LHCb: Precision beauty physics and the emergence of flavour anomalies

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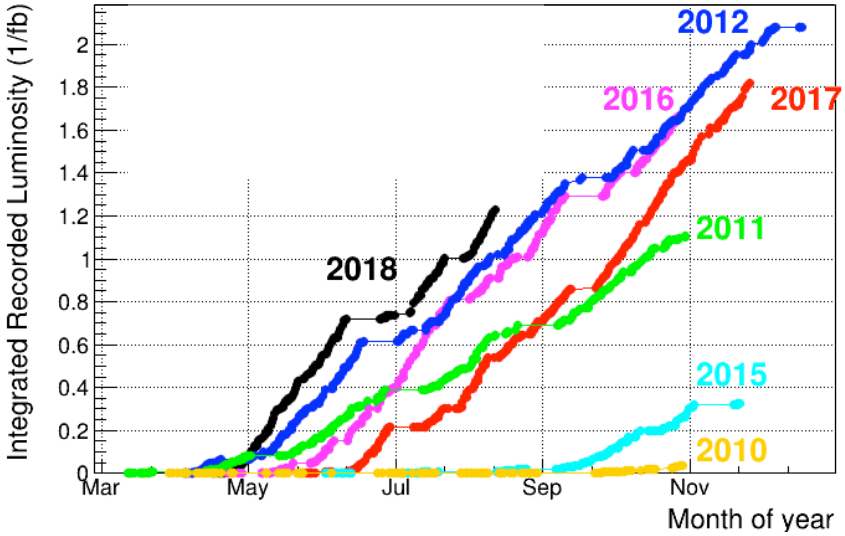
Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

erc

LHCb and beauty production

- Proton collisions at 7-13TeV: huge heavy flavour production cross sections
  - In LHCb acceptance: 75kHz $b\bar{b}$ and 1.5MHz $c\bar{c}$
  - ~1/10 events contains b or c signal



Experiment	$\int \mathcal{L}\, dt$ [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]	2035 (?)
LHCb	>8.5 (so far)	250-500 [pp at 7-13 TeV]	2035 (?)
Belle 2*	>0.25 (so far)	0.001	~2025

* 2018 run w/o vertex detector

LHCb's physics in a nutshell

- Classic, broad range measurements
  - CKM Physics, search for very rare (forbidden) decays

- Measurements in specific sectors, where anomalies are emerging in recent years
  - $b \to s \ell^+\ell^-$ transitions, specifically issues with lepton-flavour universality
  - Issues with lepton-flavour universality in $b \to c$ transitions

- Spectroscopy:
  better understand QCD in the low energy regime
  - Many striking measurements with four- and five-quark states

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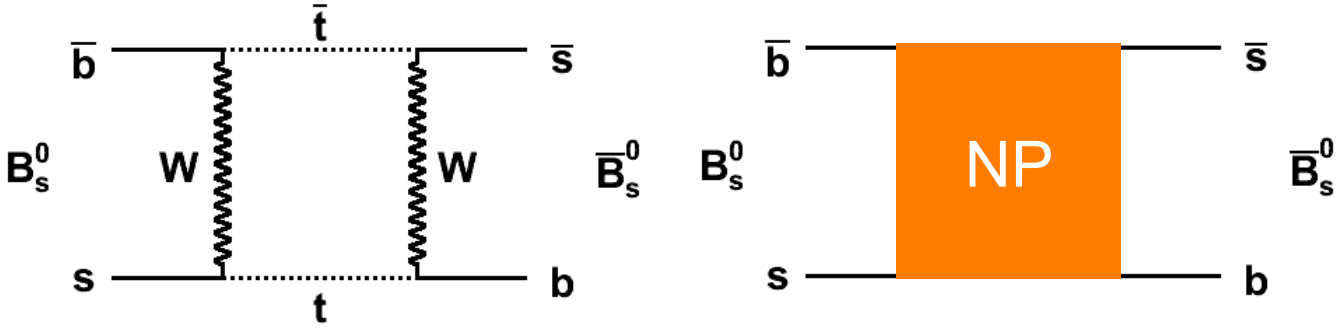
B_s-Mixing and CP ciolation



$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} = \left(M + i\frac{\Gamma}{2}\right)\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix}$$

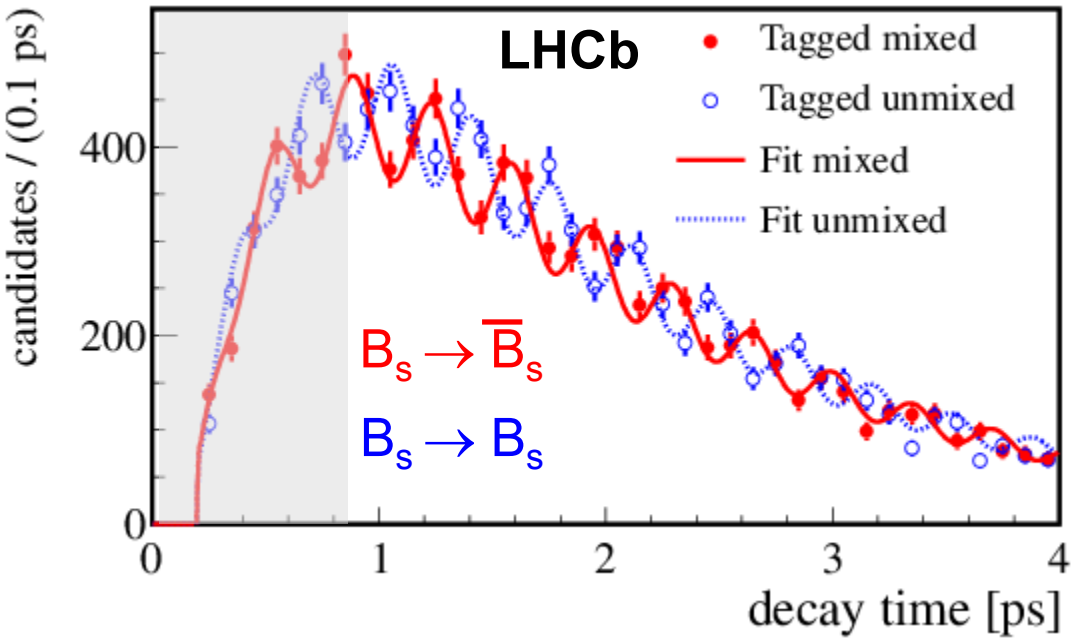
flavour $\neq$ mass eigenstate: $B_s \,\&\, \overline{B_s} \neq B_L \,\&\, B_H$

Observables:

- Δm_s = mixing frequency
- $\Delta\Gamma_s$ = decay width difference $B_L \,\&\, B_H$
- ϕ_s = CP-violating phase

Measurement of B_s mixing

New J. Phys. 15 (2013) 053021



Mixing frequency from $B_s \to D_s^- \pi^+$:

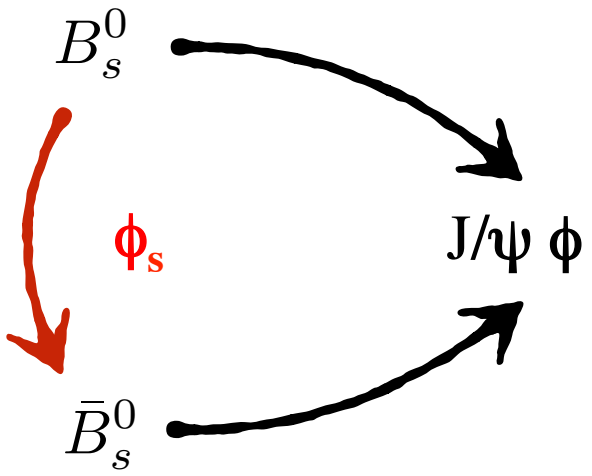
$\Delta m_s = 17.768 \pm 0.023^{stat} \pm 0.006^{syst}\ ps^{-1}$

Standard Model: $\Delta m_s = 20.31 \pm 1.34\ ps^{-1}$

(2016: A. Lenz: arXiv:1603.07770)

CP violating phase ϕ_s

- Measure CP violating phase in $B_s \to J/\psi\, \phi$ decays*



- Standard Model prediction:

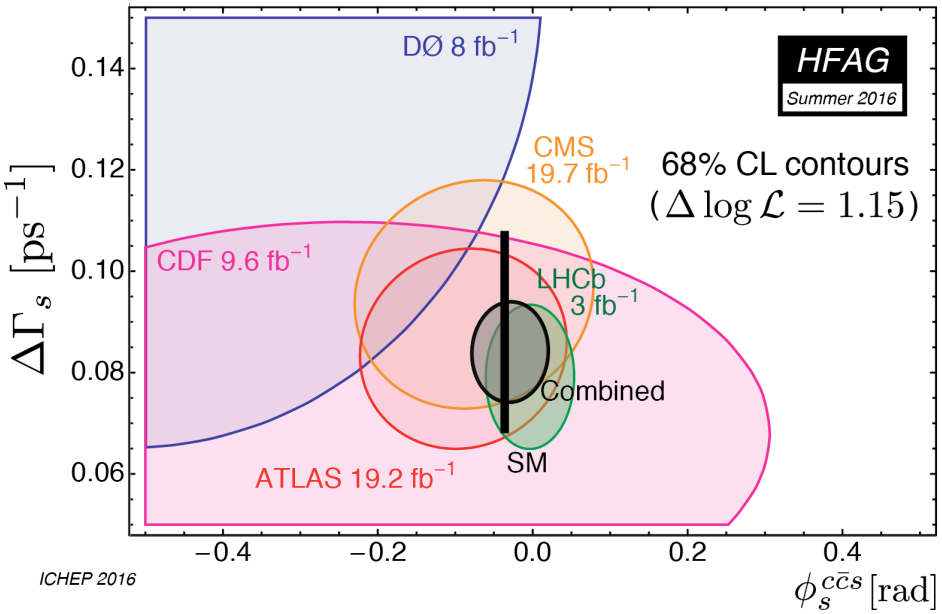
$$\phi_s = 0.04 \pm 0.01$$

A. Lenz, arXiv:0705.3802

- Measurements:

ϕ_s = 0.010±0.039
PRL 114(2015)041801

consistent with SM!

