LHCb Physics Overview

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on behalf of the LHCb collaboration

Triggering Discoveries in High Energy Physics II
Puebla City, Mexico
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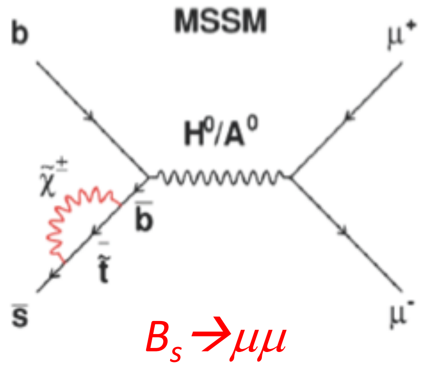
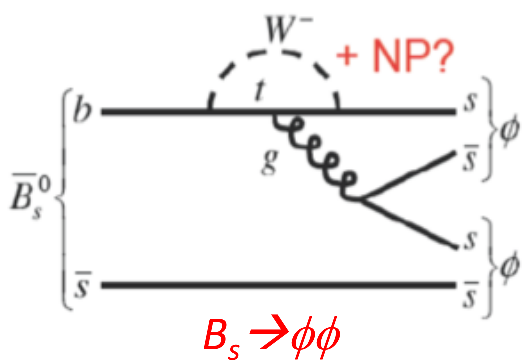
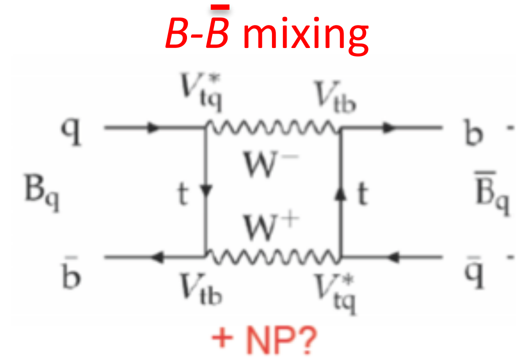
New physics searches in the flavour sector

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







- General amplitude decomposition in terms of couplings and scales → in presence of sizeable SM contributions, NP effects might be hidden

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

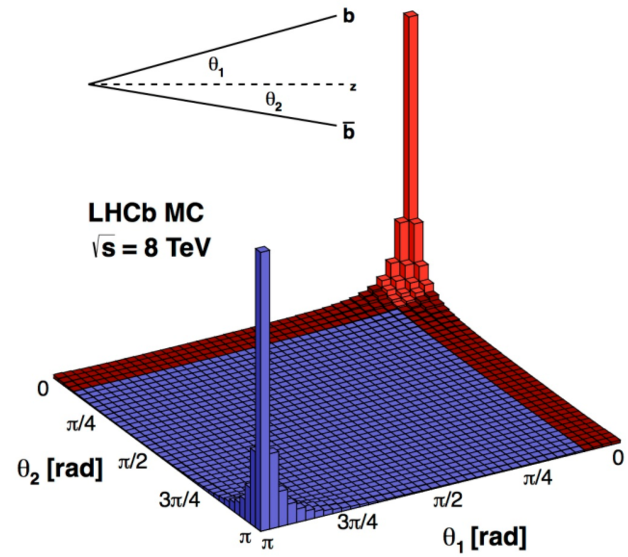
  - Need high precision measurements of theoretically clean observables
- By studying *CP*-violating and flavour-changing processes, two fundamental tasks can be accomplished
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly at a collider like LHC

Flavour physics programme in a nutshell

- Classic broad-range measurements
  - CKM physics, search for very rare decays
- Measurements in specific sectors where anomalies are emerging in recent years
  - Lepton-flavour universality in $b \to s\ell^+\ell^-$ transitions, and related $b \to s\ell^+\ell^-$ picture of decay rates
  - Lepton-flavour universality in semileptonic b-hadron decays
- Spectroscopy
  - While primarily looking for BSM physics, the LHC is also a unique laboratory to better understand QCD in the low-energy regime

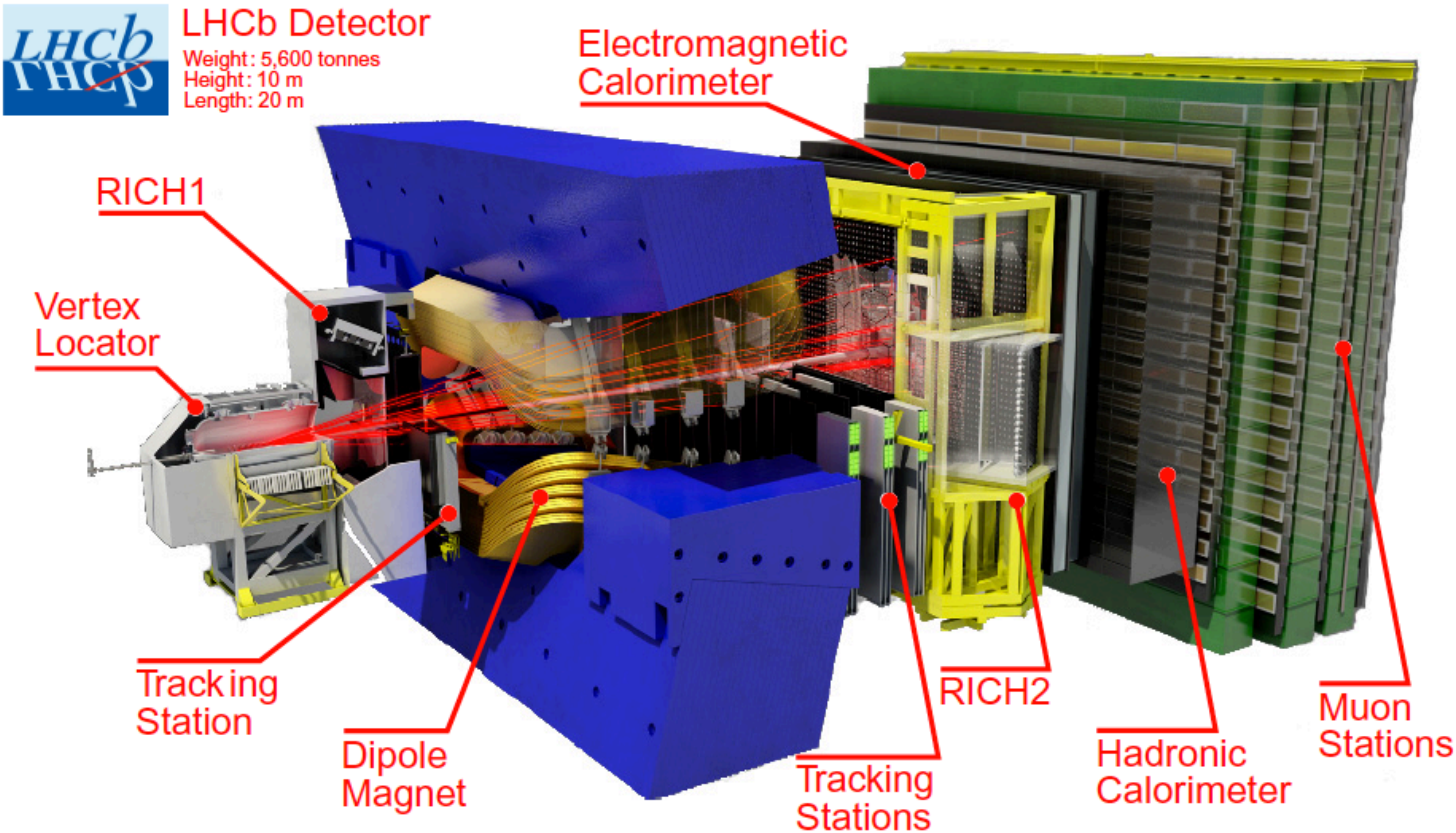
LHCb detector layout

- LHCb is mainly (but not only) studying beauty (and charm)
  - At LHC, the production of heavy quark pairs is peaked forward/backward
  - The detector is a single arm spectrometer
    - Both *b*-hadrons go together forward (or backward)
    - Acceptance $2 < \eta < 5$
  - A *b*-meson / baryon is boosted
    - It flies several millimetres before decaying
    - This is the main signature for selecting events

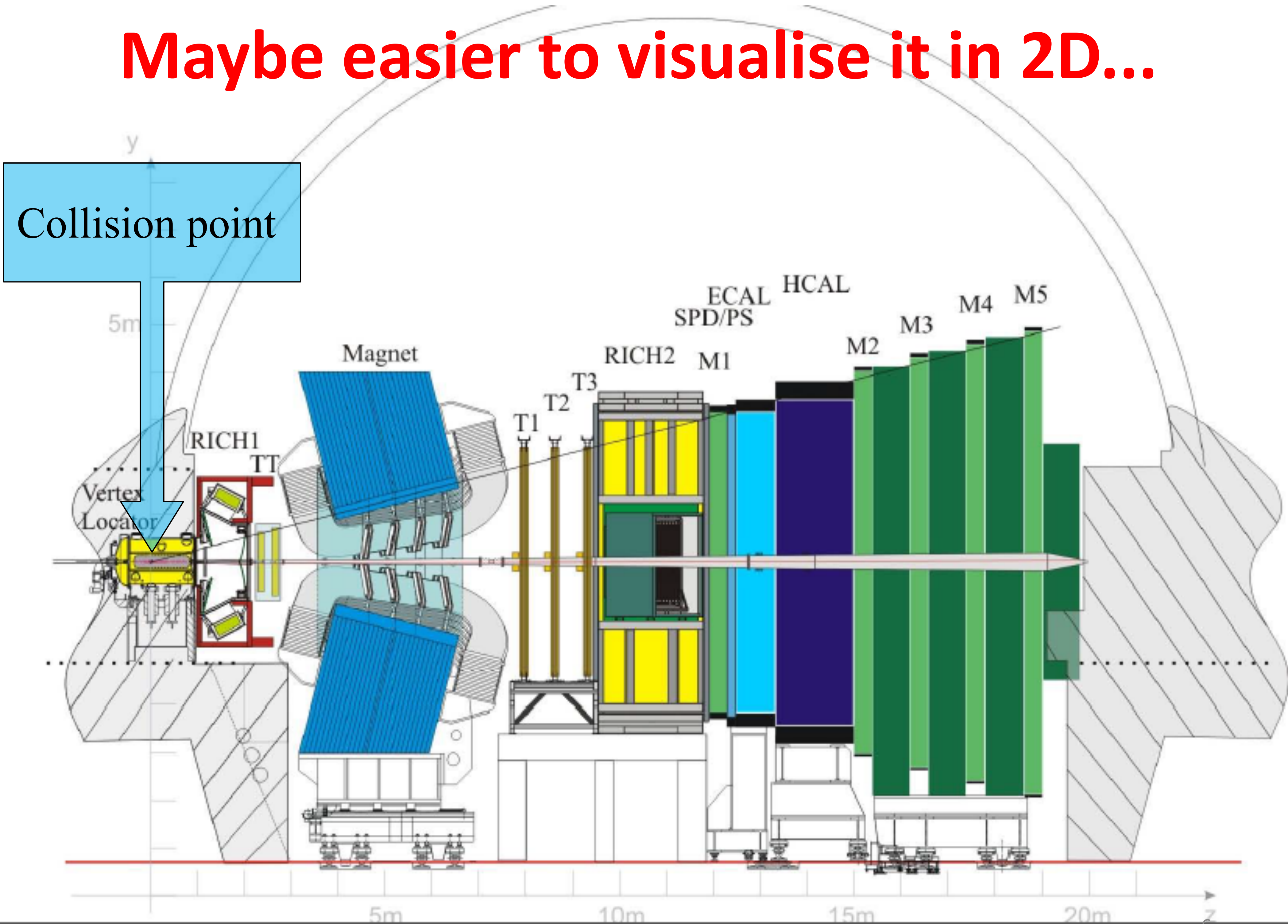


- General detector layout
  - The silicon vertex detector is a key component
  - Dipole magnet, and tracking stations after, to measure accurately the momentum
  - Particle identification by two RICH detectors, electromagnetic and hadronic calorimeters, and a muon system

LHCb 3D sketch

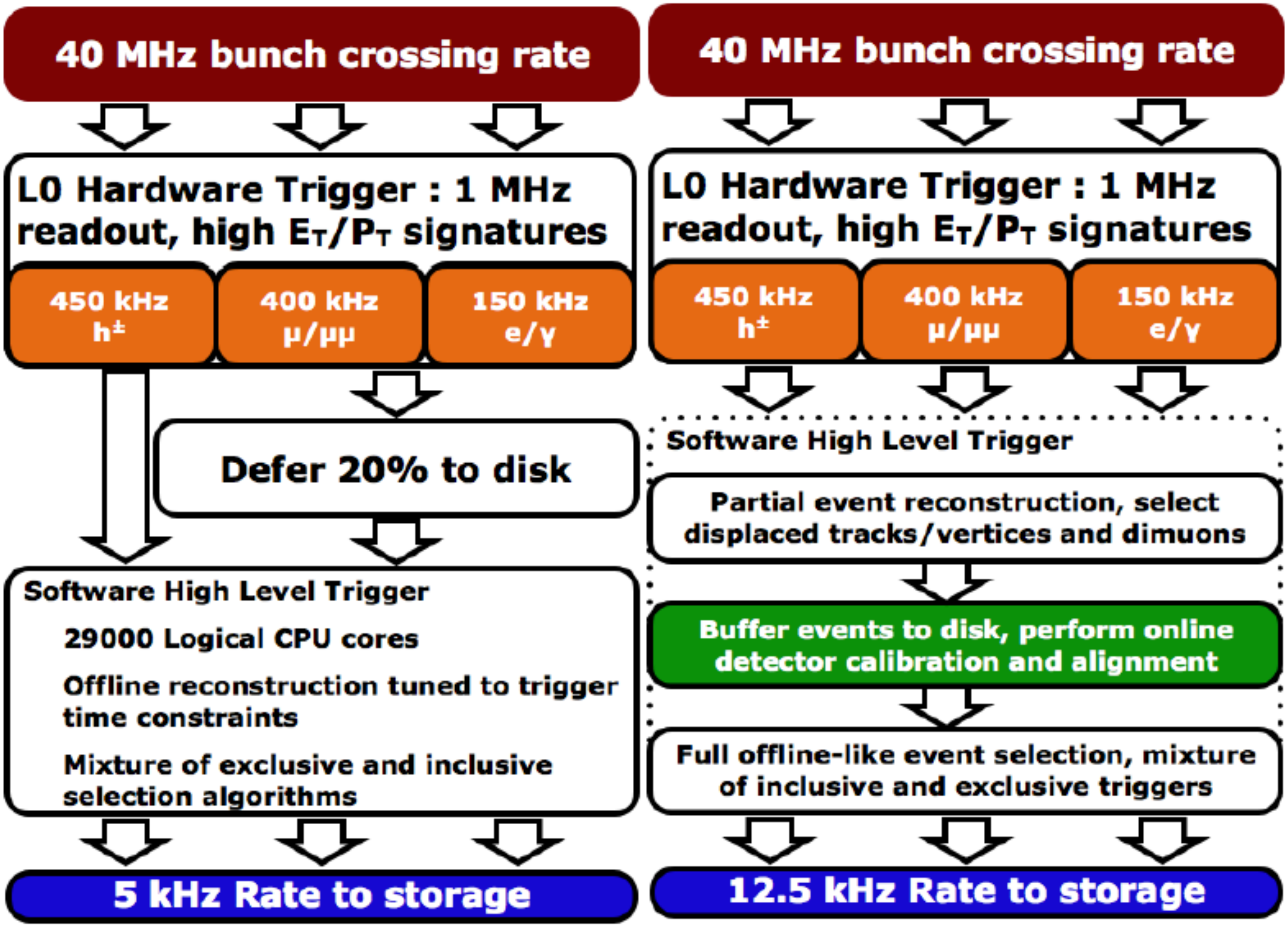


Maybe easier to visualise it in 2D...



