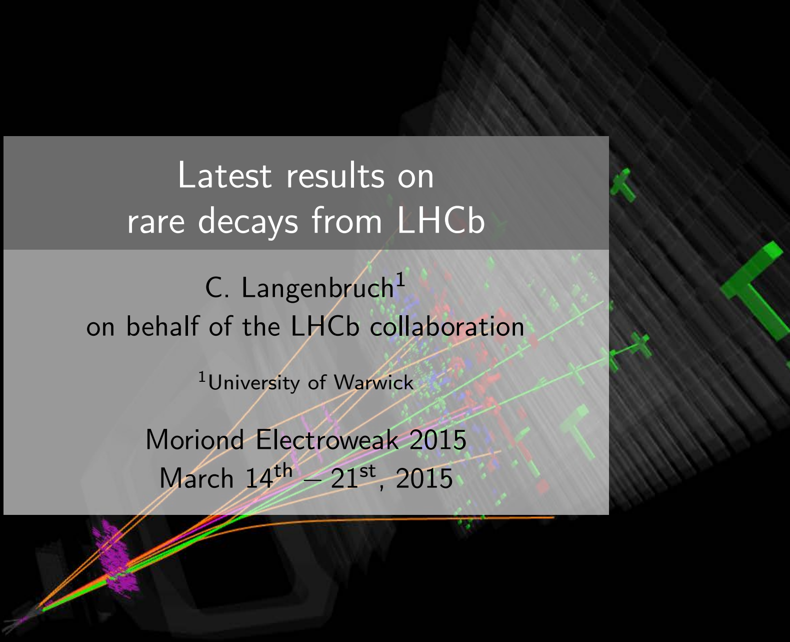


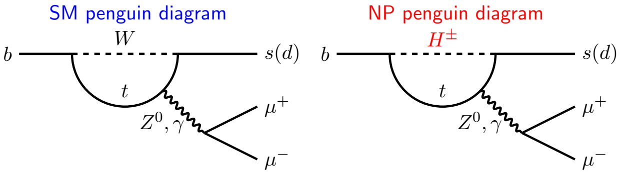
Latest results on rare decays from LHCb

C. Langenbruch[1]
on behalf of the LHCb collaboration

[1]University of Warwick

Moriond Electroweak 2015
March 14th – 21st, 2015

Rare decays as indirect probes for BSM physics



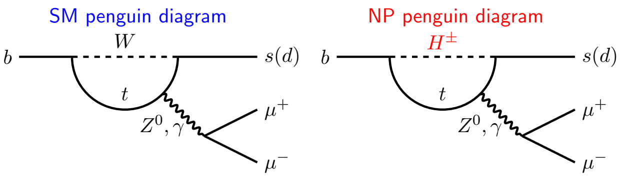
- Rare FCNC decays are loop-suppressed in the Standard Model (SM)
- New heavy particles in SM extensions can appear in competing diagrams can affect $\mathcal{B}$ and angular distributions

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{tq}}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}$$

$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin

- Model independent description in effective field theory
- Wilson coeff. $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators

Rare decays as indirect probes for BSM physics



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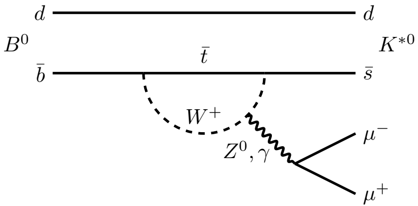
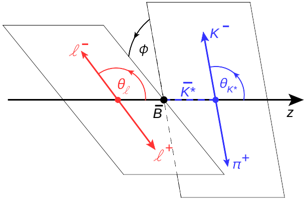
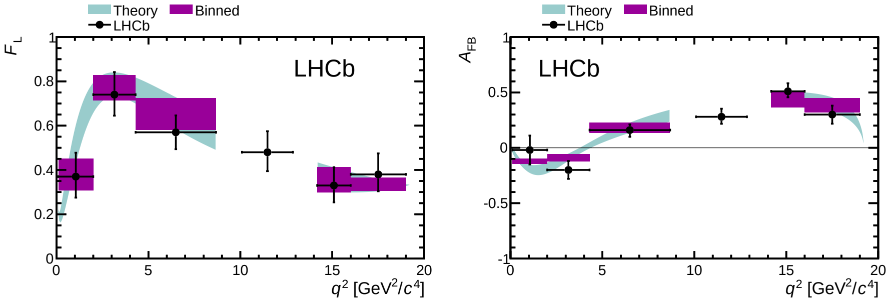
Golden decay $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$





- 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 $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$
- Large part of theory uncertainty due to hadronic form-factors

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

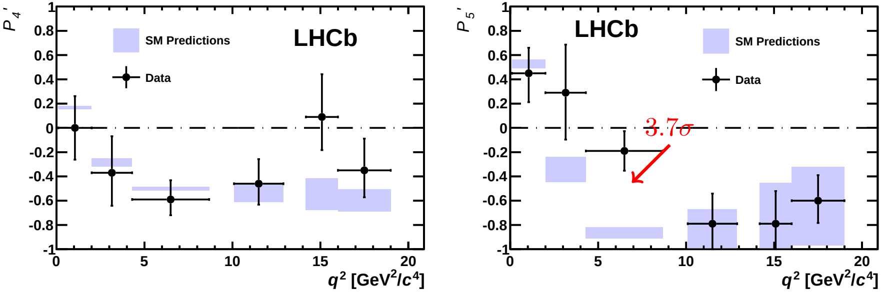


[JHEP 08 (2013) 131]

- 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]

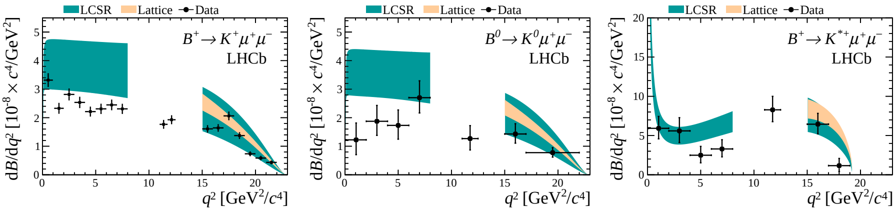
Less form factor dependent observables P'_i $(1\,\mathrm{fb}^{-1})$

- 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

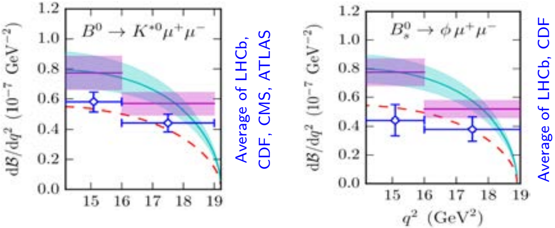


[PRL 111, 191801 (2013)]

$b \to s\mu^+\mu^-$ branching fractions



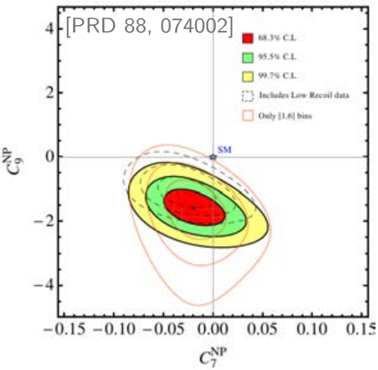
[JHEP 06 (2014) 133]

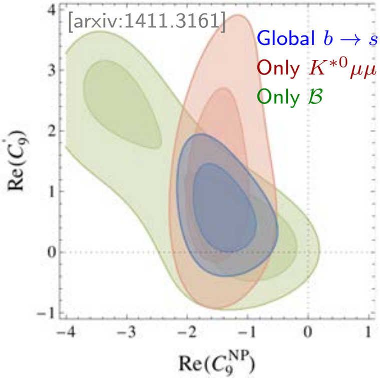


[PRL 112, 212003]

- Measured $B^0 \to (K^{*0}, K^0)\mu^+\mu^-$, $B^+ \to (K^+, K^{*+})\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$
  [JHEP 08 (2013) 131] [JHEP 06 (2014) 133] [JHEP 07 (2013) 084]
- $\mathcal{B}$ tend to lie below SM predictions
  [Horgan et al., PRL 112, 212003] [Altmannshofer et al. arxiv:1411.3161]

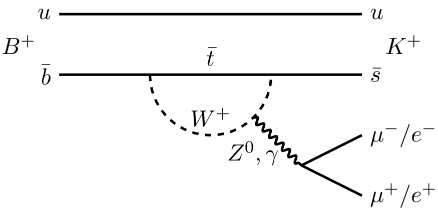
The global picture of $b \to s$ transitions

