Test of lepton flavour universality at LHCb

Geneva, Joint Annual Meeting of SPS and ÖPG

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LHCb

Outline

Motivation

LHCb

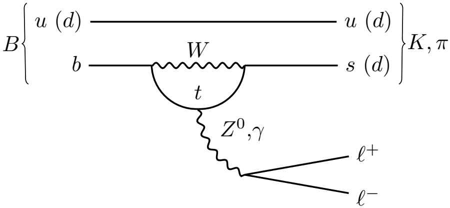
The R_K and R_{K^*} measurements

The $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ decays

Conclusions and future prospects

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

- Suppressed in the Standard Model
  - no FCNC at tree level
  - sensitive to New Physics contributions (including LFNU)



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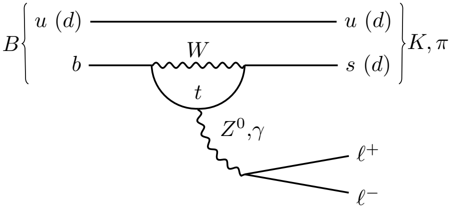

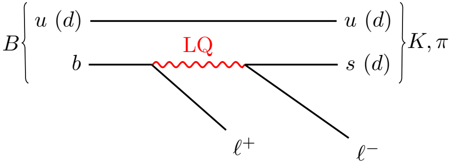

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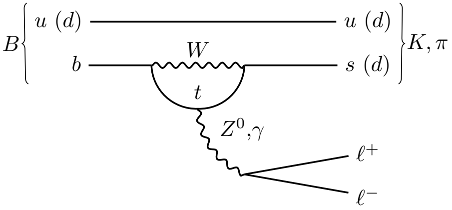
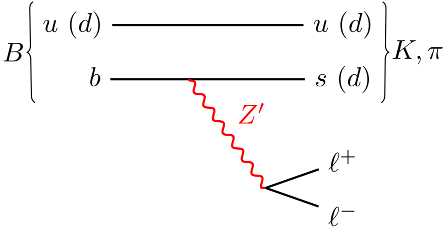




The $b \to s\ell^+\ell^-$ transition

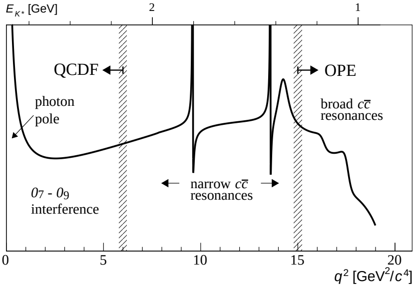
- Suppressed in the Standard Model
  - no FCNC at tree level
  - sensitive to New Physics contributions (including LFNU)
- Model-independent description

  $\Longrightarrow$ effective field theory
- Factorisation between
  - short-range contributions, Wilson coefficients $\mathcal{C}_i^{(\prime)}$
  - long-range contributions, local operators $\mathcal{O}_i^{(\prime)}$

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

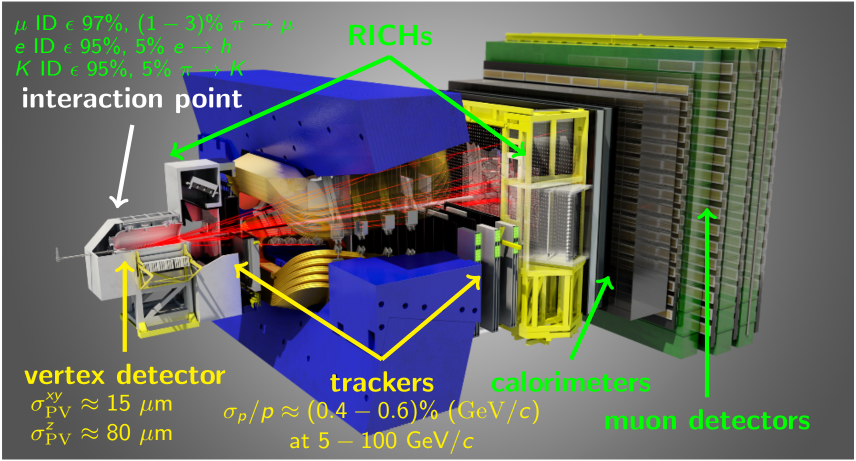
$B^0 \to K^{*0}\mu^+\mu^-$ differential decay width

Annu. Rev. Nucl. Part. Sci. 65 (2015) 113



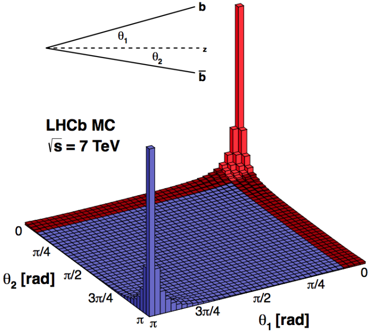
The LHCb detector

pp collisions at 7 − 13 TeV, pseudorapidity $2 < \eta < 5$



The LHCb experiment

- Tailored for heavy flavour physics at the LHC
- Ideal for studying rare *b*-hadron decays
  - excellent vertex and momentum resolution
  - good PID capabilities
- Run I
  - $3\ \mathrm{fb}^{-1}$ at $7-8$ TeV
  - large $b\bar{b}$ production cross section $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\ \mu\mathrm{b}$ in acceptance
- Run II
  - $2.6\ \mathrm{fb}^{-1}$ at 13 TeV already collected
  - increased $\sigma_{b\bar{b}}$



