Flavour Physics: A Taster

CERN Summer Student Lecture Programme 2023

Lecture 3 of 3: Flavour in the LHC era and beyond

17-19 July 2023

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Introduction

Yesterday we covered several key flavour physics ideas:

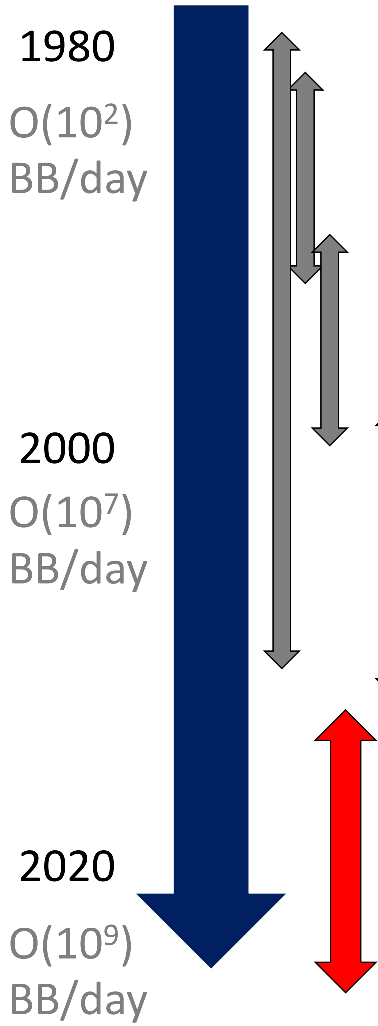
- CP violation in the SM (quark sector)
- Unitarity triangle(s)
- Measuring CKM phases
- B-factory measurements of β and α

Today we will discuss b (and c) physics in the LHC era (and beyond):

- Hadron colliders vs B-factories
- Mixing and CP violation in B_s^0 and D^0 mesons
- CKM angle gamma
- Rare decays and lepton universality
- The future

Part I: Flavour physics at hadron colliders

Overview of b experiments



Symmetric e^+e^- collider experiments: "Cleopatra" and "Caesar"

- CLEO experiments (CESR, Cornell, USA), 1980 – 2008
- ARGUS (DORIS II storage ring, DESY, Hamburg), 1982 – 1992
- LEP experiments (CERN), 1989 – 2000
  ALEPH, DELPHI, OPAL, L3

"**A R**ussian-**G**erman-**U**nited States-**S**wedish Collaboration"

Asymmetric B-factories (1999–2011):

- BaBar (PEP-II ring, SLAC, Stanford)
- Belle (KEK, Japan)

Tevatron Run II experiments ($p\bar{p}$ @ 2 TeV) at Fermilab, Chicago

- CDF and D0 (2001 – 2011)

LHC experiments, CERN, 2009 – (pp @ 7–14 TeV):

- LHCb dedicated to flavour physics
- ATLAS and CMS also doing B physics

Flavour physics at hadron colliders

	B Factories *Belle (1999-2010)* *BaBar (1999-2008)*	**Hadron colliders** *Tevatron (<2 TeV, 1983–2011)* *LHC (<14 TeV, 2008–)*
Collision environment	Asymmetric $e^+e^- \rightarrow \Upsilon(4S)$ Clean! Pure $B\bar{B}$ event ✓	pp or $p\bar{p}$ (also ions…) Busy! Proton remnants give background particles
Flavour tagging (initial B^0 or $\bar{B}^0$)	Excellent ✓ (30% ‘tagging power’)	Challenging (~5%)

Flavour physics at hadron colliders

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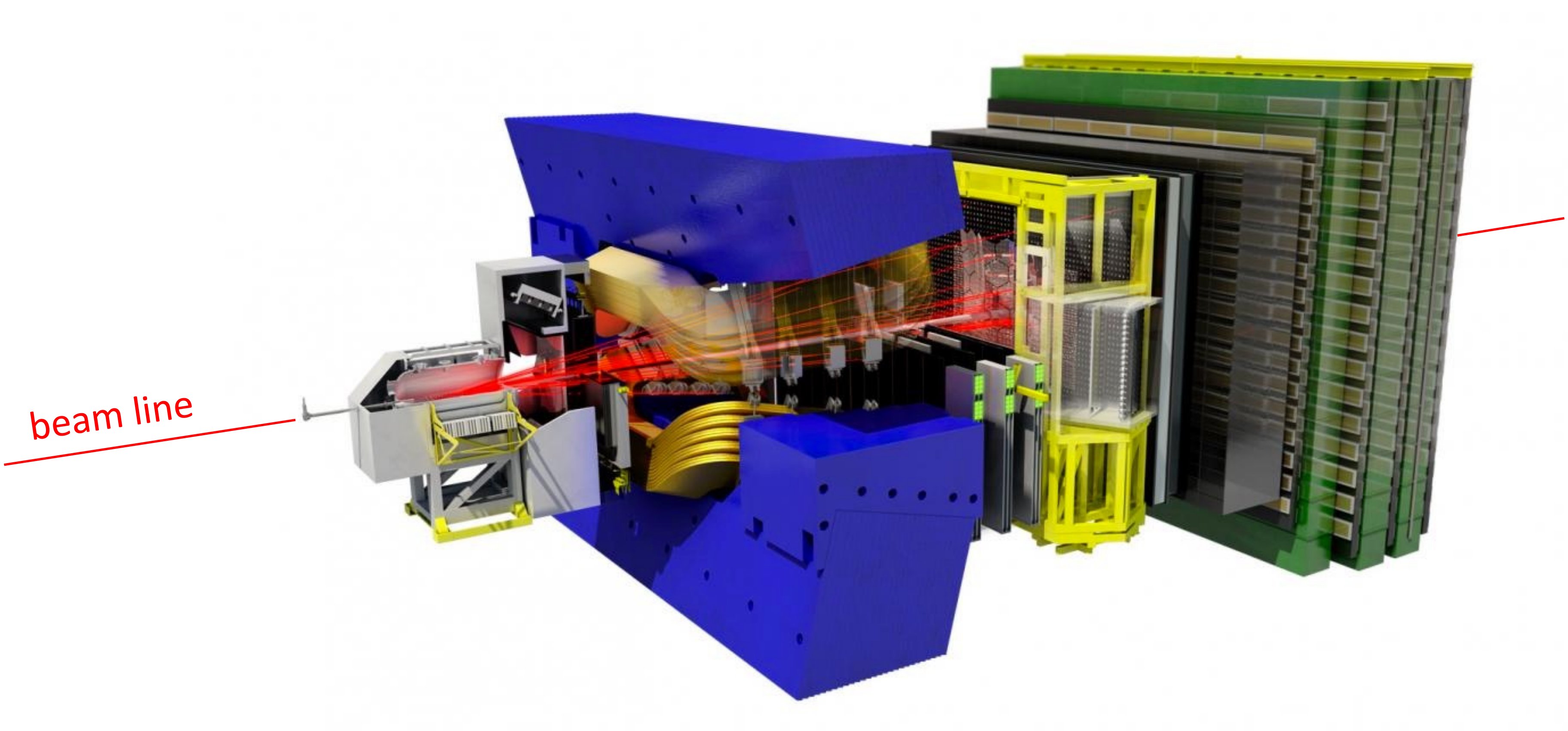
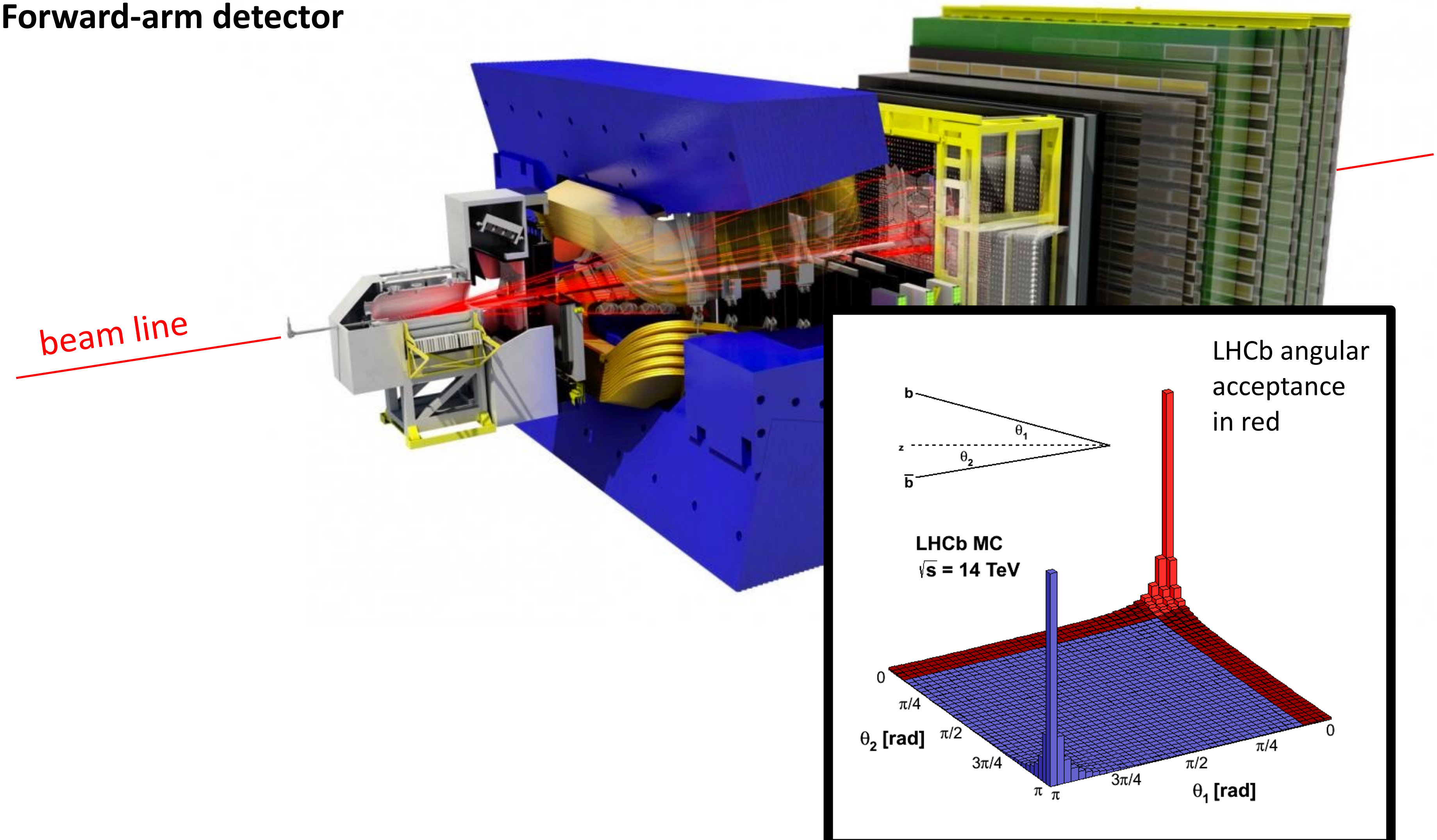
Flavour tagging (initial B^0 or $\bar{B}^0$)	Excellent ✓ (30% 'tagging power')	Challenging (~5%)
Production σ(B)	1 nb	~100–500 μb ✓
B hadron boost	Small ($\beta\gamma \approx 0.5$)	Large ($\beta\gamma \approx 100$) ✓
B hadrons created	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	$B^\pm$ (40%), B^0 (40%), B_s^0 (10%) ✓ b baryons (10%)

LHCb experiment (v2010-2018)



LHCb experiment

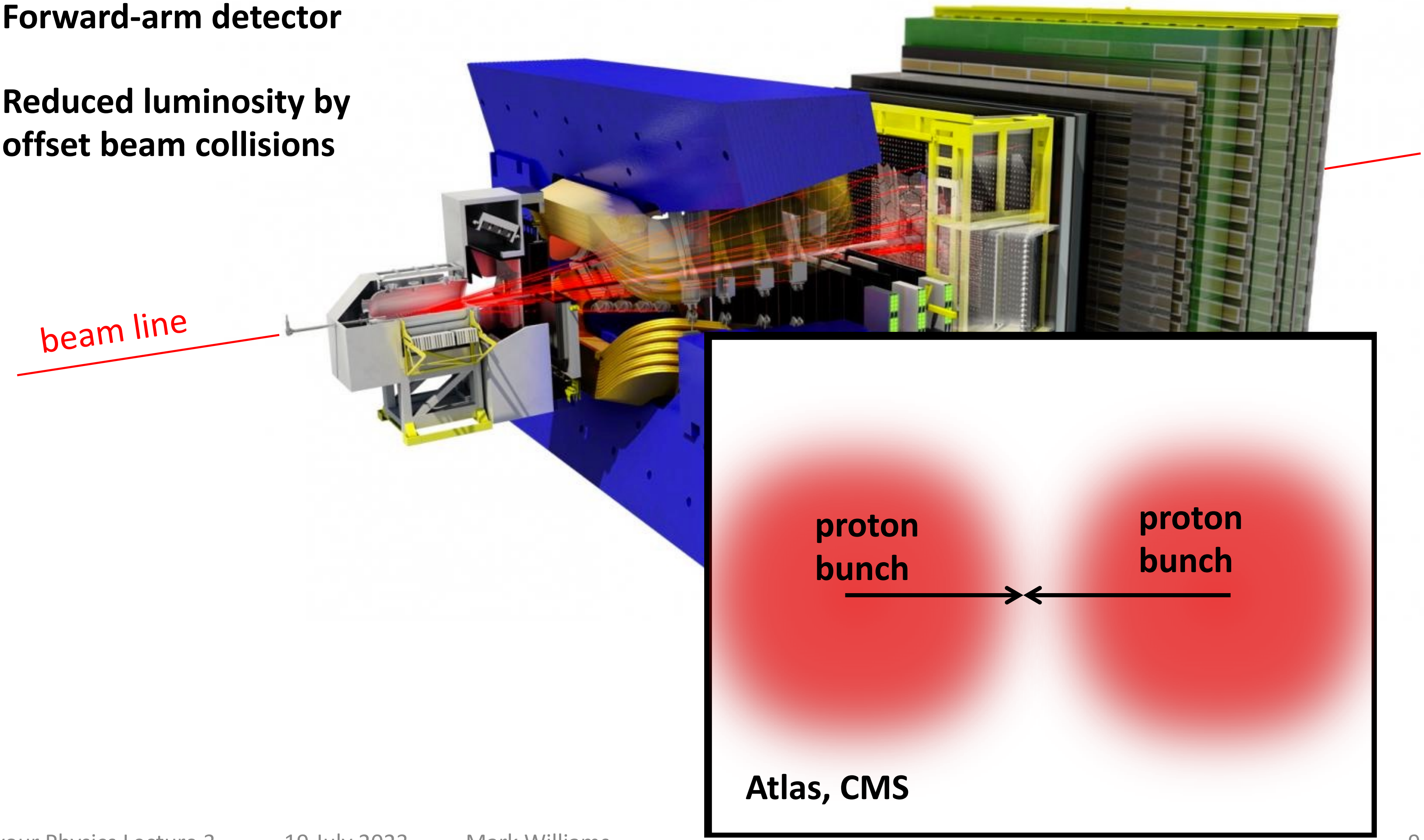
Forward-arm detector



LHCb experiment

Forward-arm detector

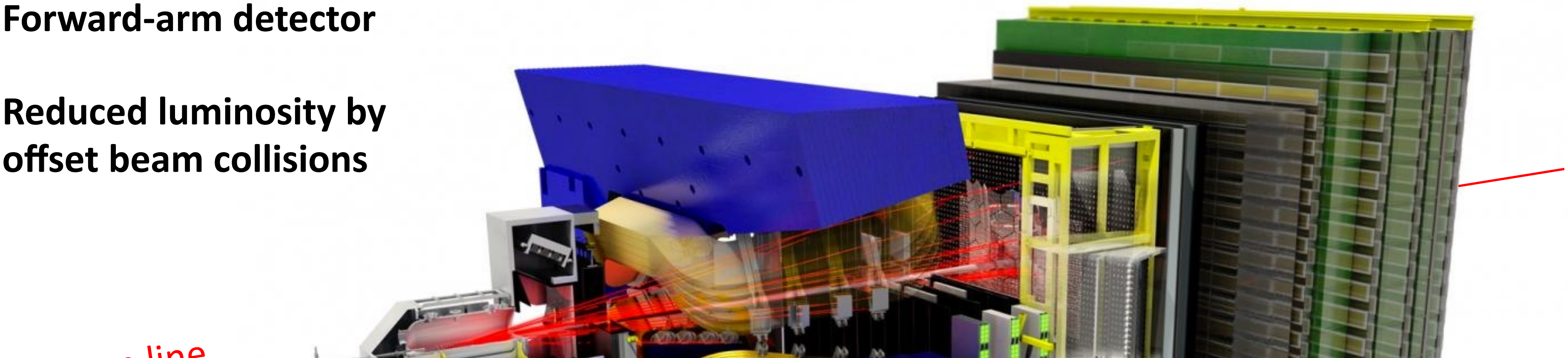
Reduced luminosity by offset beam collisions



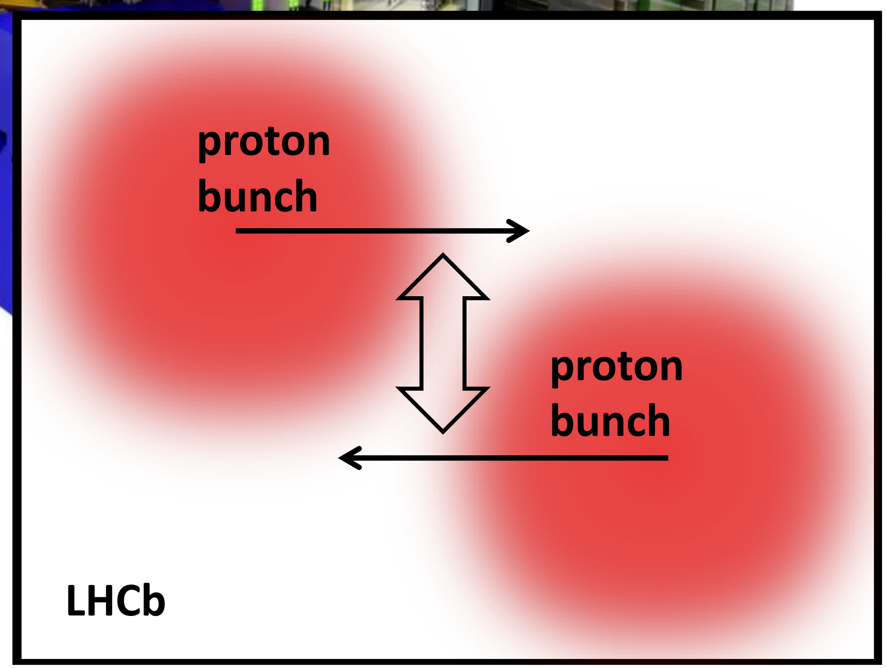
LHCb experiment

Forward-arm detector

Reduced luminosity by offset beam collisions



Beams move closer as intensity reduces over time ⇒ luminosity levelling

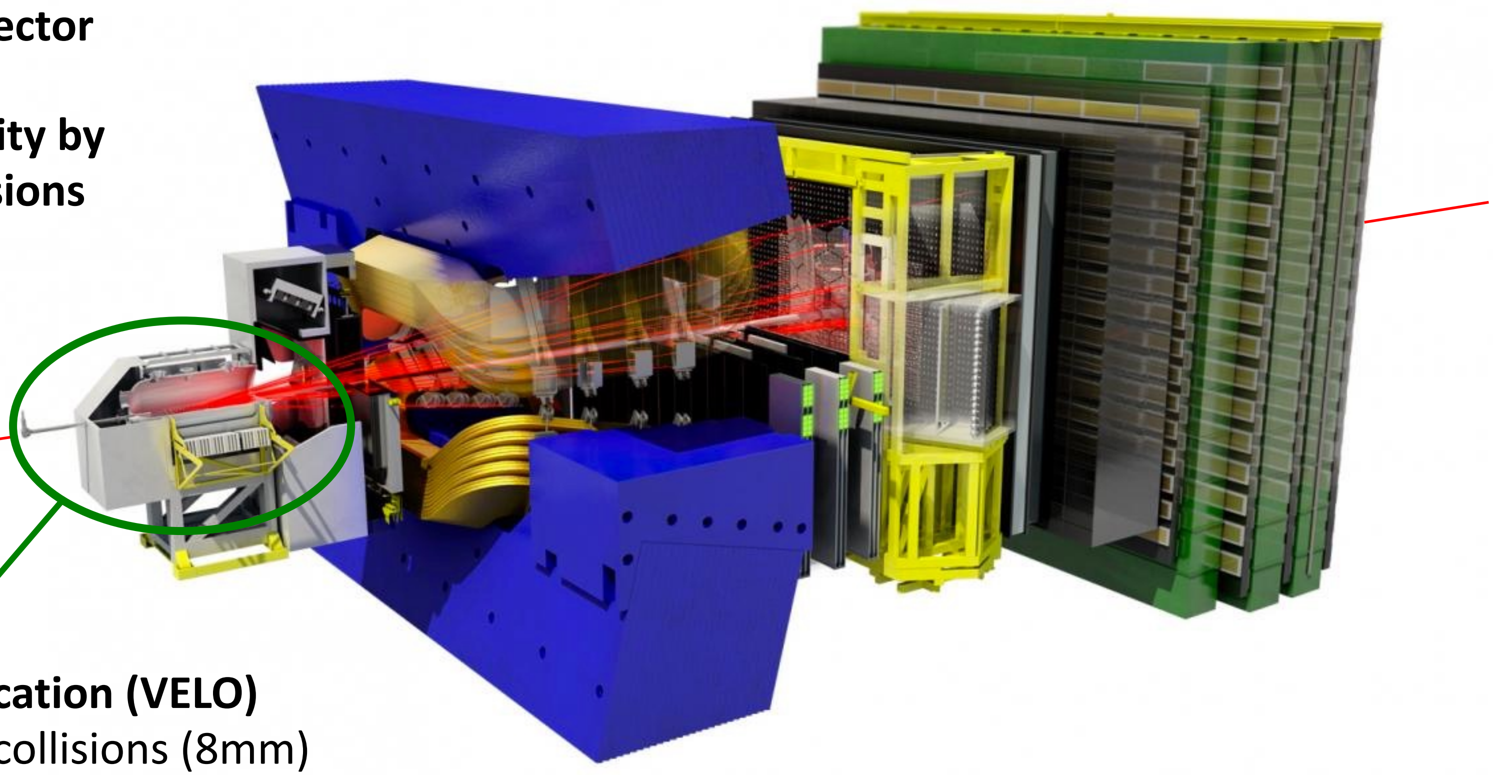


LHCb experiment

Forward-arm detector

Reduced luminosity by offset beam collisions

beam line

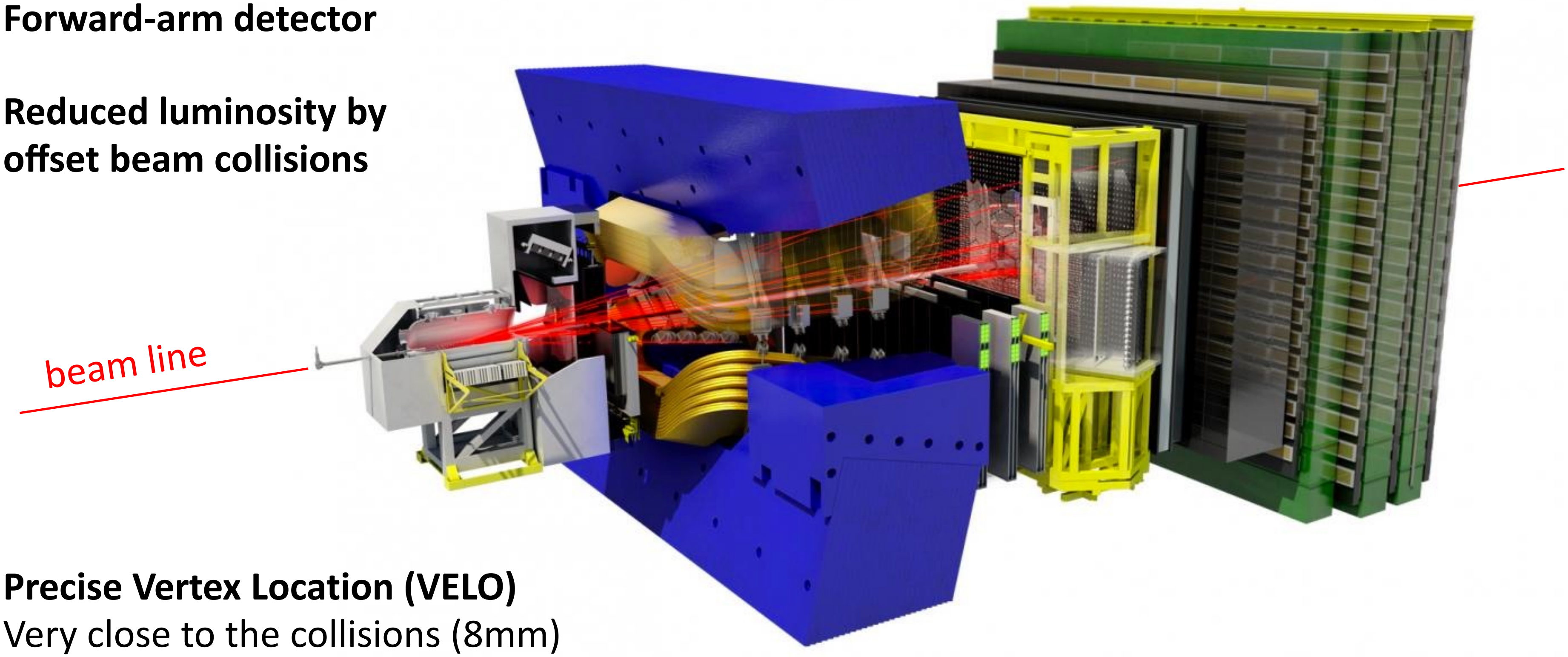


Precise Vertex Location (VELO)
Very close to the collisions (8mm)
→ must be moved away for safety every time beam is injected (!)

LHCb experiment

Forward-arm detector

Reduced luminosity by offset beam collisions



Precise Vertex Location (VELO)
Very close to the collisions (8mm)
→ must be moved away for safety every time beam is injected (!)

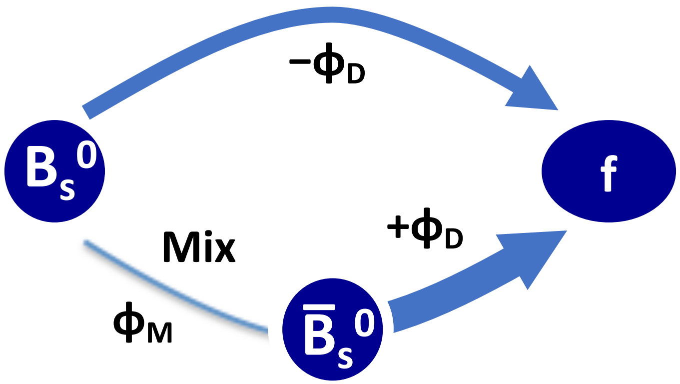
Excellent particle identification using Cherenkov radiation to measure particle speed

Powerful software-based trigger – make decisions using full event reconstruction

Part IIa: CP violation in B_s^0 mesons

CP violation in B_s^0 mixing

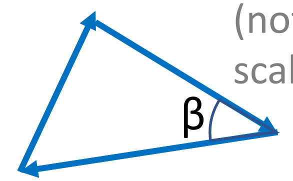
B_s^0 equivalent of sin(2β) measurement



For B_s^0 system, we are dealing with a different unitarity triangle from B^0

B^0 case: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ ⇒ angles α,β,γ

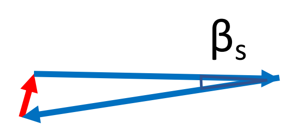
$O(\lambda^3)$ $O(\lambda^3)$ $O(\lambda^3)$



(not to scale!)

