
# Rare Decays and Flavour Anomalies

***Roger Forty*** *(CERN)*

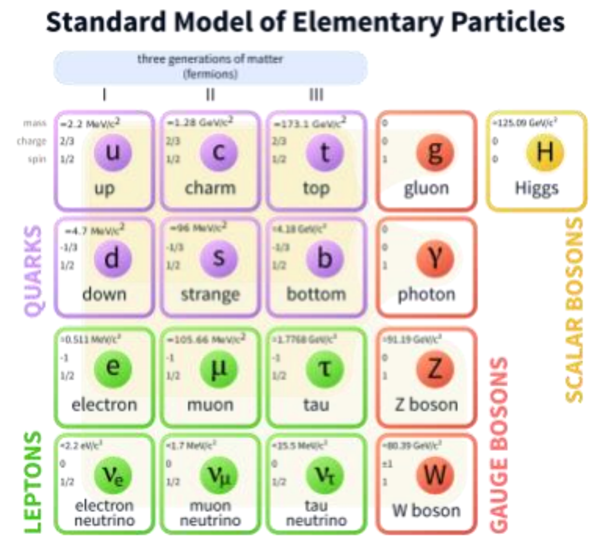
Experimental review on behalf of the LHCb Collaboration
also including results from ATLAS, BaBar, Belle and CMS

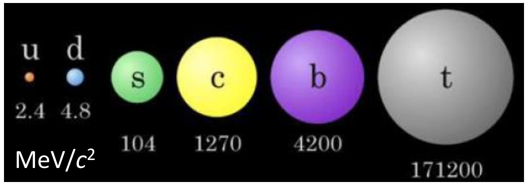
1. The LHCb experiment
2. Rare Decays
3. Flavour Anomalies

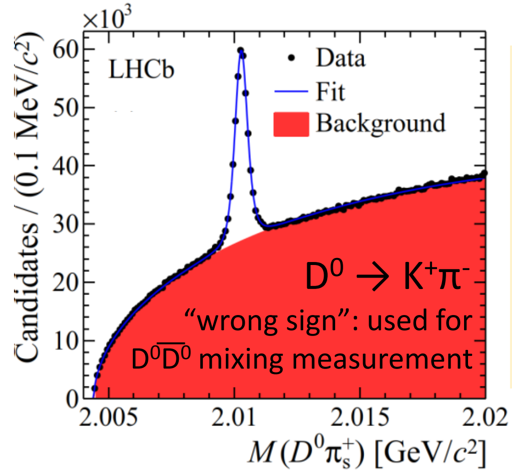
Corfu Summer Institute (3 September 2018)

# Introduction

- The Standard Model has 3 generations of pairs of quarks and leptons, differing only in mass Their study is the topic of **Flavour Physics**
- Many of open questions of the Standard Model lie in the flavour sector:
  - Why are there 3 generations? Related to being minimum required for CP violation?
  - What determines the extreme hierarchy of fermion masses *and* the CKM quark-mixing matrix elements?
  - How can the observed matter/antimatter asymmetry of the Universe be explained (Standard Model CP violation insufficient)?
- The **LHCb experiment** is dedicated to flavour physics at the LHC, has the largest samples of beauty and charm hadrons ever produced



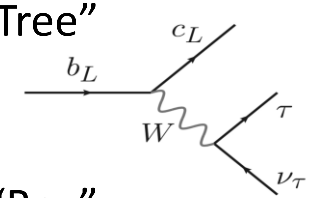




PRL 111 (2013) 251801

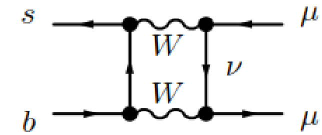
# Rare decays

- The bulk of hadron decays proceed via tree diagrams
  **Rare decays** involve loop diagrams:
- **New Physics** (i.e. beyond the SM) involves new particles, which could also participate in such loops via virtual quantum fluctuations → noticeable effects on decays, in particular since they are suppressed in the SM

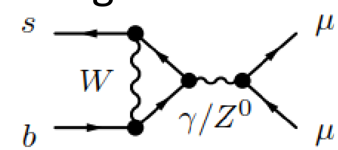
“Tree”




“Box”




“Penguin”



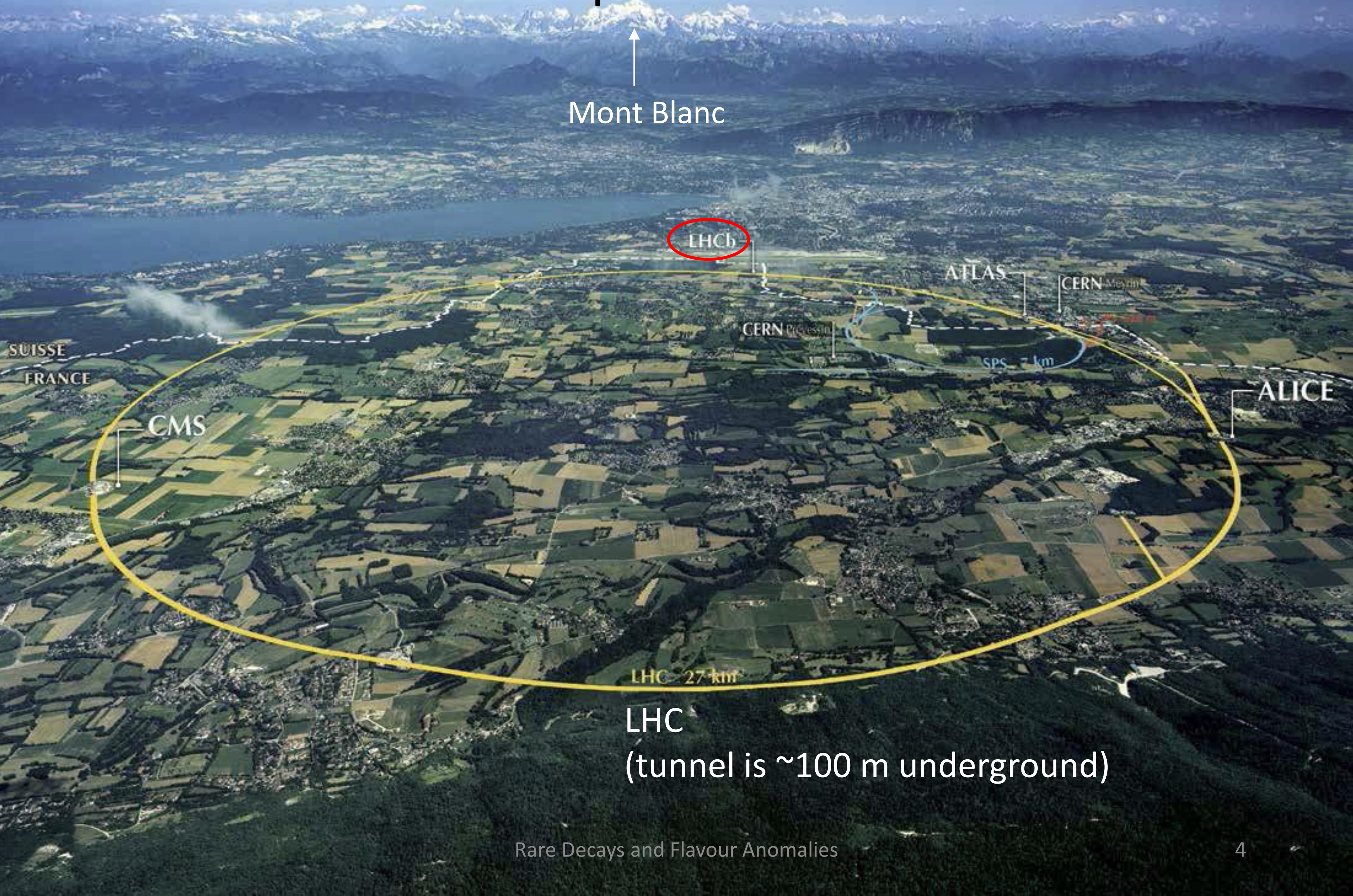

- Such “indirect” discovery of new physics via precision measurements has a long and illustrious history

N. Tuning, ICHEP2018

| Particle | Indirect | | | Direct | | |
|---|---|---|---|---|---|---|
| ν | β decay | Fermi | 1932 | Reactor ν-CC | Cowan, Reines | 1956 |
| W | β decay | Fermi | 1932 | $W\to e\nu$ | UA1, UA2 | 1983 |
| c | $K^0\to\mu\mu$ | GIM | 1970 | $J/\psi$ | Richter, Ting | 1974 |
| b | CPV $K^0\to\pi\pi$ | CKM, 3[rd] gen | 1964/ | $\Upsilon$ | Ledermann | 1977 |
| Z | ν-NC | Gargamelle | 1973 | $Z\to e^+e^-$ | UA1 | 1983 |
| t | B mixing | ARGUS | 1987 | $t\to Wb$ | D0, CDF | 1995 |
| H | $e^+e^-$ | EW fit, LEP | 2000 | $H\to 4\mu/\gamma\gamma$ | CMS, ATLAS | 2012 |

- Currently no clear signs of new physics from direct searches at the LHC, but there *are* a number of hints of non-SM behaviour in b-hadron decays —the so-called **Flavour Anomalies**

# 1. The LHCb experiment

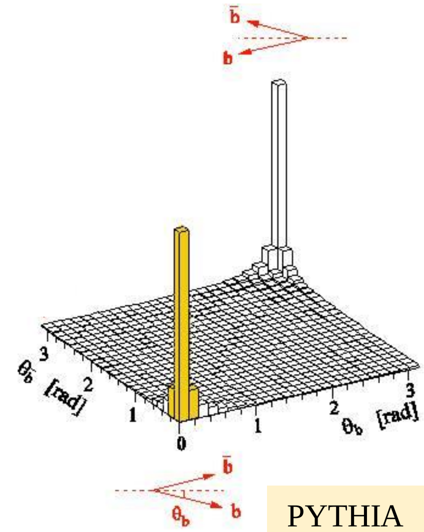


# Spectrometer

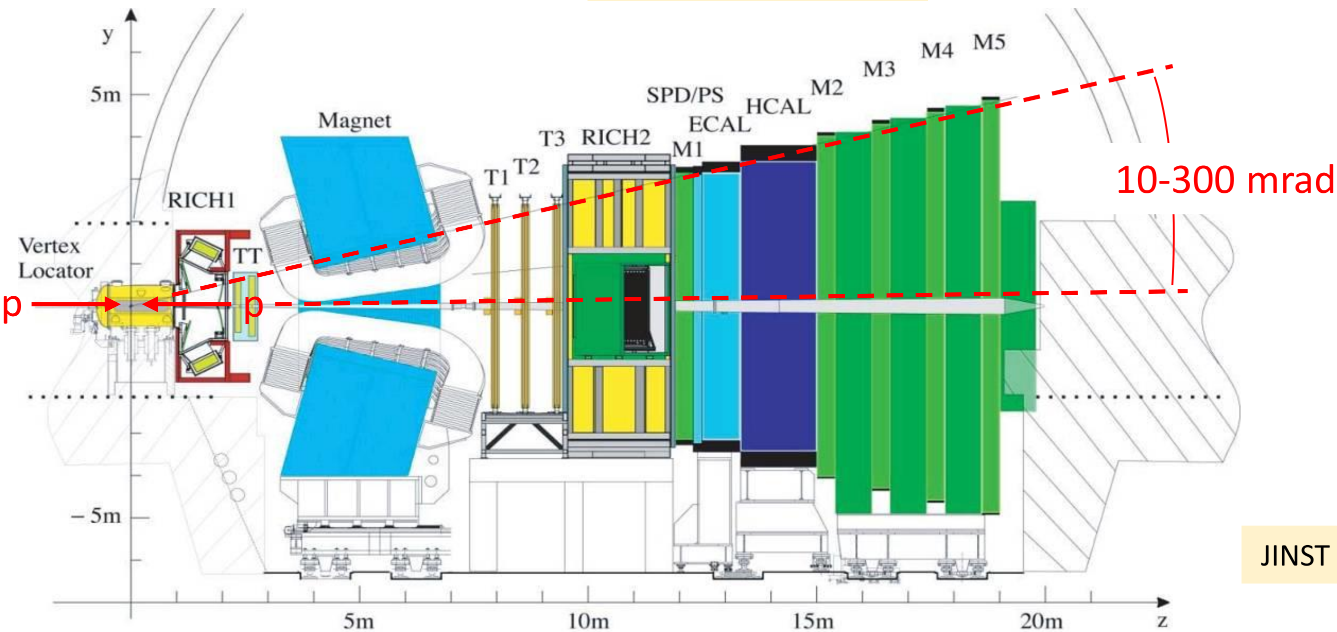
- Forward-peaked production of b-hadrons at the LHC:
  → LHCb is a forward spectrometer (in collider mode)
- $b\bar{b}$ cross-section = 154.3 ± 1.5 ± 14.3 μb at √s = 13 TeV
  → ~100,000 $b\bar{b}$ pairs produced/second ($10^4$ × B factories)
  and all species of b hadron: $B^+$, $B^0$, $B_s^0$, $B_c^+$, $\Lambda_b^0$…

  **Quark content:** $\bar{b}u$, $\bar{b}d$, $\bar{b}s$, $\bar{b}c$, bud
- Charm production ~20× higher

PRL 118 (2017) 052002




PYTHIA

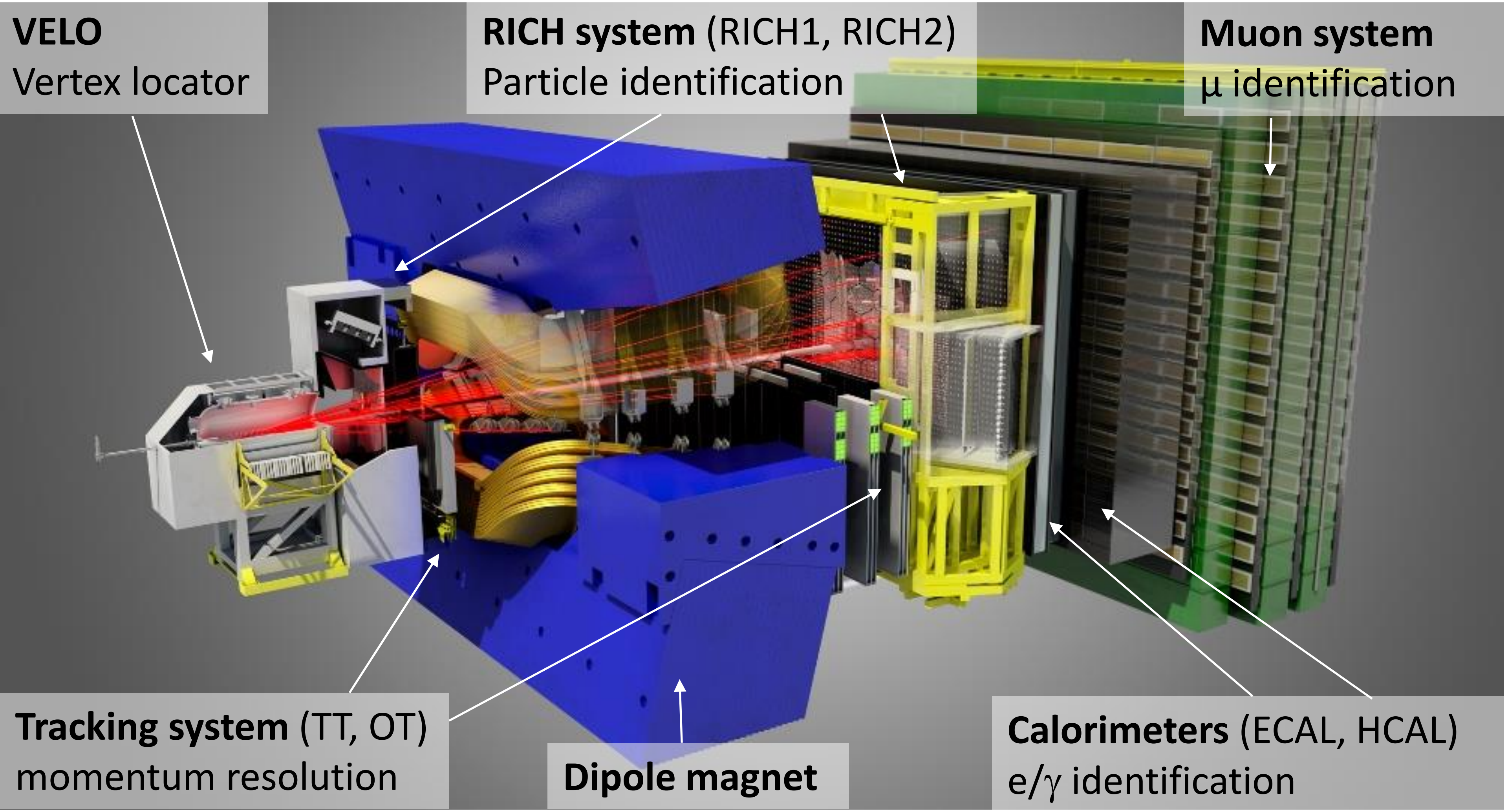



JINST 3:S08005 (2008)

