Flavored mono-tau searches at the LHC

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Portorož 2019: Precision era in High Energy Physics

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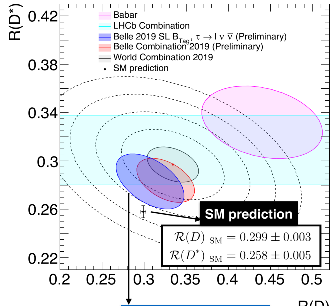
Status of the $b \to c\tau\nu$ anomalies

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

If true, find the "ultimate" collider search

- **NEW:** Belle measurement with semi-leptonic tag



This result

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

G. Caria @ Moriond EW 2019

- **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?

EFT of new-physics in $b \to c\tau\nu$

- **Low-Energy EFT** Lagrangian

$$\mathcal{L}_{\rm eff} \supset -\frac{G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^\ell)\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{c}\gamma^\mu(1-\gamma_5)b+\epsilon_R^\ell\;\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\;\bar{c}\gamma^\mu(1+\gamma_5)b$$

$$+\epsilon_{S_L}^\ell\;\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{c}(1-\gamma_5)b+\epsilon_{S_R}^\ell\;\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{c}(1+\gamma_5)b+\epsilon_T^\ell\;\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b]+\text{h.c.},$$

  - The SM + 5 New-Physics operators
  - **Matching with SMEFT:** ϵ_R^ℓ LFUV up to $\mathcal{O}(\frac{v^4}{\Lambda_{\rm NP}^4})$ 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!**

$$\mathcal{L}_{\rm eff} \supset -\frac{G_F V_{cb}}{\sqrt{2}}\tilde{\epsilon}_R^\ell\;\bar{\ell}\gamma_\mu N_R\;\bar{c}\gamma^\mu(1+\gamma_5)b$$

Consider **5** operators to explain $R_{D^{(*)}}$: ϵ_L^τ, $\tilde{\epsilon}_R^\tau$, $\epsilon_{S_L}^\tau$, $\epsilon_{S_R}^\tau$, ϵ_T^τ

Evolution of the NP scenarios from pre- to post-Moriond 2019

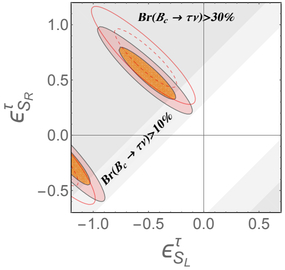
	Pre-Moriond			Post-Moriond		
	Best fit	χ^2	$\mathrm{Pull}_{\mathrm{SM}}$	Best fit	χ^2	$\mathrm{Pull}_{\mathrm{SM}}$
ϵ_L^τ	0.11(3)	0.25	4.25	0.07(2)	5.65	3.73
$\tilde{\epsilon}_R^\tau$	0.48(6)	0.25	4.25	0.39(5)	5.65	3.73
ϵ_T^τ	0.37(1)	1.01	4.16	$-0.03(1)$	6.16	3.66

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

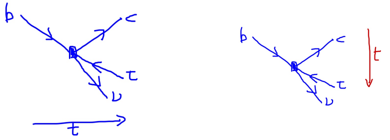
1. **"Current-current" scenarios** still perform best

$$\Lambda_L \simeq 3.7\ \text{TeV} \implies \Lambda_L \simeq 4.6\ \text{TeV}$$

2. **"Tensor" scenario** is now driven by interference piece

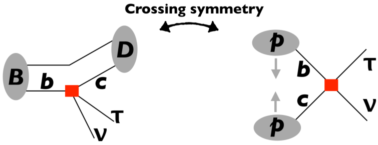


3. **"Scalar" scenarios** still limited by $B_c \to \tau\nu$
   - ★ **Crossing-symmetry in decay**



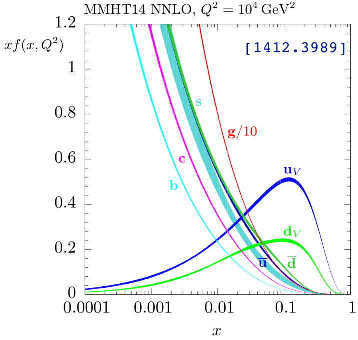
Alonso, Grinstein & JMC,PRL118, 081802, Akeroyd & Chen PRD96, 075011

Crossing-symmetry connection to the mono-tau signature at the LHC



Greljo, JMC & Ruiz-Álvarez, PRL122, 131803

- **The proton is flavored...**



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

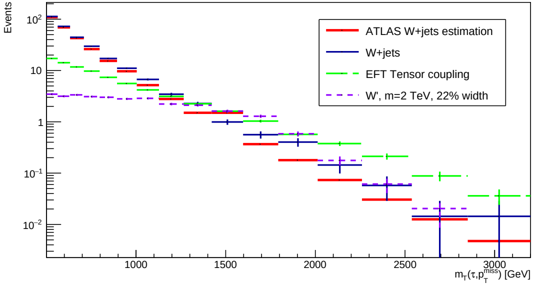
$$\frac{\sigma_{\rm NP}}{\sigma_{\rm SM}} \sim \frac{\sum_i \mathcal{L}_{ib} \otimes |V_{ib}|^2 \frac{s}{v^4} \; \left(\alpha_\Gamma |\epsilon_\Gamma^\tau|^2\right)}{\mathcal{L}_{ud} \otimes |V_{ud}|^2 \frac{s}{v^4} \; \left(\frac{M_W^2}{s}\right)^2}$$

