Experimental prospects for baryon decays

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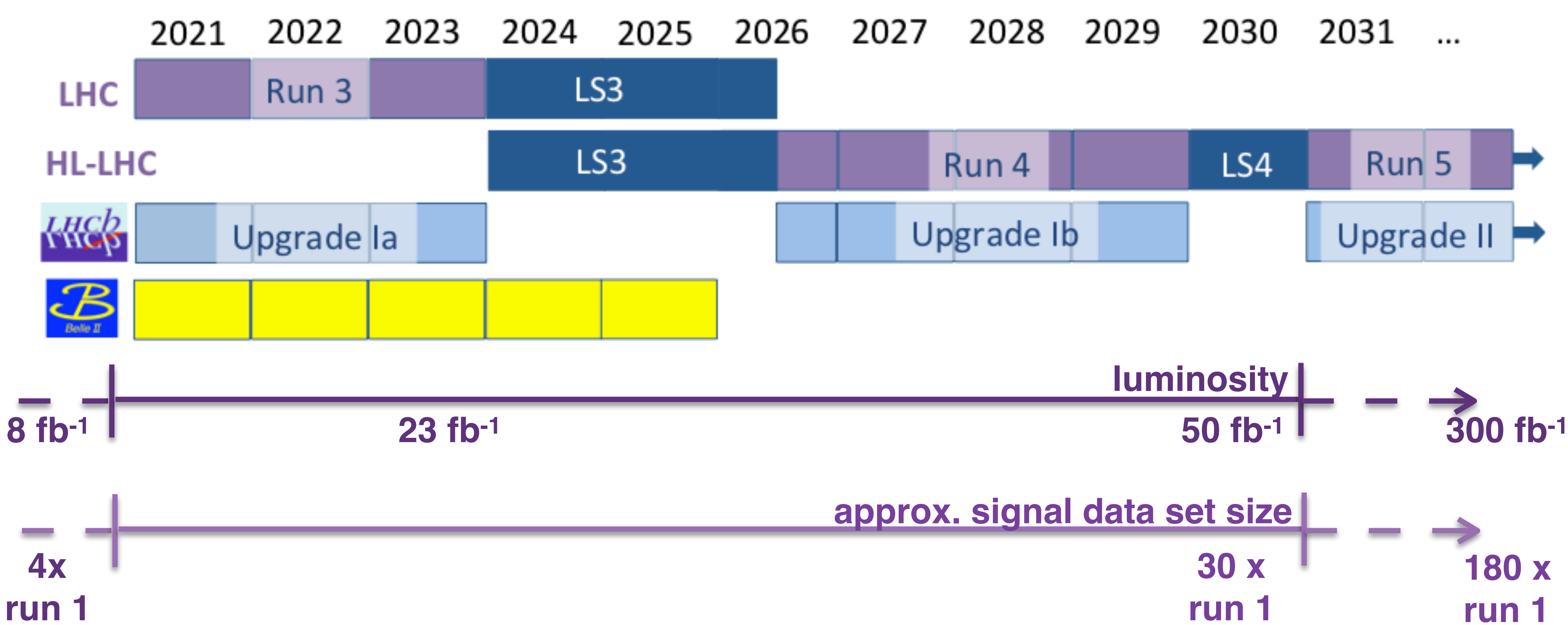
$b \to s\ell\ell$ 2019
7th Workshop on Rare Semileptonic B Decays

LHCb Upgrades



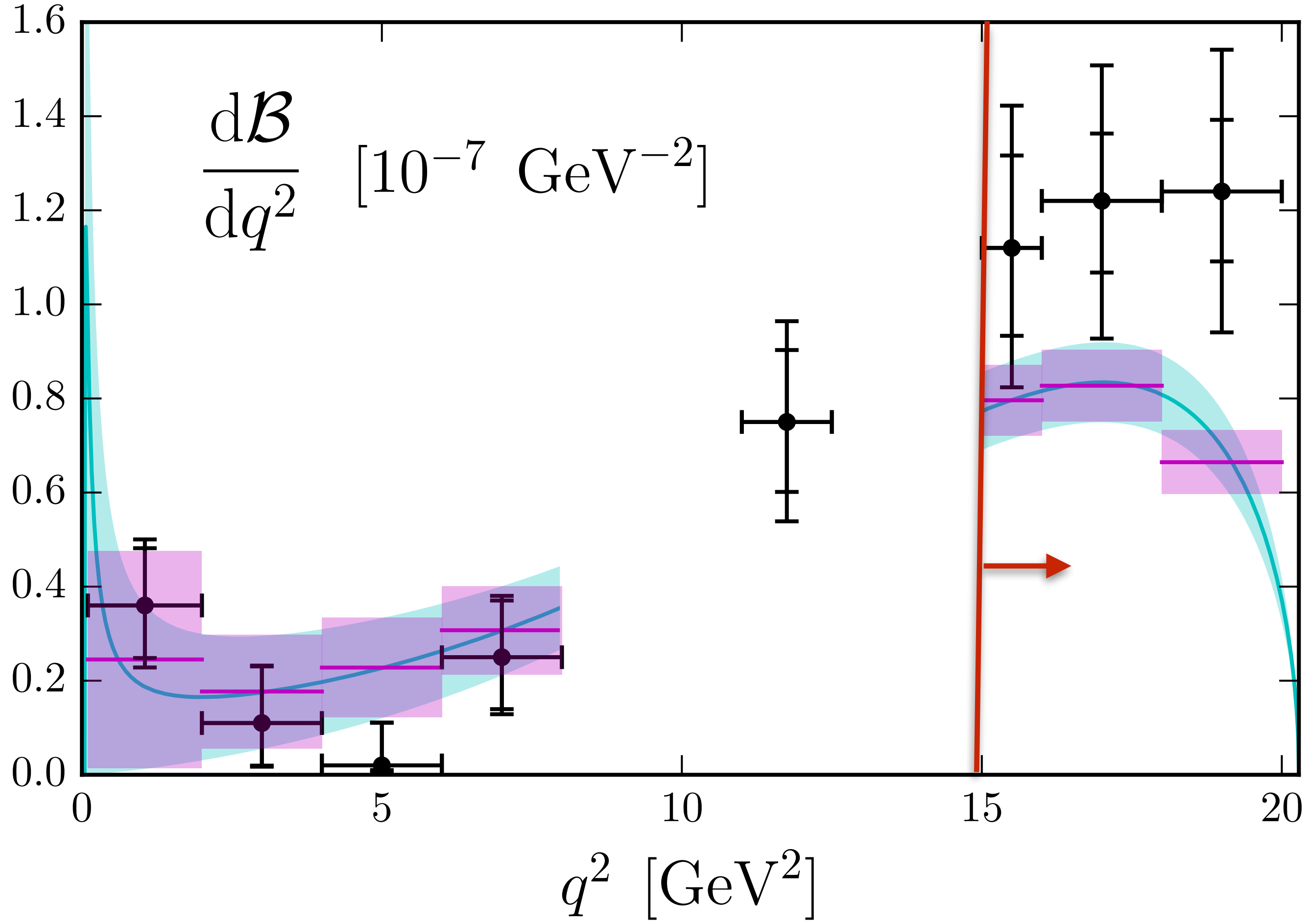
Expect a further factor of ~2 gain for channels with electrons/photons due to removal of the L0 hardware trigger.

- Focus on LHCb, but ATLAS and CMS can contribute to a number of the measurements mentioned in these slides (see talk by Greg).

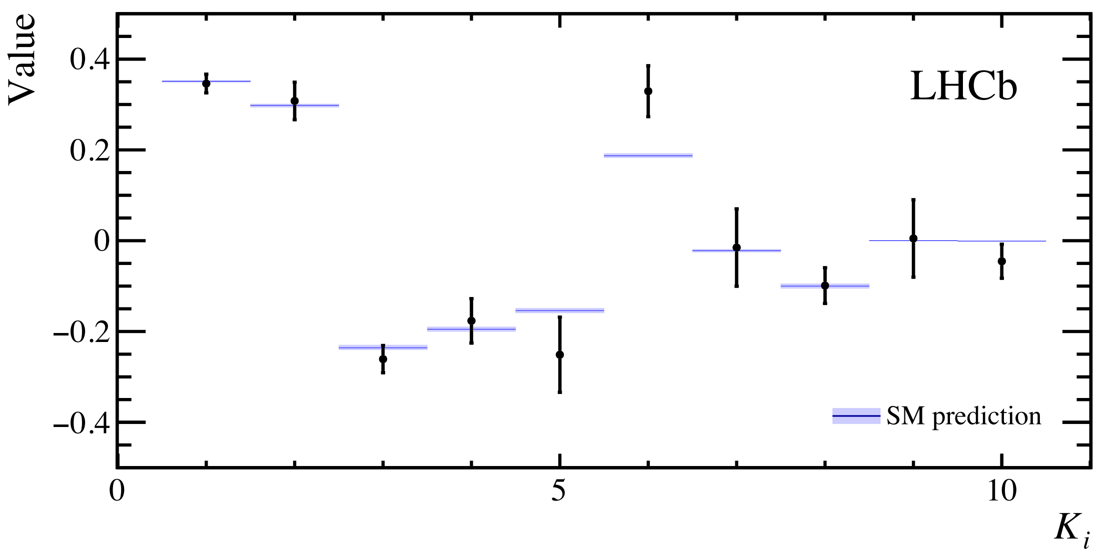
$\Lambda_b \to \Lambda \mu^+ \mu^-$

- Large number (34) of angular observables, 24 require Λ_b to be polarised at production and are consistent with zero in current dataset.

Detmold et al. arXiv:1602.01399



LHCb, arXiv:1808.00264



- SM predictions use external on α_Λ and production polarisation (small at the LHC).
- Branching fraction uncertainty currently dominated by knowledge of $\mathcal{B}(\Lambda_b \to J/\psi\Lambda)$.

