Results and prospects on binned $b \to sll$ measurements from LHCb

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Outlook

- Binned $b \to sll$ observables: pheno vs experiment
- Branching fractions: status and new $\Lambda_b \to \Lambda^{1520}\mu^-\mu^+$ results
- Angular analyses: status and prospects on $B \to K^*\mu^-\mu^+$

Binned $b \longrightarrow sll$ observables

Phenomenology perspective

- **BR**: affected by hadronic uncertainties
- **Angular observables**: first-order form-factor cancellations
- **LFU**: full cancellations in the SM

Experimental perspective

- **BR**: simple extraction, good control of efficiencies through control modes
- **Angular observables**: need to control acceptance, many parameters require large yields
- **LFU**: need control of $e^{\pm}$ vs $\mu^{\pm}$ efficiencies - very challenging at hadron machines

Binned $b \longrightarrow sll$ observables

Phenomenology perspective

This talk

- **BR**: affected by hadronic uncertainties
- **Angular observables**: first-order form-factor cancellations

After lunch

- **LFU**: full cancellations in the SM

Experimental perspective

- **BR**: simple extraction, good control of efficiencies through control modes
- **Angular observables**: need to control acceptance, many parameters require large yields
- **LFU**: need control of $e^{\pm}$ vs $\mu^{\pm}$ efficiencies - very challenging at hadron machines

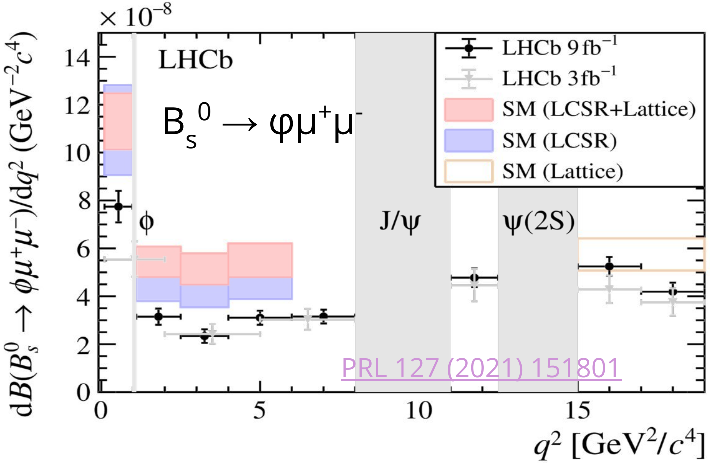
Branching fractions

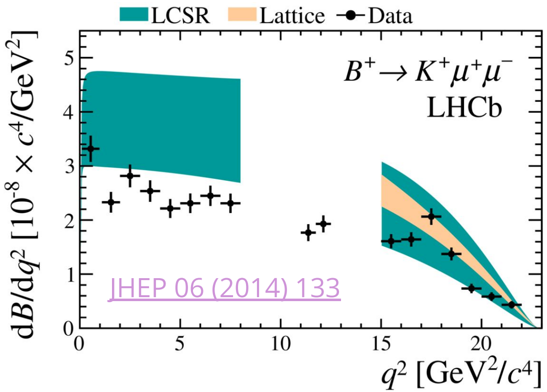
Status

Trend: systematically lower than SM

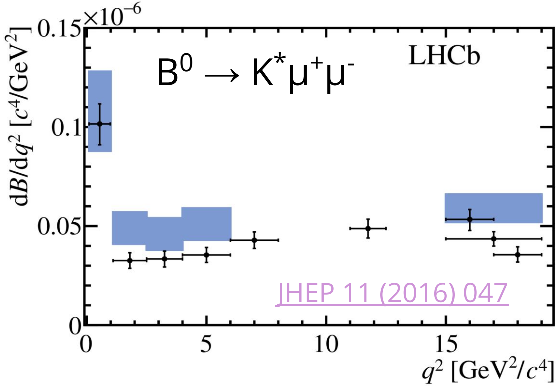
But SM has large uncertainties

Run 1+2





Run 1



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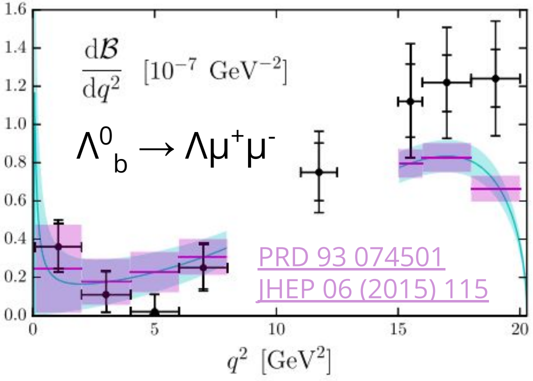