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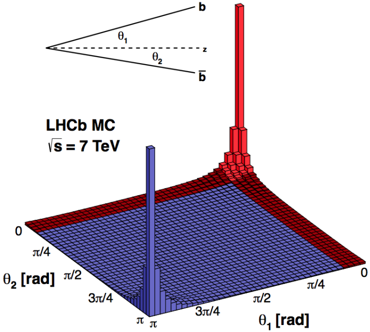


$$R_K = \frac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-}$$

The R_K measurement

- Ratio of branching fractions of $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$
  - $R_K \stackrel{\text{SM}}{=} 1 + \mathcal{O}(10^{-2})$
  - sensitive to new scalar and pseudoscalar interactions or Z' bosons
  - previously measured by BaBar and Belle

Experiment	q^2 (GeV^2)	R_K
BaBar*	$0.1 - 16.0$	$1.00^{+0.31}_{-0.25} \pm 0.07$
	$0.1 - 8.12$	$0.74^{+0.40}_{-0.31} \pm 0.06$
	> 10.11	$1.43^{+0.65}_{-0.44} \pm 0.12$
Belle**	$0.00 - 16.0$	$1.03 \pm 0.19 \pm 0.06$

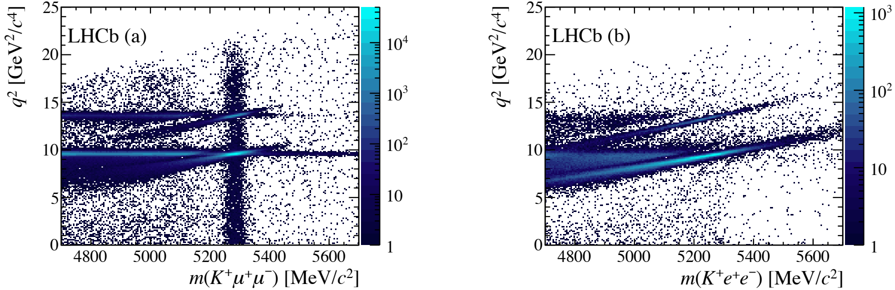
* Phys. Rev. D 86 (2012) 032012

** Phys. Rev. Lett. 103 (2009) 171801

The R_K measurement at LHCb

- $q^2 \in [1, 6]\ \mathrm{GeV}^2/c^4$
- Double ratio with respect to the resonant decay mode $B^+ \to J/\psi K^+$

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^+ \to K^+ \mu\mu)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^+ \to K^+ ee)}{dq^2} dq^2} = \left(\frac{N_{K\mu\mu}}{N_{Kee}}\right) \left(\frac{N_{KJ/\psi(ee)}}{N_{KJ/\psi(\mu\mu)}}\right) \left(\frac{\epsilon_{Kee}}{\epsilon_{K\mu\mu}}\right) \left(\frac{\epsilon_{KJ/\psi(ee)}}{\epsilon_{KJ/\psi(\mu\mu)}}\right)$$



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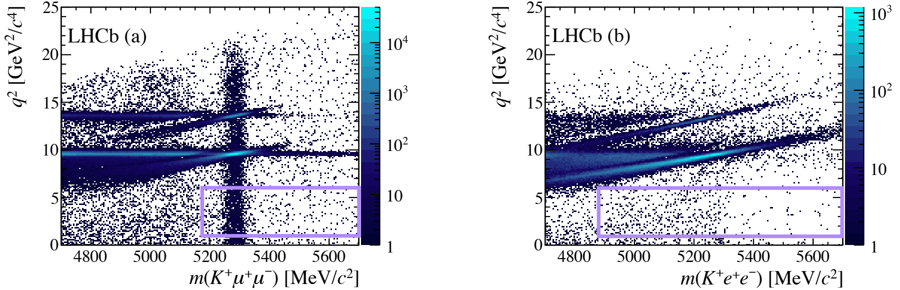
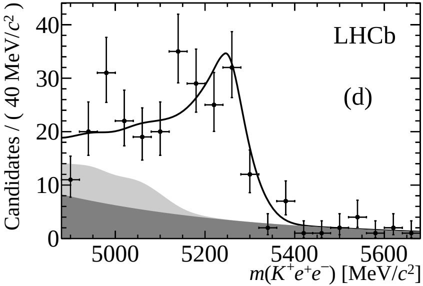


Results for R_K

- Electron reconstruction affected by
  - trigger
  - *bremsstrahlung* photons
- Most precise result to date
- Compatible with the SM at 2.6 σ

electron trigger, 172^{+20}_{-19} events



$$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

- Fundamental for future measurements of decays with electrons in the final state

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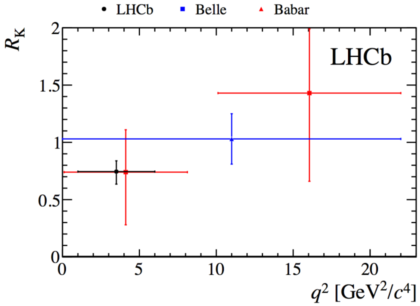

