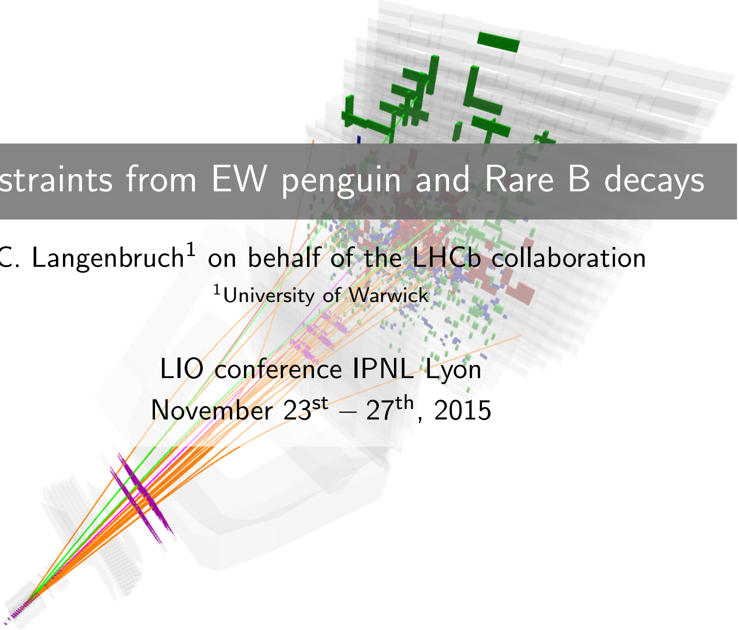


Constraints from EW penguin and Rare B decays

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

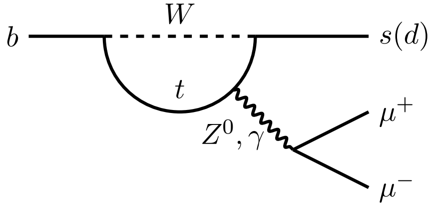
[1]University of Warwick

LIO conference IPNL Lyon

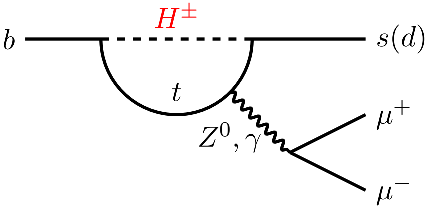
November 23$^{\text{st}}$ – 27$^{\text{th}}$, 2015

Rare decays as indirect probes for BSM physics

SM penguin diagram



NP penguin diagram



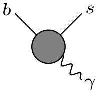
- Rare FCNC decays are loop-suppressed in the Standard Model (SM)
- New heavy particles in SM extensions (NP) can appear in competing diagrams and affect $\mathcal{B}$ and angular distributions
- NP does not need to be produced on-shell
  $\rightarrow$ masses up to $\mathcal{O}(100\,\mathrm{TeV})$ accessible [A. Buras, arXiv:1505.00618]

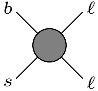
Effective field theory

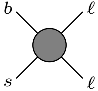
- Model independent description in effective field theory

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

- Wilson coeff. $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators







	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$ photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$ vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$ axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$ (pseudo)scalar penguin		✓	

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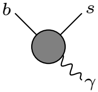

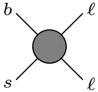

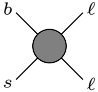

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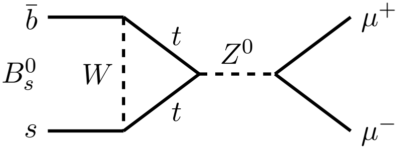
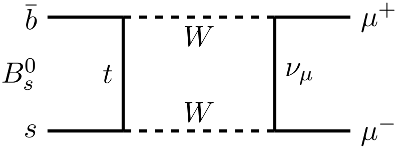
The very rare decay $B^0_{(s)} \to \mu\mu$





- Loop and additionally helicity suppressed
- Purely leptonic final state: Theoretically and experimentally very clean
- Very sensitive to NP:

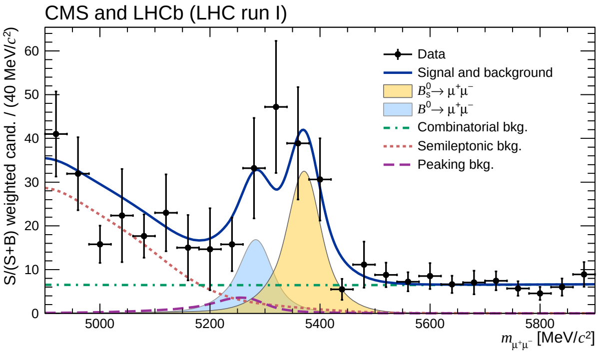
Possible scalar and pseudoscalar enhanced *wrt*. SM axialvector

$$\mathcal{B} \propto |V_{tb}V_{tq}|^2[(1-\frac{4m_\mu^2}{M_B^2})|C_S - C'_S|^2 + |(C_P - C'_P) + \frac{2m_\mu}{M_B^2}(C_{10} - C'_{10})|^2]$$

- SM prediction (accounting for $\Delta\Gamma_s \neq 0$) [C. Bobeth *et al.*, PRL 112, 101801 (2014)]

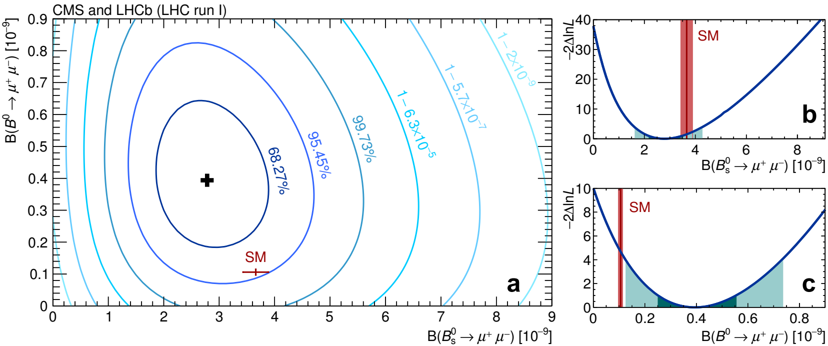
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

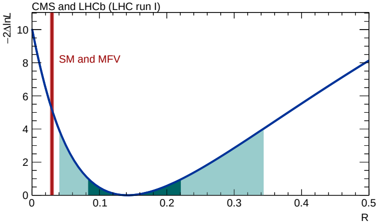
First observation of $B_s^0 \to \mu\mu$



- Combined analysis of LHCb and CMS Run 1 data, sharing signal and nuisance parameters [Nature 522 (2015) pp. 68-72]
- First obs. of $B_s^0 \to \mu^+\mu^-$ with $6.2\,\sigma$ significance (expected $7.2\,\sigma$)
  $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ compatible with SM at $1.2\,\sigma$
- First evidence for $B^0 \to \mu^+\mu^-$ with $3.0\,\sigma$ significance (expected $0.8\,\sigma$)
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ compatible with SM at $2.2\,\sigma$

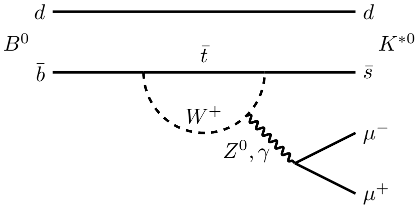
The ratio $\mathcal{R} = \mathcal{B}(B^0 \to \mu\mu)/\mathcal{B}(B^0_s \to \mu\mu)$

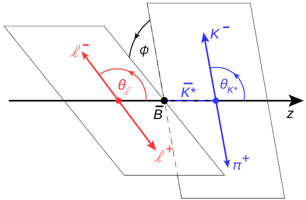




- $\mathcal{R} = \dfrac{\mathcal{B}(B^0 \to \mu\mu)}{\mathcal{B}(B^0_s \to \mu\mu)}$ test of MFV hypothesis
- $\mathcal{R}_{\rm SM} = 0.0295^{+0.0028}_{-0.0025}$
- $\mathcal{R} = 0.14^{+0.08}_{-0.06}$ compatible at $2.3\,\sigma$

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





- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\big[\tfrac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\rm FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\big]$$
- $F_{\rm L}, A_{\rm FB}, S_i$ combinations of K^{*0} spin amplitudes depending on Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ and form factors
- Perform ratios of angular obs. where form factors cancel at leading order
  Example: $P_5^\prime = \frac{S_5}{\sqrt{F_{\rm L}(1-F_{\rm L})}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]
- Relative sign between B^0 and $\overline{B}^0$ → access to CP asymmetries $A_{3,\ldots,9}$

S-wave pollution

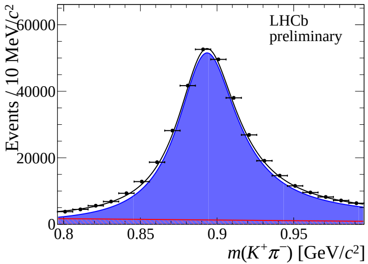
- S-wave: $K^+\pi^-$ not from $K^{*0}(892)$ but in spin 0 configuration
- Introduces two add. decay amplitudes resulting in six add. observables

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

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

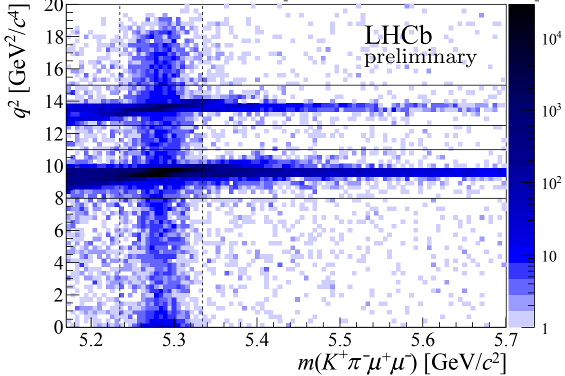
- Perform simultaneous $m_{K\pi}$ fit to constrain F_S
- P-wave described by rel. Breit-Wigner
- S-wave described by LASS model crosschecked using Isobar param.