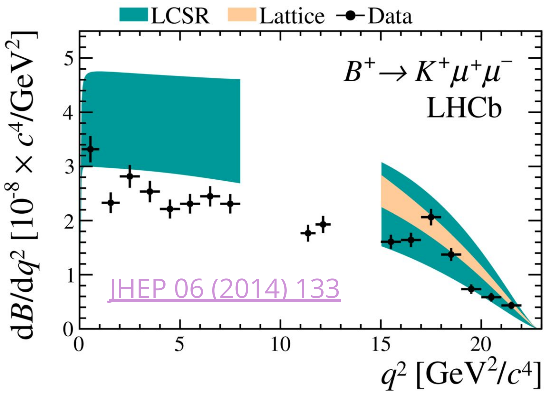
Run 1

Status

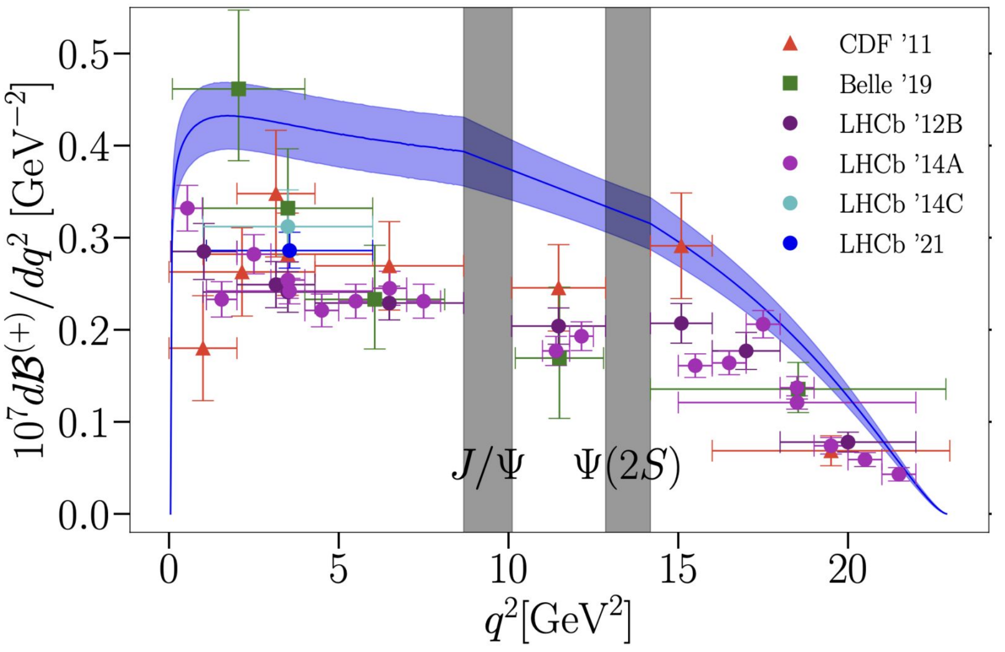
Trend: systematically lower than SM

Recent FF improvements!

NEW LQCD FF for B → K [Parrot, Buchard, Davis]
Talk by W. Parrot this afternoon



Run 1



b → sll with baryons

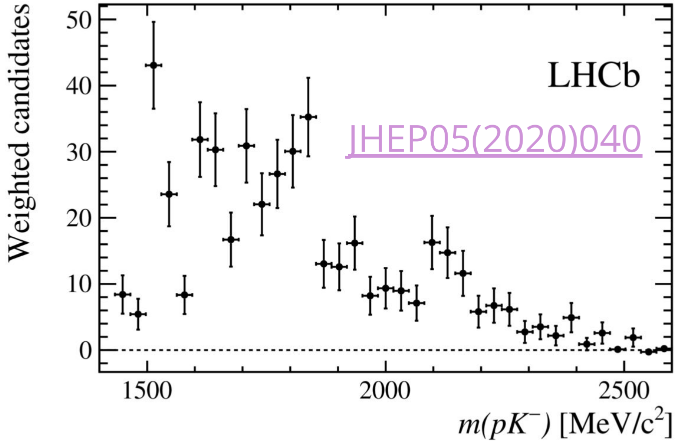
Baryons provide complementary sensitivity to NP due to **half-integer spin**

- $\Lambda^0_b \to \Lambda l^+l^-$: s = ½, experimentally challenging due to long Λ life-time
- $\Lambda^0_b \to pKl^+l^-$: experimentally easier but predictions complicated due to unknown proportions of many Λ^* contributions (with different spins)

$$\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)\big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} =$$

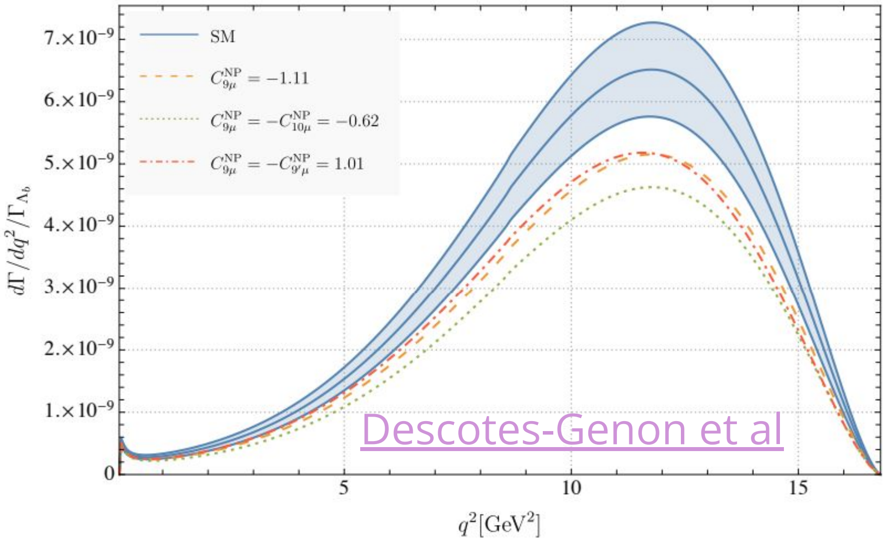
$$= \left(2.65 \pm 0.14 \pm 0.12 \pm 0.29\,^{+0.38}_{-0.23}\right) \times 10^{-7}$$

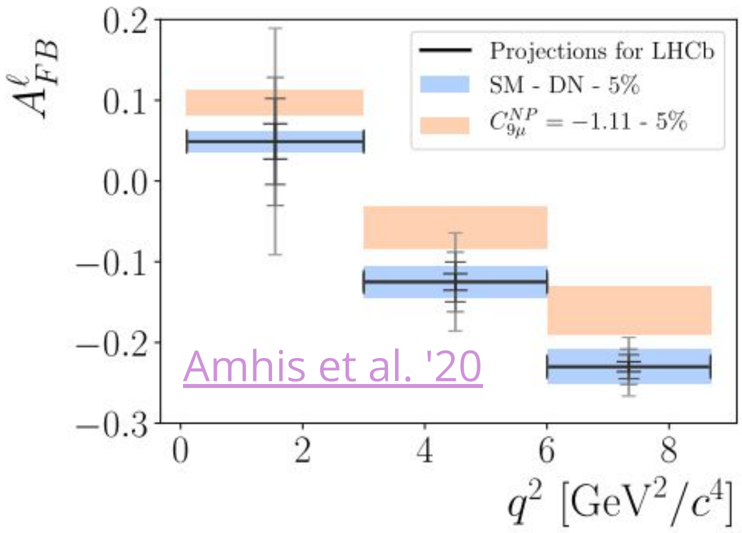
JHEP05(2020)040



$\Lambda_b \to \Lambda^{1520} l^+ l^-$

Idea: focus on dominant Λ^{1520} (s=3/2) contribution, with predictions available [Mott et al, Descotes-Genon et al, Li et al, Reboud et al, Meinel et al]





