Searching for effects beyond SMEFT in flavour physics

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Outline:

- Motivation
- Comparison SMEFT, HEFT and LEFT

- Preferred regions for semileptonic operators in $b \to c\tau\bar{\nu}_\tau$ processes.
- Angular distribution for $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu_\tau$.
- Observables that can distinguish effects beyond SMEFT

Motivation:

Standard Model Effective Field Theory (SMEFT) :

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \frac{1}{\Lambda} C^{(5)} O^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right).$$

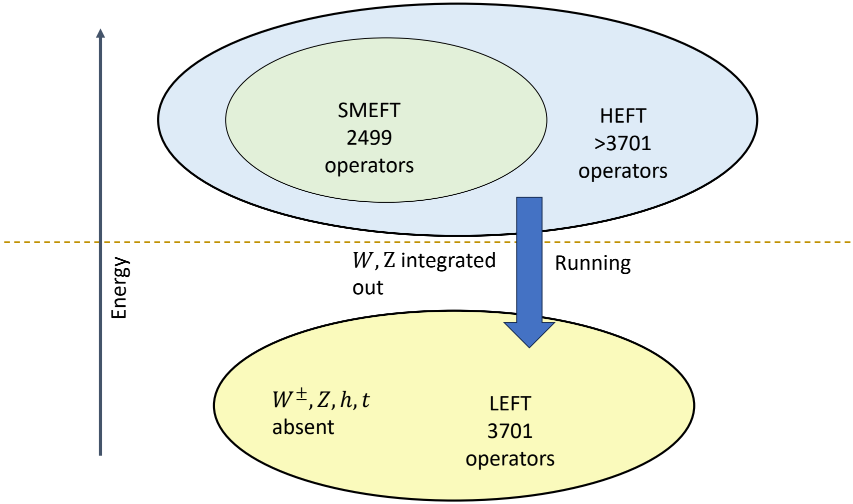
- Includes SM fields only.
- Follows $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Electroweak (EW) symmetry linearly realized.

Current uncertainties in Higgs coupling measurements allow more generalized EFTs
e.g. **Higgs Effective Field Therory (HEFT)**. In HEFT:

- $SU(2)_L \times U(1)_Y$ non-linearly realized.
- Higgs boson is not embedded in a $SU(2)_L$-doublet: $\longrightarrow$ More general coupling of Higgs.
- HEFT $\supset$ SMEFT $\supset$ SM

- In the energy scale much below the EW symmetry breaking, the relevant EFT is **Low Energy Effective Field Theory (LEFT)**
- LEFT can be derived from HEFT by integrating out the heavier particles – $W^{\pm}$, Z, Higgs and top quark.

HEFT, SMEFT and LEFT



- Certain EFT operator appears in LEFT but not in SMEFT (at dim-6).
- Example: $\mathcal{O}_V^{LR} \equiv (\bar{\tau}\gamma_\mu P_L \nu_\tau)(\bar{c}\gamma^\mu P_R b)$ which contributes to $R(D^{(*)})$, $R(J/\psi)$, $\Lambda_b \to \Lambda_c \tau \nu_\tau$ etc.
- Large contribution from $\mathcal{O}_V^{LR} \implies$ non-SMEFT effects.

Operators involved in $b \to c\tau\bar{\nu}_\tau$

$$\mathcal{H}_{\rm eff} = \frac{4\,G_F V_{cb}}{\sqrt{2}}\left[(1+g_L)\mathcal{O}_V^{LL} + g_R\mathcal{O}_V^{LR} + g_S\mathcal{O}_S + g_P\mathcal{O}_P + g_T\mathcal{O}_T\right]\,.$$

$$\mathcal{O}_V^{LL} = (\bar{\tau}\gamma_\mu P_L\nu_\tau)(\bar{c}\gamma^\mu P_L b)\,, \qquad \mathcal{O}_V^{LR} = (\bar{\tau}\gamma_\mu P_L\nu_\tau)(\bar{c}\gamma^\mu P_R b)\,, \tag{1}$$

