Rare electroweak B decays at LHCb

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on behalf of the LHCb collaboration

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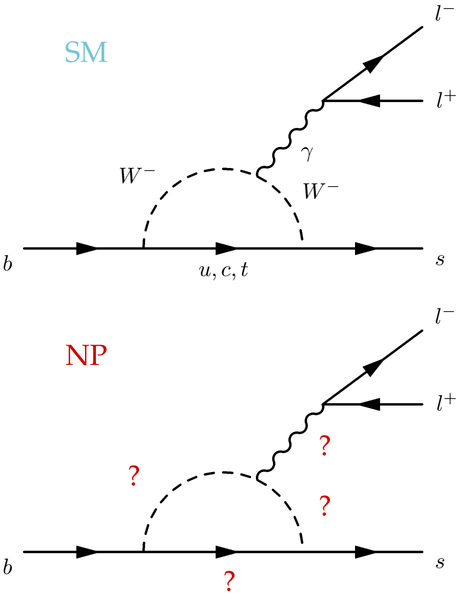
Overview

- Introduction
- $B^0_{(s)} \to \pi^+\pi^-\mu^+\mu^-$
- $\Lambda^0_b \to \Lambda\mu^+\mu^-$
- $B^0 \to K^{*0}\mu^+\mu^-$
- Conclusion

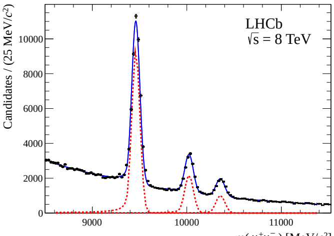
Rare electroweak B decays

- Rare FCNC processes are only possible via loop diagrams in SM
  - Highly suppressed
- New, heavy particles in SM extensions can enter the loop and modify observables ($\mathcal{B}$ and angular distributions)

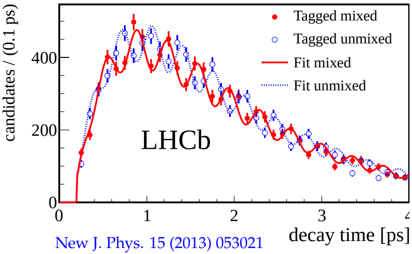


The LHCb experiment

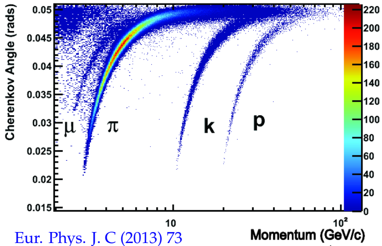
- LHCb is the dedicated heavy flavour physics experiment at the LHC
- Its primary goal is to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons
- This requires:
  1. Excellent tracking
     - momentum resolution($\Delta p/p \sim 0.4\% - 0.6\%$)
     - impact parameter resolution ($\sigma_{IP} \sim 20\ \mu$m)
     - primary vertex resolution (13 μm in x and y and 71 μm in z)
  2. Excellent decay time resolution ($\sigma_\tau \sim 45$ fs)
  3. Excellent particle identification



