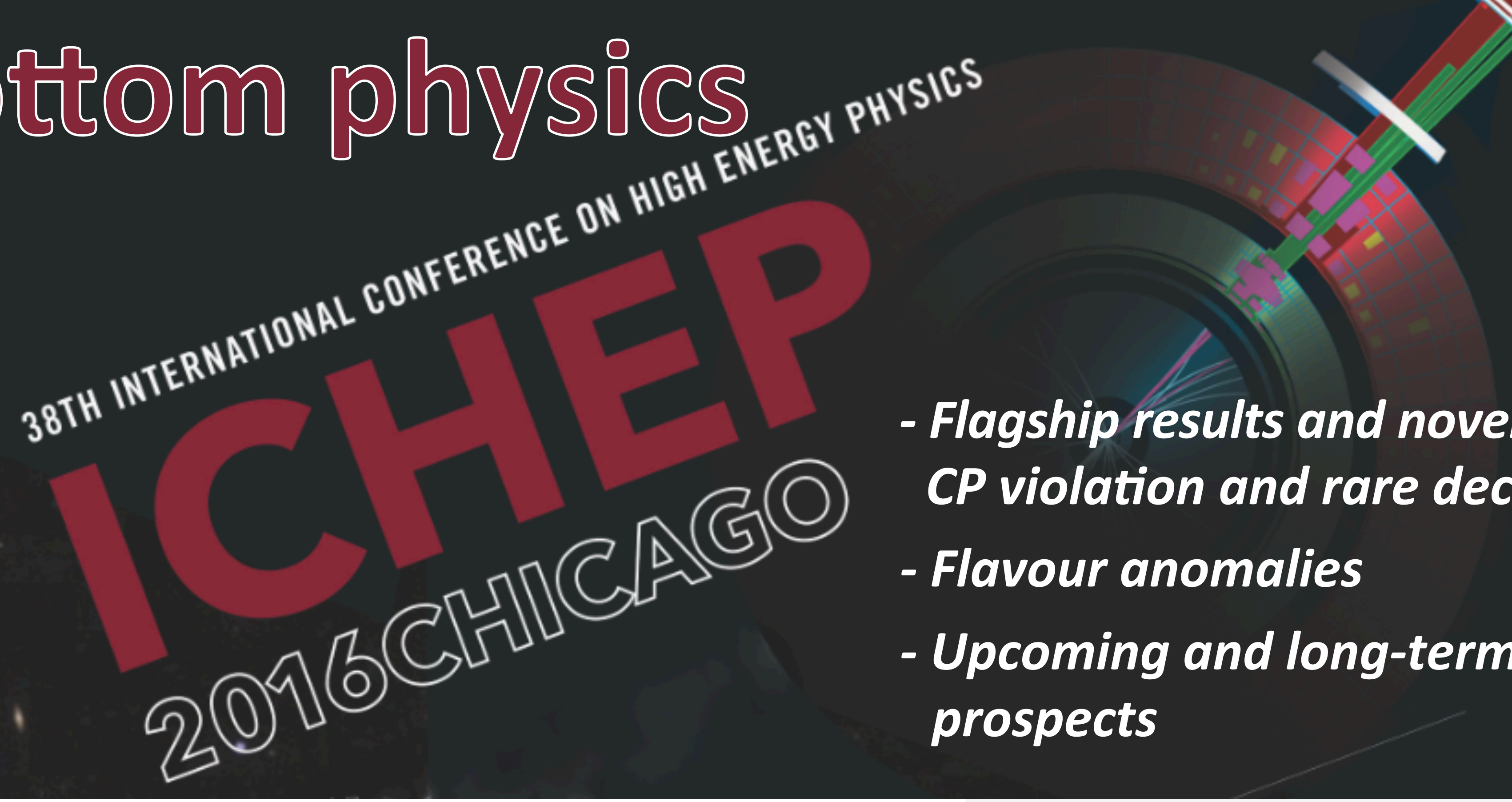
Results and prospects on bottom physics



- *Flagship results and novelties in CP violation and rare decays*
- *Flavour anomalies*
- *Upcoming and long-term prospects*

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CERN and INFN Bologna

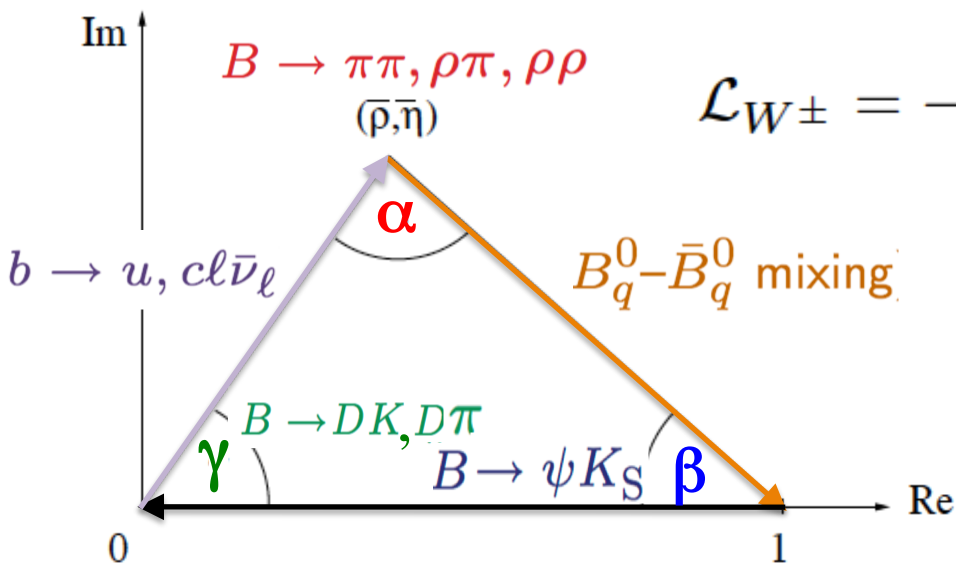
on behalf of the LHCb collaboration
with results from

ATLAS EXPERIMENT, BABAR, BELLE, CDF, CMS, DØ, LHCb

ICHEP2016CHICAGO

The CKM Unitarity Triangle

$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{pmatrix} d & s & b \\ 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} \overline{U}_i \gamma^\mu \frac{1-\gamma^5}{2} (V_{\text{CKM}})_{ij} D_j W_\mu^+ + h.c.$$

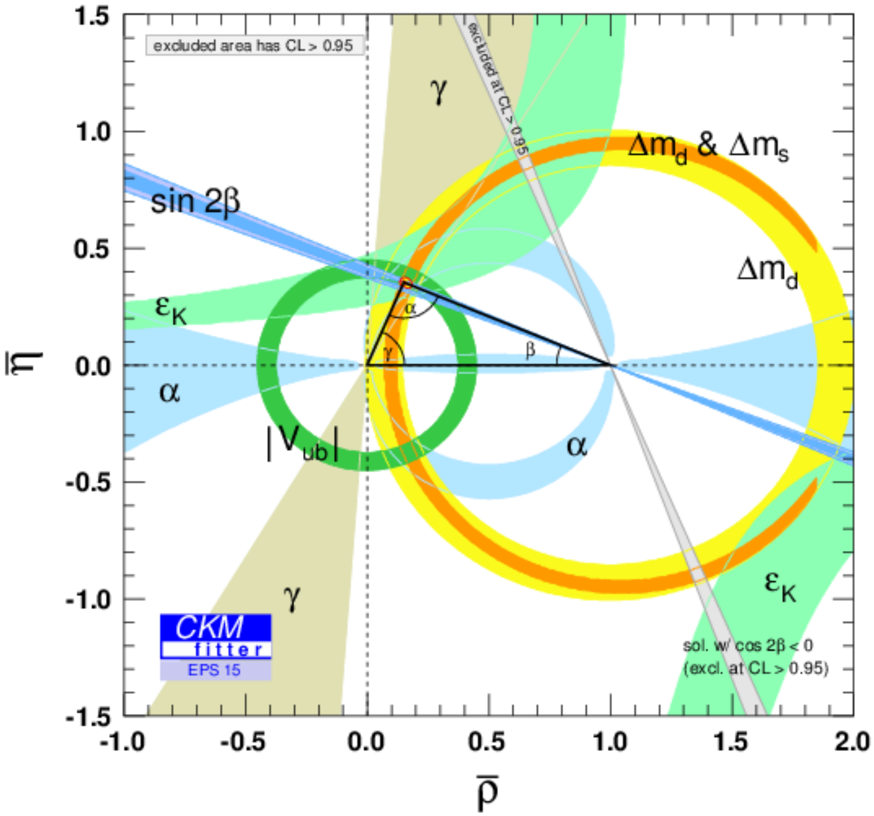
From CKM matrix unitarity

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

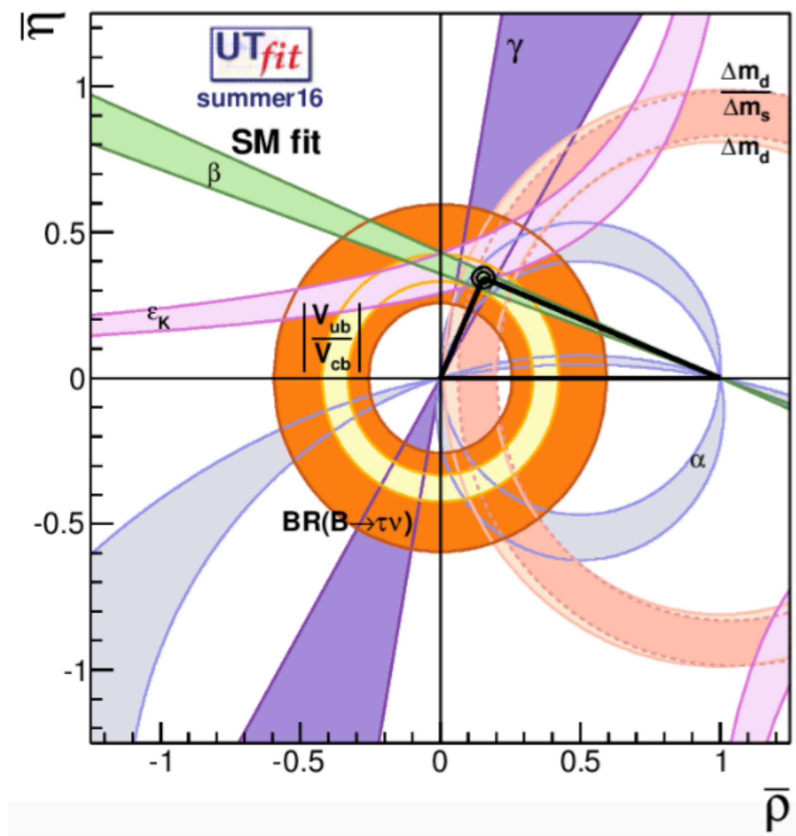
- UT defined by two parameters only → can be overconstrained
- The height (irreducible complex phase $\overline{\eta}$) controls the strength of *CP* violation in the Standard Model

