

Rare b -hadron decays

Christoph Langenbruch¹

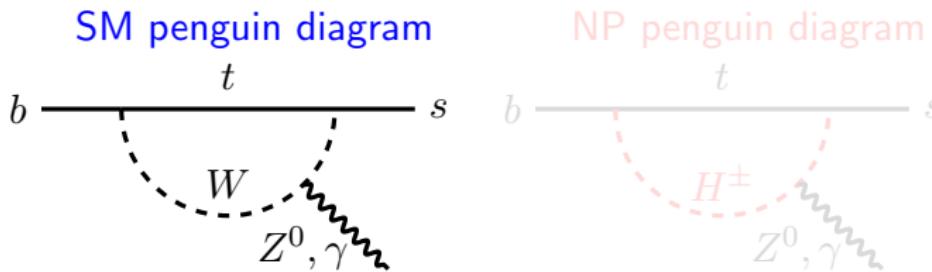
¹University of Warwick

Warwick EPP seminar

December 3rd, 2015

Rare Decays as probes for New Physics

- Rare decays: Flavour changing neutral currents (FCNCs)
 $b \rightarrow q$ decays with $q = s, d$ quark
- In the SM: FCNCs forbidden at tree-level, only W^\pm changes flavour
but: higher order *penguin* processes are possible

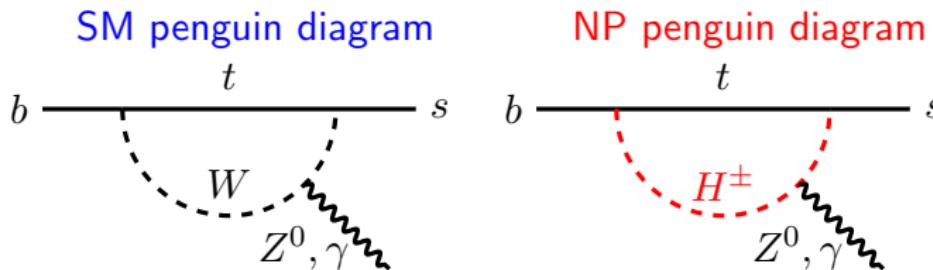


- Loop-suppression \rightarrow rare processes with \mathcal{B} typically $10^{-5} \dots 10^{-10}$
- New heavy particles beyond the SM can significantly contribute
- NP does not need to be produced on-shell
 \rightarrow masses up to $\mathcal{O}(100 \text{ TeV})$ accessible

[A. Buras,
arXiv:1505.00618]

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Effective field theory

- FCNCs a multi-scale problem:

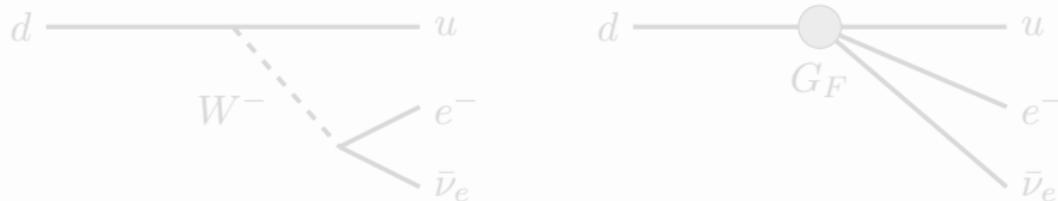
$$\begin{array}{cccccc} \Lambda_{\text{NP}} & \gg & m_W & \gg & m_b & \gg & \Lambda_{\text{QCD}} \\ ? \gtrsim 1 \text{ TeV} & & 80 \text{ GeV} & & 5 \text{ GeV} & & 0.2 \text{ GeV} \end{array}$$

- In effective field theory: Operator product expansion [A. Buras, hep-ph/9806471]

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

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

Well known analogon: β decay



$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \cos \theta_C [\bar{u} \gamma_\mu (1 - \gamma_5) d \times \bar{e} \gamma^\mu (1 - \gamma_5) \nu_e]$$

- Integrate out heavy DoF \rightarrow Contact interaction with effective coupling G_F

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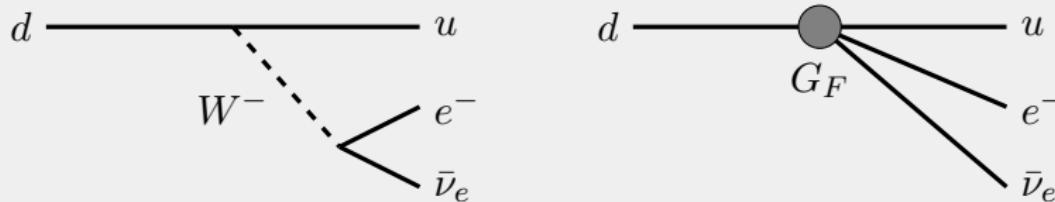
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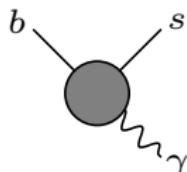


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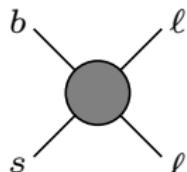
Operators

$$b \rightarrow s\gamma \quad B \rightarrow \mu\mu \quad b \rightarrow q\ell\ell$$



photon penguin

$$\mathcal{O}_7^{(\prime)} = \frac{e}{g^2} m_b (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

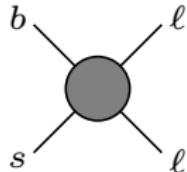


electroweak penguin

$$\mathcal{O}_9^{(\prime)} = \frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \mu)$$



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(pseudo)scalar penguin

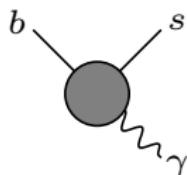
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Operators



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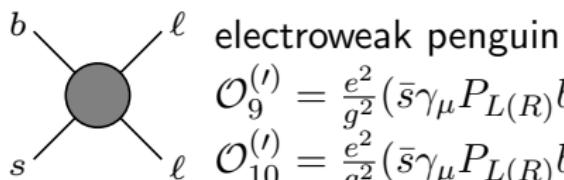
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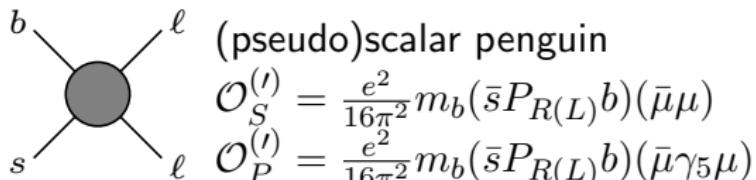
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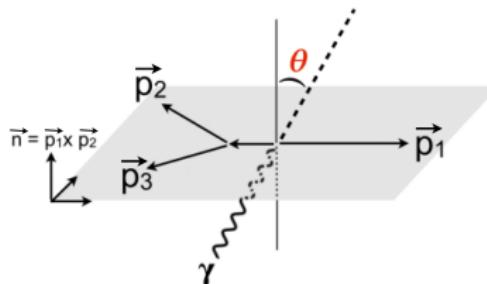
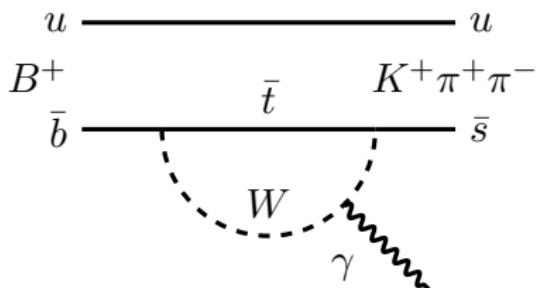


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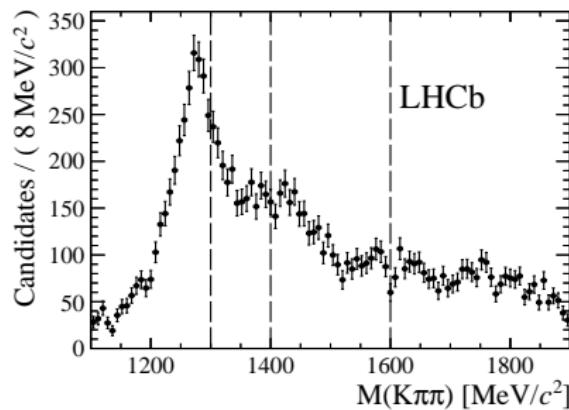
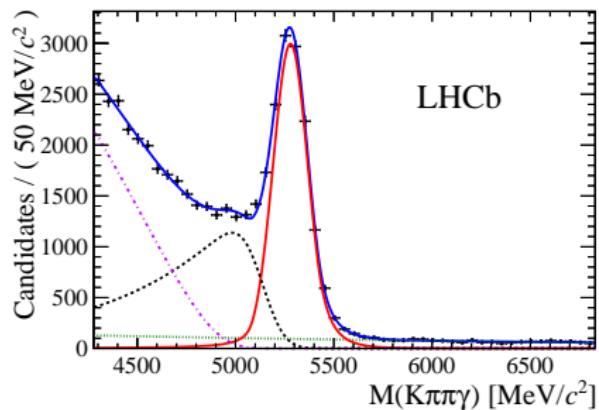
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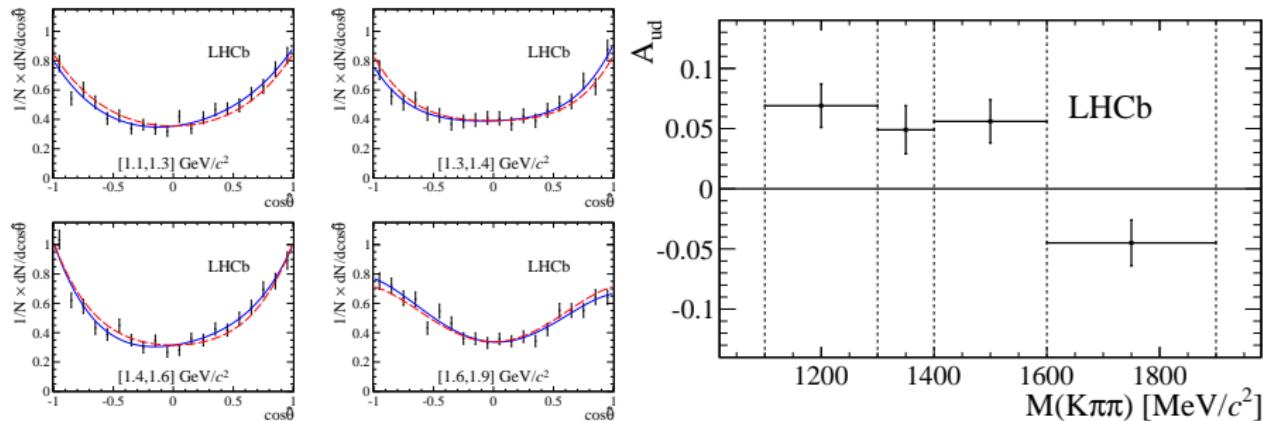


Photon polarisation λ_γ with $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ 

- In SM, photons from $b \rightarrow s\gamma$ decays left-handed ($C'_7/C_7 \sim m_s/m_b$)
- Can probe λ_γ with $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ decays [M. Gronau et al., PRD 66 (2002) 054008]
- Up-down asymmetry $A_{ud} = \frac{\int_0^{+1} d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^{+1} d\cos\theta \frac{d\Gamma}{d\cos\theta}} \propto \lambda_\gamma$

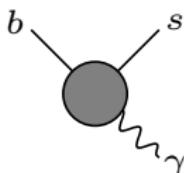
Composition of $K^+\pi^+\pi^-$ final state

- Signal yield $N_{K\pi\pi\gamma} = 13876 \pm 153$
- Final state consists of several resonances:
 $\underline{K_1(1270)^+}, K_1(1400)^+, \dots$
- 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}_{ud}
- Combination results in first obs. of non-zero photon polarisation at 5.2σ [PRL 112, 161801 (2014)]
- To determine precise value for λ_γ , resonance structure of final state needs to be resolved

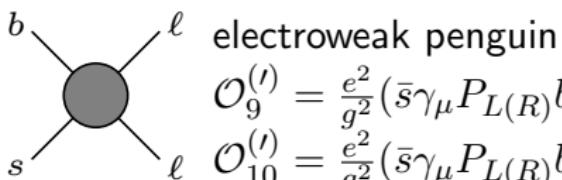
Operators



photon penguin

$$\mathcal{O}_7^{(\prime)} = \frac{e}{g^2} m_b (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

$$b \rightarrow s\gamma$$



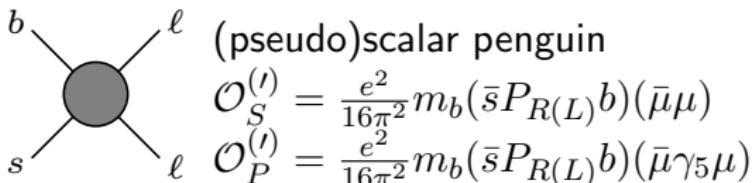
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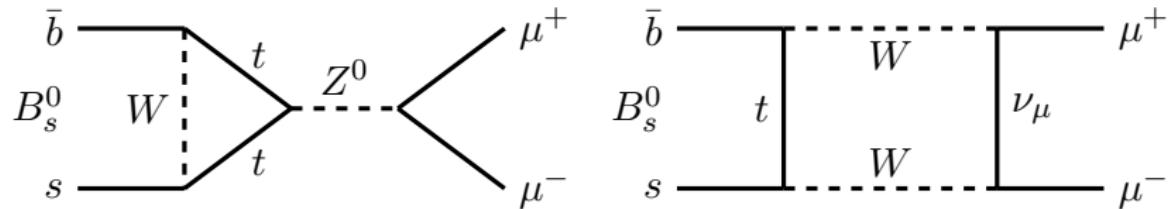


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The very rare decay $B_{(s)}^0 \rightarrow \mu\mu$ 

■ Loop and additionally helicity suppressed

■ Purely leptonic final state: Theoretically and experimentally very clean

■ Very sensitive to NP:

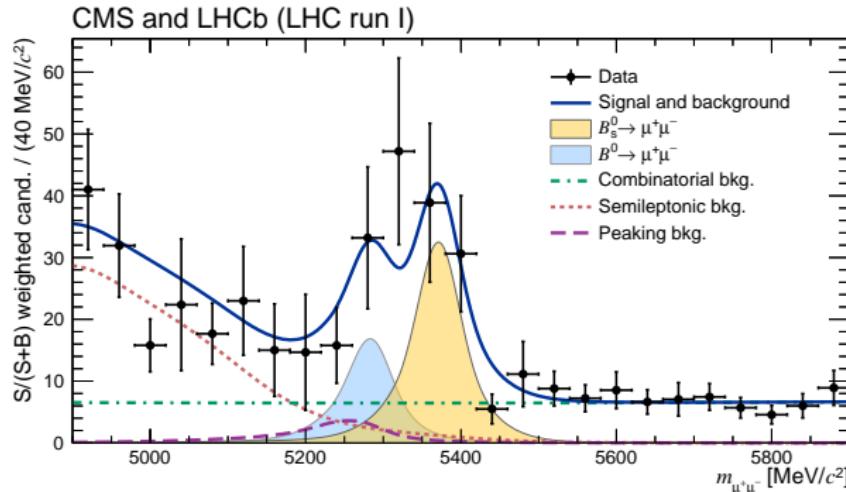
Possible **scalar** and **pseudoscalar** enhanced wrt. SM **axialvector**

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

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

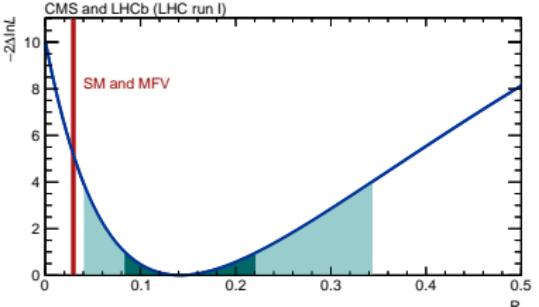
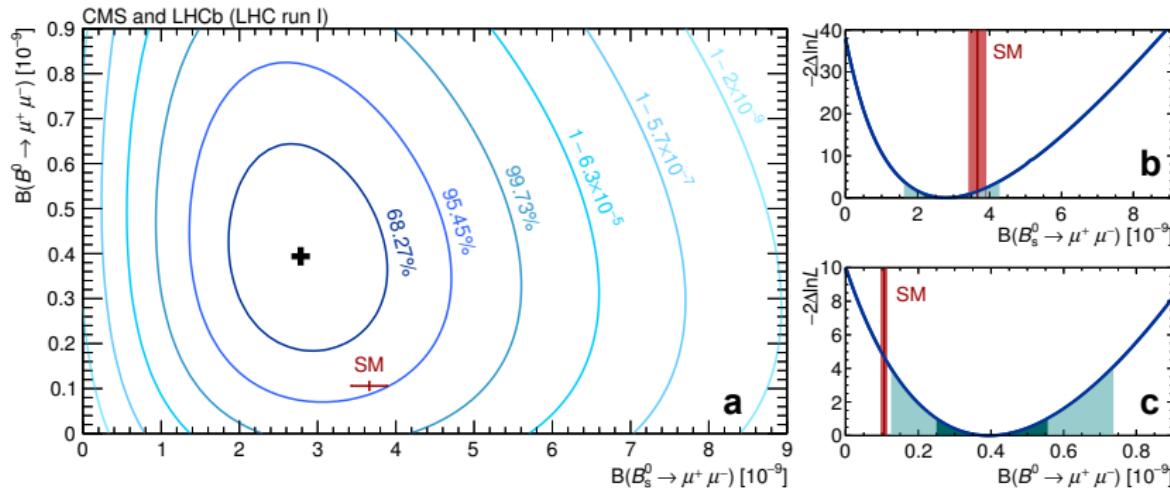
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

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

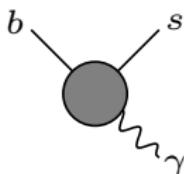
- Combined analysis of LHCb and CMS Run 1 data, sharing signal and nuisance parameters [Nature 522 (2015) pp. 68-72]
- First obs. of $B_s^0 \rightarrow \mu^+\mu^-$ with 6.2σ significance (expected 7.2σ)
 $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ compatible with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

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



- $\mathcal{R} = \frac{\mathcal{B}(B^0 \rightarrow \mu\mu)}{\mathcal{B}(B_s^0 \rightarrow \mu\mu)}$ tests MFV hypothesis
- $\mathcal{R}_{\text{SM}} = 0.0295^{+0.0028}_{-0.0025}$
- $\mathcal{R} = 0.14^{+0.08}_{-0.06}$ compatible at 2.3σ

Operators



photon penguin

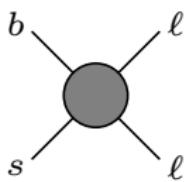
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✓



electroweak penguin

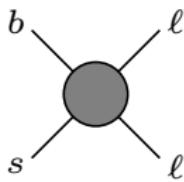
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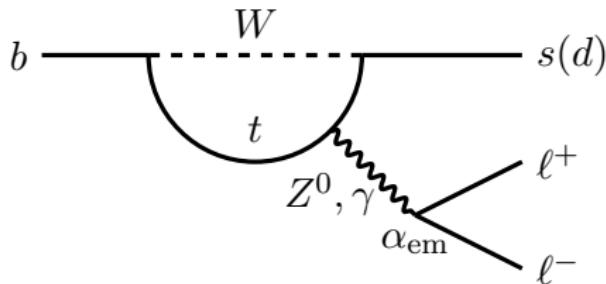
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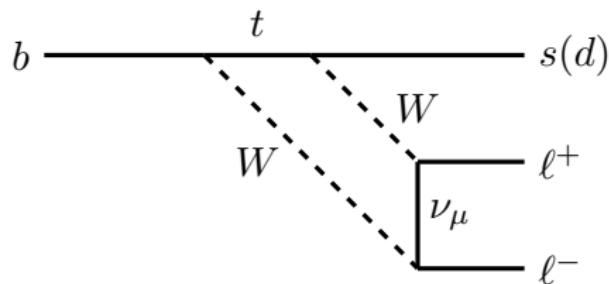
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b → s(d)ℓℓ decays