# Detector components

Int. J. Mod. Phys. A 30 (2015) 1530022

$\varepsilon(\mu \rightarrow \mu) \sim 97\%$. $\varepsilon(\pi \rightarrow \mu) \sim 1\text{-}3\%$



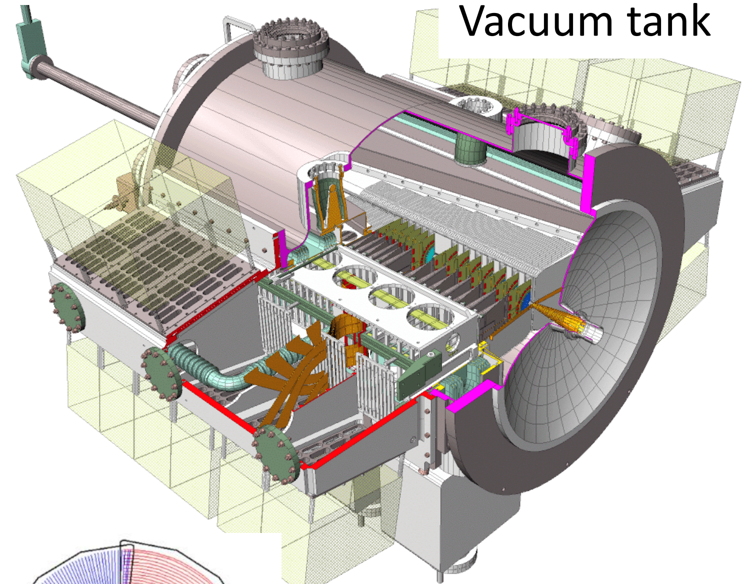

$\Delta p/p$ = 0.5-1.0% (5-100 GeV/c)

$\int B\, dL$ = 4 Tm

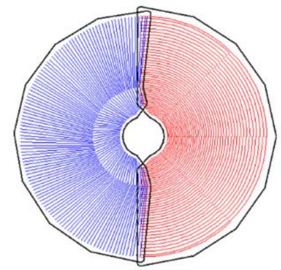
$\Delta E/E = 1\% \oplus 10\%/\sqrt{E}$(GeV)

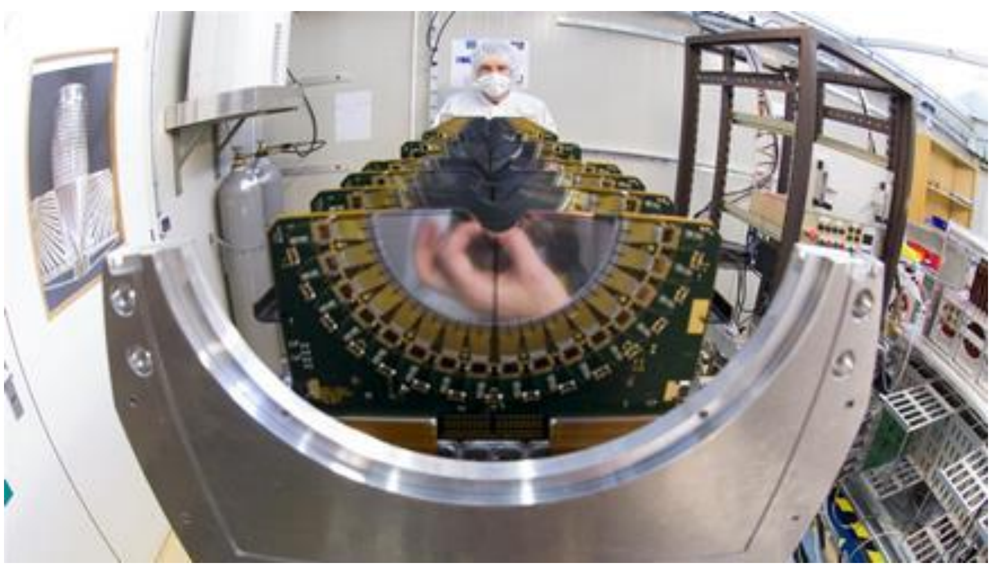
# VELO

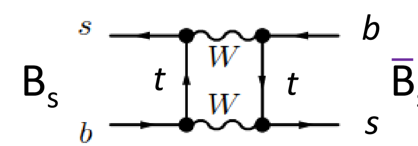
- Surrounds the interaction point for precision vertex detection
- Silicon microstrips that close around the beam, approaching to 8 mm
- 20 μm spatial resolution, corresponds to 45 fs: sufficient to resolve $B_s$-$\overline{B}_s$ oscillations



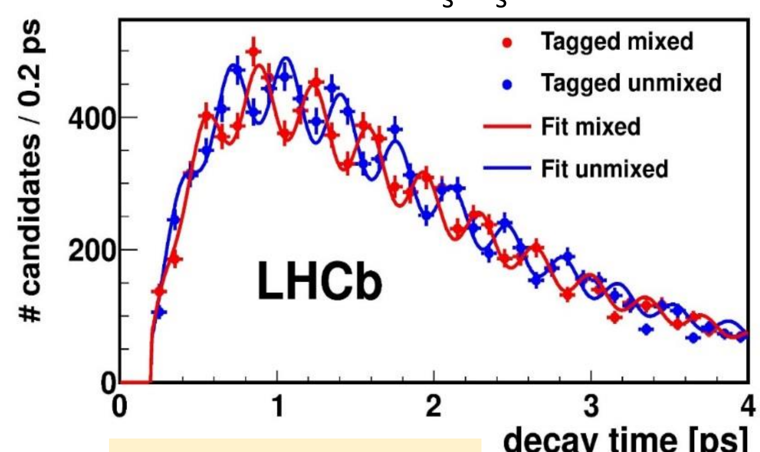

*r*-ϕ geometry:







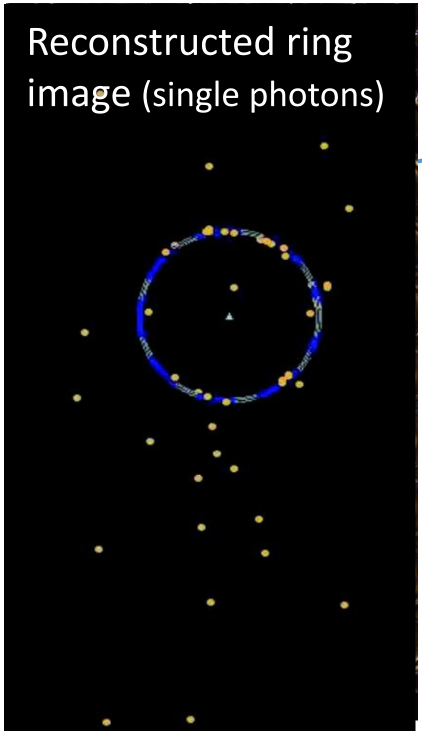

$B_s$-$\overline{B}_s$ oscillations

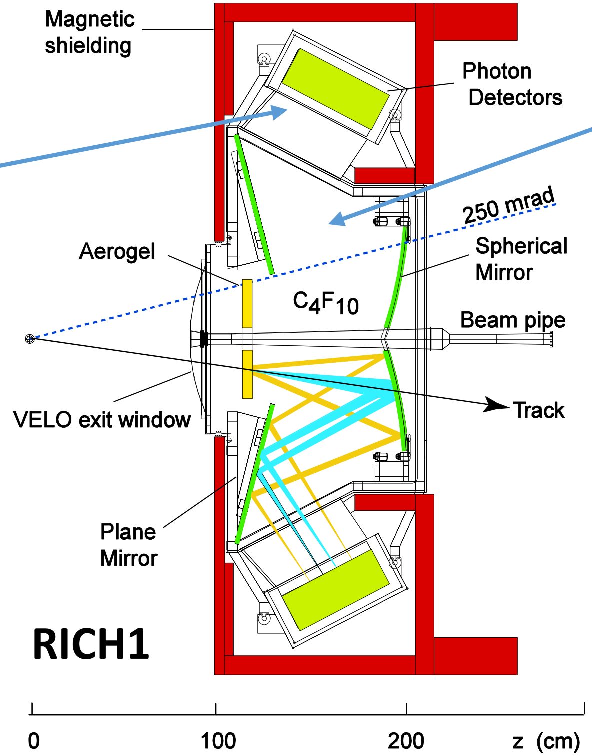


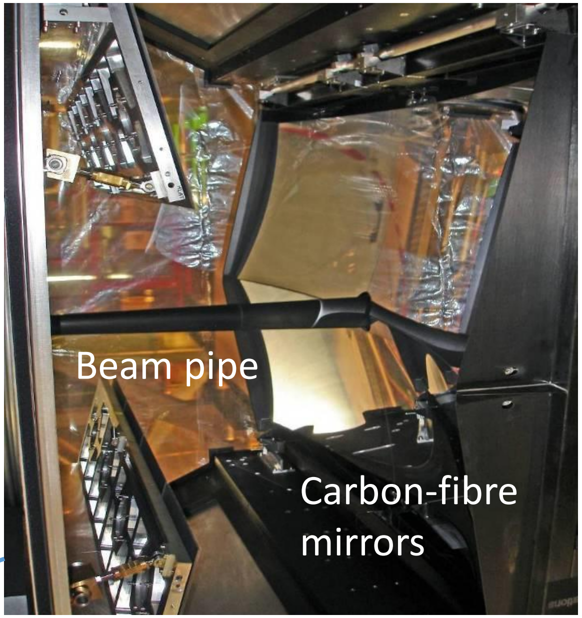

J. Phys. 15 (2013) 053021

# RICH detectors

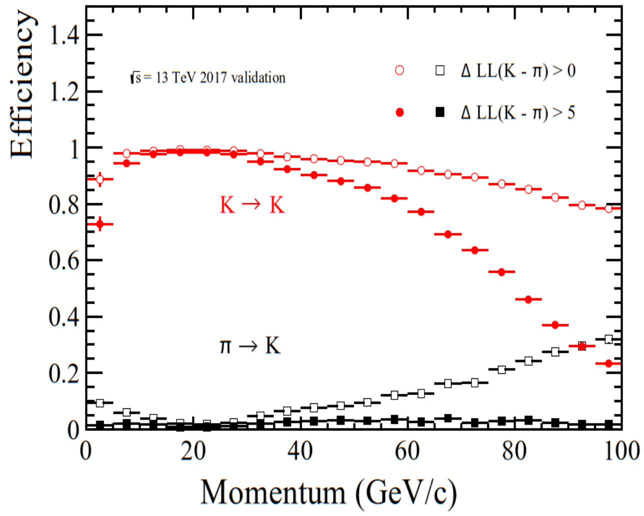
- Ring-imaging Cherenkov detectors for particle ID
- Separating charged hadrons (π, K, p) essential for flavour physics, to suppress background
  limited in ATLAS/CMS since lack RICH detectors



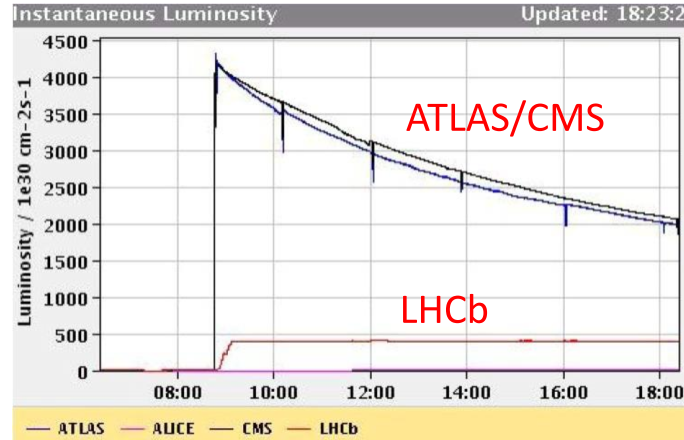




K-π separation

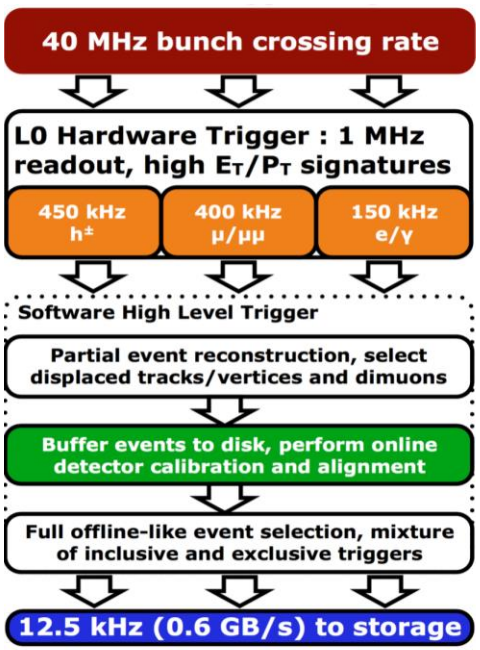


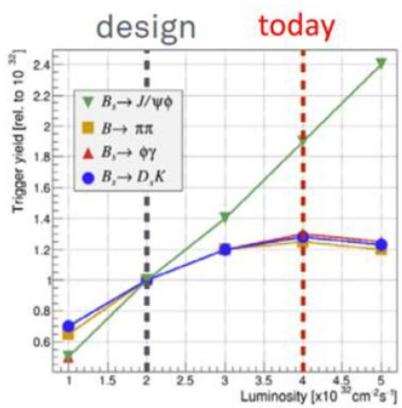
# Data taking

- LHCb luminosity levelled at $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- Chosen to maximize trigger yield, gives pile-up ~ 1 and limits radiation damage
- 8.5 fb$^{-1}$ of integrated luminosity to date
  Results shown mostly from Run1 (3 fb$^{-1}$)

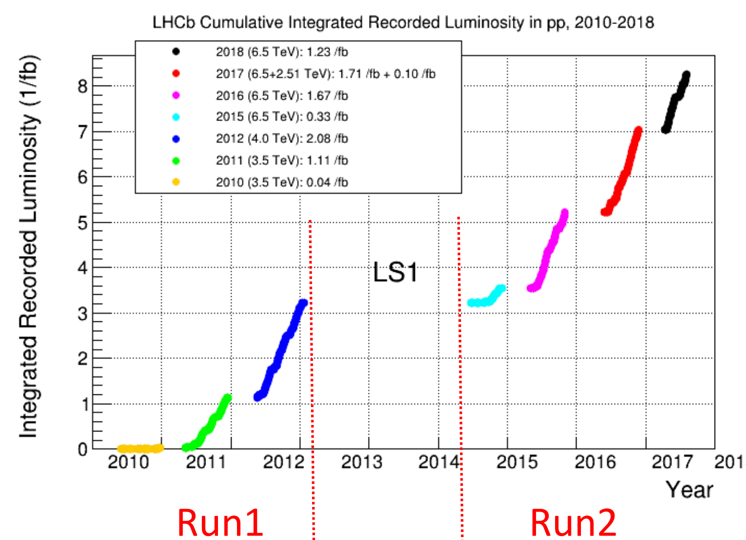



Typical LHC fill




Upgrade next year →
Fully software trigger
Run at 5× higher lumi

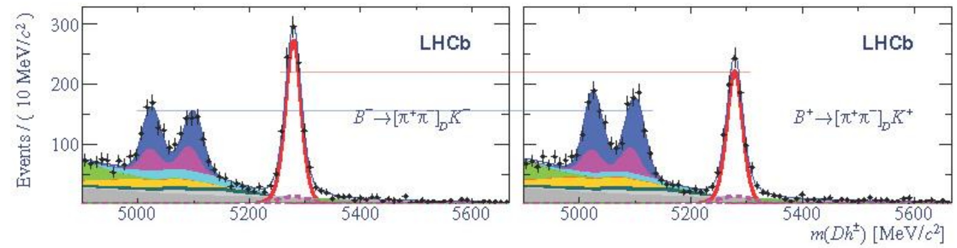


# Physics programme

See talk of Neville Harnew (next)

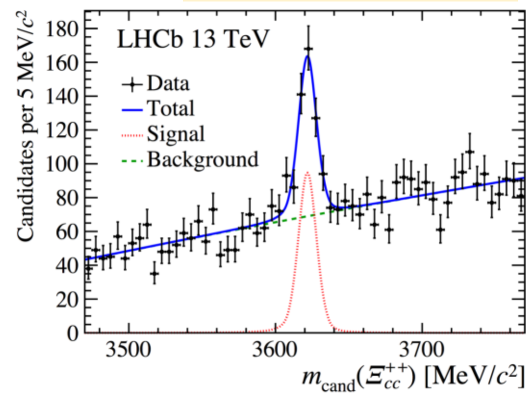
- In addition to **Rare Decays** presented here, LHCb has broad physics programme
- **CP violation:** differences in decay rates between particles and antiparticles, a key ingredient to make the Universe we see (Baryon Asymmetry)

$\mathcal{B}(B^- \to DK^-) \quad > \quad \mathcal{B}(B^+ \to DK^+)$




- **Spectroscopy:**
  - test-bed for QCD: e.g. first observation of doubly-charmed (and doubly-charged) baryon $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
  - Most hadrons mesons ($q\bar{q}$) or baryons ($qqq$) are there more **exotic** structures, **tetraquarks** ($q\bar{q}q\bar{q}$) or **pentaquarks** ($q\bar{q}qqq$)?