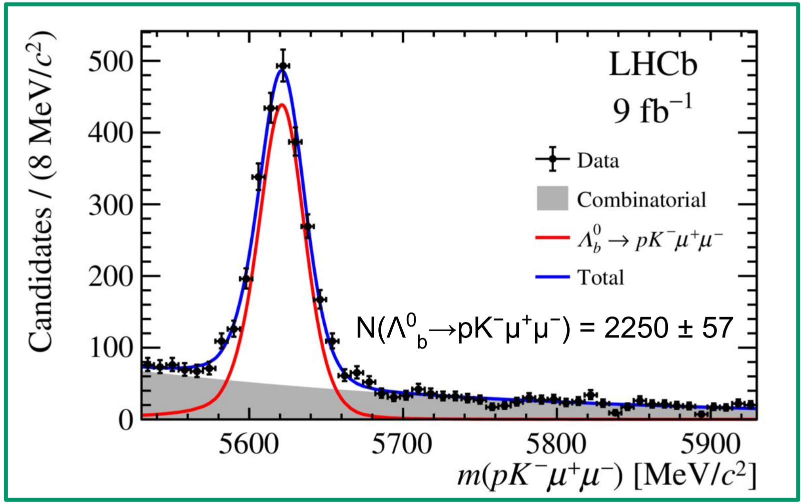
$\Lambda_b \rightarrow \Lambda^{1520}\mu^+\mu^-$: method

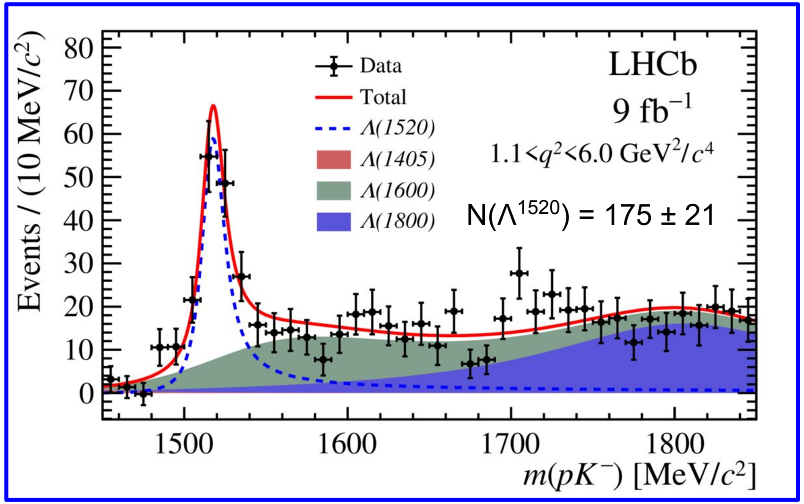
arXiv:2302.08262

LHCb Run 1+2

Challenge: experimentally disentangle other Λ^* contributions

⇒ Fit $m(pK\mu^+\mu^-)$ in q^2 bins + fit background subtracted $m(pK)$ distribution





*Angular analysis: also exploit different spin (½) of nearby resonances

$\Lambda_b \rightarrow \Lambda^{1520}\mu^+\mu^-$: results

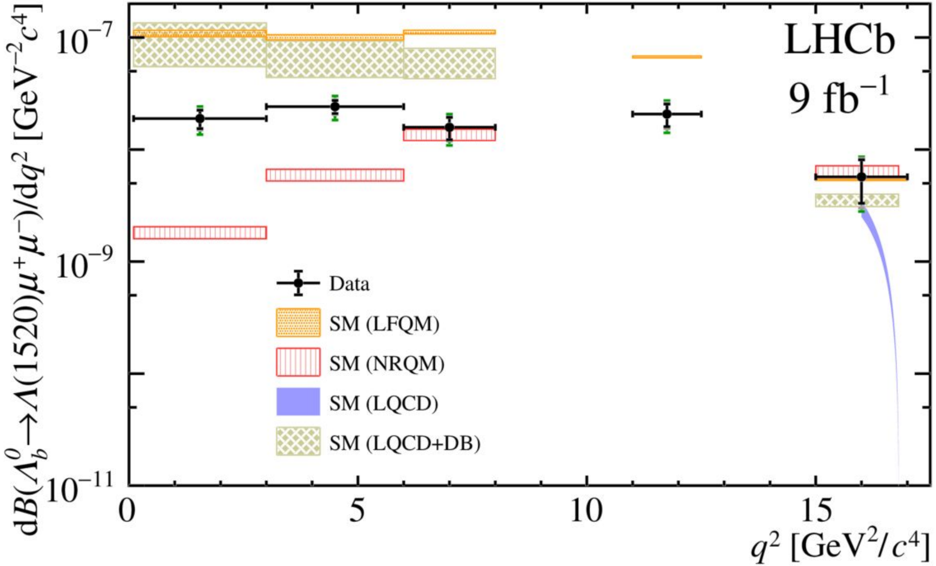
arXiv:2302.08262

LHCb Run 1+2

Measurement of BR in q^2 bins:

- compatible with SM at high q^2 (LQCD FF)
- large theory discrepancies at low q^2 → more work needed!

Measurement dominated by stat and BR($\Lambda_b \rightarrow pK^- J/\psi$) uncertainties

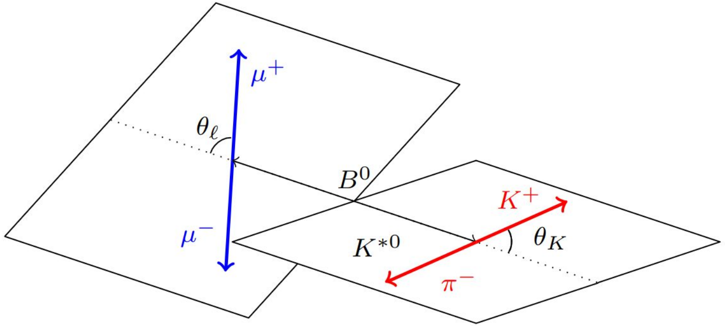


$$\left[\frac{d\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda(1520)\mu^+\mu^-)}{dq^2}\right]_{q^2_{\rm min}}^{q^2_{\rm max}} = \frac{1}{(q^2_{\rm max} - q^2_{\rm min})} \frac{\mathcal{B}(\Lambda_b^0 \rightarrow pK^- J/\psi)\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{\mathcal{B}(\Lambda(1520) \rightarrow pK^-)} \times \frac{N_{\Lambda(1520)\mu^+\mu^-}}{N_{pK^-J/\psi}} \frac{\varepsilon_{pK^-J/\psi}}{\varepsilon_{\Lambda(1520)\mu^+\mu^-}}$$

$dB/dq^2 = (1.95 \pm 0.23 \pm 0.16 \pm 0.37) \times 10^{-8}$ for $q^2 \in [1.1, 6.0]$ GeV^2