SM penguin diagram



SM box diagram



- $b \rightarrow s(d)\ell\ell$ decays proceed via penguin and box diagrams
- $\mathcal{B}(B_s^0 \rightarrow \mu\mu) \stackrel{\text{hel. supp.}}{<} \mathcal{B}(b \rightarrow s\ell\ell) \sim 10^{-6} \stackrel{\alpha_{\text{em.}}}{<} \mathcal{B}(b \rightarrow s\gamma)$
- Plenty of decays due to choice of $q = s, d$, lepton, hadronic resonance:

$b \rightarrow s\mu\mu$

$B^+ \rightarrow K^+ \mu^+ \mu^-$ [JHEP 05 [(2014) 082] [JHEP 09 [(2014) 177] [JHEP 06 [(2014) 133]]] $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ [JHEP 06 [(2014) 133]]

$B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-$ [JHEP 10 [(2014) 064]] $B^0 \rightarrow K^0 \mu^+ \mu^-$ [JHEP 05 [(2014) 082] [JHEP 06 [(2014) 133]],

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ [LHCb-PAPER-2015-051] $B_s^0 \rightarrow \phi \mu^+ \mu^-$ [JHEP 09 [(2015) 179]] $B_s^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ [PLB 743 [(2015) 46]]

$A_b^0 \rightarrow \Lambda \mu^+ \mu^-$ [JHEP 06 [(2015) 115]]

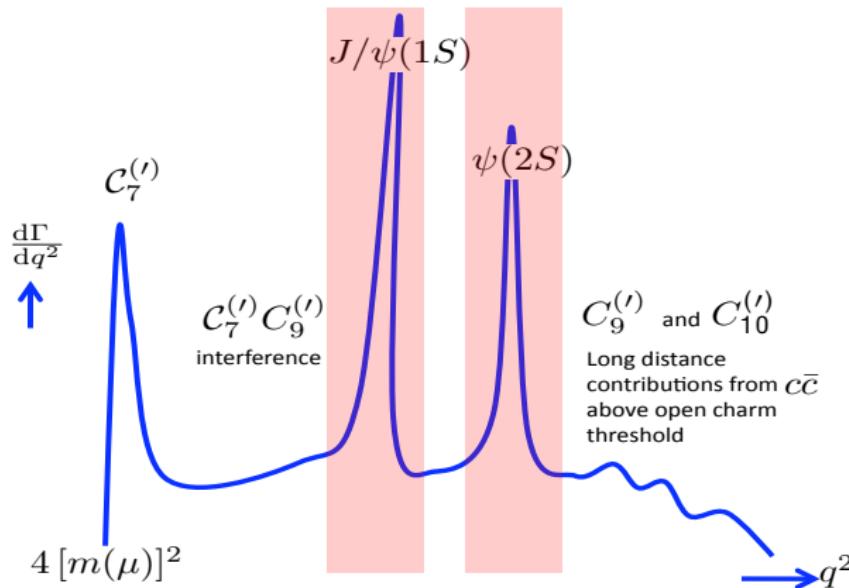
$b \rightarrow d\mu\mu$

$B^+ \rightarrow \pi^+ \mu^+ \mu^-$ [JHEP 10 [(2015) 034]] $B^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ [PLB 743 [(2015) 46]]

$b \rightarrow see$

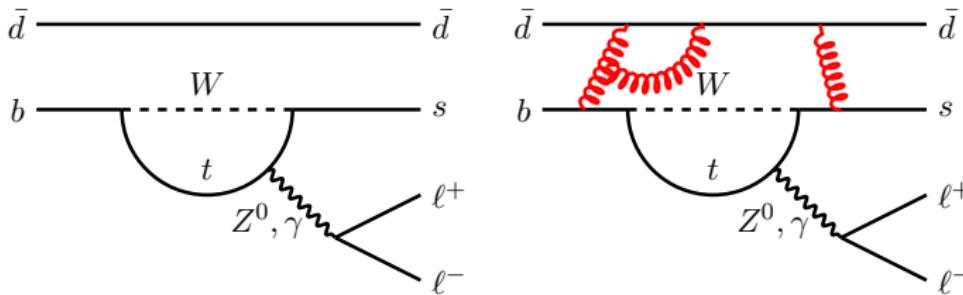
$B^+ \rightarrow K^+ e^+ e^-$ [PRL 113 [(2014) 151601]] $B^0 \rightarrow K^{*0} e^+ e^-$ [JHEP 04 [(2015) 064]]

$B \rightarrow V\ell\ell$ differential branching fraction



- $q^2 = m^2(\ell^+\ell^-)$ provides separation power between $\mathcal{C}_i \rightarrow$ bin in q^2
- Regions where J/ψ and $\psi(2S)$ dominate are vetoed \rightarrow control decays typically $8 < q^2 < 11 \text{ GeV}^2/c^4$ and $12.5 < q^2 < 15 \text{ GeV}^2/c^4$

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
 - $A_{CP} = \frac{\Gamma(B^- \rightarrow K^- \mu^+ \mu^-) - \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\Gamma(B^- \rightarrow K^- \mu^+ \mu^-) + \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}$
 - $A_I = \frac{\Gamma(B^0 \rightarrow K^0 \mu^+ \mu^-) - \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\Gamma(B^0 \rightarrow K^0 \mu^+ \mu^-) + \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}$
 - Lepton universality, $R_K = \frac{B^+ \rightarrow K^+ \mu^+ \mu^-}{B^+ \rightarrow K^+ e^+ e^-}$
 - Ratios of angular obs., $P_i^{(\prime)}$ basis
- Recent improvements from lattice (high q^2) and LCSR (low q^2)

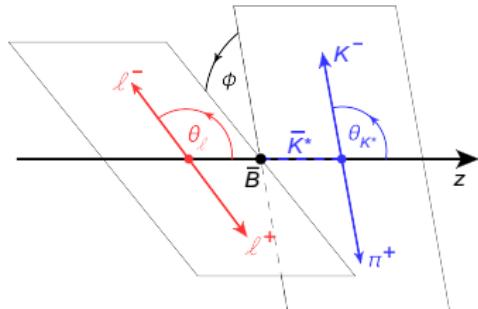
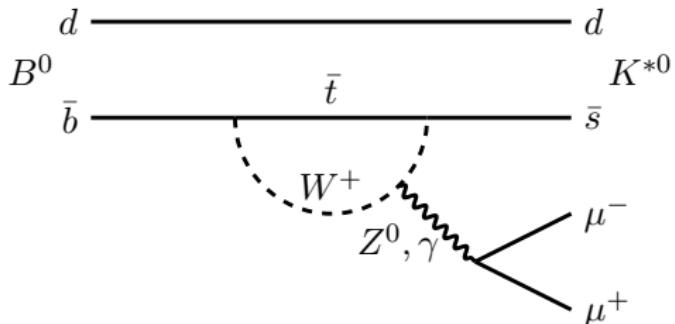
[Bharucha et al.,
arXiv:1503.05534]

[Horgan et al.,
PRD 89 (2014) 094501]

[Horgan et al.,
PoS (Lattice2014) 372]

[Du et al.,
arXiv:1510.02349]

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



- Fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m_{\mu\mu}^2$
- Differential decay rate given by

$$\frac{d^4\Gamma(\bar{B}^0 \rightarrow \bar{K}^{*0}\mu^+\mu^-)}{d\vec{\Omega} dq^2} = \frac{9}{32\pi} \sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}(B^0 \rightarrow K^{*0}\mu^+\mu^-)}{d\vec{\Omega} dq^2} = \frac{9}{32\pi} \sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

- $I_i(q^2)$ and $\bar{I}_i(q^2)$ combinations of K^{*0} spin amplitudes depending on Wilson coefficients $C_7^{(I)}, C_9^{(I)}, C_{10}^{(I)}$ and form factors

Angular observables in $B^0 \rightarrow K^{*0}\mu^+\mu^-$

- Access to CP -averages S_i and CP -asymmetries A_i [W. Altmannshofer *et al.*, JHEP 01 (2009) 019]

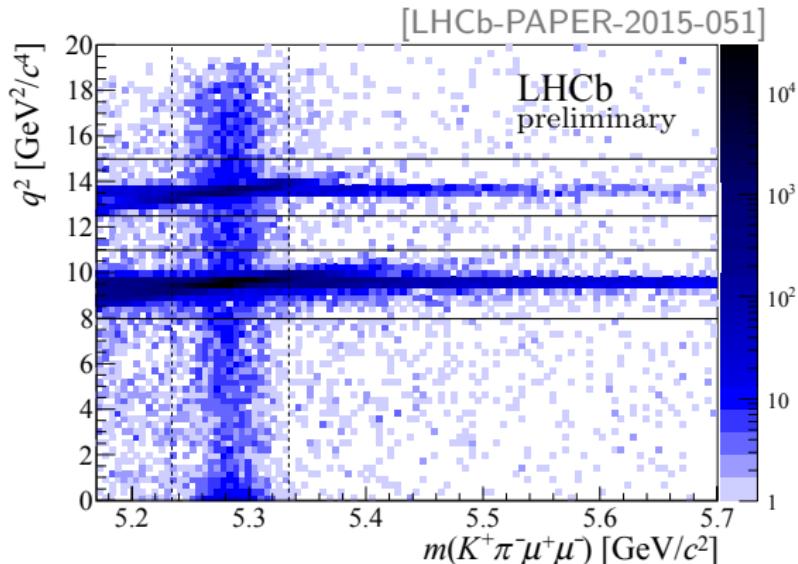
$$S_i = (I_i + \bar{I}_i) / \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2} \right)$$

$$A_i = (I_i - \bar{I}_i) / \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2} \right)$$

- CP -averaged angular distribution in bins of q^2

$$\begin{aligned} \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = & \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ & + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell \\ & + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \\ & + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + \frac{4}{3}A_{FB} \sin^2 \theta_K \cos \theta_\ell \\ & + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi \\ & \left. + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] \end{aligned}$$

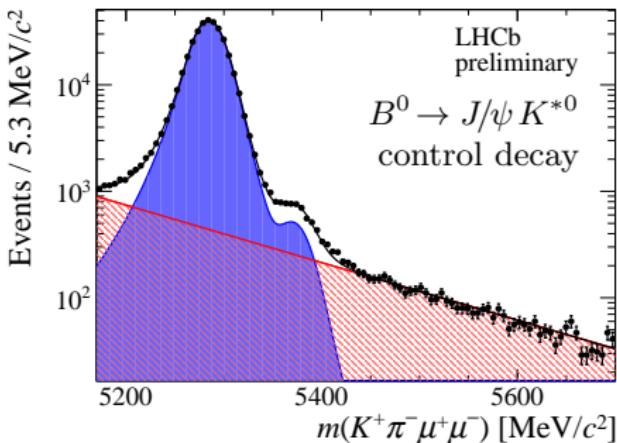
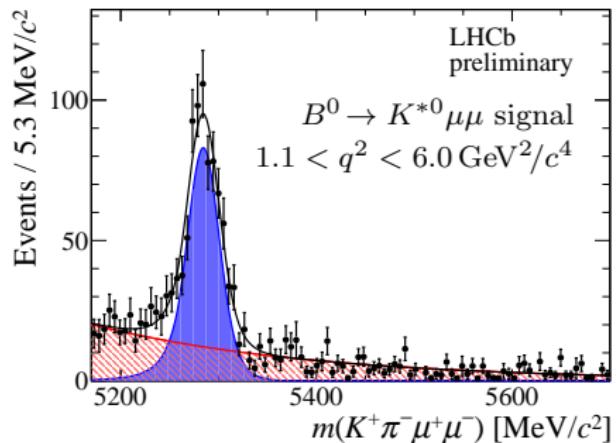
- Longitudinal polarisation fraction F_L , Forward-backward asymmetry A_{FB}
- Perform ratios of angular obs. where **form factors** cancel at leading order
Example: $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]



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

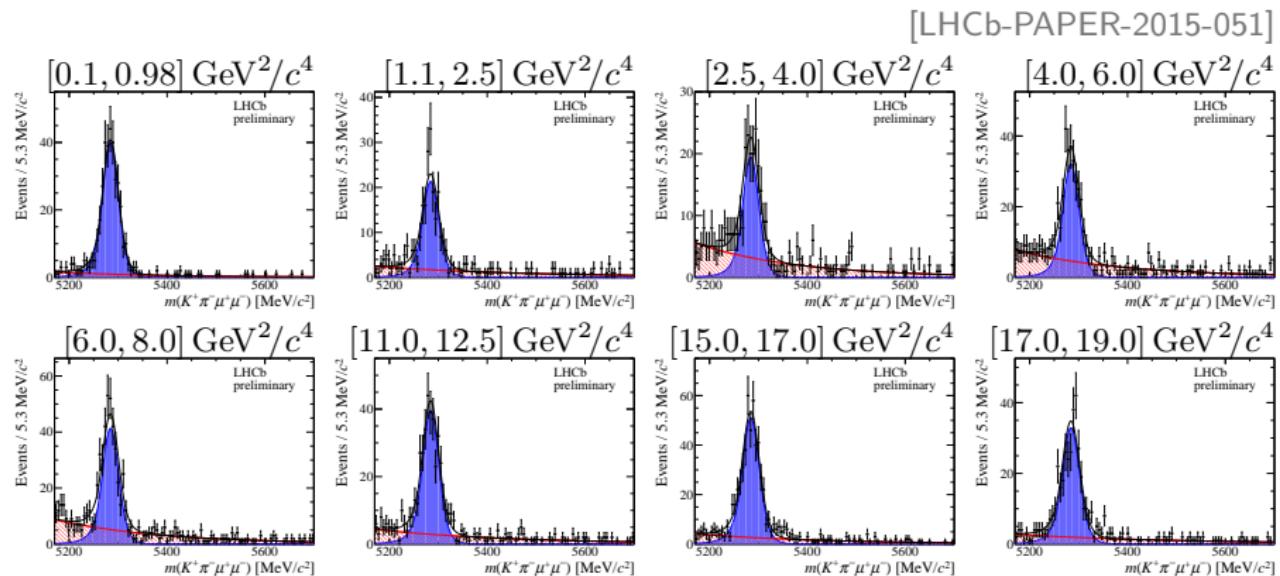
Mass model and $B^0 \rightarrow K^{*0}\mu^+\mu^-$ signal yield

[LHCb-PAPER-2015-051]

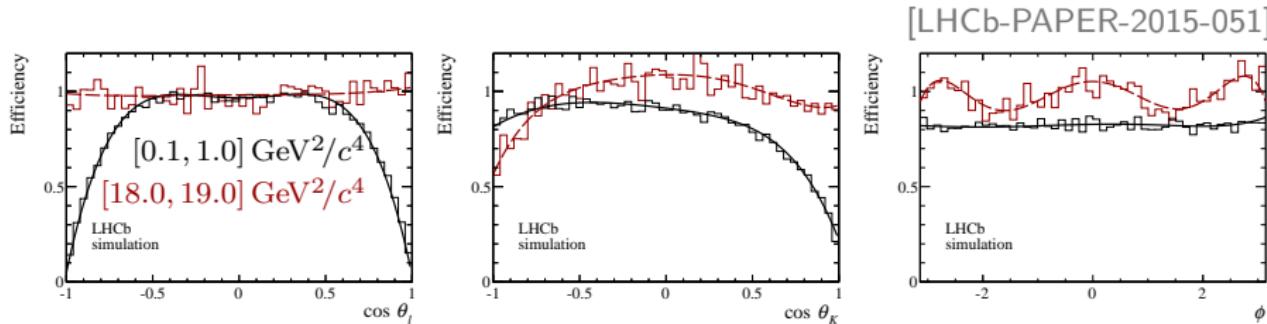


- Signal mass model from high statistics $B^0 \rightarrow J/\psi K^{*0}$
 Correction factor from simulation to account for q^2 dep. resolution
- Finer q^2 binning to allow more flexible use in theory
- Significant signal yield in all bins, q^2 integrated $N_{\text{sig}} = 2398 \pm 57$

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



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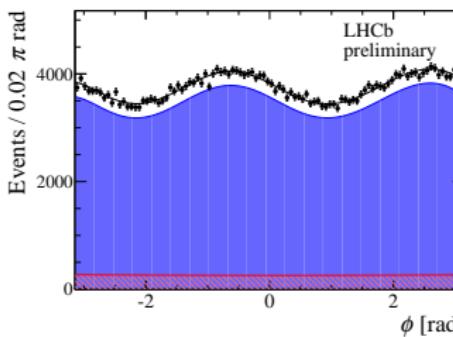
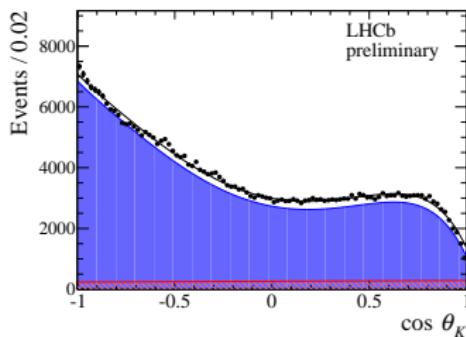
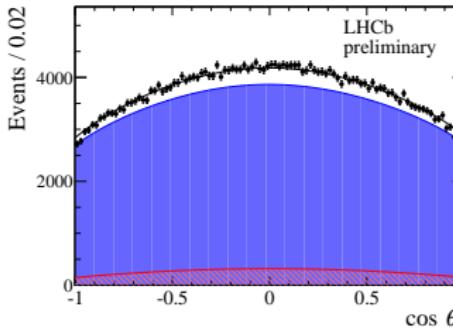
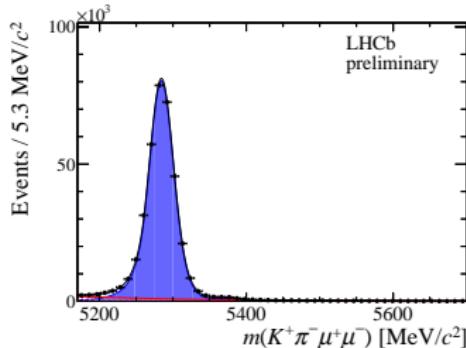


- Trigger, reconstruction and selection distorts decay angles and q^2 distribution
- Parametrize 4D efficiency using Legendre polynomials P_k

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

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

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



[LHCb-PAPER-2015-051]

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

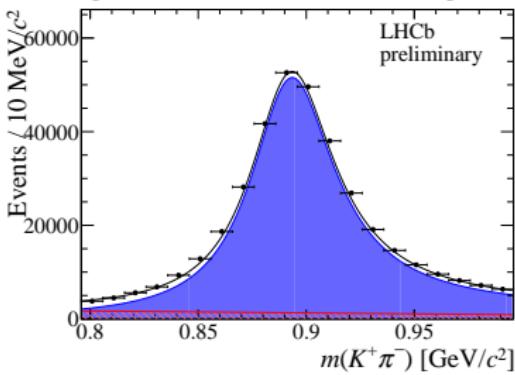
S-wave pollution

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

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

- 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]

