$\Lambda_b \to \Lambda^{(*)}$ form factors

Stefan Meinel, Carla Marin

IPPP Workshop “Beyond the Flavour Anomalies II”, 20-22 April 2021

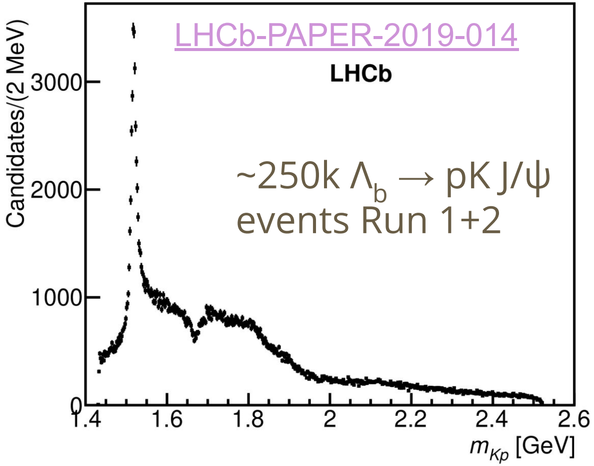
Why baryons?

- Large production at the LHC
  - higher production than B_s

$$\frac{f_{\Lambda_b}}{f_d+f_u} = 0.259 \pm 0.018$$

PRD100(2019)031102 (13 TeV)

- Rich phenomenology due to initial and final state spins
  - $s_{\Lambda b} = 1/2$
  - $s_{\Lambda} = 1/2$
  - $s_{\Lambda 1520} = 3/2$



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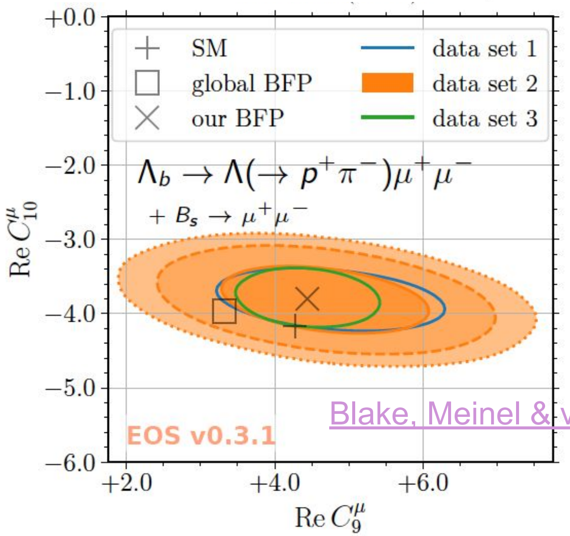
~250k $\Lambda_b \to pK\,J/\psi$ events Run 1+2



Blake, Meinel & van Dyk

Experiment

Won't give experimental details, will focus on observables, results and limitations from FF (lack of) knowledge.

What's been done so far:

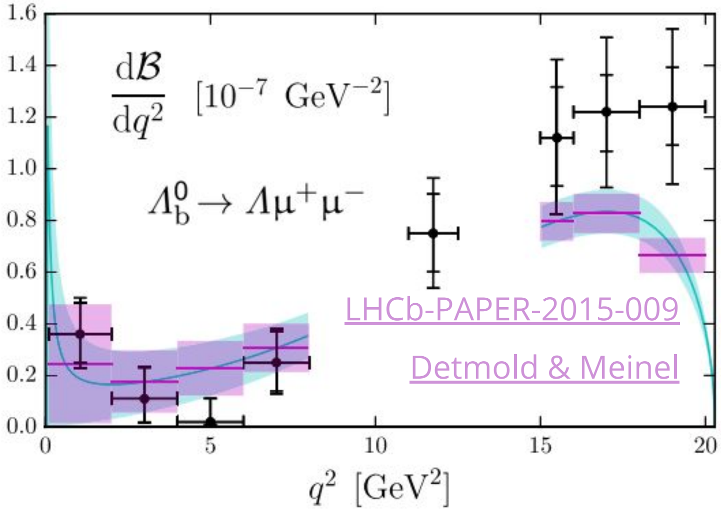
- $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$: differential BR and angular observables [LHCb-2011, LHCb-R1, LHCb-R12016]
- $\Lambda_b \rightarrow \Lambda\gamma$: observation and BR [LHCb-2016]
- $\Lambda_b \rightarrow pK/\pi\ \mu^+\mu^-$: observation, CP search and LU (R_{pK}) [LHCb-R1-pK, -pπ , LHCb-R12016]

Updates and new measurements ongoing

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

- Most data at high q^2, small excess wrt SM in this region
- Angular moments very compatible with SM
  - ○ $K_{11\text{-}34} \propto P_{\Lambda b} \approx 0$

$$\frac{d^5\Gamma}{d\Omega} = \frac{3}{32\pi^2}\sum_i^{34} K_i f_i(\Omega)$$



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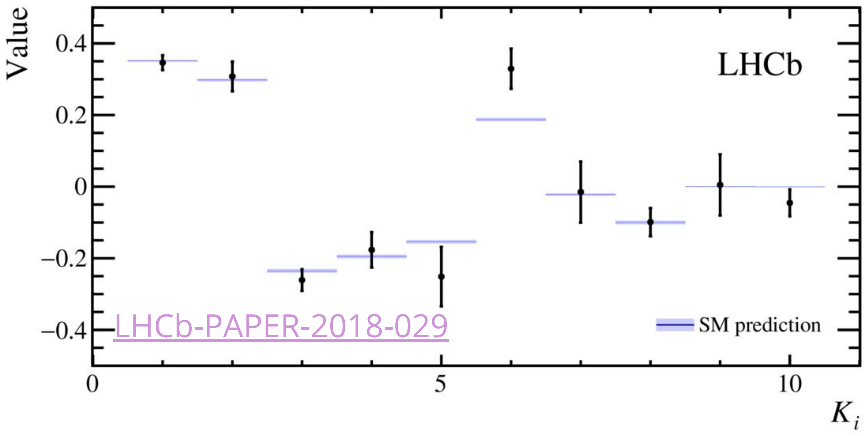
Detmold & Meinel

