(Some) LHCb highlights

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on behalf of the LHCb collaboration

Vulcano Workshop 2018
Frontier Objects in Astrophysics and Particle Physics

Setting the scene

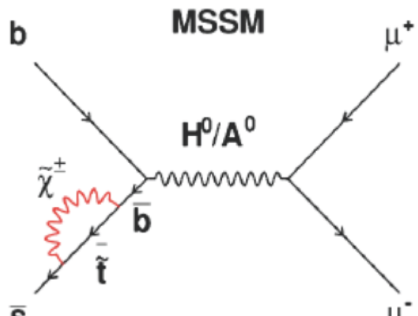
- We know nowadays that the Standard Model (of particle physics) works beautifully up to an energy scale of a few hundred GeV
- However, there are compelling reasons to state that it is incomplete, e.g.
  - Missing dark matter candidate
  - *CP* violation for dynamical generation of the BAU is largely insufficient
- As well as more fundamental reasons, such as
  - Why three families of quarks and leptons?
  - Why the masses of fundamental particles span several orders of magnitude?

Setting the scene

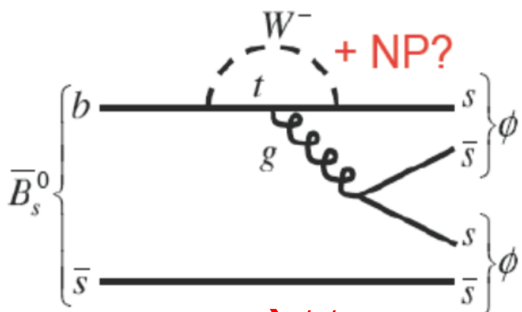
- We know nowadays that the Standard Model (of particle physics) works beautifully up to an energy scale of a few hundred GeV

New physics searches in the flavour sector

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

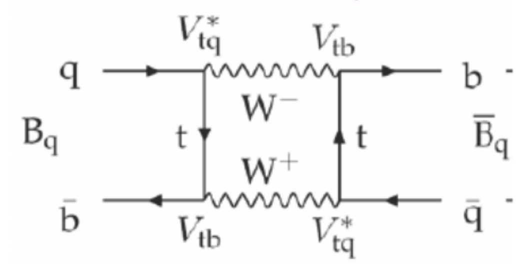


$B_s \rightarrow \mu\mu$



$B_s \rightarrow \phi\phi$

B-$\bar{B}$ mixing



+ NP?

- General amplitude decomposition in terms of couplings and scales

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

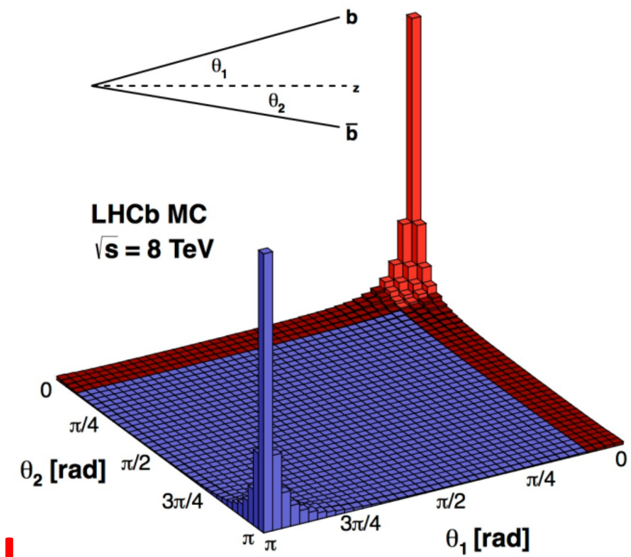
- By studying *CP*-violating and flavour-changing processes, two fundamental tasks can be accomplished
  – Identify new symmetries (and their breaking) beyond the Standard Model
  – Probe mass scales not accessible directly at a collider like the LHC

New physics searches in flavour in a nutshell

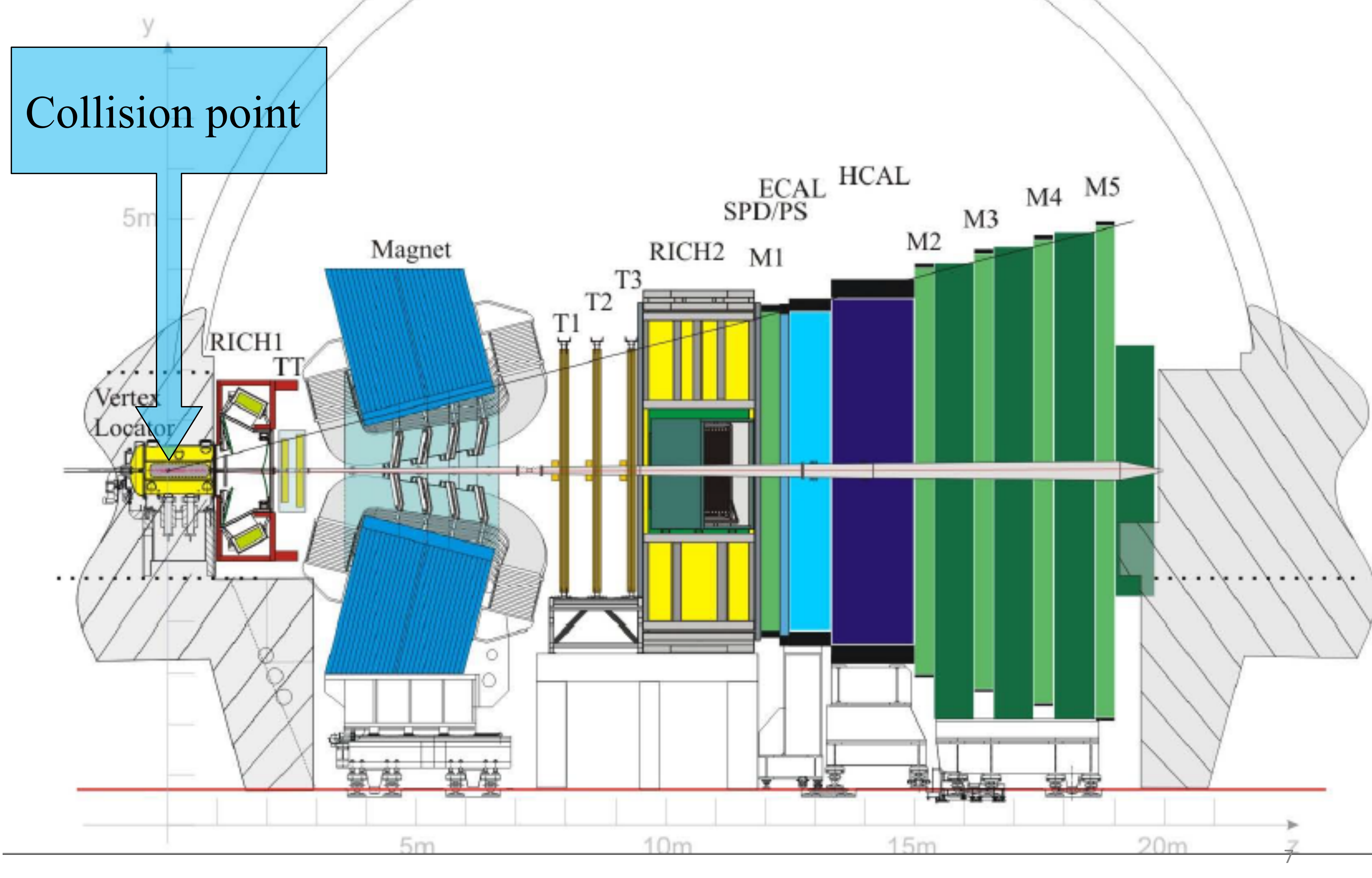
- Classic broad-range measurements
  - CKM physics, search for very rare decays
- Measurements in specific sectors where anomalies are emerging in recent years
  - Lepton-flavour universality in $b \to s\ell^+\ell^-$ quark-level transitions, and related $b \to s\ell^+\ell^-$ picture of decay rates
  - Lepton-flavour universality in semileptonic b-hadron decays

LHCb detector layout

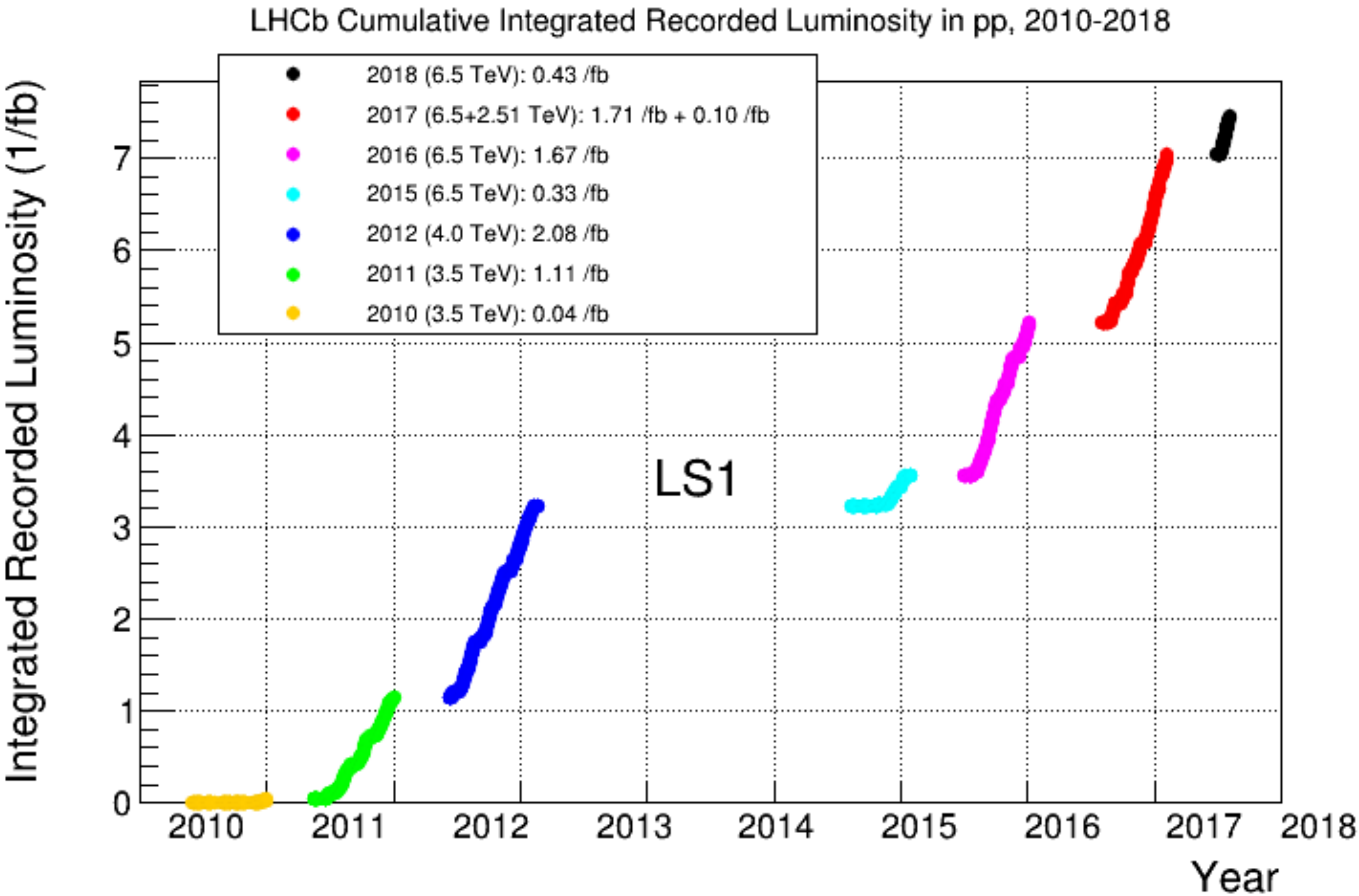
- LHCb is mainly (but not only) studying beauty (and charm) physics
  - At the LHC, the production of heavy quark pairs is peaked forward/backward
  - The detector is a single arm spectrometer
    - Both *b*-hadrons go together forward (or backward)
    - Acceptance $2 < \eta < 5$
  - A *b*-meson / baryon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



