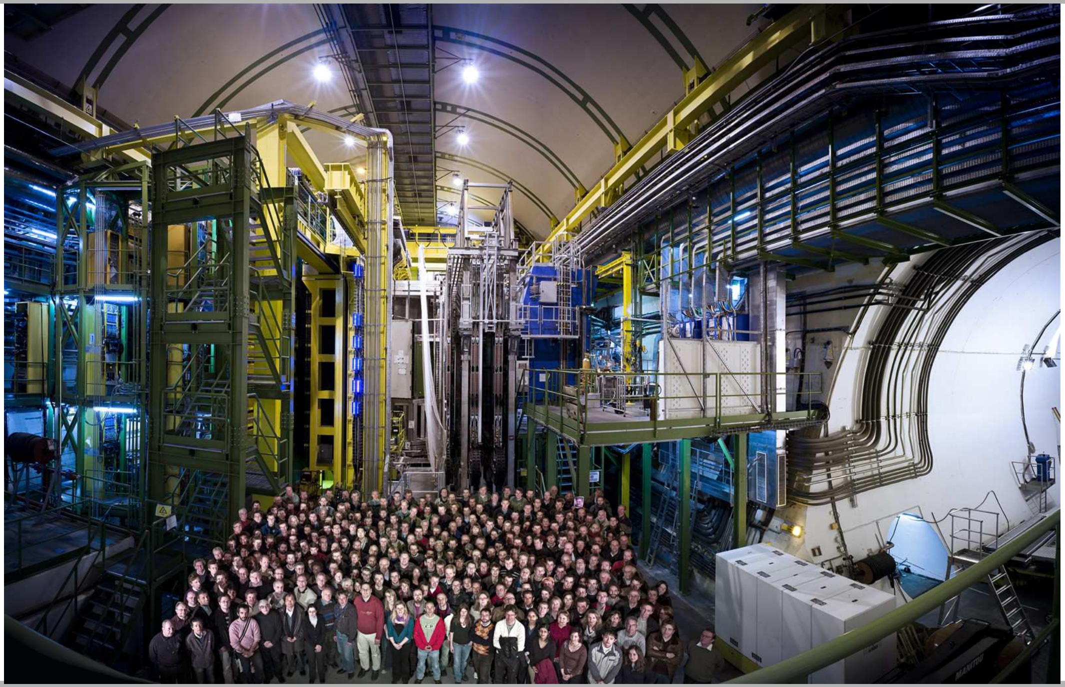
# Electroweak penguins with di-leptons

M. Kreps

Physics Department



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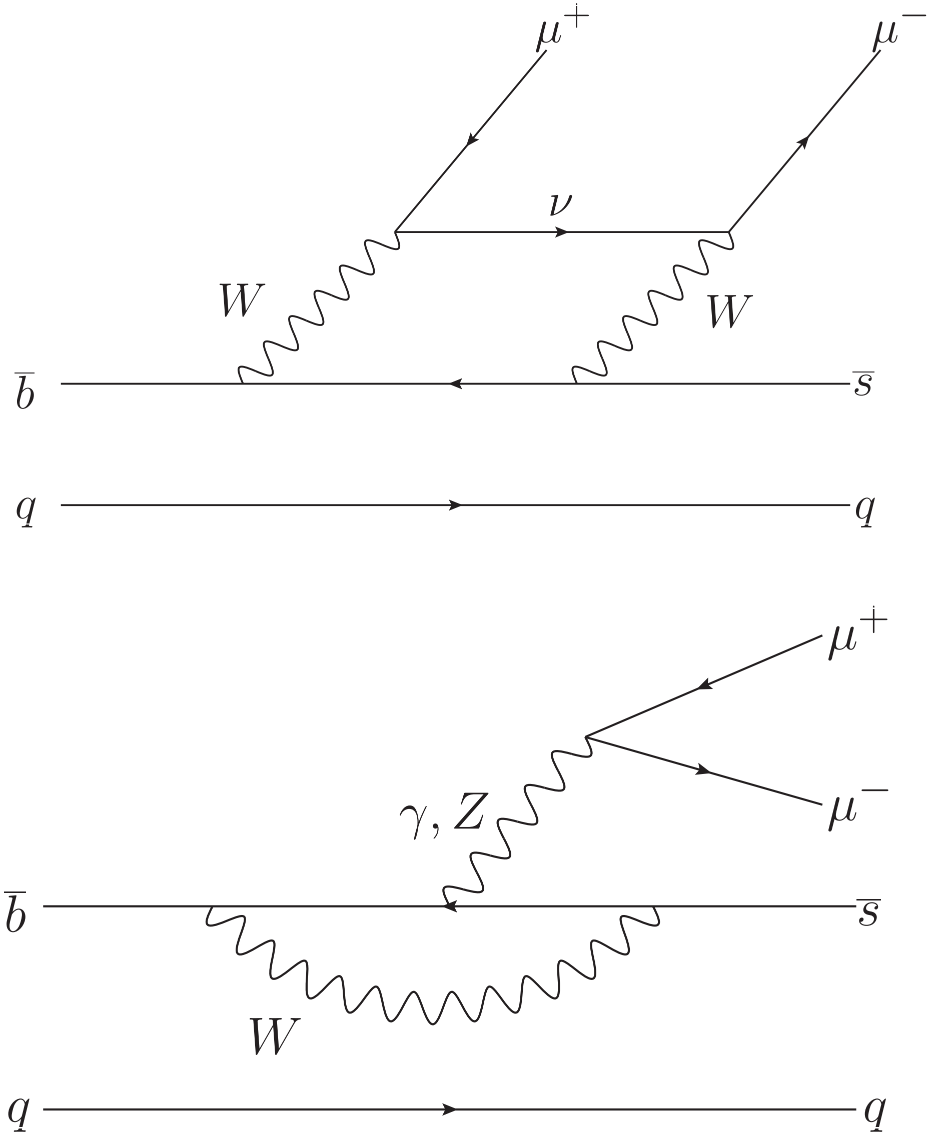
# Motivation for EWK penguins

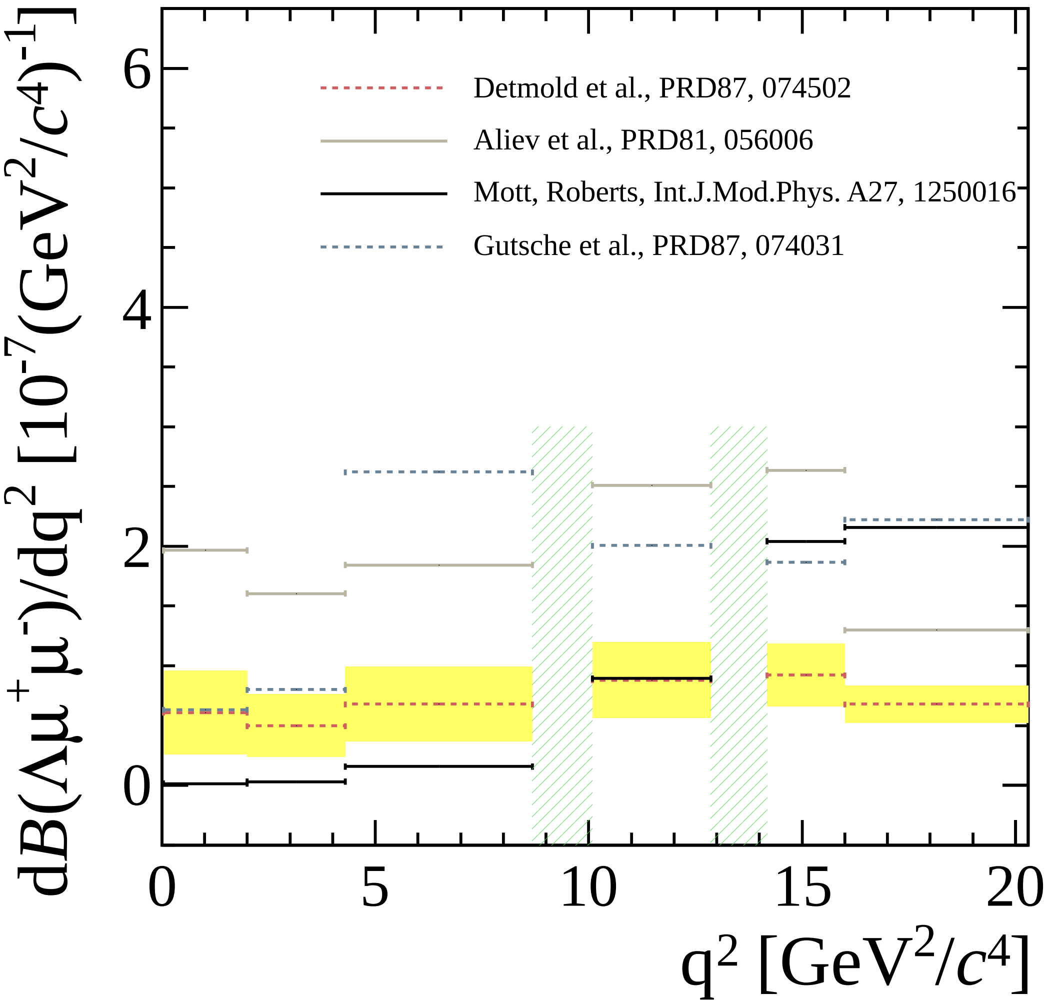
- In the SM, $b \to s$ FCNC decays
- SM BF of the order of $10^{-6}$
- With angular analysis offers variety of observables
- Allows to test some underlying details of the NP
- Form factors make prediction of some observables less precise
- But many observables are free of form factor uncertainties
- Mesons rather well studied, results on
    - $B^0 \to K^{*0}\mu^+\mu^-$
    - $B^0 \to K^{*0}e^+e^-$
    - $B^0_s \to \phi\mu^+\mu^-$



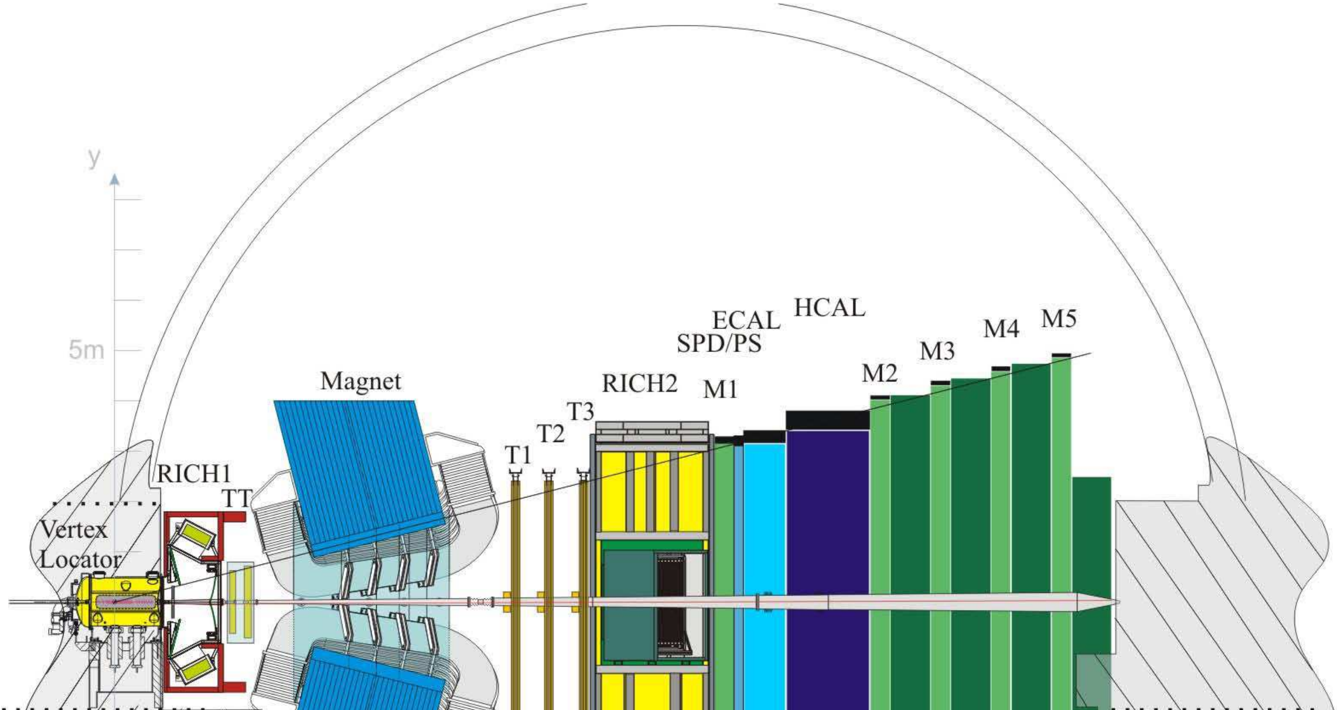
# Case of $\Lambda_b$ baryon

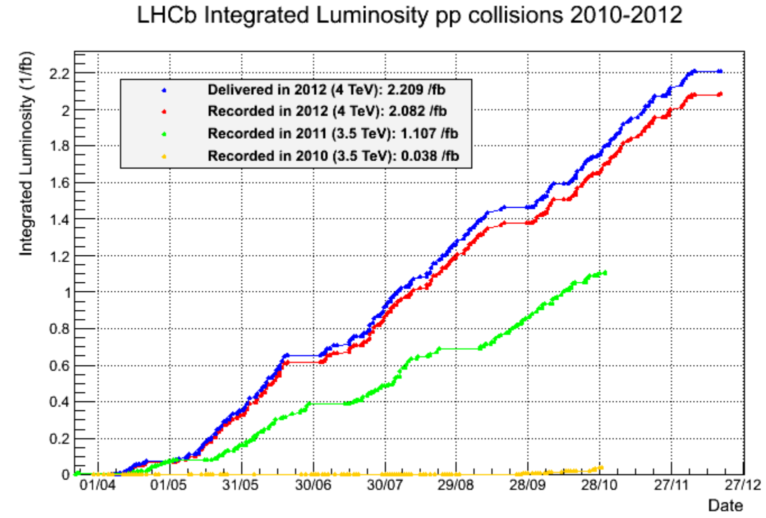
- $\Lambda_b$ has non-zero spin
- Potential to learn something new compared to mesons
- Can influence also understanding of the mesons by better understanding of hadronic physics
- First LHCb result on $\Lambda_b \to \Lambda\mu^+\mu^-$
- Discussion of some prospects

