Studies of the electroweak penguin transitions $b \to s\, \mu^+ \mu^-$ and $b \to d\, \mu^+ \mu^-$ at LHCb

ICHEP2012

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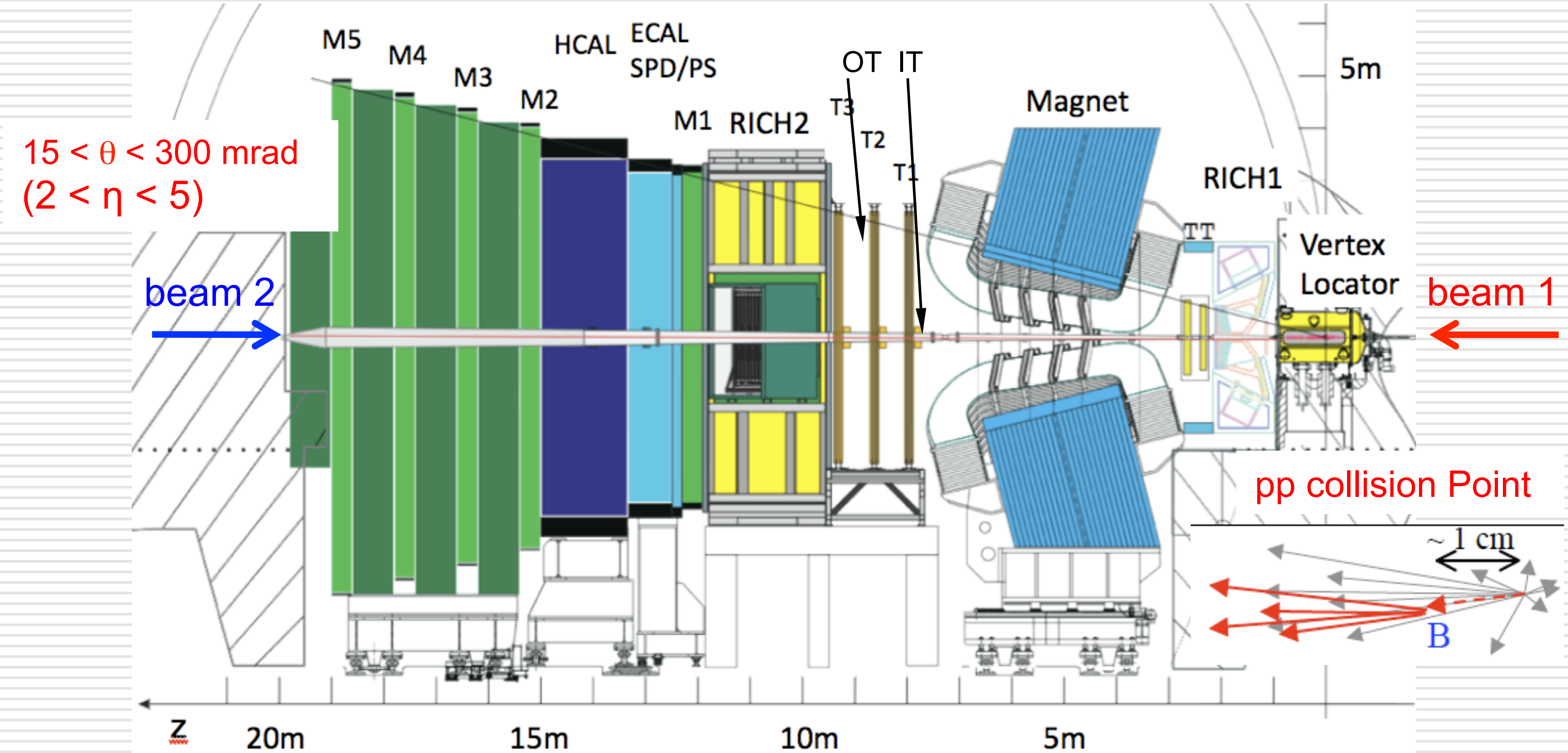
Outline:

- The LHCb detector
- $B^0 \to K^{*0}\mu^+\mu^-$ analysis:
  - Measurement of angular observables
  - Measurement of the ***A_{FB}*** zero-crossing point (***q^2_0***)
  - $B^0 \to K^{*0}\mu^+\mu^-$ and $B_s^0 \to \phi\,\mu^+\mu^-$ differential branching fractions
- First observation of the decay $B^+ \to \pi^+\mu^+\mu^-$
- Isospin asymmetry in $B \to K^{(*)}\mu^+\mu^-$
- Summary

The LHCb detector

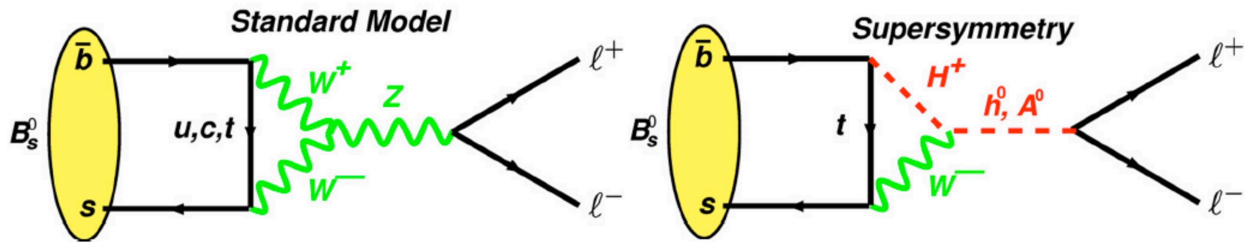
- LHCb is a forward detector designed to study heavy flavour physics at the LHC



- LHCb has excellent vertex and momentum resolution, PID, μ-ID, and efficient trigger
- Each of these are critical for studies of heavy flavor physics

Rare decays at LHCb

- LHCb is searching for physics beyond the Standard Model (SM) by studying rare B and D meson decays.
- The rare decays considered here are Flavour Changing Neutral Current processes
  - These are mediated by loop diagrams in the SM
- New physics particles can make significant contributions to these diagrams

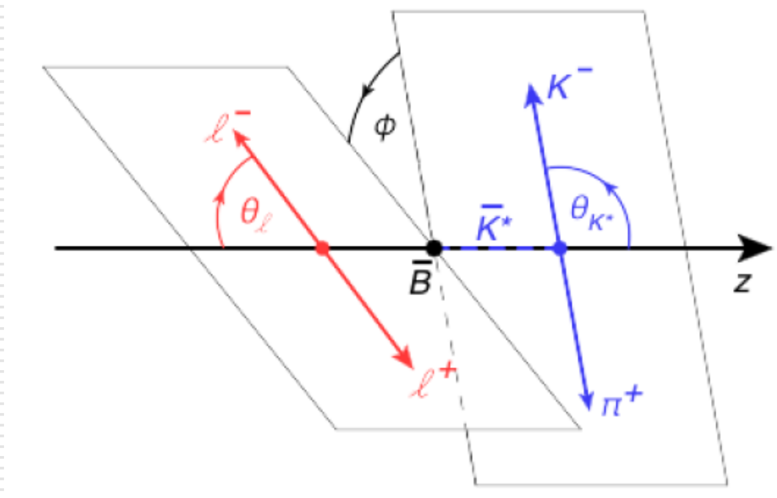


- New physics contributions can affect:
  - The total amplitude, accessible through branching fraction measurements
  - Partial amplitudes and phases, accessible through angular analyses
- Indirect searches at LHCb are complimentary to direct searches at the GPDs

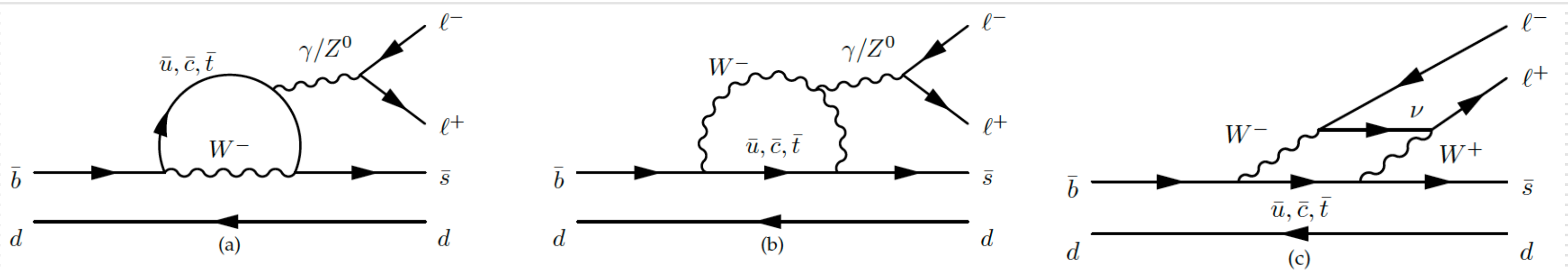
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Angular Analysis