Where we are

http://ckmfitter.in2p3.fr



http://www.utfit.org



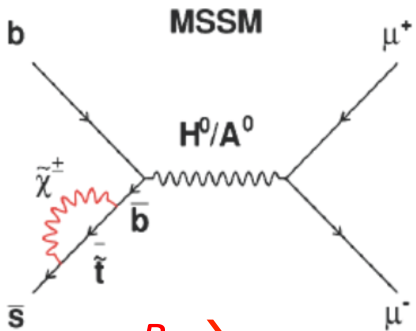
- Don't forget: relevant inputs from Lattice QCD and great work from the Heavy Flavour Averaging Group (http://www.slac.stanford.edu/xorg/hfag)
- Great success of the Standard Model CKM picture!
  - All of the measurements agree in a highly profound way
  - In the presence of relevant New Physics effects, the various contours would not cross each other in a single point
- But...

… physicists are never satisfied!

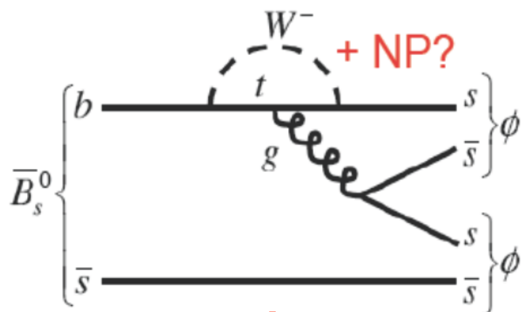
- Although the Standard Model (of particle physics) works beautifully up to a few hundred GeV, it must be an effective theory valid up to some scale Λ
- The good reasons to believe that it is incomplete are still there, e.g.
  – Missing dark matter candidate
  – *CP* violation for dynamical generation of BAU largely insufficient
  – …
- We must search for
  – New particles and interactions
  – New sources of *CP* violation

Precision measurements of *CP* violation and rare decays: why important?

- Instead of searching for NP particles directly produced, look for their indirect effects to low energy processes (e.g. *b*-hadron decays)

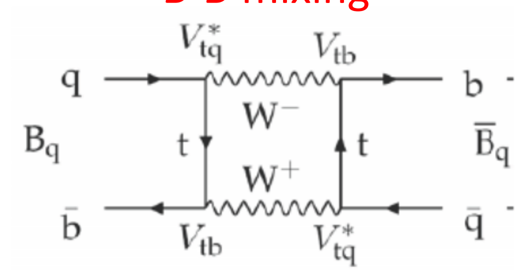


$B_s \rightarrow \mu\mu$



$B_s \rightarrow \phi\phi$

B-$\bar{B}$ mixing



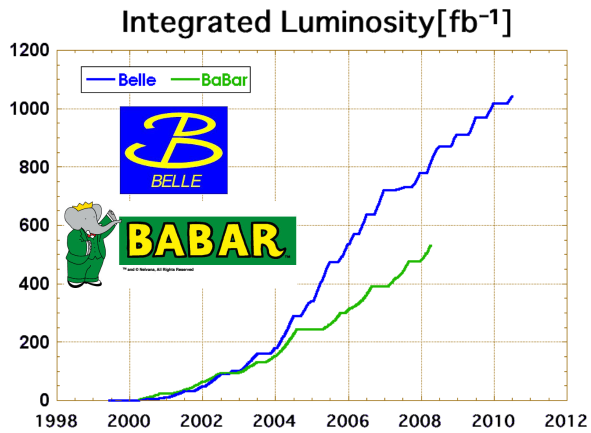
+ NP?

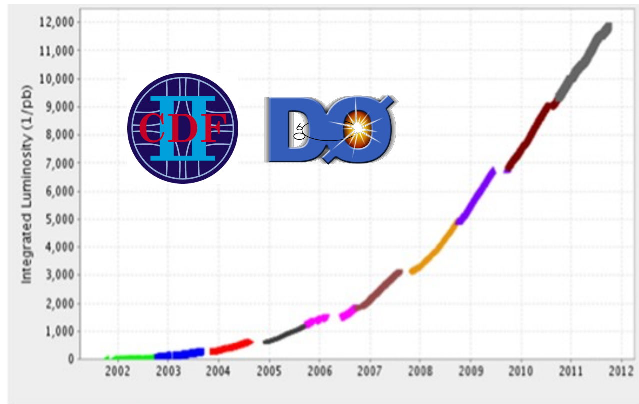
- General amplitude decomposition in terms of couplings and scales → in presence of sizeable SM contributions, NP effects might be hidden
  - Need high precision measurements of theoretically clean observables

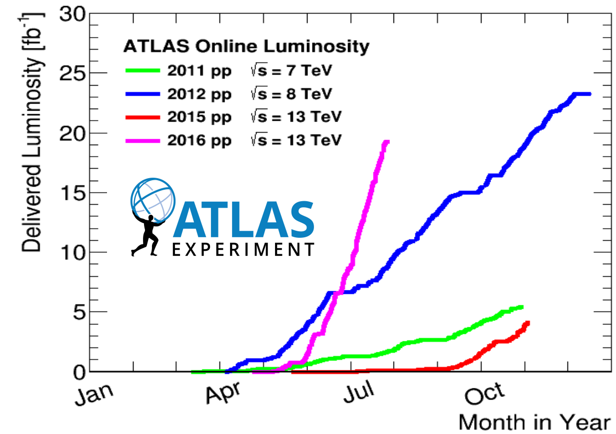
$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

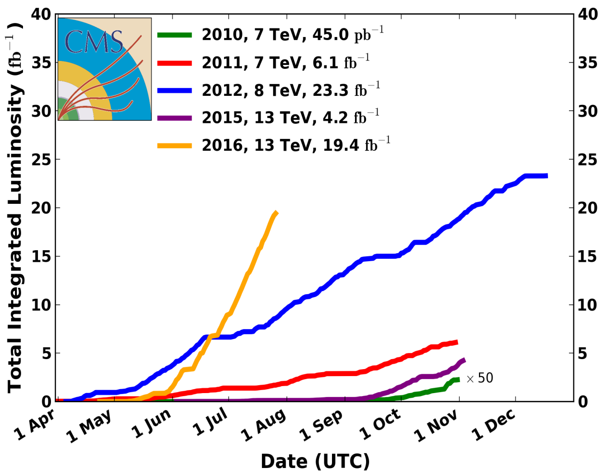
- Note: from present picture in the flavour sector, still room for NP at 10-20%
- Studying *CP*-violating and flavour-changing processes → two fundamental tasks can be accomplished
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly at nowadays colliders

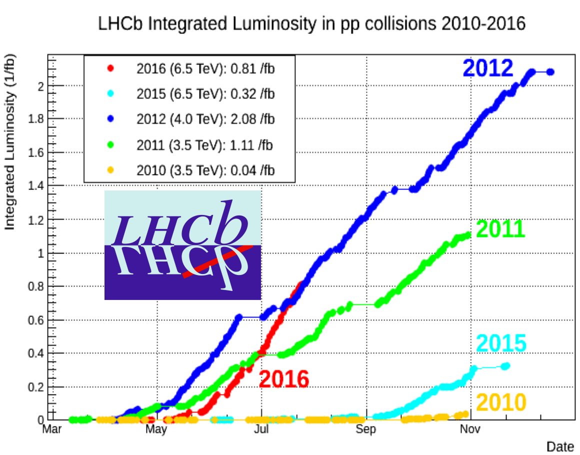
A luminous (and beautiful) world!









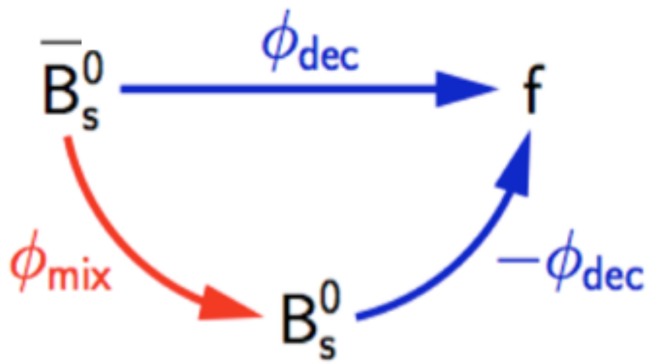


- Several experiments at different machines contributed/contributing to the field in the last 15 years

