Universität Zürich[UZH]

Implications of lepton flavor non-universality in *B* decays for high-p_T searches at LHC

Admir Greljo

Based on

1609.07138 - Darius Faroughy, AG, Jernej F. Kamenik

and

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

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

14/11/2016, Seminar at PSI

Outline

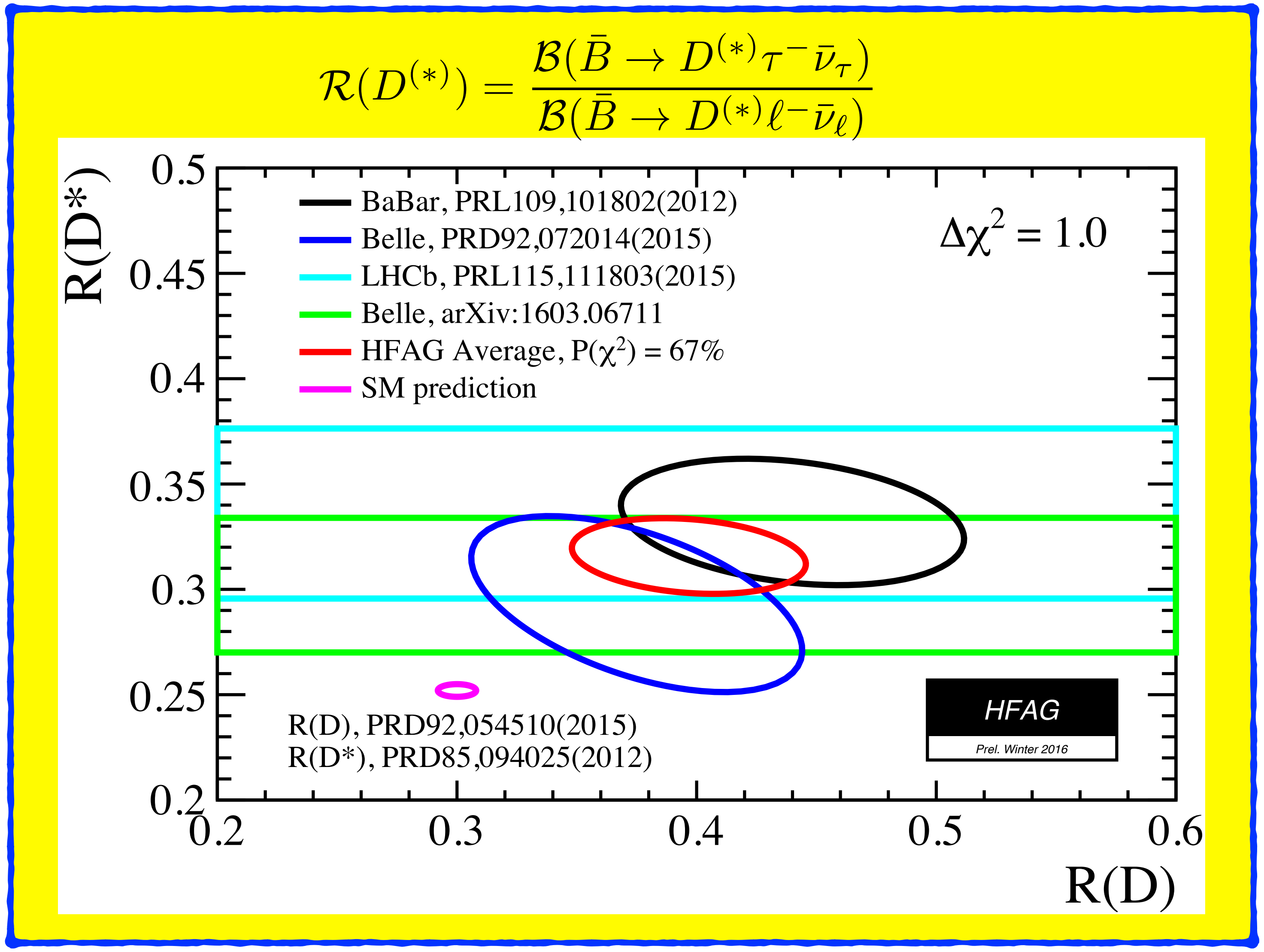
- Motivation:
  Experimental hints on LFU violation in *B* decays

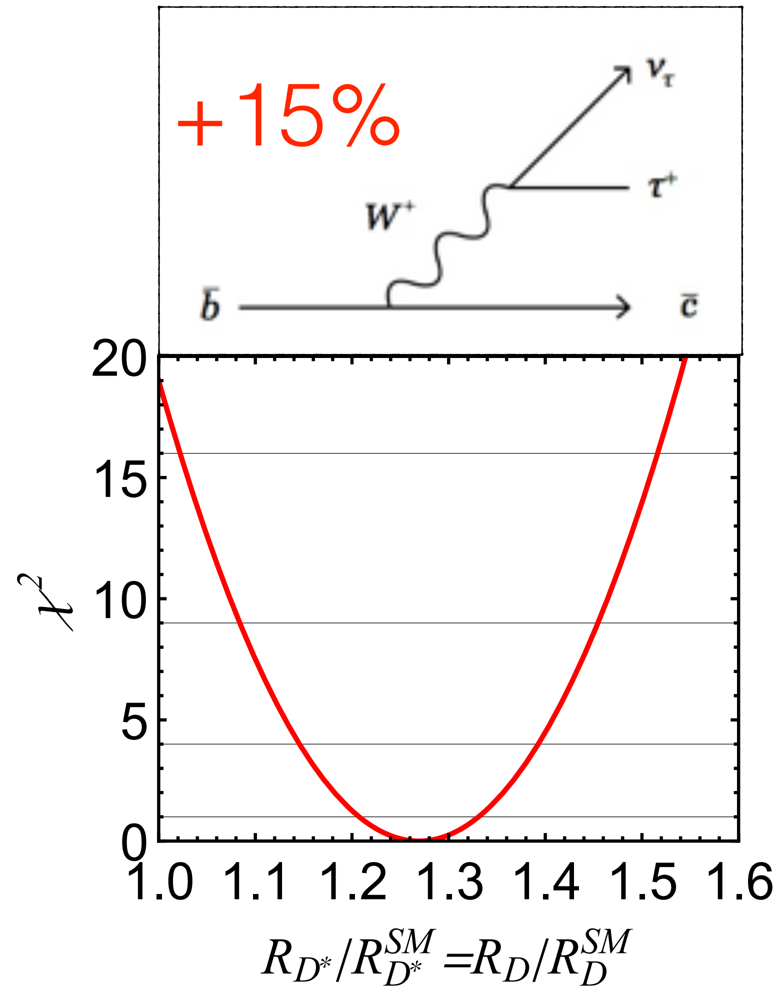
- LHC signatures:
  General discussion (focus on tau searches)

- Model examples:
  - *Real vector triplet model*
  - *2HDM*
  - *Vector & scalar leptoquark models*

- Conclusions

(Main) **Motivation**: Test of LFU in charged currents





- **~ 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: $R_0 \equiv \frac{1}{2}\left(R_{D^*}^{\tau/\ell} - 1\right) = 0.13 \pm 0.03$

(Keep-in-mind) **Motivation**: Test of LFU in neutral currents

- *μ/e universality in b → s transitions*

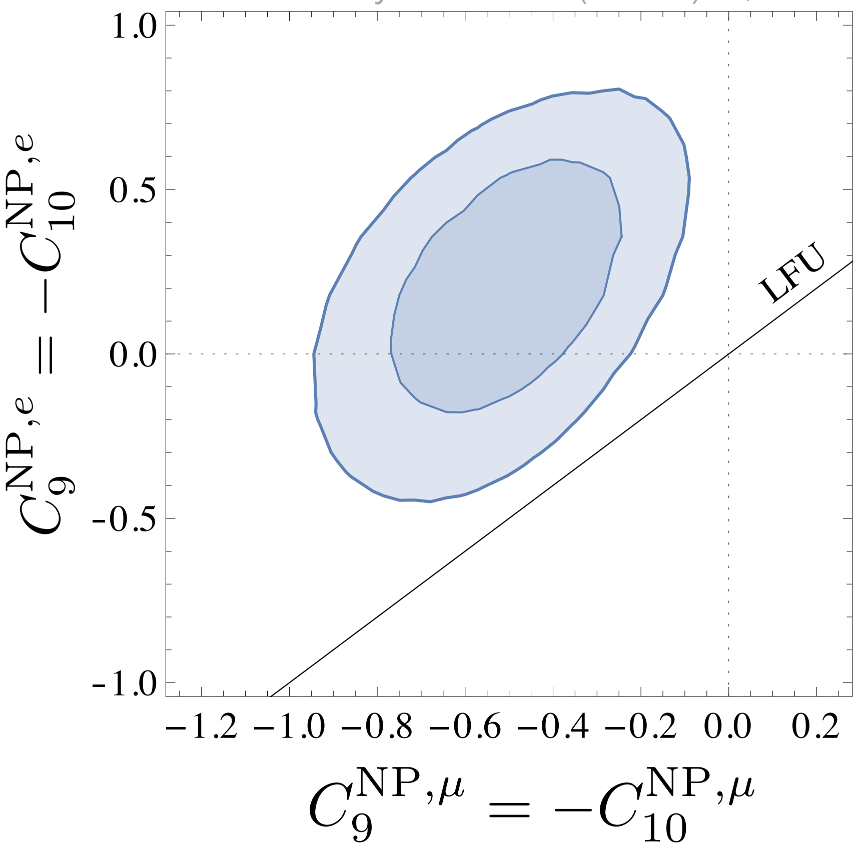
$$R_K^{\mu/e} = \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{\text{exp}}}{\mathcal{B}(B \to Ke^+e^-)_{\text{exp}}}\bigg|_{q^2\in[1,6]\text{GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Phys. Rev. Lett. 113 (2014) 151601

- *B → K*μμ angular distribution:* ***P_5'***

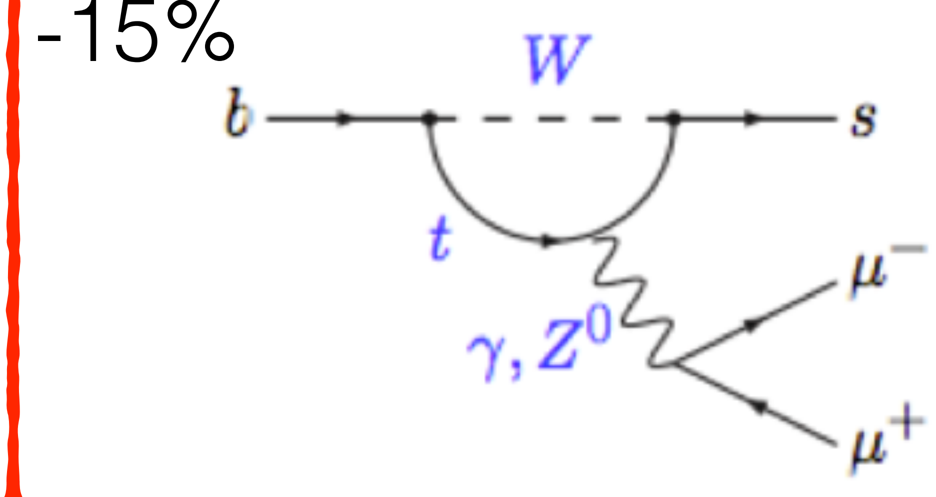
LHCb-PAPER-2015-051

Altmannshofer and Straub, Eur.Phys.J. C75 (2015) 8, 382



- Combined fit **(3.9σ)**
- New physics contribution to muonic left-left operator $(\bar{b}_L \gamma_\mu s_L)(\bar{\mu}_L \gamma^\mu \mu_L)$

$$C_9^{\text{NP},e} = -C_{10}^{\text{NP},e} = 0$$
$$C_9^{\text{NP},\mu} = -C_{10}^{\text{NP},\mu} = (-0.14 \pm 0.04)\ C_9^{\text{SM},\mu}$$



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

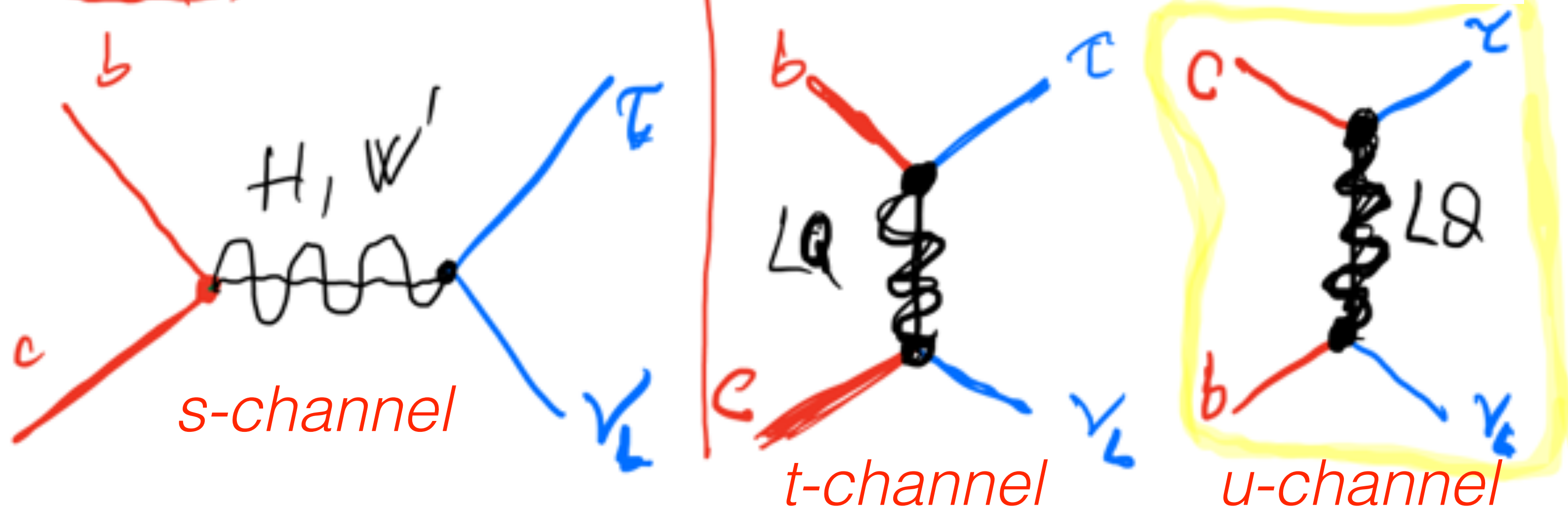
In meantime, what would:

