Imperial College London

New results on flavor anomalies at LHCb

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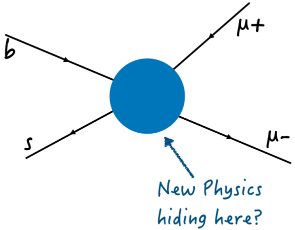
on behalf of the LHCb collaboration

Dark Matter @ LHC
Heidelberg, April 2018

The indirect approach



- Study processes that are suppressed or even forbidden in the SM - possible NP effects relatively large
- Precision measurement of observables that are very well predicted in the SM
- Access to higher mass scales, due to virtual contributions, in a model independent way

Flavour anomalies

A) Loop level $b \to s\ell^+\ell^-$ transitions

- Rates and angular observables in $b \to s\mu^+\mu^-$
- Lepton Flavour Universality tests in μ/e ratios

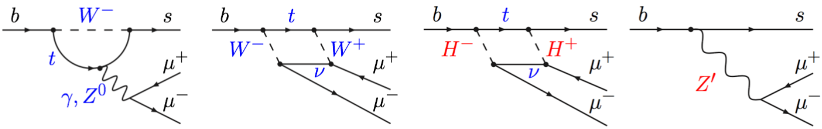
B) Tree level $b \to c\ell\nu$ transitions

- Lepton Flavour Universality tests in μ/τ ratios

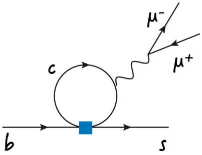
$\rightarrow$ The following results are obtained using the full Run1 LHCb sample ($3\,\text{fb}^{-1}$)

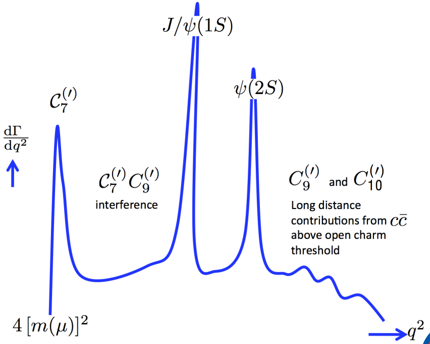
$b \to s\ell\ell$ transitions

- Flavour Changing Neutral Current (FCNC) $b \to s(d)l^+l^-$ decays, such as $B^0 \to K^{*0}\mu^+\mu^-$, are forbidden at tree level in the SM



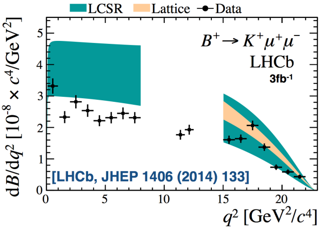
Veto out charmonium resonances, where the hadronic process dominates

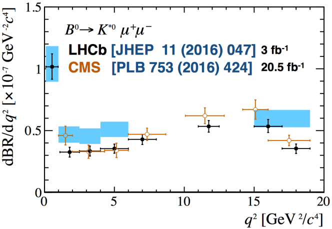


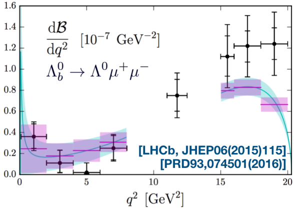


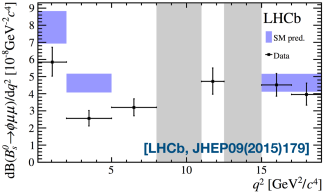
Branching fraction measurements

- Branching fractions consistently below the SM prediction for many $b \to s\mu\mu$ processes



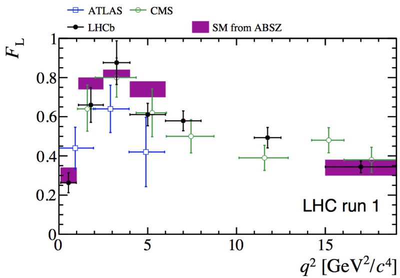


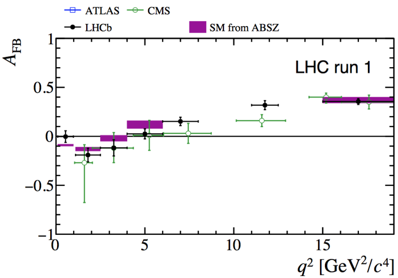




- SM predictions suffer from large hadronic uncertainties

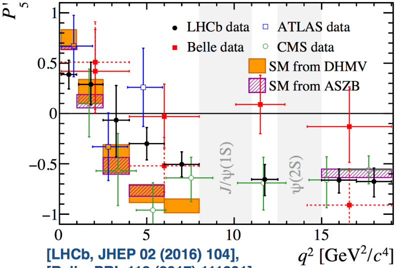
Angular observables - $B^0 \to K^{*0}\mu^+\mu^-$





