$\Lambda_b \to \Lambda(\to pK^-)\ell^+\ell^-$

Beautiful and charming baryon workshop
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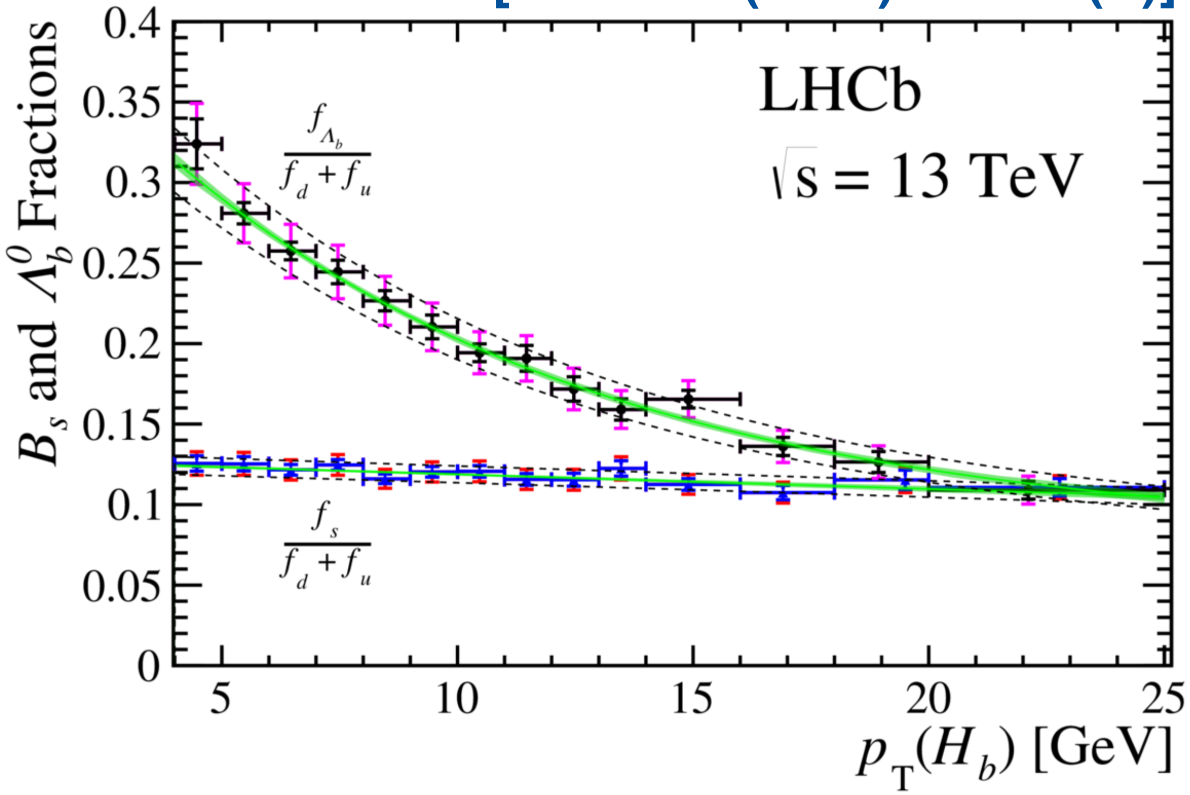
Why $\Lambda_b \to pK^-\ell^+\ell^-$ decays?

- Large data sets are available at the LHC experiments.
- Provides a consistency check of $b \to s\ell^+\ell^-$ anomalies in a different hadronic system.
- We have new measurements from the last two years to ponder on.

[PRD 100 (2019) 031102(R)]