LHCb-PAPER-2017-018




- **And much more:** Heavy Ion, Fixed Target, Electroweak physics…

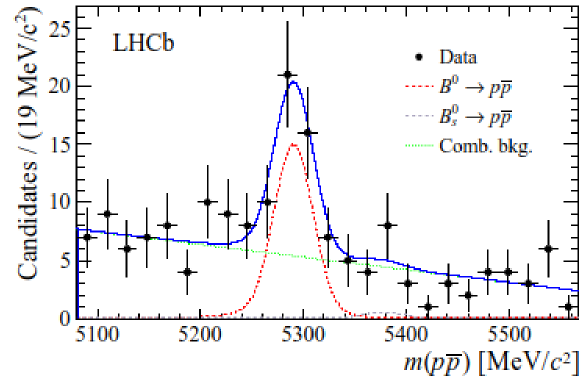
→ LHCb is a general-purpose experiment covering forward region $(2 < \eta < 5)$

# Detector in the cavern


**Collaboration**
1260 members
from 78 institutes
in 18 countries

# 2. Rare Decays

Phys. Rev. Lett. 119 (2017) 232001



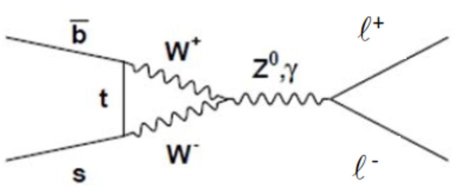

- Rarest fully-hadronic b decay observed so far

$$\mathcal{B}(B^0 \to p\overline{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$$

However, such decays are difficult to predict
→ interesting for understanding QCD,
but not for discovering New Physics

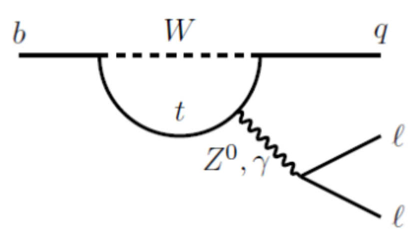
- We want to study decays which are suppressed in the Standard Model, but can be precisely calculated, sensitive to New Physics
- **Flavour Changing Neutral Currents** (FCNC) are suitable:
Since quark flavour is only changed via exchange of $W^{\pm}$ (in the SM, at least) forbidden at tree level → these decays involve loops:

① **Fully leptonic**



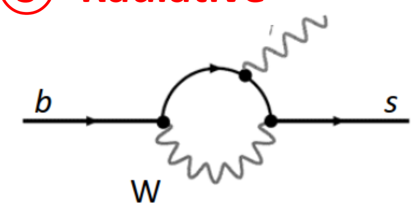

BR ~ $10^{-9}$

② **Semileptonic**



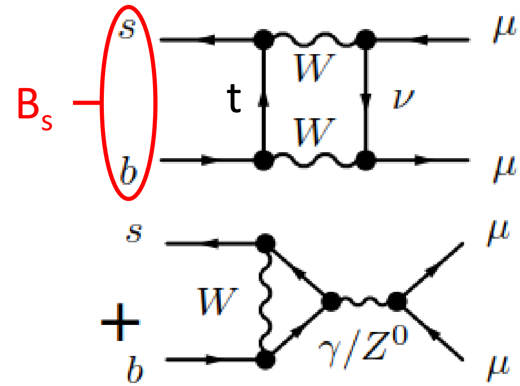

BR ~ $10^{-7}$

③ **Radiative**




BR ~ $10^{-5}$

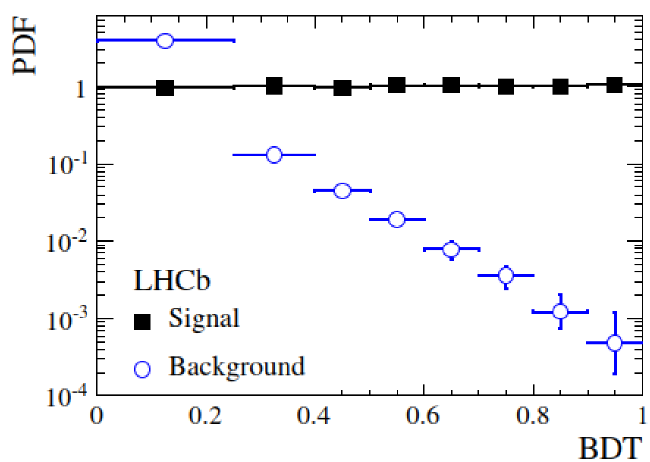
# ① Fully leptonic decays

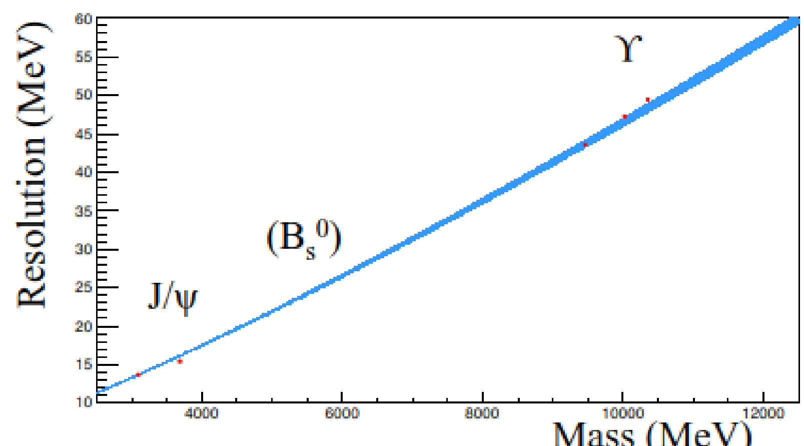



- **$B_s \to \mu^+\mu^-$** is the archetypical rare decay:
- Highly suppressed in Standard Model by loop, CKM coupling ($|V_{ts}|^2$) and helicity $(m_\mu/m_B)^2$
- *Precise* SM prediction: $B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ (~6% error)
  $B^0$ even more suppressed: $B(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Bobeth et al.
PRL 112 (2014) 101801

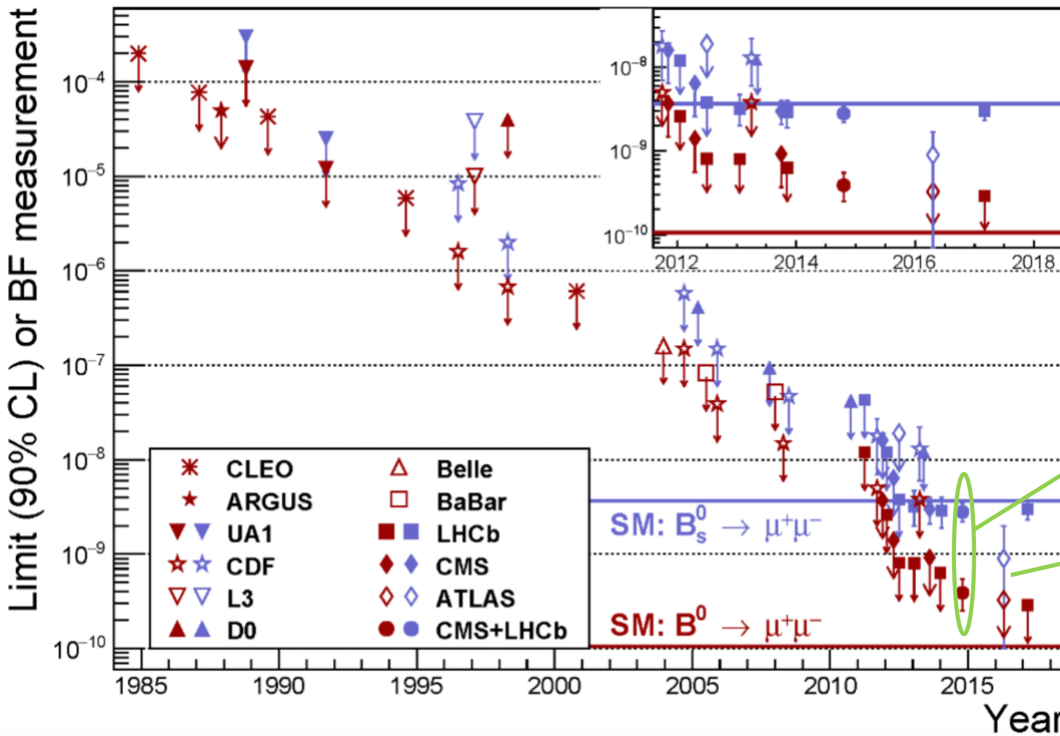
- **Challenge:** huge rate of events with 2 muons: $B(B \to \mu X) \sim 10\%$
  Use topological and muon ID information in a multivariate analysis (BDT)
  Mass resolution interpolated between J/ψ and $\Upsilon \to \mu^+\mu^-$



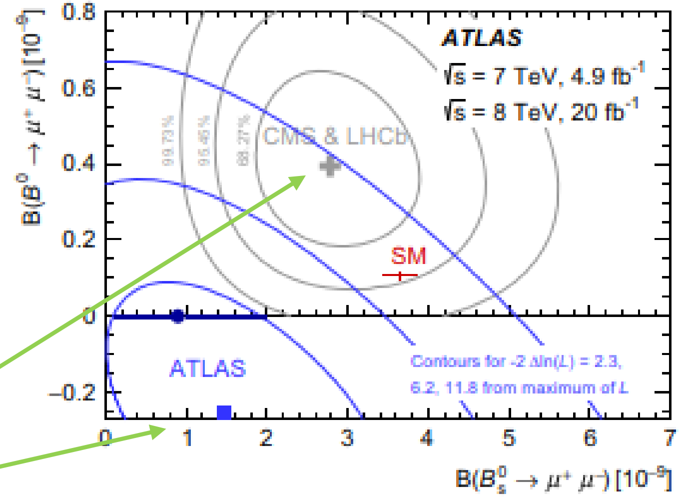




PRL 111 (2013) 101805

# $B_{(s)} \to \mu^+\mu^-$ search




CMS & LHCb, Nature 522 (2015) 68
ATLAS, EPJC 76 (2016) 513



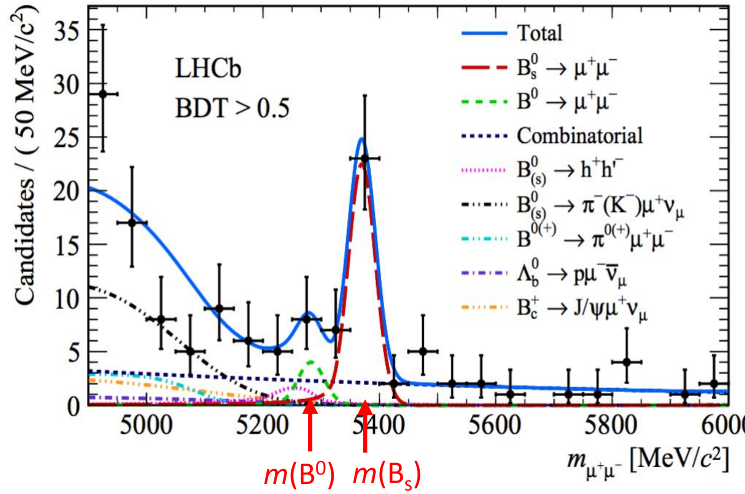

- Search for this decay has been an historical endeavour over 30 years
- Evidence eventually seen by both LHCb and CMS → joint paper
  Hint that $B^0 \to \mu^+\mu^-$ rate was high, but not seen in ATLAS data

# $B_s \to \mu^+\mu^-$ observation

PRL 118 (2017) 191801

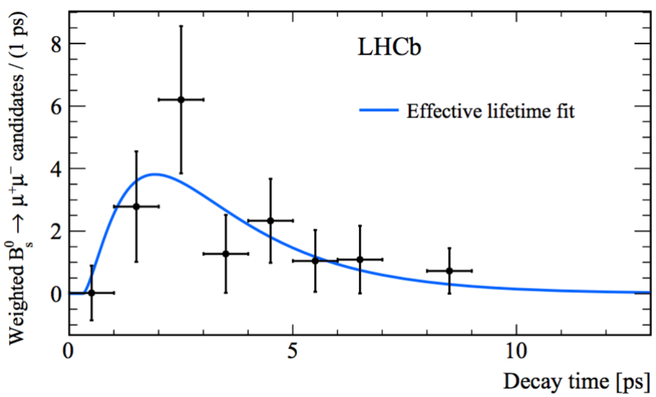
- Finally observed in a single experiment by LHCb—a milestone of flavour physics
- Used Run1 + part of Run2 (3+1.4 fb$^{-1}$)
  7.8σ significance

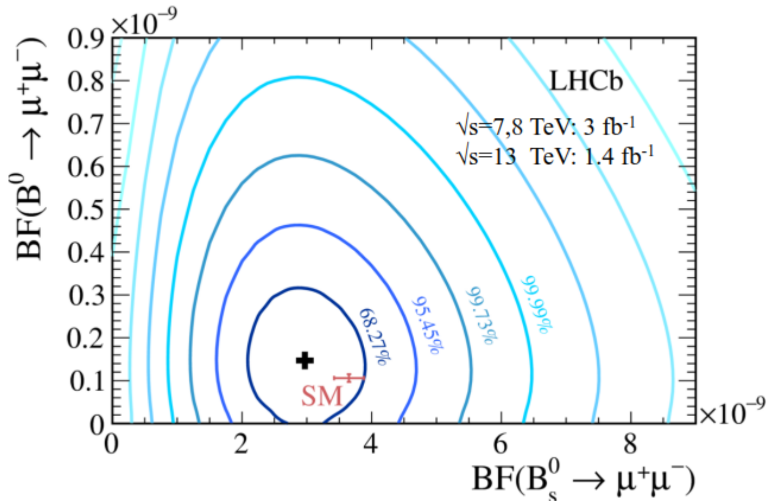
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad \text{(~20%)}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$




- Even made a first lifetime measurement

$$\tau_{\rm eff}(B_s(t) \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\, ps$$



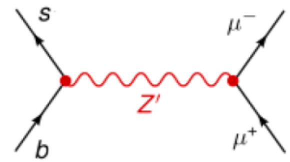

NP could affect this due to large $\Delta\Gamma_s$
(needs more data to be sensitive)

→ in agreement with Standard Model

# Implications

- *B*($B_s \to \mu^+\mu^-$) result consistent with Standard Model expectation
  Implications depend on the model of New Physics (with scale $\Lambda$)

$$BR_{exp}/BR_{SM} \equiv \mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2|V_{tb}^*V_{ts}|^2}\frac{v^2}{\Lambda^2}$$




Haisch, arXiv:1510.03341

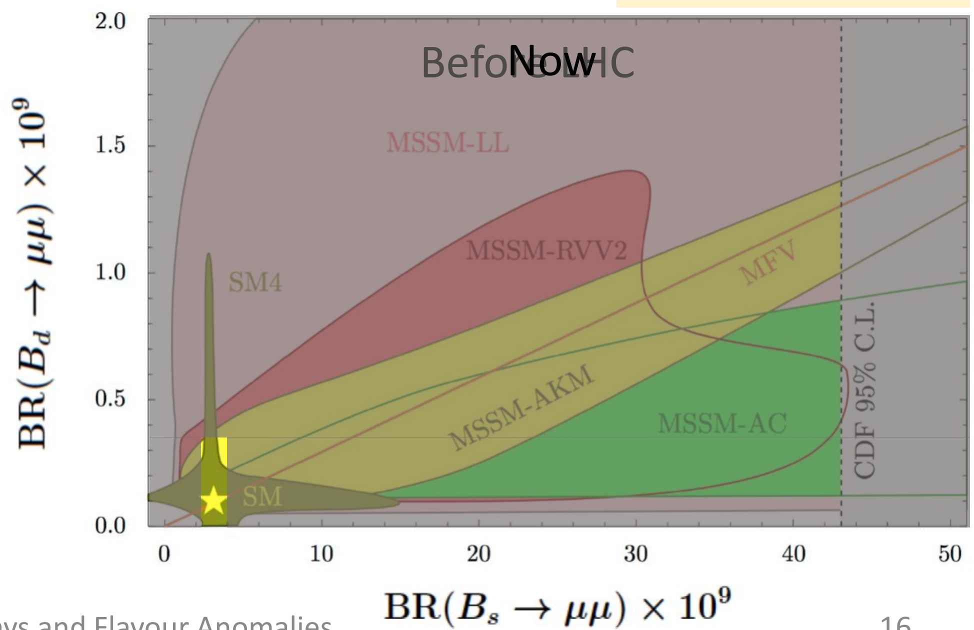
$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \frac{\sqrt{4\pi}}{g\,|V_{tb}^*V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\text{TeV} \\ 0.6\,\text{TeV} \end{cases}$$