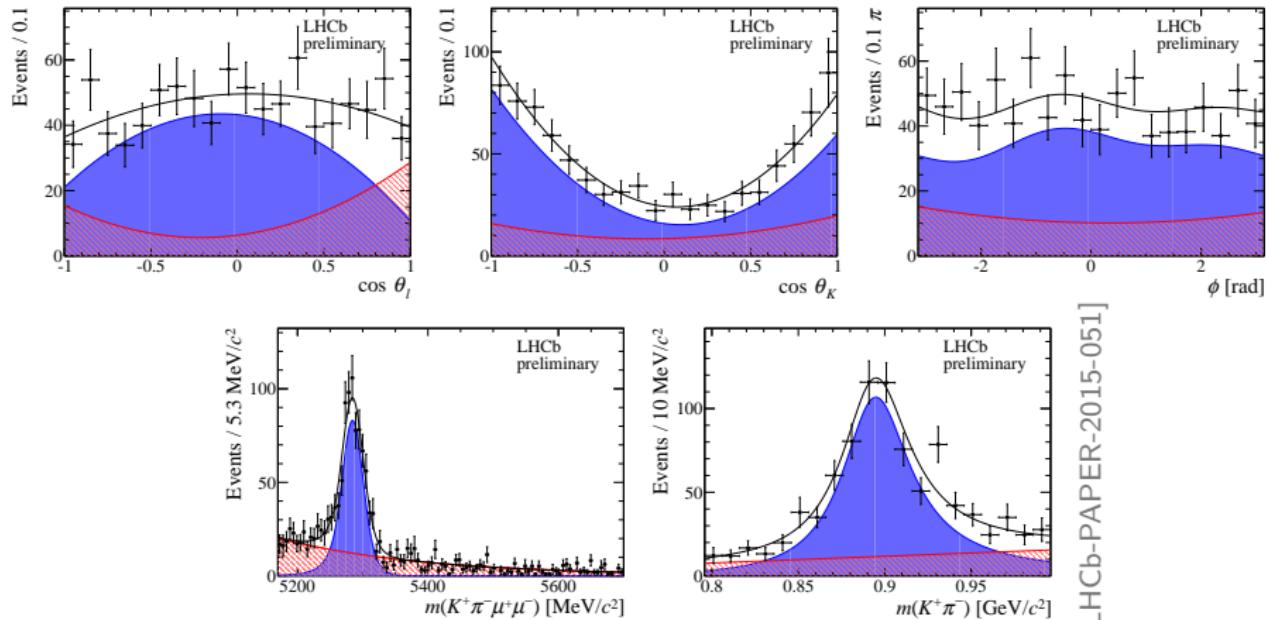


$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Likelihood fit

- Full 3 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

$$\begin{aligned}\log \mathcal{L} = & \sum_i \log \left[\epsilon(\vec{\Omega}, q^2) f_{\text{sig}} \mathcal{P}_{\text{sig}}(\vec{\Omega}) \mathcal{P}_{\text{sig}}(m_{K\pi\mu\mu}) \right. \\ & \quad \left. + (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(\vec{\Omega}) \mathcal{P}_{\text{bkg}}(m_{K\pi\mu\mu}) \right] \\ & + \sum_i \log \left[f_{\text{sig}} \mathcal{P}_{\text{sig}}(m_{K\pi}) + (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(m_{K\pi}) \right]\end{aligned}$$

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

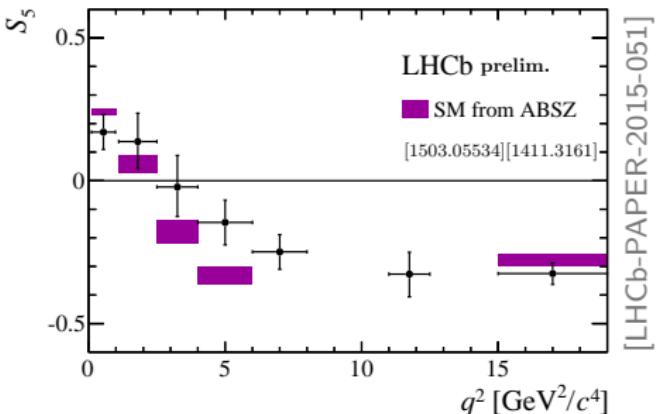
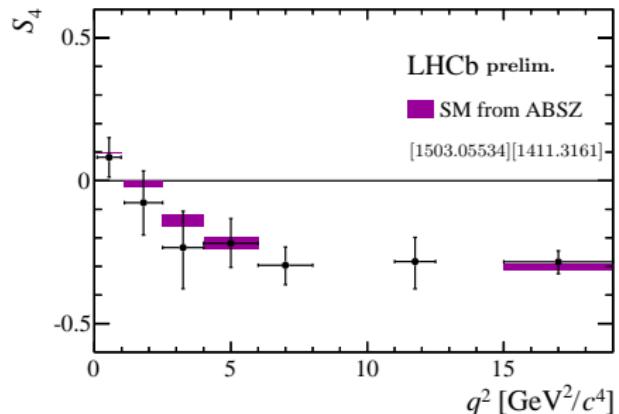
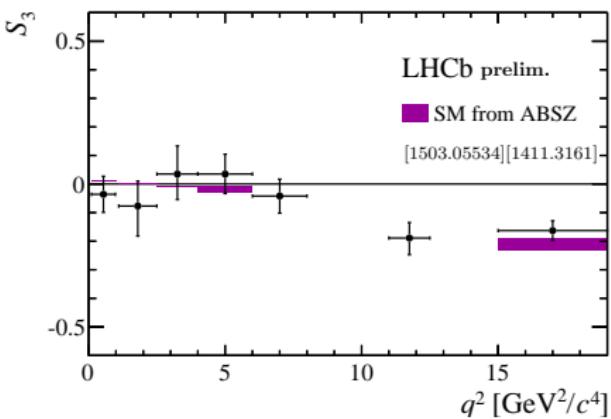
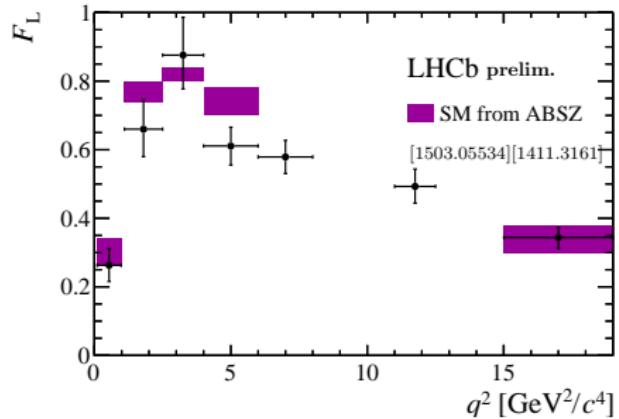
$B^0 \rightarrow K^{*0}\mu^+\mu^-$ likelihood projections [1.1, 6.0] GeV^2/c^4


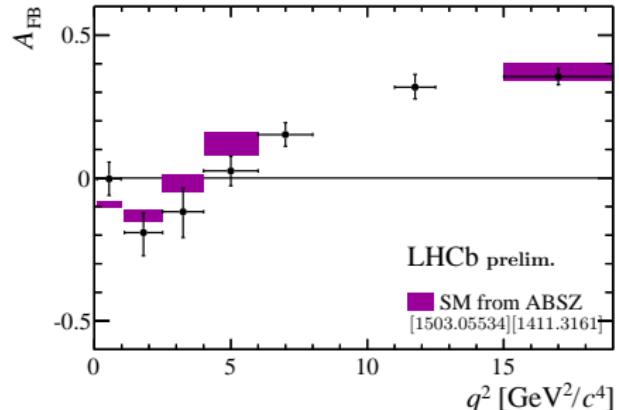
- Efficiency corrected distributions show good agreement with overlaid projections of the probability density function

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ systematic uncertainties

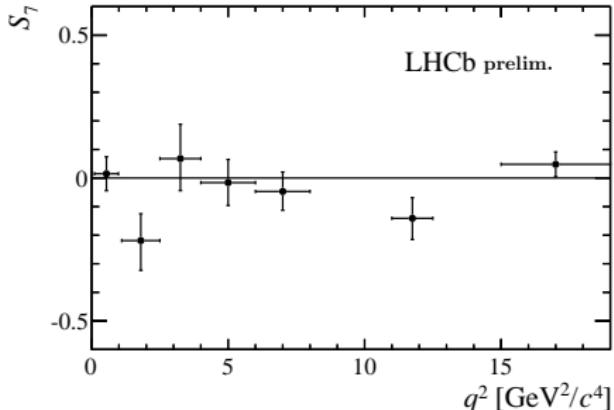
Source	F_L	$S_3 - S_9$	$A_3 - A_9$	$P_1 - P'_8$
Acceptance stat. uncertainty	< 0.01	< 0.01	< 0.01	< 0.01
Acceptance polynomial order	< 0.01	< 0.02	< 0.02	< 0.04
Data-simulation differences	0.01–0.02	< 0.01	< 0.01	< 0.01
Acceptance variation with q^2	< 0.01	< 0.01	< 0.01	< 0.01
$m(K^+\pi^-)$ model	< 0.01	< 0.01	< 0.01	< 0.03
Background model	< 0.01	< 0.01	< 0.01	< 0.02
Peaking backgrounds	< 0.01	< 0.01	< 0.01	< 0.01
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.01	< 0.01	< 0.01	< 0.02
Det. and prod. asymmetries	–	–	< 0.01	< 0.02

- Systematic uncertainties determined using high statistics toys
- Measurement is statistically dominated (and will still be in Run 2)

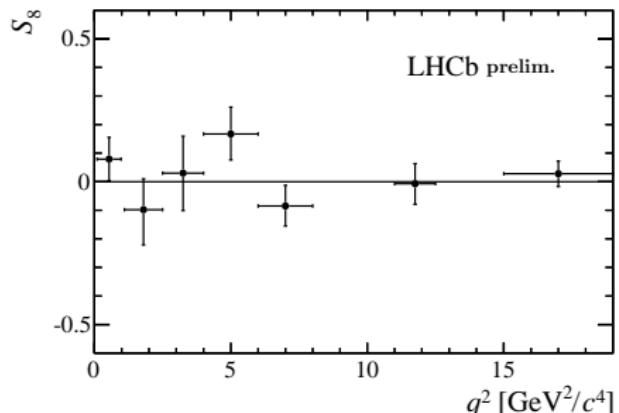
$B^0 \rightarrow K^{*0}\mu^+\mu^-$ Results: F_L , S_3 , S_4 , S_5


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


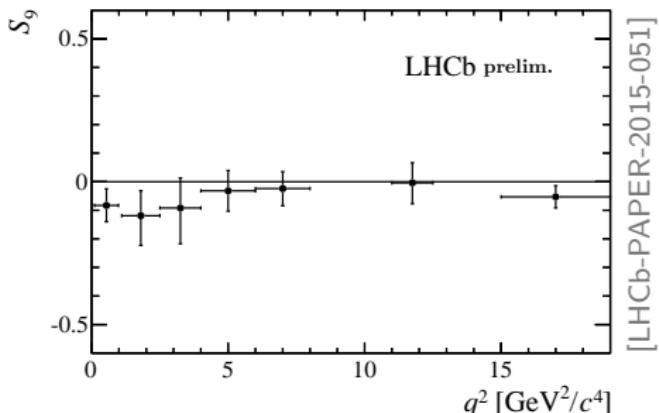
LHCb prelim.

SM from ABSZ
[1503.05534][1411.3161]

LHCb prelim.

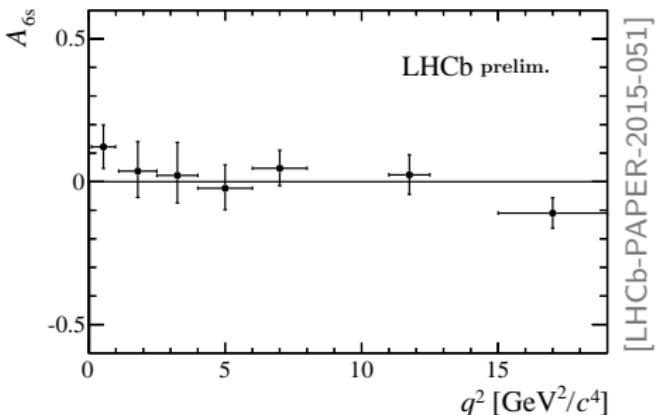
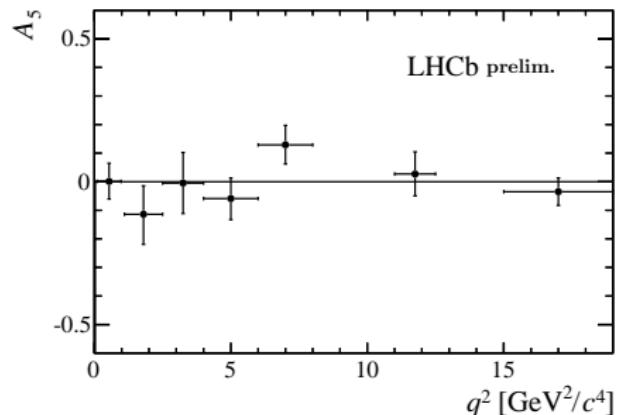
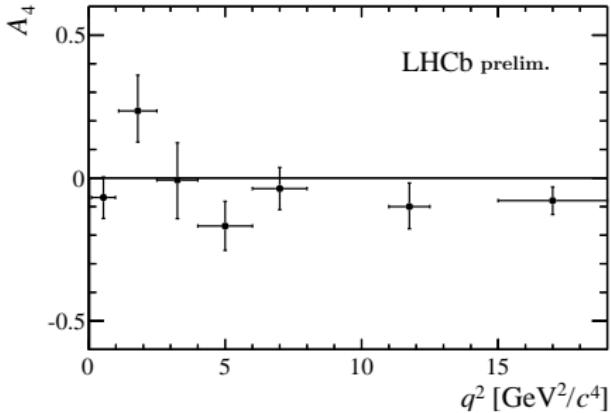
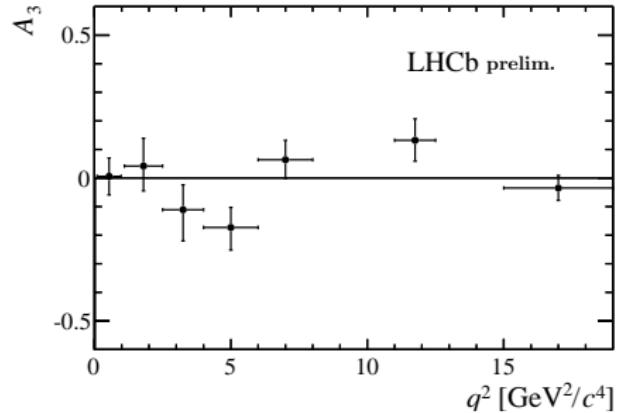


LHCb prelim.

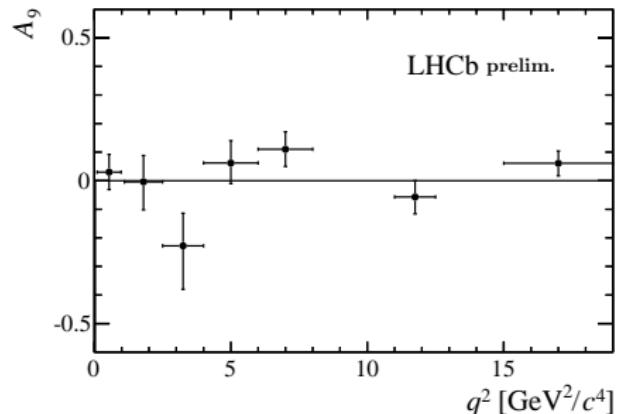
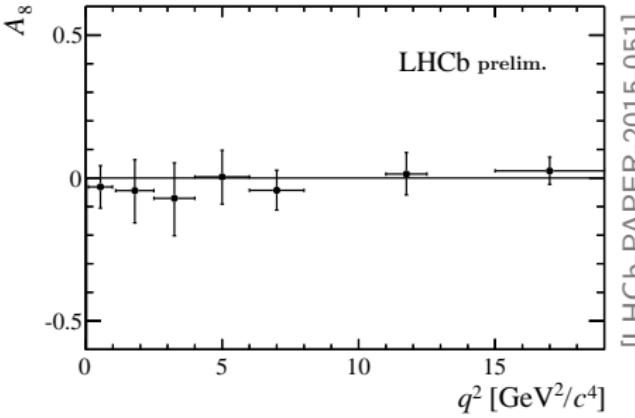
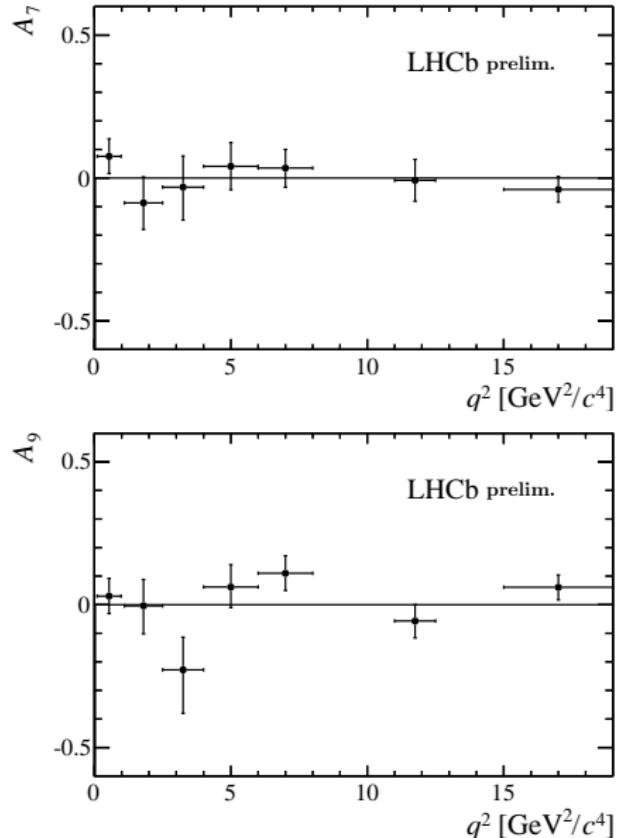


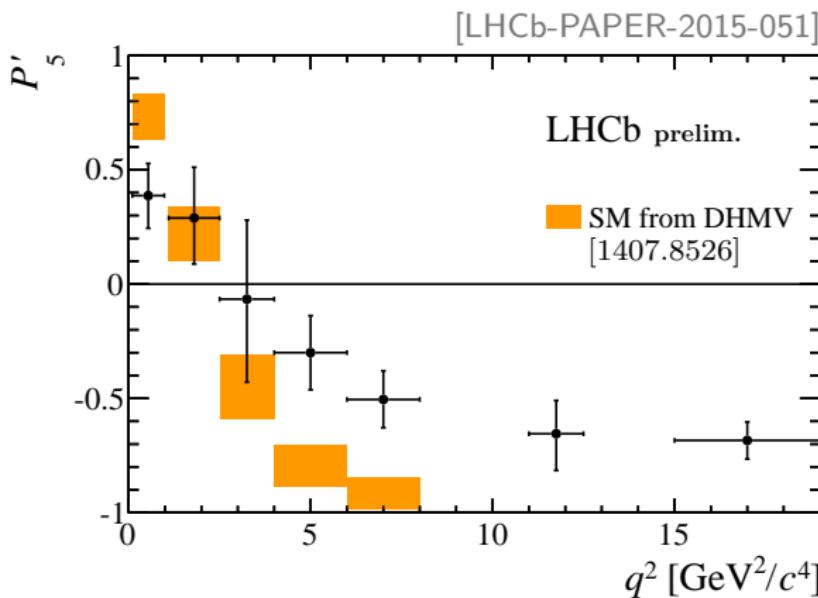
LHCb prelim.

