ZPW2015

The flavour of new physics

LHCb results on *CP* violation

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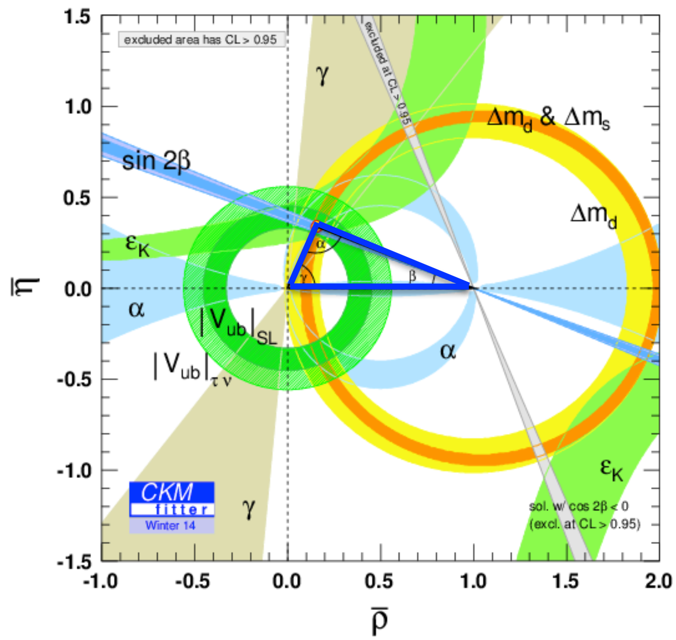
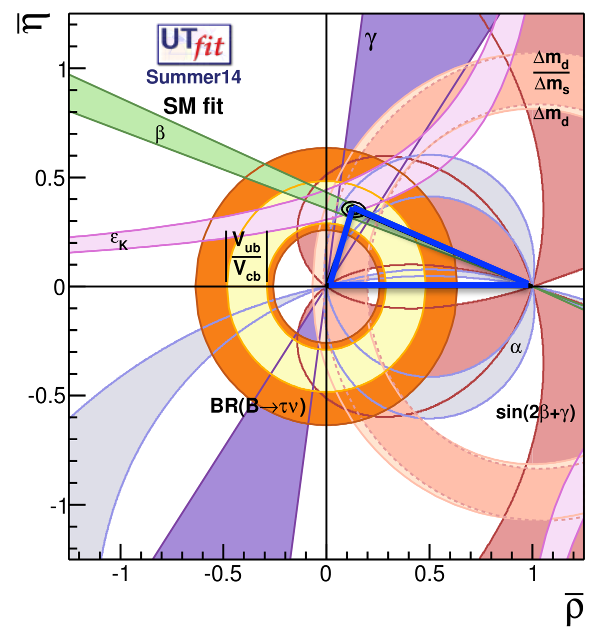
on behalf of the LHCb Collaboration

Consistency of global CKM fits

- Tremendous success of the CKM paradigm!
  - All of the measurements agree in a highly profound way





- The quark flavour sector is well described by the CKM mechanism
  - large sources of flavour symmetry breaking are excluded at the TeV scale
  - the flavour structure of NP should be very peculiar

Consistency of global CKM fits

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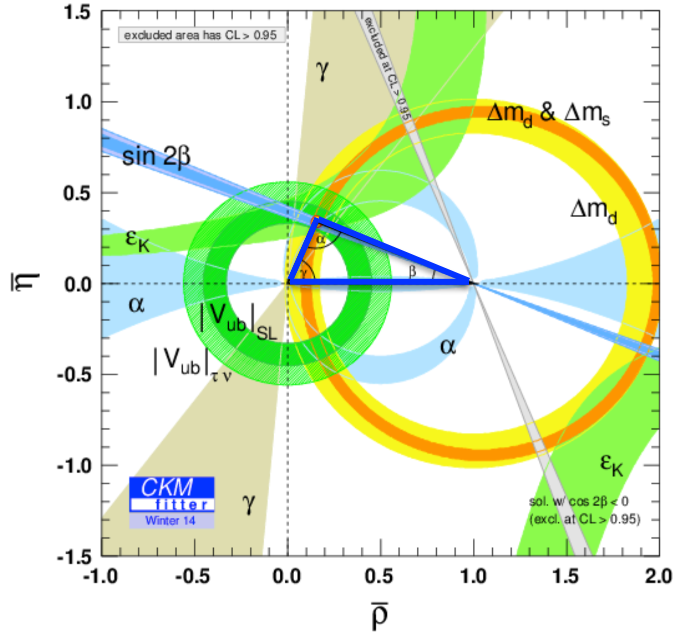
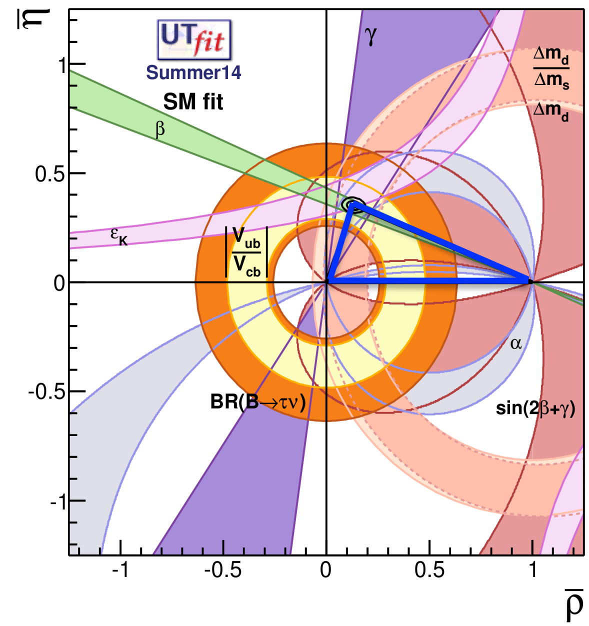
  – All of the measurements agree in a highly profound way





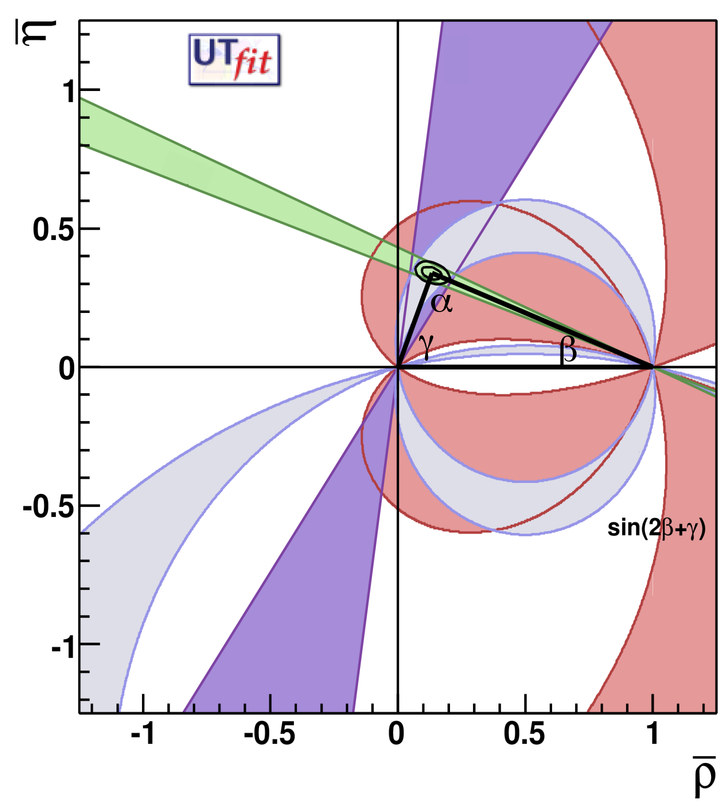
- We are leaving in a strange era
  – on the one hand we have been achieving great success
  – on the other hand, some depression sneaking around as everything looks consistent with what we already knew

Nevertheless...

- The good reasons why we believed that the SM was incomplete are still there
  - hierarchy problem
  - unification of gauge couplings
  - dark matter
  - matter-antimatter asymmetry
  - ...
- By studying *CP*-violating and flavour-changing processes we can accomplish two fundamental tasks
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly
- Measurable deviations from the SM, although not large as naively hoped, are still possible
  - need to go to high precision measurements to probe theoretically clean observables

Measurements of UT angles

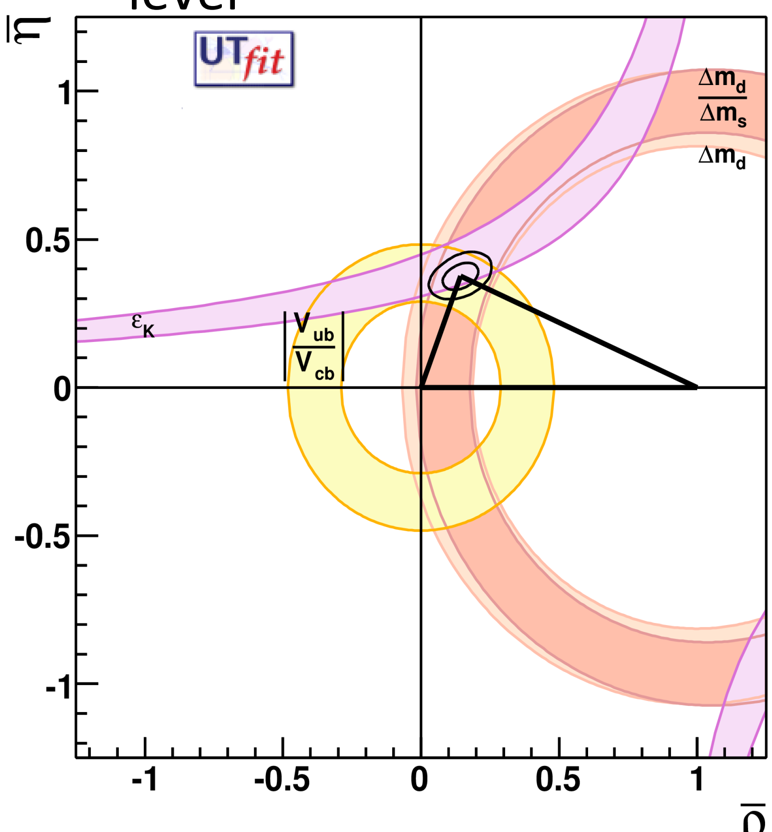
- Interpretation in terms of CKM matrix elements does not depend on strong theory inputs
  - $\sigma_{th}(\gamma)$ negligible from tree-level decays
    - Brod and Zupan, JHEP 01 (2014) 051
  - $\sigma_{th}(\beta)$ small and controllable with data-driven methods
    - Ciuchini *et al.*, PRL 95 (2005) 221804
    - Faller *et al.*, PRD 79 (2009) 014030
  - $\sigma_{th}(\beta_s)$ small and controllable with data-driven methods
    - Faller et al., PRD 79 (2009) 014005
  - $\sigma_{th}(\alpha) \approx 1^o$
    - Gronau *et al.*, PRD 60 (1999) 034021
    - Botella *et al.*, PRD 73 (2006) 071501
    - Zupan, Nucl. Phys. Proc. Suppl. 170 (2007) 33



- Measurements can be affected by NP at different levels
  - γ from tree-level is (to a large extent) unaffected
  - β (β_s) can be affected in B_d (B_s) mixing
  - α can be affected both in mixing and decay (loops in penguin diagrams)

Measurements of UT sides and ε_K

- Here theory matters a lot
  - Improvements in lattice QCD are particularly important
  - Can we go below 1% for the relevant hadronic quantities in the next decade?
    - Small effects that are typically neglected have to be considered, e.g. isospin breaking and electromagnetic effects are at the 1% level