LHCb-CONF-2012-008

- Flavour changing neutral current → loop
- The angular distribution of the rare decay $B^0 \to K^{*0}\mu^+\mu^-$ is sensitive to New Physics
- Described in terms of the decay angles θ_ℓ, θ_K, ϕ and $q^2 = m^2_{\mu\mu}$

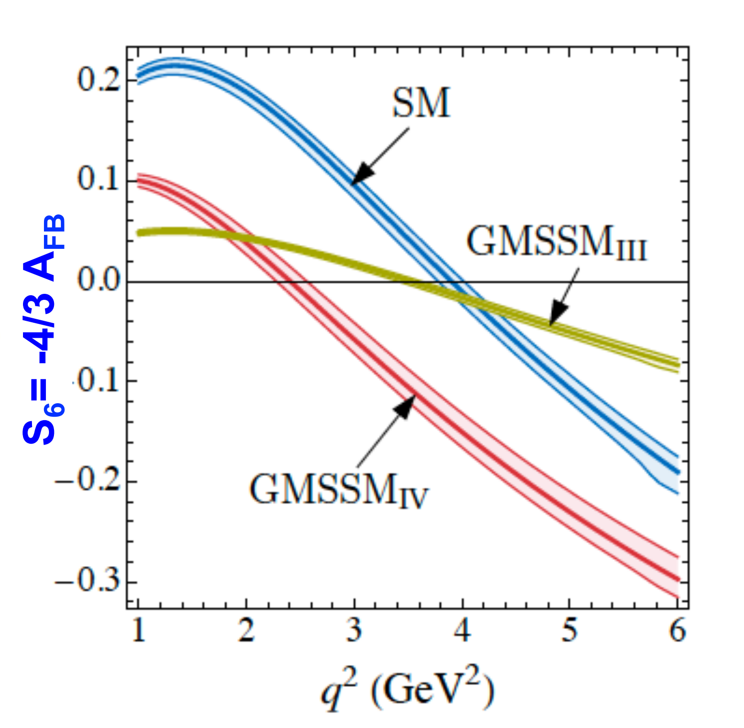


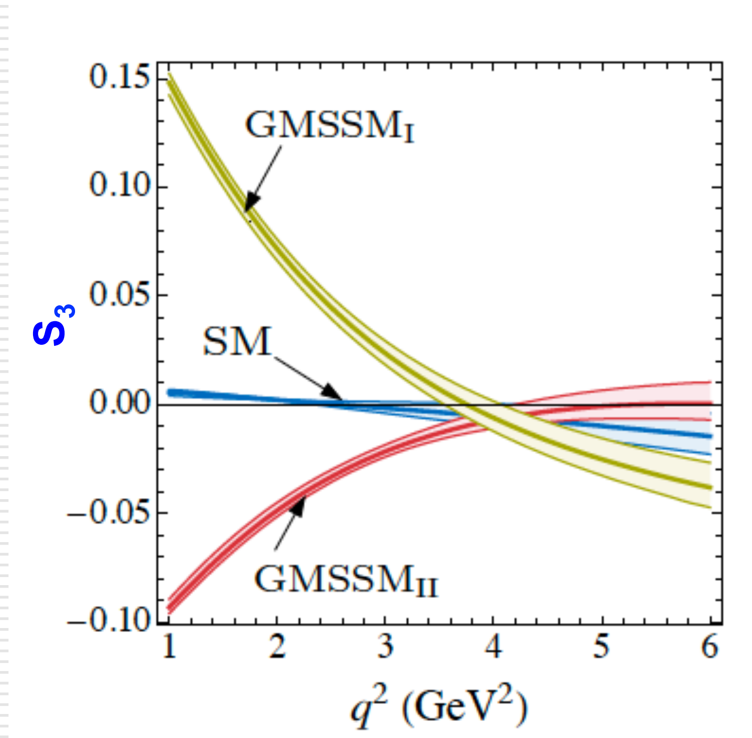
- Fitting these angles allows access to angular observables where the hadronic uncertainties are under control:
  - F_L , the fraction of the K^{*0} longitudinal polarization.
  - A_{FB}, the forward-backward asymmetry of the dimuon system
  - $S_3 \propto A^2_T(1-F_L)$, the asymmetry in K^{*0} transverse polarization
  - A_{IM}, a T-odd asymmetry



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

- Observables highly sensitive to NP contributions to C7('), C9('), C10(')



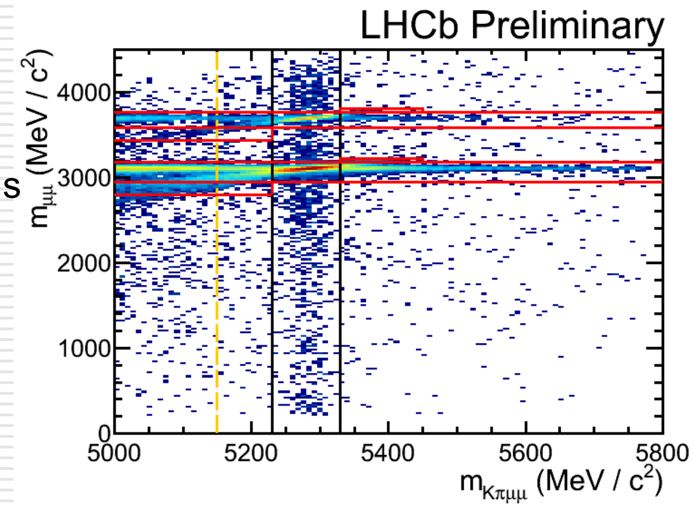


W. Altmannshofer et al. [arXiv:0811.1214]

- **A_{FB} zero-crossing point particularly well predicted by theory**

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

- Event selection with a BDT:
  - BDT trained for the Signal with $B^0 \to K^{*0} J/\psi$ (2010 data)
  - BDT trained for the Bkgrd with $B^0 \to K^{*0}\mu^+\mu^-$ mass sidebands
  - Info about evt kinematics, vertex & track quality, IP, PID



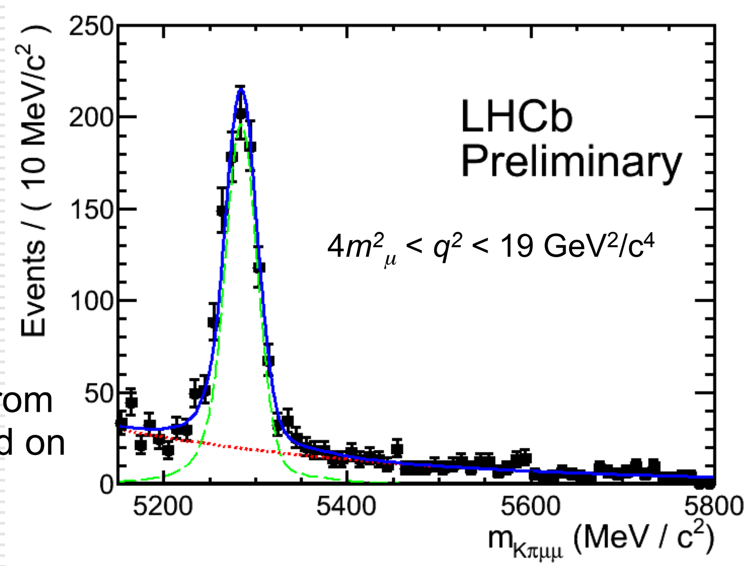
- $B^0 \to K^{*0} J/\psi$, $B^0 \to K^{*0}\Psi(2S)$ vetoes

- Isolate peaking backgrounds and reject with PID requirements: e.g. $B^0_s \to \phi\mu^+\mu^-$ with $K \to \pi$ mis-ID. Total peaking Bkg <2% of signal

- LHCb(1.0 fb^{-1}) : 900± 34 signal events
  (BaBar + Belle + CDF ~ 600)

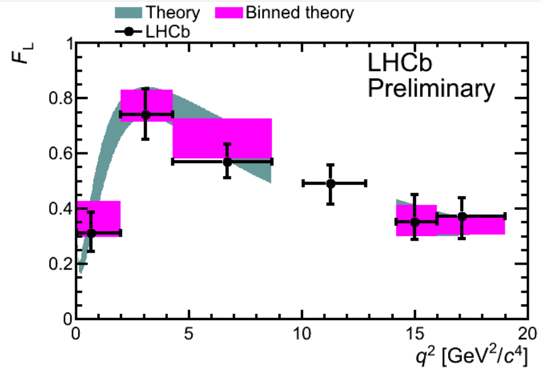
- B/S≈0.25 in region $5230 < m_{K\pi\,\mu+\mu-} < 5330$ MeV/c^2

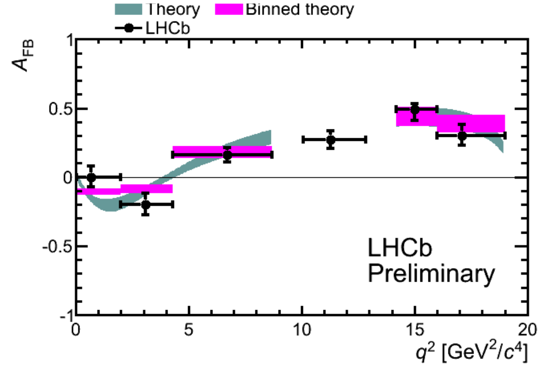
- Selection does not induce further biases in angles and q^2
  cf reconstruction/trigger- biases that are introduced primarily from the detector geometry- . Modelled using simulation and verified on data using $K^{*0} J/\psi$.

