Probing Scalar-Tensor Interactions in $b \to c\tau\nu$ with Tau Polarization at the LHC

Work in progress in collaboration with N. Košnik and A. Roy

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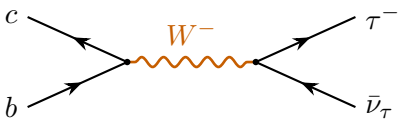
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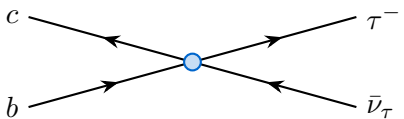
Belica, Medana, October 15, 2026

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We study charged-current b-c-τ-ν interactions:



Standard Model



New interactions

- At low energies, these interactions are tested in semileptonic B-meson decays: $B \to D\tau\nu$ and $B \to D^*\tau\nu$.
- Comparing tau modes with electron and muon modes tests lepton-flavour universality through

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}, \qquad \ell = e, \mu.$$

BaBar, Belle, Belle II and LHCb have measured $R_{D^{(*)}}$.
[BaBar, 1205.5442, 1303.0571; Belle, 1910.05864;
Belle II, 2401.02840; LHCb, 2302.02886, 2406.03387]

The experimental averages compiled by HFLAV show tension with the SM predictions.
[HFLAV, 2411.18639]

Observable	Experiment	SM prediction
R_D	0.359 ± 0.024	0.293 ± 0.008
R_{D^*}	0.280 ± 0.011	0.247 ± 0.002
$F_L(D^*)$	0.49 ± 0.05	0.46 ± 0.01

$\rho(R_D, R_{D^*}) = -0.37$

$F_L(D^*)$ is the longitudinal D^* polarization fraction.

The tension motivates considering new nonstandard contributions to $b \to c\tau\nu$.

- The SM charged current involves a left-chiral tau. We focus on scalar and tensor interactions involving a right-chiral tau.
- Starting point: use low-energy constraints on the Wilson coefficients to define collider benchmarks.
- Collider test: the monotau channel at the LHC,

$$pp \to \tau^- \bar{\nu}_\tau + X, \qquad \text{and its charge conjugate.}$$

Use tau polarization to improve sensitivity beyond event counts.

Above the electroweak scale, we retain scalar and tensor SMEFT operators:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\Big[C^{(1)}_{\substack{lequ\\prst}}(\bar{L}_p^j e_r)\,\epsilon_{jk}(\bar{Q}_s^k u_t) + C^{(3)}_{\substack{lequ\\prst}}(\bar{L}_p^j \sigma_{\mu\nu} e_r)\,\epsilon_{jk}(\bar{Q}_s^k \sigma^{\mu\nu} u_t)\Big] + \text{h.c.}$$

In the down-aligned mass basis, retain only $(p,r,s,t) = (3,3,3,2)$:

$$\mathcal{L}_{\rm NP} = \sum_{A=1,3} \frac{C^{(A)}_{\tau\tau bc}}{\Lambda^2}\Big[\underbrace{(\bar{\nu}_{\tau,L}\Gamma^A \tau_R)(\bar{b}_L \Gamma_A c_R)}_{\text{charged current}} - V_{i3}(\bar{\tau}_L \Gamma^A \tau_R)(\bar{u}_{i,L}\Gamma_A c_R)\Big] + \text{h.c.}$$

$\Gamma^1 = \mathbf{1}, \qquad \Gamma^3 = \sigma_{\mu\nu}.$

A scalar leptoquark $R_2 \sim (3, 2, 7/6)$ provides a concrete realization

- Matching its tree-level exchange amplitude and applying Fierz identities motivates the benchmark relation

$$C^{(3)}(\Lambda) = \frac{1}{4} C^{(1)}(\Lambda), \qquad \Lambda = 1.5\,\mathrm{TeV}.$$

- We allow $C^{(1)}$ to be complex in the fit to the low-energy observables.

