

Rare semileptonic b -hadron decays at LHCb

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on behalf of the LHCb collaboration

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SUSY 2016, Melbourne, Australia

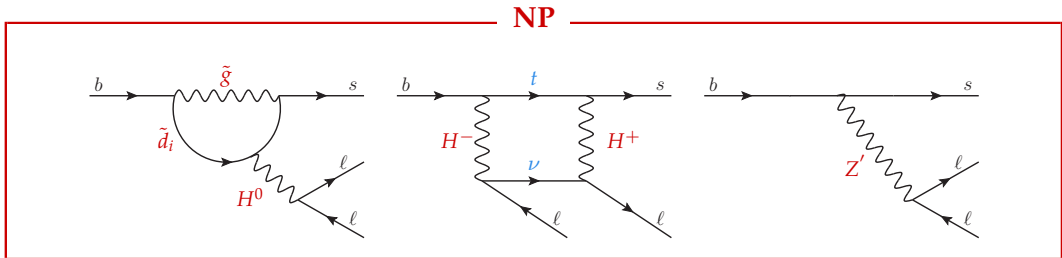
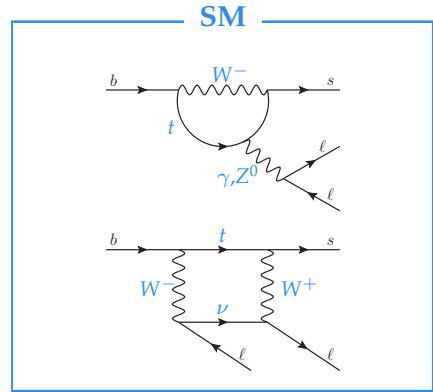


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Rare decays as a probe for New Physics

- ▶ Talk will focus on $b \rightarrow sl^+l^-$ transitions
- ▶ Rare FCNC processes are only possible via loop diagrams in SM
 - ▶ Highly suppressed
- ▶ New, heavy particles in SM extensions can enter the loop and modify observables
 - ▶ e.g. enhance/suppress \mathcal{B} , alter angular distributions, new sources of CP violation

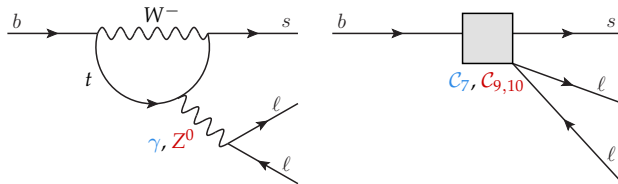


Theoretical formalism

- ▶ Rare b -hadron decays are a multi-scale problem: $m_W \gg m_b > \Lambda_{\text{QCD}}$
- ▶ Measurements interpreted in Operator Product Expansion framework
 - ▶ All degrees of freedom above a given energy scale are integrated out
 - ▶ Introduce set of Wilson coefficients, C_i , and local operators, \mathcal{O}_i , encoding coupling strength and Lorentz structure

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

- ▶ $b \rightarrow s \ell^+ \ell^-$ transitions sensitive to C_7, C_9, C_{10}



Angular analysis of $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\mu^+\mu^-$

[JHEP 02 (2016) 104]

- ▶ Decay fully described by dimuon invariant mass squared, q^2 , and three angles
 $\vec{\Omega} = (\cos \theta_\ell, \cos \theta_K, \phi)$

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} \Big|_{\text{P-wave}} =$$

$$\frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right.$$

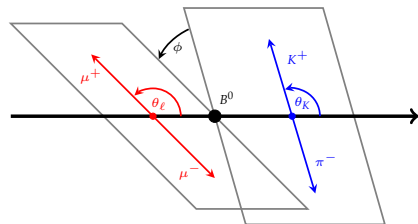
$$+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell$$

$$- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi$$

$$+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi$$

$$+ \frac{4}{3} A_{\text{FB}} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi$$

$$\left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

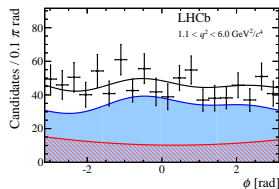
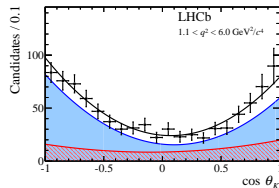
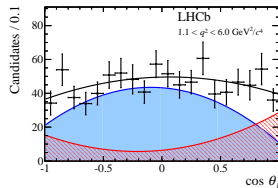
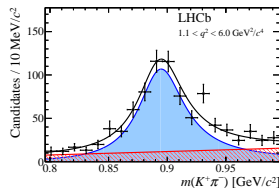
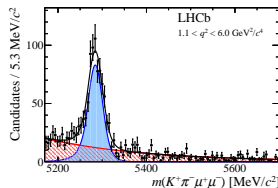


