Rare semileptonic B decays at LHCb

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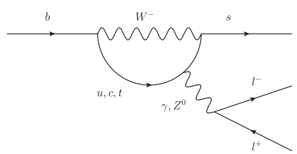
on behalf of the LHCb collaboration

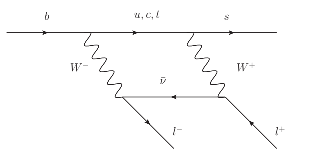
Outline

1. Motivation
2. The $B^0 \to K^{*0}\ell^+\ell^-$ decay — JHEP 02 (2016) 104
3. $B^+ \to K^+\mu^+\mu^-$ amplitude analysis — Eur. Phys. J. C 77 (2017) 161
4. The $R_{K^{(*)}}$ measurements
   Phys. Rev. Lett. 113 (2014) 151601, JHEP 08 (2017) 055
5. Conclusions and prospects

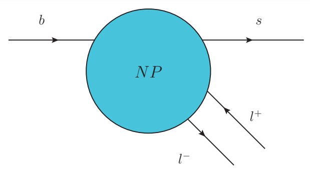
The $b \to s\ell^+\ell^-$ transition

- Flavour changing neutral currents (FCNC) are loop suppressed in the Standard Model (SM)





- Sensitivity to New Physics (NP) contributions



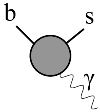
- Could affect observables such as $\mathcal{B}$ fractions and Angular Observables

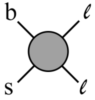
Effective theory framework

- Separate NP effects (Wilson Coefficients $\mathcal{C}_i$'s) from long distance QCD effects ($\mathcal{O}_i$'s) in an effective hamiltonian approach

$$\mathcal{H}_{eff}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i (\mathcal{C}_i \mathcal{O}_i + \mathcal{C}'_i \mathcal{O}'_i)$$

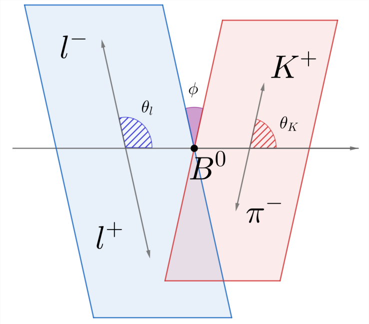
- Relevant operators for the $b \to s$ FCNC transitions

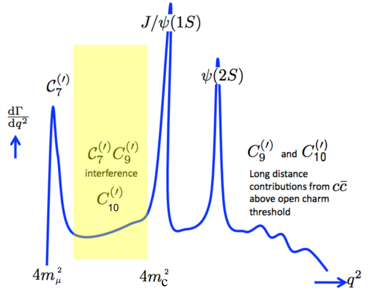




Operator $\mathcal{O}_i$	$B \to K^{*0}\gamma$	$B \to K^{*0}\mu^+\mu^-$	$B \to \mu^+\mu^-$
$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma_{\mu\nu} b_R) F_{\mu\nu}$	✓	✓	
$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$		✓	
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$		✓	✓
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$			✓

- The $B^0 \to K^{*0}(K^+\pi^-)\ell^+\ell^-$ decay provides information about the Lorentz structure of $\mathcal{H}_{eff}^{b\to s}$
- It is described by a set of angles $\vec{\Omega} = (\theta_\ell, \theta_K, \varphi)$ and the dilepton invariant mass squared $q^2 = m^2_{\ell\ell}$



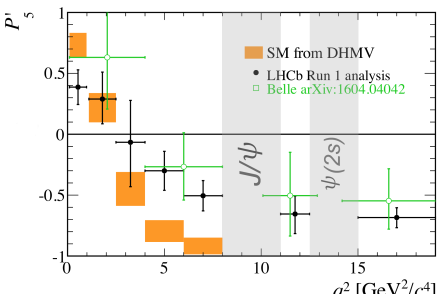


- The width for the decay is written as

$$
\begin{aligned}
\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{d\vec{\Omega}dq^2} = & \frac{9}{32\pi}[\tfrac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k \\
& +\tfrac{1}{4}(1-F_L)\sin^2\theta_k\cos 2\theta_\ell - F_L\cos^2\theta_k\cos 2\theta_\ell \\
& +S_3\sin^2\theta_k\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_k\sin 2\theta_\ell\cos\phi \\
& +S_5\sin 2\theta_k\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_k\cos\theta_\ell \\
& +S_7\sin 2\theta_k\sin\theta_\ell\sin\phi + S_8\sin 2\theta_k\sin 2\theta_\ell\sin\phi \\
& +S_9\sin^2\theta_k\sin^2\theta_\ell\sin 2\phi]
\end{aligned}
$$

