Flavour Physics

Guy Wilkinson
University of Oxford

CERN-Fermilab HCPSS
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Useful resources & acknowledgments

- Heavy Flavour Averaging Group (HFLAV) https://hflav.web.cern.ch
- CKMfitter ckmfitter.in2p3.fr Utfit www.utfit.org/UTfit/
- Particle Data Group reviews pdg.lbl.gov
- Books:
  - CP violation, I.I. Bigi and A.I. Sanda (CUP, 2000)
  - CP violation, G.C. Branco, L. Lavoura & J.P.Silva (OUP, 1999)
- Reviews & lectures:
  - M. Blanke, arXiv:1704.03753
  - O. Gedalia & G. Perez, arXiv:1005.3106
  - Y. Grossman & P. Tanedo, arXiv:1711.03624
  - J.F. Kamenik, arXiv:1708.00771
  - Z. Ligeti, arXiv:1502.01372
  - Y. Nir, arXiv:0708.1872, arXiv:1605.00433

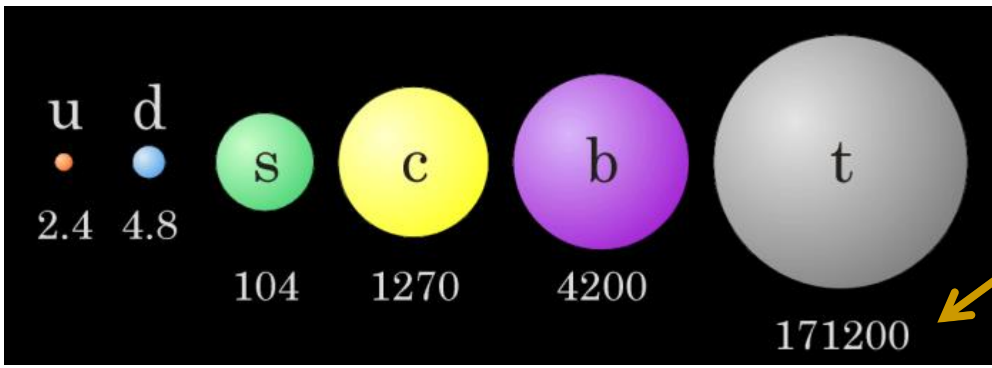
Thanks to flavour lecturers at this school in previous years, who provided inspiration for some of the material shown (esp. T. Gerson, J. Zupan & M-H. Schune).

What is flavour physics and why should we care ?

What is flavour physics?

The concept of 'flavour' in particle physics relates to the existence of different families of quarks*, and how they couple to each other

i.e. 6 known flavours of quark, grouped into 3 generations



Not to linear scale !

mass in MeV/c^2

Open questions:

- why 3 generations ?
- why do the quarks exhibit this striking hierarchy in mass ?

No answer yet !
These values (i.e. '3' & the masses) are free parameters of the SM

These mysteries make the 'flavour sector' of the Standard Model of great interest.

* the concept of flavour extends to the lepton sector too

Flavour and the CKM matrix

In the Standard Model quarks can only change flavour through emission of a W boson (*i.e.* weak force). For example a t quark can decay into a b, s or d quark:

But these decays are not equally likely. At the amplitude level they are weighted by factors that are elements of the Cabibbo-Kobyashi-Maskawa (CKM) matrix, and these factors vary dramatically – here is another hierarchy we don't understand !

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ \boxed{V_{td} \quad V_{ts} \quad V_{tb}} \end{pmatrix} = \begin{pmatrix} 0.9705-0.9770 & 0.21-0.24 & 0-0.014 \\ 0.21-0.24 & 0.971-0.973 & 0.036-0.070 \\ 0-0.014 & 0.036-0.070 & 0.997-0.999 \end{pmatrix}$$

These elements of the CKM matrix are also fundamental parameters of the Standard Model. Why they have these values is another great mystery.

Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
- strong CP parameter θ
- 6 quark masses
- 3 quark mixing angles + 1 phase [*i.e.* CKM matrix]
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase [*i.e.* PMNS matrix])

() = with Dirac neutrino masses

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This is of particular relevance…

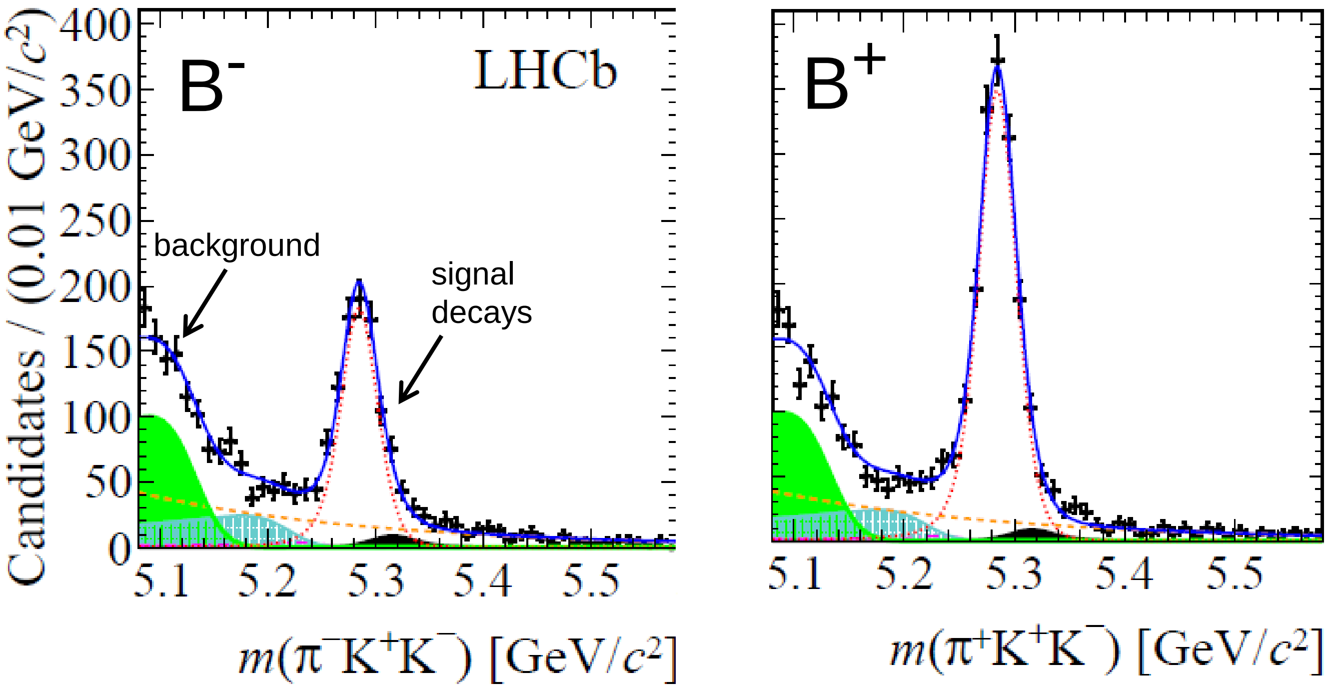
() = with Dirac neutrino masses

CP violation

CP violation (CPV) → difference in behaviour between matter and anti-matter.

First discovered in the kaon system in 1964, opportunities of study were limited until colliders arrived that could make lots & lots of b-quark hadrons, *e.g.* the LHC

A recent example from LHCb - look at B meson decaying into a pion & two kaons…

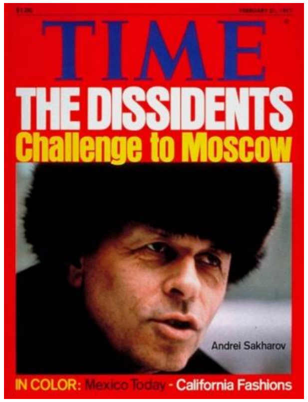


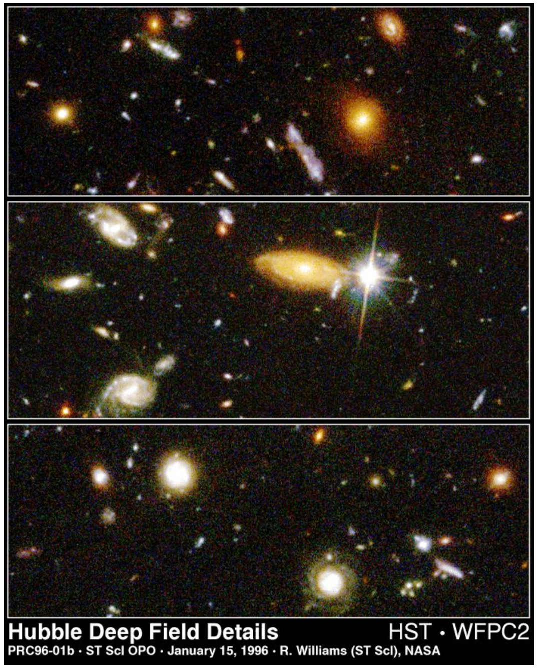
[LHCb, PRD 90 (2014) 112004]

…the decay probabilities are manifestly different for B^- & B^+ ! In the Standard Model CPV is accommodated, *but not explained*, by an imaginary phase in the CKM matrix

Cosmological connections ?

As first pointed out by Andrei Sakharov, CP-violation is one requirement for explaining *baryogenesis* – the process that took us from the equal amounts of matter and anti-matter produced in the Big Bang, to the matter dominated universe of today





The problem is that the CP-violation that appears in the Standard Model, is woefully inadequate to explain the matter-antimatter asymmetry we have today.

This is a big problem with the Standard Model !

More & better measurements may point a way forward.

Problems with the Standard Model

The Standard Model (SM) cannot be a final theory

We have already encountered the following shortcomings:

- No explanation for baryogenesis
- No explanation for the quark or CKM hierarchy
- No real explanation for CP violation, and why it is only found in the weak interaction.

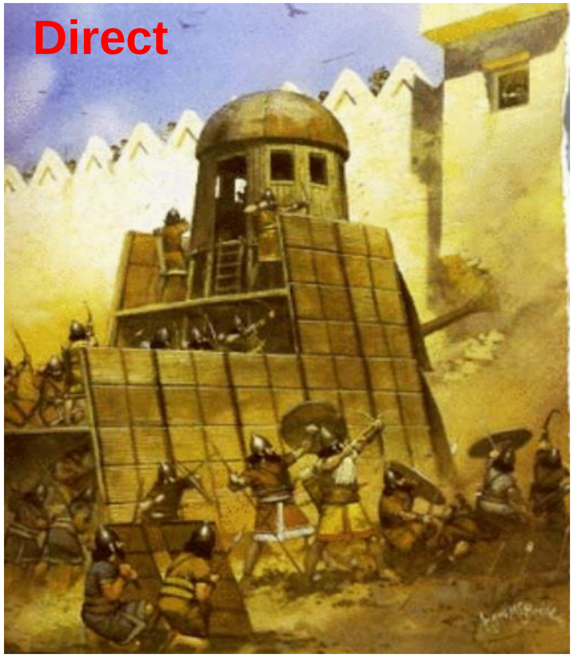
And there are plenty of others, for example:

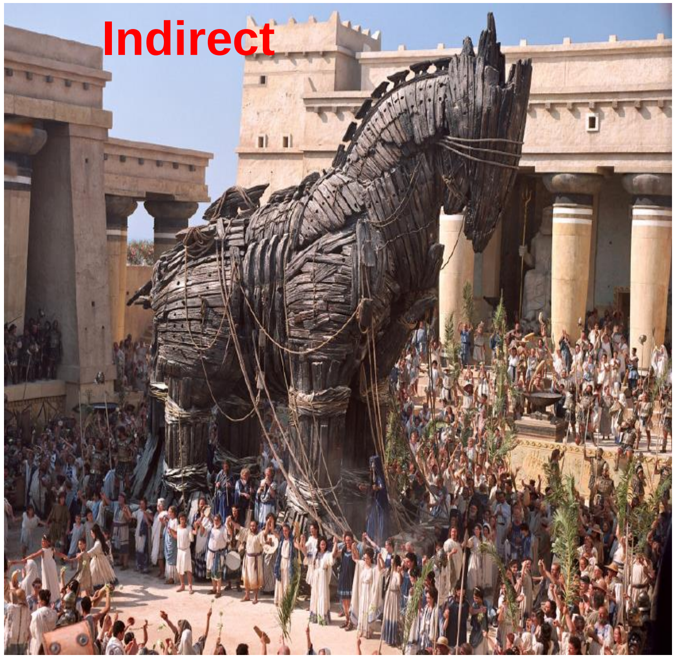
- No explanation for dark matter or dark energy
- No explanation for neutrino masses
- Gravity not included
- No explanation for why the Higgs boson has the mass it does (left to itself the theory would make it much, much heavier)

More ambitious theories (*e.g.* supersymmetry or SUSY) can solve at least some of these problems. They generally predict new particles or effects outside the SM. Finding these effects is the goal of the LHC & many other present/planned facilities !

Breaching the walls of the Standard Model

The HEP community is searching for 'New Physics' - to find this we need to penetrate the walls of the Standard Model fortress. There are two strategies used in this search.





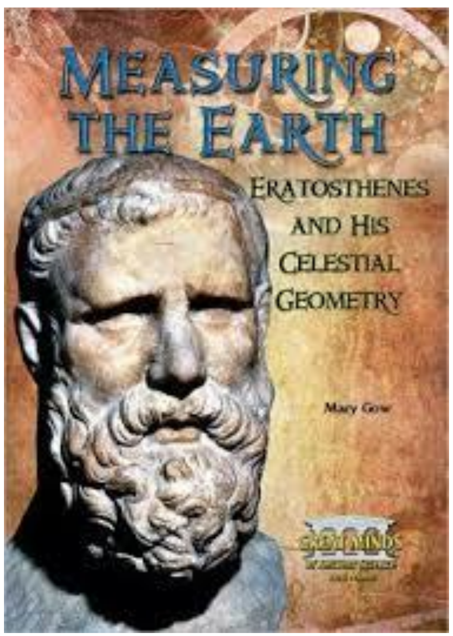
Use the high energy of, *e.g.* the LHC to produce the New Physics particles, which we then detect

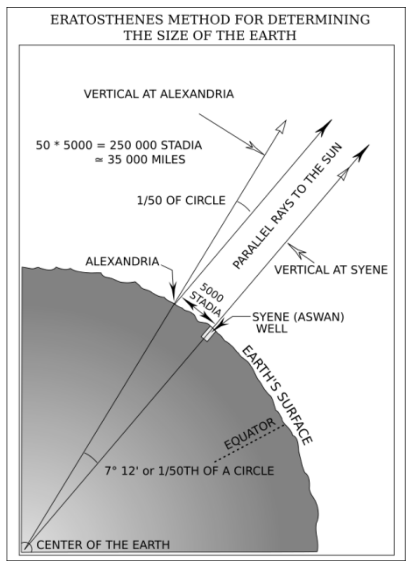
Make precise measurements of processes in which New Physics particles enter through 'virtual loops'

Both methods are powerful. Flavour physics follows the 'indirect' approach.

Indirect measurements – an established tradition in science

Eratosthenes was able to determine
the circumference of the earth
using indirect means…





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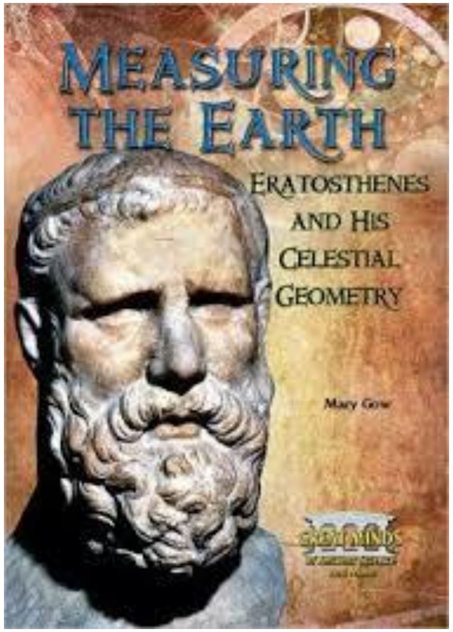
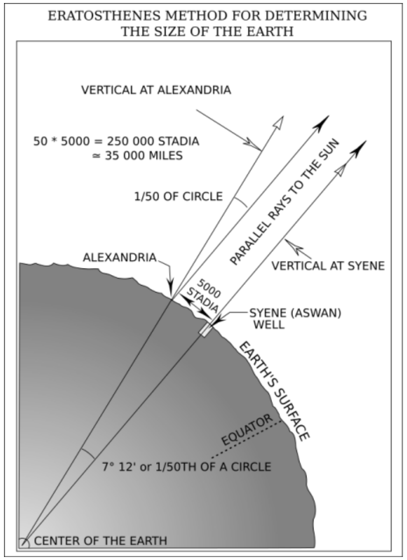
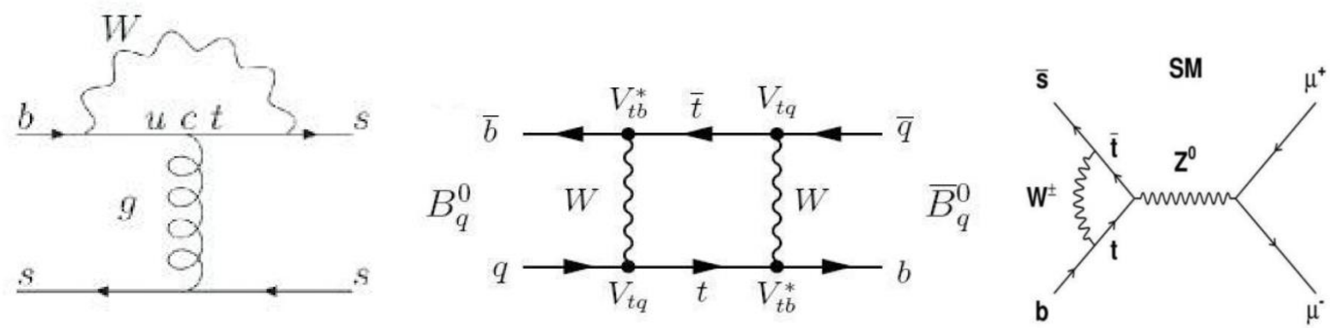




…around 2.2 thousand years prior to the direct observation.

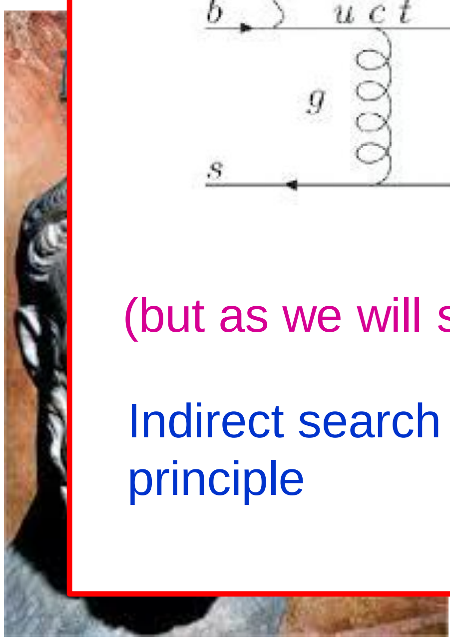
Indirect measurements – an established tradition in science

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute



(but as we will see, tree-mediated decays also have their role to play)

Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at energies *far* beyond direct searches (~10^4 TeV in some cases)



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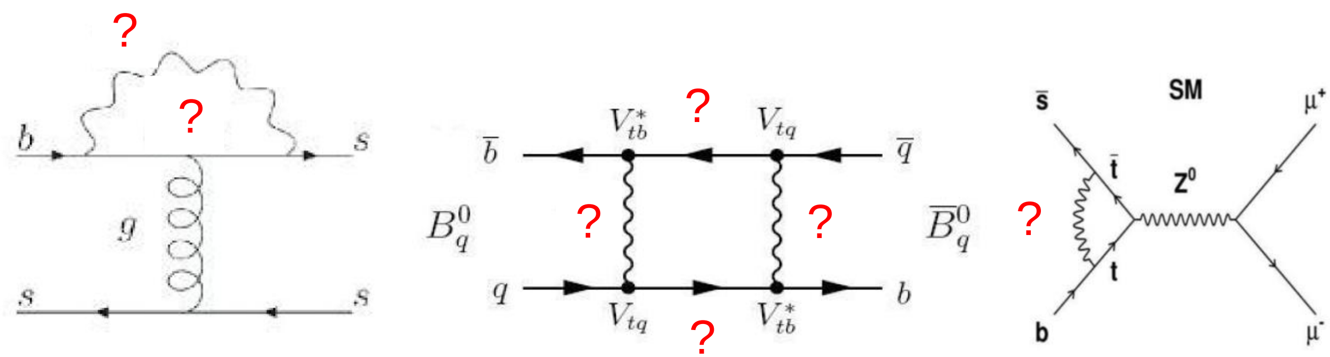

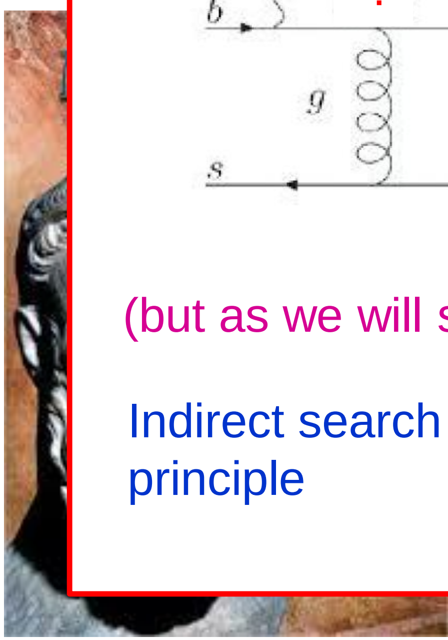

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For this reason its rather surprising that (spoiler alert !) most flavour measurements so far agree with the SM, as naturalness told us New Physics is expected at TeV scale → the **New Physics Flavour Puzzle**.

Either, there is something specific about the flavour-structure of the New Physics that is masking the effect…

…or we have put too much trust in naturalness.

Either way, flavour is central to the story !

Outline of the lecture contents and schedule

Flavour topics that we won't be covering

Flavour encompasses a huge range of areas of study & corresponding experimental activity. The following are genuine topics of flavour, but ones we will not cover.

- Kaon physics (OK, we will say a little, but not really do it justice)
- Suppressed top decays
- Flavour and CPV violation in the Higgs sector
- Charged lepton-flavour violation, *e.g.* $\mu \rightarrow e\gamma$
- (g-2) muon anomaly
- All neutrino physics

Instead we will focus on beauty physics, with some discussion on charm.

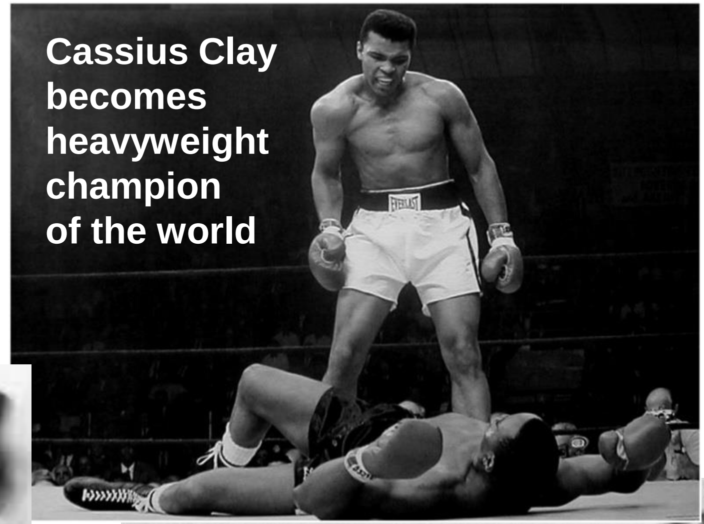
Lecture outline

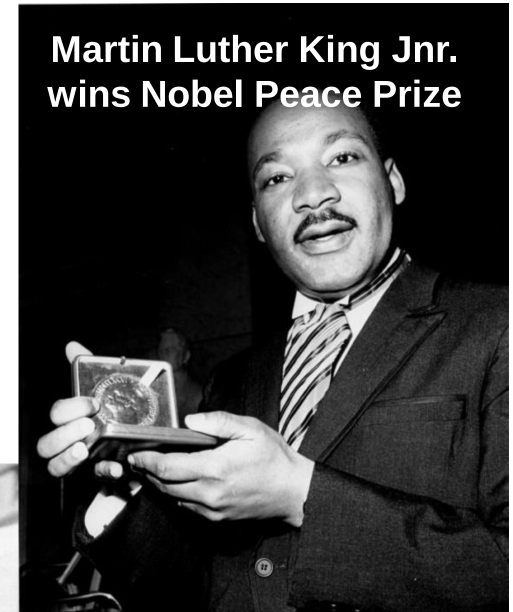
- Introduction ✓
- Birth of flavour physics & the kaon sector
- The beautiful millennium
- Flavour structure of the SM
- The Unitarity Triangle and CPV measurements
- Spectroscopy (a brief digression)
- FCNCs or ‘rare decays’
- Charm physics
- Future of flavour

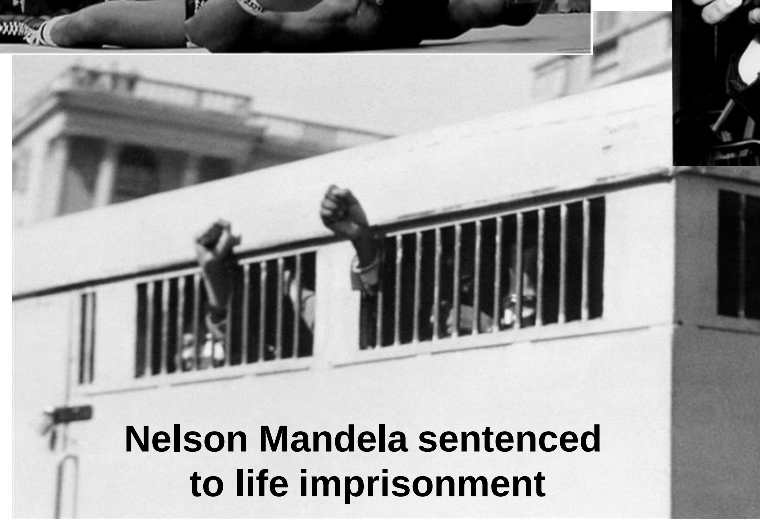
Note the approach will (necessarily) be from an experimentalist’s perspective.

The birth of experimental flavour physics and the (continuing) importance of kaon studies

Events of 1964







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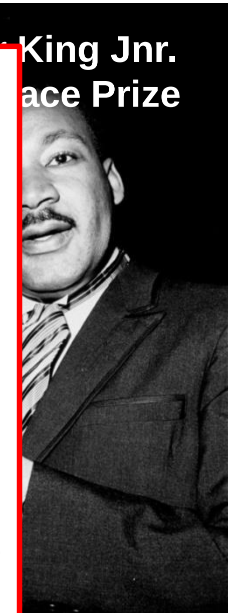

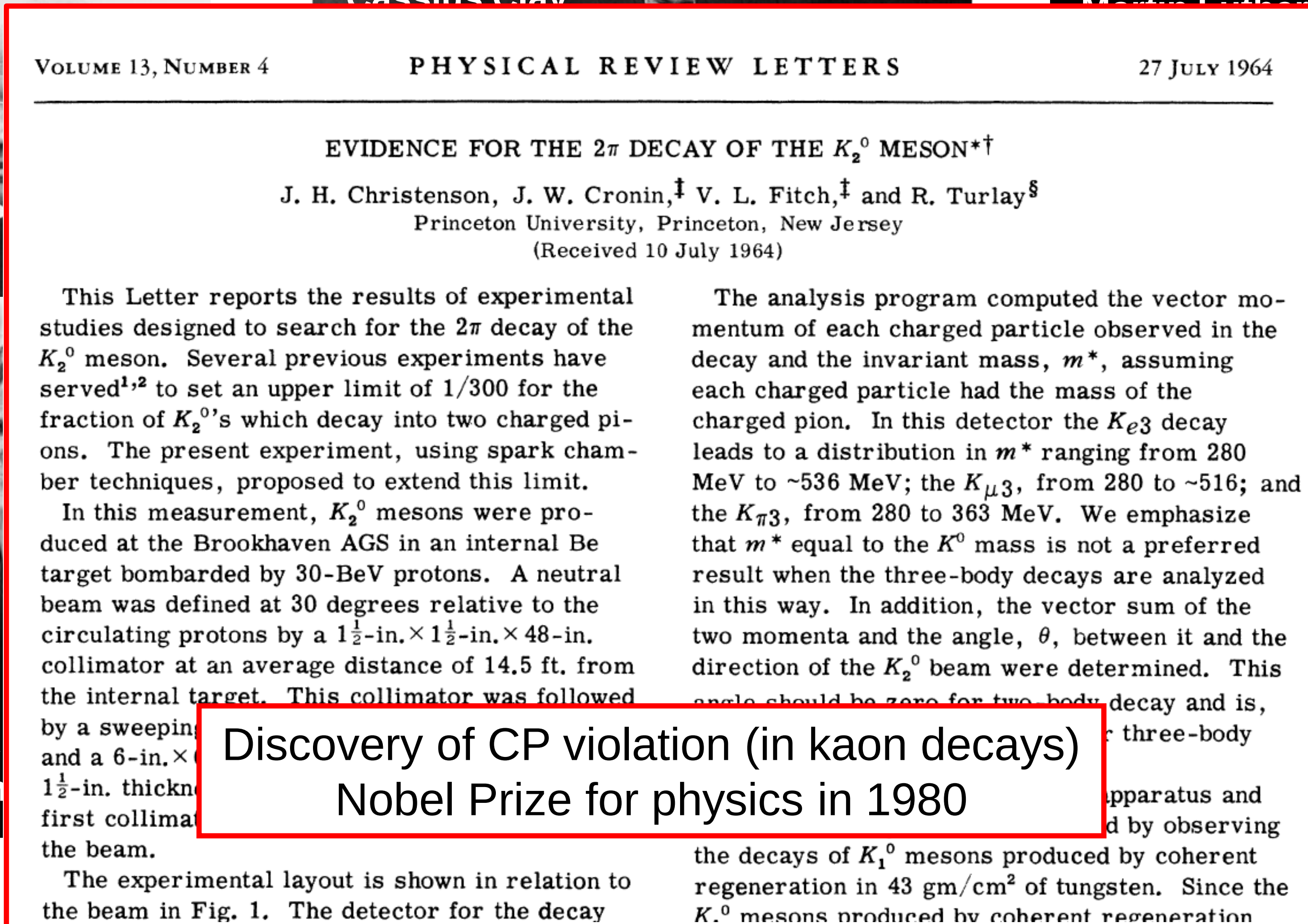

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.×$1\frac{1}{2}$-in.×48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping ... and a 6-in.× ... $1\frac{1}{2}$-in. thickn... first collimat... the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This angle should be zero for two-body decay and is, ... three-body ... apparatus and ... d by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the K_1^0 mesons produced by coherent regeneration

Discovery of CP violation (in kaon decays)
Nobel Prize for physics in 1980

Discovery of CP violation

Observation of 45 ± 10 $\pi^+\pi^-$ decays in a K^0_L beam [Christenson *et al.*, PRL 13 (1964) 138].

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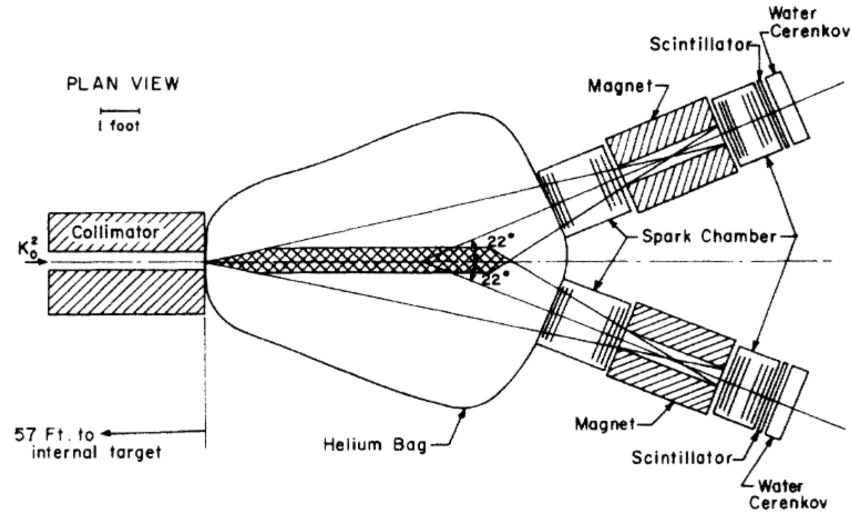
An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the K_1^0 mesons produced by coherent regeneration

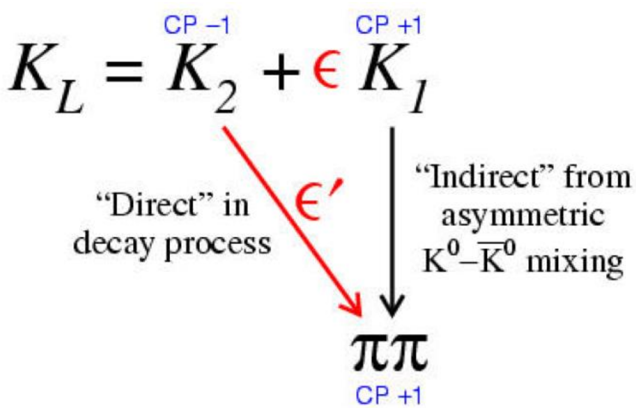


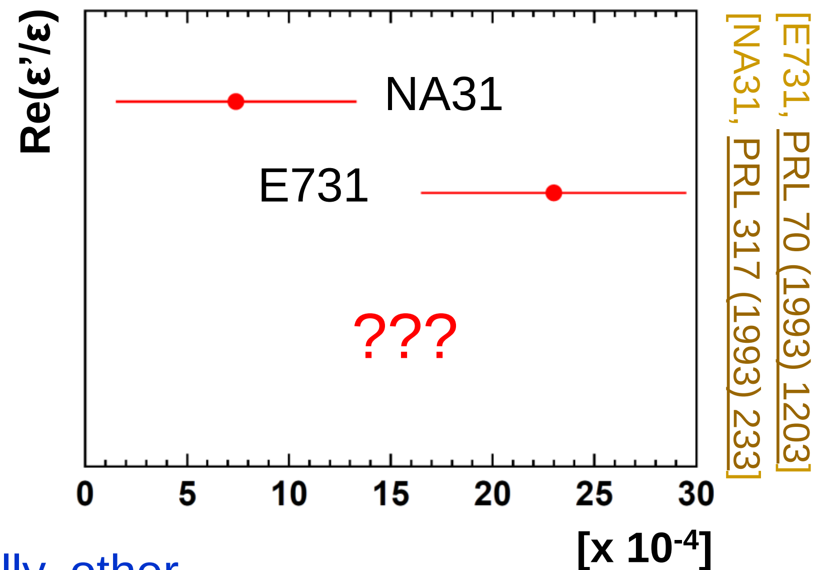
Interpretation: K^0_L not a pure CP-odd eigenstate. Level of CP-even 'contamination' given by ε, which is now measured to be $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$ [PDG].

The heroic quest for ε′

(more thorough discussion on direct & indirect CPV will come later…)

In the CKM paradigm $K^0_L \rightarrow \pi\pi$ is readily explained as *indirect* CPV. CKM also allows for the possibility of *direct* CPV, which can be revealed by measuring the relative rates of K^0_S and K^0_L into $\pi^+\pi^-$ and $\pi^0\pi^0$, which give the parameter Re(ε'/ε).





A non-zero Re(ε'/ε) implies direct CPV, & is consistent with CKM picture. Historically, other models (*e.g.* superweak [Wolfenstein, PRL 13 (1964) 562]) predicted zero direct CPV.

Effect is very small, experiment is hard, and first measurements were ambiguous.

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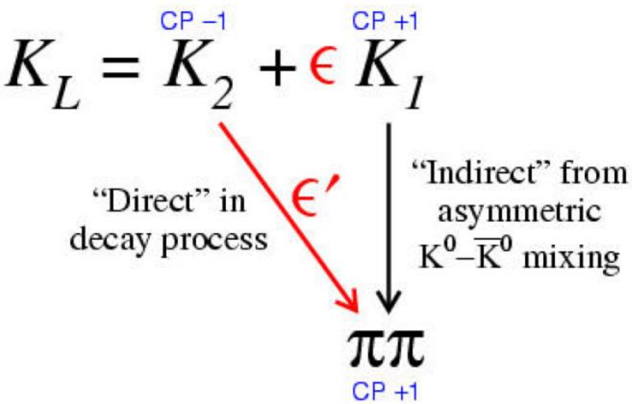

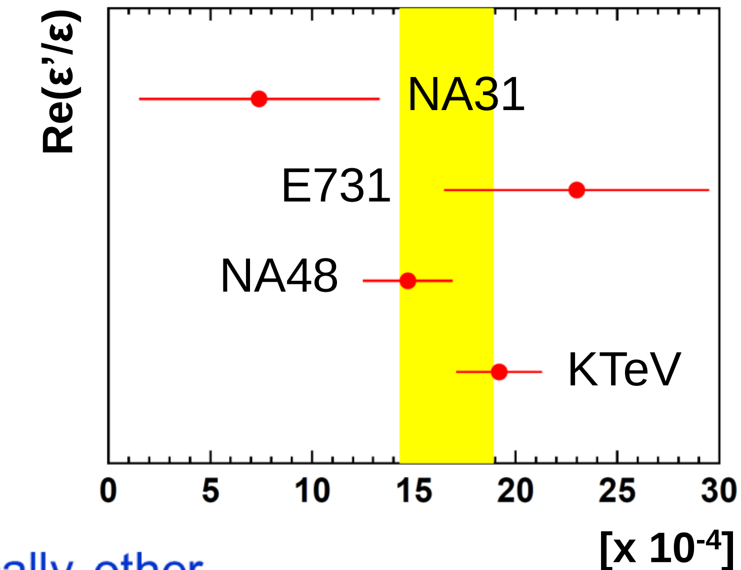

[KTeV, PRD 83 (2011) 092001]
[NA48, PLB 544 (2002) 97]

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Effect is very small, experiment is hard, and first measurements were ambiguous. A second round of experiments (NA48, KTeV) was required to show Re(ε'/ε)$\neq 0$.

Lattice QCD prediction not as precise as experiment, but progress being made.

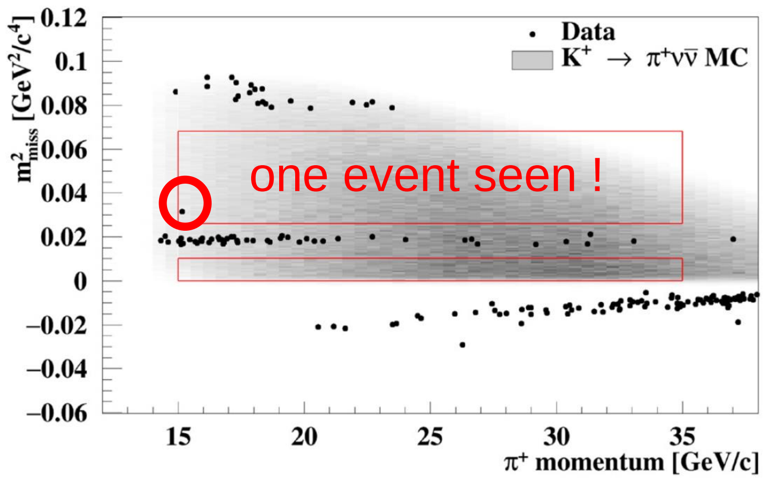
Heroic work! Kaon physics is very difficult - small effects & theoretically challenging.

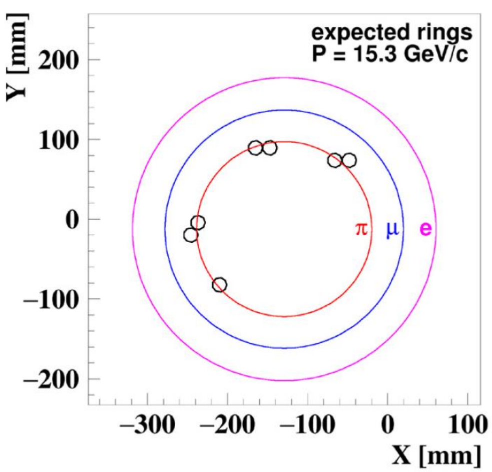
In search of the ultra-rare

CP violation is not the whole story. Kaons system is also well suited for searches for forbidden or ultra-suppressed decays, the most topical of which is $K^+ \to \pi^+ \nu\bar{\nu}$.

In SM $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11}$ [Buras *et al.*, JHEP 1511 (2015) 033], but New Physics enhancements possible with sensitivity to mass scales under 100 TeV.

BNL experiments E949 & E787 saw 3 events [PRD 77 (2008) 052003], consistent with SM. NA62, here at CERN, aims to observe ~100 and make precise measurement of BR.





Pilot measurement released [PLB 791 (2019) 156], based on a few weeks of data taking.

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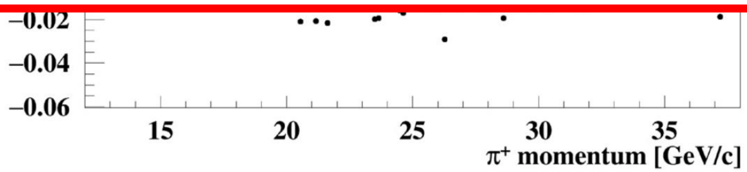
In SI … , but
New … 0 TeV.

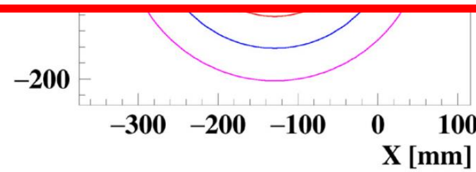
BNL … vith SM.
NA6 … of BR.

Kaon studies have played a critical role in the development of flavour physics. They will continue to do so in future.

However, in the past 2-3 decades the focus has been on beauty:

- A huge number of decays and processes to explore
- Sizable CPV effects expected (& observed)
- In many cases theoretically clean predictions are available





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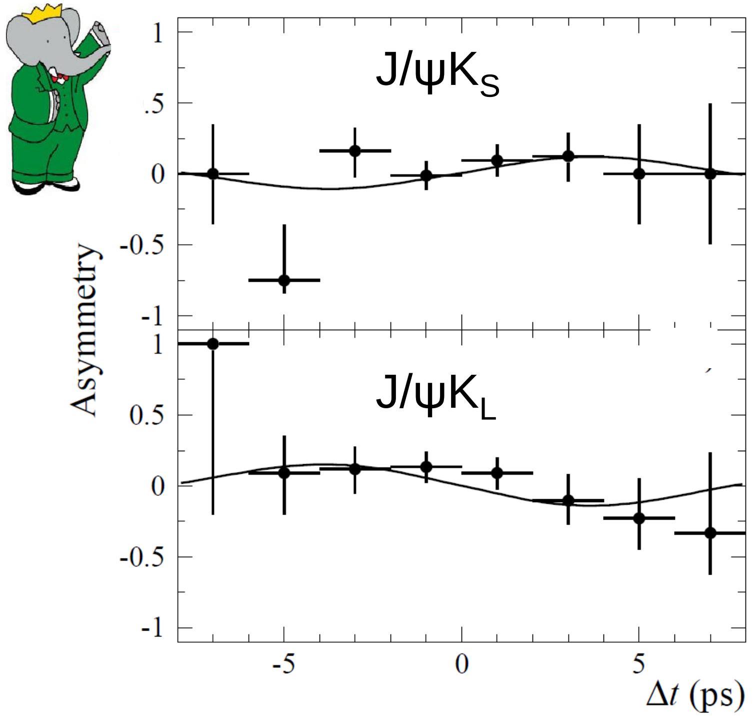
We live in a golden age of flavour !

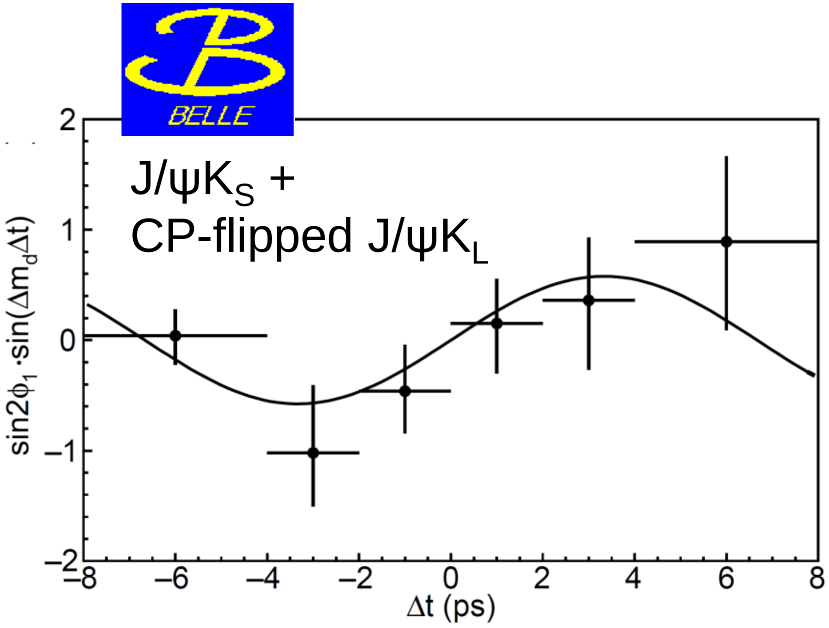
An introduction to the experiments of B physics

2001 – opening of the age of flavour

2008 Nobel Prize

We can date the start of modern flavour physics to 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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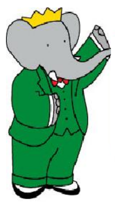
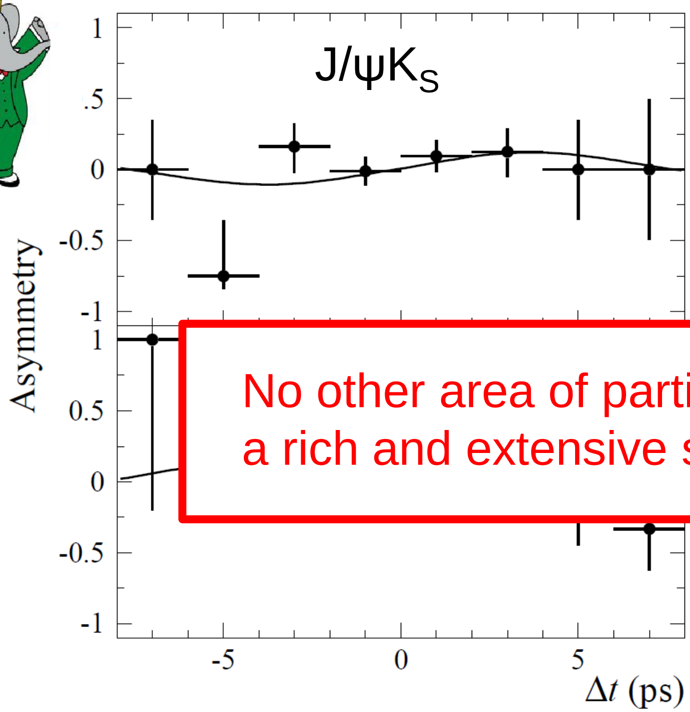
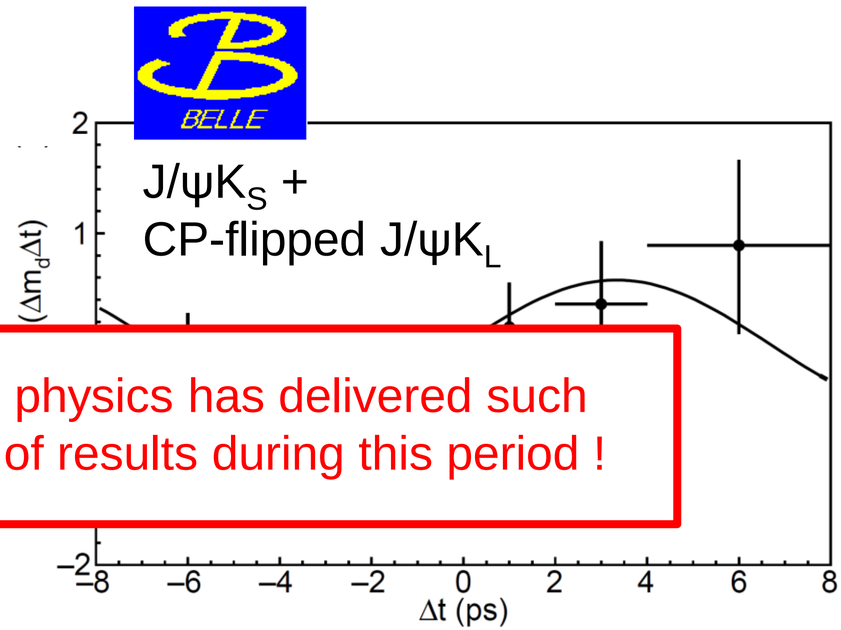






No other area of particle physics has delivered such a rich and extensive set of results during this period !

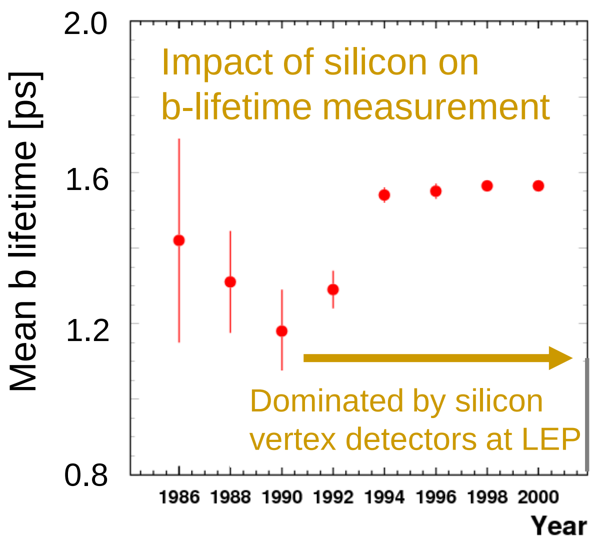
[BaBar, PRL 86 (2001) 2515] [Belle, PRL 86 (2001) 2509]

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.

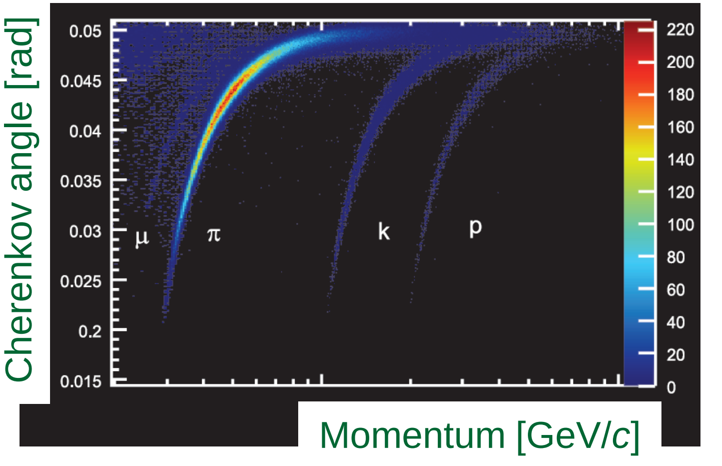
Why have we made progress?

Very important flavour-physics measurements were performed prior to 2001 (*e.g.* at ARGUS, CLEO, the SPS and LEP), but since then there has been an avalanche of results. What has enabled this explosion of progress?

- High-luminosity accelerators with large bbbar production cross-sections;
  - Number of b-hadrons produced at LEP ~ 10^7
  - Number of b-hadrons produced (so far) at LHCb ~ 10^{12}
- Improved and dedicated instrumentation, *e.g.* vertex detectors and RICHes;



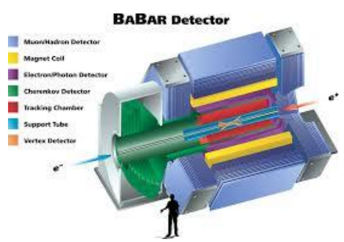
Cherenkov angle vs momentum in LHCb RICH



- Improved triggering, essential for hadron collider experiments;
- And not forgetting progress in theory, in particular lattice QCD.

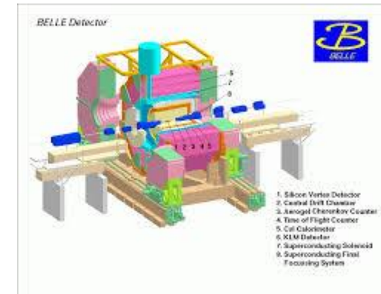
Heroes of the age of flavour

b-factories

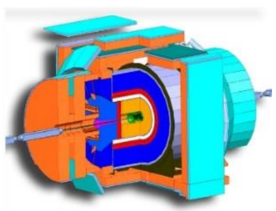


BaBar (SLAC) & Belle (KEK)

Operated in the 2000's
e^+e^- machines with asymmetric beams for time-dep studies, mainly at Y(4S), hence B^0 and B^+ samples.
Considered 'clean' environments.

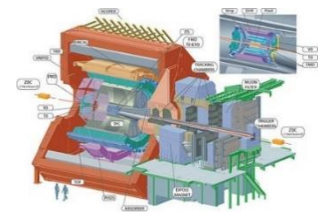


Tevatron experiments



CDF & D0

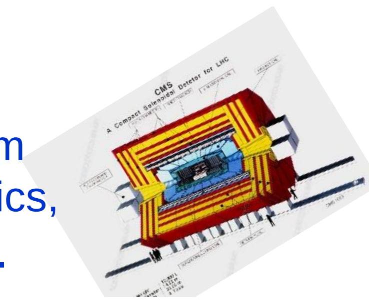
Tevatrons 'general purpose detectors'.
Pioneered *b*-physics in hadronic collisions.
Important early B_s and b-baryon studies.