50 TeV → for Z' with generic tree-level coupling modification

0.6 TeV → One-loop modification of Z penguin assuming MFV

Straub, arXiv:1107.0266

- **Minimal Flavour Violation:** new physics has similar flavour structure to SM
- Branching ratios could have been strongly modified by new physics
- Large regions of parameter space ruled out, e.g. for SUSY



# Other fully-leptonic modes

- Helicity suppression for electron mode $B_{(s)} \to e^+e^-$ is even stronger $(m_e/m_B)^2$ → SM BF is currently out of reach, $O(10^{-13})$—but interesting for new physics

Fleischer et al. arXiv:1703.10160v2

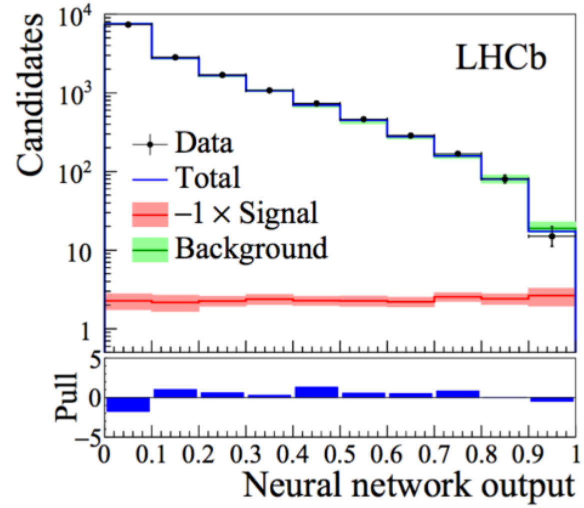
- By same token, SM rate for the $\tau^+\tau^-$ mode is larger due to $\tau$ mass

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

Bobeth et al.
PRL 112 (2014) 101801

- Challenging due to undetected neutrinos
Searched for using decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
- $B_s$-$B^0$ mass difference cannot be resolved for this channel. Limits set (at 95% CL):

$$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$$
$$\mathcal{B}(B_d \to \tau^+\tau^-) < 2.1 \times 10^{-3}$$




PRL 118 (2017) 251802

- Also search in the **strange** and **charm** sectors:

$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 0.8\ (1.0) \times 10^{-9} \text{ at } 90\%\ (95\%) \text{ CL.}$$

EPJC 77 (2017) 678

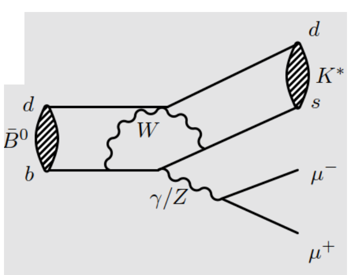
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2\ (7.6) \times 10^{-9} \text{ at } 90\%\ (95\%) \text{ CL.}$$

PLB 725 (2013) 15

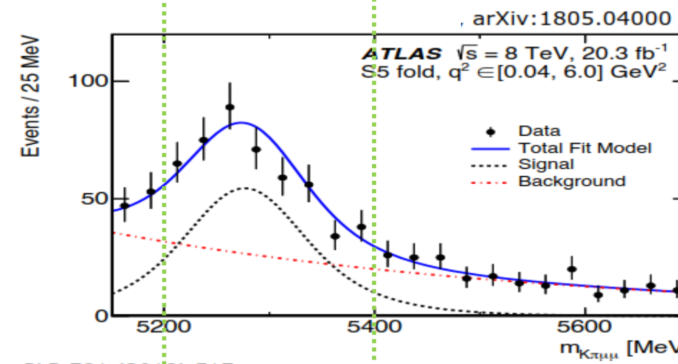
# ② Semileptonic rare decays

- **$b \to s\ell\ell$** has similar loop diagrams to $B_s \to \mu\mu$, but instead of annihilation the s quark leg is rotated to the final state
- More observables: $m(\mu\mu)$, angular information from decay products
- Contributions from many experiments: ATLAS, CMS, LHCb and the B factories
  **LHCb:** best mass resolution at the LHC highest statistics, lowest background

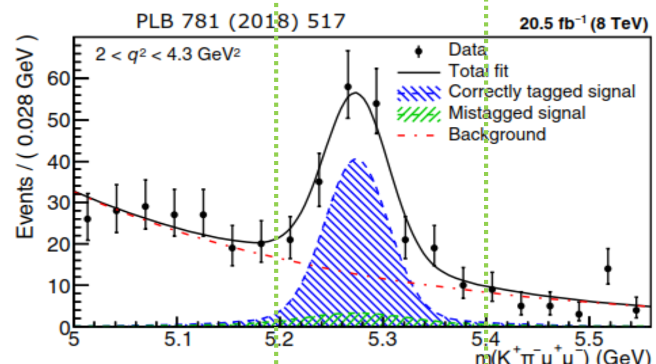
Add a spectator d quark:
**$B^0 \to K^{*0}\mu\mu$**



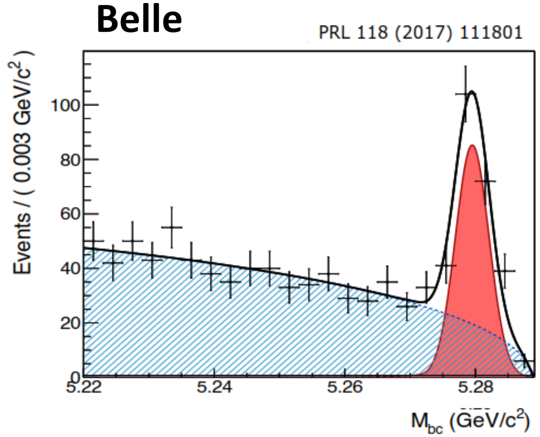

**ATLAS**

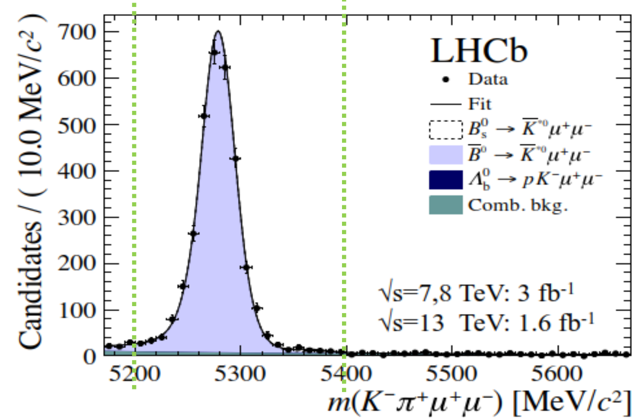



**CMS**




**Belle**



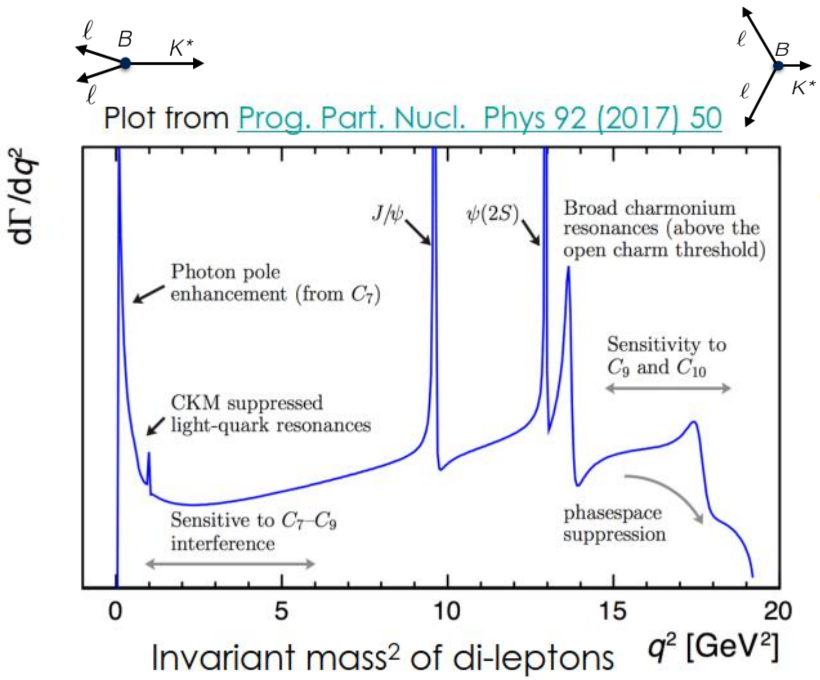




arXiv:1804.07167

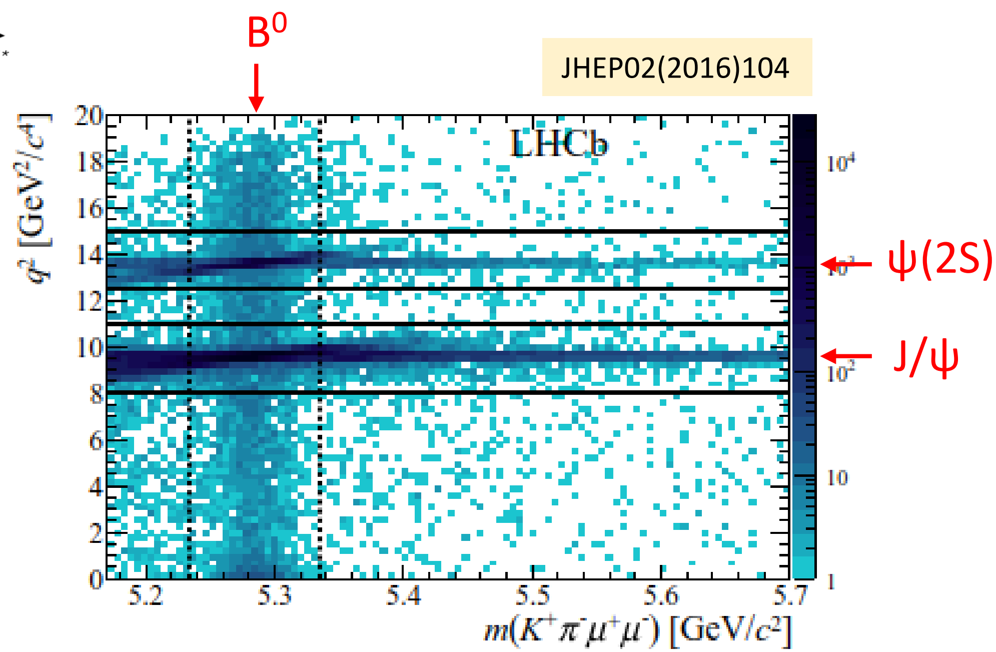
# b → sℓℓ

- b-hadron mass is reconstructed from final hadron decays (e.g. $K^{*0} \to K^- \pi^+$) and two energetic leptons
- Background events suppressed by requiring displaced vertices
- The decay width is expressed in terms of $q^2$ = invariant mass$^2$ of dileptons
- Tree level decays involving J/ψ and ψ(2S) resonances used as control samples and the $q^2$ regions removed from the analyses of b → sℓℓ decays

Plot from Prog. Part. Nucl. Phys 92 (2017) 50

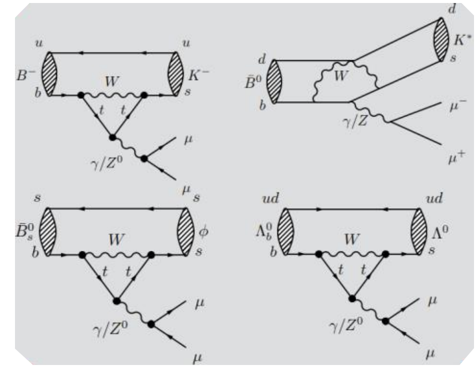



JHEP02(2016)104

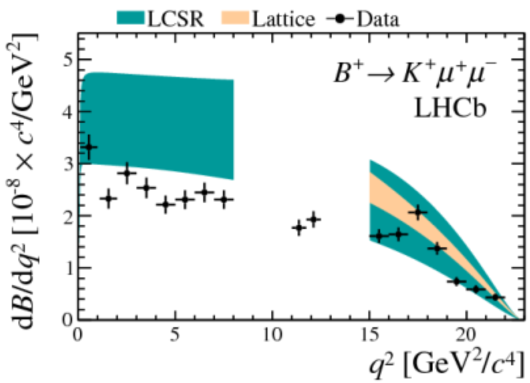


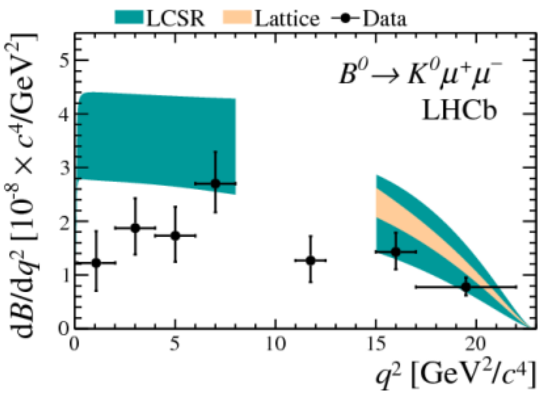
# Decay rates

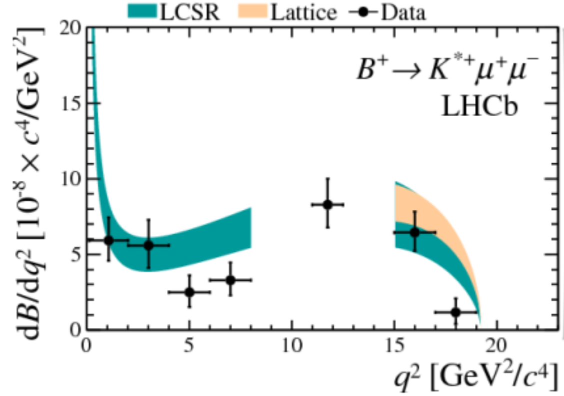
1 (potential anomaly)



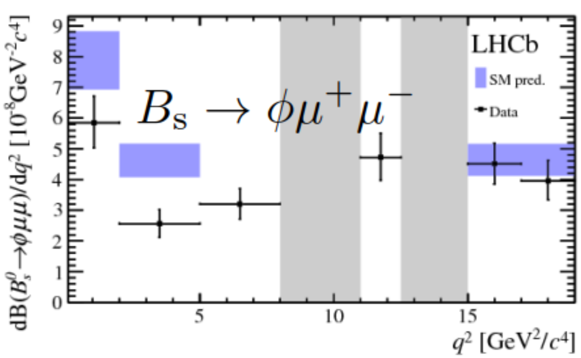
- Study same process with different spectator quark(s)
- In general, data tend to be *lower* than SM predictions
  Hadronic uncertainties limit precision of the predictions

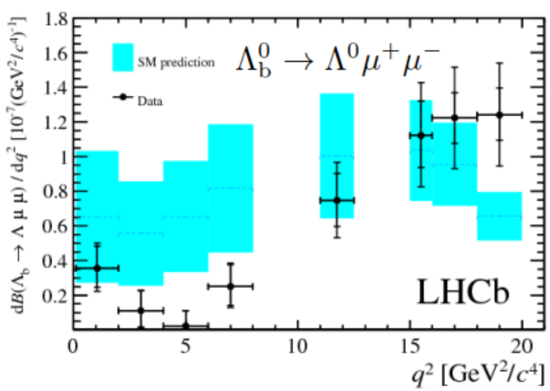


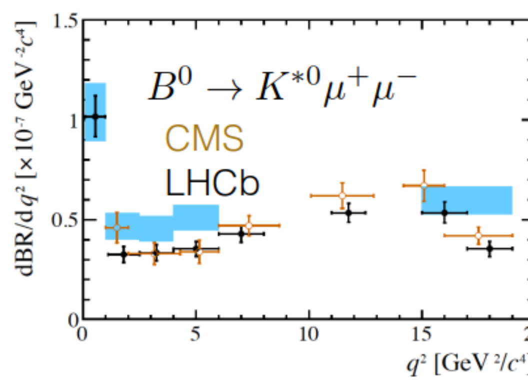




JHEP 06 (2014) 133




JHEP 09 (2015) 179

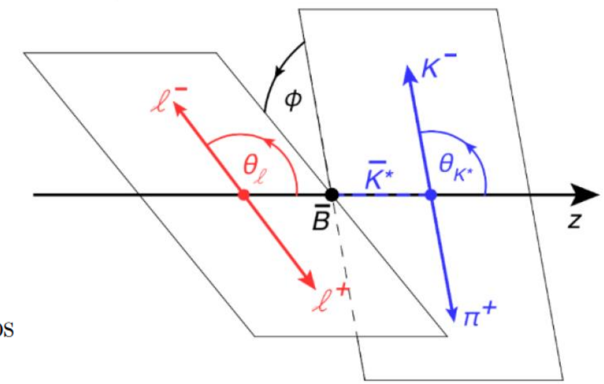
JHEP 06 (2015) 115

LHCb: JHEP 11 (2016) 047, JHEP 04 (2017) 142
CMS: PLB 753 (2016) 424

# b → sμμ angular analysis

- Study the rate as a function of the decay angles: $\theta_K$, $\theta_\ell$, $\phi$
- Complicated expression:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K \cos$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