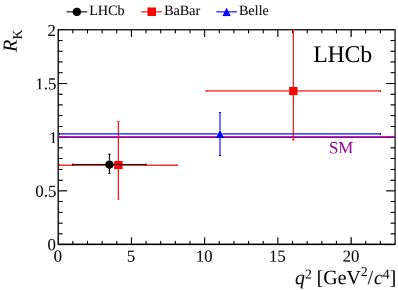




- Global fits to $b \to s$ FCNC processes prefer shift of $\mathcal{C}_9$ by ~ -1.5
  [S. Descotes-Genon et al. PRD 88, 074002] [Altmannshofer et al. arxiv:1411.3161] [Beaujean et al. EPJC 74 2897] [Hurth et al. JHEP 04 097]
- Consistent picture of the observed tensions in angular obs. and $\mathcal{B}$
- Possible NP interpretation: Z'
  [Gauld et al., arxiv:1310.1082] [Buras et al., arxiv:1311.6729]

Another interesting deviation: R_K



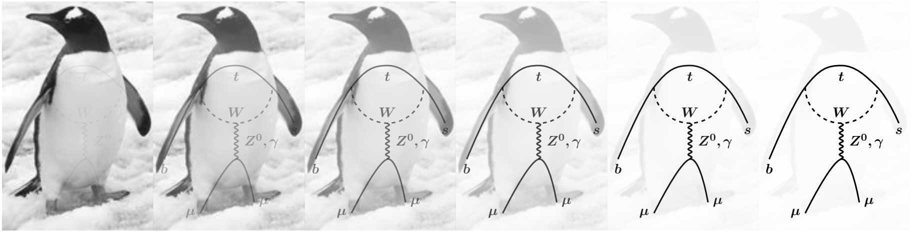


- Test of lepton universality: $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} \stackrel{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-3})$
- $\mathcal{R}_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.})$, compatible with SM at 2.6σ
- Can also be explained in a consistent way

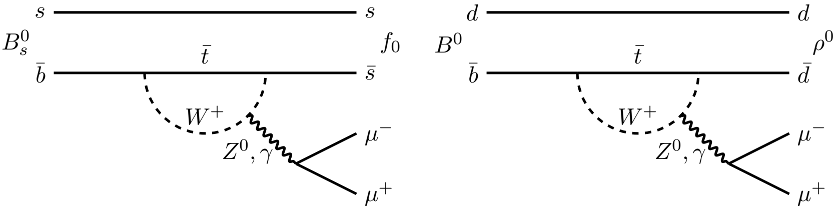
  [Hiller et al., PRD 90, 054014 (2014)] [Altmannshofer et al., PRD 89 (2014) 095033]

  [Glashow et al., PRL 114, 091801 (2015)] [Crivellin et al., arxiv:1501.00993]
- See also talk by A. Crivellin

Latest results



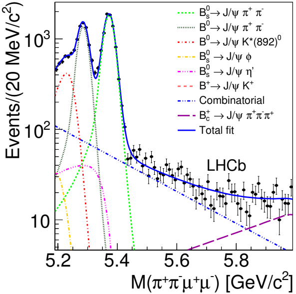
Study of rare $B^0_{(s)} \to \pi^+\pi^-\mu^+\mu^-$ decays I



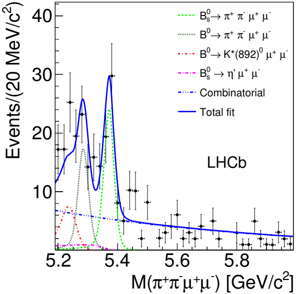
- Contributions from
  - $B_s^0 \to f_0\mu^+\mu^-$: $b \to s$ transition similar to $B^0 \to K^{*0}\mu^+\mu^-$
  - $B^0 \to \rho^0\mu^+\mu^-$: $b \to d$ transition, $|V_{td}/V_{ts}|^2$ suppressed in SM
- SM predictions show large variation
  - $\mathcal{B}_{\rm SM}(B_s^0 \to f_0\mu^+\mu^-) = 0.6 \times 10^{-9} - 5.2 \times 10^{-7}$
    [PRD 79 014013], [PRD 81 074001], [PRD 80 016009]
  - $\mathcal{B}_{\rm SM}(B^0 \to \rho^0\mu^+\mu^-) = (5-9) \times 10^{-8}$
    [PRD 56 5452-5465], [Eur.Phys.J.C 41 173-188]

Study of rare $B^0_{(s)} \to \pi^+\pi^-\mu^+\mu^-$ decays II

Resonant decay



Signal decay



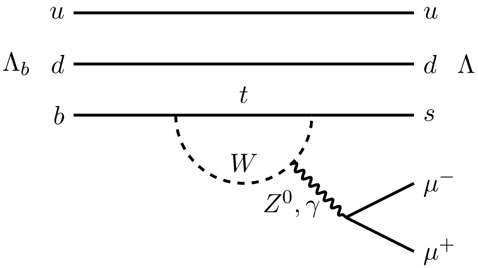
[PLB 743 (2015) 46]

- Observation of $B_s^0 \to \pi^+\pi^-\mu^+\mu^-$ with 7.6σ
- Evidence for $B^0 \to \pi^+\pi^-\mu^+\mu^-$ with 4.8σ
- Branching fractions compatible with SM predictions

$$\mathcal{B}(B_s^0 \to \pi^+\pi^-\mu^+\mu^-) = (8.6 \pm 1.5_{\text{stat.}} \pm 0.7_{\text{syst.}} \pm 0.7_{\text{norm.}}) \times 10^{-8}$$
$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.51_{\text{stat.}} \pm 0.15_{\text{syst.}} \pm 0.16_{\text{norm.}}) \times 10^{-8}$$

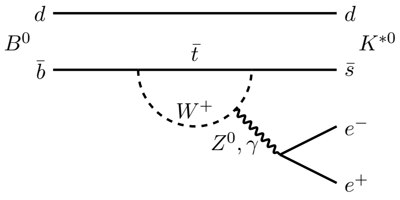
- Motivated work in theory [Wang et al., arxiv:1502.05104], [arxiv:1502.05483]

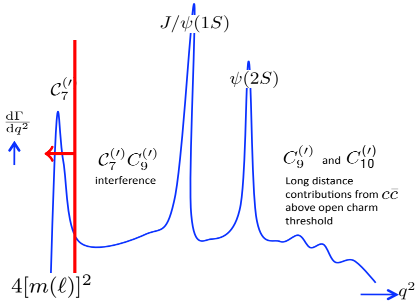
The rare decay $\Lambda_b^0 \to \Lambda\mu^+\mu^-$



- Rare Λ_b^0 baryon decays have unique features
  1. Λ_b^0 has half-integer spin
  2. Particular hadronic dynamics (heavy quark + light di-quark system)
  3. Λ decays weakly [JHEP 01 (2015) 155]
- Measured angular obs. and $\mathcal{B}$ [LHCb-PAPER-2015-009, to be submitted to JHEP]
- Presentation by L. Pescatore this afternoon

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





- Analyse $B^0 \to K^{*0}e^+e^-$ at very low q^2: $[0.0004, 1.0]\,\mathrm{GeV}^2/c^4$, accessible due to tiny e mass
- Determine angular observables F_L, $A_\mathrm{T}^{(2)}$, A_T^Re, A_T^Im sensitive to C_7 and C_7'
- Experimental challenges: Trigger and Bremsstrahlung

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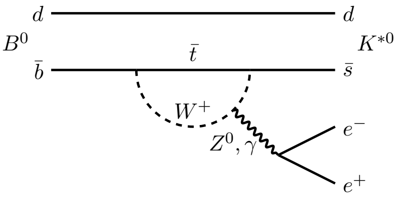
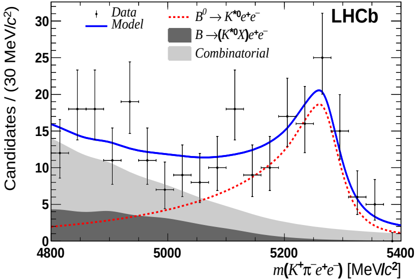


[arxiv:1501.03038]