- Complementary constraints on NP & orthogonal experimental systematics
- Good agreement with the SM in many of the observables
- Possibility to construct a set of "optimised" observables with reduced dependence on form-factor at leading order [JHEP 1204 (2012) 104]

$$P'_5 = S_5/\sqrt{F_L(1-F_L)}$$

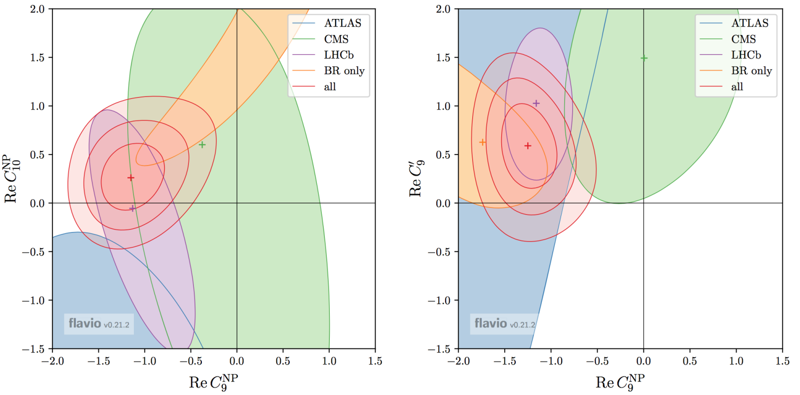


[LHCb, JHEP 02 (2016) 104], [Belle, PRL 118 (2017) 111801], [ATLAS-CONF-2017-023], [CMS-PAS-BPH-15-008]

Global fits to $b \to s\mu^+\mu^-$ observables

- Interpretation in effective theory, in terms of couplings (C_i) and local operators ($\mathcal{O}_i$), describing e.g. photon (C_7), vector (C_9) or axial-vector (C_{10}) contributions

W. Altmannshofer et al. EPJC 77 (2017) 377



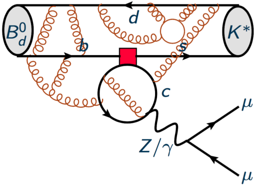
- Best fit prefers shifted vector coupling C_9 ($3-4\sigma$ depending on the group/observables included)
- Branching fractions and angular observables consistent

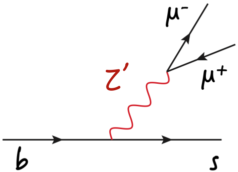
Hadronic effects or New Physics?

Dependence of observables on the vector coupling enters through

$$C_9^{\text{eff}} = C_9 + \Delta C_9^{\lambda}(q^2)$$

where $\Delta C_9^{\lambda}(q^2)$ contains all vector-like contributions





Unaccounted for $c\bar{c}$-loop contributions would mimic vector-like NP $\Rightarrow$ shifts in C_9

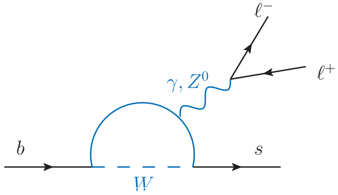
Big effort ongoing to improve both theory and experimental precision in order to solve this puzzle

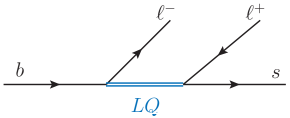
Lepton flavour universality tests

- In the Standard Model, couplings of the gauge bosons to leptons are independent of lepton flavour
  $\rightarrow$ branching fractions of e, μ and τ differ only by phase space and helicity-suppressed contributions

- **Free from QCD uncertainties that may affect other observables**

- Any sign of lepton flavour non-universality would be a direct sign for new





- NP models accomodating LFnU, often predict Lepton Flavour Violation too $\rightarrow$ *See Guido's talk tomorrow on the search for $B \rightarrow e\mu$ decays*

LFU in $B^+ \to K^+\ell^+\ell^-$

[JHEP 07 (2007) 040]

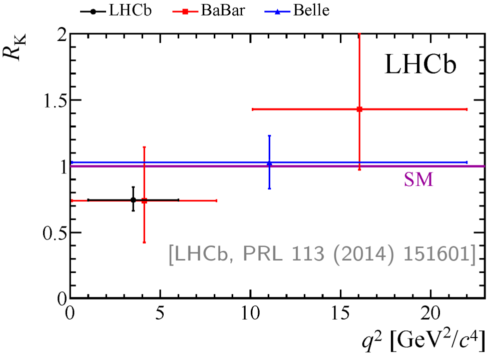
$$R_K^{SM} = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-4})\,^*$$

- Measurement performed with 3 fb^{-1} of data, in $1 < q^2 < 6\,\mathrm{GeV}/c^2$

$$R_K = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

Compatible with SM at 2.6σ

$\to$ Clear motivation to explore related LFU ratios ($R_{K^{*0}}$, R_ϕ, ...)



