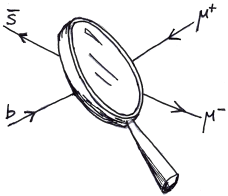
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Update on B anomalies

SM@LHC 2018,
Berlin, April 10 - 13

Michel De Cian, on behalf of the LHCb collaboration

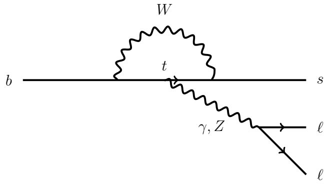
Rare decays of B hadrons

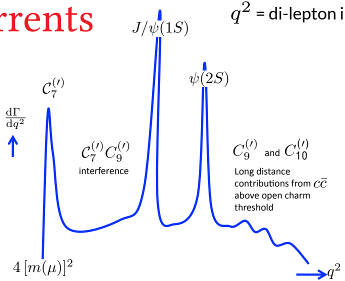


- Goal is to search for physics beyond the Standard Model (SM).
- Rare B hadron decays are strongly suppressed in SM, new physics can be at the same level.
- Effectively probing virtual particles and their effects: Can reach higher masses than direct searches.
- B hadrons are copiously produced at the LHC.

Charged and neutral currents

q^2 = di-lepton invariant mass

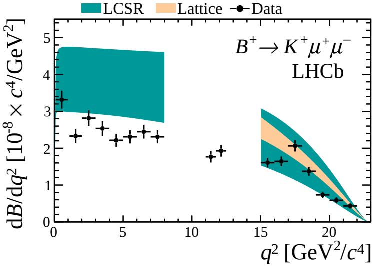


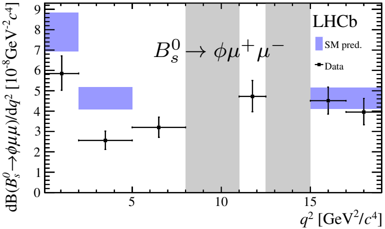


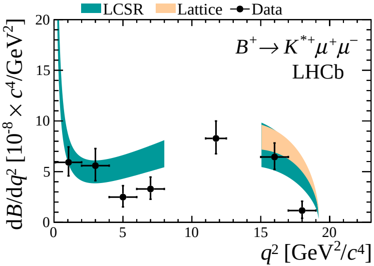
- $b \to s\ell^+\ell^-$ transitions are flavour-changing neutral currents and only occur on loop-level in the Standard Model
- In the past years, many interesting deviations from the SM predictions have appeared in several $b \to s\ell^+\ell^-$ channels, observed by different experiments.
- More anomalous results appeared in charged current $b \to c$ decays.
- Together they form the so-called "B anomalies"
- All results shown are with the Run I data set ($3\,\text{fb}^{-1}$) of LHCb.

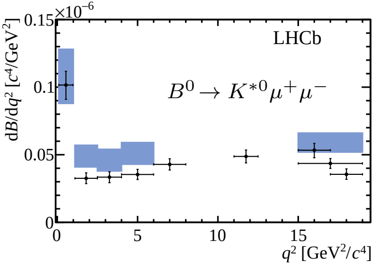
[JHEP 06 (2014) 133]
[JHEP 1308 (2013) 131] [JHEP 11 (2016) 047, JHEP 04 (2017) 142]
[theo. predictions: see exp. papers]

$b \to s\ell^+\ell^-$: Branching fractions



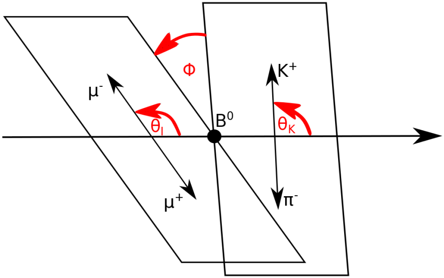






- Many measurements are below the SM prediction

$b \to s\ell^+\ell^-$: Angular analyses



- Differential decay rate of P $\to$ VV decays depends on 3 decay angles and an observable, depending on q^2.
- $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi} = \frac{9}{32\pi}\sum_i J_i(q^2) f(\cos\theta_\ell, \cos\theta_K, \phi)$
- Best studied case in LHCb: $B^0 \to K^{*0}\mu^+\mu^-$