See Fedor Ratnikov on Thursday

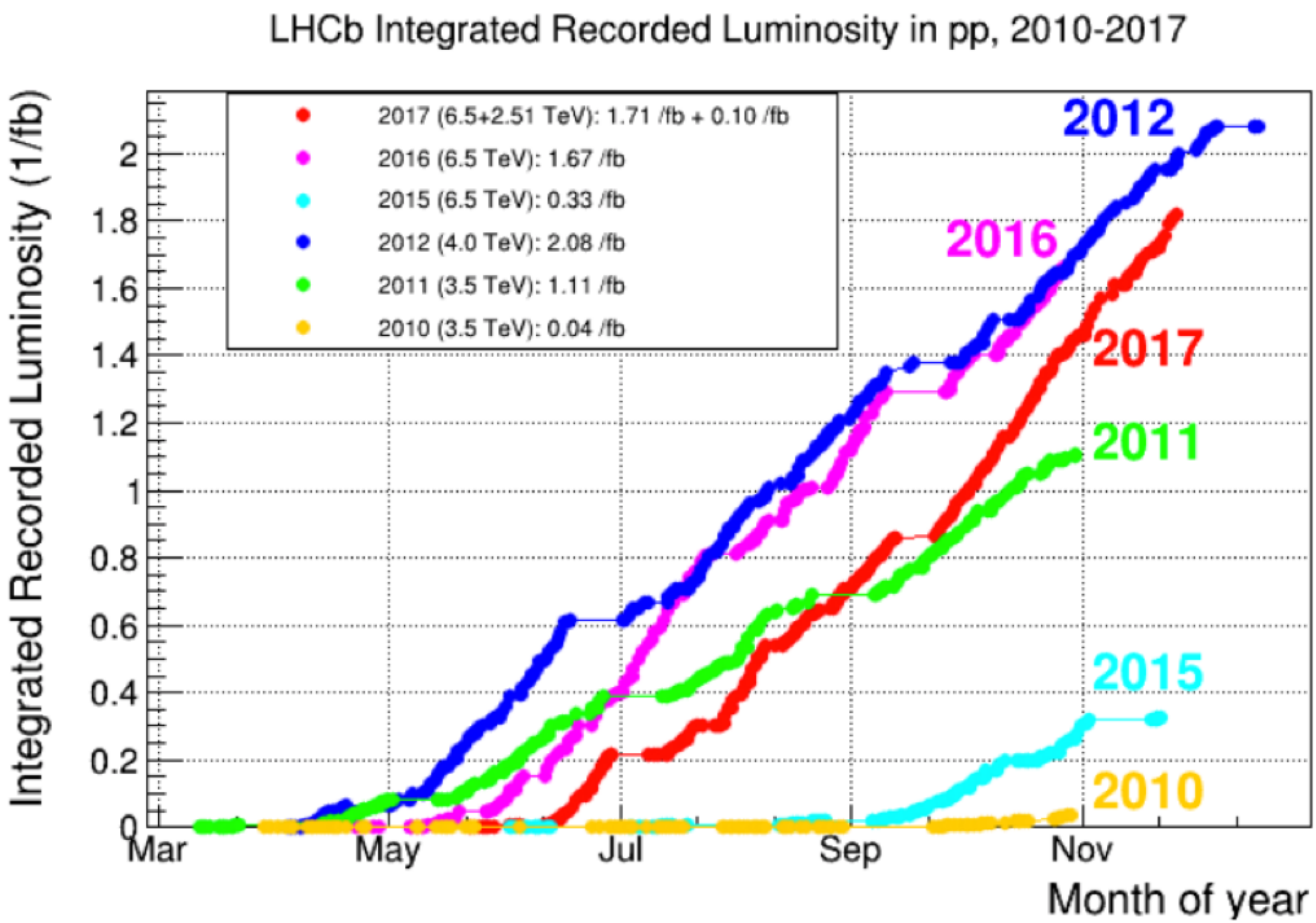
The LHCb trigger system



Run 1 (2010-12)

Run 2 (2015-18)

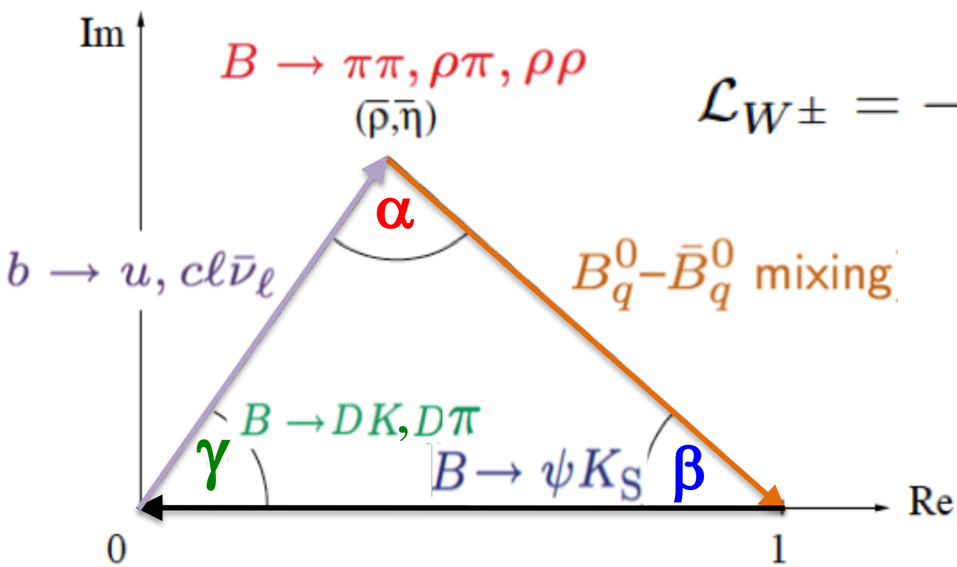
LHCb data per year



The CKM Unitarity Triangle

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

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



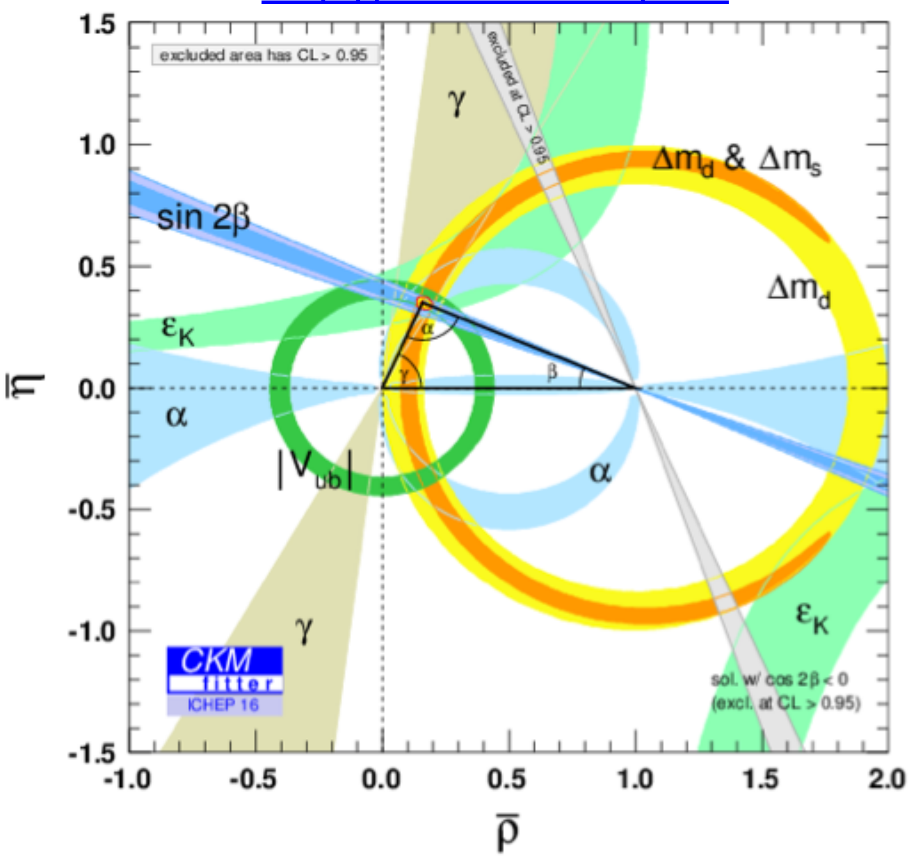
From CKM matrix unitarity

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

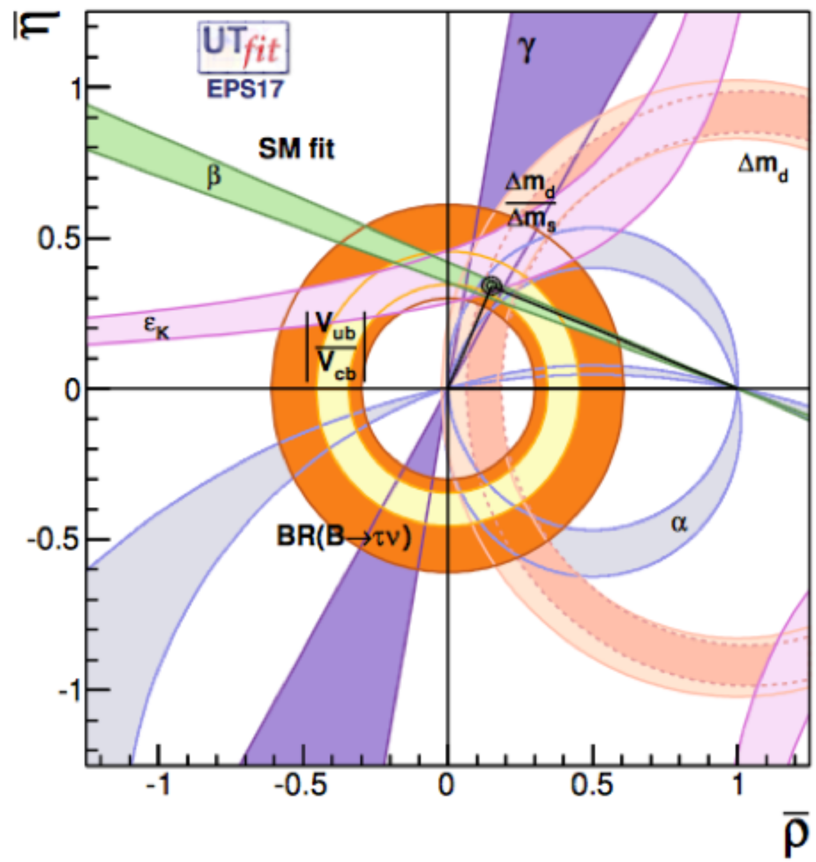
- UT defined by two parameters only → can be over-constrained
- The height (irreducible complex phase $\bar\eta$) controls the strength of *CP* violation in the Standard Model

Where we are with global UT fits

http://ckmfitter.in2p3.fr



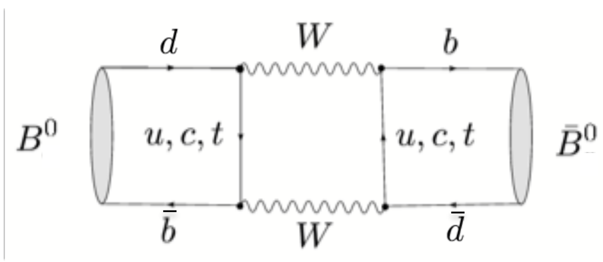
http://www.utfit.org

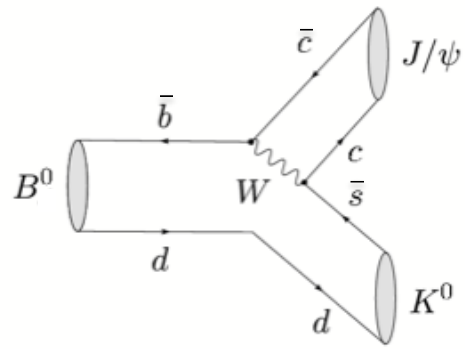


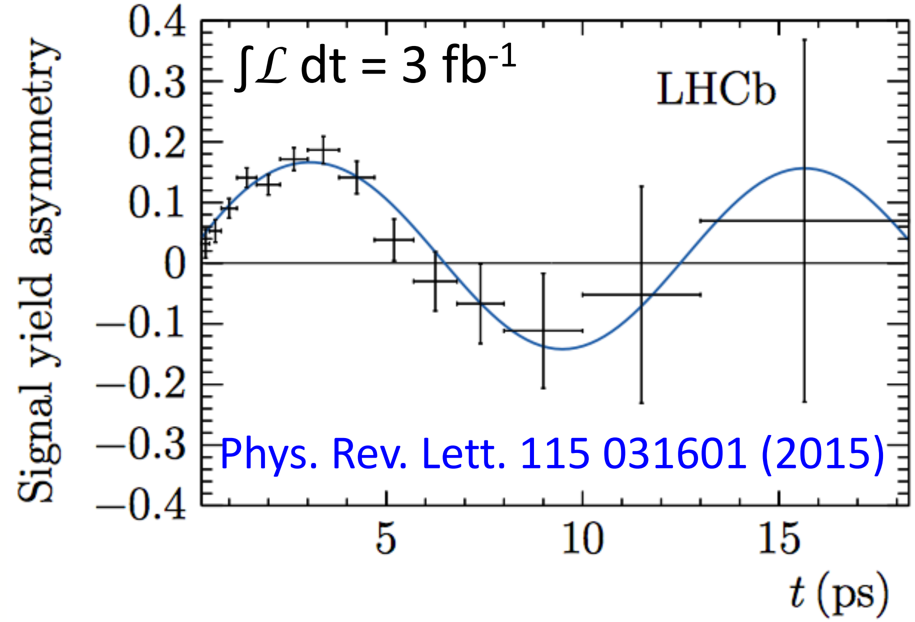
- Don’t forget: relevant inputs from LQCD, flavour theory and constant dedication from the HFLAV group (http://www.slac.stanford.edu/xorg/hflav/)
- In the presence of relevant new physics effects, the various contours would not cross each other in a single point
- Certainly that’s a great success of the Standard Model CKM picture, but there is still room for new physics at the 10%-15% level

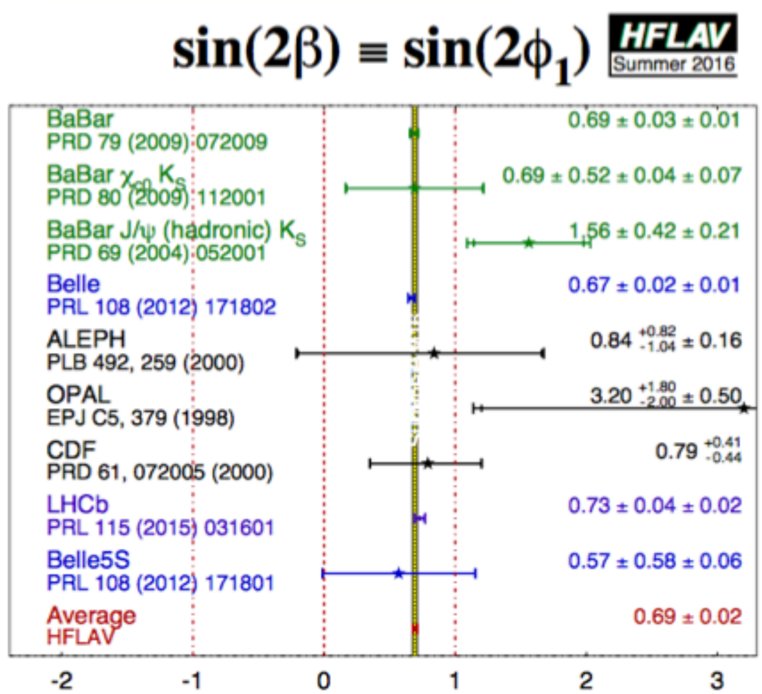
Measurement of sin2β

- *CP* violation due to interference between B^0-$\bar{B}^0$ mixing and $b \to c\bar{c}s$ transitions

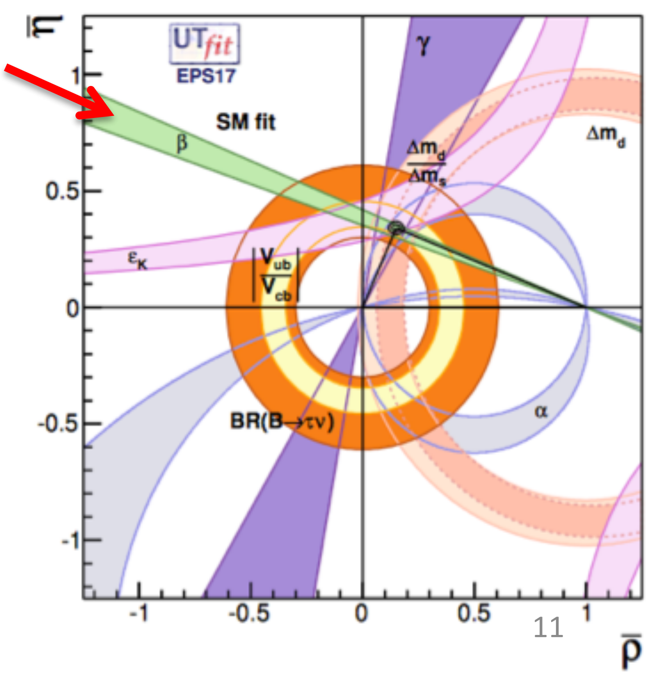




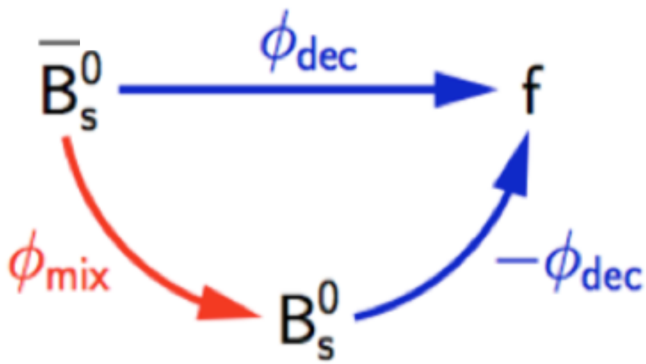




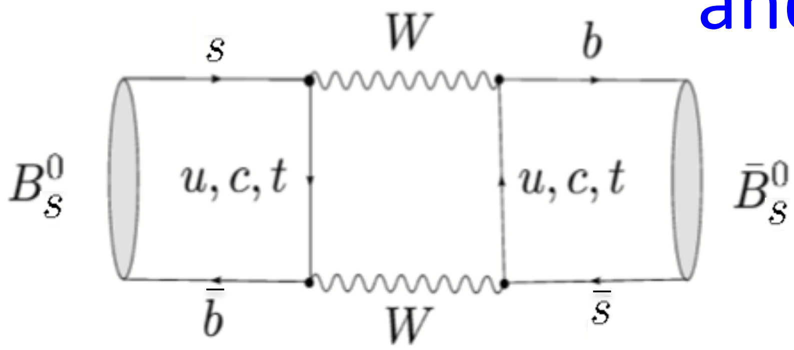
- LHCb has reached the precision of the *B factories* and will surpass that with Run-2 data

