Angular analysis of the decay $B_d \to K^* \mu^+ \mu^-$ at LHCb

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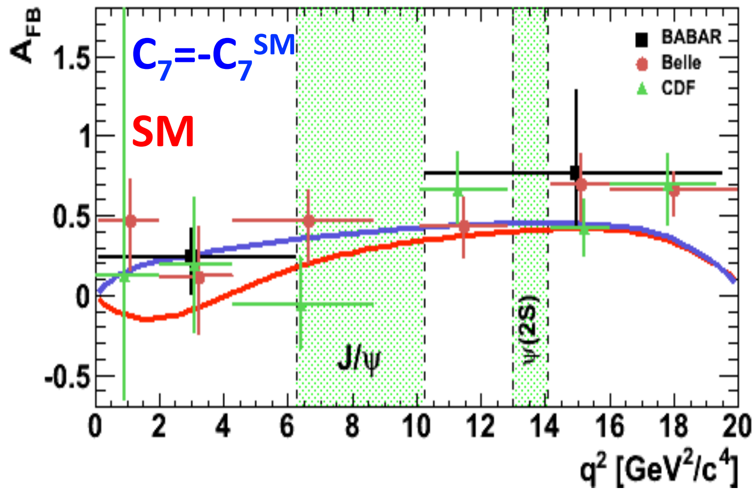
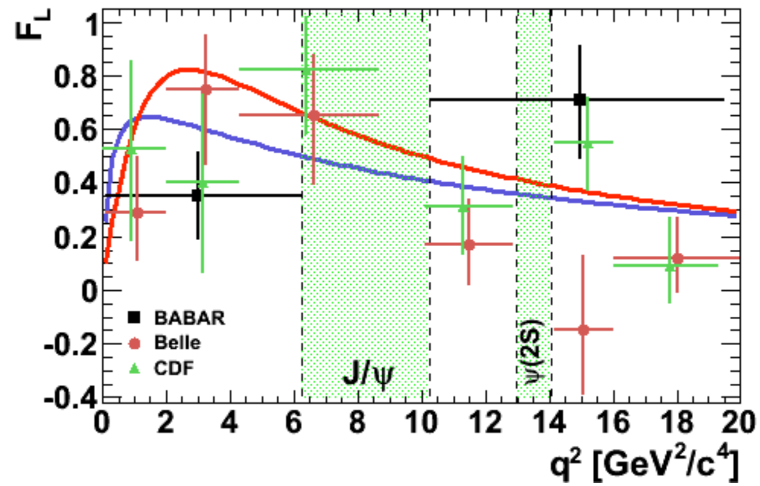
Introduction

- Flavour changing neutral current decay (→loop), described by 3 angles (θ_l, ϕ, θ_K) and di-μ invariant mass q^2
- Sensitive to magnetic and vector and axial semi-leptonic penguin operators
- Many observables where hadronic uncertainties cancel
  - Forward-backward asymmetry A_{FB} of θ_l distribution (zero-crossing point)
- Pre-EPS measurements from Babar, Belle and CDF

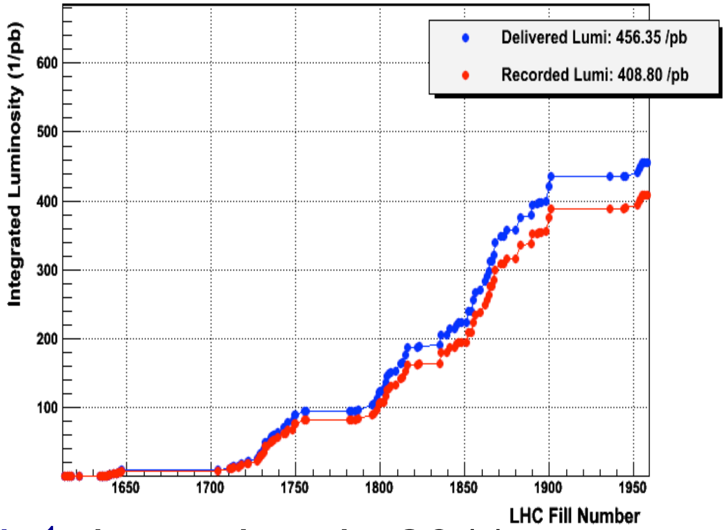




BABAR: PRL 102, 091803 (2009); CDF: Note 10047 (2010); Belle: PRL 103, 171801 (2009)

Strategy

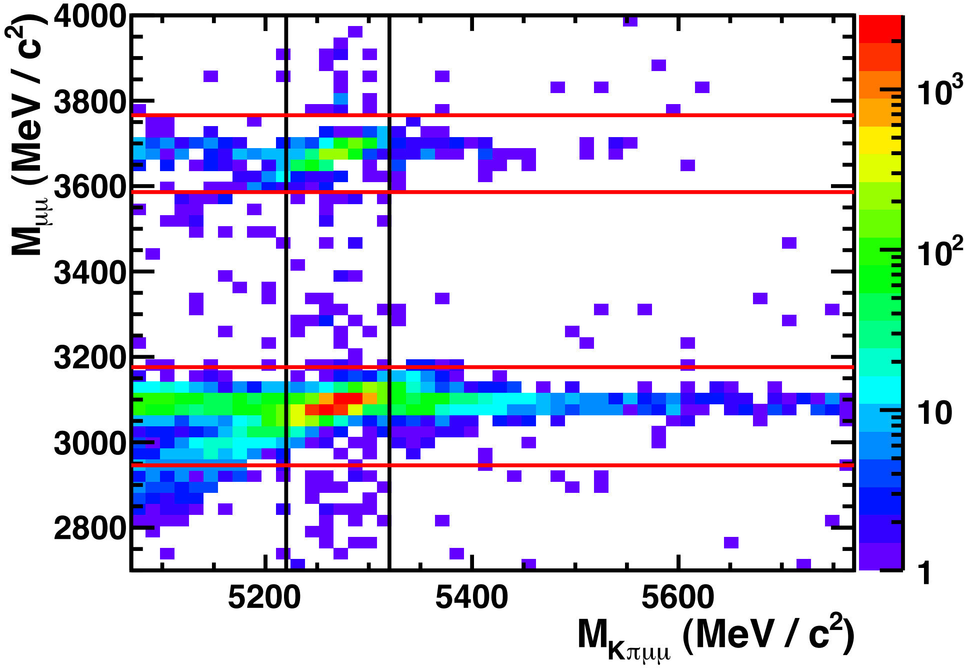
- Select signal events
- Correct for the effect of the reconstruction and selection requirements – "acceptance effect" – using simulation
  - Model independent correction
  - Validate by performing angular analysis of $B_d \rightarrow K^* J/\psi$ control channel, where physics parameters known from elsewhere
  - Check simulation with a range of control channels
- Fit for observables



- First measurements from LHCb from 309 pb^{-1} data taken in 2011
- Focus on theoretically clean angular observables e.g. A_{FB}, F_L and $d\Gamma/dq^2$

Selection

- Selection:
  - Remove $c\bar{c}$ resonances
    - $2946 < m_{\mu\mu} < 3176$ MeV/c^2
    - $3586 < m_{\mu\mu} < 3776$ MeV/c^2
  - Treat peaking backgrounds with a specific set of criteria (→ residual backgrounds ~3% of signal)
  - Combinatorial backgrounds reduced with a Boosted Decision Tree (BDT) selection

