Universität Zürich[UZH]

Hints in semi-tauonic *B* meson decays: **The physics case for high p_T LHC**

Admir Greljo

Based on:

Phys.Lett. B764 (2017) 126-134 - Darius Faroughy, AG, Jernej F. Kamenik

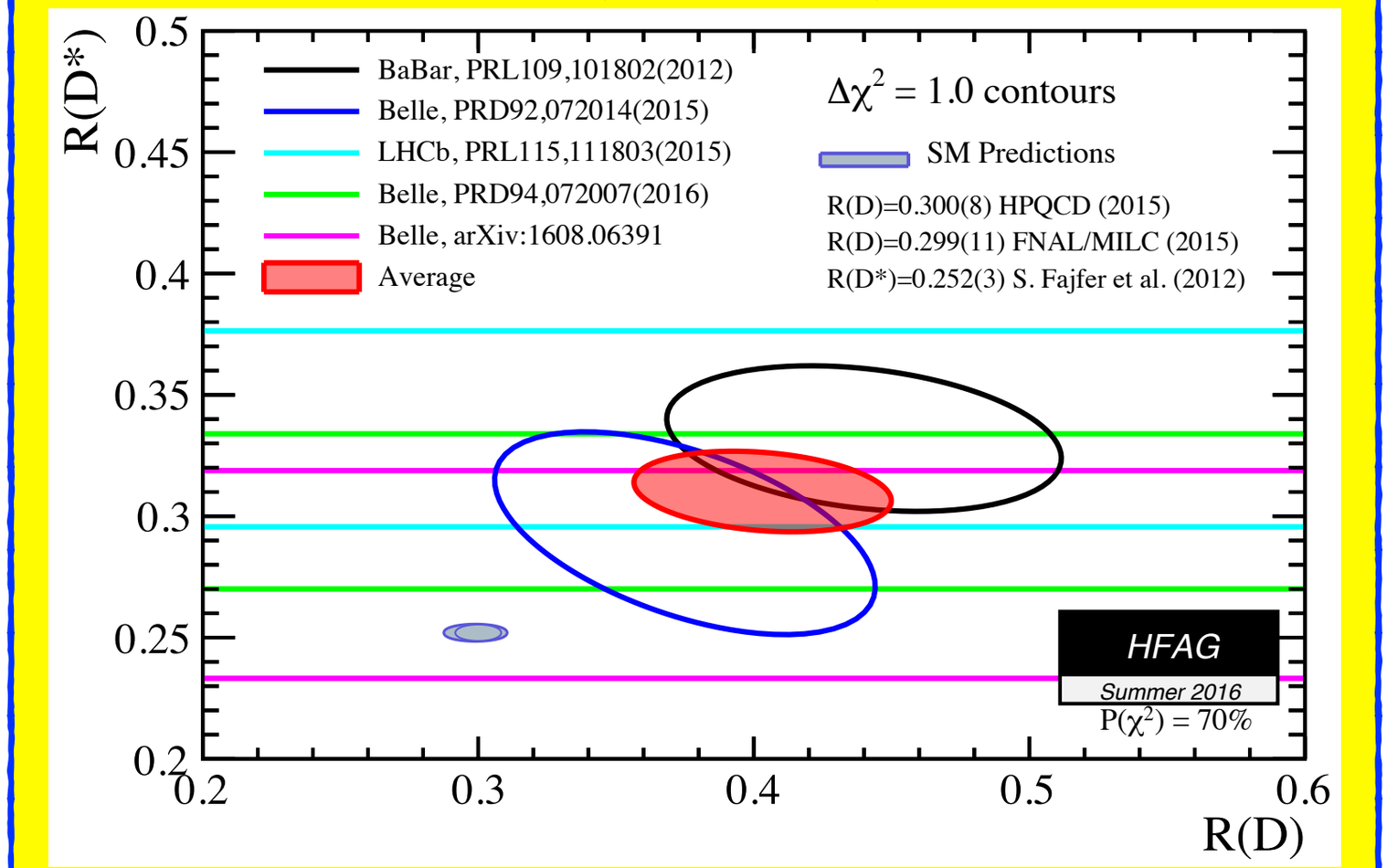
JHEP 1507 (2015) 142 - AG, Gino Isidori, David Marzocca