[LHCb-PAPER-2015-051]



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

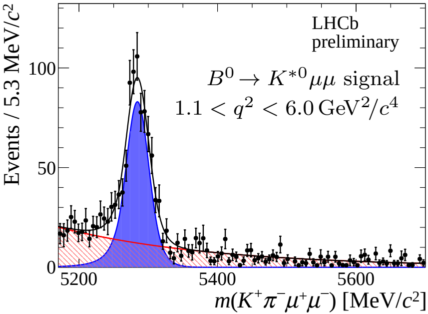
[LHCb-PAPER-2015-051]

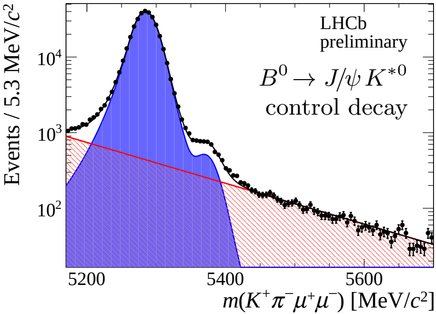


- BDT to suppress combinatorial background
  Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto of $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$ (important control decays) and peaking backgrounds using kinematic variables and PID
- Signal clearly visible as vertical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

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

[LHCb-PAPER-2015-051]

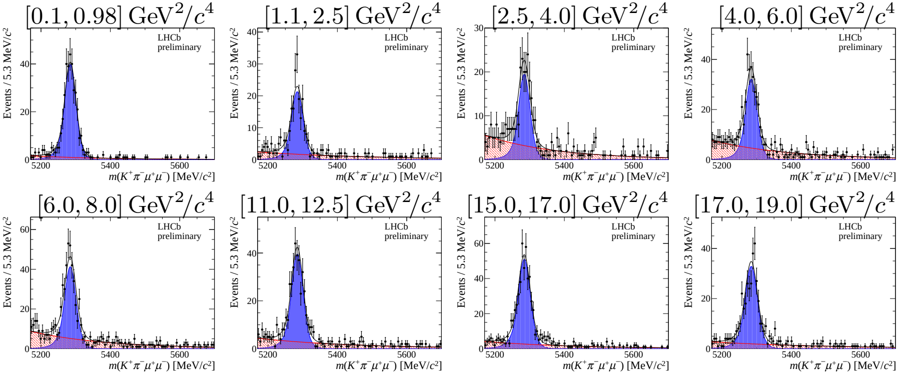




- Signal mass model from high statistics $B^0 \to J/\psi\,K^{*0}$
  Correction factor from simulation to account for q^2 dep. resolution
- Finer q^2 binning to allow more flexible use in theory
- Significant signal yield in all bins, q^2 integrated $N_{\mathrm{sig}} = 2398 \pm 57$

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

[LHCb-PAPER-2015-051]



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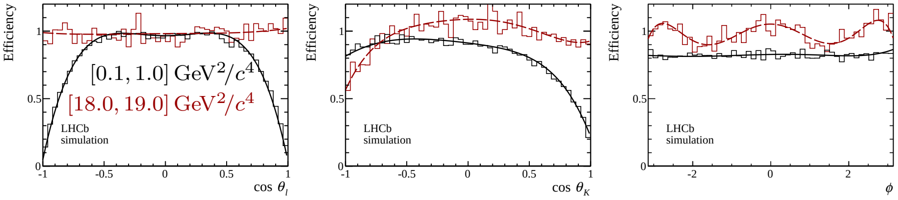
Acceptance effect

[LHCb-PAPER-2015-051]

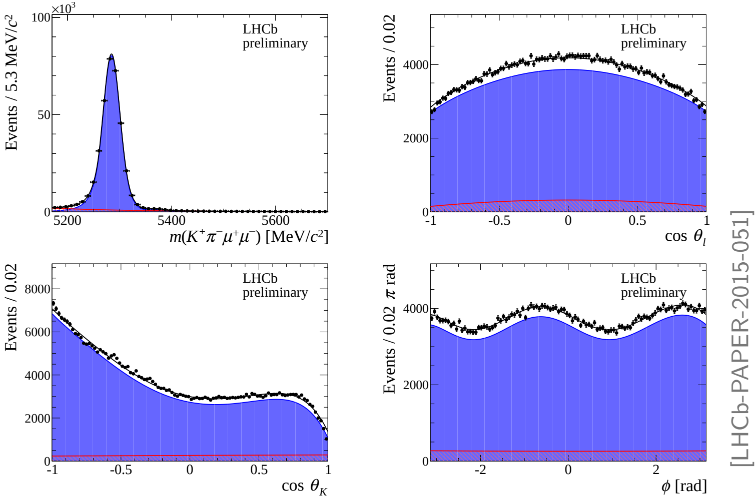


- Trigger, reconstruction and selection distorts decay angles and q^2 distribution
- Parametrize 4D efficiency using Legendre polynomials P_k

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

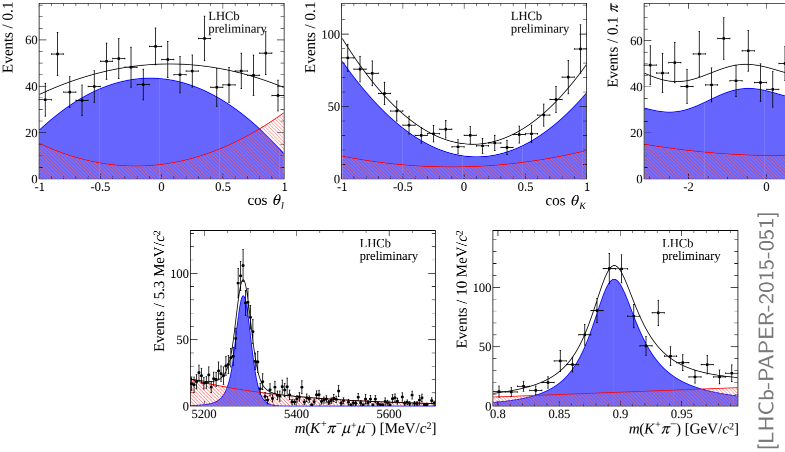
- c_{klmn} from moments analysis of $B^0 \to K^{*0}\mu^+\mu^-$ phase-space MC
- Crosscheck acceptance using $B^0 \to J/\psi K^{*0}$ control decay

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



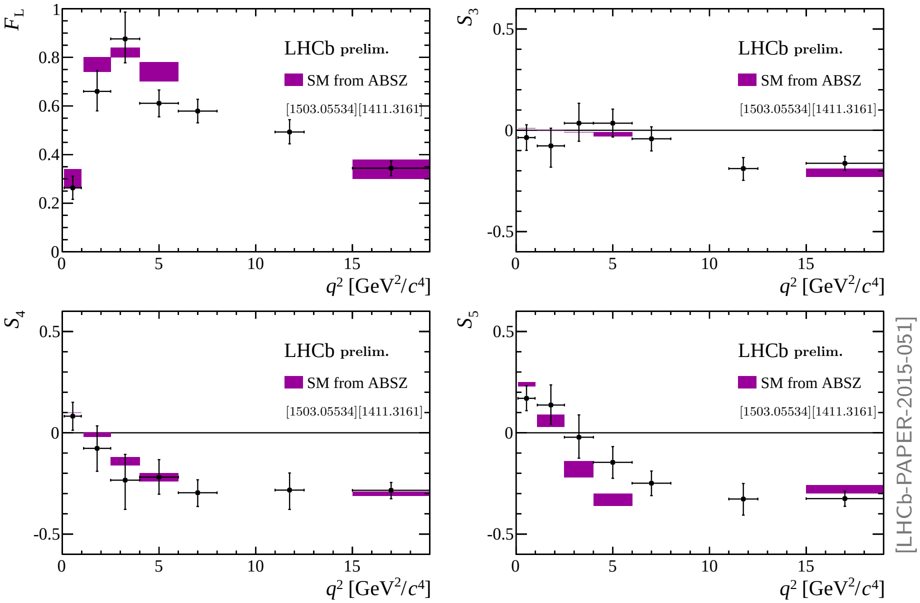
- black line: full fit, blue: signal component, red: bkg. part
- Angular observables successfully reproduced [PRD 88, 052002 (2013)]

$B^0 \to K^{*0}\mu^+\mu^-$ likelihood projections $[1.1, 6.0]\,\mathrm{GeV}^2/c^4$

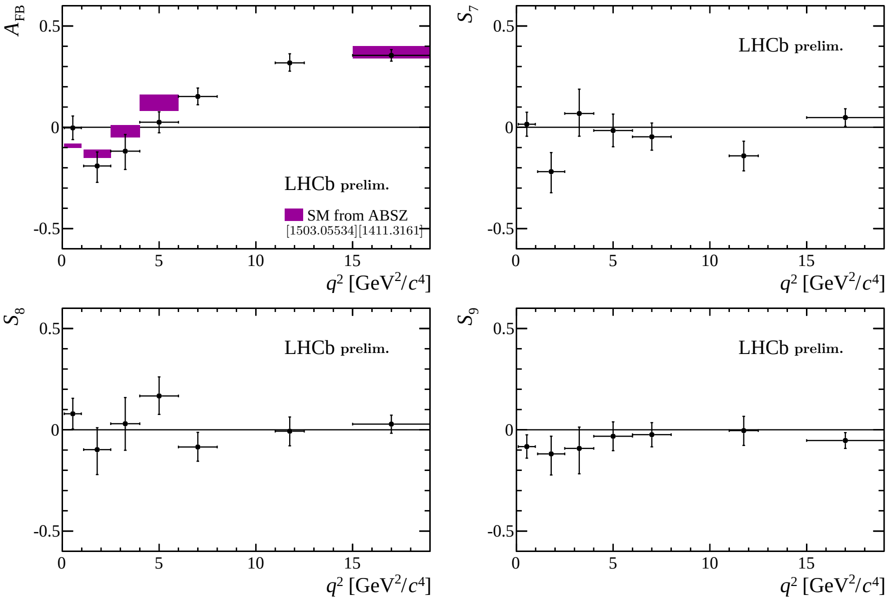


- Efficiency corrected distributions show good agreement with overlaid projections of the probability density function

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



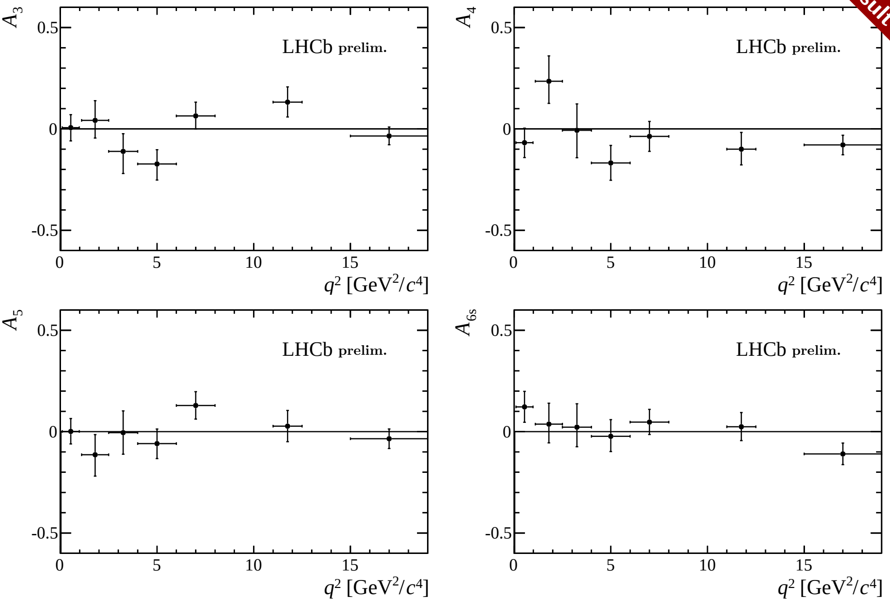
$B^0 \to K^{*0}\mu^+\mu^-$ Results: $A_{\rm FB}$, S_7, S_8, S_9