B_s^0 case: $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$ ⇒ angles $\alpha_s,\beta_s,\gamma_s$

$O(\lambda^4)$ $O(\lambda^2)$ $O(\lambda^2)$

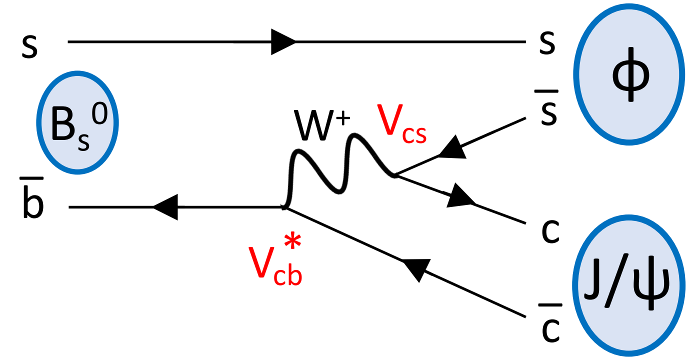


In fact we measure $\phi_s = \phi_M - 2\phi_D$ BUT for tree-level decays $b \rightarrow c\bar{c}s$: $\boxed{\phi_s = -2\beta_s}$

⇒ Just as with sin(2β) we need to pick a 'golden mode'

CP violation in $B_s^0 \to J/\psi\phi$

Decay similar to $B^0 \to J/\psi\, K_S^0$
with spectator quark exchange $d \to s$



Extra challenge – final state is not CP eigenstate
⇒ need to analyse angular distributions to disentangle three CP states

In SM, ϕ_s is not independent variable
⇒ highly constrained by CKM mechanism
(only 4 free parameters)

$$-2\beta_s = -2\arg(-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*))$$

$$= -0.0369\,^{+0.0007}_{-0.0010}\ \text{rad}\quad \text{(SM)}$$

$B_s^0 \to J/\psi\ \phi$

Pseudoscalar (spin 0)

Vector (spin 1)

Vector (spin 1)

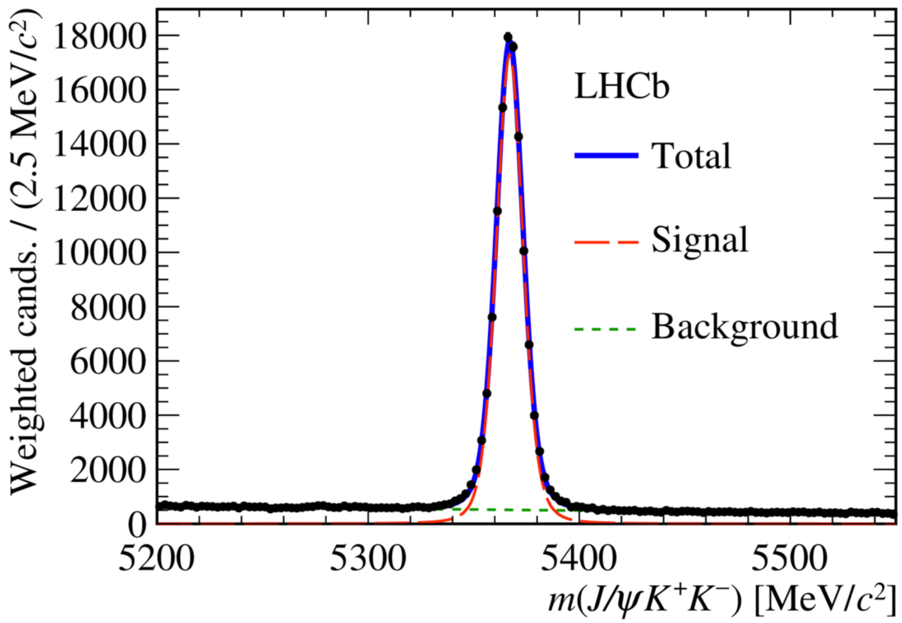
↑↑: L=2, CP even, amplitude $A_{||}(t)$
↑↓: L=0, CP even, $A_0(t)$
↑→: L=1, CP odd, $A_\perp(t)$

CP violation in $B_s^0 \to J/\psi\phi$

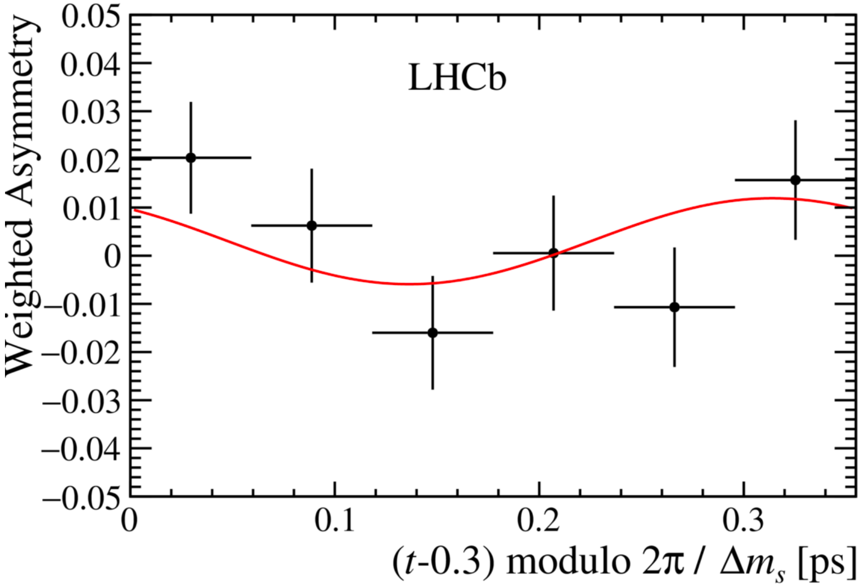
Clean decay mode: $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$

⇒ muons provide good trigger signature
⇒ ATLAS & CMS join the party!

https://doi.org/10.1140/epjc/s10052-019-7159-8



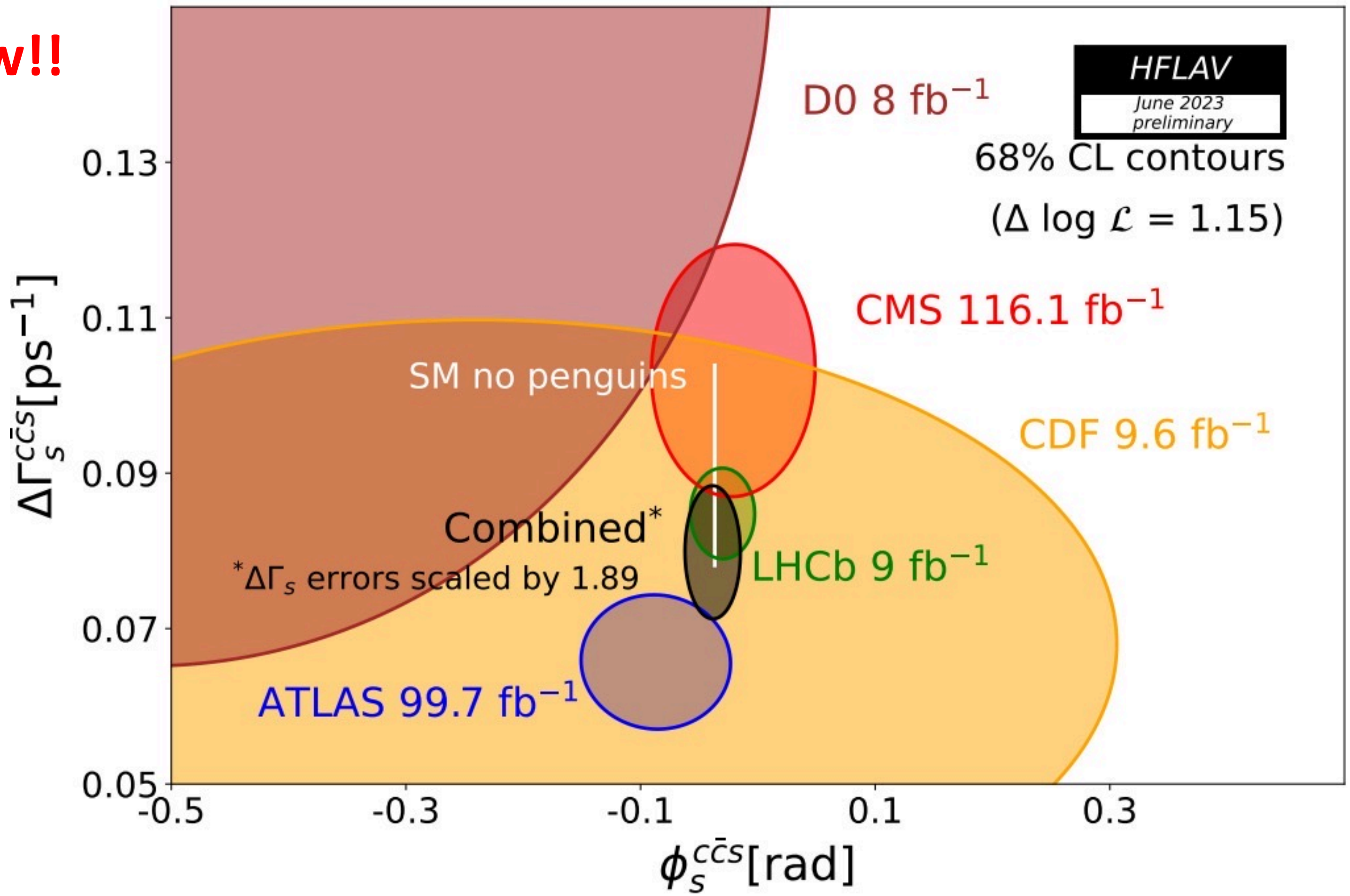
High-purity signal



Asymmetry vs decay time [c.f. sin(2β)]
No significant asymmetry ⇒ $\phi_s \approx 0$

CP violation in $B_s^0 \to J/\psi\phi$

New!!



World averages: (provisional) **$\phi_s = -0.039 \pm 0.016$ rad** **$\Delta\Gamma_s = 0.082 \pm 0.005$ ps^{-1}**

https://indico.cern.ch/event/1281612/
CERN Seminar 13 June 2023

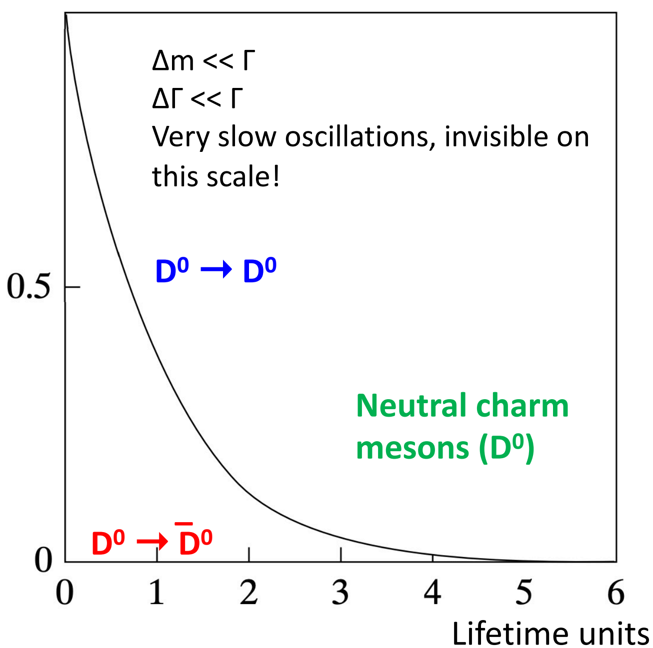
Part IIb: Charm mixing and CPV

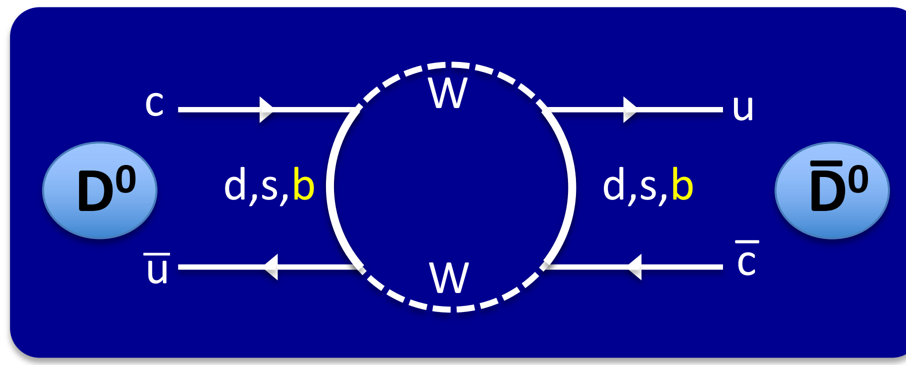
Charm mixing and CP violation

We've covered strange (K^0) and beauty (B^0, B_s^0) physics: what about the charm quark?

Neutral charm meson (D^0) can oscillate

but… both Δm and $\Delta\Gamma$ are tiny
⇒ very hard to observe oscillations





Why is charm mixing so suppressed?

Combination of:

- **CKM suppression** (contribution of b-quark loop suppressed by $V_{cb}V_{ub}$ ~$\lambda^2\ \lambda^3$)
- **GIM suppression** (d and s quarks have similar masses, so amplitudes nearly cancel)

The final frontier in meson mixing

Charm mixing

Remember the 'master' equation derived for the B^0 case (but general):

D^0 at t=0: $\Gamma(D(t) \rightarrow f) \propto e^{-\Gamma t}$

$$\times \left[\cosh(\Delta\Gamma t/2) + A_{CP}^{dir} \cos(\Delta m t) + A_{\Delta\Gamma} \sinh(\Delta\Gamma t/2) + A_{CP}^{mix} \sin(\Delta m t) \right]$$

$\overline{D}^0$ at t=0: $\Gamma(\overline{D}(t) \rightarrow f) \propto e^{-\Gamma t}$

$$\times \left[\cosh(\Delta\Gamma t/2) - A_{CP}^{dir} \cos(\Delta m t) + A_{\Delta\Gamma} \sinh(\Delta\Gamma t/2) - A_{CP}^{mix} \sin(\Delta m t) \right]$$

For charm, both Δm and $\Delta\Gamma$ are small: **$x = \Delta m/\Gamma$ $< 1\%$**

$y = \Delta\Gamma/2\Gamma$ $< 1\%$

Charm mixing

Remember the ‘master’ equation derived for the B^0 case (but general):

D^0 at t=0: $\Gamma(D(t) \to f) \propto e^{-\Gamma t}$

$$\times \left[\underset{1+\frac{1}{2}(2y\Gamma t)^2}{\cancel{\cosh(\Delta\Gamma t/2)}} + A_{CP}^{dir} \underset{1-\frac{1}{2}(x\Gamma t)^2}{\cancel{\cos(\Delta m t)}} + A_{\Delta\Gamma} \underset{y\Gamma t}{\cancel{\sinh(\Delta\Gamma t/2)}} + A_{CP}^{mix} \underset{x\Gamma t}{\cancel{\sin(\Delta m t)}} \right]$$

$\overline{D}^0$ at t=0: $\Gamma(\overline{D}(t) \to f) \propto e^{-\Gamma t}$

$$\times \left[\underset{1+\frac{1}{2}(2y\Gamma t)^2}{\cancel{\cosh(\Delta\Gamma t/2)}} - A_{CP}^{dir} \underset{1-\frac{1}{2}(x\Gamma t)^2}{\cancel{\cos(\Delta m t)}} + A_{\Delta\Gamma} \underset{y\Gamma t}{\cancel{\sinh(\Delta\Gamma t/2)}} - A_{CP}^{mix} \underset{x\Gamma t}{\cancel{\sin(\Delta m t)}} \right]$$

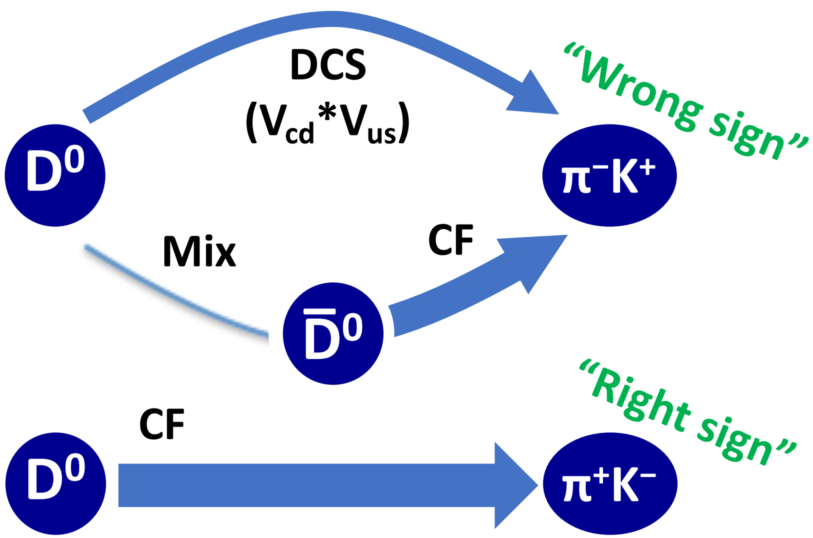
For charm, both Δm and $\Delta\Gamma$ are small: **$x = \Delta m/\Gamma$ < 1%**

$y = \Delta\Gamma/2\Gamma$ < 1%

⇒ Quadratic time dependence is very good approximation

Charm mixing: Wrong-sign Kπ

Charm mixing and CPV



Pick decay with two amplitudes that can interfere (one with oscillation)

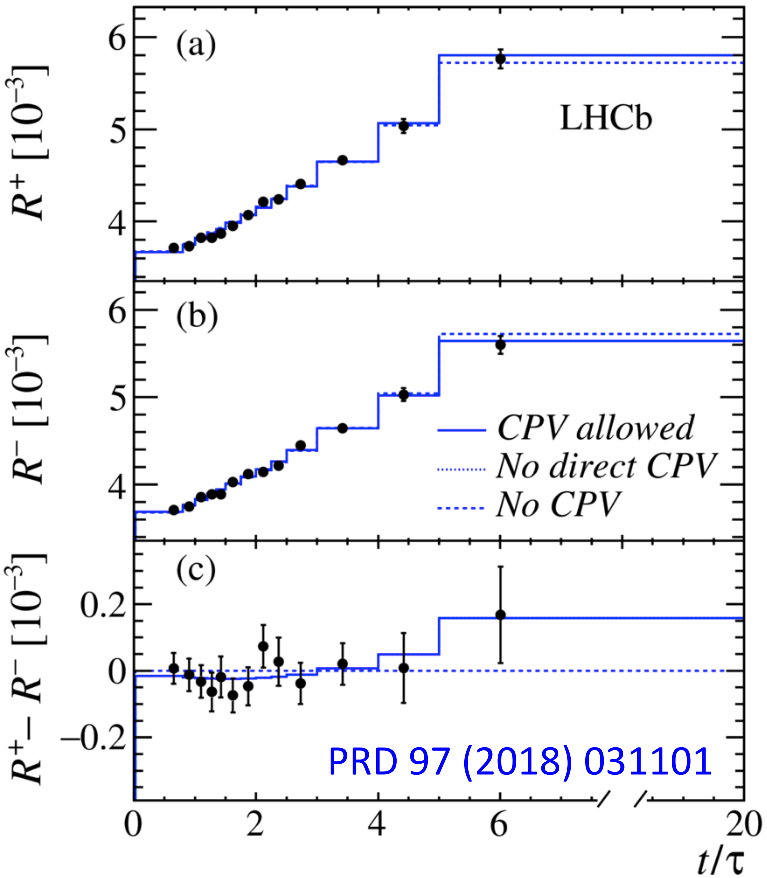
Plot ratio to non-oscillated decay $D^0 \to K^-\pi^+$

- Mixing ⇒ quadratic time dependence
- CP violation ⇒ different for D^0 and $\bar{D}^0$

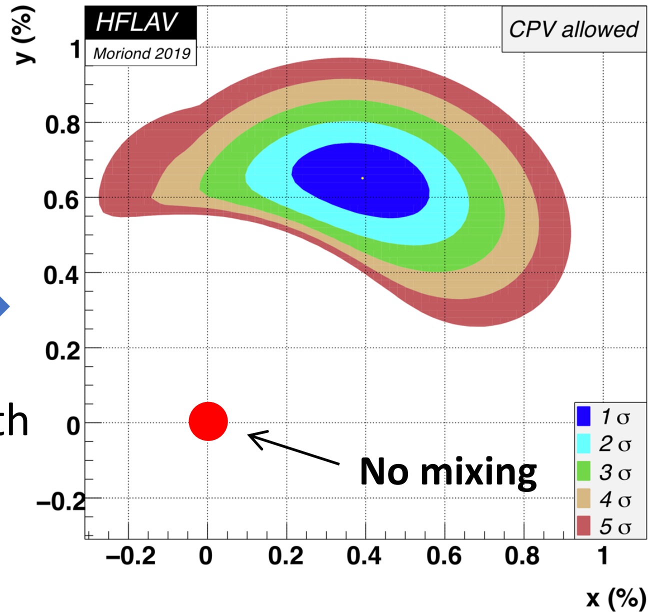
$$R(t) \;\; = \underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}y'\left(\frac{t}{\tau}\right)}_{\text{Interference term}} + \underbrace{\frac{x'^{\,2} + y'^{\,2}}{4}\left(\frac{t}{\tau}\right)^2}_{\text{Mix+CF}}$$

Charm mixing: Wrong-sign Kπ

Charm mixing and CPV

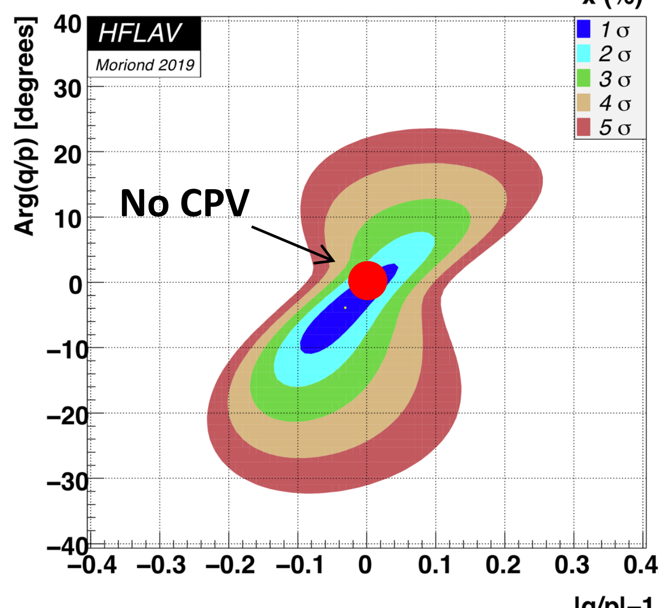


Combine with other measurements



⇒ x≤0 excluded with 3.1σ significance

No sign of CPV in charm mixing or interference ⇒ need more precision!



Charm mixing: state-of-the-art

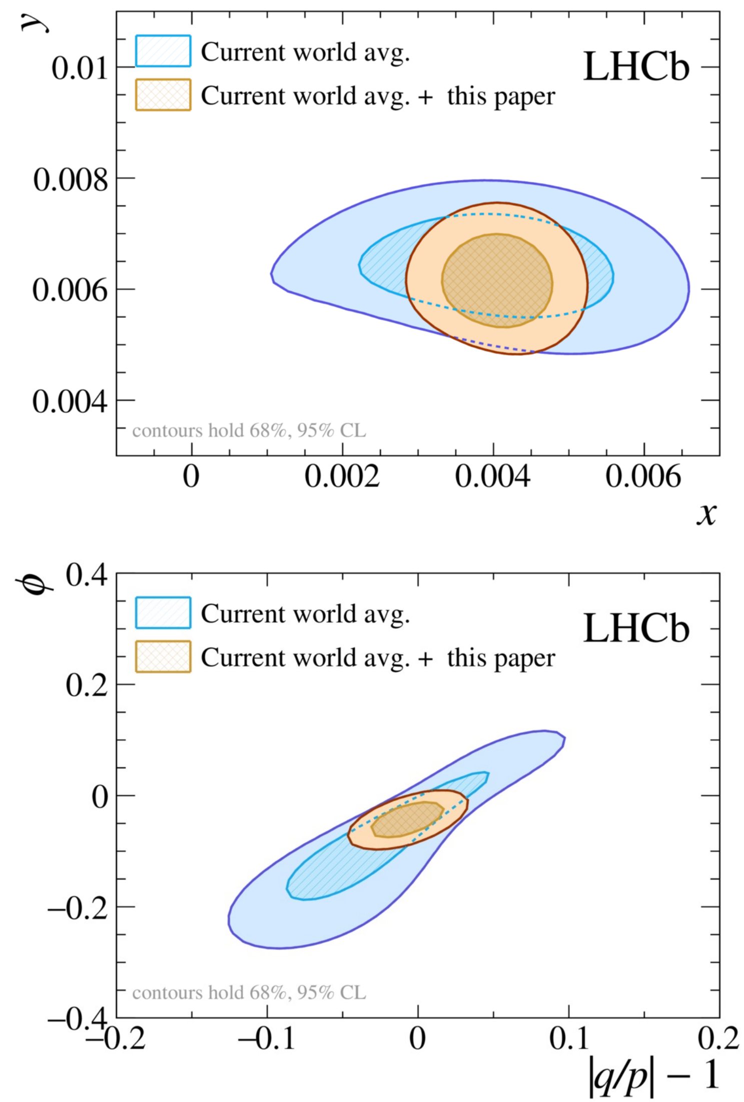
Recently LHCb published analysis of 'Golden mode' $D^0 \rightarrow K_S^0\pi^+\pi^-$
(see back-up slides)

Large impact on world-averages for mixing and CP violation parameters

First measurement of non-zero x (and Δm) (>7σ significance)

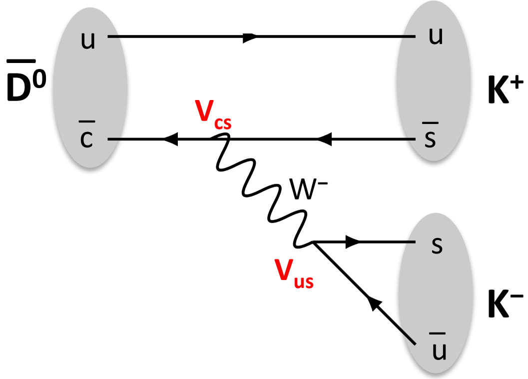
Oscillation period ~630ps
(D^0 lifetime 0.4ps)

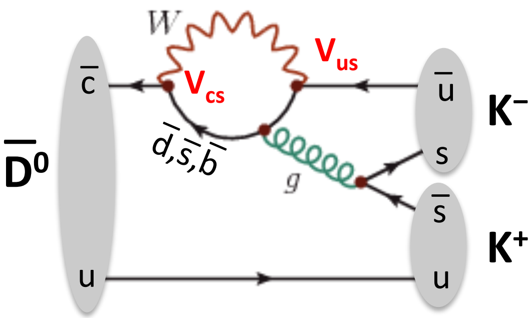
arXiv:2106.03744
Phys. Rev. Lett. 127, 111801



CP violation in charm decays

Ingredients:

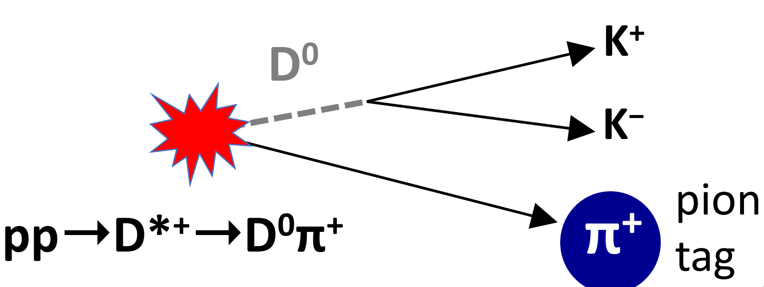




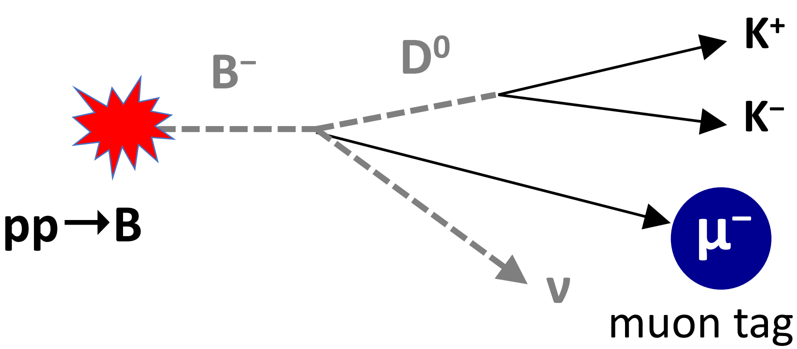
(1) Two amplitudes with same final state ⇒ interference

(2) Knowledge of flavour (D^0 or $\overline{D}^0$) at production

π-tagged ("prompt charm")



μ-tagged ("charm from B")



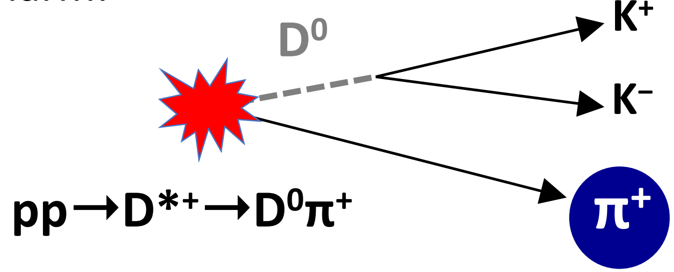
CP violation in charm decays

$$A_{CP}(D^0 \to f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

Ingredients:

(3) Detailed knowledge of production and detector asymmetries

e.g. for prompt charm:



$A_{Raw}(KK) = \mathbf{A_{CP}(KK)} + A_{Prod}(pp \to D^*) + A_{Det}(\pi_{tag})$

$A_{Raw}(\pi\pi) = \mathbf{A_{CP}(\pi\pi)} + A_{Prod}(pp \to D^*) + A_{Det}(\pi_{tag})$

CP violation in charm decays

Ingredients:

$$A_{CP}(D^0 \to f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

(3) Detailed knowledge of production and detector asymmetries

$$A_{Raw}(KK) = \mathbf{A_{CP}(KK)} + A_{Prod}(pp \to D^*) + A_{Det}(\pi_{tag})$$

$$A_{Raw}(\pi\pi) = \mathbf{A_{CP}(\pi\pi)} + A_{Prod}(pp \to D^*) + A_{Det}(\pi_{tag})$$

OR Clever method to eliminate them…

$$\boxed{\Rightarrow \quad A_{Raw}(KK) - A_{Raw}(\pi\pi) = \mathbf{A_{CP}(KK) - A_{CP}(\pi\pi) \equiv \Delta A_{CP}}}$$

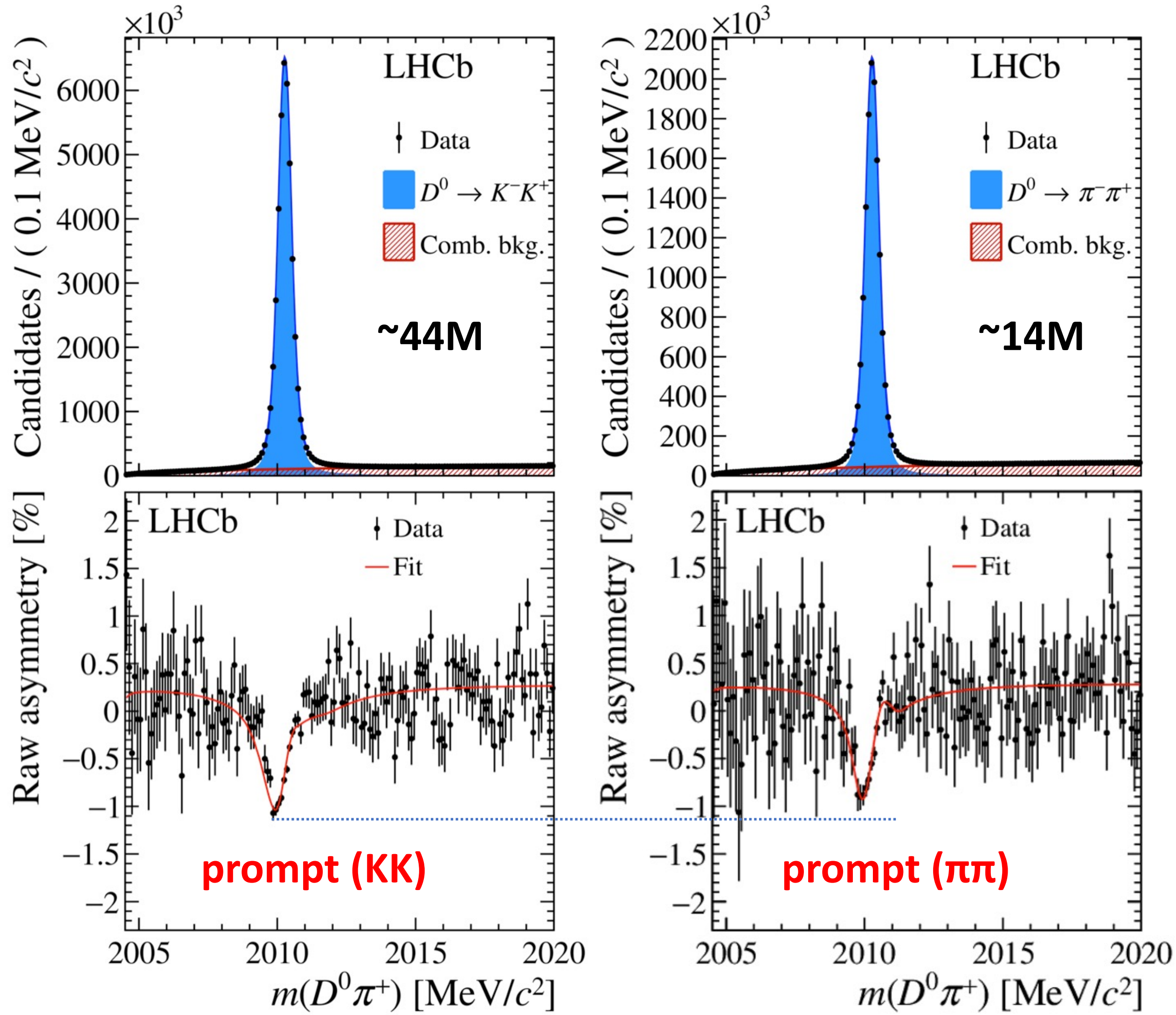
CP violation in charm decays

Huge (>10M) signal samples, high purity

$\Delta A_{CP} = (-0.154 \pm 0.029)\%$

Inconsistent with CP symmetry at 5.3σ significance ⇒ discovery!

Q: Is this from SM?
A: Not yet clear!



