Universität Zürich[UZH]

Implications of new physics in *B* decays for high-p_T searches at LHC

Admir Greljo

Based on:

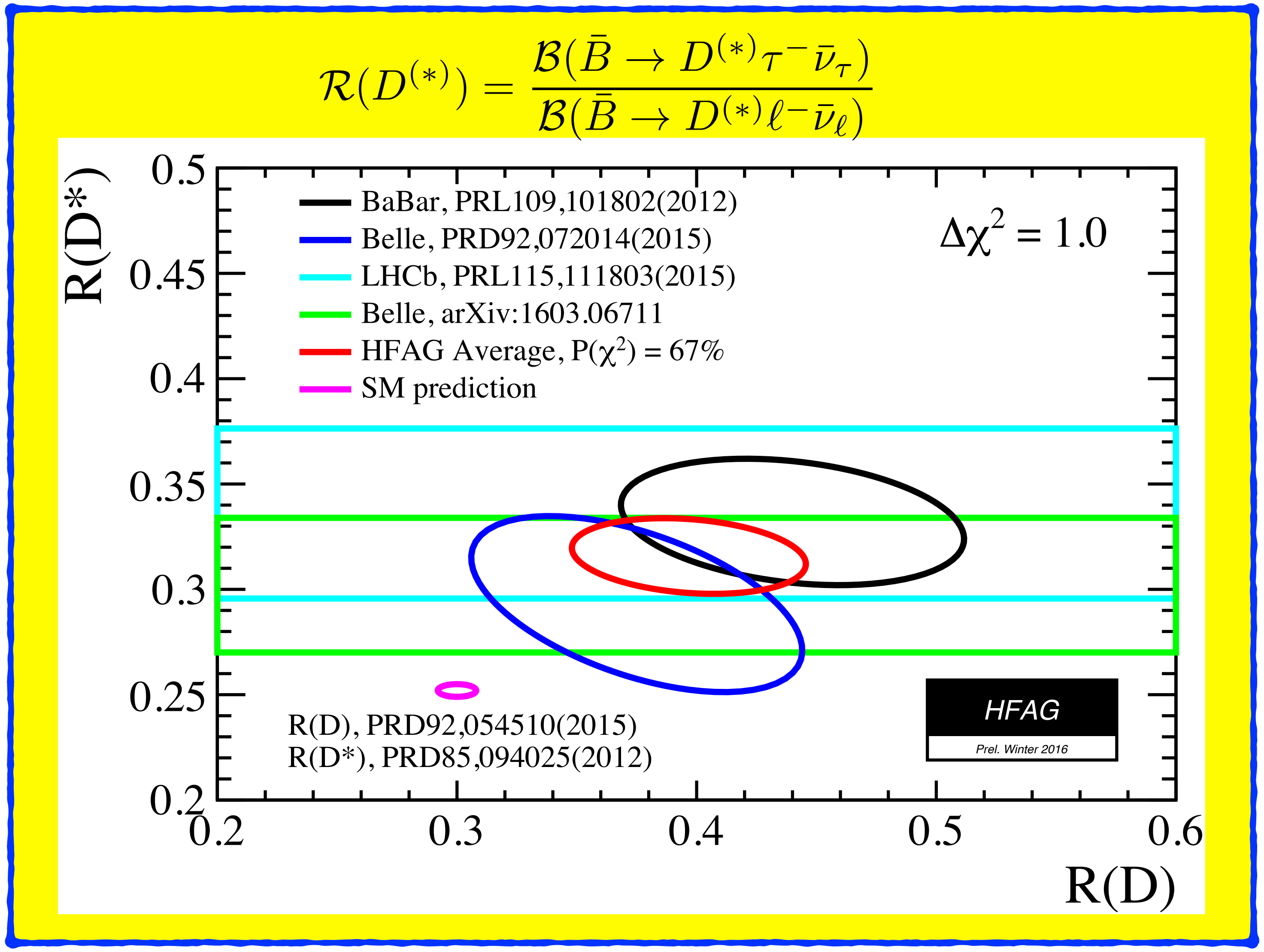
JHEP 1507 (2015) 142 - AG, Gino Isidori, David Marzocca

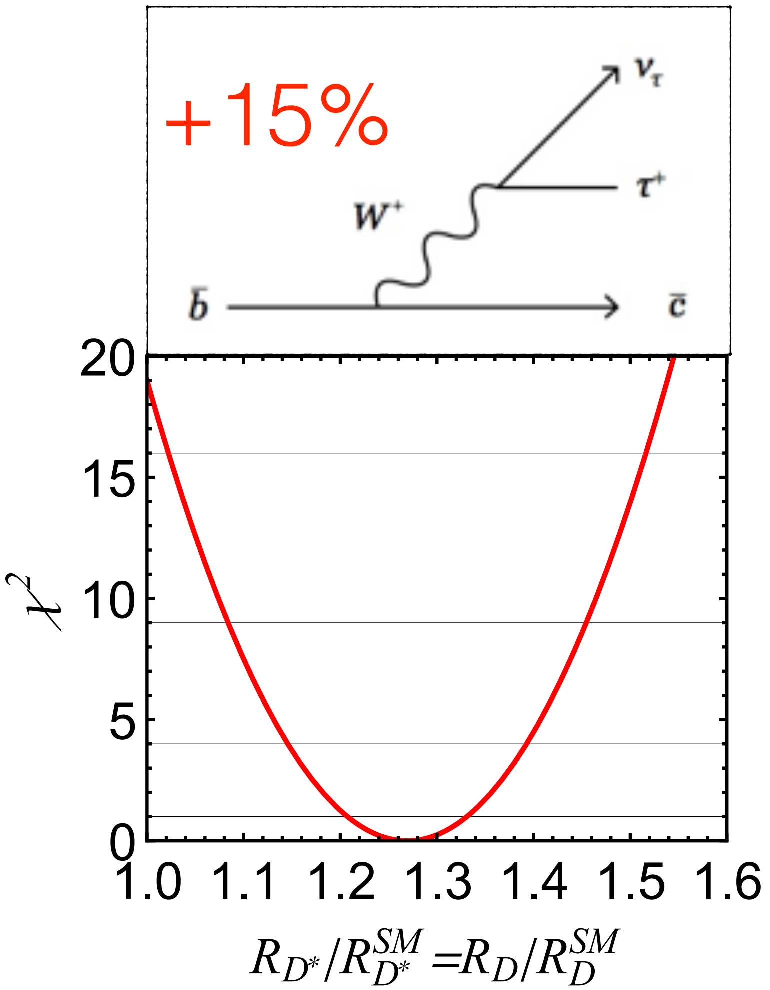
JHEP 1608 (2016) 035 - Dario Buttazzo, AG, Gino Isidori, David Marzocca

1609.xxxxx - Darius Faroughy, AG, Jernej F. Kamenik

Motivation: Test of LFU in charged currents

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$





- **~ 4σ excess** over the SM prediction
- Good agreement by three (very) different experiments
- Consistent with **~15% universal enhancement** in tree level $b_L \to c_L\ \tau_L\ \nu_L$ amplitude (left-handed currents)
- Our estimate: $R_0 \equiv \frac{1}{2}\left(R_{D^*}^{\tau/\ell} - 1\right) = 0.13 \pm 0.03$