Detector cross-section

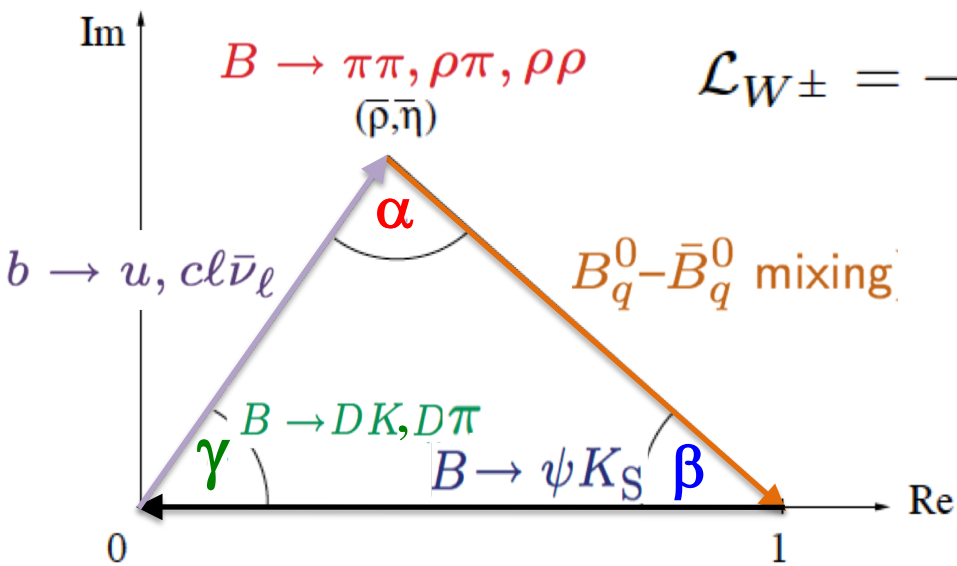


Integrated luminosity



The CKM Unitarity Triangle

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

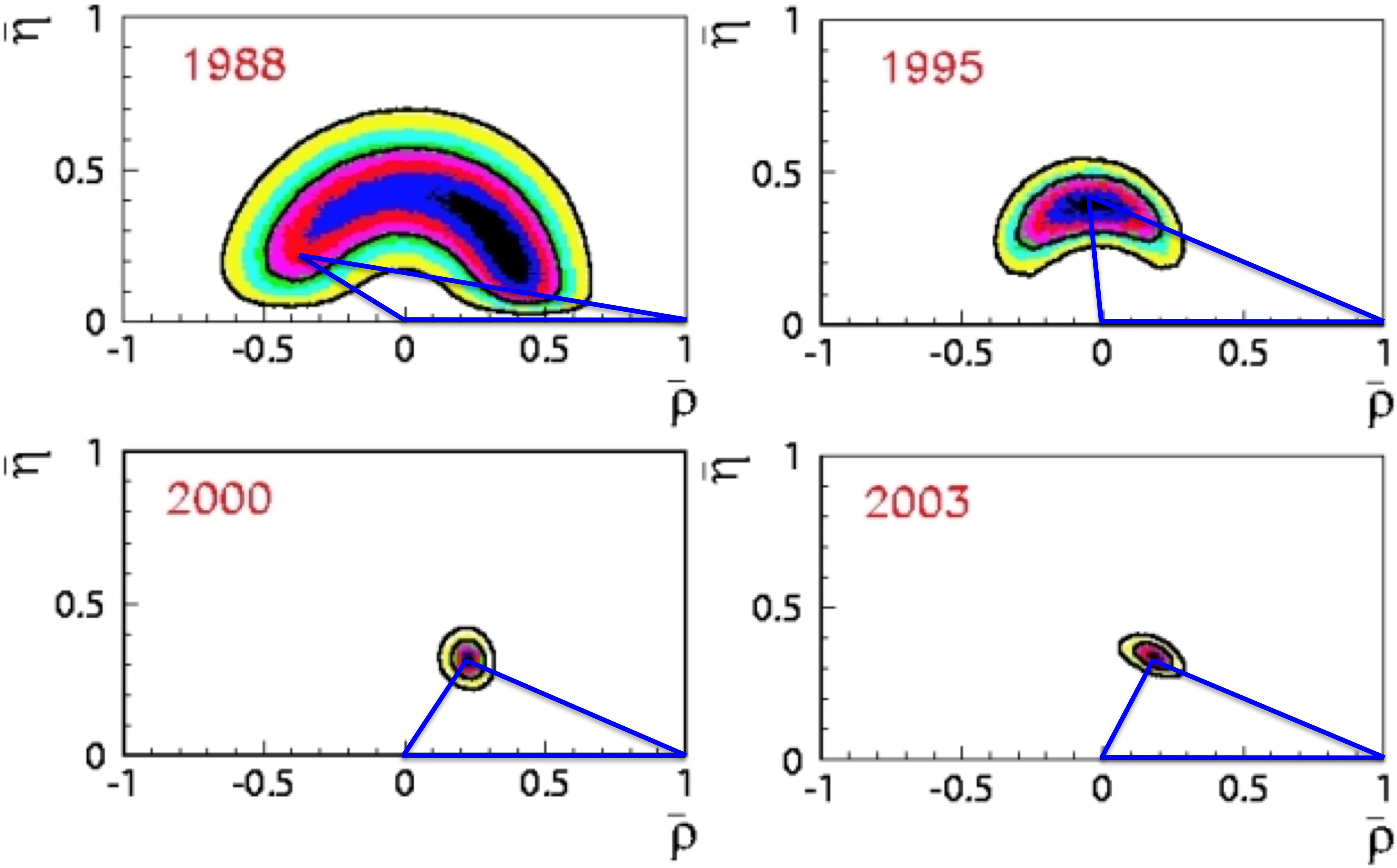


$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} \overline{U}_i \gamma^\mu \frac{1-\gamma^5}{2} (V_{\rm CKM})_{ij} D_j W_\mu^+ + h.c.$$

From CKM matrix unitarity

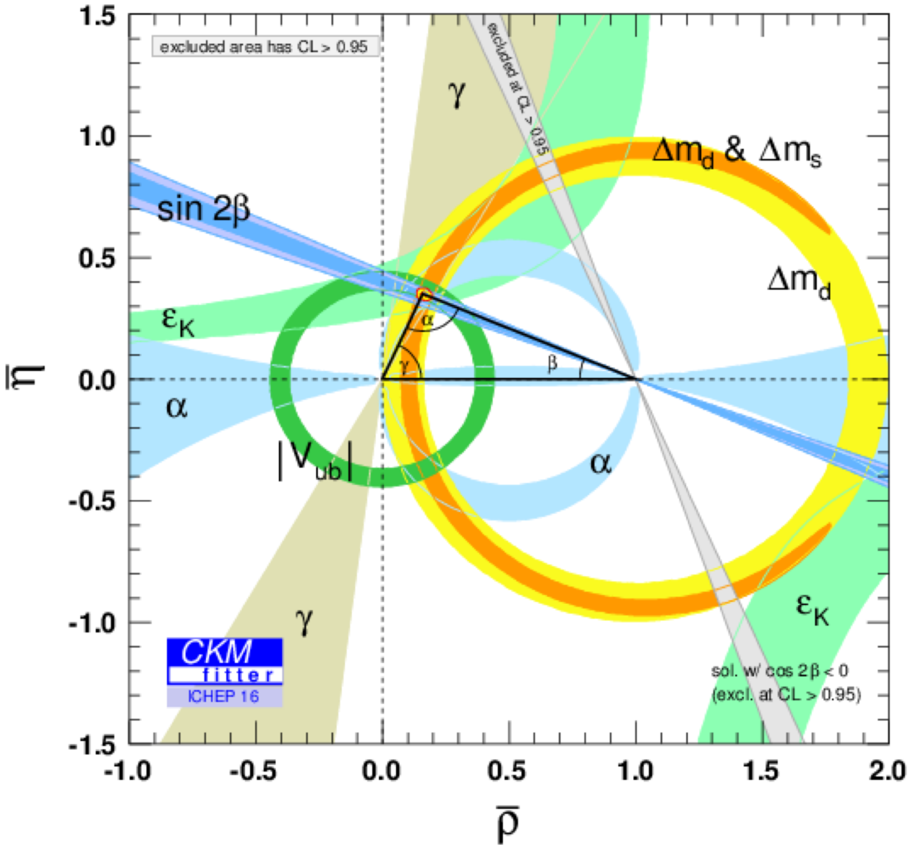
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

History of the Unitarity Triangle

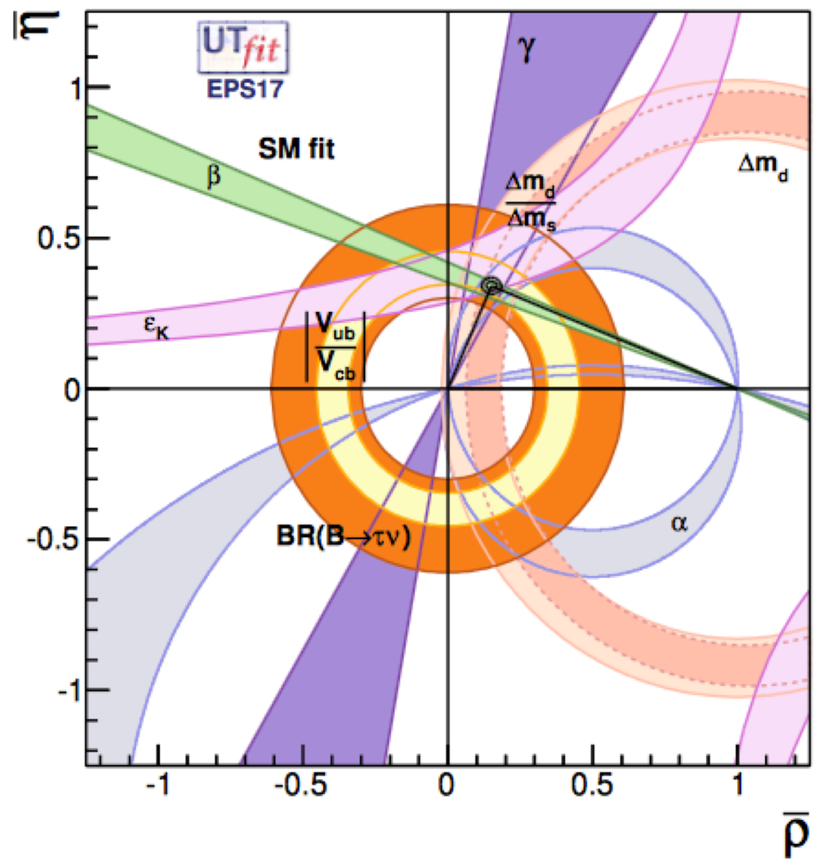


Where we are with global UT fits

http://ckmfitter.in2p3.fr



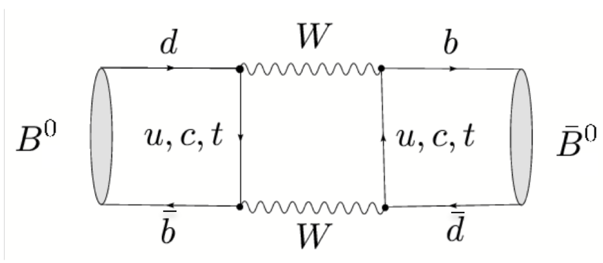
http://www.utfit.org

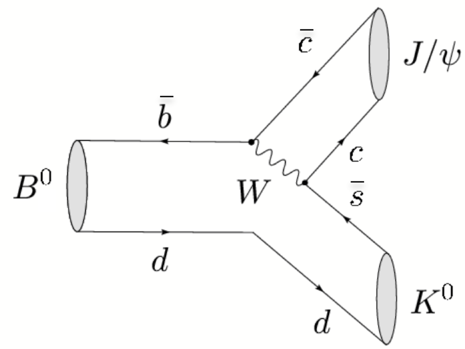


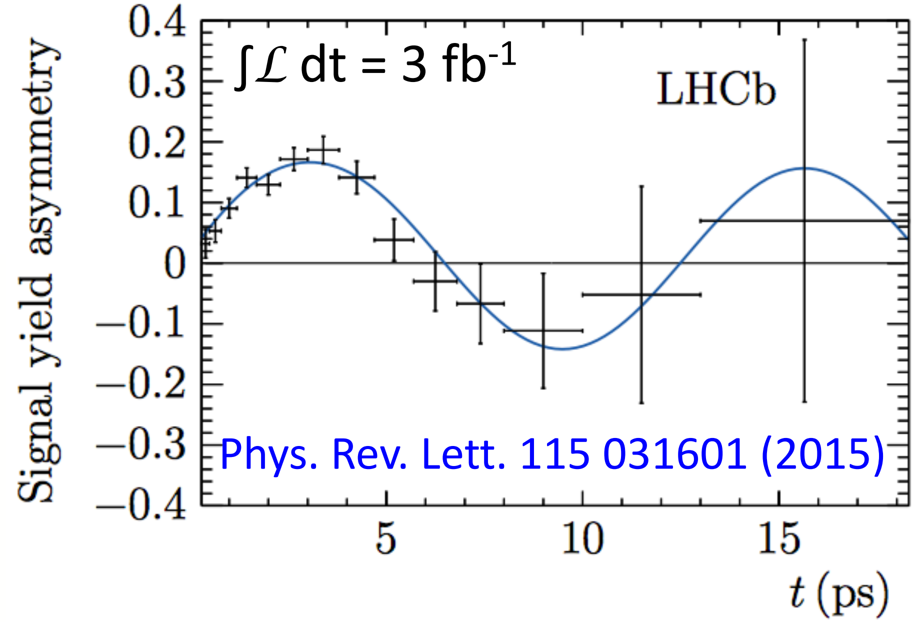
- In the presence of relevant new physics effects, the various contours would not cross each other in a single point
- Certainly that's a great success of the Standard Model CKM picture, but there is still room for new physics at the 10% level