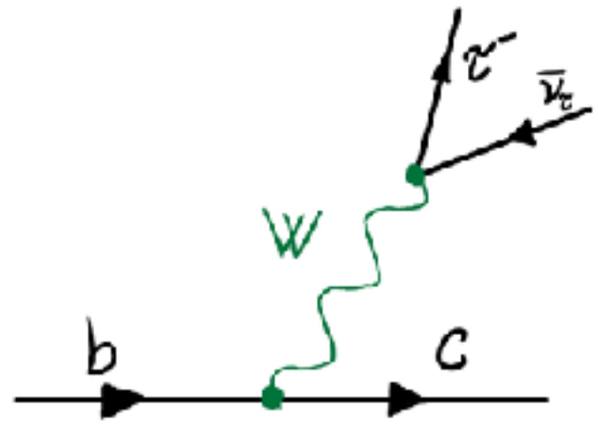
JHEP 1608 (2016) 035 - Dario Buttazzo, AG, Gino Isidori, David Marzocca

28 March 2017 - Nagoya University

Motivation: Test of LFU in charged currents

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





- **3.9σ excess** over the SM prediction
- Good agreement by <u>three (very) different</u> experiments

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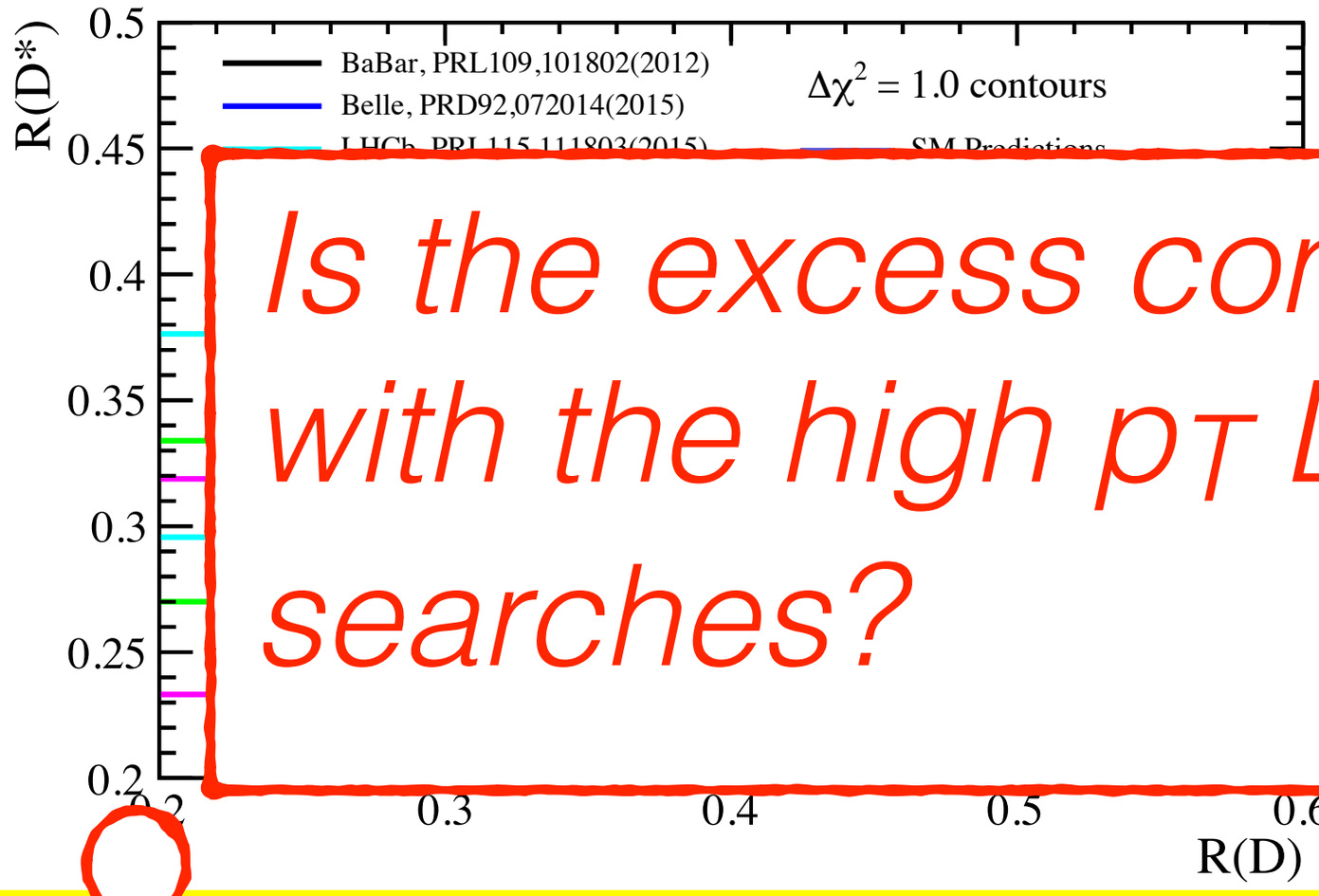
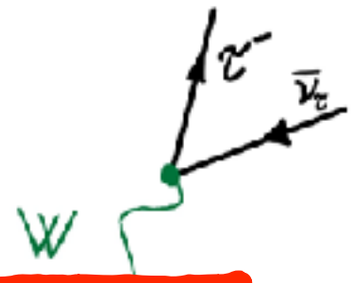