[LHCb-PAPER-2015-051]

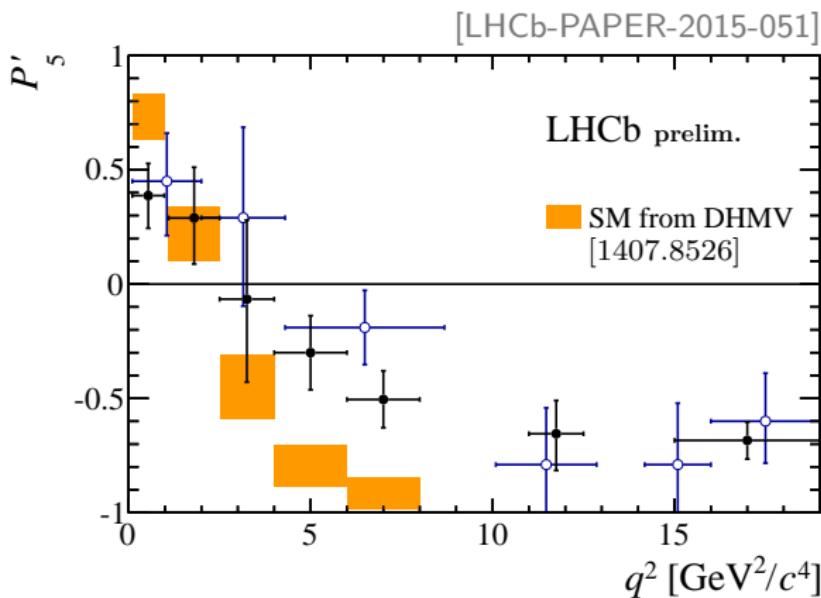
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ CP asymmetries: A_3, A_4, A_5, A_{6s}


[LHCb-PAPER-2015-051]

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


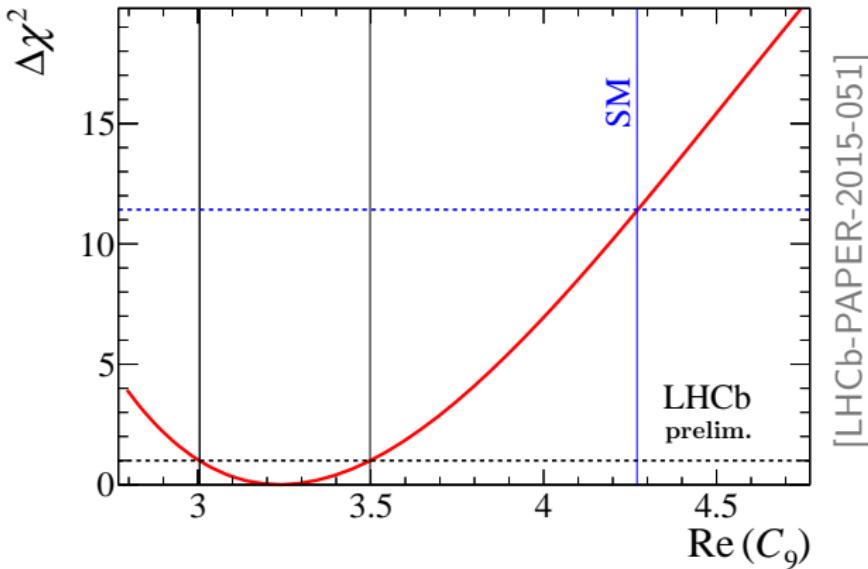
P'_5


- Tension seen in P'_5 in [PRL 111, 191801 (2013)] confirmed
- [4.0, 6.0] and [6.0, 8.0] GeV^2/c^4 local deviations of 2.8σ and 3.0σ
- Compatible with 1 fb^{-1} measurement

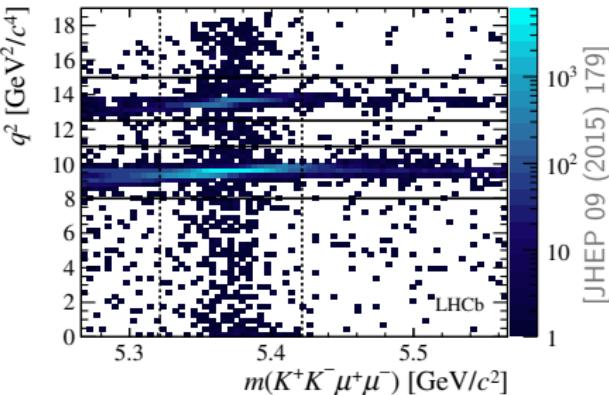
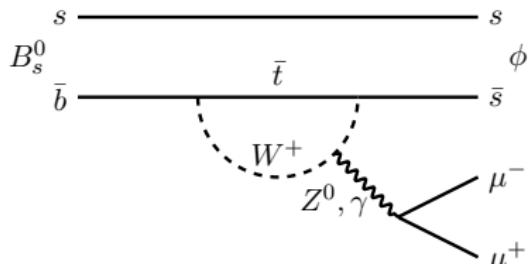
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Compatibility with the SM

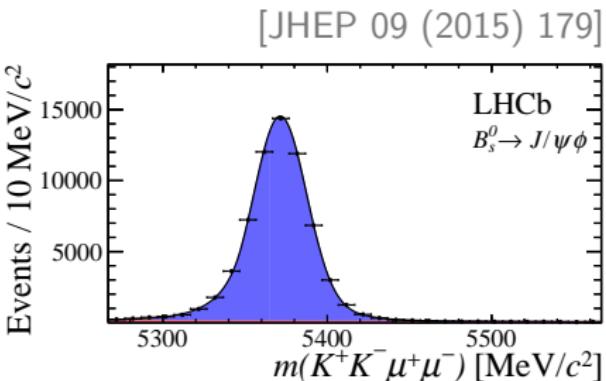
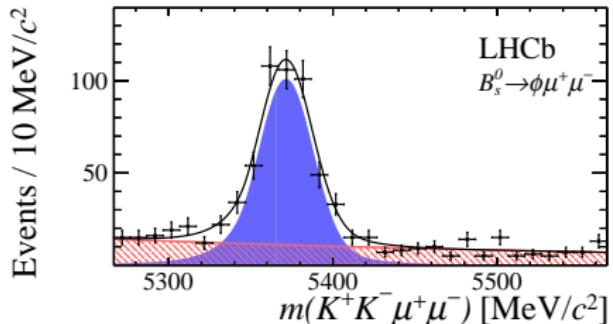


- Perform χ^2 fit of measured S_i observables using [EOS] software
- Varying $\text{Re}(C_9)$ and incl. nuisances according [F. Beaujean et al., EPJC 74 (2014) 2897]
- $\Delta\text{Re}(C_9) = -1.04 \pm 0.25$ with global significance of 3.4σ

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

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

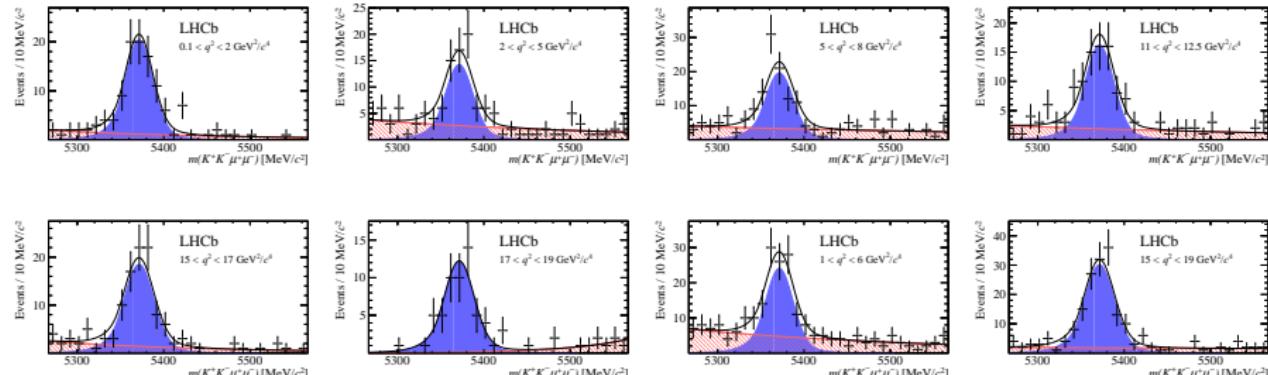
$B_s^0 \rightarrow \phi\mu^+\mu^-$ mass model



- Signal mass model (double CB) taken from $B_s^0 \rightarrow J/\psi\phi$
 q^2 dep. resolution accounted for with scale factor from simulation
- Background described using Exponential
- Signal yield $N_{\phi\mu\mu} = 432 \pm 24$ (q^2 -integrated)
- $B_s^0 \rightarrow J/\psi\phi$ yield $N_{J/\psi\phi} = 62\,033 \pm 260$

$B_s^0 \rightarrow \phi\mu^+\mu^-$ differential branching fraction

[JHEP 09 (2015) 179]

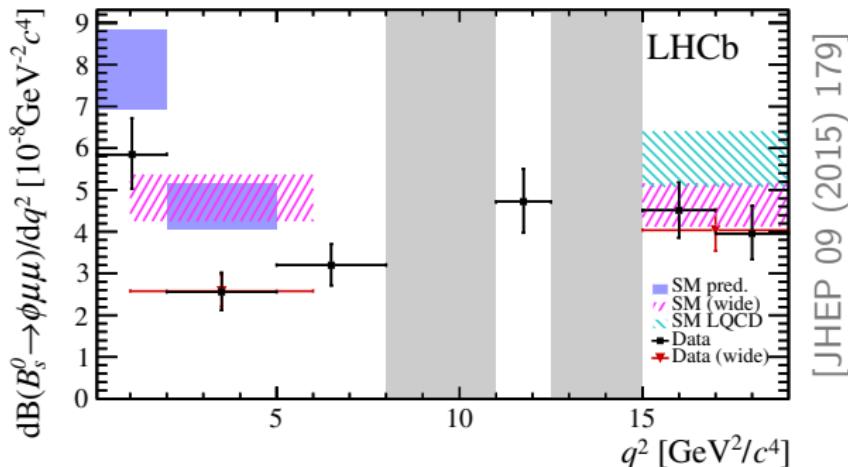


- $B_s^0 \rightarrow J/\psi\phi$ used for normalisation
- Differential branching fraction:

$$\frac{d\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)}{dq^2} = \frac{1}{q_{\max.}^2 - q_{\min.}^2} \times \frac{N_{\phi\mu\mu}}{N_{J/\psi\phi}} \times \frac{\epsilon_{\phi\mu\mu}}{\epsilon_{J/\psi\phi}} \times \mathcal{B}(B_s^0 \rightarrow J/\psi\phi) \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$$

- $\frac{\epsilon_{\phi\mu\mu}}{\epsilon_{J/\psi\phi}}$ from (corrected) simulation, many effects cancel in ratio

$B_s^0 \rightarrow \phi\mu^+\mu^-$ differential branching fraction



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

$$\frac{\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi\phi)} = (7.41^{+0.42} \pm 0.20 \pm 0.21) \times 10^{-4},$$

$$\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-) = (7.97^{+0.45} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7},$$

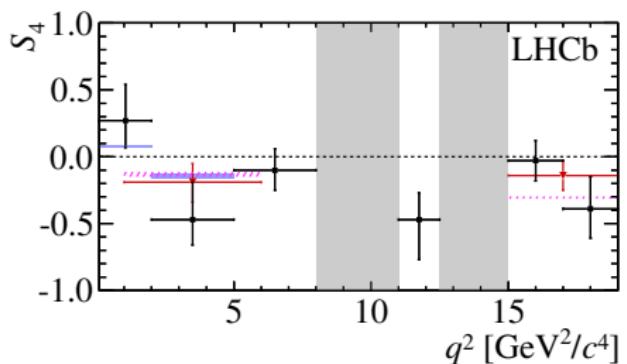
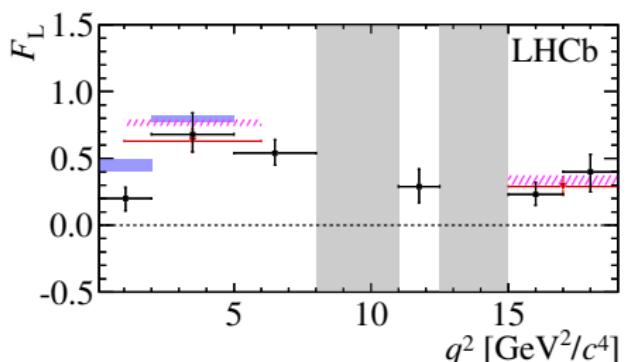
$B_s^0 \rightarrow \phi\mu^+\mu^-$ angular analysis

- Non-flavour specific final state \rightarrow reduced number of accessible observables **4 CP averages**, **4 CP asymmetries**

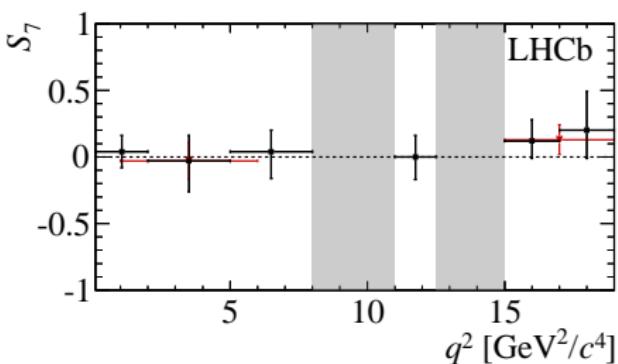
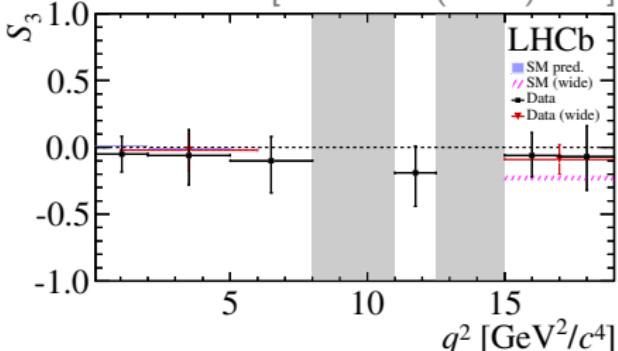
$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right.$$
$$- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi$$
$$+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + A_5 \sin 2\theta_K \sin \theta_\ell \cos \phi$$
$$+ A_6 \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi$$
$$\left. + A_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + A_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

- ub. ML fit in $m(K^+K^-\mu^+\mu^-)$ and $\{\cos \theta_\ell, \cos \theta_K, \phi\}$ in bins of q^2
- Angular background modelled with 2nd order Chebyshev polynomials
- Same acceptance method used as for $B^0 \rightarrow J/\psi K^{*0}$
cross-checked using $B_s^0 \rightarrow J/\psi \phi$
- Feldman-Cousins method due to very limited statistics

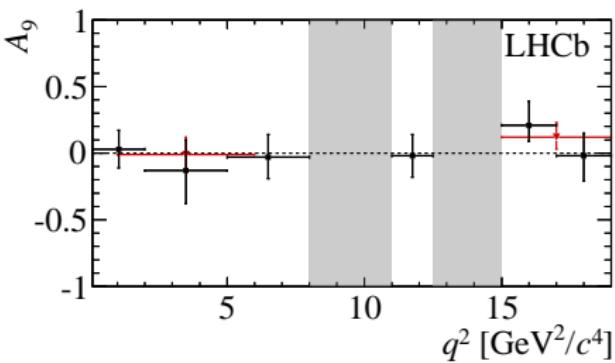
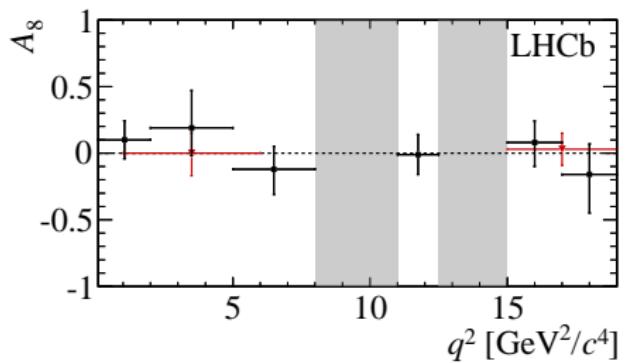
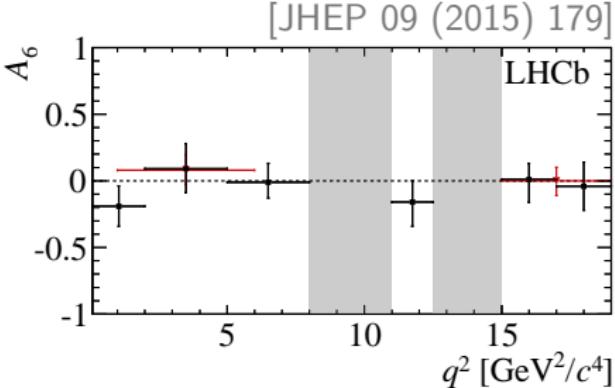
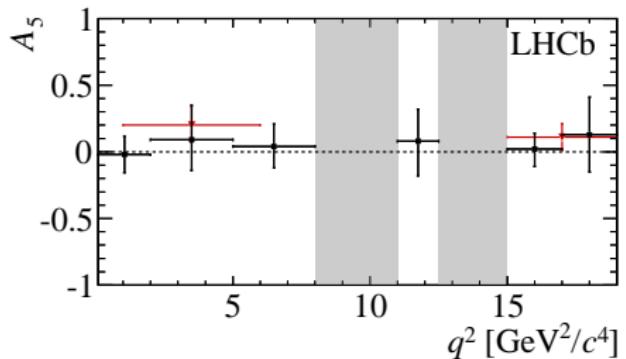
$B_s^0 \rightarrow \phi\mu^+\mu^-$ angular analysis



[JHEP 09 (2015) 179]



- Good agreement of angular obs. with SM predictions

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


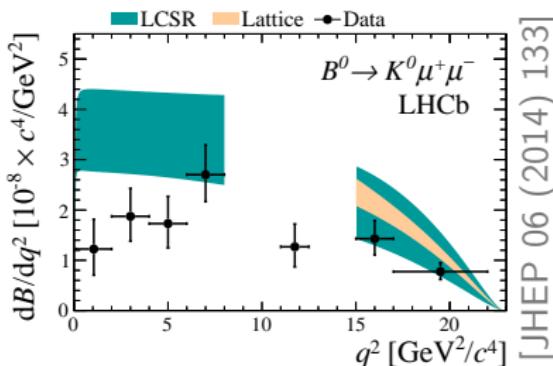
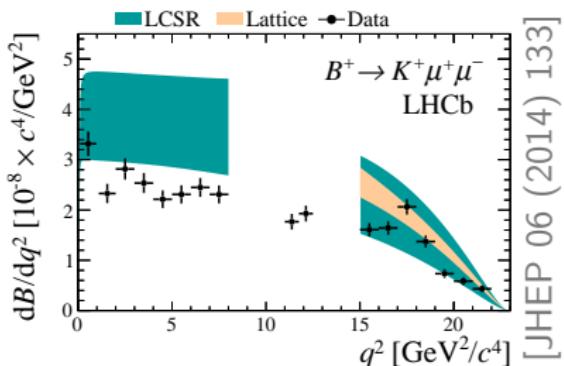
■ Good agreement of angular obs. with SM predictions

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

- Number of signal events in full 3 fb^{-1} data sample

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

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



- Compatible with but lower than SM predictions

Light cone sum rules (LCSR): $\left[\begin{array}{l} \text{P. Ball et al.,} \\ \text{PRD 71 (2005) 014029} \end{array} \right] \left[\begin{array}{l} \text{A. Khodjamirian et al.,} \\ \text{JHEP 09 (2010) 089} \end{array} \right]$

Lattice: $\left[\begin{array}{l} \text{R. Horgan et al.,} \\ \text{PRD 89 (2014) 094501} \end{array} \right] \left[\begin{array}{l} \text{C. Bouchard et al.,} \\ \text{PRD 88 (2013) 054509} \end{array} \right]$

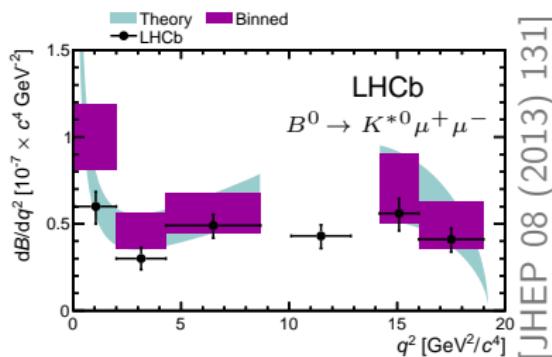
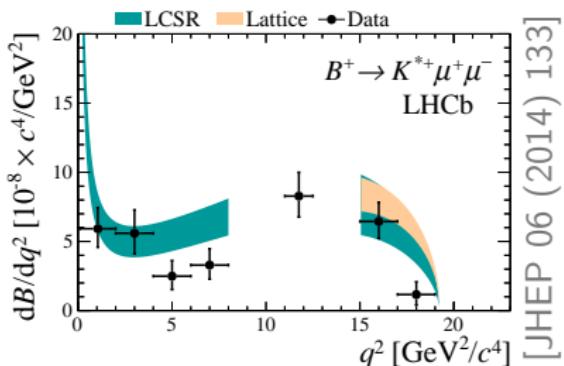
- $d\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)/dq^2$ with 3 fb^{-1} in preparation