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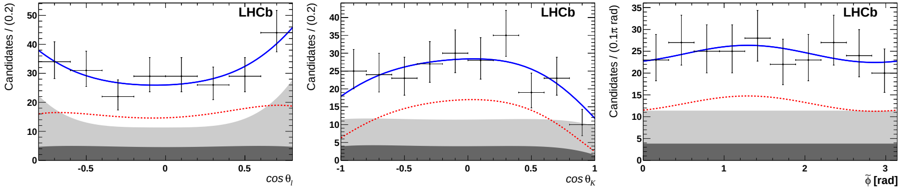
Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays



[arxiv:1501.03038]

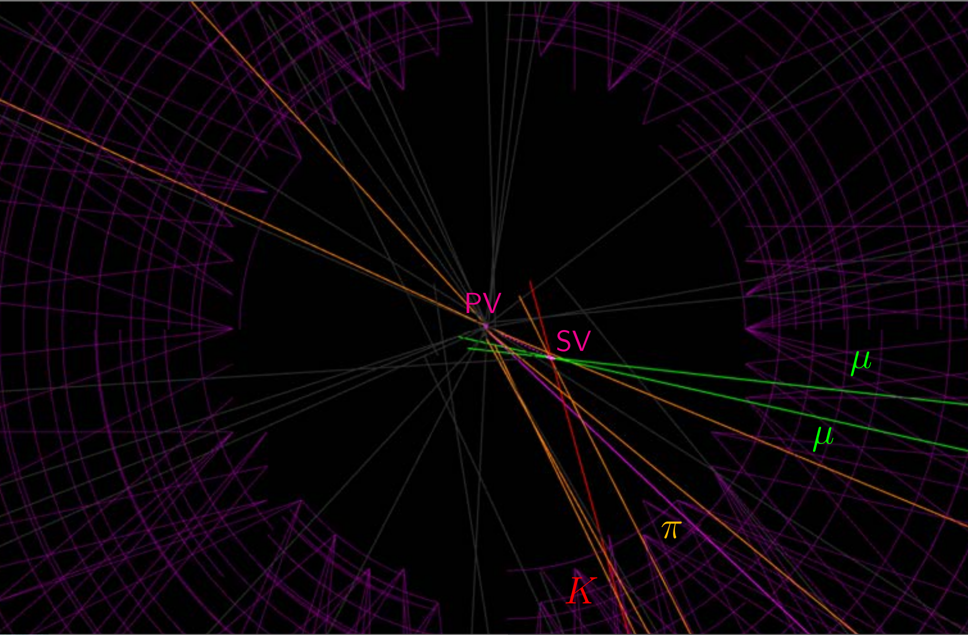
obs.	result
F_{L}	$+0.16 \pm 0.06 \pm 0.03$
$A_{\mathrm{T}}^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$
$A_{\mathrm{T}}^{\mathrm{Re}}$	$+0.10 \pm 0.18 \pm 0.05$
$A_{\mathrm{T}}^{\mathrm{Im}}$	$+0.14 \pm 0.22 \pm 0.05$

[JHEP 05 (2013) 043]

obs.	SM prediction
F_{L}	$+0.10^{+0.11}_{-0.05}$
$A_{\mathrm{T}}^{(2)}$	$+0.03^{+0.05}_{-0.04}$
$A_{\mathrm{T}}^{\mathrm{Re}}$	$-0.15^{+0.04}_{-0.03}$
$A_{\mathrm{T}}^{\mathrm{Im}}$	$(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$

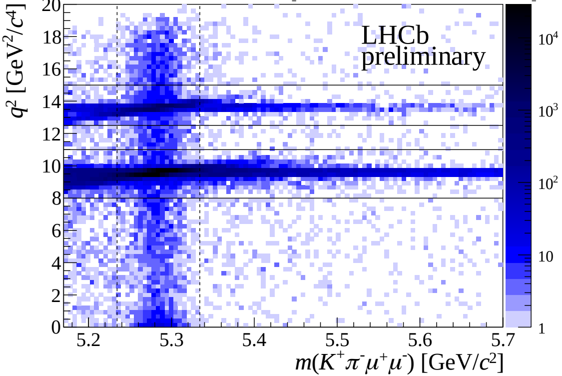
- Results are in good agreement with SM predictions
- Constraints on $C_7^{(\prime)}$ competitive with radiative decays

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ using $3\,\mathrm{fb}^{-1}$



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

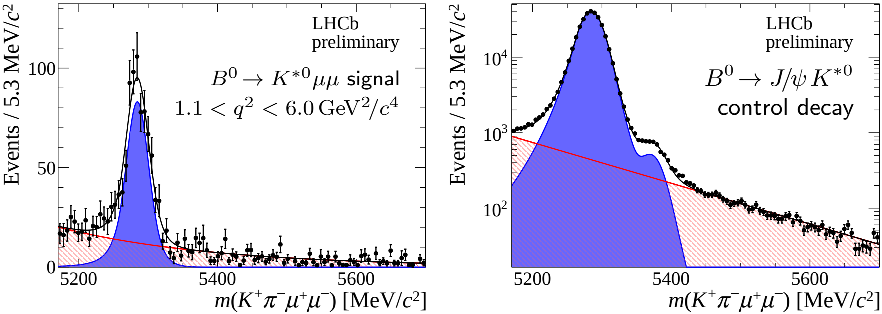
[LHCb-CONF-2015-002]



- BDT to suppress combinatorial background
  Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto of $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$ (important control decays) and peaking backgrounds using kinematic variables and PID
- Signal clearly visible as vertical band after the full selection

Mass model and $B^0 \to K^{*0}\mu^+\mu^-$ signal yield

[LHCb-CONF-2015-002]



- Signal mass model from high statistics $B^0 \to J/\psi\,K^{*0}$
  Correction factor from simulation to account for q^2 dep. resolution
- Finer q^2 binning to allow more flexible use in theory
- Significant signal yield in all bins, q^2 integrated $N_{\rm sig} = 2398 \pm 57$

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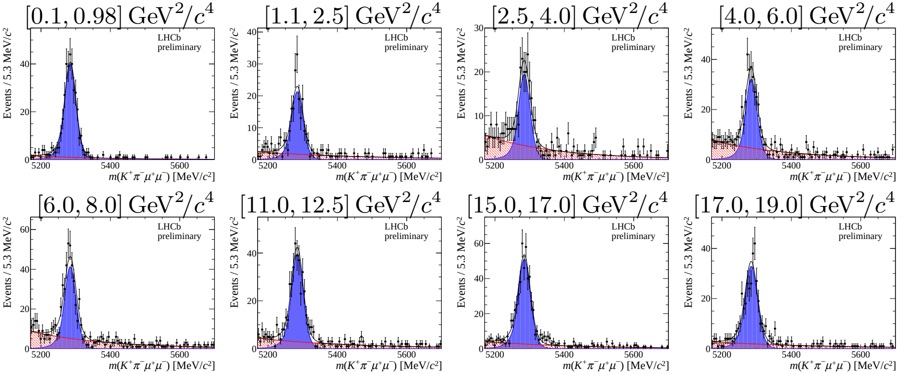
[LHCb-CONF-2015-002]



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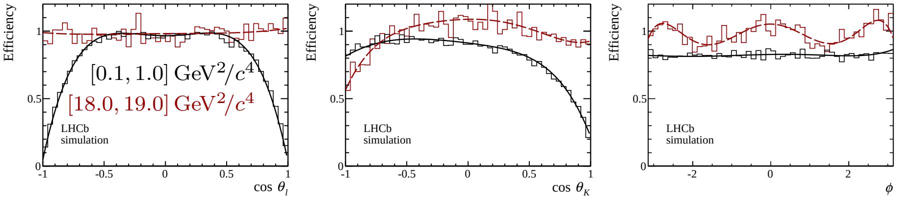
Acceptance effect

[LHCb-CONF-2015-002]

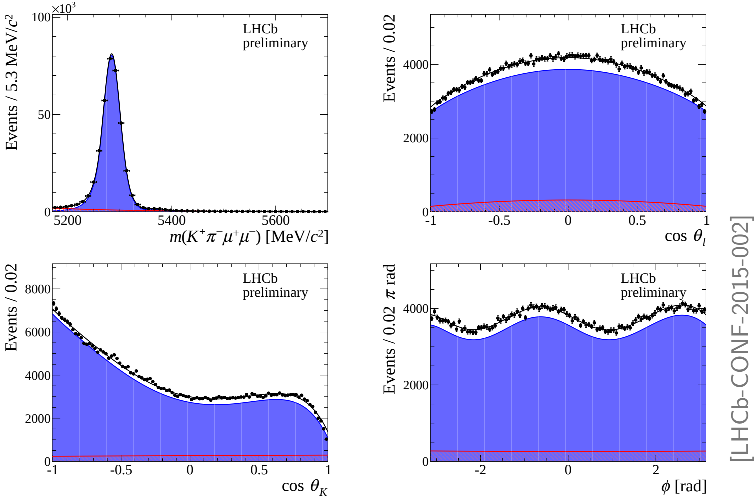


- Trigger, reconstruction and selection distorts decay angles and q^2 distribution
- Parametrize 4D efficiency using Legendre polynomials P_k

$$\varepsilon(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \sum_{klmn} c_{klmn} P_k(\cos\theta_\ell) P_l(\cos\theta_K) P_m(\phi) P_n(q^2)$$