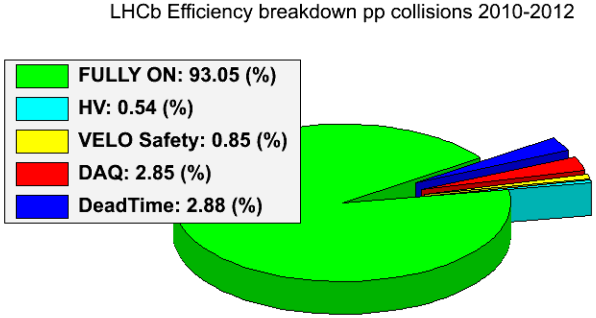
- All results shown today based on 1 fb$^{-1}$



# LHCb detector

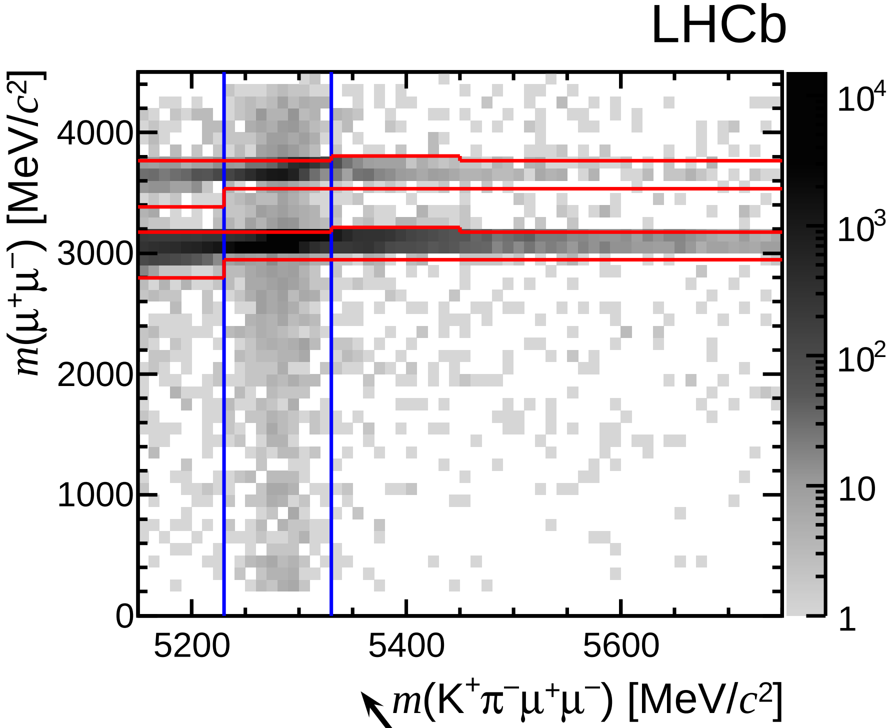



LHCb Integrated Luminosity pp collisions 2010-2012


LHCb Efficiency breakdown pp collisions 2010-2012

# Selection with dimuons

- Uses BDT or NN to combine kinematic, topological and PID inputs
- Trained on resonant ($J/\psi$) signal in data
- Relatively complicated removal of $c\bar{c}$ regions
- Decays via $J/\psi$ used for normalization



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

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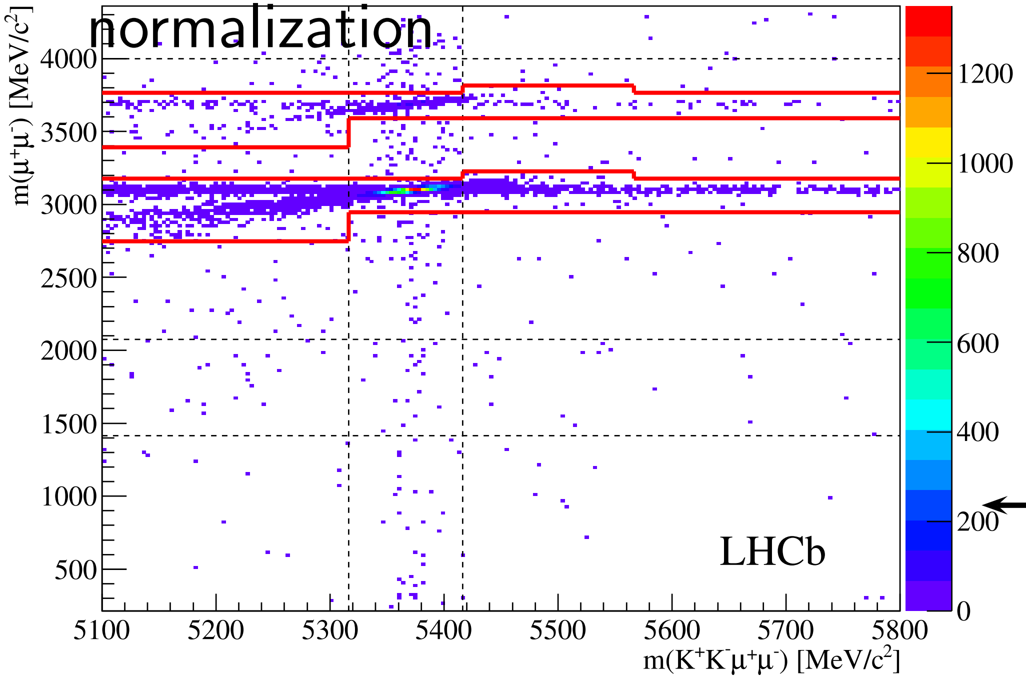

$B_s^0 \to \phi\mu^+\mu^-$

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# Peaking backgrounds

- Most obvious one are decays through charmonia resonances
  - Decays through $J/\psi$ and $\psi(2S)$ resonance are vetoed
- $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B_s^0 \rightarrow \phi\mu^+\mu^-$ cross-talk to each other
- Similar $\Lambda_b$ decays should exists and so they can contribute as well
- Thanks to good particle ID at LHCb, they give just small contribution
- Many backgrounds of this type can be vetoed rather easily
- Typically they are not very difficult to handle for differential branching fraction measuements
- More critical for angular analysis

# $B^0 \to K^{*0}\mu^+\mu^-$ — $q^2$ bins

- Extended maximum likelihood fit
- Signal: double Crystal ball function fixed from $J/\psi$ decays
- Bg: combinatorial (exponential), $B_s^0 \to K^{*0}\mu\mu$, $B_s^0 \to \phi\mu\mu$ and $B^0 \to J/\psi K^{*0}$ from MC

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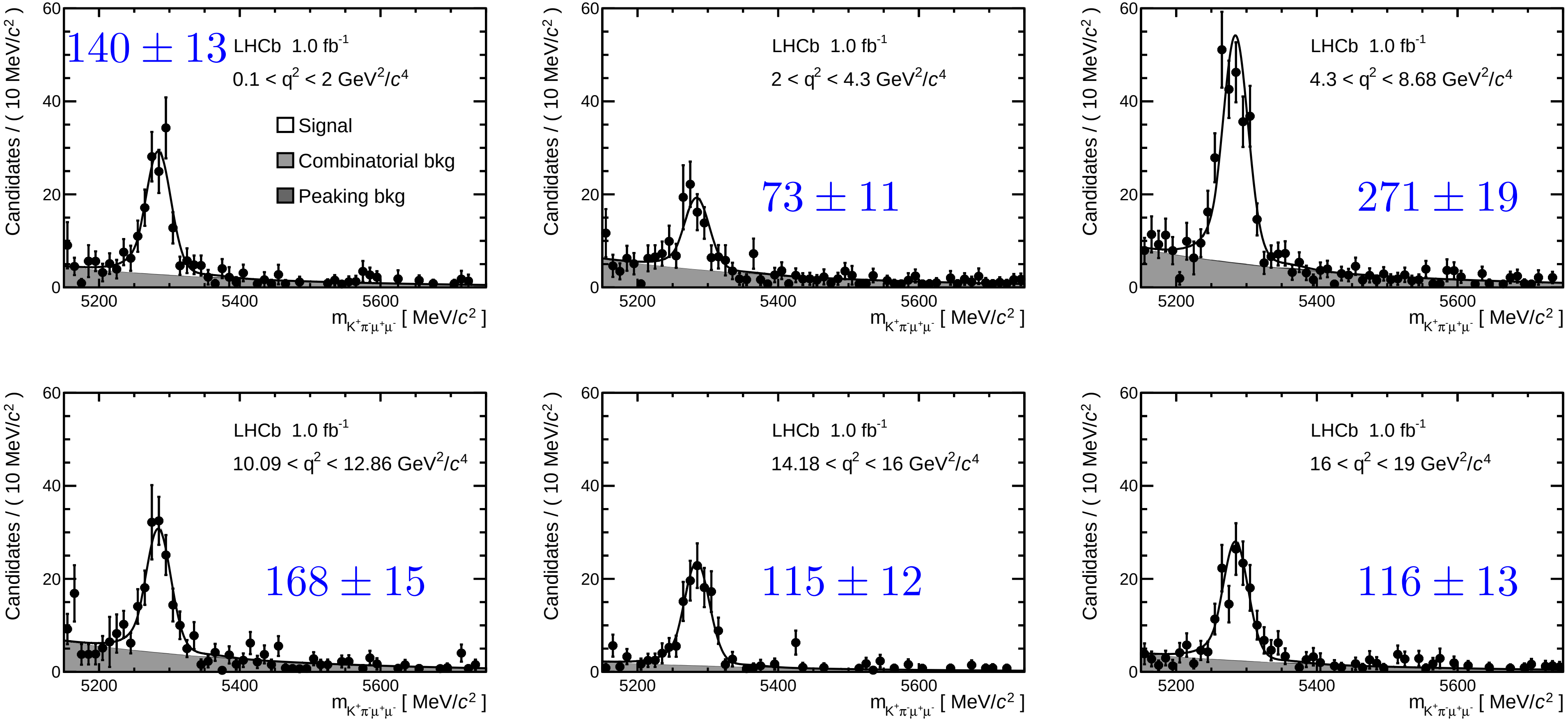

# $B_s^0 \to \phi\mu^+\mu^-$ — $q^2$ **bins**

- Extended maximum likelihood fit
- Signal: double Gaussian function fixed from $J/\psi$ decays
- Bg: combinatorial (exponential)
- Clear signal in all $q^2$ bins
- First time we see signal in all $q^2$ bins

