Lepton flavour universality tests in B decays

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on behalf of the LHCb collaboration

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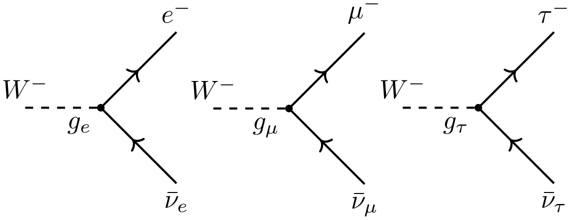
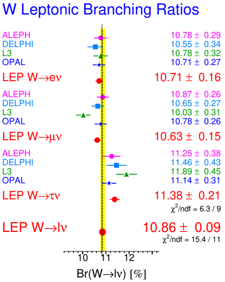
Lepton Flavour Universality in the SM

- Lepton Flavour Universality: In the Standard Model (SM), the couplings of the charged leptons to the gauge bosons are equal ($g_e = g_\mu = g_\tau$)
- Differences in branching fractions only due to lepton mass differences
- Well established in $Z \to \ell\ell$, $\tau \to \ell\nu\nu$, $J/\psi \to \ell\ell$, $\pi \to \ell\nu$, $K \to \pi\ell\nu$



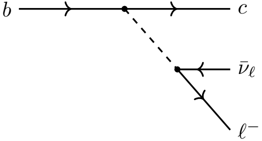


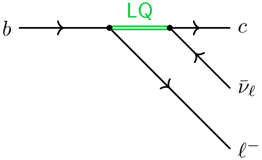
[PR 532 (2013) 119]

- Tension in $W \to \ell\nu$: $\frac{2\mathcal{B}(W\to\tau\bar{\nu}_\tau)}{\mathcal{B}(W\to e\bar{\nu}_e)+\mathcal{B}(W\to\mu\bar{\nu}_\mu)} = 1.066 \pm 0.025\ (2.6\sigma)$
  (Nb. strong constraints from $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\mu \to e\nu\nu)$)
- Large number of BSM models with non-universal couplings to third generation quarks and leptons (Charged Higgs, Leptoquarks, ...).

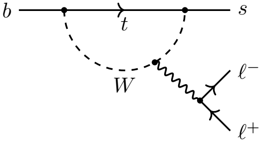
Lepton Flavour Universality in heavy flavour decays

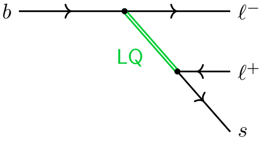
- Lepton universality tests in tree-level decays, *e.g.* $R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$
  - Abundant $b \to c\ell\nu$ semilept. decay
  - Well known in the SM
  - Possible NP coupling mainly to 3rd family





- Lepton universality tests in rare (loop-level) decays, $R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$
  - $b \to s\ell\ell$ FCNC
  - Forbidden at tree-level in SM
  - Sensitive to NP contributions in loops

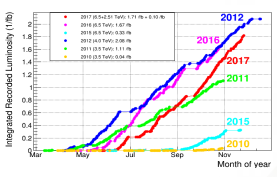


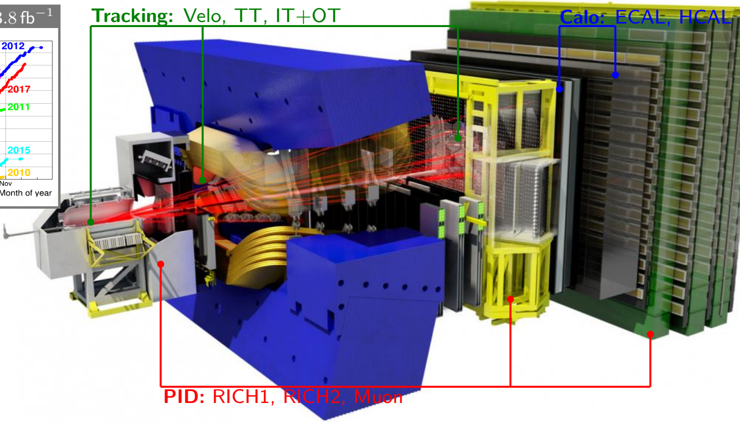


- Usually: Determine ratios of branching fractions
  - Experimentally clean: cancellation of many systematic uncertainties
  - Theoretically clean: cancellation of QCD effects

The LHCb experiment: Optimized for heavy flavour

Run 1: $3\,\mathrm{fb}^{-1}$, 2015-2017: $3.8\,\mathrm{fb}^{-1}$





- Large $\sigma_{b\bar{b}}$: $(284 \pm 53)\,\mu\mathrm{b}$ at $7\,\mathrm{TeV}$ and $(495 \pm 52)\,\mu\mathrm{b}$ at $13\,\mathrm{TeV}$ [PLB 694 (2010) 209-216] [JHEP 10 (2015) 172]
- Excellent IP resolution $\sim 20\,\mu\mathrm{m}$ to identify B decay vertices, $\Delta p/p = 0.5 - 1\%$
- Particle identification: $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$ and $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Low trigger thresholds: $p_{\mathrm{T}}(\mu) > 1.8\,\mathrm{GeV}$, $E_{\mathrm{T}}(e) > 3.0\,\mathrm{GeV}$

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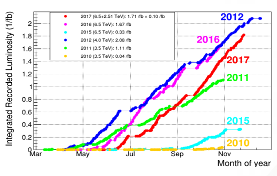
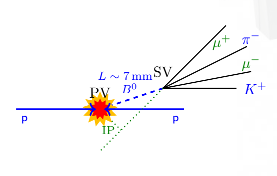
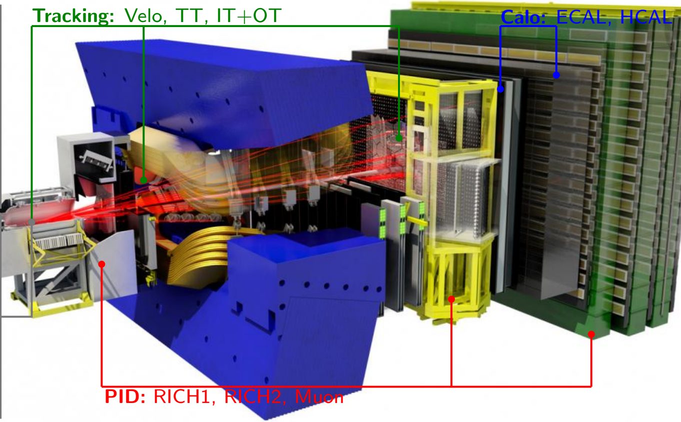


Heavy flavour signature





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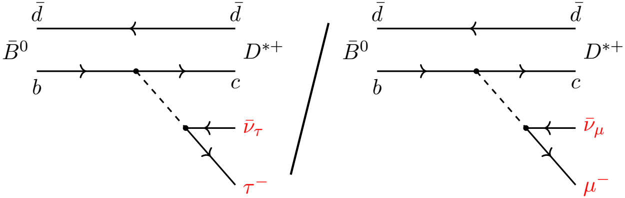
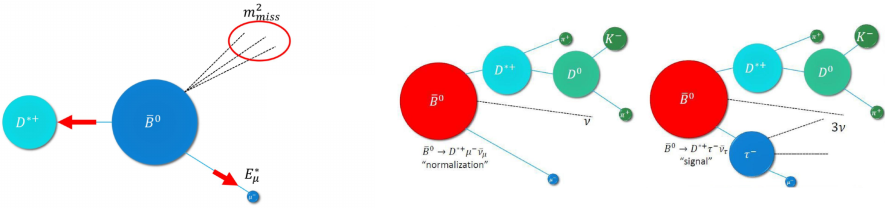
Lepton universality in semileptonic decays: R_{D^*}



decay mode	$\mathcal{B}[\%]$ [PDG2017]
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	17.39 ± 0.04
$\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$	9.31 ± 0.05
$\tau^- \to \pi^+\pi^-\pi^-\pi^0\nu_\tau$	4.62 ± 0.05

