

Window to New Physics through $\Lambda_b \rightarrow \Lambda_c \ell \nu$

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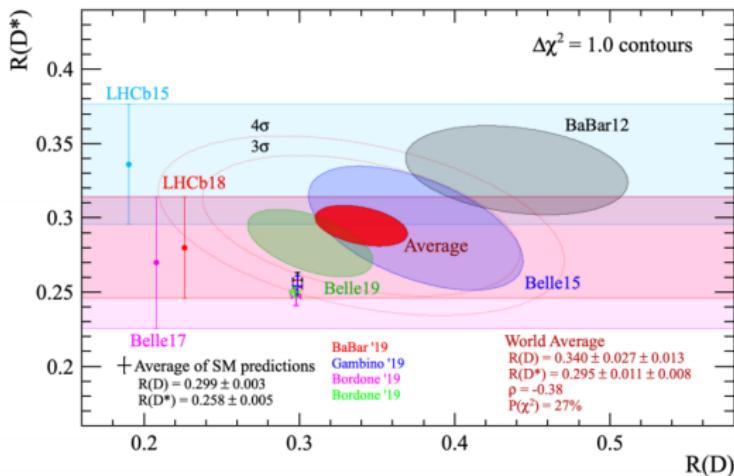
Work done in collaboration with Damir Bečirević

IJCLab

October 6, 2020

Introduction

$R_{D^{(*)}}$



$$R_{D^{(*)}} = \frac{\Gamma(B \rightarrow D^{(*)} \tau \bar{\nu}_\tau)}{\Gamma(B \rightarrow D^{(*)} l \bar{\nu}_l)} \quad l \in \{e, \mu\}$$

Measured by [BaBar, Belle, LHCb]: 3.1σ tension with SM.

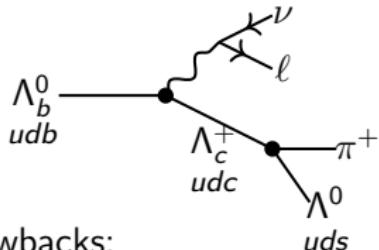
Other universality ratios:

	SM Prediction	Observation
R_D	0.299(3) [FNAL, MILC '15, HPQCD '15] cf. HFLAV	0.340(30) [BaBar, Belle, LHCb]
R_{D^*}	0.258(5) cf. HFLAV	0.295(14) [BaBar, Belle, LHCb]
$R_{J/\Psi}$	0.260(4) [HPQCD '20]	0.71(26) [LHCb]
R_{D_s}	0.297(4) [HPQCD '17]	Soon [LHCb]
$R_{D_s^*}$	0.245(8) cf. HFLAV	Soon [LHCb]
R_{Λ_c}	0.333(13) [Detmold et al. '15, Datta et al. '17]	Soon [LHCb]

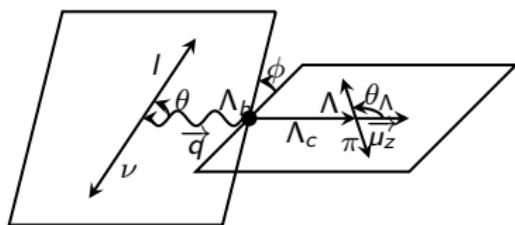
Why is R_{Λ_c} interesting?

$$R_{\Lambda_c} = \frac{\Gamma(\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu})}{\Gamma(\Lambda_b \rightarrow \Lambda_c \mu \bar{\nu})}$$

- Testing LFUV of $b \rightarrow c \ell \bar{\nu}_\ell$ with baryons,
- Independent of CKM element.
- All Form Factors already computed on the lattice.
- Rich angular/spin structure, reflected in $\Lambda_c \rightarrow \Lambda \pi^+$ secondary decay.



Some drawbacks:



- Λ_b Not produced in B-factories, only LHCb.
- $\mathcal{B}(\Lambda_c \rightarrow \Lambda \pi) = 1.30(7)\%$ compared to $\mathcal{B}(D^* \rightarrow D \pi) = 67.7(5)\%$.

