Flavour Physics lecture 2

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CERN-Fermilab HCPSS
September 2019

Useful resources & acknowledgments

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

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

Lecture outline

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

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

CKM matrix expressed in Wolfenstein parametrisation

[Wolfenstein, PRL 51 1945]

From last time

In the Wolfenstein parameterisation the matrix is expanded in orders of λ ~ 0.23.

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

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

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

V_{ub} and V_{td} are the only complex elements (at this order) → special role in CPV

‘The’ Unitarity Triangle

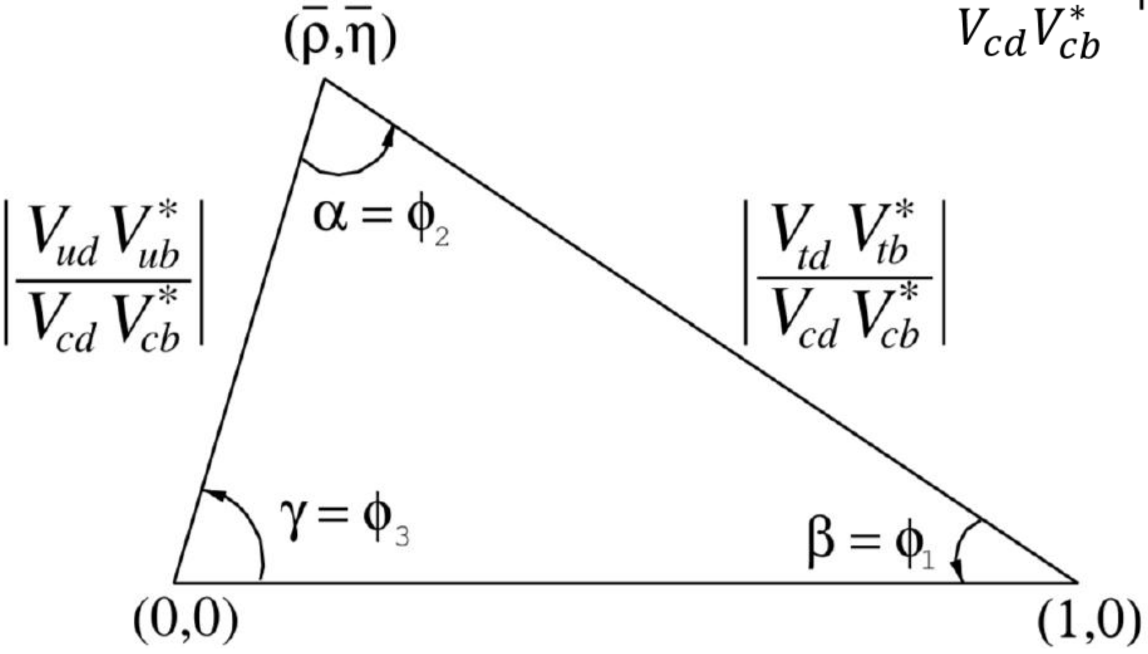
From last time

Three complex vectors sum to zero

→ triangle in Argand plane

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

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



Expressions for angles:

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

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

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

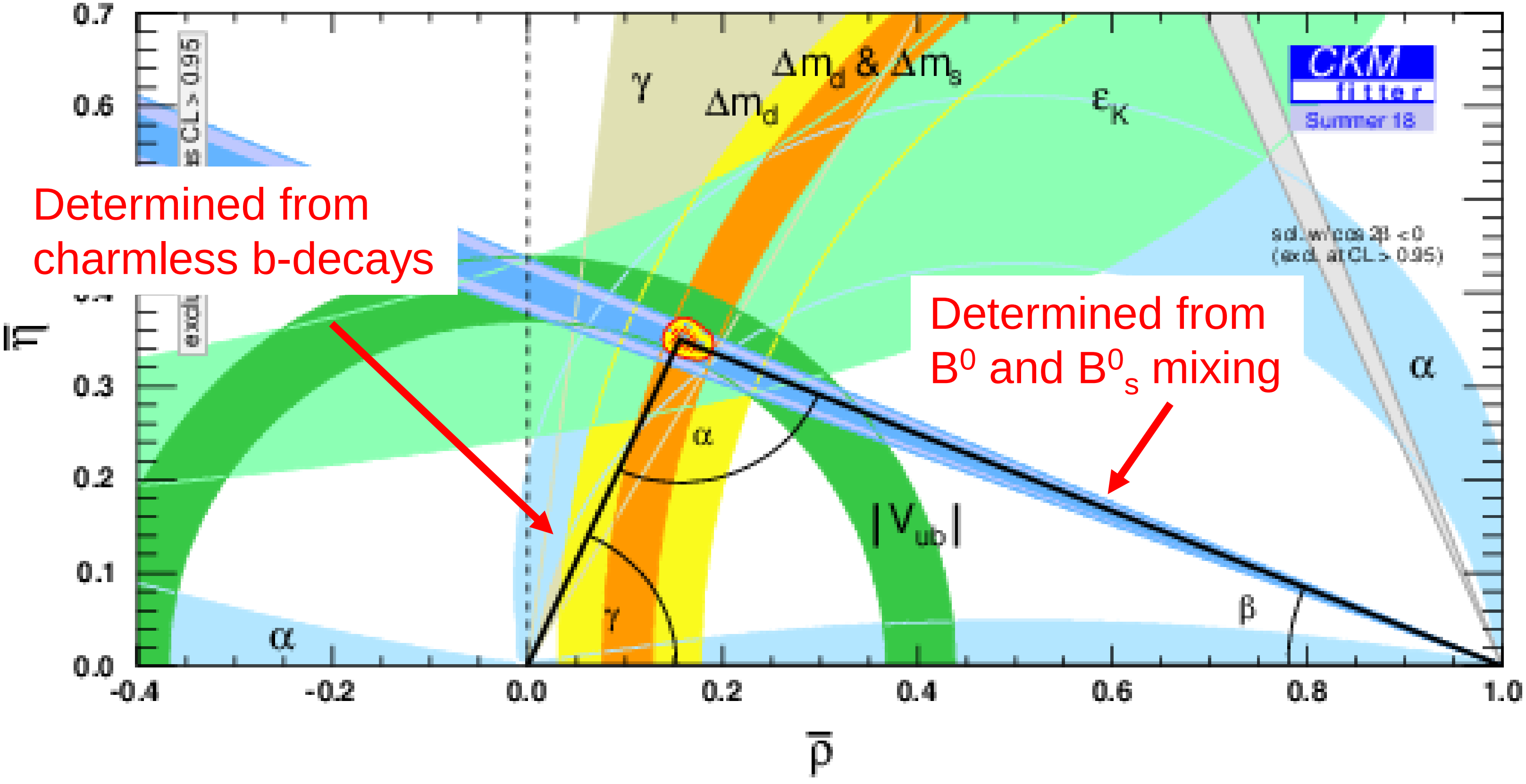
Upper vertex: $\bar\rho + i\bar\eta = -(V_{ud}V_{ub}^*)/(V_{cd}\,V_{cb}^*)$

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

(φ_2, φ_1 & φ_3 alternative notation)

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

From last time



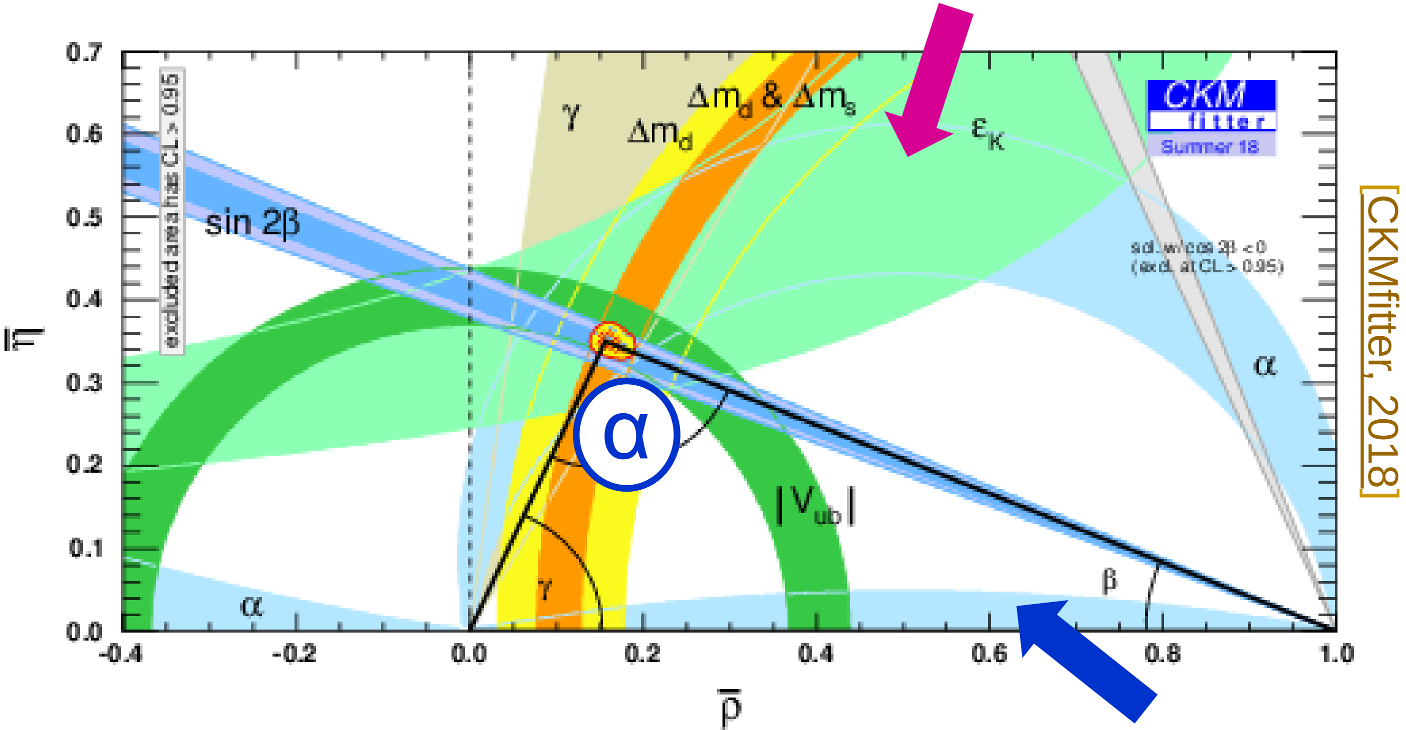
Determined from charmless b-decays

Determined from B^0 and B^0_s mixing

[CKMfitter, 2018]

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

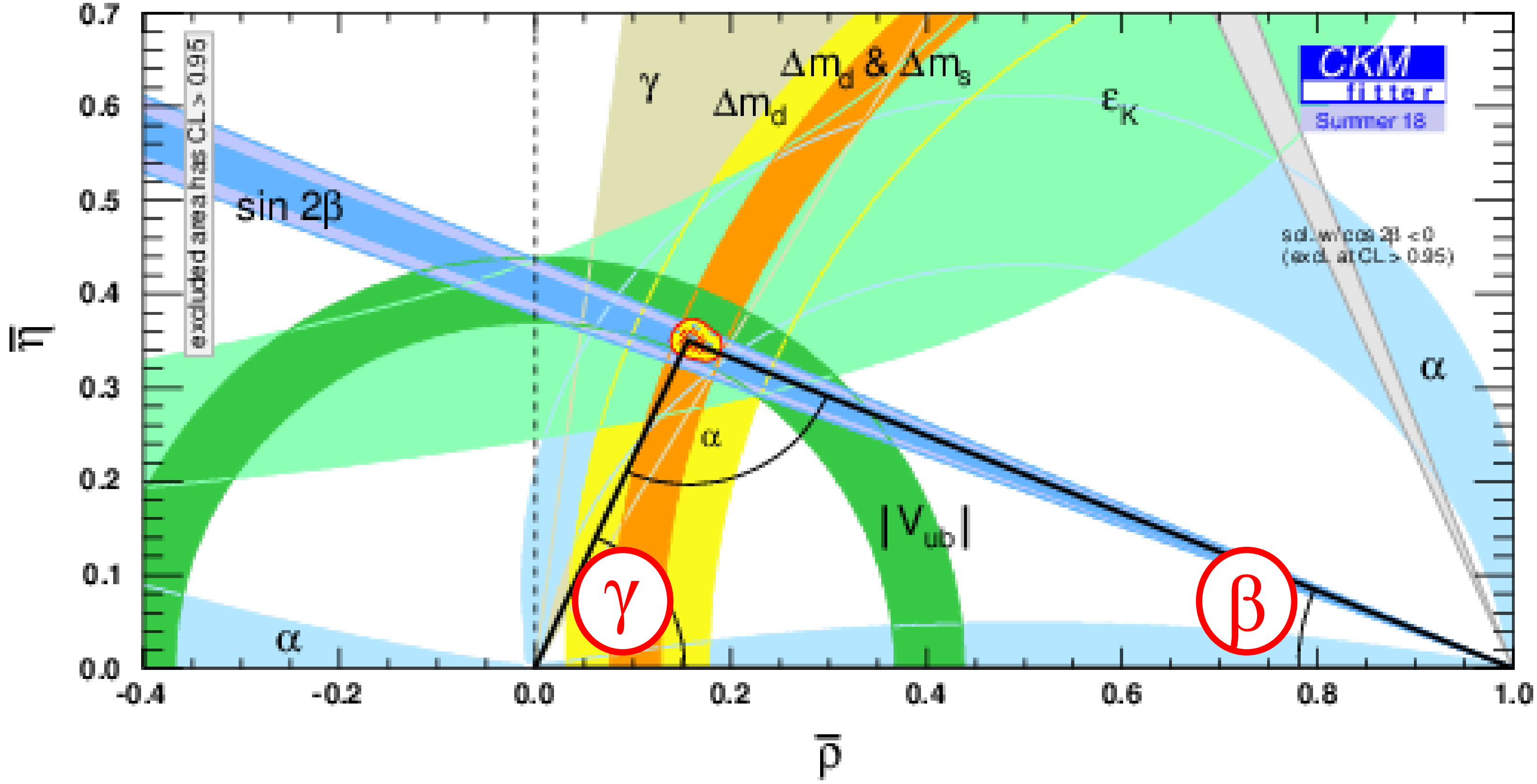
This band comes from CPV measurements in kaon decays. Theory limited.



[CKMfitter, 2018]

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

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



[CKMfitter, 2018]

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

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

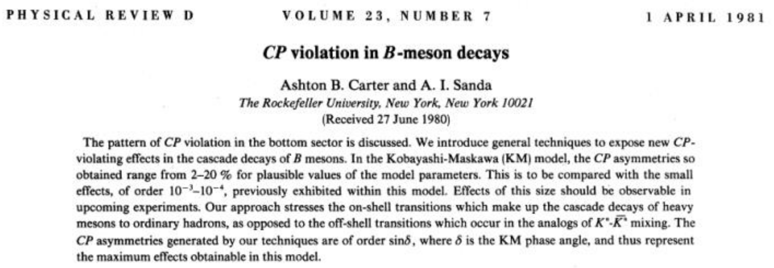
Potential for clean measurement of substantial CPV in B system first appreciated in early 1980s: [Carter and Sanda, PRD 23 (1981) 1567], [Bigi and Sanda, NPB 193 (1981) 85].

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

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

*

>750 citations



PHYSICAL REVIEW D VOLUME 23, NUMBER 7 1 APRIL 1981

CP violation in B-meson decays

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

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

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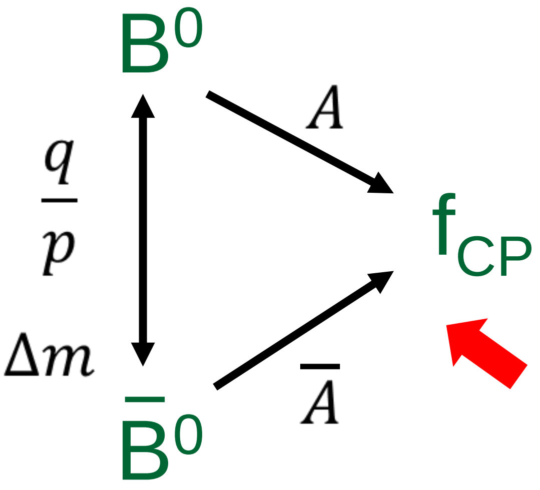
For meson that is B^0 or B^0bar at t=0, which decays into CP-eigenstate f_{CP} at time *t*:

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

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

*



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

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

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

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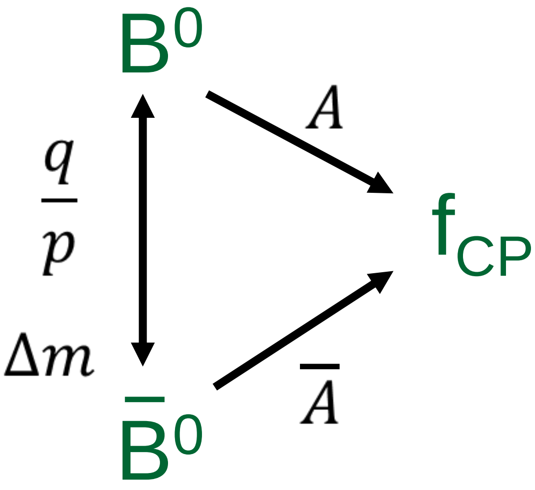

$$\begin{tikzcd}
B^0 \arrow[dr, "A"] \arrow[dd, leftrightarrow, "\frac{q}{p}" ', "\Delta m" '] & \\
& f_{CP} \\
\overline{B}^0 \arrow[ur, "\overline{A}" '] &
\end{tikzcd}$$

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

There are three ways that CP violation can appear:

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

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

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

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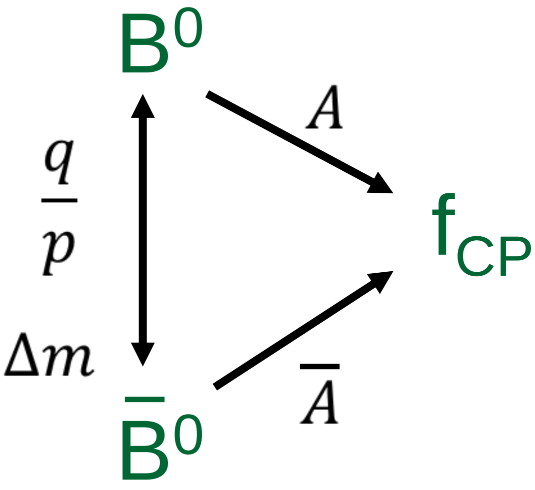

$$S = \frac{2\Im(\lambda_{CP})}{1+|\lambda_{CP}^2|} \qquad C = \frac{1-|\lambda_{CP}^2|}{1+|\lambda_{CP}^2|} \qquad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

There are three ways that CP violation can appear:

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

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

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

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

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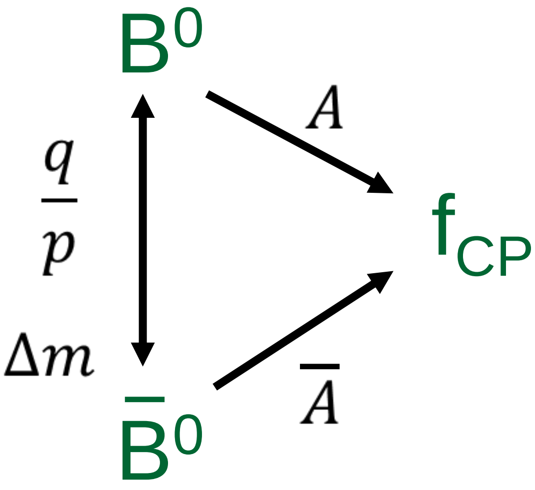

$$S = \frac{2\Im(\lambda_{CP})}{1+|\lambda_{CP}^2|} \qquad C = \frac{1-|\lambda_{CP}^2|}{1+|\lambda_{CP}^2|} \qquad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

There are three ways that CP violation can appear:

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

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

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

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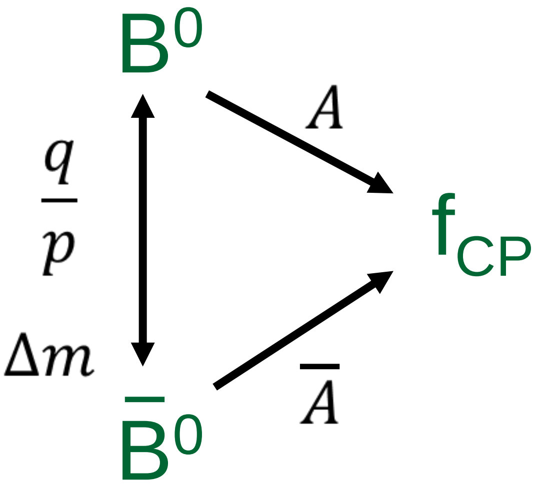

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Consider the classic case $B^0 \to J/\psi K_S$:

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

NB both these assumptions can be checked / corrected for.