PRL 122 (2019) 211803

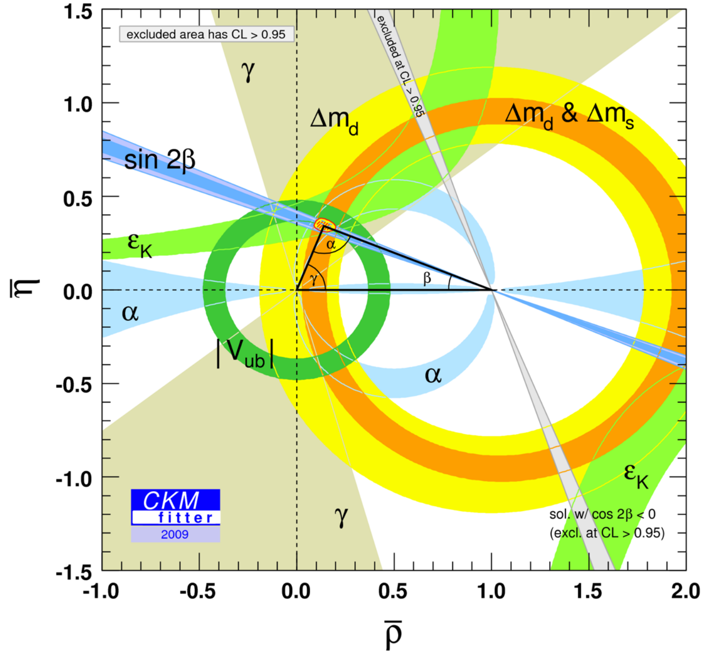
Part IIc: CKM angle γ

CKM angle γ

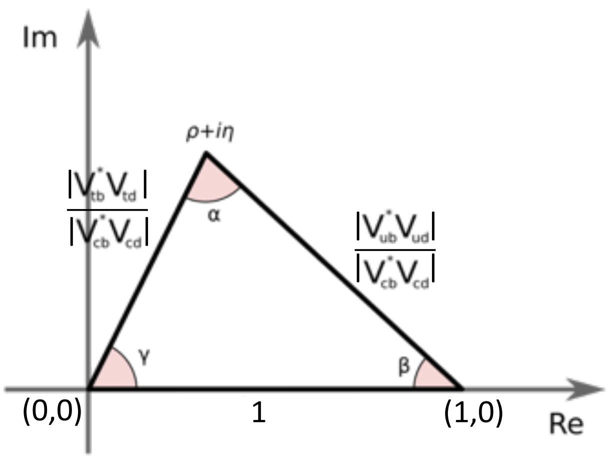
At the start of the LHC era:

- The least experimentally constrained angle
- The most precisely predicted angle (negligible theory errors)

$\sigma_{\text{theory}}(\gamma) \approx 10^{-7}$ rad https://arxiv.org/abs/1308.5663



Reminder:



$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

CKM angle γ

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$b \rightarrow cW$ transitions, with B^0 mixing
(e.g. $B^0 \rightarrow J/\psi\ K_S^0$)

$b \rightarrow uW$ transitions, with B^0 mixing
(e.g. $B^0 \rightarrow \pi^+\pi^-$)

No top loop needed! – can extract in tree-level decays ($b \rightarrow cW$ vs $b \rightarrow uW$)
⇒ Very clean SM test

Measure γ in tree-level processes ⇒ precise SM benchmark

Measure γ in loop processes ⇒ sensitive to NP

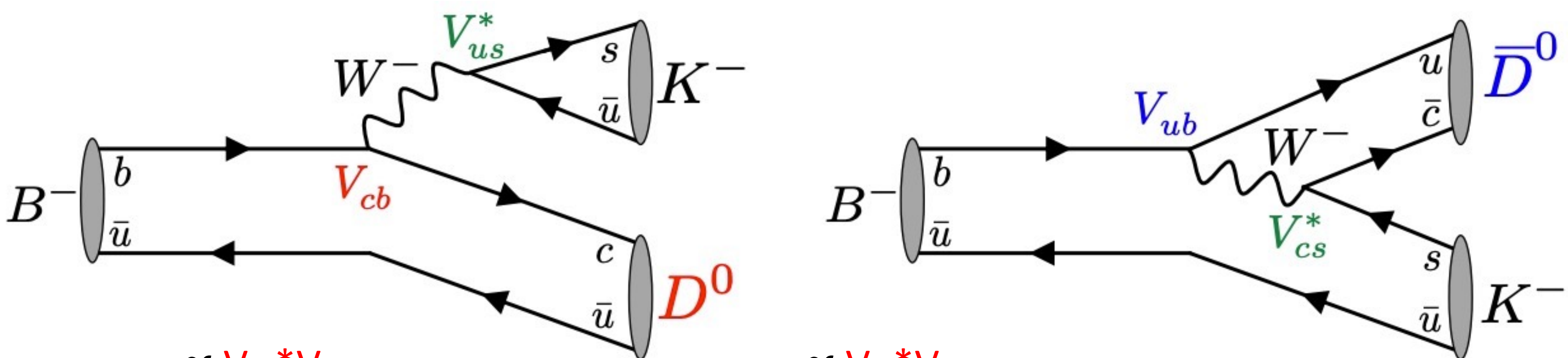
Precise γ studies were a major motivation for building the LHCb experiment

Measuring γ

Require interference between **b→cW** and **b→uW**

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Textbook case is **$B^\pm \to \overset{(-)}{D}{}^0 K^\pm$**



$\propto V_{us}{}^*V_{cb}$ $\propto V_{cs}{}^*V_{ub}$

Transitions have different final states (D^0 vs $\bar{D}^0$)

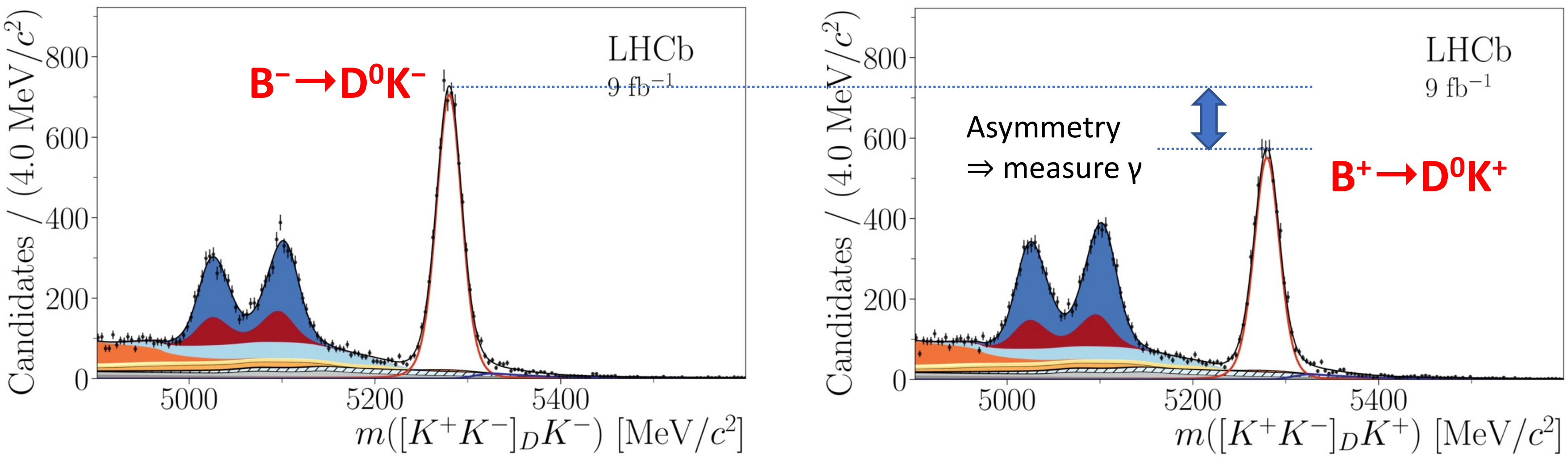
Interference **if** D^0 and $\bar{D}^0$ decay to **same final state *f***

Many different methods and decay channels – best results from combination

Measuring γ

Sensitivity to γ without time-dependent analysis – see asymmetries in yields!

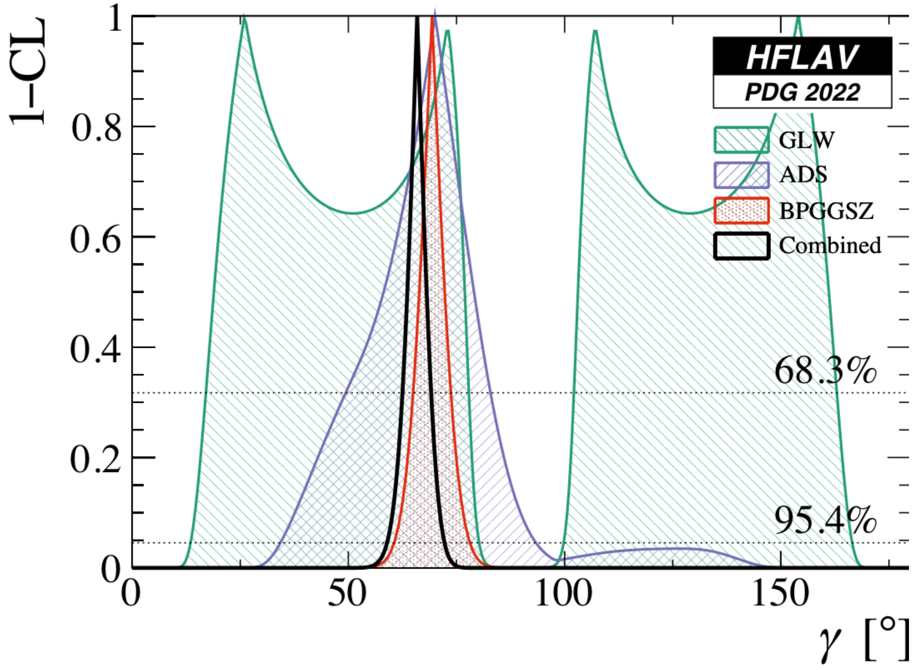
⇒ Can convert measured yields into precise γ measurement



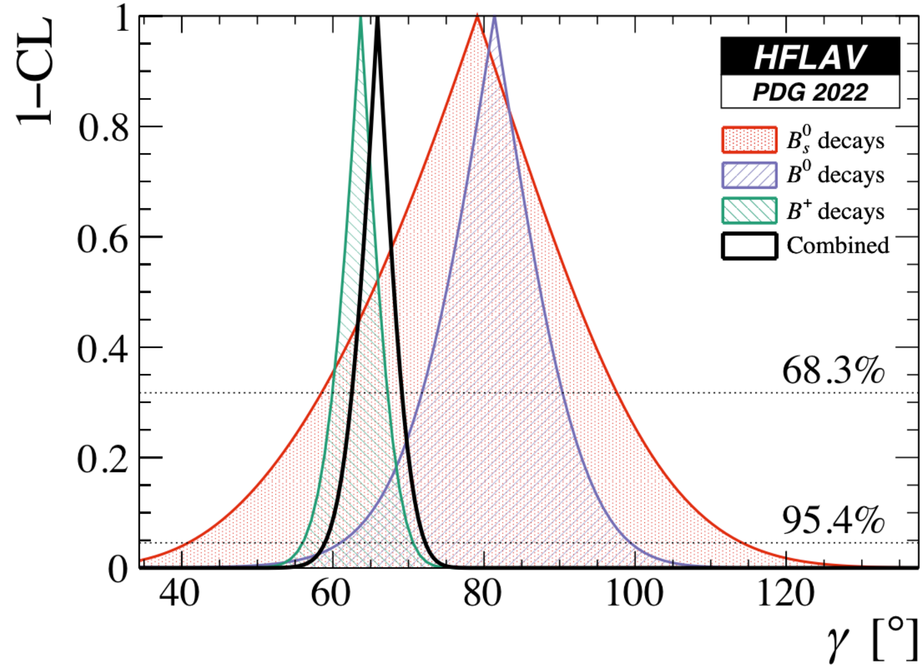
https://doi.org/10.1007/JHEP04(2021)081 (2021)

Combining all γ measurements

Split by method:



Split by B species:

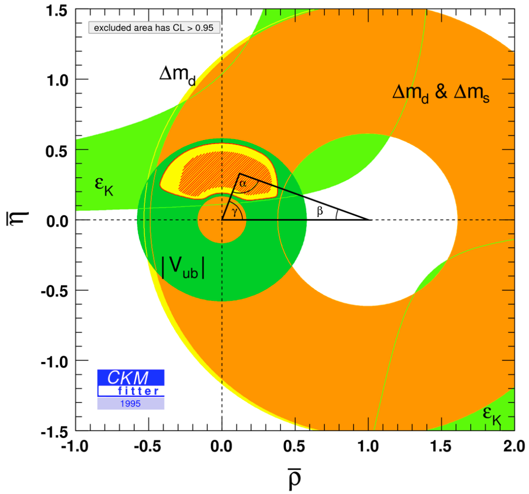


Combining all measurements: $\gamma = (65.9^{+3.3}_{-3.5})^\circ$

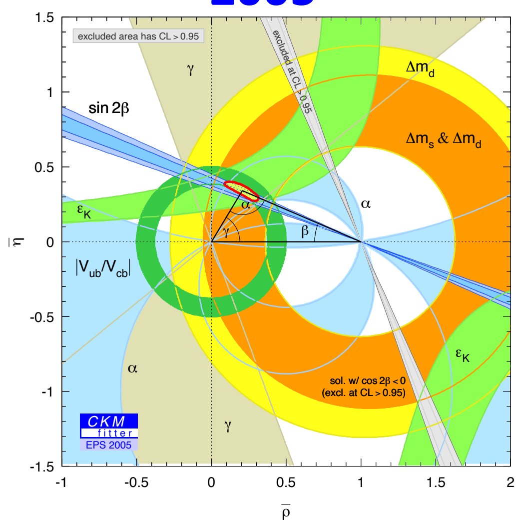
Indirect constraints: $\gamma = (65.5^{+1.1}_{-2.7})^\circ$ i.e. all other unitarity triangle measurements

Unitarity triangle fits through time

1995



2005

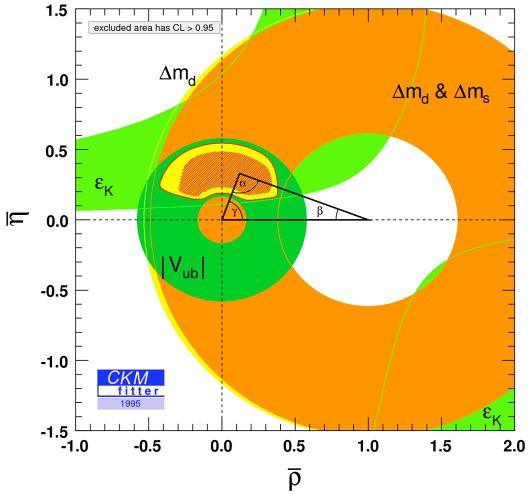


Before B-factories: minimal constraints

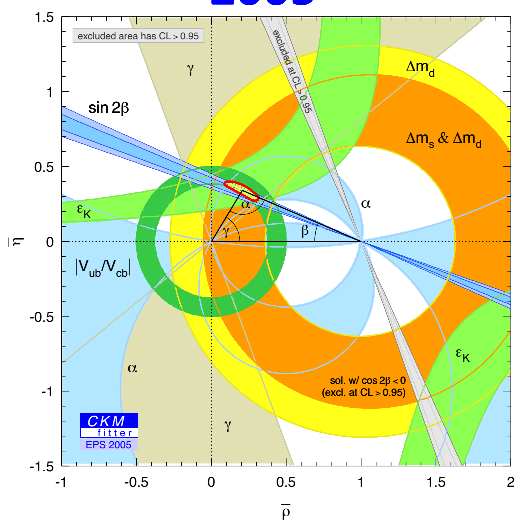
+ B-factory measurements of CKM angles

Unitarity triangle fits through time

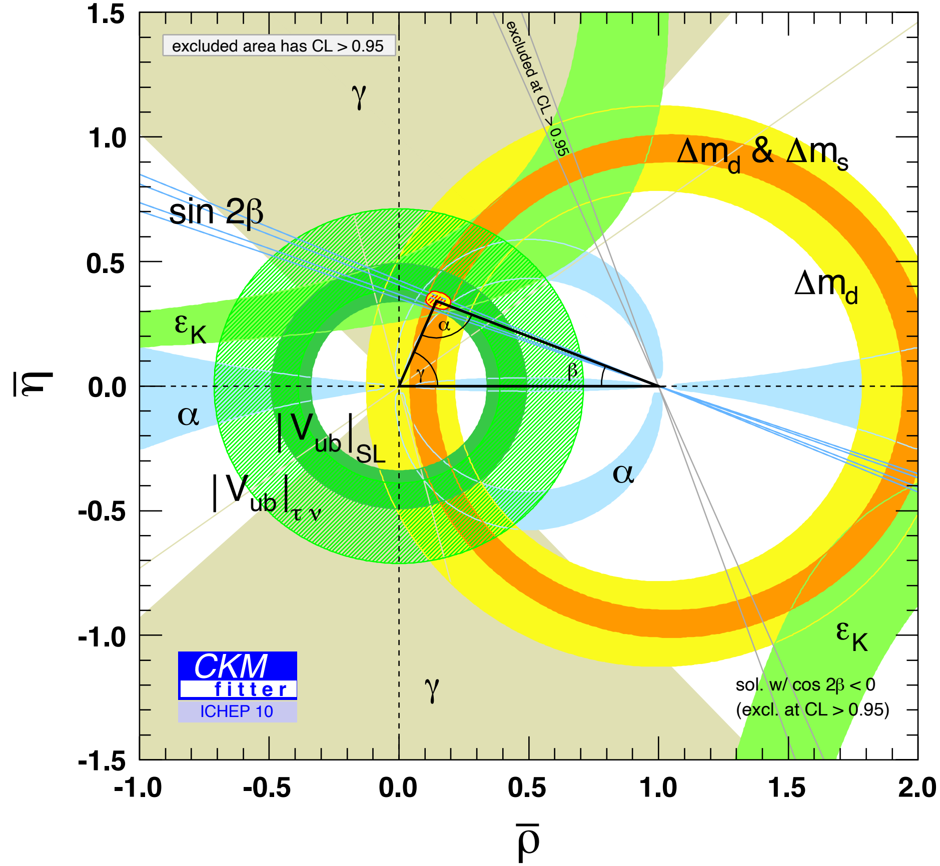
1995



2005



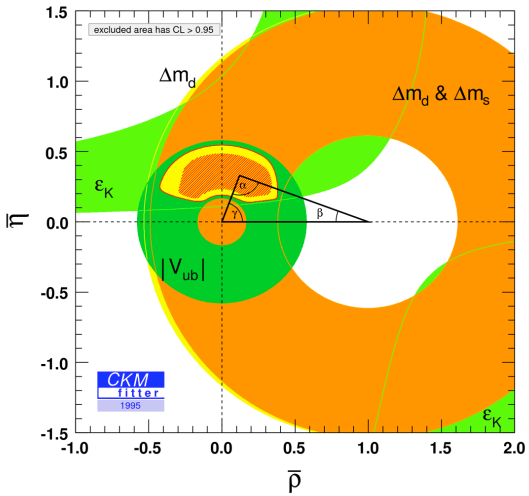
2010



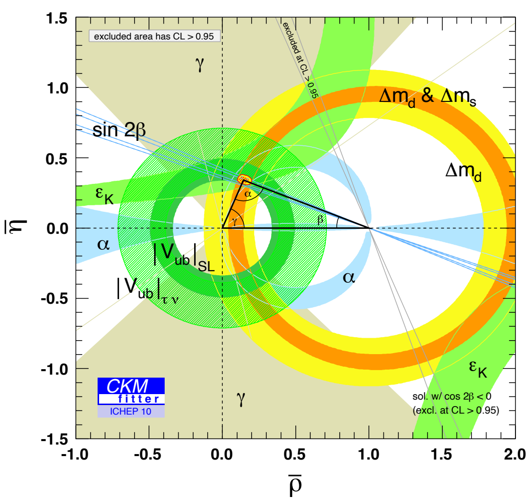
+ B_s^0 mixing from Tevatron
+ more B-factory inputs on angles

Unitarity triangle fits through time

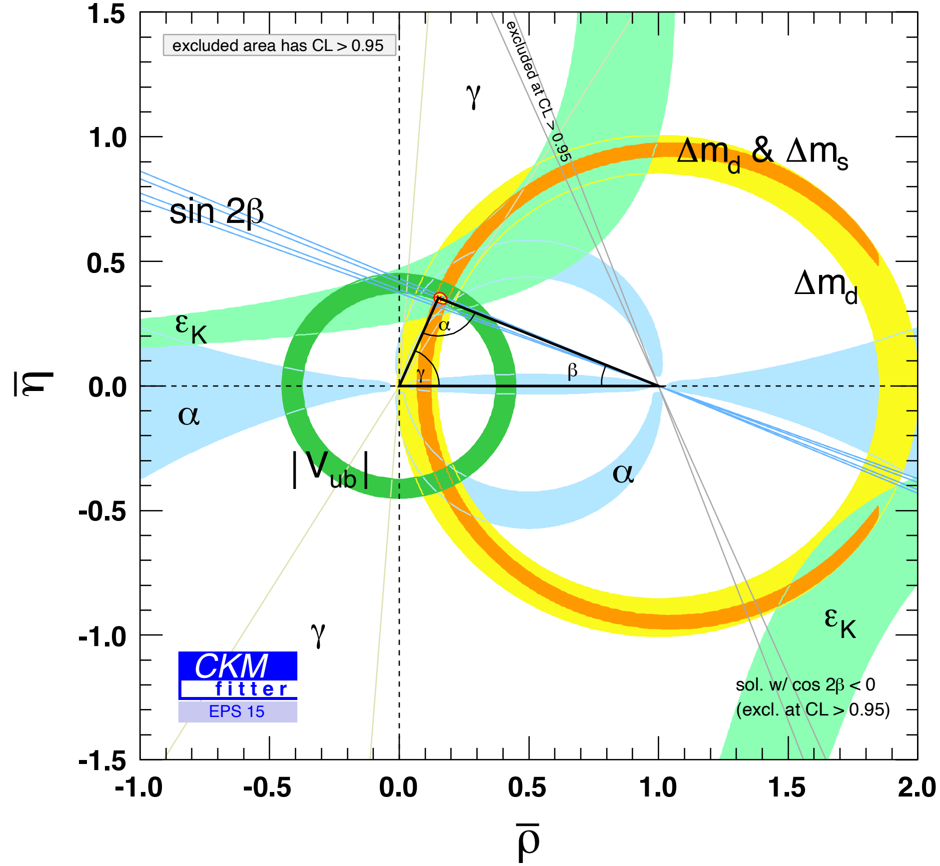
1995



2010



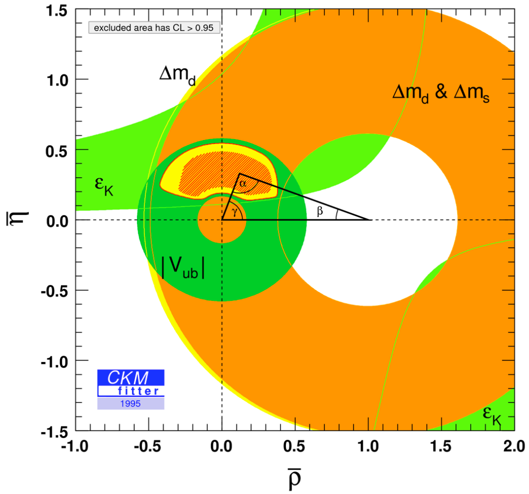
2015



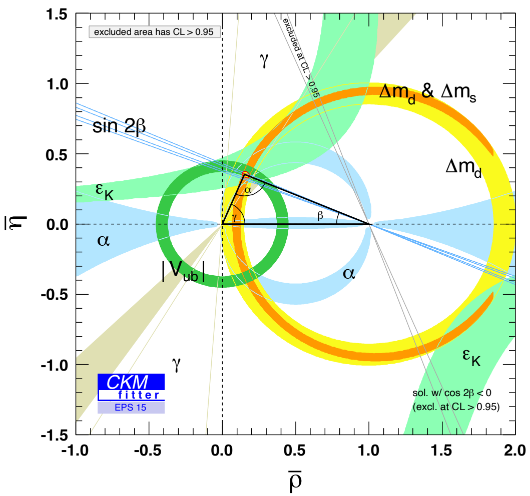
+ LHCb starts to deliver

Unitarity triangle fits through time

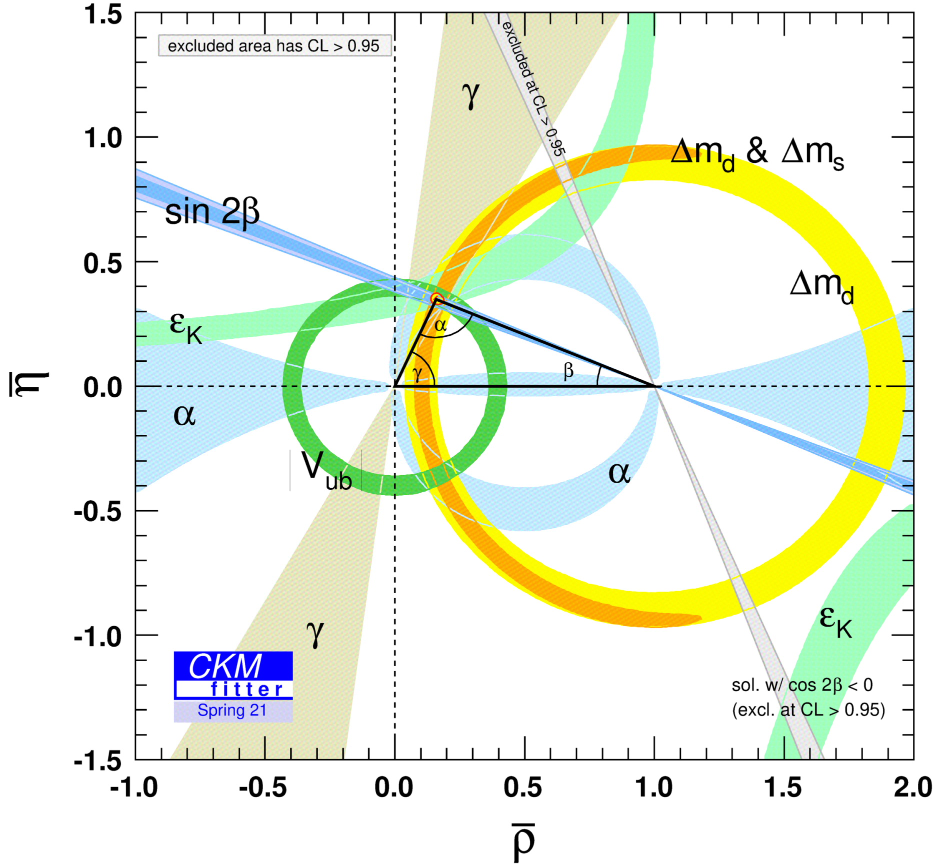
1995



2015

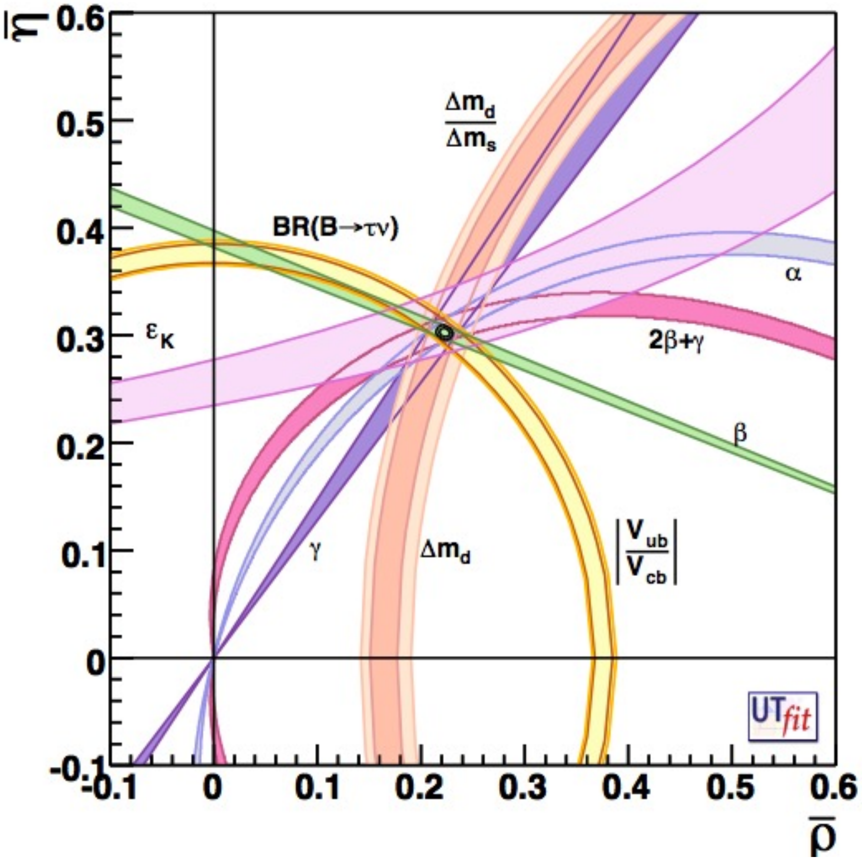


2021



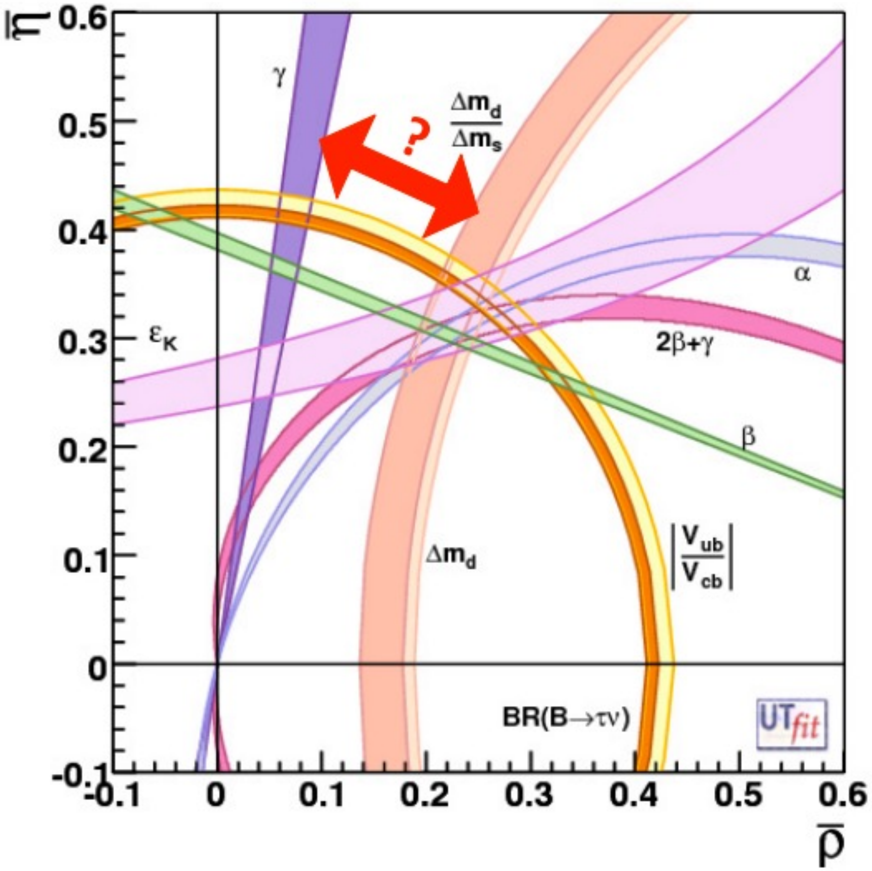
Future of CKM?

The "nightmare"



https://arxiv.org/abs/0710.3799

The "dream"



Part III: Rare decays and lepton universality

Rare b decays

Rare decays helped to shape the SM. Can they show us the way beyond it?

Studies of rare b decays are a key part of LHC physics programme

- Both overall rates, and properties (e.g. angular distributions) of rare processes can be influenced by New Physics

✅ LHC is a b-factory! Huge numbers of b quarks produced.