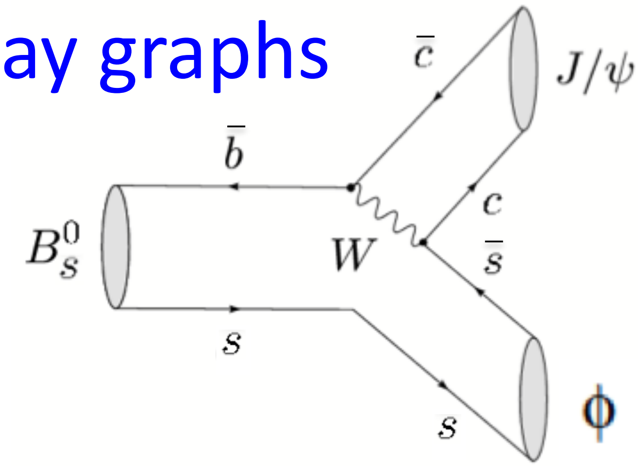


ϕ_s from $b \rightarrow c\bar{c}s$ transitions



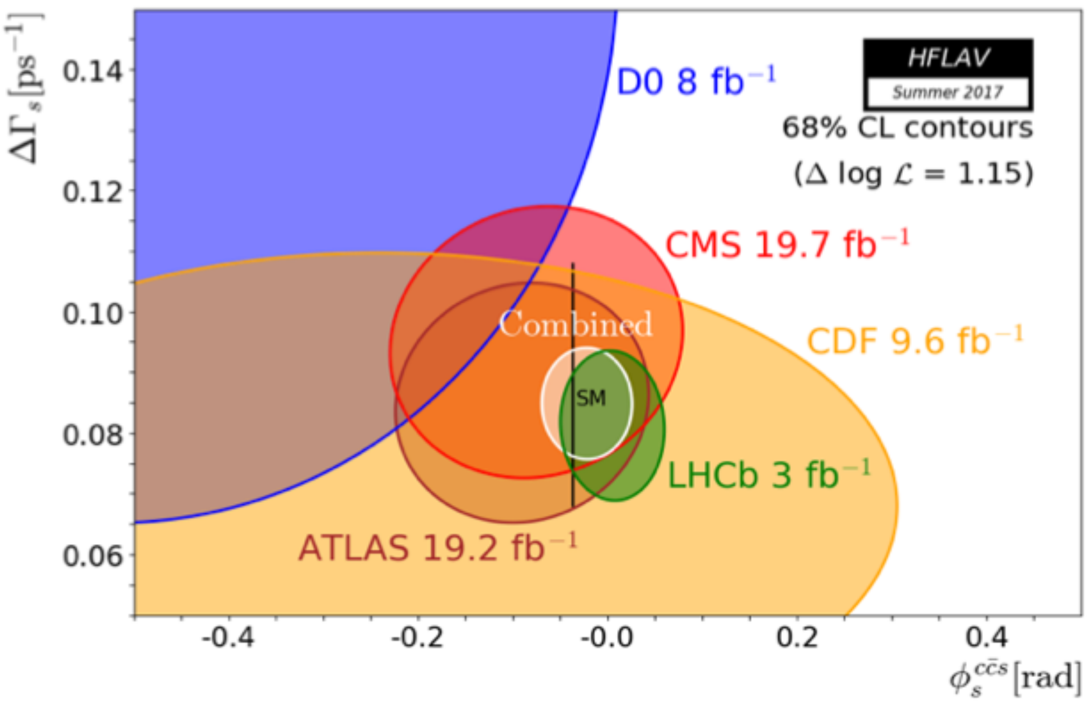
- Golden mode $B_s \rightarrow J/\psi\phi$ proceeds (mostly) via a $b \rightarrow c\bar{c}s$ tree diagram
- Interference between B_s mixing and decay graphs





- Measures the phase-difference ϕ_s between the two diagrams, precisely predicted from global CKM fits in the SM to be $\phi_s = -2\lambda^2\eta = -37.4 \pm 0.7$ mrad → can be altered by new physics
  - But also affected by small pollution of sub-leading SM amplitudes that must be taken under control via subsidiary measurements

Measurement of $\phi_s = -2\lambda^2\eta$



- ϕ_s precision mostly driven by LHCb
- Latest HFLAV world average
  - $\phi_s = -21 \pm 31$ mrad
- Still compatible with the SM at the present level of precision

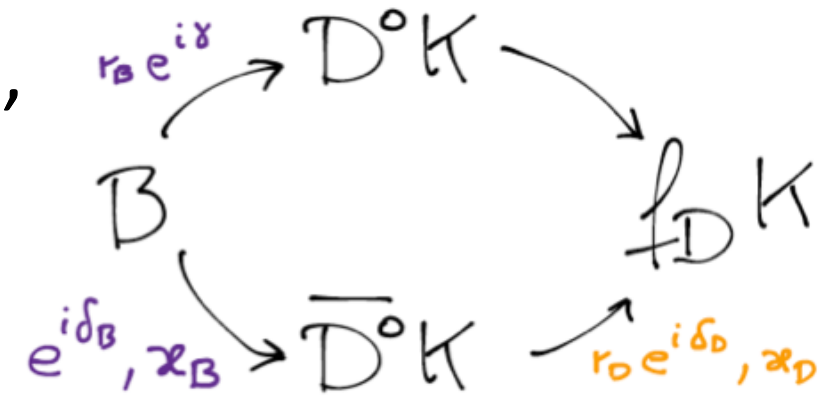
Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	9.6 fb^{-1}	$[-0.60, +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[4]
ATLAS	$J/\psi\phi$	14.3 fb^{-1}	$-0.110 \pm 0.082 \pm 0.042$	$+0.101 \pm 0.013 \pm 0.007$	[5]
ATLAS	above 2 combined		$-0.090 \pm 0.078 \pm 0.041$	$+0.085 \pm 0.011 \pm 0.007$	[5]
CMS	$J/\psi\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	[6]
LHCb	$J/\psi K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0032$	[7]
LHCb	$J/\psi\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	[8]
LHCb	$J/\psi K^+K^{-a}$	3.0 fb^{-1}	$+0.119 \pm 0.107 \pm 0.034$	$+0.066 \pm 0.018 \pm 0.010$	[9]
LHCb	above 3 combined		$+0.001 \pm 0.037$(tot)	$+0.0813 \pm 0.0073 \pm 0.0036$	[9]
LHCb	$\psi(2S)\phi$	3.0 fb^{-1}	$+0.23^{+0.29}_{-0.28} \pm 0.02$	$+0.066^{+0.41}_{-0.44} \pm 0.007$	[10]
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	[11]
All combined			-0.021 ± 0.031	$+0.085 \pm 0.006$	

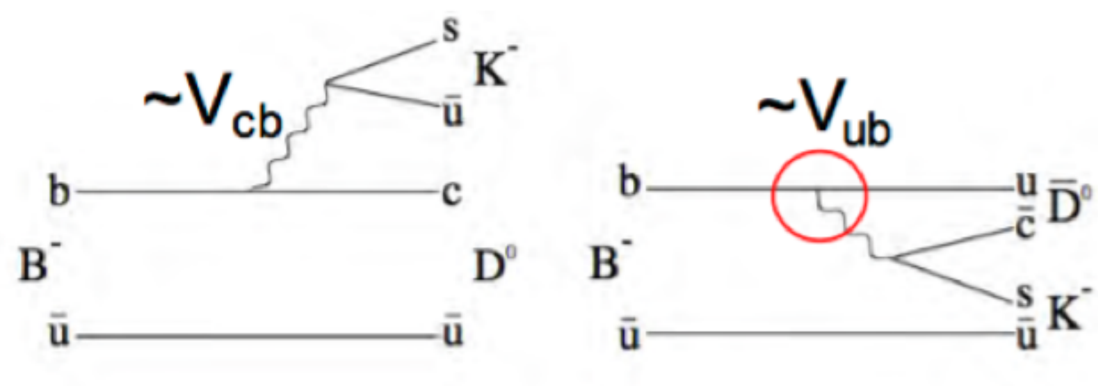
[a] $m(K^+K^-) > 1.05$ GeV/c^2.

See HFLAV page for the list of references
http://www.slac.stanford.edu/xorg/hflav/

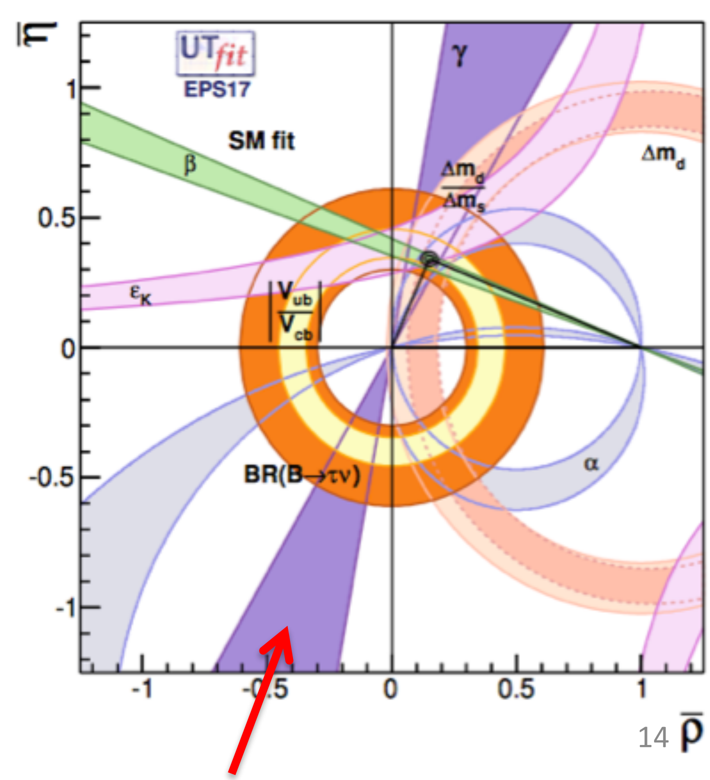
Measurement of γ

- γ is the least known angle of the UT, although not for too long yet, measured via the interference between $b \rightarrow u$ and $b \rightarrow c$ tree-level transitions





- Simple and clean theoretical interpretation, but statistically very challenging



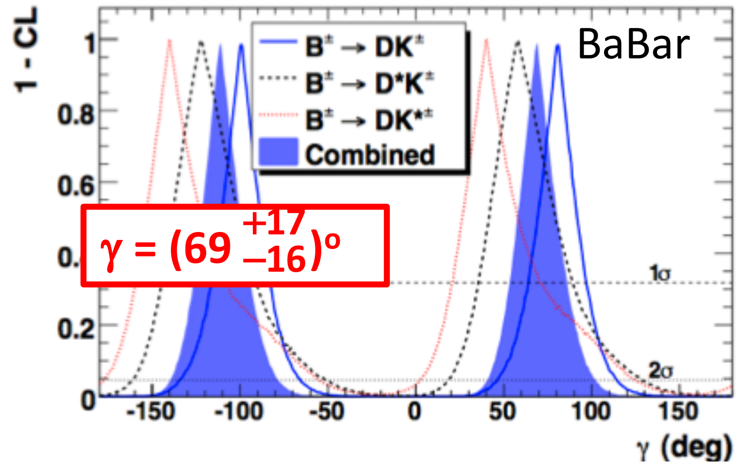
LHCb combination for γ

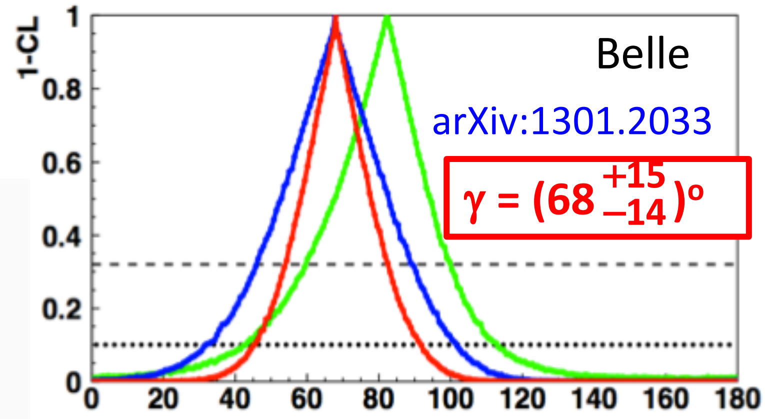
- A plethora of independent measurements exploiting different methods and decays
- Recent additions to the LHCb combination

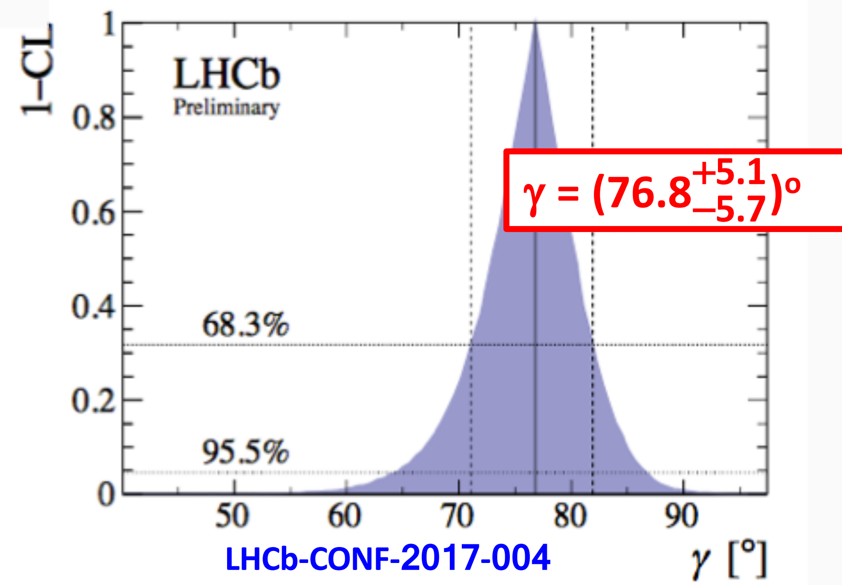
- $B^{\pm} \to D^0 K^{*\pm}$ ADS/GLW [LHCb-CONF-2016-014] NEW
- $B^{\pm} \to D^{*0} K^{*\pm}$ GLW [LHCb-PAPER-2017-021] NEW
- $B_s^0 \to D_s^{\mp} K^{\pm}$ TD [LHCb-CONF-2016-015] $1\ \text{fb}^{-1} \to 3\ \text{fb}^{-1}$
- $B^{\pm} \to D^0 K^{\pm}$ GLW [LHCb-PAPER-2017-021] $3\ \text{fb}^{-1} \to 5\ \text{fb}^{-1}$

- Significantly more precise than previous results from the *B*-factories and undergoing continuous improvements