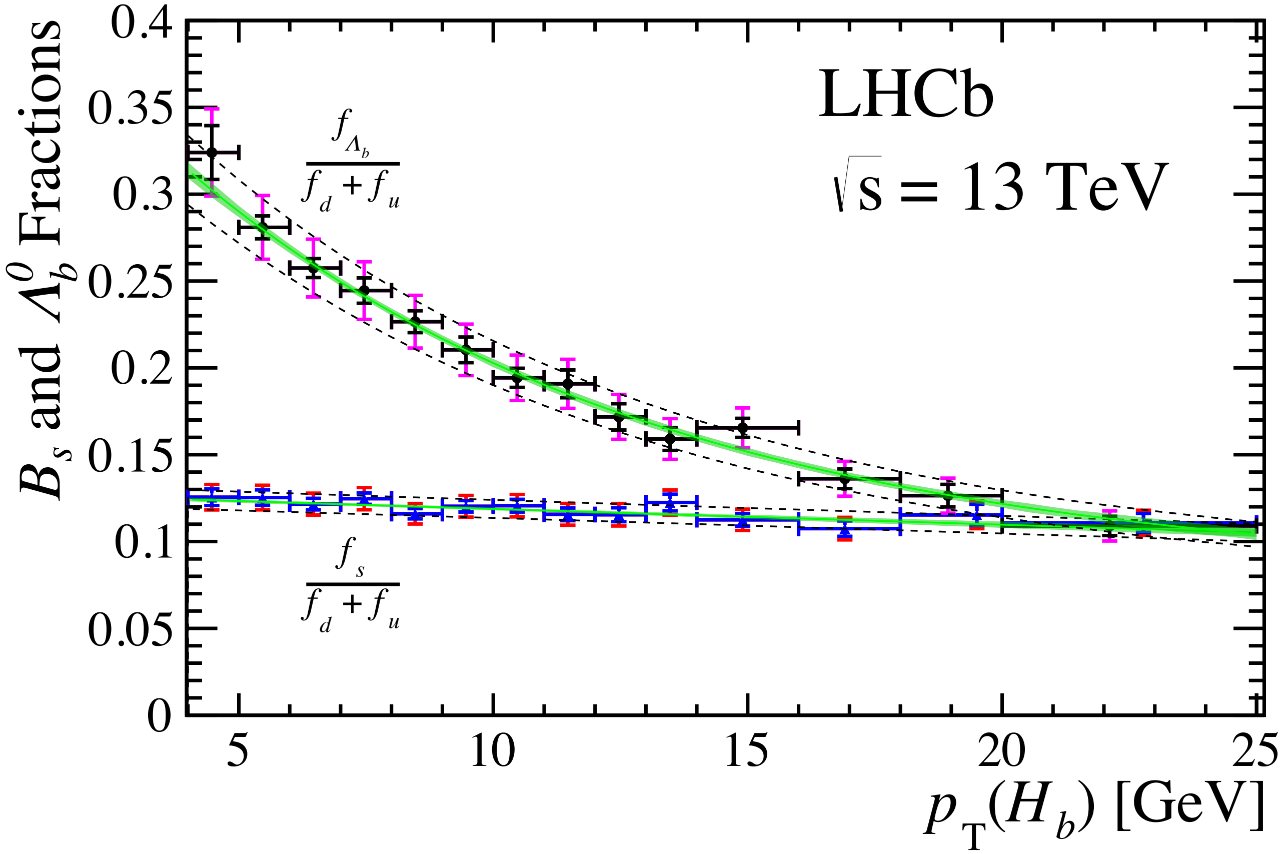
$\Lambda_b \to \Lambda\mu^+\mu^-$ branching fraction

- Existing branching fraction measurement uses CDF/D0 average of measurement of $f_{\Lambda_b} \times \mathcal{B}(\Lambda_b \to J/\psi\Lambda) = (5.8 \pm 0.8) \times 10^{-5}$, with f_{Λ_b} taken as a LEP + TeVatron average.

- Now know that the baryon production fractions exhibit strong p_T dependences in *pp* collisions.

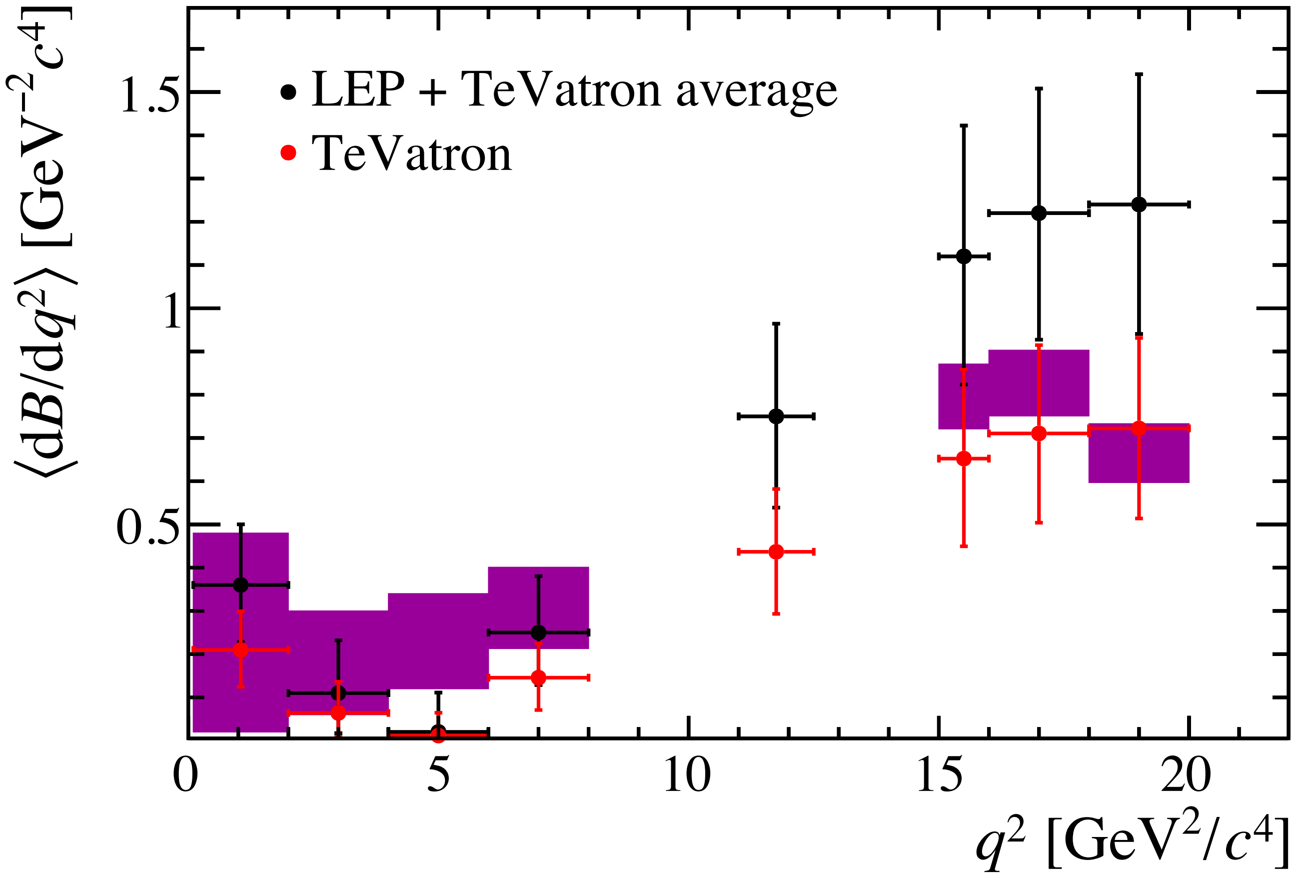
- Λ_b baryons produced with lower average p_T at the TeVatron than LEP.

[LHCb, arXiv:1902.06794]



$\Lambda_b \to \Lambda\mu^+\mu^-$ branching fraction

- Re-evaluating the branching fraction using only TeVatron inputs significantly changes the picture.
- Data consistent with, but now below SM predictions.
    - ➡ Consistent with pattern seen in other branching fraction measurements.



Data [LHCb, JHEP 06 (2015) 115]
SM [Detmold et al. arXiv:1602.01399]

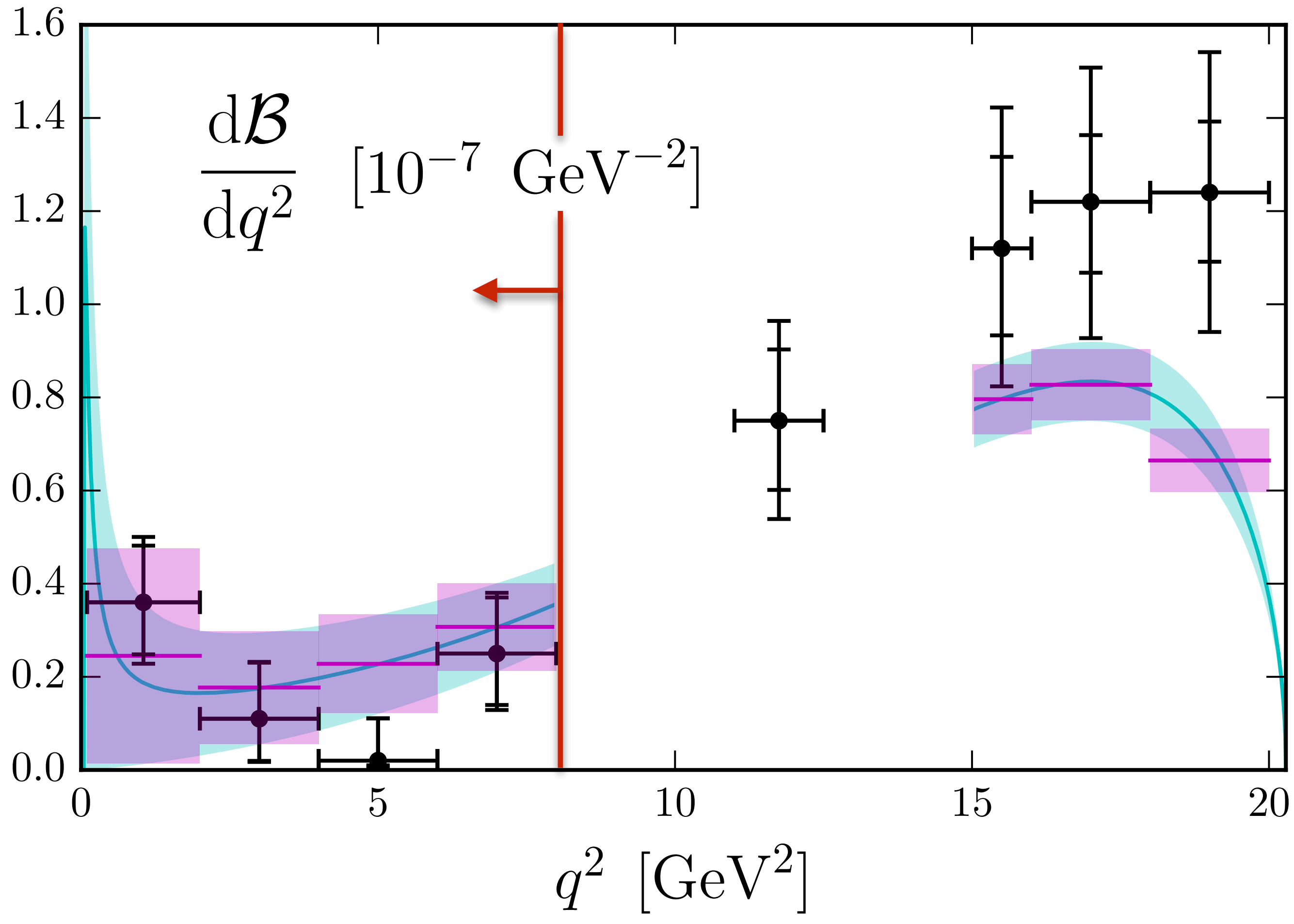
$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$ branching fraction

- Plan to measure $\mathcal{B}(\Lambda_b \to J/\psi\Lambda)$ at LHCb to improve the normalisation uncertainty.
- Ultimate precision on branching fraction measurements is limited by knowledge of $\mathcal{B}(B \to J/\psi K)$ and f_{Λ_b}/f_d .
  - ➡ Bin-by-bin measurements will be systematically limited with an 8% ($4\% \oplus 7\%$) systematic uncertainty.