- Where $F_L, A_{FB}, S_i = f(C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)})$ are combinations of K^{*0} decay amplitudes
- Theoretical uncertainties of form factors are reduced by considering optimised observables such as $P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$

- Analysis performed at LHCb in 8 bins of $q^2 \in [0.1, 19.0]\text{GeV}^2$
- Most angular observables have shown good compatibility with SM prediction
- Tension observed in P_5'
  - 2.8σ and 3.0σ local discrepancy from the SM predictions, global fit at 3.4σ
  - Compatible with previous LHCb and recent Belle measurements



- Explainable in terms of
  - NP involving $\mathcal{C}^{\mu}_{9,10}$
  - Not well understood hadronic contributions

The P_5' anomaly

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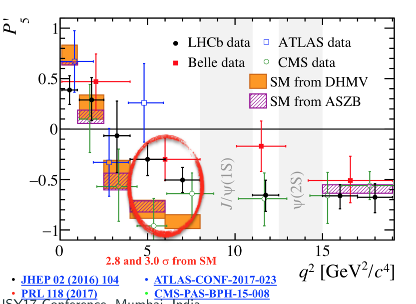

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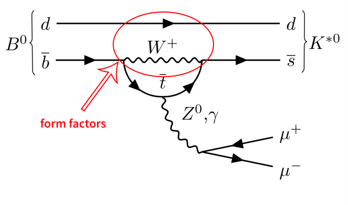
Hadronic effects

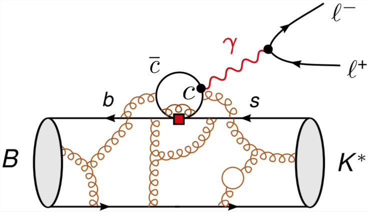
SM prediction of $B^0 \to K^{*0}\ell^+\ell^-$ requires good control over long-distance non-perturbative effects

- Matrix elements of local quark bilinear operators of type $\langle K^*|\mathcal{O}_i|B\rangle$ i.e. form factors:



- Lattice and QCD sum rules calculations available

- Resonant charmloop contributions to $\mathcal{C}_9^{eff} = \mathcal{C}_9 + Y(q^2)$



- Calculations valid below open charm threshold

- To explain such discrepancies, long-distance QCD effects would need to be sizeable in the low-q^2 region
- $J^P = 1^-$ resonances produce dimuon pairs via a virtual photon and mimic a contribution to $\mathcal{C}_9$

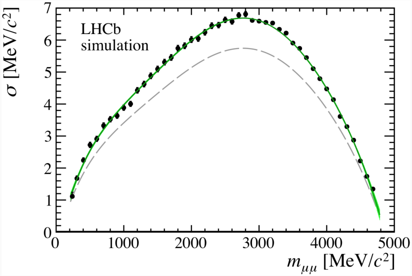
- Fit to the full dimuon mass spectrum of the decay $B^+ \to K^+\mu^+\mu^-$ describing the resonances as Breit-Wigner amplitudes

$$\frac{d\Gamma}{dq^2} = f(|\mathcal{C}_7|^2, |\mathcal{C}_9^{eff}|^2, |\mathcal{C}_{10}|^2, 2Re|\mathcal{C}_9^{eff}\mathcal{C}_7^*|)$$

where $\mathcal{C}_9^{eff} = \mathcal{C}_9 + \sum_j \eta_j e^{i\delta_j} A_j^{res}(q^2)$

Experimentally challenging since

$\Gamma_{J/\psi} << \sigma$

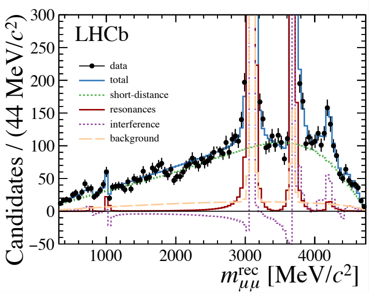


Fit results

Eur. Phys. J. C 77 (2017) 161

- The fit includes several resonances $\omega, \rho, J/\psi, \psi(2s)$ and the ψ below kinematic threshold
- Fit parameters
  - Magnitude η_j and phases δ_j of the resonances
  - $\mathcal{C}_9, \mathcal{C}_{10}$ ($\mathcal{C}_7$ fixed to SM value)