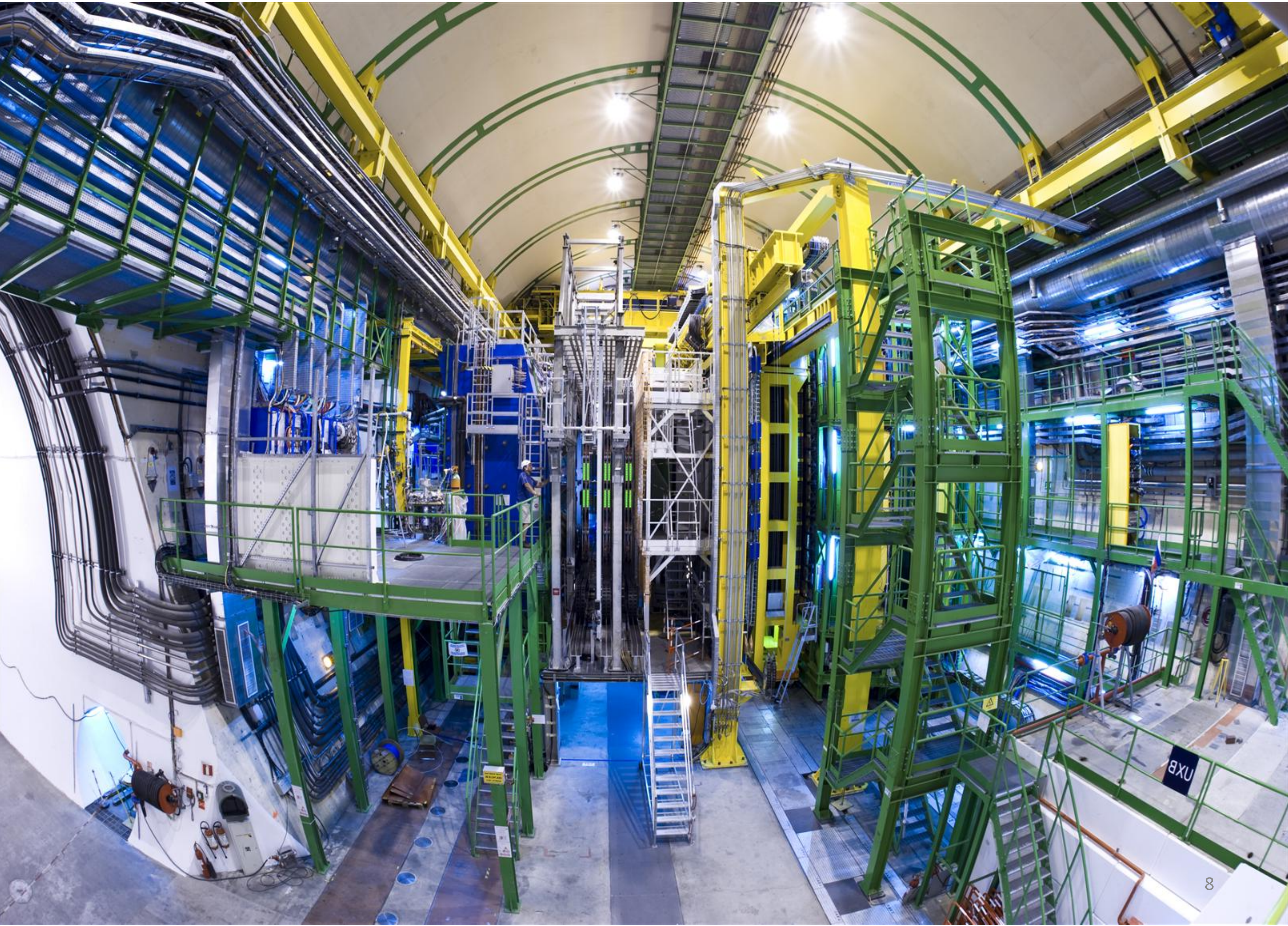
Hadronic parameter	L.Lellouch ICHEP 2002 [hep-ph/0211359]	FLAG 2013 [1310.8555]
$f_+^{K\pi}(0)$	- First Lattice result in 2004 [0.9%]	[0.4%]
$\hat{B}_K$	[17%]	[1.3%]
f_{Bs}	[13%]	[2%]
f_{Bs}/f_B	[6%]	[1.8%]
$\hat{B}_{Bs}$	[9%]	[5%]
B_{Bs}/B_B	[3%]	[10%]
$F_{D^*}(1)$	[3%]	[1.8%]
$B\rightarrow\pi$	[20%]	[10%]

- Progresses not coming for free
- The LQCD sector needs to be sustained with appropriate funding

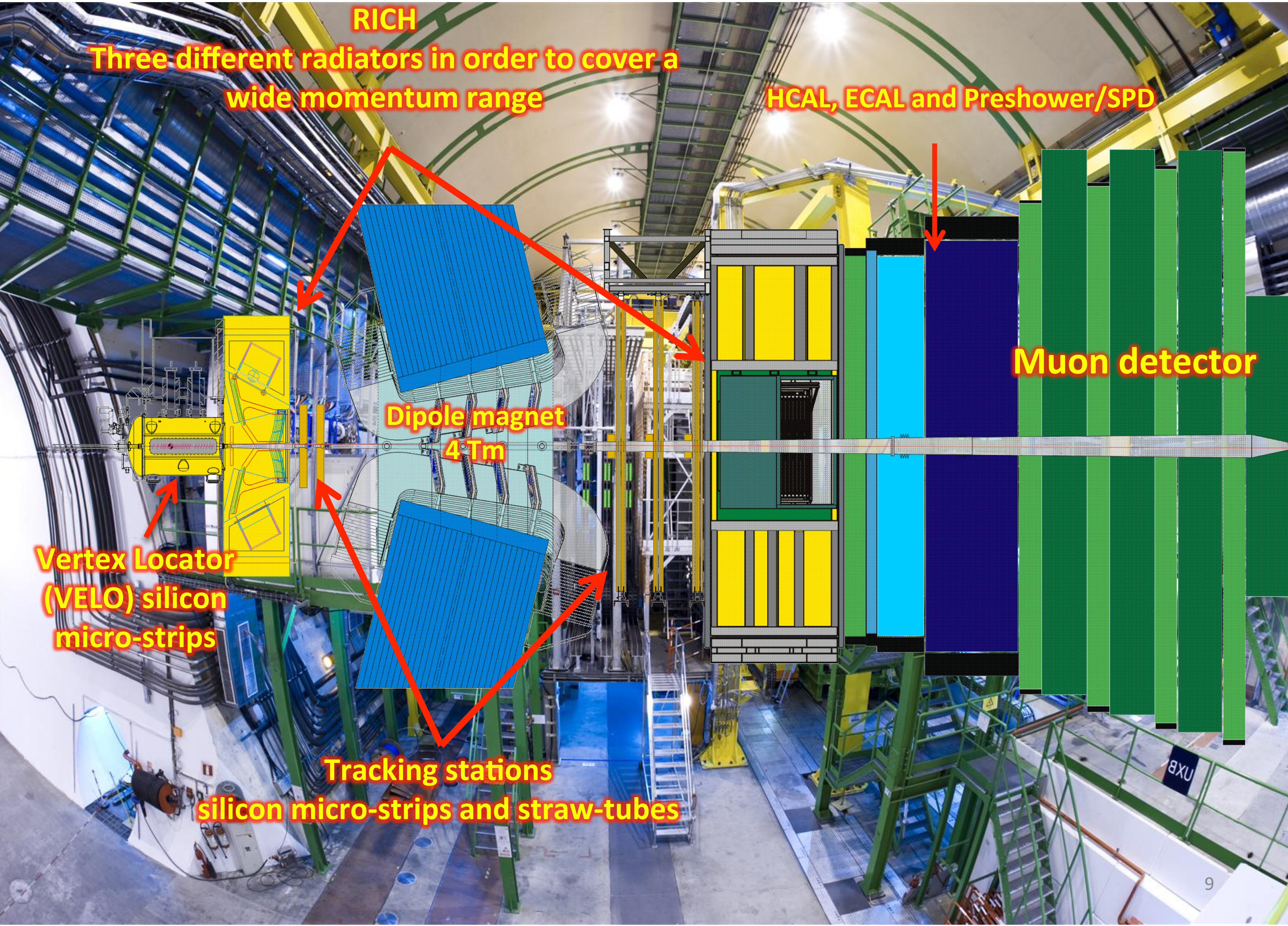
Outline

- LHCb detector and luminosity prospects
- *CP* violation in the interference between *B*-meson mixing and decay
  - from $b \to c\bar{c}s$ transitions
  - from $b \to s\bar{s}s$ transitions
- Semileptonic asymmetries of B^0 and B_s mesons
- Determination of γ
  - from tree-level decays
  - from charmless two-body decays
- Mixing and *CP* violation in charm decays
- LHCb Upgrade

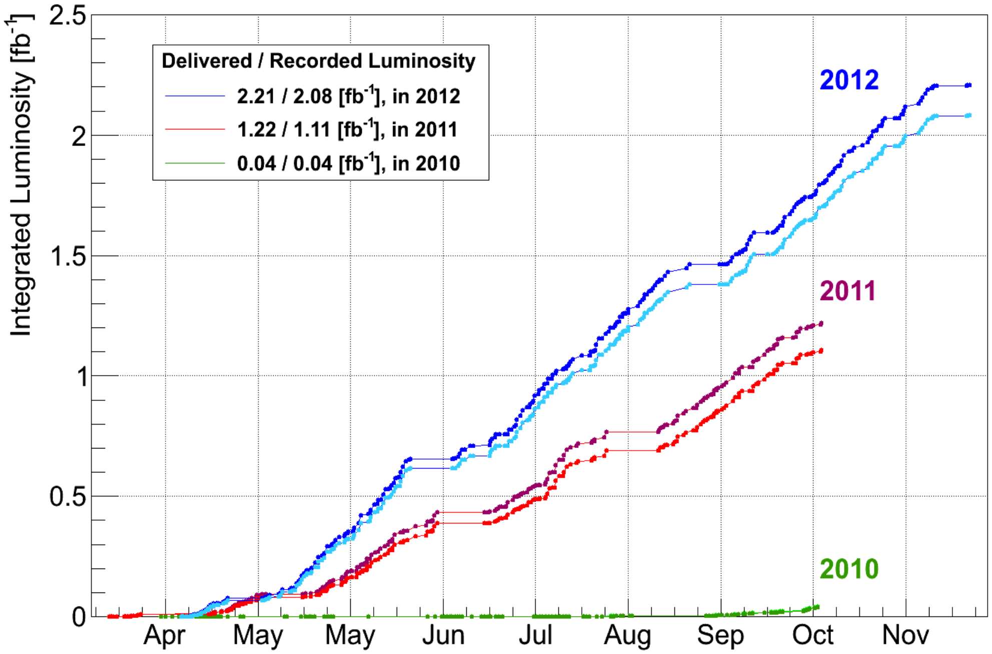
The LHCb detector



The LHCb detector



LHCb luminosity prospects



During Run 1

- 7 and 8 TeV collisions
- luminosity levelled at $4 \cdot 10^{32}$ cm^{-2}s^{-1}
- software trigger running at 1 MHz after hardware trigger and record 3-5 kHz