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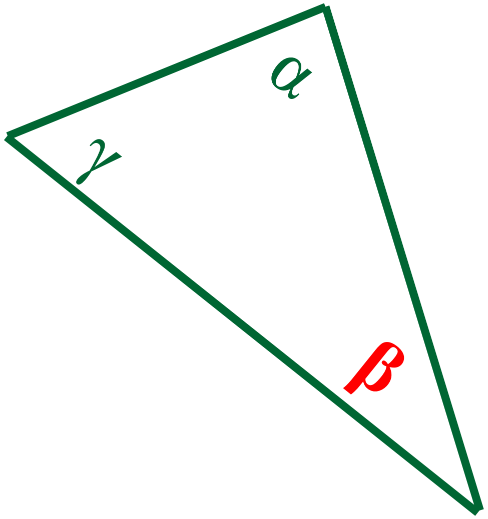

Consider the classic case $B^0 \rightarrow J/\psi K_S$:

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

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

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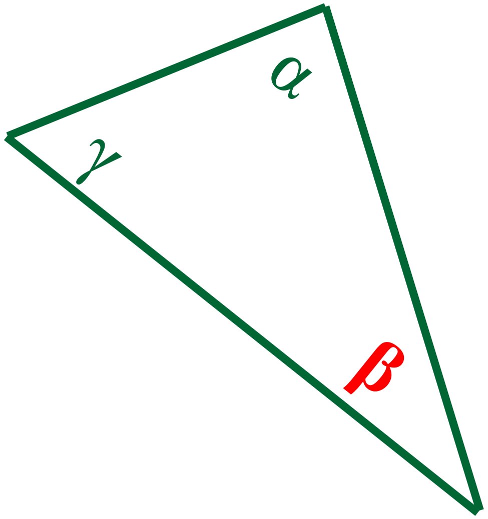

In practice we measure a *t*-dependent CP asymmetry:

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

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

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

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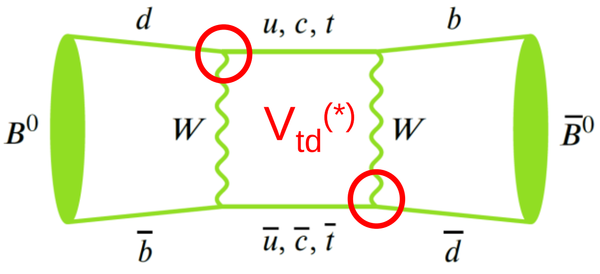
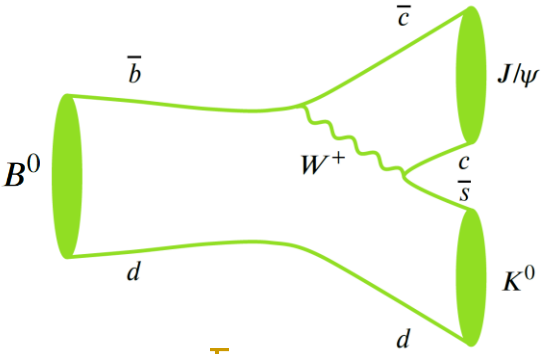
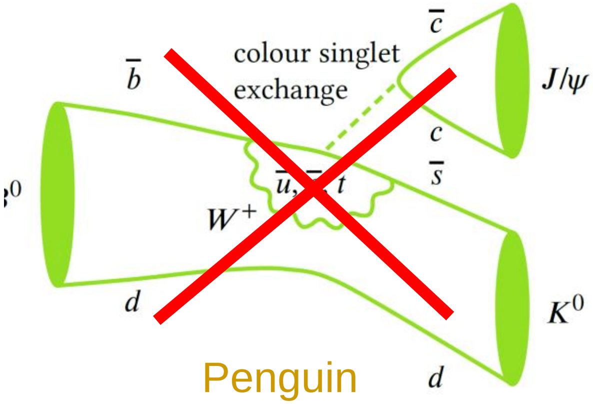
To reiterate, measurement probes interference between box and tree diagrams:



Box



Tree



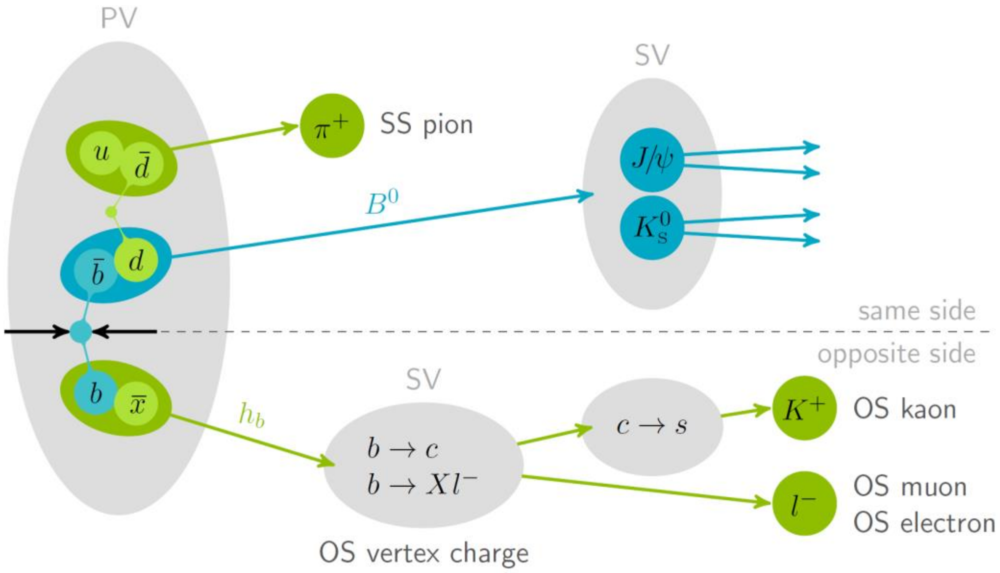
Penguin
(suppressed)

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

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

Flavour tagging & other practical considerations

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



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

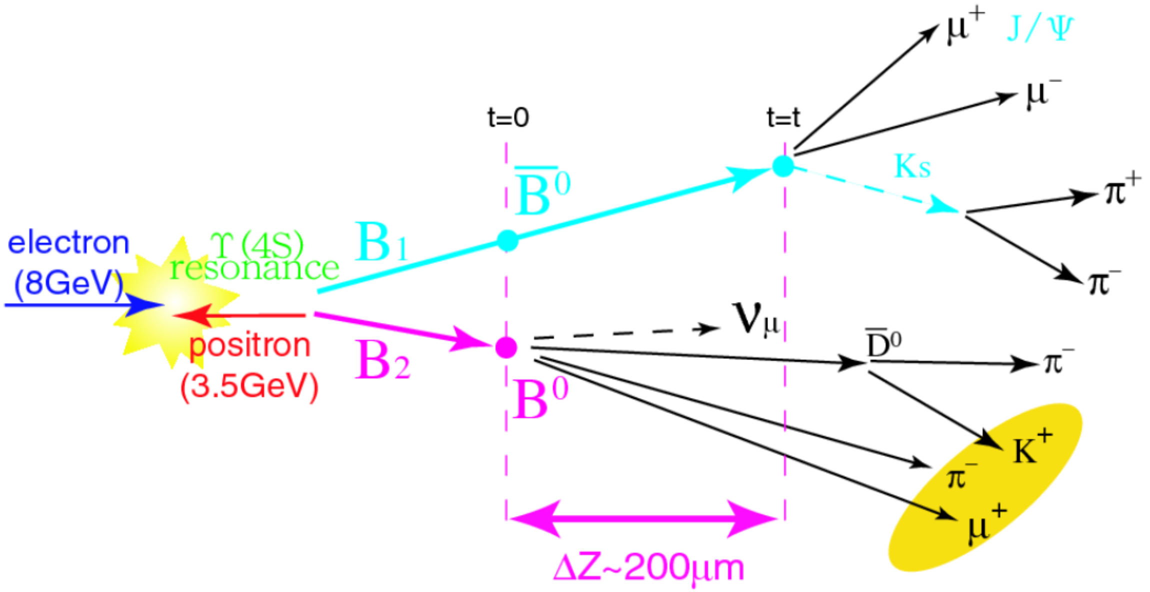
For *t* variable in asymmetry, we need to know proper time between birth & death of signal B, which at LHC is related to distance between primary and decay vertices.

---

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

Flavour tagging & other practical considerations

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



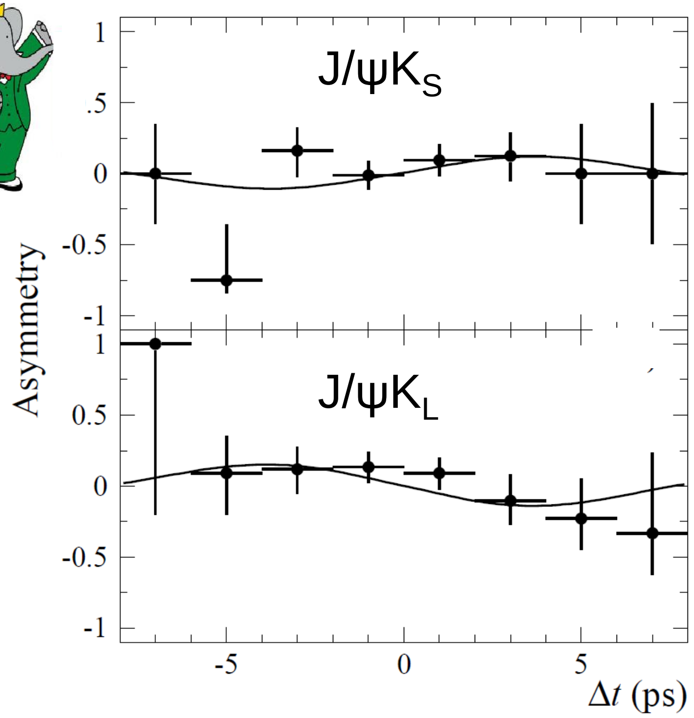
The dilution is less than at LHC, and reduces effective signal statistics by only ~1/3.

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

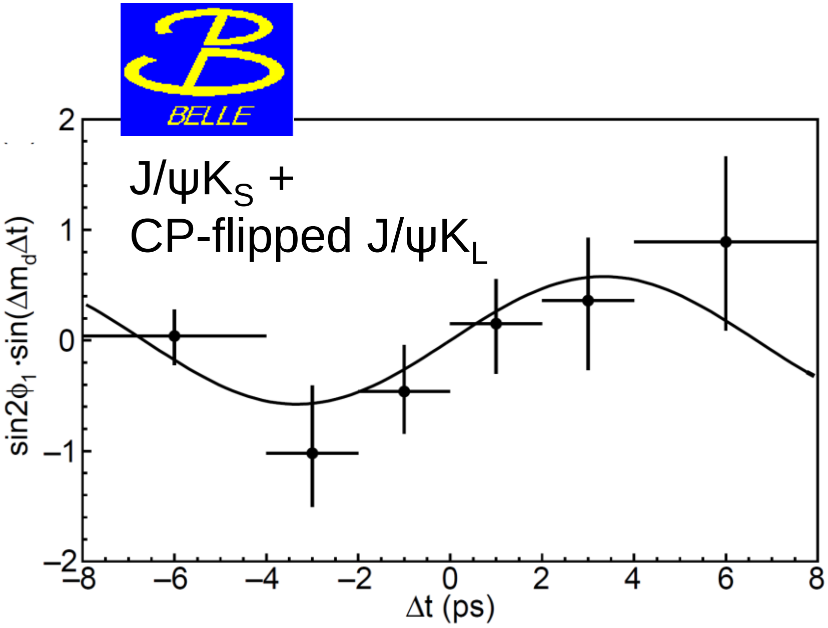
2001 - dawn of modern flavour physics

2008
Nobel
Prize

We can date the start of modern flavour physics to the 2001 measurements of the CP-violating asymmetry in $B^0 \rightarrow J/\psi K^0$ decays that give unitarity triangle angle β.



[BaBar, PRL 86 (2001) 2515]

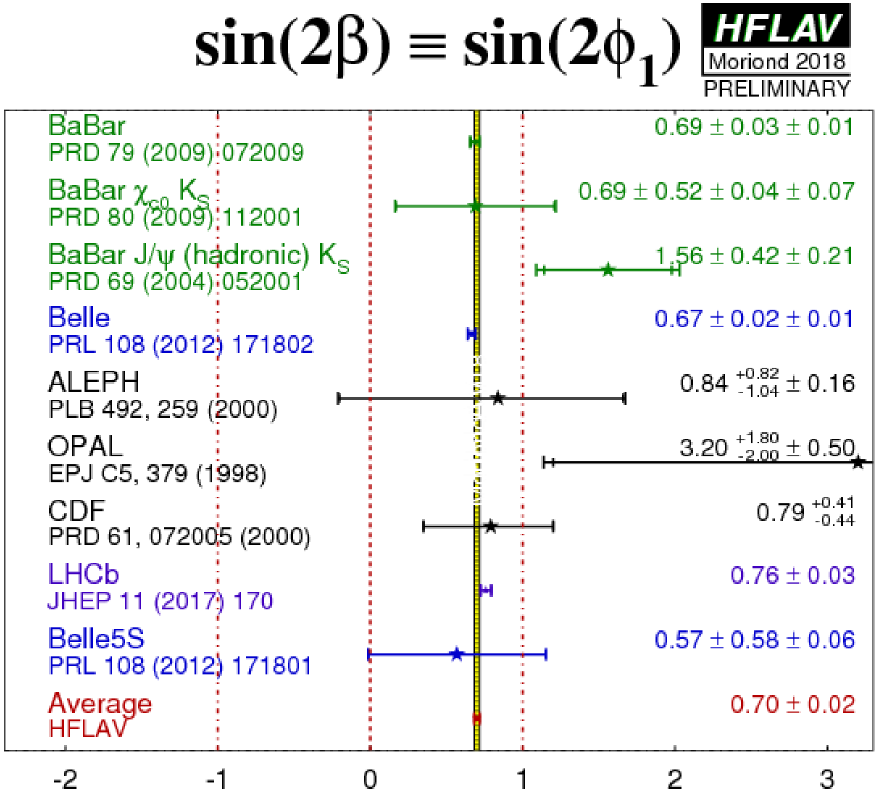


[Belle, PRL 86 (2001) 2509]

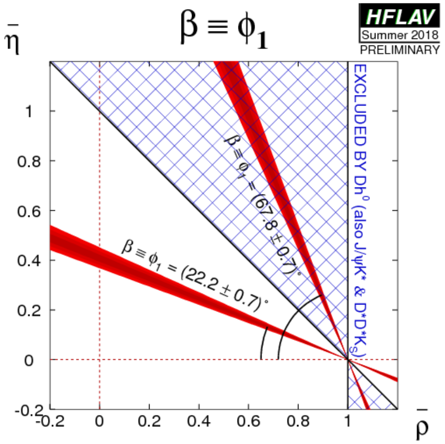
These studies, when improved with larger samples, confirmed the CKM paradigm as the dominant mechanism of CP violation in nature (→ 2008 Nobel Prize), and also opened up a rich and wide spectrum of complementary measurements.

sin2β: current status and impact of the LHC

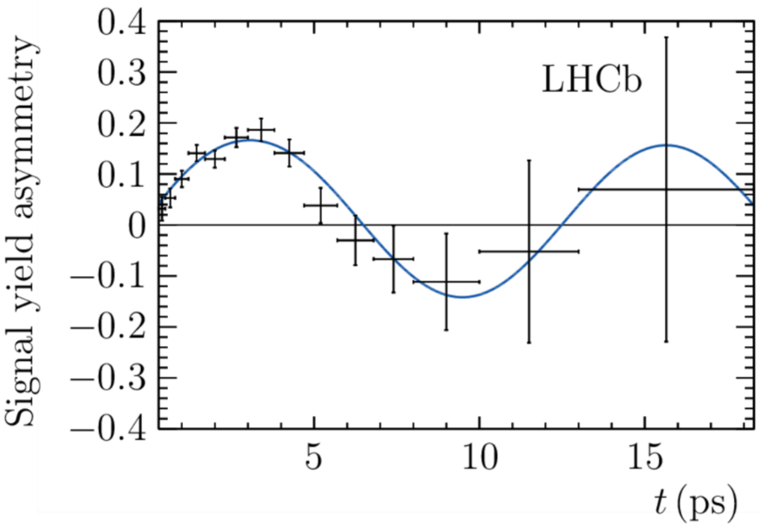
Global state of play:



Both solutions for β shown in UT plane. ➡



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



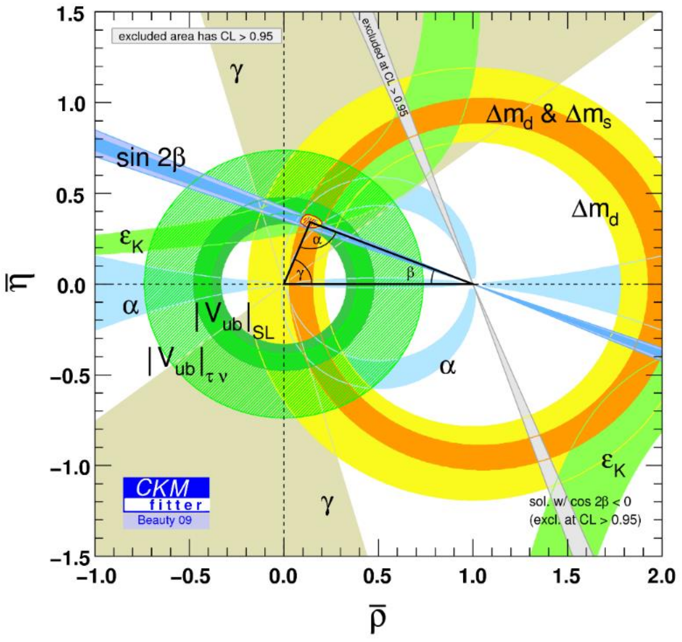
[LHCb, PRL 115 (2015) 031601]

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

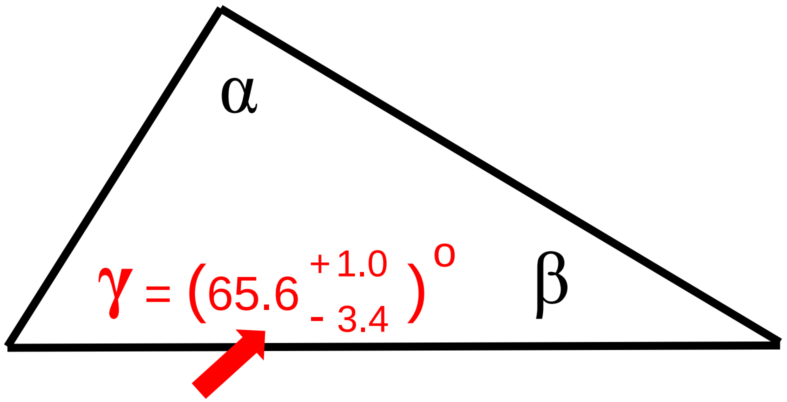
The long march: towards a precise determination of the UT angle γ

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

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



[CKMfitter, 2009]



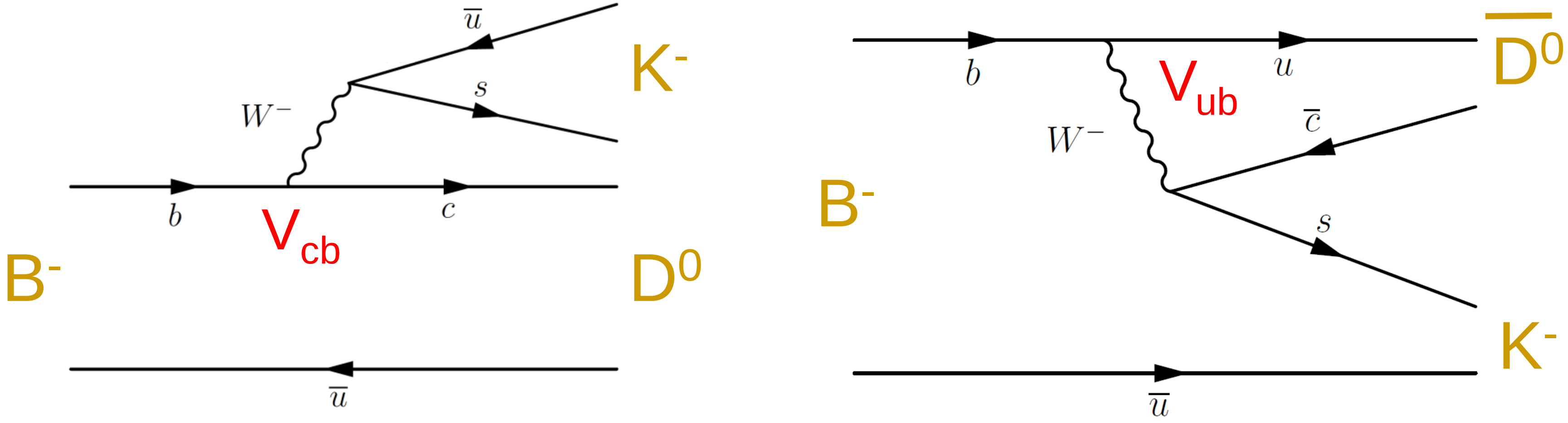
$$\gamma = (65.6\,^{+1.0}_{-3.4})^{\text{o}}$$

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

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

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

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



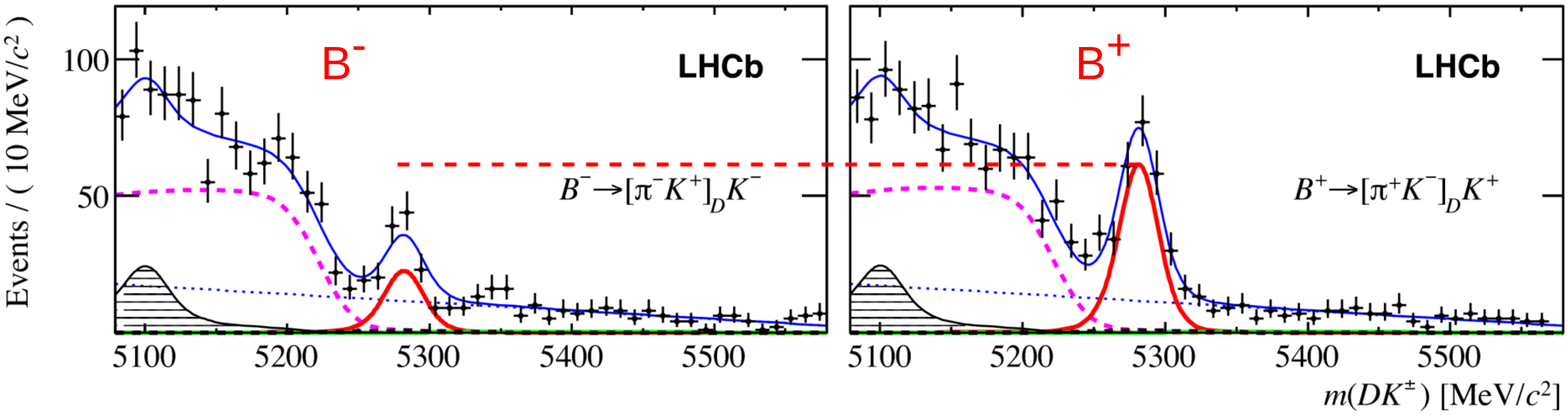
If we reconstruct D^0 and $\overline{D}^0$ in a state accessible to both, Interference occurs & decay rates become sensitive to relative phase between V_{cb} and V_{ub}, which is γ.

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

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

The Unitarity Triangle: measuring γ

To access these interference effects means looking for rather suppressed decays, *e.g.* this $B^- \rightarrow DK^-$ 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.



[PLB 760 (2016) 117]

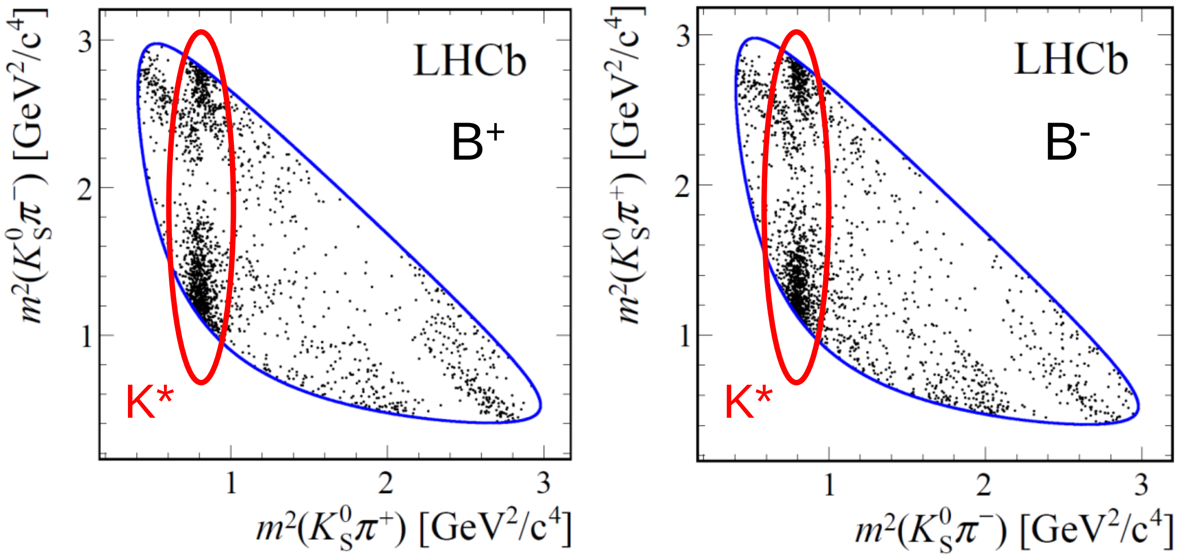
Very significant CP violation observed, that can be cleanly related to the phase γ.

