Flavored mono-tau searches at the LHC

J. Martin Camalich

Portorož 2019: Precision era in High Energy Physics

April 16th 2019
Status of the $b \rightarrow c\tau\nu$ anomalies

Why studying the $R_{D(*)}$ anomalies?

If true, find the “ultimate” collider search

NEW: Belle measurement with semi-leptonic tag

- Belle SL at $\sim 1\sigma$ from SM
  - $R_D$ consistent with SM
- Tension between Belle and BaBar . . .
- World average now at $\sim 3\sigma$ from SM . . .

Interpretation with New Physics?

$R_D = 0.307 \pm 0.037 \pm 0.016$
$R_{D^*} = 0.283 \pm 0.018 \pm 0.014$

G. Caria @ Moriond EW 2019
EFT of new-physics in $b \rightarrow c\tau\nu$

**Low-Energy EFT Lagrangian**

\[
L_{\text{eff}} \supset - \frac{G_F V_{cb}}{\sqrt{2}} [(1 + \epsilon_L^L) \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{c} \gamma^\mu (1 - \gamma_5) b + \epsilon_R^L \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{c} \gamma^\mu (1 + \gamma_5) b \\
+ \epsilon_S^L \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{c} (1 - \gamma_5) b + \epsilon_S^R \bar{\ell} (1 - \gamma_5) \nu_\ell \cdot \bar{c} (1 + \gamma_5) b + \epsilon_T \bar{\ell} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{c} \sigma^{\mu\nu} (1 - \gamma_5) b] + \text{h.c.},
\]

**The SM + 5 New-Physics operators**

**Matching with SMEFT**: $\epsilon_R^L$ LFUV up to $\mathcal{O}(\frac{v^4}{\Lambda_{NP}^4})$ Buchmuller & Wyler '86

**Introducing light right-handed neutrinos $N_R$** (See e.g. Robinson, Shakya & Zupan, JHEP 1902 (2019) 11)

**5 extra New-Physics operators**

**They do not interfere with the SM!**

\[
L_{\text{eff}} \supset - \frac{G_F V_{cb}}{\sqrt{2}} \tilde{\epsilon}_R^L \bar{\ell} \gamma_\mu N_R \bar{c} \gamma^\mu (1 + \gamma_5) b
\]

Consider 5 operators to explain $R_D^{(*)}$: $\epsilon_L^T, \tilde{\epsilon}_R^T, \epsilon_S^T, \epsilon_S^T, \epsilon_T^T$
Evolution of the NP scenarios from pre- to post-Moriond 2019

<table>
<thead>
<tr>
<th>Pre-Moriond</th>
<th>Post-Moriond</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon^T_L$</td>
<td>0.11(3)</td>
</tr>
<tr>
<td>$\epsilon^T_R$</td>
<td>0.48(6)</td>
</tr>
<tr>
<td>$\epsilon^T_T$</td>
<td>0.37(1)</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>0.25</td>
</tr>
<tr>
<td>Pull_{SM}</td>
<td>4.25</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>1.01</td>
</tr>
<tr>
<td>Pull_{SM}</td>
<td>4.16</td>
</tr>
</tbody>
</table>

Rui-xiang Shi, Li-sheng Geng, JMC, 1904.xxxxx

1. **“Current-current” scenarios** still perform best

   $\Lambda_L \simeq 3.7$ TeV $\Rightarrow \Lambda_L \simeq 4.6$ TeV

2. **“Tensor” scenario** is now driven by interference piece

3. **“Scalar” scenarios** still limited by $B_c \to \tau \nu$
   
   Crossing-symmetry in decay

Alonso, Grinstein & JMC, PRL118, 081802, Akeroyd & Chen PRD96, 075011
Crossing-symmetry connection to the mono-tau signature at the LHC

Greljo, JMC & Ruiz-Álvarez, PRL122, 131803

▶ The proton is flavored...

Cross-section at $s \gg m_W^2$

$$\frac{\sigma_{NP}}{\sigma_{SM}} \sim \frac{\sum_i L_{ib} \otimes |V_{ib}|^2}{\sqrt{4}} \left( \frac{\alpha \Gamma |e_\tau^T|^2}{M_W^2 \cdot \frac{s}{s}} \right)$$

▶ NP suppressed by CKM and PDF’s
▶ NP enhanced by $s^2 / M_W^4$
▶ NP sensitivity is quadratic

Search excess in tails of $pp \rightarrow \tau + \text{MET}$!
LHC data and simulations of $pp \rightarrow \tau h X + \text{MET}$

- **$W'$ searches available from run 2 (13 TeV)**
  - **ATLAS**: 36.1 fb$^{-1}$ [PRL120, 161802, arXiv:1801.06992 [hep-ex]]
  - **CMS**: 35.9 fb$^{-1}$ [PLB792, 107, arXiv:1807.11421 [hep-ex]]

- **Collider Simulation**: MadGraph5@NLO $\rightarrow$ Pythia8 $\rightarrow$ Delphes 3
  - LO with $\leq 2j$ at parton level
  - Kinematic cuts/Delphes configuration as reported/recommended by collaborations
  - Agreement with official simulations $\lesssim 20$

![Graph showing comparison between ATLAS W+jets estimation, W+jets, EFT Tensor coupling, and W', m=2 TeV, 22% width](image)

Greljo, JMC & Ruiz-Álvarez, PRL122, 131803, Supp. Material
LHC bounds on EFT operators

LHC is sensitive to NP scenarios addressing anomalies!

