Semi-leptonic *b*-hadron decays

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Belle Analysis Workshop 2024, IIT Hyderabad, October 19-23, 2024

Motivations

$b \to s\mu^+\mu^-$

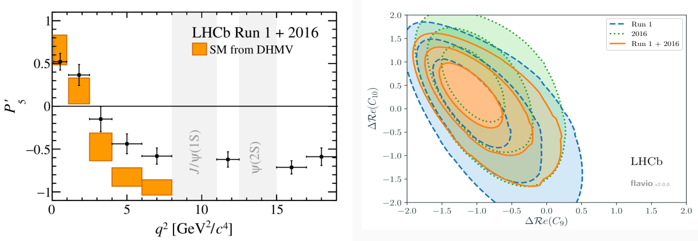
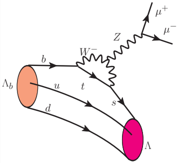


Figure 1: Figure from L Carus 2405.10882

Also the $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ lower than SM predictions

Motivations

$\Lambda_b(5620)$, *udb*, spin 1/2
$\Lambda(1115)$: *uds* spin 1/2
$\Lambda^*(1520)$: *uds* spin 3/2



New avenue to test $b \to s\ell^+\ell^-$ FCNC (LHCb, FCC-ee)

Unique features:

- In $\Lambda_b \to \Lambda(\to N\pi)\ell\ell$ the $\Lambda \to N\pi$ decay is weak $s \to d$ transition – additional observable.
- Unpolarized Λ_b decay 10 observables. Polarized Λ_b decay 34 observables
- Compared to $B \to K^*$ ff, the LQCD ff of $\Lambda_b \to \Lambda$ expected to be precise due to Λ stability under strong interaction *Detmold/Meinel Phys. Rev. D 93 (2016) no. 7, 074501*
- In $\Lambda_b \to \Lambda^*(\to N\bar{K})\ell\ell$, the $\Lambda^* \to N\bar{K}$ is strong, but Λ^* is spin 3/2

$\Lambda_b \to \Lambda(\to N\pi)\mu^+\mu^-$

- $\mathcal{B}(\Lambda_b \to \Lambda\mu^+\mu^-) = (1.73 \pm 0.42 \pm 0.55) \times 10^{-6}$, signal yield 24±5, evidence q^2 above $\psi(2S)$
  CDF Collaboration Phys. Rev. Lett. 107, 201802 (2011)

- $\mathcal{B}(\Lambda_b \to \Lambda\mu^+\mu^-) = (0.96 \pm 0.16 \pm 0.13 + 0.21) \times 10^{-6}$, yield 78±12, 1fb^{-1},
  LHCb Collaboration Phys. Lett. B 725, 25 (2013)

- *LHCb Collaboration JHEP 06, 115 (2015)* , 3fb^{-1}, angular observables in $15 < q^2 < 20\text{GeV}^2$

$$A(A^{\ell}_{\rm FB}) = -0.05 \pm 0.09 \pm 0.03\,, \quad A^{h}_{\rm FB} = -0.29 \pm 0.07 \pm 0.03$$

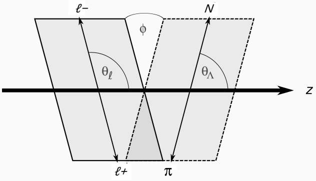
- *LHCb Collaboration JHEP 09, 146(2018)* . Angular analysis $15 < q^2 < 20\text{GeV}^2$

$$\begin{aligned} A^{\ell}_{\rm FB} &= -0.39 \pm 0.04 \pm 0.01\,, \quad A^{h}_{\rm FB} = -0.30 \pm 0.05 \pm 0.02\,, \\ A^{\ell h}_{FB} &= +0.25 \pm 0.04 \pm 0.01\,, \end{aligned}$$

Unpolarized $\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$ Decay kinematics

The decay proceeds in two steps

$$\Lambda_b(p, s_p) \to \Lambda(k, s_k)\ell^+(q_1)\ell^-(q_2) \quad \text{followed by} \quad \Lambda(k, s_k) \to N(k_1, s_N)\pi(k_2)$$



$s_{p,k,N}$: projections of baryonic spins on to the z-axis in their respective rest frames.

Independent kinematic variables are

1. dilepton invariant mass squared q^2
2. θ_ℓ: made by ℓ^- w.r.to $+z$ direction
3. θ_Λ: made by N w.r.to $+z$ direction
4. ϕ: angle between $\ell^+\ell^-$ and $N\pi$ decay planes ($N\pi = \{p^+\pi^-, n\pi^0\}$)

Effective Hamiltonian

SM basis: *Gutsche et.al., Phys. Rev. D 87, 074031 (2013), Böer et.al., JHEP 01 (2015) 155*

SM+SM′+NP, and lepton mass effects

$$\mathcal{H}^{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*}\frac{\alpha_e}{4\pi}\left(\sum_i \mathcal{C}_i\mathcal{O}_i + \sum_j \mathcal{C}'_j\mathcal{O}'_j\right), i = 7, 9, 10, V, A, S, P, j = V, A, S, P$$

The operators $\mathcal{O}^{(\prime)}$ read

$$O_7 = \frac{m_b}{e}\left[\bar{s}\sigma^{\mu\nu}P_R b\right]F_{\mu\nu}, \quad \mathcal{O}_9 = \left[\bar{s}\gamma^{\mu}P_L b\right]\left[\ell\gamma_\mu\ell\right], \quad \mathcal{O}_{10} = \left[\bar{s}\gamma^{\mu}P_L b\right]\left[\ell\gamma_\mu\gamma_5\ell\right],$$

$$\mathcal{O}_V^{(\prime)} = \left[\bar{s}\gamma^{\mu}P_{L(R)}b\right]\left[\ell\gamma_\mu\ell\right], \quad \mathcal{O}_A^{(\prime)} = \left[\bar{s}\gamma^{\mu}P_{L(R)}b\right]\left[\ell\gamma_\mu\gamma_5\ell\right],$$

$$\mathcal{O}_S^{(\prime)} = \left[\bar{s}P_R(L)b\right]\left[\ell\ell\right], \quad \mathcal{O}_P^{(\prime)} = \left[\bar{s}P_R(L)b\right]\left[\ell\gamma_5\ell\right].$$

$\mathcal{C}_{7,9}^{\rm eff}, \mathcal{C}_{10}$ are the dominant Wilson coefficients in SM ($\mathcal{C}_{V,A,S,P}^{(\prime)} = 0$)

DD Eur.Phys.J. C78, 230 (1802.09404)
DD JHEP 07 (2020) 002

$$\mathcal{O}_T = \bar{s}\sigma^{\mu\nu}b\bar{\ell}\sigma_{\mu\nu}\ell, \mathcal{O}_{T5} = \bar{s}\sigma^{\mu\nu}b\bar{\ell}\sigma_{\mu\nu}\gamma_5\ell$$

Han Yan, 1911.11568,
DD Eur.Phys.J. C78, 230 (1802.09404)

$\Lambda \to N\pi$ decay

The parity violating decay proceeds through the effective Hamiltonian *L Okun 1985*

$$\mathcal{H}^{\text{eff}}_{\Delta S=1} = \frac{4G_F}{\sqrt{2}} V^*_{ud} V_{us} \left[\bar{d}\gamma_\mu P_L u\right] \left[\bar{u}\gamma^\mu P_L s\right] . \tag{1}$$

The decay amplitudes can be written as

$$\begin{aligned} \mathcal{M}_2(s_k, s_N) &= \langle p(k_1, s_N)\pi^-(k_2)\big|[\bar{d}\gamma_\mu P_L u][\bar{u}\gamma^\mu P_L s]\big|\Lambda(k, s_k)\rangle , \\ &= \bar{u}(k_1, s_N)(\omega + \xi\gamma_5)u(k, s_k) . \end{aligned} \tag{2}$$

The hadronic parameters ξ, ω can be extracted from the decay width and polarization measurements

In the full angular distribution the only relevant quantity is the parity violating parameter

$$\alpha_\Lambda = \frac{-2\mathrm{Re}(\xi\omega)}{\sqrt{\frac{r_-}{r_+}}|\xi|^2 + \sqrt{\frac{r_+}{r_-}}|\omega|^2} , \quad r_\pm = (m_{\Lambda_b} \pm m_N)^2 - m_\pi^2 . \tag{3}$$

Böer/Feldmann/Dyk, JHEP01 (2015) 155 (1410.2115)

parity violating parameter ($N\pi = p\pi$) is $\alpha_\Lambda = 0.642 \pm 0.013$ PDG, Chin. Phys. C 40, no.10, 100001 (2016).