- 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

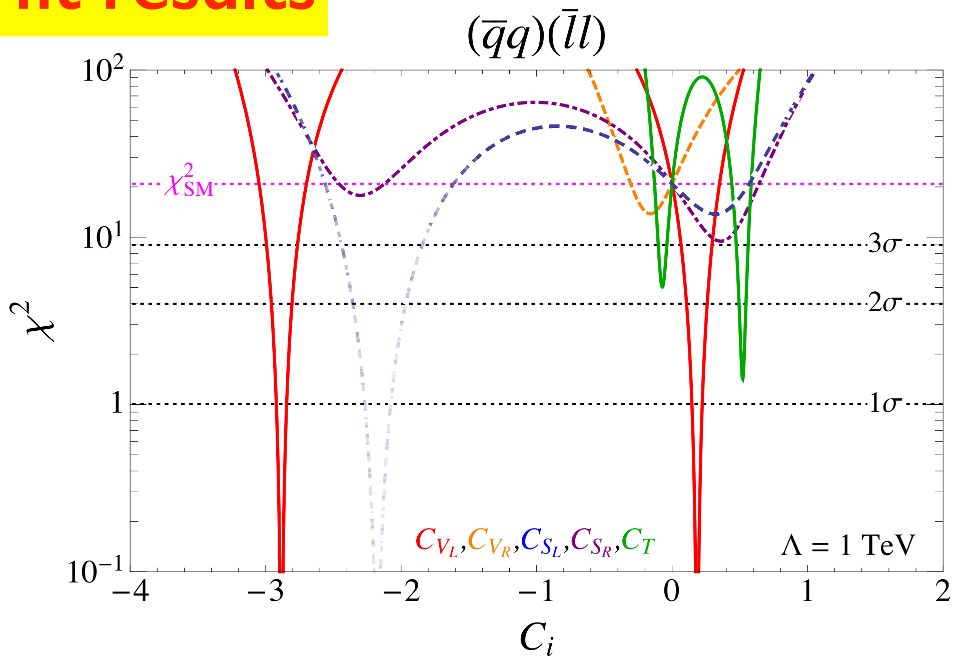
Some operator bases | **Simplified models**

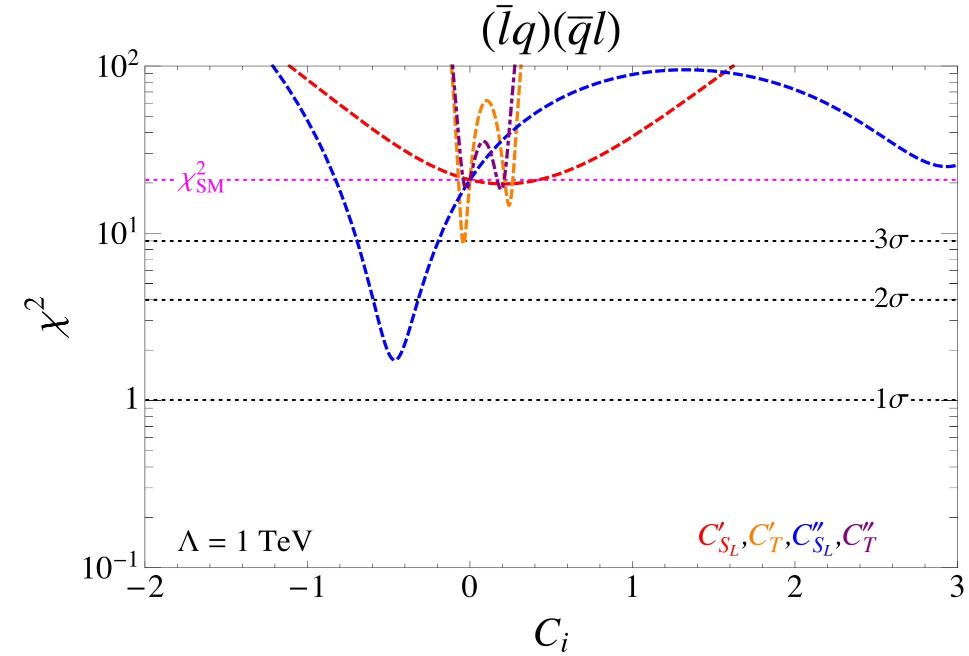
	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L) W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			
$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)\,(\bar{\tau}P_L \nu)$		$\rangle(\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)\,(\bar{\tau}P_L \nu)$			
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad \mathcal{O}_{V_L} \langle$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda \bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$
			$\rangle(\mathbf{3},\mathbf{1})_{2/3}$	$(\lambda \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda} \bar{d}_R \gamma_\mu e_R) U^\mu$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$		
$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)\,(\bar{c}P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)\,(\bar{c}P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(\mathbf{3},\mathbf{2})_{7/6}$	$(\lambda \bar{u}_R \ell_L + \tilde{\lambda} \bar{q}_L i\tau_2 e_R) R$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$	$(\bar{\mathbf{3}},\mathbf{2})_{5/3}$	$(\lambda \bar{d}^c_R \gamma_\mu \ell_L + \tilde{\lambda} \bar{q}^c_L \gamma_\mu e_R) V^\mu$
$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad \frac{1}{2}\mathcal{O}_{V_L} \langle$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$	$\lambda \bar{q}^c_L i\tau_2 \boldsymbol{\tau} \ell_L \boldsymbol{S}$
			$\rangle(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$(\lambda \bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda} \bar{u}^c_R e_R) S$
$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$		
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

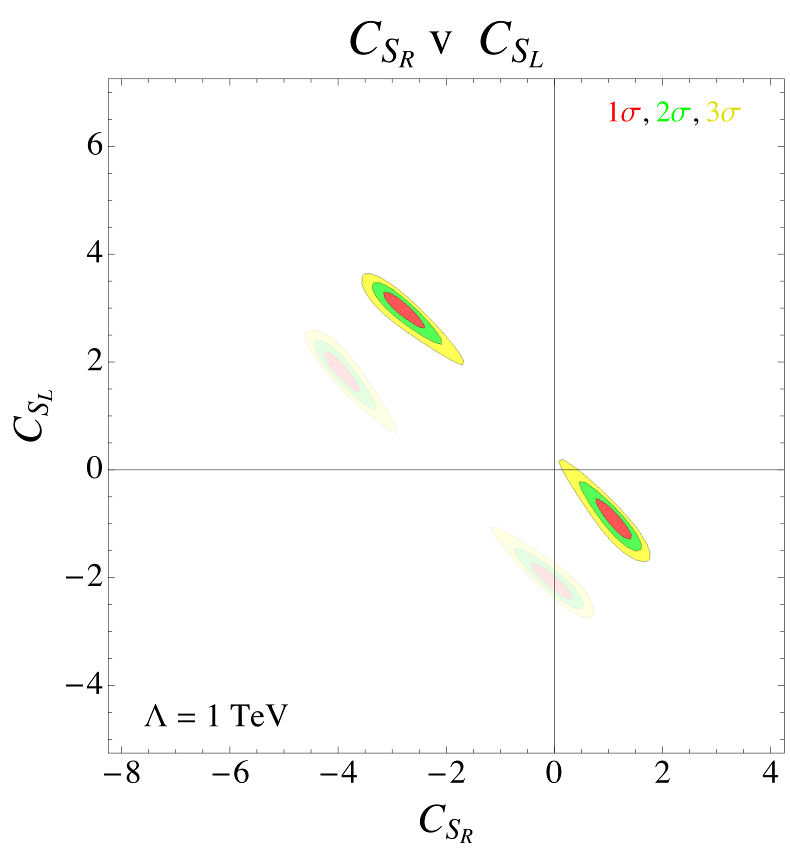
Freytsis, Ligeti, Ruderman,
Phys.Rev. D92 (2015) no.5,
054018

EFT approach: Fitting the signal

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).

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

SMEFT & Implications for high-p_T LHC

- Leading effects expected at **dim-6**: $\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \ldots$

Warsaw basis, 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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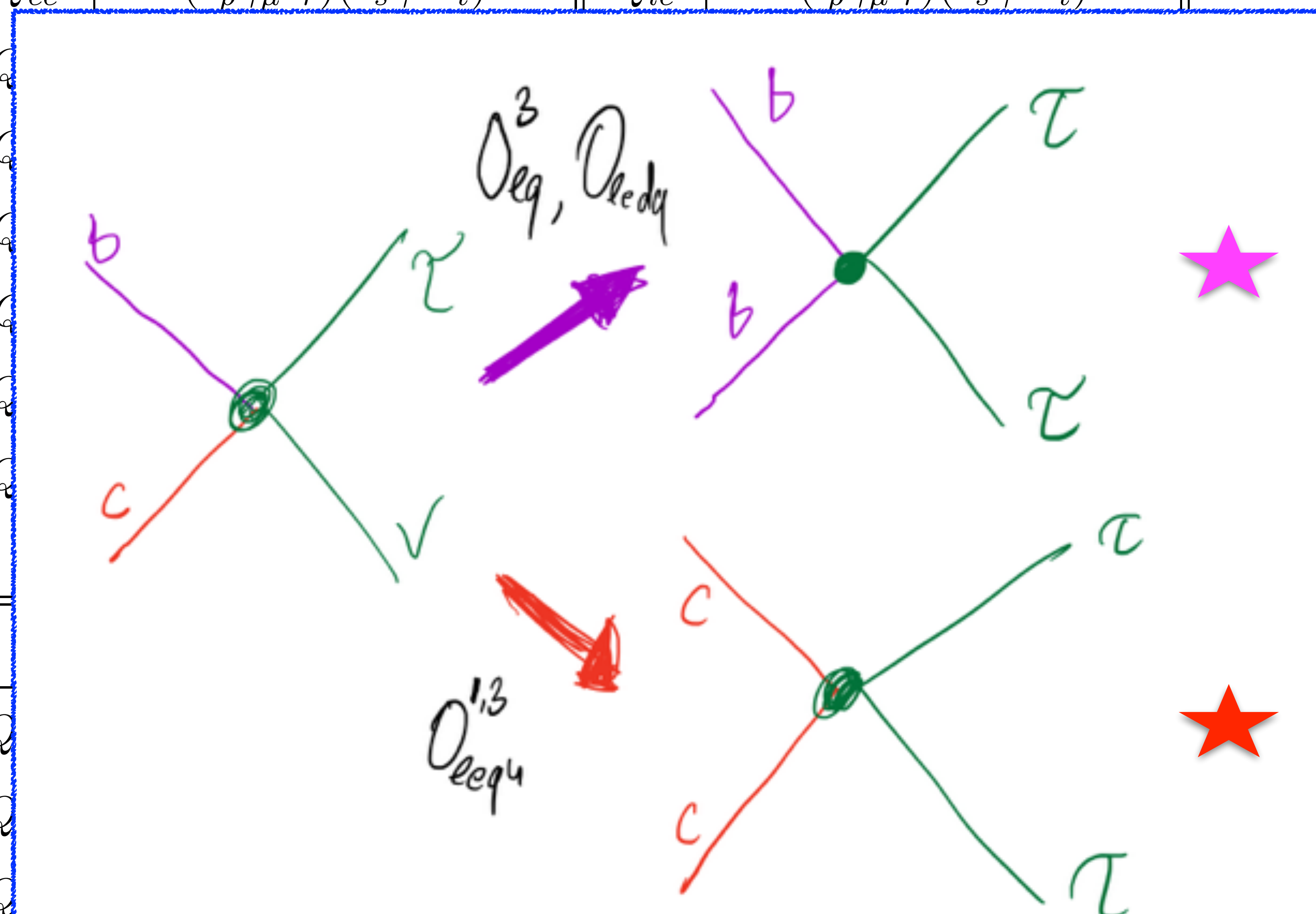
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$			
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qq\ldots}$	
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$