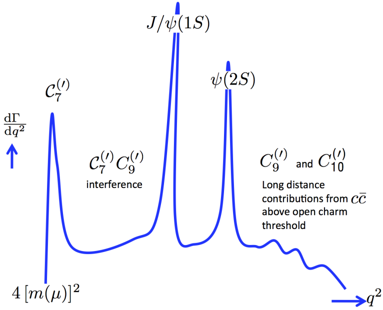
* QED corrections can be $\mathcal{O}(10^{-2})$ [EPJC 76 (2016) 8,440]

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

[EPJC 76 (2016) 440, JHEP 04 (2017) 016,
PRD 95 (2017) 035029, EPJC 77 (2017) 377, PRD 93 (2016) 014028]

$$R^{SM}_{K^{*0}} = \frac{BR(B^0 \to K^{*0}\mu^+\mu^-)}{BR(B^+ \to K^{*0}e^+e^-)} = 1 \pm \mathcal{O}(10^{-3})^*$$

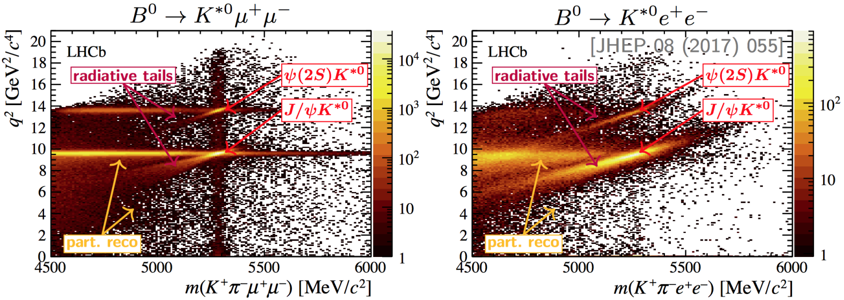
- $R_{K^{*0}}$ is measured in 2 bins in q^2
  - Low: $[0.045, 1.1]\,\mathrm{GeV}/c^2$
  - Central: $[1.1, 6.0]\,\mathrm{GeV}/c^2$



* QED corrections can be $\mathcal{O}(10^{-2})$ [EPJC 76 (2016) 8,440]

Experimental challenge

[LHCb, JHEP 08 (2017) 055]



- Differences between electrons and muons in the detector
  - Electron Bremsstrahlung → Degraded momentum, and mass/q^2 resolutions (bkg from $B \to K\pi\pi ee$)
  - Trigger less efficient for electrons

- Cancel most systematics arising from these differences by computing $R_{K^{*0}}$ as a double ratio

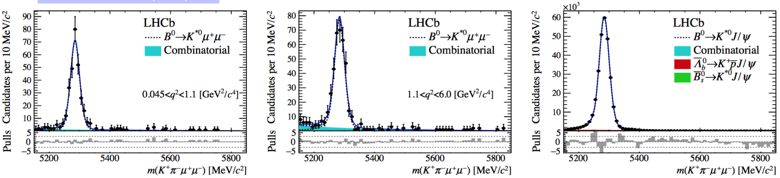
$$R_{K^{*0}} = \frac{B^0 \to K^{*0}\mu^+\mu^-}{B^0 \to K^{*0}J/\psi(\mu^+\mu^-)} \Big/ \frac{B^0 \to K^{*0}e^+e^-}{B^0 \to K^{*0}J/\psi(e^+e^-)}$$

Experimental challenge

[LHCb, JHEP 08 (2017) 055]

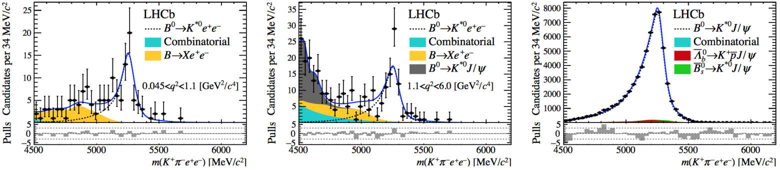
[JHEP 08 (2017) 055]

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



Low q^2: 285 ± 18 Central q^2: 353 ± 21 J/ψ: $274\,\text{k}$

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

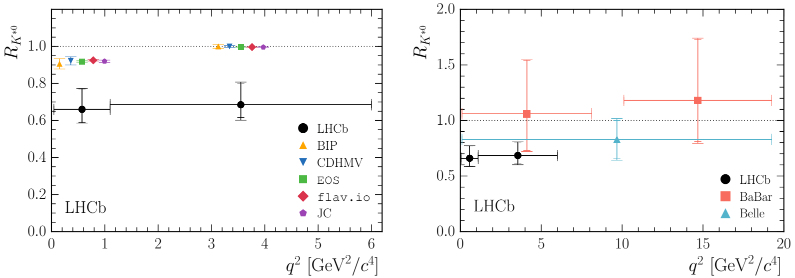


Low q^2: 89 ± 11 Central q^2: 111 ± 14 J/ψ: $58\,\text{k}$

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

$R_{K^{*0}}$ result

[LHCb, JHEP 08 (2017) 055]



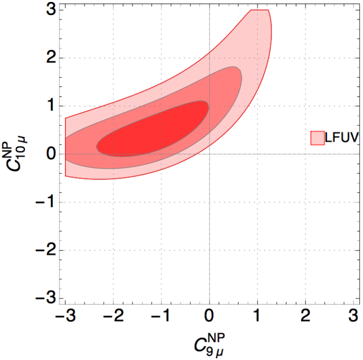
$$R_{K^{*0}}(0.045 < q^2 < 1.1\,\mathrm{GeV}/c^2) = 0.66\,^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^{*0}}(1.1 < q^2 < 6.0\,\mathrm{GeV}/c^2) = 0.69\,^{+0.11}_{-0.07} \pm 0.05$$