$\Rightarrow$ Great place to look for rare decays

⚠️ LHC is a busy environment

$\Rightarrow$ Essential to understand (and reject / account for) backgrounds

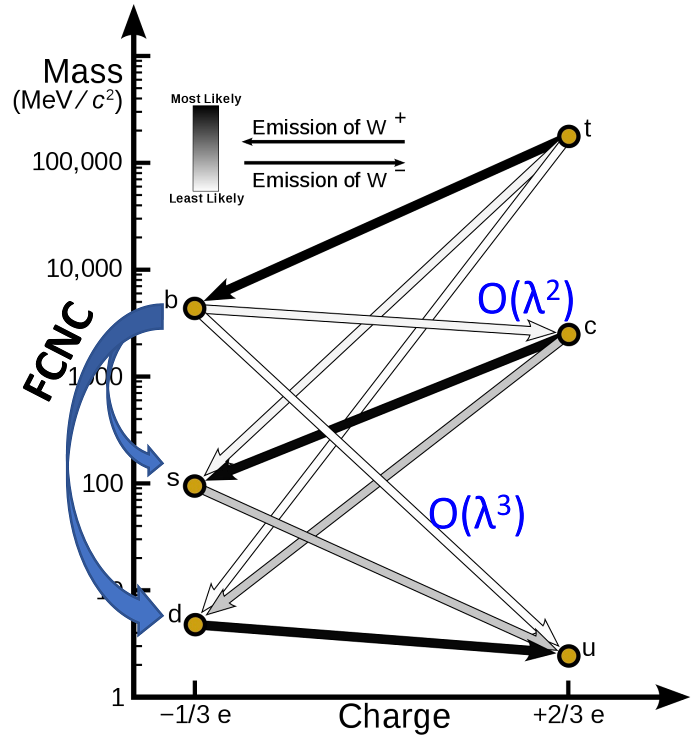
Muon modes are clean and easy to trigger: low(ish)-hanging fruit

Rare b decays

In CKM picture, all b decays are 'rare' since they change generation

Rare in this context really means not b→c

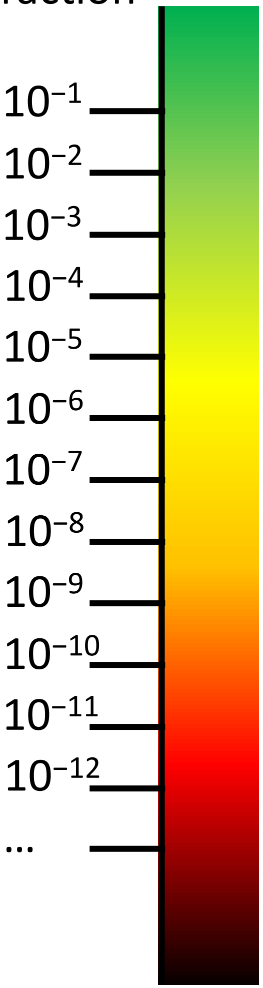
Flavour changing neutral currents (FCNC) are even more suppressed, since direct transitions are forbidden (b→s, b→d)
⇒ no tree-level SM diagrams



(From Lecture 2)

Rare b decays

Branching fraction



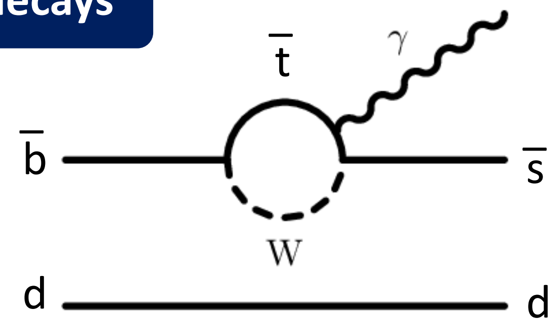
$B^0 \rightarrow D^-\mu^+\nu$ (2.3×10^{-2})

$B^0 \rightarrow J/\psi K^0$ (8.9×10^{-4})

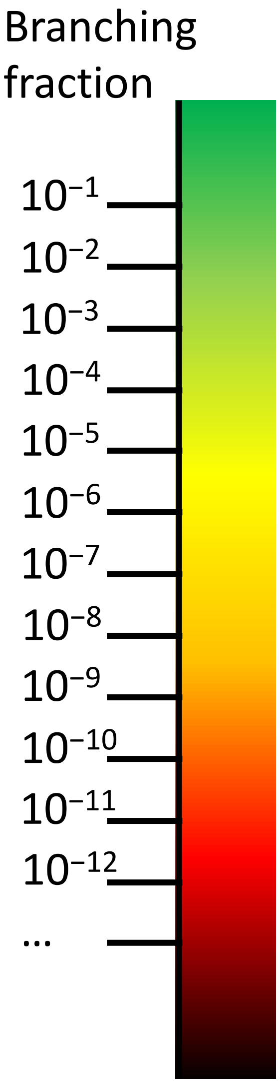
$B^0 \rightarrow K^{0*}\gamma$ (4.2×10^{-5})

$B^0 \rightarrow \omega^*\gamma$ (4.4×10^{-7})

Radiative decays



Rare b decays



$B^0 \to D^- \mu^+ \nu$ (2.3×10^{-2})

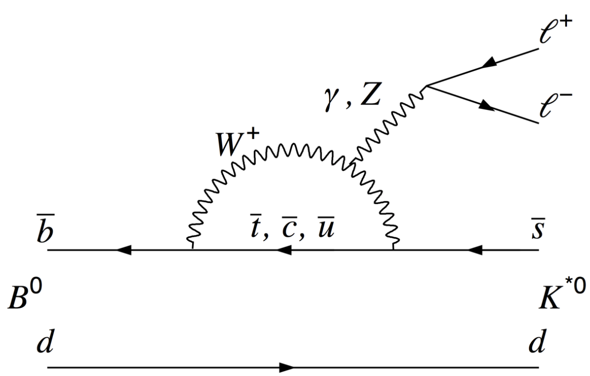
$B^0 \to J/\psi K^0$ (8.9×10^{-4})

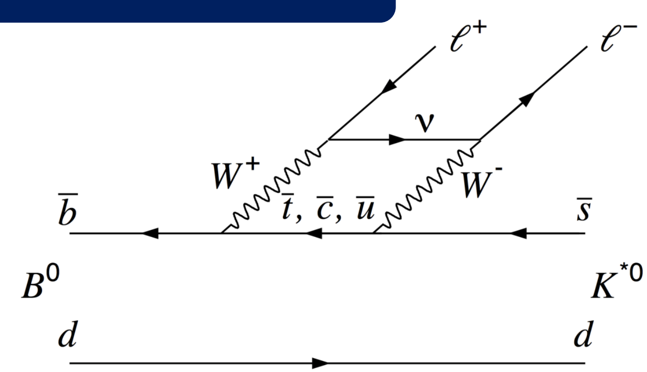
$B^0 \to K^{0*} \gamma$ (4.2×10^{-5})

$B^0 \to \omega^* \gamma$ (4.4×10^{-7})

$\boxed{B^0 \to K^{0*} \mu^+ \mu^- \quad (9.9 \times 10^{-7})}$

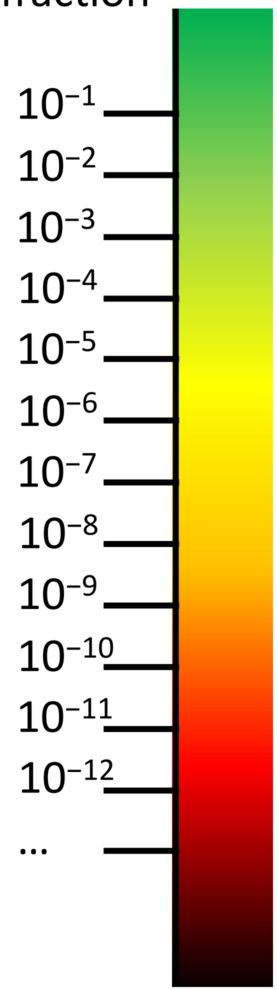
Electroweak penguins





Rare b decays

Branching fraction



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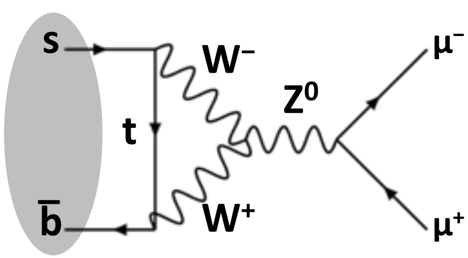
$B^0 \to K^{0*}\mu^+\mu^-$ (9.9×10^{-7})

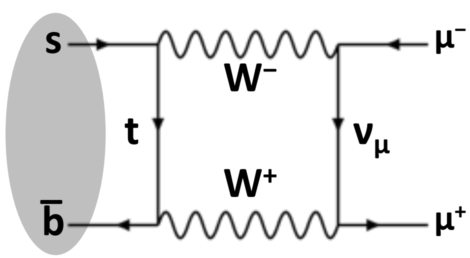
$B^0 \to \omega^*\gamma$ (4.4×10^{-7})

$B_s^0 \to \mu^+\mu^-$ (3.5×10^{-9})

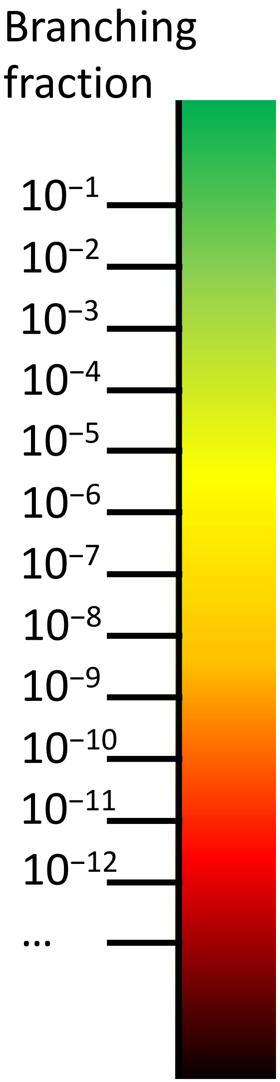
$B^0 \to \mu^+\mu^-$ $(<2 \times 10^{-10})$

Box diagrams





Rare b decays



$B^0 \rightarrow D^-\mu^+\nu$ (2.3×10^{-2})

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$B^0 \rightarrow \omega^*\gamma$ (4.4×10^{-7})

$B_s^0 \rightarrow \mu^+\mu^-$ (3.5×10^{-9})

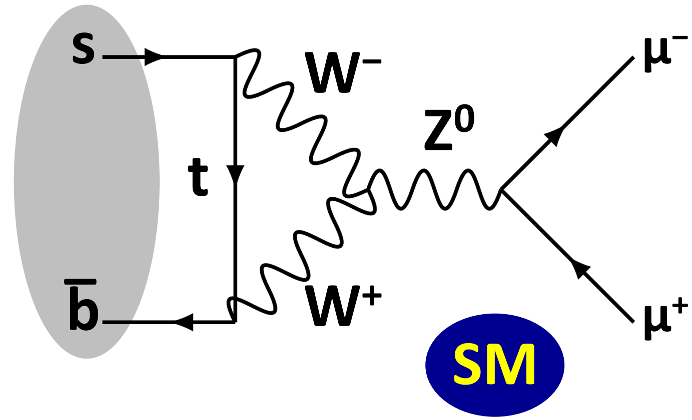
$B^0 \rightarrow \mu^+\mu^-$ $(<2 \times 10^{-10})$

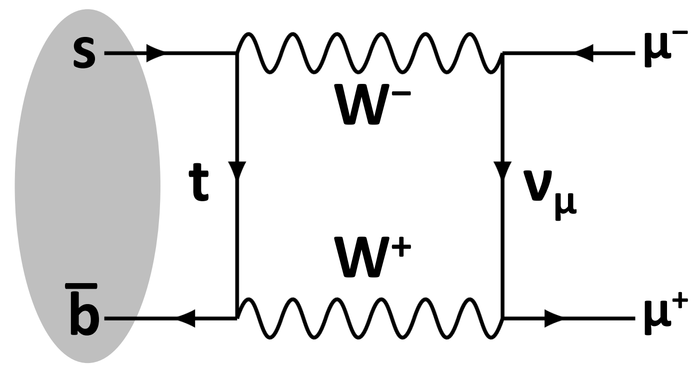
Lepton number violating
Lepton family violating
Baryon number violating …

$B_s^0 \rightarrow \mu^+\mu^-$

Similar to $\mu\rightarrow e\gamma$ from lecture 1: highly suppressed in SM with precise prediction.

$Br(B_s^0\rightarrow\mu^+\mu^-) = 3.3\times10^{-9}$





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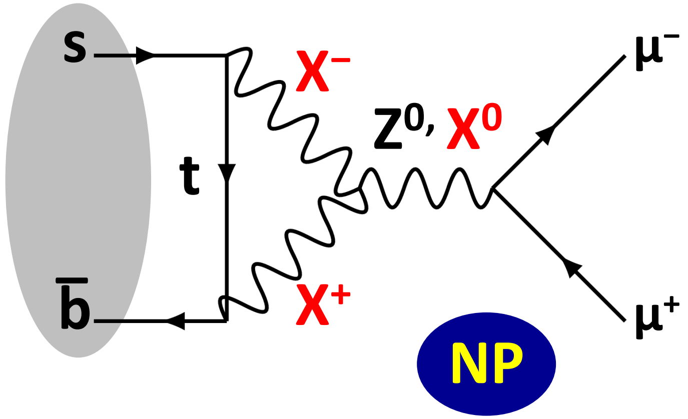
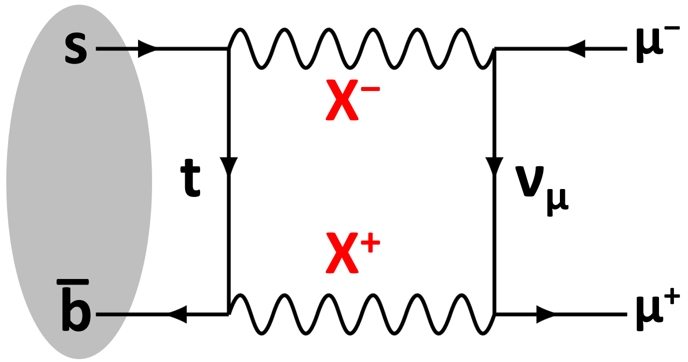


Almost all NP theories predict enhancement (or suppression)



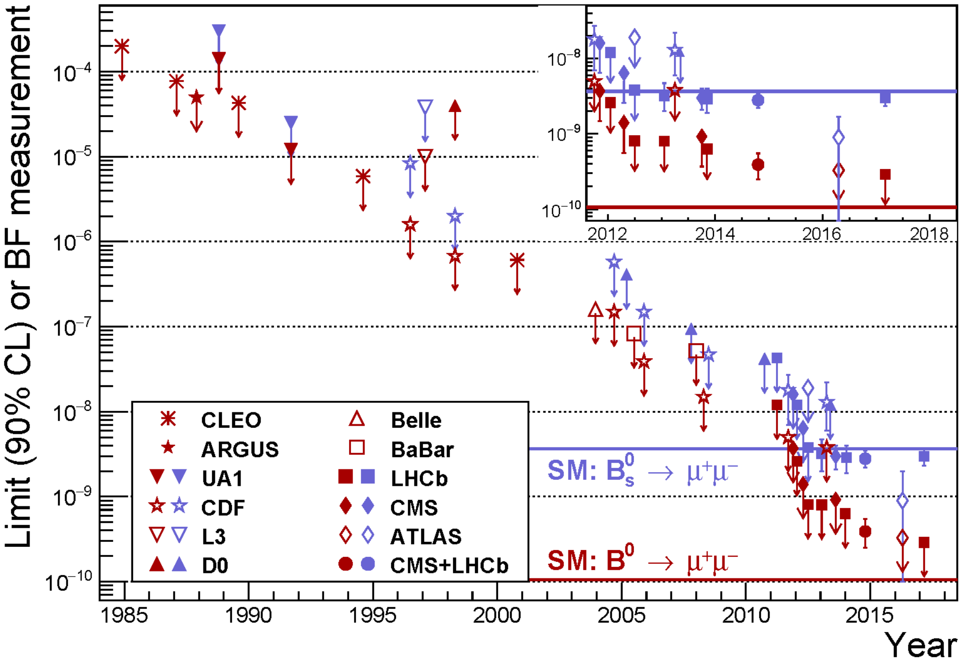
Especially strong dependence on SUSY parameter, e.g.

$Br(B_s^0 \rightarrow \mu^+\mu^-) \propto \tan^6\beta$

$B_s^0 \rightarrow \mu^+\mu^-$

For a long time – improving limits

Then in 2013 something changed…

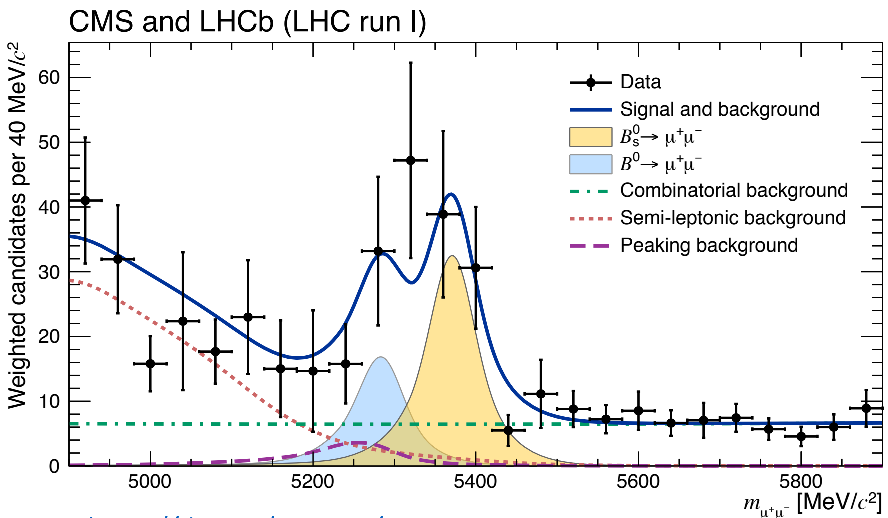


$B_s^0 \rightarrow \mu^+\mu^-$

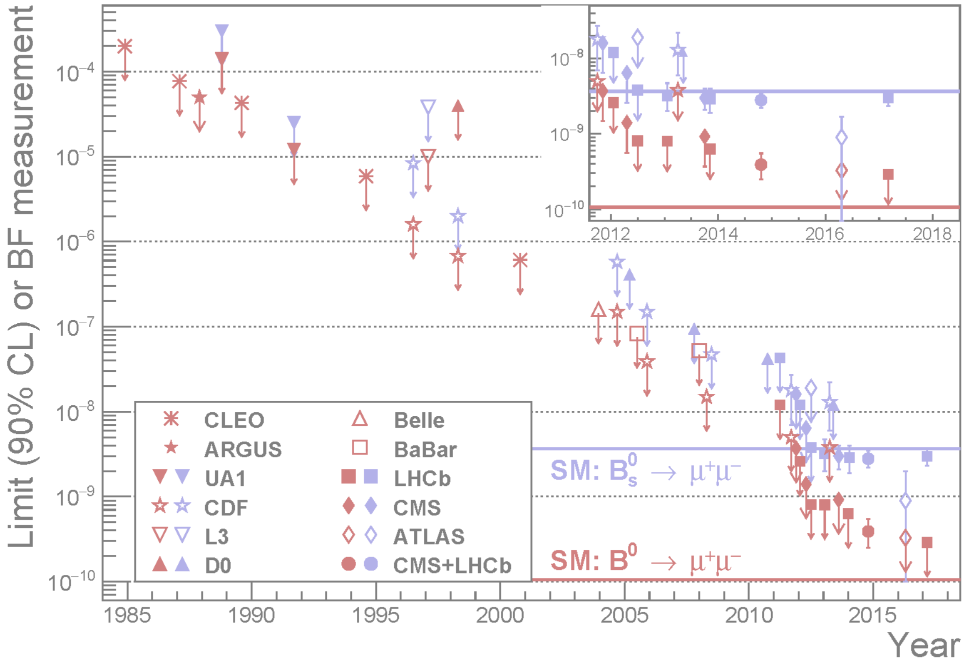
For a long time – improving limits

Then in 2013 something changed…

By combining results from CMS and LHCb, reached "5σ" standard for claiming observation



https://doi.org/10.1038/nature14474



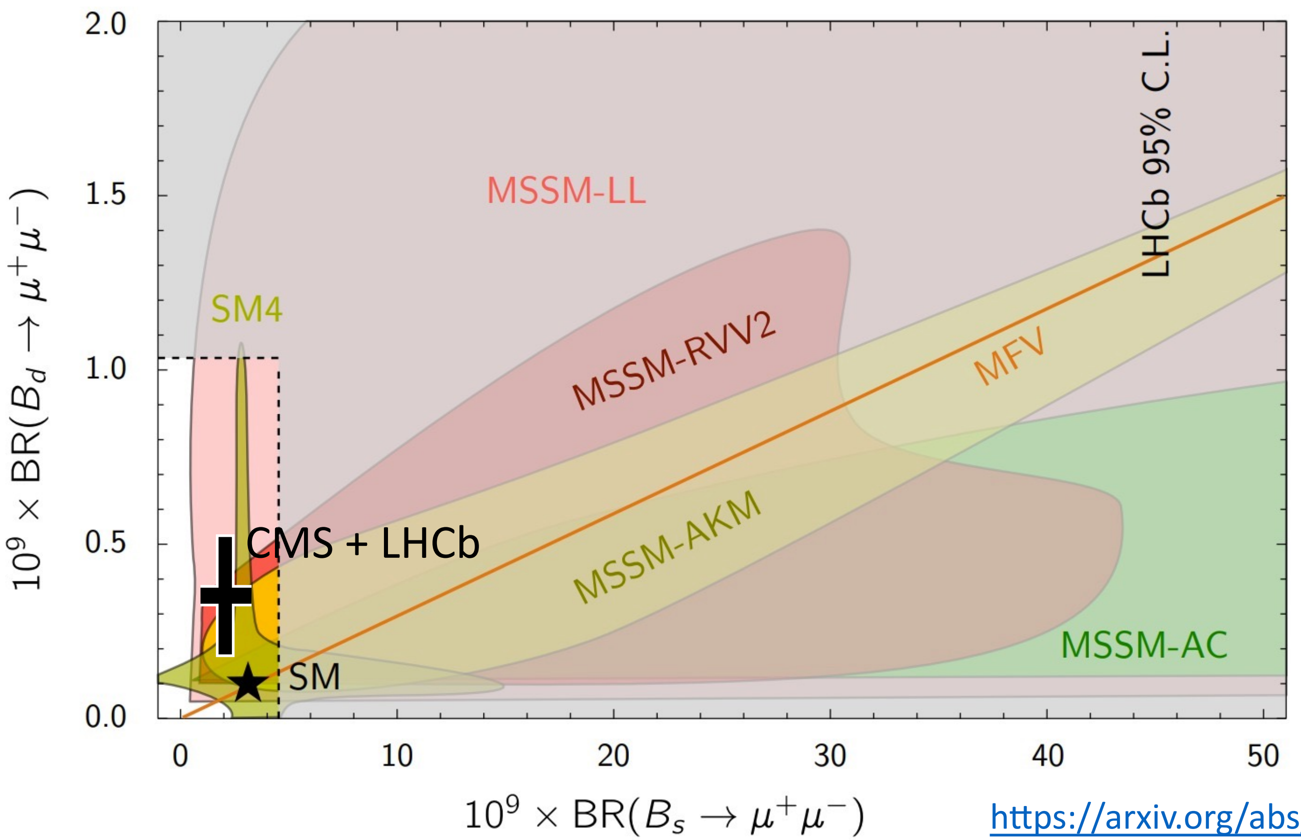
$B_s^0 \to \mu^+\mu^-$

Measurements in agreement with SM (some tension for B^0 rate)

Killed a lot of SUSY parameter space

$Br(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.7) \times 10^{-9}$

$Br(B_d^0 \to \mu^+\mu^-) = (3.9 \pm 1.5) \times 10^{-10}$

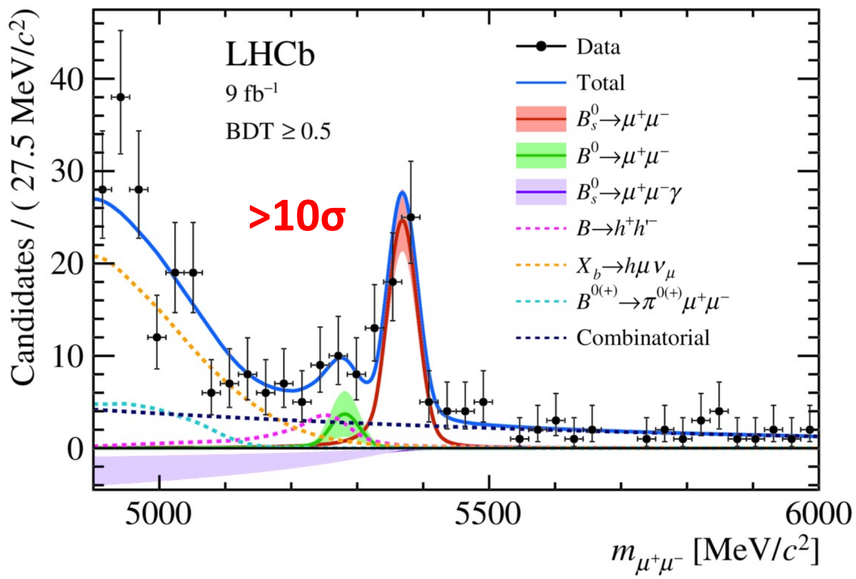


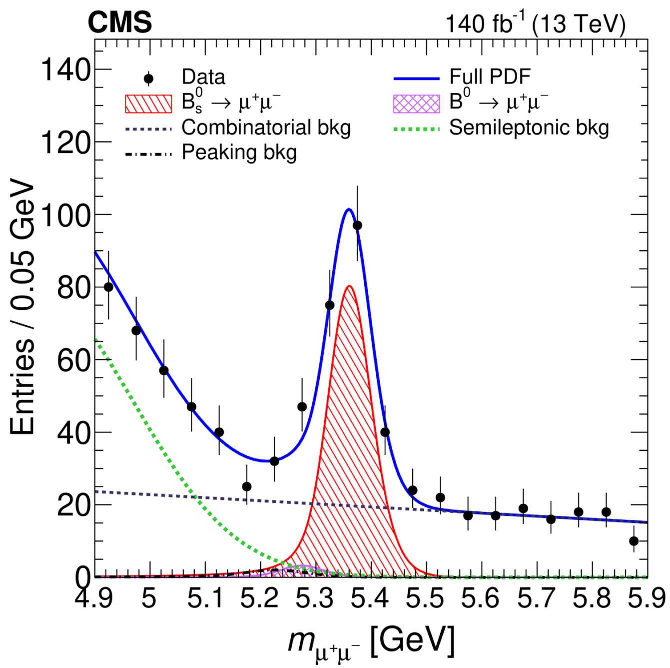
https://arxiv.org/abs/1205.6094

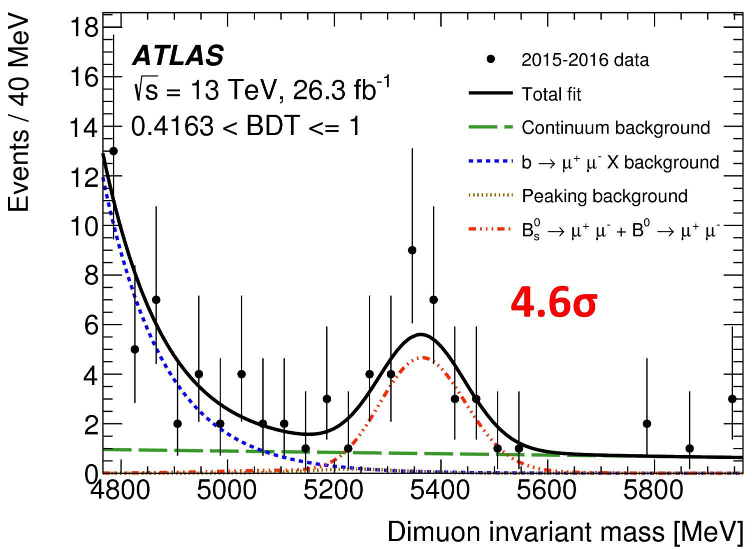
$B_s^0 \rightarrow \mu^+\mu^-$ latest

https://doi.org/10.1103/PhysRevLett.128.041801
https://doi.org/10.1016/j.physletb.2023.137955
https://doi.org/10.1007/JHEP04(2019)098

High-significance observations from LHCb, CMS (full Run 1+2), & Atlas (partial Run 1+2)





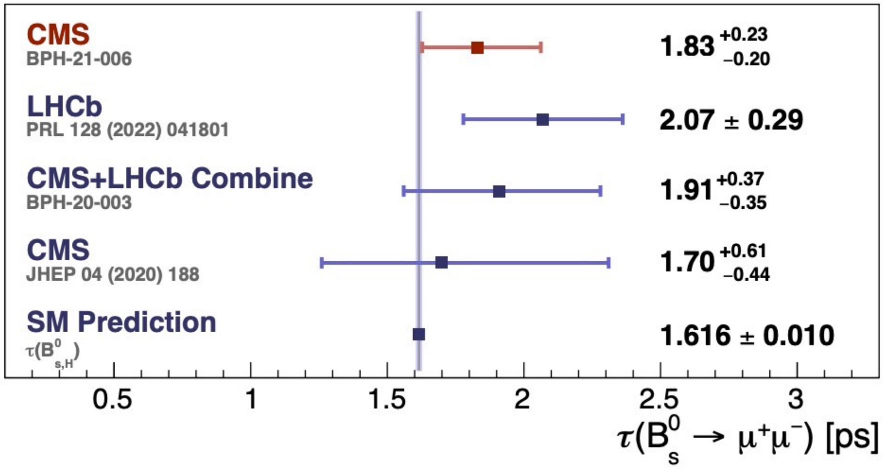


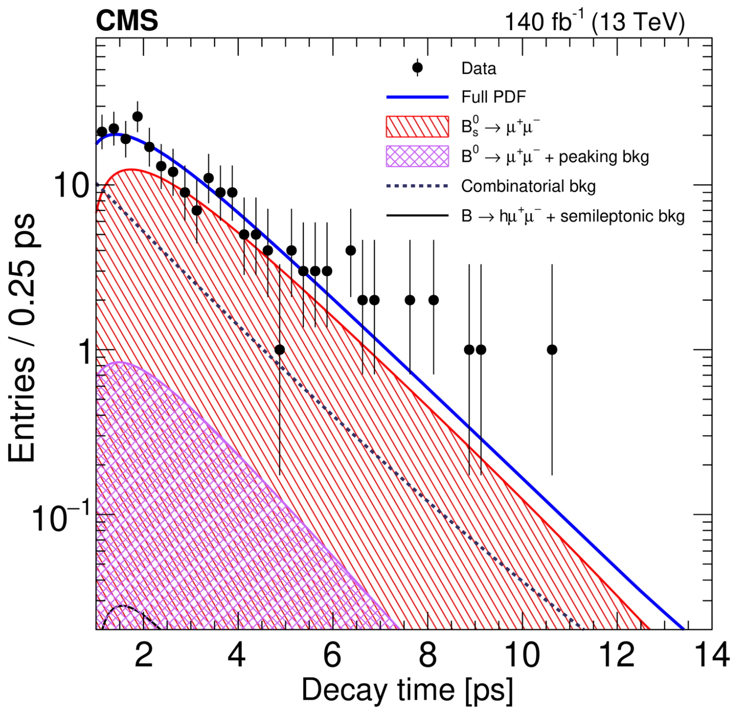
$B_s^0 \to \mu^+\mu^-$ latest

With larger signal yields, can also measure $B_s^0 \to \mu\mu$ lifetime

In SM, only heavy (**H**) mass eigenstate can decay to $\mu\mu \Rightarrow$ another probe of new physics

(SM) $\tau_H = 1.620 \pm 0.007$ ps
$\tau_L = 1.423 \pm 0.005$ ps





At current precision, cannot rule-out either τ_H or τ_L case:

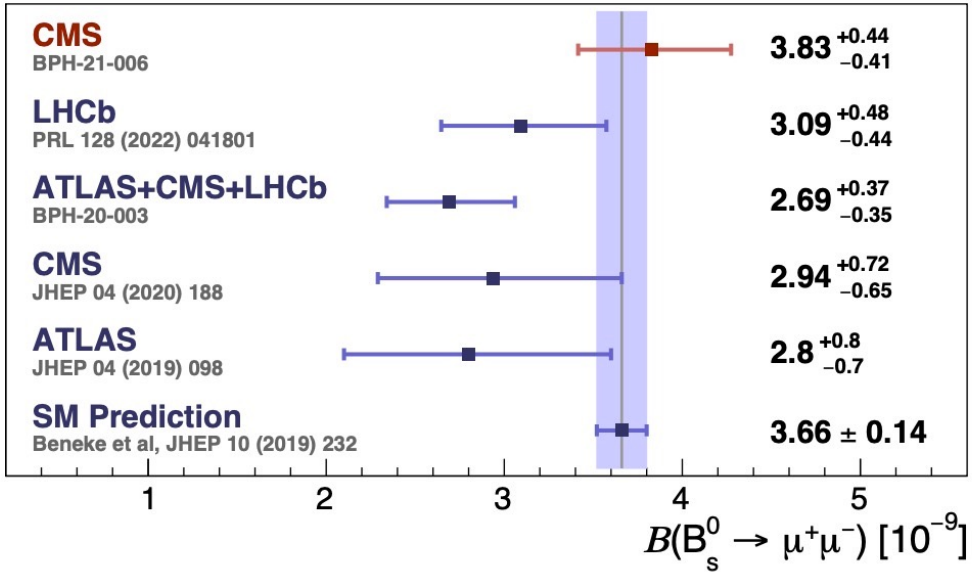
$\Rightarrow$ Need Run 3 data to fully test this

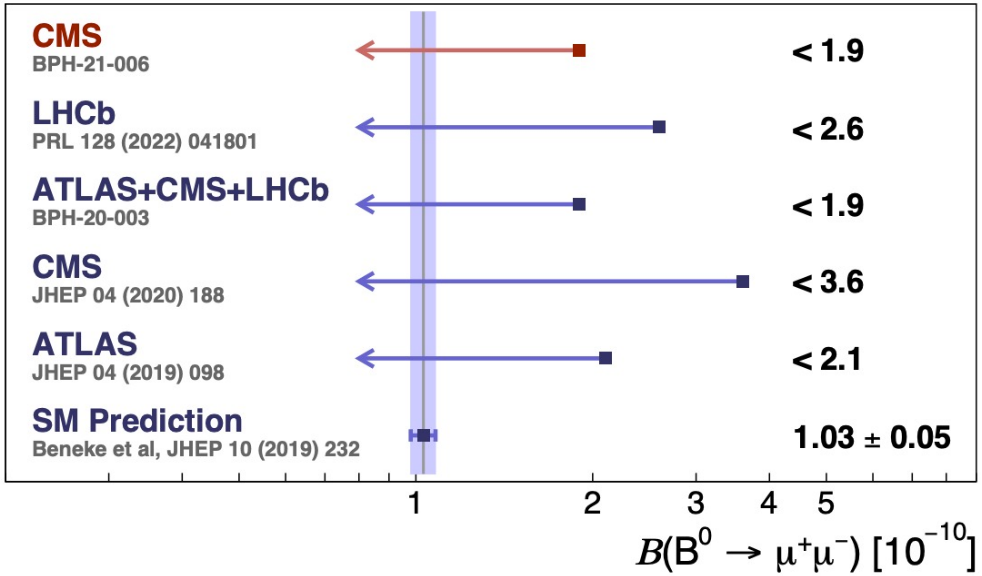
$B_s^0 \to \mu^+\mu^-$ latest

Discovering $B_s^0 \to \mu\mu$ is one of the most significant achievements of the LHC experiments

Provides very tight constraints on possible new physics models

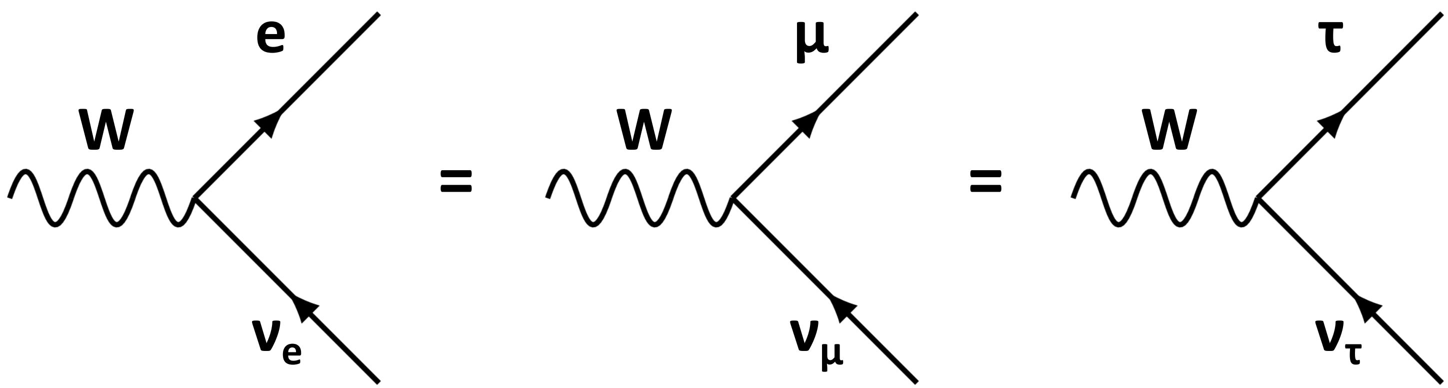
Next target is $B^0 \to \mu\mu$
⇒ stay tuned in Run 3!