[LHCb-PAPER-2015-051]

$B^0 \to K^{*0}\mu^+\mu^-$ CP asymmetries: A_3, A_4, A_5, A

New result



[LHCb-PAPER-2015-051]

$B^0 \to K^{*0}\mu^+\mu^-$ CP asymmetries: A_7, A_8, A_9

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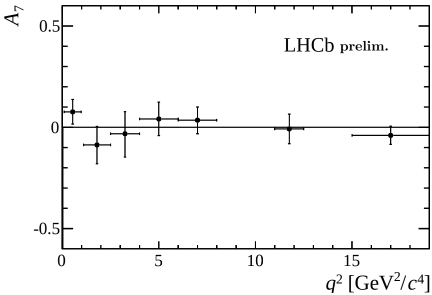
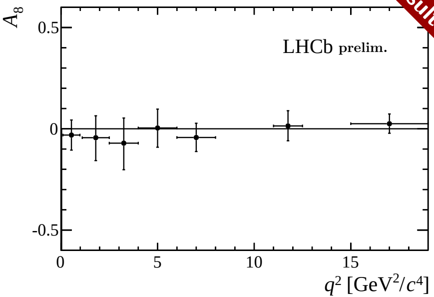
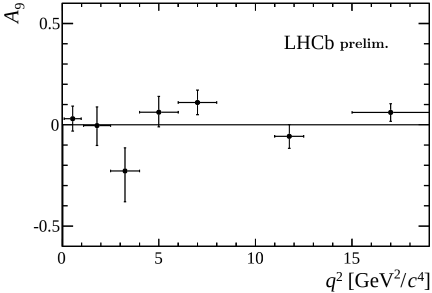


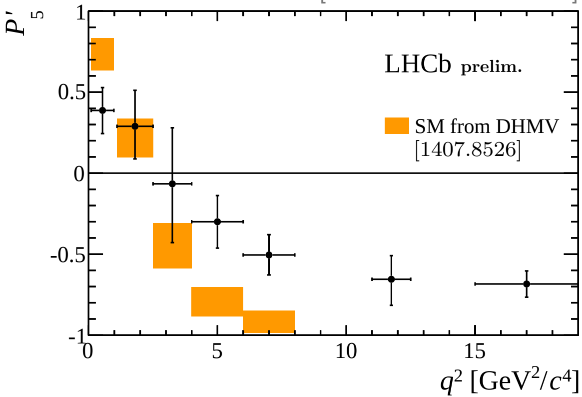




[LHCb-PAPER-2015-0...]

P_5'

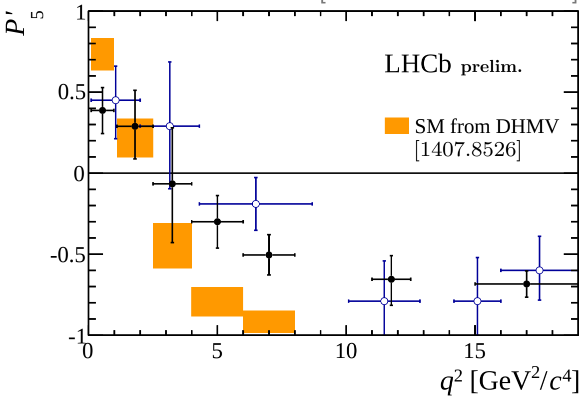
[LHCb-PAPER-2015-051]



- Tension seen in P_5' in [PRL 111, 191801 (2013)] confirmed
- $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ local deviations of 2.8σ and 3.0σ
- Compatible with $1\,\mathrm{fb}^{-1}$ measurement

P_5'

[LHCb-PAPER-2015-051]



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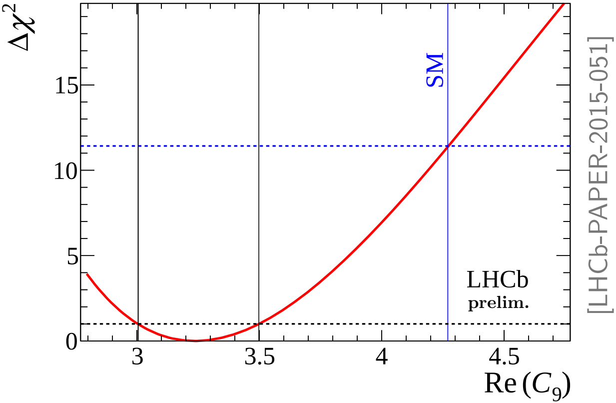
- Compatible with $1\,\mathrm{fb}^{-1}$ measurement

Compatibility with the SM

New result

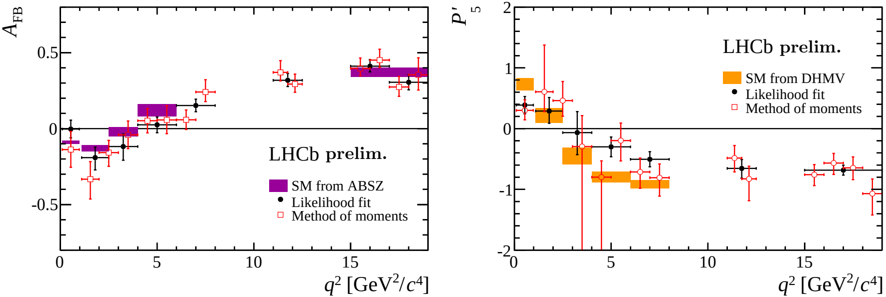


- Perform χ^2 fit of measured S_i observables using [EOS] software
- Varying $\mathrm{Re}(\mathcal{C}_9)$ and incl. nuisances according [F. Beaujean *et al.*, EPJC 74 (2014) 2897]
- $\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$ with global significance of $3.4\,\sigma$

Moments analysis

New result

[LHCb-PAPER-2015-051]

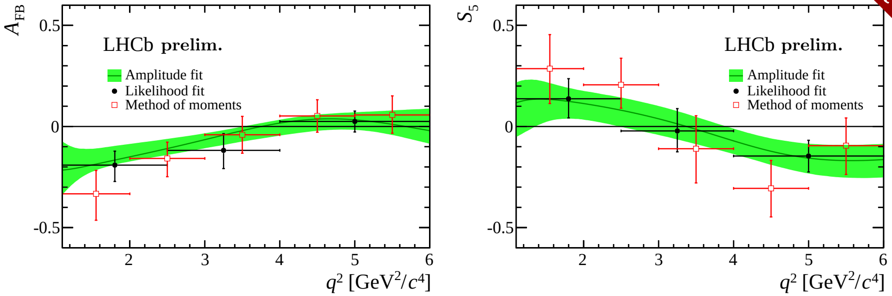


- Angular terms $f_i(\vec{\Omega})$ are orthogonal
  $\to$ can determine obs. via their moments $\hat{M}_i = \frac{1}{\sum_e w_e} \sum_e w_e f_i(\vec{\Omega}_e)$
- $10\text{-}30\%$ less sensitive than Maximum Likelihood fit [F. Beaujean *et al.*, PRD 91 (2015) 114012] but allows narrow $1\,\mathrm{GeV}^2/c^4$ wide q^2 bins
- Consistency of the results checked using toys

Amplitude fit and Zero-crossing points

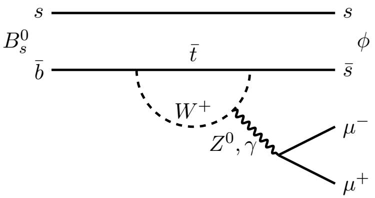
New result

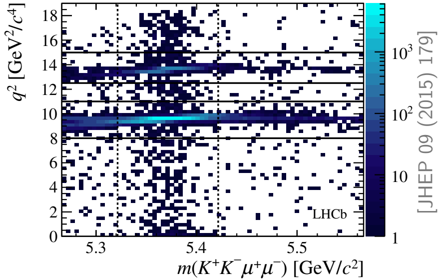
[LHCb-PAPER-2015-05



- Zero-crossing points sensitive tests of SM, form factor uncertainties cancel
- Perform q^2 dependent amplitude fit with Ansatz $\mathcal{A}^{L,R}_{0,\|,\perp} = \alpha + \beta q^2 + \gamma \frac{1}{q^2}$ in the region $1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4$
- Resulting zero crossing points in good agreement with SM predictions
  $q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4$ @ 68% CL,
  $q_0^2(S_4) < 2.65\,\mathrm{GeV}^2/c^4$ @ 95% CL,
  $q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4$ @ 68% CL

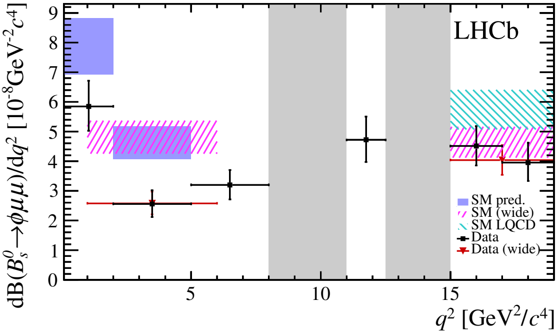
The rare decay $B_s^0 \to \phi[\to K^+K^-]\mu^+\mu^-$





- Dominant $b \to s\mu^+\mu^-$ decay for B_s^0, analogous to $B^0 \to K^{*0}\mu^+\mu^-$
- $K^+K^-\mu^+\mu^-$ final state not self-tagging
  $\to$ reduced number of angular observables: F_{L}, $S_{3,4,7}$, $A_{5,6,8,9}$
- Signal yield lower due to $\frac{f_s}{f_d} \sim \frac{1}{4}$, $\frac{\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(K^{*0} \to K^+\pi^-)} = \frac{3}{4}$
- Clean selection due to narrow ϕ resonance, S-wave negligible