- ▶ F_L, A_{FB}, S_i combinations of K^{*0} amplitudes which depend on the Wilson coefficients and the form factors
- ▶ Pollution from $K^+\pi^-$ in S-wave configuration also taken into account

Angular analysis of $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\mu^+\mu^-$

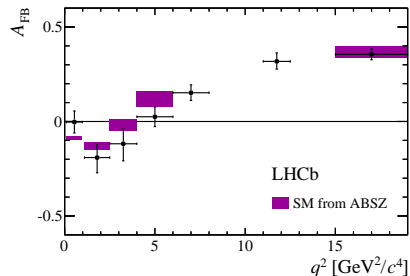
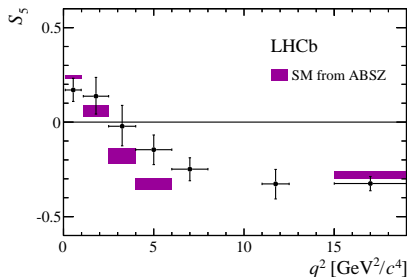
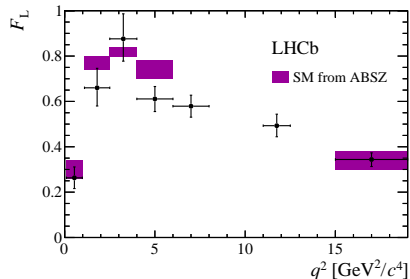
[JHEP 02 (2016) 104]

- ▶ First full angular analysis of the decay through a maximum likelihood fit to the data
- ▶ Full Run I dataset
- ▶ Fit performed in $796 < m(K^+\pi^-) < 996 \text{ MeV}/c^2$ region
- ▶ Simultaneous fit to $m(K^+\pi^-)$ to constrain S-wave fraction
- ▶ Projections shown for q^2 bin $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

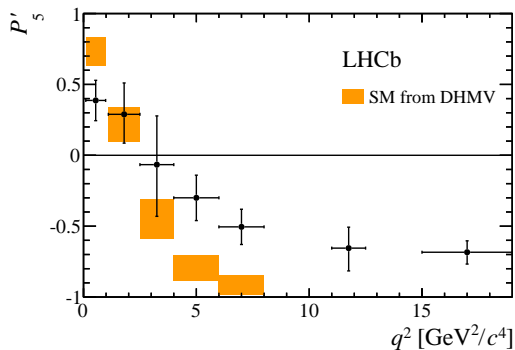


$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ fit results - F_L , A_{FB} , S_5

[JHEP 02 (2016) 104]



- ▶ Full set of CP -averaged and CP -asymmetric angular terms and their correlations
- ▶ General good agreement with the SM prediction
- ▶ Some tension observed in S_5
- ▶ SM [ABSZ]



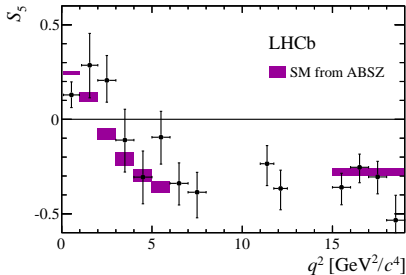
- ▶ Also determine “less form factor dependent” observables e.g.

$$P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

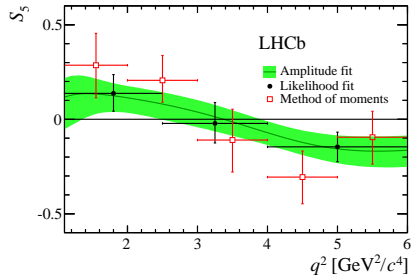
- ▶ Local tension with SM predictions (2.8σ and 3.0σ)
- ▶ SM [DHMV]

Angular moments analysis and zero crossing points [JHEP 02 (2016) 104]

- ▶ Observables also measured using angular moments analysis
- ▶ Robust estimator even for small datasets
- ▶ Allows finer binning in q^2
- ▶ Statistically less precise than result of maximum likelihood fit