Nowadays, experimental anomalies tend to go away, more data is needed…

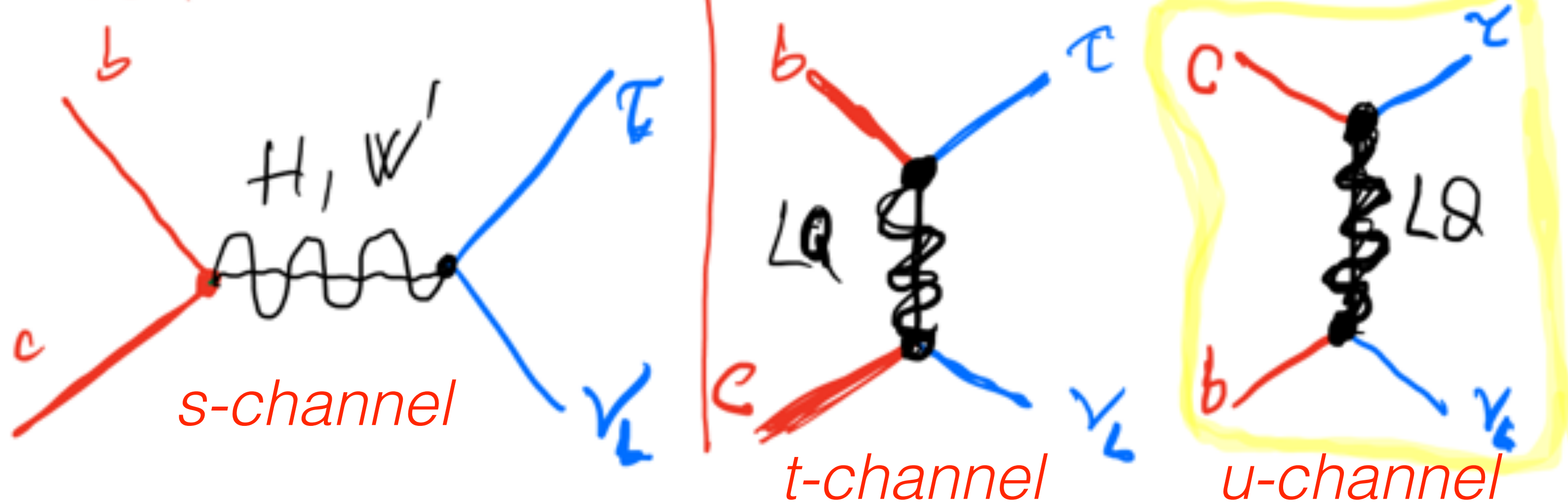
In meantime, what would:

- The nature of New Physics be giving such *LFU* violation?
- The "physics case" for high p_T LHC?

Prologue: Violation of LFU in $B \to D^{(*)} \tau \nu$ decays

- Tree level charged current process in the SM
- Relatively large NP effect required (tree level effect)

Spin \ Color	0	3
0	2HDM	Scalar LQ
1	W'	Vector LQ



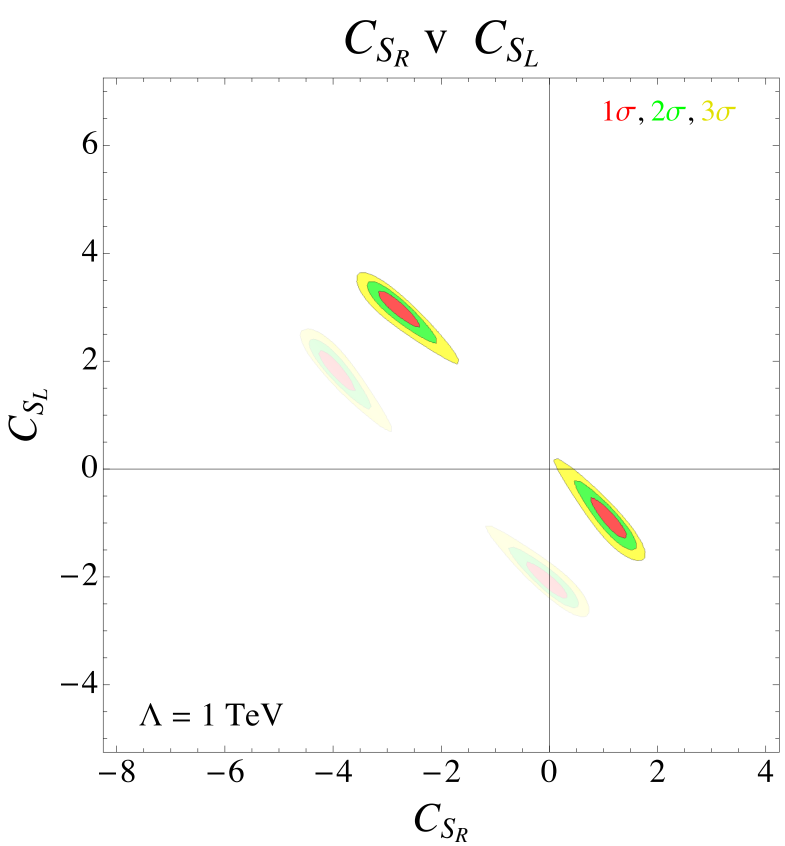
EFT approach: Fitting the signal

Operator basis

Freytsis, Ligeti, Ruderman, Phys.Rev. D92 (2015) no.5, 054018

	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L) W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			
$\mathcal{O}_{S_R}$	$(\bar{c} P_R b)\,(\bar{\tau} P_L \nu)$		$\rangle(\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
$\mathcal{O}_{S_L}$	$(\bar{c} P_L b)\,(\bar{\tau} P_L \nu)$			
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			

Selected fit results



Coefficient(s)	Best fit value(s) ($\Lambda = 1$ TeV)	
C_{V_L}	0.18 ± 0.04,	-2.88 ± 0.04
C_T	0.52 ± 0.02,	-0.07 ± 0.02
C''_{S_L}	-0.46 ± 0.09	
$(C_R,\, C_L)$	$(1.25, -1.02)$,	$(-2.84, 3.08)$
$(C'_{V_R},\, C'_{V_L})$	$(-0.01, 0.18)$,	$(0.01, -2.88)$
$(C''_{S_R},\, C''_{S_L})$	$(0.35, -0.03)$,	$(0.96, 2.41)$,
	$(-5.74, 0.03)$,	$(-6.34, -2.39)$

TABLE III. Best-fit operator coefficients with acceptable q^2 spectra and $\chi^2_{\text{min}} < 5$. For the 1D fits in Fig. 1 we include the $\Delta\chi^2 < 1$ ranges (upper part), and show the central values of the 2D fits in Fig. 2 (lower part).

SMEFT & Implications for high-p_T LHC

- Leading effects expected at **dimension-6**

$$\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \ldots$$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Warsaw basis, 1008.4884

SMEFT & Implications for high-p_T LHC

- Leading effects expected at **dimension-6**

$$\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \dots$$

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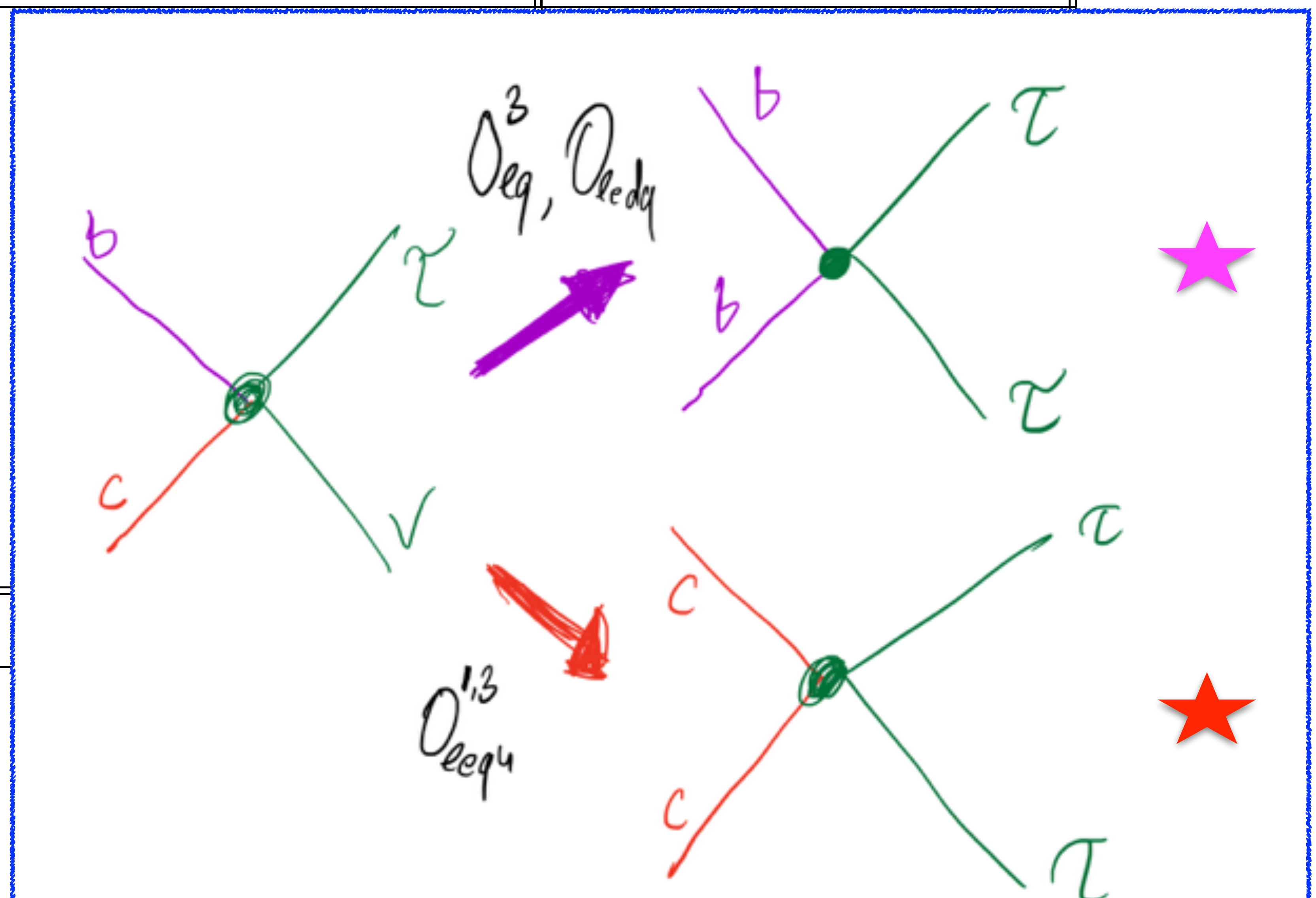
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$		