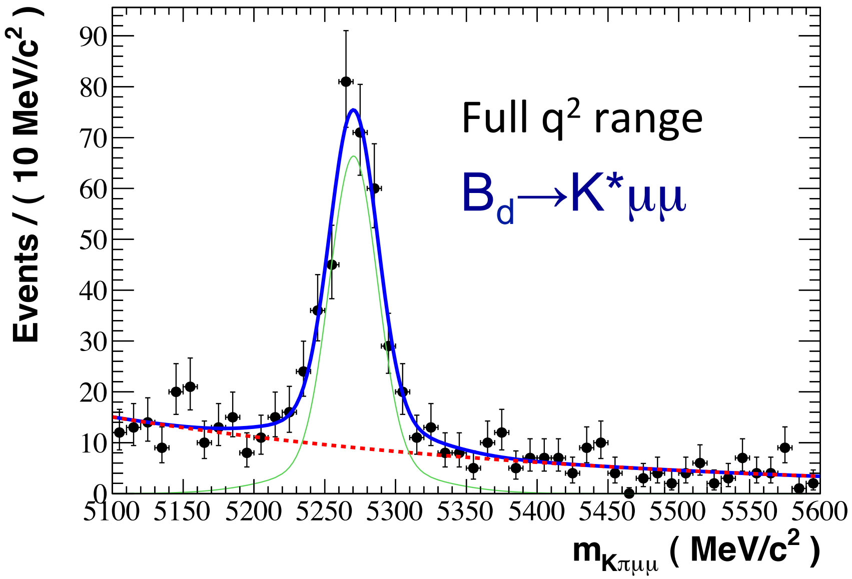


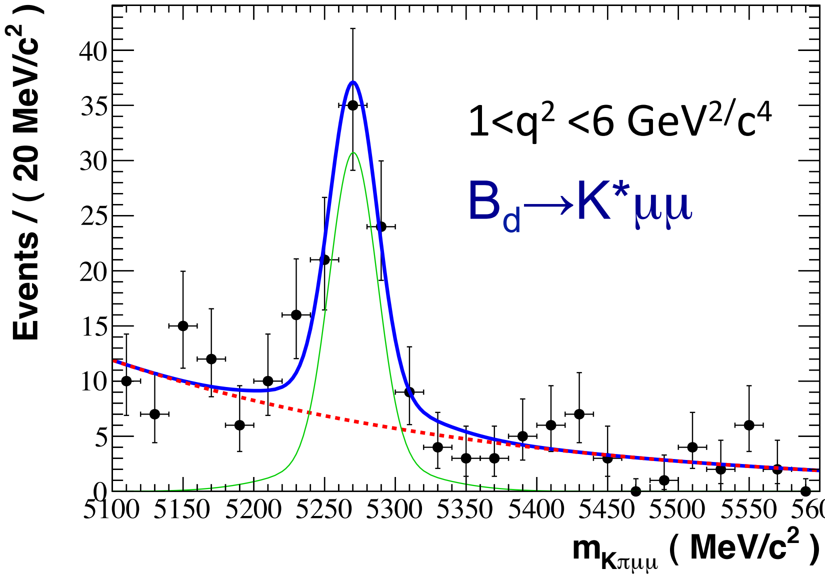
- Use Belle q^2 binning and an (overlapping) $1<q^2<6$ GeV^2/c^4 bin favoured by theorists

Boosted Decision Tree

- Train BDT on 2010 data i.e. totally independent of 2011 data sample
  - Signal sample – $B_d \to K^* J/\psi$ data
  - Bkgrd sample – $B_d \to K^* \mu\mu$ mass sideband events

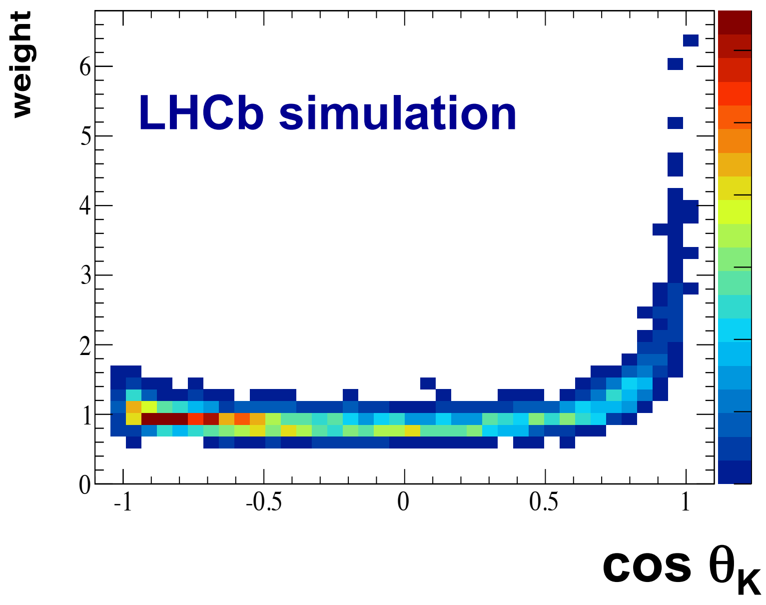
- Resulting selection
  - Background-to-signal ratio ~0.3
    Comparable to B-factories
  - Does not induce further biases in cos θ_L, cos θ_K and q^2 cf reconstruction
    biases introduced are primarily from detector geometry – easy to model





Acceptance Correction

- Correct angular and q^2 distributions for the effect of the detector and selection
- To be model independent, use an event-by-event weight which is determined on the basis of the θ_L, θ_K, q^2 of the signal candidates that are found
- Simulation quality verified with range of control channels ($B_d \rightarrow K^* J/\psi$, $J/\psi \rightarrow \mu\mu$, $D^* \rightarrow D^0(K\pi)\pi$)
  - Tracking efficiency
  - Hadron (mis-)identification probabilities
  - Muon (mis-)identification
  - Overall momentum and η distributions



