Electroweak penguin decays with di-leptons

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on behalf of the LHCb collaboration

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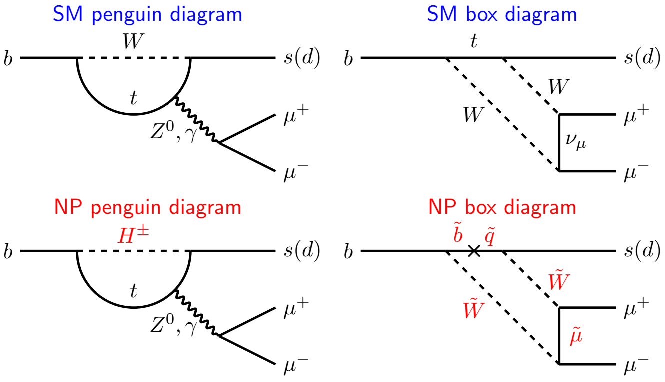
Electroweak penguin decays



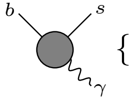
- $b \to s(d)\ell^+\ell^-$ decays are flavour changing neutral currents (FCNC)
- Forbidden at tree-level in Standard Model (SM) $\to$ loop-suppressed
- New Physics amplitudes can modify $\mathcal{B}$ and angular distributions

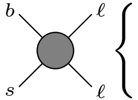
Description of FCNC processes in effective field theory

- Effective Hamiltonian for $b \to s$ FCNC transition

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

- Wilson coefficients C_i encode short-distance physics and possible NP effects
- $\mathcal{O}_i$ local operators with different Lorentz structure
- $\mathcal{O}_i'$ helicity flipped operators, m_s/m_b suppressed
- More details [Semileptonic Rare decays, C. Bobeth]





Operator		
$\mathcal{O}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu})$	photon penguin
$\mathcal{O}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$	ew. penguin
$\mathcal{O}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$	
$\mathcal{O}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$	scalar penguin
$\mathcal{O}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$	pseudoscalar penguin

Electroweak penguins at LHCb

Possible New particles beyond the SM can affect

1. Angular distributions

- $B^0 \to K^{*0}\mu^+\mu^-$ angular observables [JHEP 08 (2013) 131]
- $B_s^0 \to \phi\mu^+\mu^-$ Angular analysis [JHEP 07 (2013) 084]
- $B^0 \to K^{*0}\mu^+\mu^-$ FF indep. observables [PRL 111 191801 (2013)]
- $B \to K\mu^+\mu^-$ angular analysis [JHEP 05 (2014) 082]

2. Branching ratios

- $B \to K^{(*)}\mu^+\mu^-$ Isospin and $\mathcal{B}$ [JHEP 06 (2014) 133]
- $B^+ \to (K^+\pi^+\pi^-, \phi K^+)\mu^+\mu^-$ [LHCb-PAPER-2014-030]
- $B \to K^{(*)}\mu^+\mu^-$ CP asymmetries [LHCb-PAPER-2014-032]
- $B^+ \to K^+e^+e^-$ R_K and $\mathcal{B}$ [arXiv:1406.6482]
- $\Lambda_b \to \Lambda\mu^+\mu^-$ branching fraction [PLB 725 (2013) 25]
- $B^+ \to \pi^+\mu^+\mu^-$ first observation [JHEP 12 (2012) 125]
- $B^+ \to K^+\mu^+\mu^-$ resonances [PRL 111 112003 (2013)]

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- $B^+ \to (K^+\pi^+\pi^-, \phi K^+)\mu^+\mu^-$ [LHCb-PAPER-2014-030] New
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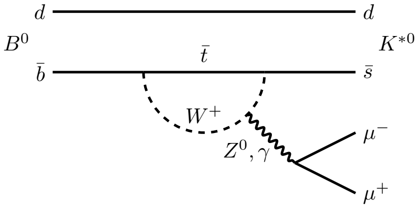
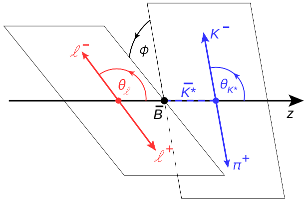
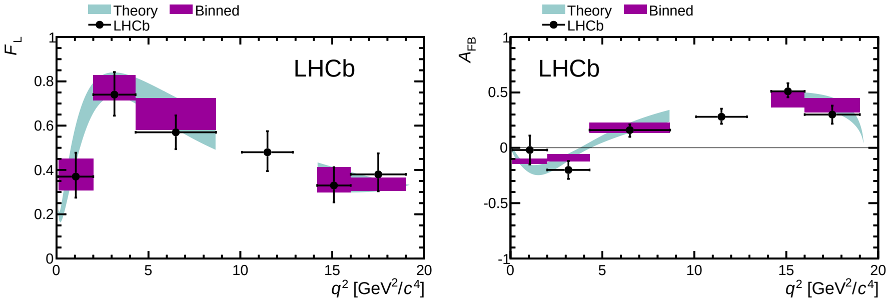
The decay $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$





- Decay fully described by three helicity angles $\theta_\ell, \theta_K, \Phi$ and $q^2 = m(\mu^+\mu^-)^2$
- $$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell d\cos\theta_K d\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\Phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\Phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\Phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\Phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\Phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\Phi\Big]$$
- $F_L(q^2), A_{FB}(q^2), S_i(q^2)$ combinations of K^{*0} spin amplitudes depending on Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$
- Large theory uncertainty due to the q^2 dependent hadronic form-factors
- Determine observables in 4D ($\cos\theta_\ell, \cos\theta_K, \phi$ and $m_{K\pi\mu\mu}$) fit in bins of q^2

$B^0 \to K^{*0}\mu^+\mu^-$ angular observables ($1\,\mathrm{fb}^{-1}$)