γ measurement at LHCb with $B \to DK$ decays: $D \to K_S\pi\pi$ (and K_SKK) with Run 2 data

[JHEP 08 (2018) 176]

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

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



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

e.g. $D \to K^*(892)\pi$

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

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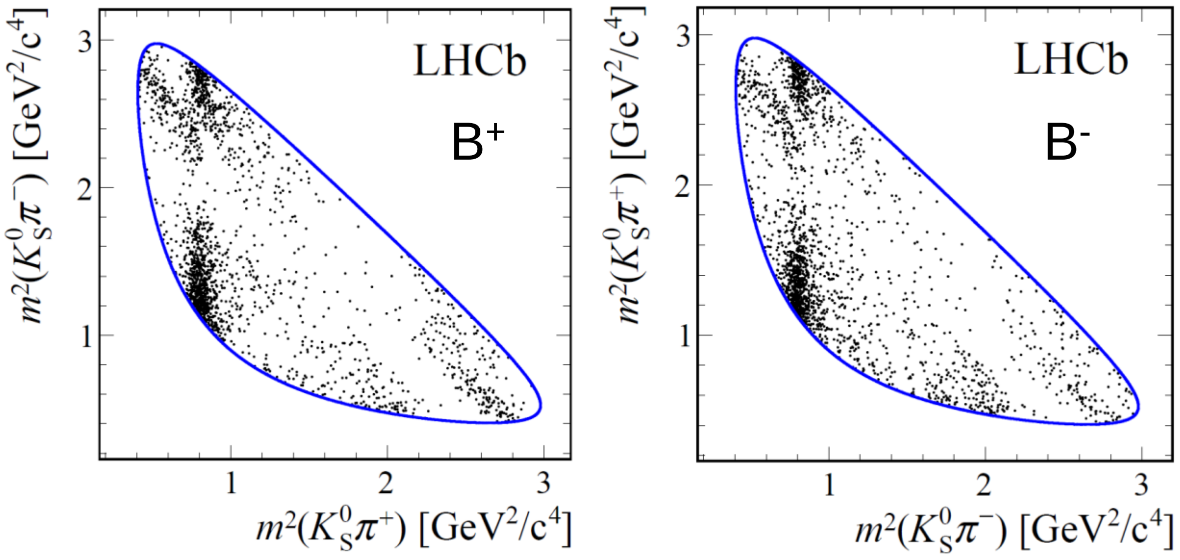
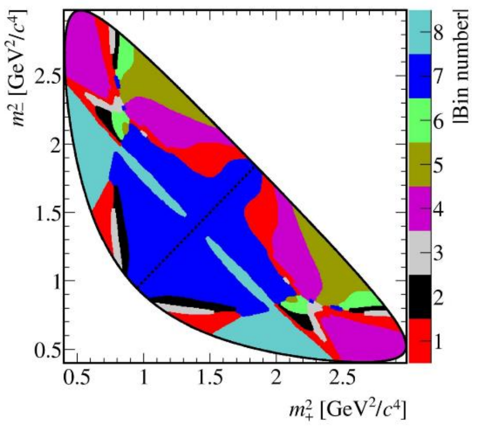


Study yields in *bins* of Dalitz space, chosen for optimal sensitivity.



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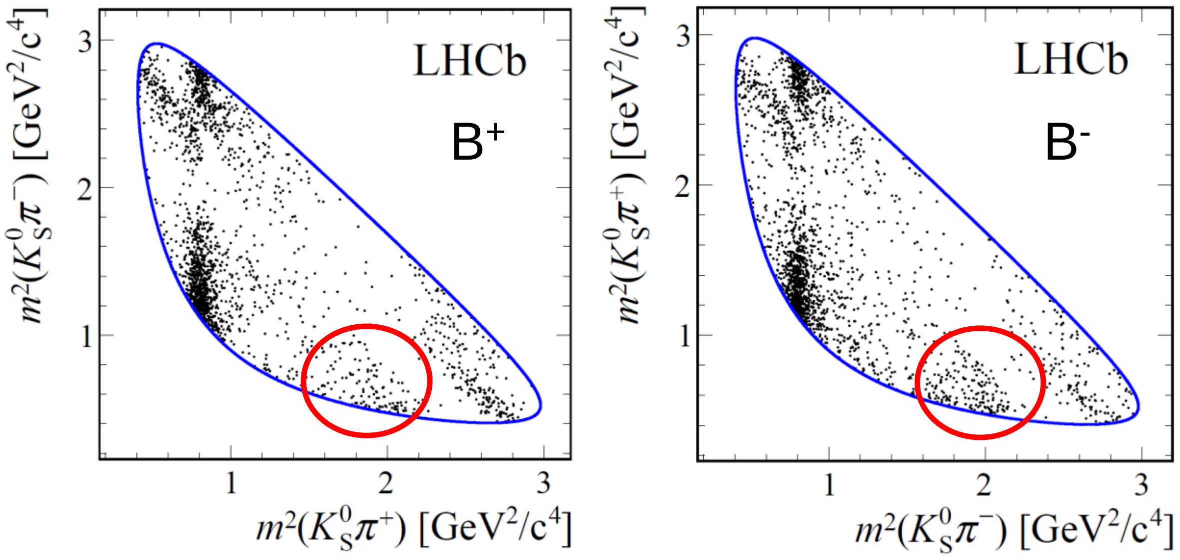

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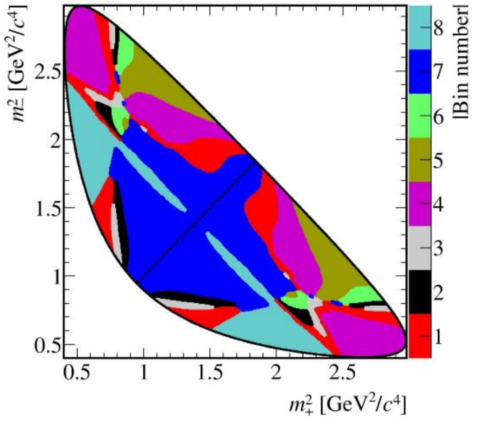
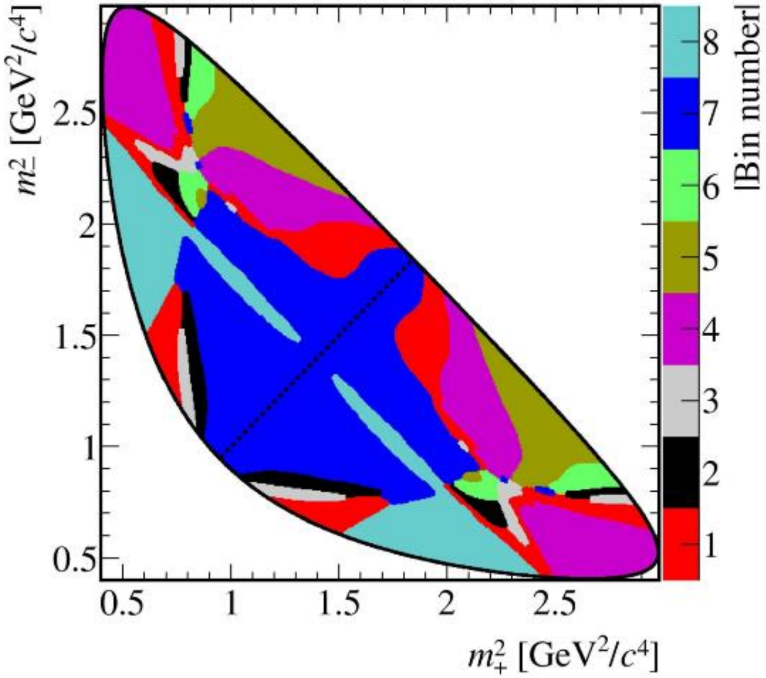


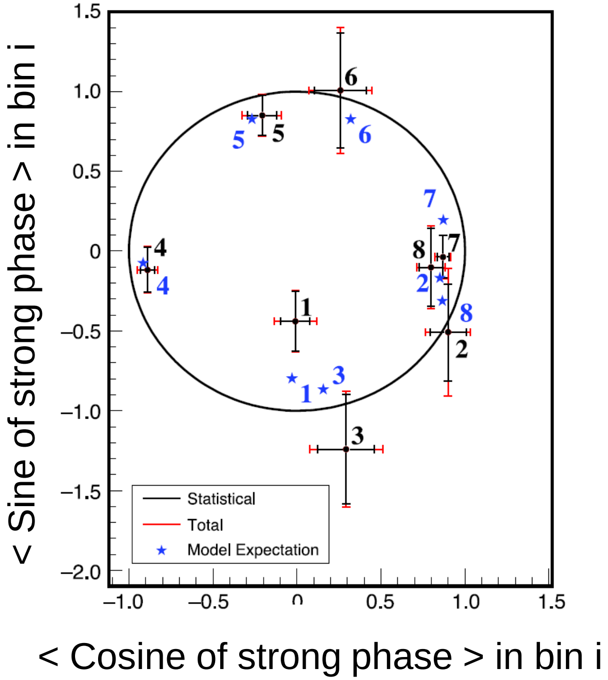
CP asymmetries visible by eye, but quantitative analysis requires external input...

Measuring γ – a synergy of experiments

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

This information can be measured in bins on the Dalitz plot from quantum-correlated ψ(3770)→DDbar events, available at CLEO-c [PRD 82 (2010) 112006].





CLEO-c data adequate for current LHCb sample sizes.

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

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

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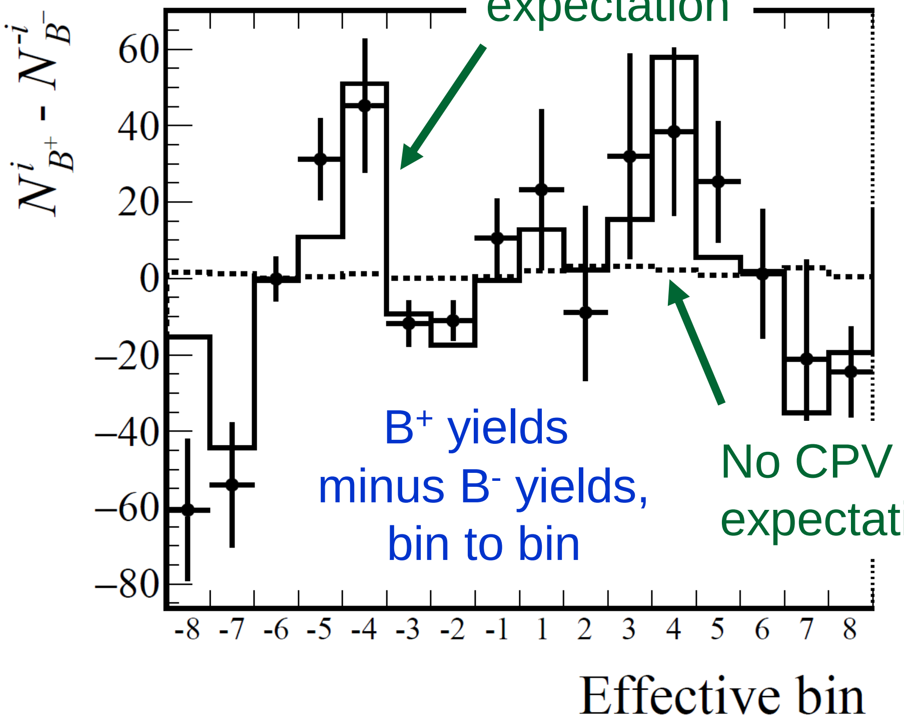
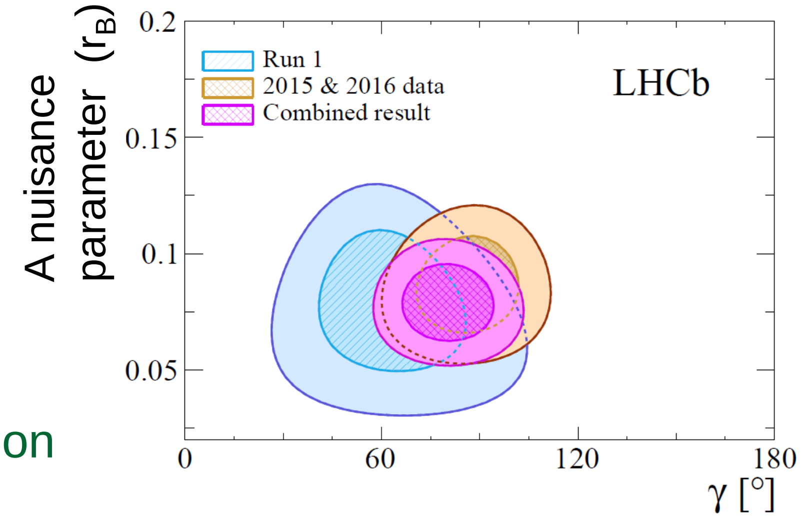


CPV expectation

B⁺ yields minus B⁻ yields, bin to bin

No CPV expectation

Compatible with Run 1 analysis of same channel



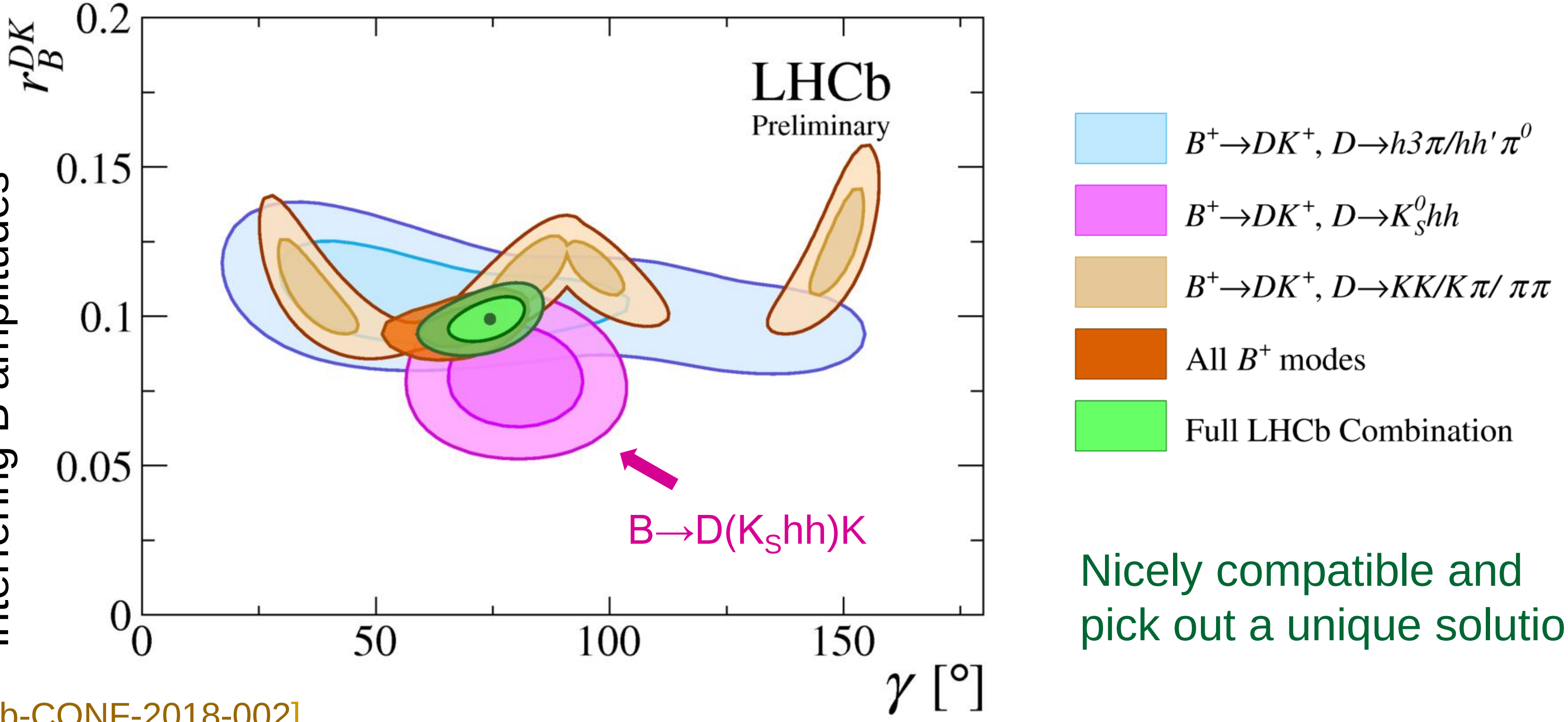
Together gives:

$$\gamma = 80^\circ\,{}^{+10^\circ}_{-9^\circ}$$

LHCb: combining B→DK modes for γ

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

Relative magnitude of interfering B amplitudes



B→D($K_S$hh)K

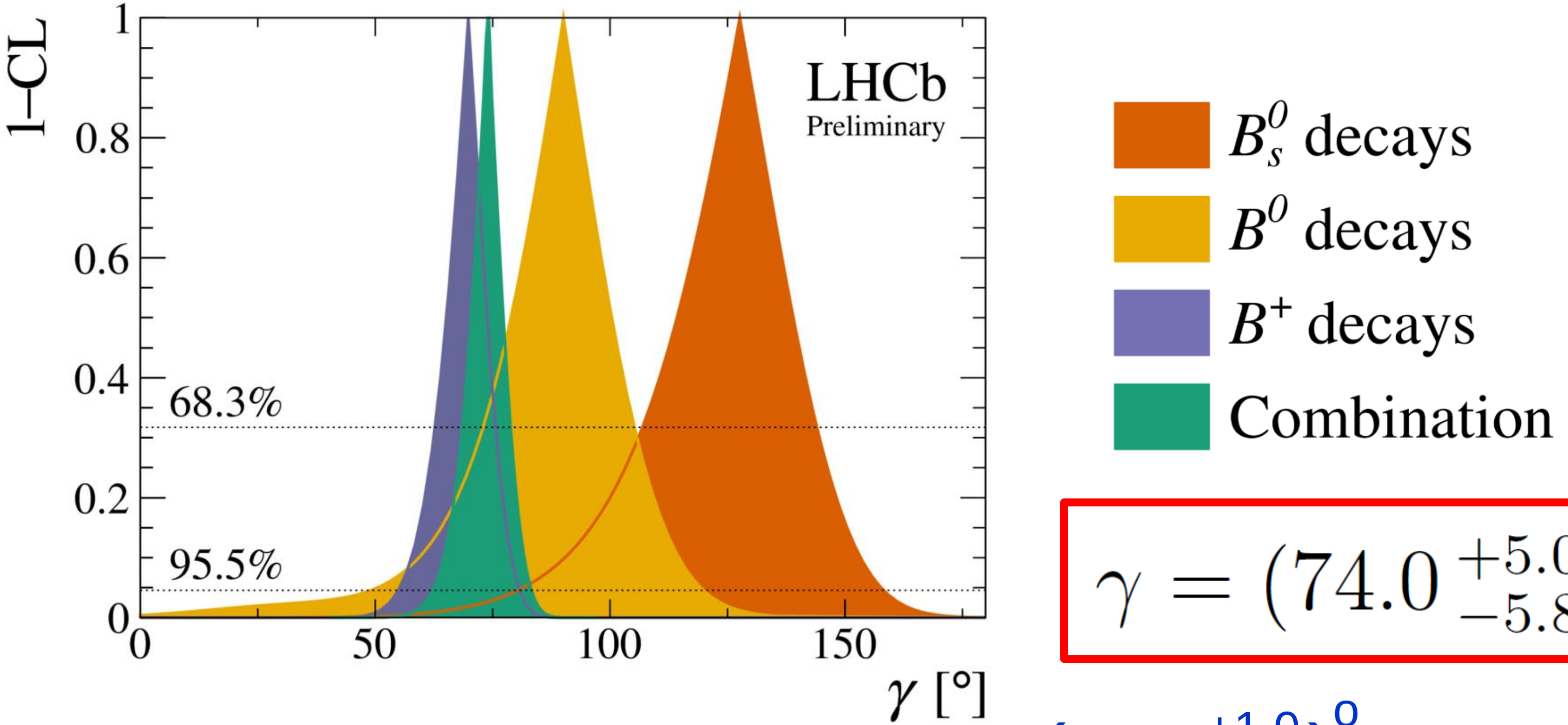
Nicely compatible and pick out a unique solution.

[LHCb-CONF-2018-002]

LHCb: current precision on γ

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

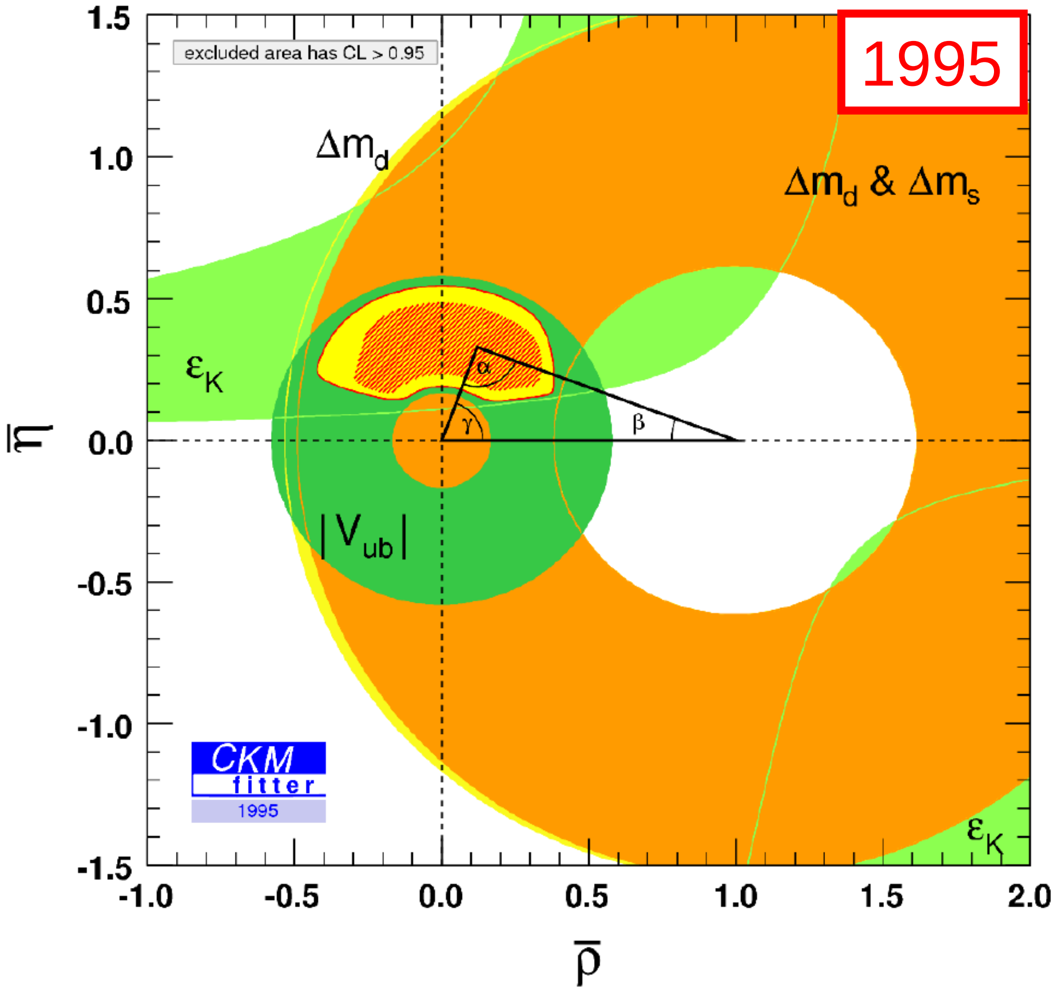
[LHCb-CONF-2018-002]