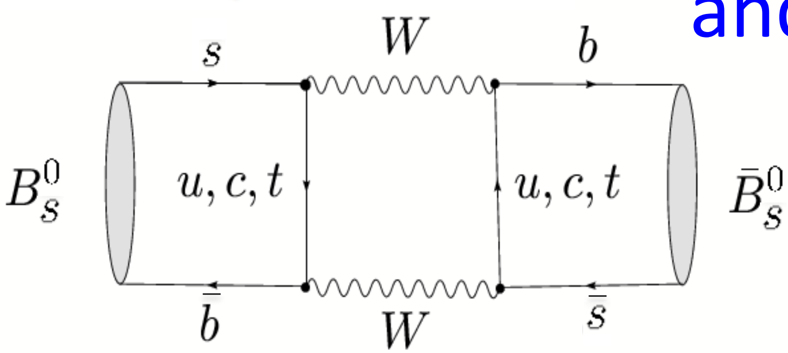
Experiment	$\int \mathscr{L}\, dt$ [fb^{-1}]	σ_{beauty} [μb]	End of life
BaBar	530 (total)	0.001 [e^+e^- at $\Upsilon(4S)$]	2008
Belle	1040 (total)	0.001 [e^+e^- at $\Upsilon(4S)$]	2010
CDF/D0	12 (total)	100 [$p\bar{p}$ at 2 TeV]	2011
ATLAS/CMS	55 (so far)	250-500 [pp at 7-13 TeV]	> 2030
LHCb*	4.2 (so far)	250-500 [pp at 7-13 TeV]	> 2030

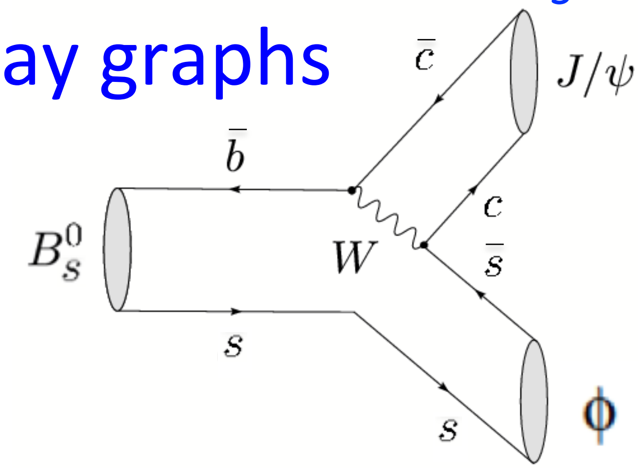
* Forward detector optimised for beauty and charm physics with levelled luminosity to limit pileup effects

One milestone of modern beauty physics



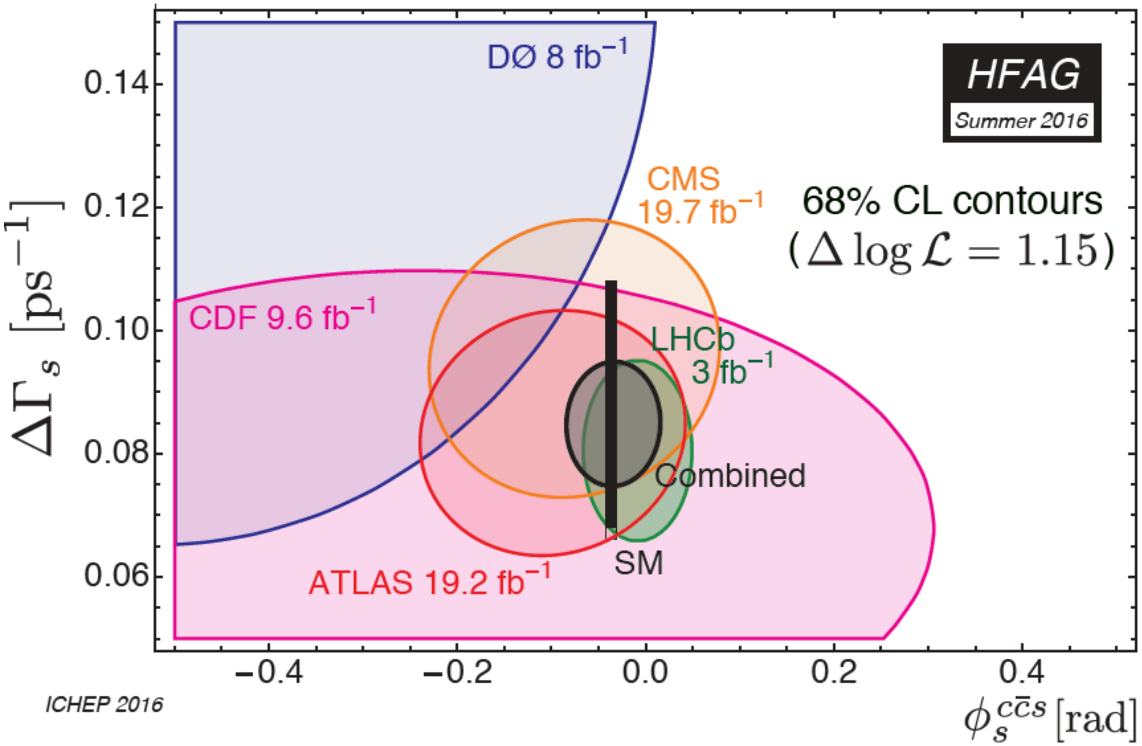
- Golden mode $B_s \to J/\psi\phi$ proceeds (mostly) via a $b \to c\bar{c}s$ tree diagram
- Interference between B_s mixing and decay graphs





- Measures the phase-difference ϕ_s between the two diagrams, precisely predicted in the SM to be $\phi_s = -37.4 \pm 0.7$ mrad → can be altered by New Physics
  – But also affected by small pollution of sub-leading SM amplitudes that must be taken under control

ϕ_s from $b \to c\bar{c}s$ transitions



- Several measurements at the Tevatron and the LHC
- World average
  - ϕ_s = –30 ± 33 mrad
- Still compatible with the SM at the present level of precision

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	9.6 fb^{-1}	$[-0.60, +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	Phys. Rev. Lett. **109**, 171802 (2012)
D0	$J/\psi\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	Phys. Rev. **D85**, 032006 (2012)
ATLAS	$J/\psi\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	Phys. Rev. **D90**, 052007 (2014)
ATLAS	$J/\psi\phi$	14.3 fb^{-1}	$-0.123 \pm 0.089 \pm 0.041$	$+0.096 \pm 0.013 \pm 0.007$	arXiv:1601.03297
ATLAS	above 2 combined		$-0.098 \pm 0.084 \pm 0.040$	$+0.083 \pm 0.011 \pm 0.007$	arXiv:1601.03297
CMS	$J/\psi\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	Phys. Lett. **B757**, 97–120 (2016)
LHCb	$J/\psi K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$	Phys. Rev. Lett. **114**, 041801 (2015)
LHCb	$J/\psi\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	Phys. Lett. **B736**, 186 (2014)
LHCb	above 2 combined		-0.010 ± 0.039(tot)	—	Phys. Rev. Lett. **114**, 041801 (2015)
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	Phys. Rev. Lett. **113**, 211801 (2014)

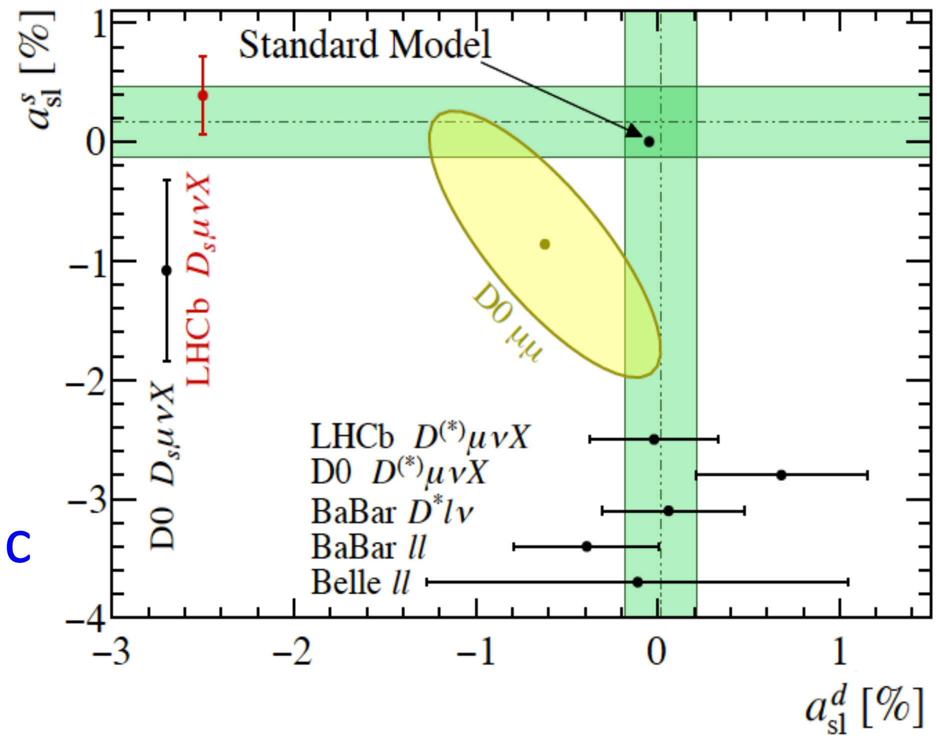
+ latest LHCb result with $B_s \to \psi(2S)\phi$ [LHCb-PAPER-2016-027 in preparation]

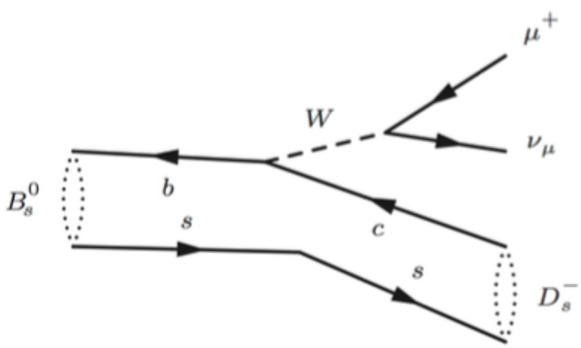
CP violation in B_s-$\bar{B}_s$ mixing

- *CP* violation in neutral *B*-meson mixing manifests itself if

$$\mathcal{P}(B_q \to \bar{B}_q) \neq \mathcal{P}(\bar{B}_q \to B_q)$$

- Interest triggered by a measurement from D0 yielding an anomalous like-sign dimuon asymmetry
  - PRD 89 (2014) 012002
- Precise measurements of semileptonic asymmetries from LHCb do not confirm the anomaly
- Latest measurement of $a_{sl}(B_s)$ using $B_s \to D_s(KK\pi)\mu\nu X$ decays





$$\frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)}$$

Note: $a_{sl}(B_d)$ and $a_{sl}(B_s)$ are very small in the SM

$$a^s_{sl} = (2.22 \pm 0.27) \times 10^{-5} \text{ for } B^0_s$$

$$a^d_{sl} = (-4.7 \pm 0.6) \times 10^{-4} \text{ for } B^0$$

Artuso, Borissov, Lenz [arXiv:1511.09466]