- ▶ Determine zero crossing points by parameterising the angular distribution in terms of q^2 dependent decay amplitudes



$$q_0^2(S_5) \in [2.49, 3.95] \text{ GeV}^2/c^4 \text{ at 68\% C.L.}$$

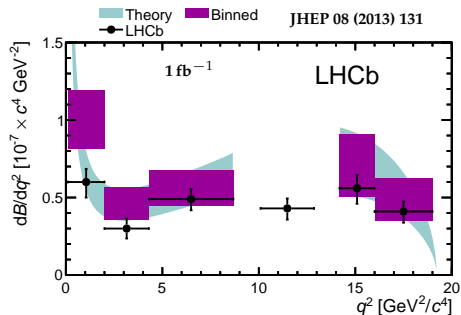
$$q_0^2(A_{\text{FB}}) \in [3.40, 4.87] \text{ GeV}^2/c^4 \text{ at 68\% C.L.}$$

$$q_0^2(S_4) < 2.65 \text{ GeV}^2/c^4 \text{ at 68\% C.L.}$$

Differential branching fraction of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

[arXiv:1606.04731]

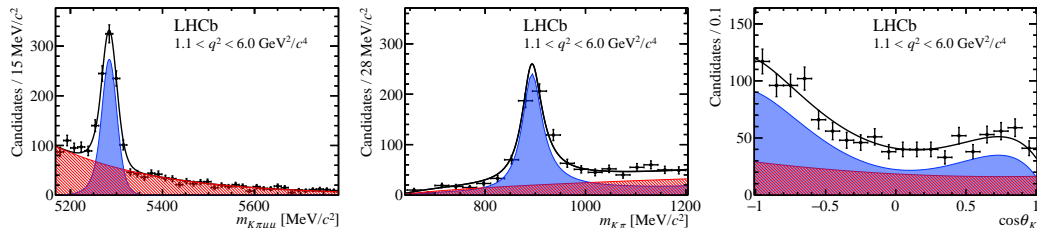
- ▶ For $796 < m(K^+ \pi^-) < 996 \text{ MeV}/c^2$ the K^{*0} found predominately in P-wave
- ▶ Previous $d\mathcal{B}/dq^2$ measurement made with 1/3 of Run I dataset
- ▶ S-wave fraction (F_S) expected at level of $< 10\%$
- Treated as a systematic uncertainty



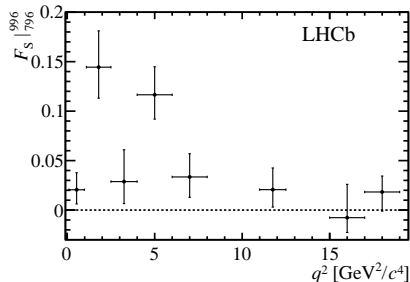
- ▶ New $d\mathcal{B}/dq^2$ measurement using full Run I dataset explicitly accounting for S-wave contribution
- ▶ F_S determined from fit to $m(K^+ \pi^-)$ and decay angle $\cos \theta_K$

Measurement of F_S in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

[arXiv:1606.04731]



- ▶ F_S determined in two regions:
 $m(K^+\pi^-) \in [644, 1200] \text{ MeV}/c^2$ and
 $m(K^+\pi^-) \in [796, 996] \text{ MeV}/c^2$
- ▶ Explicit modelling of $m(K^+\pi^-)$ system
 - ▶ P-wave: Relativistic BW
 - ▶ S-wave: LASS



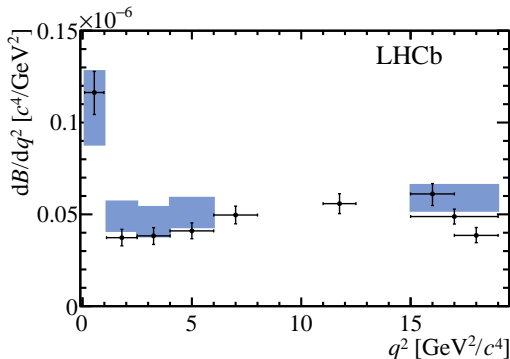
Differential branching fraction of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

[arXiv:1606.04731]

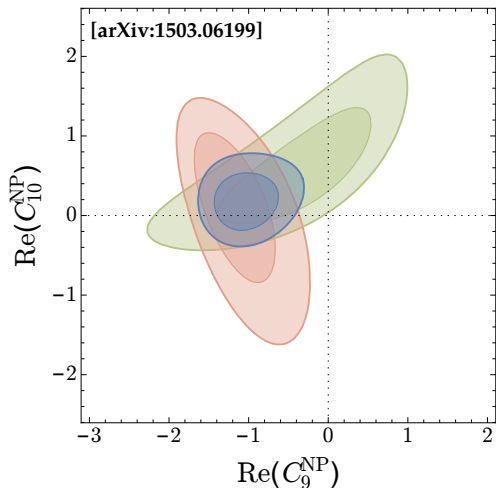
- ▶ **First** exclusive measurement of $d\mathcal{B}(B^0 \rightarrow K^*(892)^0 \mu^+ \mu^-)/dq^2$