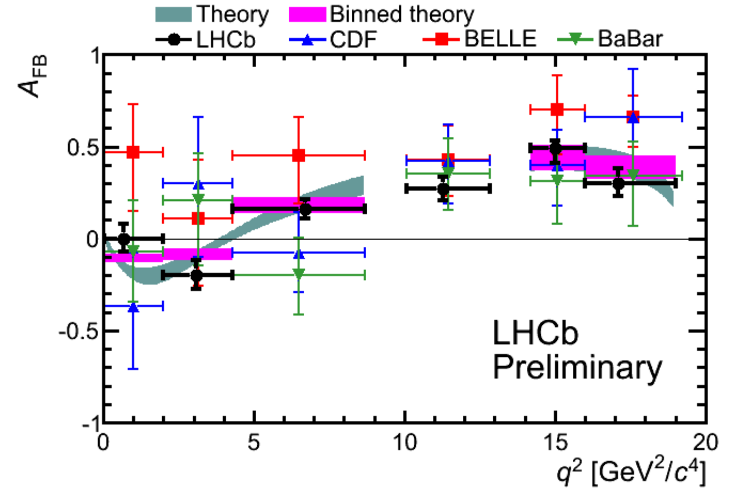


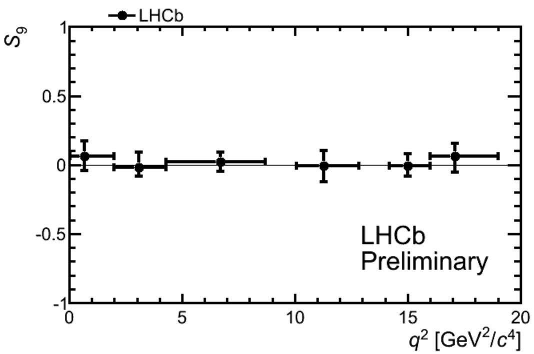
$B^0 \to K^{*0}\mu^+\mu^-$ Angular Analysis Results

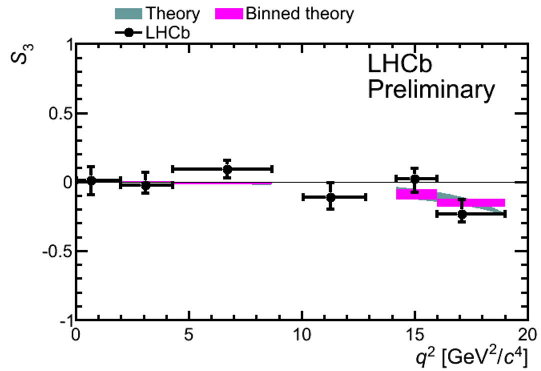
- Un-binned maximum-likelihood 4D fit to 3 angles (θ_ℓ, θ_K, ϕ) and mass distributions in bins of q^2
- Larger data sample enables measurements of S_3 and A_{IM}
- Error bars include systematic uncertainties
- Data points are centered at the $<q^2>$ of signal candidates in data
- Most precise measurements to-date- consistent with the SM prediction (*). A_{IM} $O(10^{-3})$ in SM (**)











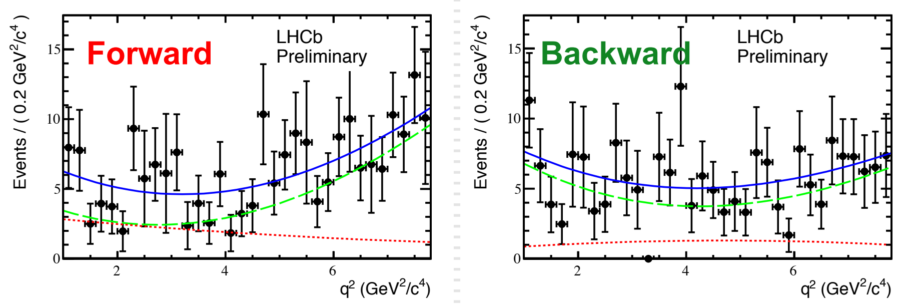
(*, **) C. Bobeth et al. [arXiv: 1105.0376; JHEP 0807 106]

$B^0 \to K^{*0}\mu^+\mu^-$ A_{FB} zero-crossing point

- The SM predicts A_{FB} to change sign at a well defined point in q^2.

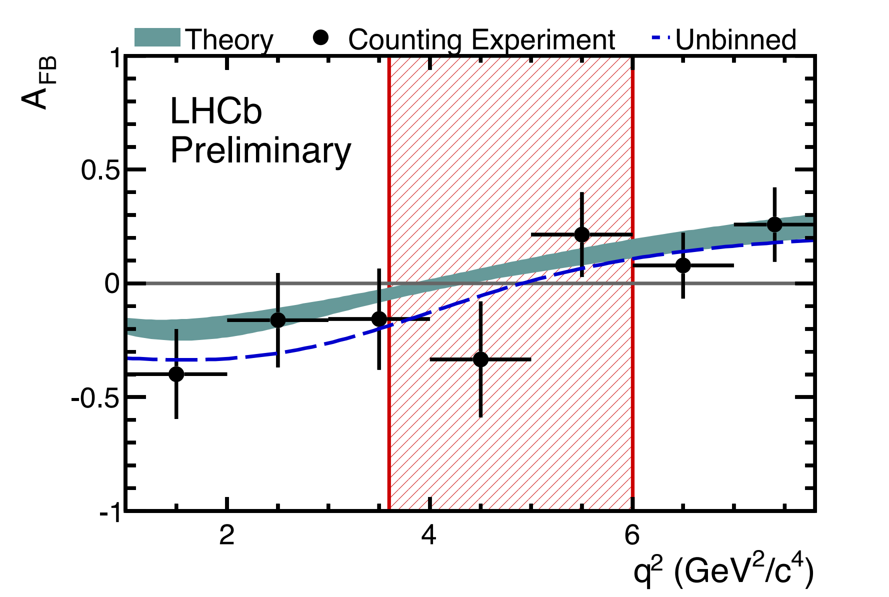
- This zero-crossing point q^2_0 is largely free from form-factors uncertainties.

- q^2_0 is extracted through a 2D fit to the forward- and backward-going $m_{K\pi\mu\mu}$ and q^2 distributions.



- The world's first measurement of q^2_0 , at $q^2_0 = 4.9^{+1.1}_{-1.3}$ GeV^2/c^4 [Preliminary]

- Consistent with the SM predictions which range from 4÷4.3 GeV^2/c^4 [arXiv:1105.0376, Eur. Phys. J. C41 (2005) 173-178, C47 (2006) 625-641]

