Anomalies in B decays

谢跃红（华中师范大学）

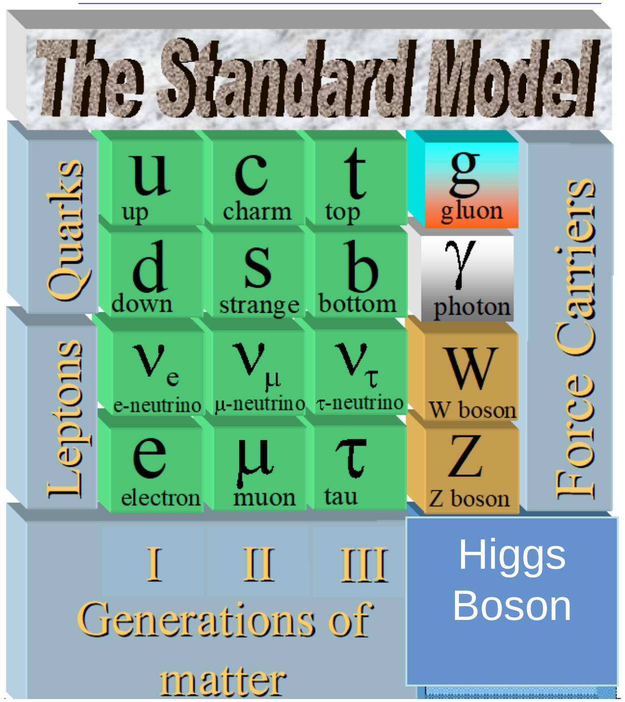
- Introduction
- Anomalies
  - ✓ $b \to cl\bar{\nu}$: lepton universality test
  - ✓ $b \to sl^+l^-$: lepton universality test & angular analysis
- Summary and outlook

华南师范大学，2018年11月12日

Introduction

Standard Model of particle physics

- **Successful but many things unexplained**
  - **Gravity**
  - **Dark matter, dark energy**
  - **Smallness of Higgs mass**
  - **Neutrino mass**
  - **Matter-antimatter imbalance**
  - **Why three generations**



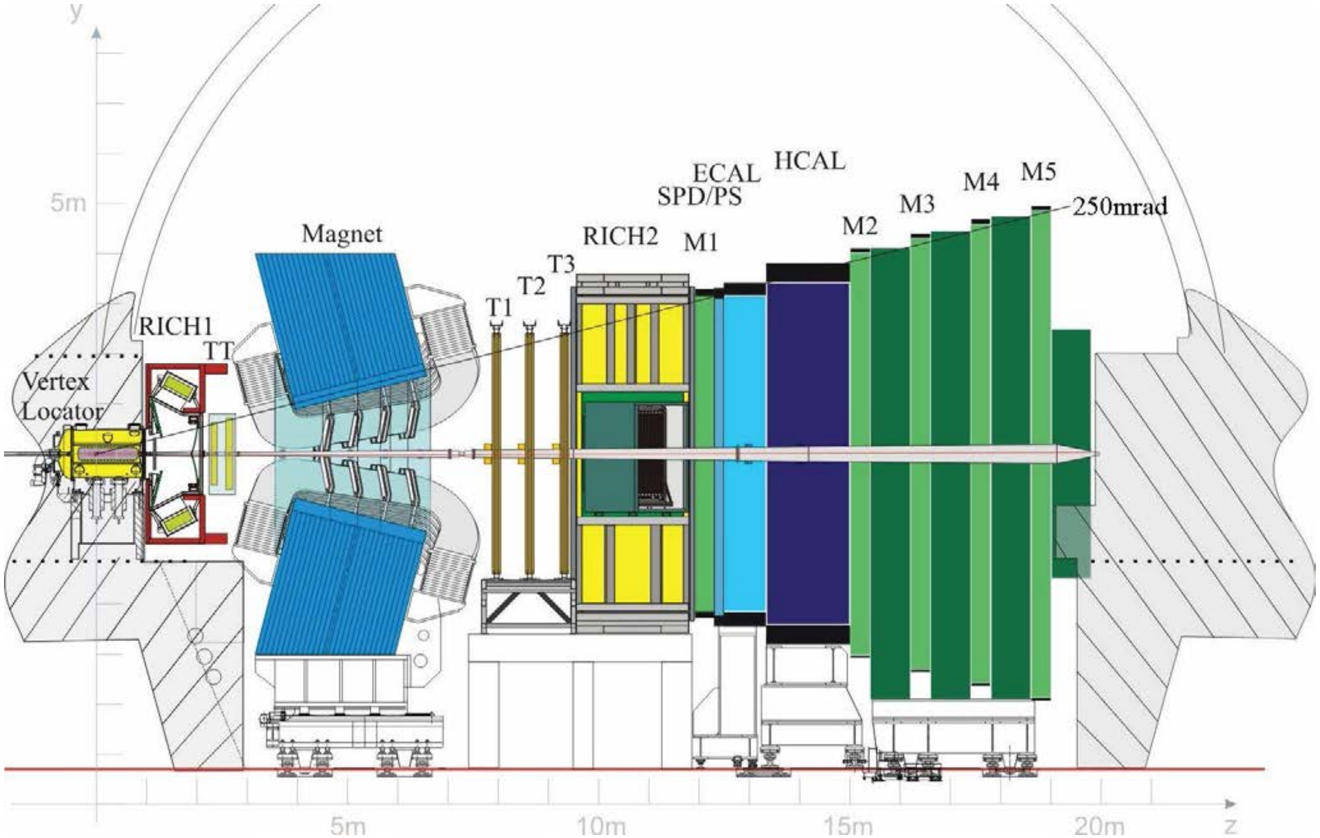
- **Hunting for new physics beyond the SM at the LHC**
  - **Direct search at energy frontier (ATLAS, CMS)**
  - **Indirect search in flavor physics (LHCb)**

LHCb Collaboration

1263 members, 77 institutes, 17 countries

中国: 清华大学，华中师大，国科大，武汉大学，高能所，华南师大

LHCb experiement



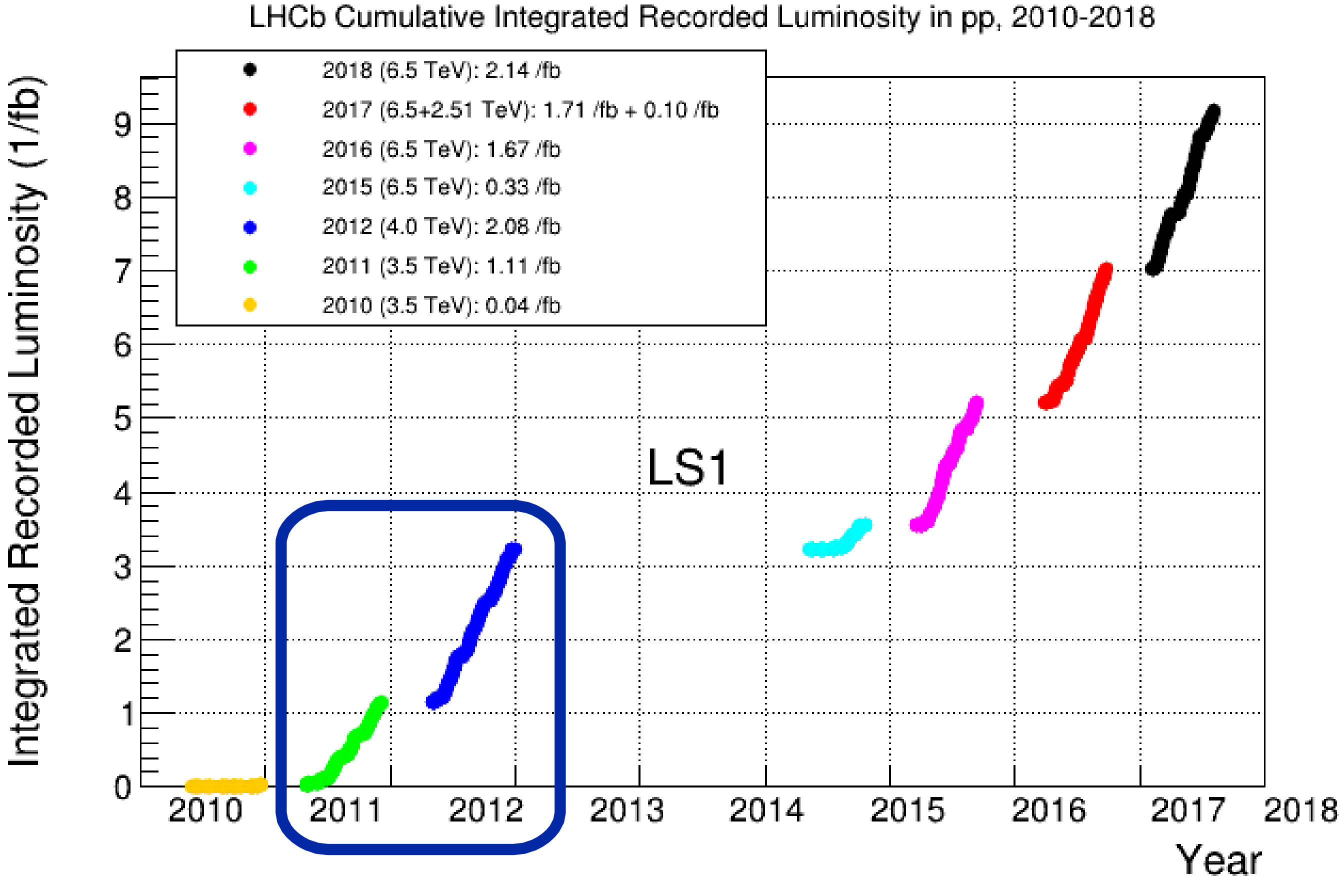
Design for flavor physics

- Charge-parity violation
- Rare B, D and K decays
- Lepton universality test
- Hadron spectroscopy

Already a general purpose detector in forward region

- Electroweak physics
- Heavy ion collisions

LHCb running (pp collisions)



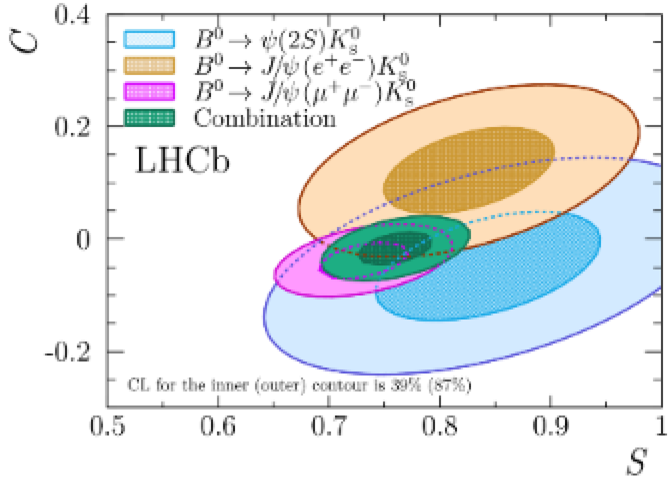
- **9 fb^{-1} accumulated after Run-2**
- **Results presented here based on Run-I data:**