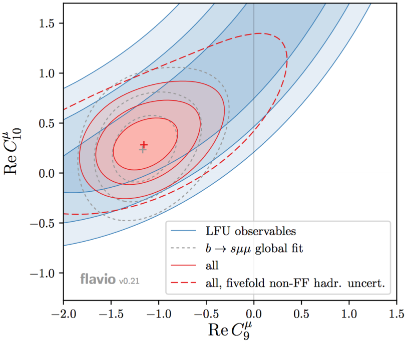
Compatibility with the SM is estimated to be at the level of $2.1 - 2.3\sigma$ for low q^2 and $2.4 - 2.5\sigma$ at central q^2

Global fits with LFU observables

- Picture is consistent with $b \to s\mu\mu$ anomalies, if NP couples only to muons and not electrons



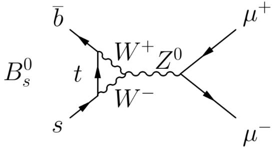
[JHEP 01 (2018) 093]



[PRD 96 (2017) 055008]

$B^0_{(s)} \to \mu^+\mu^-$ observation

[PRL 118, 191801 (2017)]



- Sensitive to new (pseudo)scalar or axial vector operators and precisely predicted in the SM

$$\mathcal{B}_{SM}(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

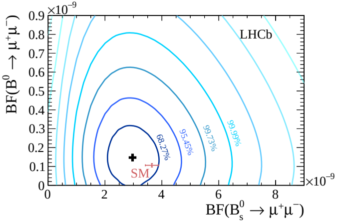
$$\mathcal{B}_{SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[PRL 112, 101801 (2014)]

- First single-experiment observation using Run1 ($3\,\mathrm{fb}^{-1}$) + Run2 ($2\,\mathrm{fb}^{-1}$) data

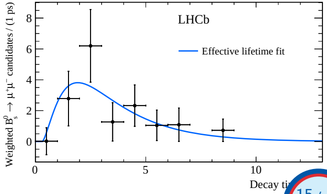
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \,@\, 95\%\,\mathrm{CL}$$



- First measurement of the effective lifetime for this decay (extremely clean theoretically and complementary sensitivity)

$$\tau_{\mu\mu} = 2.04 \pm 0.44 \pm 0.05\ \mathrm{ps}$$

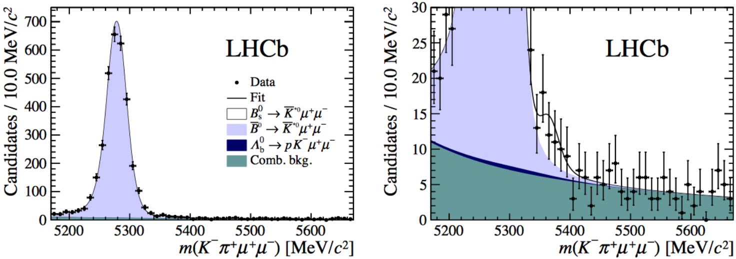


Search for $B_s^0 \to \overline{K}^{*}\mu^+\mu^-$

[LHCb-PAPER-2018-004 in preparation]

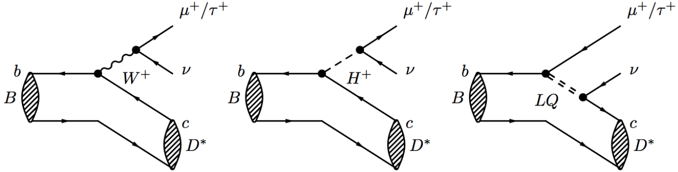
- FCNC $b \to d\ell\ell$ transition, CKM-suppressed with respect to $b \to s\ell\ell$ in the SM ($\mathcal{B} \sim \mathcal{O}(10^{-8})$)
- Interesting to probe MFV nature of new physics
- First evidence of this decay is observed with a significance of 3.4σ
- The branching ratio is estimated using $B^0 \to K^{*} J/\psi$

$$\mathcal{B}(B_s^0 \to \overline{K}^{*}\mu^+\mu^-) = (3.0 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{ext})) \times 10^{-8}$$



Dataset: Run1 ($3\,\text{fb}^{-1}$) + Run2 ($1.6\,\text{fb}^{-1}$)

LFU in trees - $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$



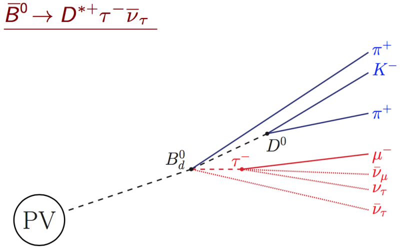
- In the SM the only difference between the two decays is the mass of the lepton
- Theoretically clean

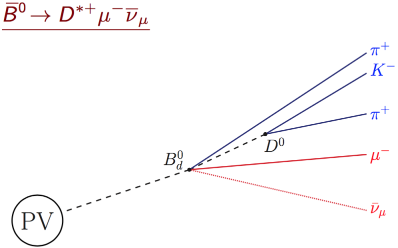
$$R(D^*)^{SM} = \frac{BR(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{BR(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} = 0.252 \pm 0.003$$