LHC high-p_T experiments

ATLAS & CMS

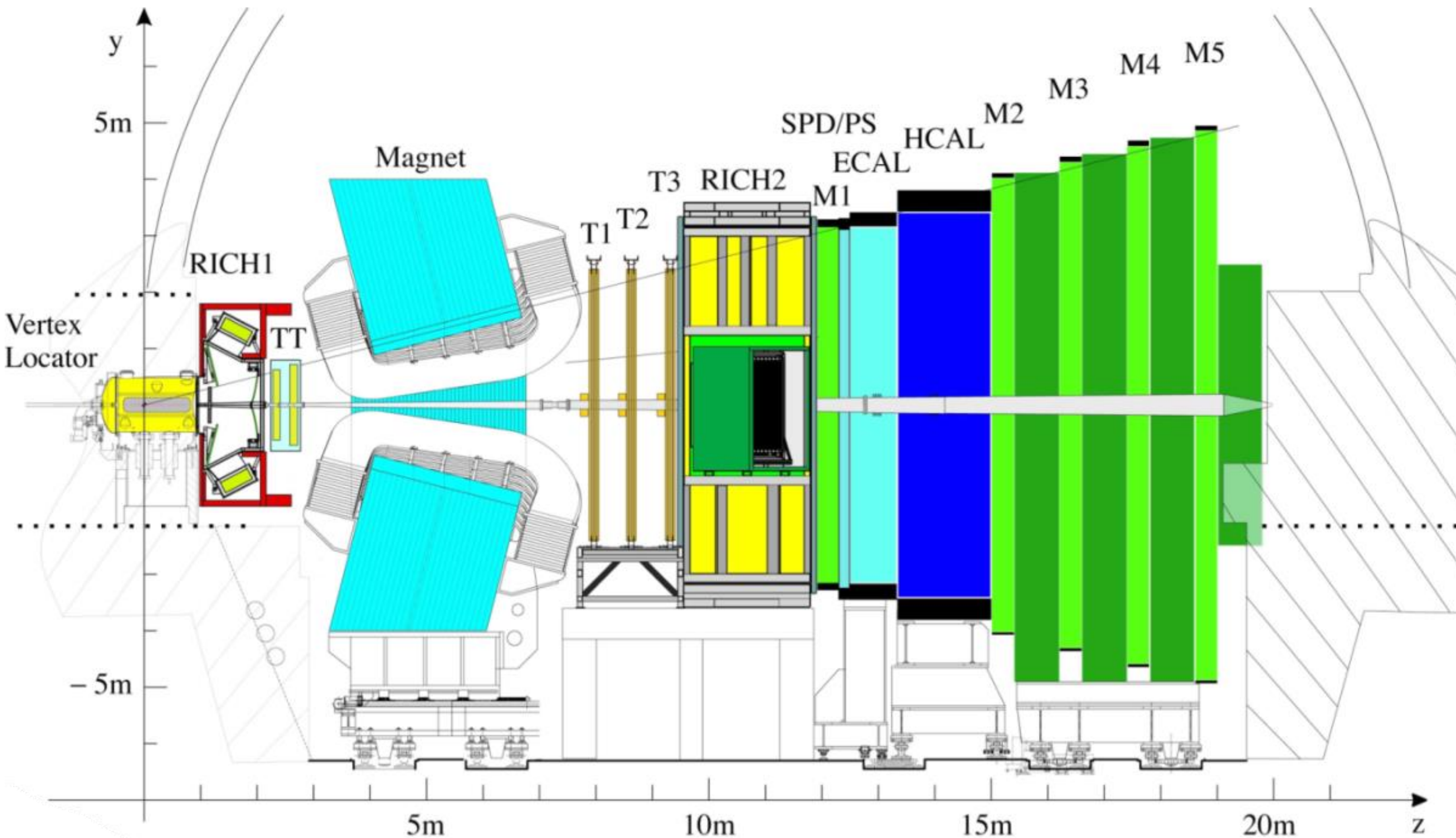
Their excellent instrumentation gives them great capabilities in certain b-physics topics, especially those with dilepton final states.



Important contributions also from BESIII, an e^+e^- experiment in Beijing. Operates below the Y(4S), but provides critical measurements of open charm & spectroscopy (at did CLEO-c).

Heroes of the age of flavour - LHCb

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



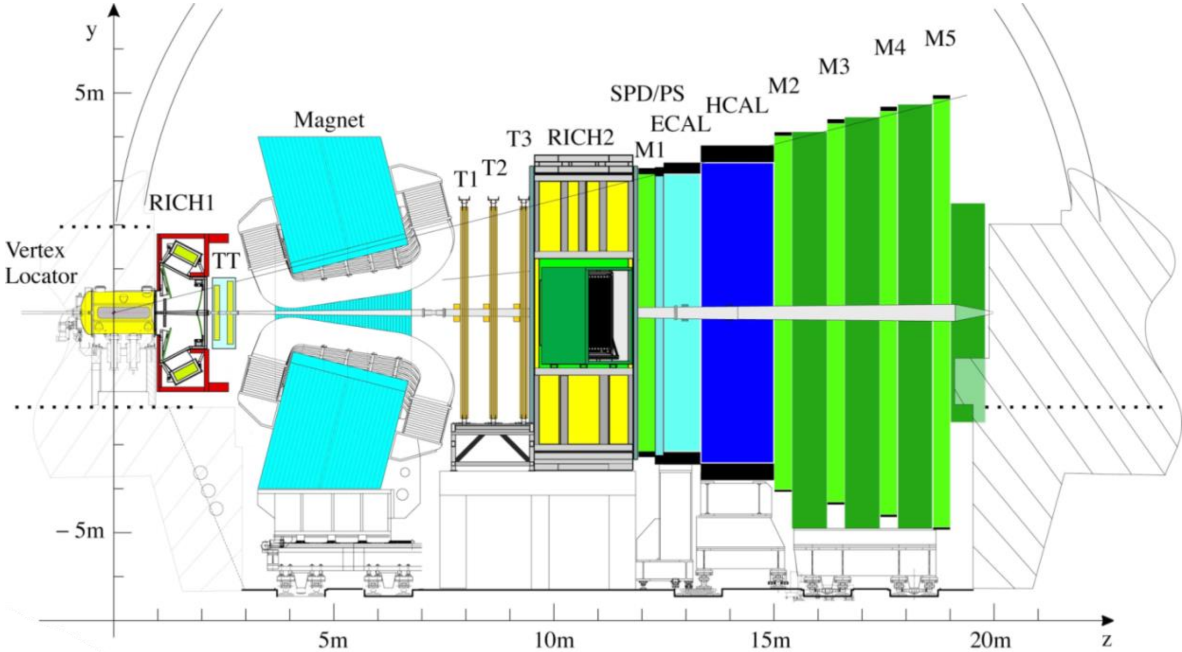
Heroes of the age of flavour - LHCb

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

Dedicated in the sense of the following attributes:

- Acceptance

  Spectrometer geometry is optimised to capture forward-peaked bbbar production.



Heroes of the age of flavour - LHCb

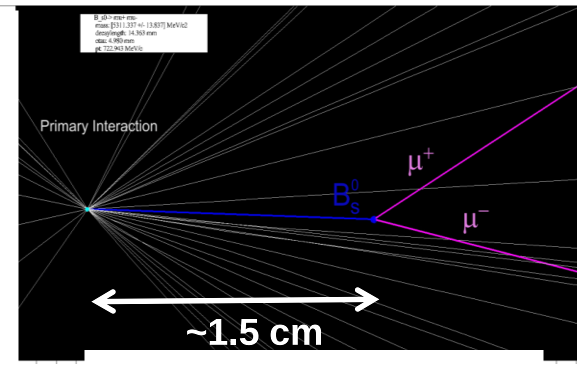
Designed to be a *dedicated* experiment for b- and c-physics at the LHC.

Dedicated in the sense of the following attributes:

- Acceptance
- Instrumentation

Vertex locator (VELO) and RICH system give unique capabilities for b-physics.

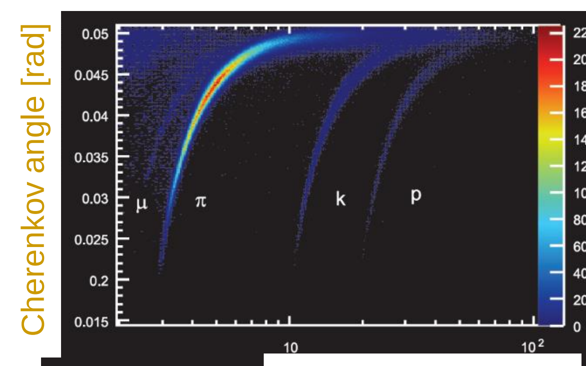

One-half of the VELO under construction



A b-hadron decay vertex


Assembling RICH 2


Array of RICH photodetectors



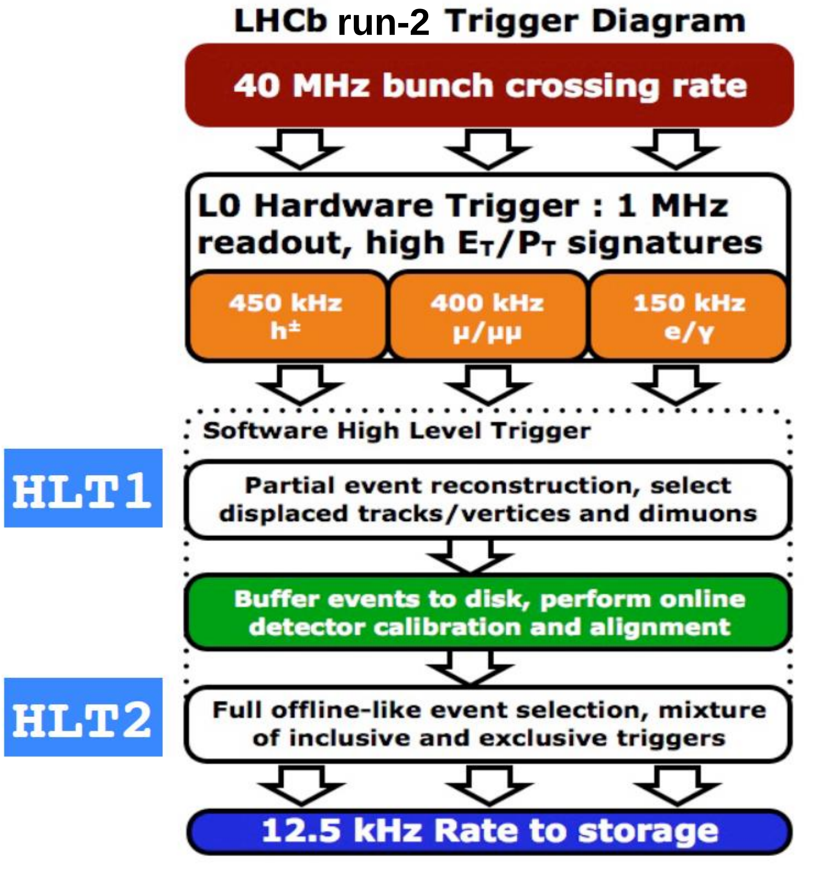
Heroes of the age of flavour - LHCb

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

Dedicated in the sense of the following attributes:

- Acceptance
- Instrumentation
- Trigger

  Trigger fully optimised for b-physics. Allows lower p_T thresholds than at ATLAS and CMS and ability to select hadronic final states.

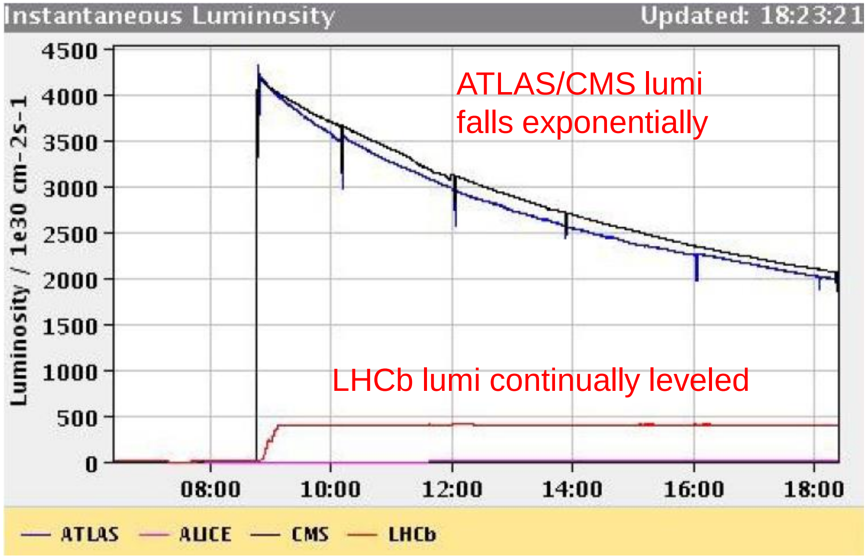


Heroes of the age of flavour - LHCb

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

Dedicated in the sense of the following attributes:

- Acceptance
- Instrumentation
- Trigger
- Operating luminosity



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

In run 1 & 2 luminosity deliberately set to be lower than at ATLAS & CMS, in order to provide best environment for b-physics measurements.

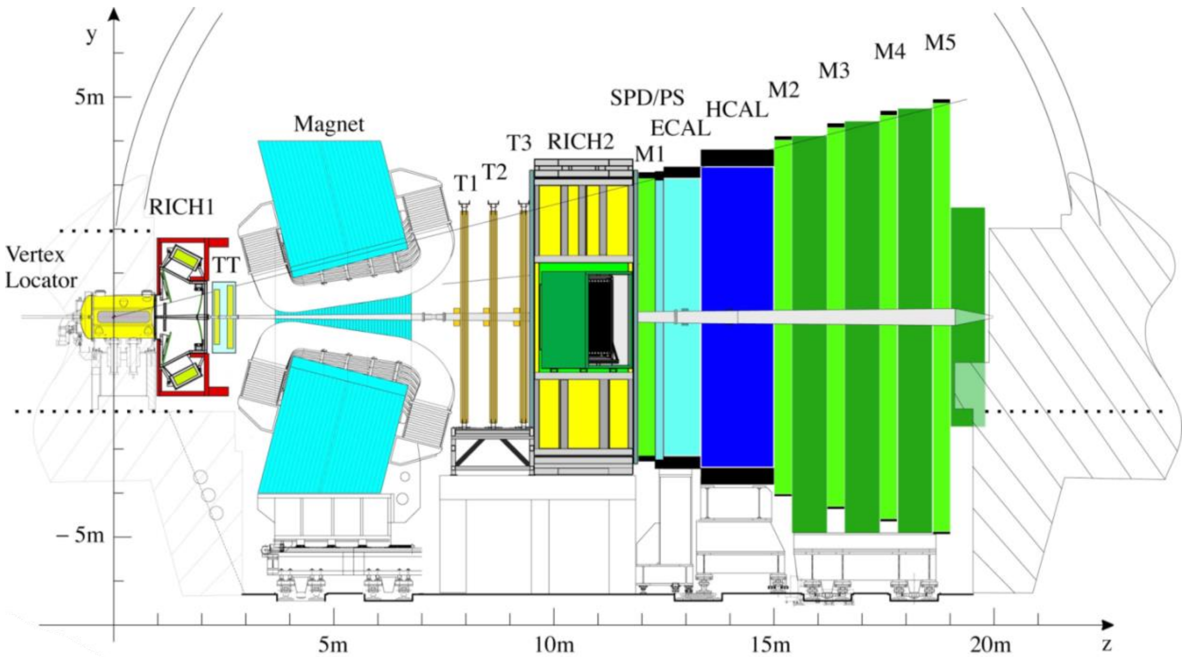
Total data sample from run 1 & run 2 around 9 fb^{-1}.

Heroes of the age of flavour - LHCb

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

Dedicated in the sense of the following attributes:

- Acceptance
- Instrumentation
- Trigger
- Operating luminosity



(But these attributes allow for important & unique studies beyond flavour, *e.g.* spectroscopy, electroweak, fixed-target proton-gas collisions…).

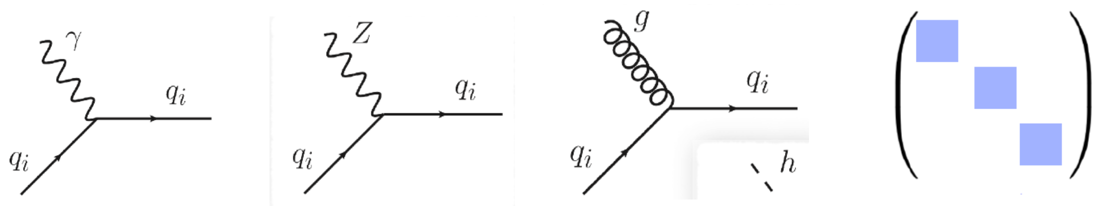
LHCb data-taking is now complete, and an upgraded detector is being installed.

Flavour structure of the Standard Model

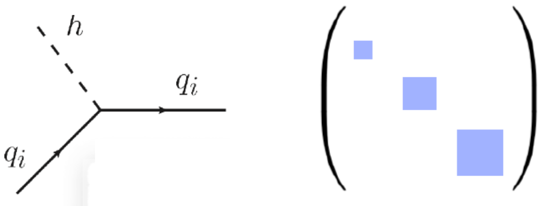
No Flavour-Changing Neutral Currents (FCNCs) at tree level

Neutral currents are flavour conserving at tree level

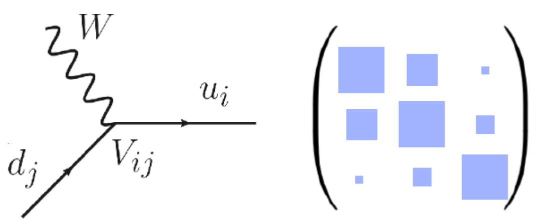
- Photon, gluon, Z have flavour (generation) –universal interactions



- Higgs has flavour-diagonal interactions proportional to quark mass



Whereas only the charged-current W couplings are flavour changing, with a very non-trivial structure → V_{CKM}



Cabibbo-Kobayashi-Maskawa matrix

The CKM matrix appears in the SM Lagrangian as a consequence of diagonalising the mass matrices. Therefore connected to quark masses (& Higgs mechanism).

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

It must be unitarity, *i.e.* $V^\dagger_{\mathrm{CKM}}\, V_{\mathrm{CKM}} = V_{\mathrm{CKM}} V^\dagger_{\mathrm{CKM}} = 1$, and can be parameterised with three angles and one imaginary phase, which is the origin of SM CPV.

This tight system of four parameters means that CKM physics is highly predictive !

One representation [Chau & Keung, PRL 53 (1984) 1802]:

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

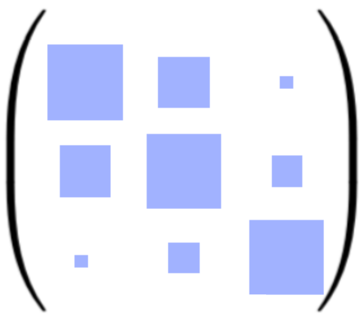
Measurements indicate a striking hierarchy: s_{12}~0.2, s_{23}~0.04, s_{12}~0.004.

Observed hierarchy of CKM matrix

A fit to data, imposing unitarity constraint [PDG review], and showing magnitudes:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

or represented graphically:



This is presumably telling us something, but what? (very different picture to one seen in neutrino sector)

Hierarchy motivates an alternative representation based on expansion in $\lambda = \sin\theta_c$.

CKM matrix expressed in Wolfenstein parametrisation

[Wolfenstein, PRL 51 (1983) 1945]

In the Wolfenstein parameterisation the matrix is expanded in orders of $\lambda \sim 0.23$.

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

This is expanded to λ^3, which will be adequate for most of our subsequent discussion, but not all…

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

CKM matrix expressed in Wolfenstein parametrisation

[Wolfenstein, PRL 51 (1983) 1945]

In the Wolfenstein parameterisation the matrix is expanded in orders of $\lambda \sim 0.23$.

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \boxed{V_{td}} & V_{ts} & V_{tb} \end{pmatrix}$$

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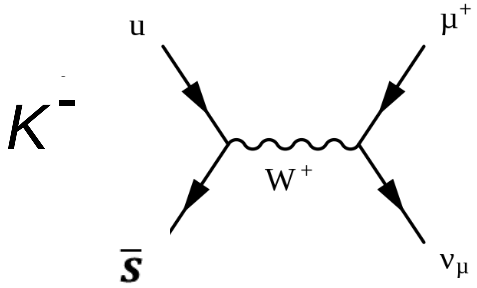
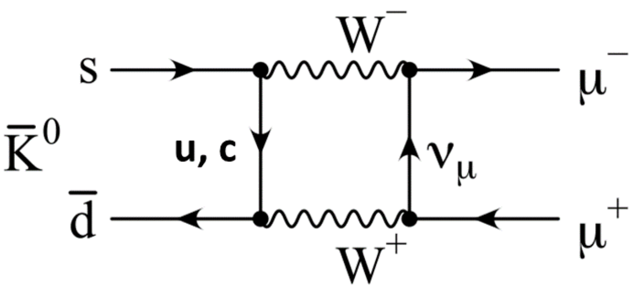
Note that at order λ^3 only two elements are complex: V_{ub} and V_{td}. Thus transitions involving these vertices will be of great interest in CPV studies (but please don't forget that it is only phase *differences* between transitions that are physical).

Back to FCNCs – although forbidden at tree level, they still occur, albeit suppressed

FCNCs do occur, but through higher-order diagrams

Charged currents	Neutral currents
$BR(K^+ \to \mu^+ \upsilon) = 64\,\%$	$BR(K_L \to \mu^+\mu^-) = 7\times 10^{-9}$
$BR(D^+ \to K^0\mu^+\nu) = 9\,\%$	$BR(D^0 \to \pi^0\mu^+\mu^-) < 1.8\times 10^{-4}$
$BR(B^- \to D^0 l\bar{\upsilon}) = 2.3\,\%$	$BR(B^- \to K^{*-}l^+l^-) = 5\times 10^{-7}$



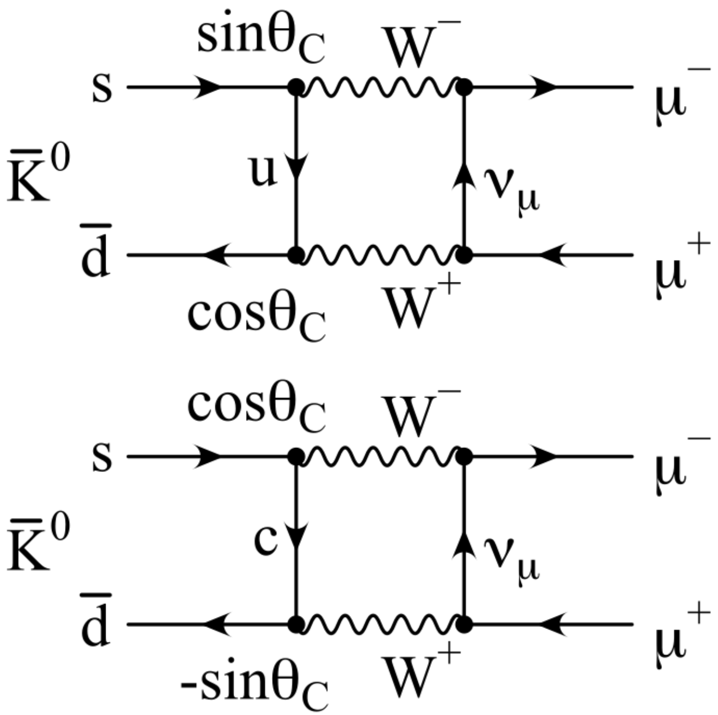


The decay rates of FCNCs tend to be highly suppressed w.r.t. tree-level processes.

Back to FCNCs – although forbidden at tree level, they still occur, albeit suppressed

Suppression of FCNCs is explained by the GIM mechanism:

- Cancellation of diagrams relies on unitarity of V_{CKM}
- Suppression set by the mass-squared difference of the virtual quarks, & would be perfect in the degenerate limit
- GIM, and the smallness of BR($K^0_L \rightarrow \mu^+\mu^-$) led to the prediction of the charm quark



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

The Unitarity Triangle 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]

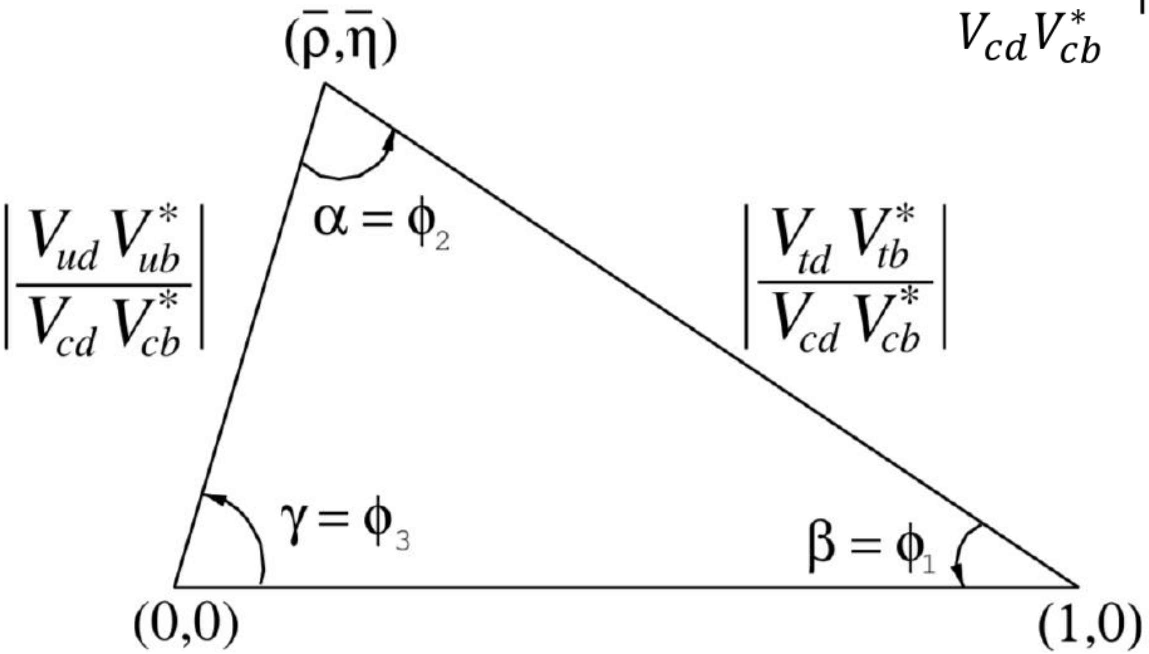
‘The’ Unitarity Triangle

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)

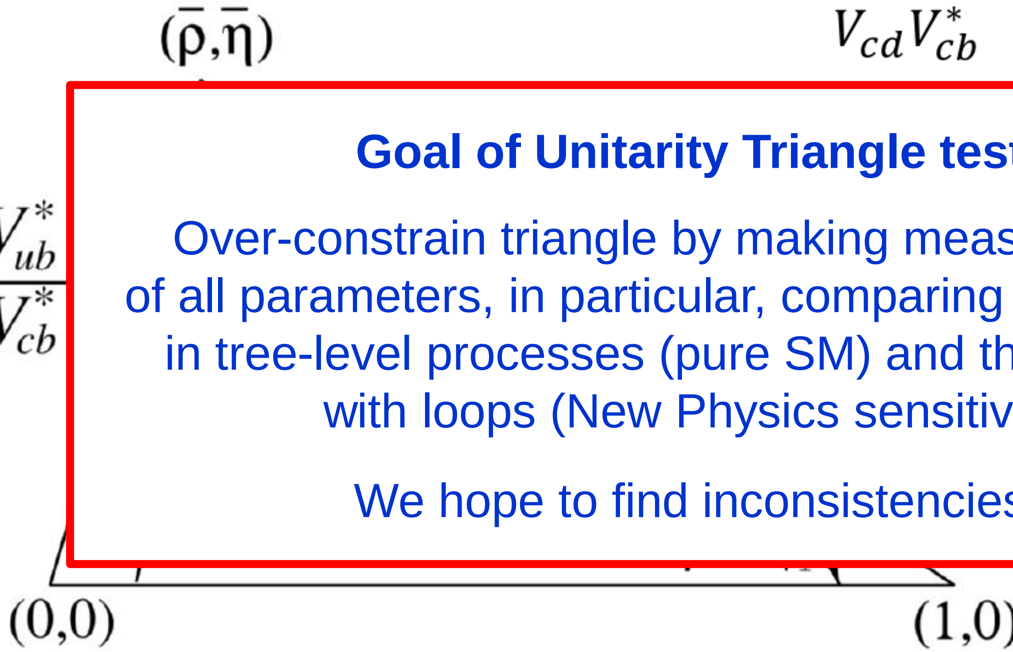
‘The’ Unitarity Triangle

Three complex vectors sum to zero

→ triangle in Argand plane

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

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



$$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$$

… for angles:

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

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

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

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 !

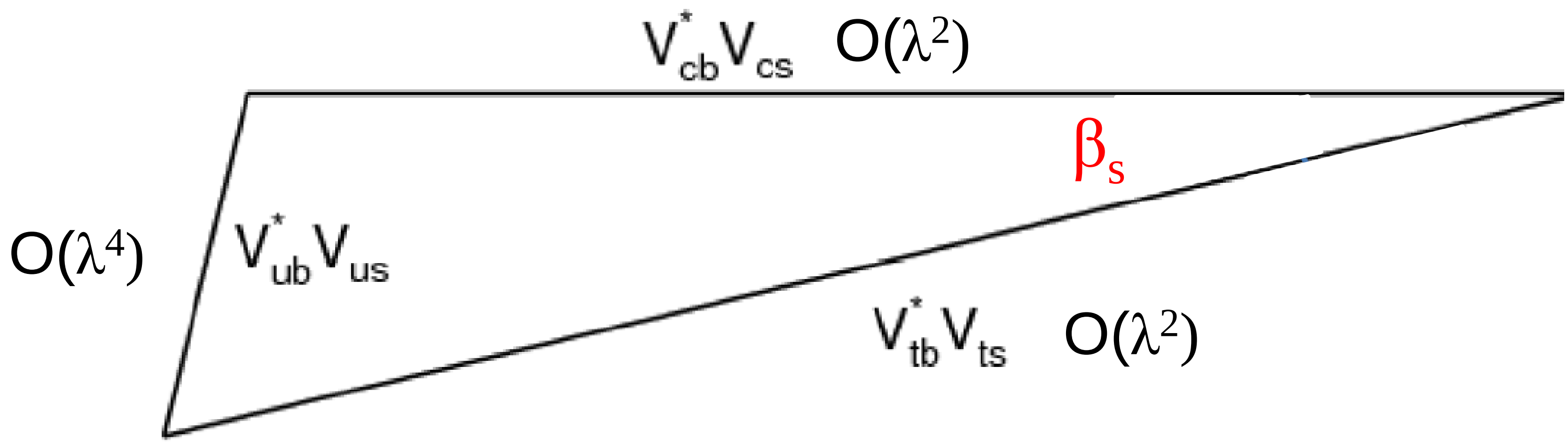
Upper vertex: $\bar{\rho} + i\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}\,V_{cb}^*)$

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

(φ_2, φ_1 & φ_3 alternative notation)

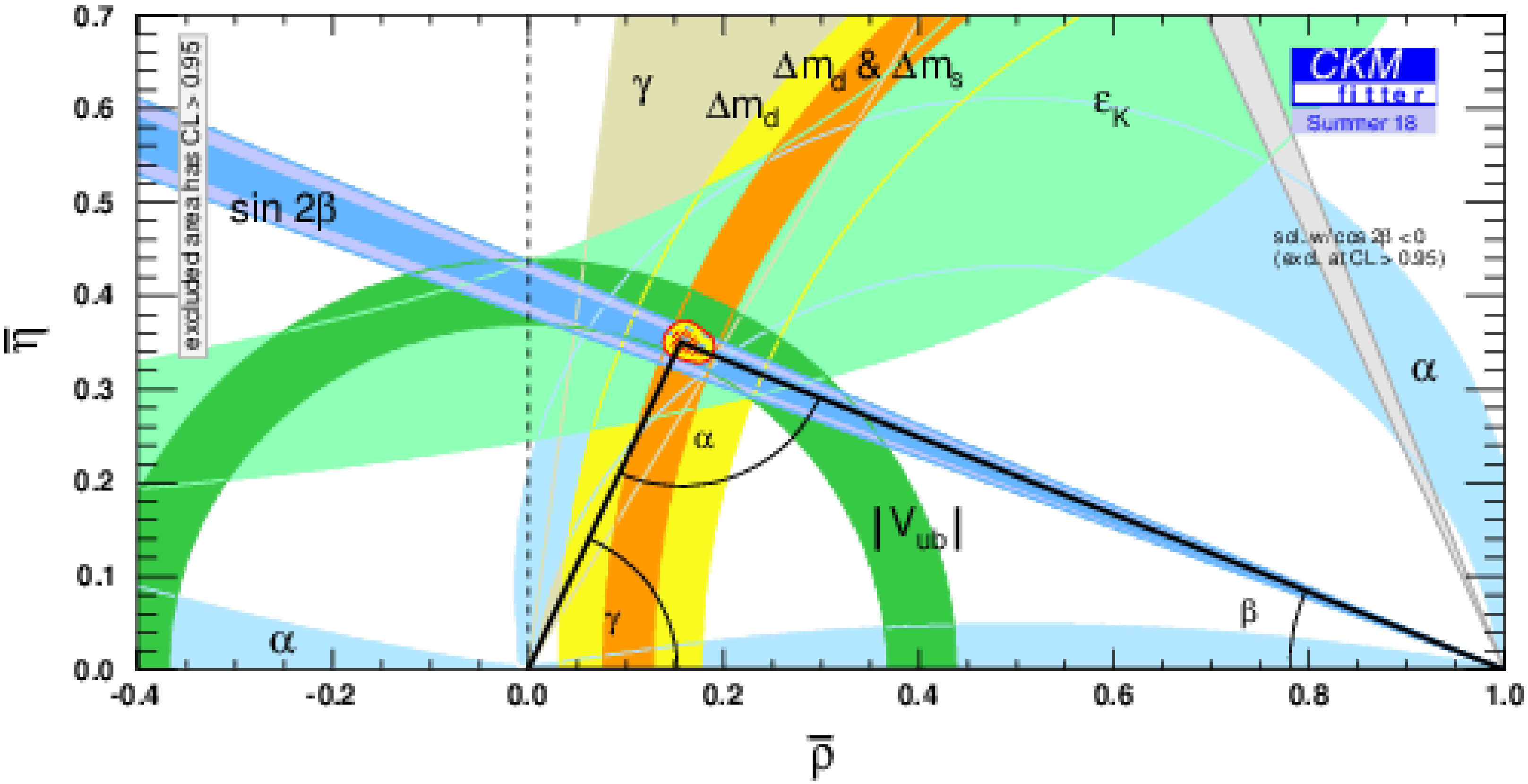
The B^0_s Unitarity Triangle

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



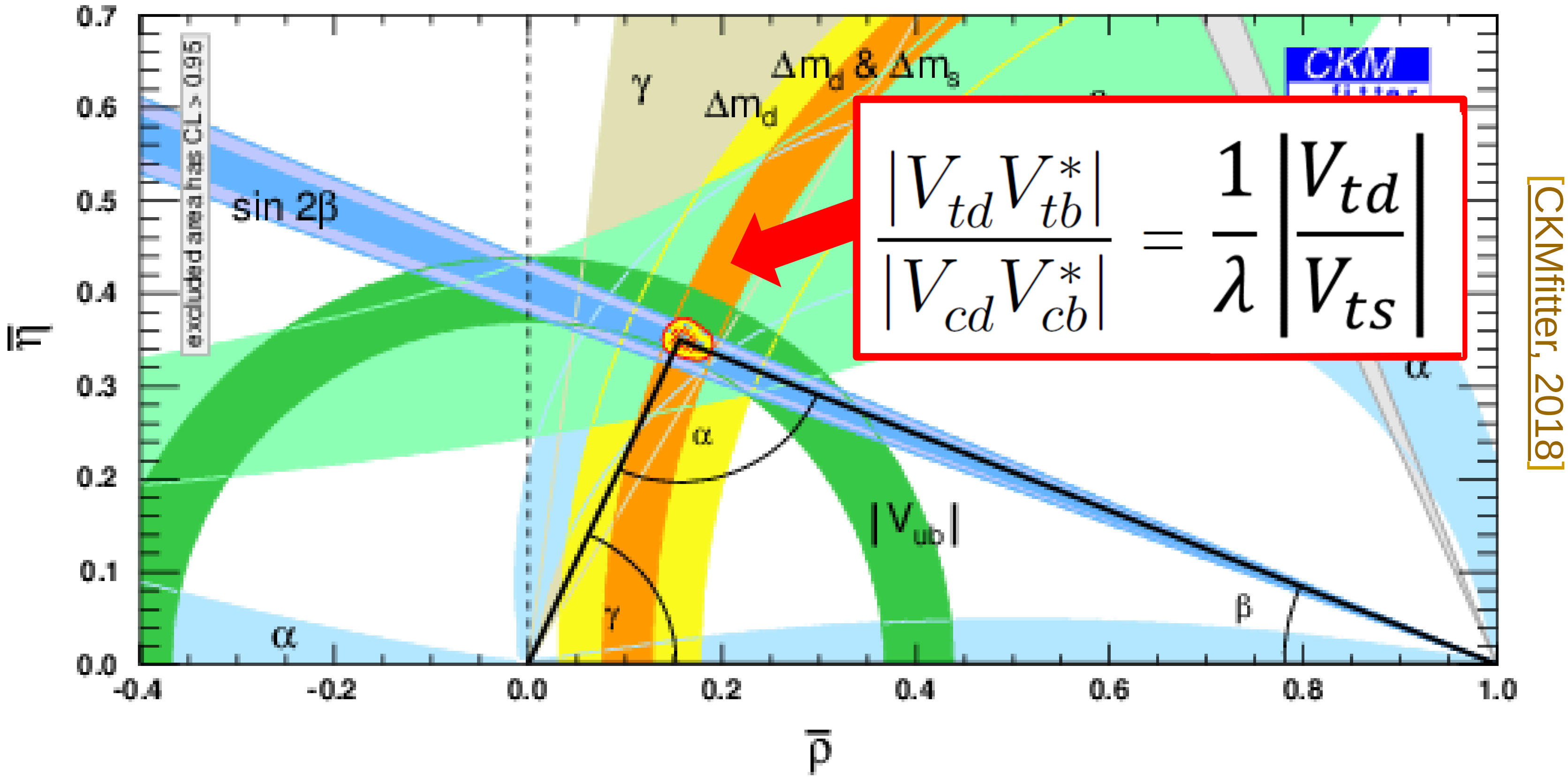
The B^0_s triangle is very squashed, & contains a small angle β_s (= $-\varphi_s/2$ – see later).

The Unitarity Triangle – how do we know what we know ?



[CKMfitter, 2018]

The Unitarity Triangle – how do we know what we know ?



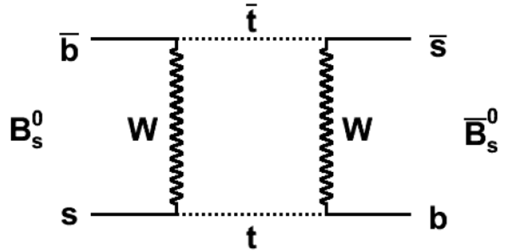
Length of side opposite γ is given by ratio of B^0 & B^0_s mixing freq.s & lattice QCD.

Digression on neutral-meson mixing

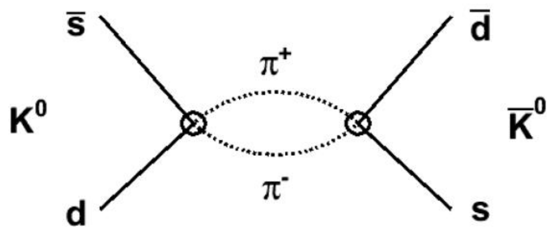
Mixing is critical for much of what follows, so warrants a recap of essentials.

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

Digression on 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.

	Δm / Γ		$\Delta\Gamma/2\Gamma$	
K^0	Large	~500	Maximal	~1
D^0	Small	0.39 ± 0.11 %	Small	$0.65 \pm 0.06\%$
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]

Aside: the New Physics flavour puzzle

Remark – mixing parameters are what they are because of SM (CKM, GIM & quark masses) and could easily be perturbed by New Physics, so bounds can be set.

Add to SM Lagrangian higher order terms that would contribute to neutral meson mixing and CPV

$$\Delta\mathcal{L}_{\rm NP} = \sum_{i \neq j} \frac{c_{ij}^{\rm NP}}{\Lambda_{\rm NP}^2} (\overline{Q}_{Li} \gamma^\mu Q_{Lj})^2 ,$$

where $c_{ij}^{\rm NP}$ is the coupling, and $\Lambda_{\rm NP}$ the mass scale of the New Physics.

If we assuming the coupling is ~1, (*i.e.* generic) obtain the following → bounds on $\Lambda_{\rm NP}$ [Nir, arXiv:1605.00433].

System	CP-conserving observables	CP-violating Observables
K^0	1×10^3 TeV	2×10^4 TeV
D^0	1×10^3 TeV	3×10^3 TeV
B^0	4×10^2 TeV	8×10^2 TeV
B^0_s	7×10^1 TeV	2×10^2 TeV

These are enormous ! And naturalness told us to expect New Physics at the TeV scale. Something is wrong…

Get out clause: couplings are not ~1. One possibility, structure is more specific *e.g.* same as in the SM ('minimal flavour violation' [Ambrosio *et al.*, NPB 645 (2002) 155]).

Digression on neutral-meson mixing

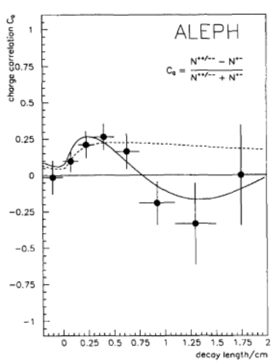
Mixing leads to an oscillation of probability to observe meson in either flavour eigenstate with proper time, *e.g.* if at t=0 we have a B^0, then at later time t:

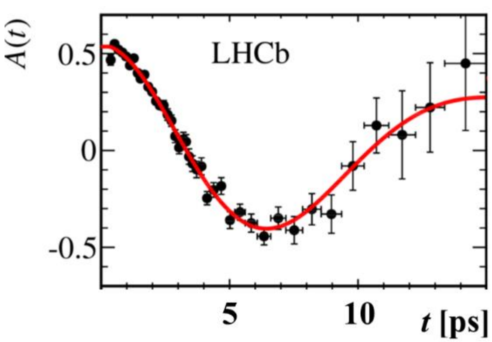
Prob. to decay as $\begin{matrix}\overline{B}^0 \\ B^0\end{matrix} \propto e^{-\Gamma_d t}(1 \mp \cos \Delta m_d\, t)$

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

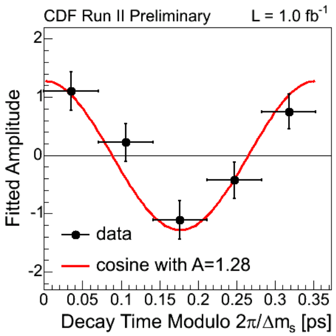
[PLB 313 (1993) 498]



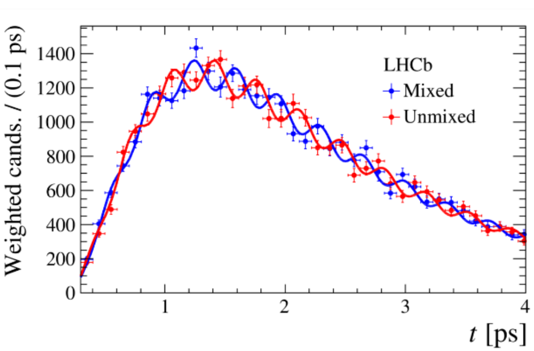


[EPJC 76 (2016) 412]

B^0_s discovery → state-of-the-art



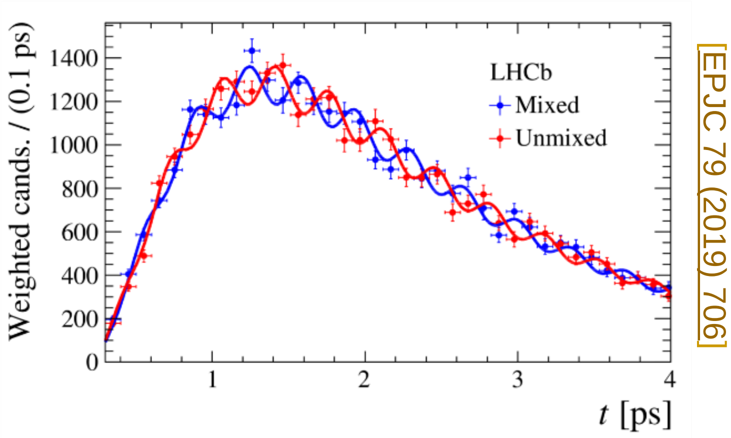
[PRL 97 (2006) 242003]

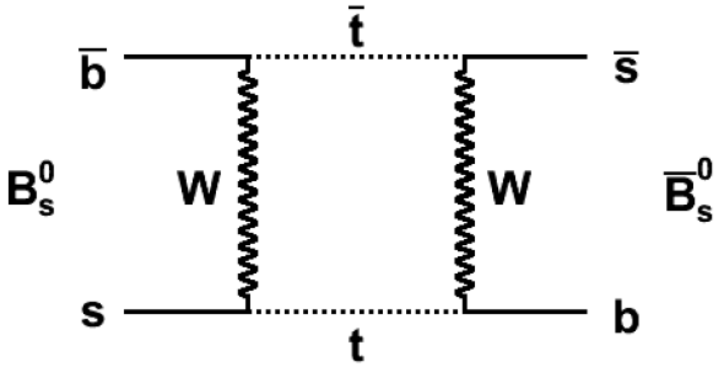


[EPJC 79 (2019) 706]

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

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





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

For B^0_s case ⟶

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

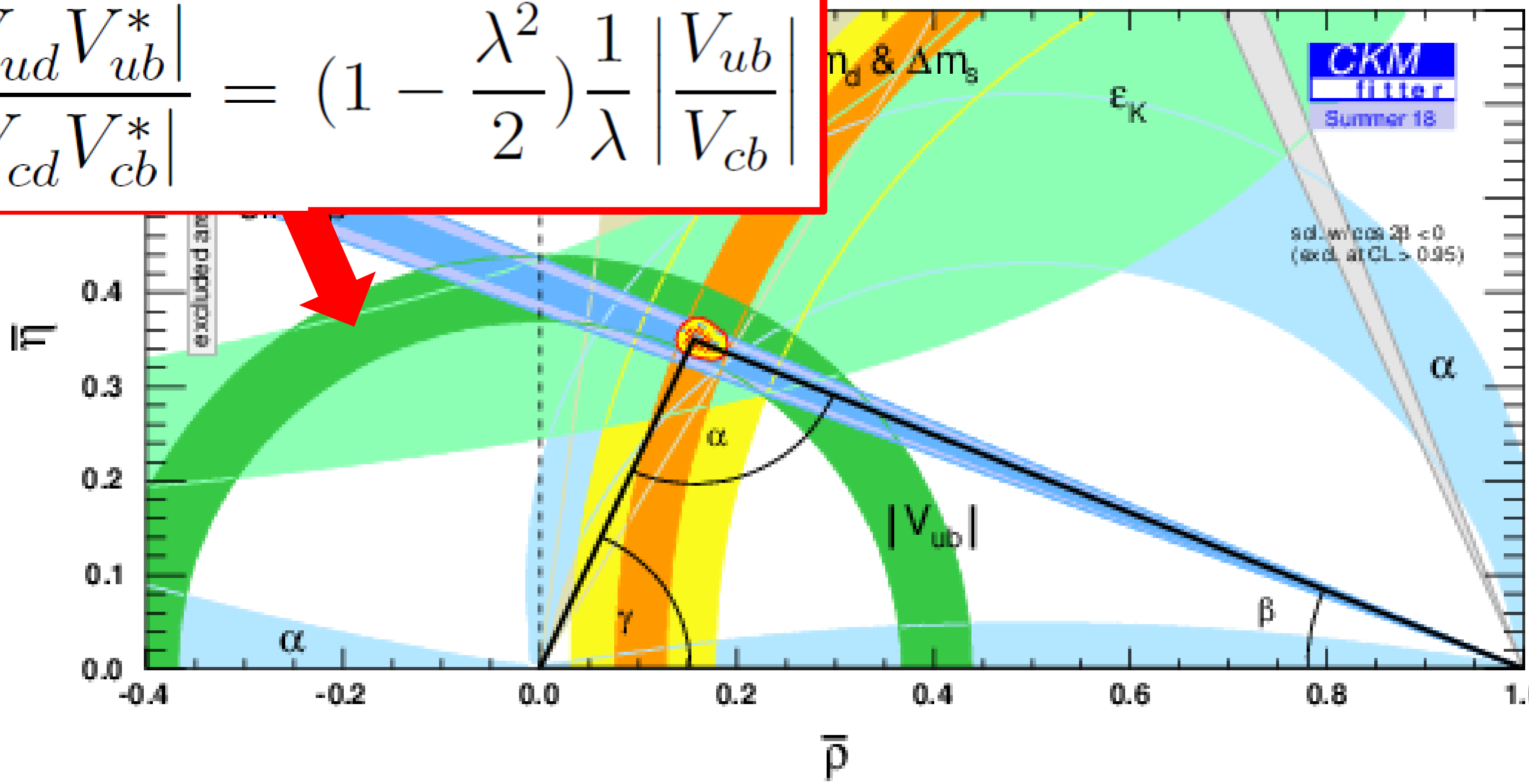
Equivalent expression for B^0 mixing, involving V_{td}. Ratio of frequencies is then

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

$\zeta_{\Delta m}$, being a ratio of QCD factors of value close to 1 can be calculated to a few % in lattice QCD, hence giving access to $|V_{td}|/|V_{ts}|$.

The Unitarity Triangle –
how do we know what we know ?

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



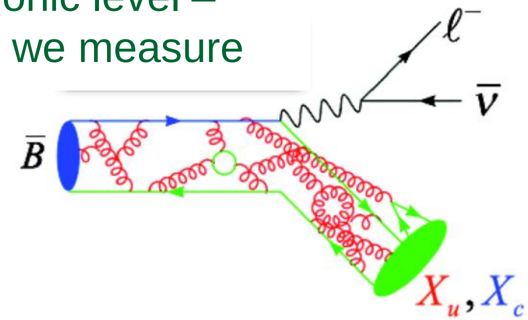
[CKMfitter, 2018]

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

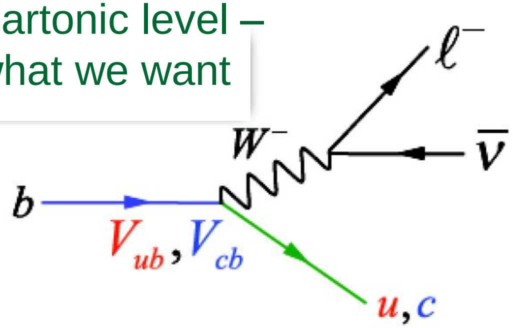
Measuring $|V_{ub}|/|V_{cb}|$

We can measure the ratio of b→ulν to b→clν 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→X_ulν, using *e.g.* endpoint of p_l spectrum to isolate signal from b→X_clν

$$|V_{ub}| = (4.49 \pm 0.28) \times 10^{-3}$$ [2018 PDG review]

- Exclusive, *e.g.* B→πlν. But then need calculation of hadronic form factor.

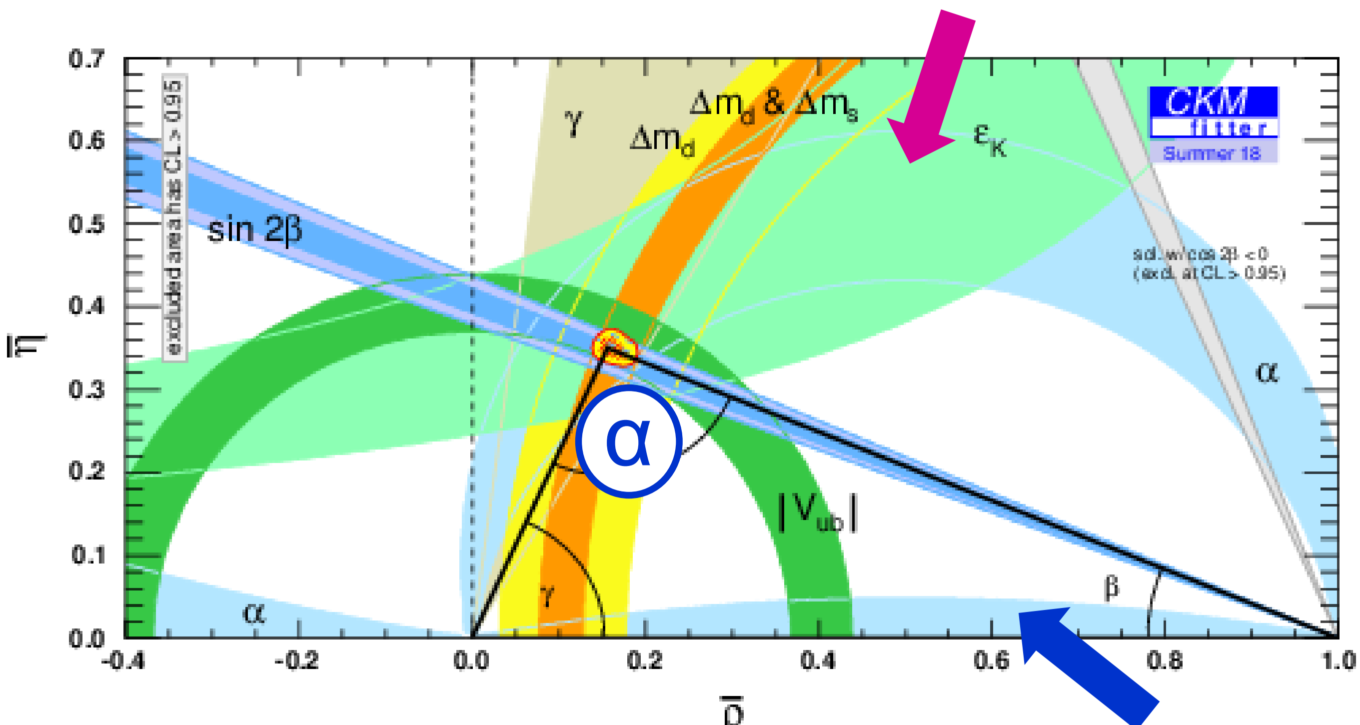
$$|V_{ub}| = (3.70 \pm 0.16) \times 10^{-3}$$ [2018 PDG review]

There is tension between these two numbers at the ~2.5σ level, which means that a conservative approach is advisable when using the results to set UT constraints.

Much activity underway to understand this issue, & we can be hopeful of progress !

The Unitarity Triangle –
how do we know what we know ?

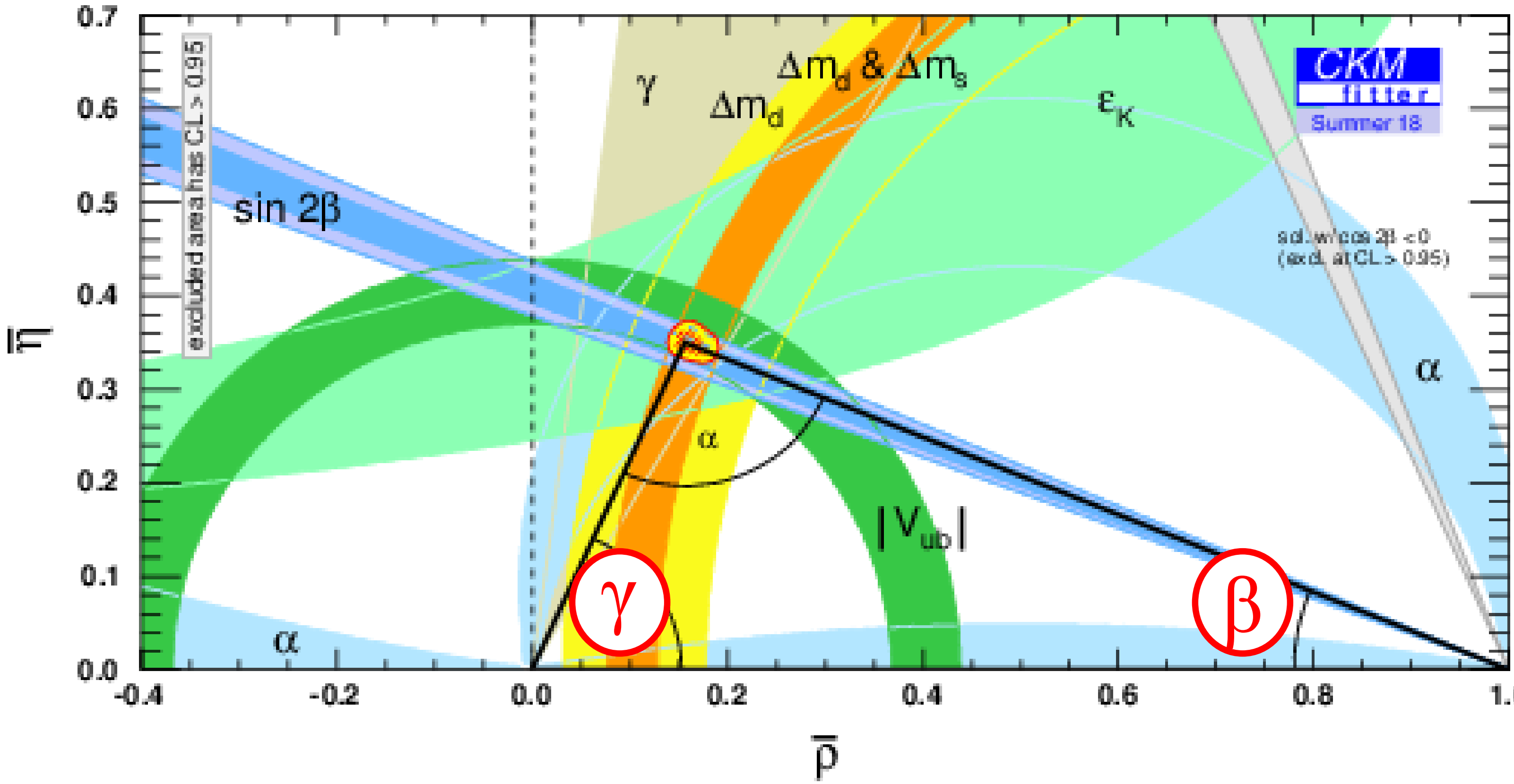
This band comes from CPV measurements in kaon decays. Theory limited.