Assumptions:

- NP happens at a scale $\Lambda > M_W \gg M_{\Lambda_b}$.
- NP only couples to τ lepton.

Effective Hamiltonian

$$\begin{aligned}\mathcal{H}_{\text{eff}} = & \frac{G_F}{\sqrt{2}} V_{cb} \left[(1 + \textcolor{red}{g_V})(\bar{c}\gamma_\mu b)(\bar{l}\gamma^\mu(1 - \gamma_5)\nu) \right. \\ & - (1 - \textcolor{red}{g_A})(\bar{c}\gamma_\mu\gamma_5 b)(\bar{l}\gamma^\mu(1 - \gamma_5)\nu) \\ & + \textcolor{red}{g_S} (\bar{c}b)(\bar{l}(1 - \gamma_5)\nu) + \textcolor{red}{g_P} (\bar{c}\gamma_5 b)(\bar{l}(1 - \gamma_5)\nu) \\ & \left. + \textcolor{red}{g_T} (\bar{c}\sigma_{\mu\nu}(1 - \gamma_5)b)(\bar{l}\sigma^{\mu\nu}(1 - \gamma_5)\nu) \right] + \text{h.c.}\end{aligned}$$

N.B. If $g_V, g_A, g_S, g_P, g_T = 0$, then $\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}}$ (Fermi theory).

Assumptions:

- NP happens at a scale $\Lambda > M_W \gg M_{\Lambda_b}$.
- NP only couples to τ lepton.

Effective Hamiltonian

$$\begin{aligned}\mathcal{H}_{\text{eff}} = & \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + g_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{l}_L \gamma^\mu \nu_L) \right. \\ & + g_{V_R} (\bar{c}_R \gamma_\mu b_R)(\bar{l}_L \gamma^\mu \nu_L) \\ & + g_{S_L} (\bar{c}_R b_L)(\bar{l}_R \nu_L) + g_{S_R} (\bar{c}_L b_R)(\bar{l}_R \nu_L) \\ & \left. + g_{T_L} (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{l}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}\end{aligned}$$

N.B $g_{V,A} = g_{V_R} \pm g_{V_L}$, $g_{S,P} = g_{S_R} \pm g_{S_L}$, $g_T = 2g_{T_L}$.

Form factors from lattice QCD

Hadronic amplitudes can be expresses in term of 10 Form Factors.

$$\langle \Lambda_c | \bar{c} \gamma^\mu b | \Lambda_b \rangle \sim F_0(q^2), F_+(q^2), F_\perp(q^2),$$

$$\langle \Lambda_c | \bar{c} \gamma^\mu \gamma_5 b | \Lambda_b \rangle \sim G_0(q^2), G_+(q^2), G_\perp(q^2),$$

$$\langle \Lambda_c | \bar{c} i \sigma^{\mu\nu} b | \Lambda_b \rangle \sim h_+(q^2), h_\perp(q^2), \tilde{h}_+(q^2), \tilde{h}_\perp(q^2),$$

$$\langle \Lambda_c | \bar{c} b | \Lambda_b \rangle \sim F_0(q^2), \quad \langle \Lambda_c | \bar{c} \gamma_5 b | \Lambda_b \rangle \sim G_0(q^2).$$

Available from LQCD with uncertainties and correlations.

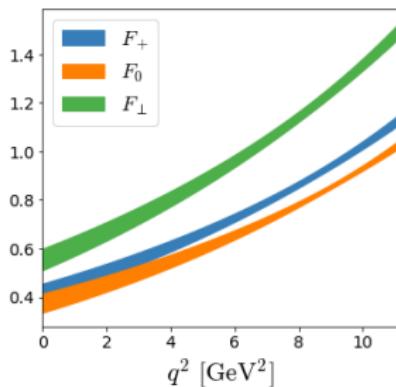
- Matrix element of vector and axial currents: [Detmold et al. '15]
- Matrix element of tensor density: [Datta et al. '17]

$$f(q^2) = \frac{1}{1 - q^2/(m_{\text{pole}}^f)^2} \left[a_0^f + a_1^f z(q^2) + a_2^f z^2(q^2) \right]$$

