

Angular distributions of rare baryon decays

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What about baryonic decays?

We've already studied the $b \rightarrow s\ell\ell$ transition for mesons, but until now not much for baryons.

Why are we just studying them now?

We don't find this decays in B-factories, but now LHCb can provide this.

What is new?

- Different systematics from different hadrons (experiment and theory)
- Spin, an extra degree of freedom.

Where do we start?

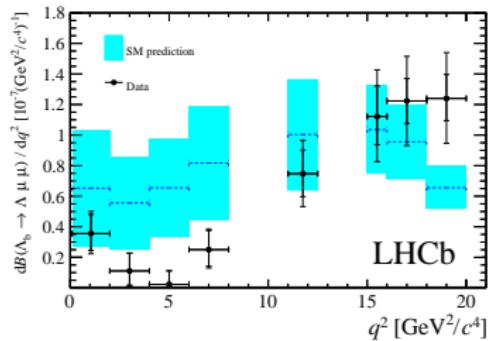
Lightest decays:

- $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\ell^+\ell^-$
- $\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-$

Experimental status of $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\ell^+\ell^-$

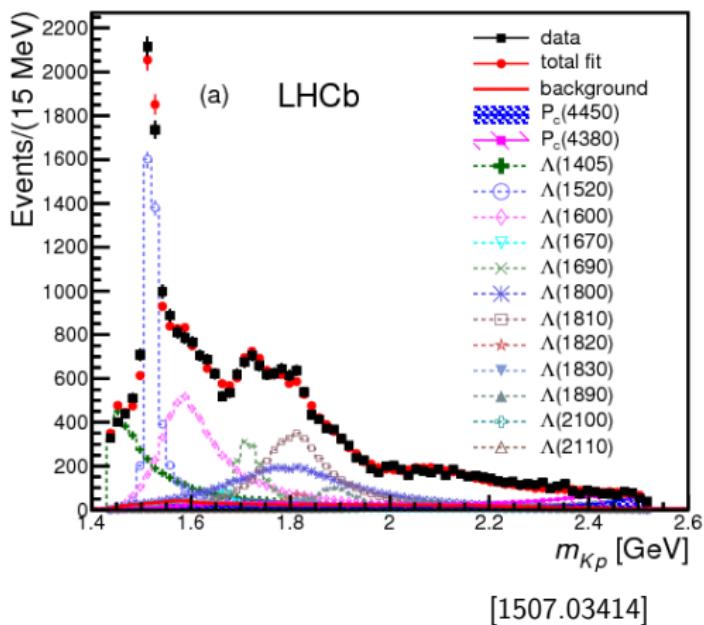
LHCb is able to test rare Λ_b semileptonic decays, in particular
 $\Lambda_b \rightarrow \Lambda(1115)\mu\mu$

- $\Lambda(1115)$ is the lightest baryon as a final state for $b \rightarrow s\ell^+\ell^-$ transition.
- $J^P = 1/2^+$
- Decays mainly into $p\pi$ through weak interaction
- Branching ratio [1503.07138] and angular observables [1808.00264] measured by LHCb.



[1503.07138]

Experimental status of $\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-$



- Not yet measured experimentally.
- We will consider the decay into $\bar{K}N$ through strong interaction (which is the most accessible experimentally)
- $\Lambda^*(1520)$ is dominant at $q_{\ell\ell}^2 = m_{J/\psi}^2$ according to LHCb study on $\Lambda_b \rightarrow J/\Psi(\rightarrow \mu\mu)Kp$
- $\Lambda^*(1520)$ is also expected to be dominant at $q^2 = 0$ according to model by Legger and Schietinger [hep-ph/0605245]
- $J^P = 3/2^-$

$b \rightarrow s\ell^+\ell^-$: Effective Hamiltonian

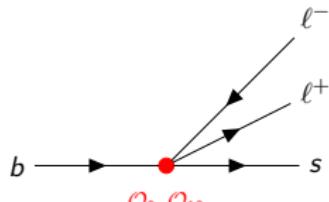
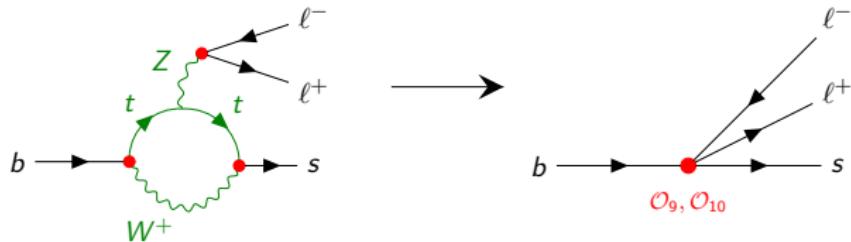
Local operator effective theory for $b \rightarrow s$ transitions. Non-local high energy processes are reduced to local operators as in Fermi Theory.

$$\mathcal{H}_{\text{eff}}(b \rightarrow s\ell^+\ell^-) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

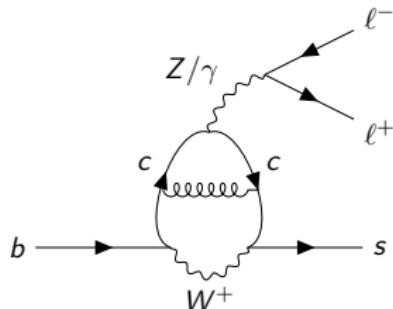
With the SM operators relevant for this analysis

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \quad \mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \quad \mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- Wilson coefficients (\mathcal{C}_i) contain short distance dynamics.
- They are accurately computed in SM and would deviate in presence of NP. Operators absent or suppressed in the SM, can be introduced by NP.



$c\bar{c}$ contributions



Two contributions:

- Resonant (Charmonia, non perturbative QCD)
- Non-Resonant (Approximated with perturbative QCD)

- These contributions go to \mathcal{C}_9 , they are q^2 dependent and **depend on external states**.
- For now we include only perturbative QCD
- LCSR could be used to determine corrections near the $q^2 = 0$ region.
- We could also follow the strategy used by Bobeth et al. [1707.07305] to parametrize $c\bar{c}$ contributions and obtain these parameters from experiment at J/Ψ and $\Psi(2S)$ poles where we expect NP to be negligible.

What has been done until now?

$$\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\ell^+\ell^-$$

- An angular analysis has been done by Böer et al. [1410.2115] and an extension for polarized Λ_b was done by Blake et al. [1710.00746]
- Form factors for the $\Lambda_b \rightarrow \Lambda$ transition have been obtained via Lattice QCD by Detmold et al. [1602.01399]

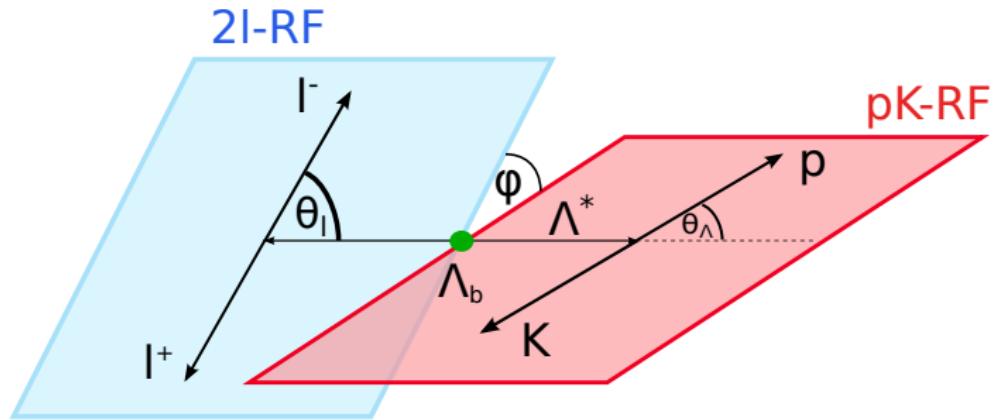
$$\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-$$

- An angular analysis has been done by Descotes-Genon et al. [1903.00448]
- In the case of the $\Lambda_b \rightarrow \Lambda^*$ transition preliminary results are available from Lattice by Meinel et al. [1608.08110]

We will explain first the analysis for $\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-$ and then show the differences with $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\ell^+\ell^-$ since they both share many features.