- $R_{D^*} = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} \stackrel{\text{SM}}{=} 0.252 \pm 0.003$ [PRD 85 (2012) 094025]
- Clean prediction as hadronic uncertainties cancel
  Below unity in the SM due to lepton mass difference
- LHCb performed two analyses with different τ decay modes
  1. Leptonic $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ decay [PRL 115 (2015) 111803]
  2. Hadronic $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$ decays [arXiv:1708.08856]
- Similar experimental challenges
  - Final state neutrinos
  - Large backgrounds from partially reconstructed and misidentified decays

Reconstructing $\overline{B}^0 \to D^{*+}\tau^-(\to \mu^-\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau$

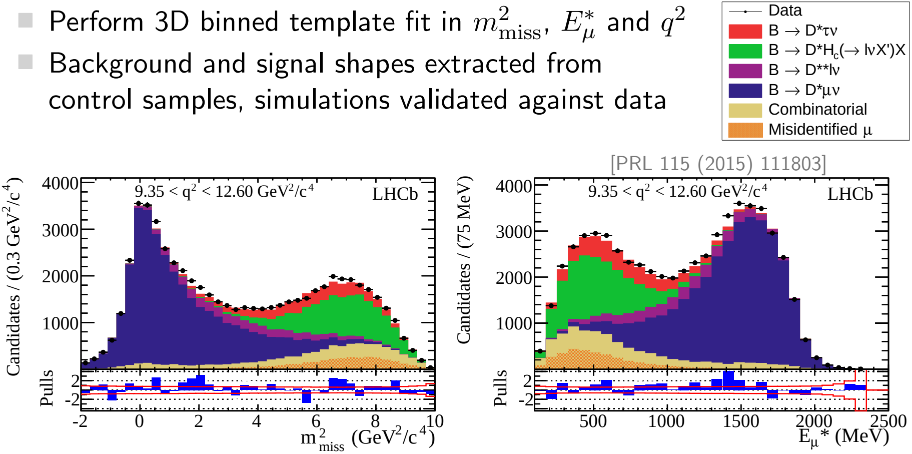


- No analytic solution for B momentum due to missing neutrinos
- Exploit vertexing to determine B flight direction: $\frac{\vec{p}(B)}{|\vec{p}(B)|} = \frac{\vec{SV}-\vec{PV}}{|\vec{SV}-\vec{PV}|}$
- Approximate $(p_B)_z = \frac{m_B}{m_{\rm reco}}(p_{\rm reco})_z$ to determine p_B with $\sim 18\%$ resolution
- Use $m^2_{\rm miss} = (p_B - p_{D^*} - p_\ell)^2$, $q^2 = (p_B - P_{D^*})^2$ and E^*_μ to separate $\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ signal from $\overline{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ normalisation

$\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ signal	$\overline{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ normalisation
$m^2_{\rm miss} > 0$	$m^2_{\rm miss} = 0$
E^*_μ spectrum soft	E^*_μ spectrum hard
$m^2_\tau \le q^2 \le 10.6\,\mathrm{GeV}^2$	$0 \lesssim q^2 \le 10.6\,\mathrm{GeV}^2$

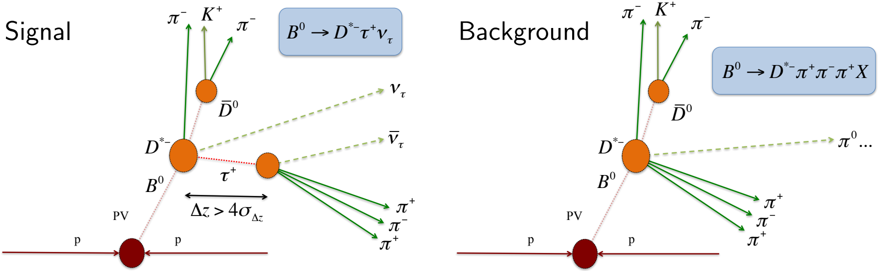
R_{D^*} with $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

- Perform 3D binned template fit in m^2_{miss}, E^*_μ and q^2
- Background and signal shapes extracted from control samples, simulations validated against data



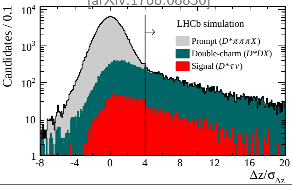
- $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ [PRL 115 (2015) 111803], compatible with the SM at $2.1\,\sigma$
- Dominant systematic uncertainty: Size of simulated samples

R_{D^*} with $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$



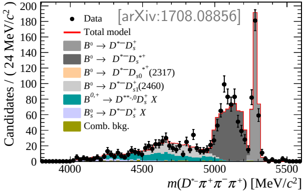
- Normalize to well known decay $B^0 \to D^{*-}3\pi$ with same final state: $R_{D^*} = \kappa \times \frac{\mathcal{B}(B^0\to D^{*-}3\pi)}{\mathcal{B}(B^0\to D^{*-})}$ with $\kappa = \frac{\mathcal{B}(B^0\to D^{*-}\tau^+(\to 3\pi(\pi^0)\bar{\nu}_\tau)\nu_\tau)}{\mathcal{B}(B^0\to D^{*-}3\pi)}$
  $\to$ many systematic uncertainties cancel
- Main background from hadronic $B \to D^*3\pi X$ decays suppressed by exploiting τ lifetime (no bkg. from $B^0 \to D^{*-}\mu^+\nu_\mu$)
- BDT to suppress $B \to DD_{(s)}X$ background

[arXiv:1708.08856]



R_{D^*} results with hadronic τ decay

- 3D binned template fit to q^2, τ-lifetime and BDT output
- Templates from simulation, validated using control samples



- $$R_{D^*} = 0.286 \pm \underbrace{0.019}_{\text{stat.}} \pm \underbrace{0.025}_{\text{syst.}} \pm \underbrace{0.021}_{\text{ext.}}$$

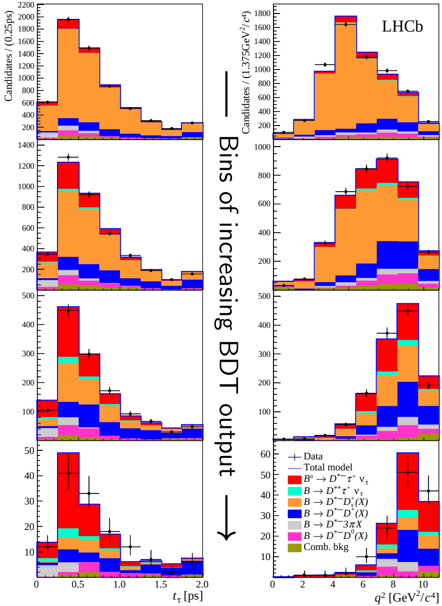
[arXiv:1708.08856] $1\,\sigma$ above SM

- External inputs [PRD 87 (2013) 092001] [arXiv:1612.07233]

$$\mathcal{B}(B^0 \to D^{*-}3\pi) = (7.23 \pm 0.51) \times 10^{-3}$$

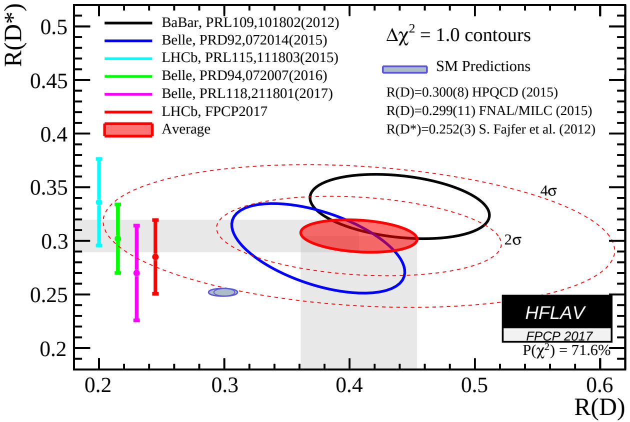
$$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10) \times 10^{-2}$$

- Dominant systematic uncertainty: Size of simulated samples



[arXiv:1708.08856]