$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$

- We should observe significant signal at low q^2 in the run 2 data set.

Detmold et al. arXiv:1602.01399



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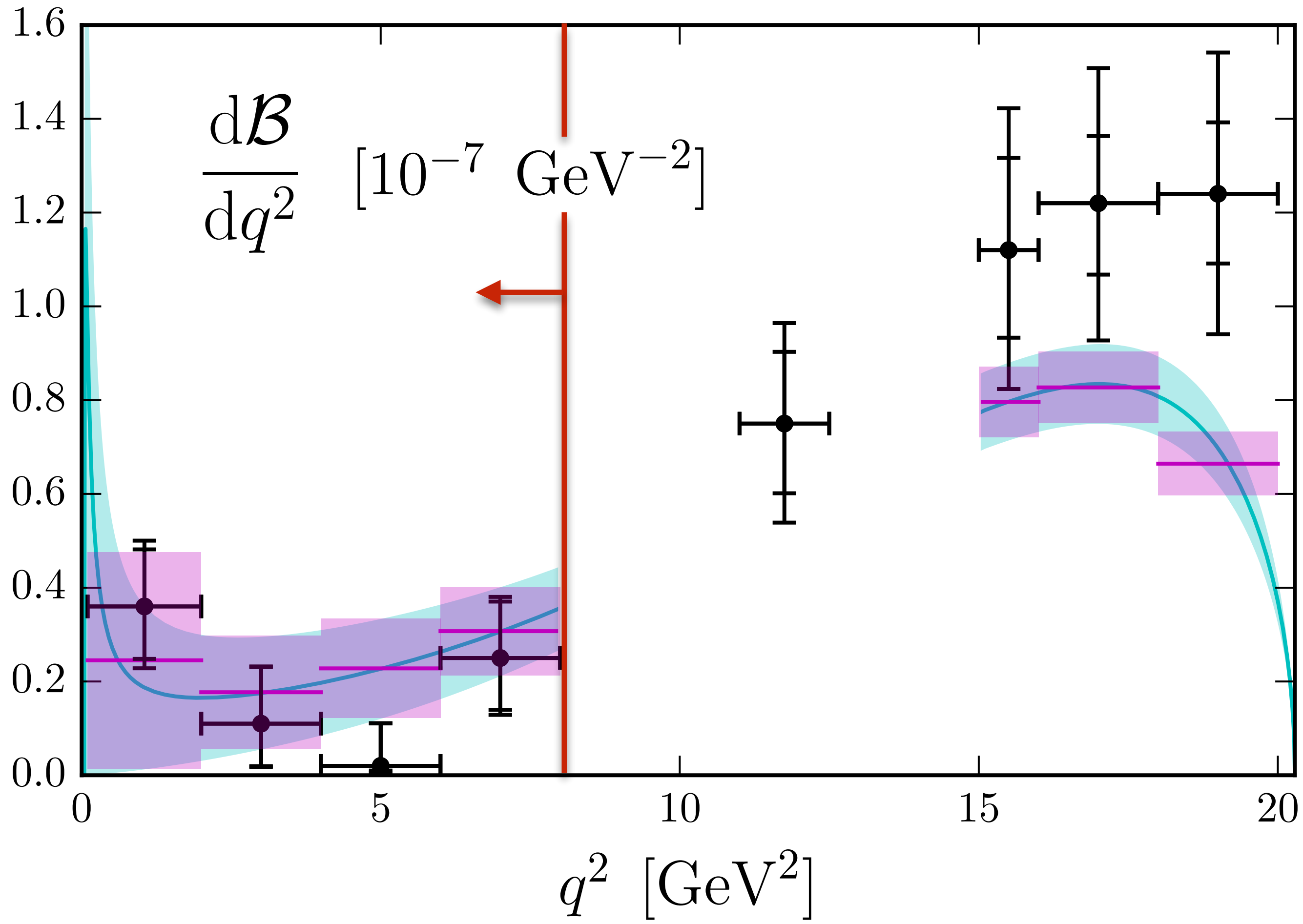
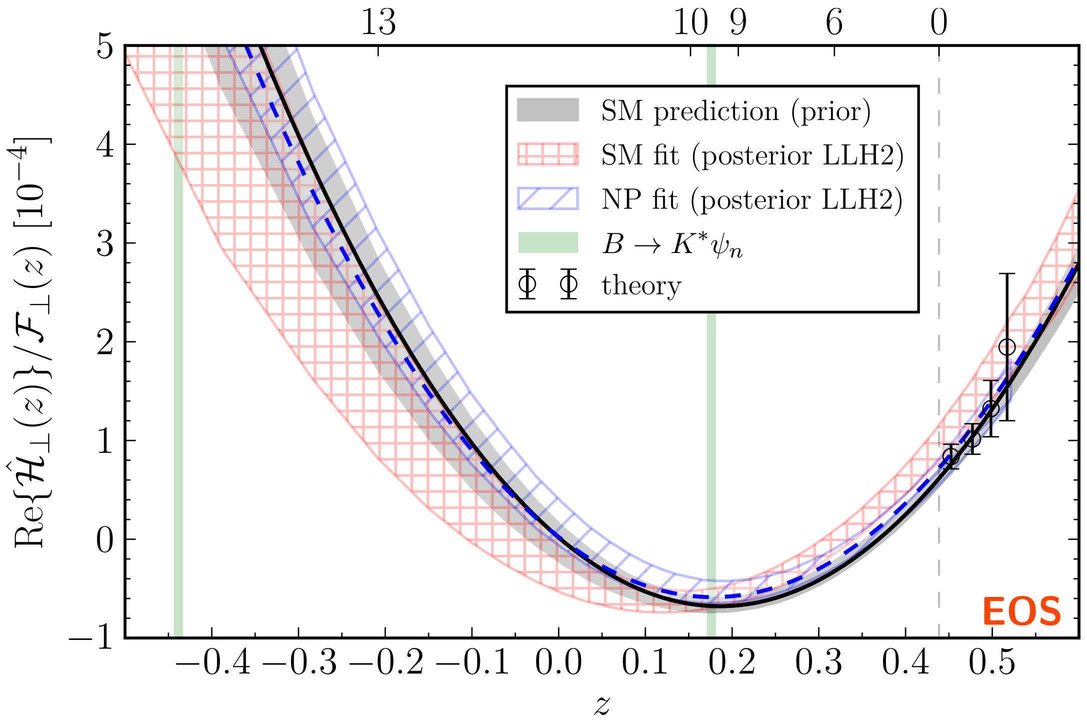


[Bobeth et al. EPJC 78 (2018) 451]

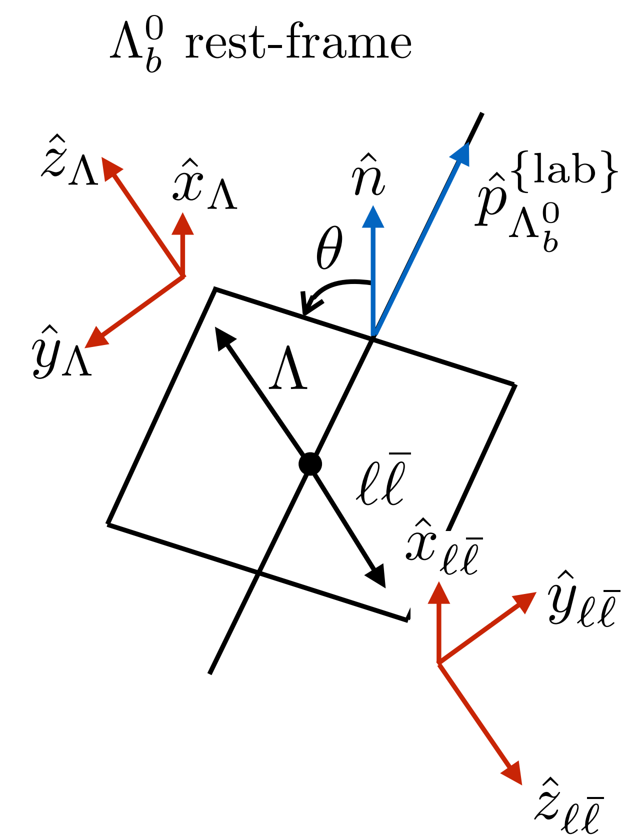


- Could also apply techniques from [EPJC 78 (2018) 451] to low q^2 region.
- External input wanted on decay amplitudes for $J/\psi\Lambda$ and $\psi(2S)\Lambda$.

$\Lambda_b \rightarrow J/\psi\Lambda$ angular distribution

- Parameterised by five decay angles:
  - ➡ Polar and azimuthal helicity angles for the Λ and J/ψ system and θ defined by. $\hat{n}$, where $\hat{n} = \hat{p}_{\mathrm{beam}} \times \hat{p}_{\Lambda_b}$.
- Described by 4 helicity amplitudes. $H_{\lambda_\Lambda, \lambda_\psi}$, the Λ_b production polarisation and the Λ asymmetry parameter α.
  - ➡ Amplitudes are

$$a_- = H_{-1/2,\,0}$$
$$a_+ = H_{+1/2,\,0}$$
$$b_- = H_{+1/2,\,+1}$$
$$b_+ = H_{-1/2,\,-1}$$



See, e.g.
T. Blake & M. Kreps arXiv:1710.00746,
J. Hrivnac et al. arXiv:hep-ph/9405231

Observables

- Large number of observables vanish if the Λ_b is unpolarised:
  - No longer have enough constraints to determine phases of the amplitudes.
- Even if the polarisation is large expect two amplitudes to be small: $a_+ \approx b_- \approx 0$.