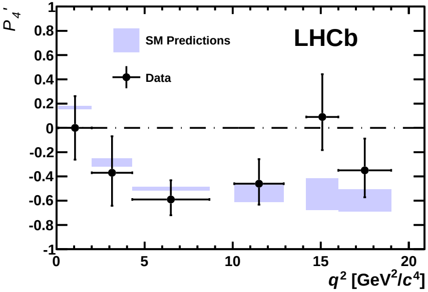


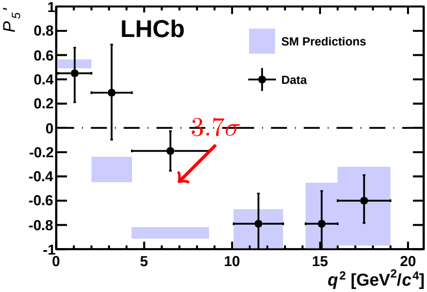
[JHEP 08 (2013) 131]

- Angular observables in good agreement with SM prediction [C. Bobeth et al. JHEP 07 (2011) 067]
- Zero crossing point of A_{FB} free from FF uncertainties
- Result $q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2$ consistent with SM prediction $q^2_{0,\mathrm{SM}} = 4.36^{+0.33}_{-0.31}\,\mathrm{GeV}^2$ [EPJ C41 (2005) 173-188]

Less form factor dependent observables P_i' $(1\,\mathrm{fb}^{-1})$

- Less FF dependent observables P_i' introduced in [JHEP 05 (2013) 137]
- For $P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$ leading FF uncertainties cancel for all q^2
- 3.7σ local deviation from SM prediction [JHEP 05 (2013) 137] in P_5'





[PRL 111, 191801 (2013)]

Interpreting the P_5' discrepancy

Possible interpretations

1. Statistical fluctuation
   Probability in 1/24 bins (Look-elsewhere effect): 0.5%
2. New Physics
   What type of NP could generate deviation?
   - Best fit with $\Delta C_9^{\rm NP} \sim -1.5$
   - Possible candidate: Z' $\mathcal{O}(1\,\mathrm{TeV})$
   - See also:
     [Altmannshofer et al. EPJC 73 (2013) 2646]
     [Beaujean et al. EPJC 74 (2014) 2897]
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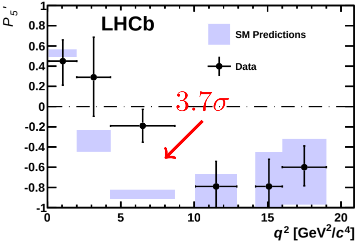
3. Theory calculation
   Λ/m_b corrections?
   Charm-loop effects not fully understood?



[PRL 111, 191801 (2013)]

Interpreting the P_5' discrepancy

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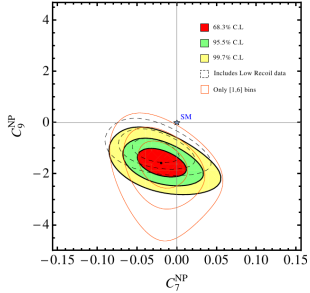

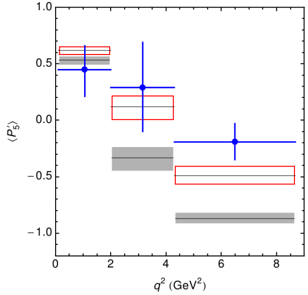

[S. Descotes-Genon et al. PRD 88, 074002 (2013)]

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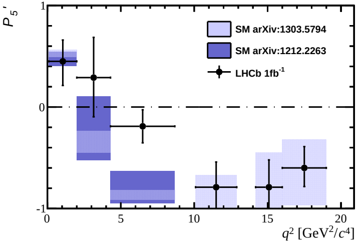
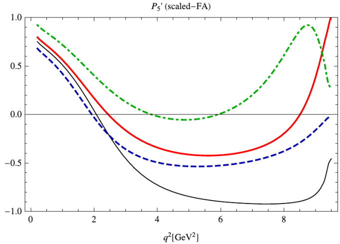
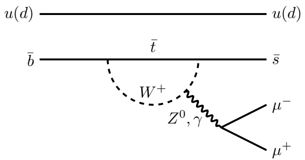


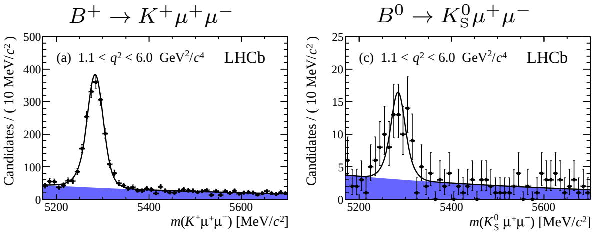
[Jäger et al., JHEP 1305 (2013) 043]



[J. Lyon, R. Zwicky arXiv:1406.0566]

Angular analysis of $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0_{\rm S}\mu^+\mu^-$





[JHEP 05 (2014) 082]

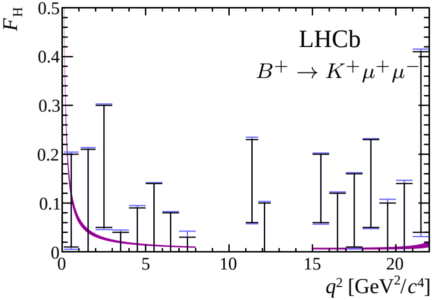
- $N_{B^+\to K^+\mu^+\mu^-} = 4746 \pm 81$ and $N_{B^0\to K^0_{\rm S}\mu^+\mu^-} = 176 \pm 17$ in $3\,{\rm fb}^{-1}$
- Experimental challenge: K^0_S reconstruction
- Differential decay rate for $B^+ \to K^+\mu^+\mu^-$

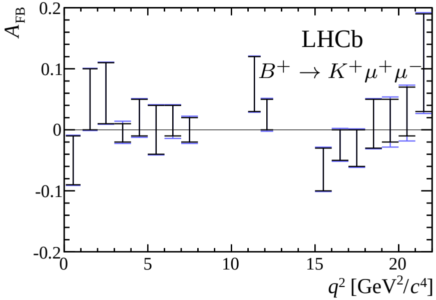
$$\frac{1}{\Gamma}\frac{{\rm d}\Gamma(B^+ \to K^+\mu^+\mu^-)}{{\rm d}\cos\theta_\ell} = \frac{3}{4}(1-F_{\rm H})(1-\cos^2\theta_\ell) + \frac{1}{2}F_{\rm H} + A_{\rm FB}\cos\theta_\ell$$