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

- Fundamental for future measurements of decays with electrons in the final state

$$R_{K^*} = \frac{B^0 \to K^{*0}\mu^+\mu^-}{B^0 \to K^{*0}e^+e^-}$$

The R_{K^*} measurement

- Analogous to R_K, but for $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$
  - $R_{K^*} \stackrel{\text{SM}}{=} 1$ (but modified by phase-space effects)
  - sensitive to LQ or Z' bosons
  - previously measured by BaBar and Belle

Experiment	q^2 (GeV^2)	R_{K^*}
BaBar*	$0.1 - 16.0$	$1.13^{+0.34}_{-0.26} \pm 0.10$
	$0.1 - 8.12$	$1.06^{+0.48}_{-0.33} \pm 0.08$
	> 10.11	$1.18^{+0.55}_{-0.37} \pm 0.11$
Belle**	$0.00 - 16.0$	$0.83 \pm 0.17 \pm 0.08$

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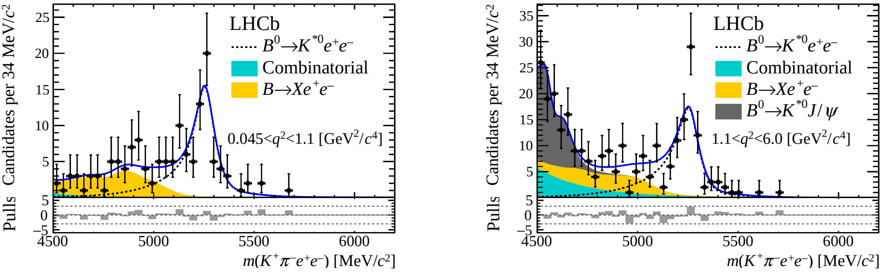
** Phys. Rev. Lett. 103 (2009) 171801

The R_{K^*} measurement at LHCb

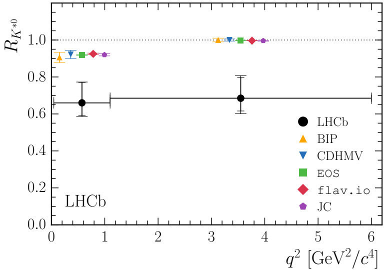
- $q^2 \in [0.045, 1.1]$ and $[1.1, 6.0]$ GeV^2/c^4
- Double ratio with respect to the resonant decay mode $B^0 \to J/\psi K^{*0}$
- Mass fit of electron channel
  (separately for three trigger categories)
- Simultaneously for resonant and non-resonant modes

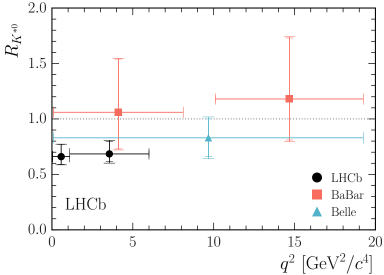


Results for R_{K^*}

- Most precise result to date
- Compatible with the SM at
  - $2.1 - 2.3\sigma$ for low q^2
  - $2.4 - 2.5\sigma$ for central q^2

$$R_{K^{*0}} = \begin{cases} 0.66 \, {}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \ \ \text{GeV}^2/c^4 \\ 0.69 \, {}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0 \ \ \text{GeV}^2/c^4 \end{cases}$$

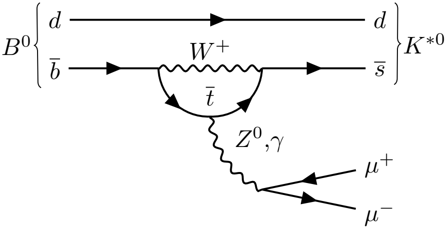


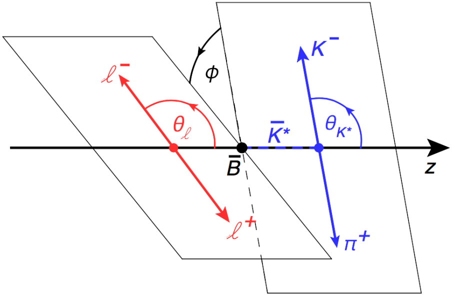


Look at muons and electrons separately...

The $B^0 \to K^{*0}\ \ell^+\ell^-$ decay

- Angular analysis in terms of $\vec{\Omega} = (\theta_l,\ \theta_k,\ \phi)$ and $q^2 = m^2_{\ell\ell}$





LHCb analysis strategy

- Determine

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{d\vec{\Omega}dq^2} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k + \tfrac{1}{4}(1-F_L)\sin^2\theta_k\cos2\theta_\ell - F_L\cos^2\theta_k\cos2\theta_\ell + S_3\sin^2\theta_k\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_k\sin2\theta_\ell\cos\phi + S_5\sin2\theta_k\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_k\cos\theta_\ell + S_7\sin2\theta_k\sin\theta_\ell\sin\phi + S_8\sin2\theta_k\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_k\sin^2\theta_\ell\sin2\phi\Big]$$

  with F_L, A_{FB}, $S_i = f(C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)})$,
  combinations of K^{*0} decay amplitudes

- Theoretical uncertainty on hadronic form factors
  $\Longrightarrow$ reduced by moving to optimised observables, *e.g.* $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$

  arXiv:1305.4808

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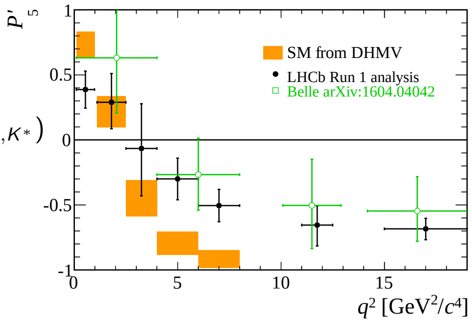
Results for $B^0 \to K^{*0}\mu^+\mu^-$