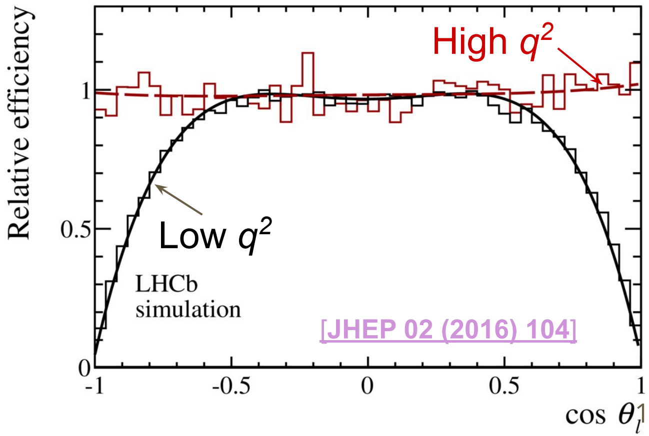
Angular analyses

Reminder: $B \longrightarrow V\ell\ell$



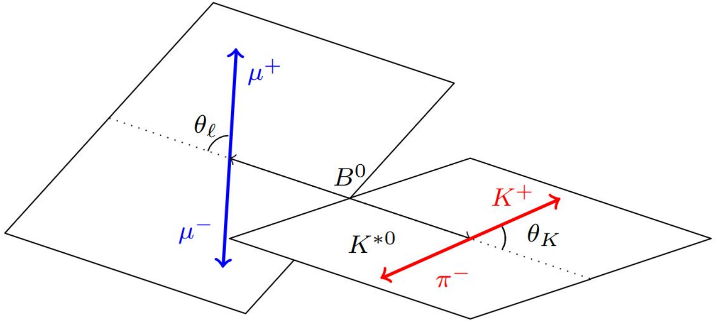
- Decay completely described by q^2, ϕ, θ_ℓ, θ_K
- 12 q^2 dependent observables are combinations of the 6 complex amplitudes
- May be contamination from *S*-wave decays into the same final state (i.e. $K\pi$)
  - A fit to $m(h_1h_2)$ can help constrain *S*-wave
- Detector acceptance and selection gives a non-flat efficiency in the angles and q^2 - must be dealt with in the analysis

$$\frac{d^5\Gamma_P}{dq^2\, dm^2_{K\pi}\, d\Omega} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + J_{2s}\sin^2\theta_K\cos 2\theta_\ell$$
$$+J_{2c}\cos^2\theta_K\cos 2\theta_\ell + J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + J_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+J_{6s}\sin^2\theta_K\cos\theta_\ell + J_{6c}\cos^2\theta_K\cos\theta_\ell$$
$$+J_7\sin 2\theta_K\sin\theta_\ell\sin\phi + J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big] \times |BW_P(m_{K\pi})|^2,$$



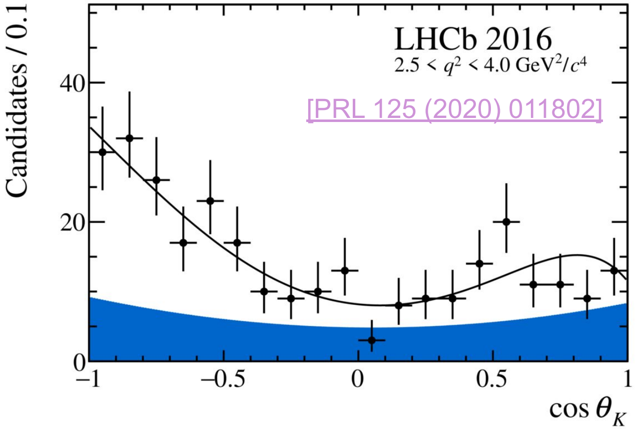
Reminder: $B \to V\ell\ell$

- Bin in q^2 and fit the angles
- Fit the rate averaged observables
  - *CP*-averaged observables S_i
  - *CP*-asymmetry observables A_i
- Integrated over the width of a q^2 bin
- Often make approximations



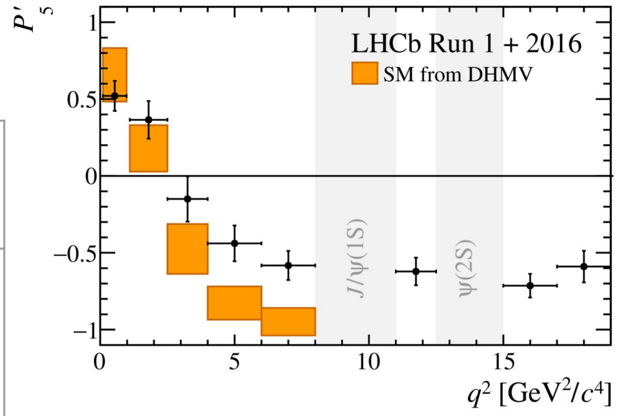
$$S_i^P = \frac{(J_i + \bar{J}_i)}{\left(\frac{\mathrm{d}\Gamma_P}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}_P}{\mathrm{d}q^2}\right)} \qquad A_i^P = \frac{(J_i - \bar{J}_i)}{\left(\frac{\mathrm{d}\Gamma_P}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}_P}{\mathrm{d}q^2}\right)}$$

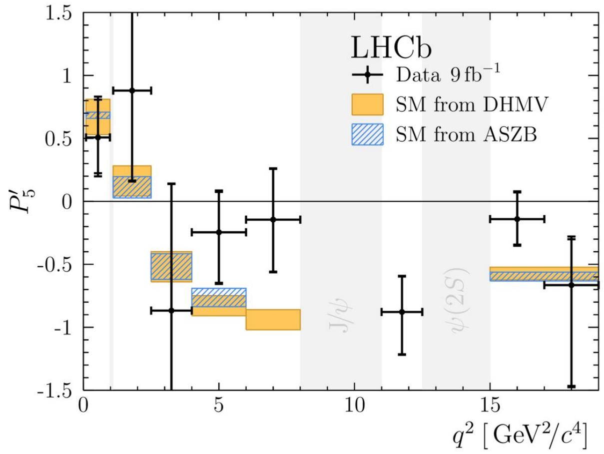
$$\begin{aligned}\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_\mathrm{P} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K \\ &+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\ &-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\ &+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\ &+\tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\ &+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]\end{aligned}$$



LHCb status

Mode	Status
$B^0 \to K^* \mu\mu$ [PRL 125 (2020) 011802]	2011-2016 - 8 q^2 bins (+ 2 wide), *CP*-averaged observables only (CP-asymmetries with 3fb^{-1}). Tension with SM.
$B^+ \to K^* \mu\mu$ [PRL 126 (2021) 161802]	9fb^{-1} *CP*-averaged only, folded fits. Local tensions with SM, similar to $B^0 \to K^* \mu\mu$
$B \to K \mu\mu$ [JHEP 05 (2014) 082]	3fb^{-1} - 17 bins for B^+, 5 for B^0. A_{FB} and F_H SM-like
$\Lambda_b \to \Lambda\mu\mu$ [JHEP 09 (2018) 146]	2011-2016 - Moments analysis for 34 observables - no *CPV*. Only high q^2. Consistent with SM
$B_s \to \varphi\mu\mu$ [JHEP 11 (2021) 043]	9fb^{-1} - 6 q^2 bins. Untagged B_s. SM-like





Binned angular fits - why and why not?