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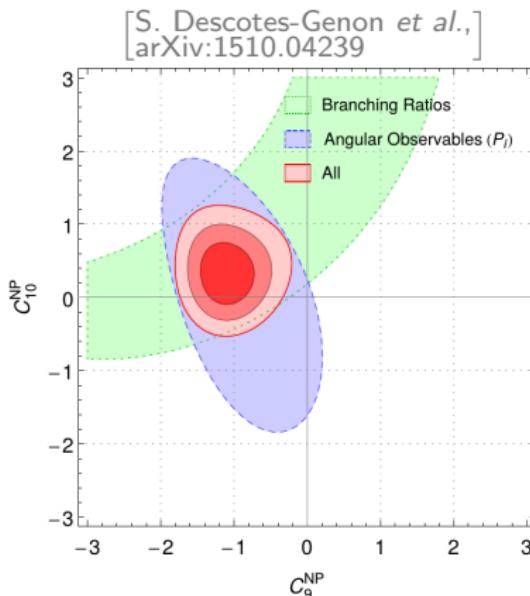
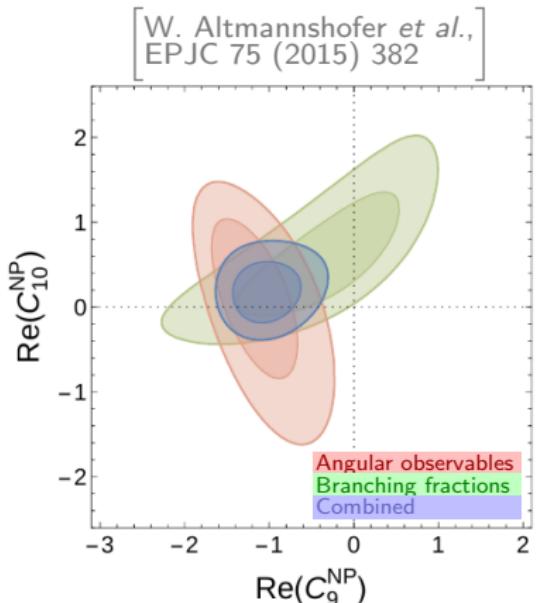
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- $d\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)/dq^2$ with 3 fb^{-1} in preparation

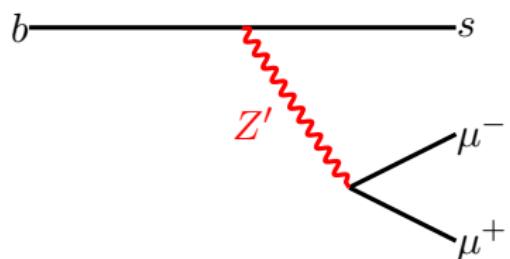
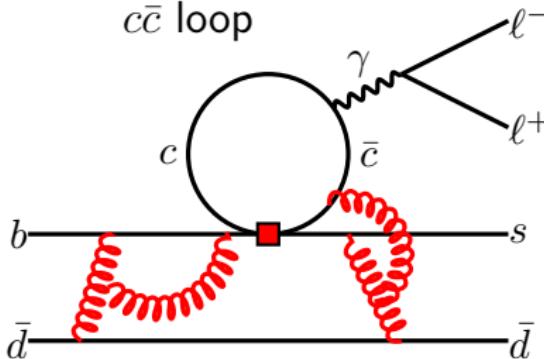
Global fits to $b \rightarrow s$ data



- Combine exp. information from rare $b \rightarrow s$ processes in global fit of \mathcal{C}_i
 - $b \rightarrow s\gamma$, $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$, Ang. $(B^0 \rightarrow K^{*0}\mu^+\mu^-)$, Ang.+ $\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)$, $\mathcal{B}(B^{0,+} \rightarrow K^{0,+(*)}\mu^+\mu^-)$, B-fact.
 - LHCb+CMS
 - LHCb 3 fb^{-1}
 - LHCb 1 fb^{-1} (3 fb^{-1})
 - LHCb 3 fb^{-1} (1 fb^{-1})
- Tension can be reduced with $\Delta \text{Re}(\mathcal{C}_9) \sim -1$, significances around 4σ
- Consistency between angular observables and branching fractions

NP or hadronic effect?

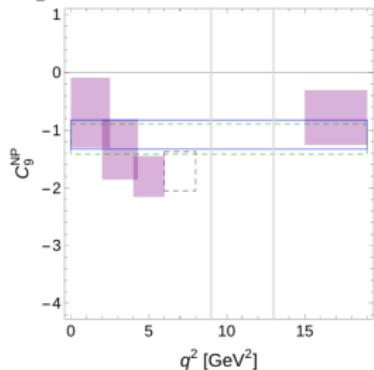
Possible NP

 $c\bar{c}$ loop■ Possible explanations for shift in C_9

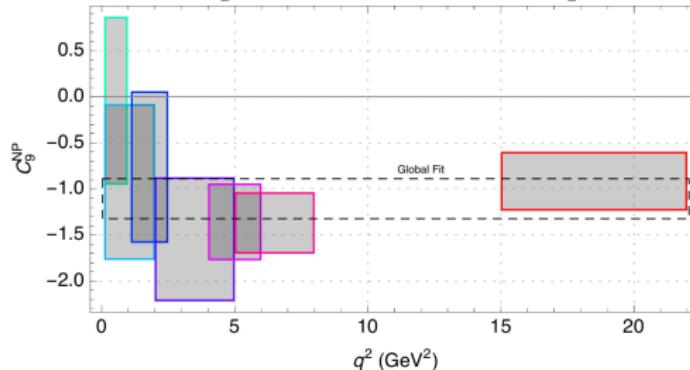
- NP e.g. Z' [Gauld et al.] [Buras et al.] [Altmannshofer et al.] [Crivellin et al.] Leptoquarks [Hiller et al.] [Biswas et al.] [Buras et al.] [Gripaios et al.]
- hadronic charm loop contributions
- q^2 dependence: $c\bar{c}$ loops rise towards J/ψ , NP q^2 -independent

NP or hadronic effect?

[W. Altmannshofer *et al.*,
arXiv:1503.06199]

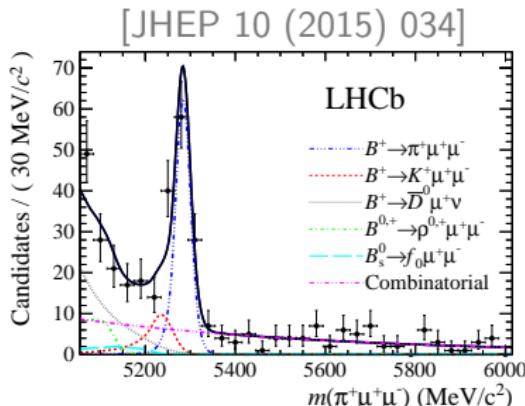
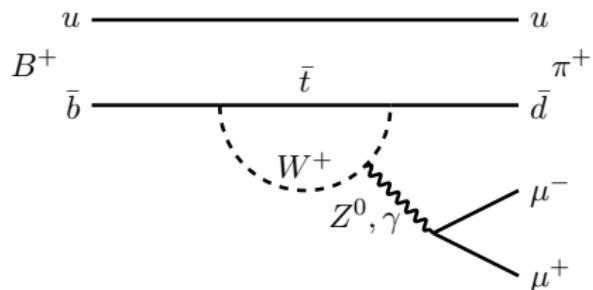


[S. Descotes-Genon *et al.*,
arXiv:1510.04239]



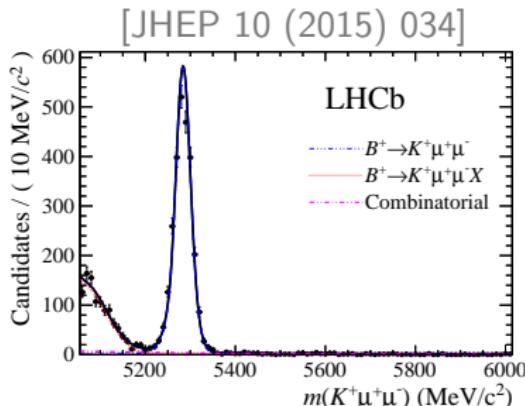
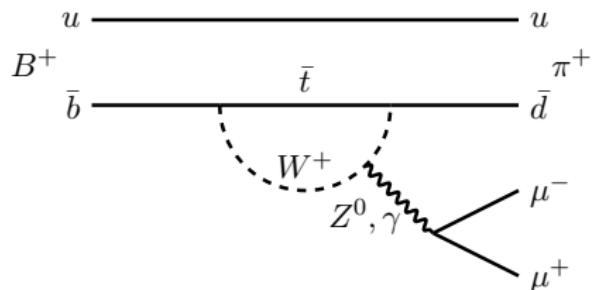
- Possible explanations for shift in C_9
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 - hadronic charm loop contributions
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The $b \rightarrow d\mu^+\mu^-$ decay $B^+ \rightarrow \pi^+ \mu^+ \mu^-$



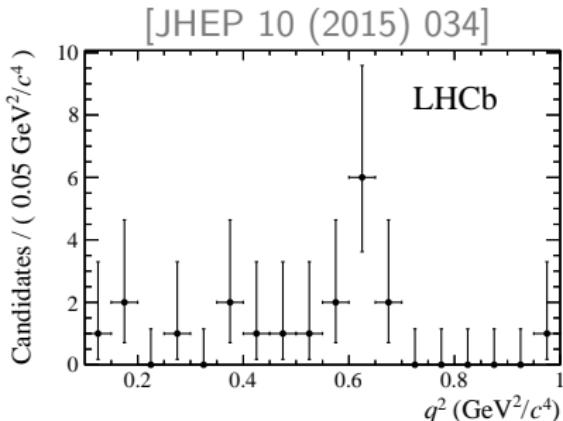
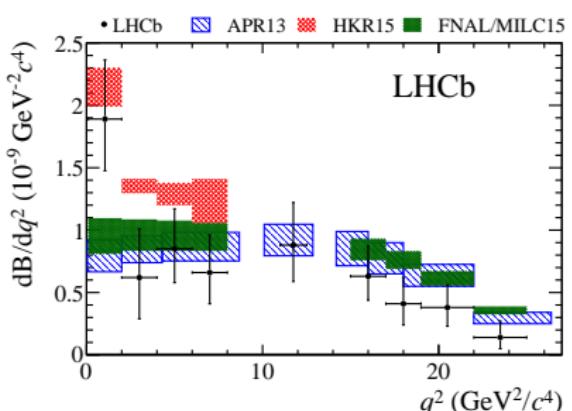
- $b \rightarrow d\mu^+\mu^-$ transition in SM sup. by $\left| \frac{V_{td}}{V_{ts}} \right|^2 \sim \frac{1}{25}$ wrt. $b \rightarrow s\mu^+\mu^-$
- Measure diff. branching fraction and \mathcal{A}_{CP} ($O(-0.1)$ in the SM)
- Assuming SM, measure $|V_{td}/V_{ts}|$, $|V_{td}|$, $|V_{ts}|$ using $B^+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

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



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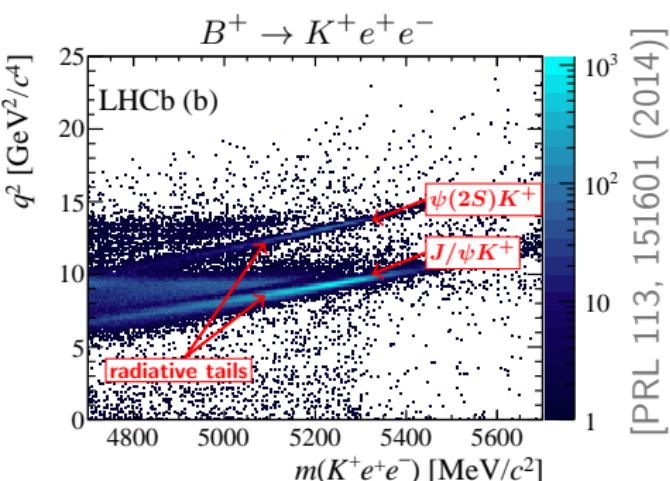
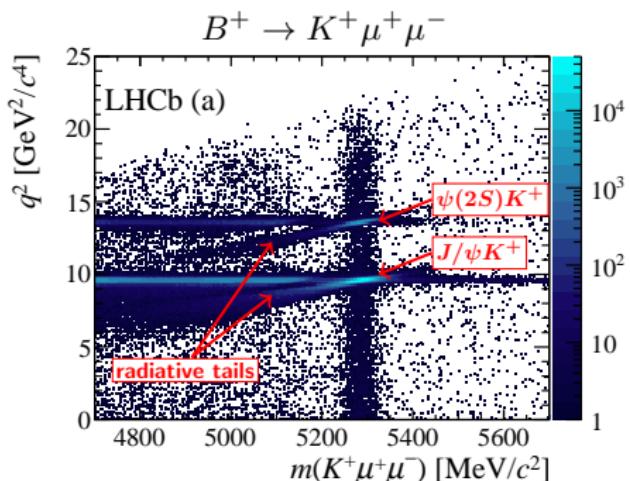
$B^+ \rightarrow \pi^+ \mu^+ \mu^-$ diff. \mathcal{B} , \mathcal{A}_{CP} and CKM matrix elements



- 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 $\mathcal{A}_{CP} = -0.11 \pm 0.12 \pm 0.01$
- $|V_{\text{td}}| = 0.24^{+0.05}_{-0.04}$, $|V_{\text{ts}}| = 7.2^{+0.9}_{-0.8} \times 10^{-3}$ and $|V_{\text{ts}}| = 3.2^{+0.4}_{-0.4} \times 10^{-2}$
- New lattice predictions from MILC collaboration [D. Du et al., arXiv:1510.02349]
→ CKM elements from RDs competitive with $B_{(s)}$ oscillation meas.
→ Combined 2σ tension of $\mathcal{B}(B^+ \rightarrow K^+(\pi^+) \mu^+ \mu^-)$ with SM prediction

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

- $\mathcal{R}_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3})$ in the SM, not affected by $c\bar{c}$ loops



[PRL 113, 151601 (2014)]

- Experimental challenges for $B^+ \rightarrow K^+ e^+ e^-$ mode

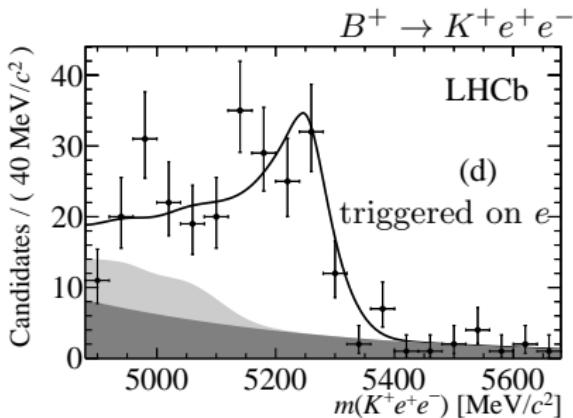
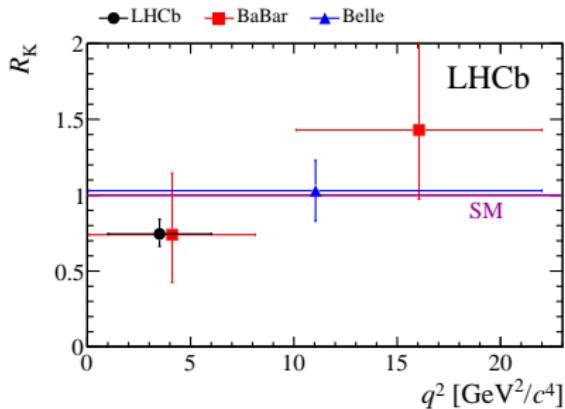
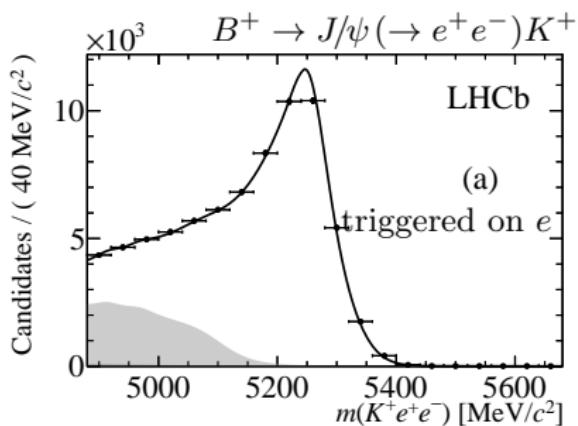
- Trigger
- Bremsstrahlung

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

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



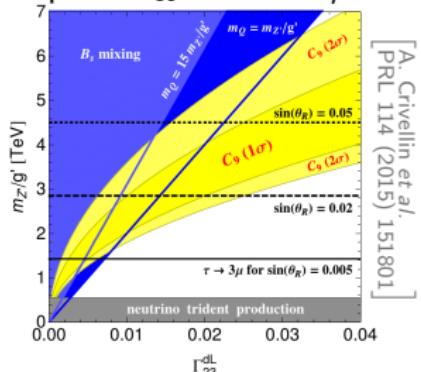
arxiv:1406.6482]

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

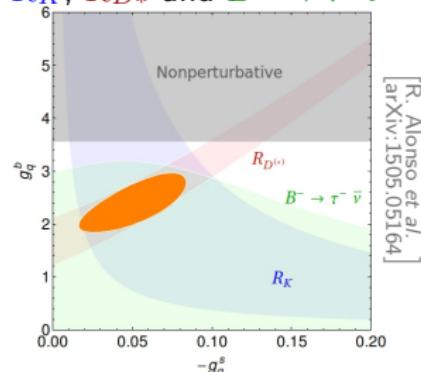
Lepton universality and lepton flavour violation

- Due to the cleanliness of the SM prediction, R_K received a lot of attention
[Glashow et al.
PRL 114 (2015) 091801] [Hiller et al.
PRD 90 (2014) 054014] [Crivellin et al.
PRL 114 (2015) 151801]
- Including R_K in global fits increases tension with SM hypothesis
- Naturally motivates $R_{K^*} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}$ and $R_\phi = \frac{\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow \phi e^+ e^-)}$
- Also motivates searches for lepton flavour violation [Glashow et al.
PRL 114 (2015) 091801]
"Lepton non-universality generally implies lepton flavour violation"
- $\mathcal{B}(B \rightarrow K^{(*)} \mu^\pm e^\mp)$ [$\mathcal{B}(B \rightarrow K^{(*)} \mu^\pm \tau^\mp)$] could be $\mathcal{O}(10^{-8})$ [$\mathcal{O}(10^{-6})$]
- Other anomalies [One Leptoquark to Rule Them All: A Minimal Explanation
for R_{D^*} , R_K and $(g-2)_\mu$, M. Bauer et al., arXiv:1511.01900]