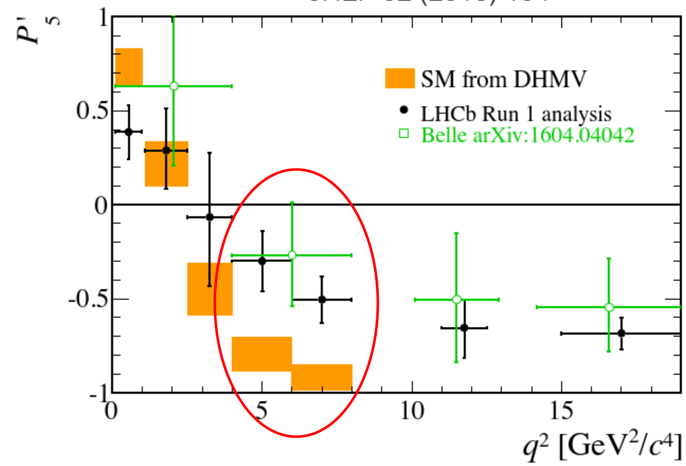



- $F_\mathrm{L}$ = fraction of longitudinal polarization of the K*
- Can define "optimized observables", with form-factor cancellations, e.g:

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Descotes-Genon et al, JHEP 05 (2013) 137

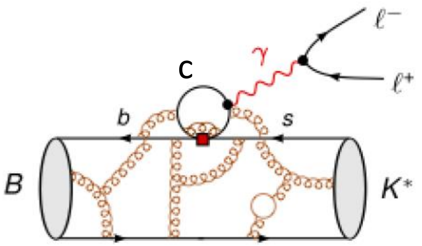
JHEP 02 (2016) 104



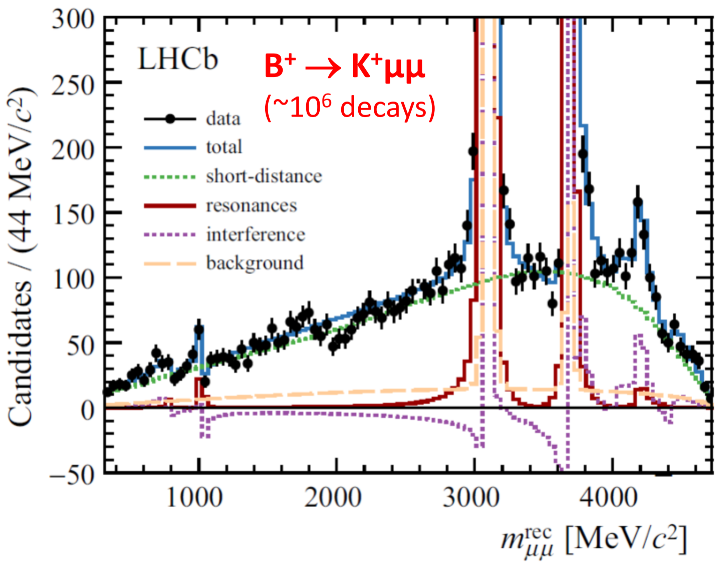

3.4 σ significance, bearing in mind look-elsewhere effect (other bins, other observables)

2

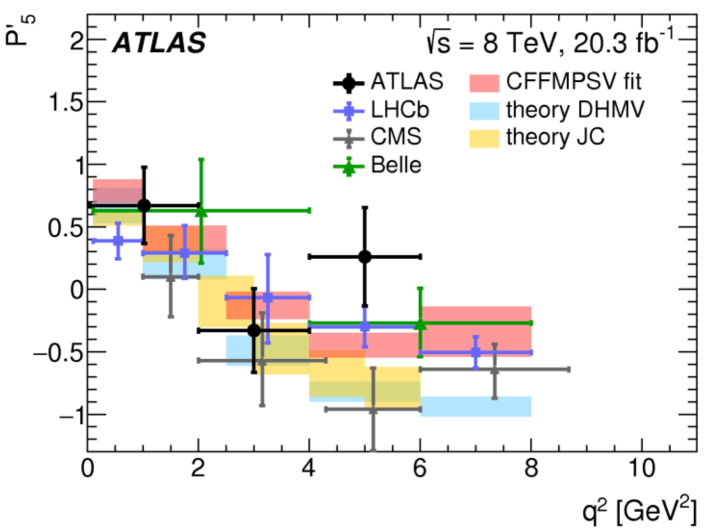
# Theoretical uncertainties




- Discrepancies of rates and angular distributions for $b \to s\ell\ell$ decays comprise the first **flavour anomalies**
- Ongoing debate about the reliability of the theoretical predictions, possible contamination from "charm loops"
- Modelling has been studied in detail using $B^+$ decays, fitting the full $q^2$ range allowing contribution from short- and long-distance effects to be constrained
- Including latest results and alternative calculations, anomaly is less striking



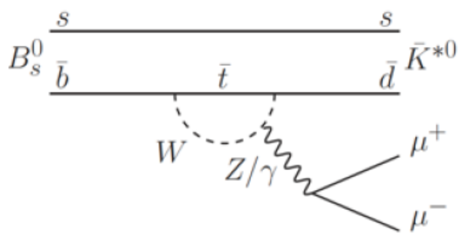

EPJ C77 (2017) 161




arXiv:1805.04000

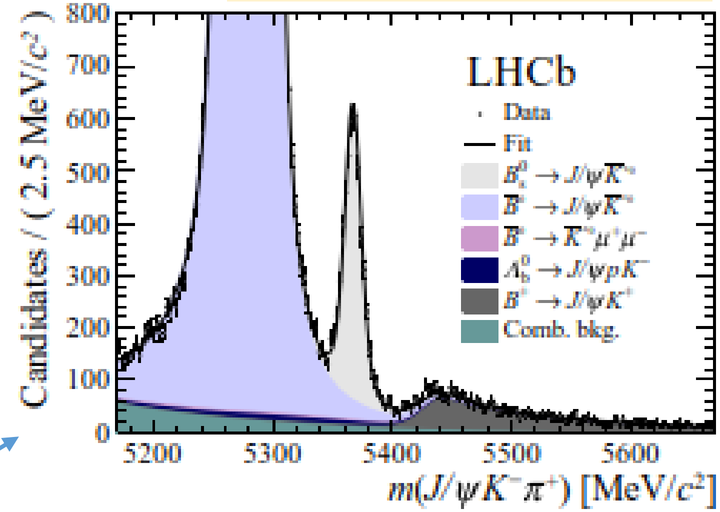
# $B_s \to K^{*0}\mu^+\mu^-$

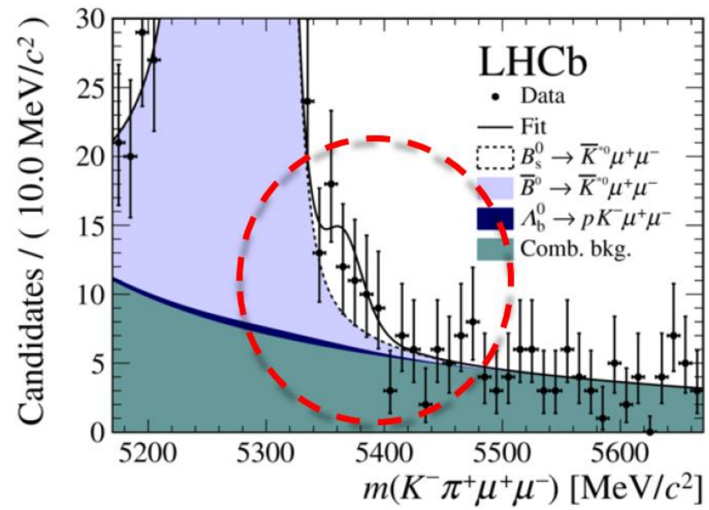
- **$B_s$** counterpart of the $B^0 \to K^{*0}\,\mu\mu$ decay




- Heavily suppressed **$b \to d\ell\ell$** transition
  SM prediction for BR $O(10^{-8})$ due to $|V_{td}|/|V_{ts}|$
- Normalize to decays with $m(\mu\mu)$ at J/ψ then search in regions of $q^2$ away from J/ψ and other resonances
- First evidence seen: 38±12 signal events (3.4σ significance) BR consistent with SM
- Sets ground work for detailed analysis of this channel in the LHCb upgrade

arXiv:1804.07167 Run1+2, 4.6 fb$^{-1}$



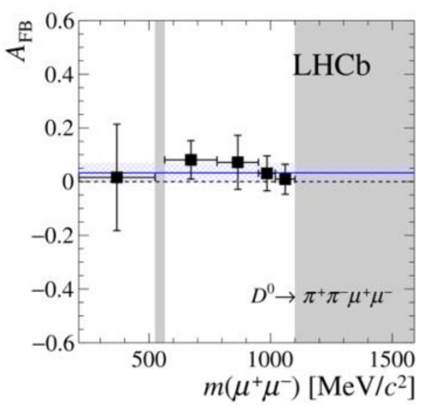
# Rare charm decays

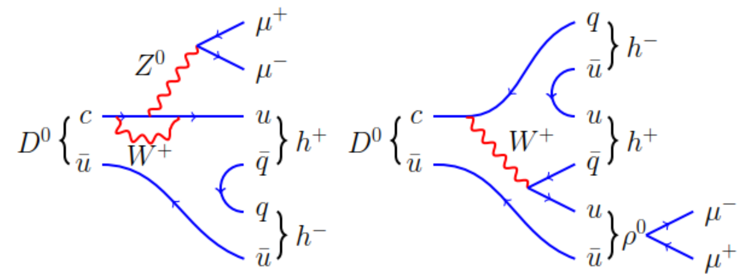
- Unique laboratory to probe FCNCs in the **up-type quark** sector
- Rare charm decays sensitive to new physics contributions, but need to separate *short-* and *long-distance* contributions
- $D^0 \to h^+h^-\mu^+\mu^-$ rarest charm decays ever seen:

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7},$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}.$$

- Now studying asymmetries, none significant seen so far:

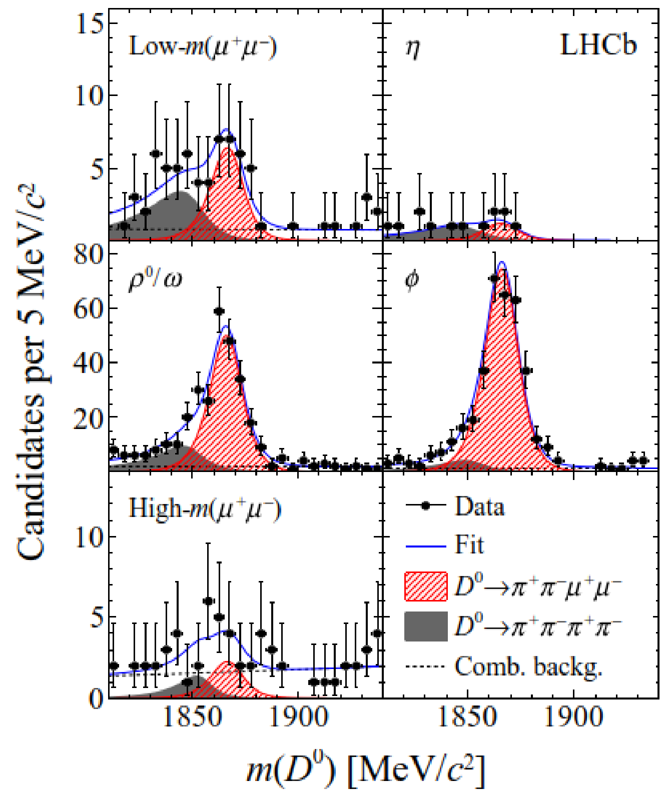
arXiv:1806.10793
Run1+2, 5 fb$^{-1}$



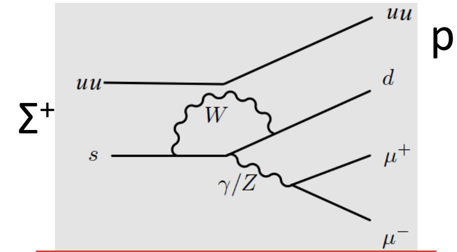




“short-distance” “long-distance”

PRL 119 (2017) 181805



# Rare hyperon decays

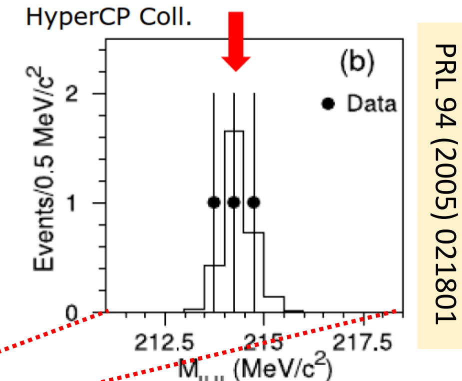


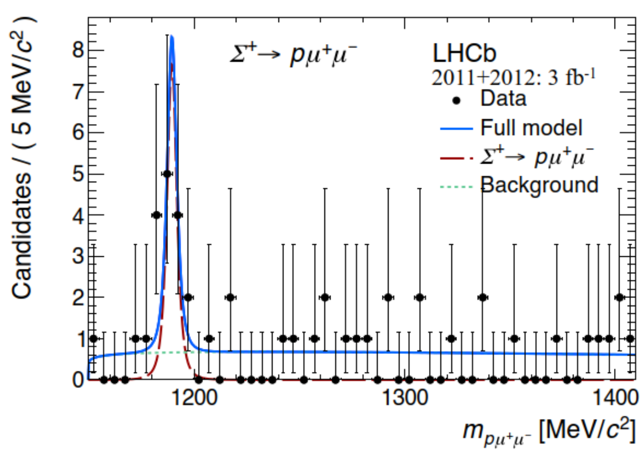

$\Sigma^+ \to pX(\to \mu^+\mu^-)$ ?

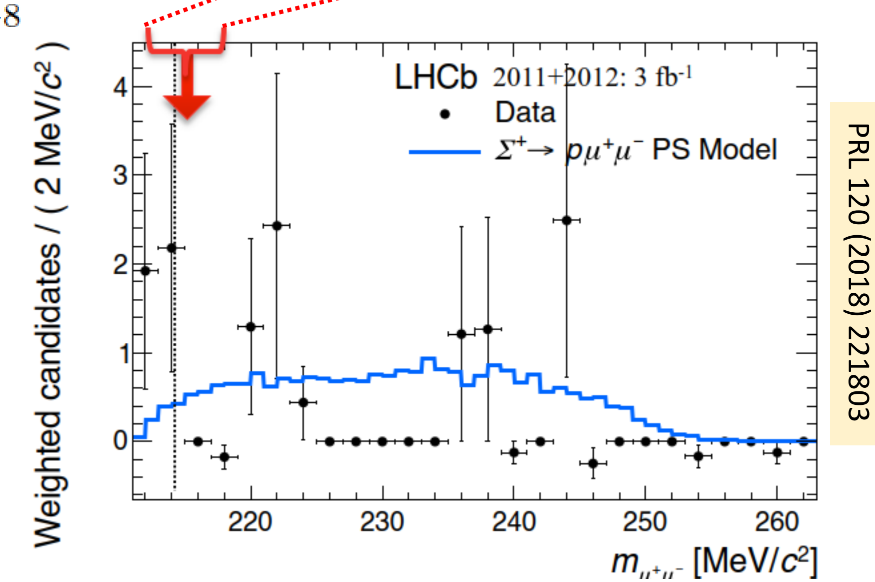
- LHCb can also contribute in the **strange quark** sector such as hyperons (baryons carrying s-quark)
- Interest since HyperCP (E871) saw 3 events in the $\Sigma^+ \to p\mu\mu$ channel that clustered in $m_{\mu\mu}$
- LHCb sees evidence for the decay with 4.1 σ significance, but no evidence for clustering in $m_{\mu\mu}$