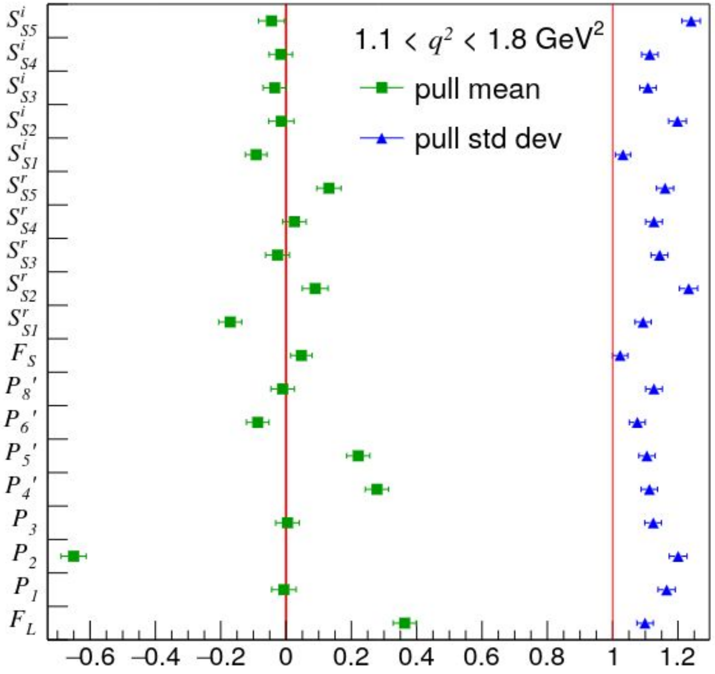
- Model independent
  - Results may be re-interpreted at any future point
  - Results from different places (i.e. Belle II and LHCb), or with new data sets (LHCb and LHCb upgrade), may be readily combined
- "Easy" to fit
  - The angular observables are mostly uncorrelated
  - Moments analysis if short on data

- Does not fully exploit the data
  - Will give less precision on the WCs than an unbinned fit in q^2
- Redundant parameters
  - Lose some experimental precision due to unnecessary correlations

Issue - statistics

- Small statistics
    - Fits can be unstable, biased, give poor coverage
    - "Optimised observables" a particular issue - large correlations with S_{2s}
    - PDF not necessarily "physical" - causes issues for the minimiser

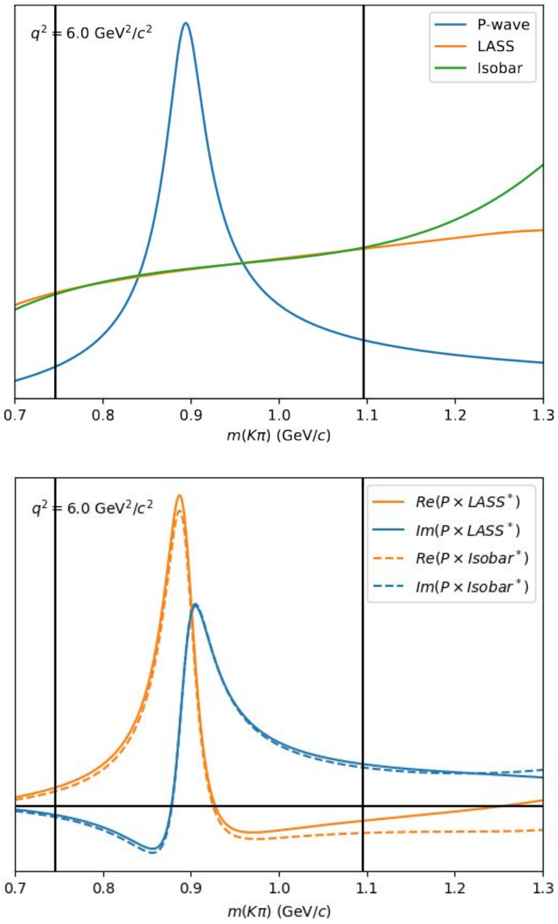
$$P_2 = \frac{S_{6s}}{8S_{2s}} \qquad P_5' = \frac{S_5}{\sqrt{-S_{2s}S_{2c}}}$$



S-wave contamination

We fit *m(Kπ)* to help control the *S*-wave and interference

- Need a model for the *P*-wave in *m(Kπ)*
    - Relativistic BW probably suffices
        - how big is a *K** - (3.0 ± 0.5) GeV^{-1}?
- Need a model for the *S*-wave in *m(Kπ)*
    - LASS parametrisation is common. Could also use an isobar model.
    - What parameters to use?



From Alex Marshall

$B^0 \to K^*\mu\mu$ - what more can we do?