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

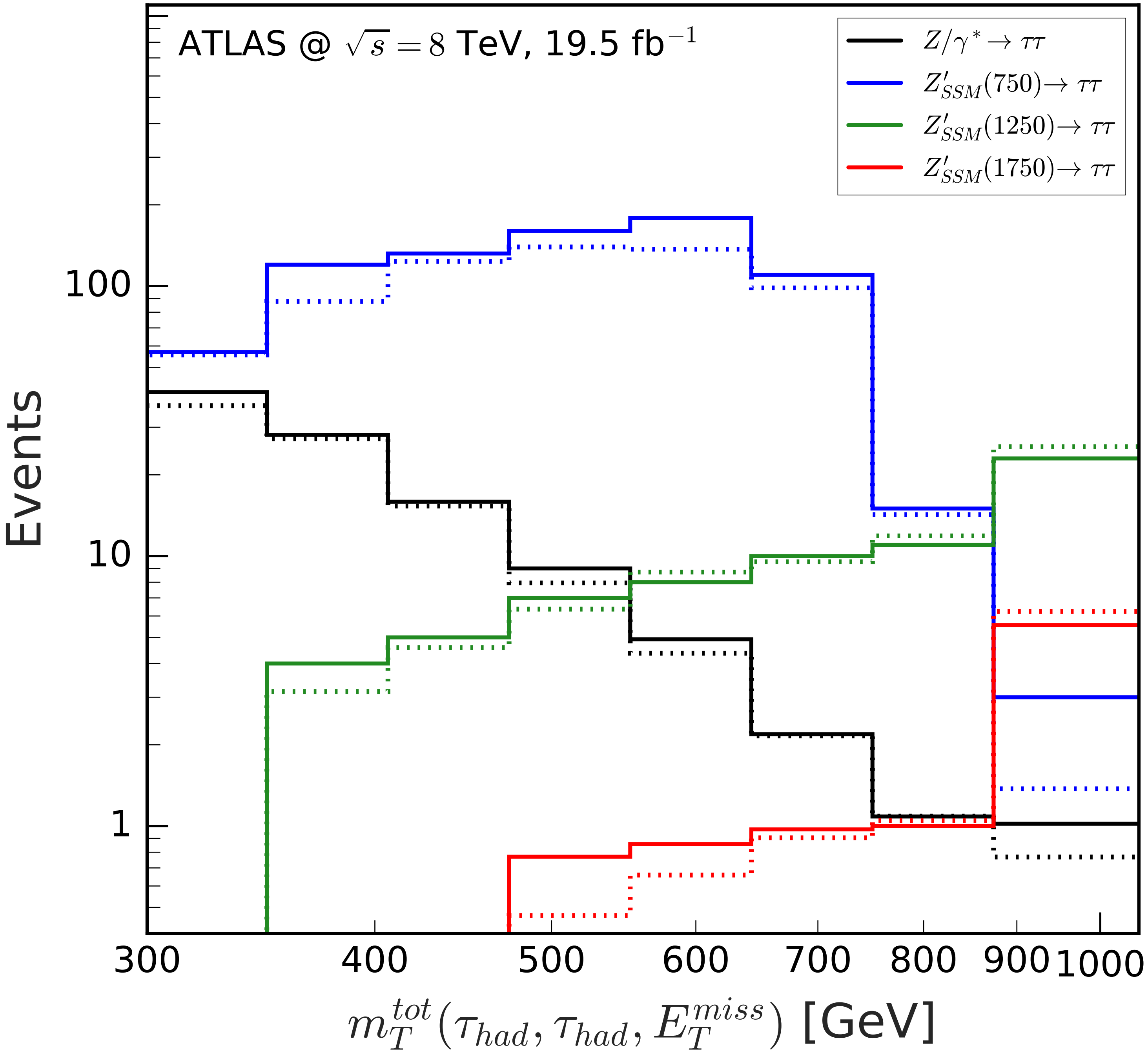
Tau searches at high-p_T

Recast of $\tau^+\tau^-$ 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}

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

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



[Faroughy, AG, F. Kamenik]
1609.07138

SMEFT: Warm up exercise

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

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

- 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 w.r.t. $b \to c$

[Faroughy, AG, F. Kamenik]
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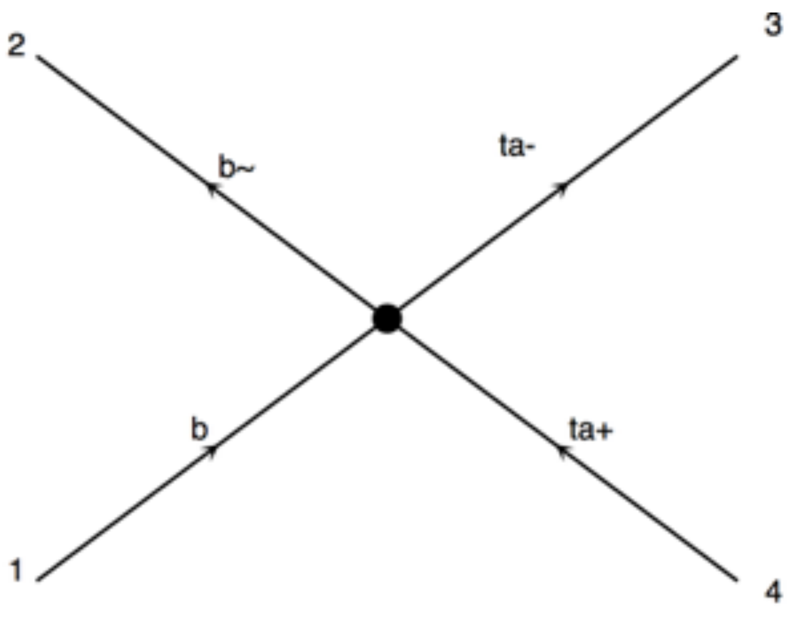
→ *$1/V_{cb}$ enhanced pure third generation neutral currents w.r.t. $b \to c$*



→

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

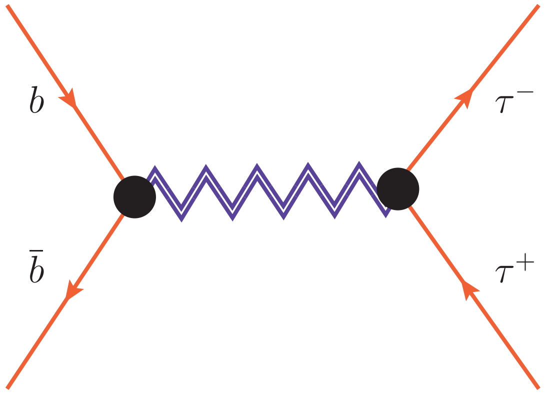
$$|c_{W'}| < 2.8 \text{ TeV}^{-2} \text{ at } 95\% \text{ CL}$$

Fit to R(D*) anomaly:

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

[Faroughy, AG, F. Kamenik] 1609.07138

Real vector triplet model



Vector triplet model (VTM)

See for example:
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

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

- Low-energy flavour physics
- Tiny shift in the Higgs couplings
- Non-universal contribution to ***Z*** and ***W*** pole obs.

VTM: ***Low-energy flavor physics***

SU(2)$_L$ triplet current:

$$J_\mu^a = g_q \lambda_{ij}^q \left(\bar{q}_L^i \gamma_\mu \tau^a q_L^j\right) + g_\ell \lambda_{ij}^\ell \left(\bar{\ell}_L^i \gamma_\mu \tau^a \ell_L^j\right)$$

$\tau^a = \sigma^a/2$

$$\Delta \mathcal{L}_{4f}^{(T)} = -\frac{1}{2m_V^2} J_\mu^a J_\mu^a$$

*integrate out $\mathcal{L} \supset \rho_\mu^a J_\mu^a$

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

VTM: ***Low-energy flavor physics***

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$\tau^a = \sigma^a/2$

$$\Delta\mathcal{L}^{(T)}_{4f} = -\frac{1}{2m_V^2} J^a_\mu J^a_\mu$$

*integrate out $\mathcal{L} \supset \rho^a_\mu J^a_\mu$

quark x lepton

$$\Delta\mathcal{L}^{(T)}_{\rm c.c.} = -\frac{g_q g_\ell}{2m_V^2}\left[(V\lambda^q)_{ij}\lambda^\ell_{ab}\left(\bar{u}^i_L\gamma_\mu d^j_L\right)\left(\bar{\ell}^a_L\gamma_\mu\nu^b_L\right) + {\rm h.c.}\right],$$

$$\Delta\mathcal{L}^{(T)}_{\rm FCNC} = -\frac{g_q g_\ell}{4m_V^2}\lambda^\ell_{ab}\left[\lambda^q_{ij}\left(\bar{d}^i_L\gamma_\mu d^j_L\right) - (V\lambda^q V^\dagger)_{ij}\left(\bar{u}^i_L\gamma_\mu u^j_L\right)\right]\left(\bar{\ell}^a_L\gamma_\mu\ell^b_L - \bar{\nu}^a_L\gamma_\mu\nu^b_L\right)$$

quark x quark

$$\Delta\mathcal{L}^{(T)}_{\Delta F=2} = -\frac{g_q^2}{8m_V^2}\left[(\lambda^q_{ij})^2\left(\bar{d}^i_L\gamma_\mu d^j_L\right)^2 + (V\lambda^q V^\dagger)^2_{ij}\left(\bar{u}^i_L\gamma_\mu u^j_L\right)^2\right],$$

lepton x lepton

$$\Delta\mathcal{L}^{(T)}_{\rm LFV} = -\frac{g_\ell^2}{8m_V^2}\lambda^\ell_{ab}\lambda^\ell_{cd}(\bar{\ell}^a_L\gamma_\mu\ell^b_L)(\bar{\ell}^c_L\gamma_\mu\ell^d_L),$$

$$\Delta\mathcal{L}^{(T)}_{\rm LFU} = -\frac{g_\ell^2}{8m_V^2}(-2\lambda^\ell_{ab}\lambda^\ell_{cd} + 4\lambda^\ell_{ad}\lambda^\ell_{cb})(\bar{\ell}^a_L\gamma_\mu\ell^b_L)(\bar{\nu}^c_L\gamma_\mu\nu^d_L).$$

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

VTM: ***Low-energy flavor physics***

SU(2)$_L$ triplet current:

$$J^a_\mu = g_q \lambda^q_{ij} \left(\bar{q}^i_L \gamma_\mu \tau^a q^j_L \right) + g_\ell \lambda^\ell_{ij} \left(\bar{\ell}^i_L \gamma_\mu \tau^a \ell^j_L \right)$$

$\tau^a = \sigma^a/2$

$$\Delta \mathcal{L}^{(T)}_{4f} = -\frac{1}{2m_V^2} J^a_\mu J^a_\mu$$

*integrate out $\mathcal{L} \supset \rho^a_\mu J^a_\mu$

quark x le

quark x qu

lepton x le

$- \bar{\nu}^a_L \gamma_\mu \nu^b_L)$

$8m_V^2$

- U(2)$_q$ flavor symmetry

Barbieri, Isidori, Jones-Perez, Lodone, Straub,
Eur. Phys. J. C 71 (2011) 1725

$$\lambda^q \cong \begin{pmatrix} \epsilon_2 |V_{td}|^2 & \epsilon_2 V^*_{td} V_{ts} & \epsilon_1^* V^*_{td} \\ \epsilon_2 V_{td} V^*_{ts} & \epsilon_2 |V_{ts}|^2 & \epsilon_1^* V^*_{ts} \\ \epsilon_1 V_{td} & \epsilon_1 V_{ts} & 1 \end{pmatrix}$$

- in the basis of charged-leptons and down-type quarks

$\epsilon_2 \sim \mathcal{O}(\epsilon_1^2)$

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

VTM: ***Combined fit to low-energy data***

- *Fit parameters:* $\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \approx g_{\ell,q} \frac{122\,\text{GeV}}{m_V}$ $\lambda^q_{bs},\ \lambda^\ell_{\mu\mu},\ \lambda^\ell_{\tau\mu}$
  - 2 flavour universal
  - 3 flavour dependent

- *Data:*

	Obs. $\mathcal{O}_i$	Exp. bound $(\mu_i \pm \sigma_i)$	Def. $\mathcal{O}_i(x_\alpha)$
1) b→c τ ν	$R_0(D^*)$	0.14 ± 0.04	$\epsilon_\ell \epsilon_q$
	$R_0(D)$	0.19 ± 0.09	$\epsilon_\ell \epsilon_q$
2) b→ cν$\mu(e)$	$\Delta R^{\mu e}_{b\to c}$	0.00 ± 0.01	$2\epsilon_\ell \epsilon_q \lambda^\ell_{\mu\mu}$
3) B_s mix	$\Delta R^{\Delta F=2}_{B_s}$	0.0 ± 0.1	$\epsilon_q^2 \lvert\lambda^q_{bs}\rvert^2 (\lvert V^*_{tb} V_{ts}\rvert^2 R^{\text{loop}}_{\text{SM}})^{-1}$
4) b→s μ μ	ΔC^μ_9	-0.53 ± 0.18	$-(\pi/\alpha_{\text{em}})\lambda^\ell_{\mu\mu}\epsilon_\ell\epsilon_q\lambda^q_{bs}/\lvert V^*_{tb}V_{ts}\rvert$
5) τ → νν$\mu(e)$	$\Delta R_{\tau\to\mu/e}$	0.0040 ± 0.0032	$2\epsilon_\ell^2 \left(\lambda^\ell_{\mu\mu} - \frac{1}{2}\lvert\lambda^\ell_{\tau\mu}\rvert^2\right)$
6) τ → 3μ	$\Lambda^{-2}_{\tau\mu}$	$(0.0 \pm 4.1) \times 10^{-9}$ [GeV^{-2}]	$(G_F/\sqrt{2})\epsilon_\ell^2 \lambda^\ell_{\mu\mu}\lambda^\ell_{\tau\mu}$
7) D mix	Λ^{-2}_{uc}	$(0.0 \pm 5.6) \times 10^{-14}$ [GeV^{-2}]	$(G_F/\sqrt{2})\epsilon_q^2 \lvert V_{ub}V^*_{cb}\rvert^2$

$$\chi^2(x_\alpha) = \sum_i \frac{(\mathcal{O}_i(x_\alpha) - \mu_i)^2}{\sigma_i^2} \longrightarrow \chi^2(x_{\text{SM}}) - \chi^2(x_{\text{BF}}) = 18.6$$