1 fb^{-1} at 7 TeV + 2 fb^{-1} at 8 TeV

LHCb highlights

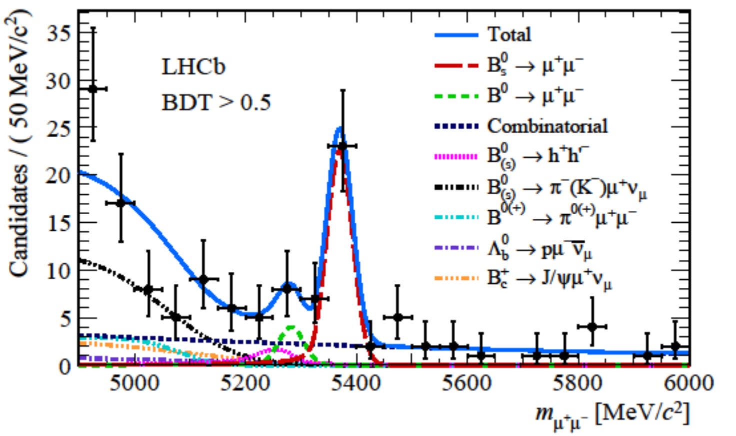
CP破坏关键参数ϕ_s的精确测量

PRL 114 (2015) 041801



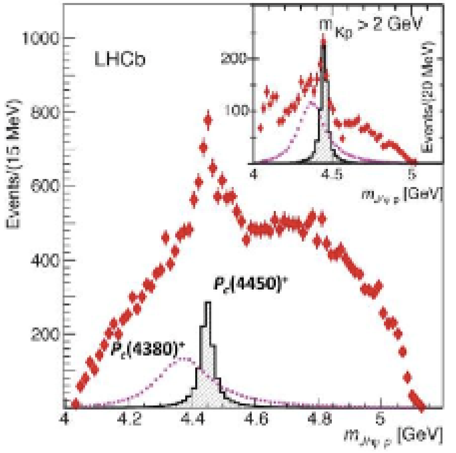
观察到极稀有衰变 $B_s \to \mu^+\mu^-$

PRL118 (2017) 191801



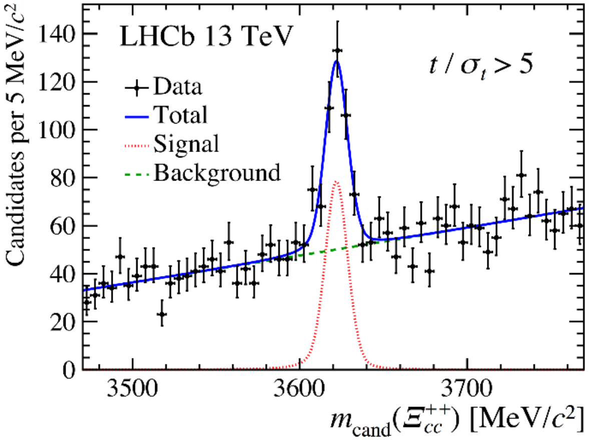
五夸克态的发现

PRL 115 (2015) 072001



双粲重子的发现

PRL 119 (2017) 112001

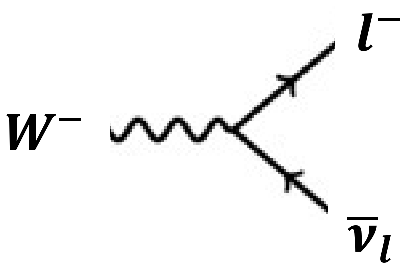


$b \to c l \bar{\nu}_l$: lepton universality test

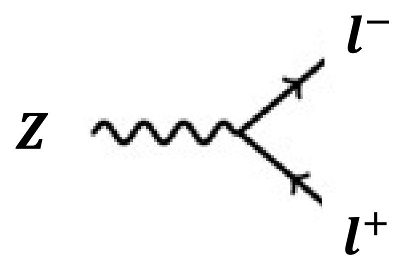
Lepton universality (LU)

- SM: couplings of gauge bosons are identical for $l = e, \mu, \tau$

Charged currents



Neutral currents



- Branching fractions to different lepton generations differ only due to lepton masses

$$R_W = \frac{B(W \to \tau\bar{\nu}_\tau)}{B(W \to \mu\bar{\nu}_\mu}$$

$$R_Z = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to \mu^+\mu^-)}$$

$$R_{D^{(*)}} = \frac{B(B \to D^{(*)}\tau\bar{\nu}_\tau)}{B(B \to D^{(*)}\mu\bar{\nu}_\mu)}$$

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

Previous LU tests

- **Lepton couplings have been thoroughly tested at LEP, NA42, BESIII, CLEO and many other experiments**
  - **Neutral currents: universal within 2% precision**
  - **Charged currents: universal within 2% for $l = e, \mu$**

LEP: 2.8σ upward tension in $W \to \tau \bar{\nu}_\tau$ **CERN-PH-EP/2005-051**

Assuming only partial lepton universality the ratio between the tau fractions and the average of electrons and muons can also be computed:

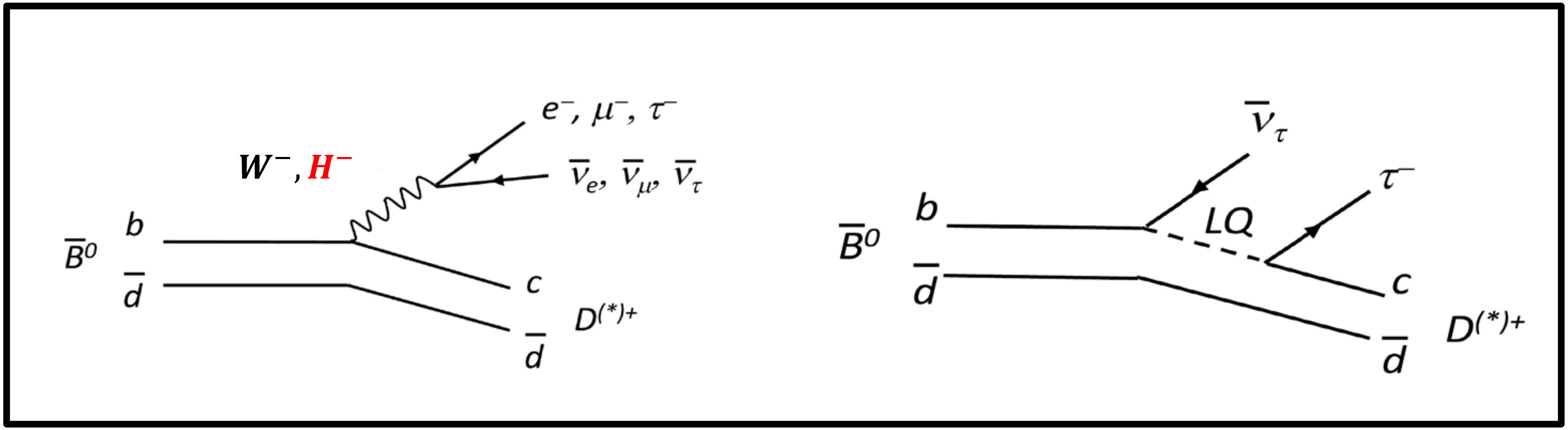
$$2\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, (\mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) + \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu)) \quad = \quad 1.077 \pm 0.026$$

resulting in a poor agreement at the level of 2.8 standard deviations, with all correlations included.

Tree-level LU tests

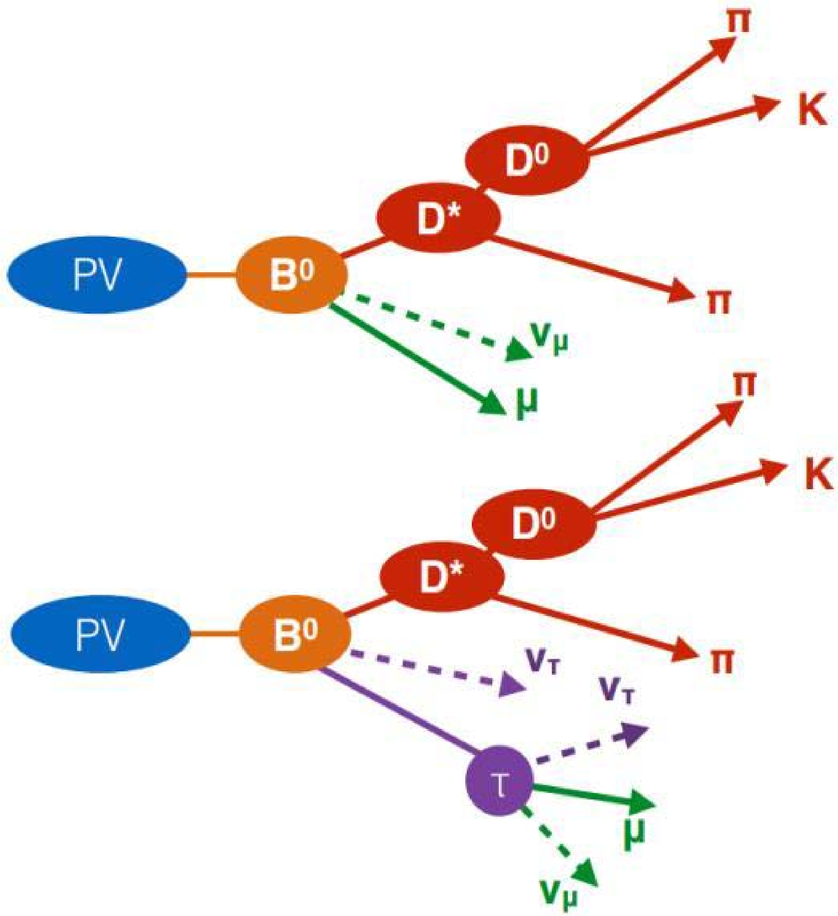
$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\bar{\nu}_\tau)}{B(B \to D^{(*)}l\bar{\nu}_l)} \qquad (l = e, \mu)$$

- Tree-level $b \to c l^- \bar{\nu}_l$ transitions are well understood in SM
- Sensitive to extended Higgs sector or Leptoquarks, which are expected to couple predominantly to 3rd generation leptons



