

BSM searches with tests of LFU and rare decays at LHCb

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- 1 Introduction
- 2 $B \rightarrow K^{(*)} \ell^+ \ell^- : R_K, R_{K^*0}$
- 3 $B^0 \rightarrow D^* \tau \nu : R(D^*)$
- 4 $B_c \rightarrow J/\psi \tau \nu : R(J/\psi) : \text{NEW!}$
- 5 Conclusions and prospects

Lepton Flavor Universality

- SM features Lepton Flavor Universality (**LFU**): equal electroweak coupling to all charged leptons. Branching ratios to e , μ and τ differ only due to their mass

- However, some deviations measured already at **LEP**

$$\frac{2\sigma(W \rightarrow \tau \nu_\tau)}{\sigma(W \rightarrow e \nu_e) + \sigma(W \rightarrow \mu \nu_\mu)} \quad 2.8\sigma \text{ above SM} \quad [\text{arXiv:0511027}]$$

- And more recently at b -factories and LHCb using semileptonic B decays:

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)-} \tau^+ \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)-} \ell^+ \nu_\ell)} \quad (\ell = \mu, e), \text{ a combined effect } 4.1\sigma \text{ above SM} \quad [\text{HFLAV}]$$

- Also the rare decay observables $R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)}$ exhibit some tensions
 2.6σ below SM [PRL,113, 151601 (2014), JHEP 08 (2017) 055]

- Possible BSM scenarios: **leptoquarks, new heavy vector bosons, H^\pm** , ...

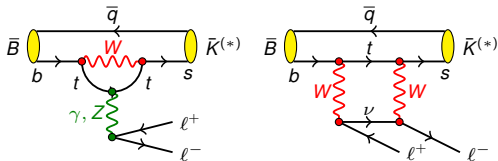
- We will present measurements of ratios of these B branching ratios at LHCb:

- Theoretically clean: cancellation of QCD effects
- Experimentally clean: cancellation of efficiency and reconstruction effects

In this talk: two front LFU tests

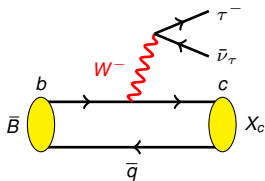
► $R(K^{(*)}) = \mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-) / \mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)$

- **FCNC $b \rightarrow s l l$**
- Rare decay forbidden at the tree level
- Very sensitive to NP contributions in the loops



► $R(X_c) = \mathcal{B}(B \rightarrow X_c \tau^+ \nu_\tau) / \mathcal{B}(B \rightarrow X_c \mu^+ \nu_\mu)$, $X_c = D, D^*$ or J/ψ

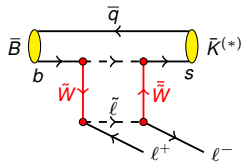
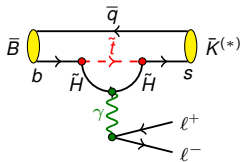
- **Tree level $b \rightarrow c \tau \nu_\tau$**
- Abundant semileptonic decay
- Very well known in SM
- Possible NP coupling mainly to the 3rd family



In this talk: two front LFU tests

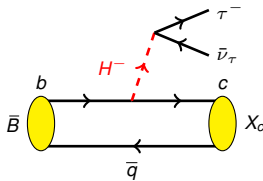
► $R(K^{(*)}) = \mathcal{B}(B \rightarrow K^{(*)} \mu^+ \mu^-) / \mathcal{B}(B \rightarrow K^{(*)} e^+ e^-)$

- **FCNC $b \rightarrow sll$**
- Rare decay forbidden at the tree level
- Very sensitive to NP contributions in the loops



► $R(X_c) = \mathcal{B}(B \rightarrow X_c \tau^+ \nu_\tau) / \mathcal{B}(B \rightarrow X_c \mu^+ \nu_\mu)$, $X_c = D, D^*$ or J/ψ

- **Tree level $b \rightarrow c\tau\nu_\tau$**
- Abundant semileptonic decay
- Very well known in SM
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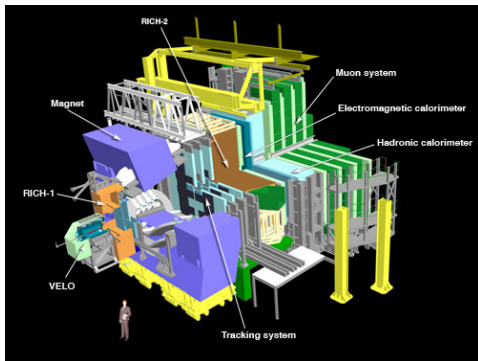
► Advantages:

- Excellent vertexing, tracking and PID
- Trigger also on low momentum hadrons
- Enormous data sample from LHC high $b\bar{b}$ cross section
- All type of b-hadrons, including B_c^+ and Λ_b

► Challenges:

- Missing neutrinos \rightarrow unconstrained kinematics
- High track multiplicity \rightarrow significant amount of background
- High particle momenta \rightarrow significant Bremsstrahlung for electrons

In this talk: ONLY Run 1 data, 3 fb^{-1} , 2011(12), $\sqrt{s} = 7(8) \text{ TeV}$



LFU with $b \rightarrow sll : R_K, R_{K^*0}$

Test of LFU with $B^+ \rightarrow K^+ \ell^+ \ell^-$ [PRL,113, 151601 (2014)]

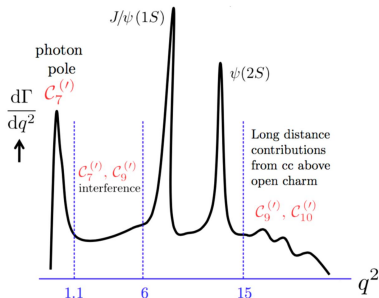
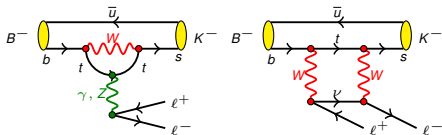
- In the SM:

$$R_K \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3})$$

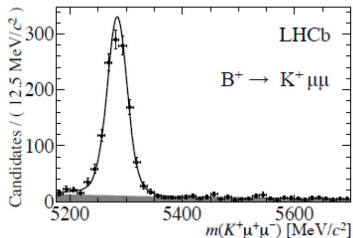
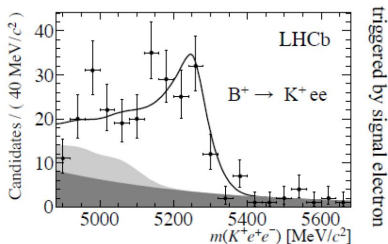
[e.g. PRL 112, 149902 (2014)]

- In 2014, LHCb measured R_K for $q^2 = m_{\ell\ell}^2 \in [1, 6] \text{ GeV}^2/c^4$ (avoid resonance regions)
- Extremely challenging due to differences in the way μ and e interact with detector: Bremsstrahlung and trigger
- Signal extracted via invariant mass fits
- Measure using double ratio to minimize uncertainties:

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-))} / \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-))}$$

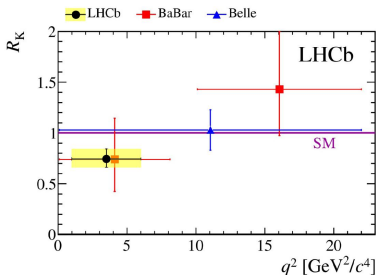


Test of LFU with $B^+ \rightarrow K^+ \ell^+ \ell^-$ [PRL,113, 151601 (2014)]



grey: partially reconstructed b -hadron decays; dark: combinatorial

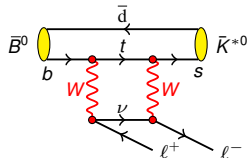
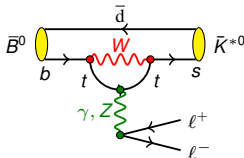
$$R_K(\text{LHCb}, 1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.745^{+0.090}_{-0.074} \pm 0.036 \text{ (2.6}\sigma \text{ below SM)}$$