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

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

Unitarity Triangle: ~25 years of progress



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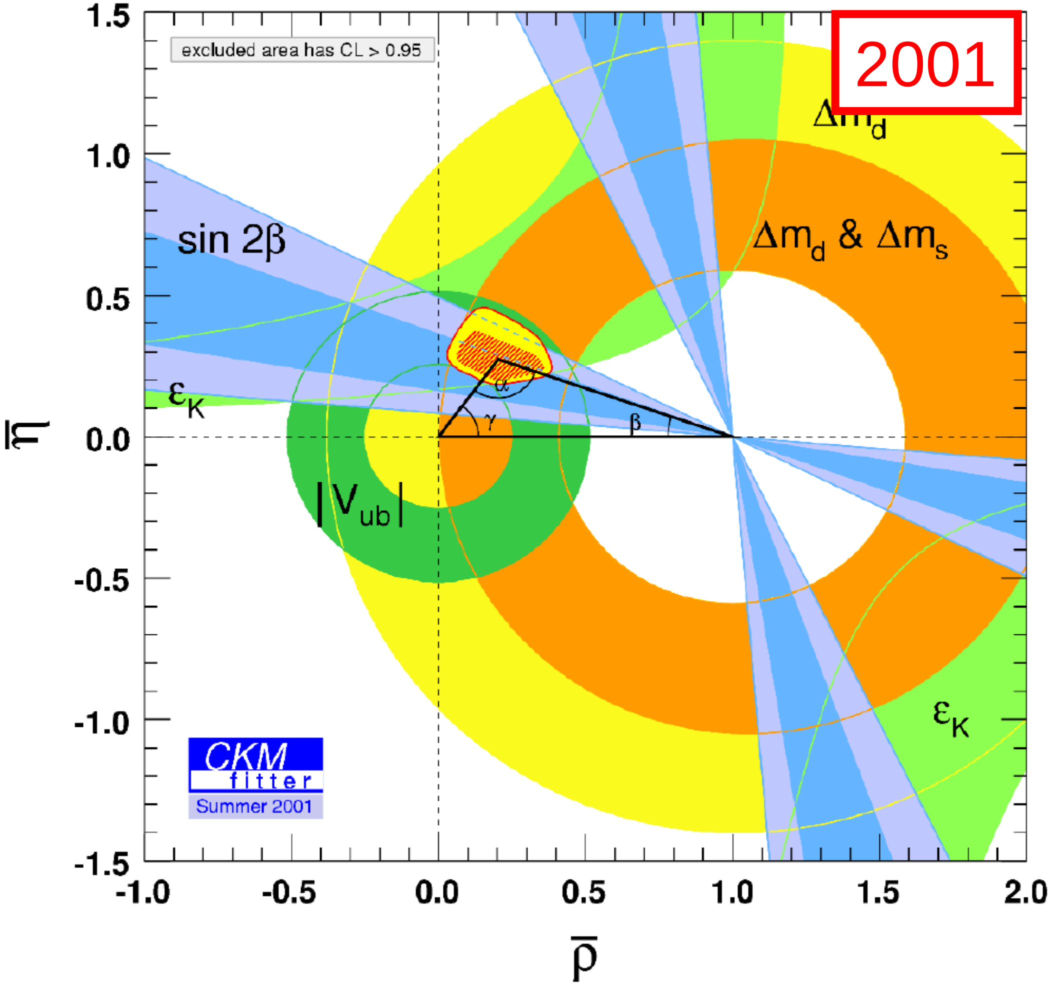

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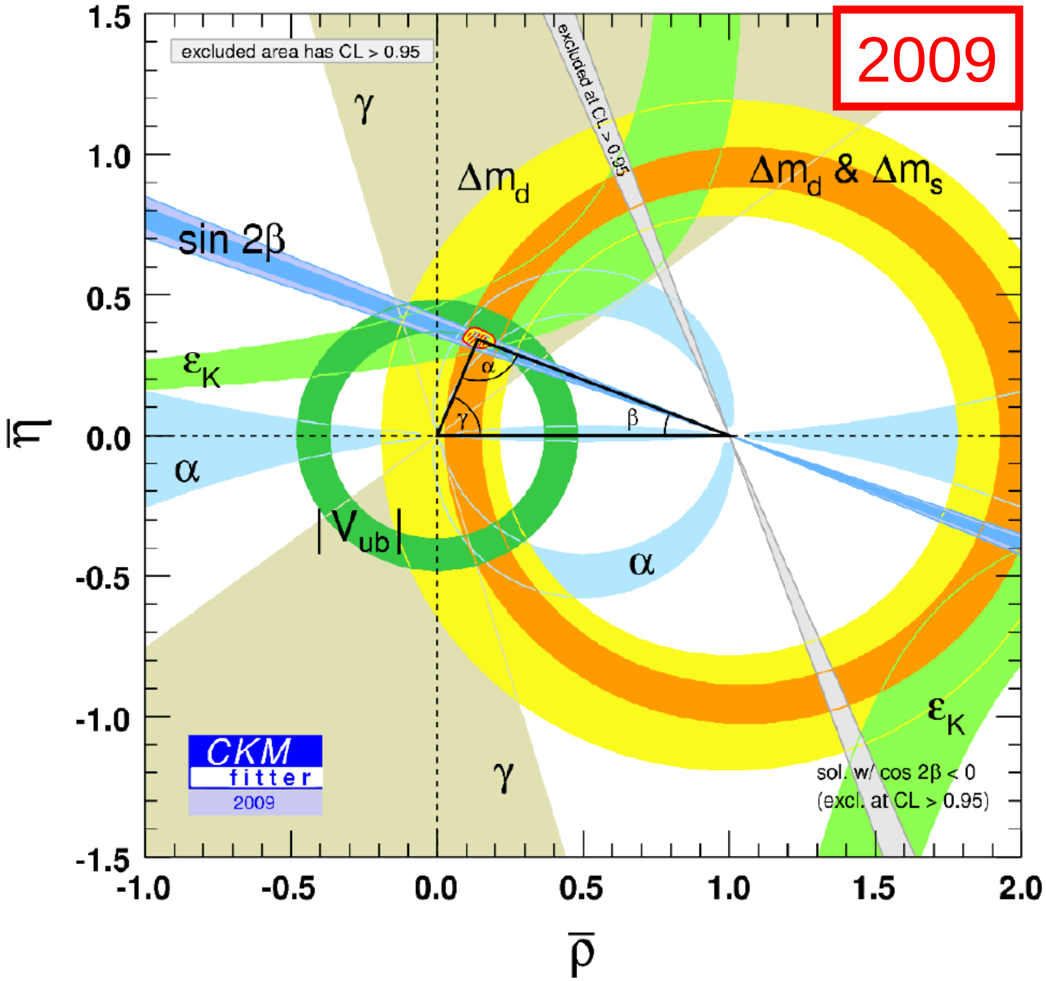

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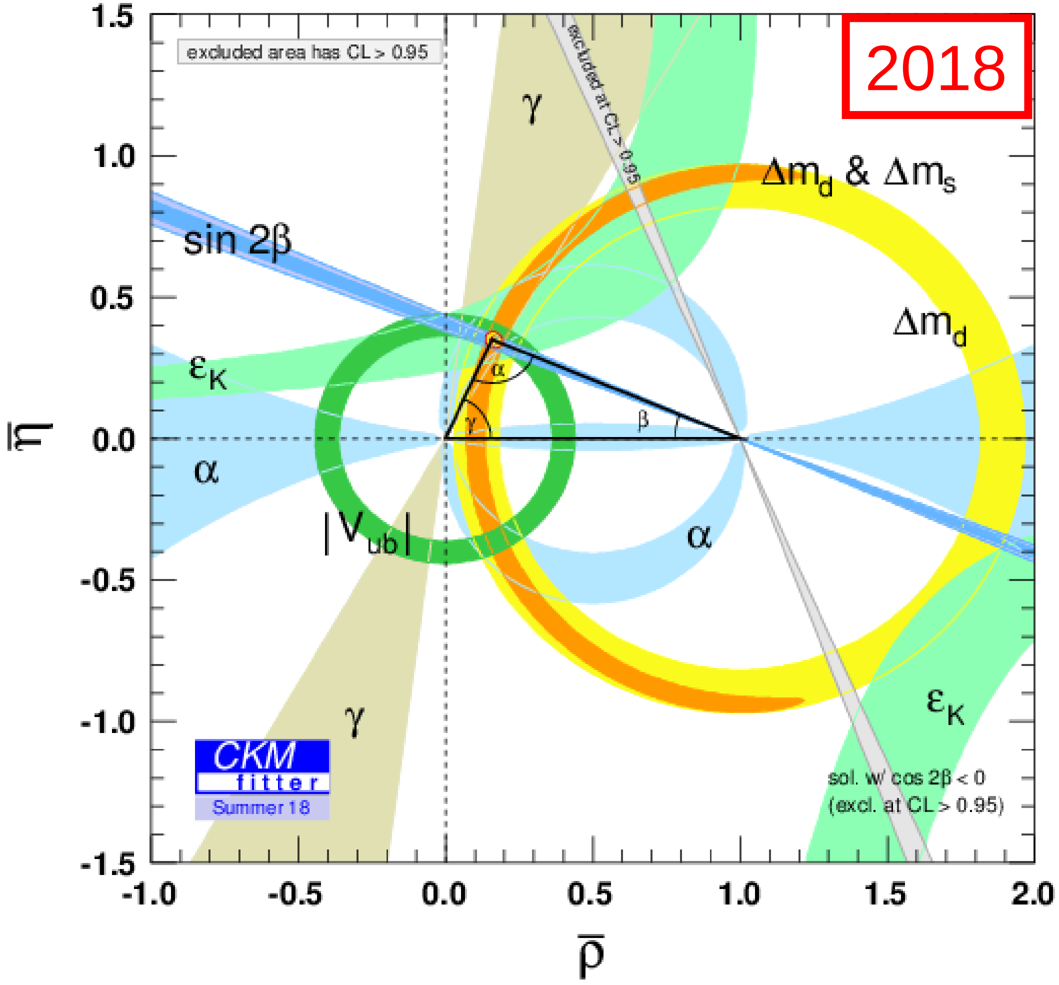
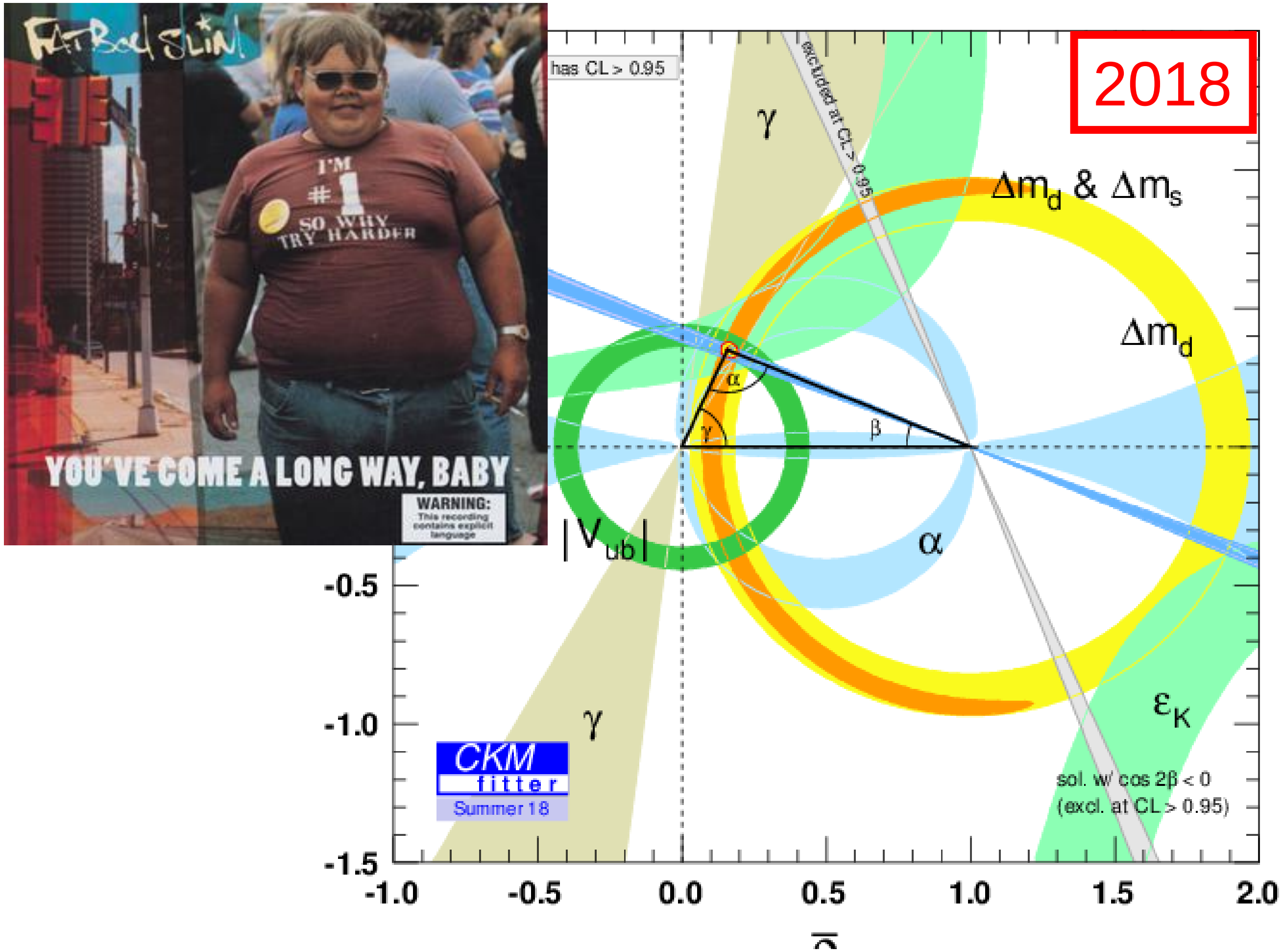


2018

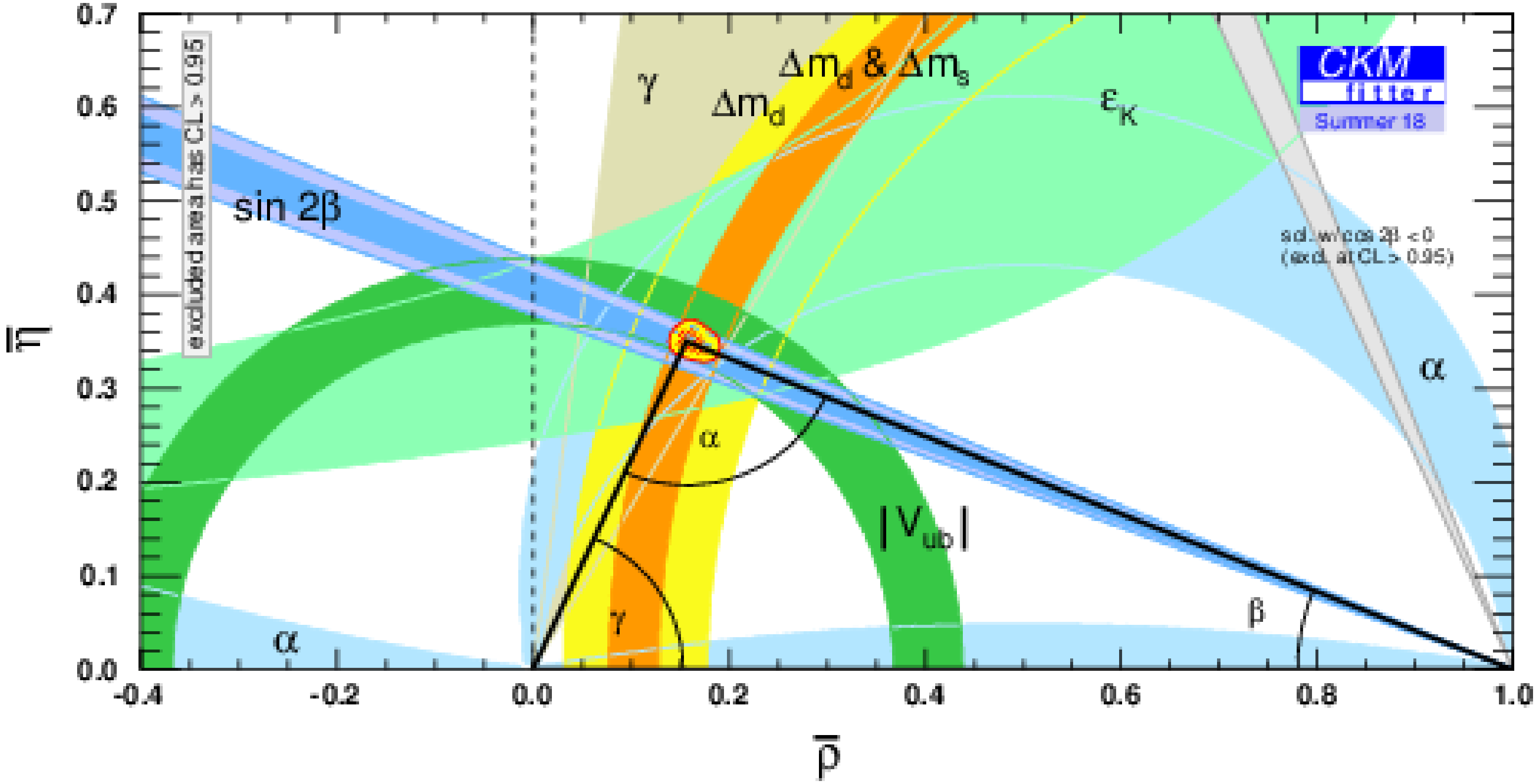
Unitarity Triangle: ~25 years of progress



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

Overall consistency of the Unitarity Triangle

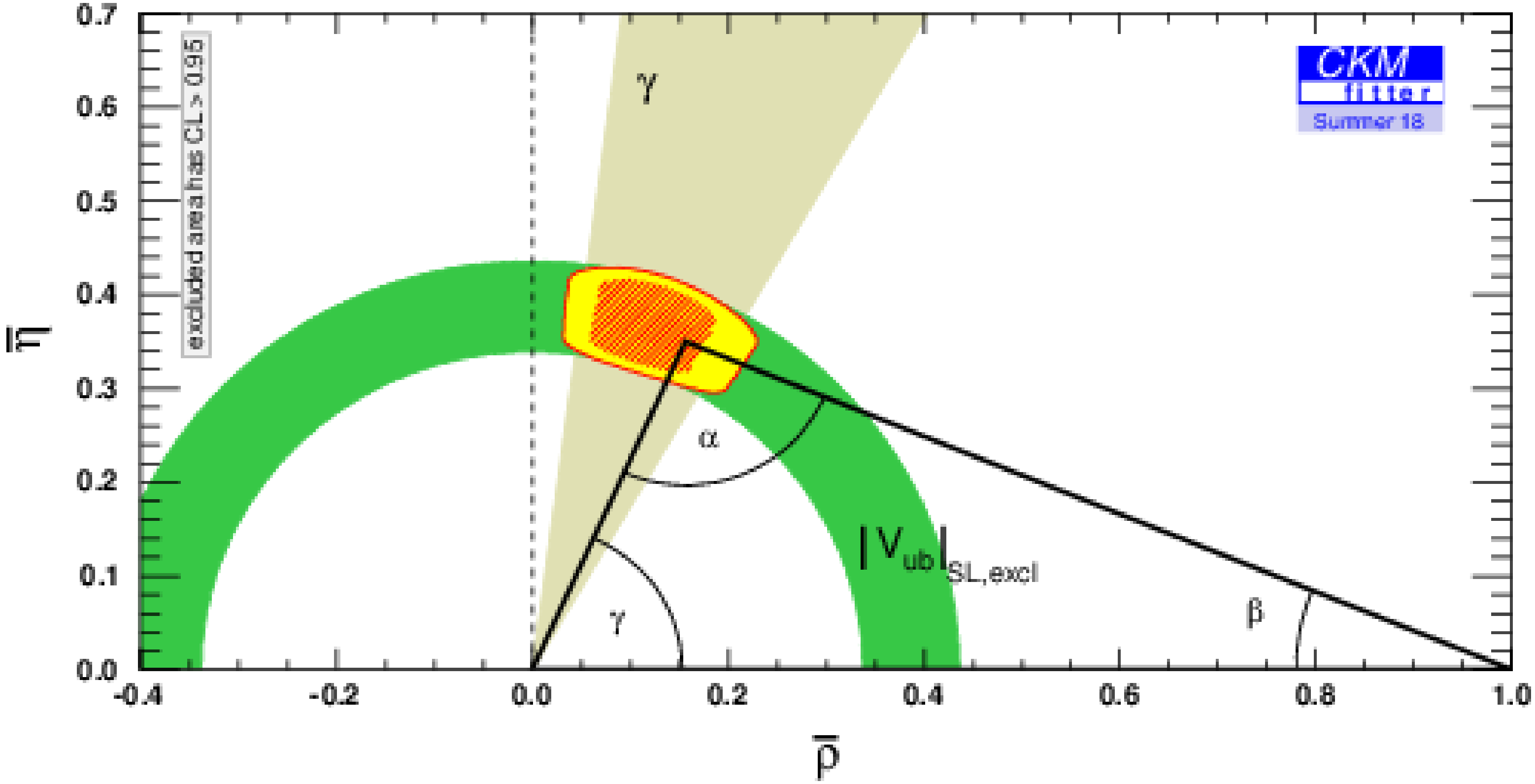
There is broad consistency between all current measurements of the UT. (But, a closer look can reveal intriguing tensions, *e.g.* [Blanke & Buras, EPJC 79 (2019) 159].)



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

Unitarity Triangle: tree-level observables

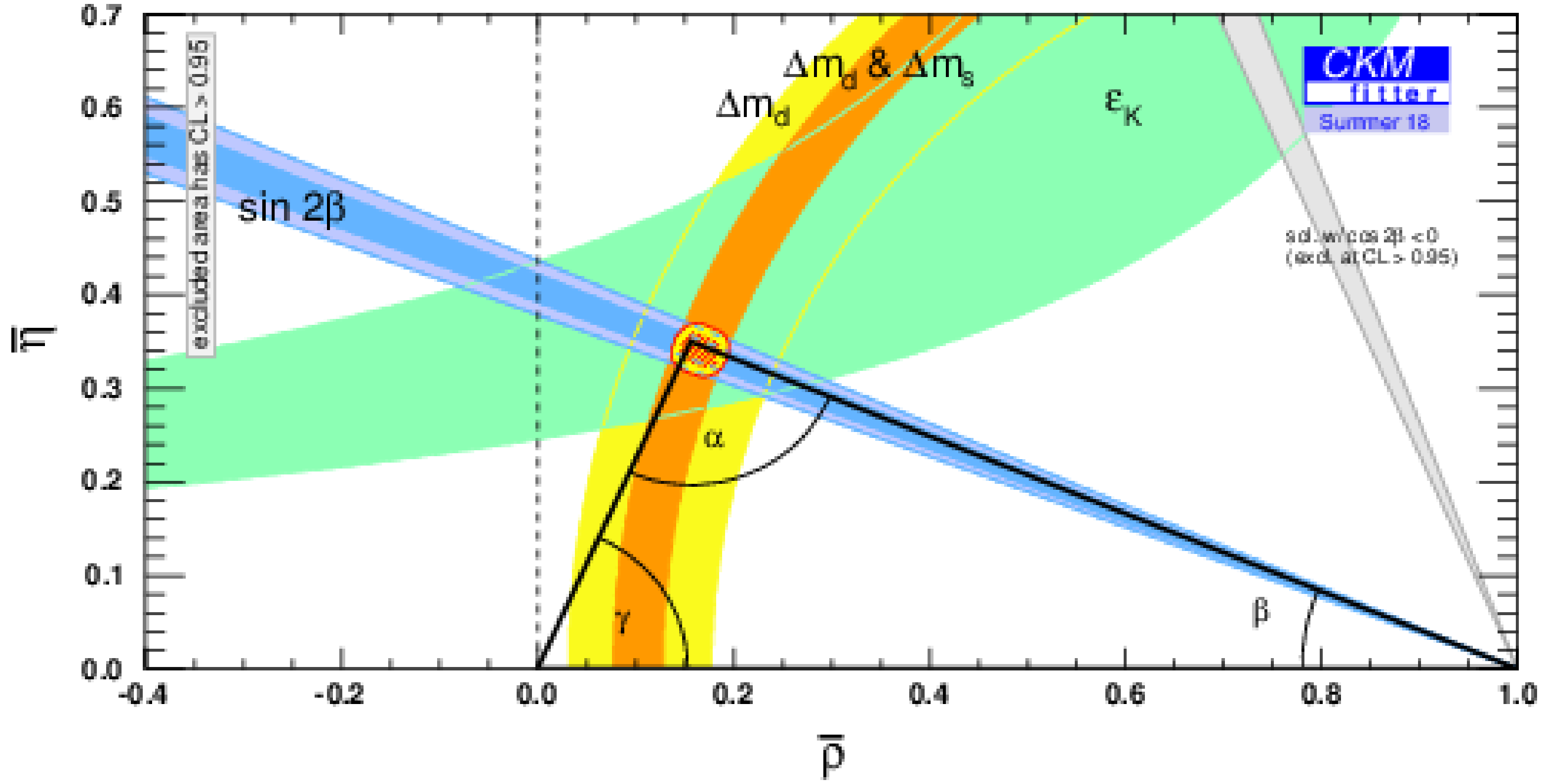
Unitarity Triangle formed from only tree-level quantities → assumed pure SM.