Moments	Amplitude dependence
M_1	$\frac{1}{4}(2\|a_+\|^2 + 2\|a_-\|^2 + \|b_+\|^2 + \|b_-\|^2)$
M_2	$\frac{1}{2}(\|b_+\|^2 + \|b_-\|^2)$
M_4	$\frac{\alpha}{4}(\|b_-\|^2 - \|b_+\|^2 + 2\|a_+\|^2 - 2\|a_-\|^2)$
M_5	$\frac{\alpha}{2}(\|b_-\|^2 - \|b_+\|^2)$
M_7	$\frac{\alpha}{\sqrt{2}}\mathrm{Re}(-b_+^* a_+ + b_- a_-^*)$
M_9	$\frac{\alpha}{\sqrt{2}}\mathrm{Im}(b_+^* a_+ - b_- a_-^*)$
M_{11}	$P_b\frac{1}{4}(\|b_+\|^2 - \|b_-\|^2 + 2\|a_+\|^2 - 2\|a_-\|^2)$
M_{12}	$P_b\frac{1}{2}(\|b_+\|^2 - \|b_-\|^2)$
M_{14}	$P_b\frac{\alpha}{4}(-\|b_-\|^2 - \|b_+\|^2 + 2\|a_+\|^2 + 2\|a_-\|^2)$
M_{15}	$-P_b\frac{\alpha}{2}(\|b_+\|^2 + \|b_-\|^2)$
M_{17}	$-P_b\frac{\alpha}{\sqrt{2}}\mathrm{Re}(b_+^* a_+ + b_- a_-^*)$
M_{19}	$P_b\frac{\alpha}{\sqrt{2}}\mathrm{Im}(b_+^* a_+ + b_- a_-^*)$
M_{21}	$-P_b\frac{1}{\sqrt{2}}\mathrm{Im}(b_+^* a_- - b_- a_+^*)$
M_{23}	$P_b\frac{1}{\sqrt{2}}\mathrm{Re}(b_+^* a_- - b_- a_+^*)$
M_{25}	$P_b\frac{\alpha}{\sqrt{2}}\mathrm{Im}(b_+^* a_- + b_- a_+^*)$
M_{27}	$-P_b\frac{\alpha}{\sqrt{2}}\mathrm{Re}(b_+^* a_- + b_- a_+^*)$
M_{30}	$P_b\alpha\mathrm{Im}(a_+ a_-^*)$
M_{32}	$-P_b\alpha\mathrm{Re}(a_+ a_-^*)$
M_{33}	$-P_b\frac{\alpha}{2}\mathrm{Re}(b_+^* b_-)$
M_{34}	$P_b\frac{\alpha}{2}\mathrm{Im}(b_+^* b_-)$

Λ asymmetry parameter

- Recent measurement by BESIII **[Nature Physics 15 (2019) 631–634]** is 17% larger than current world average value:

$$\alpha_\Lambda = 0.642 \pm 0.013 \quad \text{PDG}$$

$$\alpha_\Lambda = 0.750 \pm 0.010 \quad \text{BESIII}$$

- The larger BESIII value likely solves the problems with the existing LHCb, ATLAS and CMS analyses of $\Lambda_b \to J/\psi\Lambda$, which favour an unphysical solution **[LHCb, PLB 724 (2013) 27][ATLAS, PRD 89 (2014) 092009][CMS, PRD 97 (2018) 072010]**.
- Old measurements of α had to determine the proton polarisation from secondary scattering.
- Impacts interpretation of the $\Lambda_b \to \Lambda\mu^+\mu^-$ angular observables.

Updated global fit

- Try three scenarios:

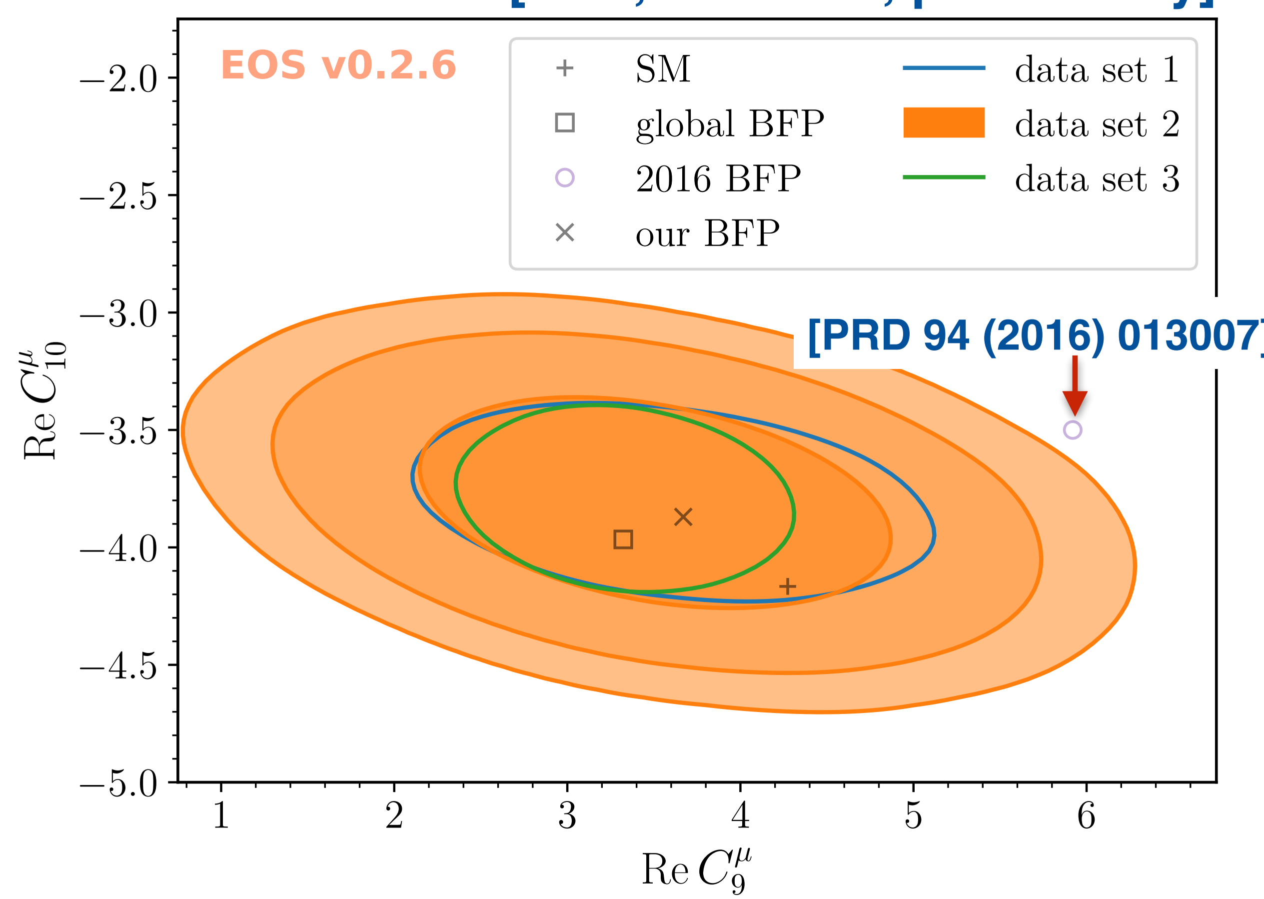
  ATLAS, CMS & LHCb $\mathcal{B}(B_s \to \mu^+\mu^-)$ + unpolarised $\Lambda\mu^+\mu^-$ angular observables.

  \+ Polarised angular observables.

  \+ Updated branching fraction.

- SM point has good p-value.
- Data are consistent with the anomalies (best-fit point is close to the one obtained using meson data).

[DvD, SM & TB, preliminary]

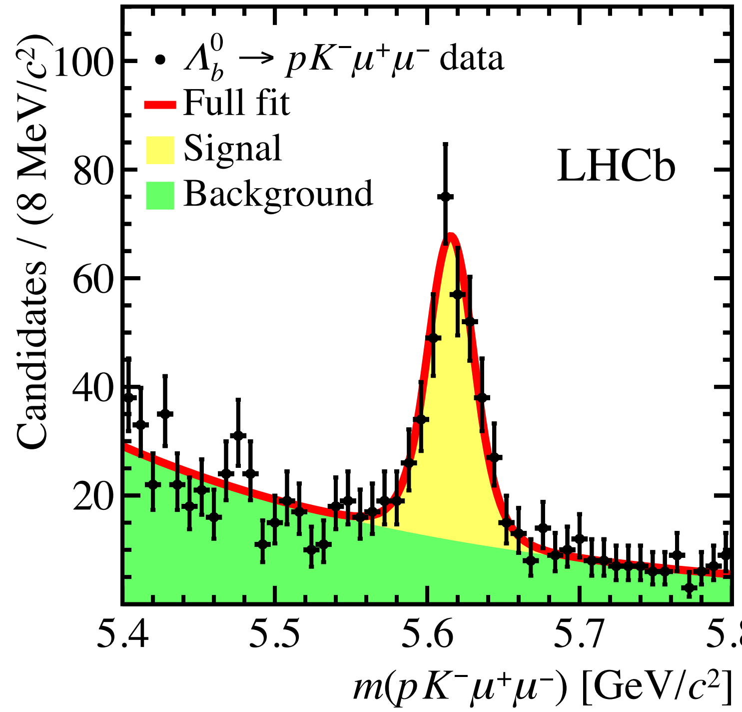


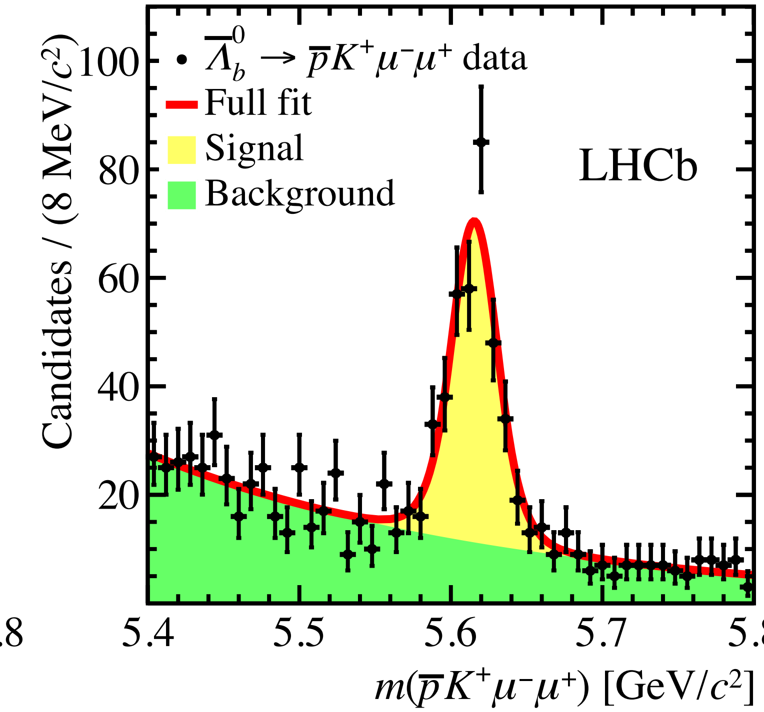
Polarised Λ_b baryons?