PRL 117 (2016) 061803

$$a^s_{sl} = (0.39 \pm 0.26(\text{stat}) \pm 0.20(\text{syst}))\%$$

Some novelties in the B^0-$\bar{B}^0$ system too

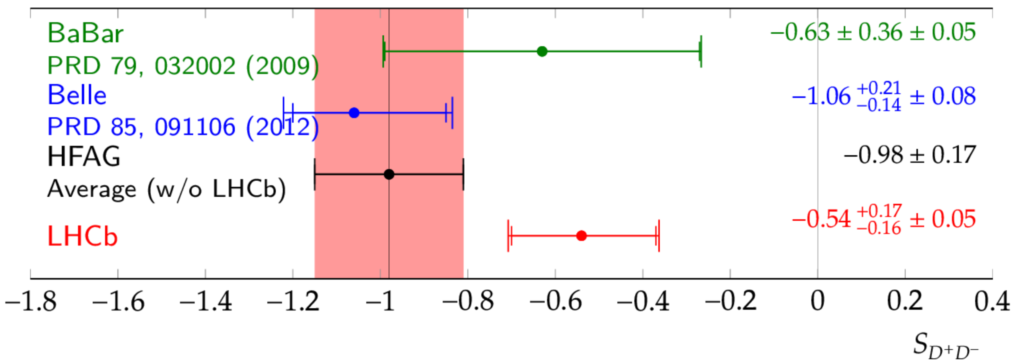
- LHCb measures time-dependent *CP* violation in the $B^0 \rightarrow D^+D^-$ decay
  - Complementary information on $\sin 2\beta$ through $b \rightarrow c\bar{c}d$ transitions
  - Comparison with $B^0 \rightarrow J/\psi K_S$ constrains penguin contributions to $B \rightarrow DD$
- Consistent with SM and no penguin pollution
  - i.e. $S \approx -0.75$ ($-\sin 2\beta$) and C=0

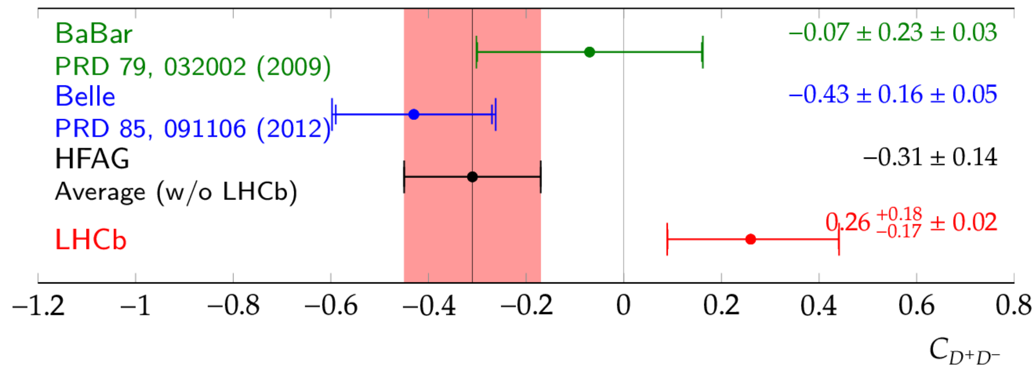
$$A_{DD}(t) = \frac{\Gamma(\overline{B}^0(t) \to D^+D^-) - \Gamma(B^0(t) \to D^+D^-)}{\Gamma(\overline{B}^0(t) \to D^+D^-) + \Gamma(B^0(t) \to D^+D^-)} = S_{CP}\sin(\Delta m_d t) - C_{CP}\cos(\Delta m_d t)$$

$$S_{CP} = -0.54\,^{+0.17}_{-0.16}\,(\mathrm{stat}) \pm 0.05(\mathrm{sys})$$

$$C_{CP} = 0.26\,^{+0.18}_{-0.17}\,(\mathrm{stat}) \pm 0.02(\mathrm{sys})$$

LHCb-PAPER-2016-037 in preparation





- New measurement of width difference $\Delta\Gamma_d/\Gamma_d$ by ATLAS
  - Comparing decay-time distributions of $B^0 \rightarrow J/\psi K_S$ and $B^0 \rightarrow J/\psi K^{*0}$

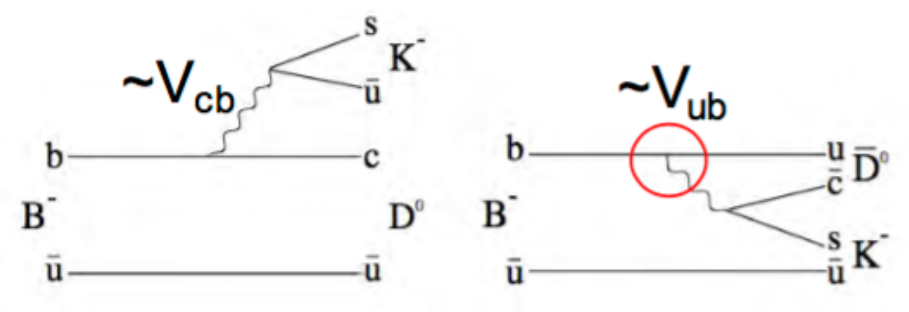
$$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1\ (\mathrm{stat.}) \pm 0.9\ (\mathrm{syst.})) \times 10^{-2}$$

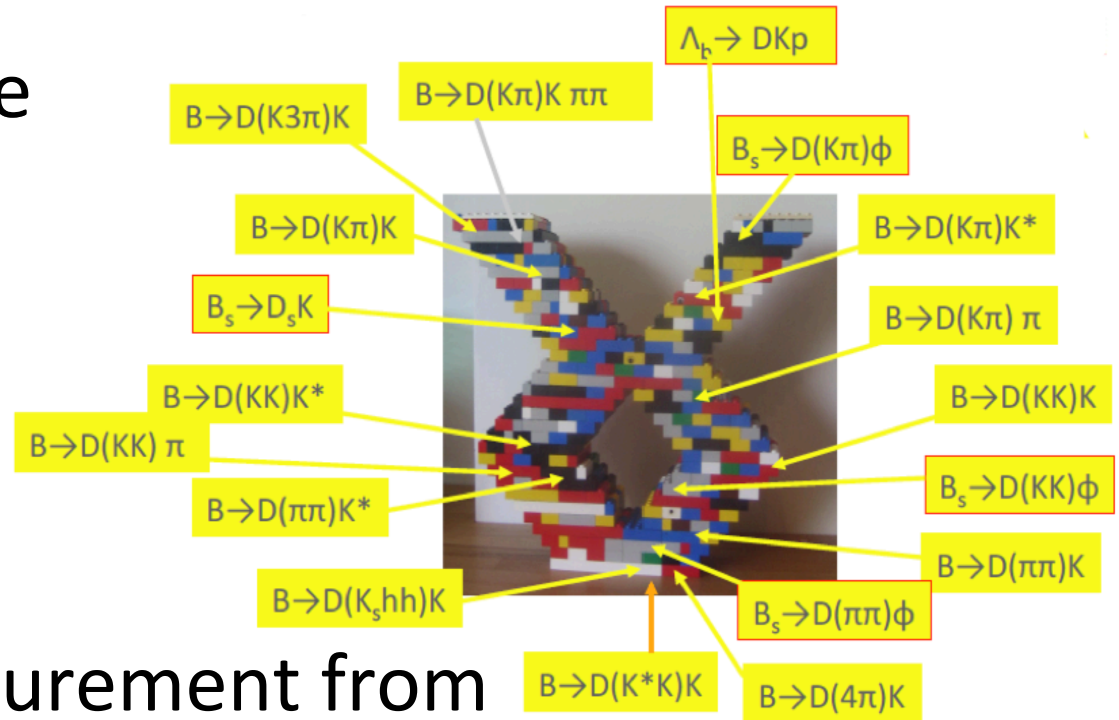
JHEP 06 (2016) 081, SM-like

- Most precise single measurement of $\Delta\Gamma_d/\Gamma_d$ to date

Tree-level determination of γ

- γ is the least known angle of the Unitarity Triangle





- Theoretically clean measurement from tree-level transitions → genuine experimental effort!
- Two main routes
  - Time-independent measurements, e.g. using *B*→*DK* decays
  - Time-dependent analyses with B_s decays, e.g. $B_s \to D_s K$
- Combining a plethora of independent decay modes is the key to achieve the ultimate precision

Experimental status for γ

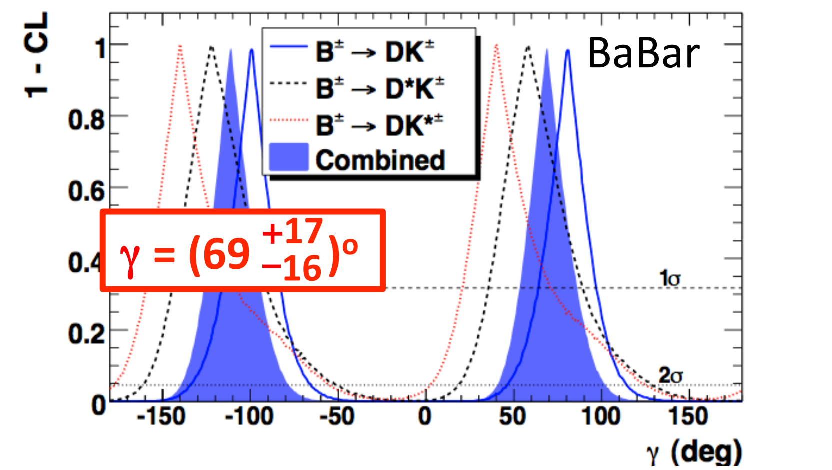
- New combination of all available measurements from LHCb