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

Unitarity Triangle: loop-level observables

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

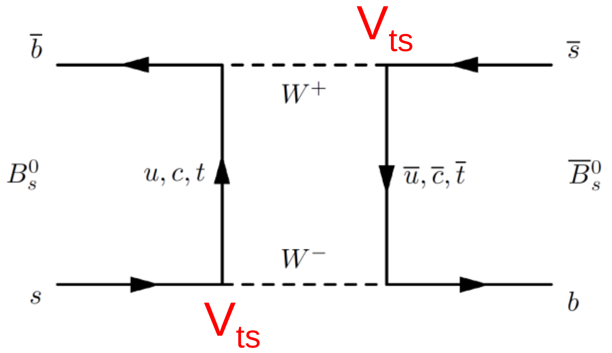


There is good consistency between the tree and loop measurements. There's a need to improve the precision of former to allow for a more sensitive comparison.

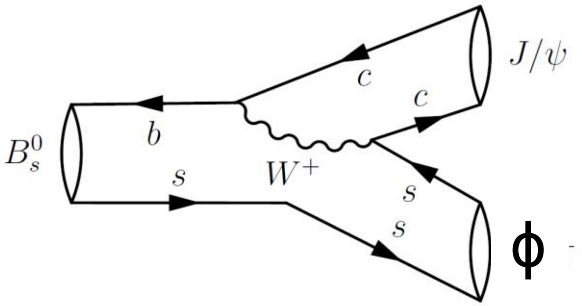
Indirect CPV in B$_s$ system: φ_s

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

Once more interference between mixing…



…and decay



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

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

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

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

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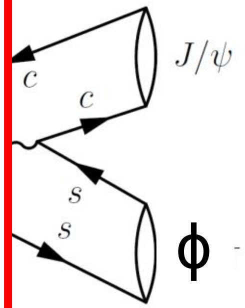
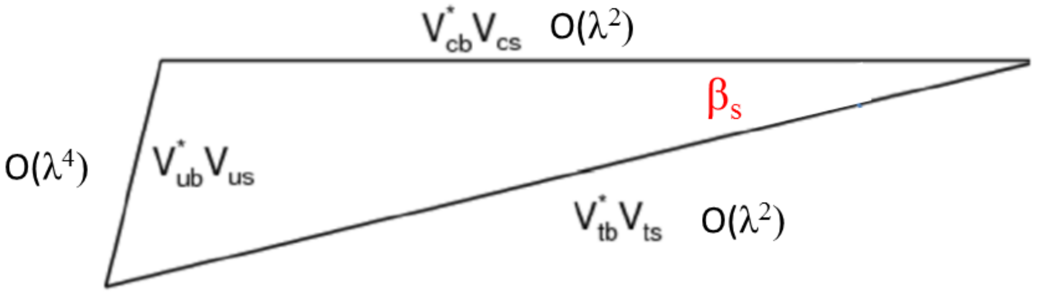


Recall the squashed B^0_s triangle:



In SM $\varphi_s = -2\beta_s$

Now we
elements
complex

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

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

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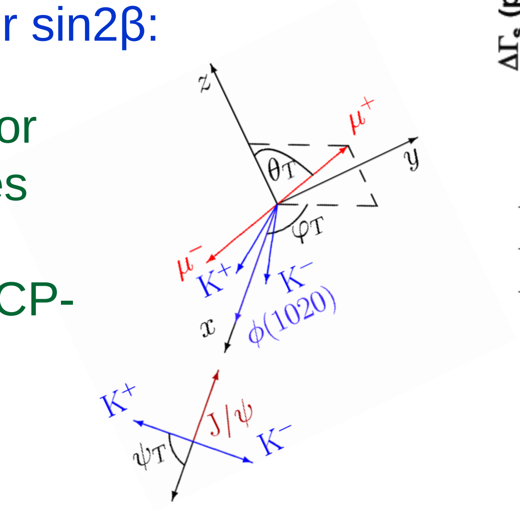
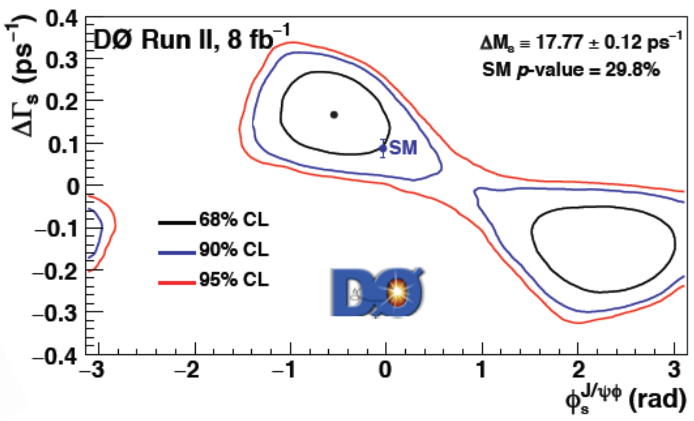
However the measurement is considerably trickier than is the case for sin2β:

- J/Ψφ is a vector-vector final state, so requires angular analysis to separate out CP+ & CP-

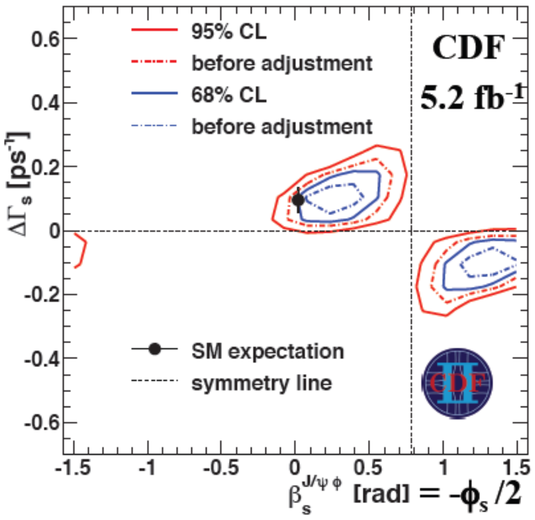


- Very fast oscillations ($\Delta m_s >> \Delta m_d$)
- Possibility of KK S-wave under φ

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



[PRD 85 (2012) 032006]



[PRD 85 (2012) 072002]

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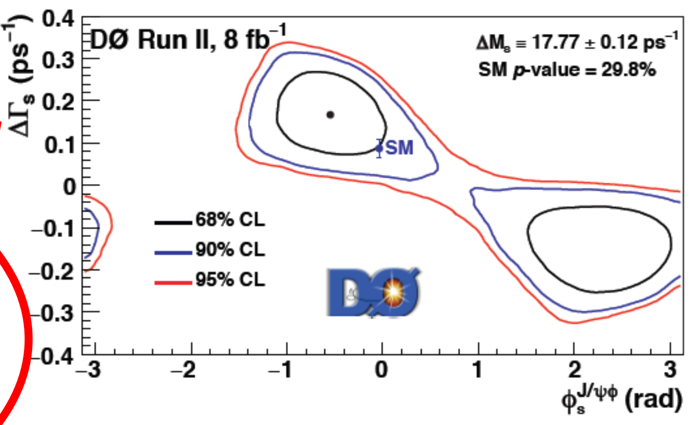
However the measurement is considerably trickier than is th

(Δm_s

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

- Possibility of KK S-wave under φ

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



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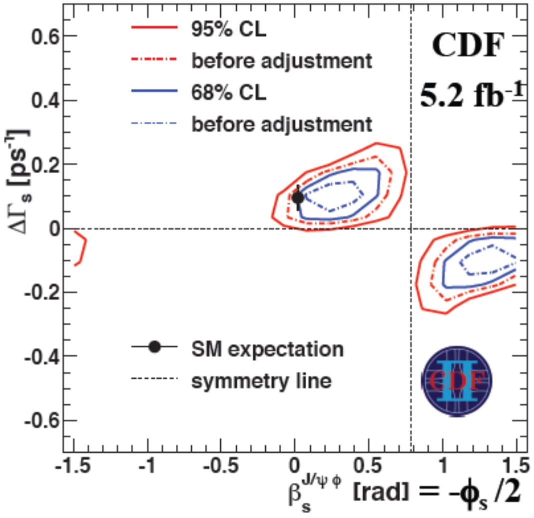
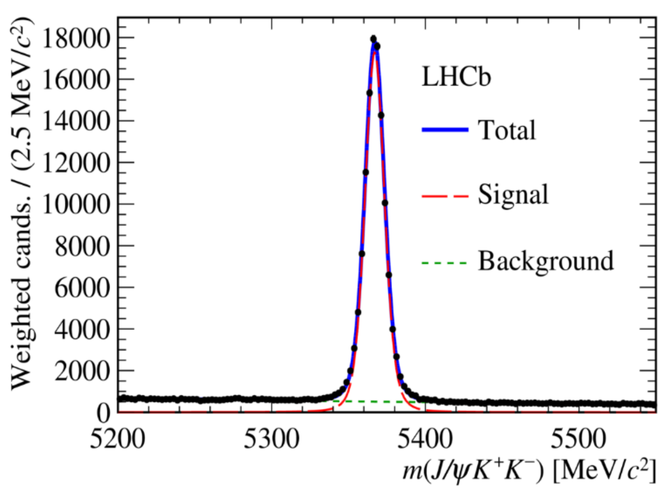


[PRD 85 (2012) 072002]

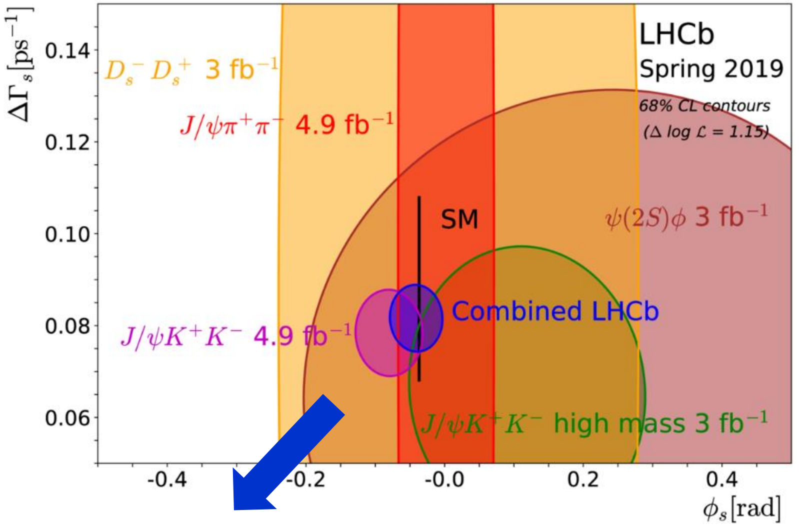
φ$_s$ – impact of LHCb

LHC has been able to go far beyond the Tevatron measurements, thanks to much larger yields, and (in case of LHCb) excellent proper time resolution, & access to complementary modes beyond J/ψφ (*e.g.* $B_s \rightarrow J/\psi\pi\pi$ pursued in [PLB 713 (2012) 378] .)

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



Results for early Run 2 J/ψφ study, together with Run 1 measurements.



[EPJC 79 (2019) 706]

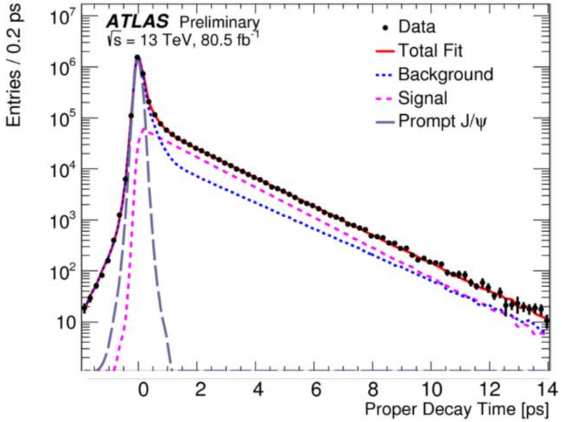
$$\phi_s = -0.041 \pm 0.025\,\mathrm{rad} \qquad \Delta\Gamma_s = 0.0816 \pm 0.0048\,\mathrm{ps}^{-1}$$

Measurement of φ_s at ATLAS and CMS

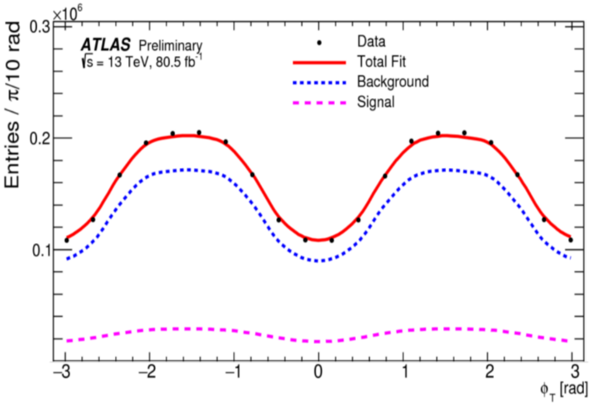
Measurement of φ_s is an key goal of the ATLAS and CMS flavour physics programme, enabled by excellent detector performance and J/Ψ→μμ trigger.

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

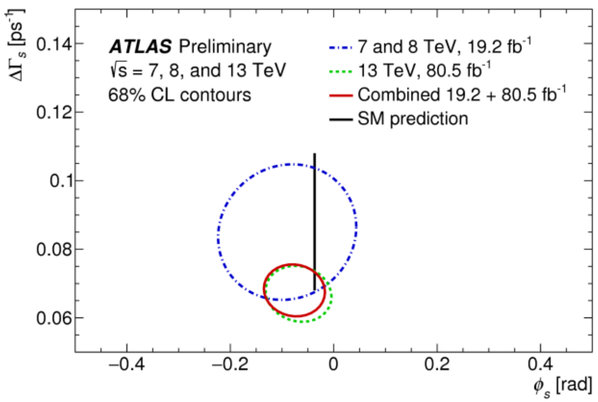
Proper decay time



Transversity angle φ_T



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



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

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

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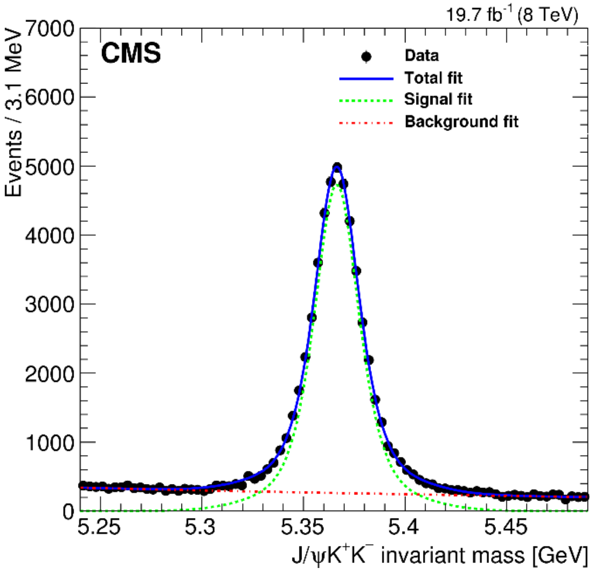
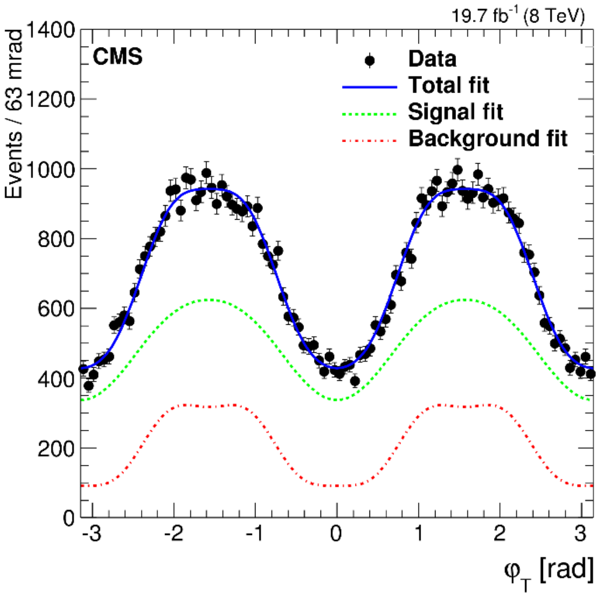
e.g. CMS $B_s\rightarrow J/\Psi\varphi$ 8 TeV analysis [PLB 757 (2016) 97]

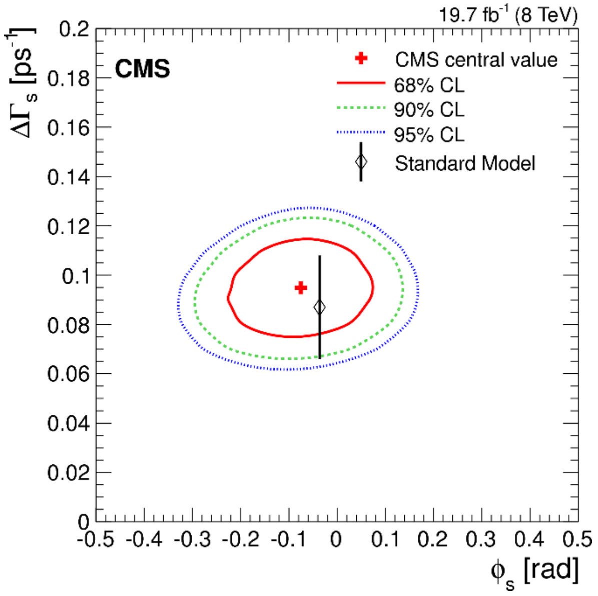
Invariant mass



Transversity angle φ_T

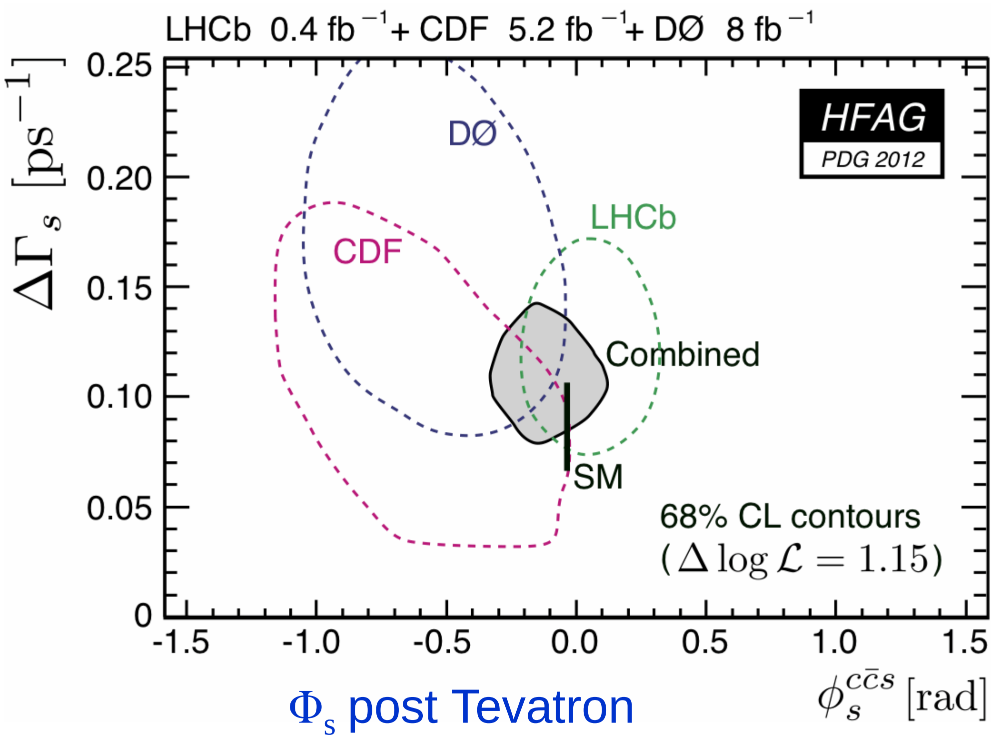


Result contours



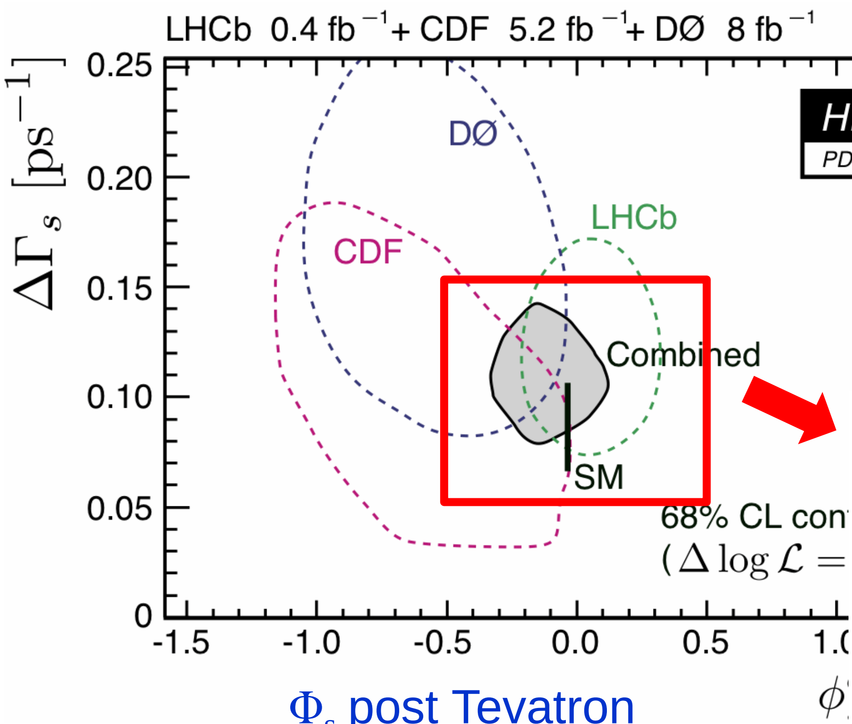
$$\boxed{\begin{aligned}\phi_s &= -0.075 \pm 0.097\,(\text{stat}) \pm 0.031\,(\text{syst})\,\text{rad},\\ \Delta\Gamma_s &= 0.095 \pm 0.013\,(\text{stat}) \pm 0.007\,(\text{syst})\,\text{ps}^{-1}.\end{aligned}}$$