Measurement of sin2β

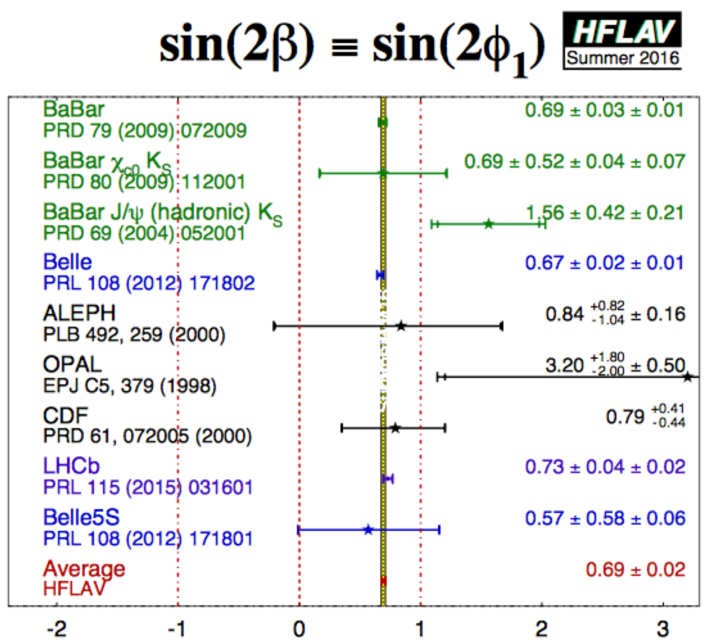
- *CP* violation due to interference between B^0-$\bar{B}^0$ mixing and $b \rightarrow c\bar{c}s$ transitions

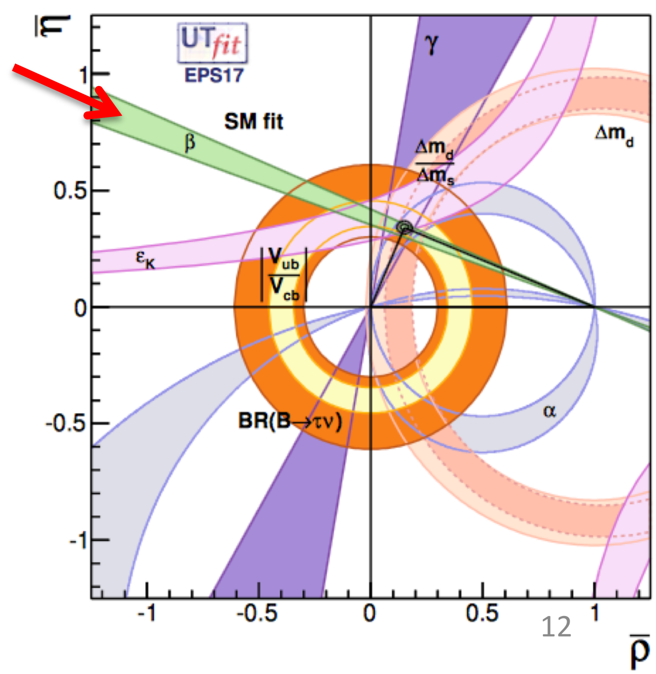




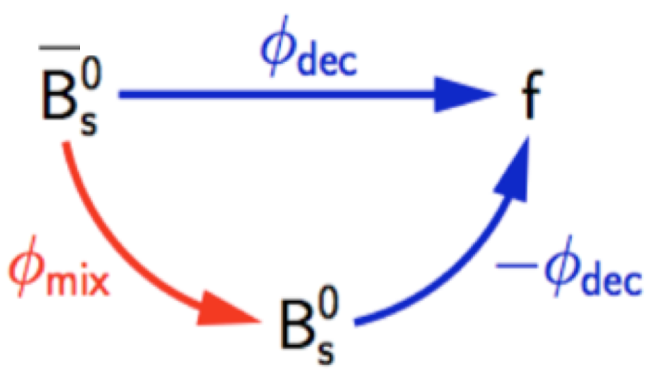


- LHCb has reached the precision of the *B* factories and will soon surpass that with Run-2 data

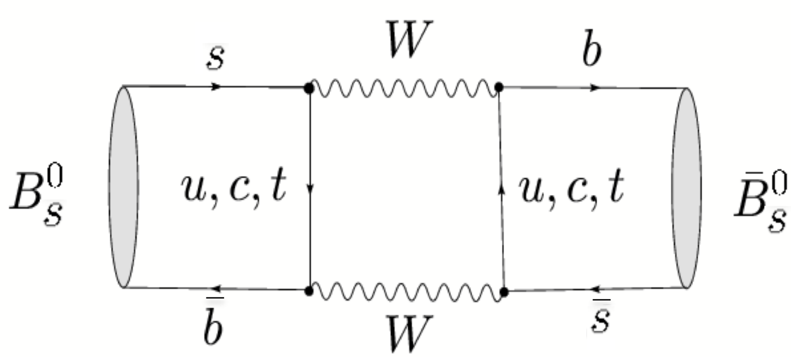


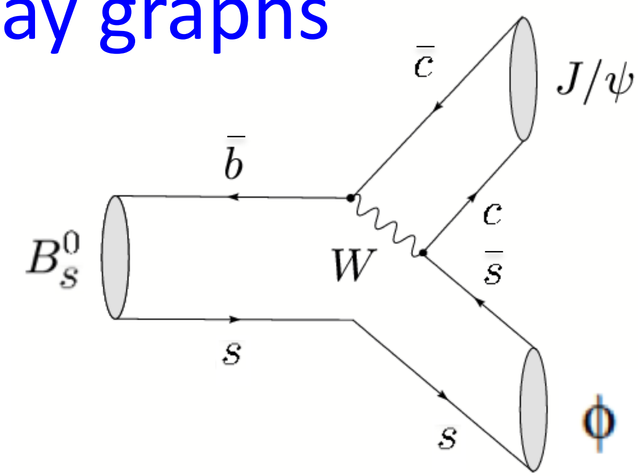


ϕ_s from $b \to c\bar{c}s$ transitions



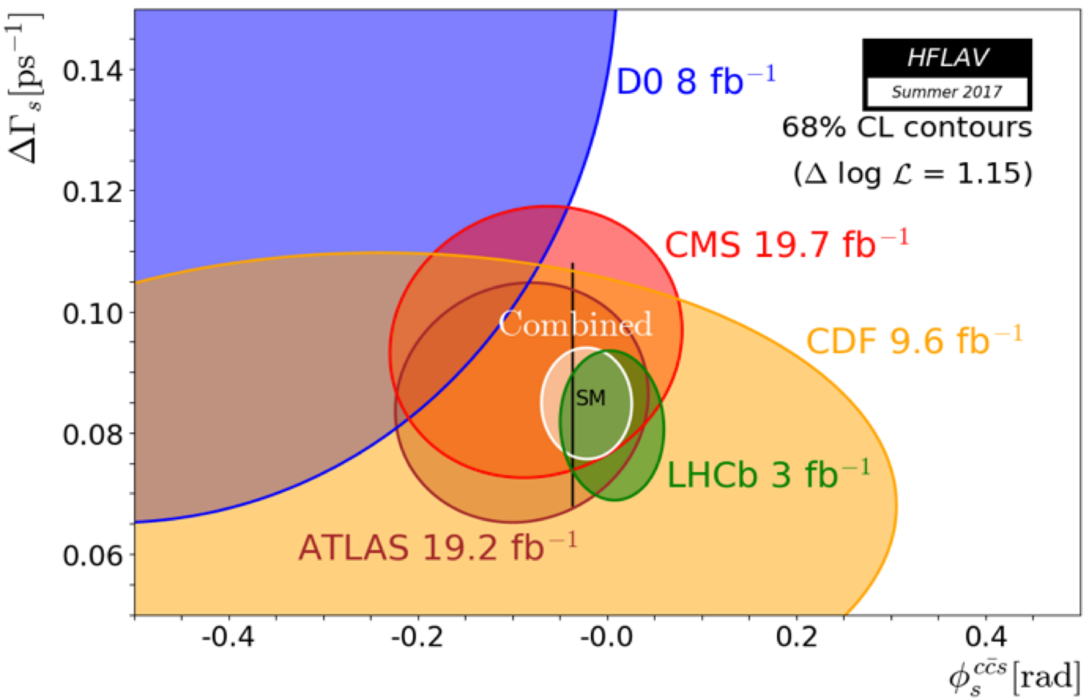
- Golden mode $B_s \to J/\psi\phi$ proceeds (mostly) via a $b \to c\bar{c}s$ tree diagram
- Interference between B_s mixing and decay graphs





- Measures the phase-difference ϕ_s between the two diagrams, precisely predicted from global CKM fits in the Standard Model to be $\phi_s = -2\lambda^2\eta = -37.4 \pm 0.7$ mrad $\to$ can be altered by new physics

Measurement of ϕ_s



- 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

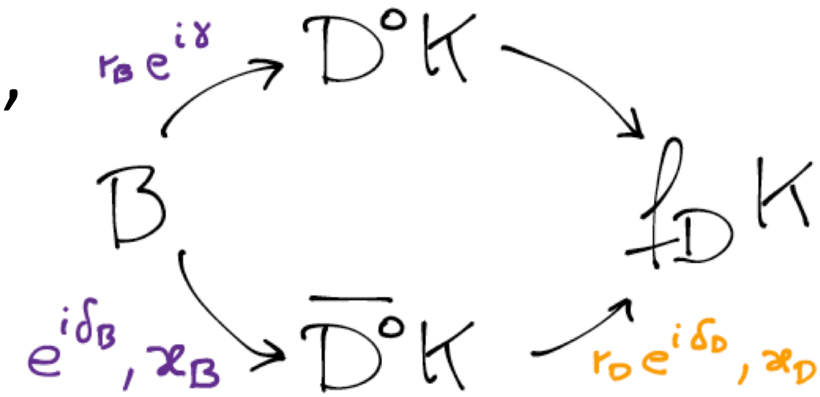
Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\,\phi$	9.6 fb^{-1}	$[-0.60, +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\,\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\,\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[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	$+0.085 \pm 0.006$	

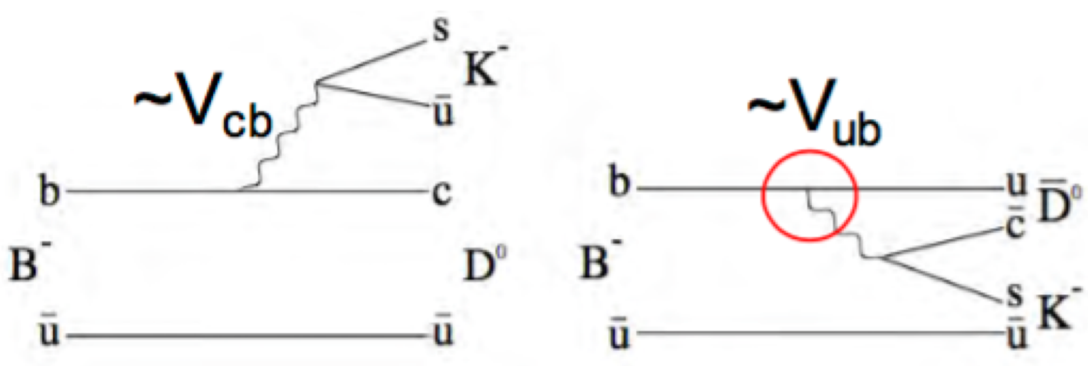
[a] $m(K^+K^-) > 1.05$ GeV$/c^2$.