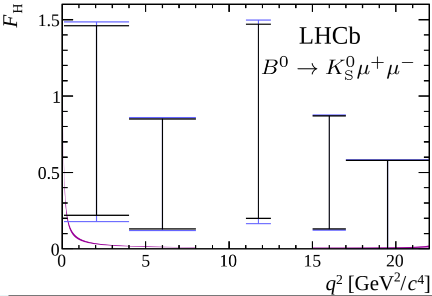
$$\frac{1}{\Gamma}\frac{{\rm d}\Gamma(B^0 \to K^0_{\rm S}\mu^+\mu^-)}{{\rm d}|\cos\theta_\ell|} = \frac{3}{2}(1-F_{\rm H})(1-|\cos\theta_\ell|^2) + F_{\rm H}$$

- Flat parameter $F_{\rm H}$ sensitive to (Pseudo)scalar contributions, small in SM
- Forward backward asymmetry $A_{\rm FB}$ zero in SM

Angular analysis of $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0_S\mu^+\mu^-$







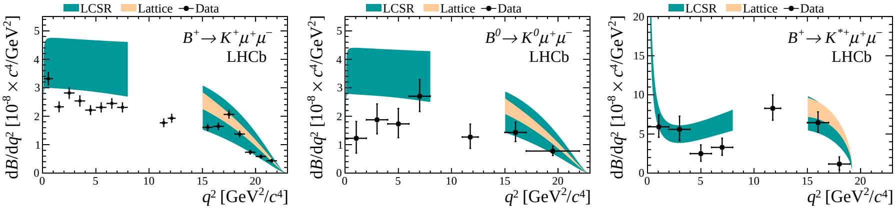
- 2D fit in $\cos\theta_\ell$ and $m(K\mu^+\mu^-)$
- [JHEP 05 (2014) 082] in good agreement with SM prediction

$B \to K\mu^+\mu^-$ branching fraction measurement

- Number of signal events in full $3\,\text{fb}^{-1}$ data sample

	$B^0 \to K^0_S\mu^+\mu^-$	$B^+ \to K^+\mu^+\mu$	$B^0 \to K^{*0}\mu^+\mu^-$	$B^+ \to K^{*+}\mu^+\mu^-$
N_{sig}	176 ± 17	4746 ± 81	2361 ± 56	162 ± 16

- Normalise with respect to $B^0 \to J/\psi\, K^0_S(K^{*0})$ and $B^+ \to J/\psi\, K^+(K^{*+})$
- Differential branching fractions



[JHEP 06 (2014) 133]

- Compatible with but lower than SM predictions

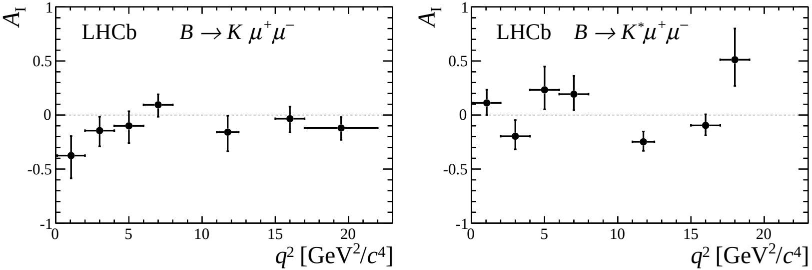
  Light cone sum rules (LCSR): [PRD 71 (2005) 014029], [JHEP 09 (2010) 089],

  Lattice: [PRD 89 (2014) 094501], [PRD 88 (2013) 054509]

- Measurement of $\mathrm{d}\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathrm{d}q^2$ with $3\,\text{fb}^{-1}$ accounting for S-wave in preparation

$B \to K^{(*)}\mu^+\mu^-$ isospin

- Isospin asymmetry $A_{\mathrm{I}} = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$
- SM prediction for A_{I} is $\mathcal{O}(1\%)$

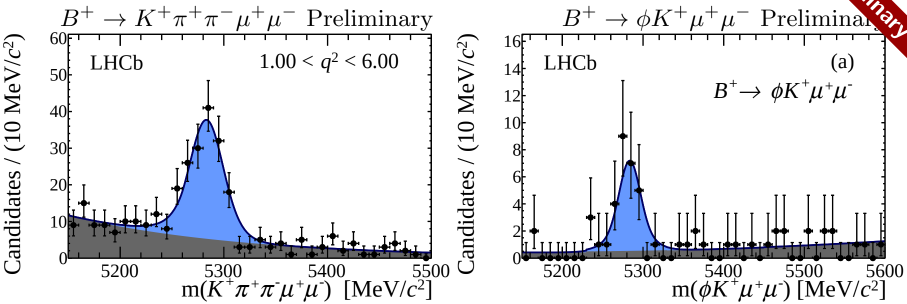


[JHEP 06 (2014) 133]

- Results with $3\,\mathrm{fb}^{-1}$ consistent with SM
- p-value for deviation of $A_{\mathrm{I}}(B \to K\mu\mu)$ from 0 is 11% (1.5σ)
- Tensions seen in the $1\,\mathrm{fb}^{-1}$ analysis reduced due to
  1. Updated reco./selection 2. Stat. approach 3. Isospin symmetry in J/ψ modes

$B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ and $B^+ \to \phi K^+\mu^+\mu^-$

Preliminary



[LHCb-PAPER-2014-030]

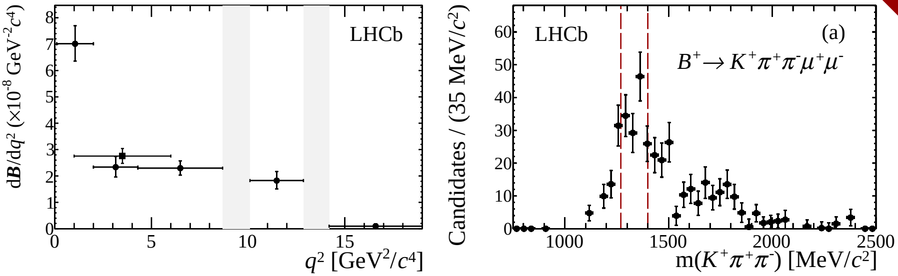
- First observation of these modes with $N_{\text{sig}}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = 367^{+24}_{-23}$ and $N_{\text{sig}}(B^+ \to \phi K^+\mu^+\mu^-) = 25.2^{+6.0}_{-5.3}$
- Normalise to $B^+ \to \psi(2S)(\to J/\psi\,\pi^+\pi^-)K^+$ and $B^+ \to J/\psi\,\phi K^+$
- Determine branching fractions

$$\mathcal{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = \left(4.36\,^{+0.29}_{-0.27}\,(\text{stat}) \pm 0.20\,(\text{syst}) \pm 0.18\,(\text{norm})\right) \times 10^{-7}$$

$$\mathcal{B}(B^+ \to \phi K^+\mu^+\mu^-) = \left(0.82\,^{+0.19}_{-0.17}\,(\text{stat}) \pm 0.04\,(\text{syst}) \pm 0.27\,(\text{norm})\right) \times 10^{-7}$$

$B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ cont.