$B \to D^{*}\tau\bar{\nu}_{\tau}$ with $\tau^{-} \to \mu^{-}\bar{\nu}_{\mu}\nu_{\tau}$

Vertices => B flight direction => B momentum=> missing mass



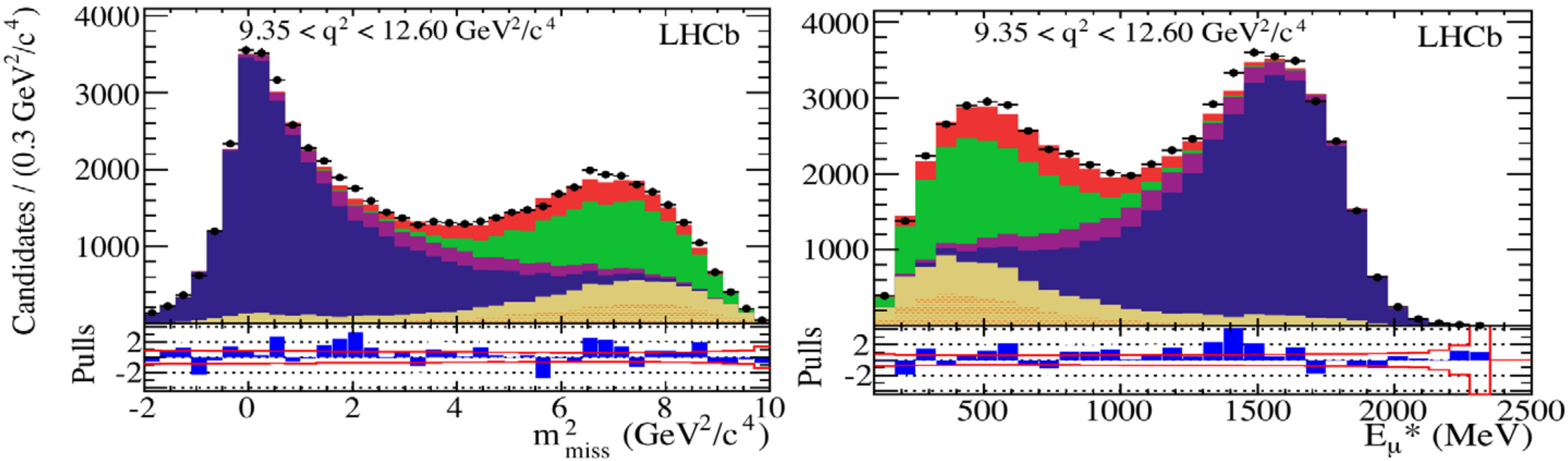
$B \to D^{*}l\bar{\nu}_{l}$

Small missing mass

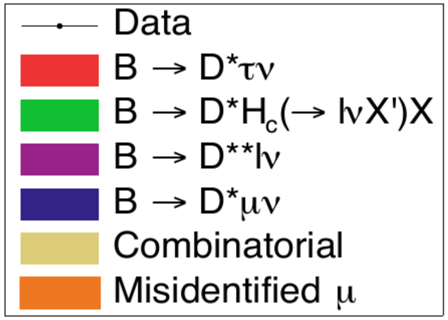
$B \to D^{*}\tau\bar{\nu}_{\tau}$

Large missing mass

$R(D^*)$ with $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$



PRL115 (2015) 11803



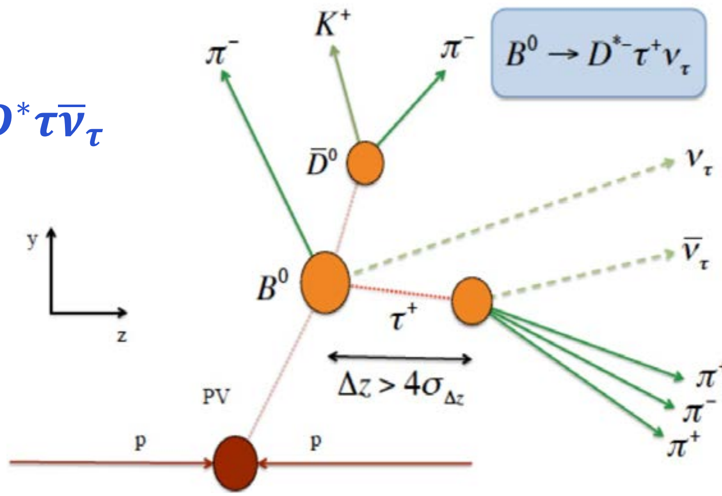
$$R(D^*) = 0.306 \pm 0.013 \pm 0.007$$

2σ above SM prediction: $R^{SM}(D^*) = 0.258 \pm 0.005$

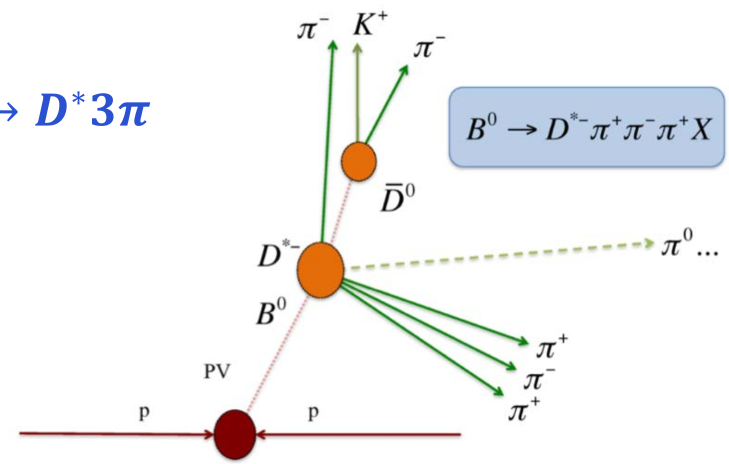
$R(D^*)$ with $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

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

$B \to D^*\tau\bar{\nu}_\tau$



$B \to D^*3\pi$



$$R(D^*) = 0.291 \pm 0.019 \pm 0.029$$

PRL120 (2018) 171802

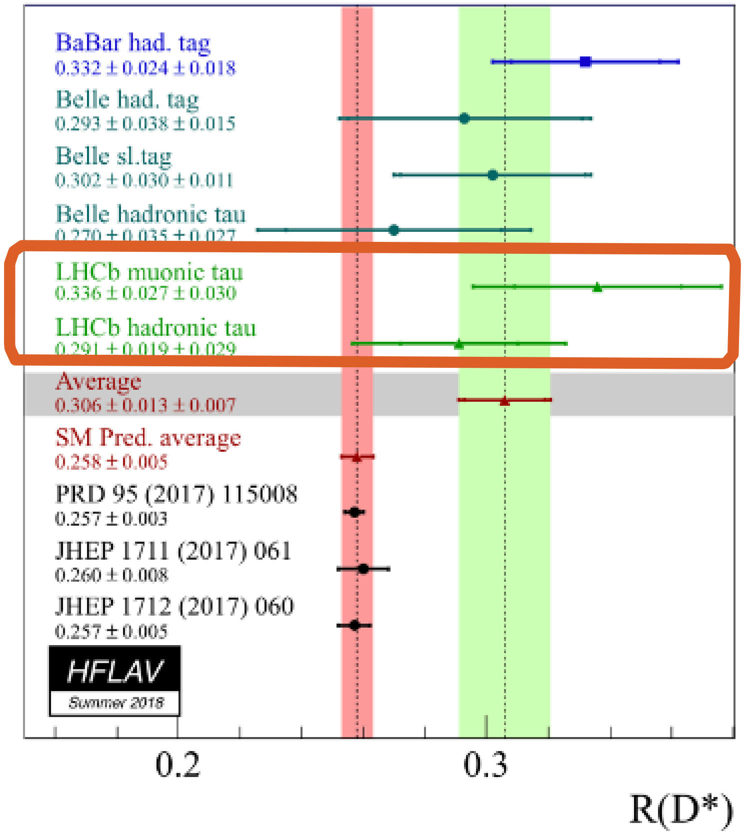
1σ above SM prediction

$R(D^*)$ results

LHCb combination

$$R(D^*) = 0.310 \pm 0.016 \pm 0.021$$

LHCb, Babar and Belle results consistent with each other, all above SM predicitons



World average: $R(D^*) = 0.306 \pm 0.013 \pm 0.007$

3σ above SM prediction: $R^{SM}(D^*) = 0.258 \pm 0.005$

$b \to c l^- \bar{\nu}_l$ LU tests: overall status

- $R(D^*)$ and $R(D)$

  $R(D^*)$: Babar, Belle, LHCb

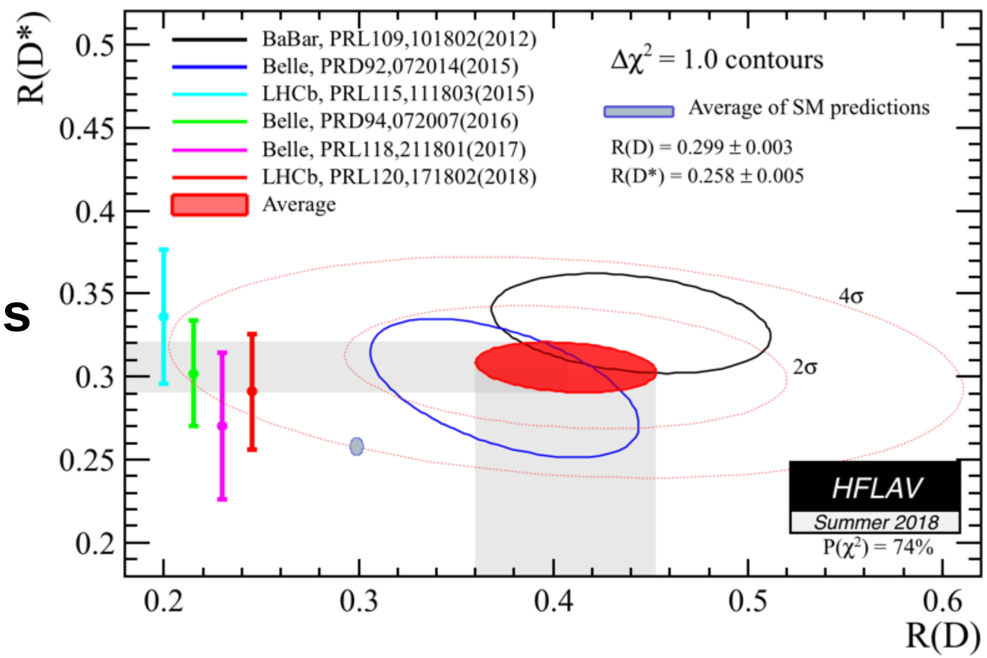
  $R(D)$: Babar, Belle

  Tension with SM predictions

  ✓ 3.0σ in $R(D^*)$

  ✓ 2.3σ in $R(D)$

  ✓ 3.8σ combined



- Recent LHCb result of $R_{J/\psi}$

$$R(J/\psi) = \frac{B(B_c^+ \to J/\psi \tau \bar{\nu}_\tau)}{B(B_c^+ \to J/\psi \mu \bar{\nu}_\mu)}$$