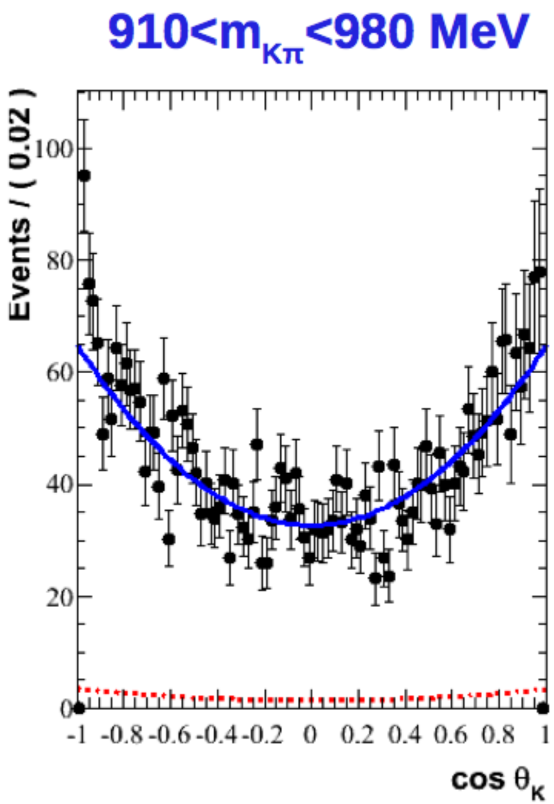
Weight depends on $\cos\theta_K$

Vast majority of events have weights ~1

Fit Procedure and Validation

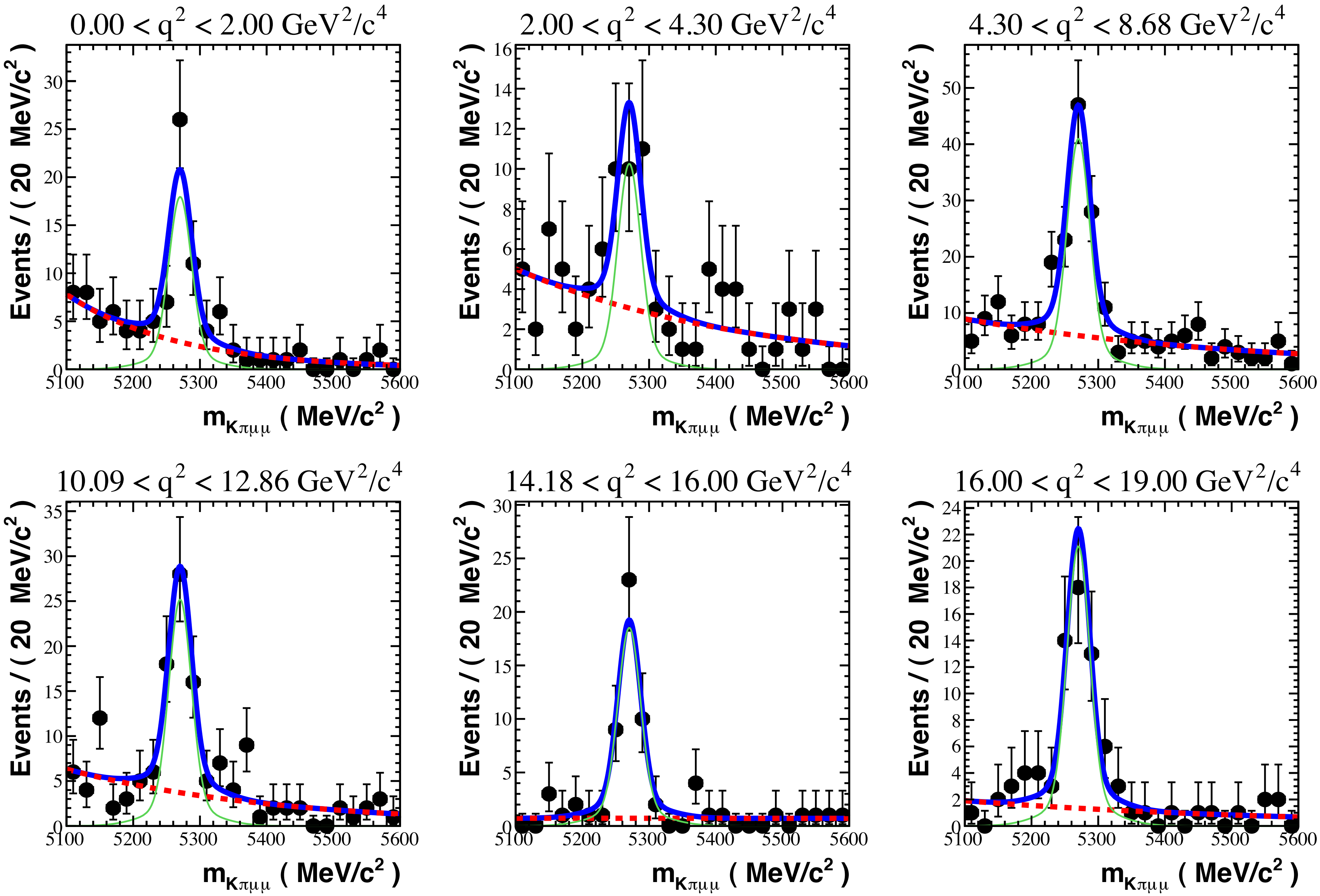
- Simultaneous fit to the 1d projections of $\cos\theta_L$, $\cos\theta_K$ and $m_{K\pi\mu\mu}$ in bins of q^2
  - Events weighted according to acceptance correction
  - Use Bayesian approach to construct stat. errors with flat prior over physical region
  - Systematics effects are very small and can be reduced with further data
  - Cross-check with a simple counting approach (don't use angular distributions)

- Validate fitting on $B_d \rightarrow K^*J/\psi$
  - A_{FB} consistent with zero, as expected
  - s-wave contribution induces an asymmetry in $\cos\theta_K$ distribution, A_{FB}^K
  - Acceptance correction makes $\cos\theta_K$ asymmetric→symmetric
  - Variation of A_{FB}^K with $m_{K\pi}$ matches BaBar data(**) across $m_{K\pi}$ range



(**) BABAR: PRD 76, 031102 (2007)

$B_d \rightarrow K^*\mu\mu$ yields



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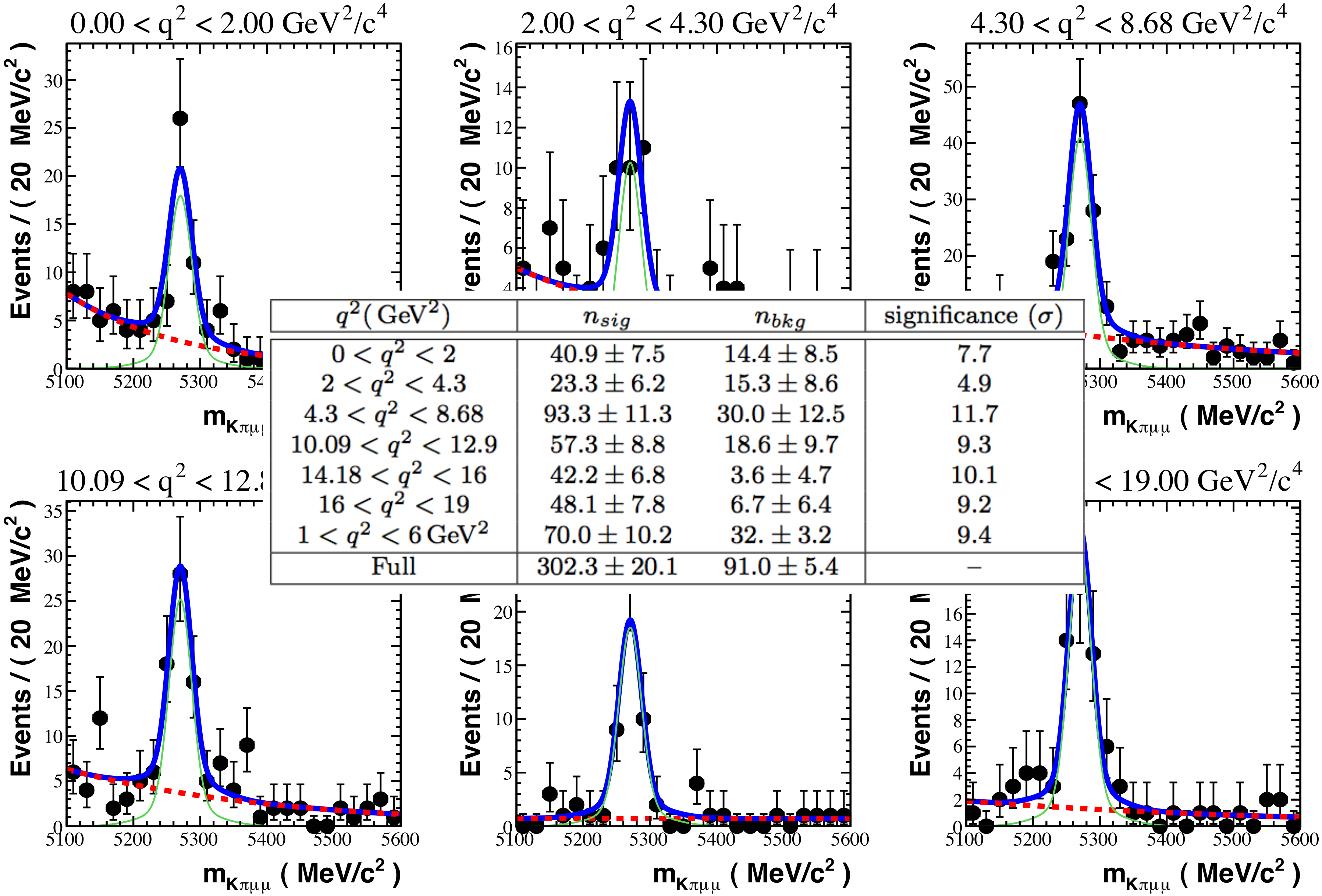
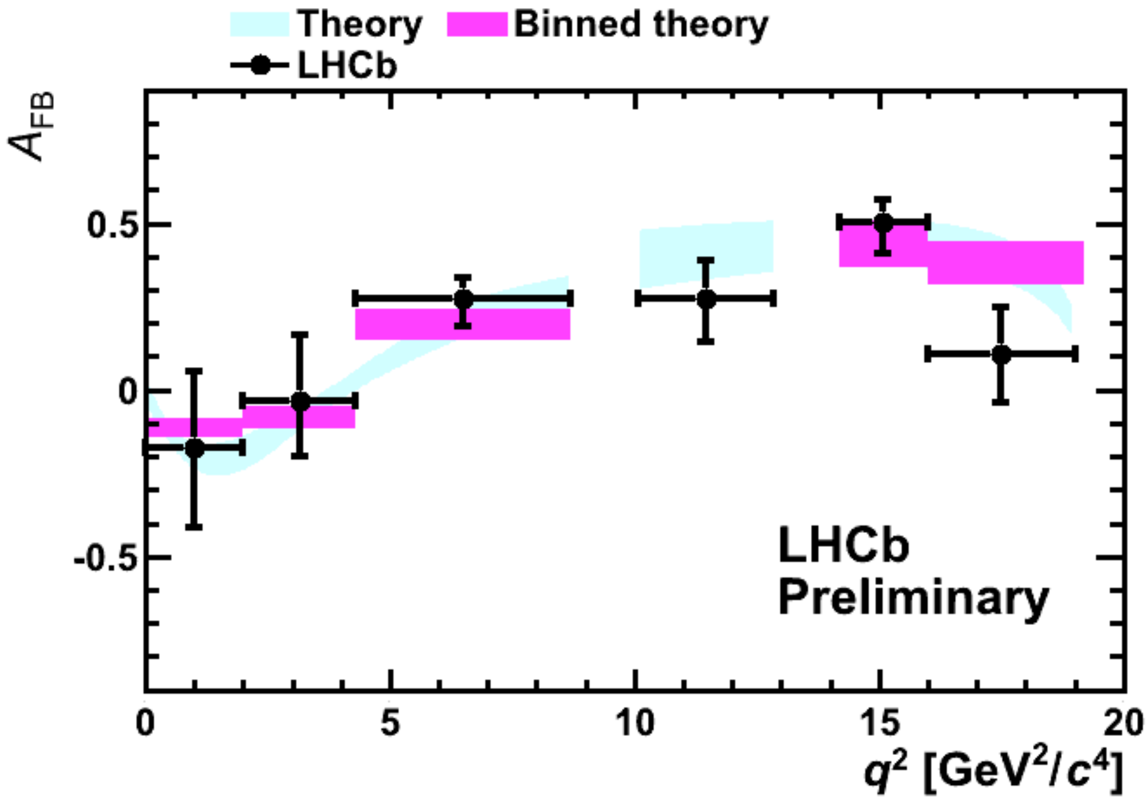