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



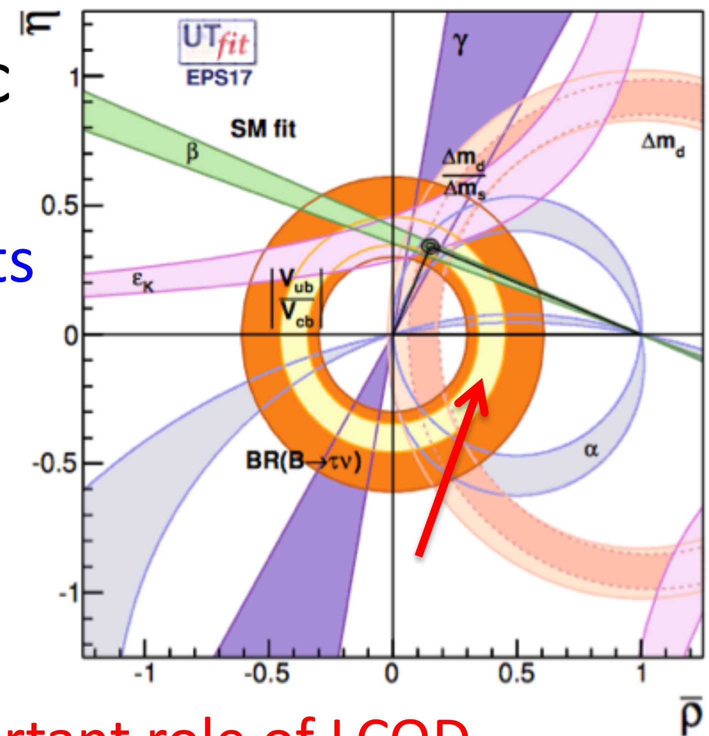




Measurement of $|V_{ub}|/|V_{cb}|$

- Measured at *B* factories and more recently by LHCb using Λ_b semileptonic decays
  - first of a rich programme of measurements with *b*-hadron semileptonics at LHCb

$$R_{exp} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

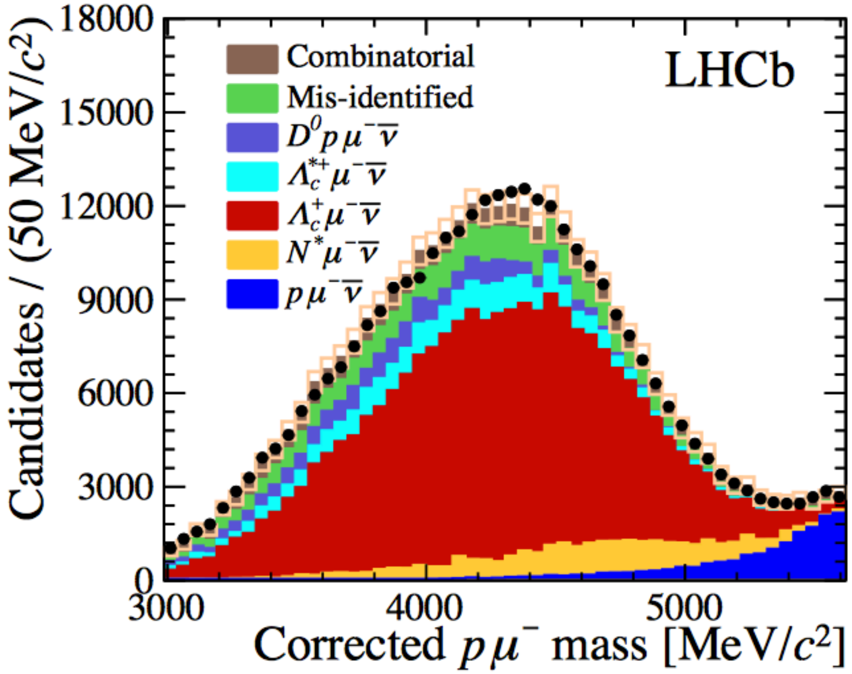


Important role of LCQD

$$R_{exp} = R_{theory}(|V_{ub}|^2/|V_{cb}|^2)$$

$$R_{theory} = 1.470 \pm 0.115(stat) \pm 0.104(syst)$$

$$\boxed{\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004}$$

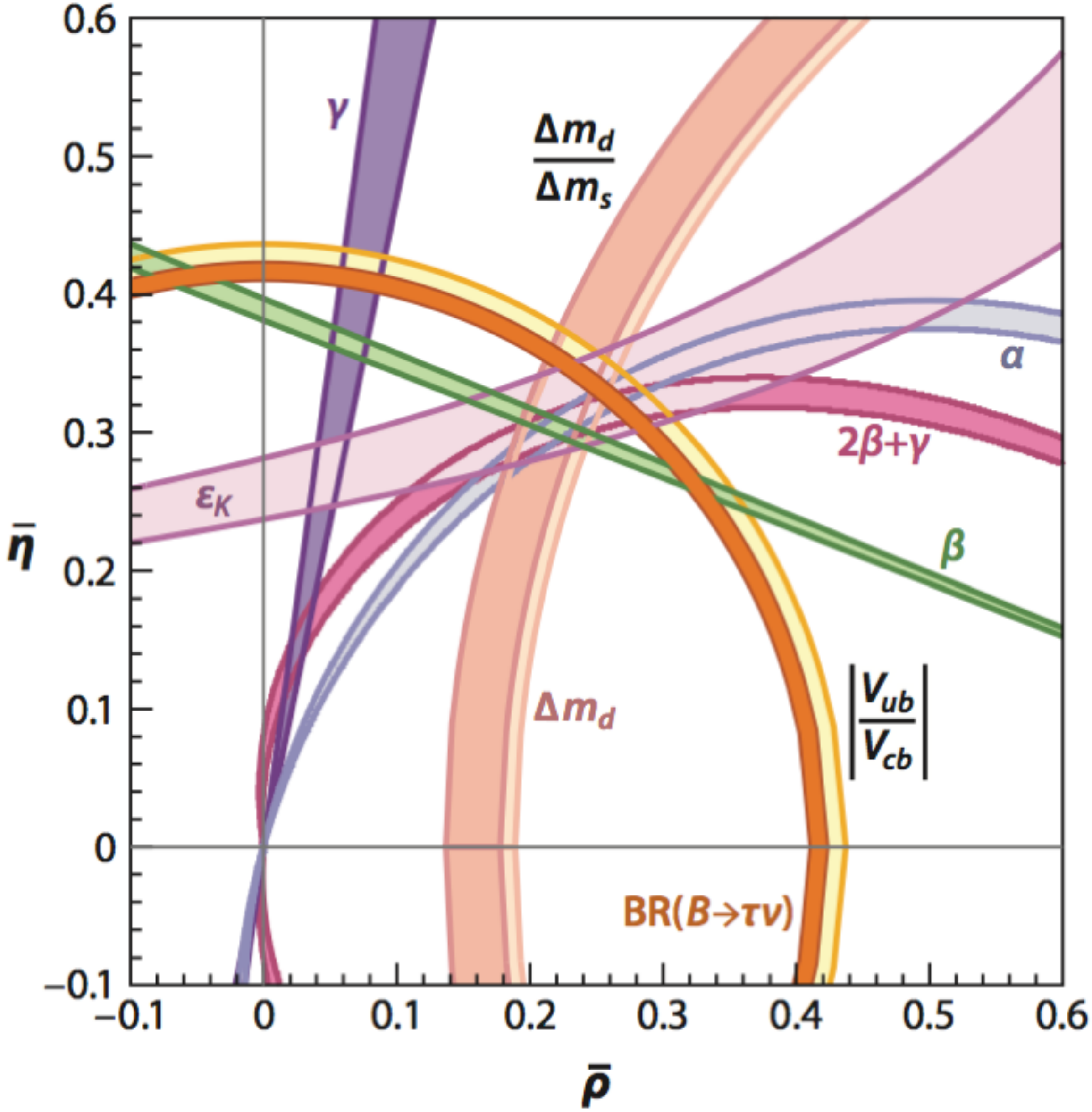


Nature Physics 10 (2015) 1038

Signal $\Lambda_b \to p\mu\nu$ decays

$$N(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = 17687 \pm 733$$

Just for illustration... a possible future scenario

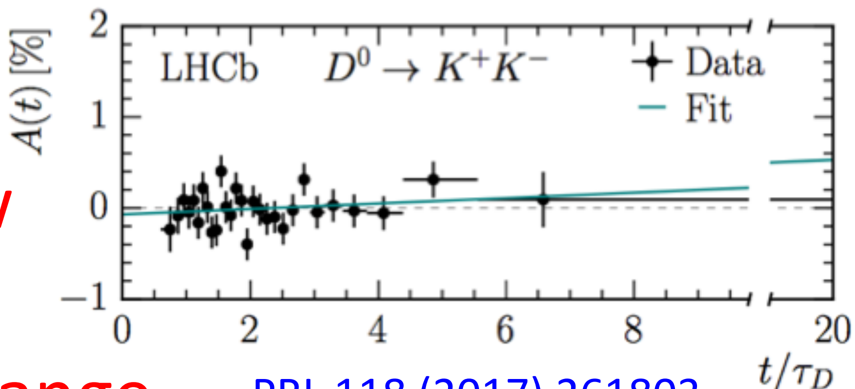


Mixing and *CP* violation in charm

- D^0-$\overline{D}^0$ mixing established by LHCb with overwhelming sensitivity measuring mainly time-dependent ratio of WS to RS $D^0 \rightarrow K\pi$ decays
- "Large" mixing encourages searches for *CP* violation
  - Both direct and indirect *CP* violation searches have been performed with unprecedented precision

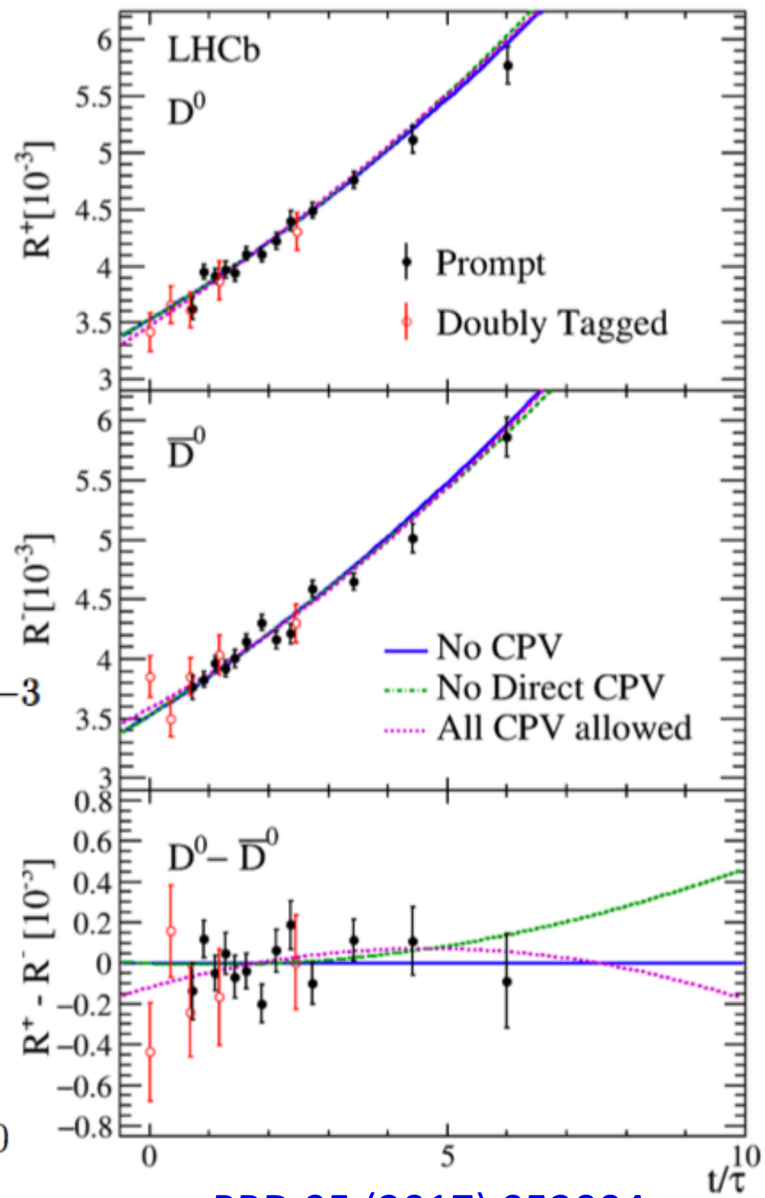
$$A_\Gamma \equiv \frac{\Gamma(D^0 \to KK) - \Gamma(\overline{D}^0 \to KK)}{\Gamma(D^0 \to KK) + \Gamma(\overline{D}^0 \to KK)} = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$

- No sign of *CP* violation yet, but now entering the interesting range



PRL 118 (2017) 261803

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



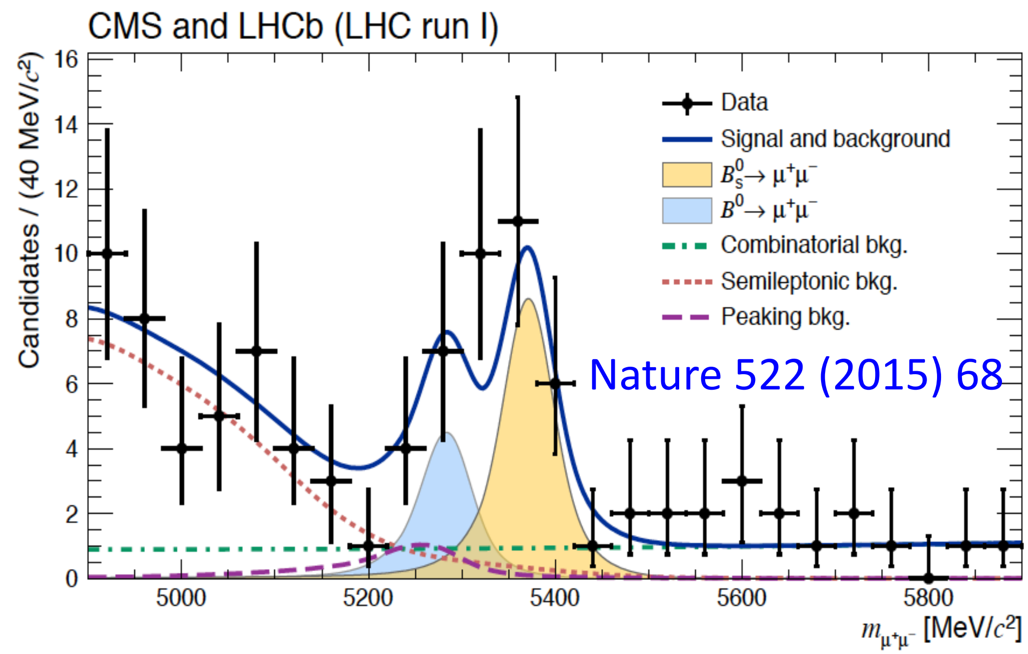
PRD 95 (2017) 052004

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

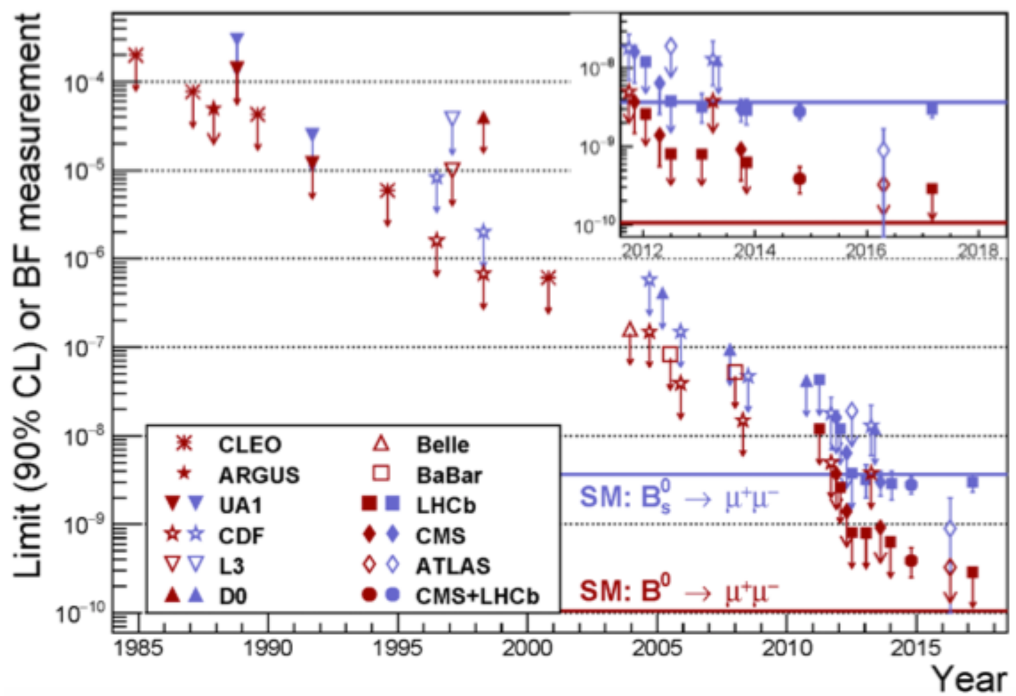
- CMS and LHCb have performed a combined fit to their full Run-1 data sets

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

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



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



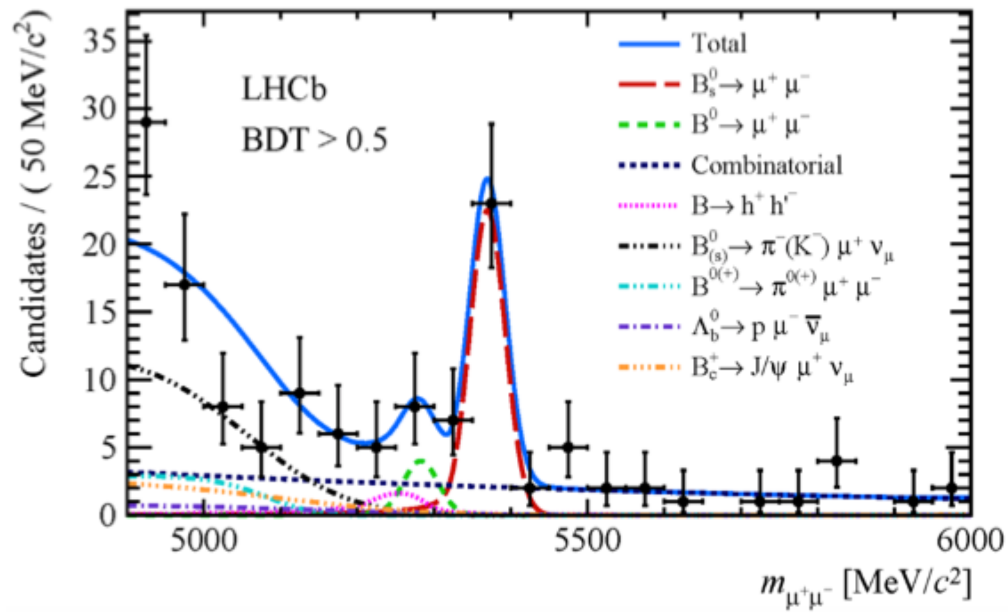
Update on $B\rightarrow\mu\mu$ by LHCb with Run-2 data