- Massive leptons
  - Some extra fit parameters
- Scalar amplitudes
  - Some extra fit parameters

$J_{1c} \neq J_{2c}$, $3J_{2s} \neq J_{1s}$

$J_{6c} \neq 0$ for massive leptons

$J_{1c} \neq -J_{2c}$

$$
\begin{aligned}
\frac{d^5\Gamma_P}{dq^2\, dm^2_{K\pi}\, d\Omega} = \frac{9}{32\pi} \Big[& J_{1s} \sin^2\theta_K + J_{1c} \cos^2\theta_K + J_{2s} \sin^2\theta_K \cos 2\theta_\ell \\
& + J_{2c} \cos^2\theta_K \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi \\
& + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi \\
& + J_{6s} \sin^2\theta_K \cos\theta_\ell + J_{6c} \cos^2\theta_K \cos\theta_\ell \\
& + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi \\
& + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big] \times |BW_P(m_{K\pi})|^2,
\end{aligned}
$$

[Alguero et al (2021)]

Symmetry relations

More angular observables (25) than amplitudes (18)

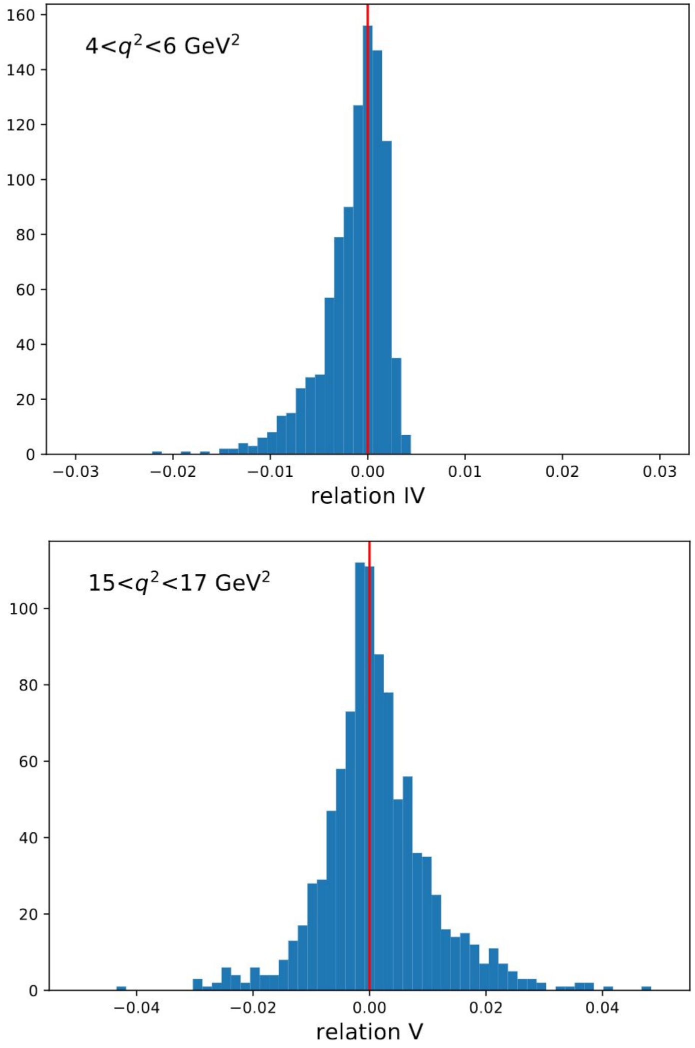
- Observables are not independent
  - You can write down relations between them
- We cannot reduce the degrees of freedom in the fit
  - Each observable is an independent, approximately orthogonal angular coefficient

IV. From the equality of the modulus of both vectors n_S and n'_S one obtains

$$|n'_S|^2 = |n_S|^2 = a'_S(n'^{\dagger}_S n_{\|}) + b'_S(n'^{\dagger}_S n_{\perp})\,, \tag{3.22}$$

which implies the following relation:

$$0 = +\frac{27}{16}\beta^2 F_S(16J_{2s}^2 - 4J_3^2 - \beta^2 J_{6s}^2 - 4J_9^2) - 2\Gamma'[-2(\beta^2 J_{6s}S^i_{S2}S^i_{S3} - \beta^2 J_9 S^i_{S3}S^r_{S4} + 4J_9 S^i_{S2}S^r_{S5} + \beta^2 J_{6s}S^r_{S4}S^r_{S5}) + 4S^{i\,2}_{S2}(J_3 + 2J_{2s}) + \beta^2 S^{i\,2}_{S3}(2J_{2s} - J_3) + \beta^2 S^{r\,2}_{S4}(J_3 + 2J_{2s}) + 4S^{r\,2}_{S5}(2J_{2s} - J_3)]. \tag{3.23}$$



All *CP*-asymmetries

- Simultaneous fit of B and $\overline{\text{B}}$ to extract CP-asymmetry observables
- To measure all the angular *CP*-asymmetries you need an extended fit
    - You must constrain A_{CP}

$$1 = \frac{3}{4}(2S_{1s} + S_{1c}) - \frac{1}{4}(2S_{2s} + S_{2c}) \qquad \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = A_{CP} = \frac{9}{16}\left[\frac{4}{3}A_{1s} + \frac{2}{3}A_{1c} - \frac{8}{9}A_{2s} - \frac{4}{9}A_{2c}\right]$$

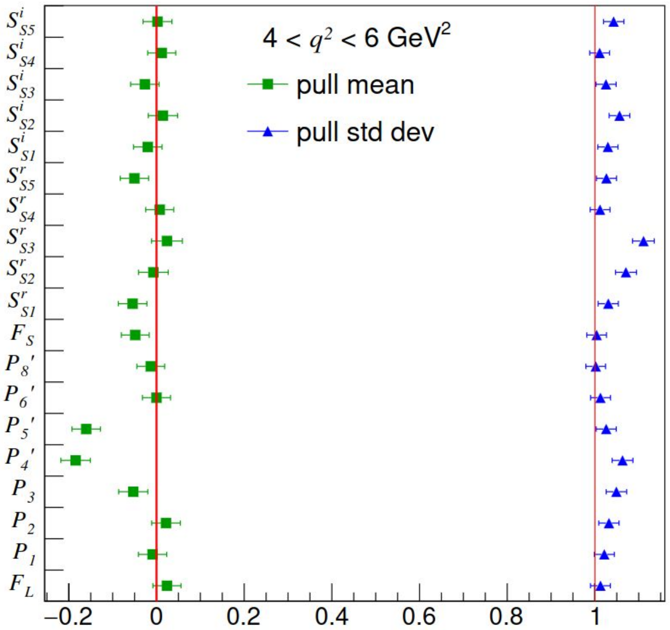
- Could fit for the branching fraction relative to J/$\psi K\pi$
    - Cancel most nuisance asymmetries
    - Integrate the efficiency over the fitted angular distribution
    - Model independent measurement of the branching fraction and A_{CP}