φ_s : the impact of the LHC



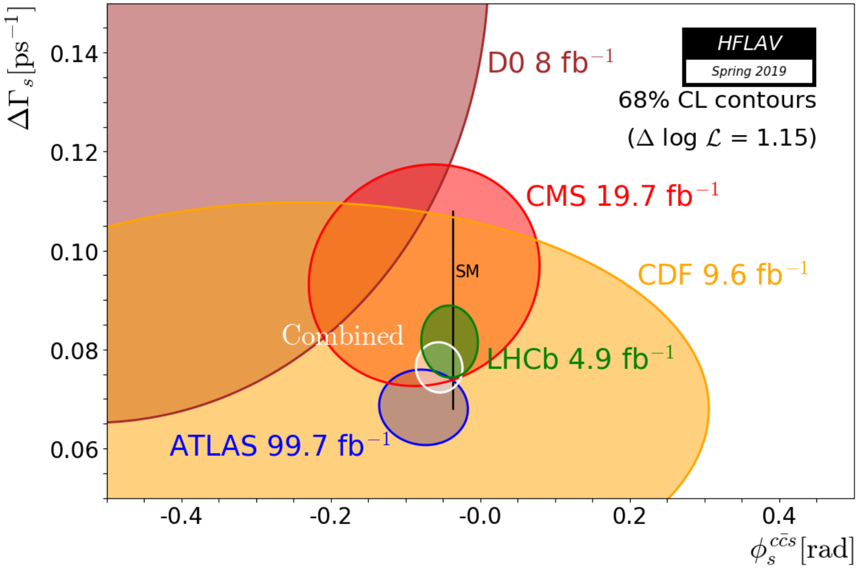
Φ_s post Tevatron
and early LHC data

φ_s : the impact of the LHC

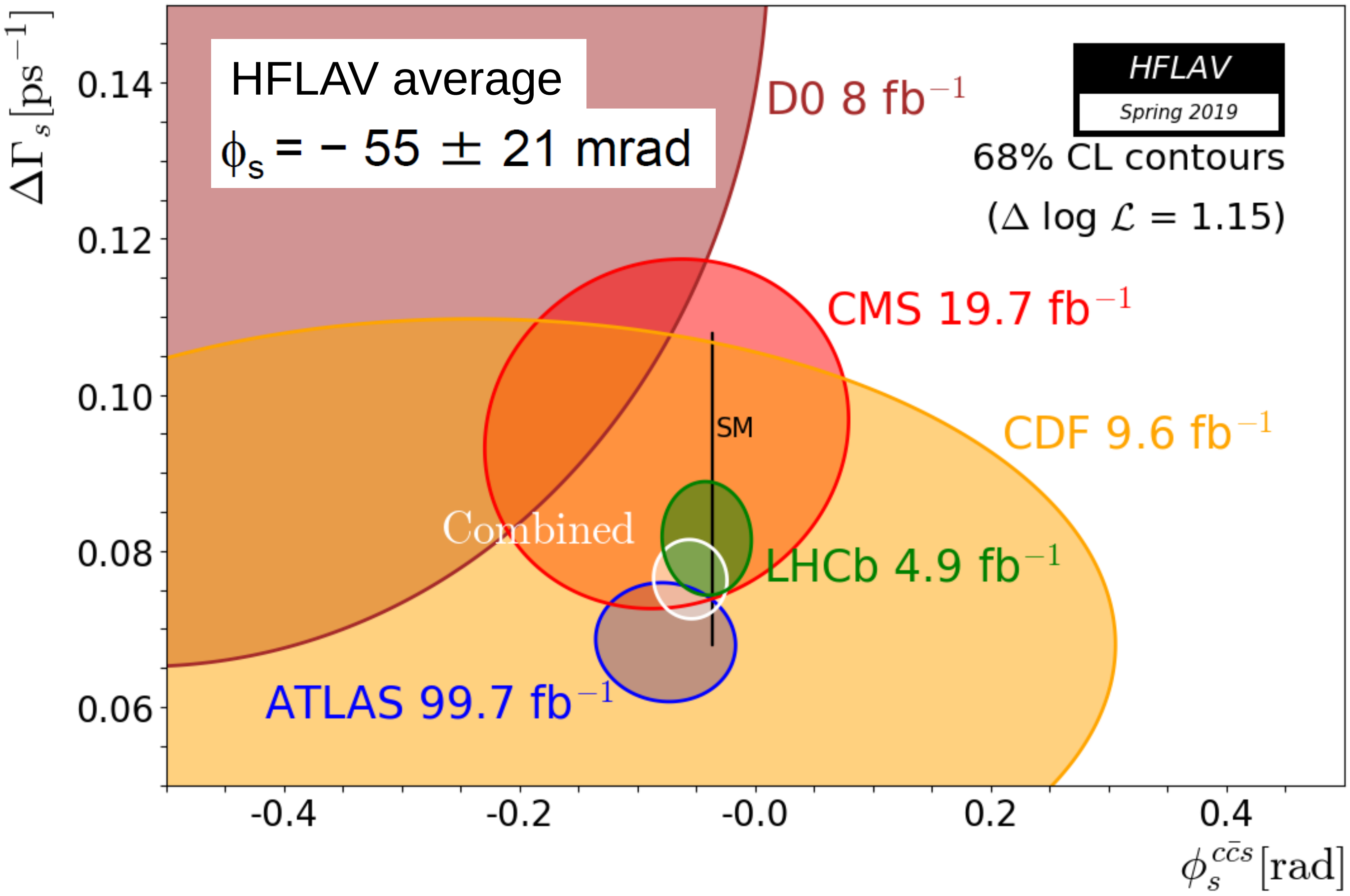


Φ_s post Tevatron
and early LHC data

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



φ_s : the current state of play



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

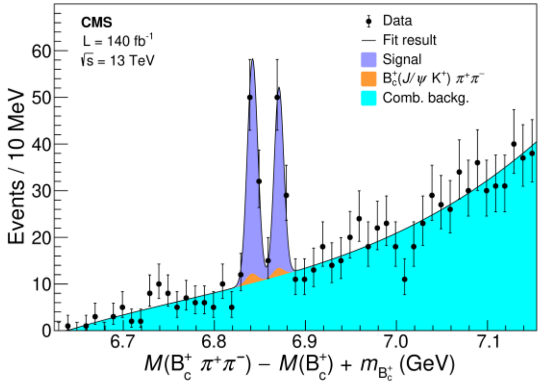
Spectroscopy (a digression)

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

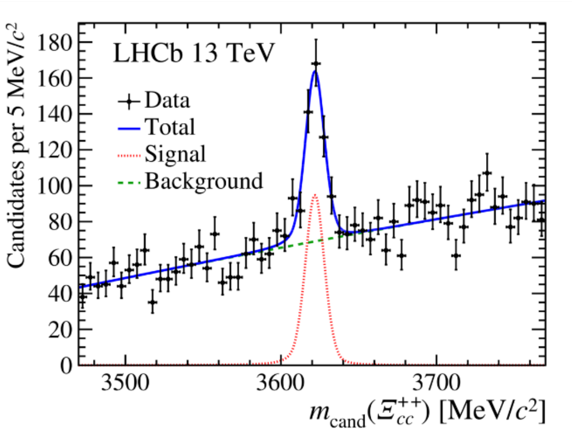
Spectroscopy - the conventional

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

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



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



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

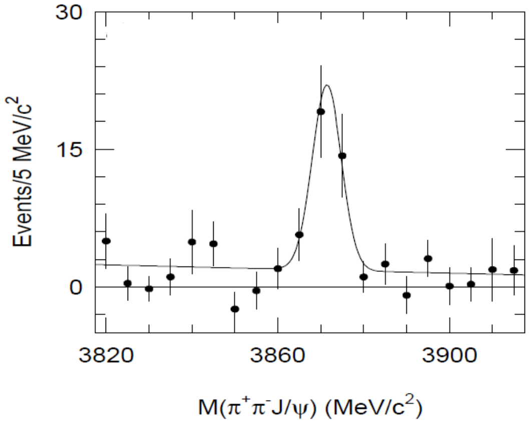
Murray Gell-Mann

Spectroscopy - the exotic

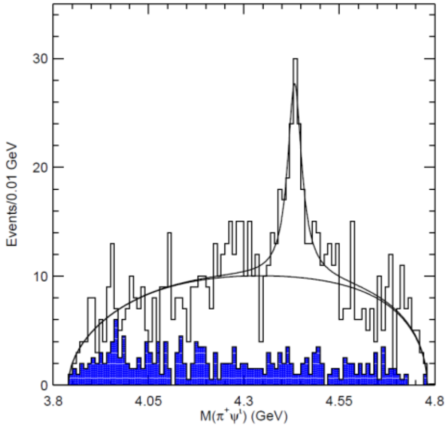
Other states, many discovered in e^+e^-, are good candidates to be 'exotic':

Both are strong candidates to be four-quark states

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



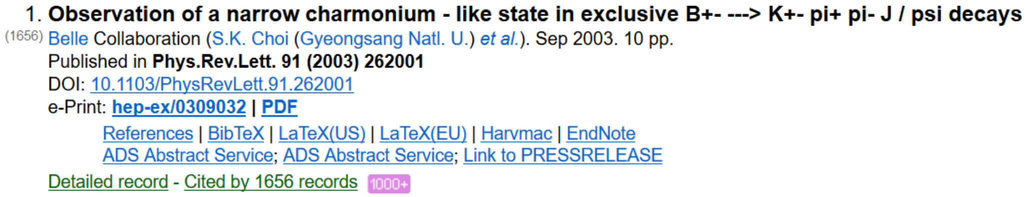
Observation of the $Z(4430)^+$ at Belle [PRL 100 (2008) 142001]



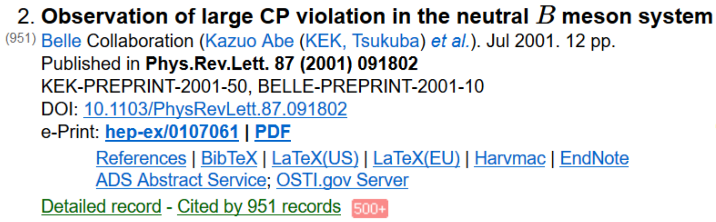
> Baryons can now be constructed from quarks by using the combinations qqq, $qqq\bar{q}q$, etc, while mesons are made out of $q\bar{q}$, $q\bar{q}q\bar{q}$, etc.
>
> **Murray Gell-Mann**

Spectroscopy results – provoke great interest among physicists

Top cited Belle physics papers

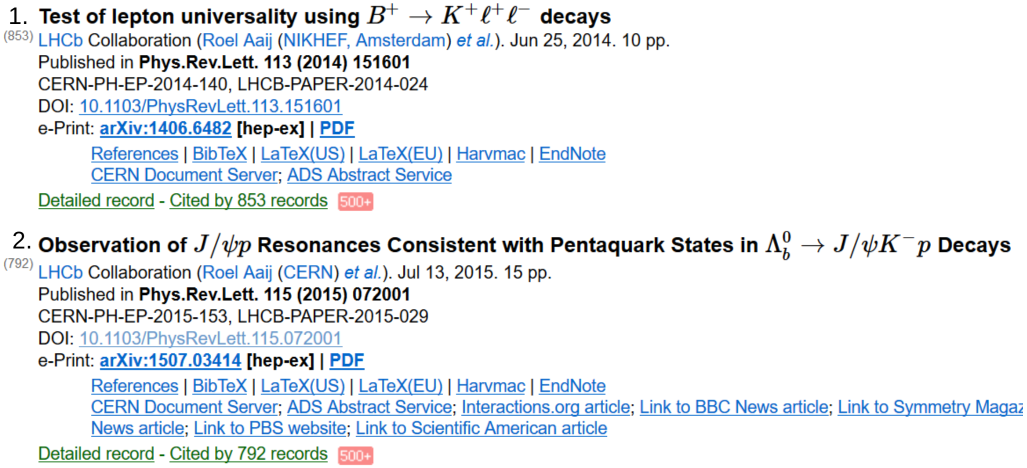


1. **Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays**
(1656) Belle Collaboration (S.K. Choi (Gyeongsang Natl. U.) *et al.*). Sep 2003. 10 pp.
Published in **Phys.Rev.Lett. 91 (2003) 262001**
DOI: 10.1103/PhysRevLett.91.262001
e-Print: **hep-ex/0309032**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



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

Top cited LHCb physics papers

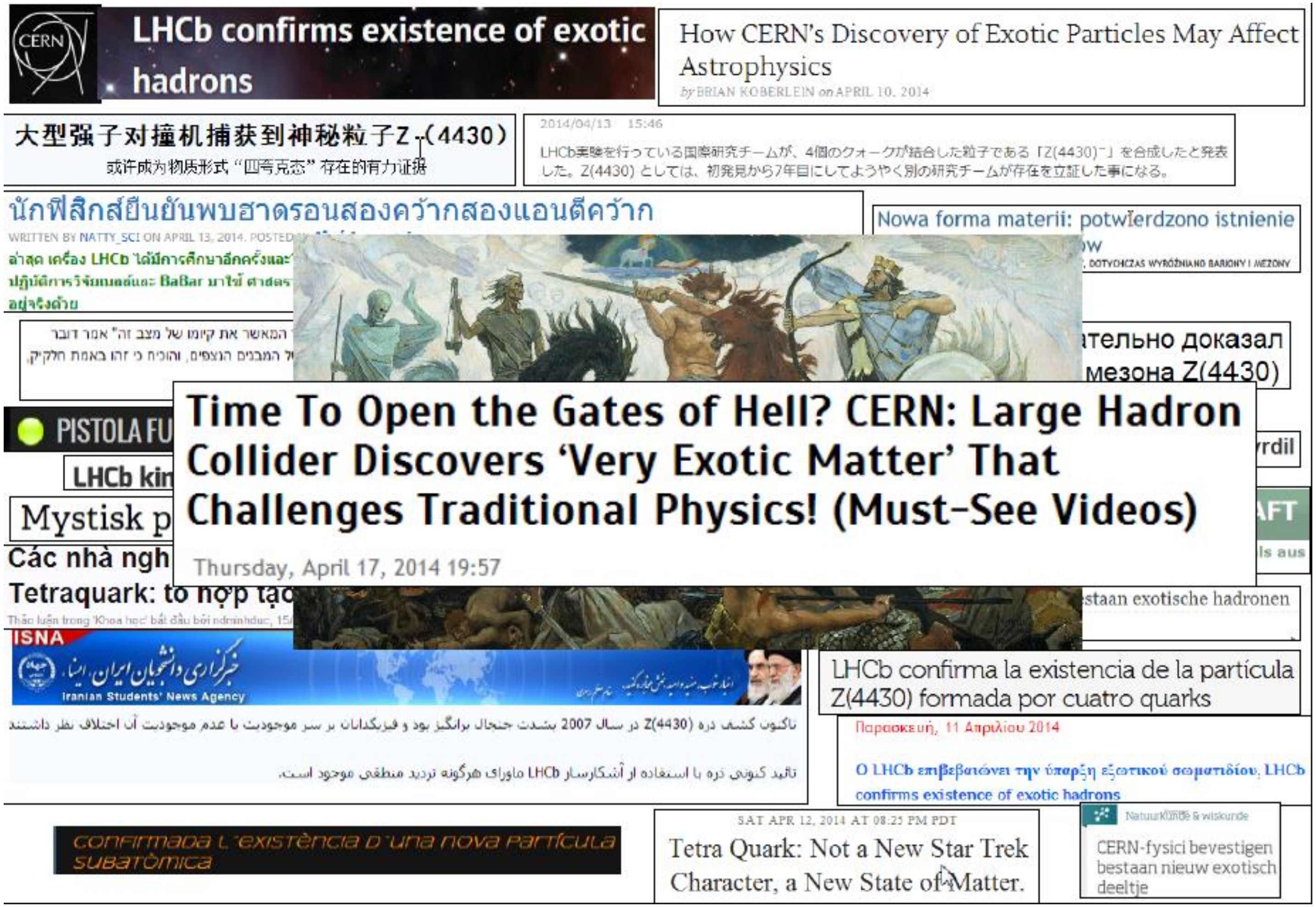


1. **Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays**
(853) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Jun 25, 2014. 10 pp.
Published in **Phys.Rev.Lett. 113 (2014) 151601**
CERN-PH-EP-2014-140, LHCB-PAPER-2014-024
DOI: 10.1103/PhysRevLett.113.151601
e-Print: **arXiv:1406.6482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

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

Spectroscopy results – provoke great interest among public too

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



LHCb confirms existence of exotic hadrons

How CERN's Discovery of Exotic Particles May Affect Astrophysics

by BRIAN KOBERLEIN on APRIL 10, 2014

大型强子对撞机捕获到神秘粒子Z-(4430)

或许成为物质形式"四夸克态"存在的有力证据

2014/04/13 15:46

LHCb実験を行っている国際研究チームが、4個のクォークが結合した粒子である「Z(4430)⁻」を合成したと発表した。Z(4430) としては、初発見から7年目にしてようやく別の研究チームが存在を立証した事になる。

นักฟิสิกส์ยืนยันพบฮาดรอนสองคว้ากสองแอนตีคว้าก

WRITTEN BY NATTY_SCI ON APRIL 13, 2014. POSTED

ล่าสุด เครื่อง LHCb ได้มีการศึกษาอีกครั้งและ

ปฏิบัติการวิจัยเบลล์และ BaBar มาใช้ ศาสตร

อยู่จริงด้วย

Nowa forma materii: potwierdzono istnienie

ów

, DOTYCHCZAS WYRÓŻNIANO BARIONY I MEZONY

המאשר את קיומו של מצב זה" אמר דובר

של המבנים הנצפים, והוכיח כי זהו באמת חלקיק.

ательно доказал

мезона Z(4430)

PISTOLA FU

LHCb kin

Mystisk p

Các nhà ngh

Tetraquark: tổ hợp tạo

Thảo luận trong 'Khoa học' bắt đầu bởi ndminhduc, 15/

Time To Open the Gates of Hell? CERN: Large Hadron Collider Discovers 'Very Exotic Matter' That Challenges Traditional Physics! (Must-See Videos)

Thursday, April 17, 2014 19:57

rdil

AFT

ls aus

staan exotische hadronen

ISNA

خبرگزاری دانشجویان ایران، ایسنا

Iranian Students' News Agency

تاکنون کشف ذره (Z(4430 در سال 2007 بشدت جنجال برانگیز بود و فیزیکدانان بر سر موجودیت یا عدم موجودیت آن اختلاف نظر داشتند

تائید کنونی ذره با استفاده از آشکارساز LHCb ماورای هرگونه تردید منطقی موجود است.

LHCb confirma la existencia de la partícula Z(4430) formada por cuatro quarks

Παρασκευή, 11 Απριλίου 2014

Ο LHCb επιβεβαιώνει την ύπαρξη εξωτικού σωματιδίου, LHCb confirms existence of exotic hadrons

Confirmada l'existència d'una nova partícula subatòmica

SAT APR 12, 2014 AT 08:25 PM PDT

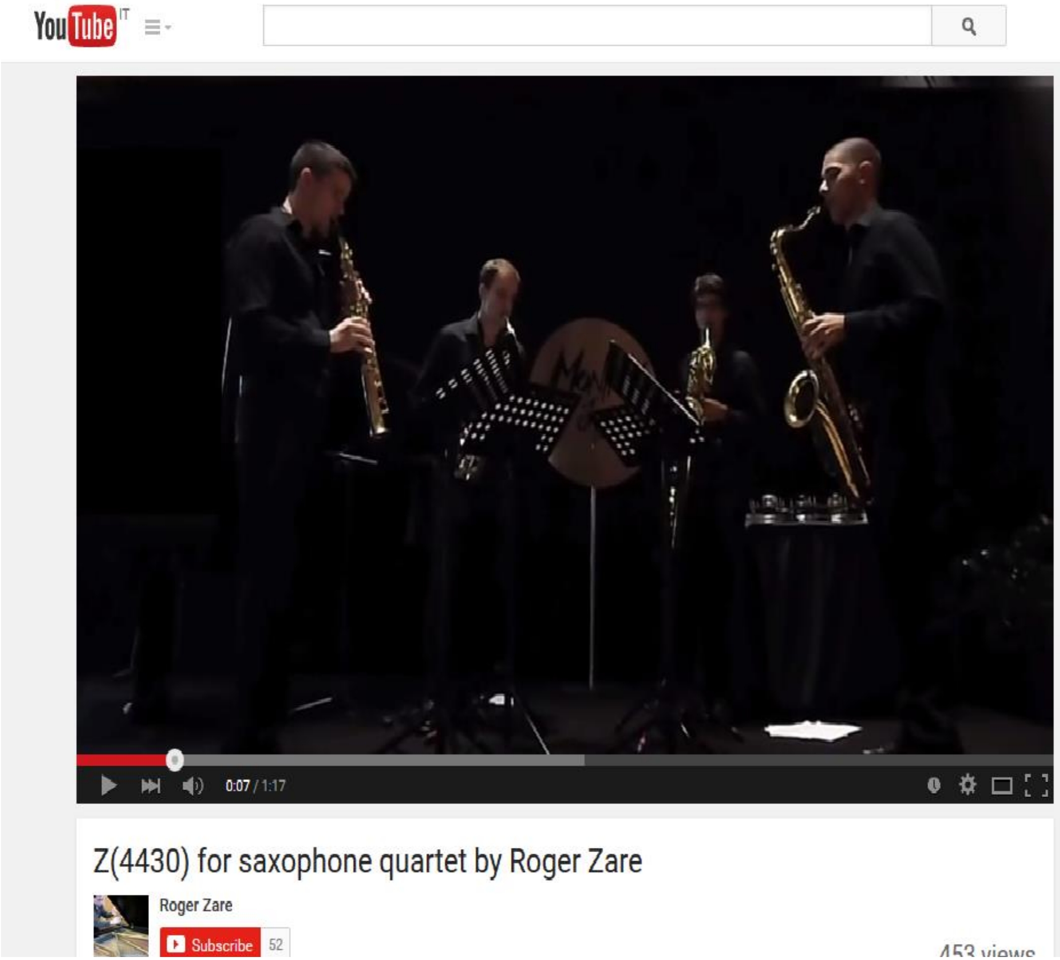
Tetra Quark: Not a New Star Trek Character, a New State of Matter.

Natuurkunde & wiskunde

CERN-fysici bevestigen bestaan nieuw exotisch deeltje

Spectroscopy results – provoke great interest among public too

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



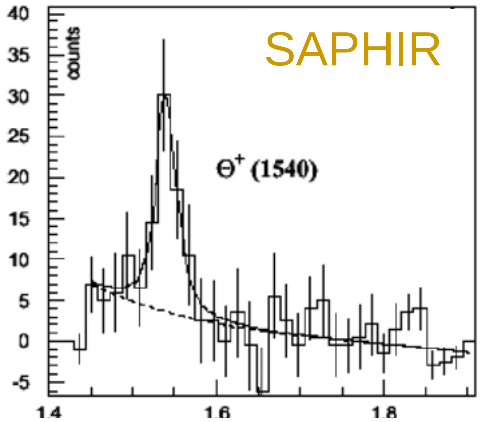
Z(4430) for saxophone quartet by Roger Zare

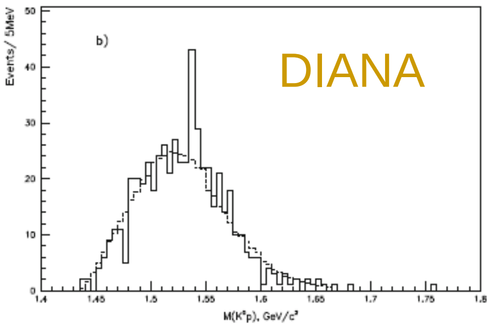
Roger Zare

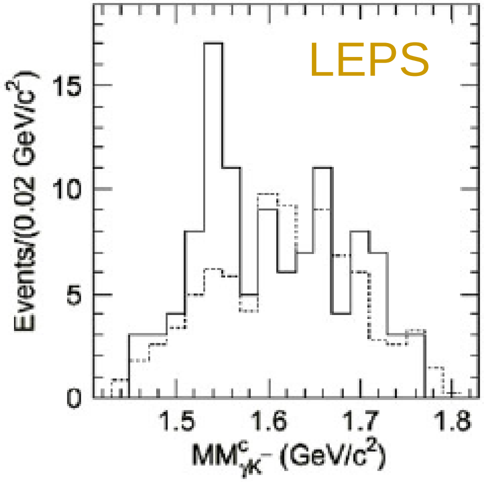
Montreux jazz festival, 2014

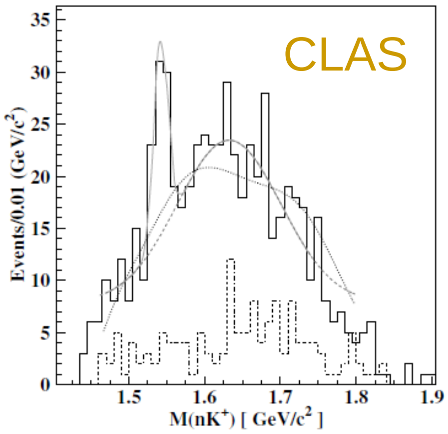
The hunt for pentaquarks – a long journey with several cul-de-sacs

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







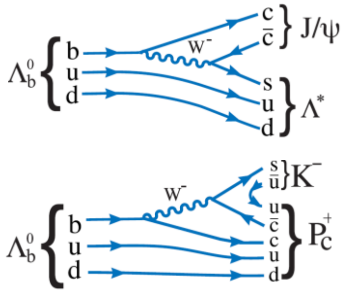


After an initial rush of confirmations, null results from more sensitive experiments appeared, & eventually it was accepted to be non-existent.