[BaBar, PRD 86, 032012]

[Belle, PRL 103, 171901]

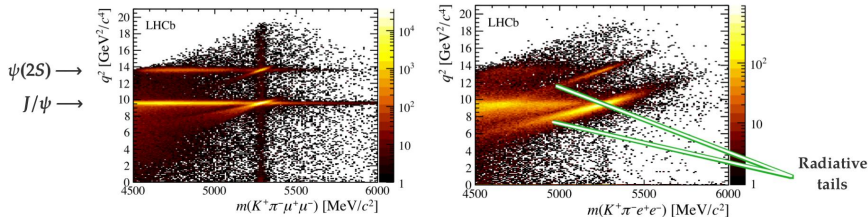
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}$$



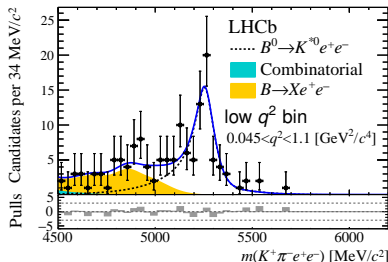
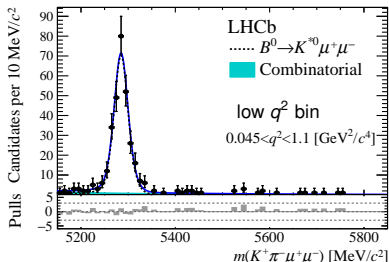
- Similar to R_K
- Measured in two q^2 bins $[0.045 - 1.1]$ and $[1.1 - 6] \text{ GeV}^2/c^4$, with $K^{*0} \rightarrow K^+ \pi^-$
- Double ratio to minimize uncertainties:

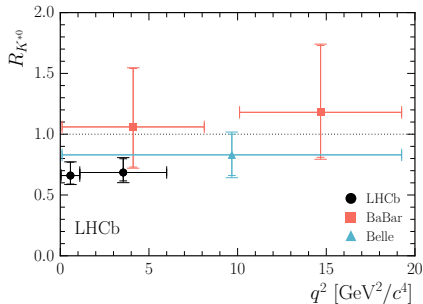
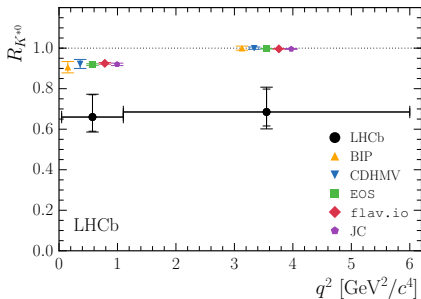
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} / \frac{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}$$

- Challenges are again trigger and Bremsstrahlung due to differences between μ and e



- Fit $K^+ \pi^- \ell^+ \ell^-$ mass in low and central q^2 bins
- Simultaneous fit to J/ψ and non-resonant channels





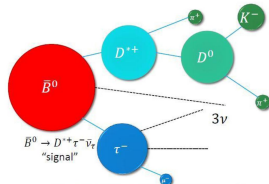
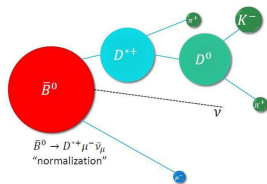
- Lower bin: $R_{K^{*0}} = 0.66_{-0.07}^{+0.11}(\text{stat}) \pm 0.03(\text{syst})$ **2.1 – 2.3 σ below SM**
- Central bin: $R_{K^{*0}} = 0.69_{-0.07}^{+0.11}(\text{stat}) \pm 0.05(\text{syst})$ **2.4 – 2.5 σ below SM**
- Attempts to interpret R_K and $R_{K^{*0}}$: see e.g. [Capdevila et al., arXiv:1704.05340]
“LFU violation favored at 3.3 σ wrt LFU”

LFU with $b \rightarrow c\tau\nu_\tau$
 $R(D), R(D^*), R(J/\psi)$

$R(D^*)$ muonic ($\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$) [PRL 115 (2015) 112001]

$$R(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}$$

with $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$



- Precise SM prediction: $R(D^*) = 0.252 \pm 0.003$

[S.Fajfer et al., PRD 85(2012) 094025]

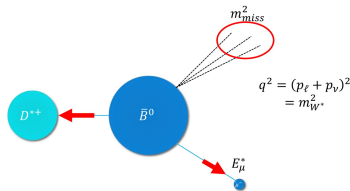
- Normalization mode with the *same final state*
- $\mathcal{B}(\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau) = (17.39 \pm 0.04)\%$
- Neutrinos: no narrow peak to fit
- Separate τ and μ via a 3D binned template fit, in the B rest frame, on:

- 1 $m_{\text{miss}}^2 = (p_B^\mu - p_{D^*}^\mu - p_\mu^\mu)^2$

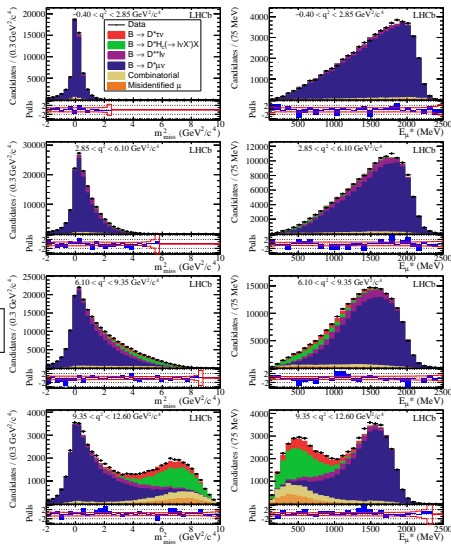
- 2 E_μ^*

- 3 $q^2 = (p_B^\mu - p_{D^*}^\mu)^2$

- Background and signal shapes extracted from control samples and simulations validated against data



- Signal more visible in the high q^2 bins (red)
- Backgrounds: feed-down from excited D states, double charm DD where one D decays semileptonically, combinatorial, muon mis-ID



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

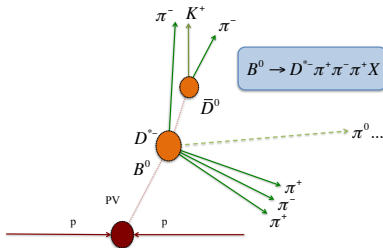
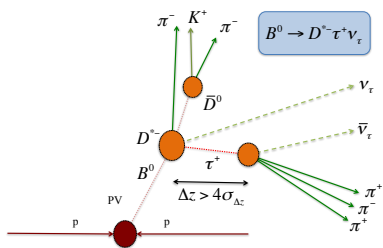
2.1 σ above SM

- Dominant systematics: size of simulation sample \rightarrow will be improved in the next iteration

$$R(D^*) = \mathcal{K}(D^*) \times \frac{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}$$

with $\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi)}$, $\tau^+ \rightarrow 3\pi(\pi^0)\nu_\tau$