$$\frac{d\mathcal{B}[B^0 \rightarrow K^*(892)^0 \mu^+ \mu^-]}{dq^2} = \frac{R_\epsilon}{(q_{\max}^2 - q_{\min}^2)} \frac{(1 - F_S|_{644}^{1200}) n_{K^{*0} \mu^+ \mu^-}}{(1 - F_S^{J/\psi K^{*0}}) n_{J/\psi K^{*0}}} \mathcal{B}(B^0 \rightarrow J/\psi K^*(892)^0) \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$$

- ▶ Results compatible with SM predictions
 - ▶ SM [arXiv:1503.05534]
- ▶ Also consistent with pattern of lower branching fractions for $b \rightarrow s \mu^+ \mu^-$ transitions than predicted by theory
 - ▶ e.g. $\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$, $\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-)$, $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-)$
 - ▶ Large theoretical uncertainties, correlated across q^2



Intepretation



Branching fractions, angular
observables, combined

- ▶ Several attempts to interpret LHCb data by performing global fits
- ▶ Consistent picture, data favours modified vector coupling (C_9^{NP}) at $\sim [3, 4]\sigma$

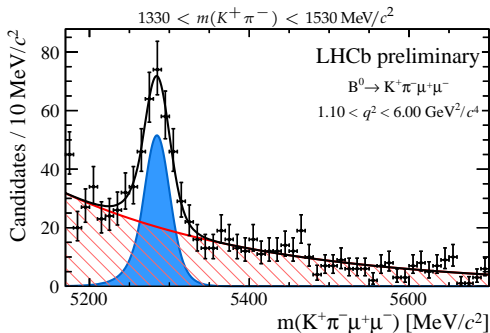
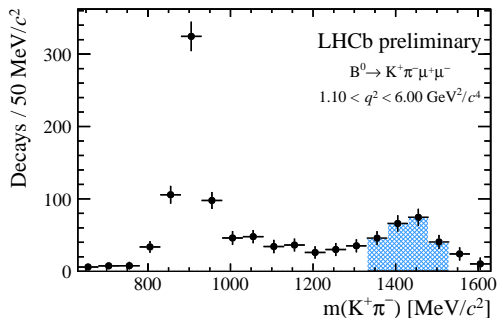
Possible intepretation

- ▶ NP physics scenario, e.g. new vector Z' , leptoquarks, etc
- ▶ Problem with our understanding of QCD, e.g. not properly estimating contribution from charm loops

New: $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ in the $K_{0,2}^*(1430)^0$ region

[LHCb-PAPER-2016-025]

- ▶ Analyses of $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ at LHCb have previously focused on the $K^*(892)^0$
- ▶ Region of $m(K^+ \pi^-) \sim 1430 \text{ MeV}/c^2$ contains contributions from $K_1^*(1410)^0$, $K_0^*(1430)^0$ and $K_2^*(1430)^0$
- ▶ Allows for a complementary measurement of $b \rightarrow s \mu^+ \mu^-$ transitions



New: $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ in the $K_{0,2}^*(1430)^0$ region

[LHCb-PAPER-2016-025]

- ◆ Measurements performed in the $1330 < m(K^+ \pi^-) < 1530 \text{ MeV}/c^2$ region at low q^2

- ① Differential branching fraction as a function of q^2
 - ▶ 5 q^2 bins: [0.1,0.98], [1.1,2.5], [2.5,4.0], [4.0,6.0], [6.0,8.0] GeV^2/c^4
 - ▶ Normalised to $B^0 \rightarrow J/\psi K^*(892)^0$

- ② Angular analysis
 - ▶ Single q^2 bin: [1.1,6.0] GeV^2/c^4
 - ▶ S-, P- and D-wave contributions considered for first time
 - ▶ Requires new orthonormal basis of angular functions

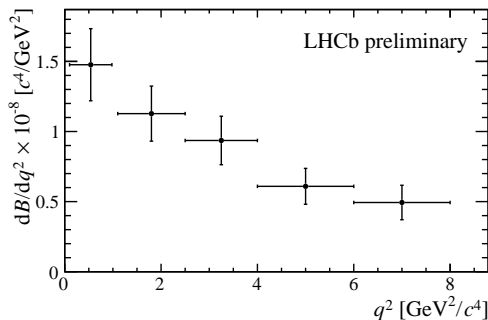
New: $d\mathcal{B}/dq^2$ in the $K_{0,2}^*(1430)^0$ region