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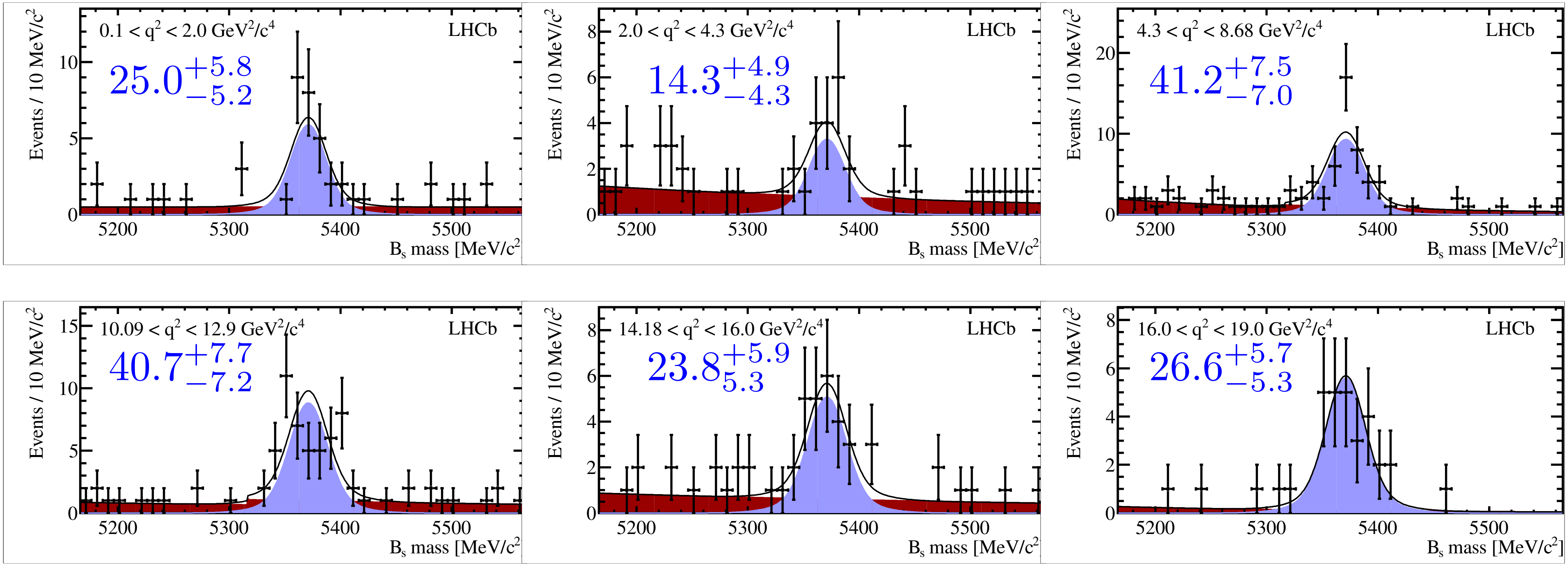
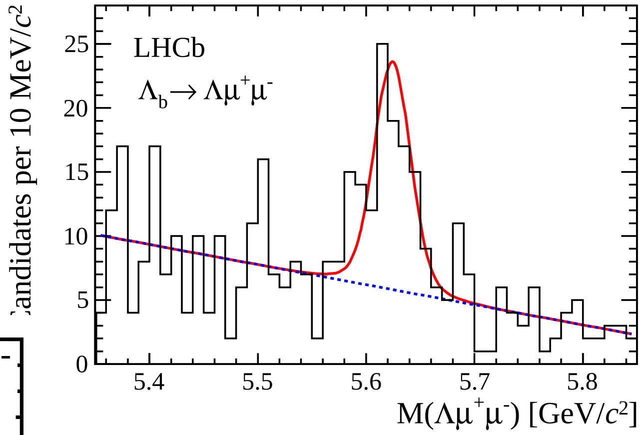
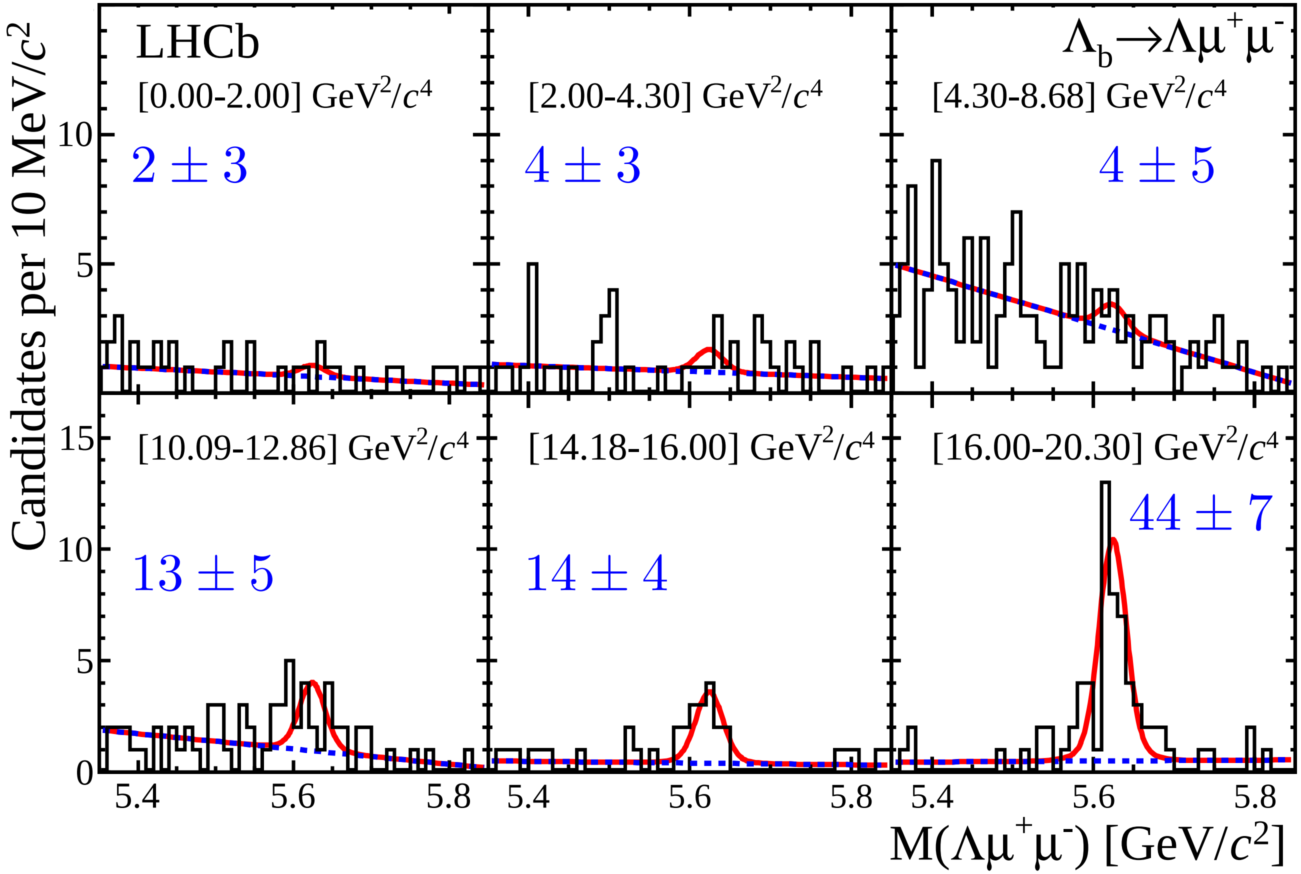


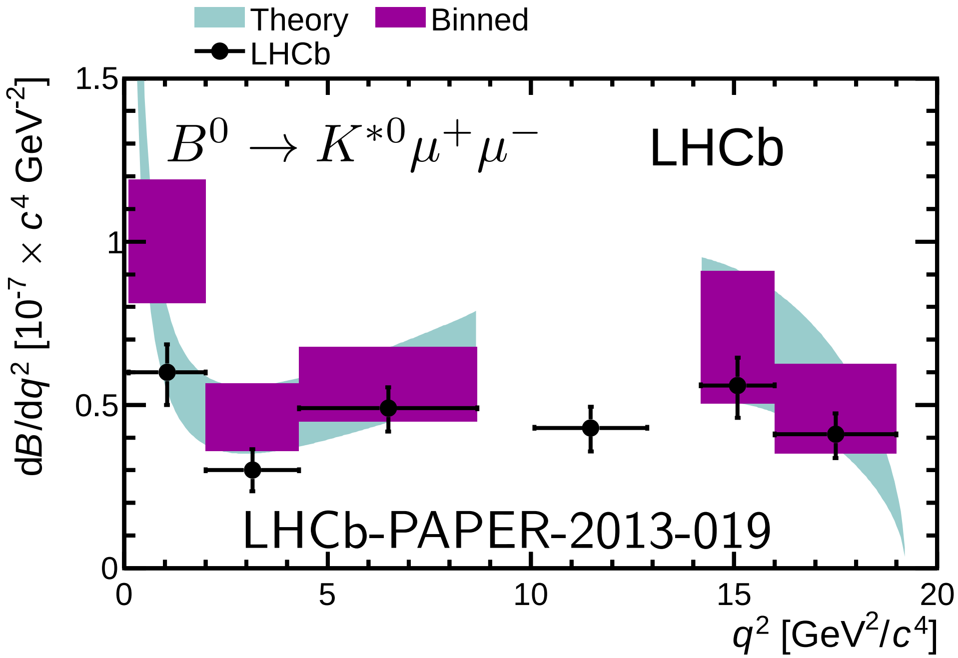
# $\Lambda_b \to \Lambda\mu^+\mu^-$ – $q^2$ bins

- No significant signal below $J/\psi$ resonance
- Only highest $q^2$ bin above $5\sigma$



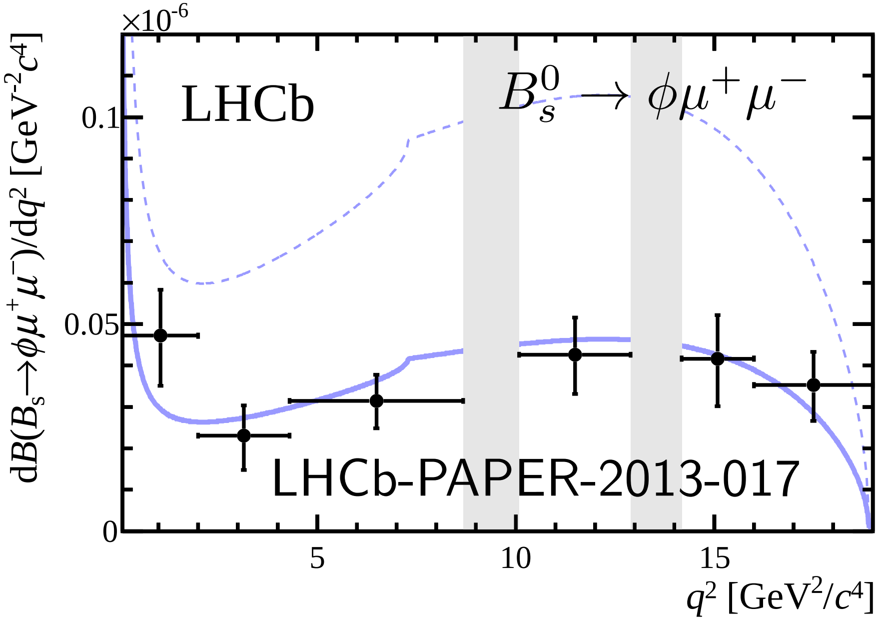


# Differential BF



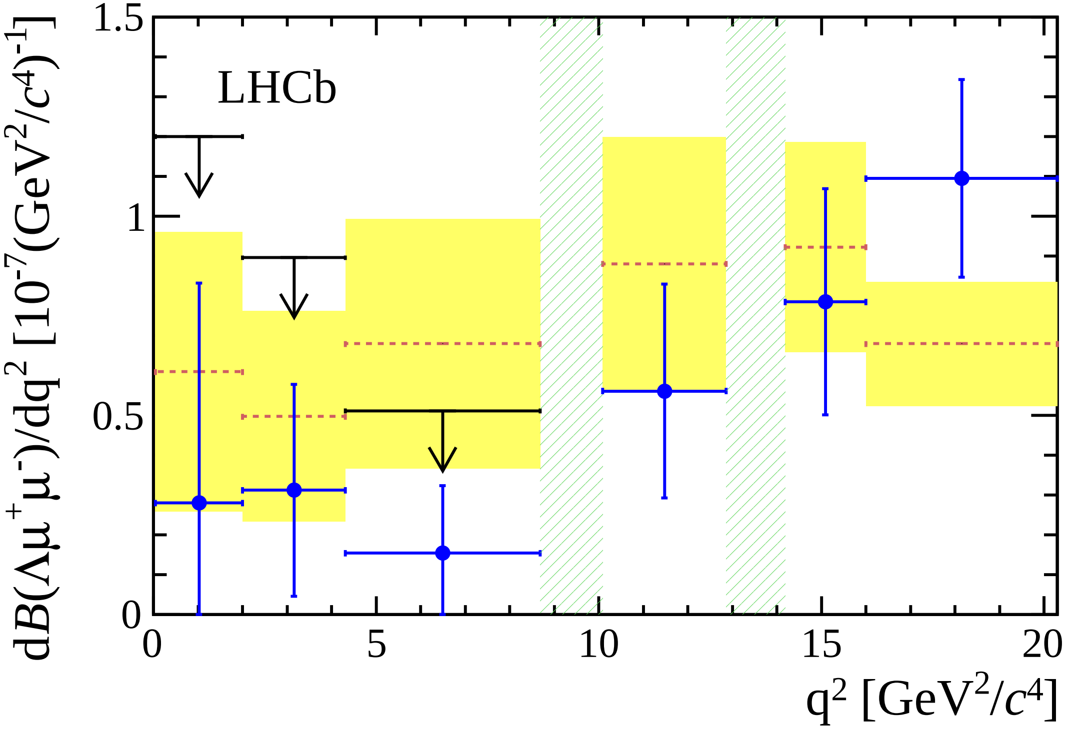
- Syst. uncertainties dominated by normalization BF
- Other contributions from Bg PDFs and data-MC differences
- Large fraction of systematic uncertainty correlated across $q^2$ bins

