Review of results on $\Lambda_b \to \Lambda\mu^+\mu^-$ and $\Lambda_b \to J/\psi\Lambda$

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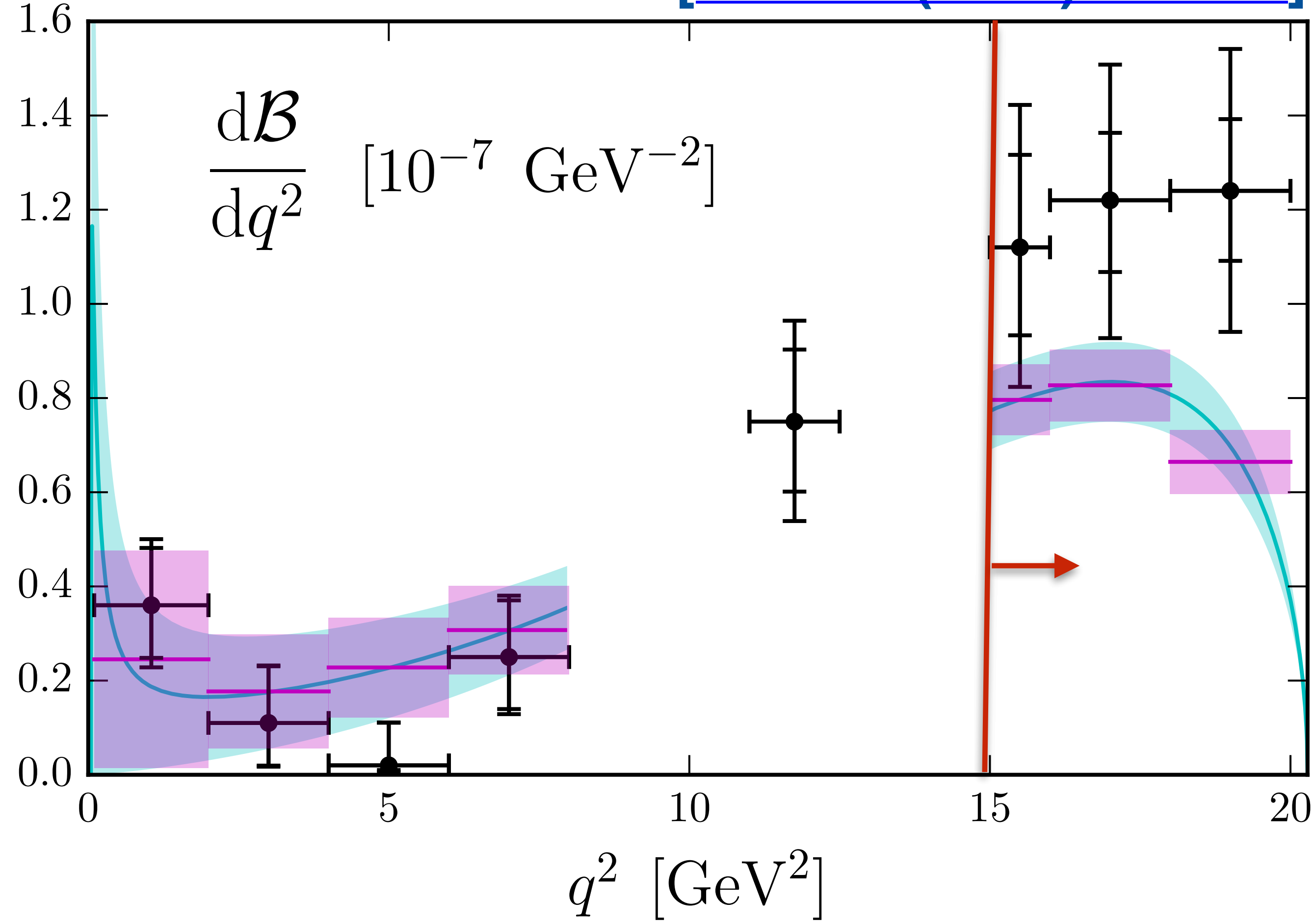
b-baryon Fest
5-6th of November 2020

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

- Qualitatively different situation to the *B* meson decay measurements:
  - Baryonic decay.
  - Λ_b can be polarised.
  - Λ decays weakly.
  - Signal is predominantly seen at large q^2.

Detmold et al. [PRD 93 (2016) 074501]



Data from LHCb
[JHEP 06 (2015) 115]
[Erratum: JHEP 09 (2018) 145]

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

- In the massless limit, the decay is described by 8 complex amplitudes:

Left-/right-handed chirality of dilepton system

$$A_{\perp_0}^{L(R)} = +\sqrt{2}N\sqrt{s_-}\frac{m_{\Lambda_b}+m_\Lambda}{\sqrt{q^2}}\left[C_{9,10,+}^{L(R)}\, f_0^V + \frac{2m_b(C_7+C_{7'})}{m_{\Lambda_b}+m_\Lambda} f_0^T + \left(\frac{4}{3}C_1+C_2\right) r_{\perp_0}\right]$$

$$A_{\parallel_0}^{L(R)} = -\sqrt{2}N\sqrt{s_+}\frac{m_{\Lambda_b}-m_\Lambda}{\sqrt{q^2}}\left[C_{9,10,-}^{L(R)}\, f_0^A + \frac{2m_b(C_7-C_{7'})}{m_{\Lambda_b}-m_\Lambda} f_0^{T5} + \left(\frac{4}{3}C_1+C_2\right) r_{\parallel_0}\right]$$

$$A_{\perp_1}^{L(R)} = -2N\sqrt{s_-}\left[C_{9,10,+}^{L(R)}\, f_\perp^V + \frac{2m_b(m_{\Lambda_b}+m_\Lambda)(C_7+C_{7'})}{q^2} f_\perp^T + \left(\frac{4}{3}C_1+C_2\right) r_{\perp_1}\right]$$

$$A_{\parallel_1}^{L(R)} = +2N\sqrt{s_+}\left[C_{9,10,+}^{L(R)}\, f_\perp^A + \frac{2m_b(m_{\Lambda_b}-m_\Lambda)(C_7-C_{7'})}{q^2} f_\perp^{T5} + \left(\frac{4}{3}C_1+C_2\right) r_{\parallel_1}\right]$$

Spin of dilepton system

Transversity basis (∥ corresponds to $\langle\Lambda|\bar{s}\gamma^\mu b|\Lambda_b\rangle$ and ⊥ to $\langle\Lambda|\bar{s}\gamma^\mu\gamma^5 b|\Lambda_b\rangle$)

see e.g. Böer et al. [JHEP 01 (2015) 155]

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

- In the massless limit, the decay is described by 8 complex amplitudes:

$$A_{\perp_0}^{L(R)} = +\sqrt{2}N\sqrt{s_-}\frac{m_{\Lambda_b}+m_\Lambda}{\sqrt{q^2}}\left[C_{9,10,+}^{L(R)}\, f_0^V + \frac{2m_b(C_7+C_{7'})}{m_{\Lambda_b}+m_\Lambda} f_0^T + \left(\frac{4}{3}C_1+C_2\right) r_{\perp_0}\right]$$

$$A_{\|_0}^{L(R)} = -\sqrt{2}N\sqrt{s_+}\frac{m_{\Lambda_b}-m_\Lambda}{\sqrt{q^2}}\left[C_{9,10,-}^{L(R)}\, f_0^A + \frac{2m_b(C_7-C_{7'})}{m_{\Lambda_b}-m_\Lambda} f_0^{T5} + \left(\frac{4}{3}C_1+C_2\right) r_{\|_0}\right]$$

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Short distance contributions

$$C_{9,10,\pm}^{\mathrm{L,R}} = (C_9 \mp C_{10}) \pm (C_9' \mp C_{10}')$$

see e.g. Böer et al. [JHEP 01 (2015) 155]

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

- In the massless limit, the decay is described by 8 complex amplitudes:

Form-factors from lattice
Detmold et al. [PRD 93 (2016) 074501]

$$A^{L(R)}_{\perp_0} = +\sqrt{2}N\sqrt{s_-}\frac{m_{\Lambda_b}+m_\Lambda}{\sqrt{q^2}}\left[C^{L(R)}_{9,10,+}f_0^V + \frac{2m_b(C_7+C_{7'})}{m_{\Lambda_b}+m_\Lambda}f_0^T + \left(\frac{4}{3}C_1+C_2\right)r_{\perp_0}\right]$$

$$A^{L(R)}_{\parallel_0} = -\sqrt{2}N\sqrt{s_+}\frac{m_{\Lambda_b}-m_\Lambda}{\sqrt{q^2}}\left[C^{L(R)}_{9,10,-}f_0^A + \frac{2m_b(C_7-C_{7'})}{m_{\Lambda_b}-m_\Lambda}f_0^{T5} + \left(\frac{4}{3}C_1+C_2\right)r_{\parallel_0}\right]$$

