Studies of $b \to s(d)\mu\mu$ EW penguin transitions at LHCb

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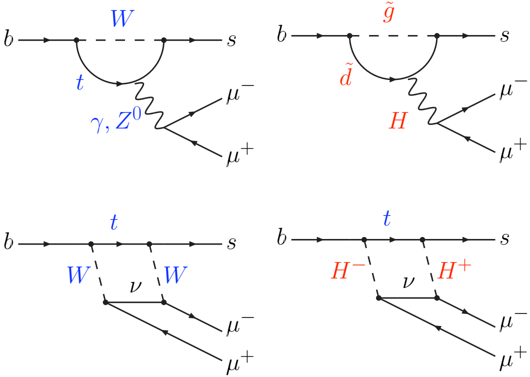
On behalf of the LHCb collaboration

DISCRETE 2012

Rare B decays

- Flavour changing neutral currents are forbidden at tree level in SM
- $b \to s(d)$ transitions mediated via a loop diagram
- In SM extensions, can receive contributions from new virtual particles
- New Physics can contribute at same level as SM giving possibility of large NP effects

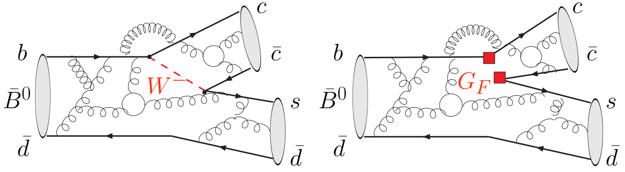


Theoretical Formalism

- Model independent approach
- "Integrate" out heavy ($m \geq m_W$) field(s) and introduce set of operators ($\mathcal{O}_i$) and Wilson coefficients (C_i)

$$\mathcal{H}_{eff} \approx -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts(d)} \sum_{i=1}^{10} (C_i^{SM} + \Delta C_i^{NP}) \mathcal{O}_i + \sum_{NP} \frac{C_{NP}}{\Lambda^2_{NP}} \mathcal{O}_{NP}$$

- c.f. Fermi interaction and G_F



- New physics enters at the Λ_{NP} scale
- New physics models can modify SM coefficients and introduce new operators

Sensitivity to New Physics

- $b \to s(d)\mu^+\mu^-$ transitions probe a range of operators

Operator $\mathcal{O}_i$	$B_{s(d)} \to X_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to X_{s(d)}\gamma$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma^{\mu\nu}b_R)F_{\mu\nu}$	✓		✓
$\mathcal{O}_9 \sim (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell)$	✓		
$\mathcal{O}_{10} \sim (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_5\gamma_\mu\ell)$	✓	✓	
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S,P}(\bar{\ell}\ell)_{S,P}$		✓	

- In SM $C_{S,P} \propto m_\ell m_b/m_W^2 \sim 0$
- In SM chirality flipped $\mathcal{O}_i$ suppressed by m_s/m_b

Decays and observables studied in LHCb

Decay	Observables
$B^0 \to K^{*0}\mu^+\mu^-$	$F_L, A_{FB}, S_3, S_9, A_{CP}$
$B^+ \to K^+\mu^+\mu^-$	$\mathcal{B}, F_H, A_{FB}$
$B \to K^{(*)}\mu^+\mu^-$	A_I
$B^+ \to \pi^+\mu^+\mu^-$	$\mathcal{B}, \lvert V_{td}\rvert/\lvert V_{ts}\rvert$ (using $B^+ \to K^+\mu^+\mu^-$)