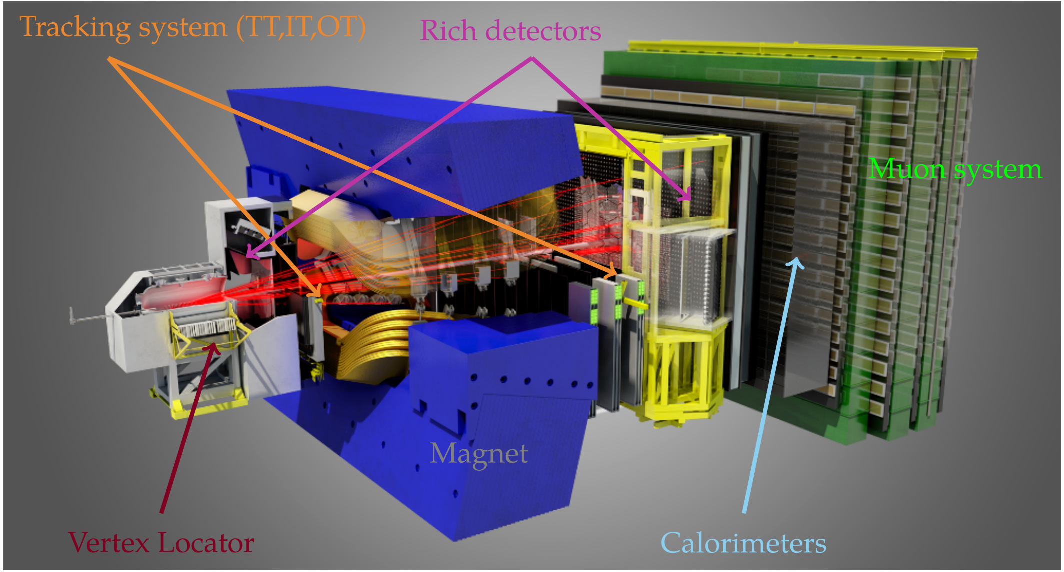
JHEP 06 (2013) 064



New J. Phys. 15 (2013) 053021



Eur. Phys. J. C (2013) 73


Tracking system (TT,IT,OT)
Rich detectors
Muon system
Magnet
Vertex Locator
Calorimeters

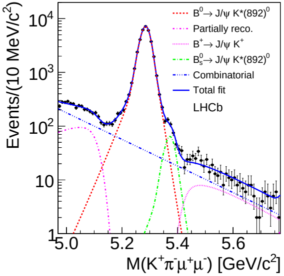
$$B^0_{(s)} \to \pi^+\pi^-\mu^+\mu^-$$

$B^0_{(s)} \to \pi^+\pi^-\mu^+\mu^-$

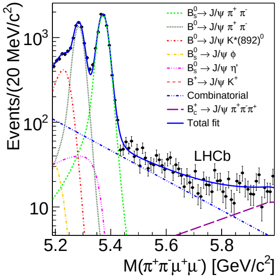
[PLB 743 (2015) 46]

- Candidates must have $m_{\pi^+\pi^-}$ in the range 0.5-1.3 GeV/c^2
- Expected to proceed mainly through $B^0_s \to f_0(980)\mu^+\mu^-$ and $B^0 \to \rho(770)^0\mu^+\mu^-$
- Current SM predictions of $\mathcal{B}$ for both vary from 10^{-7} to 10^{-9} [PRD 79 (2009) 014013] [PRD 81 (2010) 074001] [PRD 80 (2009) 016009]
- Neither decays previously observed
- $B^0 \to J/\psi(\to \mu\mu)K^{*0}(\to K\pi)$ used as normalisation mode
- $B^0_{(s)} \to J/\psi\pi^+\pi^-$ used to help fit modelling and to optimise PID requirements
- Full 3.0 fb^{-1} of Run I data

Normalisation mode



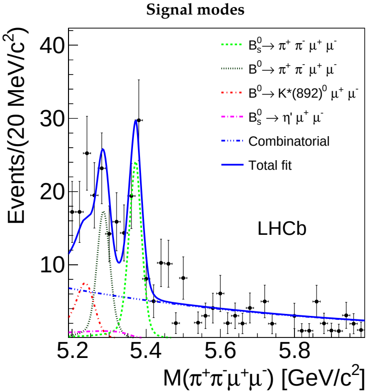
Resonant modes



$B^0_{(s)} \to \pi^+\pi^-\mu^+\mu^-$

[PLB 743 (2015) 46]