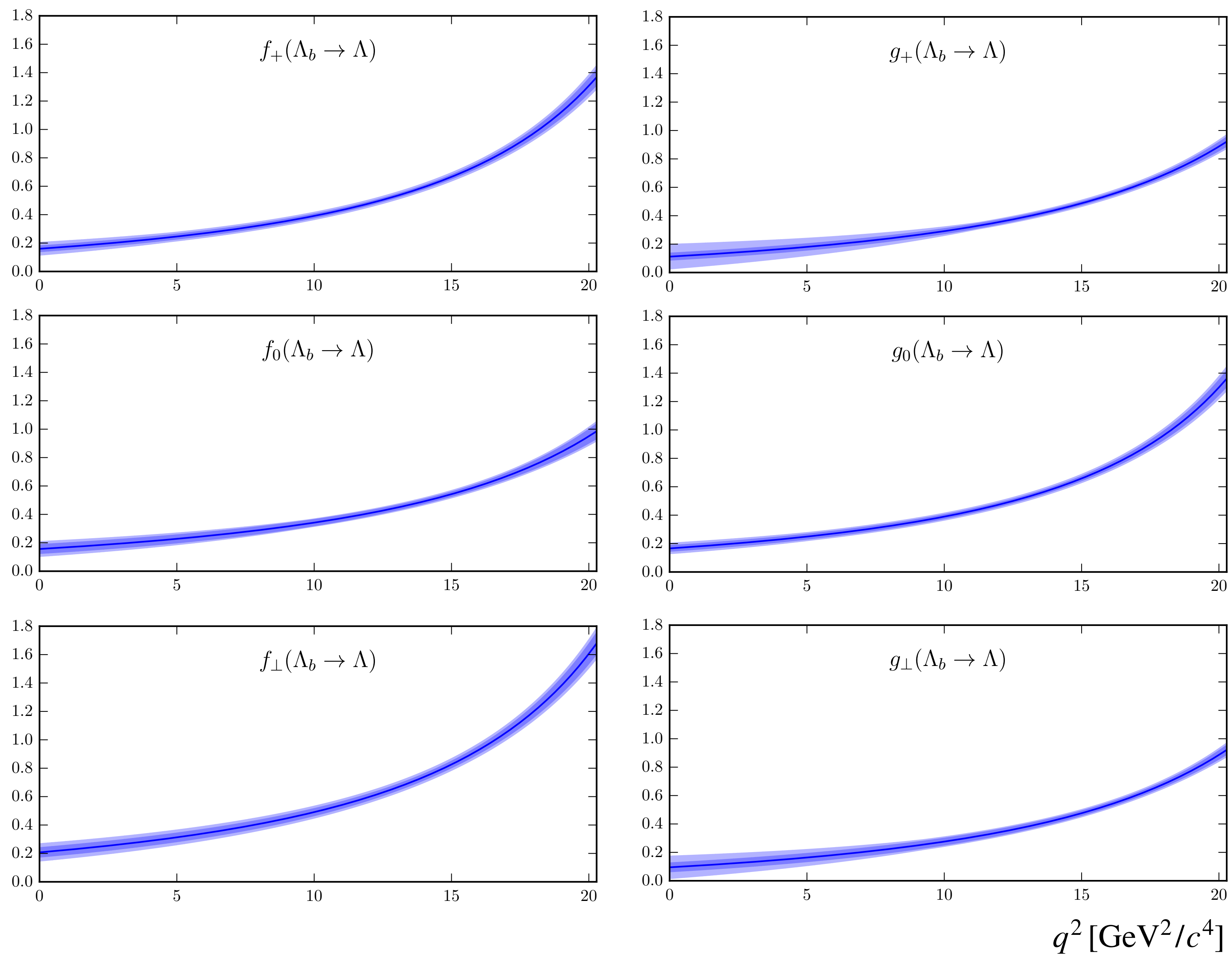
$$A^{L(R)}_{\perp_1} = -2N\sqrt{s_-}\left[C^{L(R)}_{9,10,+}f_\perp^V + \frac{2m_b(m_{\Lambda_b}+m_\Lambda)(C_7+C_{7'})}{q^2}f_\perp^T + \left(\frac{4}{3}C_1+C_2\right)r_{\perp_1}\right]$$

$$A^{L(R)}_{\parallel_1} = +2N\sqrt{s_+}\left[C^{L(R)}_{9,10,+}f_\perp^A + \frac{2m_b(m_{\Lambda_b}-m_\Lambda)(C_7-C_{7'})}{q^2}f_\perp^{T5} + \left(\frac{4}{3}C_1+C_2\right)r_{\parallel_1}\right]$$

see e.g. Böer et al. [JHEP 01 (2015) 155]

$\Lambda_b \to \Lambda$ form factors

- Form-factors are determined with impressive precision from the lattice. Detmold et al. **[PRD 93 (2016) 074501]**
- Extrapolated to full q^2 range using a z-expansion.



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

- In the massless limit, the decay is described by 8 complex amplitudes:

Power corrections

$$A_{\perp_0}^{L(R)} = +\sqrt{2}N\sqrt{s_-}\frac{m_{\Lambda_b}+m_\Lambda}{\sqrt{q^2}}\left[C_{9,10,+}^{L(R)}\, f_0^V + \frac{2m_b(C_7+C_{7'})}{m_{\Lambda_b}+m_\Lambda} f_0^T + \left(\frac{4}{3}C_1+C_2\right) r_{\perp_0}\right]$$

$$A_{\parallel_0}^{L(R)} = -\sqrt{2}N\sqrt{s_+}\frac{m_{\Lambda_b}-m_\Lambda}{\sqrt{q^2}}\left[C_{9,10,-}^{L(R)}\, f_0^A + \frac{2m_b(C_7-C_{7'})}{m_{\Lambda_b}-m_\Lambda} f_0^{T5} + \left(\frac{4}{3}C_1+C_2\right) r_{\parallel_0}\right]$$

$$A_{\perp_1}^{L(R)} = -2N\sqrt{s_-}\left[C_{9,10,+}^{L(R)}\, f_\perp^V + \frac{2m_b(m_{\Lambda_b}+m_\Lambda)(C_7+C_{7'})}{q^2} f_\perp^T + \left(\frac{4}{3}C_1+C_2\right) r_{\perp_1}\right]$$

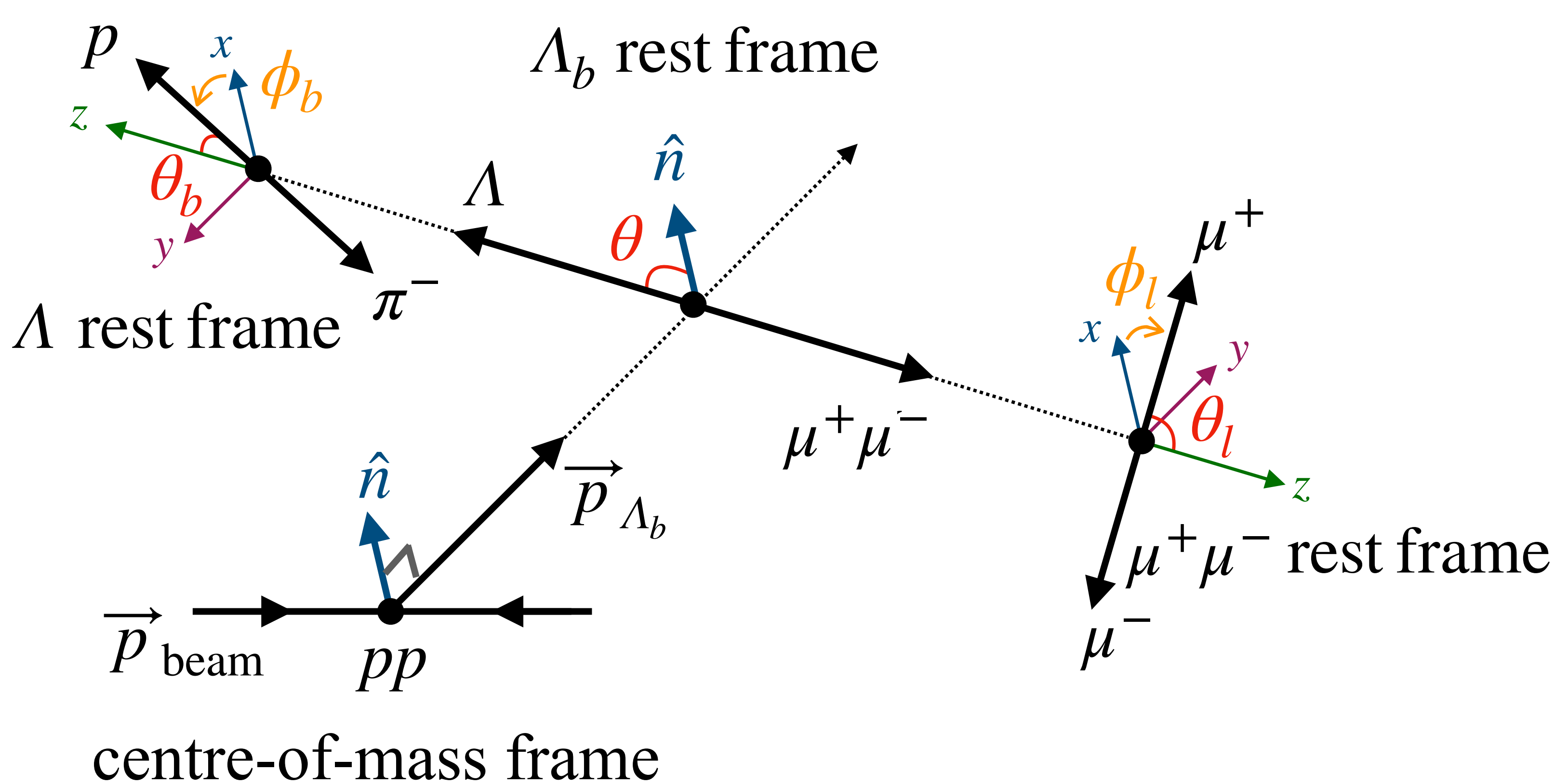
$$A_{\parallel_1}^{L(R)} = +2N\sqrt{s_+}\left[C_{9,10,+}^{L(R)}\, f_\perp^A + \frac{2m_b(m_{\Lambda_b}-m_\Lambda)(C_7-C_{7'})}{q^2} f_\perp^{T5} + \left(\frac{4}{3}C_1+C_2\right) r_{\parallel_1}\right]$$

Assume prior of 0.00 ± 0.03

see e.g. Böer et al. [JHEP 01 (2015) 155]

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

- In general can be parameterised by 5 angles:



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

- Unpolarised case:

Depend on products of transversely amplitudes

$$\frac{\mathrm{d}^4}{\mathrm{d}q^2\mathrm{d}\overrightarrow{\Omega}} = \frac{3}{8\pi}\sum_i K_i f_i(\cos\theta_b, \cos\theta_l, \phi)$$

Böer et al. [JHEP 01 (2015) 155]

- Depends on 3 decay angles ($\phi = \phi_l + \phi_b$).
- Ten observables.
- Observables also depend on the Λ asymmetry parameter Λ.