Angular analysis of $\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-$

Kinematics of $\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-$

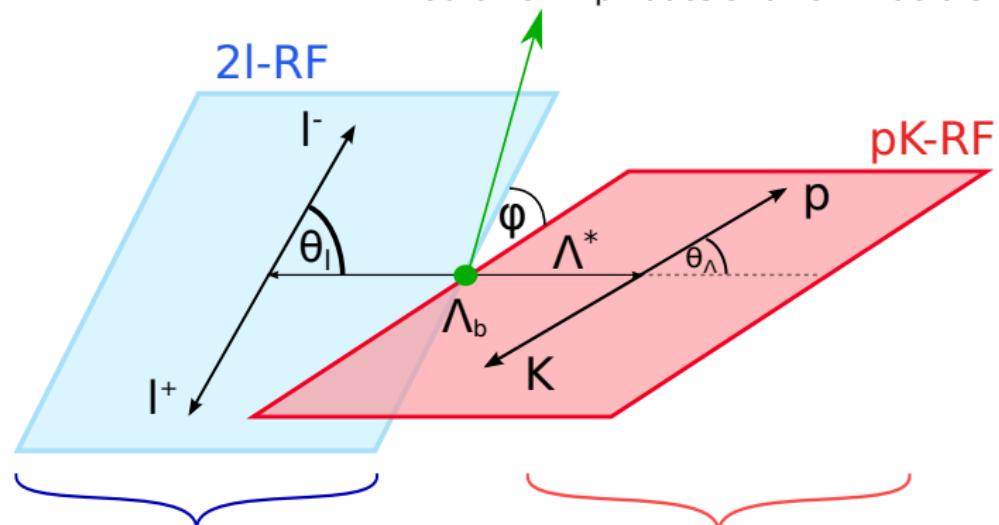


$$\Lambda_b(p, s_\Lambda) \rightarrow \Lambda^*(k, s_{\Lambda^*}) [\rightarrow K(k_1)p(k_2, s_p)] \ell^+(q_1) \ell^-(q_2)$$

$$q \equiv q_1 + q_2 = p - k$$

Kinematics of $\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-$

Effective Hamiltonian Formalism
Helicity Amplitudes
Hadronic Amplitudes and Form Factors



Explicit spin 1/2 solutions
Helicity Amplitudes

Propagation of Spin 3/2 Particle
Breitt Wigner + Narrow Width
Interaction of Spin 3/2 with Kp

Outline of the calculations

We separate the decay into different steps

$$\begin{aligned}\mathcal{M}(\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-) &= \langle \Lambda^*(\rightarrow Kp)\ell^+\ell^- | \mathcal{H}_{int} | \Lambda_b \rangle \\ &= \sum_{s_{\Lambda^*}} \frac{\langle Kp | \mathcal{H}_{int}^{3/2} | \Lambda^*(s_{\Lambda^*}) \rangle \langle \Lambda^*(s_{\Lambda^*}) \ell^+ \ell^- | \mathcal{H}_{eff} | \Lambda_b \rangle}{k^2 - m_{\Lambda^*}^2 + im_{\Lambda^*}\Gamma_{\Lambda^*}}\end{aligned}$$

- **Step 1:** Separation of hadronic and leptonic parts using the helicity amplitude approach.
- **Step 2:** Expression of $\Lambda_b \rightarrow \Lambda^*$ transition in terms of form factors.
- **Step 3:** $\Lambda^* \rightarrow Kp$ decay, narrow width approximation, propagation and explicit solutions U_α for Λ^* (not trivial for spin 3/2).
- Step 4: Take the modulus square and multiply by the phase space.

Helicity Amplitudes

Separate the hadronic and leptonic parts

$$\langle \Lambda^* \ell^+ \ell^- | \mathcal{H}_{\text{eff}} | \Lambda_b \rangle = \sum_{X=V,A,T,T5} C_X H^X [\bar{u}_{\ell^-} J^X v_{\ell^+}]$$

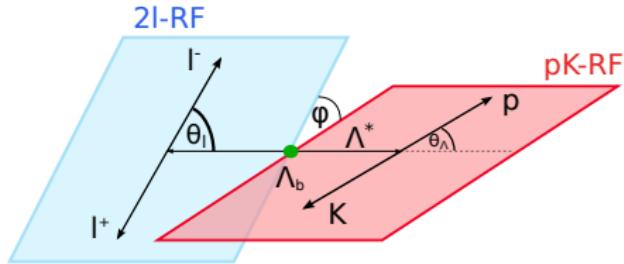
The helicity amplitude approach is particularly convenient in this case (Lorentz invariance, physical interpretation in chain decays)

$$H_m^V(s_{\Lambda_b}, s_{\Lambda^*}) \equiv \varepsilon_\mu^*(m) \langle \Lambda^*(k, s_{\Lambda^*}) | \bar{s} \gamma^\mu b | \Lambda_b(p, s_{\Lambda_b}) \rangle$$

$$L_m^V(s_{\ell^+}, s_{\ell^-}) \equiv \varepsilon_\mu(m) \bar{v}_{\ell^-} \gamma^\mu u_{\ell^+} \quad m \in \{0, +, -, t\}$$

$$\langle \Lambda^* \ell^- \ell^+ | \bar{\ell} \gamma_\mu \ell \bar{s} \gamma^\mu b | \Lambda_b \rangle = \sum_m L_m^V(s_{\ell^+}, s_{\ell^-}) H_m^V(s_{\Lambda_b}, s_{\Lambda^*})$$

They are frame independent, thus we can obtain the hadronic and leptonic amplitudes each on the simplest frame.



Hadronic Amplitudes

- Written as a function of form factors and all the Lorentz tensors available.
- Usually chosen on a base that simplifies the Helicity amplitudes.

$$\langle \Lambda^* | \bar{s} \gamma^\mu b | \Lambda_b \rangle = \bar{U}_\alpha(k, s_{\Lambda^*}) \left\{ p^\alpha \left[F_1(q^2) p^\mu + F_2(q^2) k^\mu + F_3(q^2) \gamma^\mu \right] + F_4(q^2) g^{\alpha\mu} \right\} u(p, s_{\Lambda_b})$$
$$\langle \Lambda^* | \bar{s} \gamma^\mu b | \Lambda_b \rangle = \bar{U}_\alpha(k, s_{\Lambda^*}) \left\{ p^\alpha \left[f_t^V(q^2)(M_{\Lambda_b} - m_{\Lambda^*}) \frac{q^\mu}{q^2} + f_\perp^V(q^2)(\gamma^\mu - 2 \frac{m_{\Lambda^*}}{s_+} p^\mu - 2 \frac{M_{\Lambda_b}}{s_+} k^\mu) \right. \right. \\ \left. \left. + f_0^V(q^2) \frac{M_{\Lambda_b} + m_{\Lambda^*}}{s_+} (p^\mu + k^\mu - \frac{q^\mu}{q^2} (M_{\Lambda_b}^2 - m_{\Lambda^*}^2)) \right] \right. \\ \left. + f_g^V(q^2) \left[g^{\alpha\mu} + m_{\Lambda^*} \frac{p^\alpha}{s_-} \left(\gamma^\mu - 2 \frac{k^\mu}{m_{\Lambda^*}} + 2 \frac{m_{\Lambda^*} p^\mu + m_{\Lambda_b} k^\mu}{s_+} \right) \right] \right\} u(p, s_{\Lambda_b})$$

$\Lambda_b \rightarrow \Lambda^*$ form factors

- 14 form factors in total
- Only preliminary results are available from lattice simulations [1608.08110]
- Quark model from [1108.6129] used for numerical illustration (educated guess of the errors).

