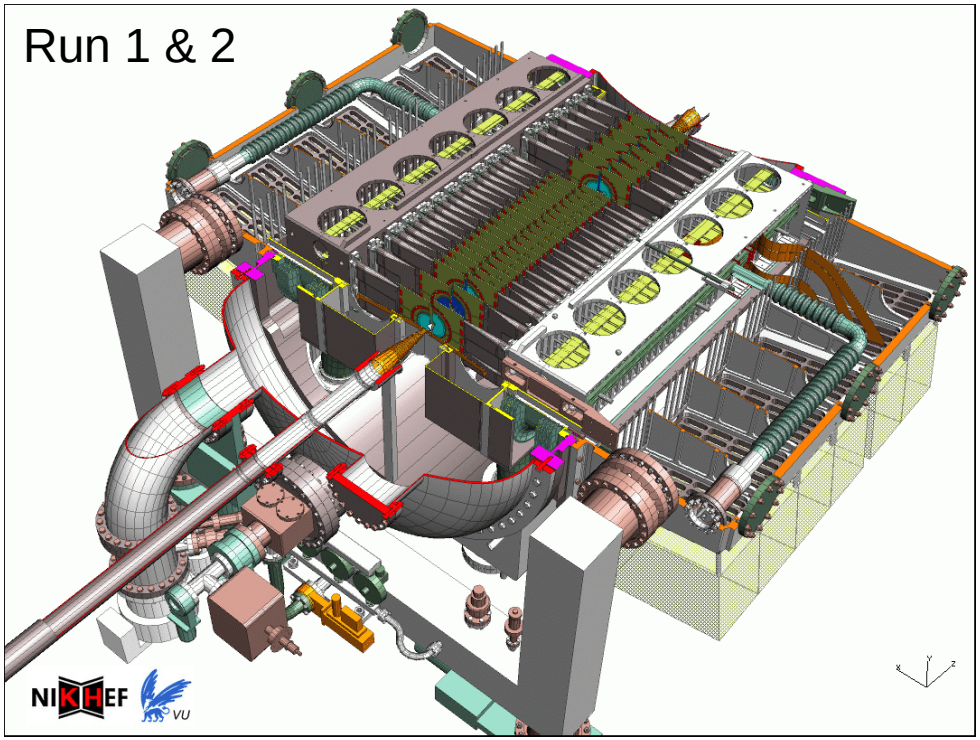
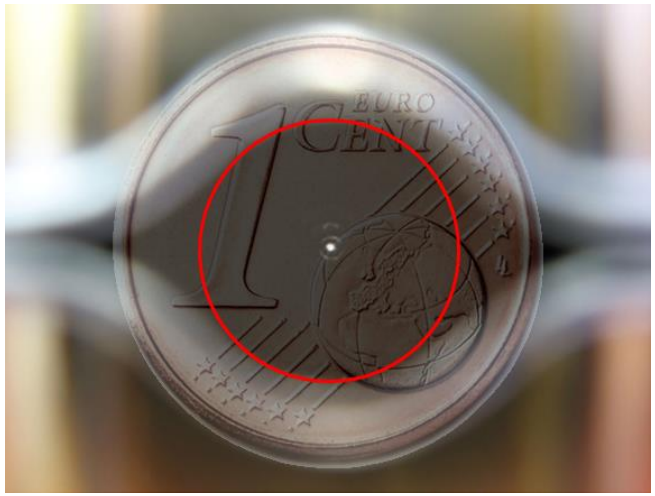
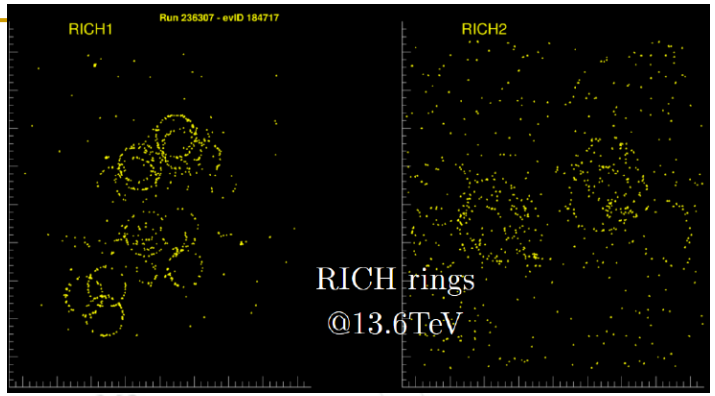


What the protons see in collisions

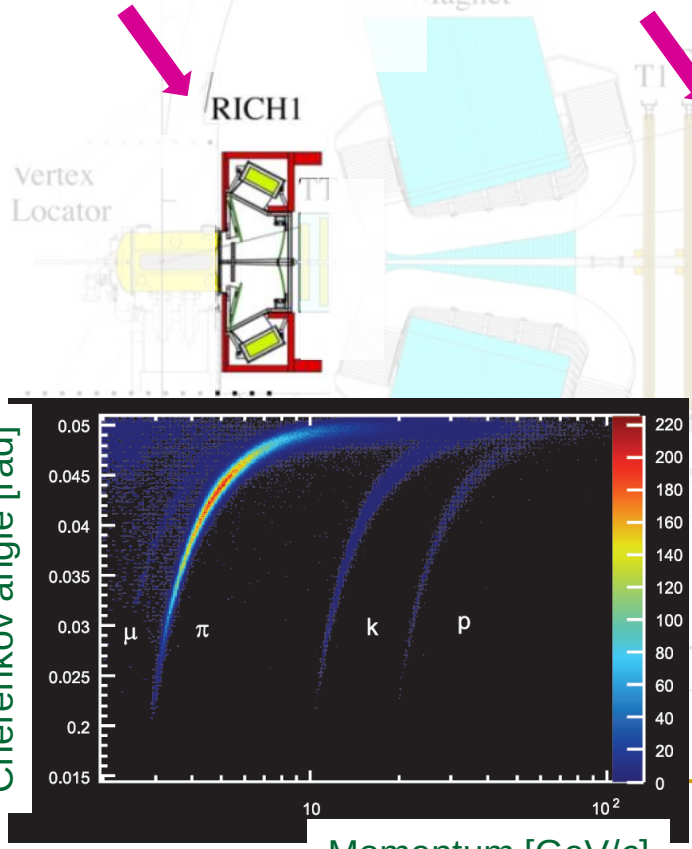


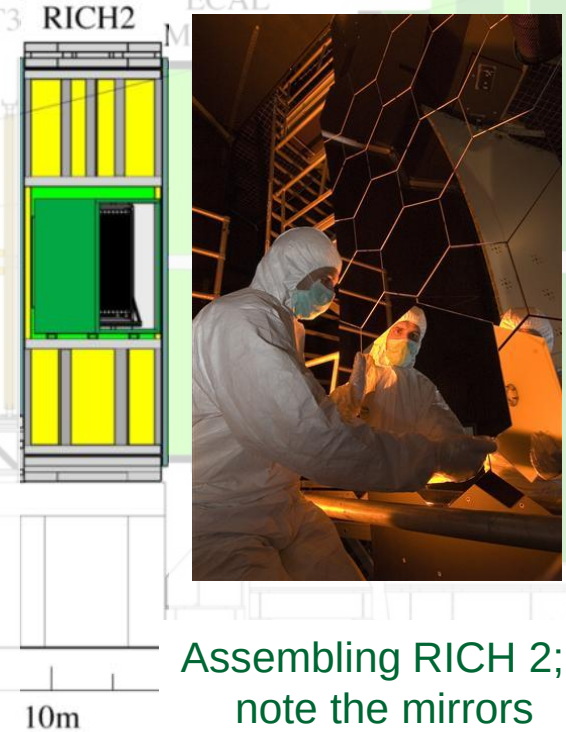
Size of beam aperture (Run 1 & 2) compared with one Euro.

LHCb – RICH system



Two Ring Imaging Cherenkov (RICH) detectors provide π-K separation from ~1 to ~100 GeV/*c*.



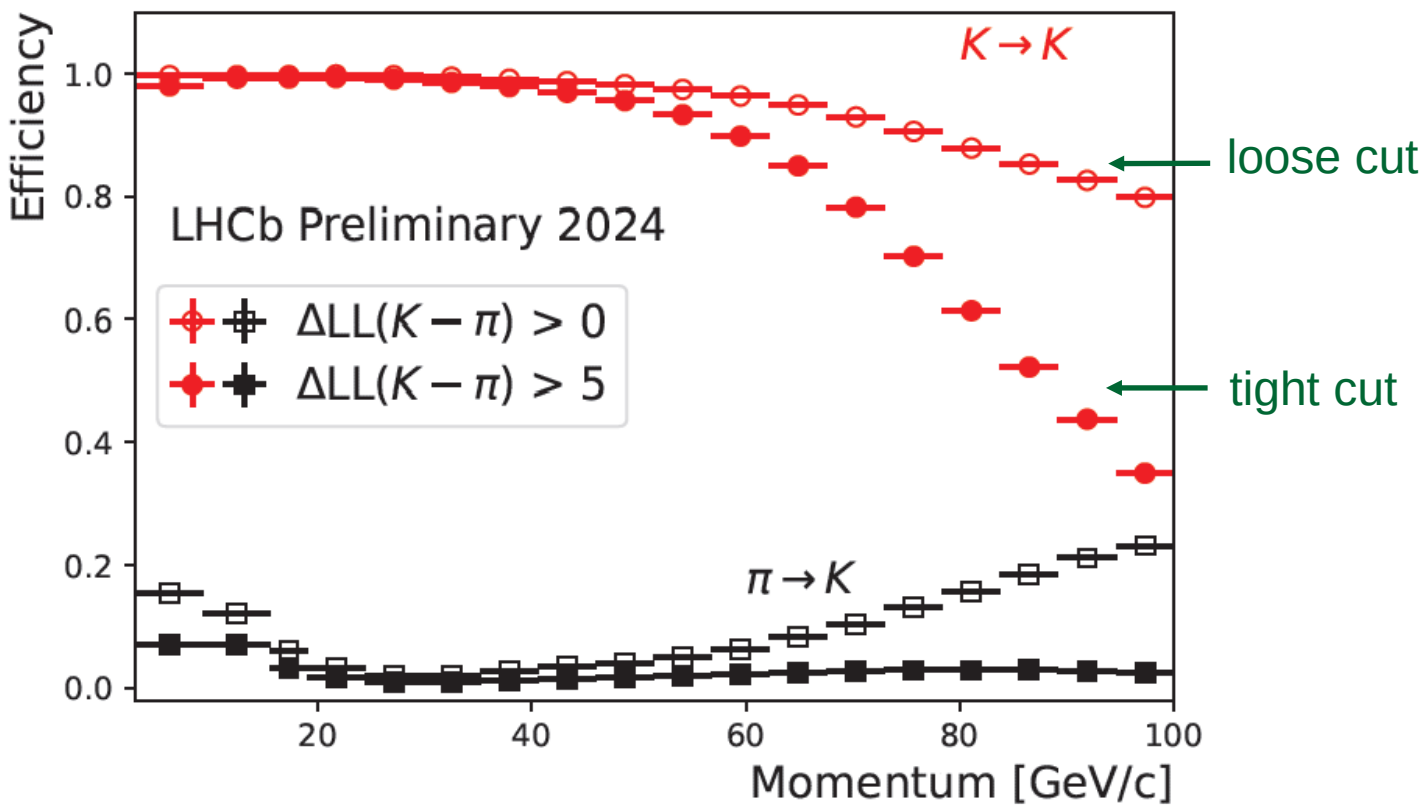


Assembling RICH 2; note the mirrors

Array of RICH 2 photodetectors (Upgrade 1)

RICH performance

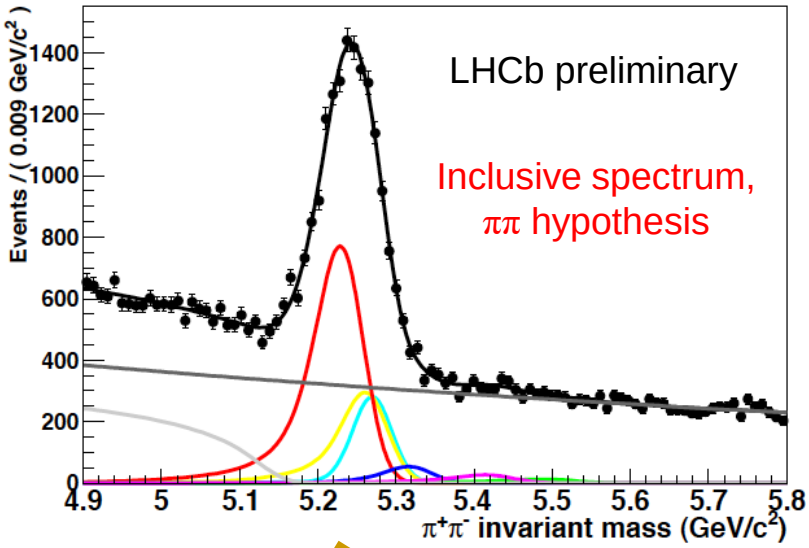
Hadron-identification requirements are very different at LHC compared to B-factories, as there is a *much* greater spread in momentum, going to *much* higher momenta.



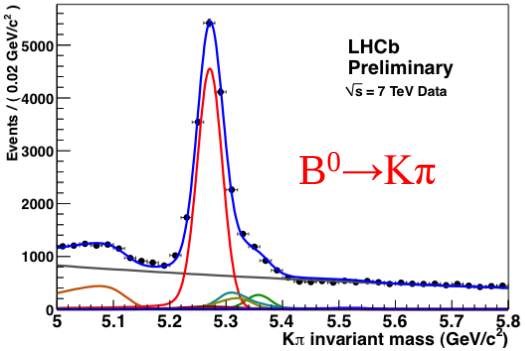
Two RICHes, one optimised for lower momentum (C_4F_{10}), the other downstream (CF_4) optimised for higher momentum, span a range of $1 < p < 100$ GeV/*c*.

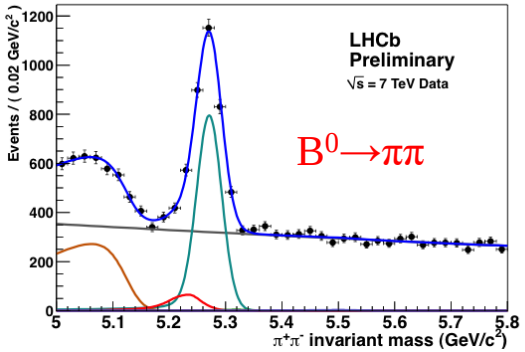
RICH in action

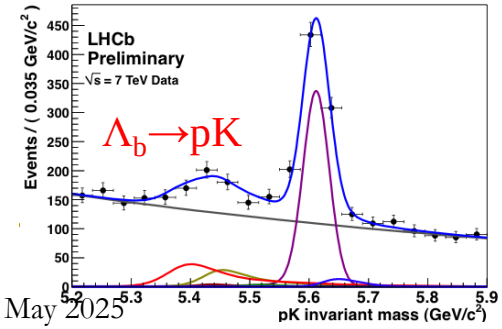
Two-body charmless B decays are central goal of LHCb physics.
Identical topologies require RICH to separate.

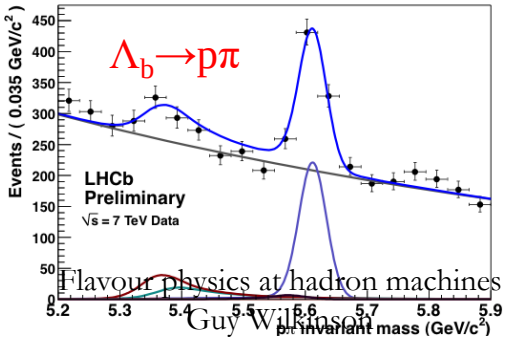


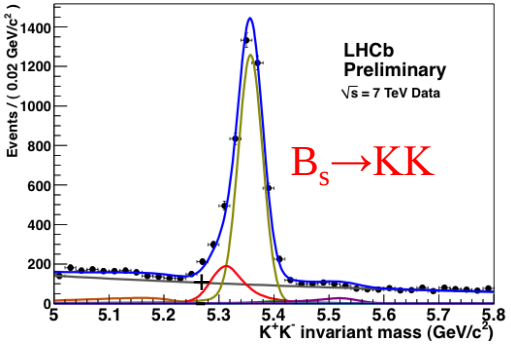
Deploy RICH to isolate each mode !







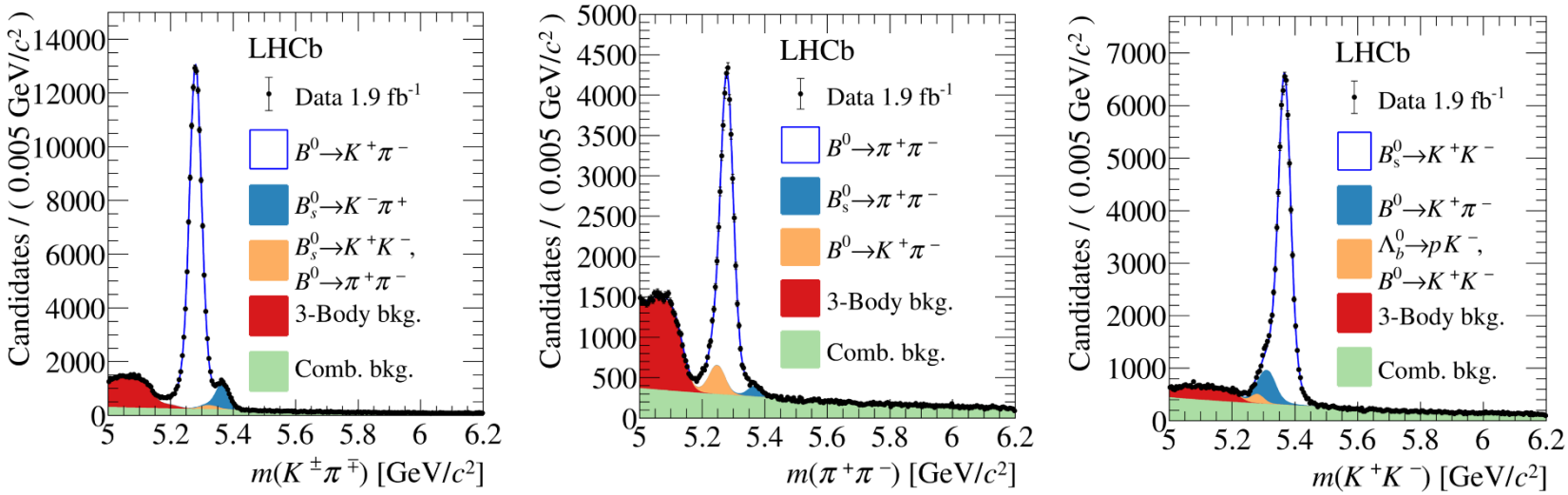


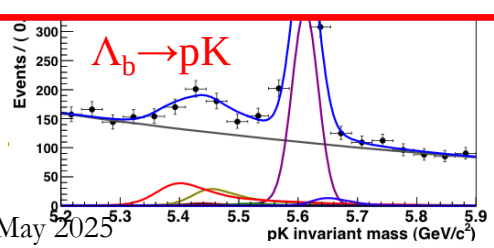


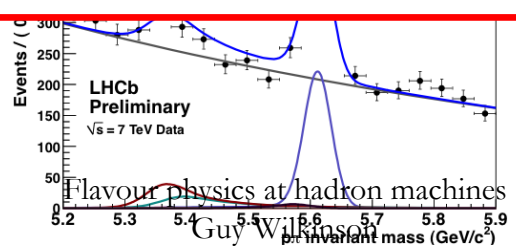
RICH in action

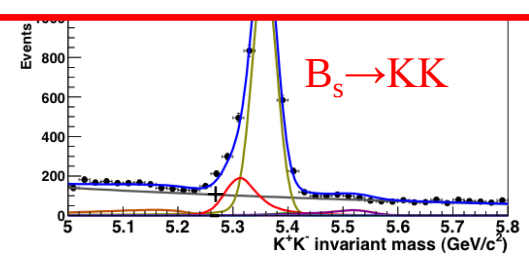
Two-body charmless B decays are central goal of LHCb physics.
Identical topologies require RICH to separate

Those plots were from early Run I data. Here are some more recent examples from Run II [JHEP 03 (2021) 075], with better control of background.

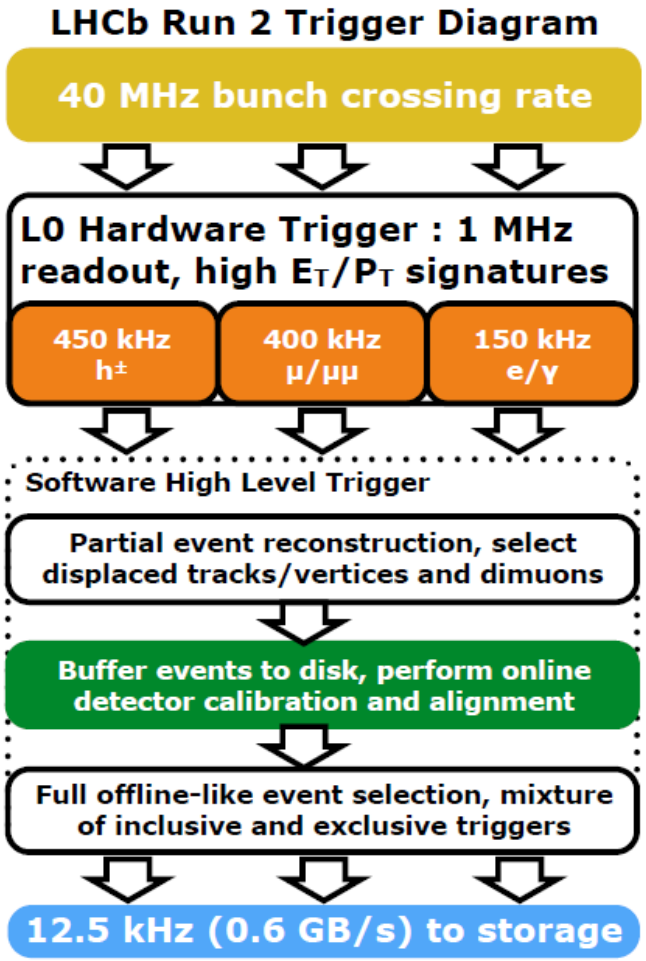








LHCb trigger – Run 2



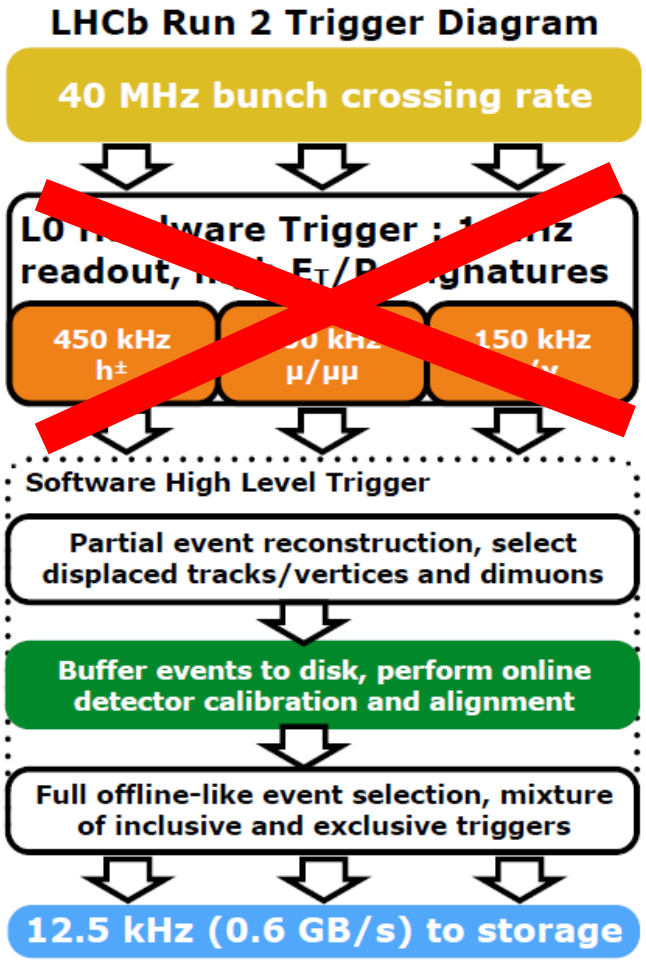
Guiding philosophy of LHCb experiment:

- Trigger at L0 on single 'high p_T' hadrons, muons, electrons and photons (high p_T in b-physics ~ few GeV/c). Not just di-muons !
- Access almost all b (& c) decays of interest
- Bandwidth (almost) fully devoted to flavour.

Approach works well up to 4 x 10^{32} $cm^{-2}s^{-1}$ (→ all results shown in these lectures), but saturates at higher luminosities.

How to gain an order of magnitude ?

LHCb trigger – Run 2



Guiding philosophy of LHCb experiment:

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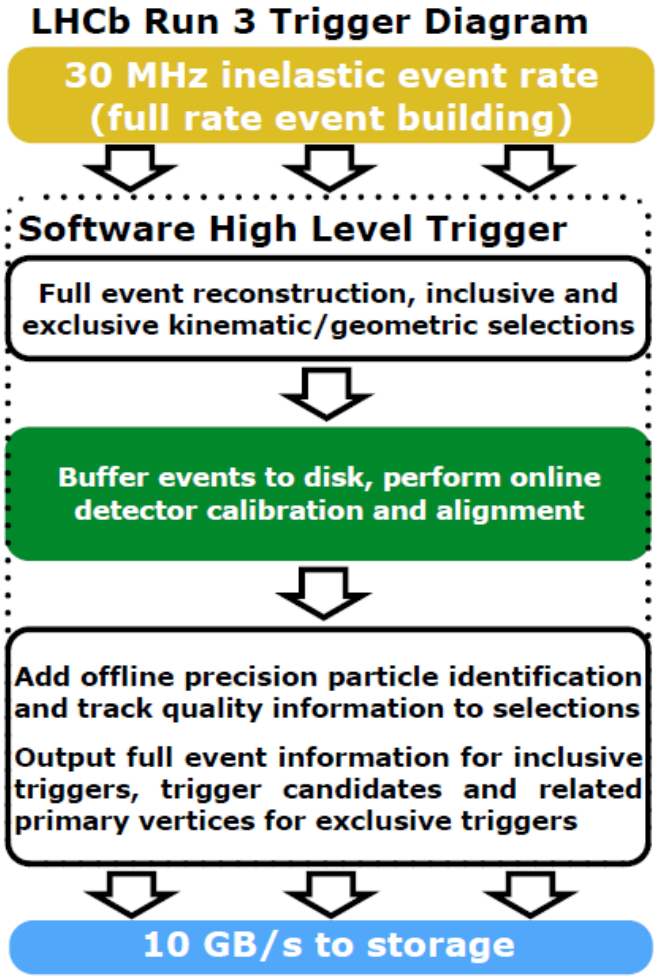
How to gain an order of magnitude ?

LHCb trigger – Runs 3 and 4



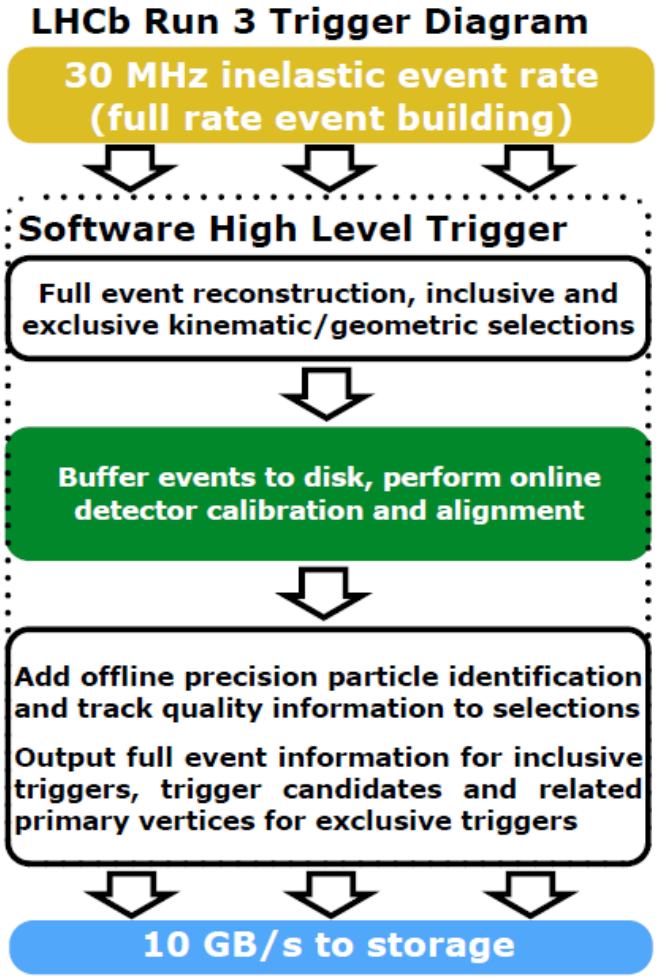
Moving software trigger to earliest stage (in GPUs) allows for:

- increased flexibility;
- increased efficiency in some modes;
- operation at 5x higher luminosity.

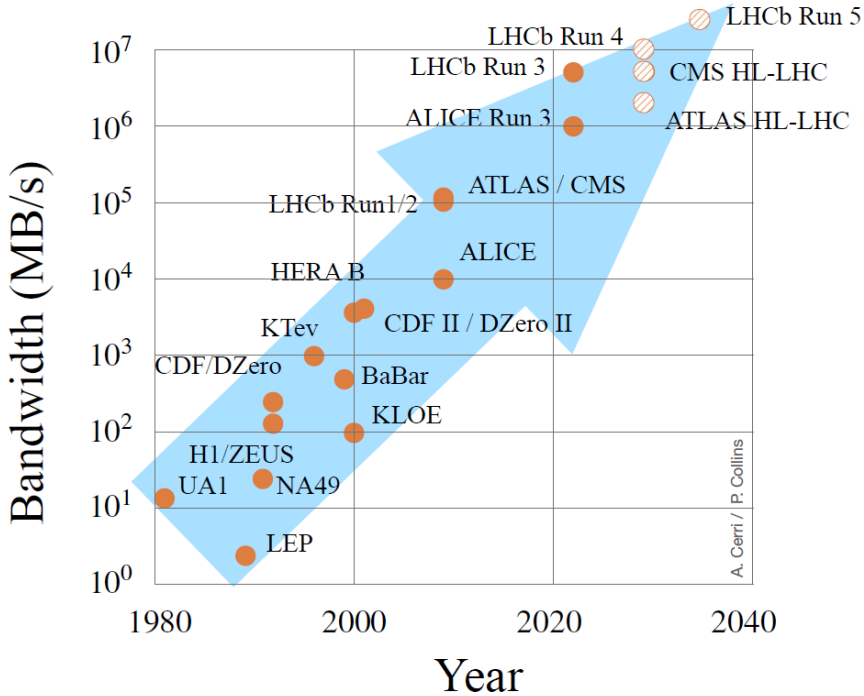
Retain feature, developed in Run 2, that events buffered on disk before final trigger decision (in CPUs) to allow for full offline-like quality ('real time analysis').

Significant fraction of events written out in reduced format, with no need for further processing ('turbo stream').

LHCb trigger – Runs 3 and 4



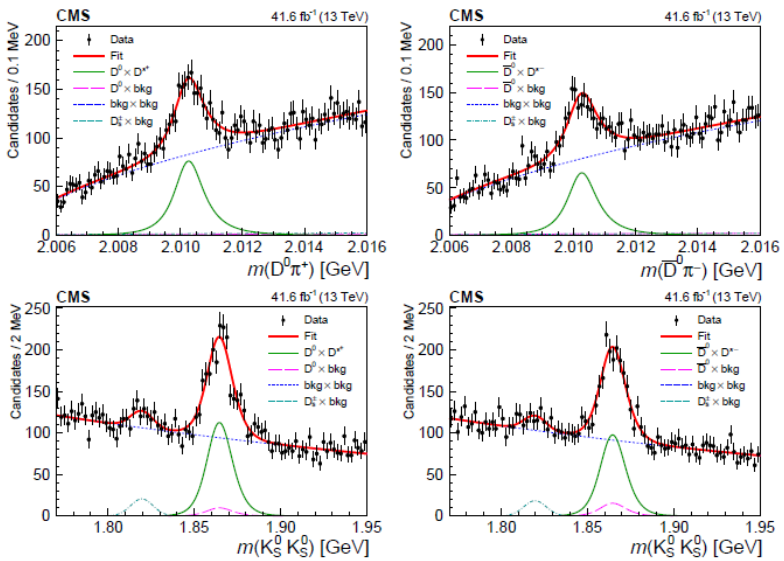
Data throughput – audacious !

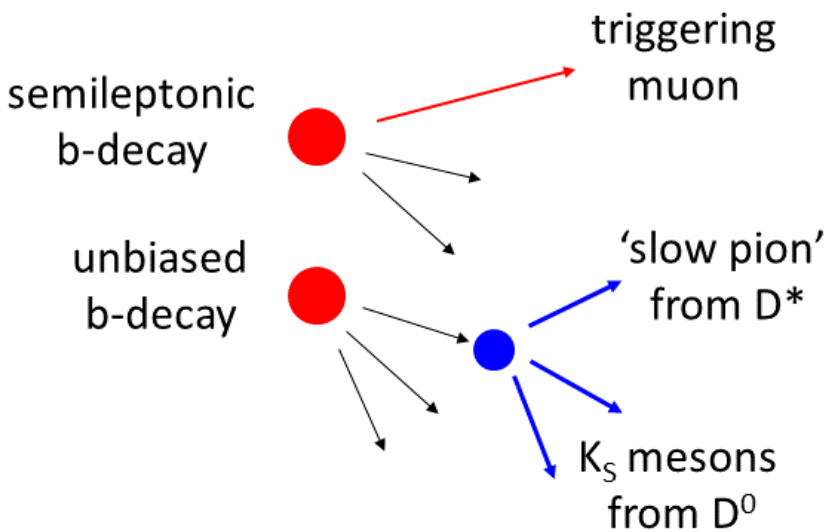


CMS – beyond dimuons

CMS now records 'B parking data' [Phys. Rept. 1115 (2025) 678]. Write out events with single muon from b-decay. Rates high, so process at end of run.

Unbiased source of decays from other B-hadron in event - opens wide analysis possibilities !





e.g. measurement of CP asymmetry in $D^0 \to K_S K_S$ [EPJC 84 (2024) 1264] .

Flavour Physics at Hadron Colliders

2) Unitarity Triangle metrology and CPV measurements

Unitarity Triangles(s)

The CKM matrix must be unitarity: $V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = 1$

This imposes various constraints, including $\sum_k V_{ik} V_{jk}^* = 0$ where $i \neq j$.

The are 6 such independent relations, which can be represented as **unitarity triangles** in the complex plane. Experimentally, the most interesting is:

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

As the sides are of similar length, & its parameters can be studied in B^0, B^+ decays.

Another, relevant for B^0_s physics is:

$$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$$

Note that the area of all triangles is the same = ½ *J*, the Jarlskog invariant.

$$J = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin\delta \approx 3 \times 10^{-5}$$

[Jarlskog, PRL 55 (1985) 1039]

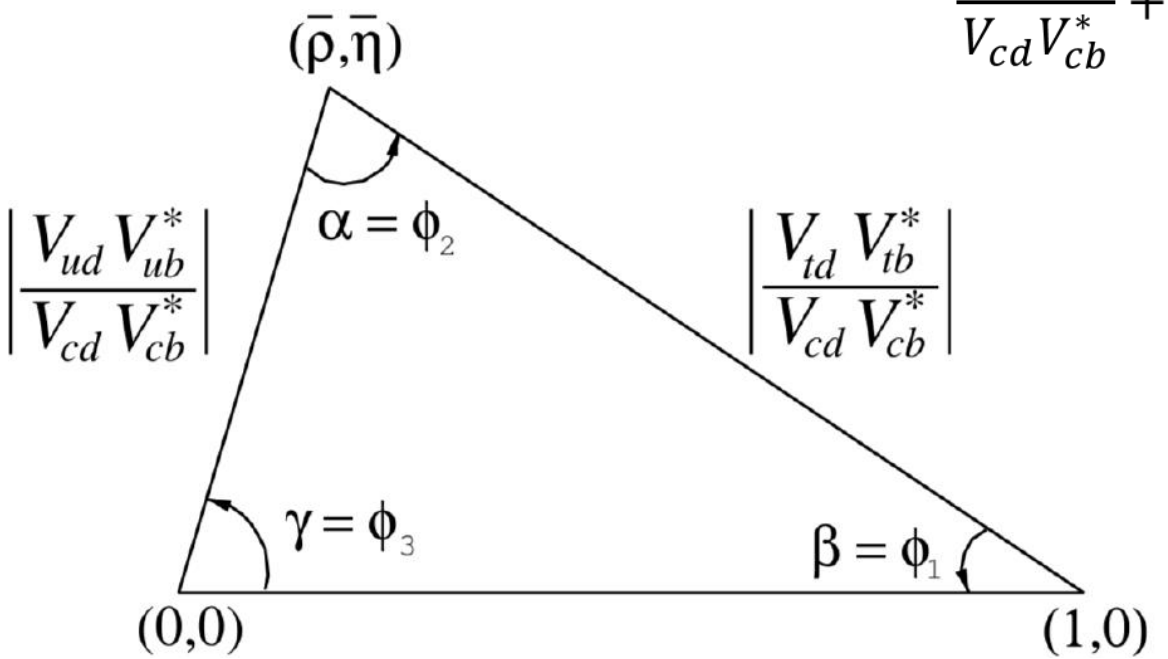
‘The’ Unitarity Triangle

Three complex vectors sum to zero

→ triangle in Argand plane

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$



Expressions for angles:

$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ub}V_{cb}^*}\right]$$

$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

Upper vertex: $\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$

$\bar{\rho} = \rho(1 - \lambda^2/2 + \cdots)$ $\bar{\eta} = \eta(1 - \lambda^2/2 + \cdots)$

(φ_2, φ_1 & φ_3 alternative notation)

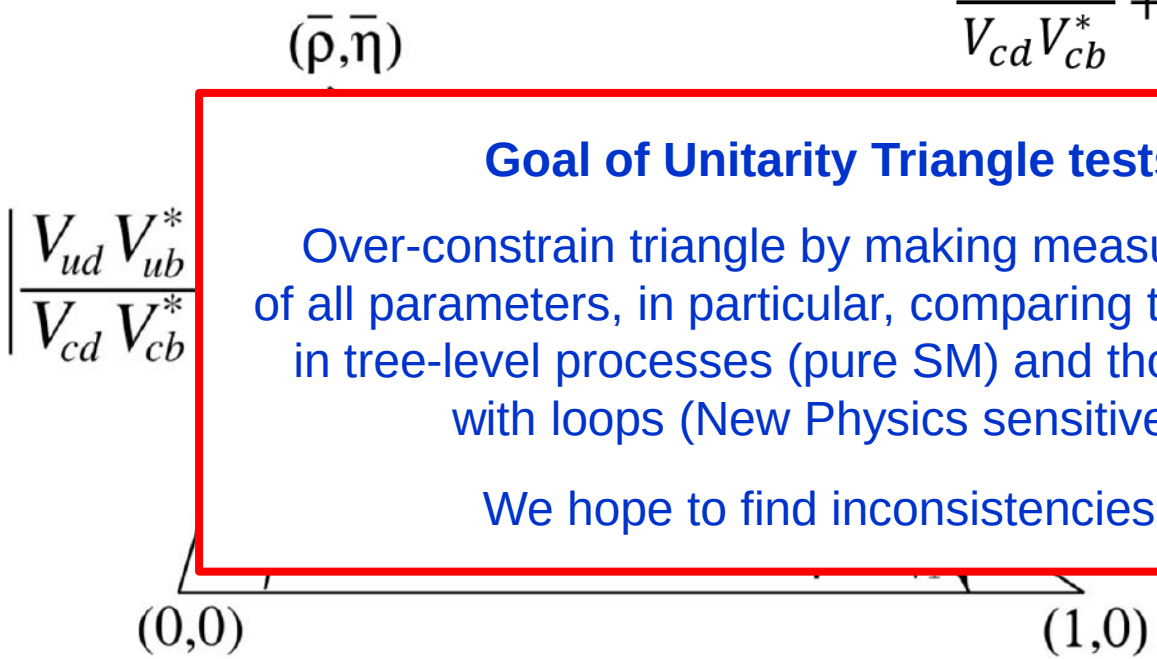
‘The’ Unitarity Triangle

Three complex vectors sum to zero

→ triangle in Argand plane

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$



Goal of Unitarity Triangle tests

Over-constrain triangle by making measurements of all parameters, in particular, comparing those made in tree-level processes (pure SM) and those made with loops (New Physics sensitive).

We hope to find inconsistencies !

for angles:

$$\left[-\frac{V_{td}V_{tb}^*}{V_{ub}V_{cb}^*}\right]$$

$$\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

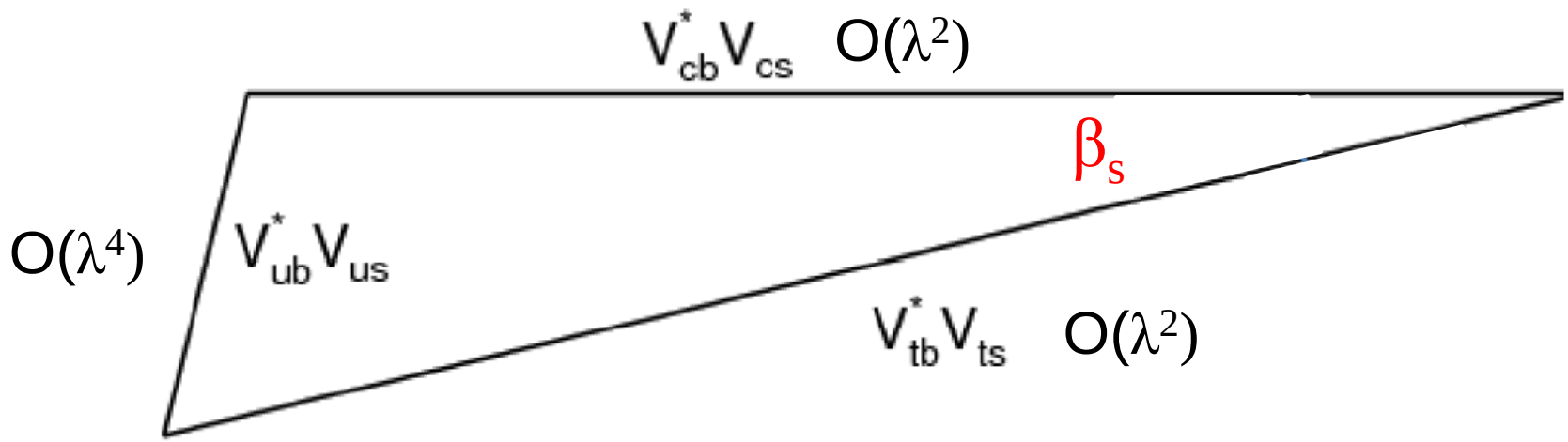
Upper vertex: $\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$

$\bar{\rho} = \rho(1-\lambda^2/2+\cdots)$ $\bar{\eta} = \eta(1-\lambda^2/2+\cdots)$

(φ_2, φ_1 & φ_3 alternative notation)

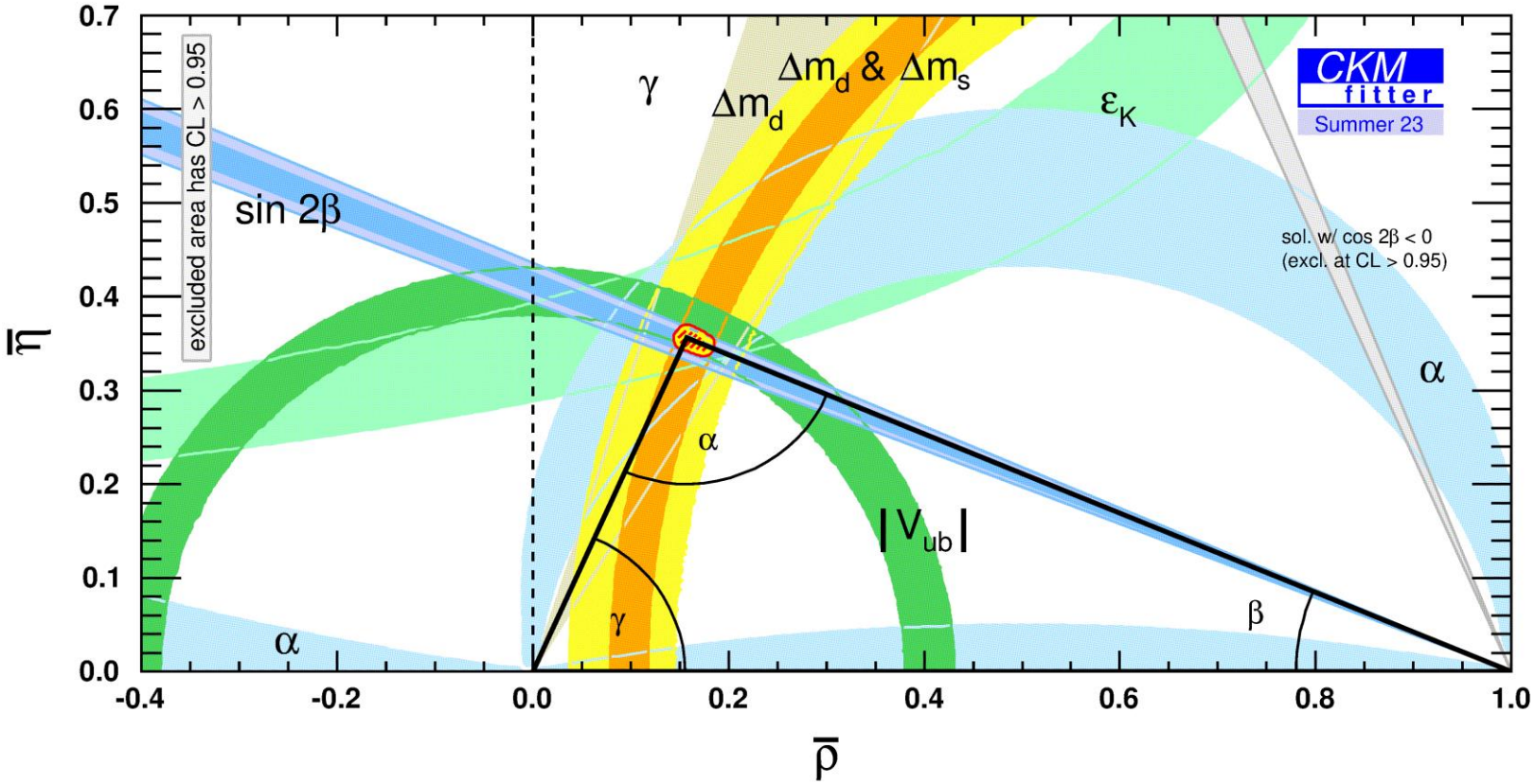
The B^0_s Unitarity Triangle

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



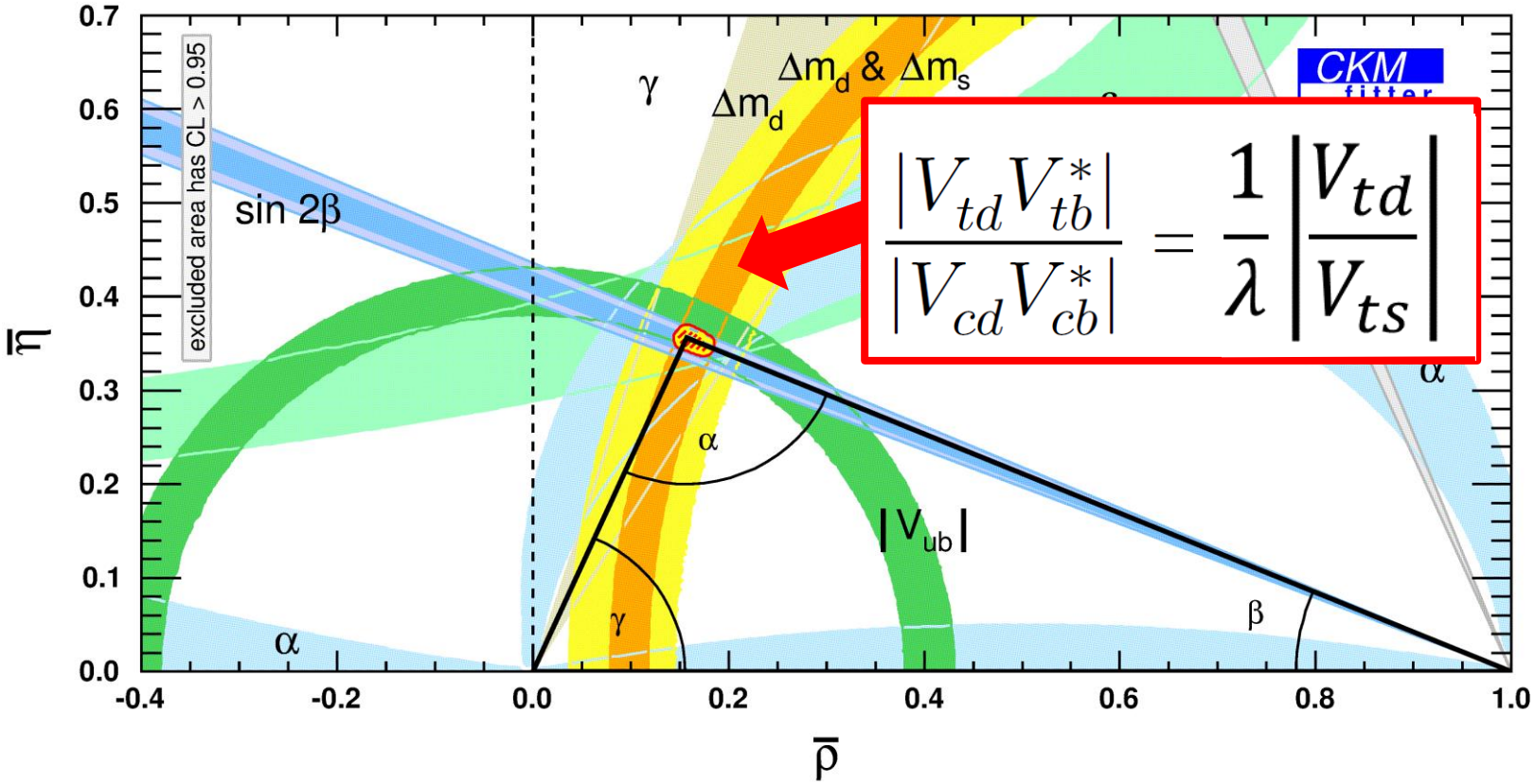
The B^0_s triangle is very squashed, & contains a small angle β_s (= $-\varphi_s/2$ – see later).