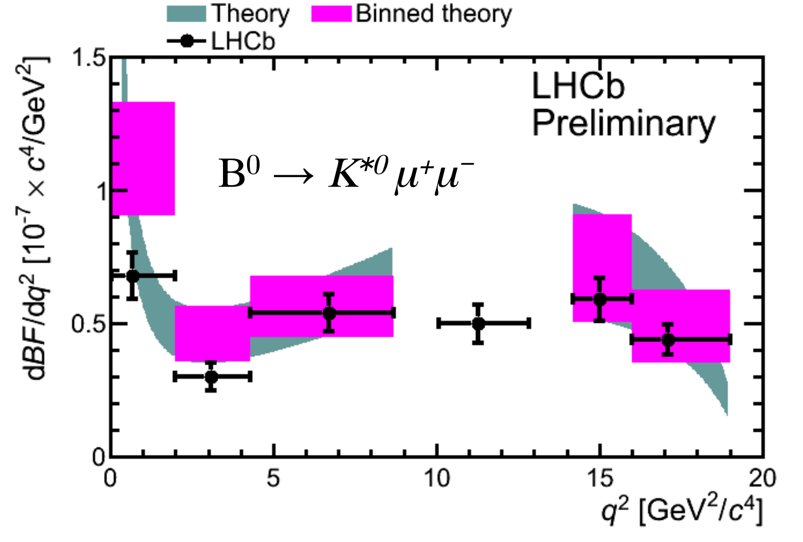


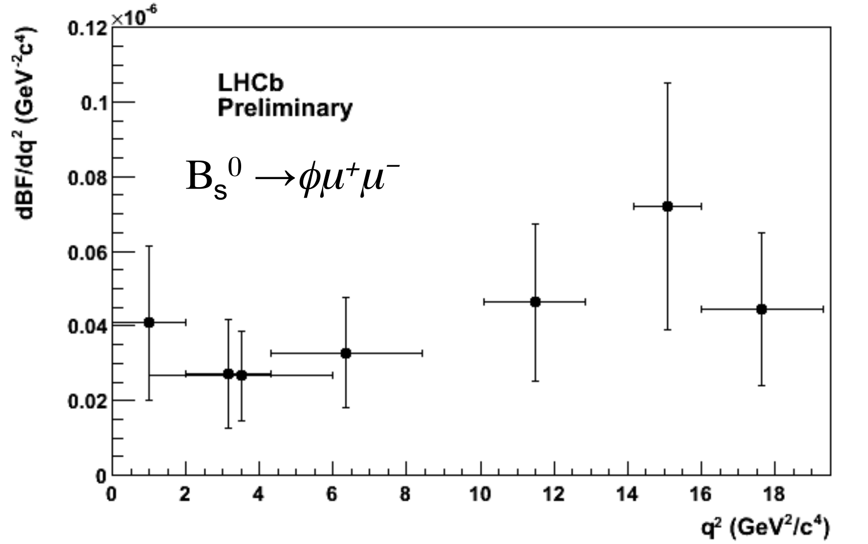
$B^0 \rightarrow K^{*0} \mu^+\mu^-$ and $B_s^0 \rightarrow \phi\, \mu^+\mu^-$
differential branching ratios

LHCb-CONF-2012-008

LHCb-CONF-2012-003

$B^0 \to K^{*0}\mu^+\mu^-$ and $B_s^0 \to \phi\,\mu^+\mu^-$ differential BF





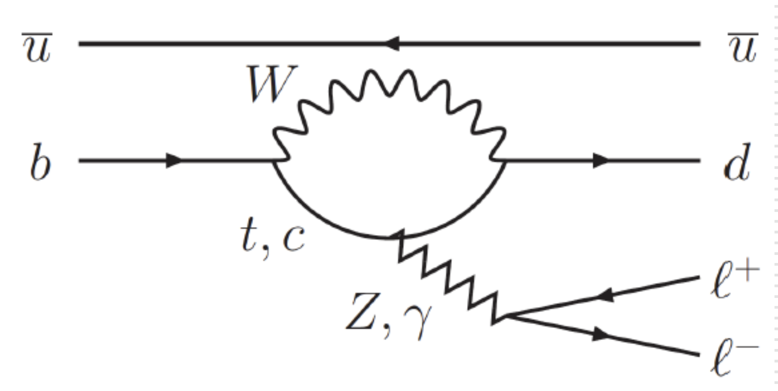
- Differential branching fraction is extracted by fitting the mass distribution and normalising to $B^0 \to K^{*0} J/\psi$, $B_s \to \phi\, J/\psi$
- $B^0 \to K^{*0}\mu^+\mu^-$: 900±34 signal events LHCb (1.0 fb^{-1})
- $B_s^0 \to \phi\,\mu^+\mu^-$: 77±10 signal events LHCb (1.0 fb^{-1})
- $\mathcal{B}(B_s^0 \to \phi\,\mu^+\mu^-) = (0.78 \pm 0.10(\mathrm{stat}) \pm 0.06(\mathrm{syst}) \pm 0.28(\mathcal{B})) \times 10^{-6}$ [Preliminary]
- These are the most precise measurements to-date and are consistent with SM expectations [arXiv:1105.0376v4;J.Phys.G G29(2003) 1103-1118]

First observation of $B^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$

LHCb-CONF-2012-006

First observation of $B^+ \to \pi^+\mu^+\mu^-$

- $B^+ \to \pi^+\mu^+\mu^-$ decay is a $b \to d\ell\ell$ transition
- In the SM the branching fraction is ~25x smaller than analogous $B^+ \to K^+\mu^+\mu^-$ ($b \to s$) transition and can be enhanced in NP models.

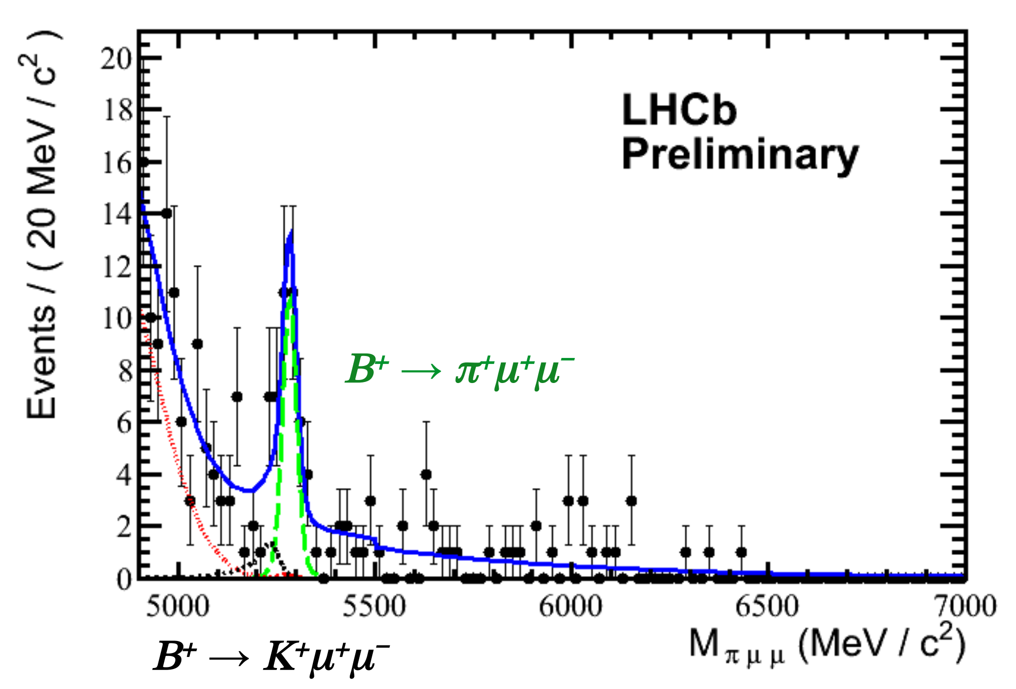


- Can also be used to measure V_{td}/V_{ts} from penguin diagrams
- SM prediction is $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = 1.96 \pm 0.21 \times 10^{-8}$ (*)
- BELLE set previous best limit at $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) < 6.96 \times 10^{-8}$ at 90% C.L. (**)
- A major background comes from misidentified $B^+ \to K^+\mu^+\mu^-$ decays
- A critical analysis issue is separating these two decays
  - The $K-\pi$ separation provided by the LHCb RICH detectors is crucial

(*) Song Hai-Zhen et al., Comm in Theo Ph 50 (2008) 696
(**) J.T. Wei et al., Phys. Rev. D78 (2008) 011101

First observation of $B^+ \to \pi^+\mu^+\mu^-$

- This is the first observation of a $b \to d\ell\ell$ transition
- LHCb (1.0 fb^{-1}): $B^+ \to \pi^+\mu^+\mu^-$: $25.3^{+6.7}_{-6.4}$ signal events
  - 5.2σ excess above background
- The measurement is consistent with the SM prediction



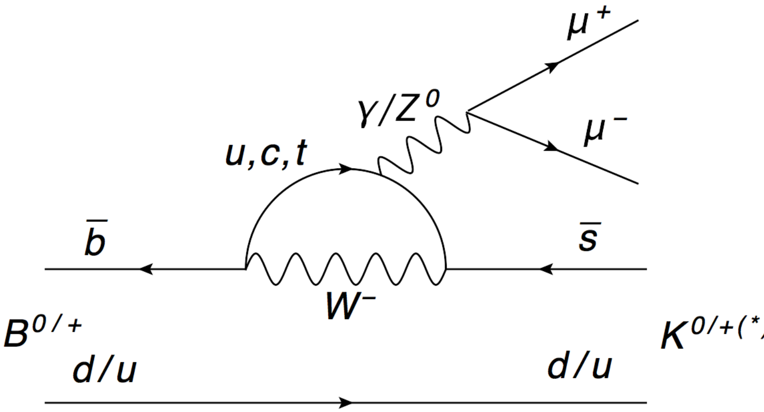
- $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)$= (2.4±0.6(stat) ±0.2(*syst*)) x 10^{-8} . Preliminary
- The rarest B decay ever observed!