Hadronic matrix elements

Hadronic matrix elements for vector and axial vector currents

$$
\begin{aligned}
\langle\Lambda(k,s_k)|\bar{s}\gamma^\mu b|\Lambda(p,s_p)\rangle =& \bar{u}(k,s_k)\bigg[f_t^V(q^2)(m_{\Lambda_b}-m_\Lambda)\frac{q^\mu}{q^2} \\
&+f_0^V(q^2)\frac{m_{\Lambda_b}+m_\Lambda}{s_+}\{p^\mu+k^\mu-\frac{q^\mu}{q^2}(m_{\Lambda_b}^2-m_\Lambda^2)\} \\
&+f_\perp^V(q^2)\{\gamma^\mu-\frac{2m_\Lambda}{s_+}p^\mu-\frac{2m_{\Lambda_b}}{s_+}k^\mu\}\bigg]u(p,s_p)\,,
\end{aligned}
$$

$$
\begin{aligned}
\langle\Lambda(k,s_k)|\bar{s}\gamma^\mu\gamma_5 b|\Lambda(p,s_p)\rangle =& -\bar{u}(k,s_k)\gamma_5\bigg[f_t^A(q^2)(m_{\Lambda_b}+m_\Lambda)\frac{q^\mu}{q^2} \\
&+f_0^A(q^2)\frac{m_{\Lambda_b}-m_\Lambda}{s_-}\{p^\mu+k^\mu-\frac{q^\mu}{q^2}(m_{\Lambda_b}^2-m_\Lambda^2)\} \\
&+f_\perp^A(q^2)\{\gamma^\mu+\frac{2m_\Lambda}{s_-}p^\mu-\frac{2m_{\Lambda_b}}{s_-}k^\mu\}\bigg]u(p,s_p)\,.
\end{aligned}
$$

Hadronic matrix elements

Hadronic matrix elements for tensor and pseudo-tensor currents and (pseudo-)scalar currents

$$\langle\Lambda|\bar{s}iq_\nu\sigma^{\mu\nu}b|\Lambda_b\rangle = -\bar{u}(k,s_k)\Bigg[f_0^T(q^2)\frac{q^2}{s_+}\left(p^\mu + k^\mu - \frac{q^\mu}{q^2}(m_{\Lambda_b}^2 - m_\Lambda^2)\right) + f_\perp^T(m_{\Lambda_b}+m_\Lambda)\left(\gamma^\mu - \frac{2m_\Lambda}{s_+}p^\mu - \frac{2m_{\Lambda_b}}{s_+}k^\mu\right)\Bigg]u(p,s_p)\,,$$

$$\langle\Lambda|\bar{s}iq_\nu\sigma^{\mu\nu}\gamma_5 b|\Lambda_b\rangle = -\bar{u}(k,s_k)\gamma_5\Bigg[f_0^{T5}\frac{q^2}{s_-}\left(p^\mu + k^\mu - \frac{q^\mu}{q^2}(m_{\Lambda_b}^2 - m_\Lambda^2)\right) + f_\perp^{T5}(m_{\Lambda_b}-m_\Lambda)\left(\gamma^\mu + \frac{2m_\Lambda}{s_-}p^\mu - \frac{2m_{\Lambda_b}}{s_-}k^\mu\right)\Bigg]u(p,s_p)\,.$$

$$\langle\Lambda(k,s_k)|\bar{s}b|\Lambda(p,s_p)\rangle = f_t^V(q^2)\frac{m_{\Lambda_b}-m_\Lambda}{m_b}\bar{u}(k,s_k)u(p,s_p)\,,$$

$$\langle\Lambda(k,s_k)|\bar{s}\gamma_5 b|\Lambda(p,s_p)\rangle = f_t^A(q^2)\frac{m_{\Lambda_b}+m_\Lambda}{m_b}\bar{u}(k,s_k)\gamma_5 u(p,s_p)\,,$$

Ten q^2 dependent form-factors: $f^V_{t,0,\perp}$, $f^A_{t,0,\perp}$, $f^T_{0,\perp}$, $f^{T5}_{0,\perp}$

Lattice QCD calculations of form-factors are valid at large q^2 , Detmold/Meinel, Phys. Rev. D 93 (2016) 074501, Detmold/Lin/Meinel/Wingate, Phys. Rev. D 87, no. 7, 074502 (2013),

Non-local contributions of the QCD penguin operators in $\Lambda_b \to \Lambda$ calculated recently *Feldmann/Gubernari 2312.14146*

Helicity Amplitudes

The matrix elements are

$$\mathcal{M}^{\lambda_1,\lambda_2}(s_p,s_k) = -\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{\alpha_e}{4\pi}\sum_{i=L,R}\left[\sum_{\lambda}\eta_\lambda H^{i,s_p,s_k}_{\mathrm{VA},\lambda}L^{\lambda_1,\lambda_2}_{i,\lambda} + H^{i,s_p,s_k}_{\mathrm{SP}}L^{\lambda_1,\lambda_2}_{i}\right].$$

where $\eta_t = 1$ and $\eta_{\pm 1,0} = -1$

$H_{\mathrm{VA},\lambda}$ - hadronic helicity amplitudes, ϵ_μ virtual gauge-boson polarization

$$\begin{aligned}
H^{L(R),s_p,s_k}_{\mathrm{VA},\lambda} &= \bar{\epsilon}^*_\mu(\lambda)\big\langle\Lambda(k,s_k)\big|\Big[\Big((\mathcal{C}_9^{\mathrm{eff}} \mp \mathcal{C}_{10}) + (\mathcal{C}_V \mp \mathcal{C}_A)\Big)\bar{s}\gamma^\mu(1-\gamma_5)b \\
&+ (\mathcal{C}'_V \mp \mathcal{C}'_A)\bar{s}\gamma^\mu(1+\gamma_5)b - \frac{2m_b}{q^2}\mathcal{C}_7^{\mathrm{eff}}\bar{s}iq_\nu\sigma^{\mu\nu}(1+\gamma_5)b\Big]\big|\Lambda_b(p,s_p)\big\rangle\,, \\
H^{L(R),s_p,s_k}_{\mathrm{SP}} &= \big\langle\Lambda(k,s_k)\big|\Big[(\mathcal{C}'_S \mp \mathcal{C}'_P)\bar{s}(1-\gamma_5)b \\
&+ (\mathcal{C}_S \mp \mathcal{C}_P)\bar{s}(1+\gamma_5)b\Big]\big|\Lambda_b(p,s_p)\big\rangle\,, \\
H^{L(R),s_p,s_k}_{\mathrm{T},\lambda\lambda'} &= i\bar{\epsilon}^*_\mu(\lambda)\bar{\epsilon}^*_\nu(\lambda')\big\langle\Lambda(k,s_k)\big|\bar{s}\sigma^{\mu\nu}b\big|\Lambda_b(p,s_p)\big\rangle(\mathcal{C}_T \mp \mathcal{C}_{T5})\,.
\end{aligned}$$