Preliminary

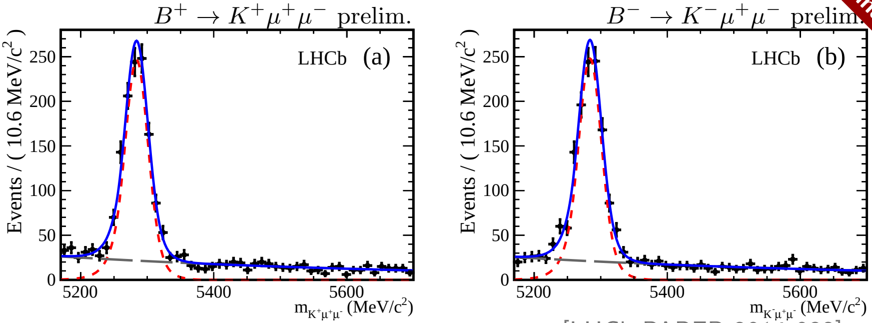


[LHCb-PAPER-2014-030]

- Performed measurement of $\mathrm{d}\mathcal{B}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-)/\mathrm{d}q^2$
- Significant contribution from $B^+ \to K_1^+(1270)\mu^+\mu^-$ expected
- Low statistics $\to$ no attempt to resolve contributions to $K^+\pi^+\pi^-$ final state
- See also [Radiate electroweak penguins, A. Puig] for $B^+ \to K^+\pi^+\pi^-\gamma$

CP-asymmetry $\mathcal{A}_{CP}$

Preliminary



[LHCb-PAPER-2014-032]

- Direct CP-Asymmetry $\mathcal{A}_{CP}$

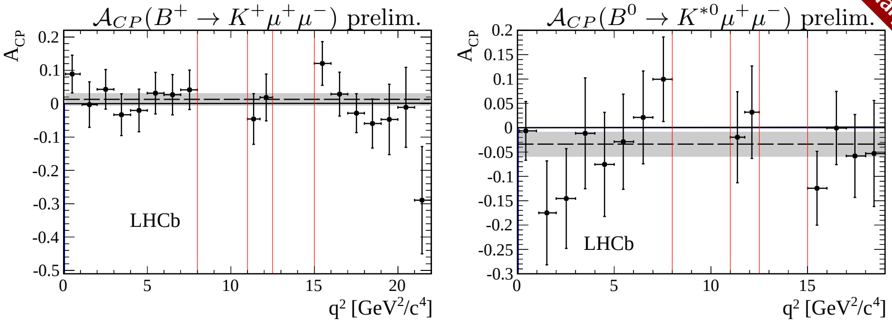
$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-) - \Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-) + \Gamma(B \to K^{(*)}\mu^+\mu^-)}$$

- $\mathcal{A}_{CP}$ tiny $\mathcal{O}(10^{-3})$ in the SM
- Correct for detection and production asymmetry using $B \to J/\psi\, K^{(*)}$

$$\mathcal{A}_{\rm raw}^{K^{(*)}\mu\mu} = \mathcal{A}_{\rm CP} + \mathcal{A}_{\rm det} + \kappa\mathcal{A}_{\rm prod}, \quad \mathcal{A}_{\rm CP} = \mathcal{A}_{\rm raw}^{K^{(*)}\mu\mu} - \mathcal{A}_{\rm raw}^{J/\psi\, K^{(*)}}$$

CP-asymmetry $\mathcal{A}_{CP}$ cont.

Preliminary



[LHCb-PAPER-2014-032]

- Measured $\mathcal{A}_{CP}$ in good agreement with SM prediction

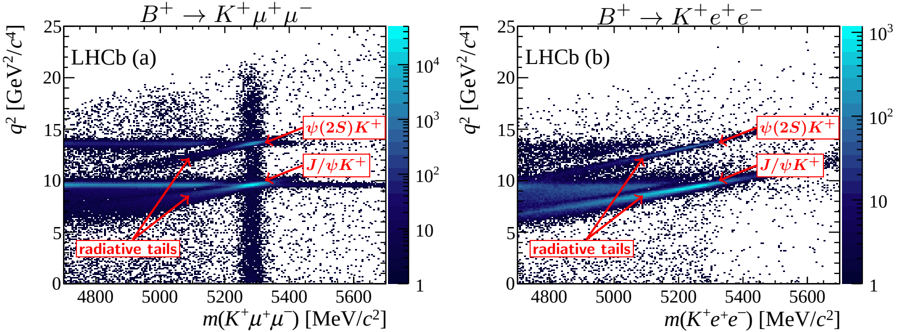
$$\mathcal{A}_{CP}(B^+ \to K^+\mu^+\mu^-) = 0.012 \pm 0.017(\text{stat.}) \pm 0.001(\text{syst.})$$

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.035 \pm 0.024(\text{stat.}) \pm 0.003(\text{syst.})$$

- Most precise measurement

Test of lepton universality in $B^+ \to K^+\ell^+\ell^-$

- $\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-3})$ in the SM
- Sensitive to new (pseudo)scalar operators

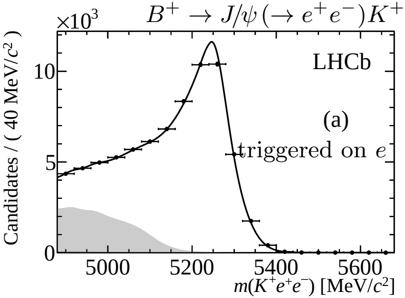


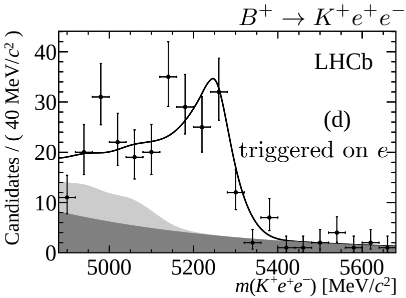
[arxiv:1406.6482]