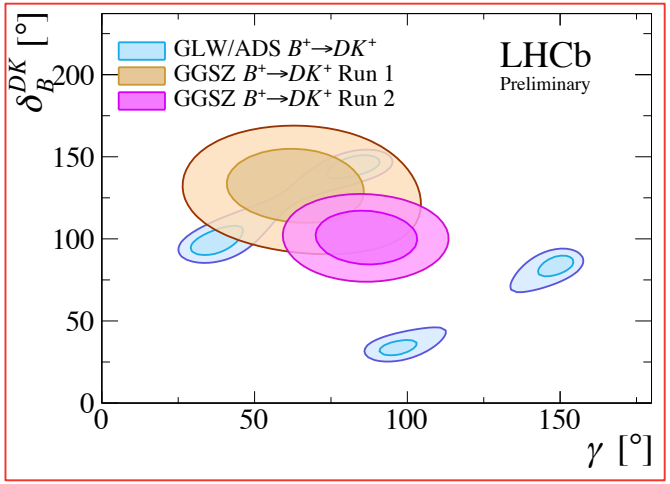


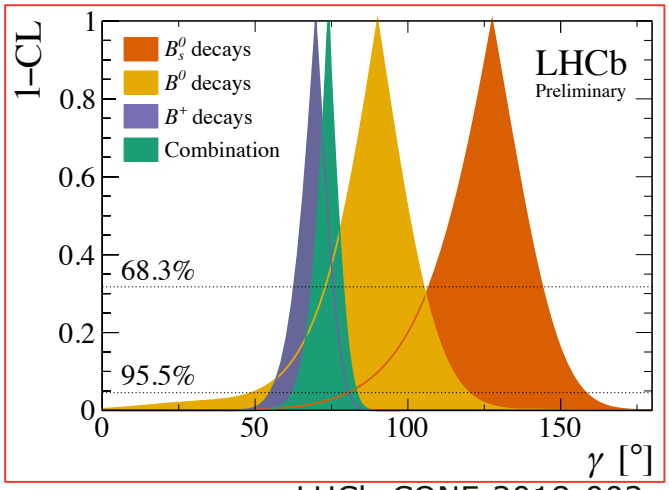
* More precisely: $B_s \to ccs$, in total 5 final states

CKM angle γ: B→ D K and friends

B decay	D decay	Method	Ref.	Dataset[†]	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

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



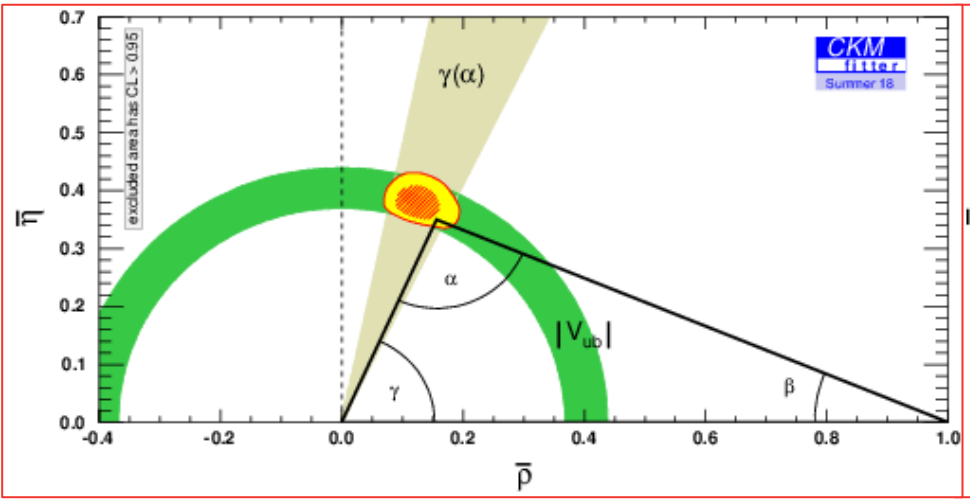


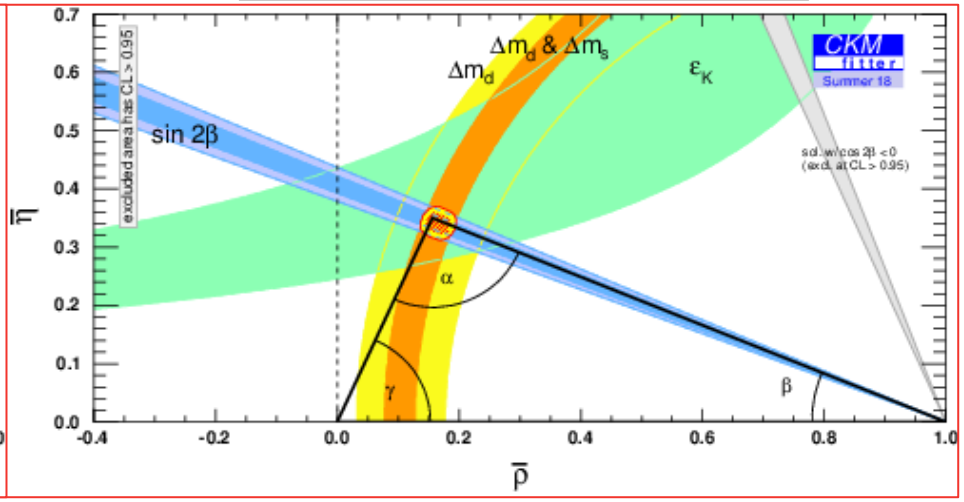
LHCb-CONF-2018-002

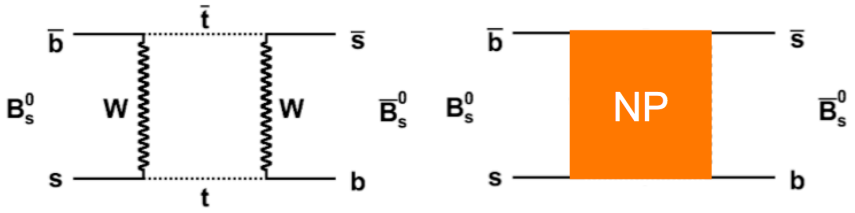
CKM matrix @ 1st Thomas Fest

Tree
(phase and magnitude of V_{ub})

Loop
(phase and magnitude of box diagram)







B_s & B_d:
~20% room for new physics

U. Nierste

Precision measurements of CP violation in the B-System continues..

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- Spectroscopy:
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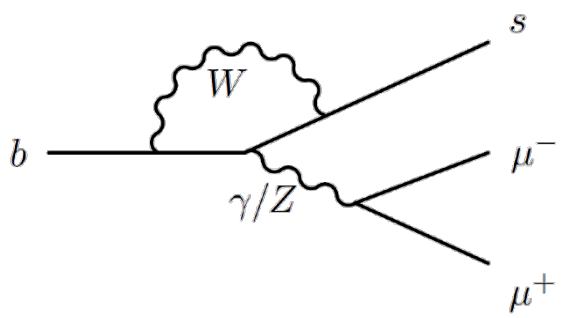
Testing $b \to s \ell^+\ell^-$ transitions

$b \to s \mu^+\mu^-$ base diagram



- Purely leptonic
  - "add nothing"

- Semileptonic
  - add d quark as spectator
    → $B^0 \to K^{*0} \mu^+\mu^-$
  - add s quark as spectator
    → $B_s \to \phi \mu^+\mu^-$
  - add u quark as spectator
    → $B^+ \to K^+ \mu^+\mu^-$

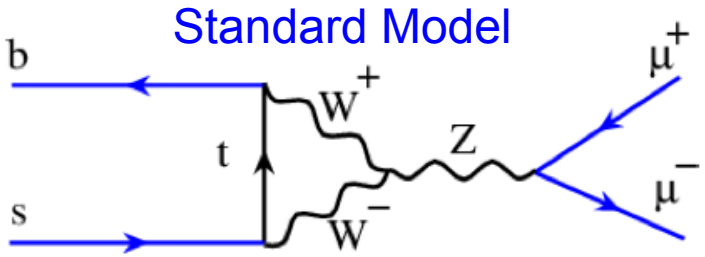
- Ratios:
  - Compare muons to electrons

Golden channel: $B_{s,d} \rightarrow \mu^+\mu^-$

Theory prediction: Standard Model

decay	SM
$B_s \rightarrow \mu^+\mu^-$	$3.5 \pm 0.3 \times 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$1.1 \pm 0.1 \times 10^{-10}$

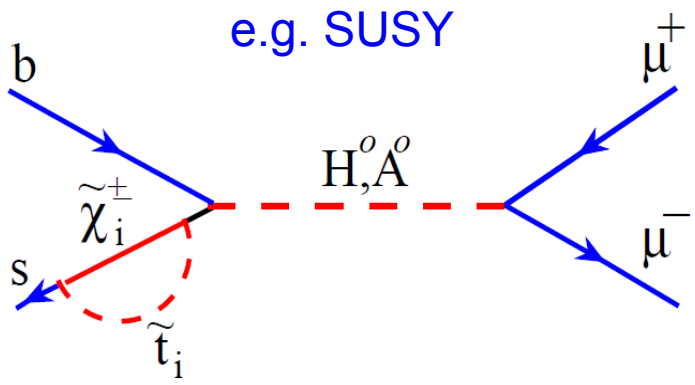
SM: Buras, Isidori et al: EPJC72(2012) 2172
Mixing effects: Fleischer et al, PRL109(2012)041801



Left handed couplings
→ helicity suppressed

Discovery channel for New Phenomena

➔ Very **sensitive to an extended scalar sector**
(e.g. extended Higgs sectors, SUSY, etc.)



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Discovery channel for New Phenomena

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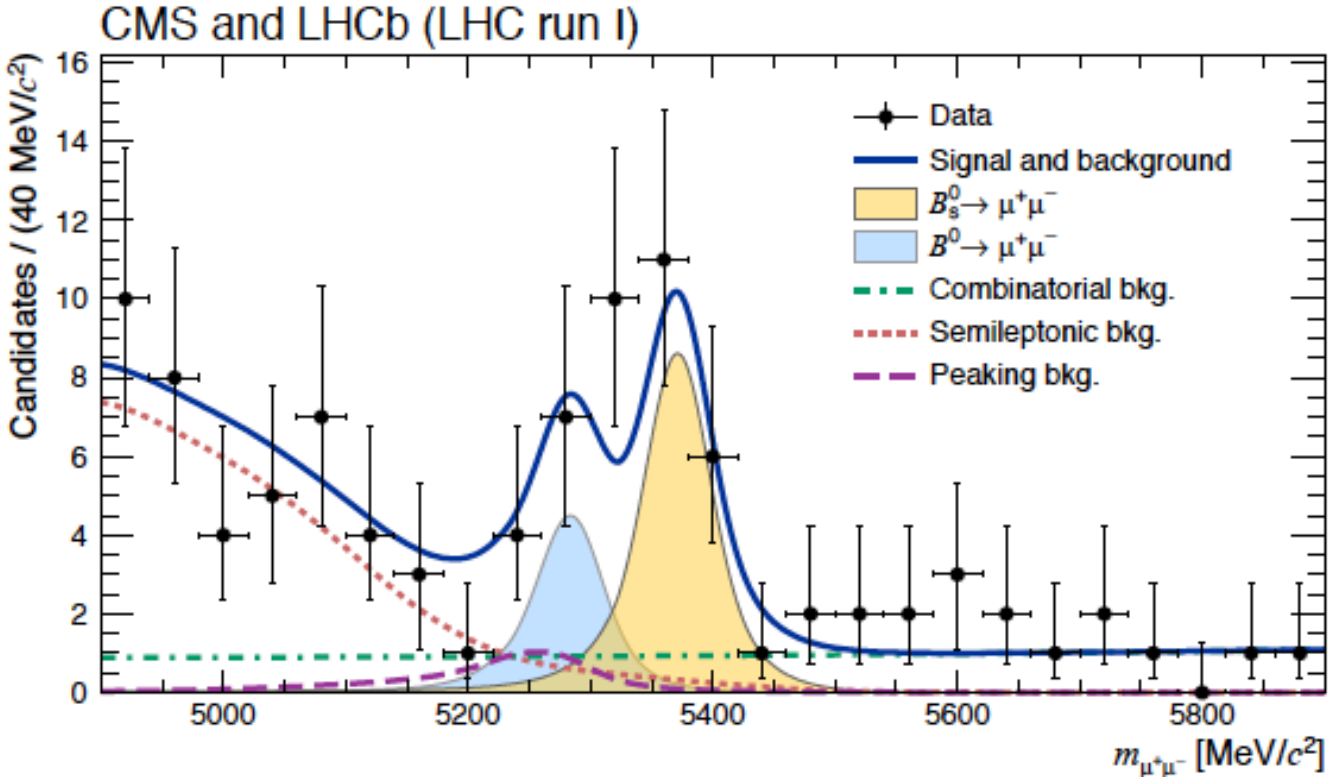
LETTER