$L_{i,\lambda}$ - leptonic helicity amplitudes

$$\begin{aligned}
&L^{\lambda_1,\lambda_2}_{L(R)} = \langle\bar{\ell}(\lambda_1)\ell(\lambda_2)|\bar{\ell}(1\mp\gamma_5)\ell|0\rangle\,, \\
&L^{\lambda_1,\lambda_2}_{L(R),\lambda} = \bar{\epsilon}^\mu(\lambda)\langle\bar{\ell}(\lambda_1)\ell(\lambda_2)|\bar{\ell}\gamma_\mu(1\mp\gamma_5)\ell|0\rangle\,, \\
&L^{\lambda_1,\lambda_2}_{L(R),\lambda\lambda'} = -i\bar{\epsilon}^\mu(\lambda)\bar{\epsilon}^\nu(\lambda')\langle\bar{\ell}(\lambda_1)\ell(\lambda_2)|\bar{\ell}\sigma_{\mu\nu}(1\mp\gamma_5)\ell|0\rangle\,.
\end{aligned}$$

Transversity Amplitudes

Transversity amplitudes for VA currents

$$
\begin{aligned}
A_{\perp_1}^{L,(R)} &= -\sqrt{2}N\left(f_\perp^V\sqrt{2s_-}\mathcal{C}_{\mathrm{VA}+}^{L,(R)} + \frac{2m_b}{q^2}f_\perp^T(m_{\Lambda_b}+m_\Lambda)\sqrt{2s_-}\mathcal{C}_7^{\mathrm{eff}}\right),\\
A_{\parallel_1}^{L,(R)} &= \sqrt{2}N\left(f_\perp^A\sqrt{2s_+}\mathcal{C}_{\mathrm{VA}-}^{L,(R)} + \frac{2m_b}{q^2}f_\perp^{T5}(m_{\Lambda_b}-m_\Lambda)\sqrt{2s_+}\mathcal{C}_7^{\mathrm{eff}}\right),\\
A_{\perp_0}^{L,(R)} &= \sqrt{2}N\left(f_0^V(m_{\Lambda_b}+m_\Lambda)\sqrt{\frac{s_-}{q^2}}\mathcal{C}_{\mathrm{VA}+}^{L,(R)} + \frac{2m_b}{q^2}f_0^T\sqrt{q^2 s_-}\mathcal{C}_7^{\mathrm{eff}}\right),\\
A_{\parallel_0}^{L,(R)} &= -\sqrt{2}N\left(f_0^A(m_{\Lambda_b}-m_\Lambda)\sqrt{\frac{s_+}{q^2}}\mathcal{C}_{\mathrm{VA}-}^{L,(R)} + \frac{2m_b}{q^2}f_0^{T5}\sqrt{q^2 s_+}\mathcal{C}_7^{\mathrm{eff}}\right),\\
A_{\perp t} &= -2\sqrt{2}Nf_t^V(m_{\Lambda_b}-m_\Lambda)\sqrt{\frac{s_+}{q^2}}(\mathcal{C}_{10}+\mathcal{C}_A+\mathcal{C}_A'),\\
A_{\parallel t} &= 2\sqrt{2}Nf_t^A(m_{\Lambda_b}+m_\Lambda)\sqrt{\frac{s_-}{q^2}}(\mathcal{C}_{10}+\mathcal{C}_A-\mathcal{C}_A').
\end{aligned}
$$

the Wilson coefficients combinations

$$
\begin{aligned}
\mathcal{C}_{\mathrm{VA},+}^{L(R)} &= (\mathcal{C}_9^{\mathrm{eff}}\mp\mathcal{C}_{10}) + (\mathcal{C}_V\mp\mathcal{C}_A) + (\mathcal{C}_V'\mp\mathcal{C}_A'),\\
\mathcal{C}_{\mathrm{VA},-}^{L(R)} &= (\mathcal{C}_9^{\mathrm{eff}}\mp\mathcal{C}_{10}) + (\mathcal{C}_V\mp\mathcal{C}_A) - (\mathcal{C}_V'\mp\mathcal{C}_A'),
\end{aligned}
$$

Angular distribution

The four-fold distribution looks

$$\frac{d^4\mathcal{B}}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} = \frac{3}{8\pi} K(q^2, \cos\theta_\ell, \cos\theta_\Lambda, \phi)\,, \tag{4}$$

with

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

The angular coefficients can be written as

$$K_{\{\dots\}} = \mathcal{K}_{\{\dots\}} + \frac{m_\ell}{\sqrt{q^2}}\mathcal{K}'_{\{\dots\}} + \frac{m_\ell^2}{q^2}\mathcal{K}''_{\{\dots\}}\,, \tag{6}$$

$\{\cdots\} = 1ss, 1cc, 1c, 2ss, 2cc, 2c, 3sc, 3s, 4sc, 4s$

DD, JHEP07 (2018) 063 (1804.08527)

Angular coefficients in SM+SM′+SP

The expressions of $\mathcal{K}^{(\prime,\prime\prime)}$ can helps us construct useful observables

$$\begin{aligned}
\mathcal{K}_{1ss} &= \frac{1}{4}\bigg(2|A^R_{\|_0}|^2 + |A^R_{\|_1}|^2 + 2|A^R_{\perp_0}|^2 + |A^R_{\perp_1}|^2 + \{R \leftrightarrow L\}\bigg) \\
&\quad + \frac{1}{4}\bigg(|A_{\mathrm{S}\perp}|^2 + |A_{\mathrm{P}\perp}|^2 + \{\perp\leftrightarrow \|\}\bigg), \\
\mathcal{K}'_{1ss} &= \mathrm{Re}\bigg(A_{\|t}A^*_{\mathrm{P}\|} + A_{\perp t}A^*_{\mathrm{P}\perp}\bigg), \\
\mathcal{K}''_{1ss} &= -\bigg(|A^R_{\|_0}|^2 + |A^R_{\perp_0}|^2 + \{R \leftrightarrow L\}\bigg) + \bigg(|A_{\perp t}|^2 - |A_{\mathrm{S}\perp}| + \{\perp\leftrightarrow \|\}\bigg) \\
&\quad + 2\mathrm{Re}\bigg(A^R_{\perp_0}A^{*L}_{\perp_0} + A^R_{\perp_1}A^{*L}_{\perp_1} + \{\perp\leftrightarrow \|\}\bigg),
\end{aligned}$$

K_{1ss}, K_{1cc}, K_{1c} are independent of parity-violating parameter α_Λ
$K_{2ss}, K_{2cc}, K_{2c}, K_{3sc}, K_{3s}, K_{4sc}, K_{4s}$ proportional to α_Λ

Few interesting observations are

- In the $m_\ell = 0$ limit the interference between VA-SP vanish.
- There is no SP contribution to K_{3sc} and K_{4sc}. These angular coefficients are therefore not sensitive to $\mathcal{C}^{(\prime)}_{S,P}$ couplings.
- There is no pseudo-scalar contribution ($A_{\mathrm{P}\|,\mathrm{P}\perp}$) to K_{1c}, K_{2c}, K_{3s} and K_{4s}. Therefore, these angular coefficients are not sensitive to $\mathcal{C}^{(\prime)}_P$.