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

PRL 120 (2018) 121801

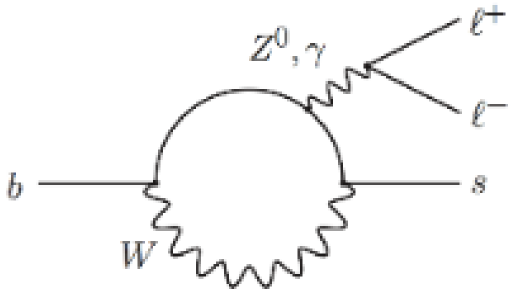
2σ above SM prediction: $R^{SM}(J/\psi) = 0.12 \sim 0.28$

$b \to s l^+ l^-$: lepton universality test & angular analysis

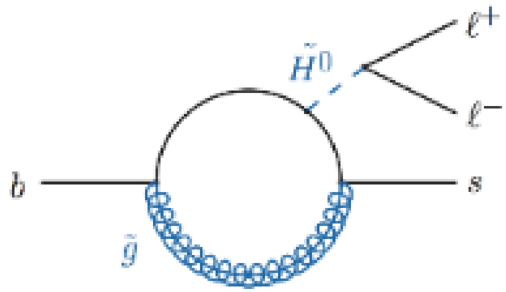
$b \to s l^+ l^-$

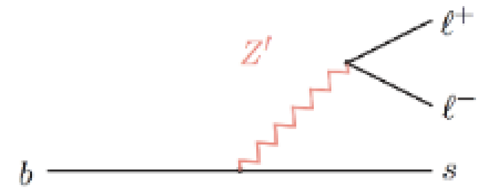
- $b \to s l^+ l^-$ decay rates sensitive to heavy non-SM particles

SM contributions

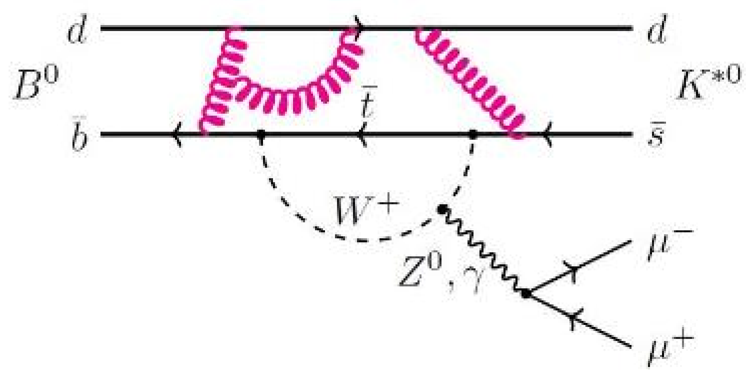


NP contributions

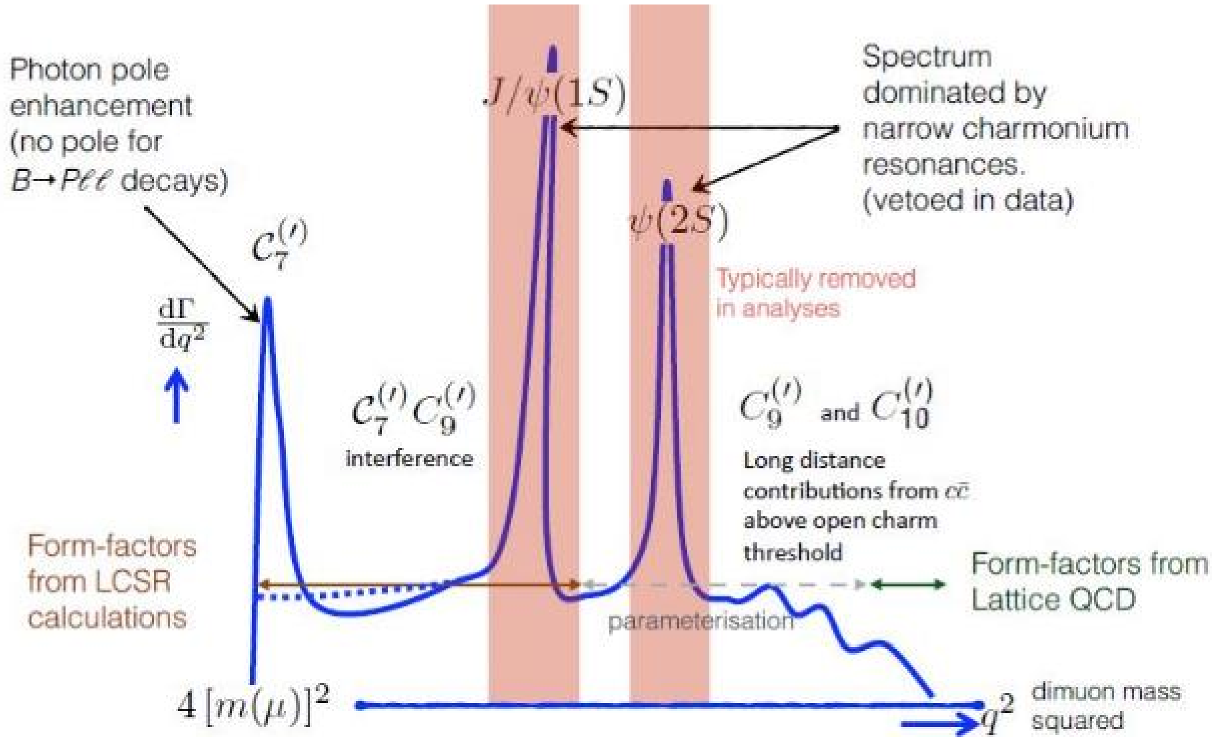




- Cannot compute hadronic form factors reliably
- Theoretically robust observables
  - ✓ BR ratios between e and μ
  - ✓ Special angular observables



Dependence on $q^2 = m^2_{l^+l^-}$



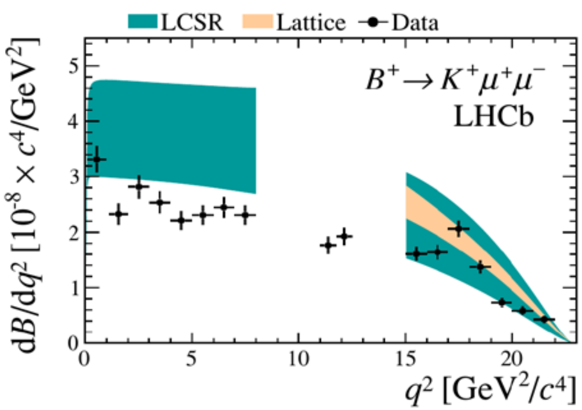
- **Veto J/ψ and $\psi(2S)$ regions**
- **Significant interference of short- and long-distance contributions remains and have been observed**

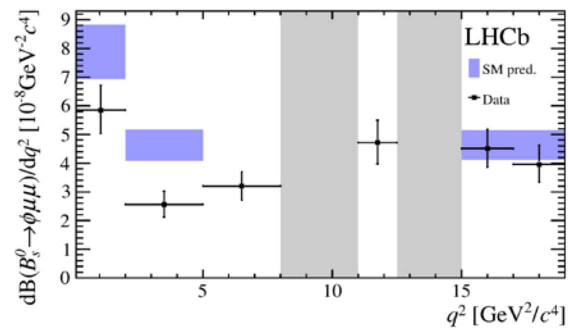
$b \to s l^+ l^-$ branching fractions

- **Measured values consistently below SM predictions**
- **But: significant theory uncertainties from hadronic form factors**

$B^+ \to K^+ \mu^+ \mu^-$

[JHEP 06(2014)133]



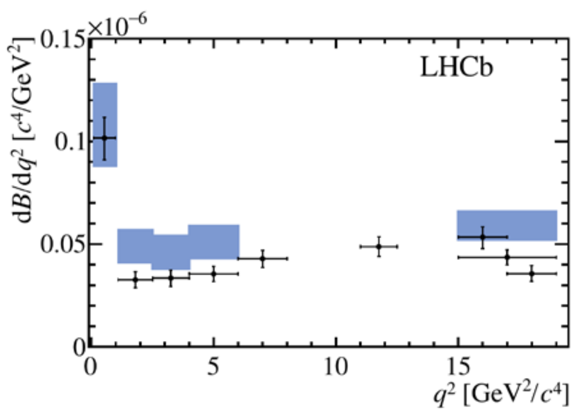


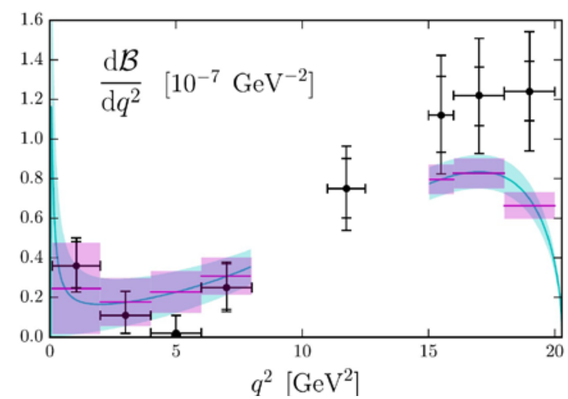
$B_s^0 \to \phi \mu^+ \mu^-$

[JHEP 09(2015)179]

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

[JHEP 04(2017)142]