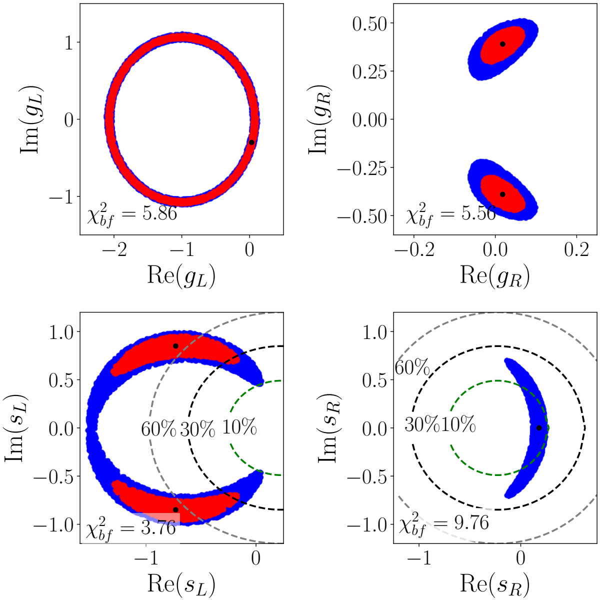
$$\mathcal{O}_S = \frac{1}{2}(\bar{\tau}P_L\nu_\tau)(\bar{c}b)\,, \qquad \mathcal{O}_P = \frac{1}{2}(\bar{\tau}P_L\nu_\tau)(\bar{c}\gamma_5 b)\,, \tag{2}$$

$$\mathcal{O}_T = (\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau)(\bar{c}\sigma^{\mu\nu}b)\,. \tag{3}$$

These operators can contribute to the following observables:

Observables	SM value	Experimental value	Recent updates
R_D	0.298 ± 0.004	0.357 ± 0.029	Belle(2020), LHCb(2023)
R_D^*	0.254 ± 0.005	0.284 ± 0.012	Belle II(2023), LHCb(2023)
$R_{j/\psi}$	0.258 ± 0.004	$0.71 \pm 0.17 \pm 0.18$	LHCb(2018)
$P_\tau^{D^*}$	-0.497 ± 0.013	$-0.38 \pm 0.51 \pm 0.21$	Belle(2017)
$F_L^{D^*}$	0.46 ± 0.04	$0.60 \pm 0.08 \pm 0.035$	Belle(2019)

Scenario	SM	g_L	g_R	s_L	s_R
Best-fit	-	$0.03 - 0.30i$	$0.018 \pm 0.39i$	$-0.73 \pm 0.85i$	$0.18 + 0.00i$
χ^2_{bf}	22.35	5.86	5.56	3.76	9.76



The branching ratio $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau)$ puts constraints on the scalar operators.

We consider–

- $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < 30\%$
- $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < 10\%$

$\Lambda_b \to \Lambda_c \tau \nu_\tau$

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Observation of the Decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

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(LHCb Collaboration)

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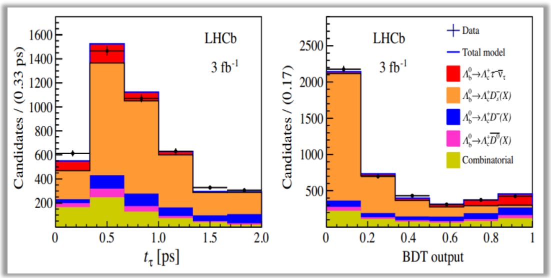
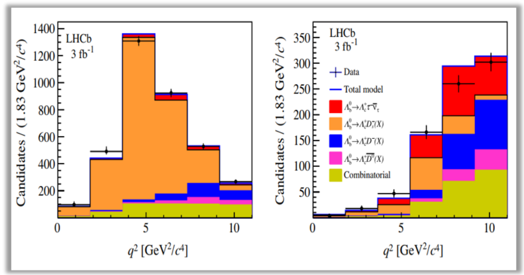
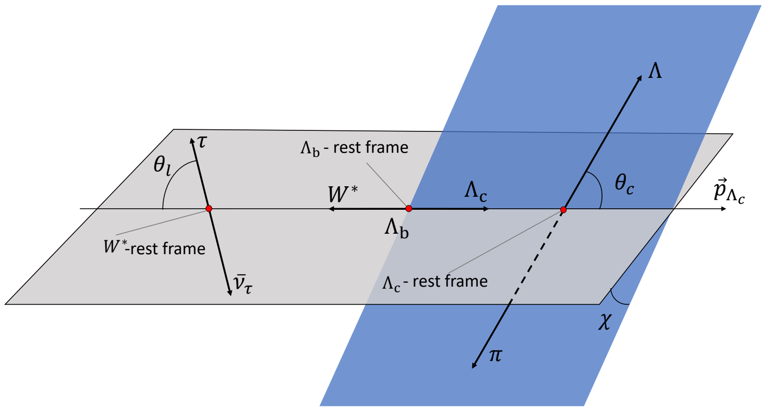
The first observation of the semileptonic b-baryon decay $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$, with a significance of 6.1σ, is reported using a data sample corresponding to 3 fb^{-1} of integrated luminosity, collected by the LHCb experiment at center-of-mass energies of 7 and 8 TeV at the LHC. The τ^- lepton is reconstructed in the hadronic decay to three charged pions. The ratio $\mathcal{K} = \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-)$ is measured to be $2.46 \pm 0.27 \pm 0.40$, where the first uncertainty is statistical and the second systematic. The branching fraction $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\%$ is obtained, where the third uncertainty is from the external branching fraction of the normalization channel $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$. The ratio of semileptonic branching fractions $\mathcal{R}(\Lambda_c^+) \equiv \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)/\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)$ is derived to be $0.242 \pm 0.026 \pm 0.040 \pm 0.059$, where the external branching fraction uncertainty from the channel $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$ contributes to the last term. This result is in agreement with the standard model prediction.