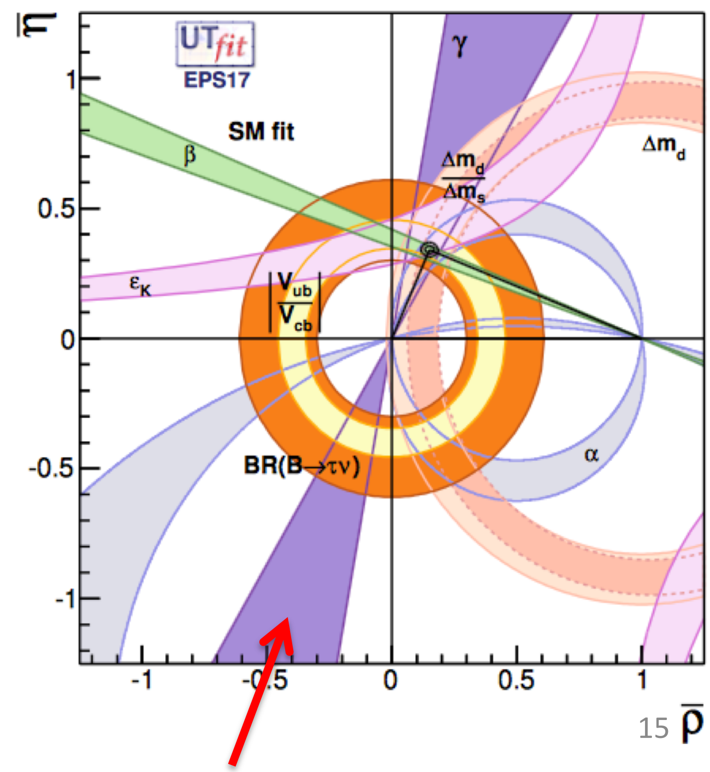
See HFLAV page for the list of references
http://www.slac.stanford.edu/xorg/hflav/

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

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

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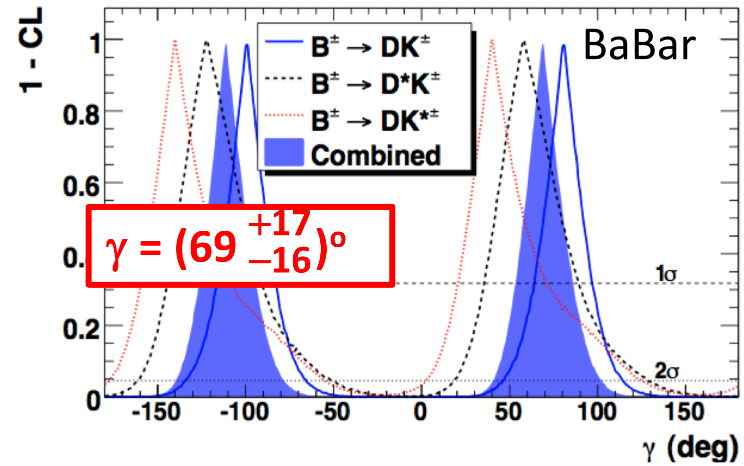

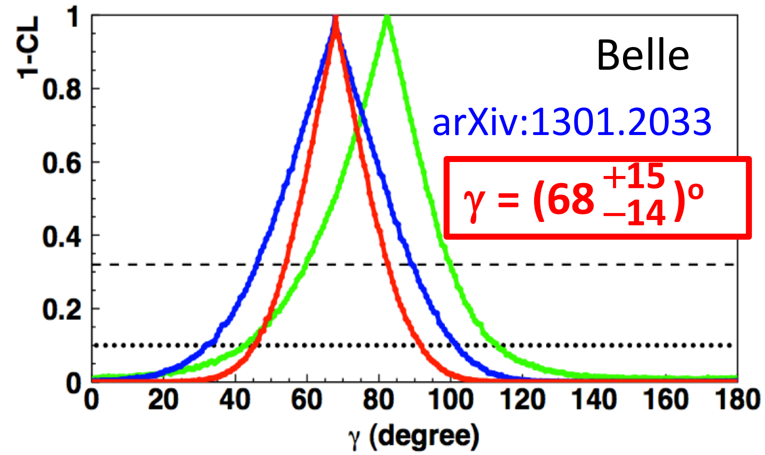

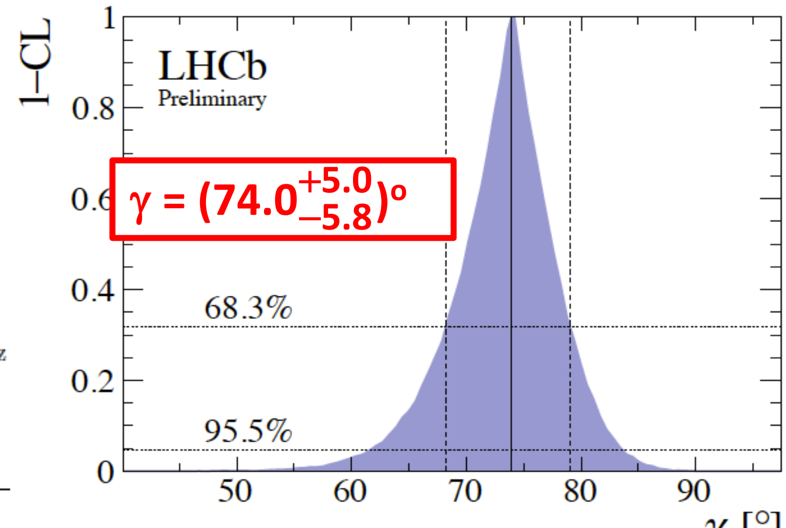

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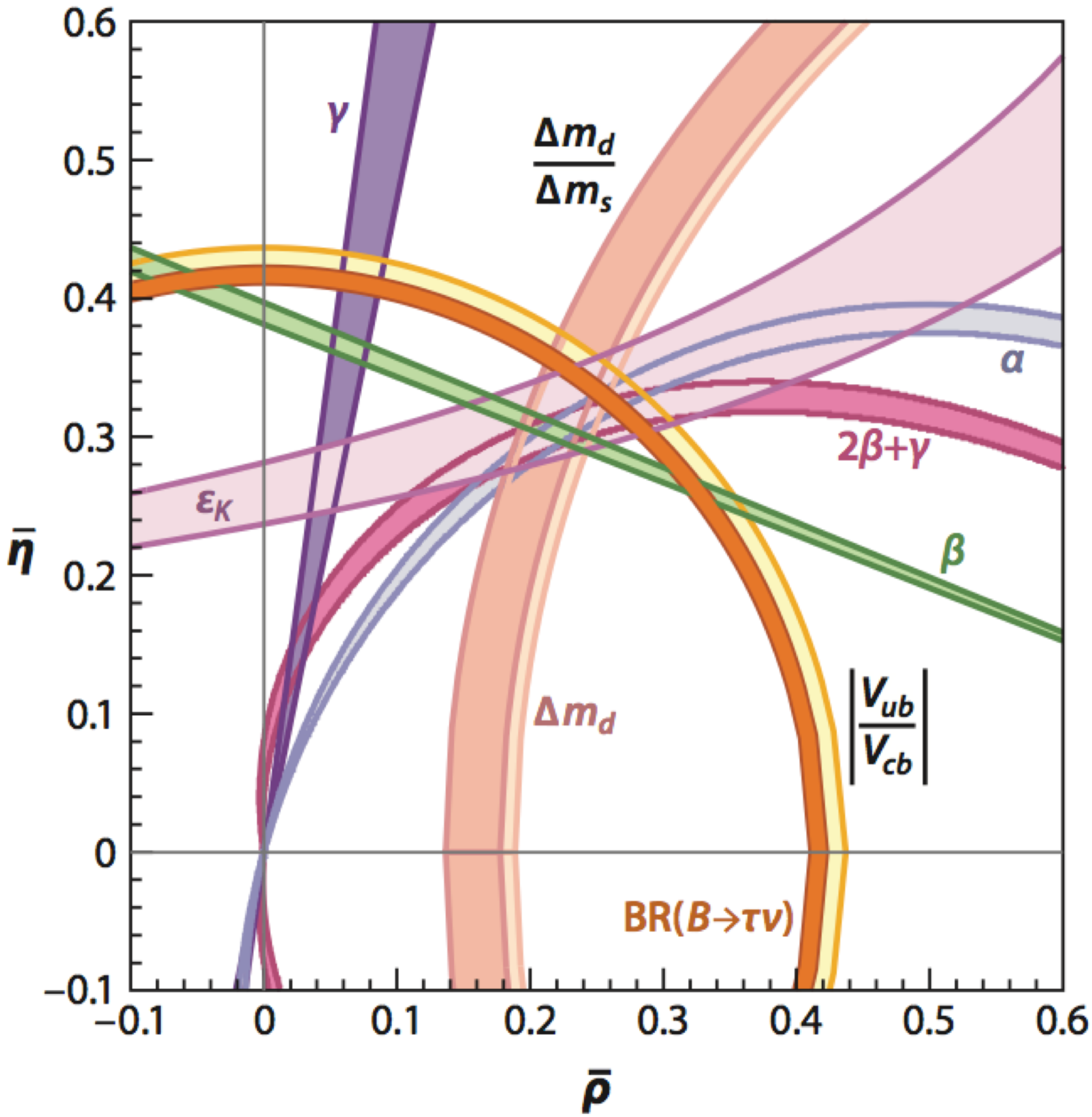
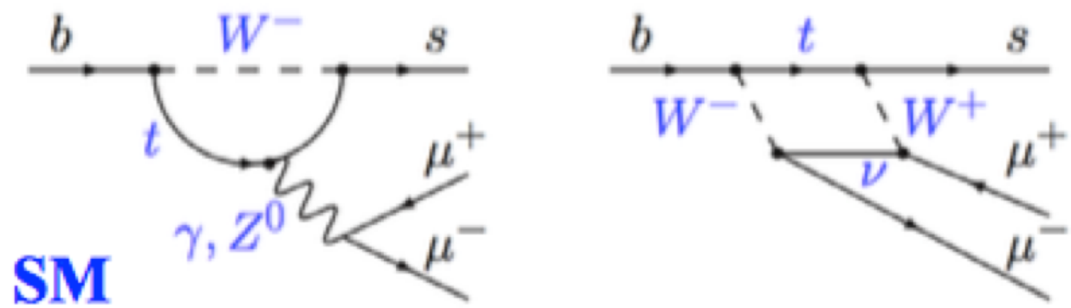
For illustration only: a possible future dream scenario…

