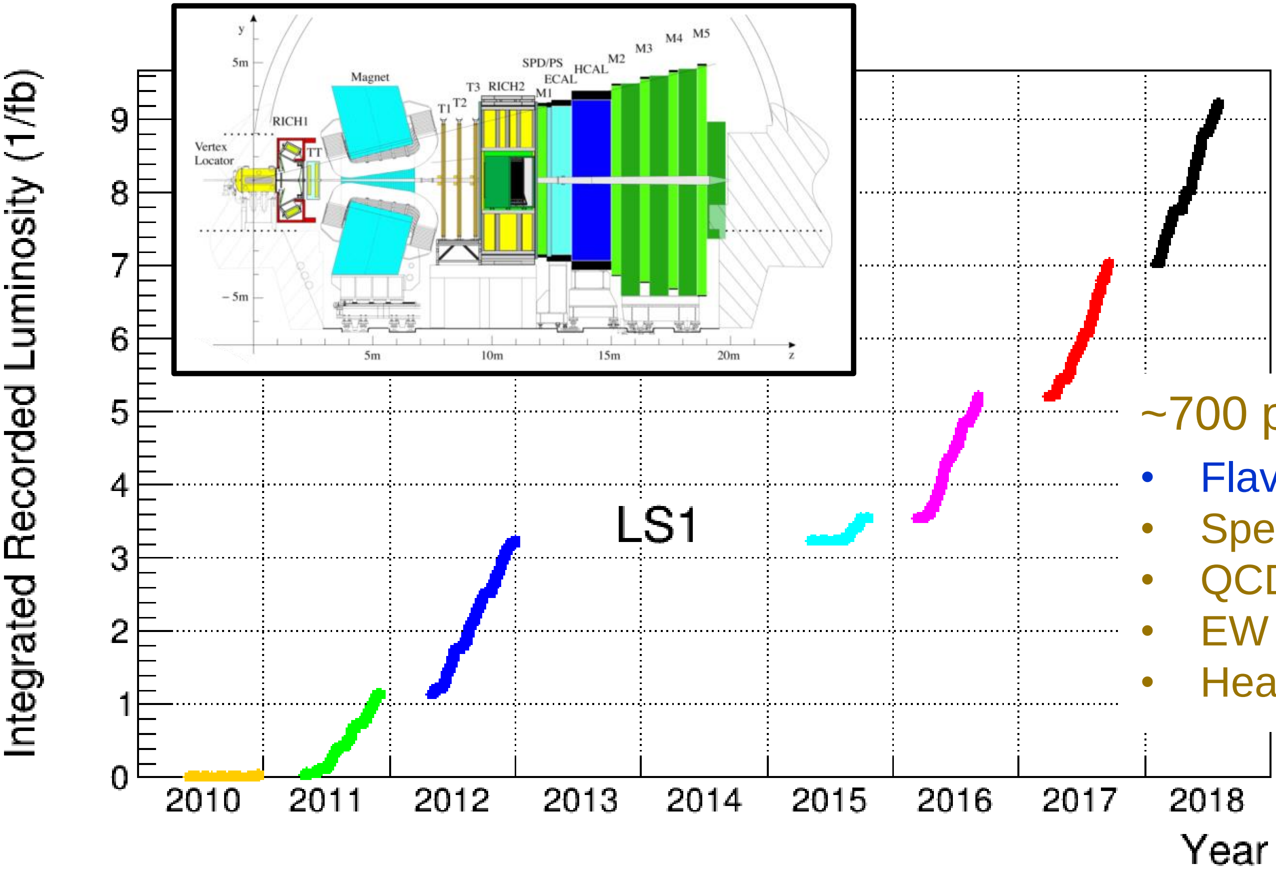
Flavour physics at LHCb: selected results and future prospects

Guy Wilkinson
University of Oxford

FTCF Hefei, January 2024

LHCb Run 1 & 2 physics output



~700 publications in:

- Flavour physics
- Spectroscopy
- QCD
- EW
- Heavy ion physics

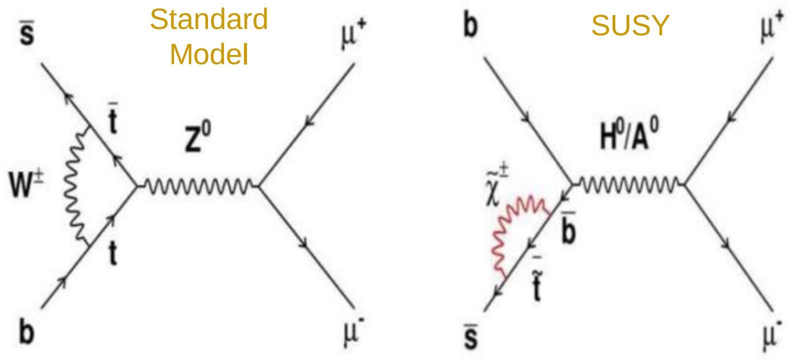
Brief tour through most significant results in FCNCs, CP violation in the b-sector, and in charm, giving due mention to other LHC experiments, where appropriate.

Search for New Physics through Flavour-Changing-Neutral-Current decays

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 ($B_s \to \mu\mu$ ~4×10^{-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.


ARGUS, 1987

B MESON DECAYS INTO CHARMONIUM STATES

ARGUS Collaboration

UA1, 1991

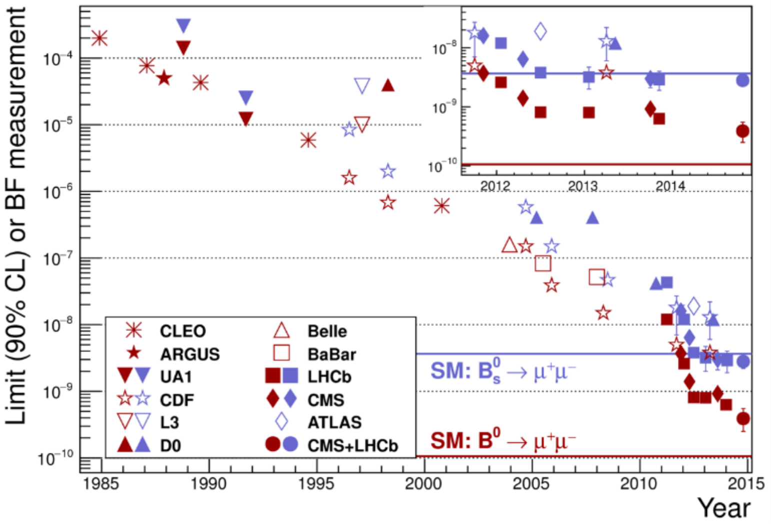
A search for rare B meson decays at the CERN SppS Collider

UA1 Collaboration, CERN, Geneva, Switzerland

CLEO, 2000

RAPID COMMUNICATIONS

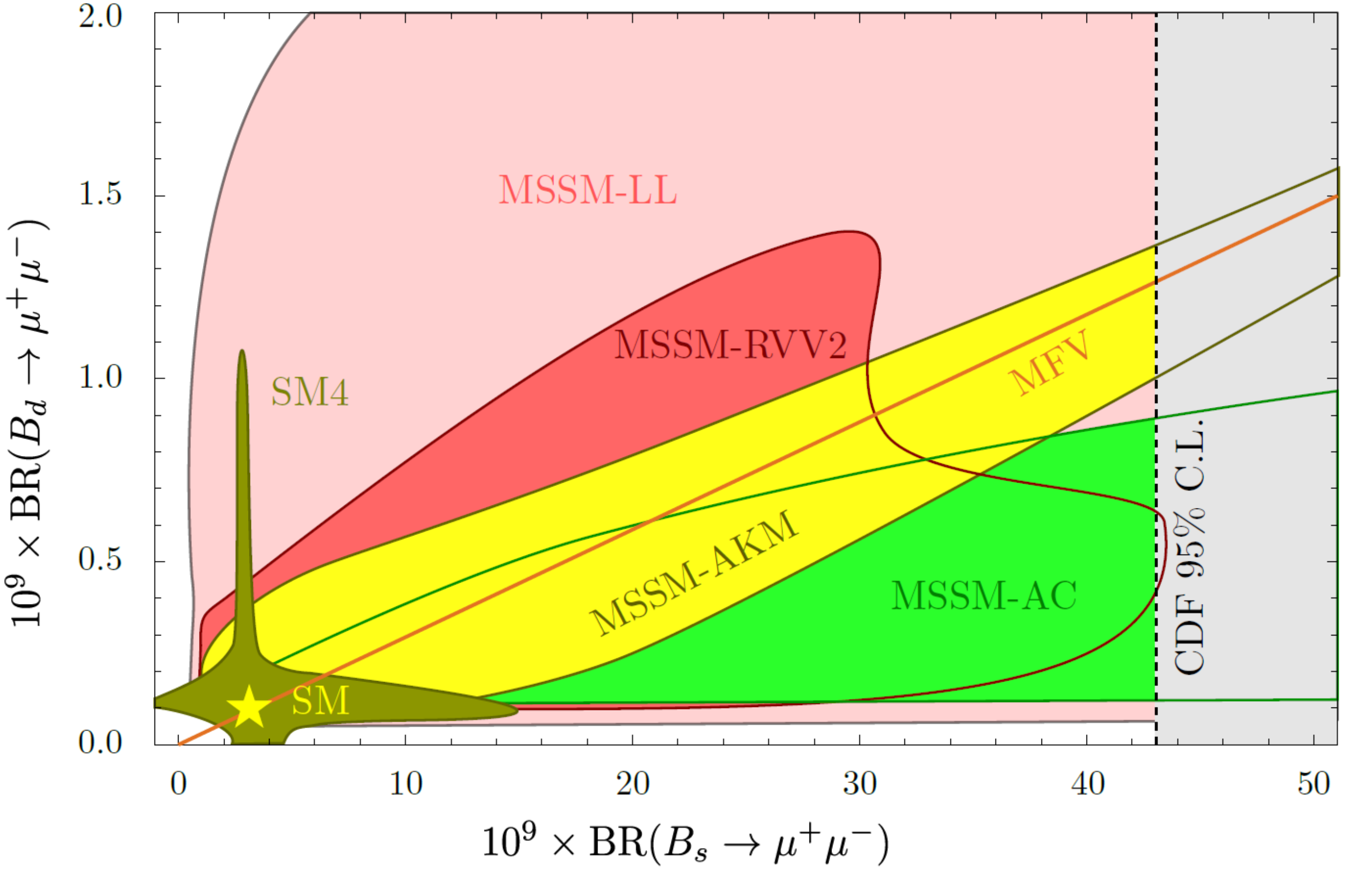
(CLEO Collaboration)



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

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

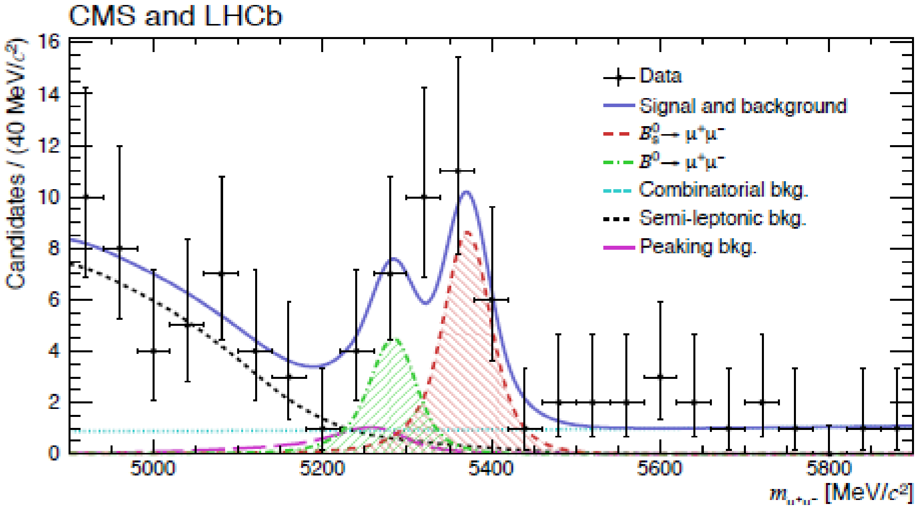
Historical plot from around the turn-on of the LHC, showing how a measurement of the BR of both modes provides powerful discrimination between New Physics models.

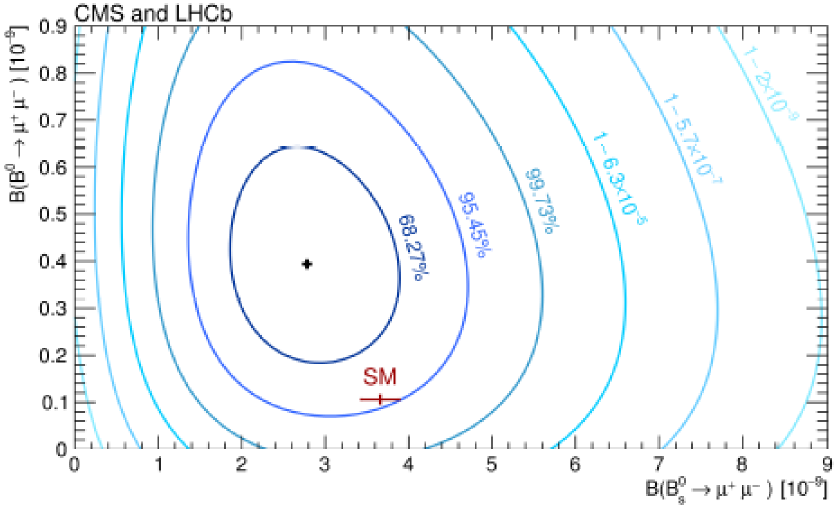


[D. Straub, arXiv:1012.3893]

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

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





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

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

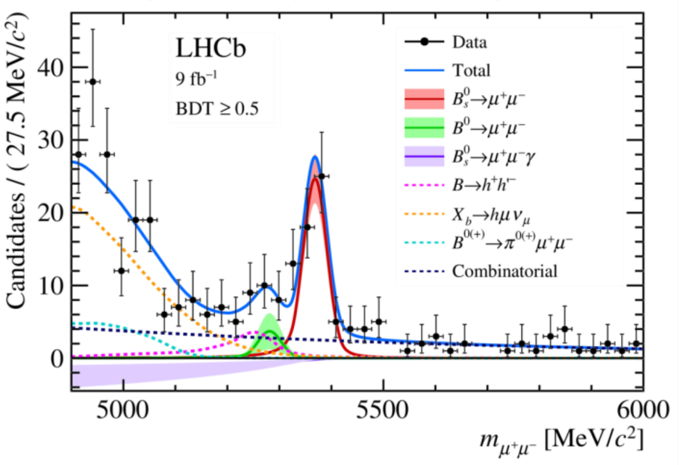
[Nature 522 (2015) 68]

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

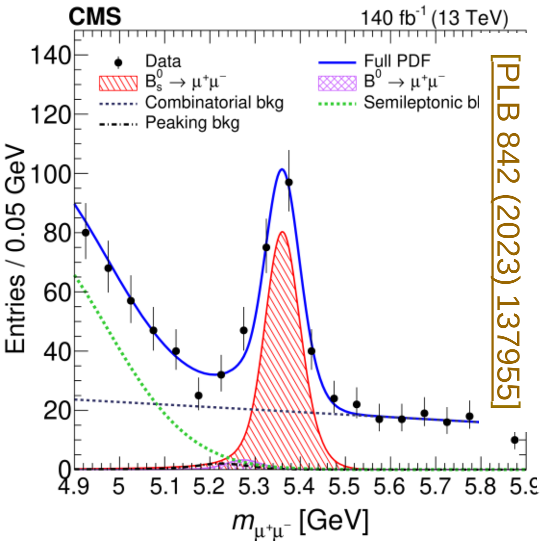
$B^0_{(s)}\to\mu^+\mu^-$ at the LHC: state of play

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

[PRL 128 (2022) 041801]



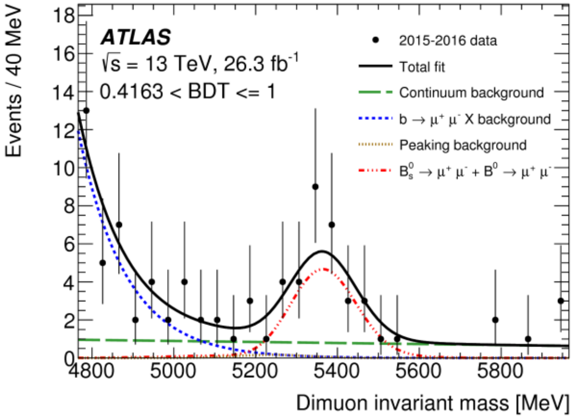
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$



[PLB 842 (2023) 137955]

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

[JHEP 04 (2019) 098]



When combined with Run 1:

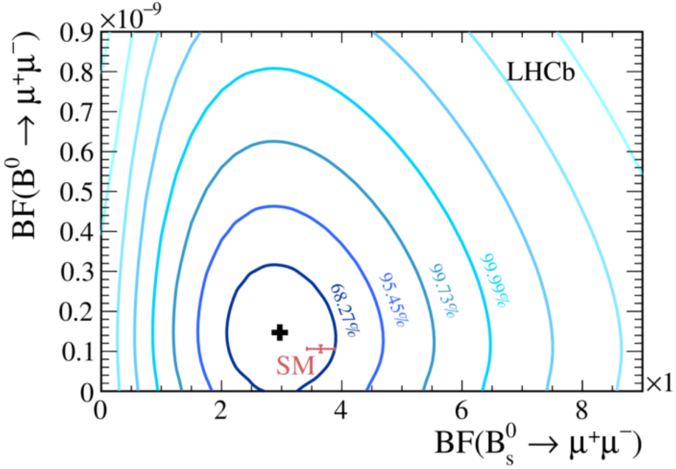
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$

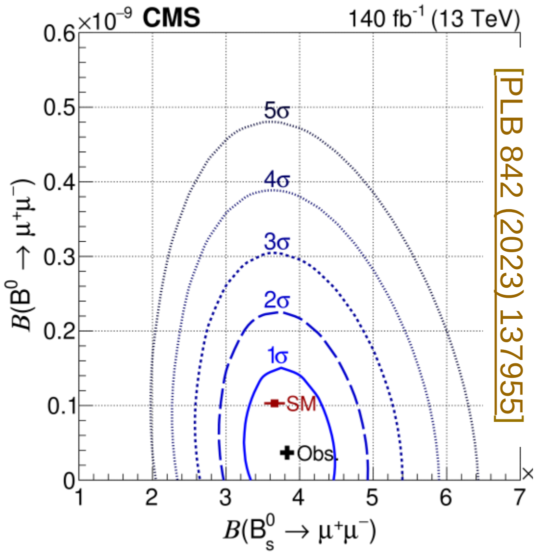
CMS currently has best measurement (this is a flavour-physics measurement well suited to the General Purpose Detectors). Precision ~10%. No sign yet of $B_d\to\mu\mu$.