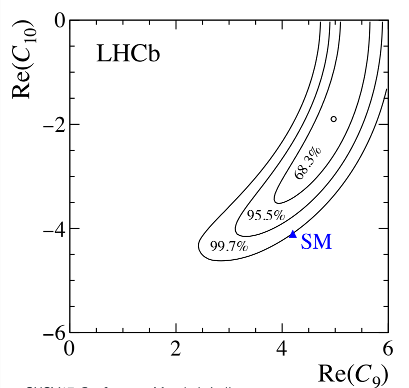
- Four solutions corresponding to the sign combinations of the J/ψ and $\psi(2s)$ phases
- The values of the J/ψ phase are compatible with $\pm\pi/2$
- Interference between short and long distance components is small in the low-q^2 region



- Assuming the model encapsulates all long-distance contributions $\mathcal{B}$ of short distance component $B^+ \to K^+\mu^+\mu^-$ obtained

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15(\text{stat}) \pm 0.23(\text{syst})) \times 10^{-7}$$

- Allows to constrain the sum $|\mathcal{C}_9|^2 + |\mathcal{C}_{10}|^2$



- Best fit point prefers $|\mathcal{C}_9| > |\mathcal{C}_9^{\text{SM}}|$ and $|\mathcal{C}_{10}| < |\mathcal{C}_{10}^{\text{SM}}|$ at 3σ
- Form factors dominate uncertainties

The $R_{K^{(*)}}$ measurements

Phys. Rev. Lett. 113 (2014) 151601, JHEP 08 (2017) 055

- Ratios of Branching fractions $\mathcal{B}$ defined as

$$R^{\mu,e}_{K^{(*)}}[q^2_{\min}, q^2_{\max}] \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B \to K^{(*)}\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B \to K^{(*)}e^+e^-)}{dq^2} dq^2}$$

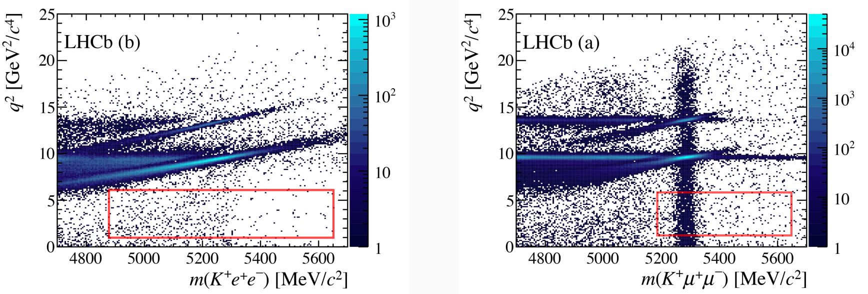
- Theoretical uncertainties cancel $R^{SM}_{K^{(*)}} = 1.00(1)$ (Eur.Phys.J. C76 (2016) no.8, 440)
- Sensitive to non-lepton flavour universal NP models (LFNU)

Experiment	q^2interval (GeV^2)	R_K	R_{K^*}
BaBar*	0.1 - 16.0	$1.00^{+0.31}_{-0.25} \pm 0.07$	$1.13^{+0.34}_{-0.26} \pm 0.10$
	0.1 - 8.12	$0.74^{+0.40}_{-0.31} \pm 0.06$	$1.06^{+0.48}_{-0.33} \pm 0.08$
	10.11 - 16.0	$1.43^{+0.65}_{-0.44} \pm 0.12$	$1.18^{+0.55}_{-0.37} \pm 0.11$
Belle**	0.0 - 16.0	$1.03 \pm 0.19 \pm 0.06$	$0.83 \pm 0.17 \pm 0.08$

* Phys. Rev. D 86 (2012) 032012 ** Phys. Rev. Lett. 103 (2009) 171801

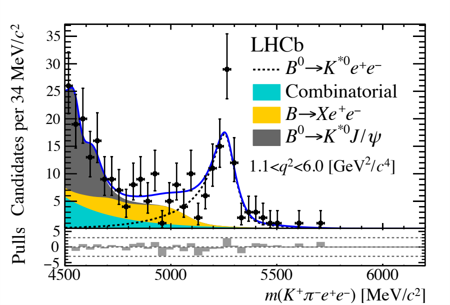
- $q^2 \in [1, 6]$ GeV^2 For R_K
  $q^2 \in [0.045, 1.1]$ and $[1.1, 6.0]$ GeV^2 For R_{K^*}
- Experimental strategy:

$$R^{exp}_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B \to K^{(*)}e^+e^-)}{\mathcal{B}(B \to K^{(*)}J/\psi(\to e^+e^-))}$$