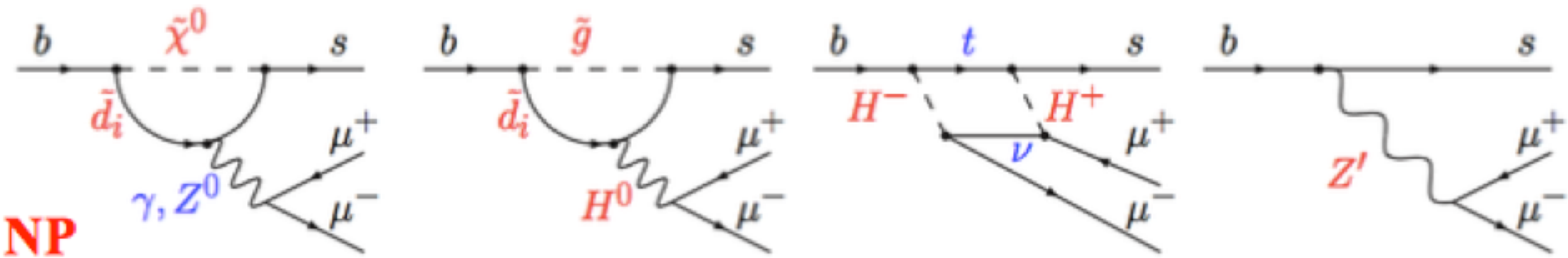


Searches for new physics in $b \to s\ell^+\ell^-$ transitions

- 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 observable effects

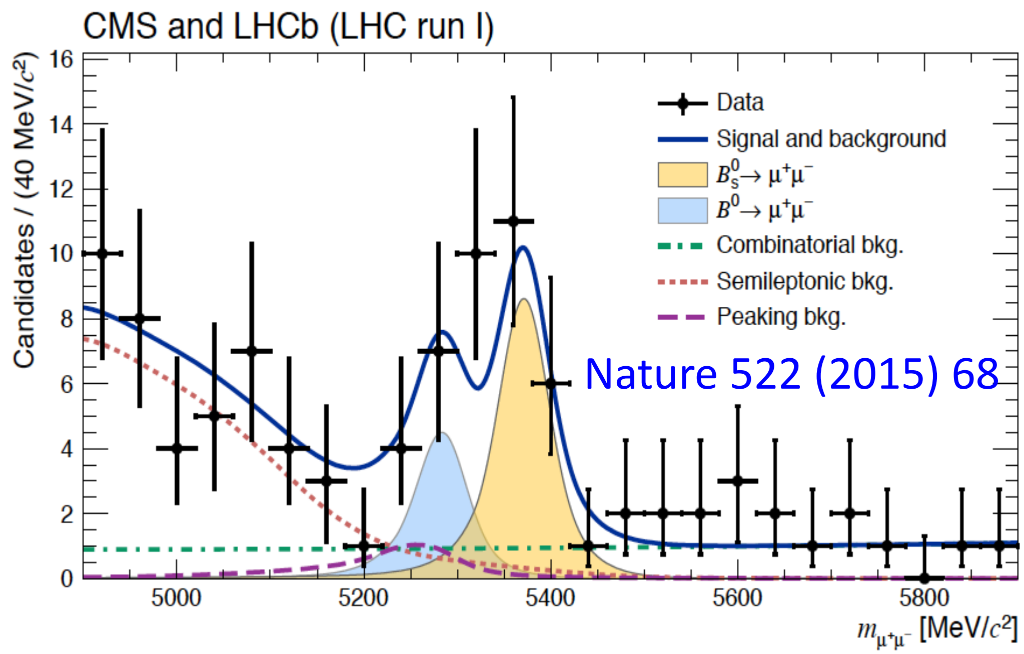


$B^0 \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$

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

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

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



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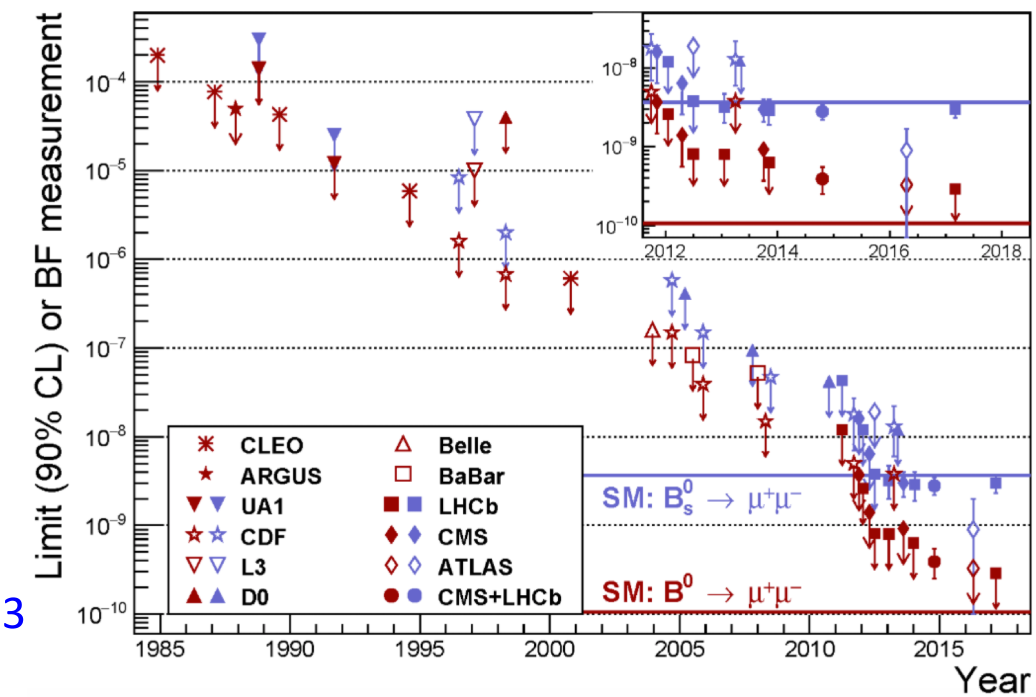
- $B_s \to \mu\mu$ 6.2σ significance was first observation
  – Well compatible with the Standard Model
- More recently, also ATLAS published a measurement with Run-1 data EPJC 76 (2016) 513



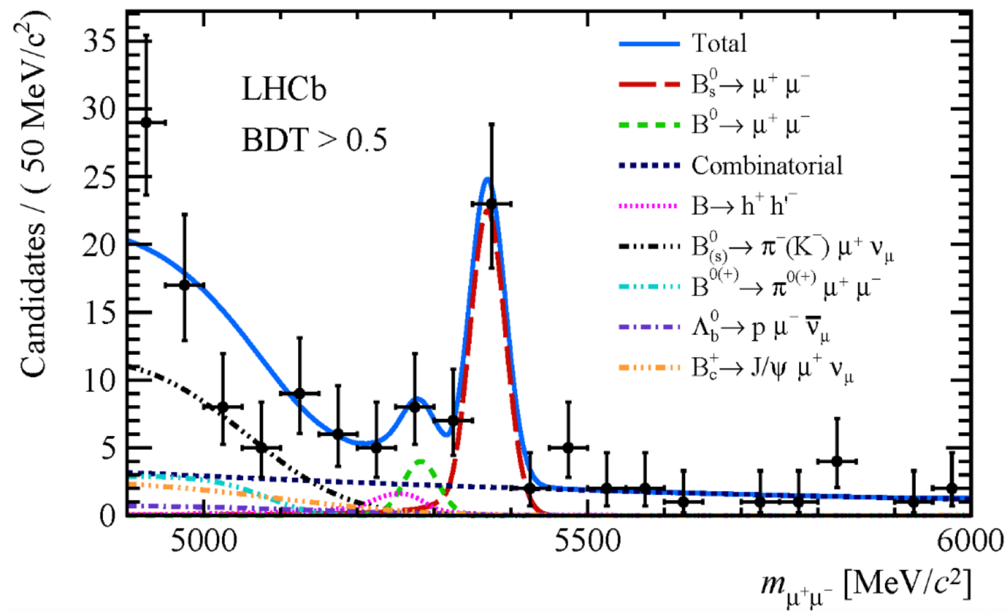
$B \rightarrow \mu\mu$ at LHCb with Run-2 data

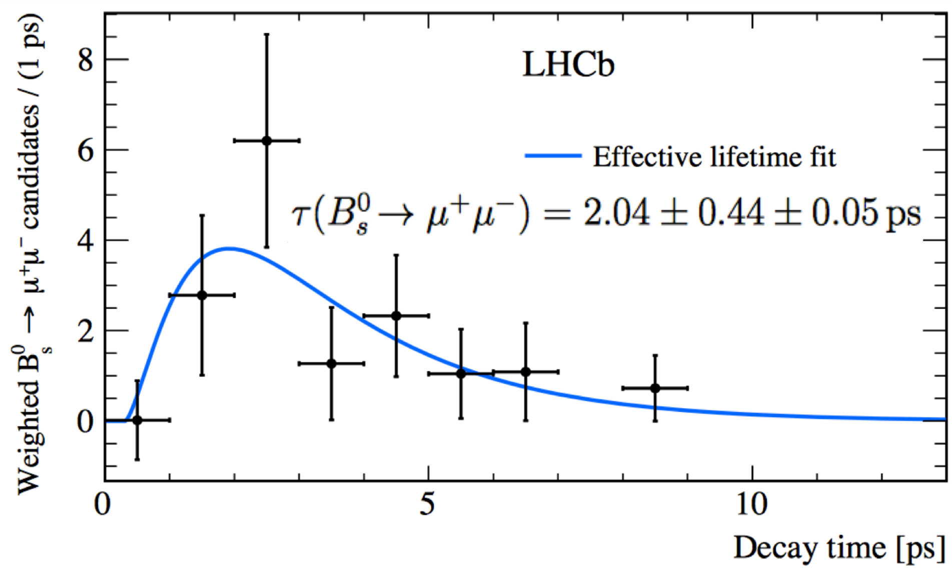
- New measurement from LHCb using Run-2 data has led in 2017 to the first observation of the $B_s \rightarrow \mu\mu$ decay from a single experiment

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

- Moreover, it starts to be possible to measure other properties, such as the "effective" lifetime, that will be useful for discriminating between new physics models

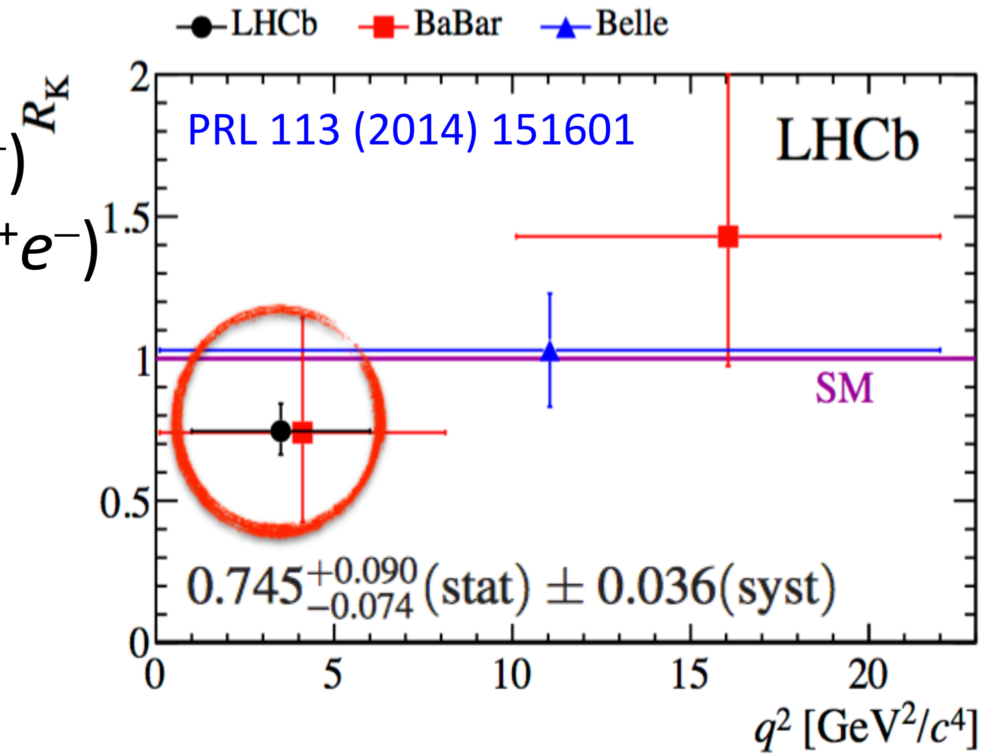
Phys. Rev. Lett. 118, 191801 (2017)