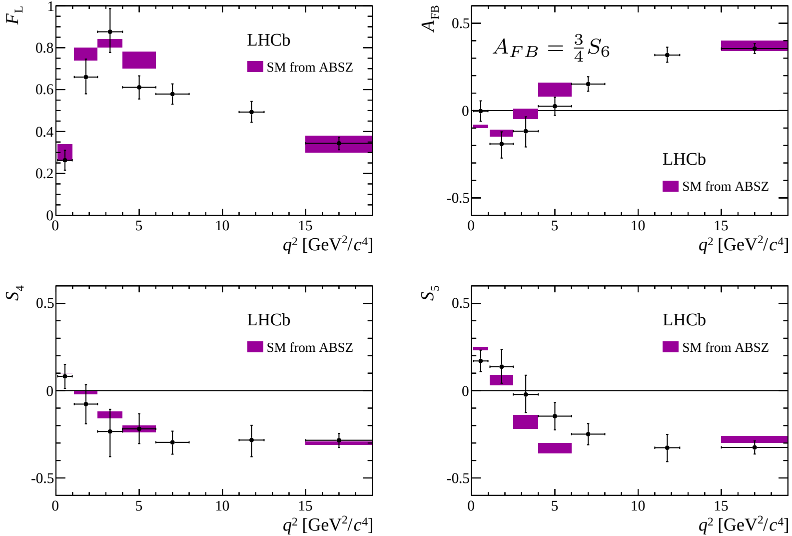
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ (I)

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

- Call the coefficient in front of the angular expressions ”observable”.
- $S_i = f(A_0^{L,R}, A_\perp^{L,R}, A_\parallel^{L,R})$
- $S_6 = \frac{4}{3}A_{FB}$: Forward-backward asymmetry of leptons
- F_L: Longitudinal polarization of K^{*0}

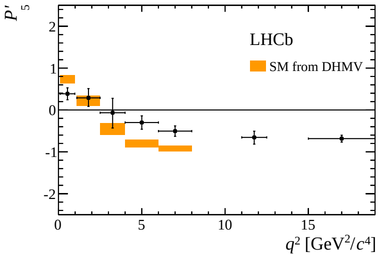
[JHEP 02 (2016) 104]
[theo. prediction: see exp. paper]

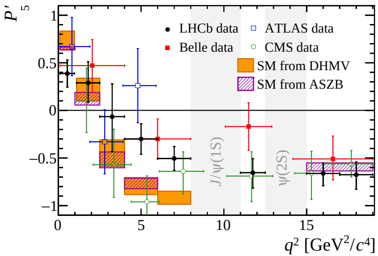
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ (II)



- Perform likelihood fit to 3 decay angles in intervals of q^2

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ (III)

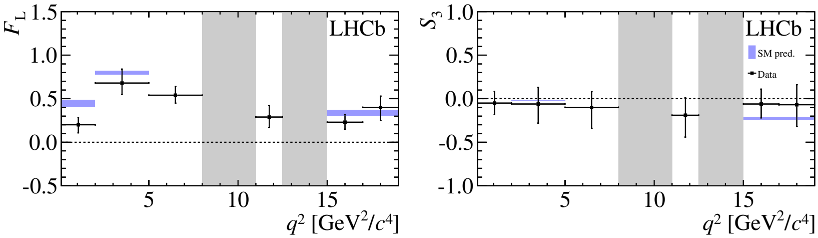




- $P'_5 = \frac{S_5}{\sqrt{1-F_L}}$
- The P'_i observables are less prone to hadronic form-factor uncertainties than the S_i ones.
- Measurements also by Belle, CMS, ATLAS, albeit with less statistical power.
- Global significance is about 3.4σ from the SM (LHCb measurement alone).