- Analysis in 8 bins of $q^2 \in [0.1, 19.0]$ GeV$^2/c^4$, $K^{*0} \to K^+\pi^-$
- Most angular observables compatible with SM predictions
- Tension observed in P'_5
  - global fit at 3.4 σ from the SM prediction
  - compatible with previous LHCb and recent Belle measurements
- Explainable in terms of
  - SM charm-loop effects (cannot explain tension in R_{K,K^*}) $\Longrightarrow$ JHEP 06 (2016) 116
  - NP involving $\mathcal{C}^{\mu}_{9,10}$ otherwise



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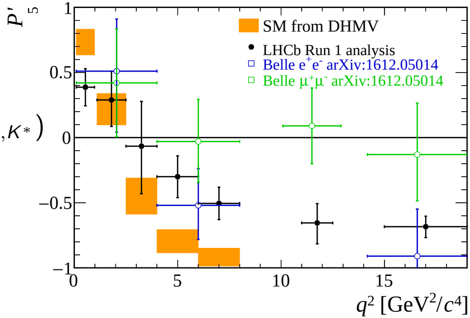
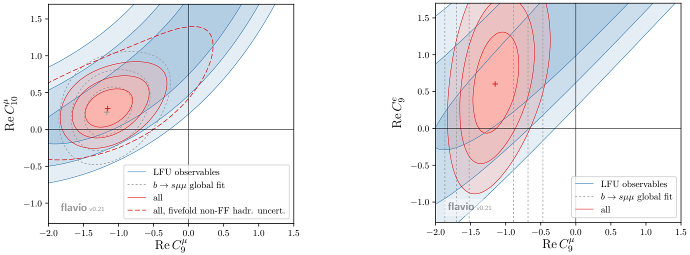


Theory interpretation in terms of NP

- Measurements in favour of a reduced $\mathcal{C}_9^\mu$
- Possible link to LFNU

  $\Longrightarrow$ arXiv:1605.03156, JHEP 12 (2014) 131, Phys. Rev. D 90, 054014 (2014)
- Can explain R_{D^*} anomaly (see Patrick's talk), assuming W' and Z'

  $\Longrightarrow$ arXiv:1506.01705



Conclusions and future prospects

- Search for NP in the $b \to s\ell^+\ell^-$ transition
  - hints of tension with SM predictions observed in R_K, R_{K^*}, and $B^0 \to K^{*0}\mu^+\mu^-$
  - possible coherent pattern in terms of $\mathcal{C}_9^\mu$ (and possibly $\mathcal{C}_{10}^\mu$)
- Updates with Run II statistics and new measurements
- Updates of R_K, R_{K^*}, and R_{D^*}
- New measurements of R_ϕ, R_D, $R_{K\pi\pi}$, and many more
- Angular analyses of $B^0 \to K^{*0}\ell^+\ell^-$ and $B^+ \to K^+\ell^+\ell^-$
- Asymmetry measurements in angular observables, *e.g.* $e-\mu$ asymmetry in P_5'

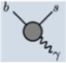
Stay tuned!

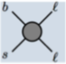
Thanks for the attention!

Spare slides

Effective Hamiltonian approach

- Combine results from several decays in order to
  - classify NP contributions
  - perform consistency checks

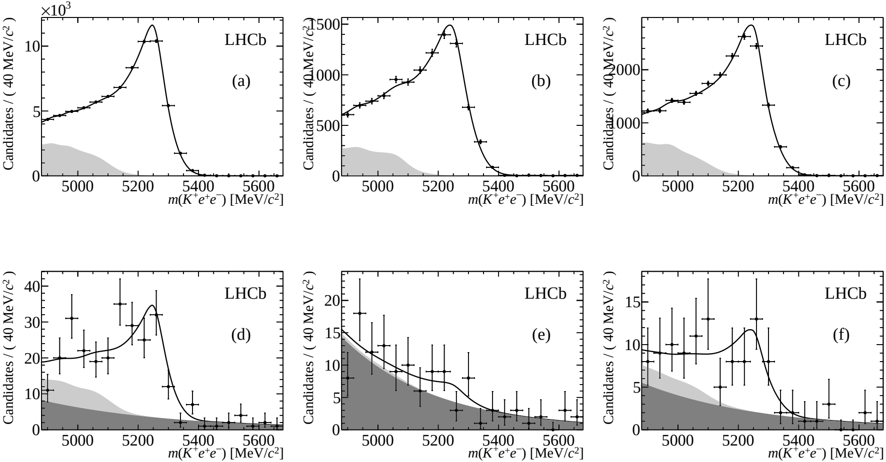




Operator $\mathcal{O}_i$	$B \to K^{*0}\gamma$	$B \to K^{*0}\mu^+\mu^-$	$B \to \mu^+\mu^-$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma_{\mu\nu}b_R)F_{\mu\nu}$	✓	✓	
$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$		✓	
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$		✓	✓
$\mathcal{O}_{S,P}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