$B^0_s \to \phi\mu^+\mu^-$ differential branching fraction



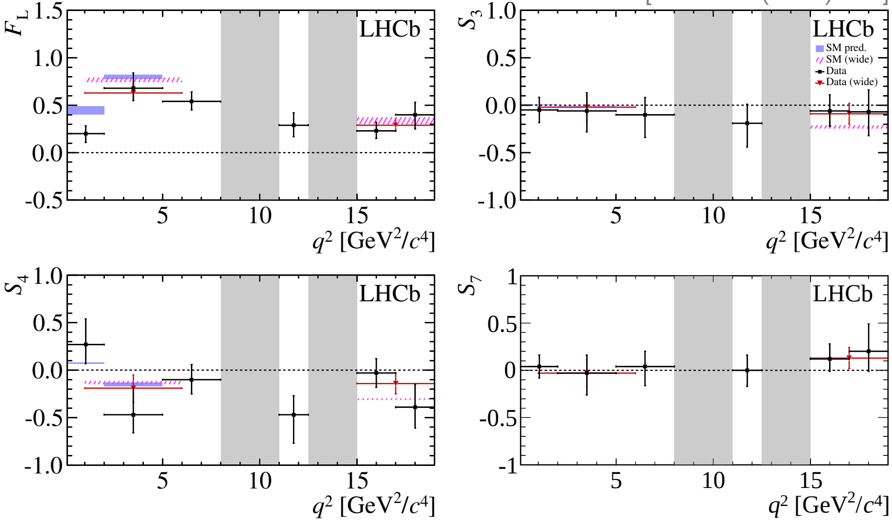
[JHEP 09 (2015) 179]

- In $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ diff. $\mathcal{B}$ more than $3\,\sigma$ below SM prediction
- Confirming deviation seen in $1\,\mathrm{fb}^{-1}$ analysis [JHEP 07 (2013) 084]
- Most precise measurement of relative and total branching fraction

$$\frac{\mathcal{B}(B^0_s \to \phi\mu^+\mu^-)}{\mathcal{B}(B^0_s \to J/\psi\,\phi)} = (7.41^{+0.42}_{-0.40} \pm 0.20 \pm 0.21) \times 10^{-4},$$
$$\mathcal{B}(B^0_s \to \phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7},$$

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

[JHEP 09 (2015) 179]



- Good agreement of angular obs. with SM predictions

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

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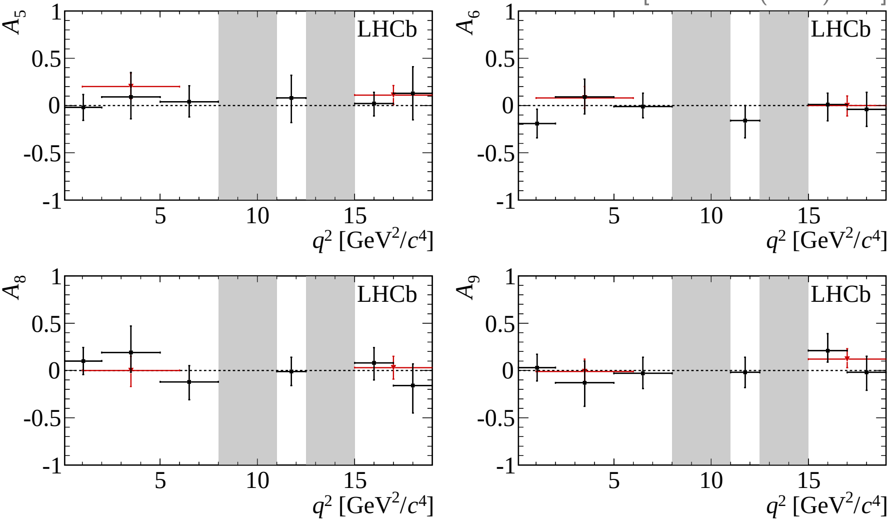


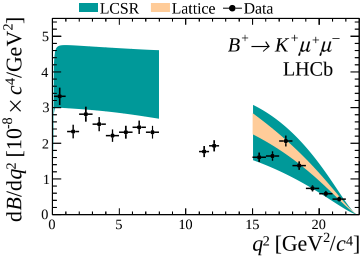
- Good agreement of angular obs. with SM predictions

$B \to K^{(*)}\mu^+\mu^-$ branching fraction measurements

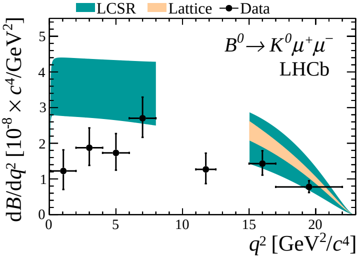
- Number of signal events in full $3\,\mathrm{fb}^{-1}$ data sample

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



[JHEP 06 (2014) 133]

- Compatible with but lower than SM predictions

Light cone sum rules (LCSR): [P. Ball *et al.*, PRD 71 (2005) 014029] [A. Khodjamirian *et al.*, JHEP 09 (2010) 089]

Lattice: [R. Horgan *et al.*, PRD 89 (2014) 094501] [C. Bouchard *et al.*, PRD 88 (2013) 054509]

- $d\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/dq^2$ with $3\,\mathrm{fb}^{-1}$ in preparation

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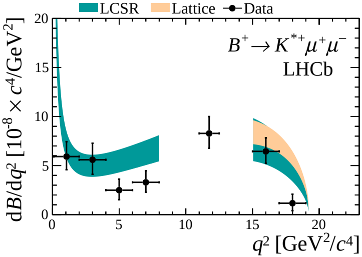
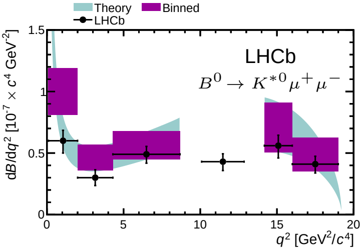


[JHEP 06 (2014) 133]



[JHEP 08 (2013) 131]

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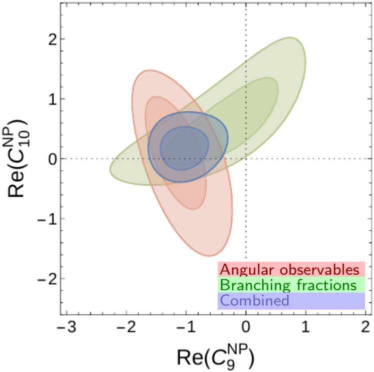
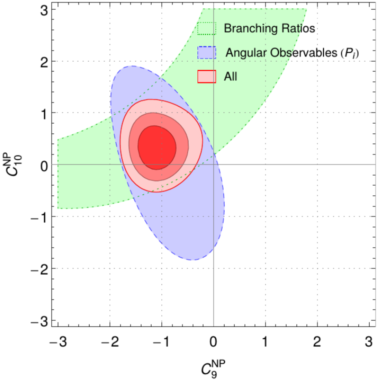
Global fits to $b \to s$ data

[W. Altmannshofer *et al.*, EPJC 75 (2015) 382]



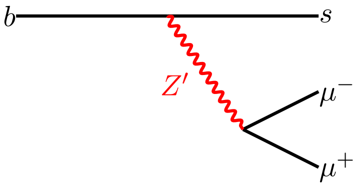
[S. Descotes-Genon *et al.*, arXiv:1510.04239]



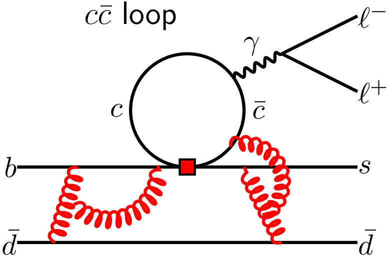
- Tension can be reduced with $\Delta\mathrm{Re}(\mathcal{C}_9) \sim -1$, significances around $4\,\sigma$
- Consistency between angular observables and branching fractions

NP or hadronic effect?

Possible NP

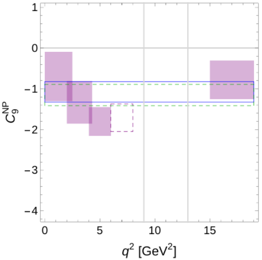


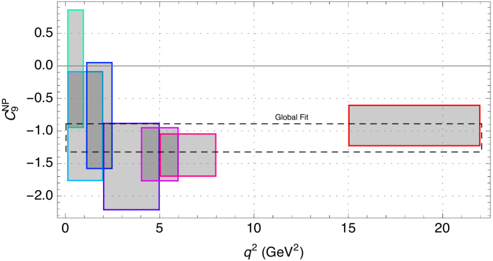
$c\bar{c}$ loop



- Possible explanations for shift in $\mathcal{C}_9$
  - NP *e.g.* Z' [Gauld et al.] [Buras et al.] [Altmannshofer et al.] [Crivellin et al.] Leptoquarks [Hiller et al.] [Biswas et al.] [Buras et al.] [Gripaios et al.]
  - hadronic charm loop contributions
- q^2 dependence: $c\bar{c}$ loops rise towards J/ψ, NP q^2-independent
- For details please see talks by J. Virto and J. Matias

NP or hadronic effect?





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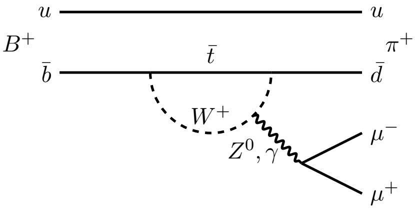
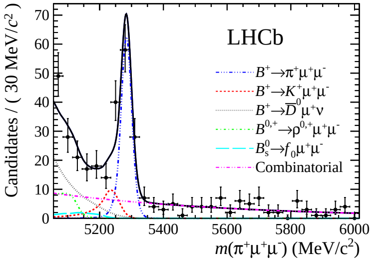
The $b \to d\mu^+\mu^-$ decay $B^+ \to \pi^+\mu^+\mu^-$



[JHEP 10 (2015) 034]



- $b \to d\mu^+\mu^-$ transition in SM sup. by $\left|\frac{V_{\rm td}}{V_{\rm ts}}\right|^2 \sim \frac{1}{25}$ *wrt.* $b \to s\mu^+\mu^-$
- Measure diff. branching fraction and $\mathcal{A}_{CP}$ ($O(-0.1)$ in the SM)
- Assuming SM, measure $|V_{\rm td}/V_{\rm ts}|$, $|V_{\rm td}|$, $|V_{\rm ts}|$ using $B^+ \to K^+\mu^+\mu^-$
  $|V_{\rm td}|^2 = \frac{\mathcal{B}(B^+\to\pi^+\mu^+\mu^-)}{\int F_\pi {\rm d}q^2}$ and $|V_{\rm ts}|^2 = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\int F_K {\rm d}q^2}$

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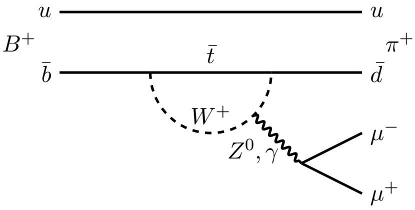
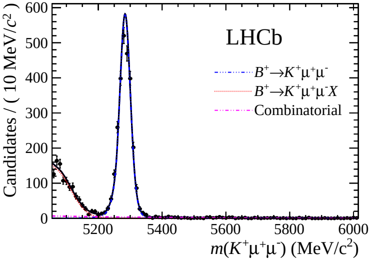