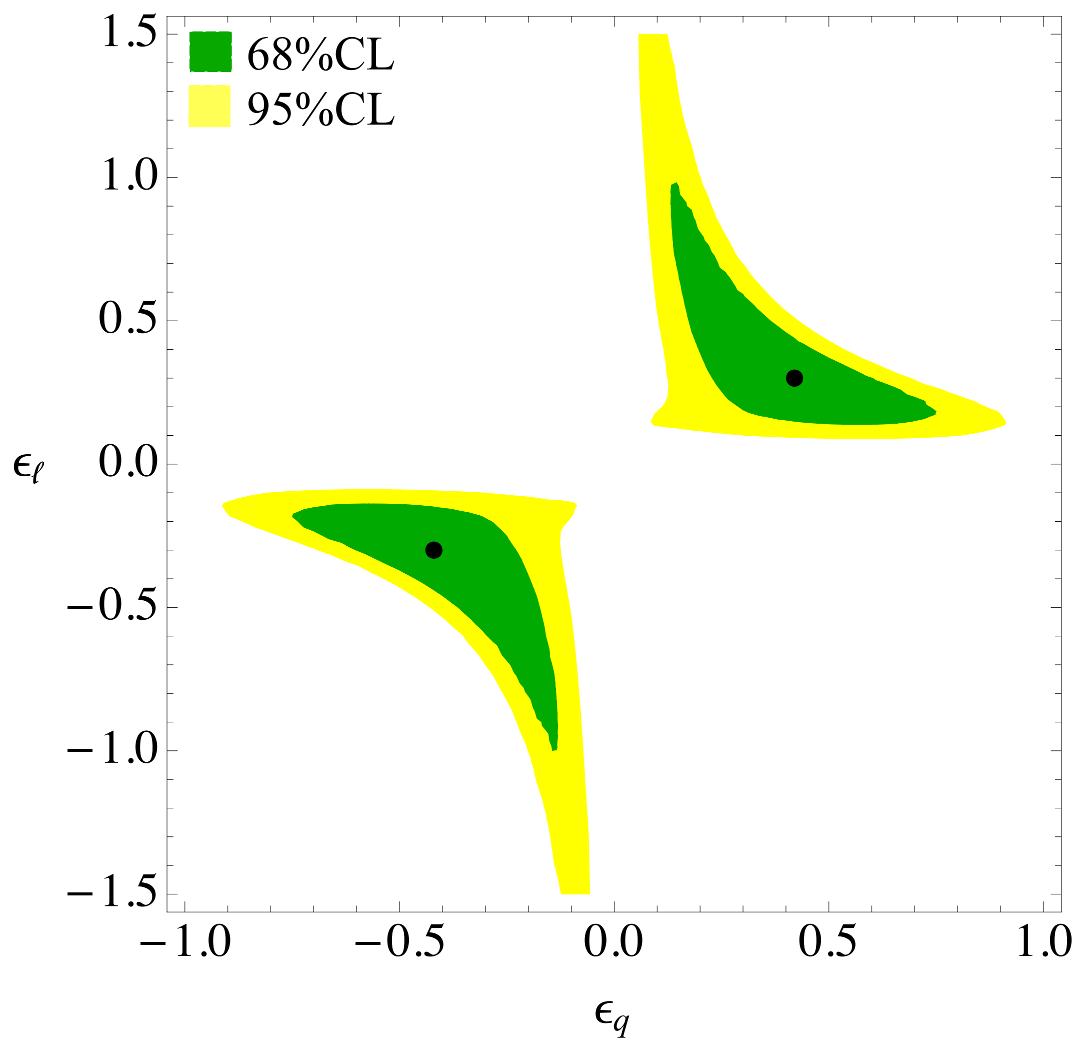
VTM: ***Combined fit to low-energy data***

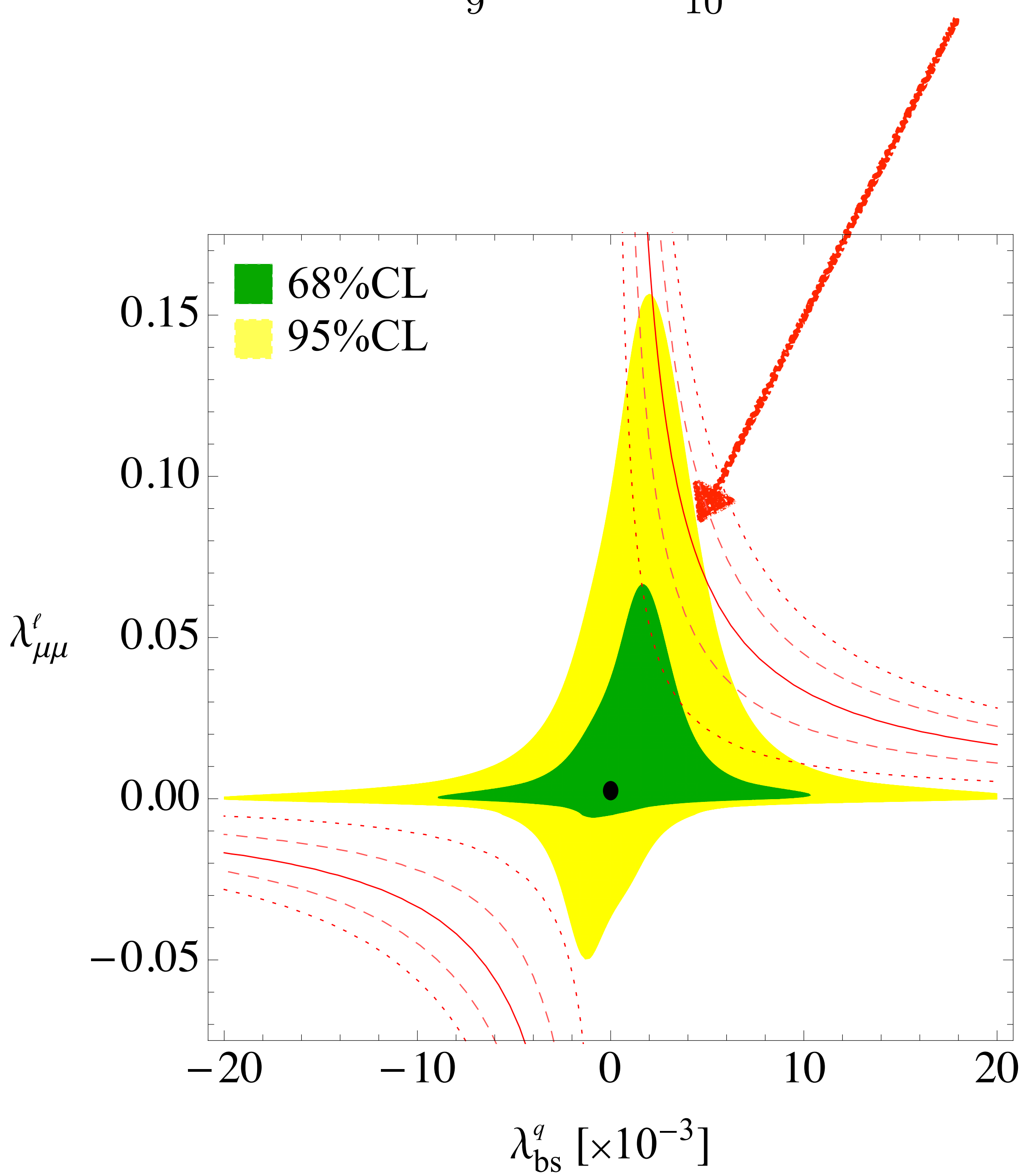
- The fit is driven by

$$R_0(D^*) = \epsilon_\ell \epsilon_q$$

- Some tension with

$$\Delta C_9^\mu = -\Delta C_{10}^\mu = -0.53 \pm 0.18$$

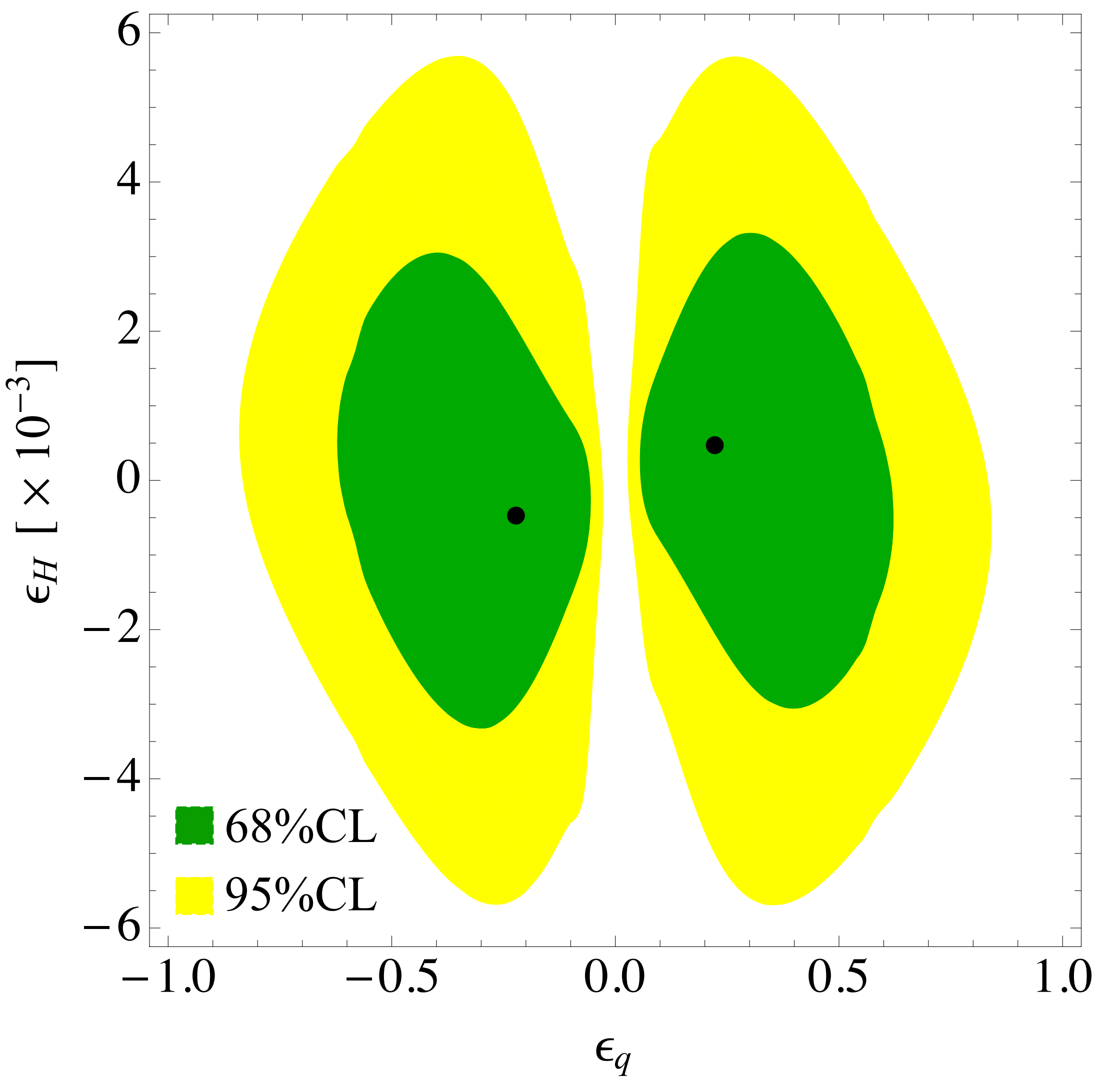




VTM: ***Bounds from LEP-I***

- Non-universal contribution to ***Z*** and ***W*** pole obs.

$$\epsilon_X \equiv g_X m_W / g m_V$$



Using the fit results from:
A. Efrati, A. Falkowski and Y. Soreq, arXiv:1503.07872

- EWPO:
(1) Small mass splitting
(2) Stringent limits on g_H

Vector triplet dominantly decays to third generation SM fermions

- Low-energy flavor physics

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

VTM: ***LHC phenomenology***

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

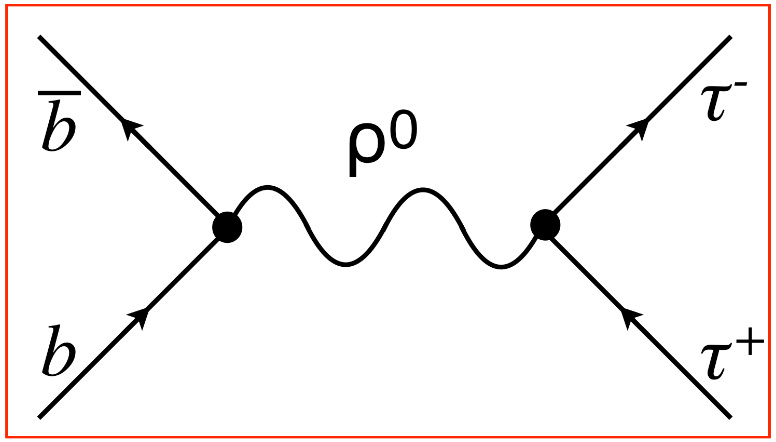
Decay modes:

- Neutral vector:
  - *τ τ*
  - *ν ν*
  - *b b*
  - *t t*
- Charged vector:
  - *τ ν*
  - *t b*