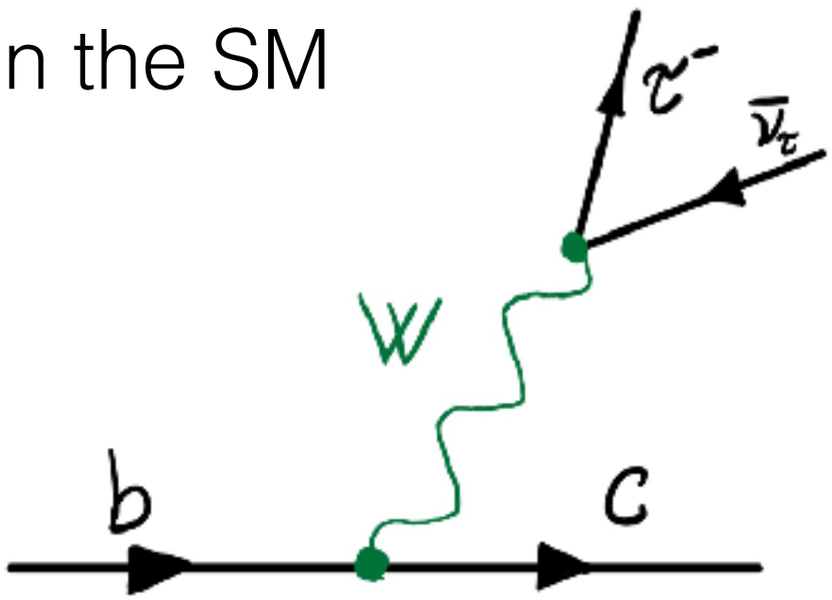
Is the excess compatible with the high p_T LHC searches?