[S.Fajfer et al., PRD85 (2012) 094025]

- 2 measurements at LHCb
  - Leptonic $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ [PRL 115 (2015) 111803]
  - Hadronic $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ [arXiv:1708.08856]

$R(D^*)$ experimental challenge



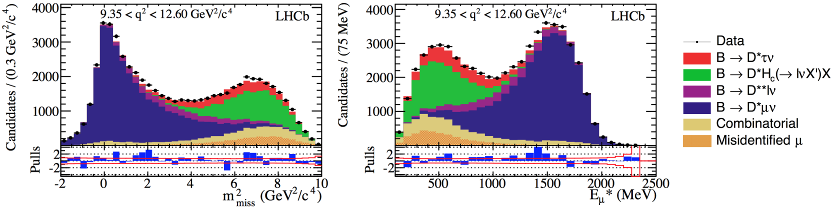


- Missing neutrinos $\Rightarrow$ No narrow peak to fit (in any distribution)
  - Calculate m^2_{missing}, q^2 and E_μ in approximate rest frame
- Main backgrounds are partially reconstructed B decays
  - $B \to D^*\mu\nu$, $B \to D^{**}\mu\nu$, $B \to D^*D(\mu X)X$ ...
- Isolation MVA used to reject physics backgrounds with additional cuts and to select control samples of specific backgrounds

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

[LHCb, PRL 115 (2015) 111803]

- Three dimensional template fit ($m^2_{missing}$, E_μ, q^2 shown)
  - Large MC samples for signal and physics backgrounds (data-driven syst.)
  - Background from μ misID and combinatorial from data
- Shape and form factor dependence systematics included in the fit



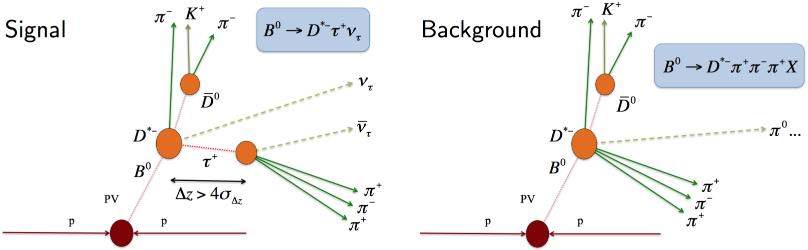
The obtained result

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

is consistent with the SM at 2.1σ level

$R(D^*)$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$

[LHCb, arXiv:1708.08856]



- Measure the $\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)$ relative to the $B^0 \to D^{*-}3\pi$
  - Use external inputs for $\mathcal{B}(B^0 \to D^{*-}3\pi)$ and $\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$ to compute $R(D^*)$
- Similar experimental challenges associated with missing neutrino
- Main backgrounds are partially reconstructed B decays
  - $B \to D^* 3\pi X$ (τ lifetime), $B \to DD_{(s)}X$ (BDT)...

$R(D^*)$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$

[LHCb, arXiv:1708.08856]

- 3D template fit to τ lifetime, q^2 and BDT output

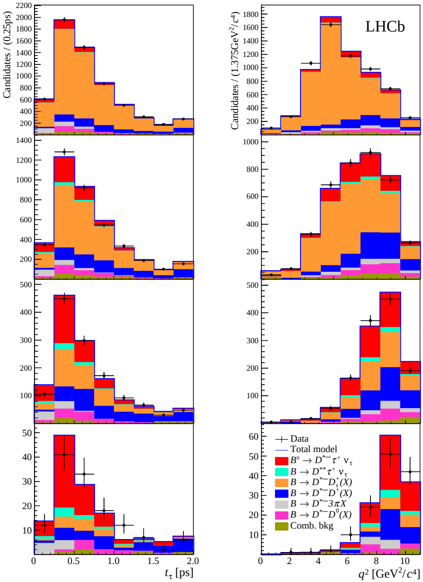
- Templates are extracted from simulation and validated in data control samples

- Result

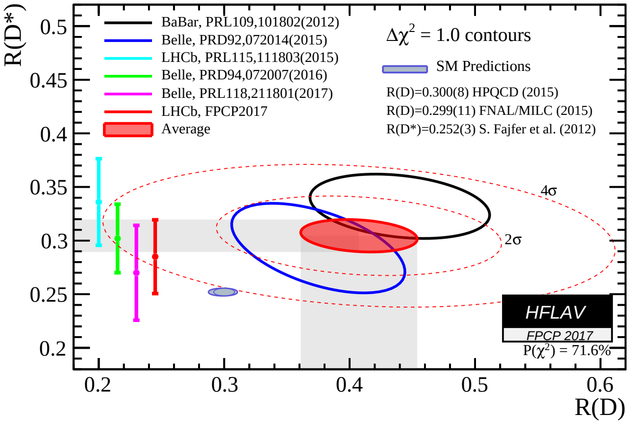
$$R(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$$

compatible with the SM at 1σ level

- Dominant systematic uncertainty comes from the size of the simulated samples



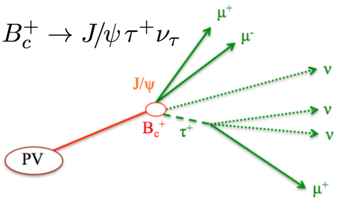
$R(D^{(*)})$ combination

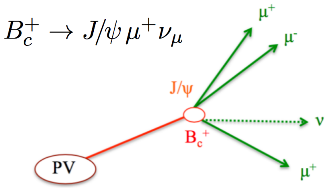


→ Latest HFAG average: 4.1σ from SM expectation
(Recent theory input reduces tension [JHEP 11 (2017) 061])