- Experimental challenges for $B^+ \to K^+e^+e^-$ mode
  1. Trigger 2. Bremsstrahlung
- Use double ratio to cancel systematic uncertainties

$$\mathcal{R}_K = \left(\frac{N_{K^+\mu^+\mu^-}}{N_{K^+e^+e^-}}\right)\left(\frac{N_{J/\psi\,(e^+e^-)K^+}}{N_{J/\psi\,(\mu^+\mu^-)K^+}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi\,(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi\,(e^+e^-)K^+}}\right)$$

Test of lepton universality in $B^+ \to K^+\ell^+\ell^-$





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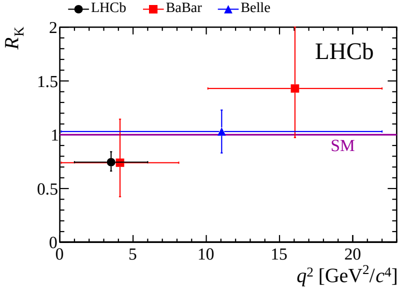
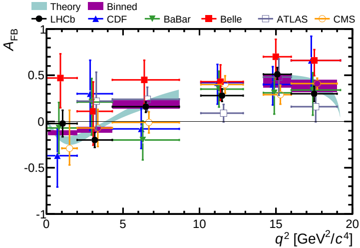


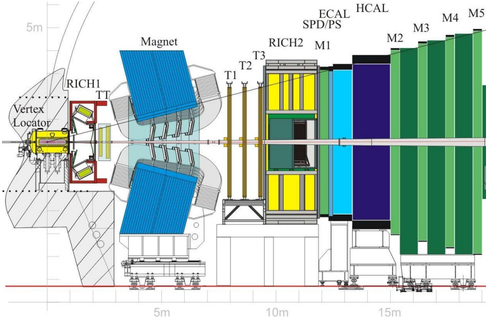
- Use theoretically and experimentally favoured q^2 region $\in [1,6]\,\mathrm{GeV}^2$
- $\mathcal{R}_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat.}) \pm 0.036(\mathrm{syst.})$, compatible with SM at 2.6σ
- $\mathcal{B}_{q^2\in[1,6]\,\mathrm{GeV}^2}(B^+ \to K^+e^+e^-) = (1.56^{+0.19+0.06}_{-0.15-0.04}) \times 10^{-7}$

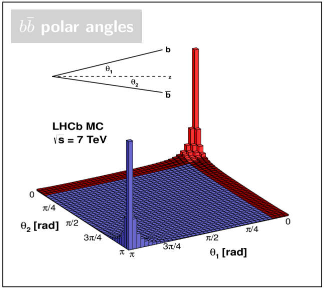
Conclusions



- Electroweak penguin decays an excellent laboratory to search for BSM effects
- LHCb an ideal environment to study these decays
- Most measurements in good agreement with the SM and provide stringent constraints on NP models
- But some interesting tensions
  - P_5' in $B^0 \to K^{*0}\mu^+\mu^-$
  - $\mathcal{R}_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat.}) \pm 0.036(\mathrm{syst.})$
- More results coming soon
  Stay tuned!

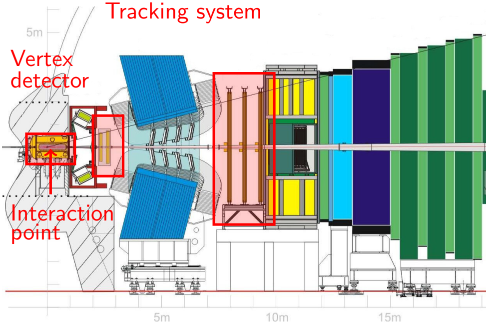
The LHC as heavy flavour factory

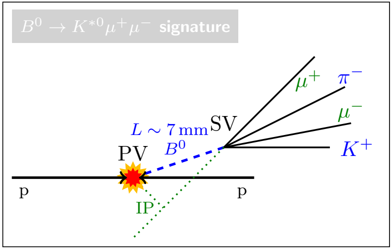




- $b\bar{b}$ produced correlated predominantly in forward (backward) direction $\rightarrow$ single arm forward spectrometer $(2 < \eta < 5)$
- Large $b\bar{b}$ production cross section $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\,\mu\text{b}$ [Phys.Lett. B694 (2010)] in acceptance
- $\sim 1 \times 10^{11}$ produced $b\bar{b}$ pairs in 2011, excellent environment to study $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and other rare decays

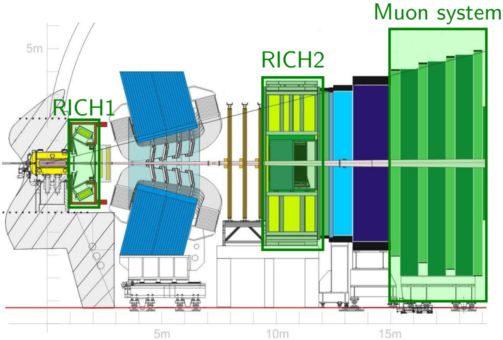
The LHCb detector: Tracking

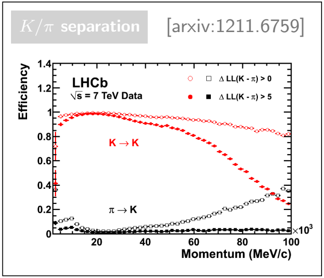




- Excellent Impact Parameter (IP) resolution ($20\,\mu\mathrm{m}$)
  $\rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim 40\,\mathrm{fs}$
  $\rightarrow$ Good separation of primary and secondary vertices
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and inv. mass resolution
  $\rightarrow$ Low combinatorial background