First observation of $B_s \rightarrow \mu^+\mu^-$

OPEN
doi:10.1038/nature14474



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

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

6.2σ significance → first observation
- compatible with SM at 1.2σ

3.0σ significance → first evidence
- compatible with SM at 2.2σ

$B \to \mu^+\mu^-$: News from run 2 data

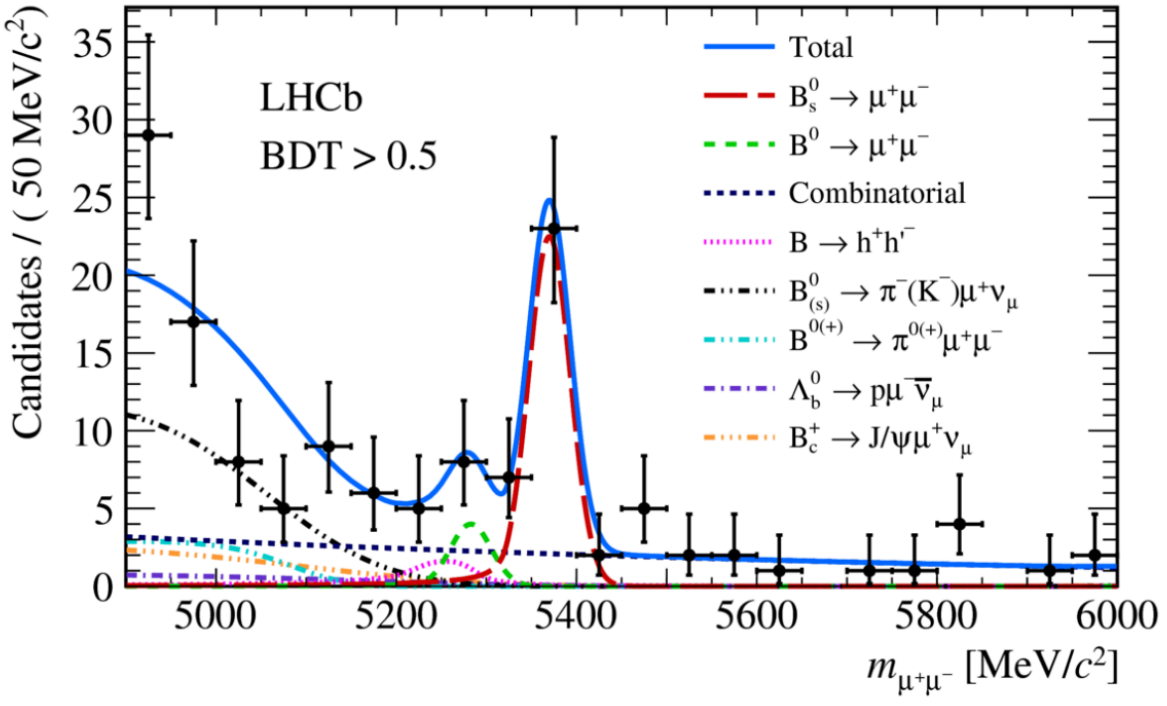
PRL118(2017)191801

LHCb has recently published a first run 1 + run 2 analysis (3+1.4fb^{-1})
updated analysis with improved background suppression

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

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

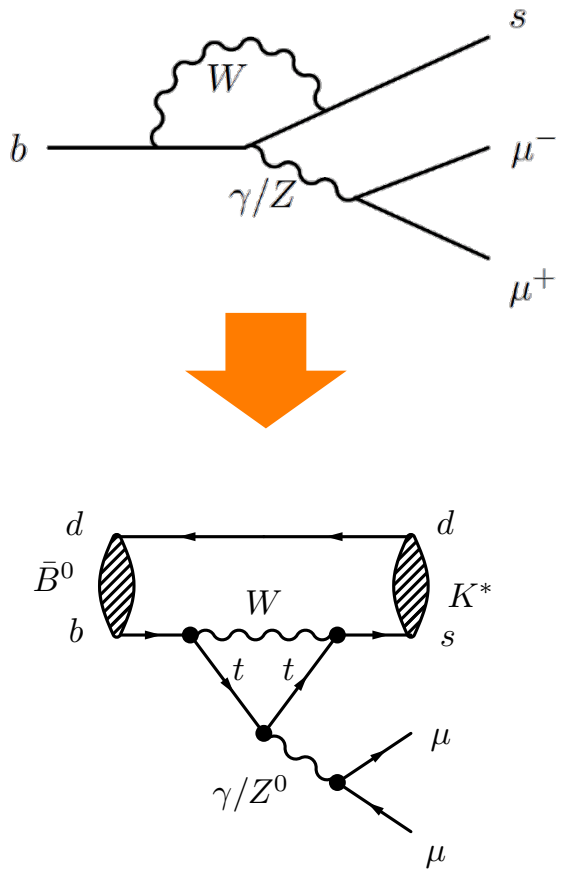
- No evidence yet of the corresponding B^0_d decay (< 3.4 x 10^{-10} at 95% C.L.)



No sign of 1st order New Physics effect!
$B \to \mu^+\mu^-$ becomes a precision test

Rare menu

$b \to s\,\mu^+\mu^-$ base diagram



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- Ratios:
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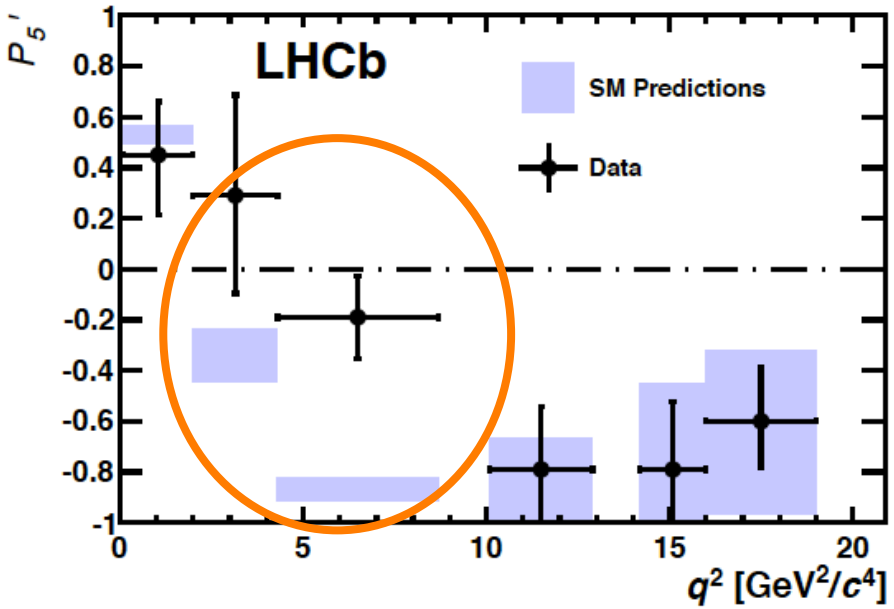
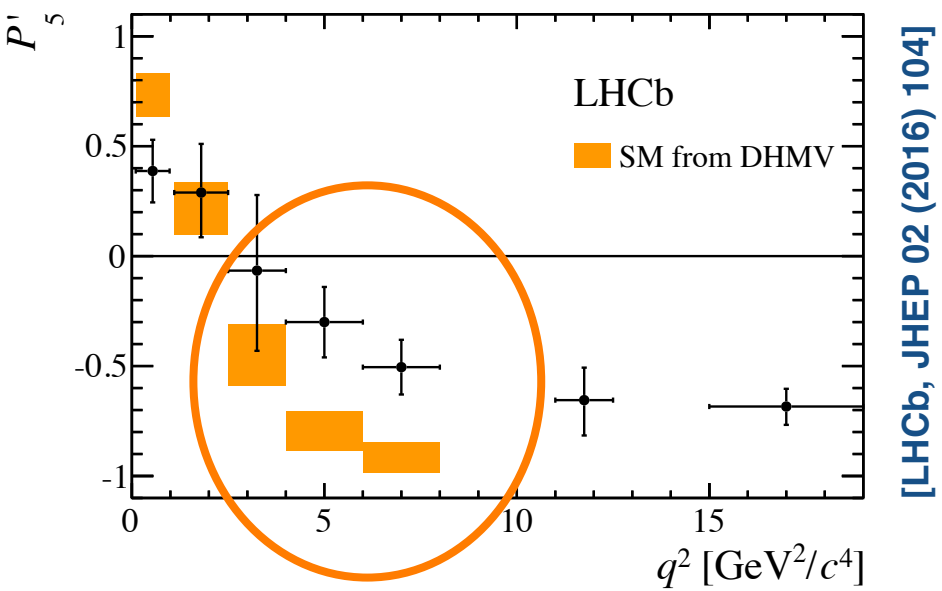
Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0} \mu^+\mu^-$ decays