$\Lambda_b \to \Lambda \mu^+ \mu^-$

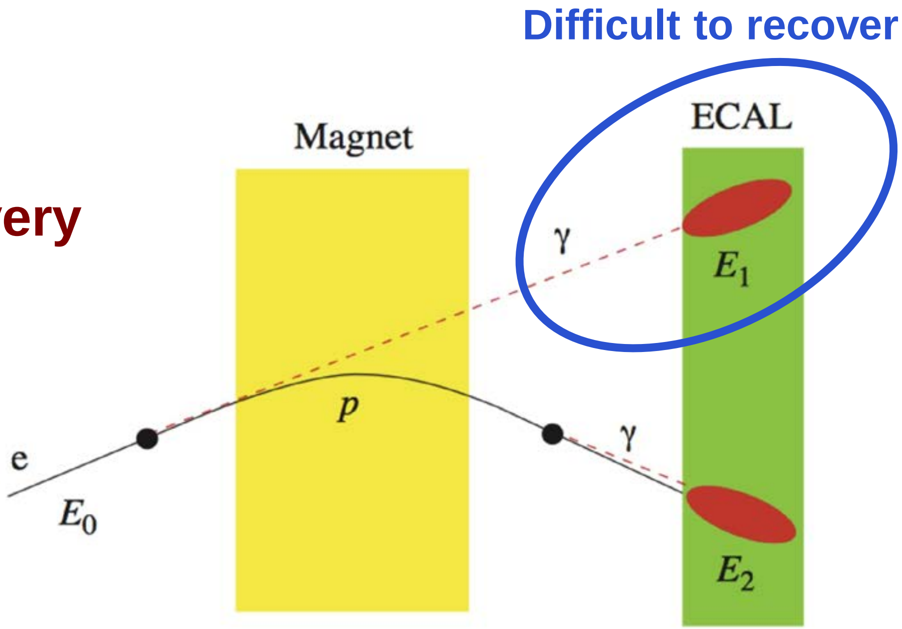
[JHEP 06(2015)115]

LU test with $R(K^{(*)})$

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

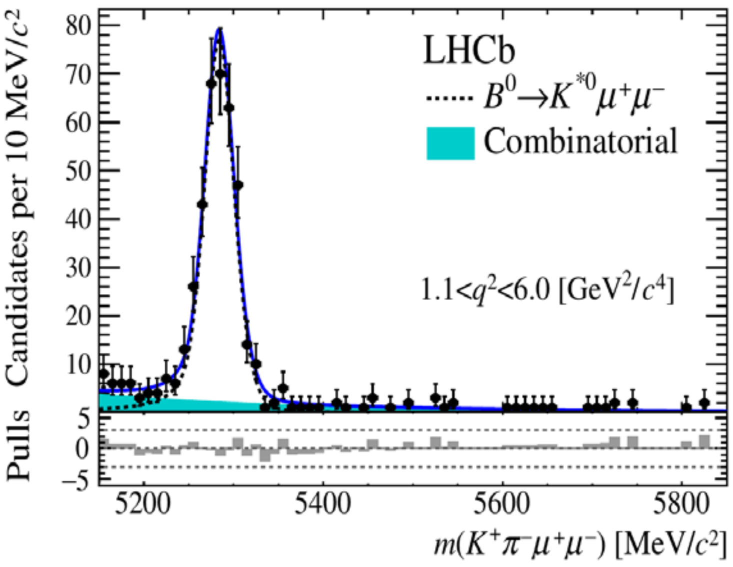
- Theoretical uncertainties in form factors largely cancel in ratio
- $R(K^{(*)})$ close to unity, predicted with precision of $O(10^{-3})$ in SM
- Experimental challenge: electron reconstruction

Electron Bremstrahlung recovery

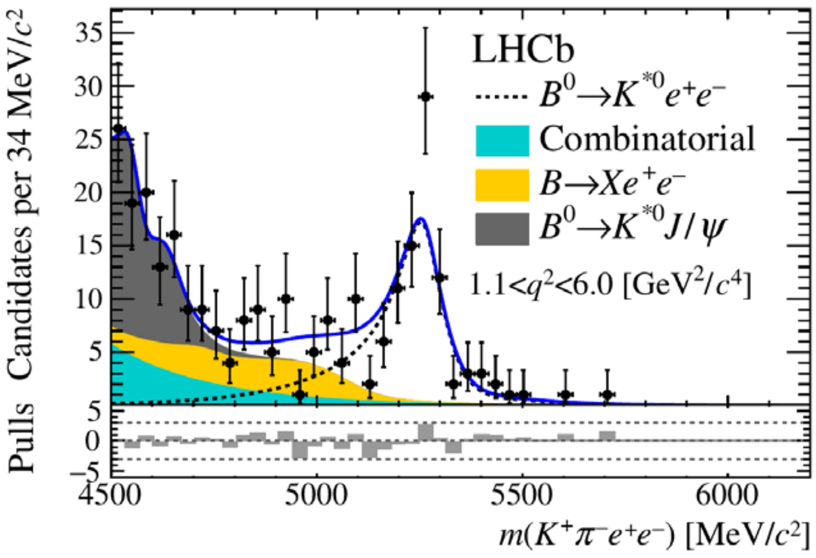


$K^+e^+e^-$ vs $K^+\mu^+\mu^-$

$B^0 \to K^*\mu^+\mu^-$



$B^0 \to K^*e^+e^-$



Electron modes suffer from

- ✓ Lower trigger efficiency
- ✓ Higher background
- ✓ Worse resolution
- ✓ Contamination from radiation tail of $J/\psi \to e^+e^-$

$R(K)$

LHCb

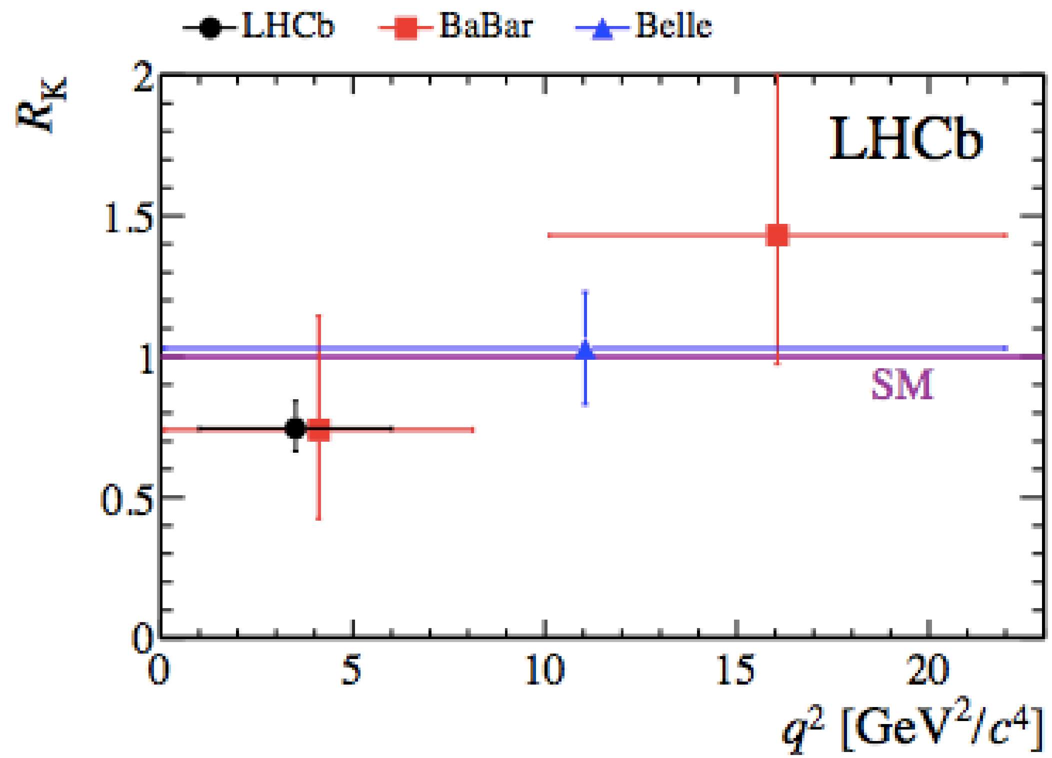
PRL 113 (2014) 151601

BaBar

[PRD 86(2012)032012]

Belle

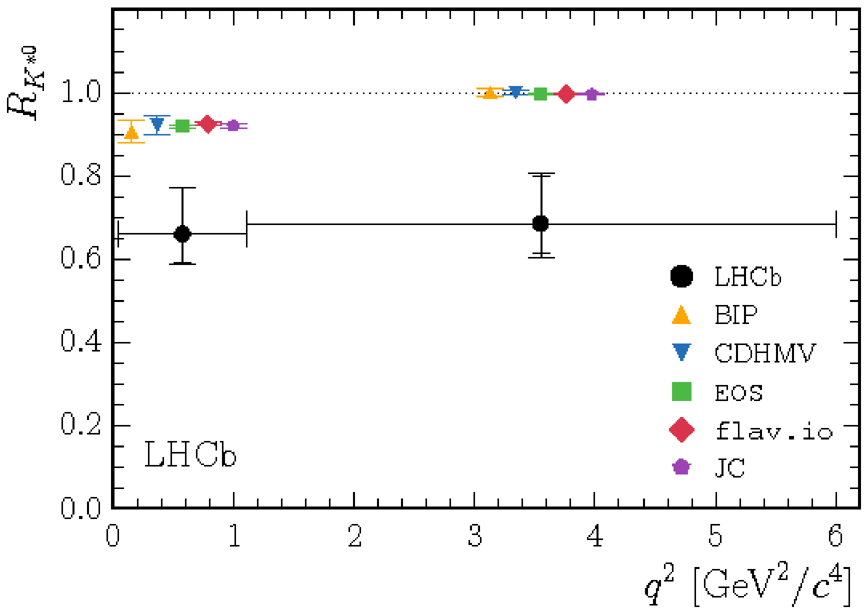
[PRL 103(2009)171801]

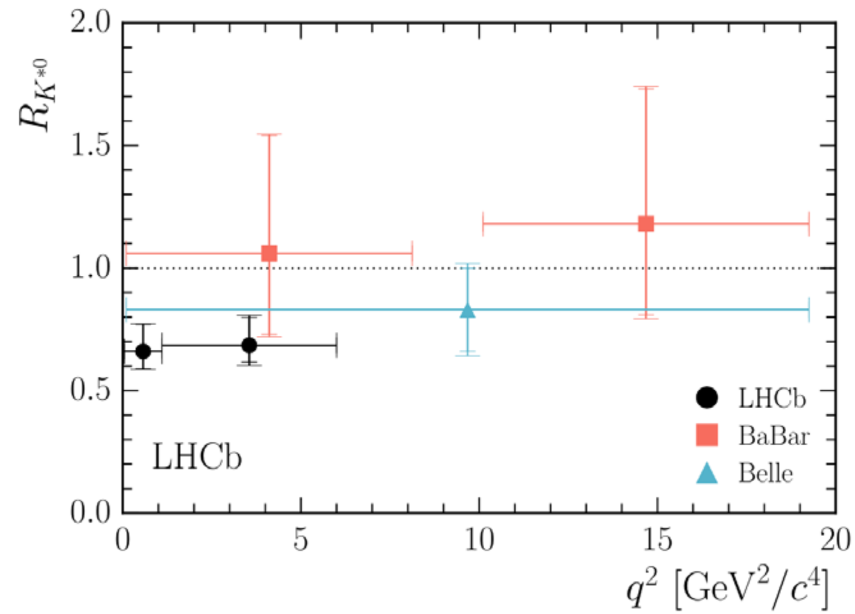


$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036; \quad 1 < q^2 < 6 \ \text{GeV}^2$$