DD, JHEP07 (2018) 063 (1804.08527)

Observables

Observables can be constructed by weighted average over $\theta_\ell, \theta_\Lambda$ and ϕ

$$X(q^2) = \int \frac{d^4\mathcal{B}}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} \omega_X(q^2, \cos\theta_\ell \cos\theta_\Lambda, \phi) d\cos\theta_\ell d\cos\theta_\Lambda d\phi \,. \qquad (7)$$

The observables that we will consider are

$$\frac{d\mathcal{B}}{dq^2} = 2K_{1ss} + K_{1cc} \,. \qquad (8)$$

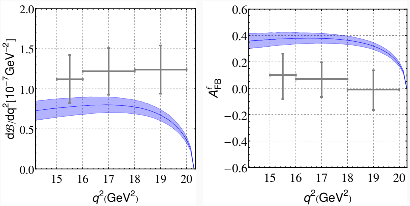
$$F_L = \frac{2K_{1ss} - K_{1cc}}{2K_{1ss} + K_{1cc}} \,, \quad A_{\rm FB}^{\Lambda} = \frac{1}{2} \frac{2K_{2ss} + K_{2cc}}{2K_{1ss} + K_{1cc}} \,. \qquad (9)$$

$$A_{\rm FB}^{\ell} = \frac{3}{2} \frac{K_{1c}}{2K_{1ss} + K_{1cc}} \,, \qquad A_{\rm FB}^{\ell\Lambda} = \frac{3}{4} \frac{K_{2c}}{2K_{1ss} + K_{1cc}} \,, \qquad (10)$$

$$R_{\Lambda_b}^{\ell/e} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 d\mathcal{B}(\Lambda_b \to \Lambda(\to p\pi)\ell^+\ell^-)/dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 d\mathcal{B}(\Lambda_b \to \Lambda(\to p\pi)e^+e^-)/dq^2} \,, \quad \ell = \mu, \tau \qquad (11)$$

Böer/Feldmann/Dyk, JHEP01 (2015) 155 (1410.2115)
DD, JHEP07 (2018) 063 (1804.08527)

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

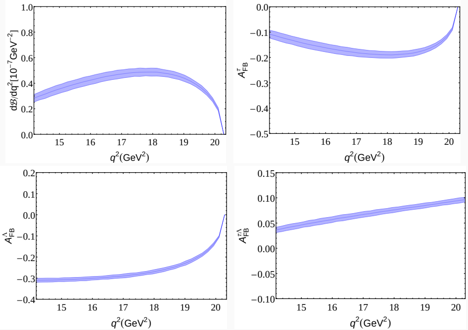


DD, JHEP07 (2018) 063 (1804.08527)

	$\langle d\mathcal{B}/dq^2\rangle$	$\langle F_L\rangle$	$\langle A^{\ell}_{\text{FB}}\rangle$	$\langle A^{\Lambda}_{\text{FB}}\rangle$	$\langle A^{\ell\Lambda}_{\text{FB}}\rangle$	$\langle \hat{K}_{2ss}\rangle$	$\langle \hat{K}_{2cc}\rangle$	$\langle \hat{K}_{4s}\rangle$	$\langle \hat{K}_{4sc}\rangle$
$[0.1, 2]$	0.25(23)	0.517(81)	0.095(15)	−0.310(18)	−0.0302(51)	−0.233(19)	−0.154(26)	−0.009(22)	0.022(22)
$[2, 4]$	0.18(12)	0.856(27)	0.057(31)	−0.306(24)	−0.0169(99)	−0.284(23)	−0.0444(87)	0.031(36)	0.013(31)
$[4, 6]$	0.23(11)	0.813(42)	−0.062(39)	−0.311(17)	0.021(13)	−0.282(15)	−0.059(13)	0.038(44)	0.001(31)
$[6, 8]$	0.307(94)	0.730(48)	−0.163(40)	−0.316(11)	0.053(13)	−0.273(10)	−0.086(15)	0.030(39)	−0.007(27)
$[1.1, 6]$	0.20(12)	0.820(32)	0.012(31)	−0.309(21)	−0.0027(99)	−0.280(20)	−0.056(10)	0.030(35)	0.009(30)
$[15, 16]$	0.796(75)	0.455(20)	−0.374(14)	−0.3069(83)	0.1286(55)	−0.2253(69)	−0.1633(69)	−0.060(13)	−0.0211(80)
$[16, 18]$	0.827(76)	0.418(15)	−0.372(13)	−0.2891(90)	0.1377(46)	−0.2080(69)	−0.1621(66)	−0.090(10)	−0.0209(60)
$[18, 20]$	0.665(68)	0.3714(79)	−0.309(15)	−0.227(10)	0.1492(37)	−0.1598(71)	−0.1344(70)	−0.1457(74)	−0.0172(40)
$[15, 20]$	0.756(70)	0.410(13)	−0.350(13)	−0.2710(92)	0.1398(43)	−0.1947(68)	−0.1526(65)	−0.1031(97)	−0.0196(55)

Detmold/Meinel Phys. Rev. D 93, 074501 (2016)

$\Lambda_b \to \Lambda\tau^+\tau^-$ in SM



$[q^2_{\min}, q^2_{\max}]$	$\langle\mathcal{B}\rangle \times 10^7$	$\langle F_L\rangle$	$\langle A^{\tau}_{\rm FB}\rangle$	$\langle A^{\Lambda}_{\rm FB}\rangle$
[14,15]	0.31 ± 0.03	0.350 ± 0.007	-0.120 ± 0.016	-0.309 ± 0.009
[15,16]	0.39 ± 0.03	0.354 ± 0.009	-0.149 ± 0.017	-0.304 ± 0.009
[16,18]	0.93 ± 0.06	0.353 ± 0.010	-0.180 ± 0.015	-0.289 ± 0.009
[18,20]	0.83 ± 0.05	0.346 ± 0.010	-0.173 ± 0.010	-0.227 ± 0.009
[15,20]	2.16 ± 0.13	0.351 ± 0.009	-0.171 ± 0.014	-0.268 ± 0.008

$[q^2_{\min}, q^2_{\max}]$	$\langle A^{\tau\Lambda}_{\rm FB}\rangle$	$\langle\hat{K}_{4sc}\rangle$	$\langle\hat{K}_{4s}\rangle$
[14,15]	0.041 ± 0.005	-0.0026 ± 0.0030	-0.0148 ± 0.0086
[15,16]	0.052 ± 0.006	-0.0037 ± 0.0036	-0.0243 ± 0.0089
[16,18]	0.067 ± 0.006	-0.0053 ± 0.0035	-0.0446 ± 0.0075
[18,20]	0.084 ± 0.005	-0.0053 ± 0.0028	-0.0827 ± 0.0050
[15,20]	0.071 ± 0.005	-0.0050 ± 0.0031	-0.0055 ± 0.0067

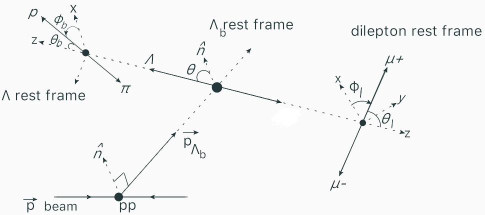
DD, JHEP07 (2018) 063 (1804.08527)

Fits and New Physics Analysis

Blake/Meinel/van Dyk Phys. Rev. D 101, 035023 (2020)
Yadav/Mohapatra/Sahoo 2409.09737
Biswas et.al., 2310.09887
Das/Dutta Phys.Rev.D 108 (2023) 9, 095051
Das/Das/Kumar/Sahoo Phys.Rev.D 108 (2023) 1, 1
Bordone/Rahimi/Vos Eur.Phys.J.C 81 (2021) 8, 756
Amhis et.al., Eur.Phys.J.Plus 136 (2021) 6, 614
Bhattacharya/Nandi/Patra/Sain Phys.Rev.D 101 (2020) 7, 073006

Polarized $\Lambda_b \to \Lambda \ell^+ \ell^-$ decay

- Λ_b is longitudinally polarized at e^+e^-
- Λ_b is transverse polarized at LHCb
- at LHCb $\mathcal{O}(10\%)$ polarization possible,
- With polarized Λ_b: 34 observables in SM, 36 observables in SM+SP



$\hat{n} = \hat{p}_{\rm beam}^{\{\rm lab\}} \times \hat{p}_{\Lambda}^{\rm lab}$, $\cos\theta = \hat{n}.\hat{p}_{\Lambda}^{\{\Lambda_{\rm b}\}}$. To describe $\Lambda \to p\pi$ and di-lepton system introduce $\{\hat{z}_b, \hat{y}_b, \hat{x}_b\}$ and $\{\hat{z}_\ell, \hat{y}_\ell, \hat{x}_\ell\}$: such that $\hat{z}_b = \hat{p}_{\Lambda}^{\{\Lambda_b\}}$ and $\hat{z}_b = \hat{p}_{\ell\ell}^{\{\Lambda_\ell\}}$ and $\hat{y}_{b,\ell} = \hat{n} \times \hat{z}_{b,\ell}$, $\hat{x}_{b,\ell} = \hat{n} \times \hat{y}_{b,\ell}$