This talk

- **3.9σ excess** over the SM prediction
- Good agreement by <u>three (very) different</u> experiments

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

In the SM



- Tree-level process
- Only mild CKM suppression

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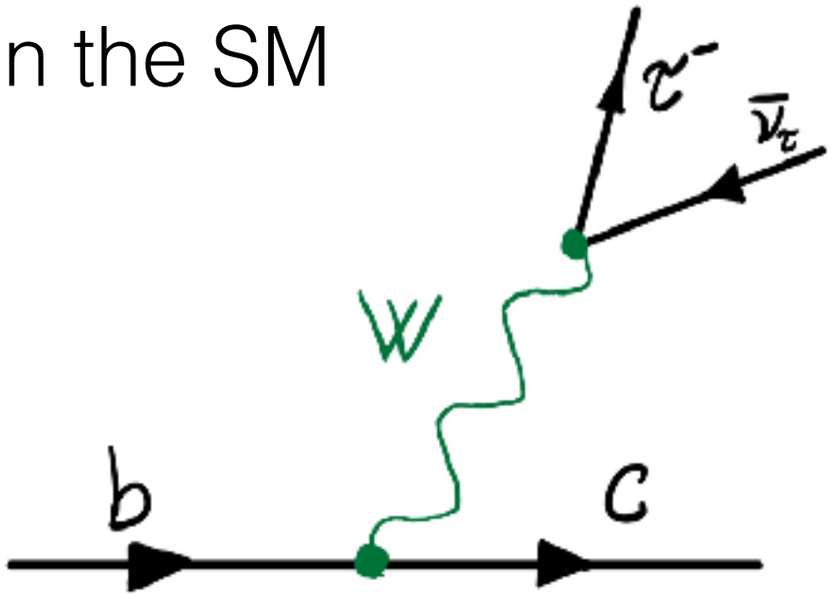

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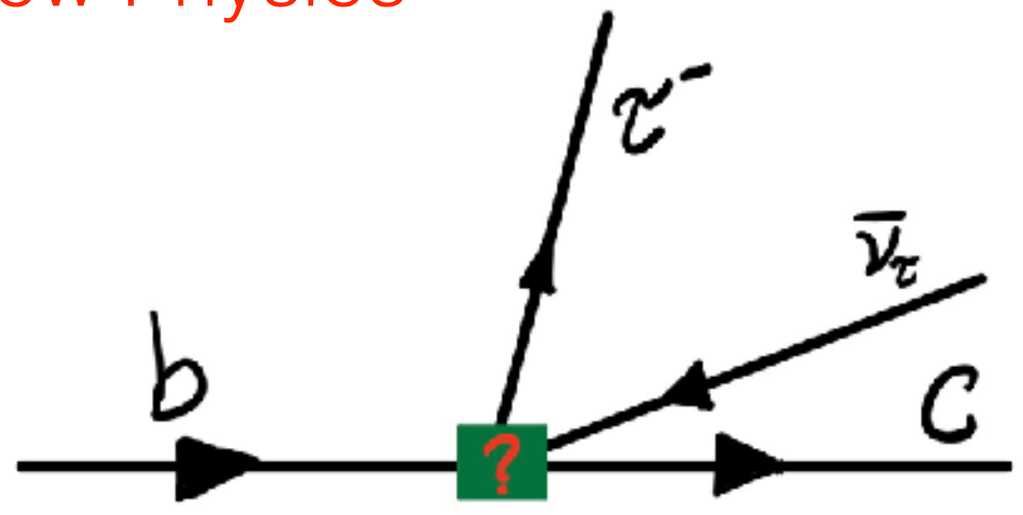
New Physics



- Large NP contribution required

Mediator mass:

$\lesssim$ several TeV (to fit the excess)

$\gtrsim$ LEP limits (charged particle in the blob)