The Unitarity Triangle – CKM metrology at hadron machines



[CKMfitter, 2023]

The Unitarity Triangle – CKM metrology at hadron machines



$$\frac{|V_{td}V_{tb}^*|}{|V_{cd}V_{cb}^*|} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|$$

[CKMfitter, 2023]

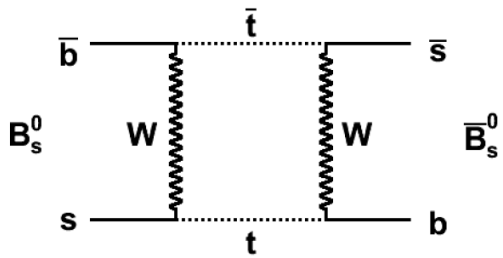
Length of side opposite γ is given by ratio of B^0 & B^0_s mixing freq.s & lattice QCD.

Neutral-meson mixing

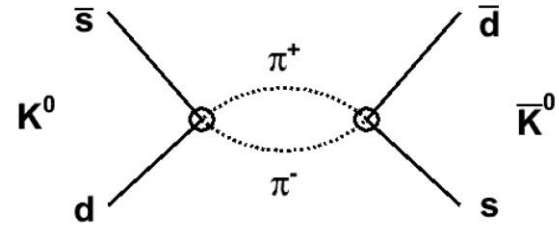
Mixing is critical for much of following discussion, so warrants a recap of essentials.

Phenomenon occurs for K^0, D^0, B^0 and B^0_s systems. Physically caused by either

Virtual, Short-range (box diagrams)



and/or



On-shell, long-range (common intermediate states)

Physical states are superposition of flavour eigenstates

Subscripts indicate Short or Long lived (see K^0 system); sometimes Heavy or Light used, or 1, 2.

$$B^0_{S,L} = pB^0 \pm q\overline{B^0}$$

p & *q* are complex and $|p|^2+|q|^2=1$

If CP is conserved the physical states = CP eigenstates, which means $\left|\frac{q}{p}\right| = 1$.

Known not to be the case in the K^0 system, where $\varepsilon = \frac{p-q}{q-p} \approx 2 \times 10^{-3}$, and the SM calculations indicate small, but finite, breaking in other systems too.

Mass and width splittings between physical states:

$$\Delta m = m_L - m_S$$

set by short-range effects

$$\Delta\Gamma = \Gamma_S - \Gamma_L$$

set by long-range effects

Neutral-meson mixing

There is a wide range in the sizes of the mixing parameters across the four systems, which has significant practical consequences for measurements.

	$\Delta m / \Gamma$		$\Delta\Gamma/2\Gamma$	
K^0	Large	~500	Maximal	~1
D^0	Small	0.39 ± 0.11 %	Small	0.65 ± 0.06%
B^0	Medium	0.769 ± 0.004	Small	$(20 \pm 5) \times 10^{-4}$
B^0_s	Large	26.81 ± 0.08	Medium	0.0675 ± 0.004

Refs: PDG, HFLAV and [Lenz & Nierste, JHEP 0706 (2007) 072]

Size of mixing effects is highly sensitive to SM parameters (CKM elements, GIM mechanism, quark masses…) and could easily be perturbed by New Physics. Indeed, mixing can be used to set severe bounds (~10^3 TeV) on most general forms of New Physics models (see *e.g.* [Nir arXiv:1605.00433]).

Neutral-meson mixing

Mixing leads to an oscillation of probability to observe meson in either flavour eigenstate with proper time, *e.g.* if at t=0 we have a B^0, then at later time t:

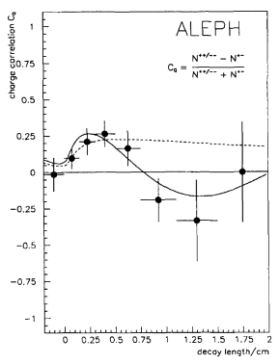
Prob. to decay as $\begin{matrix}\overline{B}^0 \\ B^0\end{matrix} \propto e^{-\Gamma_d t}(1 \mp \cos \Delta m_d\, t)$

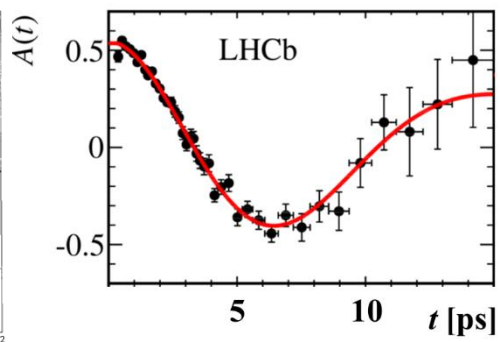
Time-integrated B-oscillations were first observed by UA1 [PLB 186 (1987) 247] & ARGUS [PLB 192 (1987) 245]. B^0 (B^0_s) oscillations first resolved by ALEPH (CDF).

B^0 discovery → state-of-the-art

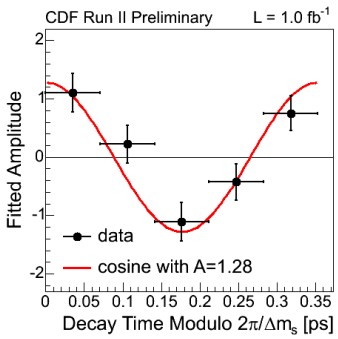
B^0_s discovery → state-of-the-art

[PLB 313 (1993) 498]

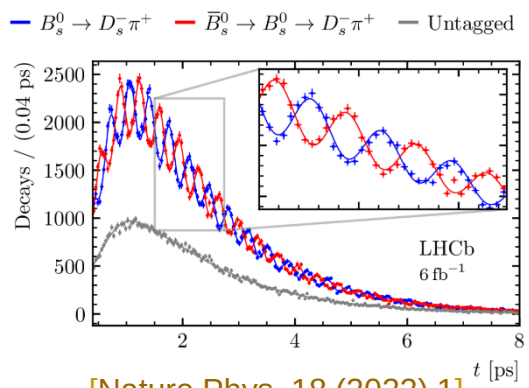




[EPJC 76 (2016) 412]



[PRL 97 (2006) 242003]

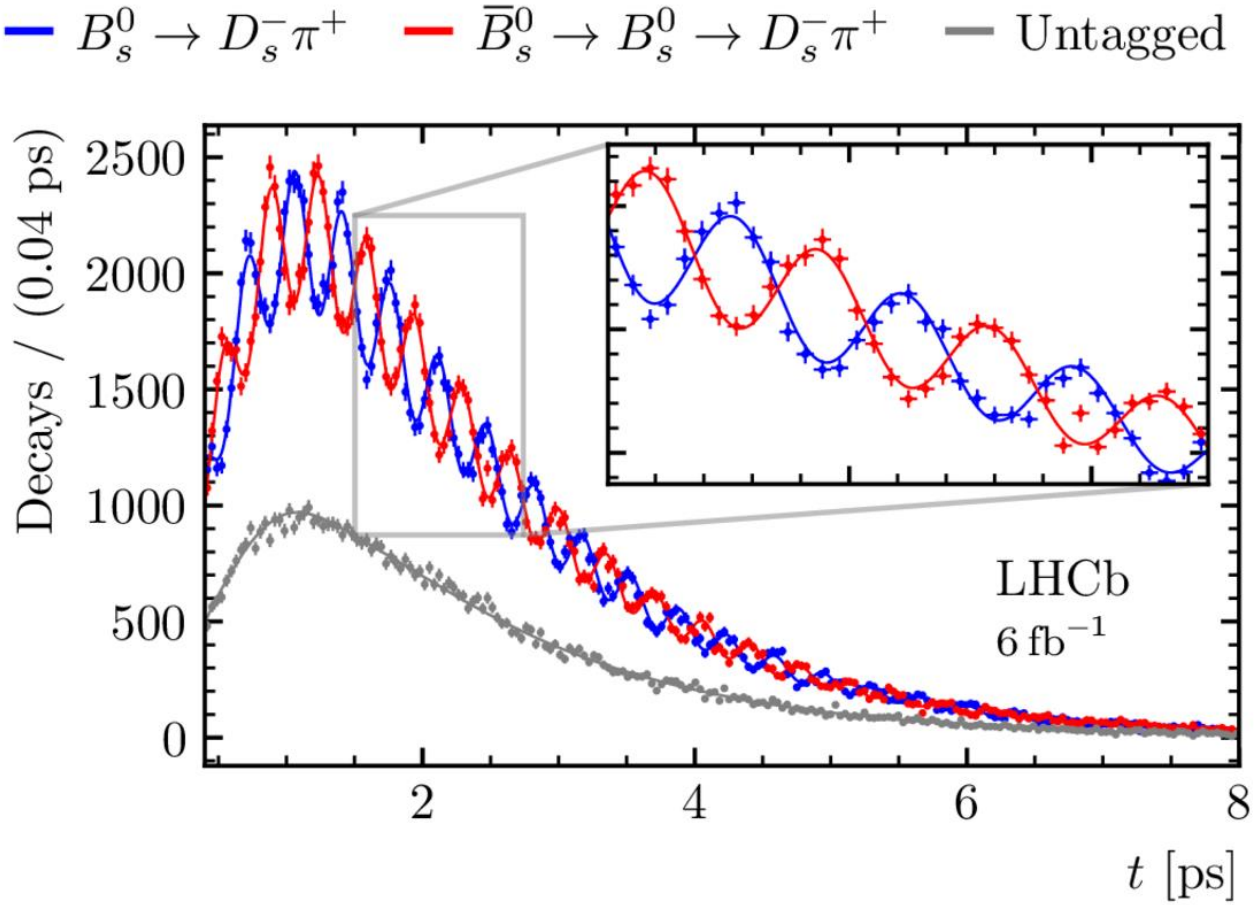


[Nature Phys. 18 (2022) 1]

State-of-the-art measurements in both B^0 and B^0_s systems are from LHCb.

B^0_s mixing – a closer look at that plot

B^0_s-mixing studies impossible at B-factories, due to E_{CM} & frequency of oscillations.

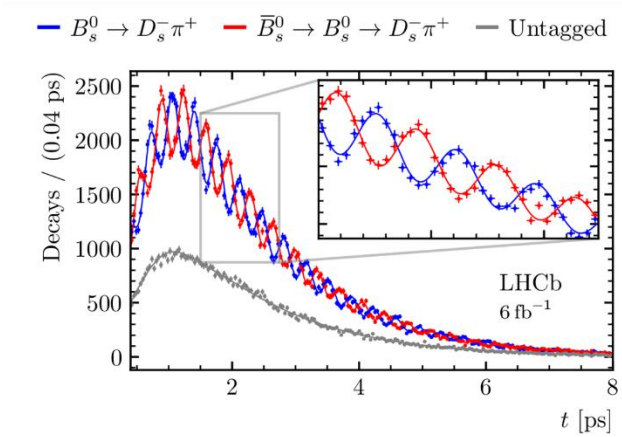


[Nature Phys. 18 (2022) 1]

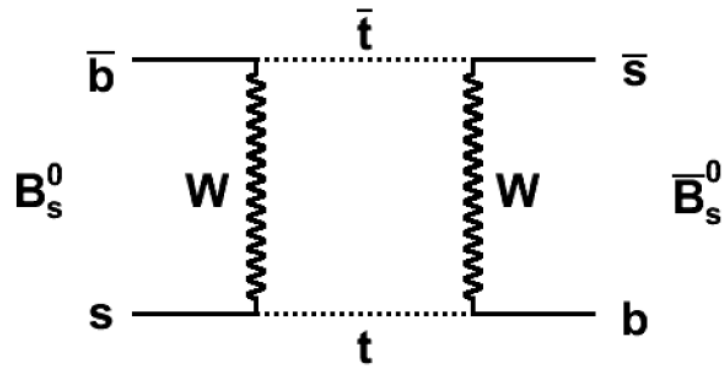
B^0_s studies are only possible at hadron machines (and at FCC-ee, but that's another story). Require significant boost and excellent proper-time resolution.

$B^0_{(s)}$-$\bar{B}^0_{(s)}$ mixing – accessing CKM elements

In B^0 and B^0_s systems, mixing driven by $\Delta m_{d(s)}$ and is calculable in SM.



[Nature Phys. 18 (2022) 1]



Depends on CKM elements in box & factors that can be calculated in lattice QCD.

For B^0_s case →

$$\Delta m_s = \frac{G_F^2}{6\pi^2} m_{B_s} m_W^2 \eta_B S_0(x_t) f_{B_s}^2 B_s \left|V_{ts} V_{tb}^*\right|^2$$

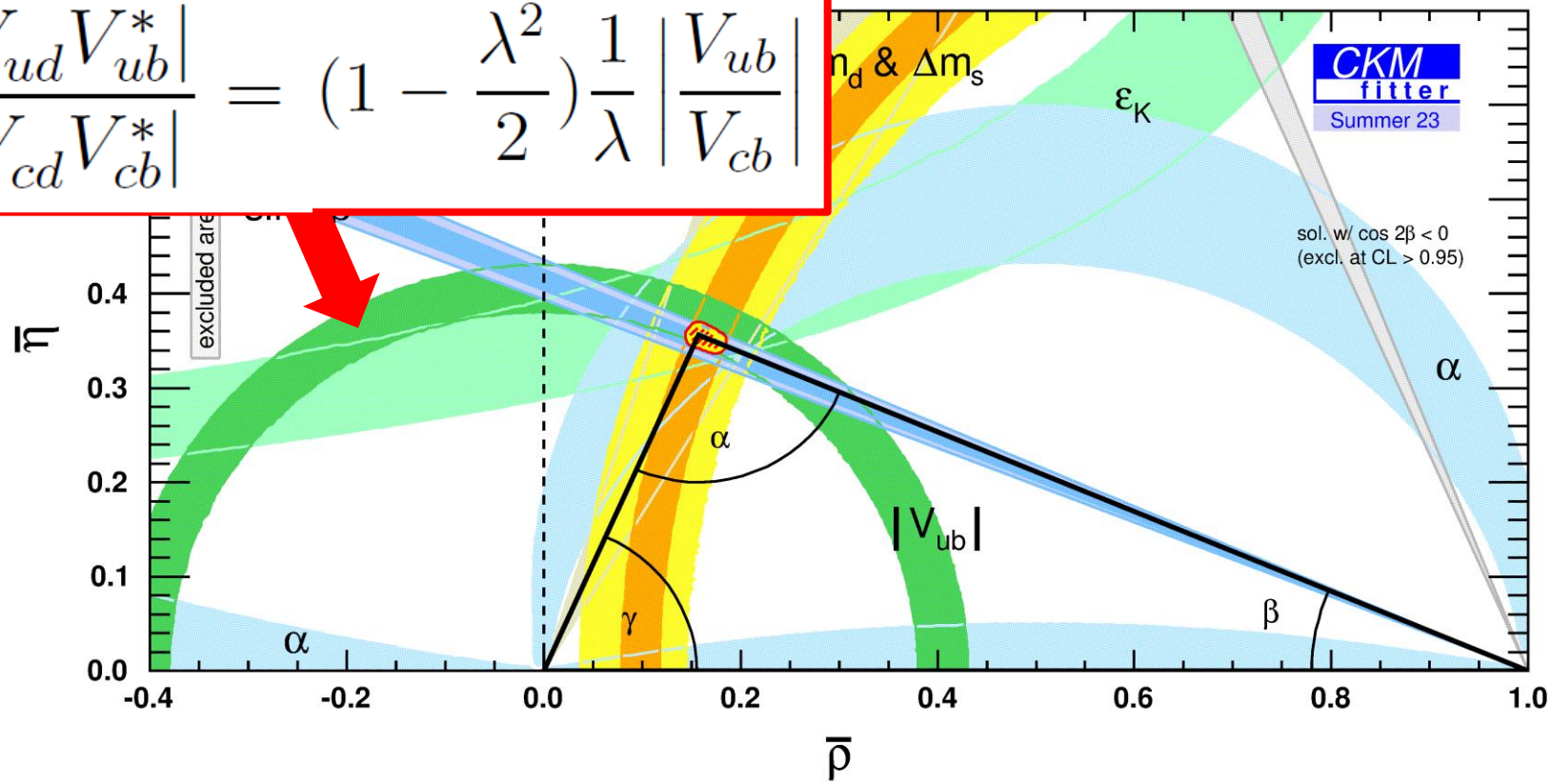
Equivalent expression for B^0 mixing, involving V_{td}. Ratio of frequencies is then

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{Bd}}{m_{Bs}} \xi_{\Delta m}^{-2} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$\zeta_{\Delta m}$, being a ratio of QCD factors of value close to 1 can be calculated to a few % in lattice QCD, hence giving access to $|V_{td}|/|V_{ts}|$. Experimental inputs dominated by LHCb, but it is lattice inputs that limit precision.

The Unitarity Triangle - CKM metrology at hadron machines

$$\frac{|V_{ud}V_{ub}^*|}{|V_{cd}V_{cb}^*|} = (1-\frac{\lambda^2}{2})\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$



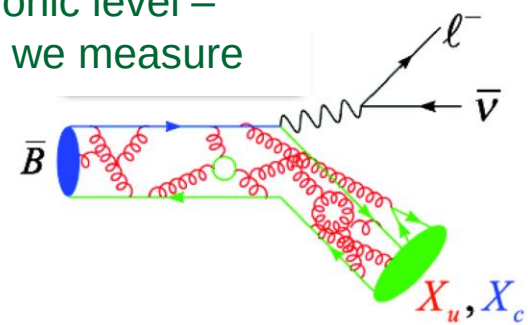
[CKMfitter, 2023]

Length of side opposite β is given by measuring $|V_{ub}|/|V_{cb}|$ from ratio b→u / b→c.

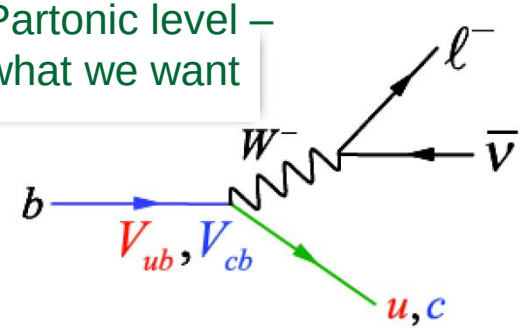
Measuring $|V_{ub}|/|V_{cb}|$

We can measure the ratio of b→ulv to b→clv processes at hadron level, but then must use theory or lattice QCD to correct back to quark level.

Hadronic level – what we measure



Partonic level – what we want



Two broad strategies followed:

- Inclusive $b \to X_u l\nu$, using *e.g.* endpoint of p_l spectrum to isolate signal from $b \to X_c l\nu$

$$|V_{ub}| = (4.12 \pm 0.26) \times 10^{-3}$$ [2024 PDG review]

- Exclusive, *e.g.* $B \to \pi l\nu$. But then need calculation of hadronic form factor.

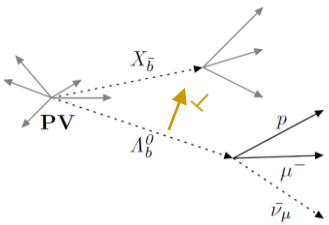
$$|V_{ub}| = (3.67 \pm 0.15) \times 10^{-3}$$ [2024 PDG review]

There is tension between these two numbers at the ~2 σ level, and a similar but worse issue with $|V_{cb}|$, which means that caution is needed when using results in UT.

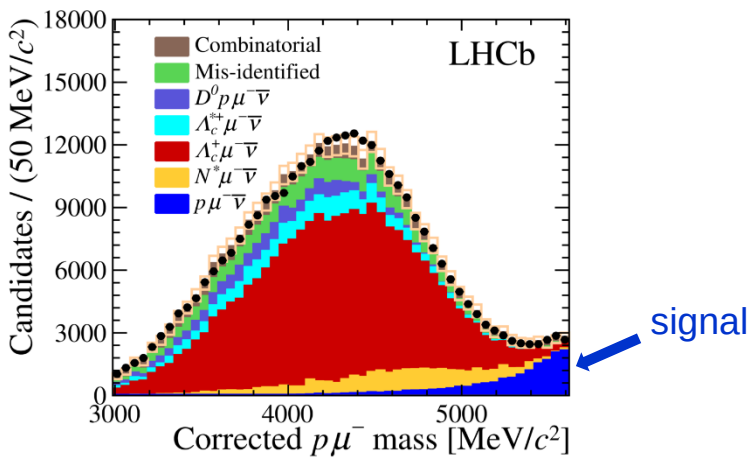
Semileptonic studies at the LHC

The e^+e^- environment is a natural laboratory for these studies, as the neutrino and backgrounds make life much more challenging at the LHC (inclusive measurements Impossible). But there are ways in which the LHC can make a unique contribution.

e.g. measurement of $|V_{ub}|$ from $\Lambda_b \to p\mu\upsilon$ decays, or more correctly $|V_{ub}|/|V_{cb}|$ through normalising the rate of these decays to those of $\Lambda_b \to \Lambda_c\mu\upsilon$ [Nature Phys. 11 (2015) 743].



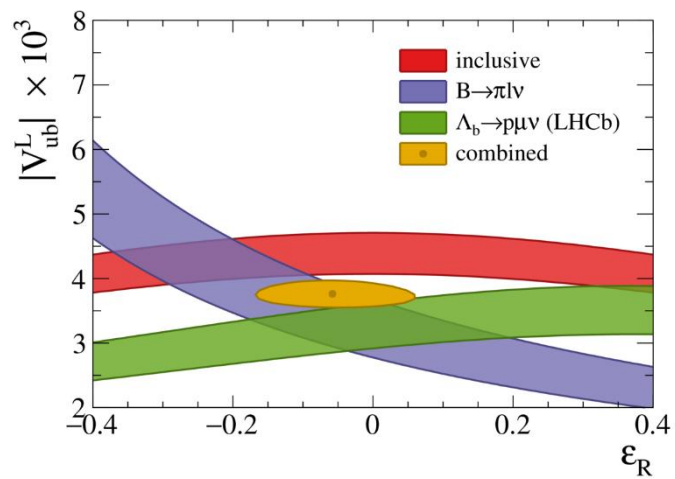
$$m_{\text{corr}} = \sqrt{m_{p\mu}^2 + p_\perp^2} + p_\perp$$



$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

expt. lattice

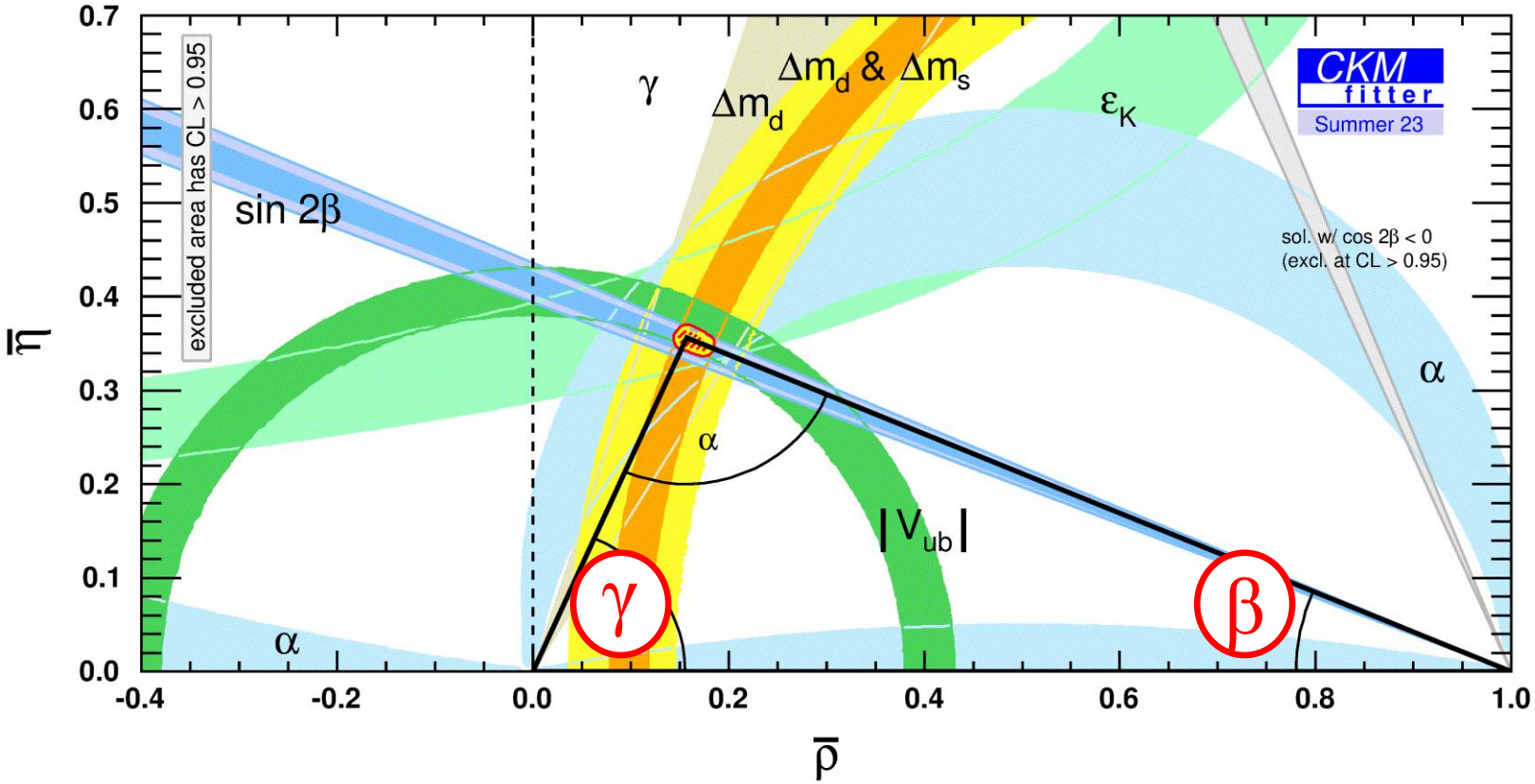
Very valuable complementary measurement as spin of Λ_b and proton brings additional info.



Helpful in *e.g.* excluding right-handed coupling invoked to explain inclusive vs exclusive tension.

Similarly, one can exploit B_s decays, *e.g.* $|V_{ub}|/|V_{cb}|$ in $B_s \to K\mu\upsilon$ [PRL 126 (2021) 081804].

The Unitarity Triangle: CP-violation measurements at hadron machines



[CKMfitter, 2023]

Now we will discuss the CPV measurements that access the angles β and γ.*

* Why not discuss α? Any α-related observable involves the same quark transitions as are probed in β and γ studies, so it is unlikely to tell us anything more. But improved measurements are always worthwhile !

Decays into CP eigenstates: $B^0 \to J/\psi K_S$

Potential for clean measurement of substantial CPV in B system first appreciated in early 1980s: [Carter and Sanda, PRD 23 (1981) 1567], [Bigi and Sanda, NPB 193 (1981) 85].

Incidentally, someone who was amongst the first to realise the potential of b-hadrons in CPV studies, and one responsible for a seminal paper, has since followed a very different career…

Obama-era U.S. defense secretary toasts the latest CP-violation results from LHCb

*

>1000 citations

PHYSICAL REVIEW D VOLUME 23, NUMBER 7 1 APRIL 1981

***CP* violation in *B*-meson decays**

Ashton B. Carter and A. I. Sanda
The Rockefeller University, New York, New York 10021
(Received 27 June 1980)

The pattern of *CP* violation in the bottom sector is discussed. We introduce general techniques to expose new *CP*-violating effects in the cascade decays of *B* mesons. In the Kobayashi-Maskawa (KM) model, the *CP* asymmetries so obtained range from 2–20 % for plausible values of the model parameters. This is to be compared with the small effects, of order 10^{-3}–10^{-4}, previously exhibited within this model. Effects of this size should be observable in upcoming experiments. Our approach stresses the on-shell transitions which make up the cascade decays of heavy mesons to ordinary hadrons, as opposed to the off-shell transitions which occur in the analogs of K^0-$\bar{K}^0$ mixing. The *CP* asymmetries generated by our techniques are of order $\sin\delta$, where δ is the KM phase angle, and thus represent the maximum effects obtainable in this model.

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Current U.S. defense secretary – no known interest in CP violation

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$$\Gamma\left(B^0_{phys} \to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$
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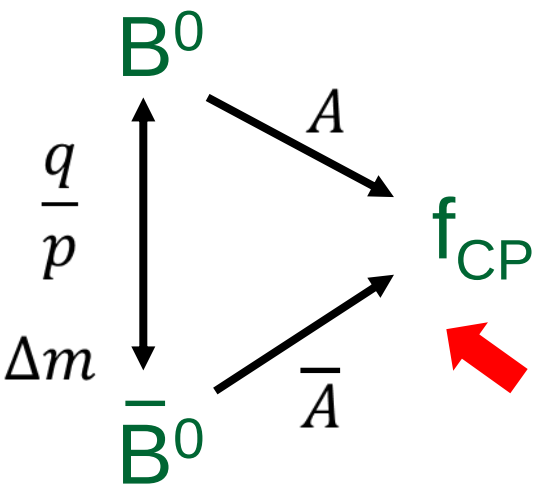

$$S = \frac{2\Im(\lambda_{CP})}{1+\left|\lambda^2_{CP}\right|} \qquad C = \frac{1-\left|\lambda^2_{CP}\right|}{1+\left|\lambda^2_{CP}\right|} \qquad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

Key point: to observe a complex phase we need to have two (or more) interfering amplitudes, as here

* These expressions assumes width-splitting $\Delta\Gamma=0$, which is an excellent approximation in B^0 system.

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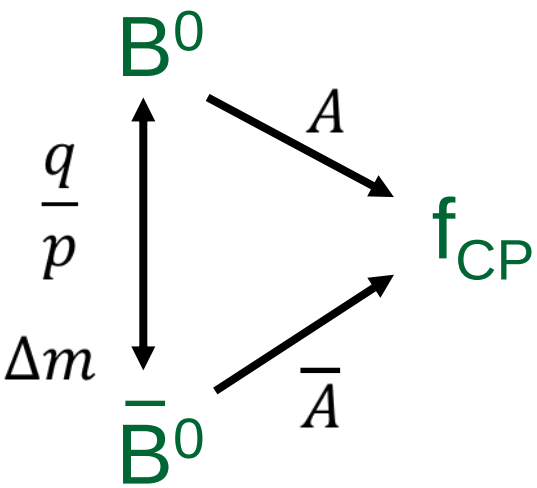

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There are three ways that CP violation can appear:

CPV in the decay (or 'direct CPV').

$$\boxed{|A| \neq |\overline{A}|}$$

(This is also the only possibility that applies for charged hadron decays, for instance in the measurement of γ.)

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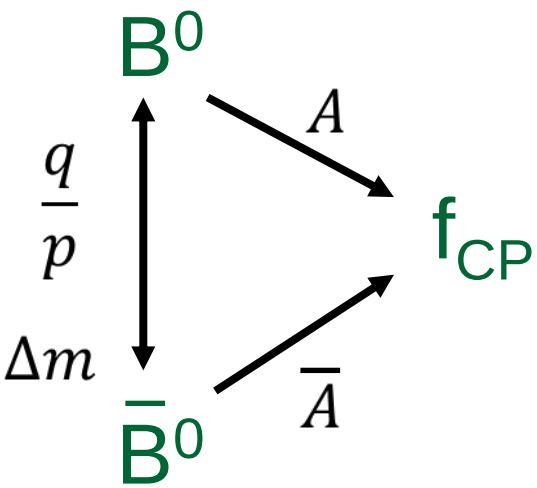

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There are three ways that CP violation can appear:

CPV in the mixing (one category of so-called 'indirect CPV').

Occurs if there are different ways to oscillate $B^0 \leftrightarrow B^0$bar. In SM very small.

$$\boxed{\left|\frac{q}{p}\right| \neq 1}$$

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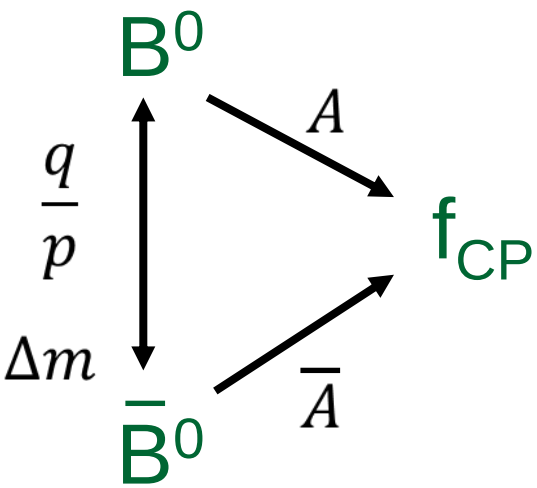
*



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There are three ways that CP violation can appear:

CPV in mixing-decay interference (also a category of 'indirect CPV', & the most relevant in the B^0B^0bar and $B^0_sB^0_s$bar systems).

$$\boxed{\mathrm{Im}\lambda_{CP} \neq 0}$$

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Decays into CP eigenstates: $B^0 \to J/\psi K_S$

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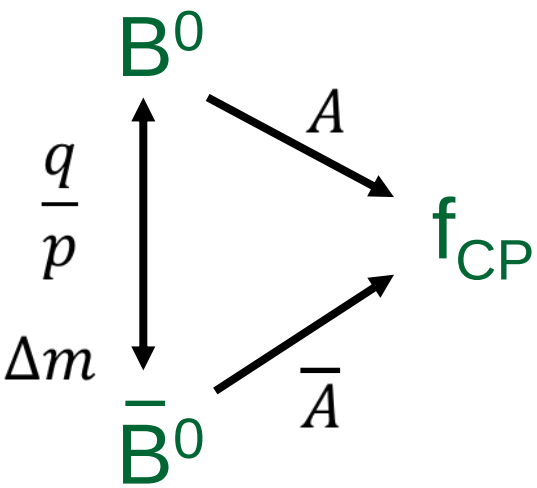

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Consider the classic case $B^0 \to J/\psi K_S$:

- Compared to the CPV signal we are expecting in B physics, we can treat K_S as a CP eigenstate.
- And in this decay C≈0, with no significant direct CPV (all the CPV comes from *mixing-decay interference*).

NB both these assumptions can be checked / corrected for.

* These expressions assumes width-splitting ΔΓ=0, which is an excellent approximation in B^0 system.

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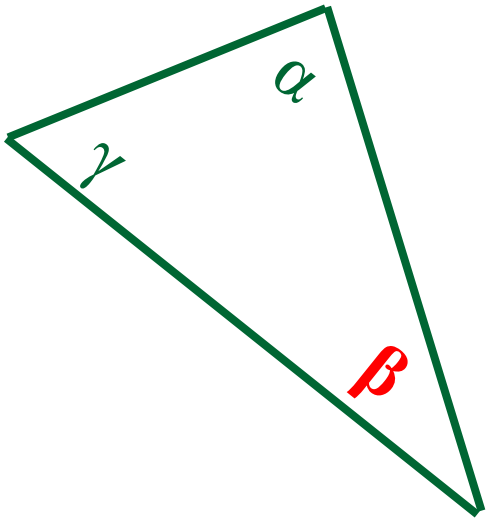

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$$\lambda_{J/\psi K_S} = \frac{V^*_{tb}V_{td}V_{cb}V^*_{cs}}{V_{tb}V^*_{td}V^*_{cb}V_{cs}} = e^{i2\beta} \qquad \mathrm{Im}\,\lambda_{J/\psi K_S} = \sin 2\beta$$

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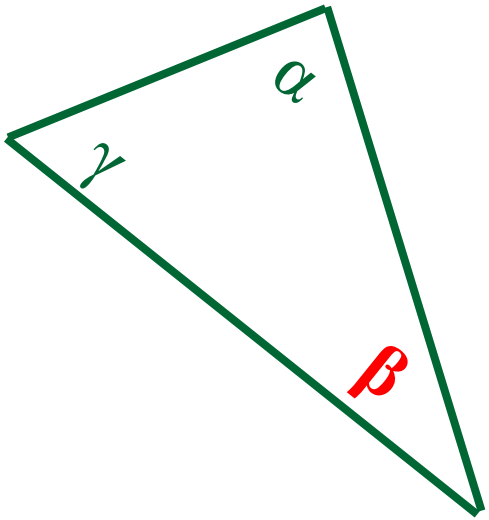

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In practice we measure a *t*-dependent CP asymmetry:

$$a_{CP}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$
$$= \sin 2\beta \ \sin(\Delta m\, t)$$

This is theoretically ***clean*** !
(at least, at current precision)

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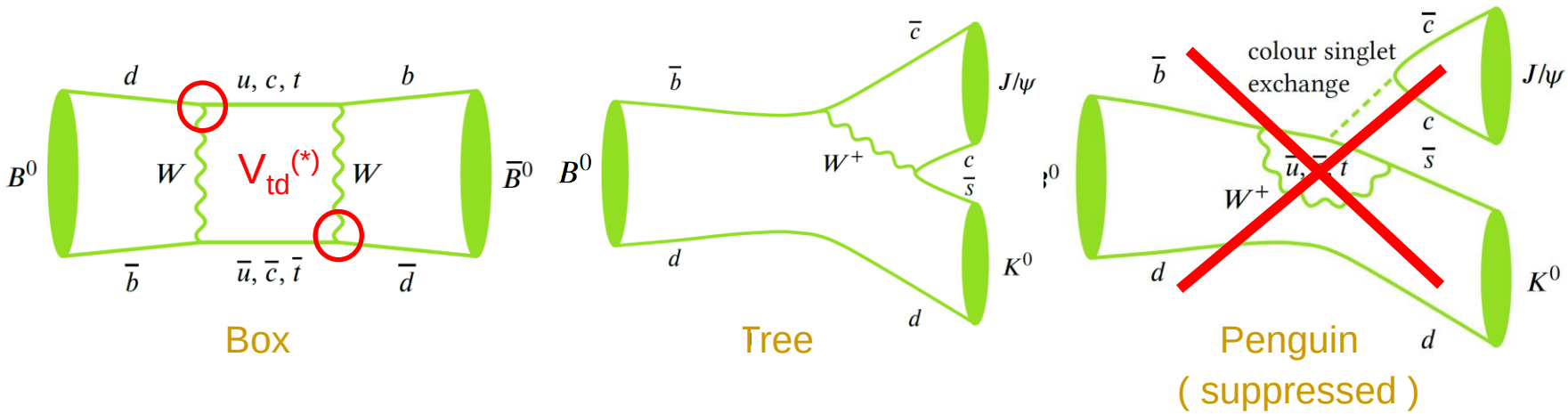
To reiterate, measurement probes interference between box and tree diagrams:



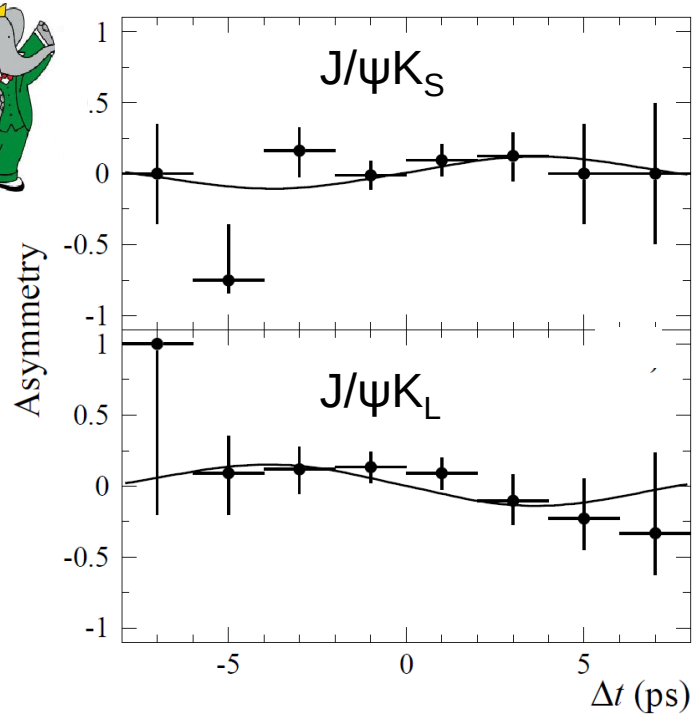
Sensitive to any CP violating phases in either, but are only expected in the box. In the SM this comes from the phase difference associated with V_{td} , but could arise from other sources through New Physics. So possible $\sin 2\beta_{meas} \neq \sin 2\beta_{SM}$!

* These expressions assumes width-splitting $\Delta\Gamma=0$, which is an excellent approximation in B^0 system.

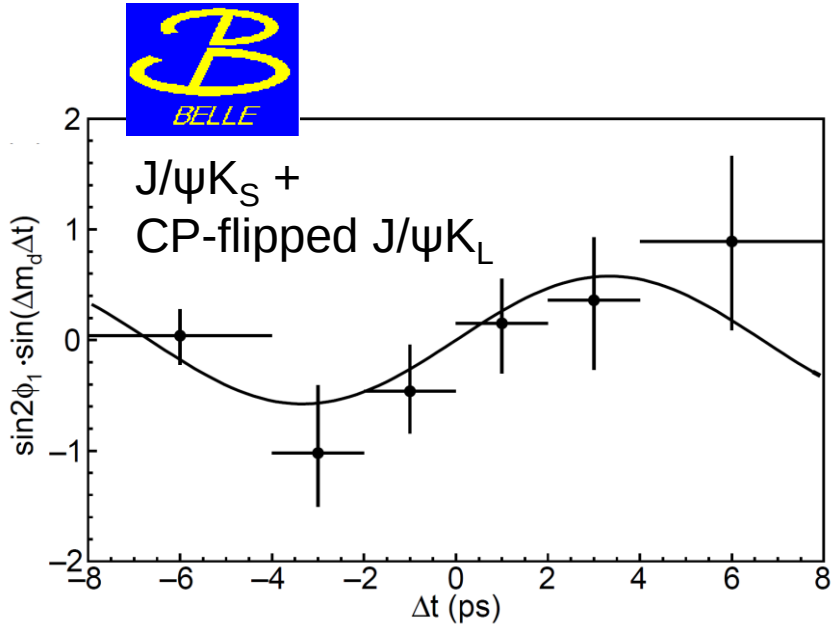
2001 – (the start of) a flavour odyssey

2008 Nobel Prize

Modern flavour physics began at the B factories with the 2001 measurements of the CP-violating asymmetry in $B^0 \to J/\psi K^0$ decays that give unitarity triangle angle β.



[BaBar, PRL 86 (2001) 2515]



[Belle, PRL 86 (2001) 2509]

These studies, when improved with larger samples, confirmed the CKM paradigm as the dominant mechanism of CP violation in nature (→ 2008 Nobel Prize), and also opened up a rich and wide spectrum of complementary measurements.

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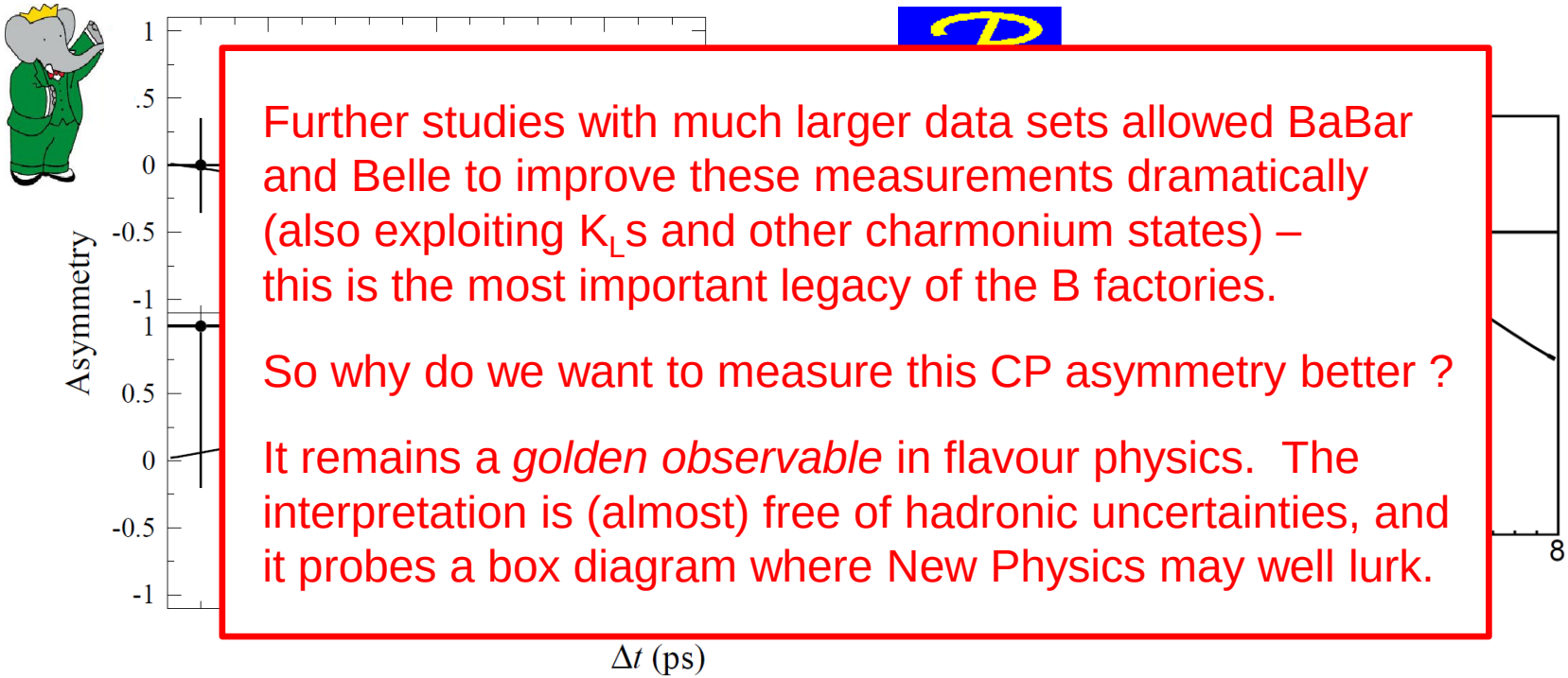

Further studies with much larger data sets allowed BaBar and Belle to improve these measurements dramatically (also exploiting K_Ls and other charmonium states) – this is the most important legacy of the B factories.

So why do we want to measure this CP asymmetry better ?

It remains a *golden observable* in flavour physics. The interpretation is (almost) free of hadronic uncertainties, and it probes a box diagram where New Physics may well lurk.

[BaBar, PRL 86 (2001) 2515] [Belle, PRL 86 (2001) 2509]

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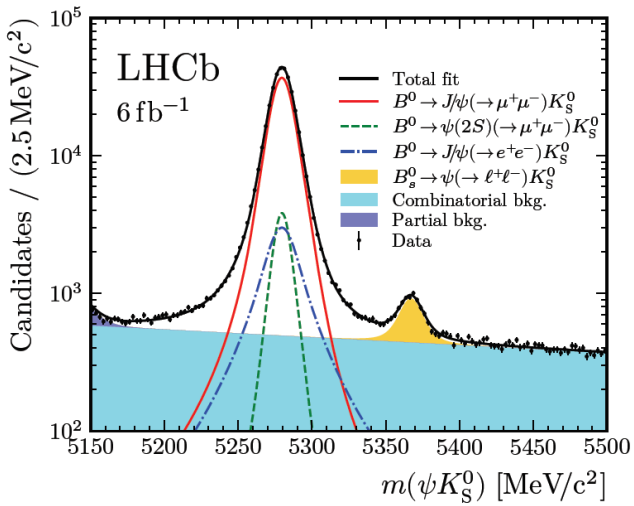
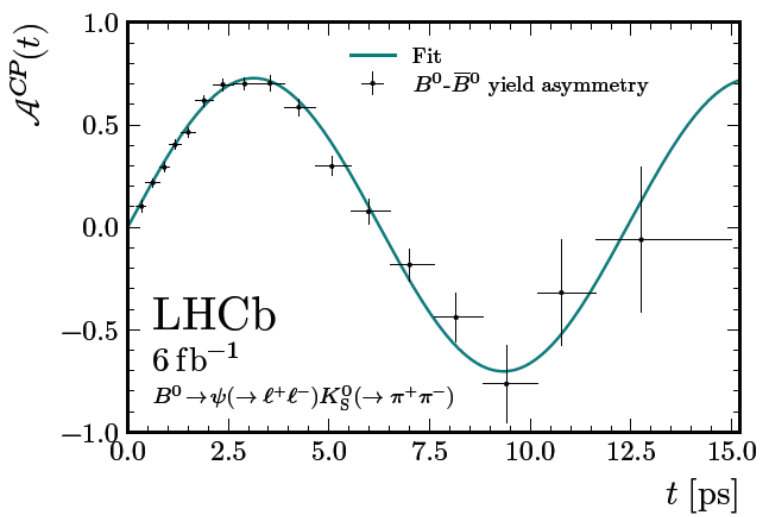
$B^0 \to J/\psi K_S$: LHCb comes to the party

Last year LHCb announced a Run 2 measurement of sin2β using $B^0 \to \psi K_S$ (J/ψ, $\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$) decays [PRL 132 (2024) 021801], which augments results from Run 1 [PRL 115 (2015) 031601, JHEP 11 (2017) 170] .





Combined result:

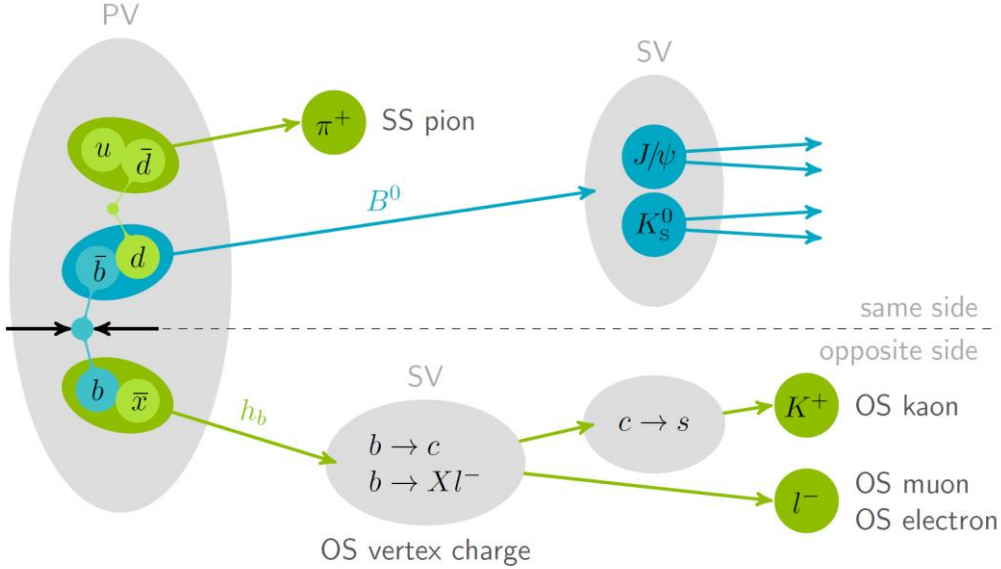
Sine coefficient	=	0.723 ± 0.014
Cosine coefficient	=	0.007 ± 0.012

As no evidence yet of direct CPV, can interpret sine coefficient as sin2β.

Now more precise than B factories ! Very large sample sizes (*e.g.* $B^0 \to J/\psi(\mu\mu)K_S$: LHCb: 420k, BaBar ~10k offsets challenges in flavour tagging at *pp* machine)

Flavour tagging at a hadron collider

Measurement demands we know whether decaying meson was B^0 or B^0bar at birth. This requires *flavour tagging* *. Look at either decay products of the other b-hadron ('opposite sign') or for fragmentation products associated with signal B ('same sign').