- ~ 55 $B^0_s \to \pi^+\pi^-\mu^+\mu^-$ decays and ~ 40 $B^0 \to \pi^+\pi^-\mu^+\mu^-$ decays observed
- First observation of $B^0_s \to \pi^+\pi^-\mu^+\mu^-$ with 7.2σ
- First evidence of $B^0 \to \pi^+\pi^-\mu^+\mu^-$ with 4.8σ
- $\mathcal{B}$ measurements compatible with SM predictions
- Third uncertainty due to $\mathcal{B}$ $(B^0 \to J/\psi K^{*0})$ from BaBar [PRD 76 (2007) 092004], Belle [PLB 538 (2002) 11] and Belle [PRL 79 (1997) 4533]



$0.5 < m_{\pi^+\pi^-} < 1.3$ GeV/c^2

$$\mathcal{B}(B^0_s \to \pi^+\pi^-\mu^+\mu^-) = (8.6 \pm 1.5(\text{stat}) \pm 0.7(\text{syst}) \pm 0.7(\text{norm})) \times 10^{-8}$$

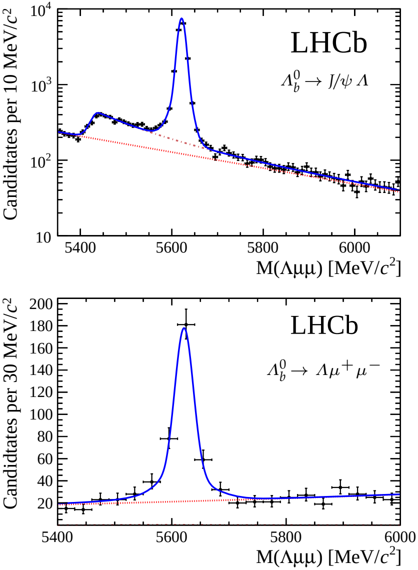
$$\mathcal{B}(B^0 \to \pi^+\pi^-\mu^+\mu^-) = (2.11 \pm 0.51(\text{stat}) \pm 0.15(\text{syst}) \pm 0.16(\text{norm})) \times 10^{-8}$$

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

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

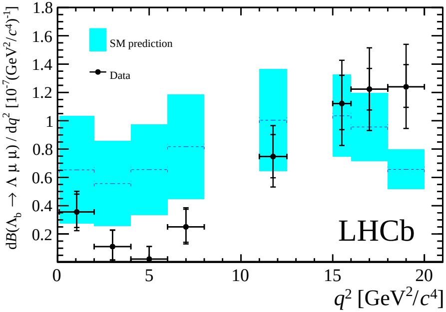
[JHEP 06 (2015) 115]

- $b \to s\ell^+\ell^-$ transition in spin-$\frac{1}{2}$ system
  - Improve the understanding of the helicity structure
- Λ decays are reconstructed in the mode $\Lambda \to p\pi^-$
- $\Lambda^0_b \to J/\psi\,\Lambda$ used as a normalisation mode
- Full 3.0 fb^{-1} of Run I data
  - $\sim$ 300 observed events



Branching fraction

[JHEP 06 (2015) 115]



- Measurement performed in several q^2 bins
- Absolute differential branching fraction obtained by multiplying by $\mathcal{B}(\Lambda^0_b \to J/\psi\,\Lambda)$
- Measurements compatible with SM at high-q^2 but lie below the predictions at low-q^2 [PRD 87 (2013) 074502]

$15 < q^2 < 20\ \text{GeV}^2/c^4$

$$\frac{d\mathcal{B}(\Lambda^0_b \to \Lambda\mu^+\mu^-)}{dq^2} = (1.18^{+0.09}_{-0.08}(\text{stat}) \pm 0.03(\text{syst}) \pm 0.27(\text{norm})) \times 10^{-7}\ (\text{GeV}^2/c^4)^{-1}$$