- $dB/dq^2 = \frac{1}{\Delta q^2}\frac{N_{sig}}{N_{norm}}\epsilon_{rel}B_{norm}$
- $B^0 \to K^{*0}\mu^+\mu^-$ agrees with SM
- Two decays have simular shape
- For $B_s^0 \to \phi\mu\mu$ we measure integrated rate $(7.07^{+0.64}_{-0.59} \pm 0.17 \pm 0.71) \times 10^{-7}$

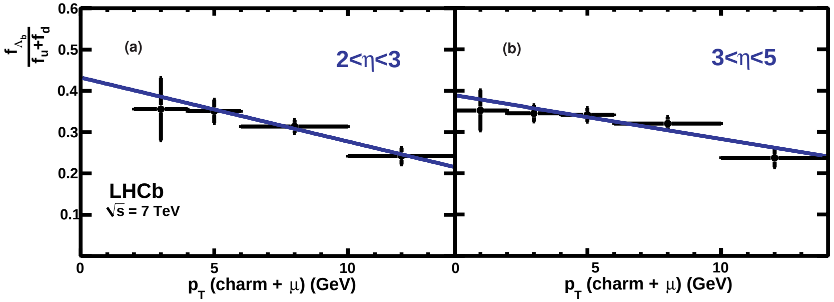


# Differential BF

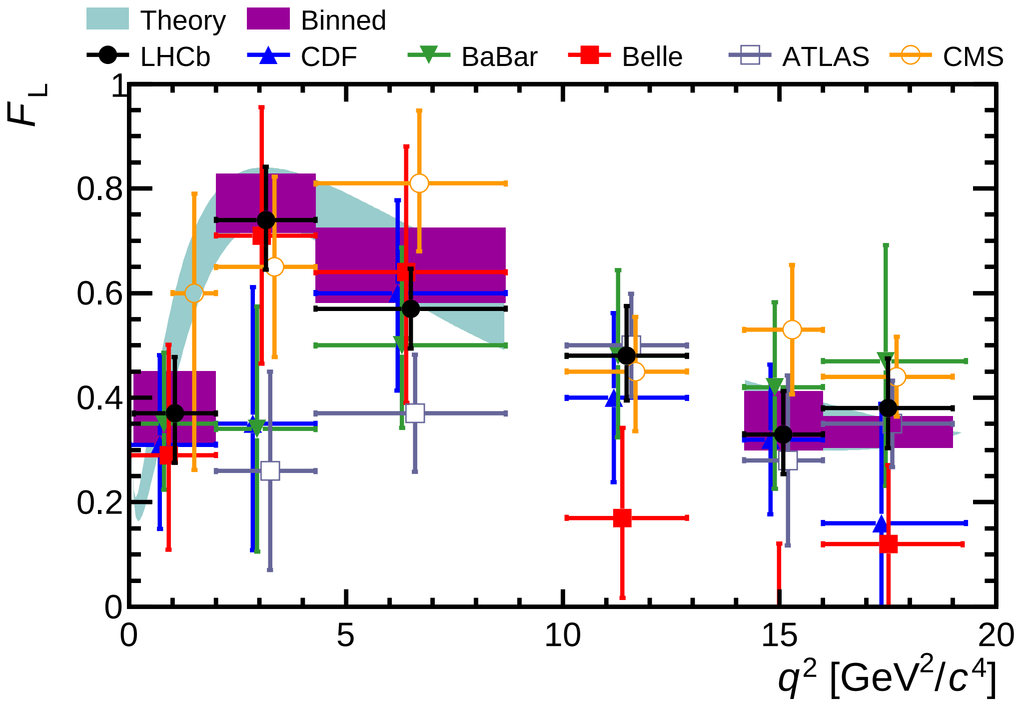
- Limits at first three bins are Bayesian at 90% C.L.
- Non-observation at low $q^2$ is not entirely by lack of sensitivity
- Will need more data to say something more
- Integrated BF (excluding $J/\psi$ and $\psi(2S)$ vetos) $(0.96 \pm 0.16(\mathrm{stat}) \pm 0.13(\mathrm{syst}) \pm 0.21\,(\mathrm{norm})) \times 10^{-6}$



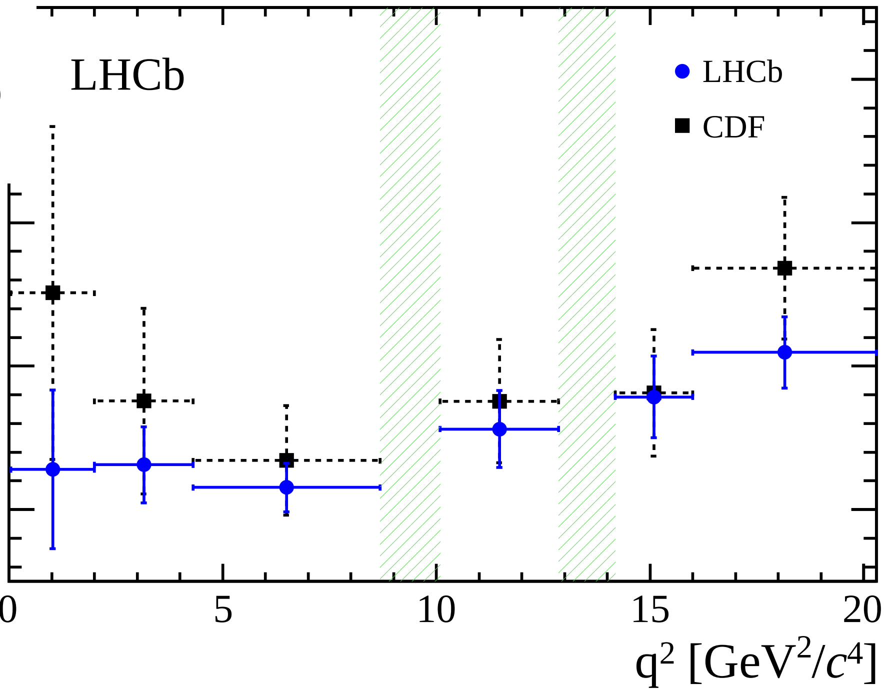
Sidenote on $\Lambda_b$ normalization:
PDG gives $f(b \to \Lambda_b) \times \mathcal{B}(\Lambda_b \to J/\psi\Lambda)$
No good $\mathcal{B}(\Lambda_b \to J/\psi\Lambda)$



# All experiments



- LHCb measurements most precise
- CMS at high $q^2$ comes close to LHCb

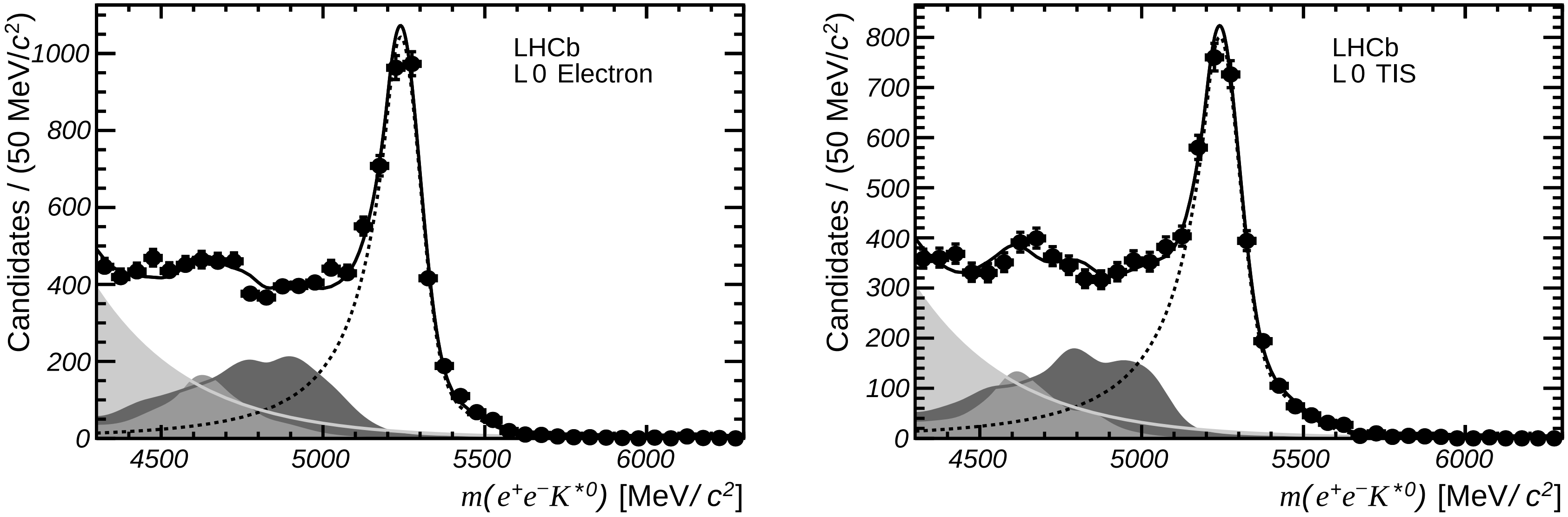


# Low $q^2$ region

- Low $q^2$ region particularly sensitive to $\gamma$ polarization
- Decay $B^0 \to K^{*0}e^+e^-$ can reach lower $q^2$ as decay with dimuons
- Never observed on its own at low $q^2$
- Before moving to angular analysis, measure differential BF in $30 < m(\ell^+\ell^-) < 1000$ MeV
- Below 30 MeV angles hard to measure
- Analysis more challenging by significantly larger brehmstralung

$\Rightarrow$ Try to recover radiated photons

- Use of BDT for selection, trained on simulated signal and bg from data



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# $B^0 \to K^{*0} e^+ e^-$ **at low** $q^2$

- Main physics background from $B^0 \to K^{*0}\gamma$ with $\gamma$ conversion
- Extended maximum likelihood fit
  - Signal: double Crystal ball
  - Combinatorial bg: exponential
  - Partially reconstructed bg from simulation
- Significance $4.6\sigma$
- Systematic uncertainties well bellow statistical
- Dominant contributions from normalization BF and fit procedure
- Resulting $B^0 \to K^{*0} e^+ e^-$ BF $(3.1^{+0.9}_{-0.8}{}^{+0.2}_{-0.3} \pm 0.3) \times 10^{-7}$ in $m(\ell^+\ell^-)$ within 30–1000 MeV