LHC era		HL-LHC era		
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

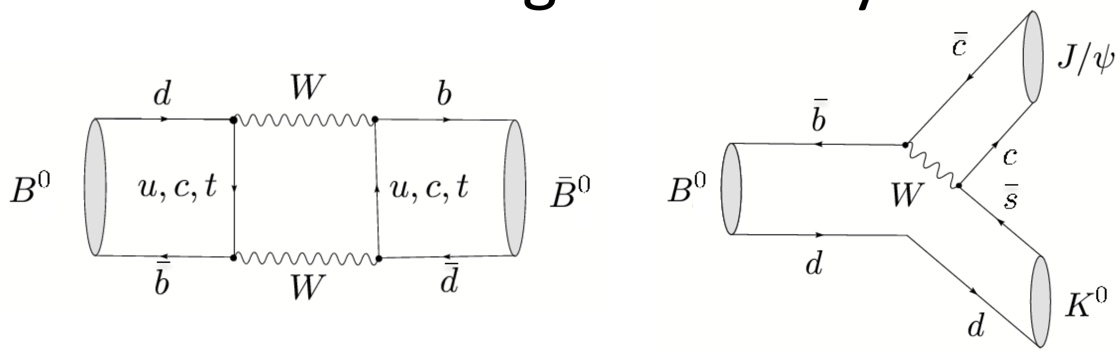
Note that beauty production cross section is roughly doubled passing from 7 TeV to 14 TeV *pp* collisions

LHCb upgrade

- running at $2 \cdot 10^{33}$ cm^{-2}s^{-1}
- replace R/O, RICH photodetectors and tracking detectors
- full software trigger, running at 40 MHz and record 20 kHz

Measurement of sin(2β)

- *CP* violation due to interference between mixing and decay



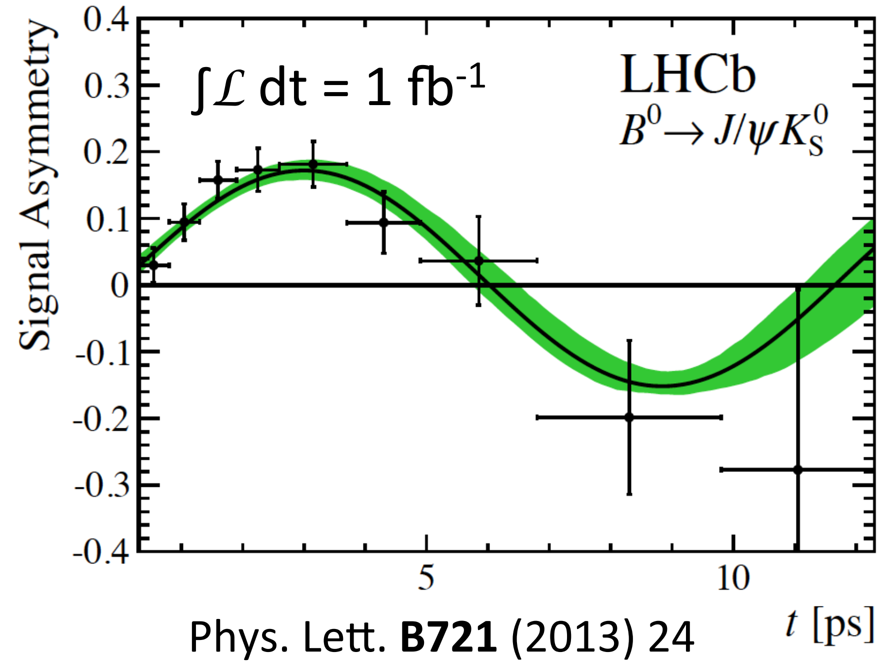
$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

$$S_{J/\psi K^0_S} = 0.73 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst})$$
$$C_{J/\psi K^0_S} = 0.03 \pm 0.09\,(\text{stat}) \pm 0.01\,(\text{syst})$$

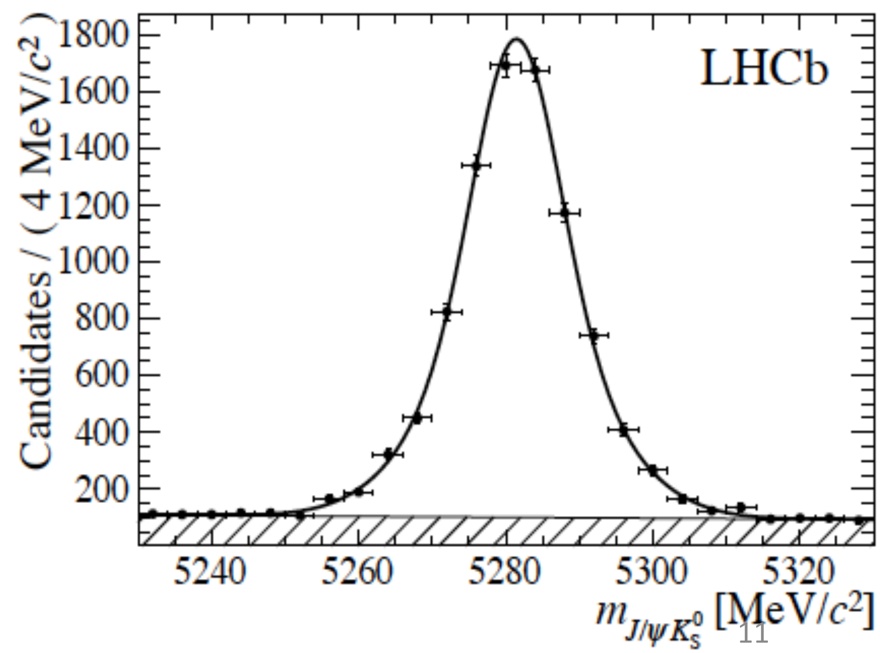
World average: sin(2β)=0.682 ± 0.019

Largely dominated by BaBar and Belle

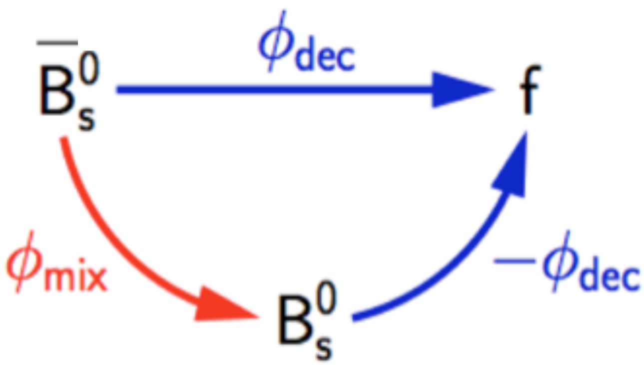
- LHCb result with 3 fb^{-1} coming soon (competitive precision is expected)



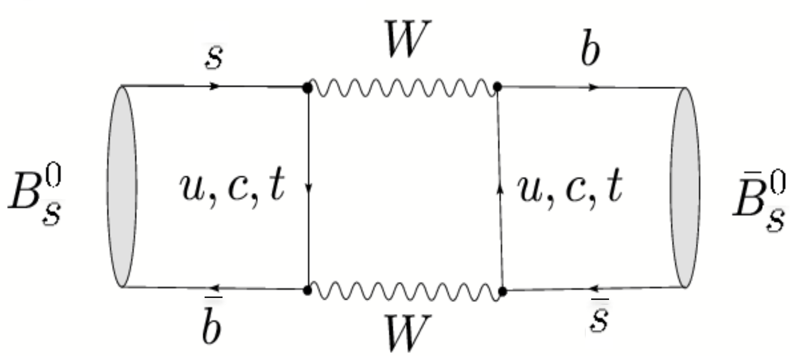
Phys. Lett. **B721** (2013) 24

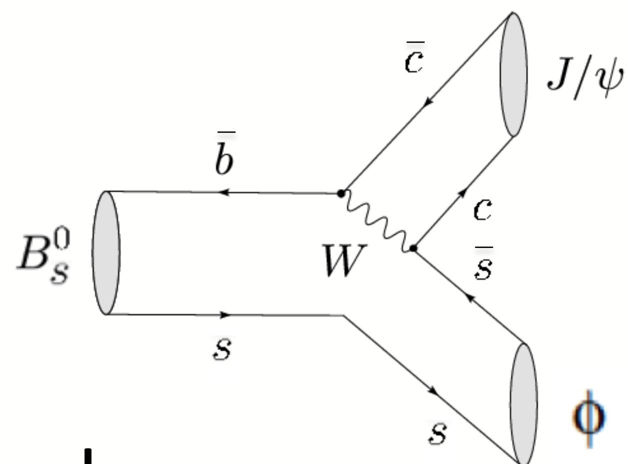


CP violation induced by B_s mixing



- Golden mode $B_s \rightarrow J/\psi\phi$ also proceeds (mostly) via a $b \rightarrow c\bar{c}s$ tree diagram

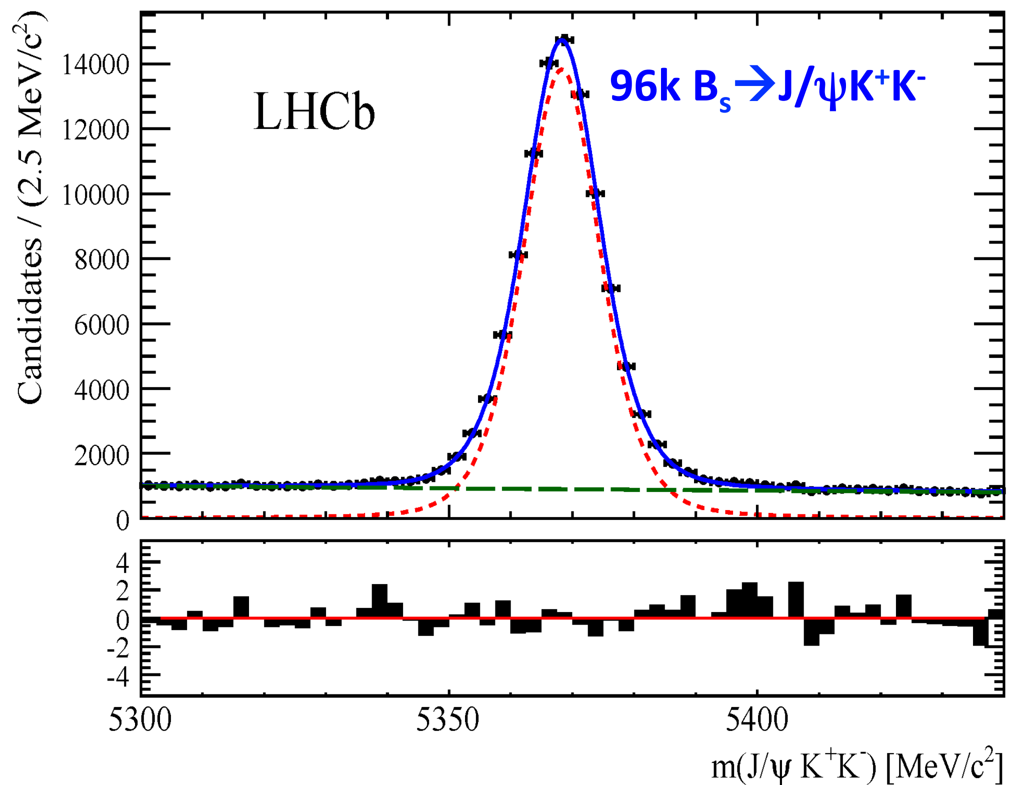




- $B_s \rightarrow \phi\phi$ is $b \rightarrow s\bar{s}s$ penguin-dominated
  - NP can show up in the mixing and/or in the decay
- $P \rightarrow VV$ decays
  - Full angular analysis is needed to disentangle *CP*-even and *CP*-odd amplitude components