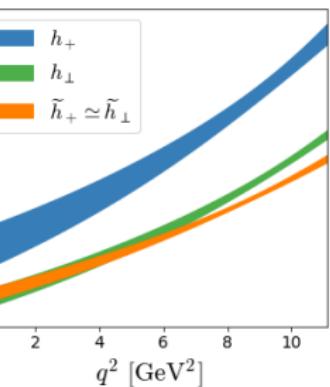
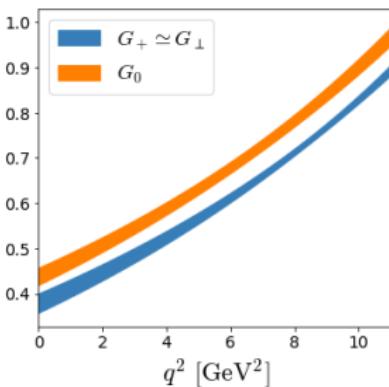
$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

$$t_0 = (m_{\Lambda_b} - m_{\Lambda_c})^2$$

$$t_+ = (m_{\text{pole}}^f)^2$$



[Detmold et al. '15]



[Datta et al. '17]

Helicity formalism

$$\frac{\mathcal{M}_{\lambda_c \lambda_l}^{\lambda_b}}{G_F V_{cb}/\sqrt{2}} = \sum_{\lambda} \delta_{\lambda} H_{\lambda_c \lambda}^{V-A, \lambda_b} L_{\lambda_l \lambda}^{V-A} + H_{\lambda_c}^{S-P, \lambda_b} L_{\lambda_l}^{S-P} + \sum_{\lambda, \lambda'} \delta_{\lambda} \delta_{\lambda'} H_{\lambda_c \lambda \lambda'}^{T-T5, \lambda_b} L_{\lambda_l \lambda \lambda'}^{T-T5},$$

SM like
Vector Leptoquark

Scalar term
2HDM

Tensor term
Scalar Leptoquark

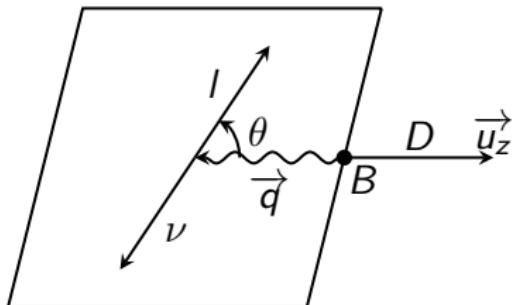
Scalar Leptoquark

$$= \sum_{\lambda \in \{\pm, 0, t\}} \tilde{H}_{\lambda_c \lambda}^{\lambda_b \lambda_l} L_{\lambda_l \lambda}^{V-A}.$$

e.g. R_2, S_3 model with

$$g_{S_L} = 4g_T \simeq 0.5i$$

Three body decay distribution



Similar to $B \rightarrow D\ell\nu$.

$$\frac{d^2\Gamma(B \rightarrow D\ell\nu)}{dq^2 d\cos\theta} = a^{\lambda_I}(q^2) + b^{\lambda_I}(q^2)\cos\theta + c^{\lambda_I}(q^2)\cos^2\theta$$

N.B.

$$\begin{cases} a^- + c^- = 0 \\ b^- = 0 \end{cases} \Rightarrow \underline{4 \text{ observables}}$$

$$\frac{d^2\Gamma(\Lambda_b \rightarrow \Lambda_c^{\lambda_c}\ell\nu)}{dq^2 d\cos\theta} = a_{\lambda_c}^{\lambda_I}(q^2) + b_{\lambda_c}^{\lambda_I}(q^2)\cos\theta + c_{\lambda_c}^{\lambda_I}(q^2)\cos^2\theta$$

N.B.

$$\begin{cases} b_+^- = a_+^- + c_+^- \\ b_-^- = -a_-^- - c_-^- \end{cases} \Rightarrow \underline{10 \text{ observables}}$$

Inclusion of the secondary decay $\Lambda_c \rightarrow \Lambda\pi^+$

Narrow width approximation:

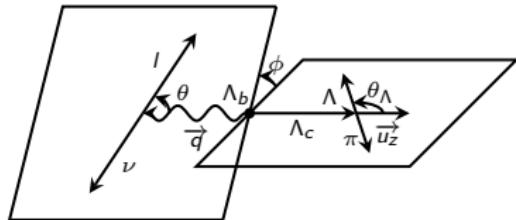
$$\mathcal{M}_{\lambda_\Lambda}^{(4)\lambda_b\lambda_I} = \sum_{\lambda_c=\pm} \left\langle \Lambda^{\lambda_\Lambda}\pi \middle| \Lambda_c^{\lambda_c} \right\rangle \mathcal{M}_{\lambda_c}^{\lambda_b\lambda_I} BW(k^2),$$

$$h_\pm = \left\langle \Lambda^\pm\pi \middle| \Lambda_c^\pm \right\rangle$$

- $|h_+|^2 + |h_-|^2$ known from $\mathcal{B}(\Lambda_c \rightarrow \Lambda\pi^+) = (1.30 \pm 0.07)\%$
- $|h_+|^2 - |h_-|^2$ known from polarization asymmetry α

$$\alpha = \frac{|h_+|^2 - |h_-|^2}{|h_+|^2 + |h_-|^2} = \begin{cases} -0.94^{+0.33}_{-0.12} & [\text{CLEO '95}] \\ -0.80 \pm 0.09 & [\text{BESIII}] \end{cases}$$

Full (four body) decay distribution



Full angular distribution

$$\begin{aligned} \frac{d^4\Gamma(\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda\pi^+) \ell^{\lambda_I}\nu)}{dq^2 d\cos\theta d\cos\theta_\Lambda d\phi} = & A_1^{\lambda_I} + A_2^{\lambda_I} \cos\theta_\Lambda \\ & + (B_1^{\lambda_I} + B_2^{\lambda_I} \cos\theta_\Lambda) \cos\theta \\ & + (C_1^{\lambda_I} + C_2^{\lambda_I} \cos\theta_\Lambda) \cos^2\theta \\ & + (D_3^{\lambda_I} \sin\theta_\Lambda \cos\phi + D_4^{\lambda_I} \sin\theta_\Lambda \sin\phi) \sin\theta \\ & + (E_3^{\lambda_I} \sin\theta_\Lambda \cos\phi + E_4^{\lambda_I} \sin\theta_\Lambda \sin\phi) \sin\theta \cos\theta. \end{aligned}$$

N.B.

$$\begin{cases} \alpha (A_1^- + C_1^-) = B_2^-, \\ \frac{1}{\alpha} (A_2^- + C_2^-) = B_1^-. \end{cases} \Rightarrow \quad \underline{18 \text{ observables}}$$

Observables

Branching fraction:

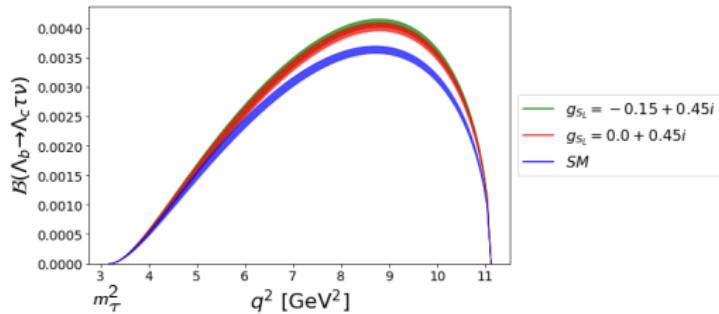
$$\frac{d\mathcal{B}}{dq^2} = 8\pi\tau_{\Lambda_b} \left(A_1^+ + A_1^- + \frac{C_1^+ + C_1^-}{3} \right)$$

q^2 -integrated observables:

$$\overline{O}_i^\pm = \frac{8\pi}{\Gamma} \int_{m_\tau^2}^{(M_{\Lambda_b} - M_{\Lambda_c})^2} O_i^\pm dq^2.$$

N.B. all \overline{O}_i are:

- CKM-free,
- (mostly) free of hadronic uncertainties.