Isospin asymmetry in $\mathrm{B} \rightarrow K^{(*)}\mu^{+}\mu^{-}$

arXiv:1205.3422

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

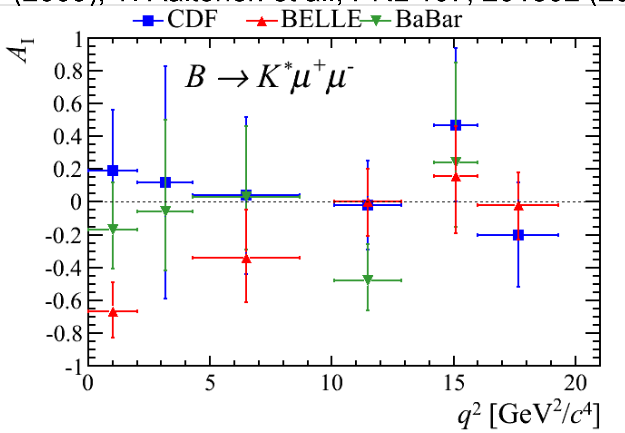
- $B \to K^{(*)} \mu^+\mu^-$ are FCNC decays:

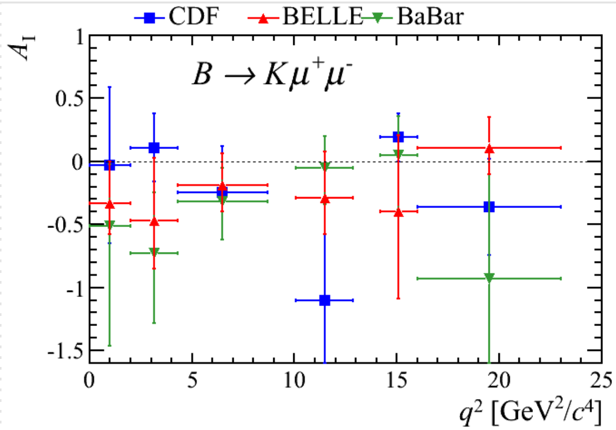


- The Isospin asymmetry **A_I** in $B \to K^{(*)} \mu^+\mu^-$ is defined as:

$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

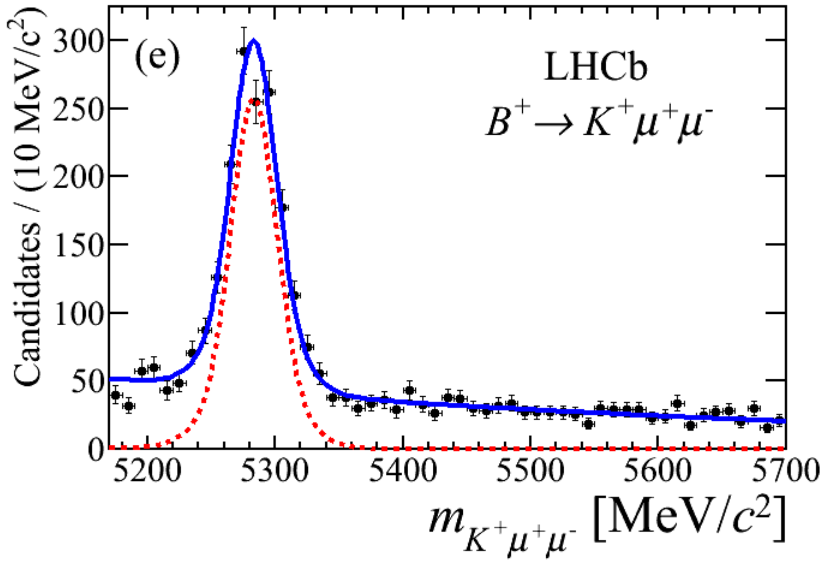
- SM prediction of **A_I** is very close to zero e.g. for $B \to K^{*}\mu^+\mu^-$ [T. Feldmann and J. Matias JHEP **01** (2003)074].
- BaBar, Belle and CDF have measured **A_I**. [B. Aubert et al., arXiv:1204.3933; J.-T. Wei et al., PRL 103, 171801 (2009); T. Aaltonen et al., PRL 107, 201802 (2011)]

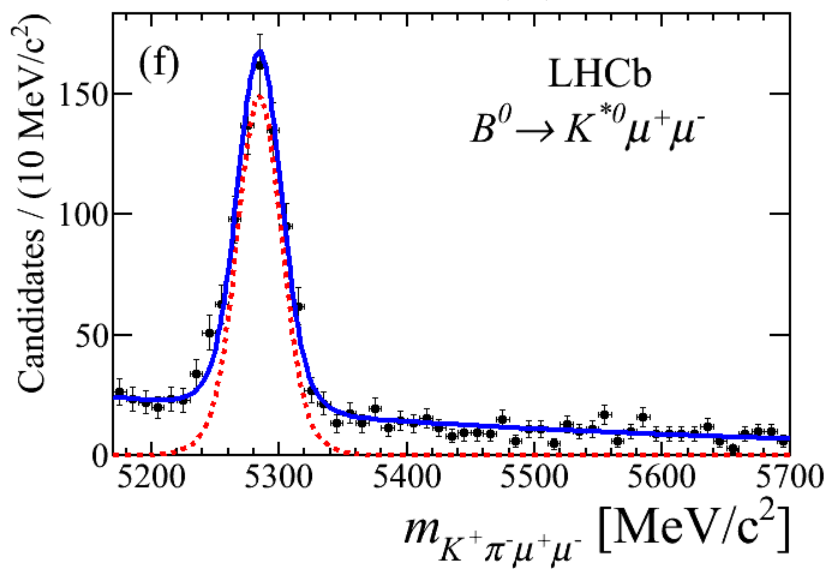




B → $K^{(*)}\mu^+\mu^-$ LHCb Analysis

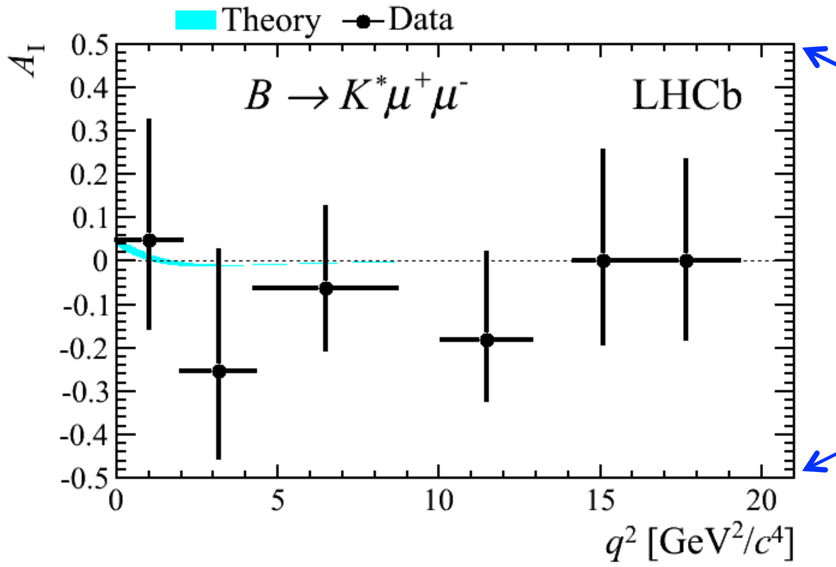
- Measure differential BF of four decay modes
  - $B^+ \to K^+\mu^+\mu^-$
  - $B^0 \to K^{*0}\mu^+\mu^-$
  - $B^+ \to (K^{*+}\to K_s^0\,\pi^+)\mu^+\mu^-$
  - $B^0 \to (K^0\to K_s^0)\mu^+\mu^-$
- Decays involving K_s^0 have a low reconstruction efficiency due to long K_s^0 lifetime.
- Correction for detector and selection effects made with simulation (verified to reproduce the data)
- $B\to (J/\psi\to\mu^+\mu^-)K^{(*)}$ decays used to normalize the branching fraction for each decay to cancel systematic uncertainties