Flavour tag decision can be wrong, either through misidentification of mixing of OS b-hadron. This leads to *dilution* of asymmetry, and reduces effective signal statistics by a large factor (up to x ~1/30) at hadron collider experiments.

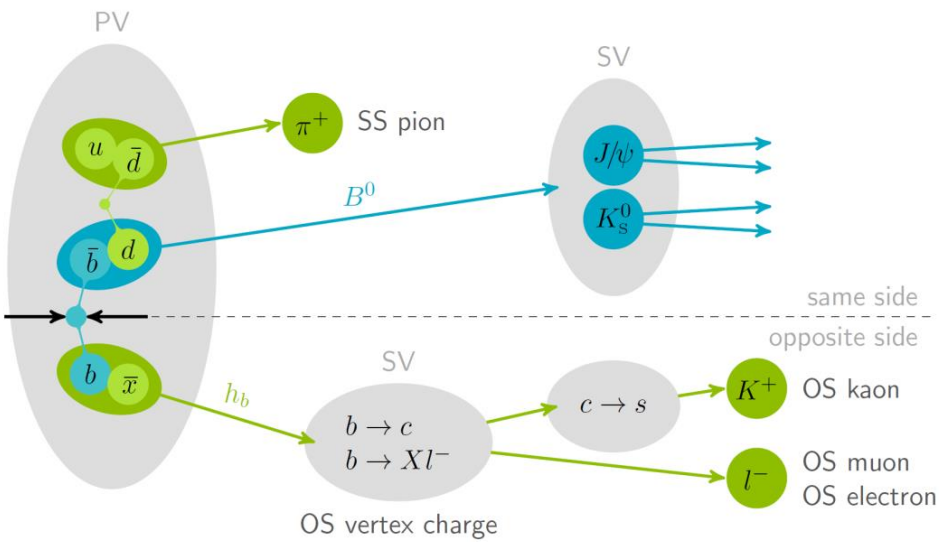
For *t* variable in asymmetry, we need to know proper time between birth & death of signal B, which at LHC is related to distance between primary and decay vertices.

* NB in high-p_T physics the term 'flavour tagging' means something different, typically 'is this jet b-like or c-like ?'.

Flavour tagging at a hadron collider

Effective tagging efficiency, or power, for a single tag is $\varepsilon_{\text{tag}}(1-2\omega_{\text{tag}})^2$ with ε_{tag} the tagging efficiency, ω_{tag} the mistag probability.

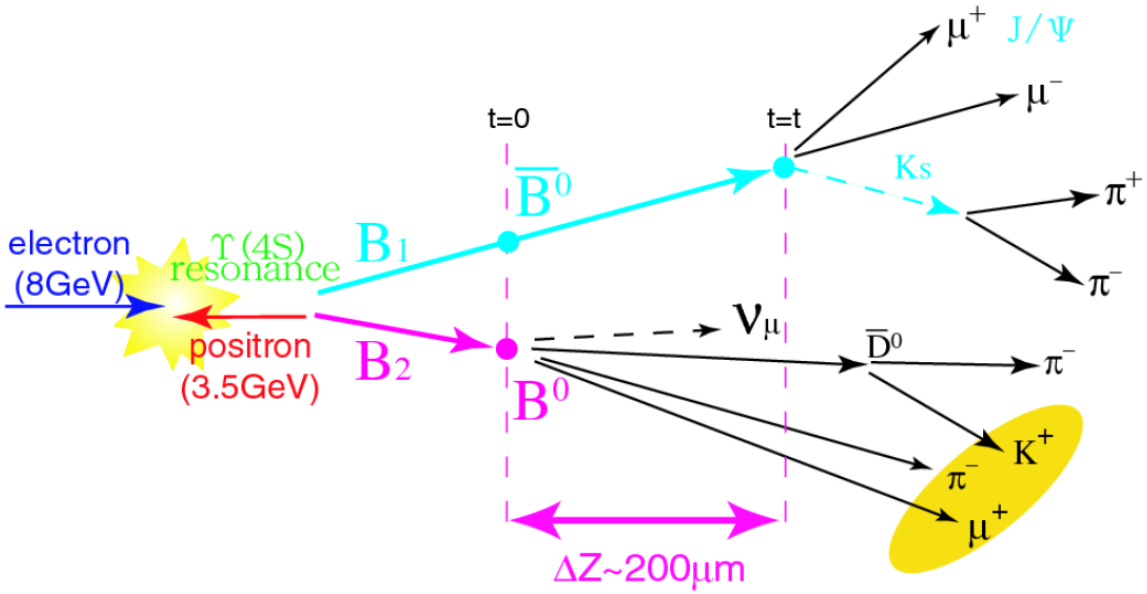
In practice such a quantity is formed for the ensemble of tags used in the analysis and gives a parameter that defines the proportion of events that, if perfectly tagged, would contribute to the measurement. Varies with meson type, how event is triggered, and with understanding of data set. Example values from LHCb studies.



Analysis	Effective tagging efficiency
Run 1 $B^0 \to J/\psi K_S$ [PRL 115 (2015) 031601]	3.02 %
Run 2 $B_s \to J/\psi KK$ [EPJC 79 (2019) 706]	4.73 ± 0.34 %
Run 2 $B_s \to D_s \pi$ [Nature Phys. 18 (2022) 1]	6.10 ± 0.15 %

Flavour tagging at the Y(4S)

Life is easier for BaBar/Belle and Belle-II At the Y(4S) one has no fragmentation particles and production of coherent B^0-B^0bar system → (i) No same sign tag (bad), (ii) many fewer mistags (very good), (iii) no mixing until one B decays (very good).



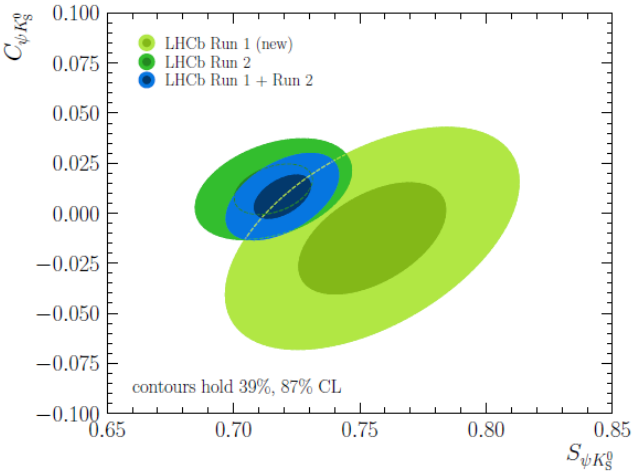
The dilution is less than at LHC, and reduces effective signal statistics by only ~1/3.

Why do B-factories have asymmetric beam energies? For coherent system what matters is the time-difference Δt *between* the two B decays. At the Y(4S) the mesons are produced at rest, & so it is necessary to *boost* system to measure Δt.

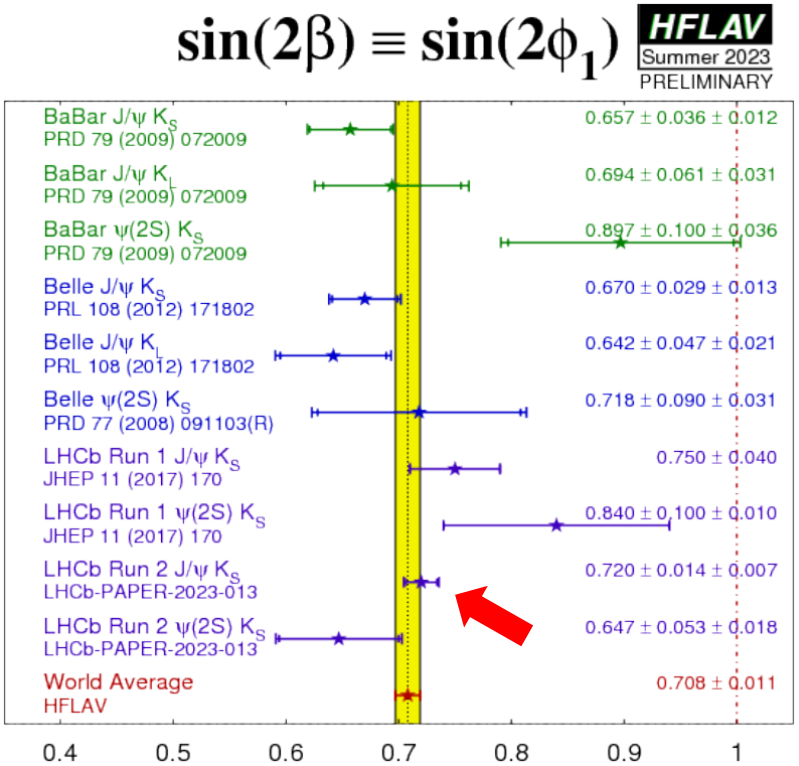
sin2β: current status and impact of the LHC

Global state of play:

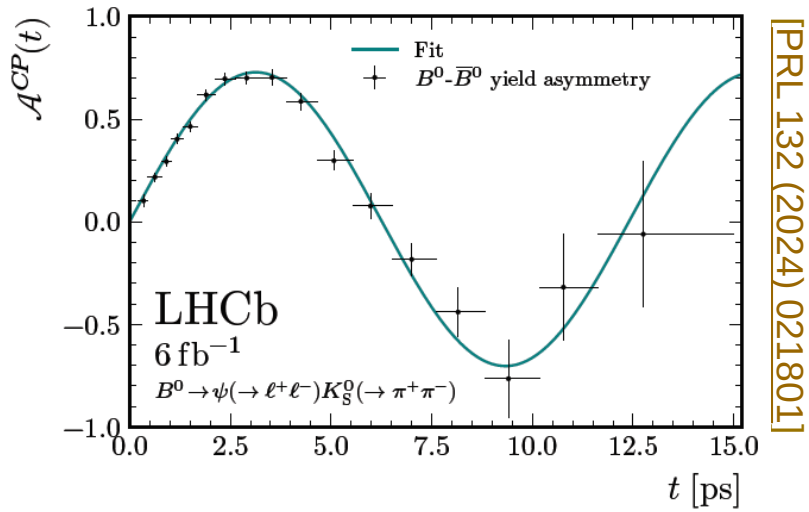
$$\beta = (22.5 \pm 0.4)^o$$



$$\sin(2\beta) \equiv \sin(2\phi_1)$$



Latest result has shrunk world average uncertainty substantially: 0.7°→0.4°.



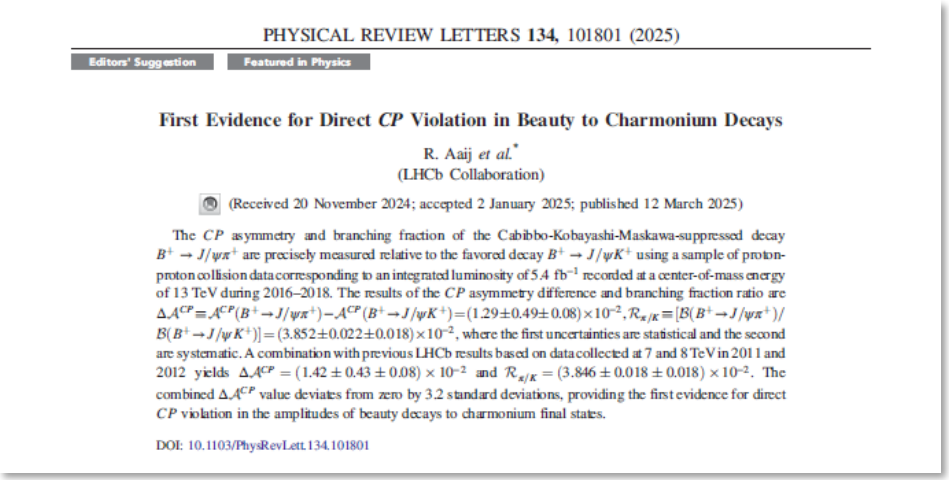
[PRL 132 (2024) 021801]

Must keep improving precision: Belle II, LHCb Run 3 and (why not?) ATLAS/CMS

The penguins are coming…

Even though current sin2β analysis shows no indication of contamination from direct CPV, this issue is likely to become important with next step-up in precision. Indeed, indication already emerging of direct CPV in charged sister modes

[LHCb, PRL 134 (2025) 101801]



PHYSICAL REVIEW LETTERS **134**, 101801 (2025)

Editors' Suggestion | Featured in Physics

First Evidence for Direct *CP* Violation in Beauty to Charmonium Decays

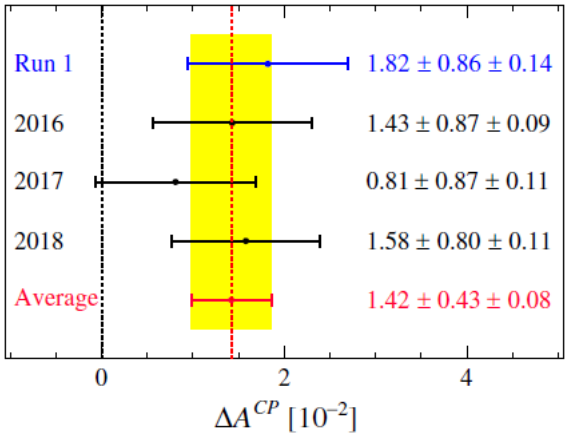
R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 20 November 2024; accepted 2 January 2025; published 12 March 2025)

The CP asymmetry and branching fraction of the Cabibbo-Kobayashi-Maskawa-suppressed decay $B^+ \to J/\psi\pi^+$ are precisely measured relative to the favored decay $B^+ \to J/\psi K^+$ using a sample of proton-proton collision data corresponding to an integrated luminosity of 5.4 fb^{-1} recorded at a center-of-mass energy of 13 TeV during 2016–2018. The results of the CP asymmetry difference and branching fraction ratio are $\Delta\mathcal{A}^{CP} \equiv \mathcal{A}^{CP}(B^+ \to J/\psi\pi^+) - \mathcal{A}^{CP}(B^+ \to J/\psi K^+) = (1.29 \pm 0.49 \pm 0.08) \times 10^{-2}$, $\mathcal{R}_{\pi/K} \equiv [\mathcal{B}(B^+ \to J/\psi\pi^+)/\mathcal{B}(B^+ \to J/\psi K^+)] = (3.852 \pm 0.022 \pm 0.018) \times 10^{-2}$, where the first uncertainties are statistical and the second are systematic. A combination with previous LHCb results based on data collected at 7 and 8 TeV in 2011 and 2012 yields $\Delta\mathcal{A}^{CP} = (1.42 \pm 0.43 \pm 0.08) \times 10^{-2}$ and $\mathcal{R}_{\pi/K} = (3.846 \pm 0.018 \pm 0.018) \times 10^{-2}$. The combined $\Delta\mathcal{A}^{CP}$ value deviates from zero by 3.2 standard deviations, providing the first evidence for direct CP violation in the amplitudes of beauty decays to charmonium final states.

DOI: 10.1103/PhysRevLett.134.101801

CP asymmetry difference between $B^+ \to J/\Psi\pi^+$ and $B^+ \to J/\Psi K^+$

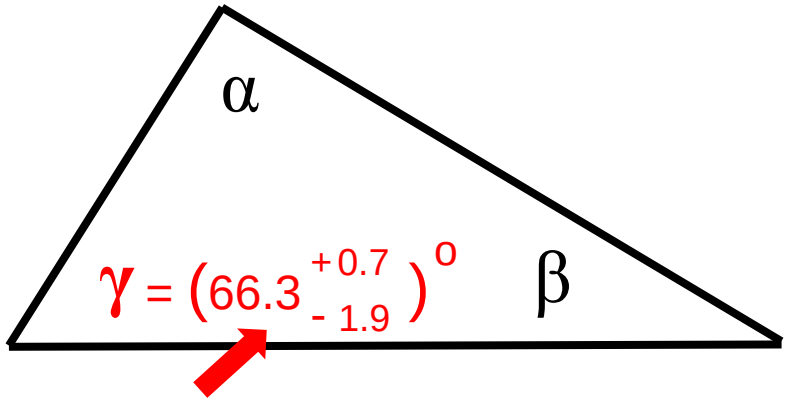


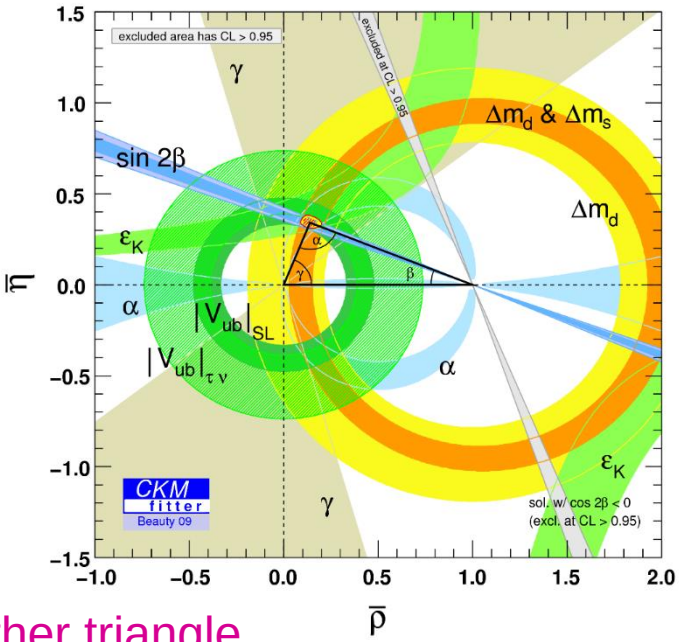
Nil desperandum ! This bias can be controlled from data using modes such as $B_s \to J/\Psi K_S$ and the above charged modes, with flavour symmetries. Same considerations apply to $B_s \to J/\Psi\Phi$ (see later) *e.g.* [De Bruyn *et al.*, arXiv:2505.06102].

The long march: towards a precise determination of the UT angle γ

A particular responsibility for flavour physics at the LHC is to improve our knowledge of the angle γ.

At LHC turn-on γ uncertainty was >20°.





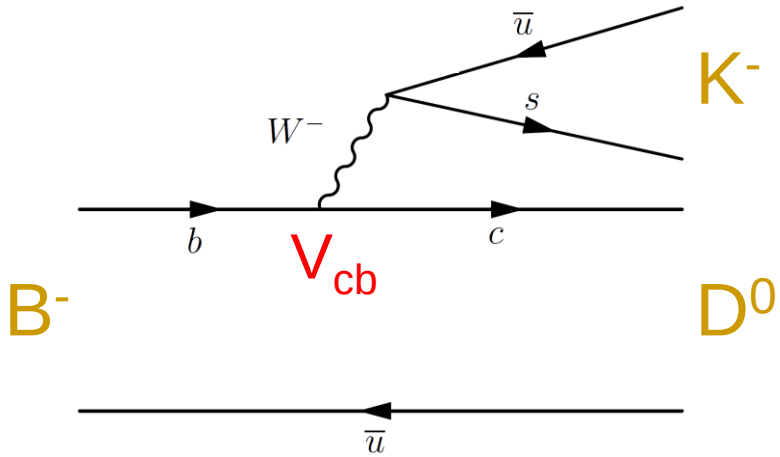
[CKMfitter, 2009]

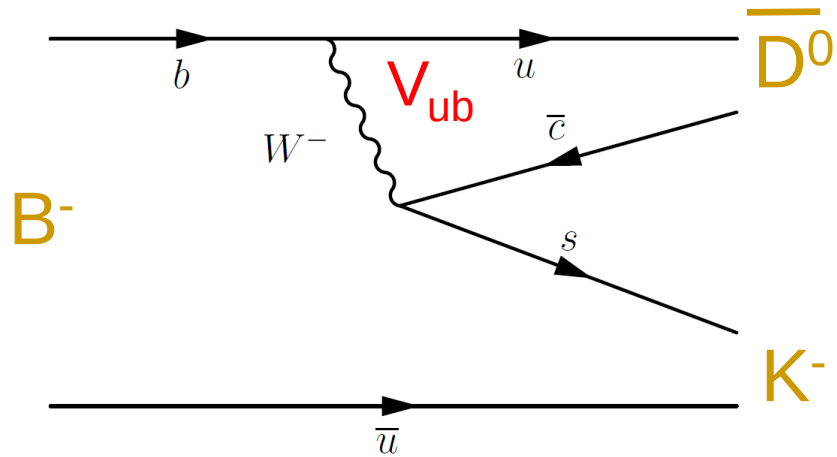
The predicted value of γ [CKMfitter, 2023] in context of SM is known very well from other triangle parameters (& will be known even better as experiment & lattice QCD improve).

A key task of flavour physics is to match this precision in a direct measurement !

The long march: towards a precise determination of the UT angle γ

This angle is special – it can be measured at tree-level through B→DK decays.





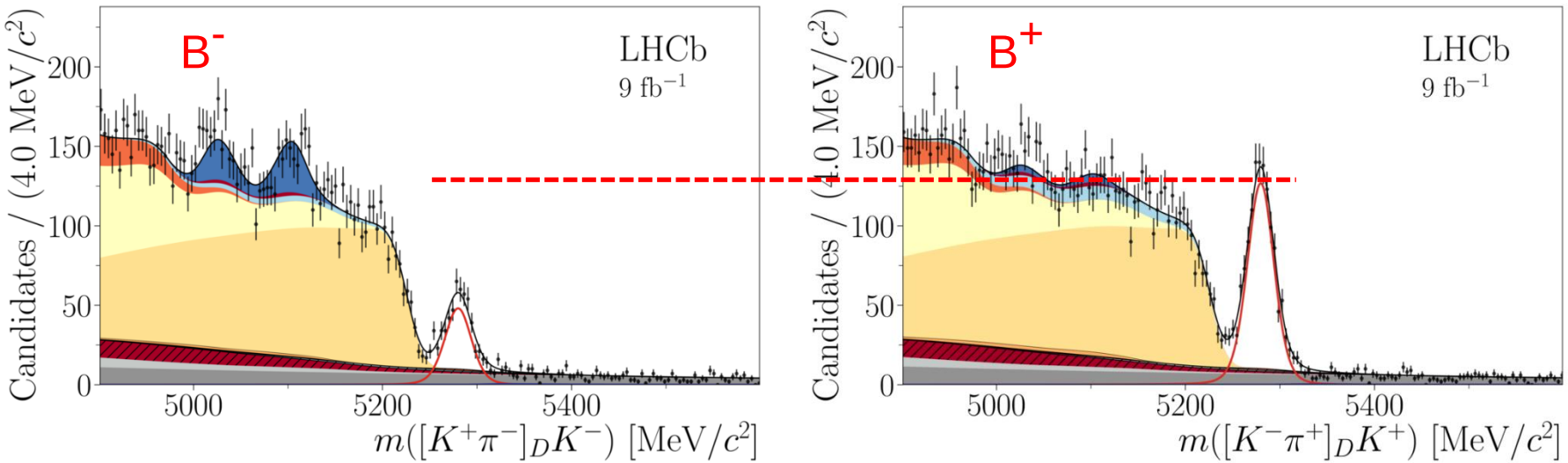
If we reconstruct D^0 and $\overline{D}^0$ in a state accessible to both, Interference occurs & decay rates become sensitive to relative phase between V_{cb} and V_{ub}, which is γ.

There are QCD nuisance parameters involved, but sufficient observables can be measured to determine these without any assumption. Theoretically ultra clean !

Tree level means New Physics unlikely to perturb measured value from the γ of the SM (*c.f.* β) , hence measurement provides 'SM benchmark' for other tests !

The Unitarity Triangle: measuring γ

To access these interference effects means looking for rather suppressed decays, *e.g.* this $B^- \to DK^-$ decay, with $D \to K^+\pi^-$ (and B^+ conjugate case): visible BR ~10^{-8}, Hence out of reach to previous generation of flavour physics experiments.



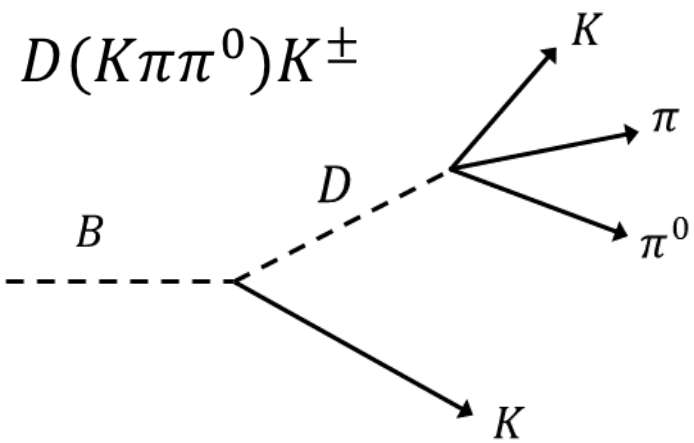
[JHEP 04 (2021) 081]

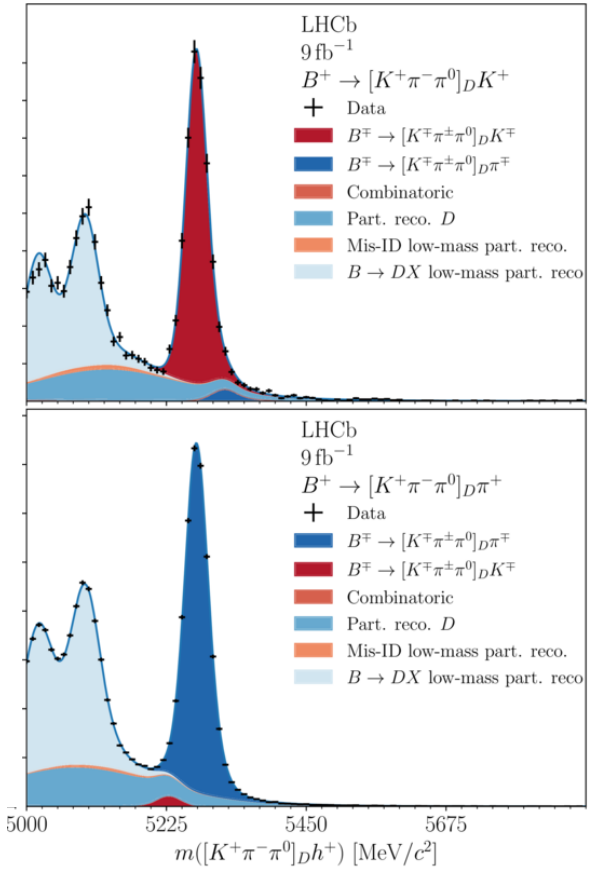
Very significant CP violation observed, that can be cleanly related to the phase γ.

Measuring γ at LHCb: remarkably clean signals

Despite the high multiplicity environment, the signals are remarkably clean, even in very challenging modes involving a π^0 [JHEP 07 (2022) 099]. The flight distance of the B & D mesons suppresses combinatoric background from prompt charged tracks.

$$B^{\pm} \to D(K\pi\pi^0)K^{\pm}$$





Furthermore, the RICH detector does an excellent job in separating the B→DK mode (top plot) from the order-of-magnitude more abundant B→Dπ mode (bottom plot).

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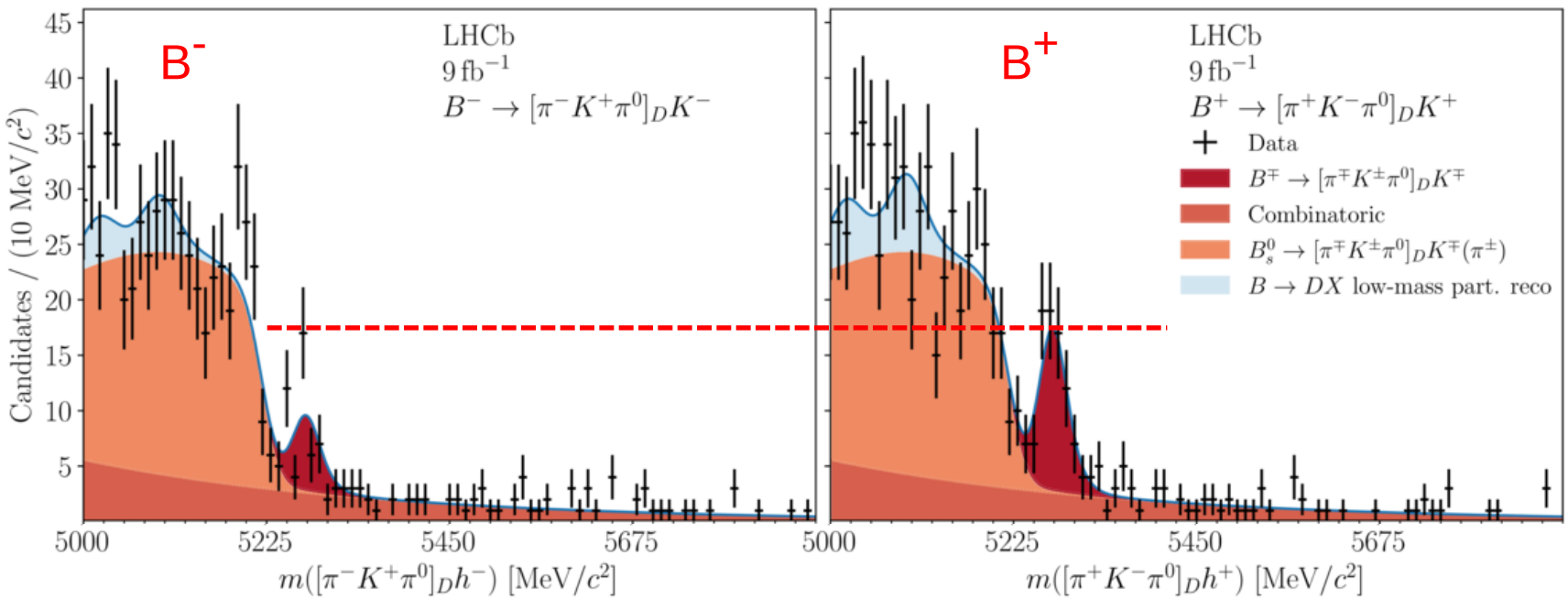
Thus, even in $B^{\pm} \to D(K\pi\pi^0)K^{\pm}$ the suppressed mode can be seen, together with its CP-violating asymmetry - again, this was not accessible at BaBar / Belle.



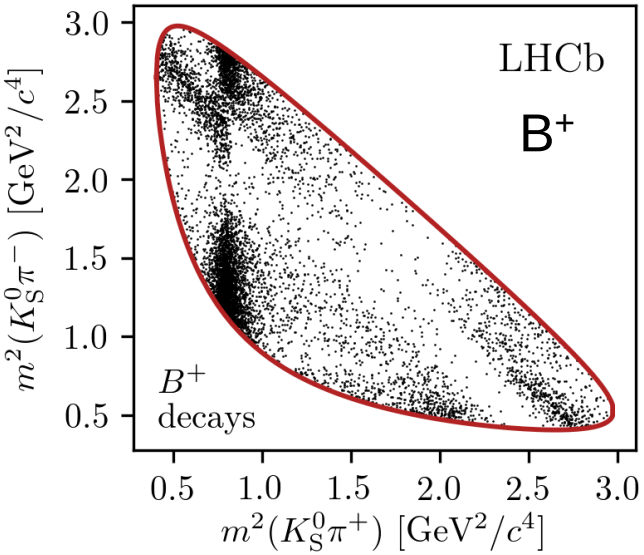
γ measurement at LHCb with B→DK decays: D→K_Sππ (and K_SKK)

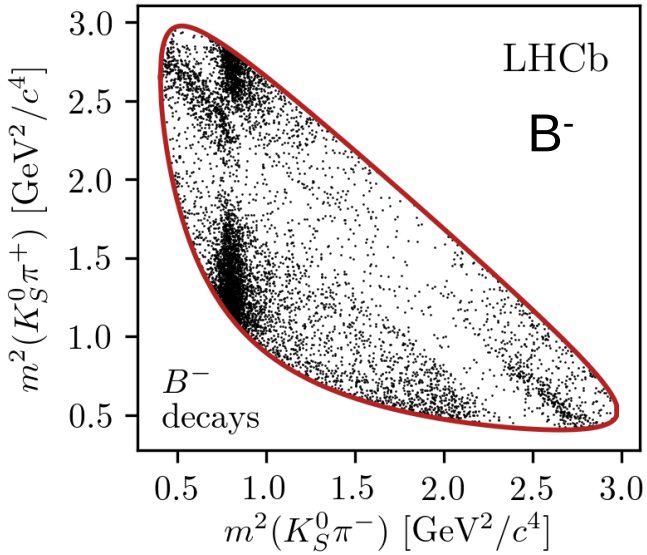
[JHEP 02 (2021) 169]

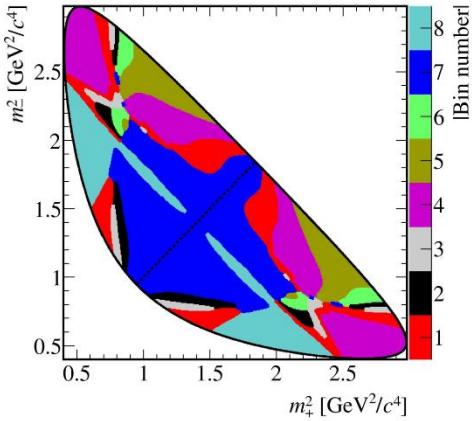
A powerful sub-set of B→DK analyses is when the D decays into a multibody final state, of which K_Sππ is the most prominent example. Variation of D strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

Analysis of ~12,500 decays from Run 1 and Run 2 data

Study yields in bins of Dalitz space, chosen for optimal sensitivity.







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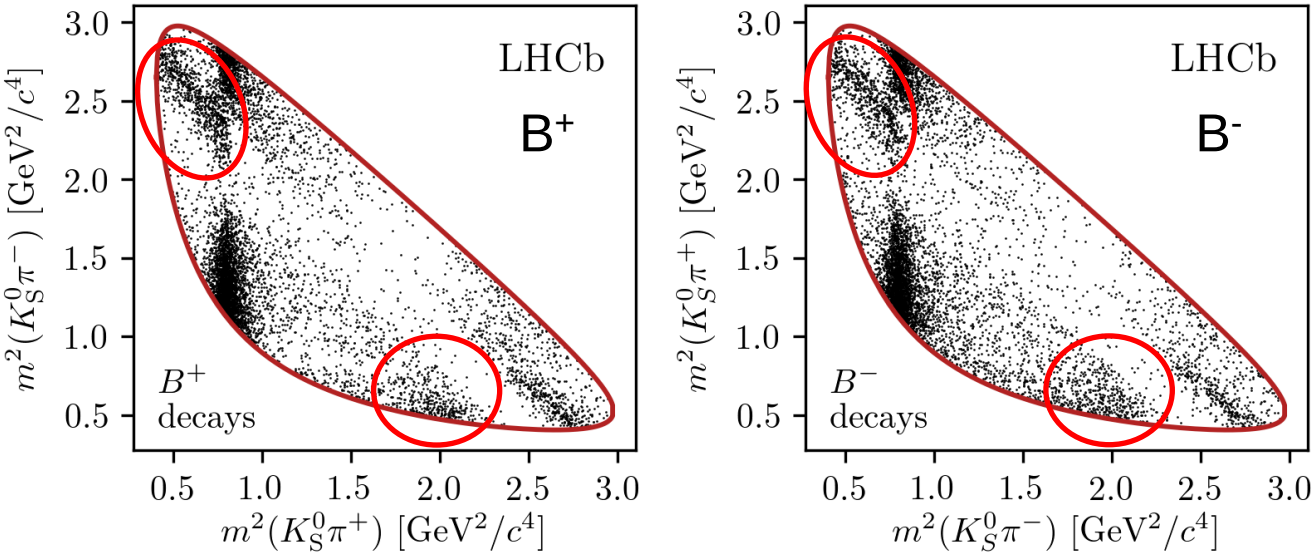
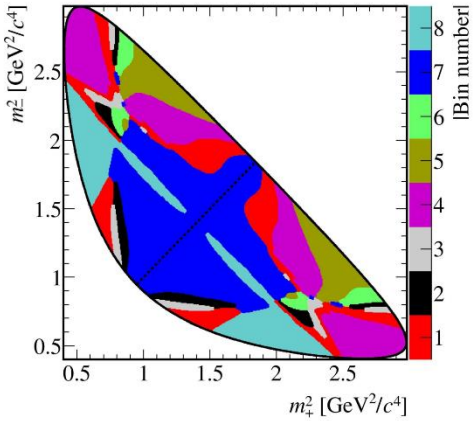


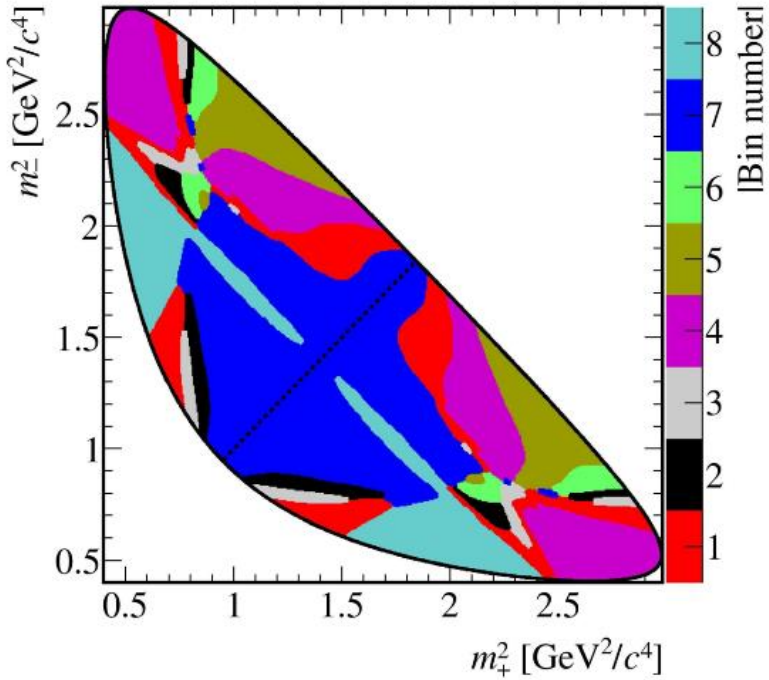


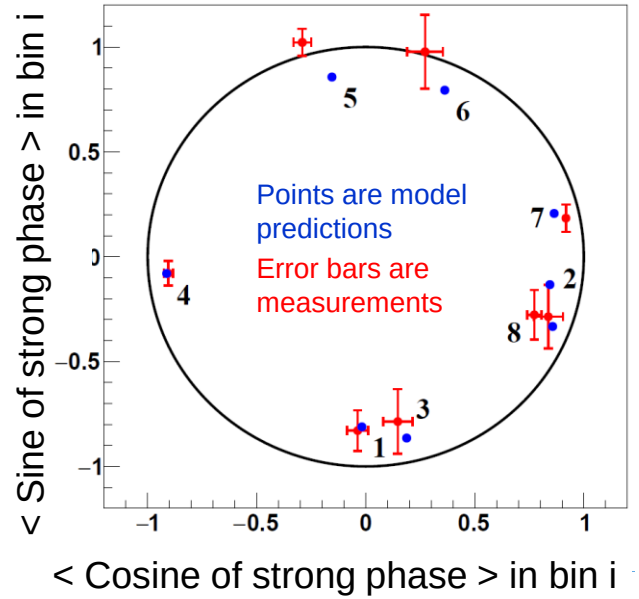
CP asymmetries visible by eye, but quantitative analysis requires external input...

Measuring γ – a synergy of experiments

In order to make sense of these *CP* asymmetries, we need to know how the CP-conserving strong phase between D & Dbar varies over the Dalitz plot.

This information can be measured in bins on the Dalitz plot from quantum-correlated ψ(3770)→DDbar events, available at BESIII [PRD 101 (2020) 112002].





BESIII data (here combined with older CLEO results) adequate for current LHCb sample sizes.

LHCb Upgrade data & Belle II will require improved measurements from BES III !

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These strong-phase measurements are an excellent example of synergy between HEP facilities !

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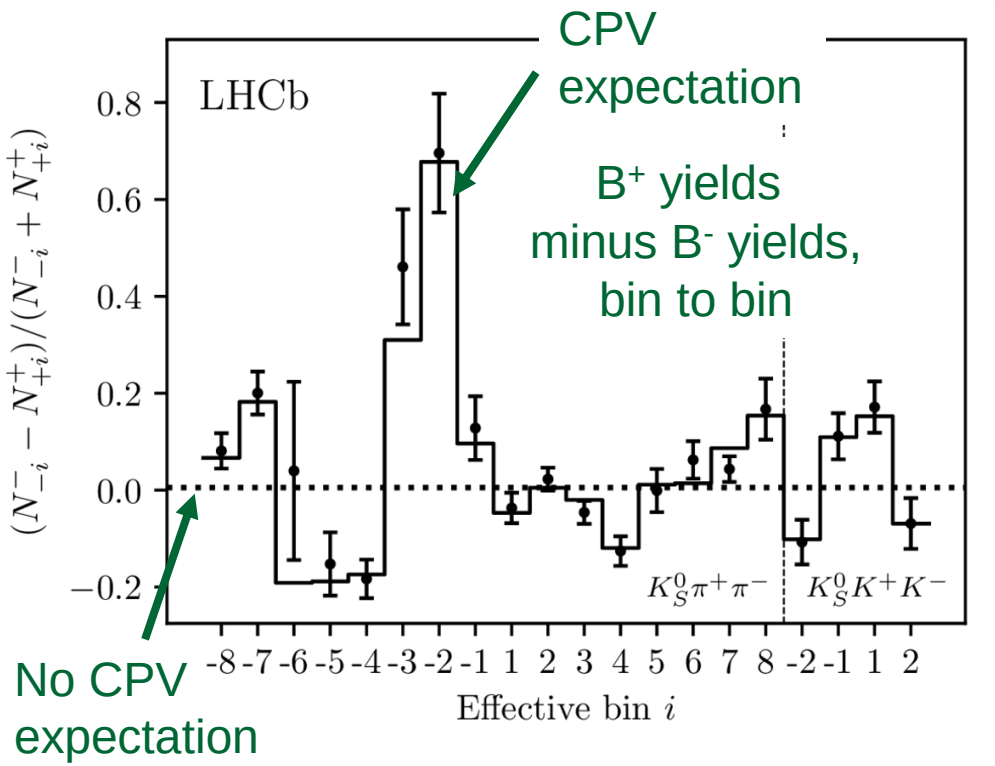


Gives a result of:

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ$$

which is the single most precise determination of γ.

This, and ensemble of other LHCb results, as of summer 2024, gives

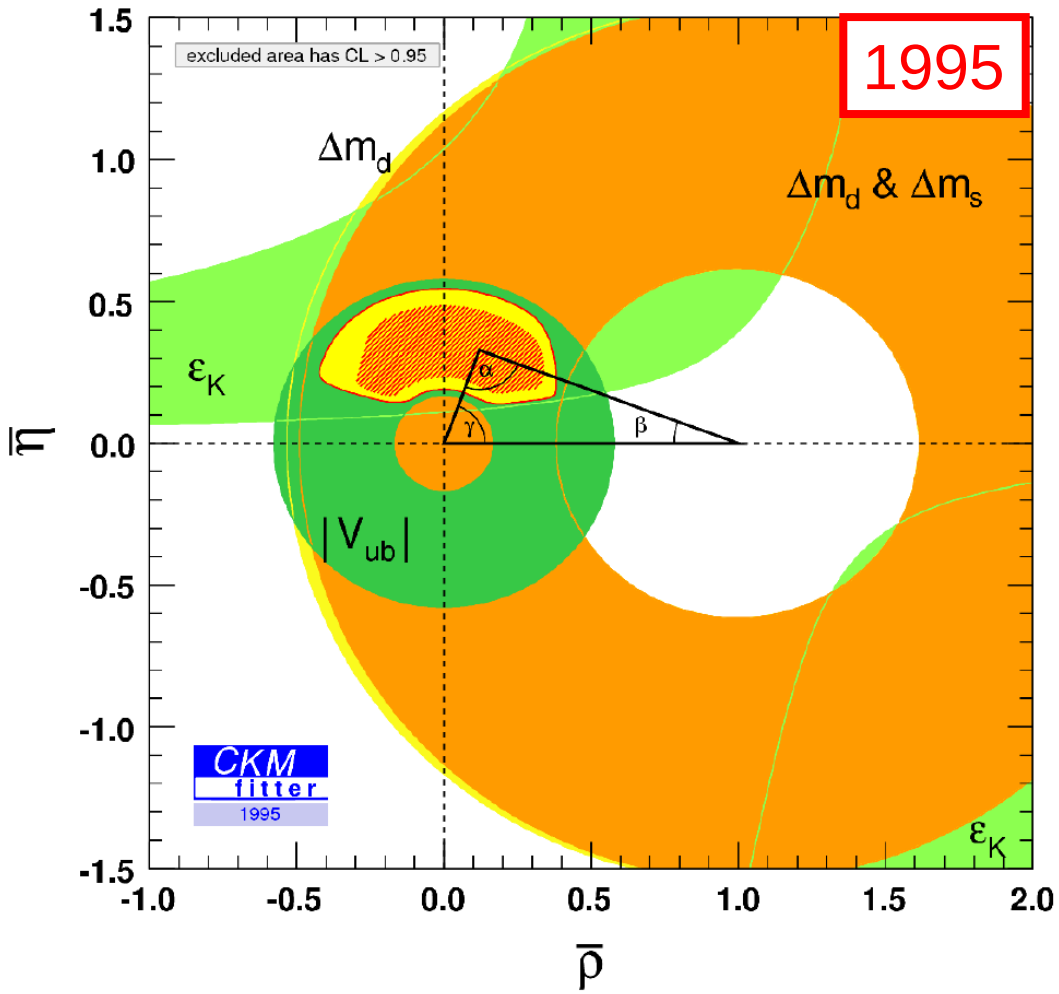
$$\boxed{\gamma = (64.6 \pm 2.8)^\circ}$$

[LHCb-CONF-2024-004]

Further improvement expected with recent & incoming Run 1 + 2 analyses. Run 3 + 4, should allow for < 1%

In agreement with indirect prediction but not yet as precise → need more data !