- Coefficients c_{klmn} from moments analysis of $B^0 \to K^{*0}\mu^+\mu^-$ PHSP MC
- Crosscheck acceptance using $B^0 \to J/\psi K^{*0}$ control decay

Control decay $B^0 \to J/\psi\, K^{*0}$



- black line: full fit, blue: signal component, red: bkg. part
- Angular observables successfully reproduced [PRD 88, 052002 (2013)]

S-wave pollution

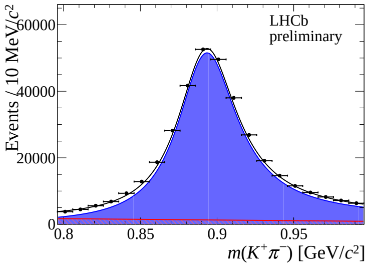
- S-wave: $K^+\pi^-$ not from $K^{*0}(892)$ but in spin 0 configuration
- Introduces two add. decay amplitudes resulting in six add. observables

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{S+P}} = (1-F_{\mathrm{S}})\,\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}} + \frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_\ell \; + \text{ S-P interference}$$

- F_{S} scales P-wave observables, needs to be determined precisely

- Perform simultaneous $m_{K\pi}$ fit to constrain F_S
- P-wave described by rel. BW
- S-wave described by LASS model crosschecked using Isobar param.

[LHCb-CONF-2015-002]



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

- Full $3\,\text{fb}^{-1}$ allows first simultaneous determination of all eight CP-averaged observables in a single fit
- Allows to quote correlation matrix to include in global fit
- Perform maximum likelihood fit to the decay angles and $m_{K\pi\mu\mu}$ in q^2 bins, simultaneously fitting $m_{K\pi}$ to constrain F_S

$$\log\mathcal{L} = \sum_i \log\Big[\epsilon(\vec{\Omega},q^2) f_{\text{sig}}\mathcal{P}_{\text{sig}}(\vec{\Omega})\mathcal{P}_{\text{sig}}(m_{K\pi\mu\mu}) + (1-f_{\text{sig}})\mathcal{P}_{\text{bkg}}(\vec{\Omega})\mathcal{P}_{\text{bkg}}(m_{K\pi\mu\mu})\Big] + \sum_i \log\Big[f_{\text{sig}}\mathcal{P}_{\text{sig}}(m_{K\pi}) + (1-f_{\text{sig}})\mathcal{P}_{\text{bkg}}(m_{K\pi})\Big]$$

  - $\mathcal{P}_{\text{sig}}(\Omega)$ given by $\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\text{S+P}}$
  - $\mathcal{P}_{\text{bkg}}(\Omega)$ modelled with 2^{nd} order Chebychev polynomials.
- Feldman-Cousins method [G. Feldman et al., PRD 57 3873-3889] to ensure correct coverage at low statistics

Systematic uncertainties

1. Systematic uncertainties related to acceptance:
   - Kinematic differences between data and simulation
   - q^2 dependence of acceptance
   - Acceptance model (order of parametrisation)
   - statistical uncertainty
2. Peaking backgrounds
   - $B_s^0 \to \phi\mu^+\mu^-$, $\Lambda_b^0 \to pK\mu^+\mu^-$, $B^0 \to K^+\pi^-_{\mathrm{rndm.}}\mu^+\mu^-$
3. PDF modeling
   - Signal mass model
   - Angular background model
   - $m_{K\pi}$ S-wave description (LASS/Isobar)
   - $m_{K\pi}$ dependent efficiency

- All determined using high statistics toys
- Measurement is statistically dominated

Systematic uncertainties

1. Systematic uncertainties related to acceptance:
   - Kinematic differences between data and simulation $\lesssim 0.01 - 0.02$
   - q^2 dependence of acceptance
   - Acceptance model (order of parametrisation) $\lesssim 0.01$
   - statistical uncertainty
2. Peaking backgrounds
   - $B_s^0 \to \phi\mu^+\mu^-$, $\Lambda_b^0 \to pK\mu^+\mu^-$, $B^0 \to K^+\pi^-_{\rm rndm.}\mu^+\mu^-$ $\lesssim 0.01 - 0.02$
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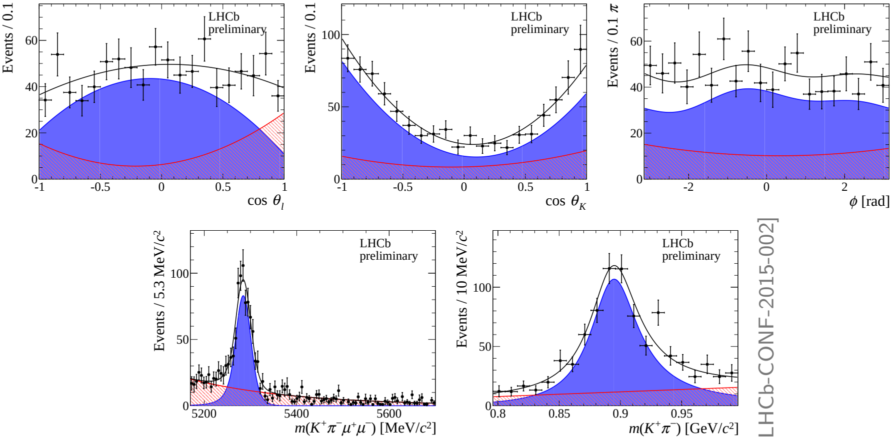
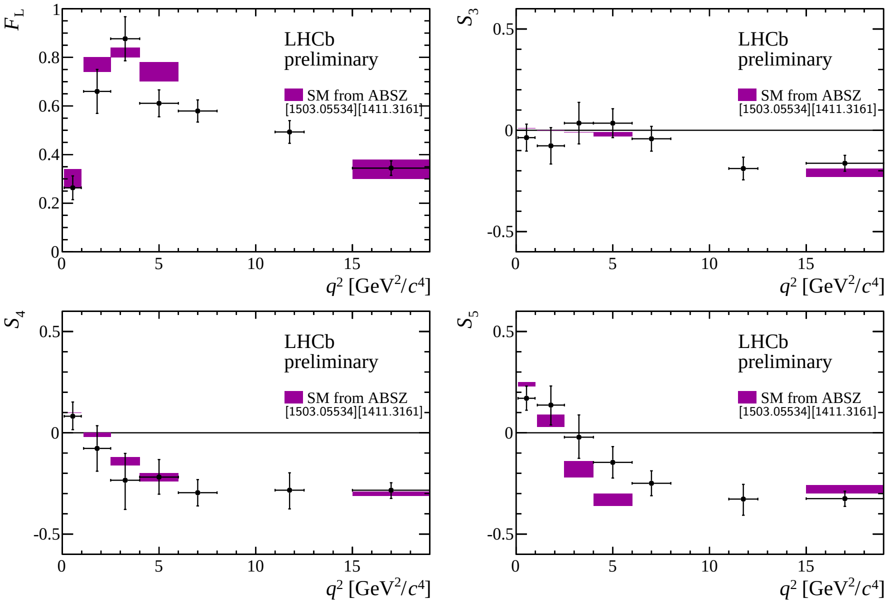
$B^0 \to K^{*0}\mu^+\mu^-$ likelihood projections $[1.1, 6.0]\,\mathrm{GeV}^2/c^4$



[LHCb-CONF-2015-002]