LHCb, Phys.Rev.Lett. 111 (2013) 191801





- Full Run 1 analysis confirms effect

Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

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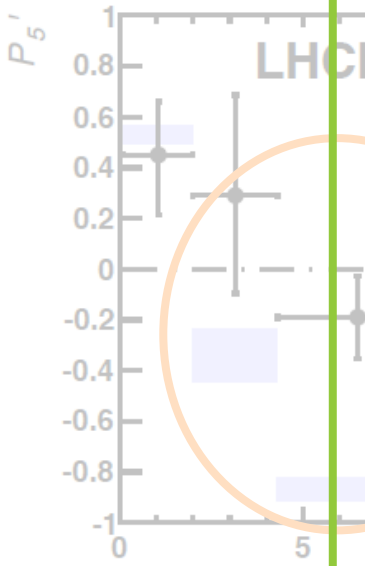
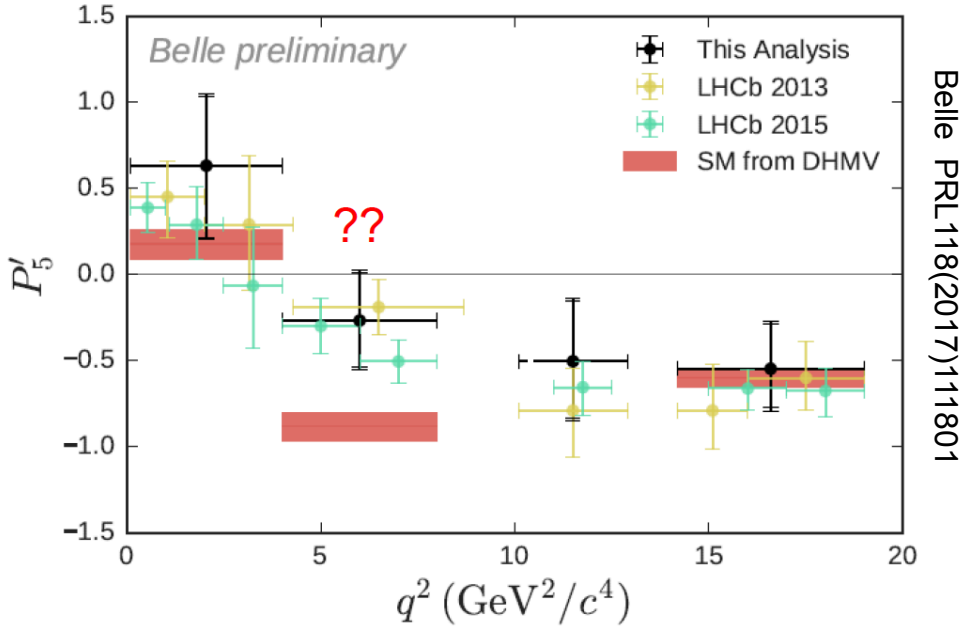
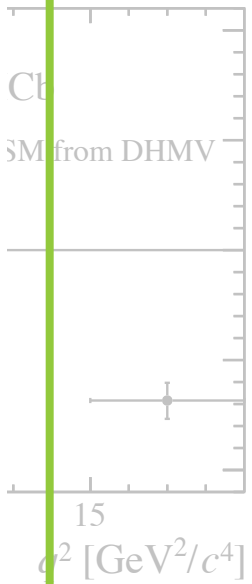
LHCb, Phys



Belle still has a word to say



Lower statistical power, but very consistent



- Full Run

Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

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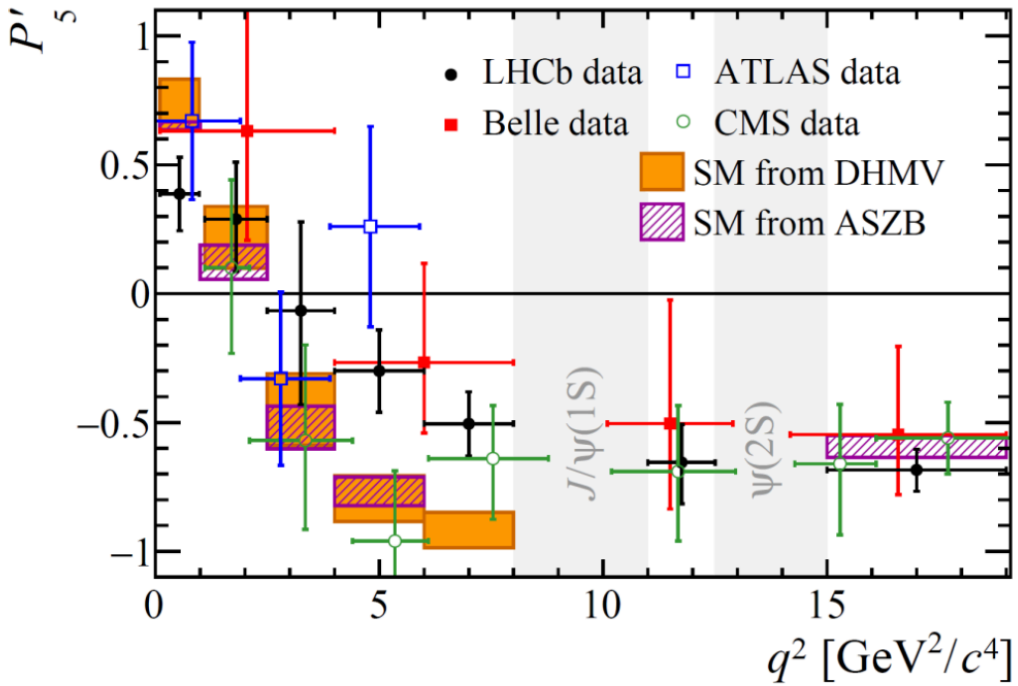
… recently ATLAS and CMS joined



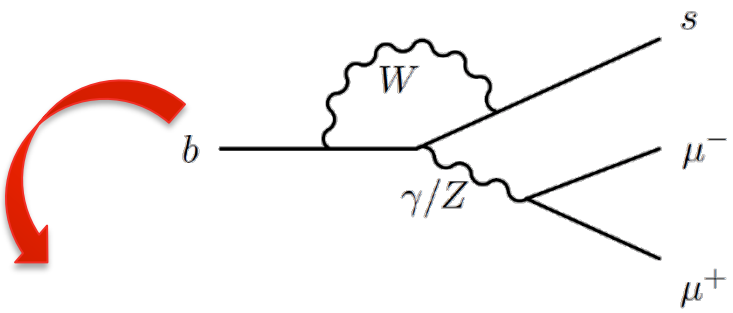
[ATLAS-CONF-2017-023, CMS-PAS-BPH-15-007]

- Full Run

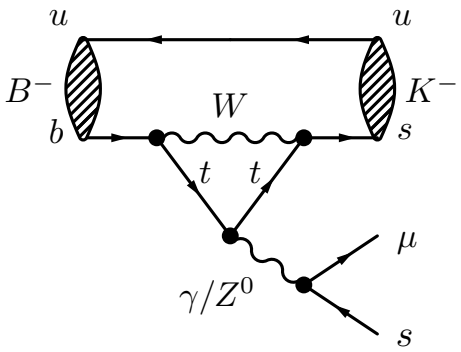
Situation unclear…. If real, expect discrepancies in **other $b \to s$ decays** ..

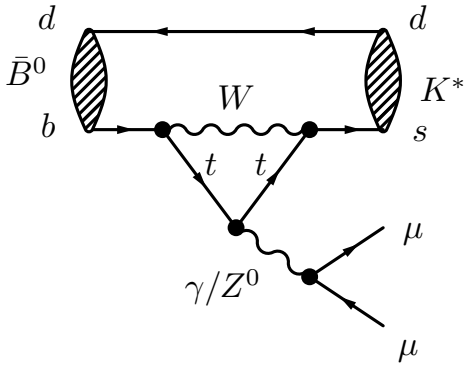
Other $b \to s\,\mu^+\mu^-$ decays

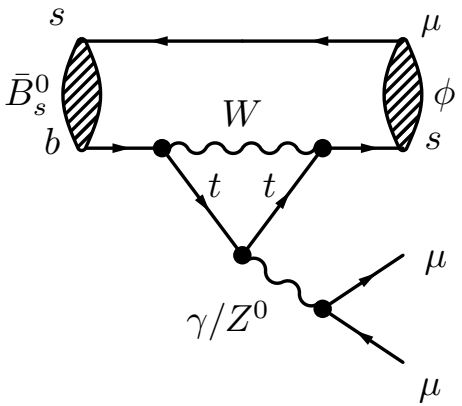
- Decay modes with same effective Feynman diagram accessible
  → different spectator quarks

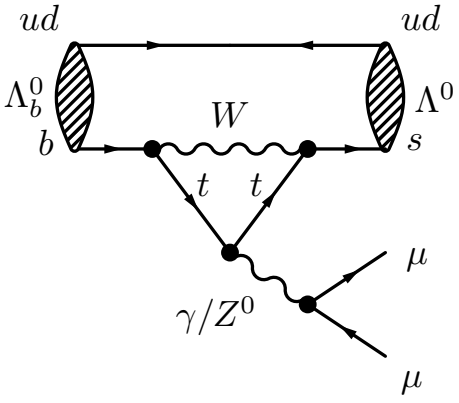


- Test for same new effects
  → expect suppressed branching fractions

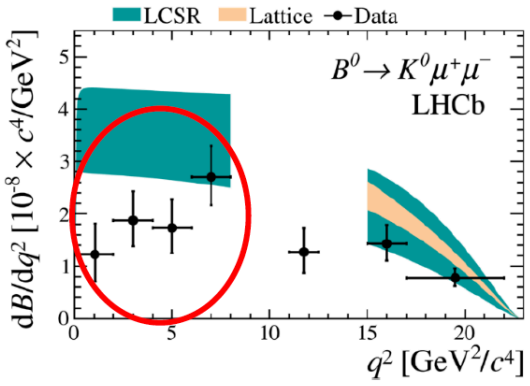


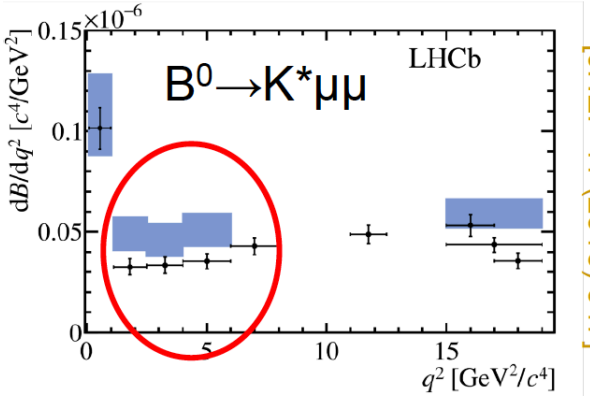




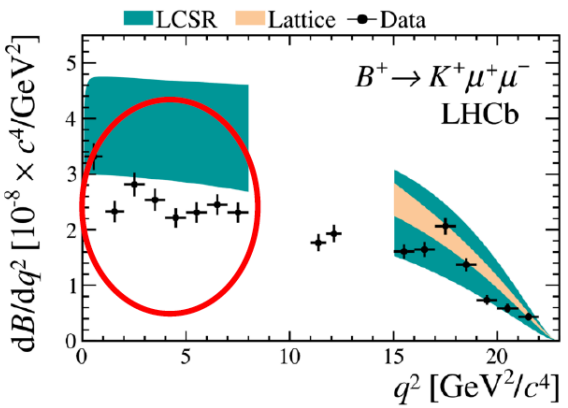


Branching fractions of $b \to s\,\mu^+\mu^-$

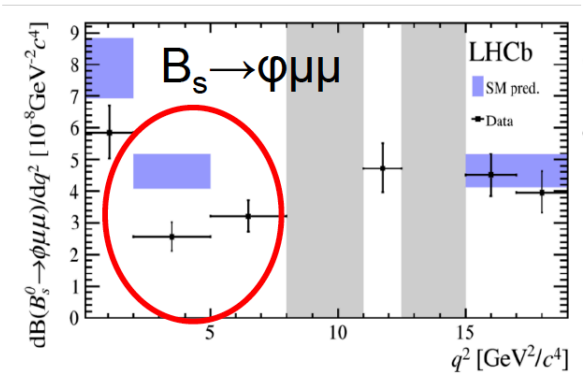


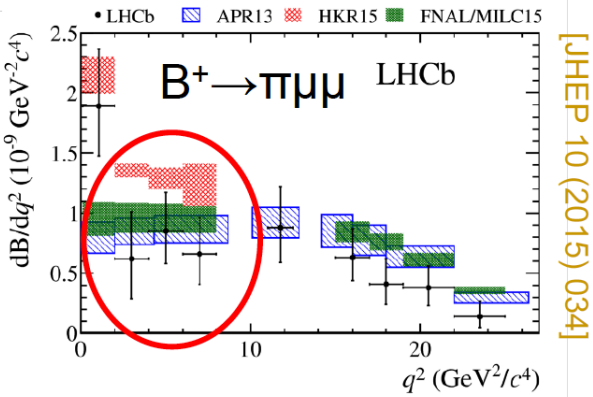


[JHEP 11 (2016) 047]