Unitarity Triangle: ~30 years of progress



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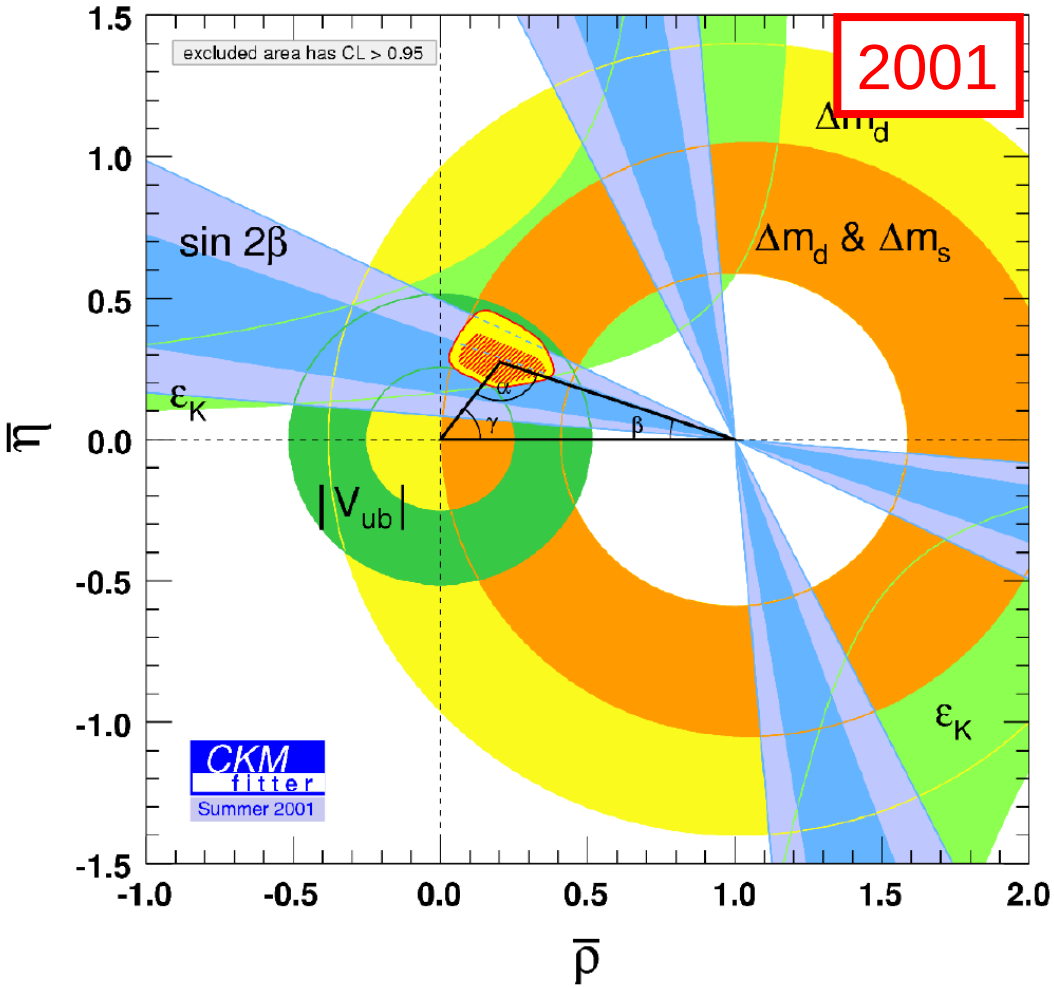

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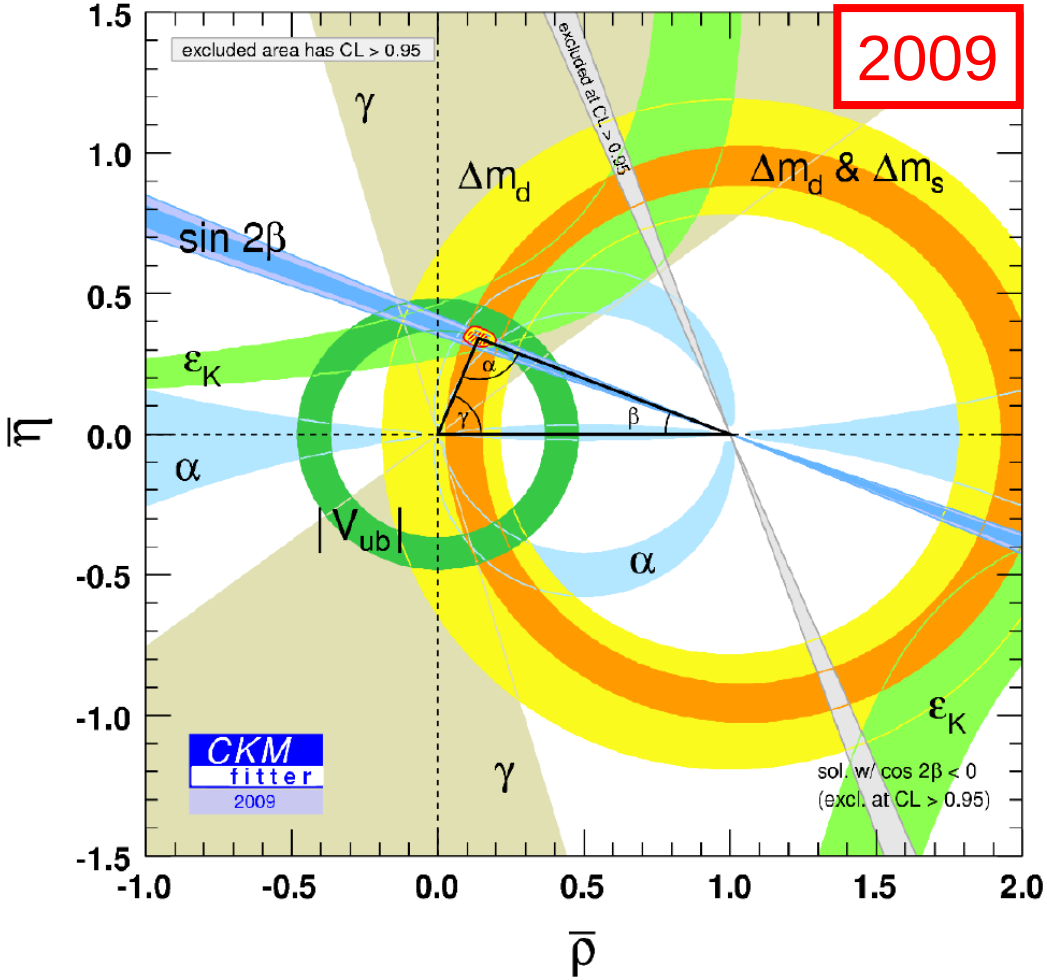

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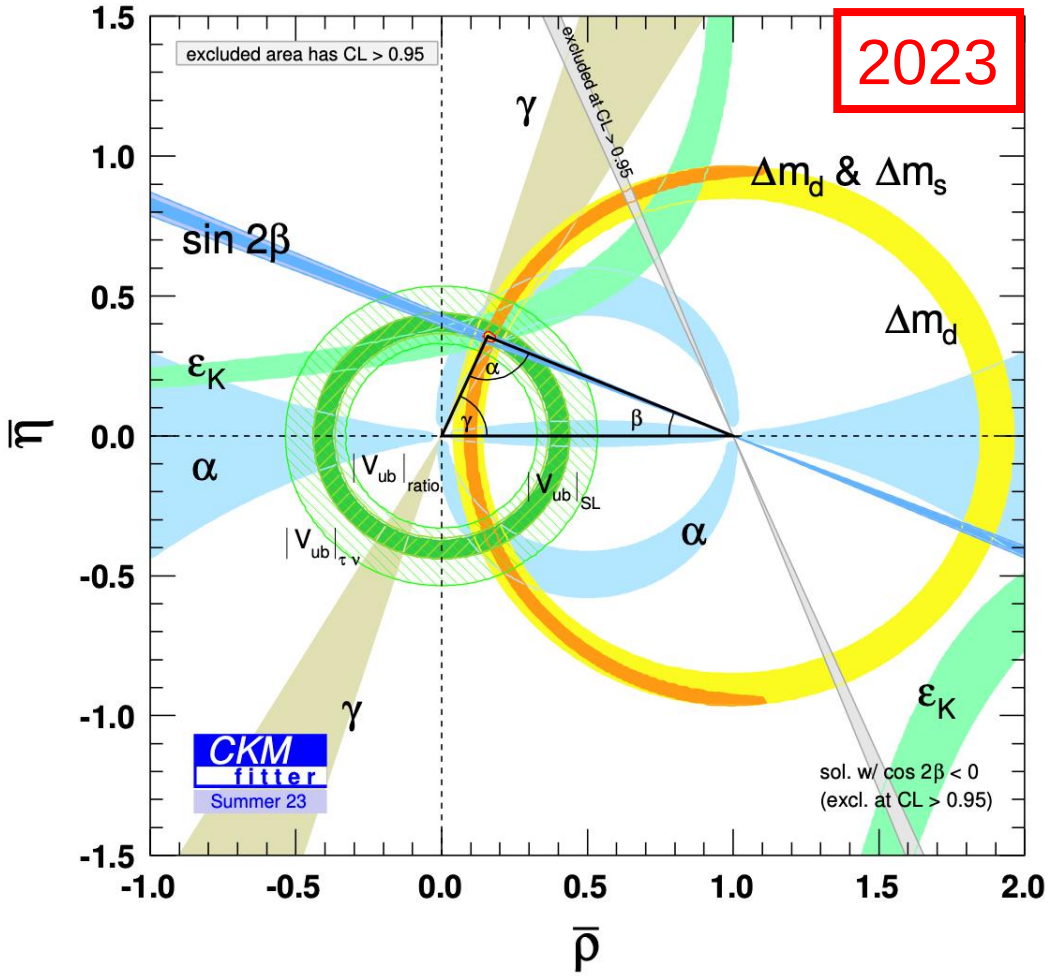

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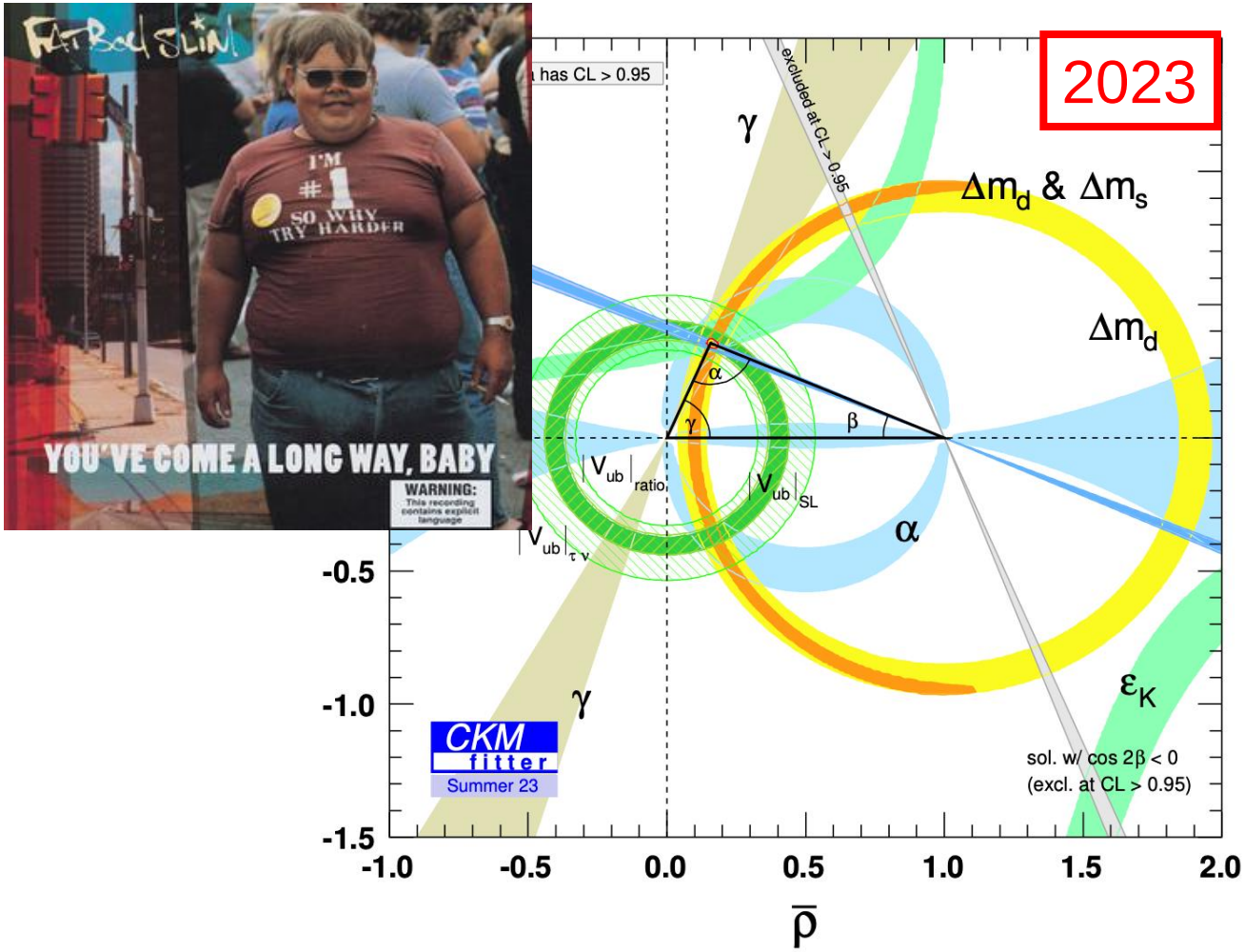
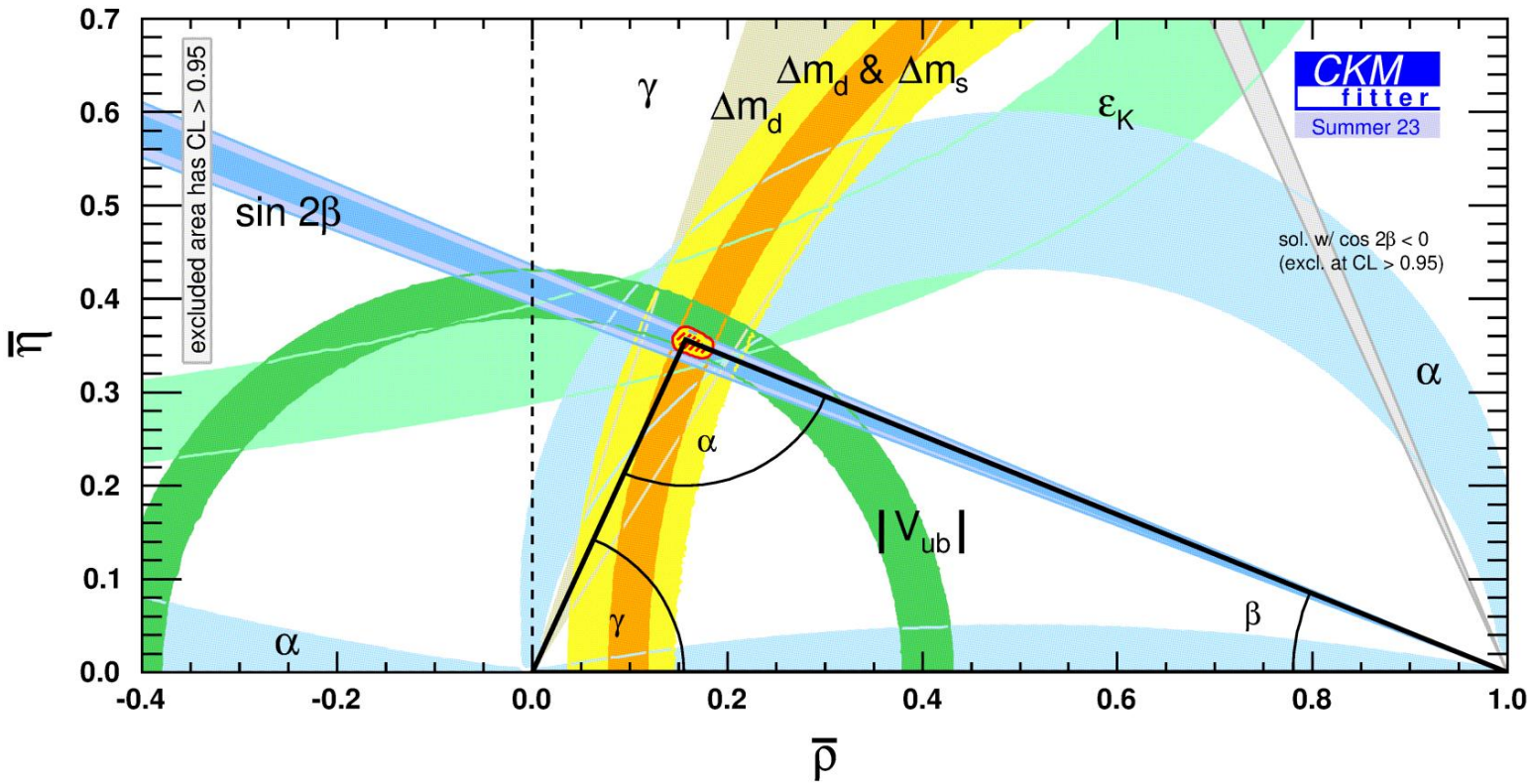


Enormous improvements in precision, thanks to both experiment and theory (esp. lattice), with LHCb playing an increasingly important role – set to continue.

Overall consistency of the Unitarity Triangle

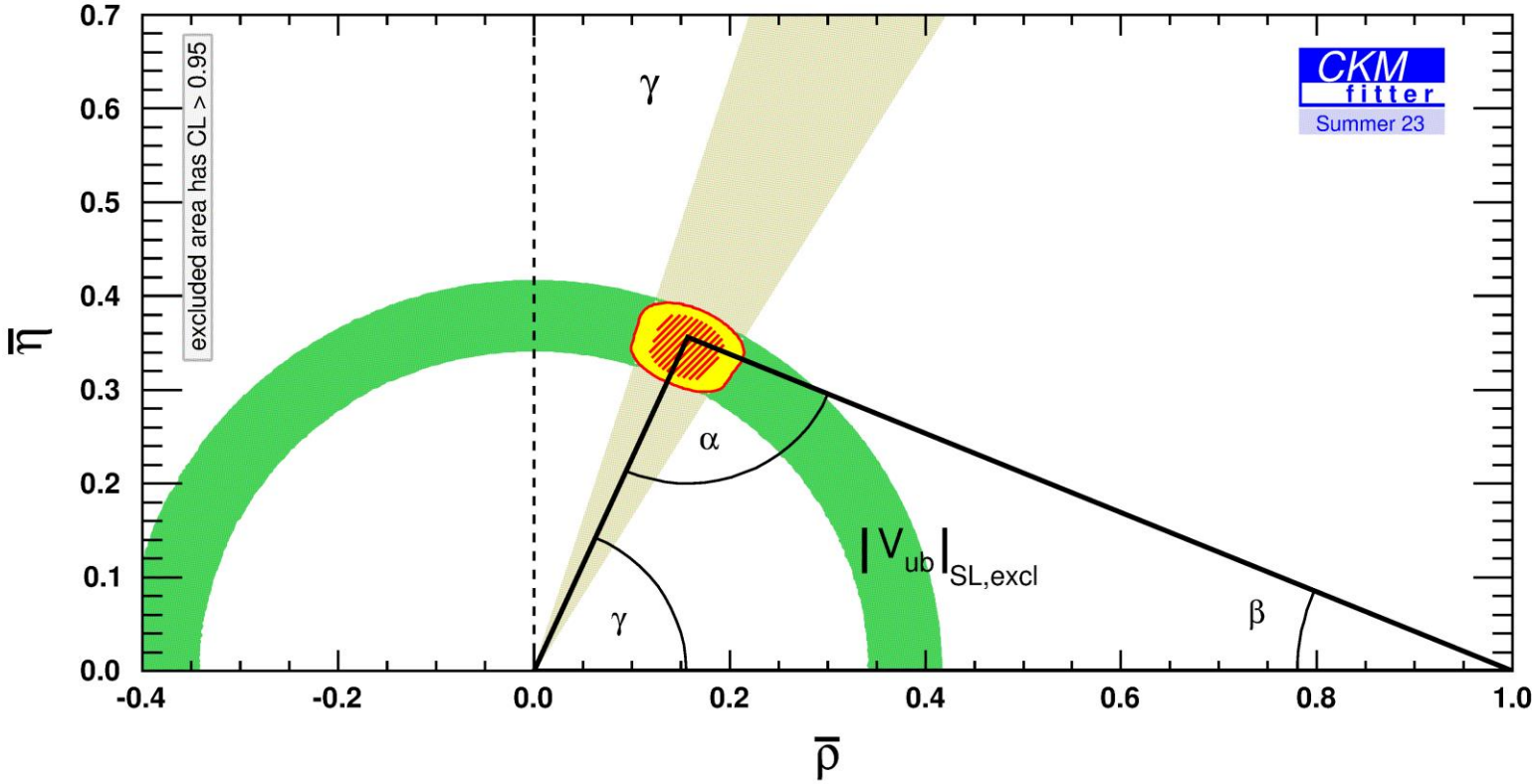
There is broad consistency between all current measurements of the UT. (But, a closer look can reveal intriguing tensions, *e.g.* [Blanke & Buras, EPJC 79 (2019) 159].)



The CKM paradigm is the dominant mechanism of CPV in nature, but it is certainly possible for New Physics to give ~10 % level effects. More measurements needed !

Unitarity Triangle: tree-level observables

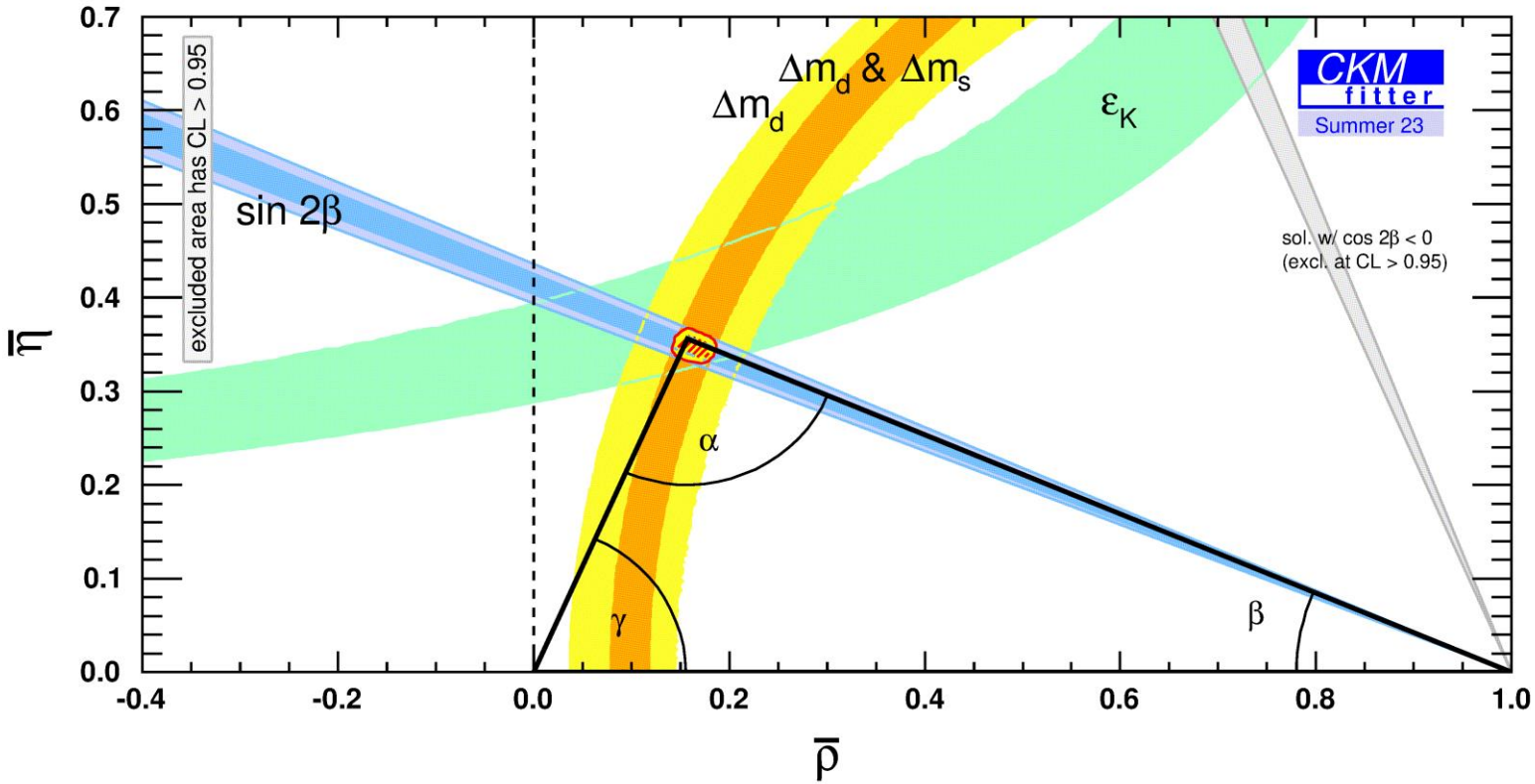
Unitarity Triangle formed from only tree-level quantities → assumed pure SM.



Tree observables are γ & the $|V_{ub}|/|V_{cb}|$ side, here showing exclusive measurement.

Unitarity Triangle: loop-level observables

Unitarity Triangle formed from only loop-level quantities → possibility of NP effects.

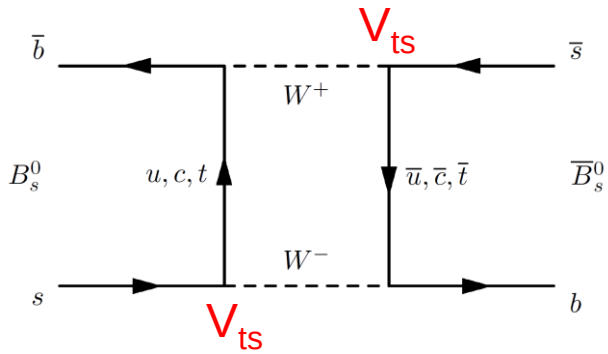


There is good consistency between the tree and loop measurements. There's a need to improve the precision of former to allow for a more sensitive comparison.

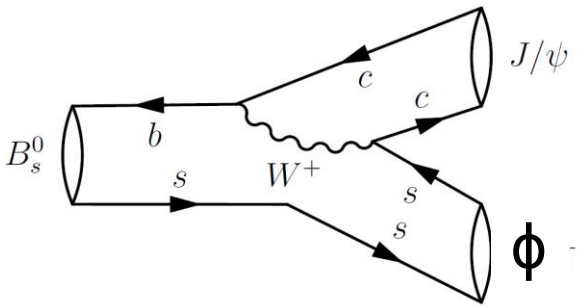
Indirect CPV in B_s system: φ_s

Measuring the CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* with $B_s \to J/\Psi\Phi$, is **the B_s analogue of the sin2β measurement**. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP !

Once more interference between mixing…



…and decay



Now we probe CKM elements that are complex only at higher order

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\begin{pmatrix} -\frac{1}{8}\lambda^4 + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^7) & 0 \\ \frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] + \mathcal{O}(\lambda^7) & -\frac{1}{8}\lambda^4(1+4A^2) + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^8) \\ \frac{1}{2}A\lambda^5(\rho+i\eta) + \mathcal{O}(\lambda^7) & \boxed{\frac{1}{2}A\lambda^4(1-2(\rho+i\eta)) + \mathcal{O}(\lambda^6)} & -\frac{1}{2}A^2\lambda^4 + \mathcal{O}(\lambda^6) \end{pmatrix}$$

$$\phi_s^{\rm SM} \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -37 \pm 1\,{\rm mrad}$$ [UTFit]

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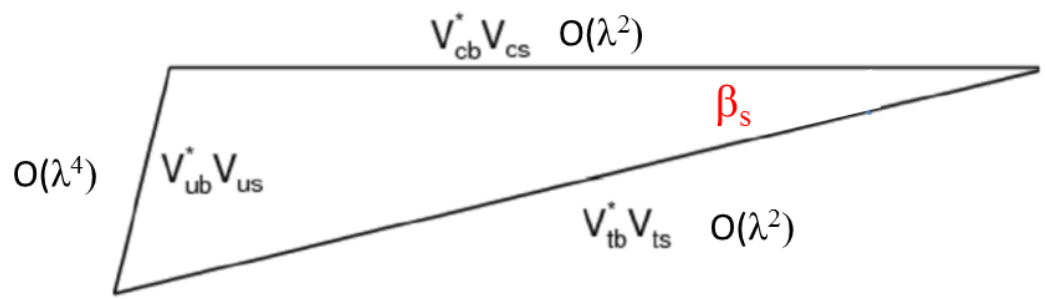
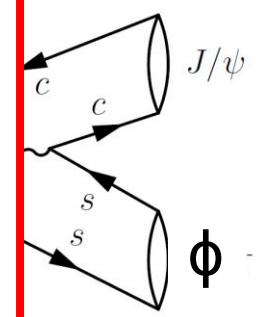
Once mo
interferen
between
mixing…

Recall the squashed B^0_s triangle:



In SM $\varphi_s = -2\beta_s$



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elements
complex

$$\left(\begin{array}{ccc} & & 0 \\ \frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] + \mathcal{O}(\lambda^7) & -\frac{1}{8}\lambda^4(1+4A^2) + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^8) \\ \frac{1}{2}A\lambda^5(\rho+i\eta) + \mathcal{O}(\lambda^7) & \boxed{\frac{1}{2}A\lambda^4(1-2(\rho+i\eta)) + \mathcal{O}(\lambda^6)} & -\frac{1}{2}A^2\lambda^4 + \mathcal{O}(\lambda^6) \end{array} \right)$$

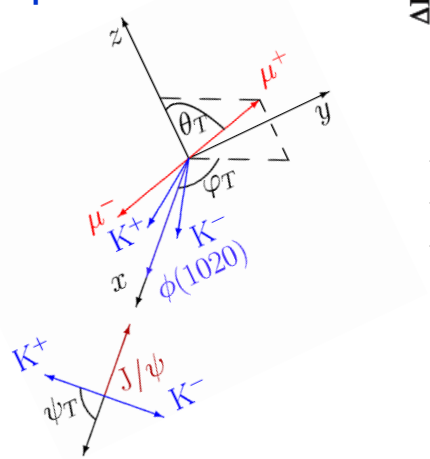
$$\phi_s^{\rm SM} \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -37 \pm 1\,\text{mrad}$$ [UTFit]

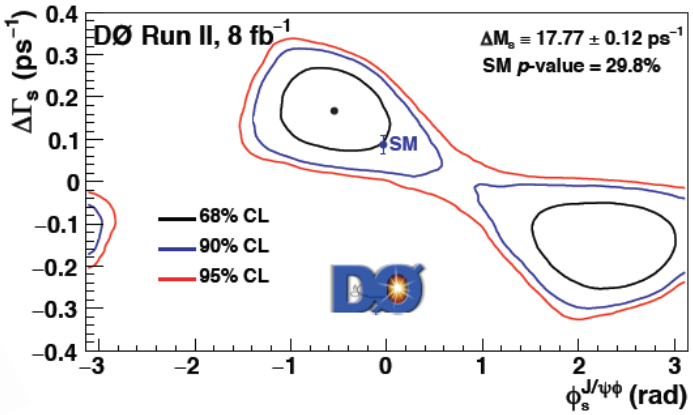
Indirect CPV in B_s system: φ_s

Measuring the CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* with $B_s \to J/\Psi\Phi$, is **the B_s analogue of the sin2β measurement**. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP !

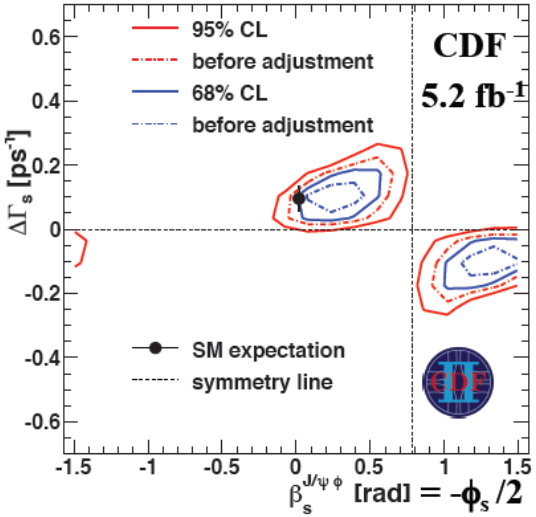
However the measurement is considerably trickier than is the case for sin2β:

- J/Ψφ is a vector-vector final state, so requires angular analysis to separate out CP+ & CP-
- Very fast oscillations ($\Delta m_s >> \Delta m_d$)
- Possibility of KK S-wave under φ





[PRD 85 (2012) 032006]



[PRD 85 (2012) 072002]

Heroic early analyses performed by Tevatron. Consistent results and mild (~1σ) tension with SM.

Indirect CPV in B_s system: φ_s

Measuring the CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* with $B_s \to J/\Psi\Phi$, is **the B_s analogue of the sin2β measurement**. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP !

However the measurement is considerably trickier than is the [illegible] sin2β:

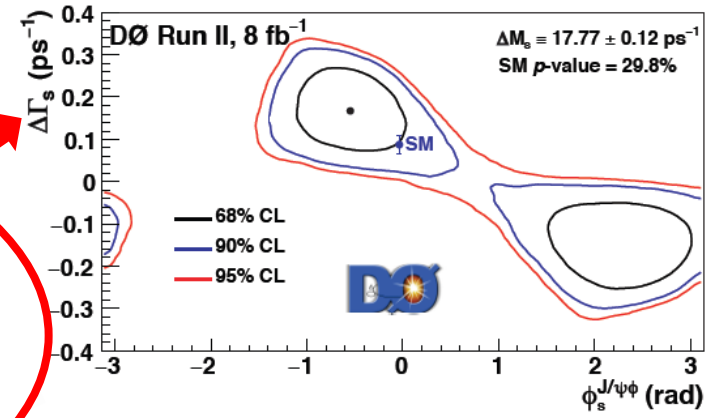
- [illegible]

(ΔΓ[illegible]

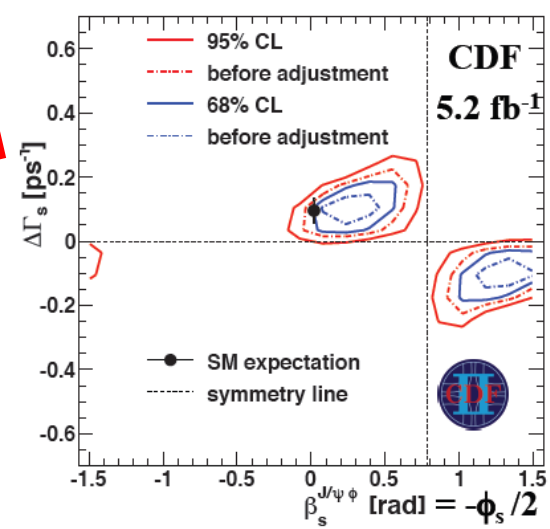
One other detail: in contrast to the B^0 case, the width-splitting $\Delta\Gamma_s$ between the mass eigenstates Is here non-negligible (~0.1). When included in the formalism this brings additional handles to the analysis, & also provides an additional observable to be measured.

- Possibility of KK S-wave under φ

Heroic early analyses performed by Tevatron. Consistent results and mild (~1σ) tension with SM.



[PRD 85 (2012) 032006]



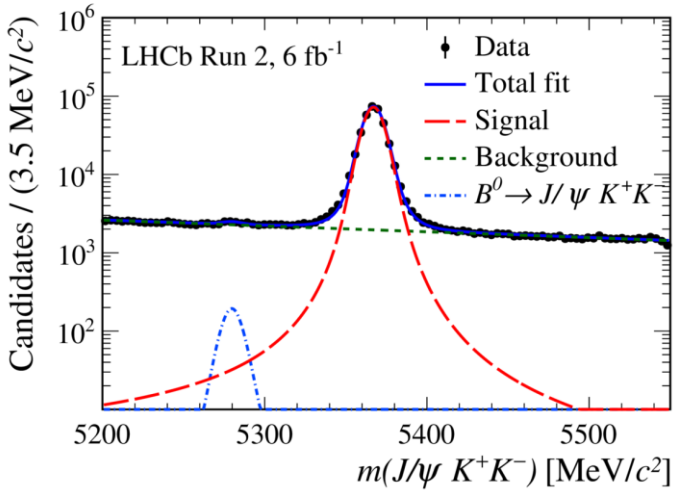
[PRD 85 (2012) 072002]

φ_s – impact of LHCb

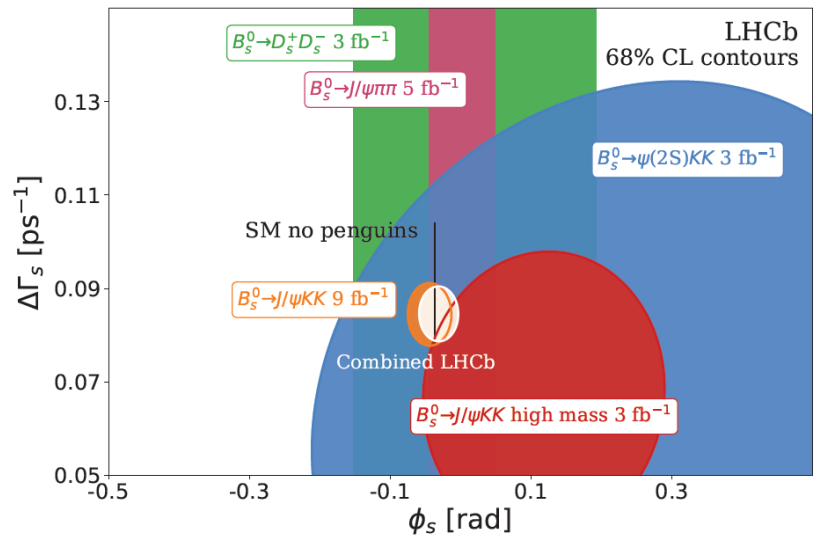
LHC has been able to go far beyond the Tevatron measurements, thanks to much larger yields, and (in case of LHCb) excellent proper time resolution, & access to complementary modes beyond J/ψφ (*e.g.* $B_s \to J/\psi\pi\pi$ [PLB 797 (2019) 134789] .)

$B_s \to J/\psi\varphi$ signal peak in Run 2. 349k decays in 6 fb^{-1} *c.f.* 6.5k at CDF. Tagging power ~ 4.4%.

[PRL 132 (2024) 051802]



Results for full Run 2 J/ψφ study, together with other LHCb measurements.



$$\phi_s = -0.039 \pm 0.022 \pm 0.006\,\text{rad} \qquad \Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024\,\text{ps}^{-1}$$

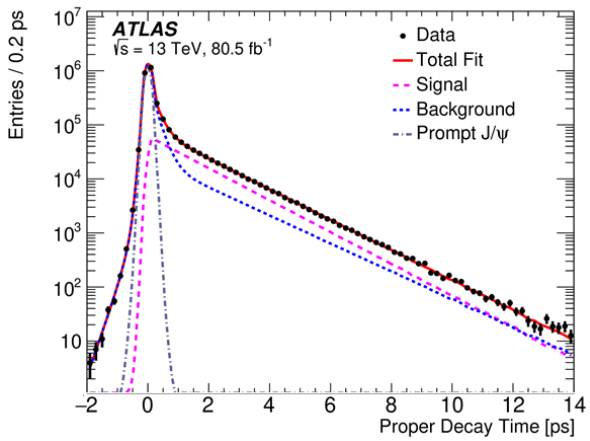
When combined with other LHCb results ➡ $\phi_s = -0.031 \pm 0.018\,\text{rad}$

Measurement of φ_s at ATLAS

Measurement of φ_s is an key goal of the ATLAS and CMS flavour physics programme, enabled by excellent detector performance and $J/\Psi \to \mu\mu$ trigger.

e.g. ATLAS $B_s \to J/\Psi\varphi$ Run 2 analysis with 80 fb^{-1} [Eur. Phys. J. C 81 (2021) 342]:

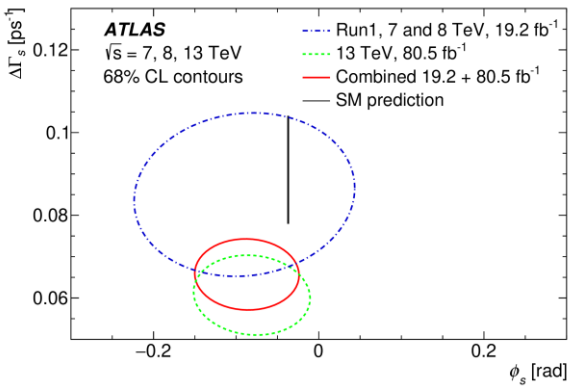
Proper decay time



Tagging performance

Tag method	Tagging power (%)
Tight muon	0.862 ± 0.009
Electron	0.274 ± 0.004
Low-p_T muon	0.278 ± 0.006
Jet	0.334 ± 0.006
Total	1.75 ± 0.01

Results, including those of Run 1 [JHEP 08 (2016) 147]



Combining with Run 1 results [JHEP 08 (2016) 147]

$$\phi_s = -0.087 \pm 0.036 \text{ (stat.)} \pm 0.021 \text{ (syst.) rad}$$
$$\Delta\Gamma_s = 0.0657 \pm 0.0043 \text{ (stat.)} \pm 0.0037 \text{ (syst.) ps}^{-1}$$

Measurement of φ_s at CMS

Measurement of φ_s is an key goal of the ATLAS and CMS flavour physics programme, enabled by excellent detector performance and $J/\Psi \to \mu\mu$ trigger.

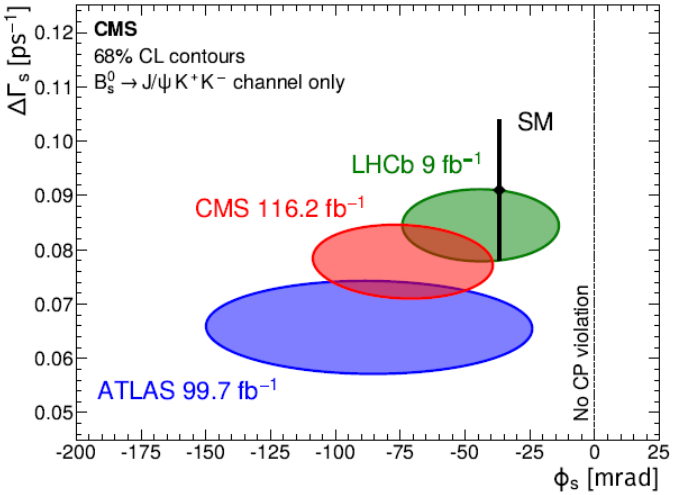
e.g. CMS $B_s \to J/\Psi\varphi$ Run 2 analysis with 96.5 fb^{-1} [arXiv:2412.19952]

Tagging performance

Category	ε_{tag} [%]	$\mathcal{D}^2_{tag,eff}$	P_{tag} [%]
Only OS muon	6.07 ± 0.05	0.212	1.29 ± 0.07
Only OS electron	2.72 ± 0.02	0.079	0.214 ± 0.004
Only OS jet	5.16 ± 0.03	0.045	0.235 ± 0.003
Only SS	33.12 ± 0.07	0.080	2.64 ± 0.01
SS + OS muon	0.62 ± 0.01	0.202	0.125 ± 0.003
SS + OS electron	2.77 ± 0.02	0.150	0.416 ± 0.005
SS + OS jet	5.40 ± 0.03	0.124	0.671 ± 0.006
Combined	55.9 ± 0.1	0.100	5.59 ± 0.02

Best in show !

Result contours

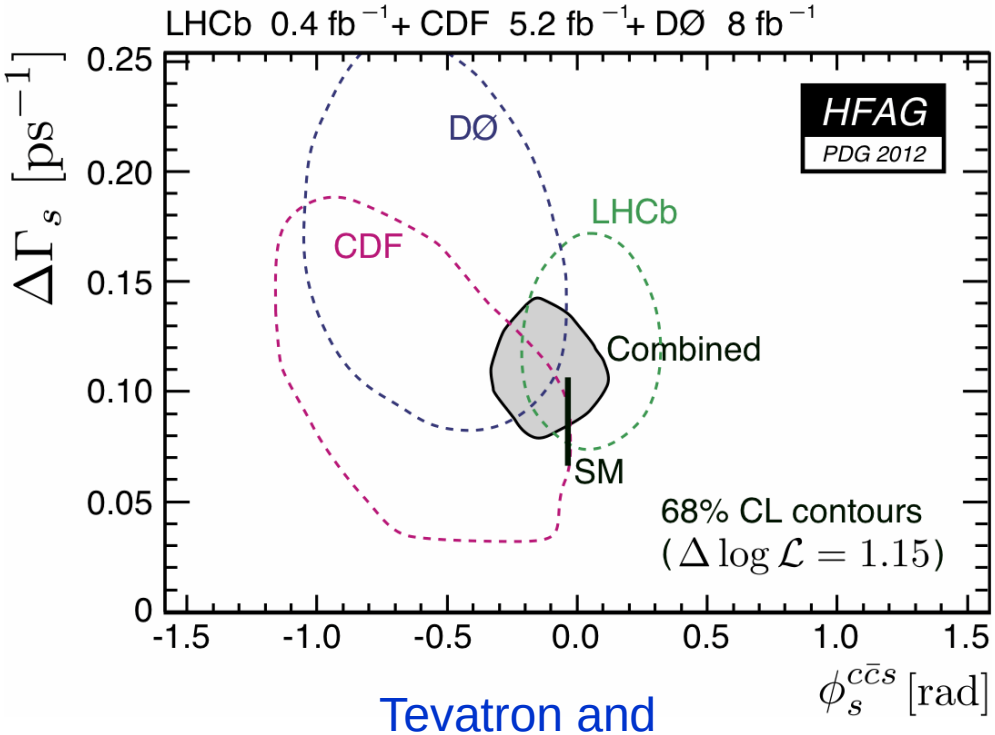


Combining with Run 1 results [PLB 757 (2016) 97]

$$\phi_s = -74 \pm 23\,\text{mrad}$$
$$\Delta\Gamma_s = 0.0780 \pm 0.0045\,\text{ps}^{-1}$$

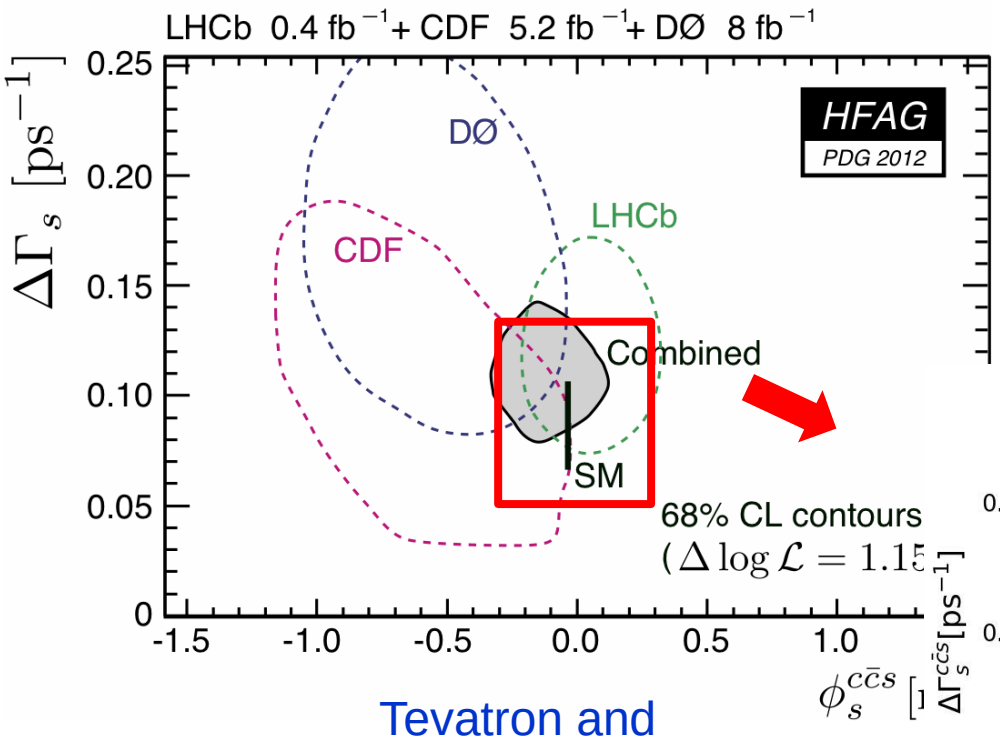
>3σ away from zero !

φ_s : the impact of the LHC



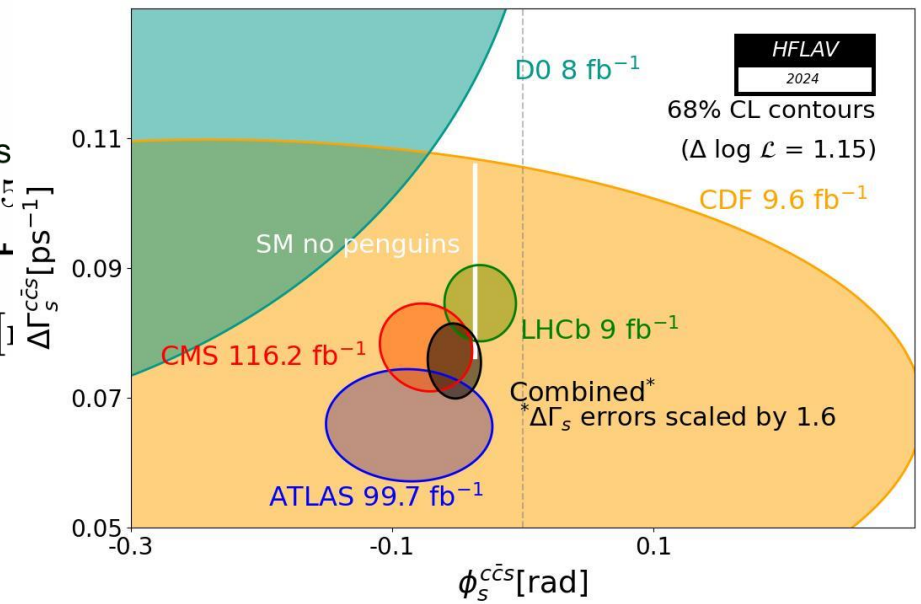
Tevatron and
early LHC data

φ_s : the impact of the LHC

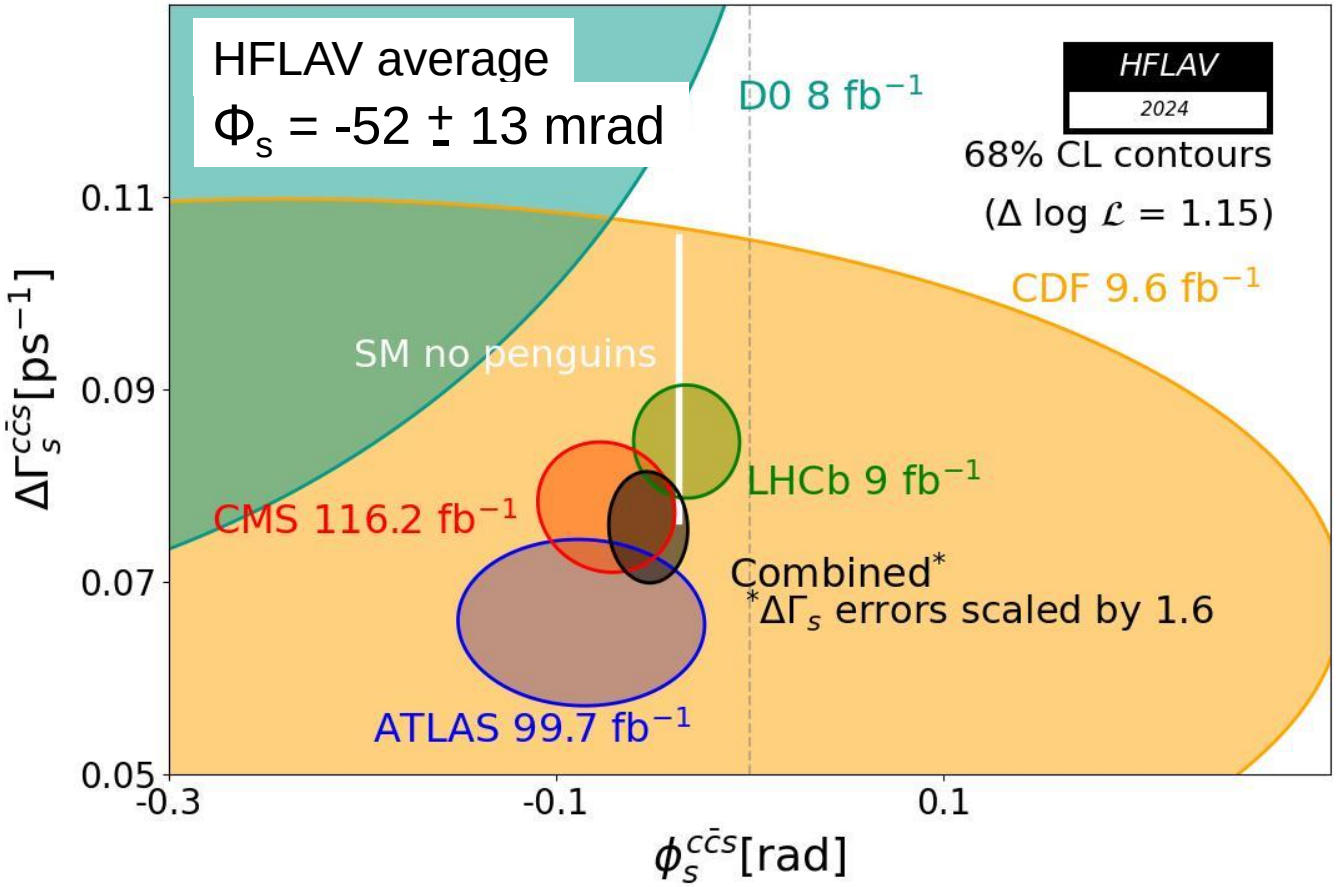


Tevatron and
early LHC data

Run1 & 2 LHC



φ_s : the current state of play

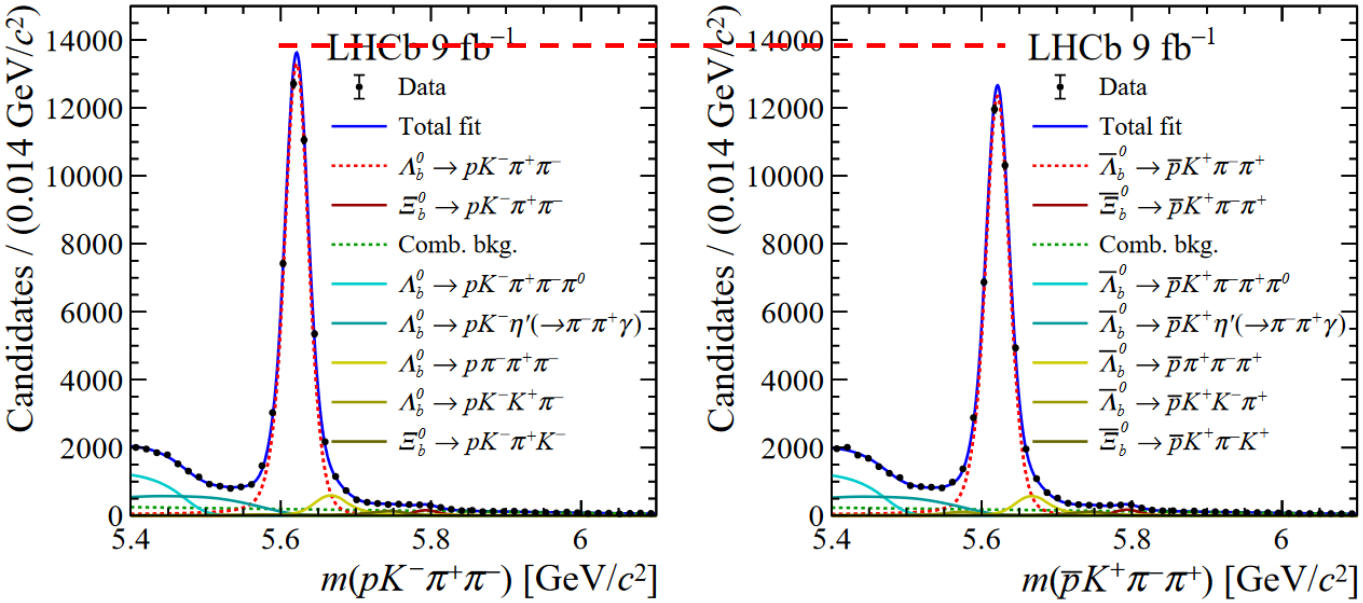


φ_s now measured with 13 mrad precision and so far compatible with SM.
Hint of non-zero value emerging – will be very interesting with Run 3 dataset !