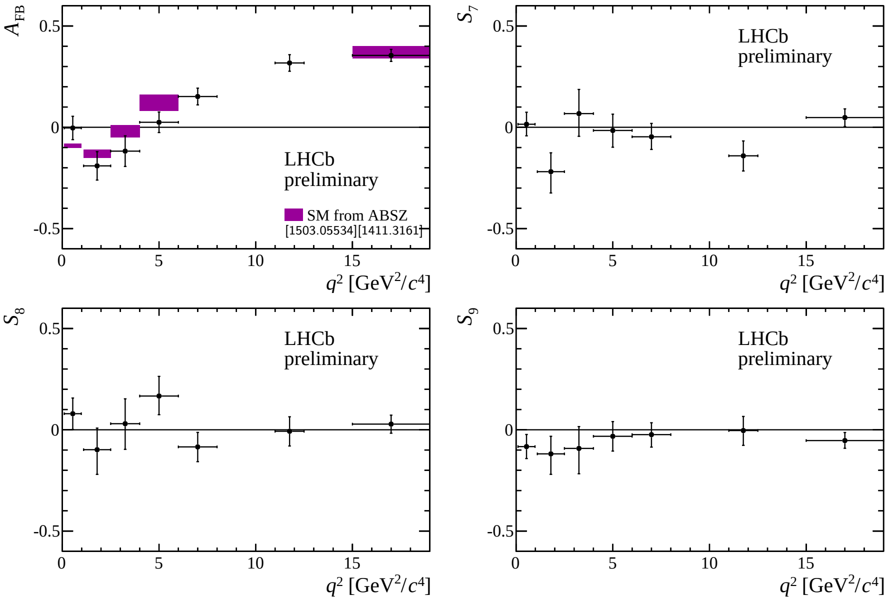
- Efficiency corrected distributions show good agreement with overlaid PDF projections

$B^0 \to K^{*0}\mu^+\mu^-$ Results: F_L, S_3, S_4, S_5



[LHCb-CONF-2015-002]

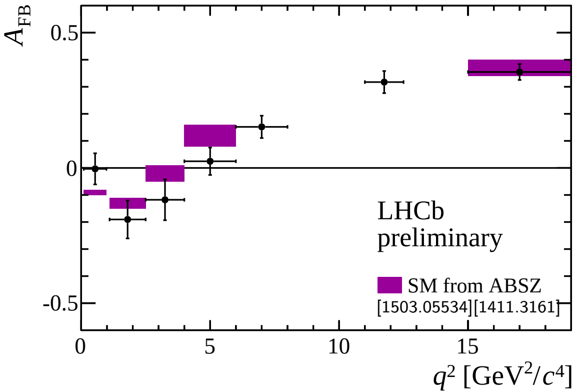
$B^0 \to K^{*0}\mu^+\mu^-$ Results: A_{FB}, S_7, S_8, S_9



[LHCb-CONF-2015-002]

Forward-backward asymmetry A_{FB}

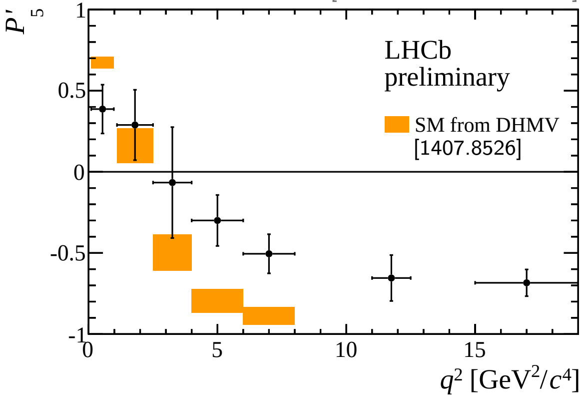
[LHCb-CONF-2015-002]



- Data points slightly below SM prediction at low q^2
- ZCP $q_0^2 = 3.7^{+0.8}_{-1.1}\,\mathrm{GeV}^2/c^4$ evaluated as in [JHEP 08 (2013) 131]

P'_5

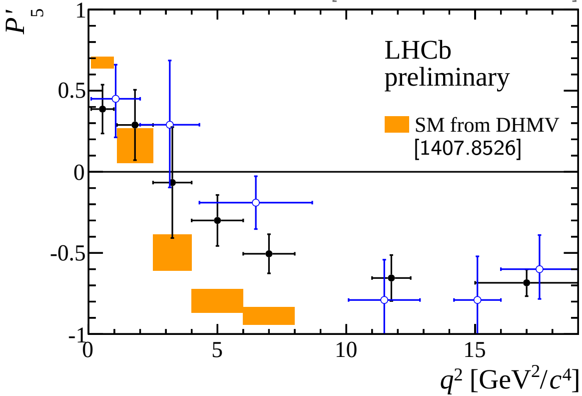
[LHCb-CONF-2015-002]



- Tension seen in P'_5 in [PRL 111, 191801 (2013)] confirmed
- $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ show deviations of 2.9σ each
- Naive combination results in a significance of 3.7σ
- Compatible with $1\,\mathrm{fb}^{-1}$ measurement

P_5'

[LHCb-CONF-2015-002]



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- Naive combination results in a significance of 3.7σ
- Compatible with $1\,\mathrm{fb}^{-1}$ measurement

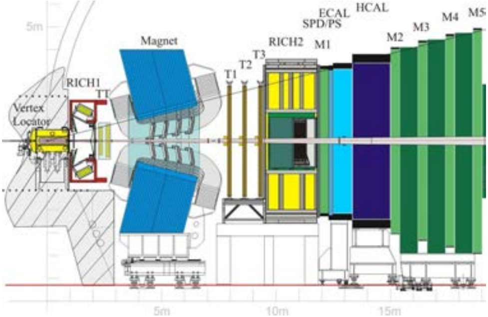
Conclusions

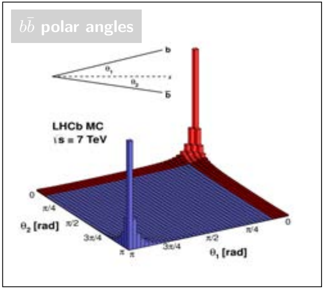
- Rare decays are an excellent laboratory to search for BSM effects
- LHCb an ideal environment to study these decays
- Presented full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ using the full $3\,\text{fb}^{-1}$ LHCb data sample
- P_5' deviation confirmed: Two q^2 bins with significance of 2.9σ each
- More interesting tensions in electroweak penguins: R_K, low $b \to s\mu\mu$ $\mathcal{B}$
- Looking forward to the theory interpretatio[n] See talks by Q. Matias, D. Straub

Non Standard Model Penguin?

[Nature Methods 11, 1242–1244 (2014)]

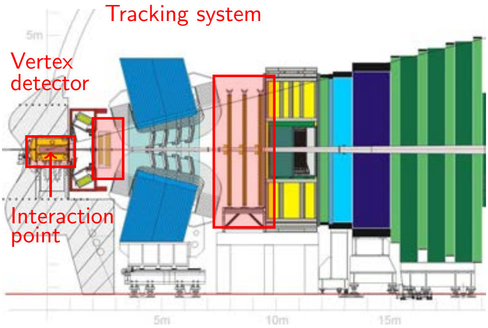
The LHC as heavy flavour factory

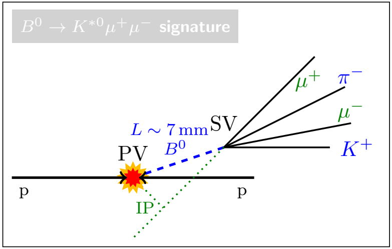




- $b\bar{b}$ produced correlated predominantly in forward (backward) direction $\rightarrow$ single arm forward spectrometer ($2 < \eta < 5$)
- Large $b\bar{b}$ production cross section $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\,\mu\mathrm{b}$ [Phys.Lett. B694 (2010)] in acceptance
- $\sim 1 \times 10^{11}$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

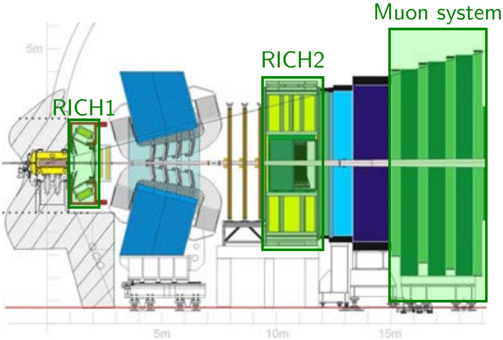
The LHCb detector: Tracking

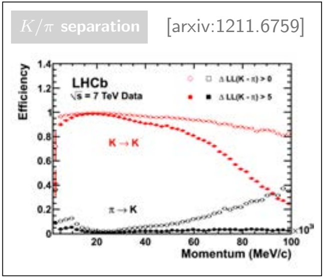




- Excellent Impact Parameter (IP) resolution ($20\,\mu\text{m}$)
  $\rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim 40\,\text{fs}$
  $\rightarrow$ Good separation of primary and secondary vertices
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$) and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