“No-loose theorem” for the discovery of NP at the LHC
Caveats of the EFT analysis

- **Cross-section in EFT diverges at** $s \to \infty$
  - EFT stops being valid for $\sqrt{s} \simeq \Lambda$
  - $\Lambda \sim 1$-10 TeV for $R_{D(*)} \sim$ Partonic $\sqrt{s}$ at the LHC

- **Sensitivity per bin of tau’s transverse mass**

  ![Graph showing sensitivity per bin of tau’s transverse mass](image)

  - For projections assume systematics scale as $1/\sqrt{\mathcal{L}}$
    - Low $M_T$ limited by SM $W \to \tau \nu$ background
    - High $M_T$ limited by statistics

  **Most sensitive bins $\lesssim$ 2 TeV!**

- **Beyond one needs explicit mediators and UV completions of the EFT**

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J. Martin Camalich (IAC)  
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Simplified mediators for the $R_D^{(\ast)}$ anomaly

1. Uncolored mediators

\[ \bar{c}, \bar{b}, W', H, \tau^+, \tau^- \]

2. Colored mediators

\[ \bar{c}, \bar{b}, LQ, \nu, \tau^+, \tau^- \]

- Jacobian bump search
- Excess in tails

<table>
<thead>
<tr>
<th>Mediator</th>
<th>$SU(3)$</th>
<th>$SU(2)$</th>
<th>$U(1)$</th>
<th>Current</th>
<th>Scalar</th>
<th>Tensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W'_\mu$</td>
<td>1</td>
<td>3, 1</td>
<td>0, +1</td>
<td>✓</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$H$</td>
<td>1</td>
<td>2</td>
<td>+1/2</td>
<td>X</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>$S_1$</td>
<td>3</td>
<td>1</td>
<td>-1/3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$R_2$</td>
<td>3</td>
<td>2</td>
<td>+7/6</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$U_{1\mu}$</td>
<td>3</td>
<td>1</td>
<td>+2/3</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
</tbody>
</table>

We do not consider charged Higgses because of $B_c \rightarrow \tau \nu$

A total of 8 different solutions!
A total of **six** leptoquark solutions

- $S_1$ and $U_1^\mu$ produce both LH and RH solutions
- $S_1$ and $R_2$ produce scalar and tensor solutions
  - One $S_1$ scalar-tensor solution: $\epsilon_T^T = -\epsilon_{SL}^T / 4$
  - One $S_1$-$R_2$ “pure” tensor solution

- All scenarios converge to EFT results for $m_{LQ} \gtrsim 2 \text{ TeV}$
$W'$ solutions

- $W'_L$ in the $SU(2)$-triplet severely constrained by $B_s$ mixing and $pp \to \tau^+ \tau^-$
  - Focus on the $W'_R$ [Greljo, Robinson, Shakya & Zupan, JHEP1809, Asadi, Buckley & Shih, JHEP 1809, 010 169]

- Famous AG plot for $W'$ in $pp \to \tau^- + \text{MET}$!

$W'_R$ solutions pushed to nonperturbative or light!

\[ |g_{bc}g_{\tau \nu}^*| / M_{W'}^2 \text{ [TeV}^{-2}] \] (for $\Delta \chi^2 = 6.2$)

- $W'_R$ model
  - $R(D^{(*)}) \to (0.5 \pm 0.1) \text{TeV}^{-2}$
The LHC flavor-physics program

- The LHC can compete with classic low-energy flavor probes!
- Take $b \rightarrow u\tau^-\bar{\nu}$ decays: Naturally linked to $R_{D(*)}$ anomalies
  - Rare processes: $\Gamma \sim |V_{ub}|^2$
  - Tricky final states: $\tau^-$, but also $\pi$, $\rho$, $p\bar{p}$...

$$\mathcal{B}(B^-(\rightarrow \tau^-\bar{\nu})=1.09(24) \times 10^{-4} \quad \text{(PDG)}, \quad \mathcal{B}(B^0\rightarrow \pi^-\tau^+\bar{\nu})<2.5 \times 10^{-4} \quad \text{(Belle)}$$

- Current operators
- Scalar and tensor operators

<table>
<thead>
<tr>
<th>Data set</th>
<th>Scalar</th>
<th>Tensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \pi^-\tau^+\bar{\nu}$</td>
<td>[-1.75, 0.94]</td>
<td>[-1.25, 0.57]</td>
</tr>
<tr>
<td>LHC</td>
<td>1.23</td>
<td>0.34</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>0.37</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Strong interplay between LHC and $B$ physics!
Conclusions

1. "$R_{D(*)}$ anomalies": $pp \rightarrow \tau_h X + MET$ currently sensitive to NP models
   - RHC solutions with $W'_R$ or LQ in tension with data

2. "No-loose theorem": HL-LHC has the potential to discover "the model"... whatever it might be...
   - Bottom-up: EFT
   - Flavor: Direct correlation between $R_{D(*)}$ and LHC
   - Conservative: Extra flavor/Lorentz components increase excess

- Additional ideas could enhance sensitivity!

3. "LHC Flavor physics program": Provide specific inputs to flavor physics
   - Promising with tau-leptons Cirigliano, Falkowski, Gonzalez-Alonso, Rodríguez-Sánchez, arXiv:1809.01161
Theoretical uncertainties

- NLO and PDF uncertainties evaluated
Evolution of the NP scenarios from pre- to post-Moriond 2019