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

- Generalisation to the polarised case:

Depend on products of transversely amplitudes

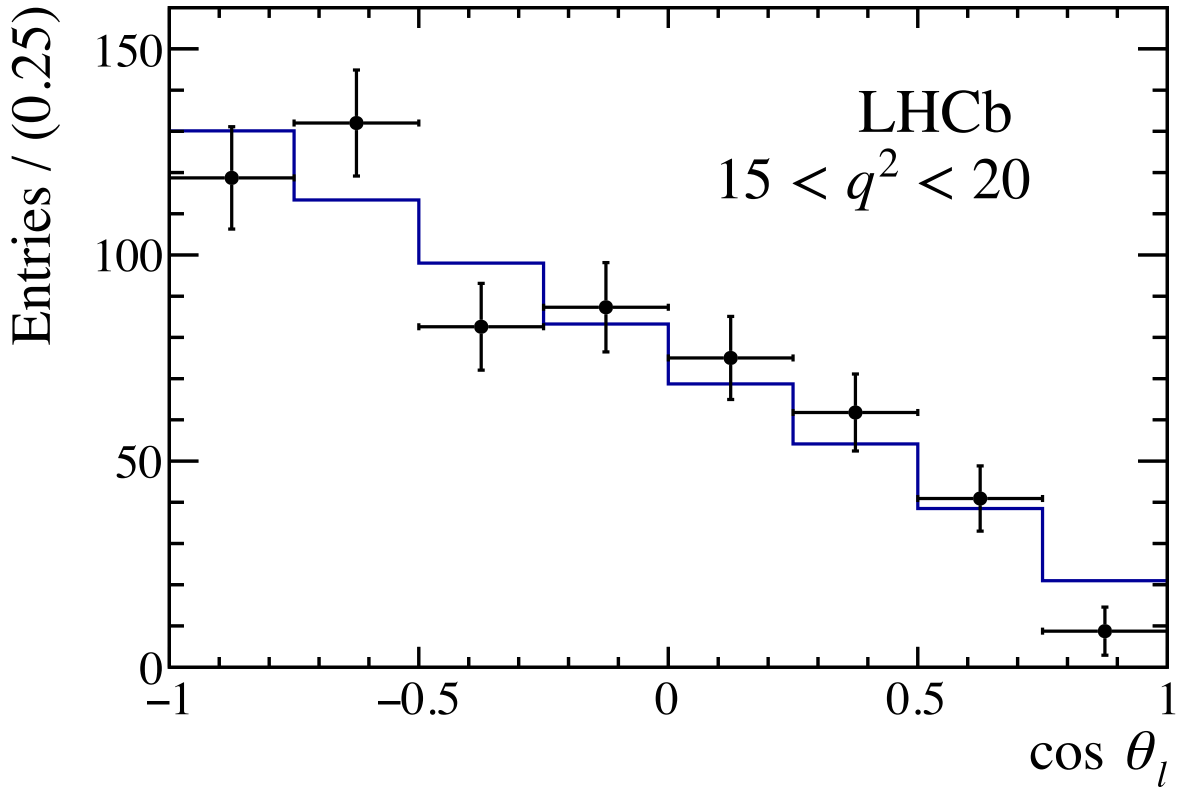
$$\frac{\mathrm{d}^6}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i K_i f_i(\cos\theta_b, \phi_b, \cos\theta_l, \phi_l, \cos\theta)$$

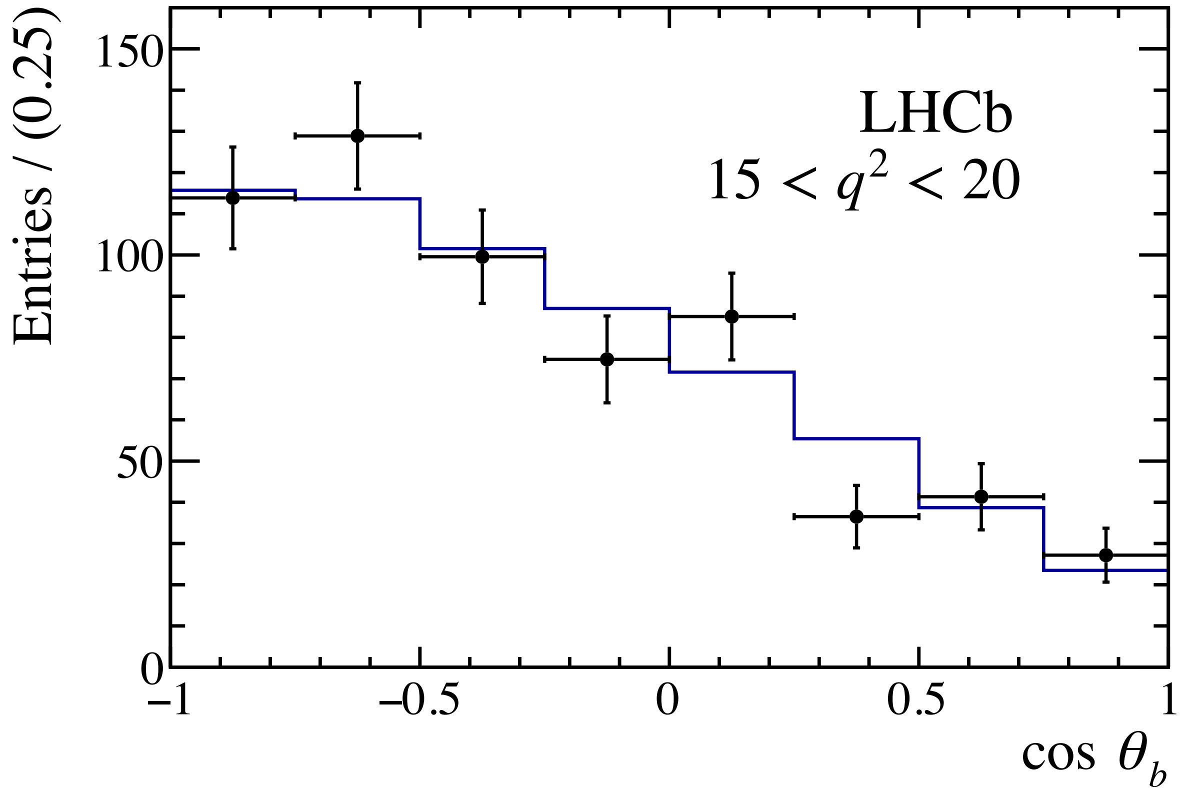
Blake et al. [JHEP 11 (2017) 138]

- Depends on 5 decay angles.
- 34 observables
(the 24 new observables are proportional to the polarisation).