[Sakaki, Tanaka, Tayduganov, Watanabe, 1309.0301;
Bečirević, Doršner, Fajfer, Faroughy, Košnik, Sumensari, 1806.05689]

At $\mu_b = m_b$, the charged-current Lagrangian is

$$\mathcal{L}_{b\to c\tau\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \Big[(\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}) + g_S (\bar{c}_R b_L)(\bar{\tau}_R \nu_{\tau L}) + g_T (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L}) \Big] + \text{h.c.}$$

- Tree-level matching and leading-order QCD running from $\Lambda = 1.5\,\text{TeV}$ give

$$g_S(\mu_b) \simeq -0.53\, C^{(1)*}(\Lambda), \qquad g_T(\mu_b) \simeq -0.28\, C^{(3)*}(\Lambda).$$

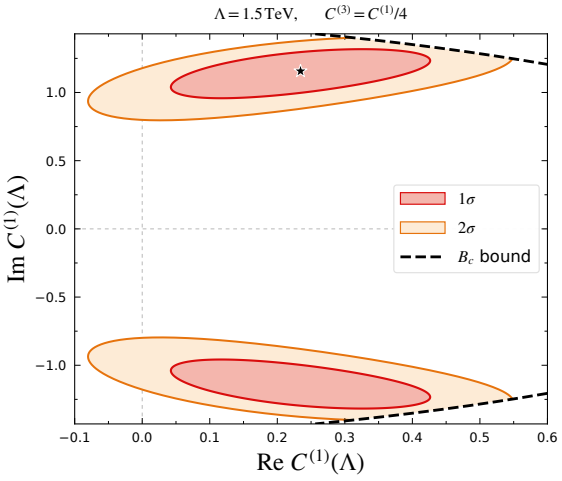
  With $C^{(3)} = C^{(1)}/4$, this gives $g_S(\mu_b)/g_T(\mu_b) \simeq 7.6$.

- Furthermore, we impose $\mathcal{B}(B_c \to \tau\nu) < 30\%$ [Alonso, Grinstein, Camalich, 1611.06676].

Form-factor treatment

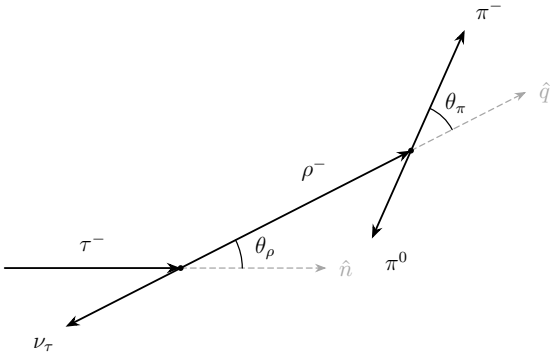
[Bečirević, Fajfer, Košnik, Pavičić, 2404.16772]

Form factors	Inputs and sources
$B \to D$: f_+, f_0	Fermilab/MILC and HPQCD lattice results, combined by FLAG. [1503.07237; 1505.03925; FLAG, 2111.09849]
$B \to D$: f_T/f_+	Lattice determination [Atoui, Bečirević, Morenas, Sanfilippo, 1310.5238]
$B \to D^*$: V, A_1, A_2	CLN shapes and ratios fitted to light-lepton data (HFLAV). [CLN, hep-ph/9712417; HFLAV, 2206.07501]
$B \to D^*$: A_0	Prescription using lattice A_0/A_1 at zero recoil [Fermilab/MILC, 2105.14019; HPQCD, 2304.03137; JLQCD, 2306.05657]
$B \to D^*$: $T_{1,2,3}$	HPQCD tensor ratios $T_{1,2,3}/A_1$ [Harrison and Davies, 2304.03137]



$$C^{(1)}_{\mathrm{bf}}(\Lambda) = 0.23 + 1.16\,i, \qquad \Lambda = 1.5\,\mathrm{TeV}.$$

Ambiguity in the sign of the imaginary part.



$\lambda_\tau, \lambda_\rho$: spin projections of τ and ρ along the axis $\hat{q}$.

Conservation of angular momentum along $\hat{q}$:

$$\lambda_\tau = \lambda_\rho + \tfrac{1}{2}$$

(neutrino spin along $\hat{q}$ is $+\frac{1}{2}$.)

$$\lambda_\tau = -\tfrac{1}{2} \;\longrightarrow\; \lambda_\rho = -1 \quad \text{(transverse } \rho\text{)}, \qquad \frac{d\Gamma_{\rho_T}}{d\cos\theta_\pi} \propto \sin^2\theta_\pi,$$

$$\lambda_\tau = +\tfrac{1}{2} \;\longrightarrow\; \lambda_\rho = 0 \quad \text{(longitudinal } \rho\text{)}, \qquad \frac{d\Gamma_{\rho_L}}{d\cos\theta_\pi} \propto \cos^2\theta_\pi.$$

For $E_\tau \gg m_\tau$:

- SM left-chiral current $\longrightarrow$ spin down along $\hat{n}$.
- BSM right-chiral currents $\longrightarrow$ spin up along $\hat{n}$.