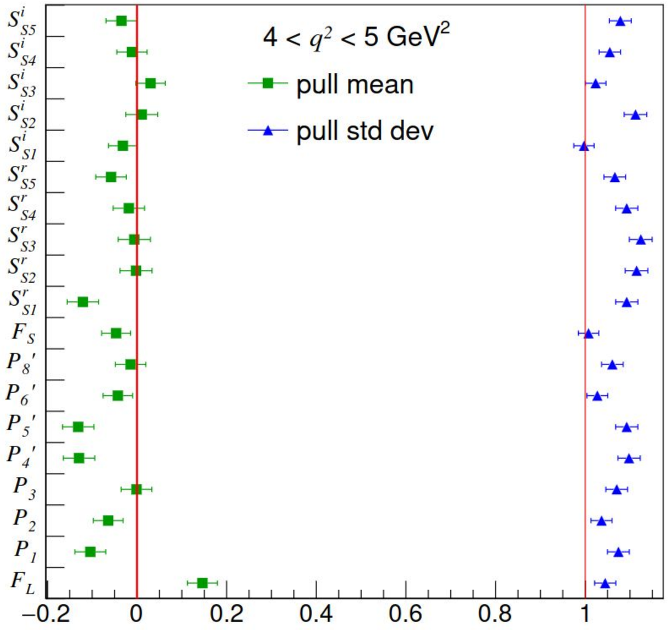
$$N_{sig} = N_{J/\psi} \times \frac{\int \Gamma_{sig}(\Omega m_{K\pi}) \cdot \epsilon_{sig}(\Omega, m_{K\pi})\mathrm{d}\Omega\mathrm{d}m_{K\pi}}{\int \Gamma_{J/\psi}(\Omega m_{K\pi}) \cdot \epsilon_{J/\psi}(\Omega, m_{K\pi})\mathrm{d}\Omega\mathrm{d}m_{K\pi}} \times \frac{\mathcal{B}(B^0 \to K^- \pi \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^- \pi^+ J/\psi)}$$

[Alguero et al (2021)]

More bins

- With more statistics we can fit more bins of q^2
  - Better resolution of the q^2 dependence of the observables
  - Will still likely need to provide a confidence interval with the Feldman-Cousins method





Conclusions

Binned measurements still a powerful tool to test SM predictions in $b \rightarrow sll$

- long standing BR discrepancies:
    - looking forward to new FF and pheno calculations
    - experimental results can “easily” improve as more data is available
    - $\Lambda_b \rightarrow \Lambda^{1520} l^+ l^-$ enables comparison to pheno predictions but work needed on this front

- long standing angular discrepancies:
    - New results in progress, with some new features
    - Still a place for binned analyses

Stay tuned!

BACK-UP

$\Lambda_b \longrightarrow \Lambda^{1520} l^+ l^-$

Table 2: Signal yields and the absolute differential branching fraction, in bins of q^2, for the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay. The first uncertainty is statistical, the second systematic, and the third due to the uncertainty on the $\Lambda_b^0 \to pK^- J/\psi$ and $J/\psi \to \mu^+\mu^-$ branching fractions.

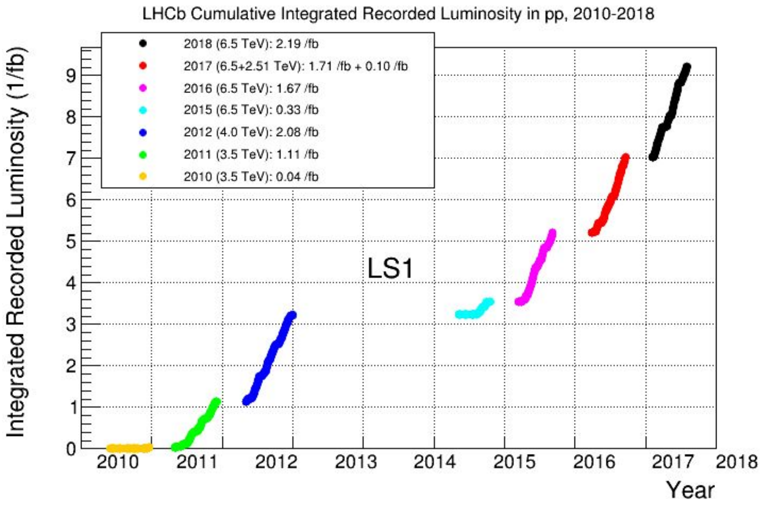
q^2 interval $[\mathrm{GeV}^2/c^4]$	$N_{\Lambda(1520)\mu^+\mu^-}$	$\frac{d\mathcal{B}(\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-)}{dq^2}$ $[10^{-8}\,\mathrm{GeV}^{-2}c^4]$
0.1–3.0	96 ± 18	$1.89 \pm 0.35 \pm 0.19 \pm 0.36$
3.0–6.0	138 ± 18	$2.42 \pm 0.32 \pm 0.17 \pm 0.45$
6.0–8.0	65 ± 14	$1.58 \pm 0.36 \pm 0.16 \pm 0.30$
11.0–12.5	59 ± 14	$2.07 \pm 0.47 \pm 0.26 \pm 0.39$
15.0–17.0	12 ± 5	$0.57 \pm 0.24 \pm 0.13 \pm 0.11$
1.1–6.0	175 ± 21	$1.95 \pm 0.23 \pm 0.16 \pm 0.37$

$\Lambda_b \rightarrow \Lambda^{1520} l^+ l^-$

Table 1: Relative systematic uncertainties [in %] of the differential branching fraction ratio measurement. The total uncertainty is obtained as the quadratic sum of the individual contributions.

Source	q^2 interval [GeV$^2/c^4$]					
	0.1–3.0	3.0–6.0	6.0–8.0	11.0–12.5	15.0–17.0	1.1–6.0
Signal fit model	9.6	6.5	9.3	9.3	15.3	7.2
Normalization fit model	1.3	1.3	1.3	1.3	1.3	1.3
Hardware trigger	0.3	0.5	0.2	0.1	0.1	0.3
PID	2.4	2.4	1.6	7.0	16.0	2.4
Simulation corrections	0.1	0.1	0.1	0.1	0.1	0.1
Decay model	1.7	2.6	4.8	4.0	5.4	0.9
Simulated sample size	0.2	0.2	0.2	0.3	0.5	0.1
$\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)/\mathcal{B}(\Lambda(1520) \rightarrow pK^-)$	2.3	2.3	2.3	2.3	2.3	2.3
Quadratic sum	10.4	7.9	10.9	12.6	22.9	8.1
$\mathcal{B}(\Lambda_b^0 \rightarrow pK^- J/\psi)$	18.8	18.8	18.8	18.8	18.8	18.8

LHCb dataset



All b-hadron species! [PRD100(2019)031102]

- B_s: $\frac{f_s}{f_d+f_u} = 0.122 \pm 0.006$
- Λ_b: $\frac{f_{\Lambda_b}}{f_d+f_u} = 0.259 \pm 0.018$