2.6σ below SM prediction

$R(K^*)$



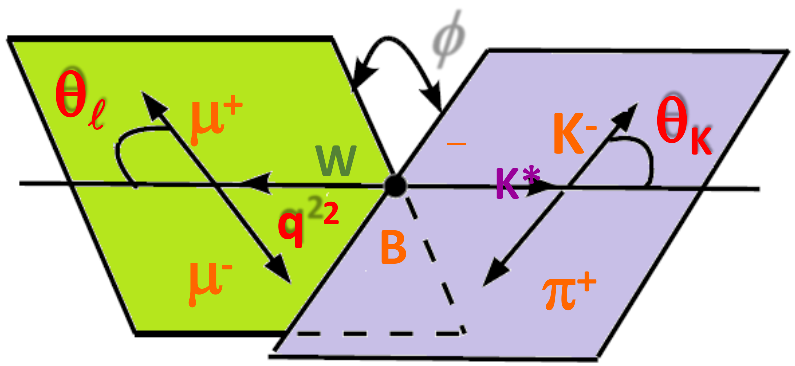


$$R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03; \quad 0.045 < q^2 < 1.1 \text{ GeV}^2$$

$$R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05; \quad 1.1 < q^2 < 6.0 \text{ GeV}^2$$

2.1σ and 2.4σ below SM predictions JHEP 08 (2017) 055

Angular analysis: $B^0 \to K^{*0}\mu^+\mu^-$



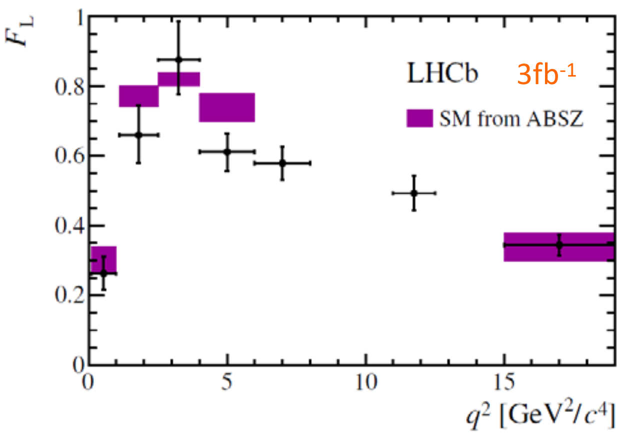
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Eight independent observables

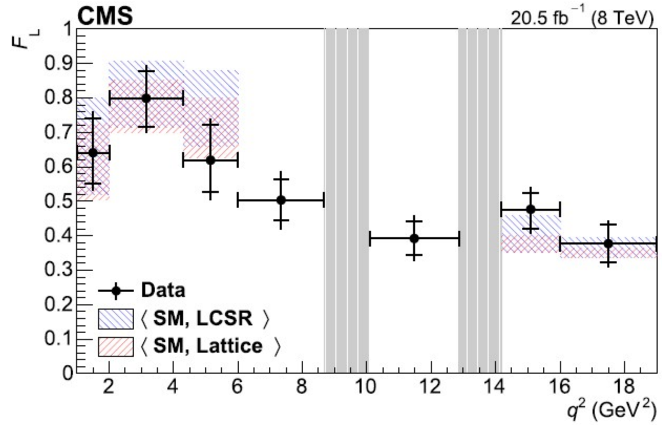
- ✓ **F_L: fraction of longitudinal polarization**
- ✓ **$S_6 = 4/3\ A_{FB}$: forward-backward asymmetry of the $\mu^+\mu^-$ system**
- ✓ **$S_{3,4,5,7,8,9}$: remaining CP-averaged observables**

F_L and A_{FB}

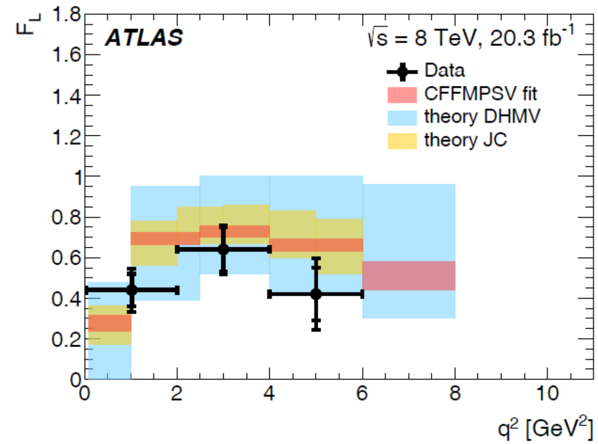
LHCb
JHEP02(2016)104

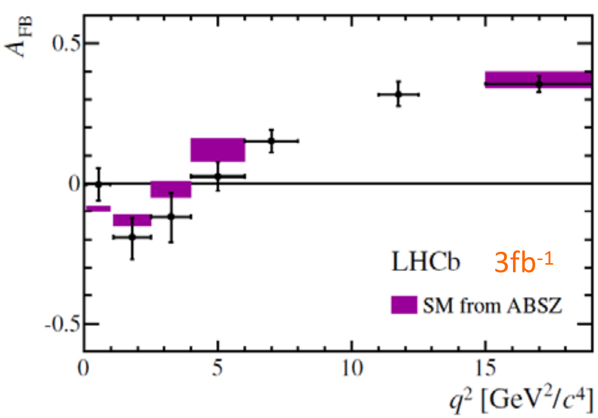


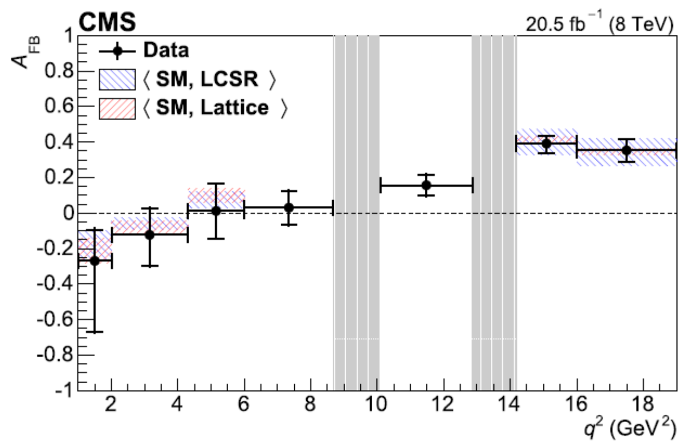
CMS
PLB 753 (2016) 424



ATLAS
arXiv:1805.04000







SM predictions
ABSZ: EPJC 75 (2015) 382
LSCR: JHEP 08 (2016) 98
Lattice: arXiv:1501.00367

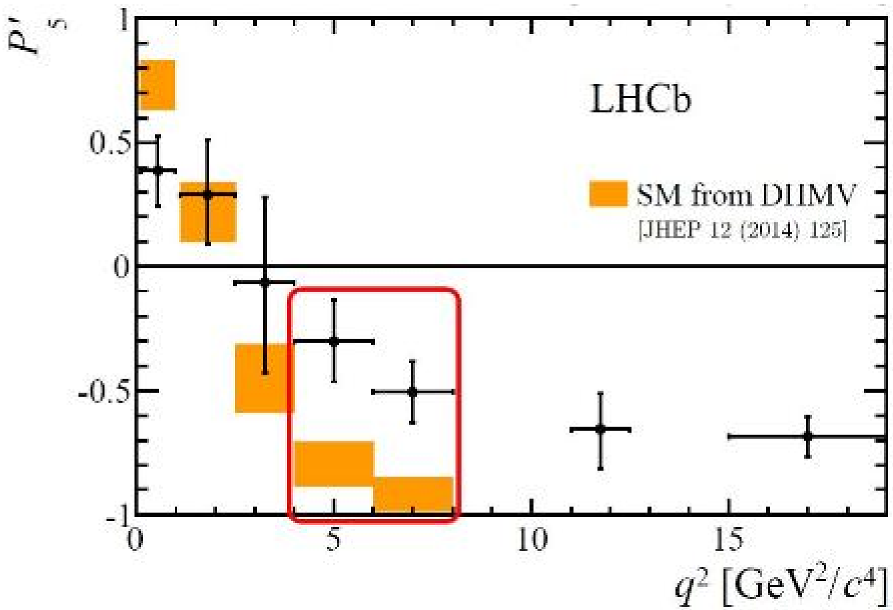
Measured values agree well with SM predictions