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$



SU(2)L prediction: **Neutral currents**

Tau searches at high-p_T

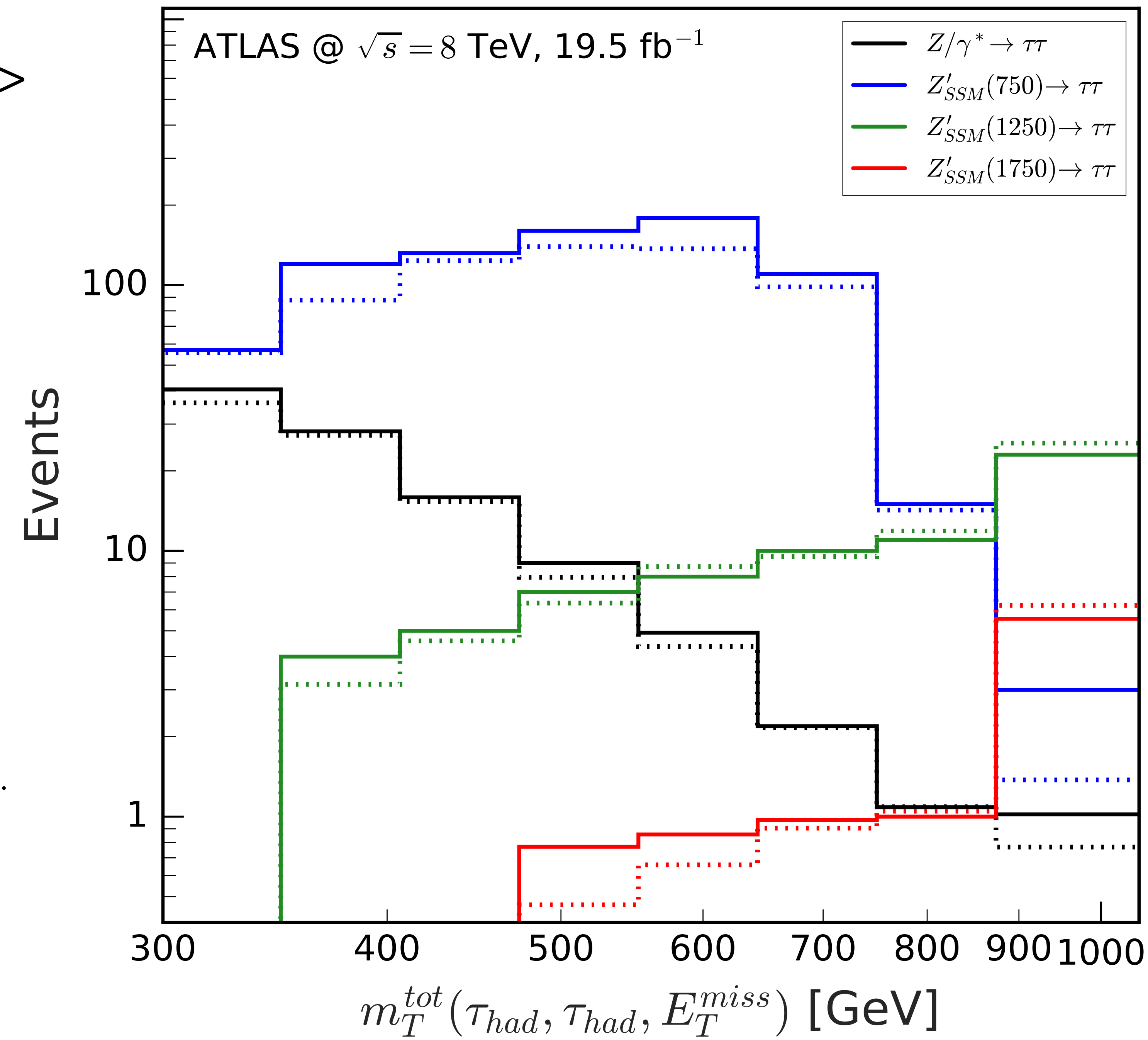
In progress

Recast of τ+τ− searches at LHC

- Simulation pipeline: Feynrules>MadGraph>Pythia> Delphes
- Hadronic τ candidates
- Validated against SM bkg, and SSM Z'.
- Fit to the total transverse mass variable m_T^{tot}

$$m_T^{\text{tot}} \equiv \sqrt{m_T^2(\tau_1,\tau_2) + m_T^2(\not{E}_T,\tau_1) + m_T^2(\not{E}_T,\tau_2)}.$$

[ATLAS Collaboration], JHEP 1507, 157 (2015)



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SMEFT: Warm up exercise

AG, Isidori, Marzocca, JHEP 1507 (2015) 142

$$\mathcal{L}^{\text{eff}} \supset c^{ijkl}_{QQLL}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l)$$

In progress

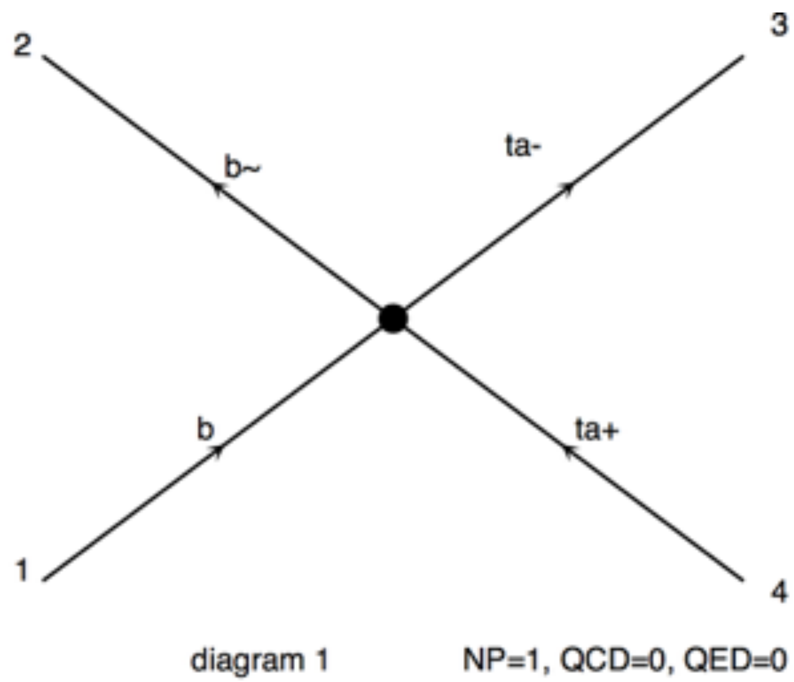
- Flavor alignment with down quarks and charged leptons (to avoid FCNC in the down sector)

$$Q_i = (V^*_{ji}u^j_L, d^i_L)^T \text{ and } L_i = (U^*_{ji}\nu^j, \ell^i_L)^T$$