Lepton universality

Lepton universality: ***weak interaction acts equally regardless of lepton flavour***



Pillar of standard model – any deviation can **only** be caused by new physics

Theoretically clean… …Experimentally challenging…

Lepton universality: "$R_{K^{(*)}}$"

Rare decays may be sensitive to new physics which doesn't respect lepton universality.

Branching ratios for FCNC $b \to s\mu^+\mu^-$ are consistently lower than expected in SM

- Could be due to hard-to-calculate QCD effects
- If so, should also see low BRs for electron modes

Measure ratio of decay rates of muons and electron channels in $\mathbf{B^+ \to K^+ \mathit{l}^+ \mathit{l}^-}$

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+e^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$

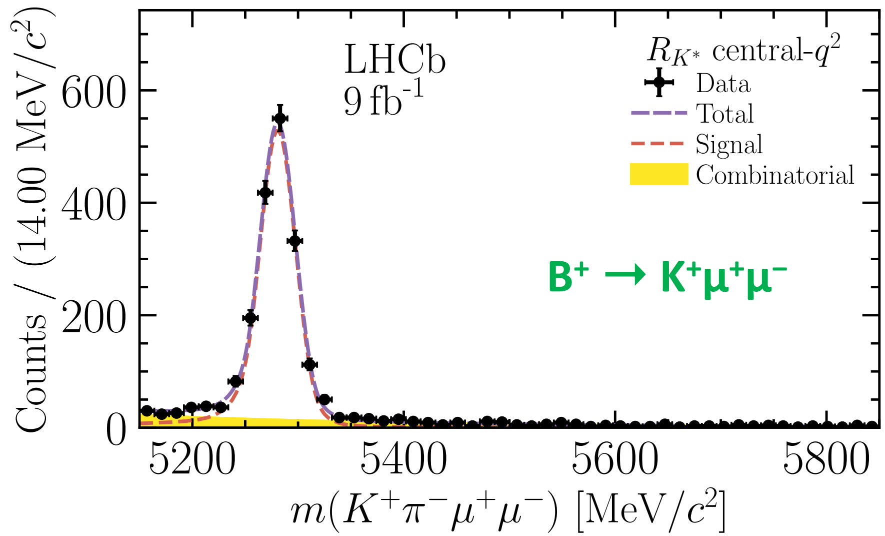
≈1 in SM
(very reliable prediction)

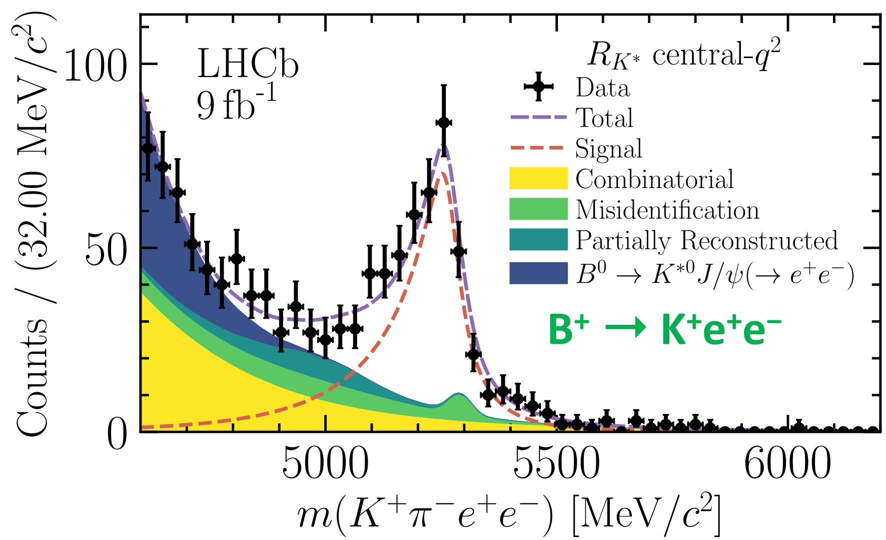
Lepton universality: "$R_{K^{(*)}}$"

Challenge: electrons and muons interact differently with matter
⇒ totally different signatures in LHCb

Muon: track + muon system hits
Electron: track + EM calorimeter shower

Electrons also suffer from *Bremsstrahlung* – lose energy in detector.





https://arxiv.org/abs/2212.09153 (sub. to PRD)

Latest R_K (and R_{K*}) results

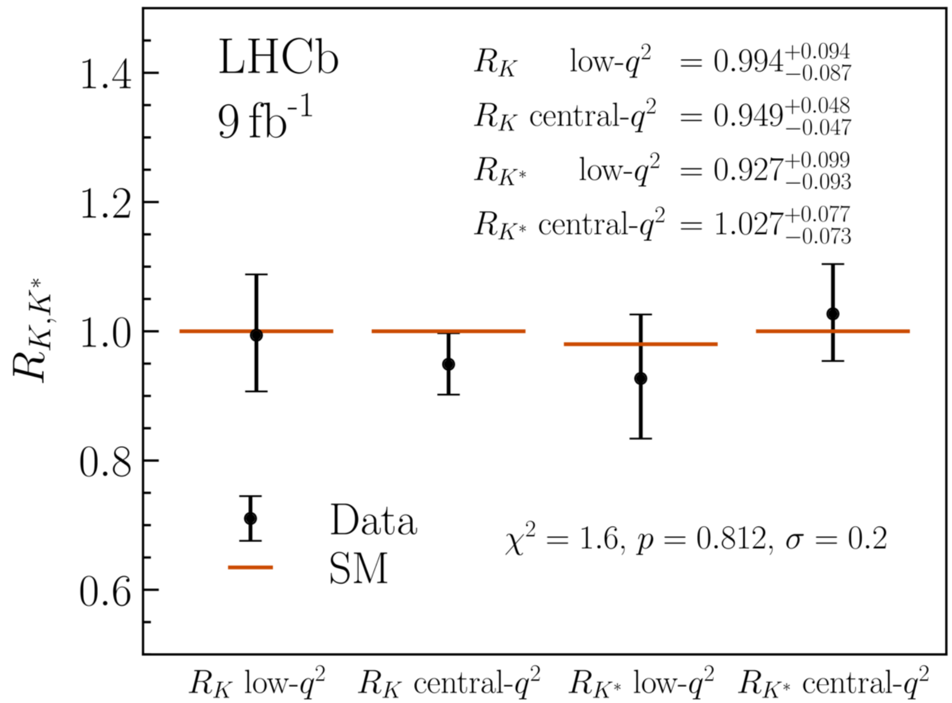
Initial LHCb measurements hinted at non-universality, R_K below SM by ~3σ

Latest result is a simultaneous measurement of R_K and R_{K*} with all Run 1-2 data

Now compatible with the SM after applying tighter cuts to reject tricky backgrounds from mis-ID particles

⇒ In these channels, the hint of disagreement with the SM has gone away

Discovering BSM physics requires a deep knowledge of detector effects and backgrounds!
(including estimates of 'unknown unknowns')



https://arxiv.org/abs/2212.09153 (sub. to PRD)

“The anomalies”

https://www.nikhef.nl/~pkoppenb/anomalies.html

Is a picture emerging of a broken Standard Model?

Could it be due to issues with calculations
(e.g. hadronic effects?)

Or… is this just cherry-picking statistical fluctuations?

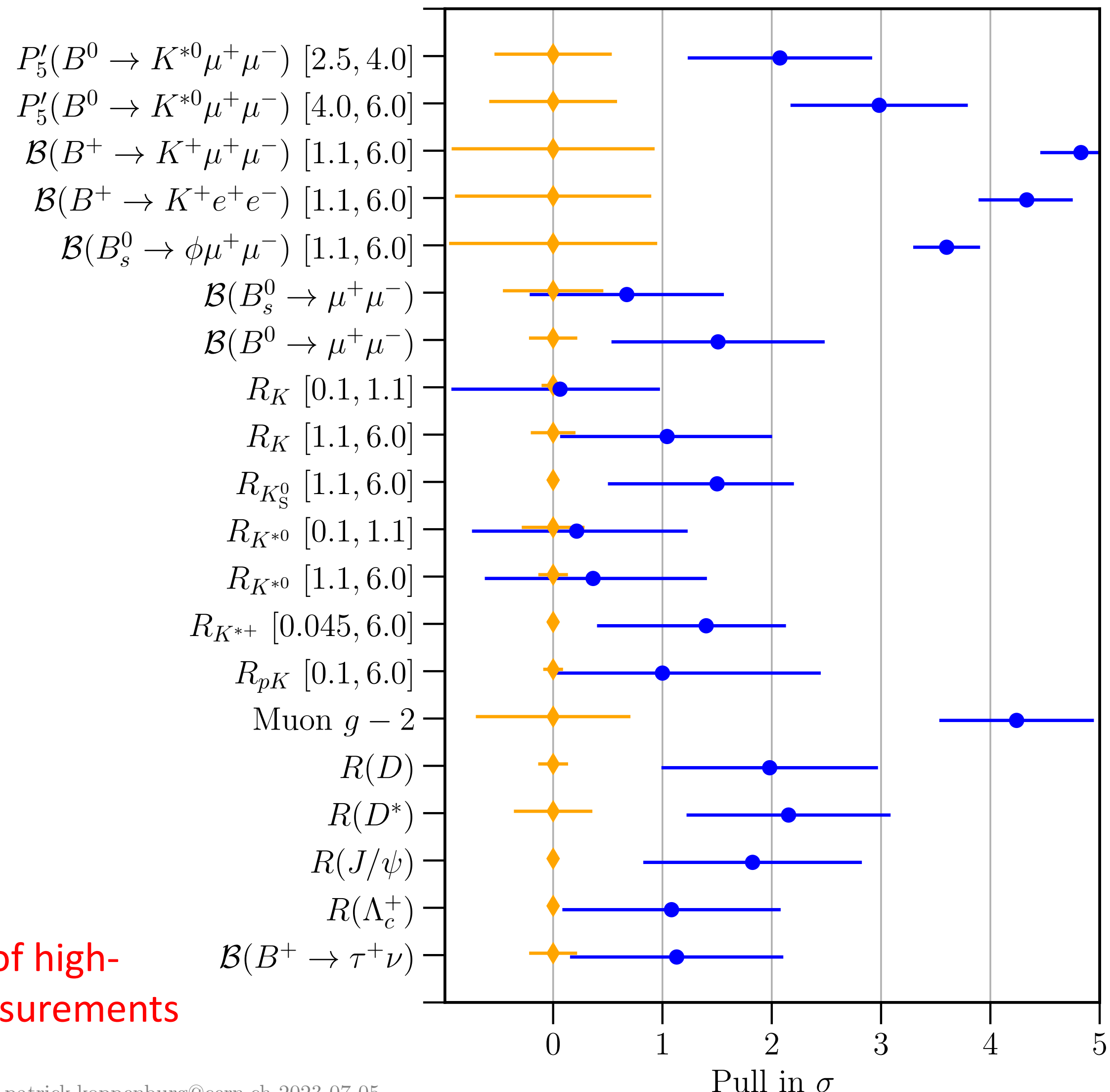
(T.S. Eliot)

Standard Model

This is the way the ~~world~~ ends
This is the way the ~~world~~ ends
This is the way the ~~world~~ ends
Not with a ~~bang~~ but a ~~whimper.~~

Direct observation

Combination of high-precision measurements



Part IV: The future of flavour

The future of flavour

The need for more precision…

> *"A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."*

- L. Okun

Remember, $B(K_L^0 \to \pi^+\pi^-) = 0.2\%$

Most measurements limited by statistical precision ⇒ need **more data**

Also need better control over systematics ⇒ **better detectors**

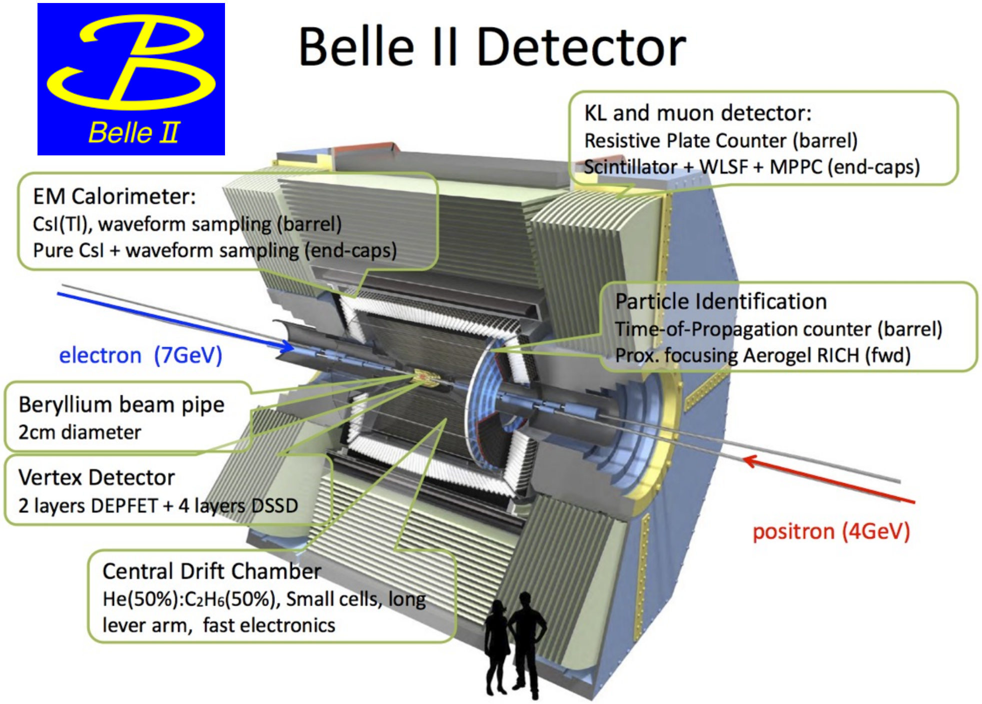
Many new experiments, or upgrades, planned in coming years…

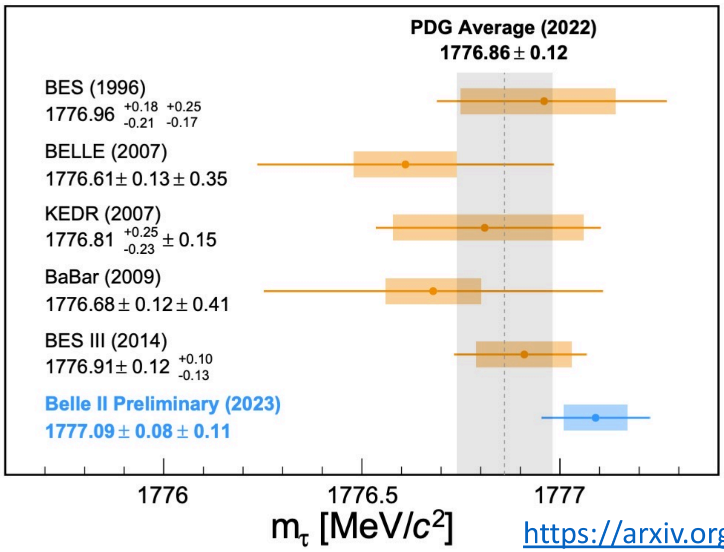
Belle II (2018 –)

Will collect 40× more data than Belle (already a world record luminosity!)

Major accelerator and detector upgrades to reach **50 ab^{-1}**

First physics run with complete detector started in March 2019



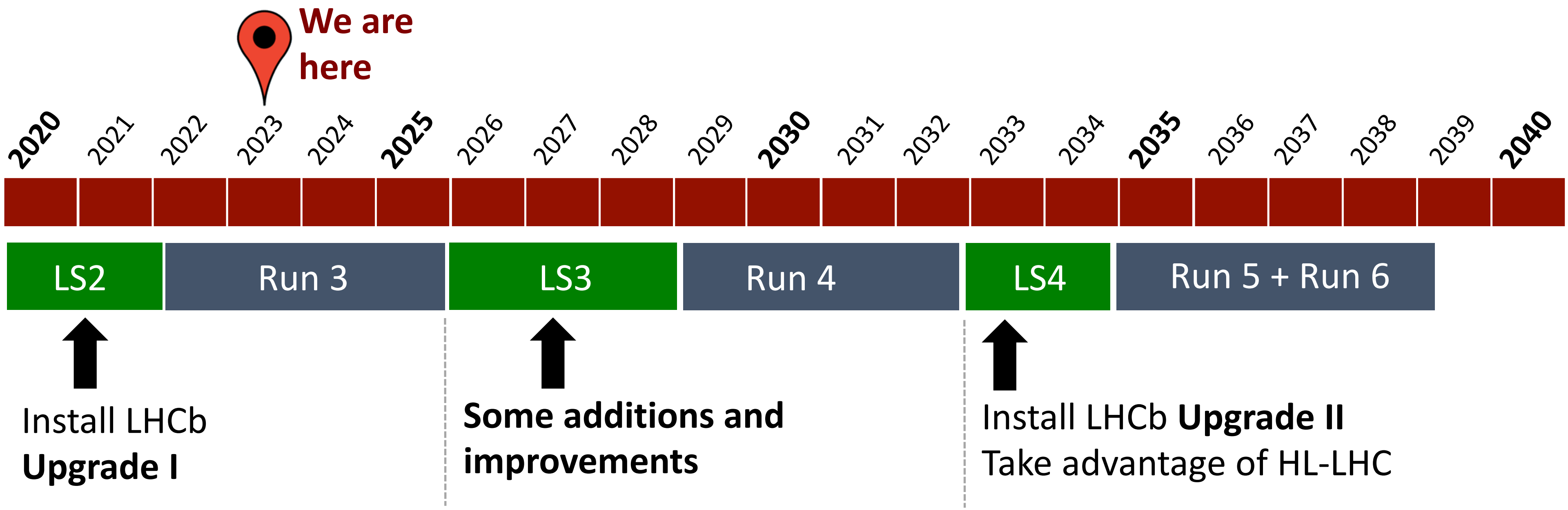


Already surpassing original Belle precision in several areas (with fraction of data)

Complementary to LHCb programme

https://arxiv.org/abs/2305.19116

LHCb Upgrades (2022 – 2040)



LHCb Upgrades (2022 – 2040)

We are here (2023)

2020 2021 2022 2023 2024 **2025** 2026 2027 2028 2029 **2030** 2031 2032 2033 2034 **2035** 2036 2037 2038 2039 **2040**

LS2	Run 3	LS3	Run 4	LS4	Run 5 + Run 6

Install LHCb **Upgrade I**

Some additions and improvements

Install LHCb **Upgrade II**
Take advantage of HL-LHC

Upgrade I

$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **(5×)**

5.5 visible interactions / crossing

Accumulate **50 fb^{-1}** total

Now running!!

LHCb Upgrades (2022 – 2040)

We are here (2023)

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040

LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5 + Run 6

Install LHCb **Upgrade I**

Some additions and improvements

Install LHCb **Upgrade II**
Take advantage of HL-LHC

Upgrade I

$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$ **(5×)**

5.5 visible interactions / crossing

Accumulate **50 fb^{-1}** total

Now running!!

Upgrade-II

$\mathcal{L} = 1.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ **(7.5×)**

41 visible interactions / crossing

Accumulate **300 fb^{-1}** total

Design & R&D phase

Kaon physics

Last frontier in kaon physics – observe **$K \to \pi\nu\nu$**

SM $\begin{cases} B(K^+ \to \pi^+\nu\nu) = (9.1 \pm 0.7) \times 10^{-11} \\ B(K_L{}^0 \to \pi^0\nu\nu) = (3.0 \pm 0.3) \times 10^{-11} \end{cases}$

https://arxiv.org/abs/1503.02693

Highest CKM suppression of $s \to d$ coupling
$\Rightarrow$ measurement sensitive to $|V_{td}|$ - compare results with B mixing

Kaon physics

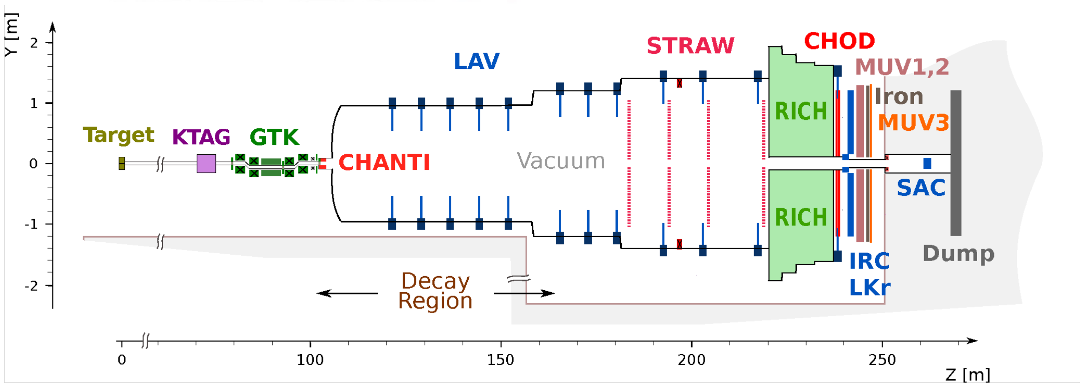
Last frontier in kaon physics – observe **K→πνν**

SM $\begin{cases} B(K^+\to\pi^+\nu\nu) = (9.1 \pm 0.7) \times 10^{-11} \\ B(K_L^0\to\pi^0\nu\nu) = (3.0 \pm 0.3) \times 10^{-11} \end{cases}$

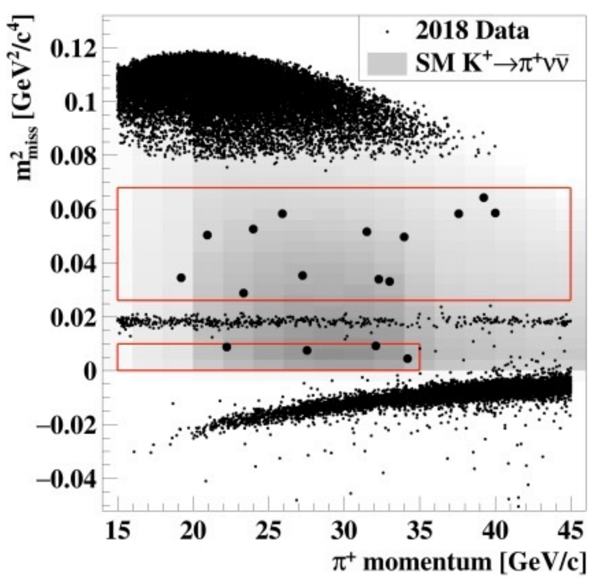
https://arxiv.org/abs/1503.02693

Highest CKM suppression of s→d coupling
⇒ measurement sensitive to $|V_{td}|$ - compare results with B mixing

NA62 @ CERN
(2015 –)



Will reconstruct ~100 $K^+\to\pi^+\nu\nu$ at SM rate ⇒ 10% precision on $|V_{td}|$



With 2016–18 data, 3.4σ evidence:

$$\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11} \text{ at } 68\% \text{ CL.}$$

Summary

Flavour physics is a powerful and versatile tool

- Challenge SM predictions ⇒ see NP indirectly

History tells us that this is often the gateway to major discoveries

A huge field, covering many areas, with many experiments past, present, future

- Many important ones not covered (including Atlas/CMS, Tevatron, BES-III, CLEO)

Future looks bright

- Many new and upgraded experiments coming
- Are we on the verge of a breakthrough?

@LHCbExperiment
@LHCbPhysics
@BelleIICollab
@QuarkWilliams

Experiments

http://lhcb-public.web.cern.ch/
https://www.belle2.org/
https://mu2e.fnal.gov/
http://muon-g-2.fnal.gov/
https://www.psi.ch/mu3e/

Resources

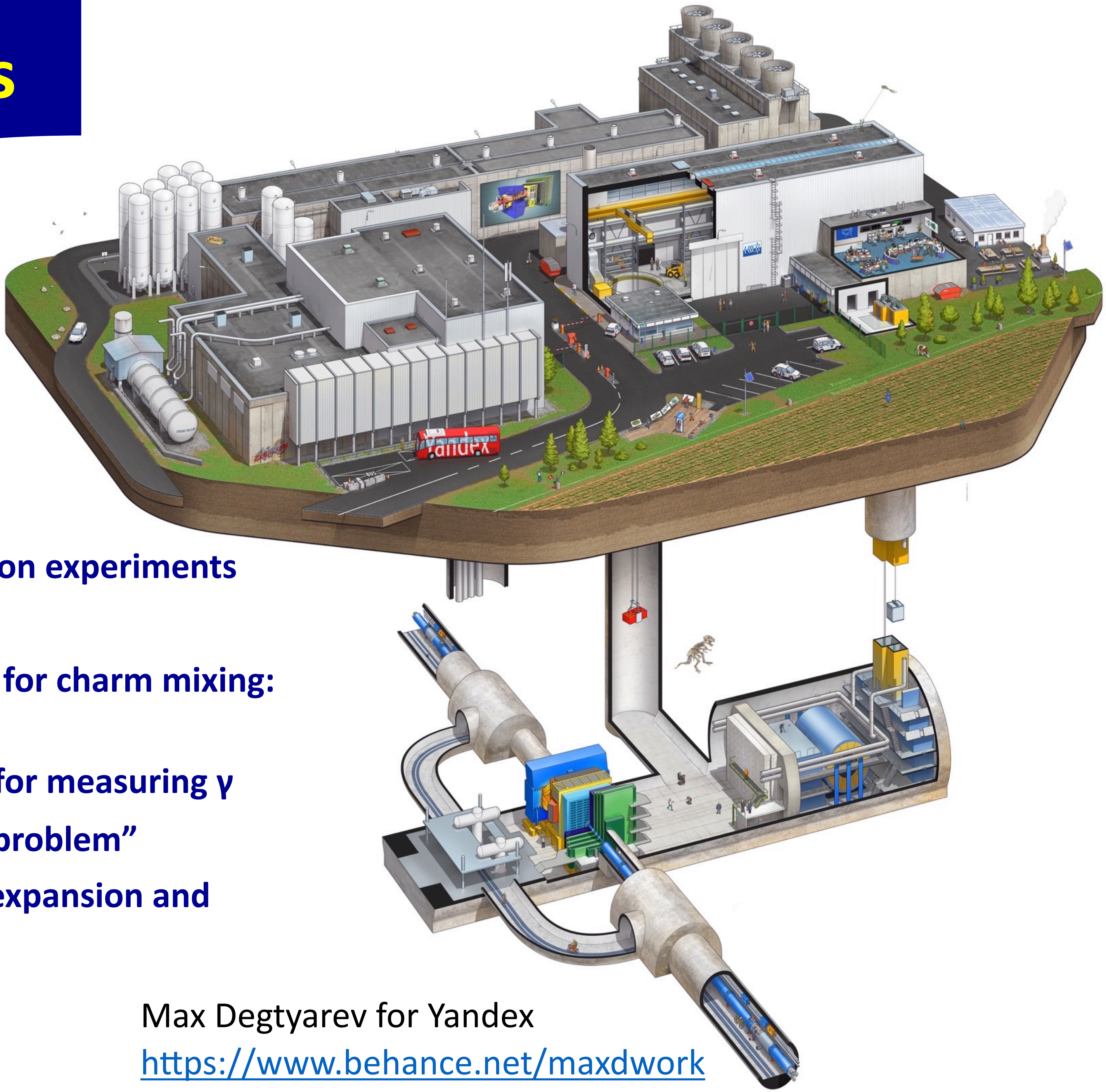
https://hflav.web.cern.ch/
http://ckmfitter.in2p3.fr/
http://www.utfit.org/
http://pdglive.lbl.gov/

Enjoy your stay!