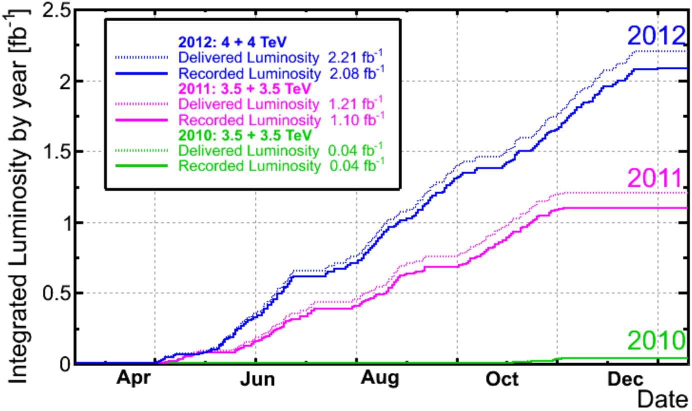
The LHCb detector: Particle identification and Trigger





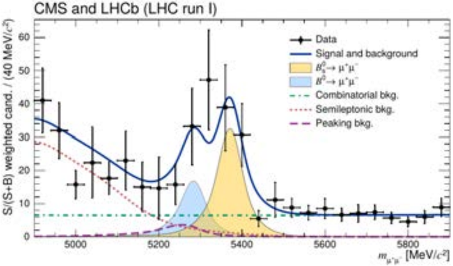
- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$ $\epsilon_{\pi\to\mu} \sim 1\text{-}3\%$
- Good $K\pi$ separation via RICH detectors $\epsilon_{K\to K} \sim 95\%$ $\epsilon_{\pi\to K} \sim 5\%$
  $\to$ Reject peaking backgrounds
- High trigger efficiencies, low momentum thresholds
 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

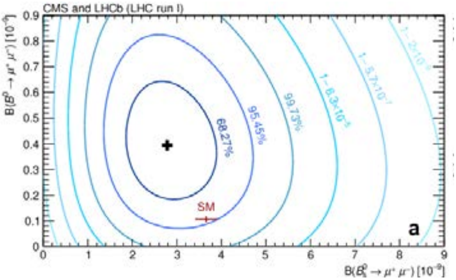
Data taken by LHCb



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

The very rare decay $B_s^0 \to \mu^+\mu^-$





- Observation of $B_s^0 \to \mu^+\mu^-$ using combined CMS and LHCb dataset [arxiv:1411.4413], submitted to Nature
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.79^{+0.66}_{-0.60}{}^{+0.26}_{-0.19}) \times 10^{-9}$, 6.2σ sign. (7.6σ expected)
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.94^{+1.58}_{-1.41}{}^{+0.31}_{-0.24}) \times 10^{-10}$, 3.2σ sign. (0.8σ expected)
- SM predictions [Bobeth et al., PRL 112 (2014) 101801]
  $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$, compatible at 1.2σ
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$, compatible at 2.2σ

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

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

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

- $I_i(q^2)$ combinations of K^{*0} spin amplitudes sensitive to $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$
- CP-averages $S_i = (I_i + \bar{I}_i)/\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2}$, CP-asymmetries $A_i = (I_i - \bar{I}_i)/\frac{\mathrm{d}(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2}$
- 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 $\propto \sin\phi, \cos\phi$

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

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

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

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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 $A_0^{L,R}$, $A_\parallel^{L,R}$, $A_\perp^{L,R}$

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

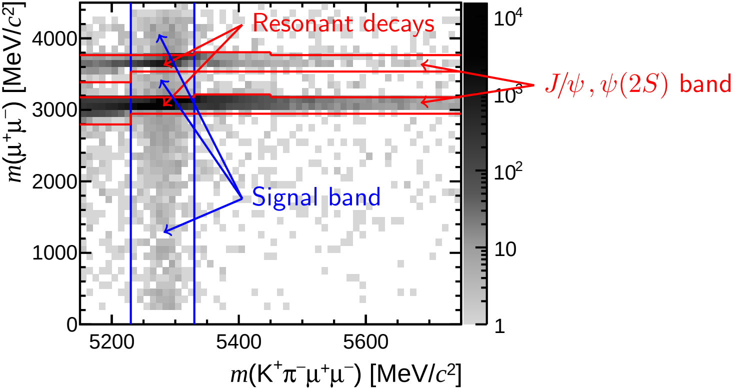
$$A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\mathbf{T_2(q^2)}\right\}$$

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

For completeness

- Wilson coefficients $C_{7,9,10}^{(\prime)\mathrm{eff}}$
- 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 $q^2 \leq 6\,\mathrm{GeV}^2$ $\rightarrow \xi_{\perp,\parallel}$ (soft form factors)
- Large $q^2 \geq 14\,\mathrm{GeV}^2$ $\rightarrow f_{\perp,\parallel,0}$ (helicity form factors)
- Theory uncertainties:
  - FF from non-perturbative calculations
  - Λ/m_b corrections ("subleading corrections")

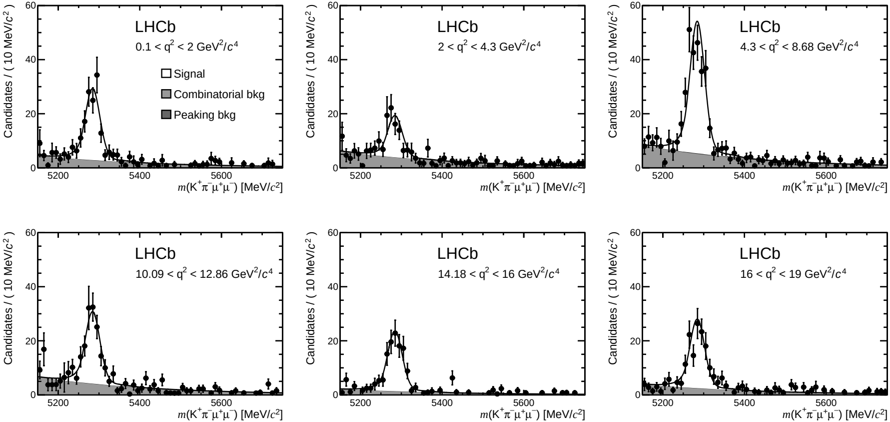
Analysis strategy



- 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

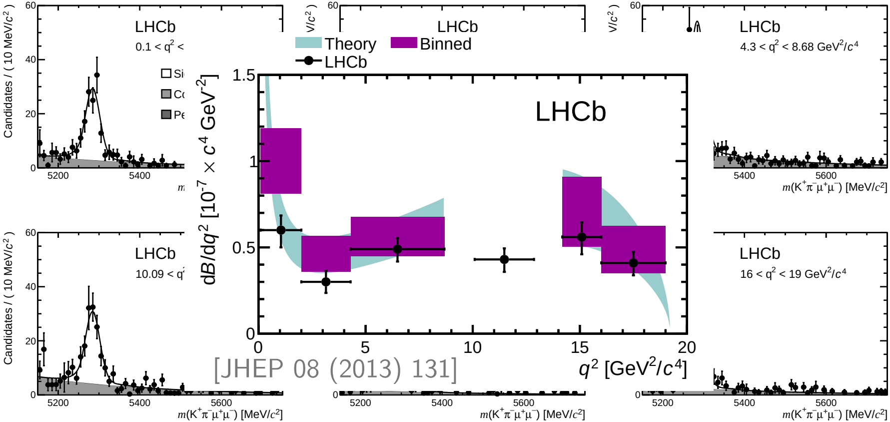
1. Determine the differential branching fraction in q^2 bins
2. Determine angular observables in multidimensional likelihood fit

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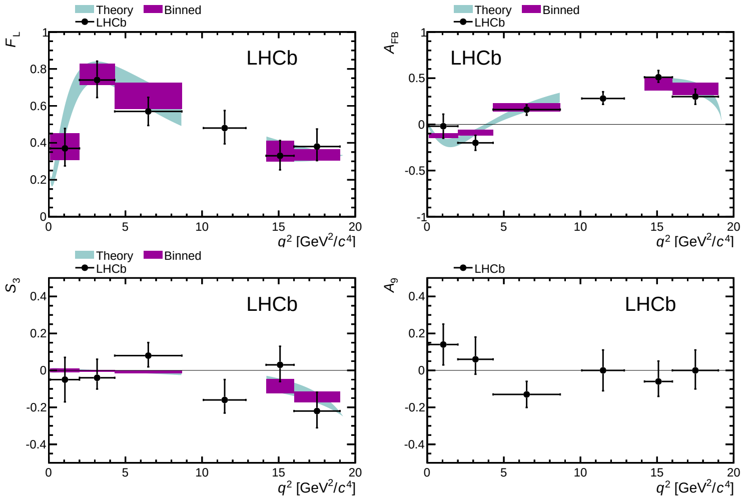
$B^0 \to K^{*0}\mu^+\mu^-$ angular observables I



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

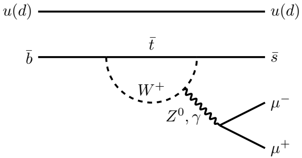
The $K\pi$ S-Wave contribution

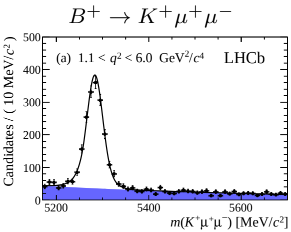
- Can have sizeable contribution with $K\pi$ system in spin 0 configuration
- Systematic in previous analysis, Can significantly bias observables for larger statistics [T. Blake et al.]
- Angular distribution [J. Matias], [D. Becirevic et al.]