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2\,^{+1.8}_{-1.3}) \times 10^{-8}$$

$$\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}$$



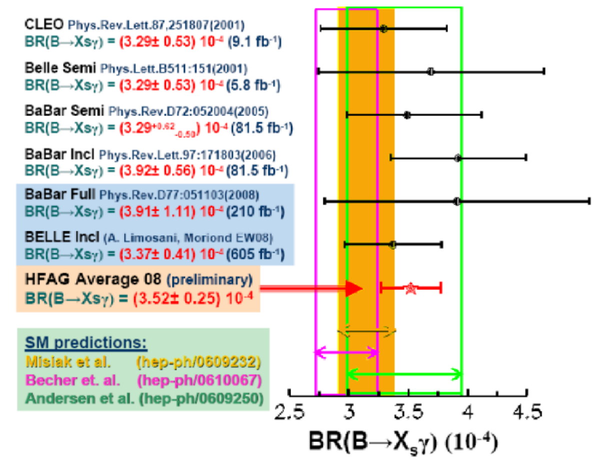



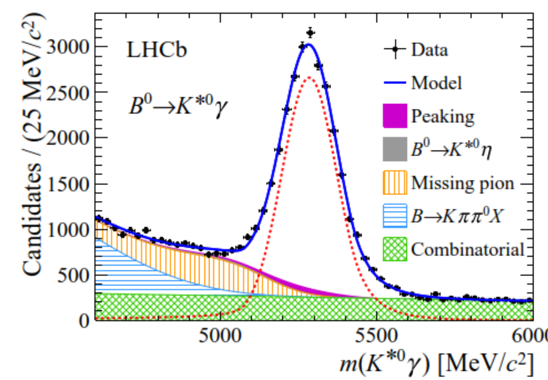



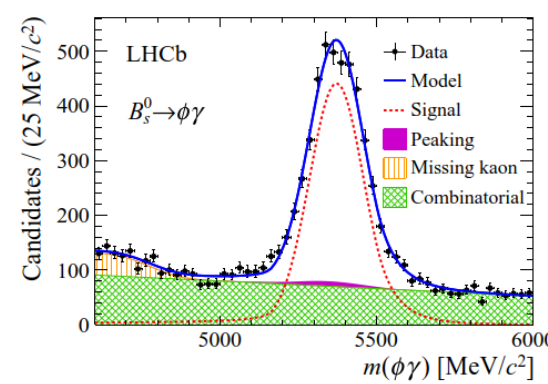
# ③ Radiative decays

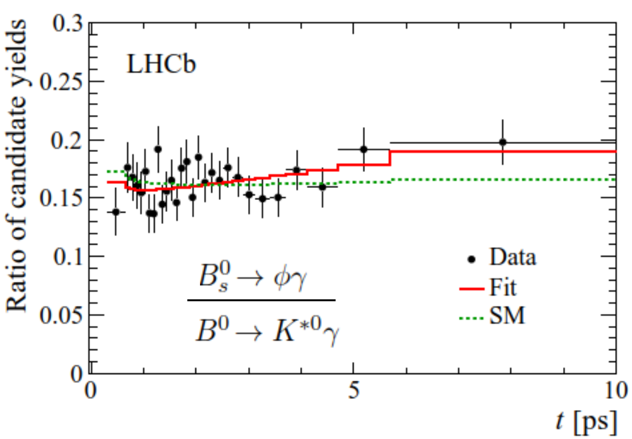
- Radiative decays ($\mathbf{b \to s\gamma}$) measured by B factory experiments BaBar and Belle, in agreement with Standard Model expectation
- LHCb has made first measurement of photon polarization in radiative $\mathbf{B_s}$ decays (dominantly left-handed in SM)
- Time-dependent analysis of ratio of $B_s \to \phi\gamma$ and $B^0 \to K^*\gamma$ to measure parameter $A^\Delta$ (related to ratio of right- and left-handed polarizations)

$$\mathcal{A}^\Delta = \sin(2\psi), \text{ where } \tan\psi \equiv |A(\overline{B}{}^0_s \to \phi\gamma_R)|/|A(\overline{B}{}^0_s \to \phi\gamma_L)|$$




$$\mathcal{A}^\Delta_{SM} = 0.047^{+0.029}_{-0.025}$$

**Result:**

$$\mathcal{A}^\Delta = -0.98\ ^{+0.46}_{-0.52}\ ^{+0.23}_{-0.20}$$

Consistent with SM value within 2σ

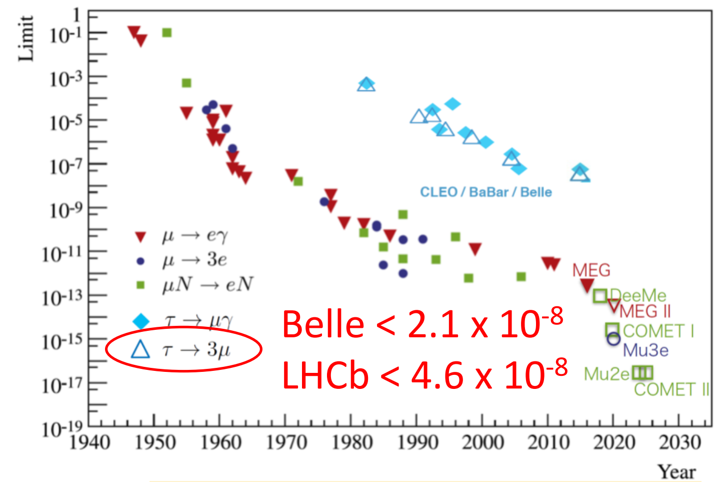
Phys. Rev. Lett. 118, 021801 (2017)

PLB 687 (2010) 139
JHEP 02 (2015) 121

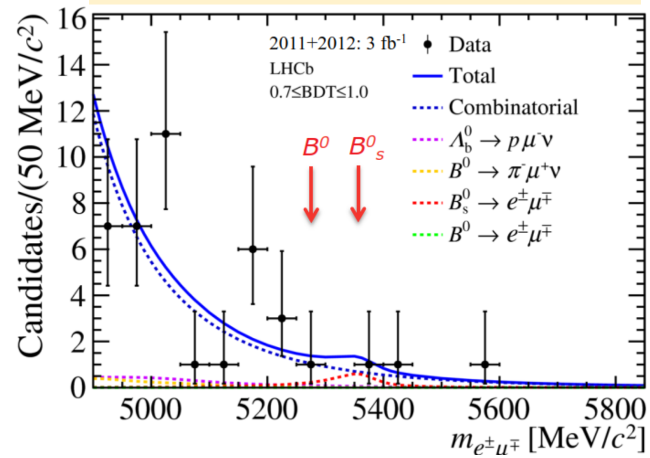
# 3. Flavour Anomalies

- Other anomalies seen concern hints for **Lepton Flavour non-Universality**
- Distinction between Lepton Flavour Violation (**LFV**) and Universality (**LFU**)
  - In the SM Charged LFV is forbidden (and has not yet been seen)
    e.g. $\tau \to 3\mu$, or $B \to e\mu$
  - On other hand, LFU is *assumed* in SM: Gauge couplings are equal for the 3 generations, which are distinguished only by their different mass

Charged LFV

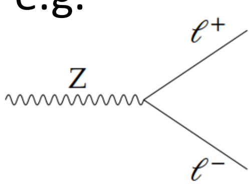



JHEP 03 (2018) 078, arXiv:1710.04111




$$B\left(B_s^0 \to e^+\mu^-\right) < 6.0\times10^{-9}\,(90\%\ \text{CL})$$
$$B\left(B^0 \to e^+\mu^-\right) < 1.0\times10^{-9}\,(90\%\ \text{CL})$$

e.g.




PDG

| Z DECAY MODES | Fraction (Γi/Γ) |
|---|---|
| $e^+e^-$ | (3.3632±0.0042 )% |
| $\mu^+\mu^-$ | (3.3662±0.0066)% |
| $\tau^+\tau^-$ | (3.3696±0.0083 )% |

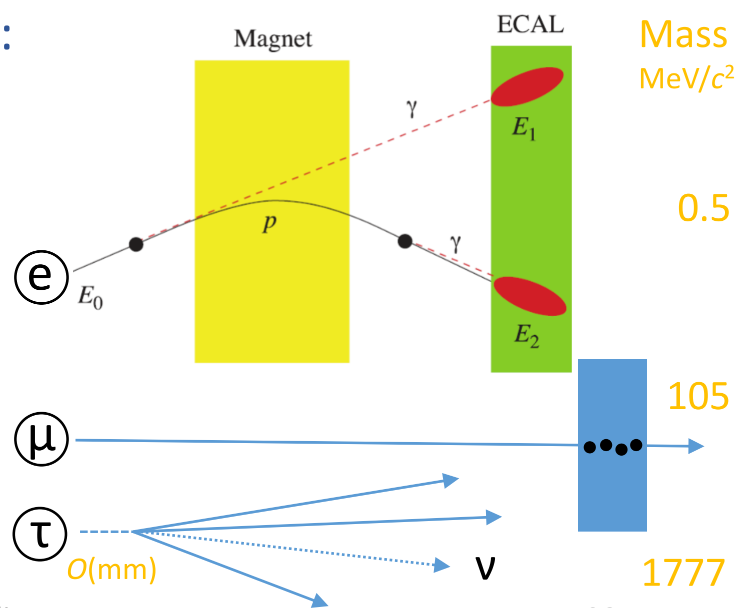
- Testing LFU probes the validity of SM

# Testing LFU in rare decays

- Compare rates of b → sμμ and b → see processes, e.g:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$ = 1.000 + O($m_\mu^2/m_b^2$) (SM)

- First example of a family of ratios $\boldsymbol{R_h}$ between hadronic b decays b → $h\ell X$ to final states which differ just by lepton flavour
  Ratios labelled using the hadron *h* in the final state as a subscript
- Precise theory prediction due to cancellation of hadronic uncertainties
- On other hand, experimental effects are tricky: particle ID performance far from universal, triggering and reconstruction of muons is much easier than electrons (or τ) in LHCb
- Mass resolution affected by electron bremsstrahlung → need to recover energy using clusters in the calorimeter
- Trigger thresholds higher for e than μ → also use signal triggered by rest of event

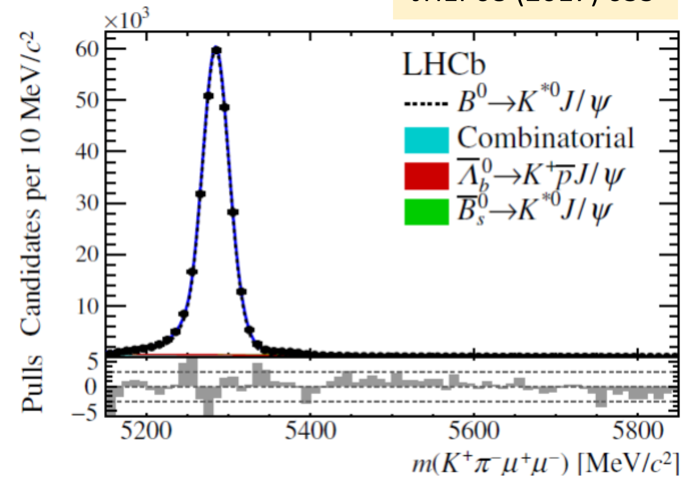


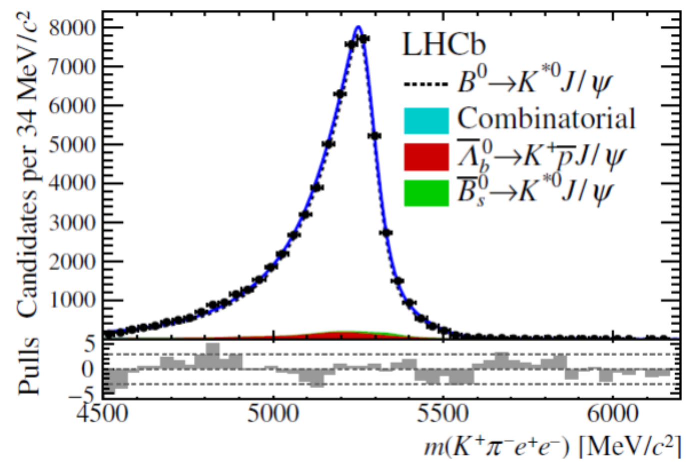
# $R_{K^*}$

- Illustrate analysis for neutral mode **$B^0 \to K^*\ell\ell$**
- Experimentally, use $B^0 \to K^* J/\psi\ (\to \mu^+\mu^-)$ and $B^0 \to K^* J/\psi\ (\to e^+e^-)$ to perform a *double ratio* to help cancel systematics

$$R_{K^{*0}} = \frac{\dfrac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}}{\dfrac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}}$$

JHEP08 (2017) 055




- e.g. lower efficiency for electron mode would cancel in the double ratio
- Computed in two bins of $q^2$:

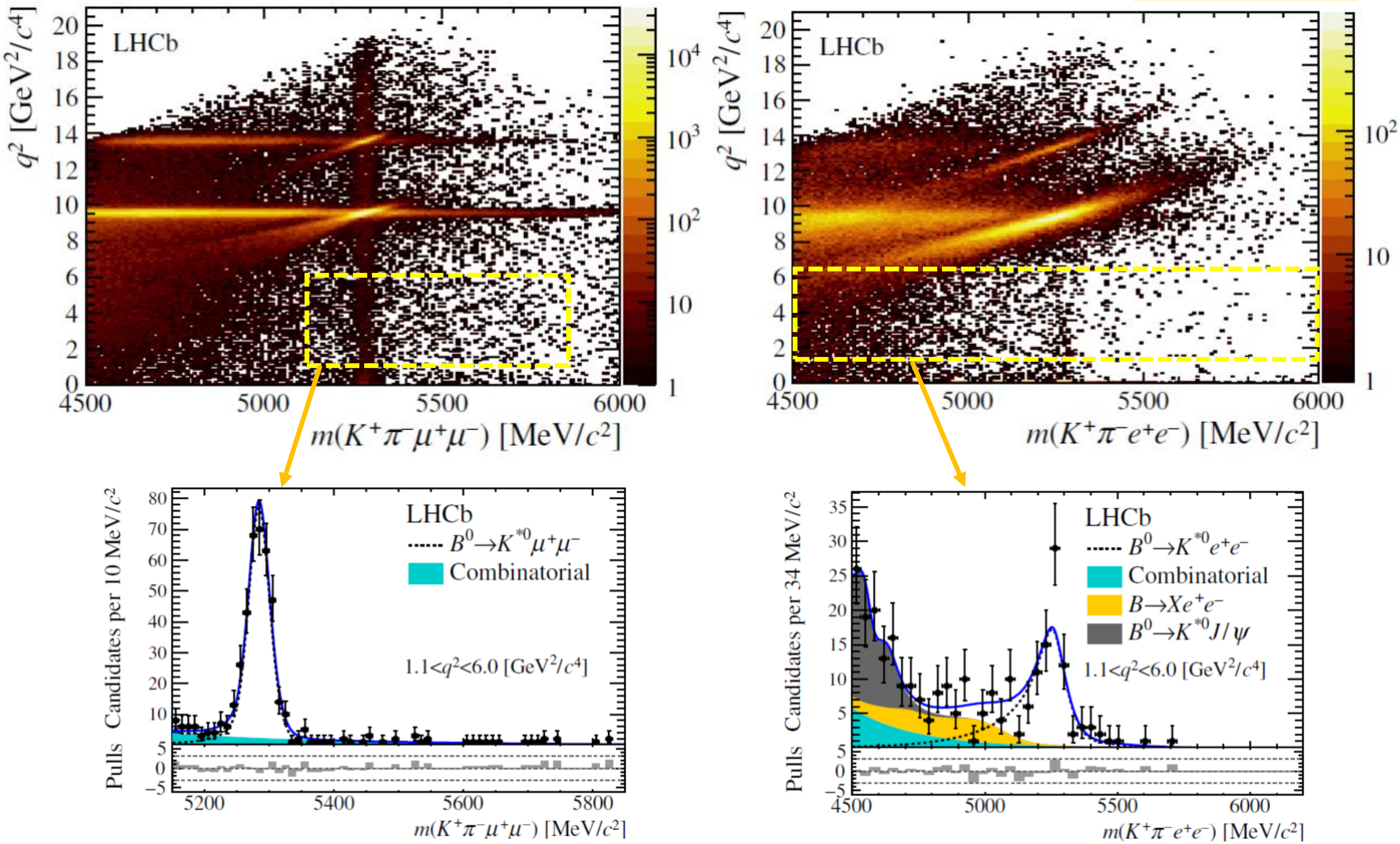
  [0.045, 1.1] GeV$^2$ avoiding photon pole
  [1.1, 6.0] GeV$^2$ avoiding radiative tail

- Many checks made, e.g.
  $B(B \to K^* J/\psi_{\mu\mu})/B(B \to K^* J/\psi_{ee}) = 1.04 \pm 0.05$

# $R_{K^*}$

$K^{*0}\ \mu\mu$ | $K^{*0}\ ee$

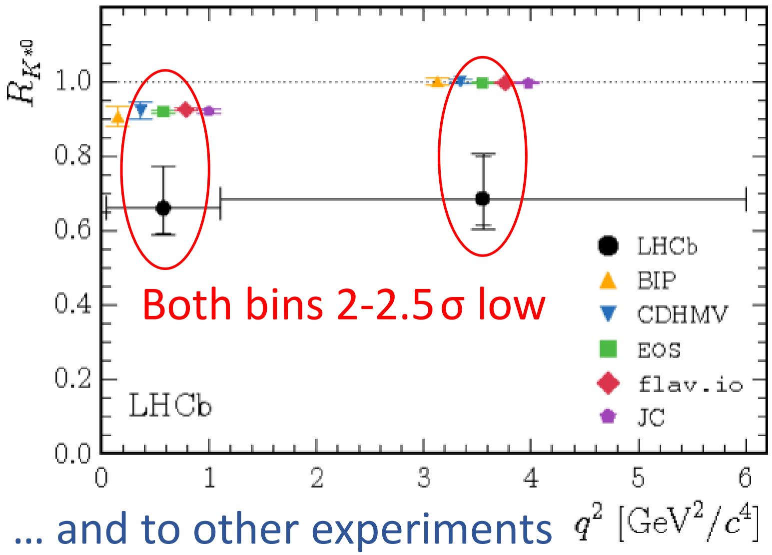
JHEP08 (2017) 055



# Results

Compared to SM…

▲ BIP [EPJC 76 (2016) 440]
▼ CDHMV [JHEP 04 (2017) 016]
■ EOS [PRD 95 (2017) 035029]
◆ flav.io [EPJC 77 (2017) 377]
⬟ JC [PRD 93 (2016) 014028]
■ BaBar [PRD 86 (2012) 032012]
▲ Belle [PRL 103 (2009) 171801]