Transversity Amplitudes

The $\Lambda_b \rightarrow \Lambda^* \ell^+ \ell^-$ decay is described by 12 transversity amplitudes.

$$TA = \left\{ B_{\perp 1}^{L(R)}, B_{||1}^{L(R)}, A_{\perp 1}^{L(R)}, A_{||1}^{L(R)}, A_{\perp 0}^{L(R)}, A_{||0}^{L(R)} \right\}$$

$$B_{\perp 1}^{L(R)} \propto \left(C_{9,10,+}^{L(R)} H_+^V(-1/2, -3/2) - \frac{2m_b(C_7 + C_{7'})}{q^2} H_+^T(-1/2, -3/2) \right)$$

⋮

$$A_{||0}^{L(R)} \propto \left(C_{9,10,-}^{L(R)} H_0^A(+1/2, +1/2) + \frac{2m_b(C_7 - C_{7'})}{q^2} H_0^{T5}(+1/2, +1/2) \right)$$

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

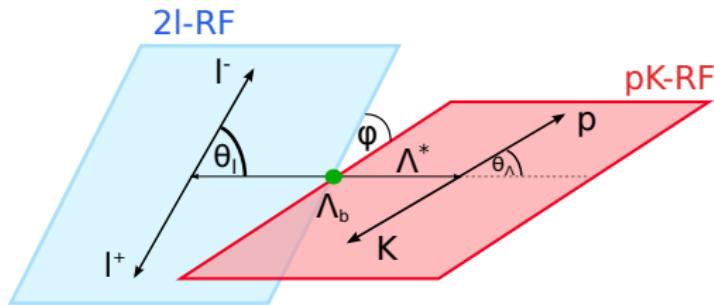
$$C_{9,10,-}^{L(R)} = (C_9 \mp C_{10}) - (C_{9'} \mp C_{10'})$$

And their normalization is such that:

$$\frac{d\Gamma(\Lambda_b \rightarrow \Lambda^* \ell^+ \ell^-)}{dq^2} = \sum_{X \in TA} |X|^2$$

s_{Λ_b}	s_{Λ^*}	Amplitudes
$\pm \frac{1}{2}$	$\pm \frac{1}{2}$	$A_{\perp 0}^{L(R)}, A_{ 0}^{L(R)}$
$\pm \frac{1}{2}$	$\mp \frac{1}{2}$	$A_{\perp 1}^{L(R)}, A_{ 1}^{L(R)}$
$\pm \frac{1}{2}$	$\pm \frac{3}{2}$	$B_{\perp 1}^{L(R)}, B_{ 1}^{L(R)}$

Angular Observables of $\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-$ [1903.00448]



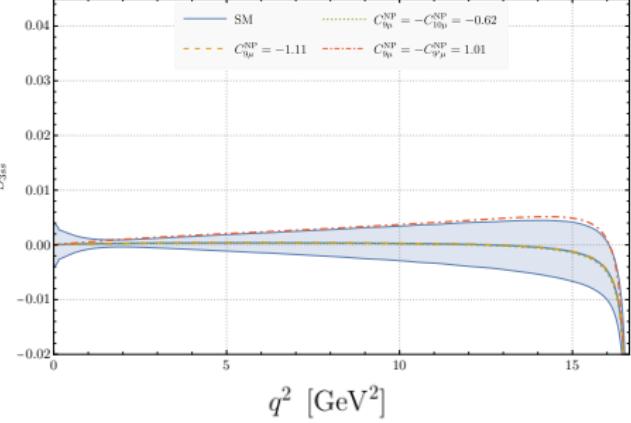
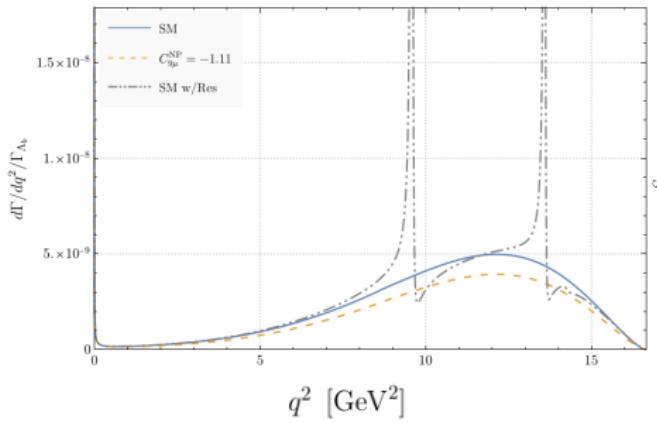
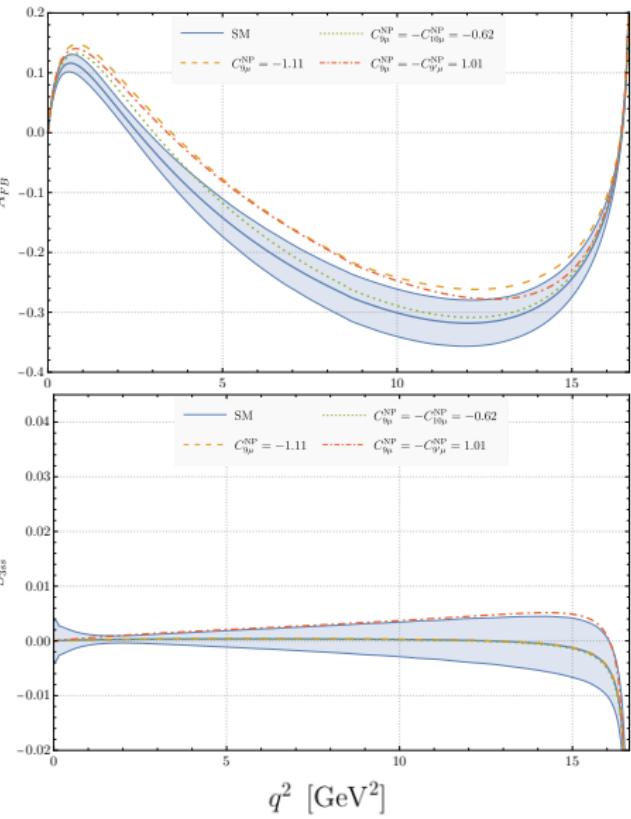
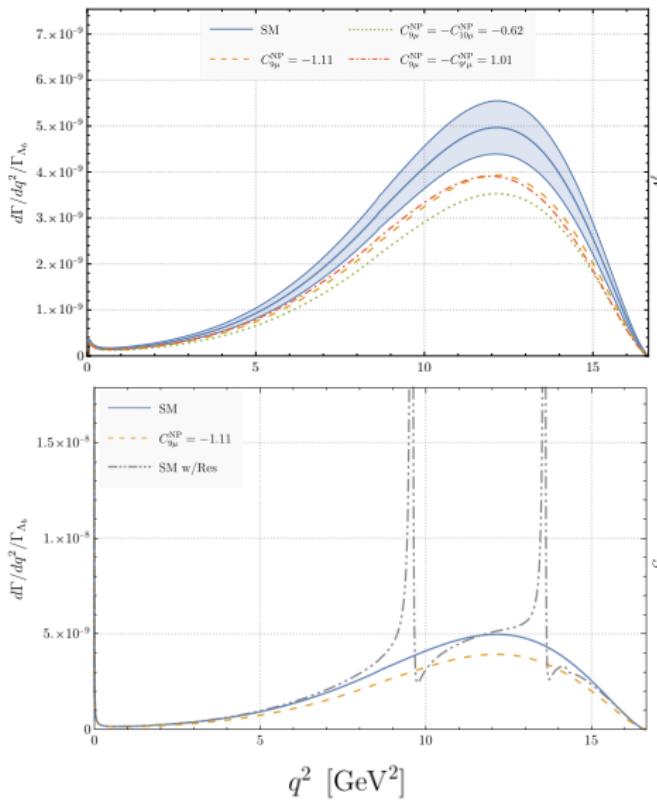
$$\frac{d^4\Gamma(\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\ell^+\ell^-)}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} = \frac{3}{8\pi} L(q^2, \theta_\ell, \theta_\Lambda, \phi)$$

$$\begin{aligned} L(q^2, \theta_\ell, \theta_\Lambda, \phi) = & \cos^2 \theta_\Lambda (L_{1c} \cos \theta_\ell + L_{1cc} \cos^2 \theta_\ell + L_{1ss} \sin^2 \theta_\ell) \\ & + \sin^2 \theta_\Lambda (L_{2c} \cos \theta_\ell + L_{2cc} \cos^2 \theta_\ell + L_{2ss} \sin^2 \theta_\ell) \\ & + \sin^2 \theta_\Lambda (L_{3ss} \sin^2 \theta_\ell \cos^2 \phi + L_{4ss} \sin^2 \theta_\ell \sin \phi \cos \phi) \\ & + \sin \theta_\Lambda \cos \theta_\Lambda \cos \phi (L_{5s} \sin \theta_\ell + L_{5sc} \sin \theta_\ell \cos \theta_\ell) \\ & + \sin \theta_\Lambda \cos \theta_\Lambda \sin \phi (L_{6s} \sin \theta_\ell + L_{6sc} \sin \theta_\ell \cos \theta_\ell) \end{aligned}$$