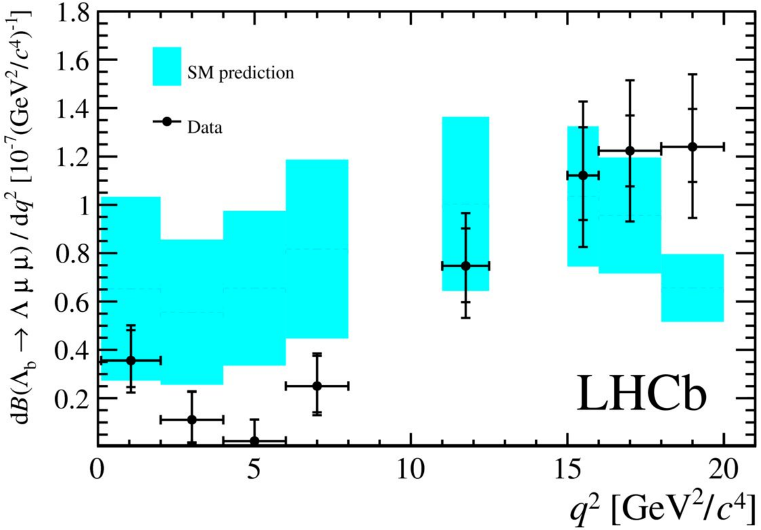


15 < q^2 < 20 GeV^2/c^4

LHCb-PAPER-2018-029

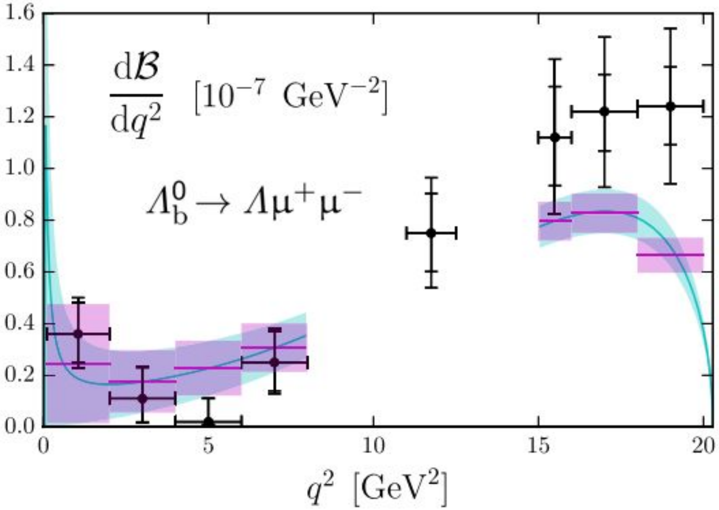
Impact of FF uncertainties

LHCb-PAPER-2015-009



SM prediction from first lattice QCD calculations for $\Lambda_b \to \Lambda$ Detmold et al (2012)

Detmold & Meinel

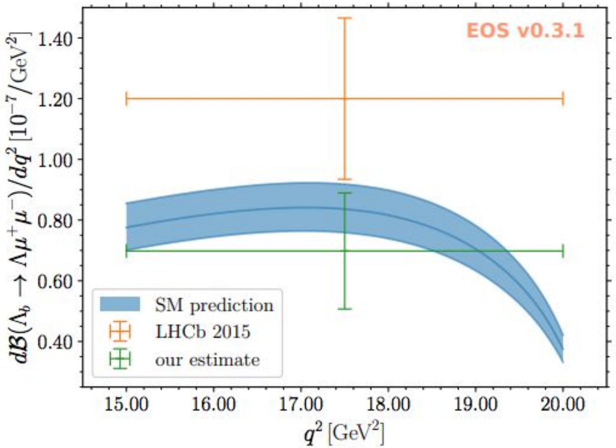


Updated lattice QCD calculations in 2016

Improving the measurements

Differential BR precision limited by systematic from normalisation mode. Only $f(b \rightarrow \Lambda_b) \times BR(\Lambda_b \rightarrow \Lambda\, J/\psi)$ has been measured so far [Tevatron]

- LHCb paper: $f(b \rightarrow \Lambda_b)$ Tevatron+LEP → $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\, \Lambda) = (6.3 \pm 1.3) \times 10^{-4}$
- Blake et al: $f(b \rightarrow \Lambda_b)$ Tevatron only → $\mathcal{B}(\Lambda_b \rightarrow J/\psi \Lambda) = (3.7 \pm 1.0) \times 10^{-4}$



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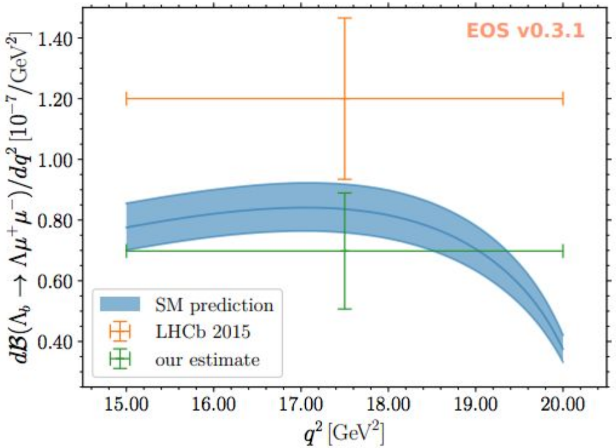
Next: measure $BR(\Lambda_b \to \Lambda\, J/\psi)$ at LHCb

- will be limited by knowledge of $f_{\Lambda b}/f_d$ ~ 7%



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Next: measure BR(Λ_b → Λ J/ψ) at LHCb

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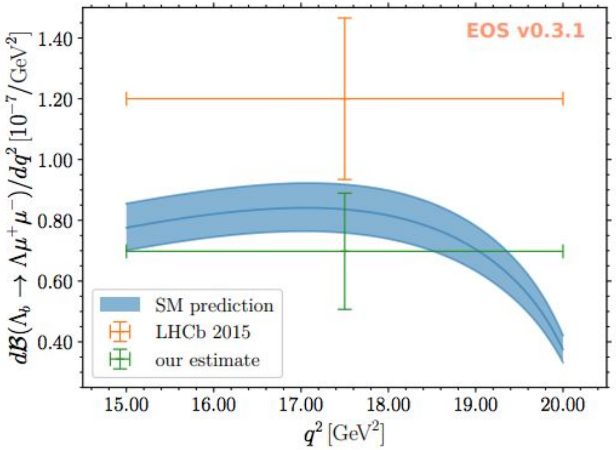
Next: measurements at low q^2 w/ full LHCb Run 2

- higher sensitivity to NP in C_9



$\Lambda_b \rightarrow \Lambda\gamma$

- BR measurement: 21% stat uncertainty
    - can reach ~10% with full Run 2

$$\boxed{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}}$$

- Range of SM predictions: (0.6 - 10)x 10^{-6}

  Wang et al., Gan et al., Gutsche et al.,Faustov&Galkin
    - SCET [Mannel&Wang] in good agreement: 7.7 x 10^{-6}
    - Lattice QCD: extrapolation to $q^2 = 0$ available but not used in BR calculations so far, assuming no NP in C_7 this measurement gives a cross-check