[JHEP09(2015)179]
[theo. prediction: see exp. paper]

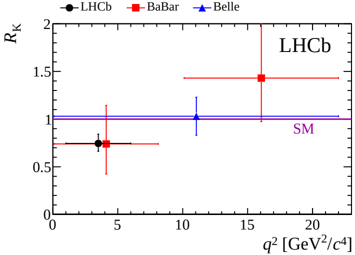
Angular analysis of $B_s^0 \to \phi\mu^+\mu^-$

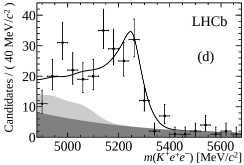


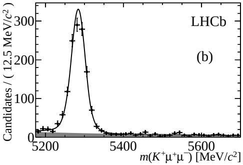
- $B_s^0 \to \phi\mu^+\mu^-$ in principle probes the same underlying physics as $B^0 \to K^{*0}\mu^+\mu^-$.
- Decay is not self-tagging $\longrightarrow$ only access to limited set of observables.
- The measured observables are all compatible with the SM predictions.

[PRL 113, 151601 (2014)]
[theo. prediction: see exp. paper]

Lepton Flavour Universality in $B^+ \to K^+\ell\ell$

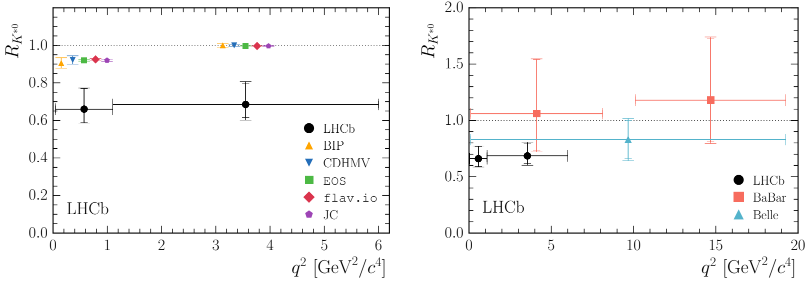






- Measure $R_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)}$ in $q^2 \in [1,6]\,\mathrm{GeV}^2/c^4$
- Use $B^+ \to J/\psi\, K^+, J/\psi \to \ell\ell$ as normalization and control channel.
- Electrons are more challenging than muons, due to lower reconstruction efficiency and energy loss due to bremsstrahlung.
- Hadronic uncertainties cancel in the ratio.
- 2.6σ deviation from the SM, $\mathcal{B}(B^+ \to K^+e^+e^-)$ compatible with SM predictions.

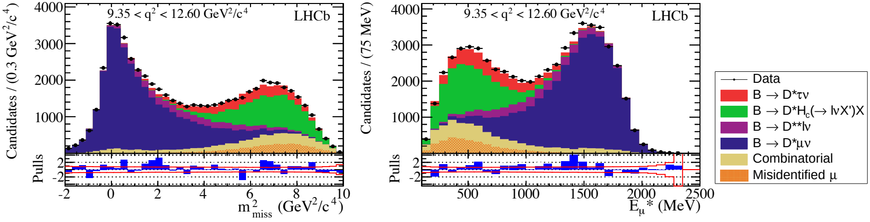
LFU in $B^0 \to K^{*0}\ell\ell$



- Consider $R_{K^*} = \dfrac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$
- Similar strategy as for R_K. Use $B^0 \to J/\psi\, K^*, J/\psi \to \ell\ell$ as normalization and control channel.
- Compatible at 2.2 and 2.4σ with SM prediction for low and intermediate q^2 region.