Full set of observables, SM prediction

	$\overline{O}_i^+ + \overline{O}_i^-$	$\overline{O}_i^+ - \overline{O}_i^-$
A_1	1.035 ± 0.001	-0.405 ± 0.006
A_2	0.658 ± 0.005	-0.261 ± 0.004
B_1	0.049 ± 0.008	0.667 ± 0.006
B_2	-0.093 ± 0.009	0.761 ± 0.002
C_1	-0.106 ± 0.003	0.293 ± 0.007
C_2	-0.112 ± 0.002	0.300 ± 0.007
D_3	0.189 ± 0.008	-0.492 ± 0.008
D_4	0	0
E_3	0.069 ± 0.002	-0.172 ± 0.006
E_4	0	0

$$\begin{cases} \alpha (A_1^- + C_1^-) = B_2^- \\ \frac{1}{\alpha} (A_2^- + C_2^-) = B_1^- \end{cases}$$

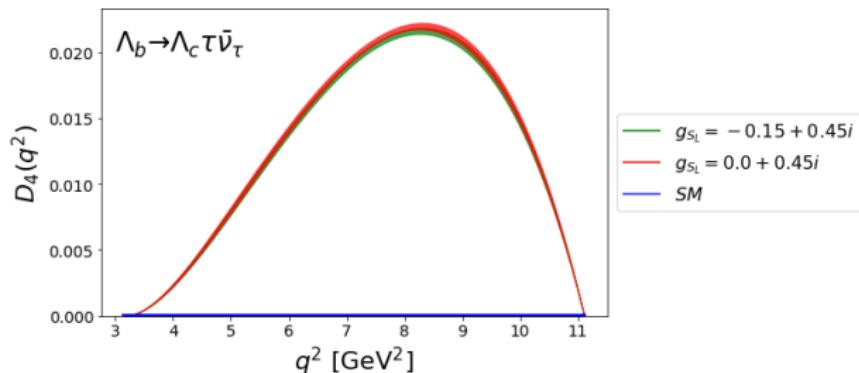
Is there a NP phase?

If there is a new physics phase accessible from this decay, its presence can be tested via

$$D_4 = D_4^+ + D_4^-$$

$$D_4^+ = 2\sqrt{2}\alpha\kappa\beta^2\mathcal{N}'m_I^2 \operatorname{Im} \left(\overline{\tilde{H}_{+t}^{++}}\tilde{H}_{--}^{++} - \overline{\tilde{H}_{++}^{-+}}\tilde{H}_{-t}^{-+} \right),$$

$$D_4^- = 2\sqrt{2}\alpha\kappa\beta^2\mathcal{N}'q^2 \operatorname{Im} \left(\overline{\tilde{H}_{-0}^{--}}\tilde{H}_{++}^{--} + \overline{\tilde{H}_{--}^{+-}}\tilde{H}_{+0}^{+-} \right).$$



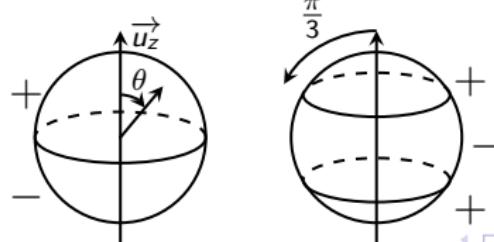
Similar with $E_4(q^2)$.

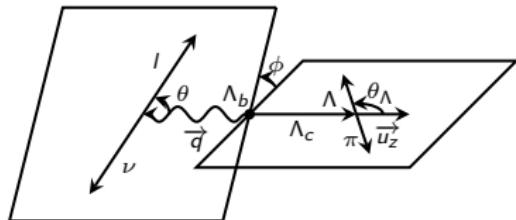
Traditional observables: Asymmetries

- A_{fb}^ℓ - Forward-backward, lepton
- $A_{\pi/3}$ - Convexity, lepton
- A_{pol} - Polarization of the lepton
- A_{fb}^Λ - Forward-backward, Λ baryon
- N.B. Polarization of the Λ baryon brings no extra information about NP.