Angular distribution

LHCb [JHEP 09 (2018) 146]





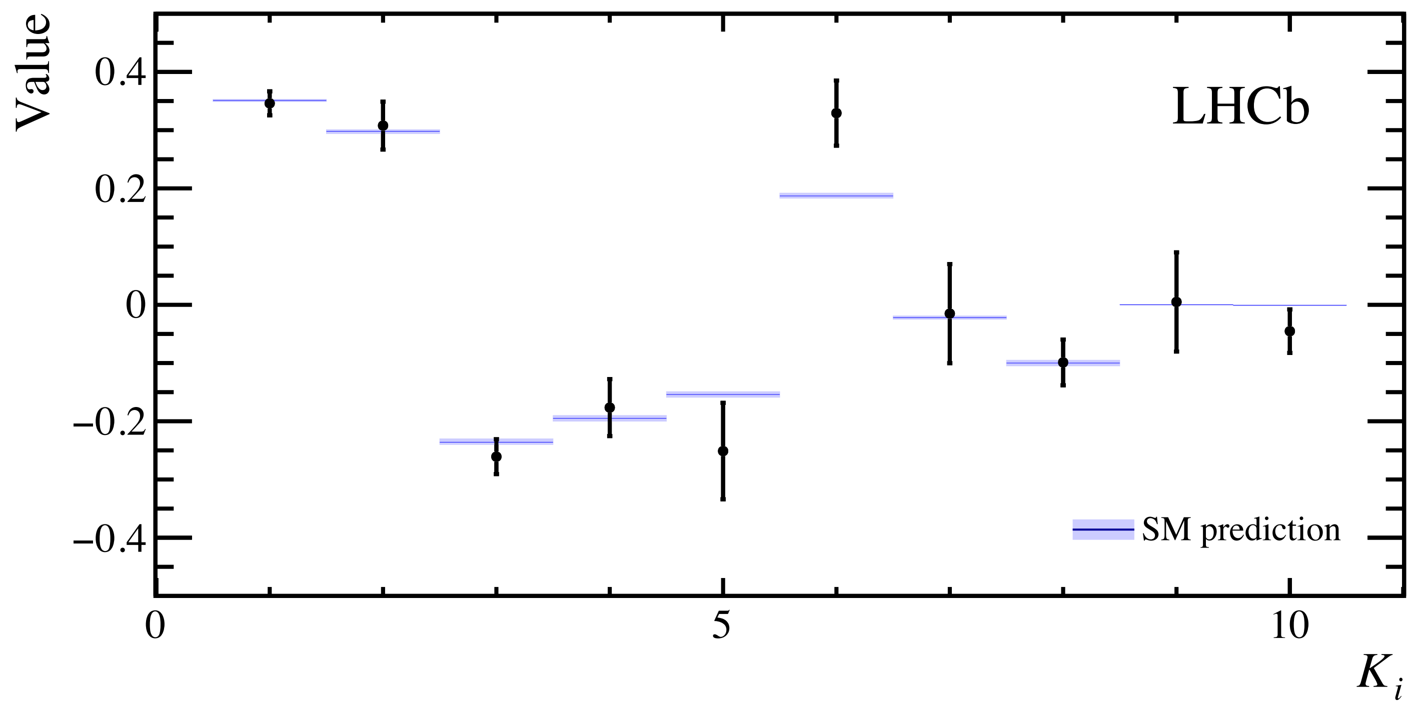
- Get large forward-backward asymmetries in $\cos\theta_l$ and in $\cos\theta_b$ (due to the weak decay of the Λ baryon):

$$A_{\rm FB}^{l} = -0.39 \pm 0.04 \pm 0.01$$
$$A_{\rm FB}^{b} = -0.30 \pm 0.05 \pm 0.02$$

Angular observables

- Determine observables using a moment analysis in $15 < q^2 < 20\,\mathrm{GeV}^2/c^4$
- Data are consistent with SM predictions and consistent with zero production polarisation.

LHCb [JHEP 09 (2018) 146]



Angular observables

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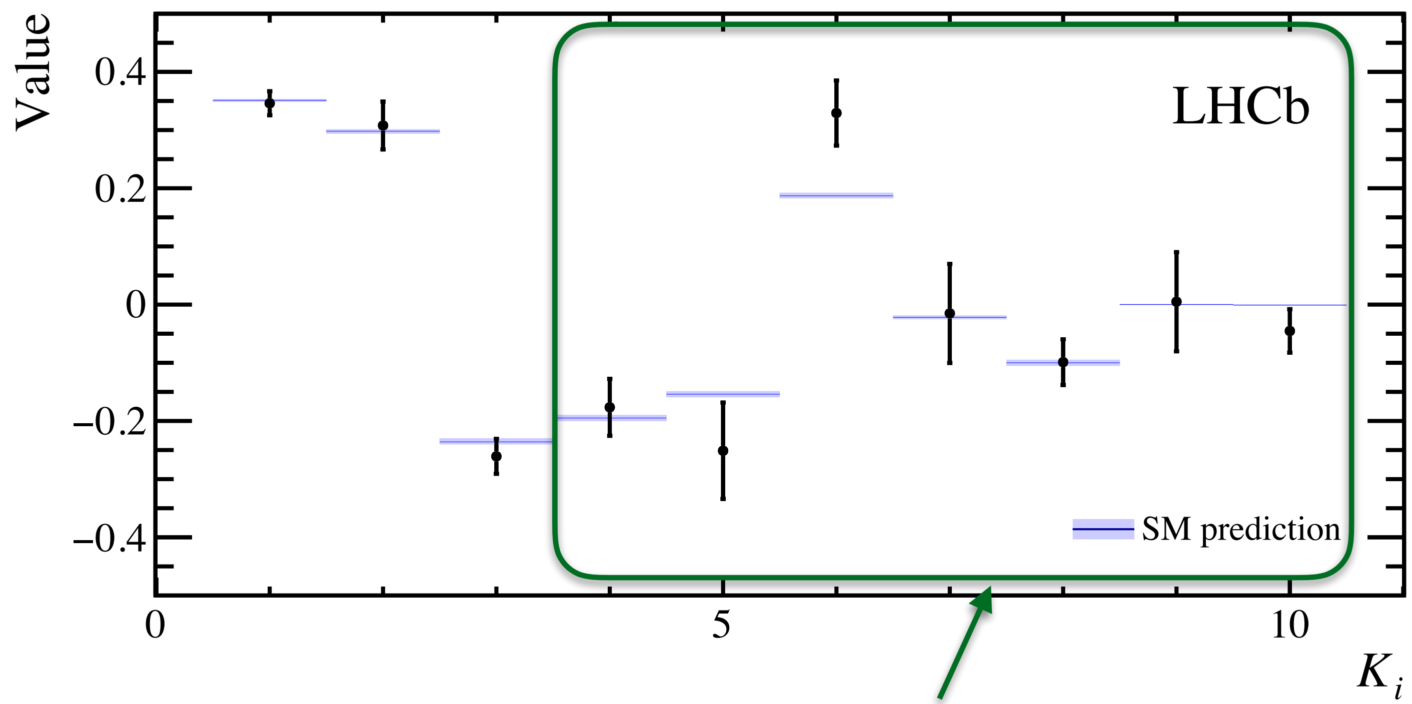
LHCb **[JHEP 09 (2018) 146]**



Note, SM predictions need to be updated to account for a change in the Λ asymmetry parameter from $\alpha_\Lambda = 0.642 \pm 0.013$ to $\alpha_\Lambda = 0.750 \pm 0.010$

c.f. BES III **[Nature Phys. 15 (2019) 631–634]**

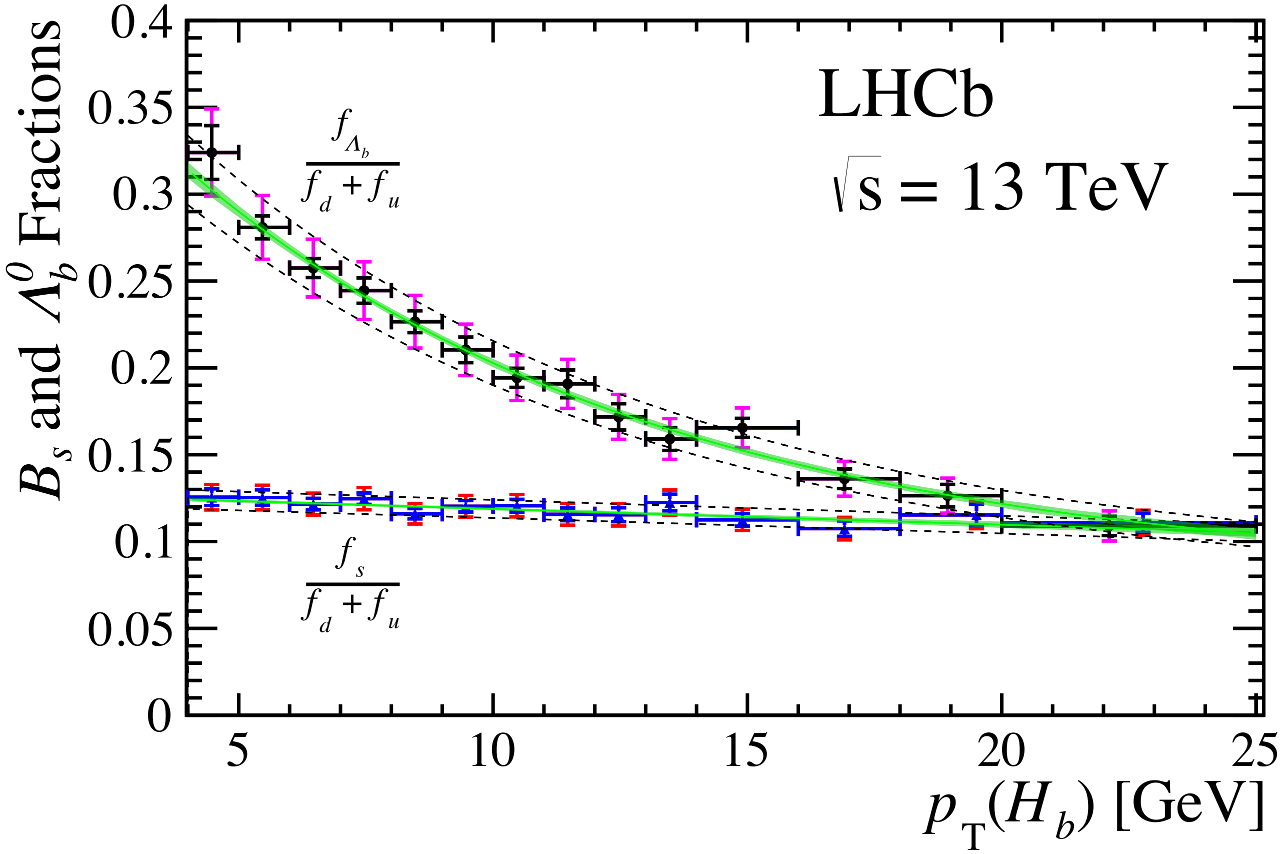
$\Lambda_b \to \Lambda\mu^+\mu^-$ branching fraction

- Existing branching fraction measurement uses CDF/D0 average 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 a strong p_T dependences in *pp* collisions.