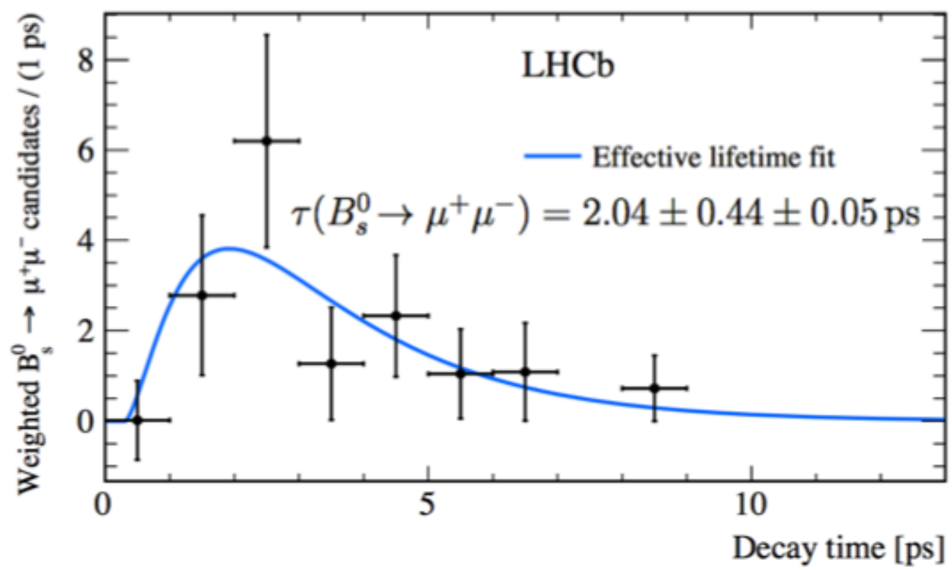
- New measurement from LHCb using Run-2 data has led this year to the first observation of the $B_s\rightarrow\mu\mu$ decay from a single experiment

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

- Moreover, it starts to be possible to measure other properties, such as the effective lifetime, that will be useful for discriminating between NP models
  - Experimental precision not yet in the interesting range, but important proof of concept

Phys. Rev. Lett. 118, 191801 (2017)





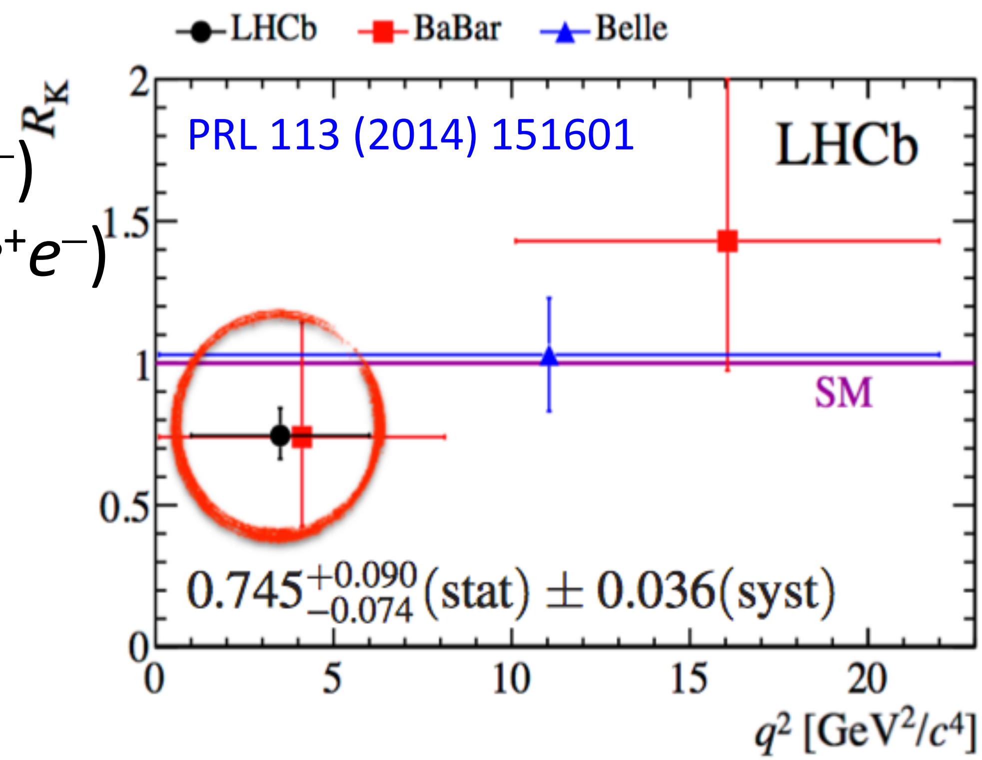
LFU tests in $b \rightarrow s\ell^+\ell^-$ transitions

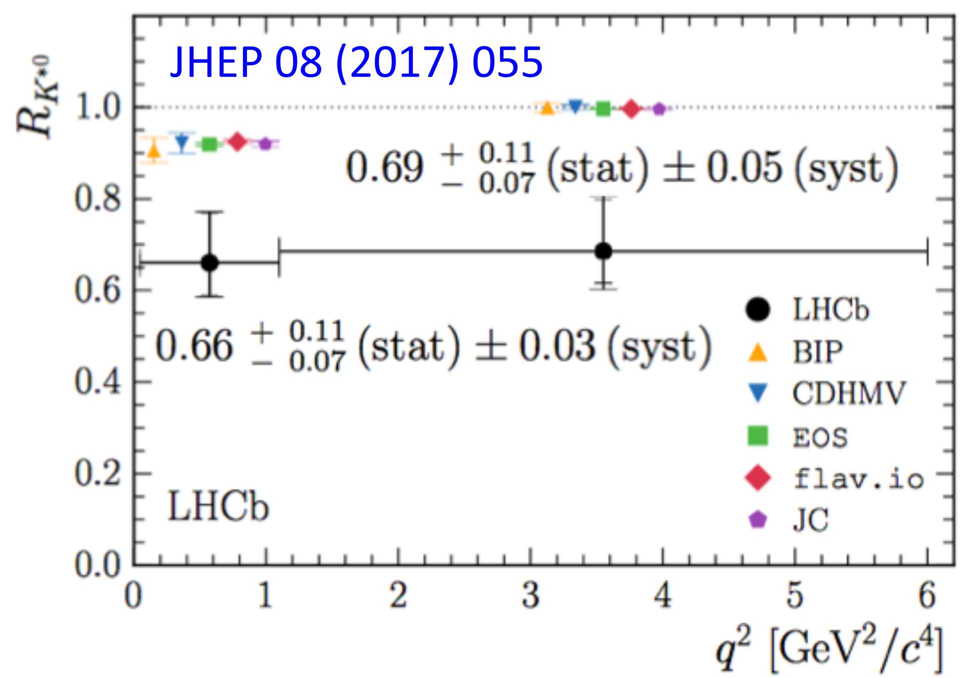
- Measure ratios

  $R_K = BF(B^+ \rightarrow K^+\mu^+\mu^-) / BF(B^+ \rightarrow K^+e^+e^-)$

  $R_{K*} = BF(B^0 \rightarrow K^{*0}\mu^+\mu^-) / BF(B^0 \rightarrow K^{*0}e^+e^-)$

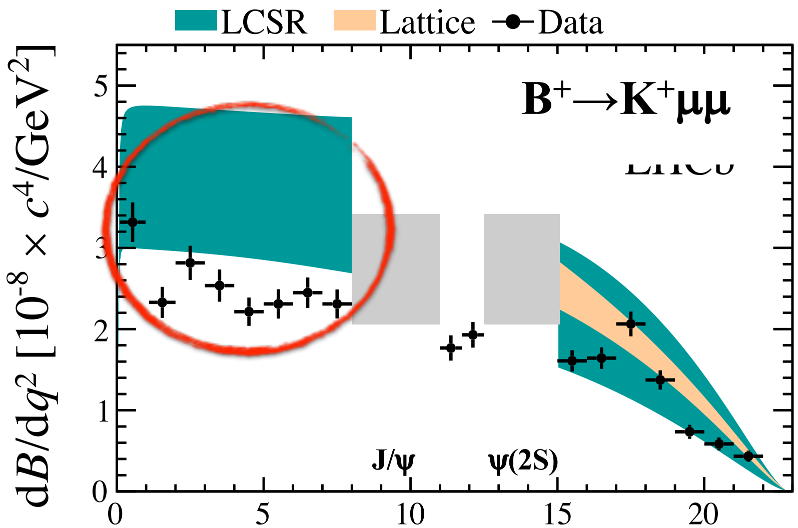
- Theoretically very clean
  - Observation of non-LFU would be a clear sign of new physics
- For the moment at the 3σ-ish level from the SM
- Updates with Run-2 as well as other new measurements with different decay modes expected during the coming year



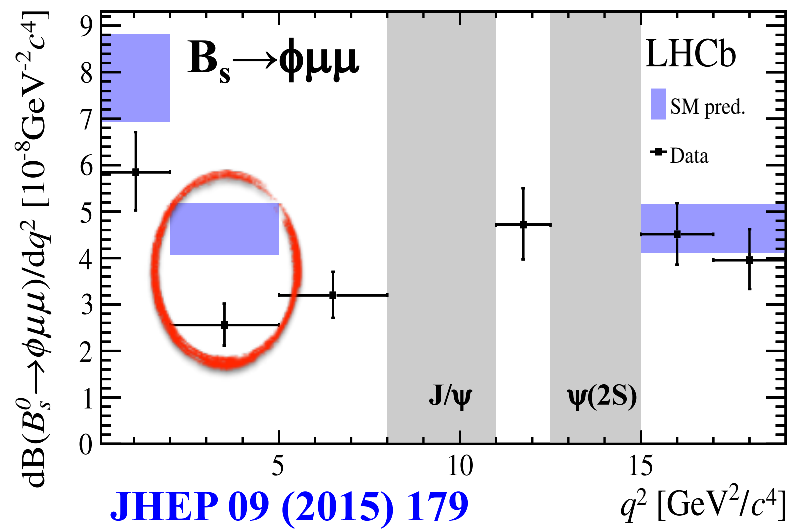


Other anomalies in the $b \rightarrow s\ell^+\ell^-$ sector

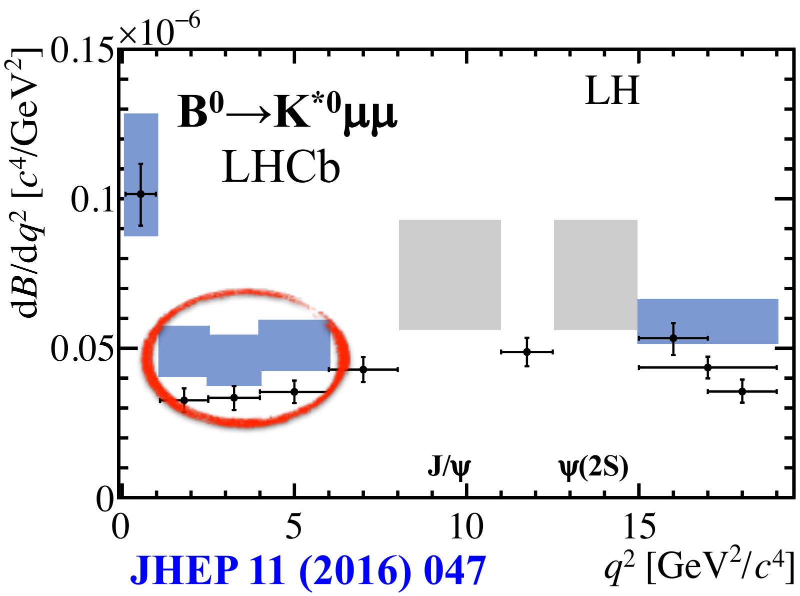
- Differential branching fractions consistently lower than SM expectations, although predictions are still matter of discussion



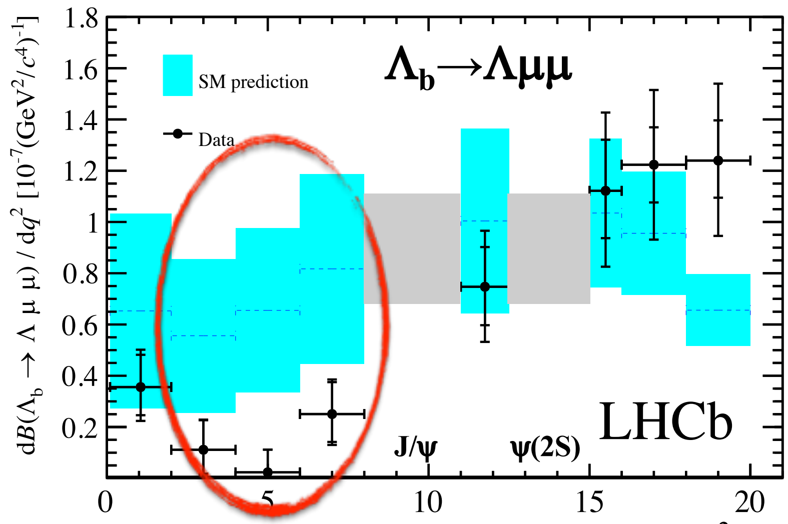
JHEP 06 (2014) 133



JHEP 09 (2015) 179



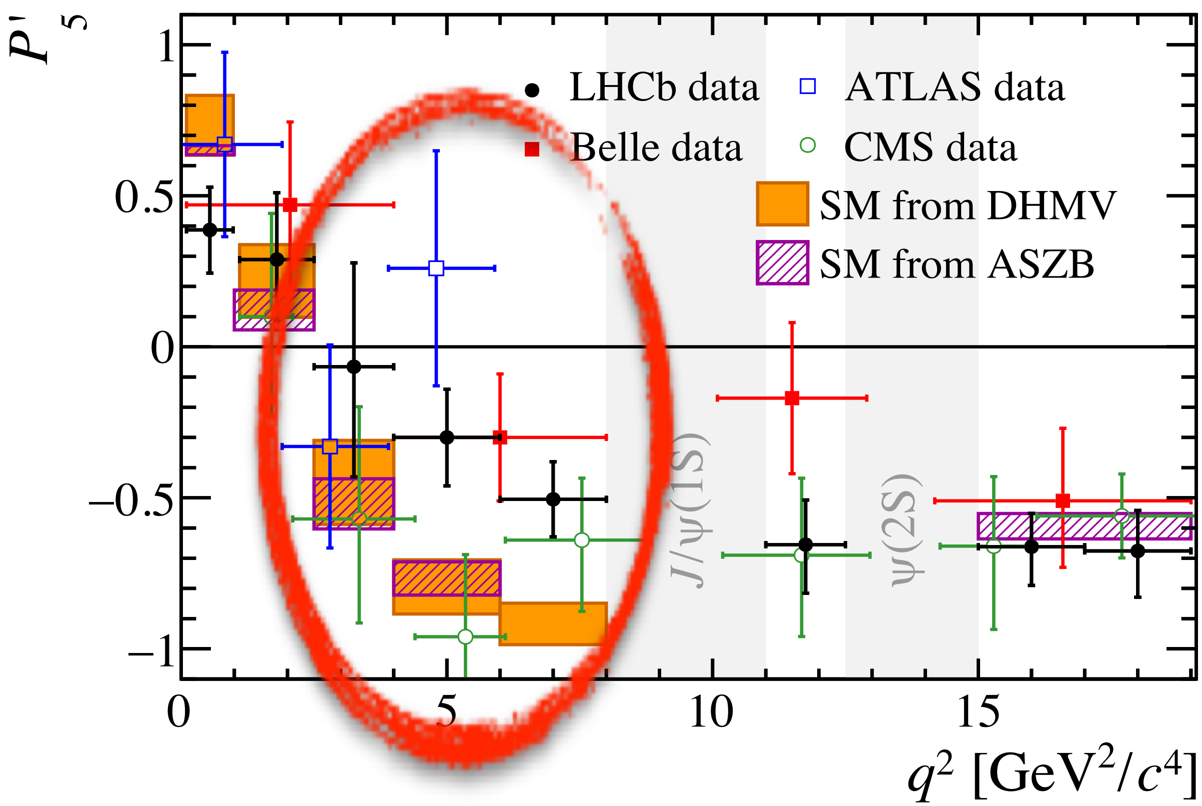
JHEP 11 (2016) 047
JHEP 04 (2017) 142



JHEP 06 (2015) 115

Other anomalies in the $b \rightarrow s\ell^+\ell^-$ sector

- Angular analysis of $B^0 \rightarrow K^{*0}\mu\mu$
- Can construct less form-factor dependent ratios of observables, like P_5'

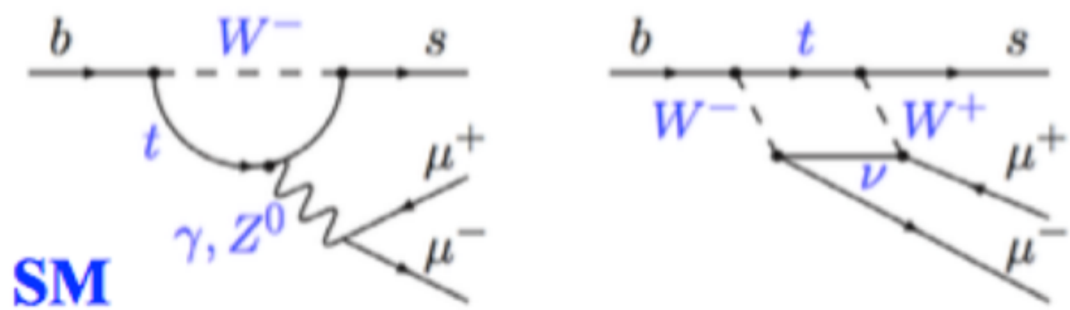


- JHEP 02 (2016) 104
- PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

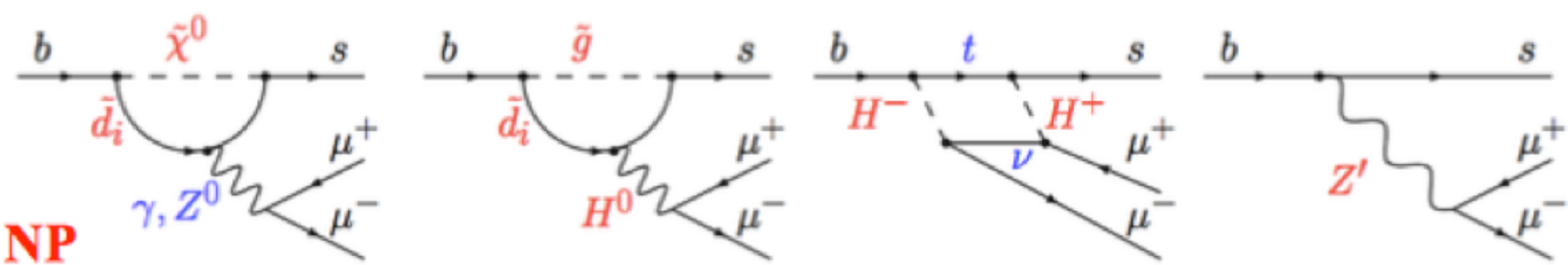
- It is important to remark that global fits by several theory groups take into account up to 90 observables from various experiments, notably including $B \rightarrow \mu\mu$ and $b \rightarrow s\ell^+\ell^-$ transitions, and nicely get a consistent overall picture

Why is $b \rightarrow s\ell^+\ell^-$ relevant?