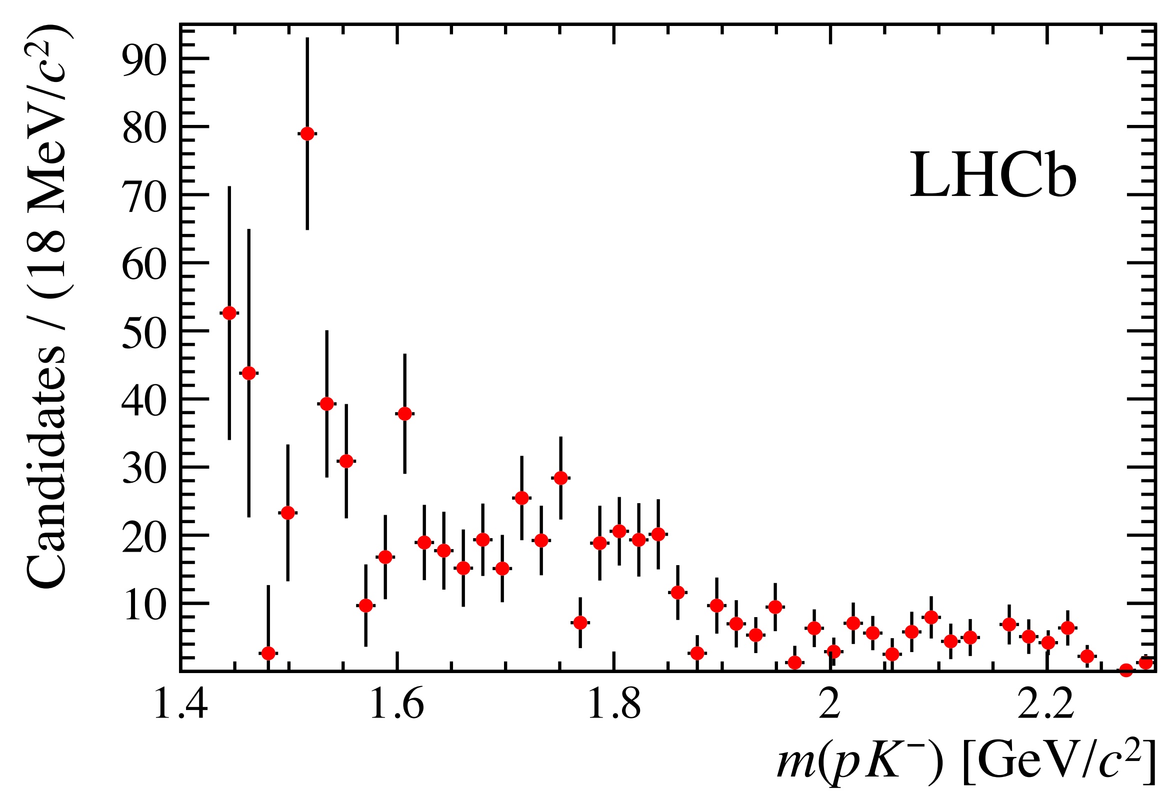
- Large number of new observables would be available if the Λ_b baryons were produced polarised, see **[T. Blake & M. Kreps JHEP 11 (2017) 138]**.
- Polarisation is small at LHC, but is large in Z^0 decays **[ALEPH, PLB 365 (1996) 437-447], [OPAL, PLB 444 (1998) 539-554], [DELPHI, PLB 474 (2000) 205-222]**
- Long-term, could perform these measurements at a future e^+e^- collider, e.g. expect 5 x 10^{12} Z^0's at FCC-*ee* **[A. Abada et al, EPJC 79 (2019) 474]**.
  - ➡ O(1000) reconstructible $\Lambda_b \to \Lambda\mu^+\mu^-$ decays at low-recoil.
- Could we also exploit the large $t\bar{t}$ cross-section at ATLAS and CMS as a source of polarised *b*-baryons?

$\Lambda_b \rightarrow pK\mu^+\mu^-$

- First observed in the LHCb Run 1 data set.
- Measured CP and triple product asymmetries (null result).
- Branching fraction measurement and angular analysis complicated by the presence of a large number of overlapping Λ^* resonances with different J^{PC}.





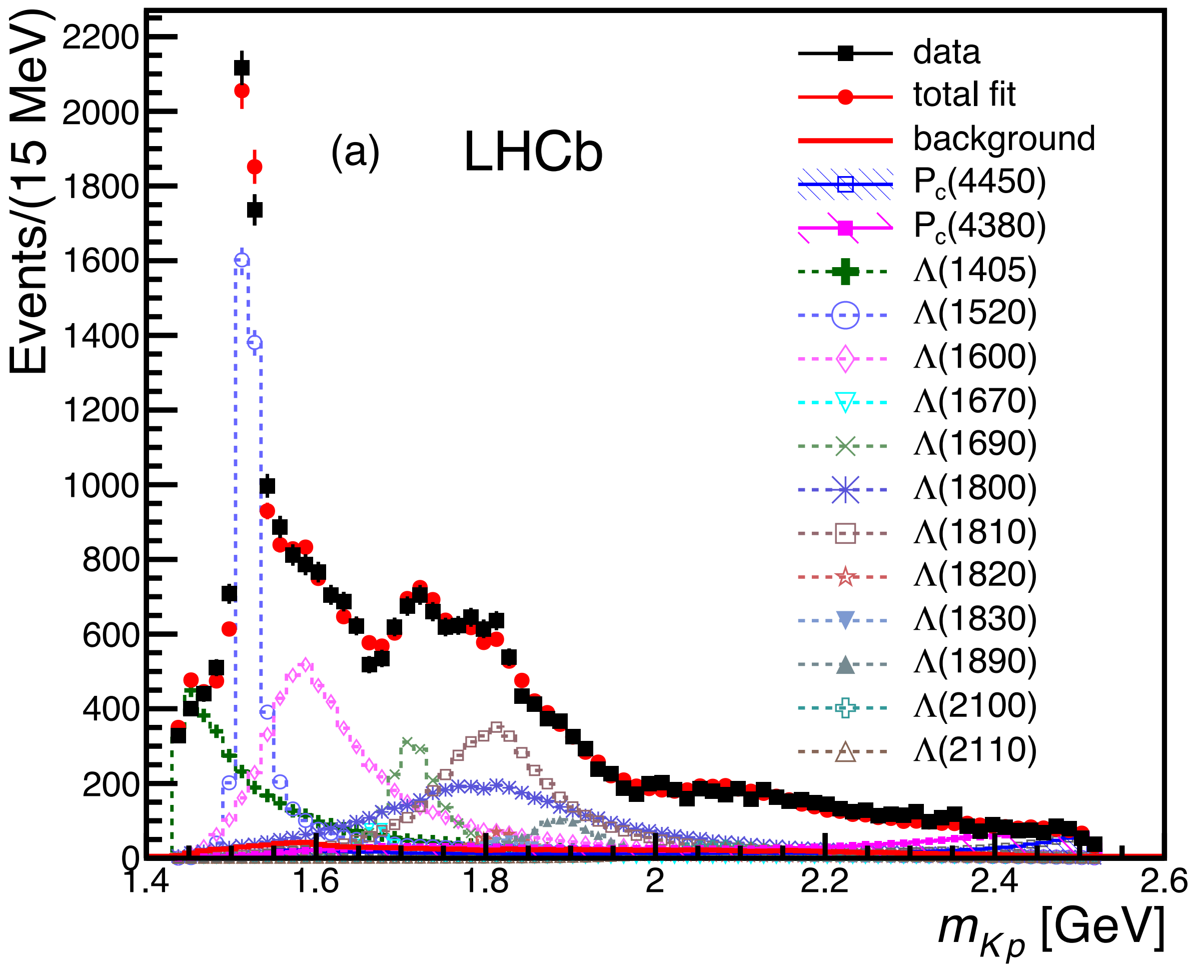


[LHCb, JHEP 06 (2017) 108]

$\Lambda_b \rightarrow J/\psi pK$

- An amplitude analysis of $J/\psi pK$ was carried out as part of the original pentaquark observation paper.
  [PRL 115 (2015) 072001]
- Data dominated by $\Lambda(1520)$ (with $J^{PC} = 3/2^-$) at low pK mass. However, there are still large contributions from other resonances that are difficult to disentangle.

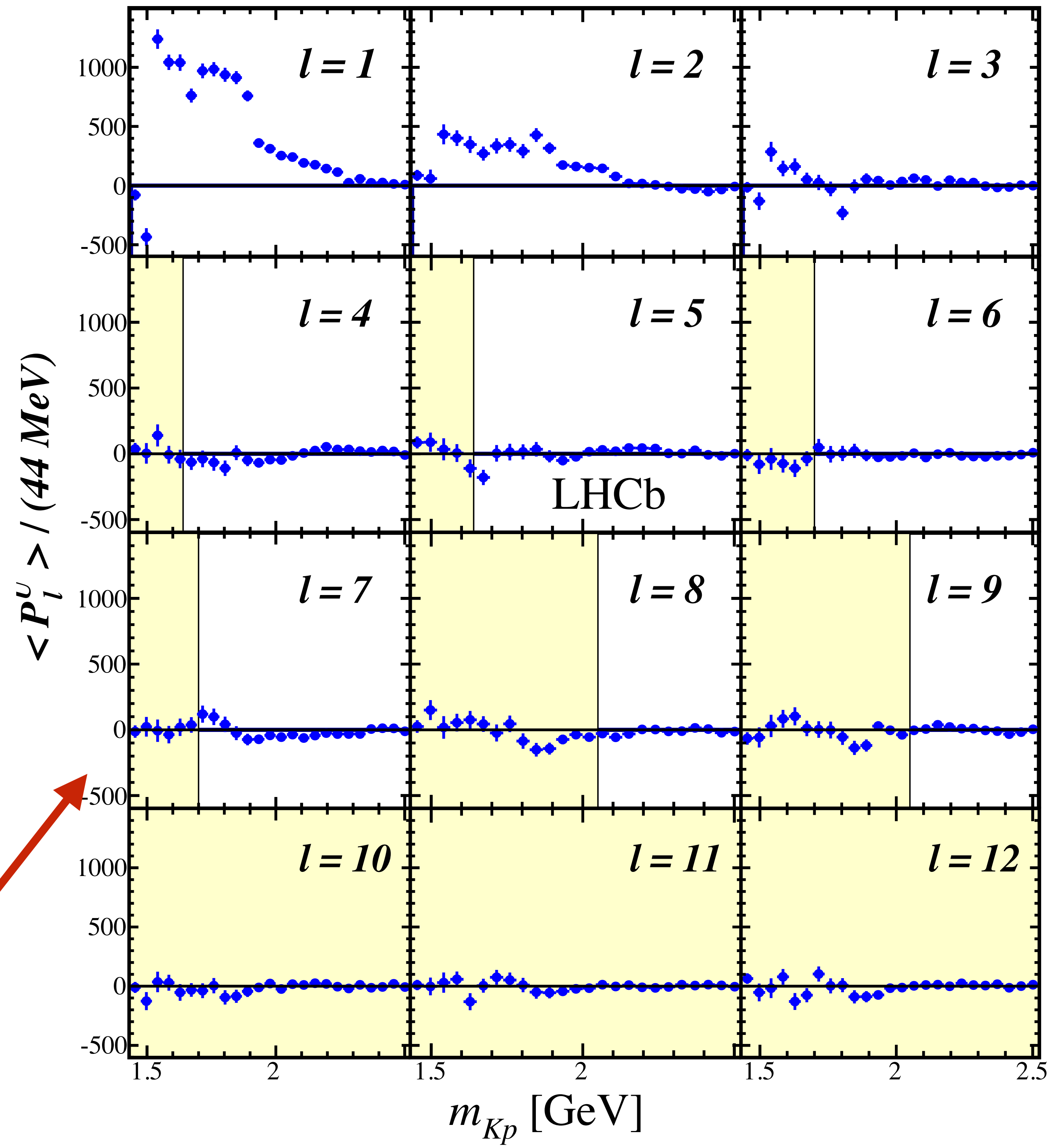
[LHCb, PRL 115 (2015) 072001]



$\Lambda_b \rightarrow pK\mu^+\mu^-$

[LHCb, PRL 117 (2016) 082002]

- Large number of overlapping Λ^* resonances with different J^{PC}.
- Can separate using an amplitude analysis of the $pK\mu^+\mu^-$ system.
- Simple first step, perform a moment analysis in bins on pK mass (and q^2).



c.f. $\Lambda_b \rightarrow J/\psi pK$ model independent analysis in [LHCb, PRL 117 (2016) 082002]

$\Lambda_b \rightarrow pK\mu^+\mu^-$

- Even if we cannot separate the different Λ^* resonances, can still perform clean tests of the SM through LFU ratios.
  - ✓ Decay has different sources of experimental background to $B \rightarrow K^{*0}\mu^+\mu^-$.

