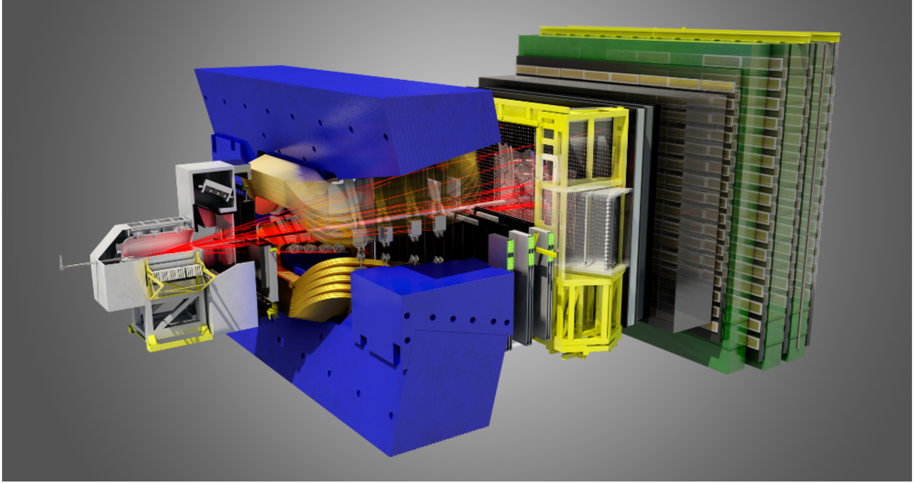


Studies of $b \to (s, d)(\mu^+\mu^-, \gamma)$ transitions at LHCb

PASCOS 2013

Monday, November 25, 2013

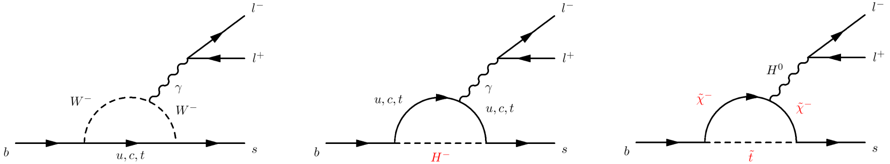
Simon Wright, University of Cambridge

on behalf of the LHCb collaboration

- $B^0 \to K^{*0}\mu^+\mu^-$
  - Angular analysis.
  - Results using form-factor independent observables.
- $B^+ \to K^+\mu^+\mu^-$
  - Observation of a low-recoil resonance.
  - Measurement of direct *CP* asymmetry.
- $B^+ \to K^+\pi^-\pi^+\gamma$
  - *CP* and up-down asymmetries.

Electroweak penguins

- Study of flavour changing neutral current decays that have no tree-level Feynman diagrams.
- Hence proceed via loop and box diagrams, and New Physics can enter through the loops.



- Theoretical framework via an effective Hamiltonian:
  - Wilson coefficients (C_i), describing short-distance interactions
  - Operators, ($\mathcal{O}_i$), describing long-distance interactions

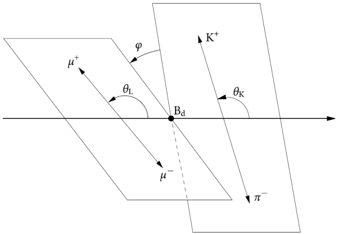
$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} (C_i^{SM} + \Delta C_i^{NP}) \mathcal{O}_i$$

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

Decay distribution summing over B^0 and $\bar{B}^0$ mesons:

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\theta_l\mathrm{d}\theta_K\mathrm{d}\varphi\mathrm{d}q^2} = \frac{9}{32\pi}[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\varphi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_l\cos\varphi + S_5\sin 2\theta_K\sin\theta_l\cos\varphi$$
$$+ S_6^s\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\varphi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_l\sin\varphi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\varphi]$$

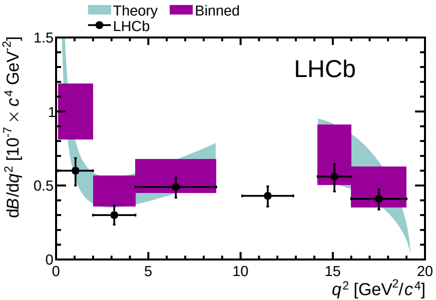
(from Altmannshofer et al JHEP 01 (2009) 019)