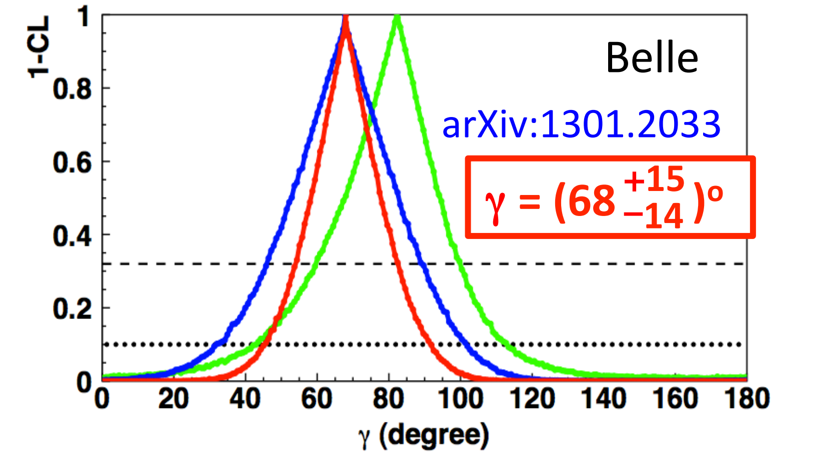
LHCb measurements used in the combination

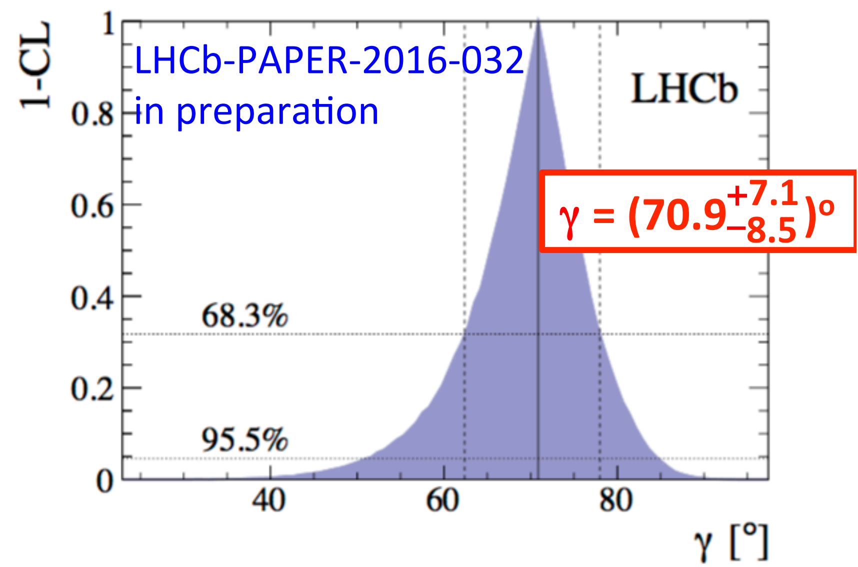
B decay	D decay	Method
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD

- Significantly more precise than previous results from the *B*-factories and the Tevatron

Phys. Rev. **D87** (2013) 052015





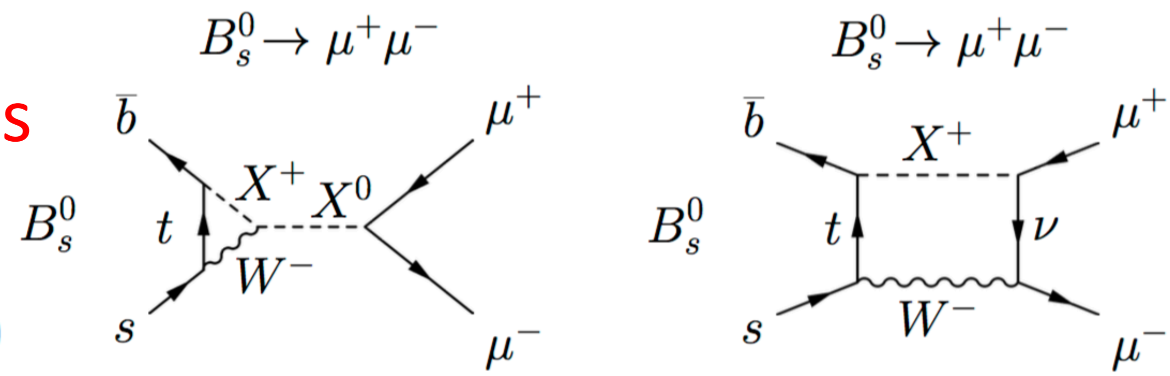


Rare decays as another avenue to New Physics
$B_{d,s} \to \mu^+\mu^-$ from CMS and LHCb

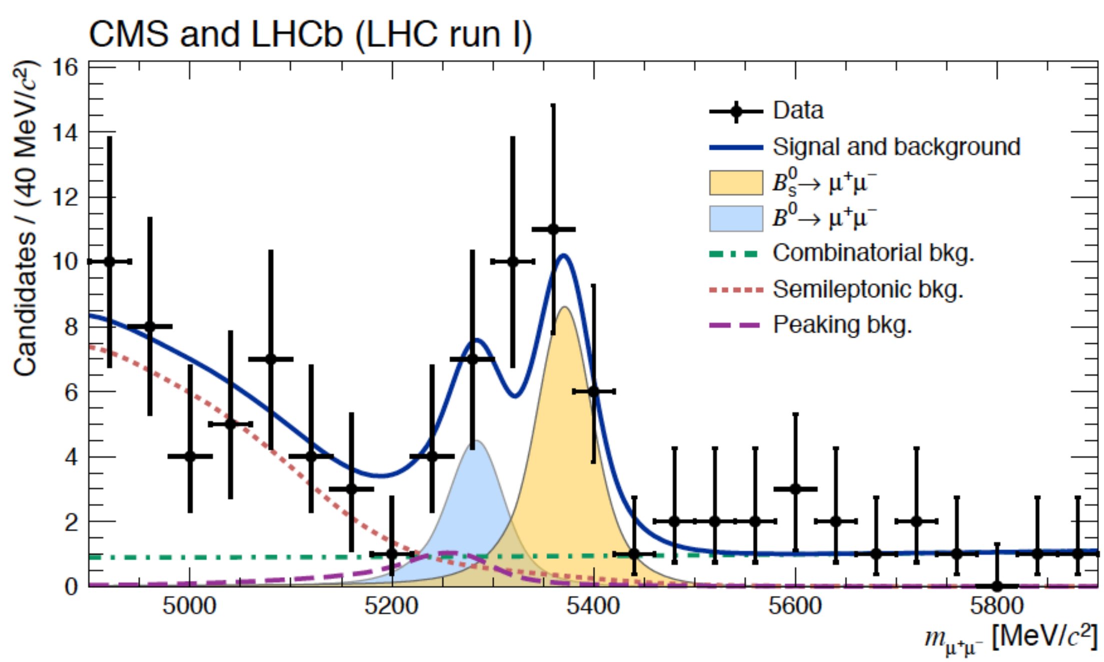
- CMS and LHCb have performed a combined fit to their full Run 1 data sets

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

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



- $B_s \to \mu\mu$ 6.2σ significance was first observation
  - Compatibility with the SM at 1.2σ
- Excess of events at the 3σ level observed for the $B^0 \to \mu\mu$ hypothesis with respect to background-only
  - Compatible with SM at 2.2σ



Nature 522 (2015) 68

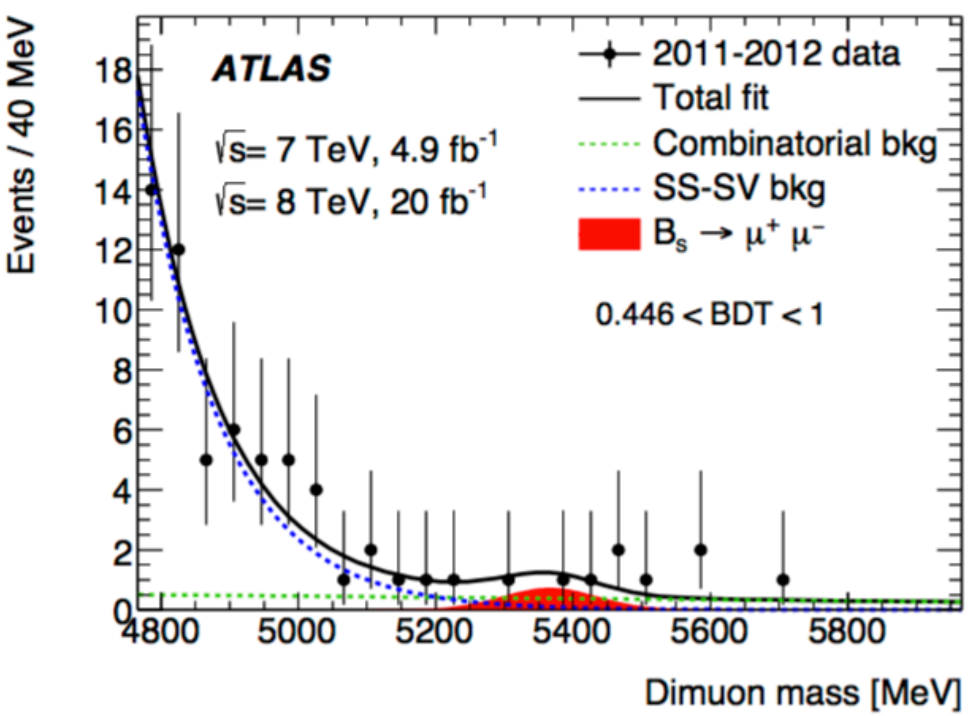
$B_{d,s} \rightarrow \mu^+\mu^-$ searches at ATLAS