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

No combination of the current individual LHC measurements yet exists…

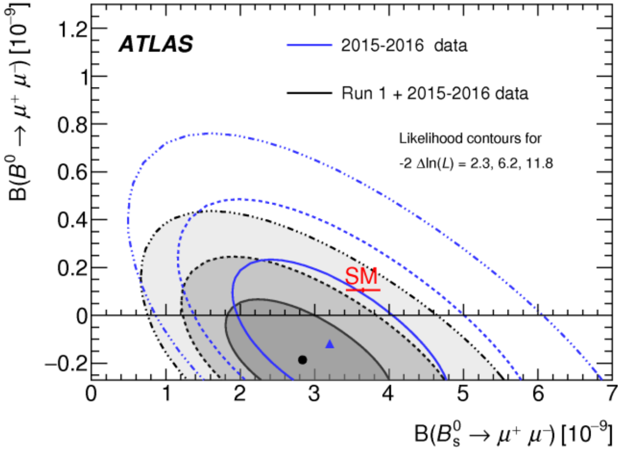
[PRL 128 (2022) 041801]





[PLB 842 (2023) 137955]

[JHEP 04 (2019) 098]



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

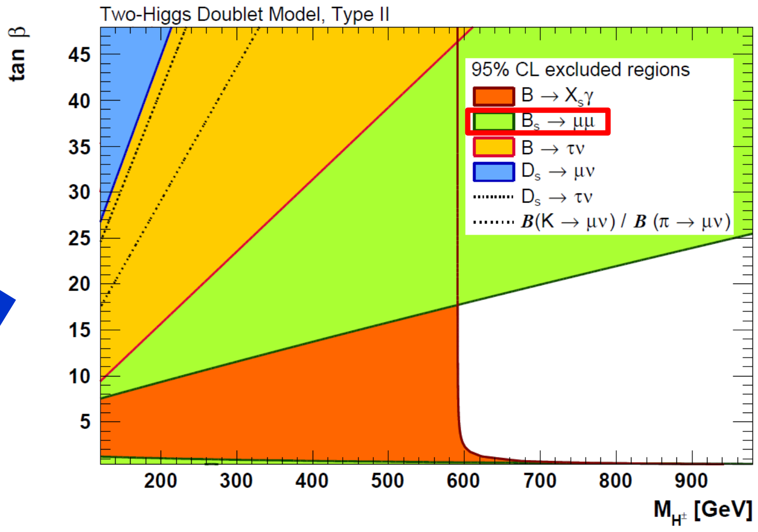
Achieving such precision on this rare process is a major achievement of LHC era !

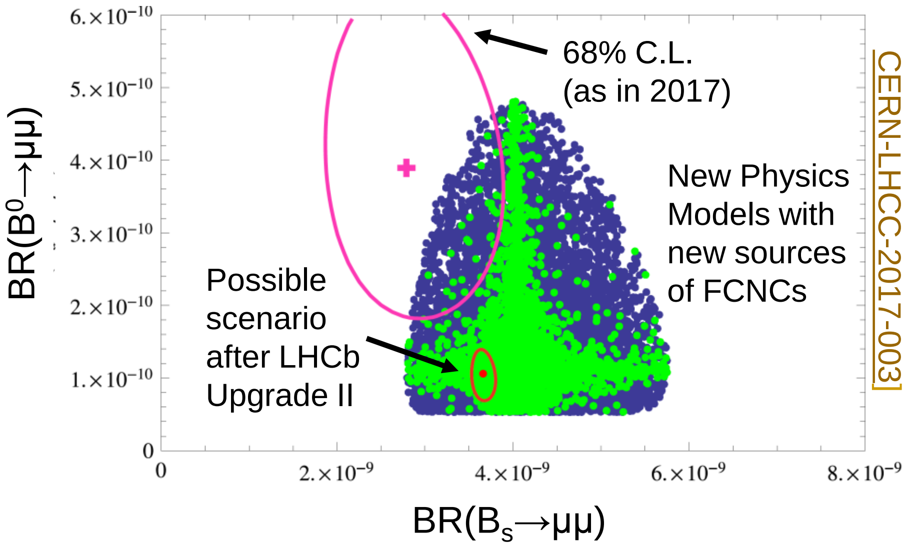
Lessons from, & future of, $B^0_{(s)}\to\mu\mu$ measurements

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

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

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





68% C.L. (as in 2017)

New Physics Models with new sources of FCNCs

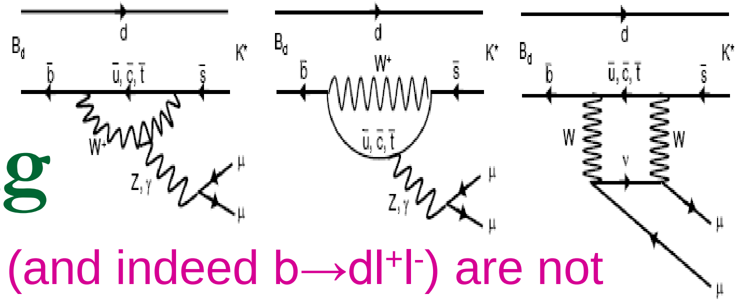
Possible scenario after LHCb Upgrade II

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

- Better measurements are *essential*, as we are still above the 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!

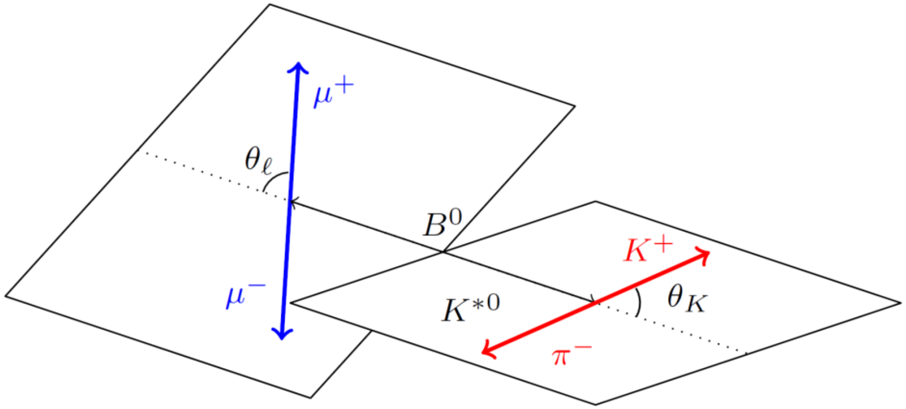
- Next step in the journey will be observation of $B^0\to\mu\mu$.

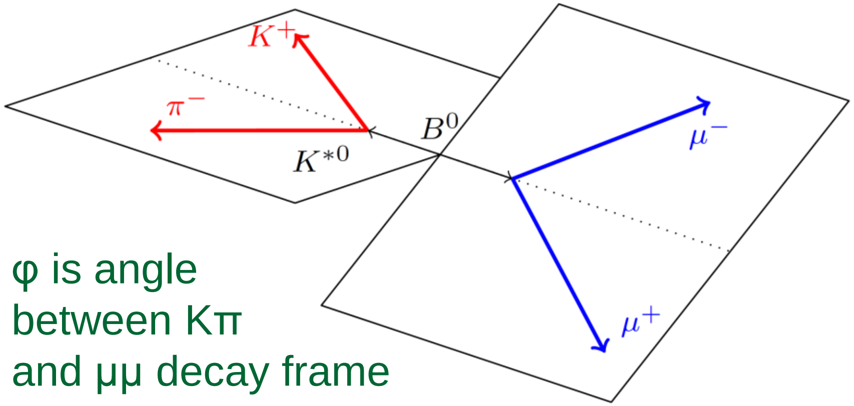
$B^0 \rightarrow K^* l^+ l^-$ and friends – the gift that keeps on giving



FCNC processes involving the transition $b \rightarrow s l^+ l^-$ (and indeed $b \rightarrow d l^+ l^-$) 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 $B^0 \rightarrow K^{*0} l^+ l^-$, with $K^{*0} \rightarrow K^+ \pi^-$.





φ is angle
between Kπ
and μμ decay frame

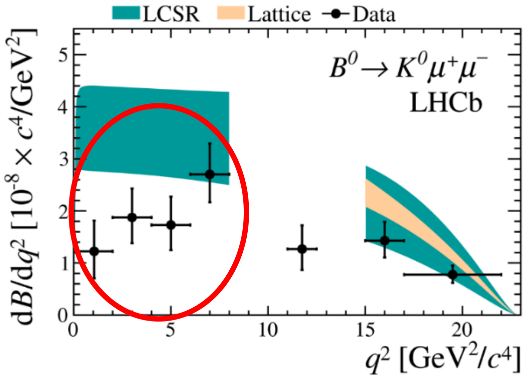
Four-body final state can be characterised in terms of three angles, Θ_l, θ_K and φ, & q^2, & the invariant-mass of the dilepton pair (see *e.g.* [LHCb, JHEP 02 (2016) 104]).

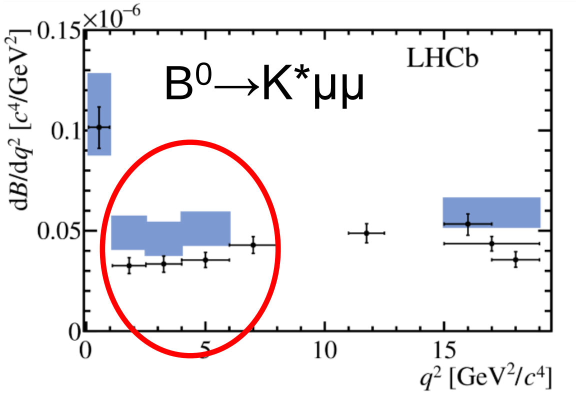
This family of decays has generated some of the most intriguing recent results in flavour physics. No time to do full justice to these here – only a whistle stop tour.

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

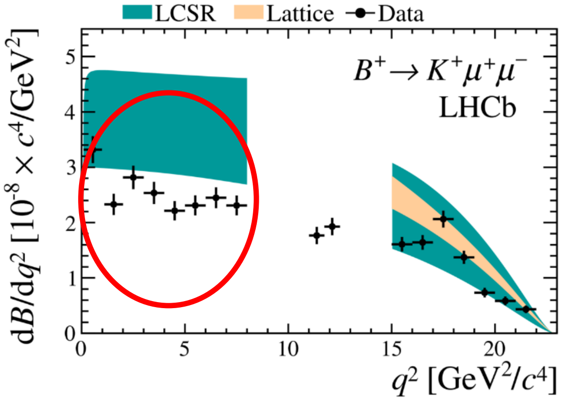
Differential cross-section for this family of decays shows eye-catching behaviour.

[JHEP 06 (2014) 133]



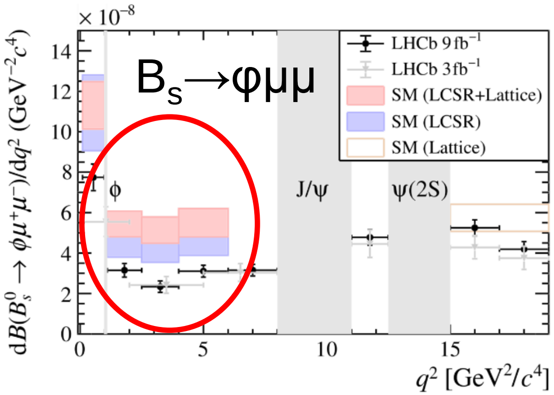


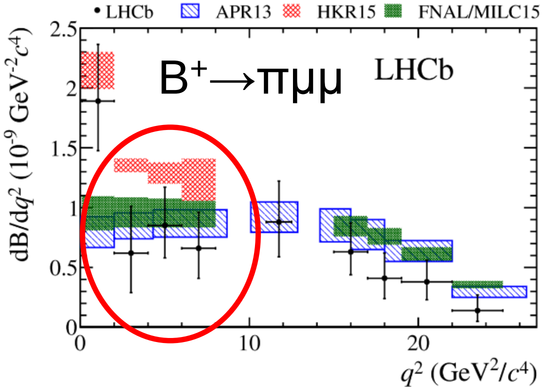
[JHEP 04 (2017) 142]



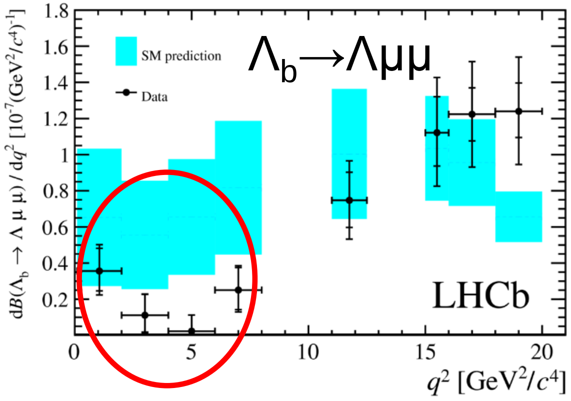
[JHEP 06 (2014) 133]

[PRL 127 (2021) 151801]





[JHEP 10 (2015) 034]

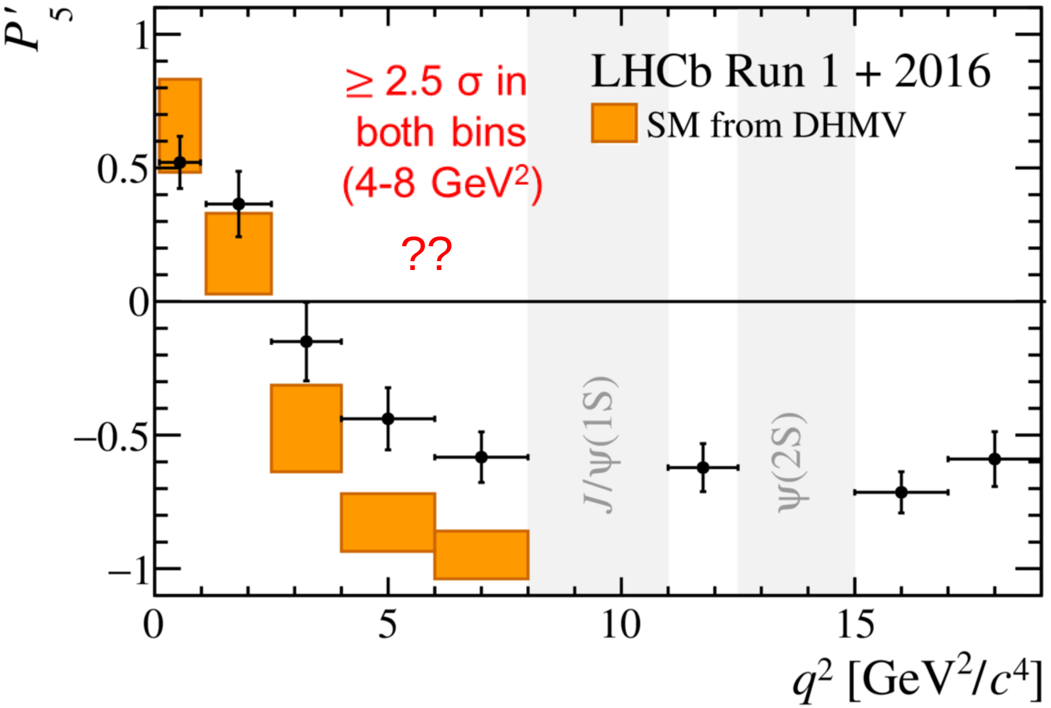


[JHEP 06 (2015) 009]

All measurements undershoot prediction at low q^2 ! (BTW, all made with *dimuons*…)
Very intriguing – but the theory calculations have uncertainties which are hard to assess. Can we measure something where this problem is less?

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

Many of the angular observables, plotted as a function of the q^2 of the lepton system are theoretically more robust. Several of these also exhibit odd behaviour, especially at low q^2. One example is the so-called $P_5^{/}$ parameter.



≥ 2.5 σ in both bins (4-8 GeV^2)

??

[LHCb, PRL 125 (2020) 011802]

Although more robust, these observables are not theoretically bullet proof ! Meanwhile, work ongoing to study behaviour with other approaches (*e.g.* amplitude analysis to probe short and long range contributions [arXiv:2312.09102, arXiv:2312.09115]).

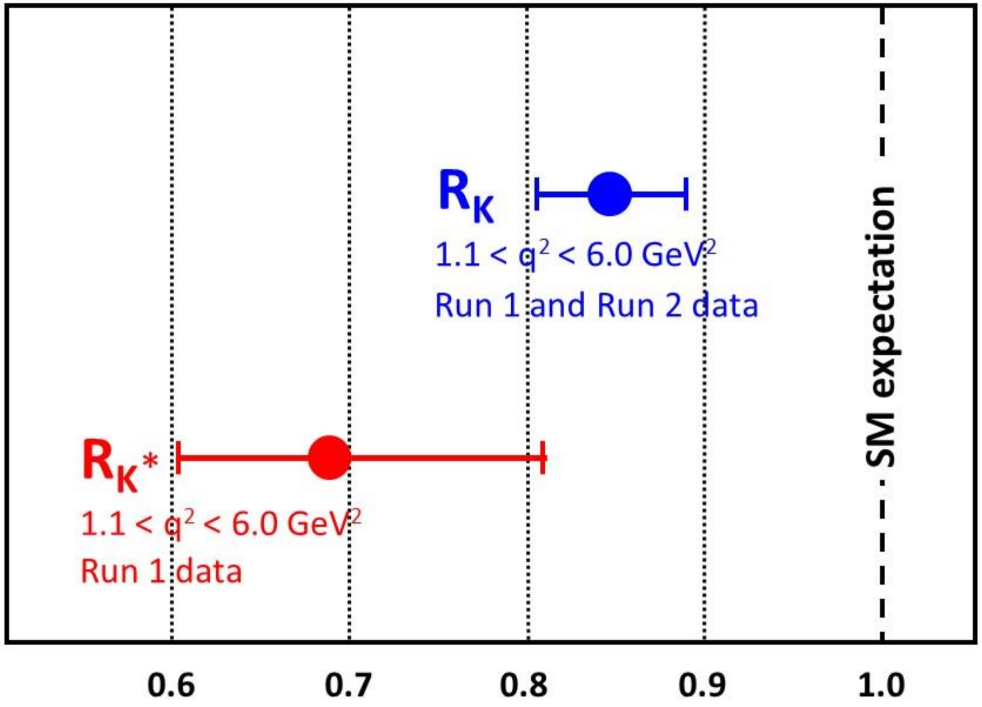
$B^0 \rightarrow K^* l^+ l^-$ and friends: lepton-universality tests

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 $b \rightarrow s\mu^+\mu^- / b \rightarrow s e^+ e^-$ for ~$1 < q^2 < 6$ GeV^2 for both $B \rightarrow K l^+ l^-$ (R_K) and $B^0 \rightarrow K^* l^+ l^-$ (R_{K^*}). In SM we expect 1 for both.