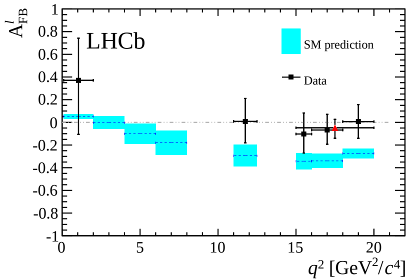
Angular analysis

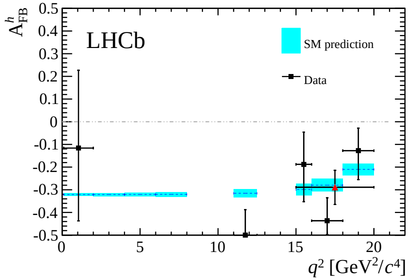
[JHEP 06 (2015) 115]

- Measure forward-backward asymmetry in both dimuon and $p\pi$ systems
- Only in q^2 bins with statistically significant yields
- $A^h_{\rm FB}$ in good agreement with predictions of the SM while $A^\ell_{\rm FB}$ lies consistently above the predictions [arXiv:1401.2685]

$15 < q^2 < 20 \text{ GeV}^2/c^4$

$$A^\ell_{\rm FB} = -0.05 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$$
$$A^h_{\rm FB} = -0.29 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$$



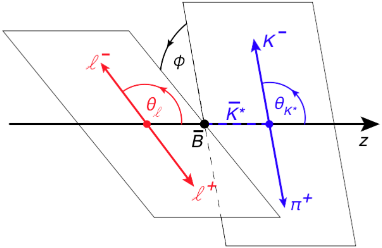


$$B^0 \to K^{*0}\mu^+\mu^-$$

$B^0 \to K^{*0}\mu^+\mu^-$ **[LHCb-CONF-2015-002]**

- Decay fully described by q^2 and three angles $\vec{\Omega} = (\cos\theta_l, \cos\theta_K, \phi)$

$$
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]
$$

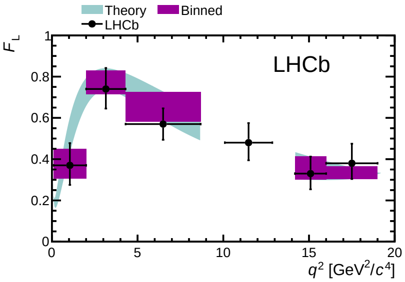


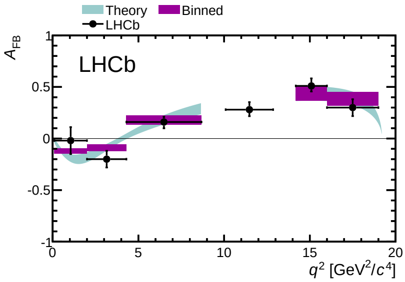
- F_{L}, A_{FB}, S_i combinations of K^{*0} amplitudes which depend on the Wilson coefficients $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$ and the form factors
- Additional sets of observables, for which the leading form-factor uncertainties cancel, can be built from F_{L} and S_3 to S_9
  - e.g. $P'_{4,5} = S_{4,5}/\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}$

Previous analyses of $B^0 \to K^{*0}\mu^+\mu^-$ at LHCb

- Two previous analyses using 1 fb^{-1}

1. Good agreement with SM predictions [JHEP 07 (2011) 067] for observables measured in [JHEP 08 (2013) 131]
2. Less form-factor dependent observables (P_i') introduced in [PRL 111, 191801 (2013)]
   - 3.7σ local deviation from SM prediction [JHEP 05 (2013) 137] in P_5'!





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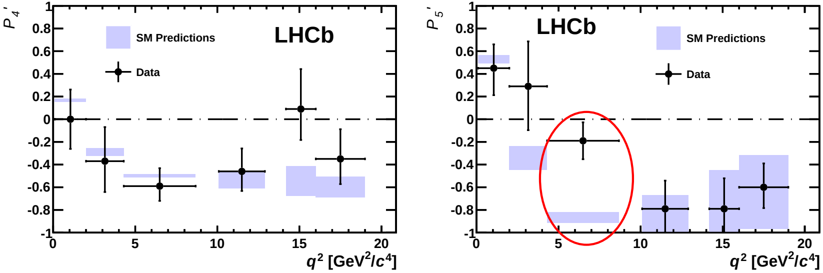
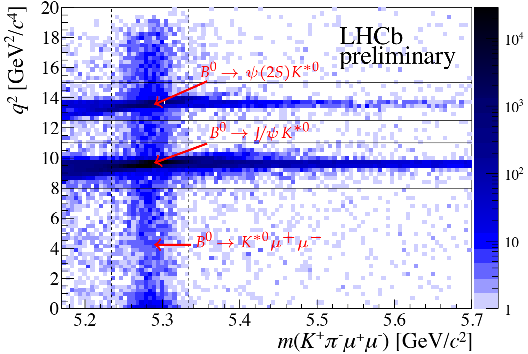