[CKMfitter, 2018]

Information on α comes from time-dependent measurements on B^0 decays to charmless final states, *e.g.* $B \rightarrow \rho^+\rho^-$. It probes a combination of the processes that occur in the β and γ measurements, and IMO does not bring independent info, & we will not discuss it further. (But of course any measurement is valuable!)

The Unitarity Triangle – how do we know what we know ?



[CKMfitter, 2018]

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

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

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].

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

*

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…

>750 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^*-$\bar{K}^*$ 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.

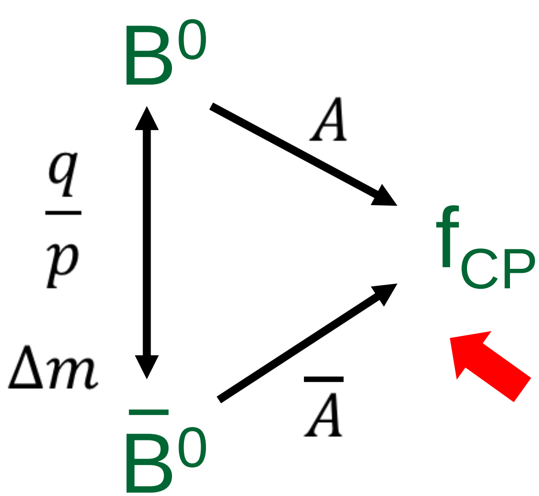
Decays into CP eigenstates: $B^0 \to J/\psi K_S$

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].

For meson that is B^0 or B^0bar at t=0, which decays into CP-eigenstate f_{CP} at time *t*:

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

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



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.

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

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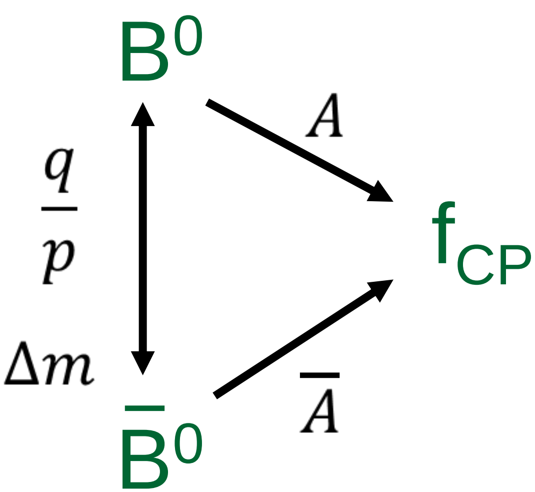

$$S = \frac{2\Im(\lambda_{CP})}{1+|\lambda^2_{CP}|} \qquad C = \frac{1-|\lambda^2_{CP}|}{1+|\lambda^2_{CP}|} \qquad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

There are three ways that CP violation can appear:

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

(This is also the only possibility that applies for charged hadron decays.)

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

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

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

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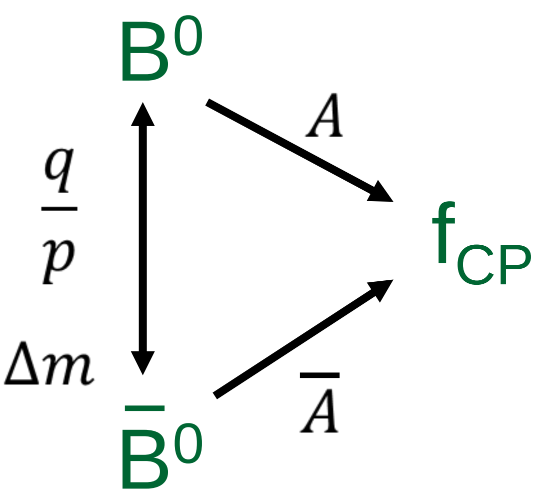

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There are three ways that CP violation can appear:

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.

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

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

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

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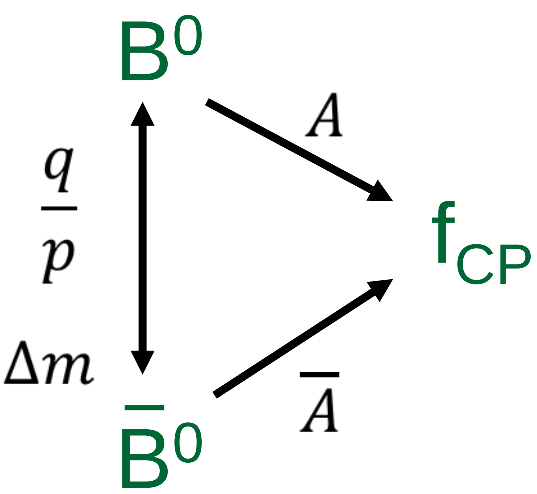

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There are three ways that CP violation can appear:

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

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

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

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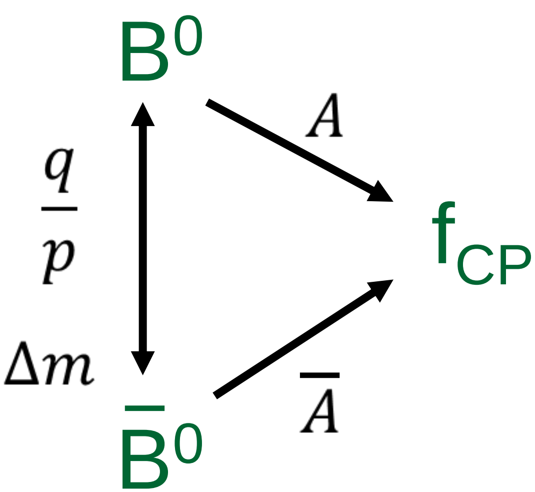

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Consider the classic case $B^0 \rightarrow J/\psi K_S$:

- Compared to the CPV signal we are expecting in B physics, we can treat K_S as a CP eigenstate.
- And in this decay $C \approx 0$, 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 $\Delta\Gamma=0$, which is an excellent approximation in B^0 system.

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

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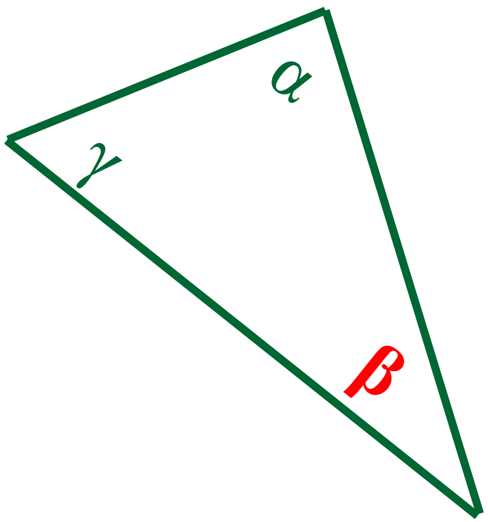

Consider the classic case $B^0 \to J/\psi K_S$:

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

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

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

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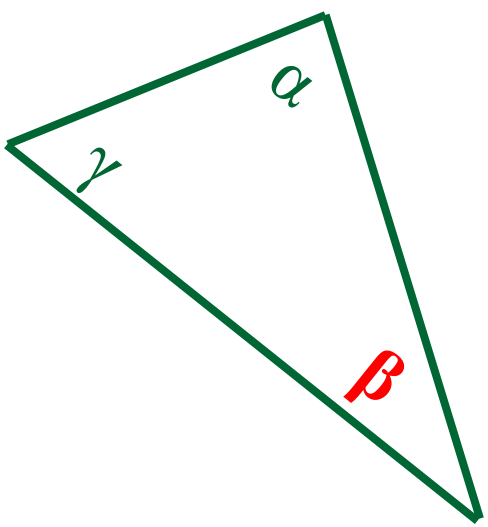

In practice we measure a *t*-dependent CP asymmetry:

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

This is theoretically ***clean*** !
(no QCD murkiness)

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

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

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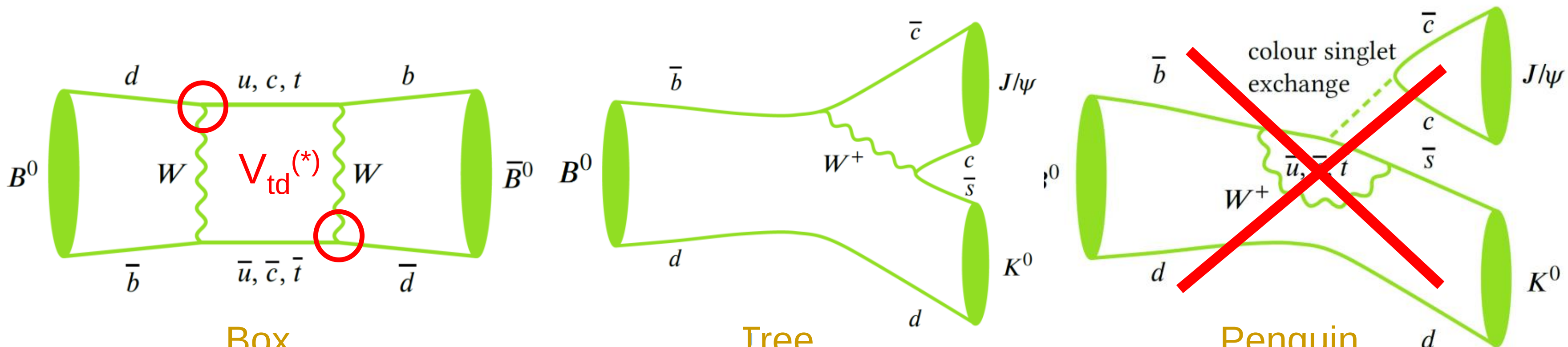
To reiterate, measurement probes interference between box and tree diagrams:



Box

Tree

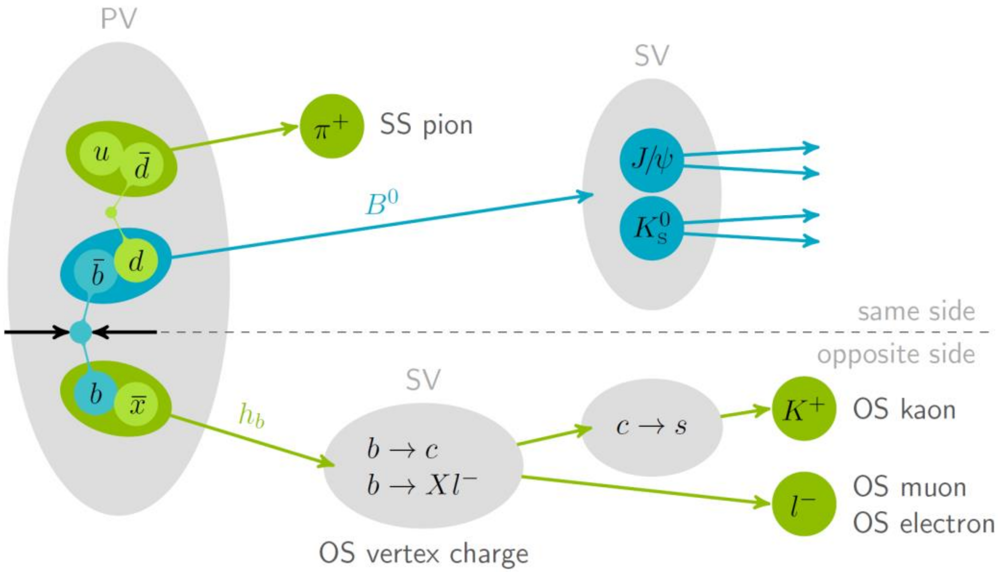
Penguin
(suppressed)

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

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

Flavour tagging & other practical considerations

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').



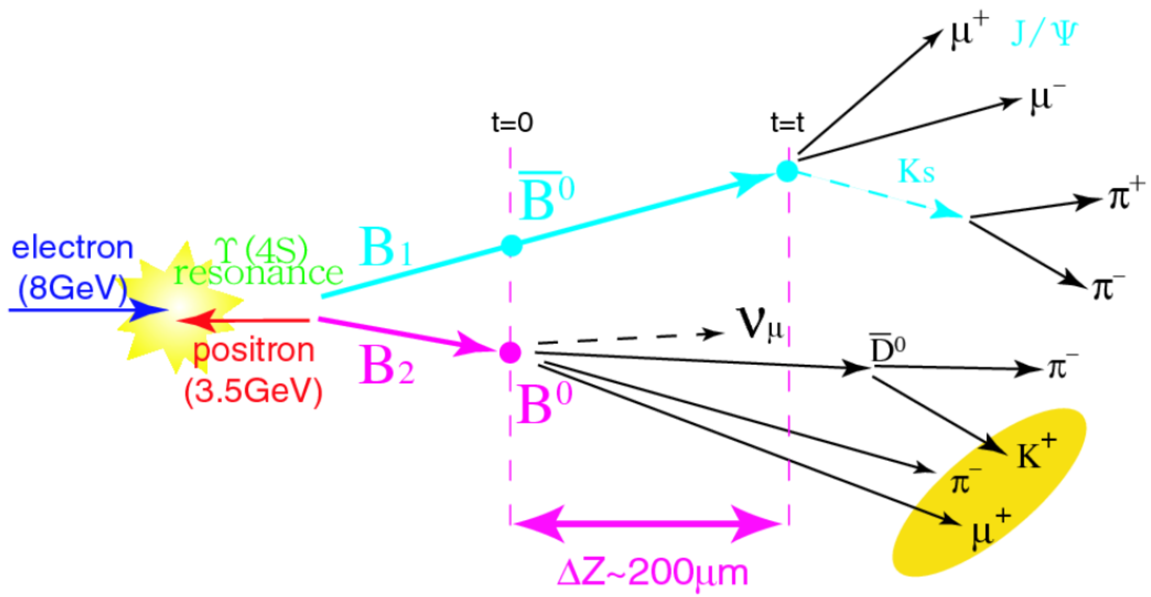
Flavour tag decision can be wrong, either through misidentification of mixing of OS b-hadron. This leads to *dilution* of asymmetry, and reduces effective signal statistics by a large factor (up to x ~1/30) at hadron collider experiments.

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 & other practical considerations

Life is easier for BaBar/Belle and Belle-II Life at the Υ(4S) means 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).



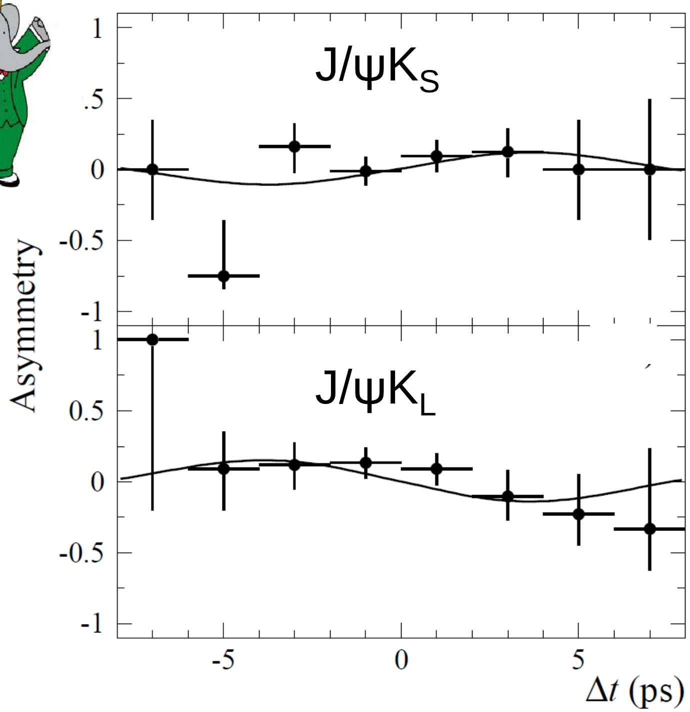
The dilution is less than at LHC, and reduces effective signal statistics by only ~1/3.

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

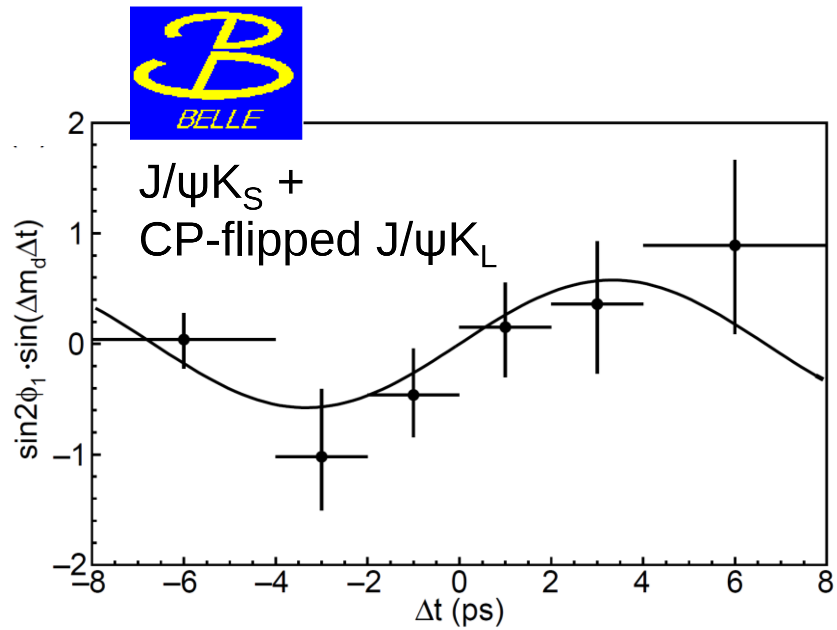
2001 - dawn of modern flavour physics

2008 Nobel Prize

We can date the start of modern flavour physics to 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]

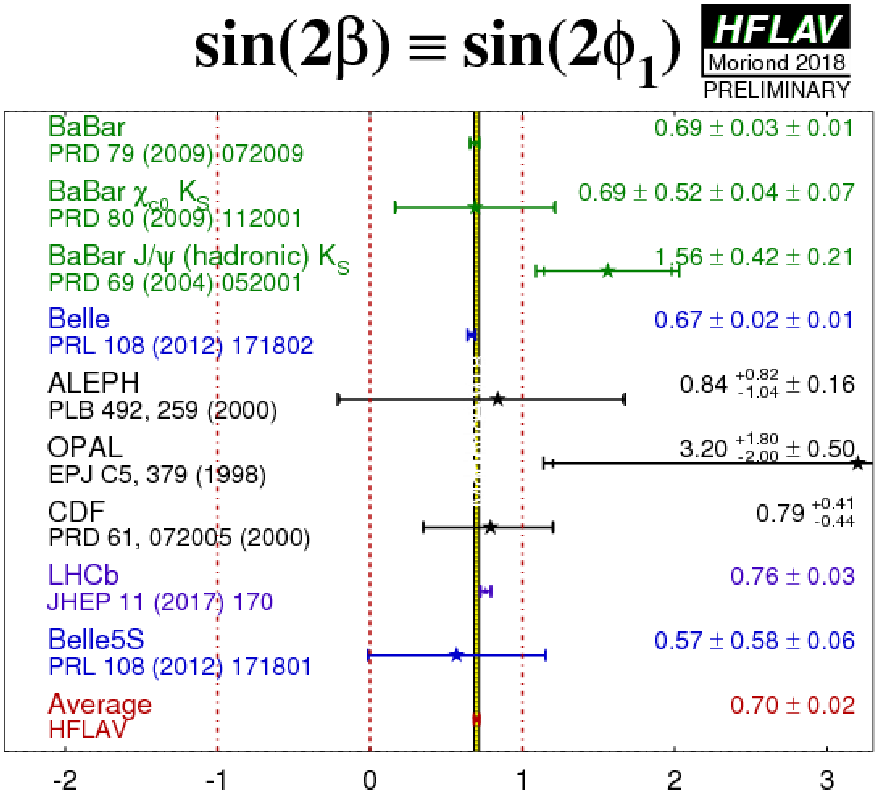


[Belle, PRL 86 (2001) 2509]

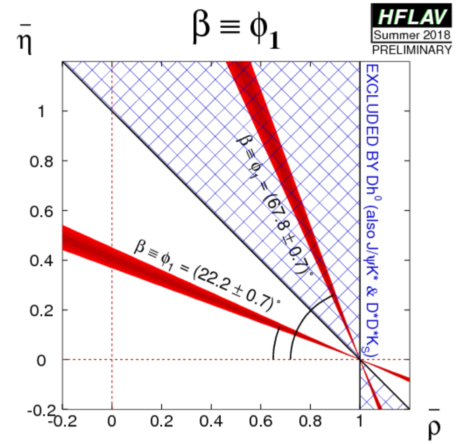
These studies, when improved with larger samples, confirmed the CKM paradigm as the dominant mechanism of CP violation in nature (→ 2008 Nobel Prize), and also opened up a rich and wide spectrum of complementary measurements.

sin2β: current status and impact of the LHC

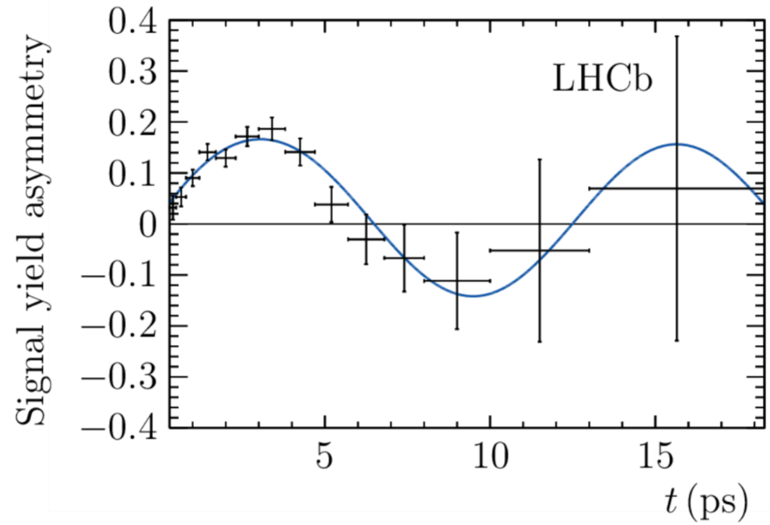
Global state of play:



Both solutions for β shown in UT plane. ➡



LHCb run 1 $J/\psi K_S$ result has similar precision to B factories



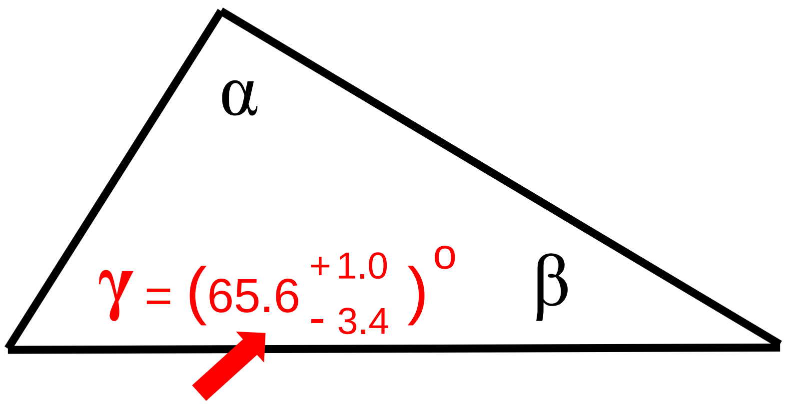
[LHCb, PRL 115 (2015) 031601]

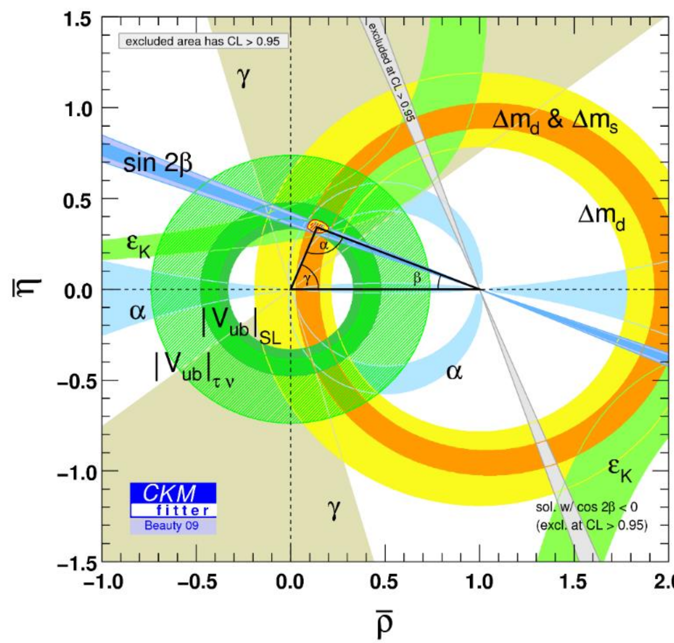
sin2β now known to 3%, with significant improvements expected in coming decade

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

A particular responsibility for flavour physics at the LHC (& Belle II) is to improve our knowledge of the angle γ.

At LHC turn-on γ uncertainty was >20^o.





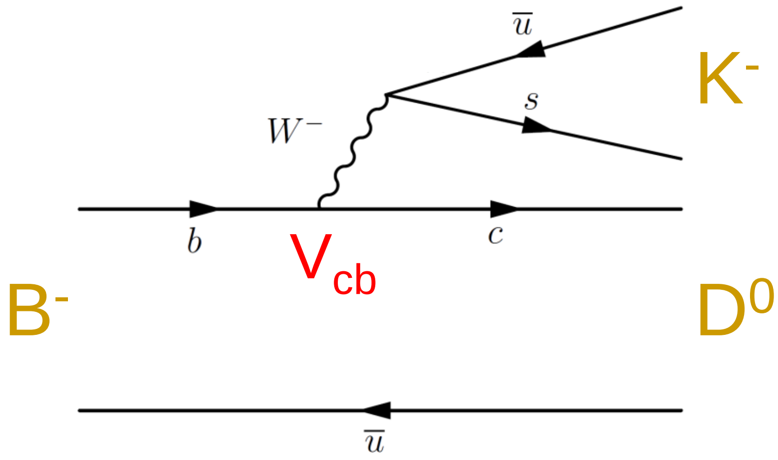
[CKMfitter, 2009]

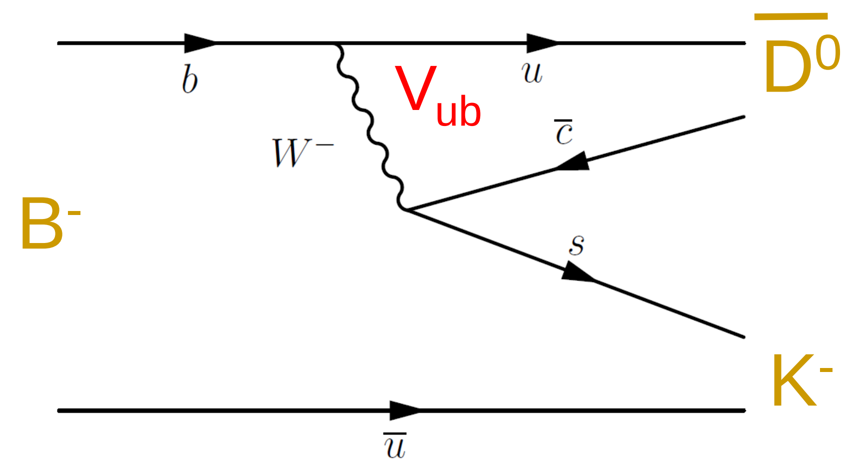
The predicted value of γ in context of SM is known very well from other triangle parameters (& will be known even better as experiment & lattice QCD improve).

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.





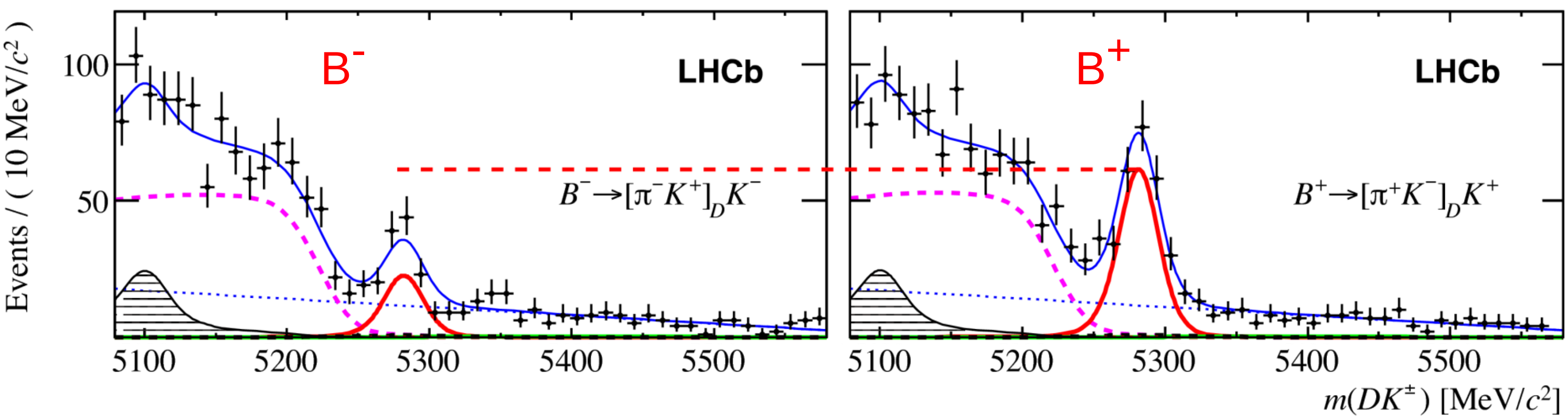
If we reconstruct D^0 and $\overline{D}^0$ in a state accessible to both, Interference occurs & decay rates become sensitive to relative phase between V_{cb} and V_{ub}, which is γ.

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.



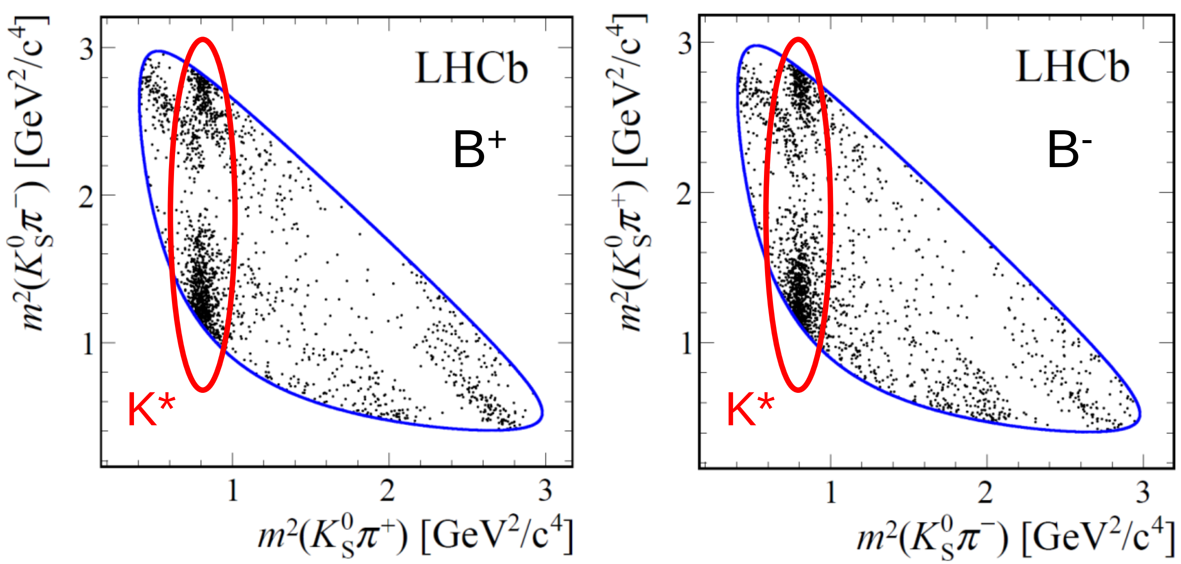
[PLB 760 (2016) 117]

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

γ measurement at LHCb with B→DK decays: D→$K_S\pi\pi$ (and K_SKK) with Run 2 data [JHEP 08 (2018) 176]

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

Analysis of ~3000 decays from 2 fb^{-1} of early Run 2 data.



A *Dalitz plot* is a 2D display of phase space for a three-body decay, where bands manifest intermediate resonances, and their spin structure

e.g. D→K*(892)π

These are the Dalitz plots of the D→$K_S\pi\pi$ decays arising from the B→DK decays.

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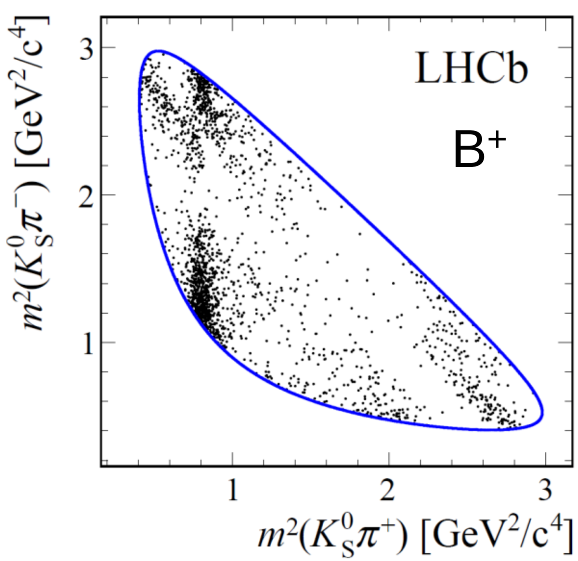
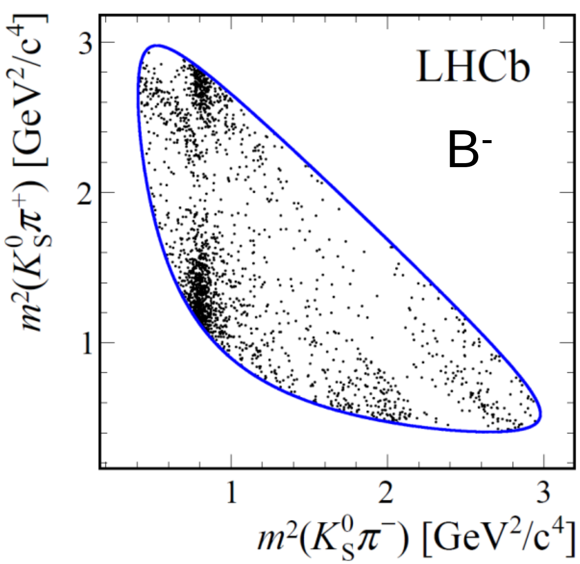
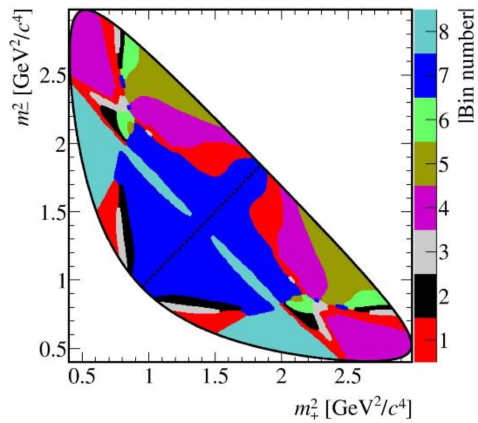




Study yields in *bins* of Dalitz space, chosen for optimal sensitivity.



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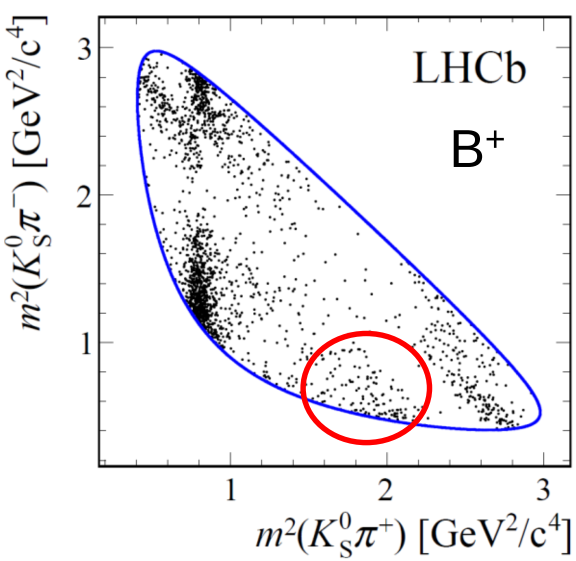

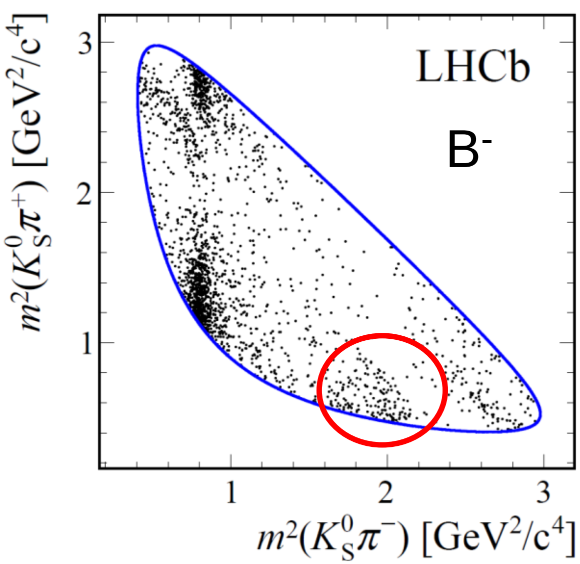

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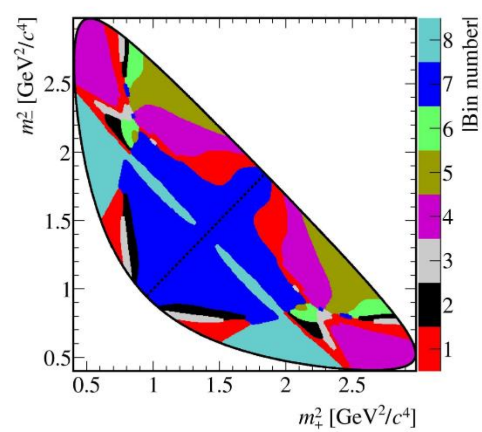
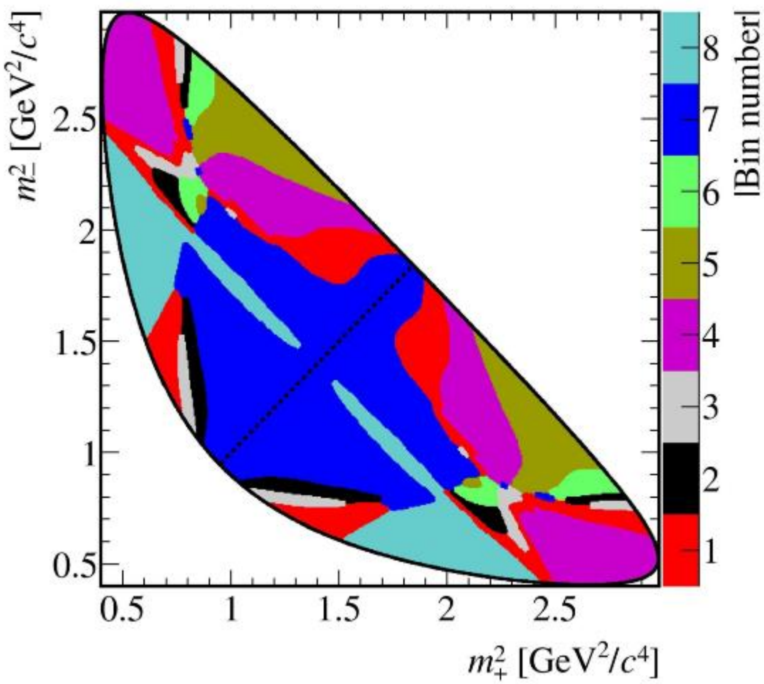


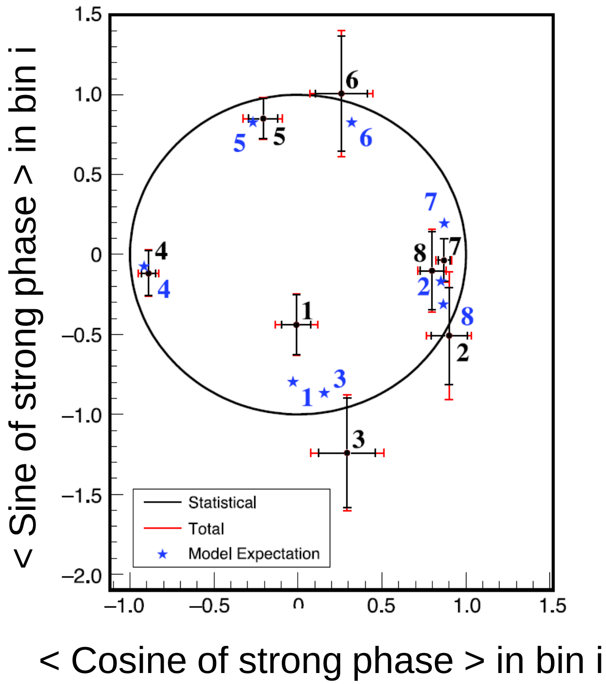
CP asymmetries visible by eye, but quantitative analysis requires external input...

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 CLEO-c [PRD 82 (2010) 112006].





CLEO-c data 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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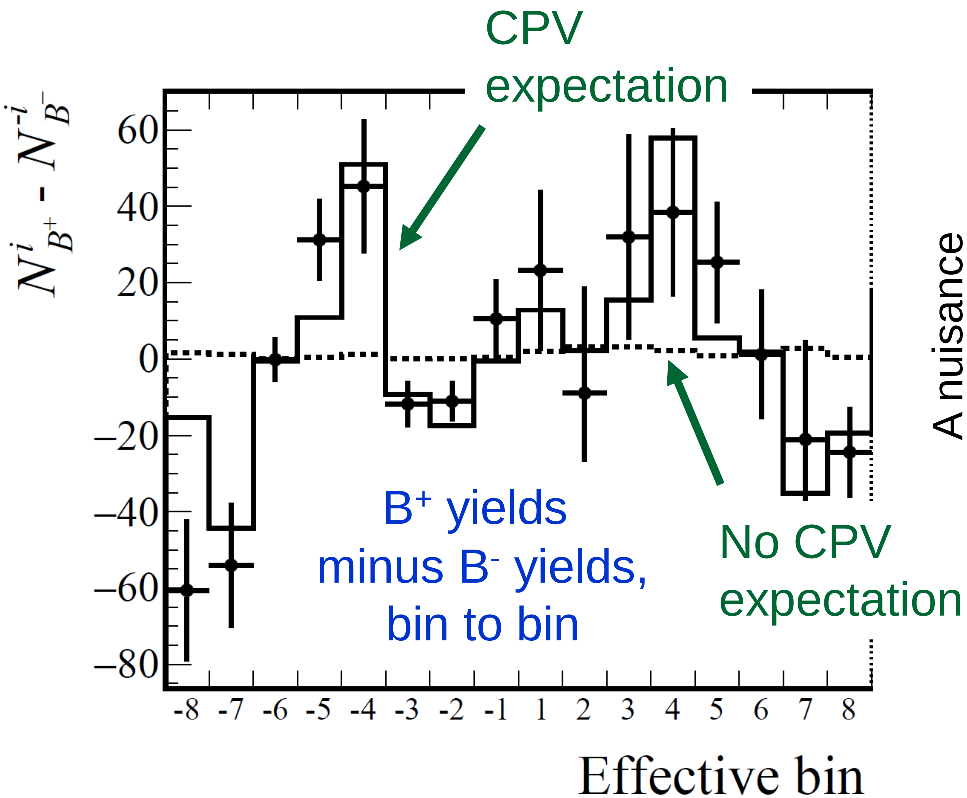
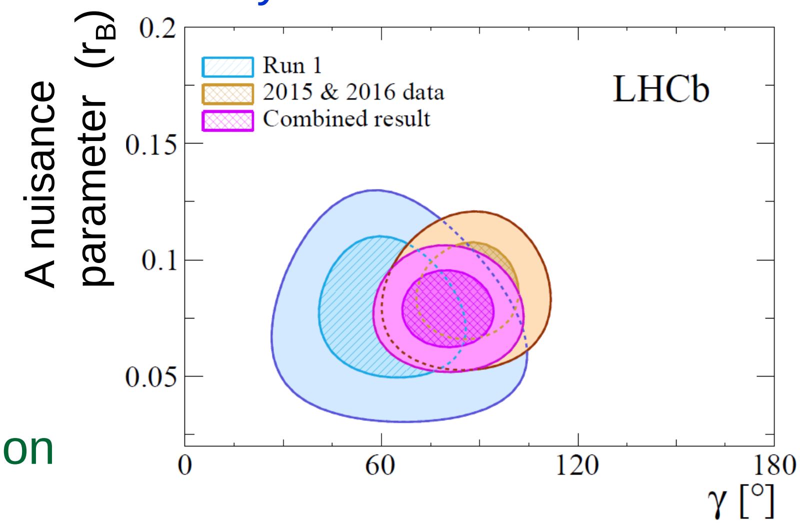


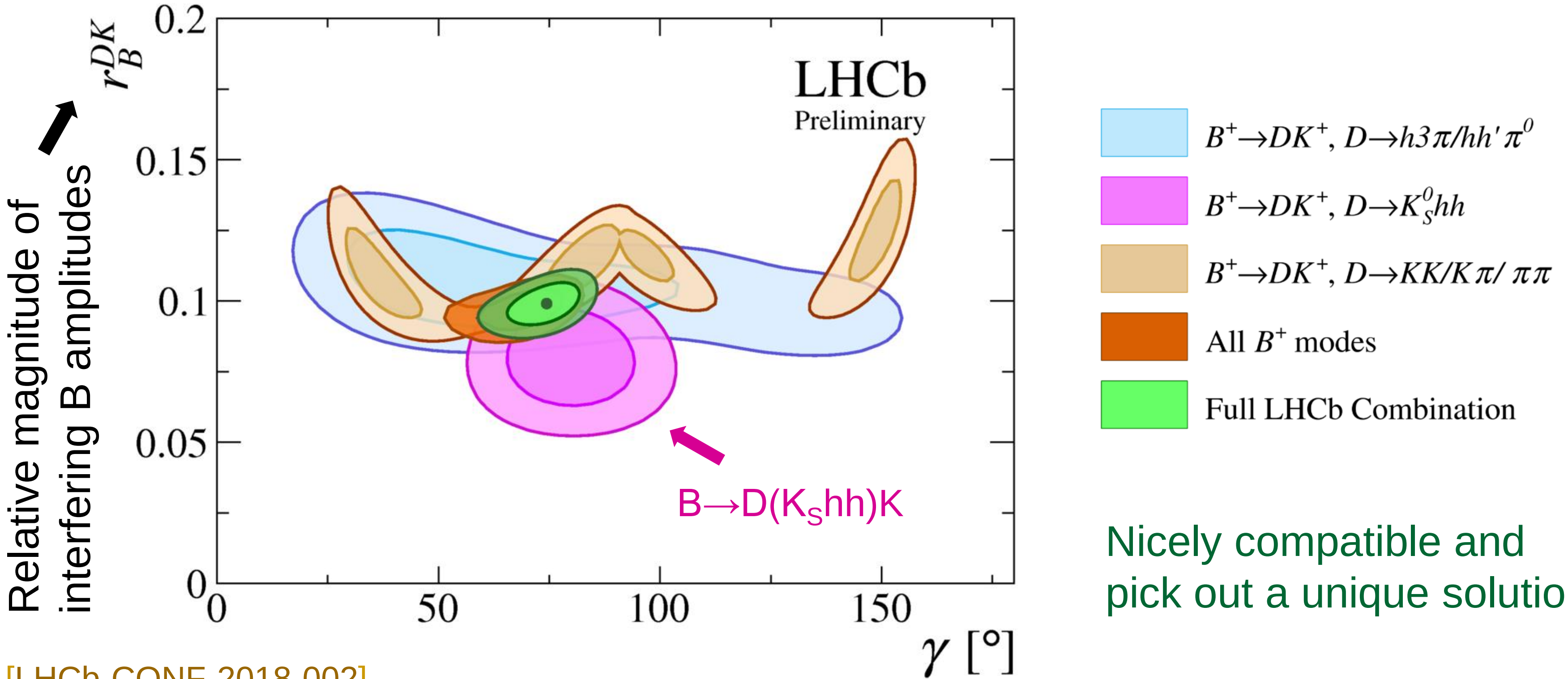
Compatible with Run 1 analysis of same channel



Together gives: $\gamma = 80^\circ\ ^{+10^\circ}_{-9^\circ}$

LHCb: combining B→DK modes for γ

The B→D($K_S\pi\pi$,K_SKK)K result may be combined together with those of other B→DK analyses. They depend on common nuisance parameters, but have difference degeneracies → whole is greater than the sum of the parts !



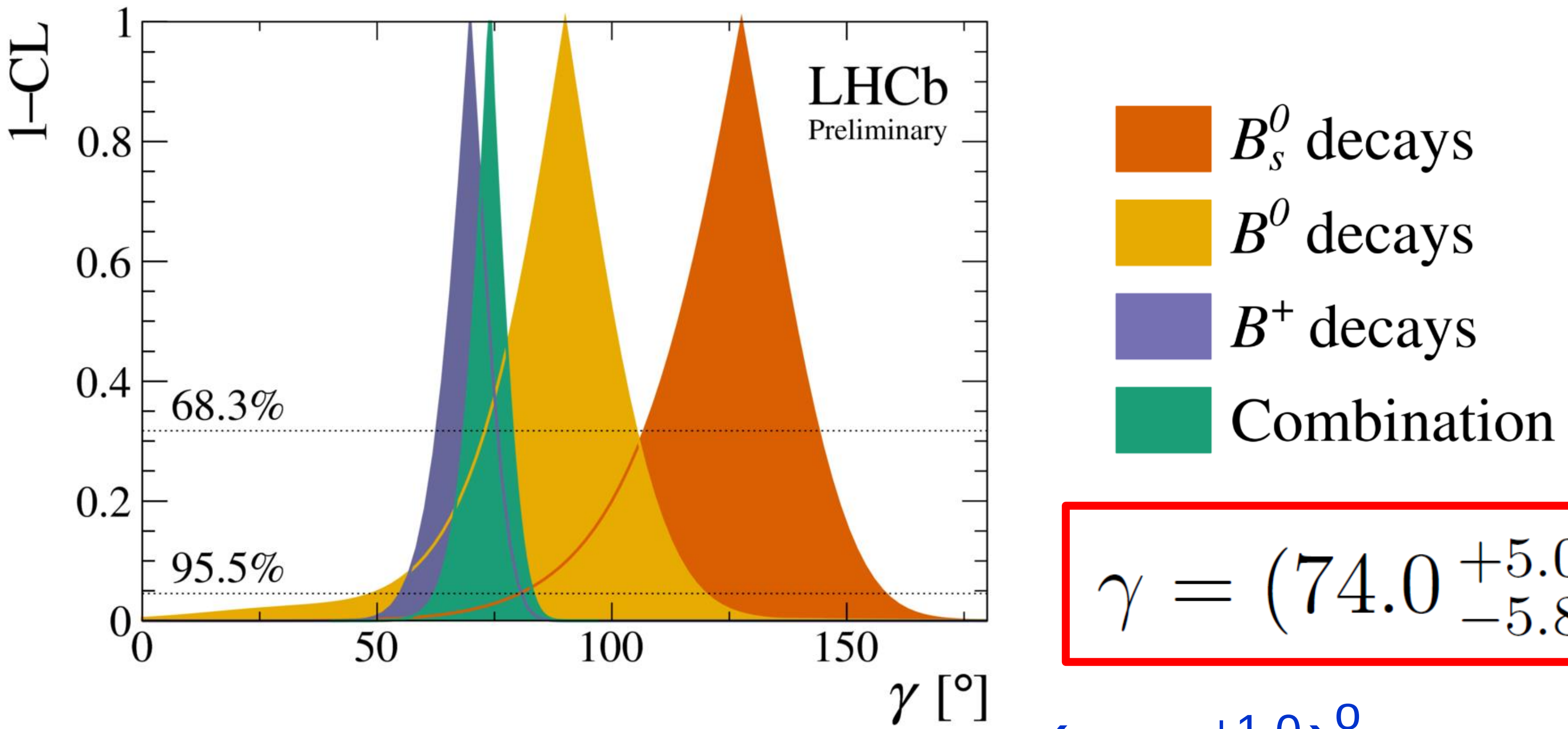
Nicely compatible and pick out a unique solution.

[LHCb-CONF-2018-002]

LHCb: current precision on γ

Global LHCb average, now including information from time-dependent analyses of Run 1 data with B_s [JHEP 03 (2018) 059] and B^0 decays [JHEP 06 (2018) 084].

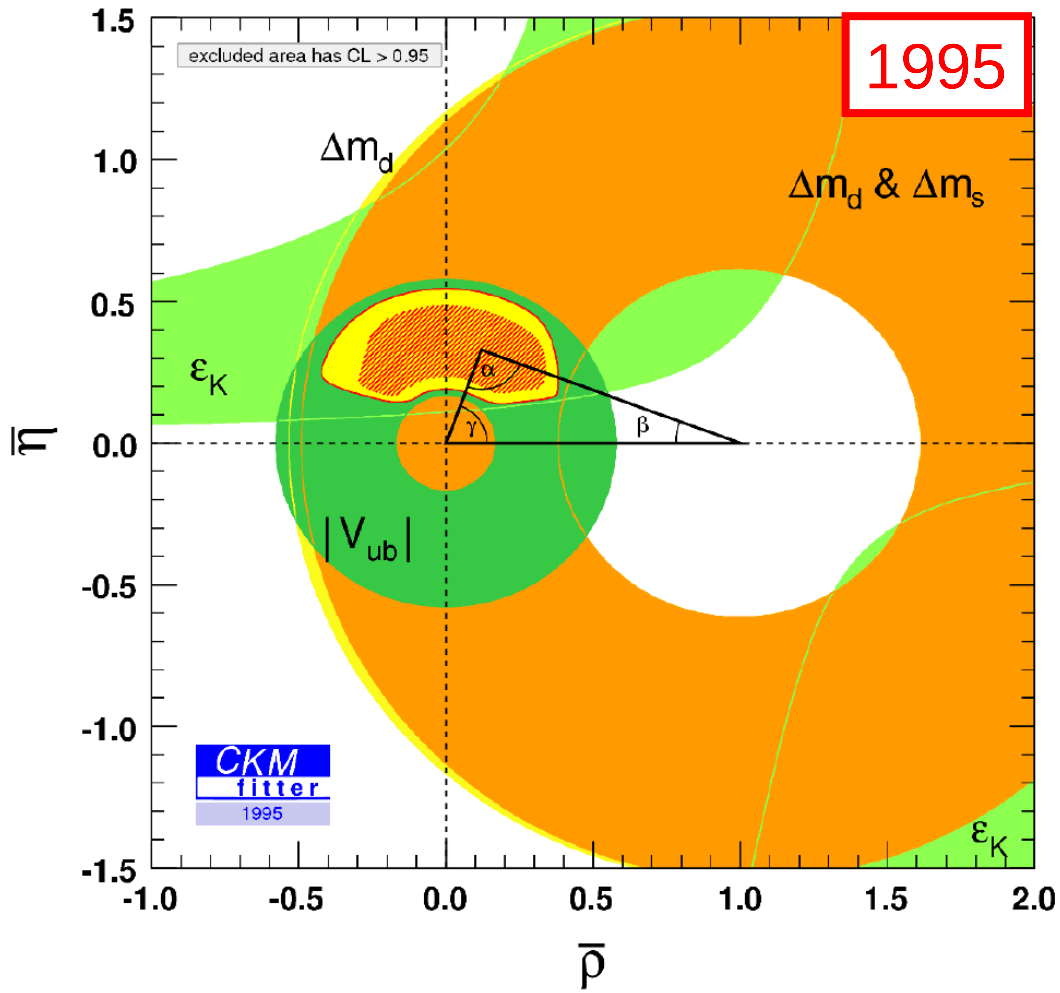
[LHCb-CONF-2018-002]



$$\gamma = (74.0\,^{+5.0}_{-5.8})^\circ$$

Result is to be compared with indirect prediction of $(65.6\,^{+1.0}_{-3.4})^{\rm o}$ [CKMfitter, 2018].
Compatible, albeit with a little tension (~2σ).
Big improvements expected in near future, as still little Run 2 data in average.