Max Degtyarev for Yandex

https://www.behance.net/maxdwork

Extra Slides



- Current/future muon experiments
- CPV in B_s^0 mixing
- The 'golden mode' for charm mixing: $D^0 \to K_S^0\pi^+\pi^-$
- Example methods for measuring γ
- CPV in decay: "$K\pi$ problem"
- Operator product expansion and radiative B decays
- R_K measurement

Max Degtyarev for Yandex
https://www.behance.net/maxdwork

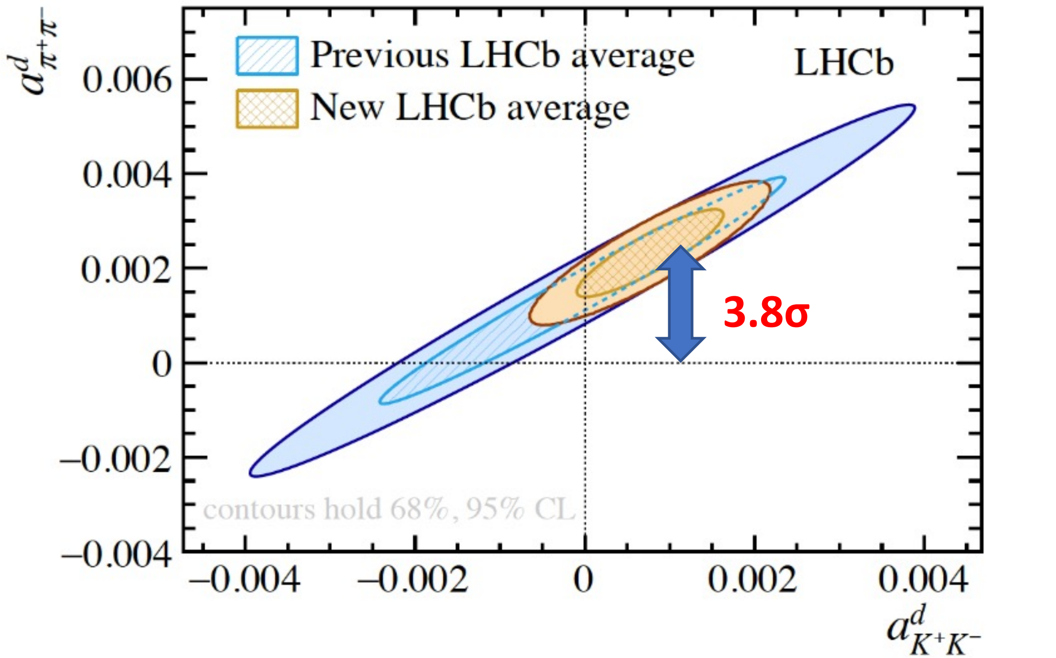
CP violation in charm decays (2022)

Separate measurement of CP asymmetry in $D^0 \rightarrow K^+K^-$
⇒ allows CP asymmetries in both channels to be measured, with constraint from ΔA_{CP}

$A_{CP}(D^0 \rightarrow \pi^+\pi^-) = (23.2 \pm 6.1) \times 10^{-4}$

3.8σ from zero

⇒ First evidence of CP violation in a specific charm quark decay channel



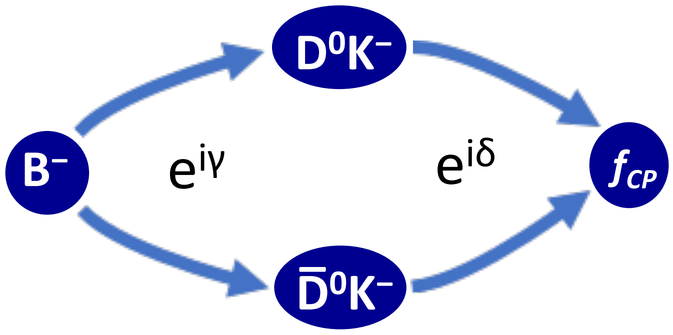
https://cerncourier.com/a/lhcb-digs-deeper-in-cp-violating-charm-decays/

https://agenda.infn.it/event/28874/contributions/169315/

Measuring γ in tree decays

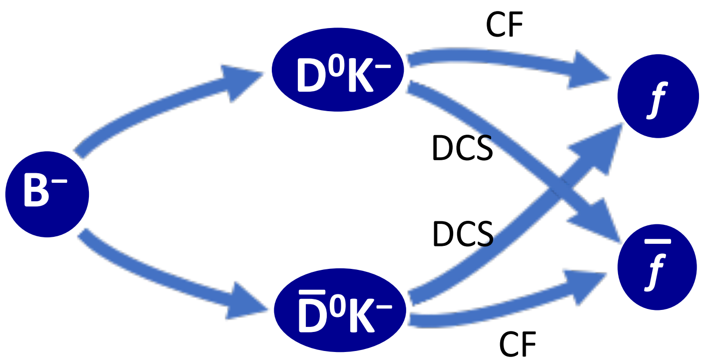
(1) 'GLW'

- CP eigenstates e.g. $f = \pi^+\pi^-, K^+K^-$
- [https://doi.org/10.1016/0370-2693(91)90034-N]
- [https://doi.org/10.1016/0370-2693(91)91756-L]



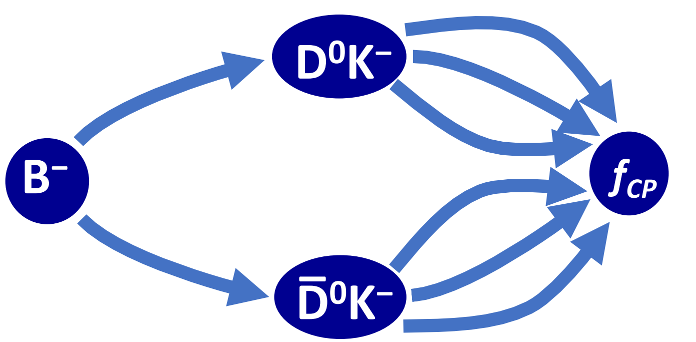
(2) 'ADS'

- Cabibbo-Favoured or Doubly-Cabibbo-Suppressed decays e.g. $f = K^-\pi^+$
- [https://doi.org/10.1103/PhysRevD.63.036005]
- [https://doi.org/10.1103/PhysRevLett.78.3257]



(3) 'BPGGSZ'

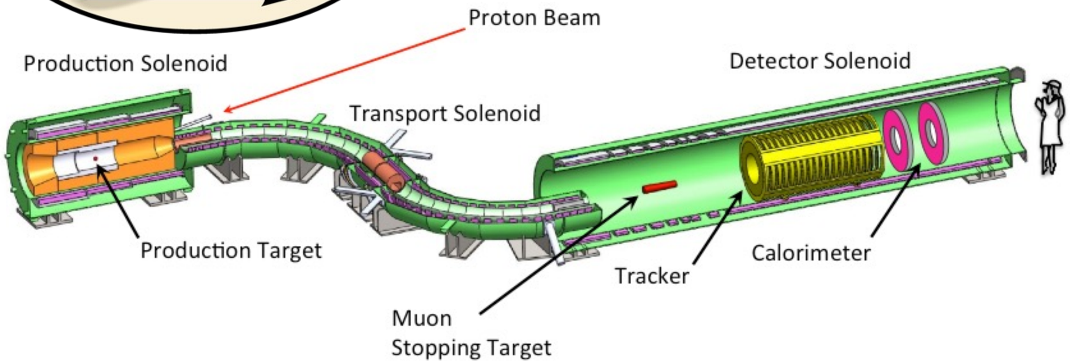
- 3-body final states e.g. $f = K_S^0\pi^+\pi^-$
- Reached via intermediate resonances
- [https://doi.org/10.1103/PhysRevD.68.054018]

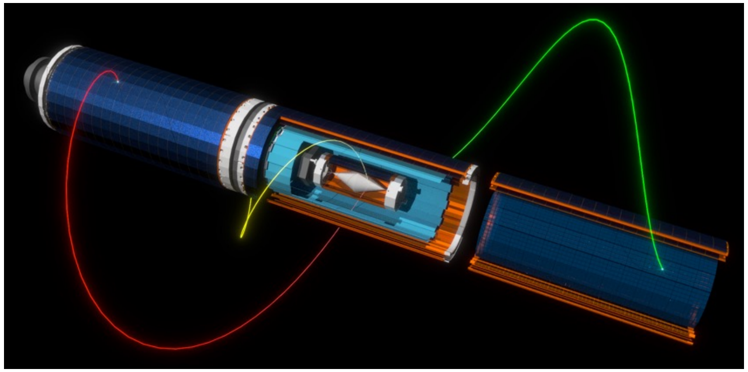


Muon physics

Search for charged lepton flavour violation in
$\mu^- \rightarrow e^-$ (**Mu2e**, FNAL) and $\mu^+ \rightarrow e^+e^+e^-$ (**Mu3e**, PSI)

$\Rightarrow \times 10^4$ improvement in limits





Muon physics

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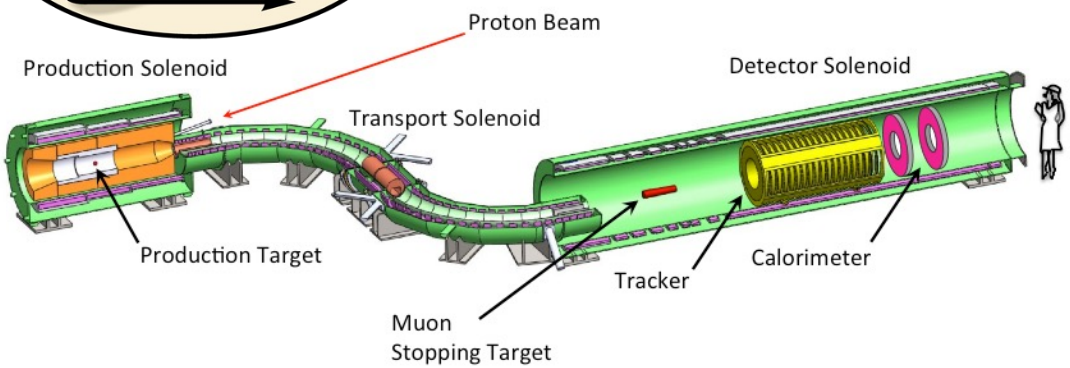
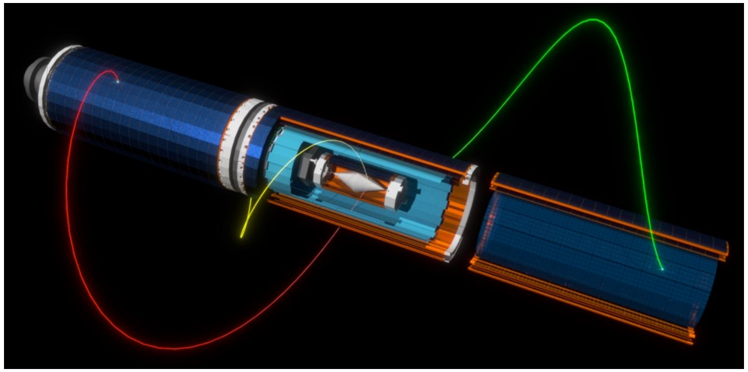
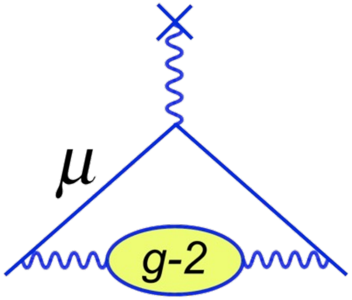






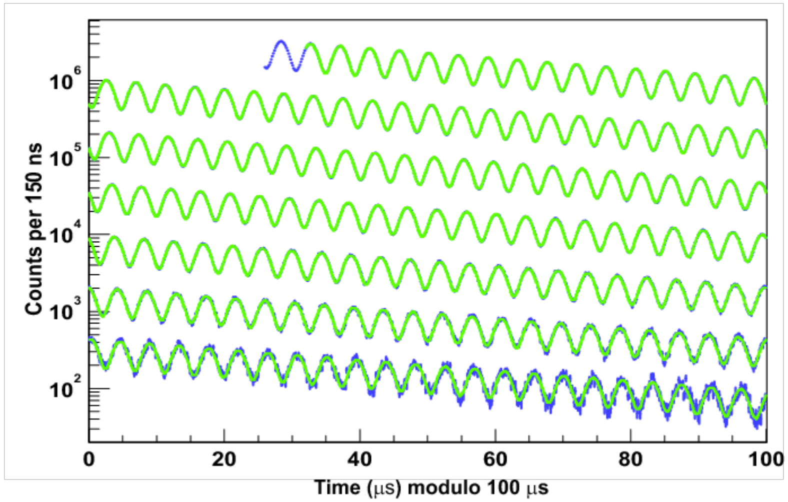
g−2 experiment (FNAL)

⇒ Precise measurement of muon magnetic moment

Previous exp. result disagrees with prediction at ~3.5σ

⇒ 4× improvement in precision

Now a 4σ discrepancy (4/2021)



Kaon physics

Last frontier in kaon physics – observe **K→πνν**

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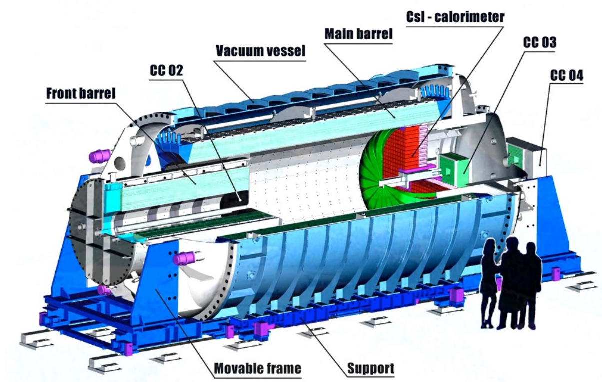
https://arxiv.org/abs/1503.02693

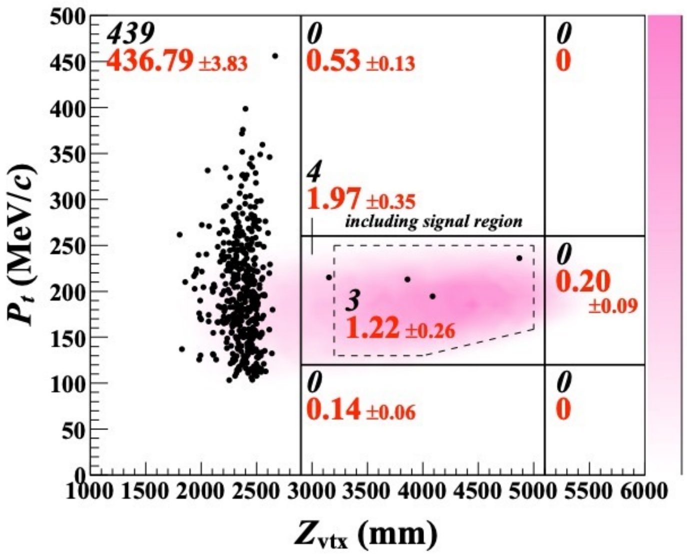
Highest CKM suppression of s→d coupling
⇒ measurement sensitive to $|V_{td}|$ - compare results with B mixing

d s ν ν

KOTO @ J-PARC
(2015 –)

Measure $B(K_L^0 \to \pi^0 \nu\nu)$ to 10% precision (@ SM rate)





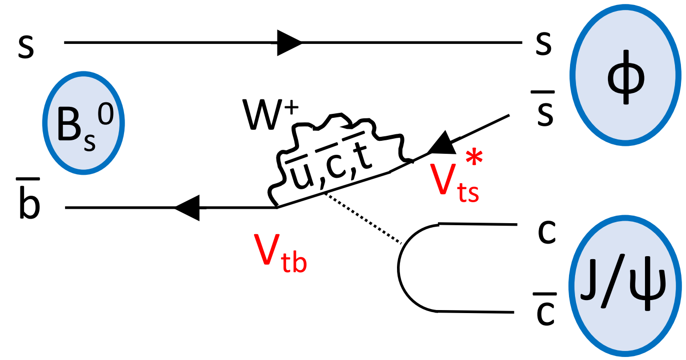
All data from 2016–18 analysed

- 3 signal-like events observed, consistent with BG
- **$B(K_L^0 \to \pi^0 \nu\nu) < 490 \times 10^{-11}$ @90% CL**

10× better than previous limit

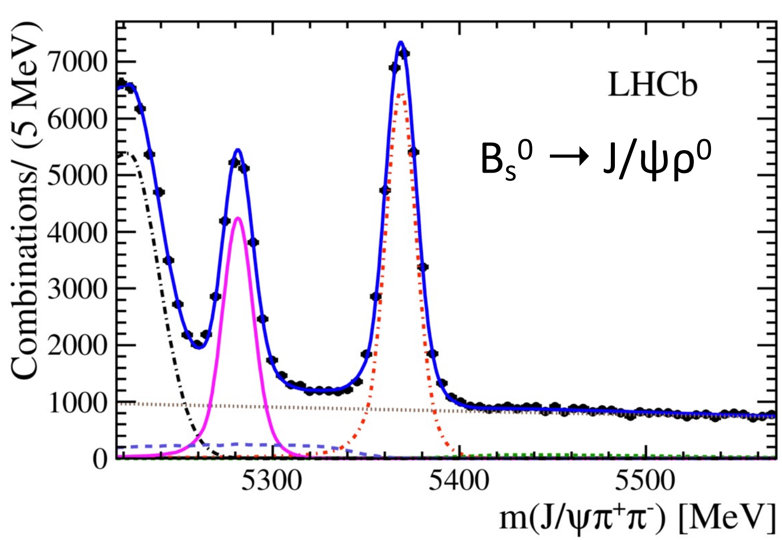
Penguin pollution in $B_s^0 \to J/\psi\phi$

Penguin pollution breaks equality $\phi_s = -2\beta_s$
$\Rightarrow$ can mimic effects of new physics

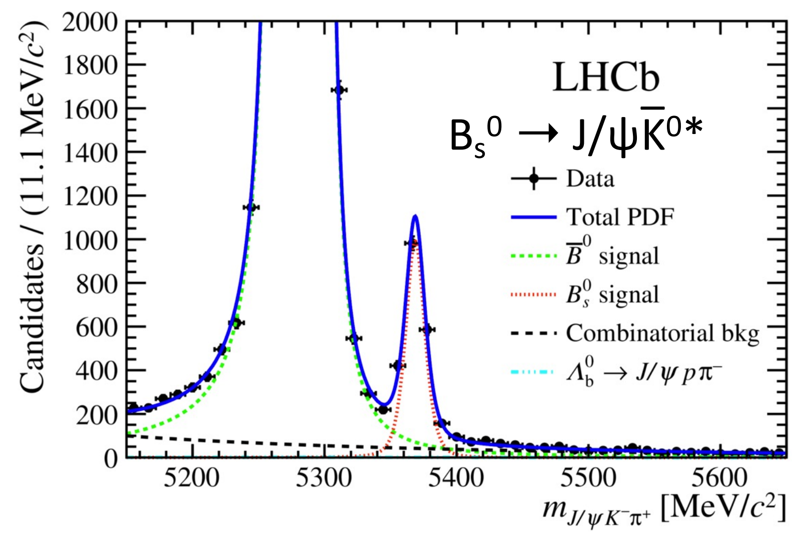


Strategy is to study in dedicated channels to set limits on the size:

$\delta\phi s$ = [−0.018, 0.021] rad at 95% confidence



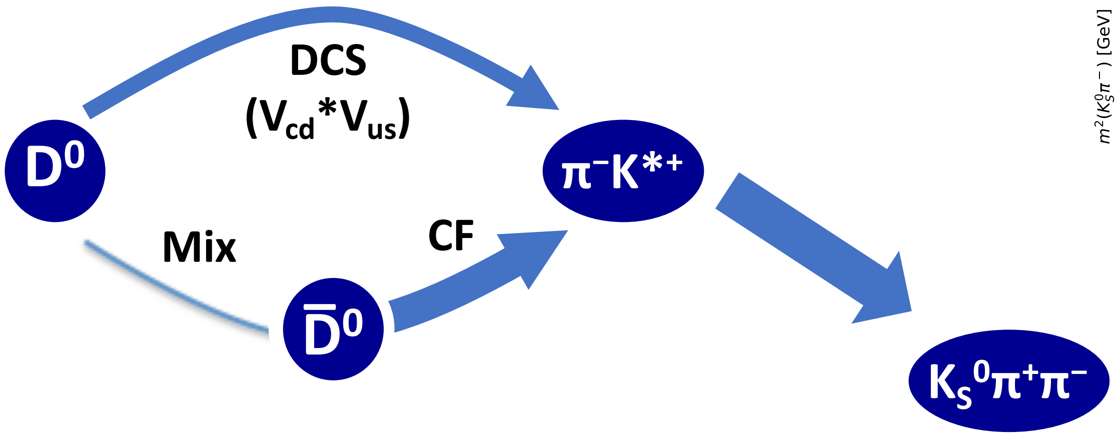
https://doi.org/10.1016/j.physletb.2015.01.008

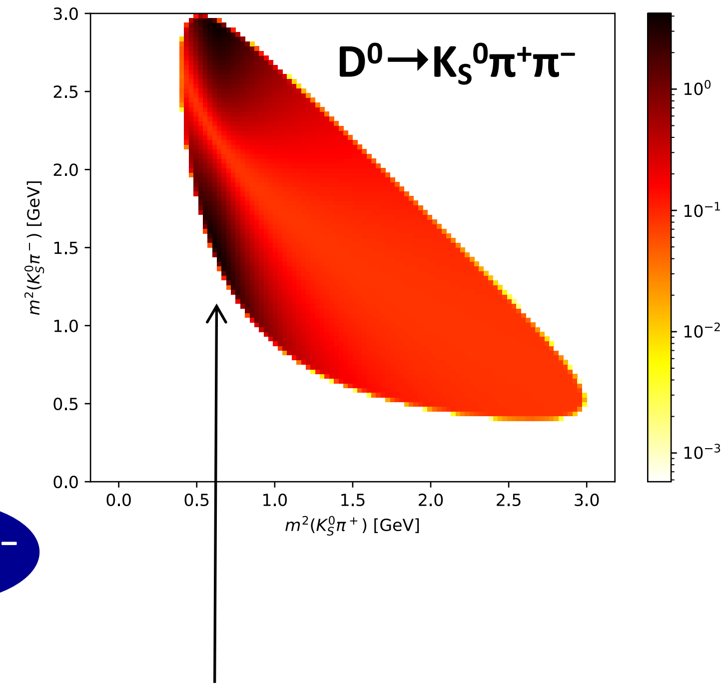


https://doi.org/10.1007/JHEP11(2015)082

Charm mixing: 'Golden mode' $D^0 \to K_S^0\pi^+\pi^-$

'Right-sign' (CF) and 'wrong-sign' (DCS or oscillated) decays to ***same final state***

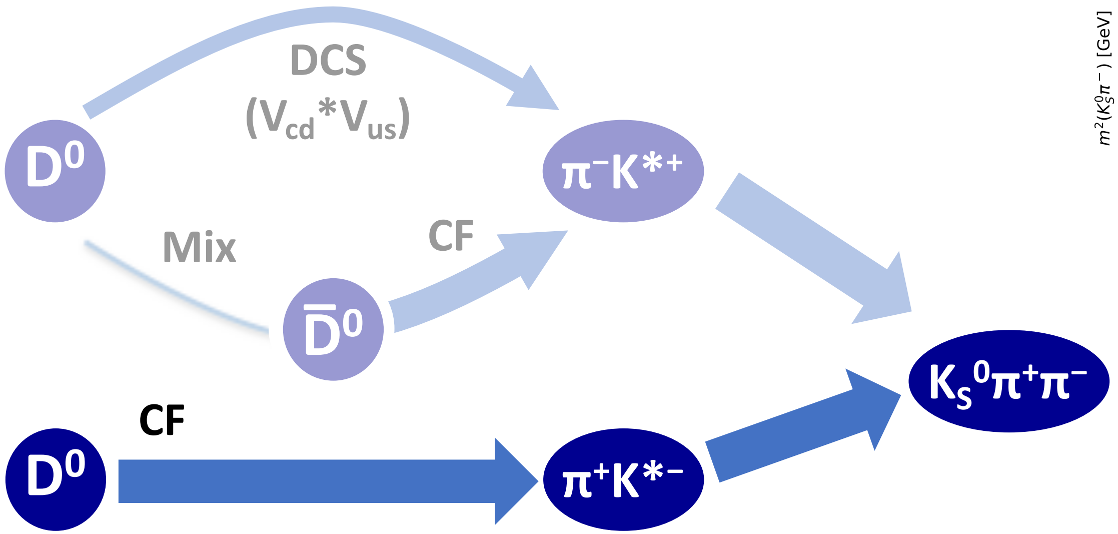


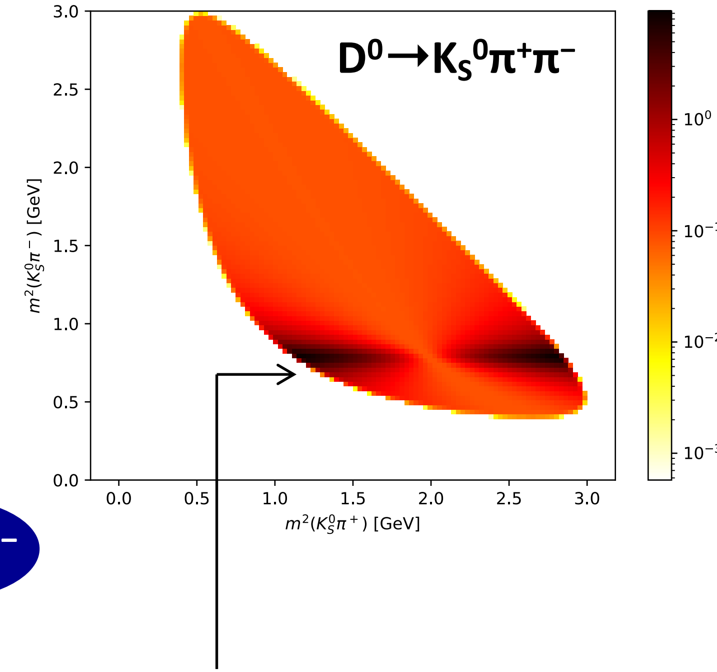


$K^*(892)^+$

Charm mixing: 'Golden mode' $D^0 \to K_S^0 \pi^+ \pi^-$

'Right-sign' (CF) and 'wrong-sign' (DCS or oscillated) decays to ***same final state***

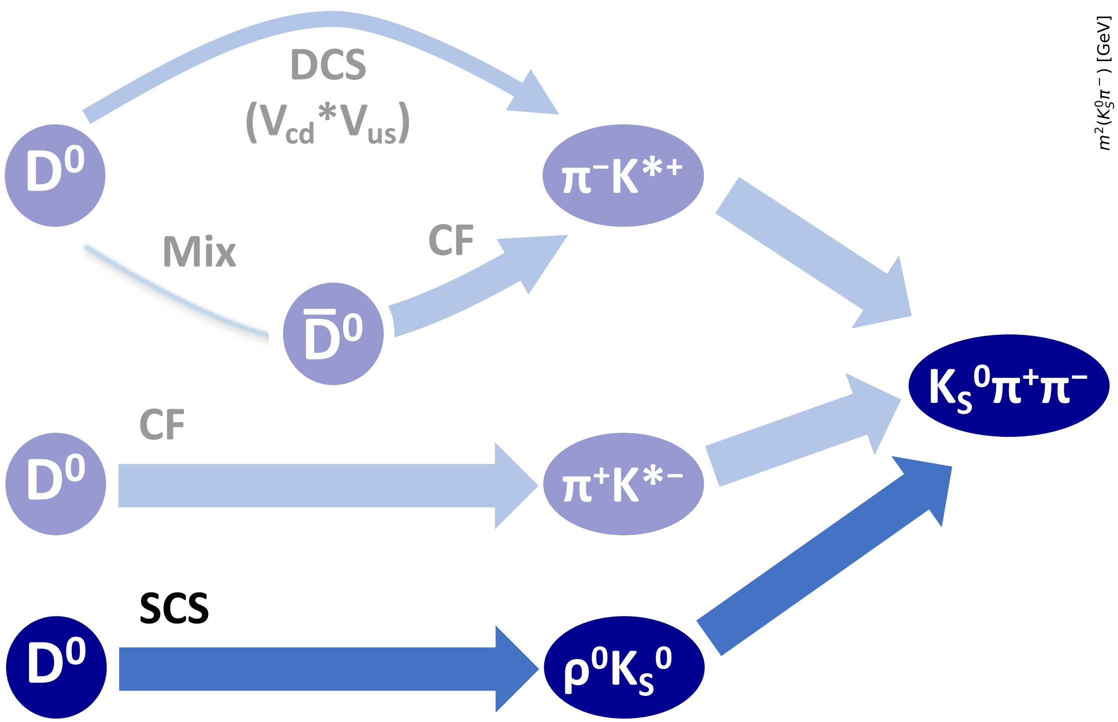


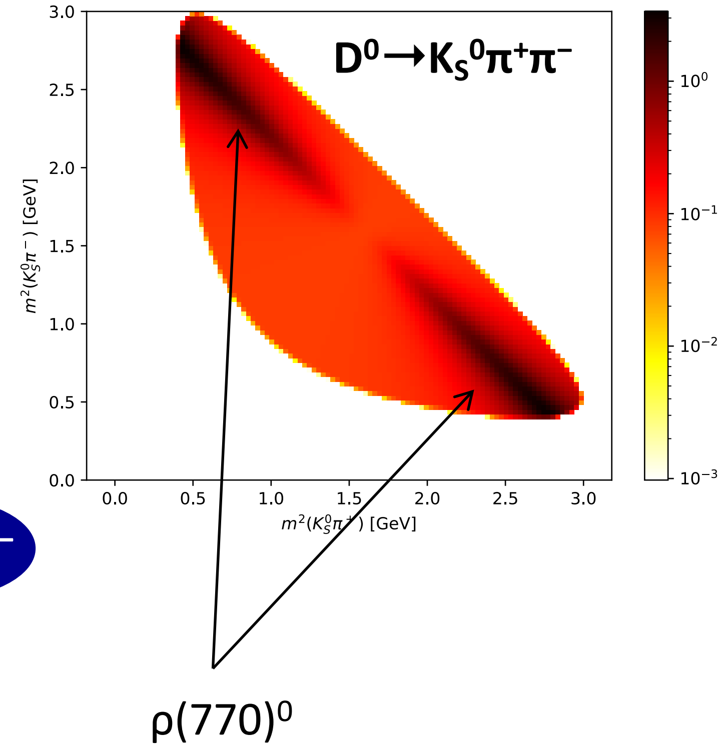


$K^*(892)^-$

Charm mixing: 'Golden mode' $D^0 \rightarrow K_S{}^0\pi^+\pi^-$

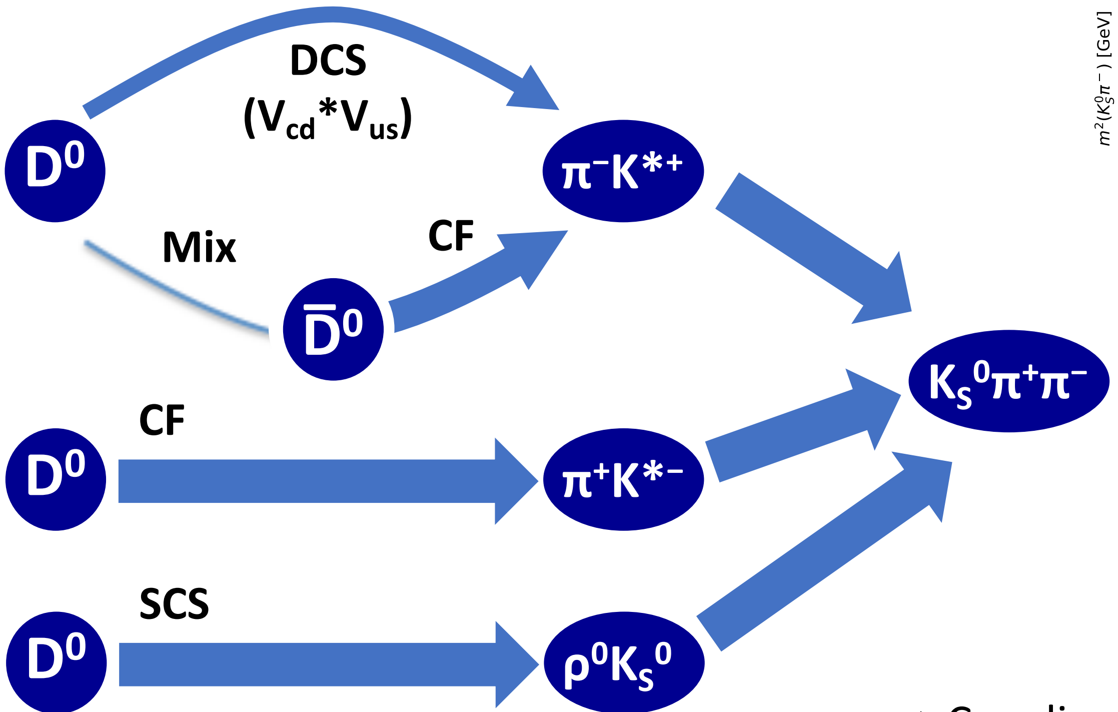
'Right-sign' (CF) and 'wrong-sign' (DCS or oscillated) decays to ***same final state***