- Angular structure in agreement with Gratrex et al. [1506.03970].
- $\theta_\Lambda \rightarrow \theta_\Lambda + \pi$ symmetry related to P-conserving nature of strong decays.
- HQET and SCET limits simplify the form factors, f_g and B amplitudes vanish.
- 3 independent observables in both limits.
- Does not allow us to derive non trivial ratios of observables only sensitive to Wilson coefficients.

$$\begin{aligned} L_{1c} &\propto \left(\text{Re}(A_{\perp 1}^L A_{||1}^{L*}) - (L \leftrightarrow R) \right), \\ L_{3ss} &\propto \left(\text{Re}(B_{||1}^L A_{||1}^{L*}) - \text{Re}(B_{\perp 1}^L A_{\perp 1}^{L*}) + (L \leftrightarrow R) \right), \\ &\vdots \end{aligned}$$

$\Lambda_b \rightarrow \Lambda^*(\rightarrow Kp)\mu^+\mu^-$ results [1903.00448]



Differences of $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\ell^+\ell^-$ [1410.2115]

- Only 8 transversity amplitudes present.
- 10 form factors in total, results by Detmold et al. [1602.01399].
- $\Lambda(1115)$ decays mainly through **weak interaction**.

Λ decay

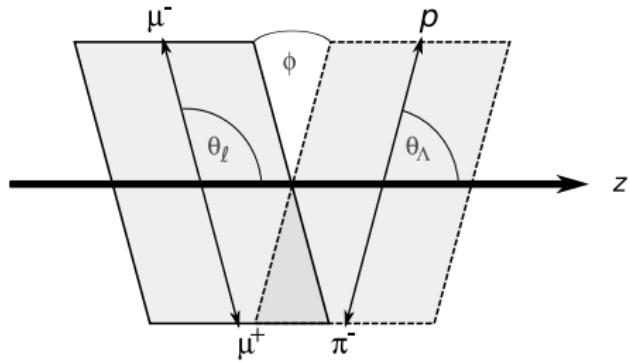
The hadronic matrix element which determines the $\Lambda \rightarrow N\pi$ decay can be parametrized as

$$\langle p(k_1, s_N) \pi^-(k_2) | [\bar{d} \gamma_\mu P_L u] [\bar{u} \gamma^\mu P_L s] |\Lambda(k, s_\Lambda) \rangle = [\bar{u}(k_1, s_N)(\xi \gamma_5 + \omega) u(k, s_\Lambda)]$$

where we find a parity violating term (not present for the strong decay studied before) parametrized by

$$\alpha = \frac{-2 \operatorname{Re} \{\omega \xi\}}{\sqrt{\frac{r_-}{r_+}} |\xi|^2 + \sqrt{\frac{r_+}{r_-}} |\omega|^2} \approx 0.7 - 0.75.$$

Angular Observables for $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\ell^+\ell^-$ [1410.2115]



- Angular structure in agreement with Gratrex et al. [1506.03970]
- $\theta_\Lambda \rightarrow \theta_\Lambda + \pi$ symmetry not present because of P-violating nature of weak decays (recovered whe $\alpha \rightarrow 0$).
- Full analysis including polarized Λ_b from Blake et al. also available [1710.00746]

$$\frac{d^4\Gamma(\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\ell^+\ell^-)}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} = \frac{3}{8\pi} K(q^2, \theta_\ell, \theta_\Lambda, \phi)$$

$$K(q^2, \cos\theta_\ell, \cos\theta_\Lambda, \phi) = (K_{1ss} \sin^2\theta_\ell + K_{1cc} \cos^2\theta_\ell + K_{1c} \cos\theta_\ell) \\ + (K_{2ss} \sin^2\theta_\ell + K_{2cc} \cos^2\theta_\ell + K_{2c} \cos\theta_\ell) \cos\theta_\Lambda \\ + (K_{3sc} \sin\theta_\ell \cos\theta_\ell + K_{3s} \sin\theta_\ell) \sin\theta_\Lambda \sin\phi \\ + (K_{4sc} \sin\theta_\ell \cos\theta_\ell + K_{4s} \sin\theta_\ell) \sin\theta_\Lambda \cos\phi.$$

$$K_{1cc}(q^2) = \frac{1}{2} \left[|A_{\perp 1}^R|^2 + |A_1^R|^2 + (R \leftrightarrow L) \right],$$

$$K_{2cc}(q^2) = +\alpha \text{Re} \left\{ A_{\perp 1}^R A_1^{*R} + (R \leftrightarrow L) \right\},$$

⋮

Angular Observables for $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\ell^+\ell^-$ [1410.2115]

Exploiting Form-Factor Symmetries at Low Recoil (HQET)

$$X_1 \equiv \frac{K_{1c}}{K_{2cc}} = -\frac{\text{Re}\{\rho_2\}}{\alpha \text{Re}\{\rho_4\}},$$

If we assume the absence of chirality-flipped operators (including $\mathcal{C}_{7'} \rightarrow 0$ in the SM), we obtain

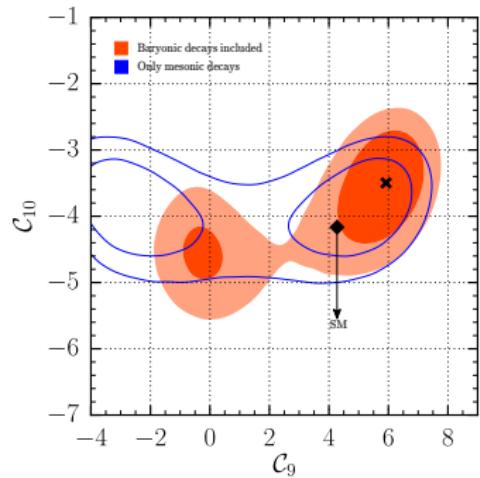
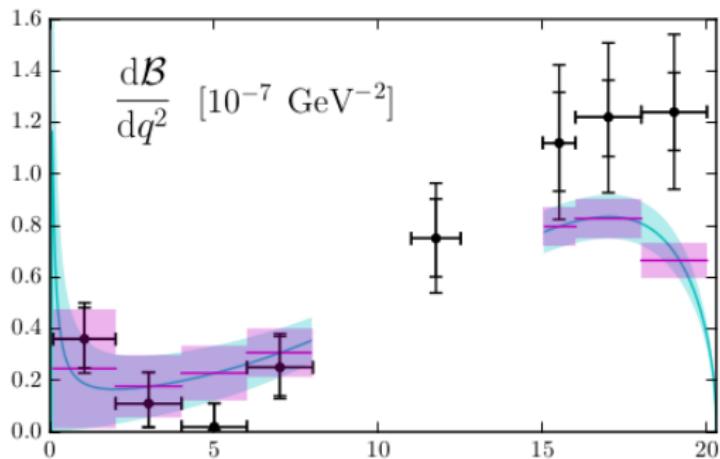
$$X_1 \rightarrow -\frac{2\rho_2}{\alpha\rho_1}, \quad X_2 \equiv \frac{K_{1cc}}{K_{2c}} = -\frac{2\alpha\rho_2}{\rho_1}.$$