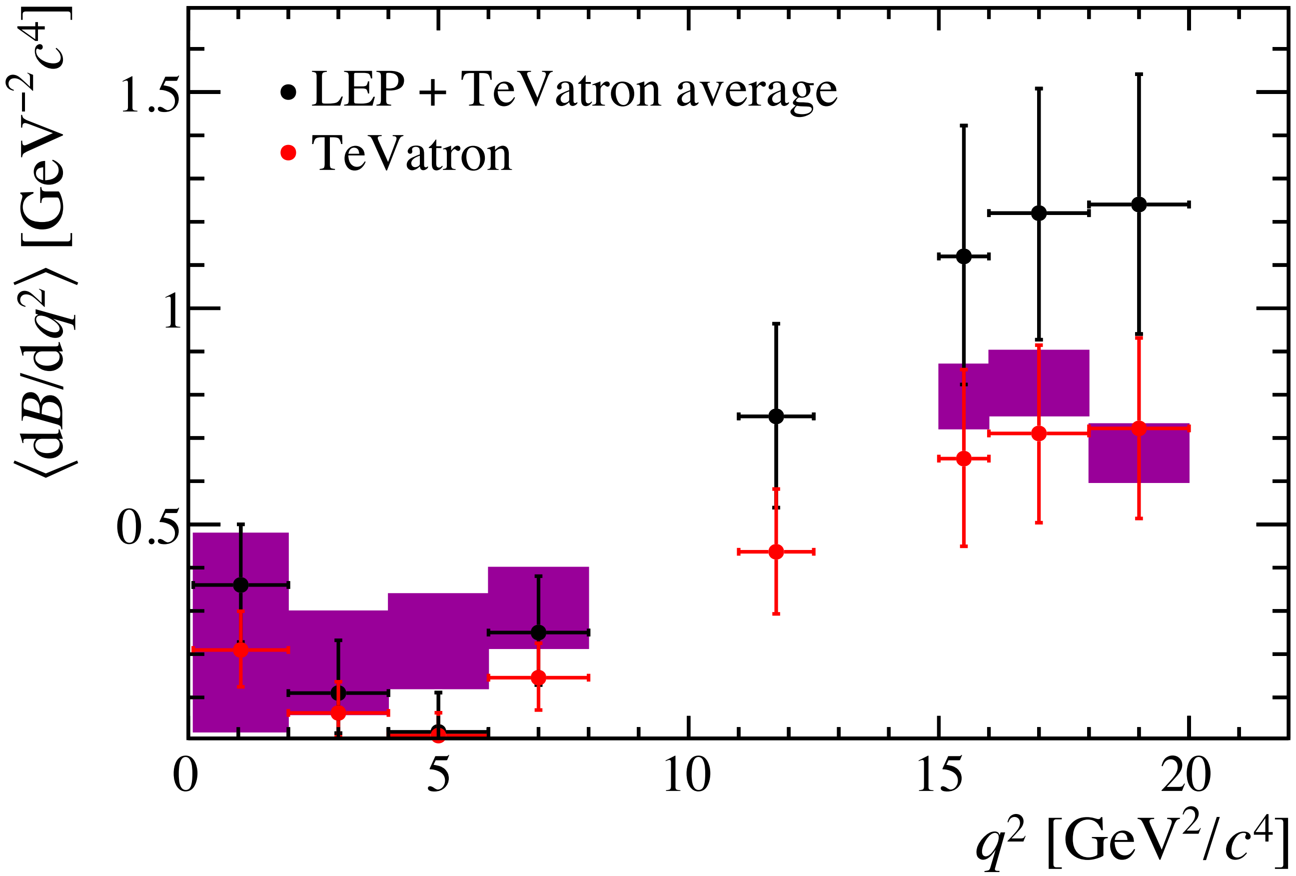
- Λ_b baryons are produced with lower average p_T at the TeVatron than LEP.

LHCb [PRD 100 (2019) 031102]



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

- Re-evaluating the branching fraction using only TeVatron inputs on $f(b \to \text{baryon})$ significantly changes the picture.
- Ultimately want to re-measure the branching fraction using $\mathcal{B}(B^0 \to J/\psi K_S)$ and the f_{Λ_b}/f_d production fraction at the LHC (this is ongoing).



Data LHCb **[JHEP 06 (2015) 115]**
SM Detmold et al. **[PRD 93 (2016) 074501]**

Bayesian analysis of $\Lambda_b \to \Lambda\mu^+\mu^-$

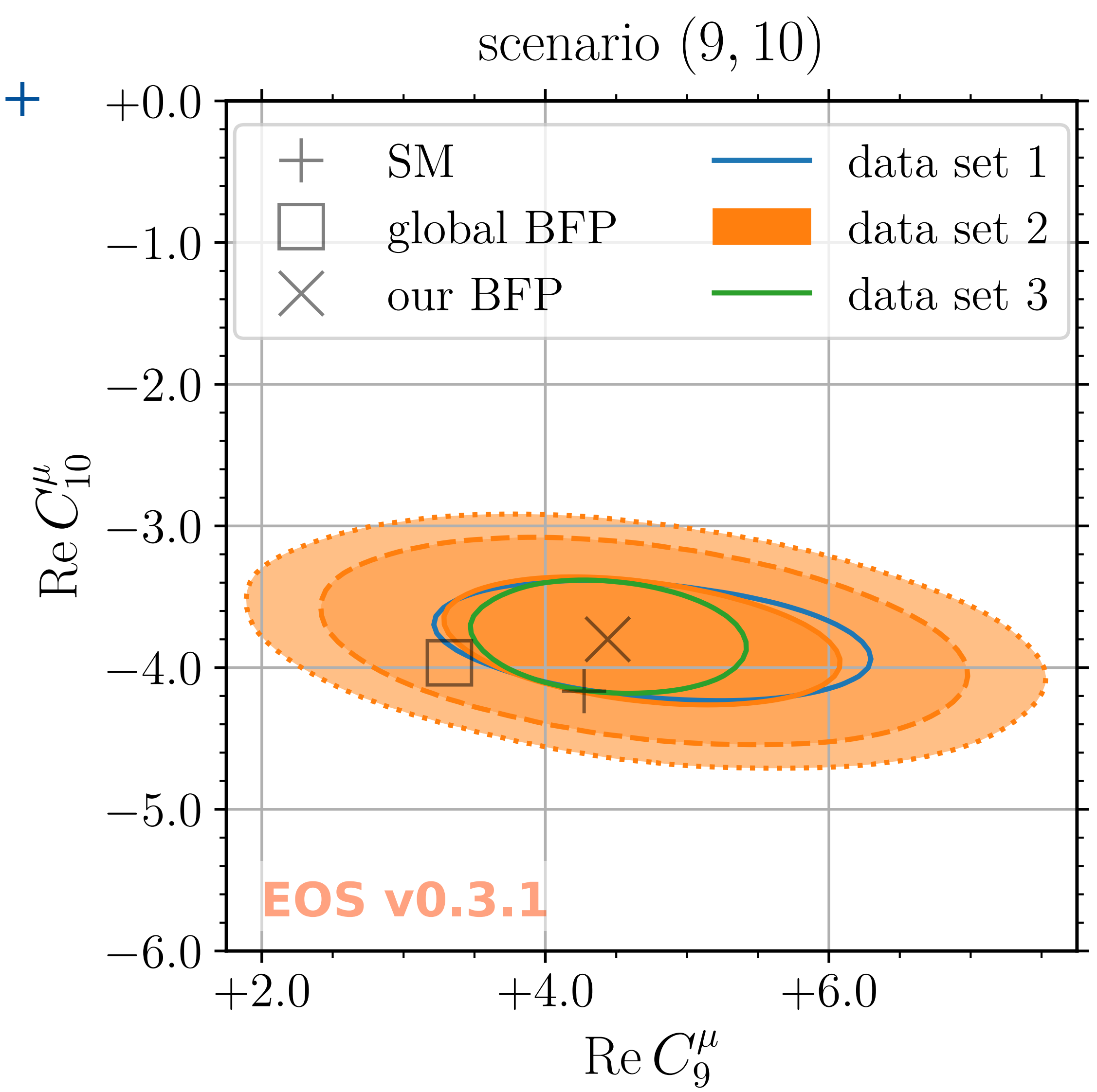
- Determine the Wilson coefficients using a Bayesian analysis.
- Try three scenarios:

  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 both the best-fit point and the point favoured by *B* meson decays.