Unitarity Triangle: ~25 years of progress



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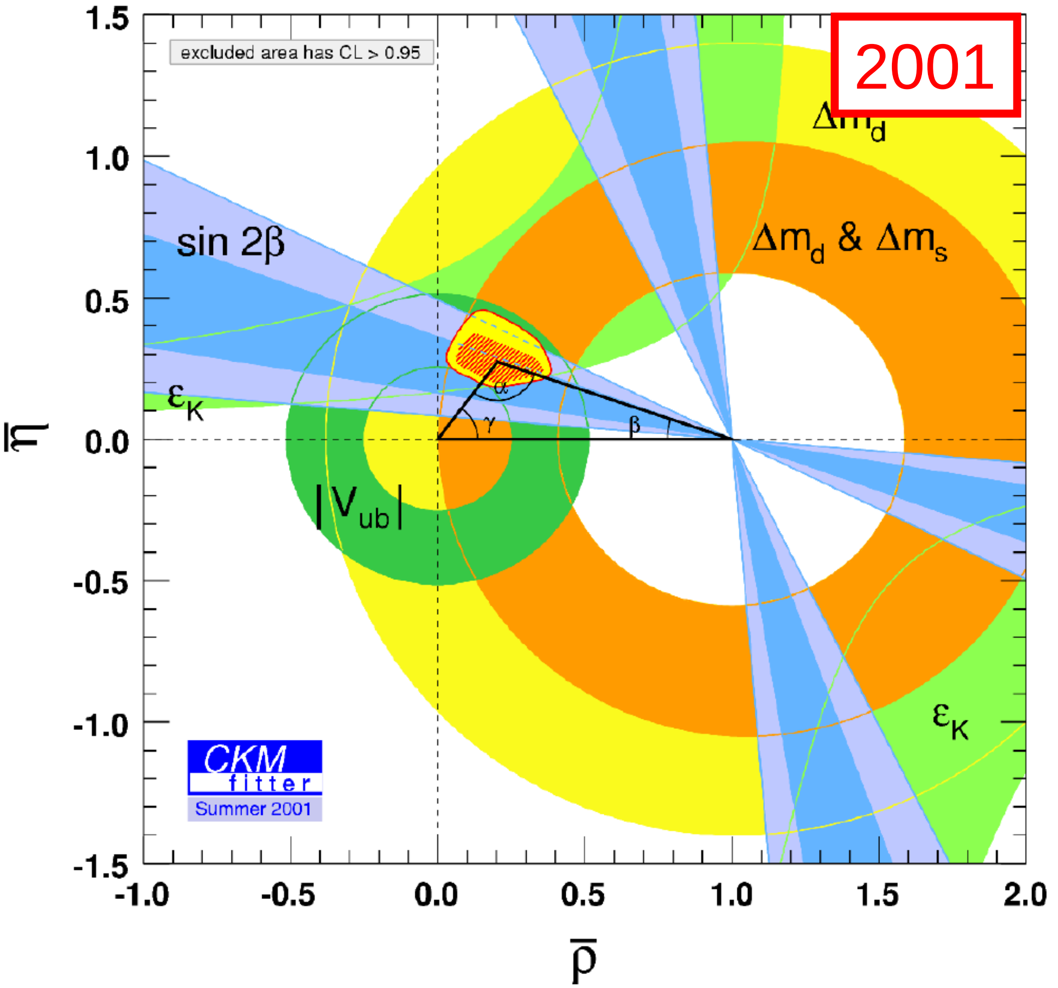

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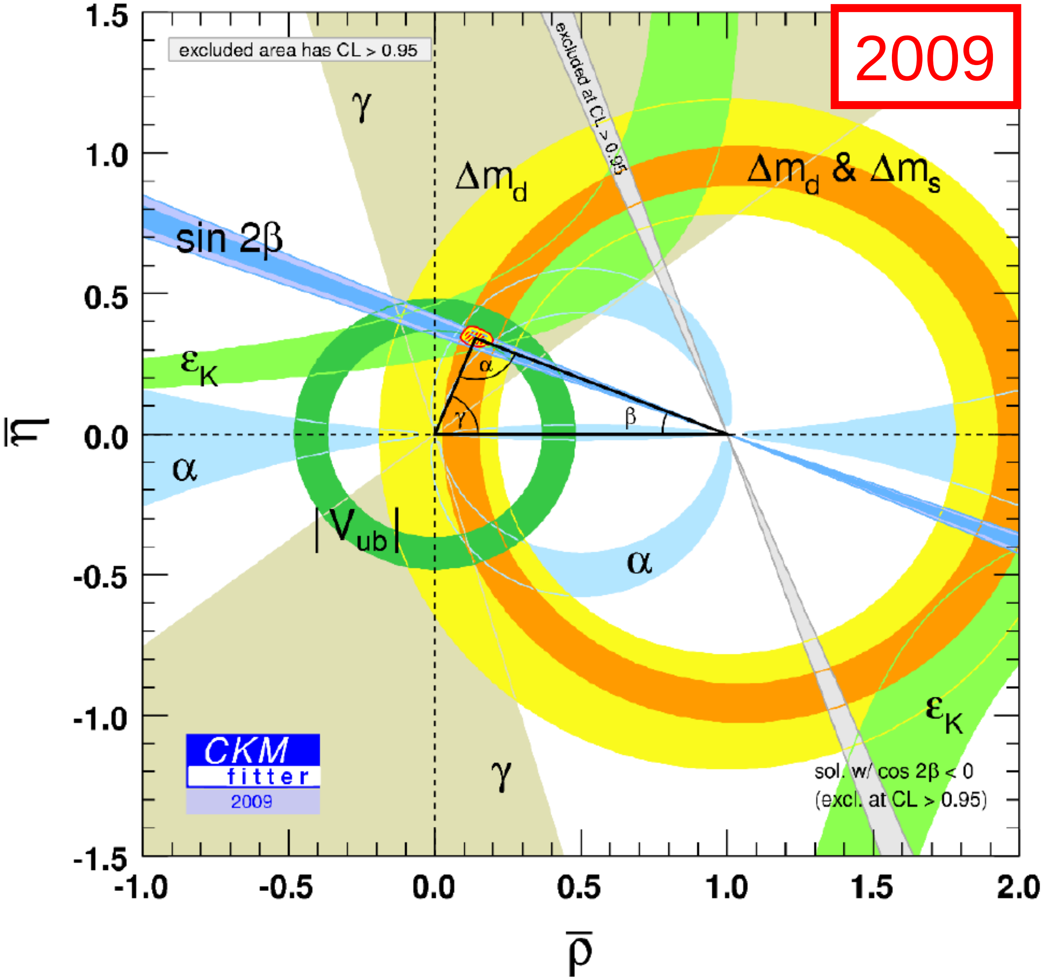

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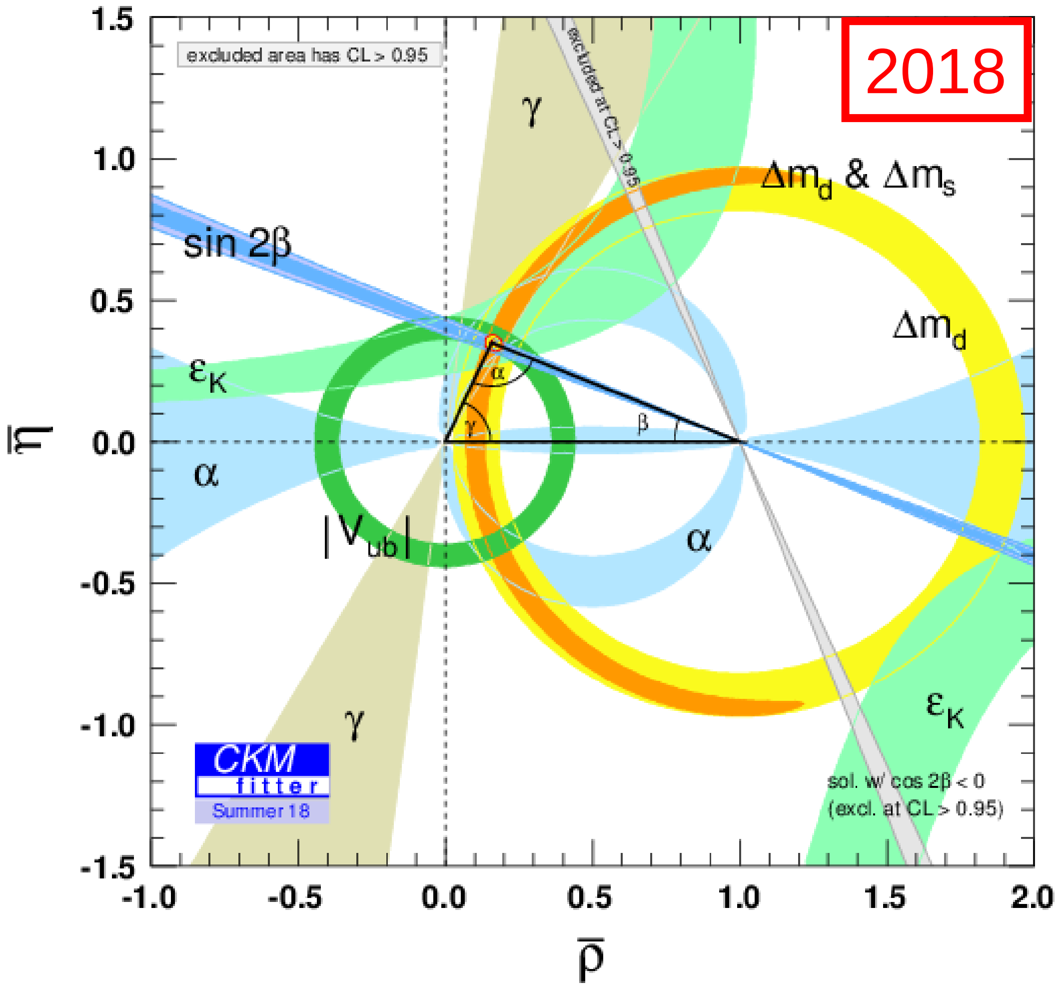

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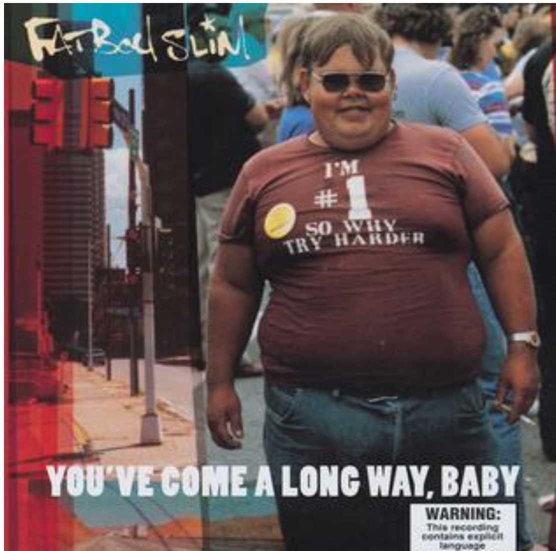
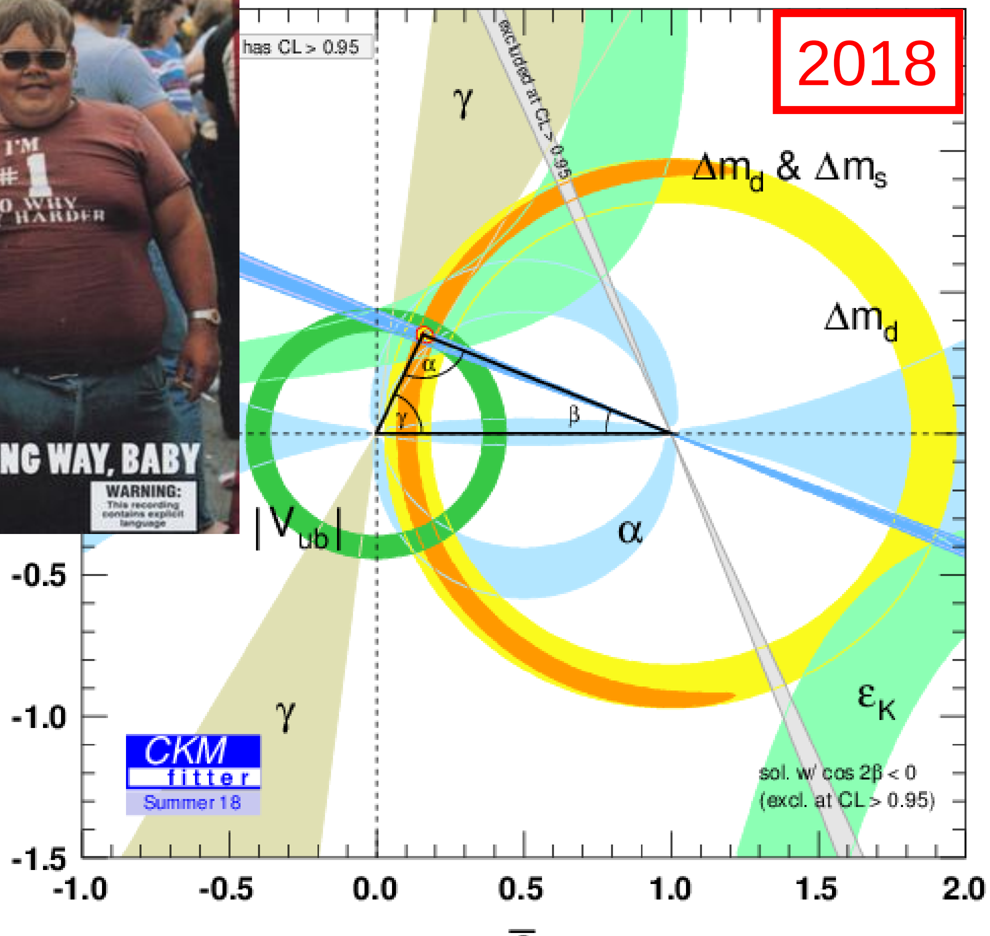
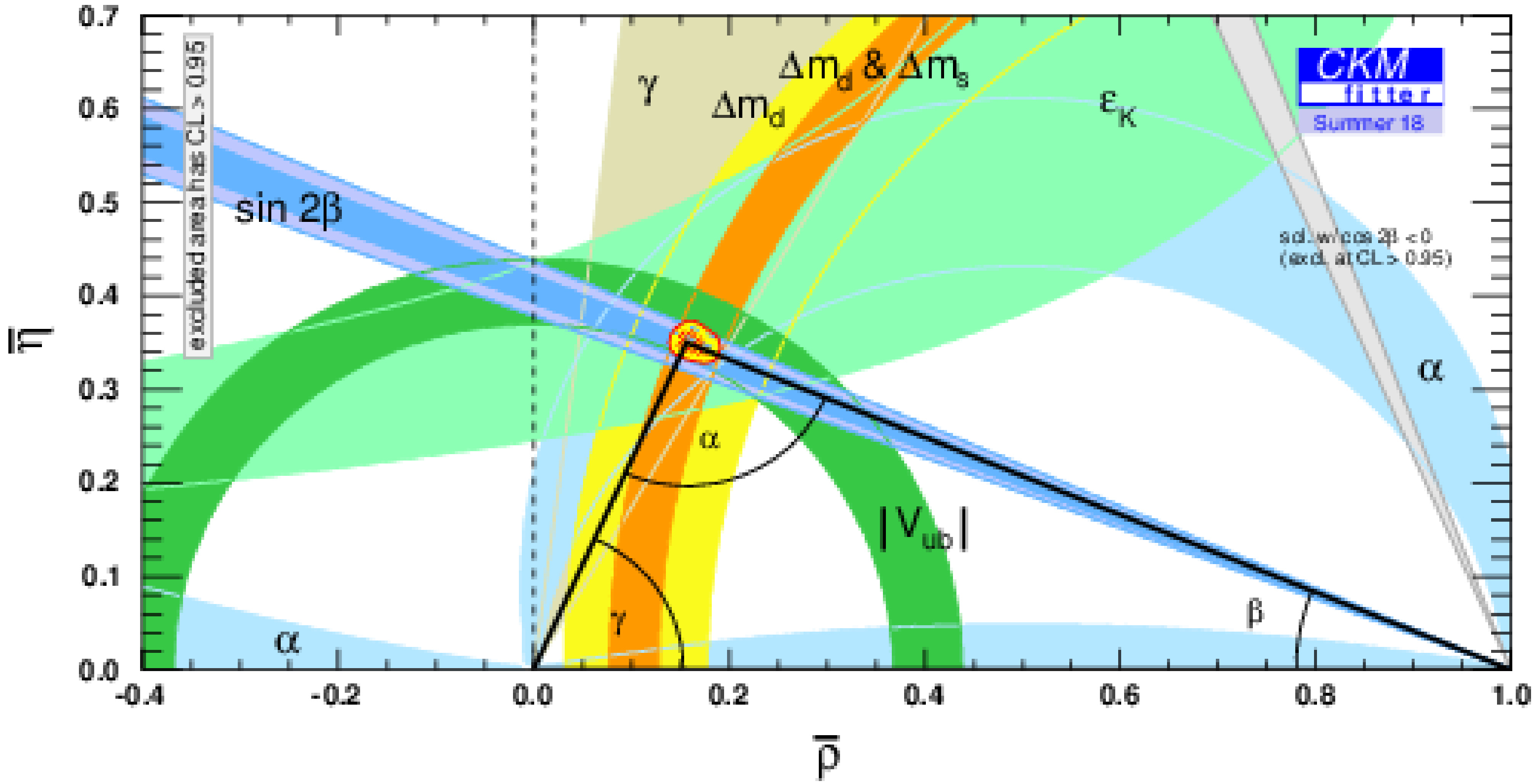




Enormous improvements in precision, thanks to both experiment and theory (esp. lattice) !

Overall consistency of the Unitarity Triangle

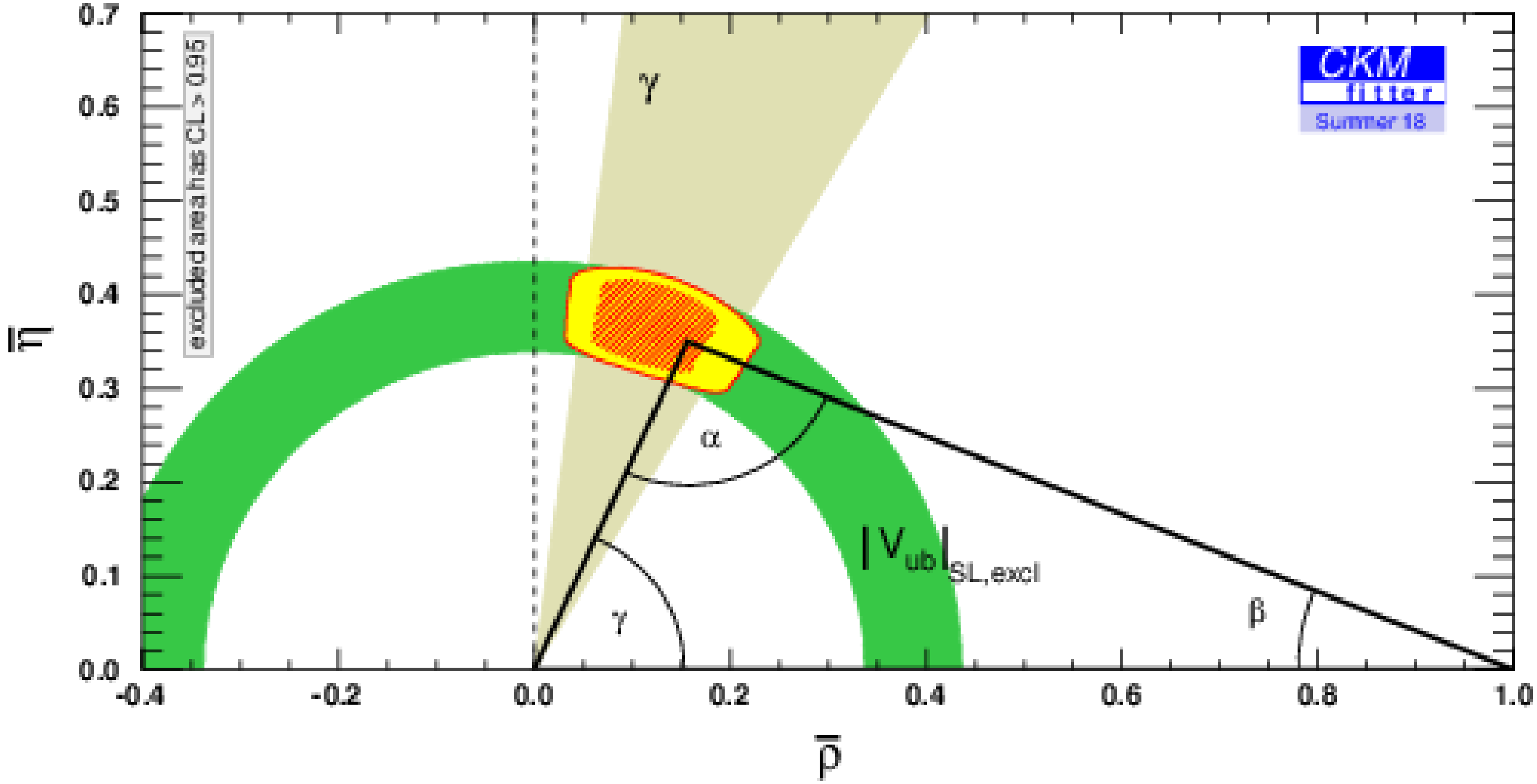
There is broad consistency between all current measurements of the UT. (But, a closer look can reveal intriguing tensions, *e.g.* [Blanke & Buras, EPJC 79 (2019) 159].)



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

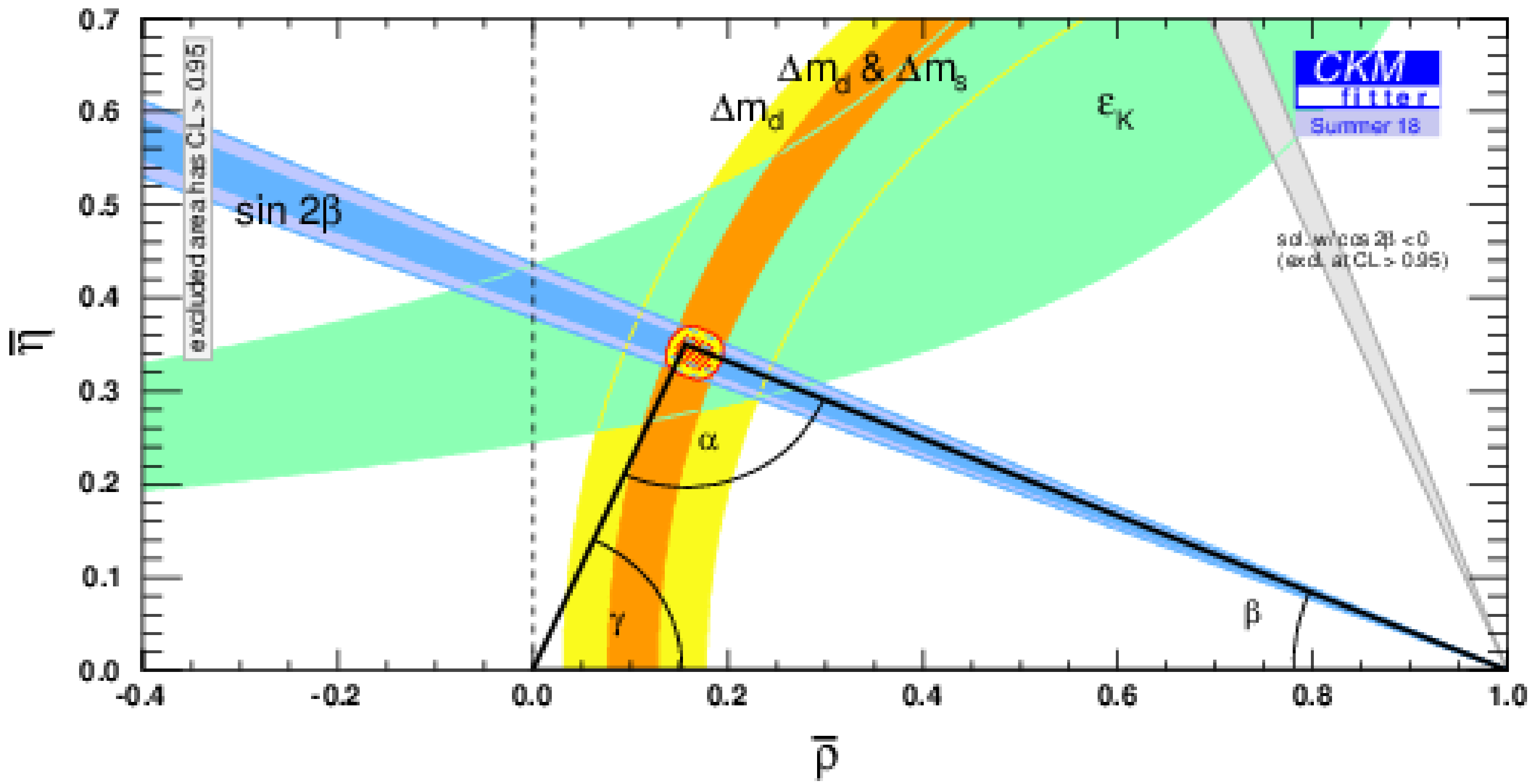
Unitarity Triangle formed from only tree-level quantities → assumed pure SM.



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.

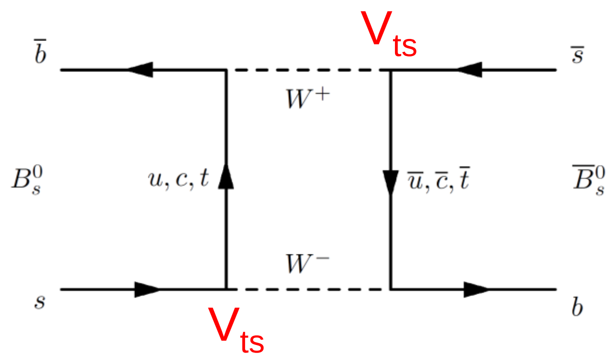


There is good consistency between the tree and loop measurements. There's a need to improve the precision of former to allow for a more sensitive comparison.

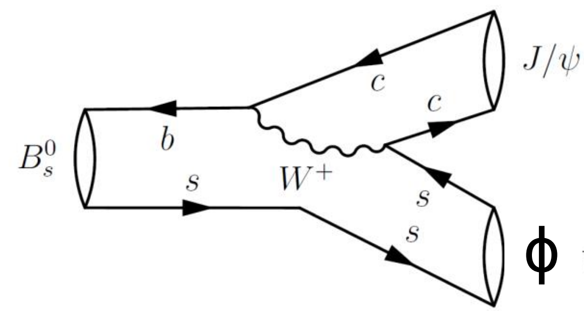
Indirect CPV in B_s system: φ_s

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

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

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

$$\phi_s^{\rm SM} \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.3^{+1.6}_{-1.5}\,{\rm mrad}$$

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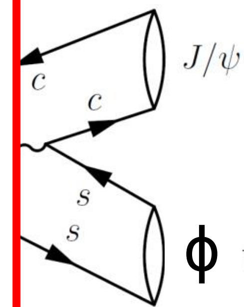
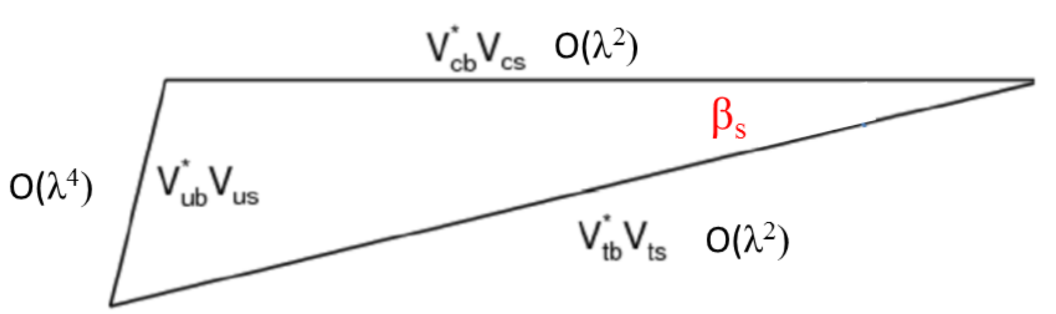


Recall the squashed B^0_s triangle:



In SM φ_s = $-2\beta_s$

Now we
elements
complex

$\eta) \Big) + \mathcal{O}(\lambda^4)$

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

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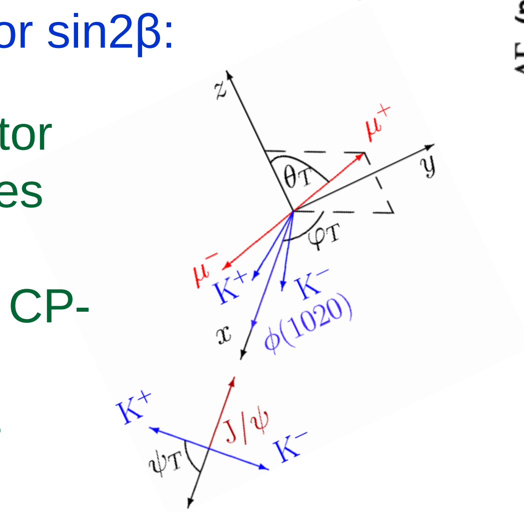
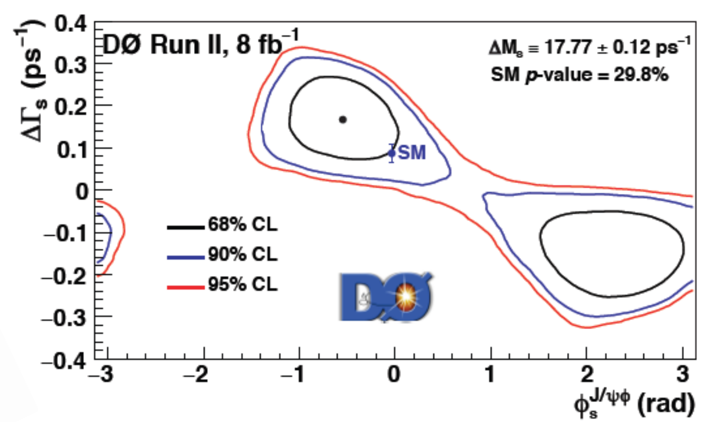
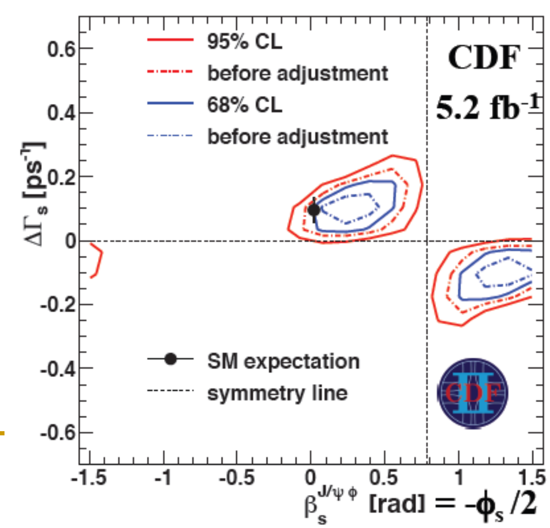
However the measurement is considerably trickier than is the case for sin2β:

- $J/\Psi\varphi$ is a vector-vector final state, so requires angular analysis to separate out CP+ & CP-
- Very fast oscillations ($\Delta m_s \gg \Delta m_d$)
- 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.

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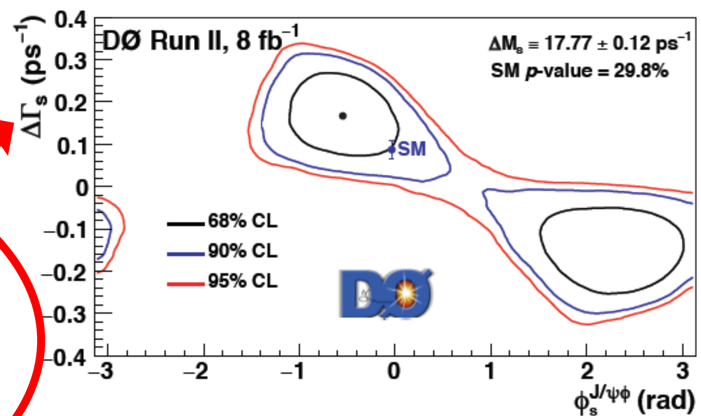
However the measurement is considerably trickier than is th… sin2β:

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.

($\Delta\Gamma_s$ …

- Possibility of KK S-wave under φ

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



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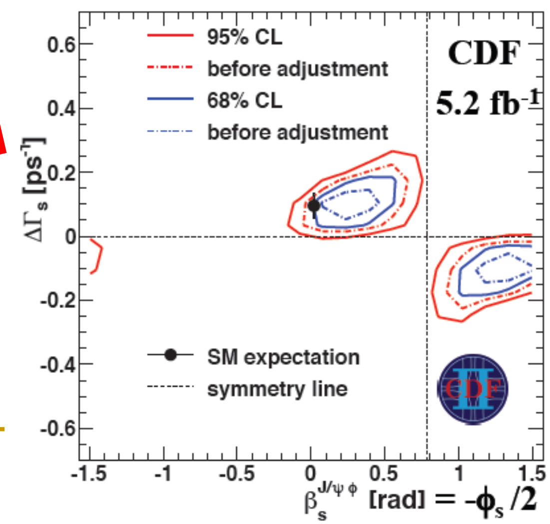
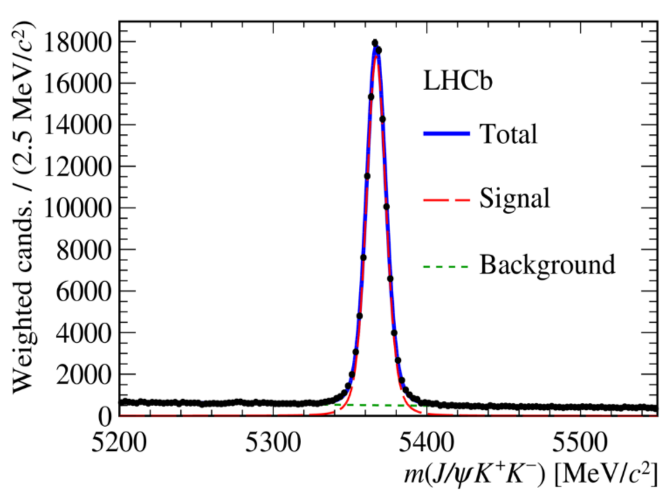


[PRD 85 (2012) 072002]

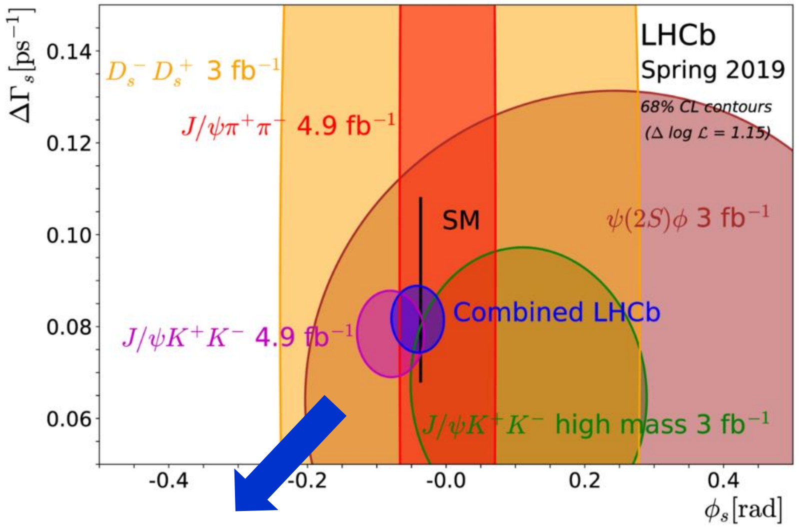
φ_s – impact of LHCb

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 $J/\psi\varphi$ (*e.g.* $B_s \to J/\psi\pi\pi$ pursued in [PLB 713 (2012) 378] .)

$B_s \to J/\psi\varphi$ signal peak in early Run 2 analysis (117k decays, in 1.9 fb^{-1} *c.f.* 6.5k at CDF).



Results for early Run 2 $J/\psi\varphi$ study, together with Run 1 measurements.



[EPJC 79 (2019) 706]

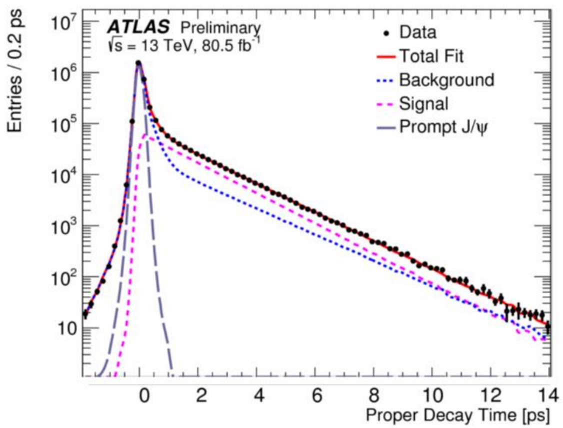
$$\phi_s = -0.041 \pm 0.025\,\text{rad} \qquad \Delta\Gamma_s = 0.0816 \pm 0.0048\,\text{ps}^{-1}$$

Measurement of φ_s at ATLAS and CMS

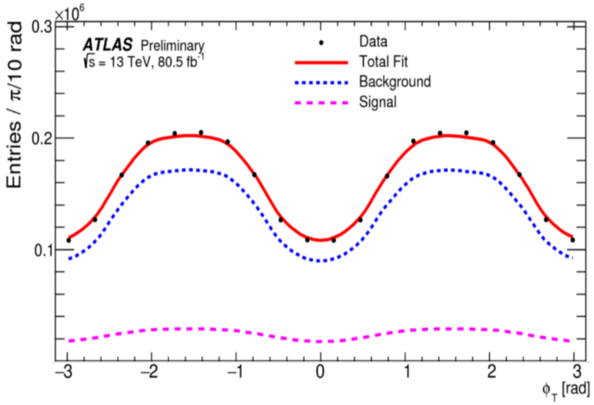
Measurement of φ_s is an key goal of the ATLAS and CMS flavour physics programme, enabled by excellent detector performance and $J/\Psi \to \mu\mu$ trigger.

e.g. ATLAS $B_s \to J/\Psi\varphi$ preliminary Run 2 analysis with 80 fb^{-1} [ATL-CONF-2019-009] :

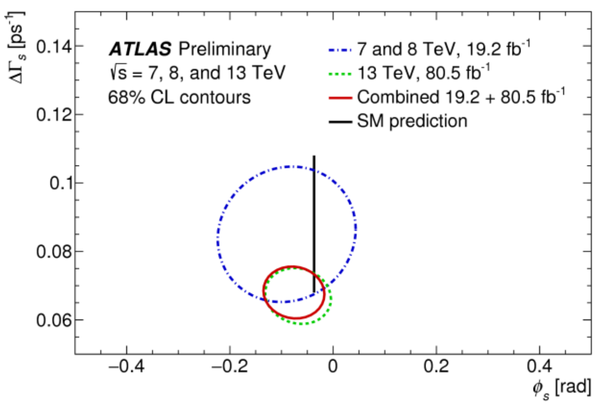
Proper decay time



Transversity angle φ_T



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



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

$$\begin{aligned} \phi_s &= -0.076 \pm 0.034\ (\text{stat.}) \pm 0.019\ (\text{syst.})\ \text{rad} \\ \Delta\Gamma_s &= 0.068 \pm 0.004\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1} \end{aligned}$$

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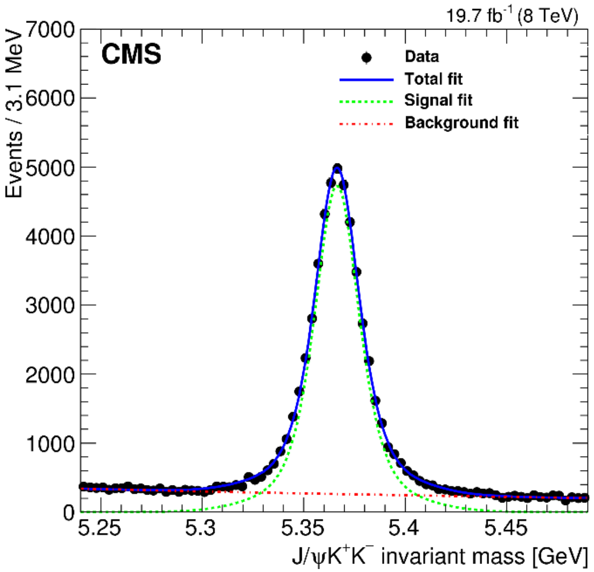
e.g. CMS $B_s \to J/\Psi\varphi$ 8 TeV analysis [PLB 757 (2016) 97]

Invariant mass



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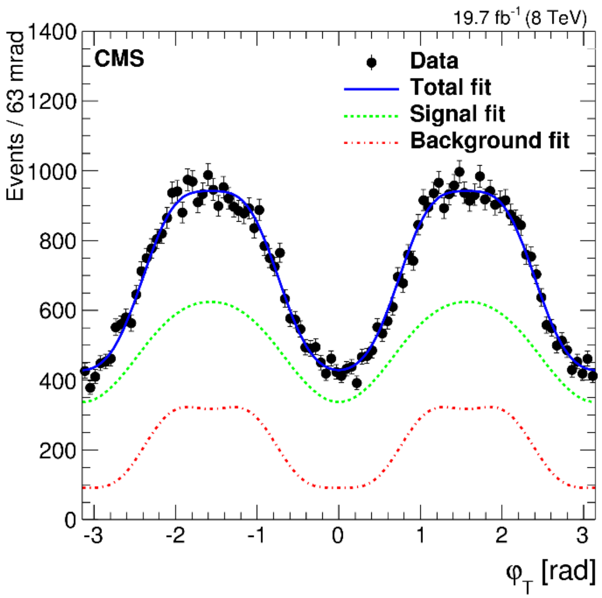
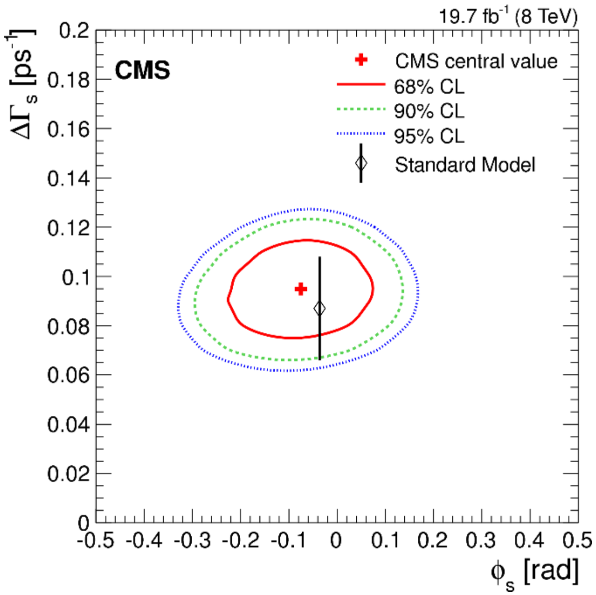
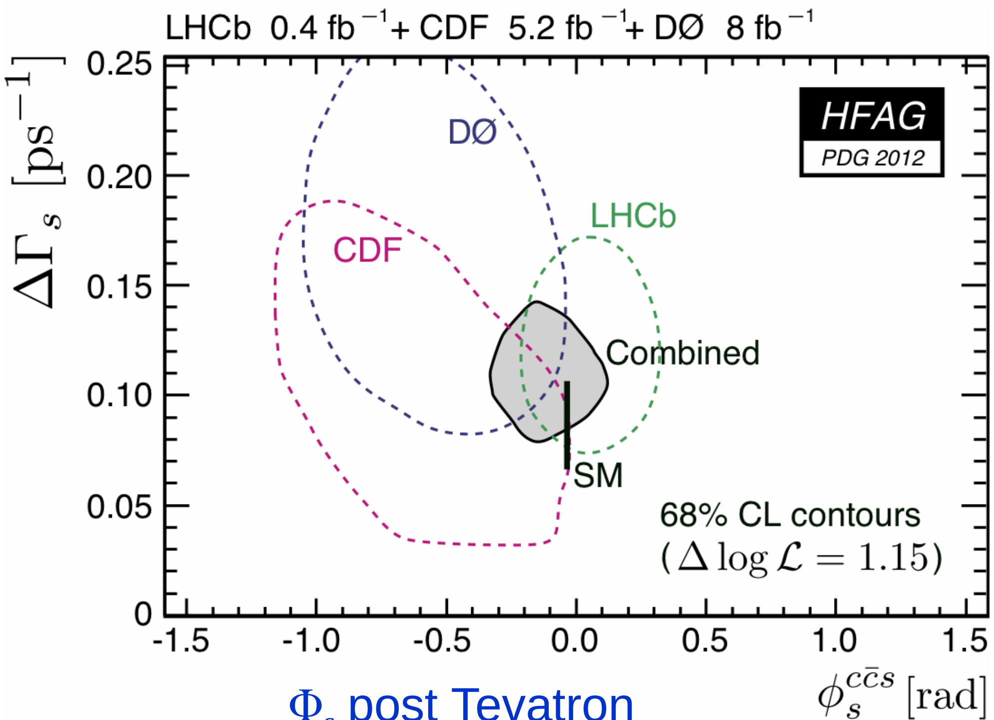


Result contours



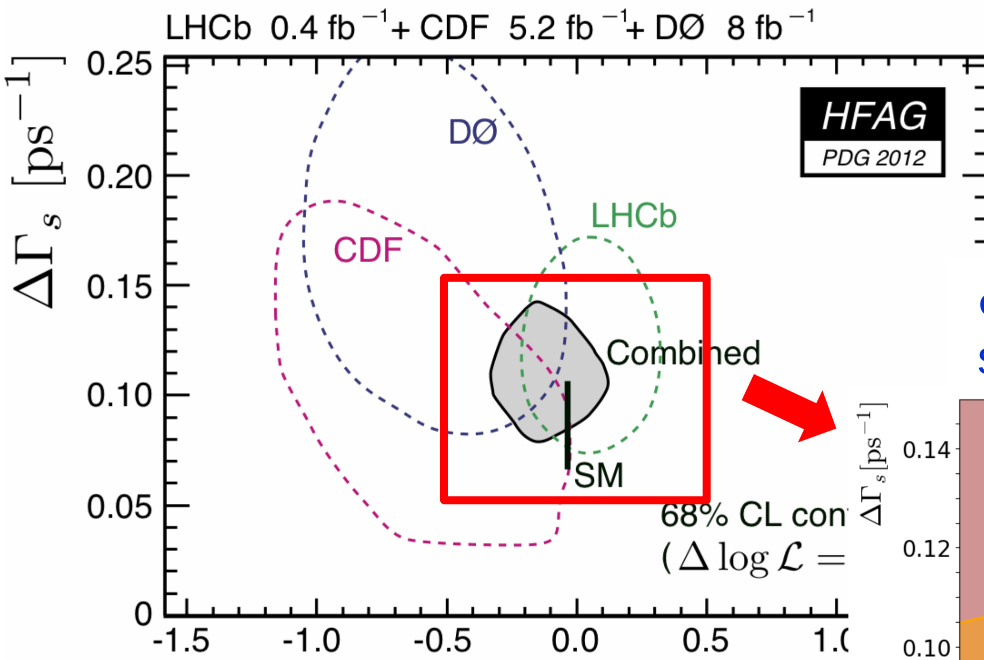
$$\phi_s = -0.075 \pm 0.097\,(\text{stat}) \pm 0.031\,(\text{syst})\,\text{rad},$$
$$\Delta\Gamma_s = 0.095 \pm 0.013\,(\text{stat}) \pm 0.007\,(\text{syst})\,\text{ps}^{-1}.$$

φ_s : the impact of the LHC



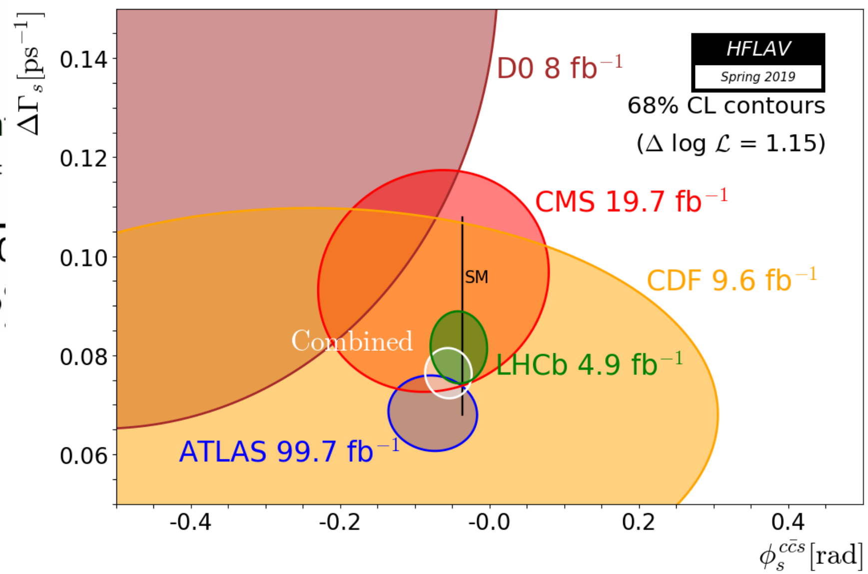
Φ_s post Tevatron
and early LHC data

φ_s : the impact of the LHC

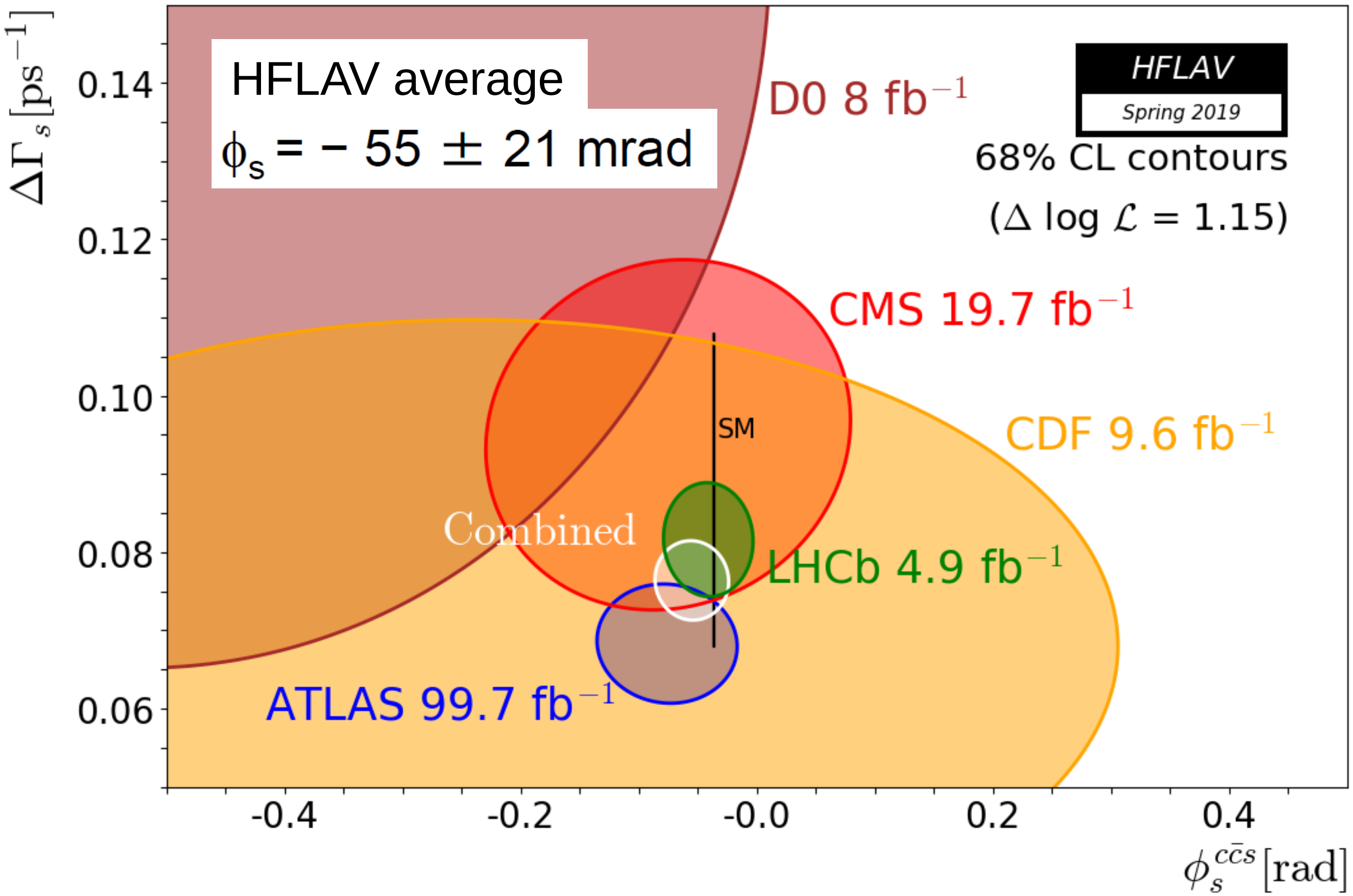


Φ_s post Tevatron
and early LHC data

φ_s post Run 1 LHC and including
some Run 2 ATLAS & LHCb data



φ_s : the current state of play



φ_s now measured with ~20 mrad precision and so far compatible with SM.
Hint of non-zero value emerging – will be interesting with full Run 2 dataset !