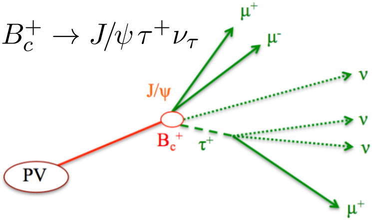
$R_{D^{(*)}}$ combination



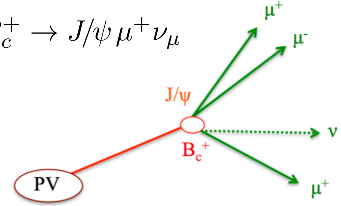
- Combine LHCb R_{D^*} measurements with B-factory results
- All measurements are above SM predictions
- Deviation of R_D/R_{D^*} combination corresponding to $\sim 4.1\,\sigma$
- Recent theory input reduces tension [JHEP 11 (2017) 061]

$R_{J/\psi}$: Lepton universality test with B_c decays

$B_c^+ \to J/\psi\, \tau^+ \nu_\tau$



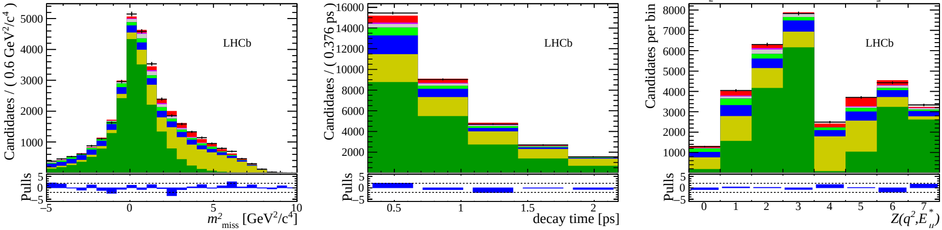
$B_c^+ \to J/\psi\, \mu^+ \nu_\mu$

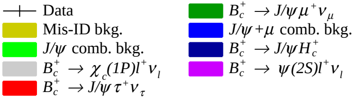


- Most recent: $R_{J/\psi} = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)}$ with $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$
  [arXiv:1711.05623]
- Prediction $R_{J/\psi}^{\mathrm{SM}} \in [0.25, 0.28]$, uncertainty due to form factors
  - Large spread of form factor parameters
    [PLB 452 (1999) 129-136] [arXiv:hep-ph/0211021] [PRD 73 (2006) 054024] [PRD 74 (2006) 074008]
  - Parameters fit on data sample enriched with normalisation decays
- Similar approximations as for R_{D^*} to determine B_c momentum

$R_{J/\psi}$ results

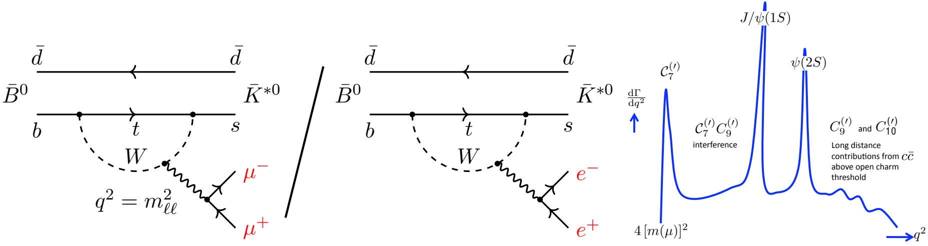
[arXiv:1711.05623]





- 3D template binned fit in m^2_{miss}, $\tau(B_c^+)$, $Z = (E^*_\mu, q^2)$
- Shapes derived from control samples or simulation validated on data
- Main background is $b \to J/\psi$ + mis-ID hadron
- First evidence for the decay $B_c^+ \to J/\psi\,\tau^+\nu_\tau$ $(3\,\sigma)$
- $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ around $2\,\sigma$ above SM [arXiv:1711.05623]
- Dominant systematics: $B_c^+ \to J/\psi$ form factors, limited MC size

Lepton Universality tests in rare decays

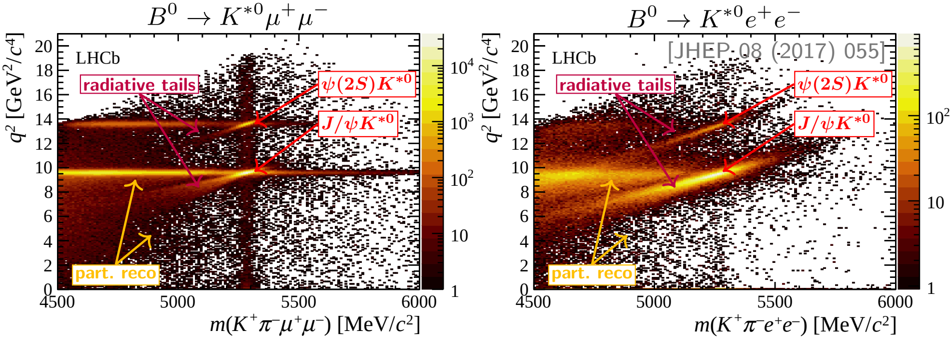


- $R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$ extremely clean test of the SM: $R_{K^*}^{\mathrm{SM}} = 1 \pm \mathcal{O}(10^{-3})$ (neglecting m_ℓ), QED effects $\mathcal{O}(10^{-2})$ [EPJC 76 (2016) 8,440]
- Hadronic uncertainties (form factors etc.) cancel in the ratio
- Strategy: Use double ratio with resonant mode $B^0 \to K^{*0} J/\psi\,(\to \ell^+\ell^-)$

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

  cancels systematic effects
- Use normalisation mode to correct simulation, determine signal shape and as important crosscheck: $r_{J/\psi} = \frac{\mathcal{B}(B^0\to J/\psi\,(\to\mu^+\mu^-)K^{*0})}{\mathcal{B}(B^0\to J/\psi\,(\to e^+e^-)K^{*0})}$ compatible with unity

R_{K^*}: Experimental challenges

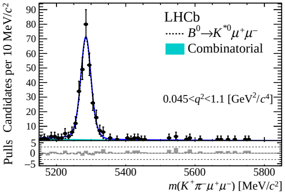


- Experimental challenges for electrons
  1. Low trigger efficiency (p_{T} thresholds $3.0\,\mathrm{GeV}$ for $e^\pm$ vs. $1.8\,\mathrm{GeV}$ for $\mu^\pm$)
  2. Bremsstrahlung: Brem-γ recovery has limited efficiency and resolution
- Partially reconstructed backgrounds, *e.g.* $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$
- Determine R_{K^*} in two regions of q^2:
  Low q^2: $q^2 \in [0.045, 1.1]\,\mathrm{GeV}^2$ Central q^2: $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2$

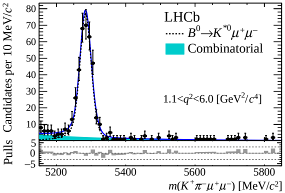
Yields

[JHEP 08 (2017) 055]

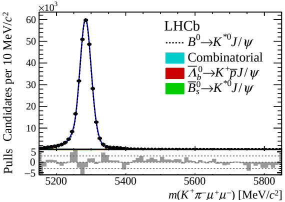
$B^0 \to K^{*0}\mu^+\mu^-$



Low q^2: 285 ± 18

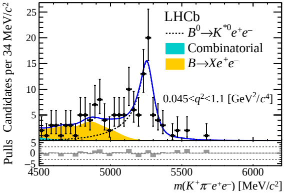


Central q^2: 353 ± 21

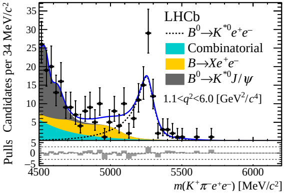


J/ψ: $274\,\mathrm{k}$

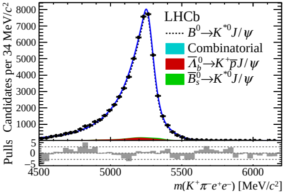
$B^0 \to K^{*0}e^+e^-$



Low q^2: 89 ± 11



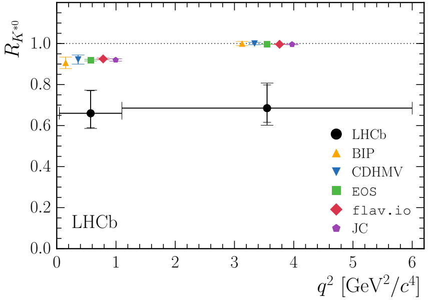
Central q^2: 111 ± 14

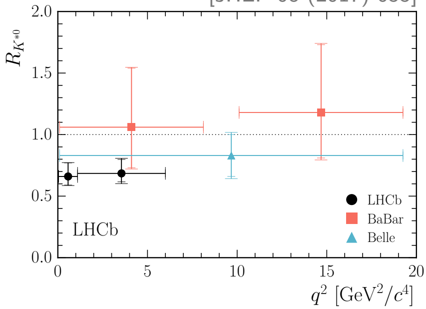


J/ψ: $58\,\mathrm{k}$

R_{K^*} Results

[JHEP 08 (2017) 055]