[LHCb-PAPER-2016-025]

$$\frac{d\mathcal{B}(B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-)}{dq^2} = \frac{1}{(q_{\max}^2 - q_{\min}^2)} f_{K^*(892)^0} \mathcal{B}(B^0 \rightarrow J/\psi K^*(892)^0) \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$$

$$\times \mathcal{B}(K^*(892)^0 \rightarrow K^+ \pi^-) \frac{N_{K^+ \pi^- \mu^+ \mu^-}}{(1 - F_S^{J/\psi K^{*0}}) N_{J/\psi K^{*0}}} \frac{\varepsilon_{J/\psi K^{*0}}}{\varepsilon_{K^+ \pi^- \mu^+ \mu^-}}$$

- ▶ **First $d\mathcal{B}/dq^2$ measurement of $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ in this region of $m(K^+ \pi^-)$**
- ▶ $B^0 \rightarrow J/\psi K^*(892)^0$ yield measured in $796 < m(K^+ \pi^-) < 996 \text{ MeV}/c^2$
 - ▶ $f_{K^*(892)^0}$ accounts for $m(K^+ \pi^-)$ window
 - ▶ $F_S^{J/\psi K^{*0}}$ corrects for S-wave fraction



New: Angular analysis in the $K_{0,2}^*(1430)^0$ region [LHCb-PAPER-2016-025]

- ▶ CP -averaged differential decay rate of $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ decays with the $K\pi$ system in a S-, P- or D-wave configuration is expanded in an orthonormal basis of angular functions, $f_i(\Omega)$, [PRD92(2015)033013]

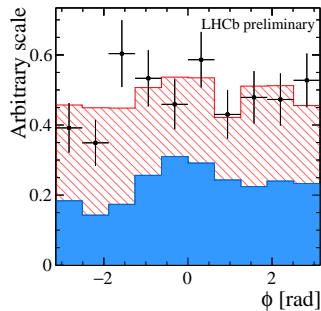
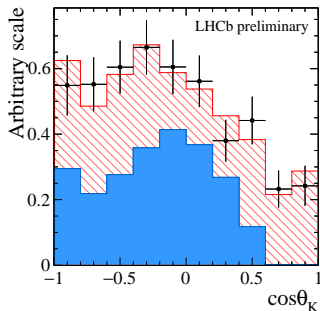
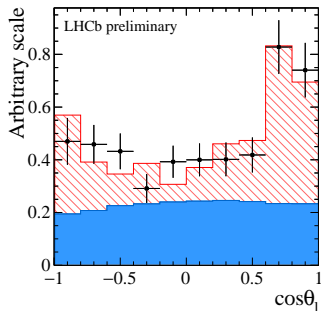
$$\frac{d\Gamma}{dq^2 d\Omega} = \mathcal{C} \times \left\{ \sum_{i=1}^{41} f_i(\Omega) \Gamma_i(q^2) \right\} \quad \text{with} \quad \Gamma_i(q^2) = \Gamma_i^L(q^2) + \eta_i^{L \rightarrow R} \Gamma_i^R(q^2)$$

- ▶ Orthonormal angular basis constructed from spherical harmonics $Y_\ell^m \equiv Y_\ell^m(\theta_\ell, \phi)$ and reduced spherical harmonics $P_\ell^m \equiv \sqrt{2\pi} Y_\ell^m(\theta_K, 0)$
- ▶ $\Gamma_i(q^2)$ combinations of K_j^{*0} amplitudes with $\Gamma_1(q^2)$ corresponding to the total rate
- ▶ Define 40 normalised angular moments which forms set of observables

$$\bar{\Gamma}_i(q^2) = \frac{\Gamma_i(q^2)}{\Gamma_1(q^2)}$$

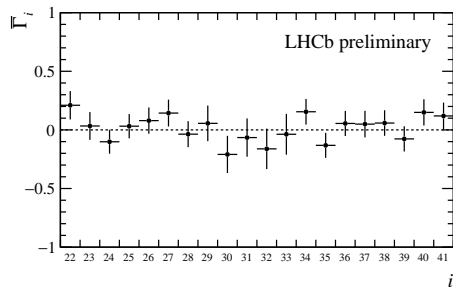
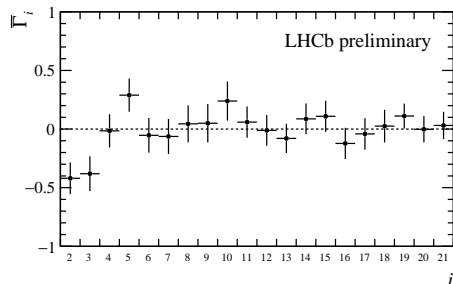
New: Angular analysis in the $K_{0,2}^*(1430)^0$ region [LHCb-PAPER-2016-025]