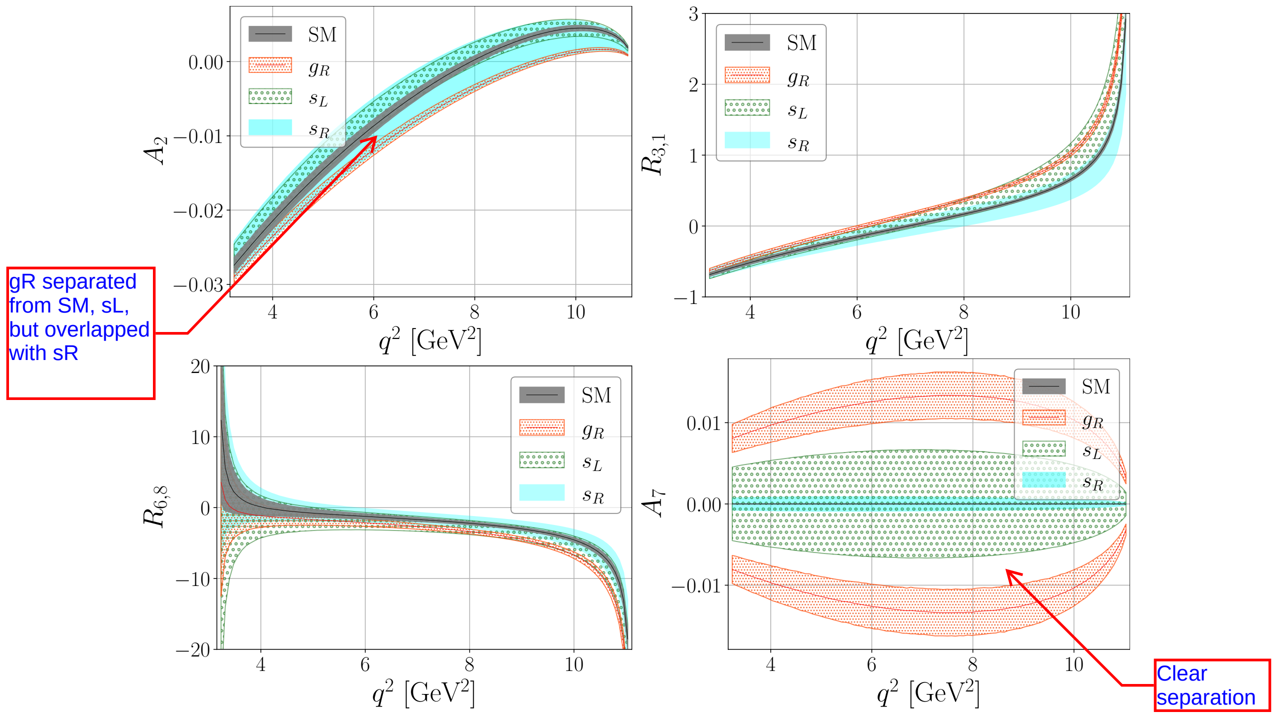


- We consider the process $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu_\tau$.
- Recently $\Lambda \to \Lambda_c\tau\nu_\tau$ was observed at LHCb for the first time.
- Angular distribution of the final state particles offer multiple observables to probe the effect of g_R.