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

[LHCb, PRL 120, 121801 (2018)]





[PLB 452 (1999) 129-136, arXiv:hep-ph/0211021, PRD 73 (2006) 054024, PRD 74 (2006) 074008]

$$R(J/\psi)^{SM} = \frac{BR(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{BR(B_c^+ \to J/\psi \mu^+ \nu_\mu)} \in [0.25, 0.28]$$

- FF parameters determined from fit to normalisation mode
- Use $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ decays: similar exp. method as for leptonic $R(D^*)$

$R(J/\psi)$ result

[LHCb, PRL 120, 121801 (2018)]

- 3D template fit to m^2_{miss}, B_c^+ lifetime and $Z(E^*_\mu, q^2)$

- Templates are extracted from simulation and validated in data control samples

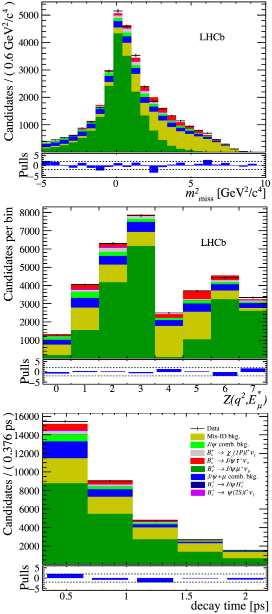
- Result

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

compatible with the SM at 2σ level

- Dominant systematic uncertainty comes from the size of the simulated samples and the $B_c^+ \to J/\psi$ FF

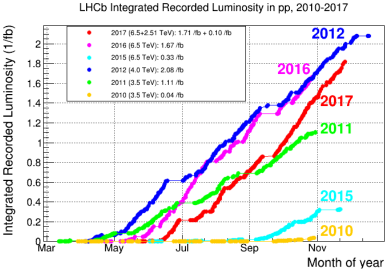
- First evidence fro the decay $B_c \to J/\psi \tau^+ \nu_\tau$



Summary

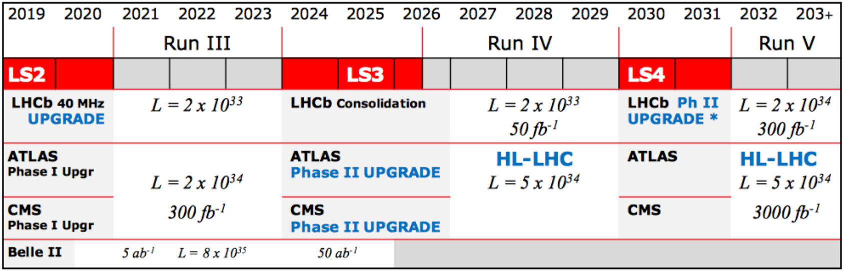
- LHCb Run1 has left us with an interesting set of anomalies
  - $\mathcal{B}$'s and angular observables in $b \to s\mu\mu$ transitions
  - Hints of lepton non-universality in loop dominated $b \to s\ell\ell$ processes...
  - ... and in tree level $b \to c\ell\nu$ decays

- Many new measuremens expected at LHCb that will confirm or disprove these results



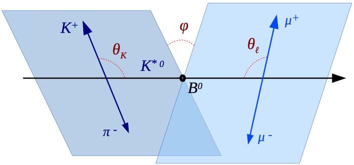
Backup

LHC schedule



Angular observables

- In multibody final states, other observables sensitive to NP are accessible through the study of the angular distribution of the decay products
  - Complementary constraints on NP & orthogonal experimental systematics



- For $B^0 \to K^{*0}\mu^+\mu^-$, the final state is described by three angles $\mathbf{\Omega} = \{\theta_K, \theta_\ell, \phi\}$ and $q^2 = m^2_{\mu\mu}$

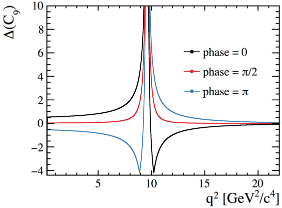
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\mathbf{\Omega}} = \frac{9}{32\pi}\big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \\ + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\ - F_L\cos^2\theta_K\cos 2\theta_\ell +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

F_L, A_{FB} and S_i contain dependence with the Wilson coefficients (C_7, C_9, C_{10}) and hadronic form factors

Interference with charmonia

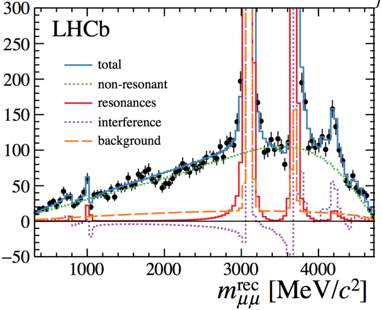
At low q^2, main SM $c\bar{c}$ contribution comes from J/ψ and extends to $q^2 = 0$