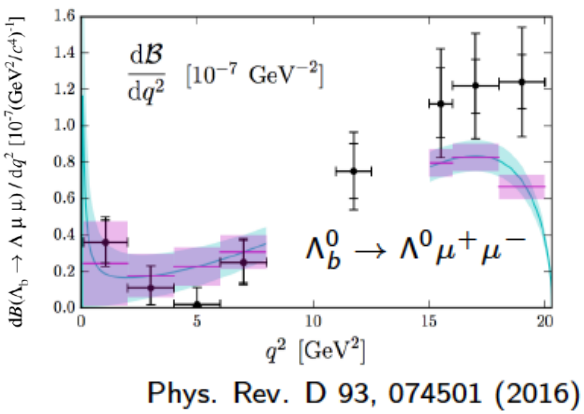


[JHEP 06 (2014) 133]





[JHEP 10 (2015) 034]



[JHEP 06 (2015) 009]

Phys. Rev. D 93, 074501 (2016)

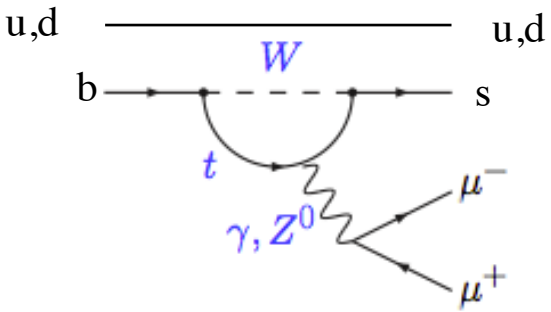
- Analysis of large class of $b \to s,d\,\mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate
  - Tendency to undershoot prediction of differential x-sections
    → **intriguing hint or TH issue in prediction?**

→ **We need cleaner tests …**

Lepton universality

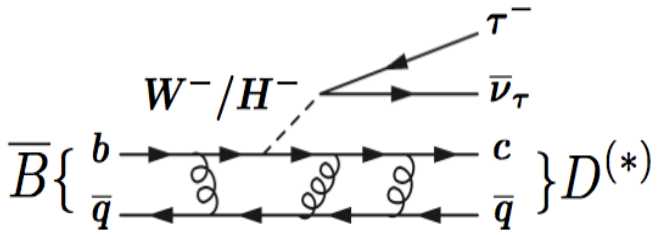
- In the SM, leptons couple universally to $W^{\pm}$ and Z^0
  → test this in ratios of semileptonic decays

electrons / muons [**b → s**]



$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

tau / muons [**b → c**]



$$R_{D^*} = \frac{BR(B^0 \to D^{*+} \tau^- \bar{\nu})}{BR(B^0 \to D^{*+} \mu^- \bar{\nu})}$$

- Ratios differ from unity only by phase space
  → hadronic uncertainties cancel in the ratio

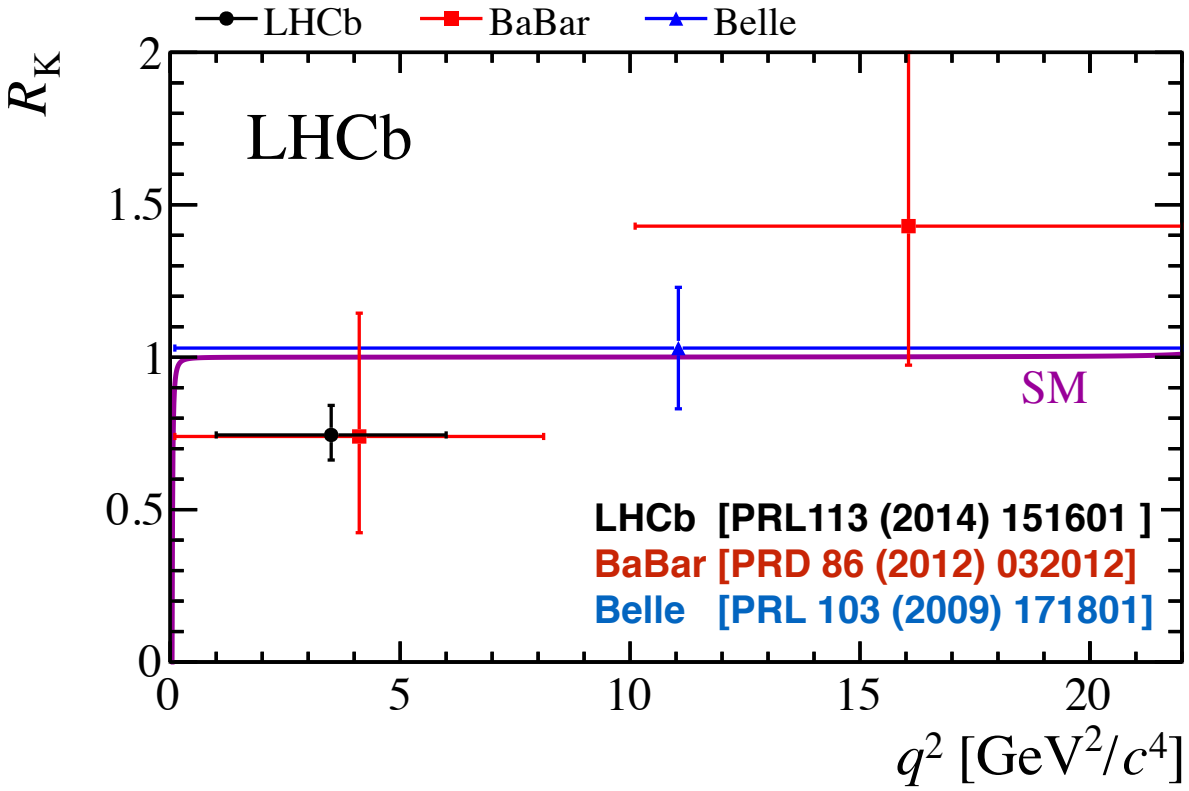
LFU: electron vs. muon (R_k)

PRL 113 (2014) 151601

LHCb measures with 3fb^{-1}

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745\ ^{+0.090}_{-0.074}\ (stat) \pm 0.036(syst)$$

(SM JHEP12(2007)040: R_k=1.0, consistent at 2.6σ)



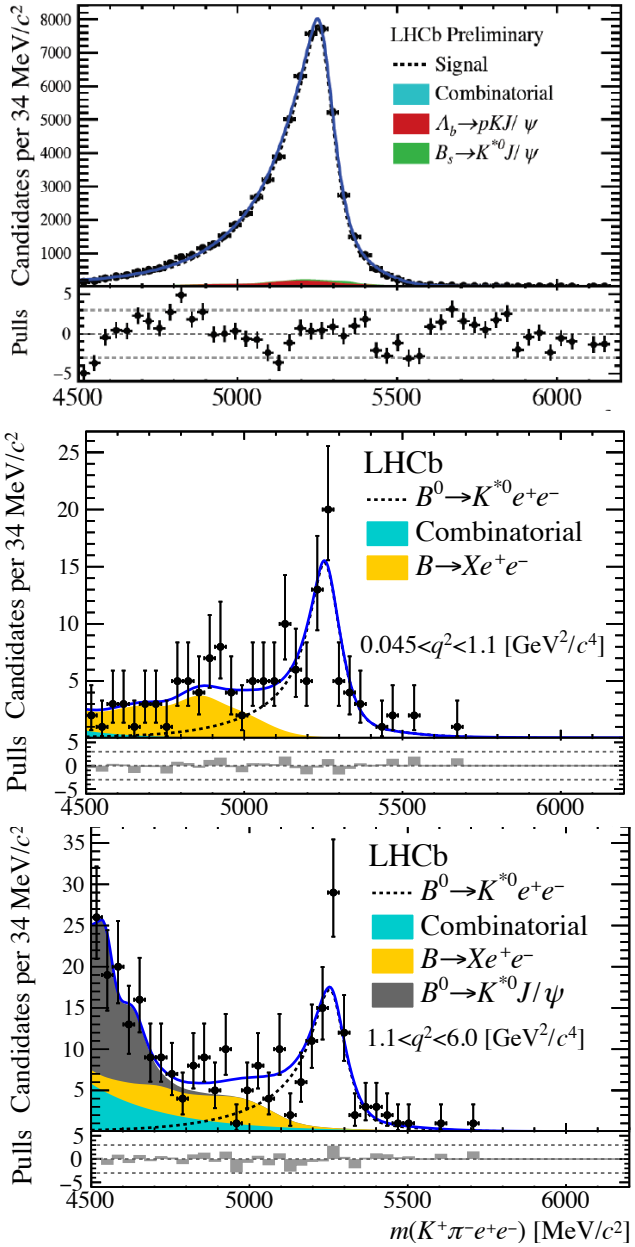
.. and R_{K^*}: Mass distributions

JHEP 08 (2017) 055

- Great efforts to check efficiencies from data with $B^0 \to J/\psi\, K^{*0}$

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006\,(\text{stat}) \pm 0.045\,(\text{syst})$$

- Similar cross check with $\psi(2S)$
- Attention paid to partially reconstructed region & potential J/ψ leakage
- Measurement performed in two regions of $q^2 = m(\mu^+\mu^-)$