[PRL 115, 111803 (2015)]
[theo. prediction: Phys. Rev. D85 (2012) 094025]

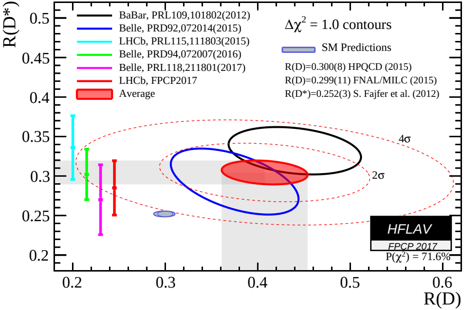
LFU in $\overline{B}^0 \to D^{*+}\ell\nu$, muonic mode

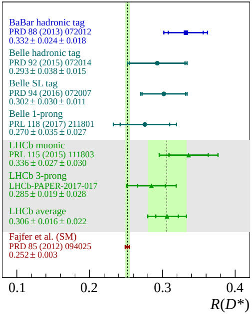


- Measure lepton flavour universality in semileptonic (tree) decays.
- Measure $R_{D^*} = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\nu)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\nu)}$
- Use $\tau^- \to \mu^-\nu\nu$, *i.e.* τ and μ modes have the same final state.
  - Distinguish with kinematical distributions
- $R_{D^*,\text{exp},\mu} = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$
- $R_{D^*,\text{SM}} = 0.252 \pm 0.003$
- $\approx 2\sigma$ from the SM prediction.

[arxiv:1708.08856]

LFU in $\overline{B}^0 \to D^{*+}\ell\nu$, 3-prong mode

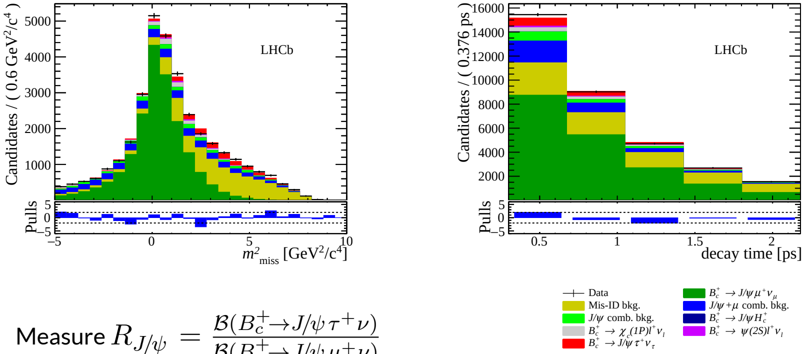




- Use $\tau^- \to \pi^-\pi^+\pi^-\nu$
- Use $\overline{B}^0 \to D^{*+}3\pi$ as normalisation channel, and known ratio $\mathcal{B}(\overline{B}^0 \to D^{*+}3\pi)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu\nu)$ to calculate R_{D^*}
- $R_{D^*,\text{exp},3\pi} = 0.286 \pm 0.019(\text{stat}) \pm 0.025(\text{sys}) \pm 0.021(\text{BR})$

[PRL 120, 121801 (2018)]
[theo. prediction: PRD73(2006)054024, PRD74(2006)074008]

LFU in $B_c^+ \to J/\psi\,\ell\nu$



- Measure $R_{J/\psi} = \dfrac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu)}$
- Including first measurement of $B_c^+ \to J/\psi\,\tau^+\nu\,(\tau^- \to \mu^-\nu\nu)$
- $R_{J/\psi,\text{theo}} = 0.25 - 0.28$
- $R_{J/\psi,\text{LHCb}} = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$ (compatible within 2σ)
- Systematic uncertainties dominated by limited size of simulation and knowledge of $B_c^+ \to J/\psi$ form factors.