[JHEP 10 (2015) 034]



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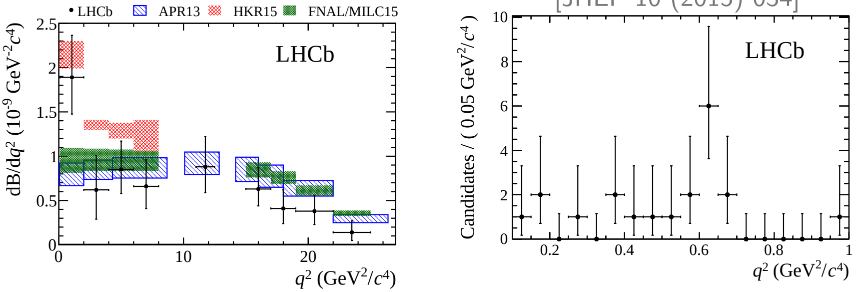
$B^+ \to \pi^+\mu^+\mu^-$ diff. $\mathcal{B}$, $\mathcal{A}_{CP}$ and CKM matrix elements

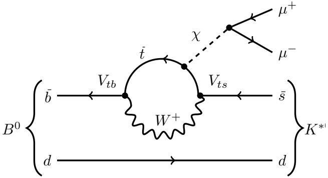
[JHEP 10 (2015) 034]

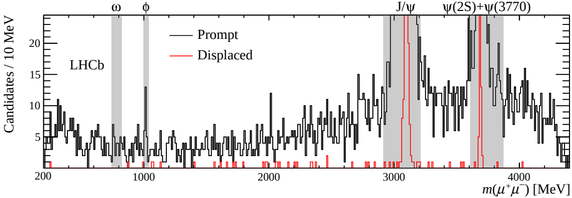


- Good agreement with but slightly lower than SM predictions
  APR13 [PRD 89 (2014) 094021] HKR15 [PRD 92 (2015) 074020] FNAL/MILC15 [PRL 115 (2015) 152002]
- $\mathcal{B} = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$ and $\mathcal{A}_{CP} = -0.11 \pm 0.12 \pm 0.01$
- $|\frac{V_{\rm td}}{V_{\rm ts}}| = 0.24^{+0.05}_{-0.04}$, $|V_{\rm td}| = 7.2^{+0.9}_{-0.8} \times 10^{-3}$ and $|V_{\rm ts}| = 3.2^{+0.4}_{-0.4} \times 10^{-2}$
- New lattice predictions from MILC collaboration [D. Du *et al.*, arXiv:1510.02349]
  → CKM elements from RDs competitive with $B_{(s)}$ oscillation meas.
  → Combined $2\,\sigma$ tension of $\mathcal{B}(B^+ \to K^+(\pi^+)\mu^+\mu^-)$ with SM prediction

Search for hidden sector boson in $B^0 \to K^{*0}\mu^+\mu^-$

[PRL 115 (2015) 161802]





- Search for hidden sector boson in $B^0 \to K^{*0}\chi$ with $\chi \to \mu^+\mu^-$
- Scan $m(\mu^+\mu^-)$ distribution for an excess of χ signal candidates
- Search for prompt and displaced $(\tau(\mu^+\mu^-) > 3\sigma_{\tau(\mu^+\mu^-)})$ χ vertices
- Narrow resonances (ω, ϕ, J/ψ, $\psi(2S)$, $\psi(3770)$) are vetoed
- Normalisation to $B^0 \to K^{*0}\mu^+\mu^-$ in $1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$
- No excess → Upper limits on $\mathcal{B}(B^0 \to K^{*0}\chi(\to \mu^+\mu^-))$ set at 95% CL

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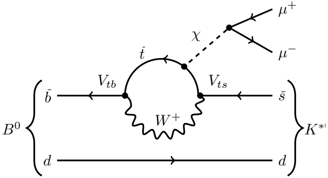

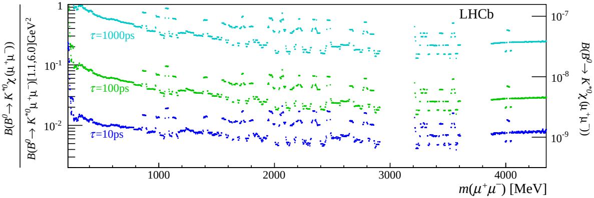

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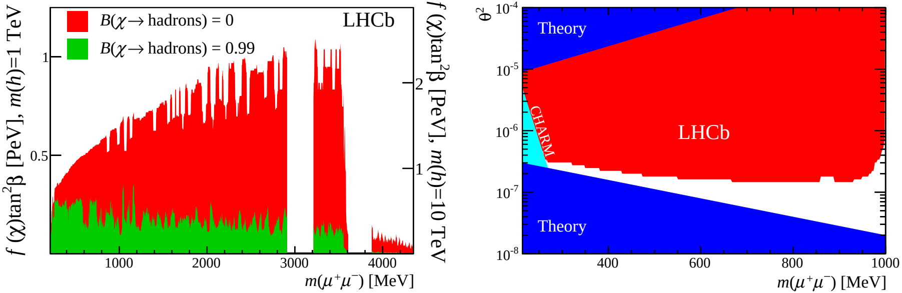
Exclusion limits for specific models

[PRL 115 (2015) 161802]



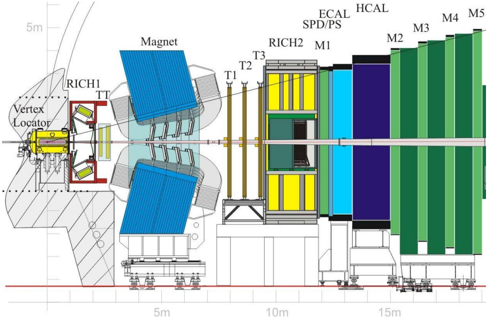
Resulting 95% CL exclusion limits for specific models

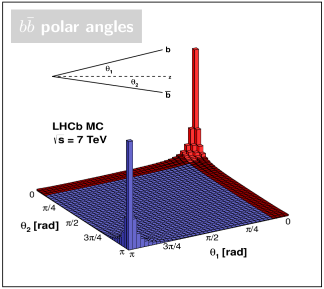
- Axion model [M. Freytsis *et al.*, PRD 81 (2010) 034001]
  Exclusion regions for large $\tan\beta$, large $m(h)$
- Inflaton model [F. Bezrukov *et al.*, PLB 736 (2014) 494]
  Constraints on mixing angle θ between Higgs and inflaton fields

Conclusions

- Rare decays are an excellent laboratory to search for BSM effects
- LHCb an ideal environment to study these decays
- Most measurements in good agreement with SM predictions, setting strong constraints on NP
- However, several interesting tensions in rare $b \to s\ell\ell$ decays: P_5' in $B^0 \to K^{*0}\mu^+\mu^-$, $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$
- Consistent NP explanations exist
- But unexpectedly large hadronic effects can not yet be excluded
- Looking forward to the additional data from Run 2
- $5\text{-}6\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$ expected

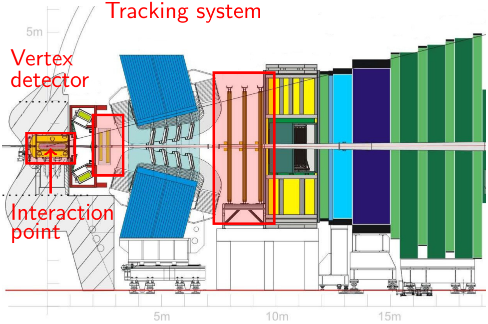
The LHC as heavy flavour factory

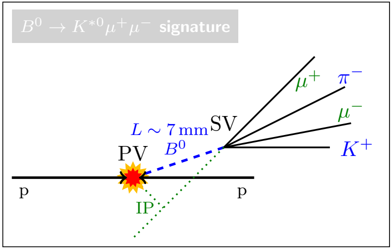




- $b\bar{b}$ produced correlated predominantly in forward (backward) direction $\rightarrow$ single arm forward spectrometer ($2 < \eta < 5$)
- Large $b\bar{b}$ production cross section $\sigma_{b\bar{b}} = (75.3 \pm 14.1)\,\mu\text{b}$ [Phys.Lett. B694 (2010)] in acceptance
- $\sim 1 \times 10^{11}$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

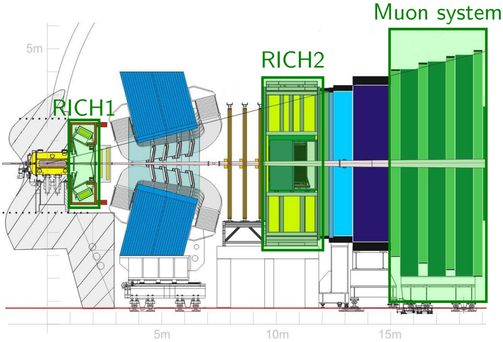
The LHCb detector: Tracking

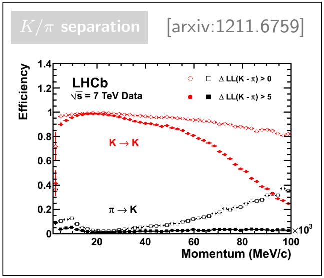




- Excellent Impact Parameter (IP) resolution ($20\,\mu\mathrm{m}$)
  $\rightarrow$ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim 40\,\mathrm{fs}$
  $\rightarrow$ Good separation of primary and secondary vertices
- Excellent momentum ($\delta p/p \sim 0.4 - 0.6\%$)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

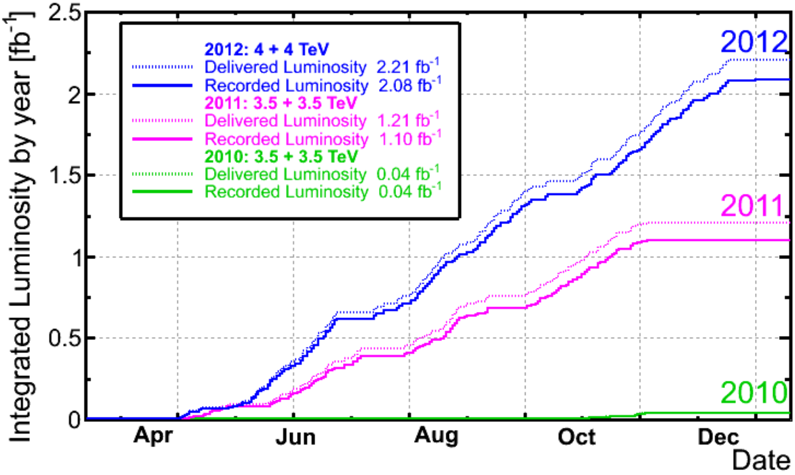
The LHCb detector: Particle identification and Trigger