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

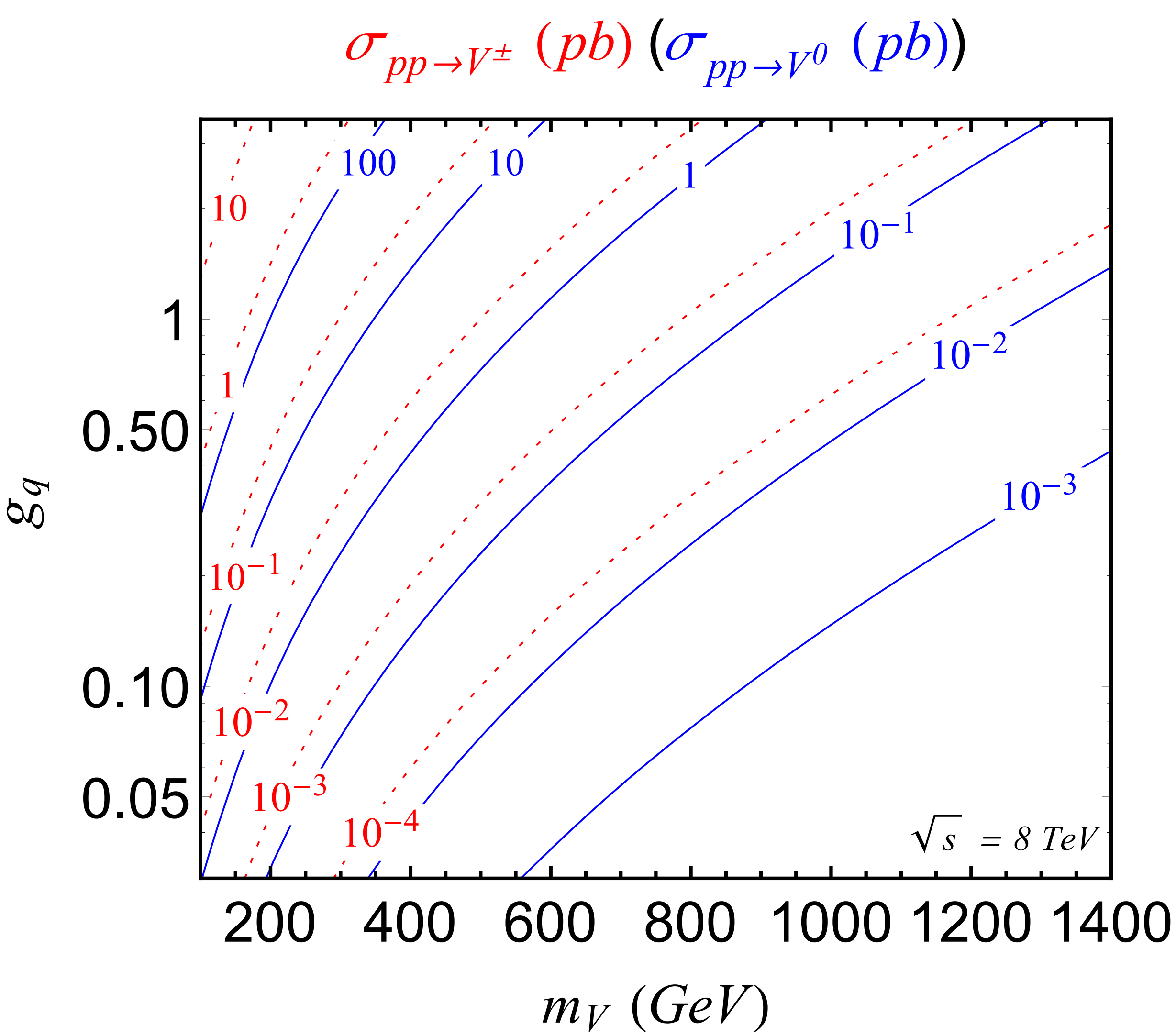
Production modes:

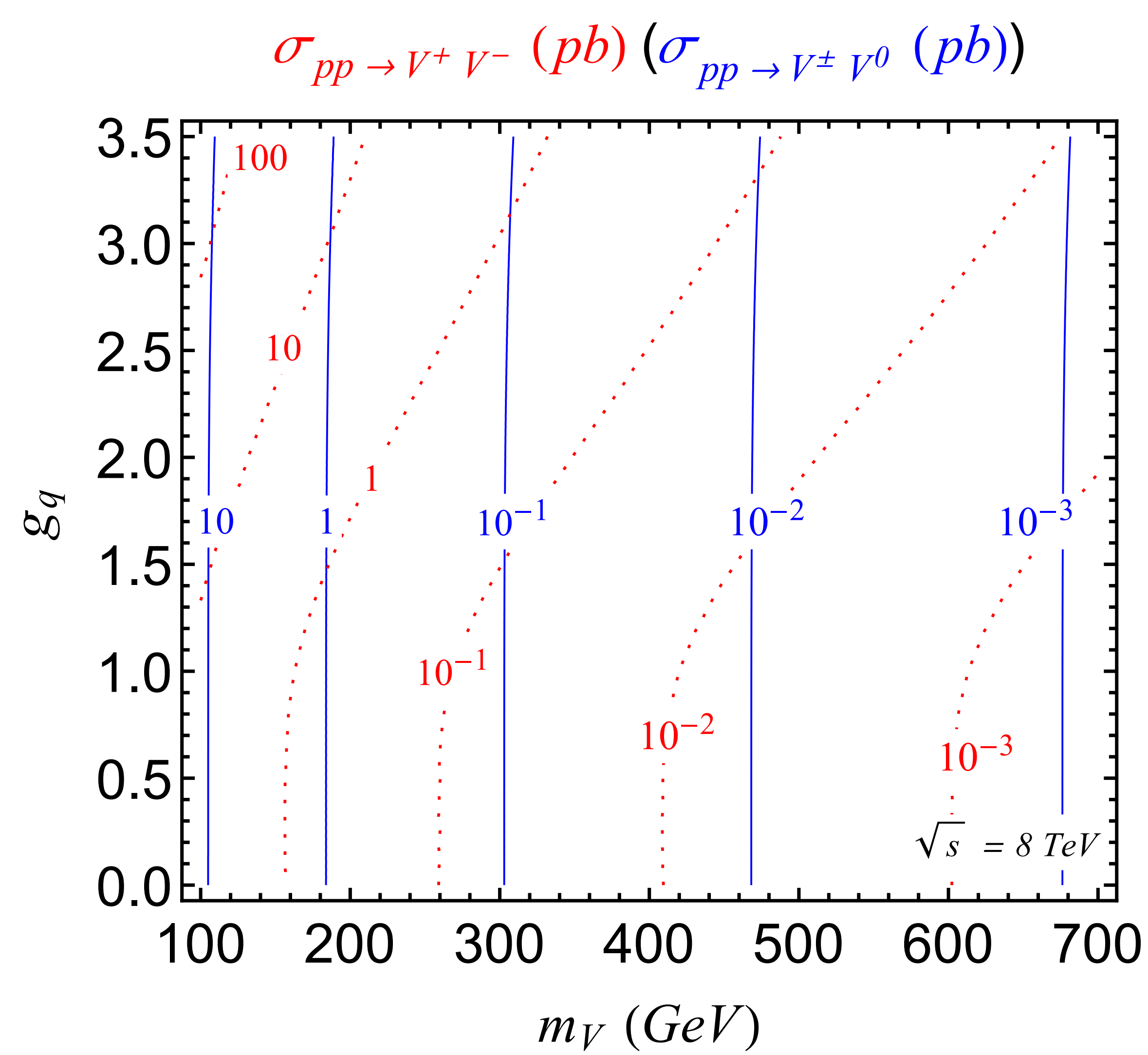
1) Single production (***b b* → V⁰**, *b c* → $V^\pm$)
2) Pair production



VTM: ***LHC phenomenology***

Production modes:





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

[AG, Isidori, Marzocca]
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VTM: ***LHC phenomenology***

Z’ production @ NLO QCD

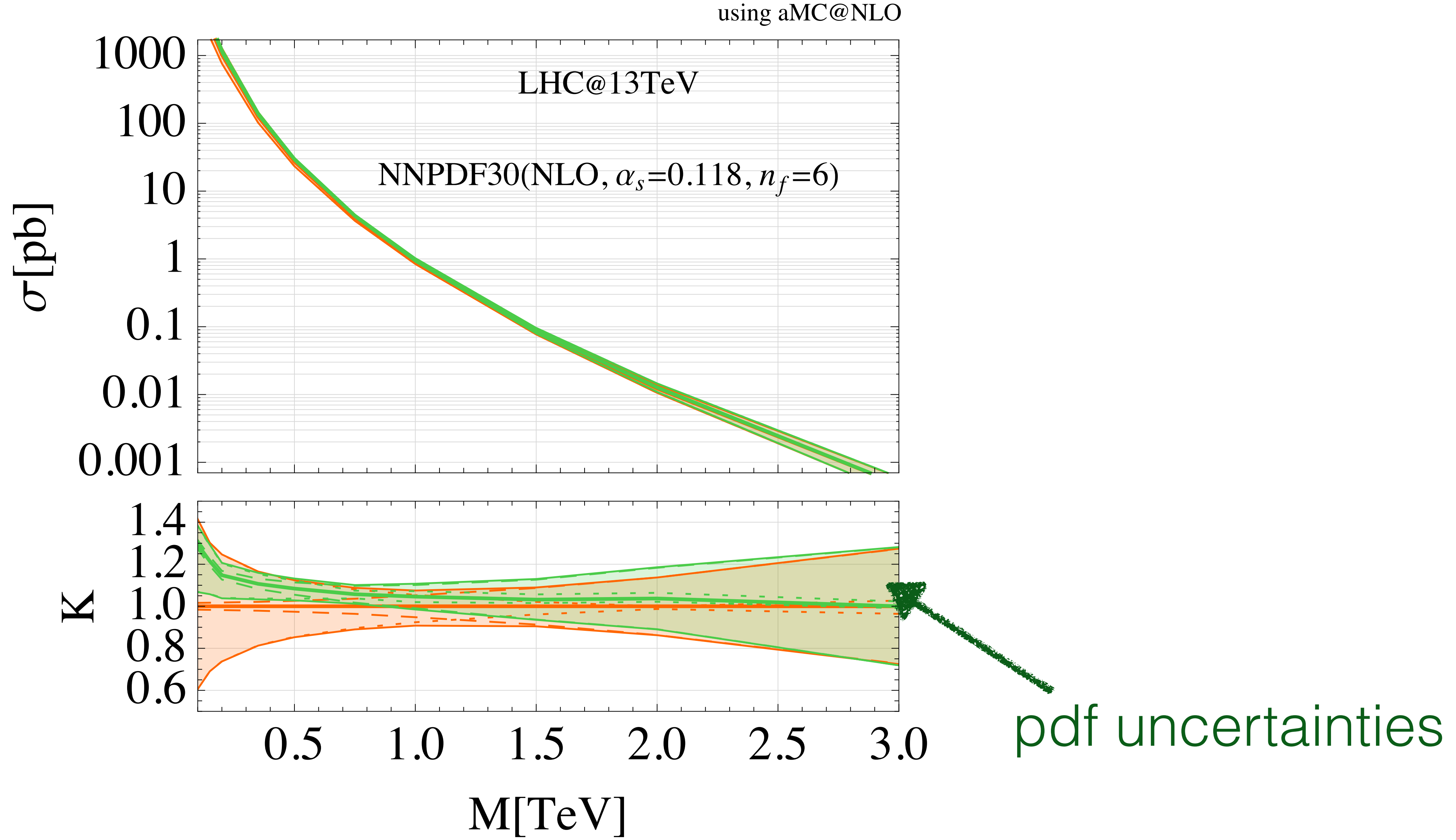

Figure 3: Next-to-leading order QCD corrections for a narrow Z' production via bottom-bottom fusion.

[Faroughy, AG, F. Kamenik]
1609.07138

VTM: ***LHC phenomenology***

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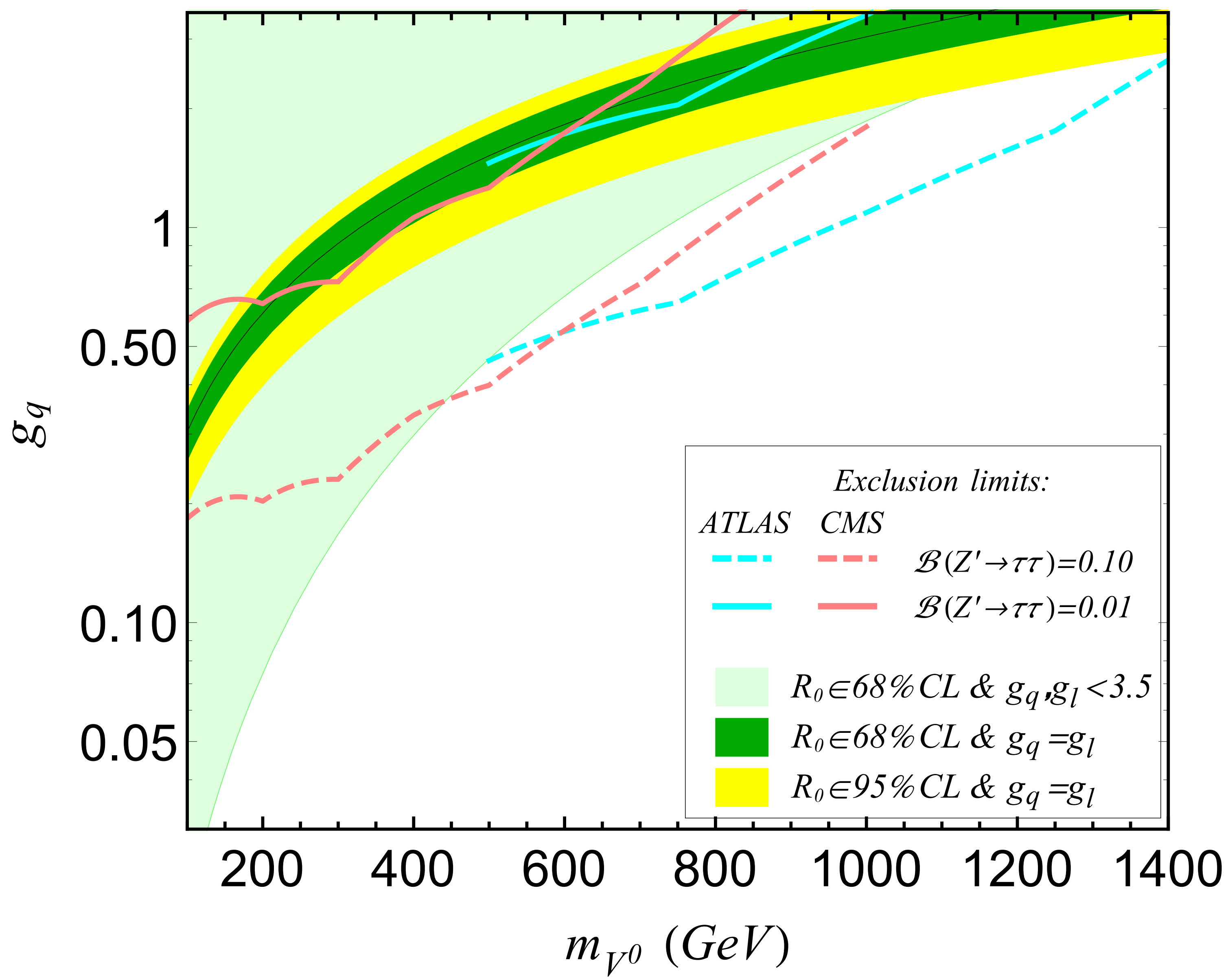
$bb \rightarrow V^0 \rightarrow \tau\,\tau$