→ ***In the ballpark of high-p_T LHC searches***

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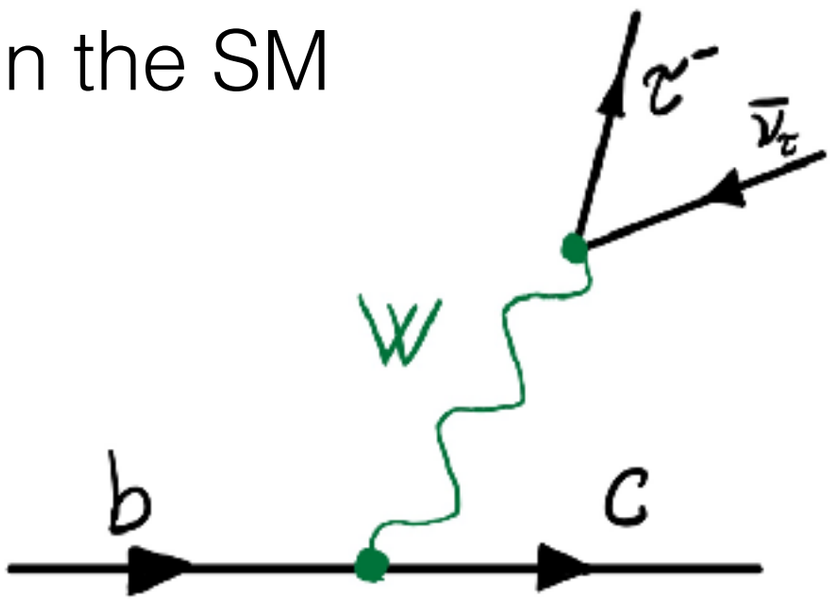

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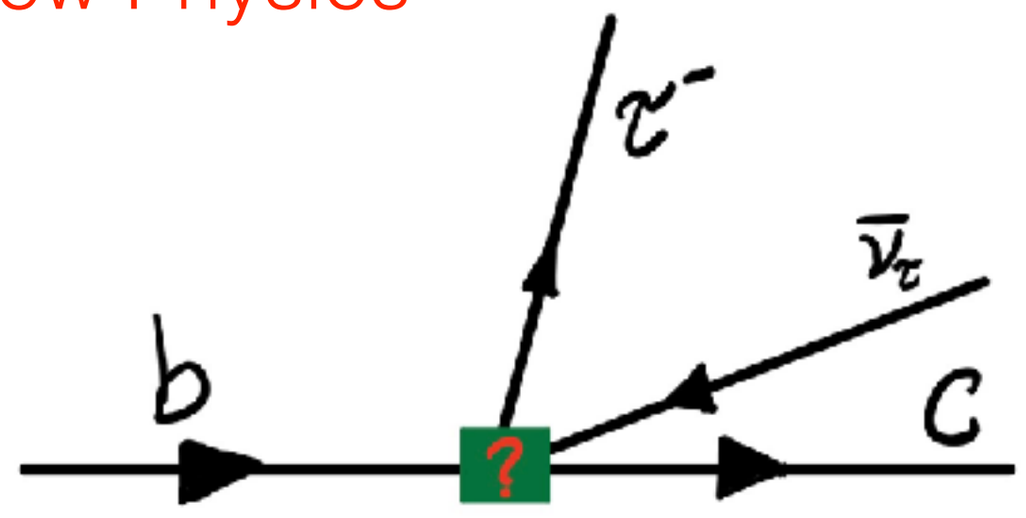

- Large NP contribution required

- Leading effects expected from dim-6 operators
  (Presumably tree-level generated):

$\mathcal{O}_{V_L}$ $(\bar{Q}_i \gamma_\mu \sigma^a Q_j)(\bar{L}_k \gamma^\mu \sigma_a L_l)$

$\mathcal{O}_{S_L}$ $(\bar{Q}_i u_R^j) i\sigma^2 (\bar{L}_k \ell_R^l)$

$\mathcal{O}_{S_R}$ $(\bar{d}_R^i Q_j)(\bar{L}_k \ell_R^l)$

$\mathcal{O}_T$ $(\bar{Q} \sigma_{\mu\nu} u_R^j) i\sigma^2 (\bar{L} \sigma^{\mu\nu} \ell_R^l)$

SM EFT consideration & Implications for high-p_T LHC

Complete dim-6 operator basis: $\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \dots$

[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}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{V_L}$ $Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
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$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{S_R}$ 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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{S_L}$ $Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_T$ $Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