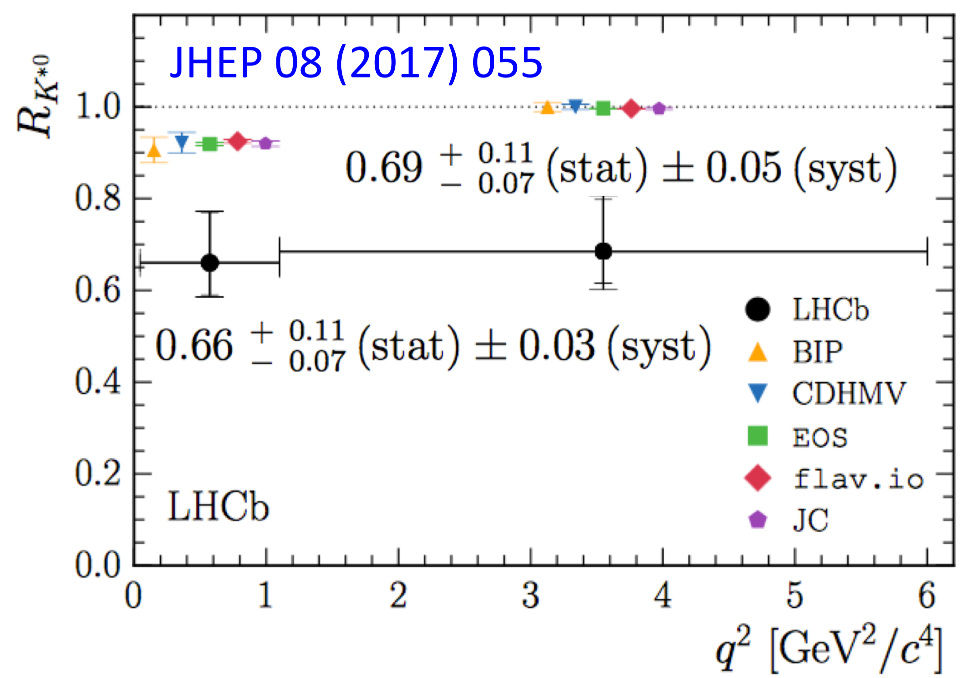




Lepton-flavour universality tests in $b \rightarrow s\ell^+\ell^-$

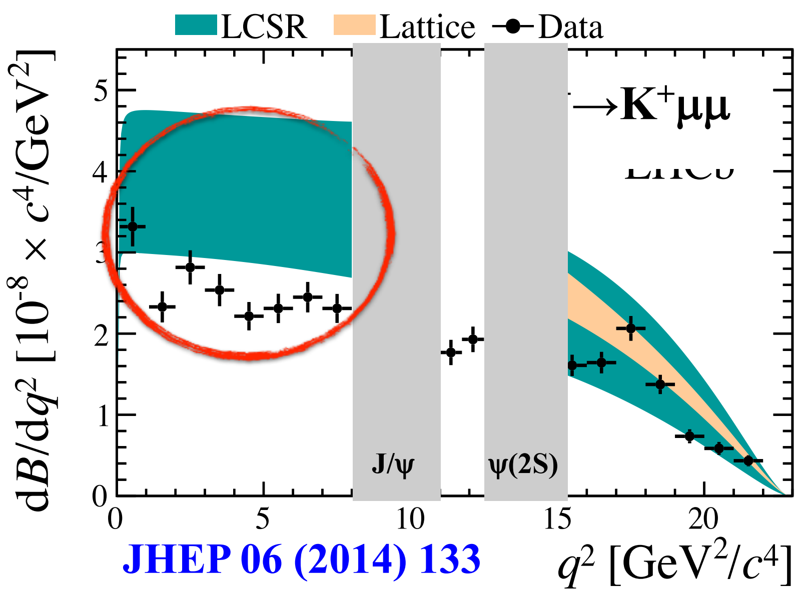
- Measure ratios
  $R_K = BF(B^+ \rightarrow K^+\mu^+\mu^-) / BF(B^+ \rightarrow K^+e^+e^-)$
  $R_{K^*} = BF(B^0 \rightarrow K^{*0}\mu^+\mu^-) / BF(B^0 \rightarrow K^{*0}e^+e^-)$
- Theoretically very clean
  - Observation of non-LFU would be a clear sign of new physics
- For the moment at the 3σ-ish level from the SM
- Updates with Run-2 data as well as other new measurements with different decay modes expected during the course of the year





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

- E.g., differential BFs consistently lower than SM expectations, although control of hadronic uncertainties in the predictions is matter of lively debates



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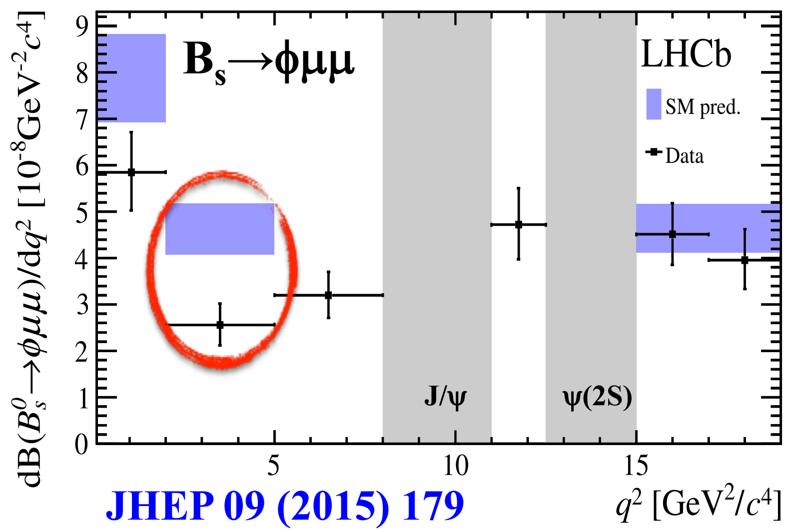

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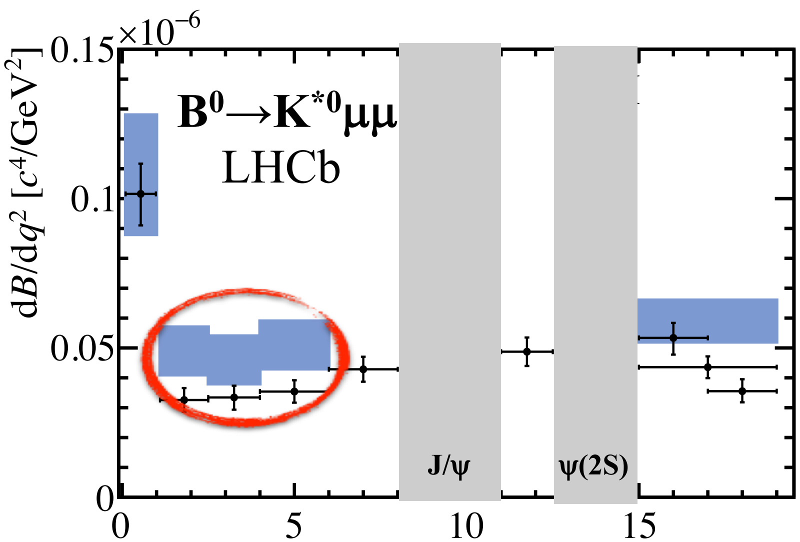

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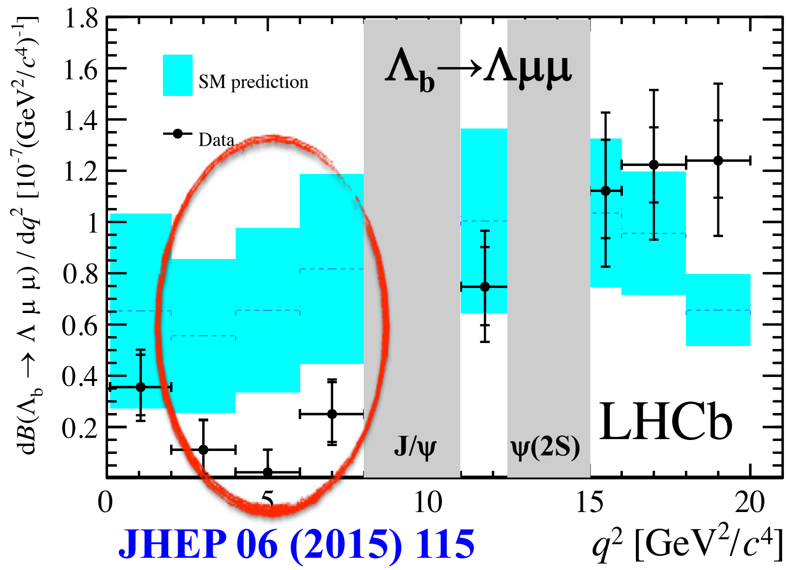

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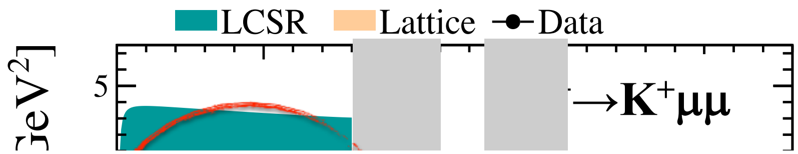
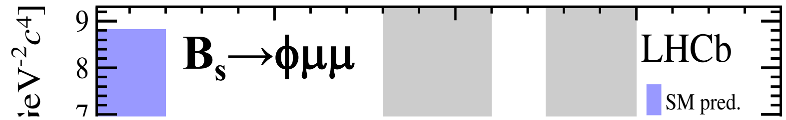
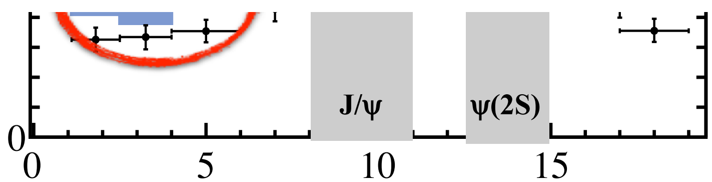




There seems to be a pattern!

- Global model-independent fits by several theory groups take into account more than 100 observables from various experiments, and nicely get a consistent overall picture pointing to the presence of physics beyond the SM



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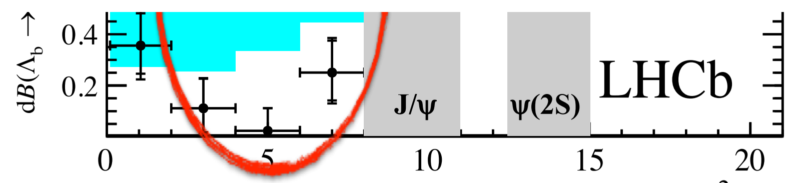

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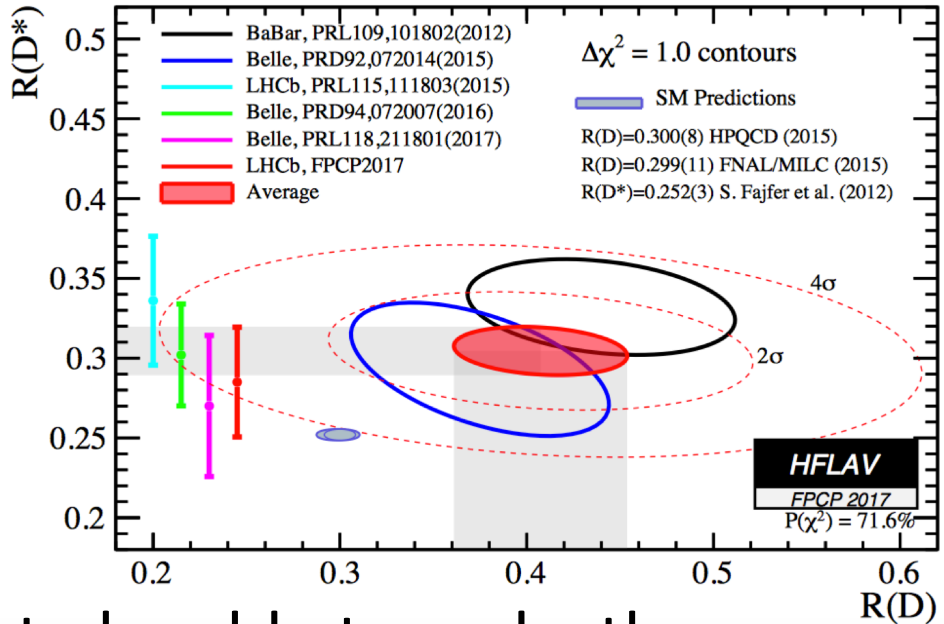
LFU tests in semileptonic *b*-hadron decays

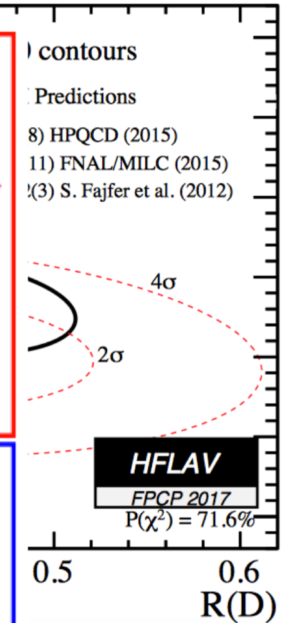
- Measure ratio
  $R_D^{(*)} = BF(B \to D^{(*)}\tau\nu) \,/\, BF(B \to D^{(*)}\mu\nu)$
- Measurements of R(D) and R(D*) by BaBar, Belle and LHCb
  - Overall average shows a 4σ discrepancy from the SM