CP violation in beauty – things we did not cover

There are *many* other CPV topics we could have discussed, *e.g.* :

- CPV in baryon decay – recently observed for first time ! [LHCb, arXiv:2503.16954]



- CPV in two-body charmless b-decays – long-standing puzzles !

see *e.g.* [Bhattacharya *et al.*, arXiv:2505.11492]

Flavour Physics at Hadron Colliders

3) New physics searches through studies of Flavour-Changing Neutral Currents

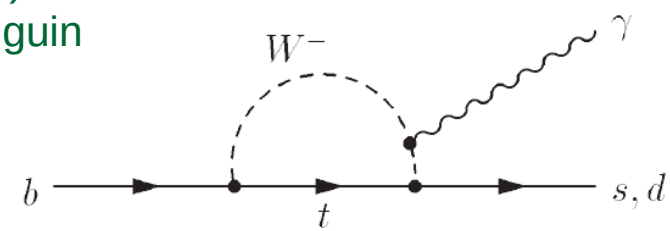
Flavour-changing Neutral Currents (FCNCs) or 'rare decays' as a probe of New Physics

FCNC decays proceed through higher order diagrams → suppressed in SM and susceptible to New Physics contributions.

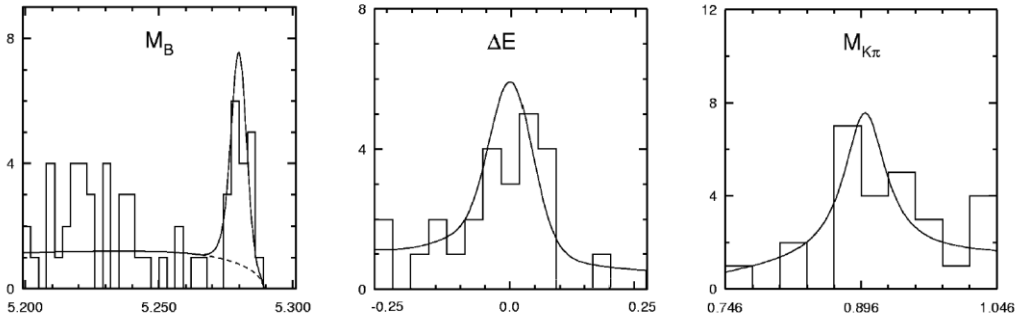
e.g. Penguin diagram (nomenclature introduced by John Ellis in 1977 after lost bet [Ellis *et al.*, NPB 131 (1977) 285].)

Most interesting measurements involve EM & weak penguins, with photon or dileptons – precise predictions.

(EM) Radiative penguin



EM penguin first discovered by CLEO in B→K*(892)γ (BR~10^{-5}) [CLEO, PRL 71 (1993) 674].



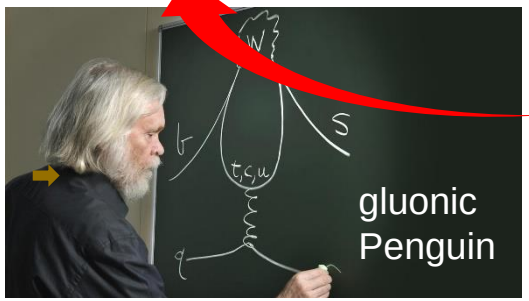
Flavour-changing N[illegible] (FCNCs) or 'rare decays' as a[illegible]sics

Mary K Gaillard

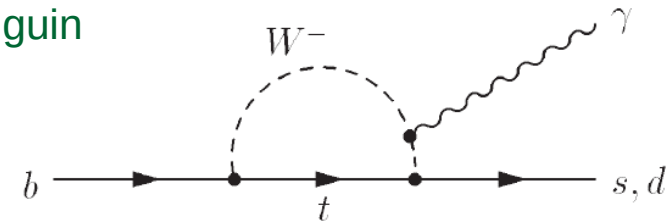
1939 - 2025

FCNC decays proceed through hi[illegible]
suppressed in SM and susceptibl[illegible]

e.g. Penguin diagram (nomencla[illegible]urements involve introduced by John Ellis in 1977 a[illegible] with photon or lost bet [Ellis *et al.*, NPB 131 (1977) 285] [illegible]edictions.



(EM) Radiative penguin



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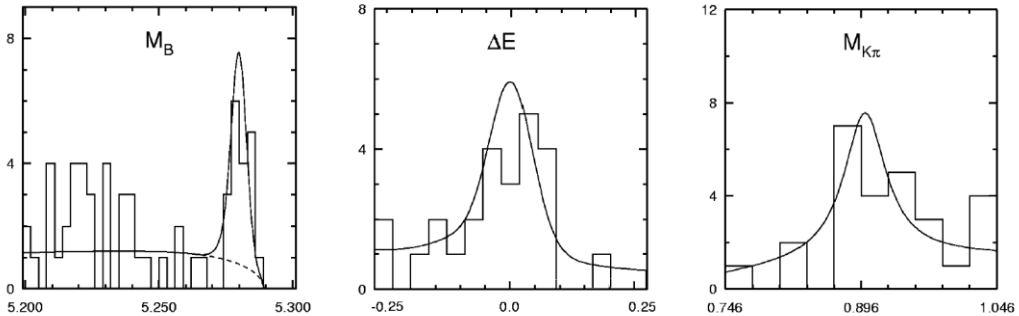
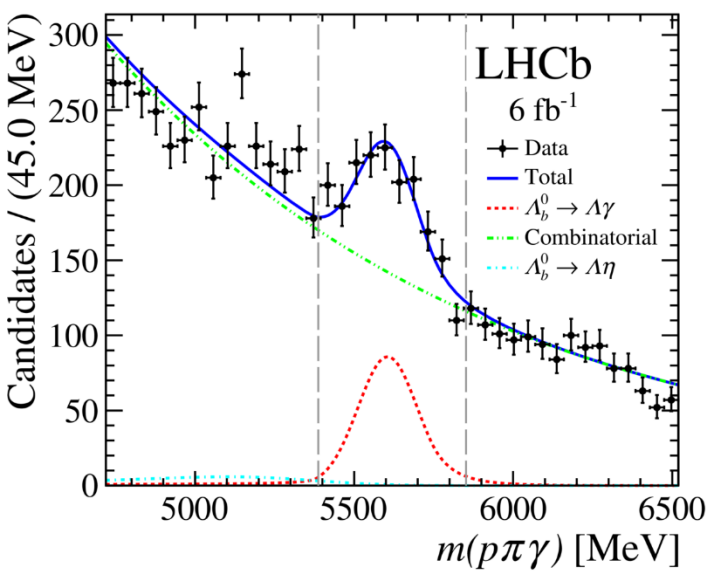
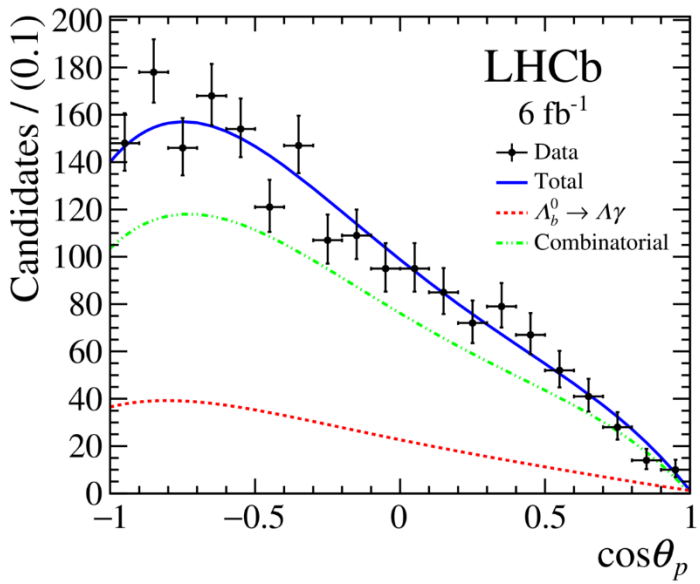


Hadron machines can study b→sγ too

Despite the high background from combinatoric π^0 decays, it is possible to study radiative penguins at the LHC, as the photon is reasonably hard. (what is much more challenging is to look at final states with > 1 neutral, or study b→sγ inclusively – that remains the province of the e^+e^- machines). Unique contributions possible.

e.g. [LHCb, PRD 105 (2022) L051104] reconstruction of $\Lambda^0_b \to \Lambda\gamma$ and measurement of photon polarisation, which is expected to be almost completely left-handed in the SM.





θ_p is angle between p momentum and negative Λ^0_b momentum in Λ rest frame

$$\alpha_\gamma \equiv \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}$$

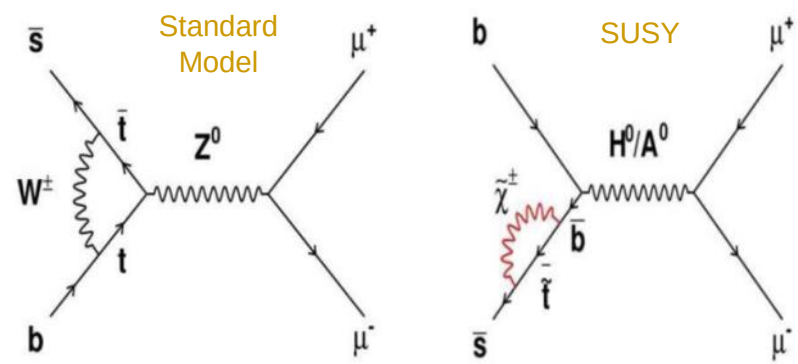
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})^{+0.04}_{-0.13}\,(\text{syst.})$$

i.e. SM like

The golden modes: $B_s \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$

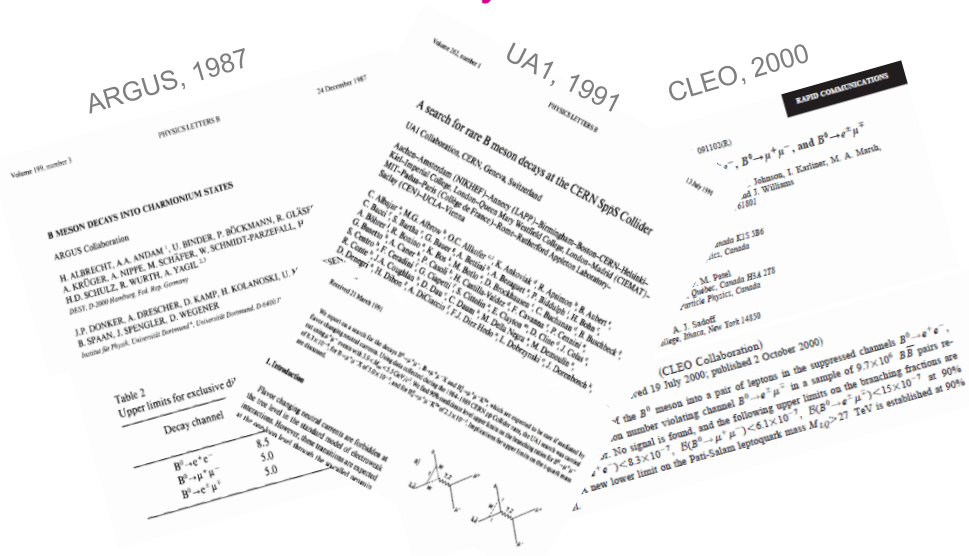
These decay modes can only proceed through suppressed loop diagrams.

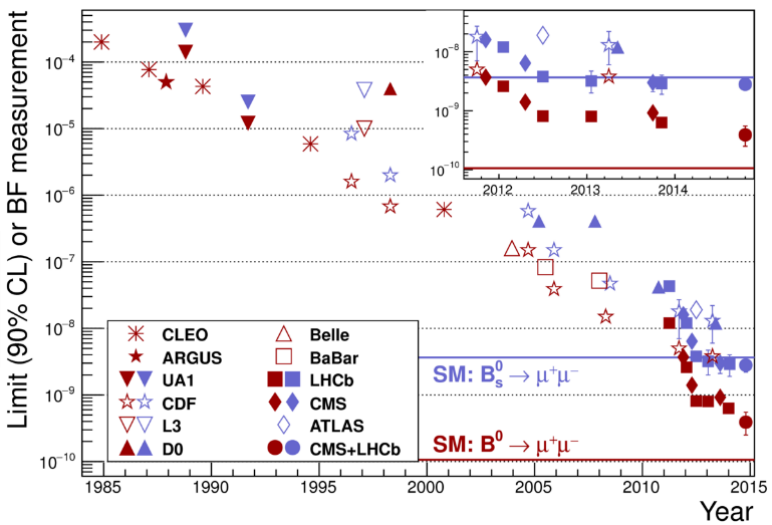
In SM they happen extremely rarely ($B_s \to \mu\mu$ ~4 x 10^{-9}, $B^0 \to \mu\mu$ 30x lower), but the rate is very well predicted (*e.g.* <5% for $B_s \to \mu\mu$).



Many models of New Physics (*e.g.* SUSY) can modify rate significantly !

A 'needle-in-the haystack' search, which has been pursued for over 25 years.

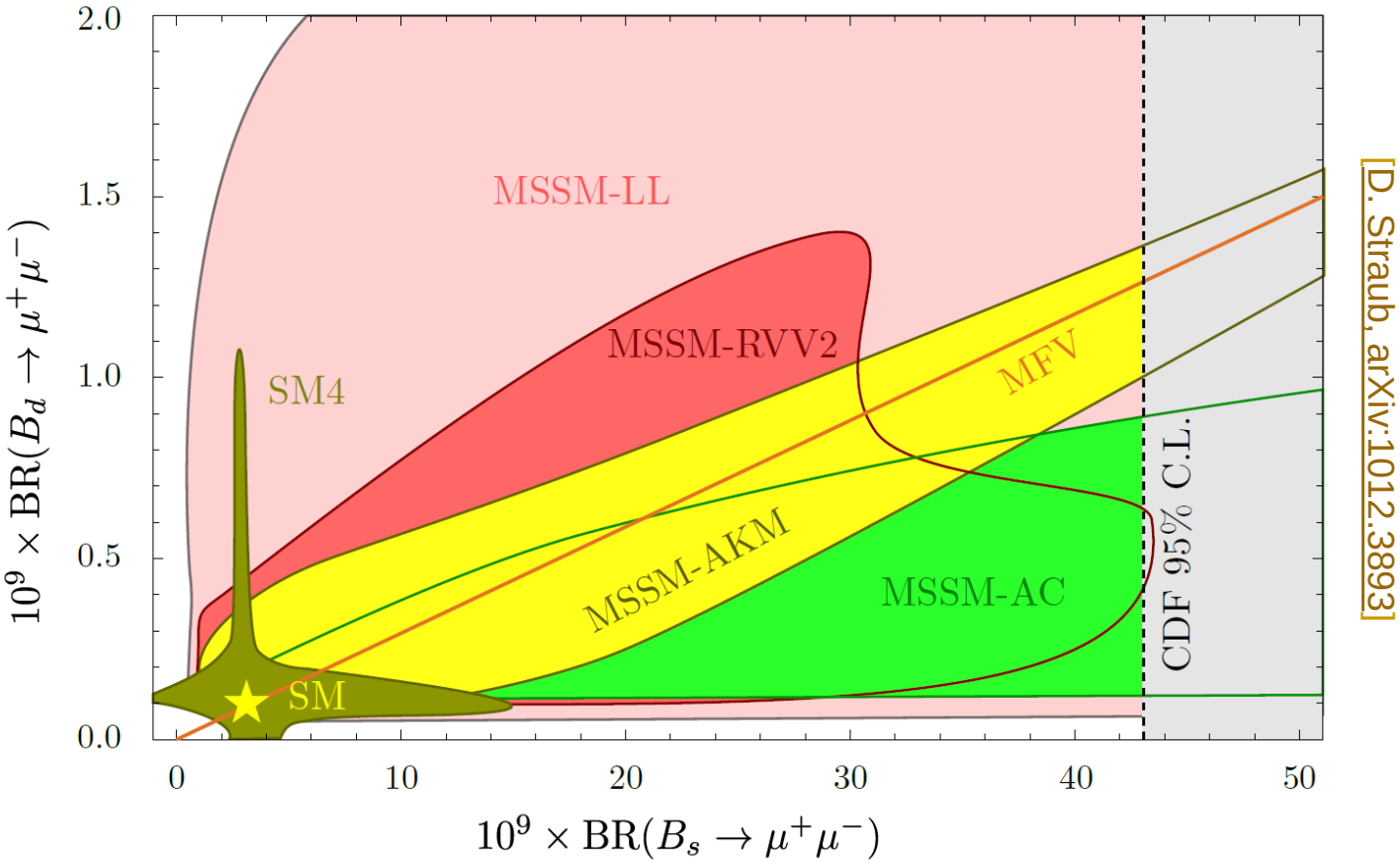




Before the LHC, Fermilab experiments were pushing the limits down towards 10^{-8}.

$B_s \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$: the model killer

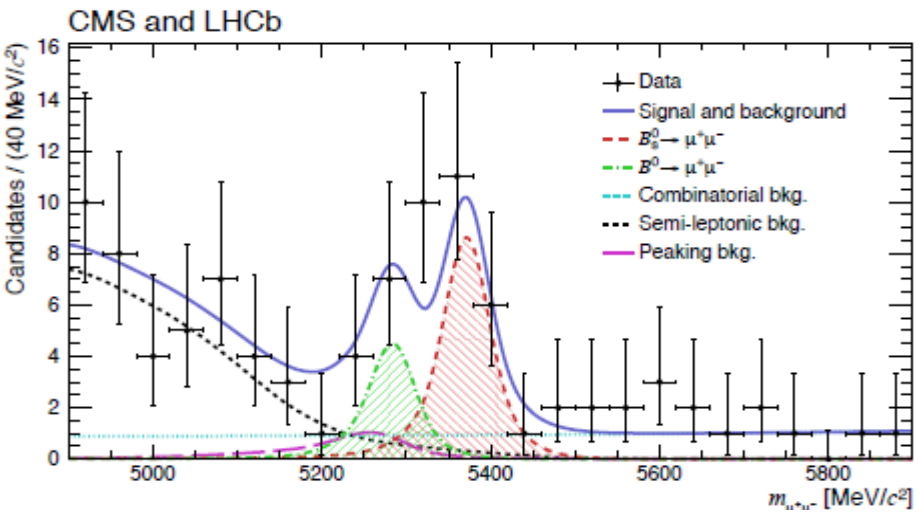
Historical plot from around the turn-on of the LHC, showing how a measurement of the BR of both modes provides powerful discrimination between New Physics models.

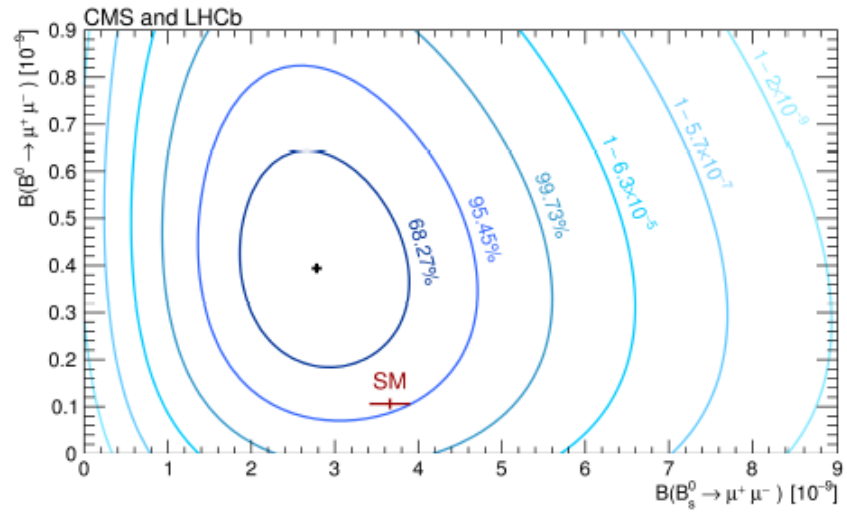


[D. Straub, arXiv:1012.3893]

The search is over: $B_s \to \mu^+\mu^-$ observed !

The signal finally showed up during Run 1, where LHCb found first evidence [PRL 110 (2013) 021801], & then a combined LHCb-CMS analysis yielded a 5σ observation [Nature 522 (2015) 68]. The BR, measured to 25%, agrees with the SM…





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \quad (6.2\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad (3.0\sigma)$$

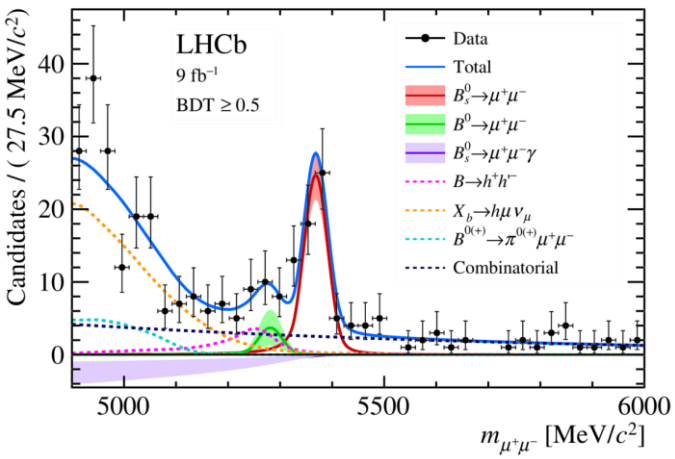
[Nature 522 (2015) 68]

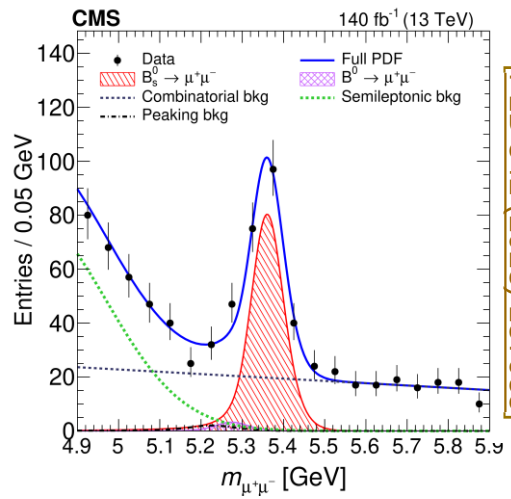
…however the analysis also searched for the even rarer $B^0 \to \mu\mu$. Here there is also a hint of a signal. Picture is intriguing & provided encouragement for Run 2 !

$B^0_{(s)} \to \mu^+\mu^-$ at the LHC: state of play

Recent results available from all experiments. Run 1 & 2 fully analysed by LHCb & CMS. Indicative plots below – these made for different data sets and BDT cuts, so take care when comparing absolute yields, but note different mass resolutions.

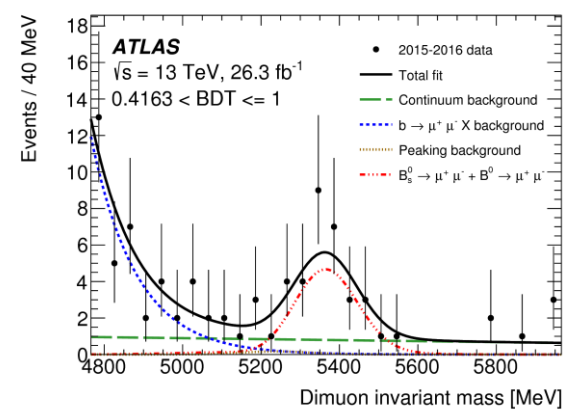
[PRL 128 (2022) 041801]





[PLB 842 (2023) 137955]

[JHEP 04 (2019) 098]



When combined with Run 1:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\ {}^{+0.19}_{-0.16}\,(\text{syst})\ {}^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9}$$

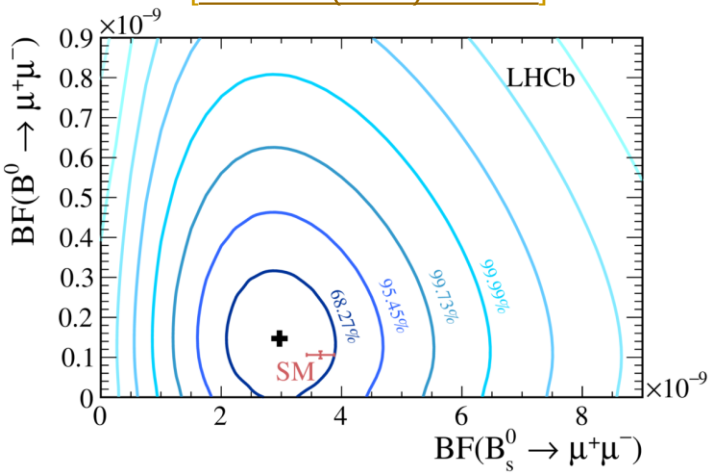
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$

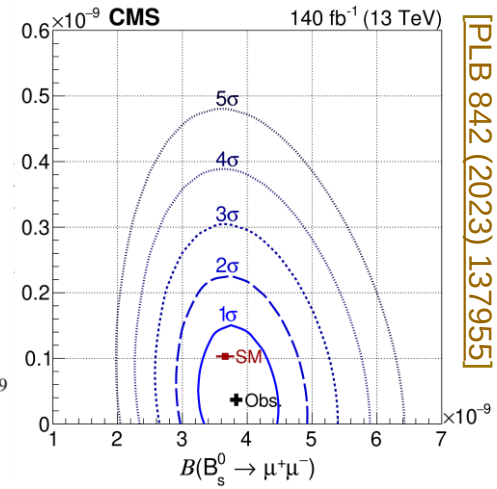
CMS currently has best measurement (this is a flavour-physics measurement well suited to the General Purpose Detectors). Precision ~10%. No sign yet of $B_d \to \mu\mu$.

$B^0_{(s)} \to \mu^+\mu^-$ at the LHC: state of play

No combination of the current individual LHC measurements yet exists…

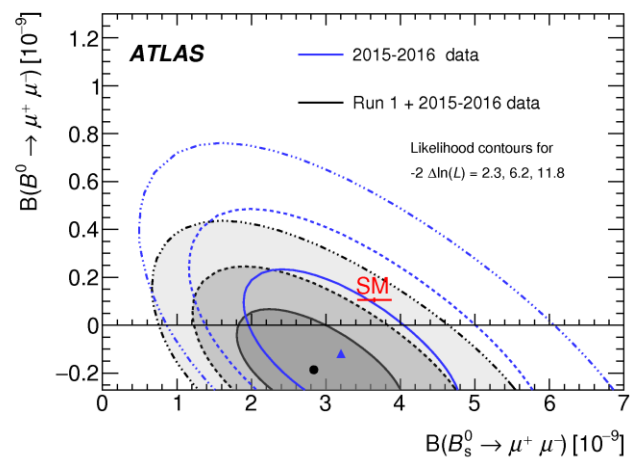
[PRL 128 (2022) 041801]





[PLB 842 (2023) 137955]

[JHEP 04 (2019) 098]



…but the overall picture is clear: broad consistency with the Standard Model.

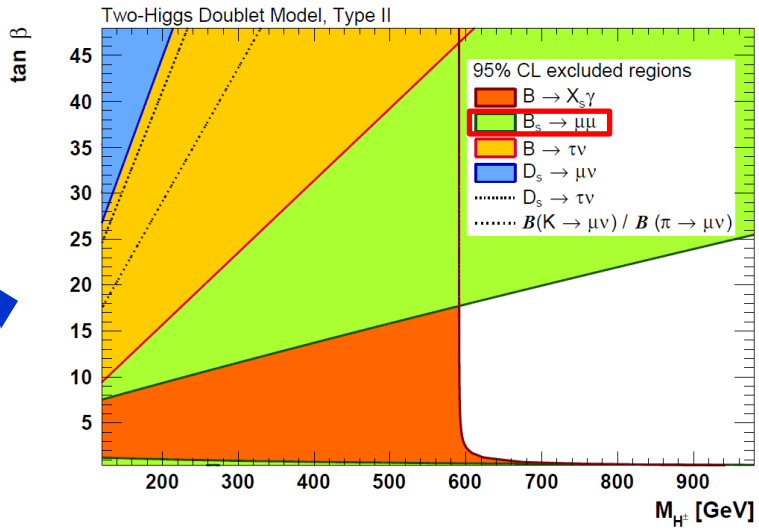
Achieving such precision on this rare process is a major achievement of LHC era !

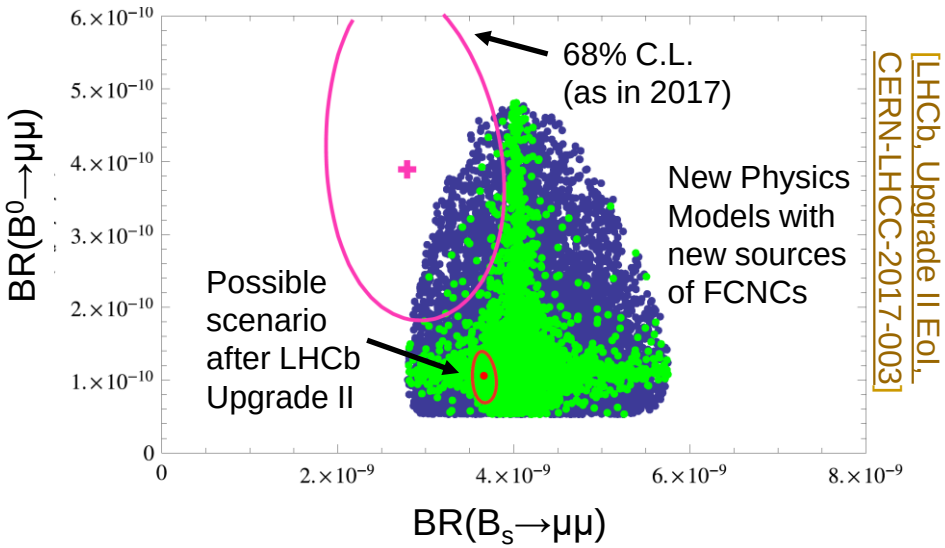
Lessons from, & future of, $B^0_{(s)} \to \mu\mu$ measurements

- Prior to LHC turn on, an enhanced $BR(B_s \to \mu\mu)$ was one of the great hopes for a rapid discovery of New Physics. This hope has not been realised.

- Nonetheless, the absence of an enhancement is a very powerful input in excluding certain classes of New Physics model.

  e.g. 95% CL excluded region in $M_{H^\pm}$ vs. tanβ space for two-Higgs doublet model [Gfitter group, Hallet *et al.*, EPJC 78 (2018) 675].





[LHCb, Upgrade II EoI, CERN-LHCC-2017-003]

- Better measurements are *essential*, as we are still far from theory limit (which will improve). Even truer for ratio $BR(B_s \to \mu\mu)/BR(B^0 \to \mu\mu)$. These decays still have much to tell us!

- Next step in the journey will be observation of $B^0 \to \mu\mu$.

Unlocking new observables with $B_s \to \mu^+\mu^-$

Remarkably, the sample of $B_s \to \mu\mu$ decays now available is sufficient to begin probing new observables. *E.g.*, since the sample is in fact constituted of both B_s & $B_s$bar mesons, a lifetime measurement brings very valuable new information.

The effective lifetime [K. De Bruyn *et al.*, PRL 109 (2012) 041801] :

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1 - y_s^2}\left(\frac{1 + 2A_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1 + A_{\Delta\Gamma}^{\mu^+\mu^-} y_s}\right)$$

where

- $y_s \equiv \tau_{B_s^0}\Delta\Gamma/2 \approx 0.06$, $\Delta\Gamma$ being the lifetime splitting between the mass eigenstates;
- $A^{\mu\mu}_{\Delta\Gamma}$ is a term that is 1 in SM, but can take any value between -1 & 1 for New Physics.

Accessing $A^{\mu\mu}_{\Delta\Gamma}$ through $\tau_{\mu\mu}$ tells us things that the BR alone does not.

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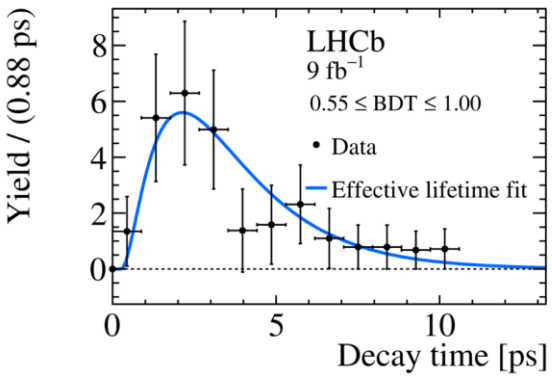
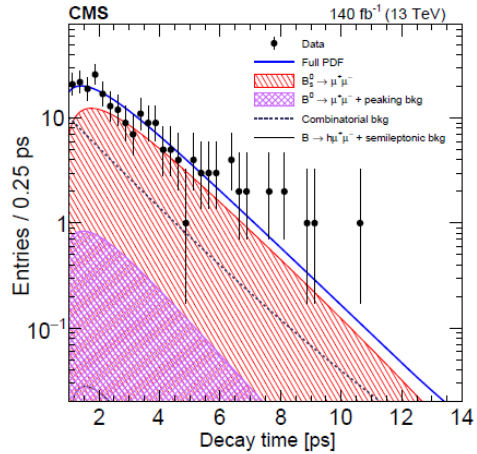
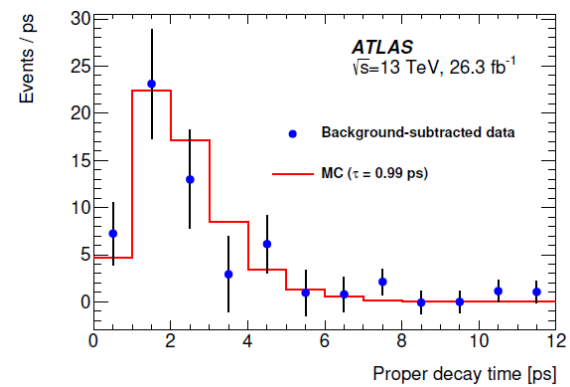
Proof-of-principle measurements conducted by all three experiments:



[PRL 128 (2022) 041801]



[PLB 842 (2023) 137955]



[JHEP 09 (2023) 199]

$\tau(B_s^0 \to \mu^+\mu^-) = (2.07 \pm 0.29 \pm 0.03)$

$\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\,\text{ps}$

$0.99^{+0.42}_{-0.07}\,(\text{stat.}) \pm 0.17\,(\text{syst.})\,\text{ps}$

Precision: 14% 12% 30%

During HL-LHC era these will reach very interesting levels of precision.

One may also dream of performing flavour-tagged CP asymmetry measurements !

Unlocking new observables with $B_s \to \mu^+\mu^-$

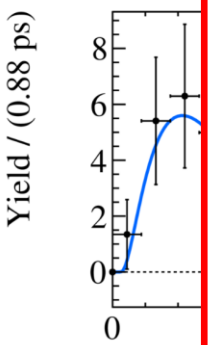
Remarkably, the sample of $B_s \to \mu\mu$ decays now available is sufficient to begin probing new observables. *E.g.*, since the sample is in fact constituted of both B_s & $B_s$bar mesons, a lifetime measurement brings very valuable new information.

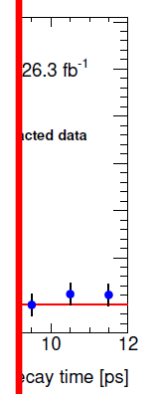
Proof-

In addition to the improved measurement of BF(Bs→μμ), its effective lifetime, & the search for $B^0 \to \mu\mu$, other tasks include:

- Search for $B_s \to \mu\mu\gamma$ [JHEP 07 (2024) 101] ;
- Search for $B^0_{(s)} \to ee$ [PRL 124 (2020) 211802] and $B^0_{(s)} \to \tau\tau$ [PRL 118 (2017) 251802];
- Measure CP asymmetries in $B_s \to \mu\mu$.

The HL-LHC has much to do !





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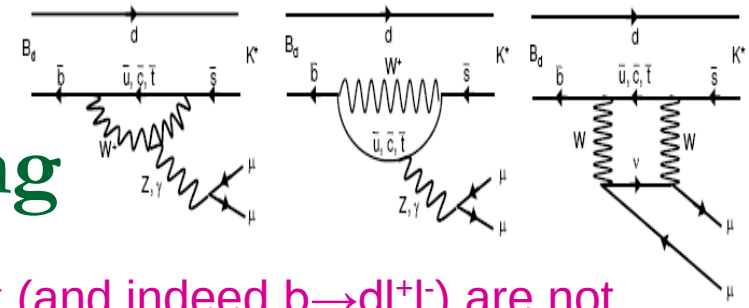
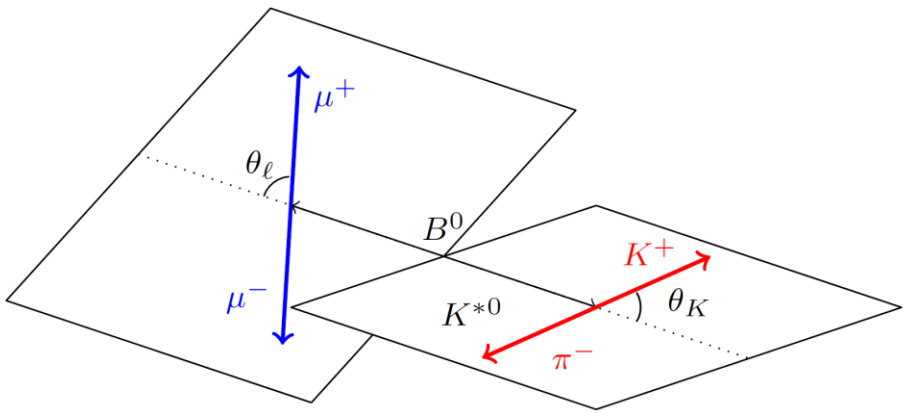
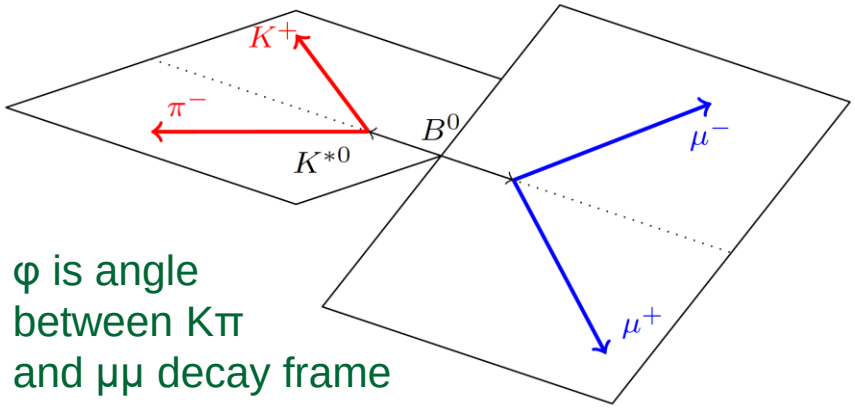
$B^0 \to K^* l^+ l^-$ and friends – the gift that keeps on giving



FCNC processes involving the transition $b \to s l^+ l^-$ (and indeed $b \to d l^+ l^-$) are not ultra rare, but provide an exceedingly rich set of observables to probe for NP effects, that are sensitive to non-SM helicity structures (and more).

Many realisations, but the poster-child decay is $B^0 \to K^{*0} l^+ l^-$, with $K^{*0} \to K^+ \pi^-$.

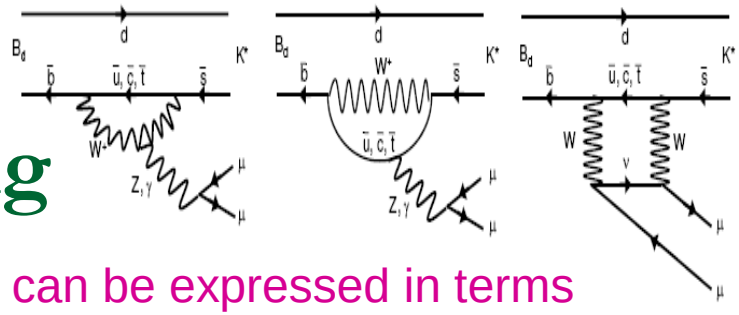




φ is angle between Kπ and μμ decay frame

Four-body final state can be characterised in terms of three angles, Θ_l, θ_K and φ, & q^2, & the invariant-mass of the dilepton pair (see *e.g.* [LHCb, JHEP 02 (2016) 104]).

$B^0 \to K^* l^+ l^-$ and friends – the gift that keeps on giving



Differential cross-section w.r.t. solid angle and q^2 can be expressed in terms of eight coefficients: F_L, A_{FB} and S_i (other choices are available):

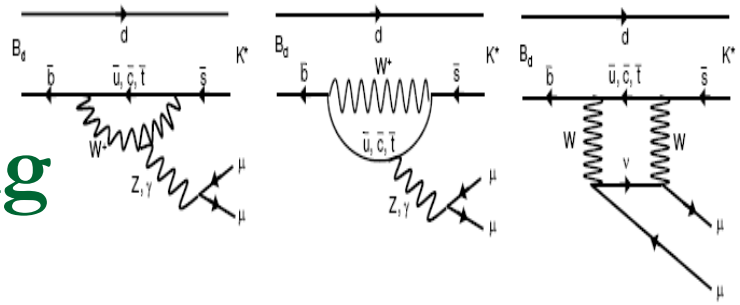
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

Note, this is the CP-averaged expression (*i.e.* assuming no CPV).

F_L – fraction of longitudinal polarisation of K*

A_{FB} – forward-backward asymmetry of dilepton pair in B-meson frame

$B^0 \to K^* l^+ l^-$ and friends – the gift that keeps on giving



Three practical considerations:

1. Analysis must allow for an S-wave contribution in Kπ system, in addition to P wave that comes from K*(892) – important, but we won't discuss it here.
2. In pp environment, it is easier to reconstruct muons than electrons, so unless stated, measurements are made with di-muon final state.
3. Form-factor (*i.e.* QCD) uncertainties in predictions of coefficients can be reduced by changing to a set of optimised observables [Descotes-Genon *et al.*, JHEP 01 (2013) 048], in which first order uncertainties cancel, *i.e.* more robust:

$$P_1 = \frac{2\,S_3}{(1-F_{\rm L})} = A_{\rm T}^{(2)}\,, \qquad P_3 = \frac{-S_9}{(1-F_{\rm L})}\,, \qquad P_6' = \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,.$$

$$P_2 = \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})}\,, \qquad P_{4,5,8}' = \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,,$$

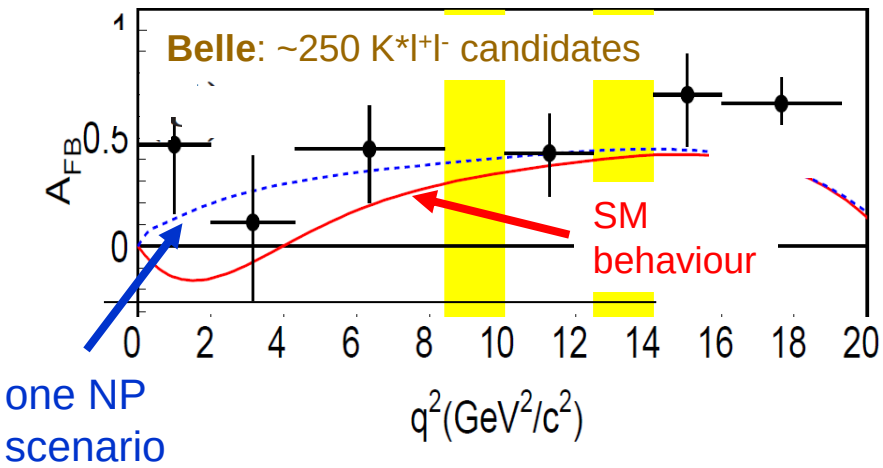
(LHCb definitions, see [JHEP 02 (2016) 104])

Hard to visualise what these mean, but they can be predicted in SM, & in terms of general NP predictions, rather well. Also very robust against detector bias !

$B^0 \to K^* l^+ l^-$ - impact of the LHC

The B factories studied $B^0 \to K^* l^+ l^-$ with enthusiasm. Initial results, *e.g.* for forward-backward asymmetry, were intriguing. But sample sizes inadequate for firm conclusions. Situation changed with the turn-on of the LHC.

[PRL 103 (2009) 171801]



(NB: the J/ψ and ψ' regions are excluded, as these ccbar resonances occur through tree-level processes and do not probe physics we are interested in.)

$B^0 \to K^* l^+ l^-$ - impact of the LHC

(unless stated otherwise, lepton at LHC means muon)

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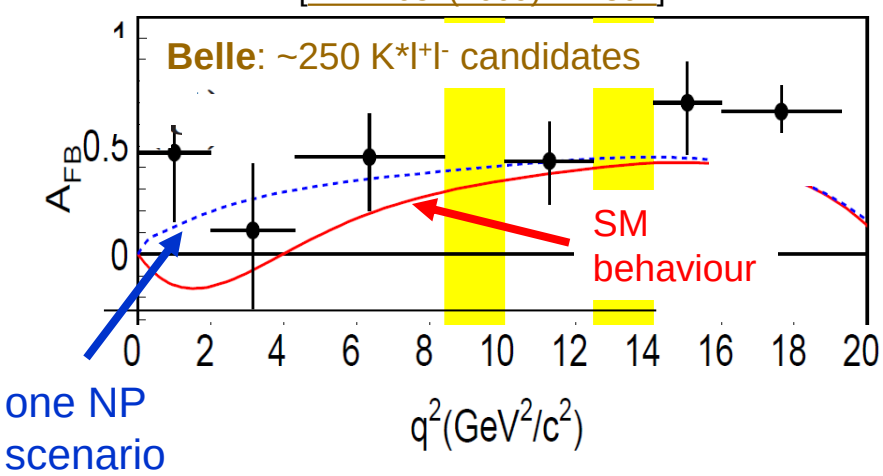
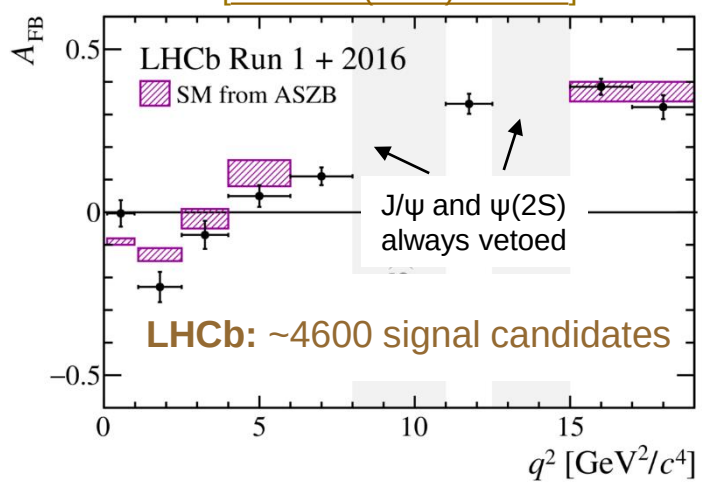


[PRL 125 (2020) 011802]



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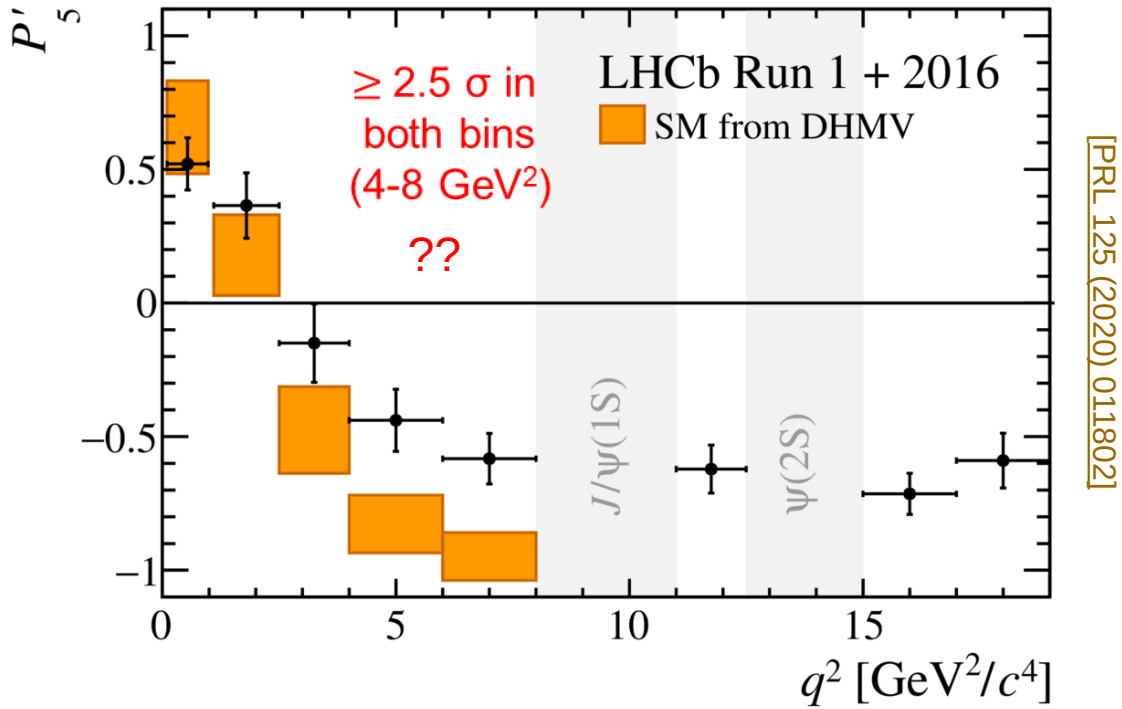
Hints of non-SM behaviour in early analyses not confirmed by high-statistics measurement (although mild tension at low q^2). What about 'optimal observables' ?

$B^0 \to K^* l^+ l^-$ and friends: the P_5' puzzle

The 'optimum observable' that has attracted most attention is P_5'. A deviation at low q^2, first seen in early LHCb analysis [PRL 108 (2012) 181806], persisted with full Run 1 + early Run 2 data set [PRL 125 (2020) 011802], & is not contradicted by other experiments.



[PRL 125 (2020) 011802]

A word of caution. The SM uncertainties shown here are from one group. There are other values on the market, and some are more conservative. Meanwhile, work is ongoing to constrain QCD uncertainties from data, *e.g.* [LHCb, EPJ C77 (2017) 161].