Selection

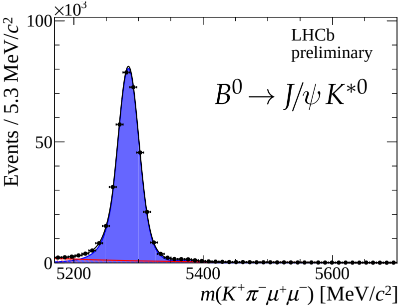
[LHCb-CONF-2015-002]



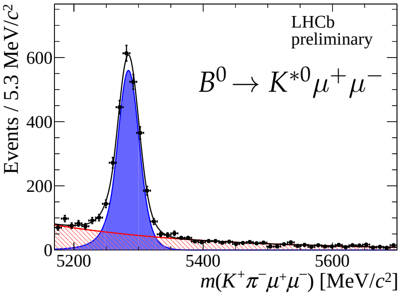
- Resonant modes ($B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$) and peaking backgrounds vetoed with kinematic and PID criteria
- Multivariate classifier used to reduce combinatorial background
  - Kinematic, particle identification and isolation variables used as input
- Full 3.0 fb^{-1} of Run I data

$m_{K\pi\mu\mu}$ distribution

[LHCb-CONF-2015-002]

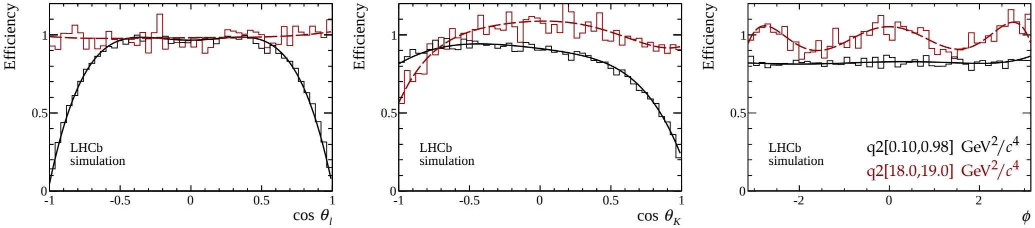


- Signal fit parameters determined from a fit to $B^0 \to J/\psi K^{*0}$ in data
- Scale factor applied to account for q^2 dependent effects
- Integrated $B^0 \to K^{*0}\mu^+\mu^-$ signal yield $N_{\rm sig} = 2398 \pm 57$



Acceptance correction

[LHCb-CONF-2015-002]



- Trigger, reconstruction and selection distort the distributions of q^2, $\cos\theta_\ell$, $\cos\theta_K$, ϕ
- Acceptance parameterised as product of Legendre Polynomials, P_i
- No factorisation is assumed
- Coefficients determined from PHSP $B^0 \to K^{*0}\mu^+\mu^-$ MC using a method of moments approach

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

S-wave pollution

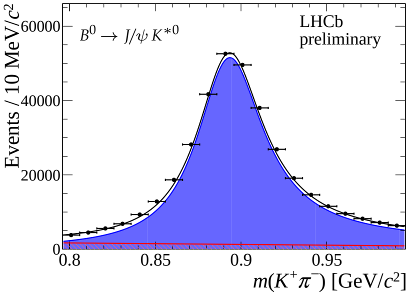
[LHCb-CONF-2015-002]