Each is a linear combination of both spin projections along $\hat{q}$, with amplitudes depending on θ_ρ. Spin information encoded in the θ_ρ–θ_π distribution:

$$\frac{1}{\Gamma_{L,R}} \frac{d^2\Gamma_{L,R}}{d\cos\theta_\rho \, d\cos\theta_\pi} \propto \frac{m_\tau^2}{m_\rho^2}(1 \mp \cos\theta_\rho)\cos^2\theta_\pi + (1 \pm \cos\theta_\rho)\sin^2\theta_\pi.$$

Upper signs: τ_L^-, lower signs: τ_R^-.

Boost to the lab frame:

$$\Upsilon_{\rm lab} = \frac{E^{\rm lab}_{\pi^-} - E^{\rm lab}_{\pi^0}}{E^{\rm lab}_{\pi^-} + E^{\rm lab}_{\pi^0}} \simeq \frac{(\beta_\rho + \cos\theta_\rho)\cos\theta_\pi + \gamma_\rho^{-1}\sin\theta_\rho \sin\theta_\pi \cos\phi_\pi}{1 + \beta_\rho \cos\theta_\rho}.$$

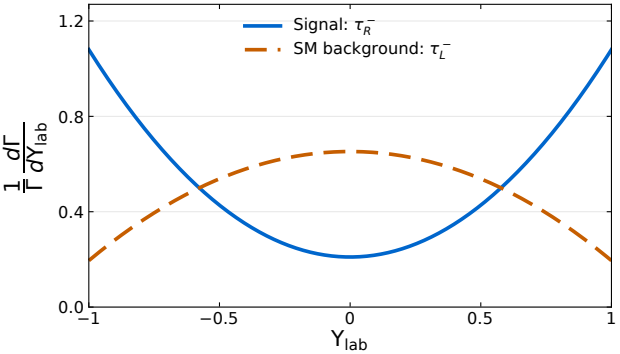
$$\frac{1}{\Gamma_{L,R}}\frac{d\Gamma_{L,R}}{d\Upsilon_{\rm lab}} \simeq A_{L,R}\,\Upsilon^2_{\rm lab} + B_{L,R}\big(1 - \Upsilon^2_{\rm lab}\big).$$

$A_L \simeq 0.2, \quad B_L \simeq 0.7$

$A_R \simeq 1.1, \quad B_R \simeq 0.2$

Left-handed τ favors $\big(1 - \Upsilon^2_{\rm lab}\big)$.

Right-handed τ favors $\Upsilon^2_{\rm lab}$.

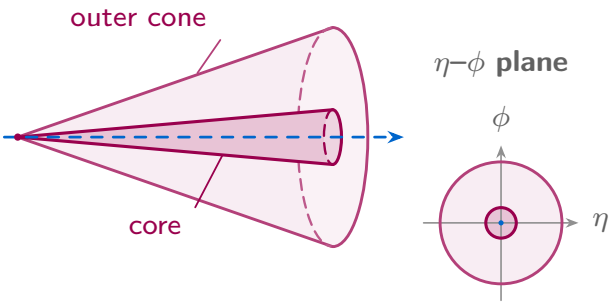


pp collisions at $\sqrt{s} = 14\,\text{TeV}$, $L_{\text{int}} = 3\,\text{ab}^{-1}$.
MadGraph5 [1405.0301], PYTHIA [1410.3012] and Delphes [1307.6346].

- Signal: the `SMEFTsim` UFO model for MadGraph. [SMEFTsim, 1709.06492]
- Tau decays: the `TauDecay` UFO model preserves production–decay spin correlations for the signal and $W \to \tau\nu$. [TauDecay, 1212.6247]
- Backgrounds: $W \to \tau\nu$, $Z(\nu\bar{\nu}) + j$, $W(\ell\nu) + j$, $t\bar{t}$, diboson and $Z/\gamma^* \to \tau^+\tau^-$.
- The $Z(\nu\bar{\nu}) + j$ and $W(\ell\nu) + j$ samples contribute through jets misidentified as taus.