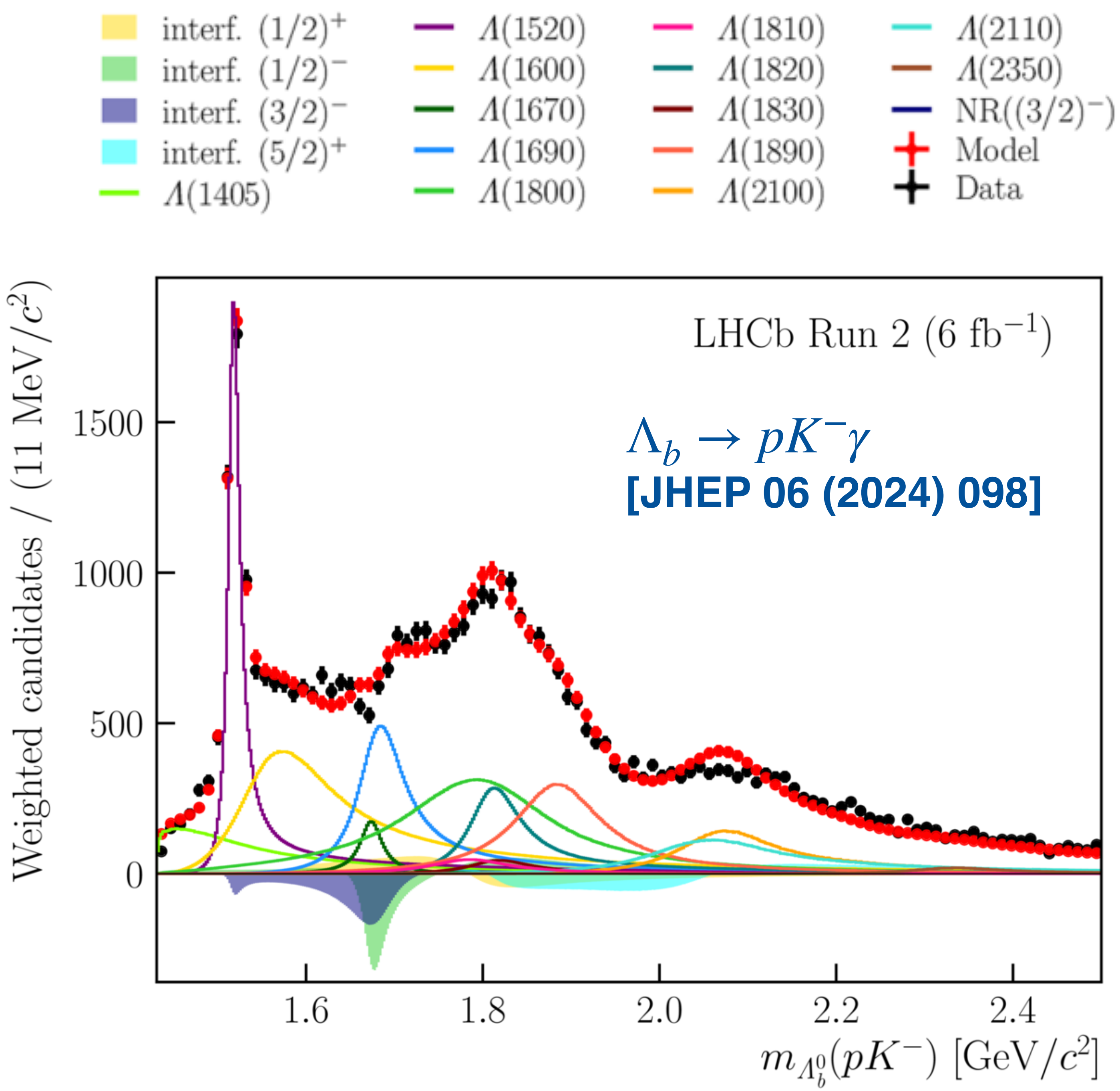
Why $\Lambda_b \to pK^-\ell^+\ell^-$ decays?

- Can access new Wilson coefficient combinations if Λ_b baryons are polarised at production:
  - Unfortunately the net polarisation is small at the LHC.

Could we exploit production in Z^0 or top or through decays of other baryons to access a polarised sample?

Challenge: complex resonance spectrum

- Final state receives contributions from large number of different Λ resonances with different J^P quantum numbers.
- Difficult to select regions of data dominated by single resonances (with possible exception of the $\Lambda(1520)$).