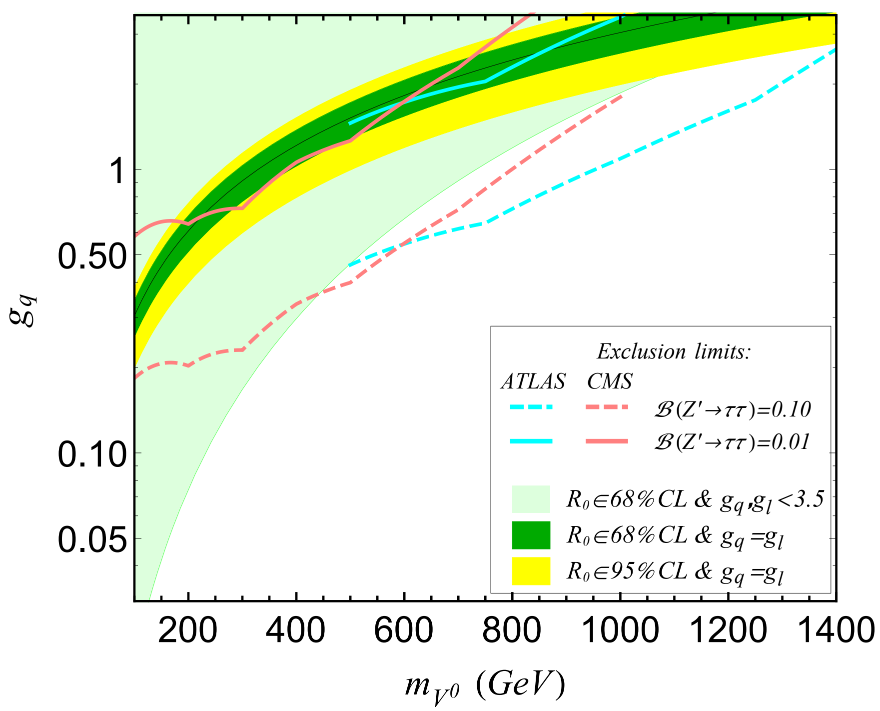


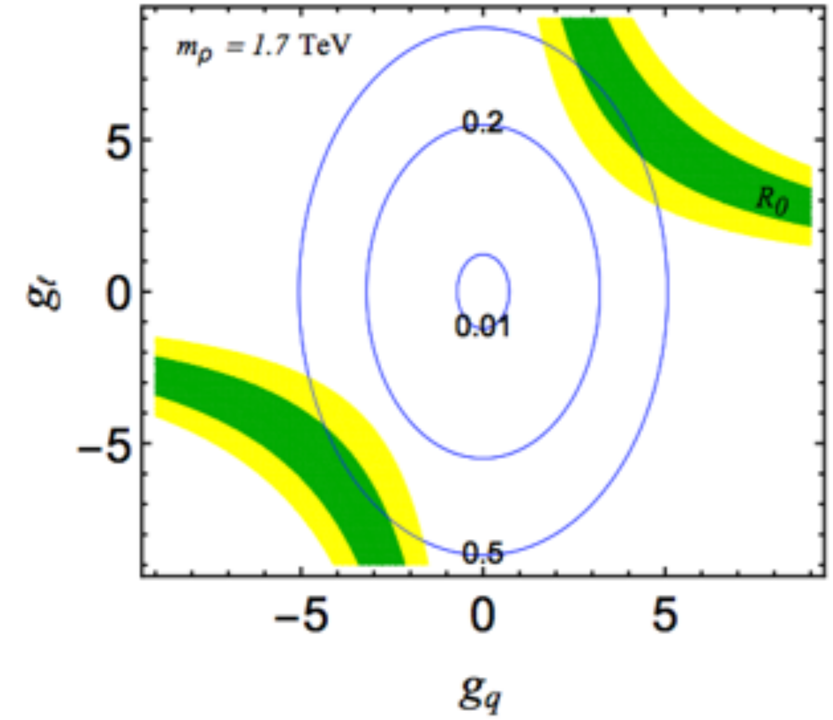
- **τ τ** resonance searches can be reconciled by having **a broad resonance** (either V^0 mass is ~ few TeV or new BSM decay channels)

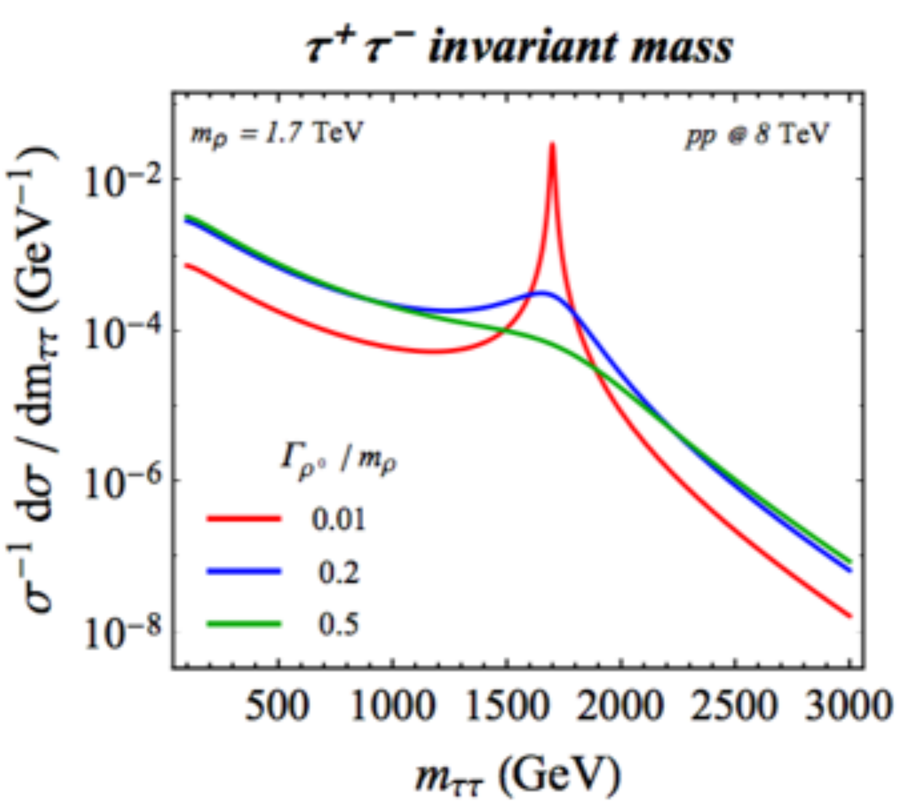
[AG, Isidori, Marzocca]
JHEP 1507 (2015) 142