QCD multijet backgrounds are not included here. An experimental analysis would require a dedicated estimate from data, for example using control regions.

Candidate axis: the highest-p_T reconstructed jet.



- Core: $\Delta R \leq 0.10$.
- Outer cone: $\Delta R \leq 0.40$.
- Annulus: $0.10 < \Delta R \leq 0.40$.

Scalar transverse-momentum sums in region A:

$$p_T^A = p_{T,\text{charged}}^A + p_{T,\gamma}^A + p_{T,\text{nh}}^A.$$

Hadronic taus tend to produce a few collimated particles with little surrounding activity. Quark and gluon jets tend to have broader activity.

- Large missing transverse momentum

$$E_T^{\text{miss}} > 500\,\text{GeV}$$

- Veto additional jets, electrons and muons.
- Exactly one charged core track, $N_{\text{charged}}^{\text{core}} = 1$.
- At least one core photon object with $p_T > 1\,\text{GeV}$.

- Momentum concentrated in the core:

$$f_{\text{core}} = \frac{p_T^{\text{core}}}{p_T^{\text{outer}}} > 0.95.$$

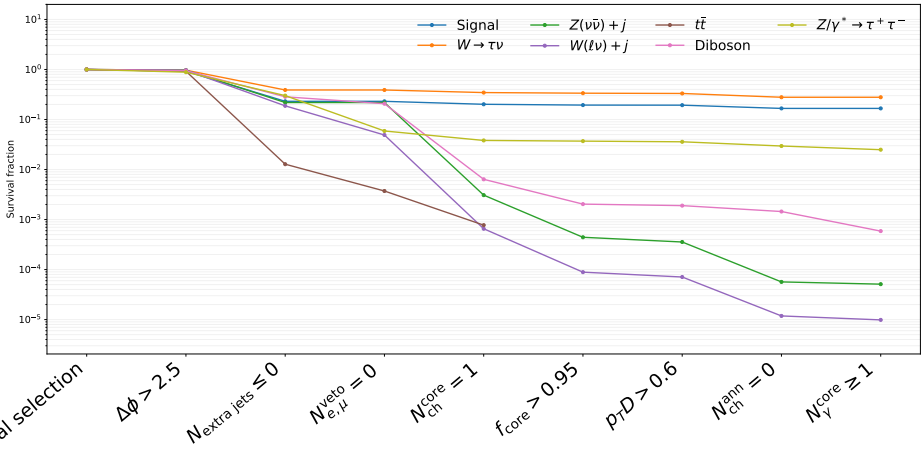
  Inspired by CMS tau identification [CMS, 1510.07488]

- No charged annulus track with $p_T > 1\,\text{GeV}$.
  [CMS-PAS-PFT-08-001]

- Transverse-momentum dispersion
  [CMS, 1202.1416; Larkoski, Thaler, Waalewijn, 1408.3122]

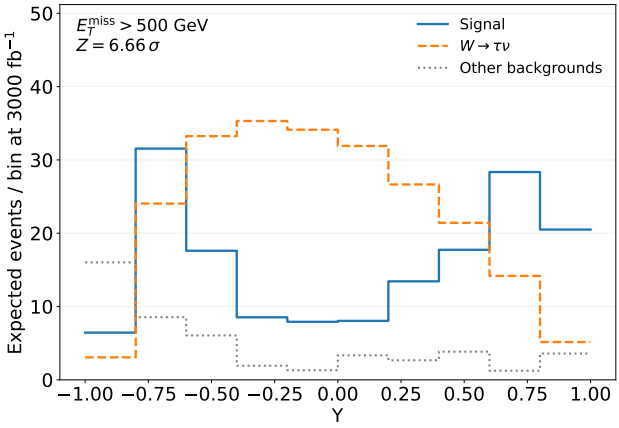
$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}} > 0.60.$$

  The sums include tracks and photon objects in the outer cone.
  p_{TD} measures p_T sharing: $1/\sqrt{N}$ for N equal-p_T objects, and 1 for a single object.



Each curve starts at one after $p_T^{\tau_{\text{vis}}} > 50\,\text{GeV}$, $|\eta_{\tau_{\text{vis}}}| < 2.5$ and $E_T^{\text{miss}} > 500\,\text{GeV}$.