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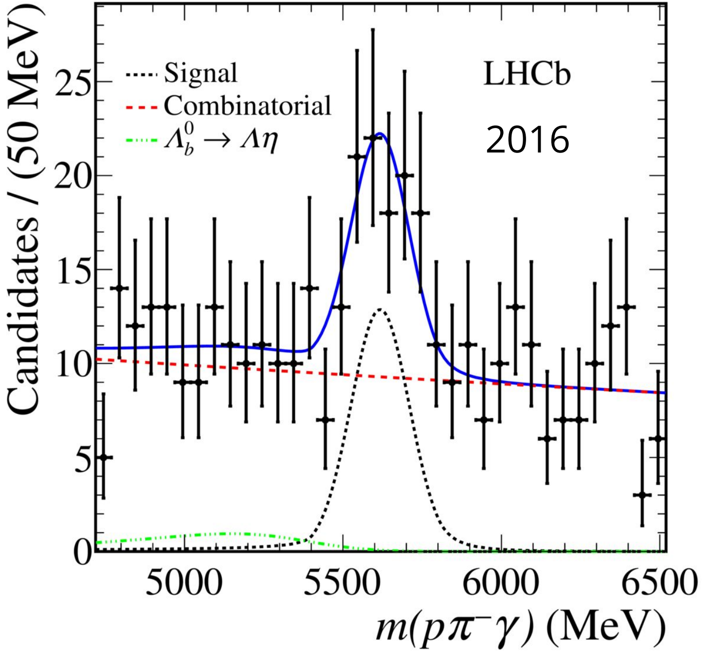

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- Photon polarisation independent of FF at LO
  - coming soon :)

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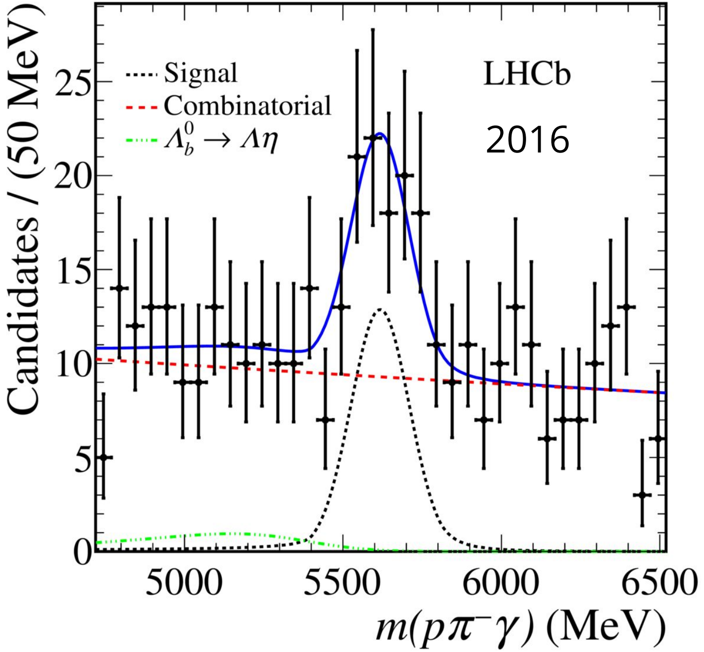


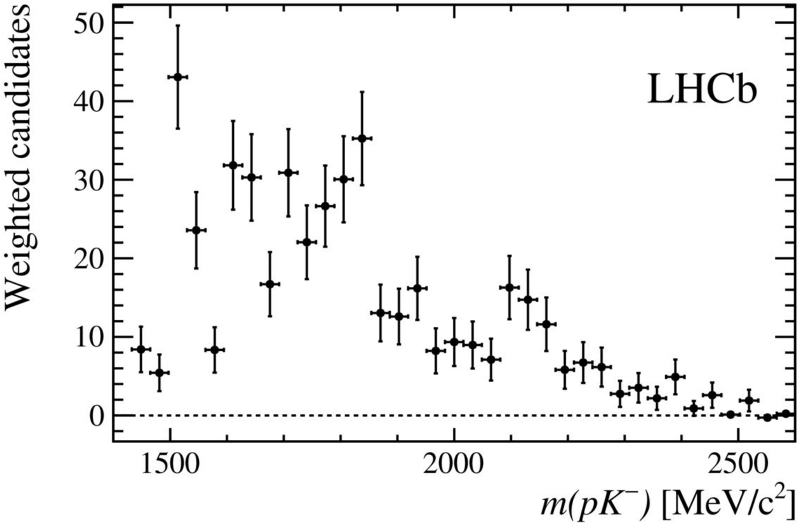
$\Lambda_b \rightarrow pKl^+l^-$

LHCb-PAPER-2019-040

- R_{pK} shows same trend as $R_{K,\,K^*}$:

$$\boxed{R_{pK}^{-1}\Big|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 1.17^{+0.18}_{-0.16} \pm 0.07}$$

- NP interpretation limited by unknown pK spectrum
    - individual FF from quark models [Mott&Roberts] and lattice QCD for Λ(1520) [Meinel&Rendon]
    - any way to compute expected interference effects from pheno?
- FF input relevant for BR and angular measurements