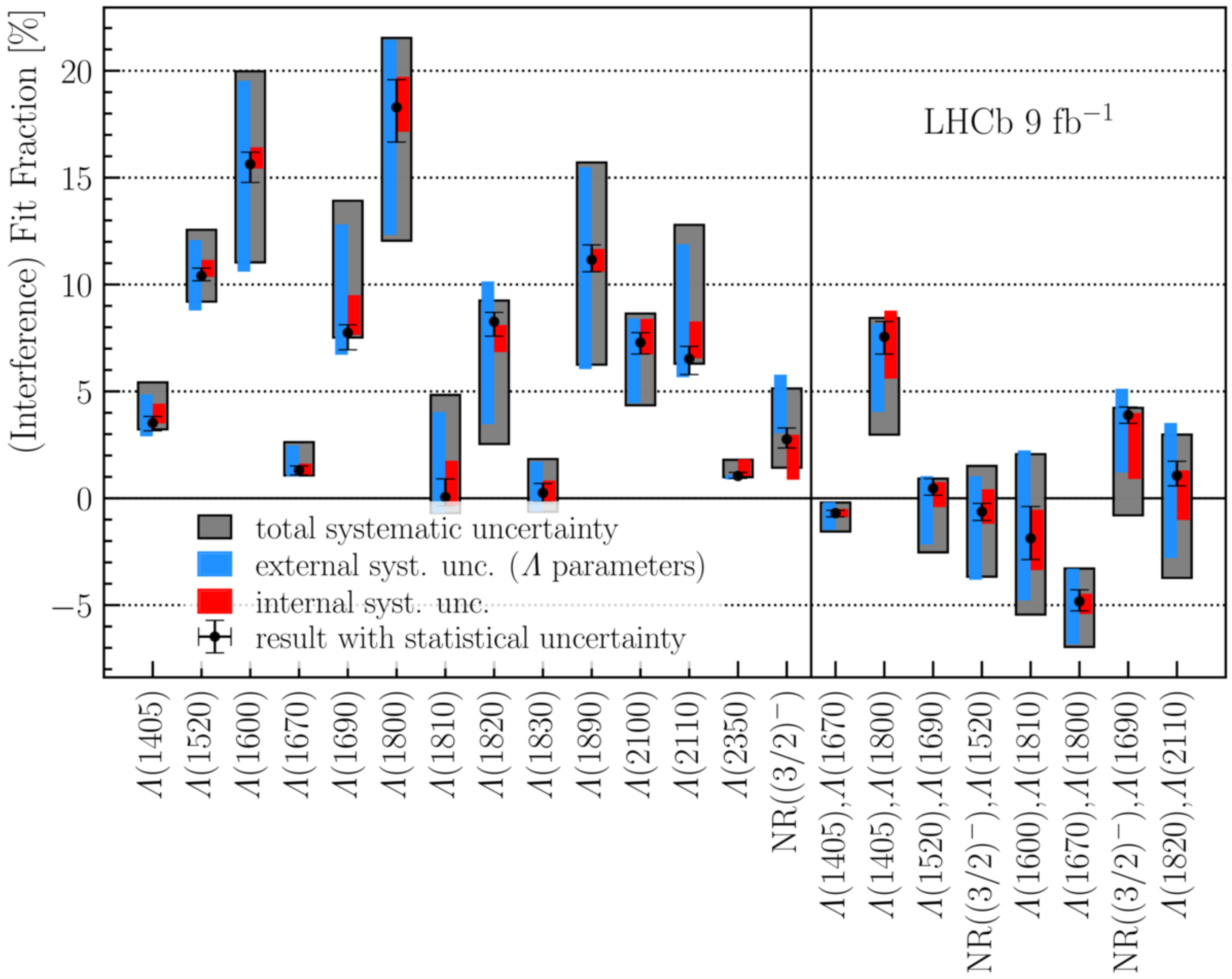


Challenge: complex resonance spectrum

- Final state receives contributions from large number of different Λ resonances with different J^P quantum numbers.
- Difficult to select regions of data dominated by single resonances.
- Spectrum is not dominated by the contribution from a single resonance.
- Largest contributions are from $\frac{3}{2}^-$ $\Lambda(1690)$ and $\frac{1}{2}^-$ $\Lambda(1800)$.

$\Lambda_b \to pK^-\gamma$

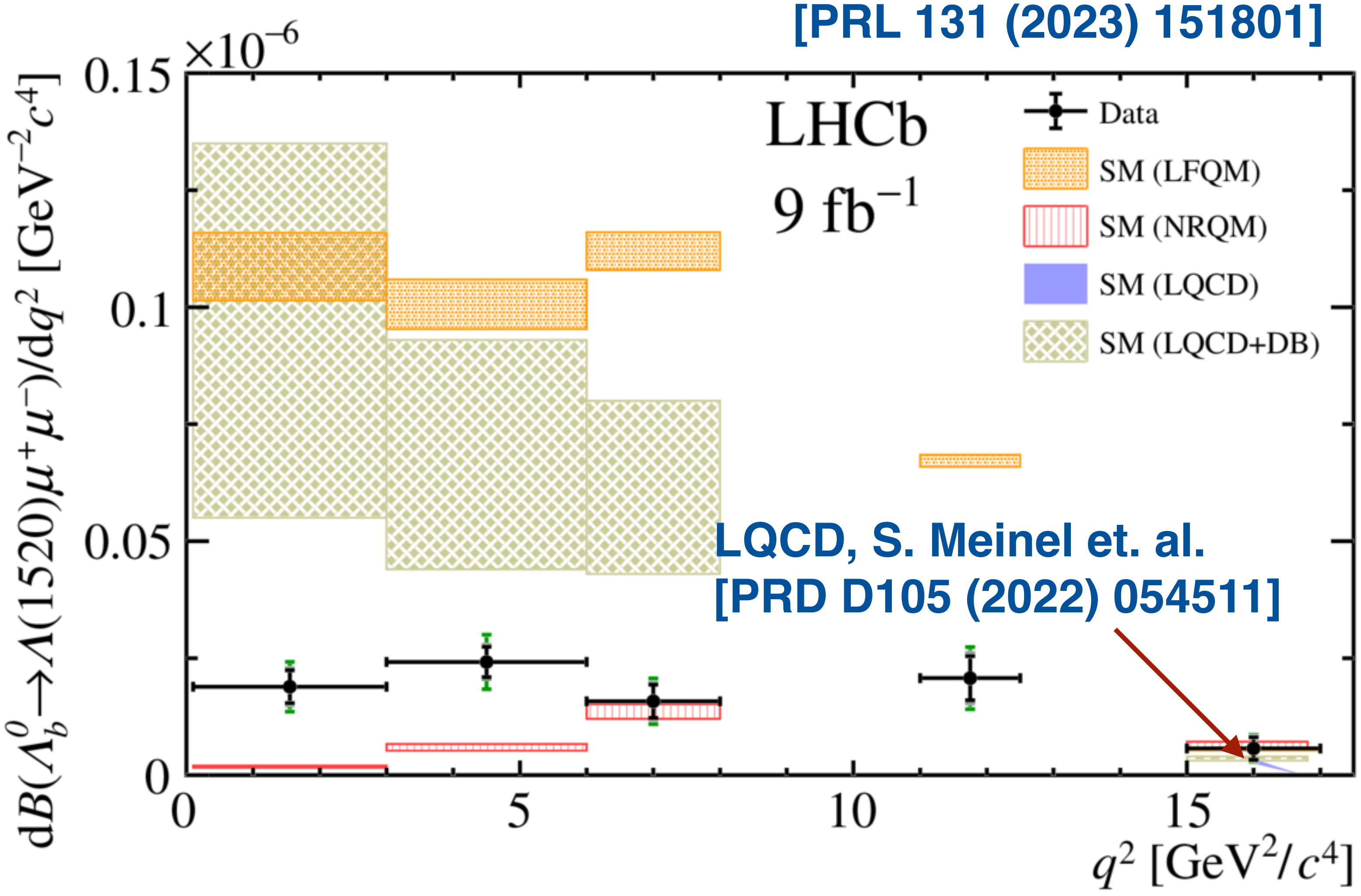
[JHEP 06 (2024) 098]



Challenge: limited knowledge of form factors

- Reliable determinations are only available for $\Lambda_b \to \Lambda(1520)$ and primarily from Lattice (at low recoil).
- Situation is poor at large recoil:
  - Weak constraints from dispersive bounds. **Y. Amhis et. al. [arXiv:2208.08937]**.
  - Quark-model predictions are not consistent with data.
- We only have quark-model predictions for most states.