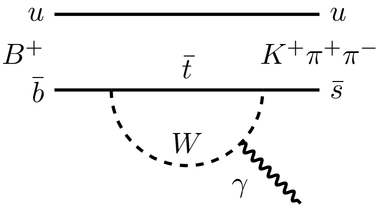


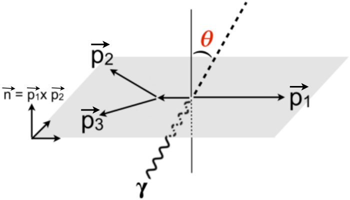
- Excellent Muon identification $\epsilon_{\mu\to\mu} \sim 97\%$ $\epsilon_{\pi\to\mu} \sim$ 1-3%
- Good $K\pi$ separation via RICH detectors $\epsilon_{K\to K} \sim 95\%$ $\epsilon_{\pi\to K} \sim 5\%$
  $\to$ Reject peaking backgrounds
- High trigger efficiencies, low momentum thresholds
  Muons: $p_{\mathrm{T}} > 1.76\,\mathrm{GeV}$ 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



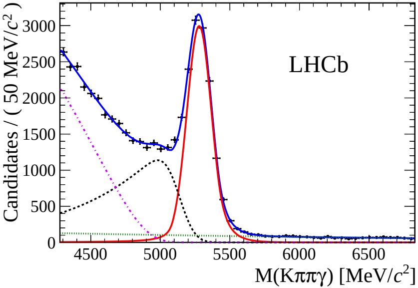
Photon polarisation λ_γ with $B^+ \to K^+\pi^-\pi^-\gamma$





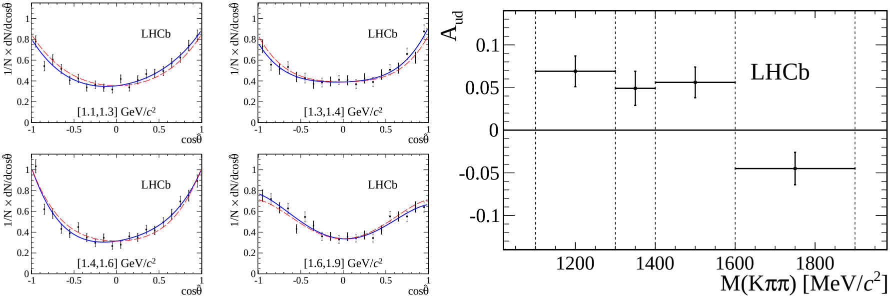
- In SM, photons from $b \to s\gamma$ decays left-handed ($C_7'/C_7 \sim m_s/m_b$)
- Can probe λ_γ with $B^+ \to K^+\pi^+\pi^-\gamma$ decays [PRD 66 (2002) 054008]
- Up-down asymmetry $\mathcal{A}_{\rm ud} = \frac{\int_0^{+1} {\rm d}\cos\theta \frac{{\rm d}\Gamma}{{\rm d}\cos\theta} - \int_{-1}^{0} {\rm d}\cos\theta \frac{{\rm d}\Gamma}{{\rm d}\cos\theta}}{\int_{-1}^{+1} {\rm d}\cos\theta \frac{{\rm d}\Gamma}{{\rm d}\cos\theta}} \propto \lambda_\gamma$

Composition of $K^+\pi^+\pi^-$ final state



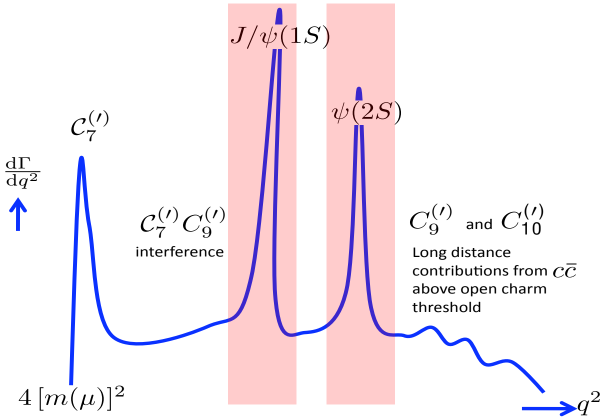
- Signal yield $N_{K\pi\pi\gamma} = 13\,876 \pm 153$
- Final state consists of several resonances: $K_1(1270)^+, K_1(1400)^+, \ldots$
- Different res. hard to separate, perform analysis in four $m_{K\pi\pi}$ bins

First observation of γ polarisation



- Perform angular fit of $\cos\theta$ distribution to determine $\mathcal{A}_{\text{ud}}$
- Combination results in first obs. of non-zero photon polarisation at $5.2\,\sigma$ [PRL 112, 161801 (2014)]
- To determine precise value for λ_γ, resonance structure of final state needs to be resolved

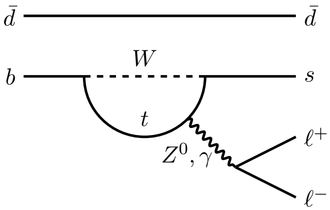
$b \to s\ell\ell$ differential branching fraction



- $B^+ \to K^+\mu^+\mu^-$ decay does not exhibit photon pole ($B^+ \to K^+\gamma$)
- Regions where J/ψ and $\psi(2S)$ dominate are vetoed

typically $8 < q^2 < 11\,\mathrm{GeV}^2/c^4$ and $12.5 < q^2 < 15\,\mathrm{GeV}^2/c^4$

Complication in theory: QCD effects



- Hadronic meson in initial and final state
  → Predictions require non-perturbative calculation of form factors
- Predictions of $\mathcal{B}$ and angular obs. affected by form factor uncertainty
- Ideally measure clean observables where form factors (largely) cancel
  - $A_{CP} = \frac{\Gamma(B^-\to K^-\mu^+\mu^-)-\Gamma(B^+\to K^+\mu^+\mu^-)}{\Gamma(B^-\to K^-\mu^+\mu^-)+\Gamma(B^+\to K^+\mu^+\mu^-)}$
  - $A_I = \frac{\Gamma(B^0\to K^0\mu^+\mu^-)-\Gamma(B^+\to K^+\mu^+\mu^-)}{\Gamma(B^0\to K^0\mu^+\mu^-)+\Gamma(B^+\to K^+\mu^+\mu^-)}$
  - Lepton universality, $R_K = \frac{B^+\to K^+\mu^+\mu^-}{B^+\to K^+e^+e^-}$
  - Ratios of angular obs., $P_i^{(\prime)}$ basis
- Recent improvements from lattice (high q^2) and LCSR (low q^2) [arXiv:1503.05534] [arXiv:1310.3722] [arXiv:1501.00367]

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

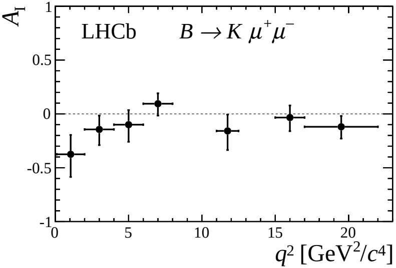
- Full $3\,\mathrm{fb}^{-1}$ allows first simultaneous determination of all eight CP-averaged observables in a single fit
- Allows to quote correlation matrix to include in global fit
- Perform maximum likelihood fit to the decay angles and $m_{K\pi\mu\mu}$ in q^2 bins, simultaneously fitting $m_{K\pi}$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

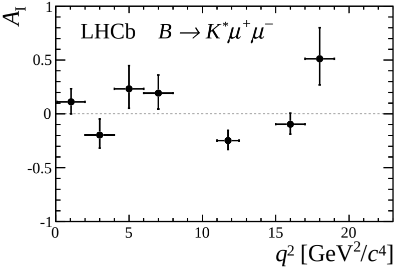
$$\log\mathcal{L} = \sum_i \log\Big[\epsilon(\vec{\Omega}, q^2) f_{\rm sig}\mathcal{P}_{\rm sig}(\vec{\Omega})\mathcal{P}_{\rm sig}(m_{K\pi\mu\mu}) + (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(\vec{\Omega})\mathcal{P}_{\rm bkg}(m_{K\pi\mu\mu})\Big] + \sum_i \log\Big[f_{\rm sig}\mathcal{P}_{\rm sig}(m_{K\pi})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

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

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

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



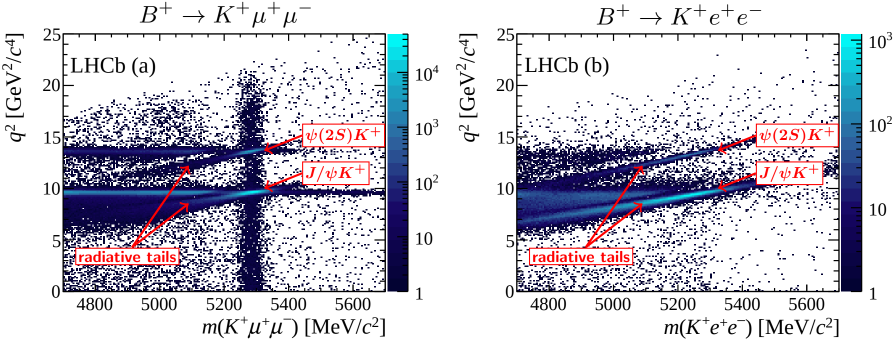


[JHEP 06 (2014) 133]

- 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)

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, not affected by $c\bar{c}$ loops



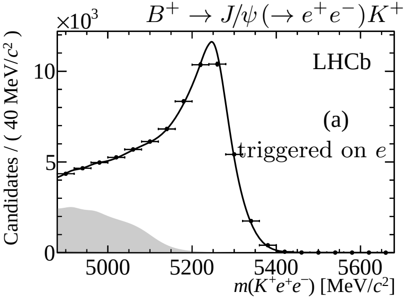
[PRL 113, 151601 (2014)]

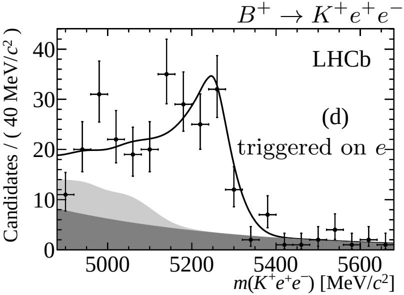
- Experimental challenges for $B^+ \to K^+e^+e^-$ mode
  1. Trigger 2. Bremsstrahlung
- Use double ratio to cancel systematic uncertainties

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

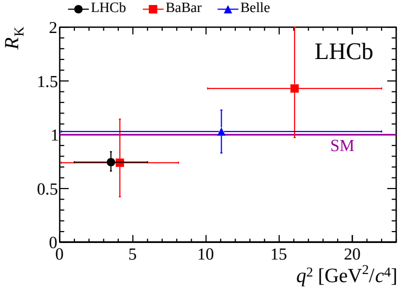
- Use $B^+ \to J/\psi K^+$ as cross-check