Polarized $\Lambda_b \to \Lambda \ell^+ \ell^-$ angular distribution

Operator basis: $\mathcal{O}_{7,9,10}$, $\mathcal{O}'_{9,10}$, $\mathcal{O}_{S,P}$, $\mathcal{O}_{S',P'}$ + massive leptons

Transversity Amplitudes: $A_{\perp 1}^{L(R)}$, $A_{||1}^{L(R)}$, $A_{\perp 0}^{L(R)}$, $A_{||0}^{L(R)}$, $A_{\perp t}$, $A_{||t}$, $A_{\perp S}^{L(R)}$, $A_{||S}^{L(R)}$

$$
\begin{aligned}
\frac{\mathrm{d}^6\mathcal{B}}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}(\theta_\ell,\phi_\ell,\theta_b,\phi_b,\theta)} = \frac{3}{32\pi^2}\Big(& \big(K_1\sin^2\theta_\ell + K_2\cos^2\theta_\ell + K_3\cos\theta_\ell\big) + \\
& \big(K_4\sin^2\theta_\ell + K_5\cos^2\theta_\ell + K_6\cos\theta_\ell\big)\cos\theta_b + \\
& (K_7\sin\theta_\ell\cos\theta_\ell + K_8\sin\theta_\ell)\sin\theta_b\cos(\phi_b+\phi_\ell) + \\
& (K_9\sin\theta_\ell\cos\theta_\ell + K_{10}\sin\theta_\ell)\sin\theta_b\sin(\phi_b+\phi_\ell) + \\
& \big(K_{11}\sin^2\theta_\ell + K_{12}\cos^2\theta_\ell + K_{13}\cos\theta_\ell\big)\cos\theta + \\
& \big(K_{14}\sin^2\theta_\ell + K_{15}\cos^2\theta_\ell + K_{16}\cos\theta_\ell\big)\cos\theta_b\cos\theta + \\
& (K_{17}\sin\theta_\ell\cos\theta_\ell + K_{18}\sin\theta_\ell)\sin\theta_b\cos(\phi_b+\phi_\ell)\cos\theta + \\
& (K_{19}\sin\theta_\ell\cos\theta_\ell + K_{20}\sin\theta_\ell)\sin\theta_b\sin(\phi_b+\phi_\ell)\cos\theta + \\
& (K_{21}\cos\theta_\ell\sin\theta_\ell + K_{22}\sin\theta_\ell)\sin\phi_\ell\sin\theta + \\
& (K_{23}\cos\theta_\ell\sin\theta_\ell + K_{24}\sin\theta_\ell)\cos\phi_\ell\sin\theta + \\
& (K_{25}\cos\theta_\ell\sin\theta_\ell + K_{26}\sin\theta_\ell)\sin\phi_\ell\cos\theta_b\sin\theta + \\
& (K_{27}\cos\theta_\ell\sin\theta_\ell + K_{28}\sin\theta_\ell)\cos\phi_\ell\cos\theta_b\sin\theta + \\
& \big(K_{29}\cos^2\theta_\ell + K_{30}\sin^2\theta_\ell + K_{35}\cos\theta_\ell\big)\sin\theta_b\sin\phi_b\sin\theta + \\
& \big(K_{31}\cos^2\theta_\ell + K_{32}\sin^2\theta_\ell + K_{36}\cos\theta_\ell\big)\sin\theta_b\cos\phi_b\sin\theta + \\
& \big(K_{33}\sin^2\theta_\ell\big)\sin\theta_b\cos(2\phi_\ell+\phi_b)\sin\theta + \\
& \big(K_{34}\sin^2\theta_\ell\big)\sin\theta_b\sin(2\phi_\ell+\phi_b)\sin\theta\Big). \qquad (3.1)
\end{aligned}
$$

Relation with unpolarized angular coefficients: $K_{1ss} = K_1$, $K_{1cc} = K_2$, $K_{1c} = K_3$, $K_{2ss} = K_4$, $K_{2cc} = K_5$, $K_{2c} = K_6$, $K_{4sc} = K_7$, $K_{4s} = K_8$, $K_{3sc} = K_9$

New coefficients in SM+SM′ basis: K_{35} and K_{36}

DD/Sain Phys.Rev.D 104 (2021) 1, 013002

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

Differential branching ratio:

$$\frac{d\mathcal{B}}{dq^2} = 2K_1 + K_2\,,$$

Define

$$M_i = \frac{K_i}{2K_1 + K_2}\,, \quad M_i = \frac{3}{32\pi^2}\int\left(\sum_{j=0}^{36} M_j f_j(\bar{\Omega})\right) g_i(\bar{\Omega})\,d\bar{\Omega}\,,$$

HQET: leading order in $1/m_b$ expansion + $\mathcal{O}(\alpha_s)$ correction

$$f_\perp^V = f_0^V = f_\perp^T = f_0^T = \xi_1 - \xi_2\,, \qquad f_\perp^A = f_0^A = f_\perp^{T5} = f_0^{T5} = \xi_1 + \xi_2\,,$$

$$\mathcal{C}_+^{L(R)} = \left((\mathcal{C}_9 + \mathcal{C}_{9'}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10'}) + \frac{2\kappa m_b m_{\Lambda_b}}{q^2}\mathcal{C}_7\right), \tag{12}$$

$$\mathcal{C}_-^{L(R)} = \left((\mathcal{C}_9 - \mathcal{C}_{9'}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10'}) + \frac{2\kappa m_b m_{\Lambda_b}}{q^2}\mathcal{C}_7\right). \tag{13}$$

For V-A current independent WCs combinations: $\rho_1^\pm, \rho_2, \rho_3^\pm, \rho_4$

In SM: $\rho_1^+ = \rho_1^- = \rho_1 = 2\mathrm{Re}(\rho_4)$, $\rho_3^+ = \rho_3^- = \rho_3$, $\mathrm{Im}(\rho_2) = 0, \mathrm{Im}(\rho_4) = 0$

With SP operators additional combinations: $\rho_S^\pm, \rho_{S1}$

DD/Sain Phys.Rev.D 104 (2021) 1, 013002

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

In SM+SM′+SP: angular coefficient ratios independent of long-distance physics

$$\frac{P_{\Lambda_b} K_8 + \alpha_\Lambda K_{24}}{K_{27} - K_{17}} = -\frac{\rho_3^-}{\rho_1^-}, \quad \frac{P_{\Lambda_b} K_8 - \alpha_\Lambda K_{24}}{K_{27} + K_{17}} = \frac{\rho_3^+}{\rho_1^+},$$

$$\frac{K_{16}}{K_{34}} = -\frac{2\mathrm{Re}(\rho_2)}{\mathrm{Im}(\rho_2)}, \quad \frac{K_{25}}{K_{22}} = -\frac{\alpha_\Lambda \mathrm{Im}(\rho_2)}{\mathrm{Im}(\rho_4)}, \quad \frac{K_{23}}{K_{10}} = -\frac{P_{\Lambda_b}\mathrm{Re}(\rho_4)}{\alpha_\Lambda \mathrm{Im}(\rho_4)}.$$

In SM+SM′+SP: angular coefficient ratios independent of short-distance physics

$$\frac{K_{18} + K_{28}}{K_3} = -P_{\Lambda_b}\alpha_\Lambda \frac{m_{\Lambda_b} + m_\Lambda}{\sqrt{q^2}} \frac{f_0^V}{f_\perp^V}, \qquad \frac{K_{18} - K_{28}}{K_3} = P_{\Lambda_b}\alpha_\Lambda \frac{m_{\Lambda_b} - m_\Lambda}{\sqrt{q^2}} \frac{f_0^A}{f_\perp^A}.$$