[PRL 131 (2023) 151801]



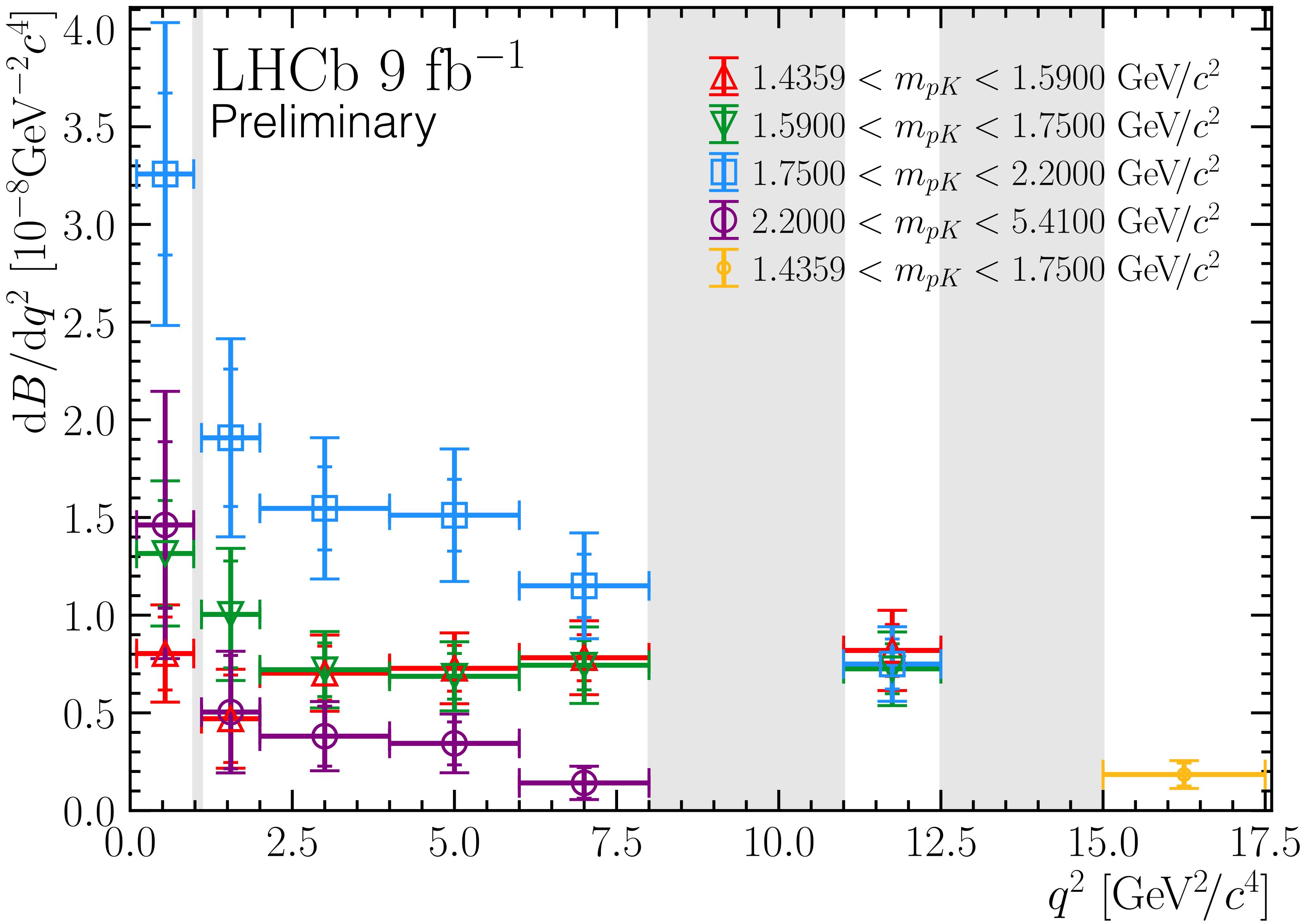
Challenge: limited knowledge of form factors

- In $B^0/B^+/B_s^0$ systems, light-cone sum-rule calculations provide powerful constraints on form factors at large recoil. **What are the prospects for similar techniques applied to baryon decays?**
- **Can first principle arguments tell us something about the pattern we would expect for the form factors of other states?** e.g.
  - limiting behaviour at low/large recoil,
  - suppression of some form factors etc.