$q^2(\mathrm{GeV}^2)$	n_{sig}	n_{bkg}	significance (σ)
$0 < q^2 < 2$	40.9 ± 7.5	14.4 ± 8.5	7.7
$2 < q^2 < 4.3$	23.3 ± 6.2	15.3 ± 8.6	4.9
$4.3 < q^2 < 8.68$	93.3 ± 11.3	30.0 ± 12.5	11.7
$10.09 < q^2 < 12.9$	57.3 ± 8.8	18.6 ± 9.7	9.3
$14.18 < q^2 < 16$	42.2 ± 6.8	3.6 ± 4.7	10.1
$16 < q^2 < 19$	48.1 ± 7.8	6.7 ± 6.4	9.2
$1 < q^2 < 6\,\mathrm{GeV}^2$	70.0 ± 10.2	$32. \pm 3.2$	9.4
Full	302.3 ± 20.1	91.0 ± 5.4	–

A_{FB} Measurement



Theory predictions from C.Bobeth *et al.*,
arXiv:1105.0376v2

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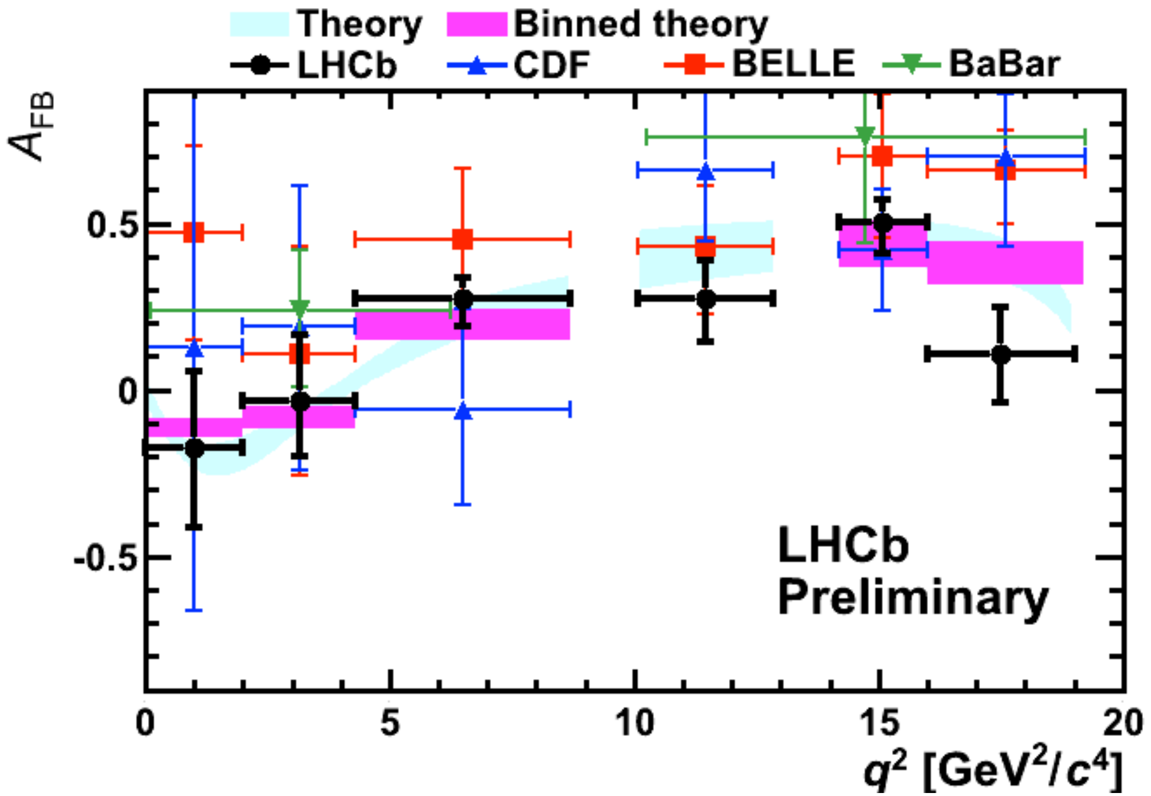

LHCb preliminary

q^2 (GeV^2)	A_{FB}	F_L	$d\Gamma/dq^2$
$0 < q^2 < 2$	$-0.17^{+0.22}_{-0.23} \pm 0.06$	$0.03^{+0.15}_{-0.03} \pm 0.06$	$0.56 \pm 0.11 \pm 0.03$
$2 < q^2 < 4.3$	$-0.04^{+0.19}_{-0.15} \pm 0.06$	$0.84^{+0.15}_{-0.13} \pm 0.06$	$0.28 \pm 0.08 \pm 0.02$
$4.3 < q^2 < 8.68$	$0.28^{+0.06}_{-0.08} \pm 0.02$	$0.60^{+0.07}_{-0.07} \pm 0.01$	$0.55 \pm 0.07 \pm 0.03$
$10.09 < q^2 < 12.9$	$0.27^{+0.11}_{-0.13} \pm 0.03$	$0.44^{+0.12}_{-0.11} \pm 0.02$	$0.53 \pm 0.09 \pm 0.03$
$14.18 < q^2 < 16$	$0.50^{+0.06}_{-0.09} \pm 0.03$	$0.33^{+0.11}_{-0.08} \pm 0.04$	$0.59 \pm 0.10 \pm 0.03$
$16 < q^2 < 19$	$0.10^{-0.13}_{-0.13} \pm 0.06$	$0.28^{+0.10}_{-0.09} \pm 0.04$	$0.48 \pm 0.08 \pm 0.03$
$1 < q^2 < 6$	$-0.10^{+0.14}_{-0.14} \pm 0.05$	$0.57^{+0.11}_{-0.10} \pm 0.03$	$0.39 \pm 0.06 \pm 0.02$