- Dominant couplings with the third generation

$$c^{ijkl}_{QQLL} \simeq c_{QQLL}\delta_{i3}\delta_{j3}\delta_{k3}\delta_{l3}$$

→ *$1/V_{cb}$ enhanced pure third generation neutral currents*



→

Recast of 8 TeV $\tau^+\tau^-$ ATLAS search:

$$|c_{W'}| < 2.8\ \text{TeV}^{-2} \text{ at } 95\% \text{ CL}$$

Fit to R(D*) anomaly:

$$c_{W'} \simeq (2.1 \pm 0.5)\ \text{TeV}^{-2}$$

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Vector triplet model

AG, Isidori, Marzocca, JHEP 1507 (2015) 142

See also:
D. Pappadopulo, A. Thamm, R. Torre
and A. Wulzer, JHEP 1409 (2014) 060

- *Introduce heavy spin-1 triplet*

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]a} + \frac{m_V^2}{2} V^a_\mu V^{\mu a} + g_H V^a_\mu (H^\dagger T^a i \overleftrightarrow{D}_\mu H) + V^a_\mu J^a_\mu$$

integrate out heavy vector
and match to the SMEFT

$$\mathcal{L}^{d=6}_{\text{eff}} = -\frac{1}{2m_V^2} J^a_\mu J^a_\mu - \frac{g_H^2}{2m_V^2} (H^\dagger T^a i \overleftrightarrow{D}_\mu H)(H^\dagger T^a i \overleftrightarrow{D}_\mu H) - \frac{g_H}{m_V^2} (H^\dagger T^a i \overleftrightarrow{D}_\mu H) J^a_\mu$$

- Low-energy flavour physics

Fit to R(D*) anomaly

- EWPO:
  (1) Small mass splitting
  (2) Stringent limits on gH
- **Vector triplet dominantly decays to third generation SM fermions**

$$\Delta\mathcal{L}_{VJ} = V^a_\mu J^a_\mu = c^V_{ij} \; \bar{f}^i_L \gamma^\mu f^j_L V_\mu$$

Vector triplet model: LHC phenomenology

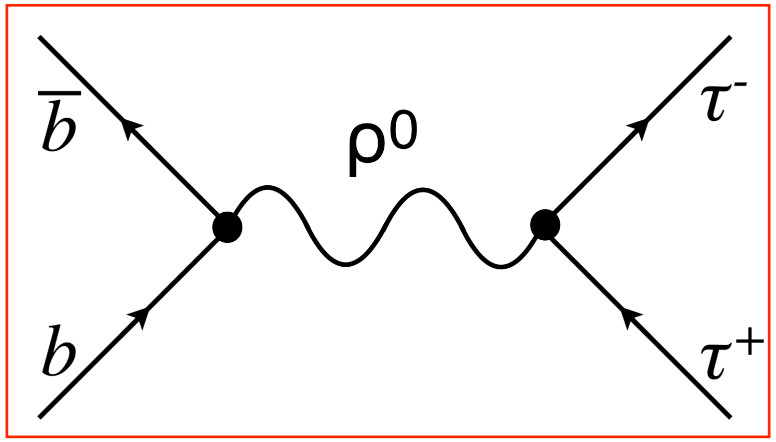
Decay modes:

- Neutral vector:
  - $\tau\ \tau$
  - $\nu\ \nu$
  - $b\ b$
  - $t\ t$
- Charged vector:
  - $\tau\ \nu$
  - $t\ b$

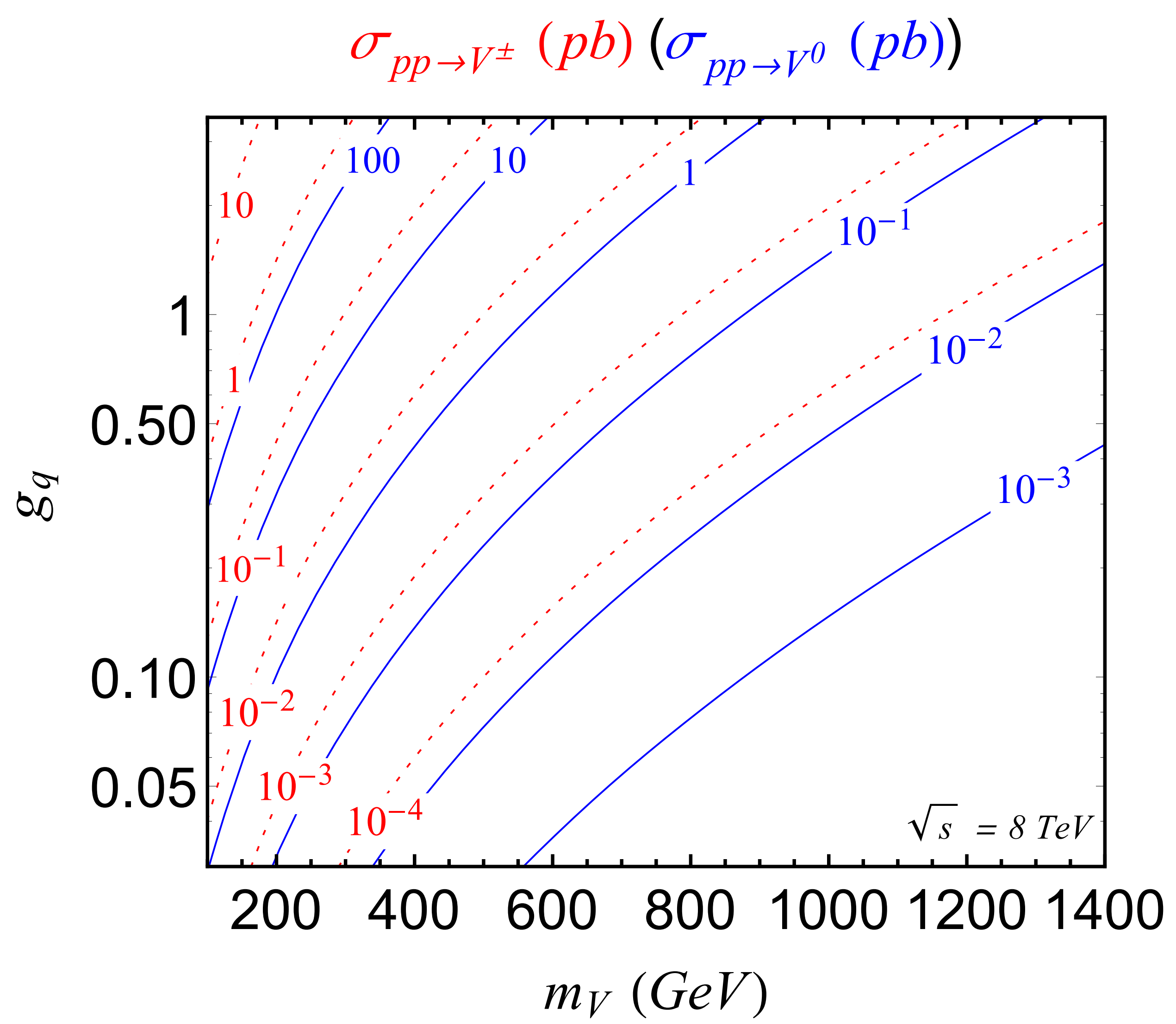
$$\frac{\Gamma_{V^\pm}}{m_{V^\pm}} \approx \frac{\Gamma_{V^0}}{m_{V^0}} \approx \frac{1}{48\pi}(g_\ell^2 + 3g_q^2)$$