3.1 σ
below SM

~2.5 σ
below SM



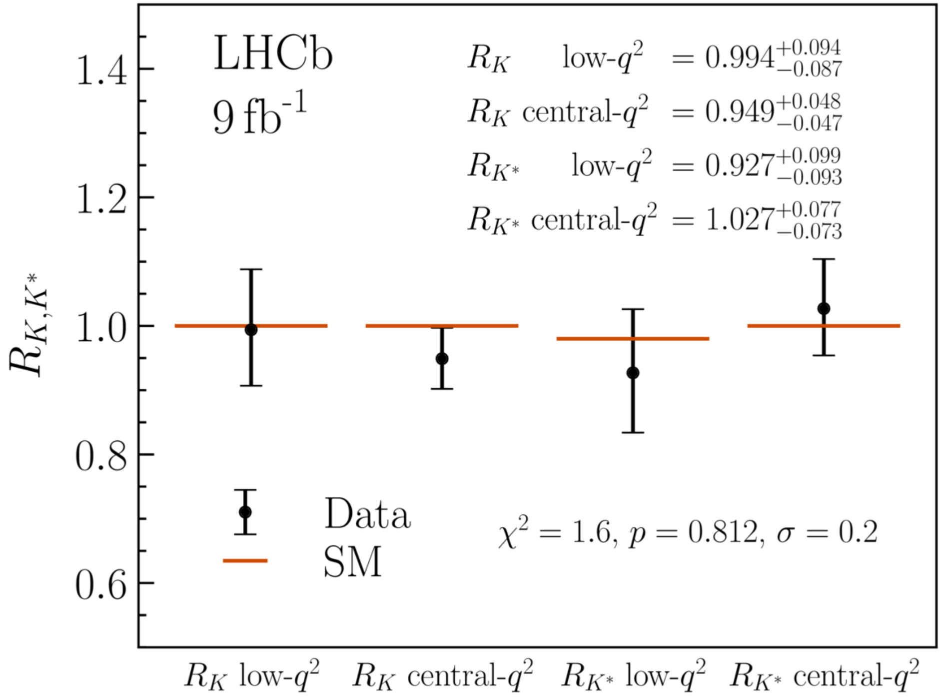
[Nat. Phys. 18 (2022) 277]

[JHEP 08 (2017) 055]

For a long time, these results generated great interest and many theory papers.

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

But measurements involving electrons at hadron colliders are hard, and a re-analysis of LHCb data involving both modes (and now two q^2 bins for each mode), revealed an unexpectedly large background and led to revised results.



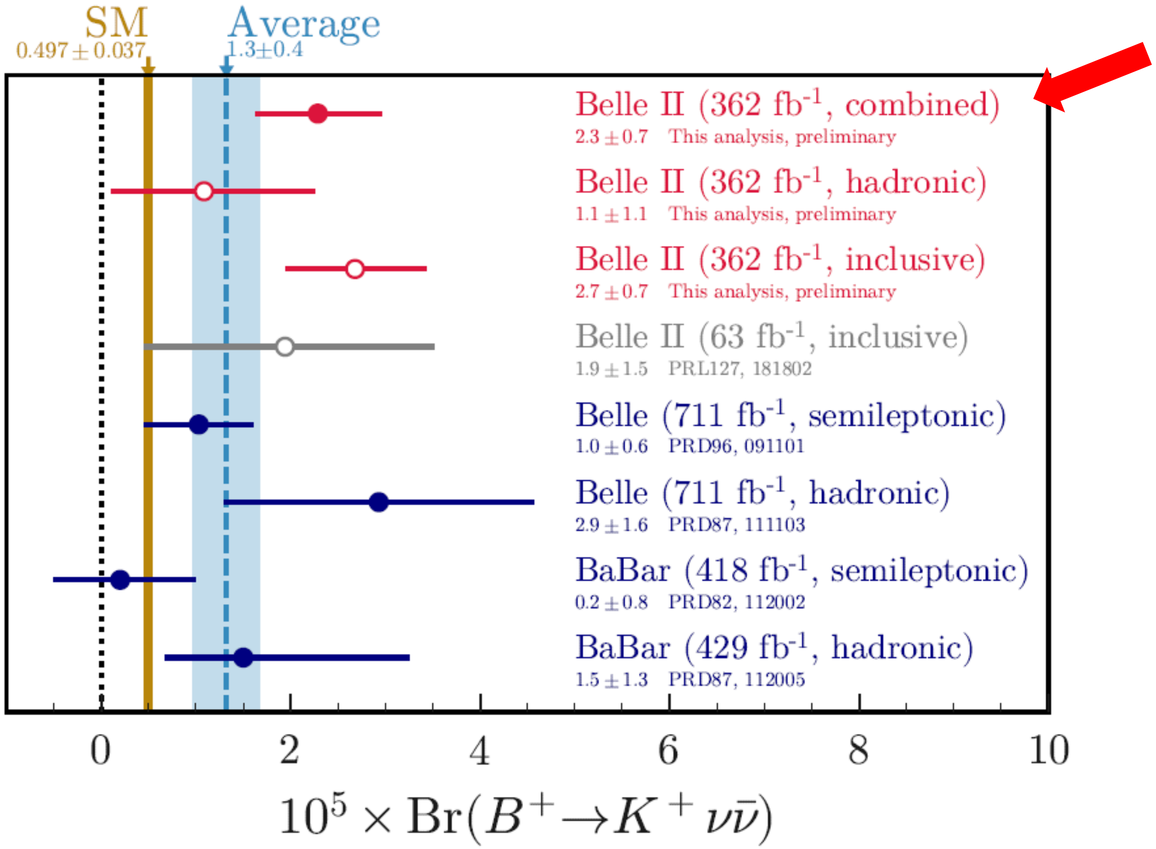
[arXiv:2212.09153]

Naturally this is disappointing, but we should celebrate that the scientific method always wins out. Nonetheless, the other b→sl^+l^- puzzles remain, and indeed, soon after the world had thought these anomalies dead and buried…

When we dead awaken

Hot news: $B^+ \to K^+ \nu\bar{\nu}$ from Belle II

Announced at last summer, 3.6σ evidence for $B^+ \to K^+$νvbar, at a rate 2.8σ above the SM [arXiv:2311.14647]. Await for confirmation in other channels and Belle data.

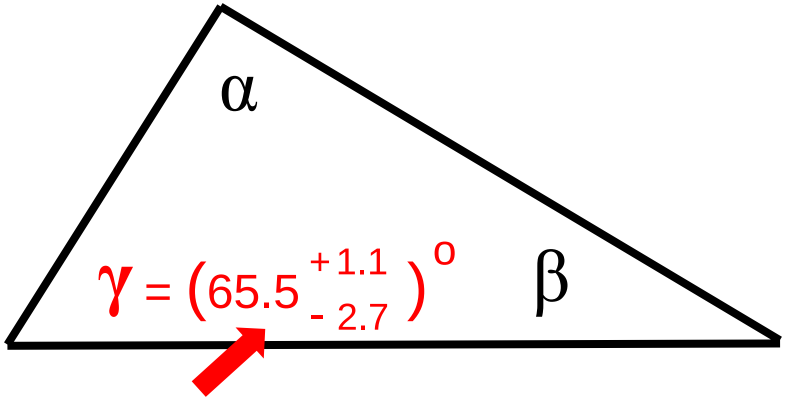


This is a measurement where LHCb cannot contribute ! Again, the message is that it is vital to have more than one flavour experiment, in different environments.

CP violation in b decays

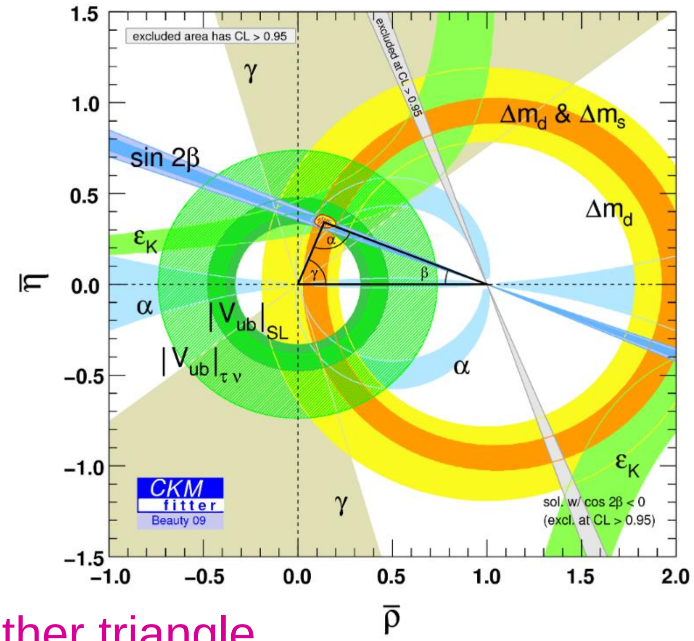
The long march: towards a precise determination of the UT angle γ

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



$\gamma = (65.5^{+1.1}_{-2.7})^{o}$

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



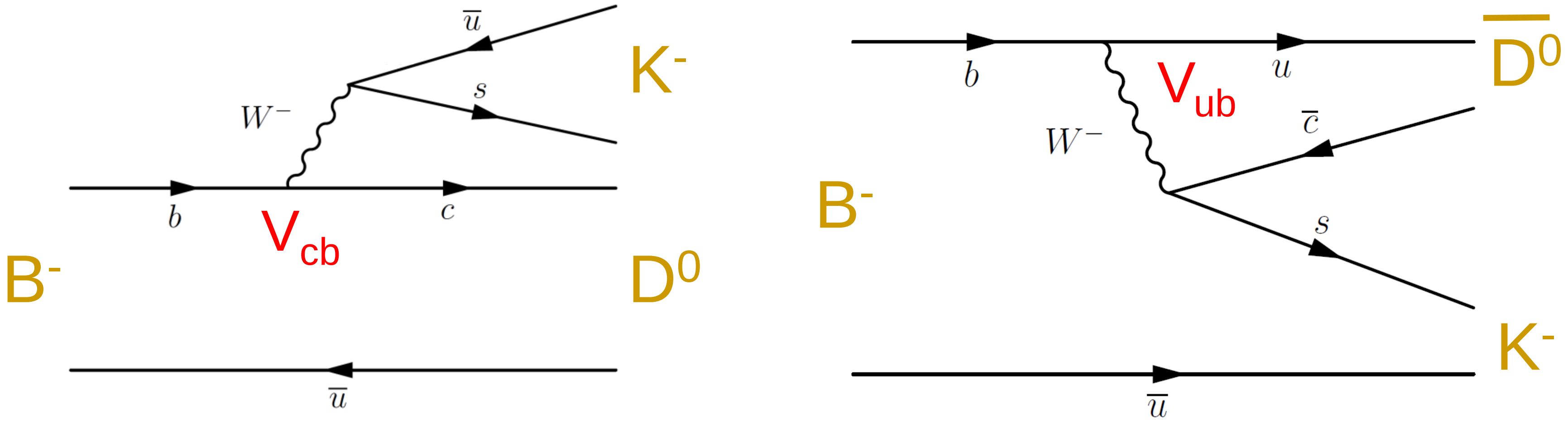
[CKMfitter, 2009]

The predicted value of γ [CKMfitter, 2021] 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.



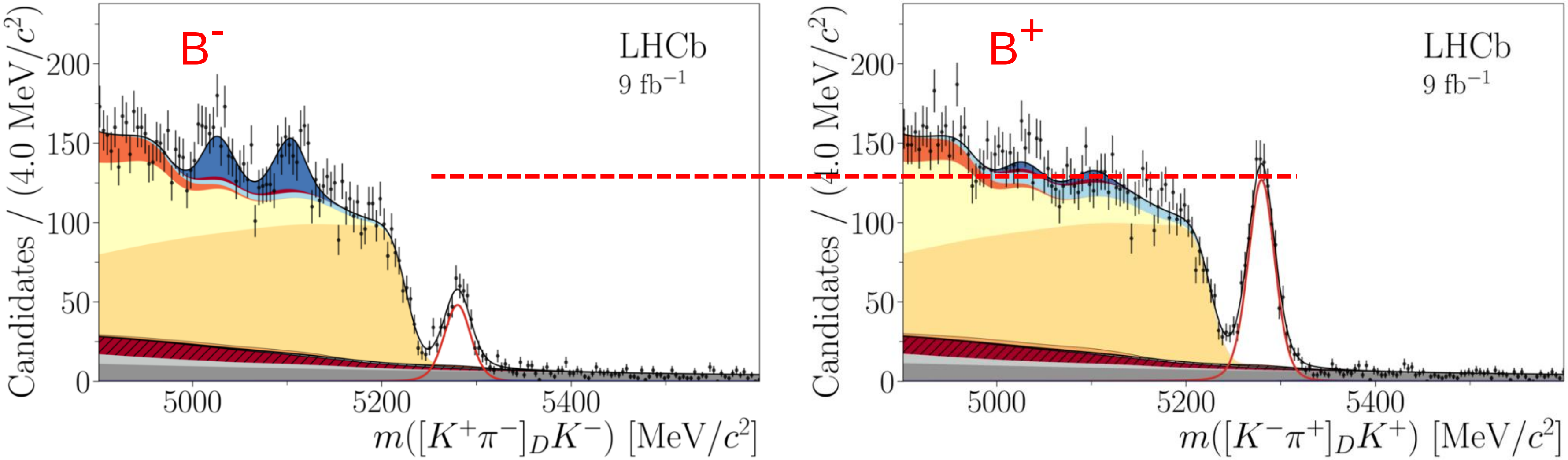
If we reconstruct D^0 and $\overline{D^0}$ in a state accessible to both, Interference occurs & decay rates become sensitive to relative phase between V_{cb} and V_{ub}, which is γ.

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 $B^- \rightarrow DK^-$ decay, with $D \rightarrow K^+\pi^-$ (and B^+ conjugate case): visible BR ~10^{-8}, Hence out of reach to previous generation of flavour physics experiments.



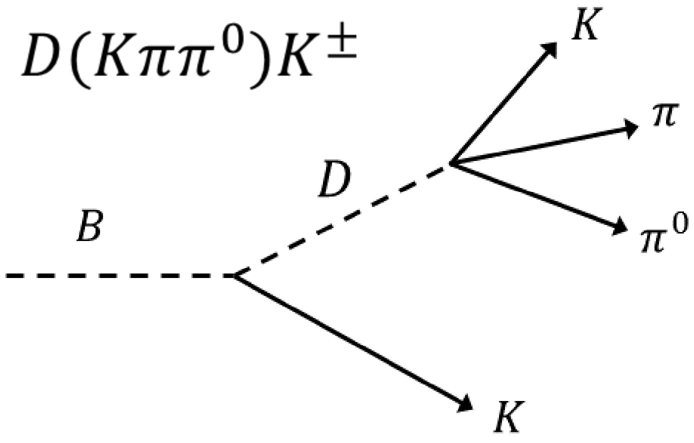
[JHEP 04 (2021) 081]

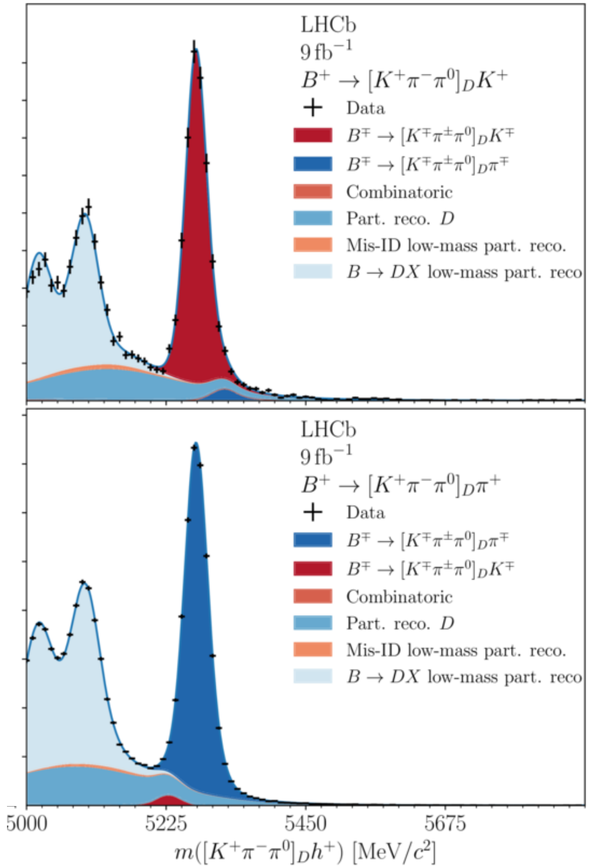
Very significant CP violation observed, that can be cleanly related to the phase γ.

Measuring γ at LHCb: remarkably clean signals

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

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





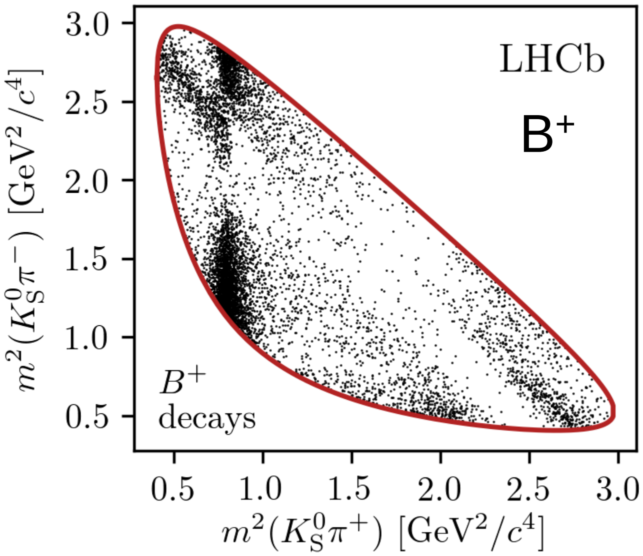
Furthermore, the RICH detector does an excellent job in separating the B→DK mode (top plot) from the order-of-magnitude more abundant B→Dπ mode (bottom plot).