$$A_{fb} = \frac{1}{\Gamma} \left(\int_0^1 - \int_{-1}^0 \right) \frac{d\Gamma}{d \cos \theta} d \cos \theta$$

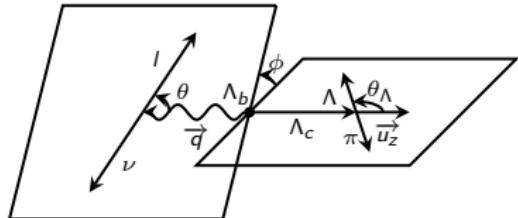
$$A_{\pi/3} = \frac{1}{\Gamma} \left(\int_{1/2}^1 - \int_{-1/2}^{1/2} + \int_{-1}^{-1/2} \right) \frac{d\Gamma}{d \cos \theta} d \cos \theta$$





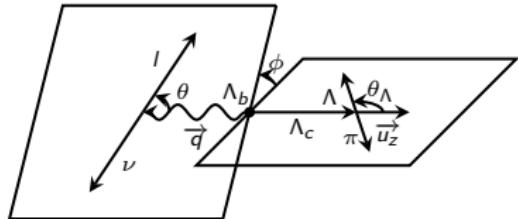
$$\begin{aligned}
 \frac{d^4\Gamma (\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda \pi^+) \ell \bar{\nu})}{dq^2 d\cos\theta d\cos\theta_\Lambda d\phi} &\propto A_{fb}^\Lambda \\
 &= A_1^{\lambda_I} + A_2^{\lambda_I} \cos\theta_\Lambda \\
 &\quad + \left(B_1^{\lambda_I} + B_2^{\lambda_I} \cos\theta_\Lambda \right) \cos\theta \\
 &\quad + \left(C_1^{\lambda_I} + C_2^{\lambda_I} \cos\theta_\Lambda \right) \cos^2\theta \\
 &\quad + \left(D_3^{\lambda_I} \sin\theta_\Lambda \cos\phi + D_4^{\lambda_I} \sin\theta_\Lambda \sin\phi \right) \sin\theta \\
 &\quad + \left(E_3^{\lambda_I} \sin\theta_\Lambda \cos\phi + E_4^{\lambda_I} \sin\theta_\Lambda \sin\phi \right) \sin\theta \cos\theta.
 \end{aligned}$$

\$\propto A_{fb}^\Lambda\$
\$\propto A_{fb}^\ell\$
\$\propto A_{\pi/3}^\ell\$



$$\begin{aligned}
 \frac{d^4\Gamma (\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda \pi^+) \ell \bar{\nu})}{dq^2 d\cos\theta d\cos\theta_\Lambda d\phi} &\propto A_{fb}^\Lambda \\
 &= A_1^{\lambda_I} + A_2^{\lambda_I} \cos\theta_\Lambda \\
 &\quad + (B_1^{\lambda_I} + B_2^{\lambda_I} \cos\theta_\Lambda) \cos\theta \\
 &\quad + (C_1^{\lambda_I} + C_2^{\lambda_I} \cos\theta_\Lambda) \cos^2\theta \\
 &\quad + (D_3^{\lambda_I} \sin\theta_\Lambda \cos\phi + D_4^{\lambda_I} \sin\theta_\Lambda \sin\phi) \sin\theta \\
 &\quad + (E_3^{\lambda_I} \sin\theta_\Lambda \cos\phi + E_4^{\lambda_I} \sin\theta_\Lambda \sin\phi) \sin\theta \cos\theta.
 \end{aligned}$$