Observables are functions of $m^2_{\mu^+\mu^-}(q^2)$

F_L: Longitudinal polarisation fraction of the K^*

A_{FB}: Di-muon forward-backward asymmetry

S_3: Asymmetry in K^* transverse polarisation

S_9: A T-odd CP asymmetry

A_{CP}: CP asymmetry of B^0 and $\bar{B}^0$ decays

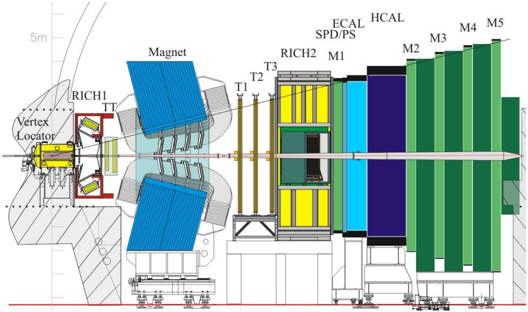
F_H: Contr. from (pseudo)-scalar/tensor to partial width (if $m_\mu = 0$)

A_I: Isospin asymmetry of B^0 and B^+ decays

$\mathcal{B}$: Branching fraction

The LHCb detector and dataset

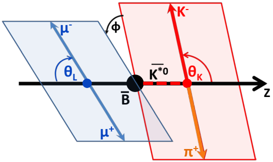
- LHCb is a forward detector ($2 < \eta < 5$) designed to study heavy flavour physics
- Excellent vertex and momentum resolution, excellent particle identification
- **Analyses presented today use $1\,\mathrm{fb}^{-1}$ of 2011 data at $\sqrt{s} = 7$ TeV**
- LHCb has recorded an additional $2\,\mathrm{fb}^{-1}$ of data in 2012 at $\sqrt{s} = 8$ TeV



Typical performance:

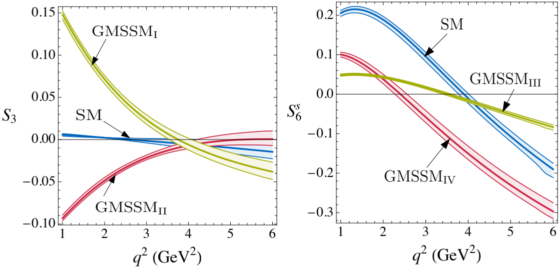
- $\Delta p/p$: $0.4\% - 0.6\%$ for $5 < p < 100$ *GeV*
- trigger eff for di-μ channels: 90%
- Kaon id eff: 95% for 5% mis-id rate
- Muon id eff: 98% for 1% mis-id rate

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ [LHCb-CONF-2012-008]



- Decay described by three angles θ_ℓ,θ_k,ϕ and q^2

- Angular distribution written in terms of six K^{*0} helicity amplitudes (ignoring m_μ and scalar contributions)
- Resulting expression depends on observables with small hadronic uncertainties: A_{FB}, F_L, S_3 and S_9

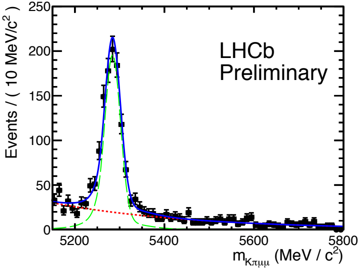


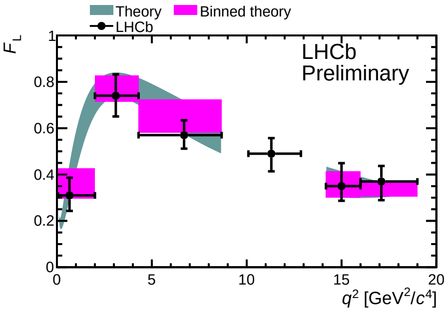
[arXiv:0811.1214]

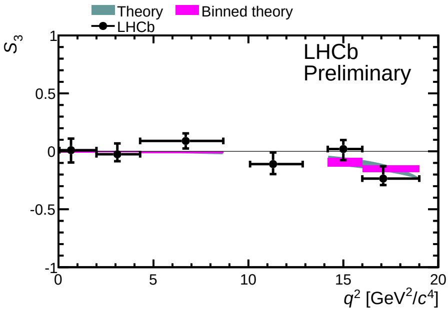
- $S_6^s \propto -A_{FB}$
- Can discriminate between NP models
- Zero crossing point largely free of form factor uncert.