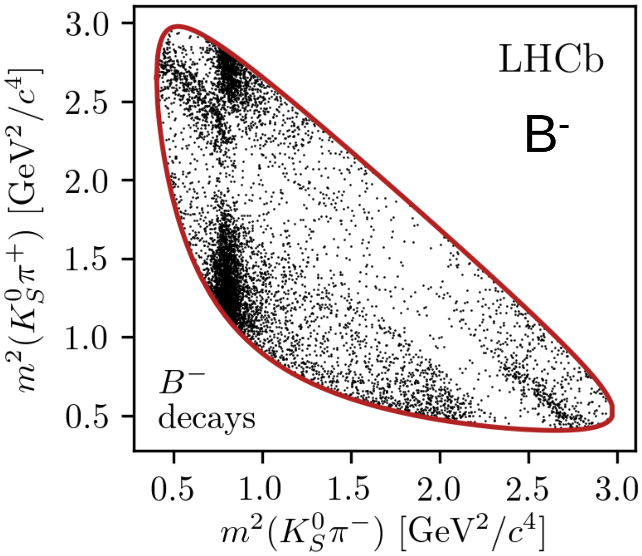
γ measurement at LHCb with B→DK decays: D→$K_S\pi\pi$ (and K_SKK)

[JHEP 02 (2021) 169]

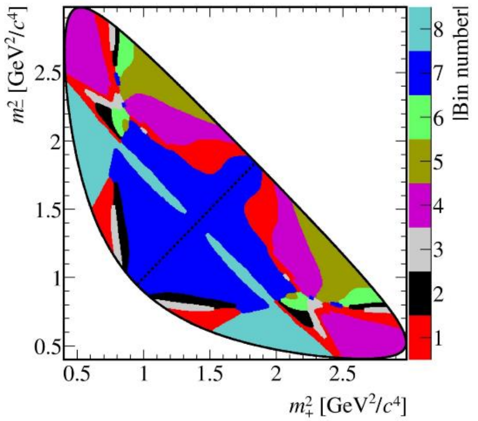
A powerful sub-set of B→DK analyses is when the D decays into a multibody final state, of which $K_S\pi\pi$ is the most prominent example. Variation of D strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

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





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



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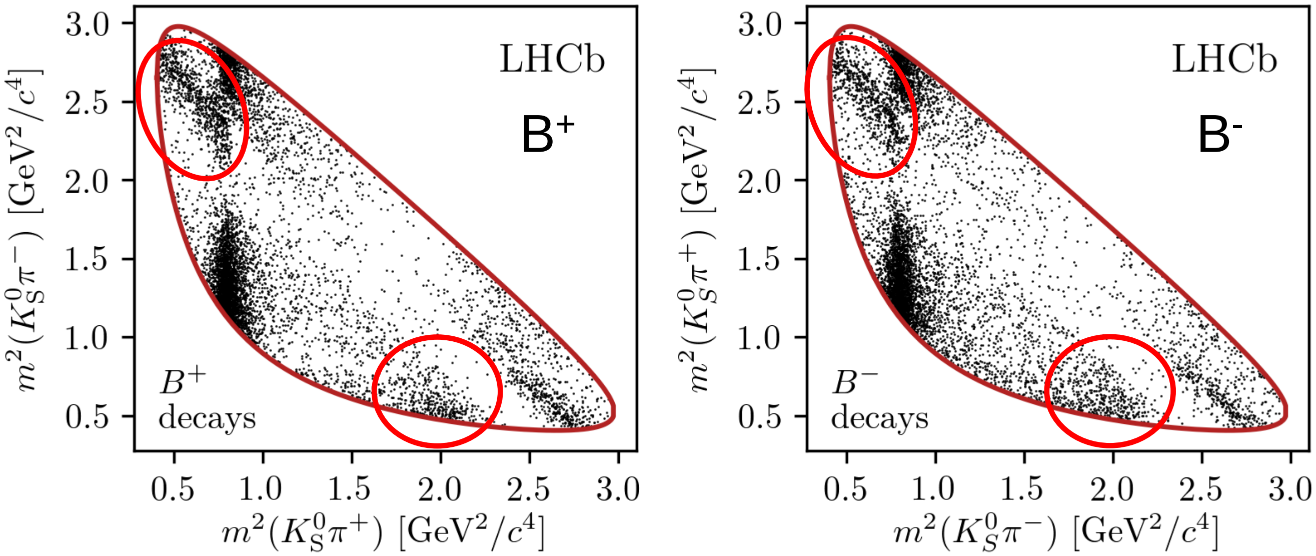

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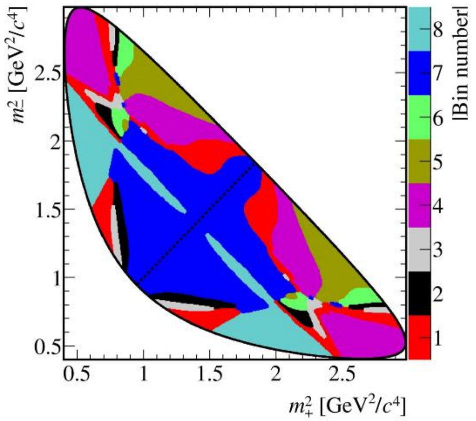
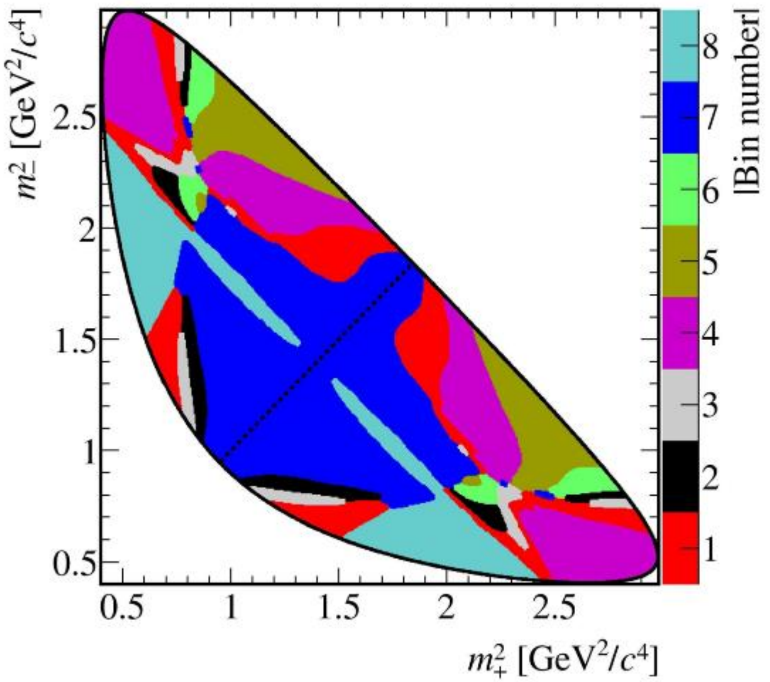


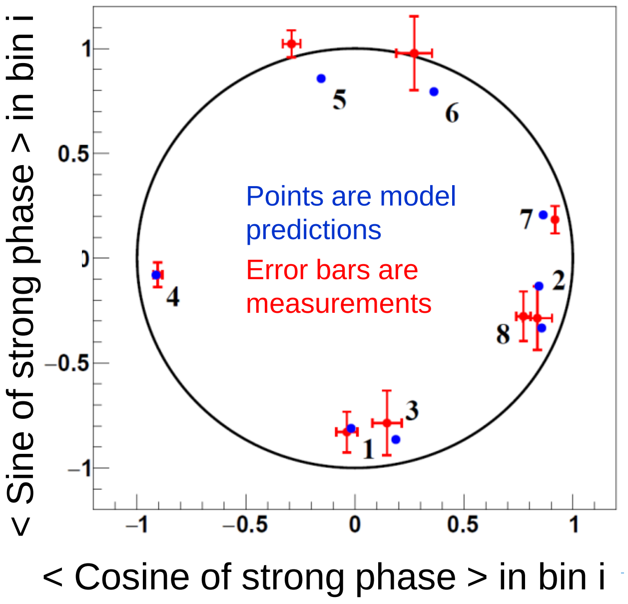
CP asymmetries visible by eye, but quantitative analysis requires external input...

Measuring γ – a synergy of experiments

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

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





Points are model predictions

Error bars are measurements

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

LHCb Upgrades & Belle II (+FCC-ee/ CEPC) will require improved results from BES III and STCF.

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

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[JHEP 02 (2021) 169]

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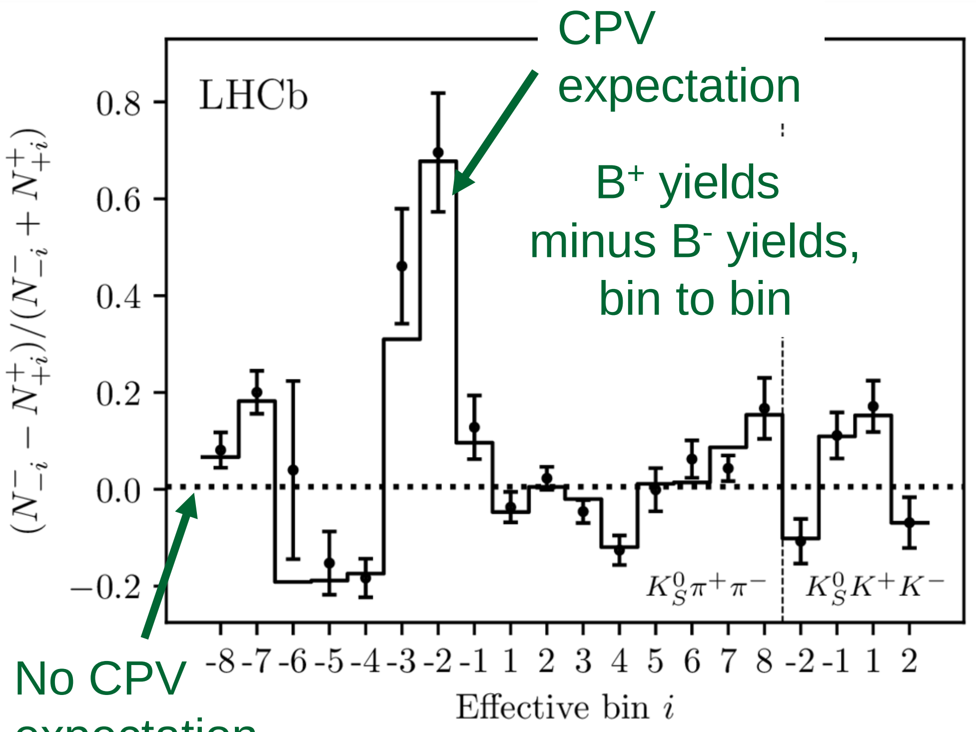


CPV expectation

B$^+$ yields minus B$^-$ yields, bin to bin

No CPV expectation

Gives a result of:

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

which is the single most precise determination of γ.

This, and ensemble of other LHCb results (but not yet including several recent results) gives

$$\gamma = (65.4\,^{+3.8}_{-4.2})^\circ$$

[JHEP 12 (2021) 141]

Final LHCb Run 1 + 2 result should have a precision of 2-3 degrees.

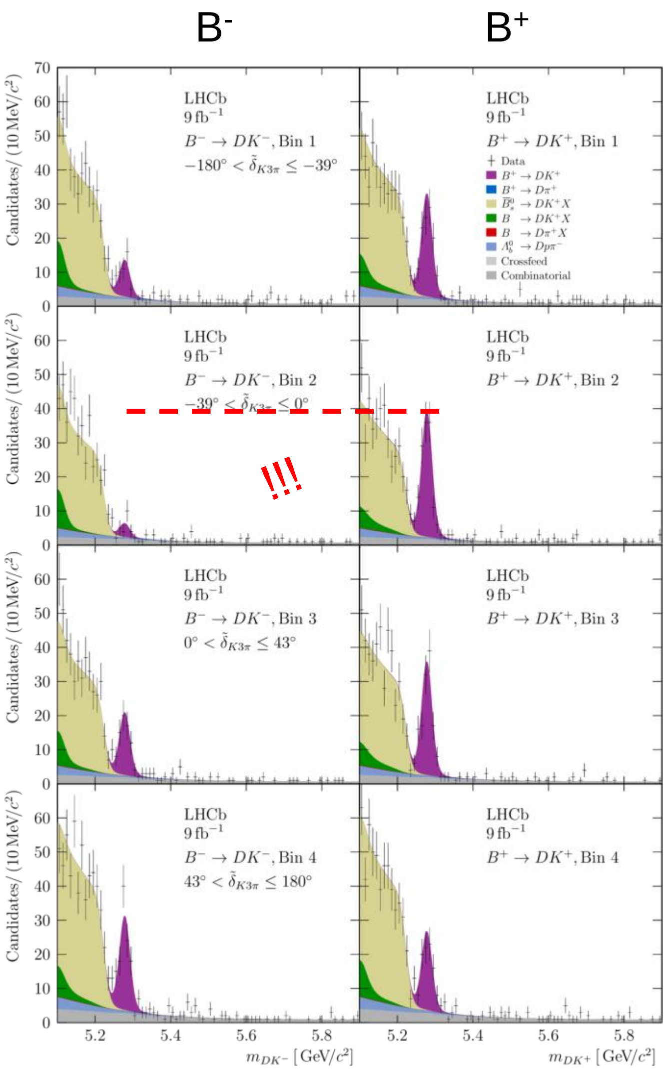
In agreement with indirect prediction but not yet as precise → need more data !

Another recent example: $B \to DK$, $D \to K\pi\pi\pi$

[JHEP 07 (2023) 138]

Inspired by the example of $D \to K_S\pi\pi$, partition the final-state phase space into four bins, with a choice guided by an LHCb amplitude model [EPJC 78 (2018) 443].

The bins are well chosen! Note, bin 2 in particular, where the CP asymmetry is the largest yet seen !



Gives a result

$$\gamma = \left(54.8 \,{}^{+\,6.0}_{-\,5.8}\,{}^{+\,0.6}_{-\,0.6}\,{}^{+\,6.7}_{-\,4.3}\right)^\circ$$

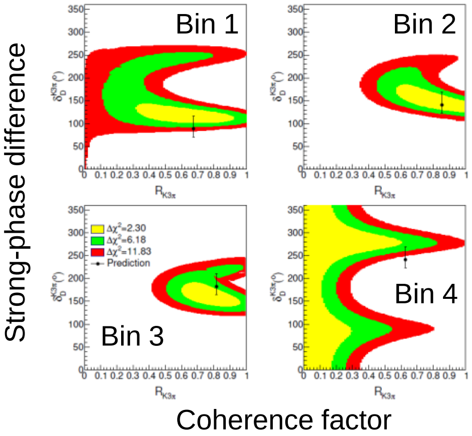
which is intrinsically second only to $K_S\pi\pi$ in precision. However, there is an external systematic that is currently limiting sensitivity…

Another recent example: B→DK, D→Kπππ

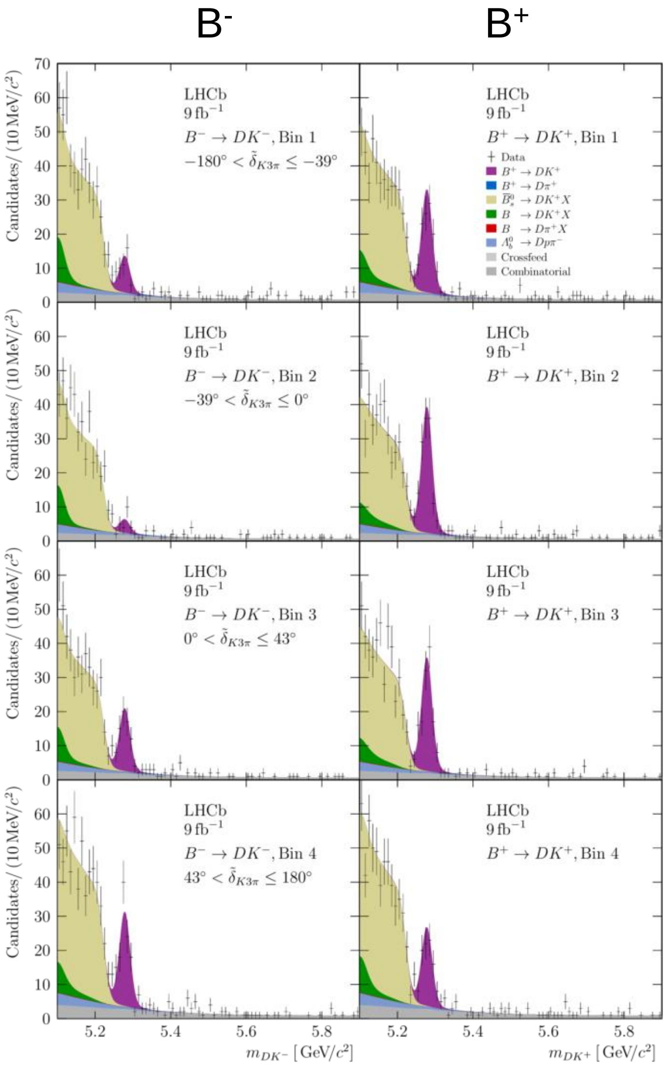
[JHEP 07 (2023) 138]

To interpret the CP-asymmetries in terms of γ and the other underlying physics parameters, requires knowledge of the strong phases and coherence factors of the charm decay.

Again, this requires charm-threshold input.

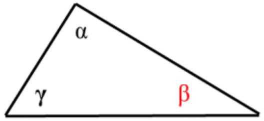


2.9 fb^{-1} BESIII plus 0.8 fb^{-1} CLEO-c data [JHEP 05 (2021) 164]

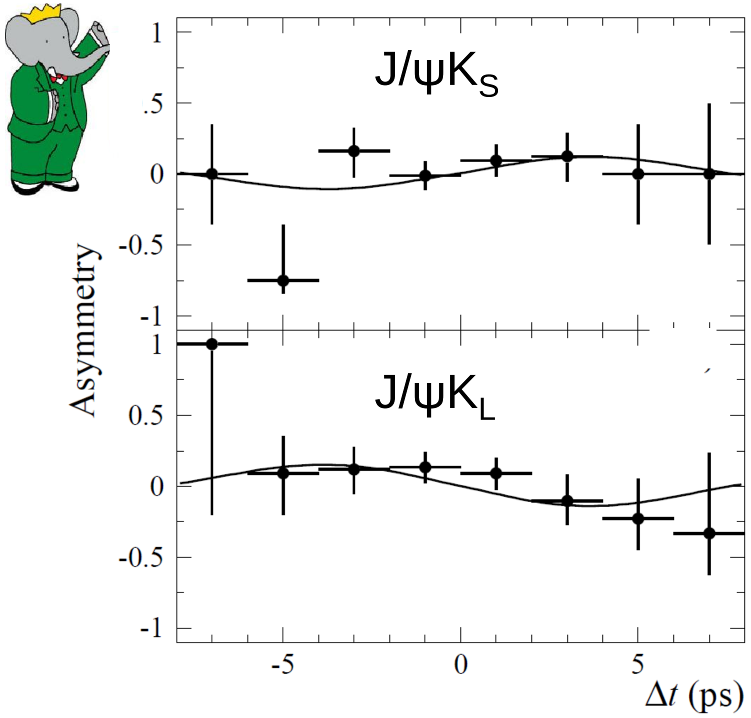


Parameters have been measured by BESIII (& CLEO-c) but greater precision is needed !