Other *b*-baryon decays

- What other $b \to s\mu^+\mu^-$ baryonic decays could we look for in the Run II/upgrade data sets?
  - ➡ $\Xi_b^- \to \Xi^- \mu^+\mu^-$ (with $\Xi^- \to \Lambda\pi^-$)
  - ➡ $\Omega_b^- \to \Omega^- \mu^+\mu^-$ (with $\Omega^- \to \Lambda K^-$)

Decay chains involve two long-lived particles ⇒ low efficiency

- From TeVatron:

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b}} = 0.167 \pm 0.037 \pm 0.012 \ ,$$

$$\frac{f_{\Omega_b^-}}{f_{\Lambda_b}} = 0.045 \pm 0.017 \pm 0.004 \ ,$$

[CDF , PRD 80 (2009) 072003]
[D0, PRL 99 (2007) 052001]

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Decay chains involve two long-lived particles ⇒ low efficiency

- Based on LHCb measurements of $\Xi_b^- \rightarrow \Xi^- J/\psi$ and $\Omega_b \rightarrow \Omega^- J/\psi$ **[PLB 736 (2014) 154]** expect:
  - ➡ O(10) $\Xi_b^- \rightarrow \Xi^- \mu^+\mu^-$
  - ➡ O(2) $\Omega_b \rightarrow \Omega^- J/\psi$

  decays to be reconstructible in the Run 2 data set.

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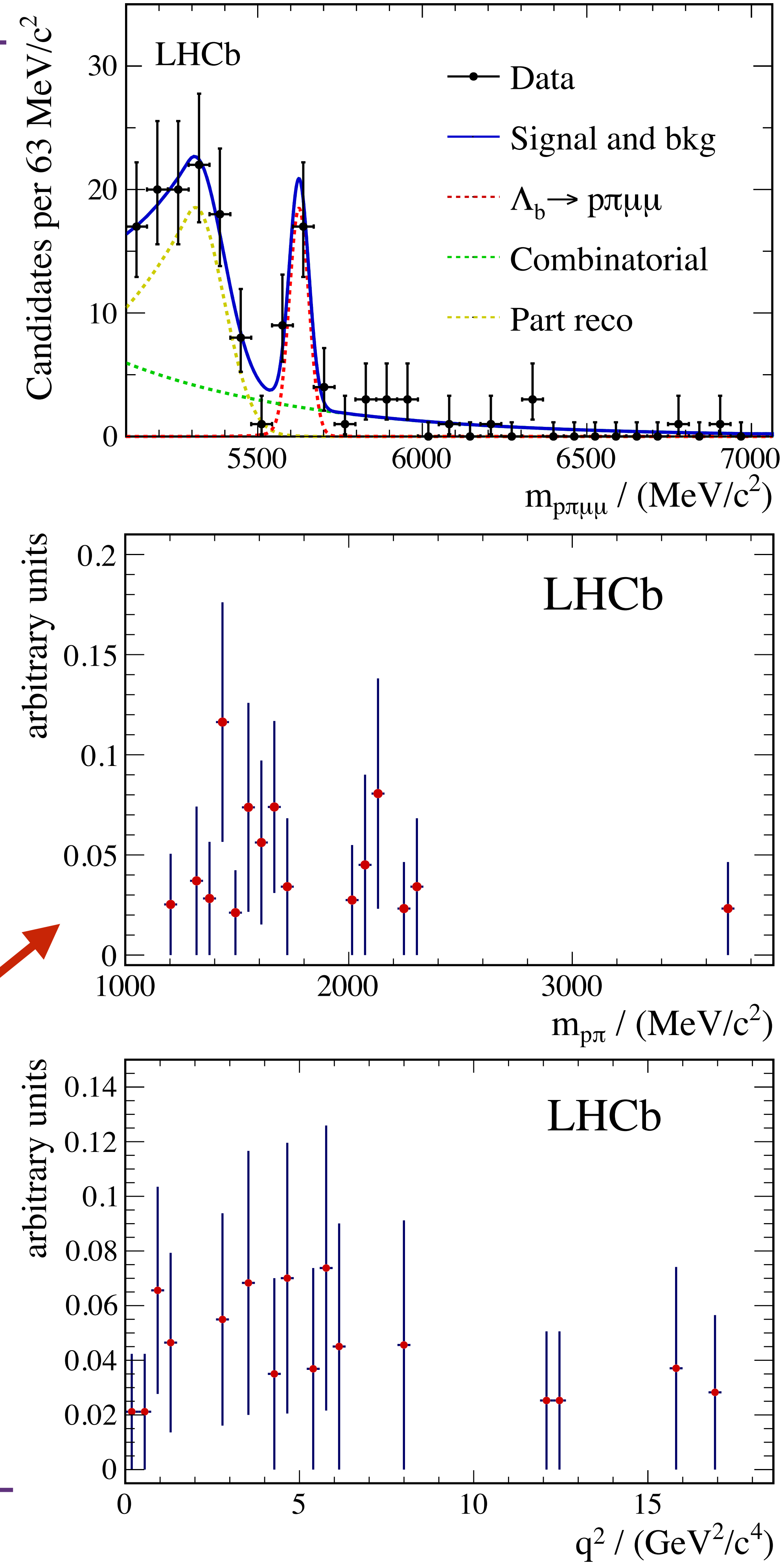
  - ➡ $\Omega_b \to \Omega^- \mu^+\mu^-$ (with $\Omega^- \to \Lambda K^-$)

Decay chains involve two long-lived particles ⇒ low efficiency

- Should be theoretically clean due to weak decays of Ξ and Ω.
- Described by a 5 or 7 (when considering the subsequent Λ decay) dimensional angular distribution:
  - ➡ Do we get additional NP sensitivity by probing the Λ helicity?

$\Lambda_b \to p\pi\mu^+\mu^-$

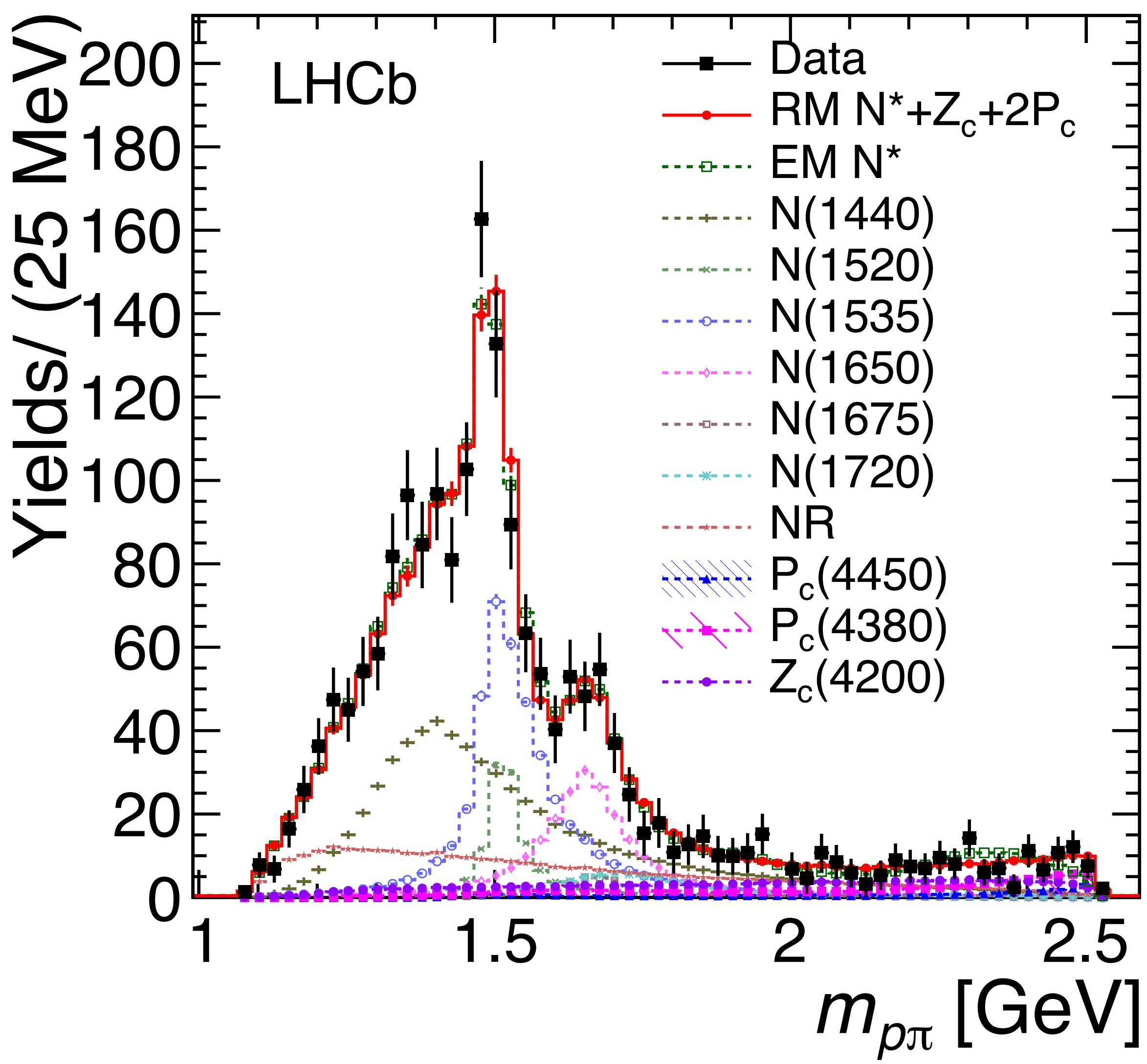
- Mediated by a $b\to d\mu^+\mu^-$ FCNC.
- First observation with 5.5σ significance (22±6 decays) in the LHCb Run 1 dataset.
- Same conceptual issue as $pK\mu^+\mu^-$ when comparing to theory predictions:
  - ➡ Large number of overlapping N* resonances with different J^{PC}.