SM EFT consideration & Implications for high-p_T LHC

Complete dim-6 operator basis: $\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \dots$

[Warsaw basis, 1008.4884]

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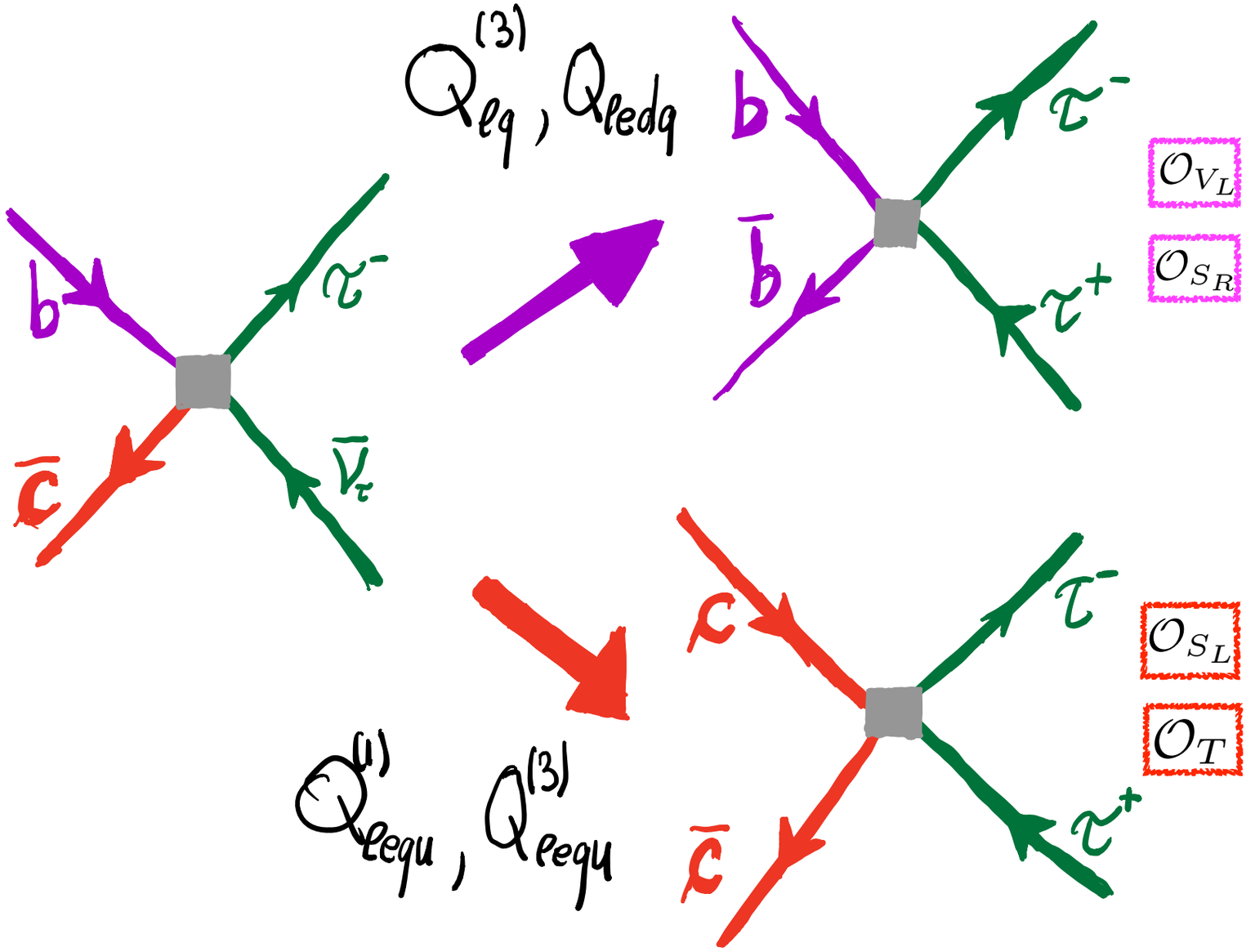
Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