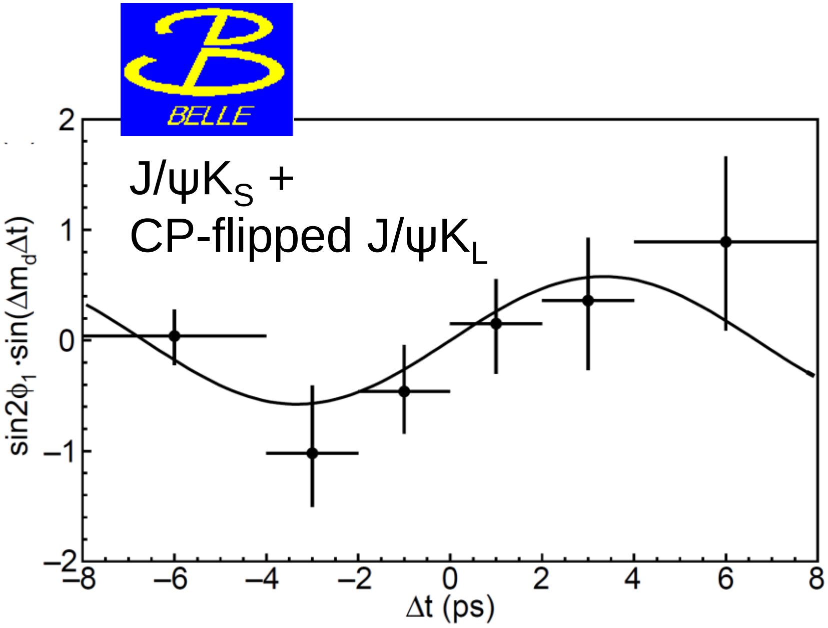
2001 – (the start of) a flavour odyssey



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



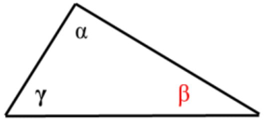
[BaBar, PRL 86 (2001) 2515]



[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.

2001 – (the start of) a flavour odyssey



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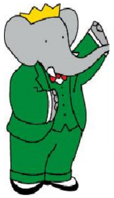
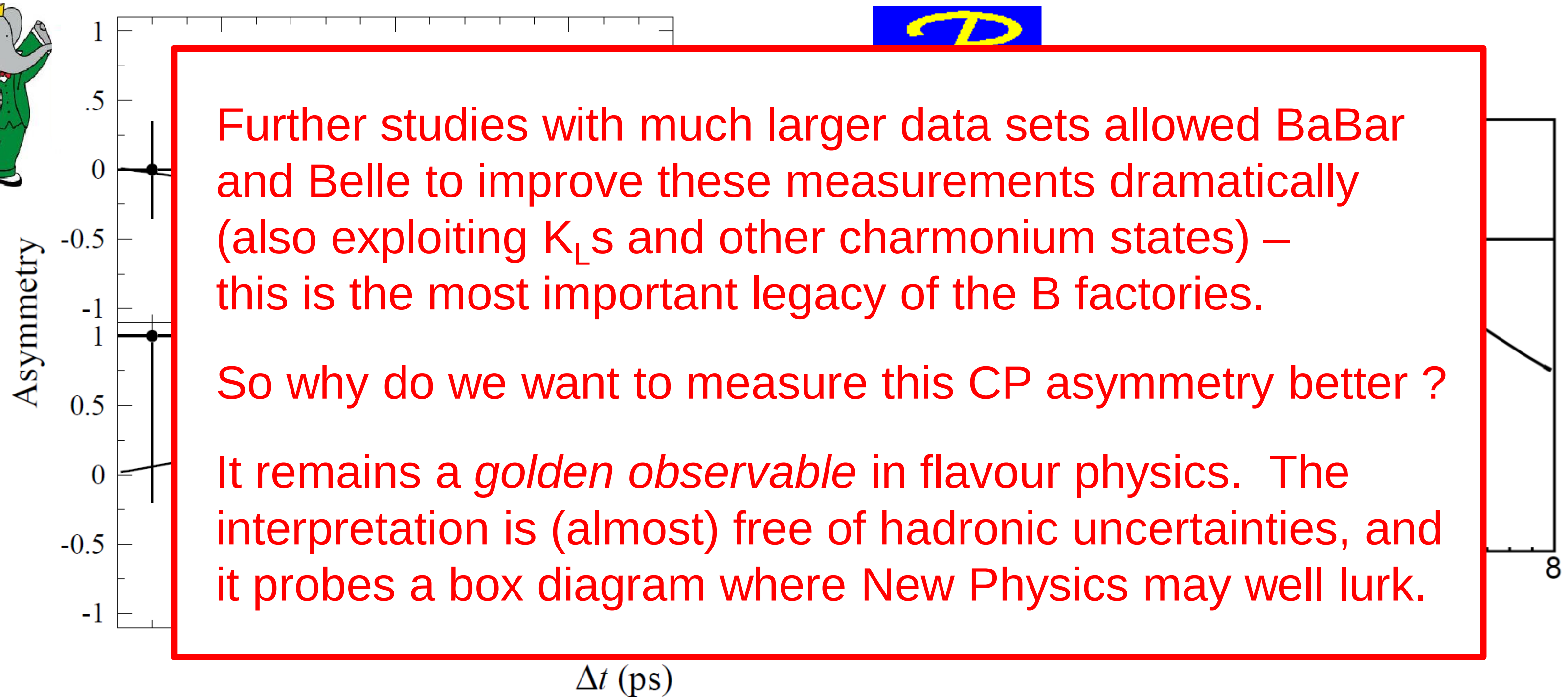




Further studies with much larger data sets allowed BaBar and Belle to improve these measurements dramatically (also exploiting K_Ls and other charmonium states) – this is the most important legacy of the B factories.

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

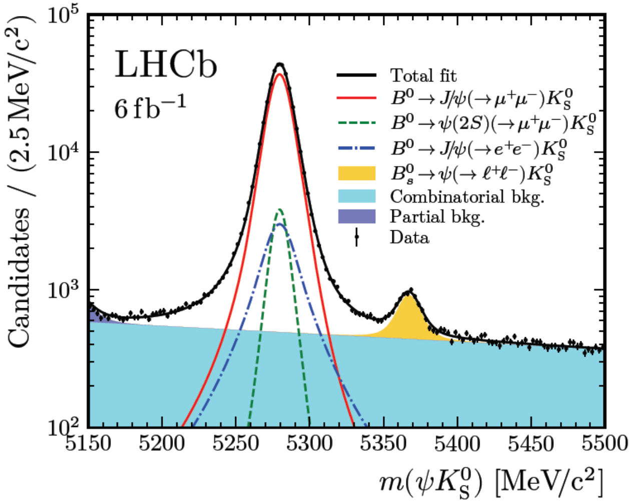
It remains a *golden observable* in flavour physics. The interpretation is (almost) free of hadronic uncertainties, and it probes a box diagram where New Physics may well lurk.

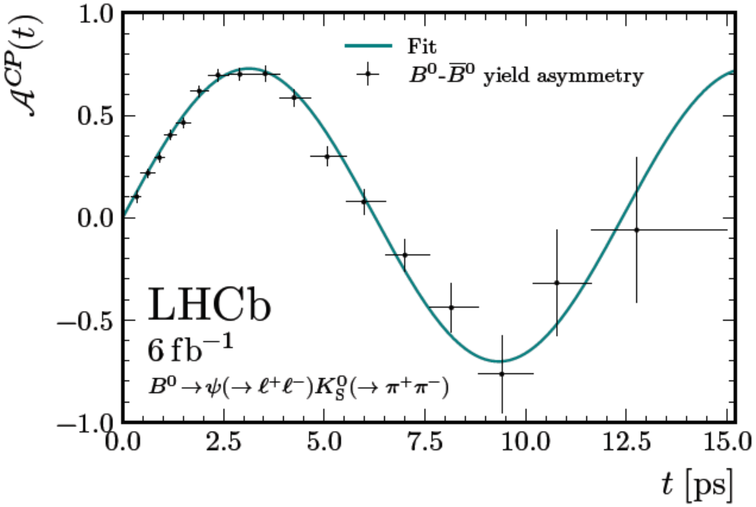
[BaBar, PRL 86 (2001) 2515] [Belle, PRL 86 (2001) 2509]

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.

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

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





Combined result:

Sine coefficient $= 0.723 \pm 0.014$

Cosine coefficient $= 0.007 \pm 0.012$

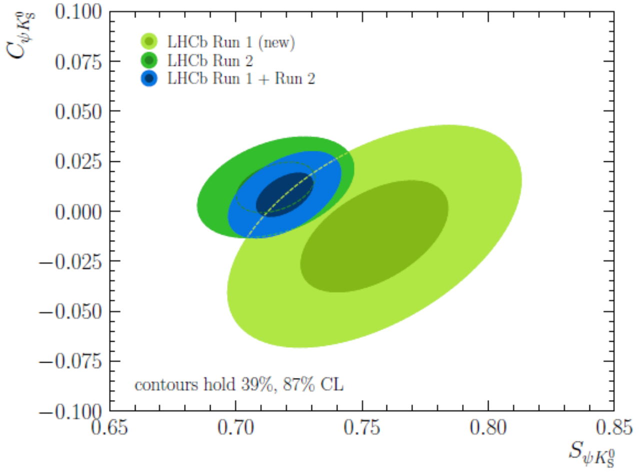
As no evidence yet of direct CPV, can interpret sine coefficient as sin2β.

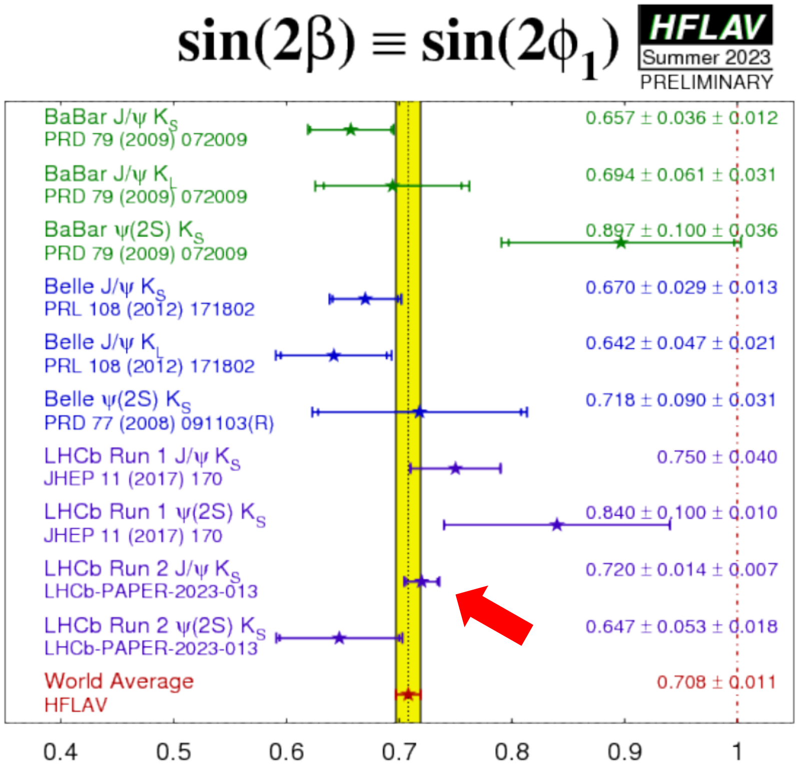
Now more precise than B factories ! Very large sample sizes (*e.g.* $B^0 \to J/\psi(\mu\mu)K_S$: LHCb: 420k, BaBar ~10k offsets challenges in flavour tagging at *pp* machine)

sin2β: current status and impact of the LHC

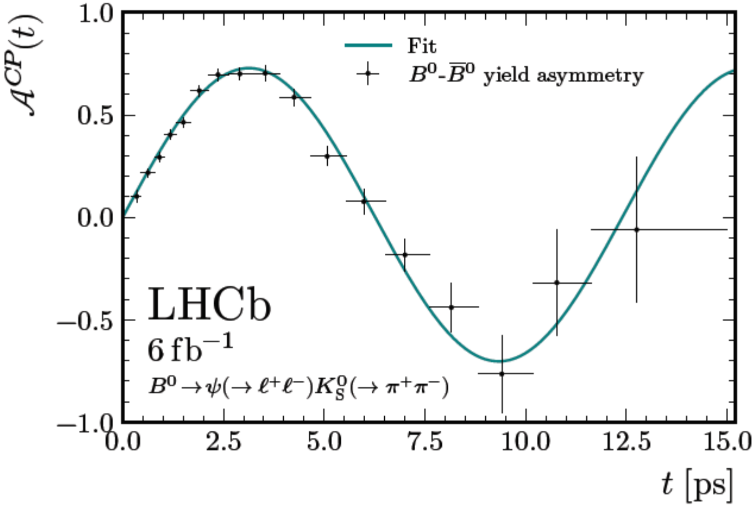
Global state of play:

$$\boxed{\beta = (22.5 \pm 0.4)^o}$$





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



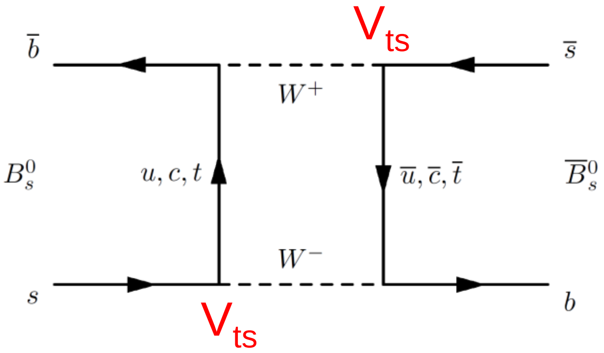
[PRL 132 (2024) 021801]

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

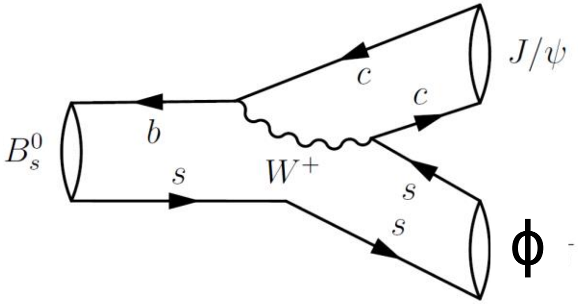
Indirect CPV in B_s system: φ_s

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…



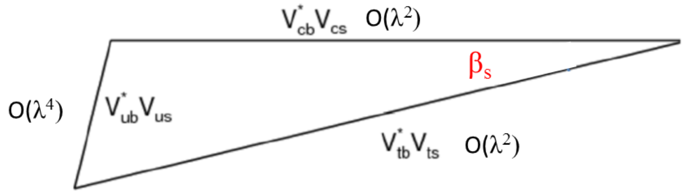
…and decay



Now we probe CKM elements that are complex only at λ^4

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

Alternative viewpoint – we are trying to measure a very small angle β_s of another, very squashed Unitarity Triangle.



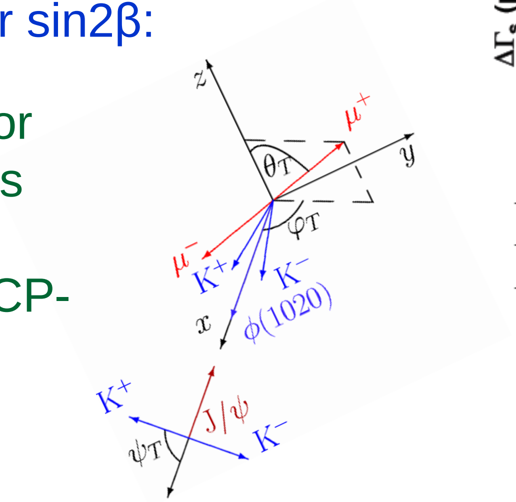
In SM $\varphi_s = -2\beta_s$ and $\phi_s^{\text{SM}} \equiv -2\arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right) = -36.3^{+1.6}_{-1.5}\,\text{mrad}$

Indirect CPV in B_s system: φ_s

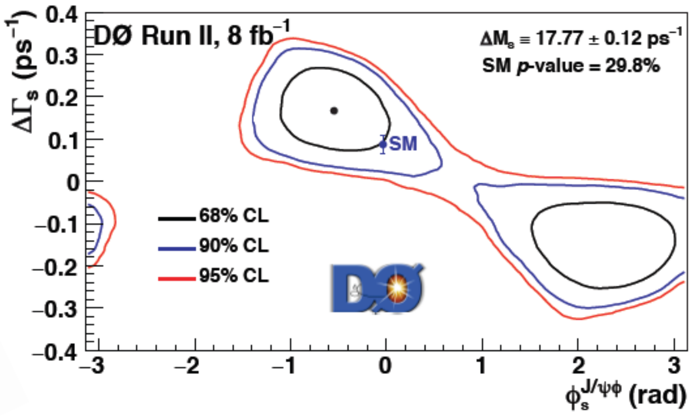
Measuring the CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* with $B_s \to J/\Psi\Phi$, is **the B_s analogue of the sin2β measurement**. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP !

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

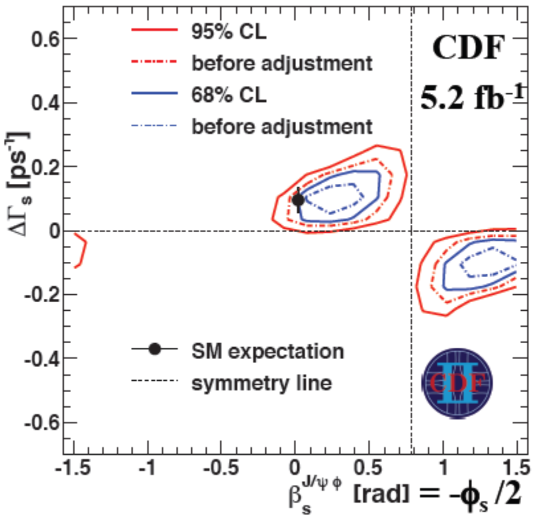
- J/Ψφ is a vector-vector final state, so requires angular analysis to separate out CP+ & CP-
- Very fast oscillations ($\Delta m_s >> \Delta m_d$)
- Possibility of KK S-wave under φ



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



[PRD 85 (2012) 032006]

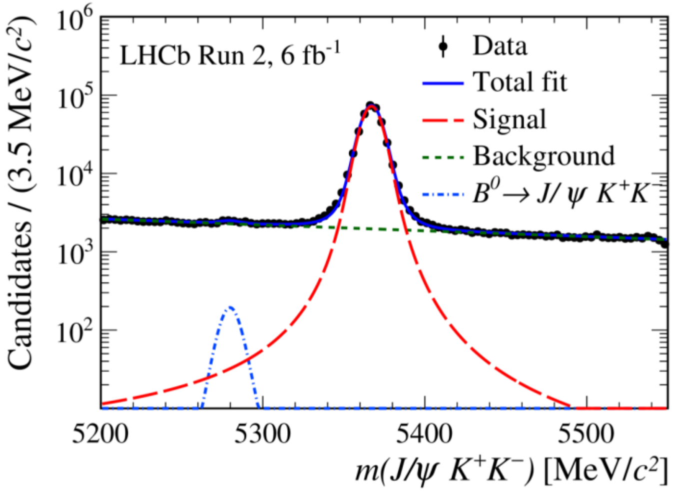


[PRD 85 (2012) 072002]

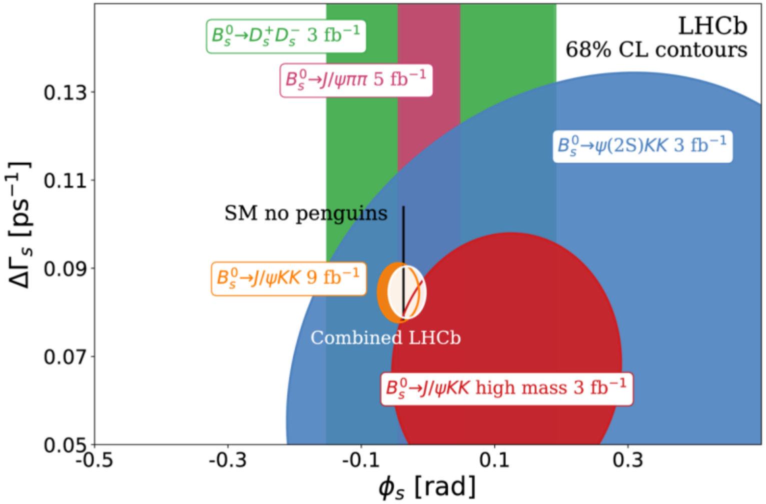
φ_s – impact of LHCb

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

$B_s \to J/\psi\varphi$ signal peak in Run 2 analysis (349k decays, in 1.9 fb^{-1} *c.f.* 6.5k at CDF).