For the commonly used large recoil bin $1 \text{ GeV}^2 \leq q^2 \leq 6 \text{ GeV}^2$, by taking $\mathcal{C}_9^{\text{BM1}} = \mathcal{C}_9^{\text{SM}} - 1$ and $\mathcal{C}_{9'}^{\text{BM1}} = 1$, we find

$$\begin{aligned} \langle X_1 \rangle^{\text{SM}} &= +0.08^{+0.12}_{-0.09}, & \langle X_1 \rangle^{\text{BM1}} &= -0.49^{+0.07}_{-0.08}, \\ \langle X_2 \rangle^{\text{SM}} &= +0.17^{+0.04}_{-0.17}, & \langle X_2 \rangle^{\text{BM1}} &= -0.22^{+0.03}_{-0.03}. \end{aligned}$$

$$\begin{aligned} \rho_1^\pm &= \frac{1}{2} \left(|\mathcal{C}_\pm^R|^2 + |\mathcal{C}_\pm^L|^2 \right) & \rho_3^\pm &= \frac{1}{2} \left(|\mathcal{C}_\pm^R|^2 - |\mathcal{C}_\pm^L|^2 \right) & C_+^{R(L)} &= \left((\mathcal{C}_9 + \mathcal{C}_{9'}) + \frac{2\kappa m_b}{q^2} (\mathcal{C}_7 + \mathcal{C}_{7'}) \pm (\mathcal{C}_{10} + \mathcal{C}_{10'}) \right) \\ \rho_2 &= \frac{1}{4} \left(\mathcal{C}_+^R \mathcal{C}_-^{R*} - \mathcal{C}_-^L \mathcal{C}_+^{L*} \right) & \rho_4 &= \frac{1}{4} \left(\mathcal{C}_+^R \mathcal{C}_-^{R*} + \mathcal{C}_-^L \mathcal{C}_+^{L*} \right) & C_-^{R(L)} &= \left((\mathcal{C}_9 - \mathcal{C}_{9'}) + \frac{2\kappa m_b}{q^2} (\mathcal{C}_7 - \mathcal{C}_{7'}) \pm (\mathcal{C}_{10} - \mathcal{C}_{10'}) \right) \end{aligned}$$

$\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\mu^+\mu^-$ results [1602.01399]



- Differential branching fraction deviation not yet statistically (1.6σ) but in the opposite direction of $B \rightarrow K^{(*)}\mu^+\mu^-$ and $B_s \rightarrow \phi\mu^+\mu^-$ deviations (could be explained by quark-hadron duality violation or Λ_b prod fraction).
- A negative shift in C_9 alone (simplest scenario for mesonic observables) would further lower the predicted $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$ differential branching fraction.
- Bayesian analysis by Meinel et al. [1603.02974] shows in detail how global fits could be affected.

Connection with $\Lambda_b \rightarrow \Lambda^{(*)}\gamma$

The branching ratio for radiative decay $\Lambda_b \rightarrow \Lambda^*\gamma$ is proportional to

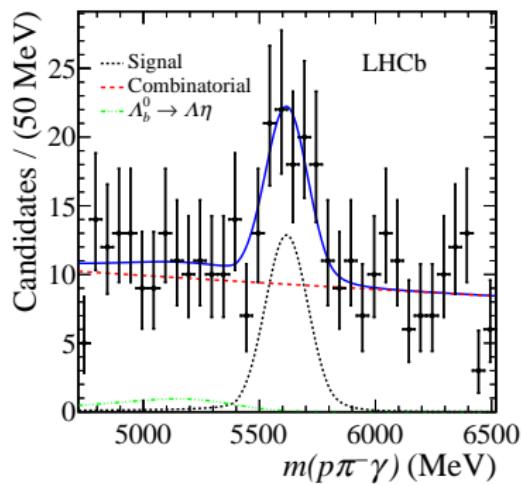
$$\lim_{q^2 \rightarrow 0} (q^2 \sum_{X=A,B} |X|^2),$$

- At $q^2 \rightarrow 0$ limit only two spin configuration contributes ($\mathcal{C}_7^{(\prime)}$)
- Number of independent form factors reduced.

$$f_\perp^{T5}(q^2), f_\perp^T(q^2) \xrightarrow[q^2 \rightarrow 0]{} f_\perp^T(0)$$

$$f_g^{T5}(q^2), f_g^T(q^2) \xrightarrow[q^2 \rightarrow 0]{} f_g^T(0)$$

- Possibility to extract information about the form factors normalization (multiplied by $\mathcal{C}_7^{(\prime)}$) from this decay.
- The same should be true for $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi)\gamma$



[1904.06697]

Conclusions

- Rare baryon decays are another way to test $b \rightarrow s\ell^+\ell^-$ and exploit LHCb data.
- Sensitivity mainly for \mathcal{C}_9 and \mathcal{C}'_9 .
- Connection with $\Lambda_b \rightarrow \Lambda^{(*)}\gamma$ to be exploited.
- We hope to stimulate the study of $\Lambda_b \rightarrow \Lambda^*\ell^+\ell^-$ on LHCb and by Lattice QCD people.
- Charmonium contribution is an open question both at low and high q^2 .

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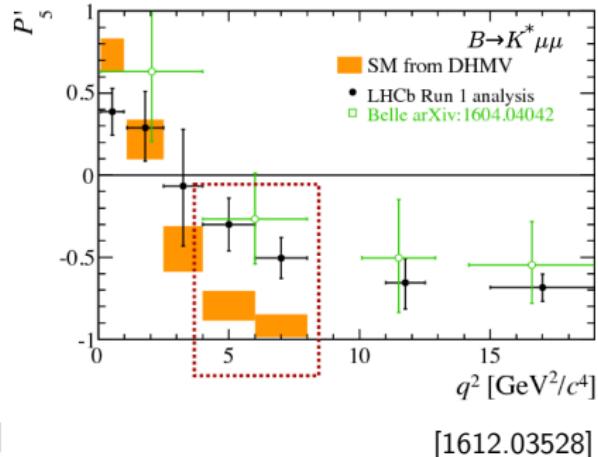
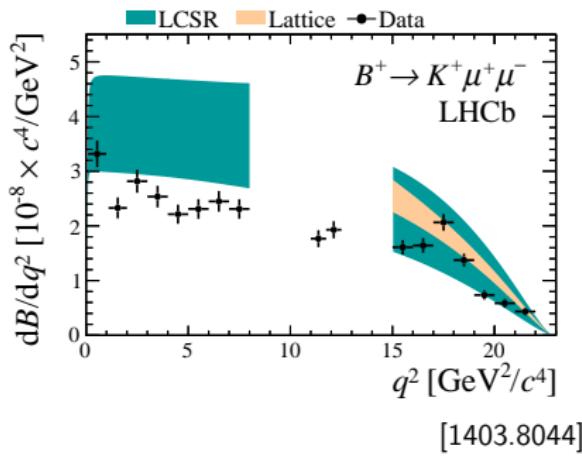


Back up

B-physics anomalies

Deviations from the SM expectations in $b \rightarrow s\ell^+\ell^-$:

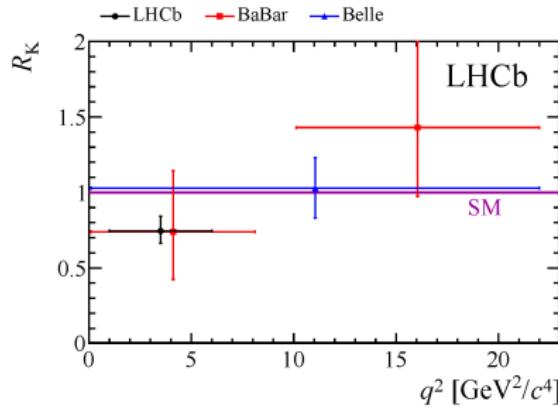
- Branching ratios and angular observables in $b \rightarrow s\mu\mu$, $B \rightarrow K\mu\mu$, $B \rightarrow K^*\mu\mu$, $B_s \rightarrow \phi\mu\mu$