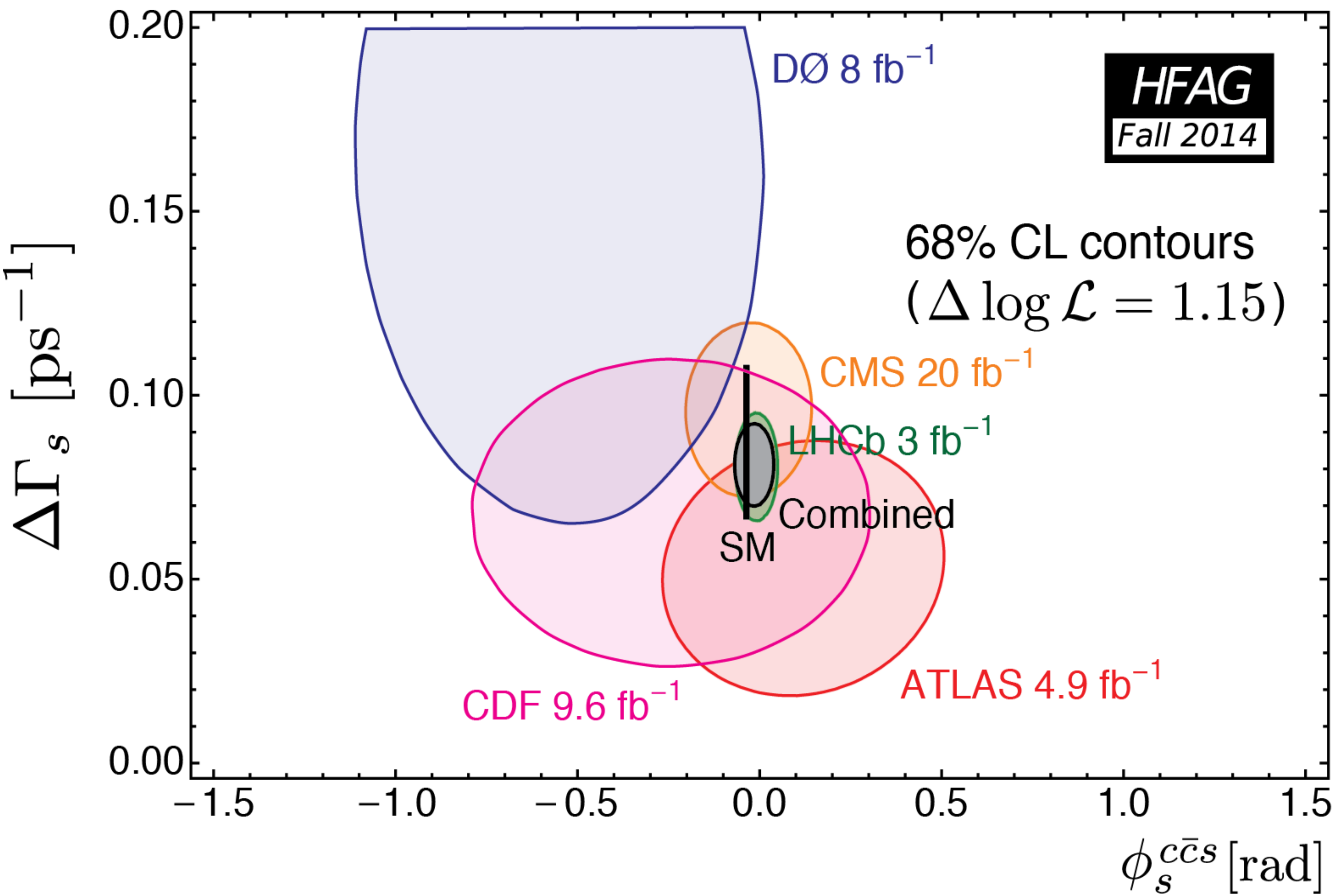
LHCb measurements of ϕ_s

- $B_s \rightarrow J/\psi K^+K^-$ (3 fb^{-1})
  - arXiv 1411.3104
    $\phi_s = -58 \pm 49 \pm 6$ mrad
- $B_s \rightarrow J/\psi \pi^+\pi^-$ (3 fb^{-1})
  - Phys. Lett. **B736** (2014) 186
    $\phi_s = 70 \pm 68 \pm 8$ mrad
- $B_s \rightarrow D_s^+D_s^-$ (3 fb^{-1})
  - Phys. Rev. Lett. **113** (2014) 211801
    $\phi_s = 20 \pm 170 \pm 20$ mrad

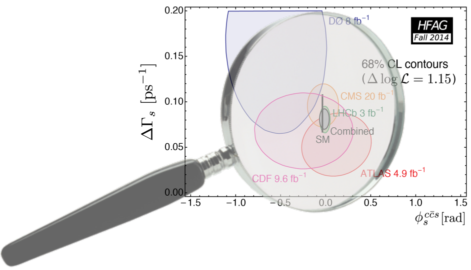


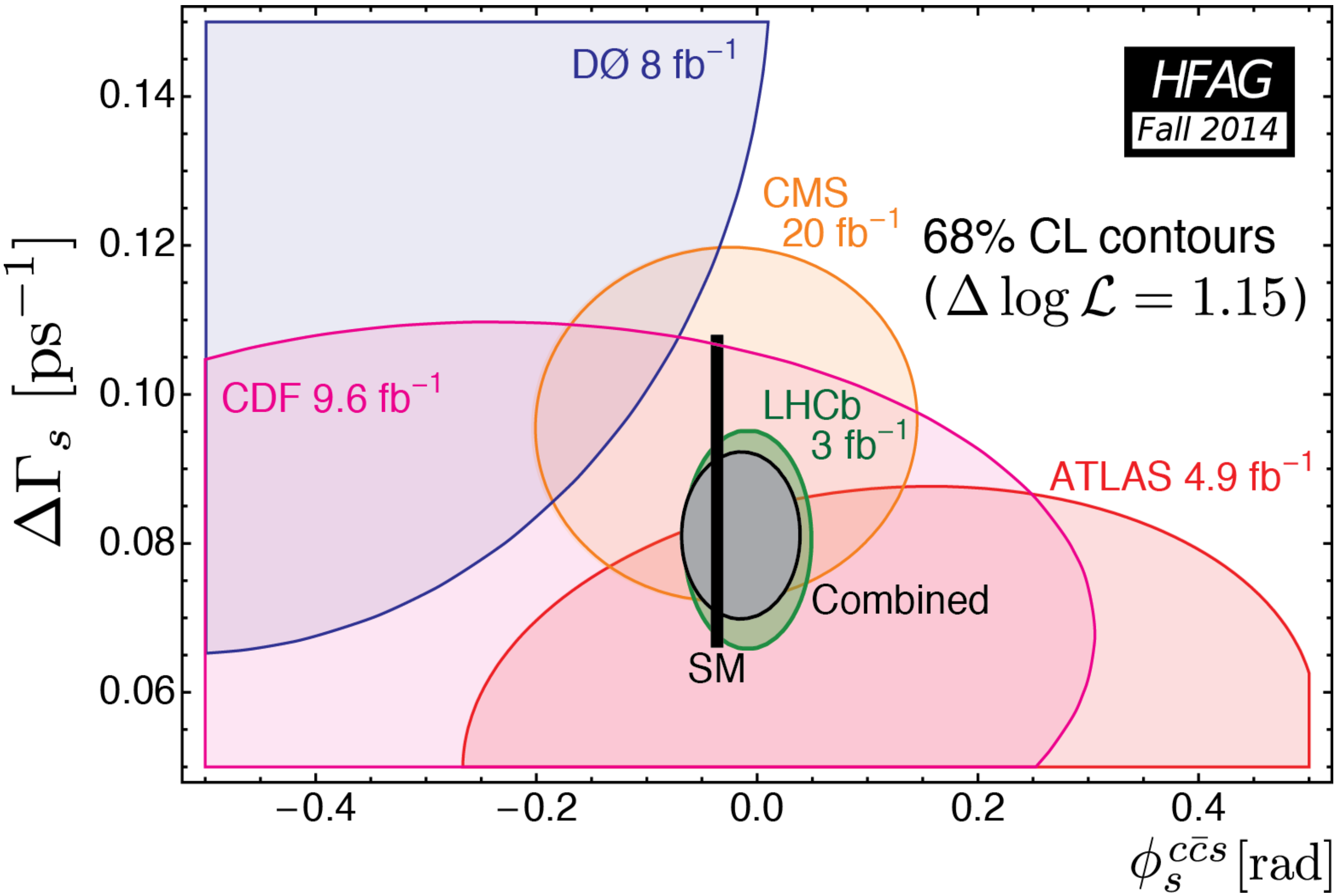
SM $\phi_s = -37.5 \pm 1.5$ mrad (UTfit)

Combination of ϕ_s measurements



Combination of ϕ_s measurements



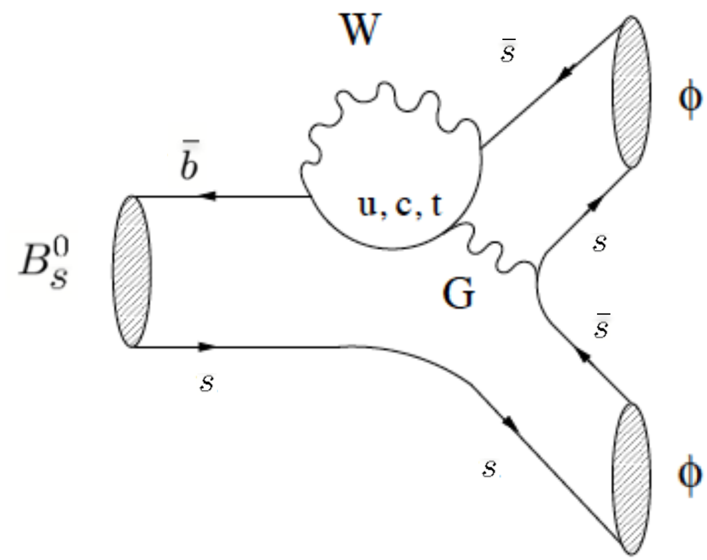


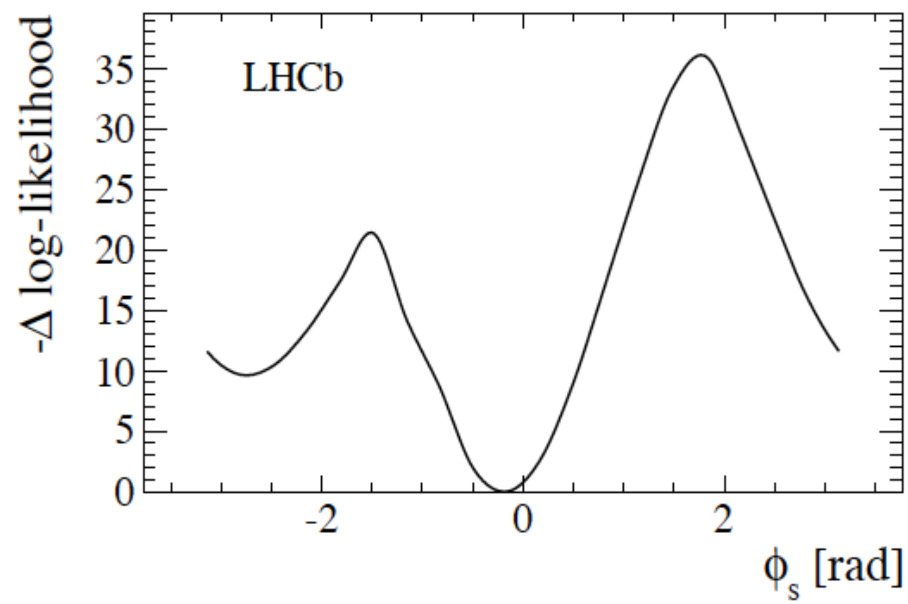
World average: ϕ_s = -15 ± 35 mrad, $\Delta\Gamma_s$ = 0.081 ± 0.007 ps^{-1}