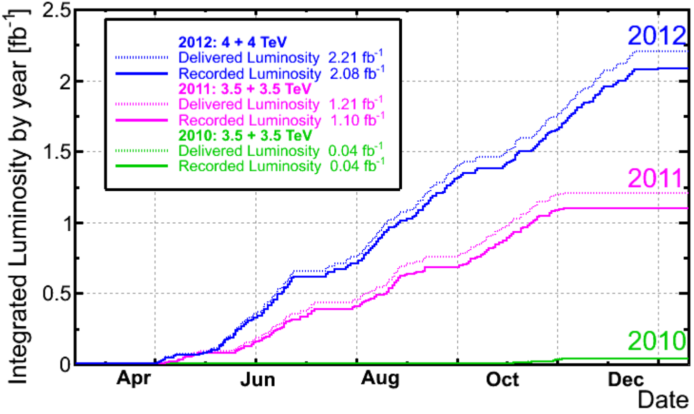
The LHCb detector: Particle identification and Trigger





- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$ $\epsilon_{\pi\to\mu} \sim$ 1-3%
- Good $K\pi$ separation via RICH detectors $\epsilon_{K\to K} \sim 95\%$ $\epsilon_{\pi\to K} \sim 5\%$
  $\to$ Reject peaking backgrounds
- High trigger efficiencies, low momentum thresholds
  Muons: $p_{\mathrm{T}} > 1.76\,\mathrm{GeV}$ at L0, $p_{\mathrm{T}} > 1.0\,\mathrm{GeV}$ at HLT1
  $B \to J/\psi X$: $\epsilon_{\text{Trigger}} \sim 90\%$

Data taken by LHCb



- Published results I will discuss today only use $1\,\text{fb}^{-1}$ taken in 2011
- Full data sample of $3\,\text{fb}^{-1}$ currently under study

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

- Four-differential decay rate for $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$

$$\frac{d^4\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\Phi} = \frac{9}{32\pi}\big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K$$
$$+ (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K)\cos 2\theta_\ell$$
$$+ I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\Phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\Phi$$
$$+ I_5 \sin 2\theta_K \sin\theta_\ell \cos\Phi$$
$$+ (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K)\cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\Phi$$
$$+ I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\Phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\Phi\big]$$

- $I_i(q^2)$ combinations of K^{*0} spin amplitudes sensitive to $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$
- CP-averages $S_i = (I_i + \bar{I}_i)/\frac{d(\Gamma+\bar{\Gamma})}{dq^2}$, CP-asymmetries $A_i = (I_i - \bar{I}_i)/\frac{d(\Gamma+\bar{\Gamma})}{dq^2}$
- For $m_\ell = 0$: 8 CP averages S_i, 8 CP-asymmetries A_i
- Simultaneous fit of 8 observables not possible with the 2011 data set
  $\to$ Angular folding $\Phi \to \Phi + \pi$ for $\Phi < 0$ cancels terms $\propto \sin\Phi, \cos\Phi$

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$I_i(q^2)$ depend on K^{*0} spin amplitudes $A_0^{L,R}$, $A_\parallel^{L,R}$, $A_\perp^{L,R}$

For completeness

$$I_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right] + \frac{4m_\mu^2}{q^2}\Re(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*})$$

$$I_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\Re(A_0^L A_0^{R*}\right]$$

$$I_2^s = \frac{\beta_\mu^2}{4}\left\{|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right\}$$

$$I_2^c = -\beta_\mu^2\left\{|A_0^L|^2 + (L\to R)\right\}$$

$$I_3 = \frac{\beta_\mu^2}{2}\left\{|A_\perp^L|^2 - |A_\parallel^L|^2 + (L\to R)\right\}$$

$$I_4 = \frac{\beta_\mu^2}{\sqrt{2}}\left\{\Re(A_0^L A_\parallel^{L*}) + (L\to R)\right\}$$

$$I_5 = \sqrt{2}\beta_\mu\left\{\Re(A_0^L A_\perp^{L*}) - (L\to R)\right\}$$

$$I_6 = 2\beta_\mu\left\{\Re(A_\parallel^L A_\perp^{L*}) - (L\to R)\right\}$$

$$I_7 = \sqrt{2}\beta_\mu\left\{\Im(A_0^L A_\parallel^{L*}) - (L\to R)\right\}$$

$$I_8 = \frac{\beta_\mu^2}{\sqrt{2}}\left\{\Im(A_0^L A_\perp^{L*}) + (L\to R)\right\}$$

$$I_9 = \beta_\mu^2\left\{\Im(A_\parallel^{L*} A_\perp^L) + (L\to R)\right\}$$

K^{*0} spin amplitudes $A_0^{L,R}$, $A_\parallel^{L,R}$, $A_\perp^{L,R}$

For completeness

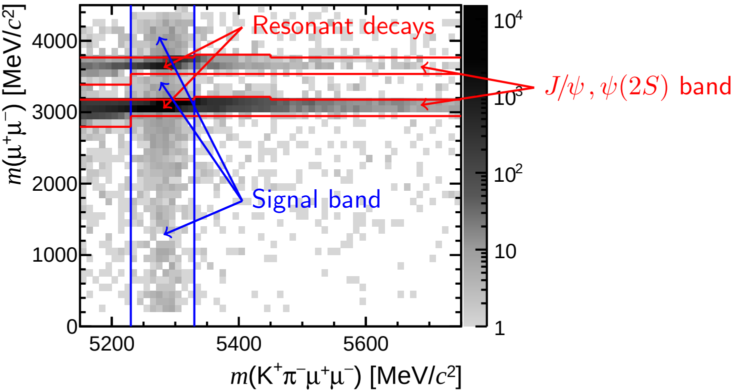
$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7^{\prime eff}})\mathbf{T_1(q^2)}\right\}$$

$$A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\mathbf{T_2(q^2)}\right\}$$

$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\}$$

- Wilson coefficients $C_{7,9,10}^{(\prime)\text{eff}}$
- Seven form factors (FF) $V(q^2)$, $A_{0,1,2}(q^2)$, $T_{1,2,3}(q^2)$ encode hadronic effects and require non-perturbative calculation
- Low $q^2 \le 6\,\text{GeV}^2$
  $\to \xi_{\perp,\parallel}$ (soft form factors)
- Large $q^2 \ge 14\,\text{GeV}^2$
  $\to f_{\perp,\parallel,0}$ (helicity form factors)
- Theory uncertainties:
  - FF from non-perturbative calculations
  - Λ/m_b corrections ("subleading corrections")