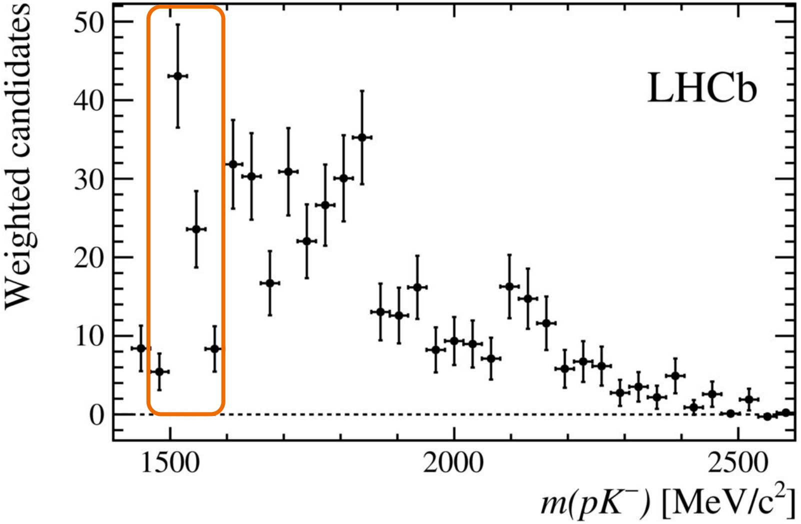


$\Lambda_b \rightarrow \Lambda(1520)l^+l^-$

LHCb-PAPER-2019-040

Focus on dominant Λ(1520) region

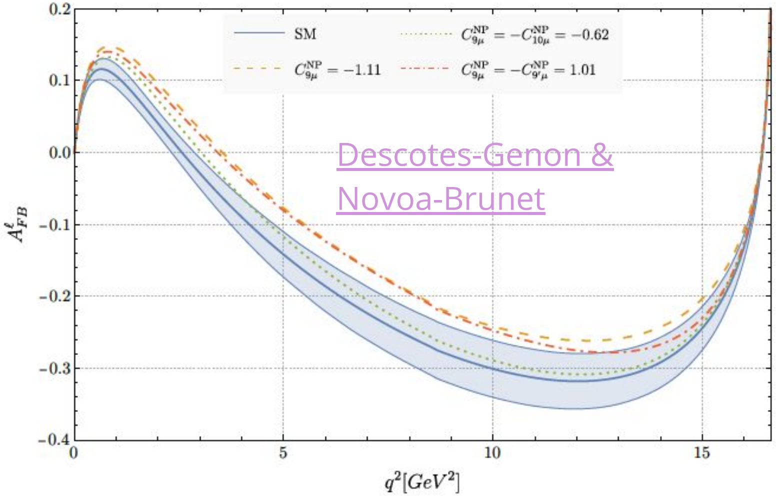
- $R_{\Lambda(1520)}$ could reach 10% (full Run 2)
    - with small contamination from other Λ^*, how critical is this?



$\Lambda_b \to \Lambda(1520)l^+l^-$

Focus on dominant Λ(1520) region

- $R_{\Lambda(1520)}$ could reach 10% (full Run 2)
    - with small contamination from other Λ^*, how critical is this?
- BR and angular observables are sensitive no NP as well
    - but we need FF as input!

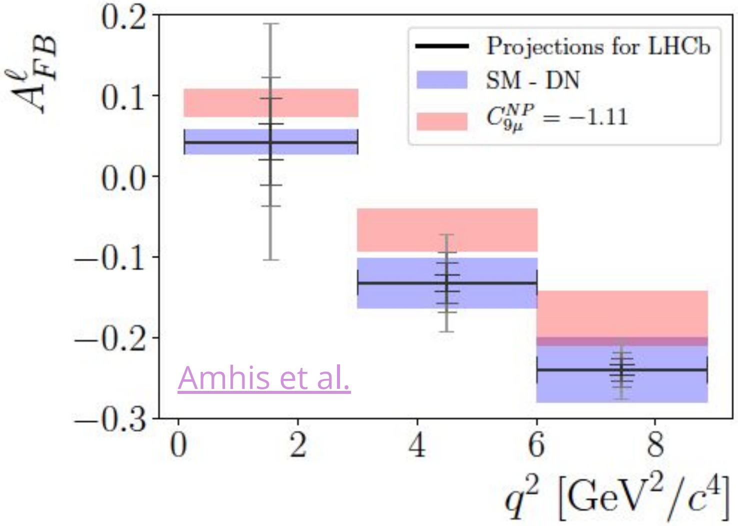


Descotes-Genon & Novoa-Brunet

FF from Mott&Roberts with 10% (30%) uncertainty on vector (tensor) FF

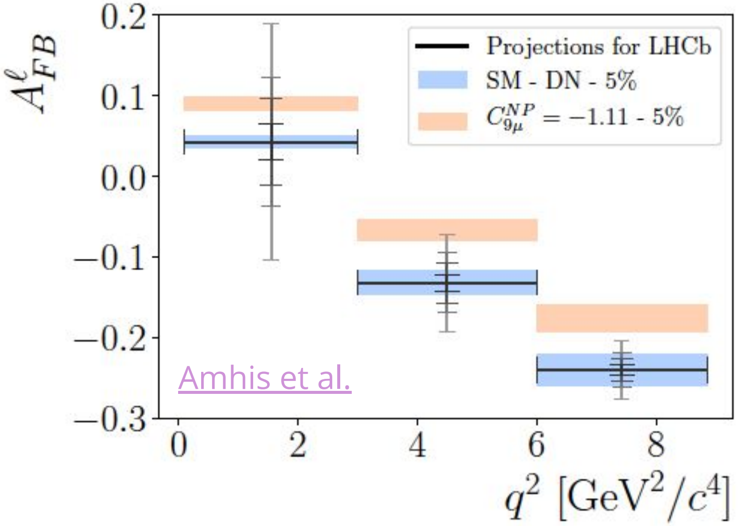
$\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$

Expected LHCb sensitivity at low q^2: impact of FF uncertainties



Amhis et al.

10% (30%) uncertainty on vector (tensor) FF



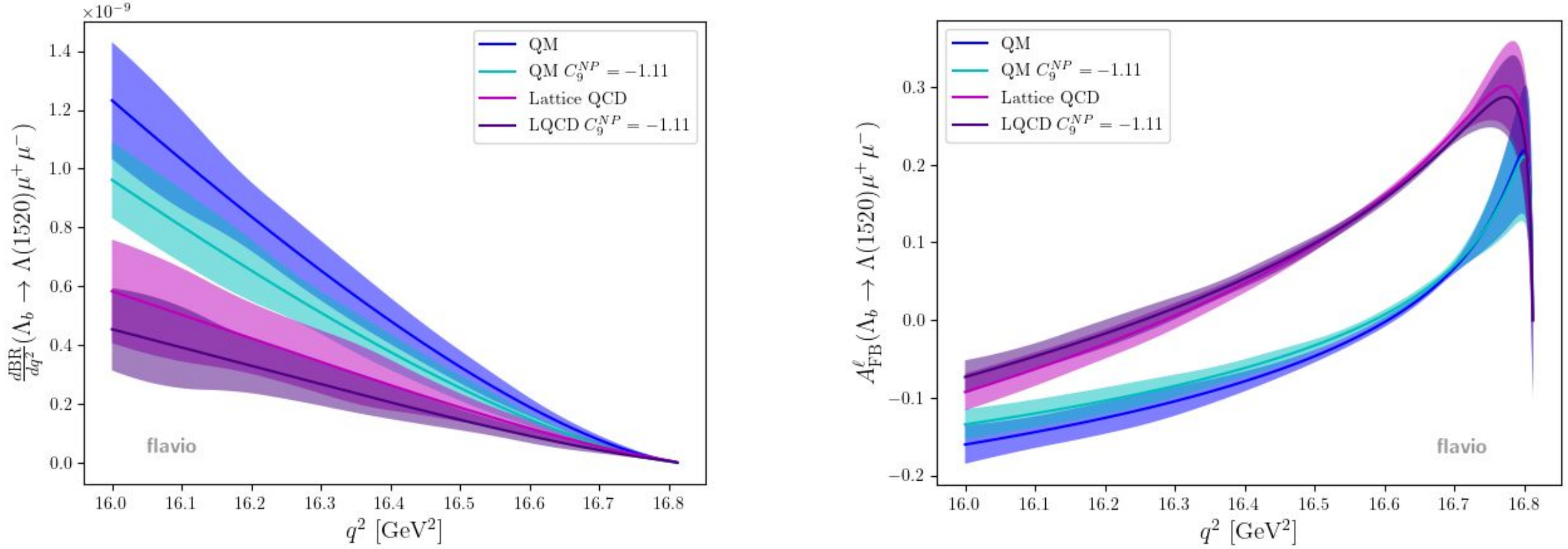
Amhis et al.