Differential branching fraction

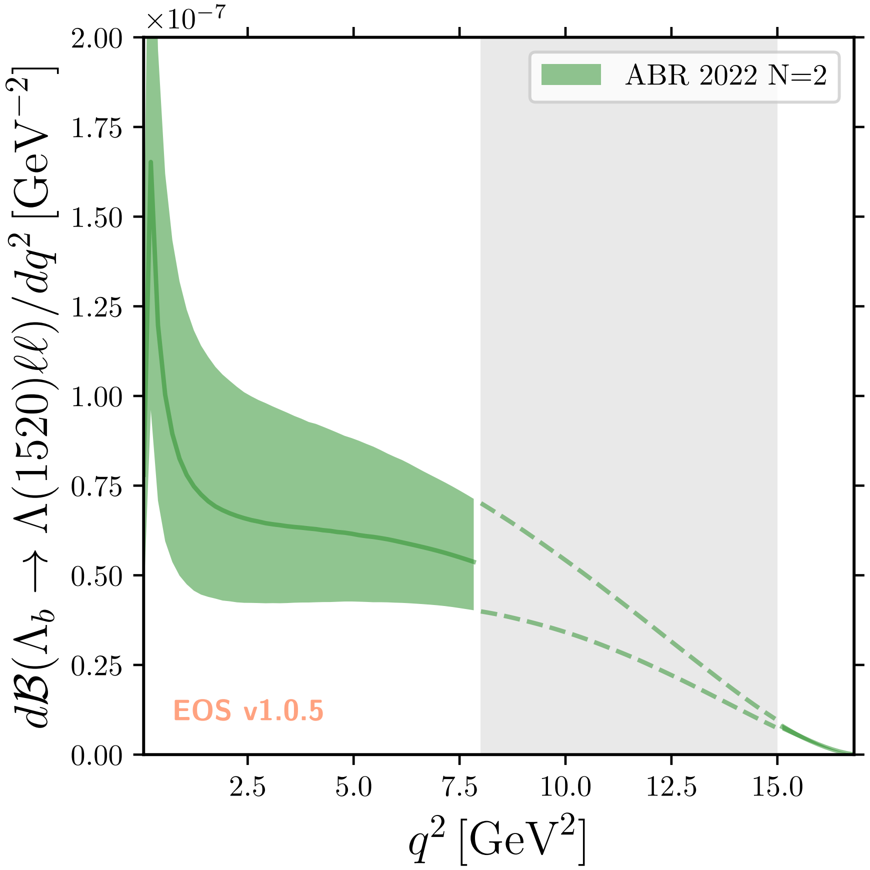
- We now also have measurements where we do not try to separate states across the full spectrum.

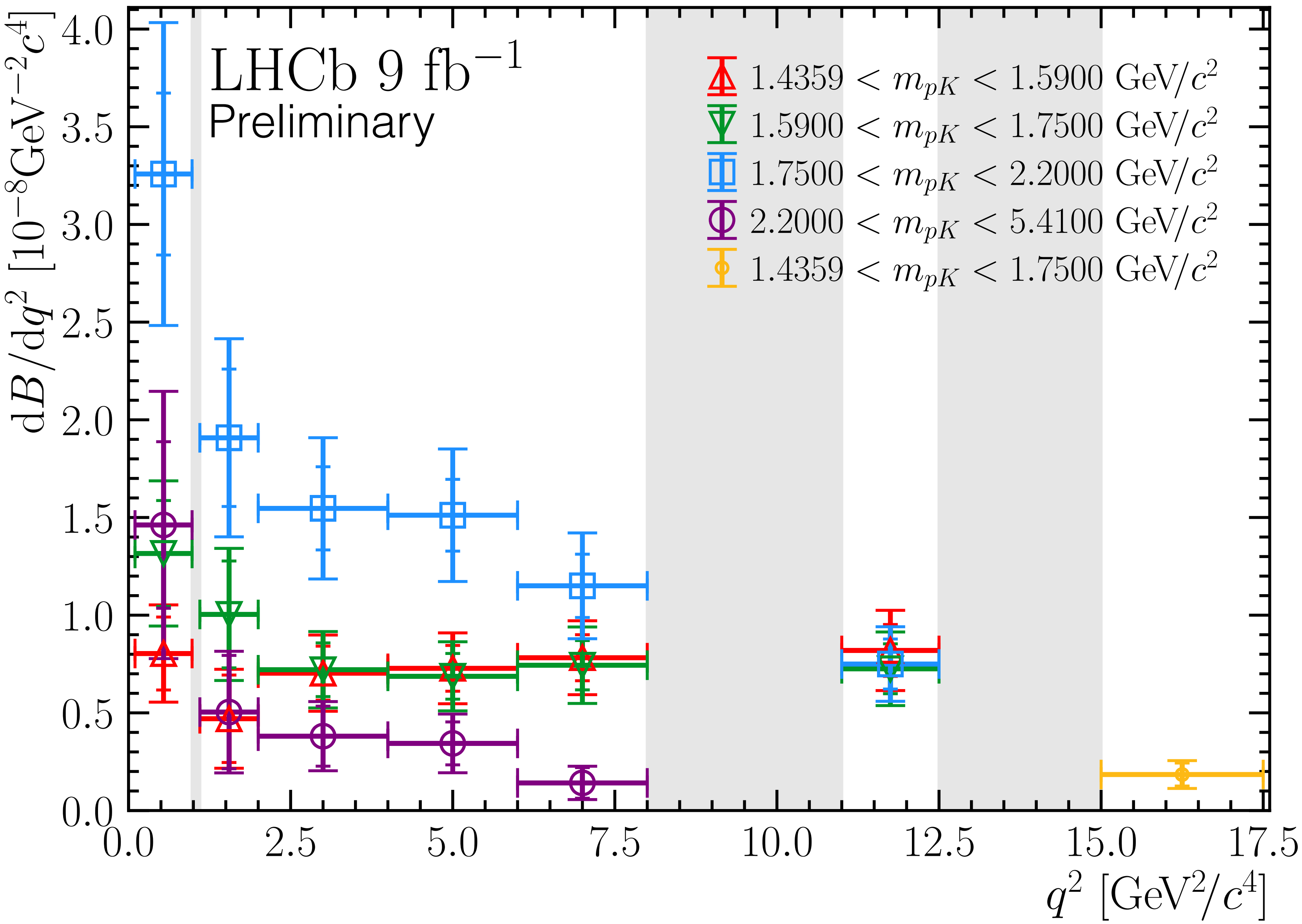
[LHCb-PAPER-2024-024]