Explain R_K and $h \rightarrow \mu\tau$



R_K , R_{D^*} and $B^- \rightarrow \tau^- \bar{\nu}$

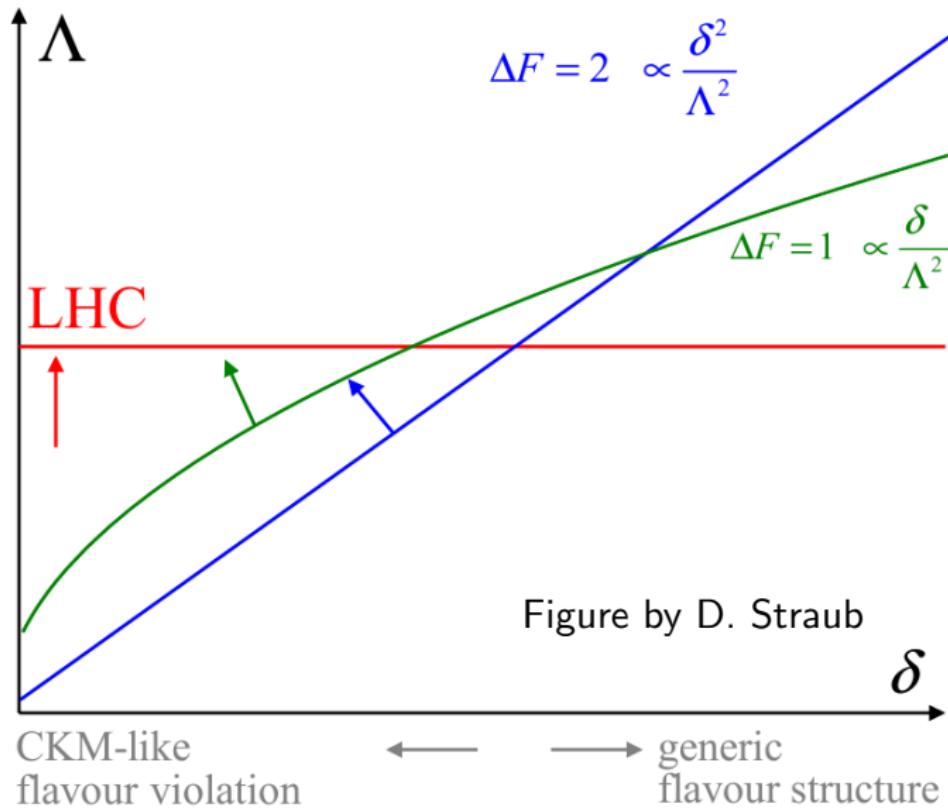


Conclusions

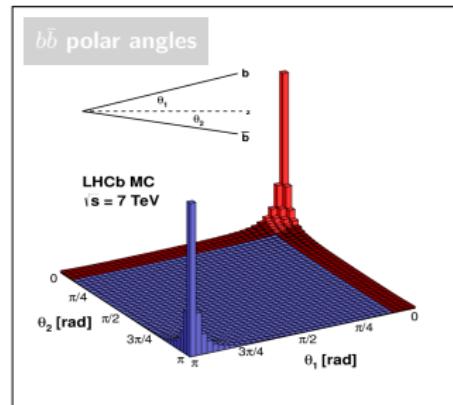
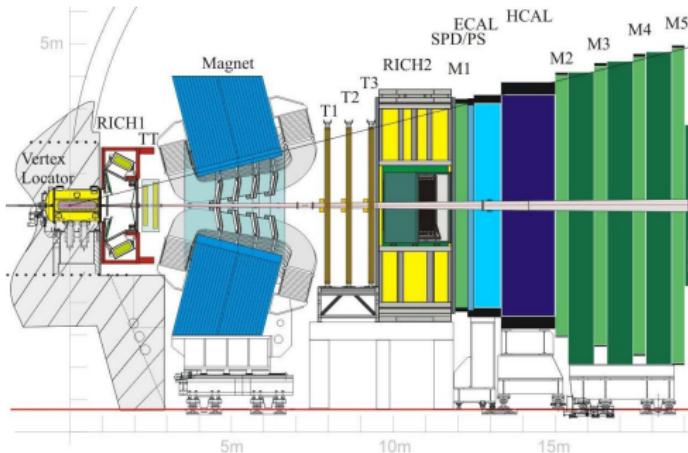
- Rare B decays are an excellent laboratory to search for BSM effects
- LHCb an ideal environment to study these decays
- Most measurements in good agreement with SM predictions, setting strong constraints on NP
- However, several interesting tensions in rare $b \rightarrow sll$ decays:
 P'_5 in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, $\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)$, R_K
- 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



Complementarity of flavour and direct searches

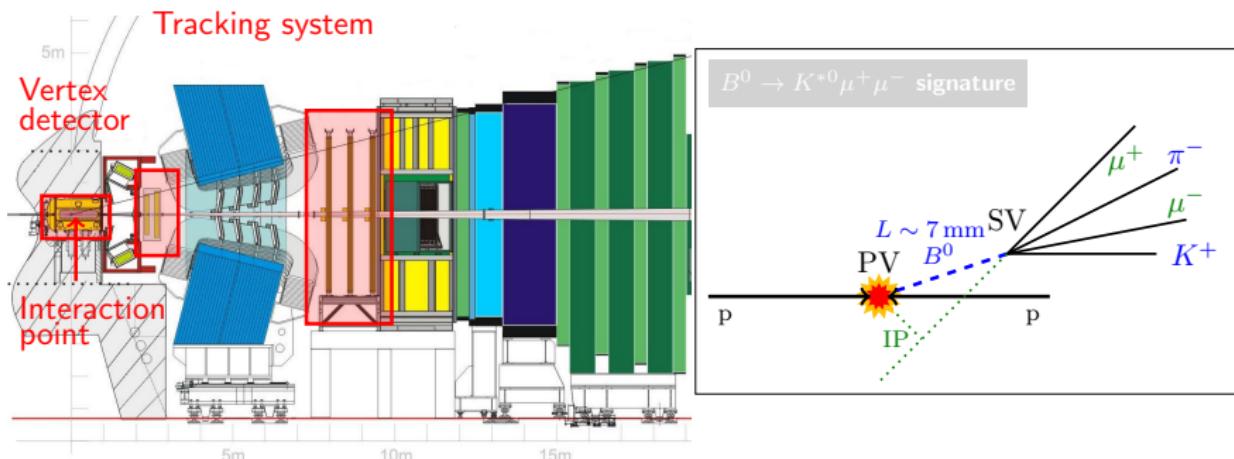


The LHC as heavy flavour factory



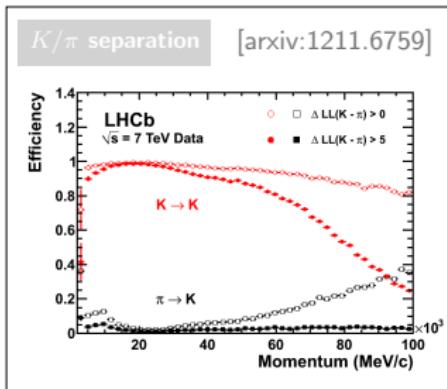
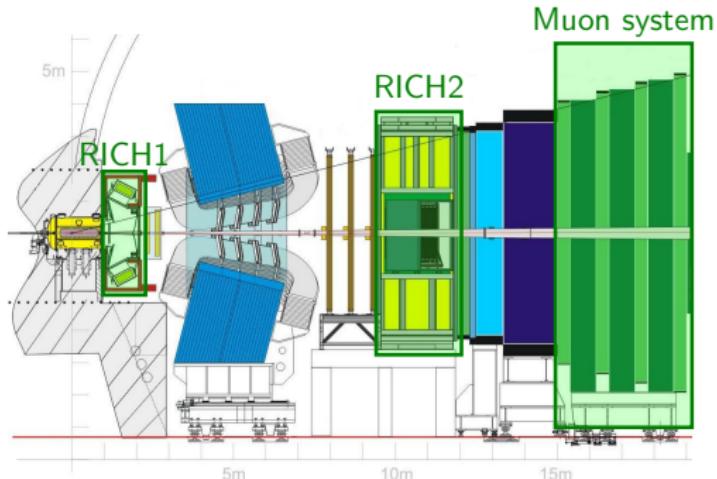
- $b\bar{b}$ produced correlated predominantly in forward (backward) direction
→ single arm forward spectrometer ($2 < \eta < 5$)
- Large $b\bar{b}$ production cross section
 $\sigma_{b\bar{b}} = (75.3 \pm 14.1) \mu\text{b}$ [Phys.Lett. B694 (2010)] in acceptance
- $\sim 1 \times 10^{11}$ produced $b\bar{b}$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

The LHCb detector: Tracking



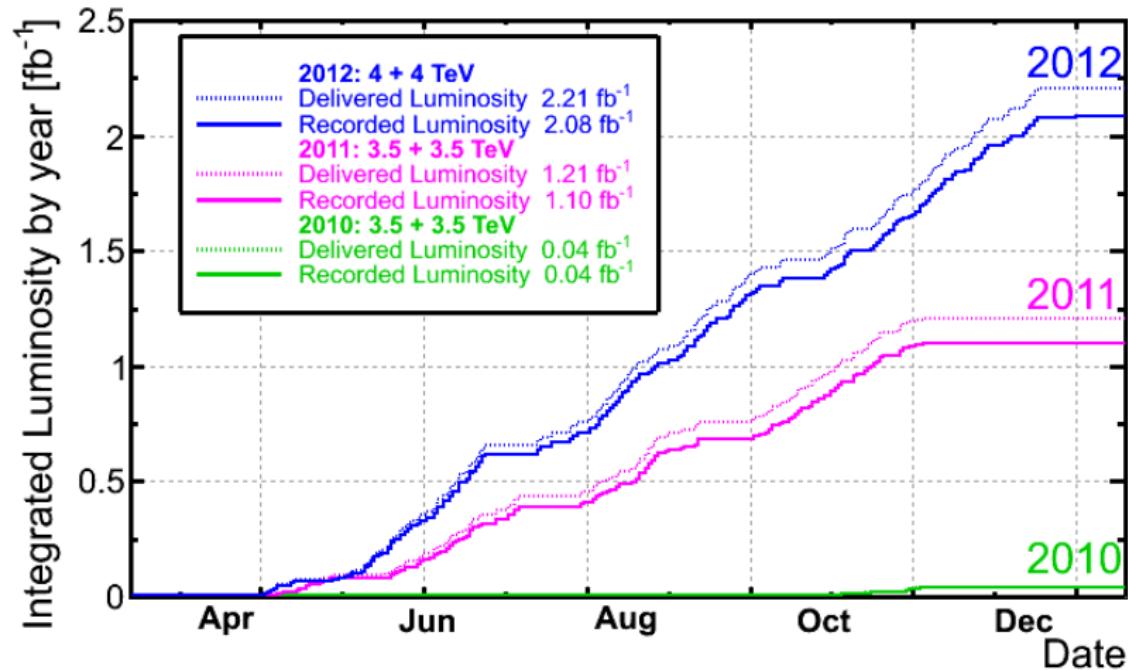
- Excellent Impact Parameter (IP) resolution ($20\text{ }\mu\text{m}$)
→ Identify secondary vertices from heavy flavour decays
- Proper time resolution $\sim 45\text{ fs}$
→ Good separation of primary and secondary vertices
- Excellent momentum ($\delta p/p \sim 0.5 - 1.0\%$) and inv. mass resolution
→ Low combinatorial background

The LHCb detector: Particle identification and Trigger

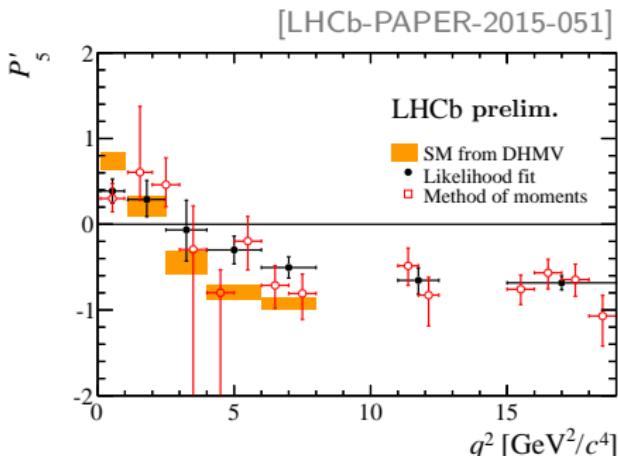
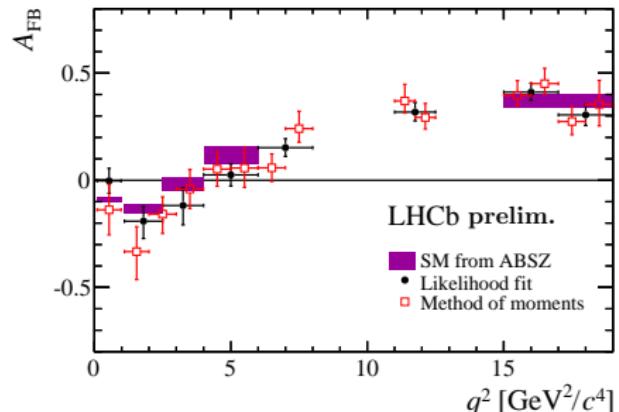


- Excellent Muon identification $\epsilon_{\mu \rightarrow \mu} \sim 97\%$ $\epsilon_{\pi \rightarrow \mu} \sim 1-3\%$
- Good $K\pi$ separation via RICH detectors $\epsilon_{K \rightarrow K} \sim 95\%$ $\epsilon_{\pi \rightarrow K} \sim 5\%$
→ Reject peaking backgrounds
- High trigger efficiencies, low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

Data taken by LHCb

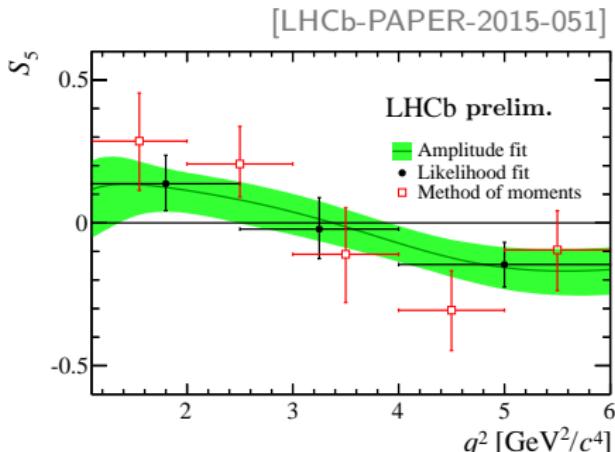
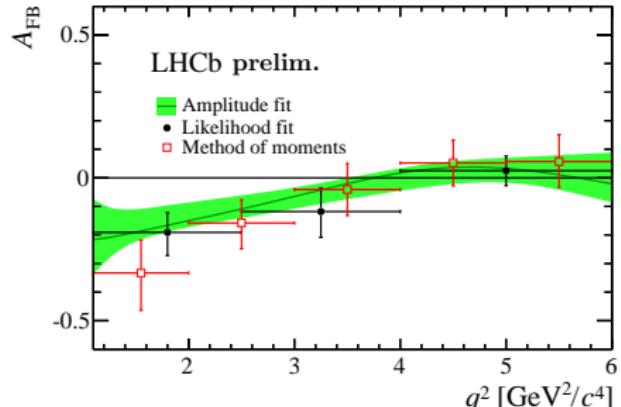


Moments analysis



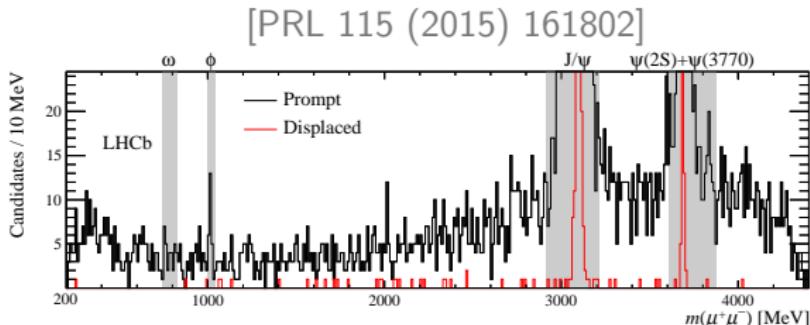
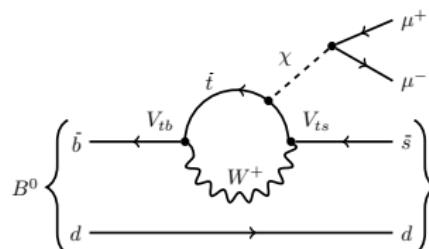
- Angular terms $f_i(\vec{\Omega})$ are orthogonal
→ can determine obs. via their moments $\hat{M}_i = \frac{1}{\sum_e w_e} \sum_e w_e f_i(\vec{\Omega}_e)$
- 10-30% less sensitive than Maximum Likelihood fit [F. Beaujean et al., PRD 91 (2015) 114012]
but allows narrow $1 \text{ GeV}^2/\text{c}^4$ wide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

Amplitude fit and Zero-crossing points



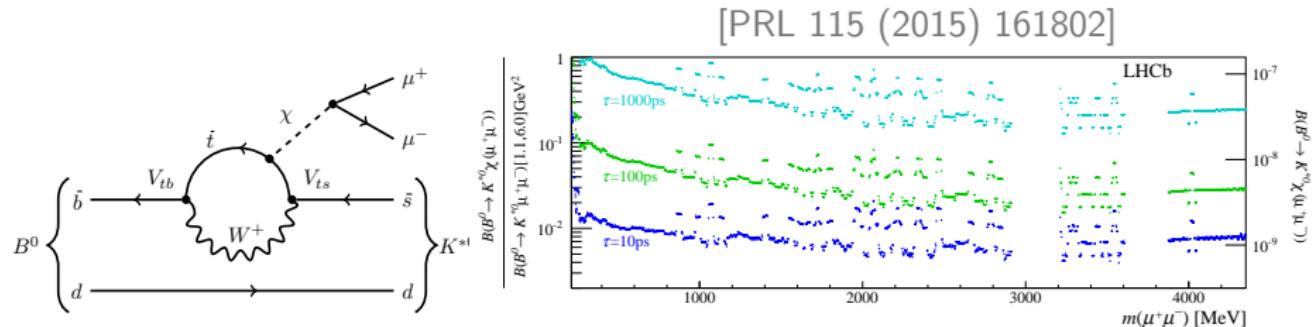
- Zero-crossing points sensitive tests of SM, form factor uncertainties cancel
- Perform q^2 dependent amplitude fit with Ansatz
$$\mathcal{A}_{0,\parallel,\perp}^{L,R} = \alpha + \beta q^2 + \gamma \frac{1}{q^2}$$
 in the region $1.1 < q^2 < 6 \text{ GeV}^2/c^4$
- Resulting zero crossing points in good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

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



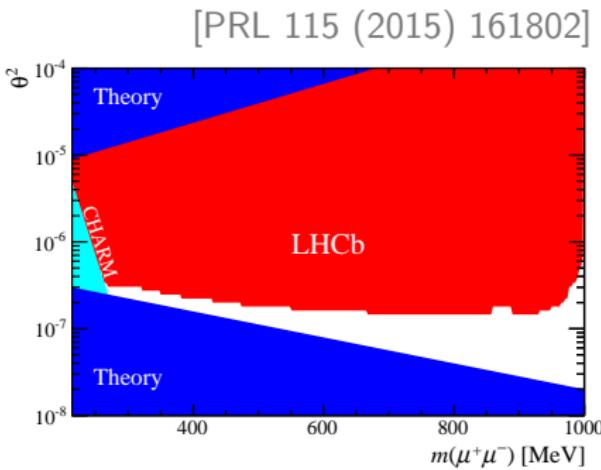
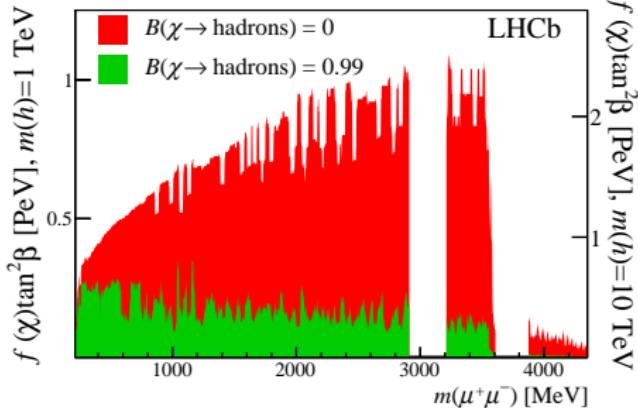
- Search for hidden sector boson in $B^0 \rightarrow K^{*0} \chi$ with $\chi \rightarrow \mu^+ \mu^-$
- Scan $m(\mu^+ \mu^-)$ distribution for an excess of χ signal candidates
- Search for prompt and displaced ($\tau(\mu^+ \mu^-) > 3\sigma_{\tau(\mu^+ \mu^-)}$) χ vertices
- Narrow resonances (ω , ϕ ,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

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



- Search for hidden sector boson in $B^0 \rightarrow K^{*0} \chi$ with $\chi \rightarrow \mu^+ \mu^-$
- 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
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Exclusion limits for specific models

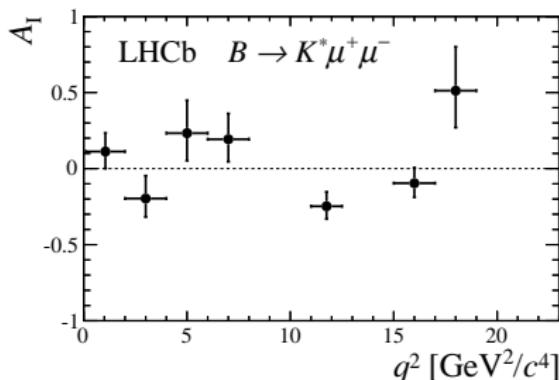
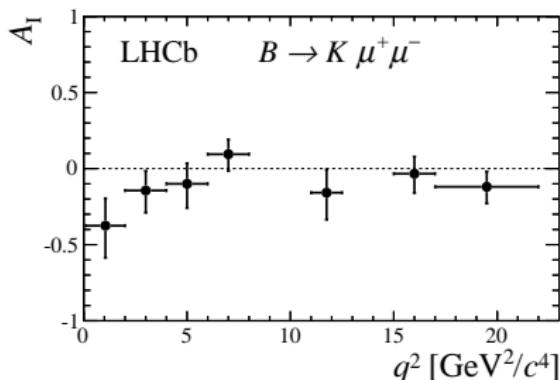