5% (30%) uncertainty on vector (tensor) FF

Impact of FF

Work by F. Volle
Flavio#118

Comparison of Mott&Roberts (QM) and Meinel&Rendon (Lattice QCD) FF:

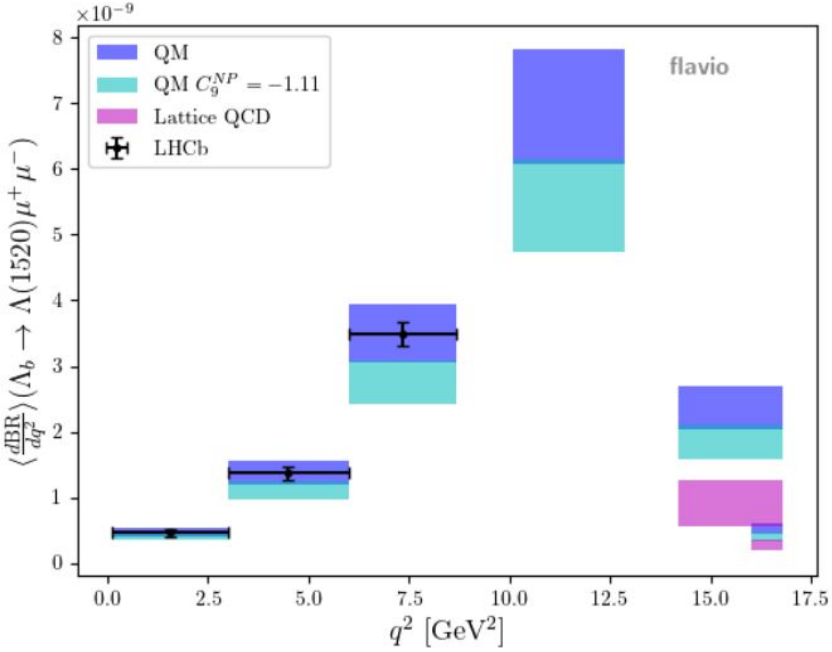


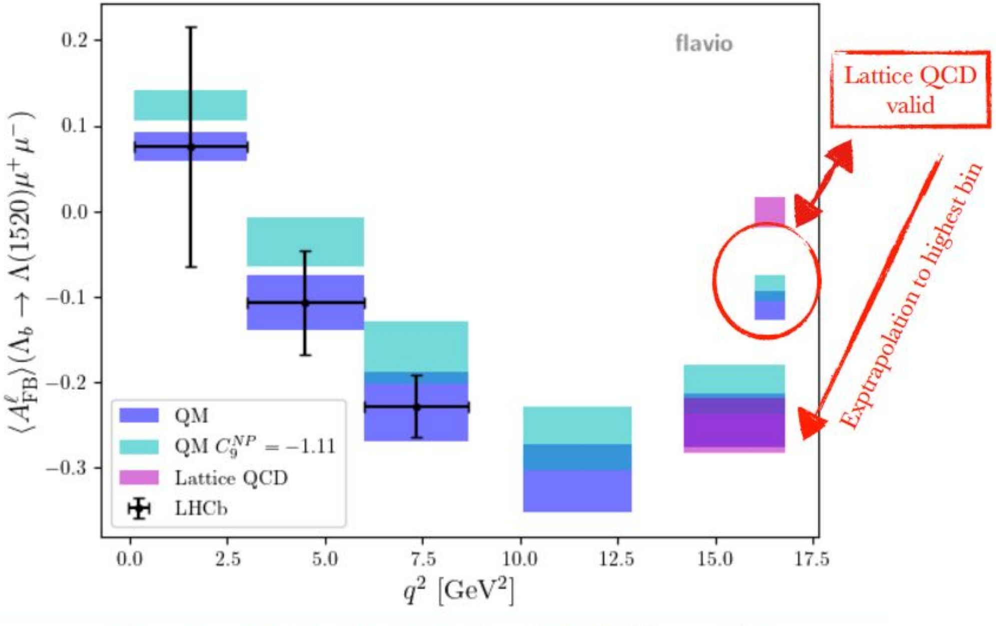
Significant discrepancy between LQCD and QM at high q^2, larger than NP effect (small here)

Impact of FF

Work by F. Volle
Flavio#118

Cannot extrapolate LQCD to low q^2, SCET calculation desirable





BACK-UP

Theoretical framework

Full angular distribution from Descotes-Genon & Novoa-Brunet [DN] [null Λ_b polarisation]:

$$
\begin{aligned}
&\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_p d\phi} \\
&\quad = \cos^2\theta_p\left(L_{1c}\cos\theta_\ell + L_{1cc}\cos^2\theta_\ell + L_{1ss}\sin^2\theta_\ell\right) \\
&\qquad + \sin^2\theta_p\left(L_{2c}\cos\theta_\ell + L_{2cc}\cos^2\theta_\ell + L_{2ss}\sin^2\theta_\ell\right) \\
&\qquad + \sin^2\theta_p\left(L_{3ss}\sin^2\theta_\ell\cos^2\phi + L_{4ss}\sin^2\theta_\ell\sin\phi\cos\phi\right) \\
&\qquad + \sin\theta_p\cos\theta_p\cos\phi(L_{5s}\sin\theta_\ell + L_{5sc}\sin\theta_\ell\cos\theta_\ell) \\
&\qquad + \sin\theta_p\cos\theta_p\sin\phi(L_{6s}\sin\theta_\ell + L_{6sc}\sin\theta_\ell\cos\theta_\ell),
\end{aligned}
$$

$\cos^2\theta_p$ dependency characteristic of s=3/2 state

Heavy quark limit

Amhis et al.