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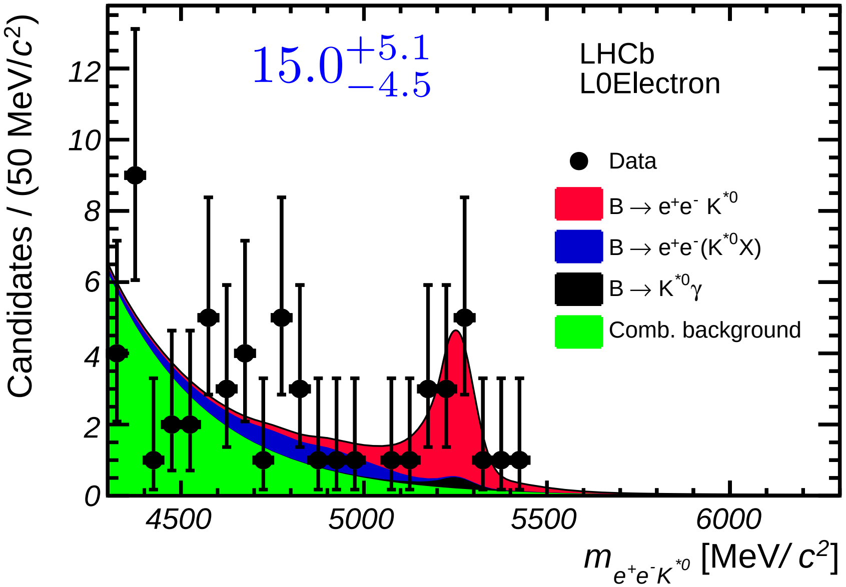
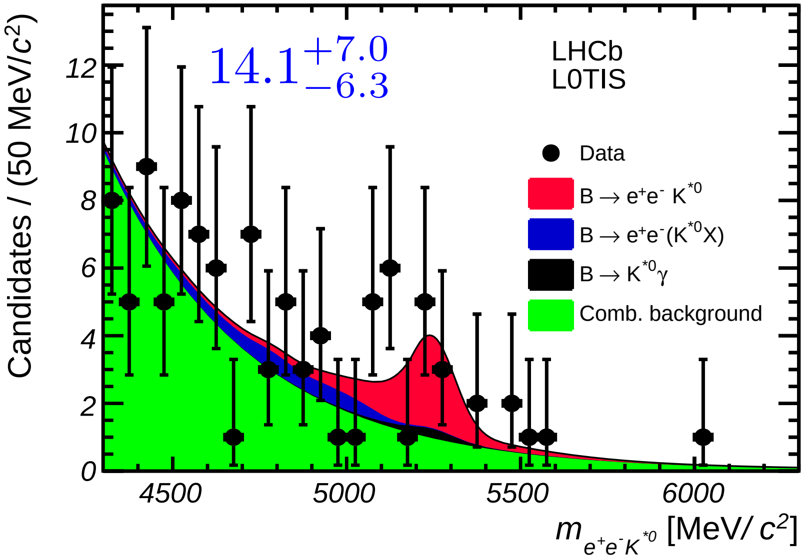


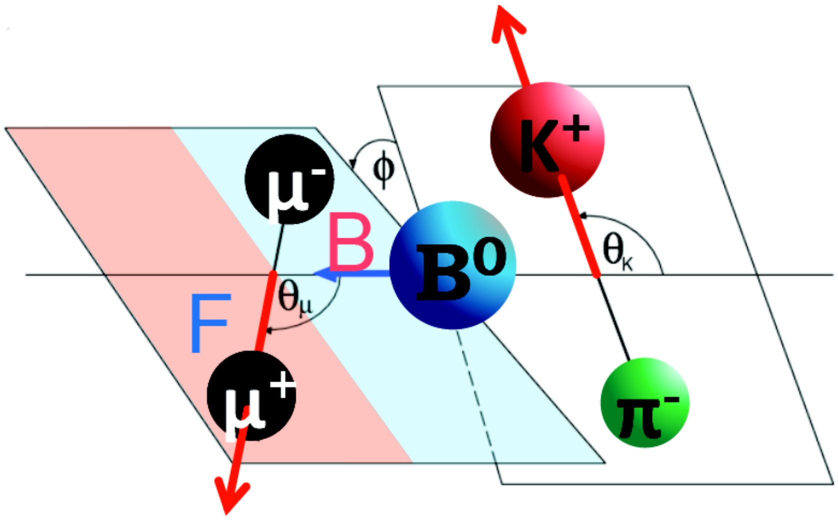


# Angular analysis

- Angular distribution

$$
\begin{aligned}
&S_1^s \sin^2\theta_K \;+\; S_1^c \cos^2\theta_K \;+\\
&S_2^s \sin^2\theta_K \cos 2\theta_\ell \;+ S_2^c \cos^2\theta_K \cos 2\theta_\ell \;+\\
&S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi \;+\\
&S_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + S_6 \cos^2\theta_K \cos\theta_\ell \;+\\
&A_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + A_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi \;+\\
&A_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi
\end{aligned}
$$

- Helicity angles $\theta_l$ and $\theta_K$ defined by $\mu^+$ ($\mu^-$) and $K$ for $B^0$ ($\bar{B}^0$)
- Angle $\phi$ is given by
  $\sin\phi = (\hat{p}_{\mu^+} \times \hat{p}_{\mu^-}).\hat{p}_{K^{*0}}$
  $\sin\phi = (\hat{p}_{\mu^-} \times \hat{p}_{\mu^+}).\hat{p}_{\overline{K}^{*0}}$



**$B^0 \rightarrow K^{*0}\,\mu\,\mu$ decay plane**

# Angular analysis

- Assuming $q^2 >> 4m_\mu^2$ and transforming $\phi$ as $\phi + \pi$ if $\phi < 0$ one can write

$$F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) \ - \ F_L \cos^2\theta_K(2\cos^2\theta_\ell - 1) \ + \ \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) \ + \ S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} \ + \ \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell \ + \ A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}$$

- The observables have to satisfy:
  $|A_{FB}| \leq \frac{3}{4}(1-F_L)$, $\quad |A_9| \leq \frac{1}{2}(1-F_L)$, $\quad |S_3| \leq \frac{1}{2}(1-F_L)$
- Those boundary conditions introduce non-trivial effects
- The statistical uncertainties estimated using Feldman-Cousins technique
- At lowest $q^2$ bin one needs also correction from breakdown of $q^2 >> 4m_\mu^2$ assumption

# $B_s^0$ angular analysis

- After adding decay rate for $B_s$ and $\bar{B}_s$ it looks very similar to $B^0$ angular distribution
- Main difference is that $B_s \to \phi\mu^+\mu^-$ is not self-tagging

→ No sensitivity to $A_{FB}$ unless production flavour is tagged

- Due to small statistics, flavour tagging not really possible
- Also full angular analysis difficult with current statistics

→ Look to 1D distributions instead

$$\theta_K : \frac{3}{4}(1-F_{\rm L})(1-\cos^2\theta_K) + \frac{3}{2}F_{\rm L}\cos^2\theta_K,$$

$$\theta_\ell : \frac{3}{8}(1-F_{\rm L})(1+\cos^2\theta_\ell) + \frac{3}{4}F_{\rm L}(1-\cos^2\theta_\ell) + \frac{3}{4}A_6^s\cos\theta_\ell,$$

$$\mathrm{d}\phi : \frac{1}{2\pi} + \frac{1}{2\pi}S_3\cos 2\phi + \frac{1}{2\pi}A_9\sin 2\phi$$

- Subsequently fit all three distributions
- Should be careful with exact meaning due to non-zero $\Delta\Gamma_s$

# Systematic uncertainties

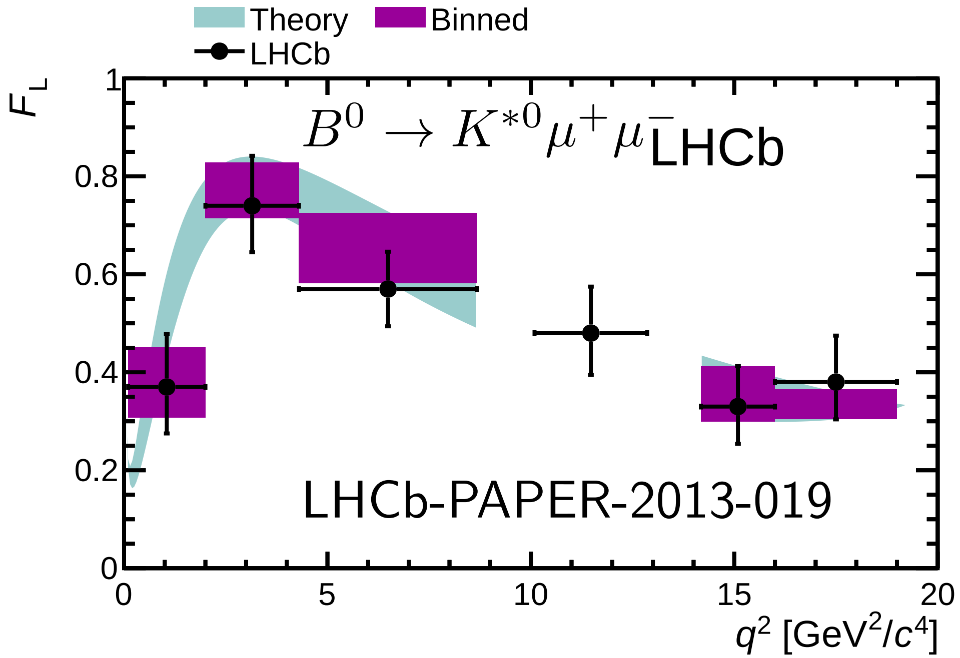
- Several sources investigated (not all for $B_s$ due to small statistics)
  - Angular acceptance (dominant for $B_s$)
  - Data-MC differences
  - Mass model
  - Peaking backgrounds
  - S-wave (spin-0 $K\pi$)
  - $B^0 \leftrightarrow \bar{B}^0$ mis-id from $K \leftrightarrow \pi$ mis-id
  - $B^0$, $\bar{B}^0$ production and detection asymmetries
- Generally no single dominant contribution across all angular observables
- Many of the sources investigated are negligible
- Typicall size for $B_s$ of order 20% – 40% of statistical uncertainty
- For $B^0$ typically of order 5% – 20% of statistical uncertainty

# Systematic uncertainties

- Several sources related to physics where we do not have any experimental information
- With increase in dataset, we gain sensitivity and can start to measure inputs
- Ultimately sources like peaking backgrounds, s-wave or production asymmetries should be improved with larger statistics
- Currently we do not think we can become systematically limited in those measurements

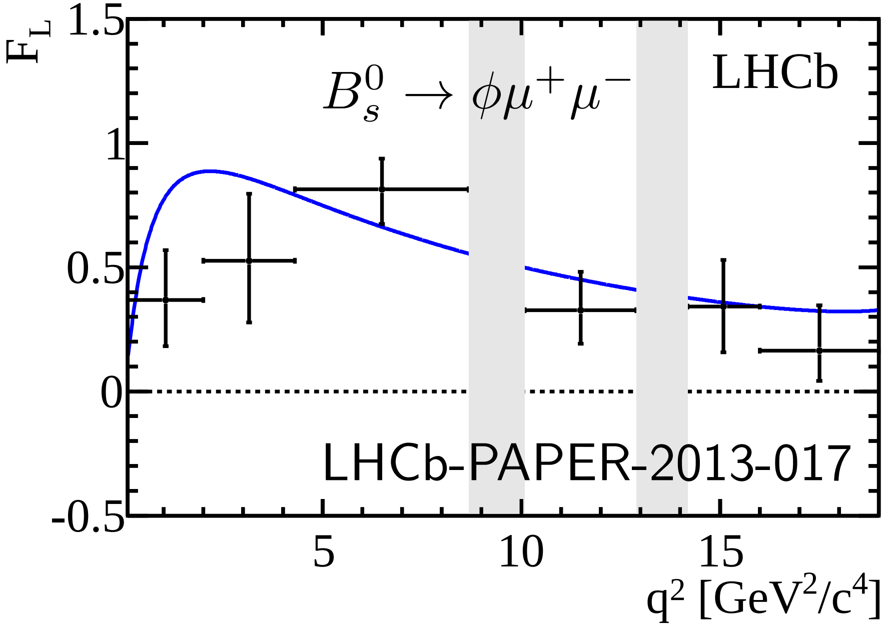
| Source | $A_{\mathrm{FB}}$ | $F_{\mathrm{L}}$ | $S_3$ | $S_9$ | $A_9$ | $A_{\mathrm{T}}^{2}$ | $A_{\mathrm{T}}^{\mathrm{Re}}$ |
|---:|---:|---:|---:|---:|---:|---:|---:|
| Acceptance model | $0.02$ | $0.03$ | $0.01$ | $< 0.01$ | $< 0.01$ | $0.02$ | $0.01$ |
| Mass model | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| $B^0 \to \overline{B}^0$ mis-id | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $0.01$ | $< 0.01$ | $< 0.01$ |
| Data-simulation diff. | $0.01$ | $0.03$ | $0.01$ | $< 0.01$ | $< 0.01$ | $0.03$ | $0.01$ |
| Kinematic reweighting | $< 0.01$ | $0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $0.01$ | $< 0.01$ |
| Peaking backgrounds | $0.01$ | $0.01$ | $0.01$ | $0.01$ | $0.01$ | $0.01$ | $0.01$ |
| S-wave | $0.01$ | $0.01$ | $0.02$ | $0.01$ | $< 0.01$ | $0.05$ | $0.04$ |
| $B^0$-$\overline{B}^0$ asymmetries | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ | $< 0.01$ |