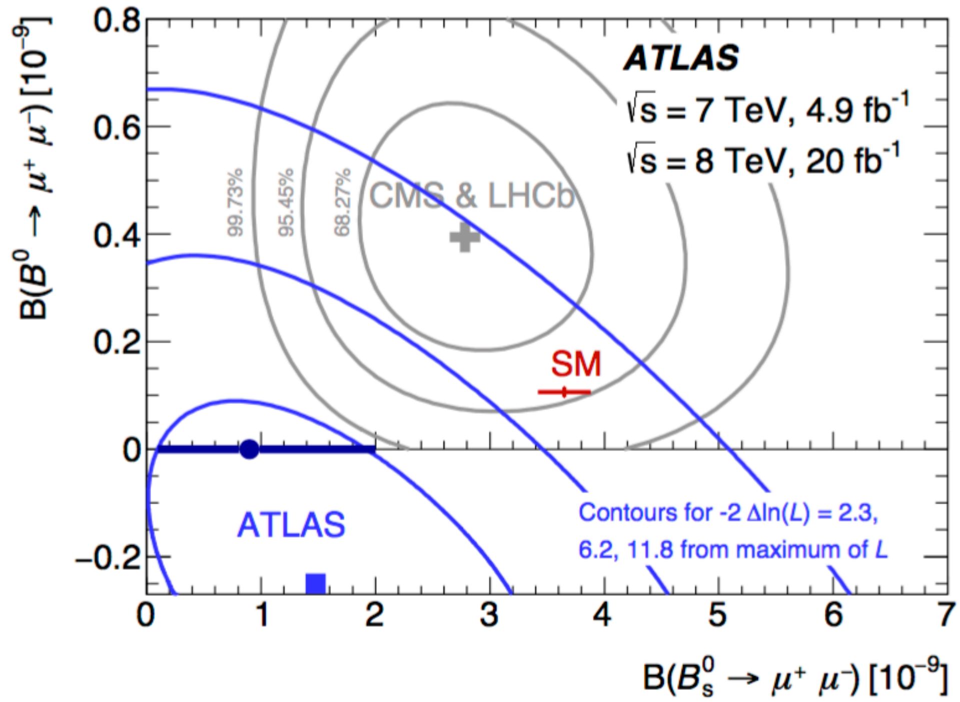
- Recently also ATLAS published their searches with the full Run-1 dataset
  - No significant signal is seen
  - A *p*-value of 4.8% is found for the compatibility of the results with the SM prediction

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(0.9^{+1.1}_{-0.8}\right) \times 10^{-9}$$

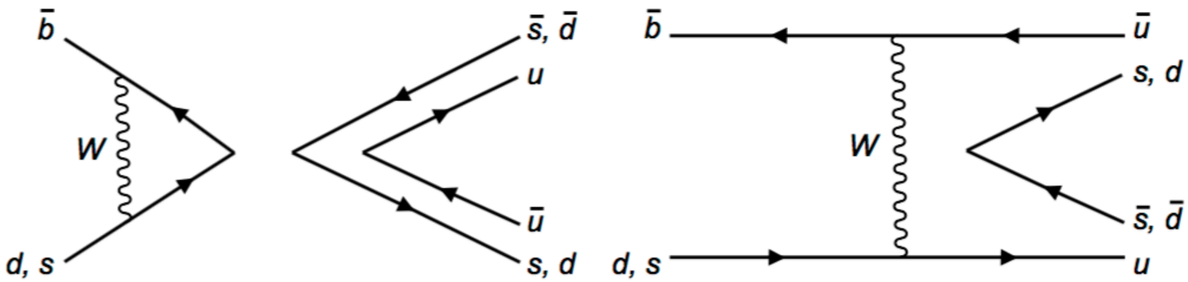
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ (95\% CL)}$$

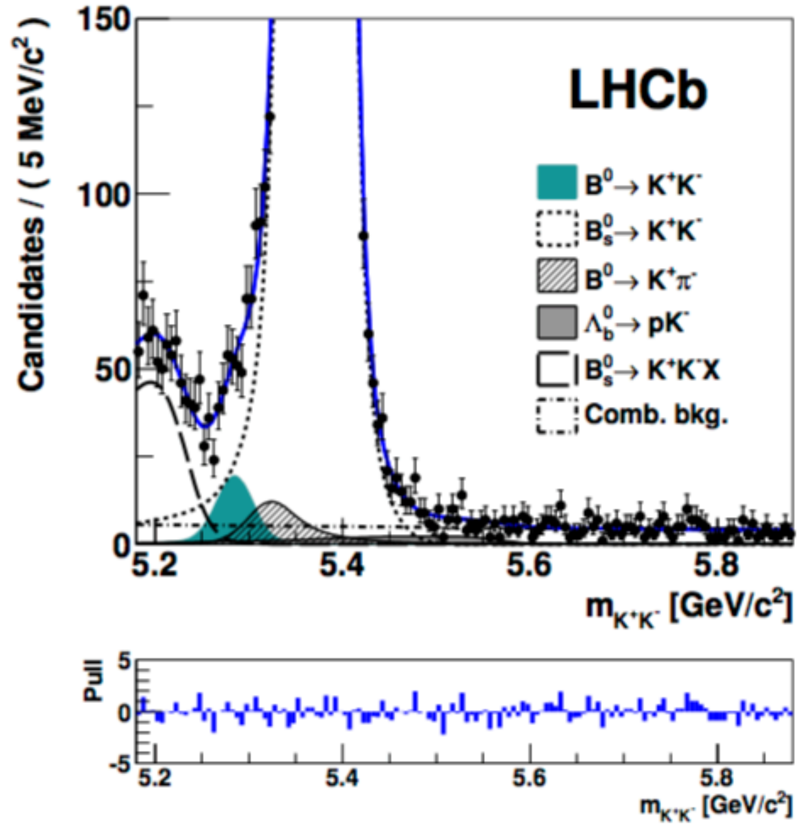
arXiv:1604.04263





Charmless rare decays from LHCb





- Particular class of decays that can proceed only through so-called annihilation diagrams
  - Very useful to test QCD calculations
- $B^0 \to K^+K^-$ decay observed for the first time after many years of searches
  - Significance 5.8σ

$$\mathcal{B}(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8},$$

$$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

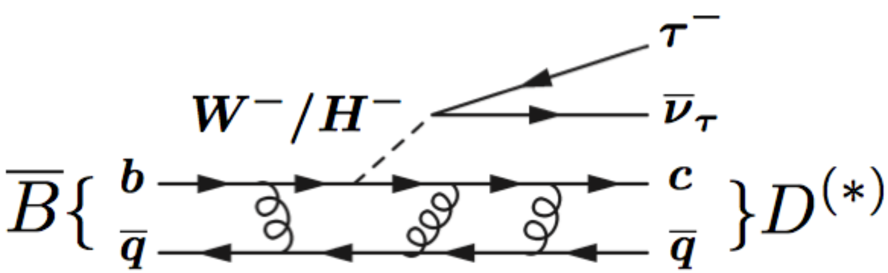
- The $B^0 \to K^+K^-$ is the rarest *B*-meson decay into a fully hadronic final state ever observed

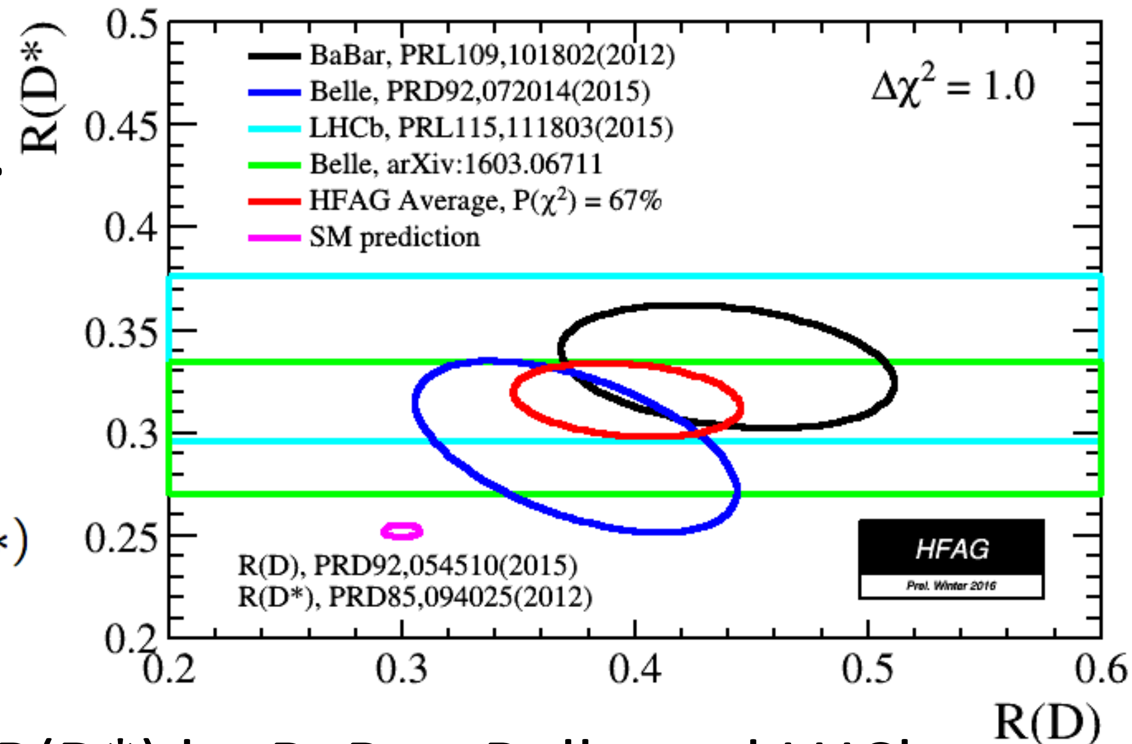
LHCb-PAPER-2016-036 in preparation

At the dawn of a revolution?