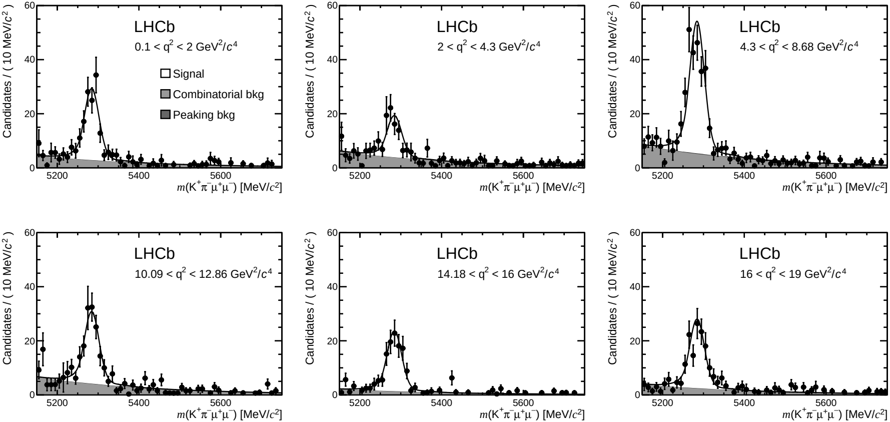
Analysis strategy



- Veto of $B^0 \to J/\psi\, K^{*0}$ and $B^0 \to \psi(2S) K^{*0}$ (valuable control channels!)
- Suppression of peaking backgrounds with PID
  Rejection of combinatorial background with BDT

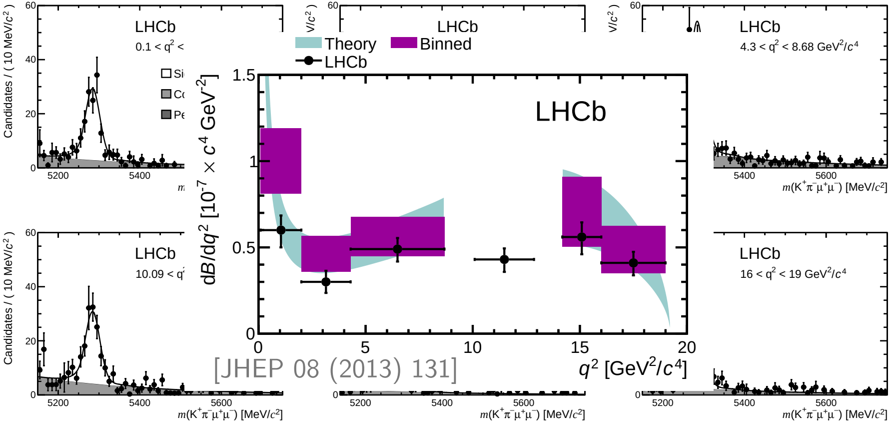
1. Determine the differential branching fraction in q^2 bins
2. Determine angular observables in multidimensional likelihood fit

$B^0 \to K^{*0}\mu^+\mu^-$ signal yield (2011)



- Fit of N_{sig} in q^2 bins
- Use $B^0 \to J/\psi K^{*0}$ as normalisation channel
- SM prediction [C. Bobeth et al. JHEP 07 (2011) 067]
- Data somewhat low but large theory uncertainties due to FF

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



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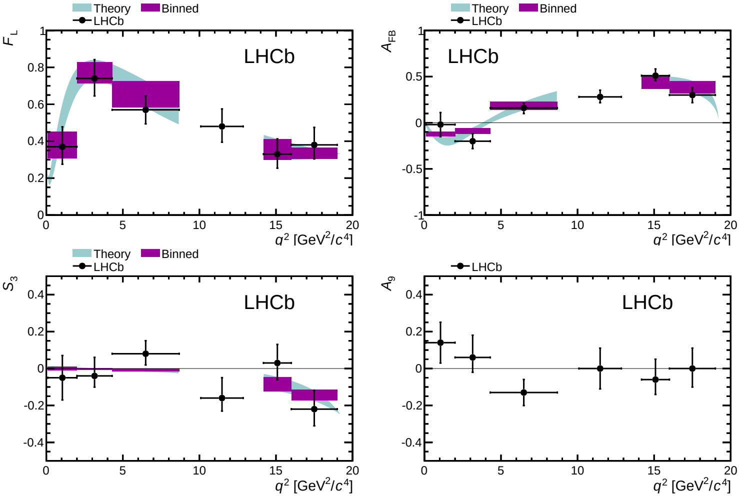
$B^0 \to K^{*0}\mu^+\mu^-$ angular observables I



- Results [JHEP 08 (2013) 131] in good agreement with SM prediction [C. Bobeth et al. JHEP 07 (2011) 067]

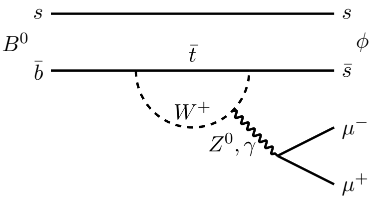
The $K\pi$ S-Wave contribution

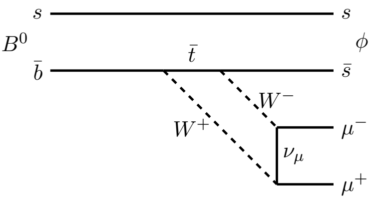
- Can have sizeable contribution with $K\pi$ system in spin 0 configuration
- Systematic in previous analysis, Can significantly bias observables for larger statistics [T. Blake et al.]
- Angular distribution [J. Matias], [D. Becirevic et al.]

$$
\begin{aligned}
\frac{1}{\Gamma_{\text{full}}}\frac{\mathrm{d}^3\Gamma_{\text{full}}}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\phi} = {} & \frac{1}{\Gamma_{K^{*0}}}\frac{\mathrm{d}^3\Gamma_{K^{*0}}}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\phi}(1-F_S) \\
& + \frac{3}{16\pi}\Big[F_S\sin^2\theta_\ell + A_{S1}\sin^2\theta_\ell\cos\theta_K \\
& \quad + A_{S2}\sin 2\theta_\ell\sin\theta_K\cos\phi + A_{S3}\sin\theta_\ell\sin\theta_K\cos\phi \\
& \quad + A_{S4}\sin\theta_\ell\sin\theta_K\sin\phi + A_{S5}\sin 2\theta_\ell\sin\theta_K\sin\phi\Big]
\end{aligned}
$$