- Present uncertainty is dominated by LHCb
  - LHCb-only average: ϕ_s = -10 ± 39 mrad
- Not yet signs of discrepancy with SM expectation

CP violation in $B_s \to \phi\phi$

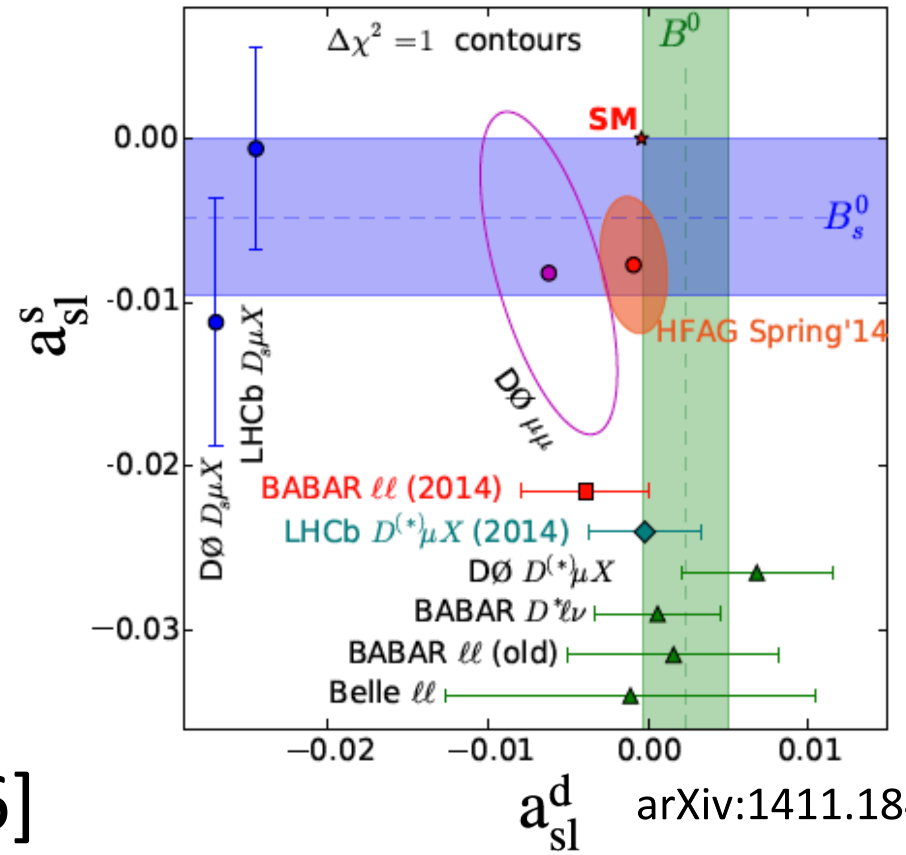
- Decay forbidden at tree level in the SM
  - proceeds predominantly via a gluonic $b \to s\bar{s}s$ penguin
  - Provides an excellent probe of new heavy particles entering the penguin quantum loops
- Latest LHCb result with full Run 1 data set
  - Phys. Rev. **D90** (2014) 052011
    $\phi_s^{\phi\phi}$ = -170 ± 150 ± 30 mrad
- No sign of discrepancy yet, but overall precision comparable to golden $b \to c\bar{c}s$ modes





The D0 anomaly

- Dimuon asymmetry measured by D0 at about 3σ from the SM
- Very difficult to repeat the same measurement at the LHC
  - However it is possible to measure $a_{sl}(B^0)$ and $a_{sl}(B_s)$
- LHCb has measured $a_{sl}(B^0)$ with 3 fb^{-1} [arXiv:1409.8586] and $a_{sl}(B_s)$ with 1 fb^{-1} [Phys. Lett. **B728** (2014) 607]
- The measurements agree with the SM, but do not exclude the dimuon result yet

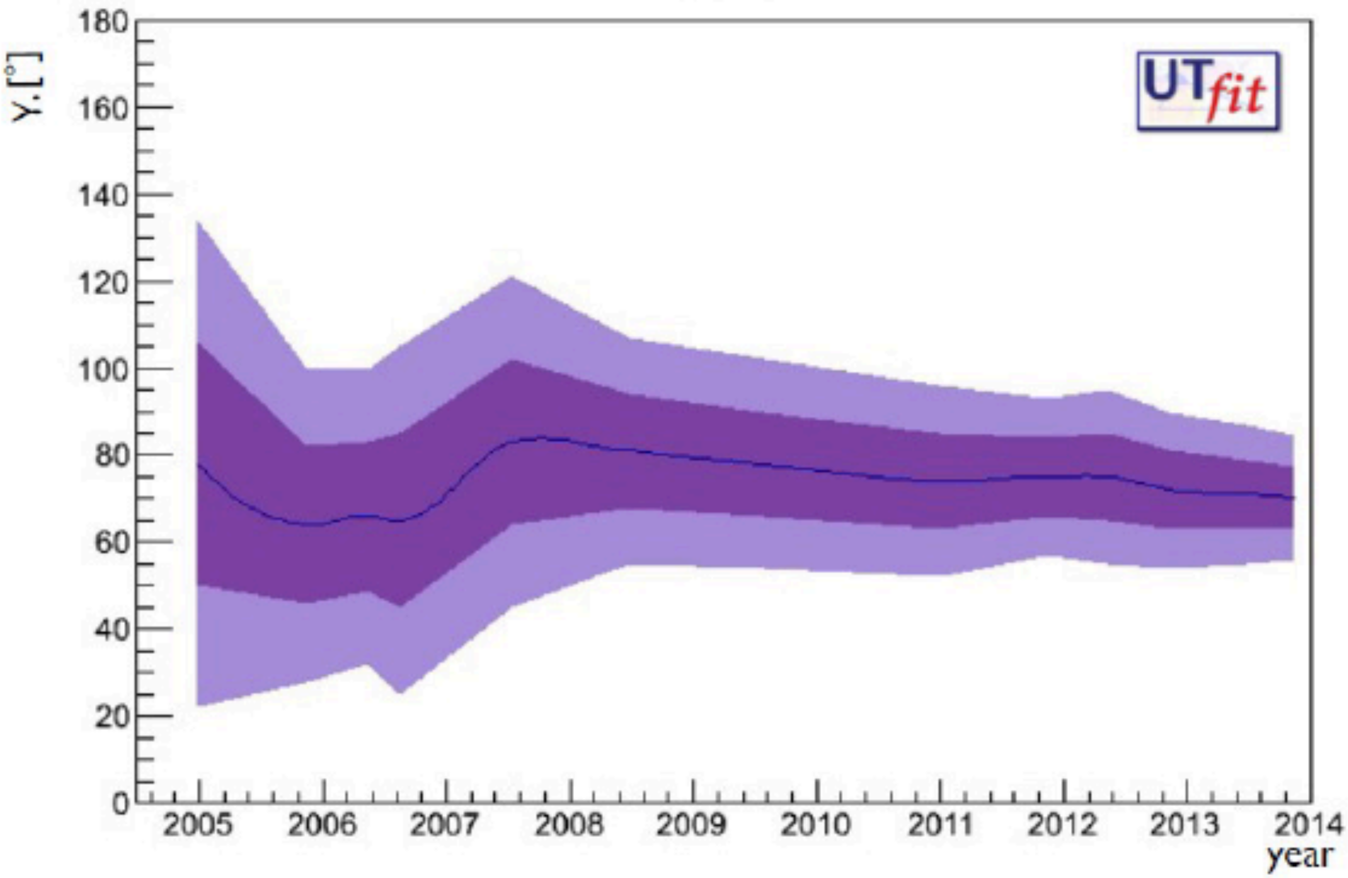


arXiv:1411.1842

Tree-level determination of γ

- γ is the least known angle of the UT
  - sensitivity comes from the interference between $b \to u$ and $b \to c$ tree-level transitions
- Two main paths
  - Time-independent, $B^{\pm} \to DK^{\pm}$, $B^{\pm} \to D\pi^{\pm}$ and $B^0 \to DK^{*0}$ decays
    - $B^+ \to Dh^+$, $D \to hh$, GLW/ADS Phys. Lett. **B712** (2012) 203
    - $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS Phys. Lett. **B723** (2013) 44
    - $B^+ \to DK^+$, $D \to K^0_S hh$, GGSZ JHEP **10** (2014) 097
    - $B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS Phys. Lett. **B733** (2014) 36
    - $B^0 \to DK^{*0}$, $D \to hh$, GLW/ADS Phys. Rev. **D90** (2014) 112002
  - Time-dependent, $B_s \to D_s K$ JHEP **11** (2014) 060
- Possible interplay with charmless *B* decays
  - Also sensitive to γ, but including penguin diagrams → NP could show up, but much more difficult to control theoretically
- Combining several independent decay modes is the key to achieve the ultimate precision

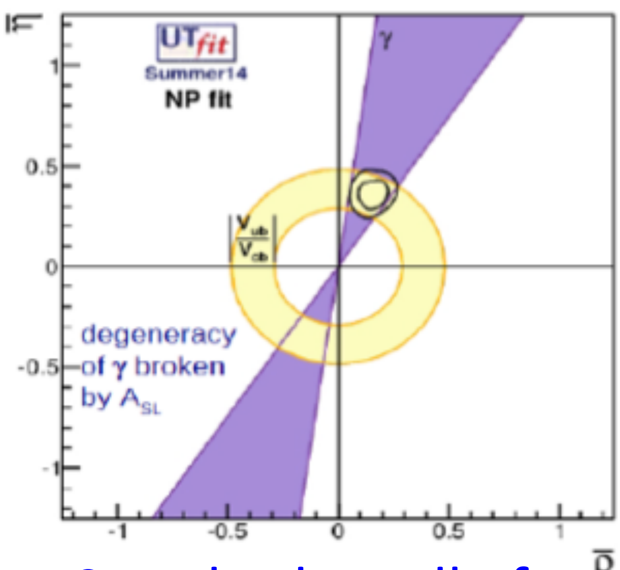
Improvements in γ from tree-level decays over the last decade



A good factor 3 in 10 years, but not yet matching the precision of the indirect determination from CKM fits (~3°)

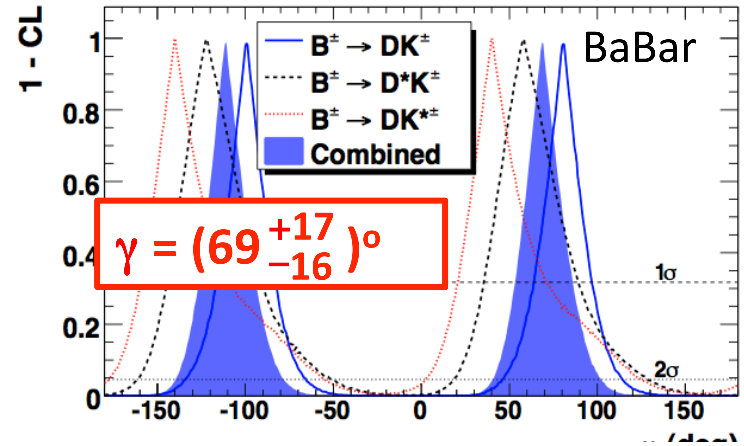
Experimental status for γ

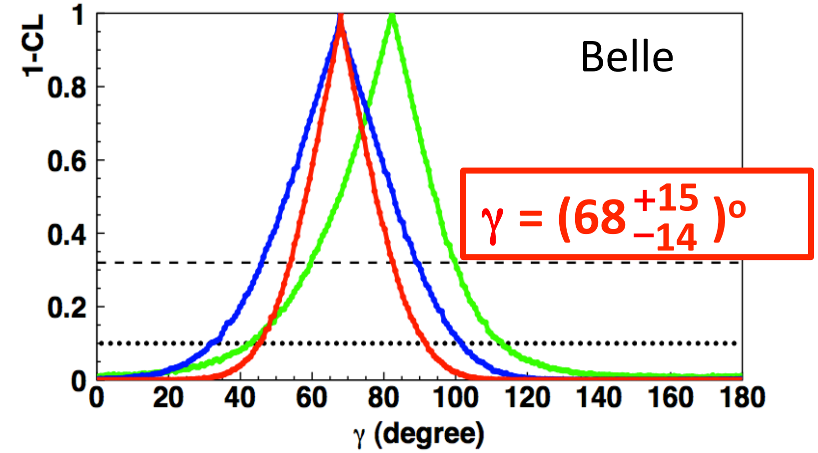
- Measured by BaBar, Belle and LHCb using ADS/GLW and GGSZ methods
  - LHCb is now starting to dominate the world average
    - still some analyses to be updated to 3 fb^{-1}