Resulting 95% CL exclusion limits for specific models

- 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

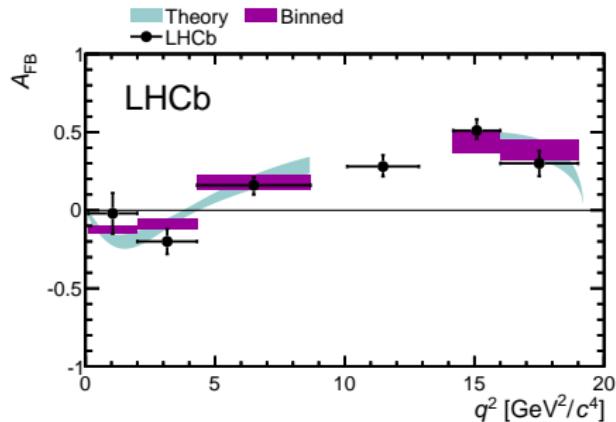
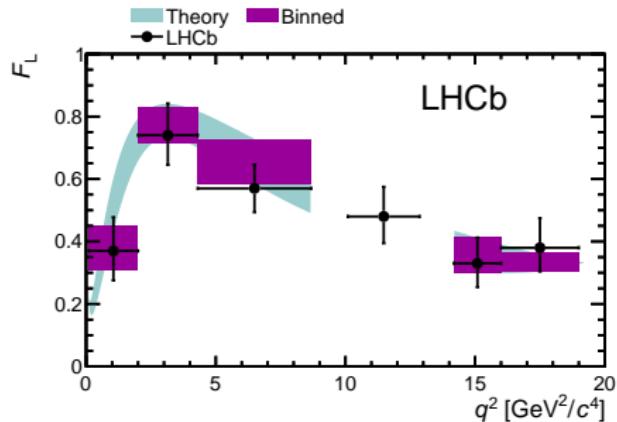
$B \rightarrow K^{(*)} \mu^+ \mu^-$ isospin

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



[JHEP 06 (2014) 133]

- Results with 3 fb^{-1} consistent with SM
- p-value for deviation of $A_I(B \rightarrow K \mu \mu)$ from 0 is 11% (1.5σ)

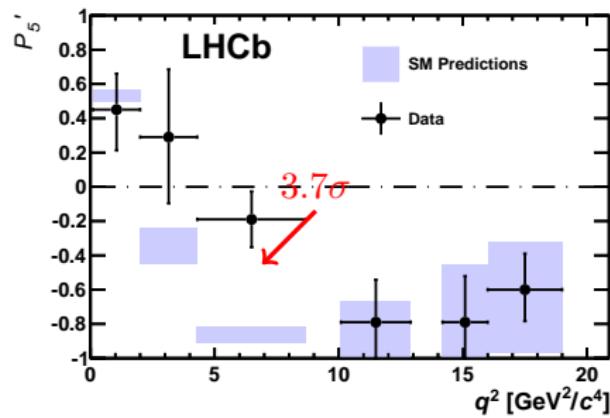
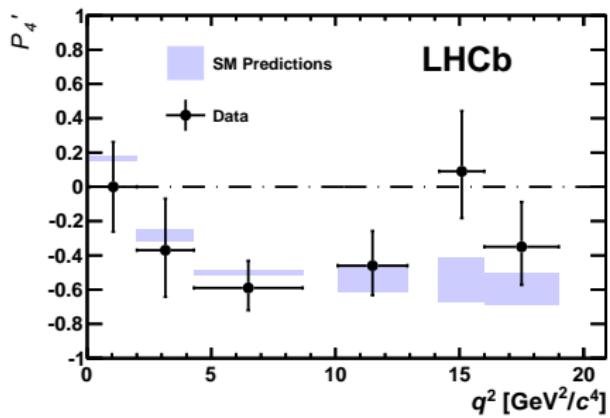
Reminder: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular observables (1 fb^{-1})

[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 $q_0^2 = 4.9 \pm 0.9 \text{ GeV}^2$ consistent with SM prediction
 $q_{0,\text{SM}}^2 = 4.36^{+0.33}_{-0.31} \text{ GeV}^2$ [EPJ C41 (2005) 173-188]

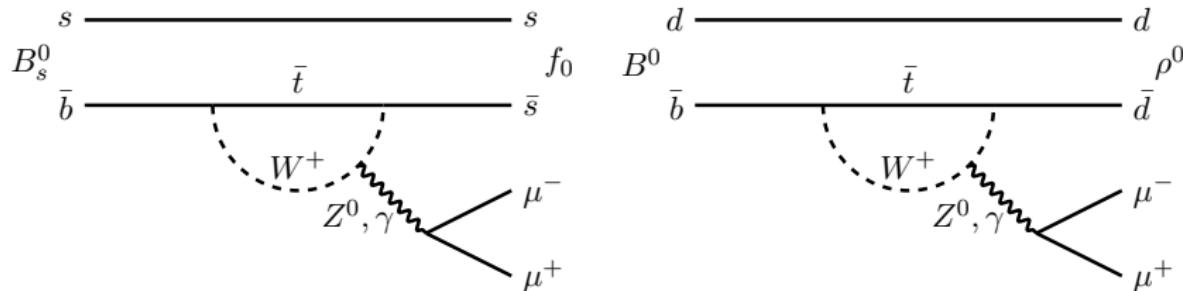
Less form factor dependent observables P'_i (1 fb^{-1})

- 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 $B_{(s)}^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays I

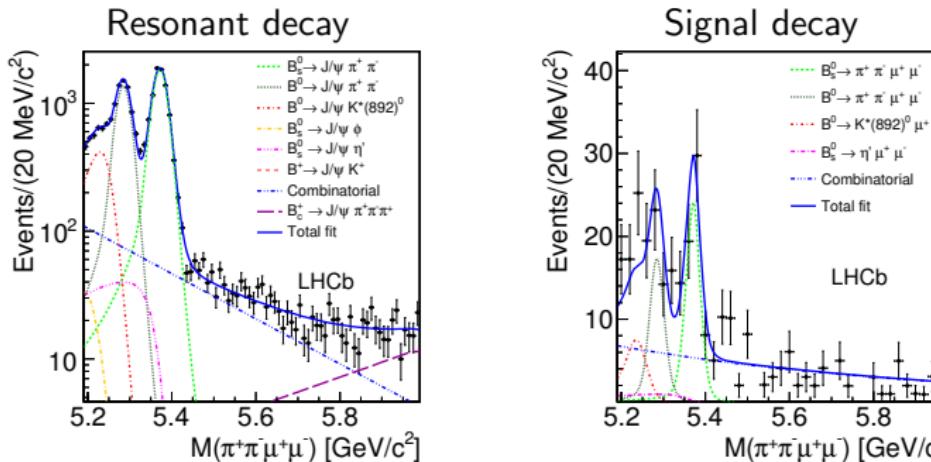


■ Contributions from

- $B_s^0 \rightarrow f_0 \mu^+ \mu^-$: $b \rightarrow s$ transition similar to $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- $B^0 \rightarrow \rho^0 \mu^+ \mu^-$: $b \rightarrow d$ transition, $|V_{td}/V_{ts}|^2$ suppressed in SM

■ SM predictions show large variation

- $\mathcal{B}_{\text{SM}}(B_s^0 \rightarrow f_0 \mu^+ \mu^-) = 0.6 \times 10^{-9} - 5.2 \times 10^{-7}$
[PRD 79 014013], [PRD 81 074001], [PRD 80 016009]
- $\mathcal{B}_{\text{SM}}(B^0 \rightarrow \rho^0 \mu^+ \mu^-) = (5 - 9) \times 10^{-8}$
[PRD 56 5452-5465], [Eur.Phys.J.C 41 173-188]

Study of rare $B_{(s)}^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays II

[PLB 743 (2015) 46]

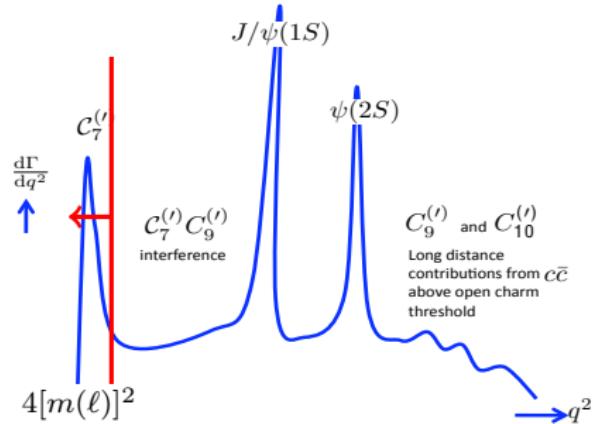
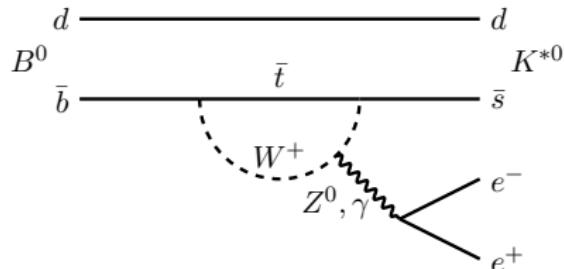
- Observation of $B_s^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ with 7.6σ
- Evidence for $B^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ with 4.8σ
- Branching fractions compatible with SM predictions

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

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

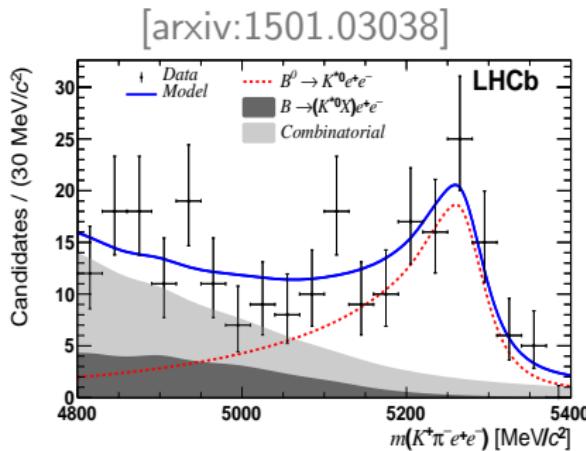
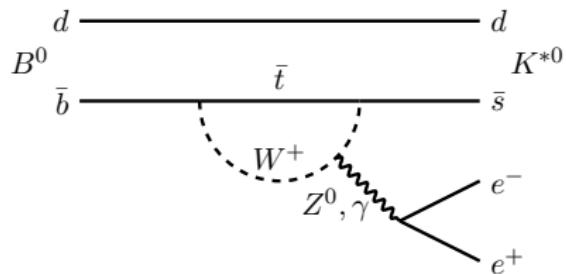
- Motivated work in theory [Wang et al., arxiv:1502.05104], [arxiv:1502.05483]

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



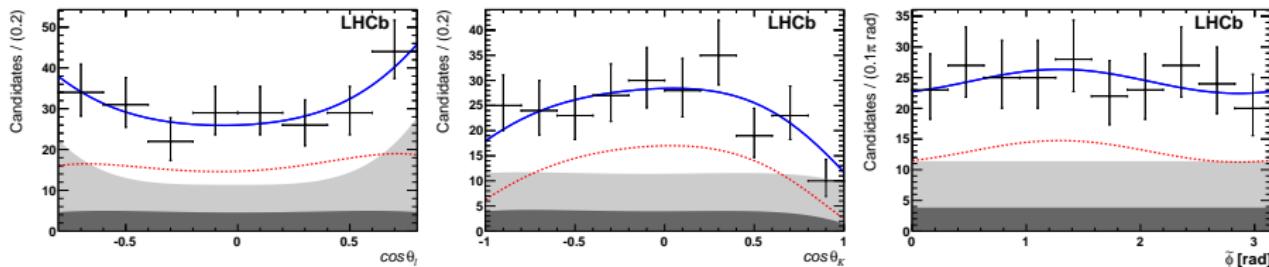
- Analyse $B^0 \rightarrow K^{*0} e^+ e^-$ at very low q^2 : $[0.0004, 1.0] \text{ GeV}^2/c^4$, accessible due to tiny e mass
- Determine angular observables F_L , $A_T^{(2)}$, A_T^{Re} , A_T^{Im} sensitive to C_7 and C_7'
- Experimental challenges: Trigger and Bremsstrahlung

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



[arxiv:1501.03038]

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

[JHEP 05 (2013) 043]

obs.	SM prediction
F_L	$+0.10^{+0.11}_{-0.05}$
$A_T^{(2)}$	$+0.03^{+0.05}_{-0.04}$
A_T^{Re}	$-0.15^{+0.04}_{-0.03}$
A_T^{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

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

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

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

- $I_i(q^2)$ 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
 \rightarrow Angular folding $\phi \rightarrow \phi + \pi$ for $\phi < 0$ cancels terms $\propto \sin\phi, \cos\phi$

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- 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
→ Angular folding $\phi \rightarrow \phi + \pi$ for $\phi < 0$ cancels terms $\propto \sin\phi, \cos\phi$

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

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

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

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

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

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

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

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

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

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

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

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

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

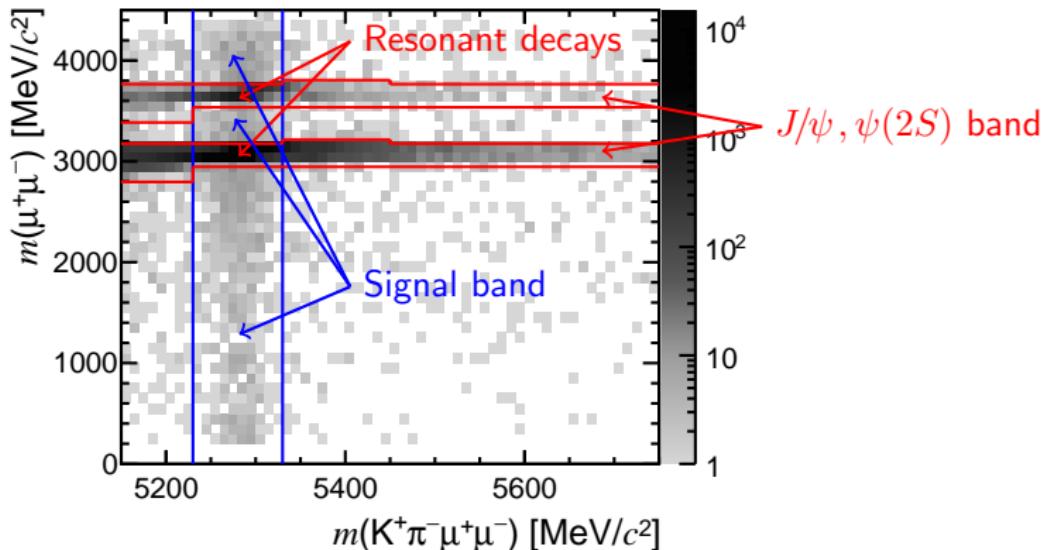
$$A_{\perp}^{L(R)} = N\sqrt{2\lambda} \left\{ [(\mathbf{C}_9^{\text{eff}} + \mathbf{C}'^{\text{eff}}_9) \mp (\mathbf{C}_{10}^{\text{eff}} + \mathbf{C}'^{\text{eff}}_{10})] \frac{\mathbf{V}(\mathbf{q}^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (\mathbf{C}_7^{\text{eff}} + \mathbf{C}'^{\text{eff}}_7) \mathbf{T}_1(\mathbf{q}^2) \right\}$$

$$A_{\parallel}^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2) \left\{ [(\mathbf{C}_9^{\text{eff}} - \mathbf{C}'^{\text{eff}}_9) \mp (\mathbf{C}_{10}^{\text{eff}} - \mathbf{C}'^{\text{eff}}_{10})] \frac{\mathbf{A}_1(\mathbf{q}^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} (\mathbf{C}_7^{\text{eff}} - \mathbf{C}'^{\text{eff}}_7) \mathbf{T}_2(\mathbf{q}^2) \right\}$$

$$\begin{aligned} A_0^{L(R)} = & -\frac{N}{2m_{K^*}\sqrt{q^2}} \left\{ [(\mathbf{C}_9^{\text{eff}} - \mathbf{C}'^{\text{eff}}_9) \mp (\mathbf{C}_{10}^{\text{eff}} - \mathbf{C}'^{\text{eff}}_{10})] [(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) \mathbf{A}_1(\mathbf{q}^2) - \lambda \frac{\mathbf{A}_2(\mathbf{q}^2)}{m_B + m_{K^*}}] \right. \\ & \left. + 2m_b (\mathbf{C}_7^{\text{eff}} - \mathbf{C}'^{\text{eff}}_7) [(m_B^2 + 3m_{K^*} - q^2) \mathbf{T}_2(\mathbf{q}^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} \mathbf{T}_3(\mathbf{q}^2)] \right\} \end{aligned}$$

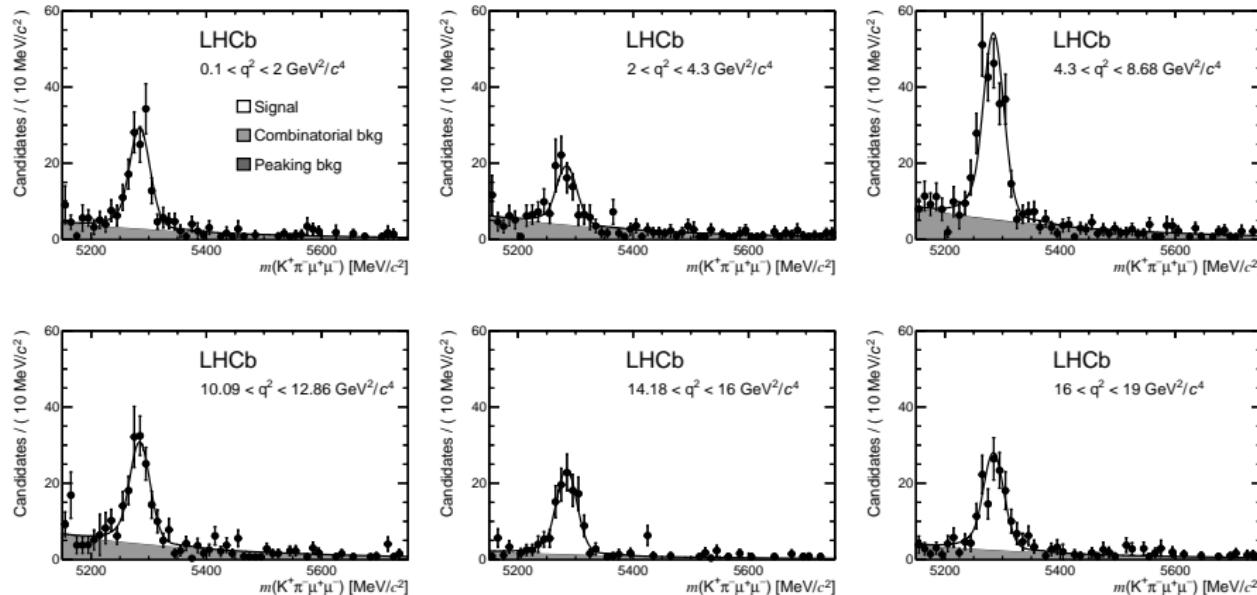
- Wilson coefficients $\mathcal{C}_{7,9,10}^{(I)\text{eff}}$
- Seven form factors (FF) $V(q^2)$, $A_{0,1,2}(q^2)$, $T_{1,2,3}(q^2)$ encode hadronic effects and require non-perturbative calculation
- Low $q^2 \leq 6 \text{ GeV}^2$
 $\rightarrow \xi_{\perp,\parallel}$ (soft form factors)
- Large $q^2 \geq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