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





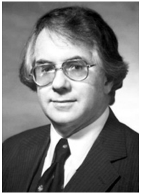
[arxiv:1406.6482]



- 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
- $\mathcal{B}_{q^2\in[1,6]\,\mathrm{GeV}^2}(B^+ \to K^+e^+e^-) = (1.56^{+0.19+0.06}_{-0.15-0.04}) \times 10^{-7}$

Tests of lepton universality and lepton flavour violation

- Due to the cleanness of the SM prediction, R_K received a lot of attention [Glashow et al.] [Hiller et al.] [Crivellin et al.]
- Including R_K in global fits gives consistent results, increasing the tension with the SM hypothesis
- Naturally motivates the ongoing measurements of $R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$ and $R_\phi = \frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \phi e^+e^-)}$
- Also motivates searches for lepton flavour violation:



S. Glashow: "Lepton non-universality generally implies lepton flavour violation"

[PRL 114, 091801 (2015)]

- $\mathcal{B}(B \to K^{(*)}\mu^\pm e^\mp)$ and $\mathcal{B}(B \to K^{(*)}\mu^\pm \tau^\mp)$ could be $\mathcal{O}(10^{-6})$ and $\mathcal{O}(10^{-8})$, respectively

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

$B^0 \to K^{*0}\mu^+\mu^-$ 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
   - $B_s^0 \to \phi\mu^+\mu^-$, $\Lambda_b^0 \to pK\mu^+\mu^-$, $B^0 \to K^+\pi^-_{\mathrm{rndm.}}\mu^+\mu^-$ $\lesssim 0.01 - 0.02$
3. PDF modeling
   - Signal mass model
   - Angular background model
   - $m_{K\pi}$ S-wave description (LASS/Isobar)
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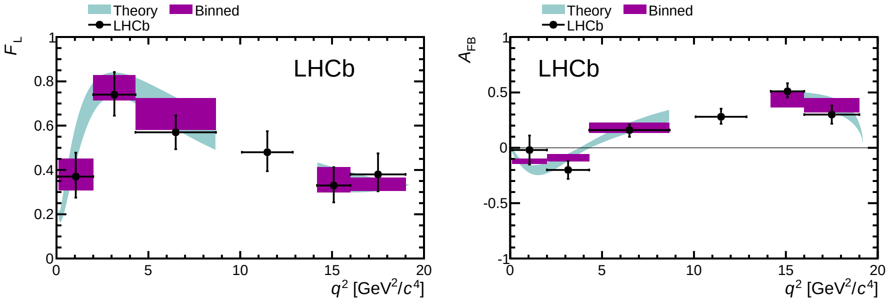
- Measurement is statistically dominated

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

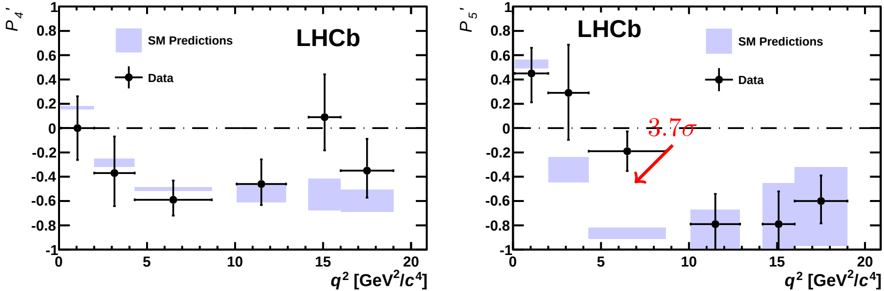


[JHEP 08 (2013) 131]

- 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]

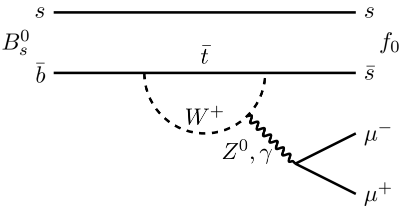
Less form factor dependent observables P_i' ($1\,\mathrm{fb}^{-1}$)

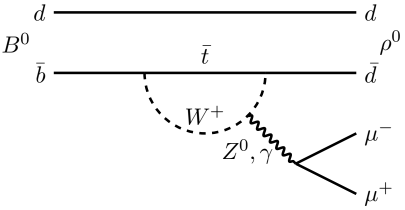
- Less FF dependent observables P_i' introduced in [JHEP 05 (2013) 137]
- For $P_{4,5}' = S_{4,5}/\sqrt{F_L(1-F_L)}$ leading FF uncertainties cancel for all q^2
- 3.7σ local deviation from SM prediction [JHEP 05 (2013) 137] in P_5'



[PRL 111, 191801 (2013)]

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

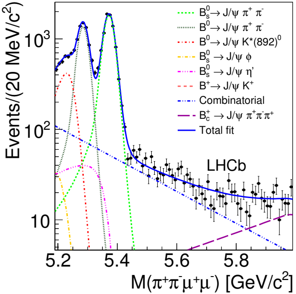




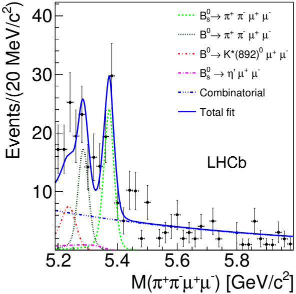
- Contributions from
  - $B^0_s \to f_0\mu^+\mu^-$: $b \to s$ transition similar to $B^0 \to K^{*0}\mu^+\mu^-$
  - $B^0 \to \rho^0\mu^+\mu^-$: $b \to d$ transition, $|V_{td}/V_{ts}|^2$ suppressed in SM
- SM predictions show large variation
  - $\mathcal{B}_{\rm SM}(B^0_s \to f_0\mu^+\mu^-) = 0.6 \times 10^{-9} - 5.2 \times 10^{-7}$
    [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



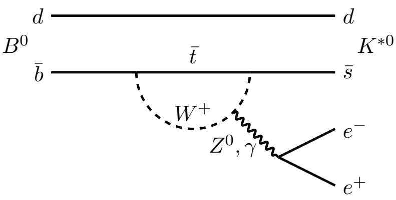
[PLB 743 (2015) 46]

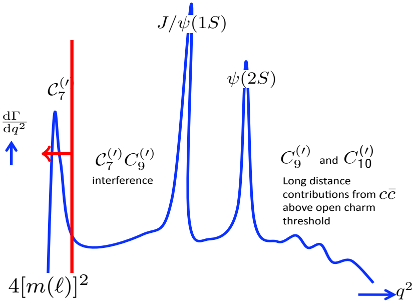
- Observation of $B^0_s \to \pi^+\pi^-\mu^+\mu^-$ with 7.6σ
- Evidence for $B^0 \to \pi^+\pi^-\mu^+\mu^-$ with 4.8σ
- Branching fractions compatible with SM predictions

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

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

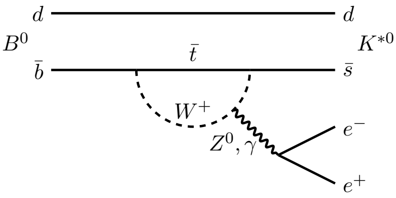
The rare decay $B^0 \to K^{*0} e^+ e^-$



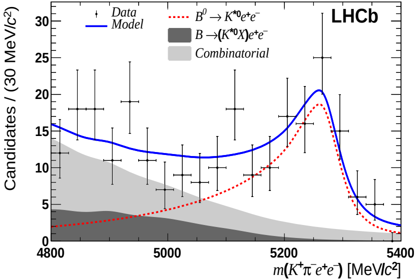


- Analyse $B^0 \to K^{*0} e^+ e^-$ at very low q^2: $[0.0004, 1.0]\,\mathrm{GeV}^2/c^4$, accessible due to tiny e mass
- Determine angular observables F_L, $A_\mathrm{T}^{(2)}$, $A_\mathrm{T}^{\mathrm{Re}}$, $A_\mathrm{T}^{\mathrm{Im}}$ sensitive to C_7 and C_7'
- Experimental challenges: Trigger and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

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

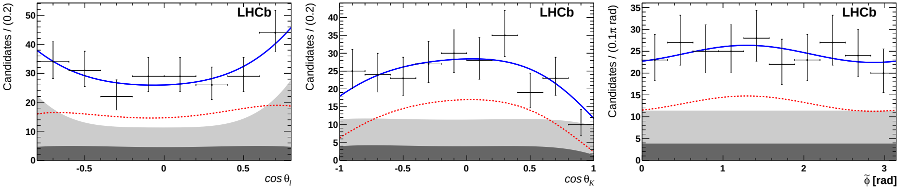


[arxiv:1501.03038]



- 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

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

$B^0 \to K^{*0}\mu^+\mu^-$ 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 $\propto \sin\phi, \cos\phi$

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

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

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

- $I_i(q^2)$ combinations of K^{*0} spin amplitudes sensitive to $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$
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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

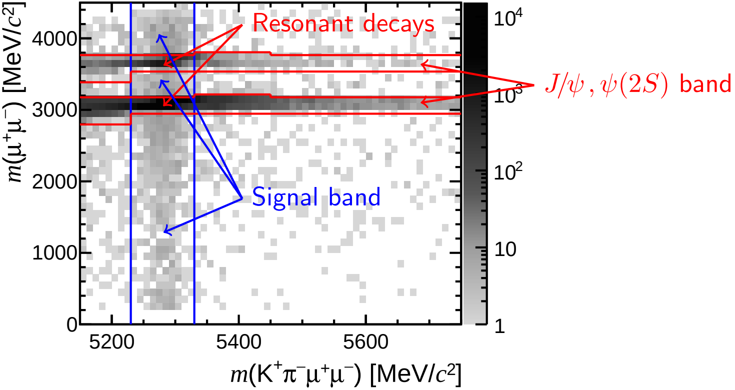
$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}'^{eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7'^{eff}})\mathbf{T_1(q^2)}\right\}$$

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

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

- Wilson coefficients $C_{7,9,10}^{(\prime)\mathrm{eff}}$
- 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")