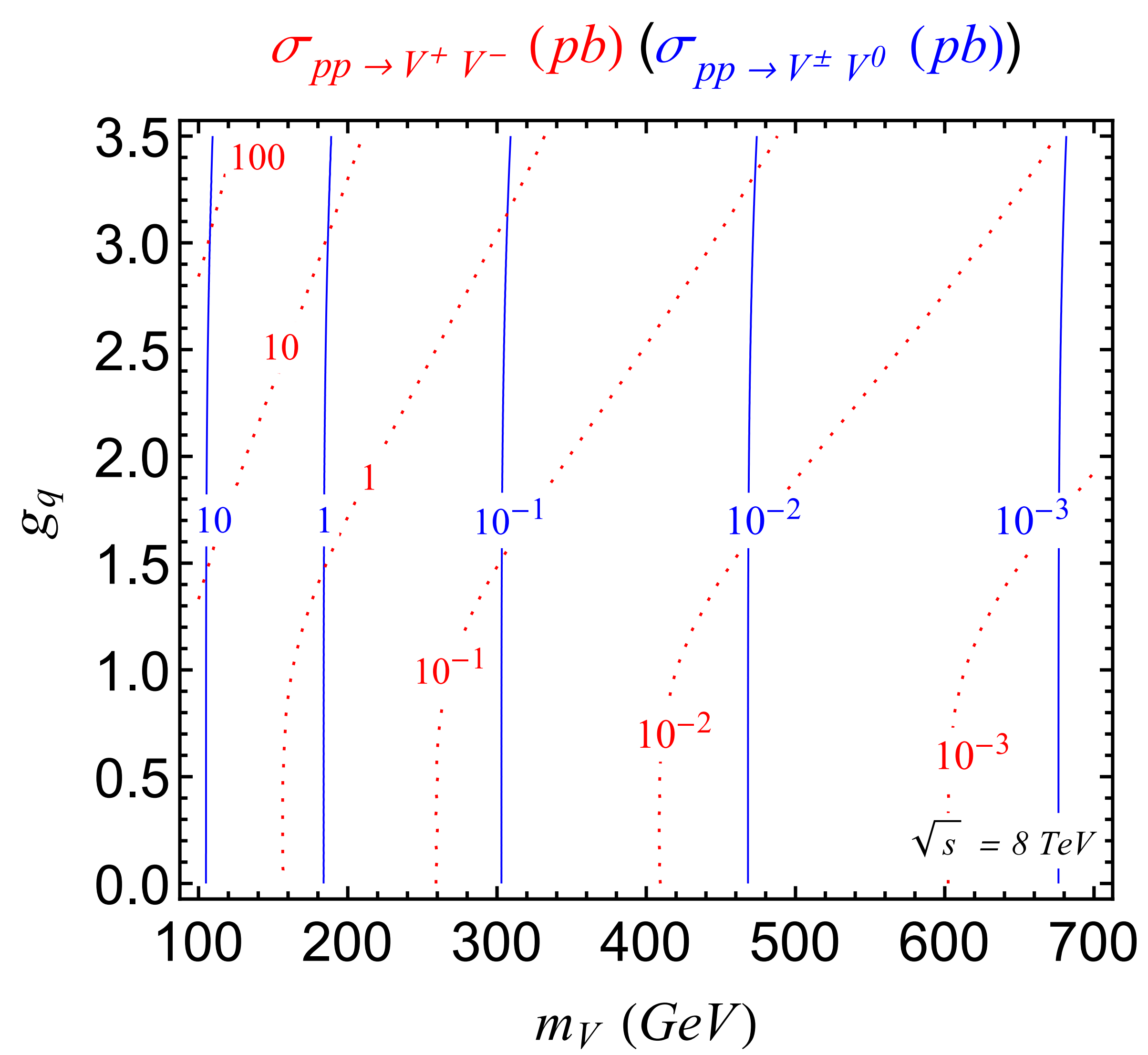
Production modes:

1) Single production (***b b* → V⁰**, *b c* → V$^\pm$)
2) Pair production



Vector triplet model: LHC phenomenology





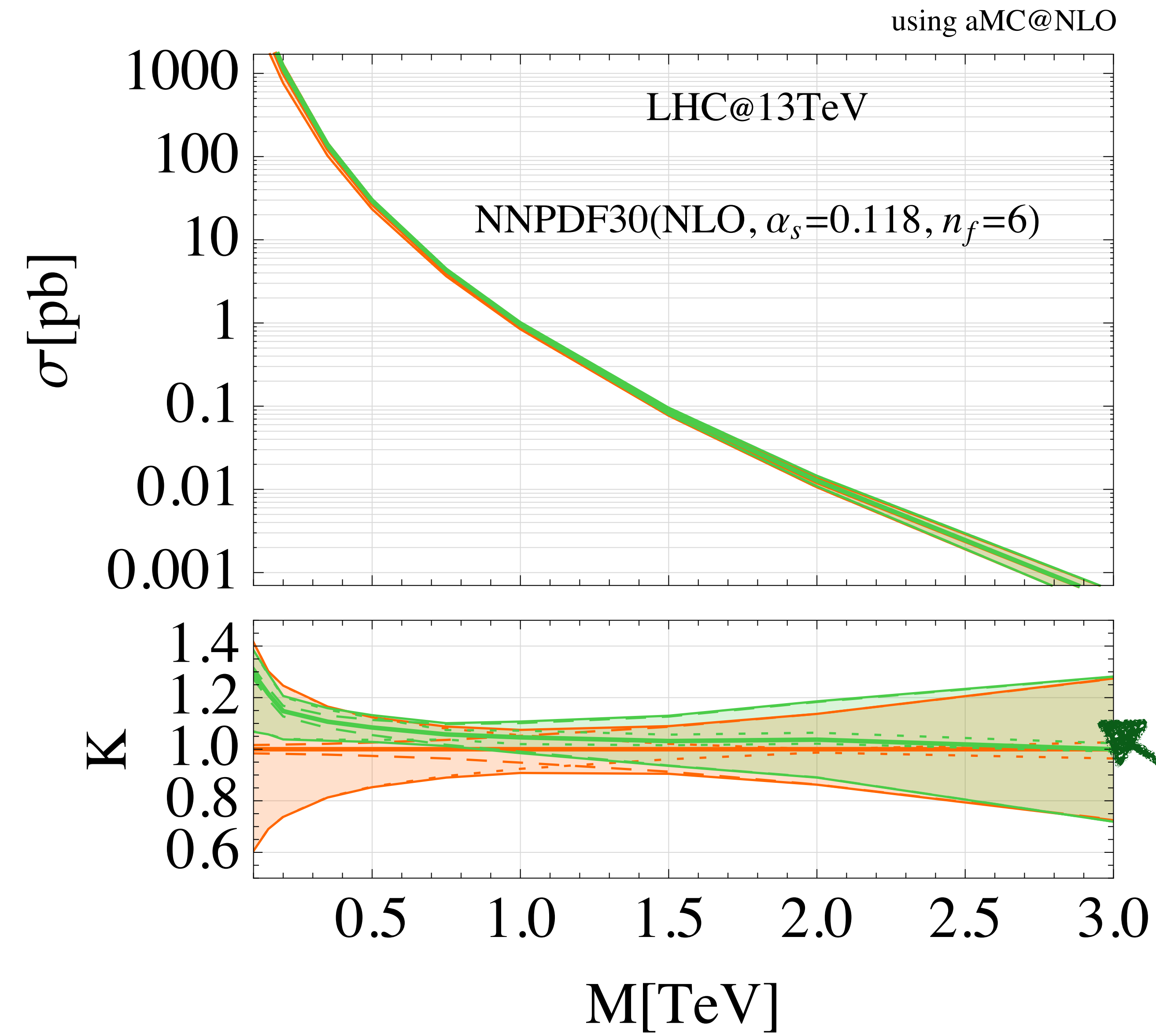
- Left: single V production ($bb \to V^0$, $b\,c \to V^+$)
- Right: pair production

AG, Isidori, Marzocca, JHEP 1507 (2015) 142

Vector triplet model: LHC phenomenology

In progress

Z' production @ NLO QCD



Uncertainty pdf dominated

Figure 3: Next-to-leading order QCD corrections for a narrow Z' production via bottom-bottom fusion.