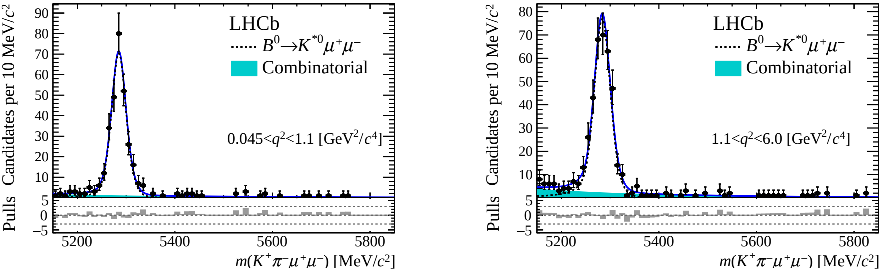
The R_K measurement at LHCb

L0 Electron | L0 Hadron | L0 TIS



The R_{K^*} measurement at LHCb

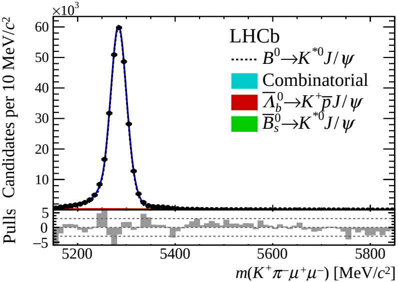
- $q^2 \in [0.045, 1.1]$ and $[1.1, 6.0]$ GeV^2/c^4
- Double ratio with respect to the resonant decay mode $B^0 \to J/\psi K^{*0}$
- Mass fit of muon channel
- Simultaneously for resonant and non-resonant modes



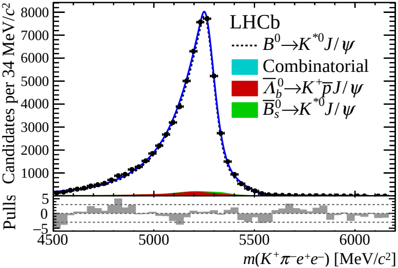
The R_{K^*} measurement at LHCb

- Mass fit of resonant decay mode $B^0 \to J/\psi K^{*0}$

$J/\psi \to \mu^+\mu^-$

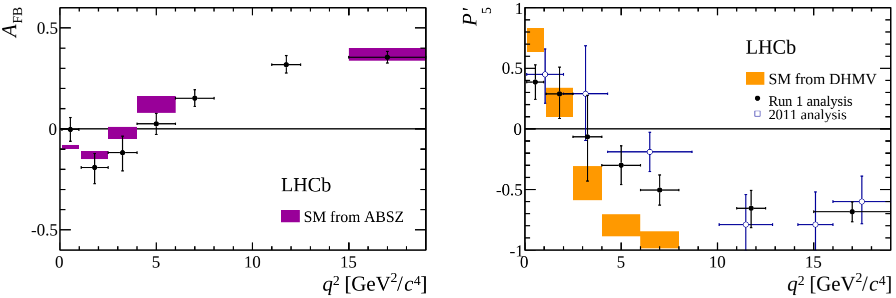


$J/\psi \to e^+e^-$



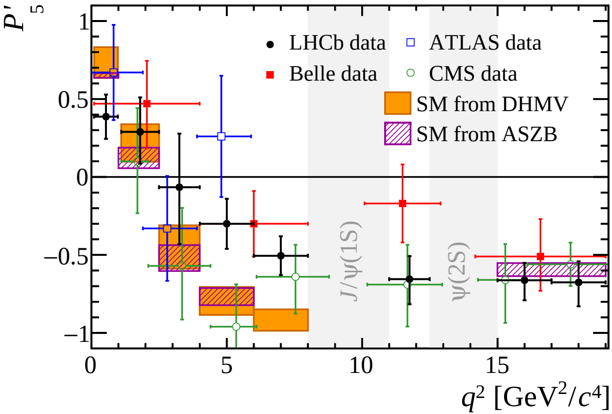
The $B^0 \to K^{*0}\mu^+\mu^-$ decay

- Most angular observables compatible with SM predictions
- However, tension in P_5'
  - data fit at 3.4 σ from SM
  - compatible with the measurement based on 1 fb^{-1}



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

- Overview of P_5' results



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

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\, d\cos\theta_\ell\, d\cos\theta_k\, d\tilde{\phi}} = \frac{9}{16\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_k + F_L\cos^2\theta_k$$
$$+\left(\tfrac{1}{4}(1-F_L)\sin^2\theta_k - F_L\cos^2\theta_k\right)\cos 2\theta_\ell$$
$$+\tfrac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_k\sin^2\theta_\ell\cos 2\tilde{\phi}$$
$$+(1-F_L)A_T^{Re}\sin^2\theta_k\cos\theta_\ell$$
$$+\tfrac{1}{2}(1-F_L)A_T^{Im}\sin^2\theta_k\sin^2\theta_\ell\sin 2\tilde{\phi}\Big]$$

$$F_L = \frac{|A_0|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$
$$A_T^{(2)} = \frac{|A_\perp|^2-|A_\parallel|^2}{|A_\perp|^2+|A_\parallel|^2}$$
$$A_T^{Re} = \frac{2\Re(A_{\parallel L}A^*_{\perp L}+A_{\parallel R}A^*_{\perp R})}{|A_\parallel|^2+|A_\perp|^2}$$
$$A_T^{Im} = \frac{2\Im(A_{\parallel L}A^*_{\perp L}+A_{\parallel R}A^*_{\perp R})}{|A_\parallel|^2+|A_\perp|^2}$$