- In $1<q^2<6$ GeV^2/c^4 bin,
  - **A_{FB} = -0.10±0.14±0.05**
    c.f. Belle $0.26^{+0.27}_{-0.30}$ ±0.07

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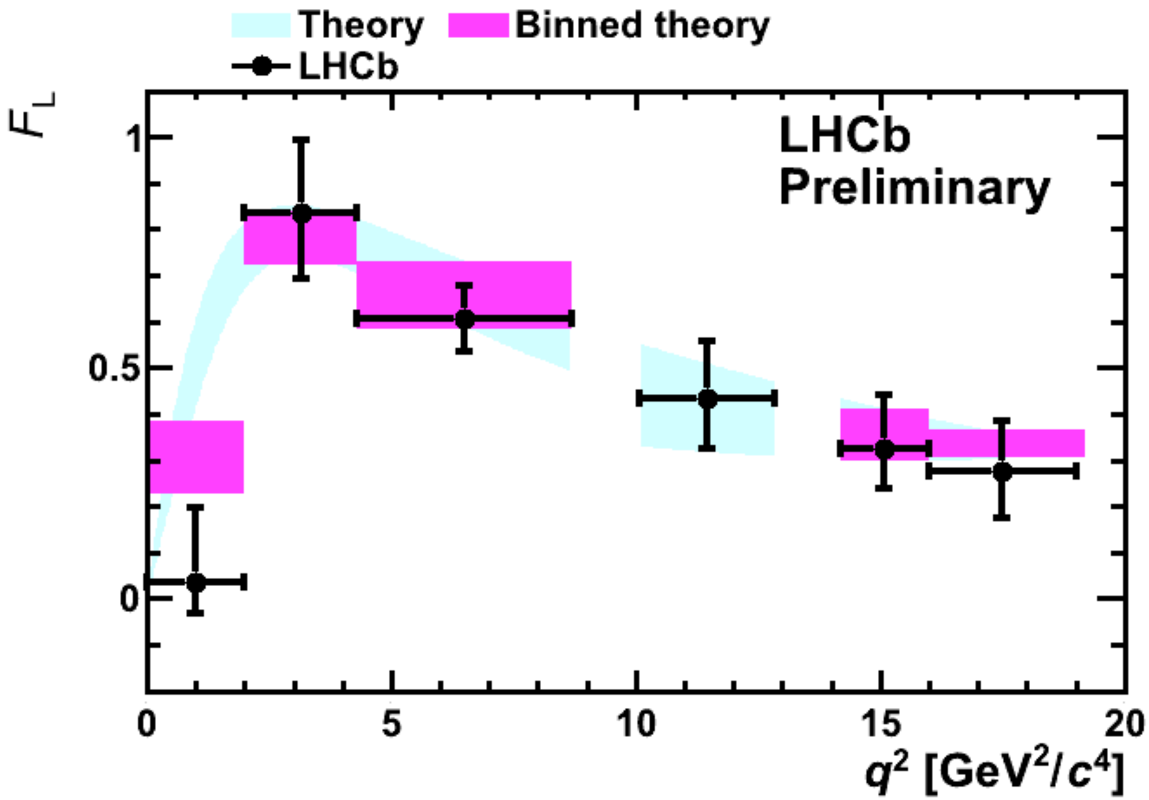
F_L Measurement



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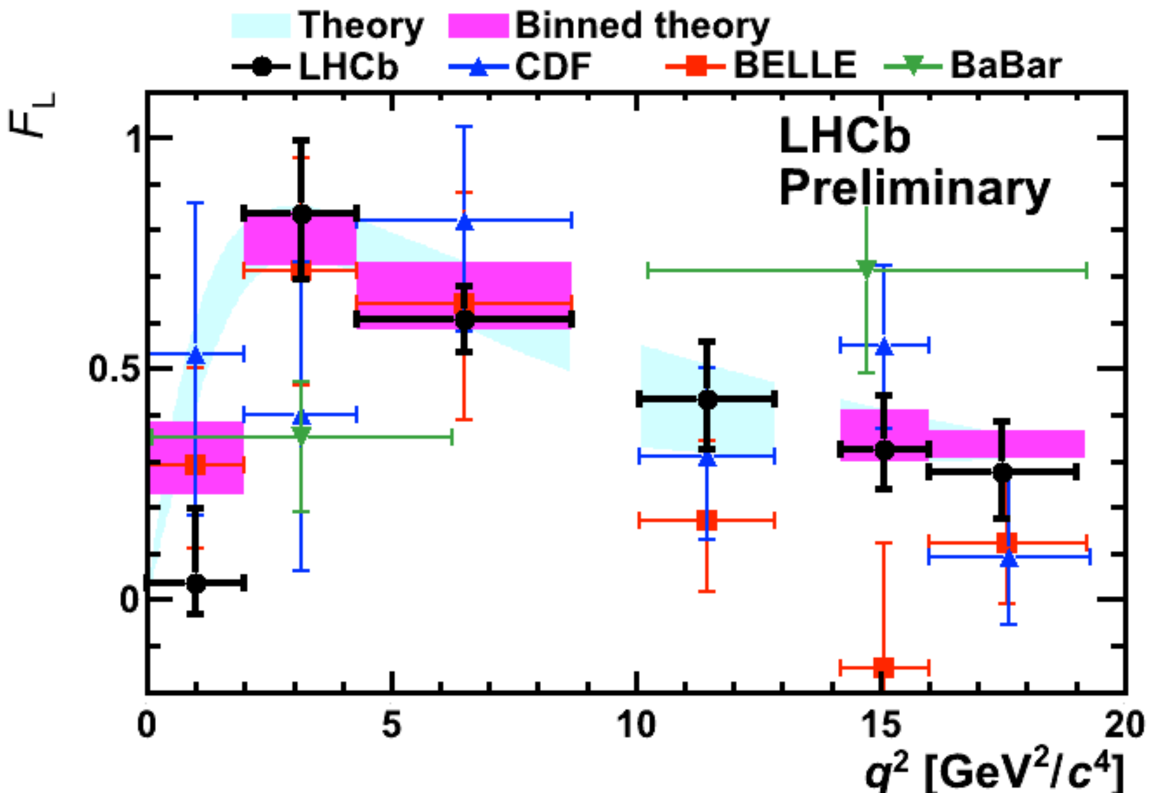

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- In $1<q^2<6$ GeV^2/c^4 bin,
  - **$F_L = 0.57^{+0.11}_{-0.10} \pm 0.03$**
  - c.f. Belle 0.67±0.23 ±0.07