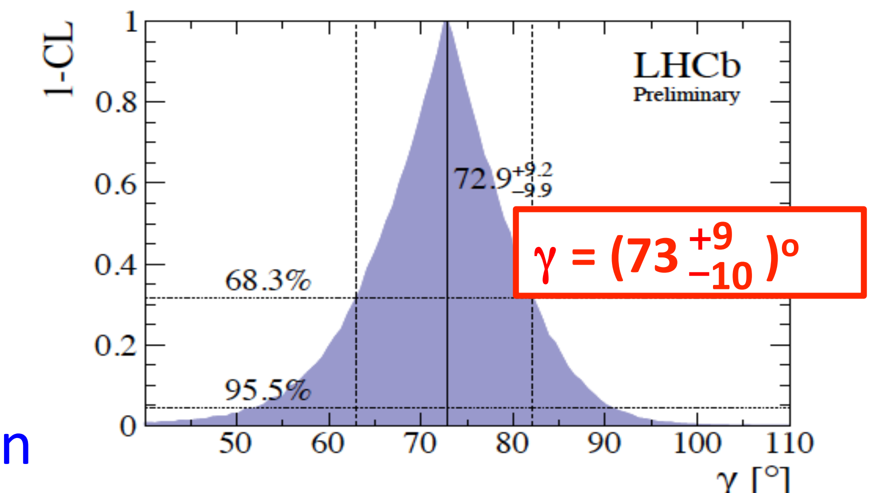


Measurements from tree-level decays are assumed to be almost insensitive to NP effects

Standard candle for the SM, crucial to distinguish between genuine SM and BSM in UT fits



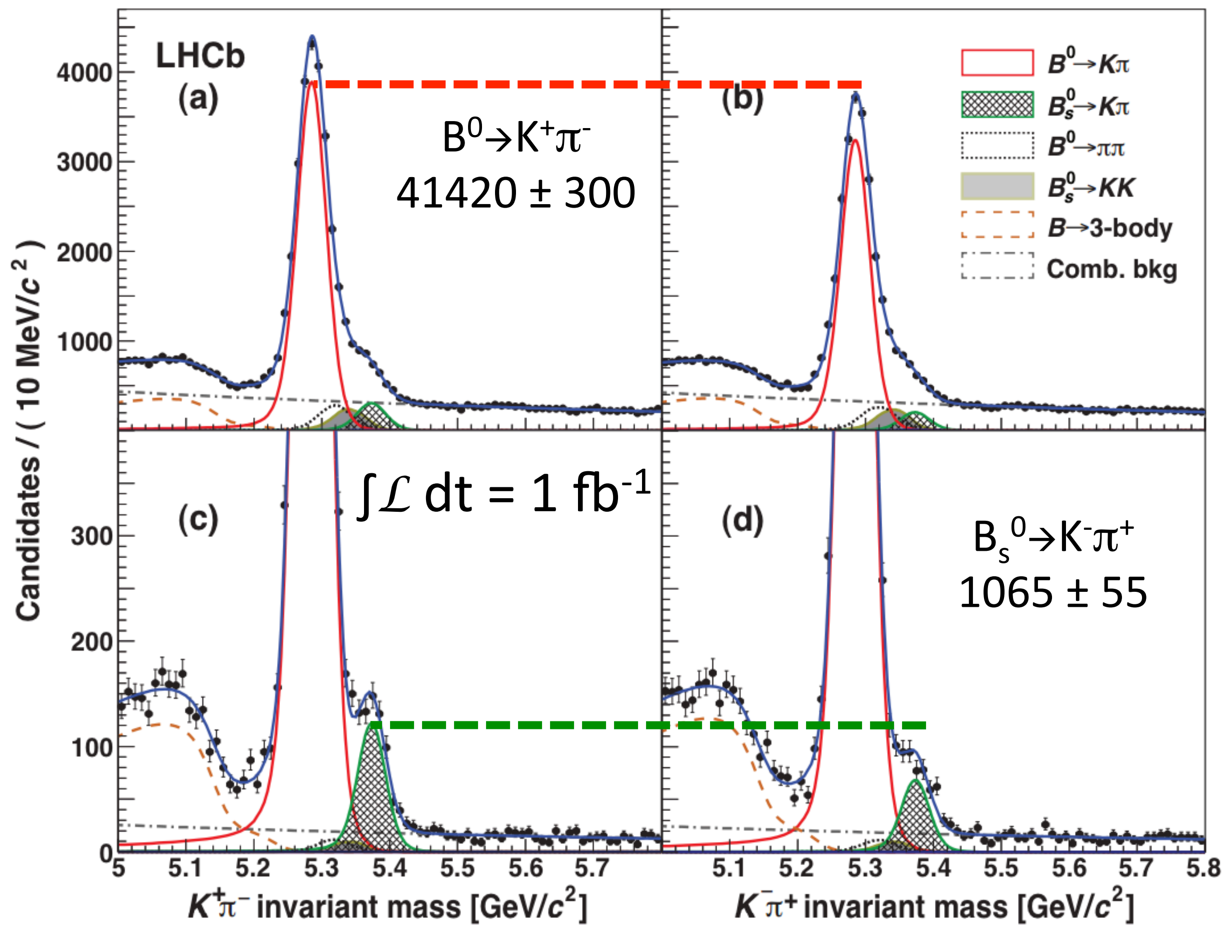




LHCb-CONF-2014-004

Direct *CP* asymmetries in $B^0_{(s)} \to K\pi$ decays

Phys. Rev. Lett. **110** (2013) 221601



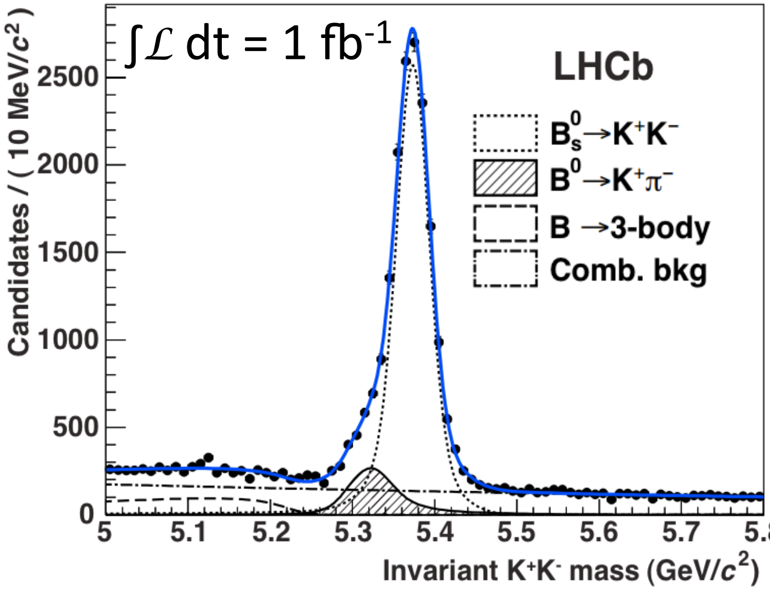
$$A_{CP}(B^0 \to K\pi) = -0.080 \pm 0.007(\text{stat}) \pm 0.003(\text{syst})$$

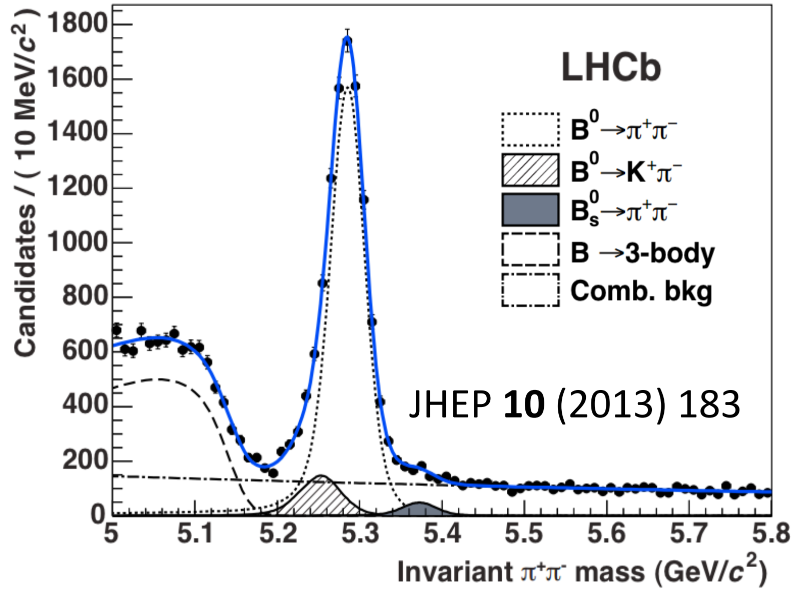
Most precise measurement of this quantity to date, 10.5σ from zero

$$A_{CP}(B_s^0 \to K\pi) = 0.27 \pm 0.04(\text{stat}) \pm 0.01(\text{syst})$$

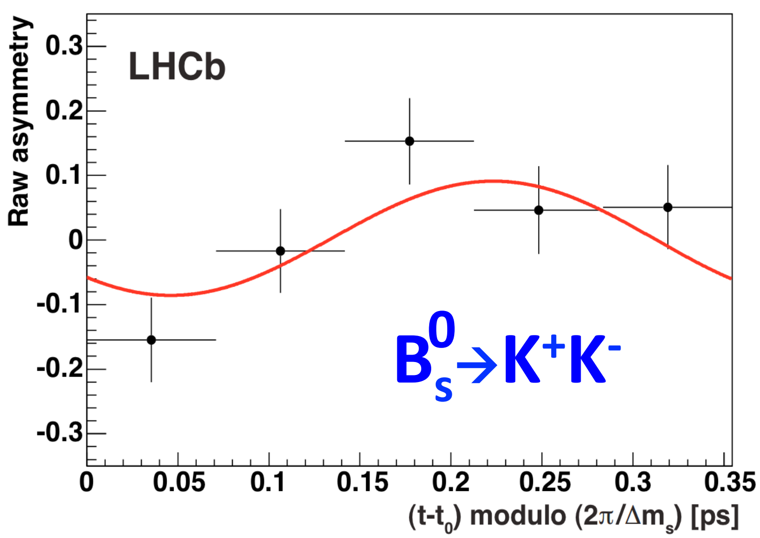
First observation of *CP* violation in B_s decays, with significance of 6.5σ