Lepton Flavour Universality in $B \rightarrow D^{(*)}\tau\nu$

- Ratio $R_D^{(*)} = BR(B \rightarrow D^{(*)}\tau\nu) / BR(B \rightarrow D^{(*)}\mu\nu)$ is sensitive e.g. to charged Higgs scenarios





- Measurements of R(D) and R(D*) by BaBar, Belle and LHCb
  - Overall average shows a 4σ discrepancy from the SM
- The ball is mainly in the experiments' court!
  - But also theory is at work

New result on $B \to D^{(*)}\tau\nu$ from Belle

– $\mathcal{R}(D^*) = 0.302 \pm 0.030(\text{stat}) \pm 0.011(\text{syst})$

Submitted to PRD
(arXiv:1607.07923)

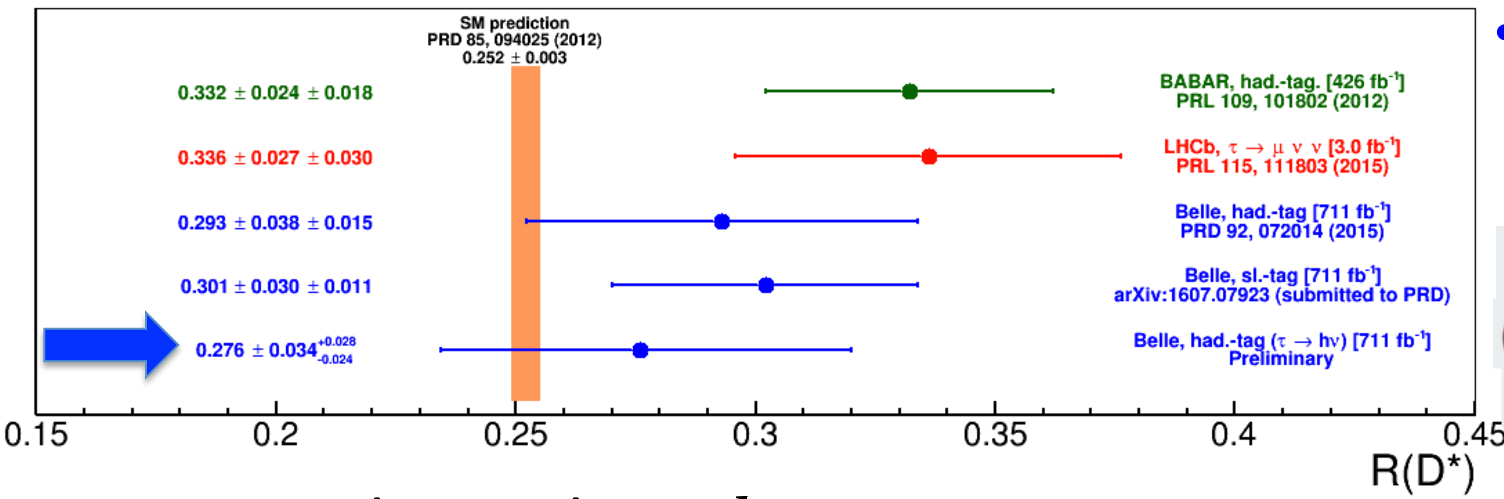
- First measurement of $\mathcal{R}(D^*)$ using semileptonic tag.

– $\mathcal{R}(D^*) = 0.276 \pm 0.034(\text{stat})^{+0.029}_{-0.026}(\text{syst})$

– $\mathcal{P}_\tau = -0.44 \pm 0.47(\text{stat})^{+0.20}_{-0.17}(\text{syst})$

Preliminary
hadronic tag $\tau \to h\nu$

- First measurement of τ polarization in $B \to D^*\tau\nu$ decay.



- Also BaBar still contributing to the global endeavour

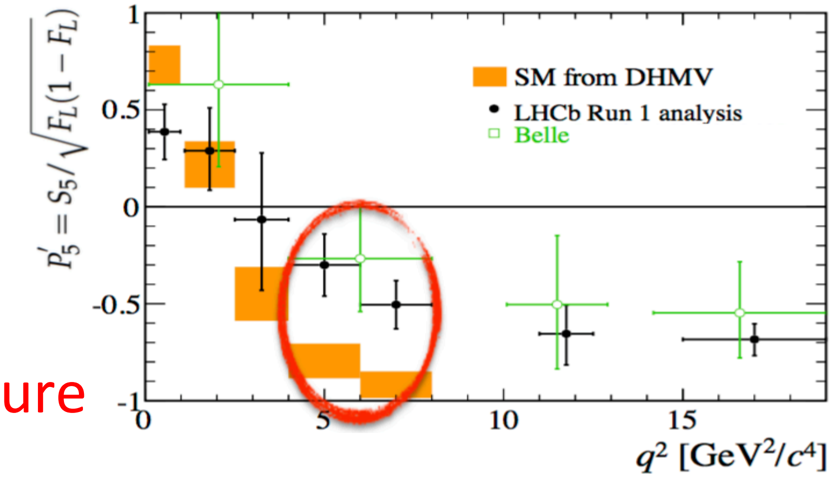
$\mathcal{B}(\bar{B}^0 \to D^{*-}\pi^+\pi^-\pi^+) = (7.26 \pm 0.11 \pm 0.31) \cdot 10^{-3}$ to be submitted to PRD

- More analyses about $b \to c\tau\nu$ are ongoing at Belle and LHCb
- LHCb can also perform measurements with other b hadrons
  – e.g. B_s, B_c and Λ_b decays will help to better understand the global picture → stay tuned!

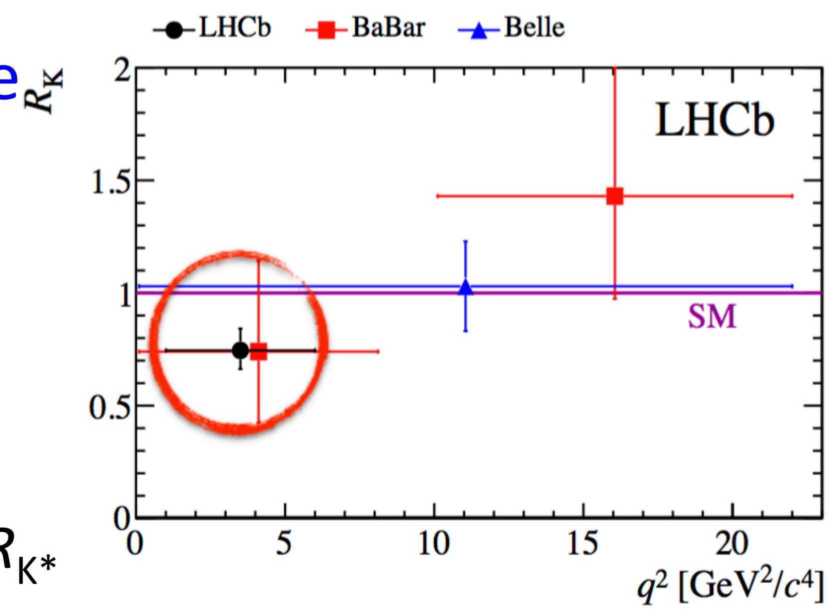
Other flavour anomalies

- Angular analysis of $B^0 \rightarrow K^* \mu^+ \mu^-$
  - Observables are q^2 (dimuon mass squared) and 3 angles (helicity basis)
  - Angular distributions provide many observables sensitive to different sources of NP see e.g. JHEP 05 (2013) 137
  - Some global theoretical fits require non-SM contributions to accommodate the data e.g. JHEP 06 (2016) 092
  - However, genuine QCD effects can also be an explanation e.g. JHEP 06 (2016) 116
    → more efforts needed to clarify the picture

JHEP 02 (2016) 104 arXiv:1604.04042

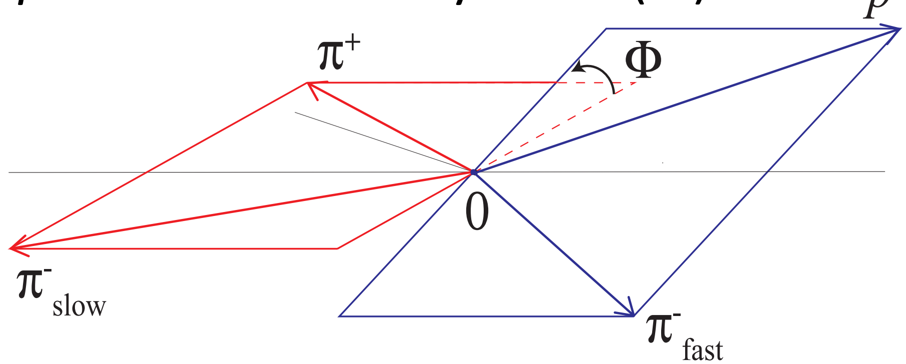


- Ratio (R_K) of branching fractions of $B^+ \rightarrow K^+ \mu^+ \mu^-$ to $B^+ \rightarrow K^+ e^+ e^-$ expected to be unity in the SM with excellent precision
  - Observation of LFU violation would be a clear sign of NP
  - LHCb observed a 2.6σ deviation from SM in the low q^2 region PRL 113 (2014) 151601
  - New measurements expected soon, e.g. R_{K^*}