# $F_L$

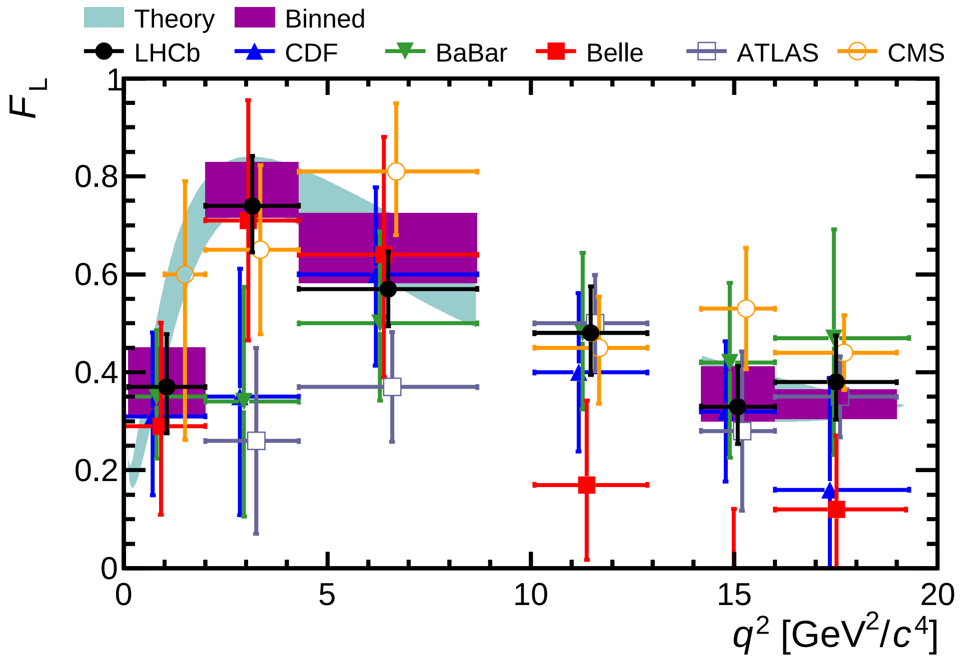


- $F_L$ is fraction of longitudinal $K^{*0}/\phi$
- Theory affected by form factors
- Good agreement between experiment and SM

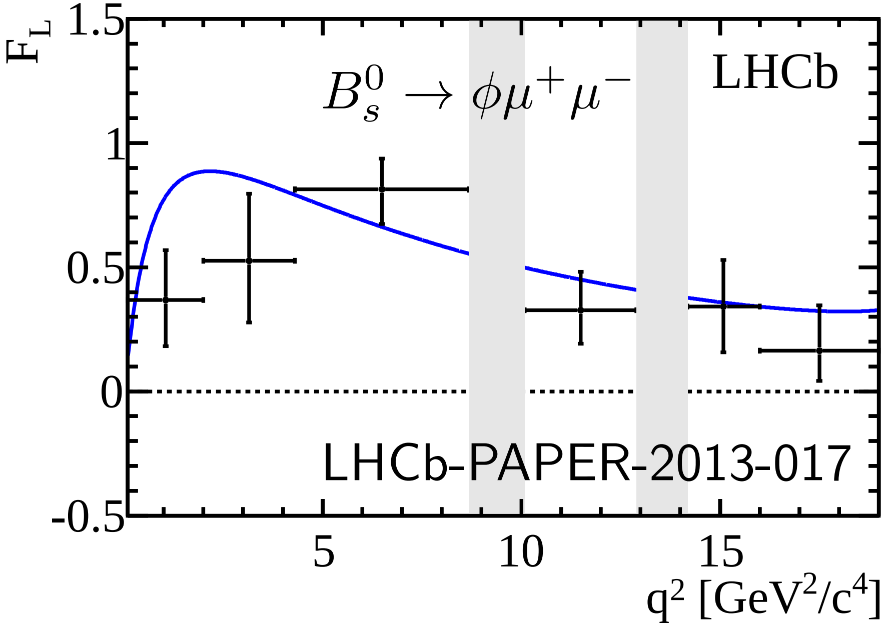
- First angular analysis of $B_s^0 \to \phi\mu^+\mu^-$
- Within limited statistics consistent with SM
- I would also say that $B^0$ and $B_s$ look consistent



# $F_L$



- $F_L$ is fraction of longitudinal $K^{*0}/\phi$
- Theory affected by form factors
- Good agreement between experiment and SM
- Consistent but more precise than previous measurments



- First angular analysis of $B_s^0 \to \phi\mu^+\mu^-$
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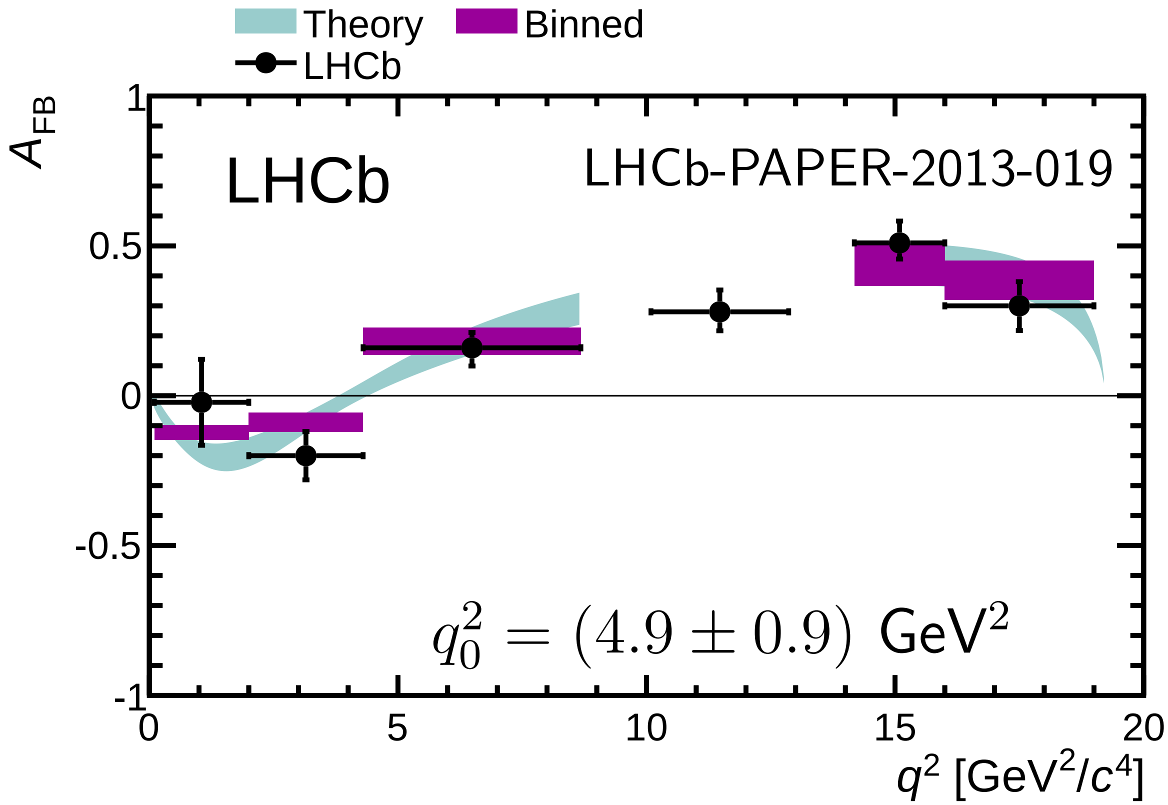
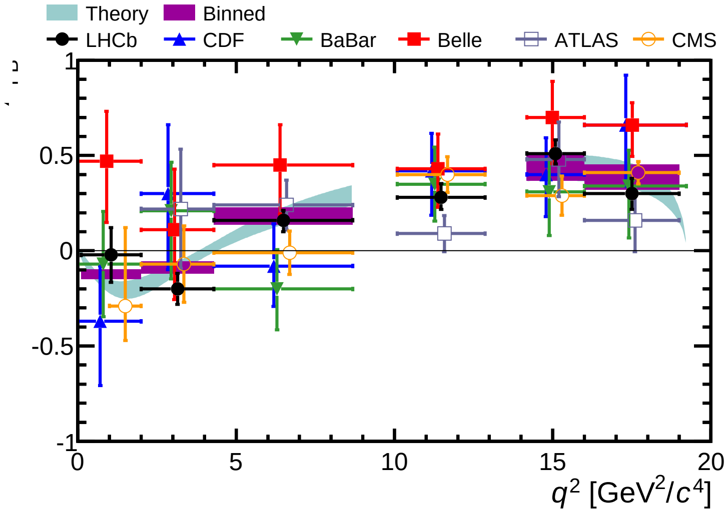
# $B^0 \to K^{*0}\mu^+\mu^-$ $A_{FB}$

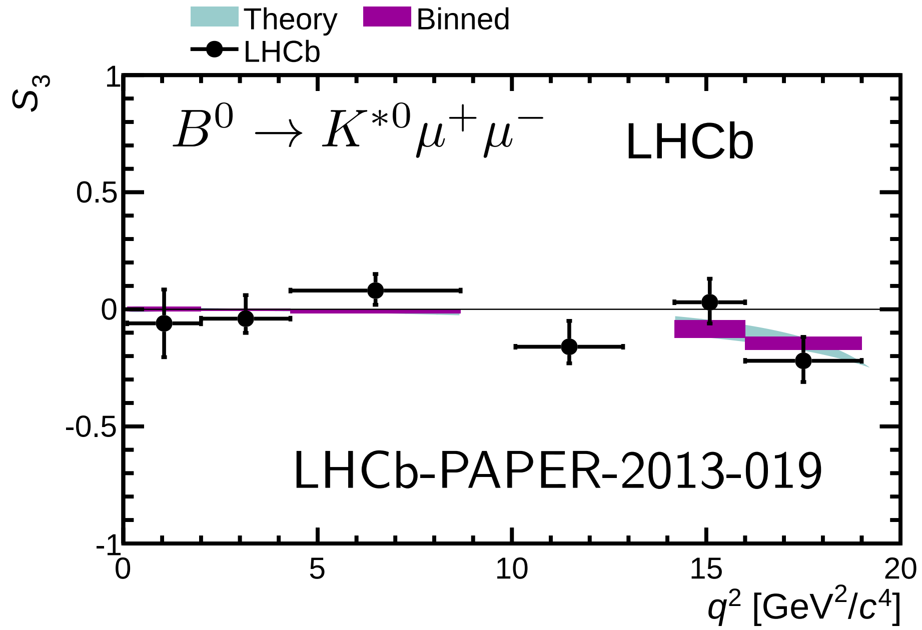


For $B_s^0 \to \phi\mu\mu$ no sensitivity without flavour tagging

- Probably best known of angular observables
- Early measurements caused some excitements
- With increased statistical power of LHCb, fully consistent with SM