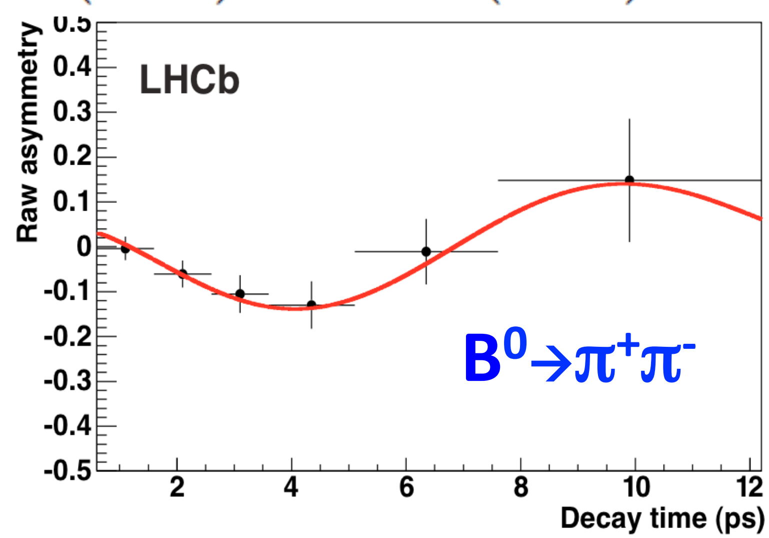
CP violation in $B_s \rightarrow K^+K^-$ and $B^0 \rightarrow \pi^+\pi^-$





$$\mathcal{A}(t) = \frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$





$$C_{KK} = 0.14 \pm 0.11\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$
$$S_{KK} = 0.30 \pm 0.12\,(\mathrm{stat}) \pm 0.04\,(\mathrm{syst})$$

$$C_{\pi\pi} = -0.38 \pm 0.15\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$$
$$S_{\pi\pi} = -0.71 \pm 0.13\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$$

γ and ϕ_s from charmless two-body decays

- Determination of γ and ϕ_s using $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow \pi^0\pi^0$, $B^\pm \rightarrow \pi^\pm\pi^0$ and $B_s \rightarrow K^+K^-$
  - approaches described in Phys. Lett. **B459** (1999) 306 and JHEP **10** (2012) 029
  - based on use of isospin and U-spin symmetries
  - impact of non-factorisable U-spin breaking effects taken into account
- Results published in Phys. Lett. **B741** (2015) 1

$$\gamma = \left(63.5^{+7.2}_{-6.7}\right)^\circ$$

$$\phi_s = -0.12^{+0.14}_{-0.16}\ \mathrm{rad}$$

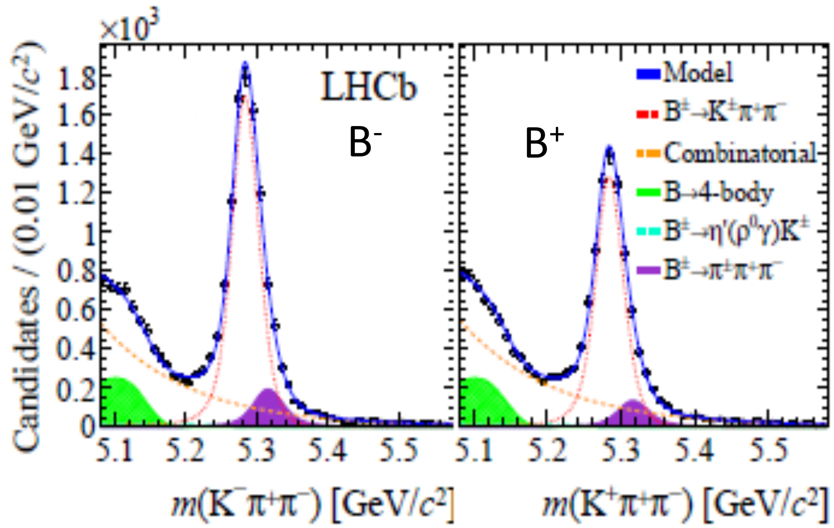
Up to 50% non-factorizable U-spin breaking effects included

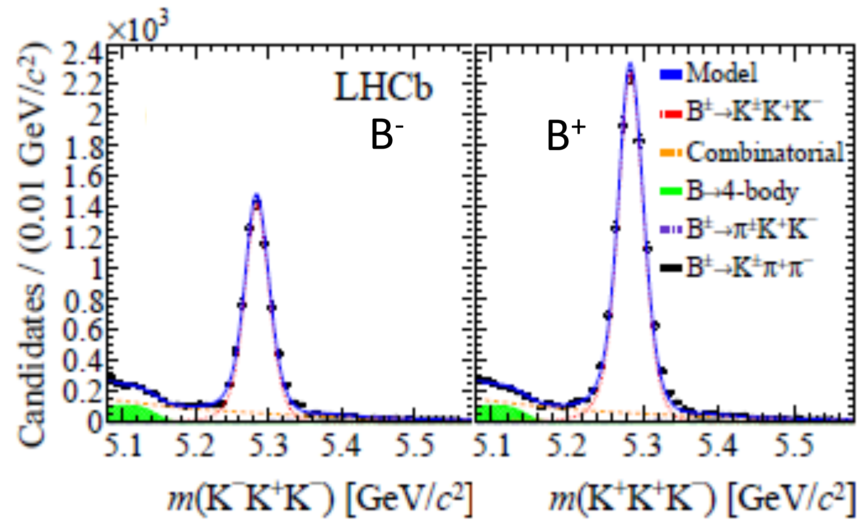
to be updated to 3 fb^{-1}

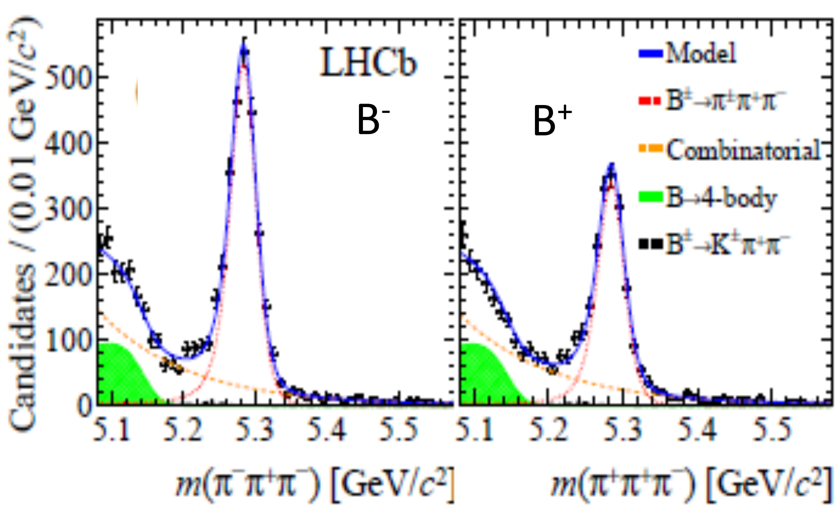
Charmless three-body decays

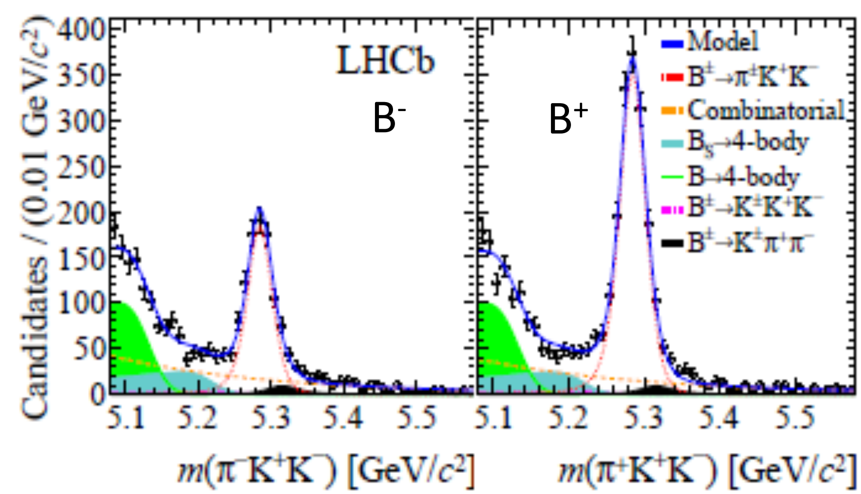
Large asymmetries observed in $B^{\pm} \rightarrow K\pi\pi$ and $B^{\pm} \rightarrow \pi\pi\pi$...

...mirrored when compared with $B^{\pm} \rightarrow KKK$ and $B^{\pm} \rightarrow KK\pi$





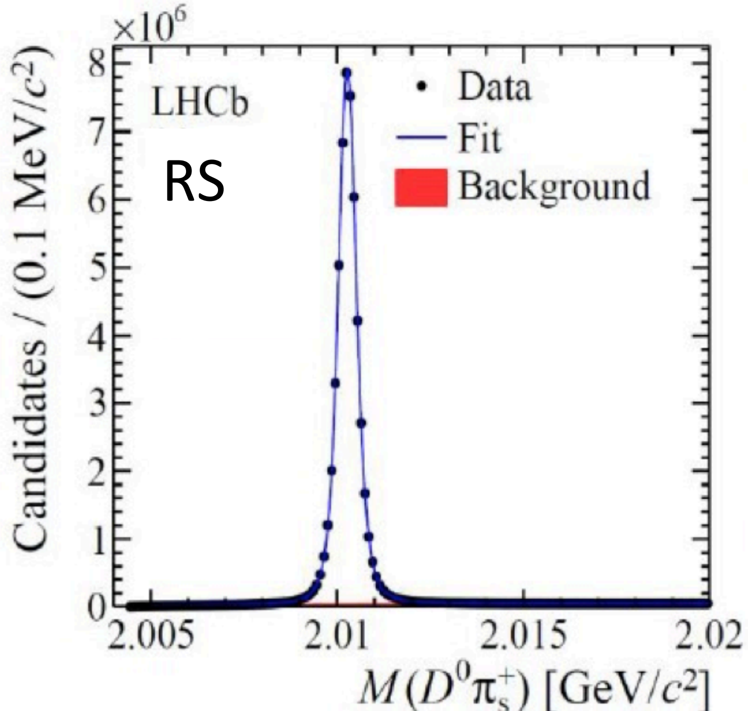




- Huge *CP* violation seen at low $\pi\pi$ and *KK* mass values, not associated to resonances
- Long-distance $\pi\pi \leftrightarrow KK$ rescattering?