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



[arXiv:2308.01468]

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

When combined with other LHCb results ➡

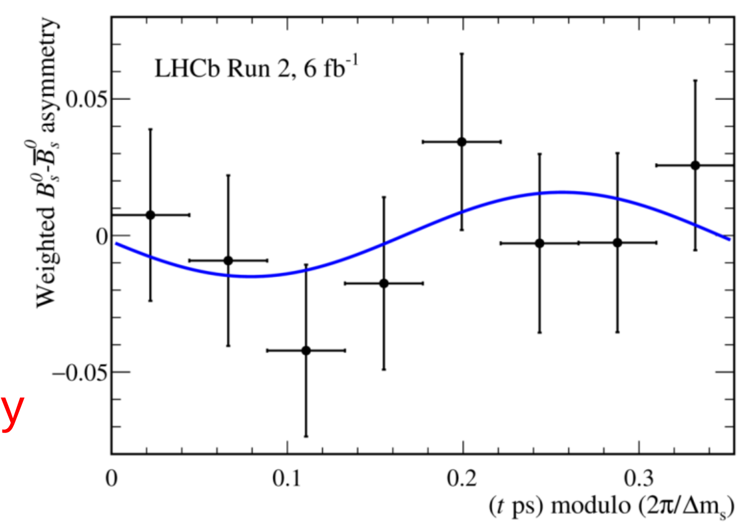
$$\phi_s = -0.031 \pm 0.018\,\text{rad}.$$

φ_s – impact of LHCb

LHC has been able to go far beyond the Tevatron measurements, thanks to much larger y s to comple

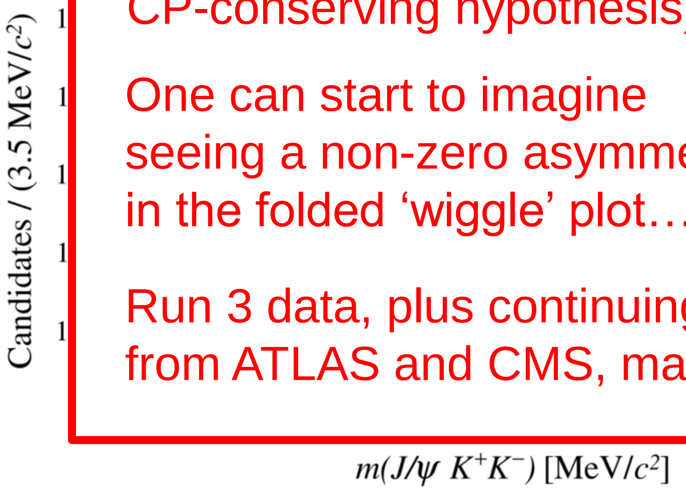
B_s ether s.

Central value very close to predicted (and tiny) SM expectation, and is almost 2σ away from zero (*i.e.* CP-conserving hypothesis).



One can start to imagine seeing a non-zero asymmetry in the folded ‘wiggle’ plot…

Run 3 data, plus continuing contributions in the measurement from ATLAS and CMS, may lead to a very interesting situation.



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

CP violation and mixing in charm

The charm renaissance

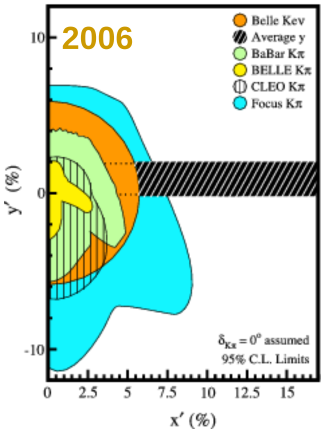
The last two decades has seen a renaissance in charm studies.

Charm oscillations are slow, and mediated by two parameters, which are hard to predict in SM.

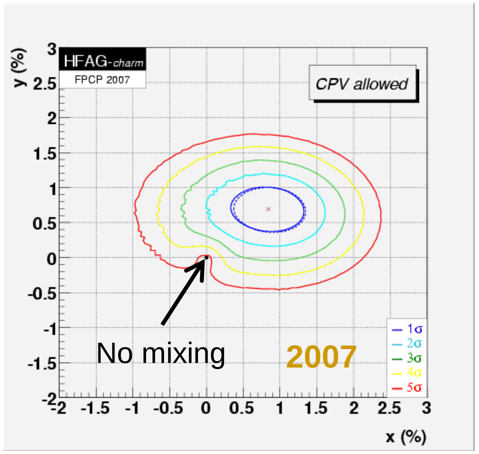
$$x \equiv \Delta m/\Gamma \qquad y \equiv \Delta\Gamma/2\Gamma$$

For many years, nothing was seen, but then ensemble of B-factory data, followed by high statistics studies from CDF & LHCb, dramatically changed picture.

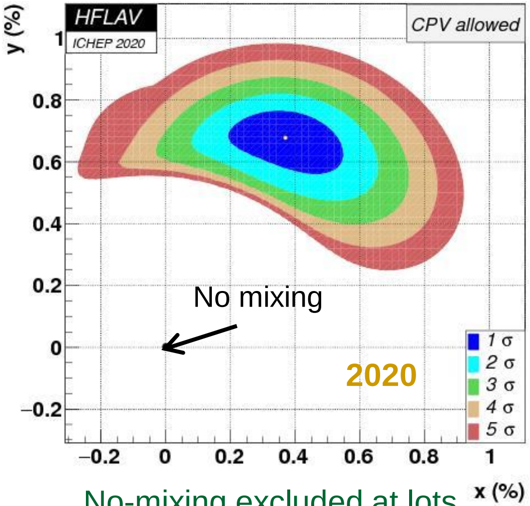
Excluded regions



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



Measurement contours;
no-mixing excluded at 5σ



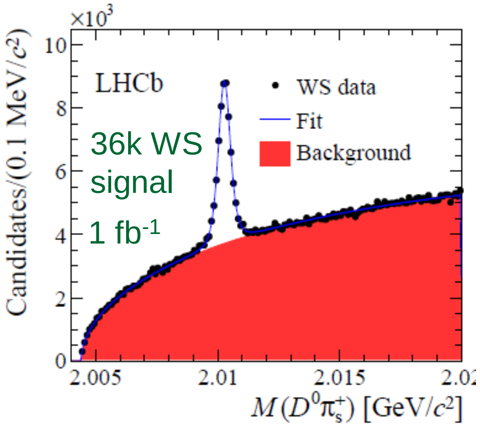
No-mixing excluded at lots and lots (but x=0 still possible…)

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.

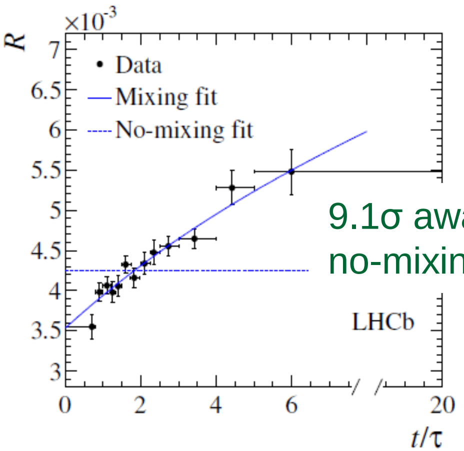
This is the WS/RS ratio vs. proper time.

Linear slope comes from mixing-decay interference.



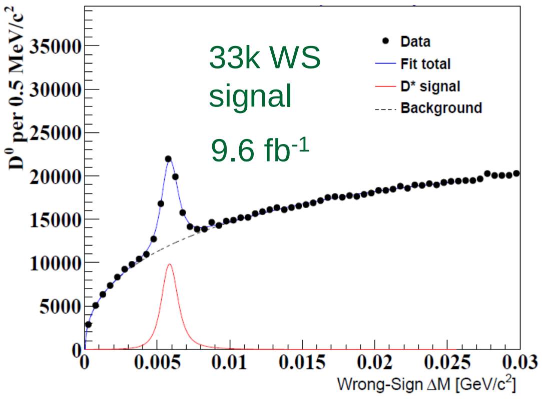
36k WS signal

1 fb^{-1}



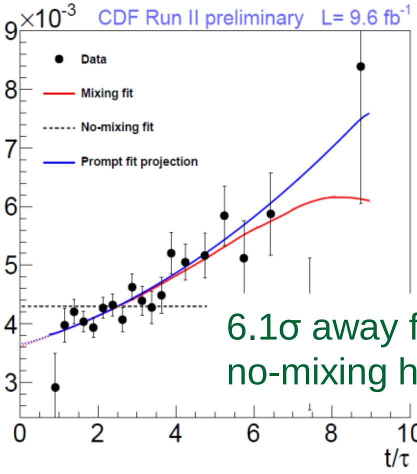
9.1σ away from no-mixing hyp.

[LHCb, PRL 110 (2013) 101802]



33k WS signal

9.6 fb^{-1}



6.1σ away from no-mixing hyp.

[CDF, PRL 111 (2013) 231802]

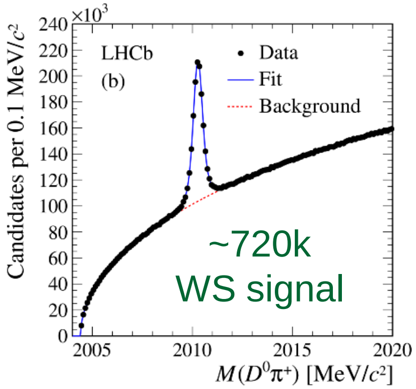
LHCb sample is a just *small* fraction of Run 1, but is *order of magnitude* larger than that of BaBar. These measurements also benefit from better time resolution.

CP violation in charm-mixing phenomena

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

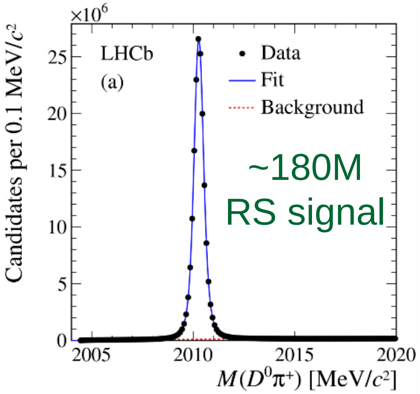
To look for these we essentially look for differences in mixing between D^0 and $\overline{D}^0$.

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

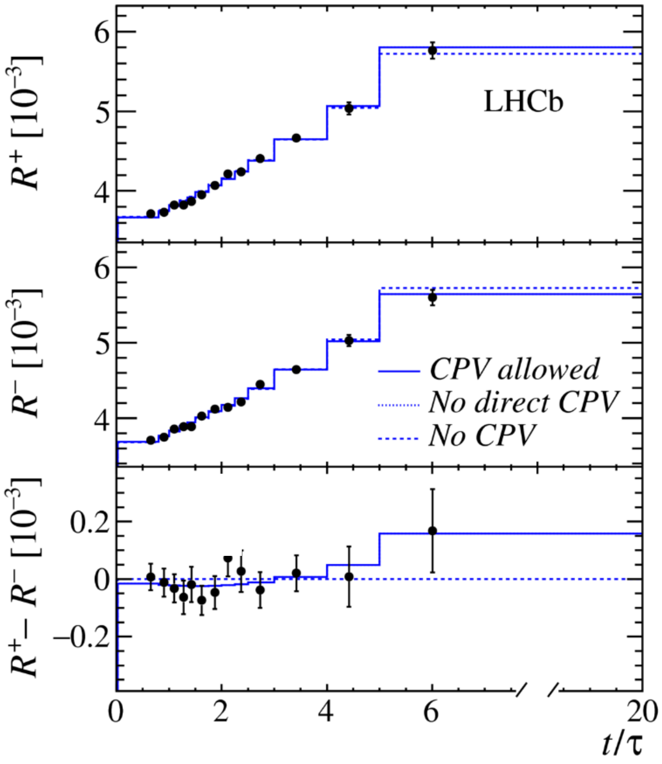


~720k WS signal

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



~180M RS signal



For D^0…

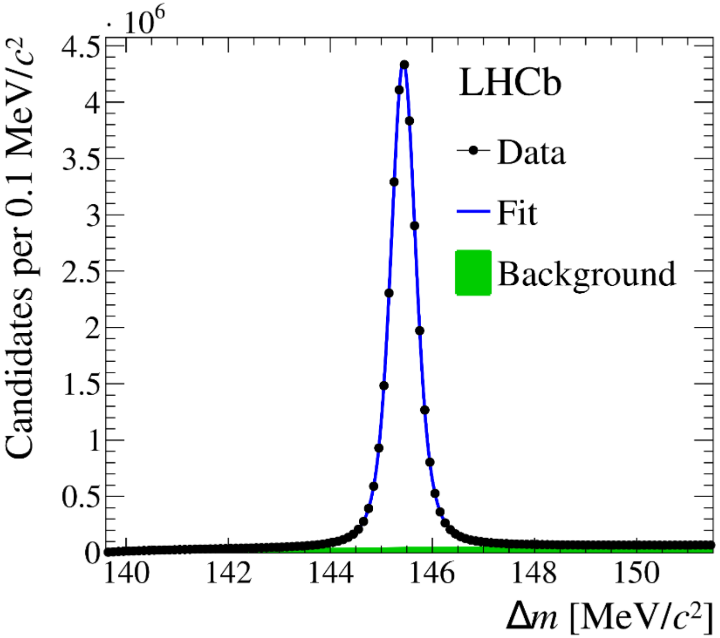
…and D^0bar…

…and difference of both.

[PRD 97 (2018) 031101]

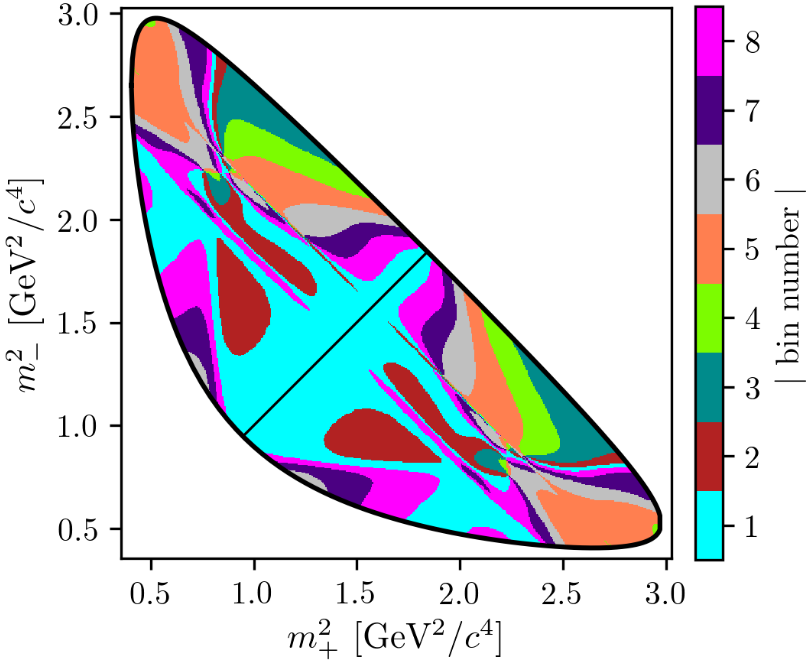
No indication of any difference, so CP violation must be very small (as expected).

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



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

Run-1/2 LHCb result [PRL 127 (2021) 111801] exploits 5.4 fb^{-1} of data, corresponding to 31 million decays (x30 B-factory samples).



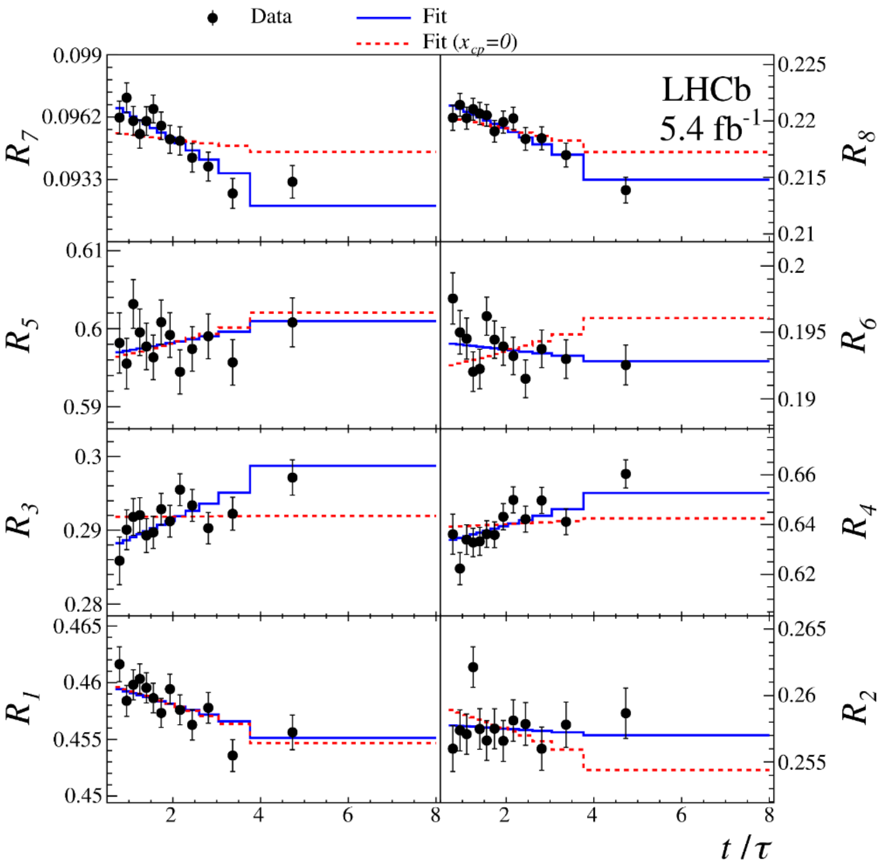
As in γ analysis, divide Dalitz plot into bins, whose strong-phase characteristics are known from BESIII measurements.