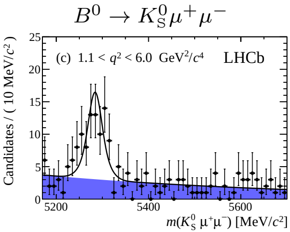
$$\frac{1}{\Gamma_{\rm full}}\frac{\mathrm{d}^3\Gamma_{\rm full}}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\phi} = \frac{1}{\Gamma_{K^{*0}}}\frac{\mathrm{d}^3\Gamma_{K^{*0}}}{\mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_K \mathrm{d}\phi}(1-F_S)$$
$$+\frac{3}{16\pi}\Big[F_S\sin^2\theta_\ell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

- 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 $m_{\rm K\pi\mu\mu}, m_{\rm K\pi}$ and $\cos\theta_K$

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







[JHEP 05 (2014) 082]

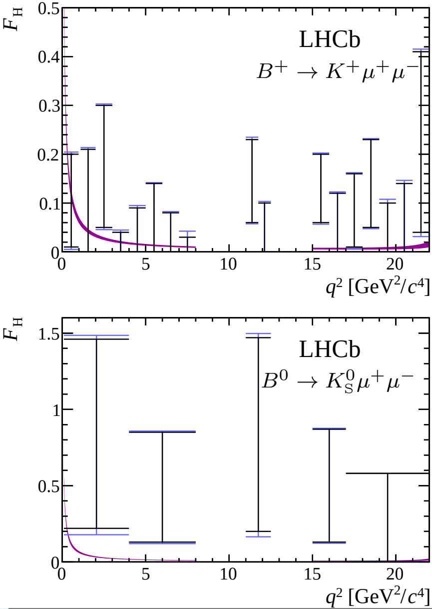
- $N_{B^+\to K^+\mu^+\mu^-} = 4746 \pm 81$ and $N_{B^0\to K^0_S\mu^+\mu^-} = 176 \pm 17$ in $3\,\mathrm{fb}^{-1}$
- Experimental challenge: K^0_S reconstruction
- Differential decay rate for $B^+ \to K^+\mu^+\mu^-$

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

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

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

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



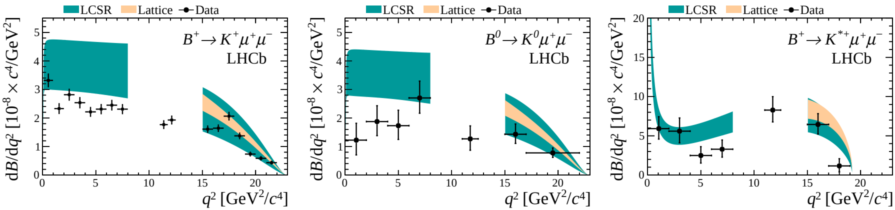
- 2D fit in $\cos\theta_\ell$ and $m(K\mu^+\mu^-)$
- [JHEP 05 (2014) 082] in good agreement with SM prediction

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

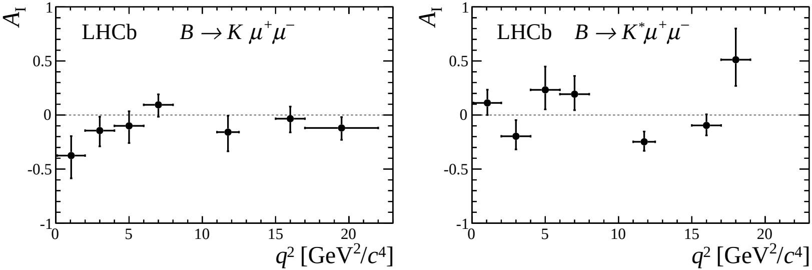
  Light cone sum rules (LCSR): [PRD 71 (2005) 014029], [JHEP 09 (2010) 089],

  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

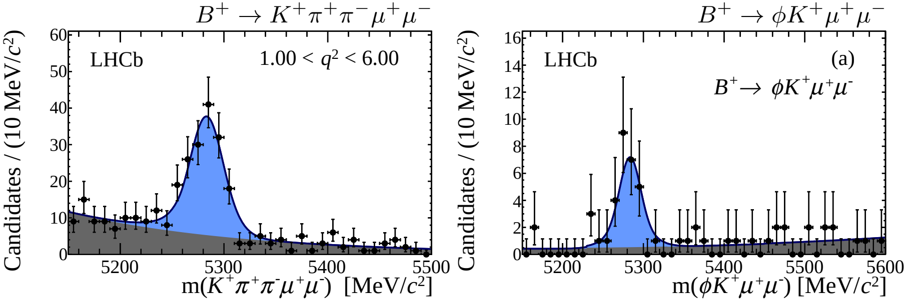
- Isospin asymmetry $A_{\mathrm{I}} = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$
- SM prediction for A_{I} is $\mathcal{O}(1\%)$



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



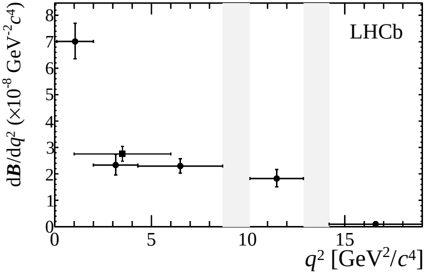
[JHEP 10 (2014) 064]

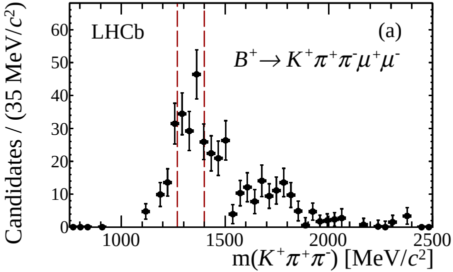
- First observation of these modes with $N_{\text{sig}}(B^+ \to K^+\pi^+\pi^-\mu^+\mu^-) = 367^{+24}_{-23}$ and $N_{\text{sig}}(B^+ \to \phi K^+\mu^+\mu^-) = 25.2^{+6.0}_{-5.3}$
- Normalise to $B^+ \to \psi(2S)(\to J/\psi\,\pi^+\pi^-)K^+$ and $B^+ \to J/\psi\,\phi K^+$
- Determine branching fractions

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

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

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

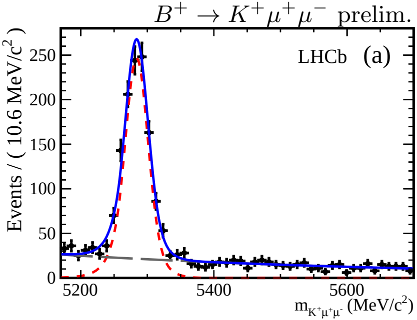


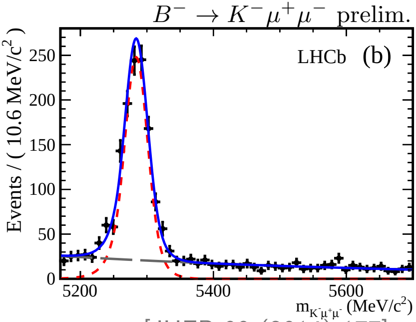


[JHEP 10 (2014) 064]

- 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

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





[JHEP 09 (2014) 177]