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

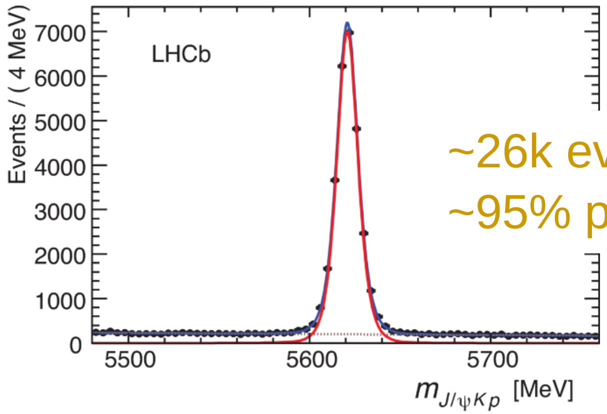
[for more information, see Hicks, Eur. Phys. J. H 37 (2012) 1]

J/Ψp resonances consistent with pentaquark states



[PRL 115 (2015) 072001]

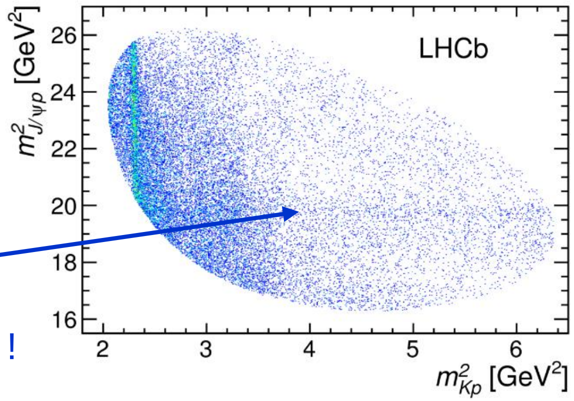
Large & pure sample of $\Lambda_b \to J/\Psi pK$ decays



~26k events

~95% purity

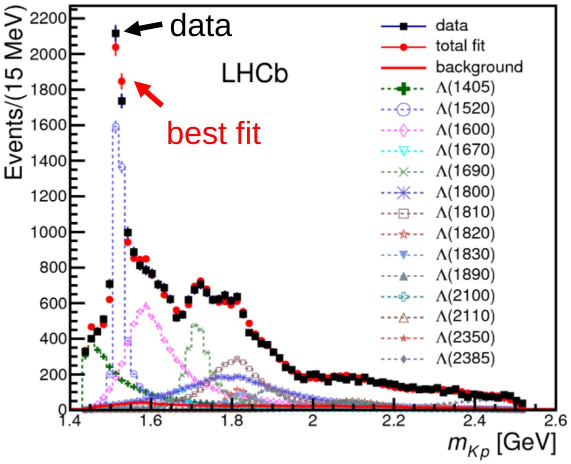
Distinctive structure in J/Ψp spectrum

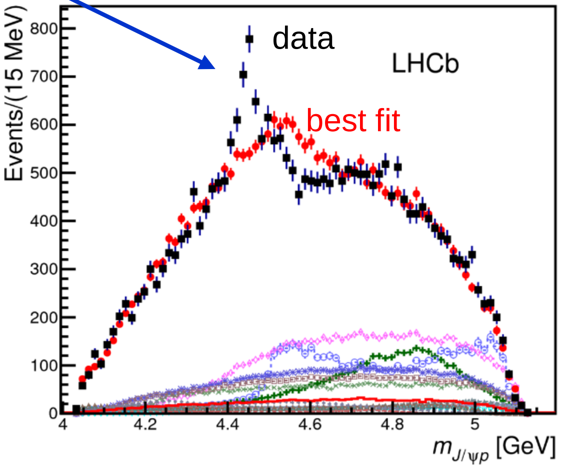


Naïve first impression: this is exotic ! (uudccbar).

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

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

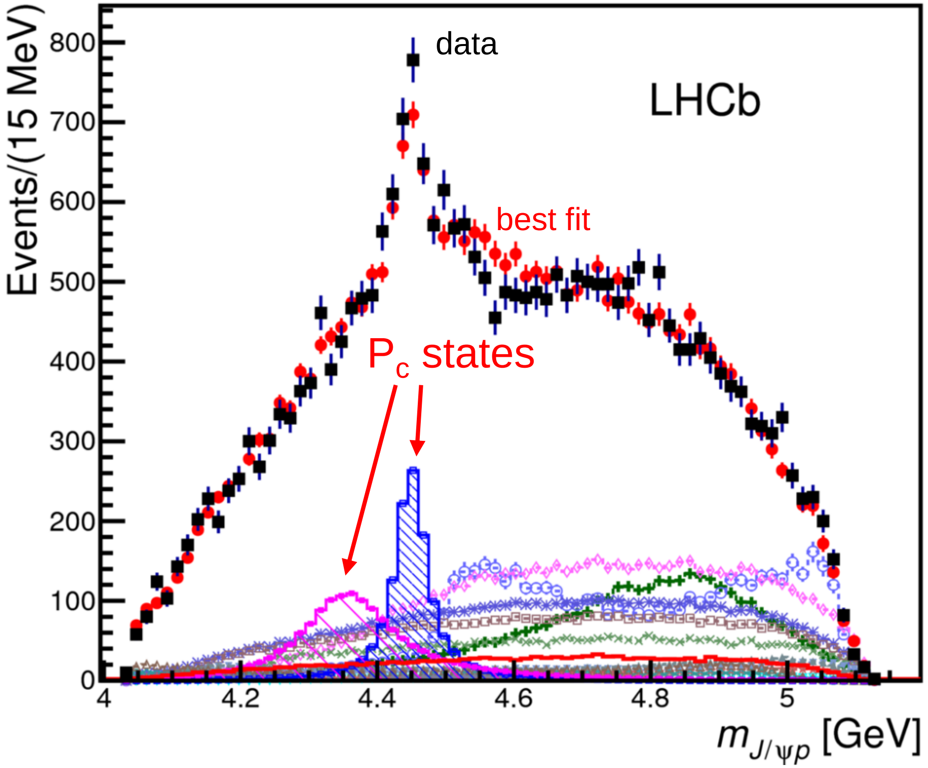




J/Ψp resonances consistent with pentaquark states

[PRL 115 (2015) 072001]

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



$P_c(4380)$:

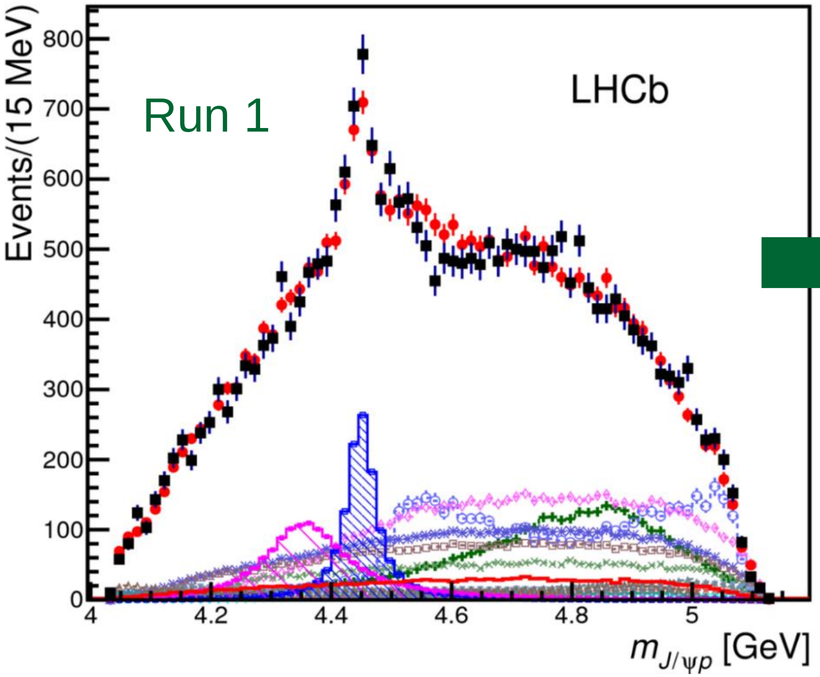
$$M = 4380 \pm 8 \pm 29\,\mathrm{MeV},$$
$$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$$

$P_c(4450)$:

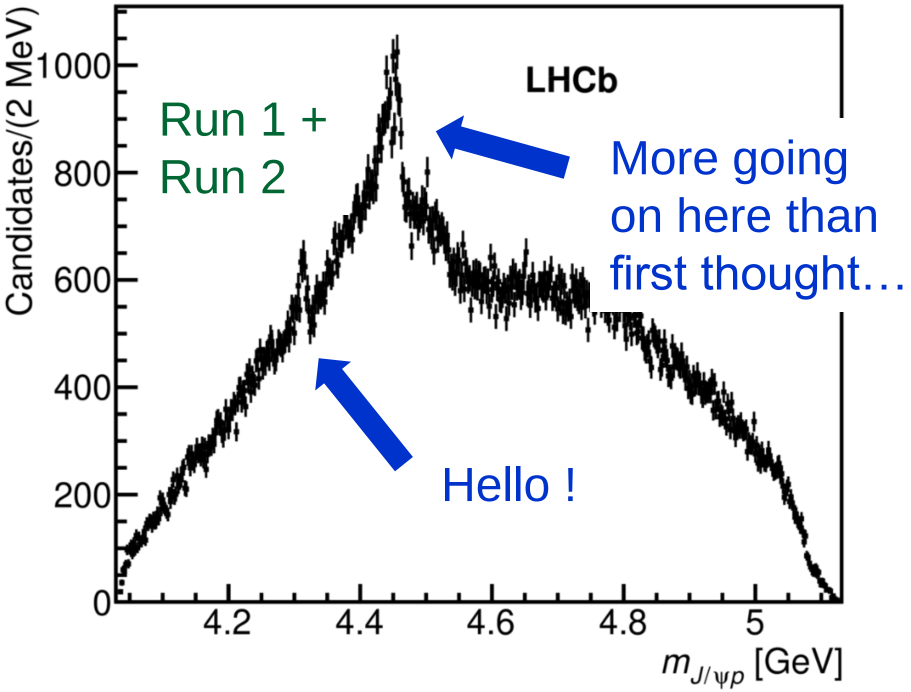
$$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$$
$$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$$

Pentaquarks – why more data matters

Run 2 data and improved selection provide x9 increase in signal



[PRL 115 (2015) 072001]



More going on here than first thought…

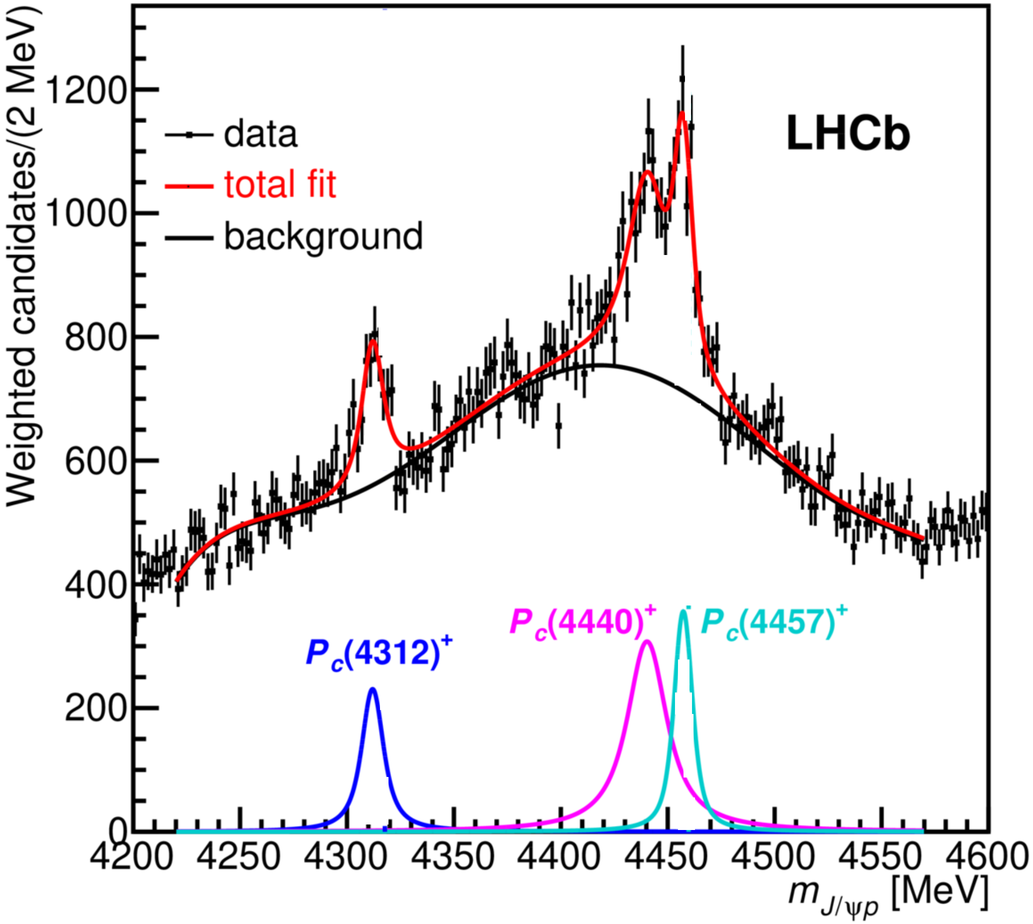
Hello !

[PRL 122 (2019) 222001]

Not one narrow state, but three

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

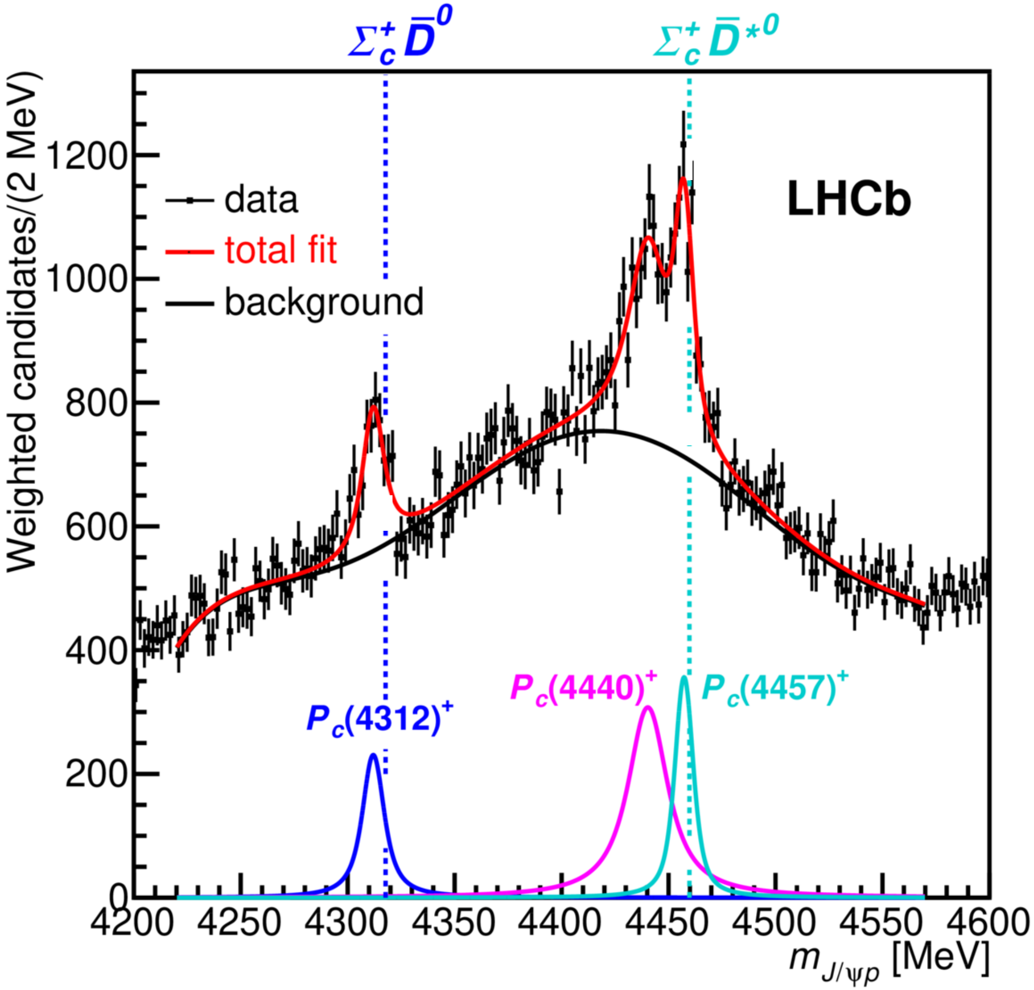
[PRL 122 (2019) 222001]



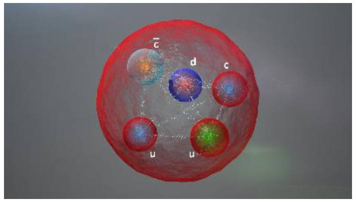
A new narrow state is observed at 4312 MeV, and the previous narrowish state is resolved into two close-lying narrower states. An amplitude analysis is required to determine J^P and decide on whether broad $P_c(4380)$ still required.

Not one narrow state, but three

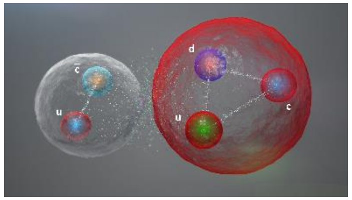
[PRL 122 (2019) 222001]



tightly-bound model



molecular model



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

FCNCs (‘rare decays’)

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

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

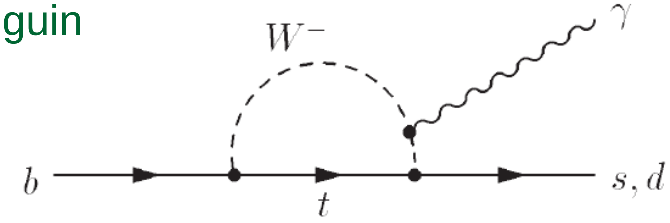
FCNC decays proceed through higher order diagrams → suppressed in SM and susceptible to New Physics contributions.

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

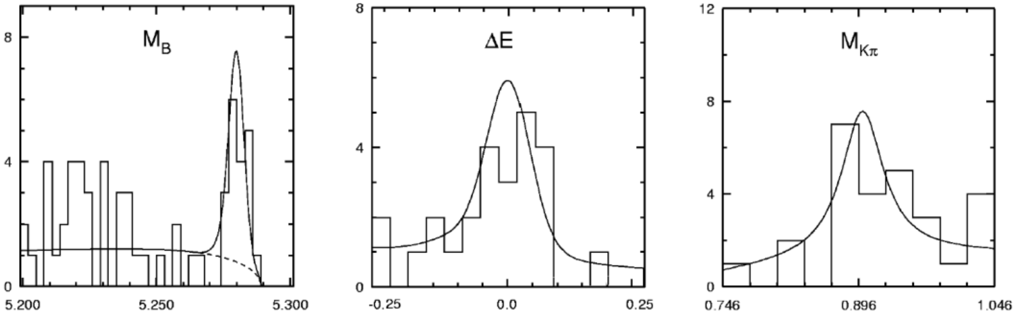
gluonic Penguin

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

(EM) Radiative penguin



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

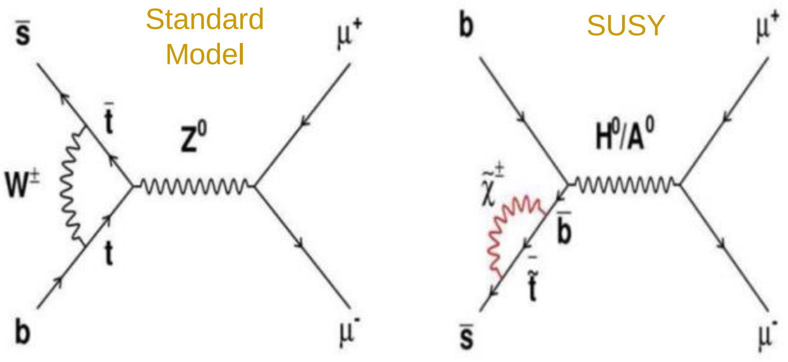


Studies of radiative penguins still very important, but we will not discuss them further.

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

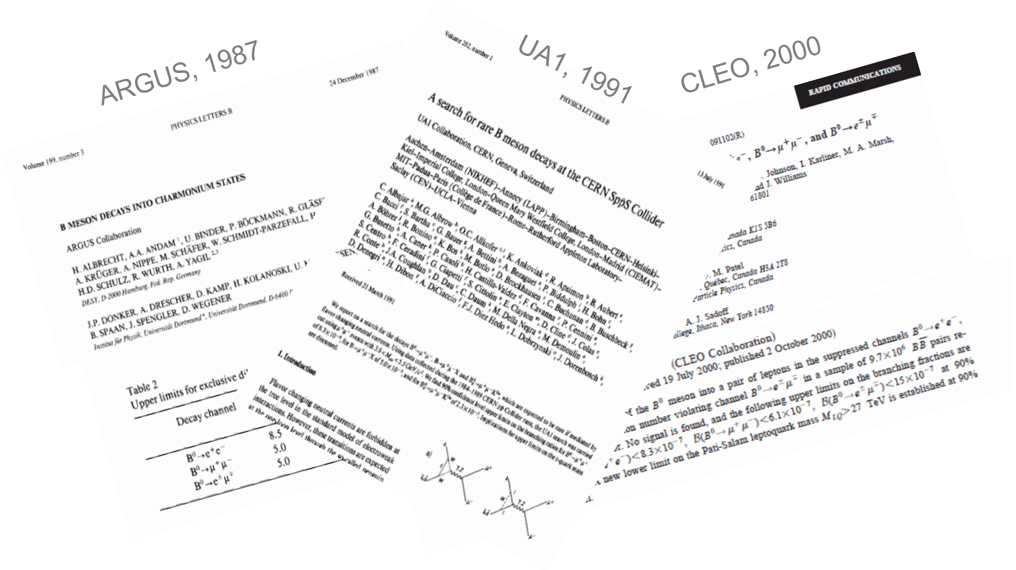
These decay modes can only proceed through suppressed loop diagrams.

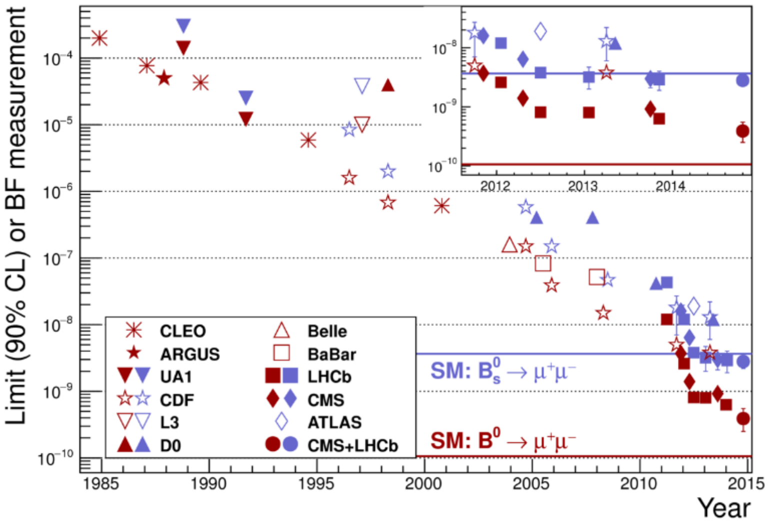
In SM they happen extremely rarely ($B_s \rightarrow \mu\mu$ ~4×10^{-9}, $B^0 \rightarrow \mu\mu$ 30x lower), but the rate is very well predicted (*e.g.* <5% for $B_s \rightarrow \mu\mu$).