- K^{*0} reconstructed through decay channel $K^{*0} \to K^+\pi^-$
- Can also have contribution due to $K^+\pi^-$ in S-wave configuration
  - ➜ 6 additional observables

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

- P-wave observables scaled by factor $(1 - F_{\mathrm{S}})$
- Simultaneous fit performed to $m_{K\pi}$ to constrain F_{S}
- P-wave modelled with relativistic BW
- S-wave modelled with Lass parameterisation

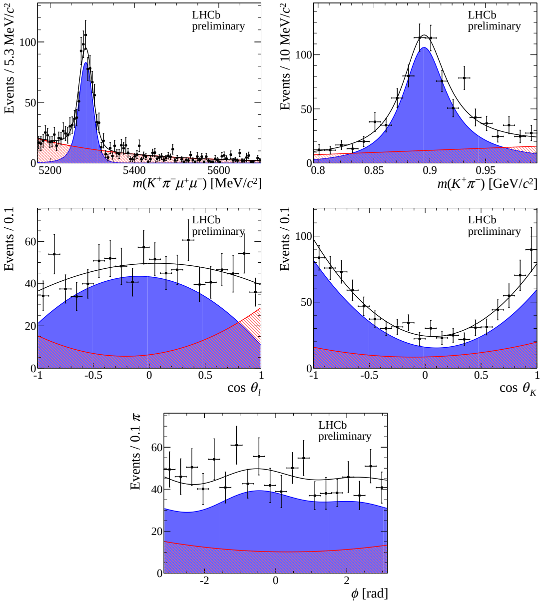
[NPB 296 (1988) 493]



Angular fit

[LHCb-CONF-2015-002]

- Analysis performed in several q^2 bins
- First analysis to allow simultaneous determination of all 8 observables
- 4D+1D simultaneous fit to $m_{K\pi\mu\mu}$, $\cos\theta_\ell$, $\cos\theta_K$, ϕ and $m_{K\pi}$
- Projections shown for q^2 bin $1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$
- Feldman-Cousins method used to ensure correct coverage [PRD 57 (1998) 3873]

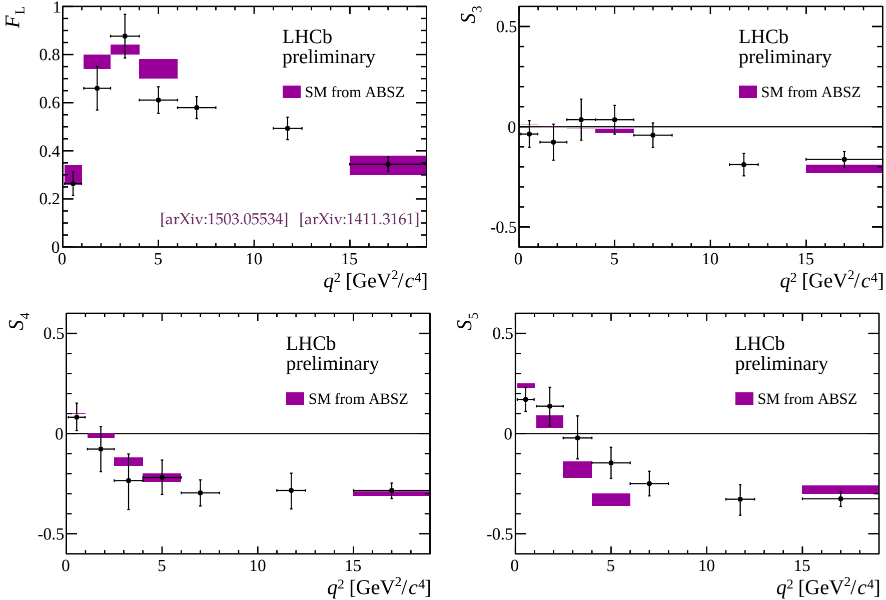


Systematics

[LHCb-CONF-2015-002]