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

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

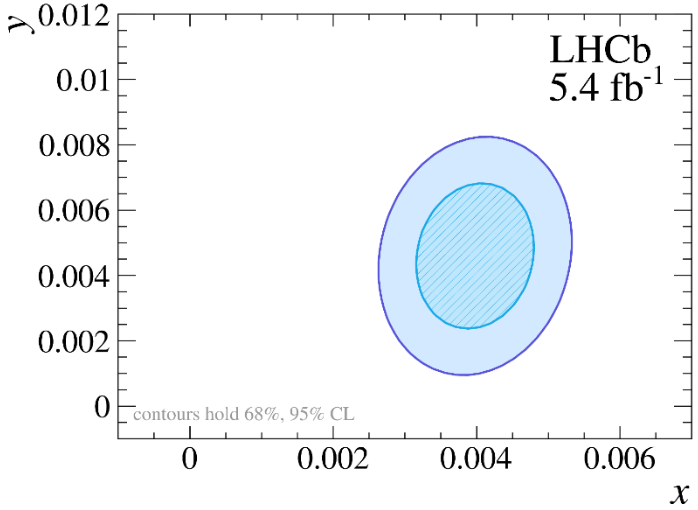
D^0-$\bar{D}^0$ oscillations with $D^0 \to K_S\pi^+\pi^-$ at LHCb

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



$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3},$$
$$|q/p| = 0.996 \pm 0.052,$$
$$\phi = 0.056^{+0.047}_{-0.051}.$$

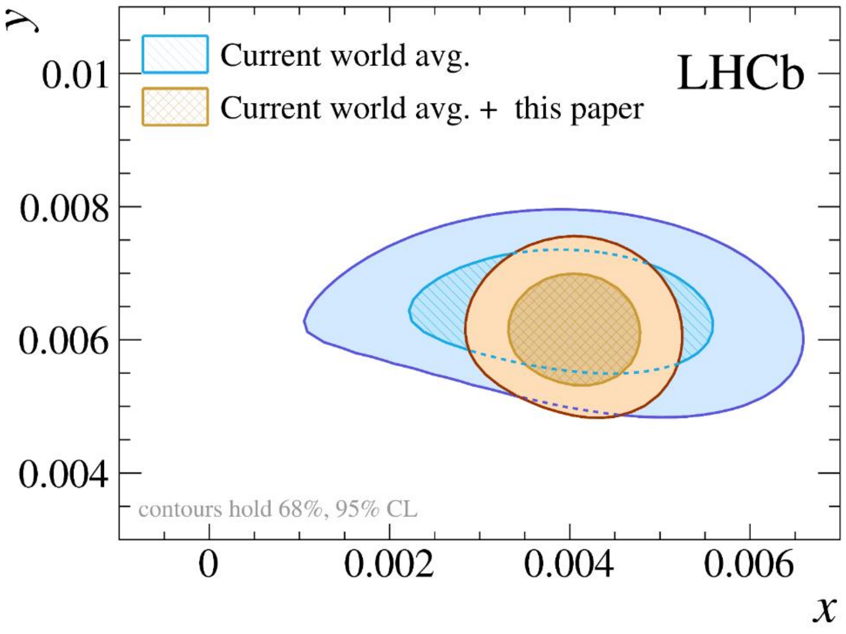
CPV parameters
No CPV when
|q/p|=1 & ϕ = 0

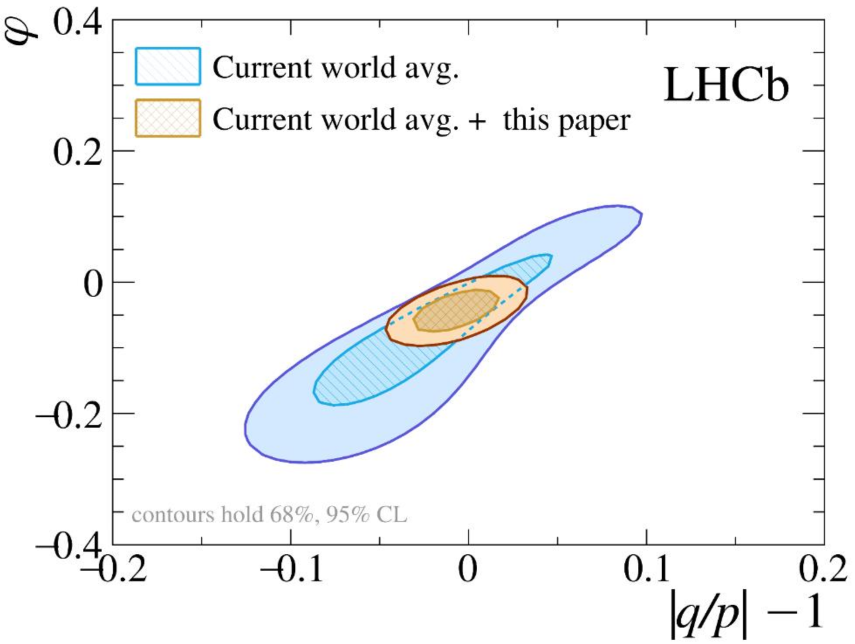


x non-zero with significance of >7σ !

D^0-$\overline{D}^0$ oscillations with $D^0 \rightarrow K_S\pi^+\pi^-$ at LHCb

These result represents a huge step forward in precision for mixing & CPV searches.



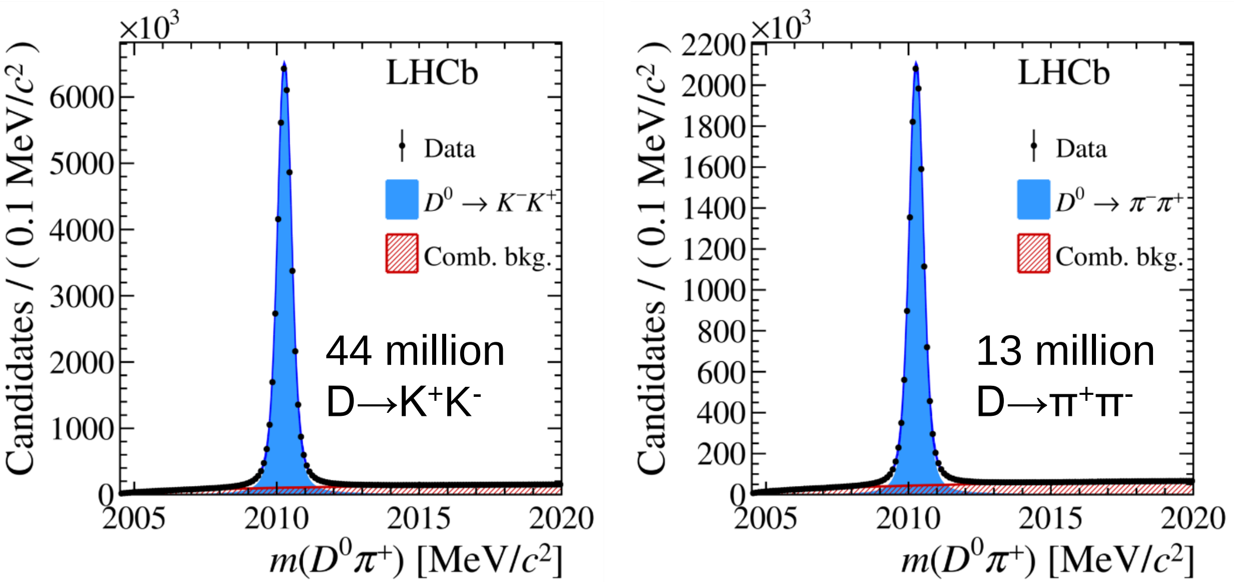


Knowing that both x and y are non-0, & significantly larger than once was guessed, bodes well for mixing-related CPV searches, as they pre-multiply any asymmetry. SM CPV may lie ~10x below current sensitivity, New Physics could be larger !

Observation of (direct) CPV in charm

But CPV in decay *has* been seen [PRL 122 (2019) 211803] . Observed in *difference* of time-integrated CP asymmetries in D→KK and D→ππ (ΔA_{CP}). Choice of observable necessary to cancel out systematic effects common to both modes.

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



44 million $D \to K^+K^-$

13 million $D \to \pi^+\pi^-$

Run 1 +
Run 2 ➡

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

5.3σ
from 0 !

As with mixing, the effect is larger than had been expected, but can (probably) be accommodated in SM. Observation opens a new frontier of measurement !

Is the CPV coming from $D^0 \to K^+K^-$ or $D^0 \to \pi^+\pi^-$

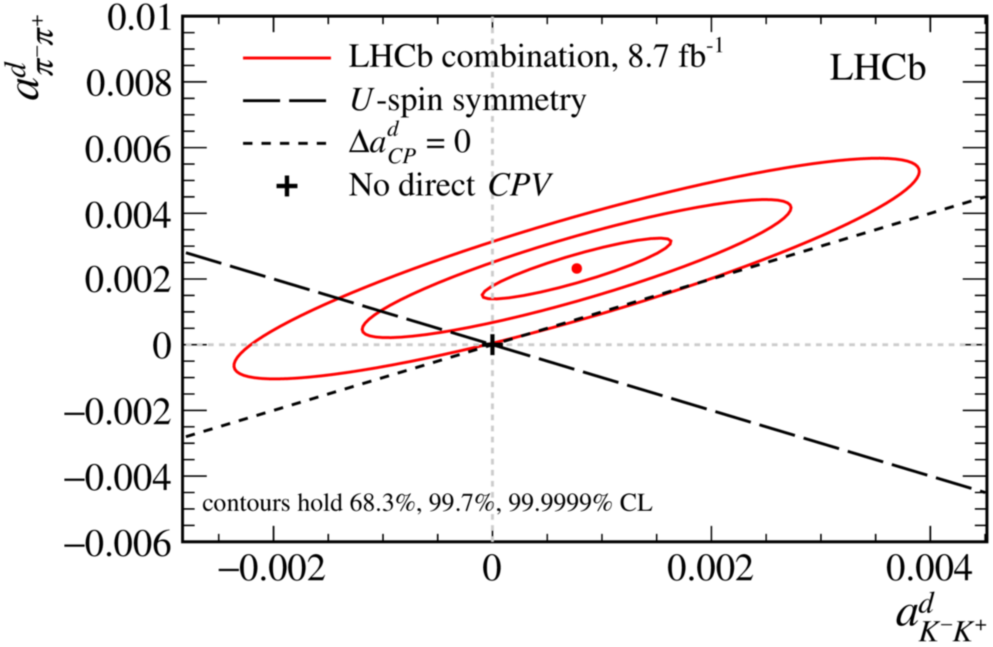
In a recent paper [PRL 131 (2023) 091802], LHCb has measured the CP asymmetry in $D^0 \to K^+K^-$ alone. This necessitates constraining the 'nuisance parameters' of the production and detection asymmetries from measurements in several Cabibbo-favoured control channels where the CPV is expected to be negligible.

Find $\mathcal{A}_{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$

which, being consistent with zero, implies the ΔA_{CP} result is driven by $D^0 \to \pi^+\pi^-$.

This is somewhat surprising, as the naïve expectation (from `U-spin symmetry') is that the direct CPV in the two channels should be equal and opposite.

Await more data !



The need for improved precision

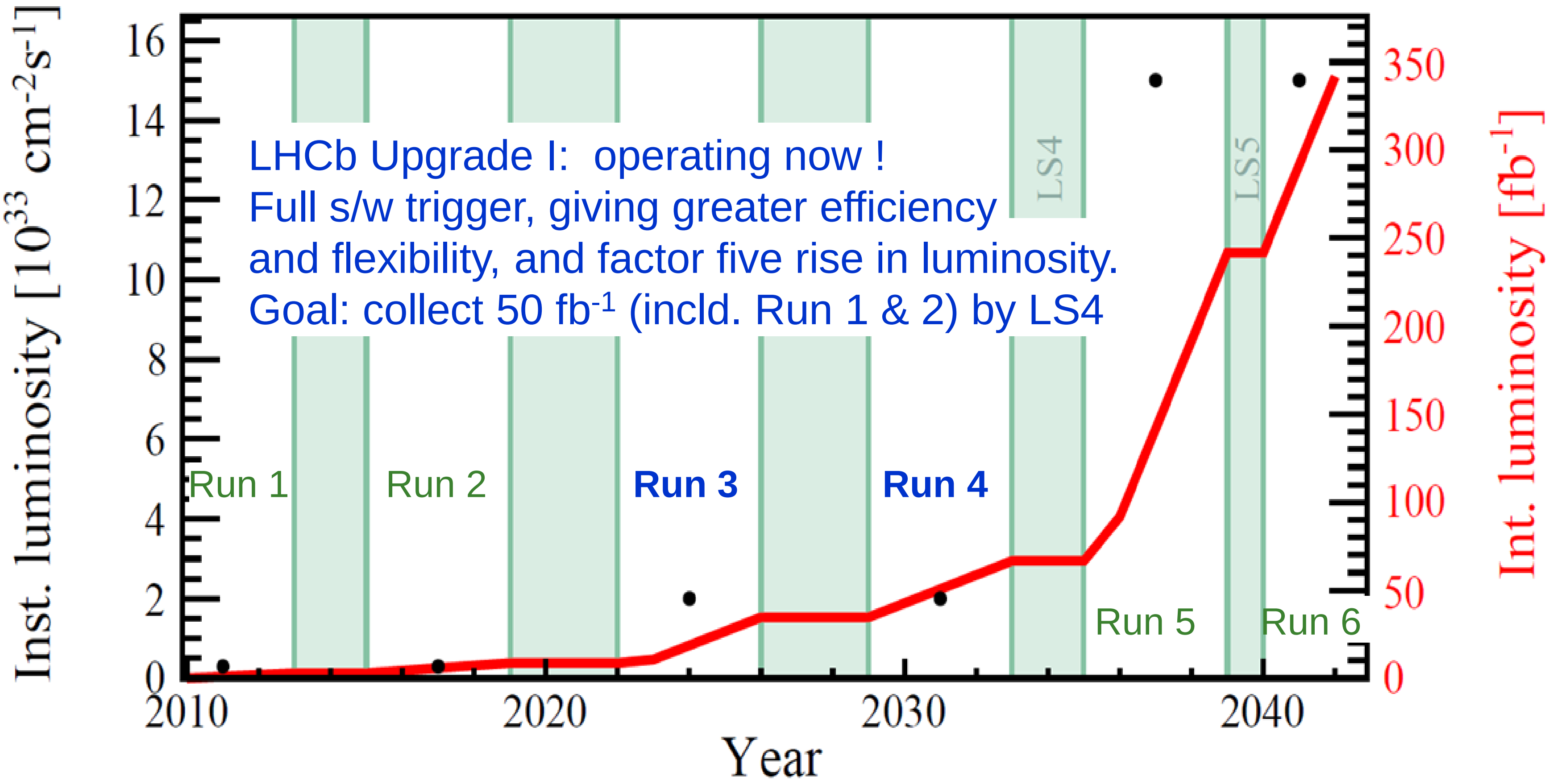
Charm is one topic where higher precision is required. There are many more:

- Improved measurements of the angle γ;
- Improved measurements of $B^0_{(s)} \rightarrow \mu\mu$;
- Studies of semi-leptonic asymmetries (not discussed here);
- Improved measurements of ϕ_s and $\sin 2\beta$;
- Further exploration of observables in electroweak penguins with muons and electrons;
- ... Many others.

Roughly ordered in terms of theoretical purity

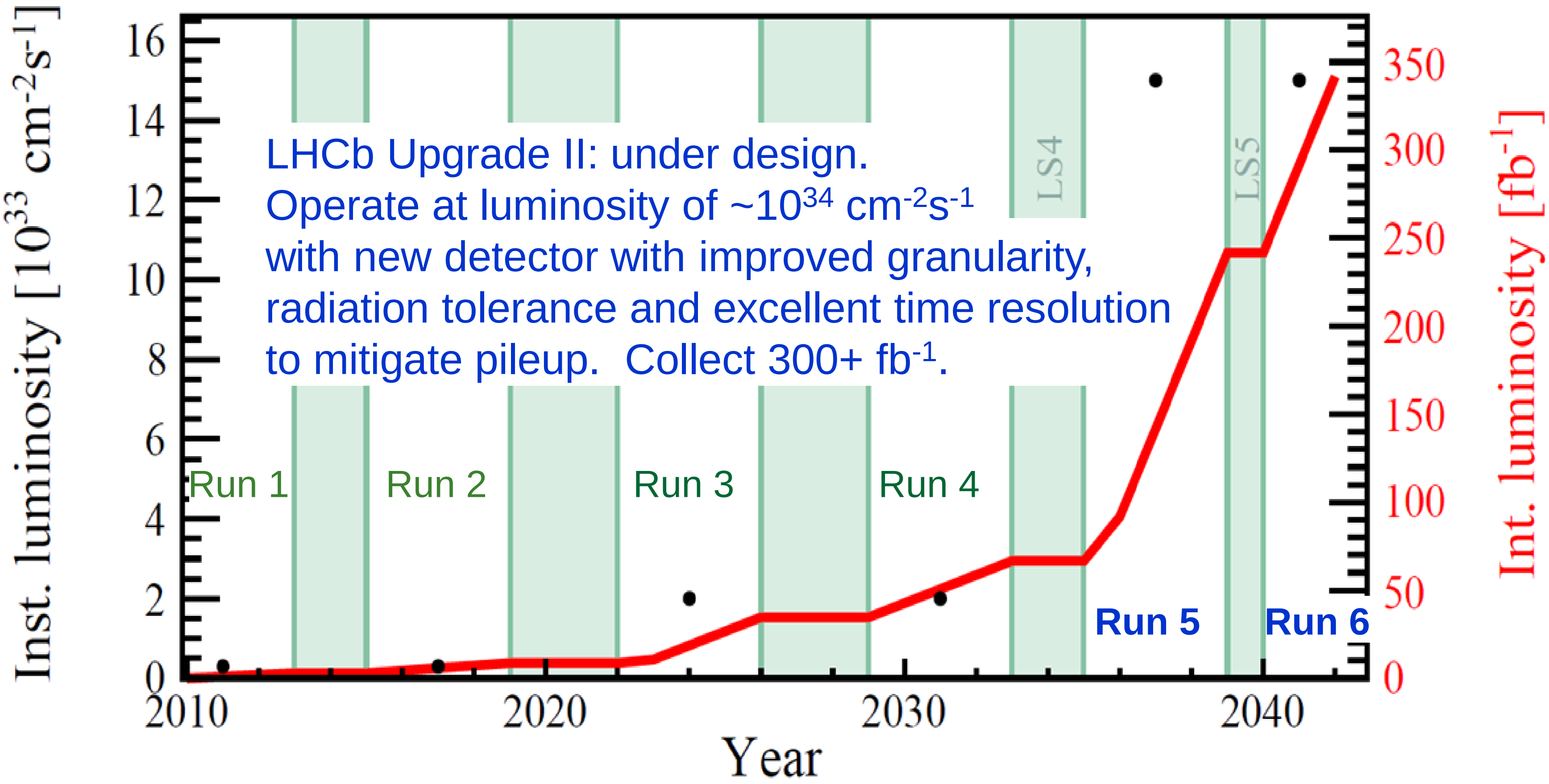
Significant increases in precision will not come from continuing to operate the Run 1 / 2 LHCb detector. A step change in sensitivity requires radical changes.