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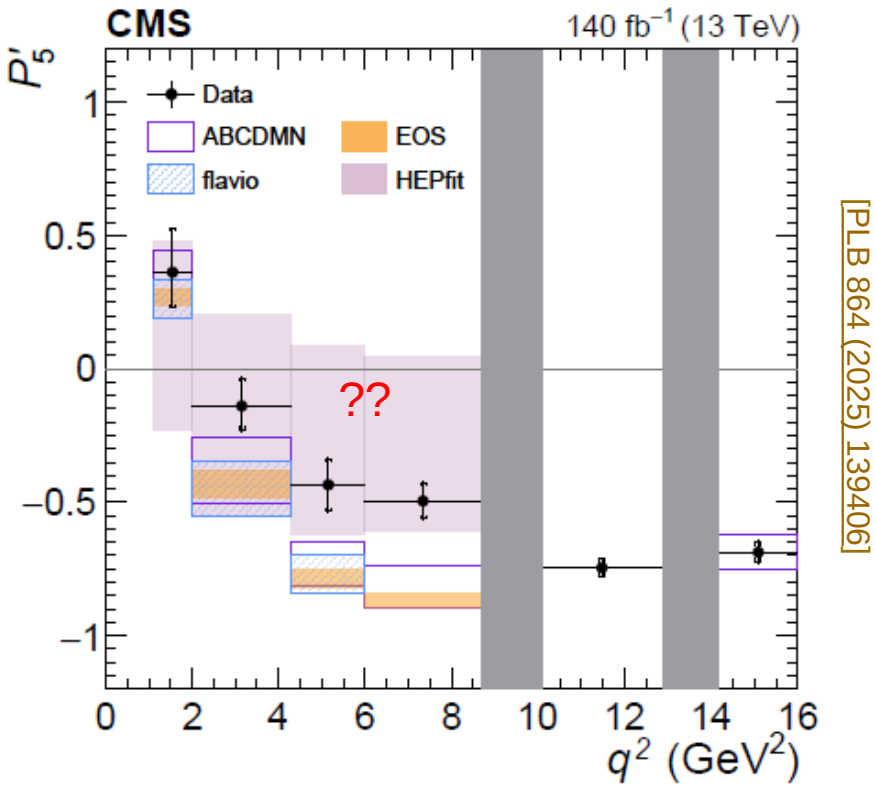

[PLB 864 (2025) 139406]

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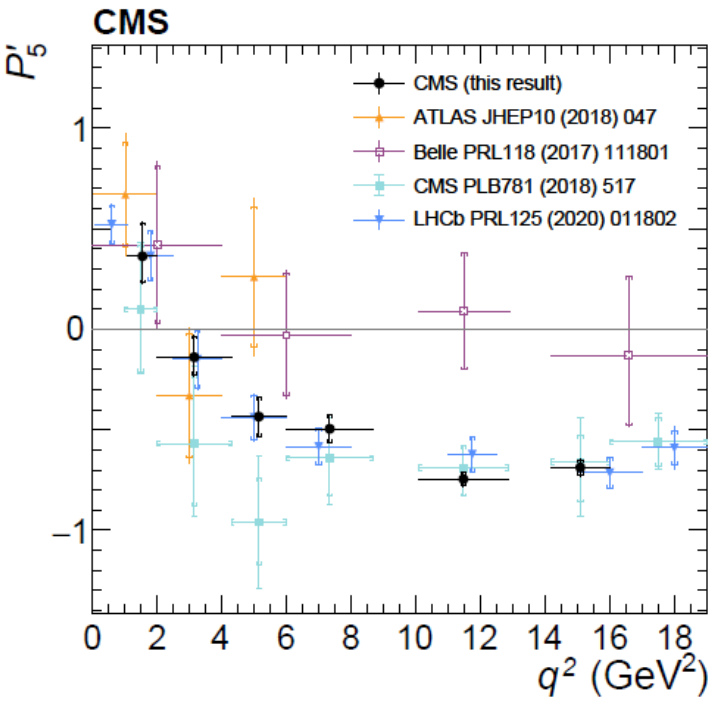
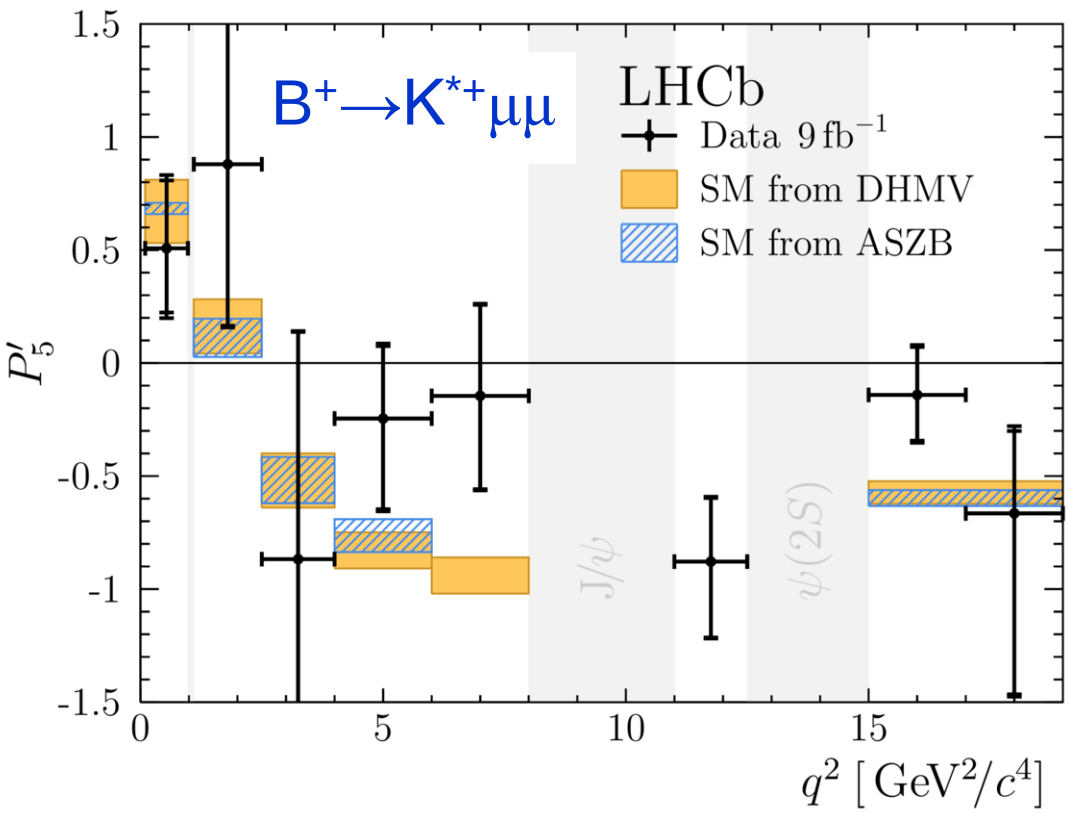


[LHCb, PRL 125 (2020) 011802]
[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]
[CMS, PLB 864 (2025) 139406]

Looks to be a genuine effect, and P_5' is not the only observable that shows tension.

$B^0 \to K^* l^+ l^-$ and friends: the P_5' puzzle

Measurements of the same / similar observables in different channels (*e.g.* $B^+ \to K^{*+}\mu\mu$ [PRL 126 (2021) 161802], $B_s \to \phi\mu\mu$ [JHEP 11 (2021) 043]) although less precise, provide a qualitatively similar picture.

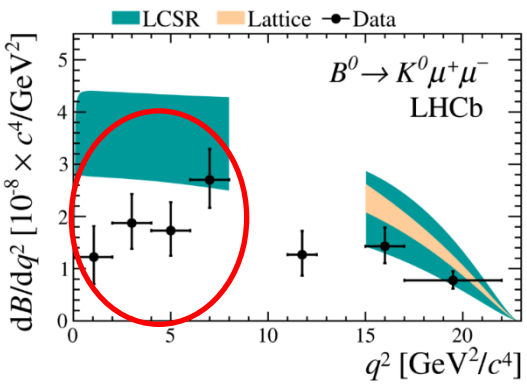


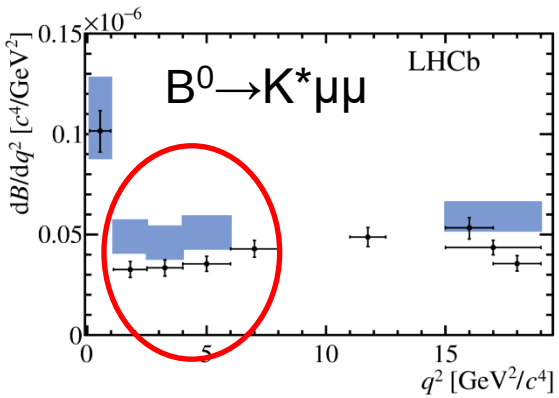
[LHCb, PRL 126 (2021) 161802]

$B^0 \to K^* l^+ l^-$ and friends: differential x-secs

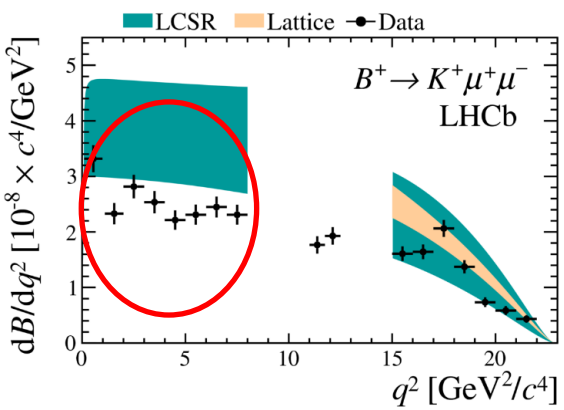
P_5' is not the only funny thing going on in $b \to (s,d) l^+ l^-$ decays.

[JHEP 06 (2014) 133]



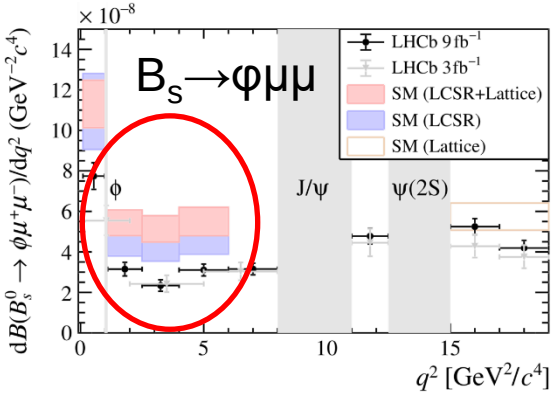


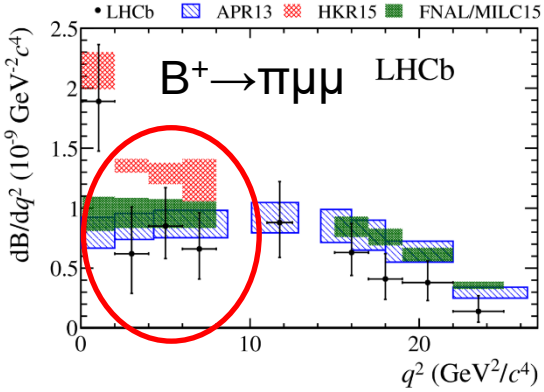
[JHEP 04 (2017) 142]



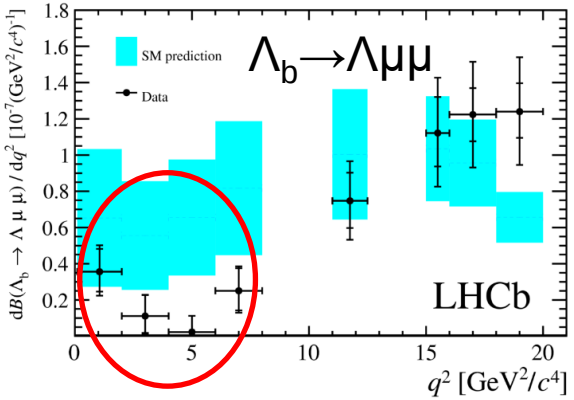
[JHEP 06 (2014) 133]

[PRL 127 (2021) 151801]





[JHEP 10 (2015) 034]

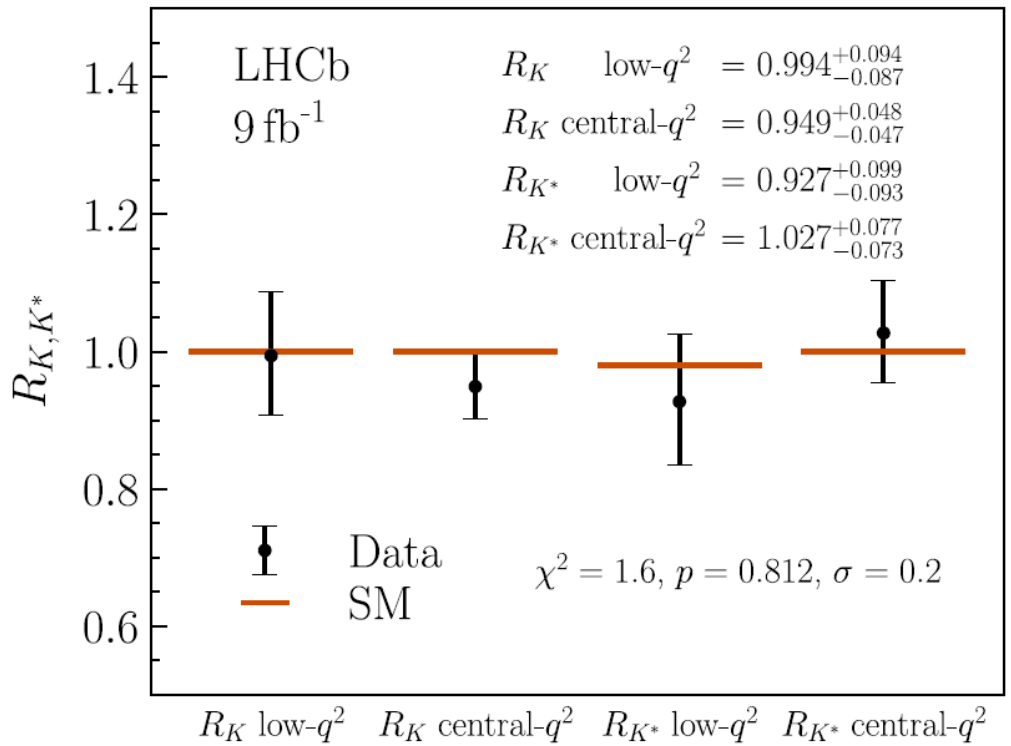


[JHEP 06 (2015) 009]

All measurements undershoot prediction at low q^2. Intriguing – but maybe the uncertainties in theory are larger than claimed, or is there a common systematic ?

$B^0 \to K^* l^+ l^-$ and friends: lepton-universality tests

I have chosen to say nothing about lepton-universality tests (R_K, R_{K^*}), concerning the relative rates of b→sμμ and b→see. For now, IMO, this discussion is over, and should not distract from the other intriguing questions that b→sll decays are asking.

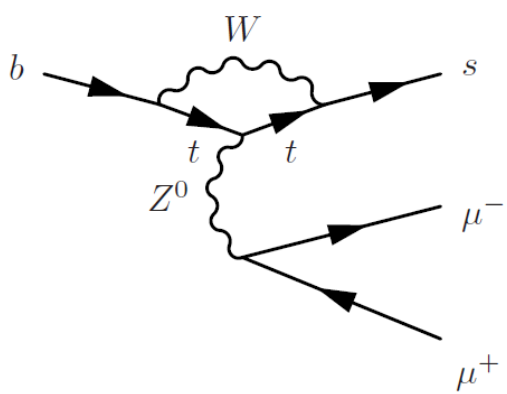


[PRL 131 (2023) 051803, PRD 108 (2023) 032002]

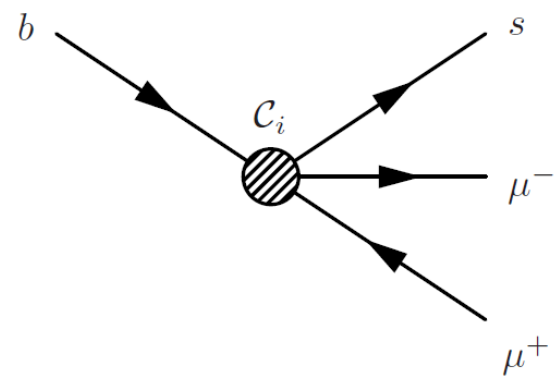
Analysing FCNC data in context of effective field theory

The $b \to s l^+ l^-$ results can be analysed in the context of effective field theory.

Real theory



Effective theory



$$\mathcal{A}(i \to f) = \langle f | \mathcal{H}_{eff} | i \rangle$$

See, *e.g.* [Buchalla *et al.*, Rev. Mod. Phys. 68 (1996) 1125].

Analysing FCNC data in context of effective field theory

Operator product expansion:

$$H_{eff} \propto V_{tb} V_{ts}^* \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

Model independent ! Expansion performed in a complete basis of four-body operators that contribute differently to each FCNC process.

$$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$
$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu l)$$
$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l)$$
$$O_S^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l} l)$$
$$O_P^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l}\gamma_5 l)$$

Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$b \to s\gamma$	X			
$b \to \ell^+\ell^-$			X	X
$b \to s\ell^+\ell^-$	X	X	X	

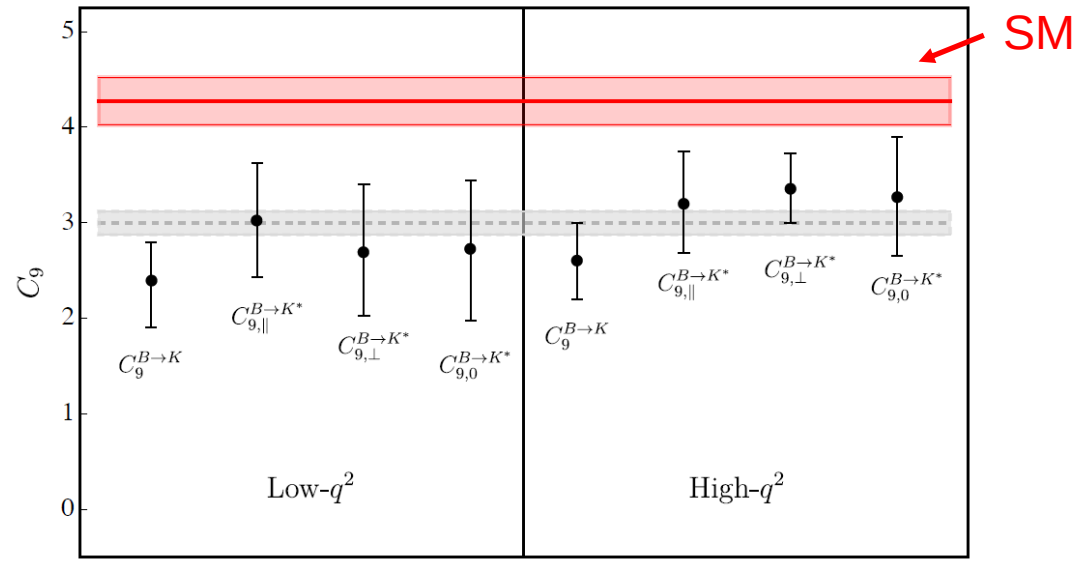
C_i are the *Wilson coefficients*. Calculable in SM, but can be affected by New Physics.

Analysing FCNC data in context of effective field theory

A key question, however, is whether short-term physics, encoded in the Wilson coefficients (with C_9 being of particular interest in b→sll), can be extracted independently of SM long-distance effects from charm re-scattering.

e.g. analysis using dispersive approach with CMS & LHCb B→K*μμ B→Kμμ data [Bordone *et al.* , arXiv:2401.18007].

C_9 determined in two q^2 bins and separately for different helicity amplitudes.



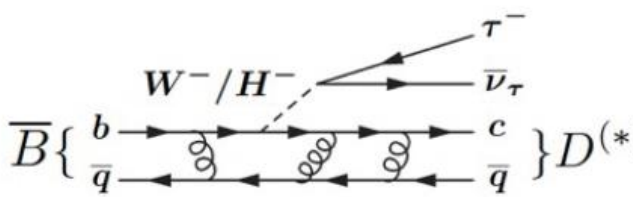
Results show a ~25% offset w.r.t. SM. Self-consistency of results is encouraging, as charm re-scattering effects would not be expected to be independent of q^2.

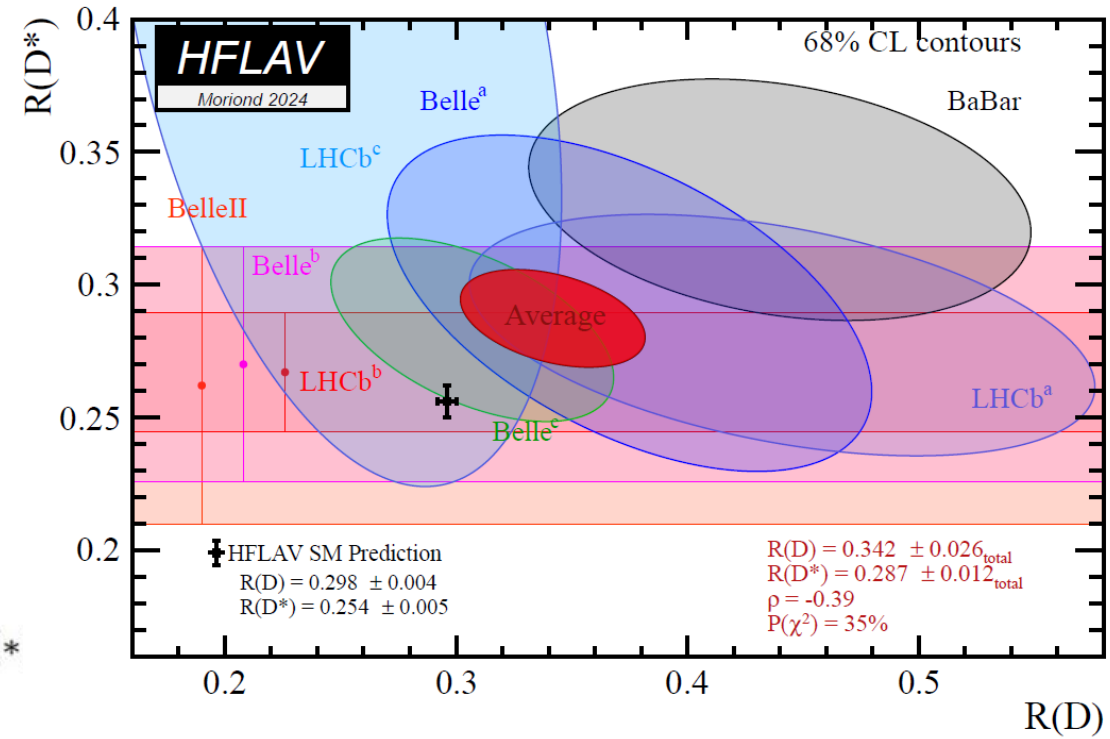
See also LHCb amplitude analysis of K*μμ [PRL 132 (2024) 131801, PRD 109 (2024) 052009].

Trouble with trees: hints of third generation lepton-universality violation

There is another class of decays, b→clv, (tree level – not a FCNC!) where there is a stubborn longstanding tension between data and the SM expectation.

$$R(D^{(*)}) \equiv \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$$



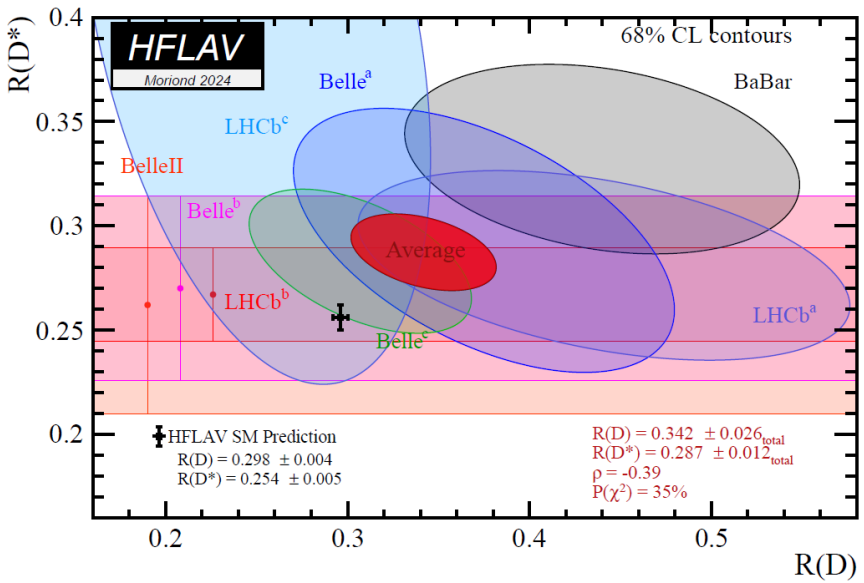


Studies originally motivated by sensitivity to charged Higgs, but results do not favour this explanation and fit better with leptoquark explanation. Tree-level process, so this New Physics particle has to be quite light to compete with SM.

Missing energy means that measurements are ideal for B-factories, but competitive studies have come from LHCb in a variety of channels.

R(D)-R(D*) anomaly

Remarkable that these measurements can be performed at LHC, but very hard !



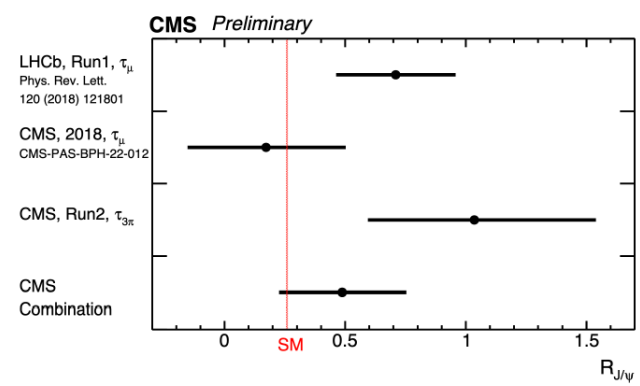
[plot and references – HFLAV]

Tension currently at 3.3σ. Compare with 2015, when it was 3.9σ – many new measurements have appeared in past decade, but overall tension changes little !

A unique complementary contribution at LHC:

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)}$$

LHCb Run 1 [PRL 120 (2018 121801] and CMS Run2 [CMS-PAS-BPH-23-001] . Keep watching this space !



Flavour Physics at Hadron Colliders

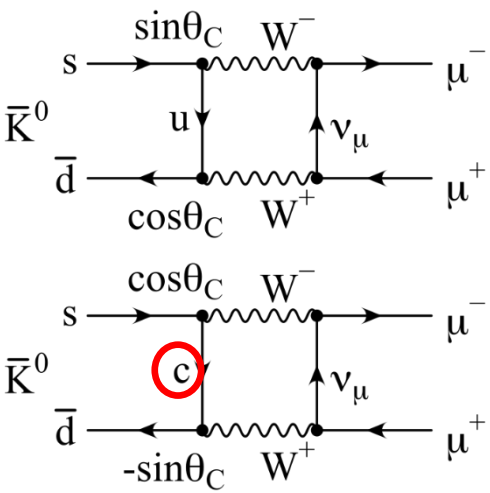
4) Charm physics at the LHC

Charm – a glorious history

Charm played a key role in the foundation of the Standard Model of particle physics.

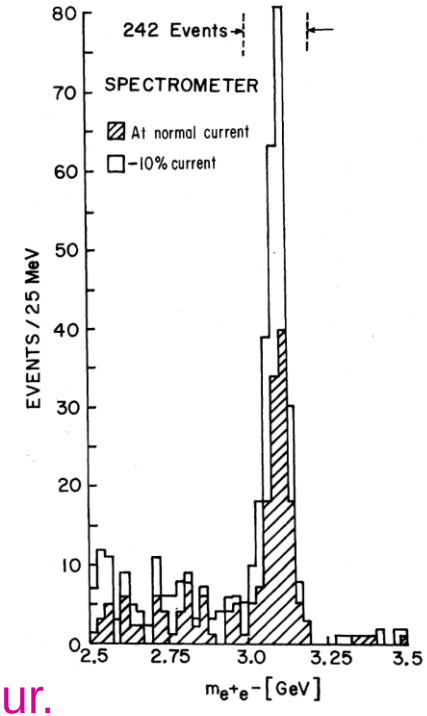
[Glashow, Iliopoulos & Maiani, PRD 2 (1970)1285]

Its existence was predicted to explain the suppression of $K_L \to \mu\mu$



This 'GIM mechanism' is central to the flavour structure of the SM.

The discovery of the J/ψ, in 1974, brought immediate acceptance of the existence of quarks.



[J.-E. Augustin *et al.*, PRL 33 (1974) 1406]

[J.J. Aubert *et al.*, PRL 33 (1974) 1404]

But since then charm has largely fallen out of favour.

"I know she invented fire, but what has she done recently?" [I. Bigi, arXiv:0808.1773]

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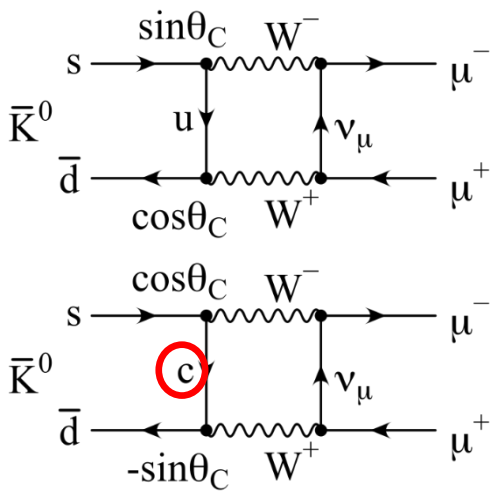

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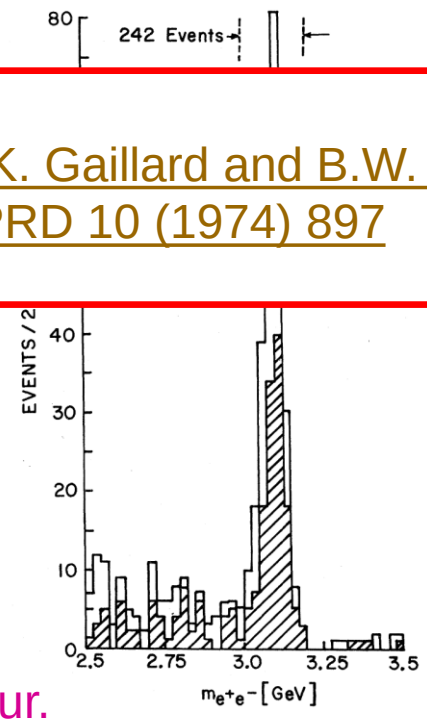
See M.K. Gaillard and B.W. Lee, PRD 10 (1974) 897



[J.-E. Augustin et al., PRL 33 (1974) 1406]

[PRL 33 (1974) 1404]

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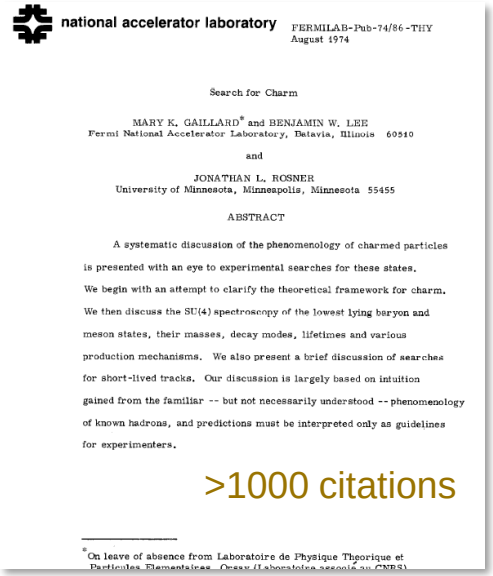
Giants of the field, who left us in May 2025

Jon Rosner was another hugely important figure in flavour physics, who worked with MKG in the early days of charm, and continued to write seminal papers in flavour and spectroscopy until last year.



national accelerator laboratory FERMILAB-Pub-74/86-THY August 1974

Search for Charm

MARY K. GAILLARD* and BENJAMIN W. LEE
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

JONATHAN L. ROSNER
University of Minnesota, Minneapolis, Minnesota 55455

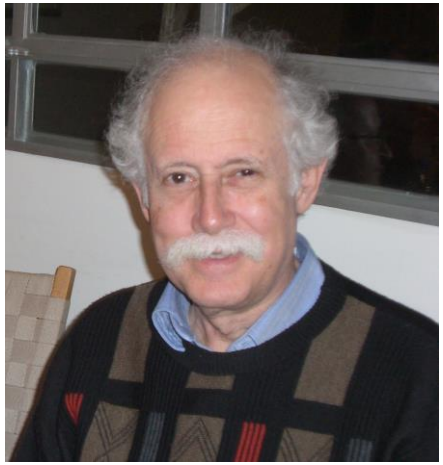
ABSTRACT

A systematic discussion of the phenomenology of charmed particles is presented with an eye to experimental searches for these states. We begin with an attempt to clarify the theoretical framework for charm. We then discuss the SU(4) spectroscopy of the lowest lying baryon and meson states, their masses, decay modes, lifetimes and various production mechanisms. We also present a brief discussion of searches for short-lived tracks. Our discussion is largely based on intuition gained from the familiar -- but not necessarily understood -- phenomenology of known hadrons, and predictions must be interpreted only as guidelines for experimenters.

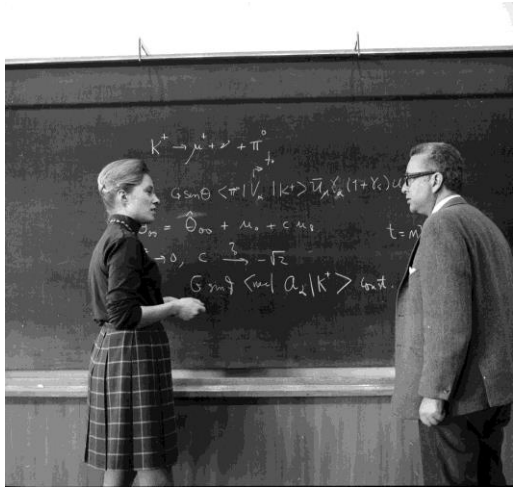
*On leave of absence from Laboratoire de Physique Theorique et Particules Elementaires, Orsay (Laboratoire associé au CNRS)

>1000 citations

[Rev. Mod. Phys. 47 (1975) 277]



Jon Rosner, 1941-1925



Mary K Gaillard, 1939-2025
(and Murray Gell-man, CERN, 1972)

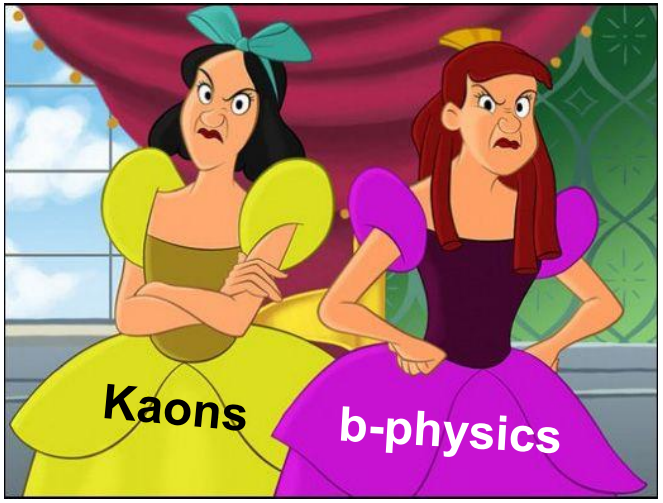
See also, the MaryKFest in 2019, at which Jon Rosner spoke. And read MKG's reflections here.

Charm – the years of neglect

In flavour studies, charm has certain disadvantages compared to strange & beauty:

1. Neutral meson mixing effects (see later) expected to be very small;
2. CPV effects also expected to be very small;
3. Theoretical predictions somewhat imprecise, because of hadronic effects, which are resistant to techniques developed for handling the 'light' kaon system and the 'heavy' beauty system.

Due to these reasons, and due to ~30 years of experiment confirming 1 & 2, charm became the 'Cinderella' of flavour studies, being eclipsed by her step-sisters.



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Yet, this neglect was always unjustified:

- Points 1 & 2 can be seen positively, as very small expectations in the Standard Model provides a low 'background' above which larger New Physics effects may manifest themselves.
- In contrast to strange and beauty, charm is an up-type quark, which gives it unique access to potential New Physics effects.

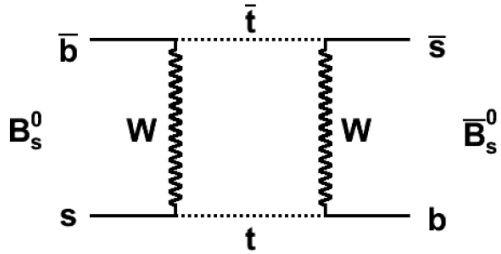
And indeed, early this century, charm's fairy-godmother moment arrived.

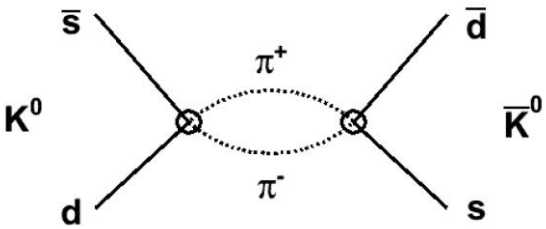
Neutral meson mixing - reminder

Flavour oscillations, or mixing, are an important phenomenon in neutral meson physics, and for have been established for many years in K^0, B^0 and B^0_s systems.

Caused by either: or:

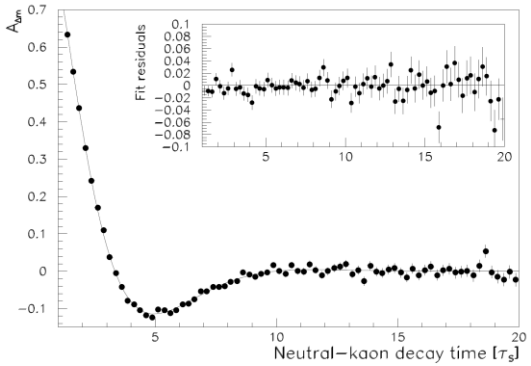
Virtual, short-range (box diagrams)



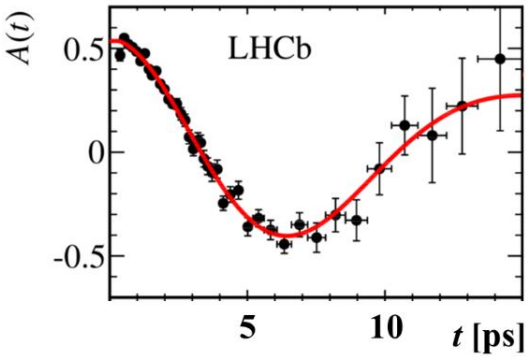


On-shell, long-range (common intermediate states)

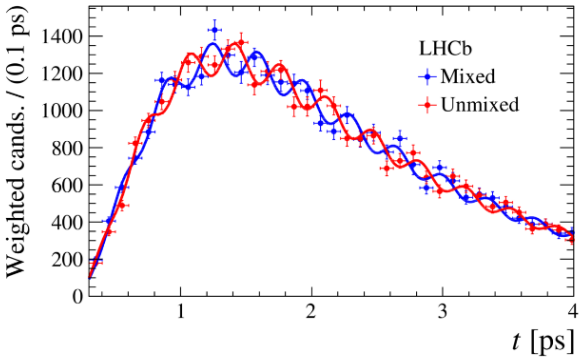
Slow for K^0 mesons … quicker for B^0 mesons… even quicker for B^0_s mesons.



[CPLEAR, PLB 444 (1998) 38]



[LHCb, EPJC 76 (2016) 412]



[LHCb, EPJC 79 (2019) 706]

Of great interest, because box diagrams are sensitive to possible New Physics effects, modifying the oscillation frequency, and also because the process provides several ways for CP violation to manifest itself ('indirect CPV').

D^0-$\overline{D}^0$ oscillations

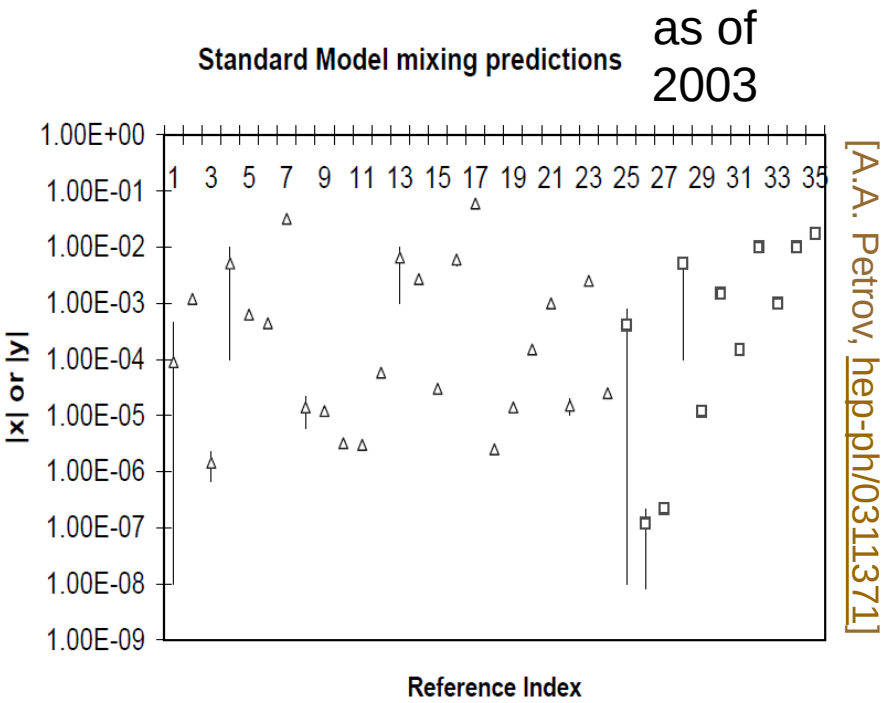
In charm the parameters that describe the mixing / oscillations are

$x \equiv \Delta m/\Gamma$ short range $\qquad$ $y \equiv \Delta\Gamma/2\Gamma$ long range

where Δm ($\Delta\Gamma$) is the mass (width) splitting between the mass eigenstates.

Because of difficulties of making calculations in the charm system, the range in predicted values for *x* and *y* was very wide.

The situation has since improved, no doubt guided by the results we will discuss, but the question remains a challenging one (see, *e.g.* [Lenz and Wilkinson, Ann. Rev. Nucl. Part. Sci. 71 (2021) 59]).

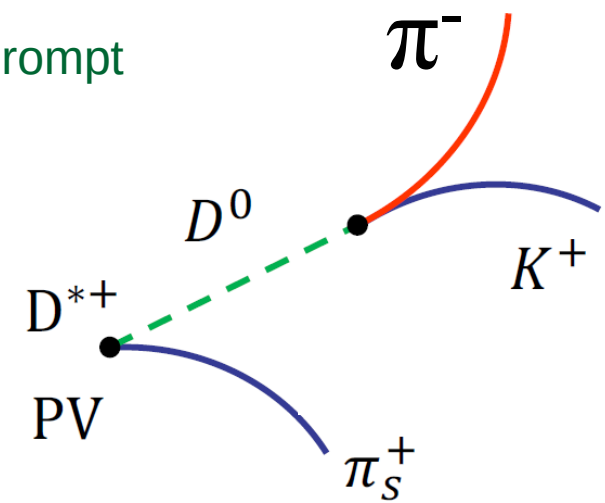


Charm mixing with 'wrong-sign' $D^0 \to K^+\pi^-$

As charm mixing is small, look for mixing-decay interference effects that are linear in the amplitude, rather than pure mixing effects that are quadratic. Compare time-dep. rate of suppressed $D^0 \to K^+\pi^-$ 'wrong sign' decay with favoured $D^0 \to K^-\pi^+$ 'right sign'.

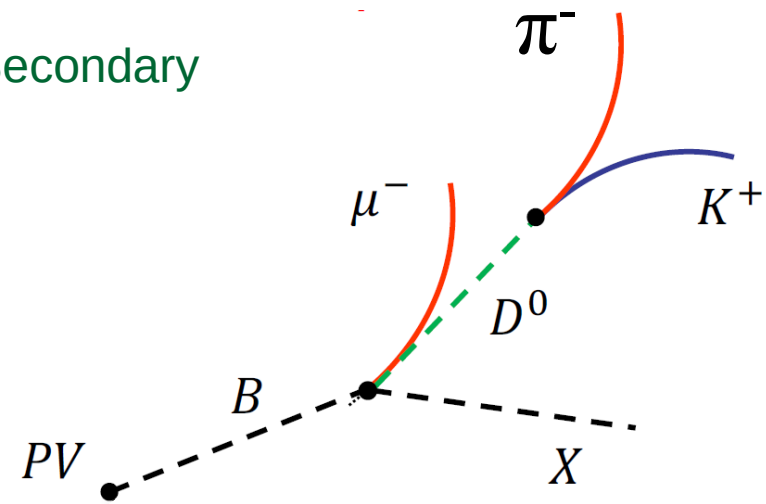
Experimentally this is done by flavour tagging the D^0 at birth, which is easier to do than in the B meson case, because the signatures are cleaner and more efficient.

Prompt



Using a 'slow pion' from D^{*+} decay – the most powerful method

Secondary



Using charm produced in semileptonic B decays, and looking at the charge of muon – useful addition at LHCb

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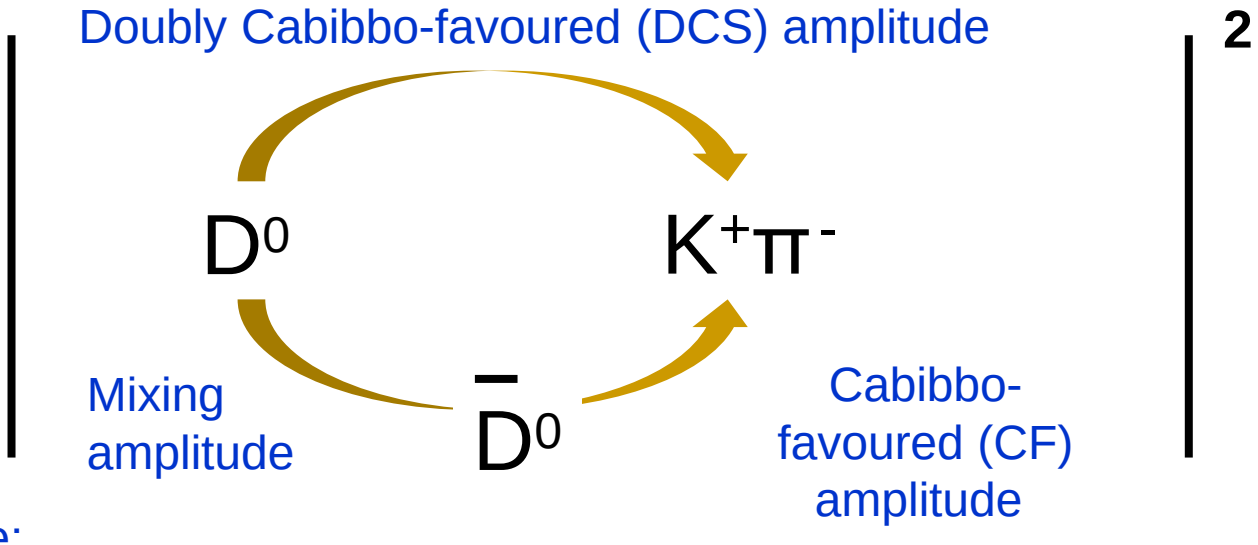
Decay-time dependent rate $\approx$



Normalise by right-sign decay rate:

$$R(t) \approx R_D + \sqrt{R_D}\, y' \, \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

$\left|\frac{\text{DCS amp}}{\text{CF amp}}\right|^2 \sim 1/300$

Mixing–decay interference

Mixing

x' and y' are mixing parameters rotated by a strong phase…

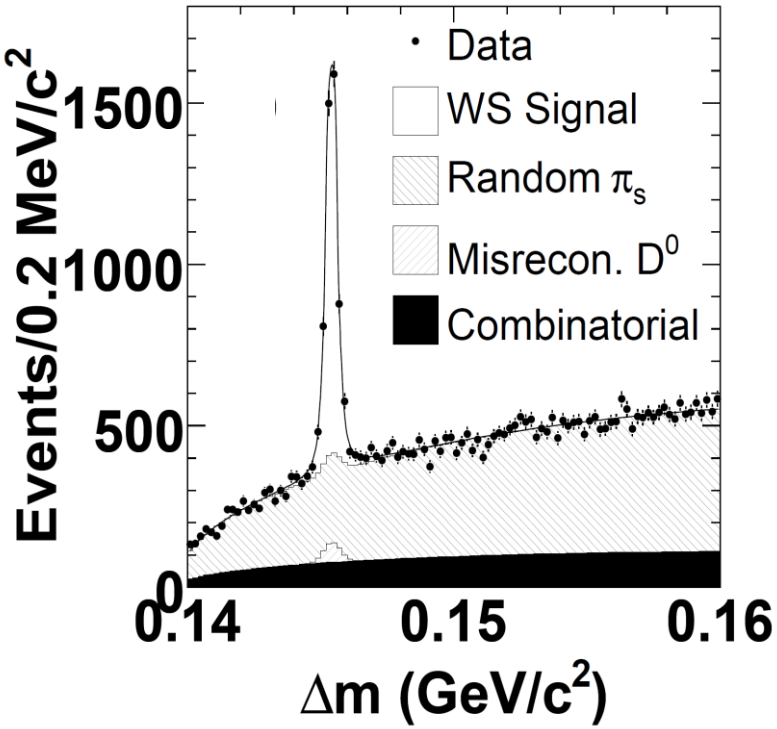
…these small, so mixing signature is a linear, not oscillatory effect.

Nothing seen in this analysis (or others) for many, many years.