- BIP [EPJC 76 (2016) 440]
- CDHMV [JHEP 04 (2017) 016]
- EOS [PRD 95 (2017) 035029]
- flav.io [EPJC 77 (2017) 377]
- JC [PRD 93 (2016) 014028]

- Babar [PRD 86 (2012) 032012]
- Belle [PRL 103 (2009) 171801]

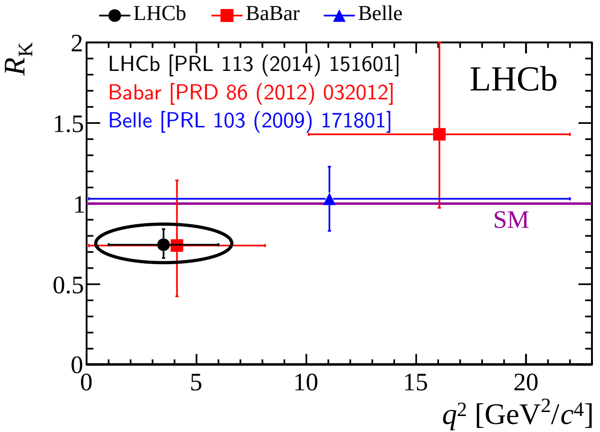
- Numerical result and compatibility with SM prediction(s):

$$R_{K^*}(0.045 < q^2 < 1.1\,\mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03 \quad 2.1\text{-}2.3\,\sigma \text{ at low } q^2$$

$$R_{K^*}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05 \quad 2.4\text{-}2.5\,\sigma \text{ at central } q^2$$

- Compatible with Babar and Belle with smaller uncertainties

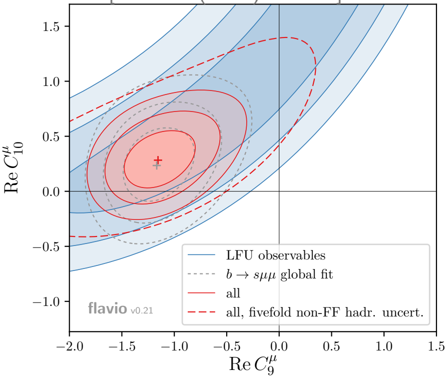
R_K Results



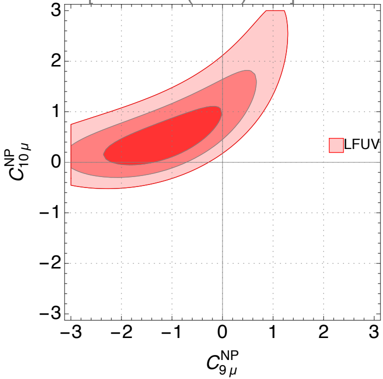
- LHCb determines $R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$ in central q^2 region $[1,6]\,\mathrm{GeV}^2$:
  $\mathcal{R}_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat.}) \pm 0.036(\mathrm{syst.})$,
- Compatible with SM at $2.6\,\sigma$

Combination of LFU observables

[PRD 96 (2017) 055008]



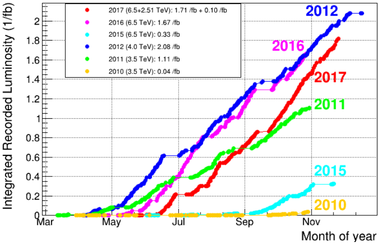
[JHEP 01 (2018) 093]



- Combine LFU observables in effective theory framework to determine Wilson coefficients (here: eff. Vector- and axialvector coupling $\mathcal{C}_9$ and $\mathcal{C}_{10}$)
- Combination of R_{K^*}, R_K and [arXiv:1612.05014] shows tension with SM prediction at $\sim 4\,\sigma$ [PRD 96 (2017) 055008]
- Addition of $b \to s\mu\mu$ $\mathcal{B}$ and angular obs. further increases significance (Details in pesentation by F. Dettori)

Conclusions and Outlook

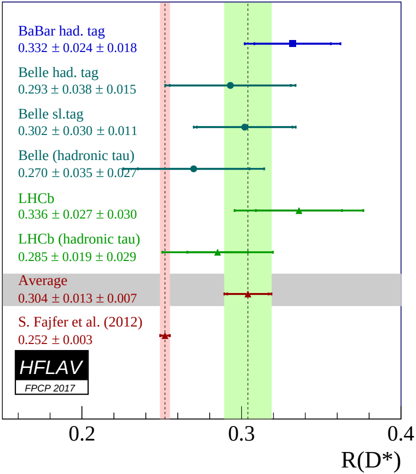
- Tests of LFU show interesting discrepancies with the clean SM prediction
- $b \to c\tau\nu$ tree-level decays:
  - $R_{D^{(*)}}$ above prediction
  - Combined significance (LHCb+B-factories) $\sim 4\,\sigma$
- $b \to s\ell\ell$ loop-level decays:
  - $R_{K^{(*)}}$ below predictions
  - Combined significance $\sim 4\,\sigma$
  - Compatible with $b \to s\mu\mu$ anomalies in $\mathcal{B}$ and angular observables
- LHCb has already collected an additional $3.8\,\text{fb}^{-1}$ of data in Run 2
- Look forward to LHCb Run 2 updates and additional decay modes
- Measurements of LFV decays also ongoing
- Please stay tuned!



Backup

R_{D^*} results

- R_{D^*} world average
  $R_{D^*} = 0.304 \pm 0.013 \pm 0.007$
- Impact of LHCb R_{D^*} hadronic on world average:
  - R_{D^*}: $3.3\,\sigma \to 3.5\,\sigma$
  - Adding R_D: $4.0\,\sigma \to 4.1\,\sigma$
- LHCb-only R_{D^*} average:
  $R_{D^*} = 0.309 \pm 0.016 \pm 0.024$
  $2\,\sigma$ from SM prediction



R_{D^*} semileptonic systematic uncertainties

Model uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ 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
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

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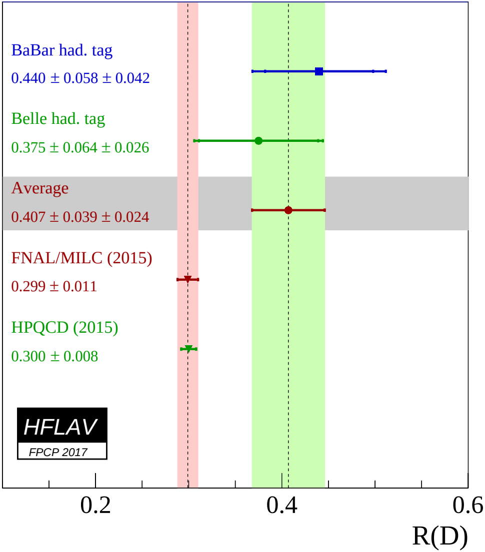
R_{D^*} hadronic systematic uncertainties

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
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