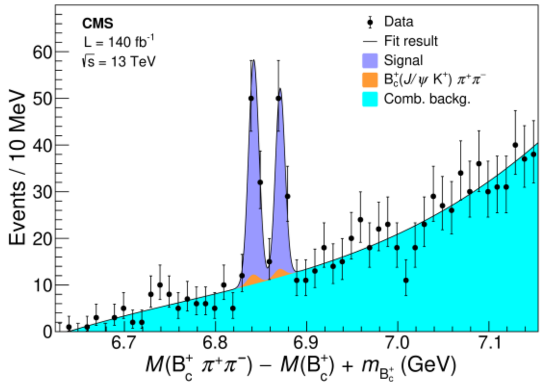
Spectroscopy (a digression)

Hadron spectroscopy is not flavour physics. However flavour-physics experiments are ideally suited for discovering and studying new states, and many high impact results have emerged of this nature.

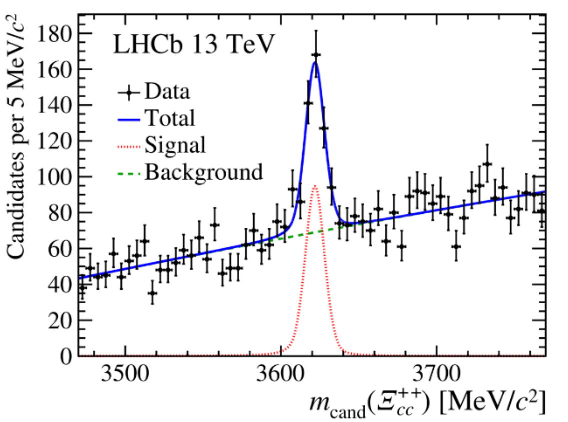
Spectroscopy - the conventional

Many new states found at the LHC, most of which fit within the 'vanilla' quark model

CMS discovery of excited B_c states [PRL 122 (2019) 132001]



LHCb discovery of the Ξ_{cc}^{++} [PRL 119 (2017) 112001]



"Baryons can now be constructed from quarks by using the combinations qqq, $qqq\bar{q}q$, etc, while mesons are made out of $q\bar{q}$, $q\bar{q}q\bar{q}$, etc."

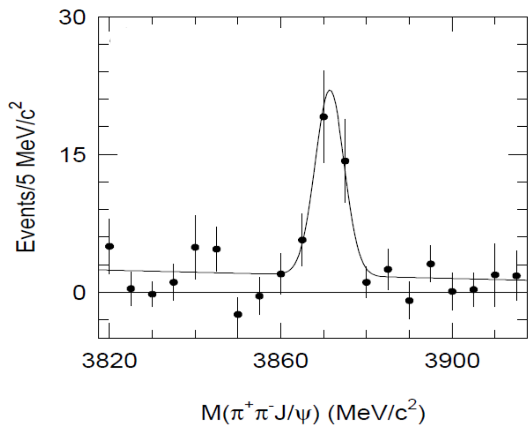
Murray Gell-Mann

Spectroscopy - the exotic

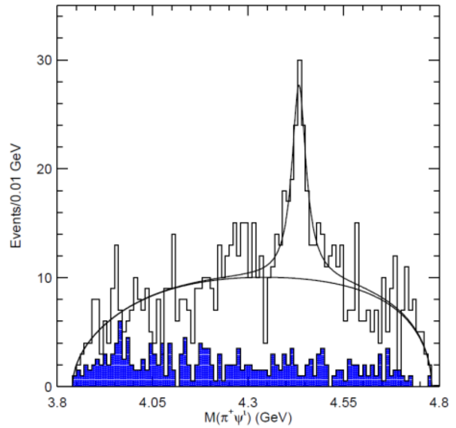
Other states, many discovered in e^+e^-, are good candidates to be 'exotic':

Both are strong candidates to be four-quark states

Observation of the X(3872) at Belle [PRL 91 (2003) 262001]



Observation of the $Z(4430)^+$ at Belle [PRL 100 (2008) 142001]



"Baryons can now be constructed from quarks by using the combinations qqq, $qqqq\bar{q}$, etc, while mesons are made out of $q\bar{q}$, $q\bar{q}q\bar{q}$, etc."

Murray Gell-Mann

Spectroscopy results – provoke great interest among physicists

Top cited Belle physics papers

1. **Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays**
(1656) Belle Collaboration (S.K. Choi (Gyeongsang Natl. U.) *et al.*). Sep 2003. 10 pp.
Published in **Phys.Rev.Lett. 91 (2003) 262001**
DOI: 10.1103/PhysRevLett.91.262001
e-Print: **hep-ex/0309032** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; ADS Abstract Service; Link to PRESSRELEASE
Detailed record - Cited by 1656 records 1000+

2. **Observation of large CP violation in the neutral B meson system**
(951) Belle Collaboration (Kazuo Abe (KEK, Tsukuba) *et al.*). Jul 2001. 12 pp.
Published in **Phys.Rev.Lett. 87 (2001) 091802**
KEK-PREPRINT-2001-50, BELLE-PREPRINT-2001-10
DOI: 10.1103/PhysRevLett.87.091802
e-Print: **hep-ex/0107061** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 951 records 500+

Top cited LHCb physics papers

1. **Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays**
(853) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Jun 25, 2014. 10 pp.
Published in **Phys.Rev.Lett. 113 (2014) 151601**
CERN-PH-EP-2014-140, LHCB-PAPER-2014-024
DOI: 10.1103/PhysRevLett.113.151601
e-Print: **arXiv:1406.6482 [hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 853 records 500+

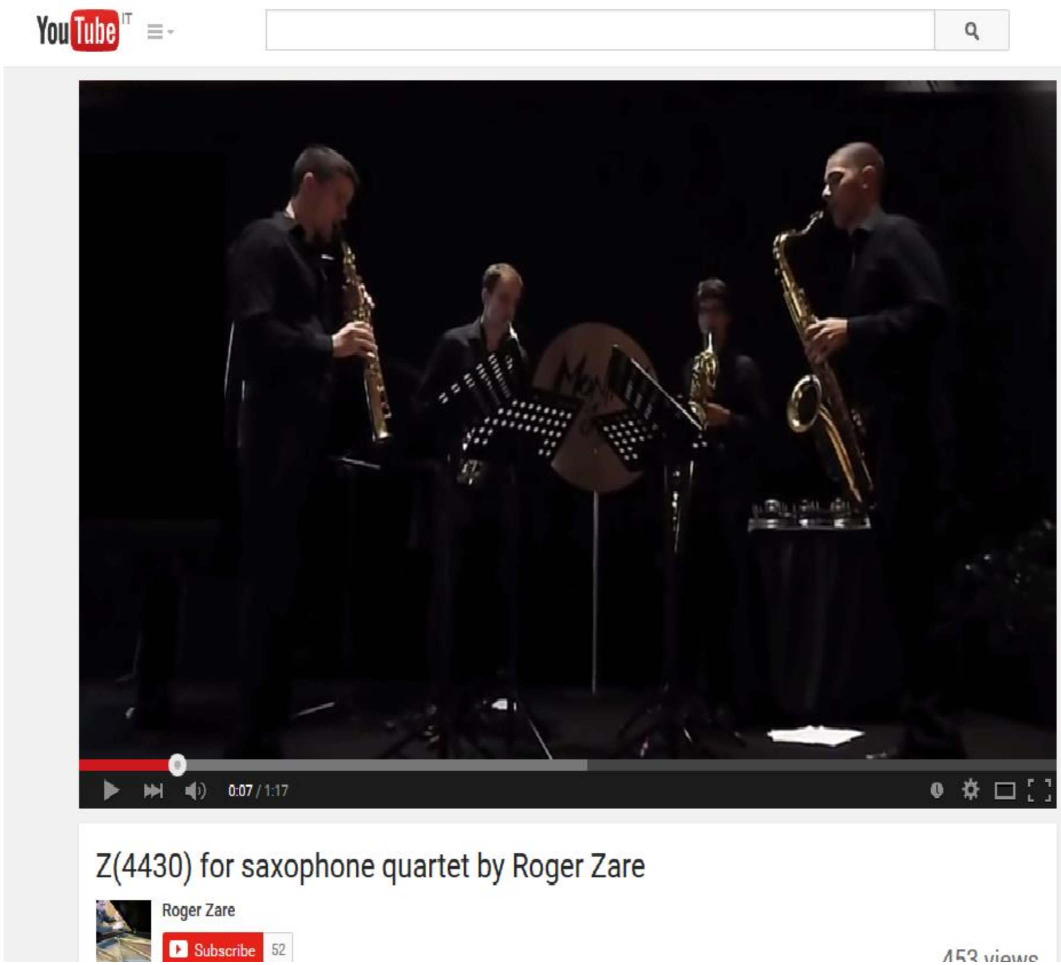
2. **Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays**
(792) LHCb Collaboration (Roel Aaij (CERN) *et al.*). Jul 13, 2015. 15 pp.
Published in **Phys.Rev.Lett. 115 (2015) 072001**
CERN-PH-EP-2015-153, LHCB-PAPER-2015-029
DOI: 10.1103/PhysRevLett.115.072001
e-Print: **arXiv:1507.03414 [hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Interactions.org article; Link to BBC News article; Link to Symmetry Magaz
News article; Link to PBS website; Link to Scientific American article
Detailed record - Cited by 792 records 500+

Spectroscopy results – provoke great interest among public too

e.g. reactions to LHCb study of resonant nature of $Z(4430)^-$ [PRL 112 (2013) 222002]

Spectroscopy results – provoke great interest among public too

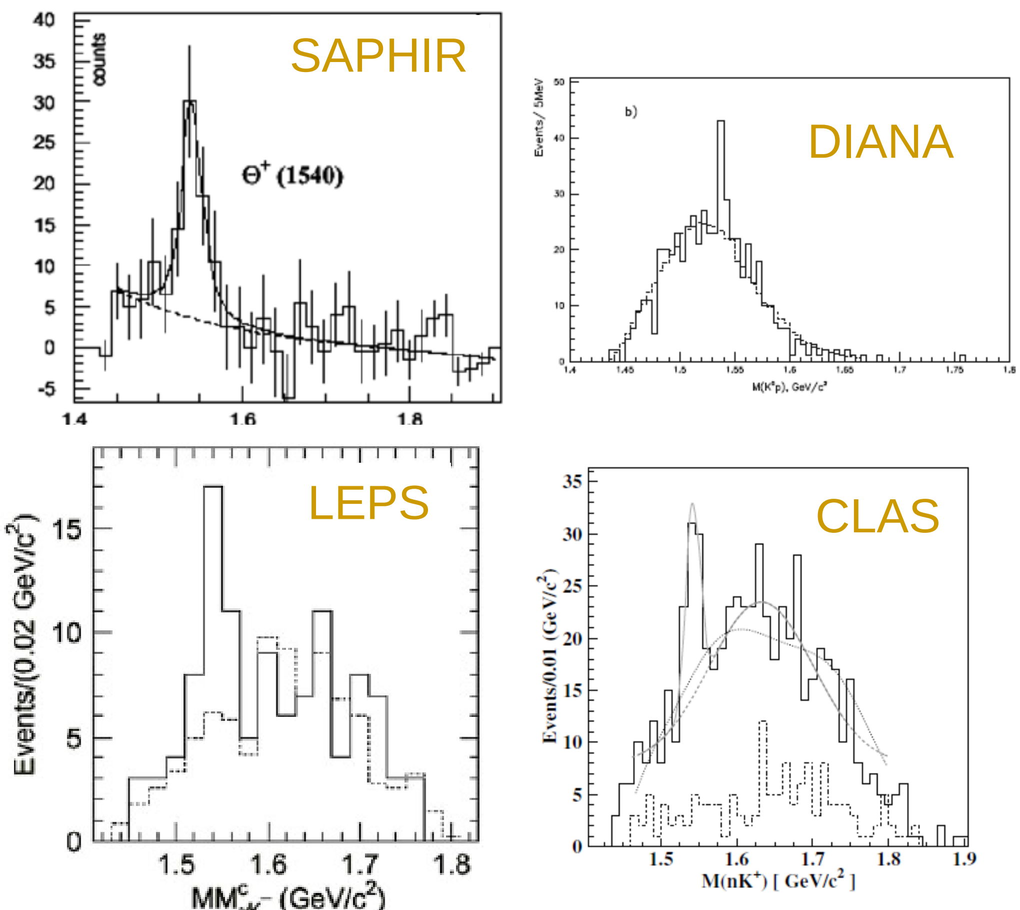
e.g. reactions to LHCb study of resonant nature of Z(4430)$^-$ [PRL 112 (2013) 222002]



Montreux jazz festival, 2014

The hunt for pentaquarks – a long journey with several cul-de-sacs

Pentaquark signals have been claimed before, for example the θ^+ (sbar uudd) ‘seen’ by several experiments in the early 2000s.

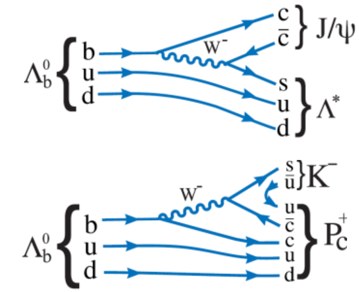


After an initial rush of confirmations, null results from more sensitive experiments appeared, & eventually it was accepted to be non-existent.

“ The whole story – the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual ‘undiscovery’ - is a curious episode in the history of science.” PDG 2008

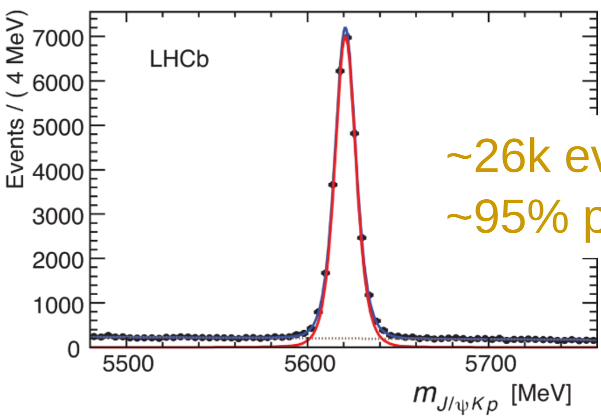
[for more information, see Hicks, Eur. Phys. J. H 37 (2012) 1]

J/Ψp resonances consistent with pentaquark states



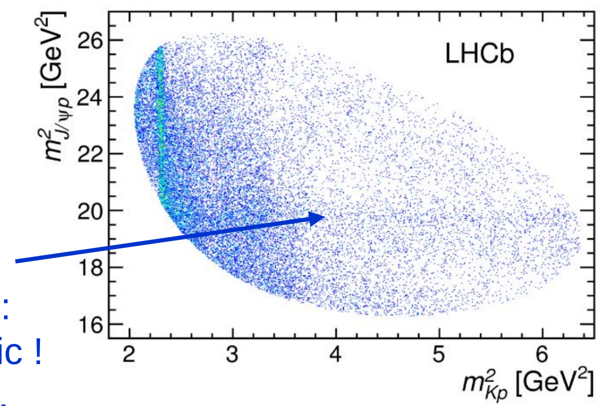
[PRL 115 (2015) 072001]

Large & pure sample of $\Lambda_b \rightarrow J/\Psi pK$ decays



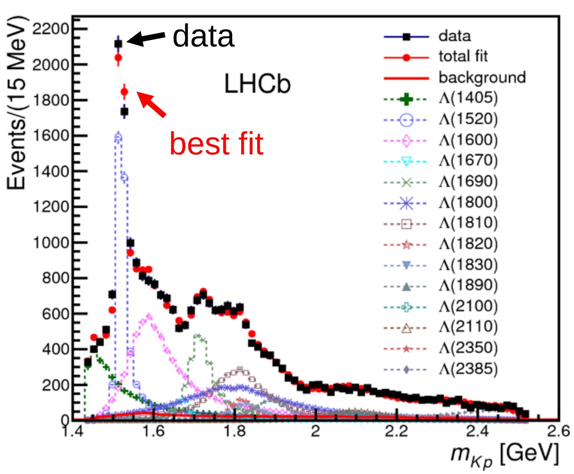
~26k events
~95% purity

Distinctive structure in J/Ψp spectrum

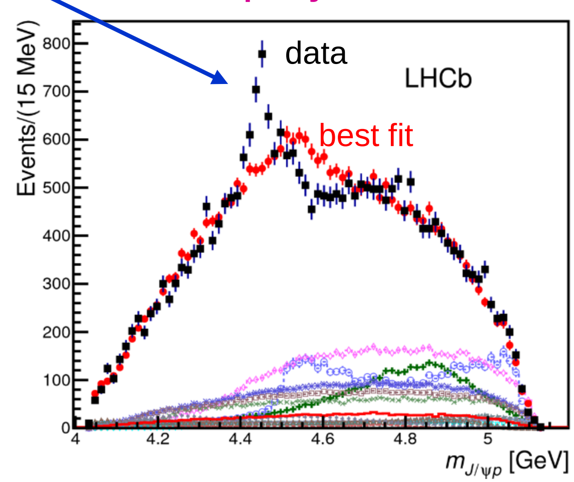


Naïve first impression: this is exotic ! (uudccbar).

Amplitude model of conventional states can reproduce Kp spectrum well enough…



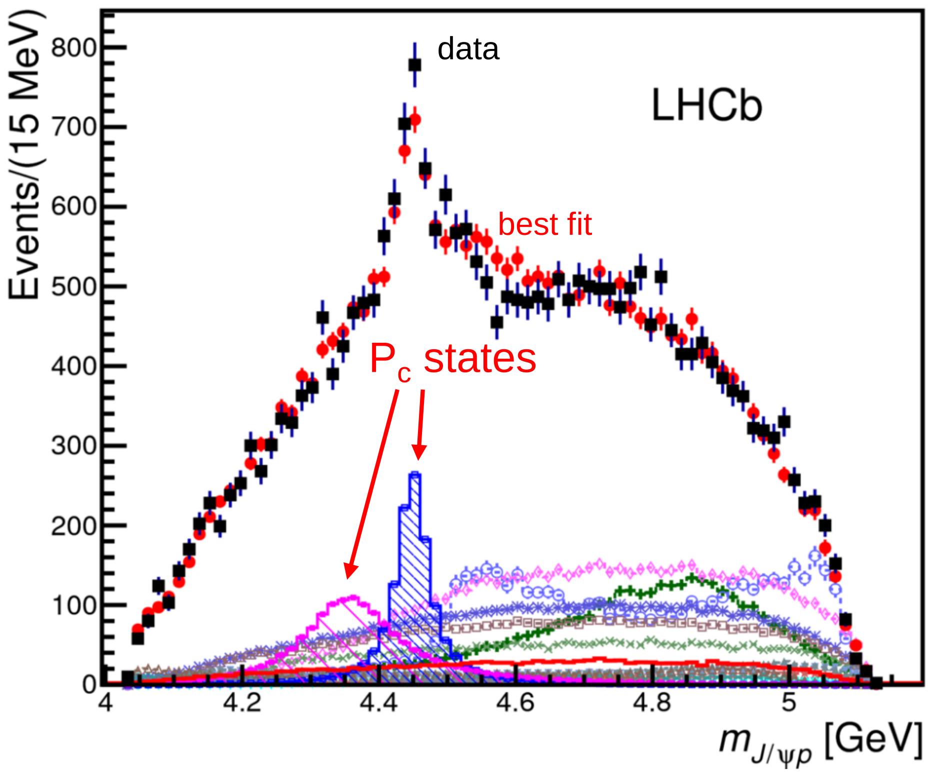
…but cannot describe the J/Ψ projection at all.



J/Ψp resonances consistent with pentaquark states

[PRL 115 (2015) 072001]

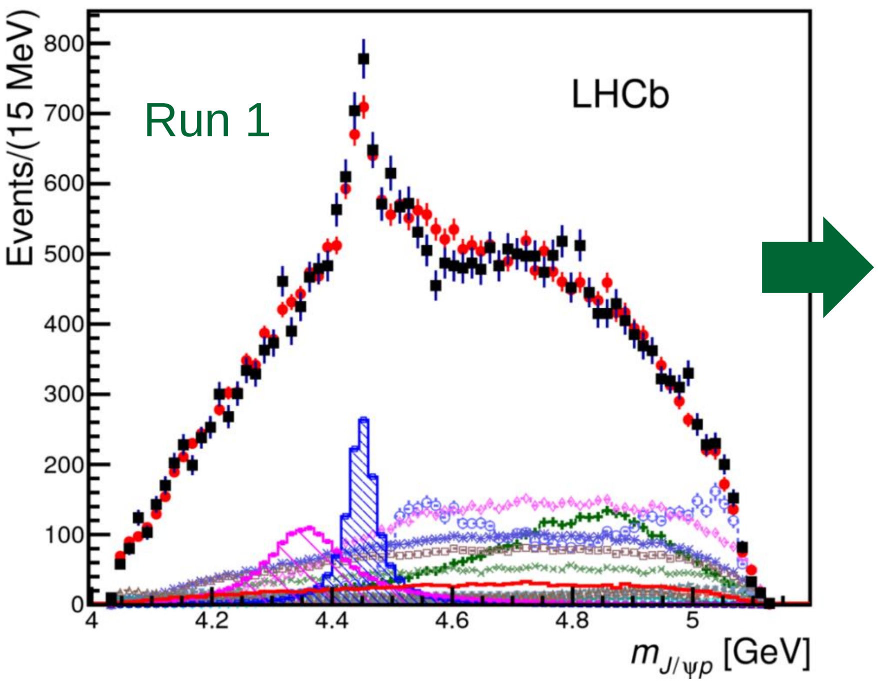
Can only describe data satisfactorily by adding two exotic pentaquark states with content uudccbar. Best fit has J=3/2 and 5/2 with opposite parities.



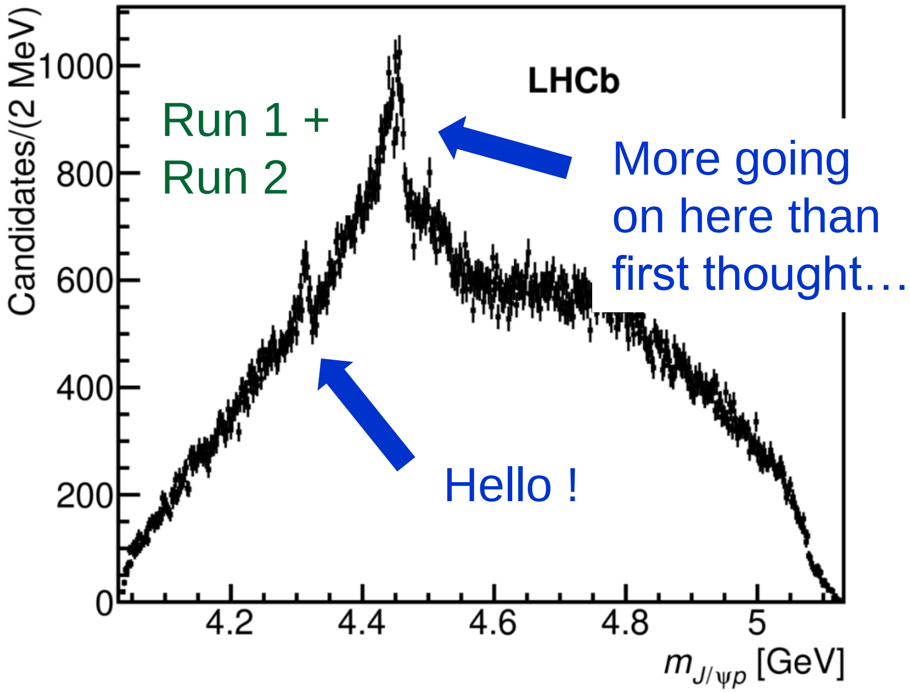
$P_c(4380)$:
$M = 4380 \pm 8 \pm 29\,\mathrm{MeV}$,
$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$
$P_c(4450)$:
$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$
$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$

Pentaquarks – why more data matters

Run 2 data and improved selection provide x9 increase in signal



[PRL 115 (2015) 072001]

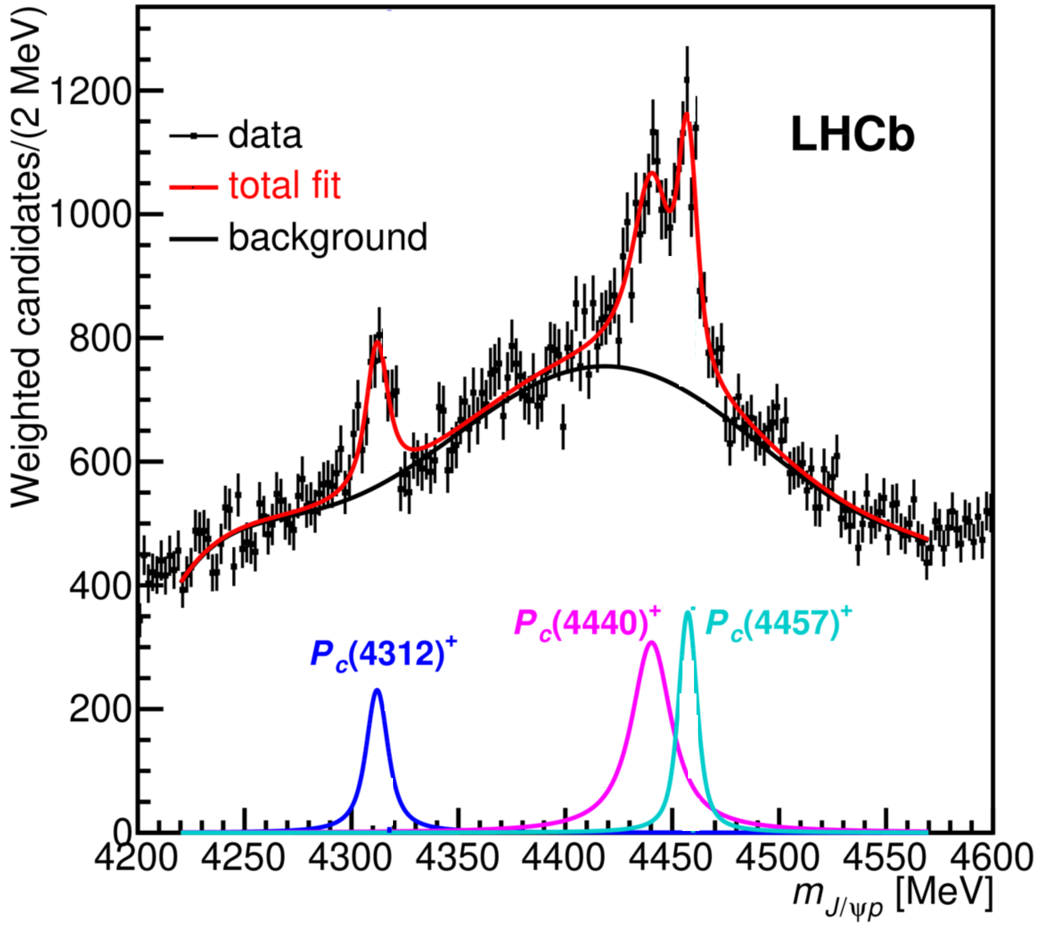


[PRL 122 (2019) 222001]

Not one narrow state, but three

A closer look at Run 2 data, after weighting to suppress effect of Λ* background.

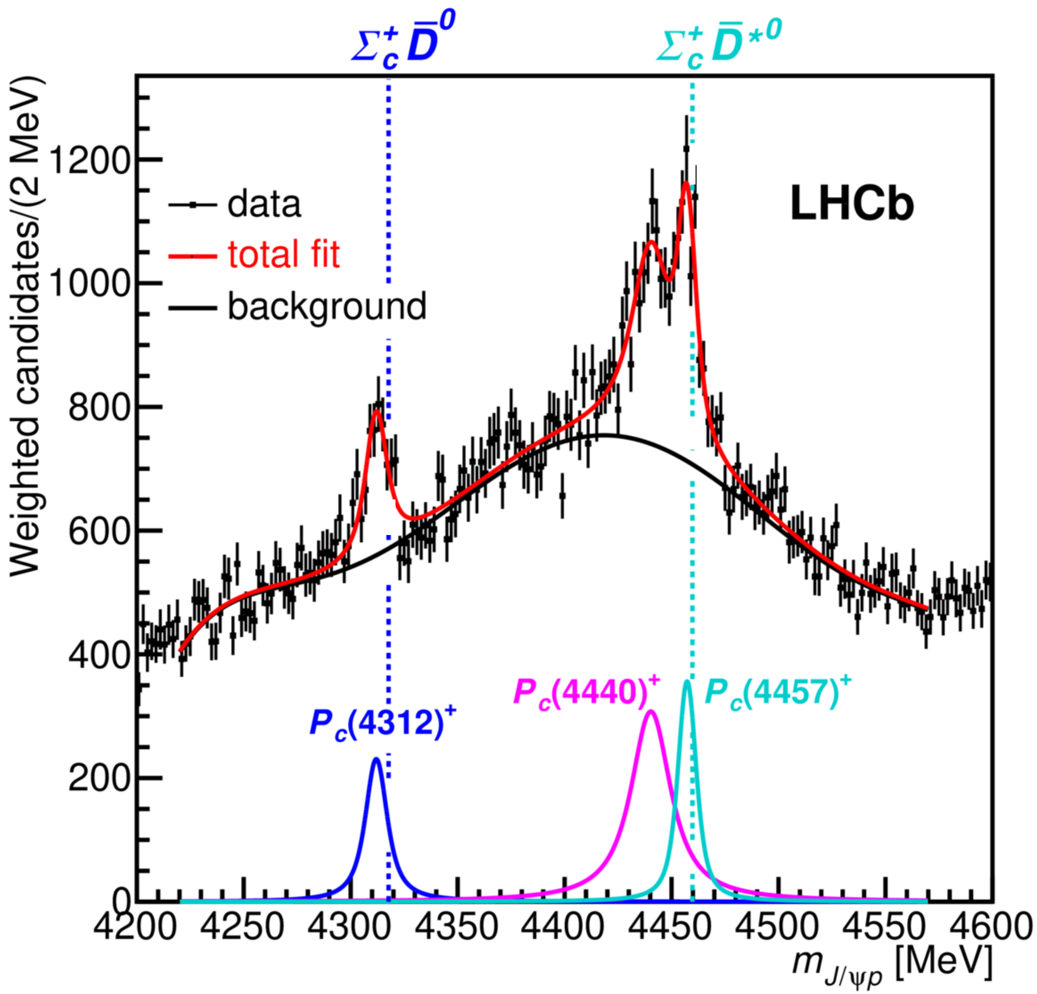
[PRL 122 (2019) 222001]



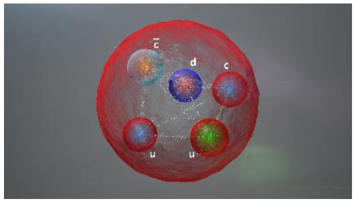
A new narrow state is observed at 4312 MeV, and the previous narrowish state is resolved into two close-lying narrower states. An amplitude analysis is required to determine J^P and decide on whether broad $P_c(4380)$ still required.

Not one narrow state, but three

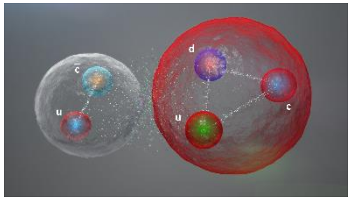
[PRL 122 (2019) 222001]



tightly-bound model



molecular model



Intriguingly, two of the states lie just below the $\Sigma_c D^{(*)0}$ thresholds, which supports a molecular meson-baryon bound state picture of the pentaquarks. See *e.g.* [Wang *et al.*, PRC 84 (2011) 015203], [Zhang *et al.*, CPC 36 (2012) 6], [Wu *et al.*, PRC 85 (2012) 044002].

FCNCs ('rare decays')

We have been talking a lot about FCNCs already
in the context of mixing, but now we switch the focus
to very rare FCNC decay modes.

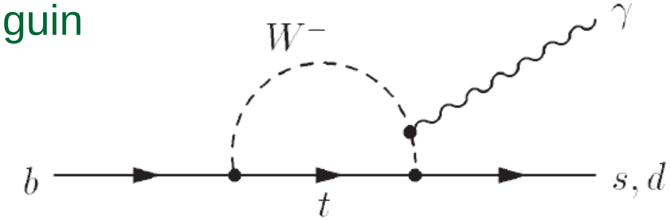
Flavour-changing Neutral Currents (FCNCs) or 'rare decays' as a probe of New Physics

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

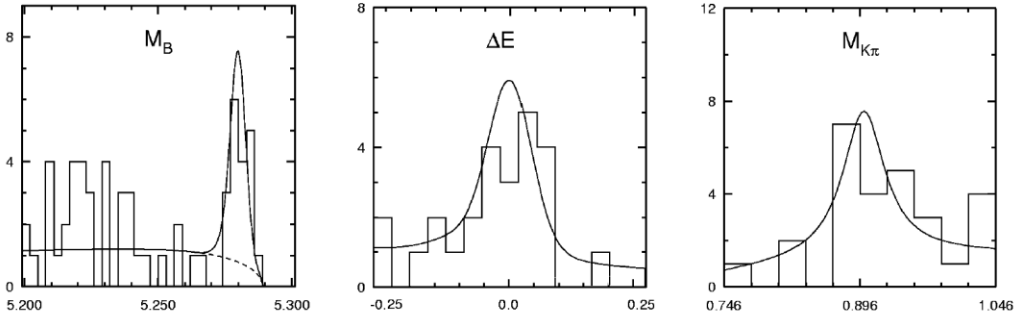
e.g. Penguin diagram (nomenclature introduced by John Ellis in 1977 after lost bet [Ellis *et al.*, NPB 131 (1977) 285].)

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].

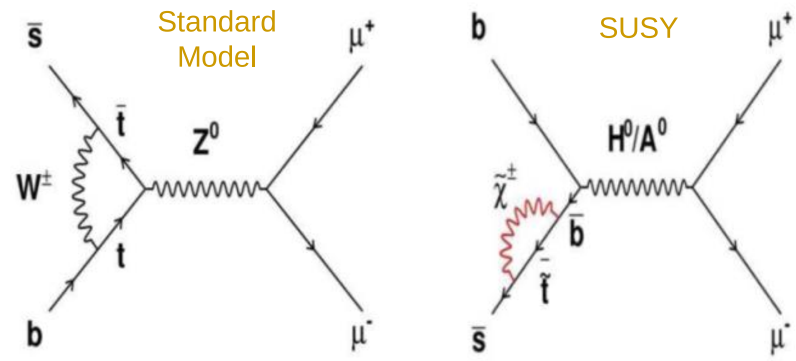


Studies of radiative penguins still very important, but we will not discuss them further.

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

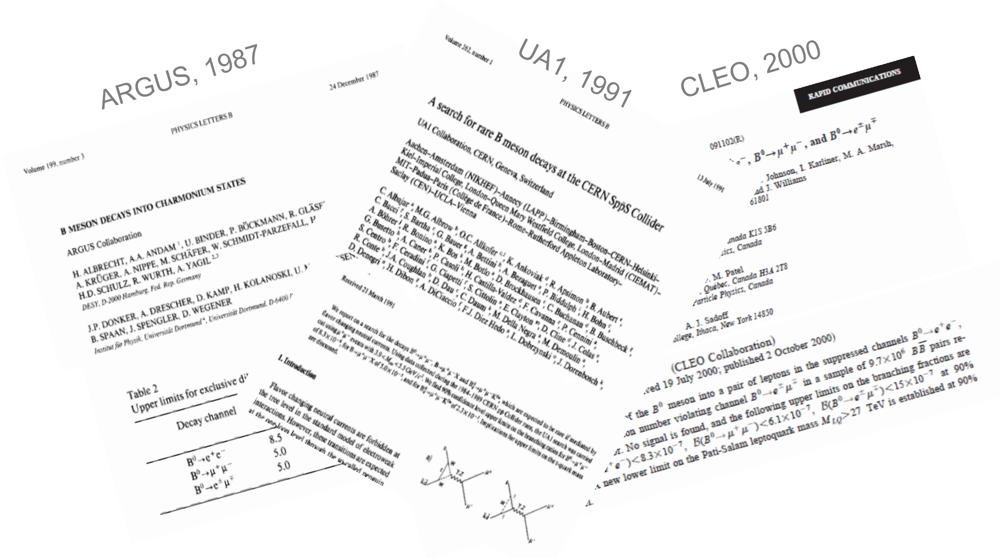
These decay modes can only proceed through suppressed loop diagrams.

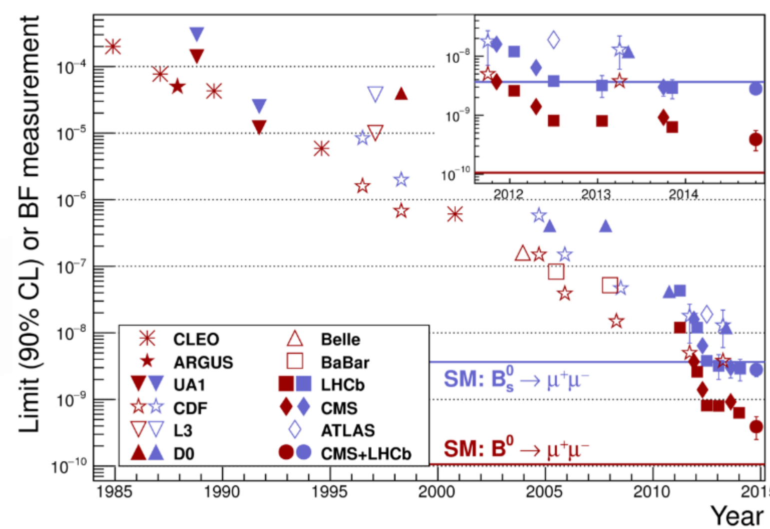
In SM they happen extremely rarely ($B_s \to \mu\mu$ ~4 x 10^{-9}, $B^0 \to \mu\mu$ 30x lower), but the rate is very well predicted (*e.g.* <5% for $B_s \to \mu\mu$).



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.

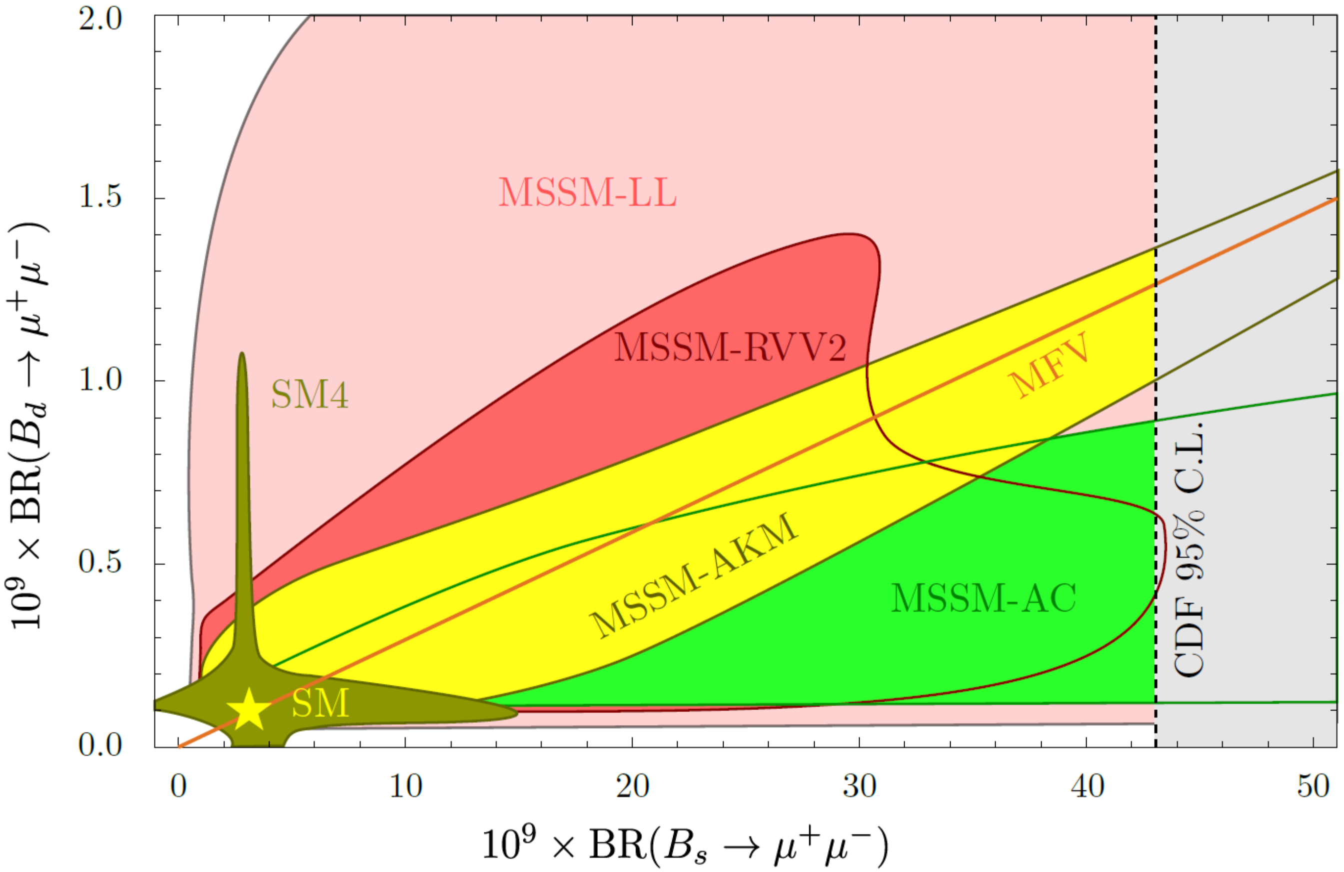




Before the LHC, Fermilab experiments were pushing the limits down towards 10^{-8}.

$B_s \to \mu^+\mu^-$, $B^0 \to \mu^+\mu^-$: 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]

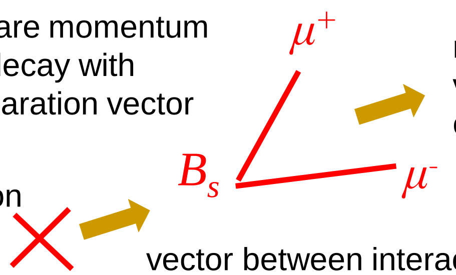
Finding the needle in the haystack

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 (LHCb, CMS) do not rely on traditional 'cut-based' approach. 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 $B_s \to \mu\mu$

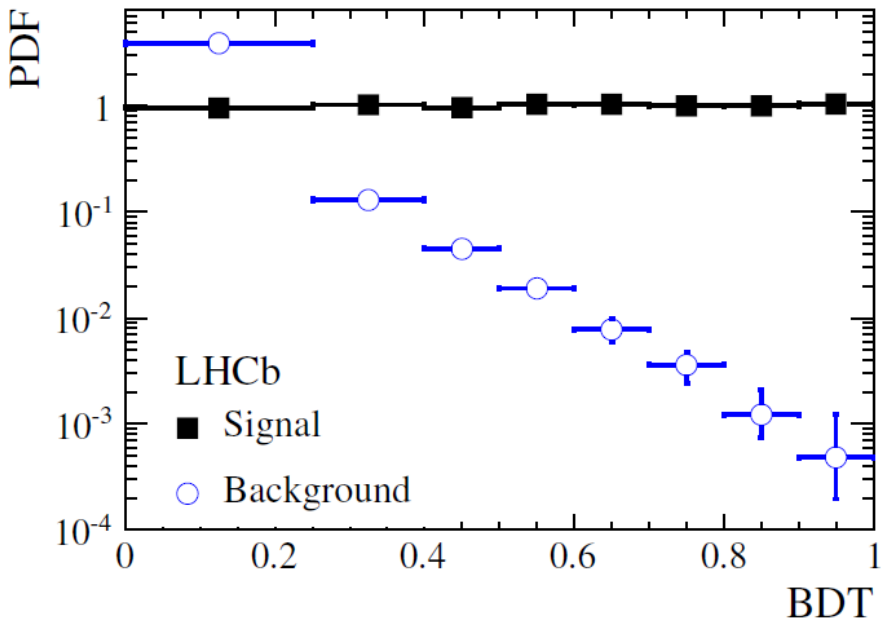
e.g. compare momentum vector of decay with vertex separation vector



momentum vector of candidate

interaction point

vector between interaction point & secondary vertices

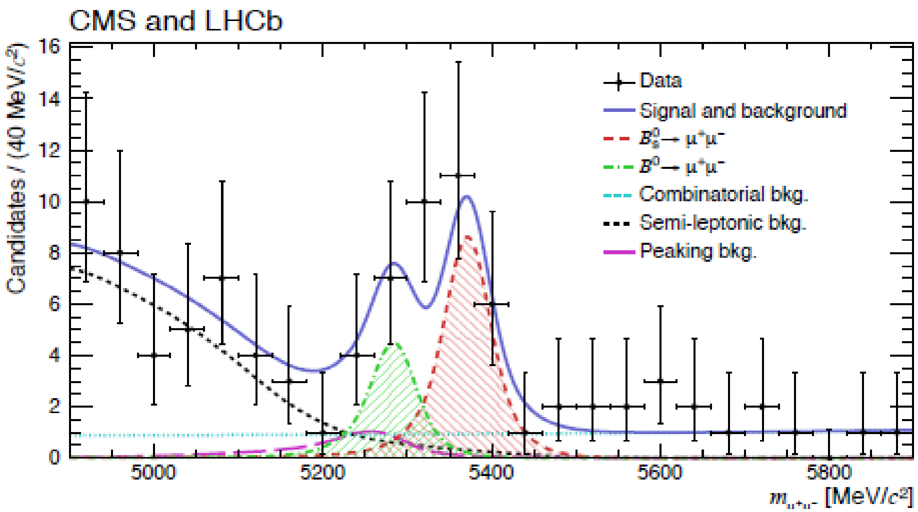


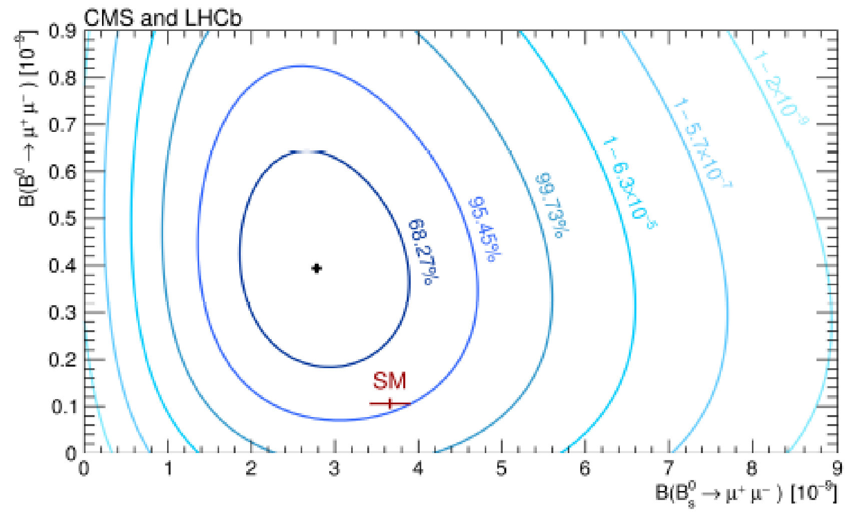
[LHCb, PRL 111 (2013) 101805]

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.

The search is over: $B_s \rightarrow \mu^+\mu^-$ 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…





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

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

[arXiv:1411.4413, Nature 522 (2015) 68]

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

LHCb $B^0_{(s)} \to \mu^+\mu^-$ run 2 update

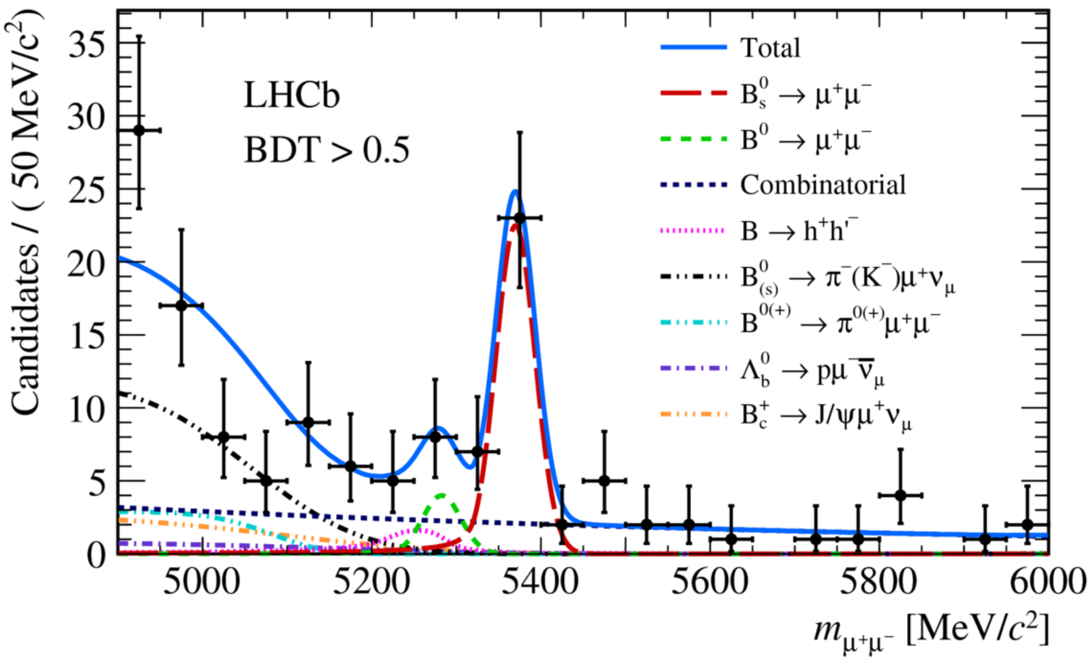
[PRL 118 (2017) 191801]

Early in Run 2 LHCb returned to this critical observable with an improved analysis (~50% combinatoric background than previously). Run 1 + 1.4 fb^{-1} of Run 2 data.

- 7.8 σ signal & first single-experiment observation !
- Precise measurement of branching fraction

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

- No evidence yet of the corresponding B^0 decay.



Uses only 1/4 of Run 2 data, so ‘legacy’ Run 1+2 result will be much more precise.

CMS $B^0_{(s)} \to \mu^+\mu^-$ run 2 update

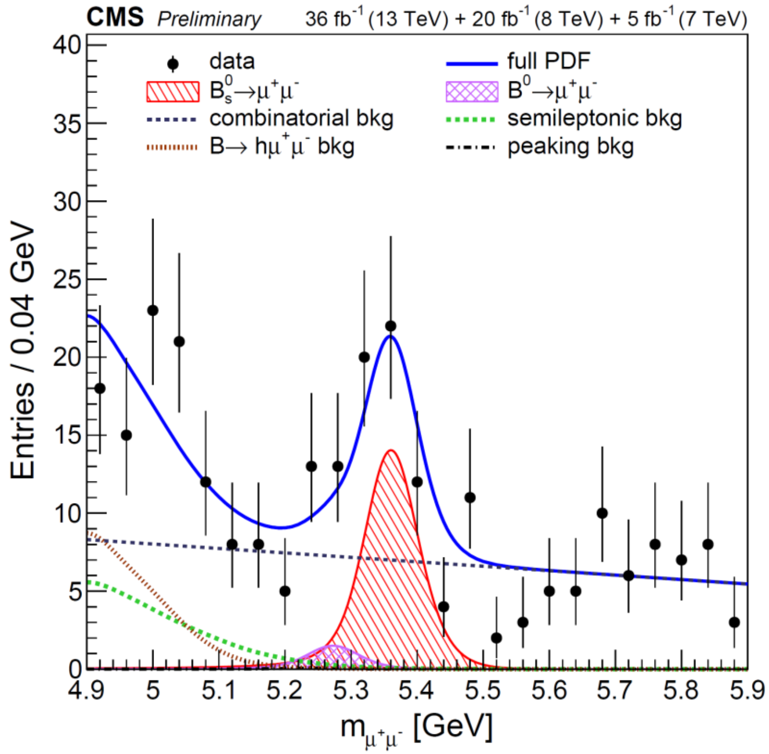
[CMS PAS BPH-16-004]

Last month: a CMS preliminary update based on Run 1 (25 fb^{-1}) & 2016 Run 2 (36 fb^{-1}).

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = [2.9^{+0.7}_{-0.6}\,(\text{exp}) \pm 0.2\,(\text{frag})] \times 10^{-9}$$

The ‘frag’ systematic concerns knowledge of ratio of production of B_s to B^+ mesons (*i.e.* fragmentation). This enters because of $B^+ \to J/\psi K^+$ normalisation mode.

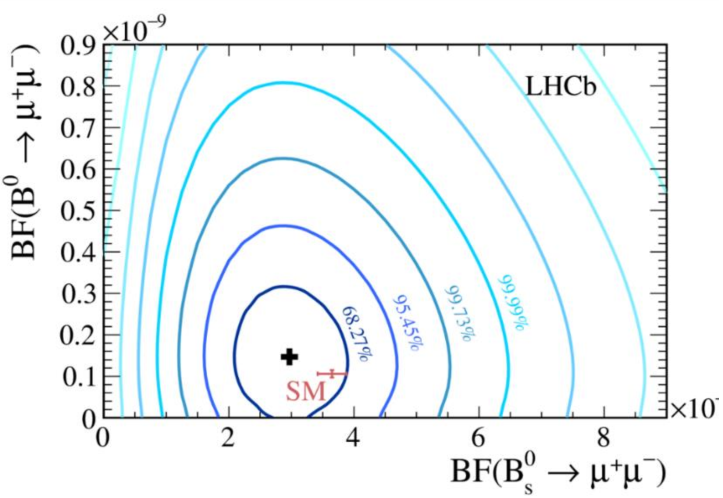
Measured by LHCb and extrapolated into kinematic acceptance of CMS.

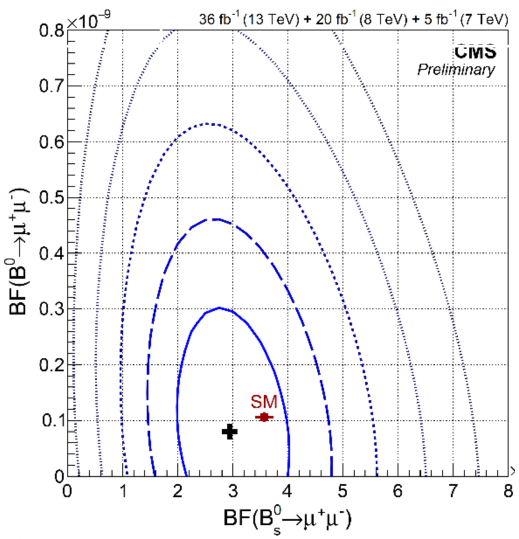


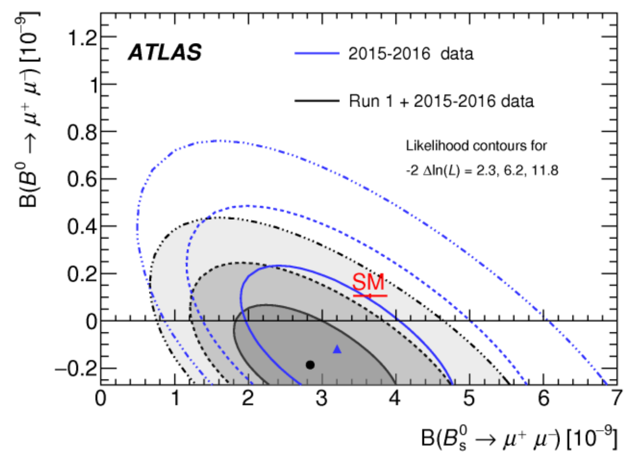
Also this year, ATLAS published a 2015-16 run 2 update [JHEP 04 (2019) 098] to augment their Run 1 result [EPJC 76 (2016) 513]. We await full Run 2 results from all experiments !