- Signal and normalization modes chosen to have the same final state
- $\mathcal{B}(\tau \rightarrow 3\pi(\pi^0)\nu_\tau) \simeq 13.9\%$ (was $\sim 17\%$ for the muonic case)
- No charged lepton in final state: zero bkg from $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ and good τ vertex reconstruction but large hadronic bkg: $B \rightarrow D^* 3\pi X$ (BR $\sim 100\times$ signal), $B \rightarrow D^* D_s X$ (BR $\sim 10\times$ signal)
- Main bkg ($B \rightarrow D^* 3\pi X$) suppressed by requiring the τ vertex to be downstream wrt B vertex along beam direction
- BDT used to suppress the remaining background

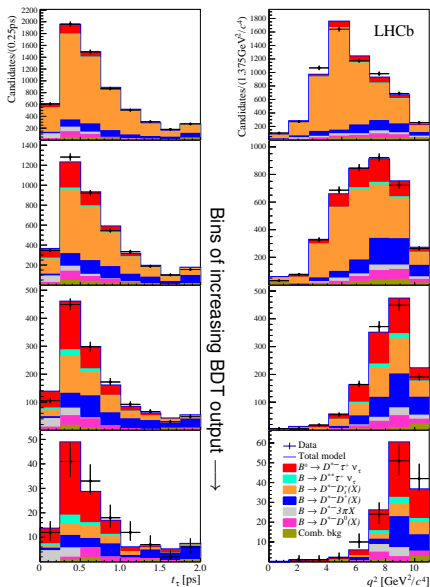


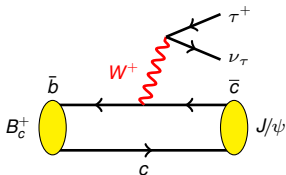
- $N(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)$ from 3D binned fit on BDT output, τ decay time and q^2
- Templates extracted from simulation and data control samples
- $N(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = 1300 \pm 85$

$$R(D^*) = 0.285 \pm 0.019(\text{stat}) \pm 0.025(\text{syst}) \pm 0.015(\text{ext})$$

1.0 σ above SM

- Dominant systematics: size of simulation samples and external BR





- Generalization of $R(D^*)$ to B_c^+

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)}$$

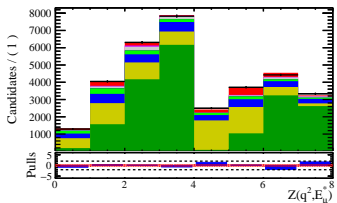
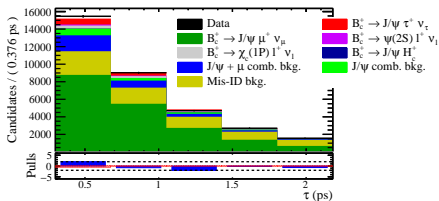
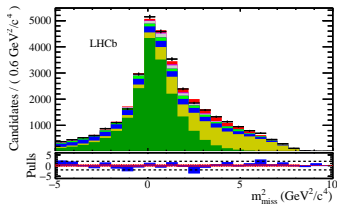
- B_c^+ decay form factors unconstrained experimentally: theoretical prediction not yet precise $R^{\text{theo}}(J/\psi) \in [0.25, 0.28]$

[PLB452 (1999) 120, arXiv:0211021, PRD73 (2006) 054024, PRD74 (2006) 074008]

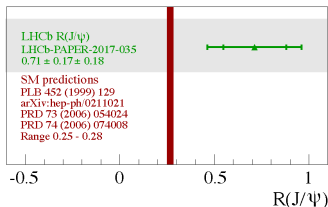
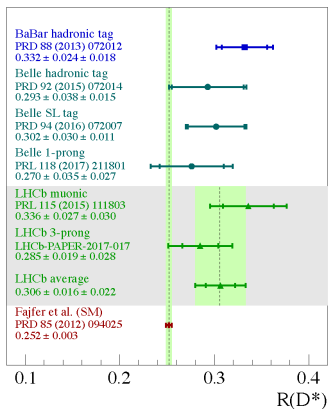
- Reconstruct signal with $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$
- Like in $R(D^*)$, use m_{miss}^2 , E_μ^* and q^2 . Add information from B_c^+ decay time

- 3D template binned fit
 - Shapes of various components are represented by a template distribution derived from control samples or simulations validated against data
 - Main background is $b \rightarrow J/\psi + \text{mis-ID hadron}$
 - First evidence for the decay $B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau$ (3σ)
- $$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

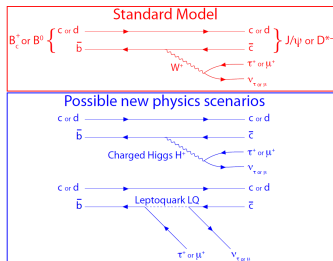
About 2σ above SM
- Main systematics: Form factor and size of simulation sample



$R(D^*)$ and $R(J/\psi)$ summary



ALL $R(D^*)$ and $R(J/\psi)$
 measurements lie **ABOVE**
 the SM expectations!



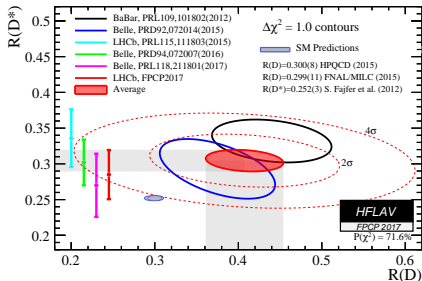
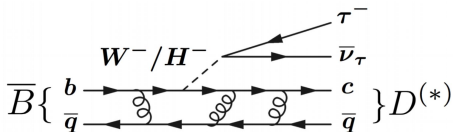
$R(D^*)$ and $R(D)$ summary

- Similarly to $R(D^*)$, the ratio is defined for D^- mesons:

$$R(D) = \frac{\mathcal{B}(B^0 \rightarrow D^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^- \ell^+ \nu_\ell)}$$

and has been measured by Belle and BaBar

- Theoretical predictions: $R(D) = 0.300 \pm 0.008$, [HPQCD, PRD 92, 054510 (2015)]



- Combination of LHCb, Belle and BaBar: **4.1 σ wrt SM!**

► Exciting time for LFU tests with TWO anomalies:

- **Charged current $b \rightarrow c\tau\nu$** , 4.1σ tension in $R(D) - R(D^*)$ when combining BaBar, Belle and LHCb results. Recent 2σ discrepancy in the same direction observed by LHCb in $B_c^+ \rightarrow J/\psi\tau^+\nu_\tau$
- **FCNC $b \rightarrow s\ell\ell$** , notably R_K and R_{K^*0}
Not mention here but also tensions in angular observables (P'_5, \dots)

► Measurements presented performed with Run 1 and limited by stat. Many more to come with larger data sets:

- $b \rightarrow c\tau\nu$: $R(D^0)$, $R(D^+)$, $R(D_s^{(*)})$, $R(\Lambda_c^{(*)})$, ...
- $b \rightarrow s\ell\ell$: R_ϕ , R_{pK} , $R_{K\pi\pi}$, $R_{K_S^0}$, $R_{K^{*+}}$, ...

► LHCb Run 2 (2015-2018) \simeq Run 1 $\times 3$.

Then, Upgrade, Run 3, 4 and 5 until 2035!