14 form factors enter decay rate: 8 vector/axial + 6 tensor, large uncertainties

Reduced in heavy quark limit: $m_b \to \infty$

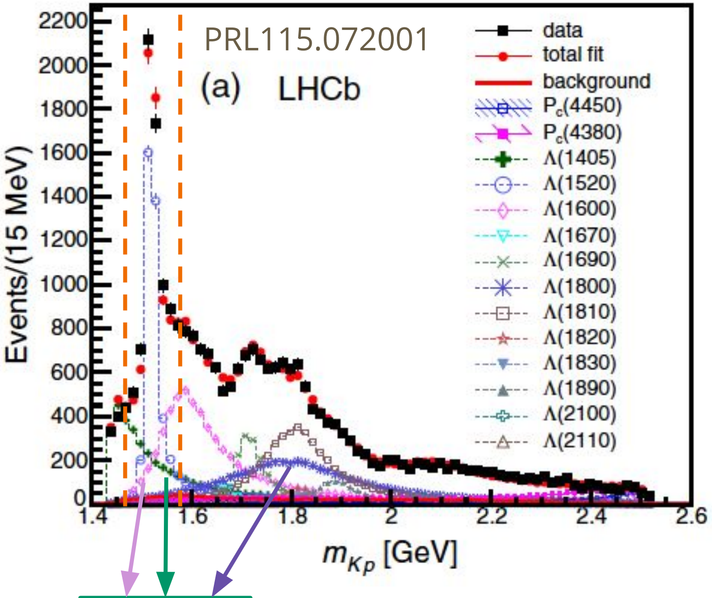
- low-recoil limit [large q^2]: HQET → 2 form factors, tensor ones vanish
- large-recoil limit [low q^2]: SCET → 1 form factor, tensor ones vanish

Neglecting tensor form factors, angular expression largely simplified:

$$\boxed{\begin{aligned}&\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_p d\phi}\\ &\qquad\simeq \frac{1}{4}(1+3\cos^2\theta_p)\left(L_{1c}\cos\theta_\ell + L_{1cc}\cos^2\theta_\ell + L_{1ss}\sin^2\theta_\ell\right)\end{aligned}}$$

Contamination from other Λ^* states

Only s=½ states around Λ(1520):


PRL115.072001

s = 1/2

Hadron distribution to disentangle them:

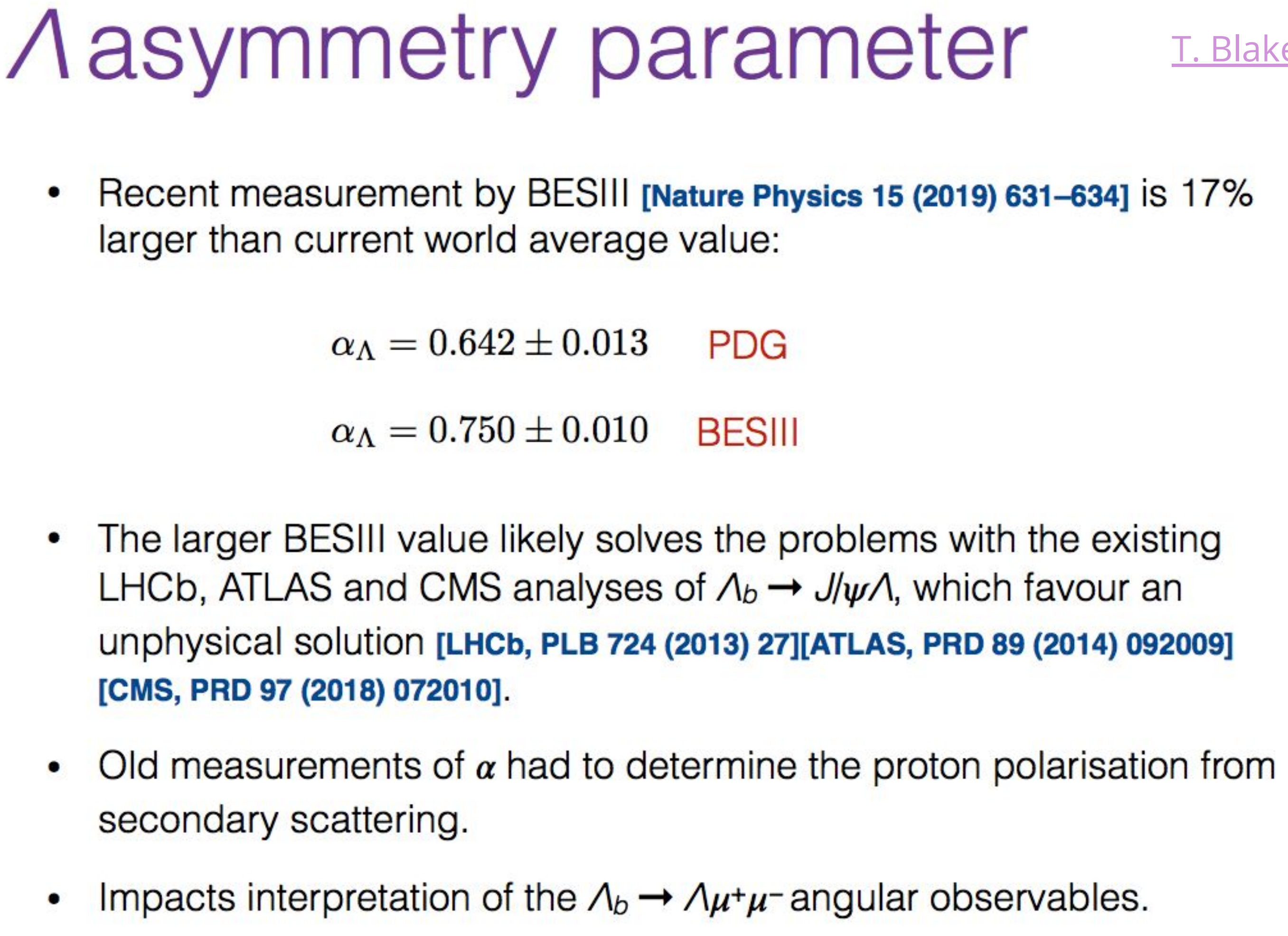
- s = 3/2: $\cos^2\theta_p$ terms
- s = 1/2: flat in θ_p (strong decay!)
- fit m(pK) simultaneously

$$\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_p d\phi}$$

$$\boxed{\simeq \frac{1}{4}(1+3\cos^2\theta_p)\left(L_{1c}\cos\theta_\ell + L_{1cc}\cos^2\theta_\ell + L_{1ss}\sin^2\theta_\ell\right)}$$

$$\boxed{\simeq L_{1c}^{1/2}\cos\theta_l + L_{1cc}^{1/2}\cos^2\theta_l + L_{1ss}^{1/2}\sin^2\theta_l}$$

*interference terms more complicated



Λ asymmetry parameter

T. Blake @b2sll WS

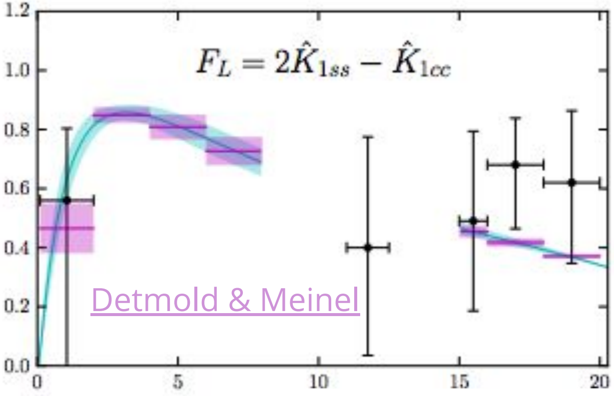
- Recent measurement by BESIII **[Nature Physics 15 (2019) 631–634]** is 17% larger than current world average value:

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

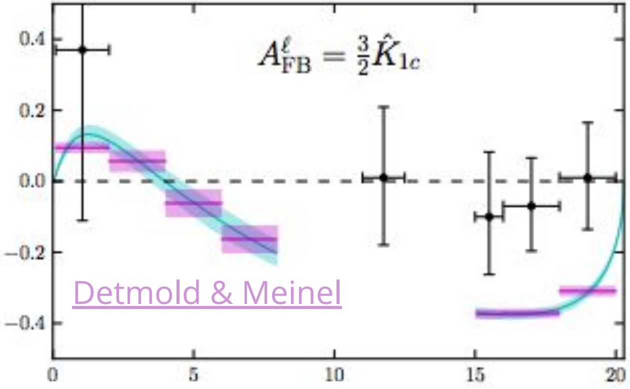
$$\alpha_\Lambda = 0.750 \pm 0.010 \quad \text{BESIII}$$

- 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.

Angular observables vs moments



Detmold & Meinel



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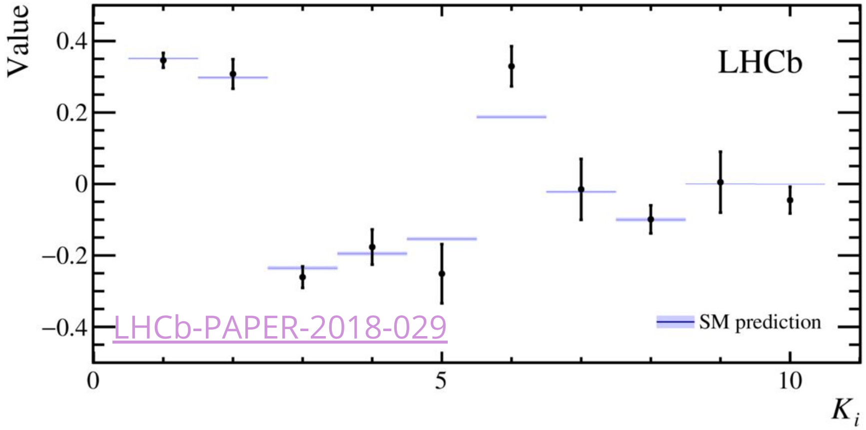

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$15 < q^2 < 20\ \mathrm{GeV}^2/c^4$

$\Lambda_b \longrightarrow \Lambda^*$ FF from Mott & Roberts

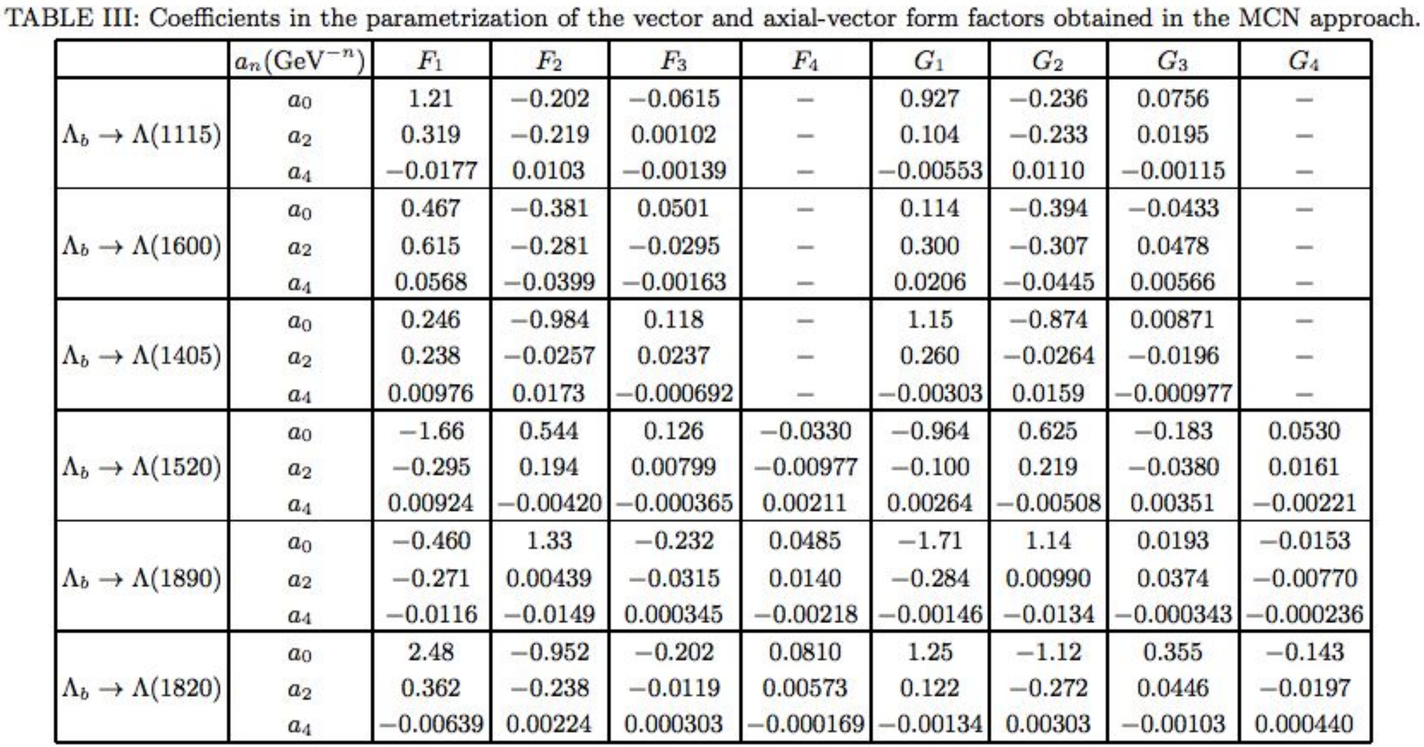

TABLE III: Coefficients in the parametrization of the vector and axial-vector form factors obtained in the MCN approach.