VTM: ***LHC phenomenology***

[Buttazzo, AG, Isidori, Marzocca]
Γ_{ρ^0} / m_ρ JHEP 1608 (2016) 035



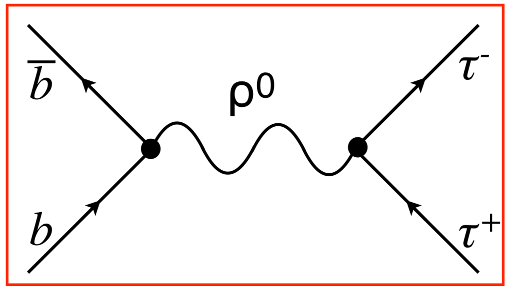


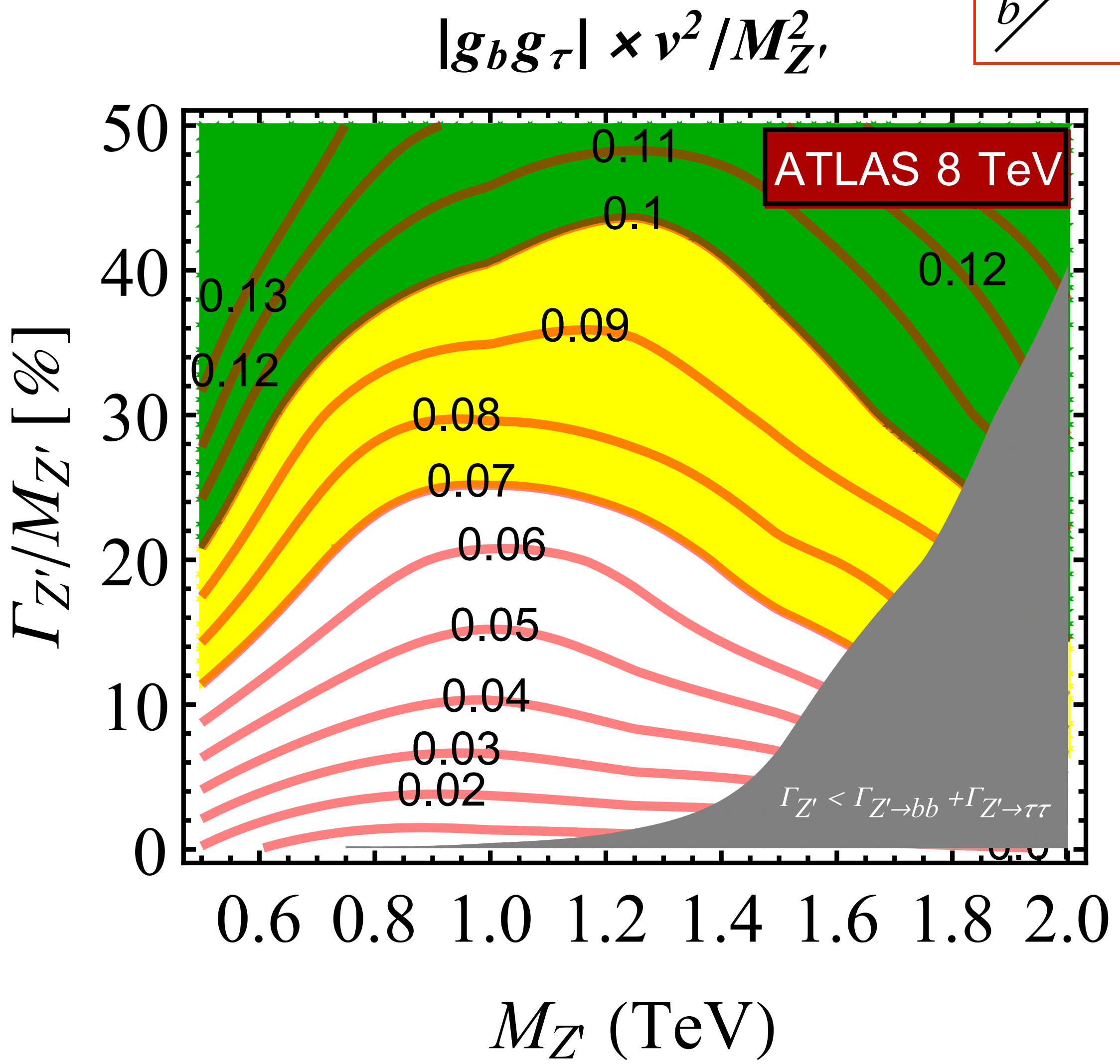


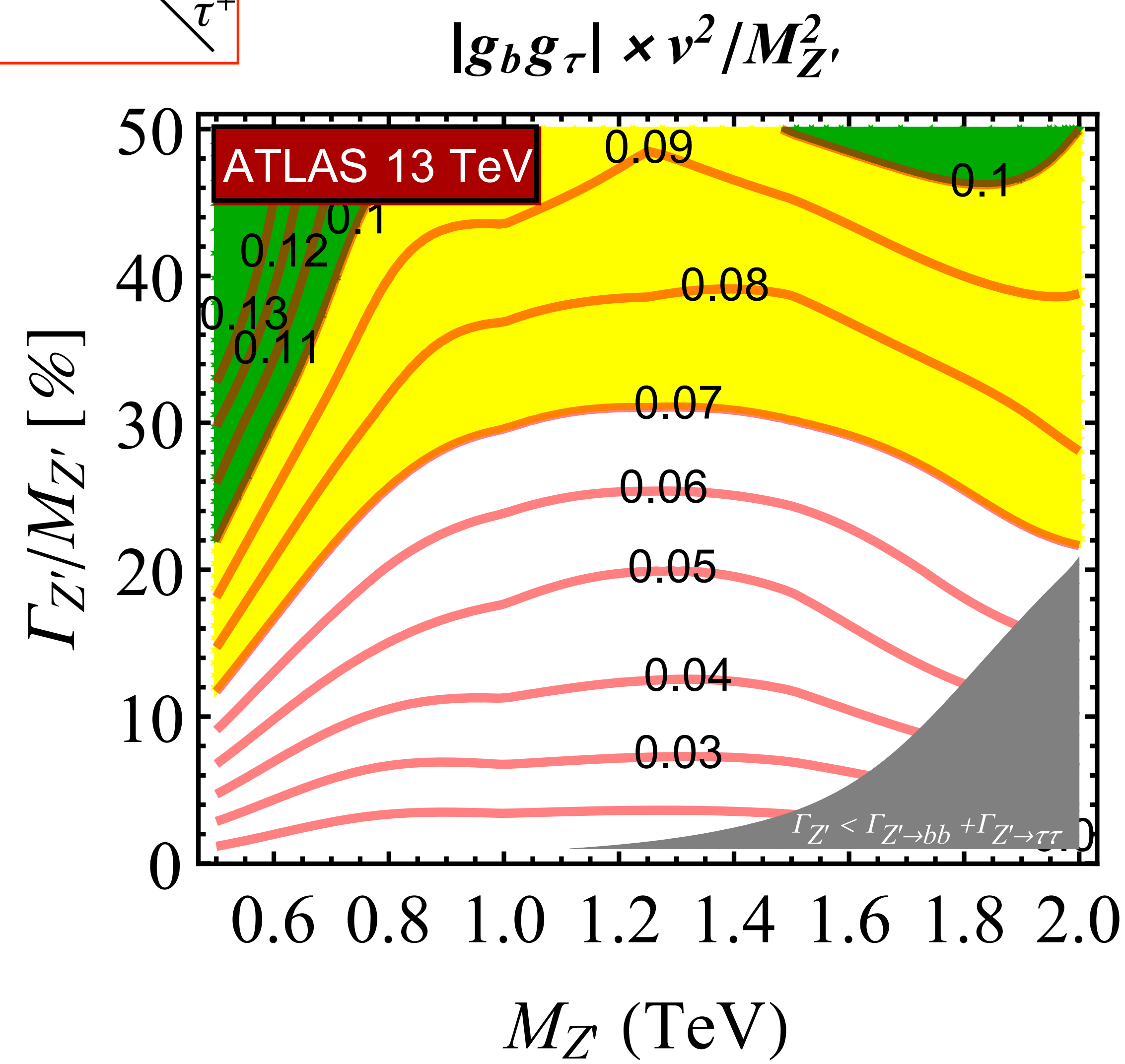
- Important to optimize searches for broad resonances

- Careful extraction of the present bounds is in order (recast)

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



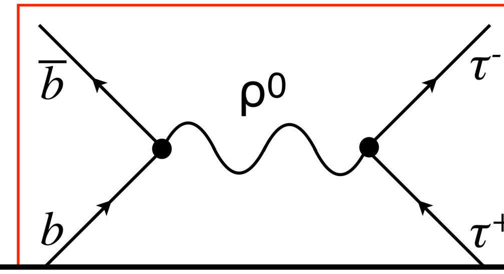


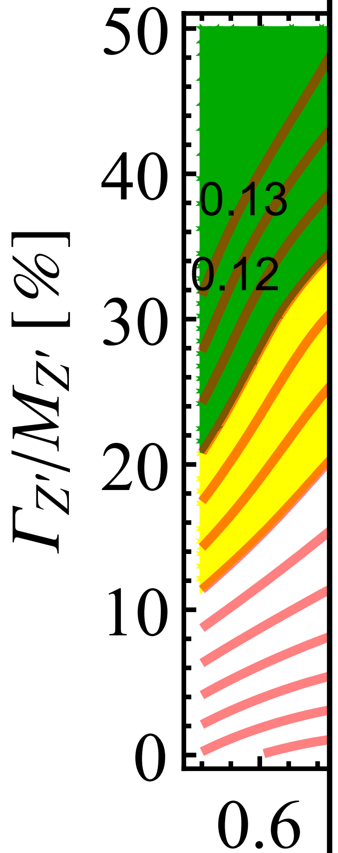


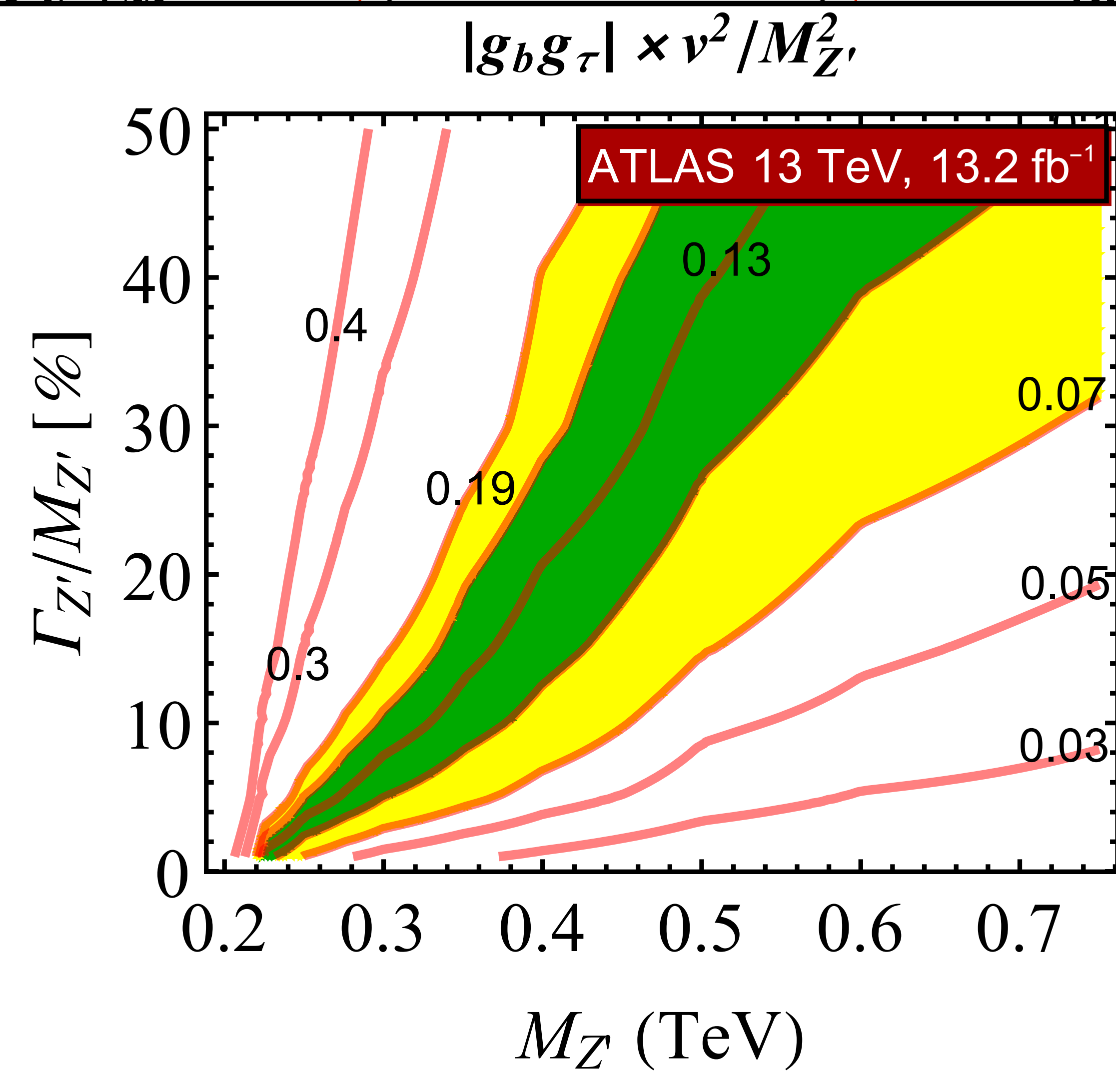
- Recast of the ATLAS $\tau\tau$ searches at 8 TeV, 19.5 fb^{-1} (left) and 13 TeV, 3.2 fb^{-1} (right)

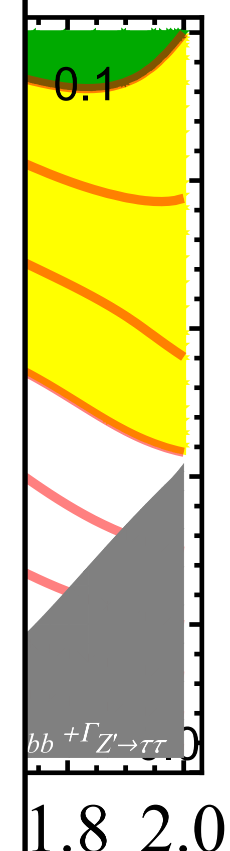
[Faroughy, AG, F. Kamenik]
1609.07138

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









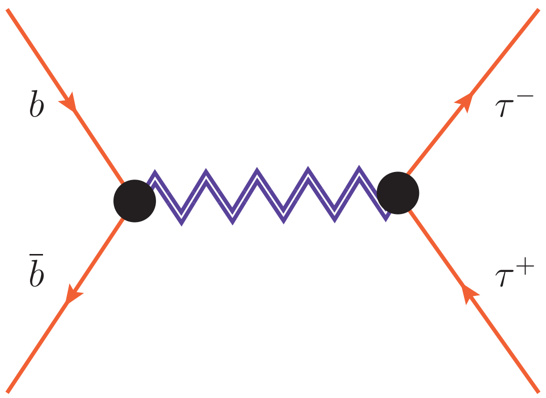
- Rec
  13 T

nd

- Need for improvements in the low mass region!

[Faroughy, AG, F. Kamenik]
1609.07138

Two Higgs doublet model (2HDM)



Two Higgs doublet model

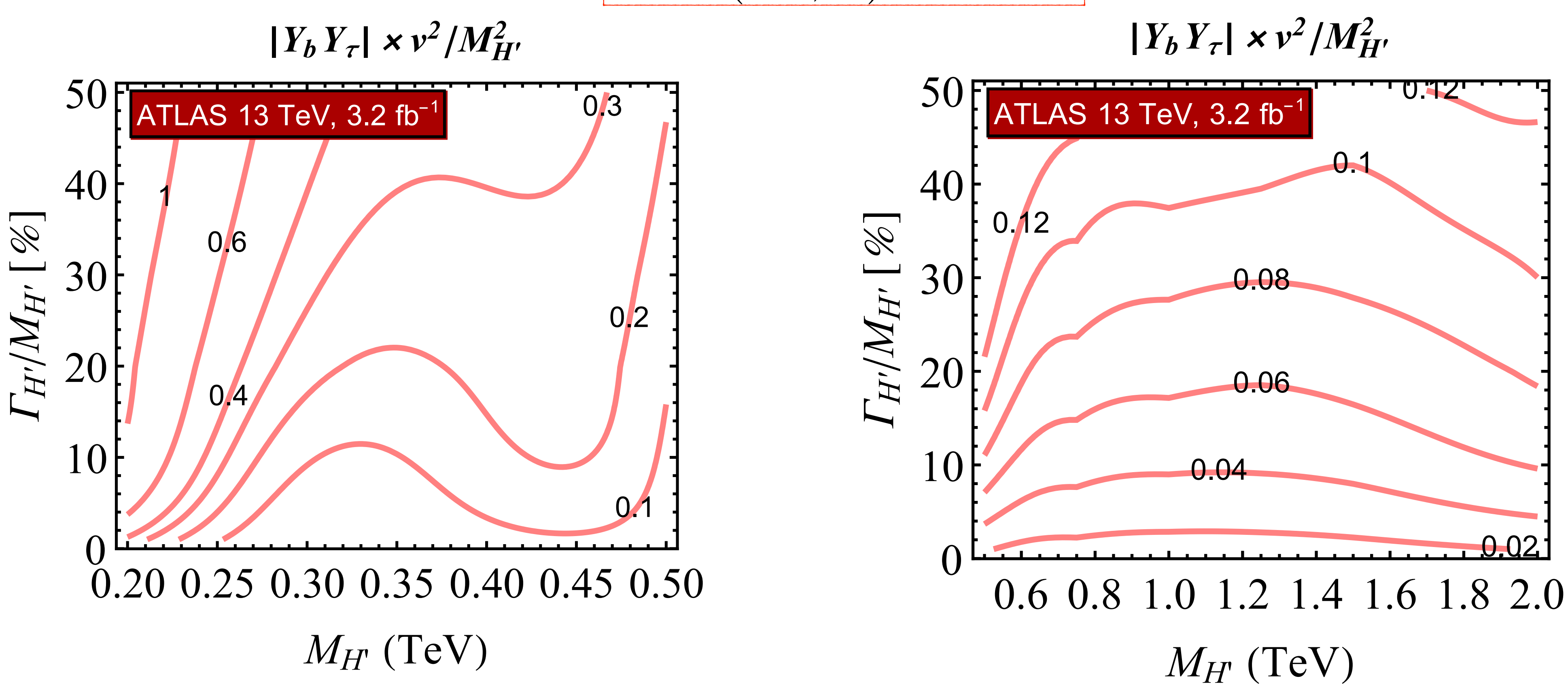
$$H' \sim (H^+, (H^0 + iA^0)/\sqrt{2})$$