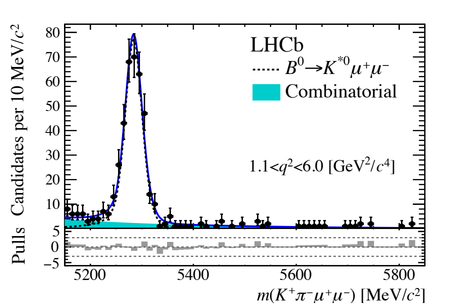


Electron reconstruction is affected by:

- *Bremsstrahlung* photons
- How the event was triggered: by one of the *electrons*, by the K or by other particles in the event



Electron channel

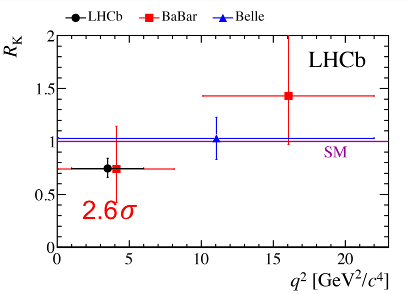


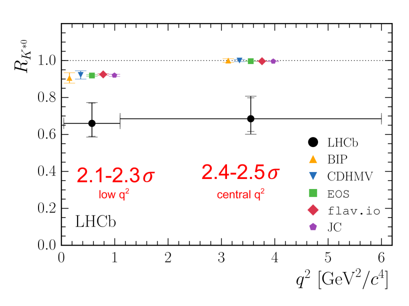
Muon channel

Most precise measurements up to date, integrated luminosity of $3fb^{-1}$

$$R_K = 0.745^{+0.090}_{-0.074}\ (\mathrm{stat}) \pm 0.036\ (\mathrm{syst}) \qquad R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})\ [0.045 - 1.1]\ \mathrm{GeV}^2 \\ 0.69^{+0.11}_{-0.05}\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})\ [1.1 - 6.0]\ \mathrm{GeV}^2 \end{cases}$$

Compatible with SM at



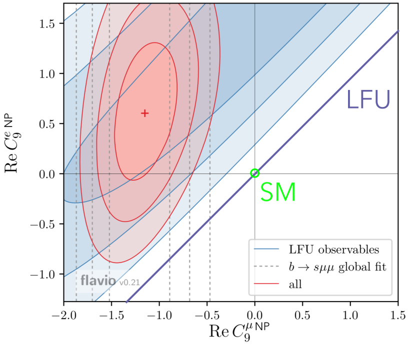


Conclusions and prospects

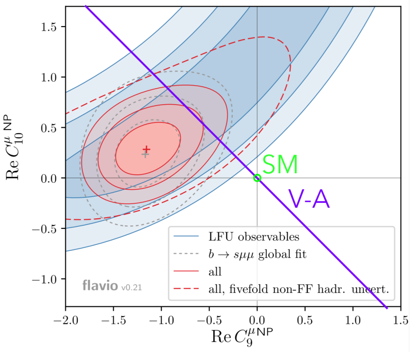
A coherent pattern?

Model independent fits of $\mathcal{C}_i$ prefer a shift in $\mathcal{C}_9$ or $\mathcal{C}_9$ and $\mathcal{C}_{10}$

- $\mathcal{C}_{9,10}^{NP}$ could be different for e and μ, LFUV



- Hypothesis that V-A structure holds in NP



from Phys. Rev. D 96, 055008 (2017)

Conclusion and Prospects

- Rare decays are useful tools to search for NP beyond SM
- Hints of tension with the SM predictions are observed in the $b \to s\ell^+\ell^-$ transitions
- A possible coherent explanation of these anomalies in terms of $\mathcal{C}_9$ or $\mathcal{C}_9$ and $\mathcal{C}_{10}$
- Hence in order to better understand these tensions:
  - New $\mathcal{B}$ fraction ratios measurements are necessary

    $$R_\phi, R_{K\pi\pi}, R_{\Lambda_c^*} \ldots$$

    As well as asymmetry measurements in angular observables

    $$e - \mu \text{ asymmetry in } P_5'$$

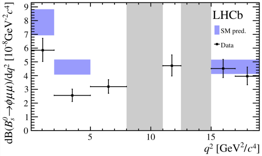
  - Update the existing measurements with RUN II statistics
  - Improve the estimate of non-resonant contributions from charmloop at low-q^2 regions

Thanks for the attention

Spare slides

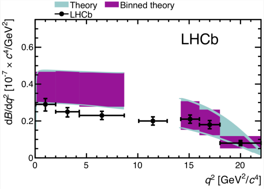
Branching fractions

Small deviations in $\mathcal{B}$ are observed which are numerically consistent with a shift in $\mathcal{C}^{\mu}_{9/10}$.