- ▶ Observables measured using an angular moments analysis
 - ▶ Likelihood fit impossible due to complicated angular expression and limited statistics
- ▶ Distributions of the decays angles within $\pm 50 \text{ MeV}/c^2$ of the nominal B^0 mass
 - ▶ Blue: estimated signal distribution obtained from the angular moments model
 - ▶ Red: projected background from upper mass sideband



New: Angular analysis in the $K_{0,2}^*(1430)^0$ region [LHCb-PAPER-2016-025]

- ▶ Specific moments point towards large interference between S- and P-wave states
- ▶ Evidence for a suppressed D-wave contribution
 - ▶ $F_D < 0.29$ @ 95% C.L.
 - ▶ Low w.r.t expectation from amplitude analysis of $B^0 \rightarrow J/\psi K\pi$ [PRD90(2014)112009]
- ▶ Access to full information, including extraction of Wilson coefficients requires form-factor predictions
 - ◆ Only very preliminary predictions exist
 - ★ Hope measurement will stimulate further theory effort



Summary

- ▶ Flavour observables in rare decays allow for NP searches and can place many strong constraints on NP models
- ▶ Several interesting tensions observed in $b \rightarrow s\ell^+\ell^-$ processes
- ▶ Still many interesting results are foreseen with LHCb Run I dataset
 - ▶ Major effort to compare observables between $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow se^+e^-$ e.g. $\phi, K^{*0}, \Lambda^{(*)}$
 - ▶ Understand the effect of $c\bar{c}$ resonances by measuring the interference of resonant and penguin contributions in $B^+ \rightarrow K^+\mu^+\mu^-$
- ▶ Run II data will boost precision even further!

Further LHCb talks @ SUSY2016

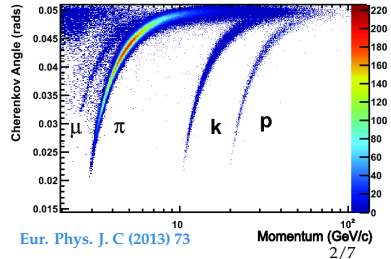
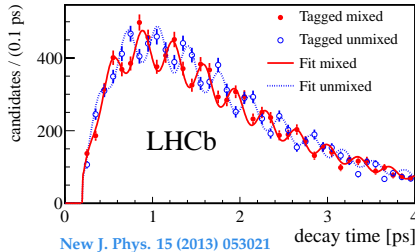
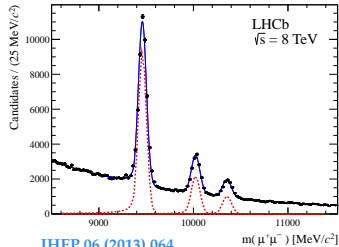
Gerco Onderwater, "Tests of Lepton Flavour Universality and searches for Lepton Flavor Violation at LHCb", tomorrow

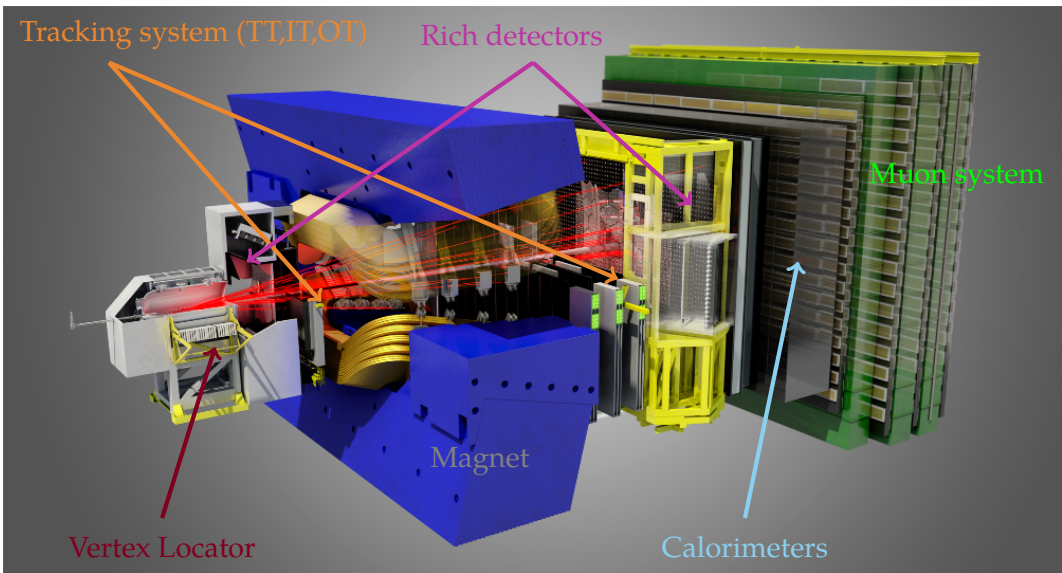
An aerial night view of a city skyline, likely Denver, Colorado, featuring a prominent skyscraper (1960 Broadway) and a river (Cherry Creek) winding through the urban landscape. The city is illuminated with lights from buildings and streets, creating a vibrant scene against the dark blue twilight sky. The word "Backup" is overlaid in white serif font in the upper right quadrant.