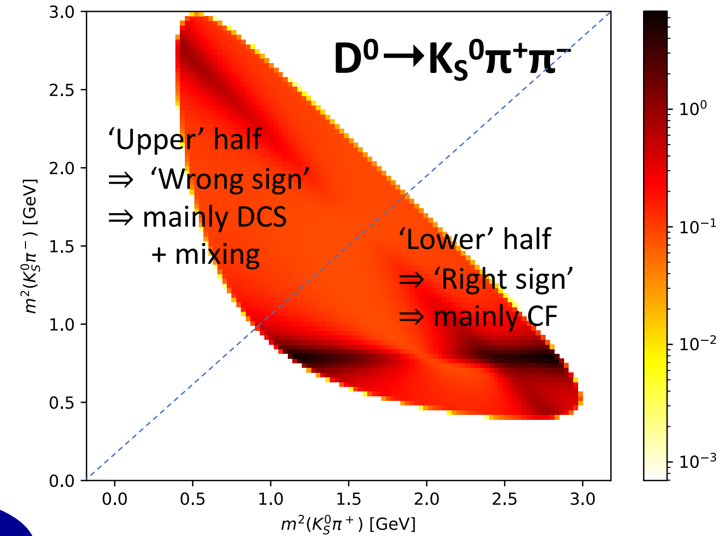




Charm mixing: ‘Golden mode’ $D^0 \to K_S^0\pi^+\pi^-$

‘Right-sign’ (CF) and ‘wrong-sign’ (DCS or oscillated) decays to ***same final state***





$K^*(892)^+ + K^*(892)^- + \rho(770)^0$

⇒ Can directly measure all four mixing and CPV parameters x, y, |q/p|, arg(q/p)

Requires **time and phase-space dependent analysis**

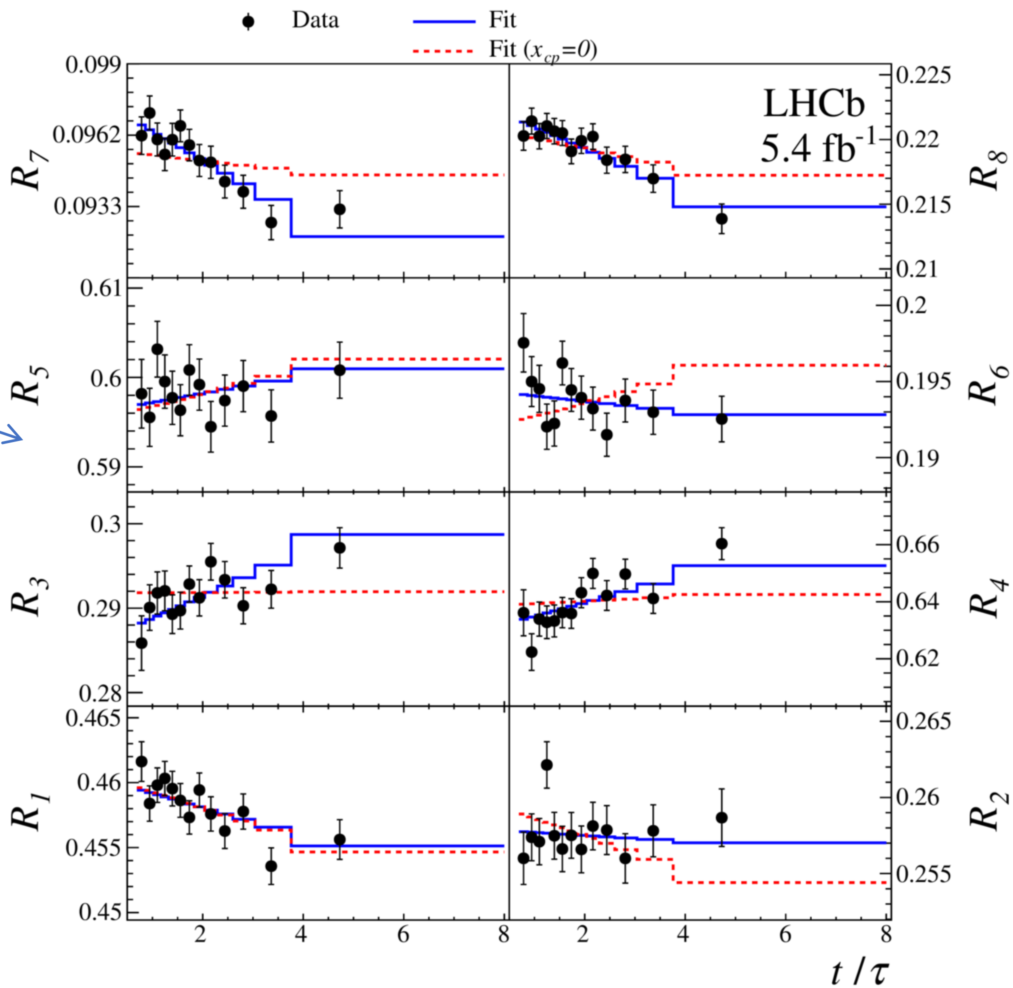
Charm mixing: ‘Golden mode’ $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

Plot ratio of candidates in upper/lower half of Dalitz plane

⇒ 8 ratios in Dalitz bins $R_1 - R_8$

⇒ Fit to extract parameters

Clear time dependence from mixing



$x \equiv \Delta m/\Gamma = [0.397 \pm 0.046 \pm 0.029]\%$
$y \equiv \Delta\Gamma/2\Gamma = [0.459 \pm 0.120 \pm 0.085]\%$

First measurement of non-zero x (>7σ significance)

Oscillation period ~630ps (D^0 lifetime 0.4ps)

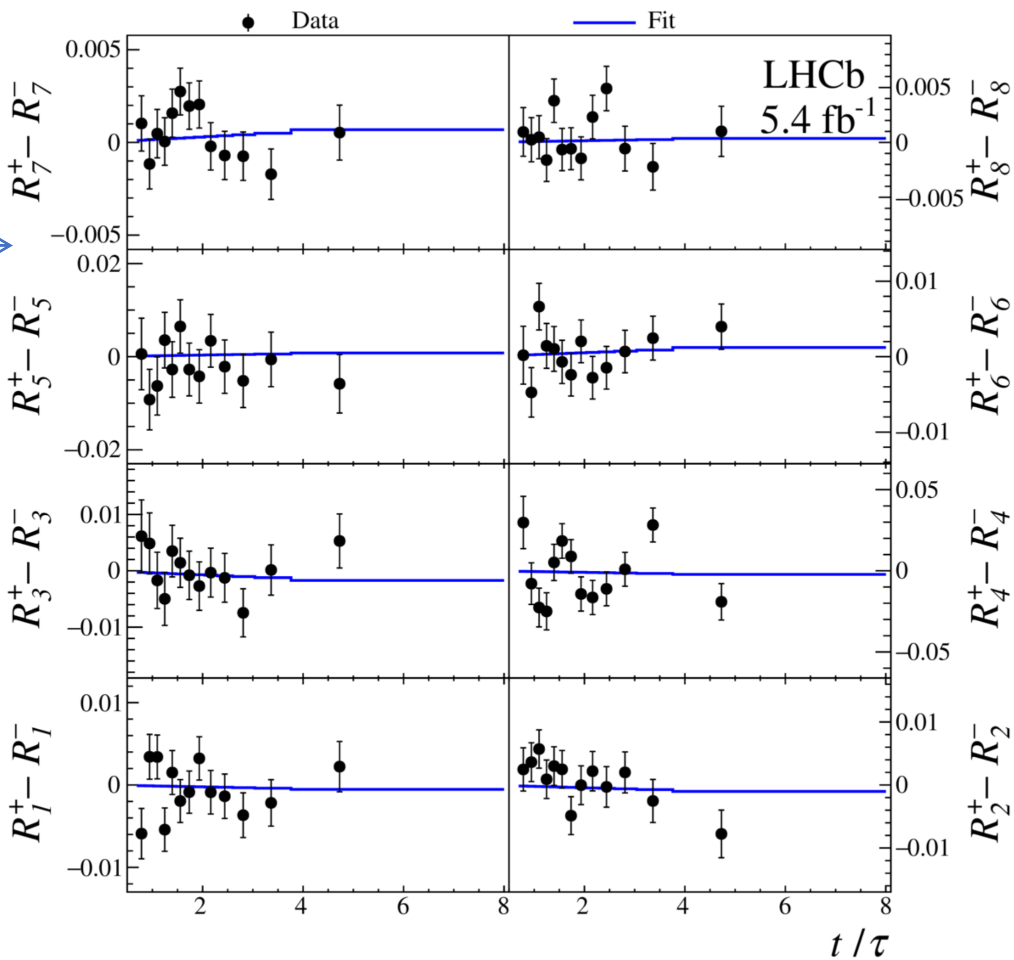
arXiv:2106.03744

Phys. Rev. Lett. 127, 111801

Charm mixing: 'Golden mode' $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

No significant differences D^0 vs $\overline{D}^0$

$\Rightarrow$ no evidence for CP violation



arXiv:2106.03744

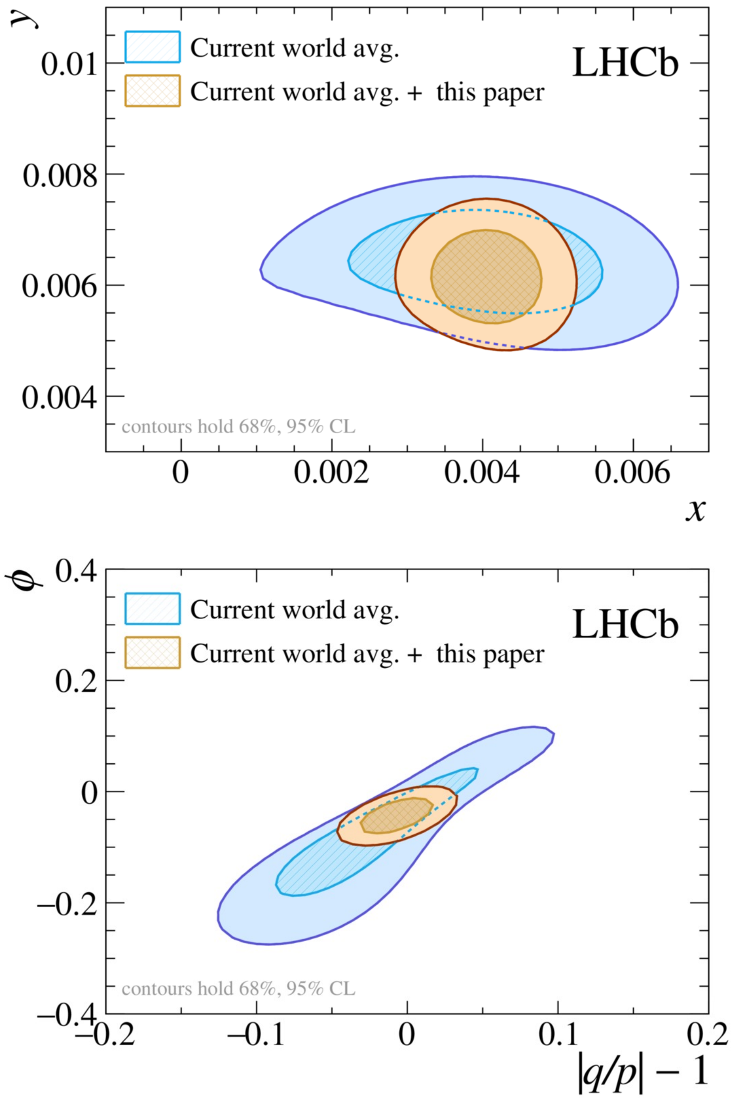
Phys. Rev. Lett. 127, 111801

Charm mixing: 'Golden mode' $D^0 \to K_S^0 \pi^+ \pi^-$

Combine with all previous measurements

⇒ **Significant improvements in WA** for both mixing and CPV parameters

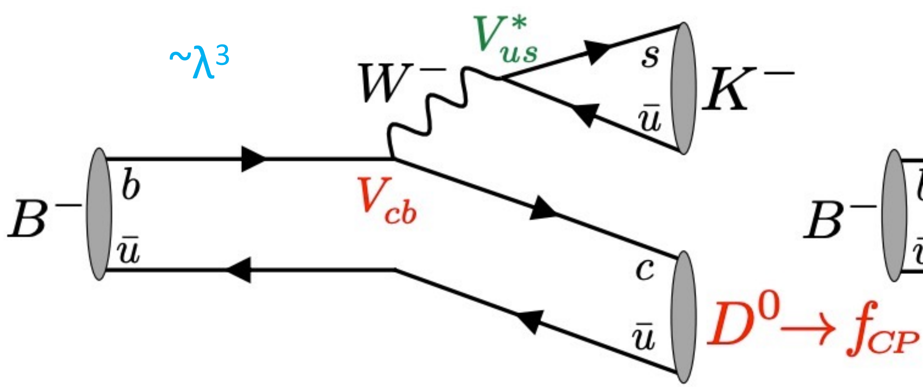
⇒ Hence the 'Golden Mode' for charm

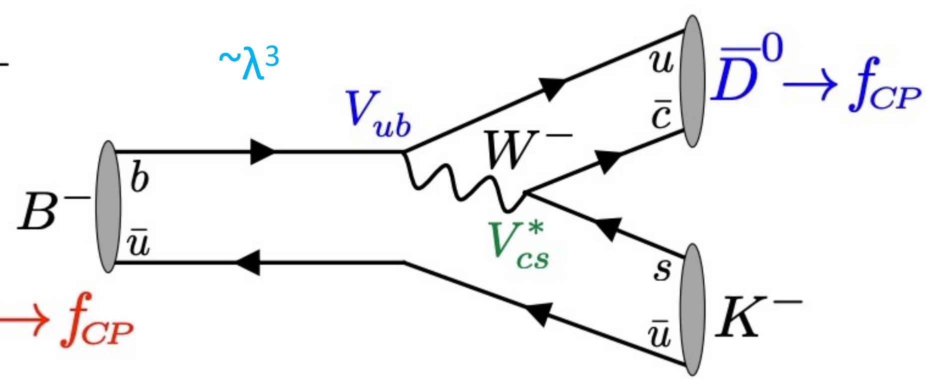


Measuring γ: GLW method

Colour favoured: $b \to cW$
- Magnitude $|F|$
- Weak phase ϕ_F, strong phase δ_F

Colour suppressed: $b \to uW$
- Magnitude $|S|$
- Weak phase ϕ_S, strong phase δ_S





Amplitudes to final state f_{CP}:

B^-: $A_f = |F|e^{i(\delta F + \phi F)} + |S|e^{i(\delta S + \phi S)}$

B^+: $A_f = |F|e^{i(\delta F - \phi F)} + |S|e^{i(\delta S - \phi S)}$

Under CP operation:
- Weak phases change sign
- Strong phases unchanged

Measuring γ: GLW method

'Trick': Weak phase difference $\phi_F - \phi_S = \gamma$ always
while $\delta_B \equiv \delta_F - \delta_S$ and $r_B = |S|/|F|$ depend on the decay

(F^+: fraction of D^0 decay to CP=+1 eigenstate)

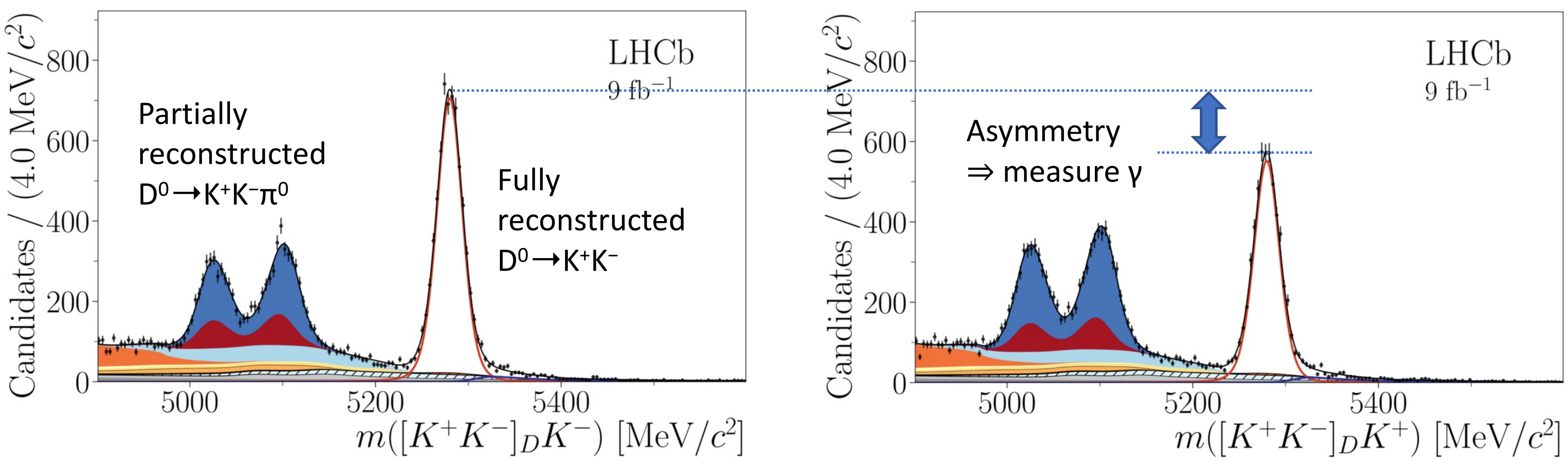
GLW observables

Asymmetry (B^+ vs B^-):

$$A_{CP} = \frac{\pm 2r_B(2F^+ + 1)\sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2r_B(2F^+ + 1)\cos(\delta_B)\cos(\gamma)}$$

Total rate:

$$R_{CP} = 1 + r_B^2 \pm 2r_B(2F^+ + 1)\cos(\delta_B)\cos(\gamma)$$



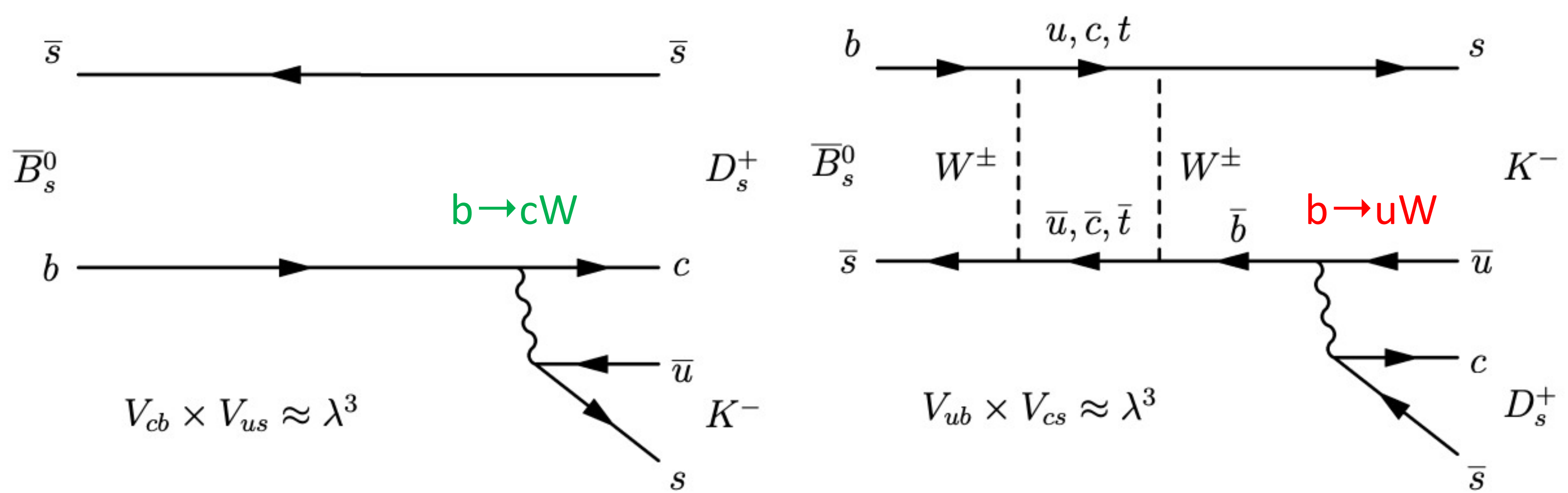
https://doi.org/10.1007/JHEP04(2021)081 (2021)

Measuring γ with B_s^0 mixing

Can also measure γ with B_s^0 meson mixing providing interference [compare sin(2β)]

$\overline{B}_s^0 \rightarrow D_s^+ K^-$ (tree)

$\overline{B}_s^0 \rightarrow D_s^+ K^-$ (loop, with B_s^0 mixing)



- Weak phase difference is **(γ – 2β_s)** ⇒ need input from B_s^0 measurements
- Need time-dependent analysis to observe oscillations

Measuring γ with B_s^0 mixing

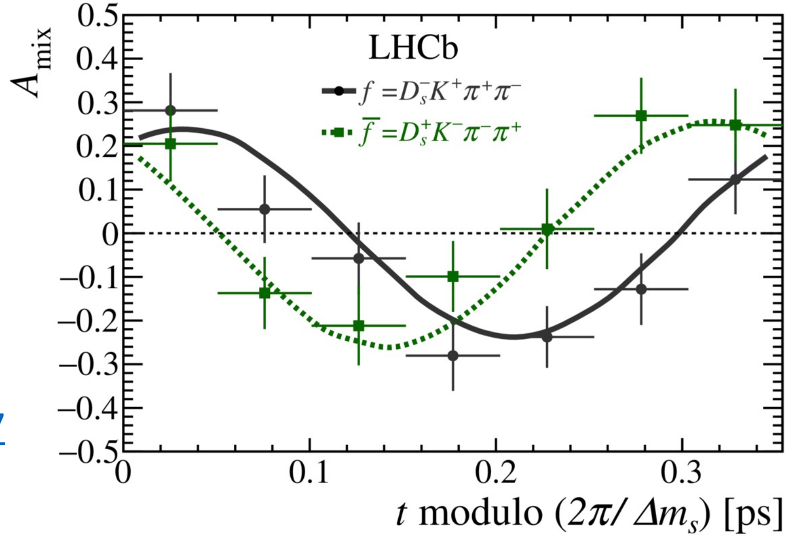
Fit for time-dependent asymmetry

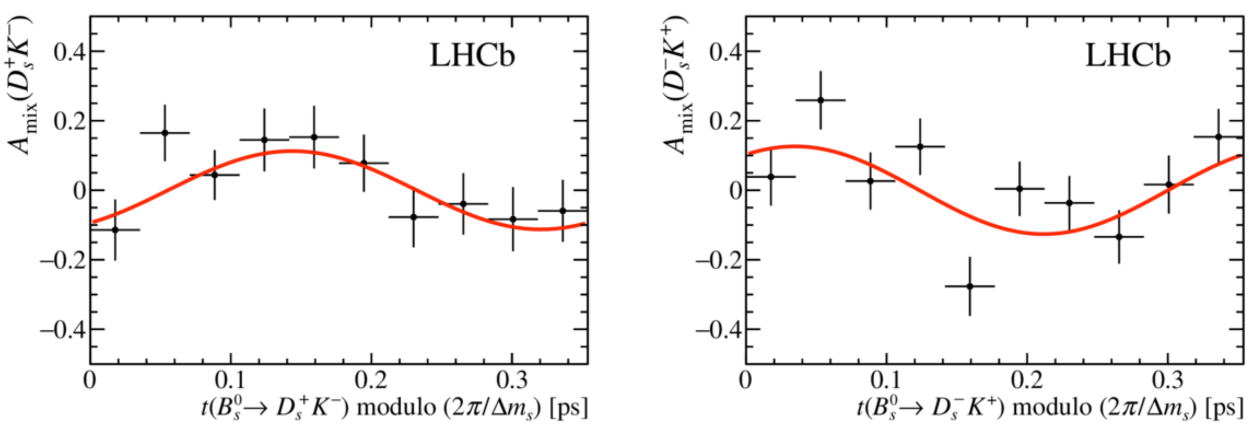
$B_s^0 \to D_s^- K^+ \pi^+ \pi^-$

γ = (44 ± 12)° modulo 180°

Full LHCb Run 1+2 (9fb^{-1})

https://doi.org/10.1007/JHEP03(2021)137





$B_s^0 \to D_s^- K^+$

γ = $(128\ ^{+17}_{-22})°$ modulo 180°

LHCb Run 1 (3fb^{-1})

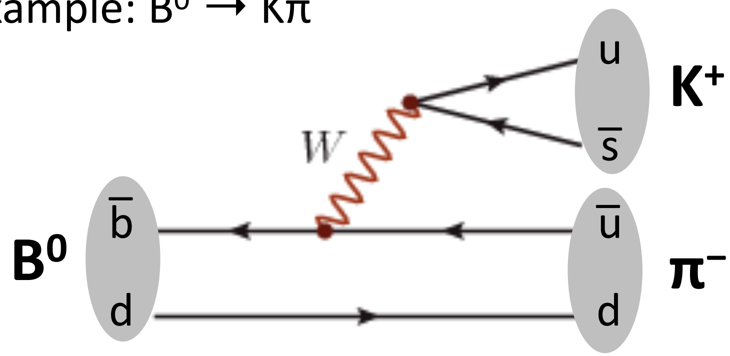
https://doi.org/10.1007/JHEP03(2018)059

CPV in B decay: “Kπ problem”

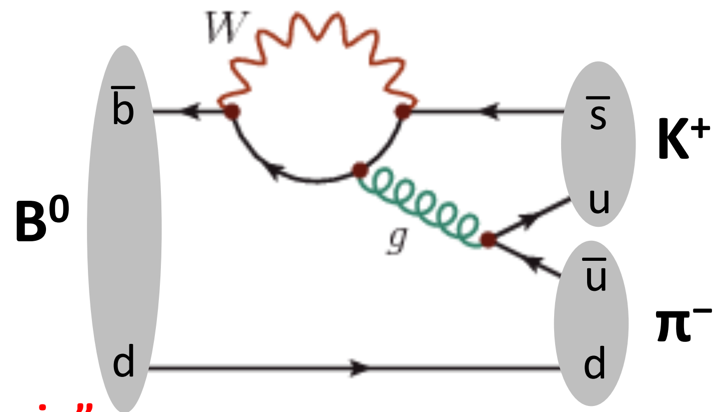
CPV in decay

Remember – need ≥2 interfering processes (preferably with similar magnitudes)

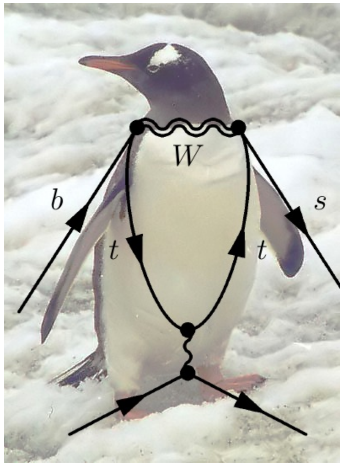
Example: $B^0 \rightarrow K\pi$



Tree-level



“Penguin”

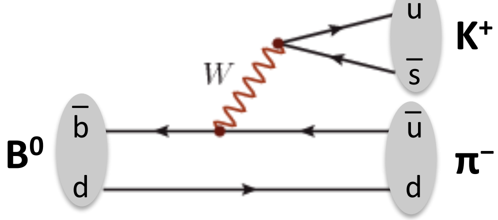


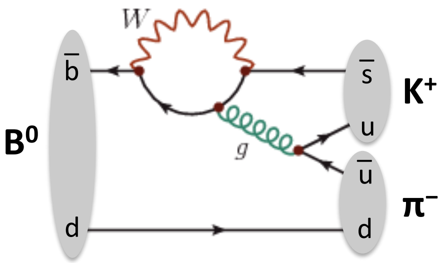
Weak phase between amplitudes = γ

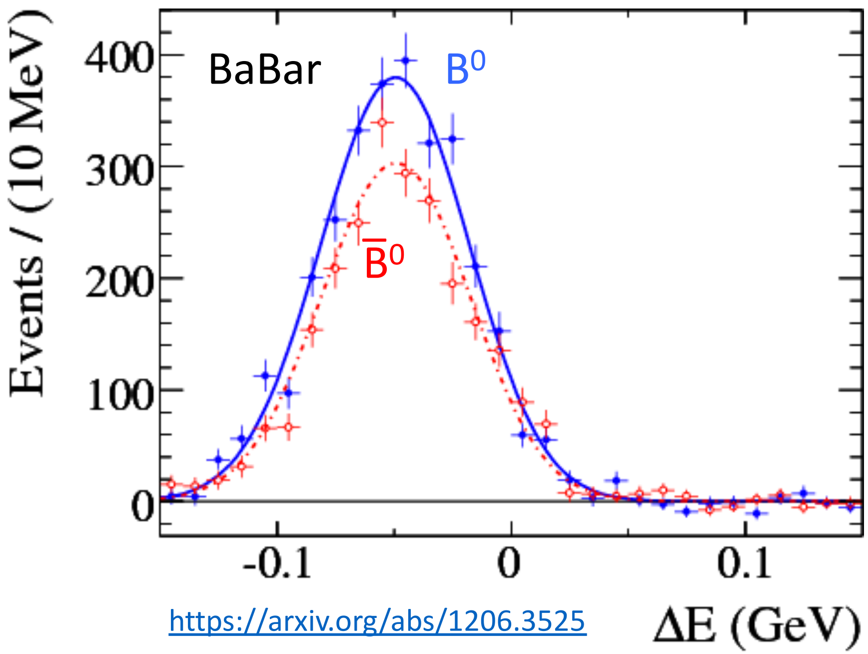
CPV in B decay: "Kπ problem"

CPV in decay

Example: $B^0 \rightarrow K\pi$







https://arxiv.org/abs/1206.3525

Problem: CPV should be same for corresponding B+ decay (only difference is spectator quark), but…

$A_{CP}(B^0 \rightarrow K^+\pi^-) = (-8.4 \pm 0.4)\%$

$A_{CP}(B^+ \rightarrow K^+\pi^0) = (+4.0 \pm 2.1)\%$

Averages from HFLAV

Sign of new physics?
Could be from subtle QCD effects…

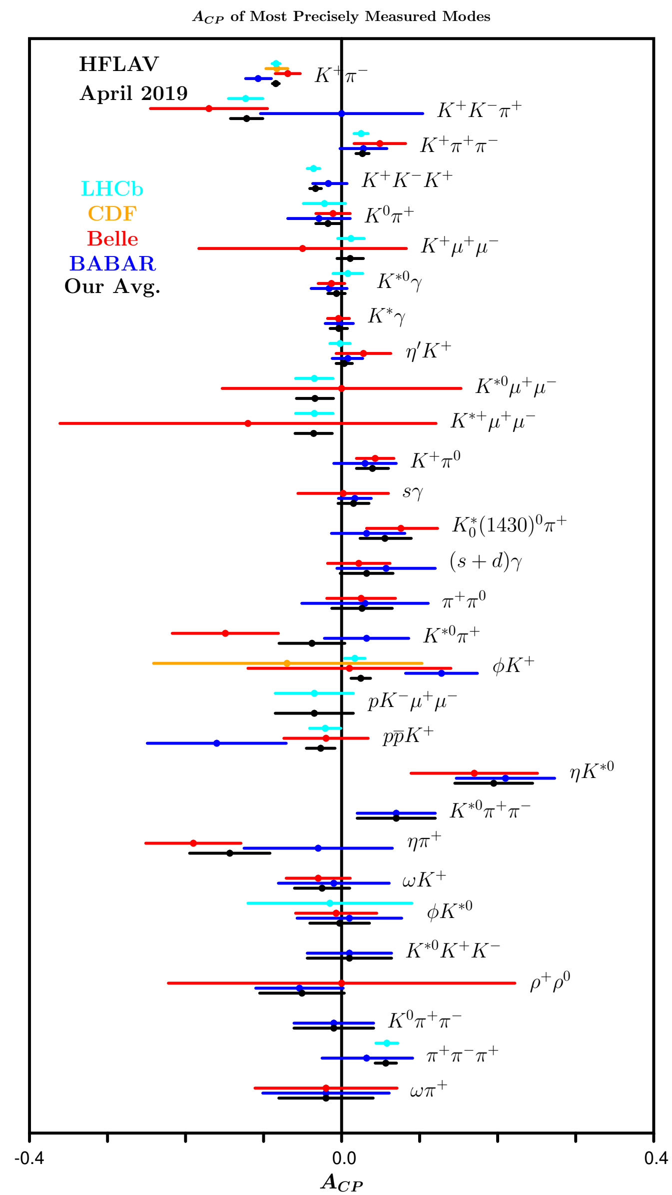
CPV in B decay: “Kπ problem”

CPV in decay

Only small sample of results
(for B^0 and B^+)