The state of play

	LHCb [PRL 118 (2017) 191801]	CMS (prelim) [CMS PAS BPH-16-004]	ATLAS [JHEP 04 (2019) 098]
BR($B_s \to \mu\mu$)	$3.0^{+0.7}_{-0.6} \times 10^{-9}$	$2.9^{+0.7}_{-0.6} \times 10^{-9}$	$2.8^{+0.8}_{-0.7} \times 10^{-9}$
BR($B^0 \to \mu\mu$) [upper limit @ 95% C.L.]	$< 3.4 \times 10^{-10}$	$< 3.6 \times 10^{-10}$	$< 2.1 \times 10^{-10}$







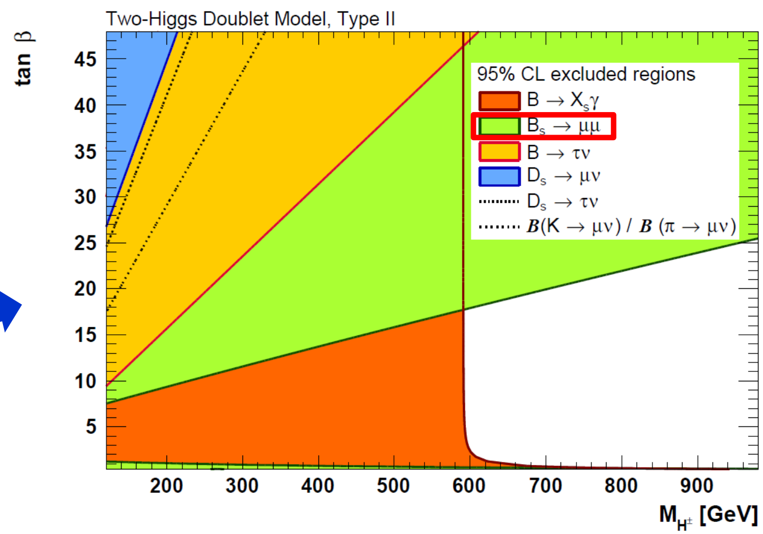
- Each result is compatible with the SM;
- $B_s \to \mu\mu$ measurements are clustering at a slightly lower value than SM (at level of ~2σ);
- $B^0 \to \mu\mu$ is proving elusive;
- Full Run 2 results will be interesting;

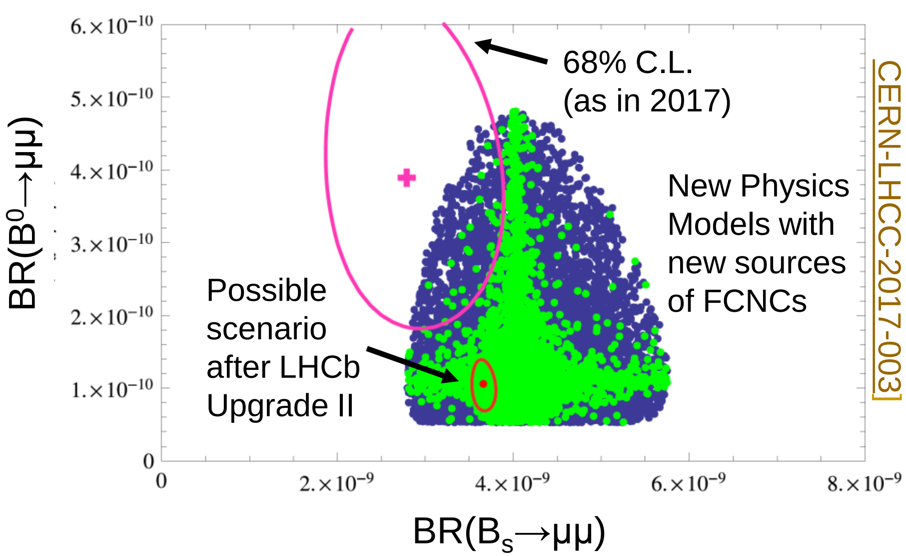
Lessons from, & future of, $B^0_{(s)}\to\mu\mu$ measurements

- 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

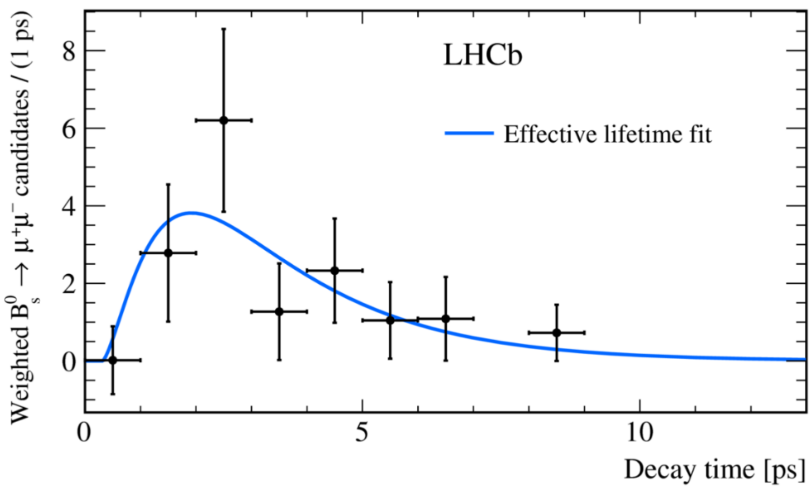
- $y_s \equiv \tau_{B_s^0} \Delta\Gamma/2 \approx 0.06$, $\Delta\Gamma$ being the lifetime splitting between the mass eigenstates;
- $A^{\mu\mu}_{\Delta\Gamma}$ is a term that is 1 in SM, but can take any value between -1 & 1 for New Physics.

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

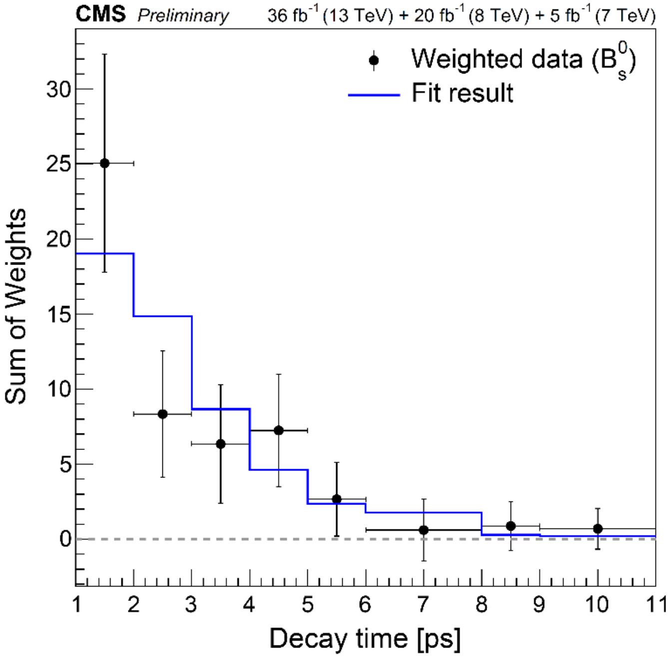
Unlocking new observables with $B_s \to \mu^+\mu^-$

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-of-principle measurements conducted by LHCb and CMS:



[PRL 118 (2017) 191801]

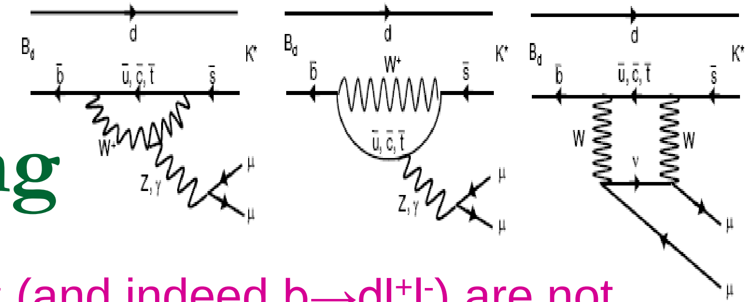


[CMS PAS BPH-16-004]

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

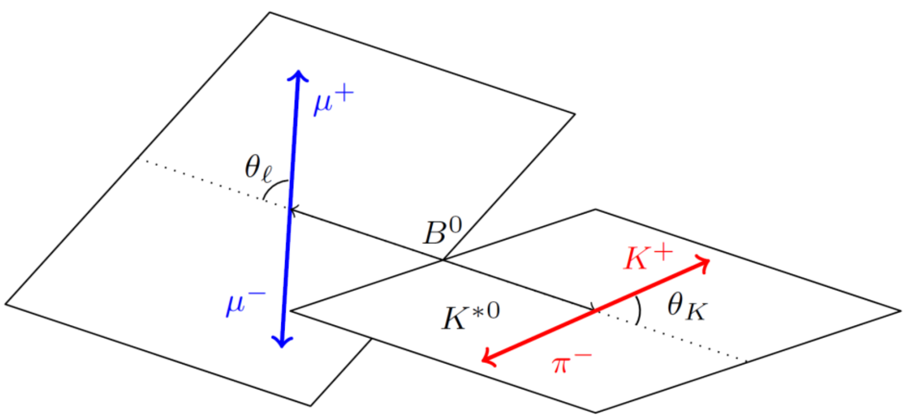
One may also dream of performing flavour-tagged CP asymmetry measurements !

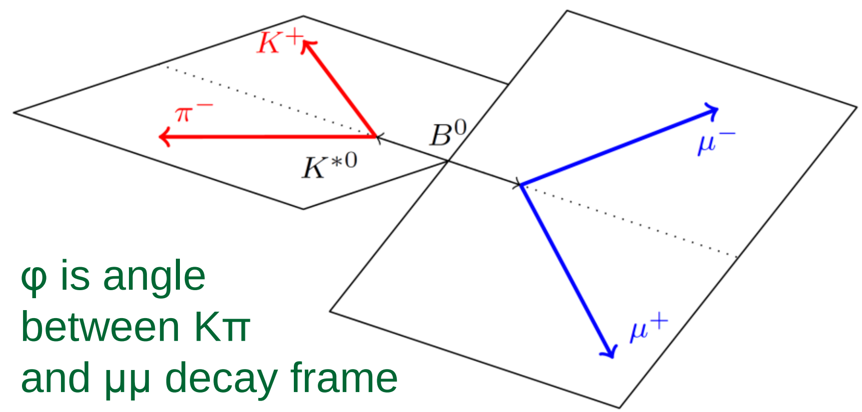
$B^0 \to K^* l^+ l^-$ and friends – the gift that keeps on giving



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 $K^{*0} \to K^+ \pi^-$.

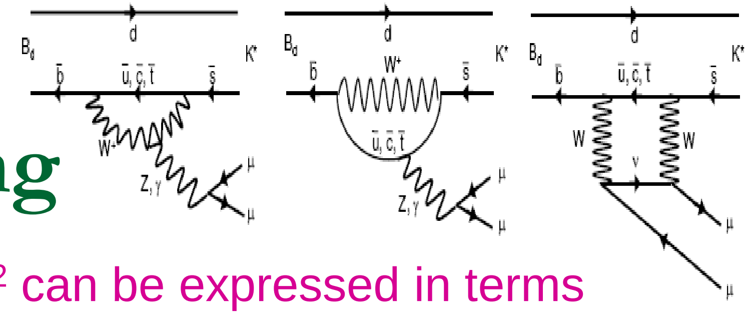




φ is angle between Kπ and μμ decay frame

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, PRL 111 (2013) 191801]).

$B^0 \to K^* l^+ l^-$ 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):

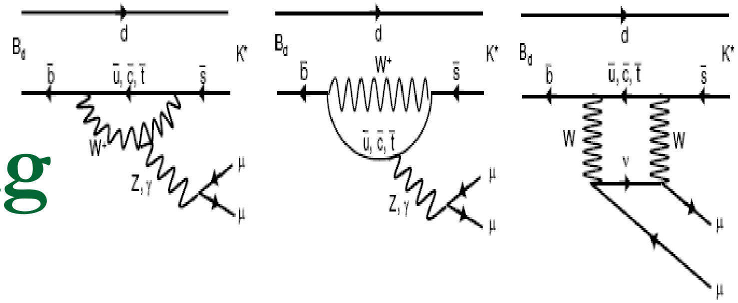
$$
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K
+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l
-F_{\mathrm{L}}\cos^2\theta_K\cos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

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 uncertainties [Descotes-Genon *et al.*, JHEP 01 (2013) 048], in which first order uncertainties cancel, *i.e.* more robust:

$$P_1 = \frac{2\,S_3}{(1-F_L)} = A_T^{(2)}\,, \qquad P_3 = \frac{-S_9}{(1-F_L)}\,, \qquad P_6' = \frac{S_7}{\sqrt{F_L(1-F_L)}}\,.$$

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

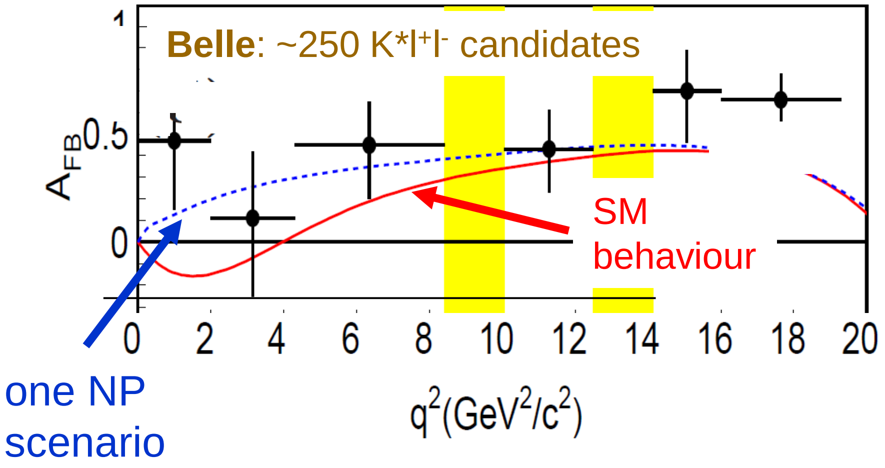
(LHCb definitions, see [JHEP 02 (2016) 104])

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.)

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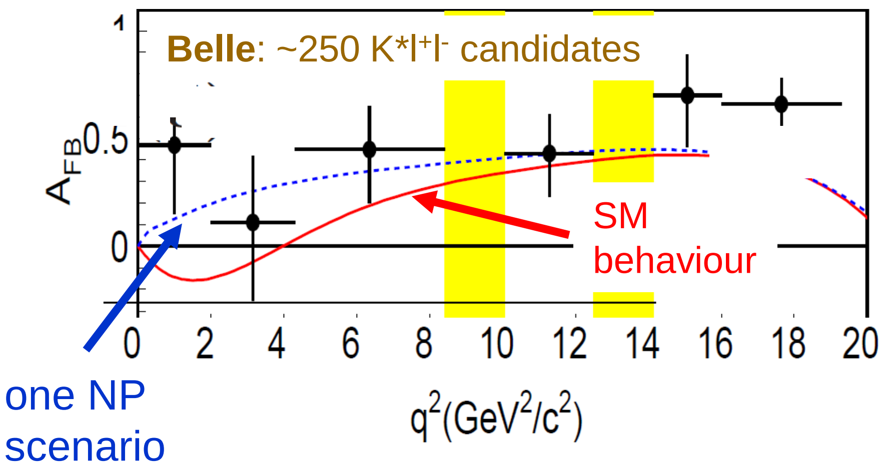
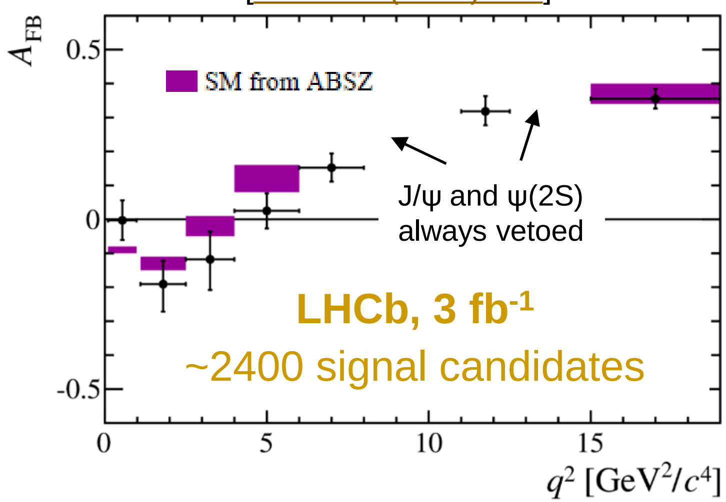


[JHEP 02 (2016) 104]

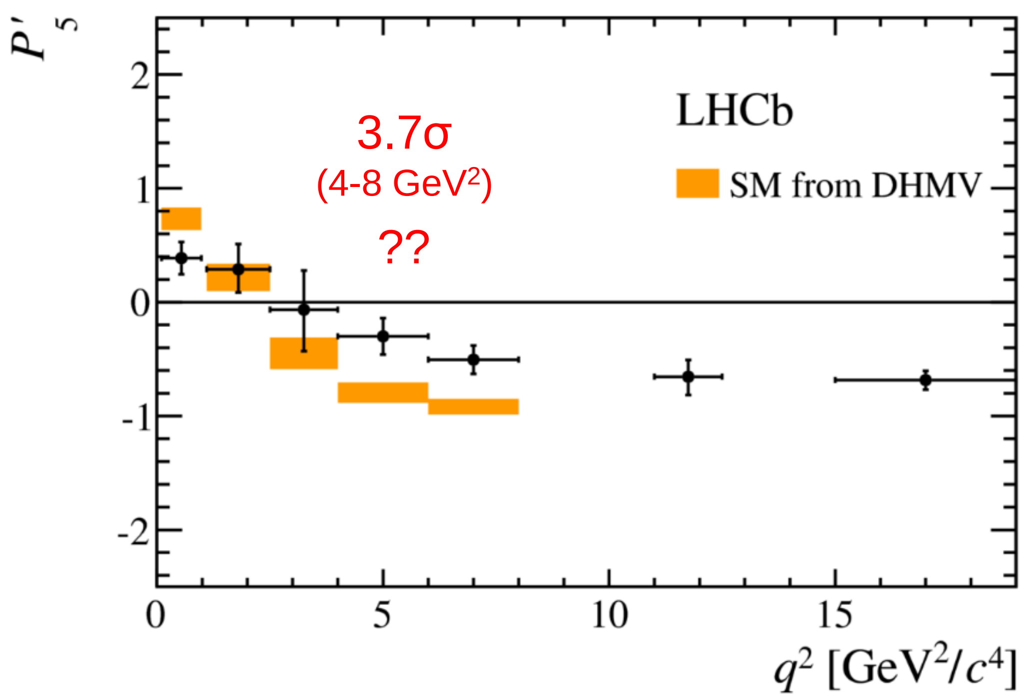


(NB: the J/ψ and ψ' regions are excluded, as these ccbar resonances occur through tree-level processes and do not probe physics we are interested in.)

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' ?

$B^0 \rightarrow K^* l^+ l^-$ 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 an early LHCb analysis [PRL 108 (2012) 181806], persisted with the full Run 1 data set [JHEP 02 (2016) 104], & is not contradicted by other experiments.



[JHEP 02 (2016) 104]

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].

$B^0 \rightarrow K^* l^+ l^-$ and friends: the $P_5^{\prime}$ puzzle

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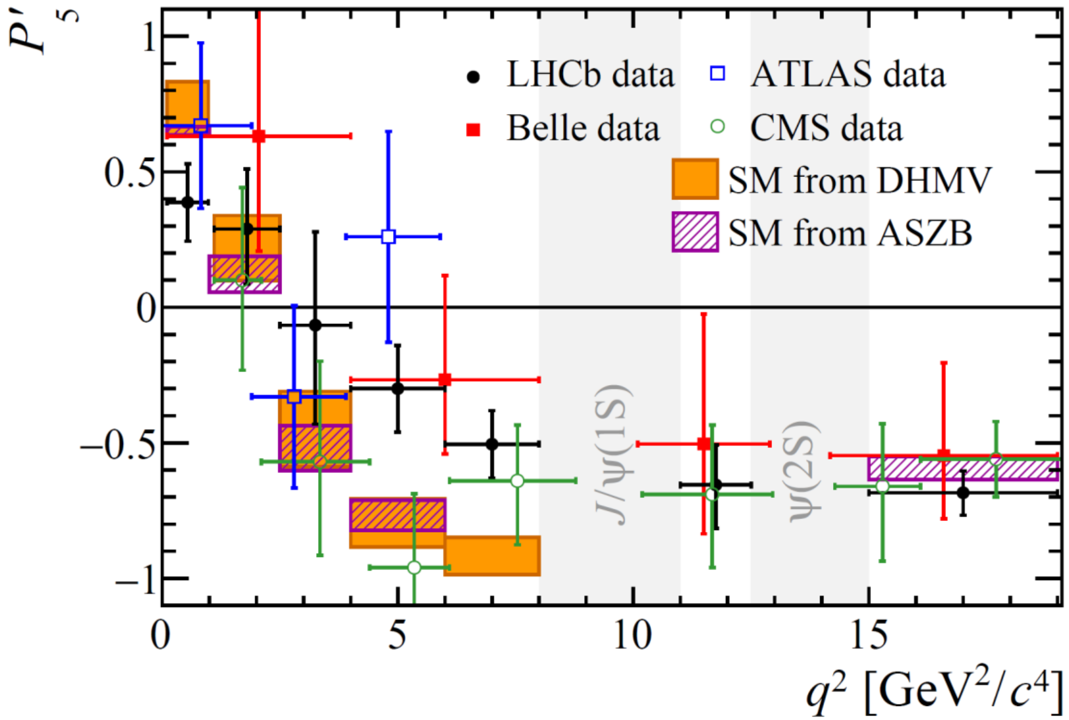
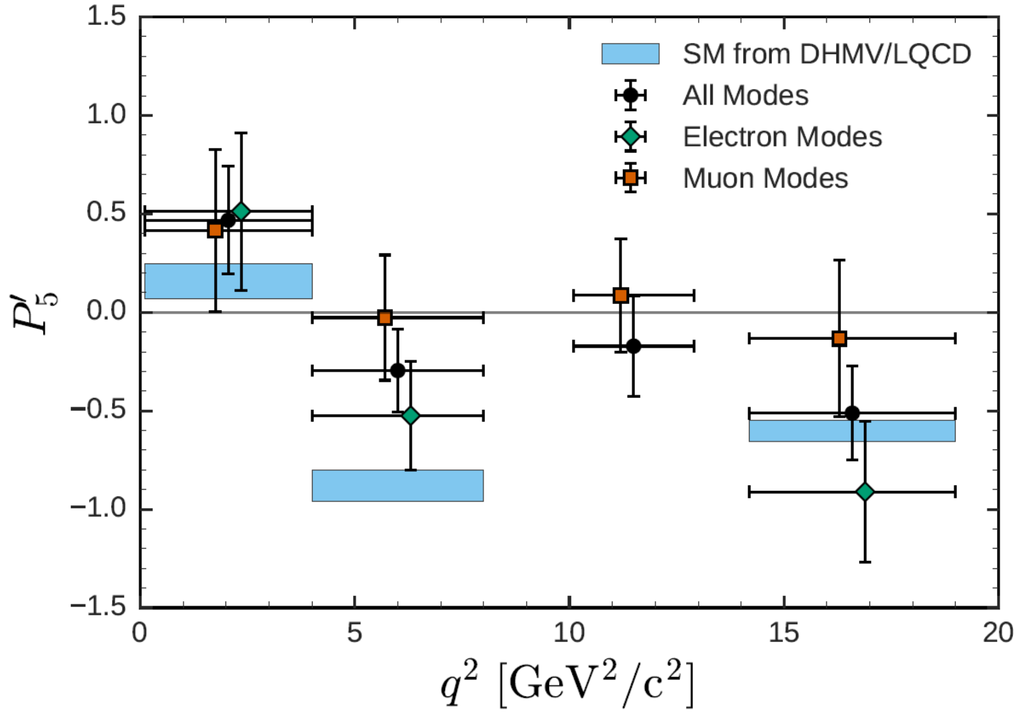


[Belle, PRL 118 (2017) 111801]
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]

Same pattern seen by Belle and ATLAS, whereas CMS sees more SM-like behaviour. None of these measurements are individually precise, but the overall picture is very similar to LHCb. Does not smell like a statistical fluctuation…

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

There is another interesting observation. All the LHC measurements are made with dimuons, whereas the Belle result comes from dimuons and dielectrons. Individual results are also available for each lepton final state.

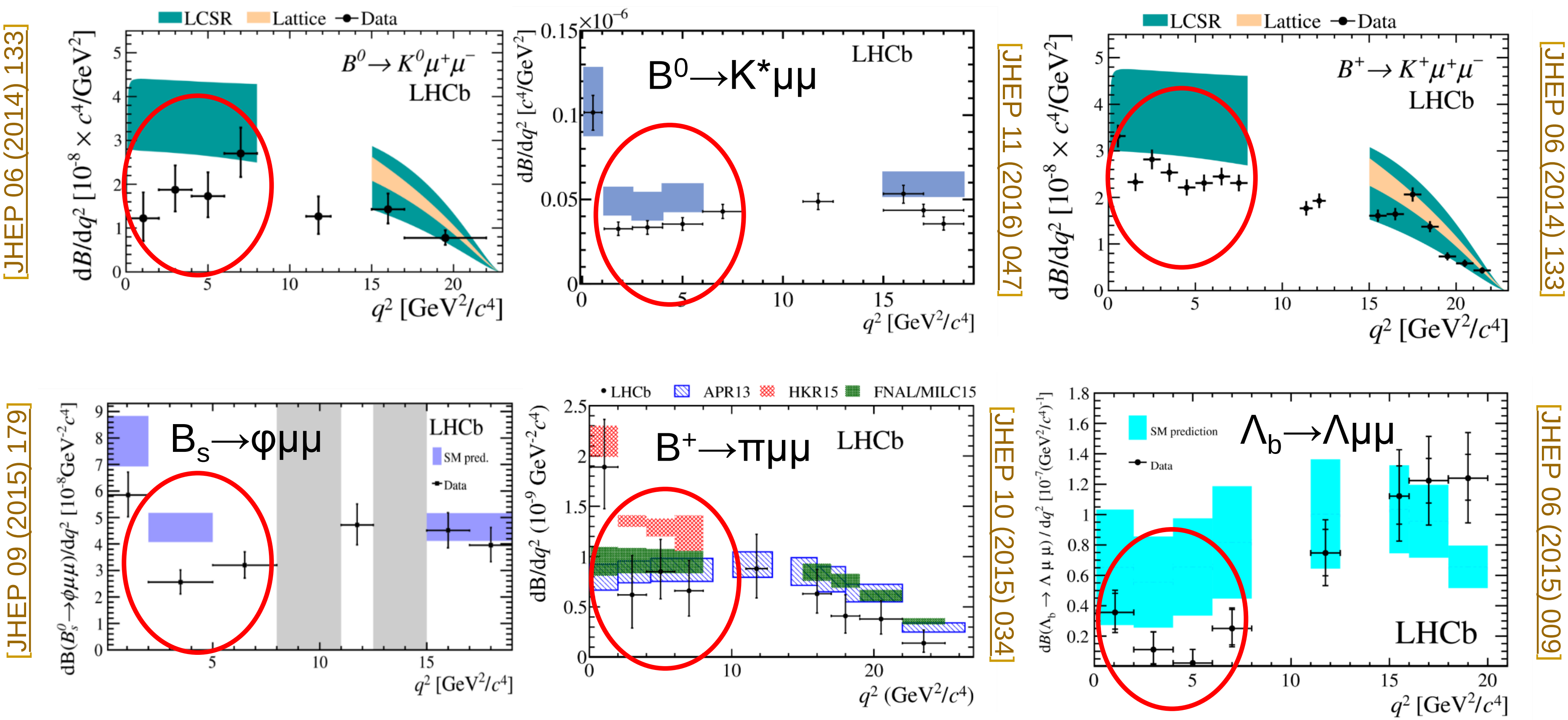


[Belle, PRL 118 (2017) 111801]

In the bin of interest it is the dimuon result that is most discrepant, although with the small sample size there is consistency between both final states.

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

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



All measurements undershoot prediction at low q^2. (BTW, all made with *dimuons*…)
Intriguing – but maybe the uncertainties in theory are larger than claimed ?

Can we identify an observable where the theory uncertainties are negligible ?

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

The cleanest way to probe these decays are with lepton universality (LU) tests, *i.e.* comparing decays with di-electrons and di-muons. *Negligible* theory uncertainty.

Ratios of decay rates have been measured for $b \to s\mu^+\mu^- / b \to se^+e^-$ for $\sim 1 < q^2 < 6$ GeV^2 for both $B \to K l^+ l^-$ (R_K) and $B^0 \to K^* l^+ l^-$ (R_{K^*}). In SM we expect ≈1 for both.

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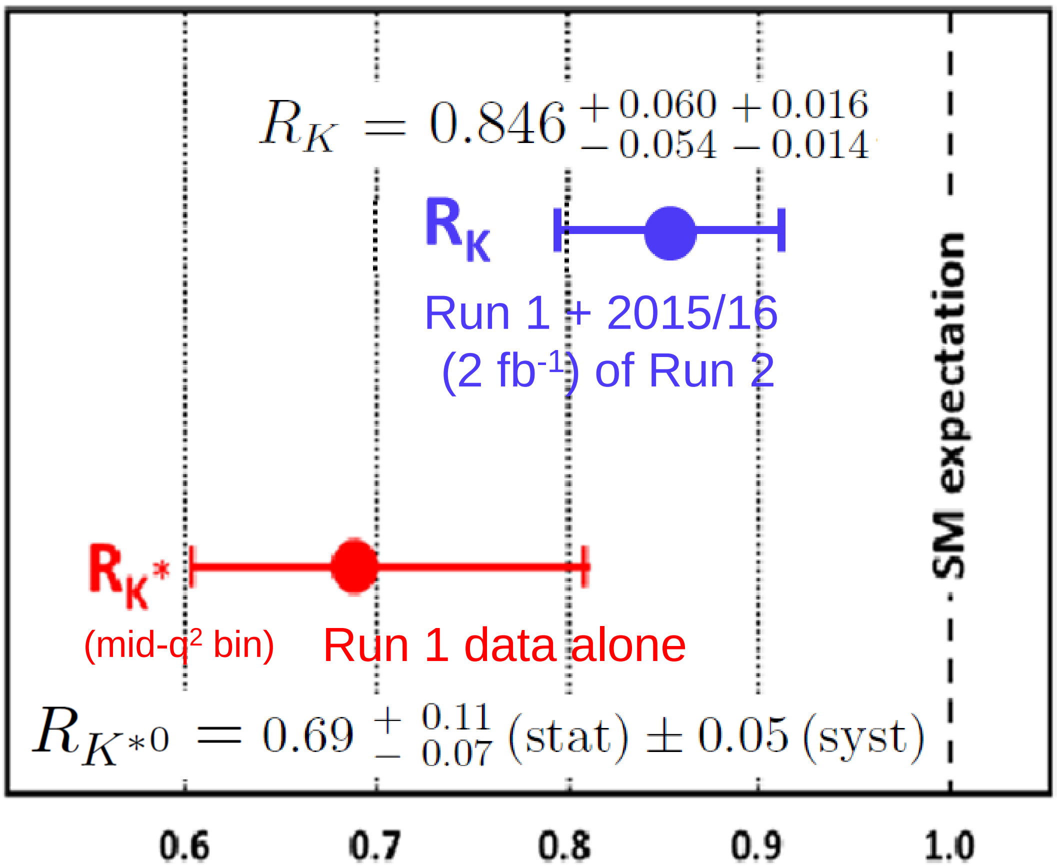
In both cases measurements are ~2.5 σ below SM !

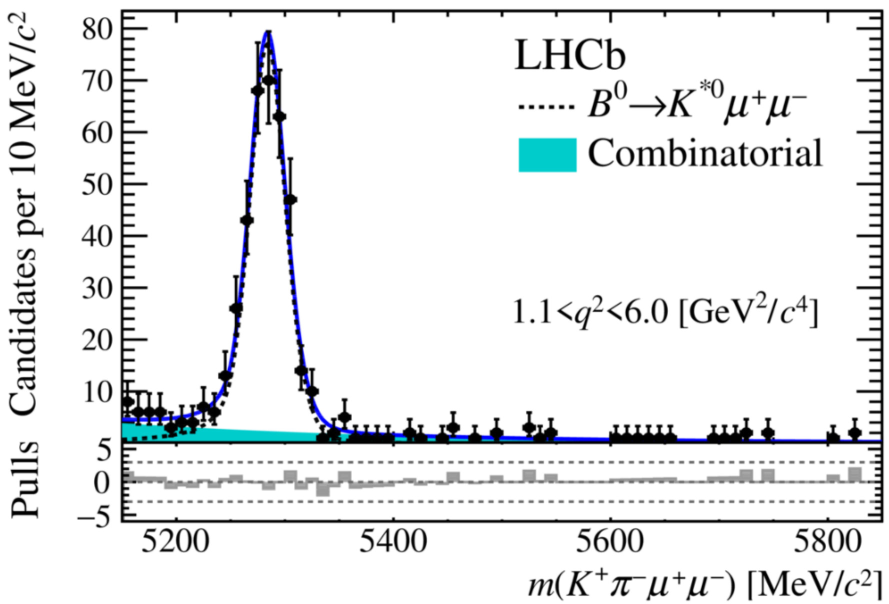


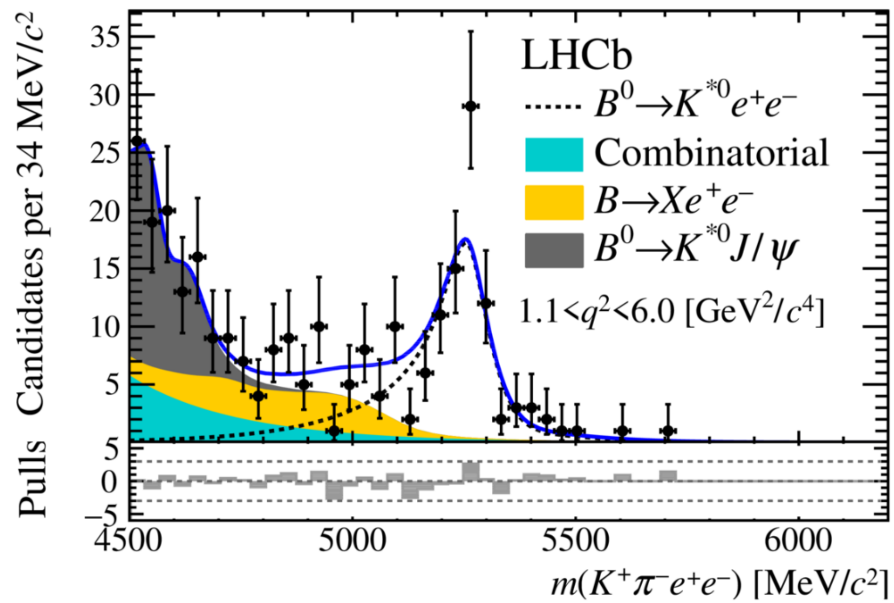
[PRL 122 (2019) 191801]

[JHEP 08 (2017) 055]

$b \to s l^+ l^-$ lepton universality tests – more about the measurements (with focus on R_{K*}) [JHEP 08 (2017) 055]

Precision is limited by size of electron sample, which is ~100 decays in bin of measurement (muon sample is around 3-4 x larger).





$b \to s l^+ l^-$ lepton universality tests – more about the measurements (with focus on R_{K*}) [JHEP 08 (2017) 055]

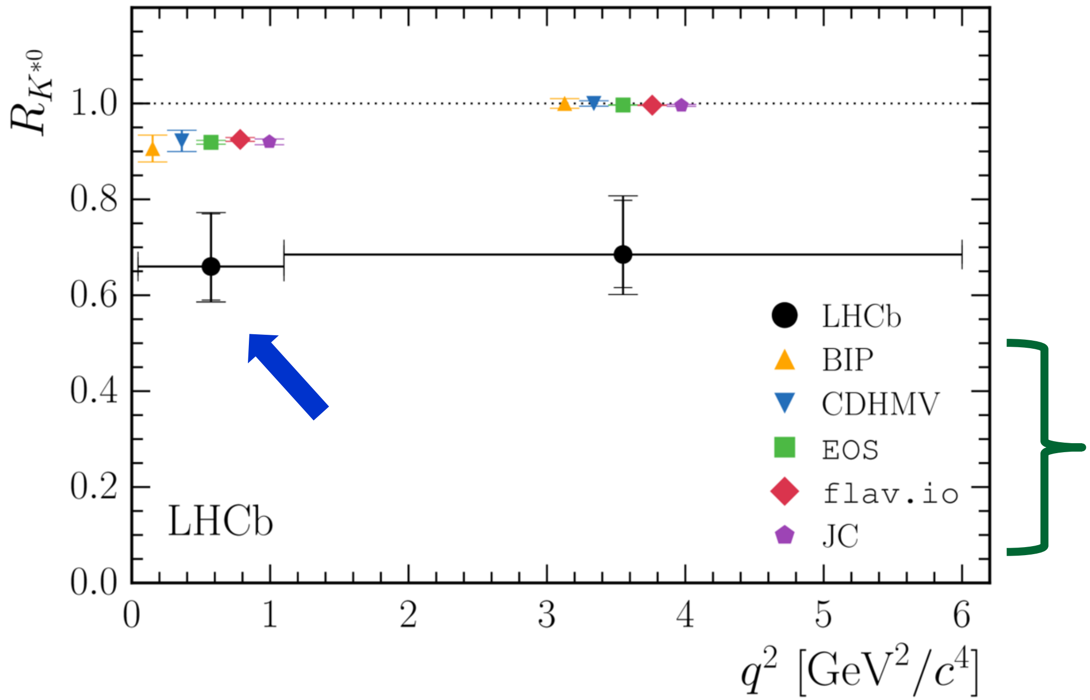
Isn't measurement vulnerable to knowledge of lepton id efficiency? No, because R_{K*} is normalised to $B^0 \to K^* J/\psi$ (and its known $J/\psi \to l^+ l^-$ obeys lepton universality) which makes all such dependencies second order.

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

Nonetheless, checks are made by measuring whether the relevant ratios for $B^0 \to K^* J/\psi$ and indeed $B^0 \to K^* \psi(2S)$ are compatible with unity – they are.

$b \to s l^+ l^-$ lepton universality tests – more about the measurements (with focus on R_{K*}) [JHEP 08 (2017) 055]

Measurements are made below J/ψ – it is the low q^2 region where odd behaviour has been seen in other studies. High q^2 measurements will come in future.

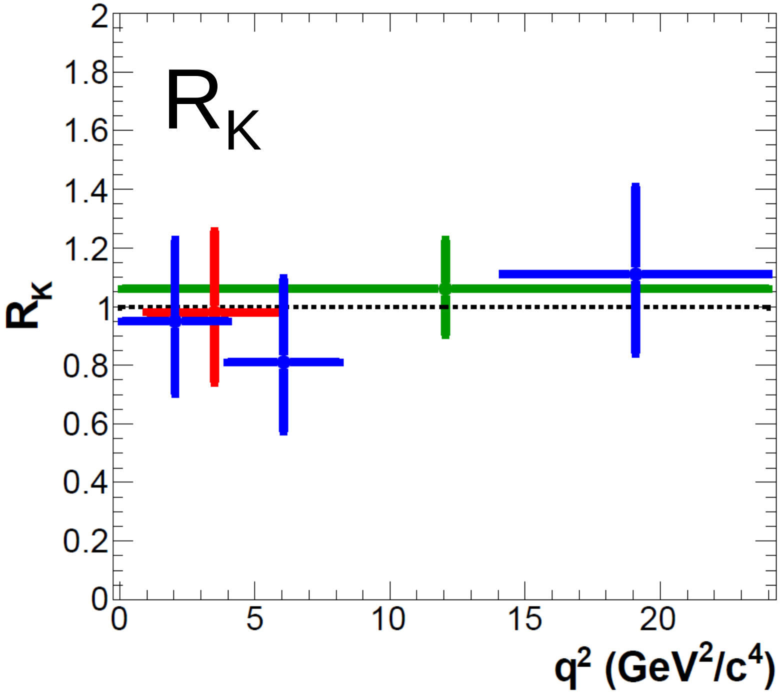


various calculations of SM prediction

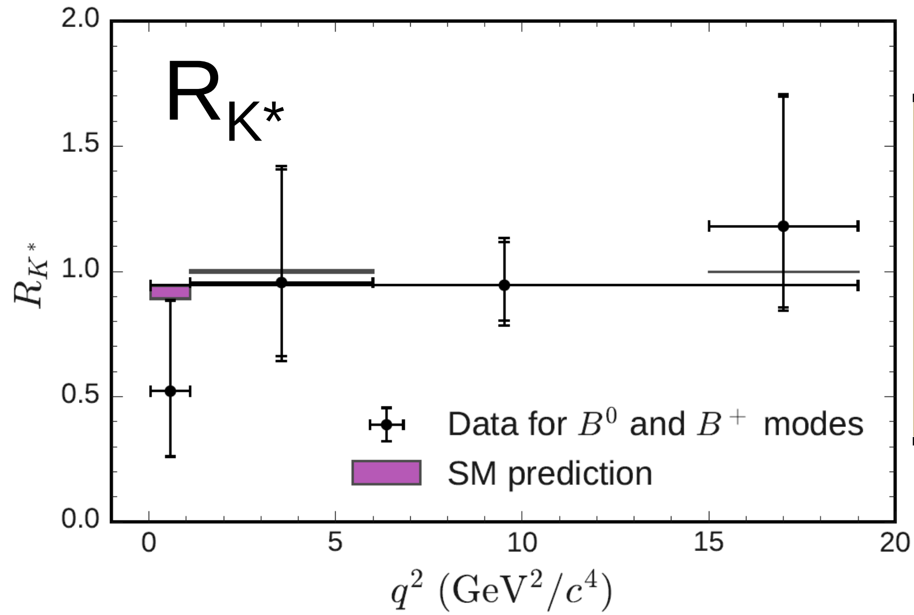
However a second R_{K*} measurement exists at very low q^2. This also is >2σ low w.r.t. SM. Interesting! However, any deviation in this region is harder to explain by New Physics (see later), as 'photon pole' dominates decay process.

$b \to s l^+ l^-$ lepton universality tests – Belle results

Belle has recently released R_K and R_{K^*} measurements (both exploiting B^0 and B^+ modes, assuming isospin conservation) in a variety of binning schemes.



[arXiv:1908.01848]



[arXiv:1904.02440]

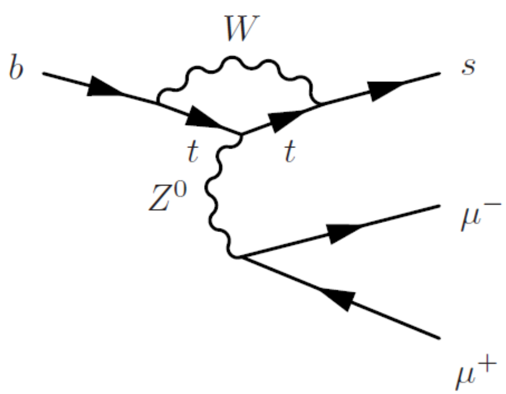
All results compatible with LHCb & SM (but significantly less precise than LHCb).

Analysing FCNC data in context of effective field theory

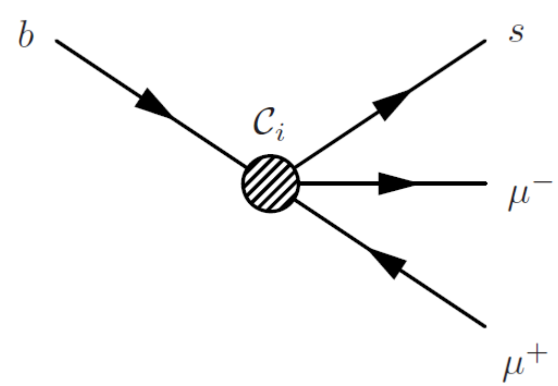
The $b \to s l^+ l^-$ results can be qualitatively 'explained' by hypothesising that $b \to s e^+ e^-$ largely obeys the SM, but New Physics intervenes for $b \to s \mu^+ \mu^-$ at low q^2.

A more quantitative analysis can be made in 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.

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

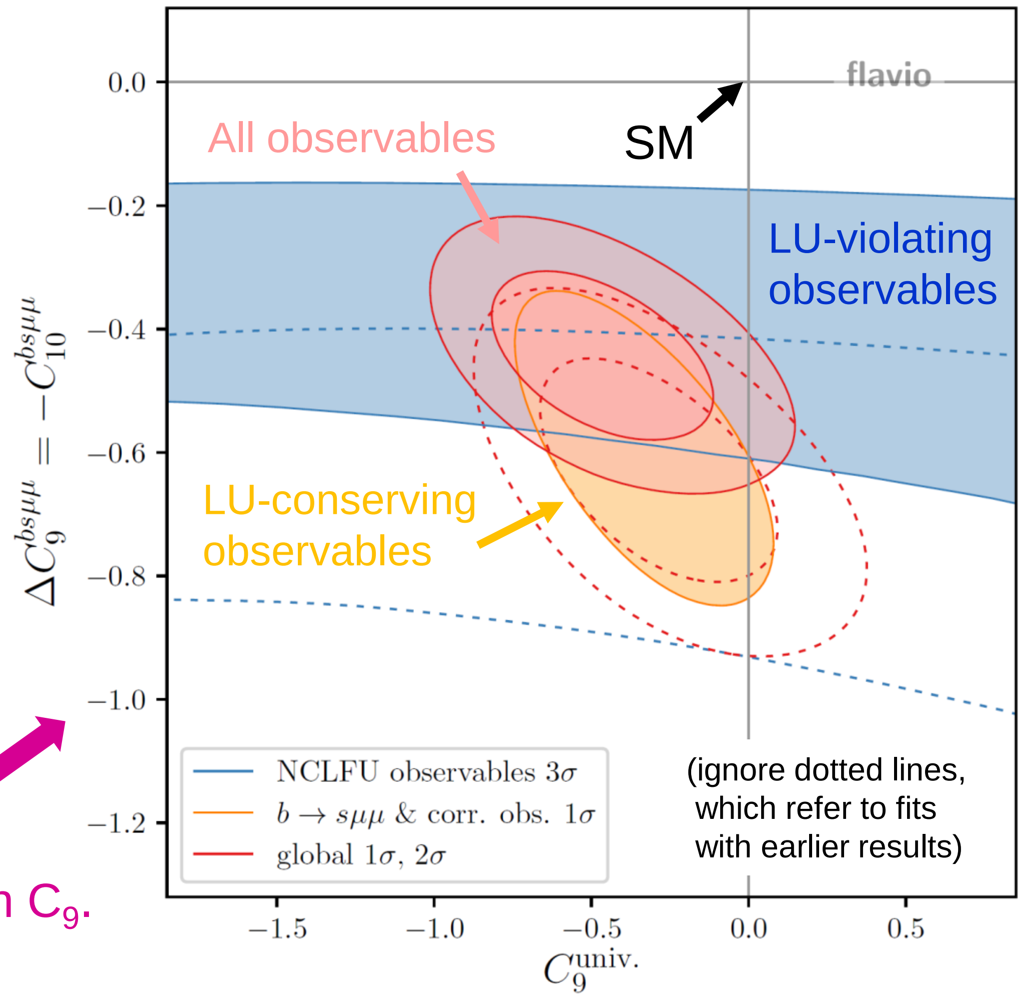
Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$b\to s\gamma$	X			
$b\to \ell^+\ell^-$			X	X
$b\to s\ell^+\ell^-$	X	X	X	

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

Current status of fits to FCNC data

[Aebischer, Straub *et al.*, arXiv:1903.10434]

- Ensemble of *all* FCNC data gives a consistent picture
- Best fit is inconsistent with SM by more than 5σ !
- *BUT*, this assumes taking uncertainties on SM predictions for, *e.g.*, P_5' at face value.
- One excellent fit allows for NP shift for muons alone of opposite sign in C_9 & C_{10}, & a modest lepton-universal shift in C_9.



Current status of fits to FCNC data

[Aebischer, Straub *et al.*, arXiv:1903.10434]

- Ens give
- Bes SM
- *BU* unc prec at fa
- One NP opp mod

Popular explanations of these effects include:

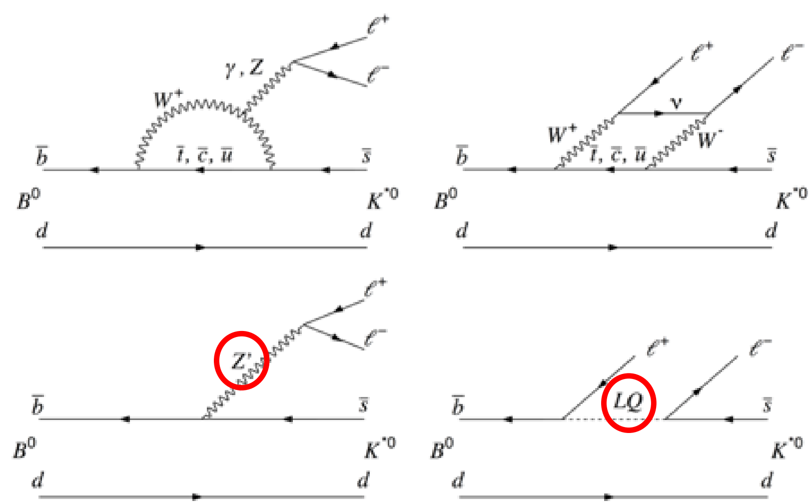
Standard Model

- Flavour-changing Z'

e.g. [Altmannshofer & Straub, EPJC 73 (2013) 2646], [Gauld, Goertz & Haisch, PRD 89 (2014) 015005], [Altmannshofer & Straub, EPJC 75 (2015) 382], [Crivellin *et al.*, PRD 92 (2015) 054013].

- Leptoquarks

e.g. [Hiller & Schmaltz, PRD 90 (2014) 054014], [Alonson *et al.*, arXiv:1505.05164], [Fajfer & Ksnik, PLB 755 (2016) 270].



New Physics

These may be within reach of direct detection at ATLAS & CMS.

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$b \rightarrow (s,d) l^+ l^-$: near-term experimental prospects

New experimental input is mandatory to conclude on the $b \rightarrow s l^+ l^-$ anomalies.

- LHCb Run 2 dimuon results on P_5' and other optimal observables, and equivalent studies with dielectrons

- LHCb full Run 2 results on R_K (so far only 2015-16 analysed) and on R_{K^*} (so far only Run 1 analysed), and analogous modes, *e.g.* $\Lambda_b \rightarrow p K l^+ l^-$, $B_s \rightarrow \varphi l^+ l^-$.

- R_K and R_{K^*} results from other LHC experiments.

- Results from Belle II.

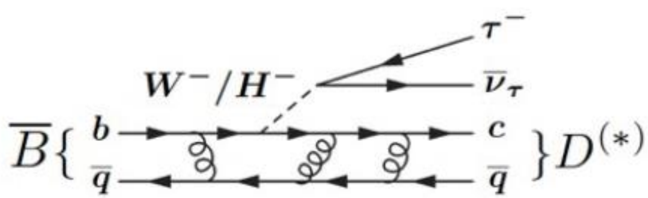
Most valuable will be *theoretically clean* observables that test lepton universality.

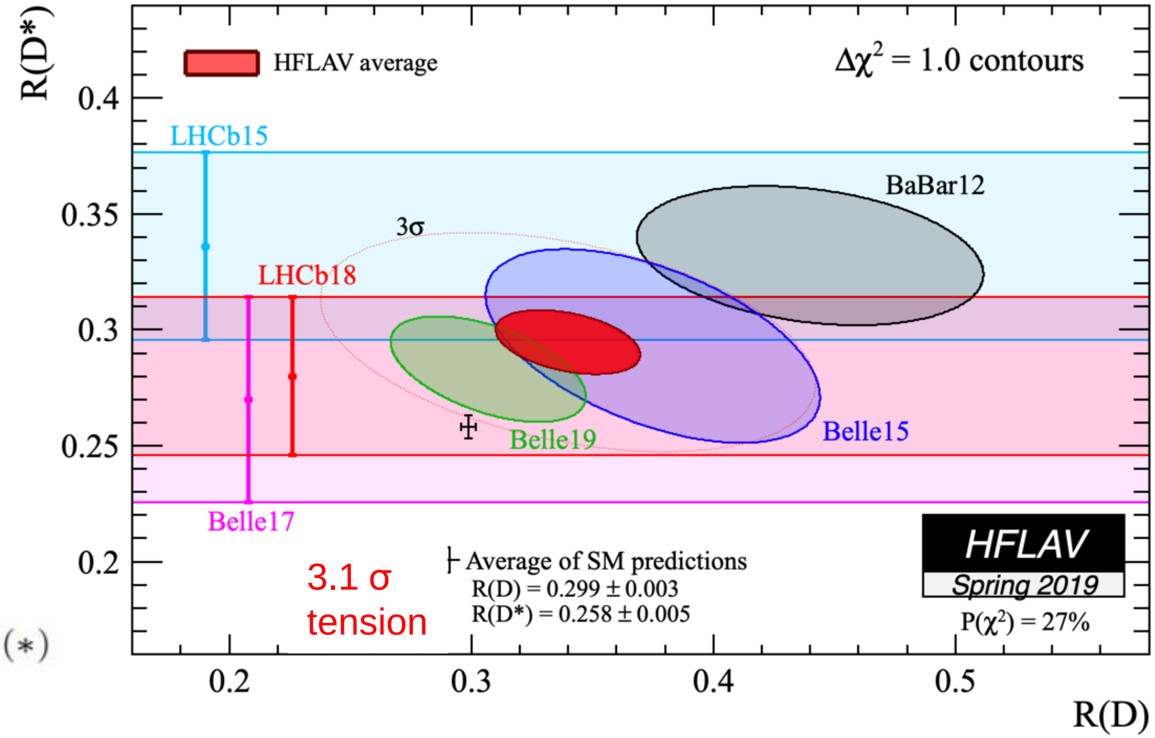
Personal opinion: even if current anomaly dissipates, the story has been very useful for focusing attention on one of the less well understood features of the SM (lepton universality), & also illustrating the power of a complementary ensemble of measurements. Whatever, $b \rightarrow (s,d) l^+ l^-$ studies are sure to remain of great interest !

Other hints of lepton universality violation

There is another class of decays, b→clν, (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, but requires some ingenuity to simultaneously explain this and $b\to sl^+l^-$ anomaly.

Missing energy means that measurements are ideal for B-factories, but competitive studies have come from LHCb. More experimental input essential !

Charm physics

Mixing and CPV in charm

~15 years ago, a flavour-physics lecturer would have been strongly tempted to skip over charm. A subject with a glorious past (*e.g.* GIM, J/ψ), but little future.

Why so ? Firstly, mixing known to be small (GIM cancellations almost exact, due to absence of super-heavy quarks in loops), maybe very small.