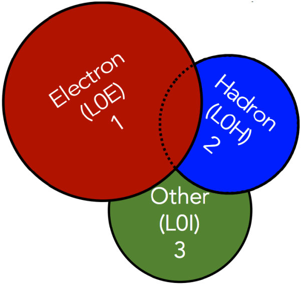
$R_{J/\psi}$ systematic uncertainties

Source of uncertainty	**Size ($\times 10^{-2}$)**
Limited size of simulation samples	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Misidentification background strategy	5.6
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
Semitauonic $\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau)$	0.2
B_c^+ lifetime	included in statistical uncertainty
Total systematic uncertainty	**17.7**
Statistical uncertainty	**17.3**

R_D results


BaBar had. tag
0.440 ± 0.058 ± 0.042
Belle had. tag
0.375 ± 0.064 ± 0.026
Average
0.407 ± 0.039 ± 0.024
FNAL/MILC (2015)
0.299 ± 0.011
HPQCD (2015)
0.300 ± 0.008
HFLAV
FPCP 2017
0.2
0.4
0.6
R(D)

Trigger for electron final states



L0E: trigger fired on one of the electrons

L0H: trigger fired on the final state hadron(s)

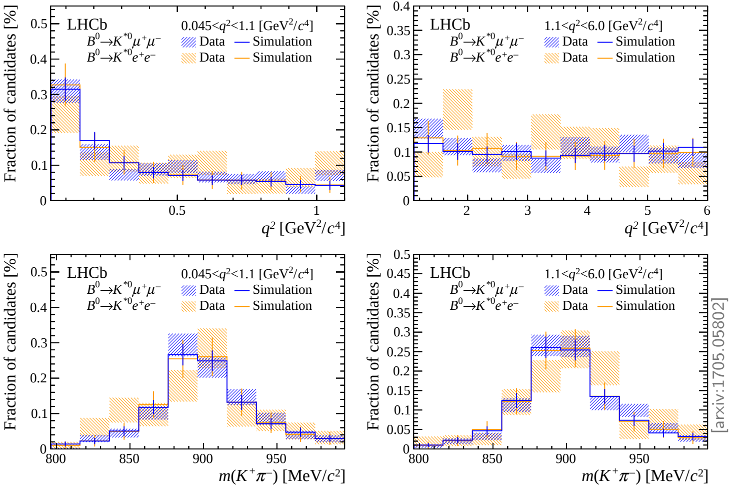
L0I: trigger fired by other particles in the event

- Calorimeter occupancy high:
  $\rightarrow$ Trigger thresholds for electron final states higher than for muons

	muons	electrons	hadrons
p_{T} threshold (Run 1)	$1.5 - 1.8\,\mathrm{GeV}$	$2.5 - 3.0\,\mathrm{GeV}$	$3.5\,\mathrm{GeV}$

- Combination of different triggers used to increase yields
- Using exclusive trigger categories: Different resolutions/purities

Further checks



- Background subtracted, normalized to same area
- Good agreement between electrons/muons and data/simulation

Systematic uncertainties

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	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

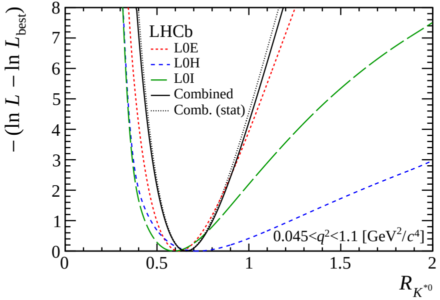
Bremsstrahlung tail description

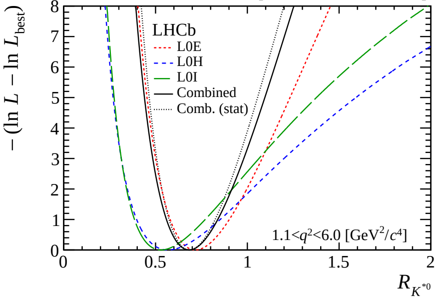
Residual bkgs. from $B^0 \to K^{*0} J/\psi(ee)$ with $h \leftrightarrow e$ swap

- Many systematic effects cancel in the double-ratio
- Measurement statistically dominated ($\sigma_{\text{stat}} \sim 16\%$)

Likelihood Fit

[arxiv:1705.05802]

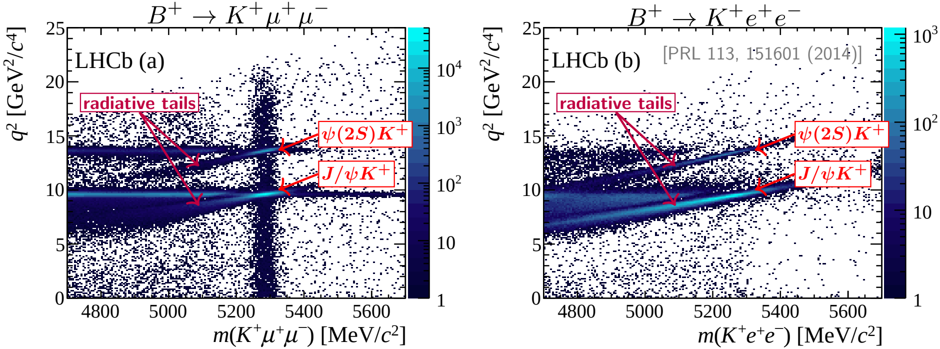




	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$

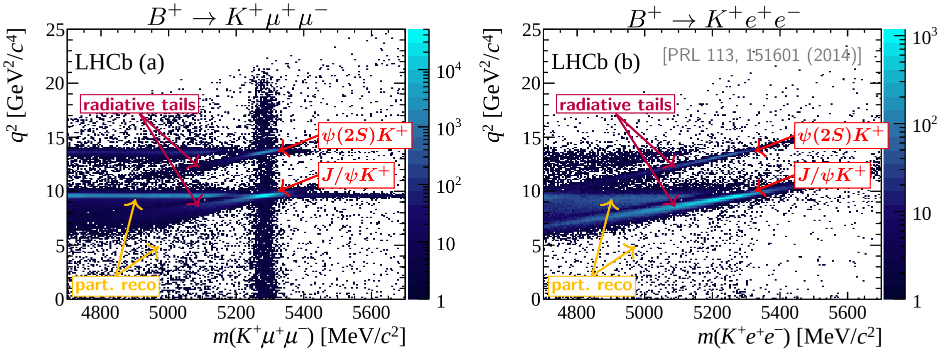
- Good agreement between trigger categories

Electron reconstruction (R_K)



- Resolution degraded by energy loss from Bremsstrahlung
  - Recovery of Bremsstrahlung not 100% efficient
  - Recovery of Bremsstrahlung γ in ECAL has limited resolution $\frac{\sigma_E}{E} \sim 1\% \otimes \frac{10\%}{\sqrt{E(\text{ GeV})}}$
- Contribution from partially reconstructed backgrounds *e.g.* $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$ where π^- is not reconstucted

Electron reconstruction (R_K)



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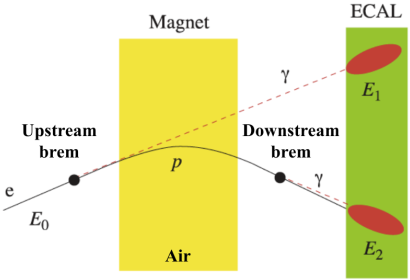
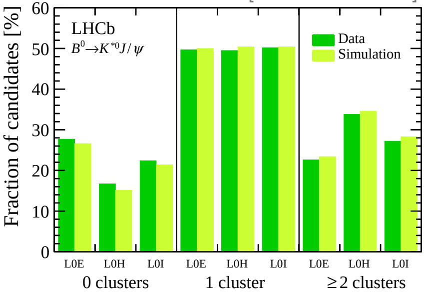
- Contribution from partially reconstructed backgrounds *e.g.* $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$ where π^- is not reconstucted