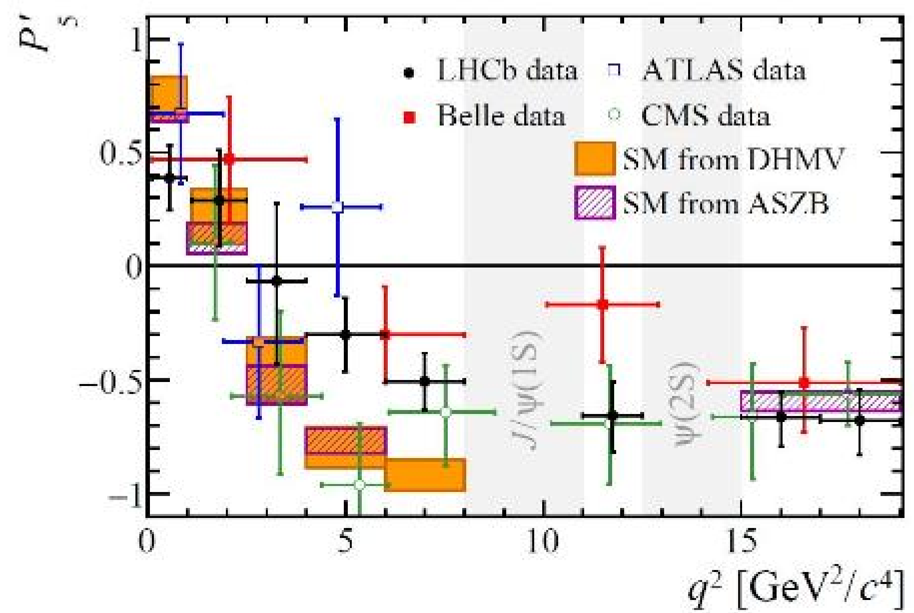
P_5' puzlle

Form factors cancel at leading order in new observable

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

JHEP 04 (2016) 104





Local deviations from SM : 2.8σ **for 4**$< q^2 <$ **6 GeV² ;**

3.0σ **for 6**$< q^2 <$ **8 GeV² .**

Global deviation from SM: 3.4σ

Possible explanations

- **Statistical fluctuation?**

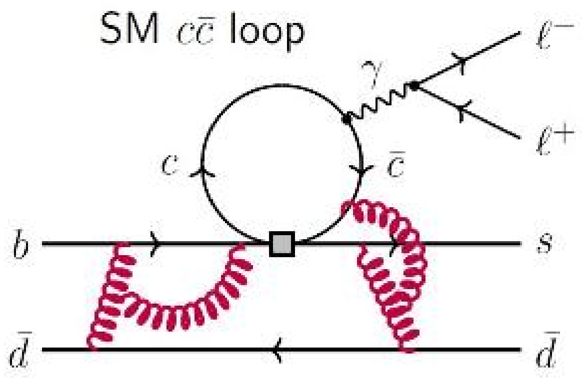
More data will shed light

- **Experimental artefacts?**

e and τ are difficult to reconstruct

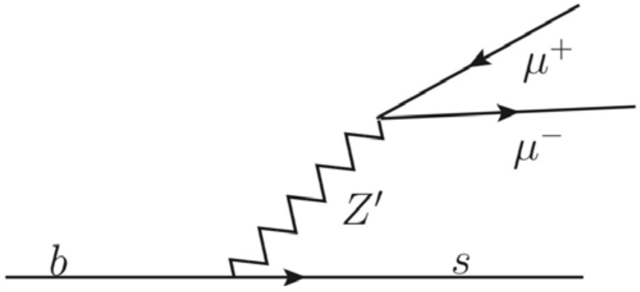
- **Underestimated SM charm loop effect?**

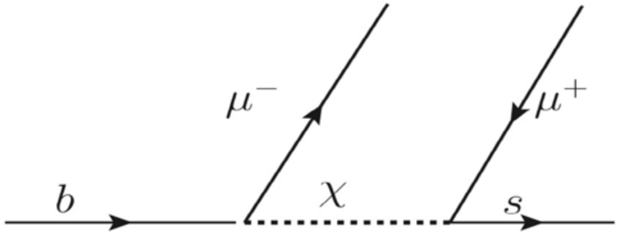
Possible, but LU observables should be robust …



- **New physics if all above are excluded**

Z' or leptoquark could explain the anomalies

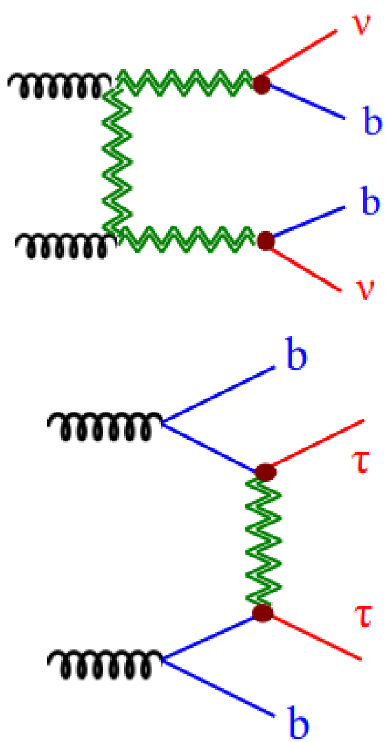


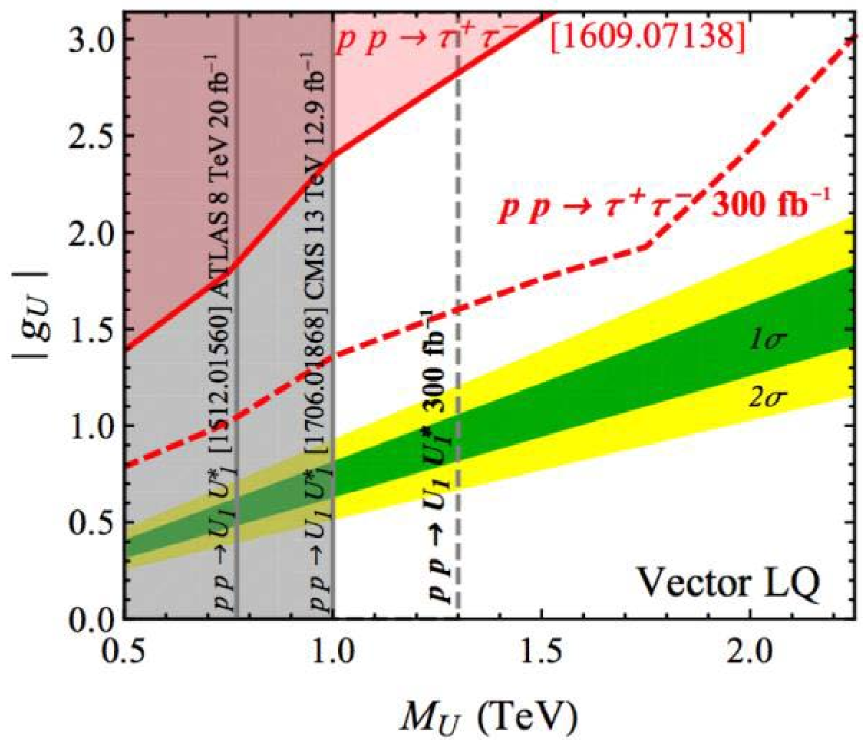


Interplay with direct search

- If the flavor anomalies are due to exchange of a new particle, it could be searched for at high p_T
- No sign seen yet

  Example: leptoquark search at LHC
- May need HL-LHC to see them if they are there …



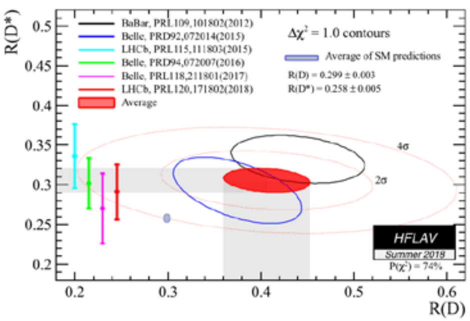


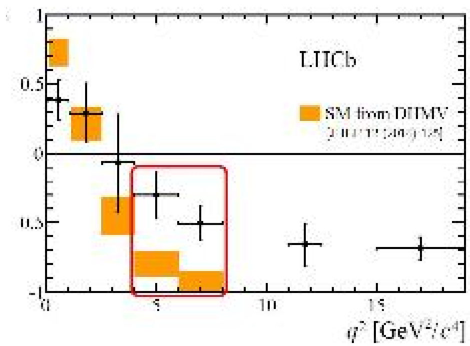
Summary and outlook

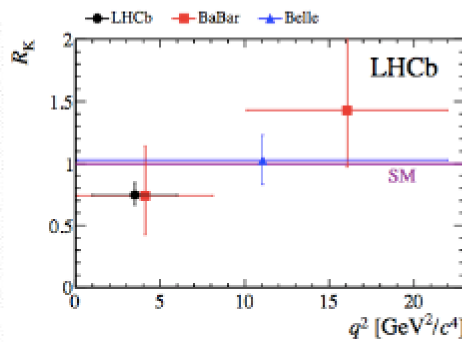
Summary

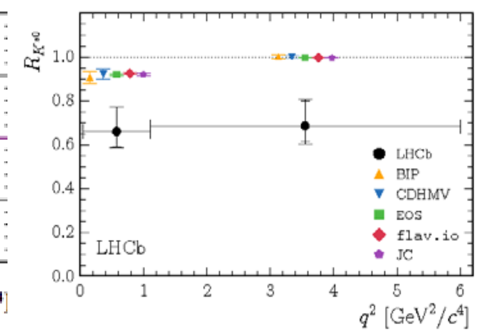
- **Intriguing tension with Standard Model predictions**

$R(D^{(*)})$: 3.8σ P_5': 3.4σ $R(K)$: 2.6σ $R(K^*)$: >2.5σ



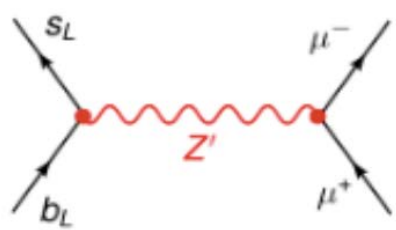




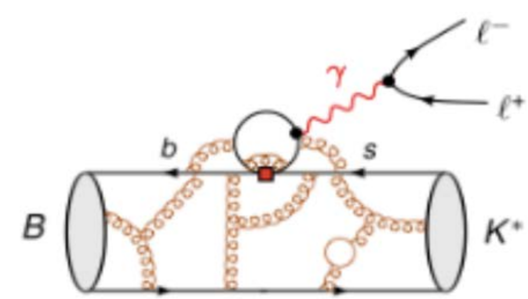


- **Many possibilities remain**

Optimist's view point

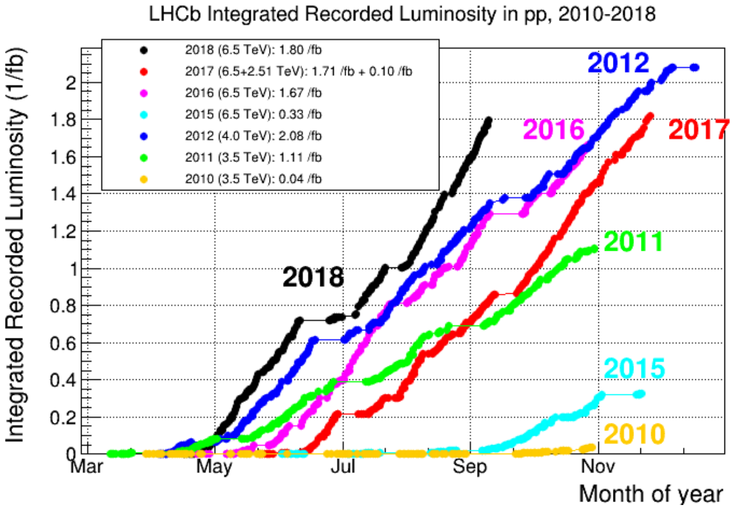


Pessimist's view point

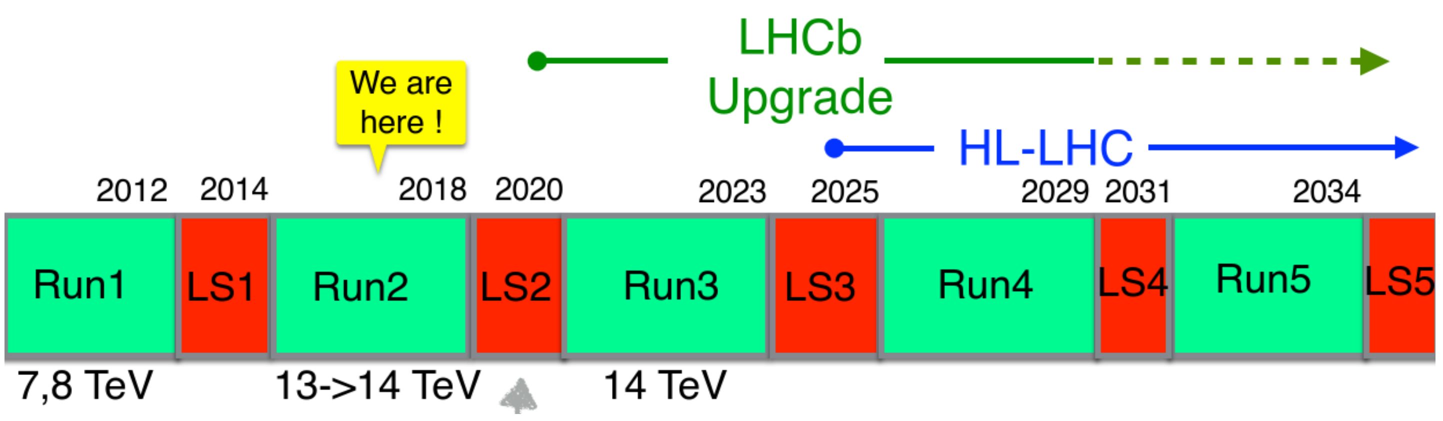


Outlook

- **Significant progress expected in next five years with new measurements from the LHC and from Belle II**