.. and R_{K^*}: Measurement

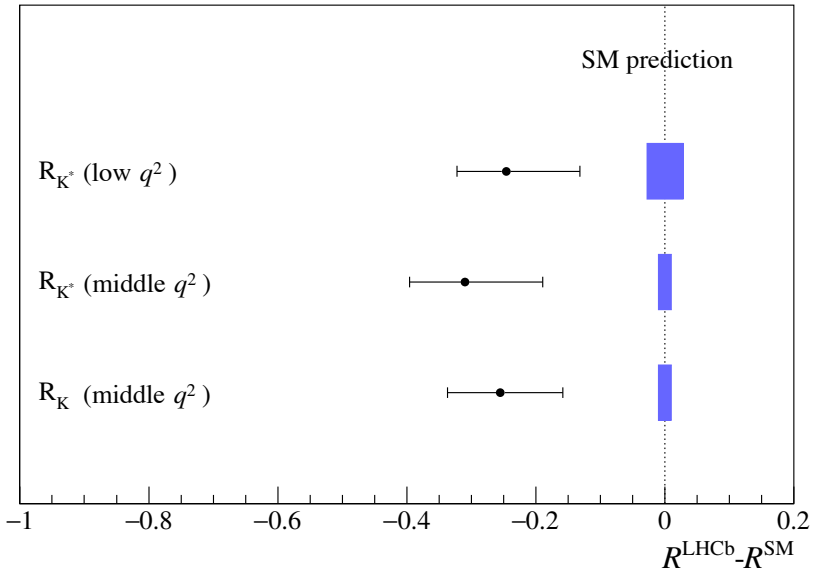
JHEP 08 (2017) 055

- Reconstructed event yields

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0} J/\psi (\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	$285 \pm 18 \pm 18$	$353 \pm 21 \pm 21$	$274416 \pm 602 \pm 654$
e^+e^- (L0E)	$55 \pm 9 \pm 8$	$67 \pm 10 \pm 10$	$43468 \pm 222 \pm 221$
e^+e^- (L0H)	$13 \pm 5 \pm 5$	$19 \pm 6 \pm 5$	$3388 \pm 62 \pm 61$
e^+e^- (L0I)	$21 \pm 5 \pm 4$	$25 \pm 7 \pm 6$	$11505 \pm 115 \pm 114$

- Measurement intension with SM
  - Low-q^2 / mid-q^2 : 2.4σ / 2.2σ

LFU measurements summary



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JHEP 08 (2017) 055

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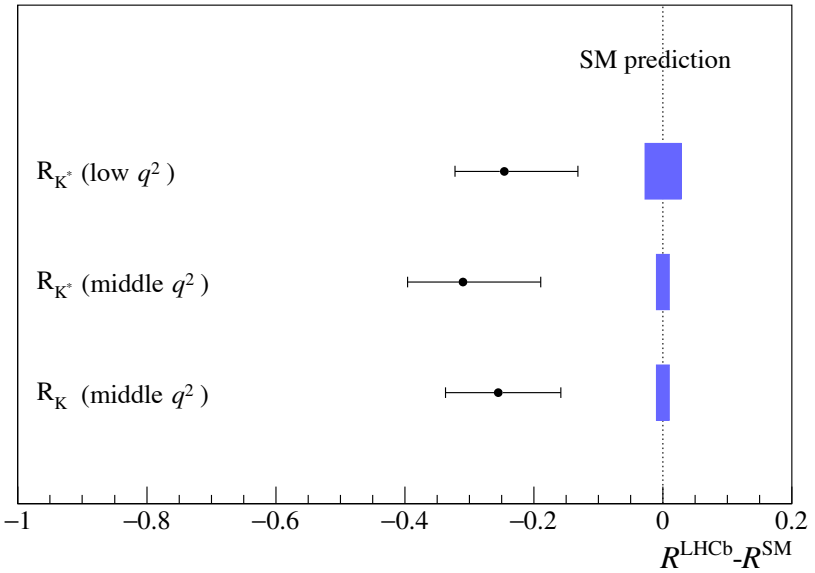
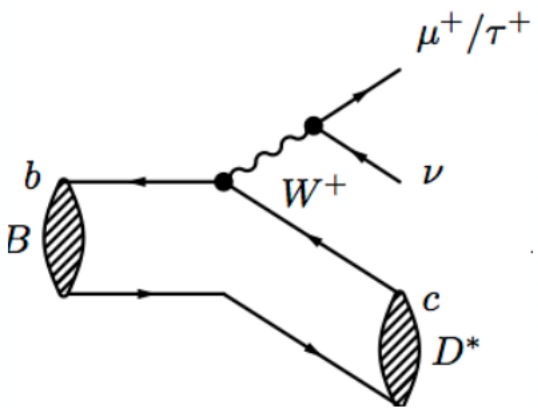


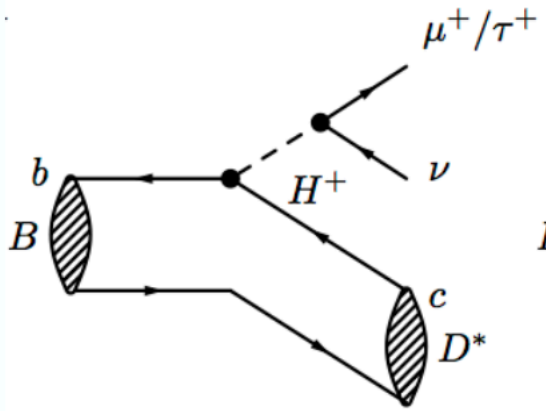
- Interpretation?
  - Typical approach: global analysis of all observables & fit to Wilson coefficients
  - Intriguing: a coherent picture seems to emerge
    some analyses: large significances (e.g. arXiv:1704.05340 > 5σ) which has lead to excited discussions of Z's, leptoquarks etc
  - **Experimentalists view: Hypotheses non fingo**
    Excitement premature: we need significant individual measurements

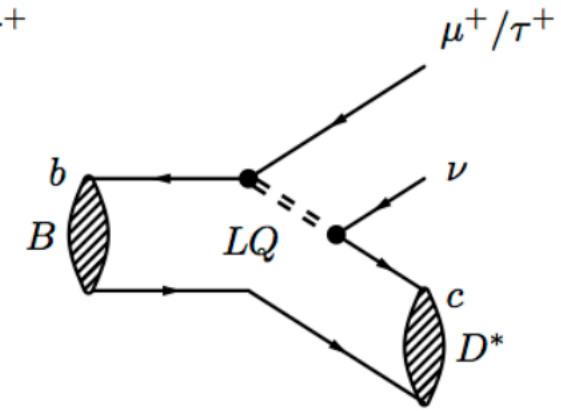
Lepton flavour universality in $\mathbf{b \to c}$

- Surprises possible in tree-level analyses
- $B^0 \to D^{(*)} \ell \nu$ Measures ratio τ^- / μ^-
  - Multiple experiments: Belle, Babar, LHCb
  - Multiple D-modes: D, D*
  - Multiple tau final states: $\mu^-\nu$, 1-prong, 3 prong
- Challenging Analyses
  - Missing neutrino, complex backgrounds (e.g. $B \to D^{**} \mu$)

$$R_{D^*} = \frac{BR(B^0 \to D^{*+} \tau^- \bar{\nu})}{BR(B^0 \to D^{*+} \mu^- \bar{\nu})}$$

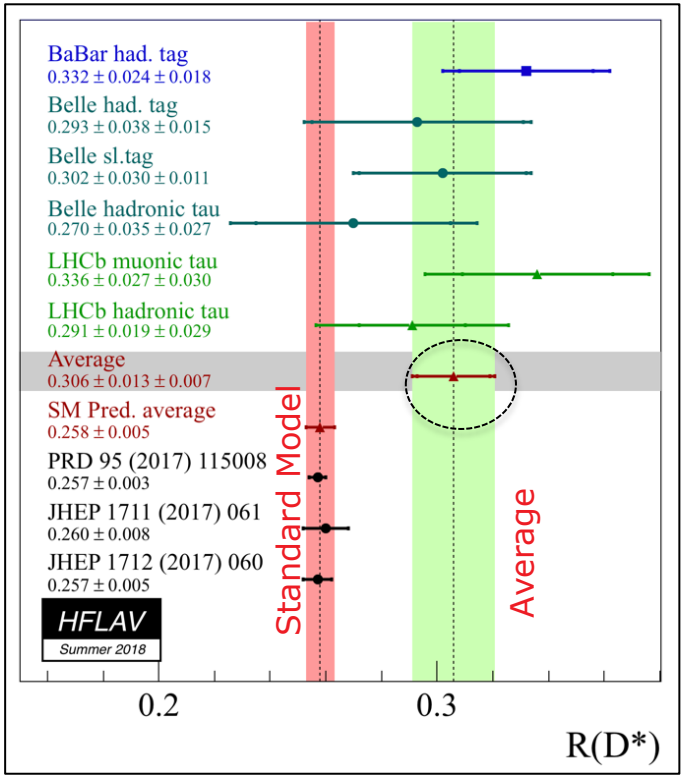


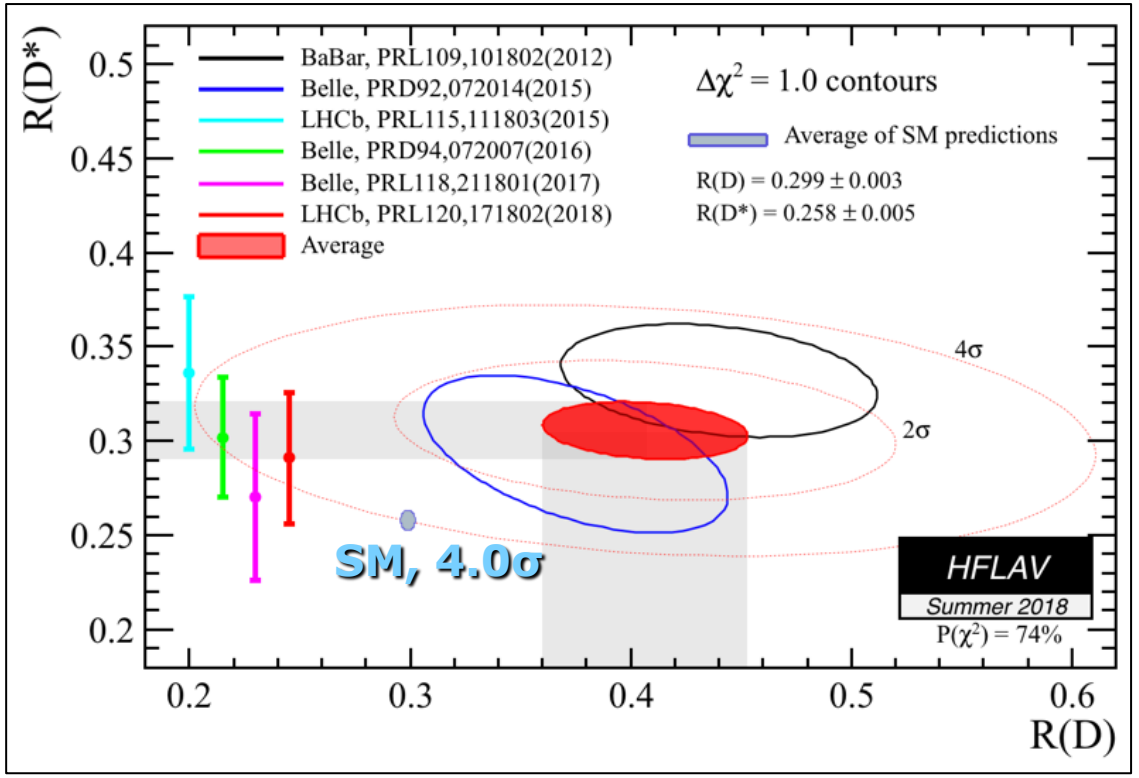




Lepton flavour universality in $b \to c$

Measurements from BaBar, Belle, LHCb show anomalies





R(D) from FLAG working group [EPJC 77 (2017) 112].
R(D*) from S. Fajfer et al. [PRD 85 (2012) 094025].