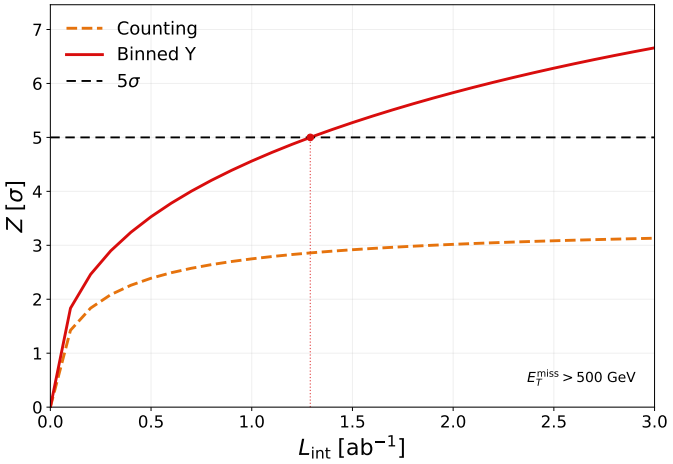
Requiring one charged core track and isolation around the candidate suppress fake taus.



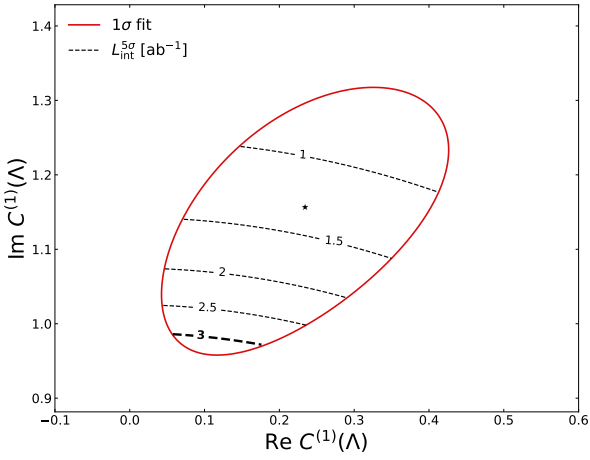
Best-fit point benchmark, both charges combined.

Expected significance, with 20% normalization uncertainties for $W \to \tau\nu$ and $Z(\nu\bar{\nu}) + j$.

Expected significance versus luminosity for best fit point



The binned Υ analysis improves the expected sensitivity compared with counting total number of events.



Luminosity needed for an expected 5σ discovery with binned Υ.

- Scalar-tensor contributions in $b \to c\tau\nu$ compatible with the low-energy fit produce a characteristic tau-polarization signature in the monotau channel.
- Charged-neutral energy sharing retains this information after selection and reconstruction, adding discrimination beyond the event count
- The expected sensitivity for scalar-tensor scenario improves substantially with the Υ distribution.

$\sqrt{s} = 14\,\text{TeV}, \qquad L_{\text{int}} = 3\,\text{ab}^{-1}.$

Sample	N_{gen}	σ_{gen} [fb]	w	n_{sel}	Expected yield	MC uncertainty
Signal, τ^-	40 000	0.82	0.06	1 316	81.0	2.2
Signal, τ^+	40 000	0.82	0.06	1 293	79.1	2.2
$W^- \to \tau^- \bar{\nu}_\tau$	200 000	0.20	$3.1 \cdot 10^{-3}$	21 502	65.6	0.4
$W^+ \to \tau^+ \nu_\tau$	300 000	0.48	$4.8 \cdot 10^{-3}$	33 913	163.5	0.9
$Z(\nu\bar{\nu}) + j$	3 000 000	681	0.68	55	37.5	5.1
$W(\ell\nu) + j$	1 500 000	441	0.88	5	4.4	2.0
$t\bar{t}$	1 000 000	104	0.31	0	0.0	< 0.94
Diboson	100 000	6.9	0.2	13	2.7	0.7
$Z/\gamma^* \to \tau^+\tau^-$	40 000	0.16	0.01	335	4.0	0.2
Total signal					160.1	
Total background					277.7	

Generation cuts $E_{T,\text{gen}}^{\text{miss}} > 400\,\text{GeV}$ for all backgrounds and $200\,\text{GeV}$ for signal.