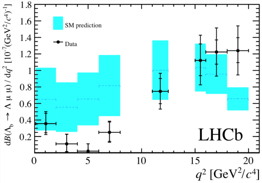
$B_s \to \phi\mu^+\mu^-$

JHEP 09 (2015) 179



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

JHEP 1302 (2013) 105



$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

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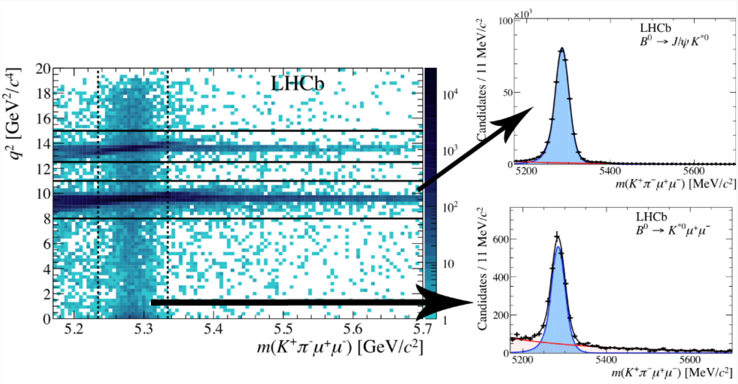
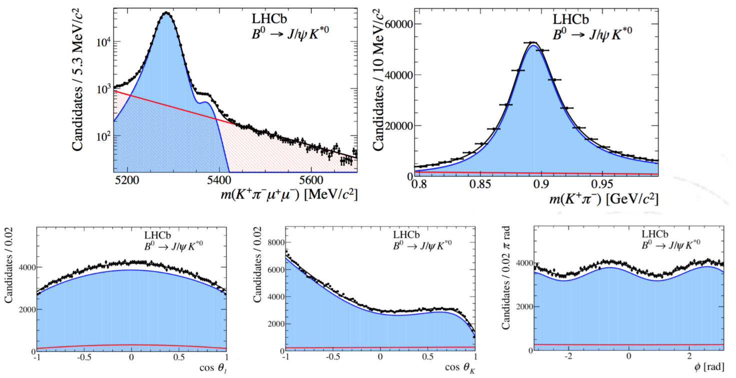
Angular analysis: Checks I

$B^0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$



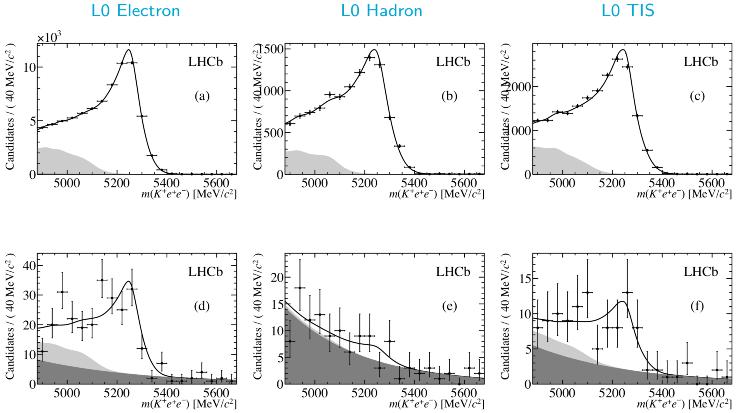
Three methods to determine the angular observables (method of moments, likelihood fit and amplitude analysis) leading to compatible results

Angular analysis: Checks II



Very good agreement with the expected angular distributions in the control channel

3 trigger categories



R_{K^*} cross checks I

- Control of the absolute scale of the efficiencies

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

- Cancellation of residual systematics verified by measuring

$$R_{\psi(2s)} \equiv \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2s)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2s)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

Measured with 2% statistical precision and compatible with unity within 1σ

Relative population of bremmstrahlung categories compared between data and simulation using $B^0 \to K^{*0} J/\psi(\to e^+e^-)$ and $B^0 \to K^{*0}\gamma(\to e^+e^-)$ events