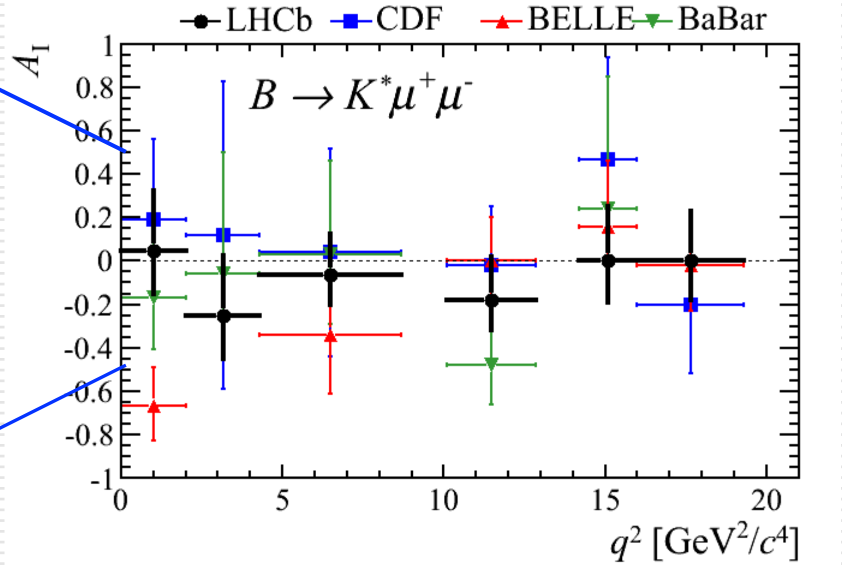




A_l for $B \to K^* \mu^+ \mu^-$

- A_l for $B \to K^* \mu^+ \mu^-$ is consistent with zero, as predicted by the SM
- LHCb results in agreement with previous measurements

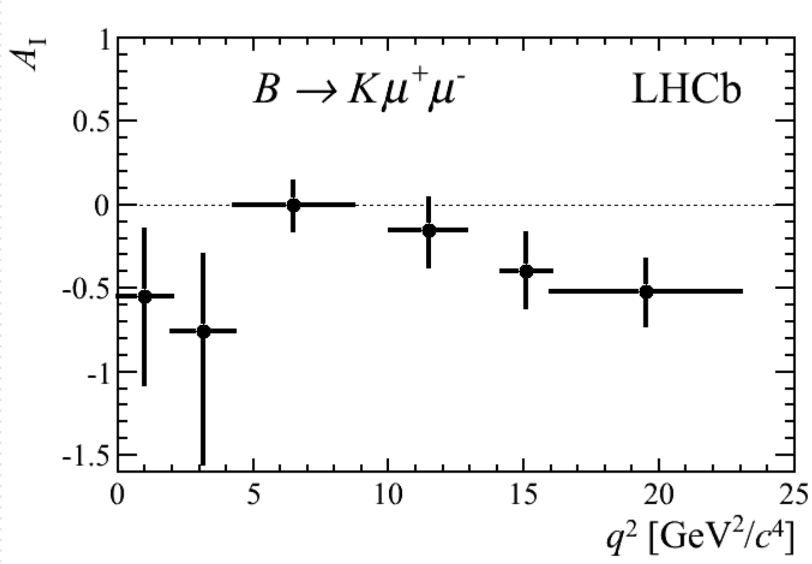


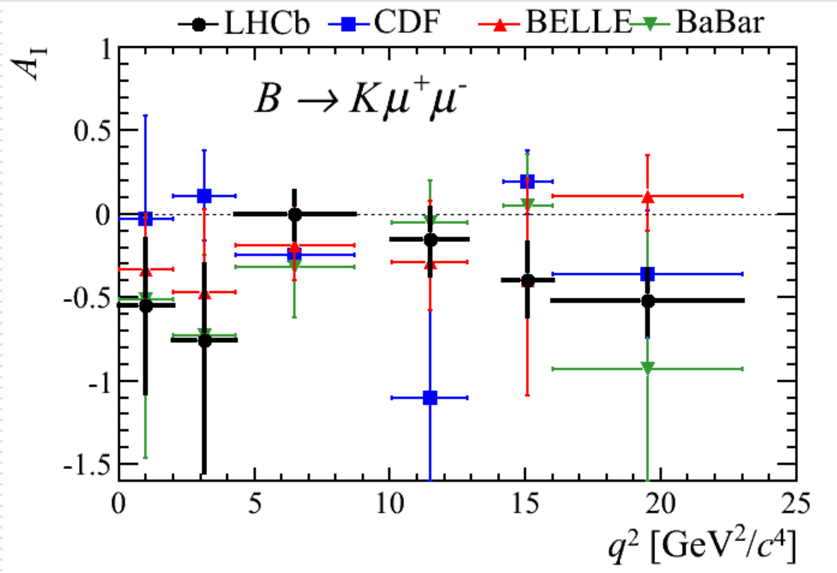


Theoretical predictions below q^2 = 8.68 GeV/c^2 by C. Bobeth, G. Hiller and D. van Dyk]

A_I for $B \to K\mu^+\mu^-$

- A_I for $B\to K\mu^+\mu^-$ tends to sit below the SM prediction, which is zero.
- Results agree with previous measurements but nearly all measurements of A_I are negative
- Ignoring the small correction of (syst) errors between each q^2 bin, the significance of the deviation from zero across q^2 is 4.4σ (LHCb alone)



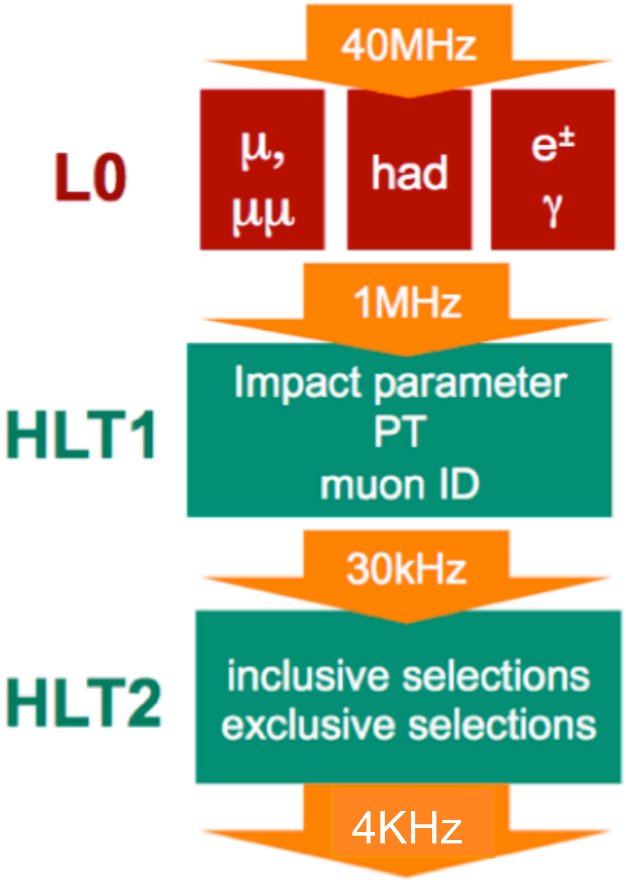


Summary

- $B^0 \to K^{*0}\mu^+\mu^-$: [LHCb-CONF-2012-008]
  - World's most precise measurement of the angular observables
  - World's first measurement of the A_{FB} zero-crossing point (q^2_0)
  - World's most precise measurement of the branching fraction
- $B_s^0 \to \phi\,\mu^+\mu^-$: [LHCb-CONF-2012-003]
  - World's most precise measurement of the branching fraction
- $B^+ \to \pi^+\mu^+\mu^-$: [LHCb-CONF-2012-006]
  - First observation ($b \to d\ell\ell$ transition)
  - Branching fraction measurement consistent with SM (Rarest B decay ever observed)
- Isospin asymmetry in $B \to K^{(*)}\mu^+\mu^-$: [arXiv:1205.3422 to be submitted to JHEP]
  - $B \to K^*\mu^+\mu^-$, A_I results consistent with zero, as expected in SM
  - $B \to K\mu^+\mu^-$, A_I results below SM in the q^2 region < 4.3 GeV^2/c^4 and > 16 GeV^2/c^4
- **LHCb will improve these measurements and has many more in prospect with 2012 (expect ~1.5 fb^{-1}) data!**

Backup slides

The LHCb Trigger



L0 Hardware	"high p_T" signals in calorimeter and muon systems
HLT1 Software	Partial reconstruction, selection based on one or two (dimuon) displaced tracks, muon ID
HLT2 Software	Global reconstruction (very close to offline) dominantly inclusive signatures – use MVA