Analysis strategy



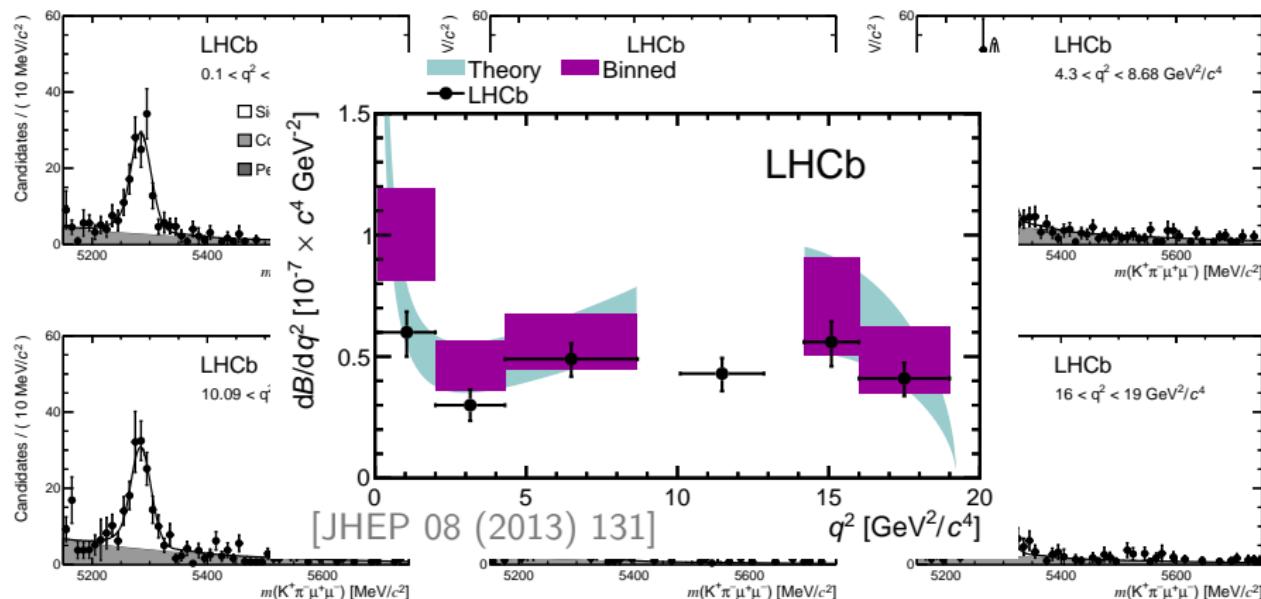
- Veto of $B^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow \psi(2S)K^{*0}$ (valuable control channels!)
- Suppression of peaking backgrounds with PID
Rejection of combinatorial background with BDT
- 1 Determine the differential branching fraction in q^2 bins
- 2 Determine angular observables in multidimensional likelihood fit

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



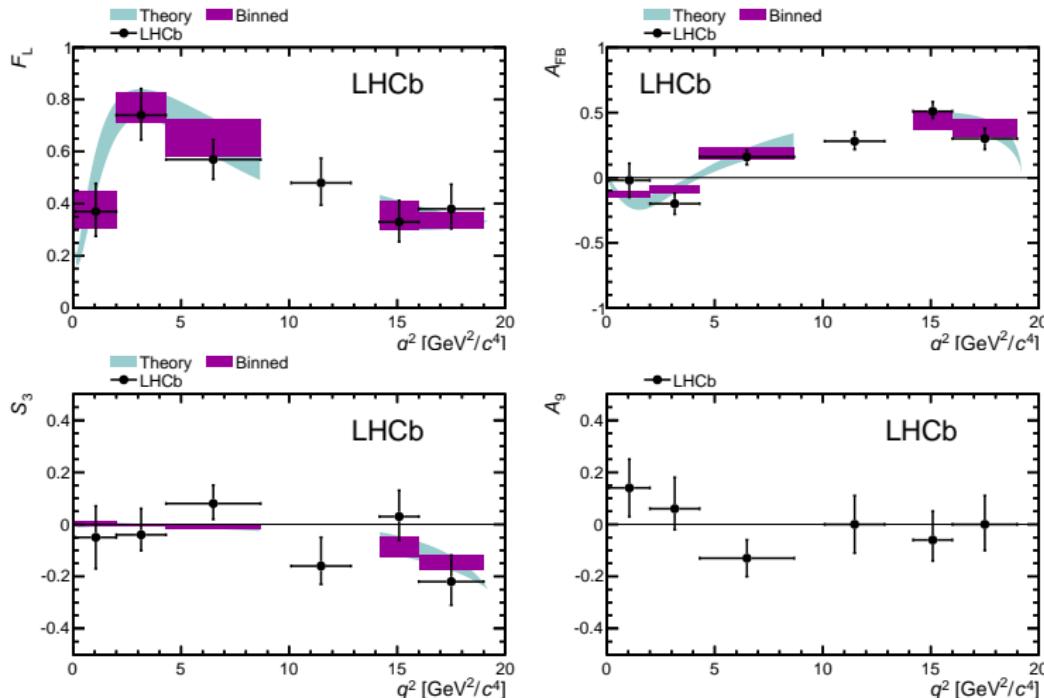
- Fit of N_{sig} in q^2 bins
- Use $B^0 \rightarrow J/\psi K^{*0}$ as normalisation channel
- SM prediction [C. Bobeth et al. JHEP 07 (2011) 067]
- Data somewhat low but large theory uncertainties due to FF

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



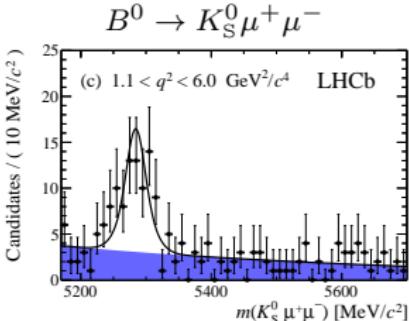
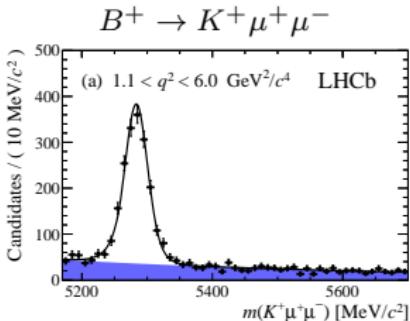
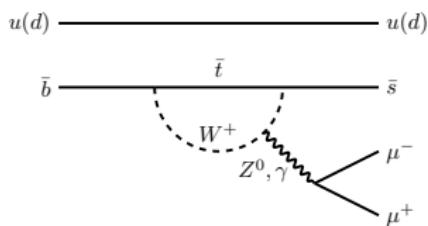
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$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular observables I



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

Angular analysis of $B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^0 \rightarrow K_S^0 \mu^+ \mu^-$



[JHEP 05 (2014) 082]

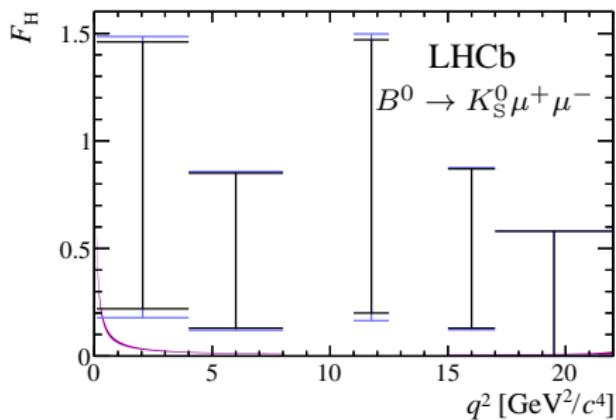
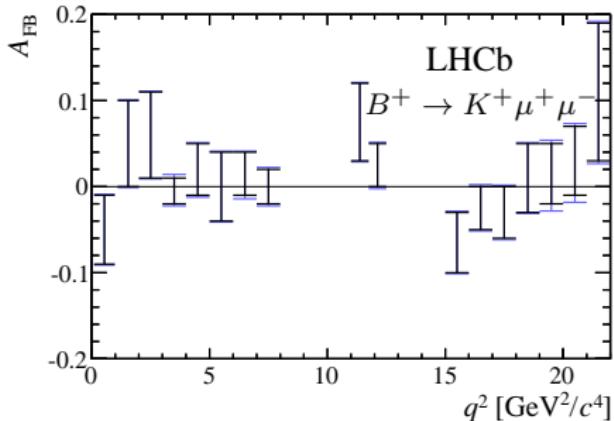
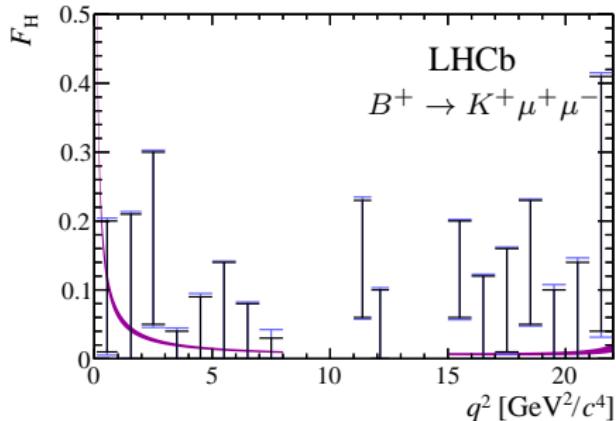
- $N_{B^+ \rightarrow K^+ \mu^+ \mu^-} = 4746 \pm 81$ and $N_{B^0 \rightarrow K_S^0 \mu^+ \mu^-} = 176 \pm 17$ in 3 fb^{-1}
- Experimental challenge: K_S^0 reconstruction
- Differential decay rate for $B^+ \rightarrow K^+ \mu^+ \mu^-$

$$\frac{1}{\Gamma} \frac{d\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{d \cos \theta_\ell} = \frac{3}{4} (1 - \textcolor{blue}{F}_H) (1 - \cos^2 \theta_\ell) + \frac{1}{2} \textcolor{blue}{F}_H + A_{FB} \cos \theta_\ell$$

$$\frac{1}{\Gamma} \frac{d\Gamma(B^0 \rightarrow K_S^0 \mu^+ \mu^-)}{d |\cos \theta_\ell|} = \frac{3}{2} (1 - \textcolor{blue}{F}_H) (1 - |\cos \theta_\ell|^2) + \textcolor{blue}{F}_H$$

- Flat parameter $\textcolor{blue}{F}_H$ sensitive to (Pseudo)scalar contributions, small in SM
- Forward backward asymmetry A_{FB} zero in SM

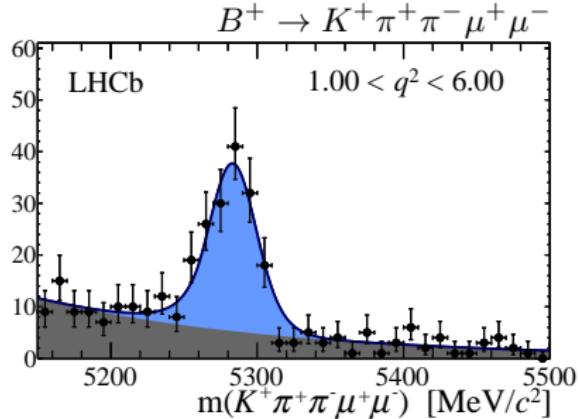
Angular analysis of $B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^0 \rightarrow K_s^0 \mu^+ \mu^-$



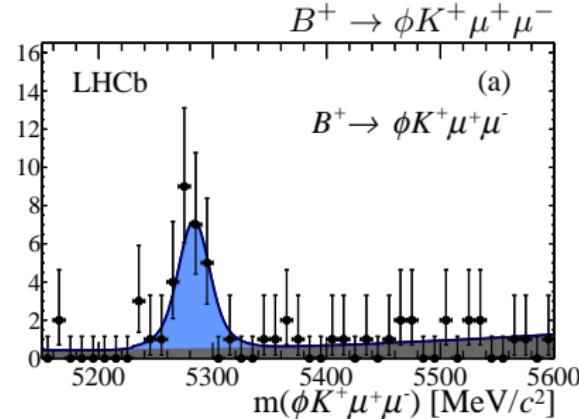
- 2D fit in $\cos \theta_\ell$ and $m(K\mu^+\mu^-)$
- [JHEP 05 (2014) 082] in good agreement with SM prediction

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

Candidates / (10 MeV/c²)



Candidates / (10 MeV/c²)

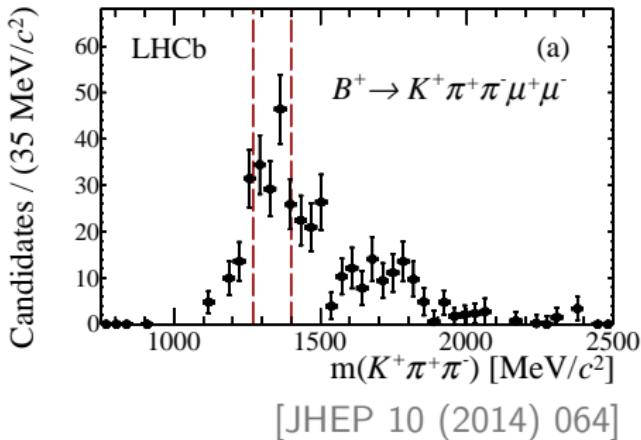
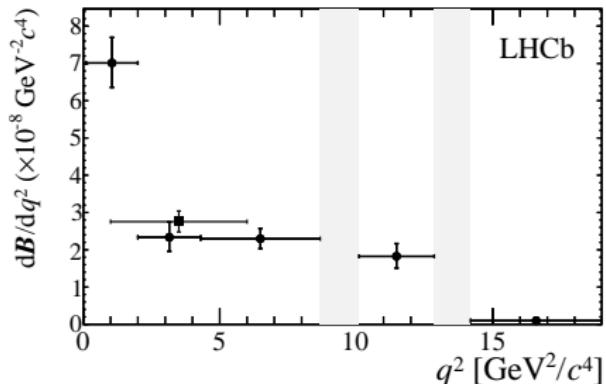


[JHEP 10 (2014) 064]

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

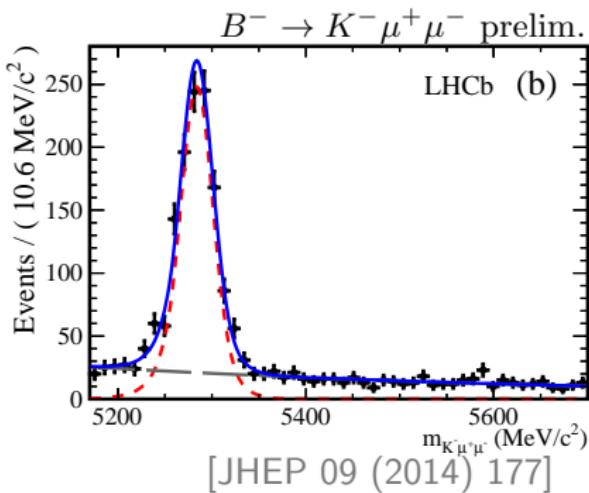
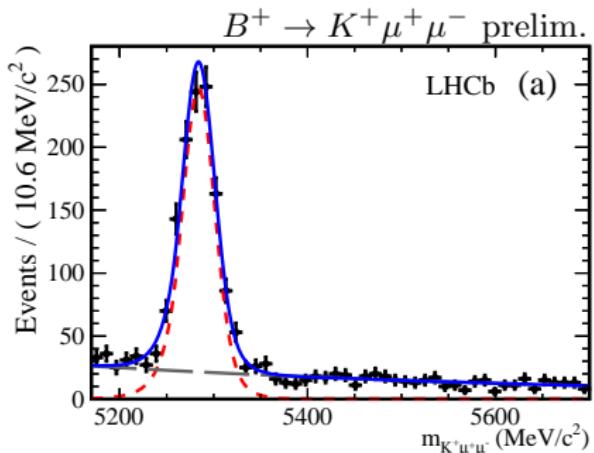
$$\mathcal{B}(B^+ \rightarrow K^+\pi^+\pi^-\mu^+\mu^-) = (4.36^{+0.29}_{-0.27} \text{ (stat)} \pm 0.20 \text{ (syst)} \pm 0.18 \text{ (norm)}) \times 10^{-7}$$

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

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

- Performed measurement of $d\mathcal{B}(B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-)/dq^2$
- Significant contribution from $B^+ \rightarrow K_1^+(1270)\mu^+ \mu^-$ expected
- Low statistics → no attempt to resolve contributions to $K^+ \pi^+ \pi^-$ final state

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



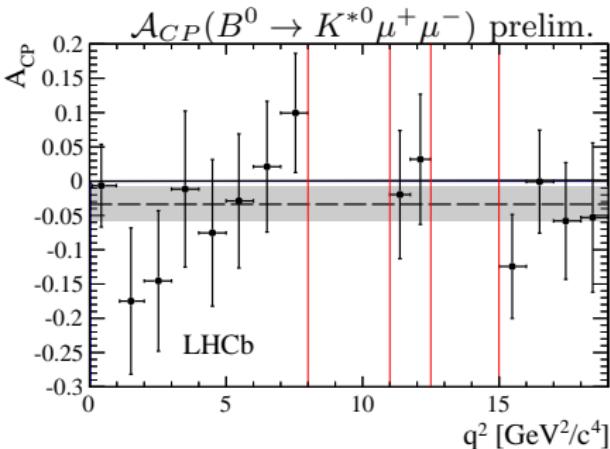
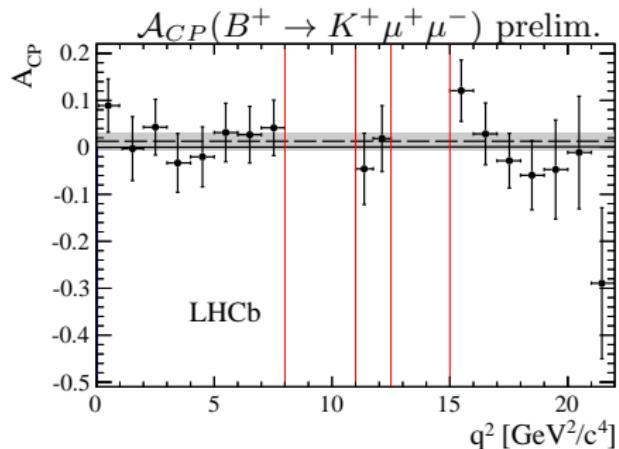
■ Direct CP-Asymmetry \mathcal{A}_{CP}

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

■ \mathcal{A}_{CP} tiny $\mathcal{O}(10^{-3})$ in the SM

■ Correct for detection and production asymmetry using $B \rightarrow J/\psi K^{(*)}$

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

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

[JHEP 09 (2014) 177]

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

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

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

- 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	$\phi_s(B_s^0 \rightarrow J/\psi \phi)$ (rad)	0.049	0.025	0.009	~ 0.003
	$\phi_s(B_s^0 \rightarrow J/\psi f_0(980))$ (rad)	0.068	0.035	0.012	~ 0.01
	$A_{sl}(B_s^0) (10^{-3})$	2.8	1.4	0.5	0.03
Gluonic penguin	$\phi_s^{\text{eff}}(B_s^0 \rightarrow \phi\phi)$ (rad)	0.15	0.10	0.018	0.02
	$\phi_s^{\text{eff}}(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	0.023	< 0.02
	$2\beta^{\text{eff}}(B^0 \rightarrow \phi K_S^0)$ (rad)	0.30	0.20	0.036	0.02
Right-handed currents	$\phi_s^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)$ (rad)	0.20	0.13	0.025	< 0.01
	$\tau^{\text{eff}}(B^0 \rightarrow \phi\gamma)/\tau_{no}$	5%	3.2%	0.6%	0.2 %
Electroweak penguin	$S_3(B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.04	0.020	0.007	0.02
	$q_0^2 A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$	10%	5%	1.9%	$\sim 7\%$
	$A_l(K\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.09	0.05	0.017	~ 0.02
	$\mathcal{B}(B^+ \rightarrow \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$	14%	7%	2.4%	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) (10^{-9})$	1.0	0.5	0.19	0.3
	$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	220%	110%	40%	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \rightarrow D^{(*)}K^{(*)})$	7°	4°	0.9°	negligible
Charm	$A_\Gamma(D^0 \rightarrow K^+K^-) (10^{-4})$	3.4	2.2	0.4	–
CP violation	$\Delta A_{CP} (10^{-3})$	0.8	0.5	0.1	–