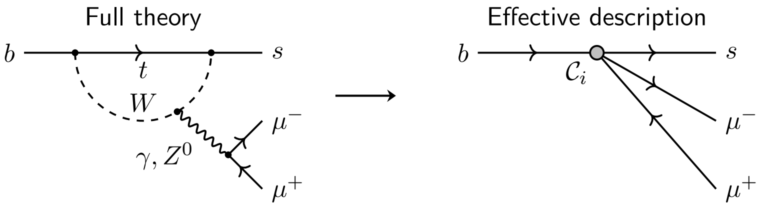
Bremsstrahlung in data and simulation



[arxiv:1705.05802]



Rare decays in effective field theory



- Rare b decays a multi-scale problem: $\Lambda_{\text{NP}} \gg m_W \gg m_b > \Lambda_{\text{QCD}}$
- Model-independent description in effective field theory

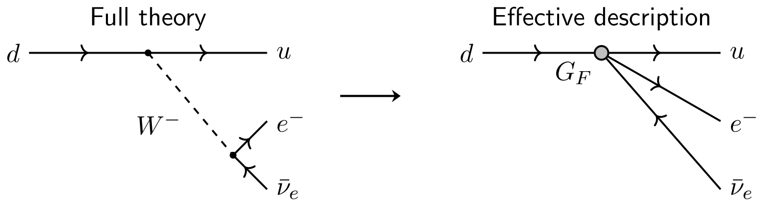
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

Effective coupling
"Wilson-coefficient"
short distance physics

Local operator
long distance physics

- Analogous to β-decay: Integrate out heavy degrees of freedom
  $\rightarrow$ point-interaction with Fermi-coupling

Rare decays in effective field theory



- Rare b decays a multi-scale problem: $\Lambda_{\text{NP}} \gg m_W \gg m_b > \Lambda_{\text{QCD}}$
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$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

Effective coupling
"Wilson-coefficient"
short distance physics

Local operator
long distance physics

- Analogous to **β-decay**: Integrate out heavy degrees of freedom
  $\rightarrow$ point-interaction with Fermi-coupling

NP contributions and relevant effective couplings

- NP can contribute to different operators $\mathcal{O}_i$ depending on its type

Local operator

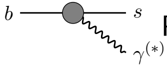
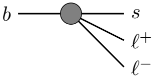
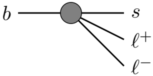
Flavour-violating coupling

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i} \qquad \Delta\mathcal{H}_{\text{NP}} = \frac{\boxed{c}}{\boxed{\Lambda_{\text{NP}}^2}} \mathcal{O}_i$$

Wilson coefficient
("effective coupling")

NP scale

- Relevant effective couplings for rare decays

	Coupling	Operator
 Photon penguin	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
 EW penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
 (Pseudo)scalar penguin	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

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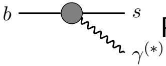
NP contributions and relevant effective couplings

- NP can contribute to different operators $\mathcal{O}_i$ depending on its type

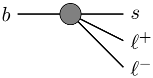
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^{*} \sum_i \underbrace{\boxed{\mathcal{C}_i}}_{\text{Wilson coefficient (“effective coupling”)}} \overbrace{\boxed{\mathcal{O}_i}}^{\text{Local operator}}$$

$$\Delta\mathcal{H}_{\text{NP}} = \frac{\overbrace{\boxed{c}}^{\text{Flavour-violating coupling}}}{\underbrace{\boxed{\Lambda^2_{\text{NP}}}}_{\text{NP scale}}} \mathcal{O}_i$$

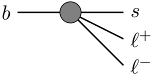
- Relevant effective couplings for rare decays



Photon penguin



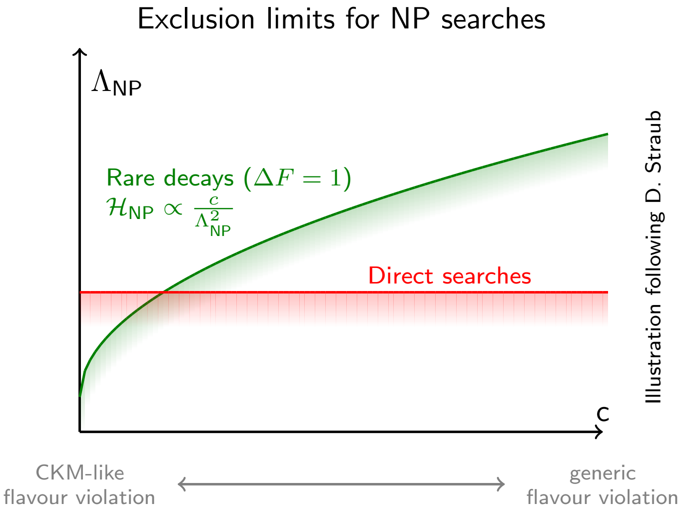
EW penguin



(Pseudo)scalar penguin

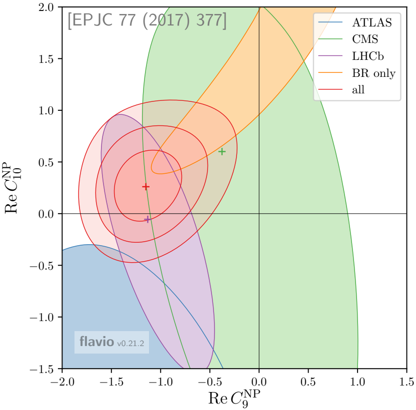
Coupling	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{C}_7^{(\prime)}$	✓		✓
$\mathcal{C}_9^{(\prime)}$			✓
$\mathcal{C}_{10}^{(\prime)}$		✓	✓
$\mathcal{C}_S^{(\prime)}$		✓	
$\mathcal{C}_P^{(\prime)}$		✓	

The complementarity of NP searches with rare decays



- Direct searches limited by beam energy, $\Lambda_{\text{NP}} < \sqrt{s}$
- Reach with rare decays up to $\Lambda_{\text{NP}} \sim 100\,\text{TeV}$, depending on coupling

Global fits without R_{K,K^*}

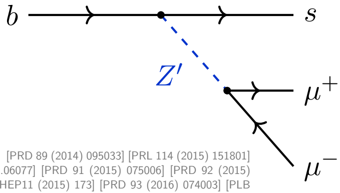


Coeff.	best fit	1σ	pull
C_9^{NP}	-1.21	$[-1.41, -1.00]$	5.2σ
C_9'	$+0.19$	$[-0.01, +0.40]$	0.9σ
C_{10}^{NP}	$+0.79$	$[+0.55, +1.05]$	3.4σ
C_{10}'	-0.10	$[-0.26, +0.07]$	0.6σ
$C_9^{\mathrm{NP}} = C_{10}^{\mathrm{NP}}$	-0.30	$[-0.50, -0.08]$	1.3σ
$C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}}$	-0.67	$[-0.83, -0.52]$	4.8σ
$C_9' = C_{10}'$	$+0.06$	$[-0.18, +0.30]$	0.3σ
$C_9' = -C_{10}'$	$+0.08$	$[-0.02, +0.18]$	0.8σ
$C_9^{\mathrm{NP}}, C_{10}^{\mathrm{NP}}$	$(-1.15, +0.26)$	—	5.0σ
C_9^{NP}, C_9'	$(-1.25, +0.59)$	—	5.3σ
$C_9^{\mathrm{NP}}, C_{10}'$	$(-1.34, -0.39)$	—	5.4σ
$C_9', C_{10}^{\mathrm{NP}}$	$(+0.25, +0.83)$	—	3.2σ
C_9', C_{10}'	$(+0.23, +0.04)$	—	0.5σ
$C_{10}^{\mathrm{NP}}, C_{10}'$	$(+0.79, -0.05)$	—	3.0σ

- Global fit of the $b \to s\mu^+\mu^-$ measurements incl. $\mathcal{B}$ and angular obs.
- Tensions can be reduced by shift in $\mathcal{C}_9$, significances $\sim$ 4-5 σ
- Consistency between angular observables and branching fractions
- Many other global fits [arxiv:1704.05340] [JHEP 06 (2016) 092] [NPB 909 (2016) 737] ...