Backup

The LHCb experiment

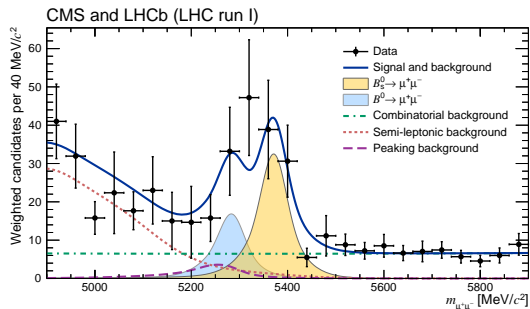
- ▶ LHCb is the dedicated heavy flavour physics experiment at the LHC
- ▶ Its primary goal is to look for indirect evidence of new physics in CP violation and rare decays of b - and c -hadrons
- ▶ Requirements:
 1. Excellent tracking
 - ▶ momentum resolution ($\Delta p/p \sim 0.4\% - 0.6\%$)
 - ▶ impact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





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

LHCb+CMS [Nature 522 (2015)]



SM prediction

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

C. Bobeth et al., PRL 112, 101801 (2014)

LHCb +CMS

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8_{-0.6}^{+0.7}) \times 10^{-9}$$

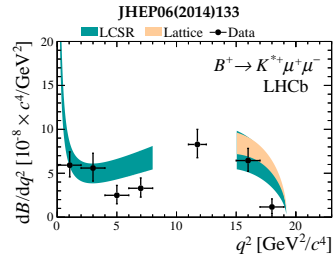
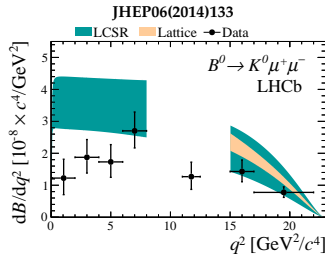
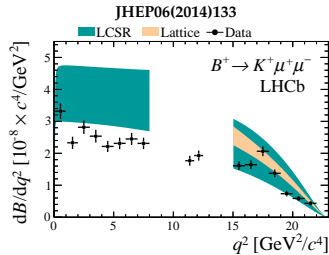
Significance of 6.2σ and compatible with SM at 1.2σ

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.9_{-1.4}^{+1.6}) \times 10^{-10}$$

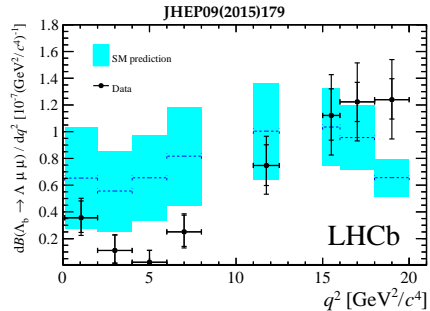
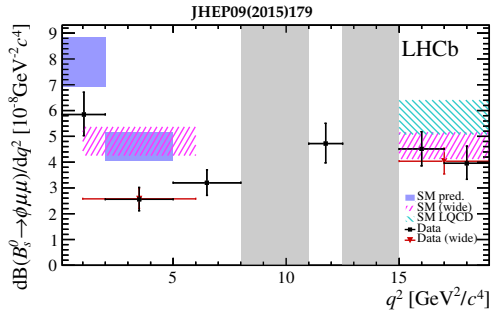
Significance of 3.0σ and compatible with SM at 2.2σ

Differential branching fractions - volume I

- ▶ Large LHCb datasets allows for precise measurements of the $d\mathcal{B}/dq^2$ of $b \rightarrow s\mu^+\mu^-$ processes
- ▶ Results hint towards lower rates than predicted by theory
 - ▶ Theory uncertainty are correlated across q^2