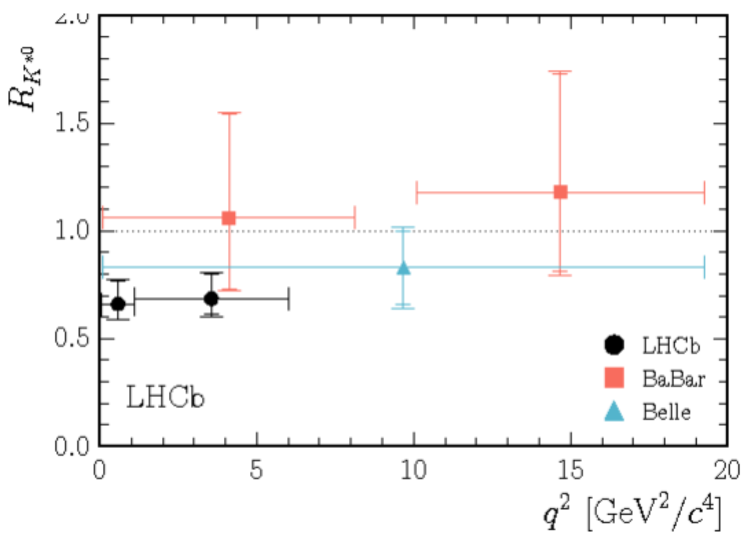

Central $q^2$: [1.1-6 GeV$^2$]: SM = 1.000(6)

$$R_{K^{*0}} = 0.69 \, {}^{+\,0.11}_{-\,0.07} \, (\text{stat}) \pm 0.05 \, (\text{syst})$$

Low $q^2$ [0.045-1.1 GeV$^2$]: SM = 0.922(22)

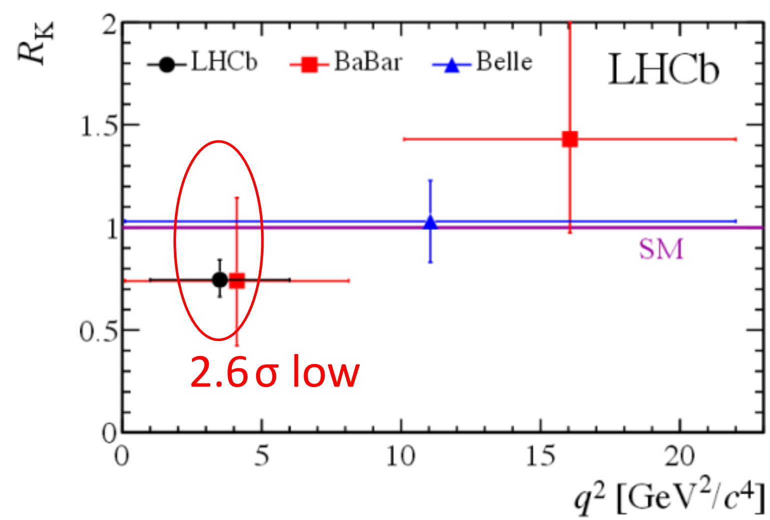
$$R_{K^{*0}} = 0.66 \, {}^{+\,0.11}_{-\,0.07} \, (\text{stat}) \pm 0.03 \, (\text{syst})$$

… and to other experiments




**Charged mode: $B^+ \to K^+ \ell\ell$**

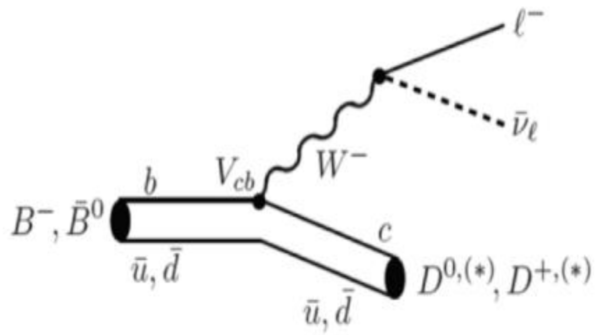
$$R_K = 0.745^{+0.090}_{-0.074} \, (\text{stat}) \pm 0.036 \, (\text{syst})$$




PRL 113 (2014) 151601

# Tree-level anomaly?

- Hints for deviation from the SM also seen in




$$R_{D^*} \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} \overset{\text{SM}}{=} 0.252 \pm 0.003$$

PRD 85 (2012) 094025

- This is a *tree-level* semileptonic **b → c*ℓν*** decay, far from being rare!

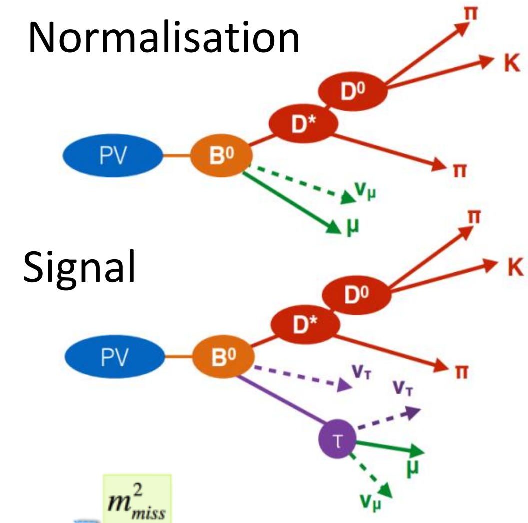
  But not previously studied in detail due to difficulty of tau reconstruction
  SM expectation differs from 1 due to the effect of the tau mass

- Reconstructing decay to tau is difficult because of missing neutrinos from tau decay → no clear peak in invariant mass

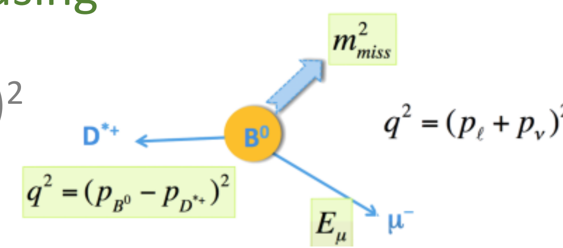
- LHCb has performed two *independent* measurements using
  - Leptonic mode $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$
  - Hadronic mode $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$

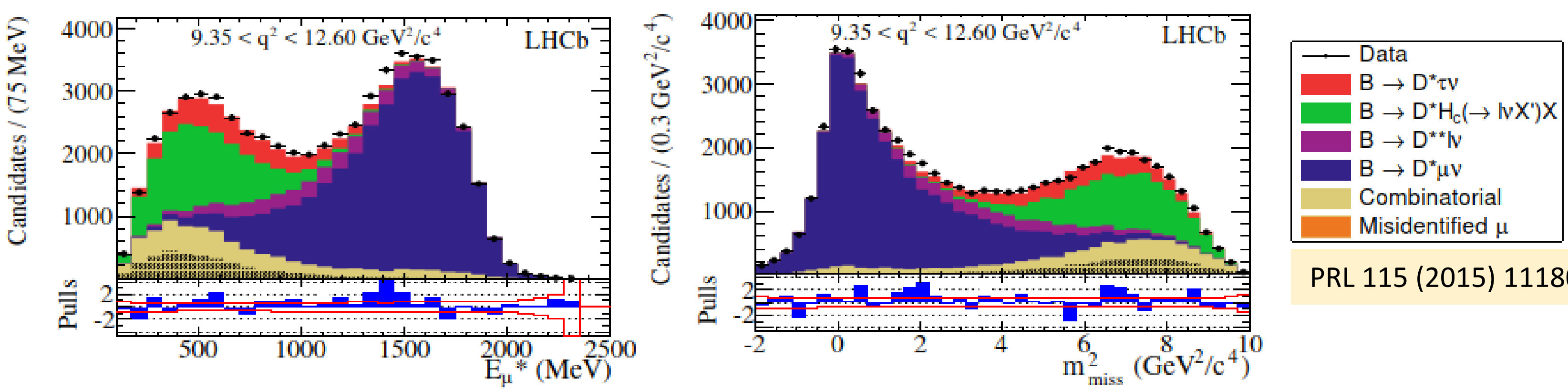
- B flight direction determined using vertexing from vector between primary and secondary vertices

# $R_{D*}$ leptonic mode




- Tau decay reconstructed as $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$
  Signal and normalization channels have same visible final state
- Separate according to kinematic differences from tau mass and additional neutrinos using
  $E_\mu^*$ = muon energy in the B rest frame,
  $m^2_{\text{miss}} = (p_B - p_D - p_\mu)^2$, and $q^2 = (p_B - p_D)^2$
- Yield extracted from 3D template fit



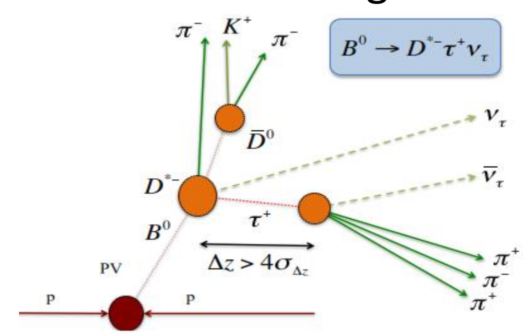

PRL 115 (2015) 111803

$$R_{D^*} = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

2σ above SM prediction

# $R_{D*}$ hadronic mode

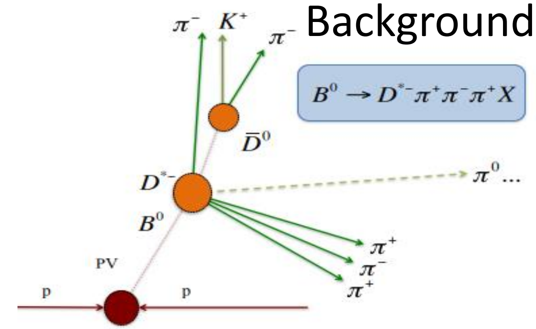
Signal



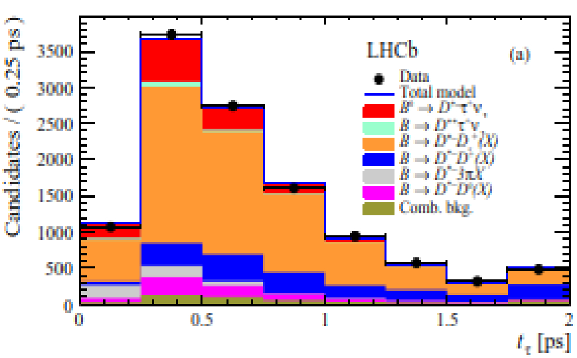

- Use $B^0 \to D^*\, 3\pi$ as a normalization mode
  same visible final state as signal
- Then:

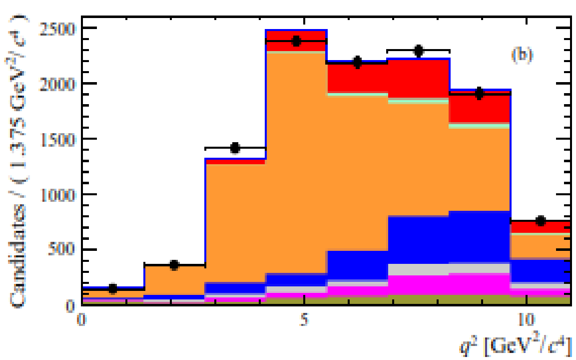
$$R_{D^*} = \underbrace{\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}}_{\textbf{measured ratio } \mathcal{K}(\mathbf{D^{*-}})} \cdot \underbrace{\frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}}_{\textbf{external inputs}}$$

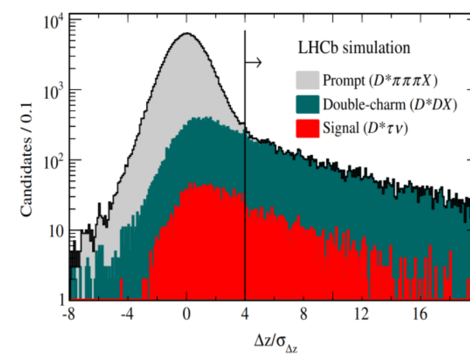
Background




- $B^0 \to D^*\, 3\pi X$ background suppressed with vertex cut:
- Yield extracted from 3D fit to $t_\tau$, $q^2$, BDT (against DD$X$)



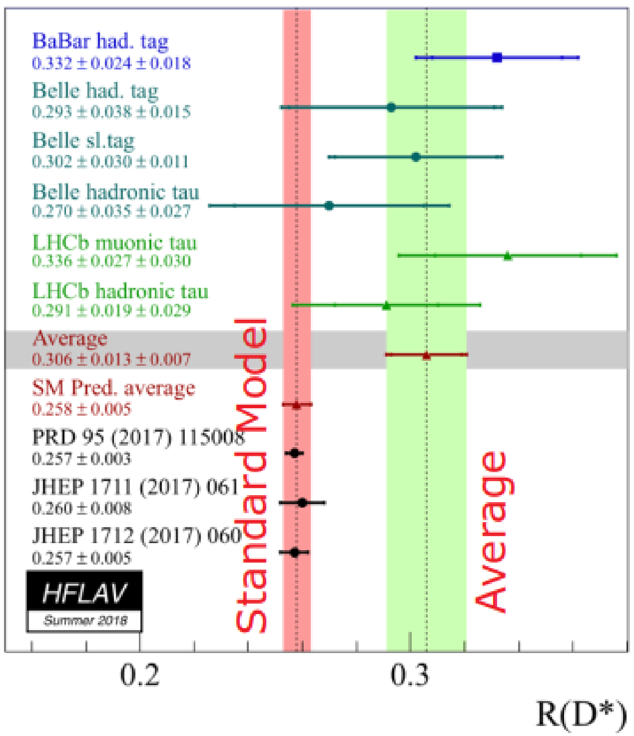

PRD 97 (2018) 072013

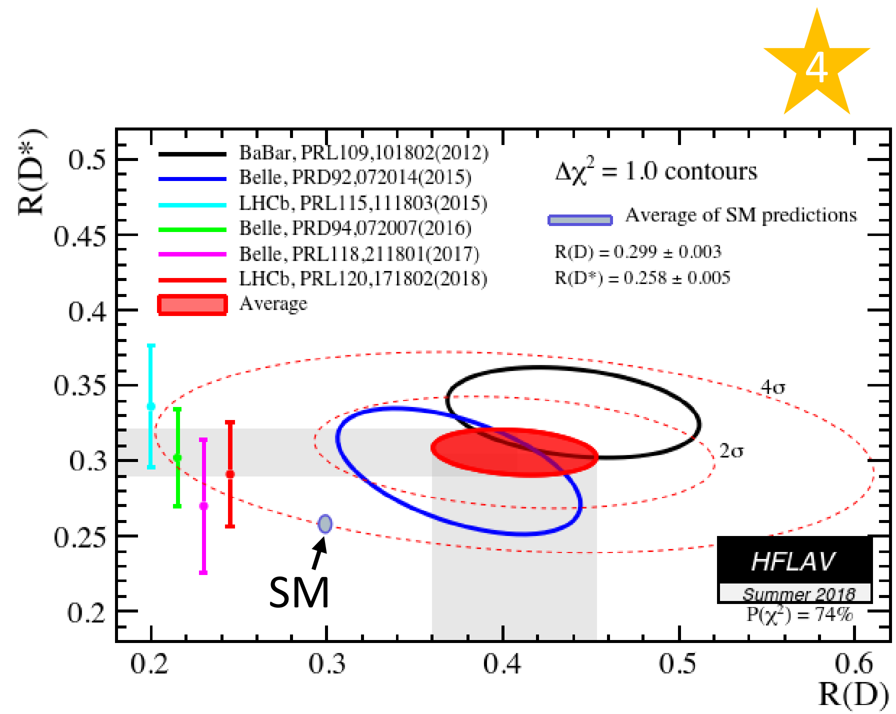
$$R_{D^*} = 0.291 \pm \underbrace{0.019}_{\text{stat}} \pm \underbrace{0.026}_{\text{svs}} \pm \underbrace{0.013}_{\text{ext}}$$