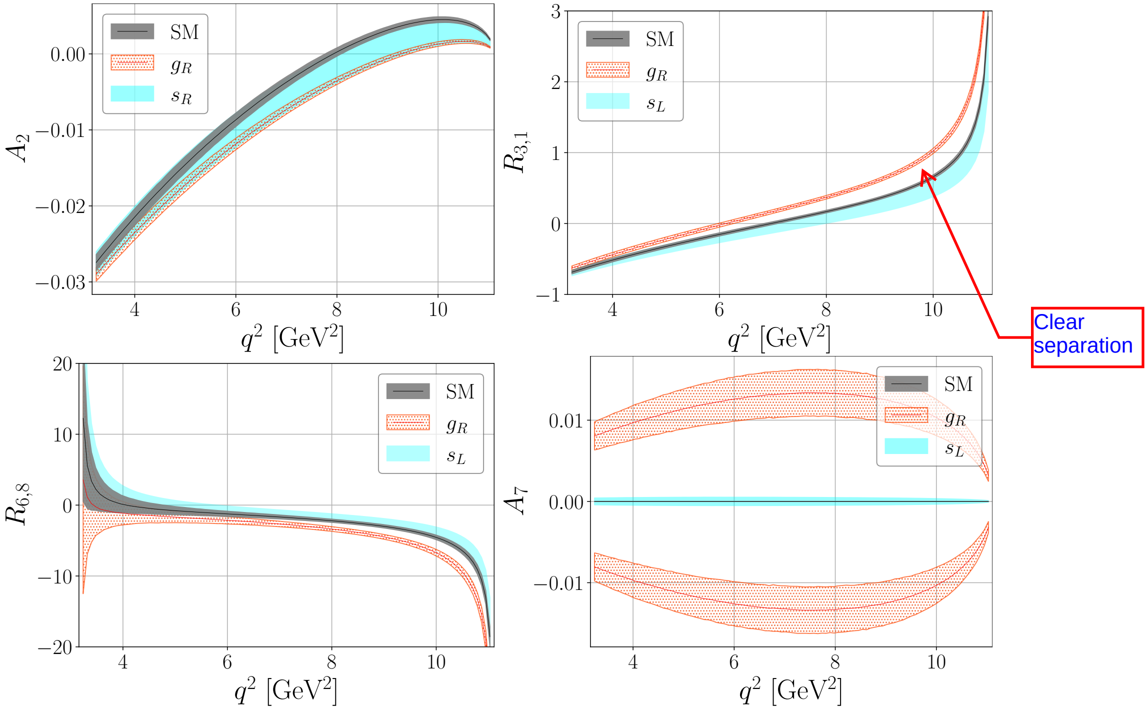
$$\frac{1}{(d\Gamma/dq^2)}\frac{d\Gamma}{dq^2\, d\cos\theta_c\, d\cos\theta_l\, d\chi}$$
$$= A_0 + A_1\,\cos\theta_c + A_2\,\cos\theta_l + A_3\,\cos\theta_c\,\cos\theta_l + A_4\,\cos^2\theta_l + A_5\,\cos\theta_c\cos^2\theta_l$$
$$+ A_6\,\sin\theta_c\sin\theta_l\cos\chi + A_7\,\sin\theta_c\sin\theta_l\sin\chi + A_8\,\sin\theta_c\sin\theta_l\cos\theta_l\cos\chi$$
$$+ A_9\,\sin\theta_c\sin\theta_l\cos\theta_l\sin\chi\ .$$

Angular Observables with $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < 30\%$



Angular observables A_2, $R_{3,1}$, $R_{6,8}$ and A_7. The values of s_L and s_R are varied within their 2σ allowed ranges, while g_R kept fixed at its best-fit value. For each scenario, 2σ errors from the hadronic form factors and the polarization asymmetry α have been included.

Angular Observables with $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < 10\%$