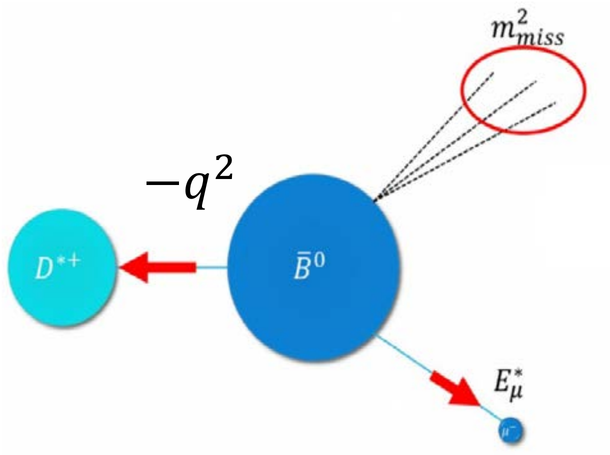
- **LHCb will run at 5X higher instant luminosity after LS2, and has expressed interest to further increase it by 10X after LS4 at 2031**

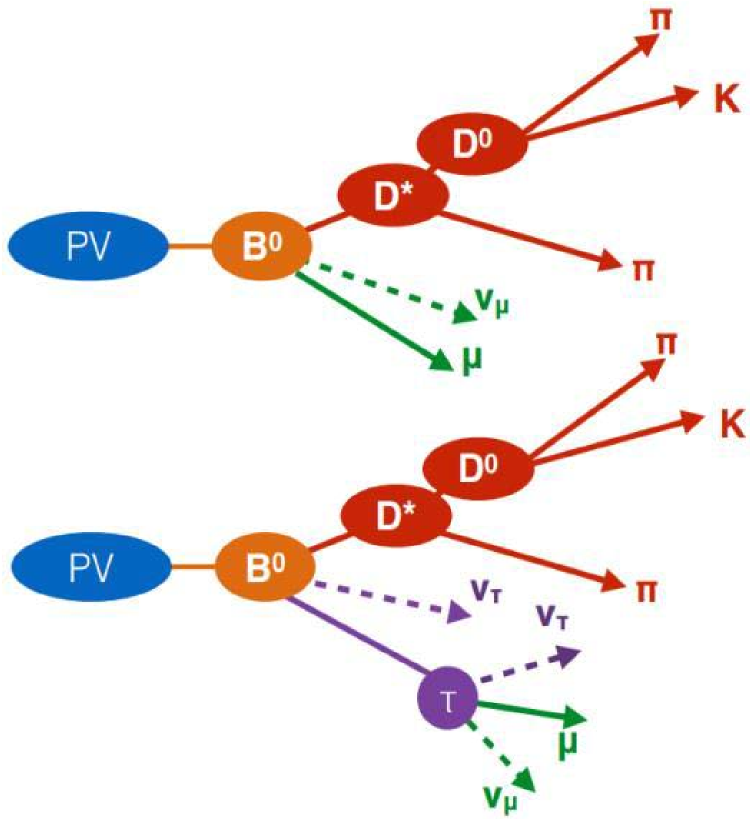


Backup slides

$R(D^*)$ with $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

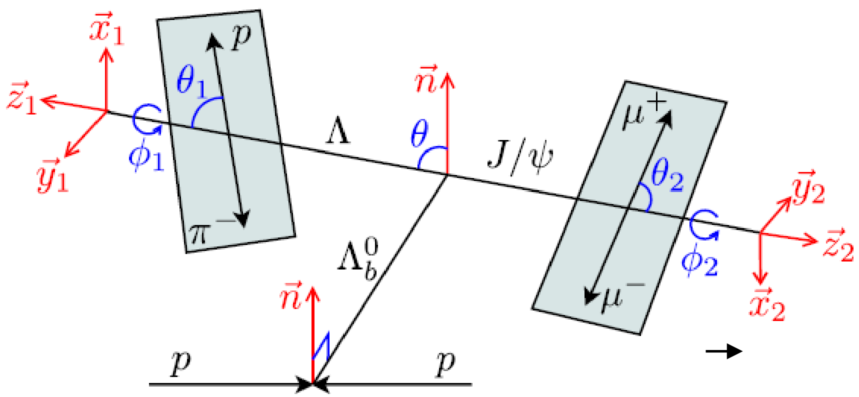
- With neutrinos missing, B momentum is estimated using D^* and μ^-, and flight direction
- Look at variables in B rest frame





	$D^{*+}\tau^-\nu_\tau$	$D^{*+}\mu^-\nu_\mu$
E_M^*	Softer	harder
m_{miss}^2	> 0	≈ 0
q^2	$> m_\tau^2$	> 0

Angular analysis: $\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-$

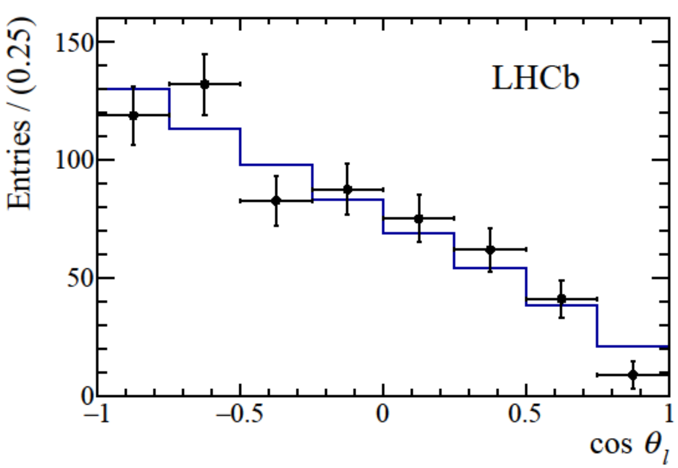


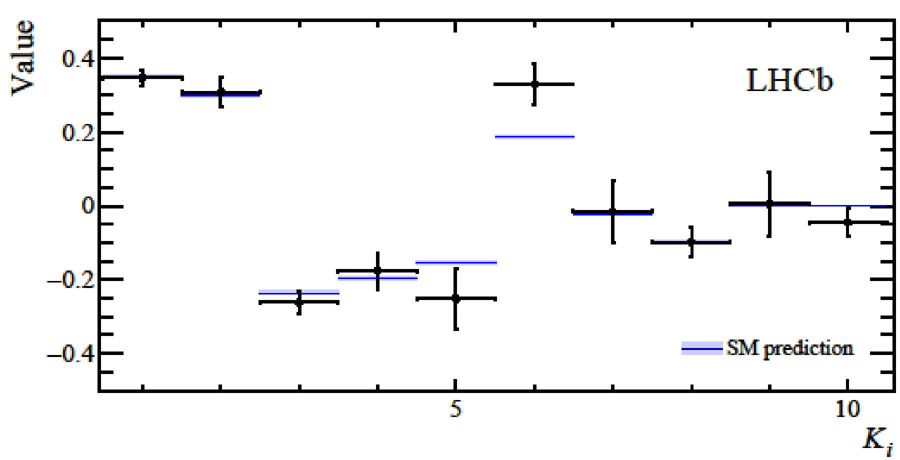
$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2} \sum_i^{34} K_i(q^2) f_i(\vec{\Omega})$$

- **5 angles**
- **q^2-dependent observables K_i**
- **Method of moment**
- **Signals only observed in $15 < q^2 < 20$ GeV2**

Results compatible with SM predictions
[Boër et al, JHEP 01 (2015) 155]
[Detmold et al. PRD 93 (2016) 074501]

arXiv: 1808.00264 Run 1+II, 5 fb^{-1}

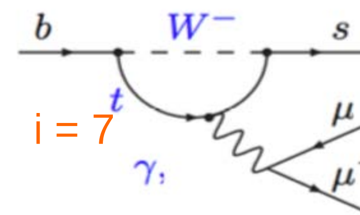


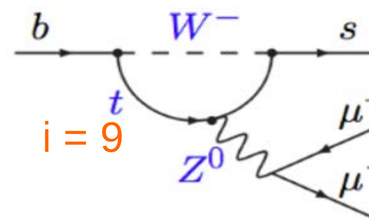


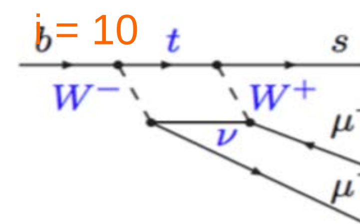
Effective theory for $b \to s l^+ l^-$

- **Described by an effective Hamiltonian**

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$







Operators O_i | **Wilson coefficients C_i**

0.2 GeV	...	4 GeV	...	80 GeV	...	10-100 TeV
Λ_{QCD} (non-perturbative)		Λ_b b mass		Λ_{EW} W mass		Λ_{BSM} BSM scale

Global fit to $b \rightarrow sl^+l^-$ results

- **Include angular and LU results in $b \rightarrow sl^+l^-$ transitions**
- **Allow for $C_{ie}^{NP} \neq C_{i\mu}^{NP}$**
  - ✓ **Preference for $C_{9\mu}^{NP} \neq 0$**
  - ✓ **Data disagree with SM by more than 3.5σ**