► Exciting work-plan in the coming years, with **crucial interplay between experiment and theory**

Backups

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Tantalizing tensions with respect to the SM

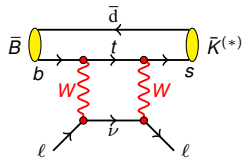
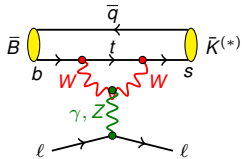
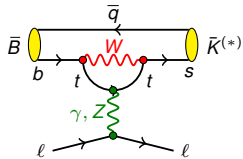
| Observable | Tension wrt SM | Limited by |
|--|----------------|--------------|
| $B \rightarrow D^{(*)} \tau \nu / B \rightarrow D^{(*)} \ell \nu, \ell = \mu, e$ | 4.1σ | experiment |
| $(g-2)_\mu$ | 3.6σ | exp. & theo. |
| $B^0 \rightarrow K^{*0} \mu \mu$ angular dist., BR | 3.4σ | exp. & theo. |
| $B_s^0 \rightarrow \phi \mu \mu$ BR | 3.0σ | experiment |
| $2\sigma(W \rightarrow \tau \nu_\tau) / (\sigma(W \rightarrow e \nu_e) + \sigma(W \rightarrow \mu \nu_\mu))$ | 2.8σ | experiment |
| $B^+ \rightarrow K^+ \mu \mu / B^+ \rightarrow K^+ e e$ | 2.6σ | experiment |
| $B^0 \rightarrow K^{*0} \mu \mu / B^0 \rightarrow K^{*0} e e$ | 2.4σ | experiment |
| $B_c \rightarrow J/\psi \tau \nu / B_c \rightarrow J/\psi \mu \nu$ | 2.0σ | exp. & theo. |

Many other interesting results exhibit no tension today, but put strong constraints on NP models.

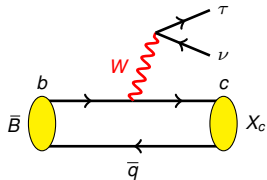
They remain fundamental for future searches, e.g.: γ , B^0 - D^0 - K^0 -mixing, ϕ_s , $\sin 2\beta$, $B_s^0 \rightarrow \mu \mu$, $B \rightarrow X_S \gamma$, V_{cb} , $B \rightarrow \tau \nu$, CPV in charm, CLVF, $K \rightarrow \pi \nu \bar{\nu}$, ...

Flavor Anomalies

- $b \rightarrow sll$



- $b \rightarrow cTV_\tau$



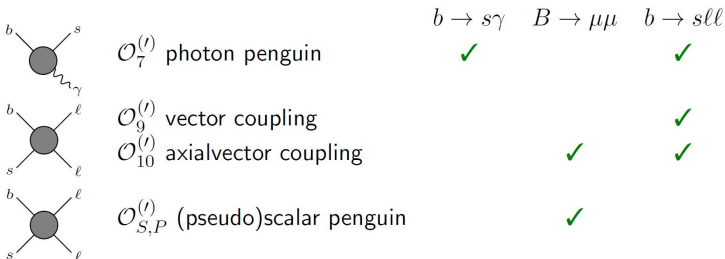
Effective field theory

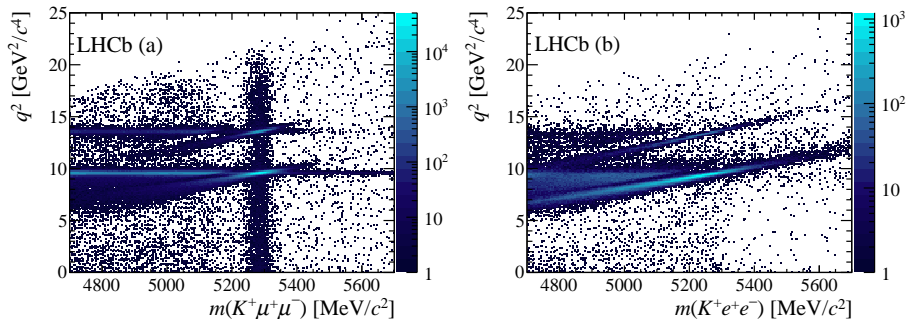
Transition $B \rightarrow f$ described by an effective Hamiltonian $\langle f | \mathcal{H}_{\text{eff}} | B \rangle$, with

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i \left(\underbrace{C_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{C'_i \mathcal{O}'_i}_{\text{Right-handed}} \right)$$

Computed by splitting into:

- C_i (Wilson coefficients): short distance (perturbative) effective couplings, can be computed in terms of fundamental couplings of the SM and beyond
- $\langle f | \mathcal{O}_i | B \rangle$: long distance (non perturbative), computed using QCD at low energy or extracted by phenomenological analysis. \mathcal{O}_i are local operators:

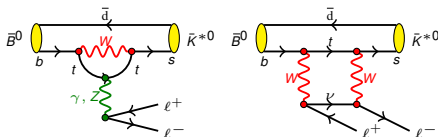




$$R_K(\text{LHCb}, 1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.745_{-0.074}^{+0.090} \pm 0.036 \text{ (2.6}\sigma \text{ from SM)}$$

The dominant sources of systematic uncertainty are due to the parametrization of the $B^+ \rightarrow J/\psi K e^+ e^-$ mass distribution and the estimate of the trigger efficiencies that both contribute 3% to the value of R_K

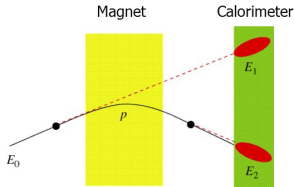
$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}$$



- Similar to R_K
- Measured in two q^2 bins $[0.045 - 1.1]$ and $[1.1 - 6]$ GeV^2/c^4 , with $K^{*0} \rightarrow K^+ \pi^-$
- Double ratio to minimize uncertainties:

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

- Challenges are again trigger and Bremsstrahlung due to differences between μ and e
- Electrons \rightarrow larger Bremsstrahlung \rightarrow degraded momentum and mass resolution
- Recovery momentum procedure: extrapolation of the electron track upstream of the magnet and addition of calorimeter cluster to the electron momentum

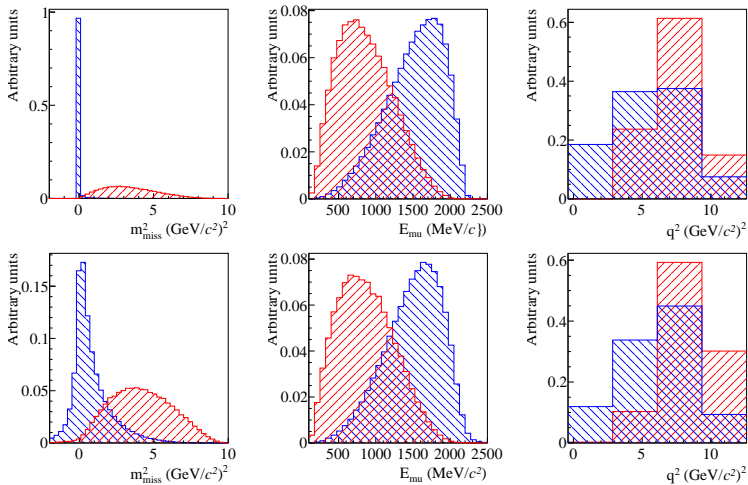


Problem of missing neutrino: no analytical solution for p_B .

Approximate B momentum $p_B^z = \frac{m_B}{m_{D\mu}} p_{D\mu}^z$.

m_B is the known B mass, $m_{D\mu}$ is the reconstructed one.

This leads to $\sim 18\%$ resolution on q^2 , m_{miss}^2 and E_μ^* , enough to preserve the discriminating feature of the original variables.