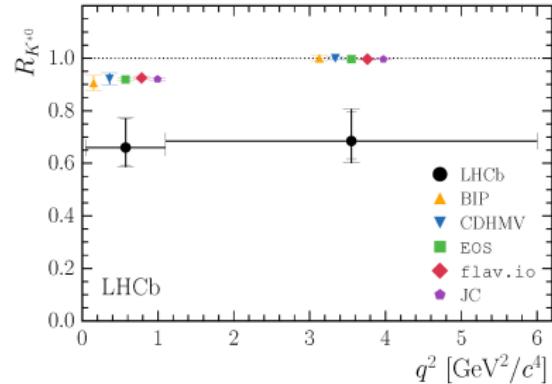
B-physics anomalies

Deviations from the SM expectations in $b \rightarrow s\ell^+\ell^-$:

- Branching ratios and angular observables in $b \rightarrow s\mu\mu$, $B \rightarrow K\mu\mu$, $B \rightarrow K^*\mu\mu$, $B_s \rightarrow \phi\mu\mu$
- Lepton-flavour universality ratio comparing $b \rightarrow s\mu\mu$ and $b \rightarrow s ee$, $B \rightarrow K\ell^+\ell^-$, $B \rightarrow K^*\ell^+\ell^-$



[1406.6482]



[1705.05802]

Spin 3/2 Field treatment

Rarita-Schwinger Equations

Equation for a 3/2 spin field obtained combining $1 \otimes \frac{1}{2} = \frac{3}{2} \oplus \frac{1}{2}$

$$(\square - m^2)\Psi^\nu(x) = 0 \quad \partial_\nu\Psi^\nu(x) = 0 \quad (\not{\partial} + m)\Psi^\nu(x) = 0$$

$\gamma_\nu\Psi^\nu(x) = 0 \rightarrow$ Preserve only the 3/2 spin part

$$U_{3/2,m}^\nu(\vec{p}) = \sum_{\lambda=-1}^1 \sum_{r=-1/2}^{1/2} \epsilon_\lambda^\nu(\vec{p}) u_r(\vec{p}) \langle 1, \lambda; \frac{1}{2}, r | \frac{3}{2}, m \rangle$$

[10.1140/epjc/s2002-01026-1]

Λ^* propagation and decay

3/2 spin Propagator

$$P_{RS}^{\alpha\beta} = \frac{\not{k} + M}{k^2 - M^2} \left(g^{\alpha\beta} - \frac{1}{3}\gamma^\alpha\gamma^\beta - \frac{2k^\alpha k^\beta}{3M^2} + \frac{\gamma^\beta k^\alpha - \gamma^\alpha k^\beta}{3M} \right)$$

[nucl-th/9812043]

ΛKp interaction

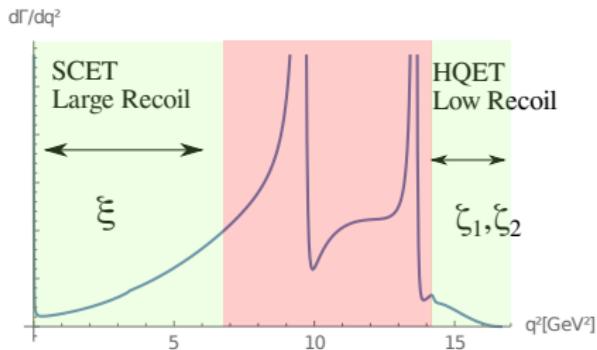
$$\mathcal{L}_{int}^{3/2} = g \varepsilon^{\mu\nu\alpha\beta} (\partial_\mu \Psi_\nu) \gamma_\alpha \psi \partial_\beta \phi + h.c.$$

[10.1103/PhysRevD.58.096002]

- Lowest order lorentz invariant coupling for a 3/2 spin field.
- Preserves only the 3/2 spin component.
- Done in analogy with $\Delta \rightarrow \pi N$

Low- and large- recoil limits (HQET and SCET)

- SCET and HQET approximations reduce the number of form factors on leading order $\left(\mathcal{O}\left(\alpha_s, \frac{\Lambda_{QCD}}{m_b}\right)\right)$:

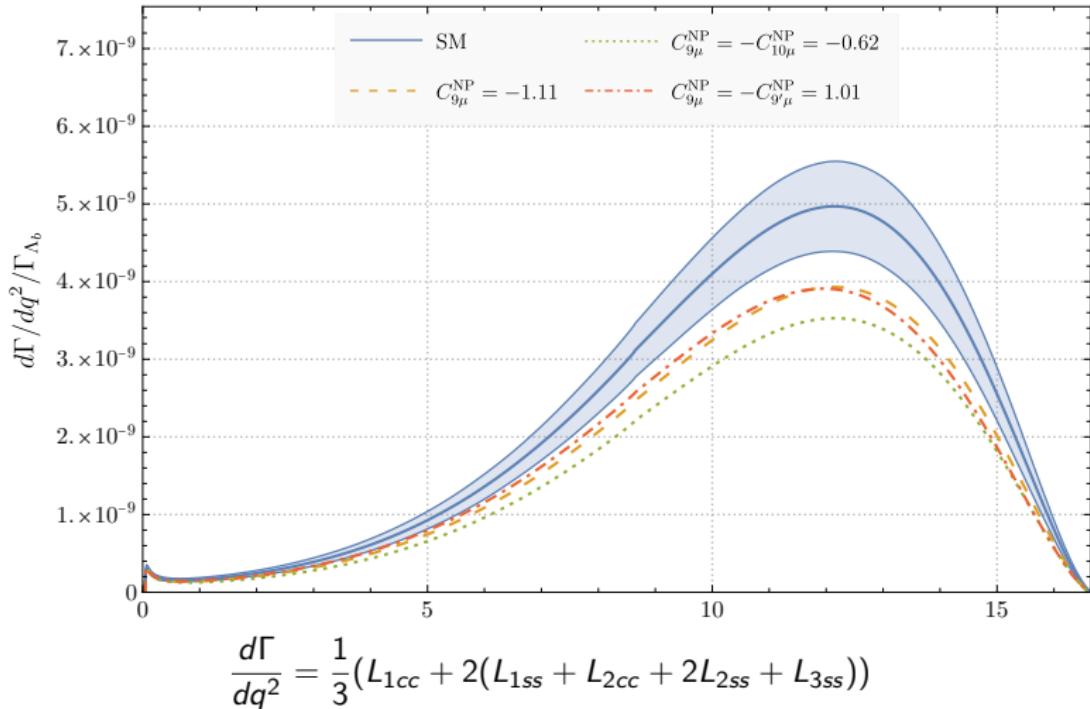


- SCET → 1 Form factor (ξ)
- HQET → 2 Form factor (ζ_1, ζ_2)

- Corrections on $\mathcal{O}(\alpha_s)$ are computable and they don't affect the amount of form factors.
- Corrections on $\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)$ will add new form factors to consider.
- These limits can be used to identify combinations of angular observables with smaller hadronic uncertainties

Simple Observables

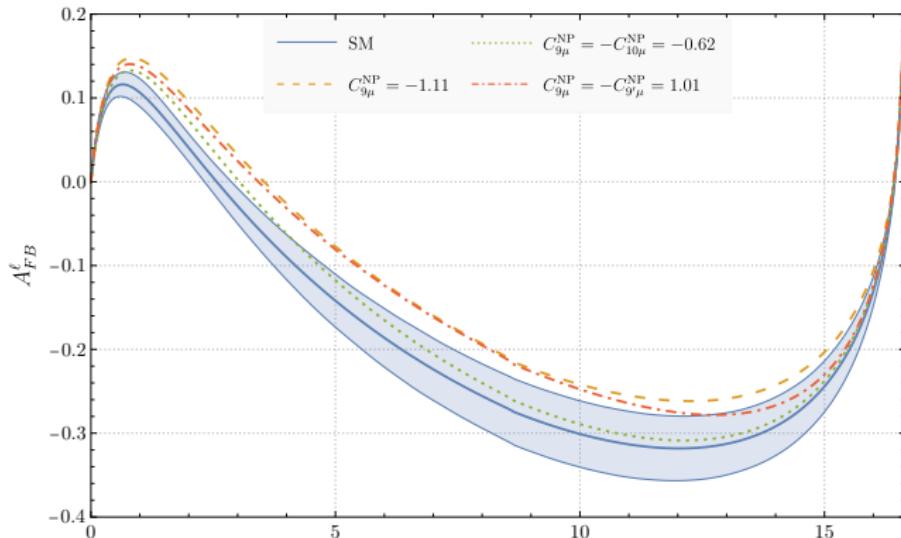
- Differential decay width



Simple Observables

- Forward-Backward asymmetry for the leptonic scattering angle

$$A_{FB}^{\ell} = \frac{3(L_{1c} + 2L_{2c})}{2(L_{1cc} + 2(L_{1ss} + L_{2cc} + 2L_{2ss} + L_{3ss}))}$$