- Quark-level transitions entering some of the most relevant decay amplitudes to search for new physics effects

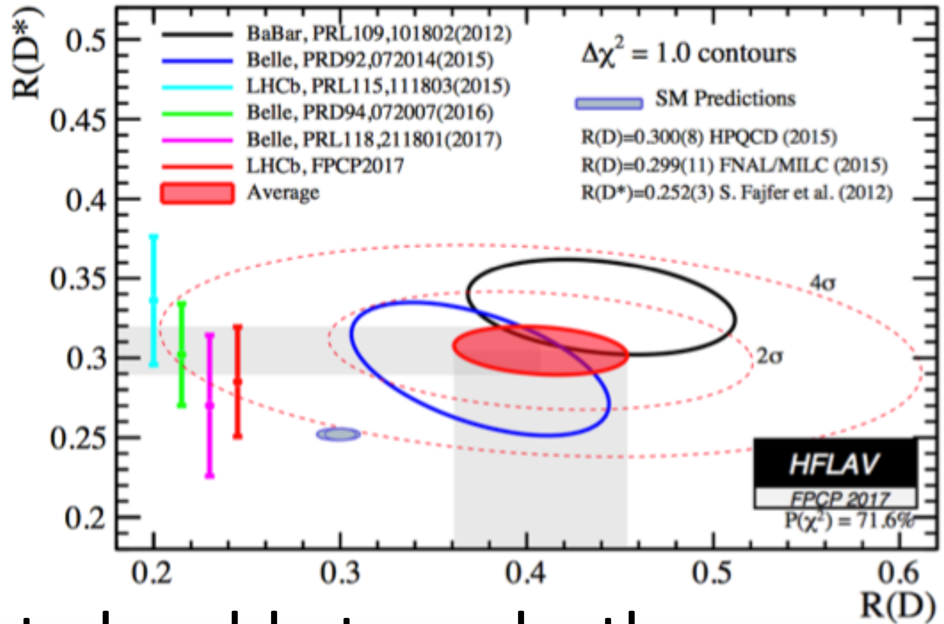


- The presence of new particles may lead to sizeable effects beyond the Standard Model



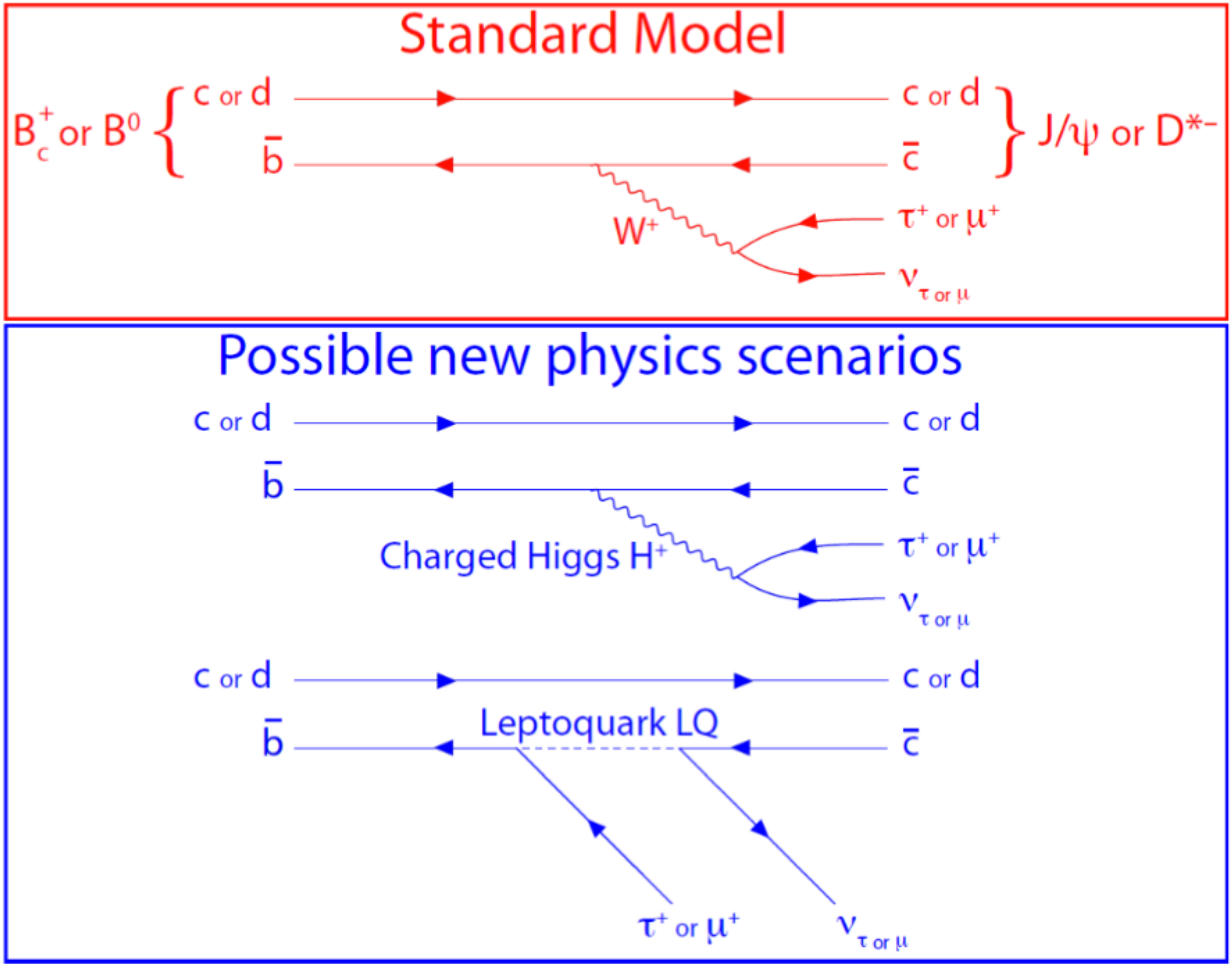
LFU tests in semileptonic *b*-hadron decays

- Measure ratio
  $R_D^{(*)} = BF(B \to D^{(*)}\tau\nu) \,/\, BF(B \to D^{(*)}\mu\nu)$



- Measurements of R(D) and R(D*) by BaBar, Belle and LHCb
  – Overall average shows a 4σ discrepancy from the SM
  – LHCb has recently demonstrated to be able to make the measurement also with 3-prong τ decays [arXiv:1708.08856]
- LHCb can also perform measurements with other *b* hadrons
  – Recent determination of $R(J/\psi) = BF(B_c \to J/\psi\tau\nu) \,/\, BF(B_c \to J/\psi\mu\nu)$ at about 2σ from the SM [arXiv:1711.05623]
  – Other modes with B_s and Λ_b decays will also come

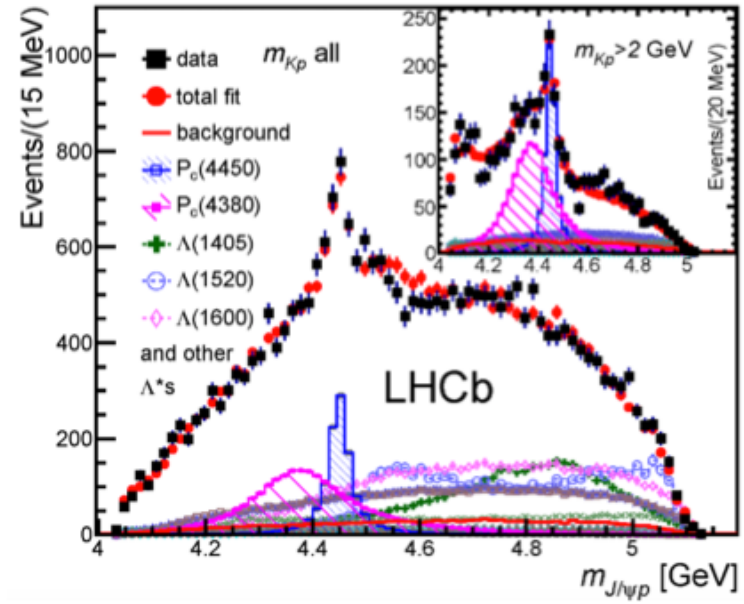
LFU tests in semileptonic *b*-hadron decays



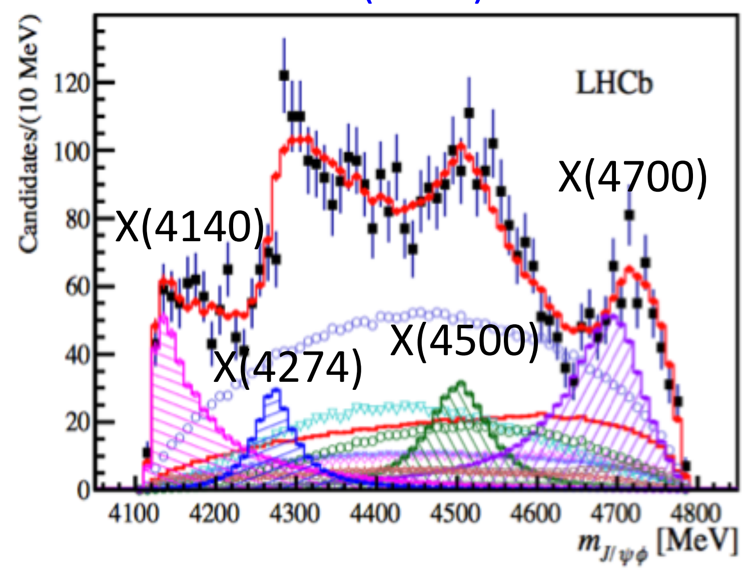
Tetraquarks and pentaquarks

- Sector in great expansion over the last decade
  - A renaissance of QCD in the non-perturbative regime
- Several “exotic” candidates have been identified and are now under the magnifying glass of experiments
  - Lots of work still needed to clarify the global picture and understand the nature of these states

PRL 115 (2015) 072001



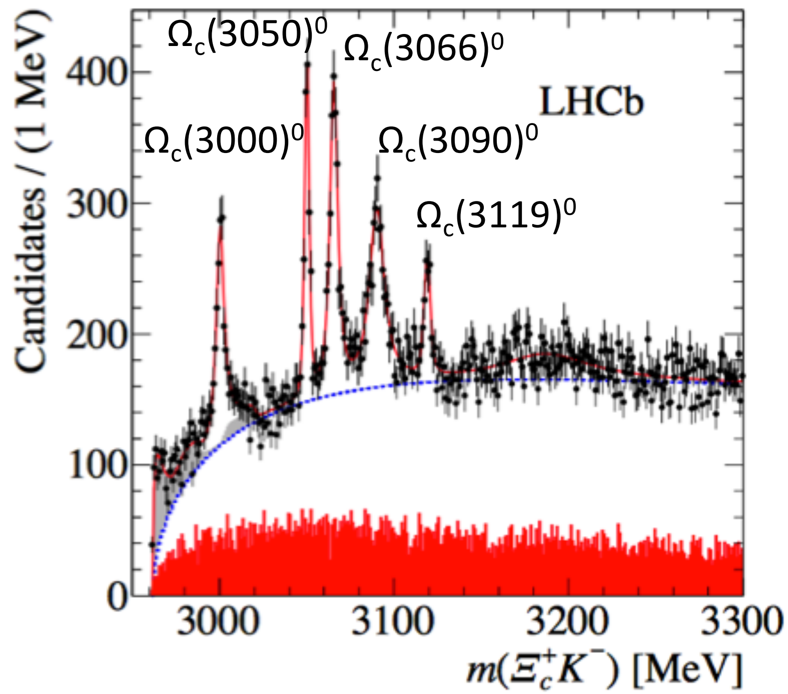
PRL 118 (2017) 022003



Spectroscopy: excited Ω_c (?) states

- Besides new physics searches, LHCb can do relevant measurements to improve our understanding of QCD
- This is an example of a recent analysis that led to the discovery of five new states, most likely excited versions of the Ω_c baryon decaying to a Ξ_c baryon and a kaon, but some of them could also have a more exotic origin (e.g., multiquark states)

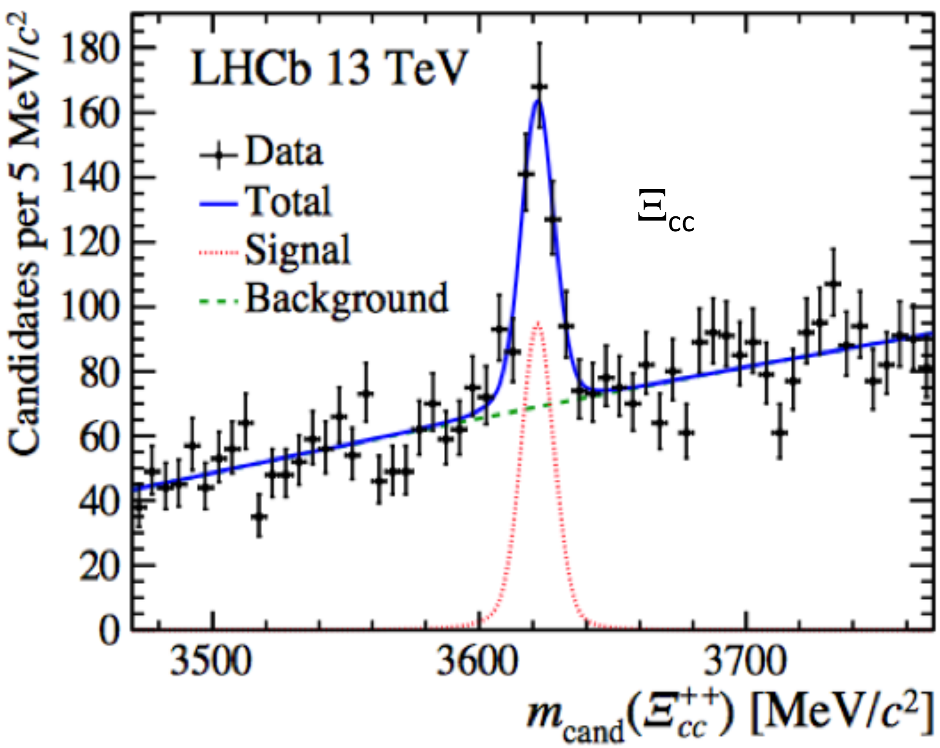
Phys. Rev. Lett. 118 (2017) 182001



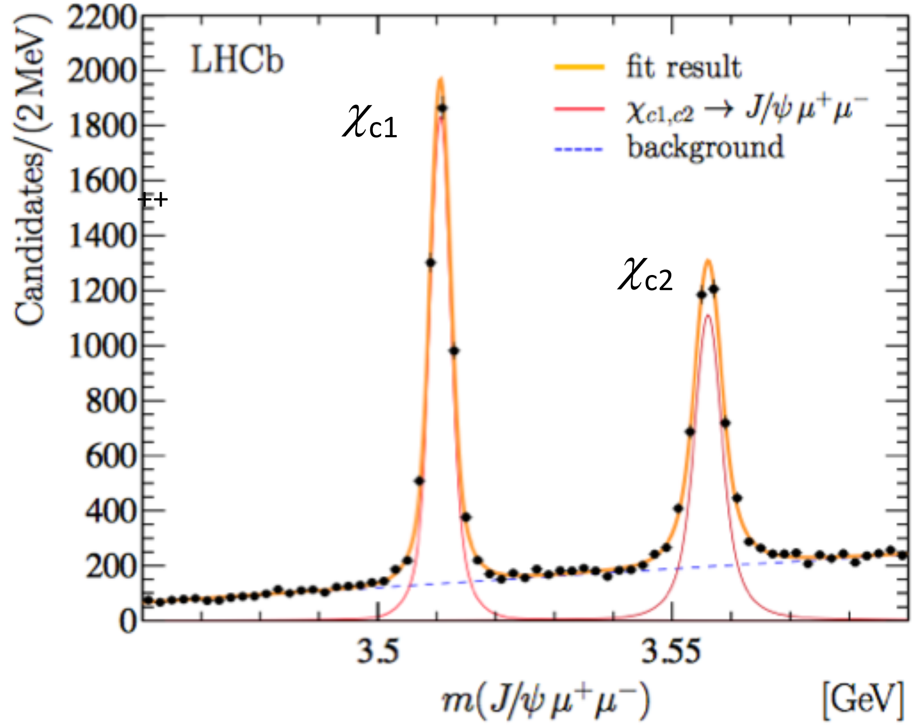
Other observations and measurements

- First observation of a doubly-charmed baryon, the Ξ_{cc}^{++}
- Precision measurements of masses and widths of χ_{c1} and χ_{c2} mesons via a newly observed decay mode $\chi_{c2} \rightarrow J/\psi\mu\mu$