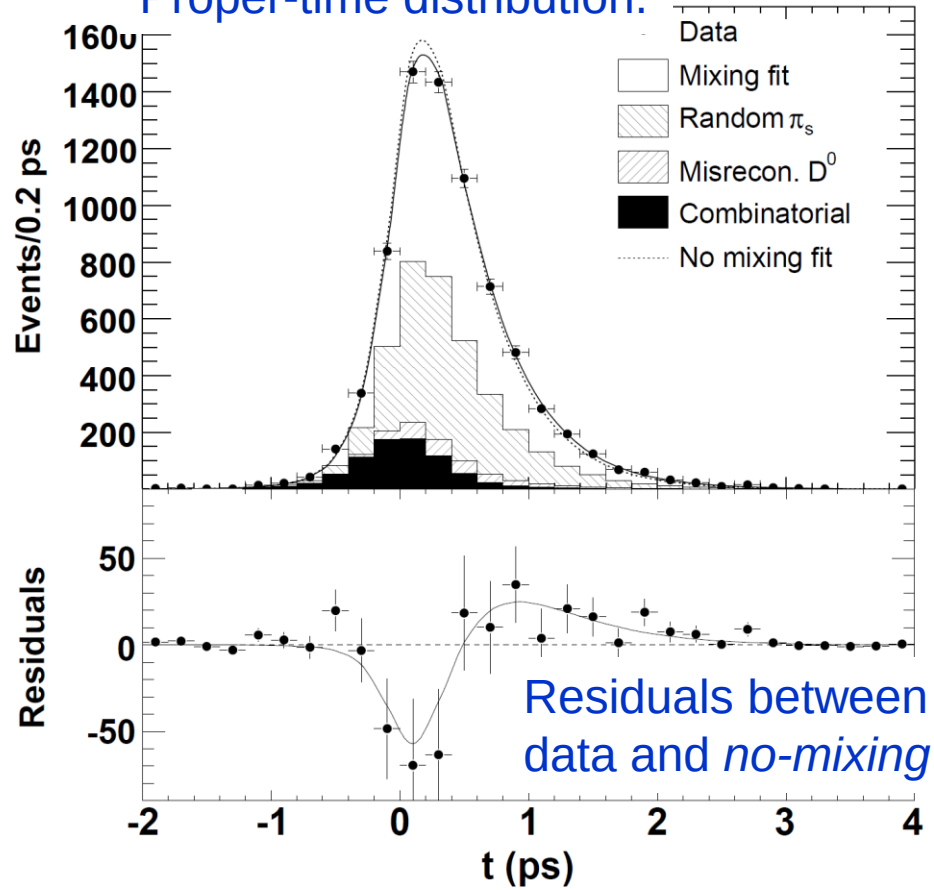
First evidence from the B-factories !

B factories produced large amounts of charm as well as beauty hadrons.
As data accumulated at the B-factories, a non-zero mixing signal began to emerge.

BaBar: 4k WS Kπ signal decays with 384 fb^{-1}.



Proper-time distribution.



[BaBar, PRL 98 (2007) 211802]

Residuals between data and *no-mixing* fit.

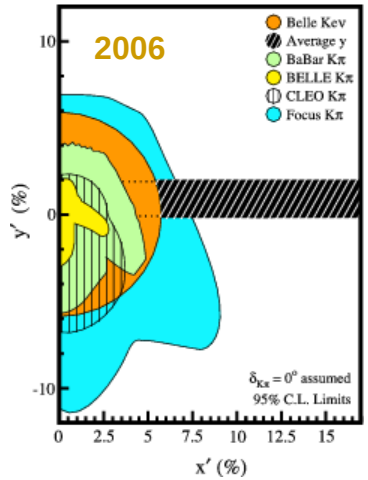
A rekindling of interest, and the rise of the hadron machines

As the B factory results firmed up, the picture changed very rapidly.

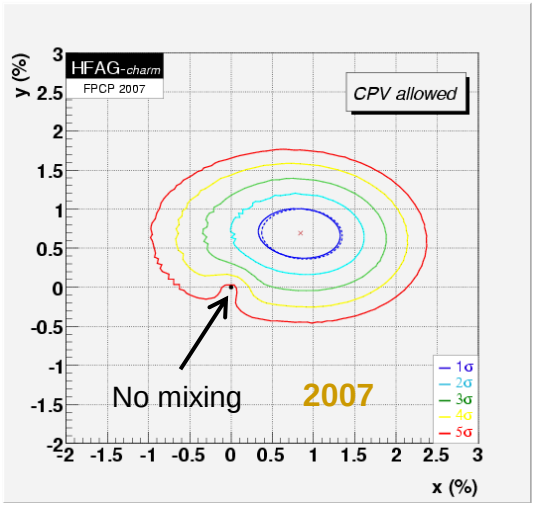
The ensemble of results showed that mixing was happening, but was less clear on the values of the parameters driving it (especially *x*).

This rekindled interest in charm, particularly for hadron machines where the potential is enormous.

Excluded regions



"All results are null."
Ian Shipsey, Charm 2006.



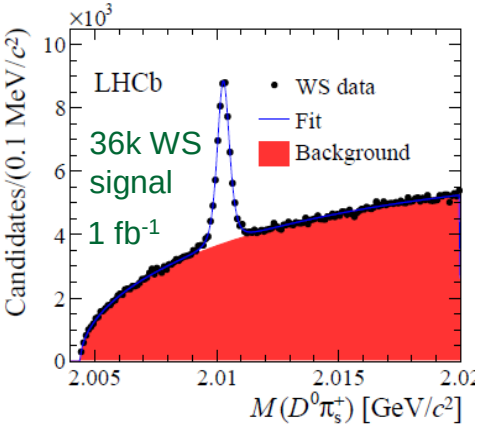
Measurement contours;
no-mixing excluded at 5σ

e.g. the charm cross section at the LHC is around 20x that of beauty production !

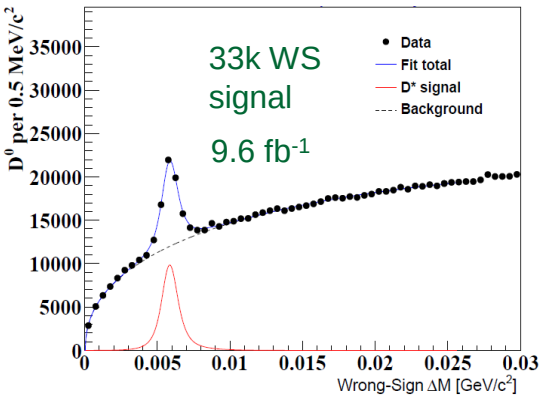
All considerations that apply to beauty physics (*e.g.* acceptance, instrumentation & trigger) remain true for charm. Its just a little harder to trigger on, as it has lower p_T.

Rise of the hadron machines

First observation of signal in *single* measurement required statistical muscle of hadron machines. In 2013 LHCb & CDF published first (>)>5σ measurements.



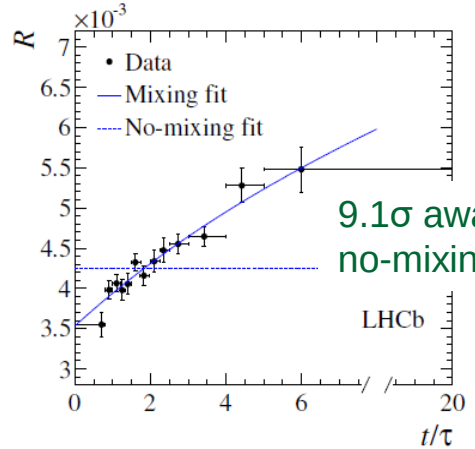
[LHCb, PRL 110 (2013) 101802]



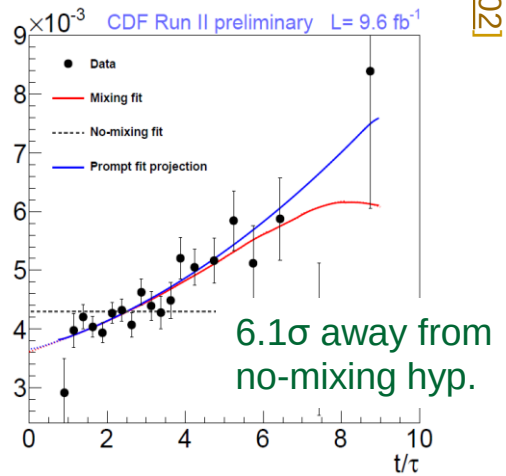
[CDF, PRL 111 (2013) 231802]

This is the WS/RS ratio vs. proper time.

Linear slope comes from mixing-decay interference.



9.1σ away from no-mixing hyp.

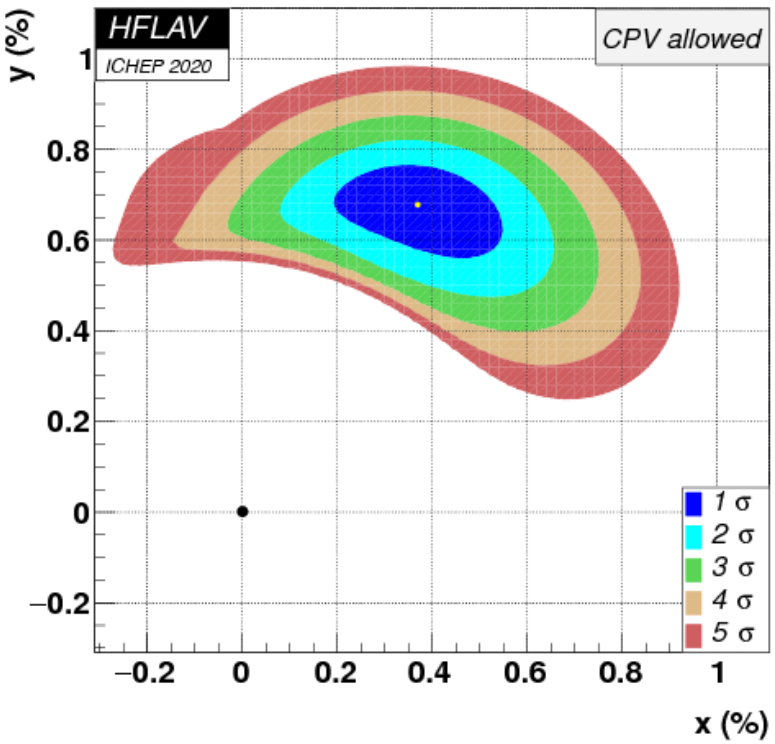


6.1σ away from no-mixing hyp.

LHCb sample is a just *small* fraction of Run 1, but is *order of magnitude* larger than that of BaBar. These measurements also benefit from better time resolution.

From discovery to precision

'Wrong sign' Kπ and parallel measurements refined with growing LHCb data sets. Precision on mixing signal increased, and by ~2020 *y* is very well known.

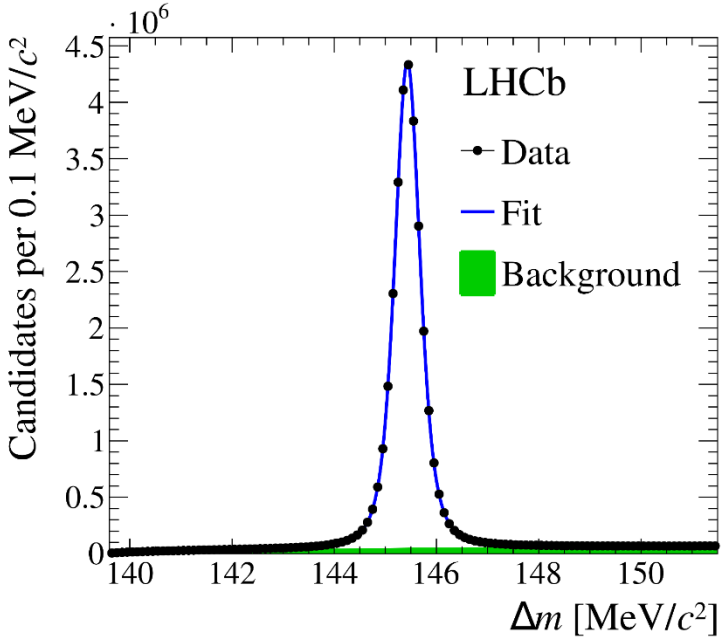


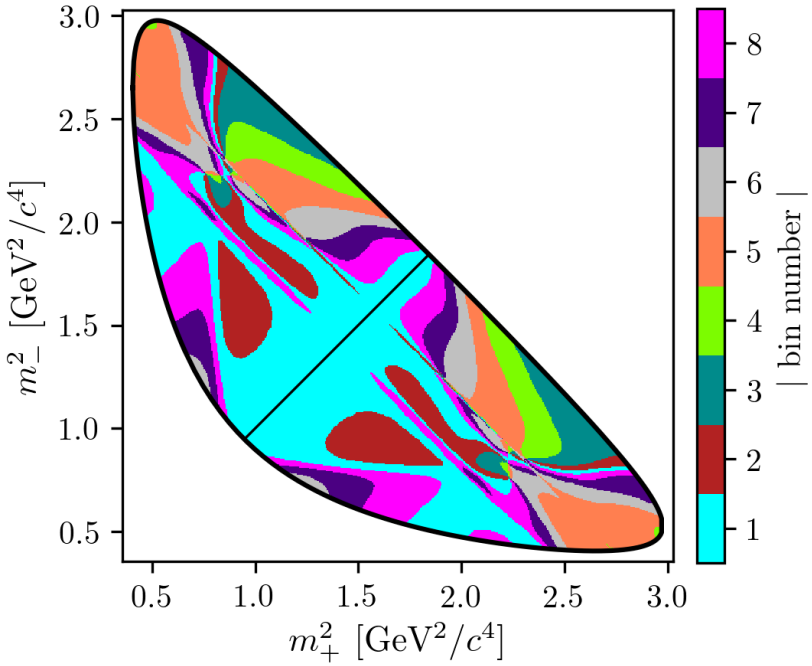
However, ensemble of measurements still do not exclude a zero value of *x*.

D^0-$\bar{D}^0$ oscillations with $D^0 \to K_S\pi^+\pi^-$ at LHCb

The rich resonance structure of $D^0 \to K_S\pi^+\pi^-$ very advantageous for mixing & CPV studies.

Recent LHCb result [PRL 127 (2021) 111801] exploits 5.4 fb^{-1} of data, corresponding to 31 million decays (x30 B-factory samples).





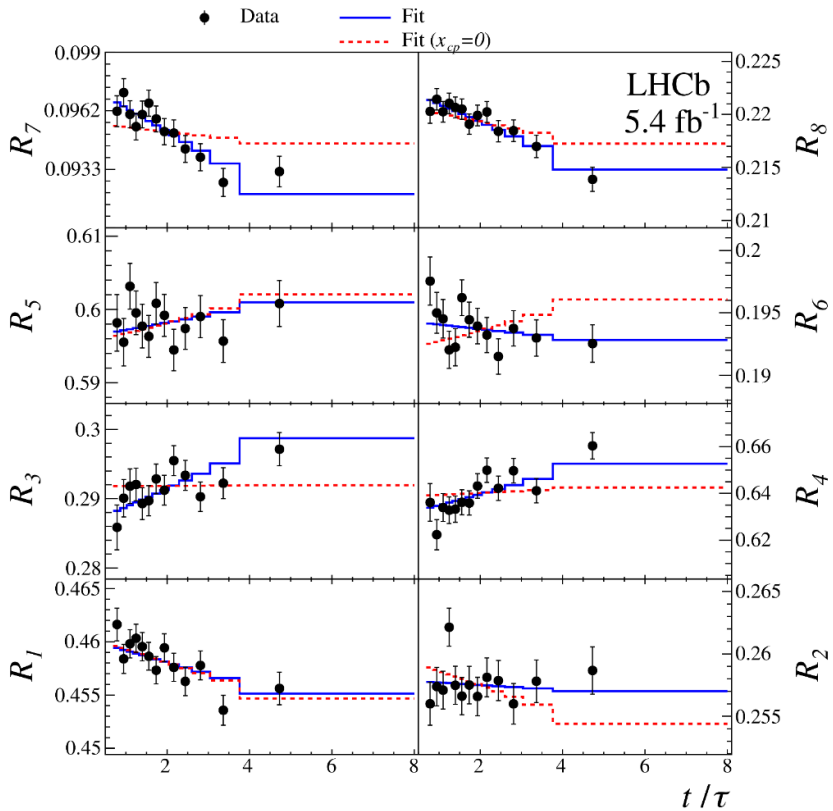
As in γ analysis, divide Dalitz plot into bins, whose strong-phase characteristics are known from BESIII measurements.

Study time-dependence of ratio of symmetric bins (the 'bin flip' method [PRD 99 (2019) 012007] . Particularly sensitive to x.

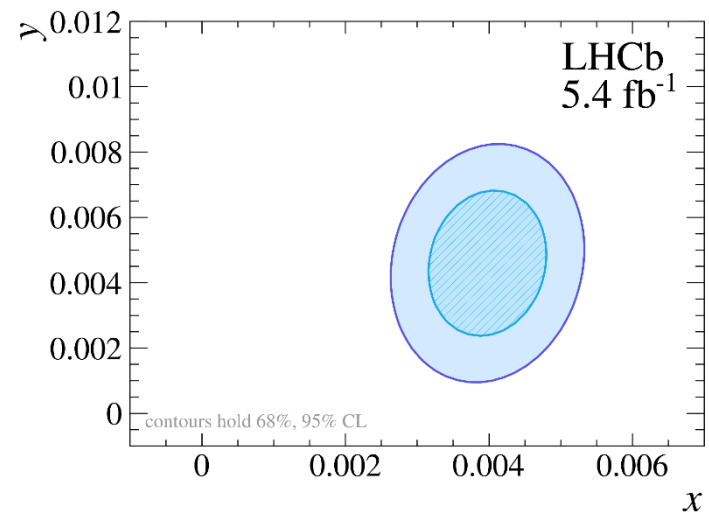
Use data-driven method to correct for trigger-induced correlations between decay time and phase space.

D^0-$\bar{D}^0$ oscillations with $D^0 \to K_S\pi^+\pi^-$ at LHCb

Ratio of bin populations vs. proper time.
Slope indicates presence of mixing.



$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3},$$



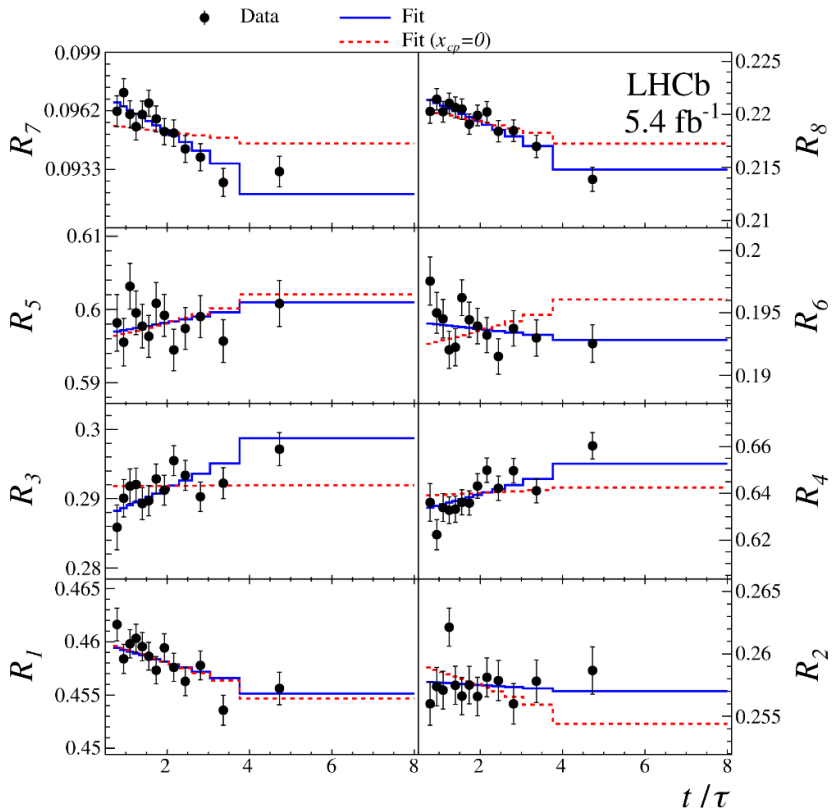
[PRL 127 (2021) 111801]

x non-zero with significance of >7σ !

(Just like WS Kπ measurement, but strong phase, and thus slope, varies bin to bin)

D^0-$\bar{D}^0$ oscillations with $D^0 \to K_S \pi^+ \pi^-$ at LHCb

Ratio of bin populations vs. proper time.
Slope indicates presence of mixing.



$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
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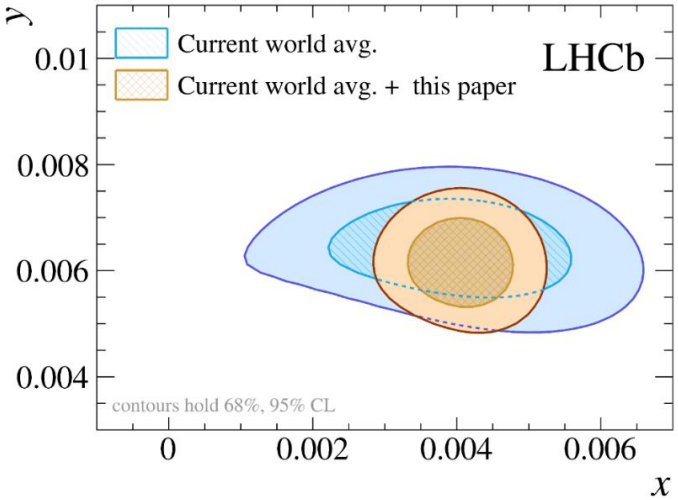


[PRL 127 (2021) 111801]

A huge step forward in precision !

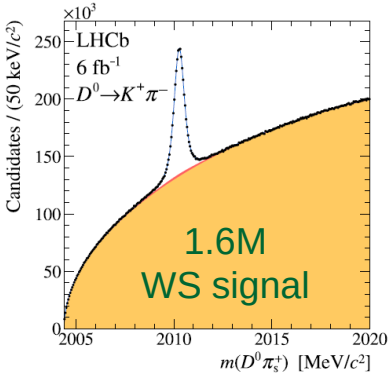
(Just like WS Kπ measurement, but strong phase, and thus slope, varies bin to bin)

CP violation in charm-mixing phenomena

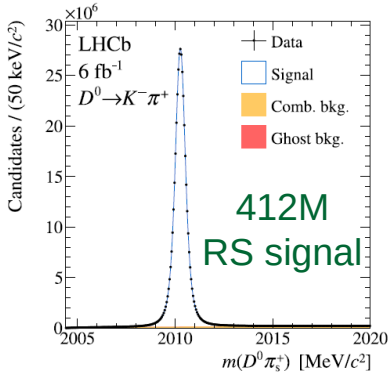
Seeing charm oscillations is exciting in itself, but the fact that the mixing parameters are not too small is excellent news for CP violation searches in mixing-related phenomena (*i.e.* effects analogous to those observed in neutral kaon and beauty).

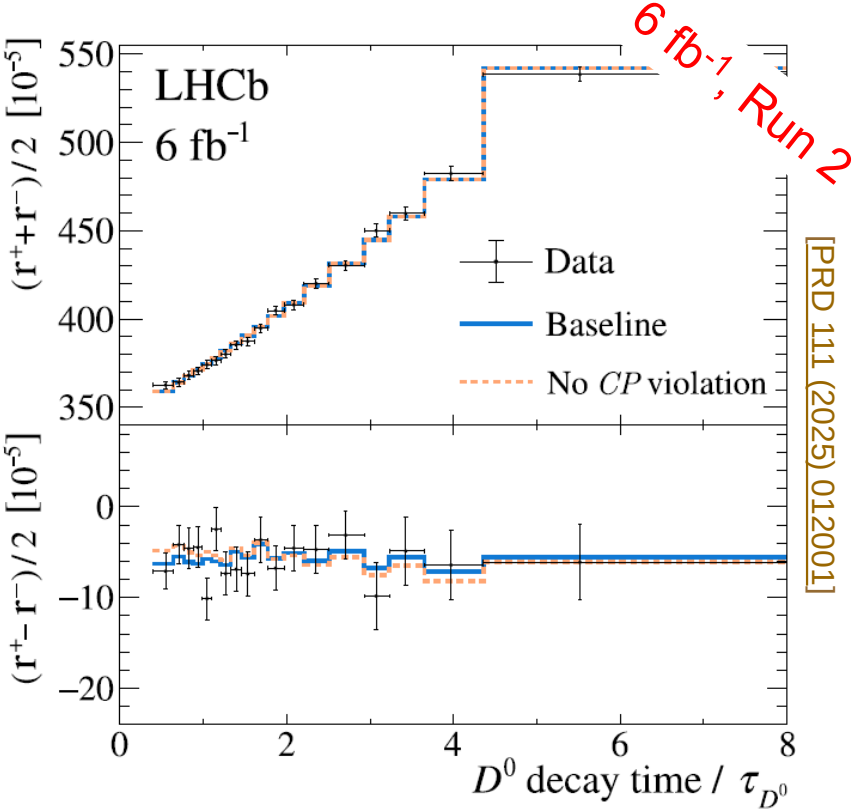
To look for these we essentially look for differences in mixing between D^0 and $\bar{D}^0$.

Study ratio of WS (*i.e.* $D^0 \to K^+\pi^-$)…



…to RS (*i.e.* $D^0 \to K^-\pi^+$), vs. proper decay time





[PRD 111 (2025) 012001]

No indication of any difference, so CP violation must be very small (as expected).

CP violation in charm-mixing phenomena

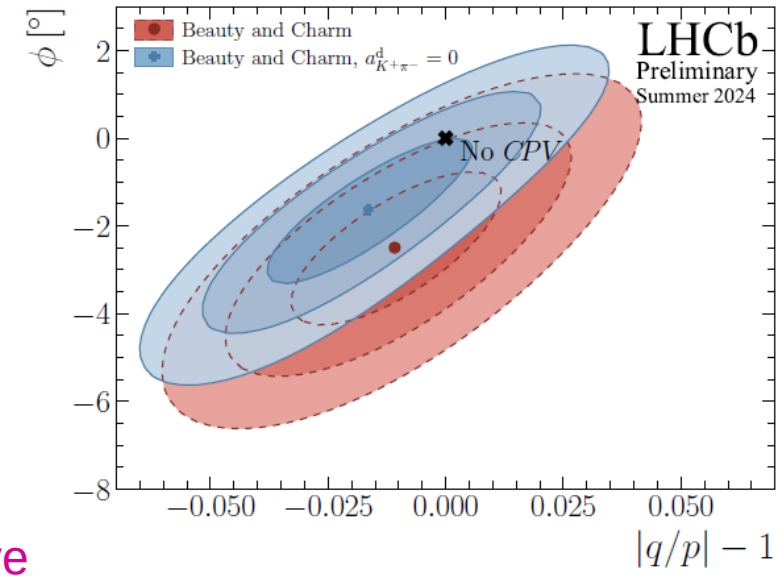
Taking *p* and *q* to be the coefficients that relate the mass eigenstates to the flavour eigenstates,

$$D_{1,2} = pD^0 \mp q\overline{D}^0$$

and ϕ_D to be the weak phase between the mixing and decay amplitudes, then CP violation would manifest itself in either $|q/p| \neq 1$ or $\phi_D \neq 1$.

Current LHCb data, which saturate world average, give a precision of +/- 0.015 on $|q/p|$ and +/- 1.2 on ϕ_D.

Results are compatible with no CP violation, with 1 or 2 sigma tension, depending on assumption made for whether there is direct CPV in DCS D→Kπ decays.



[LHCb-CONF-2024-004]

It would be really, really helpful to have a theory prediction of the size of these parameters in the SM. We must avoid a repeat of the 'ΔA_{CP}' saga. Recall, that *direct* CPV in charm *has* been observed (see [PRL 122 (2019) 211803] and backups), but here the 'predictions' were a posteriori. No consensus on whether the result agrees with SM or not !

CP violation in charm-mixing phenomena

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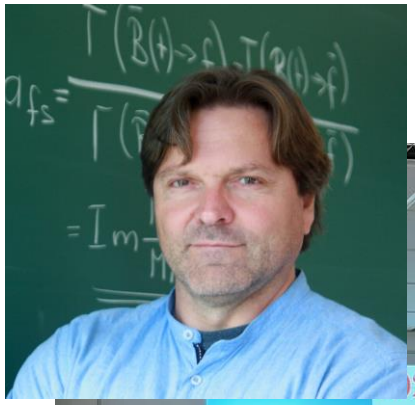


If you happen to see this man, ask him

subatomic_heroes 23 w
Subatomic hero Alex Lenz gave a recap of the past year, highlighting our progress, collaborations, and achievements in particle physics. 🌌 ✨

A great way to reflect on the work we've done and look forward to what's next. What are you curious about for the coming year? Let us know in the comments! 👇

#SubatomicHeroes #PhysicsInstitute #YearInReview"

impatient.experimentalist
'Subatomic hero' maybe, but still no reliable prediction for CPV in charm mixing ?

#Fedupwaiting
#GetamoveonAlex

$|q/p| - 1$

It would be really, really helpful to have
a theory prediction of the size of these parameters in the SM. We must avoid a repeat of the 'ΔA_{CP}' saga. Recall, that *direct* CPV in charm *has* been observed (see [PRL 122 (2019) 211803] and backups), but here the 'predictions' were a posteriori. No consensus on whether the result agrees with SM or not !

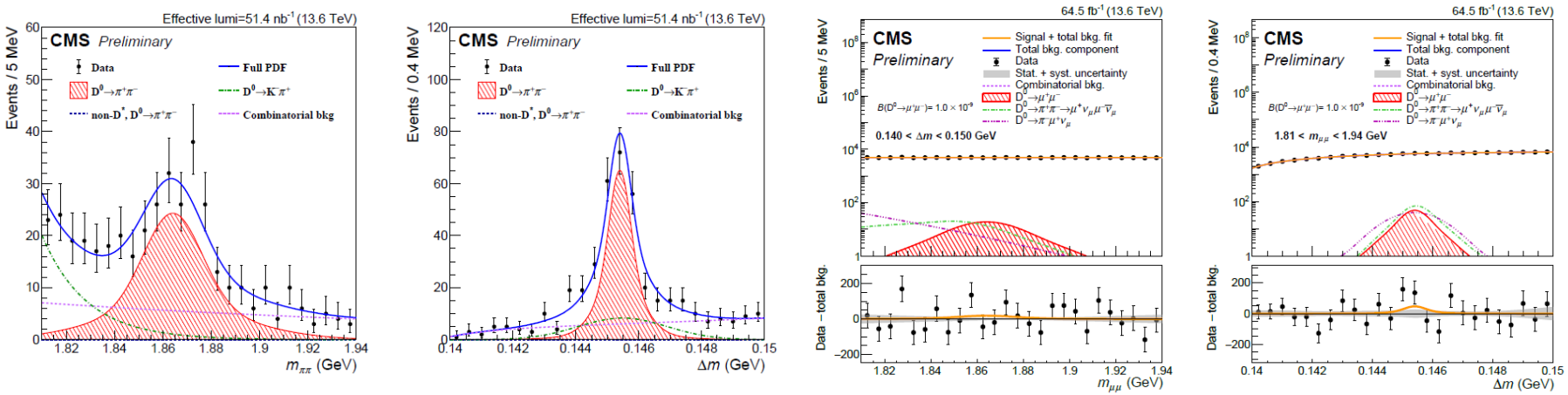
Rare charm decays

As with beauty, there is much to be learned from searching for, & studying, FCNCs in charm (although here the long-distance effects can be more problematic). Much done by LHCb, *e.g.* $\Lambda_c \to p\mu\mu$ [PRD 111 (2025) L091102], $D \to hh\mu\mu$ [PRL 128 (2022) 221801]…

Flagship mode is $D^0 \to \mu\mu$. SM estimate is ~10^{-13} [Burdman *et al.*, PRD 66 (2002) 014009]. With full Run 1 + 2 data set, LHCb sets limit of 3.1 x 10^{-9} 90% CL [PRL 131 (2023) 4].

Preliminary result from CMS [PAS BPH-23-008], benefitting from new soft di-μ trigger.

Normalisation mode: $D^0 \to \pi\pi$ Signal mode



World best limit of 2.6 x 10^{-9} at 9% CL. Great progress! (Pre-LHC, limit was ~10^{-7}.)

Cinderella comes to the ball

Charm physics is now firmly re-established as a leading discipline in flavour studies.

The B factories played an critical role in initiating this revival, but is the statistical power of the LHC that has revolutionised the field.

The discovery of CP violation in decay has opened a new era in flavour studies, and the sensitivity to mixing-related CPV has now reached a very interesting level.

LHCb has led the way, but CMS is now contributing strongly.

What we need now is a further step up in precision…

Flavour Physics at Hadron Colliders

5) Future prospects for flavour physics at hadron colliders

The need for improved precision

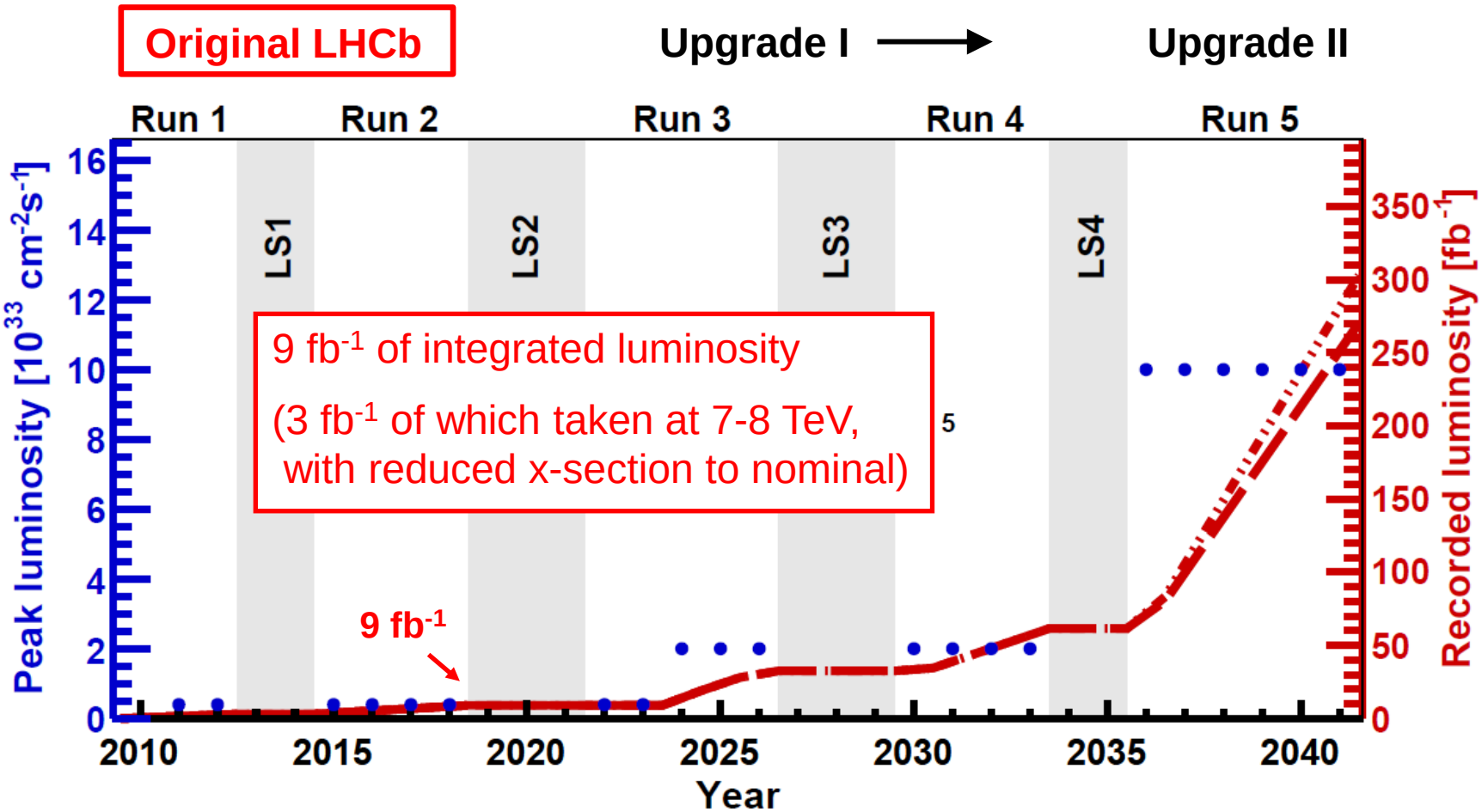
Charm is one topic where higher precision is required. There are many more:

- Improved measurements of the angle γ;
- Improved measurements of $B^0_{(s)} \to \mu\mu$;
- Studies of semi-leptonic asymmetries (not discussed here);
- Improved measurements of ϕ_s and sin2β;
- Further exploration of observables in electroweak penguins;
- ... Many others.

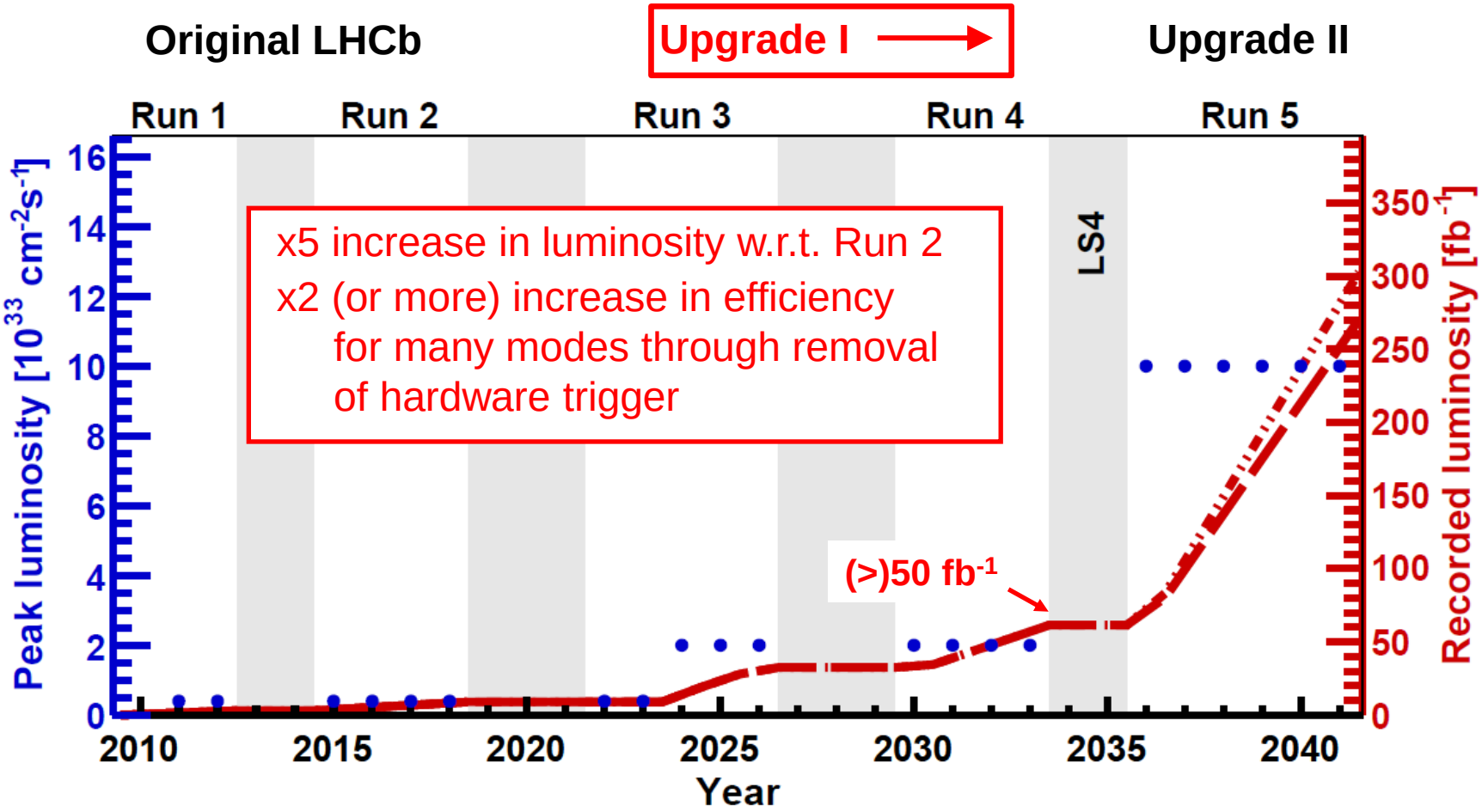
Roughly ordered in terms of theoretical purity

Achieving this goal cannot be achieved by continuing to operate the current detectors as in Runs 1-2. A step change in sensitivity requires radical changes.

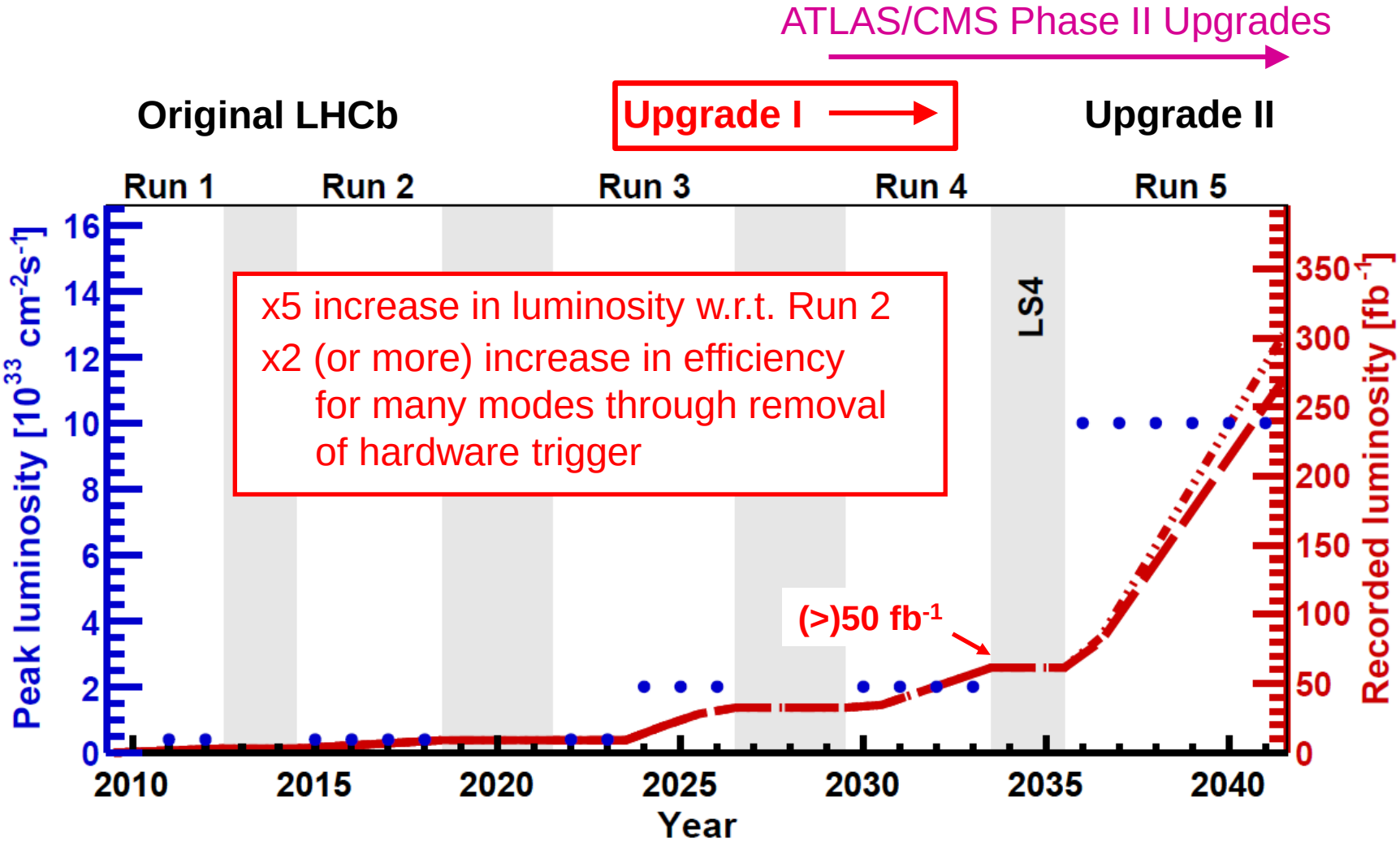
LHCb timeline: Upgrades I and II



LHCb timeline: Upgrades I and II



LHCb timeline: Upgrades I and II



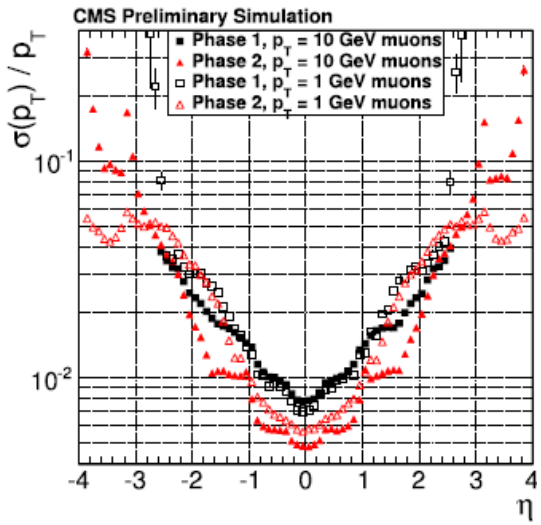
Run 4 is also when the High Luminosity LHC will begin. This makes little difference for LHCb Upgrade I, but is when ATLAS and CMS Phase II Upgrades will start.

ATLAS and CMS Phase II Upgrades

In Runs 1 and 2 ATLAS and CMS have already made high quality B-physics measurements in modes with di-muon final states.

New capabilities of experiments after Phase-II Upgrade (CMS in particular) will strengthen their capabilities in flavour physics

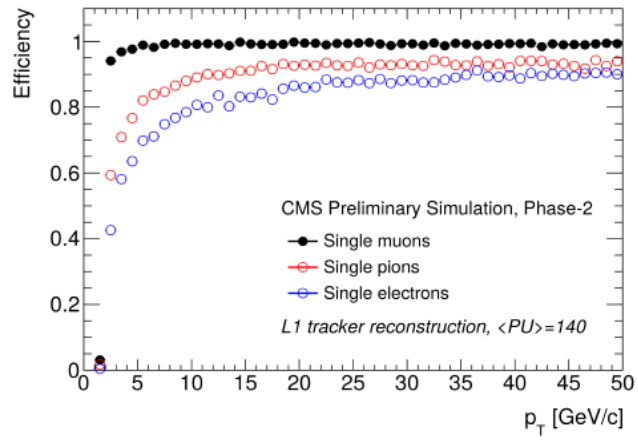
e.g. new CMS tracker



Jeremiah Mans, ECFA HL LHC, Aix-les-Bains, Oct 2014

Significantly improved p resolution

e.g. CMS new L1 track trigger

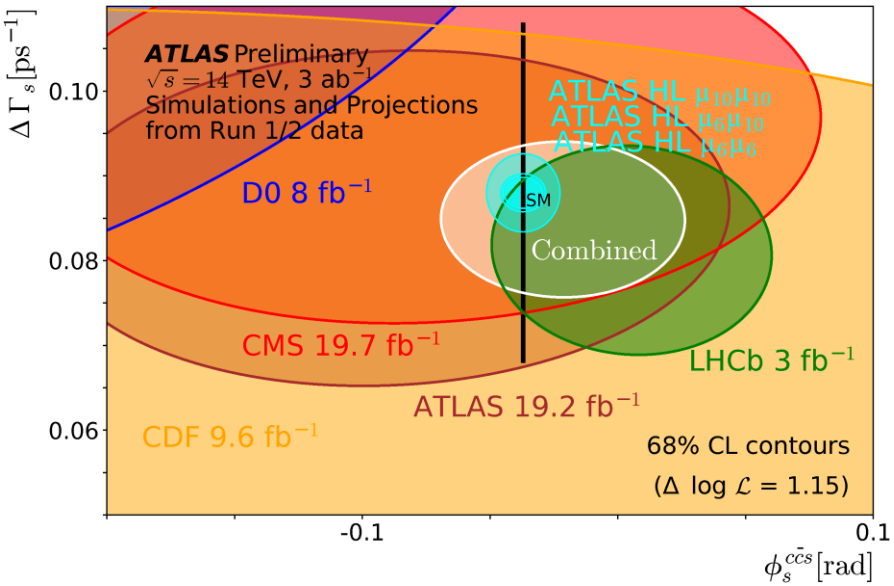


Anders Ryd, ECFA HL LHC, Aix-les-Bains, Oct 2014

Could allow CMS to accumulate large samples even in hadronic modes!

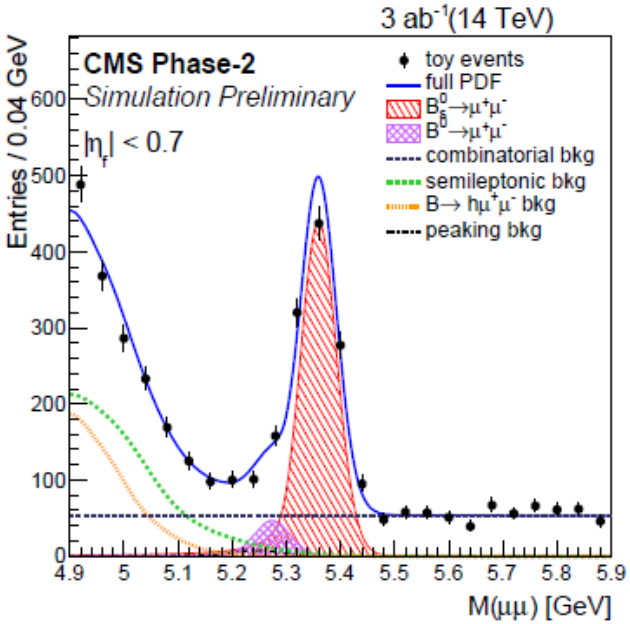
B-physics prospects at the HL-LHC with ATLAS and CMS

ATLAS prospects for φ_s with 3 ab^{-1} for different trigger thresholds.