- Baryonic and combined Forward-backward asymmetry

$$A_{FB}^{\Lambda} = 0 \quad A_{FB}^{\ell\Lambda} = 0$$

Simple Observables

- CP-averages and CP-assymetry

$$S_i = \frac{L_i + \bar{L}_i}{d(\Gamma + \bar{\Gamma})/dq^2} \quad A_i = \frac{L_i - \bar{L}_i}{d(\Gamma + \bar{\Gamma})/dq^2}$$

$$S_{1c} \propto \text{Re}(A_{\perp 1}^R A_{\parallel 1}^{R*}) - (L \leftrightarrow R)$$

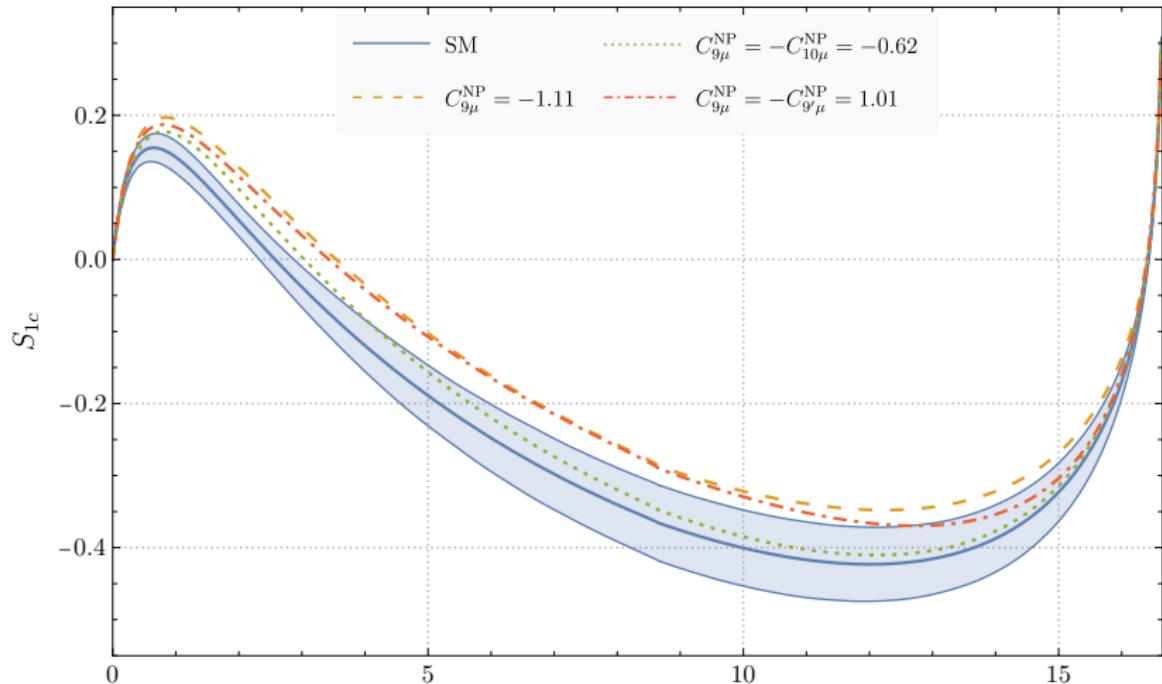
$$S_{3ss} \propto \sum_{R(L)} \text{Re}(B_{\parallel 1}^{R(L)} A_{\parallel 1}^{R(L)*}) - \text{Re}(B_{\perp 1}^{R(L)} A_{\perp 1}^{R(L)*})$$

$$S_{2cc} - \frac{S_{1cc}}{4} \propto \sum_{R(L)} |B_{\parallel 1}^{R(L)}|^2 + |B_{\perp 1}^{R(L)}|^2$$

$$S_{5sc} \propto \sum_{R(L)} \text{Re}(B_{\parallel 1}^{R(L)} A_{\parallel 0}^{R(L)*}) - \text{Re}(B_{\perp 1}^{R(L)} A_{\perp 0}^{R(L)*})$$

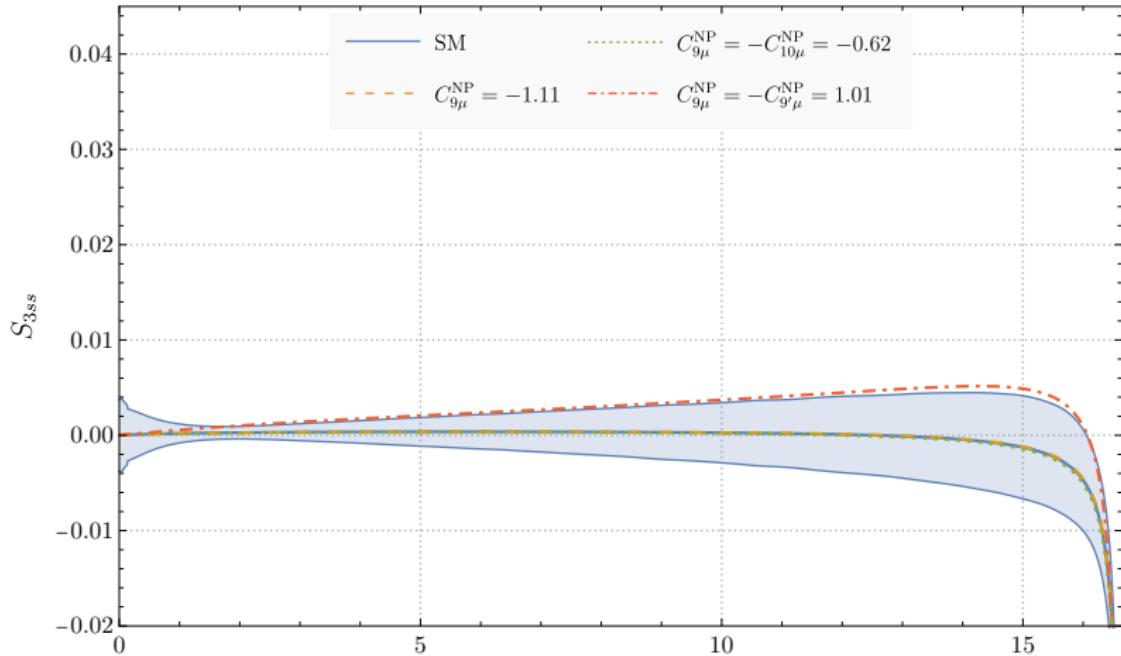
Simple Observables

$$S_{1c} \propto \text{Re}(A_{\perp 1}^R A_{\parallel 1}^{R*}) - (L \leftrightarrow R)$$