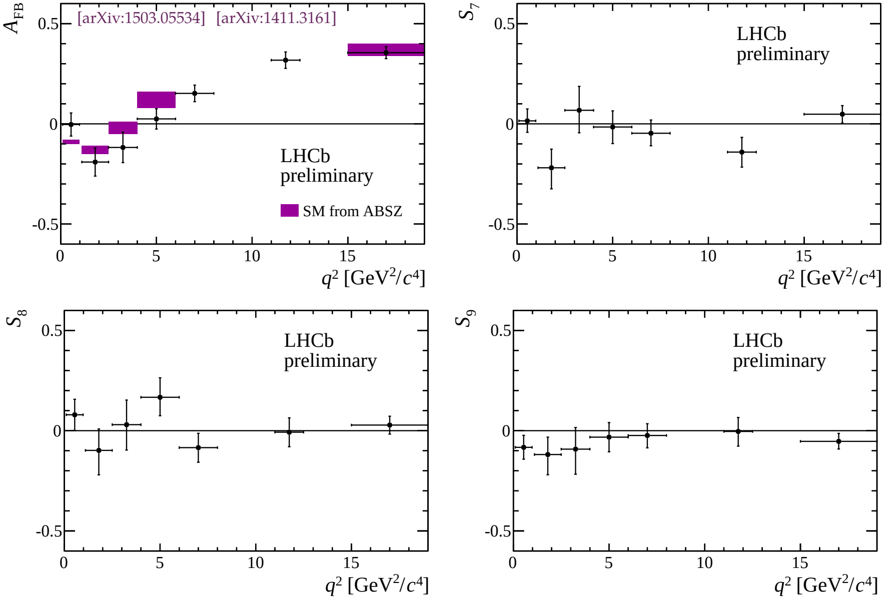
- Many sources of systematic uncertainty are investigated
  - Acceptance correction ($\lesssim 0.01$-0.02)
    1. Limited size of simulation sample
    2. Residual data-simulation differences
    3. Parameterisation of the efficiency function
    4. Evaluation at a fixed point in q^2
  - Peaking backgrounds ($\lesssim 0.01$-0.02)
    1. $B^0_s \to \phi\mu^+\mu^-$
    2. $\Lambda^0_b \to pK^-\mu^+\mu^-$
    3. $B^0 \to K^{*0}\mu^+\mu^-$ double mis-id
  - PDF modelling ($\lesssim 0.01$)
    1. Signal models for $m_{K\pi\mu\mu}$ and $m_{K\pi}$
    2. Background angular models
- All estimated using high statistics pseudo-experiments
- Measurement is **statistically dominated**

Results - F_L, S_3, S_4, S_5 **[LHCb-CONF-2015-002]**



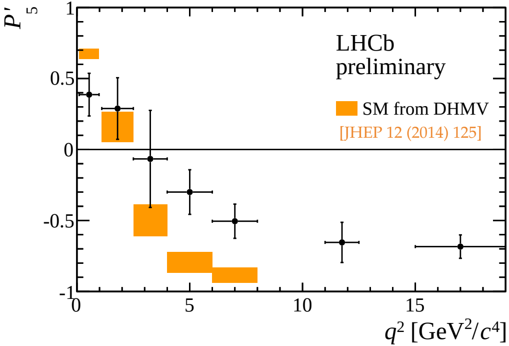
Results - A_{FB}, S_7, S_8, S_9

[LHCb-CONF-2015-002]



Results - P'_5

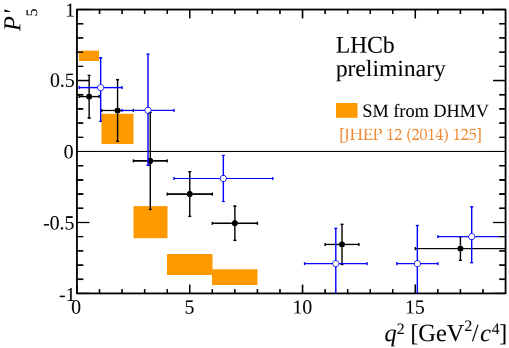
[LHCb-CONF-2015-002]