# $S_3$ and $A_6$



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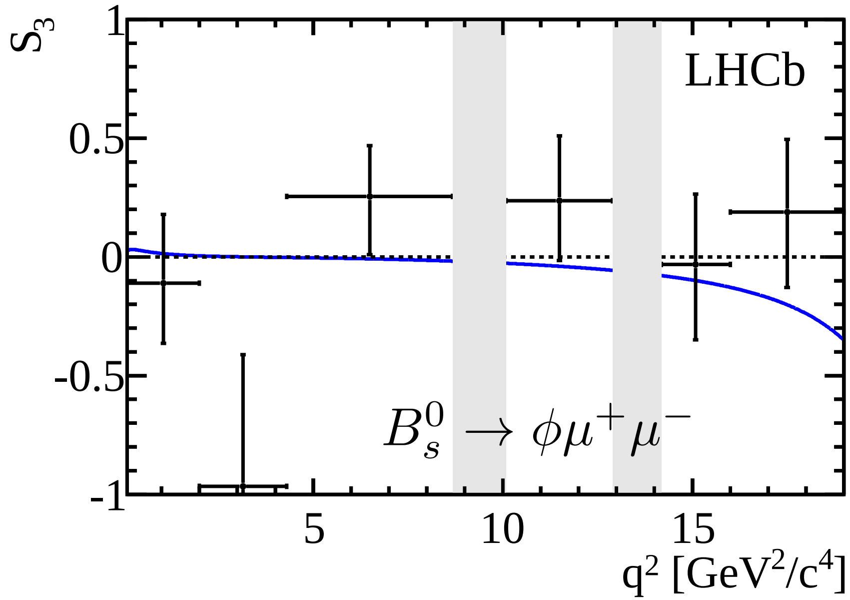
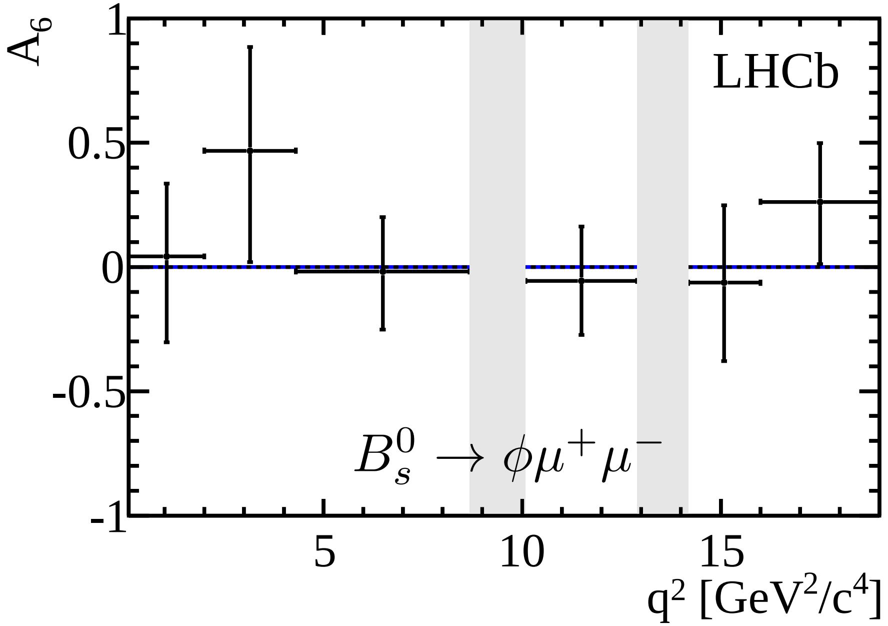
- $S_3$ is asymmetry between two transverse $K^{*0}$ amplitudes (averaged $B^0$ and $\bar{B}^0$)
- $A_6$ is asymmetry between $B_s^0$ and $\bar{B}_s^0$ of real part of transverse amplitudes interference
- Both agree with SM





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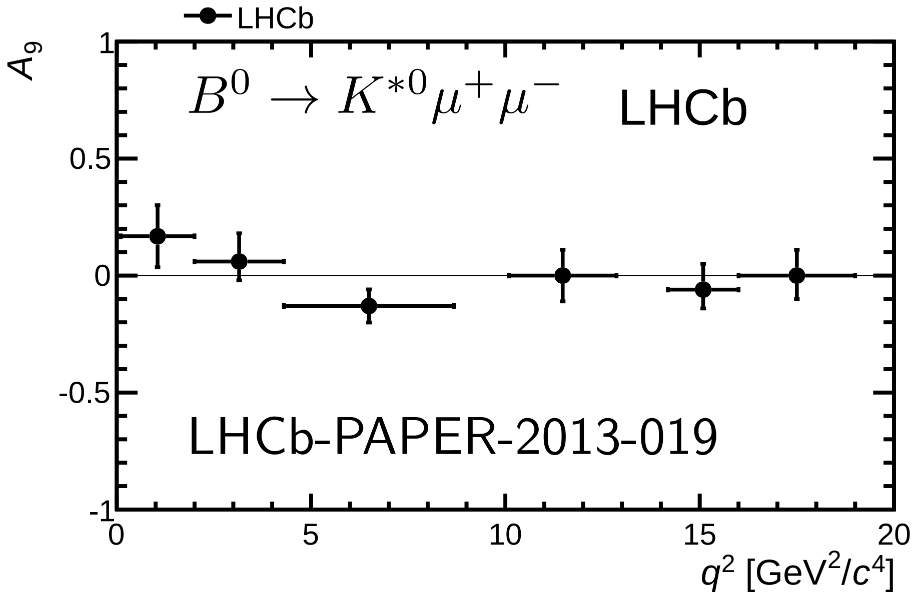
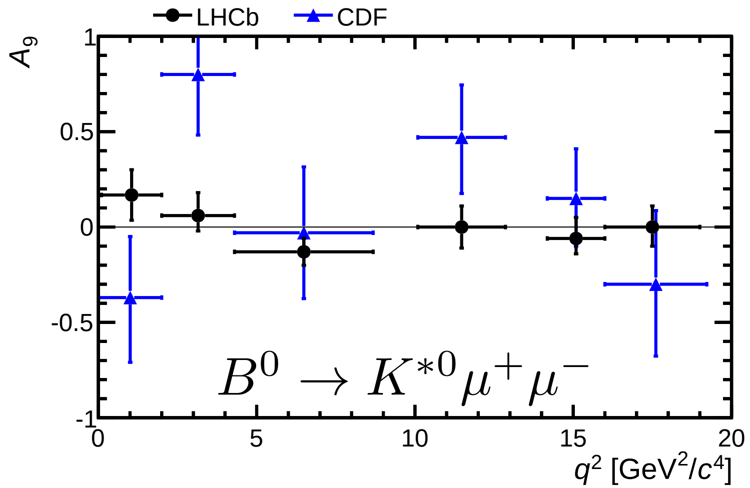
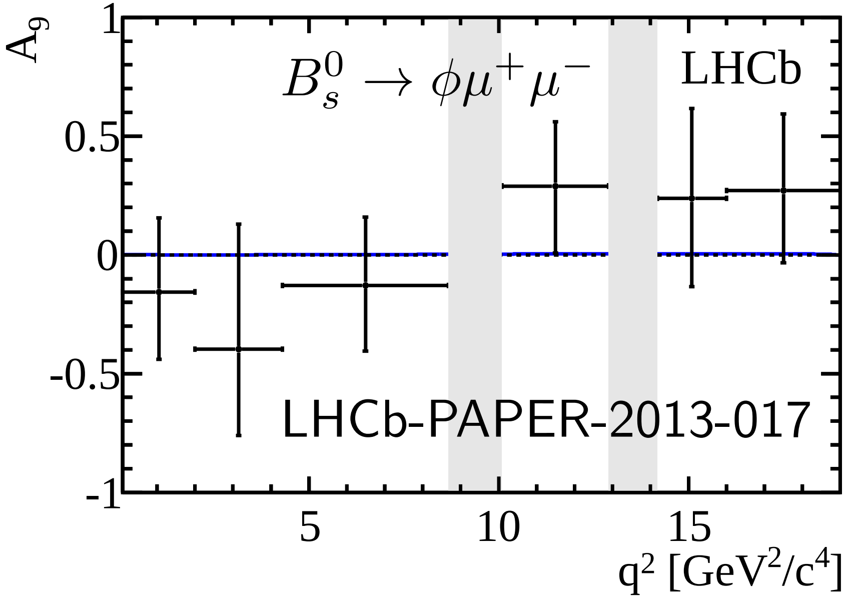
# $A_9$

- T-odd asymmetry from interference of transverse $K^{*0}$ amplitudes
- Sensitive when strong phase would make $CP$ violation zero
- High sensitivity to right handed currents



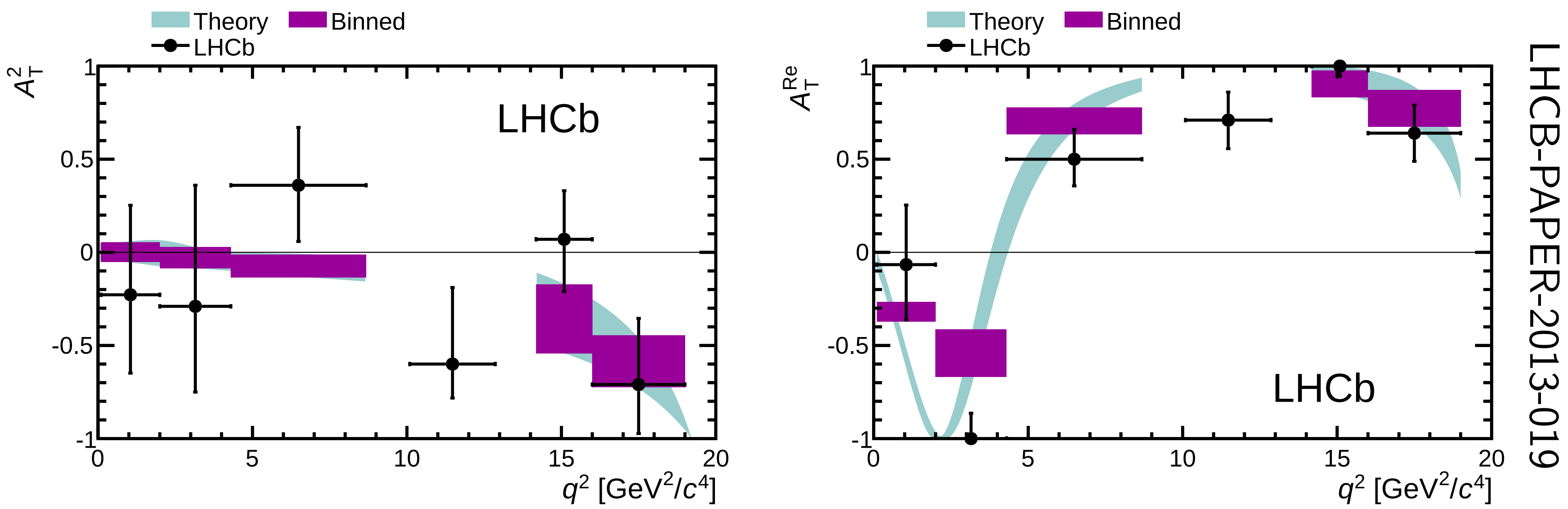




# $B^0$ reparametrisation

- One can define alternative set of observables by $S_3 = \frac{1}{2}(1 - F_L)A_T^2$ and $A_{FB} = \frac{3}{4}(1 - F_L)A_T^{Re}$
- In large recoil limit the observables $A_T^2$ and $A_T^{Re}$ have reduced form-factor uncertainties
- It is not easy to handle correlations while maintaining solid meaning of uncertainties

→ Extract also $A_T^2$ and $A_T^{Re}$



# Prospects

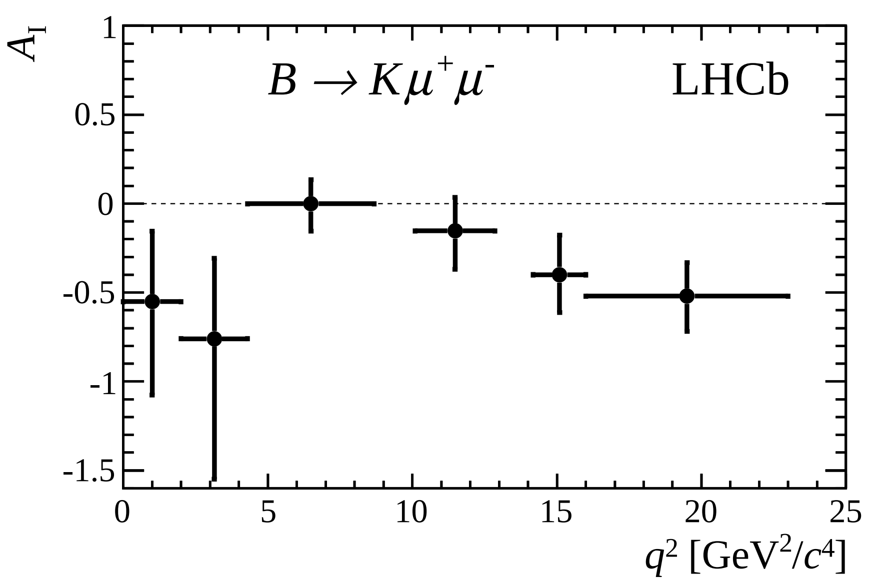
- Angular distribution for $B^0 + \bar{B}^0$