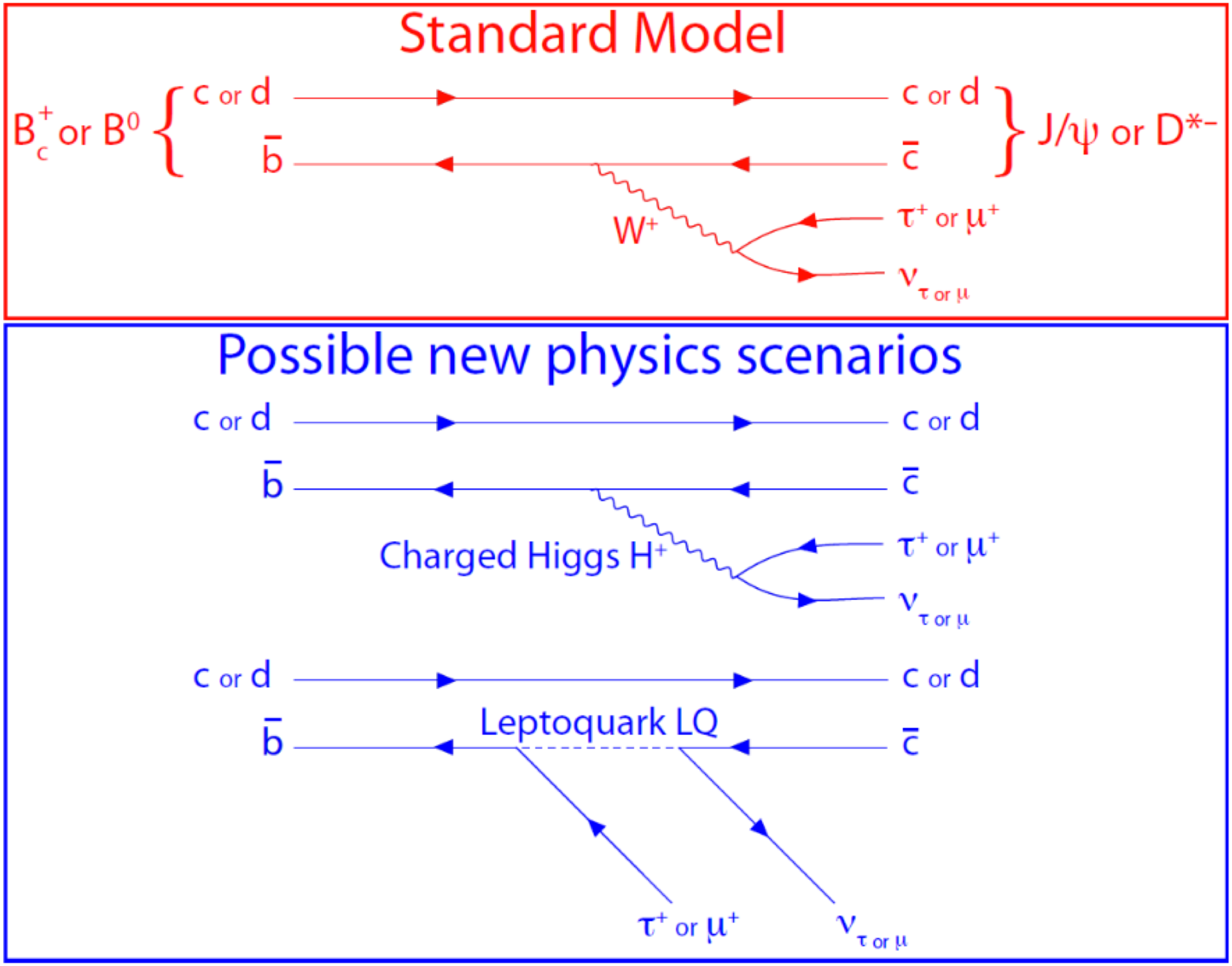


  - LHCb has recently demonstrated to be able to make the measurement also with 3-prong τ decays [arXiv:1708.08856]
- LHCb can also perform measurements with other *b* hadrons
  - Recent determination of $R(J/\psi) = BF(B_c \to J/\psi\tau\nu) \,/\, BF(B_c \to J/\psi\mu\nu)$ at about 2σ from the SM [arXiv:1711.05623]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

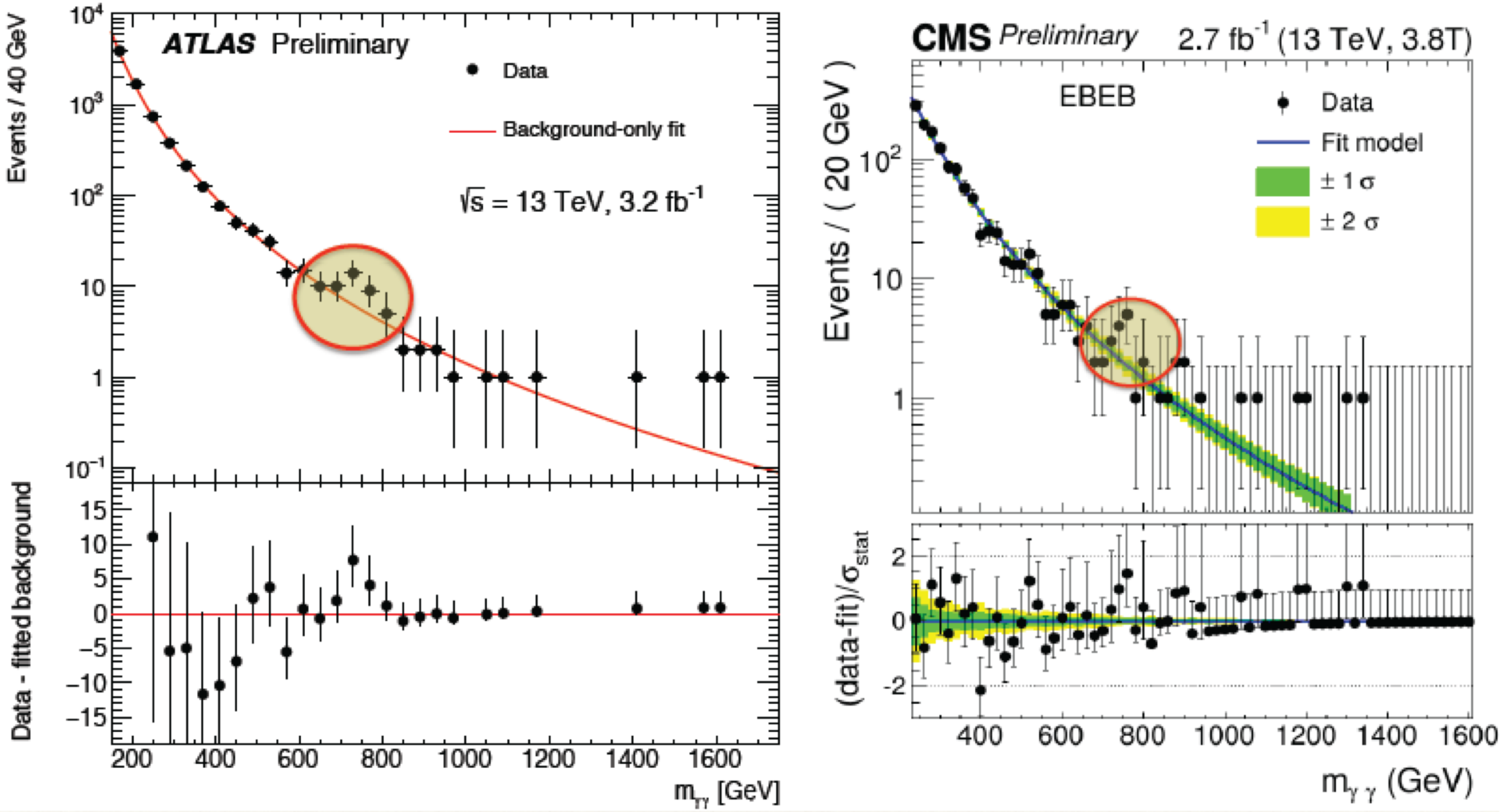
LFU tests in semileptonic *b*-hadron decays

- Measure ratio
  $R_D^{(*)}$ =
- Meas
  R(D*
  – Ov
    dis
  – LH
    me
    3856]
- LHCb
  hadr
  – Re
    at
    $\rightarrow J/\psi\mu\nu)$
  – Other modes with D_s and Λ_b decays will also come





But even weird fluctuations happen!



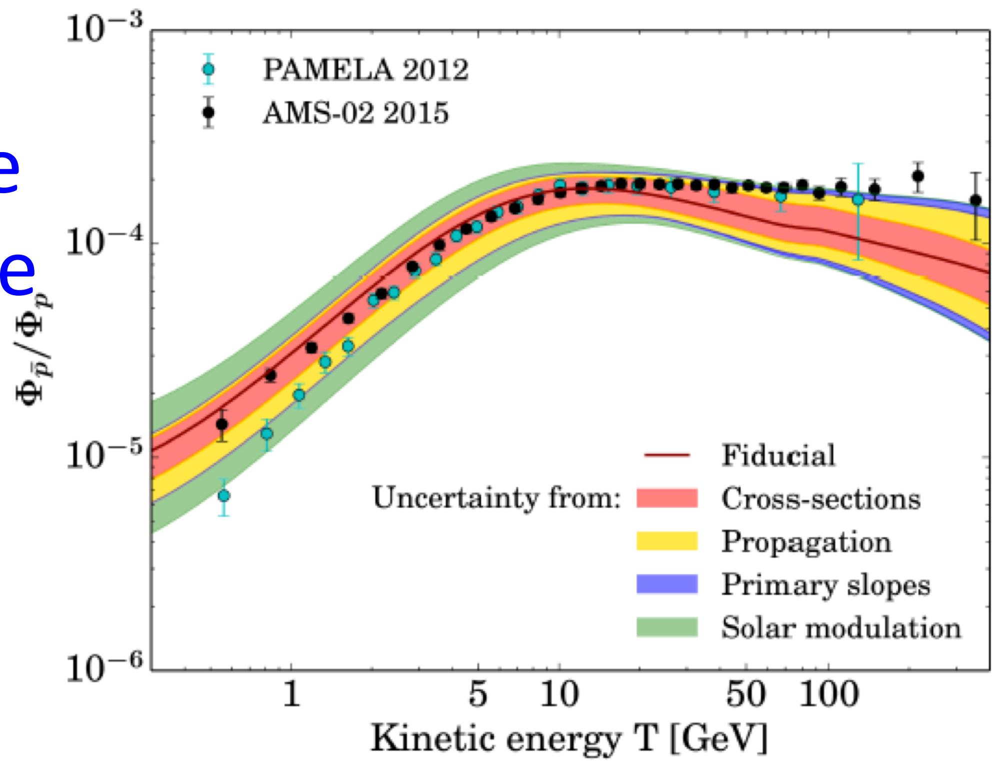
- Further data and then independent confirmations are necessary before getting too excited…

LHCb and Astrophysics

Antiproton production in fixed-target *p*He collisions

LHCb-CONF-2017-002
(paper in preparation)

- Measurement motivated by the need to understand energy dependence of $\bar{p}$ component from cosmic rays in space

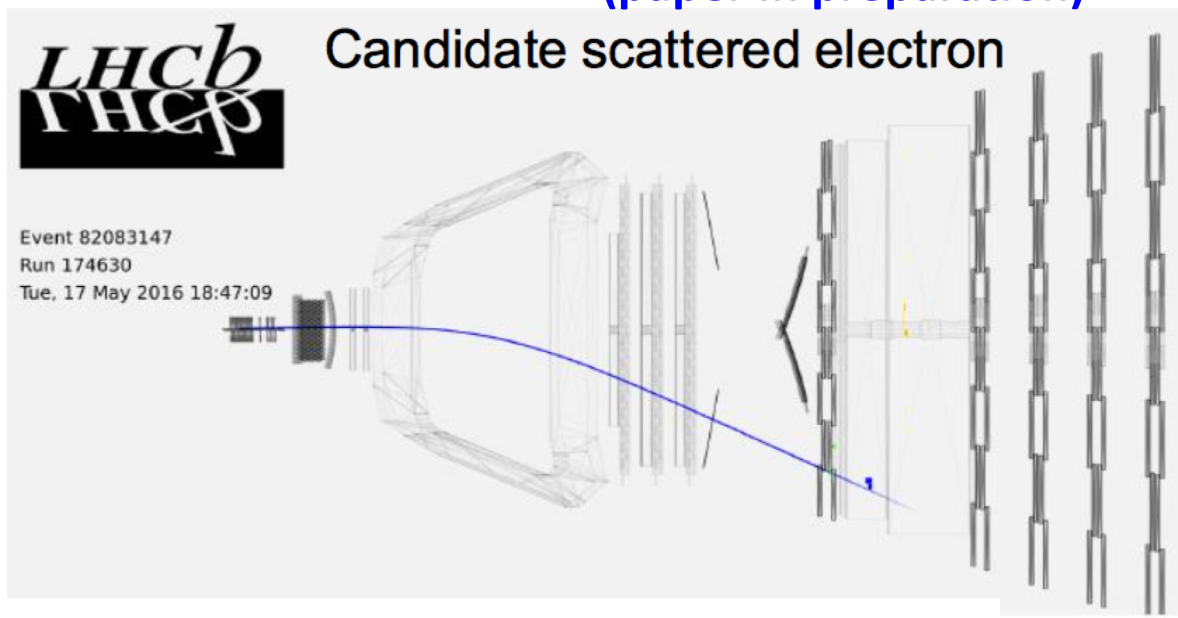


- Theoretical uncertainties are limited by precise knowledge of cross sections for basic processes in the interstellar medium, like those arising from *p*He collisions
- LHCb can inject gas into the beam pipe for relevant cross-section measurements in the sector