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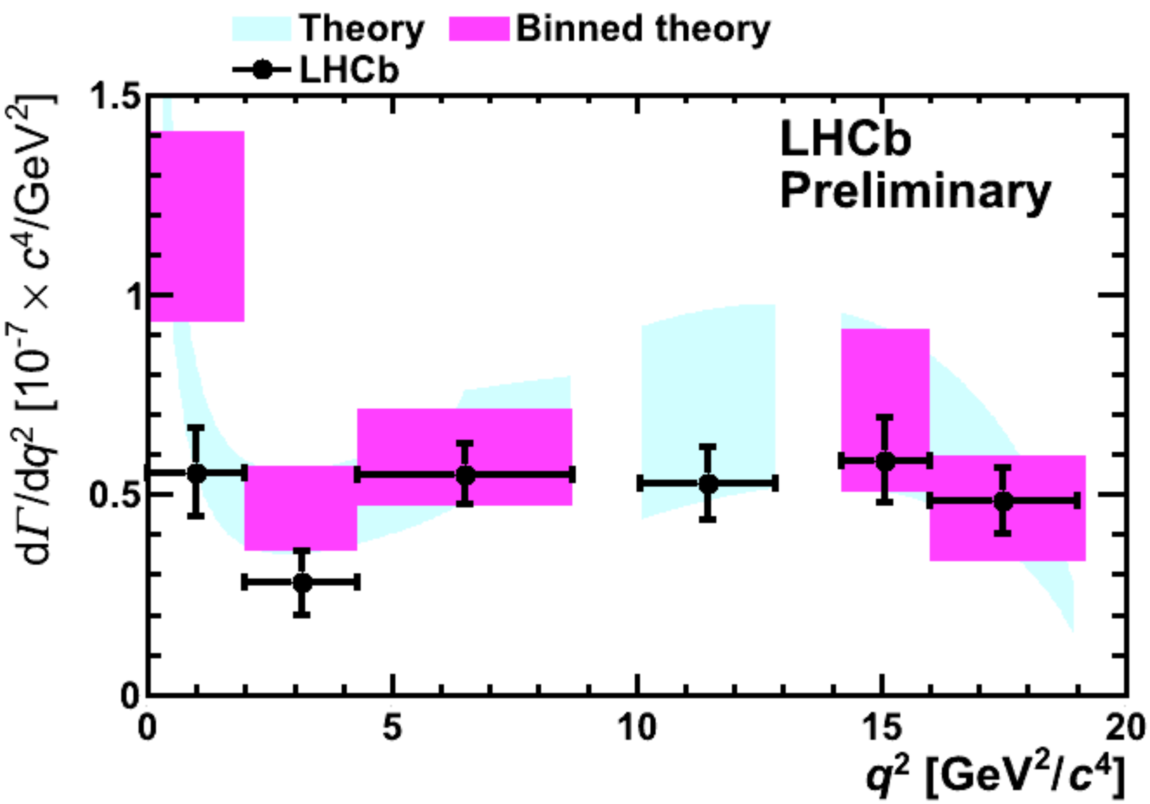
dΓ/dq^2



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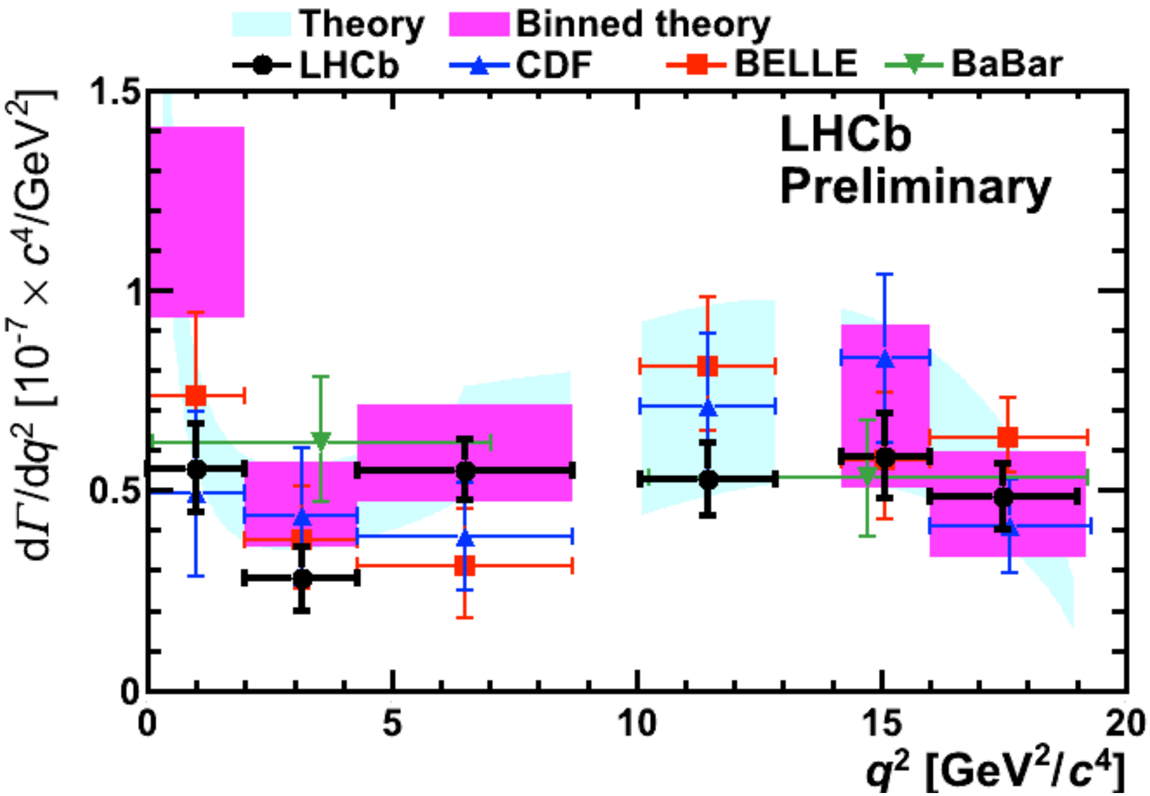
$d\Gamma/dq^2$



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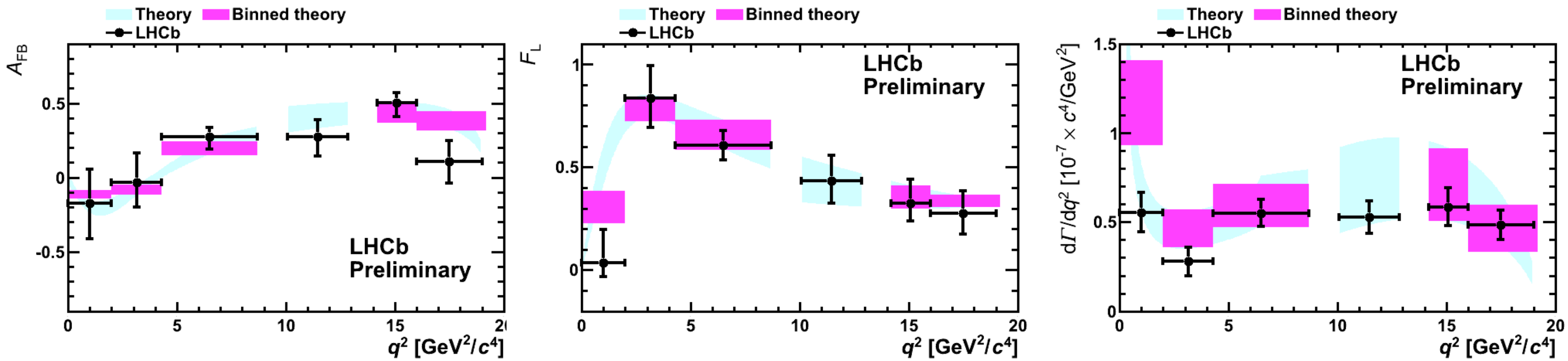
Conclusions