Charm mixing parameters

off-shell intermediate (short-range) states sensitive to New Physics

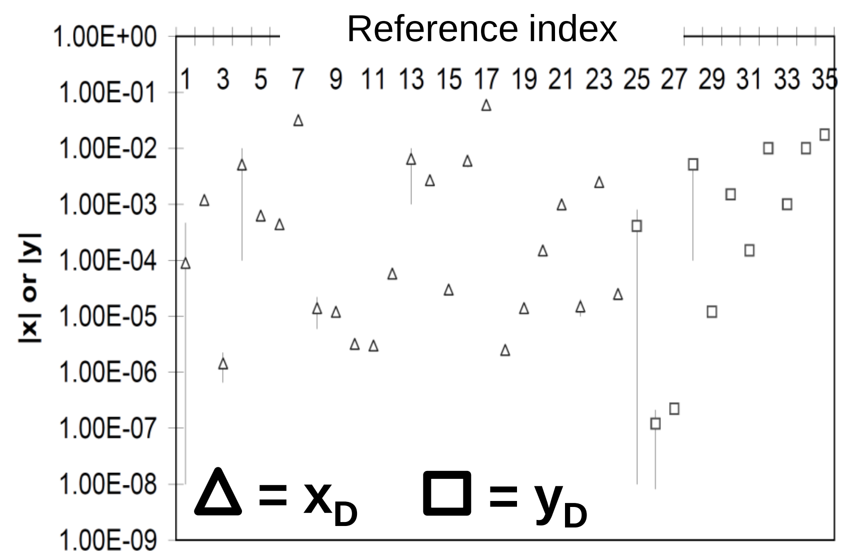
$$x_D = \frac{\Delta m}{\Gamma}$$

on-shell intermediate (long-range) states

$$y_D = \frac{\Delta\Gamma}{2\Gamma}$$

(Δ's refer to splittings between neutral-D mass eigenstates)

How small is small? ~ 0.01? << 0.01?? This is the other problem. Charm is neither 'heavy' or 'light' & so hadronic calculations are tough.



[A.Petrov, arXiv:hep-ph/0311371]

Infamous plot, first made by Nelson, & here updated by Petrov, showing (very) wide range in predicted values of x_D & y_D.

Mixing and CPV in charm

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Similarly, CPV, both indirect (*i.e.* in mixing-related phenomena) and direct, is also expected to be very small, once more because of absence of third-generation participating in virtual loops (a 2x2 CKM matrix is almost real…).

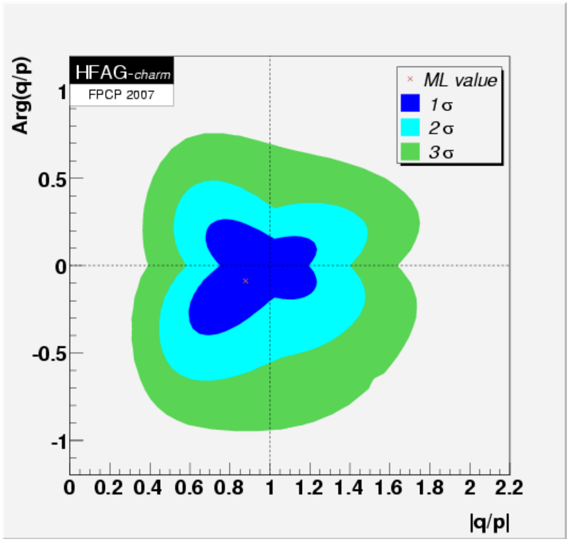
Reminder:

- CPV in mixing →

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

- CPV in decay-mixing interference →

$$\phi = \arg\left(\frac{qAbar}{pA}\right) \neq 0$$



10+ years ago, the constraints on indirect CPV in charm were very weak (unsurprising, as one first needs sensitivity to mixing).

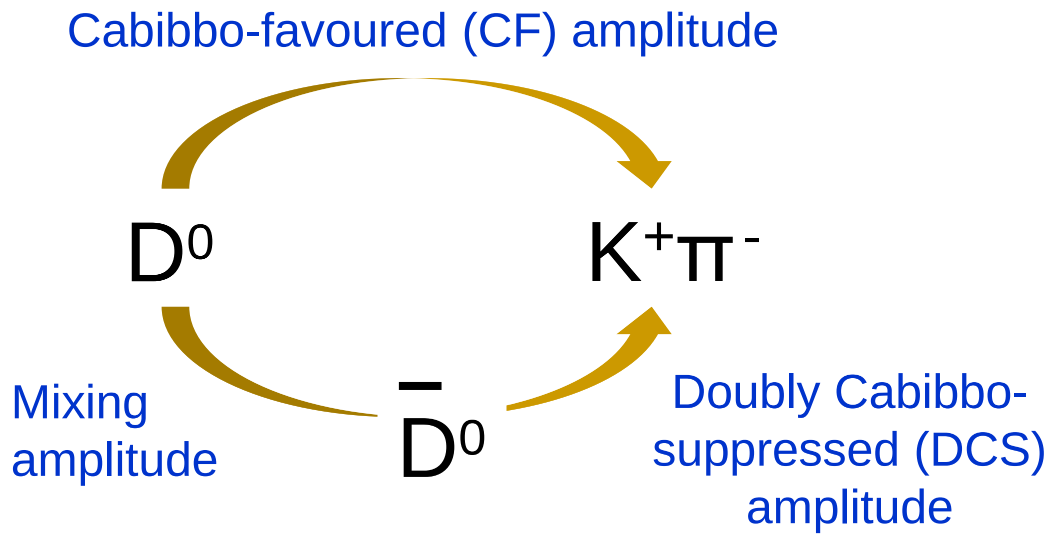
But charm *is* a priori a good place to look for New Physics (NP) effects !
(i) Only system in which virtual loops involving up-type quarks can be probed;
(ii) NP effects will be easier to see when the SM ‘background’ is so small.

Mixing studies with 'wrong-sign' $D^0 \to K^+\pi^-$

cf. 'right-sign' $K^-\pi^+$

Several ways to access mixing. One sensitive way is to search for interference effects involving Doubly Cabibbo-Suppressed decays, *e.g.* $D^0 \to K^+\pi^-$.

Decay-time dependent rate ≈ $\left| \quad \right|^2$



Normalise by right-sign decay rate:

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

$x' = x_D\cos\delta + y_D\sin\delta$

$y' = y_D\cos\delta - x_D\sin\delta$

$\left|\frac{\text{DCS amp}}{\text{CF amp}}\right|^2 \sim |0.06|^2$

Mixing–decay interference

Mixing

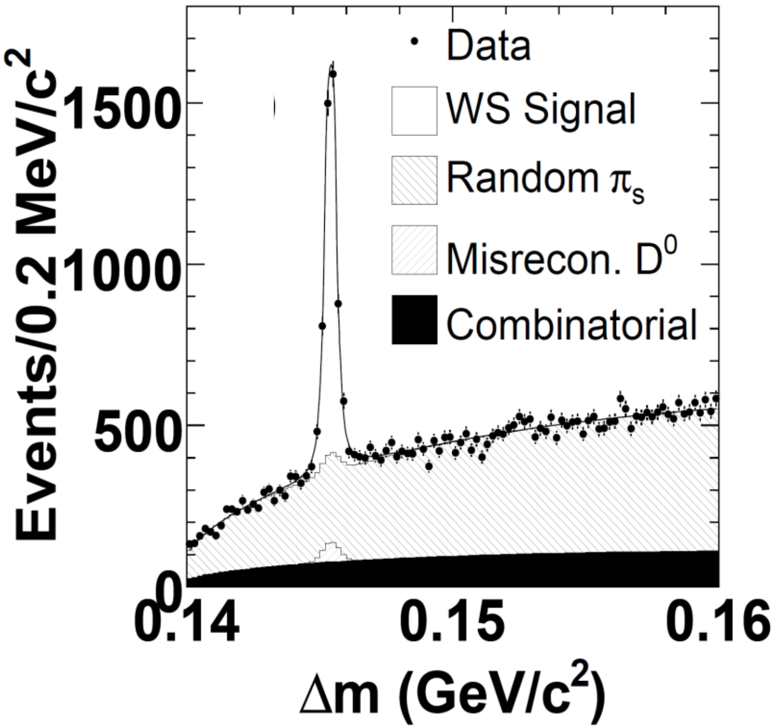
Where δ ~ 10º is strong-phase difference between CF & DCS amplitudes

(expansion in x' & y', which are small)

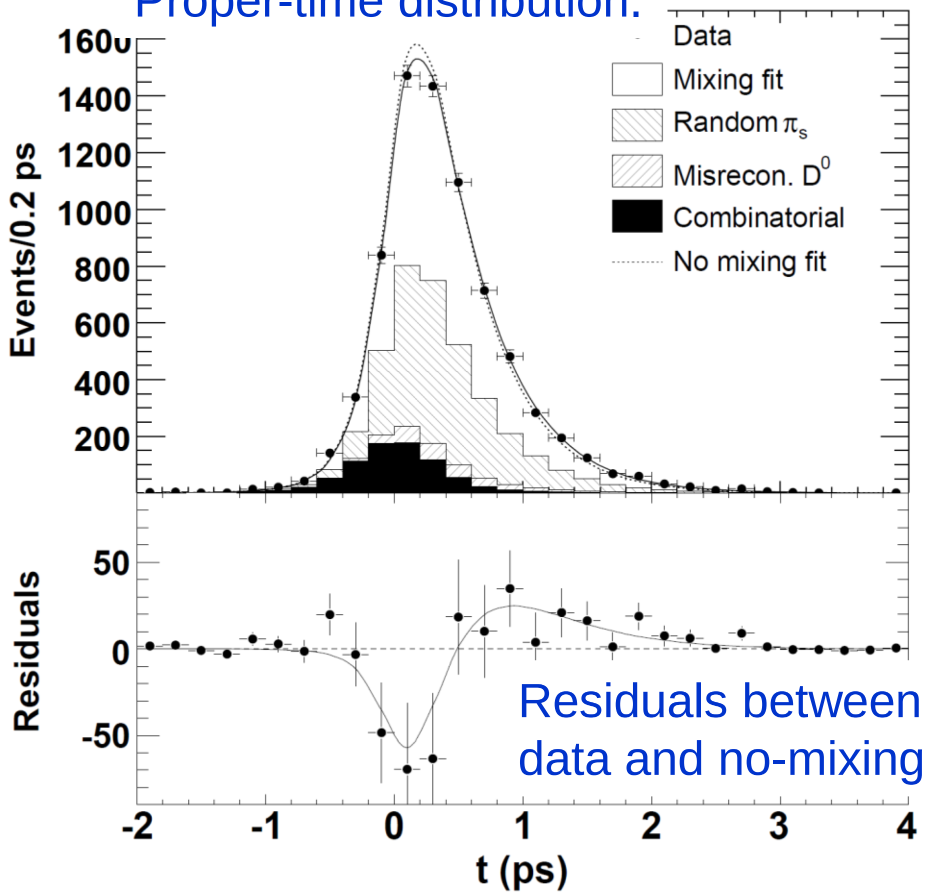
First evidence from the B-factories !

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.

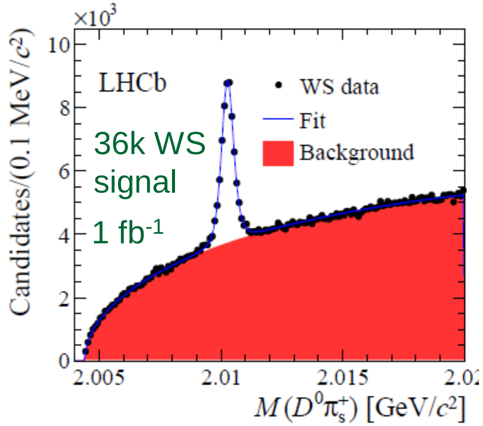


Residuals between data and no-mixing fit.

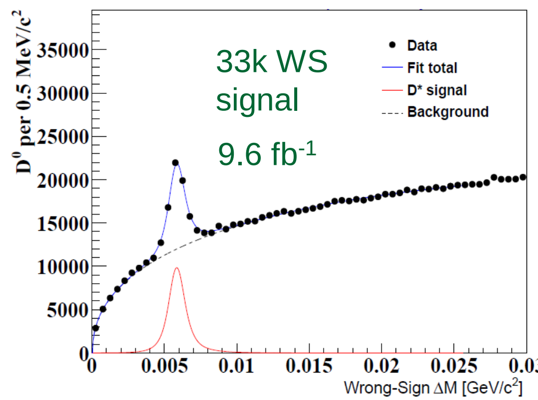
[BaBar, PRL 98 (2007) 211802]

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.



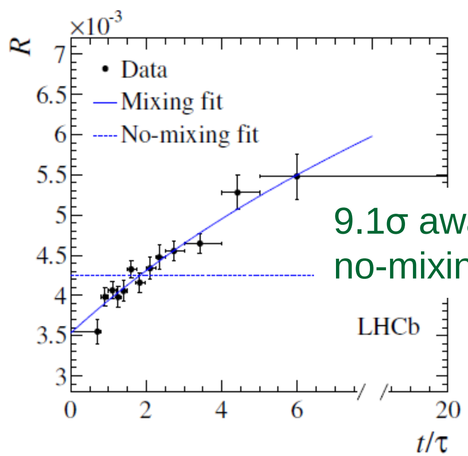
[LHCb, PRL 110 (2013) 101802]



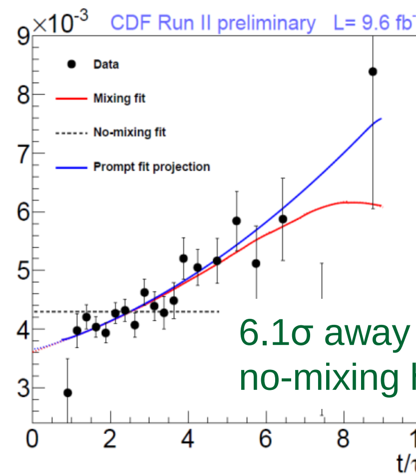
[CDF, PRL 111 (2013) 231802]

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

Linear slope comes from mixing-decay interference.



9.1σ away from no-mixing hyp.

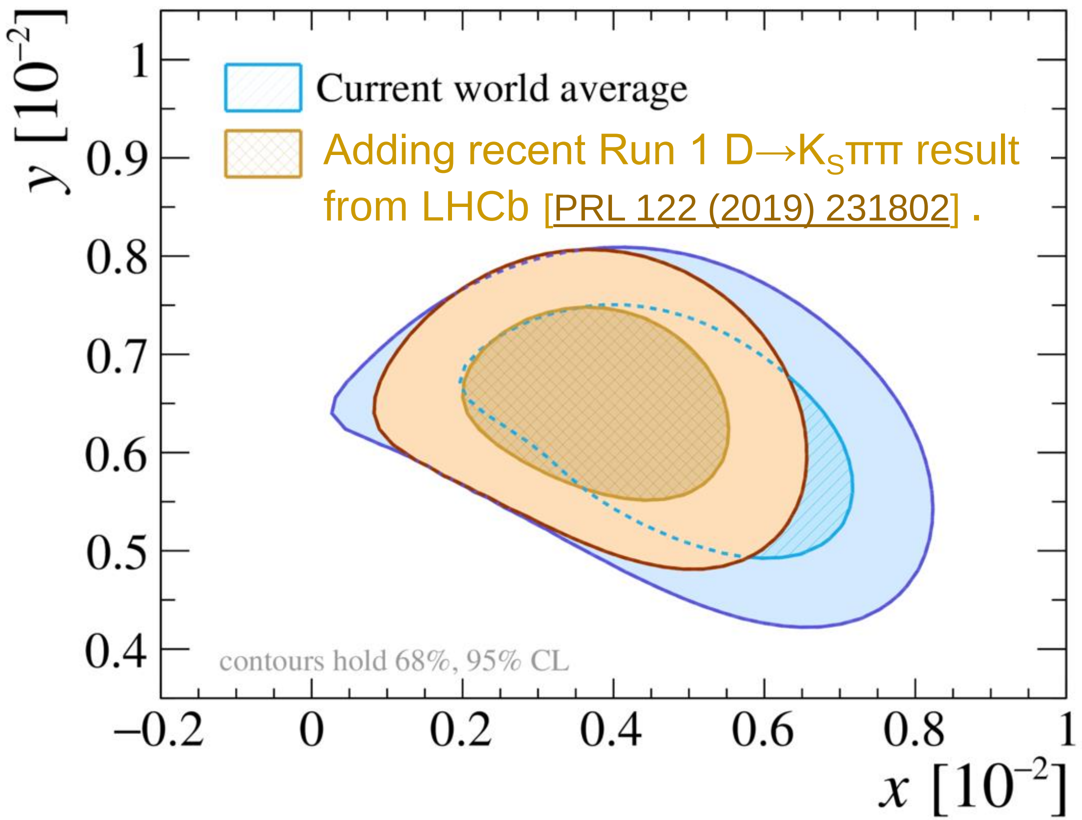


6.1σ away from no-mixing hyp.

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.

Where are we now with charm mixing ?

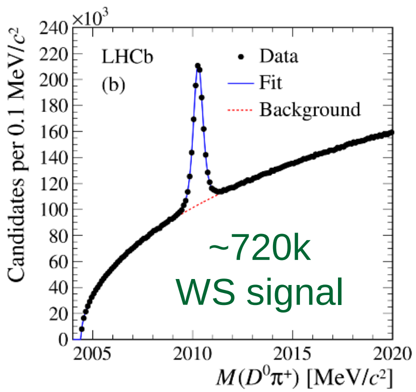
y_D is now reasonably well known, but x_D less so. In fact there is still only ~3 σ evidence that x_D is non zero. Important to improve our knowledge of x_D, as size of mixing parameters modulated size of any indirect CPV observable.



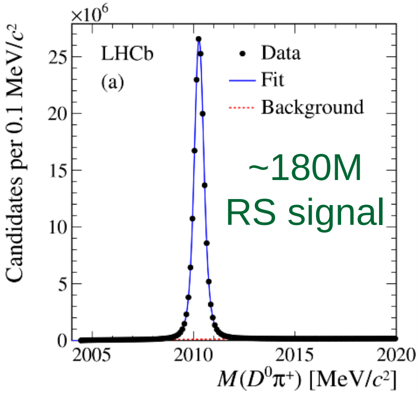
Search for indirect CPV in charm with Run 2 data

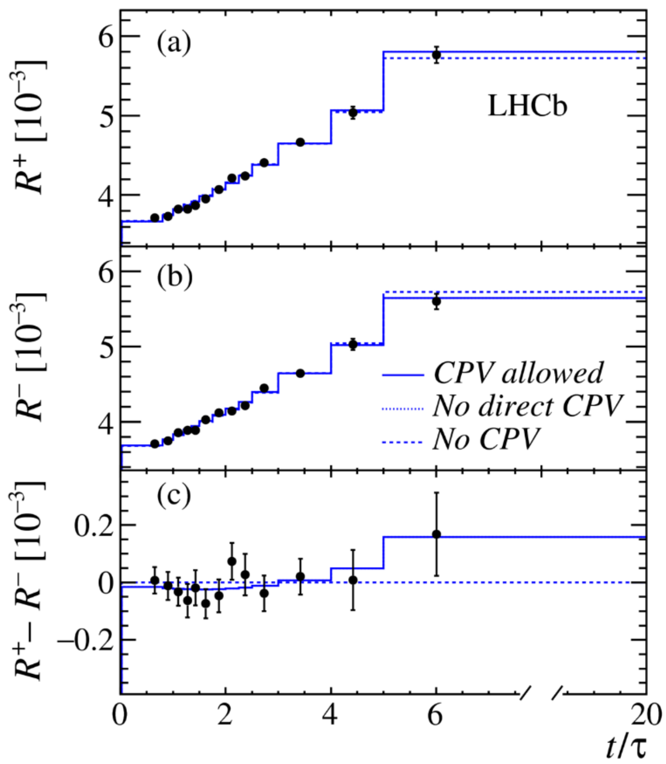
LHCb samples have grown rapidly, and now allow for high sensitivity searches for mixing-induced CPV, *e.g.* take WS Kπ analysis used for mixing discovery, now updated with full Run 1 data & 2 fb^{-1} from Run 2, and study D^0 & D^0bar separately.

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



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





For D^0…

…and D^0bar…

…and difference of both.

[PRD 97 (2018) 031101]

Difference flat → no sign of indirect CPV (yet).

Search for indirect CPV in charm with Run 2 data

LHCb samples have grown rapidly, and now allow for high sensitivity searches for
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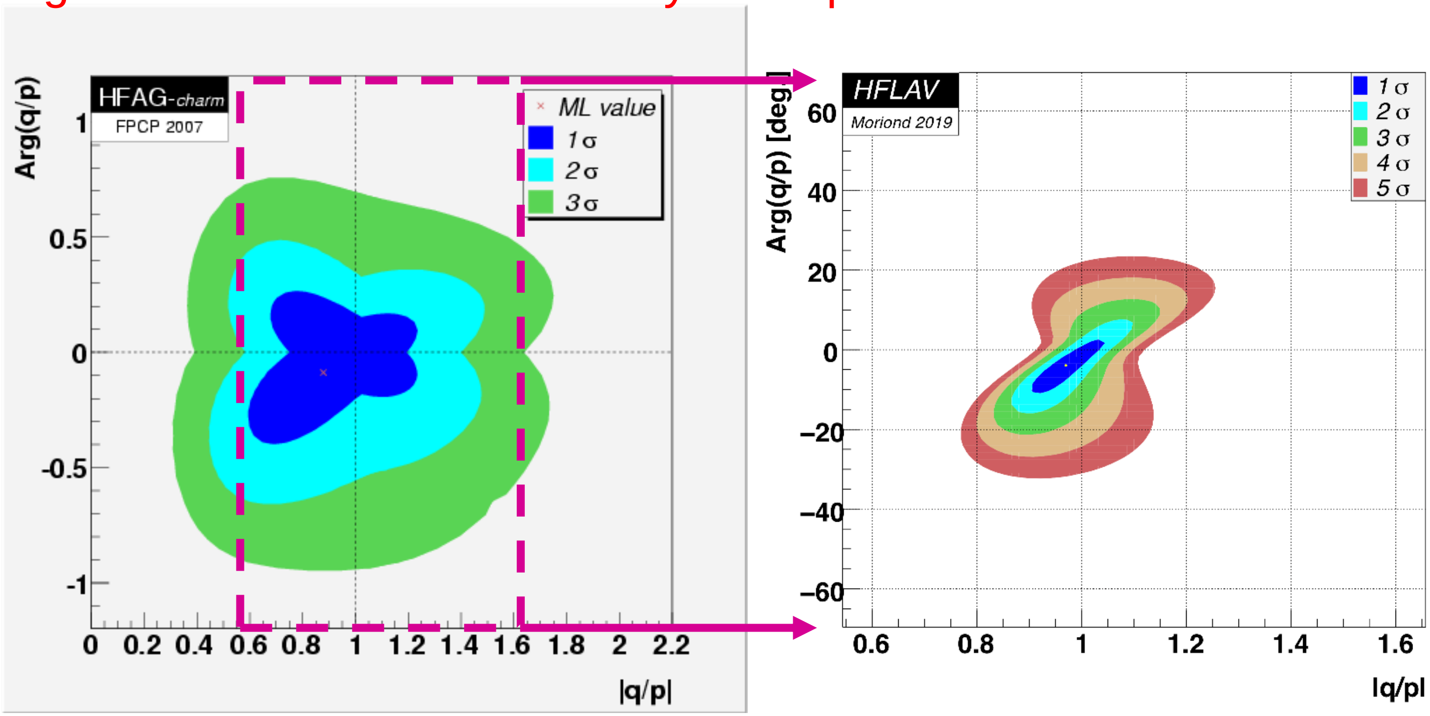
Significant increase in sensitivity since pre-LHC era…



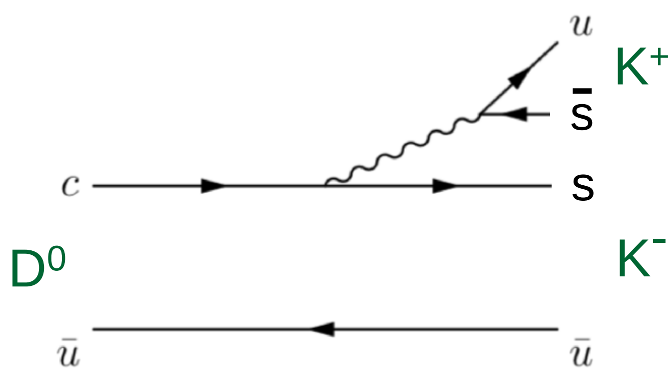
…now starting to approach the region where indirect CPV could lurk !

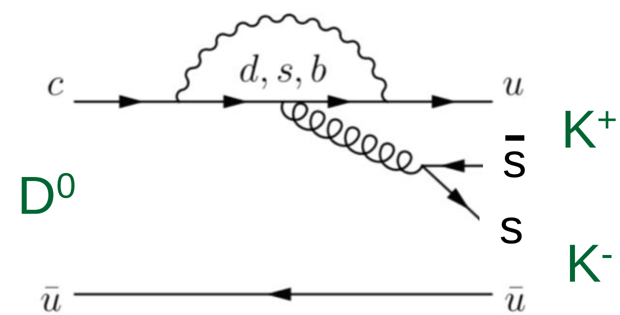
[PRD 97 (2018) 031101]

Difference flat → no sign of indirect CPV (yet).

Searches for direct CPV in charm

And what of direct CPV ? Recall 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.* $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$.





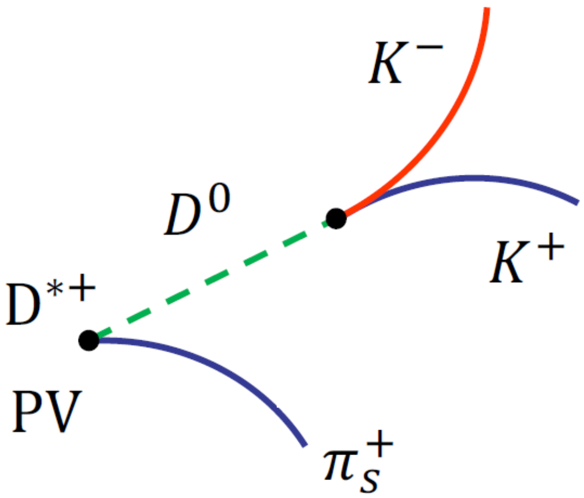
We measure an asymmetry

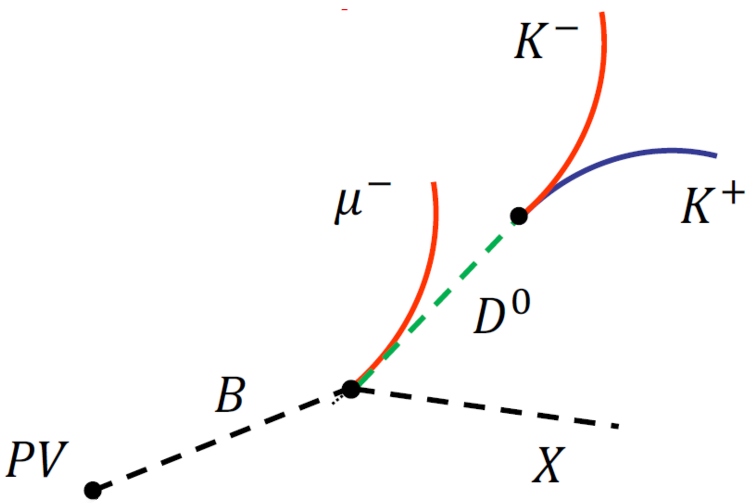
$$\mathcal{A}_{CP} = \frac{D^0 \to K^+K^- - \overline{D}^0 \to K^+K^-}{D^0 \to K^+K^- - \overline{D}^0 \to K^+K^-}$$

The meson is neutral, but we are interested in direct CPV, so measure the time-integrated asymmetry (still, possible residual indirect CPV effects must be accounted for in interpretation - a charged decay, *e.g.* $D^+ \to \pi^+\pi^-\pi^+$, does not have this issue).

Direct CPV measurements – practical considerations

At the LHC can exploit two production modes, prompt (*i.e.* from primary interaction / vertex (PV)), or secondary (from B decay). Prompt is more abundant.





Furthermore, in prompt case, choose to reconstruct $D^{*+} \rightarrow D^0\pi_S^+$ decays, as the charge of the 'slow pion' tags flavour (D^0 or D^0bar) - needed to construct A_{CP}.
In secondary case the tag comes from charge of muon in a semileptonic B decay.

Direct 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*:

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

- $\mathcal{A}_{CP}(f)$: what we are after
- $\mathcal{A}_D(f)$: detection asymmetry for final state
  must be zero for decays of D^0 into two pseudoscalars !
- $\mathcal{A}_D(\pi_s)$: detection asymmetry for slow pion
- $\mathcal{A}_P(D^{*+})$: production asymmetry: there can be different numbers of D^{*+} and D^{*-} produced in acceptance

* Analogous expression for semileptonic tags

Direct 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*:

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

what we are after

detection asymmetry for slow pion

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

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:

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

taking care to weight samples so both have same distribution in phase space.

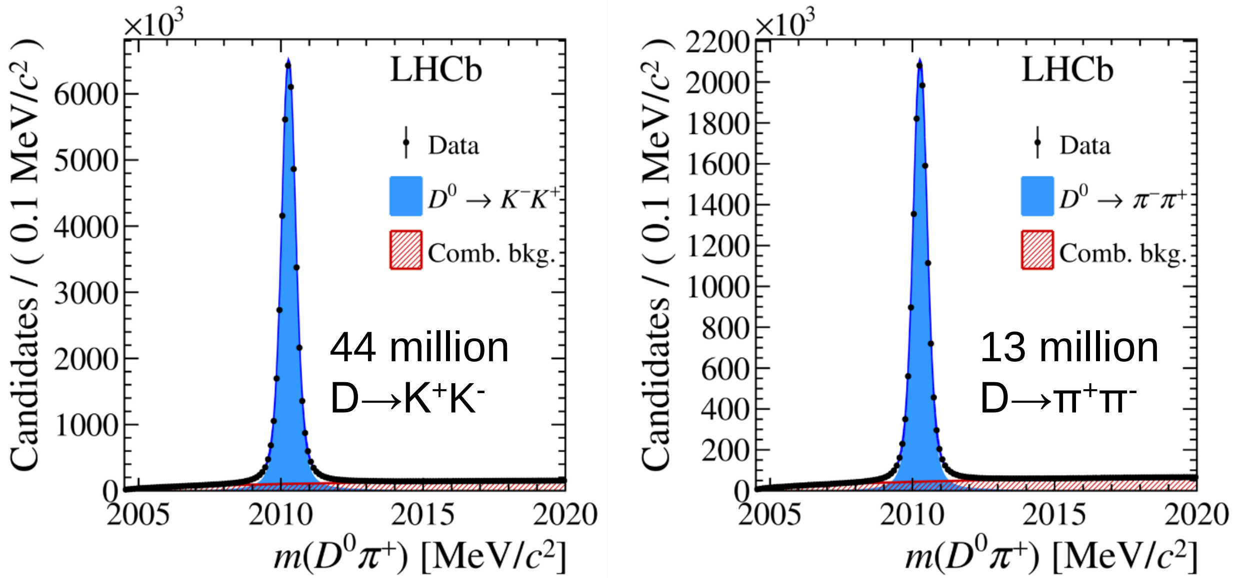
Dawn of a new era: observation of (direct) CPV in charm

[PRL 122 (2019) 211803]

ΔA_{CP} measurement, published earlier this year by LHCb, harnesses full statistical might of experiment, being first to use full Run 2 data set.

Method is intrinsically robust: *e.g.* syst. uncertainty on prompt analysis is $< 10^{-4}$.

Dull plots, because effect is tiny, and almost impossible to visualise



Run 1 + Run 2 ➡

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

5.3σ from 0 !

Dawn of a new era: observation of (direct) CPV in charm

[PRL 122 (2019) 211803]

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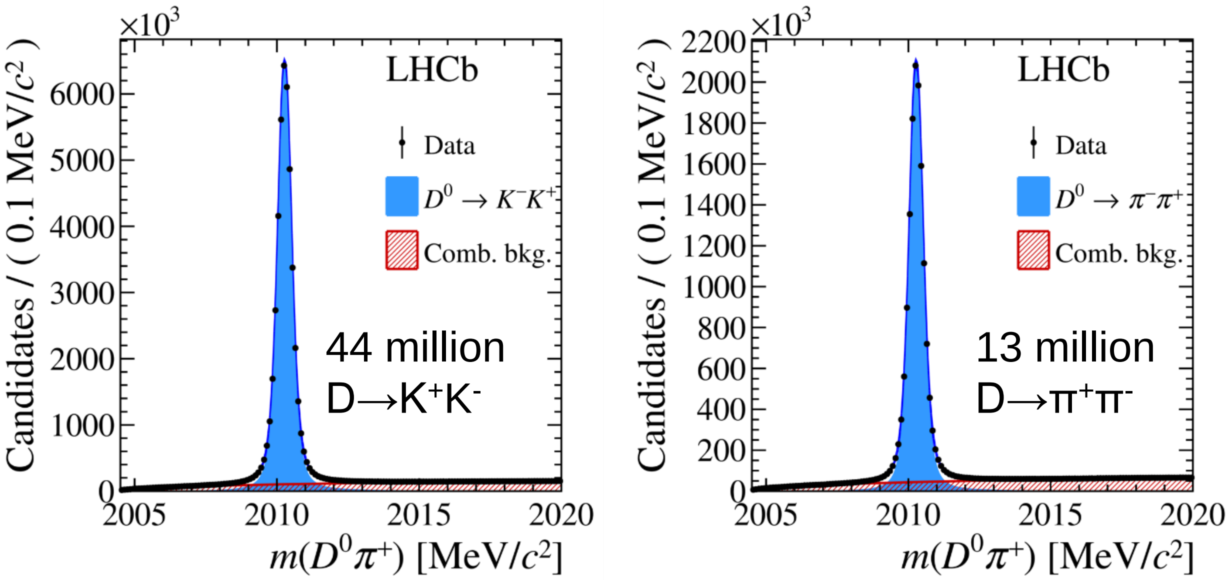

Using indirect CPV constraints in these channels can deduce

$$\Delta a_{CP}^{\mathrm{dir}} = (-15.7 \pm 2.9) \times 10^{-4}$$

i.e. direct CPV saturates result

Dawn of a new era: observation of (direct) CPV in charm

[PRL 122 (2019) 211803]

ΔA measurement, published earlier this year by LHCb, harnesses full
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- Is the size of the effect compatible with SM expectations, or is it too high, indicating possible NP contributions ? The theoretical community is (inevitably) divided. (*e.g.* compare [Chala, Lenz, Rusov & Scholz arXiv:1903.10490] with [Grossman and Schacht arXiv:1903.10952])

- Next tasks for experiment: measure individual asymmetries & intensify searches in other modes. A very exciting programme lies ahead !

- Charm is certainly no longer the 'poor relation' of flavour physics !

Using indirect CPV constraints in these channels can deduce

$$\Delta a_{CP}^{\rm dir} = (-15.7 \pm 2.9) \times 10^{-4}$$

i.e. direct CPV saturates result

Future of flavour

Why persevere with flavour studies ?

Devil's advocate: given that CKM mechanism does a good job, and given that we have observed $B^0_s \to \mu\mu$ at (roughly) the right BR, why continue?

The big picture answer:

- The SM is incomplete;
- Many of the mysteries in the SM (& the cosmos) are related to flavour;
- Flavour observables can probe much higher mass scales than direct searches.

And some specific considerations:

- We *know* there are important phenomena still to be observed (*e.g.* mixing-induced CPV in B^0_s system, mixing related CPV in charm, $B^0 \to \mu\mu$ *etc.*);
- Similarly, there are many important measurements that can be made, which are unfeasible with current sample sizes (*e.g.* electroweak Penguin studies with $b \to d l^+ l^-$ decays, or precise study of P_5' with $B^0 \to K^* e^+ e^-$);
- A very large number of current observables are *theoretically clean* &/or *statistics limited*, so higher precision is strongly motivated (*e.g.* $\sin 2\beta$, γ, φ_s, R_K, R_{K^*}, $BR(B^0_s \to \mu\mu)/BR(B^0 \to \mu\mu)$ *etc*);
- A rich field where surprises are guaranteed (*e.g.* no one was expecting charm mixing, direct charm CPV, the X(3872), pentaquarks…).

Unwise to assume ~10% (or even 0.1%) is 'good enough'

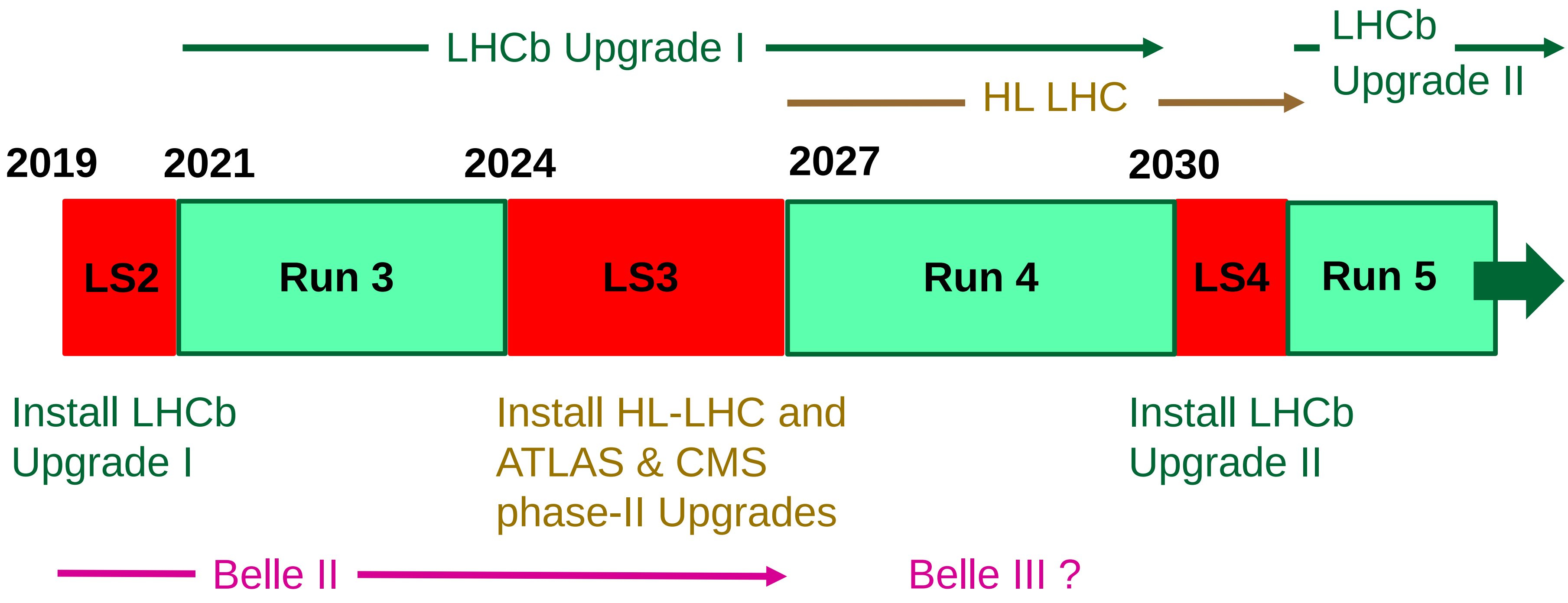
Courtesy Browder and Soni

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

BR ($K^0_L \rightarrow \pi\pi$) ~ 2 x 10^{-3} Cronin, Fitch *et al.* , 1964

The LHC schedule – current planning



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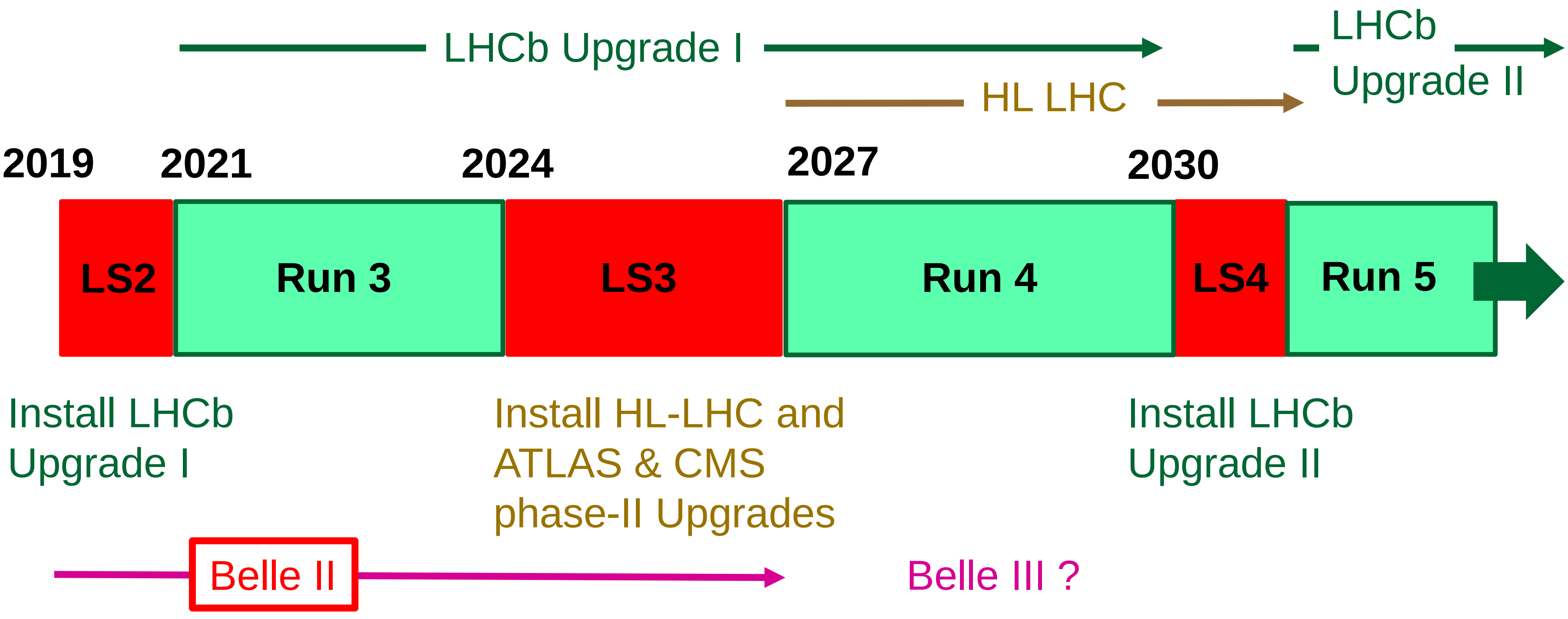
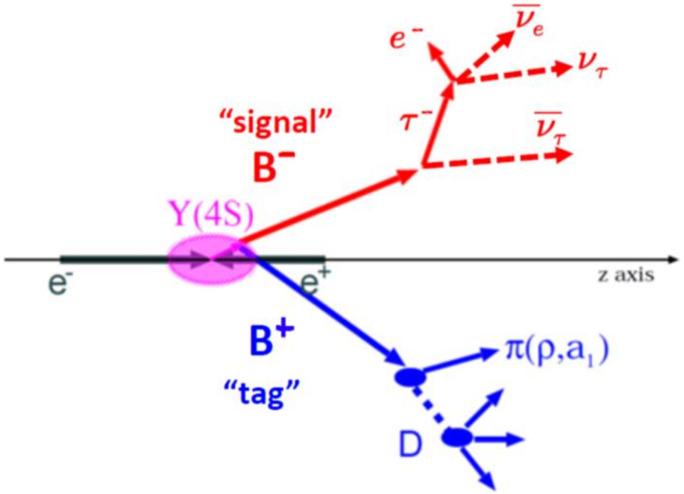


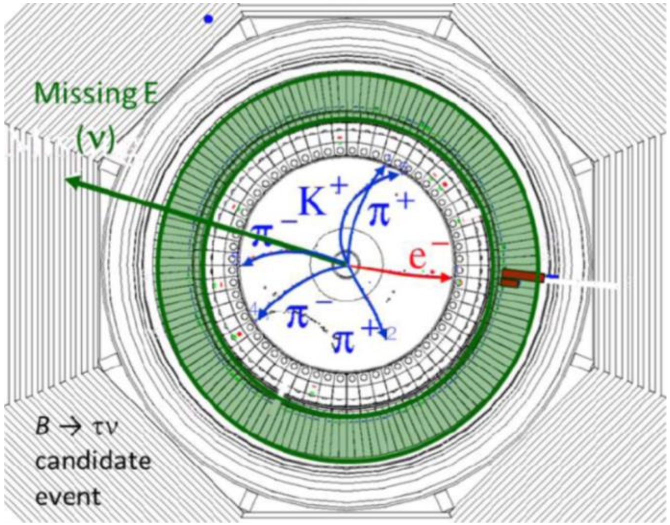
Why Belle II ?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

e.g. B→τν





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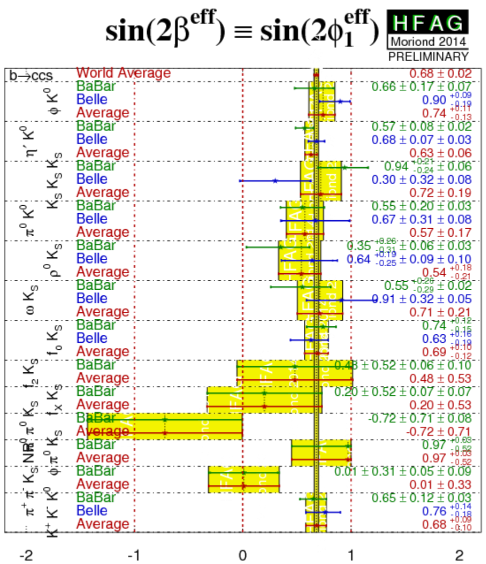
- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

e.g. most modes suitable for sin2β measurements involving Penguin loops (b→ccbar s) are rather tough at LHCb…



…and other important decays *e.g.* $D^0\to\gamma\gamma$, $B^0\to\pi^0\pi^0$… are essentially inaccessible.

Why Belle II ?

B production at the Υ(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

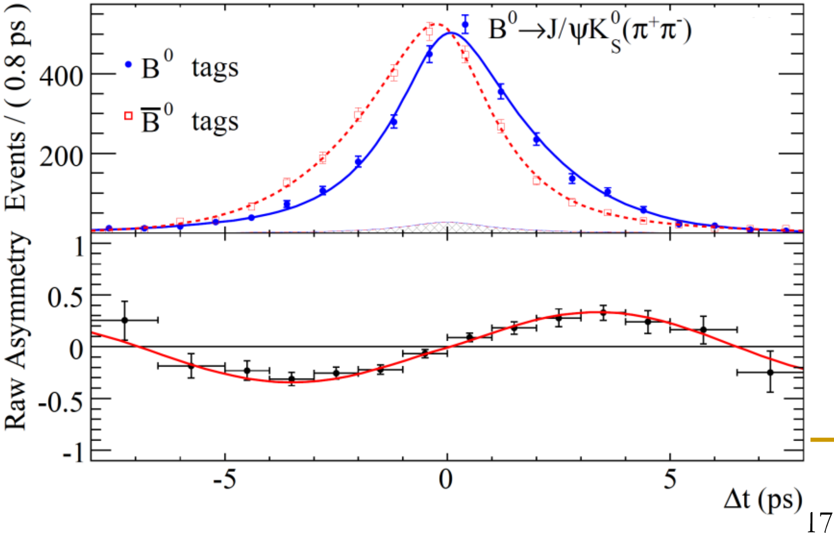
- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

- Coherent B^0B^0bar production at Υ(4S) makes flavour tagging easier and compensates for lower sample sizes in time-dependent CP measurements

e.g. in sin2β measurement with $B^0 \to J/\psi K_S$

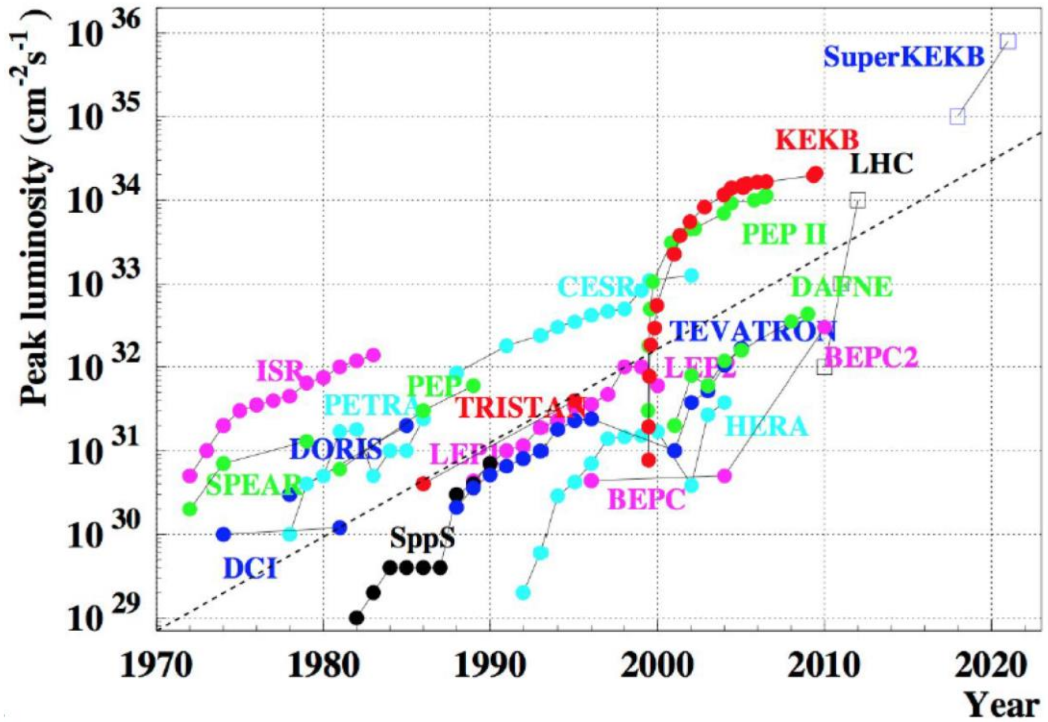
ε (tag effective) BaBar ~ 31 %
[PRD 79 (2009) 072009]

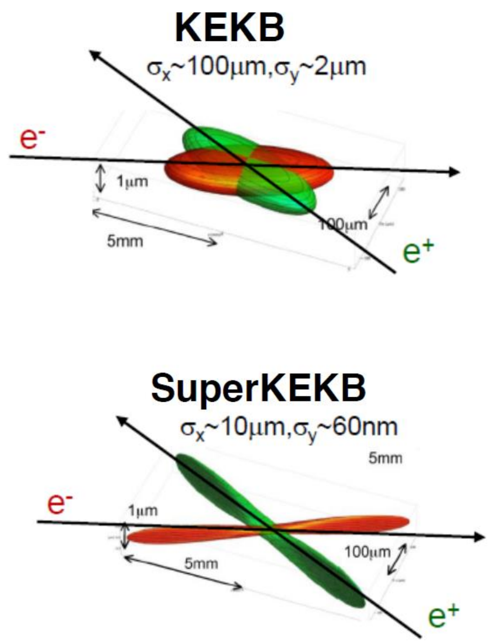
ε (tag effective) LHCb ~ 3 %
[PRL 115 (2015) 031601]



SuperKEKB

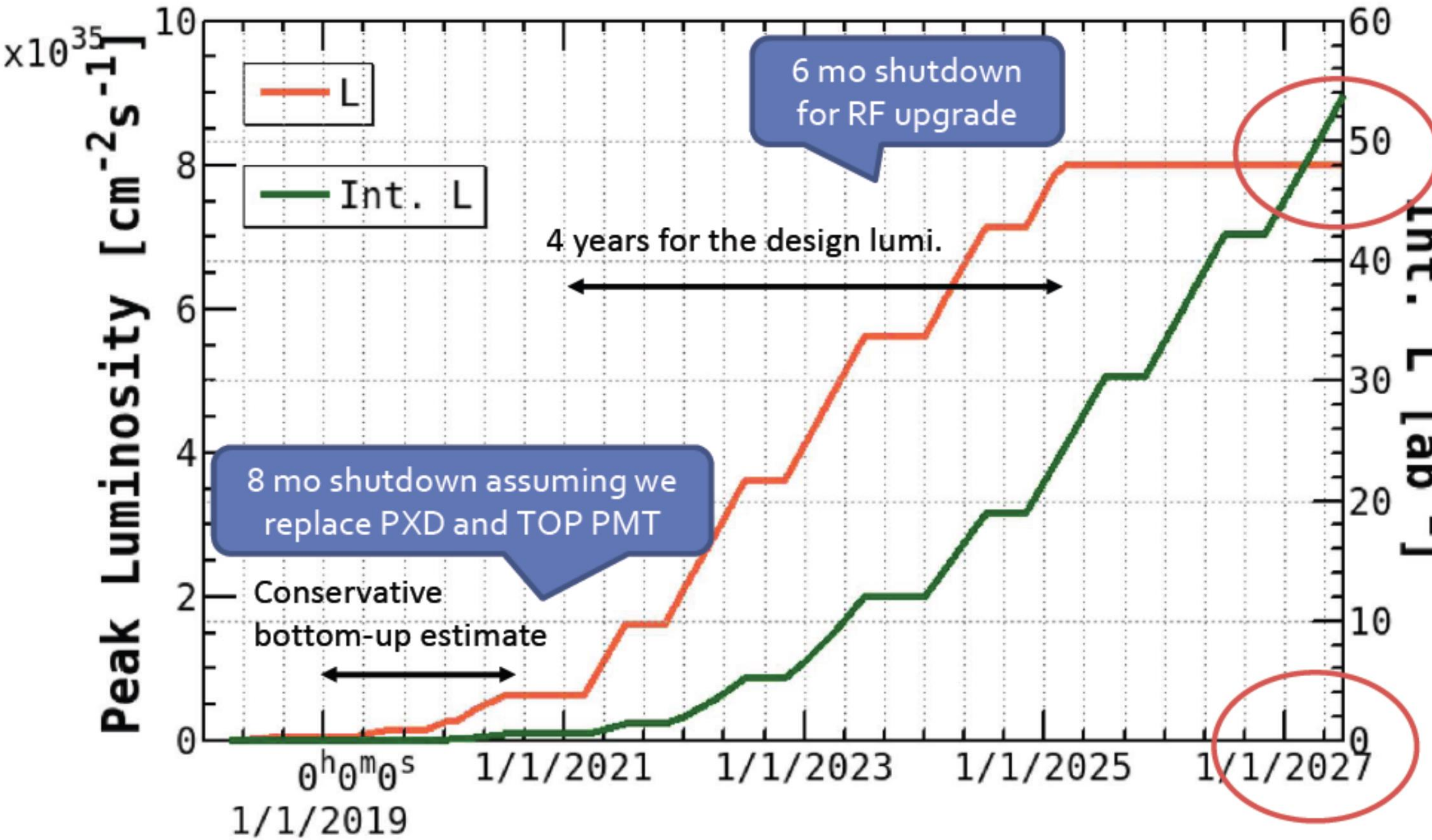
SuperKEKB goals: luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ and 50 ab^{-1} by 2027





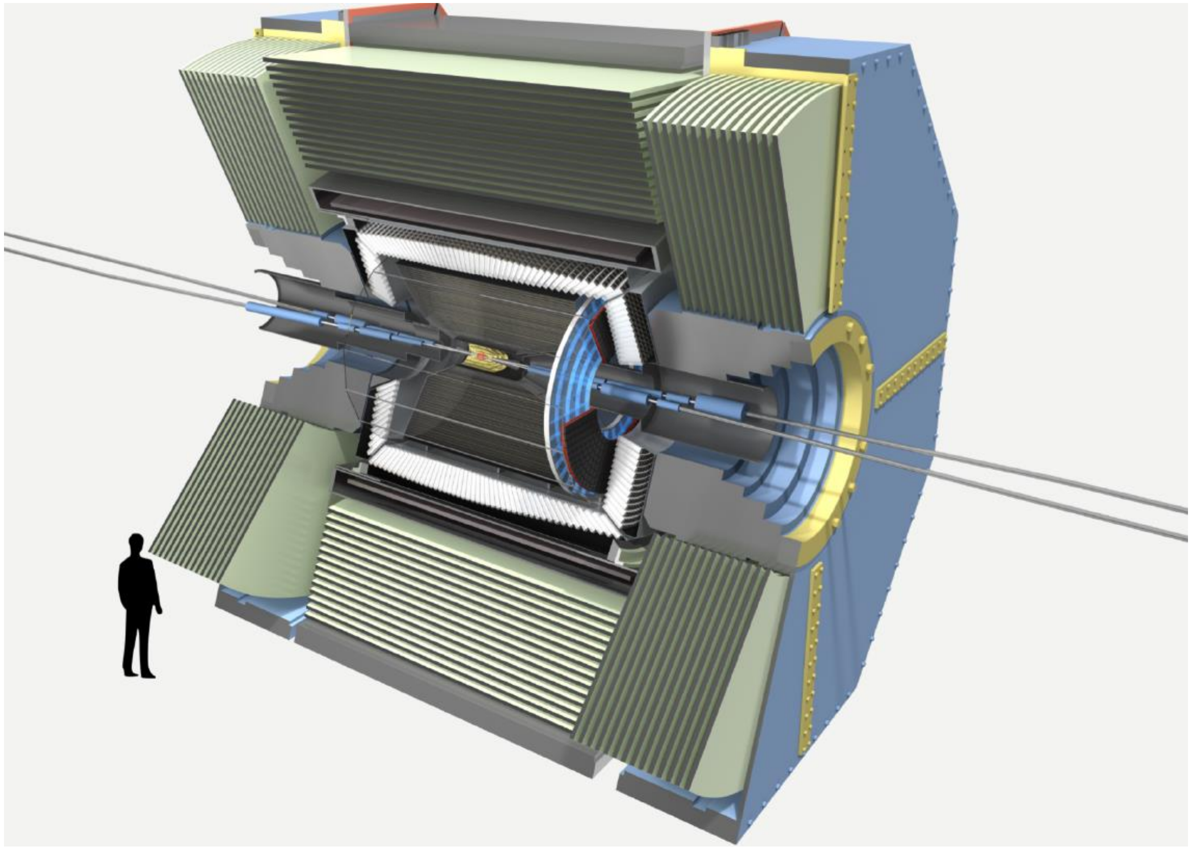
An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by ~1/20 and doubling the currents.