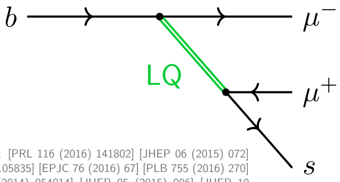
Possible NP explanations

New heavy bosons Z'



Some refs.: [PRD 89 (2014) 095033] [PRL 114 (2015) 151801] [arxiv:1503.06077] [PRD 91 (2015) 075006] [PRD 92 (2015) 015007] [JHEP11 (2015) 173] [PRD 93 (2016) 074003] [PLB 766 (2017) 77] [JHEP 03 (2017) 117] [arxiv:1704.06005] [arxiv:1705.03447] [arxiv:1705.00915] ...

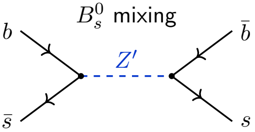
Leptoquarks

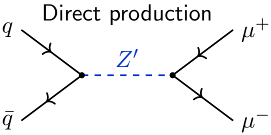


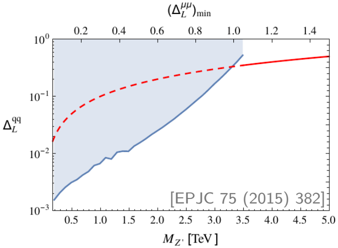
Some refs.: [PRL 116 (2016) 141802] [JHEP 06 (2015) 072] [arxiv:1704.05835] [EPJC 76 (2016) 67] [PLB 755 (2016) 270] [PRD 90 (2014) 054014] [JHEP 05 (2015) 006] [JHEP 10 (2015) 184] [PRL 115 (2015) 181801] [PR 641 (2016) 1] [JHEP 11 (2016) 035] [JHEP 12 (2016) 027] [arxiv:1704.05849] ...

- Many possible models on the market
- Most popular: Z' or Leptoquarks
- Can be tree- or loop-level [arxiv:1704.06005] [PRD 92 (2015) 055021]
- MSSM explanations of anomalies difficult [EPJC 75 (2015) 382]

Z' models







- Repr. $SU(2)_L$ singlet or $SU(2)_L$ triplet ($Z' + W'$) [JHEP07 (2015) 142] [Phys. Lett. B 760 (2016) 214]
- Masses typically heavy $m_{Z'} \sim \mathcal{O}(\text{TeV})$ but on-shell light also possible $100\,\text{MeV} < m_{Z'} < m_b$ [arxiv:1704.06188] [arxiv:1705.03465]
- Other constraints:
  - B_s^0 mixing $g_{bsZ'}/m_{Z'} \lesssim 0.01/2.5\,\text{TeV}$ [EPJC 73 (2013) 2646]
  - Direct searches $Z' \to \mu^+\mu^-$ [EPJC 75 (2015) 382]
    $m_{Z'} < 3.5\,\text{TeV}$: coupling to light q must be suppressed [EPJC 75 (2015) 382] [arxiv:1704.09015]
  - Neutrino trident production [PRL 113 (2014) 091801]

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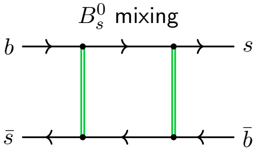
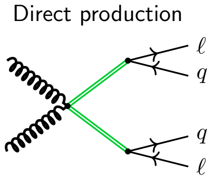
Leptoquark models

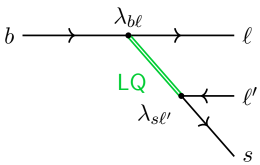




S	G	Topo.	Ref.
0	$(\bar{3},1)_{1/3}$	loop	[PRL 116 (2016) 141802]
0	$(\bar{3},3)_{1/3}$	tree	[JHEP 06 (2015) 072]
1	$(\bar{3},2)_{7/6}$	loop	[arxiv:1704.05835]
1	$(\bar{3},1)_{2/3}$	tree	[EPJC 76 (2016) 67]
1	$(\bar{3},3)_{2/3}$	tree	[PLB 755 (2016) 270]

- Models predict $\mathcal{C}_9^\mu = -\mathcal{C}_{10}^\mu$
- LQ masses typically $\mathcal{O}(10\,\mathrm{TeV})$ @ tree-level, $\mathcal{O}(1\,\mathrm{TeV})$ @ loop-level
- Other constraints:
  - Constraints from B_s^0 mixing at loop-level
  - Limits from direct searches $0.5 - 1.0\,\mathrm{TeV}$

Lepton flavour violation

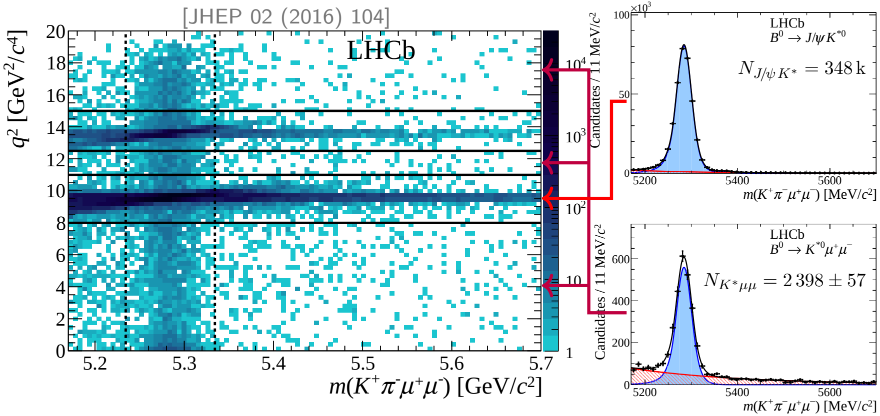


observable	limit @ 90% CL	constraint (λ_{ql} LQ coupling matrix)
$\mathcal{B}(\mu \to e\gamma)$	$5.7 \cdot 10^{-13}$ MEG	$\lvert\lambda_{qe}\lambda^*_{q\mu}\rvert \lesssim \frac{M^2}{(34\,\mathrm{TeV})^2}$
$\mathcal{B}(\tau \to e\gamma)$	$1.2 \cdot 10^{-8}$ Belle	$\lvert\lambda_{qe}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(1\,\mathrm{TeV})^2}$
$\mathcal{B}(\tau \to \mu\gamma)$	$4.4 \cdot 10^{-8}$ Babar	$\lvert\lambda_{q\mu}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(0.7\,\mathrm{TeV})^2}$
$\mathcal{B}(\tau \to \mu\eta)$	$6.5 \cdot 10^{-8}$ Belle	$\lvert\lambda_{s\mu}\lambda^*_{s\tau}\rvert \lesssim \frac{M^2}{(3.7\,\mathrm{TeV})^2}$
$\mathcal{B}(B \to K\mu^\pm e^\mp)$	$3.8 \cdot 10^{-8}$ Babar	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(19.4\,\mathrm{TeV})^2}$
$\mathcal{B}(B \to K\tau^\pm e^\mp)$	$3.0 \cdot 10^{-5}$ PDG	$\sqrt{\lvert\lambda_{s\tau}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\tau}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(3.3\,\mathrm{TeV})^2}$
$\mathcal{B}(B \to K\tau^\pm \mu^\mp)$	$4.8 \cdot 10^{-5}$ PDG	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{b\tau}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{s\tau}\rvert^2} \lesssim \frac{M^2}{(2.9\,\mathrm{TeV})^2}$
$\mathcal{B}(B \to \pi\mu^\pm e^\mp)$	$9.2 \cdot 10^{-8}$ Babar	$\sqrt{\lvert\lambda_{d\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{de}\rvert^2} \lesssim \frac{M^2}{(15.6\,\mathrm{TeV})^2}$

[JHEP 06 (2015) 072]

- Lepton Non-universality generally implies Lepton Flavour violation
  [Glashow et al., PRL 114 (2015) 091801]
- Motivates searches for $B^+ \to K^+\mu^\pm e^\mp$, $B^0 \to K^{*0}\mu^\pm e^\mp$, ...
- Branching fractions just below current upper limits possible
- Observation of LFV modes would be a clear sign of NP
- LHCb will probe below current limits for $B \to Xe\mu$
- Decays with τ final states more challenging, but improvements possible