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

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

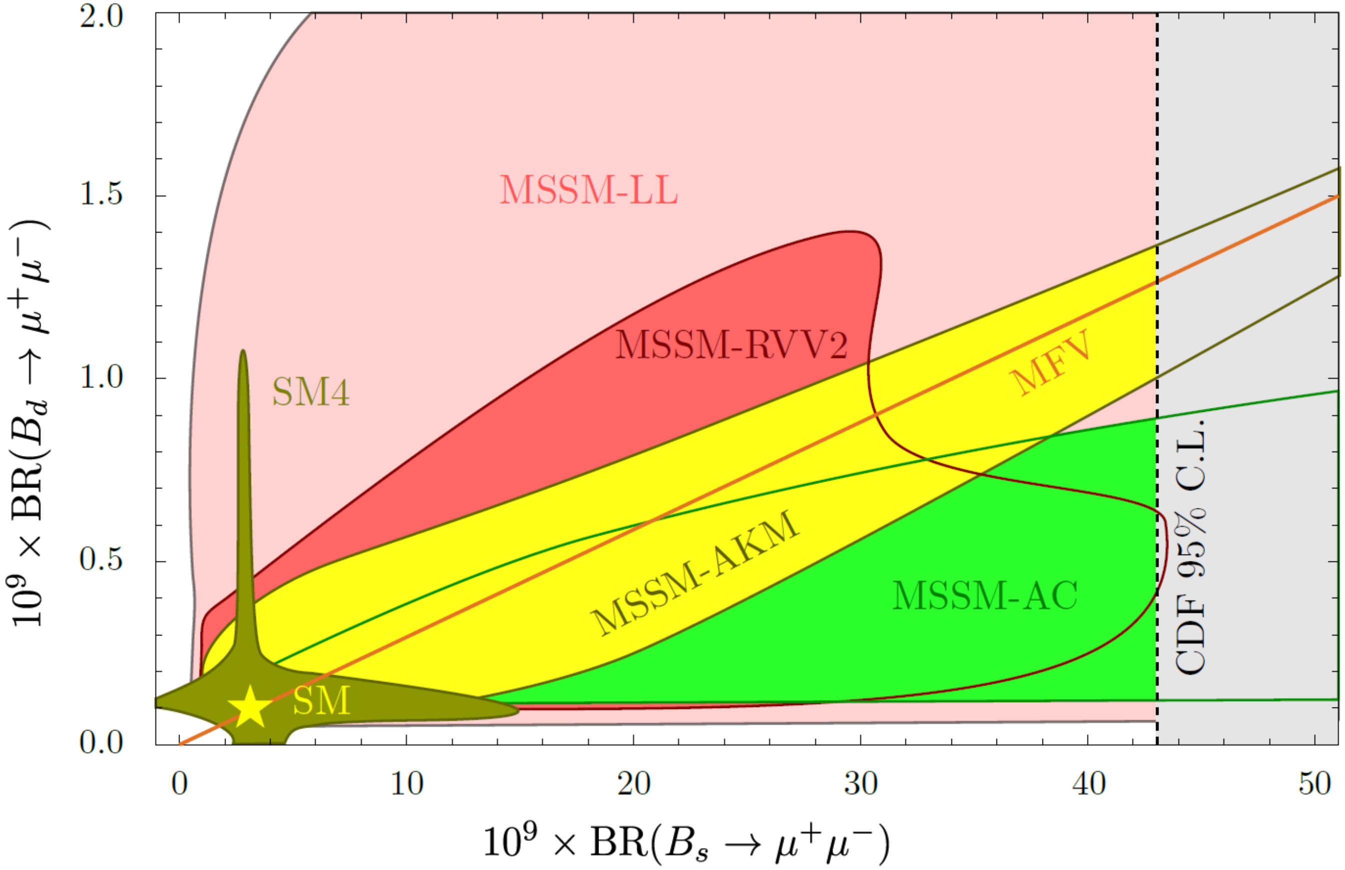




Before the LHC, Fermilab experiments were pushing the limits down towards 10^{-8}.

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

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



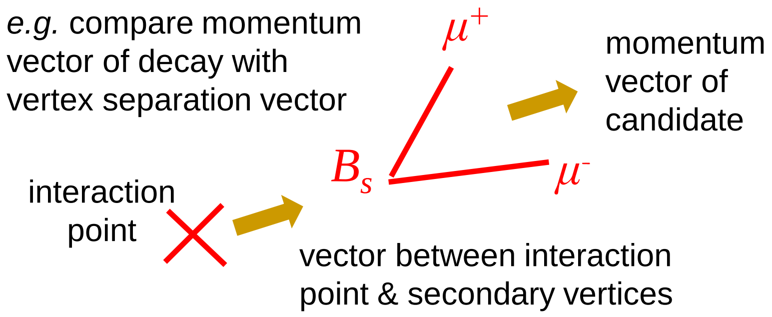
[D. Straub, arXiv:1012.3893]

Finding the needle in the haystack

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

Most sensitive analyses (LHCb, CMS) do not rely on traditional ‘cut-based’ approach. Rather, they employ a sequence of two boosted decision trees (BDTs).

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

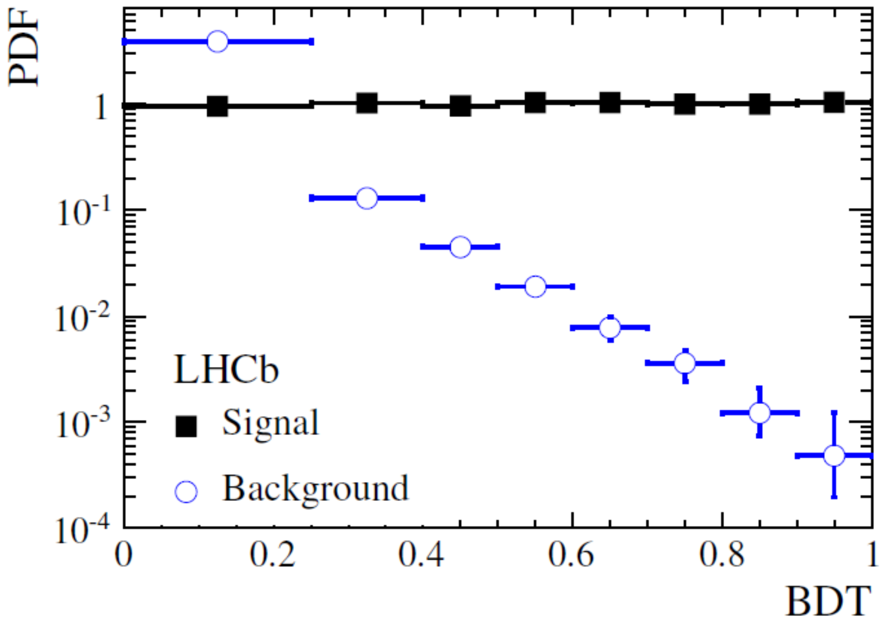


e.g. compare momentum vector of decay with vertex separation vector

momentum vector of candidate

interaction point

vector between interaction point & secondary vertices

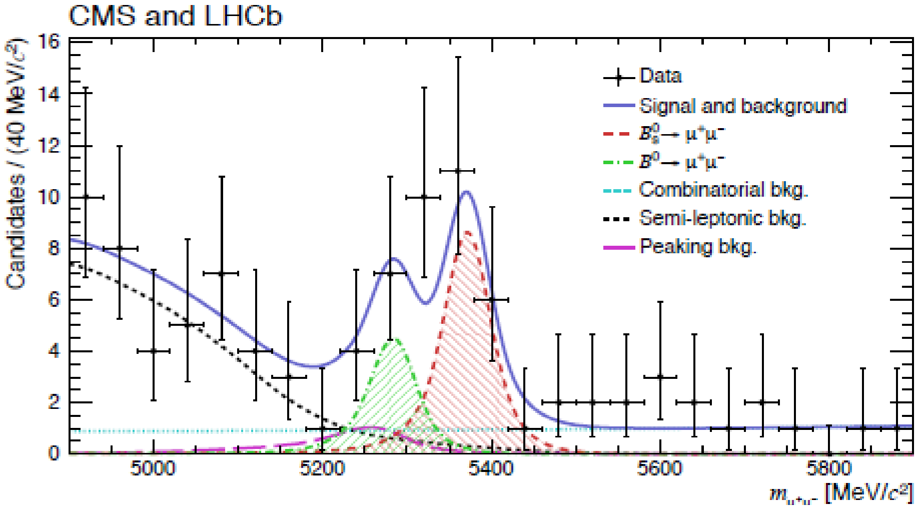


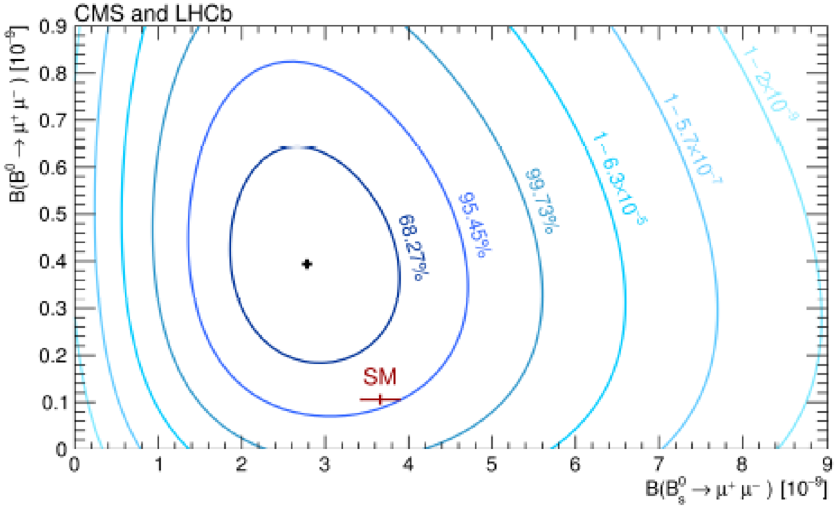
[LHCb, PRL 111 (2013) 101805]

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

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

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





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

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

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

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

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

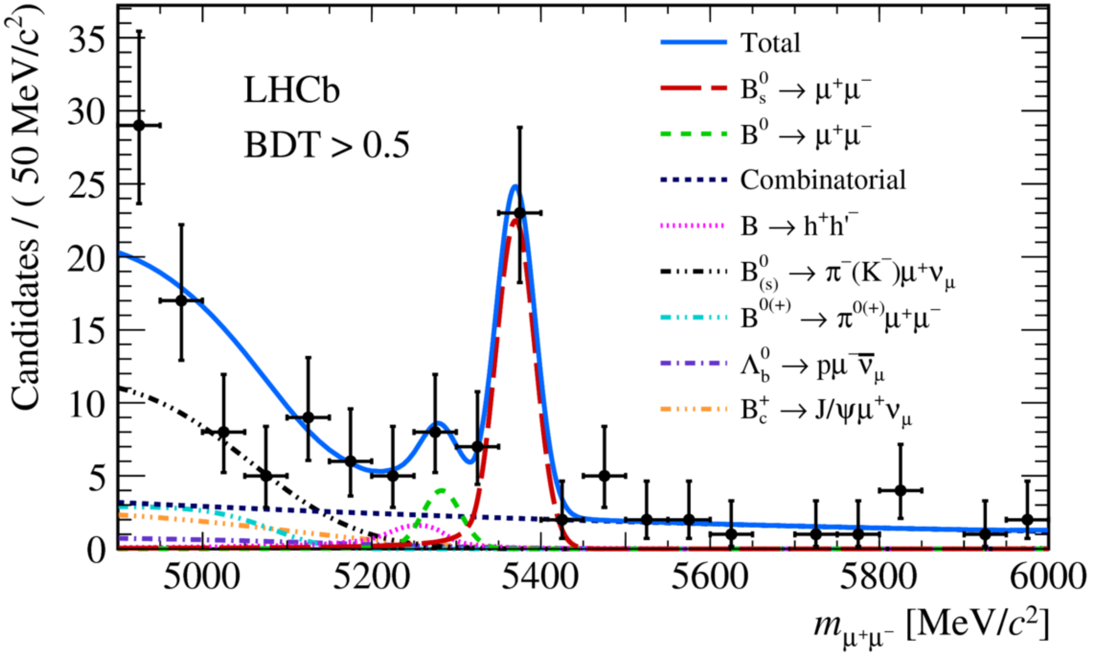
[PRL 118 (2017) 191801]

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

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

$$\mathcal{B}(B^0_s\to\mu^+\mu^-) = (3.0\pm0.6\,^{+0.3}_{-0.2})\times10^{-9}$$

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



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

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

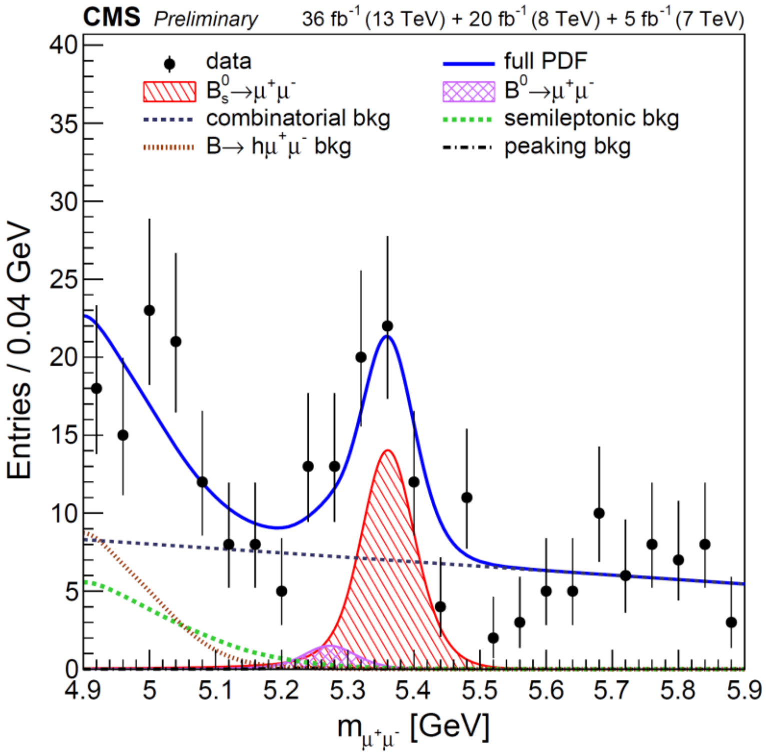
[CMS PAS BPH-16-004]

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

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

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

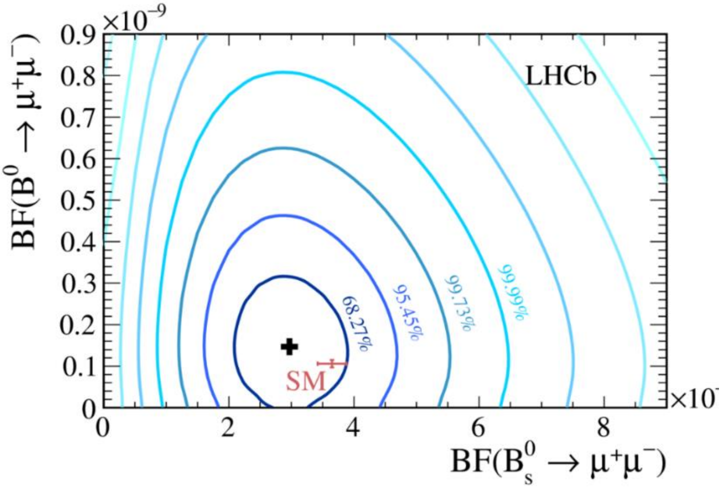
Measured by LHCb and extrapolated into kinematic acceptance of CMS.

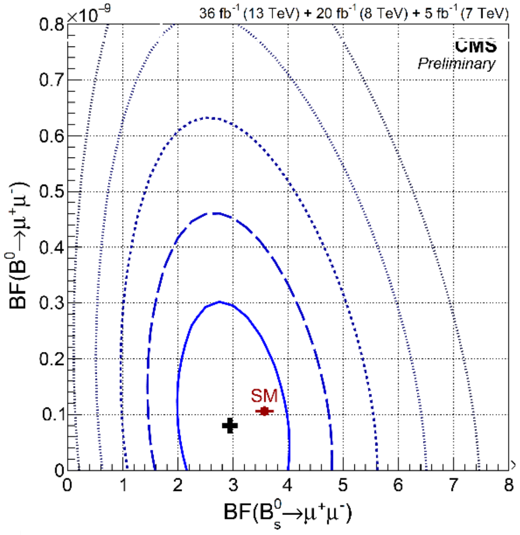


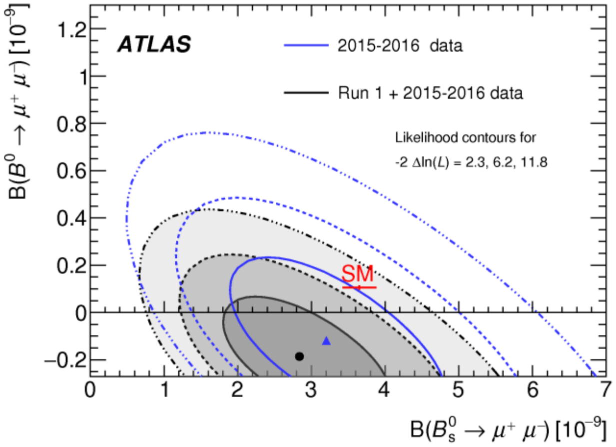
Also this year, ATLAS published a 2015-16 run 2 update [JHEP 04 (2019) 098] to augment their Run 1 result [EPJC 76 (2016) 513]. We await full Run 2 results from all experiments !

The state of play

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







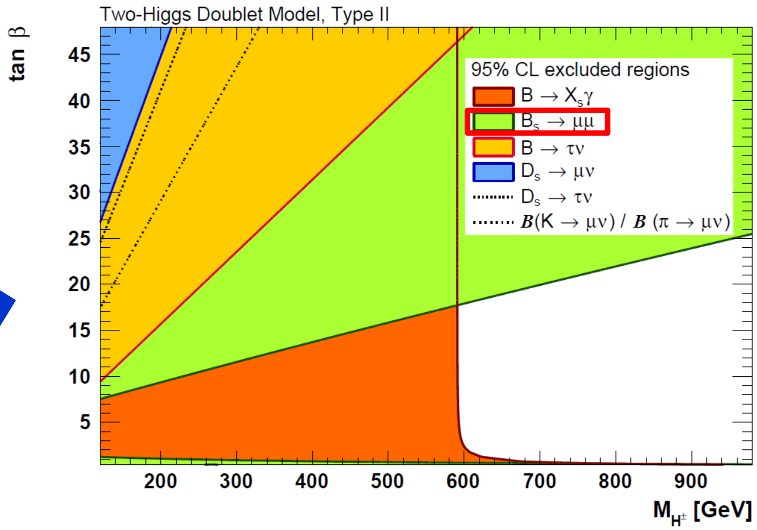
- Each result is compatible with the SM;
- $B_s \to \mu\mu$ measurements are clustering at a slightly lower value than SM (at level of ~2σ);
- $B^0 \to \mu\mu$ is proving elusive;
- Full Run 2 results will be interesting;

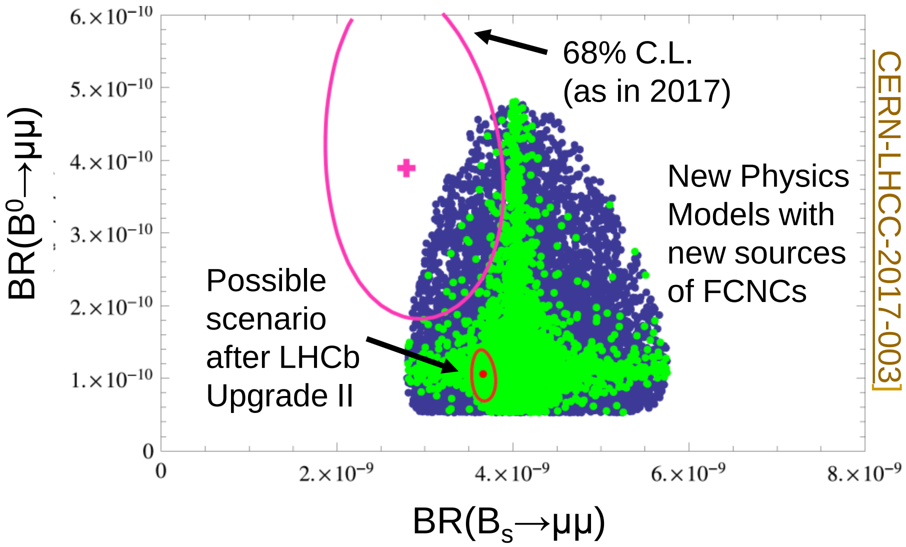
Lessons from, & future of, $B^0_{(s)}\to\mu\mu$ measurements

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

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

  e.g. 95% CL excluded region in $M_{H^\pm}$ vs. $\tan\beta$ 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 far from theory limit (which will improve). Even truer for ratio BR($B_s\to\mu\mu$)/BR($B^0\to\mu\mu$). These decays still have much to tell us!

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

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

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

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

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

where

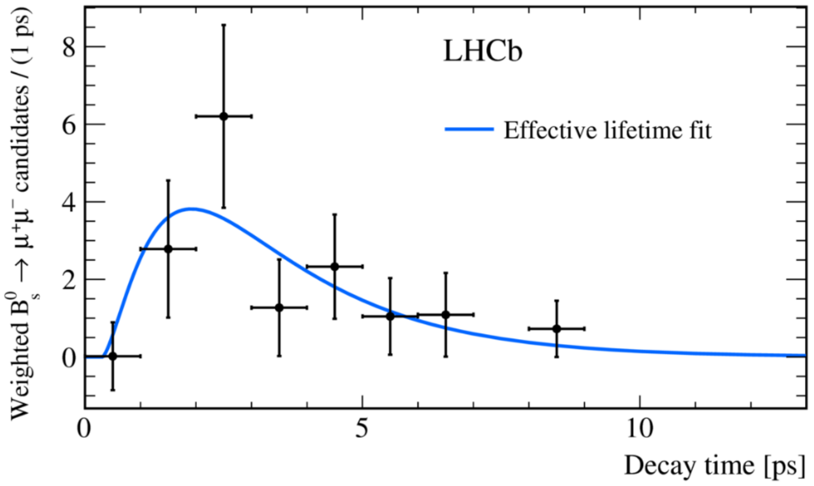
- $y_s \equiv \tau_{B_s^0}\Delta\Gamma/2 \approx 0.06$, $\Delta\Gamma$ being the lifetime splitting between the mass eigenstates;
- $A^{\mu\mu}_{\Delta\Gamma}$ is a term that is 1 in SM, but can take any value between -1 & 1 for New Physics.

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

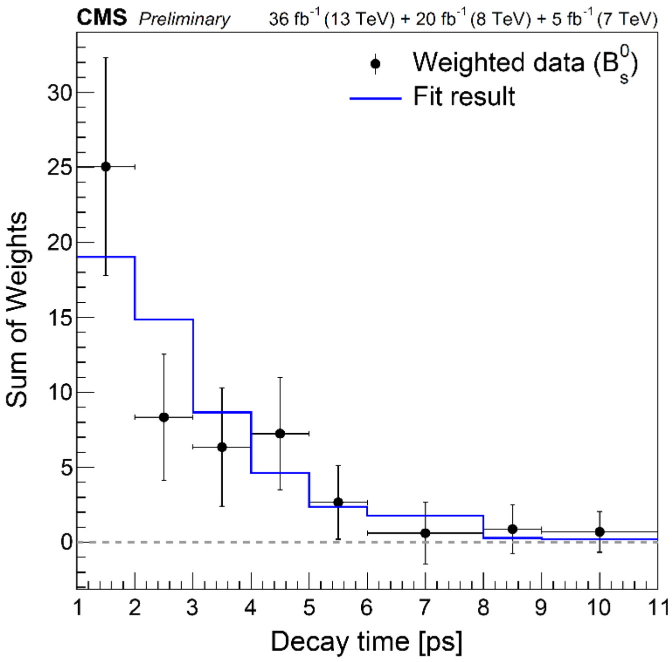
Unlocking new observables with $B_s \to \mu^+\mu^-$

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

Proof-of-principle measurements conducted by LHCb and CMS:



[PRL 118 (2017) 191801]



[CMS PAS BPH-16-004]

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

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