- NP **suppressed** by CKM and PDF's
- NP **enhanced** by s^2/M_W^4
- NP sensitivity is **quadratic**

Search excess in tails of $pp \to \tau +$ MET!

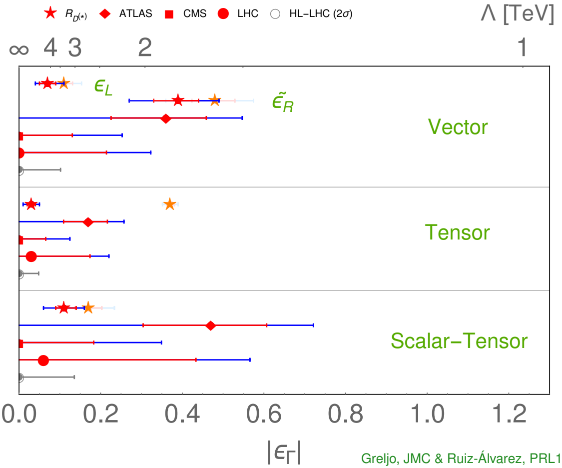
LHC data and simulations of $pp \to \tau_h X$ + MET

- ***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` ▶ `Pythia8` ▶ `Delphes 3`
  - LO with $\leqslant 2j$ at parton level
  - Kinematic cuts/Delphes configuration as reported/recommended by collaborations
  - **Agreement with official simulations** $\lesssim$ 20%



Greljo, JMC & Ruiz-Álvarez, PRL122, 131803, Supp. Material

LHC bounds on EFT operators



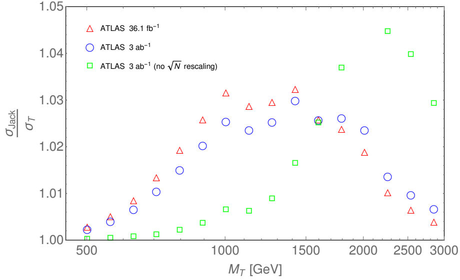
Greljo, JMC & Ruiz-Álvarez, PRL122, 131803 (updated)

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**



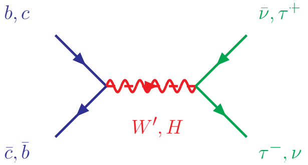
- **For projections assume systematics scale as $1/\sqrt{\mathcal{L}}$** *HL/HE-LHC Yellow Report*
  - ★ Low M_T limited by SM $W \to \tau\nu$ background
  - ★ High M_T limited by statistics

Most sensitive bins $\lesssim$ 2 TeV!

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

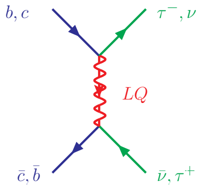
Simplified mediators for the $R_{D^{(*)}}$ anomaly

1. Uncolored mediators



- Jacobian bump search

2. Colored mediators



- Excess in tails

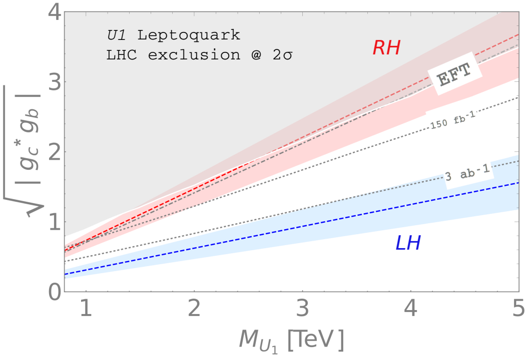
Mediator	$SU(3)$	$SU(2)$	$U(1)$	Current	Scalar	Tensor
W'_μ	**1**	**3, 1**	0, +1	✓	✗	✗
H	**1**	**2**	$+1/2$	✗	✓	✗
S_1	**3**	**1**	-1/3	✓	✓	✓
R_2	**3**	**2**	+7/6	✓	✓	✓
U_1^μ	**3**	**1**	+2/3	✓	✓	✗

- We do not consider charged Higsses because of $B_c \to \tau\nu$

A total of 8 different solutions!