Probe for scalar NP

$$P_{\Lambda_b}(K_4 - K_5) - \alpha_\Lambda K_{11} = P_{\Lambda_b}\alpha_\Lambda f_t^A f_t^V \frac{(m_{\Lambda_b}^2 - m_\Lambda^2)}{m_b^2} \sqrt{s_+ s_-}\mathrm{Re}(\rho_{S1}),$$

DD/Sain Phys.Rev.D 104 (2021) 1, 013002

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

Obs.	Value	68% interval	Obs.	Value	68% interval
M_1	0.459	$[0.453, 0.465]$	M_6	0.000	$[-0.005, 0.006]$
M_2	0.081	$[0.071, 0.094]$	M_7	-0.025	$[-0.034, -0.014]$
M_3	-0.005	$[-0.014, -0.001]$	M_8	-0.003	$[-0.016, 0.012]$
M_4	-0.280	$[-0.290, -0.262]$	M_9	0.002	$[0.001, 0.002]$
M_5	-0.045	$[-0.053, -0.037]$	M_{10}	0.002	$[0.001, 0.002]$
M_{11}	-0.366	$[-0.383, -0.338]$	M_{23}	-0.147	$[-0.162, -0.133]$
M_{12}	0.071	$[0.058, 0.081]$	M_{24}	0.132	$[0.120, 0.150]$
M_{13}	0.001	$[-0.010, 0.007]$	M_{25}	-0.001	$[-0.001, -0.000]$
M_{14}	0.243	$[0.230, 0.254]$	M_{26}	0.004	$[0.003, 0.005]$
M_{15}	-0.052	$[-0.060, -0.045]$	M_{27}	0.089	$[0.081, 0.099]$
M_{16}	0.003	$[0.001, 0.009]$	M_{28}	-0.089	$[-0.100, -0.080]$
M_{17}	0.004	$[-0.012, 0.018]$	M_{29}	0.000	$[0.000, 0.000]$
M_{18}	0.029	$[0.018, 0.037]$	M_{30}	0.000	$[0.000, 0.000]$
M_{19}	-0.001	$[-0.002, -0.001]$	M_{31}	0.000	$[0.000, 0.000]$
M_{20}	-0.003	$[-0.003, 0.002]$	M_{32}	0.075	$[0.035, 0.118]$
M_{21}	0.002	$[0.001, 0.003]$	M_{33}	0.007	$[0.001, 0.012]$
M_{22}	-0.005	$[-0.006, -0.003]$	M_{34}	0.000	$[-0.000, 0.000]$

Obs.	Value	68% interval	Obs.	Value	68% interval
M_1	0.351	$[0.349, 0.353]$	M_6	0.187	$[0.183, 0.192]$
M_2	0.298	$[0.294, 0.301]$	M_7	-0.022	$[-0.025, -0.019]$
M_3	-0.236	$[-0.240, -0.230]$	M_8	-0.100	$[-0.105, -0.095]$
M_4	-0.195	$[-0.200, -0.190]$	M_9	0.000	$[0.000, 0.001]$
M_5	-0.154	$[-0.159, -0.149]$	M_{10}	-0.001	$[-0.001, -0.000]$
M_{11}	-0.064	$[-0.069, -0.058]$	M_{23}	-0.299	$[-0.303, -0.295]$
M_{12}	0.240	$[0.235, 0.245]$	M_{24}	0.337	$[0.335, 0.338]$
M_{13}	-0.292	$[-0.295, -0.288]$	M_{25}	-0.001	$[-0.001, -0.000]$
M_{14}	0.034	$[0.031, 0.038]$	M_{26}	0.001	$[0.000, 0.001]$
M_{15}	-0.191	$[-0.196, -0.186]$	M_{27}	0.221	$[0.216, 0.226]$
M_{16}	0.151	$[0.146, 0.156]$	M_{28}	-0.187	$[-0.191, -0.183]$
M_{17}	0.102	$[0.096, 0.107]$	M_{29}	0.000	$[0.000, 0.000]$
M_{18}	0.021	$[0.018, 0.024]$	M_{30}	-0.001	$[-0.001, -0.000]$
M_{19}	0.000	$[0.000, 0.000]$	M_{31}	0.000	$[0.000, 0.000]$
M_{20}	-0.001	$[-0.001, -0.001]$	M_{32}	-0.046	$[-0.050, -0.043]$
M_{21}	0.000	$[0.000, 0.001]$	M_{33}	-0.053	$[-0.056, -0.050]$
M_{22}	-0.002	$[-0.002, -0.001]$	M_{34}	0.000	$[0.000, 0.000]$

Figure 2: Polarized $\Lambda_b \to \Lambda\mu^+\mu^-$ observables with $P_{\Lambda_b} = 1$ in $1 < q^2 < 6\text{GeV}^2$ (left) and $P_{\Lambda_b} = 1$ in $15 < q^2 < 20\text{GeV}^2$ (right) from Blake/Creps JHEP 11 (2017) 138

LHCb measurement on the 34 observables *LHCb JHEP 09, 146(2018)*.

The $\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$ decay

Dominant contribution to semi-leptonic Λ_b decay comes from $\Lambda^*(1520)$ ($J^P = \frac{3}{2}^-$)

Close by $\Lambda(1405)$ and $\Lambda(1600)$ differentiated by their spin-parity (both 1/2)

$$\Lambda_b(p, s_{\Lambda_b}) \to \Lambda^*(k, s_{\Lambda^*})\ell^+(q_1)\ell^-(q_2)\,,$$
$$\Lambda^*(k, s_{\Lambda^*}) \to N(k_1, s_N)\bar{K}(k_2)\,,$$

$\Lambda_b \to \Lambda^*$ HMA in terms of fourteen form factors: $f^V_{t,0,\perp,g}$, $f^A_{t,0,\perp,g}$, $f^T_{0,\perp,g}$, $f^{T5}_{0,\perp,g}$
Meinel/Rendon Phys. Rev. D 103, no.7, 074505 (2021), Phys. Rev. D 105, no.5, 054511 (2022)

$$B^{L(R)}_{\perp_1} = \sqrt{2}N\left(f^V_g\sqrt{s_+}\mathcal{C}^{L(R)}_{\mathrm{VA}+} + \frac{2m_b}{q^2}f^T_g\sqrt{s_+}(\mathcal{C}_7 + \mathcal{C}'_7)\right),$$

$$B^{L(R)}_{\parallel_1} = \sqrt{2}N\left(f^A_g\sqrt{s_-}\mathcal{C}^{L(R)}_{\mathrm{VA}-} + \frac{2m_b}{q^2}f^{T5}_g\sqrt{s_-}(\mathcal{C}_7 - \mathcal{C}'_7)\right),$$

$$A^{L(R)}_{\perp_0} = -\sqrt{2}N\left(f^V_0\frac{(m_{\Lambda_b}+m_{\Lambda^*})}{\sqrt{q^2}}\frac{s_-\sqrt{s_+}}{\sqrt{6}m_{\Lambda^*}}\mathcal{C}^{L(R)}_{\mathrm{VA}+} + \frac{2m_b}{q^2}f^T_0\sqrt{q^2}\frac{s_-\sqrt{s_+}}{\sqrt{6}m_{\Lambda^*}}(\mathcal{C}_7 + \mathcal{C}'_7)\right),$$

$$A^{L(R)}_{\parallel_0} = \sqrt{2}N\left(f^A_0\frac{(m_{\Lambda_b}-m_{\Lambda^*})}{\sqrt{q^2}}\frac{s_+\sqrt{s_-}}{\sqrt{6}m_{\Lambda^*}}\mathcal{C}^{L(R)}_{\mathrm{VA}-} + \frac{2m_b}{q^2}f^{T5}_0\sqrt{q^2}\frac{s_+\sqrt{s_-}}{\sqrt{6}m_{\Lambda^*}}(\mathcal{C}_7 - \mathcal{C}'_7)\right),$$