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

Fit to R(D*) anomaly

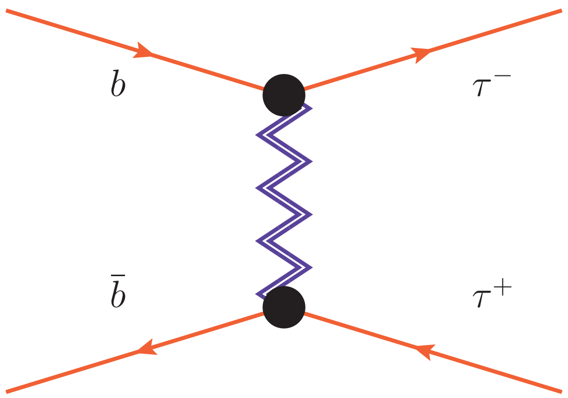
$$Y_b Y_\tau^* \times v^2 / M_{H+}^2 = (2.9 \pm 0.8)$$

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



[Faroughy, AG, F. Kamenik]
1609.07138

Leptoquark models



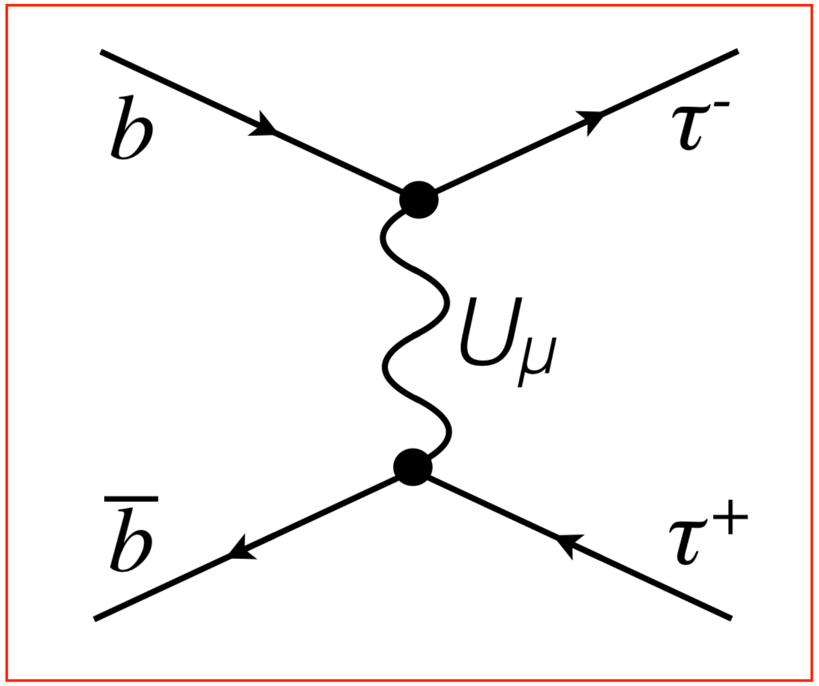
Vector Leptoquark: (**3**,**1**,2/3)

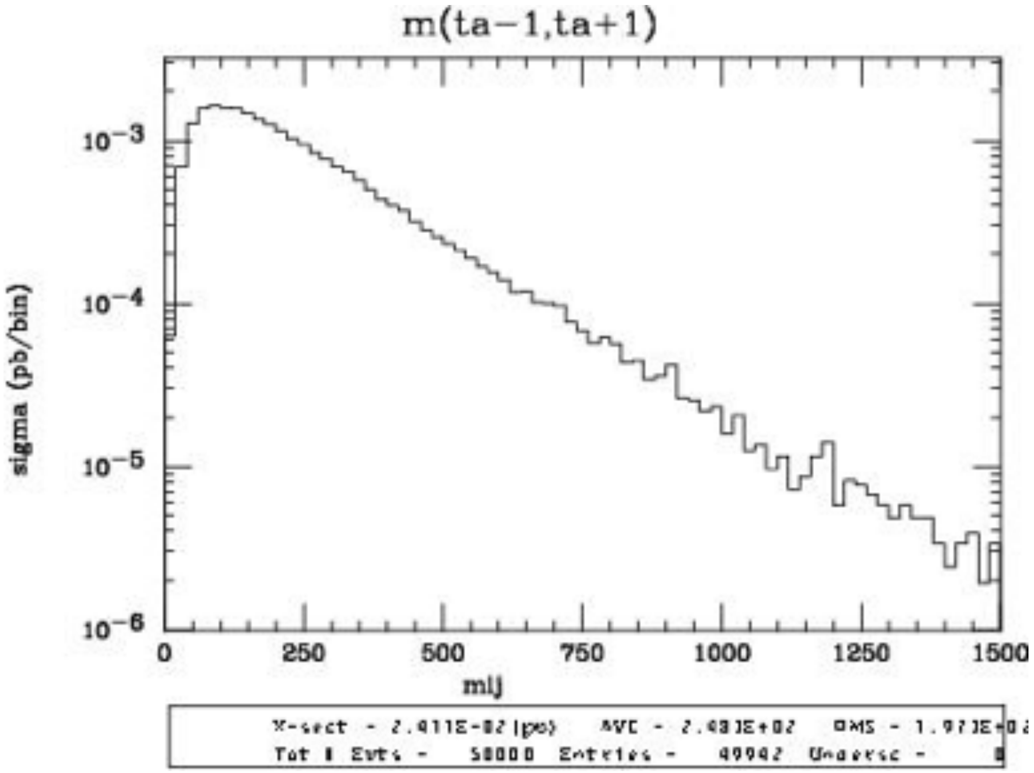
$$\mathcal{L}_U \supset -\frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + m_U^2 U^\dagger_\mu U^\mu + (J_U^\mu U_\mu + \text{h.c.}),$$

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

where $\beta_{33} = 1$. Integrating out (U_μ) at tree level,

$$\mathcal{L}_U^{\text{eff}} \supset -\frac{1}{m_U^2} J_U^{\mu\dagger} J_U^\mu + \text{h.c.} \; .$$





[Faroughy, AG, F. Kamenik]
1609.07138

Vector Leptoquark Model: ***bb* → *τ τ* recast at 8 & 13 TeV**

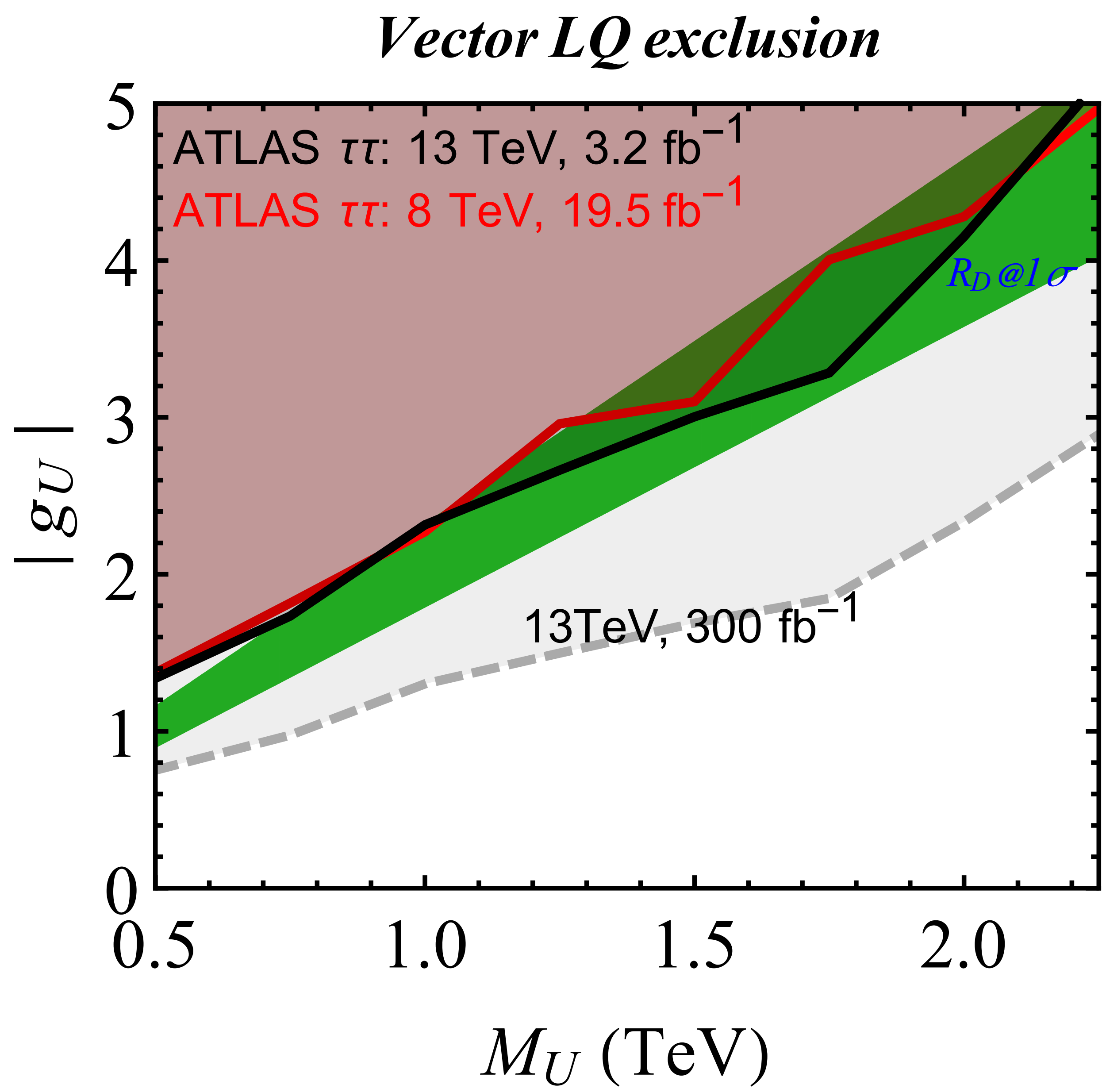
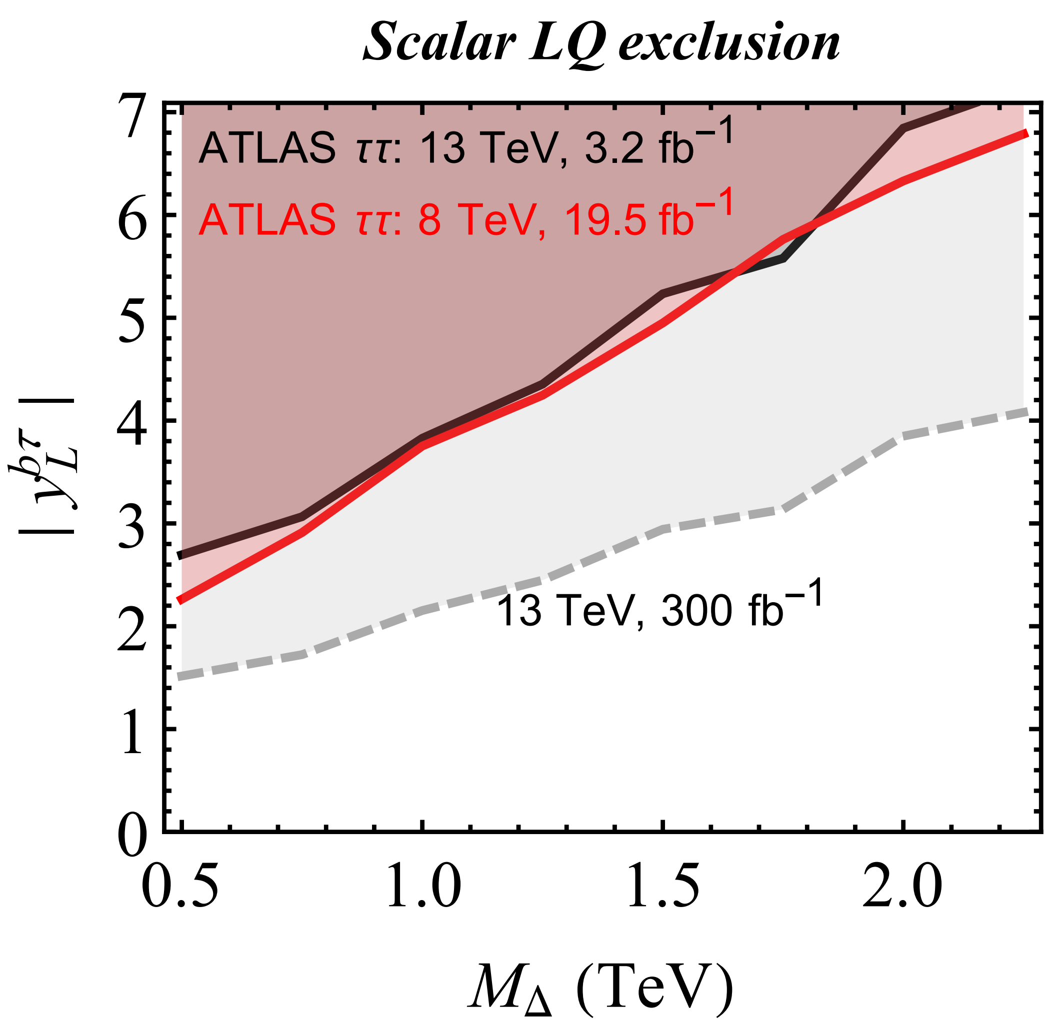


Figure 4: 8 TeV (13 TeV) ATLAS $\tau\tau$ search exclusion limits are shown in red (black) and $R(D^{(*)})$ preferred region in green for the vector LQ model. Projected 13 TeV limits for 300 fb^{-1} are shown in grey.

[Faroughy, AG, F. Kamenik]
1609.07138

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

[Faroughy, AG, F. Kamenik]
1609.07138

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*