$B^0 \to K^{*0}\mu^+\mu^-$ Results [LHCb-CONF-2012-008]

- Observe $\sim$ 900 signal candidates in $1\ fb^{-1}$ $\sqrt{s} = 7\ TeV$ data
  - More candidates than all previous experiments combined
- Good agreement with SM prediction of observables
- SM predictions from arXiv:1105.0376 and references therein

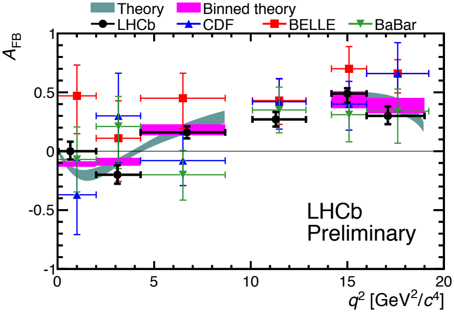


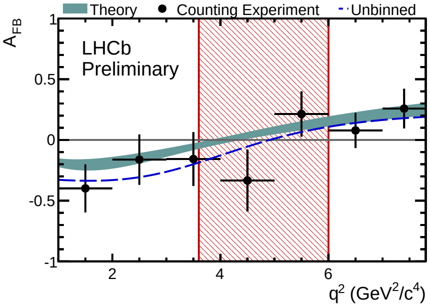




$B^0 \to K^{*0}\mu^+\mu^-$ Results [LHCb-CONF-2012-008]

- The zero crossing point of A_{FB} in the SM is at $q^2 = 4.0 - 4.3\,\text{GeV}^2$ [arXiv:1105.0376]





- The zero crossing point is measured to be at $q^2 = 4.9^{+1.1}_{-1.3}\,\text{GeV}^2$
- **World's first measurement of A_{FB} zero crossing point**
- CDF [PRL 108 (2012) 081807], Belle [PRL 103 (2009) 171801], BaBar [arXiv:1204.3993]

Constraints on scale of New Physics

- Interpret measurements of angular observables in terms of Wilson coefficients which in turn can be translated in scale of NP (Λ_{NP})
- arXiv:1111.1257 and updates from Altmannshofer, Paridisi and Straub
  - Using $B \to X_s\gamma$ information as well

- Tree level O(1) couplings:

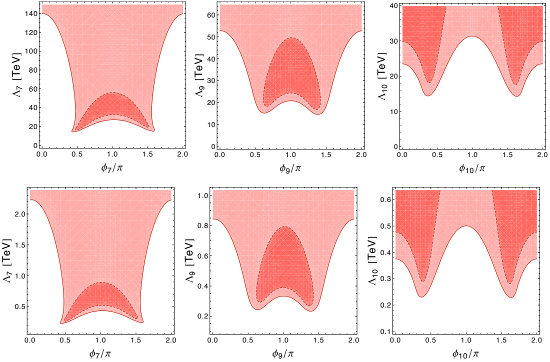
$$L_{NP} \sim \frac{e^{i\phi_{NP}}}{\Lambda_{NP}^2}\mathcal{O}_{NP}$$

$$\boldsymbol{\Lambda_{NP} > O(15\,\mathrm{TeV})}$$

- Loop and CKM like couplings:

$$L_{NP} \sim \frac{V_{tb}V_{ts}^*}{(4\pi)^2}\frac{e^{i\phi_{NP}}}{\Lambda_{NP}^2}\mathcal{O}_{NP}$$

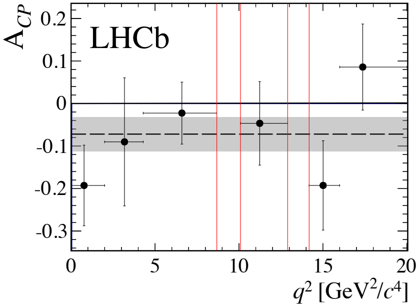
$$\boldsymbol{\Lambda_{NP} > O(300\,\mathrm{GeV})}$$