1σ above SM prediction

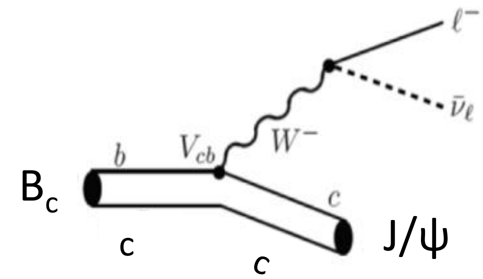
# $R_{D^{(*)}}$ combination

- Measurements all consistent, and all lie above Standard Model prediction
- B Factory experiments also measure equivalent ratio with D rather than D* in the final state, that also tend to be above the Standard Model
- Combined fit gives a discrepancy of 3.8σ significance from SM
  (but note that significance of discrepancy for individual results each < 3σ)



# $R_{J/\psi}$



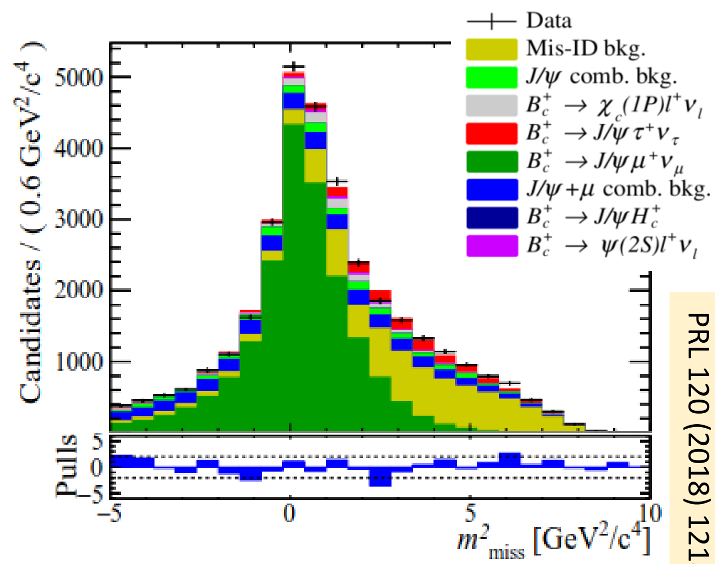

- Similar analysis made for equivalent decay in **B$_c$** sector i.e. with a different spectator quark (c)

$$R_{J/\psi} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} \overset{\text{SM}}{\in} [0.25, 0.28]$$

- Tau reconstructed as $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$
- Identifical visible final states for the two modes: $(\mu^+\mu^-)\,\mu^+$
- Separate according to kinematic differences from tau mass and additional neutrinos, adding also the decay time
- First evidence (3σ) of B$_c$ → J/ψ τν

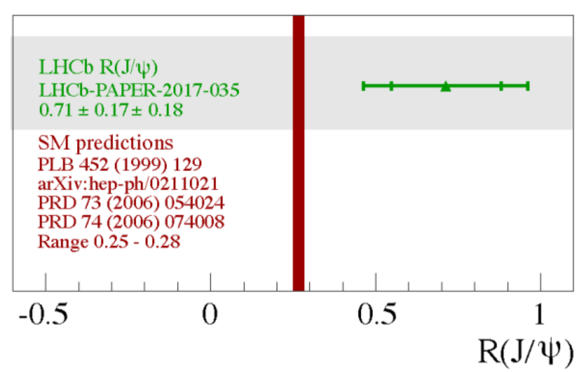
$$R_{J/\psi} = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

- Result lies above SM prediction, but within 2σ




PRL 120 (2018) 121801

5



# Effective Field Theory

See e.g. Buras & Fleischer, hep-ph/9704376

- Effective Field Theory can be used to compare and combine the various hints of non-Standard Model behaviour in b $\to s\ell\ell$ decays
  This is an approximation that is valid below the scale of any New Physics (c.f. Fermi theory of beta decay, valid at low energy compare to $m_W$)
- Amplitude of decay process described by expanding over series of operators:

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|O_i(\mu)|M\rangle$$

Hadronic Matrix Elements

Effective Hamiltonian    CKM couplings    Wilson coefficients (μ = scale)

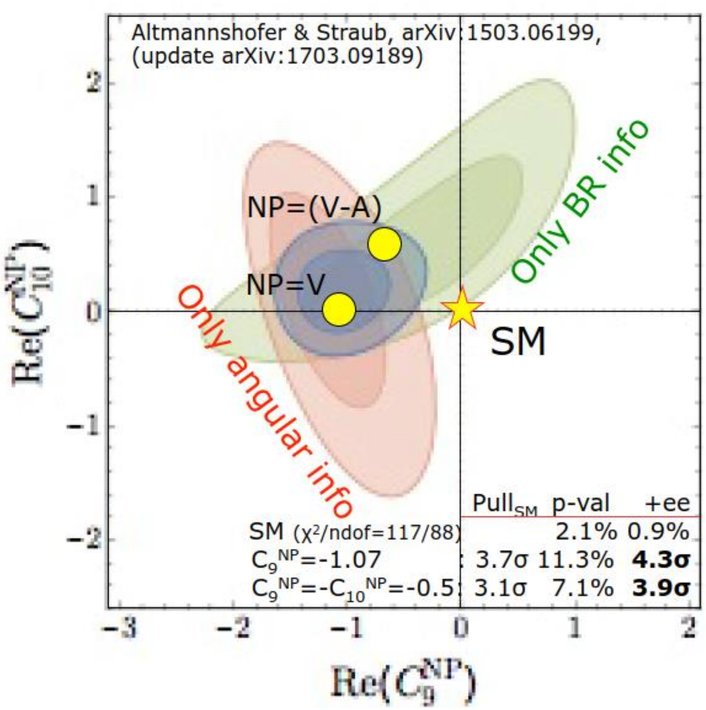
- Operators describe effective vertices:

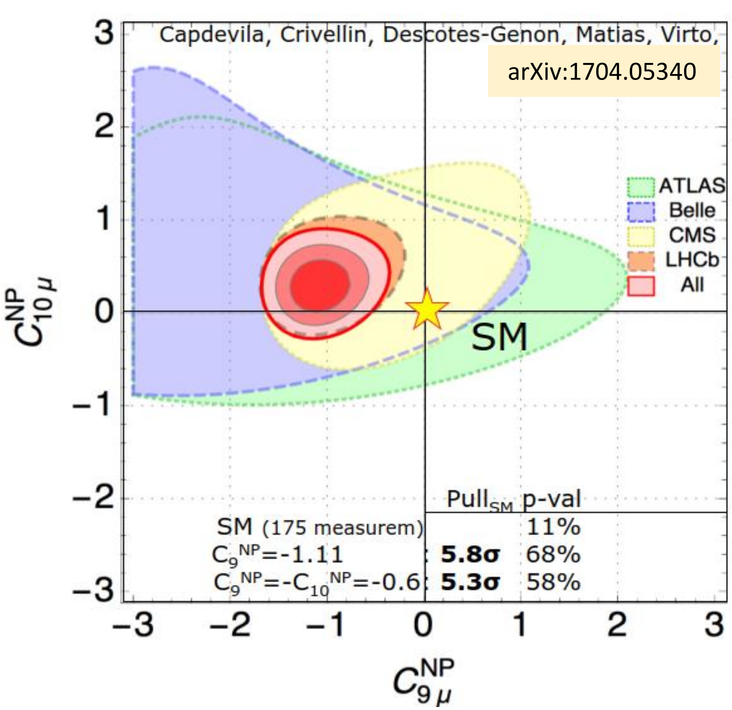

| | *Left-handed* | *Right-handed (suppressed in SM)* |
| --- | --- | --- |
| *Coupling to photon* | $O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$, | $O_7' = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$, |
| *Vector coupling* | $O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$, | $O_9' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$, |
| *Axial coupling* | $O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$, | $O_{10}' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$, |

- SM can be considered as a specific example, with $C_7$ = -0.33, $C_9$ = 4.27, $C_{10}$ = -4.17 (at $\mu = m_b$)—allows to fit for new physics in a model-independent way

# Effective couplings

- High interest because pattern of deviations is consistent with a shift of Wilson coefficients $C_9$ and $C_{10}$, which deviate from SM value by around **5σ**
- All input measurements (175) agree with the simple shift…
- Independent fits made by many groups, favour: $\Delta C_9 = -1$ or $\Delta C_9 = -\Delta C_{10}$



# Possible explanations

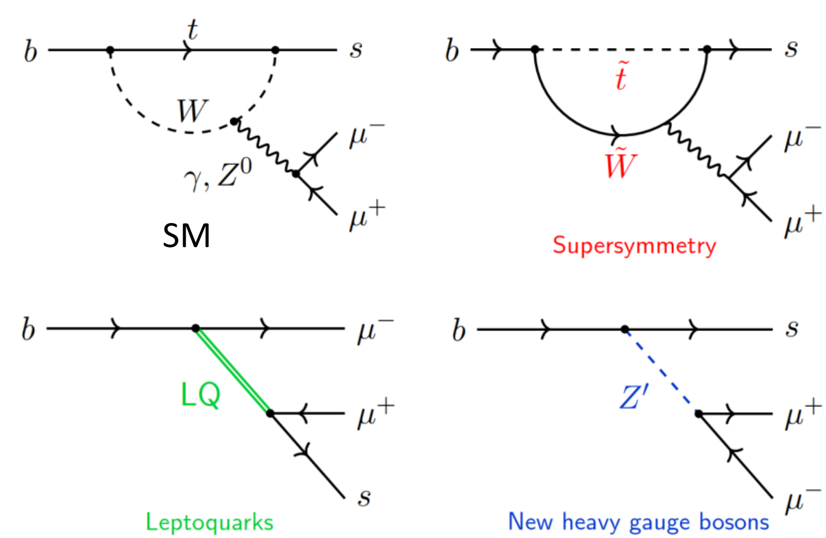
1. **Statistical fluctuations:** unlikely given the number and pattern of effects?
2. **Experimental artefacts:** these are difficult measurements (e and τ)— have the systematic errors been correctly estimated? However, seen by different experiments at LHC and B factories
3. **Theoretical uncertainties:** may effect $P_5'$, but LFU tests should be robust?
4. **Some combination of the above?**
5. **New Physics:** once all the above have been excluded…

Many **models** proposed: leptoquarks, Z'… coupling to 3rd generation preferentially?

See for example: *B-physics anomalies: a guide to combined explanations*

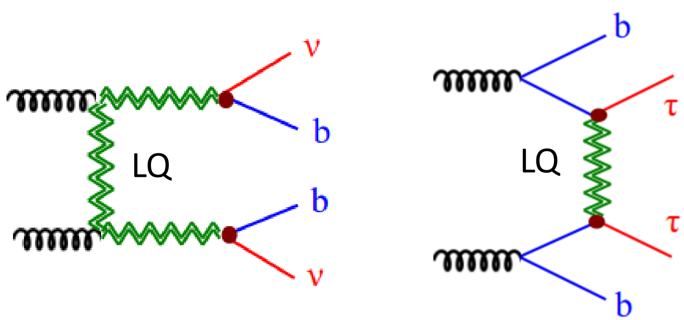
D. Buttazzo et al., JHEP 1711 (2017) 044, arXiv:1706.07808

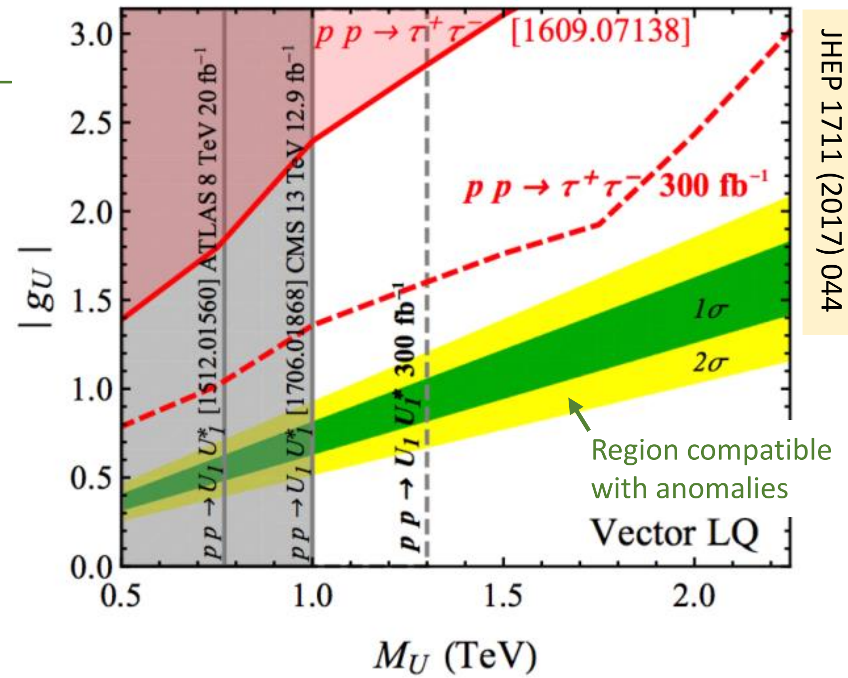
"The case of an $SU(2)_L$-singlet vector leptoquark emerges as a particularly simple and successful framework"



# Interplay with direct searches

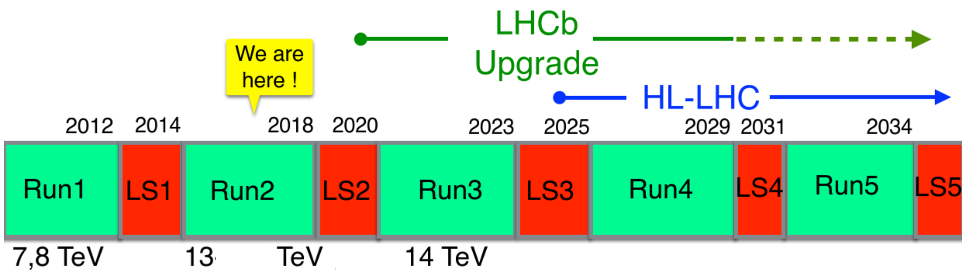
- If the lepton flavour anomalies *are* due to the exchange of a new particle, then it should be possible to detect it in direct searches at high $p_T$
- No such signs seen yet
- **Example:** searches for LQ pairs and $\tau^+\tau^-$ at ATLAS and CMS




- May require high luminosity (HL-LHC) to be seen, if it is there…
- "It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]
  - Further experimental input is now required to clarify the situation

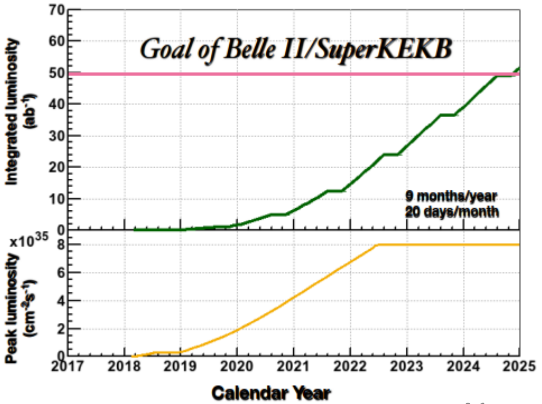
# Outlook




- Most LHCb results presented are from Run1 data
- Updates from Run2 "soon"
  Effects are (surprisingly?) large $O$(20%) so should be straightforward to verify
- The experiment will be upgraded during the next LHC shutdown (LS2) to 40 MHz readout, a fully software trigger and 5× higher luminosity

| | LHC Run | Period of data taking | Maximum $\mathcal{L}$ [$\mathrm{cm^{-2}s^{-1}}$] | Cumulative $\int \mathcal{L}\,dt$ [$\mathrm{fb^{-1}}$] |
|---|---|---|---|---|
| Current detector | 1 & 2 | 2010–2012, 2015–2018 | $4 \times 10^{32}$ | 8 |
| Phase-I Upgrade | 3 & 4 | 2021–2023, 2026–2029 | $2 \times 10^{33}$ | 50 |
| Phase-II Upgrade | 5 → | 2031–2033, 2035 → | $2 \times 10^{34}$ | 300 |

- Further upgrade of LHCb proposed for the HL-LHC era, to handle 10× more luminosity
- Looking forward to competition from **Belle II**: Super B factory has complementary strengths for neutral modes, full event reconstruction, etc.



# Conclusions

- **The LHCb experiment** is dedicated to flavour physics at the LHC
  - Running successfully, many world-best results (444 papers to date)
- **Rare Decays** can be studied with unprecedented precision using the enormous statistics available of beauty and charm decays
  - First observation of $B_s \to \mu^+\mu^-$ in a single experiment
  - Detailed analysis of $b \to s\ell\ell$ decays
- **Flavour Anomalies:** interesting hints of non-Standard Model behaviour seen when combining results from different experiments and channels
  - Mostly concern Lepton Flavour non-Universality in b decays
  - Before claiming new physics, want clear observation in single experiment
  - More data already available, but the measurements are complicated…
- **Longer term:** Belle II start up + LHCb has comprehensive upgrade programme
  
  → can expect definitive answers in the coming years
  - It is an exciting time for flavour physics!