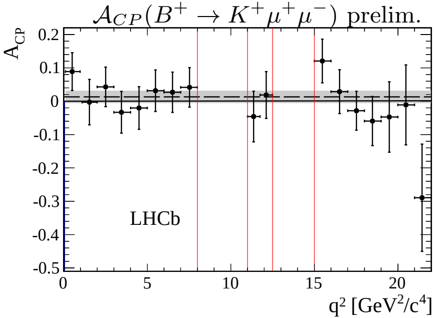
- Direct CP-Asymmetry $\mathcal{A}_{CP}$

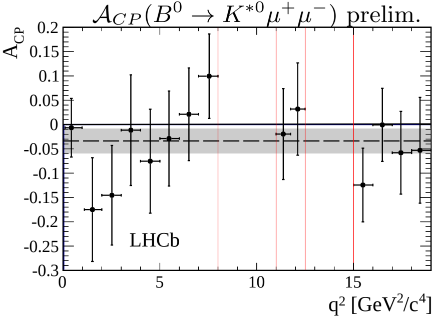
$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-) - \Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-) + \Gamma(B \to K^{(*)}\mu^+\mu^-)}$$

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





[JHEP 09 (2014) 177]

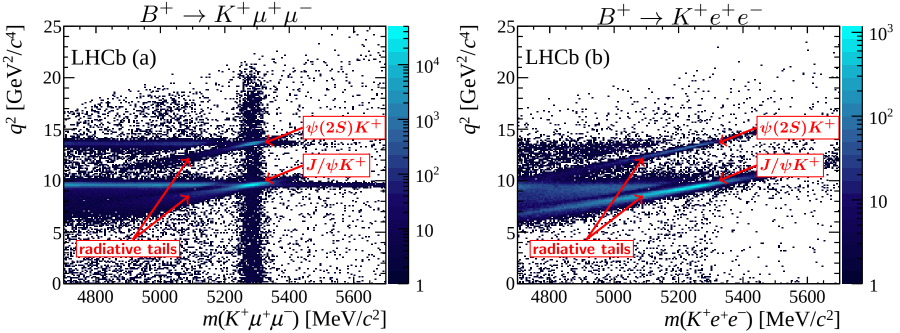
- Measured $\mathcal{A}_{CP}$ in good agreement with SM prediction

$$\mathcal{A}_{CP}(B^+ \to K^+\mu^+\mu^-) = 0.012 \pm 0.017(\text{stat.}) \pm 0.001(\text{syst.})$$
$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.035 \pm 0.024(\text{stat.}) \pm 0.003(\text{syst.})$$

- 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

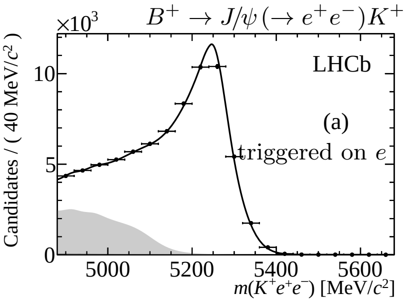


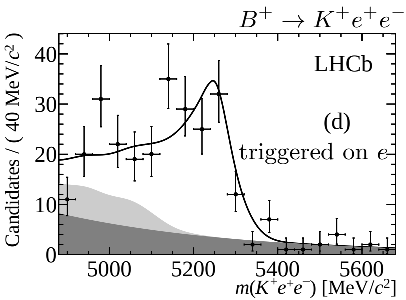
[arxiv:1406.6482]

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

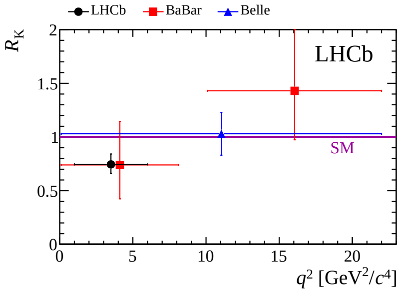
$$\mathcal{R}_K = \left(\frac{N_{K^+\mu^+\mu^-}}{N_{K^+e^+e^-}}\right)\left(\frac{N_{J/\psi\,(e^+e^-)K^+}}{N_{J/\psi\,(\mu^+\mu^-)K^+}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi\,(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi\,(e^+e^-)K^+}}\right)$$

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



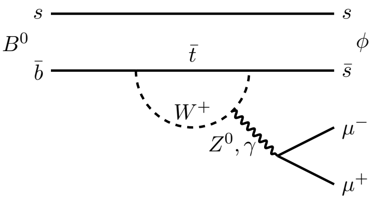


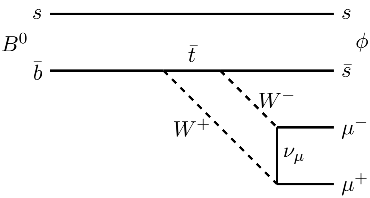
[arxiv:1406.6482]



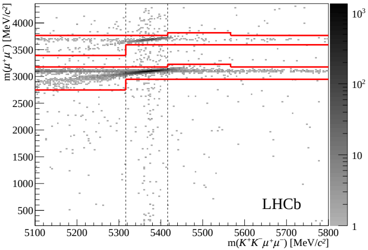
- Use theoretically and experimentally favoured q^2 region $\in [1,6]\,\mathrm{GeV}^2$
- $\mathcal{R}_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat.}) \pm 0.036(\mathrm{syst.})$, compatible with SM at 2.6σ
- $\mathcal{B}_{q^2\in[1,6]\,\mathrm{GeV}^2}(B^+ \to K^+e^+e^-) = (1.56^{+0.19+0.06}_{-0.15-0.04}) \times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

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

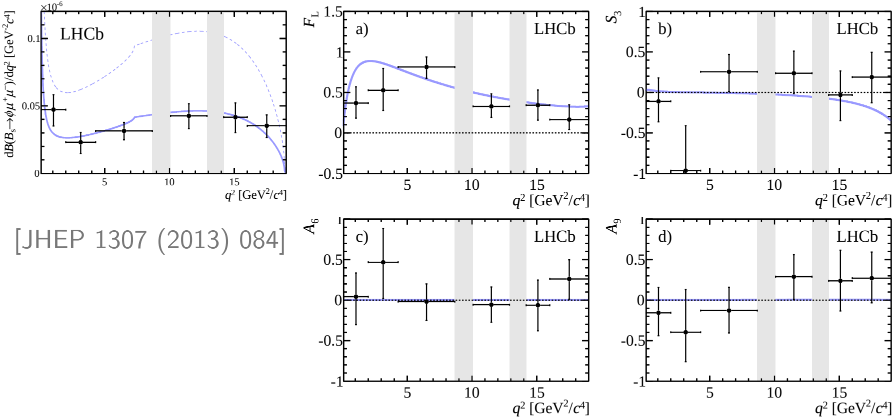
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_K} = \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) + \frac{3}{2}F_\mathrm{L}\cos^2\theta_K$$

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

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

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

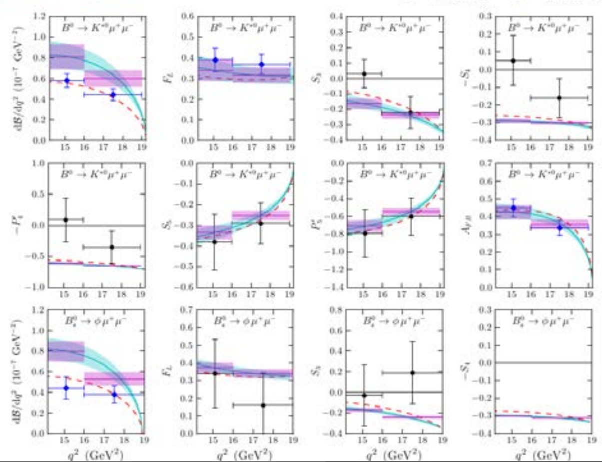


[JHEP 1307 (2013) 084]

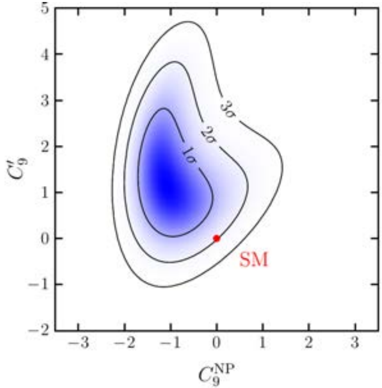
- Angular observables in good agreement with predictions
- Differential $\mathcal{B}$ low

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 $B_s^0 \to \phi\mu^+\mu^-$ 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 rare decays in 2018 and beyond

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2%
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–