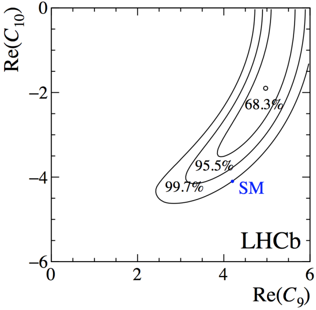
Effect on C_9^{eff} strongly depends on the phase difference with the short distance process



- Fit $B \to K\mu\mu$ data including resonance region with

$$C_9^{\text{eff}}(q^2) = C_9 + \sum_j |n_j| e^{i\delta_j} \text{BW}_i(q^2)$$





$R_{K^{*0}}$ systematics

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low- q^2			central- q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

$R_{K^{*0}}$ xchecks - control ratios

- Control the absolute scale of the efficiencies with the single ratio

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

$\rightarrow$ Independent of the decay kinematics, such as and η of the B^0 candidate and final-state particles, and the charged-track multiplicity in the event

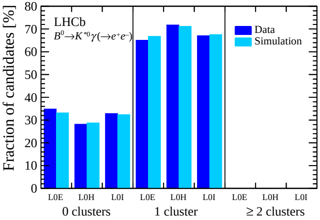
- Extra checks

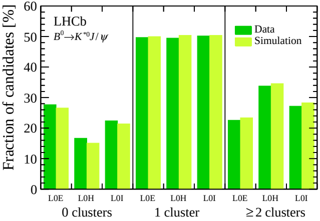
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(e^+e^-))} \; [2\%]$$

$$r_\gamma = \frac{\mathcal{B}(B^0 \to K^{*0}\gamma(e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(e^+e^-))} \; [7\%]$$

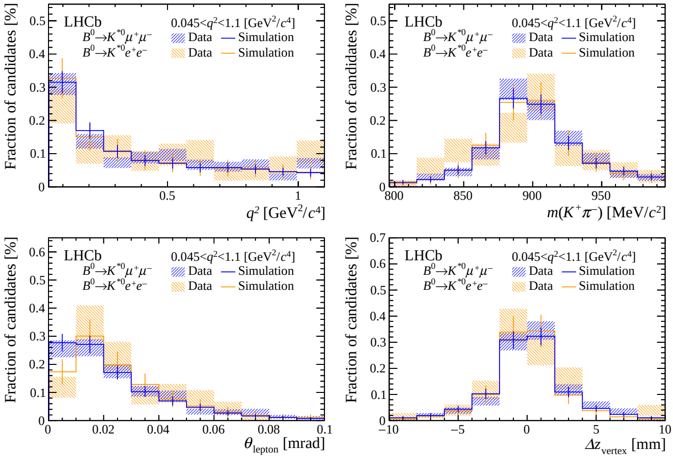
$\rightarrow$ $\mathcal{B}(B^0 \to K^{*0}\gamma(e^+e^-))$ in good agreement with [JHEP 04 (2017) 142]

$R_{K^{*0}}$ x-checks - Brem. recovery

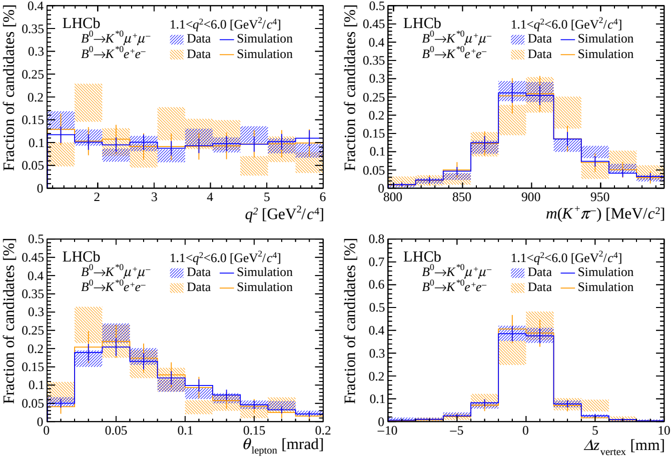




$R_{K^{*0}}$ distributions - low q^2

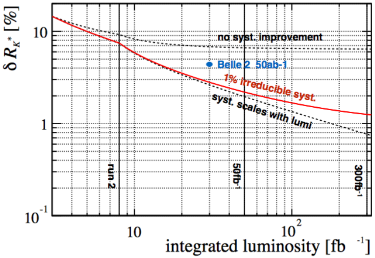


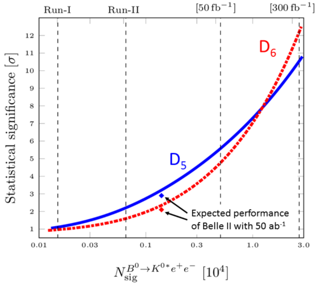
$R_{K^{*0}}$ distributions - central q^2



LFU prospects

- For ratios of $\mathcal{B}$'s (e.g. R_K, $R_{K^{*0}}$) we could reach 1-2% precision
  - For comparison Belle 2 expects to reach a precision of 4-5% with a 50 ab^{-1} dataset [S. Sandilya at CKM 2016]