Differential branching fraction

[LHCb-PAPER-2024-024]





Qualitatively similar in shape to predictions for $\Lambda(1520)\mu^+\mu^-$ from **Y. Amhis et. al. [arXiv:2208.08937]**

Challenges: complex angular distribution

- Can expand in terms of the helicity basis with $J \leq \frac{5}{2}$.
- Can express distribution in terms of associated Legendre polynomials:

$$\frac{32\pi^2}{3} \frac{\mathrm{d}^7\Gamma}{\mathrm{d}q^2\,\mathrm{d}m_{pK}\,\mathrm{d}\vec{\Omega}} = \sum_{i=1}^{178} K_i(q^2, m_{pK}) f_i(\vec{\Omega})\,.$$

- 178 (46) observables in the polarised (unpolarised) case **[JHEP 02 (2023) 189]**.

i	$f_i(\vec{\Omega})$	i	$f_i(\vec{\Omega})$
1	$\frac{1}{\sqrt{3}}P_0^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	24	$\frac{1}{2}\sqrt{\frac{7}{3}}P_3^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$
2	$P_0^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	25	$\frac{1}{2}P_4^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$
3	$\sqrt{\frac{5}{3}}P_0^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	26	$\frac{3}{2\sqrt{5}}P_4^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$
4	$P_1^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	27	$\frac{1}{3}\sqrt{\frac{11}{6}}P_5^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$
5	$\sqrt{3}P_1^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	28	$\sqrt{\frac{11}{30}}P_5^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$
6	$\sqrt{5}P_1^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	29	$\sqrt{\frac{5}{6}}P_1^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
7	$\sqrt{\frac{5}{3}}P_2^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	30	$\sqrt{\frac{3}{2}}P_1^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
8	$\sqrt{5}P_2^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	31	$\frac{5}{3\sqrt{6}}P_2^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
9	$\frac{5}{\sqrt{3}}P_2^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	32	$\sqrt{\frac{5}{6}}P_2^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
10	$\sqrt{\frac{7}{3}}P_3^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	33	$\frac{1}{6}\sqrt{\frac{35}{3}}P_3^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
11	$\sqrt{7}P_3^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	34	$\frac{1}{2}\sqrt{\frac{7}{3}}P_3^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
12	$\sqrt{\frac{35}{3}}P_3^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	35	$\frac{1}{2}P_4^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
13	$\sqrt{3}P_4^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	36	$\frac{3}{2\sqrt{5}}P_4^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
14	$3P_4^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	37	$\frac{1}{3}\sqrt{\frac{11}{6}}P_5^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
15	$\sqrt{15}P_4^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	38	$\sqrt{\frac{11}{30}}P_5^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
16	$\sqrt{\frac{11}{3}}P_5^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	39	$\frac{5}{12\sqrt{6}}P_2^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\cos 2\phi$
17	$\sqrt{11}P_5^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	40	$\frac{1}{12}\sqrt{\frac{7}{6}}P_3^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\cos 2\phi$
18	$\sqrt{\frac{55}{3}}P_5^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	41	$\frac{1}{12\sqrt{2}}P_4^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\cos 2\phi$
19	$\sqrt{\frac{5}{6}}P_1^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$	42	$\frac{1}{12}\sqrt{\frac{11}{42}}P_5^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\cos 2\phi$
20	$\sqrt{\frac{3}{2}}P_1^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$	43	$\frac{5}{12\sqrt{6}}P_2^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\sin 2\phi$
21	$\frac{5}{3\sqrt{6}}P_2^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$	44	$\frac{1}{12}\sqrt{\frac{7}{6}}P_3^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\sin 2\phi$
22	$\sqrt{\frac{5}{6}}P_2^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$	45	$\frac{1}{12\sqrt{2}}P_4^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\sin 2\phi$
23	$\frac{1}{6}\sqrt{\frac{35}{3}}P_3^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$	46	$\frac{1}{12}\sqrt{\frac{11}{42}}P_5^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\sin 2\phi$