	$a_n(\mathrm{GeV}^{-n})$	F_1	F_2	F_3	F_4	G_1	G_2	G_3	G_4
$\Lambda_b \to \Lambda(1115)$	a_0	1.21	−0.202	−0.0615	–	0.927	−0.236	0.0756	–
	a_2	0.319	−0.219	0.00102	–	0.104	−0.233	0.0195	–
	a_4	−0.0177	0.0103	−0.00139	–	−0.00553	0.0110	−0.00115	–
$\Lambda_b \to \Lambda(1600)$	a_0	0.467	−0.381	0.0501	–	0.114	−0.394	−0.0433	–
	a_2	0.615	−0.281	−0.0295	–	0.300	−0.307	0.0478	–
	a_4	0.0568	−0.0399	−0.00163	–	0.0206	−0.0445	0.00566	–
$\Lambda_b \to \Lambda(1405)$	a_0	0.246	−0.984	0.118	–	1.15	−0.874	0.00871	–
	a_2	0.238	−0.0257	0.0237	–	0.260	−0.0264	−0.0196	–
	a_4	0.00976	0.0173	−0.000692	–	−0.00303	0.0159	−0.000977	–
$\Lambda_b \to \Lambda(1520)$	a_0	−1.66	0.544	0.126	−0.0330	−0.964	0.625	−0.183	0.0530
	a_2	−0.295	0.194	0.00799	−0.00977	−0.100	0.219	−0.0380	0.0161
	a_4	0.00924	−0.00420	−0.000365	0.00211	0.00264	−0.00508	0.00351	−0.00221
$\Lambda_b \to \Lambda(1890)$	a_0	−0.460	1.33	−0.232	0.0485	−1.71	1.14	0.0193	−0.0153
	a_2	−0.271	0.00439	−0.0315	0.0140	−0.284	0.00990	0.0374	−0.00770
	a_4	−0.0116	−0.0149	0.000345	−0.00218	−0.00146	−0.0134	−0.000343	−0.000236
$\Lambda_b \to \Lambda(1820)$	a_0	2.48	−0.952	−0.202	0.0810	1.25	−1.12	0.355	−0.143
	a_2	0.362	−0.238	−0.0119	0.00573	0.122	−0.272	0.0446	−0.0197
	a_4	−0.00639	0.00224	0.000303	−0.000169	−0.00134	0.00303	−0.00103	0.000440

$\Lambda_b \longrightarrow \Lambda^*$ FF from Mott & Roberts

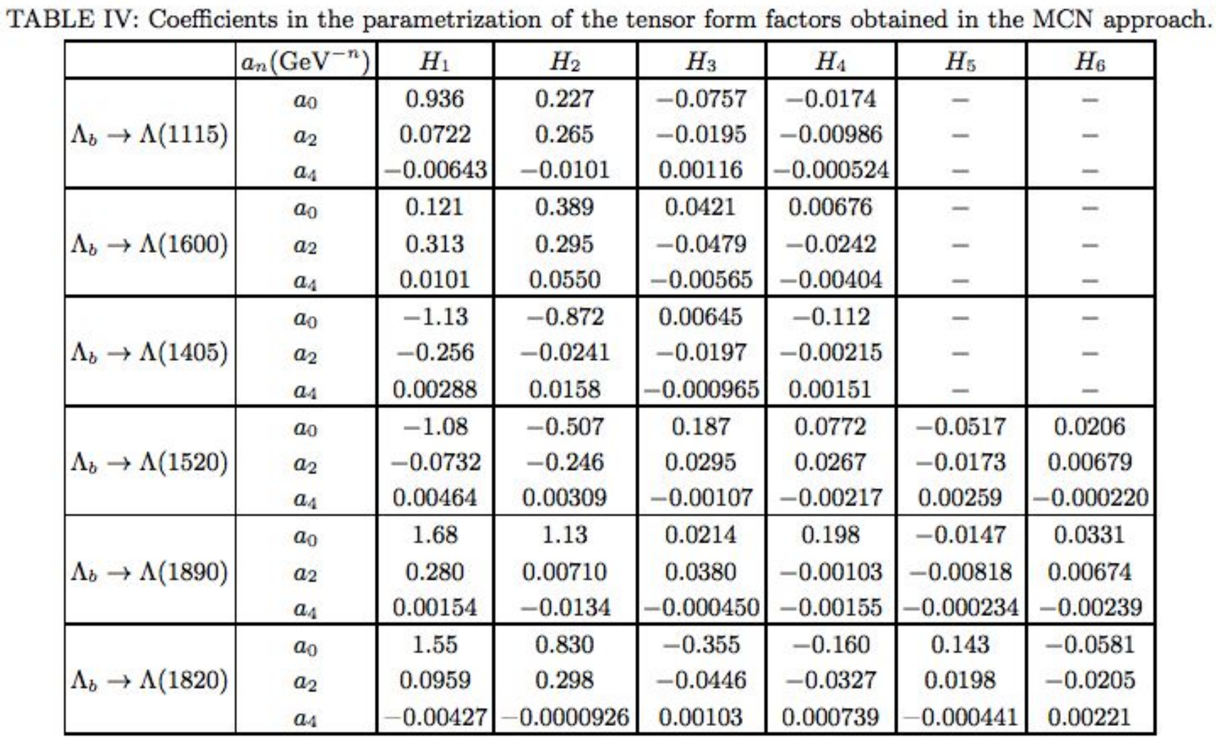

TABLE IV: Coefficients in the parametrization of the tensor form factors obtained in the MCN approach.

	$a_n(\mathrm{GeV}^{-n})$	H_1	H_2	H_3	H_4	H_5	H_6
$\Lambda_b \to \Lambda(1115)$	a_0	0.936	0.227	−0.0757	−0.0174	–	–
	a_2	0.0722	0.265	−0.0195	−0.00986	–	–
	a_4	−0.00643	−0.0101	0.00116	−0.000524	–	–
$\Lambda_b \to \Lambda(1600)$	a_0	0.121	0.389	0.0421	0.00676	–	–
	a_2	0.313	0.295	−0.0479	−0.0242	–	–
	a_4	0.0101	0.0550	−0.00565	−0.00404	–	–
$\Lambda_b \to \Lambda(1405)$	a_0	−1.13	−0.872	0.00645	−0.112	–	–
	a_2	−0.256	−0.0241	−0.0197	−0.00215	–	–
	a_4	0.00288	0.0158	−0.000965	0.00151	–	–
$\Lambda_b \to \Lambda(1520)$	a_0	−1.08	−0.507	0.187	0.0772	−0.0517	0.0206
	a_2	−0.0732	−0.246	0.0295	0.0267	−0.0173	0.00679
	a_4	0.00464	0.00309	−0.00107	−0.00217	0.00259	−0.000220
$\Lambda_b \to \Lambda(1890)$	a_0	1.68	1.13	0.0214	0.198	−0.0147	0.0331
	a_2	0.280	0.00710	0.0380	−0.00103	−0.00818	0.00674
	a_4	0.00154	−0.0134	−0.000450	−0.00155	−0.000234	−0.00239
$\Lambda_b \to \Lambda(1820)$	a_0	1.55	0.830	−0.355	−0.160	0.143	−0.0581
	a_2	0.0959	0.298	−0.0446	−0.0327	0.0198	−0.0205
	a_4	−0.00427	−0.0000926	0.00103	0.000739	−0.000441	0.00221