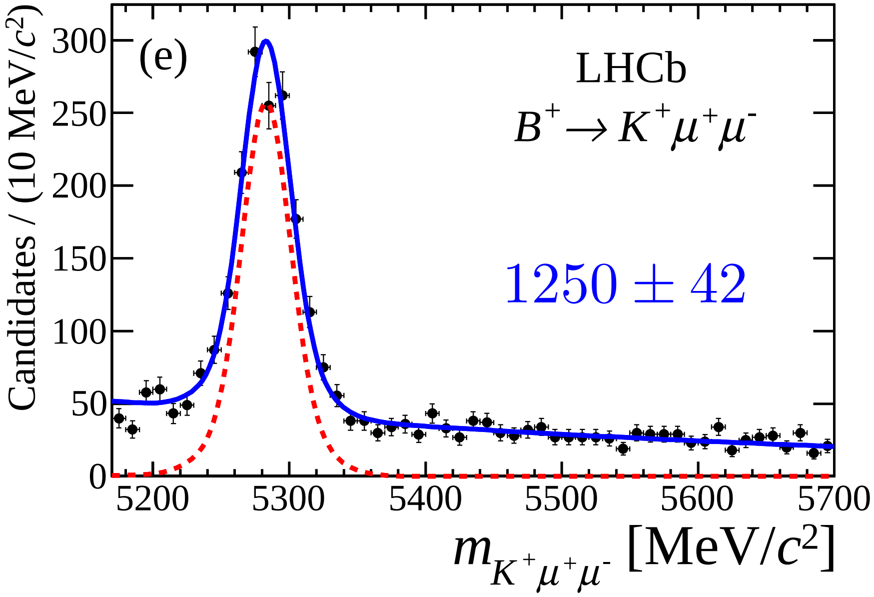
$$
\begin{aligned}
& S_1^s \sin^2\theta_K + S_1^c \cos^2\theta_K + \\
& S_2^s \sin^2\theta_K \cos 2\theta_\ell + S_2^c \cos^2\theta_K \cos 2\theta_\ell + \\
& S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + \\
& S_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + S_6 \cos^2\theta_K \cos\theta_\ell + \\
& A_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + A_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + \\
& A_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi
\end{aligned}
$$

- $S_1^{c,s}$ and $S_2^{c,s}$ related to $F_L$
- $S_6$ generates $A_{FB}$
- There are still few terms we did not touch
- Watch for EPS talk of Nicola Serra and LHCb-PAPER-2013-037
- In several terms it can be interesting to measure both sum of $B^0$ and $\bar{B}^0$ and also difference between $B^0$ and $\bar{B}^0$

# Prospects

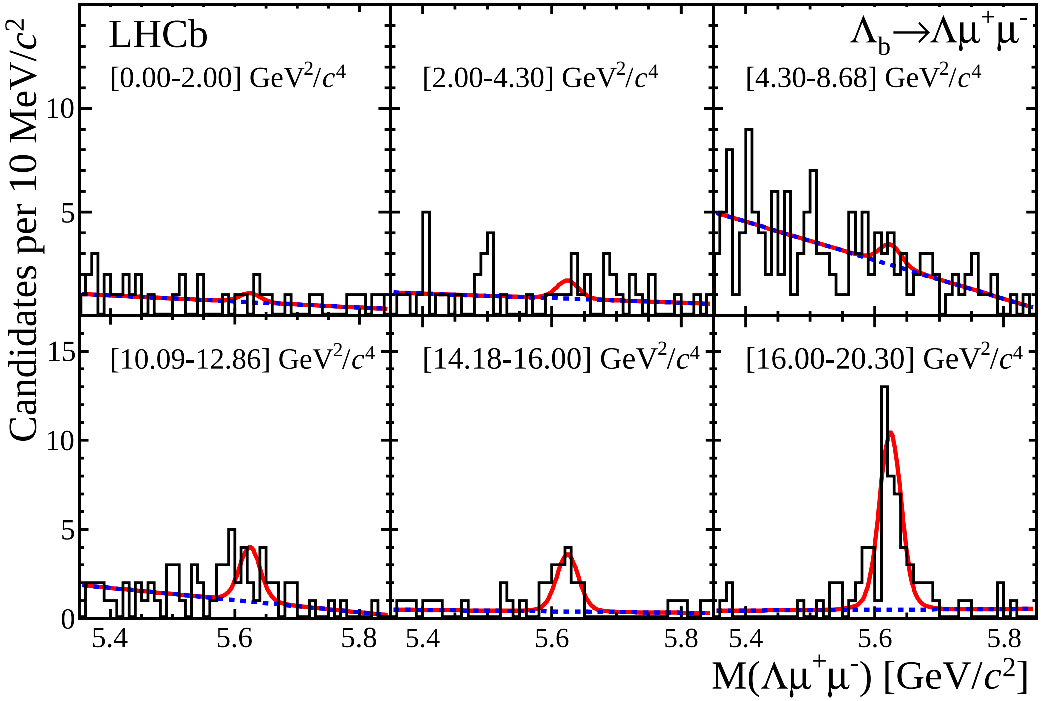
- Isospin asymmetry (difference between $B^+$ and $B^0$ rate) expected to be close to zero
- With 1 fb$^{-1}$ there is an effect at large $q^2$ for $B \to K\mu^+\mu^-$
- Working on update of this analysis
- In current dataset we expect about 3.7k $B^+ \to K^+\mu^-\mu^+$ events
- Useful to remember that low mass resonances ($\phi$, $\omega$) decay to two muons with $\mathcal{B} \approx 10^{-5}$–$10^{-4}$
- Also charmonia above open charm threshold can go to two muons





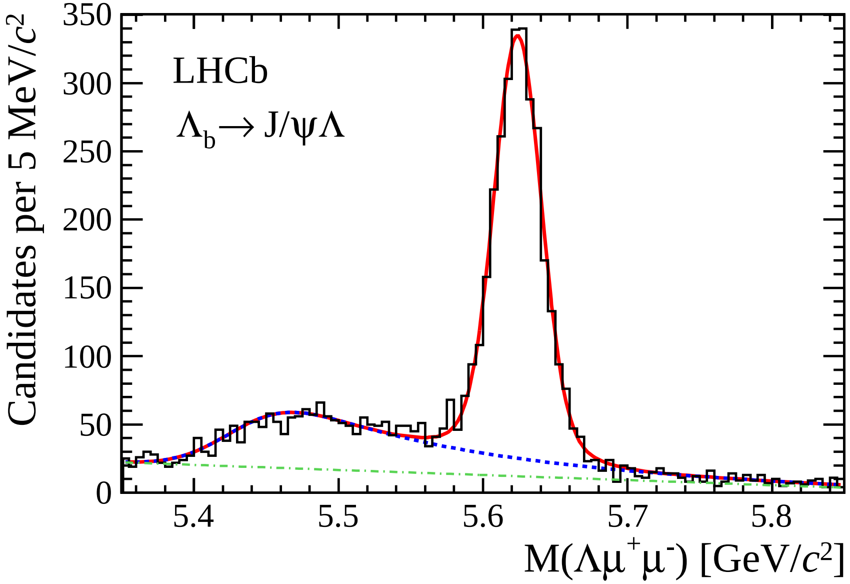
# Prospects

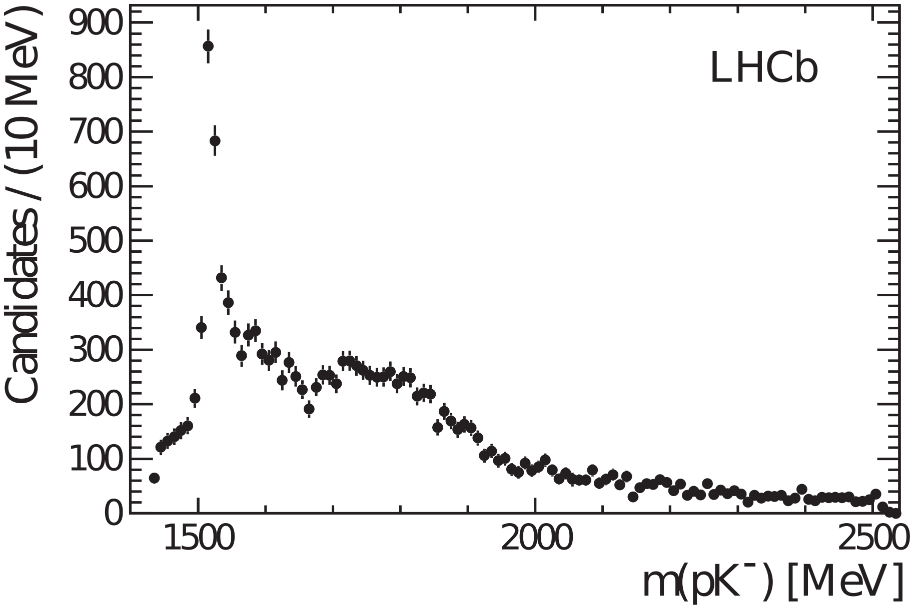
- For $\Lambda_b \to \Lambda\mu^+\mu^-$ yield in highest $q^2$ is larger than for $B_s \to \phi\mu^+\mu^-$
- Selection is optimized globaly, but signal at high $q^2$ and bg at low $q^2$
- There is room for improvement
- At high $q^2$ we could start to look for other observables
- Easy to do $A_{FB}$ by counting, but doing more needs work to define observables and corresponding angular distributions

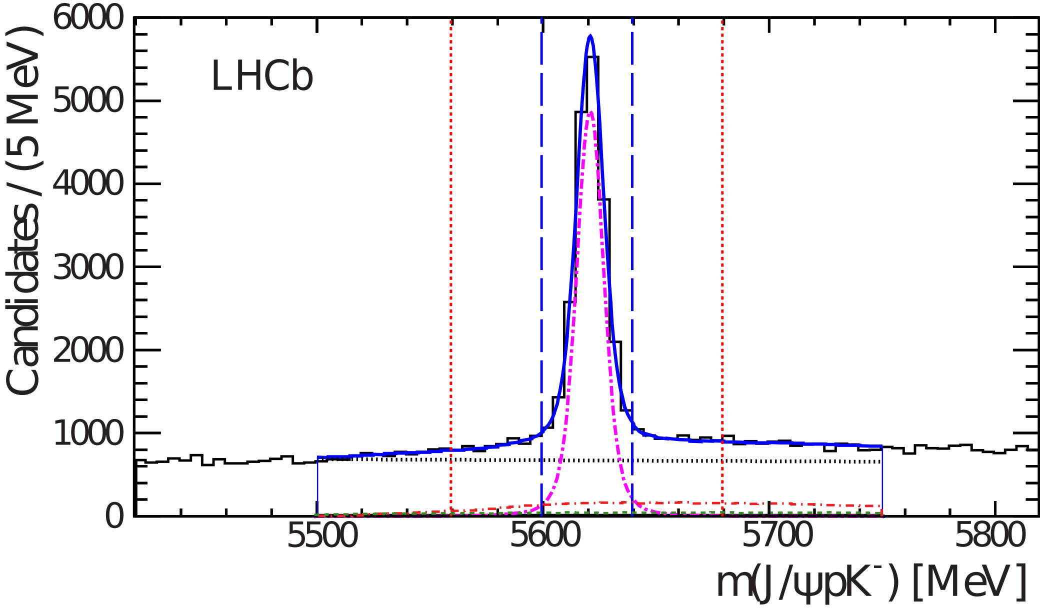


# Prospects

- $\Lambda_b \to \Lambda\mu^+\mu^-$ difficult due to long $\Lambda$ lifetime
- Should be easier when looking to excited $\Lambda \to pK$
- In $J/\psi$ channel we see much larger signal
- Unfortunately no region dominated by single resonance







# Prospects

- I used to work on CPV in $B_s \to J/\psi\phi$ decays, so one crazy speculative idea from there
- When discussing $B_s$ angular analysis, I mentioned non-zero $\Delta\Gamma_s$
- Theory typically predicts what happens at $t = 0$
- But experiment measures in this time-integrated mode average over decay time
- Our flavour tagging is not good enough to sensibly separate $B_s$ from $\bar{B}_s$
- In $B_s \to J/\psi\phi$ there is access to CPV even without flavour tagging
  - This comes from interference of CP-even with CP-odd final state and non-zero $\Delta\Gamma_s$
- With some luck we perhaps might get access to more observables also in $B_s \to \phi\mu^+\mu^-$ once decay time dependence is taken into account

# Conclusions

- Presented latest results on rare EWK decays
- First time we did multidimensional angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ (LHCb-PAPER-2013-019)
- First convincing signal for $B^0 \to K^{*0}e^+e^-$ at low $q^2$ (LHCb-PAPER-2013-005)
- First angular analysis of $B_s \to \phi\mu^+\mu^-$ (LHCb-PAPER-2013-017)
- Start to be in stage to do more with $\Lambda_b \to \Lambda\mu^+\mu^-$ (LHCb-PAPER-2013-025)
- All results are worlds best
- All consistent with SM

→ But placing strong constraints on new physics

- Three new results in this area will be shown at EPS

- $B^0$ theory based on JHEP 07 (2011) 067, NP B612 (2001) 25, PR D70 (2004) 114005, EPJ C71 (2011) 1635, PR D71 (2005) 014029, JHEP 11 (2008) 032
- $B_s^0$ prediction from JHEP 01 (2009) 019, JHEP 0807 (2008) 106, PR D71 (2005) 014029