Method-of-moments

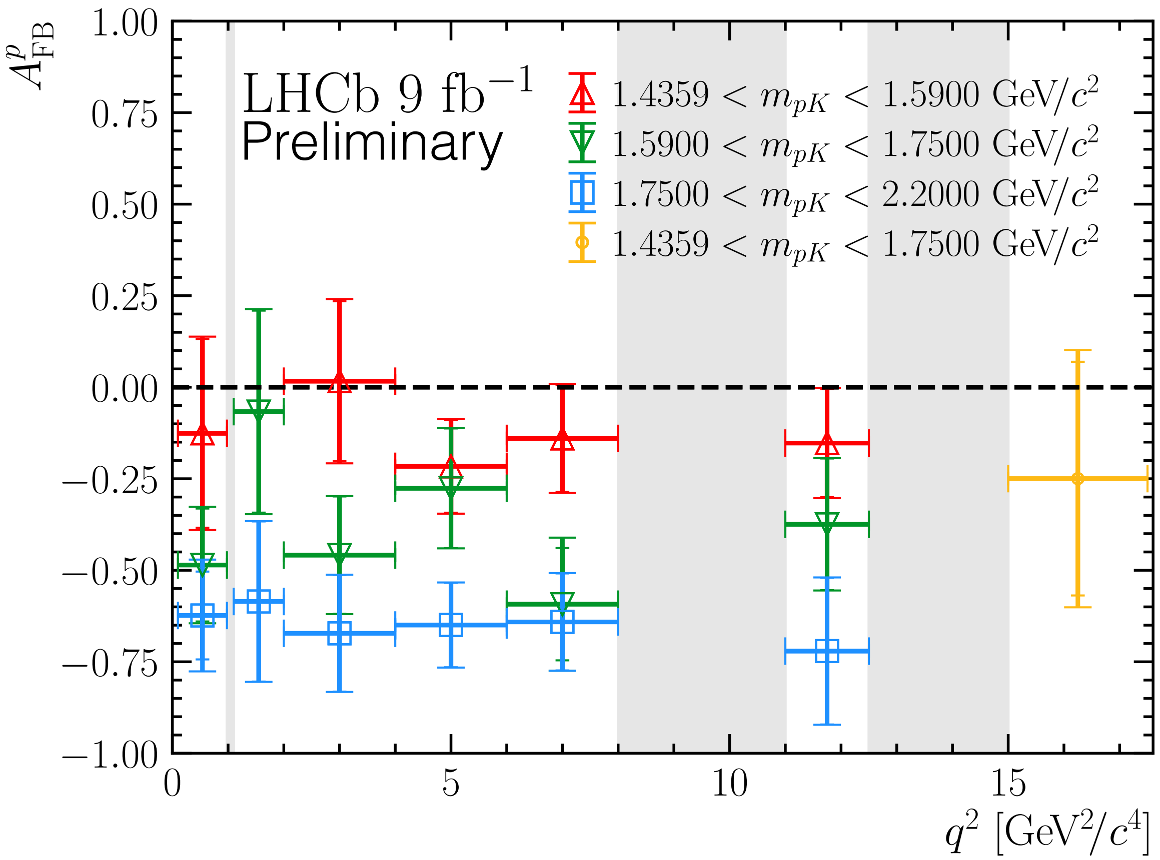
- Number of observables is too large to measure in using a maximum likelihood fit to the angular distribution (at least with existing data sets).
- Instead use the method-of-moments (e.g. **[PRD 91 (2015) 114012]**).
- Define a set of weighting functions that project out the observables:

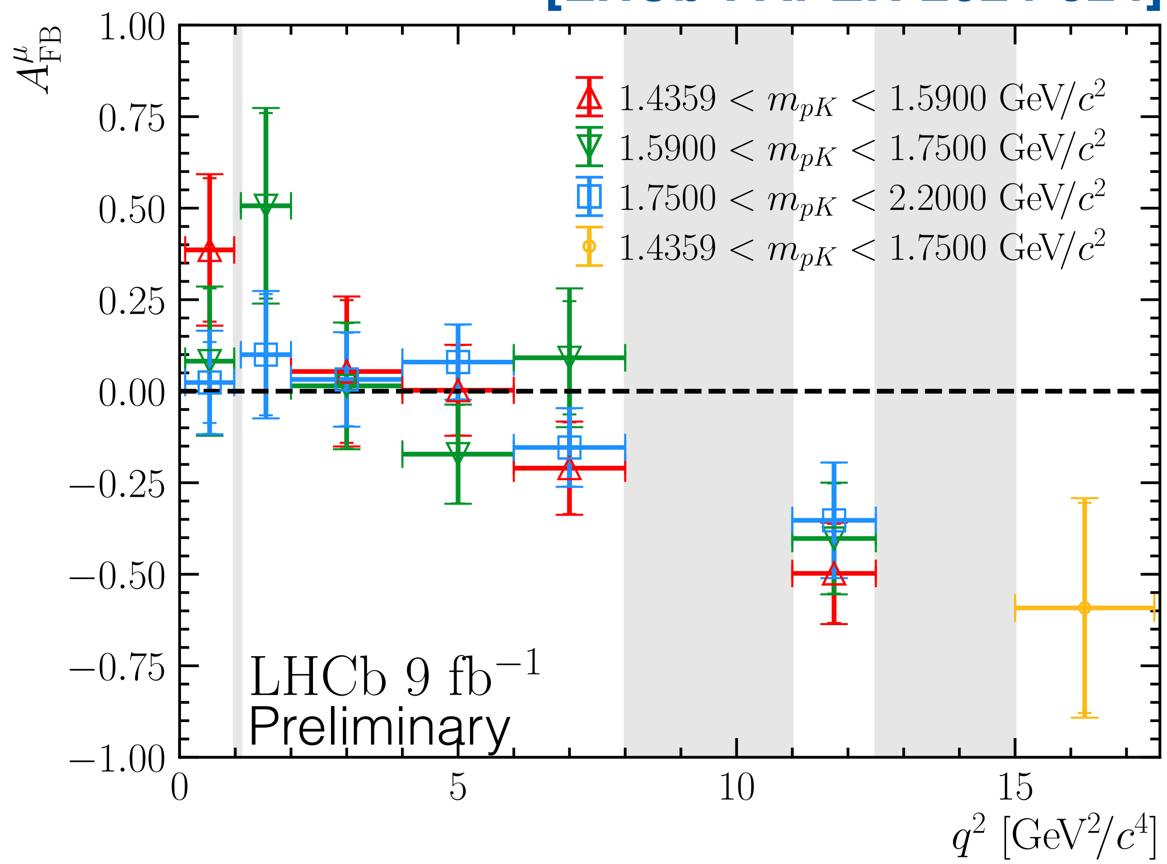
$$\int w_i(\vec{\Omega}) \frac{\mathrm{d}^7\Gamma}{\mathrm{d}q^2\,\mathrm{d}m_{pK}\,\mathrm{d}\vec{\Omega}} \mathrm{d}\vec{\Omega} = \frac{3}{32\pi^2} \int w_i(\vec{\Omega}) \sum_j K_j(m_{pK}, q^2) f_j(\vec{\Omega}) \mathrm{d}\vec{\Omega} = K_i(m_{pK}, q^2)$$