with

$$|A_0|^2 = |A_{0L}|^2+|A_{0R}|^2$$
$$|A_\parallel|^2 = |A_{\parallel L}|^2+|A_{\parallel R}|^2$$
$$|A_\perp|^2 = |A_{\perp L}|^2+|A_{\perp R}|^2$$

$$A_T^{(2)}(q^2\to 0) = \frac{2\mathcal{R}e(C_7 C_7'^*)}{|C_7|^2+|C_7'|^2}$$
$$A_T^{Im}(q^2\to 0) = \frac{2\mathcal{I}m(C_7 C_7'^*)}{|C_7|^2+|C_7'|^2}$$

Local operators

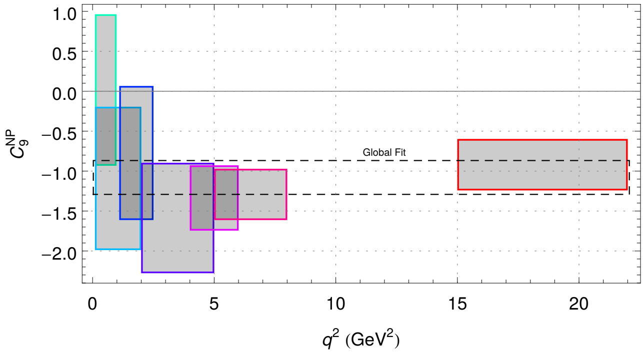
$$\begin{array}{llll} \mathcal{O}_7 = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_R bF_{\mu\nu}\,, & \mathcal{O}_7' = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_L bF_{\mu\nu} \\ \mathcal{O}_8 = g_s\frac{m_b}{e^2}\bar{s}\sigma^{\mu\nu}P_R T^a bG^a_{\mu\nu}\,, & \mathcal{O}_8' = g_s\frac{m_b}{e^2}\bar{s}\sigma^{\mu\nu}P_L T^a bG^a_{\mu\nu} \\ \mathcal{O}_9 = \bar{s}\gamma_\mu P_L b\,\bar{\ell}\gamma^\mu\ell\,, & \mathcal{O}_9' = \bar{s}\gamma_\mu P_R b\,\bar{\ell}\gamma^\mu\ell \\ \mathcal{O}_{10} = \bar{s}\gamma_\mu P_L b\,\bar{\ell}\gamma^\mu\gamma_5\ell\,, & \mathcal{O}_{10}' = \bar{s}\gamma_\mu P_R b\,\bar{\ell}\gamma^\mu\gamma_5\ell \end{array} \quad (1)$$

$$\begin{array}{ll} \mathcal{O}_\mathrm{S} = \bar{s}P_R b\,\bar{\ell}\ell\,, & \mathcal{O}_\mathrm{S}' = \bar{s}P_L b\,\bar{\ell}\ell \\ \mathcal{O}_\mathrm{P} = \bar{s}P_R b\,\bar{\ell}\gamma_5\ell\,, & \mathcal{O}_\mathrm{P}' = \bar{s}P_L b\,\bar{\ell}\gamma_5\ell \end{array} \quad (2)$$

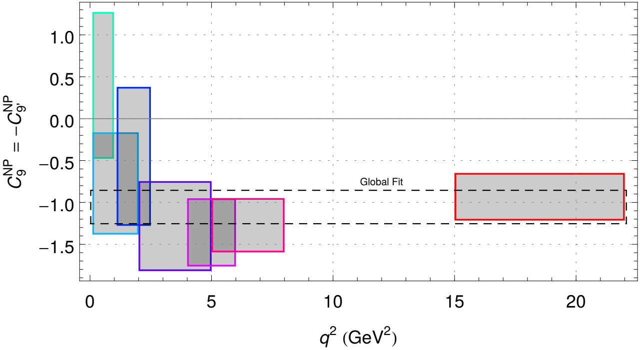
$$\mathcal{O}_\mathrm{T} = \bar{s}\sigma_{\mu\nu}b\,\bar{\ell}\sigma^{\mu\nu}\ell\,, \quad \mathcal{O}_\mathrm{T5} = \bar{s}\sigma_{\mu\nu}b\,\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell \quad (3)$$

$$\mathcal{O}_1 = \frac{4\pi}{\alpha_e}\bar{s}\gamma_\mu P_L b\,\bar{c}\gamma^\mu P_L c\,, \quad \mathcal{O}_2 = \frac{4\pi}{\alpha_e}\bar{s}\gamma_\mu P_L c\,\bar{c}\gamma^\mu P_L b\,. \quad (4)$$