+ Global Event Cuts for events with high multiplicity

	Charm	Had. B	Lept. B
Overall efficiency	~10%	~40%	~75-90%

- Small event size (60kB) → large bandwidth
- Allows low thresholds

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

$$\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_\ell \, d\cos\theta_K \, d\hat{\phi} \, dq^2} = \frac{9}{16\pi}\Big[F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) \; + $$

$$F_L \cos^2\theta_K (2\cos^2\theta_\ell - 1) \; +$$

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

$$S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} \; +$$

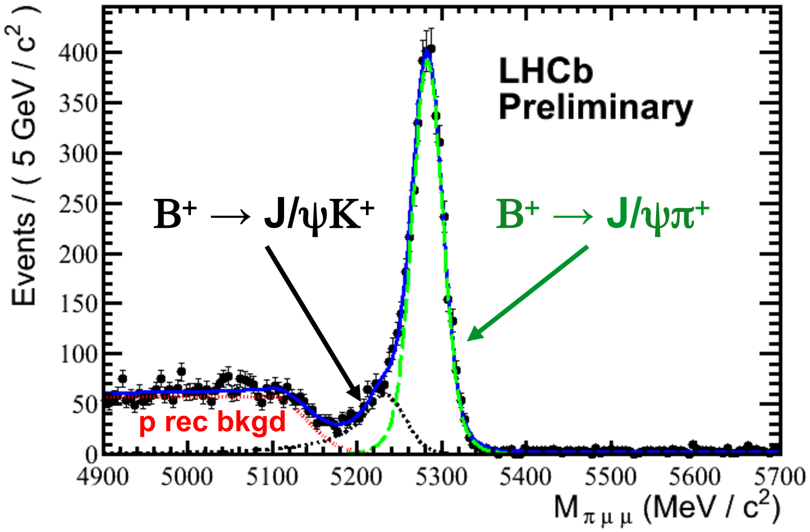
$$\frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell \; +$$

$$A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big]$$

Where $\hat{\phi}$ is $\hat{\phi} = \phi + \pi$ if $\phi < 0$ and $\hat{\phi} = \phi$ if $\phi \geq 0$.

$B^+ \to \pi^+\mu^+\mu^-$ Analysis

- The issue: separating $B^+\to\pi^+\mu^+\mu^-$ from misidentified $B^+\to K^+\mu^+\mu^-$ ($K^+\to\pi^+$)
- Use BDT to make selection:
  - Kinematic properties of the B candidate and daughters. B vertex, daughter track and PV quality properties included
  - No PID requirements in the BDT, applied separately
  - $B^+\to(J/\psi, \Psi(2S))K^+$ vetoes
  - Peaking backgrounds:
    - $B^+\to\pi^+\pi^+\pi^-$ expectation and shape from MC included in the fit yield constrained to 0.39±0.04 from MC
    - $B^+\to h^+h^+h^-$ and $B^+\to J/\psi\pi^+$ negligible



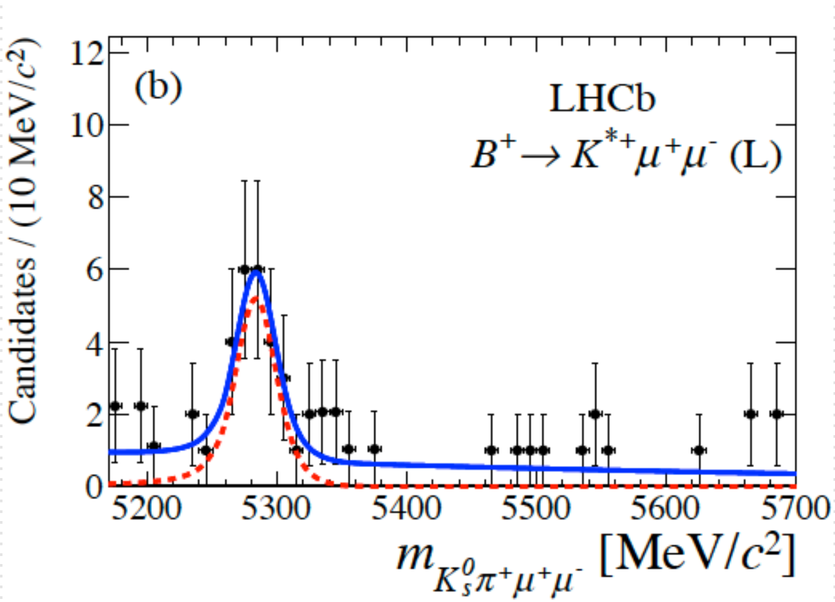
- Fitting
  - Use $B^+\to J/\psi K^+$ events to define signal shape and, under $\pi^+\mu^+\mu^-$ hypothesis, shape of mis-identified events from $B^+\to K^+\mu^+\mu^-$ ($K^+\to\pi^+$)
  - Components for partial reconstructed B decays and combinatorial background
  - Validation of the fit method by separating $B^+\to J/\psi K^+$ and $B^+\to J/\psi\pi^+$ decays
  - Normalize branching fraction using $B^+\to J/\psi K^+$

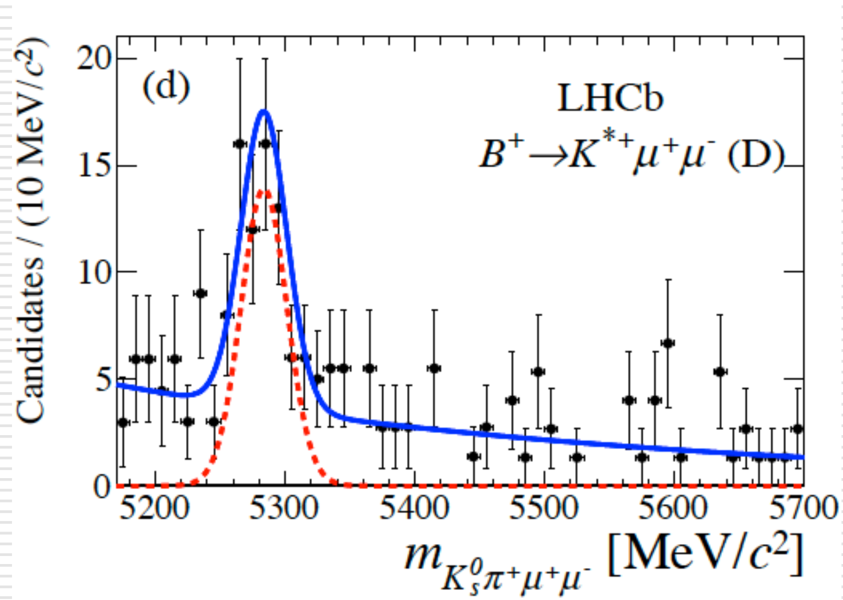
$B \to K^{(*)} \mu^+\mu^-$ Selection

- The channels involving K_s^0 are split into two categories based on how the K_s^0 is reconstructed:
  - "**Long**" (**L**): Both pions from the K_s^0 have hits inside the VELO and the downstream tracking detectors
  - "**Downstream**" (**D**): daughter pions without hits inside the VELO but with hits in the TT upstream the magnet
- **L**-events have less background - use a cut-based selection
- **D**-events – use a BDT selection
- Insofar as possible, use similar selections for the K^+ channels
- $B \to (J/\psi \to \mu^+\mu^-)K^{(*)}$ decays used to normalize the branching fraction for each decay to cancel systematic uncertainties.
  - The normalization of $B^0 \to K^0\mu^+\mu^-$ assumes that $\mathcal{B}(B^0 \to K^0\mu^+\mu^-) = 2 \times \mathcal{B}(B^0 \to K_s^0\mu^+\mu^-)$