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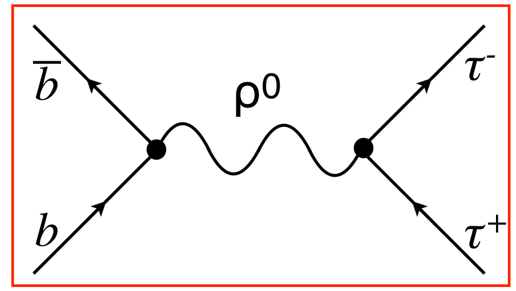
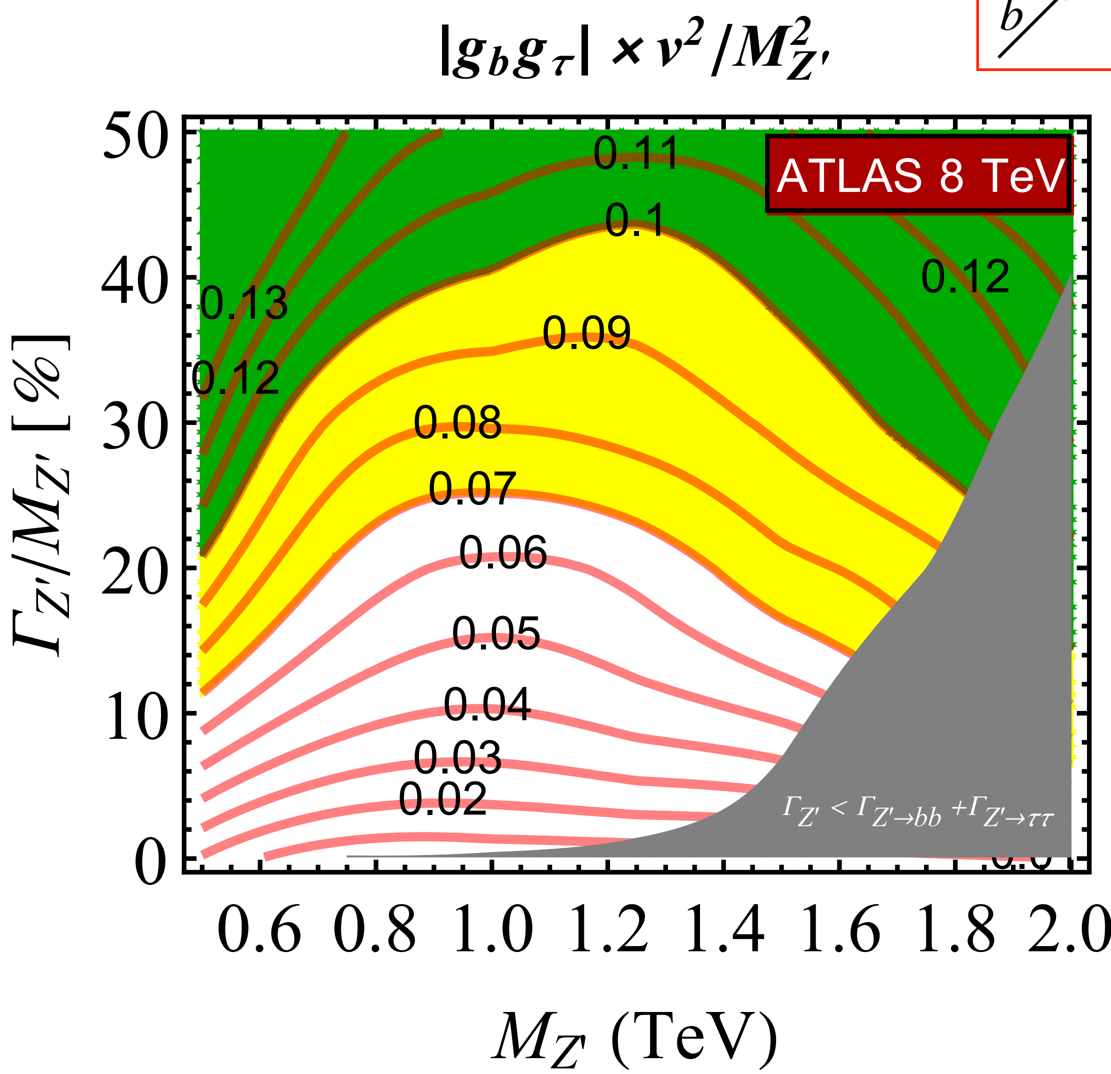
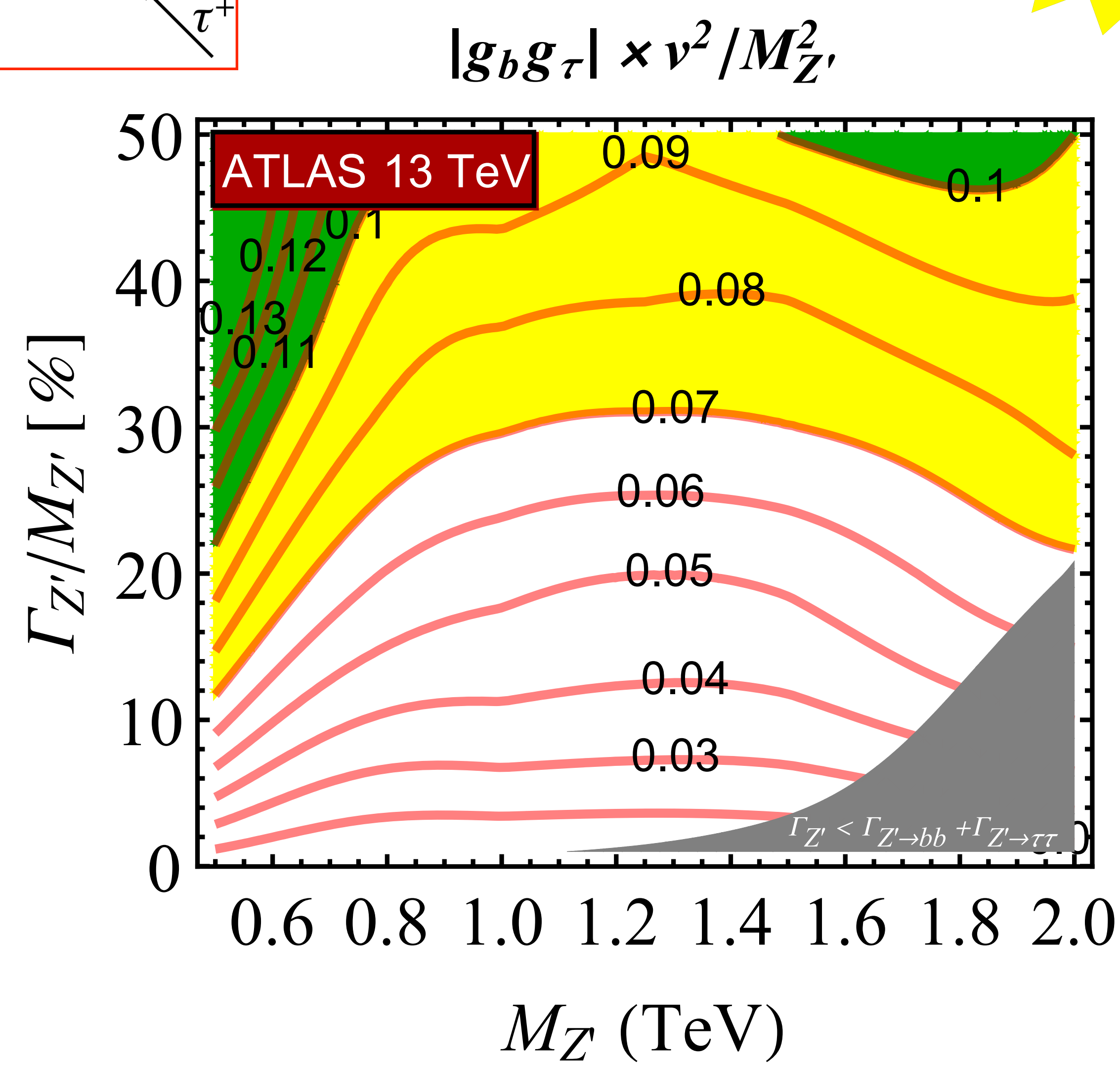
Vector triplet model: **8 & 13 TeV recast bounds**

In progress







- Recast of the ATLAS $\tau\tau$ searches at 8 TeV, 19.5 fb^{-1} (left) and 13 TeV, 3.2 fb^{-1} (right)