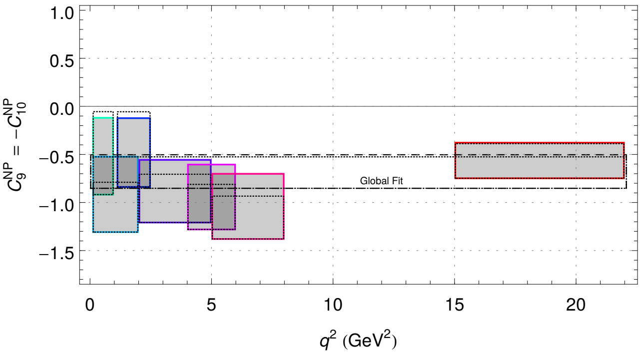
Theory interpretation in terms of NP



Theory interpretation in terms of NP

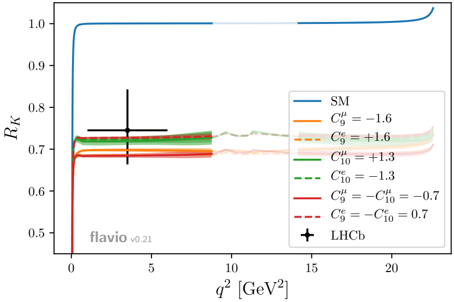


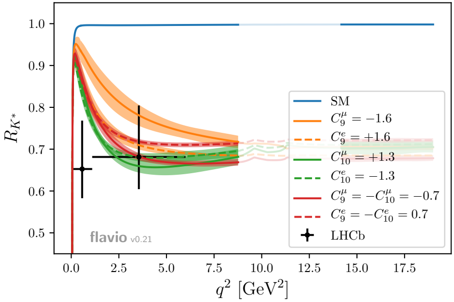
Theory interpretation in terms of NP



Predictions for R_K and R_{K^*}

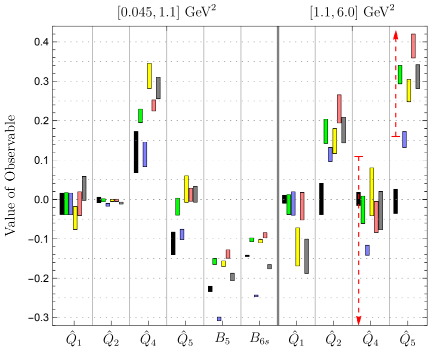
- SM and NP predictions for
  - R_K
  - R_{K^*}

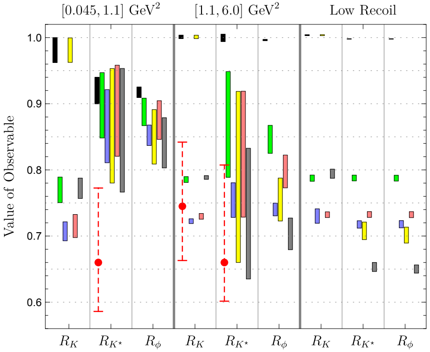




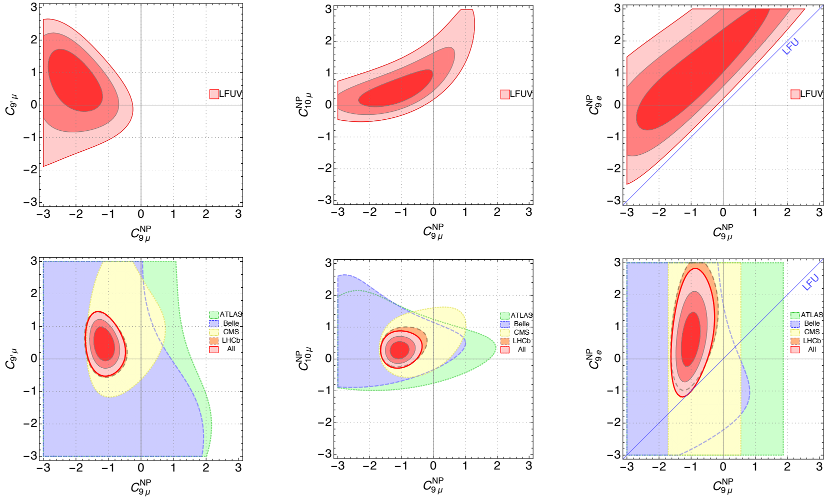
Predictions for Q_i and R_j

- SM and NP predictions for
  - LFU angular asymmetries Q_i
  - LFU ratios of branching ratios R_j



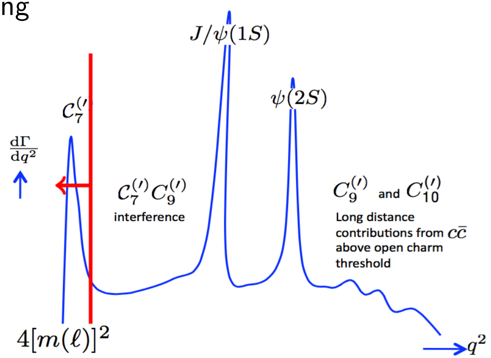


Theory interpretation in terms of NP



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

- Simplified formalism, 4 angular observables
  - K^{*0} longitudinal polarisation fraction F_L
  - transverse asymmetries $A_T^{(2)}$, A_T^{Im} and A_T^{Re}
- Experimentally more challenging
  - statistics
  - resolution
  - trigger
  - *bremsstrahlung* photons
- $q^2 \in [0.002, 1.120]\ \text{GeV}^2/c^4$
  - photon polarisation
- $K^{*0} \to K^+ \pi^-$
- ML fit of $\vec{\Omega}$ and $m_{K\pi ee}$