Combination yields 3.8σ tension …

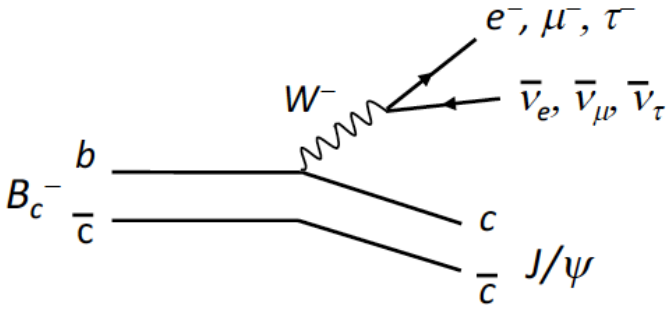
.. need more data for conclusion

LFU in B_c decays

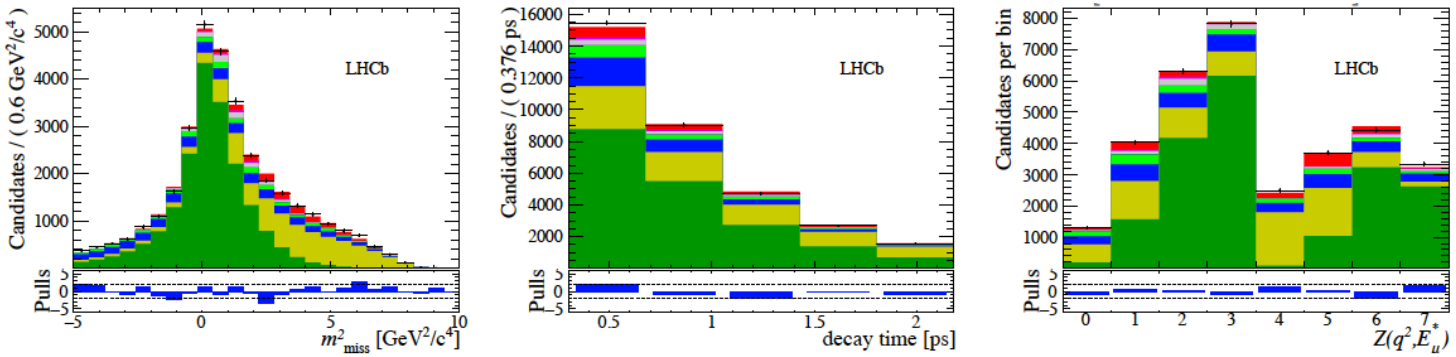
PRL120 (2018) 121801

- Test the same effective Feynman diagram in B_c decays:

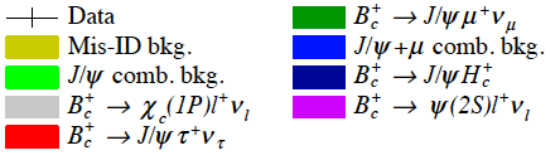
$$R_{J/\psi} = \frac{BR(B_c^+ \to J/\psi\, \tau^+ \nu)}{BR(B_c^+ \to J/\psi\, \mu^+ \nu)}$$



$R(J/\psi)_{SM} = 0.25 - 0.28$ PLB452(1999)129, arXiv:0211021, PRD73(2006)054024, PRD74(2006)074008



- 3D templated binned ML fit to m^2_{miss}, τ_μ, and $Z=(E_\mu, q^2)$
- Shapes derived from control samples or simulation validated on data

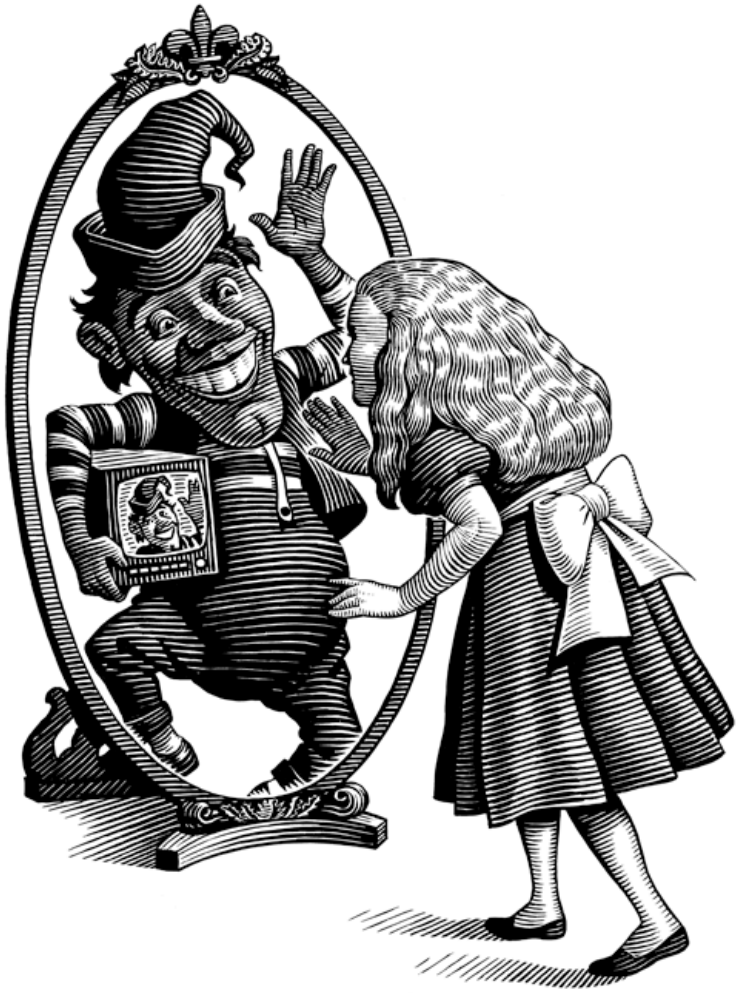


$$R_{J/\psi} = 0.71 \pm 0.17(stat) \pm 0.18(syst)$$

Compatible with the SM at ~2σ

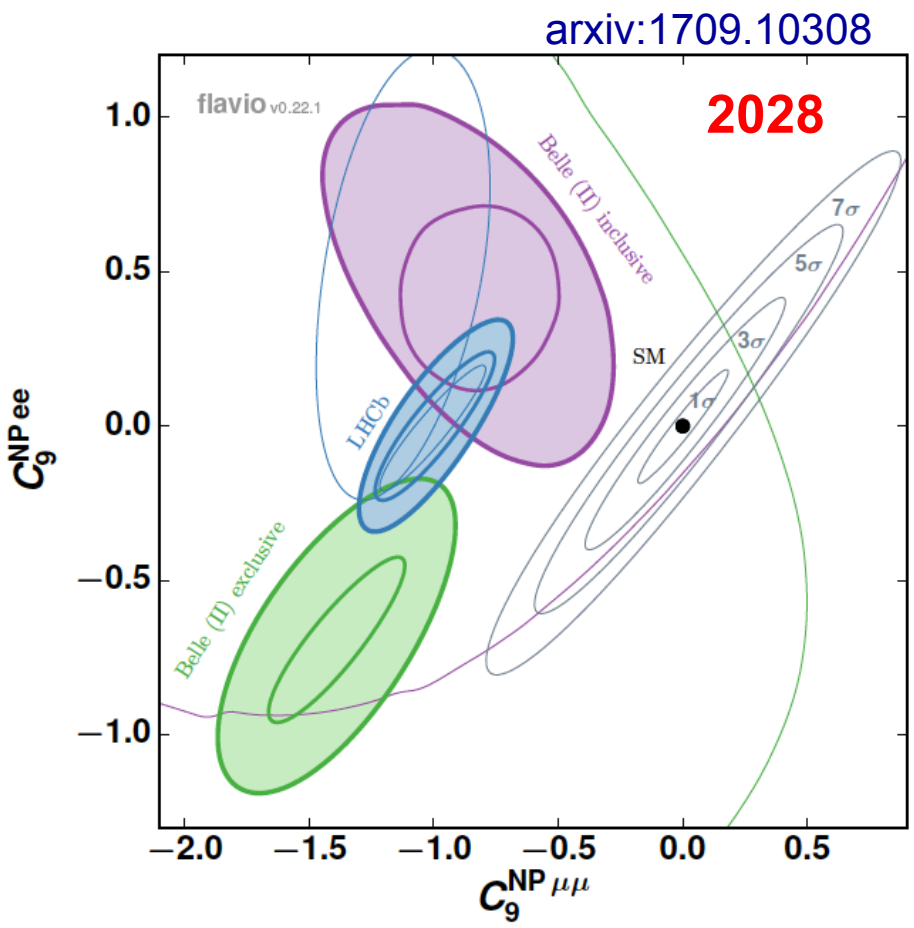
Summary

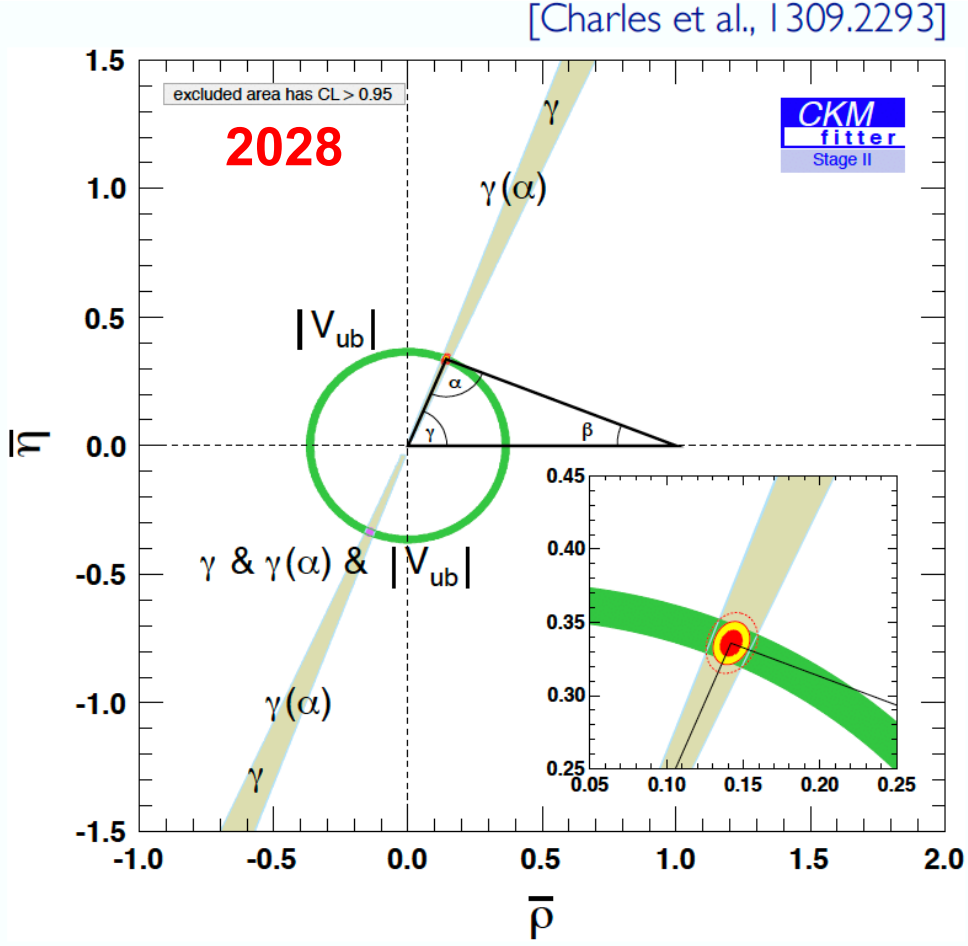
- No summary needed
- Instead, Thorsten borrowed me his magic looking glass