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Two Higgs doublet model

In progress

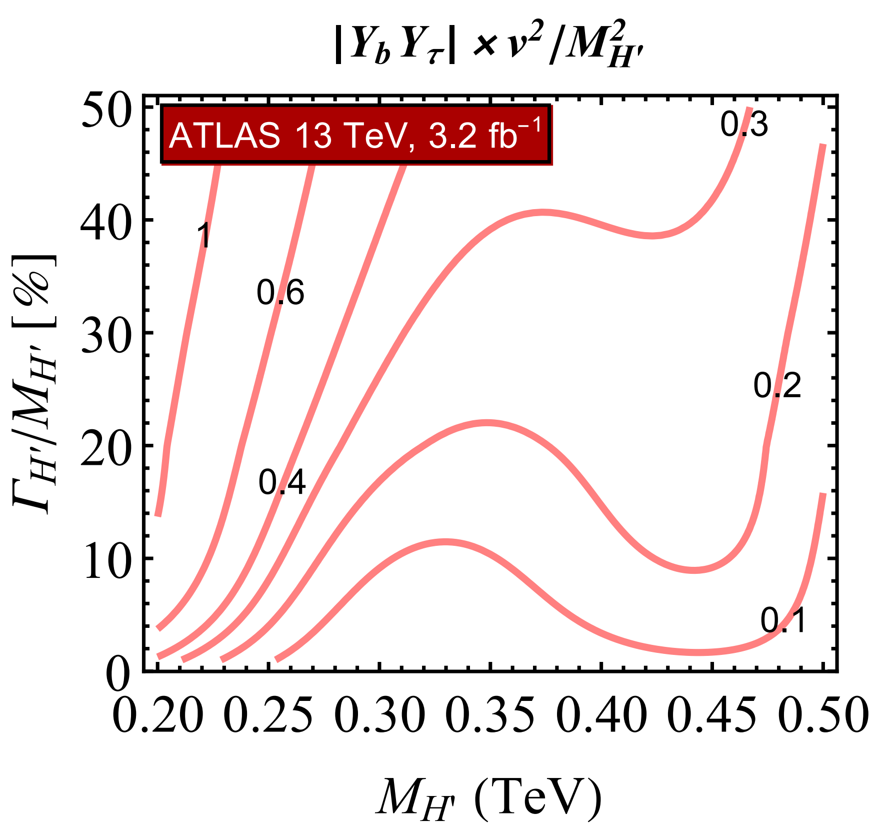
$$H' \sim (H^+, (H^0 + iA^0)/\sqrt{2})$$

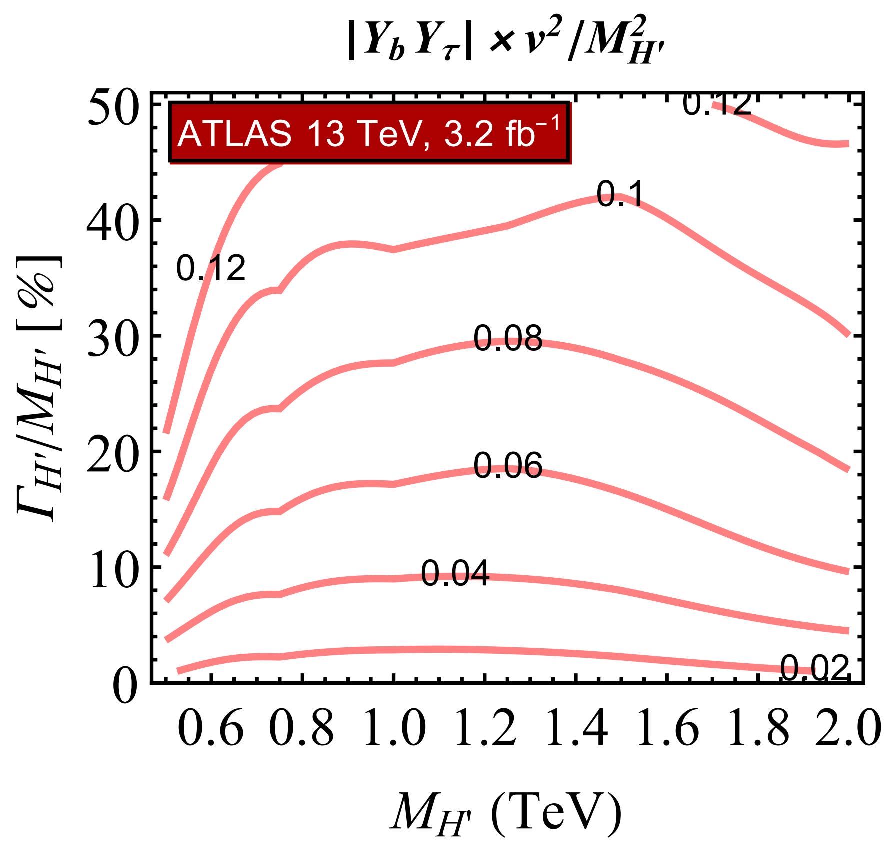
$$\mathcal{L}_{H'} = |D^\mu H'|^2 - M_{H'}^2 |H'|^2 - \lambda_{H'} |H'|^4 - \delta V(H', H$$
$$- Y_b \bar{Q}_3 H' b_R - Y_c \bar{Q}_3 \tilde{H}' c_R - Y_\tau \bar{L}_3 H' \tau_R + \text{h.c.}\,,$$