Antiproton production in fixed-target pHe collisions

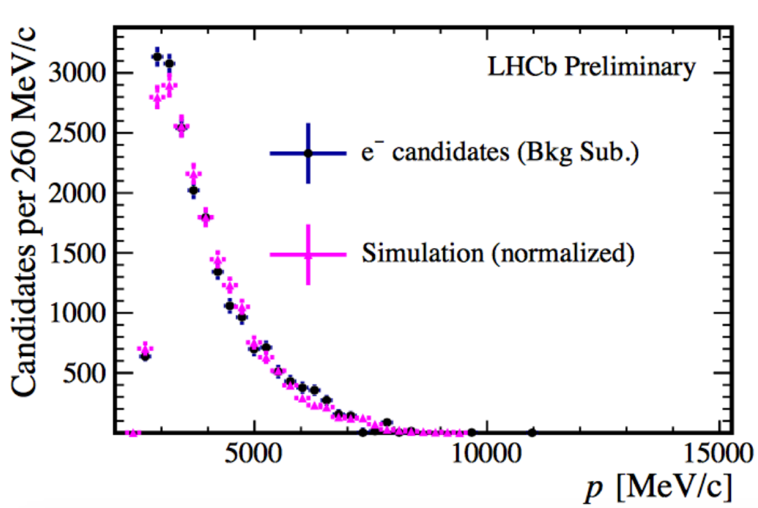
LHCb-CONF-2017-002 (paper in preparation)

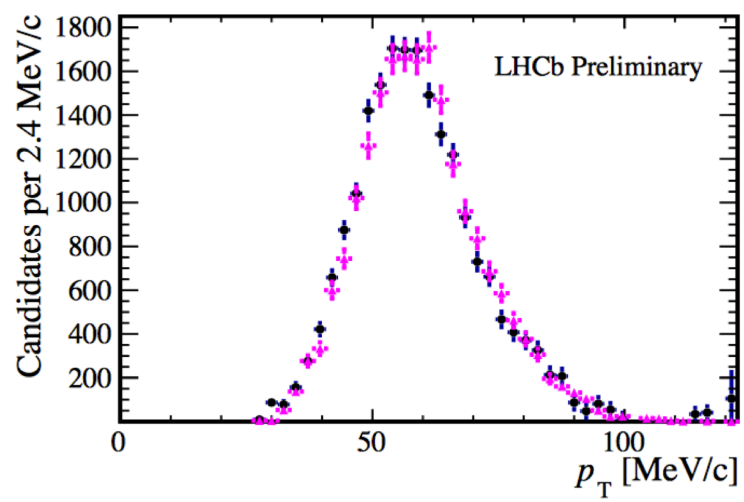
- One difficulty to measure absolute cross sections with gas injection is the determination of luminosity
  - A novel method has been developed to exploit elastic pe^- interactions



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

- Very good agreement between simulation and data

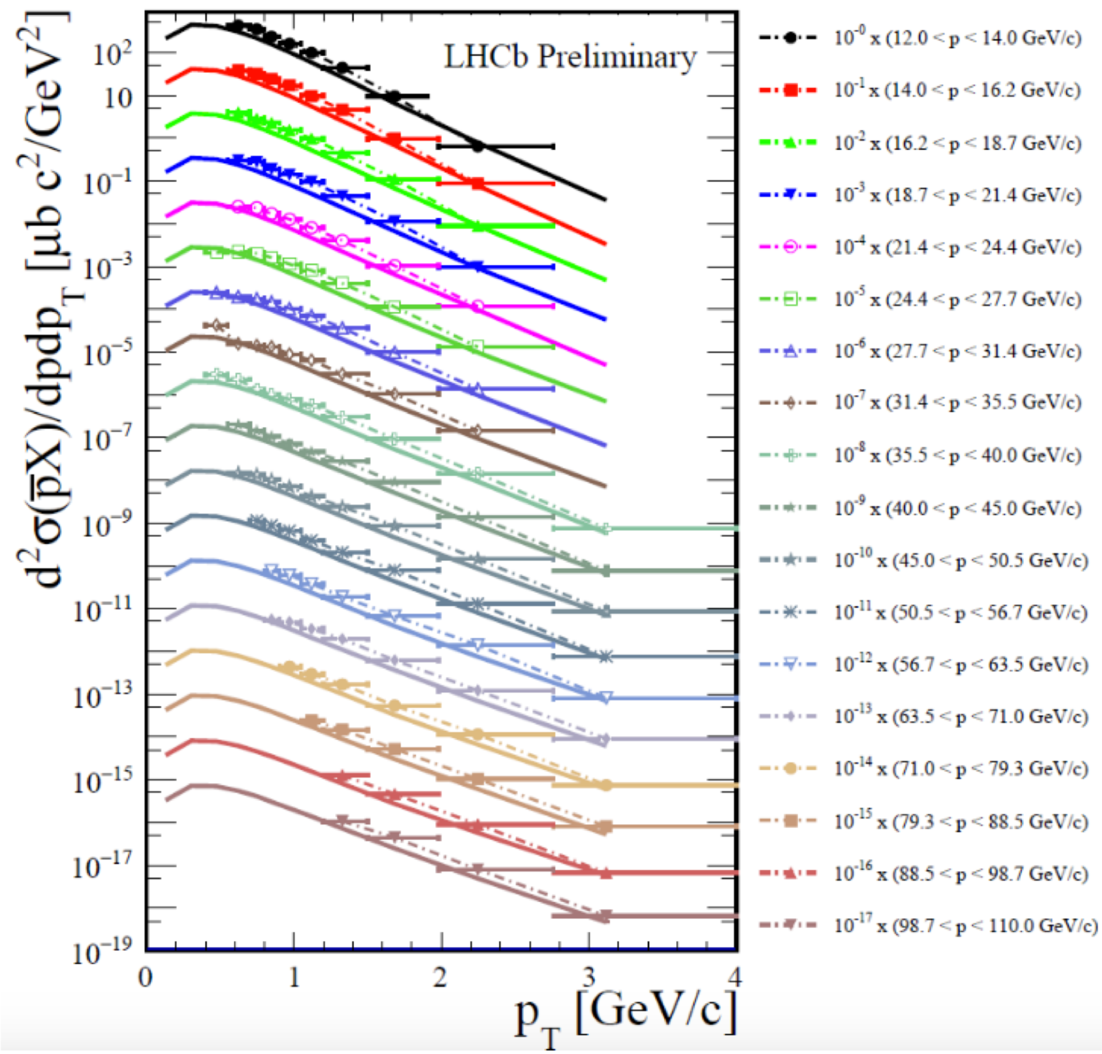




Antiproton production in fixed-target *p*He collisions

LHCb-CONF-2017-002
(paper in preparation)

- Antiproton cross section measured with 10% precision
- Theoretical interpretation on its way
- Additional production measurements are also important
  - E.g., antiprotons from Λ decays
- Further results expected in the near future



In closing

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}	23 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

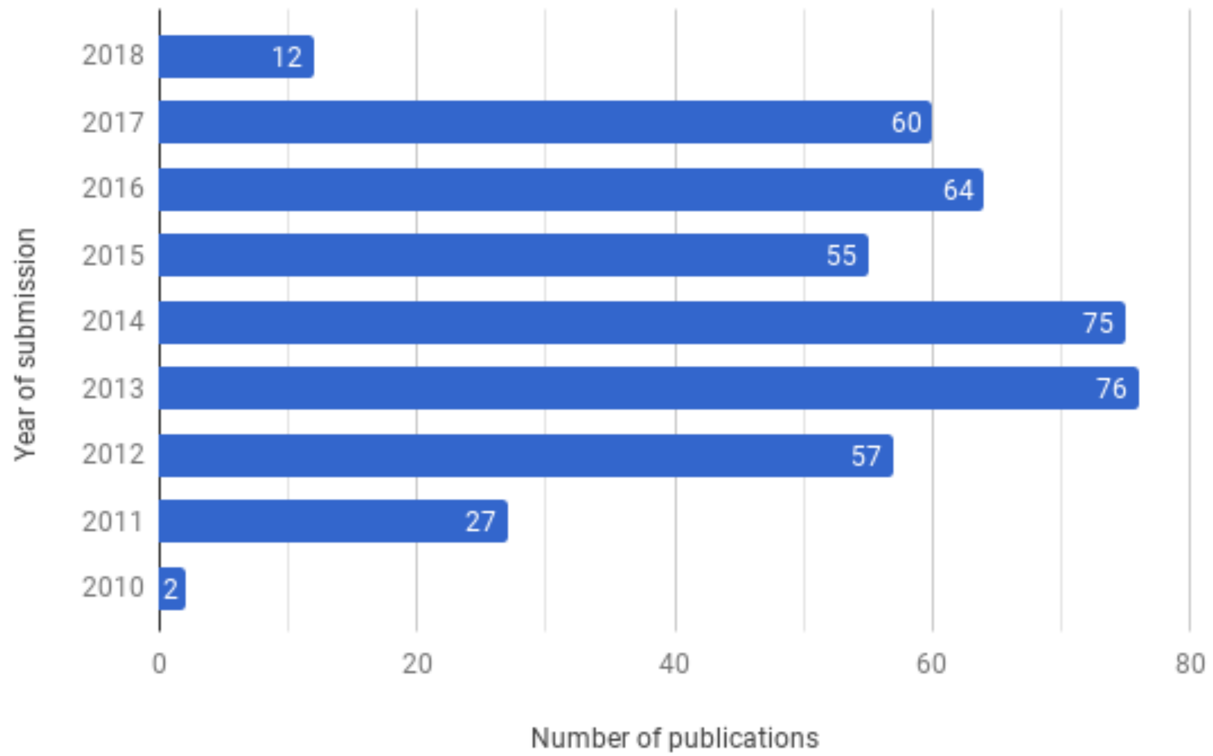
* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2\text{x}10^{34}\ cm^{-2}s^{-1}$

- A first LHCb upgrade comes already in Run 3 (to raise the instantaneous luminosity to $2\text{x}10^{33}\ cm^{-2}s^{-1}$), whereas the HL ATLAS and CMS upgrades come in Run 4
- LHCb has submitted at the beginning of 2017 an Expression of Interest for a further upgrade during LS4 to reach $2\text{x}10^{34}\ cm^{-2}s^{-1}$

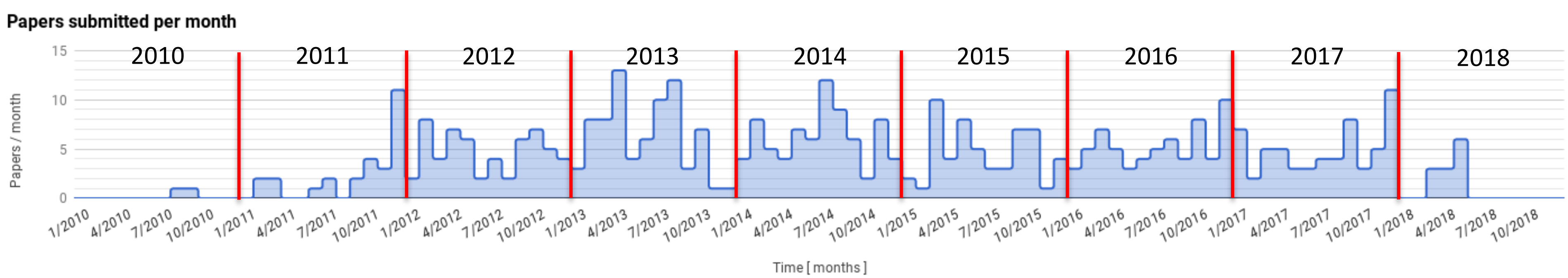
CERN-LHCC-2017-003 https://cds.cern.ch/record/2244311

LHCb is much more than shown today!

428 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 anomalies in the flavour sector will consolidate, it will be of paramount importance to seek confirmation from multiple experiments
- Furthermore, new physics should affect different modes coherently
  - Maintaining the broadest possible physics programme in the long term will be crucial
- Stay tuned in the next couple of years!