SuperKEKB and Belle II roadmap

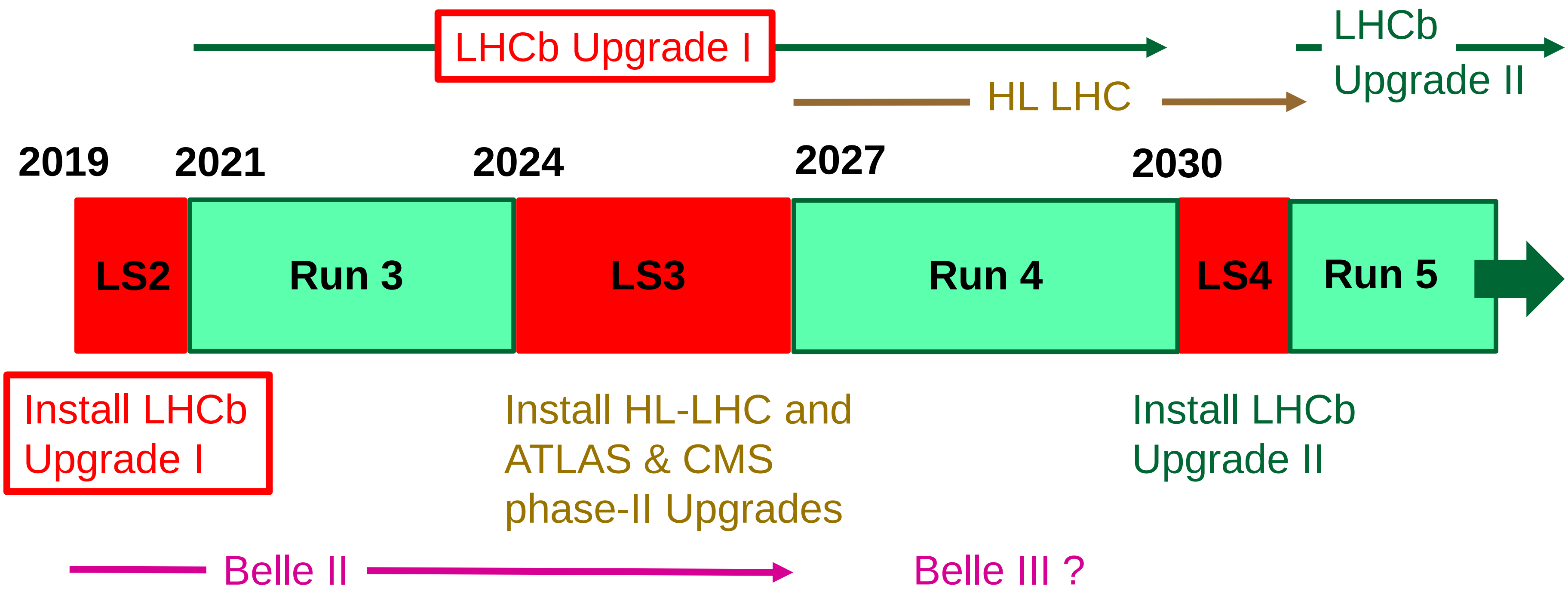


Belle II detector

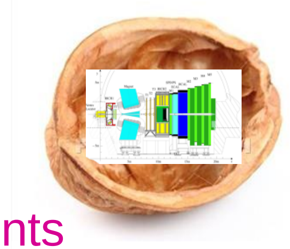
All sub-detectors upgraded from Belle, except for ECL crystals and part of the barrel KLM



The LHC schedule – current planning



LHCb Upgrade 1 (LS2) in a nutshell



Indirect search strategies for New Physics, *e.g.* precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive following the experience of Runs1 & 2 that direct signals are elusive

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond Run 2 requires significant changes.

The LHCb Upgrade

1) Full software trigger
- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

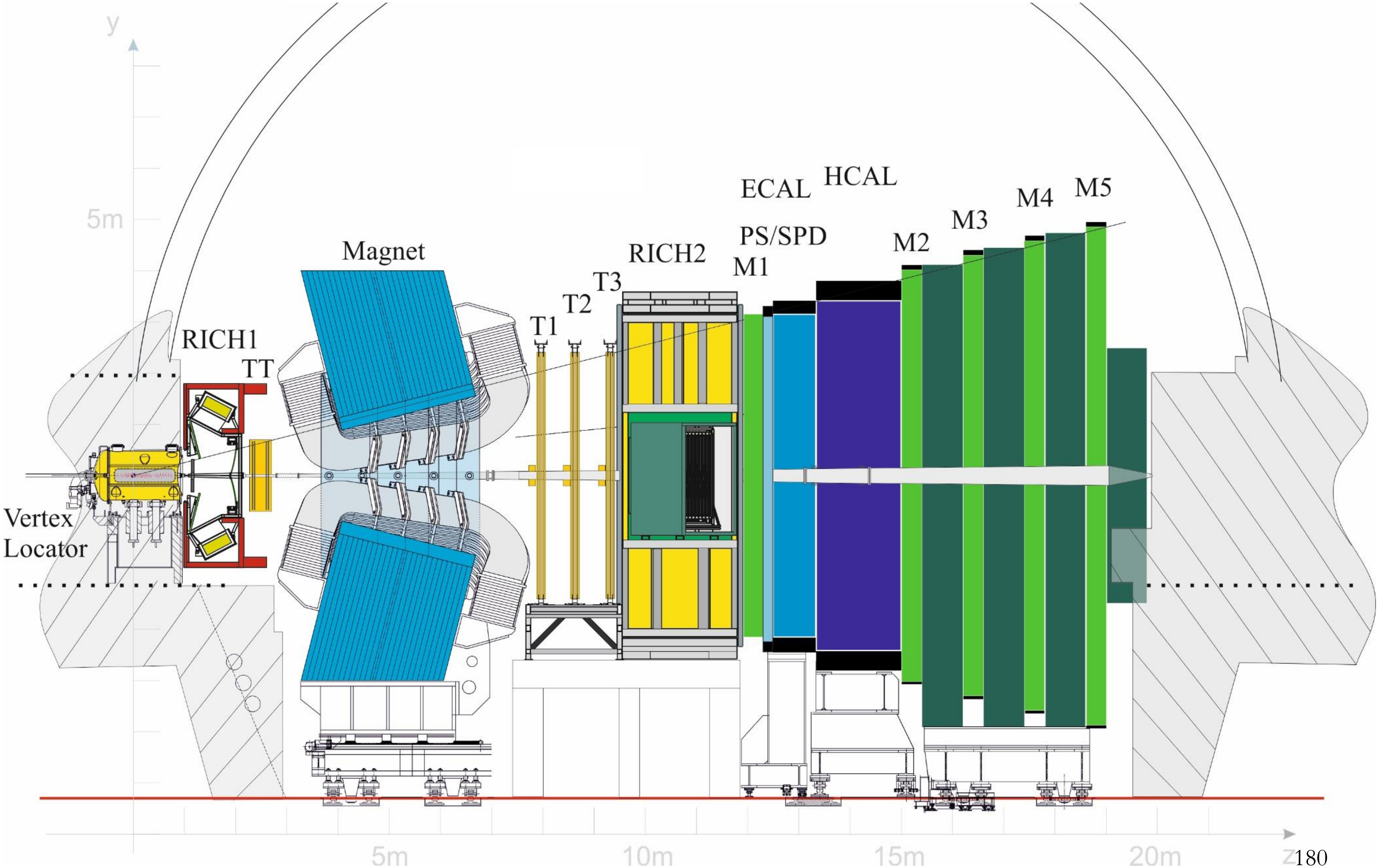
2) Raise operational luminosity to 2×10^{33} cm^{-2} s^{-1}

Necessitates redesign of several sub-detectors & overhaul of readout

Huge increase in precision: Upgrade + Run 2 yield in hadronic modes ~ 60x that of Run 1; also perform studies *beyond the reach of the current detector*.

Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour ('a general purpose detector in the forward region').

Run 1 & 2 detector



Required modifications

Full s/w trigger →

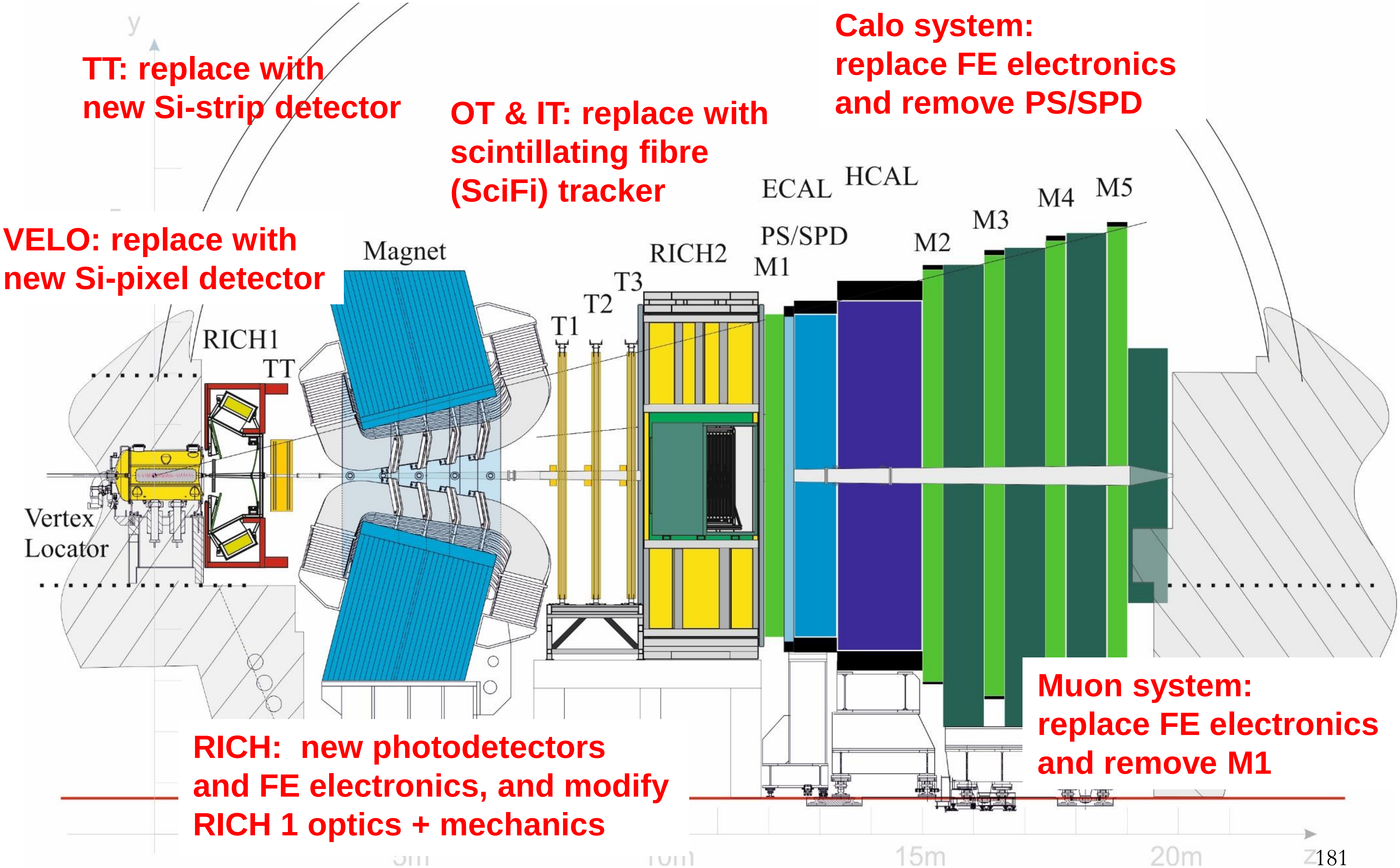
Replace read-out boards and DAQ

TT: replace with new Si-strip detector

OT & IT: replace with scintillating fibre (SciFi) tracker

Calo system: replace FE electronics and remove PS/SPD

VELO: replace with new Si-pixel detector

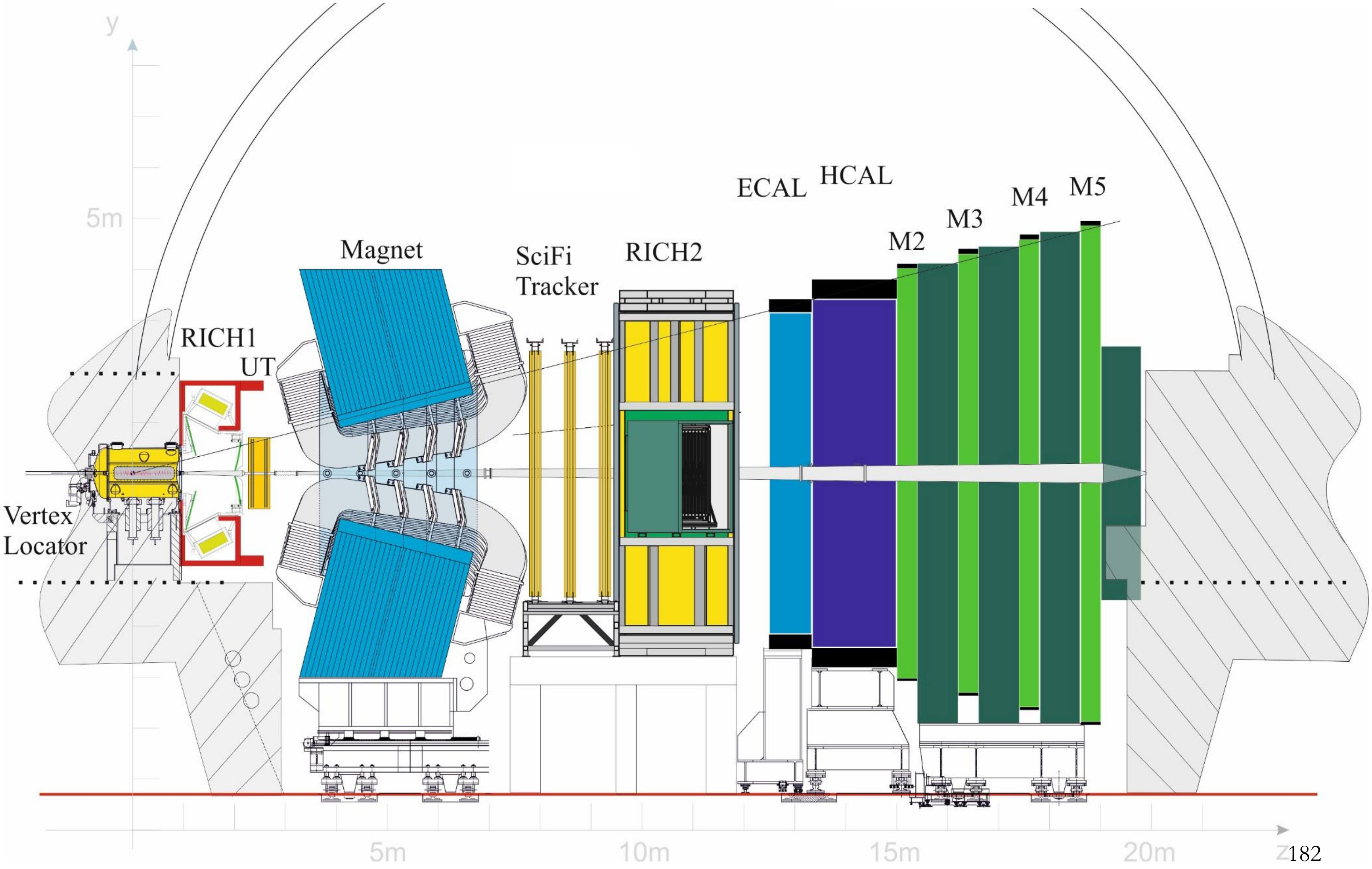


RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

Muon system: replace FE electronics and remove M1

Upgrade I detector

Installation is occurring in LS2, *i.e.* right now! For monthly progress videos look here.



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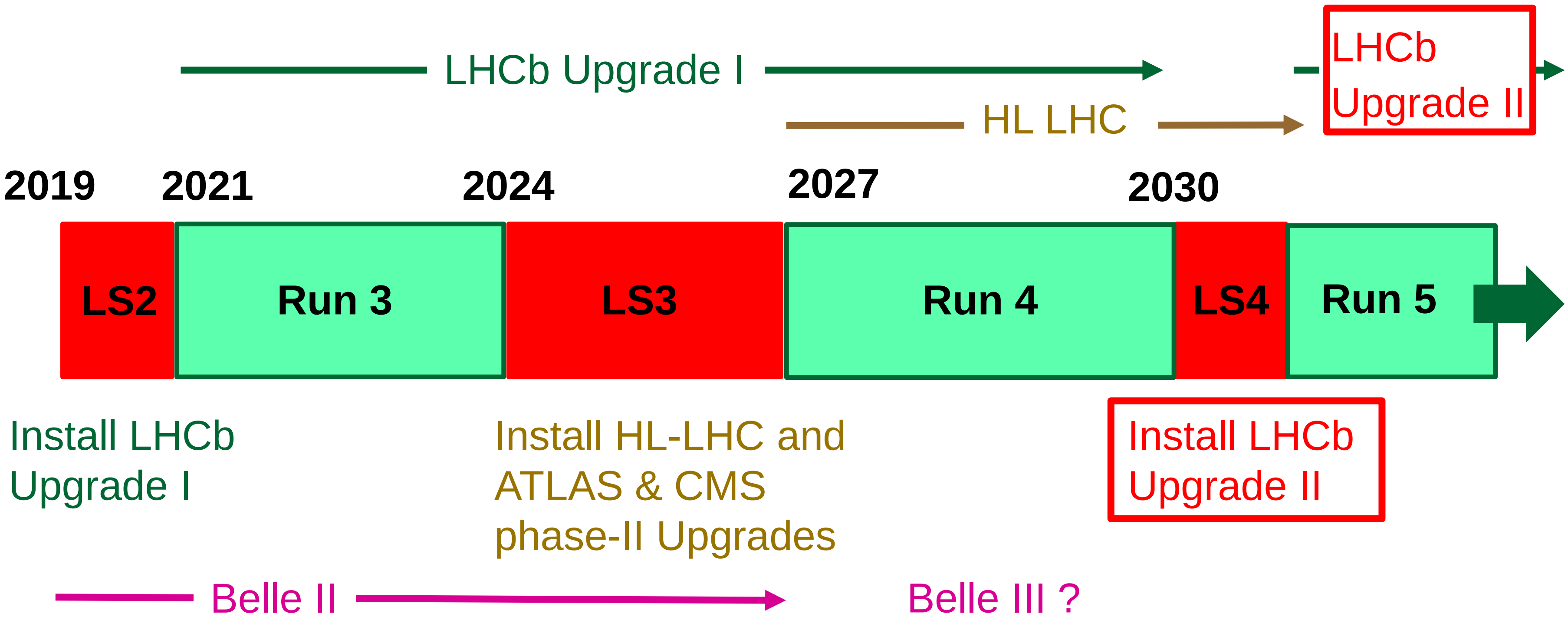
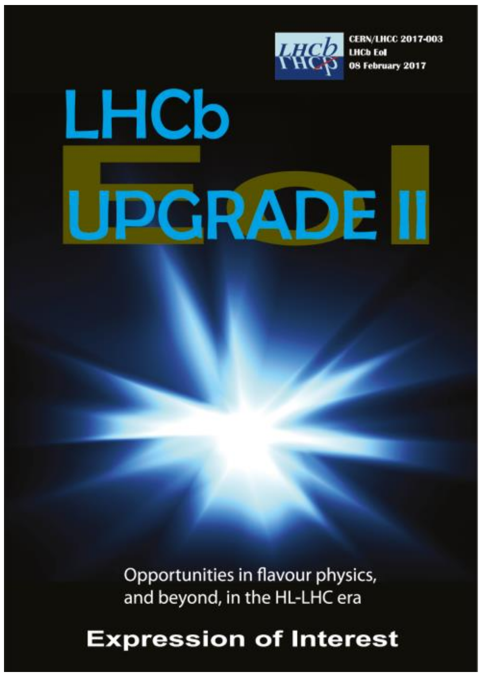


LHCb Upgrade II – the ultimate LHC flavour experiment

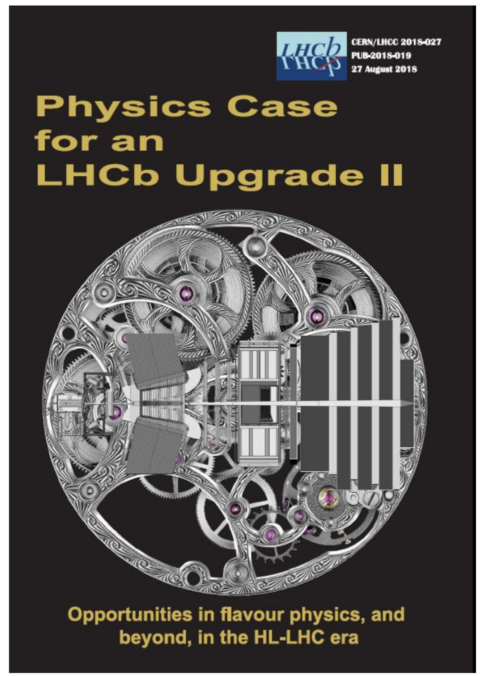
Begin after LS4 (2030). Operate at up to 2 x 10^{34} $cm^{-2}s^{-1}$ & collect (at least) 300 fb^{-1}.

Expression of interest



[CERN-LHCC-2017-003]

Full physics case



[CERN-LHCC-2018-027, also arXiv:1808.08865]

In parallel, many studies from the machine side, summarised in a report which identifies

"a range of potential solutions for operating LHCb Upgrade II at a luminosity of up to 2 x 10^{34} $cm^{-2}s^{-1}$ and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC"

[CERN-ACC-NOTE-2018-038]

LHCb Upgrade II – the ultimate LHC flavour experiment

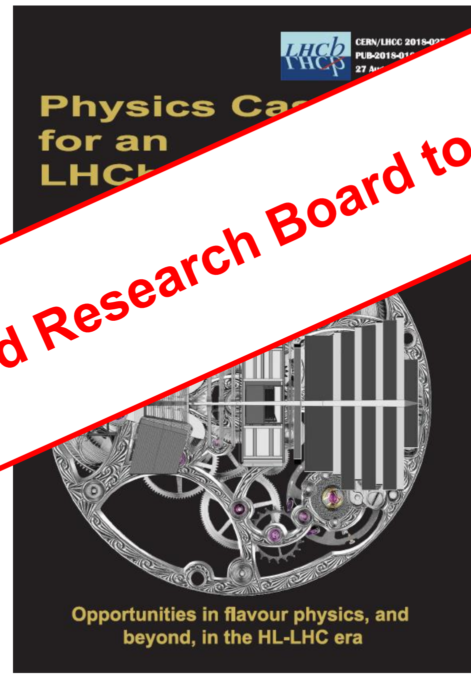
Begin after LS4 (2030). Operate at up to 2 x 10^{34} $cm^{-2}s^{-1}$ & collect (at least) 300 fb^{-1}.

Approved by LHCC and Research Board to proceed to TDRs

Expression of interest

[CERN-LHCC-2017-003]

Full physics case

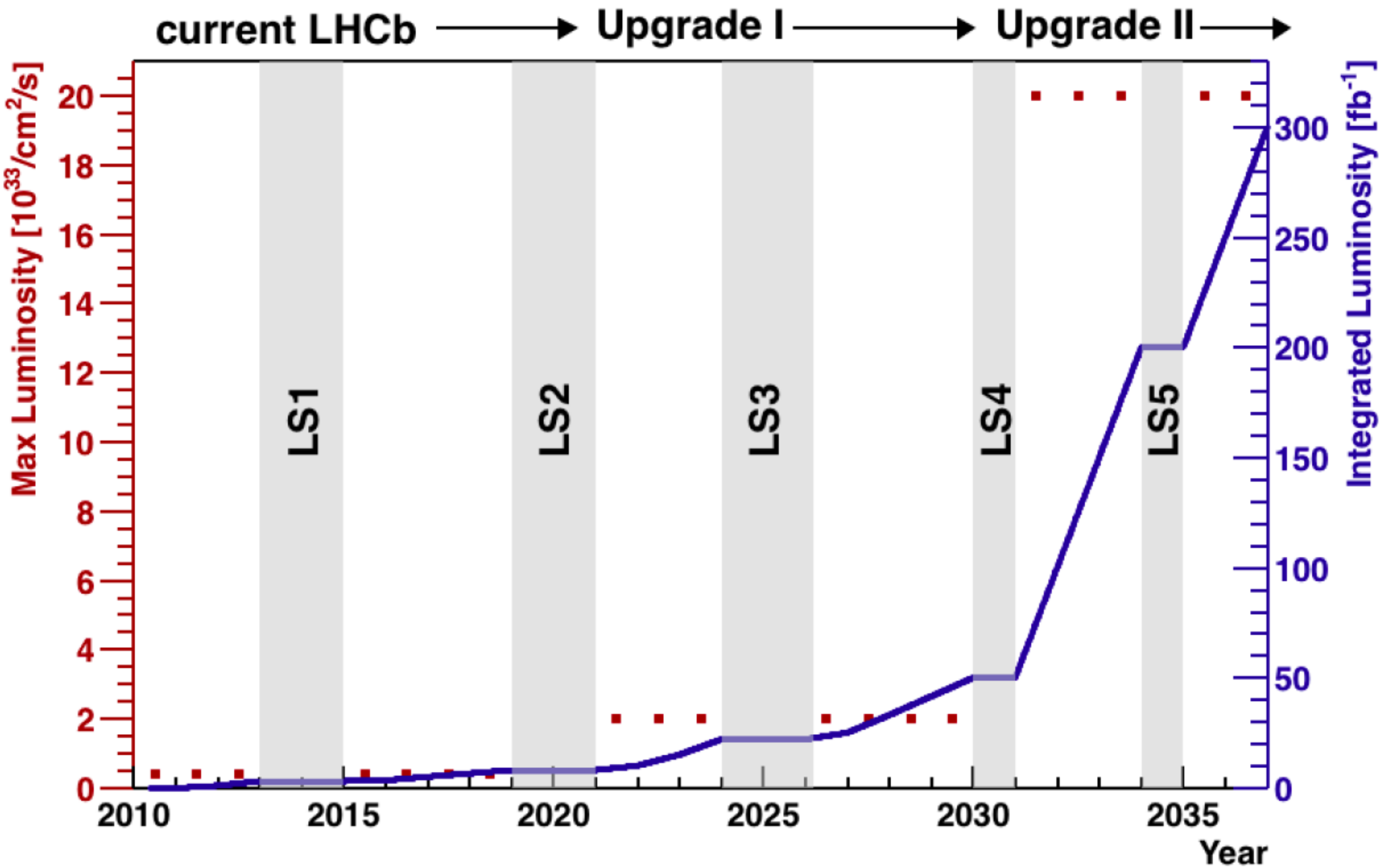


[CERN-LHCC-2018-027, also arXiv:1808.08865]

In parall… …dies fr… …e, …port …ntifies …ange of potential solutions for operating LHCb Upgrade II at a luminosity of up to 2 x 10^{34} $cm^{-2}s^{-1}$ and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC"

[CERN-ACC-NOTE-2018-038]

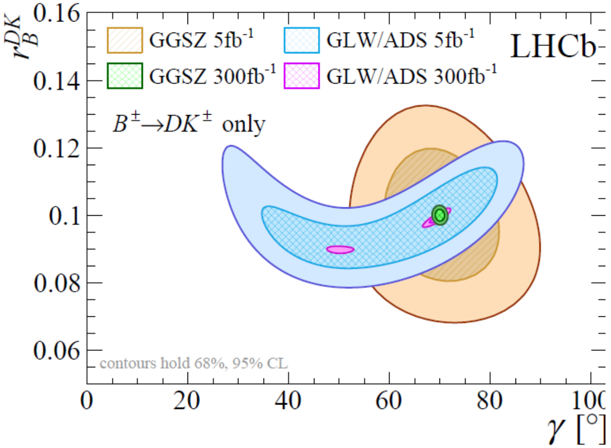
LHCb Upgrade II – the ultimate LHC flavour experiment



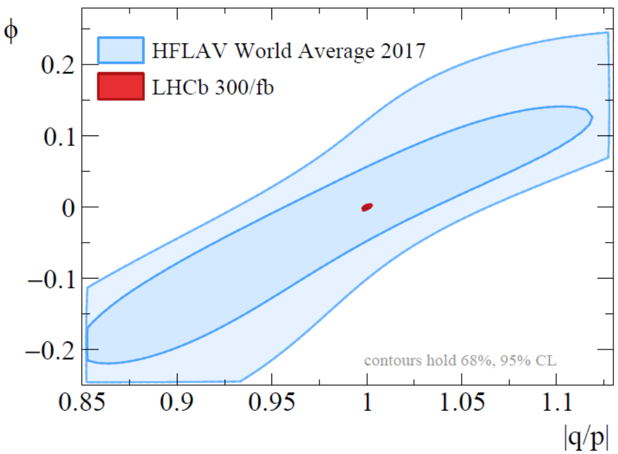
Upgrade-II physics highlights

Too much to cover – here are a few examples:

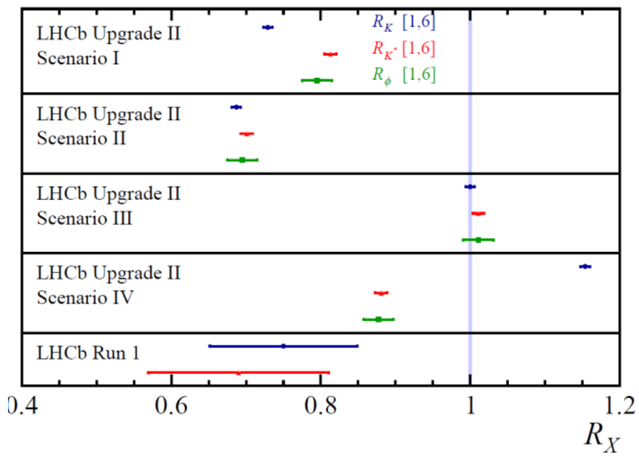
γ determination:
sub-degree precision



CPV in charm
down to 10^{-5}



Resolving New Physics
models with R_K and friends



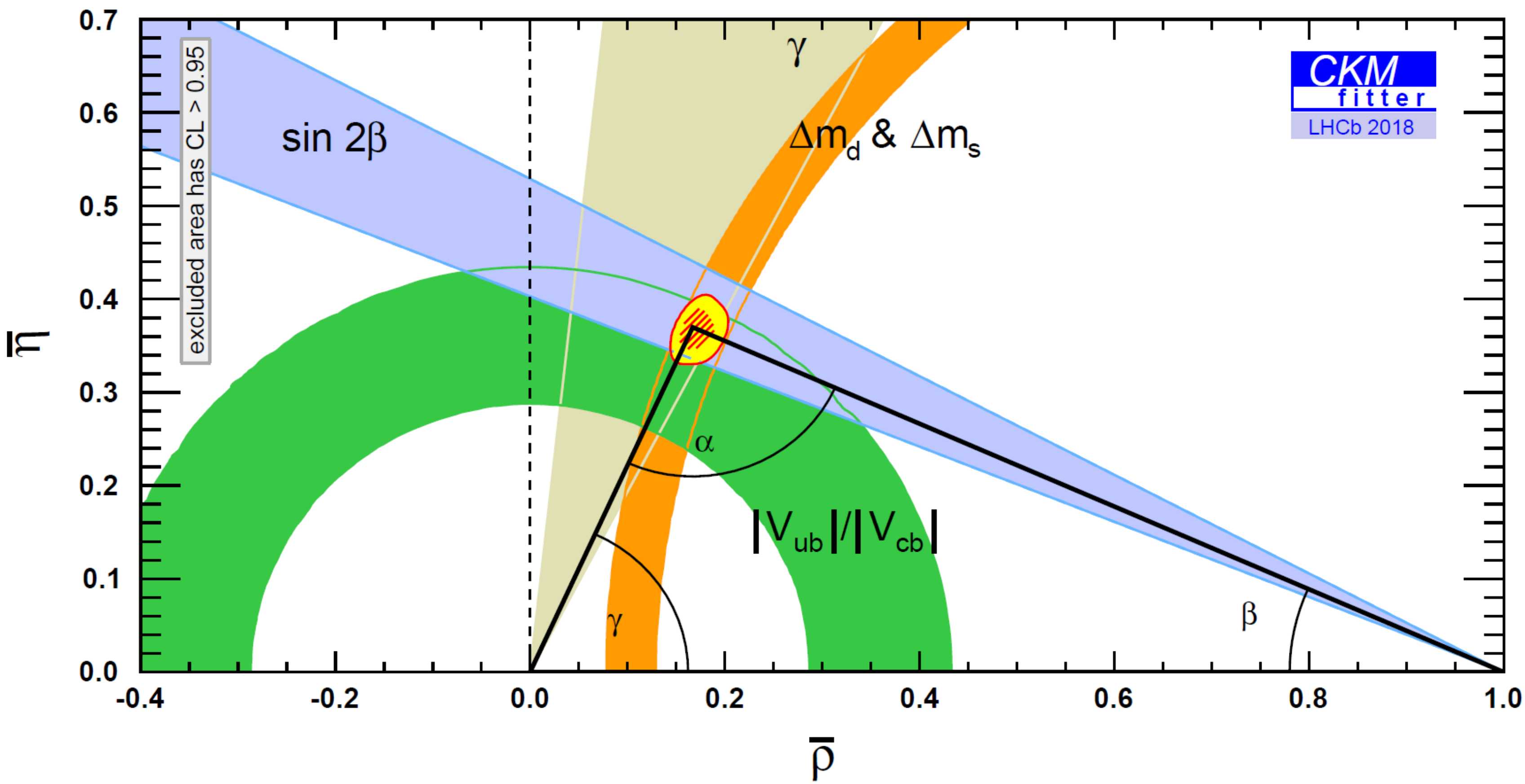
Two key points:

- Many key theoretically clean observables will remain statistics limited even after Upgrade I (*e.g.* γ, φ_s, sin2β, R_K and friends, $B(B^0\to\mu\mu)/B(B_s\to\mu\mu)$…
- Also, will be able to access new observables *e.g.* angular studies of $b\to de^+e^-$.

This will enable great advances in CPV tests, and will give an almost doubling of the New Physics mass scale (w.r.t. start of HL-LHC era) to which we are sensitive.

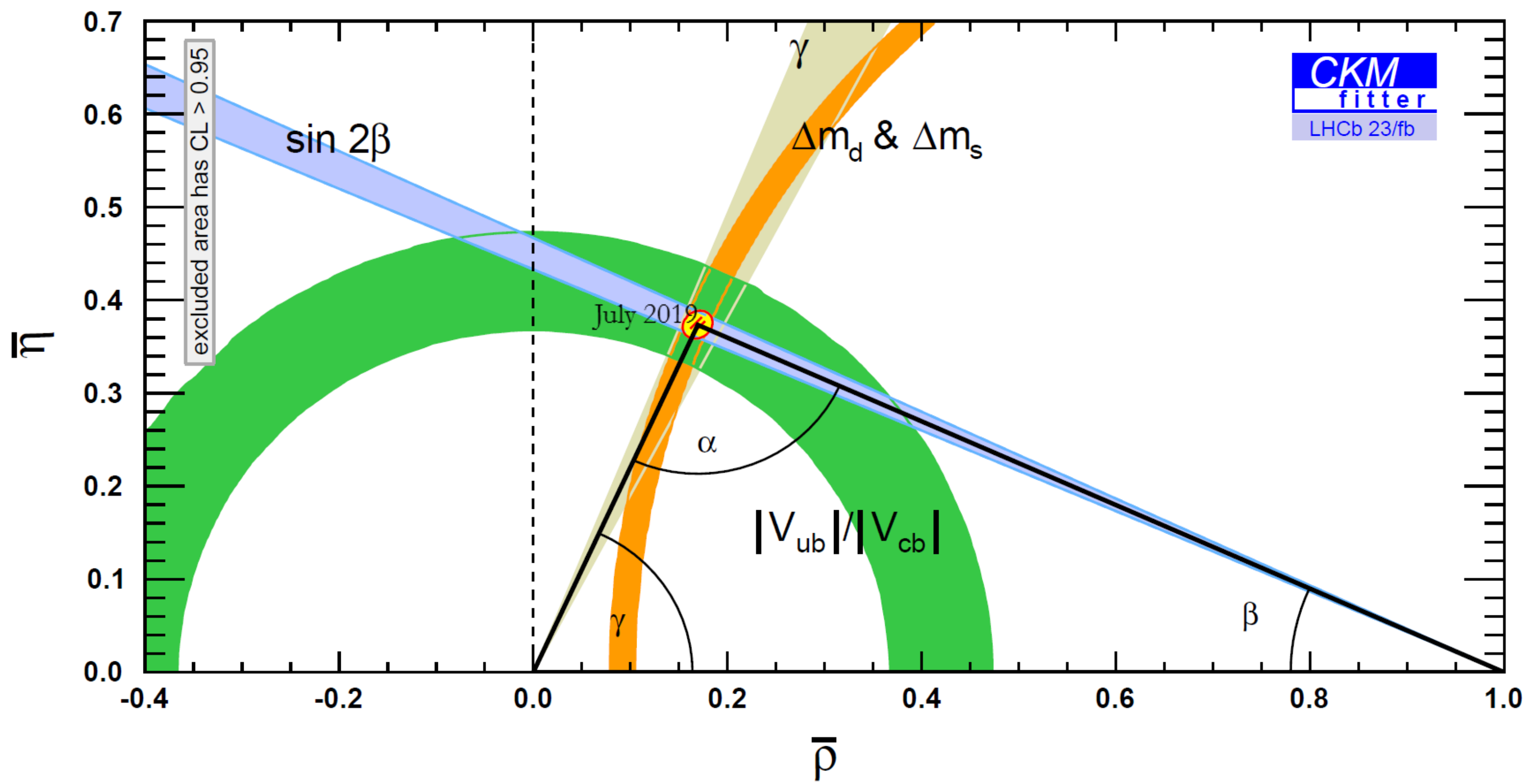
Evolution of constraints on Unitarity Triangle

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



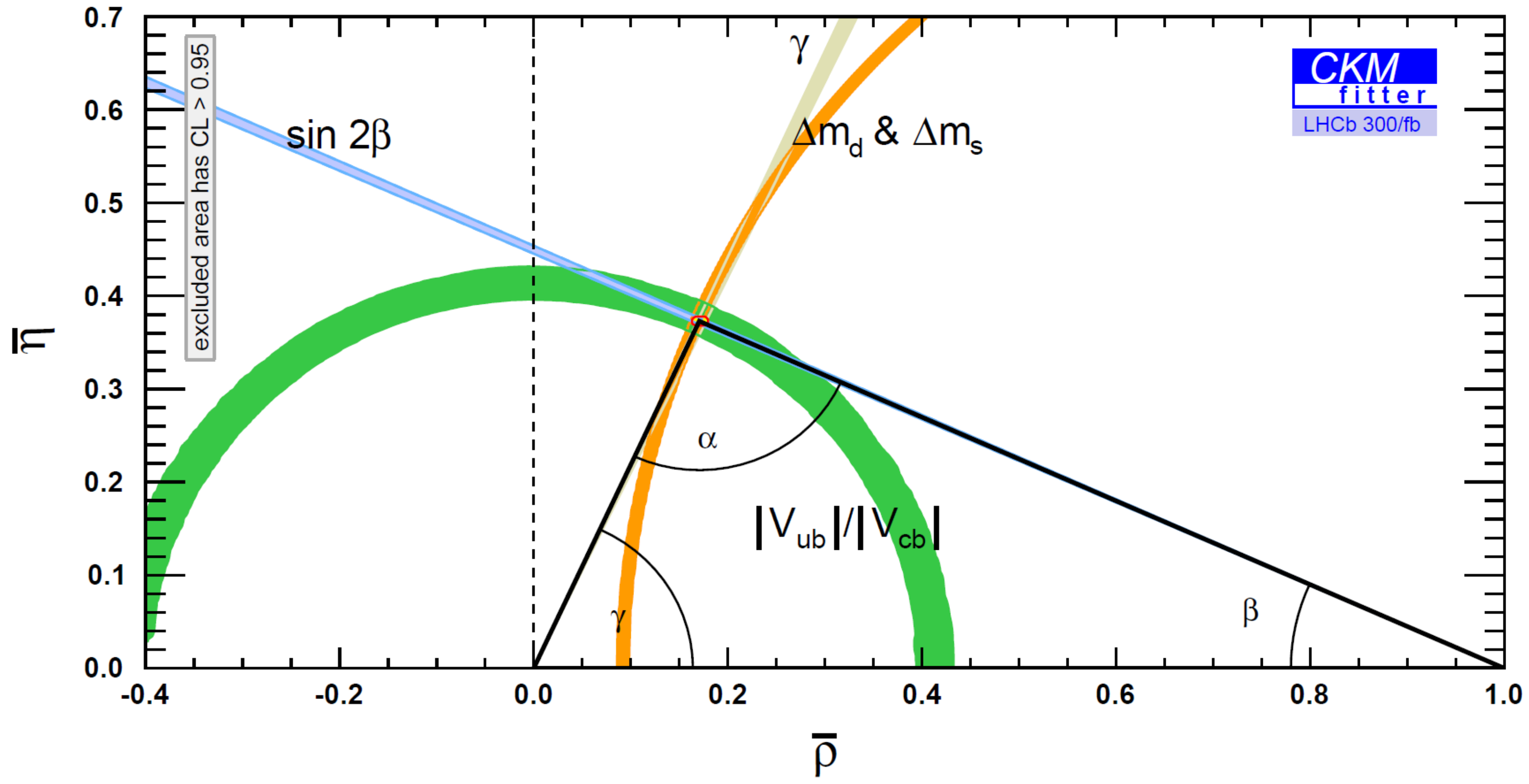
Evolution of constraints on Unitarity Triangle

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

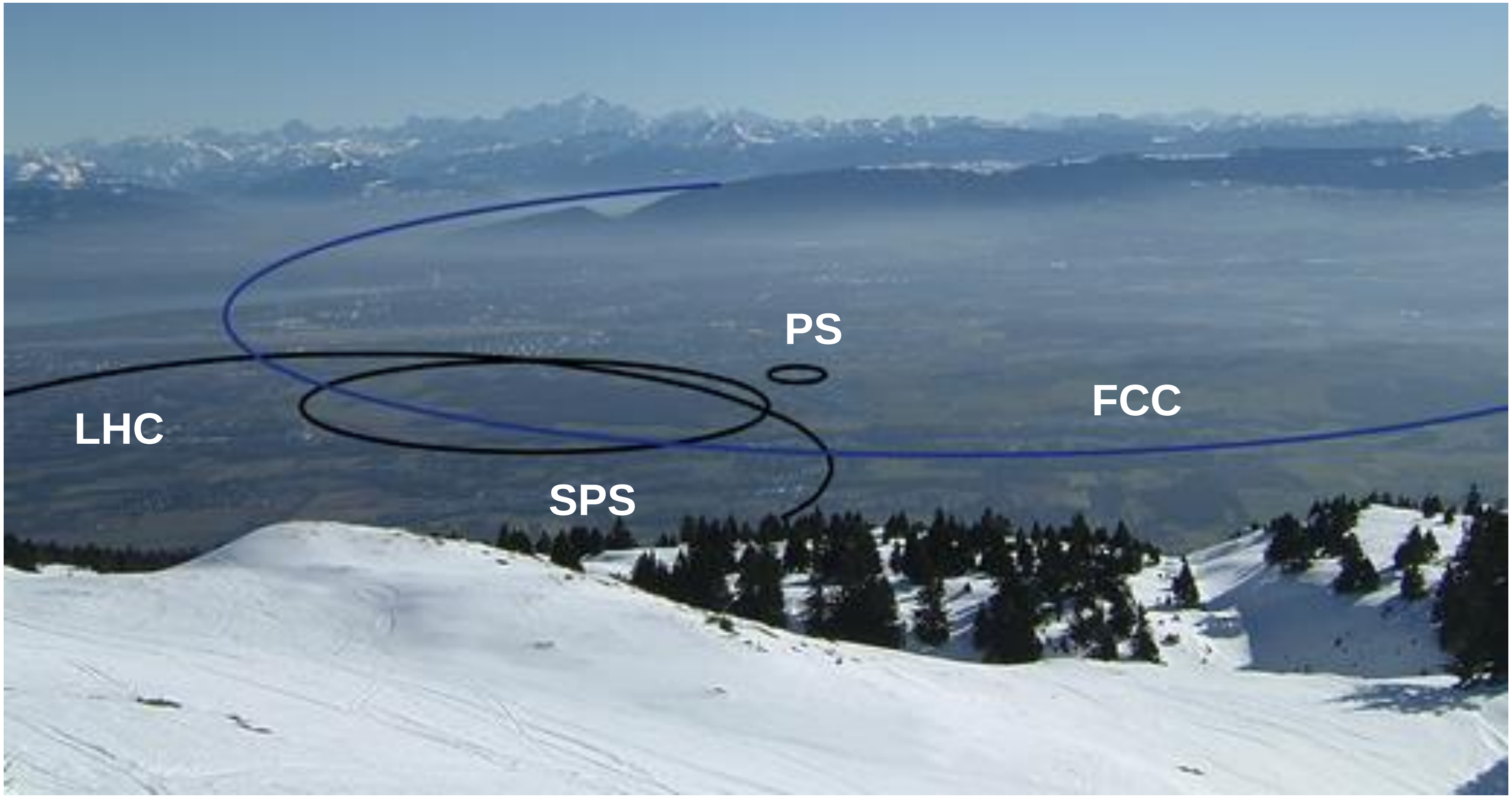


Evolution of constraints on Unitarity Triangle

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



Opportunities at the Z pole: FCC-ee

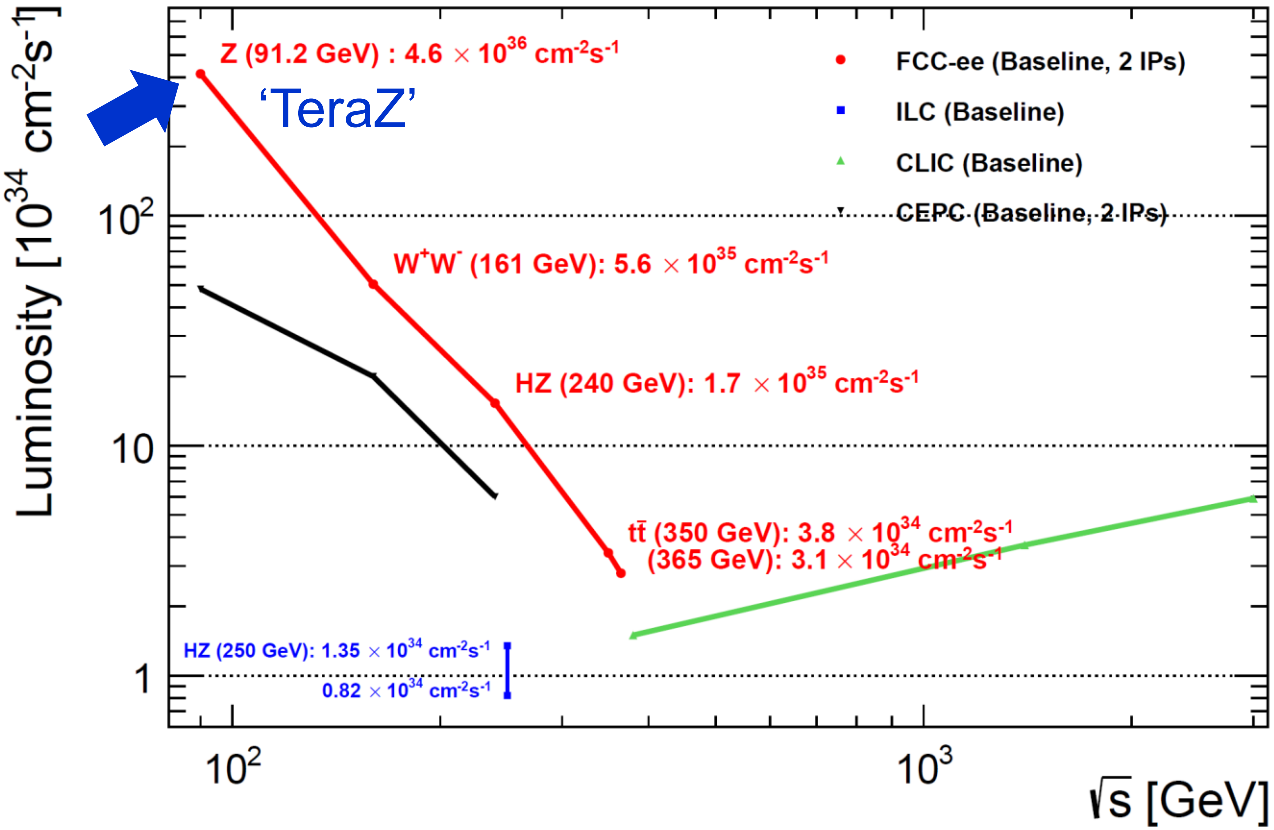


FCC-ee is a proposed e^+e^- collider for 2039→ that would run at the Z pole (91 GeV), WW threshold (161 GeV), HZ energies (240 GeV), ttbar energies (350 & 365 GeV).

(CEPC is a parallel Chinese project, with shorter timescale & ~lower design lumi.).

Opportunities at the Z pole: FCC-ee

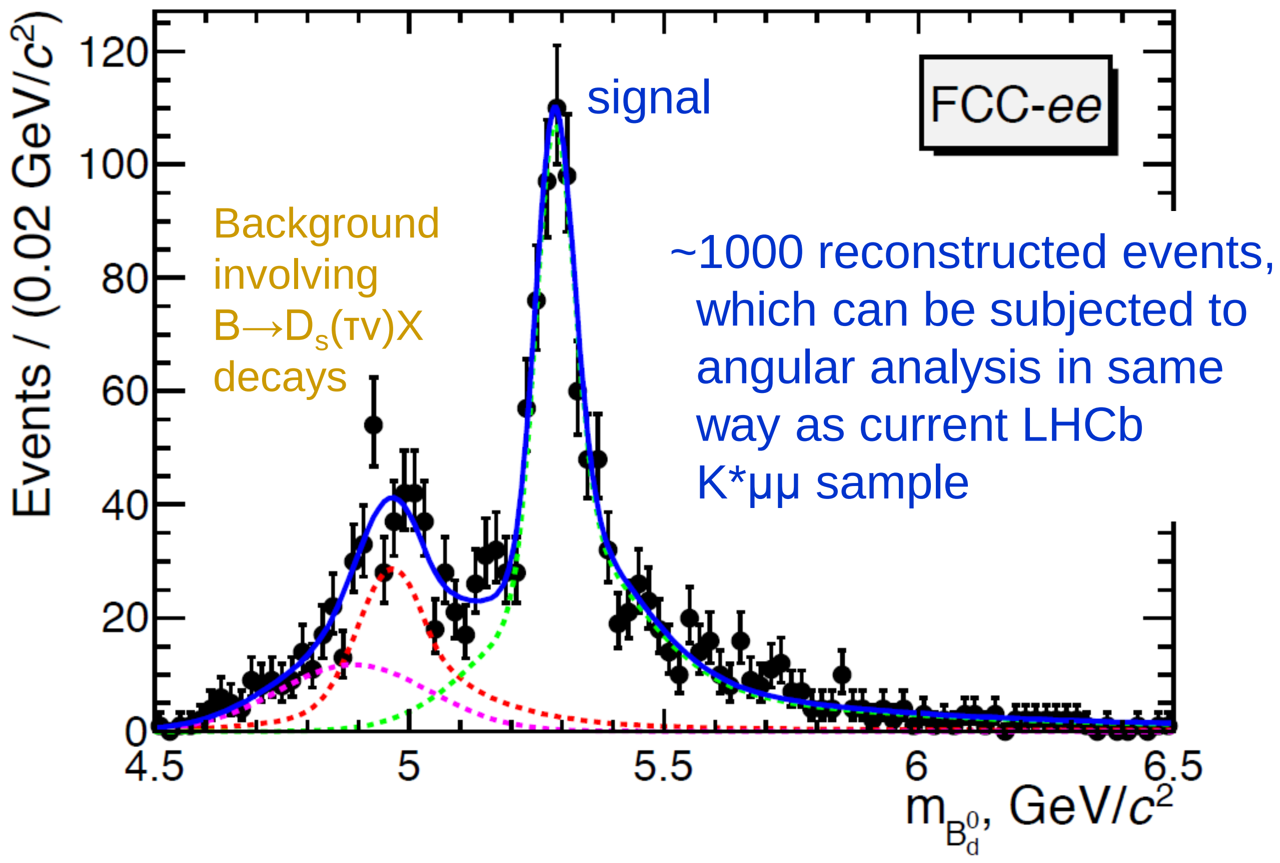
FCC-ee was initially conceived as a facility for precision-Higgs physics, but it could also operate at Z^0 with ultra-high luminosity (10^5 [!] above LEP). Extremely interesting possibilities for electroweak physics, and also b-physics.



[arXiv:1906.02693]

Opportunities at the Z pole: FCC-ee

100 ab^{-1} at Z pole → >10^{12} bbar pairs. Exciting b-physics programme, particularly promising for channels including neutrals & missing energy, *e.g.* $B_s \to \tau^+\tau^-$, $B^0 \to K^*\tau^+\tau^-$.



Conclusions

The last ~20 years has delivered a rich and extensive set of results in the field of quark-flavour physics.

The measurements are important because they both address many of the open questions of the Standard Model, and they are intrinsically sensitive to very high mass scales.

The programme is ongoing. Belle II and the LHCb Upgrades will bring great leap forwards in precision, and will make new observables accessible. New experiments in very different facilities will bring complementary information.

We are truly living through a golden age of flavour !

Backups

New Physics sensitivity through FCNCs

Improving sensitivity to the Wilson coefficient C_9 and the corresponding limits on New Physics mass scales, under different assumptions, from R_K and R_{K^*} .