$$A^{L(R)}_{\perp_1} = -\sqrt{2}N\left(f^V_\perp\frac{s_-\sqrt{s_+}}{\sqrt{3}m_{\Lambda^*}}\mathcal{C}^{L(R)}_{\mathrm{VA}+} + \frac{2m_b}{q^2}f^T_\perp(m_{\Lambda_b}+m_{\Lambda^*})\frac{s_-\sqrt{s_+}}{\sqrt{3}m_{\Lambda^*}}(\mathcal{C}_7 + \mathcal{C}'_7)\right),$$

$$A^{L(R)}_{\parallel_1} = -\sqrt{2}N\left(f^A_\perp\frac{s_+\sqrt{s_-}}{\sqrt{3}m_{\Lambda^*}}\mathcal{C}^{L(R)}_{\mathrm{VA}-} + \frac{2m_b}{q^2}f^{T5}_\perp(m_{\Lambda_b}-m_{\Lambda^*})\frac{s_+\sqrt{s_-}}{\sqrt{3}m_{\Lambda^*}}(\mathcal{C}_7 - \mathcal{C}'_7)\right),$$

$$A^{L(R)}_{\perp_t} = \mp\sqrt{2}Nf^V_t\frac{(m_{\Lambda_b}-m_{\Lambda^*})}{\sqrt{q^2}}\frac{s_+\sqrt{s_-}}{\sqrt{6}m_{\Lambda^*}}(\mathcal{C}_{10} + \mathcal{C}_{10'})\,,$$

$$A^{L(R)}_{\parallel_t} = \pm\sqrt{2}Nf^A_t\frac{(m_{\Lambda_b}+m_{\Lambda^*})}{\sqrt{q^2}}\frac{s_-\sqrt{s_+}}{\sqrt{6}m_{\Lambda^*}}(\mathcal{C}_{10} - \mathcal{C}_{10'})\,,$$

The $\Lambda^* \to N\bar{K}$ decay

The $\Lambda^*(\to N\bar{K})$ decay effective Hamiltonian Nath/Etemadi/Kimel Phys. Rev. D 3, 2153-2161 (1971)

$$\mathcal{L}_1 = g m_{\Lambda^*} \bar{\psi}_\mu (g^{\mu\nu} + a\gamma^\mu\gamma^\nu)\gamma_5 \Psi \partial_\nu \phi + h.c., \quad \mathcal{M}^{\Lambda^*}(s_{\Lambda^*}, s_N) = g m_{\Lambda^*} k_2^\mu \bar{u}^{s_N} \gamma_5 U_\mu^{s_{\Lambda^*}},$$

Rarita-Schwinger spinor in Λ_b RF

$$u_{\Lambda^*}(-3/2) = \frac{1}{2\sqrt{m_{\Lambda_b}}} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \sqrt{s_+} & 0 & -\sqrt{s_-} \\ 0 & -i\sqrt{s_+} & 0 & i\sqrt{s_-} \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

$$u_{\Lambda^*}(-1/2) = \frac{\sqrt{s_- s_+}}{4\sqrt{3} m_{\Lambda_b}^{3/2} m_{\Lambda^*}} \begin{pmatrix} 0 & 2\sqrt{s_+} & 0 & -2\sqrt{s_-} \\ \frac{2 m_{\Lambda^*} m_{\Lambda_b}}{\sqrt{s_-}} & 0 & \frac{2 m_{\Lambda^*} m_{\Lambda_b}}{\sqrt{s_+}} & 0 \\ -\frac{2 i m_{\Lambda^*} m_{\Lambda_b}}{\sqrt{s_-}} & 0 & -\frac{2 i m_{\Lambda^*} m_{\Lambda_b}}{\sqrt{s_+}} & 0 \\ 0 & \frac{s_- + s_+}{\sqrt{s_-}} & 0 & -\frac{s_- + s_+}{\sqrt{s_+}} \end{pmatrix},$$

$$u_{\Lambda^*}(+1/2) = \frac{\sqrt{s_- s_+}}{4\sqrt{3} m_{\Lambda_b}^{3/2} m_{\Lambda^*}} \begin{pmatrix} 2\sqrt{s_+} & 0 & 2\sqrt{s_-} & 0 \\ 0 & -\frac{2 m_{\Lambda^*} m_{\Lambda_b}}{\sqrt{s_-}} & 0 & \frac{2 m_{\Lambda^*} m_{\Lambda_b}}{\sqrt{s_+}} \\ 0 & -\frac{2 i m_{\Lambda^*} m_{\Lambda_b}}{\sqrt{s_-}} & 0 & \frac{2 i m_{\Lambda^*} m_{\Lambda_b}}{\sqrt{s_+}} \\ \frac{s_- + s_+}{\sqrt{s_-}} & 0 & \frac{s_- + s_+}{\sqrt{s_+}} & 0 \end{pmatrix},$$

$$u_{\Lambda^*}(+3/2) = \frac{1}{2\sqrt{m_{\Lambda_b}}} \begin{pmatrix} 0 & 0 & 0 & 0 \\ -\sqrt{s_+} & 0 & -\sqrt{s_-} & 0 \\ -i\sqrt{s_+} & 0 & -i\sqrt{s_-} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

$$\begin{aligned}
\frac{d^4\mathcal{B}}{dq^2 d\cos\theta_\ell d\cos\theta_{\Lambda^*} d\phi} = \frac{3}{8\pi}\Bigg[&\Big(K_{1c}\cos\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1ss}\sin^2\theta_\ell\Big)\cos^2\theta_{\Lambda^*} \\
&+\Big(K_{2c}\cos\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2ss}\sin^2\theta_\ell\Big)\sin^2\theta_{\Lambda^*} \\
&+\Big(K_{3ss}\sin^2\theta_\ell\Big)\sin^2\theta_{\Lambda^*}\cos\phi + \Big(K_{4ss}\sin^2\theta_\ell\Big)\sin^2\theta_{\Lambda^*}\sin\phi\cos\phi \\
&+\Big(K_{5s}\sin\theta_\ell + K_{5sc}\sin\theta_\ell\cos\theta_\ell\Big)\sin\theta_{\Lambda^*}\cos\theta_{\Lambda^*}\cos\phi \\
&+\Big(K_{6s}\sin\theta_\ell + K_{6sc}\sin\theta_\ell\cos\theta_\ell\Big)\sin\theta_{\Lambda^*}\cos\theta_{\Lambda^*}\sin\phi\Bigg]. \qquad (3.1)
\end{aligned}$$

In the $m_b \to \infty$ limit and to leading order $1/m_b$

$$\begin{aligned}
f_\perp^V = f_0^V = f_t^A = f_\perp^T = f_0^T &= \frac{\xi_1 - \xi_2}{m_{\Lambda_b}}, \\
f_\perp^A = f_0^A = f_t^V = f_\perp^{T5} = f_0^{T5} &= \frac{\xi_1 + \xi_2}{m_{\Lambda_b}}, \\
f_g^V = f_g^A = f_g^T = f_g^{T5} &= 0.
\end{aligned}$$

$\Lambda_b \to \Lambda^*(\to N\bar{K})\ell^+\ell^-$ decay:

In the $m_b \to \infty$ limit and to leading order $1/m_b + \mathcal{O}(\alpha_s)$ correction Grinstein/Pirjol Phys. Rev. D 70, 114005 (2004)

$$
\begin{aligned}
f_\perp^{V,A} &= C_0^{(v)} \frac{(\xi_1 \mp \xi_2)}{m_{\Lambda_b}} \,, \\
f_0^{V,A} &= \left(C_0^{(v)} + \frac{C_1^{(v)} s_\pm}{2m_{\Lambda_b}(m_{\Lambda_b} \pm m_{\Lambda^*})} \right) \frac{\xi_1}{m_{\Lambda_b}} \mp \left(C_0^{(v)} - \frac{(2C_0^{(v)} + C_1^{(v)}) s_\pm}{2m_{\Lambda_b}(m_{\Lambda_b} \pm m_{\Lambda^*})} \right) \frac{\xi_2}{m_{\Lambda_b}} \,, \\
f_\perp^{T(5)} &= C_0^{(t)} \left(\frac{(\xi_1 \mp \xi_2)}{m_{\Lambda_b}} \pm \frac{s_\pm}{m_{\Lambda_b}(m_{\Lambda_b} \pm m_{\Lambda^*})} \frac{\xi_2}{m_{\Lambda_b}} \right) , \\
f_0^{T(5)} &= C_0^{(t)} \frac{(\xi_1 \mp \xi_2)}{m_{\Lambda_b}} \,, \\
f_t^V(q^2) &= \frac{1}{m_{\Lambda_b}} \xi_1 \left(C_0^{(v)} + C_1^{(v)} \left(1 - \frac{s_-}{2m_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda^\star})} \right) \right) \\
&\quad + \frac{1}{m_{\Lambda_b}} \xi_2 \left(C_0^{(v)} \left(1 - \frac{s_-}{m_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda^\star})} \right) + C_1^{(v)} \left(1 - \frac{s_-}{2m_{\Lambda_b}(m_{\Lambda_b} - m_{\Lambda^\star})} \right) \right) , \\
f_t^A(q^2) &= \frac{1}{m_{\Lambda_b}} \xi_1 \left(C_0^{(v)} + C_1^{(v)} \left(1 - \frac{s_+}{2m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda^\star})} \right) \right) \\
&\quad - \frac{1}{m_{\Lambda_b}} \xi_2 \left(C_0^{(v)} \left(1 - \frac{s_+}{m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda^\star})} \right) + C_1^{(v)} \left(1 - \frac{s_+}{2m_{\Lambda_b}(m_{\Lambda_b} + m_{\Lambda^\star})} \right) \right) .
\end{aligned}
$$

$\Lambda_b \to \Lambda^*(\to N\bar{K})\mu^+\mu^-$ decay: SM

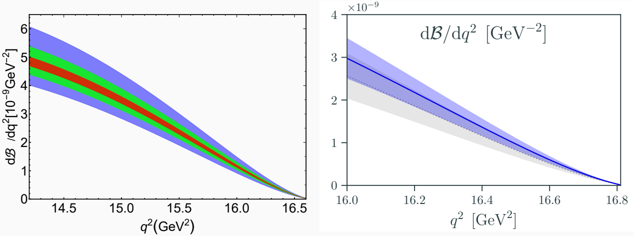


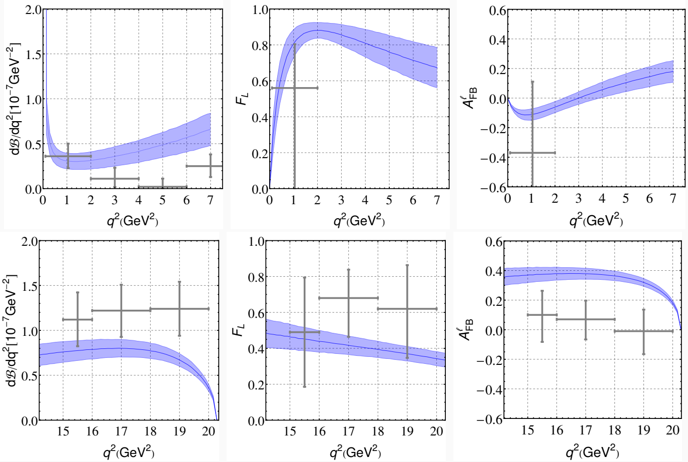
Figure 3: Left: using quark model ff, right: using lattice QCD ff.

Mott/Roberts Int. J. Mod. Phys. A 27, 1250016 (2012), Meinel/Rendon 2021 & 2022

- Interestingly, the ratios K_{1c}/K_{2c}, K_{1cc}/K_{2cc} and K_{1ss}/K_{2ss} remain independent of both short- and long-distance physics in the extended set of operators.
- If only SM′ NP is present, then both K_{1c}/K_{1cc} and K_{2c}/K_{2cc} are sensitive to it. Irrespective of the presence of SM′ NP, the ratios are sensitive to scalar NP.
- For K_{1ss}/K_{1cc} and K_{2ss}/K_{2cc} the dependence on the new physics follow the same pattern as in K_{1c}/K_{1cc} and K_{2c}/K_{2cc}.

thank you

$\Lambda_b \to \Lambda\mu^+\mu^-$ observables: SM



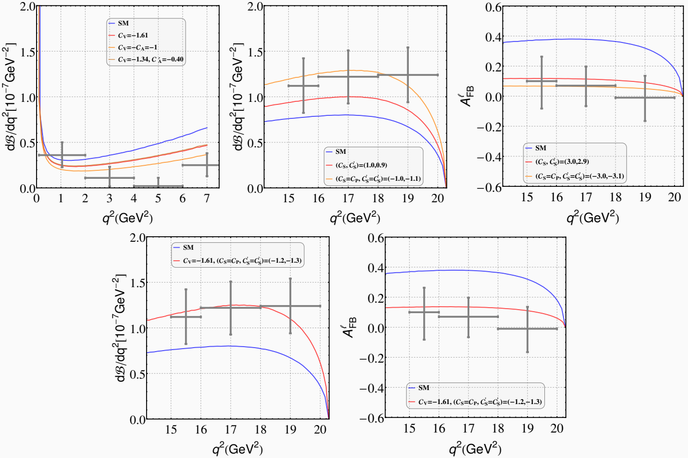
Crosses indicate LHCb data: Aaij, JHEP **1506**, 115 (2015),

$$R^{\mu/e}_{\Lambda_b} = 0.9987 \pm 0.0001\Big|_{[1-6]\ \text{GeV}^2}\,, \quad 0.9989 \pm 0.0001\Big|_{[15-(m_{\Lambda_b}-m_\Lambda)^2]\ \text{GeV}^2}\,,$$

DD, Eur.Phys.J. C78, 230 (1802.09404)

$\Lambda_b \to \Lambda\mu^+\mu^-$ observables: NP

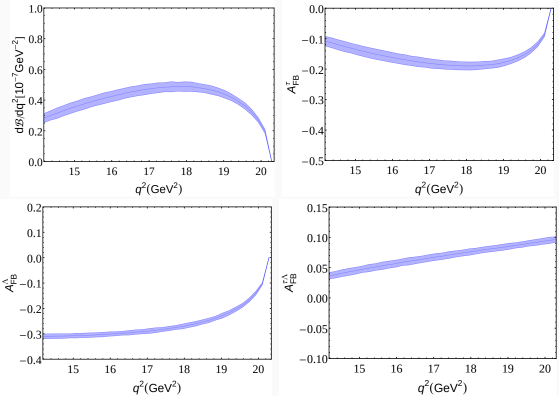
NP fits for benchmark values. VA couplings constrained by global fits to $b \to s\mu^+\mu^-$ data. The SP couplings are constrained through $\mathcal{B}(B_s \to \mu^+\mu^-)$ and $\mathcal{B}(B \to X_s\mu^+\mu^-)$.



DD, Eur.Phys.J. C78, 230 (1802.09404)

$\Lambda_b \to \Lambda(\to N\pi)\tau^+\tau^-$: SM

No data on $b \to s\tau^+\tau^-$ mode. NP poorly constrained. Models that explain $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies predict large $b \to s\tau^+\tau^-$ rates Alonso *et.al.*, JHEP 1510, 184 (2015), Crivellin *et.al.*, JHEP 1709, 040 (2017), Capdevila *et.al.*, arXiv:1712.01919, Kamenik *et.al.*, Eur. Phys. J. C 77, no. 10, 701 (2017).



$$R_{\Lambda_b}^{\tau/e} = 0.5315 \pm 0.0189\Big|_{[15-(m_{\Lambda_b}-m_{\Lambda})^2]\ \mathrm{GeV}^2} . \qquad (14)$$

DD, JHEP07 (2018) 063 (1804.08527)