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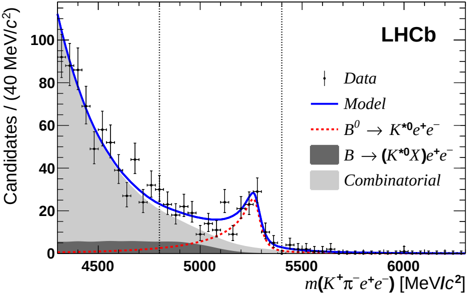
124 signal events



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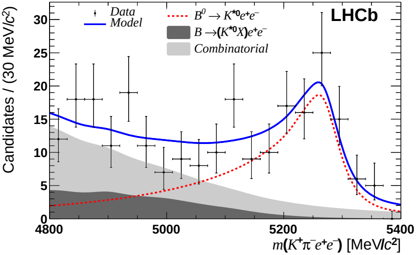
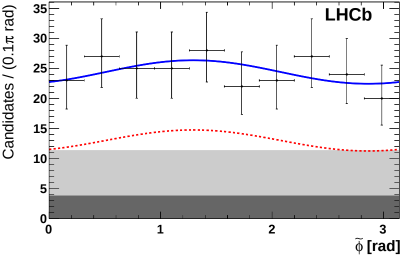
Results for $B^0 \to K^{*0} e^+ e^-$





$$F_L = +0.16 \pm 0.06 \pm 0.03$$
$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_T^{Im} = +0.14 \pm 0.22 \pm 0.05$$
$$A_T^{Re} = +0.10 \pm 0.18 \pm 0.05$$

$$F_L \overset{\text{SM}}{=} +0.10^{+0.11}_{-0.05}$$
$$A_T^{(2)} \overset{\text{SM}}{=} +0.03^{+0.05}_{-0.04}$$
$$A_T^{Im} \overset{\text{SM}}{=} (-0.2^{+1.2}_{-1.2}) \times 10^{-4}$$
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Phys. Rev. D 93, 014028 (2016)

In agreement with SM

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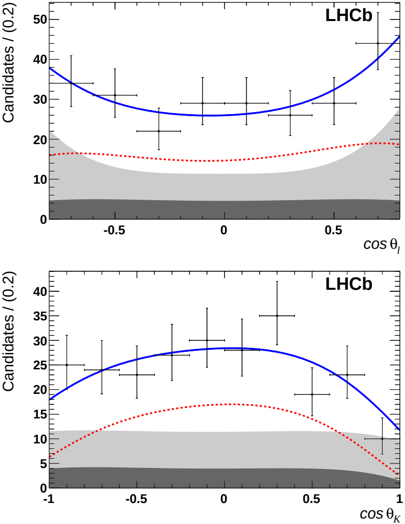

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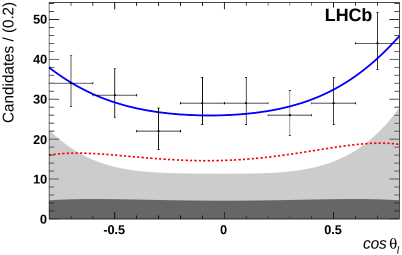

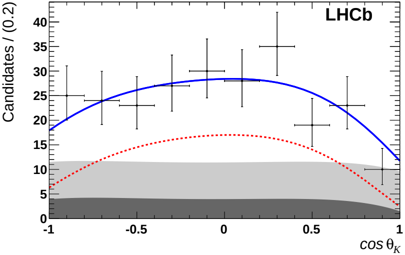

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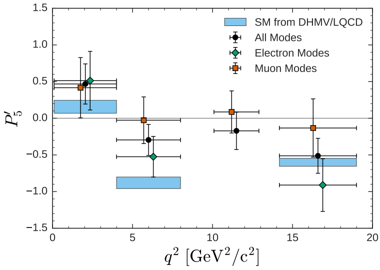
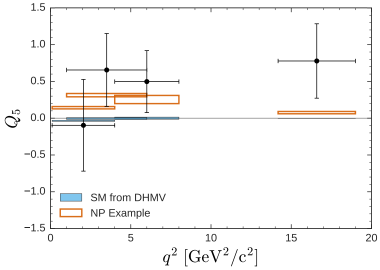
Phys. Rev. D 93, 014028 (2016)

...and consistent with $B^0 \to K^{*0}\mu^+\mu^-$ anomaly, since contribution from $\mathcal{C}_7$ only

LFU angular asymmetries

- Intriguingly, discrepancies in R_{K,K^*} explainable by reduced $C^{\mu}_{9,10}$
  - would explain pattern of deviations observed in $b \to s\mu\mu$ transitions too, including P'_5
- Best way to connect directly P'_5 and R_{K^*} would be to measure LFU angular asymmetries
  - $Q_i = P_i(\mu\mu) - P_i(ee)$, in particular $Q_5 = P'_5(\mu\mu) - P'_5(ee)$ $\Longrightarrow$ arXiv:1605.03156





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  - same information accessible using $\Delta S_i = S_i(ee) - S_i(\mu\mu)$, in particular $\Delta S_5 = S_5(ee) - S_5(\mu\mu)$ and $\Delta A_{FB} = A_{FB}(ee) - A_{FB}(\mu\mu)$ $\Longrightarrow$ arXiv:1503.06199
  - in addition, D_i, in particular $D_5 = \frac{dB^e}{dq^2} S^e_5 - \frac{dB^\mu}{dq^2} S^\mu_5$, combining branching ratios and angular asymmetries $\Longrightarrow$ arXiv:1610.08761