[LHCb, JHEP 04 (2017) 029]

$\Lambda_b \to J/\psi p \pi$

[LHCb, PRL 117 (2016) 082003]



- An amplitude analysis of $\Lambda_b \to J/\psi p \pi$ has been carried out to search for exotic states in **[LHCb, PRL 117 (2016) 082003]**.
- To describe the data need to consider a number of overlapping N* resonances along with a broad non-resonant contribution.

Other *b*-baryon decays

- What about $b \rightarrow d\mu^+\mu^-$ decays to ground-state baryons?
  - ➡ $\Lambda_b \rightarrow n\mu^+\mu^-$ *x* **neutron in final-state**
  - ➡ $\Xi_b \rightarrow \Lambda\mu+\mu-$
  - ➡ …

Decays are isospin violating, expect negligible rate.

Radiative Λ_b decays

- Photon polarisation can be determined from the angular distribution of baryonic decays,

$$\alpha_\gamma = \frac{P(\gamma_{\mathrm{L}}) - P(\gamma_{\mathrm{R}})}{P(\gamma_{\mathrm{L}}) + P(\gamma_{\mathrm{R}})}$$

- $\Lambda_b \to \Lambda\gamma$ **[G. Hiller & A. Kagan, PRD 65 (2002) 074038]**

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\gamma} = \tfrac{1}{2}(1 - \alpha_\gamma P_b \cos\theta_\gamma) \qquad \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_p} = \tfrac{1}{2}(1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p)$$

- $\Lambda_b \to \Lambda^*\gamma$ **[F. Legger & T. Schietinger, PLB 645 (2007) 204-212]**

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\gamma} = \tfrac{1}{2}(1 - \alpha_\gamma \alpha_{3/2} P_b \cos\theta_\gamma) \qquad \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_p} \propto \tfrac{1}{2}(1 - \alpha_{p,3/2} \cos^2\theta_p)$$

- Only have sensitivity from θ_p in $\Lambda_b \to \Lambda\gamma$ given due to small size of P_b.

Radiative Λ_b decays

- Using $\Lambda_b \to \Lambda\gamma$ expect sensitivity to α_γ of:
  - ➡ 25% with Run 2 dataset
  - ➡ 15% with 23fb^{-1}
  - ➡ 4% with 300fb^{-1}

[LHCb, Upgrade II physics case, arXiv:1808.08865].

Note, this uses the old PDG value of α_Λ.

Expect a 17% improvement with the larger BESIII value.

- We will also measure the *CP* asymmetry of $\Lambda_b \to pK\gamma$ and $\Lambda_b \to p\pi\gamma$.

Other radiative decays

- Could also look at $\Xi_b^- \to \Xi^- \gamma$ (with $\Xi^- \to \Lambda \pi^-$):
  - ➡ Involves two weak decays and will be challenging to reconstruct experimentally.
  - ➡ Expect O(10) candidates in the LHCb Run 2 data set.
- More complex angular distribution given by:

$$\frac{d^2\Gamma}{d\cos\theta_\Lambda \, d\cos\theta_p} = \frac{1}{4}(1 - \alpha_\gamma \alpha_\Xi \cos\theta_\Lambda + \alpha_\Lambda \cos\theta_p (\alpha_\Xi - \alpha_\gamma \cos\theta_\Lambda))$$

α_Ξ: −0.39±0.01 α_Λ: +0.75±0.01

- Expect sensitivity of 40% (10%) on α_γ with 23fb^{-1} (300fb^{-1}) **[LHCb, Upgrade II physics case, arXiv:1808.08865]**.

Summary

- Large number of different processes could be studied with the data collected during Runs 2+ of the LHC.
- Often have a trade-off between ease of the experimental measurement and theoretical complexity,

    e.g. in dealing with overlapping states in $ph^{-}\mu^{+}\mu^{-}$.

$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$ branching fraction

- New numbers use:

$$f_{\Lambda_b} \times \mathcal{B}(\Lambda_b \to J/\psi\Lambda) = (5.8 \pm 0.8) \times 10^{-5} \ , \qquad \text{[PDG 2018]}$$

with

$$f_{\text{baryon}} = 0.218 \pm 0.047 \qquad \text{[HFLAV 2017]}$$

assuming

$$f_{\text{baryon}} = f_{\Lambda_b}\left(1 + 2\frac{f_{\Xi_b^-}}{f_{\Lambda_b}} + \frac{f_{\Omega_b^-}}{f_{\Lambda_b}}\right) \ ,$$

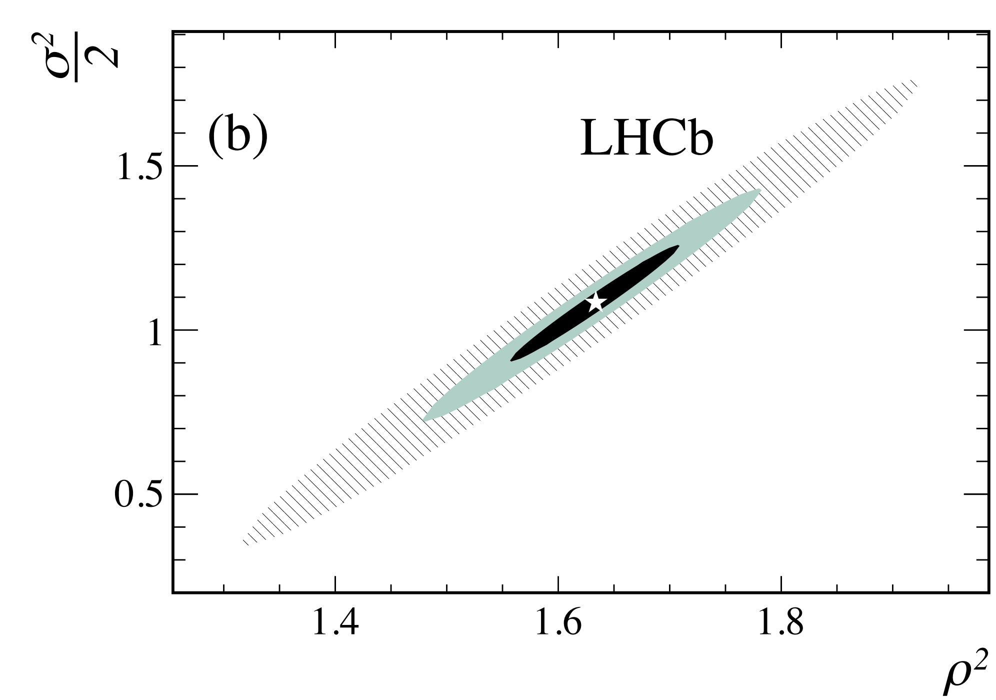
where

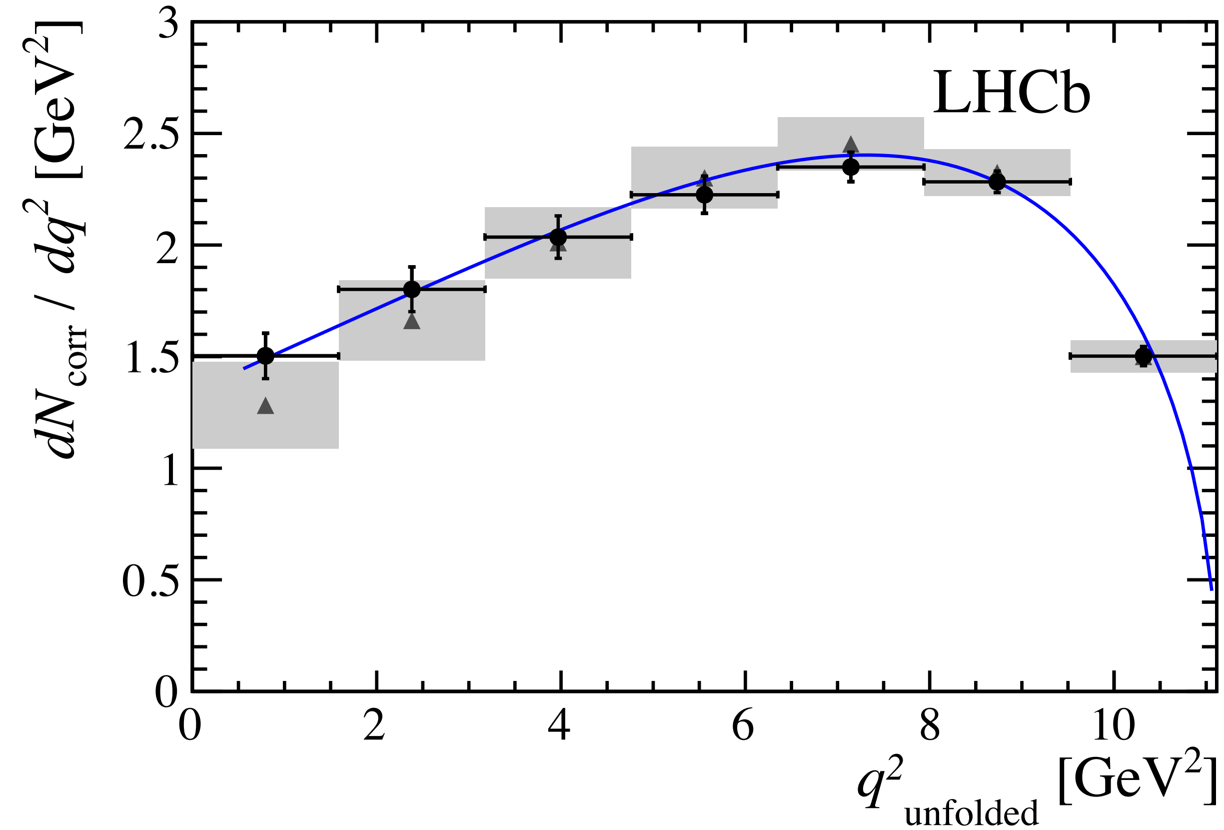
$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b}} = 0.167 \pm 0.037 \pm 0.012 \ , \qquad \text{[PDG 2018]}$$

$$\frac{f_{\Omega_b^-}}{f_{\Lambda_b}} = 0.045 \pm 0.017 \pm 0.004 \ ,$$

$\Lambda_b \rightarrow \Lambda_c^+ l^- \nu$

- Only existing measurement is of $\Lambda_b \rightarrow \Lambda_c^+ l^- \nu$ form-factors.
- Reconstruct neutrino momentum up-to two-fold ambiguity by exploiting large Λ_b flight distance.
- Unfold q^2 and Isgur-Wise parameters.
- Good agreement between data/HQET/lattice.