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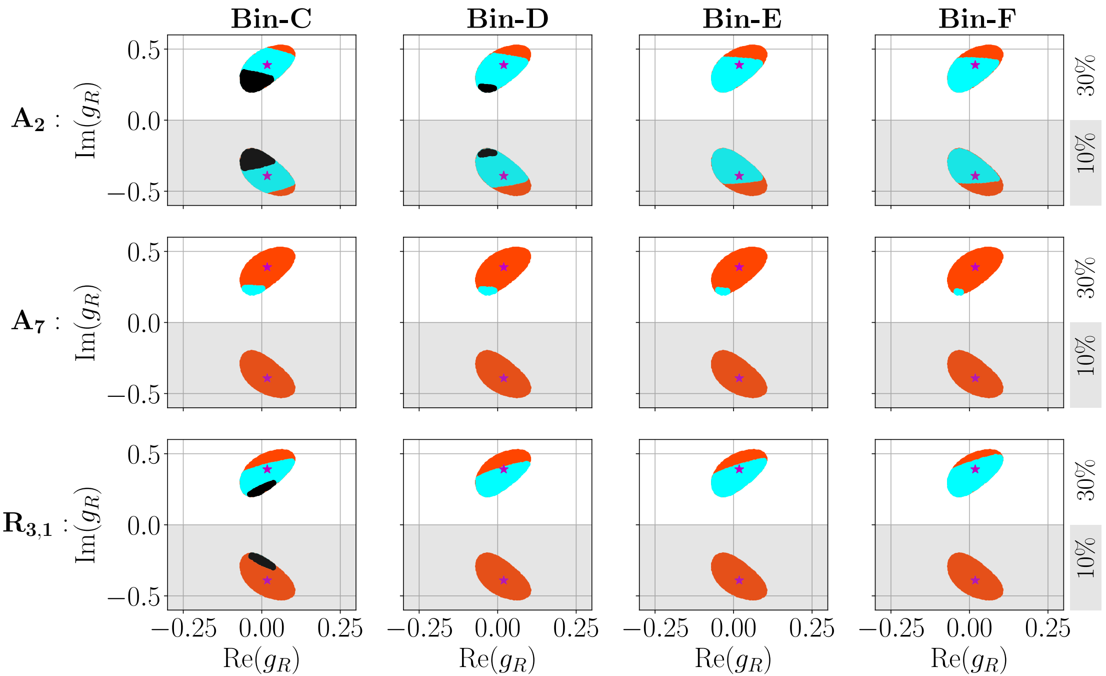
Angular Observables

ObservableScenario	$\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < 30\%$			$\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < 10\%$		
	SM , g_L	s_L	s_R	SM , g_L	s_L	s_R
$d\Gamma/dq^2$	$\times$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
A_0	$\times$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
A_1	$\times$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
A_2	$\checkmark$	$\checkmark^{(\times)}$	$\times$	$\checkmark$	$\checkmark$	$\times$
A_3	$\checkmark^{(\times)}$	$\times$	$\times$	$\checkmark^{(\times)}$	$\checkmark$	$\checkmark^{(\times)}$
A_4	$\times$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
A_5	$\times$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
A_6	$\times$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
A_7	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
A_8	$\times$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
A_3/A_1	$\checkmark$	$\times$	$\times$	$\checkmark$	$\checkmark$	$\checkmark$
A_3/A_5	$\checkmark$	$\checkmark^{(\times)}$	$\times$	$\checkmark$	$\checkmark$	$\checkmark$
A_6/A_8	$\checkmark$	$\checkmark^{(\times)}$	$\times$	$\checkmark$	$\checkmark$	$\checkmark^{(\times)}$

The effectiveness of angular observables and their ratios in distinguishing the g_R scenario from the SM and other NP scenarios. Results for $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < 30\%$ and $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) < 10\%$ are shown.

Bin-wise possibility of distinguishing g_R contribution



Regions where the g_R scenario can be distinguished from SM, g_L, s_L and s_R (orange), from only SM and g_L (cyan) and from neither (black). Bins C, D, E and F corresponds to q^2 ranges ($3.67 - 5.5$, $5.50 - 7.33$, $7.33 - 9.17$, $9.17 - 11.13$) GeV^2.

Summary

- Effects beyond SMEFT can be probed indirectly in low energy flavour physics observables.
- We find the effectiveness of different angular observables in $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu_\tau$ decay which can distinguish non-SMEFT effects from other NP scenarios present within SMEFT.
- It is observed that their effectiveness strongly depends on the constraints on the branching ratio $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau)$.
- We find that the angular observables A_7 (asymmetry w.r.t the angle between the decay planes) shows the most distinguishable effects coming from non-SMEFT contributions.
- Reduction in the hadronic uncertainties, better constraints on $\mathcal{B}(B_c \to \tau\bar{\nu}_\tau)$ and precise measurement of Λ_b decay distribution in future will improve the sensitivity of angular observables in understanding the distinct effects of SMEFT vs HEFT and how the $SU(2)_L \times U(1)_Y$ symmetry is realized above EW scale.

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Thank you for your attention!