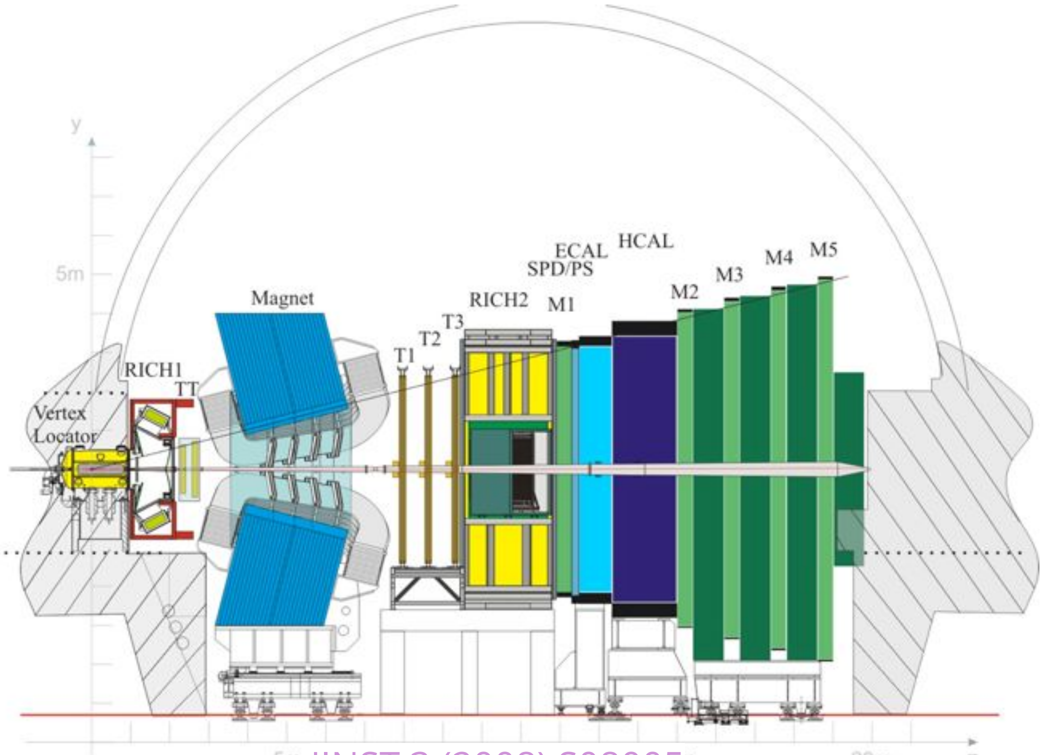
and more: Ξ_b, Ω_b, B_c, B^* ...

Total recorded luminosity ~9 fb^{-1}:

- Run 1 (2010-2012) ~ 3 fb^{-1}
- Run 2 (2015-2018) ~ 6 fb^{-1}

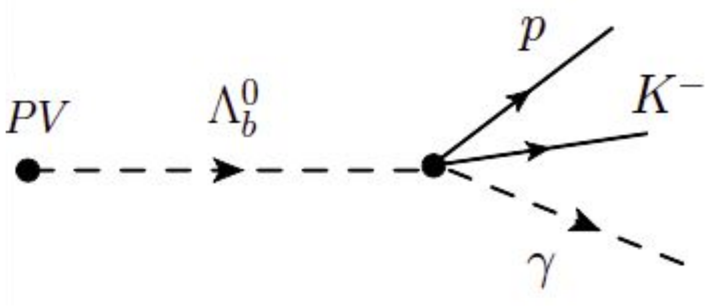
x2 b-quark production from 7 to 13 TeV pp collisions
→ around x4 b-hadrons in Run 2

Experimental setup



[JINST 3 (2008) S08005]

Typical decay signature

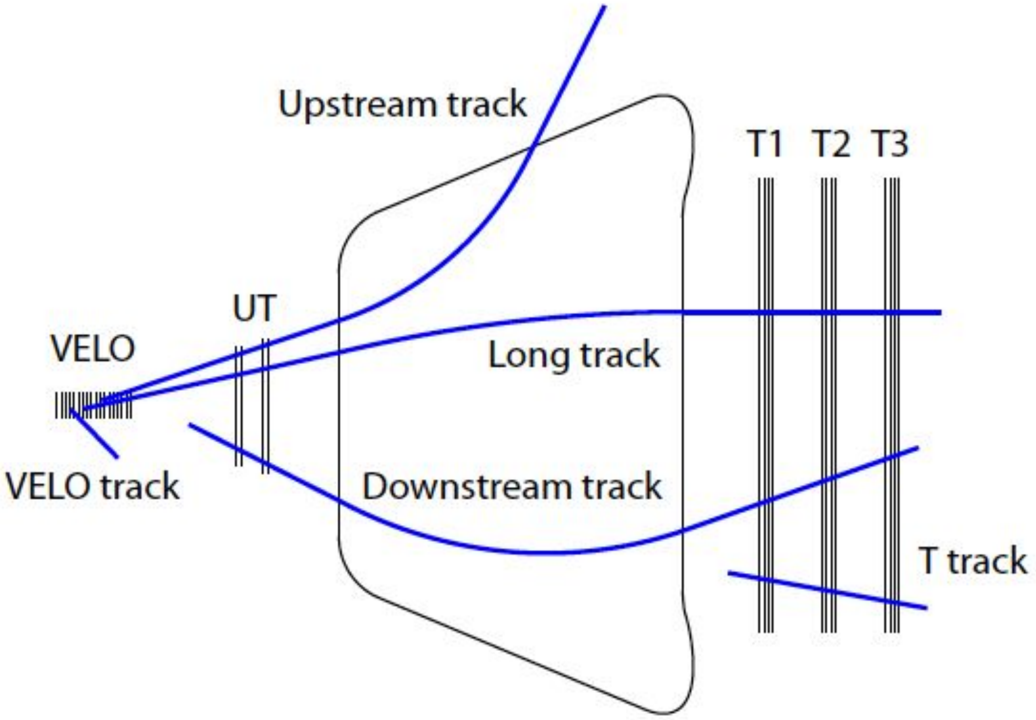


Tracking system

Reconstruct trajectories of charged particles

Identify pp and b-decay vertex

Measure particle momentum from bending in magnetic field



Run 2 performance:
$\Delta p / p = 0.5 - 1.0\%$
$\Delta IP = (15 + 29/p_T[\mathrm{GeV}])\ \mu m$