CP Asymmetry of $B^0 \to K^{*0}\mu^+\mu^-$ [arXiv:1210:4492]

$$A_{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}$$

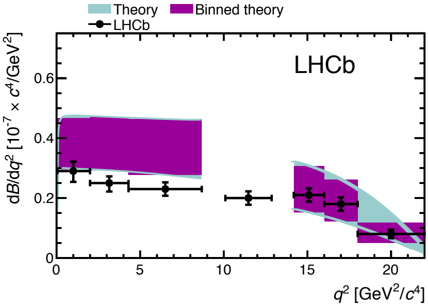
- A_{CP} predicted to be $O(10^{-3})$ in SM [JHEP**07** (2008) 106,JHEP**01**(2009) 019]
- Use ratio between two magnet polarities to cancel detector related asymmetries
- Use $B^0 \to J/\psi K^*$ to account for production related asymmetries



- $A_{CP} = -0.072 \pm 0.040(stat.) \pm 0.005(syst.)$
- Consistent with SM prediction
- **World's most precise measurement**

The decay of $B^+ \to K^+\mu^+\mu^-$ [arXiv:1209.4284]

- Differential branching fraction as function of q^2 is sensitive to the combination of $(C_9 + C_9')$, $(C_{10} + C_{10}')$ and $(C_7 + C_7')$



World's most precise measurement

Theory: [JHEP07 (2011) 067], [JHEP01 (2012) 107]

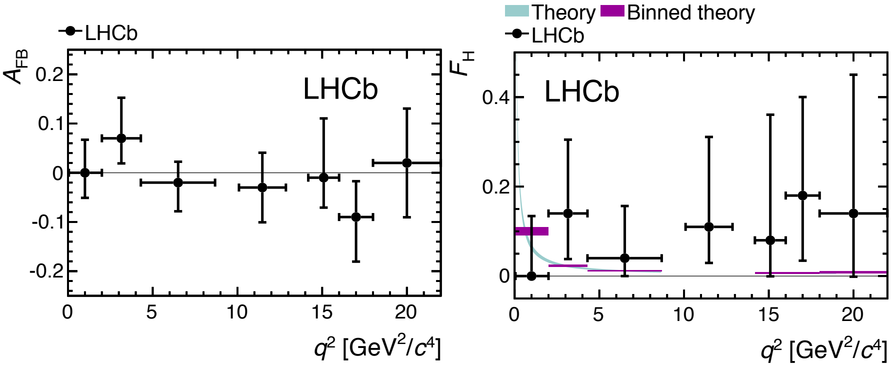
- Fit the $K^+\mu^+\mu^-$ invariant mass distribution in bins of q^2
- Normalize to $B^+ \to K^+ J/\psi$
- Low q^2 measurement slightly below SM prediction
  - Large theoretical uncertainties
  - Uncertainties Correlated across q^2 bins

Angular analysis of $B^+ \to K^+\mu^+\mu^-$ [arXiv:1209.4284]

- Can describe decay with single angle θ_ℓ

$$\frac{d\Gamma}{d\cos\theta_\ell} \propto \frac{3}{4}(1-F_H)(1-\cos^2\theta_\ell) + \frac{1}{2}F_H + A_{FB}\cos\theta_\ell$$

- In SM $F_H \approx 0$ and $A_{FB} = 0$
- Theory: [JHEP07 (2011) 067], [JHEP01 (2012) 107]

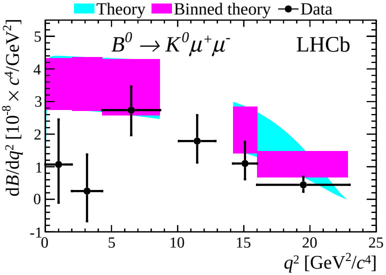


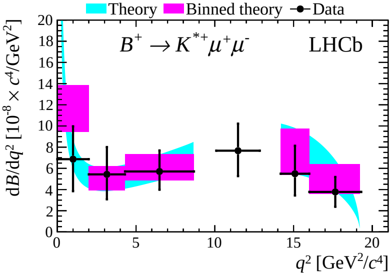
World's most precise measurements

Isospin Asymmetries in $B \to K^{(*)}\mu^+\mu^-$ [JHEP 07 (2012) 133]