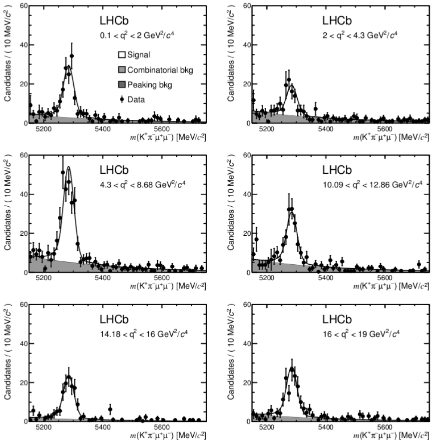


Observables include:

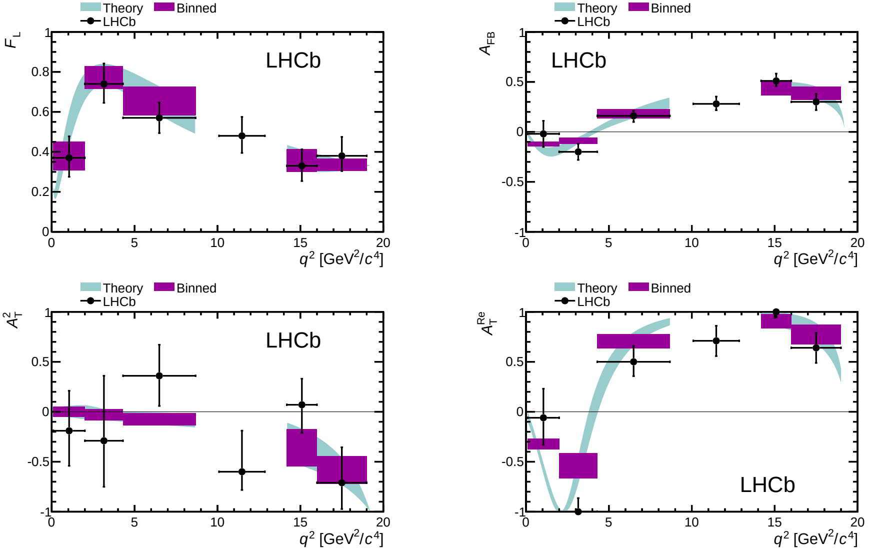
- F_{L}, the K^{*0} longitudinal polarisation fraction.
- $A_{\mathrm{FB}} = \frac{4}{3}S_6^s$, the $\mu^+\mu^-$ forward-backward asymmetry.
- $A_{\mathrm{T}}^2 = 2S_3/(1-F_{\mathrm{L}})$ and $A_{\mathrm{T}}^{\mathrm{Re}} = \frac{4}{3}A_{\mathrm{FB}}/(1-F_{\mathrm{L}})$, a pair of K^{*0} transverse asymmetries.

- Differential branching fraction obtained by performing an extended unbinned maximum likelihood fit to the $K^+\pi^-\mu^+\mu^-$ invariant mass distribution in each of six q^2 bins.





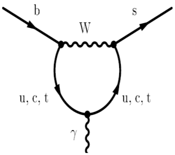
Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ (JHEP 1308 (2013) 131)



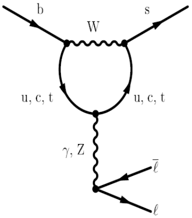
- Good agreement with theory predictions.