- Deviation at level of 2.9σ in both bins [4.0,6.0] and [6.0,8.0] GeV$^2/c^4$
- Naive combination results in significance of 3.7σ
- Discrepancy in P'_5 confirmed!
- Compatible with 1 fb^{-1} analysis [PRL 111, 191801 (2013)]

Results - P_5'

[LHCb-CONF-2015-002]



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- Naive combination results in significance of 3.7σ
- Discrepancy in P_5' confirmed!
- Compatible with 1 fb^{-1} analysis [PRL 111, 191801 (2013)]

Conclusion

- Rare decays are powerful probes in the search for NP
- Presented first observation of $B^0_s \to \pi^+\pi^-\mu^+\mu^-$ and first evidence of $B^0 \to \pi^+\pi^-\mu^+\mu^-$
- Presented branching fraction and angular analysis of $\Lambda^0_b \to \Lambda\mu^+\mu^-$
- Presented full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$
  - Deviation in P'_5 confirmed!

Further LHCb talks @ DPF

Michael Koplin, $B^0_s \to \phi\mu^+\mu^-$ at LHCb, next talk

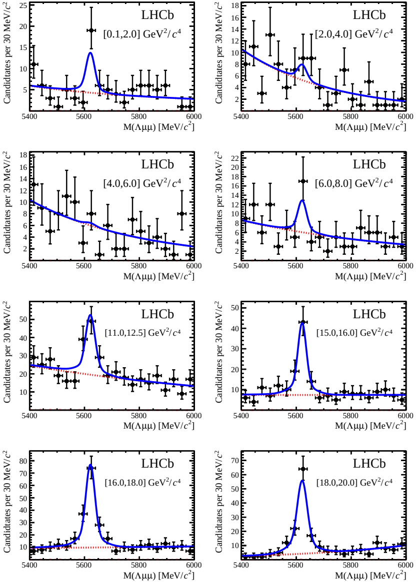
Tobias Tekampe, First measurement of the differential branching fraction and CP asymmetry of the $B^+ \to \pi^+\mu^+\mu^-$ decay, tomorrow

- With Run II beginning, exciting times are ahead!


Backup

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

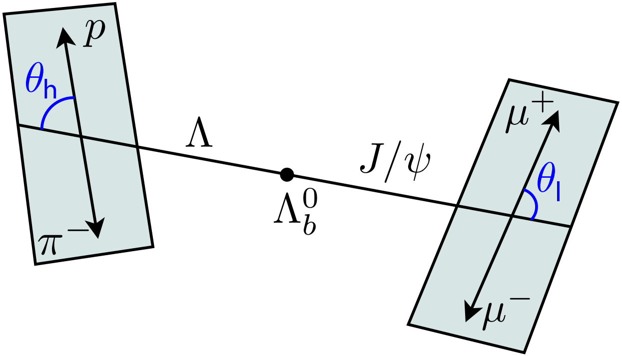
[JHEP 06 (2015) 115]



q^2 interval [GeV^2/c^4]	Total signal yield	Significance
0.1 – 2.0	16.0 ± 5.3	4.4
2.0 – 4.0	4.8 ± 4.7	1.2
4.0 – 6.0	0.9 ± 2.3	0.5
6.0 – 8.0	11.4 ± 5.3	2.7
11.0 – 12.5	60 ± 12	6.5
15.0 – 16.0	57 ± 9	8.7
16.0 – 18.0	118 ± 13	13
18.0 – 20.0	100 ± 11	14
1.1 – 6.0	9.4 ± 6.3	1.7
15.0 – 20.0	276 ± 20	21

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

[JHEP 06 (2015) 115]



$B^0_{(s)} \to \pi^+\pi^-\mu^+\mu^-$

[PLB 743 (2015) 46]