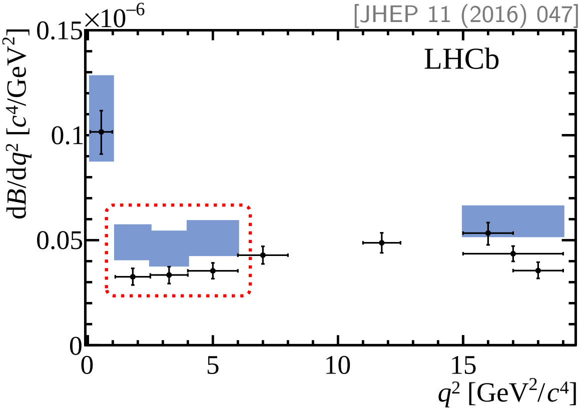
$B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ at LHCb



- BDT to suppress combinatorial background
  Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto q^2 range $[8, 11] \cup [12.5, 15]\,\mathrm{GeV}^2/c^4$ containing tree level decays $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$ (important control modes)
- Signal clearly visible as vertical band after the full selection

The $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ branching fraction

[JHEP 11 (2016) 047]



- Measurement relative to normalisation mode $B^0 \to J/\psi\, K^{*0}$

$$\frac{d\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2} = \frac{1}{q^2_{\text{max.}} - q^2_{\text{min.}}} \times \frac{1 - F_S^{K^*\mu\mu}}{1 - F_S^{J/\psi K^*}} \times \frac{N_{K^*\mu\mu}}{N_{J/\psi K^*}} \times \frac{\epsilon_{K^*\mu\mu}}{\epsilon_{J/\psi K^*}} \times \mathcal{B}(B^0 \to J/\psi\, K^{*0}) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

- $\frac{\epsilon_{K^*\mu\mu}}{\epsilon_{J/\psi K^*}}$ from (corrected) simulation, many effects cancel in ratio
- In agreement with but lower than SM prediction [arXiv:1503.05534] [PRD 89 (2014) 094501]

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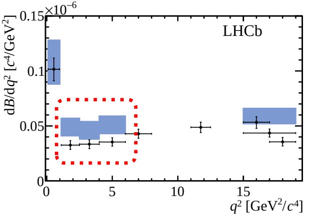
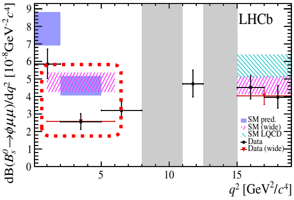
Similar to the rates of many other $b \to s\mu^+\mu^-$ decays

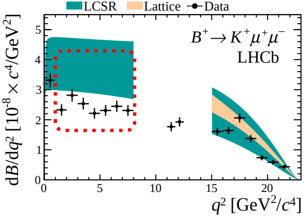
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



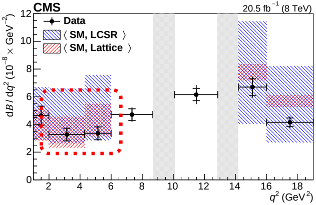
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



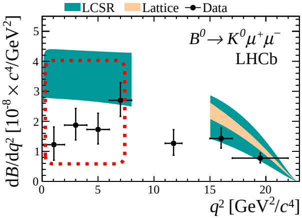
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



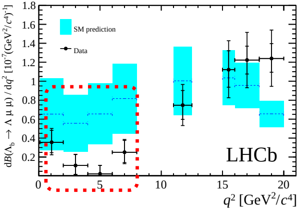
CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]

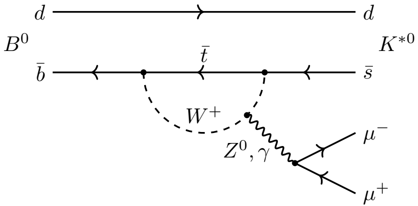


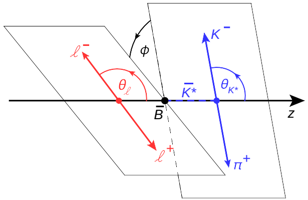
LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



- Data consistently below SM predictions (particularly at low q^2)

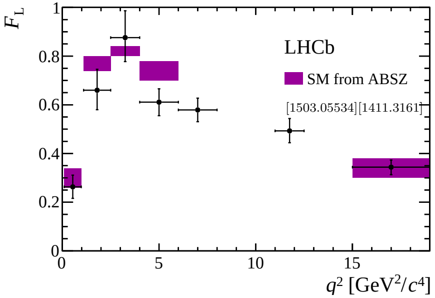
Angular analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$

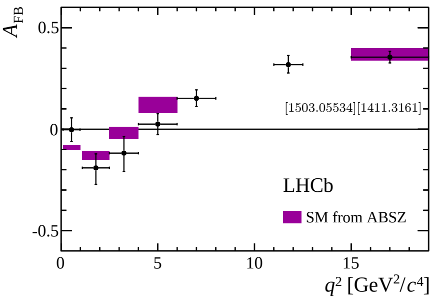




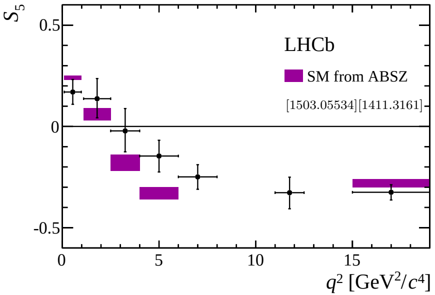
- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$
- $F_\mathrm{L}, A_\mathrm{FB}, S_i$ combinations of K^{*0} spin amplitudes depending on Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ and form factors
- Perform ratios of observables where form factors cancel at leading order
  Example: $P_5' = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]

$B^0 \to K^{*0}\mu^+\mu^-$ Results: F_L, A_{FB} and S_5





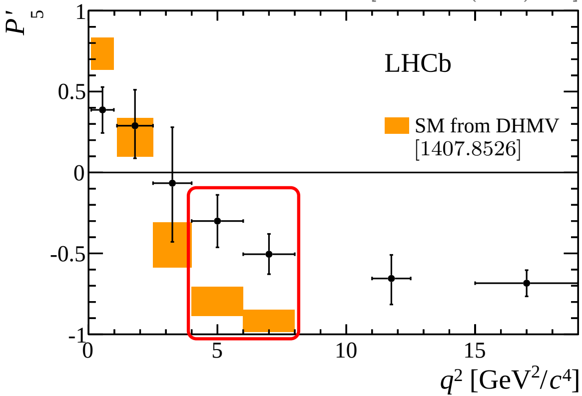
[JHEP 02 (2016) 104]



- Generally good agreement with SM predictions
- Mild tension in A_{FB}
- Some tension in S_5

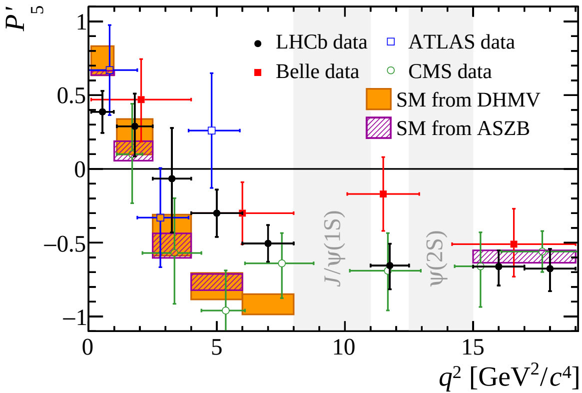
Less form-factor dependent observable P_5'

[JHEP 02 (2016) 104]



- In q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ local deviations of $2.8\,\sigma$ and $3.0\,\sigma$
- Global $B^0 \to K^{*0}\mu^+\mu^-$ analysis finds deviation corresponding to $3.4\,\sigma$
- [LHCb, JHEP 02 (2016) 104] consistent with [Belle, PRL 118 (2017) 111801] [CMS-PAS-BPH-15-008] [ATLAS-CONF-2017-023]

Less form-factor dependent observable P_5'



- In q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ local deviations of $2.8\,\sigma$ and $3.0\,\sigma$
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