A lot of measurements of a lot of modes!
Most consistent with CP symmetry

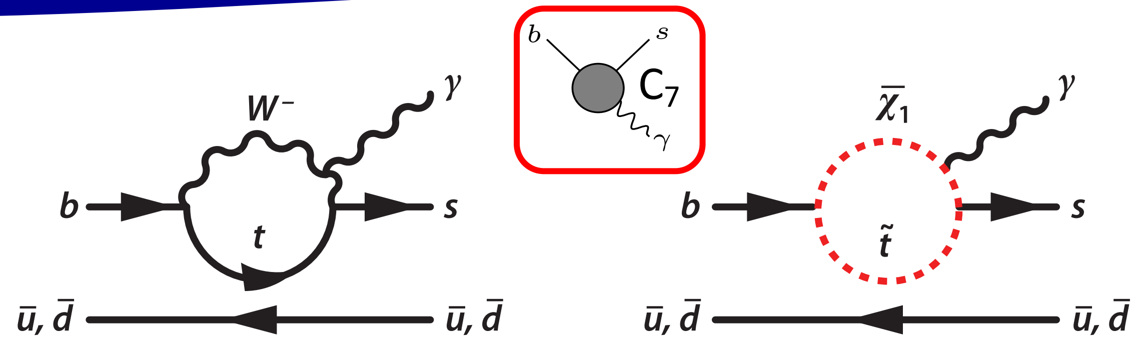
⇒ Remember: only 1 CP violating phase in SM!



https://hflav-eos.web.cern.ch/hflav-eos/rare/April2019/ACP/index.html

Radiative penguins: b → sγ

Radiative penguins give access to new physics, via Wilson Coefficient C_7



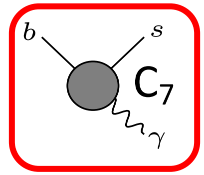
Two approaches:

- *Exclusive*, to specific final state (e.g. $B^0 \to K^{0*}\gamma$)
  ⇒ experimentally easier, theoretically messier
- *Inclusive*, including any strange hadrons in final state ($B^0 \to X_s\gamma$)
  ⇒ experimentally challenging (one for the B factories!), theoretically clean

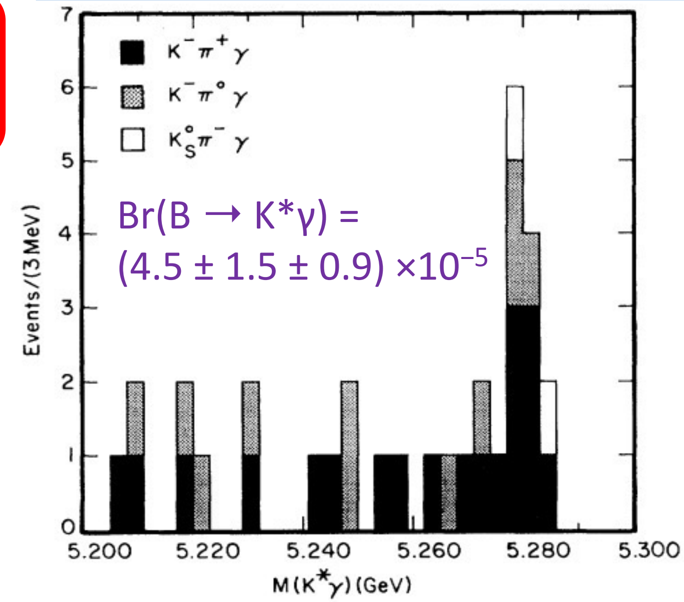
Can also study $b \to d\gamma$ decays (e.g. $B \to \rho\gamma$)
⇒ further suppressed by $|V_{td}/V_{ts}|^2 \approx (\lambda^3/\lambda^2)^2 \approx 0.05$

Radiative penguins: Exclusive

$B^{(0,\pm)} \rightarrow K^{(0,\pm)*}\gamma$ discovered by CLEO-II in 1993



https://doi.org/10.1103/physrevlett.71.674



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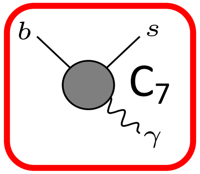

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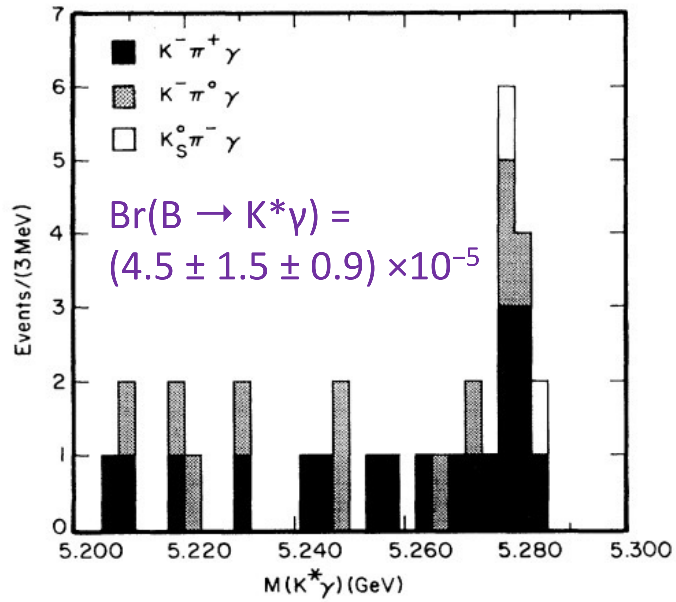
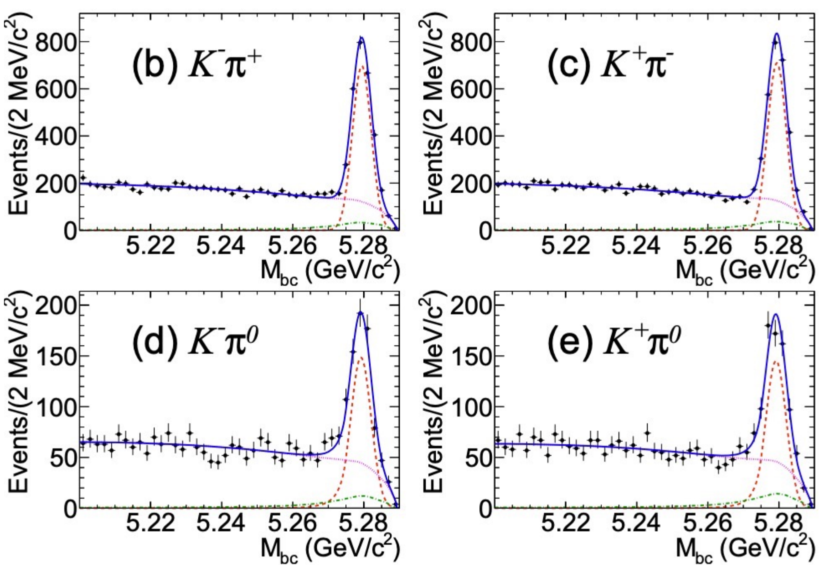


$\mathrm{Br}(B \rightarrow K^*\gamma) = (4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$

The B-factories later made high-precision measurements

e.g. Belle (2017):

https://doi.org/10.1103/PhysRevLett.119.191802



Current world-averages:

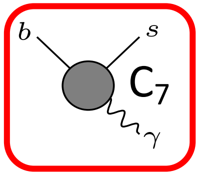
$\mathrm{Br}(B^0 \rightarrow K^{0*}\gamma) = (4.18 \pm 0.25) \times 10^{-5}$

$\mathrm{Br}(B^\pm \rightarrow K^{\pm *}\gamma) = (3.92 \pm 0.22) \times 10^{-5}$

Theory predictions in range $3.5 - 7.0 \times 10^{-5}$

Easier to calculate CP or isospin asymmetries

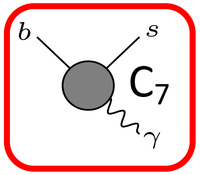
Radiative penguins: Inclusive



Much trickier experimentally! Final state is **photon** (γ) + **anything strange** (X_s)

No perfect method – several options (fully-inclusive, semi-inclusive, summed exclusive, …) each with pros and cons.

Radiative penguins: Inclusive



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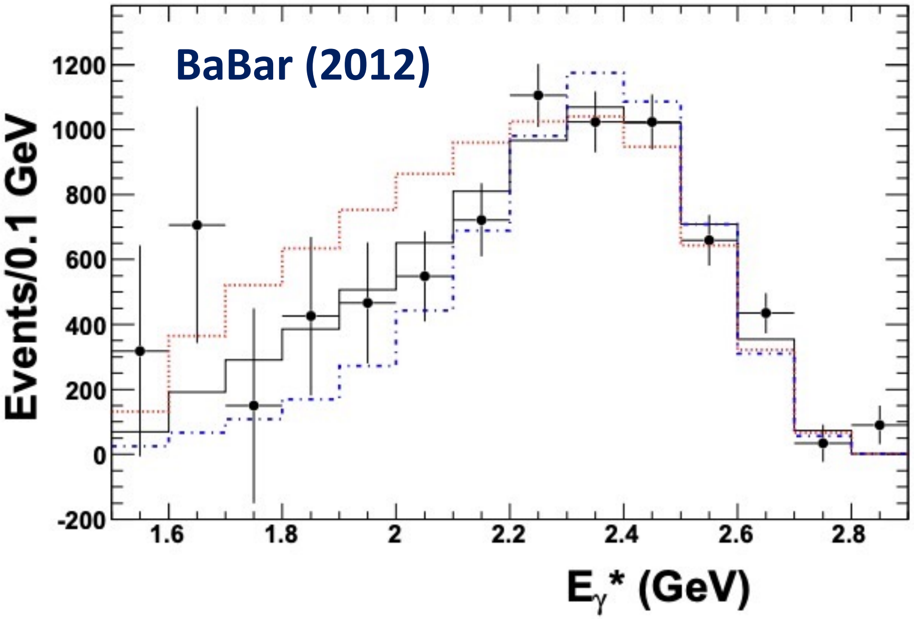
https://doi.org/10.1103/PhysRevD.86.112008

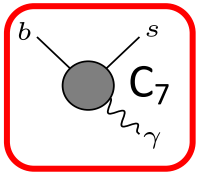
Need clean environment of B-factory:

- Look for (relatively) high energy photon
- Identify X_s topology using multivariate tools trained on simulation
- Plot **photon energy spectrum** after subtracting backgrounds
- Input from theory to convert to BR measurement



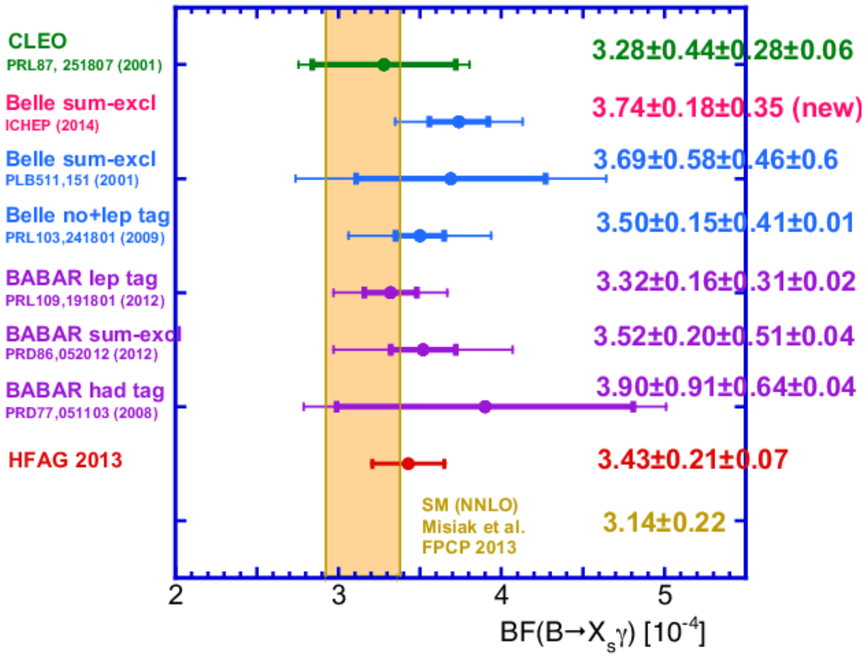
Data (markers) versus three theory models (histograms)

Radiative penguins: Inclusive

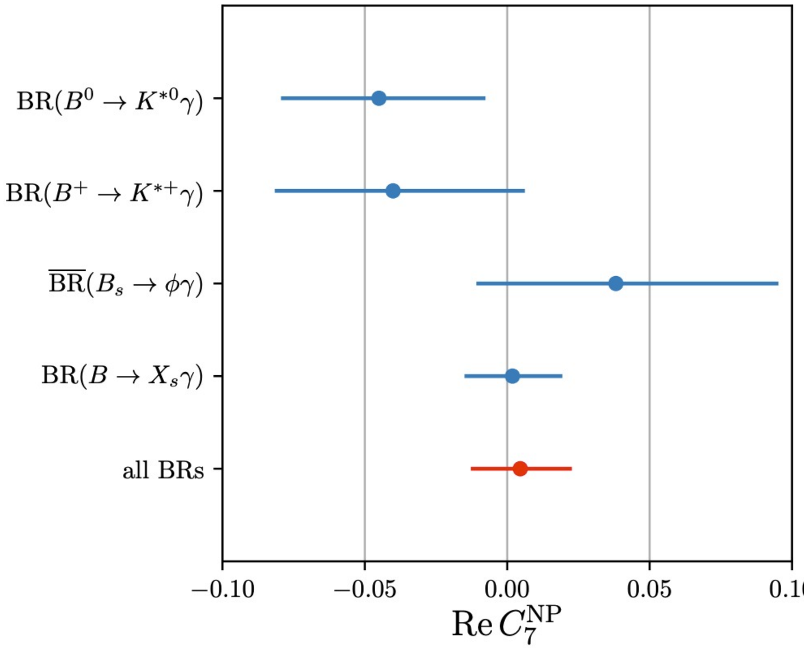


Can combine results from all experiments and use to constrain C_7

Measurements in good agreement



Constraints on new physics in C_7



https://doi.org/10.1007/JHEP04(2017)027

Latest exp.: $Br(B \to X_s\gamma) = (3.32 \pm 0.15) \times 10^{-4}$

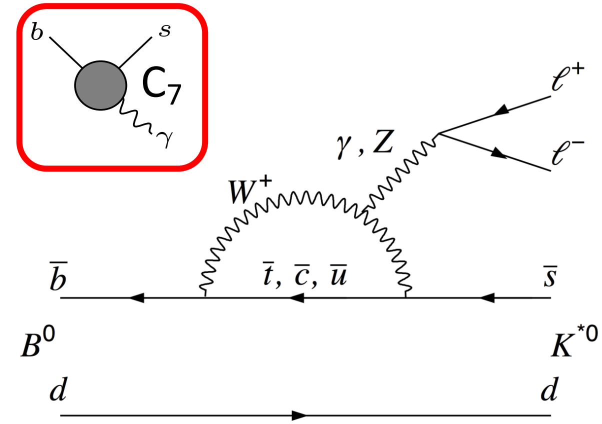
Latest SM: $Br(B \to X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$

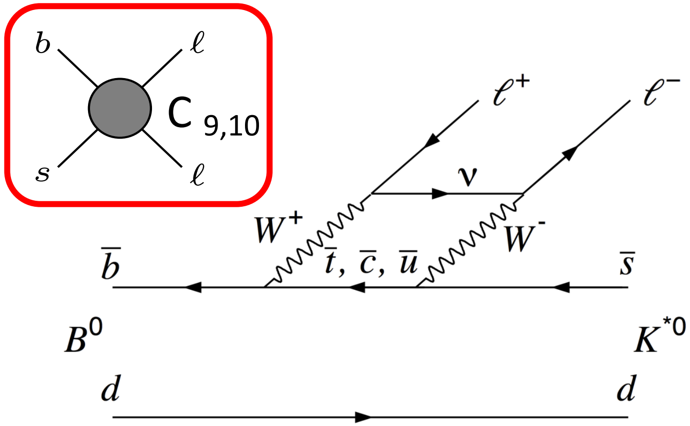
Electroweak penguins: $b \to s l^+ l^-$

Experimentally easier: two charged leptons + hadrons

`Golden mode' here is **$B^0 \to K^{0*}\mu^+\mu^-$**

Much richer decay structure – many observables which can constrain new physics models…

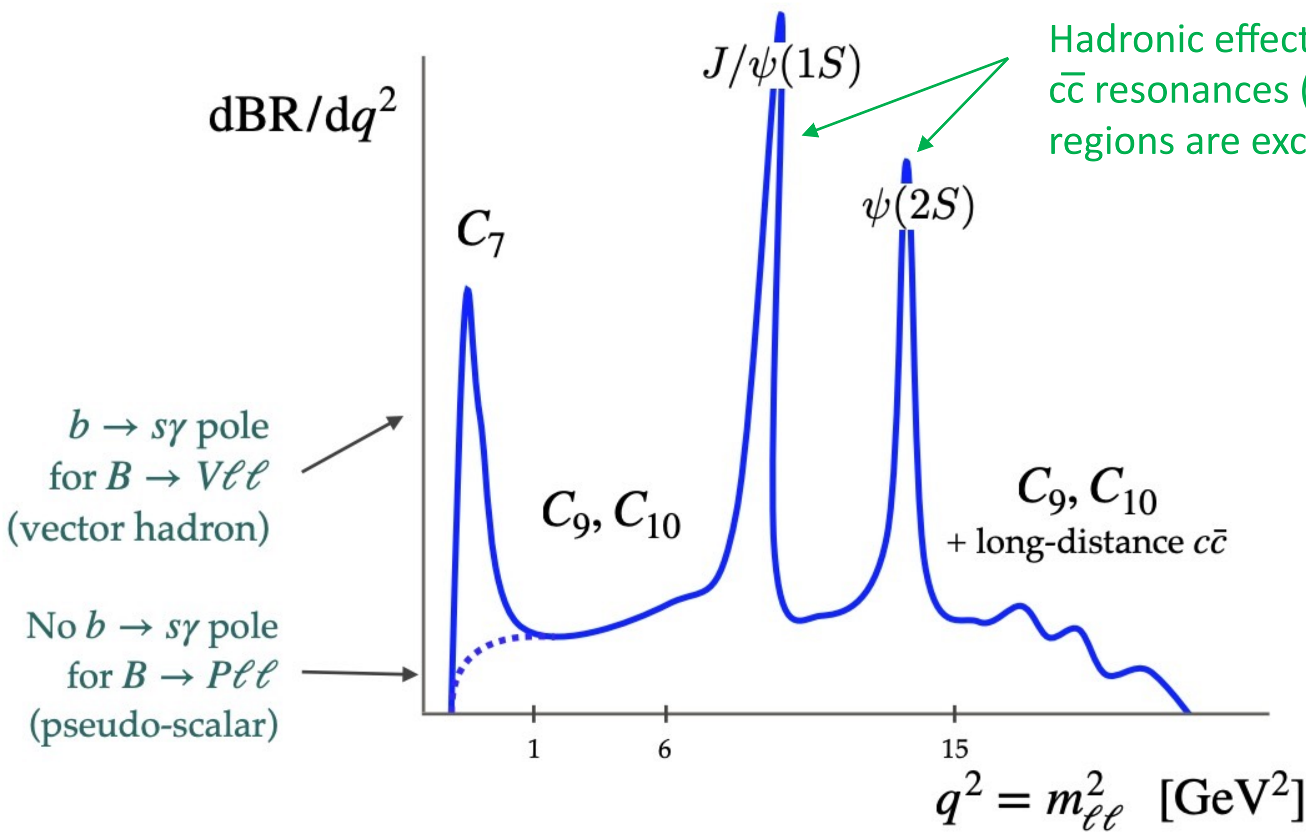




Electroweak penguins: $b \to s l^+ l^-$

Decay dynamics depend strongly on dimuon mass (= momentum transfer, q^2)

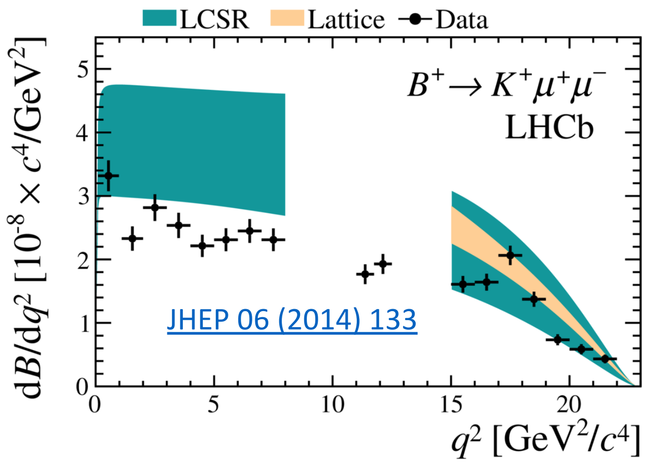
Hadronic effects dominate around $c\bar{c}$ resonances (J/ψ, (2S)) so these regions are excluded

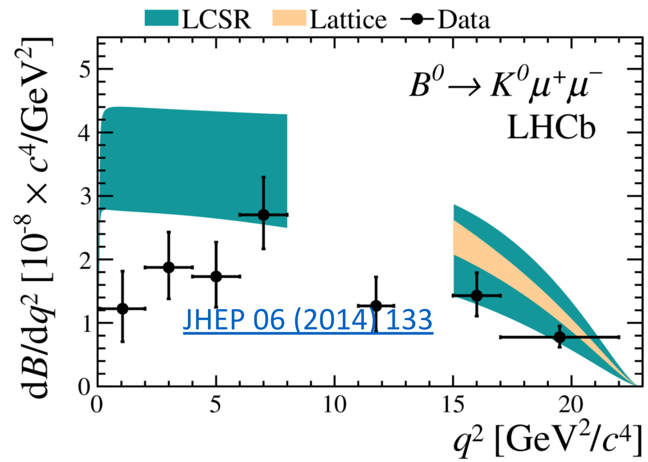


Electroweak penguins: b → sl^+l^-

Branching ratios for different b → $s\mu^+\mu^-$ channels tend to undershoot SM prediction

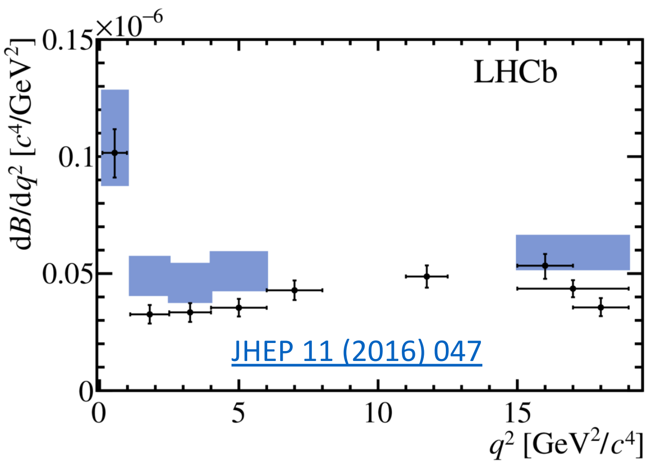
$B^+ \rightarrow K^+\mu^+\mu^-$

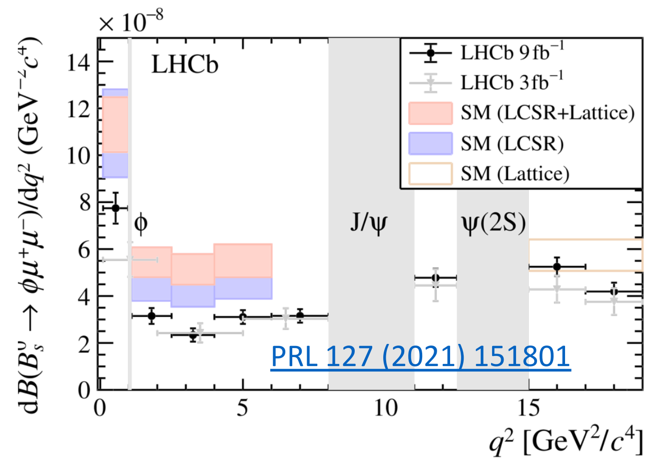




$B^0 \rightarrow K^0\mu^+\mu^-$

$B^0 \rightarrow K^{0*}\mu^+\mu^-$





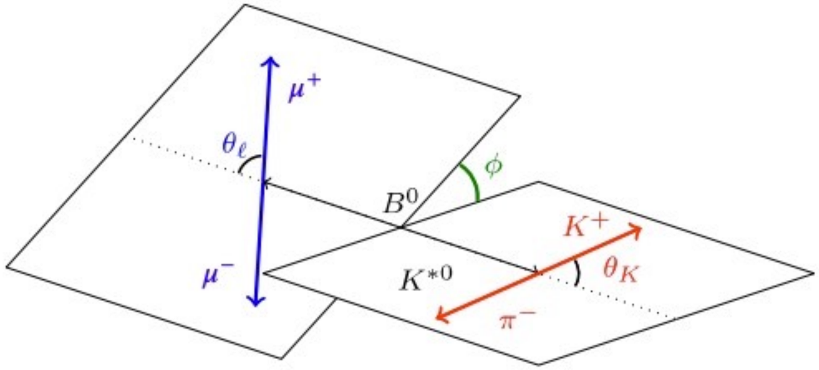
$B_s^0 \rightarrow \phi\mu^+\mu^-$

Electroweak penguins: b → sl^+l^-

For B → K*μμ, can do more:

⇒ K* is a vector meson

⇒ Decay rate depends on three angles



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

$S_1 \equiv F_L$ (longitudinal polarization fraction of K*)

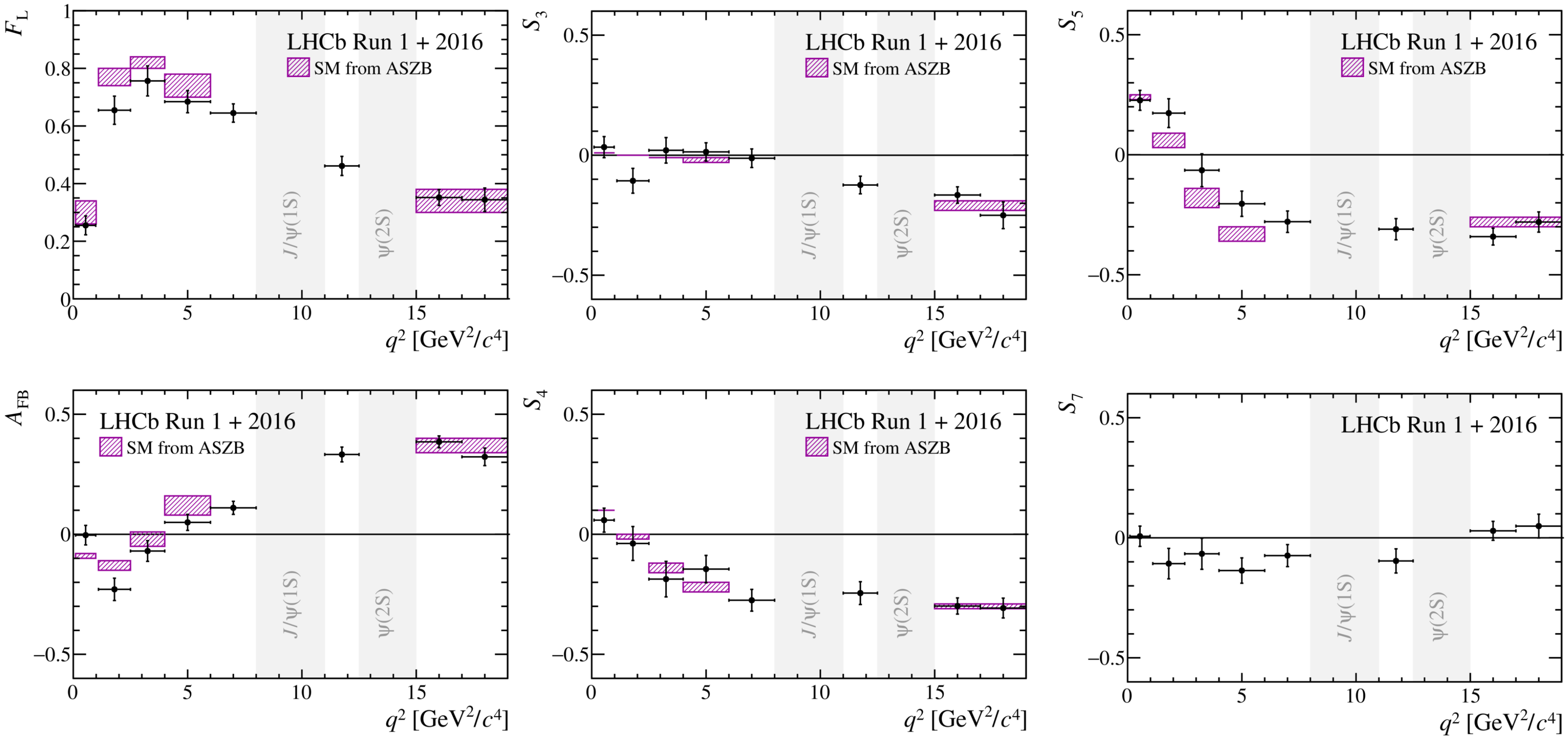
$S_6 \propto A_{FB}$ (forward-backward asymmetry of dimuon system)

Measure the observables: F_L, A_{FB}, S_i

+ also examine CP asymmetries (where $S_i \rightarrow A_i$)

Electroweak penguins: $b \to s l^+ l^-$

At first glance, most observables in agreement with SM …
… but hampered by large hadronic uncertainties in SM predictions



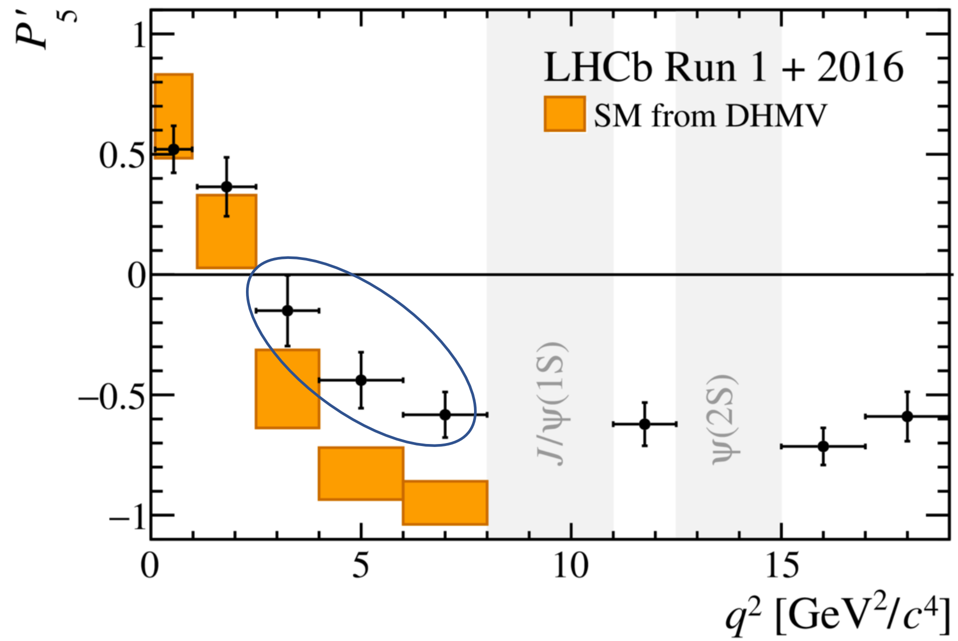
PRL 125 (2020) 011802

Electroweak penguins: b → sl^+l^-

Build new observables designed to ensure cancellation of major SM uncertainties

$$P_1 = \frac{2\,S_3}{(1-F_\mathrm{L})} = A_\mathrm{T}^{(2)}\,,$$
$$P_2 = \frac{2}{3}\frac{A_\mathrm{FB}}{(1-F_\mathrm{L})}\,,$$
$$P_3 = \frac{-S_9}{(1-F_\mathrm{L})}\,,$$
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,,$$
$$P'_6 = \frac{S_7}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,.$$

PRL 125 (2020) 011802



Largest discrepancy in P_5' variable, at low q^2

Prompted a lot of interest from theoretical community

Crucial to check with other experiments…

Electroweak penguins: b → sl^+l^-

Seems to be a consistent disagreement between experiment and theory, but need more precision

Full Run 1+2 data yet to be analysed