(A_{fb}^Λ)
(A₁^{λ_I})
(A₂^{λ_I})
(B₁^{λ_I})
(B₂^{λ_I})
(C₁^{λ_I})
(C₂^{λ_I})
(D₃^{λ_I})
(D₄^{λ_I})
(E₃^{λ_I})
(E₄^{λ_I})



$$\propto A_{fb}^\Lambda$$

$$\begin{aligned}
 \frac{d^4\Gamma(\Lambda_b \rightarrow \Lambda_c (\rightarrow \Lambda \pi^+) \ell \bar{\nu})}{dq^2 d\cos\theta d\cos\theta_\Lambda d\phi} &= A_1^{\lambda_I} + A_2^{\lambda_I} \cos\theta_\Lambda \\
 &\quad + (B_1^{\lambda_I} + B_2^{\lambda_I} \cos\theta_\Lambda) \cos\theta \\
 &\quad + (C_1^{\lambda_I} + C_2^{\lambda_I} \cos\theta_\Lambda) \cos^2\theta \\
 &\quad + (D_3^{\lambda_I} \sin\theta_\Lambda \cos\phi + D_4^{\lambda_I} \sin\theta_\Lambda \sin\phi) \sin\theta \\
 &\quad + (E_3^{\lambda_I} \sin\theta_\Lambda \cos\phi + E_4^{\lambda_I} \sin\theta_\Lambda \sin\phi) \sin\theta \cos\theta.
 \end{aligned}$$

$\propto A_{fb}^\ell$
 $\propto A_{\pi/3}^\ell$

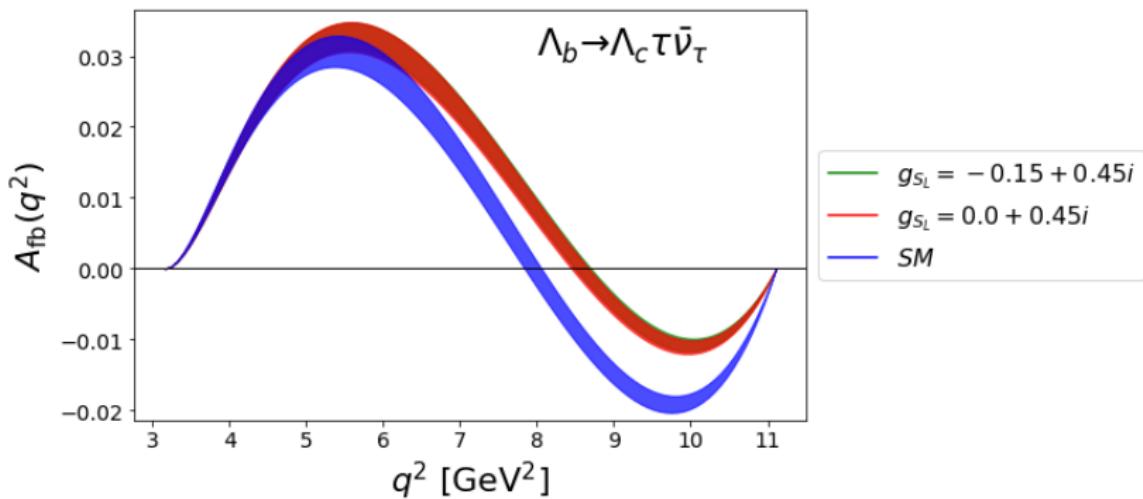
q^2 -shape of asymmetries are important

Example: A_{fb}^τ almost cancels in the Standard Model

⇒ sensitive to g_{S_L}, g_{S_R}, g_T .

$$A_{fb}^\tau(q^2) \propto B_1^+ + B_1^-$$

$$= 2\kappa\beta^2 N' q^2 \left(\left| \tilde{H}_{++}^{--} \right|^2 - \left| \tilde{H}_{--}^{+-} \right|^2 - 2 \operatorname{Re} \left(\overline{\tilde{H}_{-t}^{-+}} \tilde{H}_{-0}^{-+} + \overline{\tilde{H}_{+t}^{++}} \tilde{H}_{+0}^{++} \right) \right)$$



Conclusion

- Full angular distribution of $\Lambda_b \rightarrow \Lambda_c(\rightarrow \Lambda\pi)\ell\nu$, including all possible NP contribution.
- All Form Factors (SM+Tensor) are known from LQCD.
- Checked against [Böer et al. '19, Mu et al. '19, Datta et al. '17], but with simpler expressions and explicit spin structure.
- Exhaustive set of 18 angular observables.