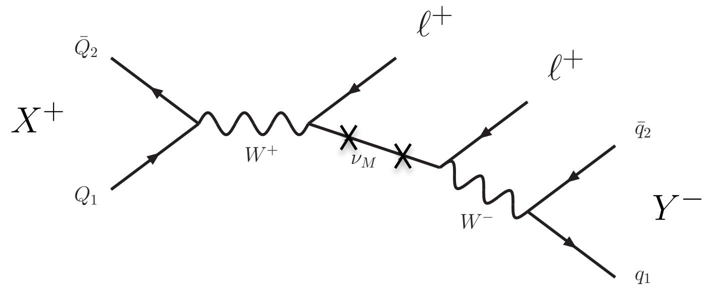
- Angular analysis of $B_d \rightarrow K^* \mu^+ \mu^-$
  - A_{FB}, F_L and $d\Gamma/dq^2$ measured as function of q^2 with $309 pb^{-1}$ of LHCb data taken in 2011
  - All three measurements show good agreement with the SM, no evidence for a large asymmetry in the low q^2 region as hinted at by previous experiments
  - Errors smaller than previous measurements and are statistically dominated



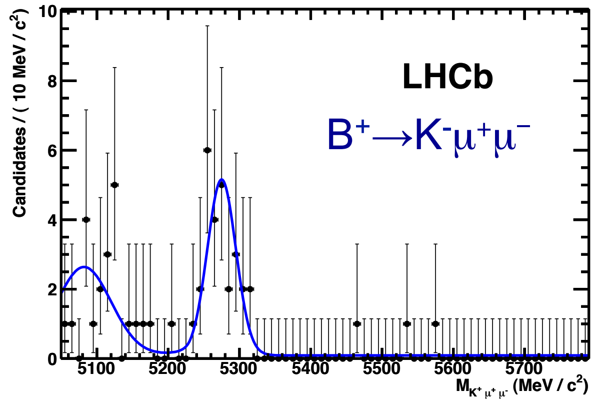
Backup

Search for $B^+\to\pi^-\mu^+\mu^+$ and $B^+\to K^-\mu^+\mu^+$

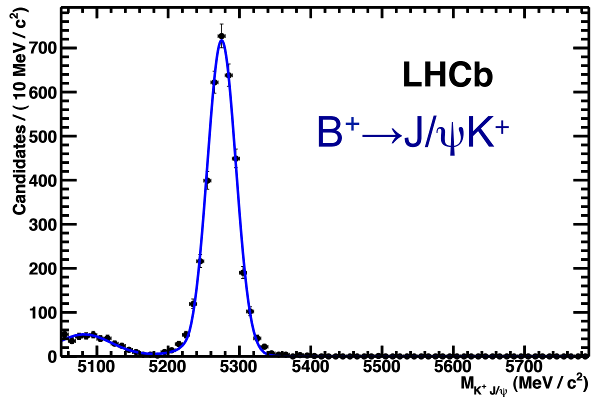
- Lepton Flavour Violating decays
  - ($\Delta L=2$) strictly forbidden in SM
  - Sterile Majorana ν of mass $O(1 GeV/c^2)$ could enhance BR significantly



- Analysis Strategy
  - Tight selection, use 'opposite sign' $B^+\to K^-\mu^+\mu^-$ decays as a proxy for signal
  - Normalise to $B^+\to J/\psi K^+$
  - Detector performance measured from control channels used to estimate peaking bkgrd



- Observed signal / background
  - <0.3 (0.1) bkgrd evts expected in $\pi\mu\mu$ ($K\mu\mu$)
  - **Zero events observed in both signal and mass sideband regions**



Search for $B^+ \to \pi^- \mu^+ \mu^+$ and $B^+ \to K^- \mu^+ \mu^+$

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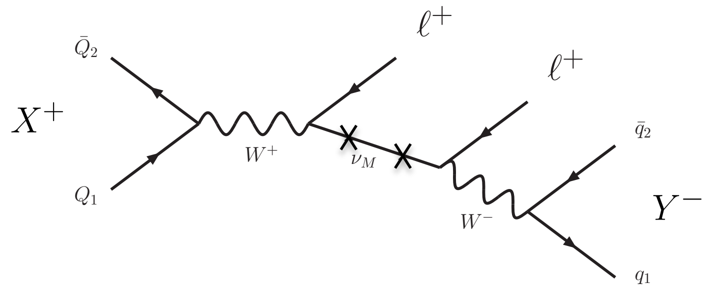
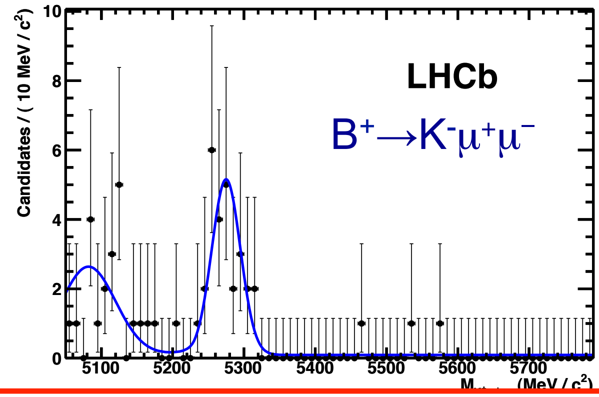




Observed limit @ 90% CL

$BR(B^+ \to K^- \mu^+ \mu^+) < 4.3 \times 10^{-8}$

$BR(B^+ \to \pi^- \mu^+ \mu^+) < 4.5 \times 10^{-8}$

Factor 40(30) improvement cf previous best limit (CLEO)

$M_{K^+ J/\psi}$ (MeV / c^2)

- Search for $B^+ \to \pi^- \mu^+ \mu^+$, $B^+ \to K^- \mu^+ \mu^+$
  - Observed limit @ 90% CL
    - $BR(B^+ \to K^- \mu^+ \mu^+) < 4.3\times10^{-8}$
    - $BR(B^+ \to \pi^- \mu^+ \mu^+) < 4.5\times10^{-8}$
  - Factor 40(30) improvement cf previous best limit (CLEO)

Peaking Backgrounds

- A number of vetos are introduced to deal with peaking bkgrds e.g.
  - $B_s \to \phi\mu\mu$ with $K \to \pi$
  - $B_d \to K^* J/\psi$ with $\pi(K) \to \mu$ and $\mu \to \pi(K)$ swaps [evades J/ψ vetos]
  - $B_d \to K^*\mu\mu$ with $K \to \pi$ and $\pi \to K$

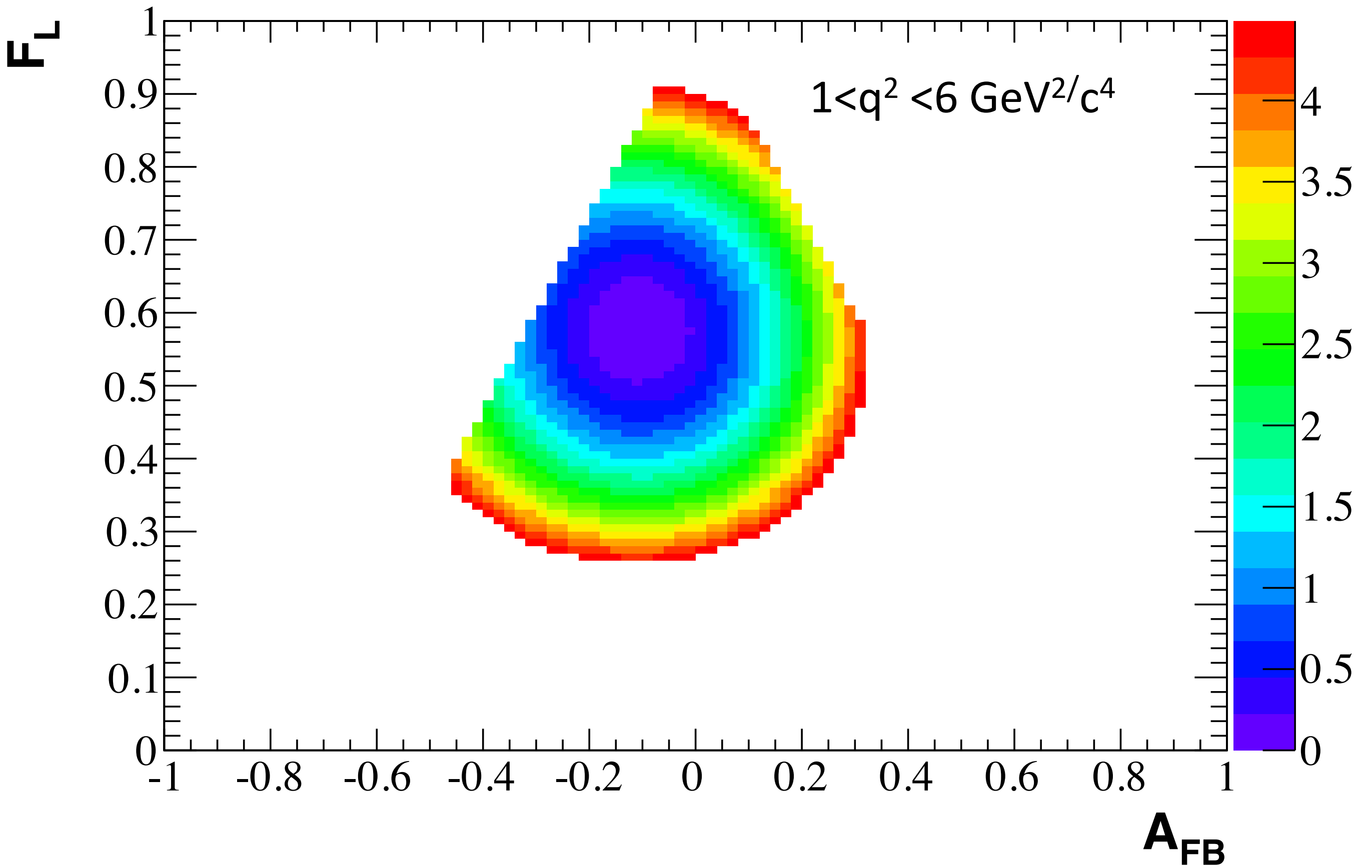
  Completely negligible impact on signal