[ATL-PHYS-PUB-2018-041]

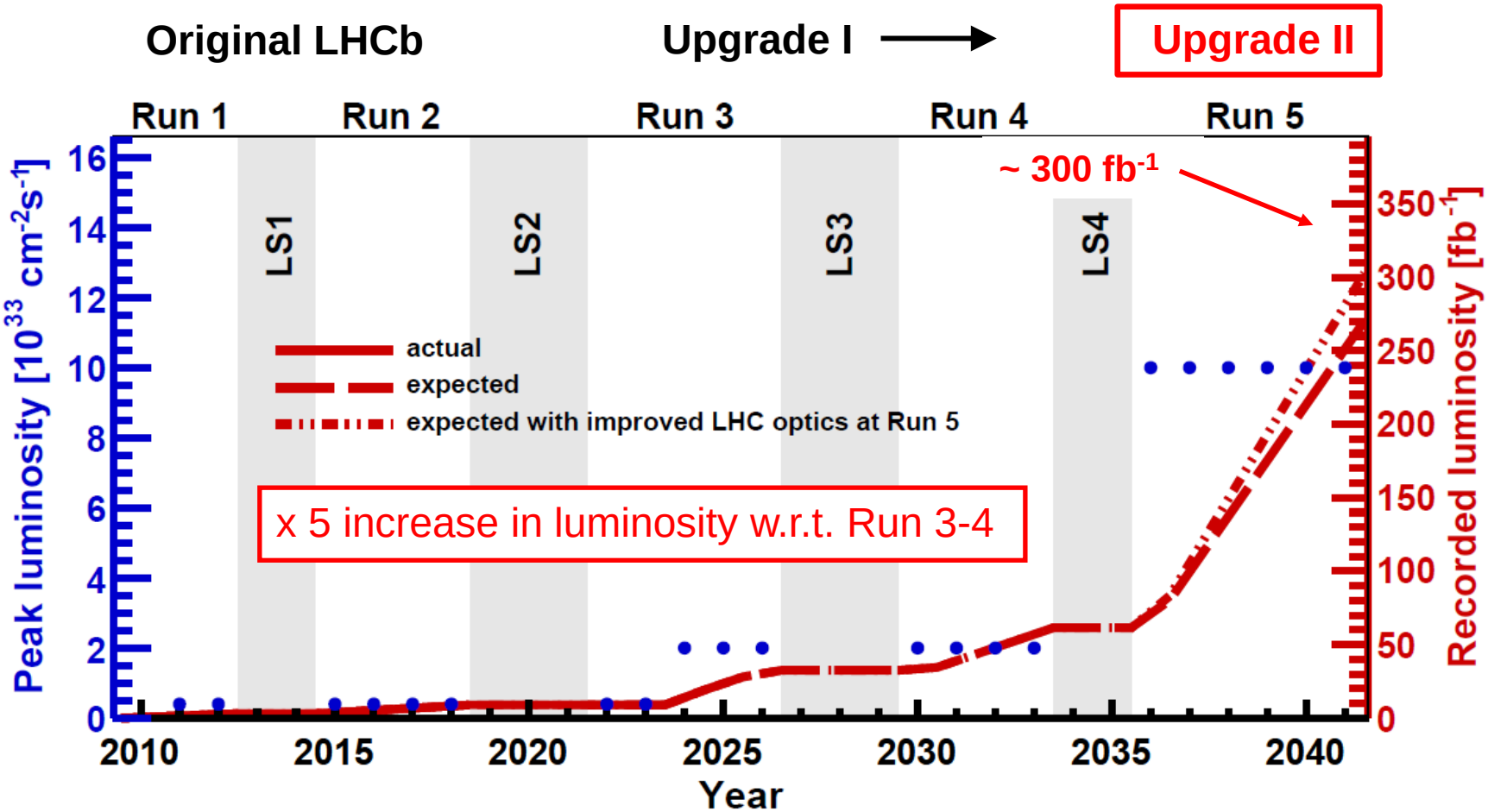
CMS prospects for $B^0_{(s)} \to \mu\mu$ in barrel region with 3 ab^{-1}.



[CMS-PAS-FTR-18-013]

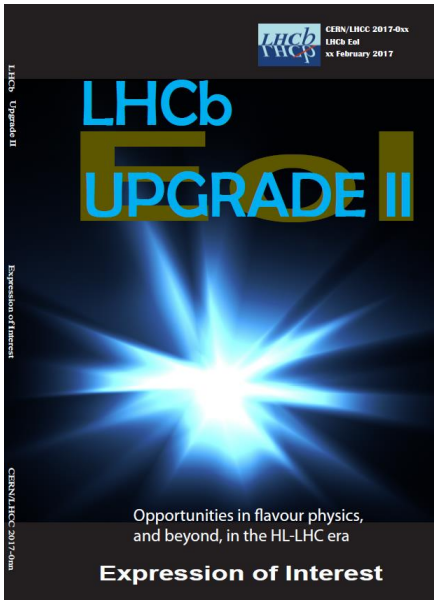
Also see Snowmass White Paper [ATL-PHYS-PUB-2022-018,CMS-PAS-FTR-22-001] and input to ESPPU [arXiv:2503.24346] (to be discussed shortly).

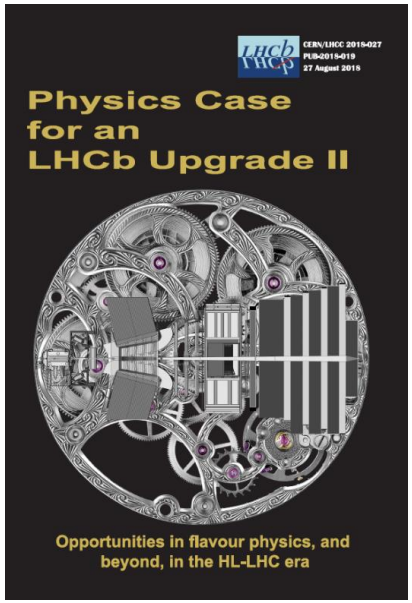
LHCb timeline: Upgrades I and II

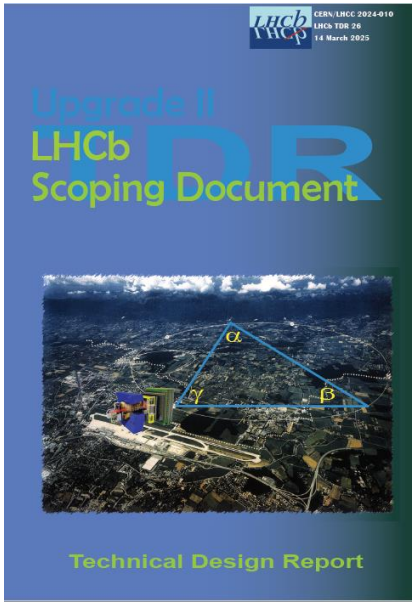


LHCb Upgrade II

Steady progress towards plans for an Upgrade II, that will operate in Runs 5 and 6.





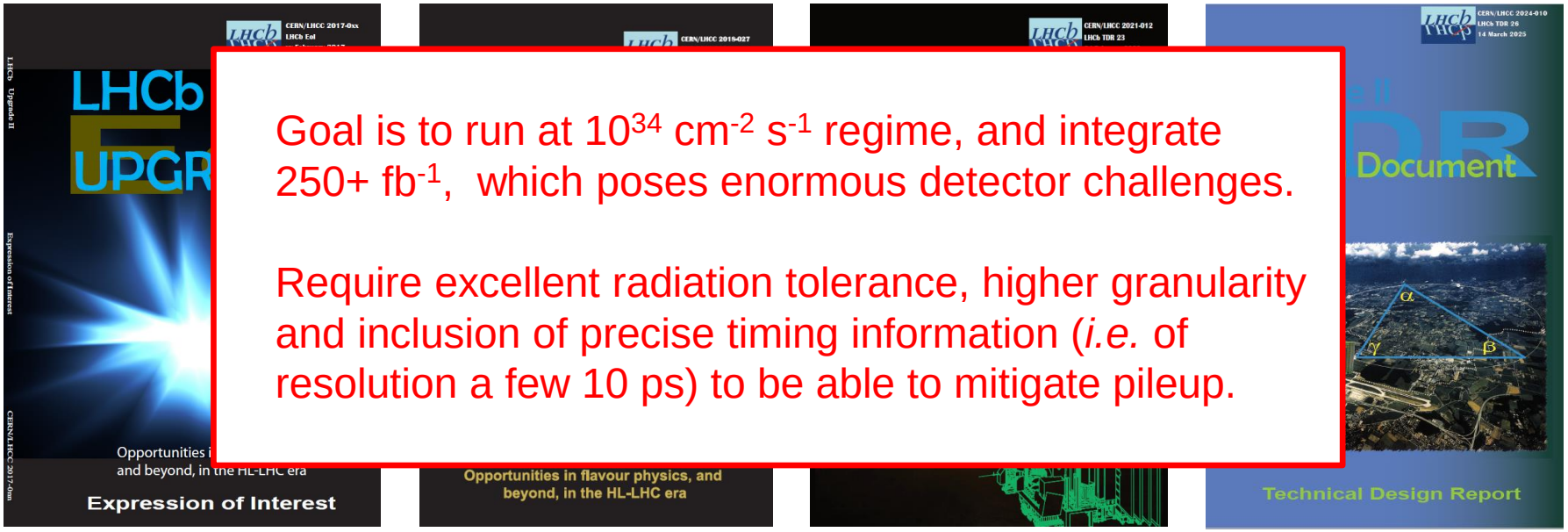


[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012] [CERN-LHCC-2024-010]

Now part of the CERN baseline. ‘Scoping document’ recently approved by LHCC.

LHCb Upgrade II

Steady progress towards plans for an Upgrade II, that will operate in Runs 5 and 6.



Goal is to run at 10^{34} cm^{-2} s^{-1} regime, and integrate 250+ fb^{-1}, which poses enormous detector challenges.

Require excellent radiation tolerance, higher granularity and inclusion of precise timing information (*i.e.* of resolution a few 10 ps) to be able to mitigate pileup.

[CERN-LHCC-2017-003] [CERN-LHCC-2018-027] [CERN-LHCC-2021-012] [CERN-LHCC-2024-010]

Now part of the CERN baseline. 'Scoping document' recently approved by LHCC.

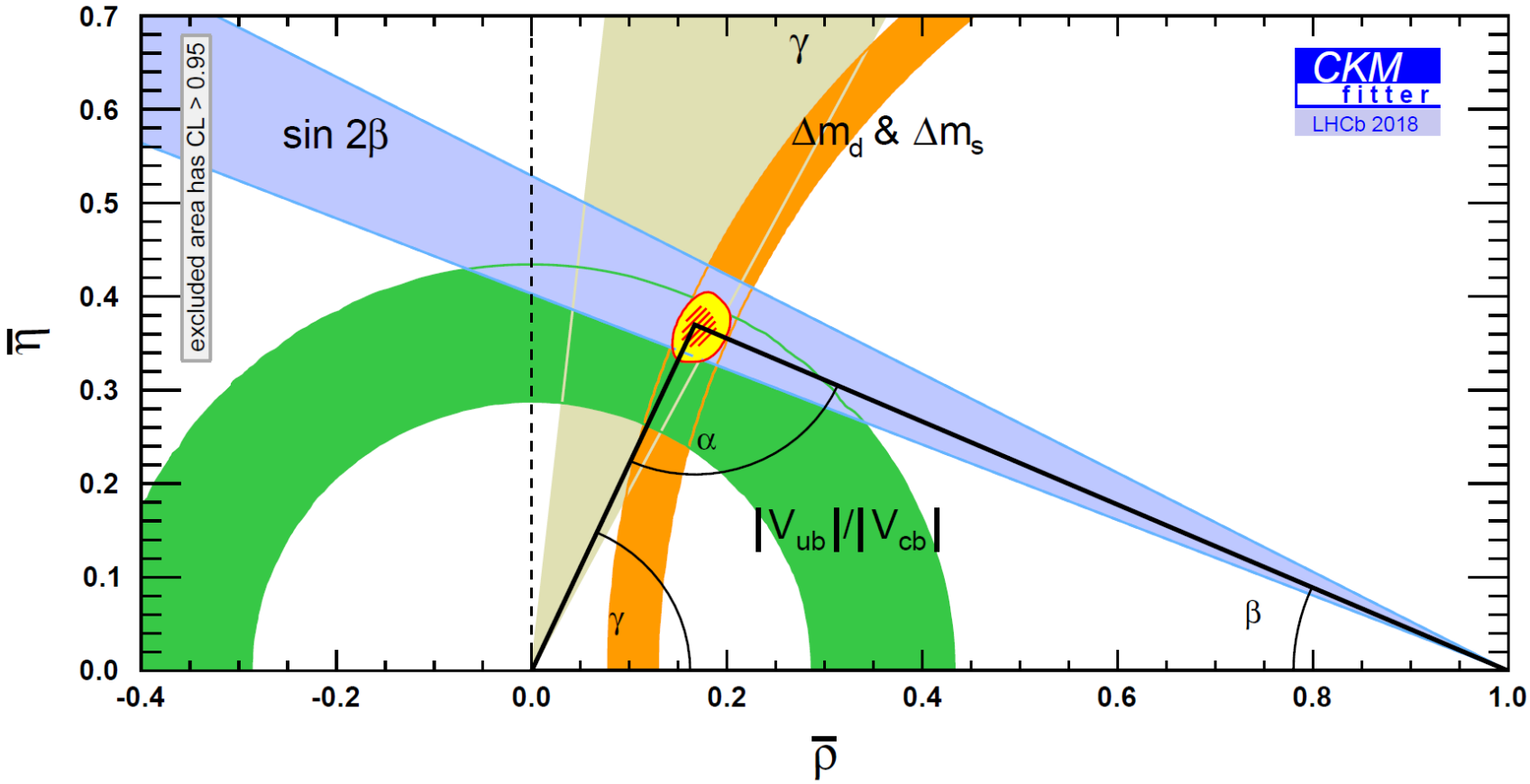
Projected uncertainties for representative observables

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9,10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29,30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_{\rm S}^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40,41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62,64]	0.007	0.005	0.002

[CERN-LHCC-2021-012]

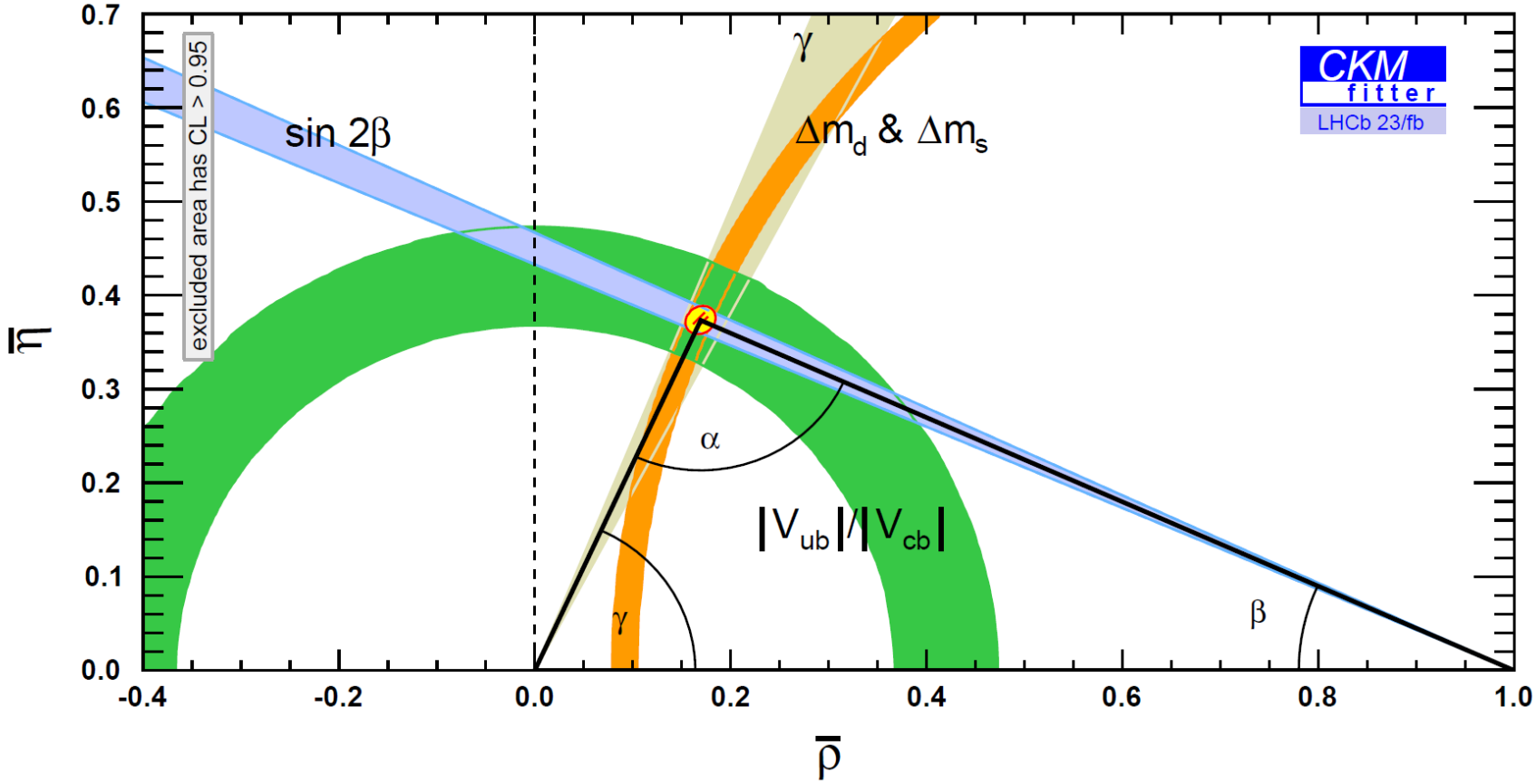
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): 2018 status



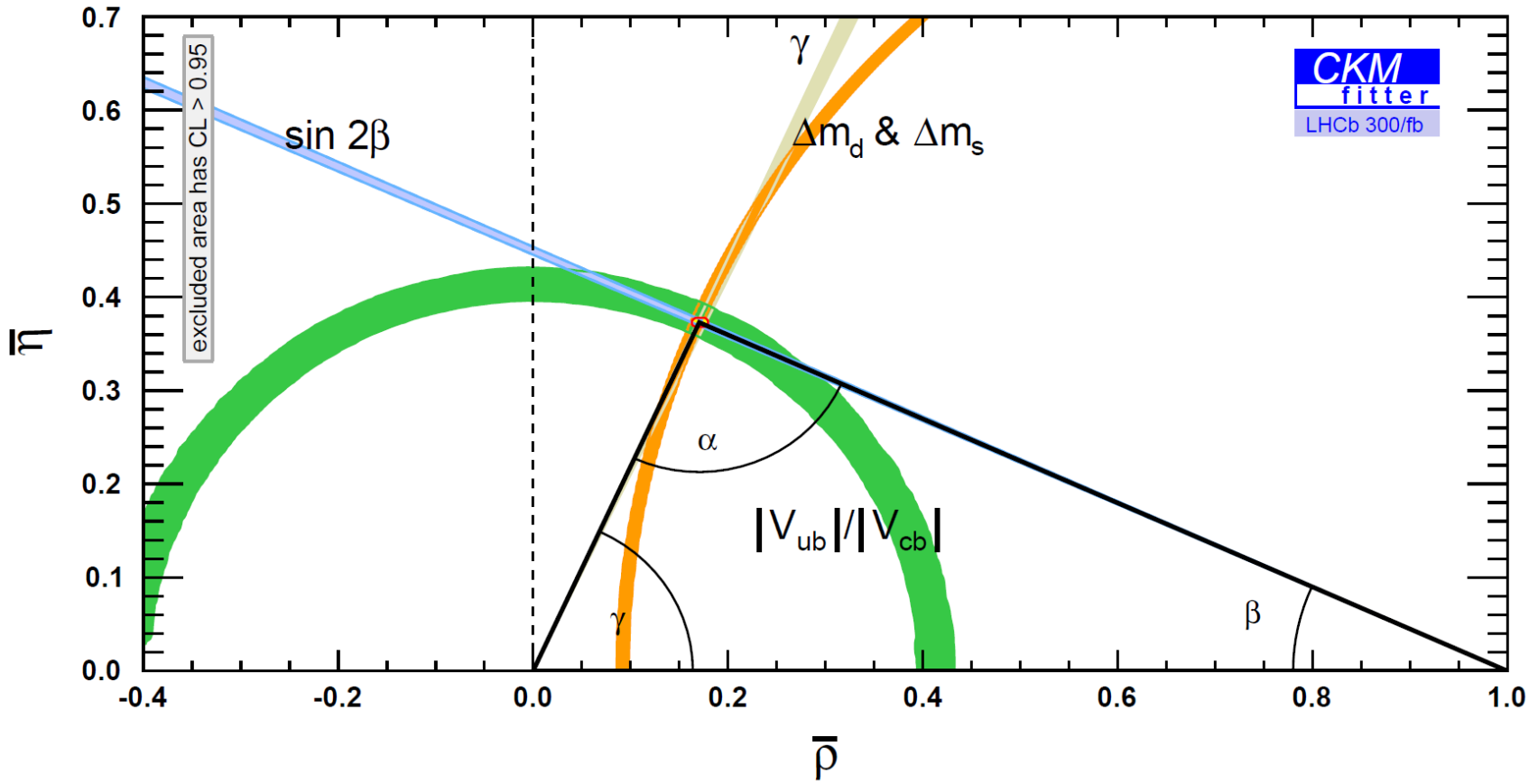
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): start of HL-LHC



Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): after Upgrade II

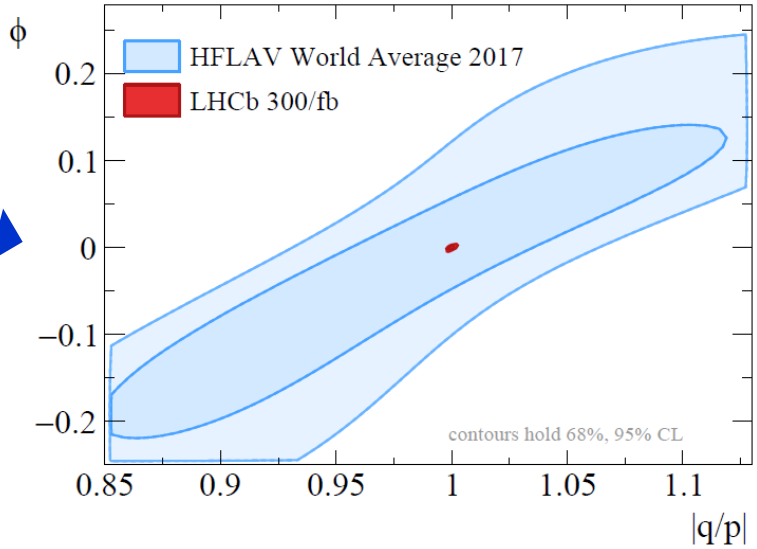


Charm physics potential of LHCb Upgrade II

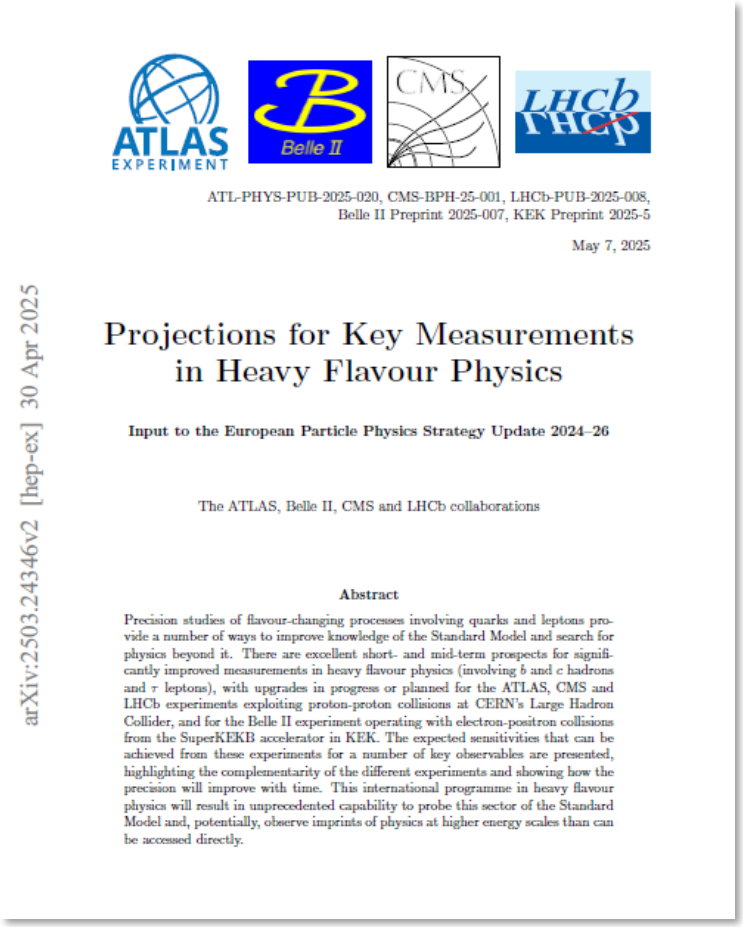
Upgrade II will allow for an order-of-magnitude improvement in precision in current benchmark analyses, such as ΔA_{CP} [arXiv:1808.08865].

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.01	0.03
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

New measurements will become accessible. Exquisite precision will be attainable in searches (and studies) of indirect CPV (*i.e.* mixing related, characterised by φ and |q/p| parameters).



Summary of future prospects at HL-LHC (and Belle II)



ATL-PHYS-PUB-2025-020, CMS-BPH-25-001, LHCb-PUB-2025-008,
Belle II Preprint 2025-007, KEK Preprint 2025-5

May 7, 2025

arXiv:2503.24346v2 [hep-ex] 30 Apr 2025

Projections for Key Measurements in Heavy Flavour Physics

Input to the European Particle Physics Strategy Update 2024–26

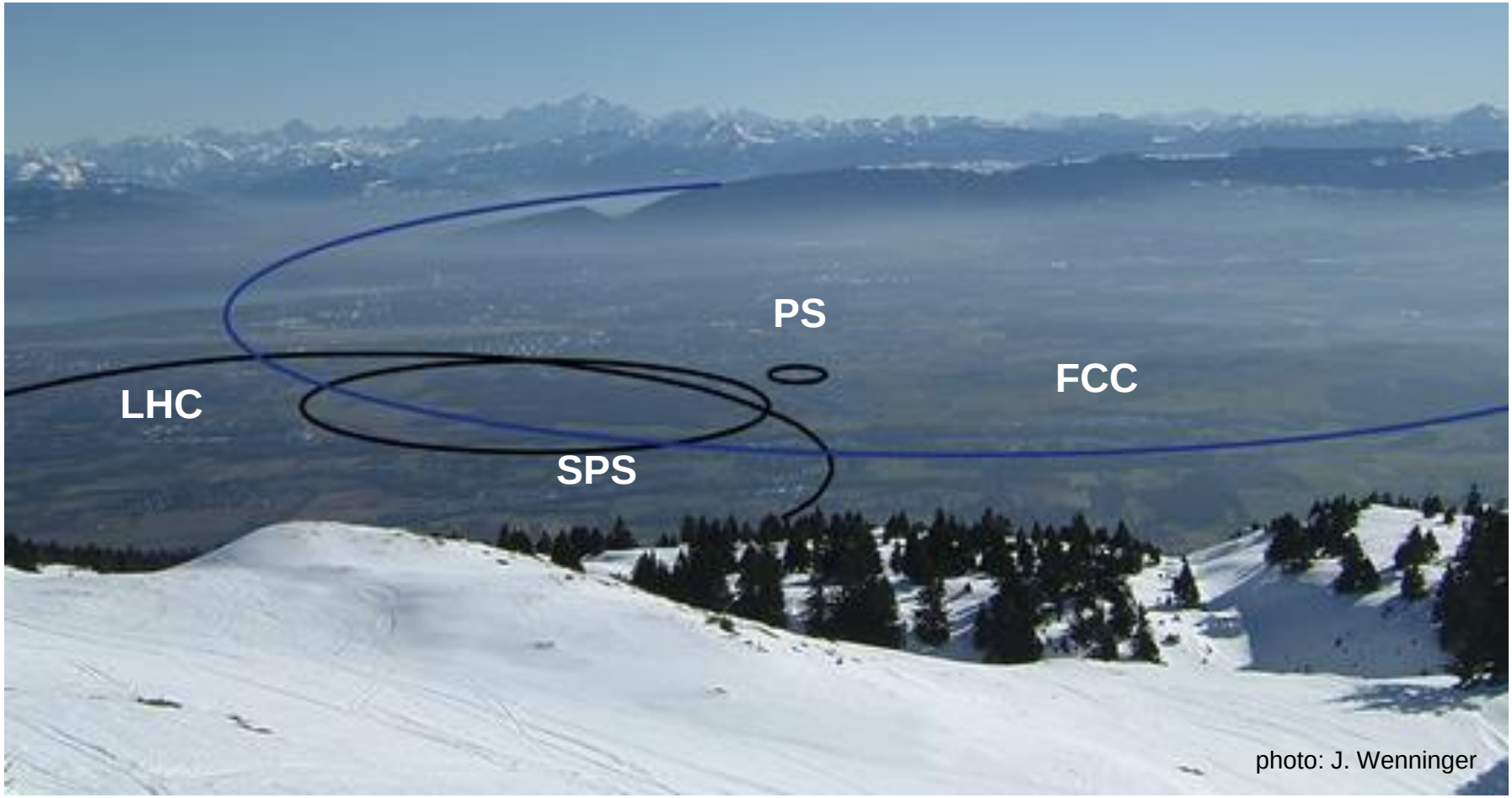
The ATLAS, Belle II, CMS and LHCb collaborations

Abstract

Precision studies of flavour-changing processes involving quarks and leptons provide a number of ways to improve knowledge of the Standard Model and search for physics beyond it. There are excellent short- and mid-term prospects for significantly improved measurements in heavy flavour physics (involving b and c hadrons and τ leptons), with upgrades in progress or planned for the ATLAS, CMS and LHCb experiments exploiting proton-proton collisions at CERN's Large Hadron Collider, and for the Belle II experiment operating with electron-positron collisions from the SuperKEKB accelerator in KEK. The expected sensitivities that can be achieved from these experiments for a number of key observables are presented, highlighting the complementarity of the different experiments and showing how the precision will improve with time. This international programme in heavy flavour physics will result in unprecedented capability to probe this sector of the Standard Model and, potentially, observe imprints of physics at higher energy scales than can be accessed directly.

[arXiv:2503.24346]

Flavour physics beyond the LHC

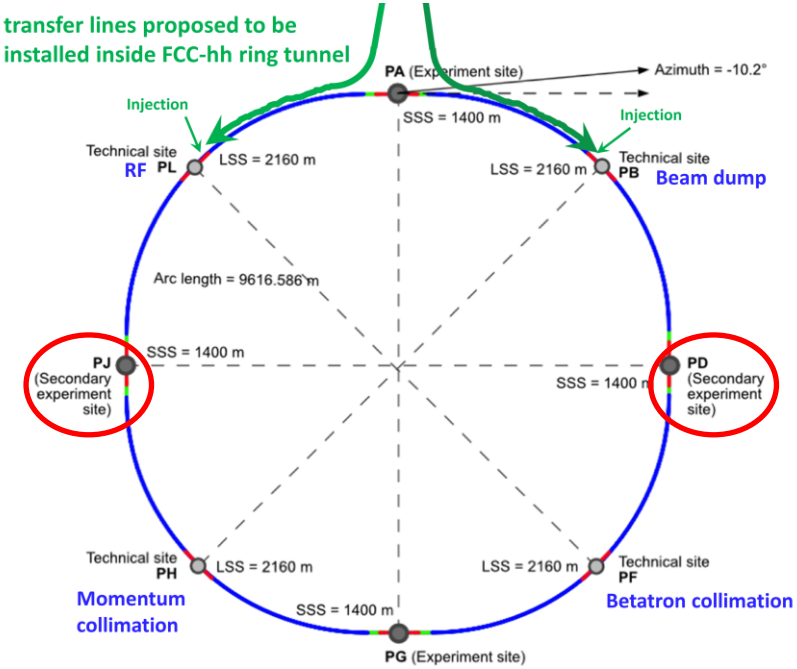


Flavour physics beyond the LHC

FCC-ee offers outstanding prospects for advancing the study of flavour through b and c decays (only high luminosities circular colliders, such as FCC-ee, offer this possibility). But this goes beyond the remit of these lectures…

Flavour in the 2070s

Many flavour measurements will remain statistics limited in 2070. FCC-hh will have a bbbar production cross-section ~5x above LHC and a production rate ~150x above LHCb Upgrade II. Is it feasible to have FCC-hh flavour experiment?



Well, there is certainly space around the ring. FCC-hh will re-inhabit the same four experimental caverns of FCC-ee.

The big ones will be for the General Purpose Detectors, the `secondary caverns' are smaller, but still large, & could house *e.g.* FCCb & FCC-ALICE.

FCCb could have a similar layout to LHCb [Chobonova *et al.*, arXiv:2012.02692].

But can we build detectors that can survive and operate in this environment ? This also is the opportunity ! If the radiation-hardness challenges can be overcome, we can hope that the advances in computing power will allow an even higher proportion of b-decays to be captured and used for physics, than at the HL-LHC.

The future of flavour remains bright !

Thanks for your attention

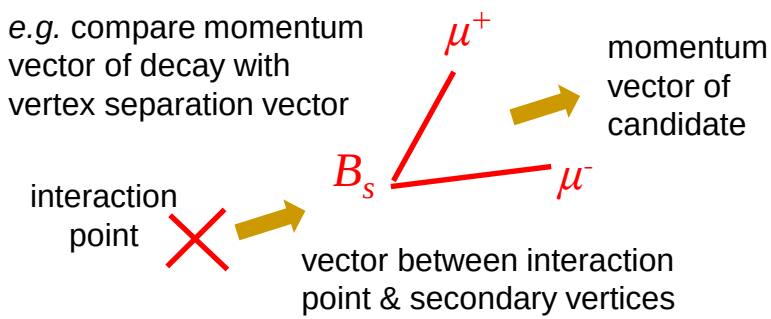
Backups

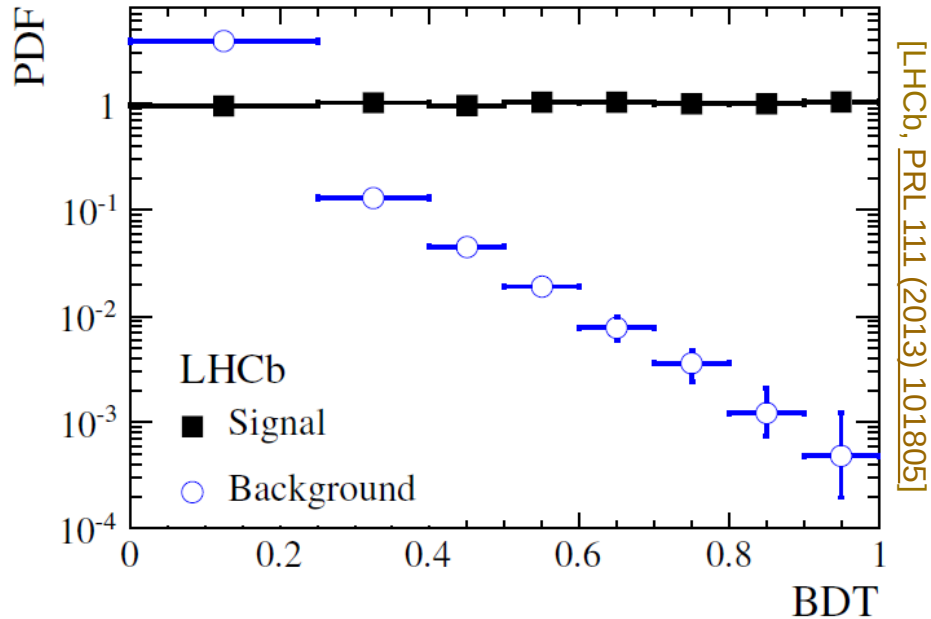
Finding the needle in the haystack

There are lots of B-decays that look rather similar to $B_s \to \mu\mu$. And 'rather similar' is very dangerous when you are searching for such a rare decay.

Most sensitive analyses (pioneered by LHCb & CMS) are not 'cut-based' . Rather, they employ a sequence of two boosted decision trees (BDTs).

BDTs must not just search for a B-decay, as in trigger, but must look for one which is $B_s \to \mu\mu$





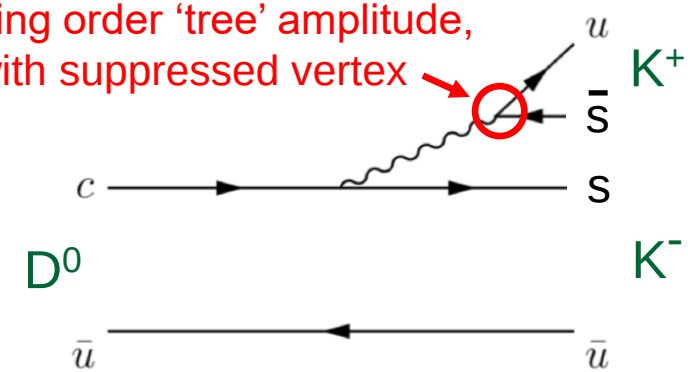
Above, just one of many signatures that are used. Where possible calibrate BDTs on data (*e.g.* same topology $B^0 \to K\pi$ decays). Normalise signal yield to $B_s \to J/\psi K$ or $B^0 \to K\pi$ to determine BR.

Searches for direct CPV in charm

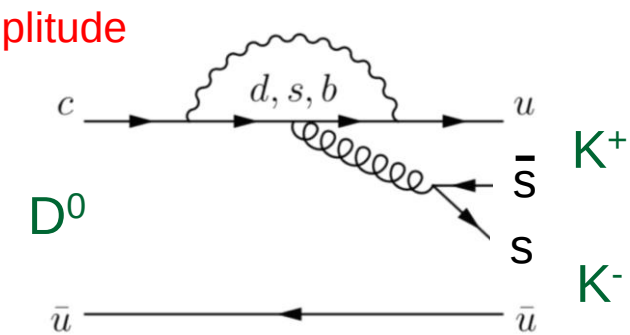
'direct CPV' or 'CPV in decay'

Recall that to be sensitive to CPV we need (at least) two interfering diagrams, so we should pick a decays where leading tree diagram is not overwhelmingly dominant → singly Cabibbo-suppressed (SCS) decays, *e.g.* $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$.

Leading order 'tree' amplitude, but with suppressed vertex



Suppressed 'loop' amplitude



We measure an asymmetry

$$\mathcal{A}_{CP} = \frac{D^0 \to K^+K^- - \overline{D}^0 \to K^+K^-}{D^0 \to K^+K^- + \overline{D}^0 \to K^+K^-}$$

Measurement is performed using pion-tagged D^0's from D^*'s and muon-tagged D^0's from B's.

The meson is neutral, but we are interested in so-called 'direct' CPV, so measure the asymmetry integrated over all decay times (still, possible residual 'indirect' CPV coming from mixing effects must be accounted for in interpretation).

CPV measurements – practical considerations

When probing a sub-% A_{CP}, one must worry about sources of fake asymmetry that will contribute to raw value. So for D* tagged events* & final state *f*:

$$\mathcal{A}_{\text{raw}}(f) = \mathcal{A}_{CP}(f) + \mathcal{A}_D(f) + \mathcal{A}_D(\pi_s) + \mathcal{A}_P(D^{*+})$$

what we are after

detection asymmetry for final state

must be zero for decays of D^0 into two pseudoscalars !

detection asymmetry for slow pion

production asymmetry: there can be different numbers of D^{*+} and D^{*-} produced in acceptance

- Analogous expression for semileptonic tags

CPV measurements – practical considerations

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Consider A_{raw} for two final states: K^+K^- and $\pi^+\pi^-$:

- A_{CP} is not expected to be the same, as direct CP violation is final-state specific (indeed the naïve expectation if hadronic physics works just the same for both is that $A_{CP}(KK) = - A_{CP}(\pi\pi)$);
- But $A_D(\pi_S)$ & $A_P(D^{*+})$ is independent of final state, in given phase space region.

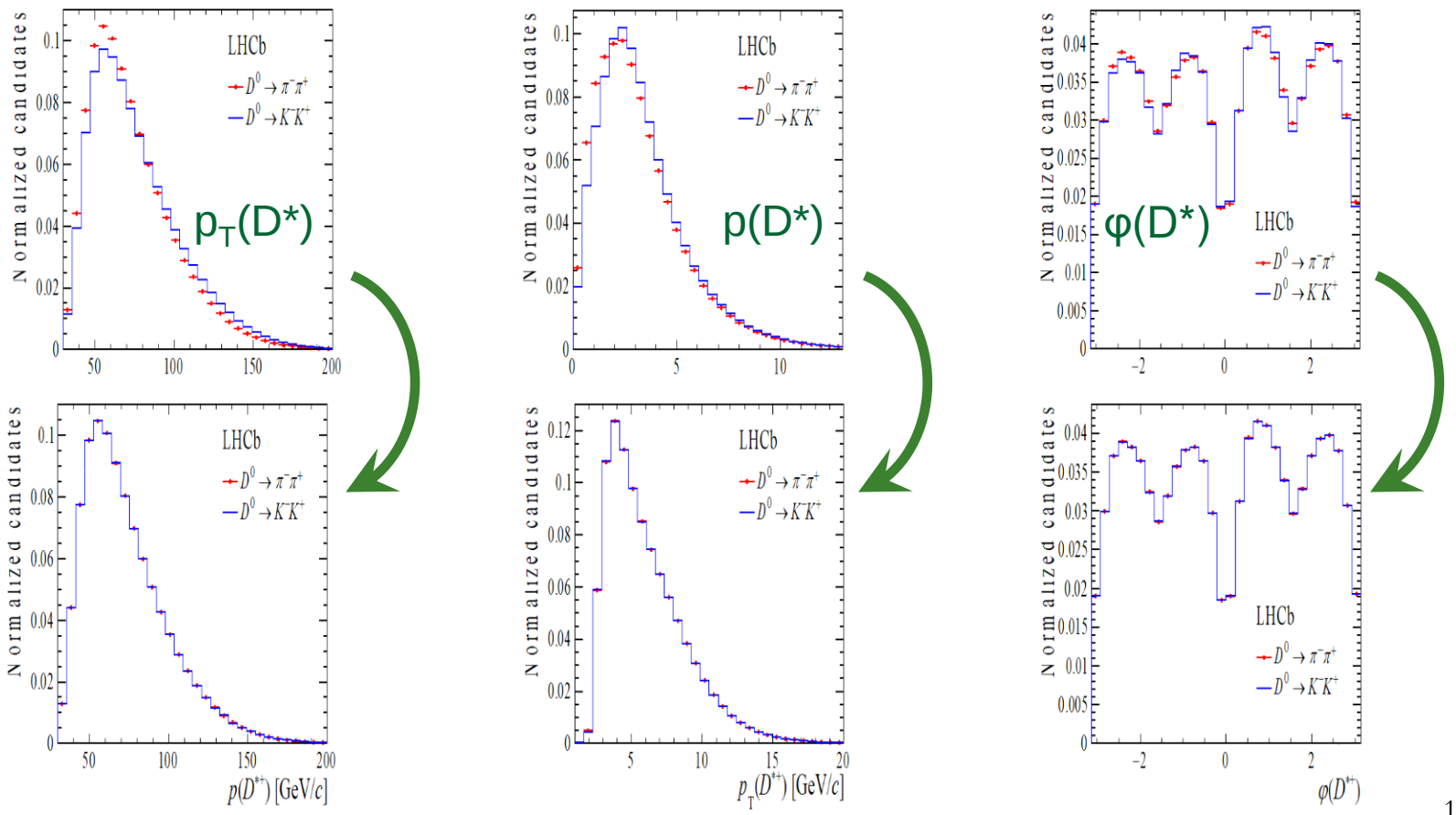
So measure ΔA_{CP} , the *difference* between the two raw asymmetries:

$$\Delta\mathcal{A}_{CP} \equiv A_{raw}(KK) - \mathcal{A}_{raw}(\pi\pi) = \mathcal{A}_{CP}(KK) - \mathcal{A}_{CP}(\pi\pi)$$

Kinematic re-weighting

Event selection induces small differences in kinematics between $D^0 \to KK$ and $D^0 \to \pi\pi$.

To achieve perfect cancellation of detection & production asymmetries in ΔA_{CP} it is necessary to re-weight KK sample to $\pi\pi$ kinematics. *e.g.* for π tagged sample:

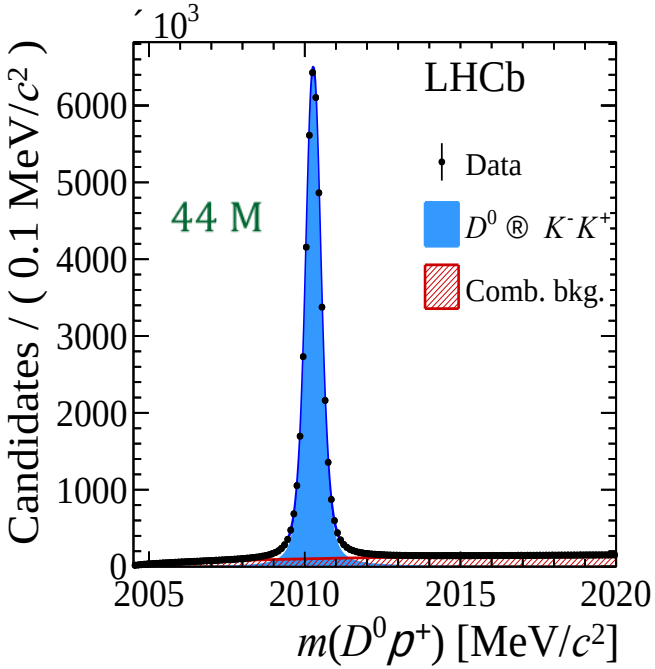


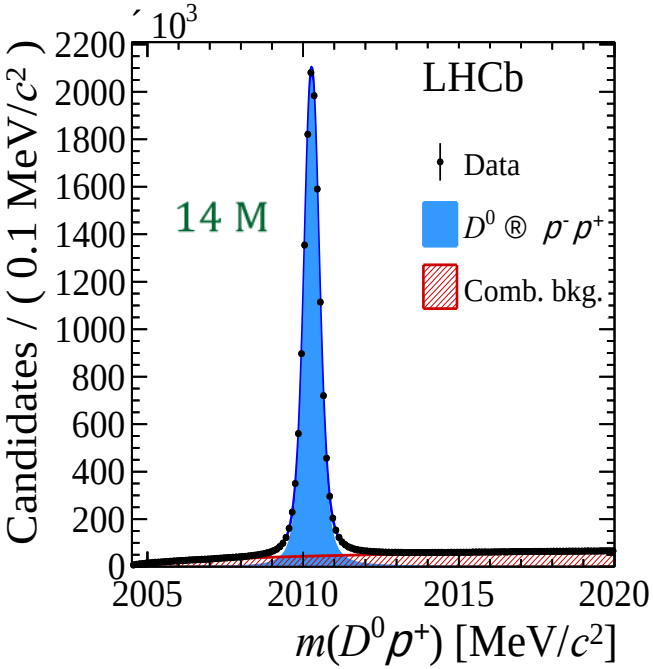
Determination of A_{raw}

In the π-tagged analysis we fit the $m(D^0\pi)$ distributions corresponding to the two flavour tags.

$$A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

About 44 million signal decay for K^+K^- and 14 million for $\pi^+\pi^-$ are used.



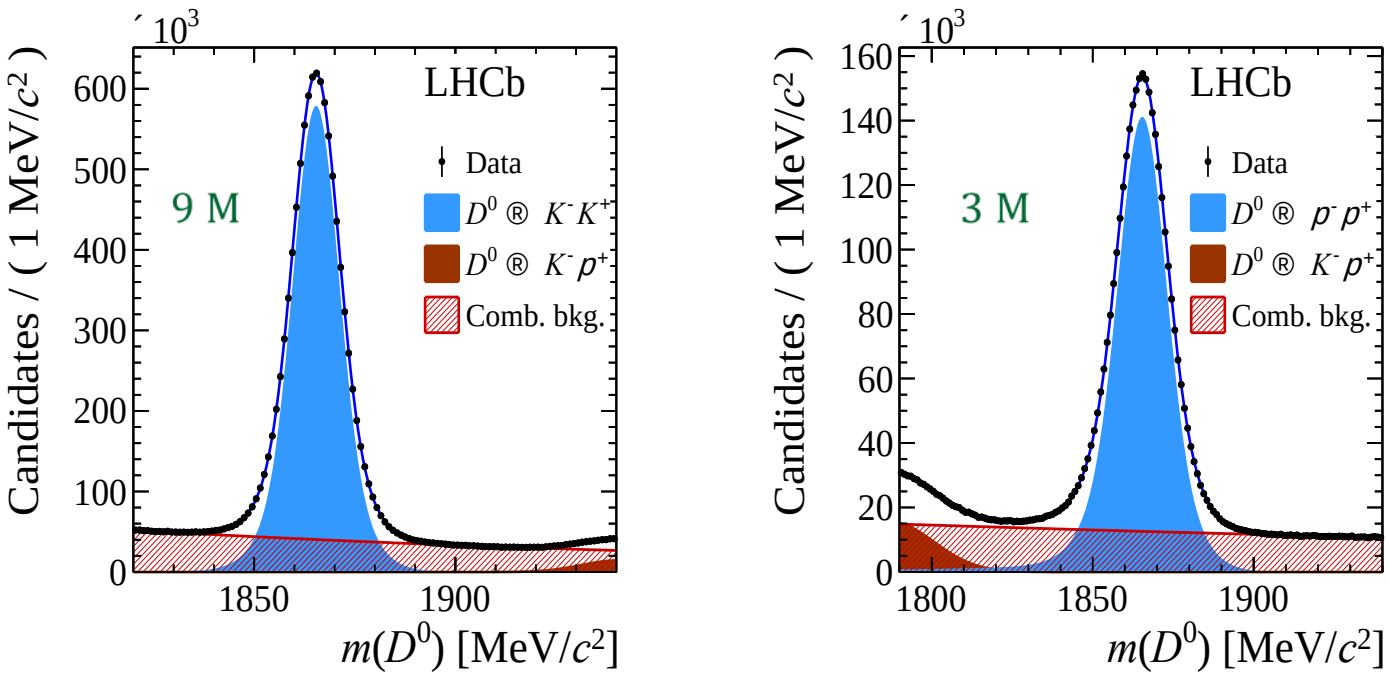


Determination of A_{raw}

In the μ-tagged analysis we fit the $m(D^0)$ distributions corresponding to the two flavour tags.

$$A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)}$$

About 9 million signal decay for K^+K^- and 3 million for $\pi^+\pi^-$ are used.



Systematic uncertainties

π-tagged dominated by:

Fit model

Evaluated by generating pseudo-experiments and fitting alternative models;

Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B^0 fraction	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

Physics backgrounds

e.g. $D^0 \to K^- \pi^+ \pi^0$, $D^0 \to \pi^- l^+ \upsilon_l$ peaking in $m(D^0\pi)$.
Potential bias estimated by measuring the yields and asymmetries of backgrounds from the $m(D^0)$ distributions.

μ-tagged dominated by

Mistag (wrong muon)

Evaluated on the $B \to D^0(\to K^- \pi^+)\mu X$ control sample.

Most systematic uncertainties are assigned from data studies, and in all cases are <(<) statistical.

ΔA_{CP} results

Run 2 data (6 fb^{-1}) [PRL 122 (2019) 211803] :

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

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Compatible with Run 1 results [JHEP 07 (2014) 041; PRL 116 (2016) 191601].

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CP violation observed at $\mathbf{5.3\sigma}$!!

Does result agree with the Standard Model ?

Hard to say. Hadronic effects mean that calculations are very difficult in the charm system. Most theorists had expected a lower value.

e.g. prediction using QCD sum rules

- A. Khodjamirian and A. Petrov [Phys. Lett. B774 (2017) 235]
- $|\Delta A_{CP}| \leq (2.0 \pm 0.3) \times 10^{-4}$
- Prediction smaller than the measured value by a factor of 7!

But few would say that observed value is *impossible* within the SM (*e.g.* QCD sum rules work well in B physics, but could break down for charm).

Far too early to be invoking non-SM explanations, however:

- Light Z′: M. Chala, A. Lenz, A. V. Rusov & J. Scholtz [JHEP 1907 (2019) 161]
- Various scenarios with heavy new particles: A. Dery & Y. Nir [arXiv:1909.11242]

Best hope of progress is experimental:

- Individual measurements of $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ [PRL 131 (2023) 091802];
- Make measurements in other modes where less, *e.g.* $A_{CP}(D^+ \to \pi^+\pi^0)$, or more, *e.g.* $A_{CP}(D^0 \to K_S K_S)$ CPV is expected in SM;
- Intensify search for CPV in mixing-related observables.