$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)0}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)0}\mu^+\mu^-)}$$

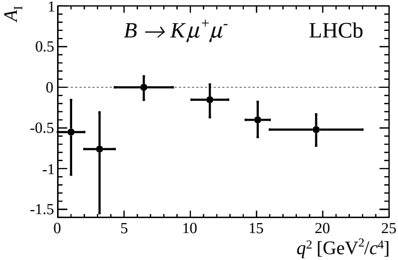
- Expect A_I close to 0 in SM
- Measured in two modes
  - $B^0 \to K^0\mu^+\mu^-$ vs $B^+ \to K^+\mu^+\mu^-$ (K^0 recoed as $K^0_s \to \pi^+\pi^-$)
  - $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$ vs $B^+ \to K^{*+}(K^0\pi^+)\mu^+\mu^-$

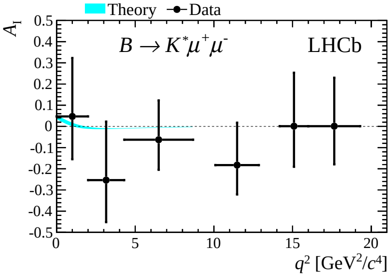




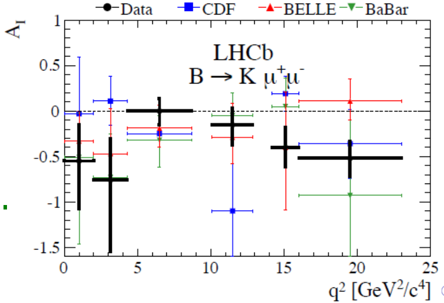
- Theory: [JHEP07 (2011) 067], [JHEP01 (2012) 107]
- Deficit in $B^0 \to K^0\mu^+\mu^-$

Isospin Asymmetries in $B \to K^{(*)}\mu^+\mu^-$ [JHEP 07 (2012) 133]



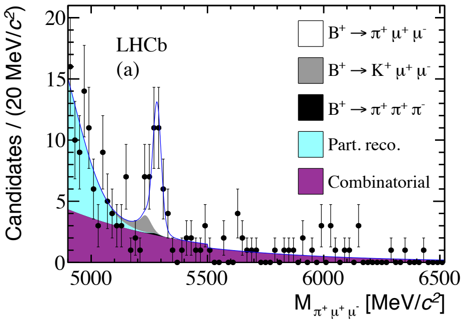


- $B \to K\mu^+\mu^-$ asymmetry systematically low. Naive average over q^2 gives 4.4σ deviation
- $B \to K^*\mu^+\mu^-$ asymmetry agrees with SM prediction
- No theoretical explanation yet within SM or otherwise



$B^+ \to \pi^+\mu^+\mu^-$ [arXiv:1210.2645]

- $b \to d$ penguin, suppressed by $|V_{td}|^2/|V_{ts}|^2$ relative to $b \to s$ in SM
- SM prediction: $\mathcal{B} = 2.0 \pm 0.2 \times 10^{-8}$ [PRD77(2008)014017]