Leptoquark solutions

- A total of **six** leptoquark solutions
  - S_1 and U_1^μ produce **both LH** and **RH solutions**
  - S_1 and R_2 produce **scalar** and **tensor solutions**
    - ★ **One S_1 scalar-tensor solution:** $\epsilon_T^\tau = -\epsilon_{S_L}^\tau/4$
    - ★ **One S_1-R_2 "pure" tensor solution**

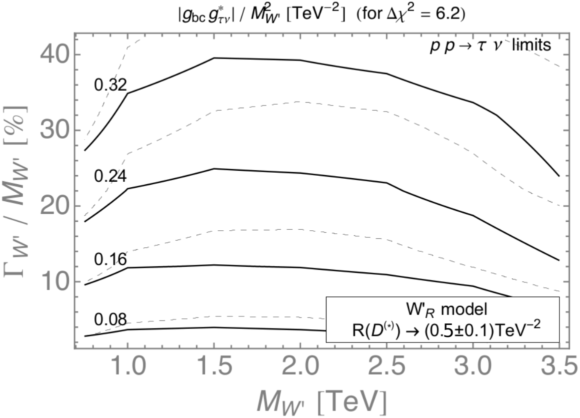


Greljo, JMC & Ruiz-Álvarez, PRL122, 131803 (updated)

- All scenarios converge to EFT results for $m_{\rm LQ} \gtrsim 2$ 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 $pp \to \tau^-$ + MET!**



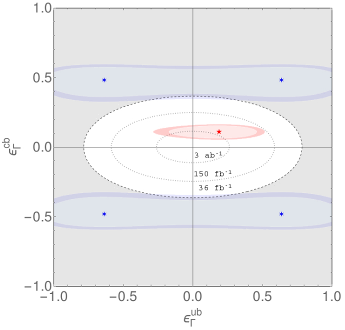
W'_R solutions pushed to nonperturbative or light!

The LHC flavor-physics program

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

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

- Current operators



- Scalar and tensor operators

Data set	Scalar	Tensor
$B^0 \to \pi^- \tau^+ \bar{\nu}$	[-1.75, 0.94]	[-1.25, 0.57]
LHC	1.23	0.34
HL-LHC	0.37	0.10

Strong interplay between LHC and *B* physics!

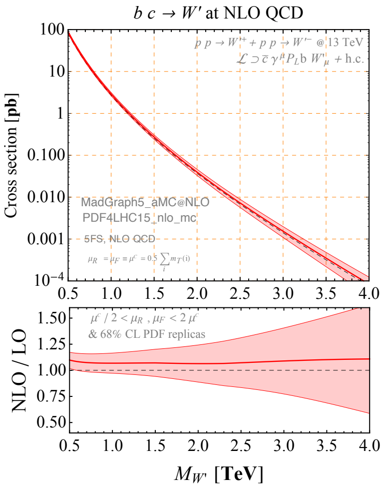
Conclusions

1. **"$R_{D^{(*)}}$ anomalies":** $pp \to \tau_h\, X$ + 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 ► Simplified mediators
   - **Flavor:** Direct correlation between $R_{D^{(*)}}$ and LHC
   - **Conservative:** Extra flavor/Lorentz components increase excess

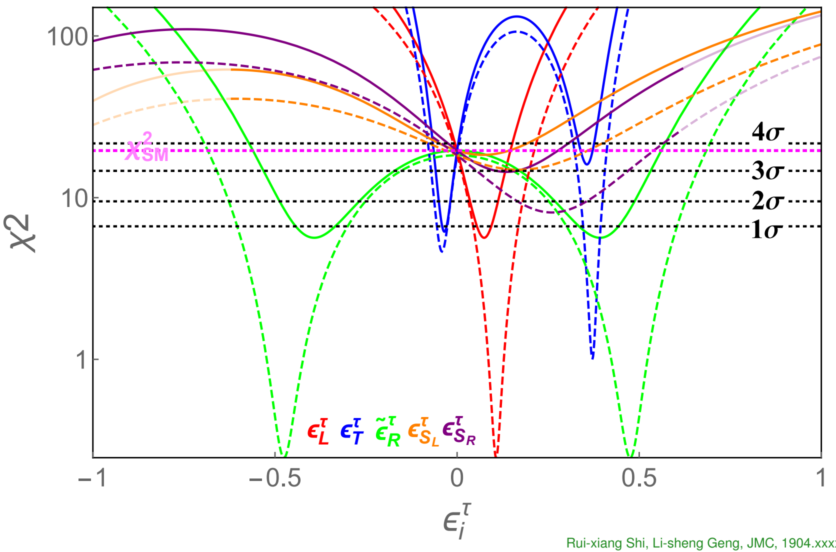
     Baker, Fuentes-Martín, Isidori, König, arXiv: 1901.10480
   - **Additional ideas could enhance sensitivity!**
3. **"LHC Flavor physics program":** Provide specific inputs to flavor physics
   - Promising with tau-leptons Cirigliano, Falkowski, Gonzalez-Alonso, Rodríguez-Sánchez, arXiv:1809.01161

Theoretical uncertainties

- **NLO and PDF uncertainties evaluated**



Evolution of the NP scenarios from pre- to post-Moriond 2019



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