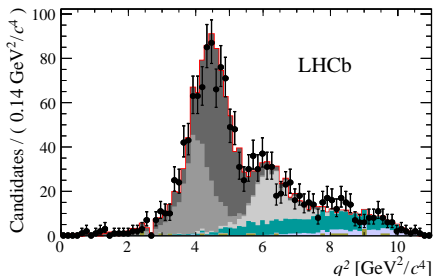
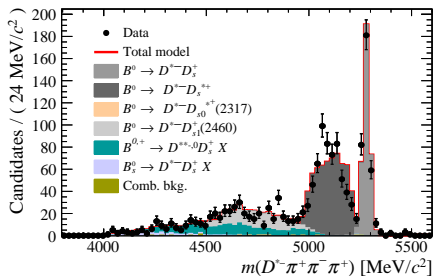
Signal(red) and normalization mode (blue) using truth(top) and reconstructed(bottom) quantities

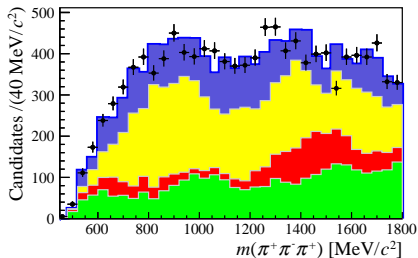
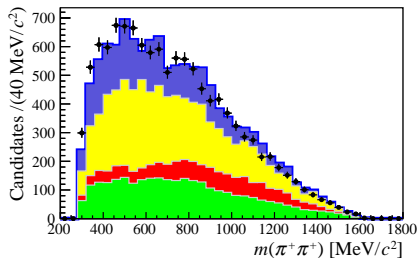
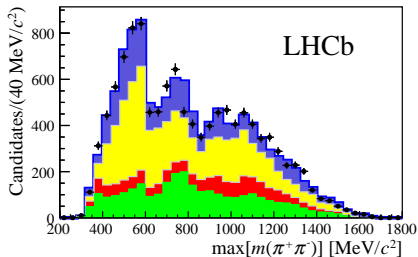
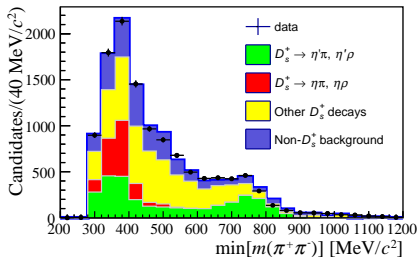
| Model uncertainties | Absolute size ($\times 10^{-2}$) |
|---|--|
| Simulated sample size | 2.0 |
| Misidentified μ template shape | 1.6 |
| $\bar{B}^0 \rightarrow D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors | 0.6 |
| $\bar{B} \rightarrow D^{*+}H_c(\rightarrow \mu\nu X')$ X shape corrections | 0.5 |
| $\mathcal{B}(\bar{B} \rightarrow D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \rightarrow D^{**}\mu^-\bar{\nu}_\mu)$ | 0.5 |
| $\bar{B} \rightarrow D^{**}(\rightarrow D^*\pi\pi)\mu\nu$ shape corrections | 0.4 |
| Corrections to simulation | 0.4 |
| Combinatorial background shape | 0.3 |
| $\bar{B} \rightarrow D^{**}(\rightarrow D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors | 0.3 |
| $\bar{B} \rightarrow D^{*+}(D_s \rightarrow \tau\nu)X$ fraction | 0.1 |
| Total model uncertainty | 2.8 |
| Normalization uncertainties | Absolute size ($\times 10^{-2}$) |
| Simulated sample size | 0.6 |
| Hardware trigger efficiency | 0.6 |
| Particle identification efficiencies | 0.3 |
| Form-factors | 0.2 |
| $\mathcal{B}(\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau)$ | < 0.1 |
| Total normalization uncertainty | 0.9 |
| Total systematic uncertainty | 3.0 |

$$R(D^*) = \mathcal{K}(D^*) \times \frac{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}$$

with $\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi)} = \frac{N_{D^* \tau \nu_\tau}}{N_{D^* 3\pi}} \times \frac{\varepsilon_{D^* 3\pi}}{\varepsilon_{D^* \tau \nu_\tau}} \times \frac{1}{\mathcal{B}(\tau^+ \rightarrow 3\pi(\pi^0)\bar{\nu}_\tau)}$

- Signal and normalization modes chosen to have the same final state
- $\mathcal{B}(\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau) = (9.31 \pm 0.05)\%$
- $\mathcal{B}(\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \pi^0 \bar{\nu}_\tau) = (4.62 \pm 0.05)\%$
- $N_{D^* 3\pi}$ from unbinned fit to $D^* 3\pi$ invariant mass
- $N_{D^* \tau \nu_\tau}$ from binned templated fit
- $\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi)$ from [\[BaBar, PRD94 \(2016\) 091101\]](#) ($\sim 4\%$ precision)
- $\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)$ from PDG ($\sim 2\%$ precision)



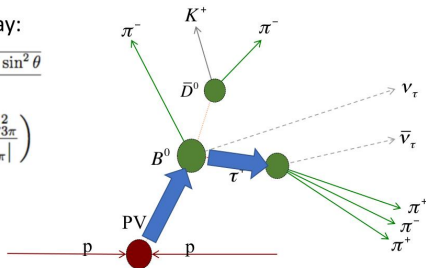
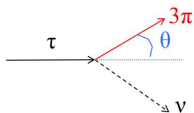


Signal reconstruction

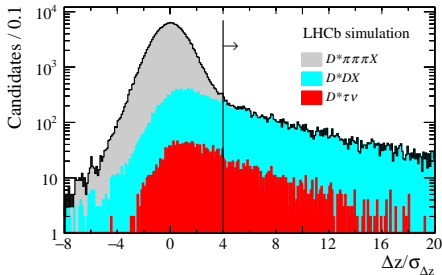
- 2-fold ambiguity when reconstructing the τ decay:

$$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}| \cos \theta \pm E_{3\pi} \sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2 \sin^2 \theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2 \cos^2 \theta)}$$

- Can be lifted by choosing $\theta_{max} = \arcsin\left(\frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau|\vec{p}_{3\pi}|}\right)$



- Same argument for B decay
- Possible to reconstruct rest frame variables such as τ decay time and q^2 .**
- Negligible biases**, and **sufficient resolution** to preserve good discrimination between signal and background.



Distribution of the distance between the B^0 vertex and the 3π vertex along the beam direction, divided by its uncertainty, obtained using simulation. The grey area corresponds to the prompt background component, the cyan and red areas to double-charm and signal components, respectively. The vertical line shows the 4σ requirement used in the analysis to reject the prompt background component

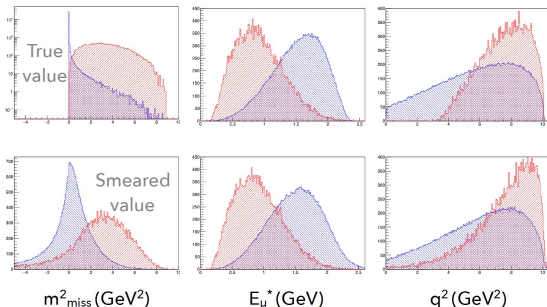
$$R(D^*) = 0.285 \pm 0.019(\text{stat}) \pm 0.025(\text{syst}) \pm 0.015(\text{ext})$$

| Source | $\delta R(D^{*-})/R(D^{*-})[\%]$ |
|--|----------------------------------|
| Simulated sample size | 4.7 |
| Empty bins in templates | 1.3 |
| Signal decay model | 1.8 |
| $D^{*-} \tau \nu$ and $D_s^{*-} \tau \nu$ feeddowns | 2.7 |
| $D_s^+ \rightarrow 3\pi X$ decay model | 2.5 |
| $B \rightarrow D^{*-} D_s^+ X$, $B \rightarrow D^{*-} D^+ X$, $B \rightarrow D^{*-} D^0 X$ backgrounds | 3.9 |
| Combinatorial background | 0.7 |
| $B \rightarrow D^{*-} 3\pi X$ background | 2.8 |
| Efficiency ratio | 3.9 |
| Total uncertainty | 8.9 |