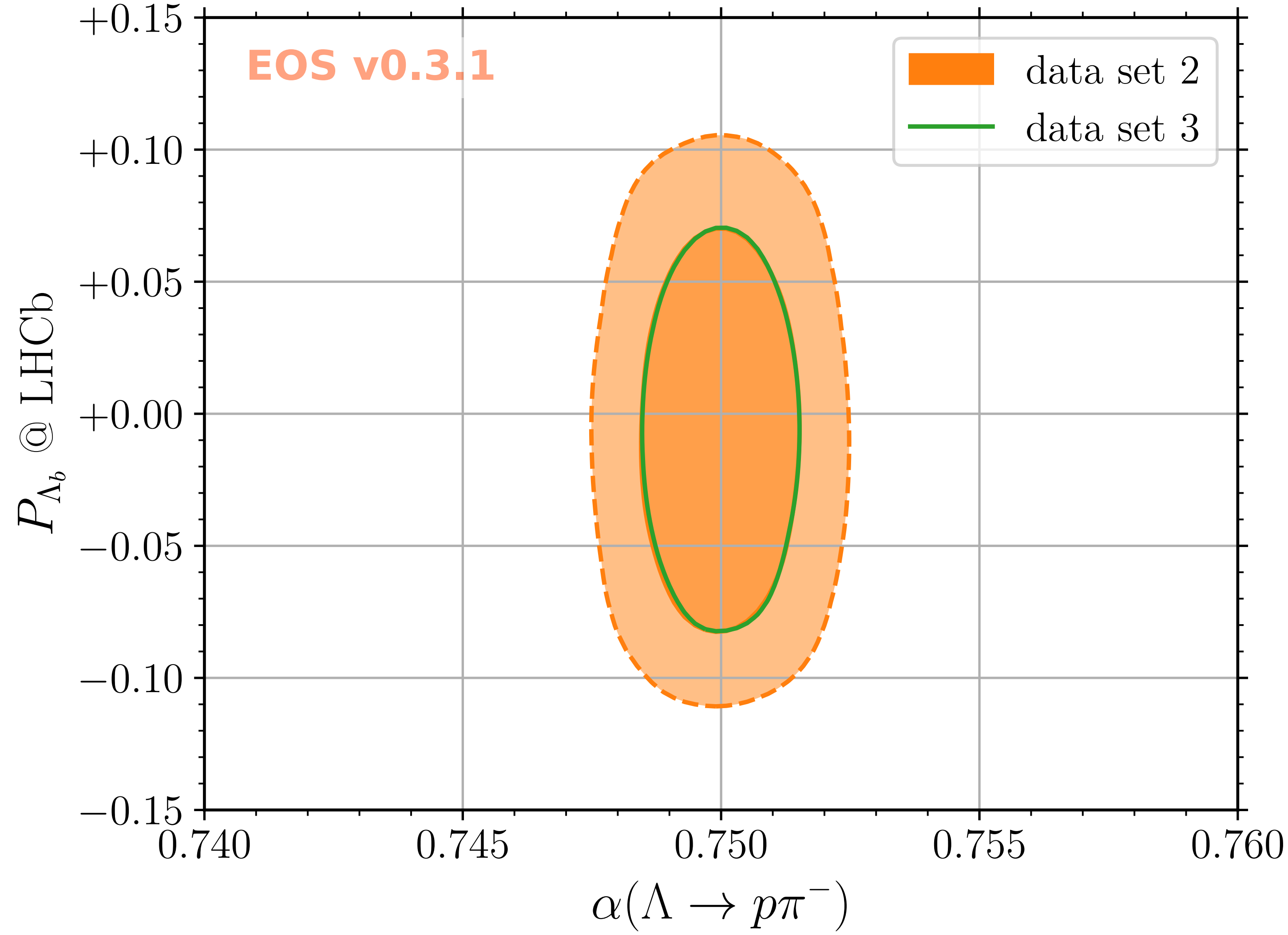
TB, SM and DvD [**PRD 101 (2020) 035023**]



Bayesian analysis of $\Lambda_b \to \Lambda\mu^+\mu^-$

- Can also determine polarisation from the moments assuming no $\sqrt{s}$ dependence.
- Result is compatible with zero production polarisation.

TB, SM and DvD [**PRD 101 (2020) 035023**]



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

- Described by four helicity amplitudes, $H_{\lambda_\Lambda,\lambda_\psi}$, the Λ_b production polarisation, P_b, and the Λ asymmetry parameter, α_Λ.
- Use the convention:

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

see e.g.: Hrivnac et al. [J.Phys. G21 (1995) 629-638]

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}	$P_b\frac{\alpha}{2}\mathrm{Im}(b_+^* b_-)$

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

- 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	$\frac{1}{4}(2\lvert a_+\rvert^2 + 2\lvert a_-\rvert^2 + \lvert b_+\rvert^2 + \lvert b_-\rvert^2)$
M_2	$\frac{1}{2}(\lvert b_+\rvert^2 + \lvert b_-\rvert^2)$
M_4	$\frac{\alpha}{4}(\lvert b_-\rvert^2 - \lvert b_+\rvert^2 + 2\lvert a_+\rvert^2 - 2\lvert a_-\rvert^2)$
M_5	$\frac{\alpha}{2}(\lvert b_-\rvert^2 - \lvert b_+\rvert^2)$
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}	$P_b\frac{1}{4}(\lvert b_+\rvert^2 - \lvert b_-\rvert^2 + 2\lvert a_+\rvert^2 - 2\lvert a_-\rvert^2)$
M_{12}	$P_b\frac{1}{2}(\lvert b_+\rvert^2 - \lvert b_-\rvert^2)$
M_{14}	$P_b\frac{\alpha}{4}(-\lvert b_-\rvert^2 - \lvert b_+\rvert^2 + 2\lvert a_+\rvert^2 + 2\lvert a_-\rvert^2)$
M_{15}	$-P_b\frac{\alpha}{2}(\lvert b_+\rvert^2 + \lvert b_-\rvert^2)$
M_{17}	$-P_b\frac{\alpha}{\sqrt{2}}\mathrm{Re}(b_+^* a_+ + b_- a_-^*)$
M_{19}	$P_b\frac{\alpha}{\sqrt{2}}\mathrm{Im}(b_+^* a_+ + b_- a_-^*)$
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M_{30}	$P_b\alpha\mathrm{Im}(a_+ a_-^*)$
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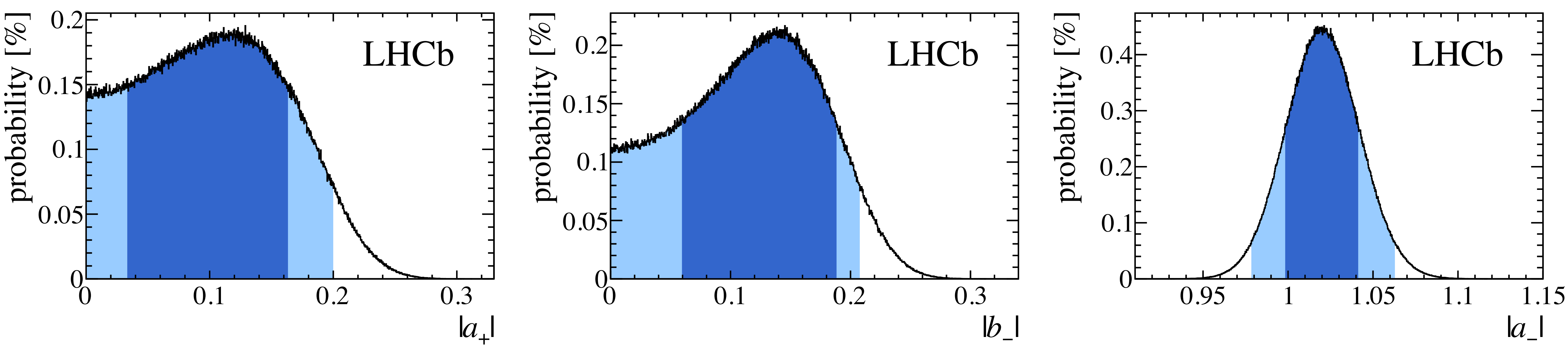
M_{33}	$-P_b\frac{\alpha}{2}\mathrm{Re}(b_+^* b_-)$
M_{34}	$P_b\frac{\alpha}{2}\mathrm{Im}(b_+^* b_-)$

$\Lambda_b \to J/\psi \Lambda$ amplitudes

- Determine $M_1 - M_{34}$ using a moment analysis.
- Determine amplitudes and polarisation using Bayesian inference from $M_1 - M_{34}$.
- Fix the magnitude and phase such that:
  - $\mathrm{Re}(b_+) = 1$ and $\mathrm{Im}(b_+) = 0$
- Posterior distributions with uniform priors:

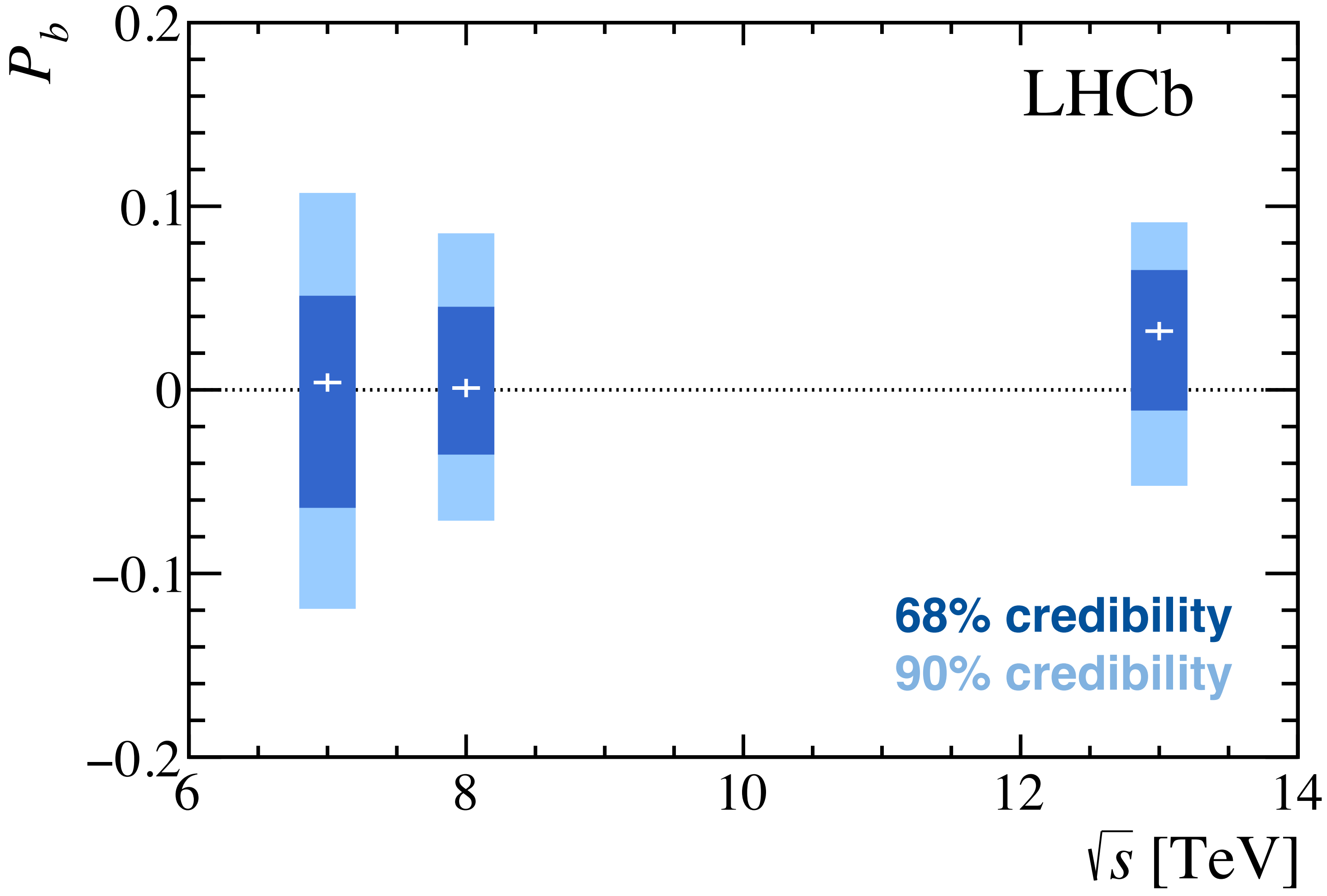
LHCb [JHEP 06 (2020) 110]



Λ_b production polarisation

LHCb [JHEP 06 (2020) 110]

- Data are consistent with zero production polarisation in *pp* collisions.

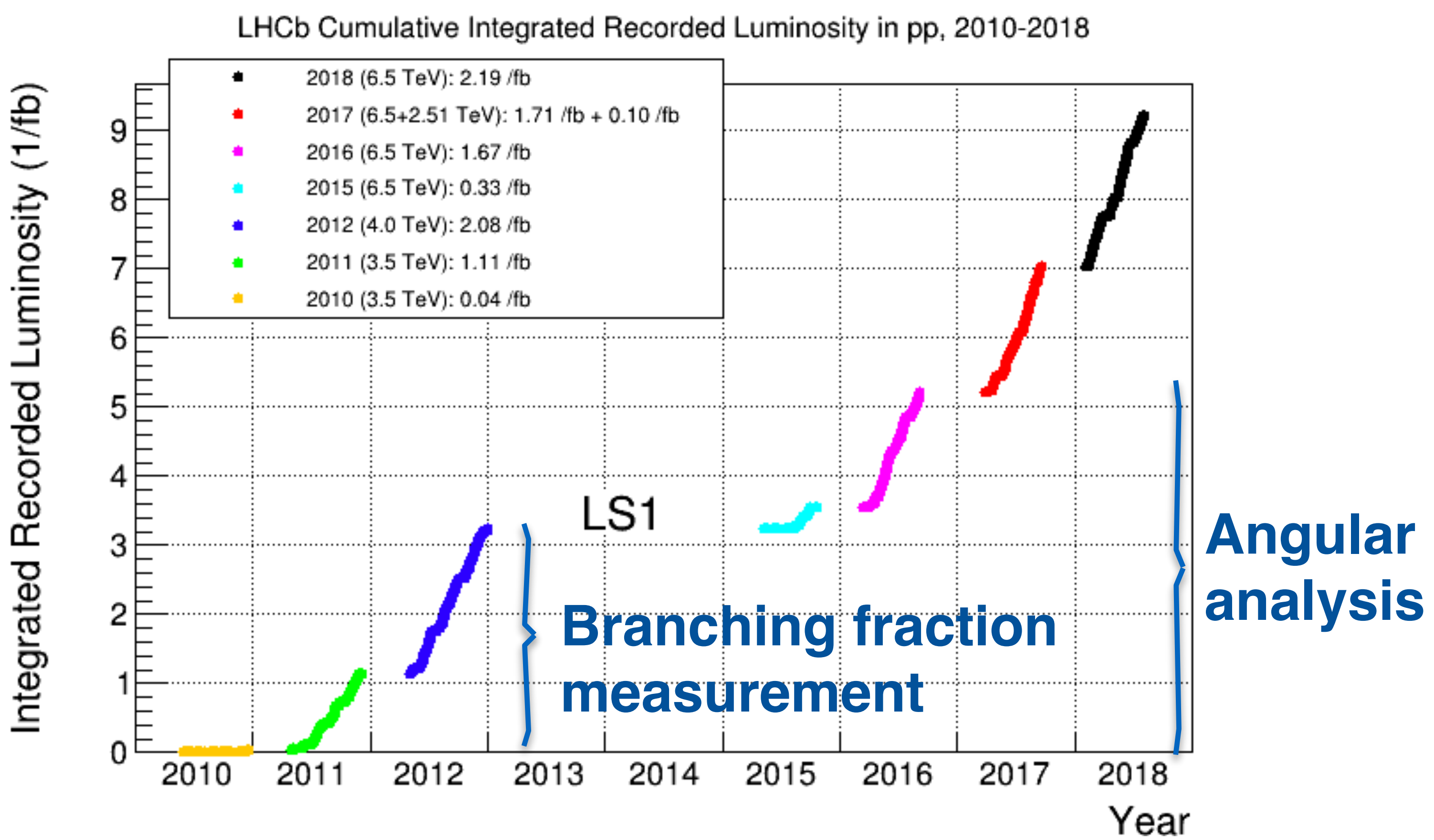


Summary

- The branching fraction and angular distribution of $\Lambda_b \to \Lambda\mu^+\mu^-$ decays are consistent with SM expectations.
- The results of a Bayesian analysis of observables in $\Lambda_b \to \Lambda\mu^+\mu^-$ decays are consistent with both the SM and with the point favoured by the analysis of *B* meson decays.
- A Bayesian model comparison favours the SM (nuisance only) and modified C_9 scenarios over scenarios with (C_9, C_{10}) varied.
- The production polarisation of Λ_b baryons is consistent with zero in *pp* collisions at the LHC (which is unfortunate!)