New observables in $B^0 \to K^{*0}\mu^+\mu^-$ (arXiv:1308.1707)

- The large theoretical uncertainties on these observables are, in part, due to large contributions the hadronic form factors.
- Combinations of F_L and S_i can have reduced form factor uncertainties.
- At large recoil (low q^2), the combination $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$ is largely free of these uncertainties (arXiv:1303.5794).
- These observables are sensitive to New Physics in the Wilson coefficients C_7, C_9 and C_{10}:



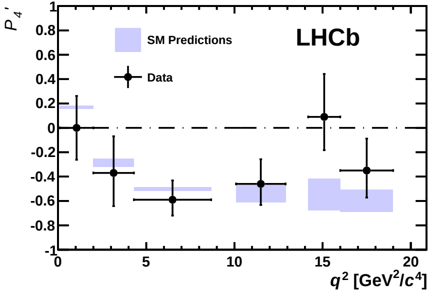
C_7

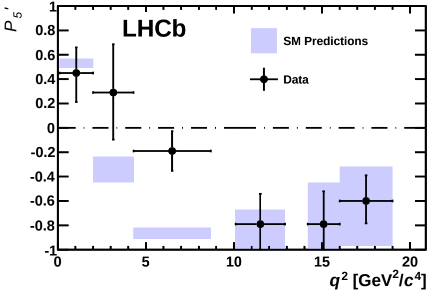


C_9 = vector component
C_{10} = axial-vector component

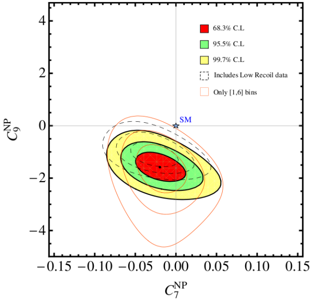
New observables in $B^0 \to K^{*0}\mu^+\mu^-$ (arXiv:1308.1707)

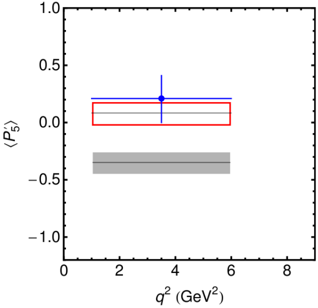
- P_6' and P_8' found to be close to their SM predictions, which are close to zero, over the full q^2 range.





- In the $4.30 < q^2 < 8.68\,\mathrm{GeV}^2/c^4$ bin for P_5', there is a 3.7σ discrepancy between the measurement and the prediction.
- Considering 24 independent measurements, the significance drops to 2.8σ.
- In the range $1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$, the deviation from SM is 2.5σ.





Data
SM prediction
$C_9^{NP} = -1.5$

(Descotes-Genon et al, PRD 88, 074002 (2013))

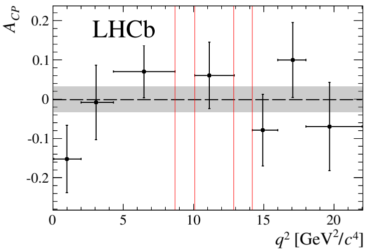
- Can potentially explain this discrepancy by a negative New Physics contribution to the Wilson coefficient C_9.
- However, this cannot occur in models such as MSSM or partial-compositeness (Altmannshofer and Straub, arXiv:1308.1501)...
- ...but it could in models with a flavour-changing neutral gauge boson, a Z', with $m_{Z'} \sim 7\,\mathrm{TeV}$. (Gauld et al, arXiv:1308.1959; Buras and Girrbach, arXiv:1309.2466)

$$\mathcal{A}_{CP}(q^2) = \frac{\Gamma(B^- \to K^-\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^- \to K^-\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)}$$

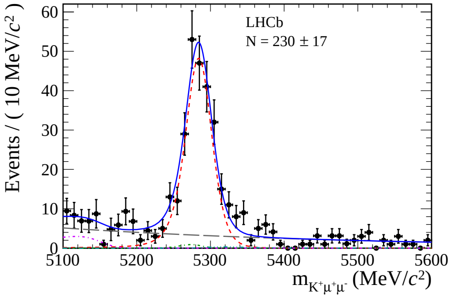
- $\mathcal{A}_{CP} \sim 10^{-4}$ in the Standard Model, and should be similar to $\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.072 \pm 0.040$ (PRL 110 031801).
- Analysis performed using 2011 LHCb data set ($1.0\,\mathrm{fb}^{-1}$).
- Use $B^+ \to J/\psi K^+$ as a control channel to account for production and detection asymmetries:

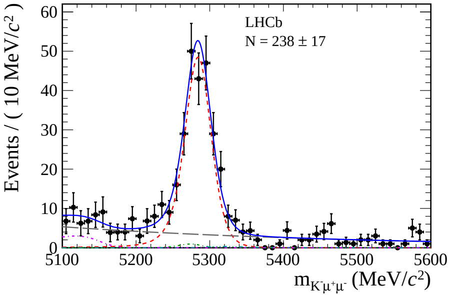
$$\mathcal{A}_{CP} = \mathcal{A}_{RAW}(B^+ \to K^+\mu^+\mu^-) - \mathcal{A}_{RAW}(B^+ \to J/\psi K^+) + \mathcal{A}_{CP}(B^+ \to J/\psi K^+).$$

- *CP* asymmetry extracted from simultaneous unbinned likelihood fit of $B^+ \to J/\psi K^+$ and $B^+ \to K^+\mu^+\mu^-$ $m_{K\mu\mu}$ distributions in bins of q^2.
- Average of results for both magnet polarities taken to reduce detector effects.



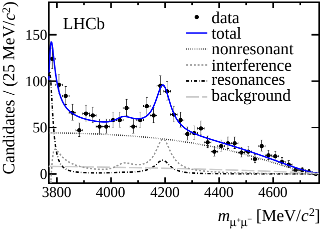
- $\mathcal{A}_{CP}$ over the full q^2 range is the average of each q^2 bin weighted by signal yield and efficiency.
- $\mathcal{A}_{CP} = 0.000 \pm 0.033(\text{stat.}) \pm 0.005(\text{syst.}) \pm 0.007(J/\psi K)$.
- World's best measurement by a factor of 4, and consistent with both SM and $B^0 \to K^{*0}\mu^+\mu^-$ measurement.
- Mass fits for one polarity below:





$B^+ \to K^+\mu^+\mu^-$ low-recoil resonance (PRL 111 (2013) 112003)

- Using both the 2011 and 2012 data sets ($3\,\mathrm{fb}^{-1}$), look at low-recoil region (high q^2).
- For high q^2, able to investigate the structure of the resonances coming from above the open charm threshold.

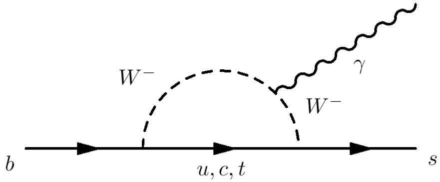


	Unconstrained	$\psi(4160)$
$\mathcal{B}[\times 10^{-9}]$	$3.9\,^{+0.7}_{-0.6}$	$3.5\,^{+0.9}_{-0.8}$
Mass $[\mathrm{MeV}/c^2]$	$4191\,^{+9}_{-8}$	4190 ± 5
Width $[\mathrm{MeV}/c^2]$	$65\,^{+22}_{-16}$	66 ± 12
Phase [rad]	-1.7 ± 0.3	-1.8 ± 0.3

Resonance at low-recoil observed with significance $> 6\sigma$.

Consistent with $\psi(4160)$ resonance seen by the BES collaboration.

- Radiative decays are also mediated by penguin diagrams in the SM.
- However, their signature is a high-E_{T} photon in the final state.



- For the above $b \to s\gamma$ transition, the SM photon is predominantly left-handed, with weak amplitudes satisfying $|c_L|^2 \gg |c_R|^2$.

- Define photon polarisation λ_γ:

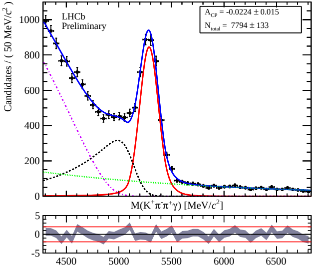
$$\lambda_\gamma = \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$$

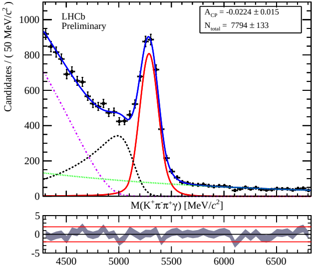
so that $\lambda_\gamma \simeq -1$ $(+1)$ for B^- (B^+) decays.

- However, several BSM models predict that the photon acquires a significant right-handed component.