PRL 119 (2017) 112001

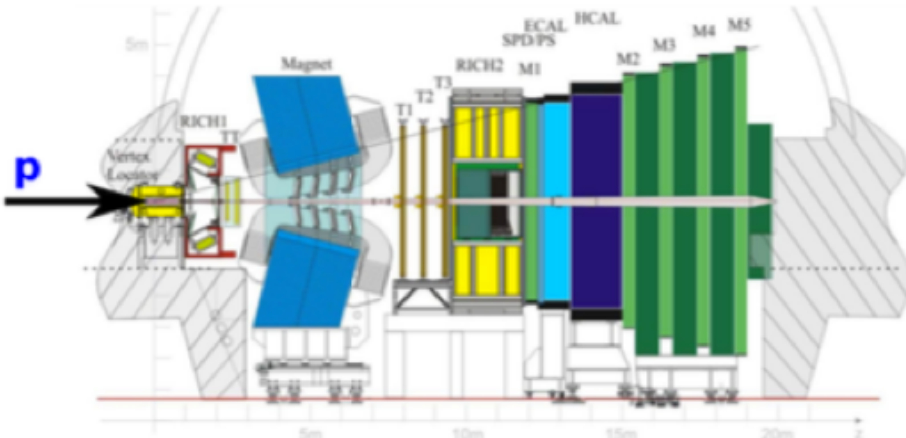


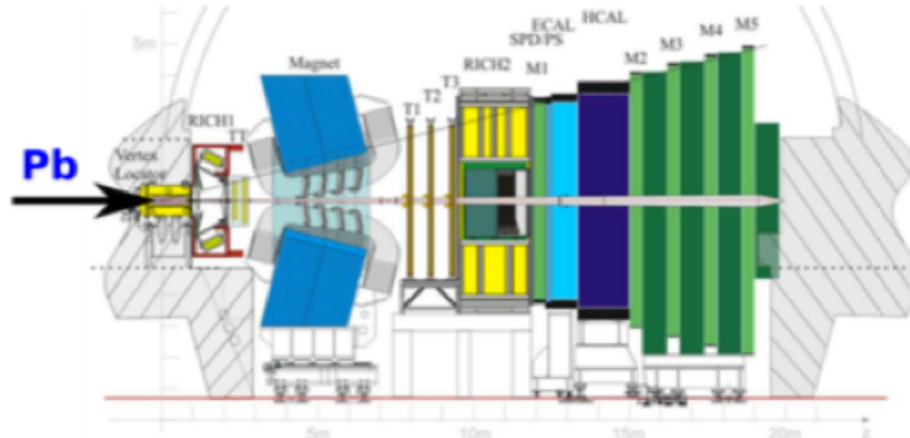
PRL 119 (2017) 221801



Heavy-ion collisions

Data taken during 2016 p-Pb and Pb-p runs @ $\sqrt{s_{NN}} = 8.16$ TeV





Forward

$$1.5 < y^* < 4.5$$

$$y^* = y_{lab} - 0.465$$

Backward

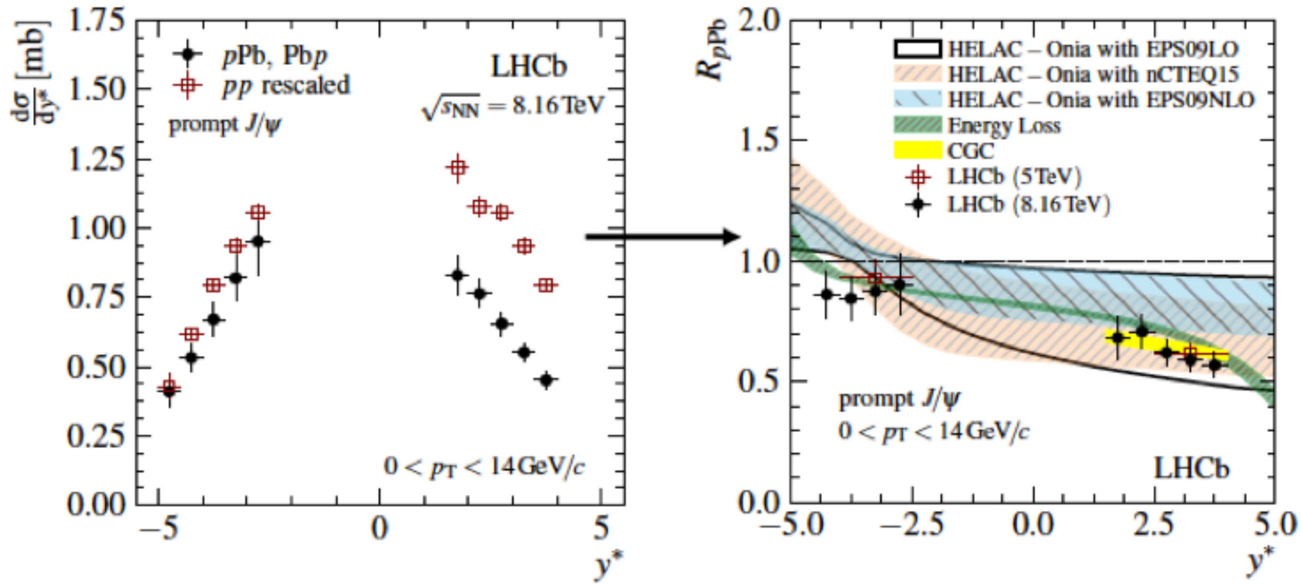
$$-5.5 < y^* < -2.5$$

$$y^* = -(y_{lab} + 0.465)$$

J/ψ production in pPb at 8 TeV

- Nuclear effects seen in the comparison with pp collisions and in the comparison of pPb with Pbp

$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$ and $$R_\mathrm{FB}(p_\mathrm{T}, y^*) \equiv \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, +y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, -y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$



- Color glass condensate (saturation of gluon density at low x) and energy loss (scattering of the colliding gluon in nuclear matter) are found to be very accurate when comparing with data

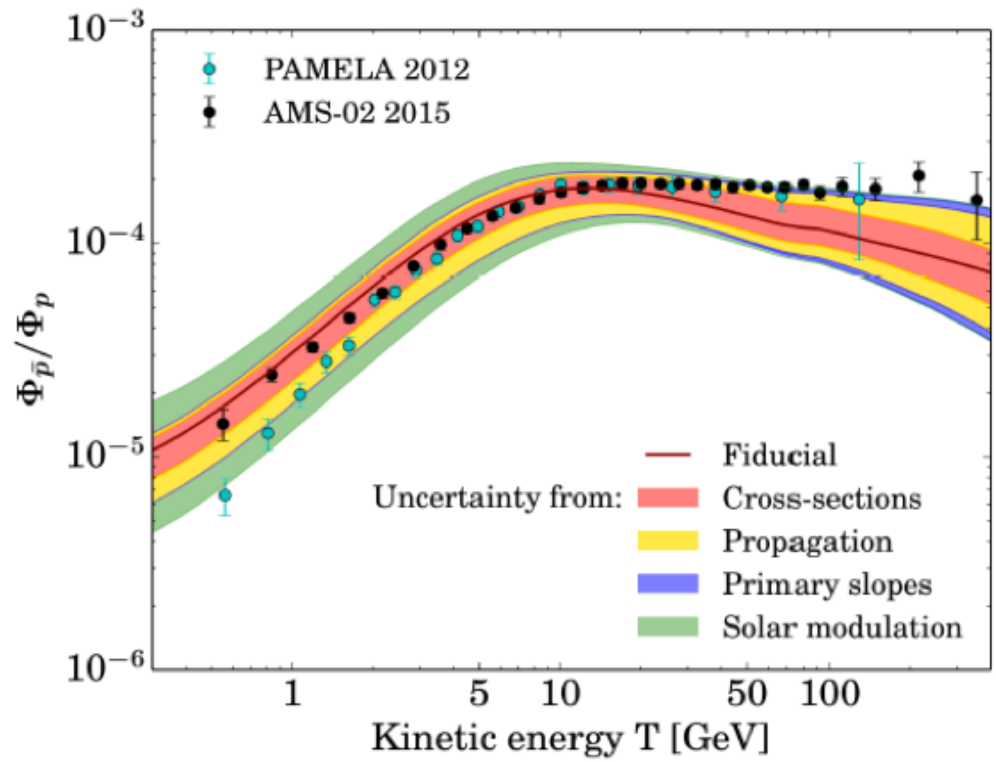
Phys. Lett. B774 (2017) 159

- First LHC paper with 2016 data, out of the Turbo trigger!

Antiproton production in fixed-target pHe collisions

LHCb-CONF-2017-002

- Measurement motivated by the need to understand energy dependence of $\bar{p}$ component from cosmic rays in space
- Theoretical uncertainties are limited by precise knowledge of cross section for basic processes in the interstellar medium, like those arising from pHe collisions

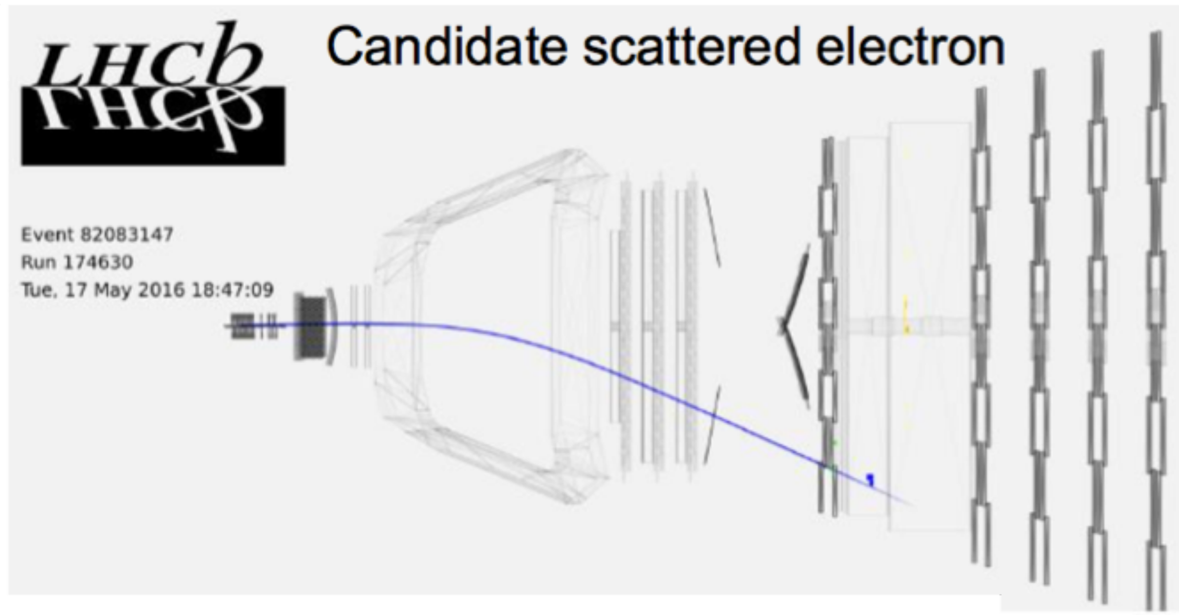


- LHCb can inject gas into the beam pipe for relevant cross-section measurements in the sector

Antiproton production in fixed-target *p*He collisions

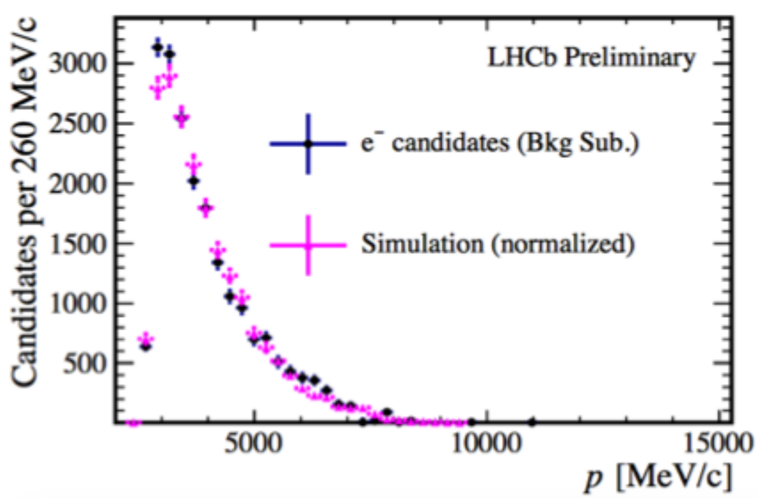
LHCb-CONF-2017-002

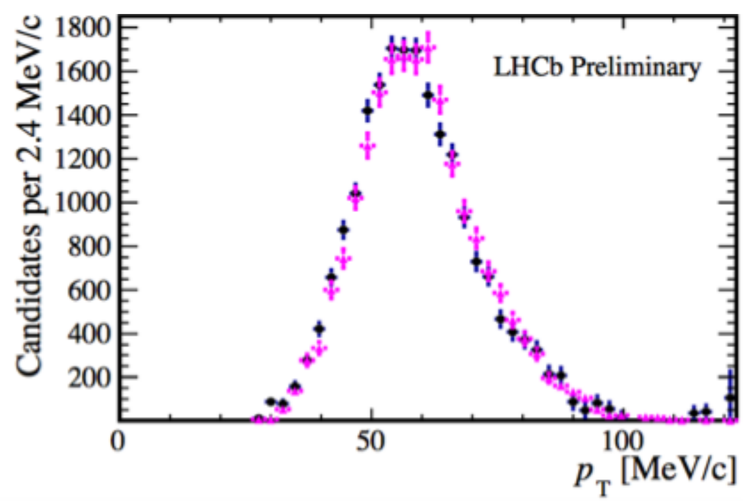
- One difficulty to measure absolute cross sections with gas injection is the determination of luminosity
  - A novel method has been developed to exploit elastic pe^- interactions