Differential branching fractions - volume II



- ▶ Similar experiment/theory disagreement seen in other channels
 - ▶ $\frac{d\mathcal{B}}{dq^2}[B_s^0 \rightarrow \phi \mu^+ \mu^-]$ is 3.3σ from SM prediction in $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$
- ▶ All branching fraction measurements potentially point to new physics in C_9
 - ▶ e.g. new vector Z'

New: Angular analysis in the $K_{0,2}^*(1430)^0$ region [LHCb-PAPER-2016-025]

- The transversity-basis moments of the first 10 (of 41) orthonormal angular functions outlined in [PRD92(2015)033013]

i	$f_i(\Omega)$	$\Gamma_i^{L,\text{tr}}(q^2)$	$\eta_i^{L \rightarrow R}$
1	$P_0^0 Y_0^0$	$ H_0^L ^2 + H_{\parallel}^L ^2 + H_{\perp}^L ^2 + S^L ^2 + D_0^L ^2 + D_{\parallel}^L ^2 + D_{\perp}^L ^2$	$+(L \rightarrow R)$
2	$P_1^0 Y_0^0$	$2 \left[\frac{2}{\sqrt{5}} \text{Re}(H_0^L D_0^{L*}) + \text{Re}(S^L H_0^{L*}) + \sqrt{\frac{3}{5}} \text{Re}(H_{\parallel}^L D_{\parallel}^{L*} + H_{\perp}^L D_{\perp}^{L*}) \right]$	"
3	$P_2^0 Y_0^0$	$\frac{\sqrt{5}}{7} (D_{\parallel}^L ^2 + D_{\perp}^L ^2) - \frac{1}{\sqrt{5}} (H_{\parallel}^L ^2 + H_{\perp}^L ^2) + \frac{2}{\sqrt{5}} H_0^L ^2 + \frac{10}{7\sqrt{5}} D_0^L ^2 + 2 \text{Re}(S^L D_0^{L*})$	"
4	$P_3^0 Y_0^0$	$\frac{6}{\sqrt{35}} \left[-\text{Re}(H_{\parallel}^L D_{\parallel}^{L*} + H_{\perp}^L D_{\perp}^{L*}) + \sqrt{3} \text{Re}(H_0^L D_0^{L*}) \right]$	"
5	$P_4^0 Y_0^0$	$\frac{2}{7} \left[-2(D_{\parallel}^L ^2 + D_{\perp}^L ^2) + 3 D_0^L ^2 \right]$	"
6	$P_0^0 Y_2^0$	$\frac{1}{2\sqrt{5}} (D_{\parallel}^L ^2 + D_{\perp}^L ^2) + (H_{\parallel}^L ^2 + H_{\perp}^L ^2) - 2 S^L ^2 - 2 D_0^L ^2 - 2 H_0^L ^2$	"
7	$P_1^0 Y_2^0$	$\frac{\sqrt{3}}{5} \text{Re}(H_{\parallel}^L D_{\parallel}^{L*} + H_{\perp}^L D_{\perp}^{L*}) - \frac{2}{\sqrt{5}} \text{Re}(S^L H_0^{L*}) - \frac{4}{5} \text{Re}(H_0^L D_0^{L*})$	"
8	$P_2^0 Y_2^0$	$\frac{1}{14} (D_{\parallel}^L ^2 + D_{\perp}^L ^2) - \frac{2}{7} D_0^L ^2 - \frac{1}{10} (H_{\parallel}^L ^2 + H_{\perp}^L ^2) - \frac{2}{5} H_0^L ^2 - \frac{2}{\sqrt{5}} \text{Re}(S^L D_0^{L*})$	"
9	$P_3^0 Y_2^0$	$-\frac{3}{5\sqrt{7}} \left[\text{Re}(H_{\parallel}^L D_{\parallel}^{L*} + H_{\perp}^L D_{\perp}^{L*}) + 2\sqrt{3} \text{Re}(H_0^L D_0^{L*}) \right]$	"
10	$P_4^0 Y_2^0$	$-\frac{2}{7\sqrt{5}} \left[D_{\parallel}^L ^2 + D_{\perp}^L ^2 + 3 D_0^L ^2 \right]$	"

- The S-, P- and D-wave transversity amplitudes are denoted as $S^{\{L,R\}}$, $H_{\{0,\parallel,\perp\}}^{\{L,R\}}$ and $D_{\{0,\parallel,\perp\}}^{\{L,R\}}$, respectively.