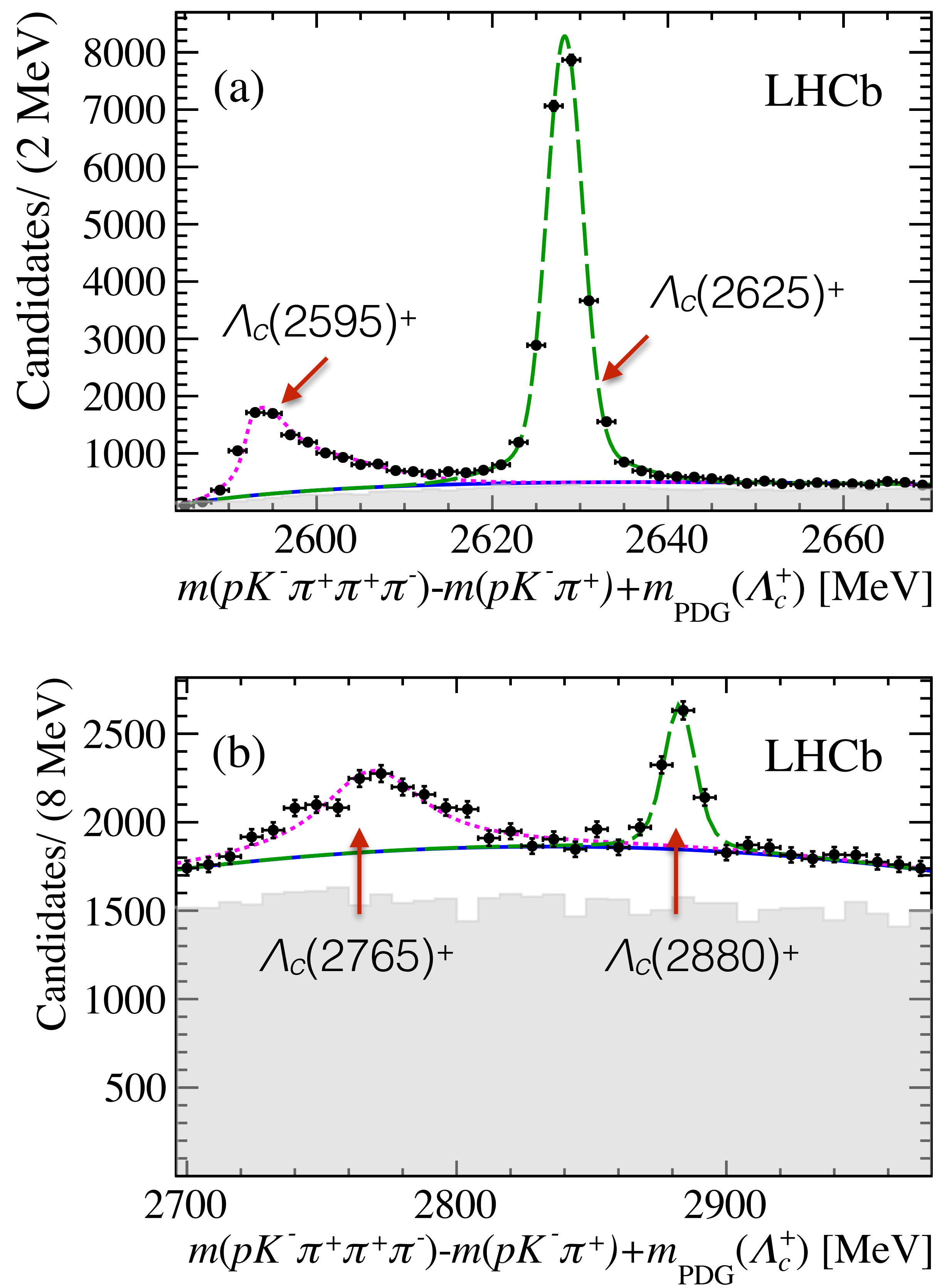
Lattice predictions from

[Detmold et al. PRD 92 (2015) 034503]

[LHCb, PRD 96 (2017) 112005]

$\Lambda_b \rightarrow \Lambda_c^{(*)} l^- \nu$

- Background studies show large number of different Λ_c^* states in the data.
- Next steps are to:
  - ➡ perform an angular analysis of $\Lambda_b \rightarrow \Lambda_c^{(*)} l^- \nu$.
  - ➡ measure R(Λ_c).



[LHCb, PRD 96 (2017) 112005]

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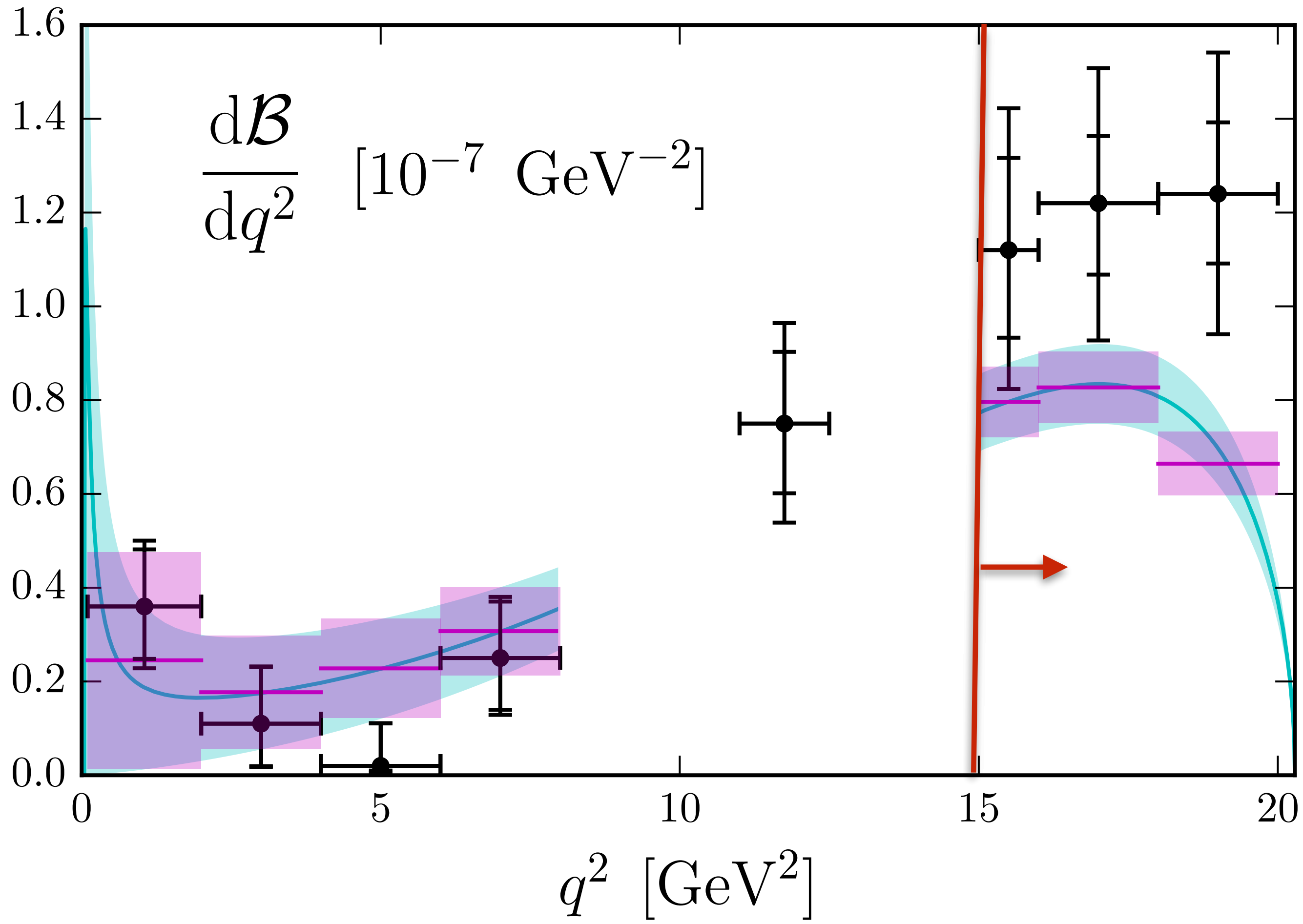
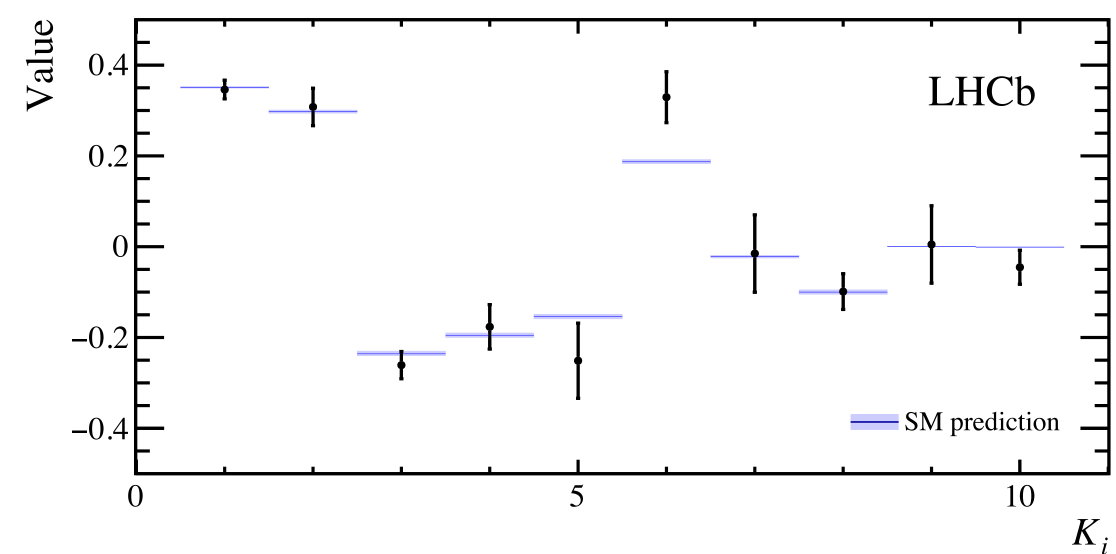
- Large number (34) of angular observables, 24 require Λ_b to be polarised at production and are consistent with zero in current dataset.

Detmold et al. arXiv:1602.01399



LHCb, arXiv:1808.00264



- $\Lambda_b \rightarrow D\bar{D}\Lambda$ can provide useful input on long-distance contributions.
- SM predictions use external on α_Λ and production polarisation (small at the LHC).
- Branching fraction uncertainty currently dominated by knowledge of $\mathcal{B}(\Lambda_b \rightarrow J/\psi\Lambda)$.