$$\mathcal{L} = 0.443 \pm 0.011 \pm 0.027\ \mathrm{nb}^{-1}$$

- Very good agreement between simulation and data

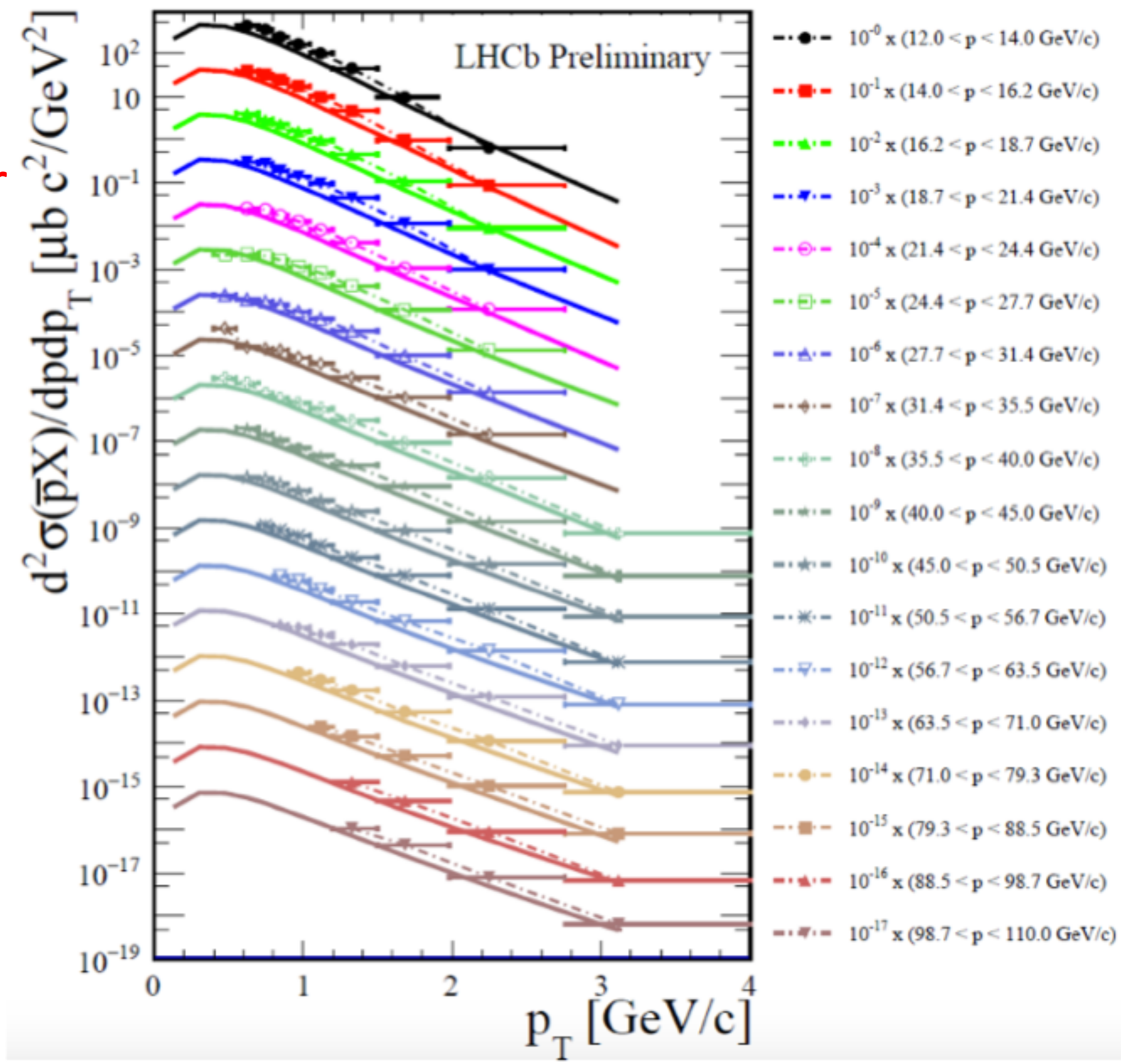




Antiproton production in fixed-target *p*He collisions

LHCb-CONF-2017-002

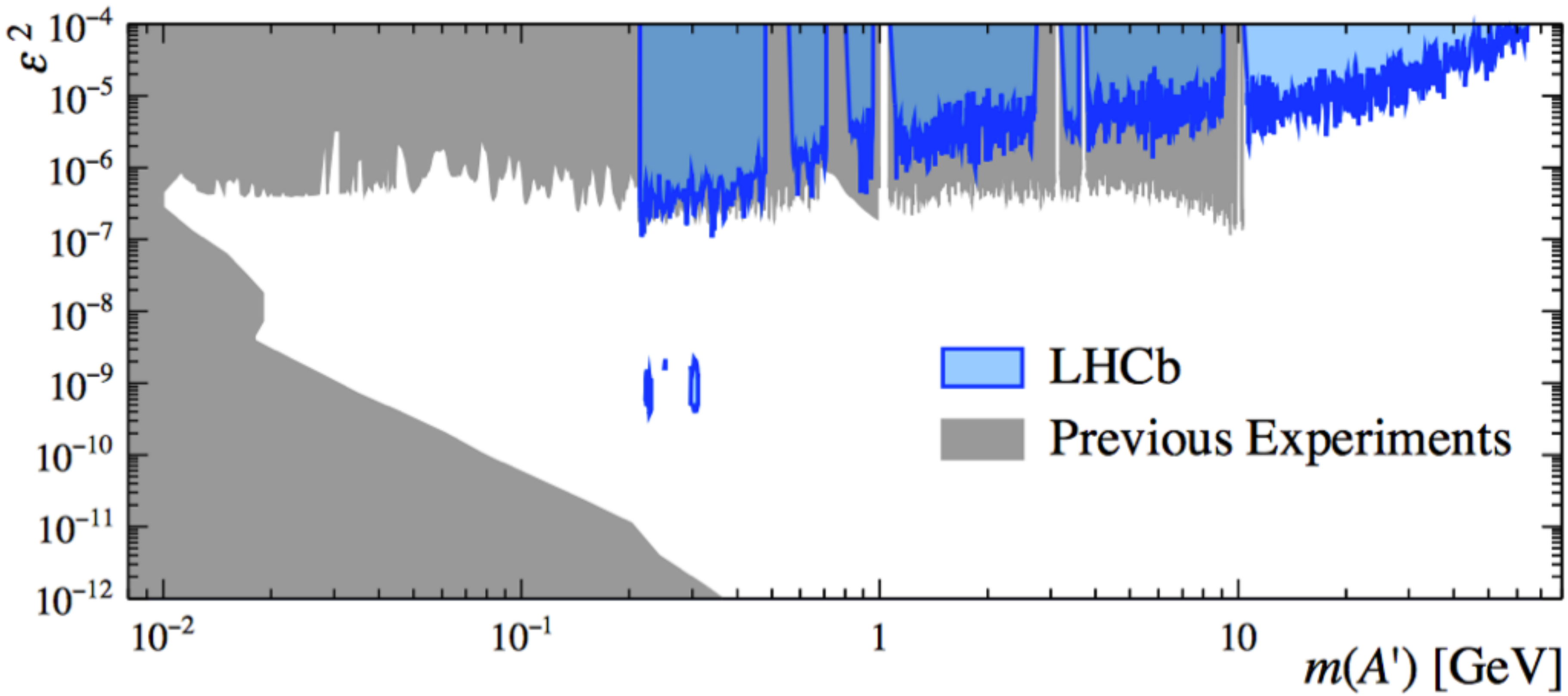
- Antiproton cross section measured with 10% precision
  - The measurement is larger by 1.5 with respect to EPOS LHC event generator
- Theoretical interpretation ongoing
- Additional production measurements are also important
  - E.g., antiprotons from Λ decays
- Rich programme to develop with fixed target!



Search for dark photons decaying to a dimuon

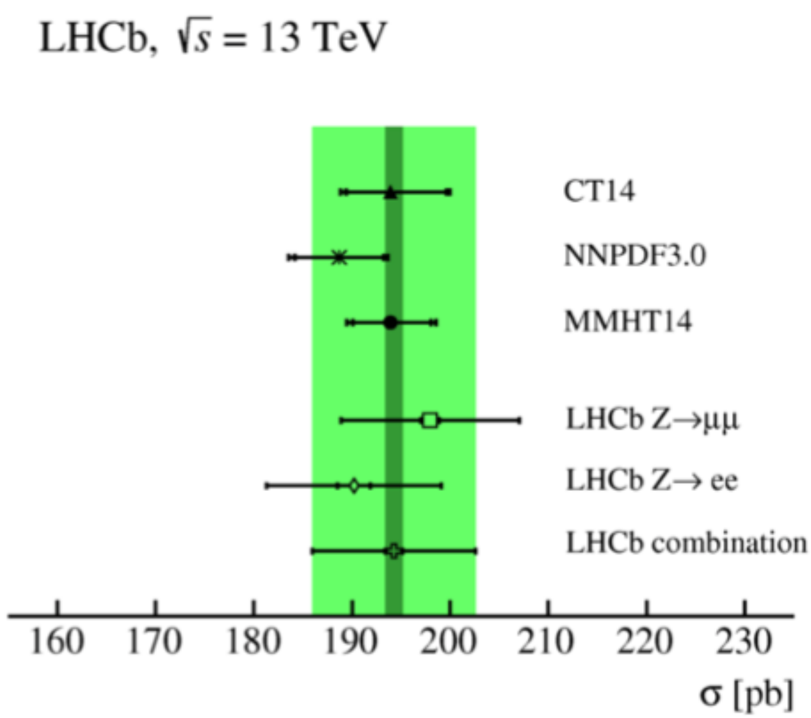
arXiv:1710.02867

First LHCb search for A' is complete. Despite O(10%) L0 efficiency at low mass— and only have 1.5/fb of data — we already equal BaBar in the prompt search. Above 10 GeV, these are the first limits. The displaced search excludes a small region — first ever non-beam-dump long-lived sensitivity — and a large region is within reach for Run 2.



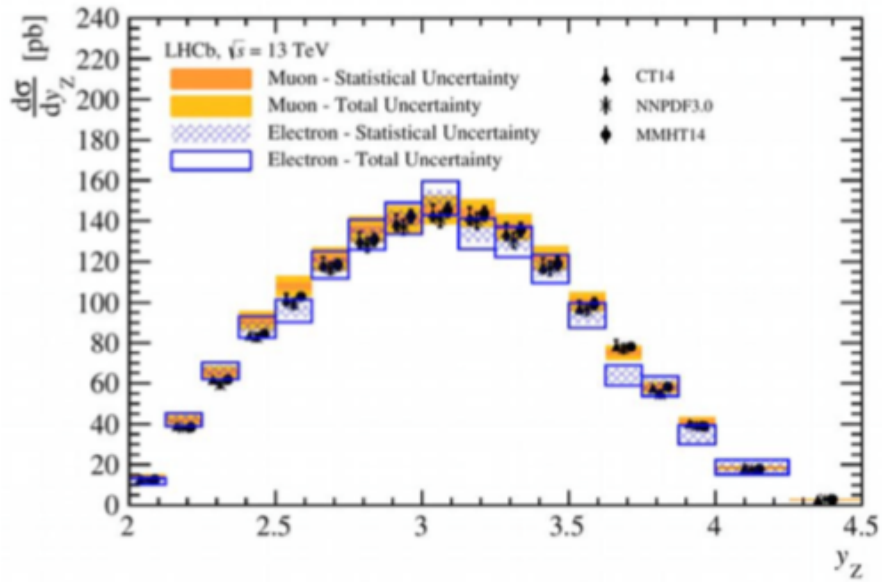
Forward Z^0 boson production

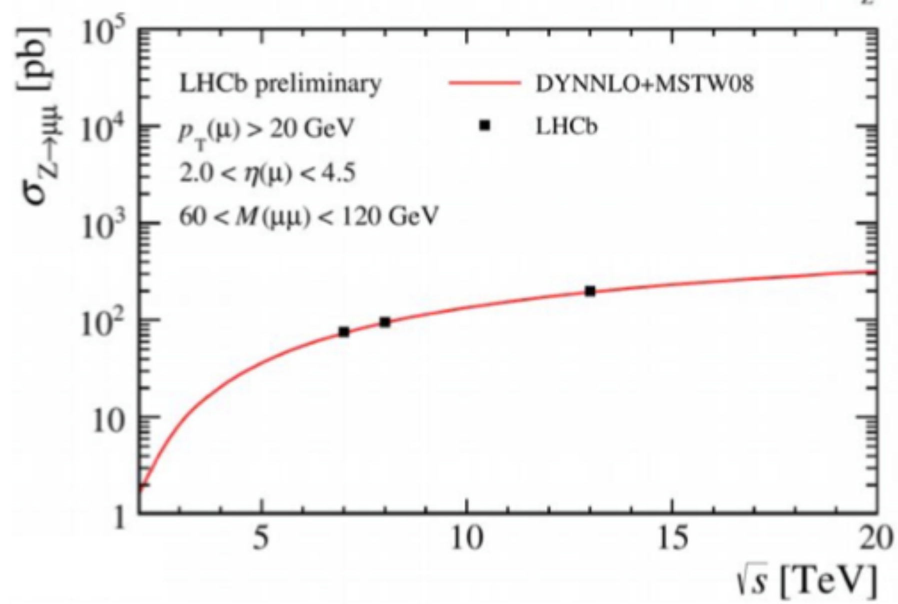
- $Z^0 \rightarrow \mu\mu$ and $Z^0 \rightarrow ee$ cross section at 13 TeV measured in LHCb acceptance



$$\sigma_{\mathrm{Z}}^{\ell\ell} = 194.3 \pm 0.9 \pm 3.3 \pm 7.6\,\mathrm{pb}$$

JHEP 09 (2016) 136





LHCb 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+)
3 fb^{-1}	9 fb^{-1}	30 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

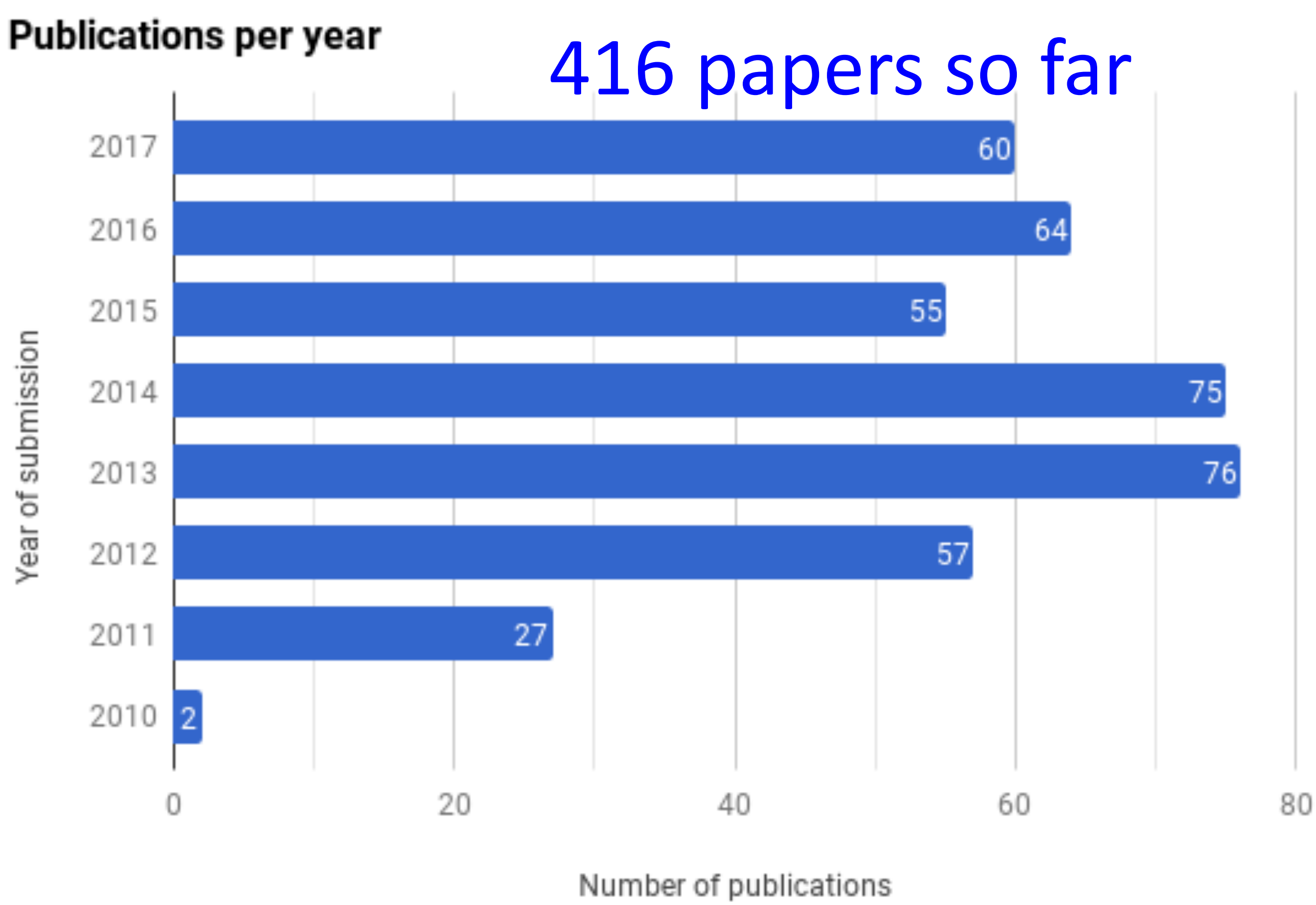
* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2x10^{34}$ $cm^{-2}s^{-1}$

- A first LHCb upgrade comes already in LS2 (to raise the instantaneous luminosity to $2x10^{33}$ $cm^{-2}s^{-1}$), whereas the HL ATLAS and CMS upgrades come in LS3
- LHCb has submitted at the beginning of 2017 an Expression of Interest for a further upgrade during LS4 to reach $2x10^{34}$ $cm^{-2}s^{-1}$

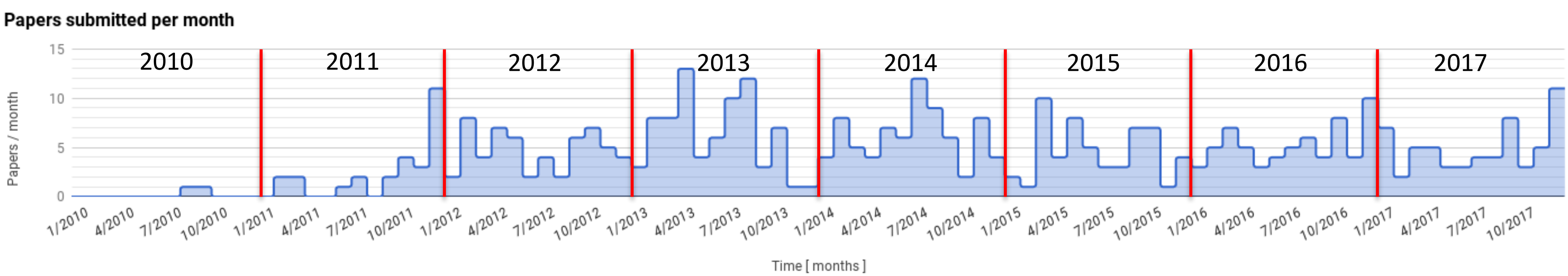
CERN-LHCC-2017-003 https://cds.cern.ch/record/2244311

There's much more!

416 papers so far



http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html



Concluding remarks

- In the current state with fundamental physics, it is necessary to have a programme as diversified as possible
- If we will see new physics in flavour, e.g. from LHCb in Run 2, we should seek confirmation from multiple experiments
  - Belle-II confirmation if new physics comes from $b \to s\ell^+\ell^-$ and (non) LFU, as well as other measurements not accessible at LHCb like $B \to \tau\nu$
  - ATLAS/CMS in time-dependent B_s physics, $B \to \mu\mu$, ...
- Furthermore, new physics should affect different modes coherently
  - Maintaining the broadest possible physics programme in the long term will be crucial → upgrade of LHCb to further raise the luminosity in Run-5

Concluding remarks cont.d

- In the unfortunate event that no direct evidence of new physics pops out of the LHC, flavour physics can play a key role in indicating the way for future developments of elementary particle physics
- If instead new particles will be detected in direct searches, flavour physics will be a fundamental ingredient in understanding the structure of what lies beyond the Standard Model
- In any case, performing precision physics at very high pileup will be a huge detector, **trigger** and reconstruction challenge → let’s try hard