The road to 50 fb^{-1}: LHCb Upgrade I



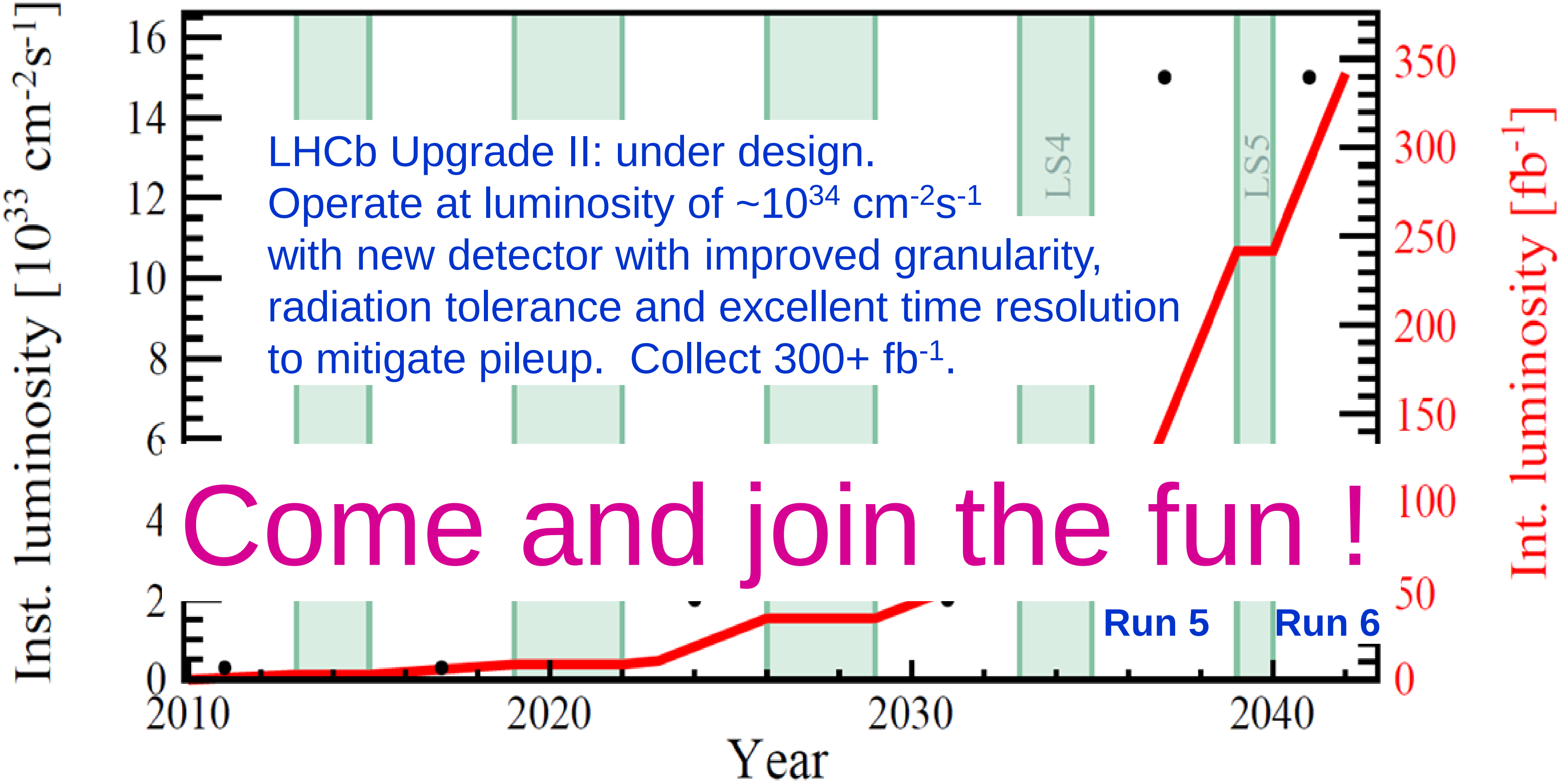
LHCb Upgrade I: operating now !
Full s/w trigger, giving greater efficiency
and flexibility, and factor five rise in luminosity.
Goal: collect 50 fb^{-1} (incld. Run 1 & 2) by LS4

The road to 300+ fb^{-1}: LHCb Upgrade II



LHCb Upgrade II: under design.
Operate at luminosity of ~10^{34} cm^{-2}s^{-1}
with new detector with improved granularity,
radiation tolerance and excellent time resolution
to mitigate pileup. Collect 300+ fb^{-1}.

The road to 300+ fb^{-1}: LHCb Upgrade II



LHCb Upgrade II: under design.
Operate at luminosity of ~10^{34} cm^{-2}s^{-1}
with new detector with improved granularity, radiation tolerance and excellent time resolution to mitigate pileup. Collect 300+ fb^{-1}.

Come and join the fun !

Backups

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

Remarkably, the sample of $B_s \rightarrow \mu\mu$ 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]:

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

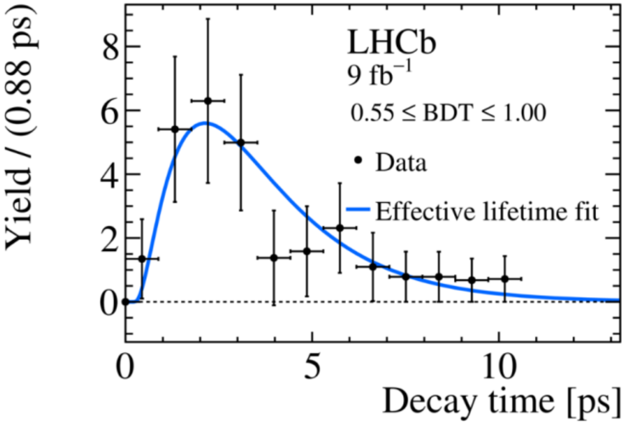
where

- $y_s \equiv \tau_{B_s^0} \Delta\Gamma/2 \approx 0.06$, $\Delta\Gamma$ 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.

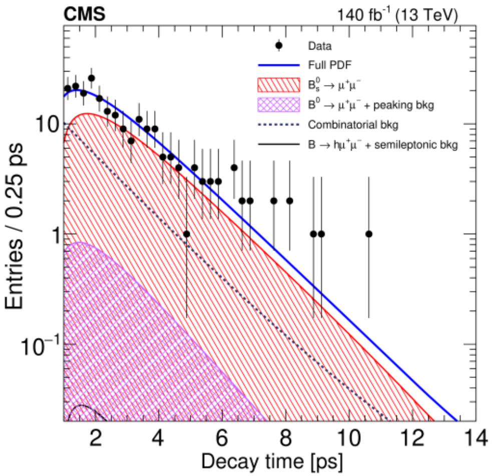
Accessing $A^{\mu\mu}_{\Delta\Gamma}$ through $\tau_{\mu\mu}$ tells us things that the BR alone does not.

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

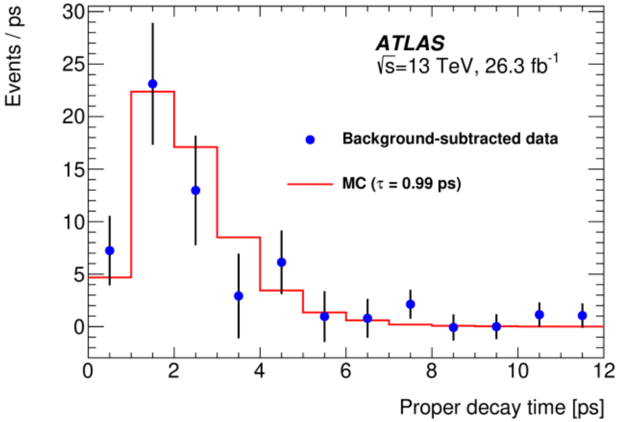
Measurements of effective lifetime now available from all three experiments.



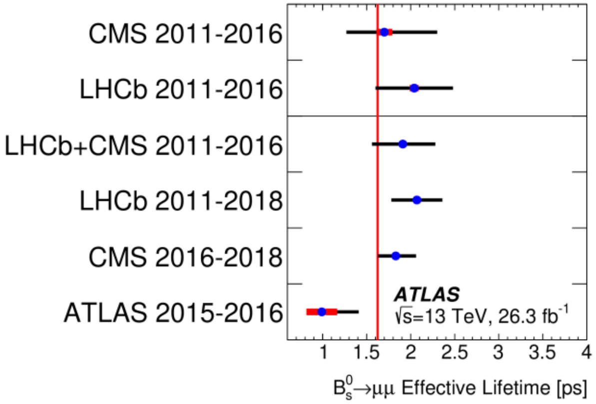
[PRL 128 (2022) 041801]



[PLB 842 (2023) 137955]

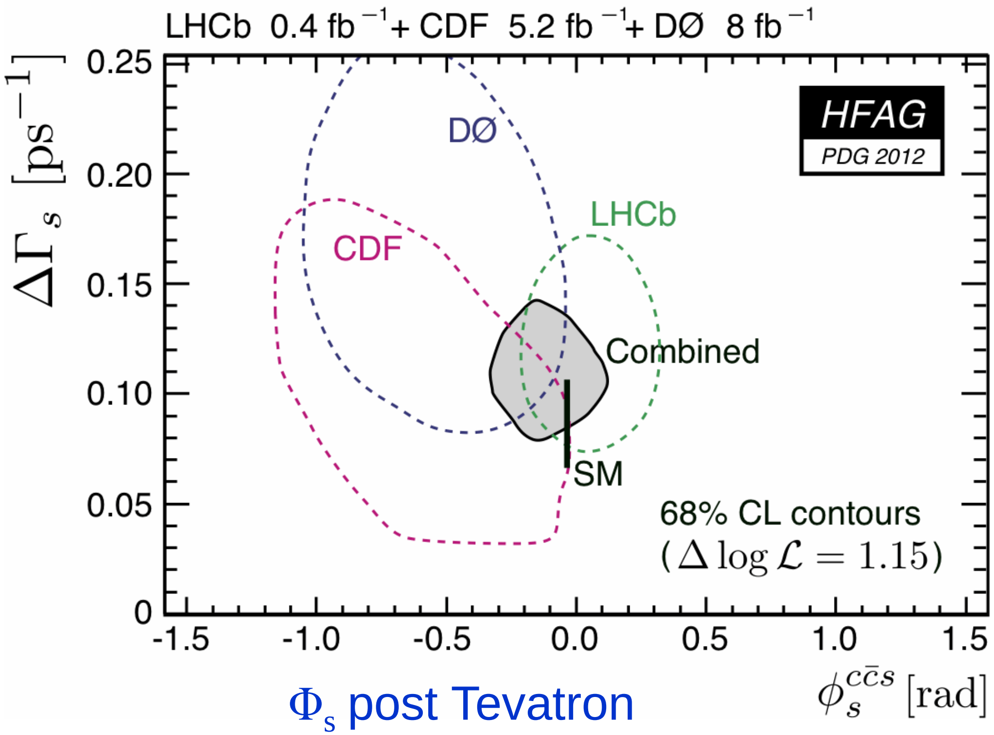


[JHEP 09 (2023) 199]



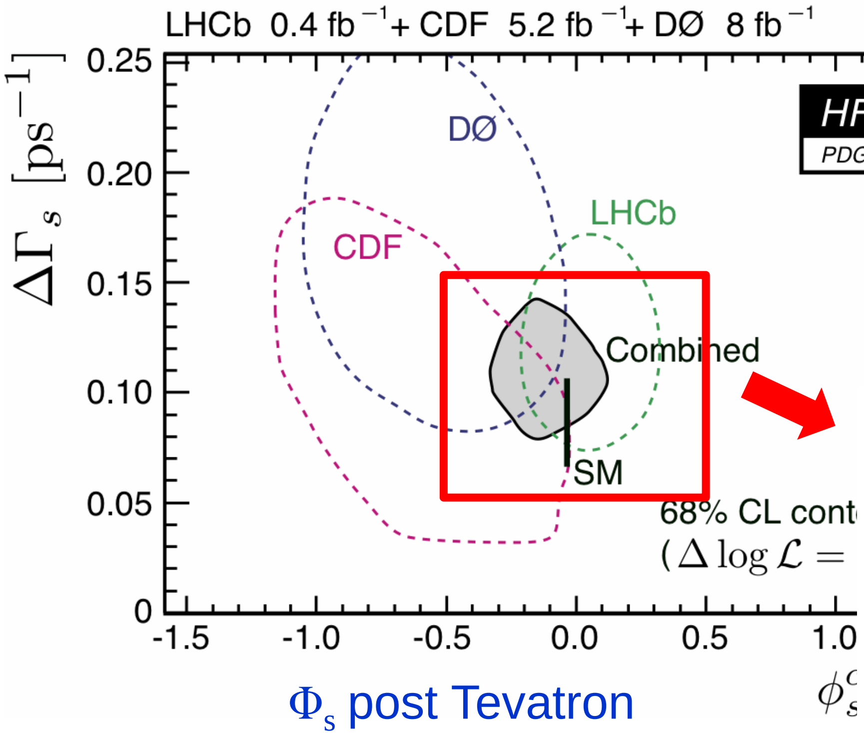
Precision now similar to lifetime splitting $\Delta\Gamma_s$. Very interesting prospects for HL-LHC era. Also, can start to plan for flavour-tagged CP asymmetry measurements !

φ_s : the impact of the LHC



Φ_s post Tevatron
and early LHC data

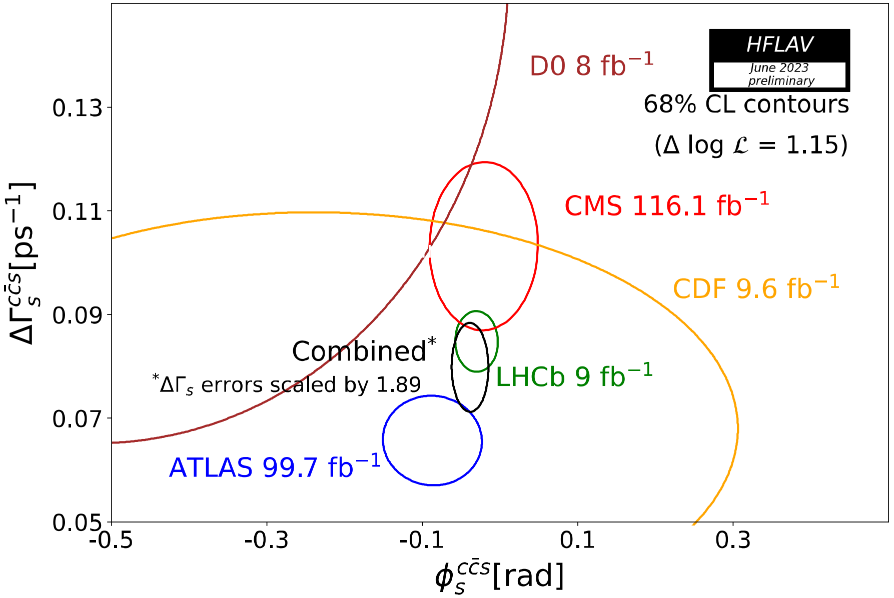
φ_s : the impact of the LHC



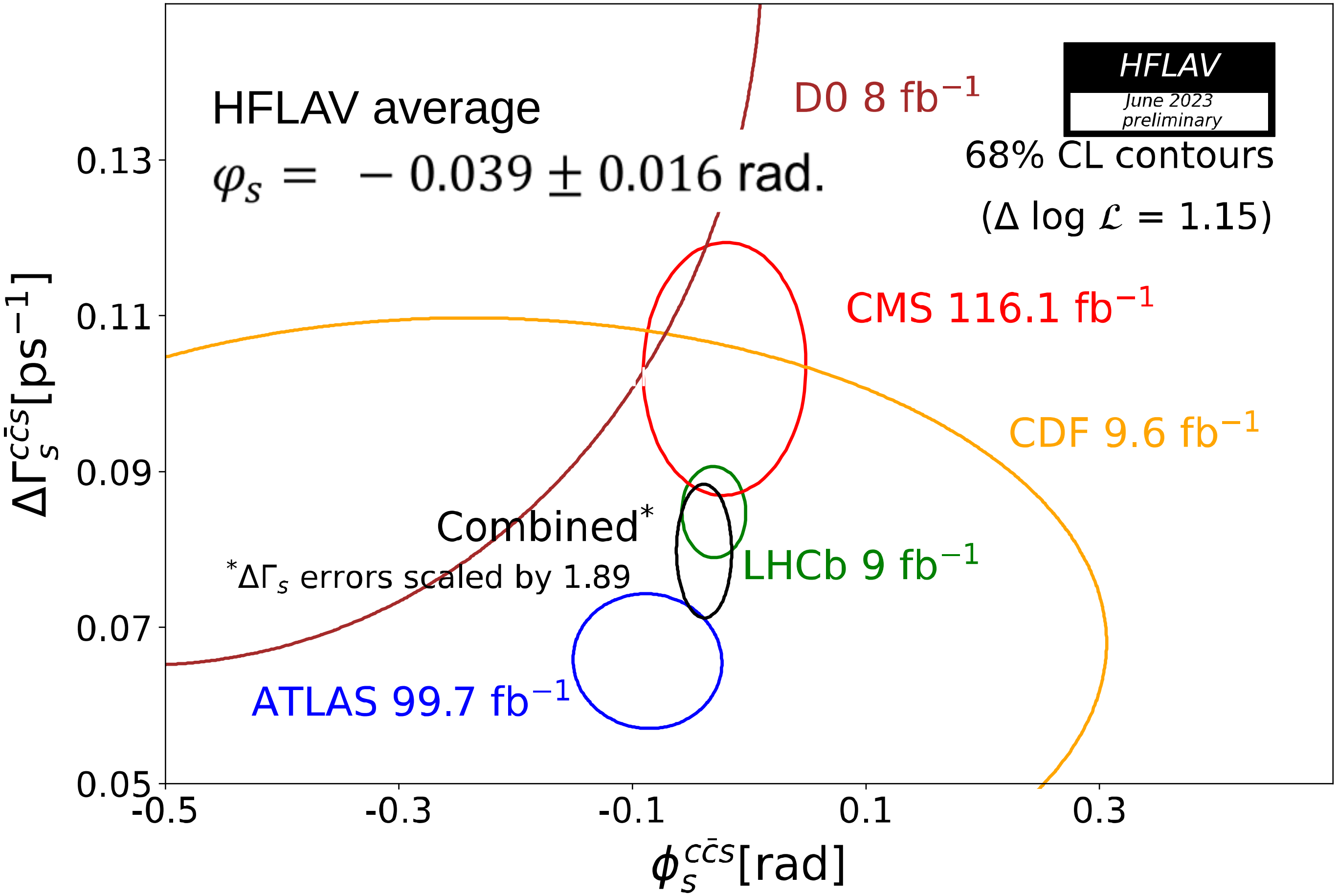
Φ_s post Tevatron and early LHC data

Note, important contributions from ATLAS and CMS also.

φ_s current LHC



φ_s : the current state of play



φ_s now measured with 16 mrad precision and so far compatible with SM.
Hint of non-zero value emerging – will be very interesting with Run 3 data set !