Summary

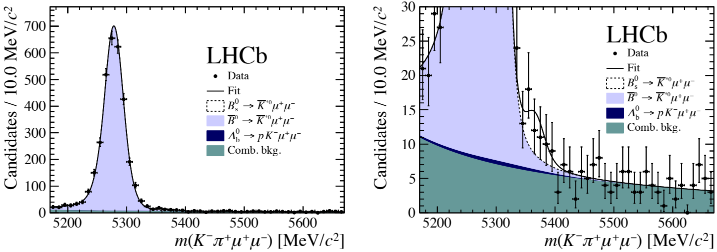
- Deviations from the SM appeared in the last years in observables in $b \to s\ell^+\ell^-$ and semileptonic decays in LHCb.
- They were confirmed by measurements from other experiments.
- The deviations show a consistent pattern and in combination (might) become significant (see Sebastian's talk on Thursday).
- Many updates from LHCb (R_{K,K^*,D,D^*}, angular analysis of $B^0 \to K^{*0}\mu^+\mu^-, B^0 \to K^{*0}e^+e^-$) will come up in the near future.

The B anomalies are alive and well!

15

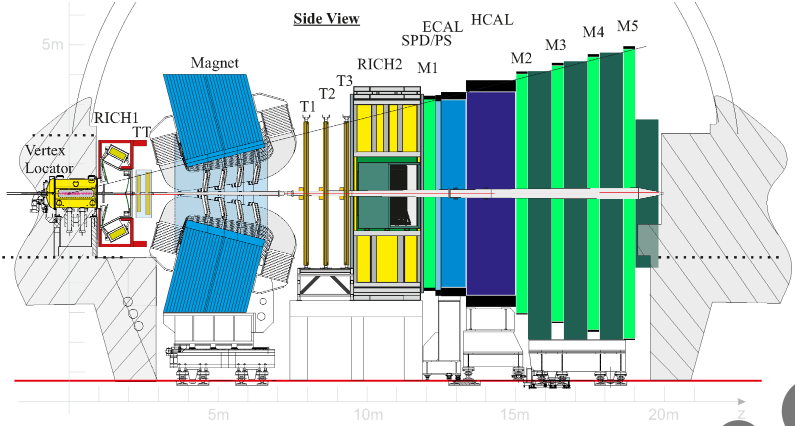
BACKUP

Analyses of $b \to d\ell\ell$ transitions



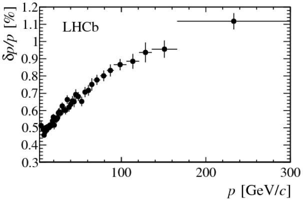
- First evidence of $B_s^0 \to K^*\mu^+\mu^-$ (3.4σ)
- Using 3 fb^{-1} of Run I and 1.6 fb^{-1} of Run II.
- $\mathcal{B}(B_s^0 \to K^*\mu^+\mu^-) = (3.0 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{ext})) \cdot 10^{-8}$
- With the upgrade of LHCb from 2021, differential decay rates can be measured.

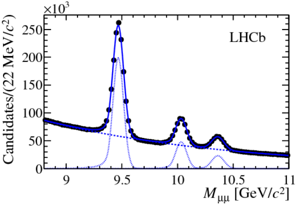
LHCb

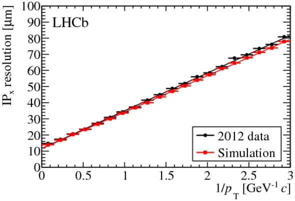

Side View
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
M5
5m
10m
15m
20m
z

[Int. J. Mod. Phys. A 30, 1530022 (2015)]
[Eur. Phys. J. C 73 (2013) 2431]

LHCb: Performance numbers







- Excellent momentum / mass resolution:
  - $\frac{\delta p}{p}$ = 0.5% (10 GeV/c) - 1.0% (200 GeV/c)
  - $\sigma_m(B_s^0 \to \mu^+\mu^-) \approx 20\,\mathrm{MeV}/c^2$
- Impact parameter resolution:
  - 15 +29/p_T [GeV/c]) μm
- High particle identification efficiency.
  - ε_μ $\approx$ 97% with 1-3% $\pi \to \mu$ misidentification
  - ε_K $\approx$ 95% with $\approx$ 5% $\pi \to K$ misidentification