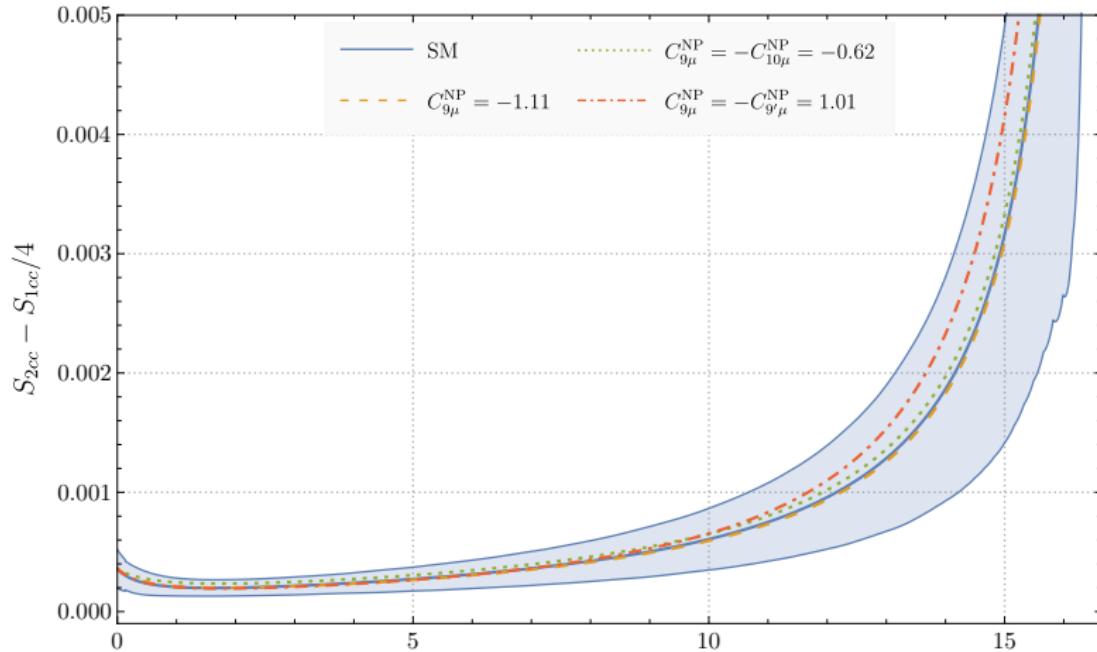
Simple Observables

$$S_{3ss} \propto \sum_{R(L)} \text{Re}(B_{\parallel 1}^{R(L)} A_{\parallel 1}^{R(L)*}) - \text{Re}(B_{\perp 1}^{R(L)} A_{\perp 1}^{R(L)*})$$



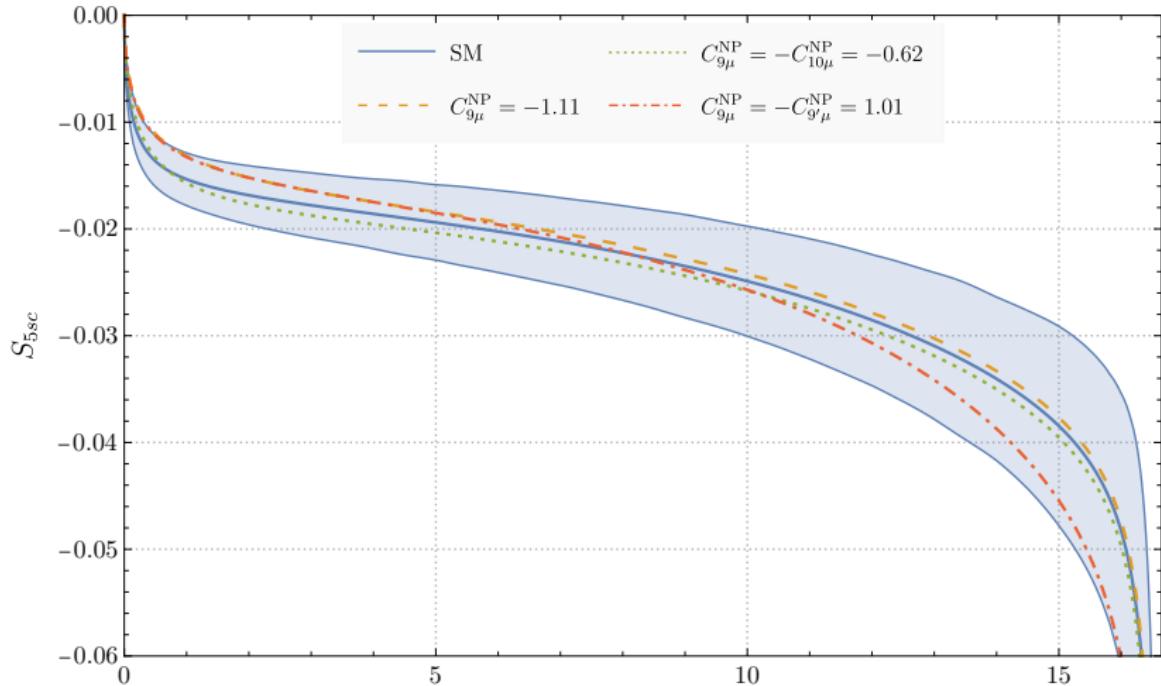
Simple Observables

$$S_{2cc} - \frac{S_{1cc}}{4} \propto \sum_{R(L)} |B_{||1}^{R(L)}|^2 + |B_{\perp 1}^{R(L)}|^2$$

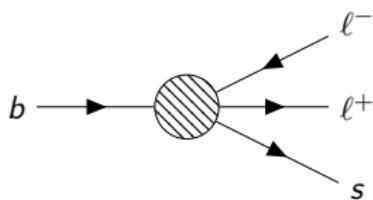


Simple Observables

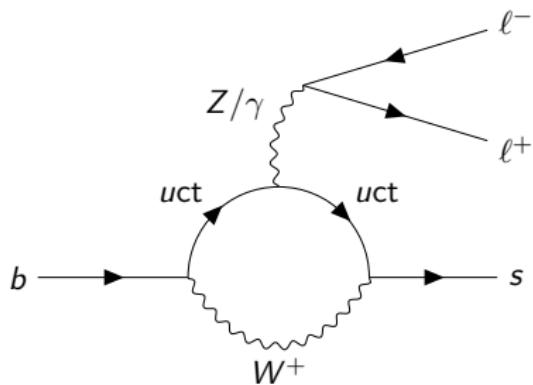
$$S_{5sc} \propto \sum_{R(L)} \text{Re}(B_{\parallel 1}^{R(L)} A_{\parallel 0}^{R(L)*}) - \text{Re}(B_{\perp 1}^{R(L)} A_{\perp 0}^{R(L)*})$$



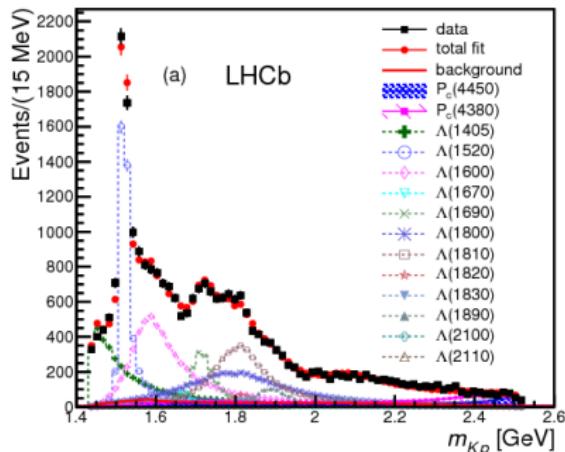
$b \rightarrow s\ell^+\ell^-$ transition



- Consistent pattern of deviations from the SM
- FCNC process, which is loop suppressed in the SM (potential sensitivity to NP)
- Several studies have been done for this transition on the meson side ($B \rightarrow K^{(*)}\ell^+\ell^-$, $B_s \rightarrow \phi\ell^+\ell^-$).



Separating the different $\Lambda_b \rightarrow K p \ell^+ \ell^-$ signals



[1507.03414]

- Highly complex to compute all different contributions, we would need to compute FF for each of them and understand how they interfere (relative strong phase).
- Possibility to separate the signals because of their different nature (spin).
- We can build observables that would differ strongly for spin 1/2 and 3/2 (this can be used to check the selection is correctly done)

$$\Lambda(1115) \rightarrow 1/2^+$$

$$\Lambda(1405) \rightarrow 1/2^-$$

$$\Lambda(1520) \rightarrow 3/2^-$$

$$\Lambda(1600) \rightarrow 1/2^+$$

$$\Lambda(1670) \rightarrow 1/2^-$$

$$\Lambda(1690) \rightarrow 3/2^-$$

Form Factors

$\Lambda_b \rightarrow \Lambda$ form factors

- 10 form factors in total
- Results are available from lattice simulation [1602.01399]

$\Lambda_b \rightarrow \Lambda^*$ form factors

- 14 form factors in total
- Only preliminary results are available from lattice simulations [1608.08110]