- Consider $B \to K_{\rm res}(\to K^+\pi^-\pi^+)\gamma$ decays corresponding to $\mathcal{L} = 2\,\text{fb}^{-1}$.
- $\mathcal{A}_{CP}$ is calculated similarly to $B^+ \to K^+\mu^+\mu^-$, using $B^+ \to J/\psi K^+$ as a control mode again to account for production and detection asymmetries.

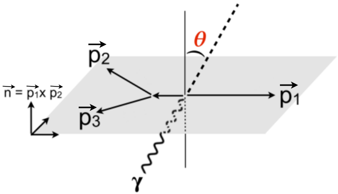
Partially reconstructed background
Missing pion background
Combinatorial background
Signal





$$\mathcal{A}_{CP} = -0.007 \pm 0.015(\text{stat.}) \pm 0.008(\text{syst.})$$

$B^+ \to K^+\pi^-\pi^+\gamma$ (LHCb-CONF-2013-009)



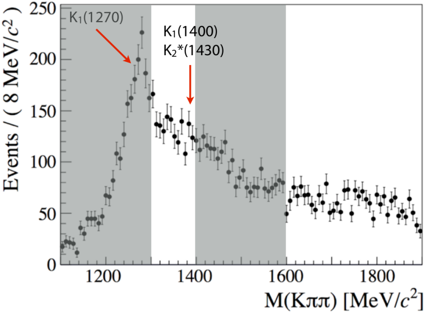
- Also measure the up-down asymmetry:

$$\mathcal{A}_{ud} = \frac{\int_0^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} - \int_{-1}^0 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}}{\int_{-1}^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}} = \frac{3}{4}\lambda_\gamma \frac{\int \mathrm{d}s\mathrm{d}s_{13}\mathrm{d}s_{23}\mathrm{Im}[n\cdot(\mathcal{J}\times\mathcal{J}*)]}{\int \mathrm{d}s\mathrm{d}s_{13}\mathrm{d}s_{23}|\mathcal{J}^2|}$$

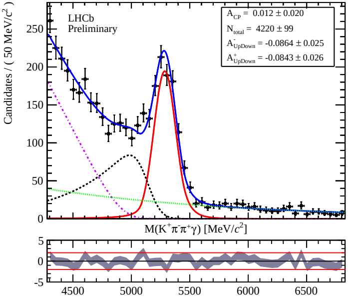
- So $\mathcal{A}_{ud} \propto \lambda_\gamma$, and we extract the significance compared to a no polarisation hypothesis.

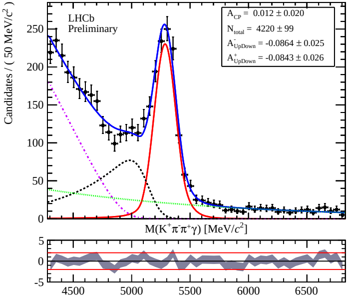
- Perform mass fits for $\mathcal{A}_{ud}$ simultaneously on separated B^+ and B^- data sets.

- Choose specific region in $m_{K^+\pi^-\pi^+}$ to conduct analysis (PRD 66 (2002) 054008).



Mass fits for B^+ mesons:





$$\mathcal{A}_{ud}^{+} = -0.084 \pm 0.026(\text{stat.}) \pm {}^{0.003}_{0.004}(\text{syst.})$$

$$\mathcal{A}_{ud}^{-} = -0.086 \pm 0.025(\text{stat.}) \pm 0.002(\text{syst.})$$

- These are significances of 3.2σ and 3.4σ from the no polarisation hypothesis.
- When combined, we obtain the first evidence of photon polarisation in $b \to s\gamma$ with a significance of 4.6σ

$$\mathcal{A}_{ud} = -0.085 \pm 0.019(\text{stat.}) \pm 0.003(\text{syst.})$$

Summary

- With the 2011 data set ($1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$), LHCb has produced multiple interesting results:
  - Angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$, highlighting a potential discrepancy in the observable P_5'.
  - World's best measurement of CP asymmetry in $B^+ \to K^+\mu^+\mu^-$.
  - The most accurate measurement of $\mathcal{B}(\Lambda_b \to \Lambda\mu^+\mu^-)$.
- Using the $2\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 8\,\mathrm{TeV}$ data taken in 2012, evidence has been found for photon polarisation in $b \to s\gamma$ transitions.
- And combining both data sets, a resonance at low-recoil has been observed in $B^+ \to K^+\mu^+\mu^-$ decays.
- This is just the start of the improvements and new discoveries that could arise from the full analysis of the 2012 data!