© Michael Custode

One slide from the Thomas Fest 2028

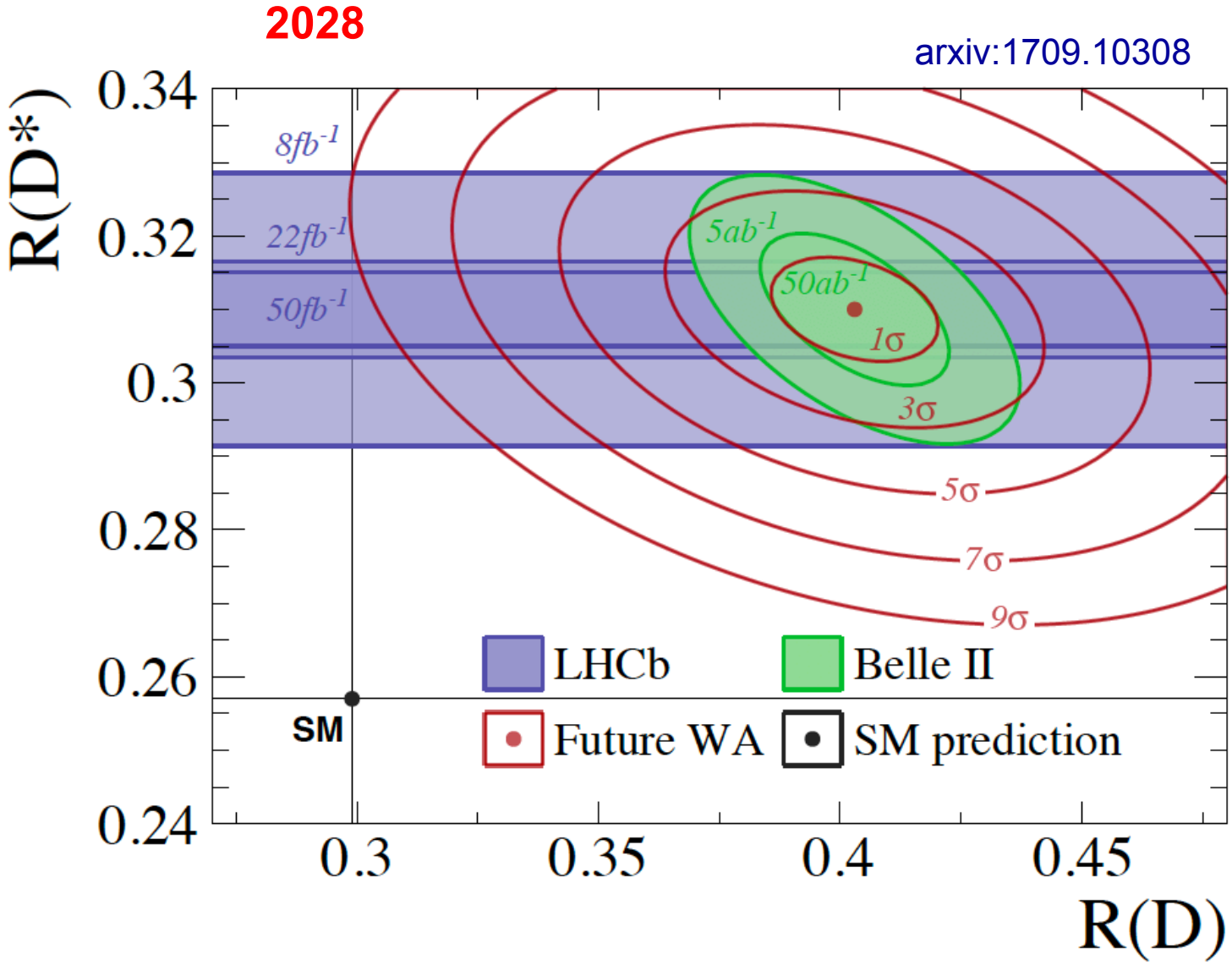




Flavour anomalies ($b \to s$ and LFU) very significantly measured by the LHCb, CMS and Belle2 experiments

All CKM angles tested below 1 degree. Lots of room for new effects to be uncovered

Future $b \to c$


2028
arxiv:1709.10308
R(D*)
0.34
0.32
0.3
0.28
0.26
0.24
8fb-1
22fb-1
50fb-1
5ab-1
50ab-1
1σ
3σ
5σ
7σ
9σ
LHCb
Belle II
SM
Future WA
SM prediction
0.3
0.35
0.4
0.45
R(D)

Expected sensitivity: LFU in $b \to s$

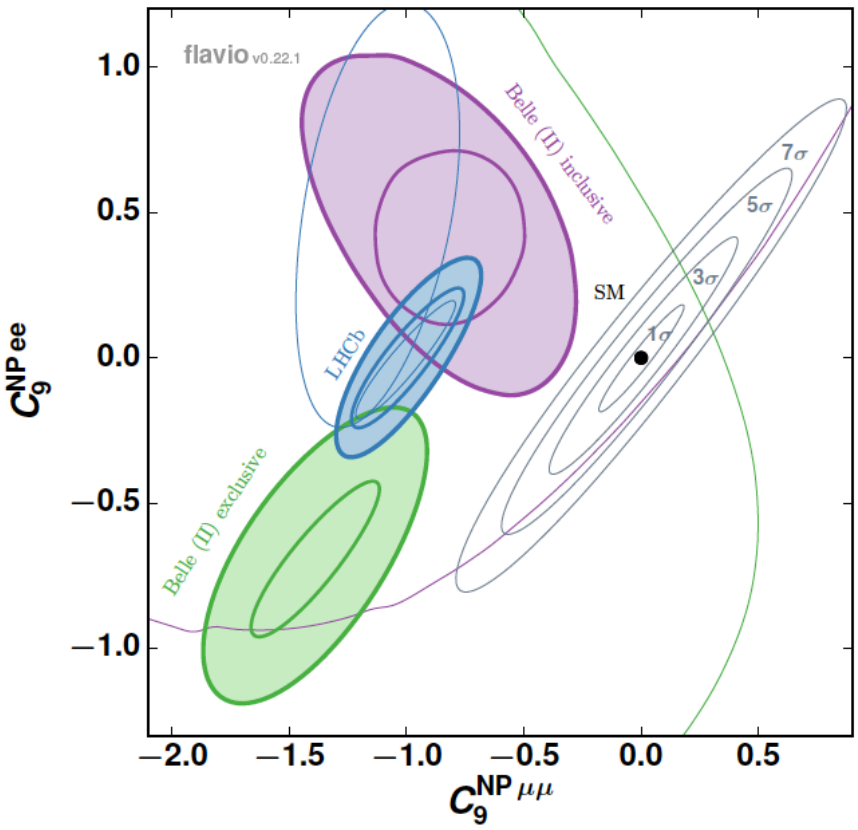
Effective Hamiltonian:

$$H = \sum_i \left(C_i^{SM} + C_i^{NP} \right) O_i$$

i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

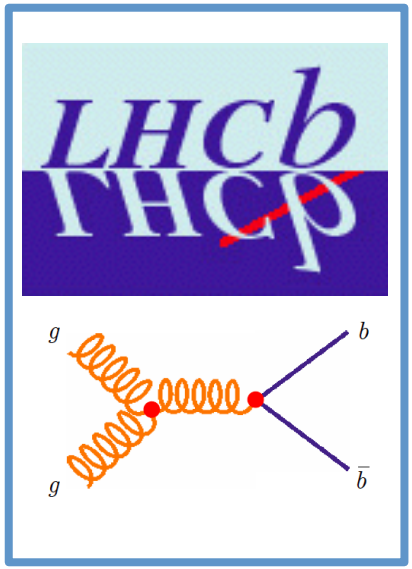
- Global fit to $b \to s$ data: Current data well consistent with C_9 – 25%
- If current tensions persist, they will will be **established with >5σ** by LHCb (Run 2), **and then also by Belle2**

arxiv:1709.10308

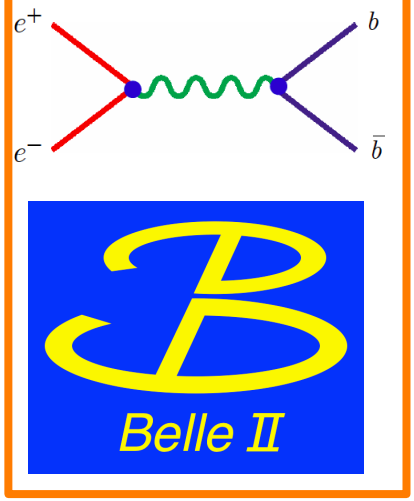


Central values shifted for illustration

Complementarity LHCb – Belle 2



- Time dependent B_s physics
  - CPV in $B_s \to J/\psi\,\phi$, $B_s \to \phi\phi$
- $B_s \to \mu^+\mu^-$
- CKM angle γ
- CPV in B_d
- $B \to X_s\,\ell^+\ell^-$ (exclusive) → **LFU**
- $B \to X_s\,\gamma$ (exclusive)
- Charm physics
- Semileptonic B decays
- $B \to D\,\tau^-\,\nu$, $B \to D^*\,\tau^-\,\nu$
- Dark matter
- τ − physics: LFV
- $B \to \tau^-\,\nu$, $B \to \mu^-\,\nu$
- $B \to K^*\,\nu\nu$, $B \to \nu\nu$
- $B \to X_s\,\ell^+\ell^-$ (inclusive)
- $B \to X_s\,\gamma$ (inclusive)



"B_s & charged tracks"

Important overlap: sporty competition!

"inclusive & neutrals "