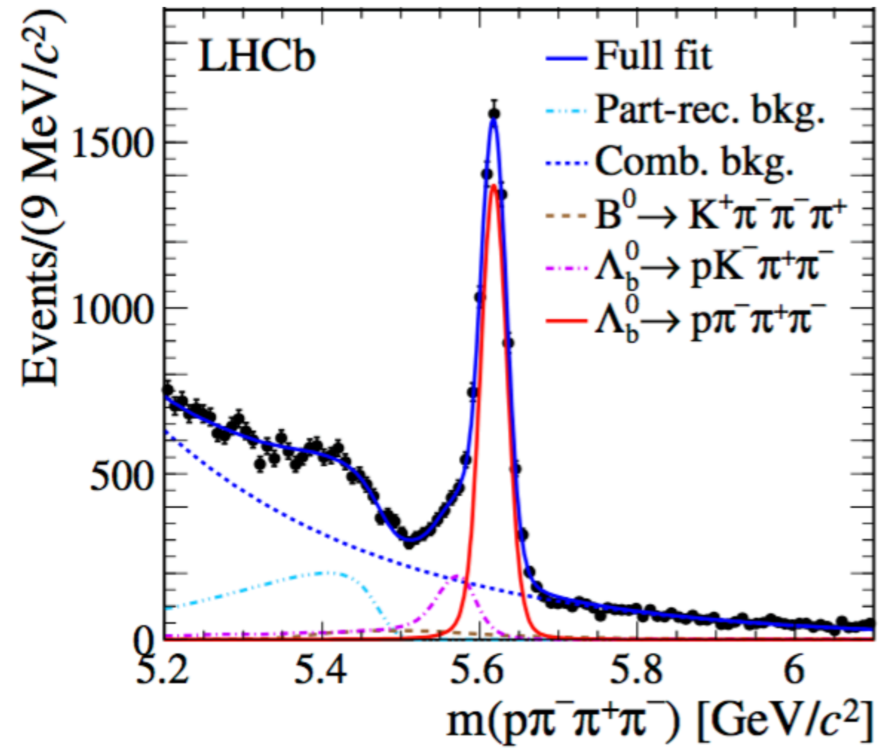


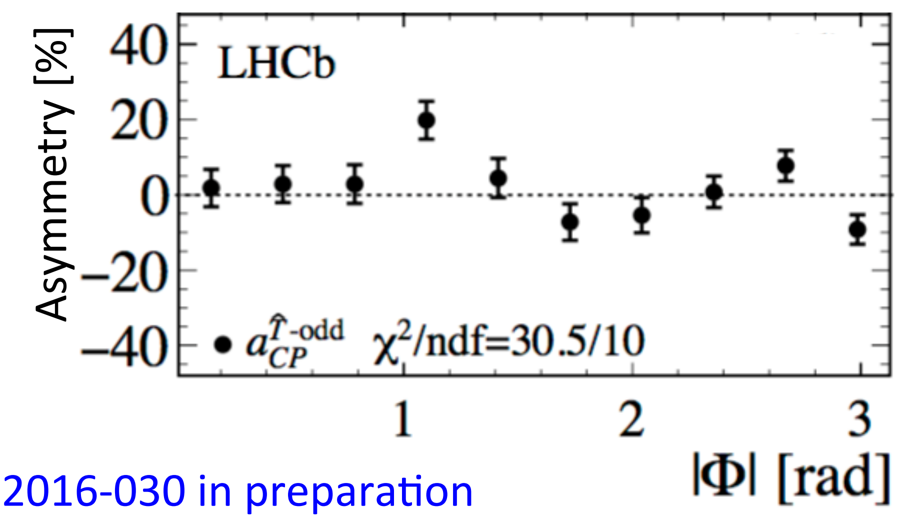
First evidence for *CP* violation in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays from LHCb

- *CP* violation has never been observed in the decays of any baryonic particle
- $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays used to search for *CP*-violating asymmetries in triple products of final-state particle momenta
  - Local *CP*-violating effects studied as a function of the the relative orientation between the decay planes formed by the $p\pi^-$ and the $\pi^+\pi^-$ systems (Φ)



- An evidence for *CP* violation at the 3.3σ level is found
- This represents the first evidence of *CP* violation in the baryon sector

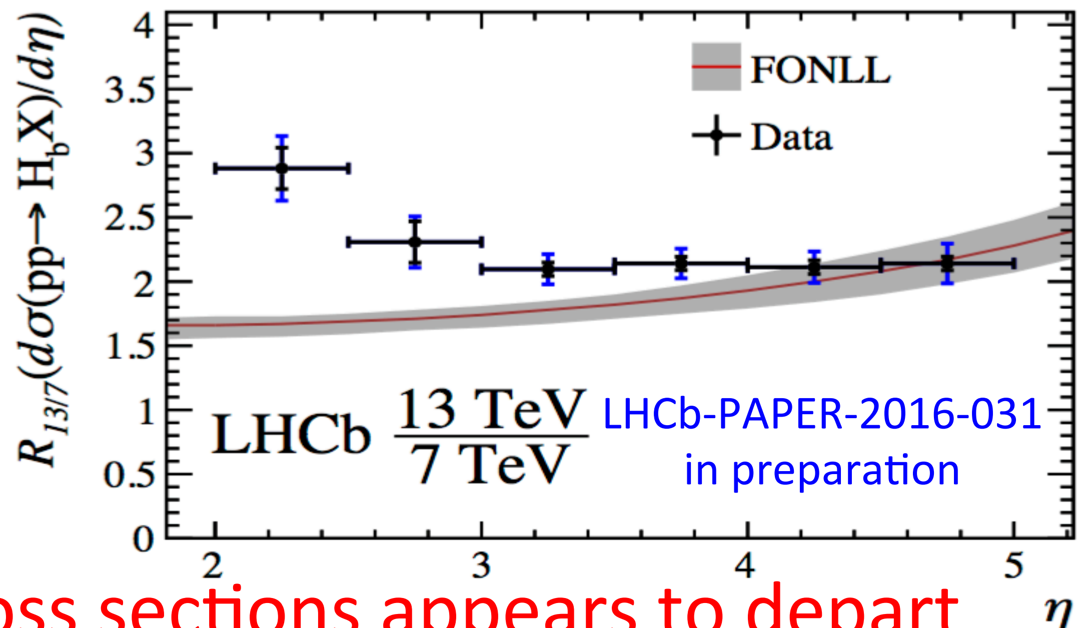




LHCb-PAPER-2016-030 in preparation

Beauty cross section at 7 and 13 TeV

- Production of *b* quarks in high energy *pp* collisions at the LHC provides a sensitive test of QCD computations and constraints for PDFs
- LHCb measured the cross-section for the process $pp \rightarrow b\bar{b}X$ at two different centre-of-mass energies within $2 < \eta < 5$
- Measurement done using semileptonic decays of *b*-flavored hadrons decaying into a charmed hadron in association with a muon



- The ratio of 13 to 7 TeV cross sections appears to depart from FONLL theory predictions at low η
  - Upcoming measurements with exclusive decays will provide further inputs to drive theory developments

LHC luminosity prospects

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	$\longrightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	25 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2×10^{34} $cm^{-2}s^{-1}$

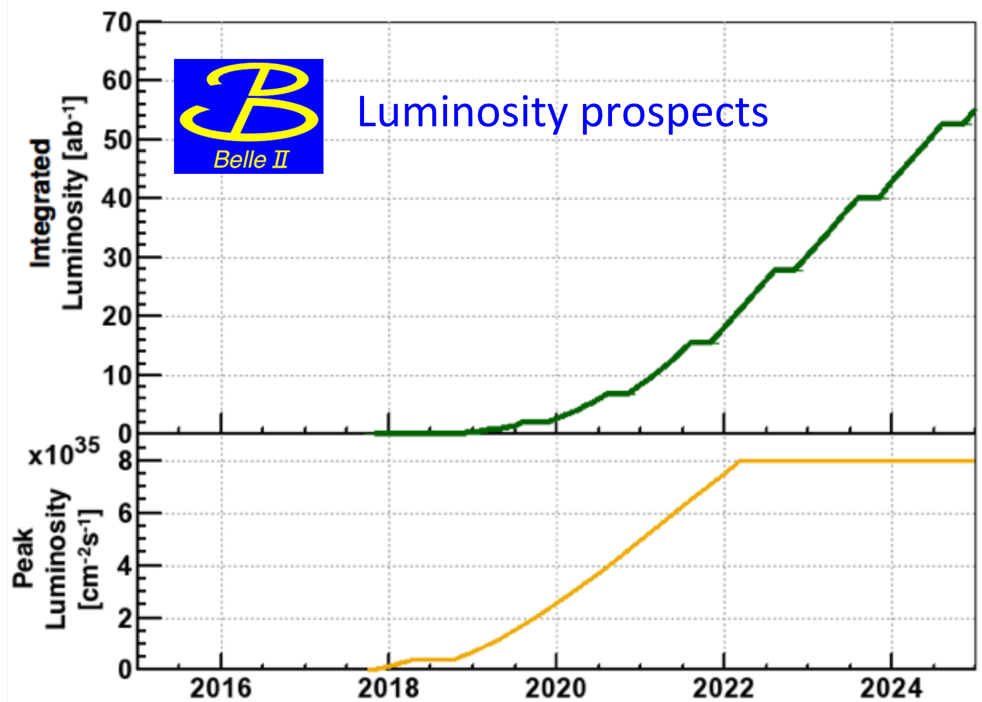
- LHC is delivering luminosity at an incredibly high pace in Run-2
  - Prospects in the table above might be conservative
- Note that beauty production cross section roughly doubles passing from 7 to 13-14 TeV *pp* collisions
- LHCb upgrade comes already after Run-2, whereas the HL (phase-2) ATLAS and CMS upgrades come after Run-3
- LHCb is starting to consider a phase-2 upgrade for Run 5+

http://www.hep.manchester.ac.uk/theatre-of-dreams/index.html

Forthcoming LHCb upgrade and Belle II

- LHCb upgraded detector after Run-2 → instantaneous luminosity will be raised by a factor 5 from $4 \cdot 10^{32}$ cm^{-2}s^{-1} to $2 \cdot 10^{33}$ cm^{-2}s^{-1}
- The hardware trigger stage will be eliminated, and the trigger will become fully software based
  - running at 40 MHz and recording 20 kHz of output rate
- Some changes to the readout system, plus replacement of RICH photodetectors and of tracking detectors

- Very exciting prospects from the SuperKEKB machine and new Belle II detector
  - SuperKEKB will deliver almost two orders of magnitude larger integrated luminosity than KEKB
- Expected to start ramping up some time in 2019
- Eagerly waiting for new outstanding results!



Concluding remarks

- The SM is a stubborn animal, indeed!
- In the current unclear state with perspectives in fundamental physics, it is necessary to have a programme as diversified as possible

- In the unfortunate event that no direct evidence of NP pops out of the LHC, flavour physics can play a key role to indicate the way for future developments of elementary particle physics
- If instead, as we all hope, new particles will be detected in direct searches, flavour physics will be a crucial ingredient to understand the structure of what lies beyond the SM