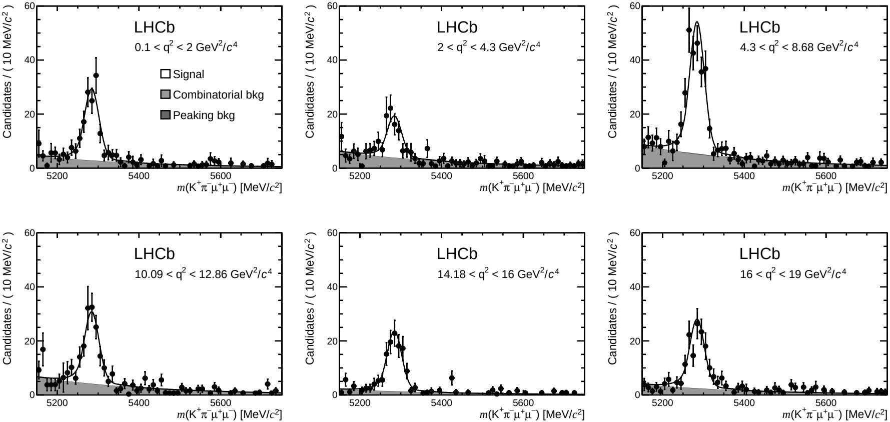
Analysis strategy



- 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

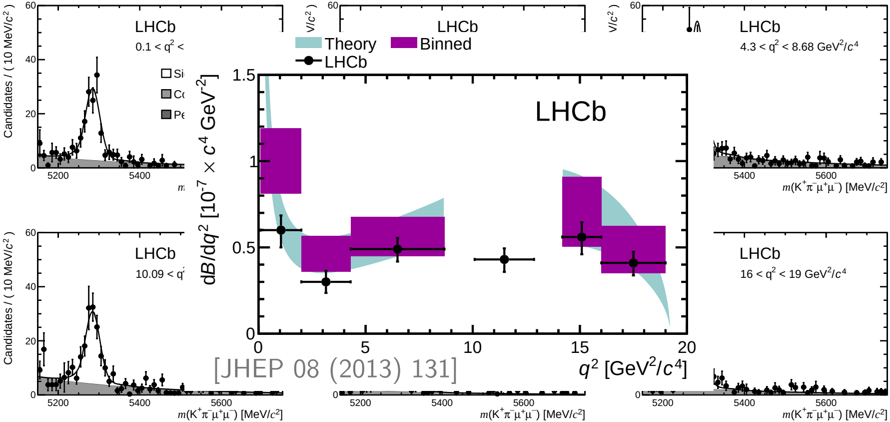
1. Determine the differential branching fraction in q^2 bins
2. Determine angular observables in multidimensional likelihood fit

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

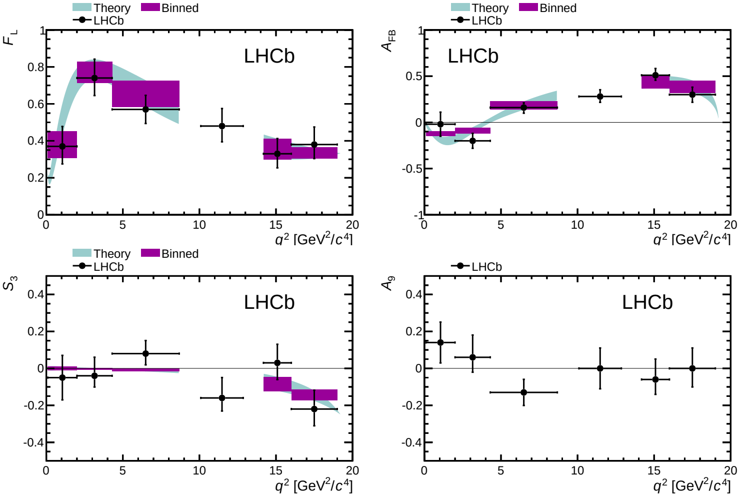
$B^0 \to K^{*0}\mu^+\mu^-$ differential decay rate



[JHEP 08 (2013) 131]

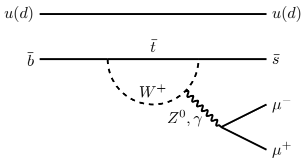
- Fit of $N_{\rm sig}$ in q^2 bins
- Use $B^0 \to J/\psi K^{*0}$ as normalisation channel
- SM prediction [C. Bobeth et al. JHEP 07 (2011) 067]
- Data somewhat low but large theory uncertainties due to FF

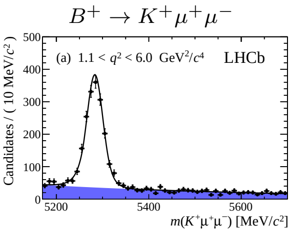
$B^0 \to K^{*0}\mu^+\mu^-$ angular observables I

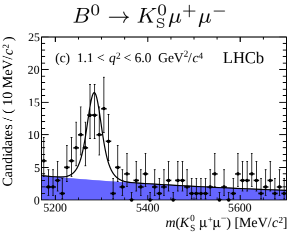


- Results [JHEP 08 (2013) 131] in good agreement with SM prediction [C. Bobeth et al. JHEP 07 (2011) 067]

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







[JHEP 05 (2014) 082]

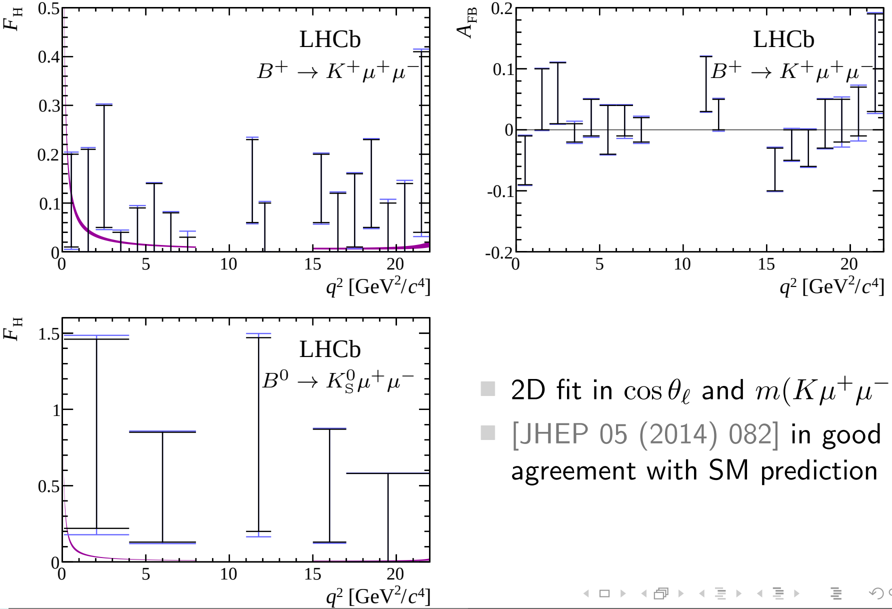
- $N_{B^+\to K^+\mu^+\mu^-} = 4746 \pm 81$ and $N_{B^0\to K^0_{\rm S}\mu^+\mu^-} = 176 \pm 17$ in $3\,\text{fb}^{-1}$
- Experimental challenge: K^0_S reconstruction
- Differential decay rate for $B^+ \to K^+\mu^+\mu^-$

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

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

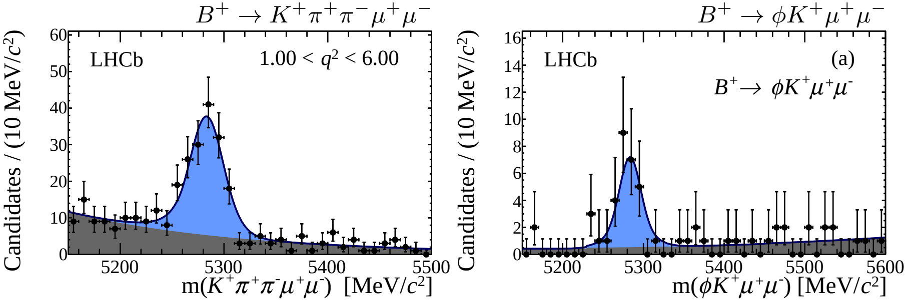
- Flat parameter $F_{\rm H}$ sensitive to (Pseudo)scalar contributions, small in SM
- Forward backward asymmetry $A_{\rm FB}$ zero in SM

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

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



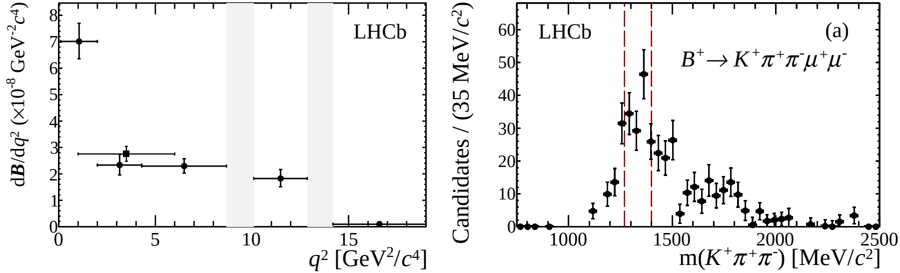
[JHEP 10 (2014) 064]

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

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

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

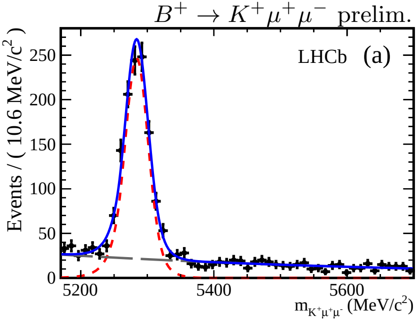
$B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ cont.

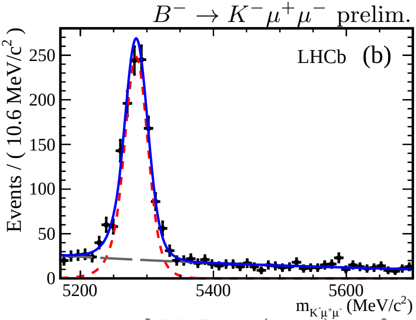


[JHEP 10 (2014) 064]

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





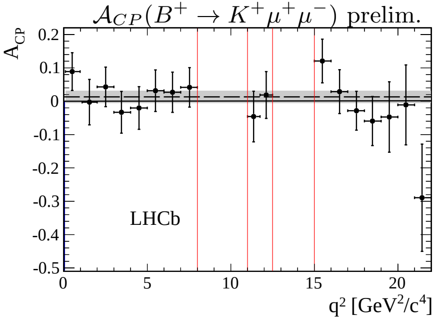
[JHEP 09 (2014) 177]

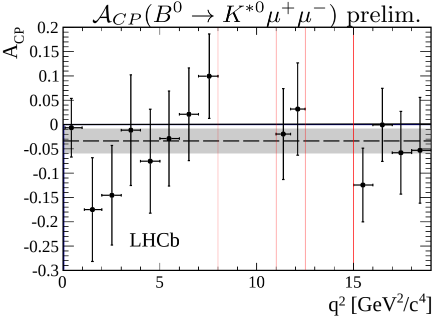
- Direct CP-Asymmetry $\mathcal{A}_{CP}$

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

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





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- 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

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**	–