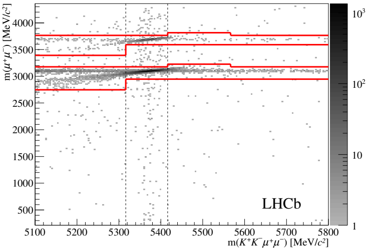
- 6 additional observables, challenging
- Separate analysis to determine $\mathrm{d}\mathcal{B}(B^0\to K^{*0}\mu^+\mu^-)/\mathrm{d}q^2$ and the S-wave fraction using fit to $m_{\mathrm{K}\pi\mu\mu}, m_{\mathrm{K}\pi}$ and $\cos\theta_K$

The rare decay $B_s^0 \to \phi[\to K^+K^-]\mu^+\mu^-$





- $K^+K^-\mu^+\mu^-$ final state not self-tagging → reduced number of observables: $F_{\rm L}$, $S_{3,4,7}$, $A_{5,6,8,9}$
- Signal yield lower due to $f_s/f_d \sim 1/4$
- Clean selection due to narrow ϕ resonance
- Less S-wave pollution than $K^{*0}\mu^+\mu^-$



Angular analysis of $B_s^0 \to \phi\mu^+\mu^-$

- In total 174 ± 15 signal events in $1\,\text{fb}^{-1}$ $\to$ Not enough for full 3D fit
- Integrate over 2 of 3 angles and fit one-dimensional distributions

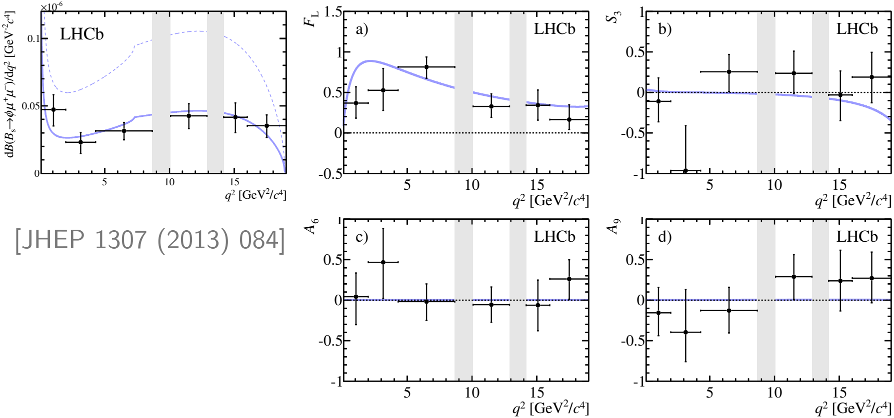
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_K} = \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) + \frac{3}{2}F_\mathrm{L}\cos^2\theta_K$$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell} = \frac{3}{8}(1-F_\mathrm{L})(1+\cos^2\theta_\ell) + \frac{3}{4}F_\mathrm{L}(1-\cos^2\theta_\ell) + \frac{3}{4}A_6\cos\theta_\ell$$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\Phi} = \frac{1}{2\pi} + \frac{1}{2\pi}S_3\cos 2\Phi + \frac{1}{2\pi}A_9\sin 2\Phi$$

- Remaining parameters F_L, S_3, A_6, A_9
- Updated analysis with $3\,\text{fb}^{-1}$ will allow for 3D angular analysis

Observables in $B_s^0 \to \phi\mu^+\mu^-$

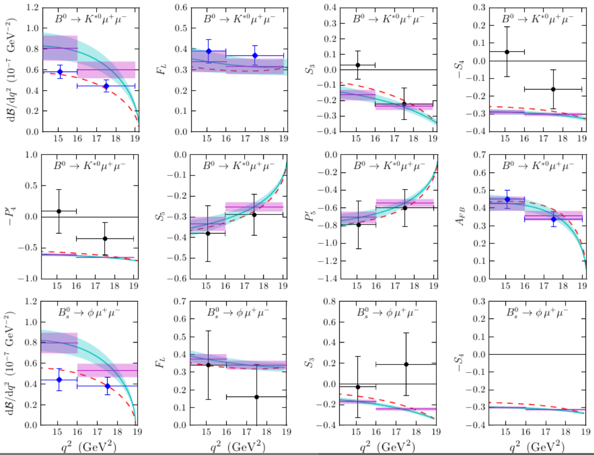


[JHEP 1307 (2013) 084]

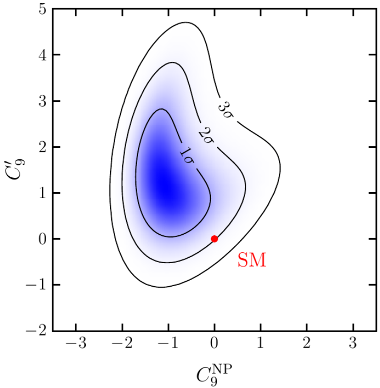
- Angular observables in good agreement with predictions
- Differential $\mathcal{B}$ low

Formfactors from lattice calculations

- FF from LCSR are calculated at low q^2 and extrapolated to high q^2
- Recent FF from lattice at high q^2 [R. Horgan et al. PRD 89, 094501 (2014)]
- [R. Horgan et al. PRL 112, 212003 (2014)] combine $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0_s \to \phi\mu^+\mu^-$ at high q^2



Fit of high q^2 region using lattice FF



- Best fit value $\mathcal{C}_9^{\rm NP} = -1.1$, $\mathcal{C}'_p = +1.1$
- Deviation from SM driven by the low branching fractions of both $B^0 \to K^{*0}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$ at high q^2

Prospects for $B^0 \to K^{*0}\mu^+\mu^-$ in 2018 and beyond

- LHCb is expected to collect an additional $5\,\text{fb}^{-1}$ in 2015-2017
- Afterwards LHCb upgrade [CERN-LHCC-2012-007]

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_sK$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\,K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–