Summary

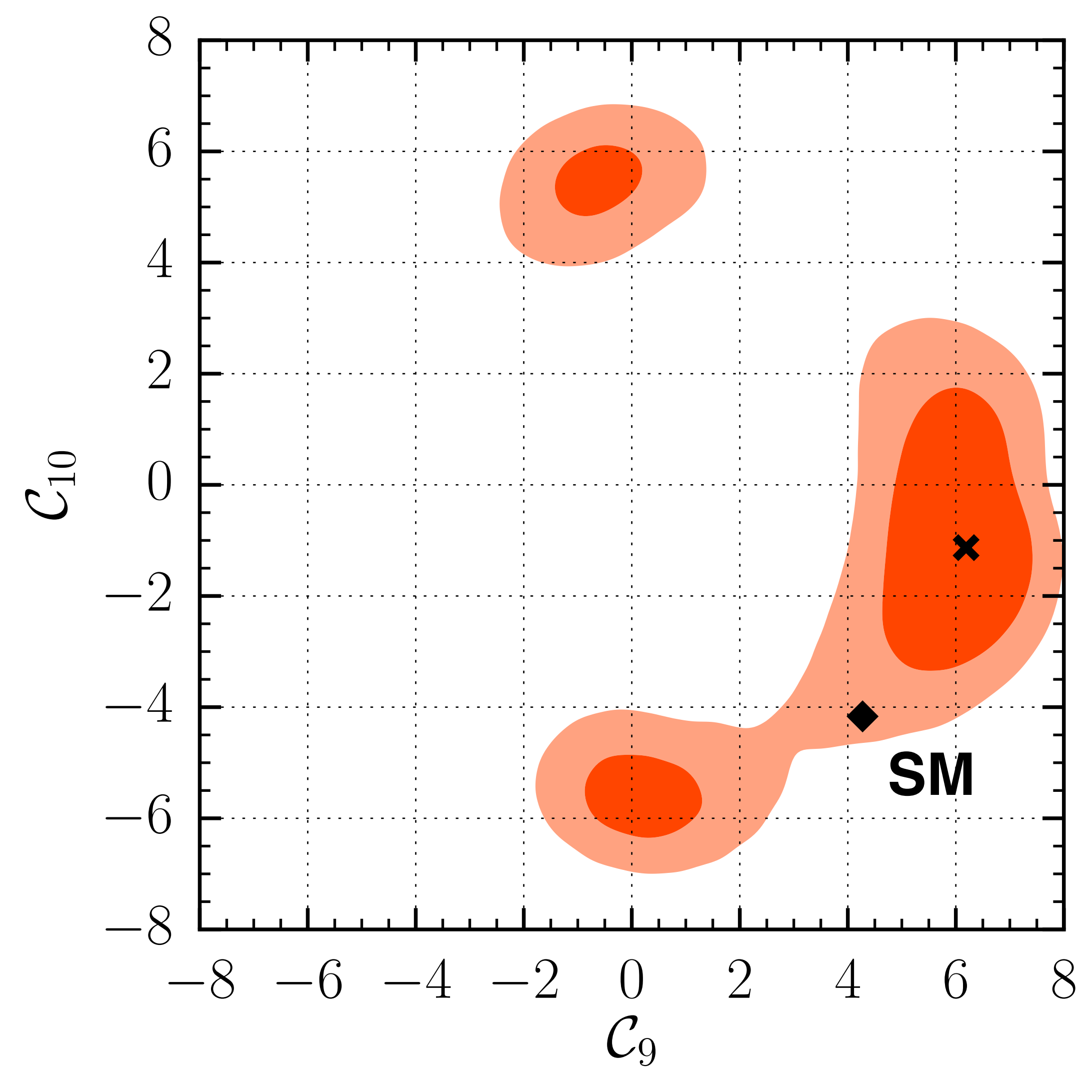
- Expect more to come with the full Run 2 dataset:



Using $\Lambda_b \to \Lambda\mu^+\mu^-$ data within a Bayesian analysis of |ΔB|=|ΔS|=1 decays

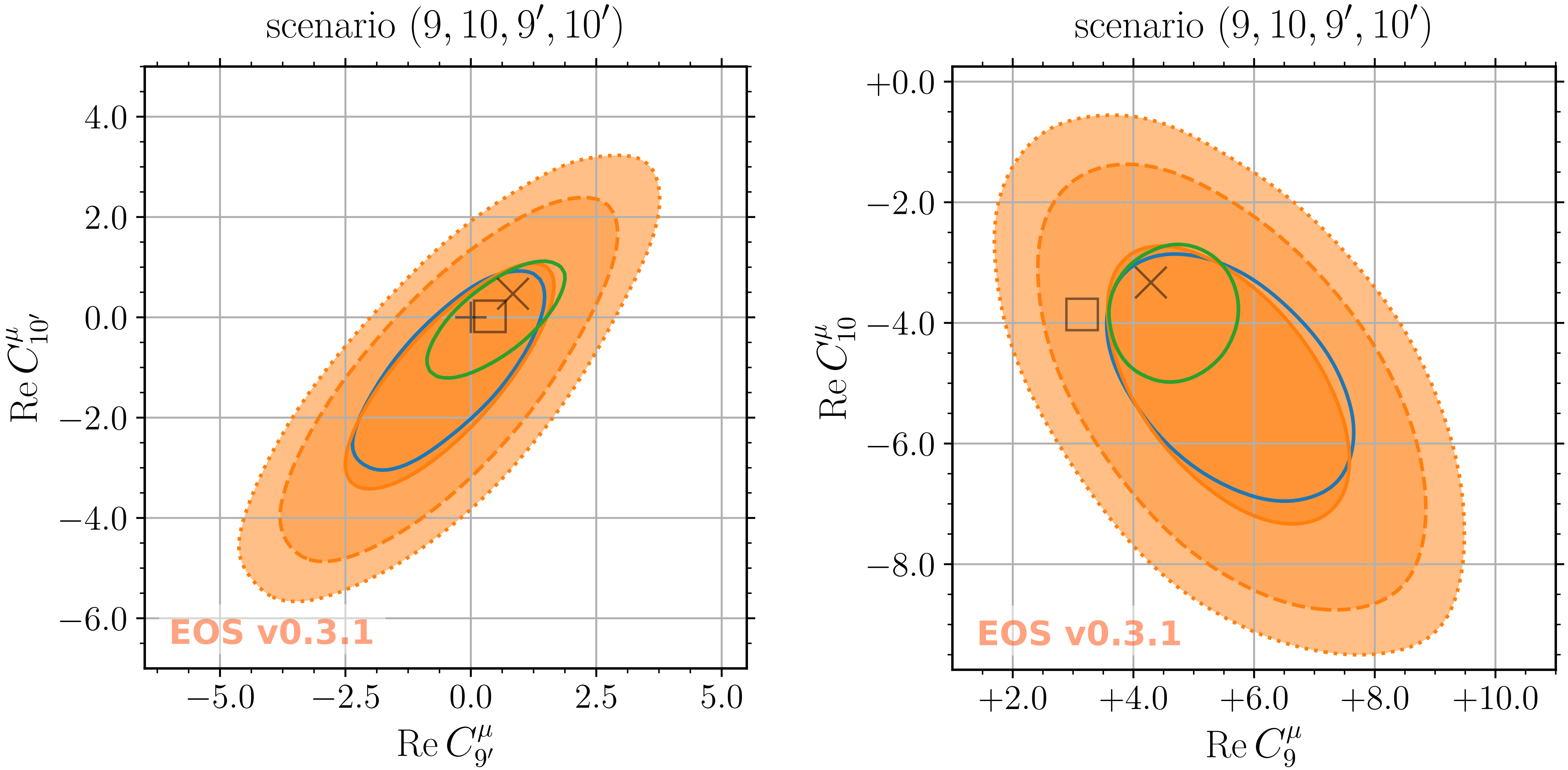
Meinel et al. [PRD 94 (2016) 013007]

- A previous Bayesian analysis favoured a shift in C_9 with an opposite sign to the *B* meson data.
- There are several changes between the two analyses:
  - Updated value of α_Λ from BESIII.
  - Updated $B_s^0 \to \mu^+\mu^-$ branching fraction measurements from ATLAS, CMS and LHCb.
  - Inclusion of the complete set of angular observables from LHCb.
  - LHCb erratum affecting $A_{\rm FB}^l$. ← Has the largest impact on the best-fit point



Bayesian posteriors in the (9,10,9',10') scenario

- Including primed Wilson coefficients:



Blake et al. [PRD 101 (2020) 035023]

Λ asymmetry parameter

- Recent measurement by BESIII **[Nature Phys. 15 (2019) 631–634]** is 17% larger than the old world average value from secondary scattering.

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

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

- The larger BESIII value likely solves the problems with the older LHCb, the 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]**.

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

- Can expand the angular distribution in terms of helicity states:

$$\frac{\mathrm{d}^6\Gamma}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} \propto \sum_{\substack{\lambda_1,\lambda_2,\lambda_p,\lambda_{\ell\ell},\lambda'_{\ell\ell},\\ J,J',m,m',\lambda_\Lambda,\lambda'_\Lambda,}} \Big((-1)^{J+J'} \times \\ \rho_{\lambda_\Lambda-\lambda_{\ell\ell},\lambda'_\Lambda-\lambda'_{\ell\ell}}(\theta)\times \\ H^{m,J}_{\lambda_\Lambda,\lambda_{\ell\ell}}(q^2) H^{\dagger\, m',J'}_{\lambda'_\Lambda,\lambda'_{\ell\ell}}(q^2)\times \\ h^{m,J}_{\lambda_1,\lambda_2}(q^2) h^{\dagger\, m',J'}_{\lambda_1,\lambda_2}(q^2)\times \\ D^{J\,*}_{\lambda_{\ell\ell},\lambda_1-\lambda_2}(\phi_l,\theta_l,-\phi_l) D^{J'}_{\lambda'_{\ell\ell},\lambda_1-\lambda_2}(\phi_l,\theta_l,-\phi_l)\times \\ h^{\Lambda}_{\lambda_p,0} h^{\dagger\,\Lambda}_{\lambda_p 0}\times \\ D^{1/2\,*}_{\lambda_\Lambda,\lambda_p}(\phi_b,\theta_b,-\phi_b) D^{1/2}_{\lambda'_\Lambda,\lambda_p}(\phi_b,\theta_b,-\phi_b)\Big)$$

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

- Unpolarised case:

$$\frac{\mathrm{d}^4}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} = \frac{3}{8\pi}\Big((K_{1ss}\sin^2\theta_l + K_{1cc}\cos^2\theta_l + K_{1c}\cos\theta_l) +$$

$$(K_{2ss}\sin^2\theta_l + K_{2cc}\cos^2\theta_l + K_{2c}\cos\theta_l)\cos\theta_b +$$

$$(K_{3sc}\sin\theta_l\cos\theta_l + K_{3s}\sin\theta_l)\sin\theta_b\sin\phi$$

$$(K_{4sc}\sin\theta_l\cos\theta_l + K_{4s}\sin\theta_l)\sin\theta_b\cos\phi \Big)$$

Böer et al. [JHEP 01 (2015) 155]

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