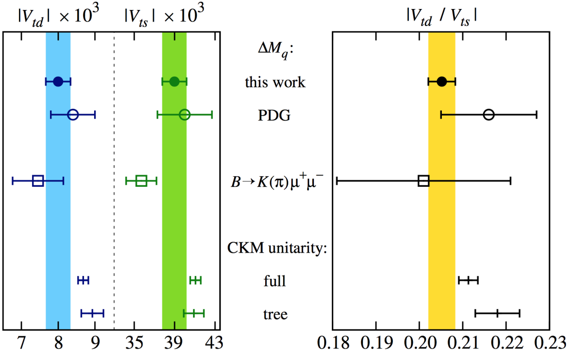


[LHCb, EOI for phase II upgrade CERN-LHCC-2017-003]

- Angular analyses with electrons have orthogonal systematics with respect to R_X's and these can also be kept under control
- Expect good sensitivity to differences in the angular distributions for electron/muon final states

$b \to d\ell^+\ell^-$ transitions

- As for $B_d \to \mu^+\mu^- / B_s \to \mu^+\mu^-$ and $\Delta m_d / \Delta m_s$, ratio of $b \to s$ and $b \to d$ decays is a test of MFV

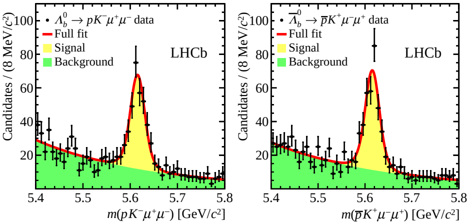


FNAL/MILC PRD93,113016 (2016)

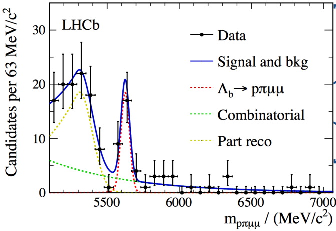
- EW penguins have additional uncertainty from ratio of form factors, will need improvements from Lattice too

Baryonic decays

- Give access to different combinations of Wilson coefficients
- Unique sensitivity to these processes at LHCb



[JHEP 06 (2017) 108]



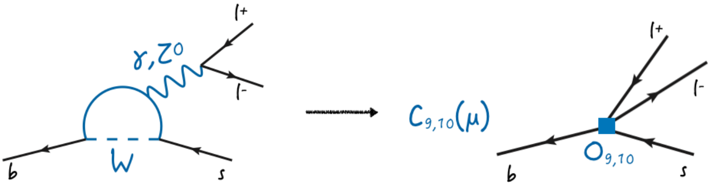
[JHEP 04 (2016) 029]

Effective theory

- Can describe these interactions in terms of an effective Hamiltonian that describes the full theory at lower energies (μ)

$$\mathcal{H}_{\text{eff}} \sim \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

$C_i(\mu) \rightarrow$ Wilson coefficient (integrating out scales above μ)
$\mathcal{O}_i \rightarrow$ Local operators with different Lorentz structures



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$\mathcal{O}_i \rightarrow$ Local operators with different Lorentz structures

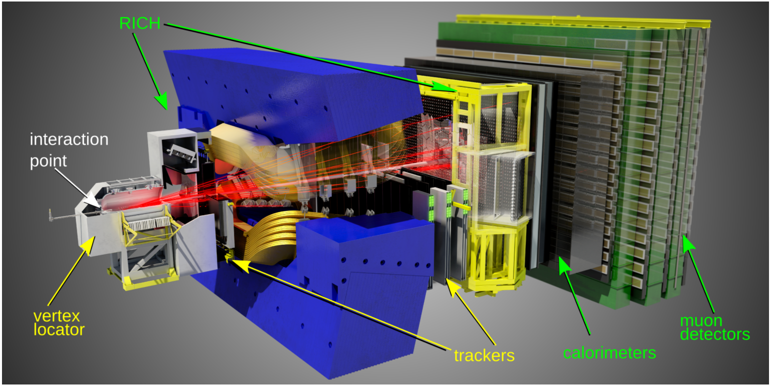
- Contributions from New Physics will modify SM contributions (Wilson coefficients) or introduce new operators

$$\Delta\mathcal{H}_{\text{eff}} = \frac{c_{NP}}{\Lambda_{NP}}\mathcal{O}_{NP}$$

Depending on the choice of coupling c_{NP} (e.g. MFV inherits SM CKM suppression), access to different NP scales Λ_{NP} (up to hundreds of TeV)

$\rightarrow$ Complementarity with direct searches for new particles

The LHCb detector



- Forward arm spectrometer to study b- and c-hadron decays $(2 < \eta < 5)$
  - Good vertex and impact parameter resolution $(\sigma(IP) = 15 + 29/pT)m)$
  - Excellent momentum resolution $(\sigma(m_B) \sim 25\,\mathrm{MeV}/c^2$ for 2-body decays)
  - Excellent particle ID (μ ID 97% for $(\pi \to \mu)$ misID of 1-3%)
  - Versatile & efficient trigger

[JINST 3 (2008) S080005]