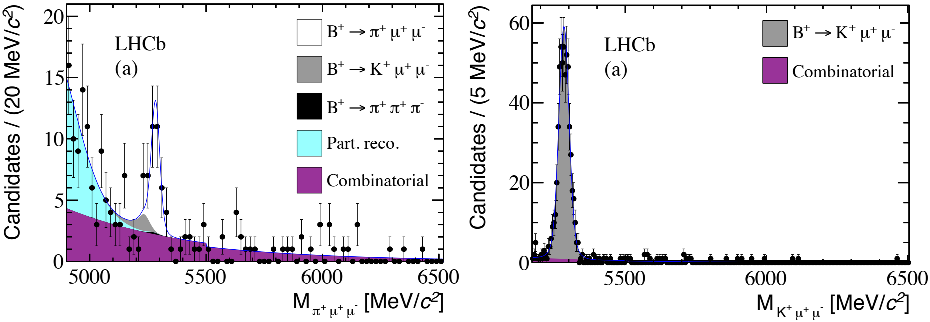


- Normalize to $B^+ \to J/\psi K^+$
- Observe $25.3^{+6.7}_{-6.4}$ with 5.2σ
- **Rarest B decay ever observed!**

- $B_F = 2.3 \pm 0.6(stat.) \pm 0.1(syst.) \times 10^{-8}$
- Compatible with SM prediction

$B^+ \to \pi^+\mu^+\mu^-$ [arXiv:1210.2645]

- Can measure $R = \dfrac{B_F(B^+ \to \pi^+\mu^+\mu^-)}{B_F(B^+ \to K^+\mu^+\mu^-)}$ and tranlsate into $|V_{td}|/|V_{ts}|$ measurement from penguin decays



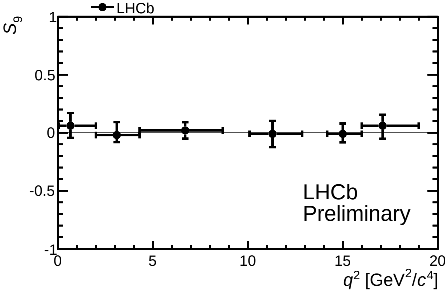
- $R = 0.053 \pm 0.014(stat.) \pm 0.001(syst.)$
- $|V_{td}|/|V_{ts}| = 0.266 \pm 0.035(stat.) \pm 0.007(syst.)$
- Neglecting theoretical uncertainties
- Compatible with previous measurements in $b \to s(d)\gamma$

Summary

- Presented status of LHCb studies on $b \to s(d)\mu^+\mu^-$ EW penguins
- Using $1\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 7\,\mathrm{TeV}$ data LHCb has an array of precision measurements:
  - Most precise determination of angular and CP observables in $B^0 \to K^*\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$
  - Isospin asymmetry in $B \to K\mu^+\mu^-$ decays resulting in $\sim 4\sigma$ deviation from zero
  - First $b \to d\mu^+\mu^-$ transition observed
- **Bottom line: The SM is holding strong!**
- LHCb has additional $2\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 8\,\mathrm{TeV}$ on tape
- Updates of current analyses as well as new analyses are expected!

Backup

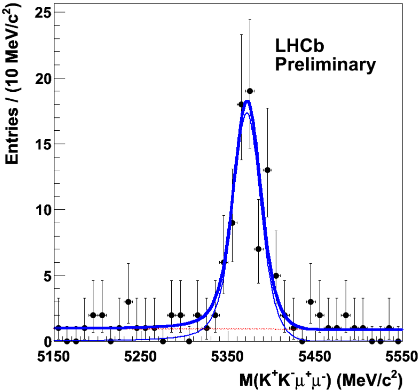
$B^0 \to K^{*0}\mu^+\mu^-$ results [LHCb-CONF-2012-008]



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

$$\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{16\pi}\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) \; - \\ F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) \; + \\ \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) \; + \\ S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} \; + \\ \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell \; + \\ S_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big]$$

$B_s \to \phi\mu^+\mu^-$ [LHCb-CONF-2012-003]



- Observe 77 ± 10 signal candidates in $1\,\text{fb}^{-1}$
- Measure $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$ relative to $\mathcal{B}(B_s \to J/\psi\phi)$
- $\mathcal{B}(B_s \to \phi\mu^+\mu^-) = 0.78 \pm 0.1(stat.) \pm 0.06(syst.) \pm 0.28(\mathcal{B}) \times 10^{-6}$