- Residual background (after application of BDT selection also) :

Source	Quantity	Signal Loss (%)
$B_s \to \phi\mu^+\mu^-$	2.3	0.1
$B^0 \to K^{*0}J/\psi$	0.7	0.1
$B^0 \to K^{*0}\mu^+\mu^-$	1.2	0.3
Total	4.2	0.5

→ residual background is ~3% of signal – only ~0.7% of this can affect asymmetry - $B_d \to K^*\mu\mu$ background flips B and B

Likelihoods



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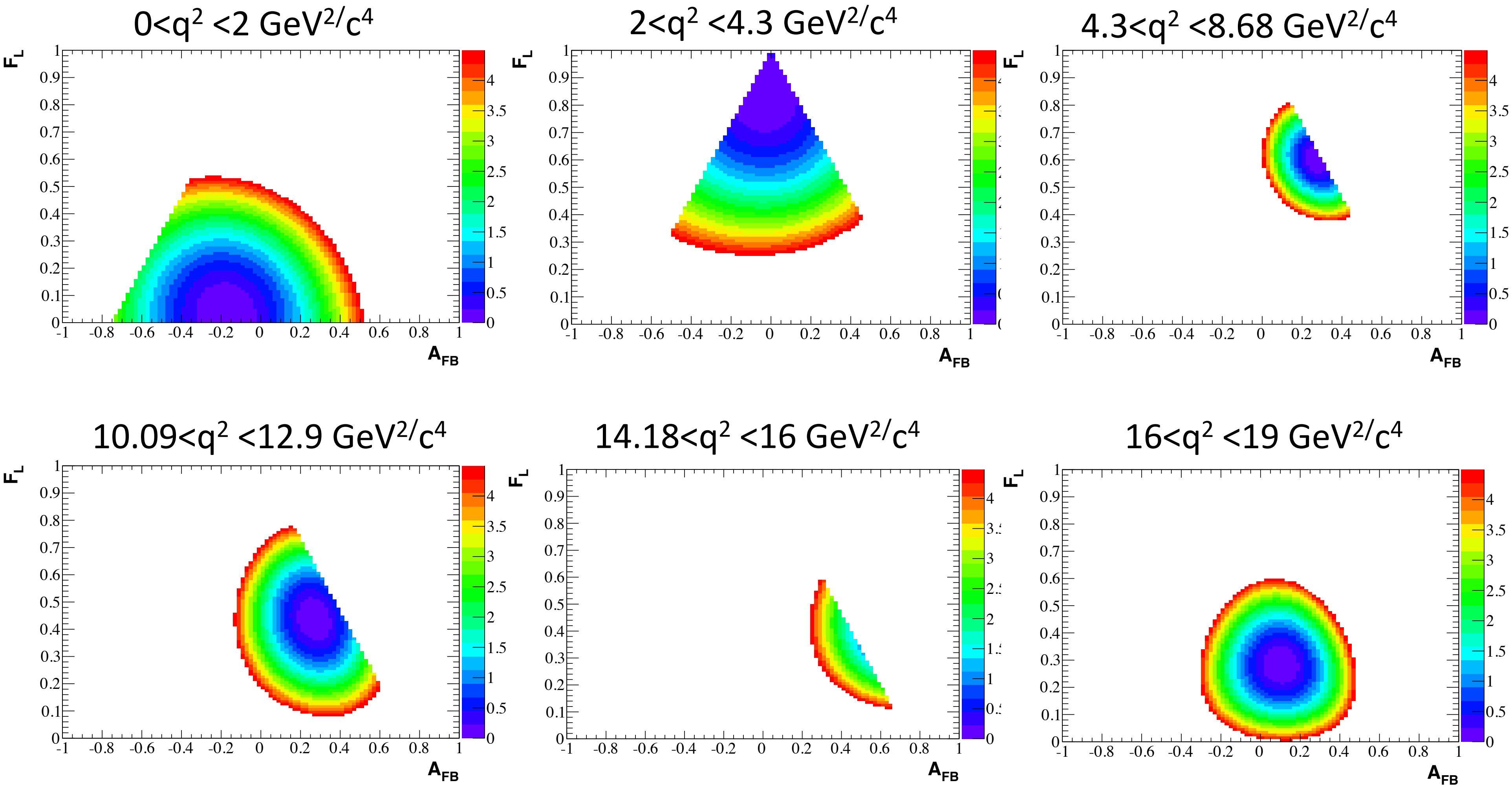
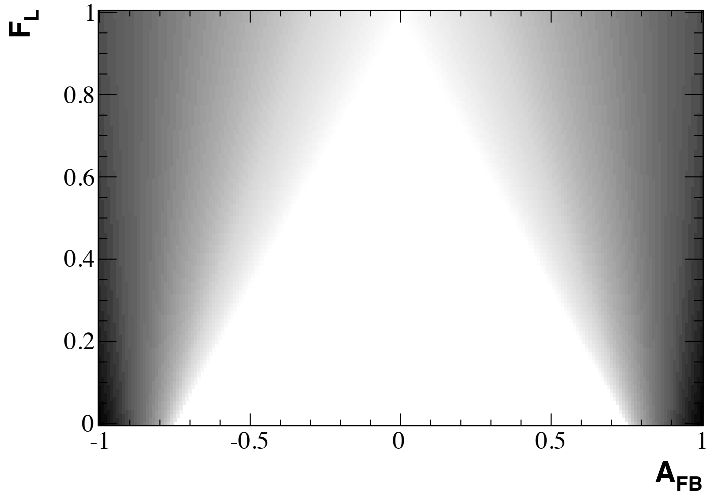


Errors and Physical Region

- Angular equations → pdf negative if $A_{FB} < 3/4(1-F_L)$

- Statistical errors
  - Use Bayesian approach to construct errors with flat prior over physical region
    - The central value quoted is that with the largest likelihood
    - Errors estimated by performing a profile-likelihood scan over the plane and integrating a 68% CL region of the likelihood distribution



- Systematics effects are small and can be reduced with further data