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

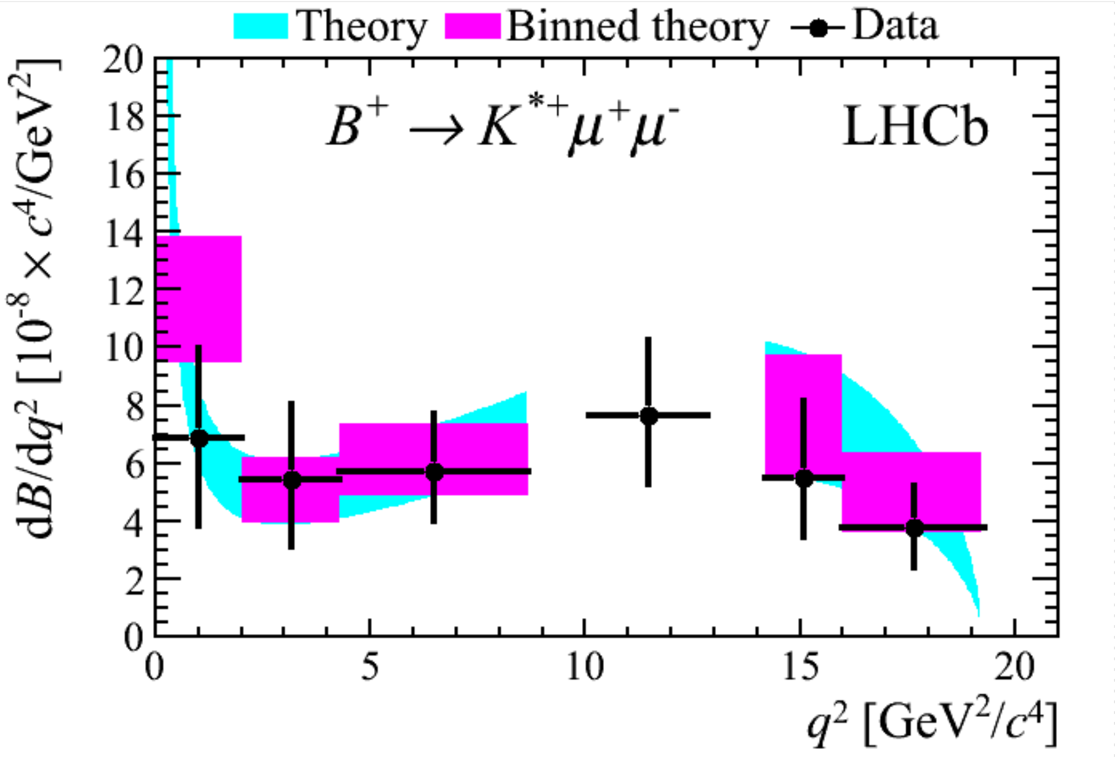
- LHCb measurement: $\mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-) = (1.16 \pm 0.19) \times 10^{-6}$
- C.f. PDG: $\mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-) = (1.16 \pm 0.30) \times 10^{-6}$





dBF/q^2($B^+ \to K^{*+}\mu^+\mu^-$)

- Measurements are consistent with the SM:

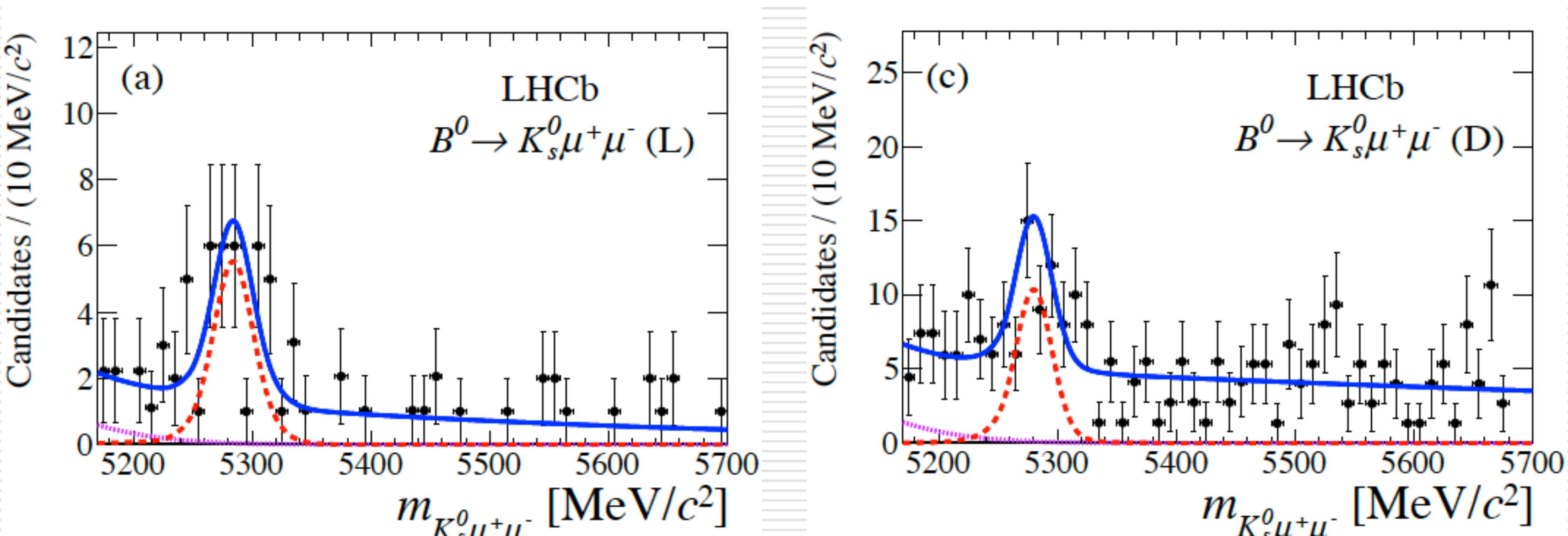


Theory prediction from [C. Bobeth, G. Hiller, and D. van Dyk, JHEP 07 (2011) 067, arXiv:1105.0376

$\mathcal{B}(B^0 \to K^0 \mu^+ \mu^-)$

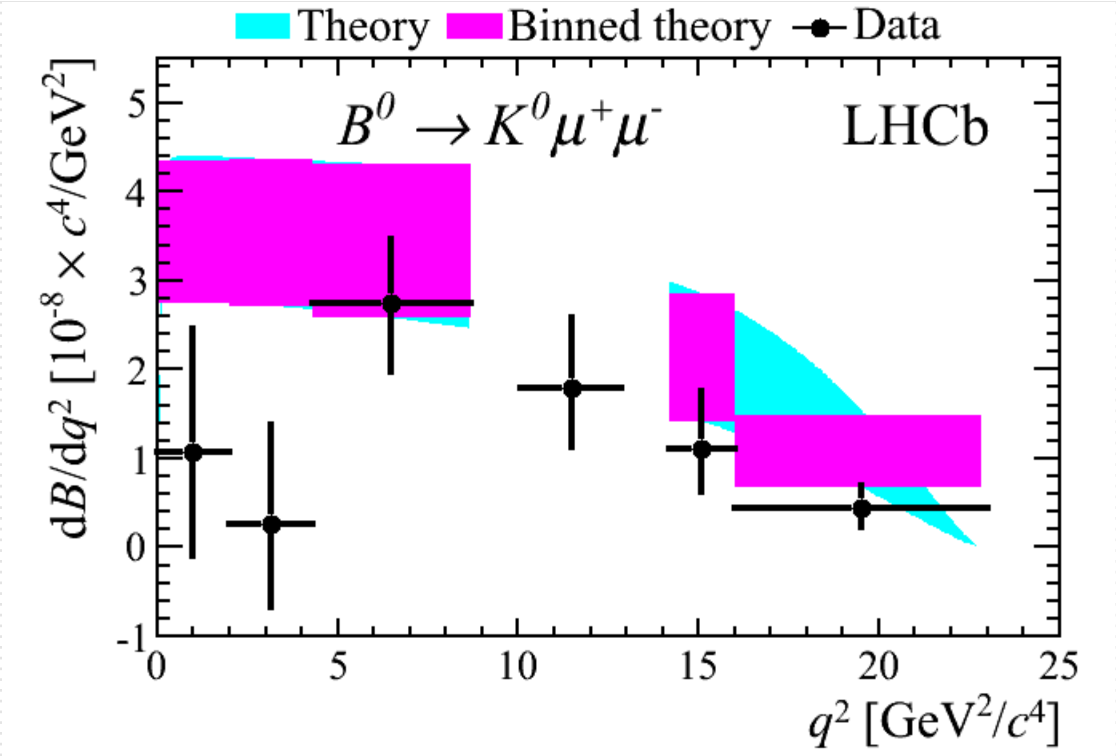
- Assuming a factor 2 for $K^0 \to K_s^0$ *and accounting for* $K_s^0 \to \pi^+\pi^-$ branching fraction:
- LHCb measurement: $\mathcal{B}(B^0 \to K^0 \mu^+ \mu^-) = (3.1^{+0.7}_{-0.6})\text{x } 10^{-7}$
- cf PDG: $\mathcal{B}(B^0 \to K^0 \mu^+ \mu^-) = (4.5 \pm 1.1)\text{x } 10^{-7}$
- $\mathcal{B}(B^0 \to K^0 l^+ l^-) = (3.1^{+0.8}_{-0.7})\text{x } 10^{-7}$

- 5.7σ excess above background $B^0 \to K_s^0 \mu^+ \mu^-$



$dBF/q^2(B^0 \rightarrow K^0\mu^+\mu^-)$

- There is a deficit of $B^0 \rightarrow K^0\mu^+\mu^-$ signal in the q^2 regions which are not adjacent to the charmonium resonances:



Theory prediction from [C. Bobeth, G. Hiller, and D. van Dyk, JHEP 01 (2012) 107, arXiv:1111.2558.