Fit to R(D*) anomaly

$$Y_b Y_\tau^* \times v^2 / M_{H+}^2 = (2.9 \pm 0.8)$$

$$b\bar{b} \to (H^0, A) \to \tau^+ \tau^-$$





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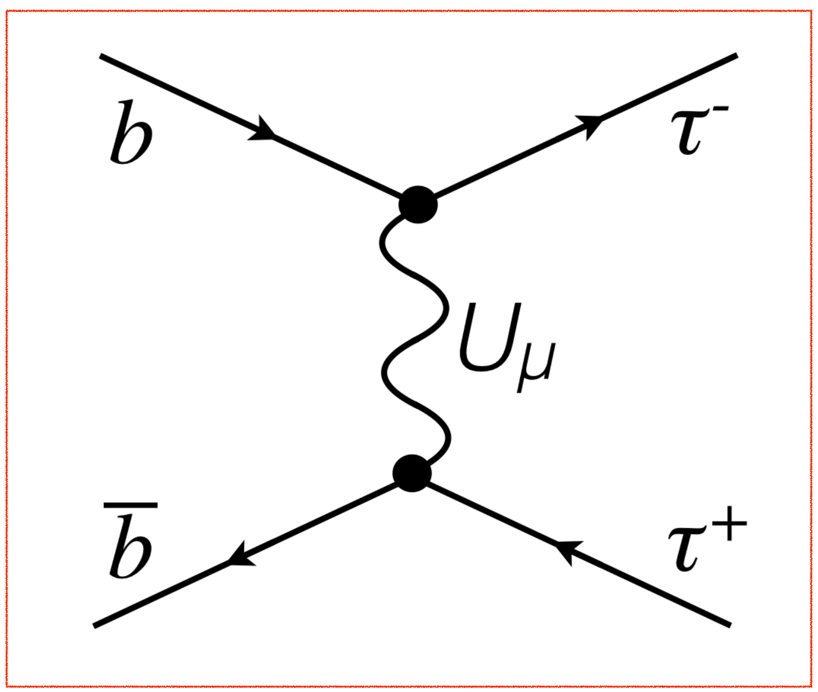
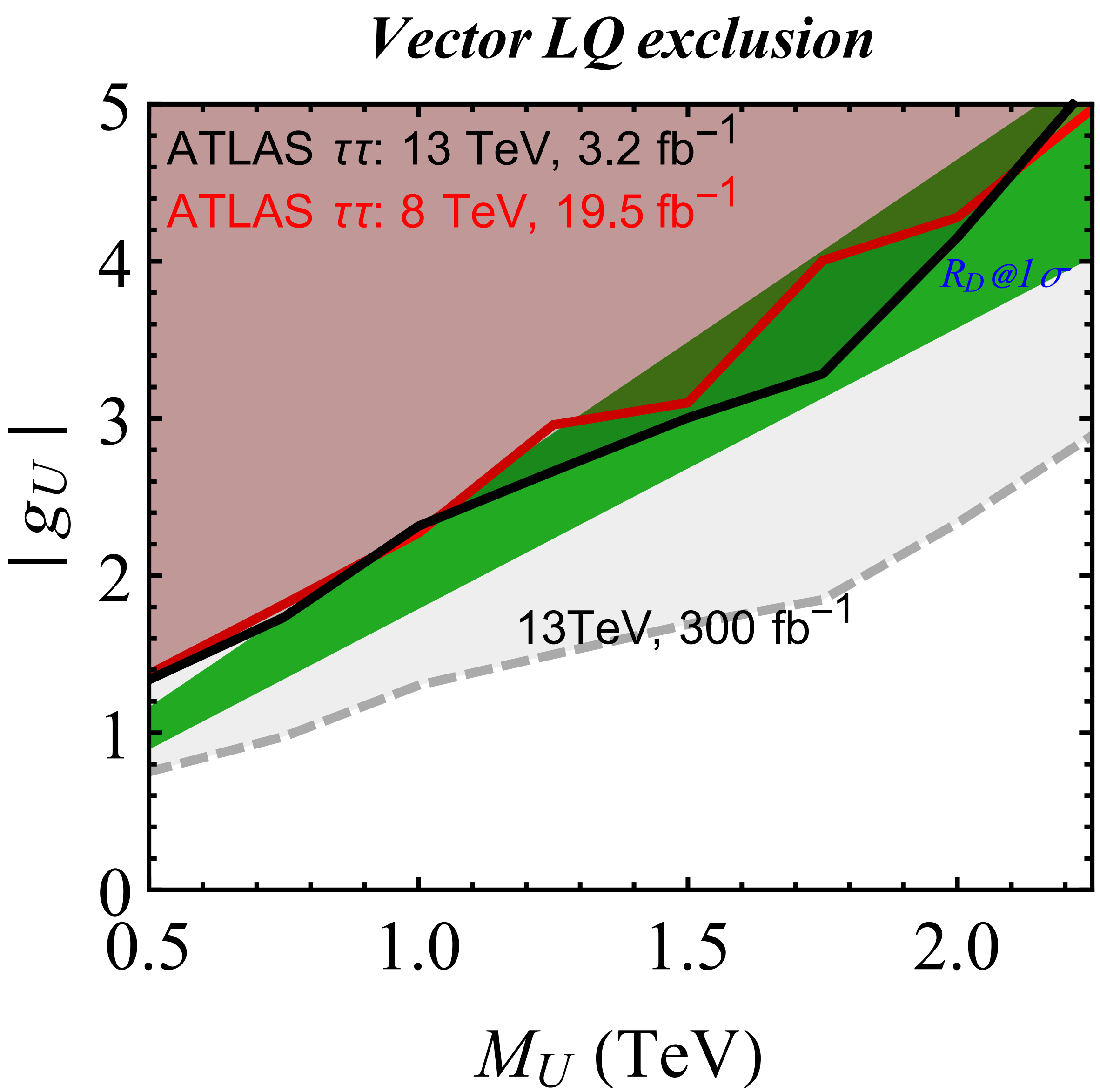
Vector Leptoquark: (**3**,**1**,2/3)

$$\mathcal{L}_U \supset -\frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + m_U^2 U^\dagger_\mu U^\mu + (J^\mu_U U_\mu + \text{h.c.}),$$

$$J^\mu_U \equiv g_U \; \beta_{ij} \; \bar{Q}_i \gamma^\mu L_j \; .$$





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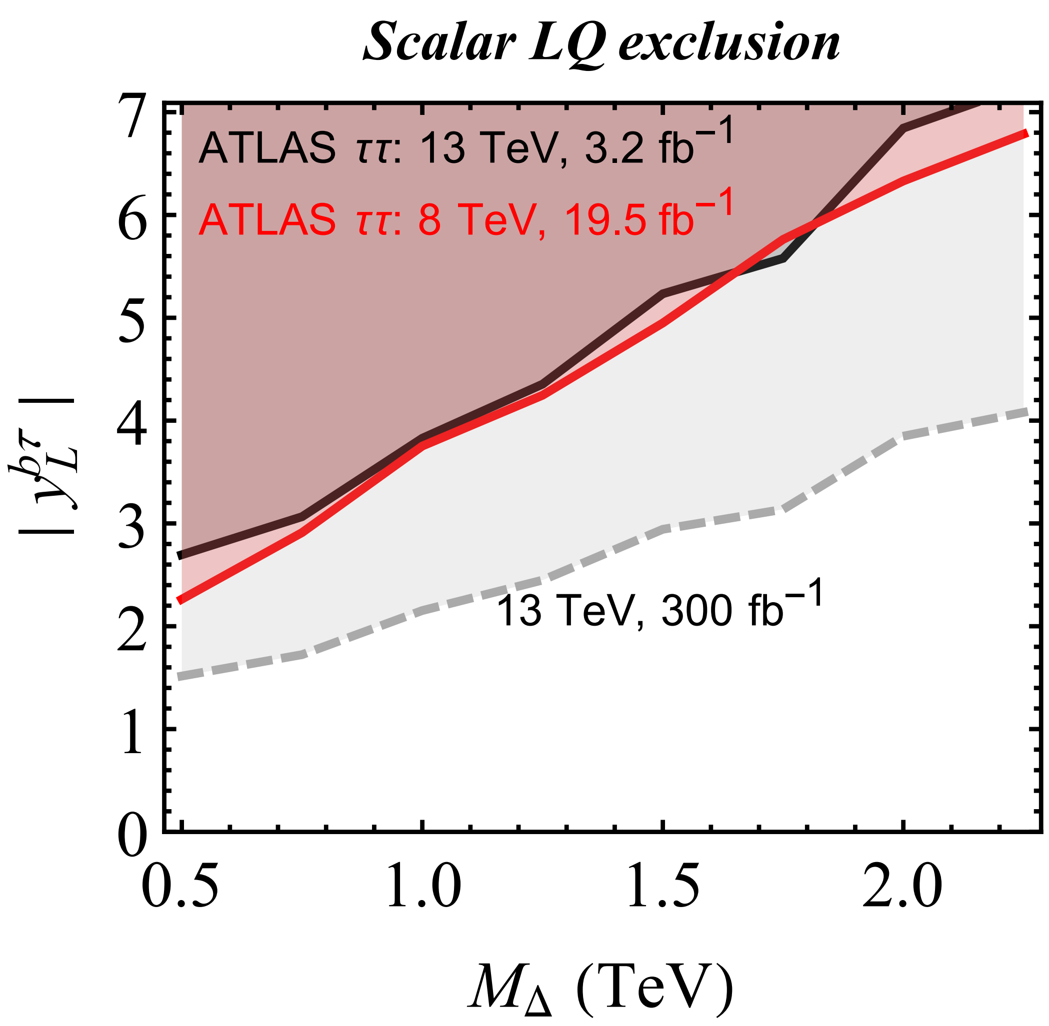
Scalar Leptoquark: (**3**,**2**,1/6)

$$\mathcal{L}_\Delta \supset Y_L^{ij} \bar{d}_i (i\sigma_2 \Delta^*)^\dagger L_j + Y_R^{i\nu} \bar{Q}_i \Delta \nu_R + \text{h.c.}\ .$$



Fit to R(D*) anomaly

$$\left(\frac{Y_R^{b\nu}\ Y_L^{b\tau *}}{g_w^2}\right)\left(\frac{M_W}{M_\Delta}\right)^2 = 1.2 \pm 0.3$$

$Y_R^{b\tau}$ is pushed to non-perturbative values

- QCD LQ pair production limits are getting stronger (~1 TeV)
- Third generation LQ searches very important

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Conclusions

- ***LFU*** *is not a fundamental symmetry. Important to test it.*
- *Anomaly in* $B \to D^{(*)} \tau \nu$ *decays interplays with high-*p_T *LHC physics*
- *Tau-tau searches provide stringent limits*
- *Other signatures involving third generation fermions important*
- *Do not miss wide or light resonances, nor tails*