- Generalization of $R(D^*)$ to B_c^+

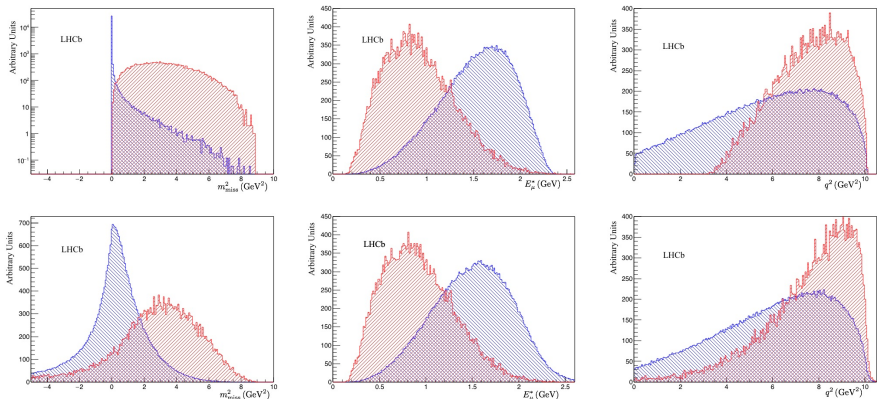
$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)}$$

- B_c^+ decay form factors unconstrained experimentally: theoretical prediction not yet precise 0.25-0.28
- Reconstruct signal with $\tau \rightarrow \mu \nu_\mu \nu_\tau$ (17%)
- Like in $R(D^*)$, use m_{miss}^2 , E_μ^* and q^2 . Add information from B_c^+ decay time
- Imperfect reconstruction due to missing neutrinos. The broad shapes of the distributions are smeared but their discriminating power is preserved



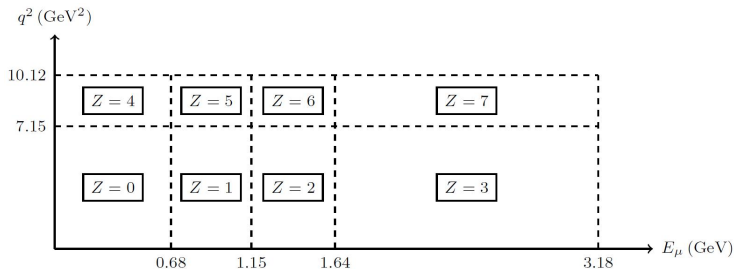
Systematic uncertainties

| Model uncertainties | Size (eff. corrected) ($\times 10^{-2}$) |
|---|--|
| Uncertainty due to finite size of simulation data | 8.0 |
| $B_c^+ \rightarrow J/\psi$ form factors | 12.1 |
| $B_c^+ \rightarrow \psi(2S)$ form factors | 3.2 |
| Bias correction | 5.4 |
| $B_c^+ \rightarrow J/\psi H_c X$ cocktail composition | 3.6 |
| Z binning strategy | 5.6 |
| Misidentification background strategy | 5.4 |
| Combinatorial background cocktail | 4.5 |
| Combinatorial J/ψ sideband scaling | 0.9 |
| Empirical reweighting | 1.6 |
| Semitauonic $\psi(2S)$ and χ_c feed-down | 0.9 |
| Fixing $A_2(q^2)$ slope to zero | 0.3 |
| Efficiency ratio | 0.6 |
| $\mathcal{B}(\tau \rightarrow \mu \nu \nu)$ | 0.2 |
| B_c^+ lifetime | included in stat. |
| Total systematic uncertainty | 17.7 |
| Statistical uncertainty | 17.3 |

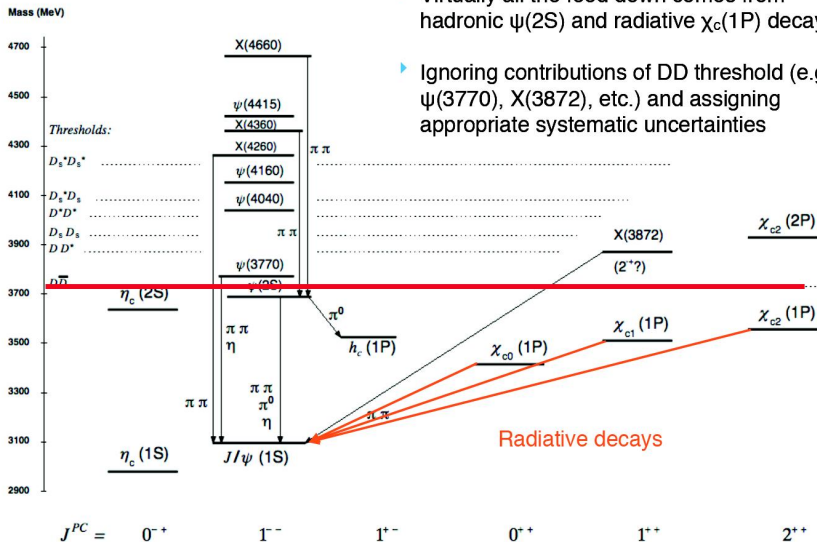


For each fit variable (save the mostly unaltered decay time), the distributions of the quantity calculated using the simulated true B_C^+ momentum and the approximated momentum are shown. In each plot, the normalization $B_C^+ \rightarrow J/\psi \mu^+ \nu_{\mu}$ decay is shown in blue, while the signal $B_C^+ \rightarrow J/\psi \tau^+ \nu_{\tau}$ is shown in red. The smearing induced by the rest frame approximation does not wash out the discriminating power of these variables.

Trick to make a 3D fit with 4 variables: the Z variable merge information from q^2 and E_μ^*



Charmonium feed-down background



- ▶ Virtually all the feed down comes from hadronic $\psi(2S)$ and radiative $\chi_c(1P)$ decays
- ▶ Ignoring contributions of DD threshold (e.g. $\psi(3770)$, $X(3872)$, etc.) and assigning appropriate systematic uncertainties

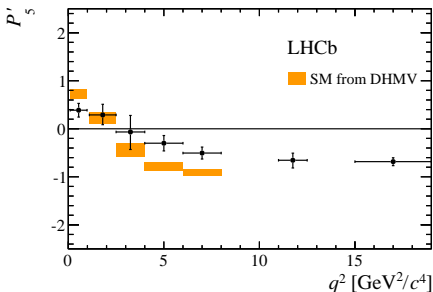
About the Form Factors

The templates are derived from simulation for the signal and the normalization modes, which requires knowledge of the $B_c \rightarrow J/\psi$ form factors. These have not yet been precisely determined and the theoretical predictions, e.g. those from Kiselev, Ebert, Faustov, and Galkin have been tested against data. Thus, for this measurement, the shared form factors for the signal and normalization channels are determined directly from the data by employing a z-expansion parametrization [BCL] to fit a sub-sample of the data that is enriched in the normalization mode.

The Decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Measured by 4 different experiments: Belle, LHCb, ATLAS, CMS
- Most precise measurement from LHCb

LHCb Only

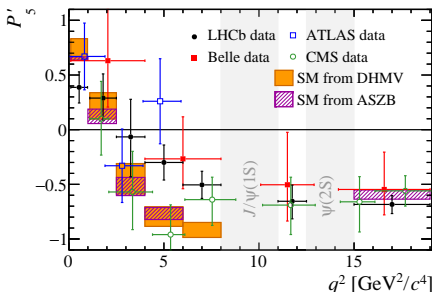


LHCb, JHEP02 (2016) 104,

arxiv:1512.04442

- Significance: 3.4σ
 - Ongoing discussion about the interpretation and theory predictions
 - Situation is not as clear cut as for the R -measurements

All Together



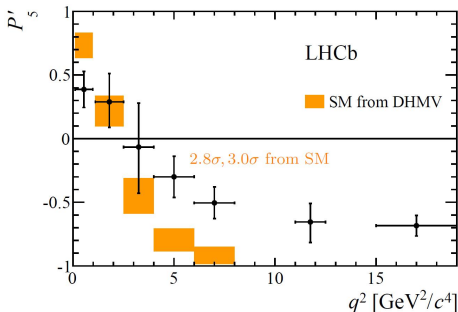
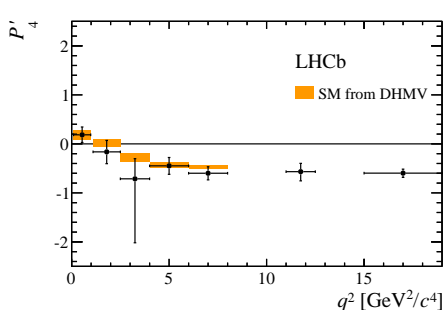
Belle, arxiv:1604.04042

ATLAS, ATLAS-CONF-2017-023

CMS, CMS-PAS-BPH-15-008

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

[LHCb, arXiv:1512.04442], [DHMV = Descotes-Genon et al., JHEP 12 (2014) 125]



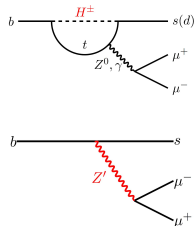
- Mainly compatible with the SM except one angular variable

- Local $2.8\text{--}3.0\sigma$ discrepancy with SM prediction in bins $q^2 \equiv m_{\mu\mu}^2 \in [4, 8] \text{ GeV}^2/c^4$ of P'_5

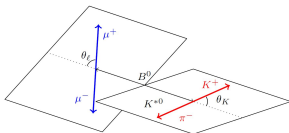
- LHCb fit of the EW penguin Wilson coeff C_9 , including $S_3 - S_9, F_L, A_{FB}$: 3.4σ from SM

- Theoretical work ongoing to better understand this effect: NP or unexpectedly large hadronic effect? see e.g. [Descotes-Genon et al., arXiv:1510.04239]

- Channel also studied by BaBar [arXiv:1508.07960], Belle [PRL 103, 171801], CMS [PLB 753(2016)424], ATLAS [ATLAS-CONF-2013-038] and CDF [PRL 108, 081807]



- Same motivations as $B^- \rightarrow K^- \ell^+ \ell^-$.
Same SM loops, but with a **vector** in the final state, sensitive to $C_7^{(\prime)}$, $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$
- Complicated angular analysis with many observables:



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

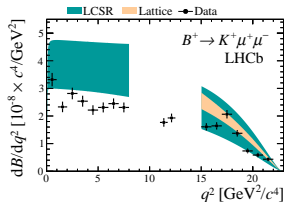
- Can parameterize the angular coeff to be largely free of form factor uncertainties

[Descotes-Genon et al, JHEP, 1305:137, (2013)]

e.g. $P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$ where F_L is the fraction of longitudinal polarization

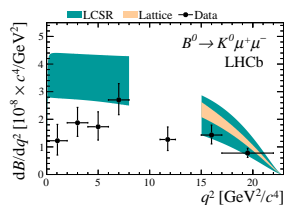
Other $b \rightarrow s\mu^+\mu^-$ Branching Fractions

$$\underline{B^+ \rightarrow K^+\mu^+\mu^-}$$



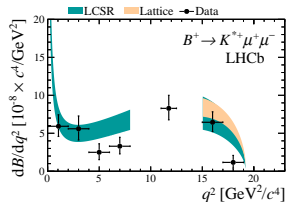
- Also used for R_K

$$\underline{B_d^0 \rightarrow K^{*0}\mu^+\mu^-}$$



- Also used for R_{K^*}

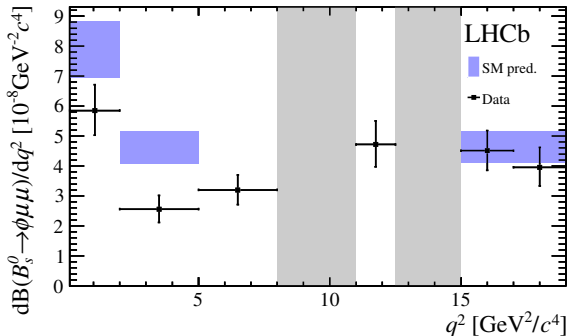
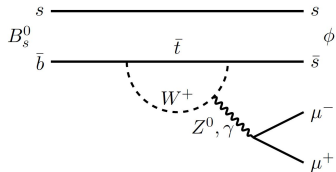
$$\underline{B^+ \rightarrow K^{*+}\mu^+\mu^-}$$



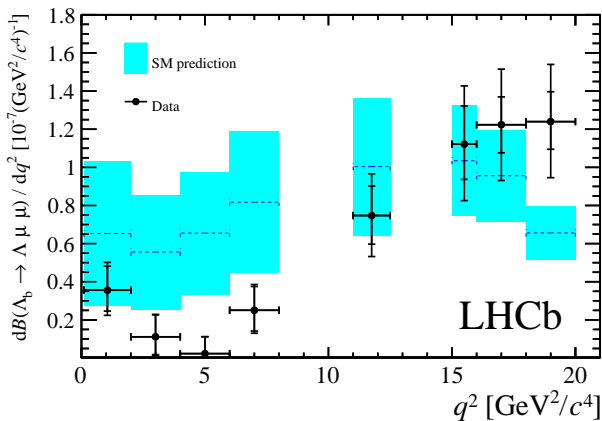
LHCb, JHEP06 (2014) 133, [arxiv:1403.8044](https://arxiv.org/abs/1403.8044)

- Measure branching fractions as a function of q^2
 - All are below the theory predictions
- ⇒ Same trend as for R_K and R_{K^*}

- Similar to $B^0 \rightarrow K^* \mu^+ \mu^-$, but not self-tagged (no CP observable accessible)
- Narrow ϕ resonance gives clean signal peak
- Full angular analysis
- At low q^2 , BR also below SM [Altmannshofer, Straub, EPJ C75 (2015) 382], [Bharucha et al, arXiv:1503.05534]

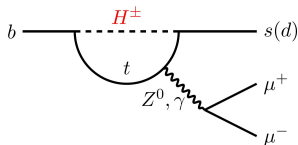


- Similar to $B^0 \rightarrow K^* \mu^+ \mu^-$
- Baryonic system provides sensitivity to additional observables
- Rate still too low to perform a full angular analysis.
- Again, BR lower than SM at low q^2 : deficit of muons?