Phys. Rev. **D90** (2014) 112004

Mixing in charm decays

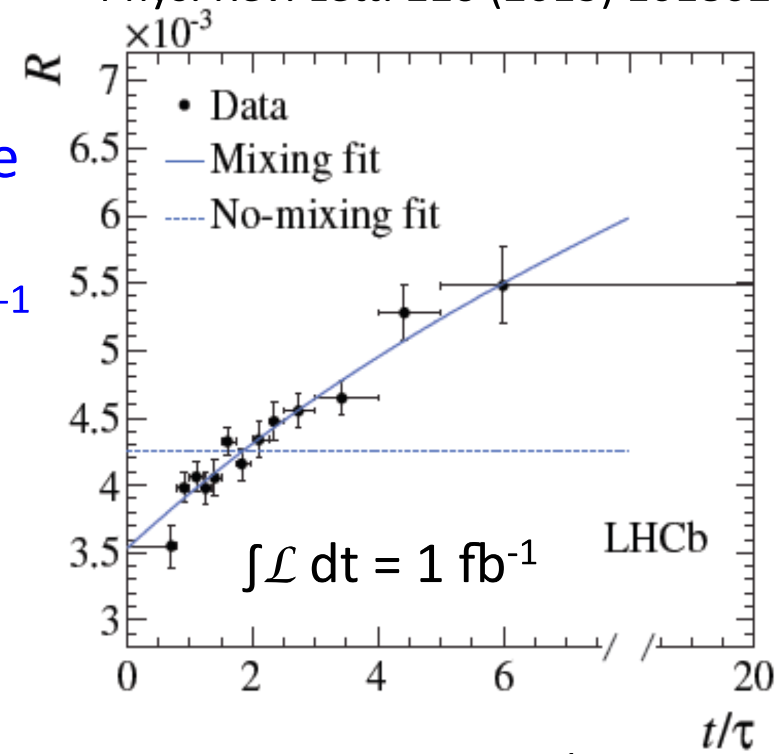


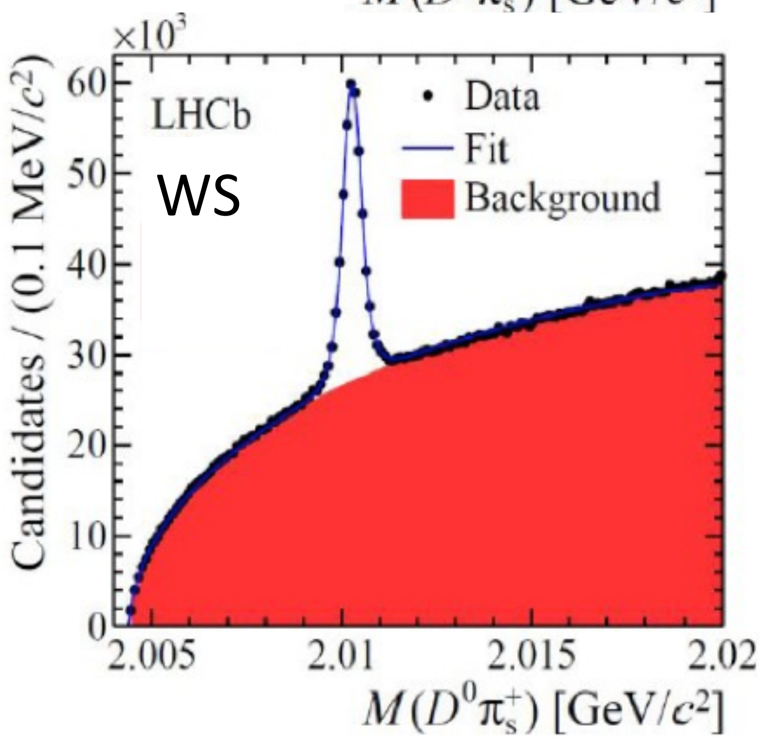
- Measure time-dependent ratio of D^0 decays "wrong sign" to "right sign"

$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

Phys. Rev. Lett. **110** (2013) 101802

No mixing hypothesis is excluded at the 9.1σ level by LHCb with 1 fb^{-1}





- Results then superseded with 3 fb^{-1} in Phys. Rev. Lett. **111** (2013) 251801

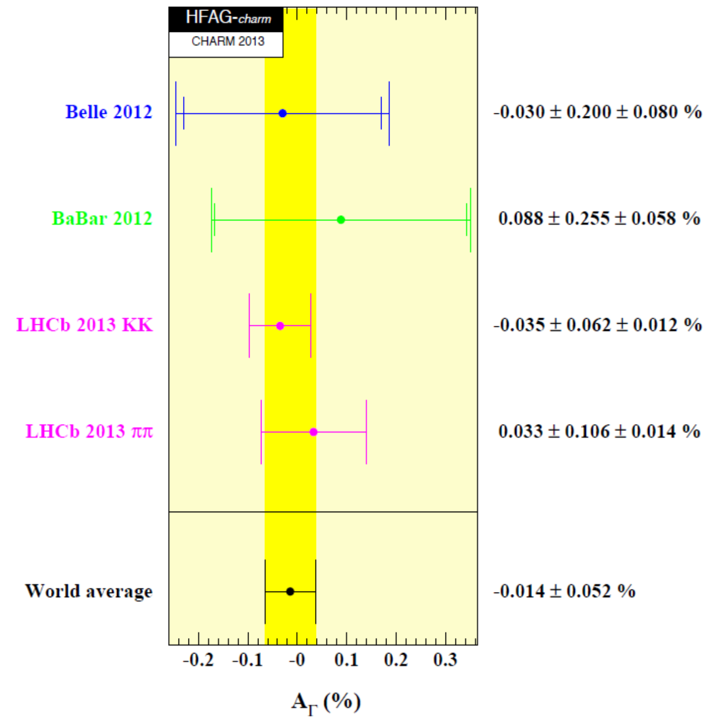
Searches for *CP* violation in D^0 mixing

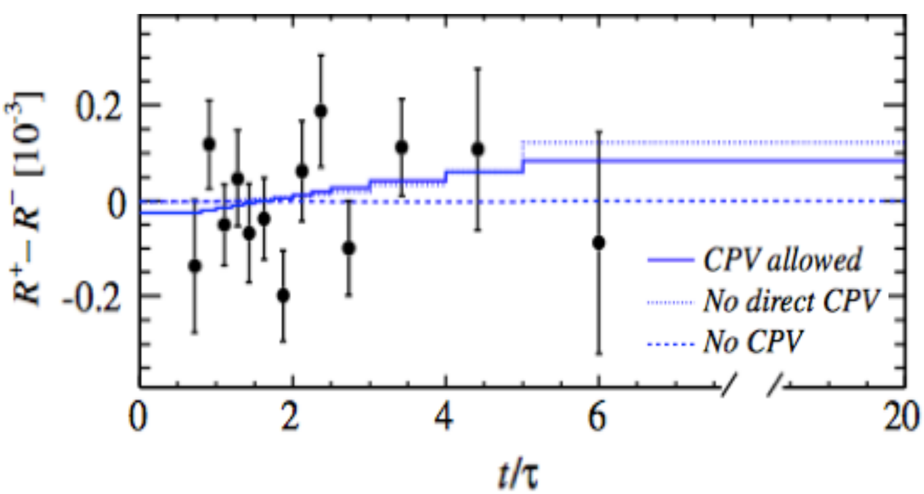
- "Large" mixing encourages searches in this very important sector
  - A nonzero CPV signal would indicate NP
- Searches done with dedicated observables, such as

$$A_\Gamma \equiv \frac{\Gamma(D^0 \to KK) - \Gamma(\overline{D}^0 \to KK)}{\Gamma(D^0 \to KK) + \Gamma(\overline{D}^0 \to KK)}$$

  - Current precision is 0.05% (LHCb driven)

Phys. Rev. Lett. 112 (2014) 041801





- or by generalising the WS $K\pi$ fit to D^0 and $\overline{D}^0$
  - Phys. Rev. Lett. **111** (2013) 251801

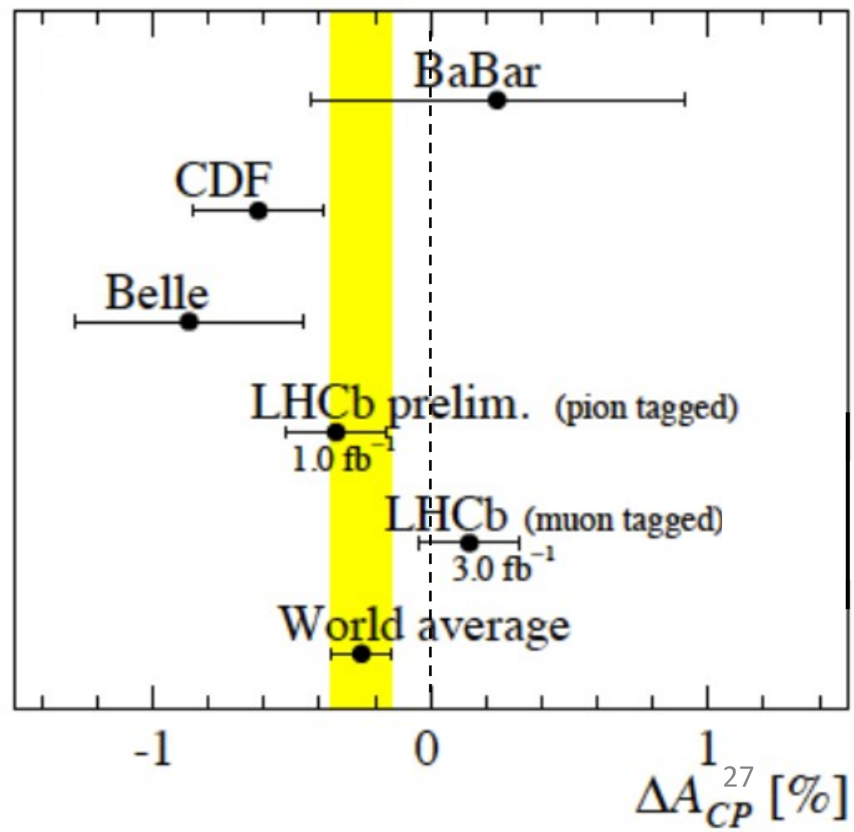
Not yet signs of discrepancies, but very promising on the experimental side

Searches for direct *CP* violation in charm

- $\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$
  - robust observable against detector systematics and production asymmetries
- Early LHCb result [Phys. Rev. Lett. **108** (2012) 111602] with 0.6 fb^{-1} triggered great interest

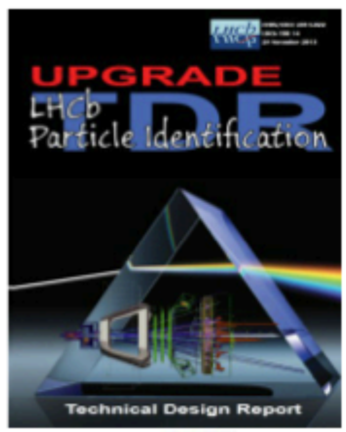
$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$$

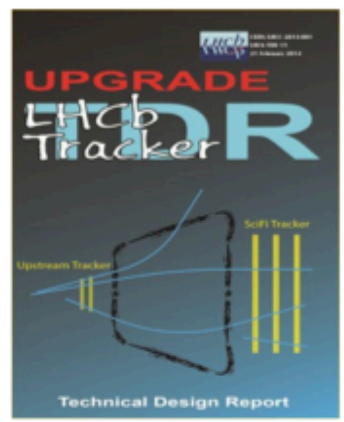
- Also owing to CDF and Belle, a consistent picture was emerging for direct CPV at the 0.5% level
- But LHCb updates later indicated that the effect was reduced
  - 1 fb^{-1} D^* update [CONF-2013-003]
  - 3 fb^{-1} $B \to D^0 \mu X$ [JHEP **07** (2014) 041]
- Final LHCb D^* results from full Run 1 data set coming soon



The LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity with the present detector is the Level-0 (hardware) trigger
  - Level-0 output rate < 1 MHz (readout rate) requires raising thresholds
- To overcome this limitation, LHCb will be upgraded during the 2018-19 shutdown
  - Full software trigger with all sub-detectors readout at 40 MHz
  - Increase operational luminosity to $2 \cdot 10^{33}$ $cm^{-2}s^{-1}$
  - Tracking detectors and RICH photodetectors also need to be upgraded





- All TDRs approved by CERN research board
- Construction going to start soon

Conclusions

- LHCb has performed spectacularly well in Run 1 confirming so far the robustness of the Standard Model
  - No striking smoking guns of NP
    - Areas where we had discrepancies seem now heading back to the SM
  - But many new results to come, and full impact of Run 1 data is still to be seen
- Big improvements will come in Run 2, and much more are expected with the LHCb Upgrade
  - The standard detector will take data till 2018 and the upgraded detector will start taking data in 2020
- Experimental prospects are excellent
  - Key measurements are still far from being limited by systematic uncertainties
- *CP* violation at LHCb has large room for improvements!

Where are we heading?