Happy St. Catharine's Day!

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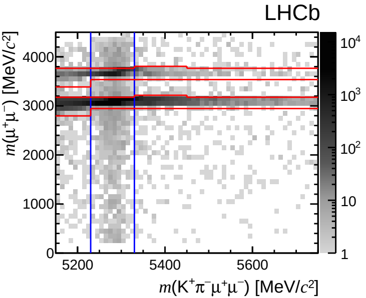
Catherine of Alexandria

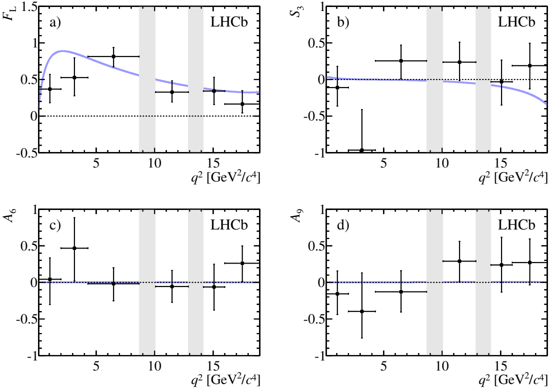
BACKUP

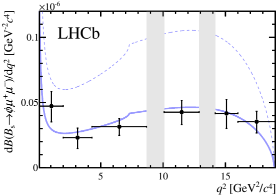


- Analysis performed in six bins of q^2, as well as the region $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$.
- The charmonium resonance regions corresponding to $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$ are vetoed.

- The signal is selected using a boosted decision tree, and several additional vetoes are implemented to remove peaking backgrounds.
- An acceptance correction, compensating for discrepancies in the angular distributions caused by the selection, is performed using simulated Monte Carlo samples.
- The mode $B^0 \to J/\psi K^{*0}$ is used to improve the agreement between data and simulation.

- Physics similar to $B^0 \to K^{*0}\mu^+\mu^-$, but final state does not self-tag.
- Perform a very similar angular analysis.

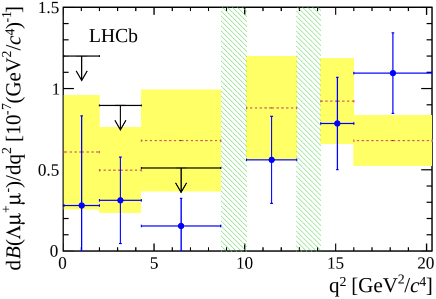


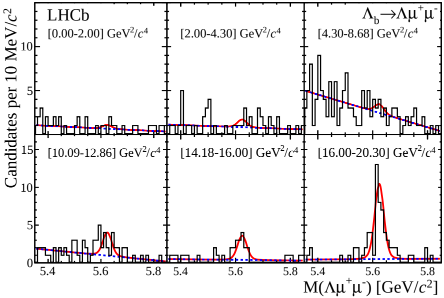


- $B_s^0 \to \phi\mu^+\mu^-$ branching fraction lower than the Standard Model (dashed line).
- Angular observables agree with SM predictions.

$\Lambda_b \to \Lambda\mu^+\mu^-$ (PLB 725 (2013) 25)

- Analysis on baryonic modes can probe helicity structure of Hamiltonian, and also different hadronic physics than the B meson decays.
- Using $1\,\text{fb}^{-1}$, start by measuring the differential branching fraction, using the control mode $\Lambda_b \to J/\psi\,\Lambda$.





78 ± 12 $\Lambda_b \to \Lambda\mu^+\mu^-$ decays found, predominantly at high q^2.

$\mathcal{B}(\Lambda_b \to \Lambda\mu^+\mu^-) = 0.96 \pm 0.16(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.21(\text{norm.})$