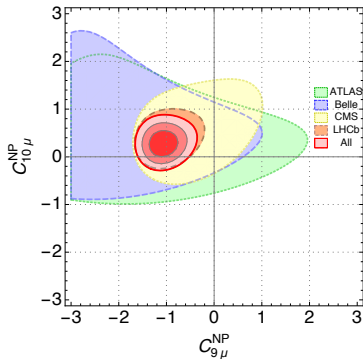


SM from [Detmold et al., PRD 87, (2013) 074502]

Neutral current anomalies $b \rightarrow sll$



- Several measurements involving $b \rightarrow sll$, ($l = \mu, e$) deviate from their SM expectation ($2 - 3\sigma$)
- $R_K = \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)$, R_{K^*} , BR de $B^0 \rightarrow K^* \mu^+ \mu^-$, $B_s^0 \rightarrow \phi \mu^+ \mu^-$, $\Lambda_b \rightarrow \Lambda^0 \mu^+ \mu^-$, P'_5
- The combined effect of these “small” deviations point towards the same direction: $C_{9\mu}^{\text{NP}} = -1$, implying **violation of the leptonic universality $\mu \neq e$** . Significance of global fits $\sim 5\sigma$ [arXiv:1704.05340](https://arxiv.org/abs/1704.05340)
- Deficit of muons? Theoretical uncertainties or experimental?



[arXiv:1704.05340](https://arxiv.org/abs/1704.05340)

LHCb plans

- **Run 2** (2016-2018): 5 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$, improved trigger
- Some major experimental measurements (e.g. γ , $B_s^0 \rightarrow \phi\phi$) are not yet at the level of theoretical prediction
- Above a luminosity of $\sim 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, LHCb efficiency to trigger hadronic modes saturates, because of the L0-trigger bottleneck which can not cope with more than 1 MHz output rate.

⇒ **upgrade** the LHCb experiment in 2018–2019:

- Full software trigger: read all detector at 40 MHz → $\times 2$ efficiency for hadronic final state.
- Luminosity up to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, new challenges: high pile-up, large occupancies, radiation damages
- Detector upgrades: VELO (pixels), tracker (Silicon strips and scintillating fibers), RICH (multi-anode PMTs), CALO& MUON (new electronics), ...
- Aim to collect $\sim 50 \text{ fb}^{-1}$. Annual yields wrt published analyses: $\times 10$ for muonic final states and $\times 20$ for hadronic modes.



APPROVED



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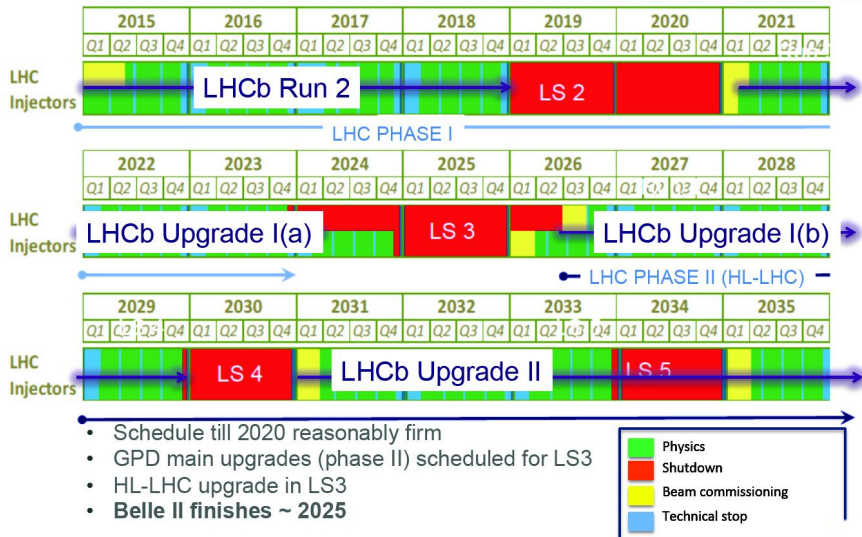
APPROVED

Expected performances of LHCb upgrade [LHCb-PUB-2014-040]

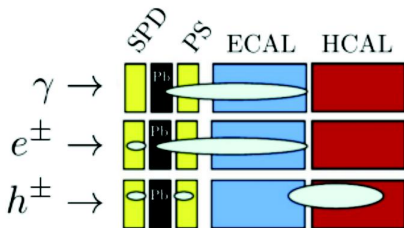
| Type | Observable | LHC Run 1 | LHCb 2018 | LHCb upgrade | Theory |
|--------------------------------|---|-------------|-------------|--------------------------------|--------------|
| B_S^0 mixing | $\phi_S(B_S^0 \rightarrow J/\psi \phi)$ (rad) | 0.049 | 0.025 | 0.009 | ~ 0.003 |
| | $\phi_S(B_S^0 \rightarrow J/\psi f_0(980))$ (rad) | 0.068 | 0.035 | 0.012 | ~ 0.01 |
| | $A_{sl}(B_S^0)$ (10^{-3}) | 2.8 | 1.4 | 0.5 | 0.03 |
| Gluonic penguin | $\phi_S^{\text{eff}}(B_S^0 \rightarrow \phi \phi)$ (rad) | 0.15 | 0.10 | 0.018 | 0.02 |
| | $\phi_S^{\text{eff}}(B_S^0 \rightarrow K^{*0} \bar{K}^{*0})$ (rad) | 0.19 | 0.13 | 0.023 | < 0.02 |
| | $2\beta^{\text{eff}}(B^0 \rightarrow \phi K_S^0)$ (rad) | 0.30 | 0.20 | 0.036 | 0.02 |
| Right-handed currents | $\phi_S^{\text{eff}}(B_S^0 \rightarrow \phi \gamma)$ (rad) | 0.20 | 0.13 | 0.025 | < 0.01 |
| | $\tau^{\text{eff}}(B_S^0 \rightarrow \phi \gamma) / \tau_{B_S^0}$ | 5% | 3.2% | 0.6% | 0.2% |
| Electroweak penguin | $S_3(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$ | 0.04 | 0.020 | 0.007 | 0.02 |
| | $q_0^2 A_{\text{FB}}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$ | 10% | 5% | 1.9% | $\sim 7\%$ |
| | $A_1(K \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$ | 0.09 | 0.05 | 0.017 | ~ 0.02 |
| | $\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$ | 14% | 7% | 2.4% | $\sim 10\%$ |
| Higgs penguin | $\mathcal{B}(B_S^0 \rightarrow \mu^+ \mu^-)$ (10^{-9}) | 1.0 | 0.5 | 0.19 | 0.3 |
| | $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) / \mathcal{B}(B_S^0 \rightarrow \mu^+ \mu^-)$ | 220% | 110% | 40% | $\sim 5\%$ |
| Unitarity triangle | $\gamma(B \rightarrow D^{(*)} K^{(*)})$ | 7° | 4° | 0.9° | negligible |
| angles | $\gamma(B_S^0 \rightarrow D_S^\mp K^\pm)$ | 17° | 11° | 2.0° | negligible |
| | $\beta(B^0 \rightarrow J/\psi K_S^0)$ | 1.7° | 0.8° | 0.31° | negligible |
| Charm \mathcal{CP} violation | $A_\Gamma(D^0 \rightarrow K^+ K^-)$ (10^{-4}) | 3.4 | 2.2 | 0.4 | – |
| | $\Delta A_{\mathcal{CP}}$ (10^{-3}) | 0.8 | 0.5 | 0.1 | – |

- $\phi_S^{\text{eff}}(B_S^0 \rightarrow \phi \phi)$ with a precision of 0.018
- γ with a precision below 1°

Planning LHC 2035



LHCb Calorimeters



- Composed of a Scintillating Pad Detector (SPD), a Preshower (PS), an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL)
- The SPD and the PS consist of a plane of scintillator tiles (2.5 radiation lengths, but to only $\sim 6\%$ hadronic interaction lengths)
- The ECAL has shashlik-type construction, i.e. a stack of alternating slices of lead absorber and scintillator (25 radiation lengths)
- The HCAL is a sampling device made from iron and scintillator tiles being orientated parallel to the beam axis (5.6 interaction lengths)