- Reduces analysis to a counting experiment:
  - ✓ Works with a finite data set even with an arbitrarily large number of observables.
  - x Less optimal in terms of precision than a maximum-likelihood estimate.

$\Lambda_b \to pK^-\mu^+\mu^-$ angular distribution

[LHCb-PAPER-2024-024]





Hadron-side asymmetry is due to interference between states.

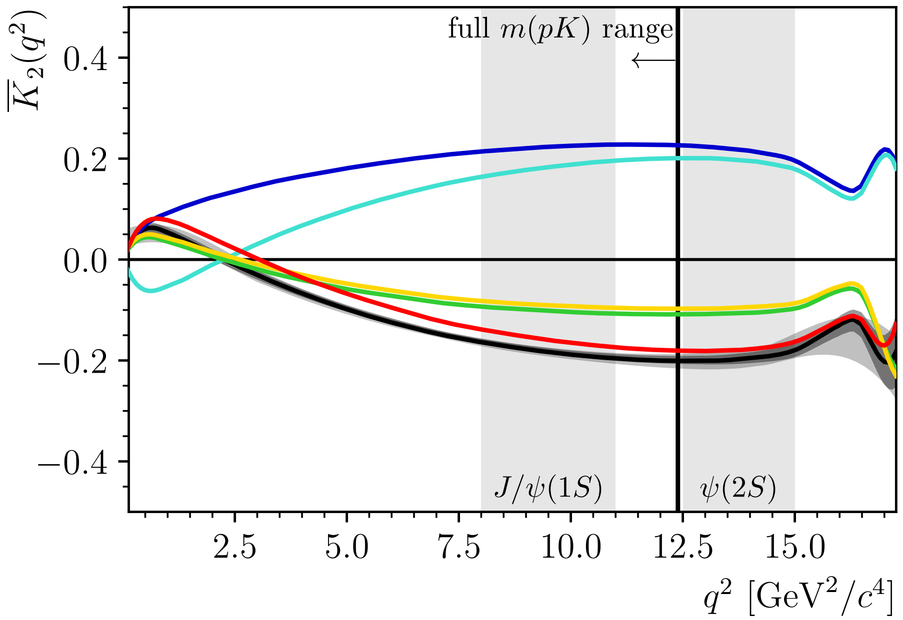
Lepton-side asymmetry with familiar zero-crossing.

$\Lambda_b \to pK^-\ell^+\ell^-$ predictions?

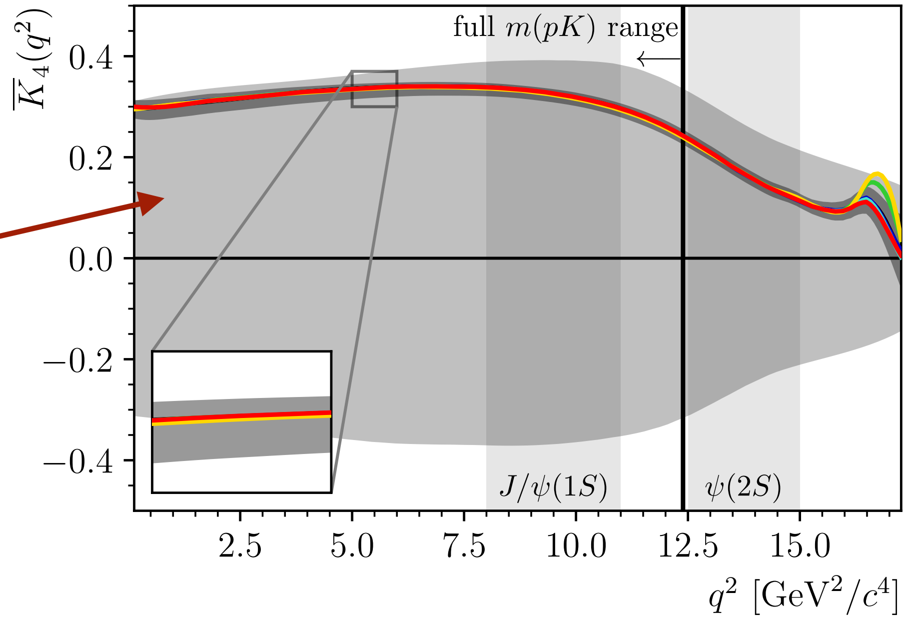
[JHEP 02 (2023) 189]

- Some observables appear more-or-less sensitive to the unknown properties of the hadronic systems.

- **Can we build observables to compensate for the lack of knowledge on the form-factors?**
  c.f. P_i' observables in $B^0 \to K^{*0}\mu^+\mu^-$



Large uncertainty associated to unknown strong phase differences between states



Differential branching fraction