$SU(2)_L$ prediction: **Neutral currents**



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$(B)(B)$	
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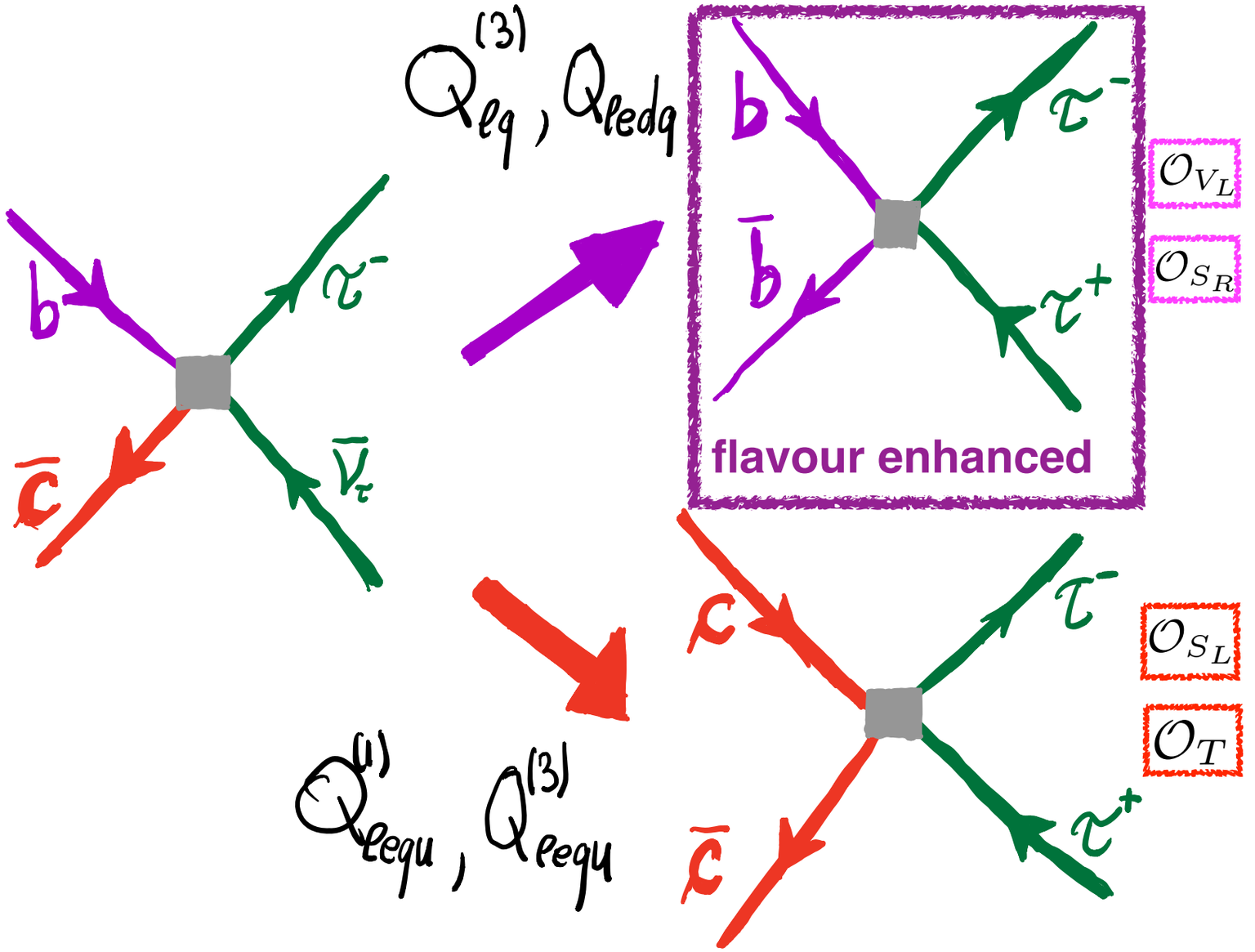
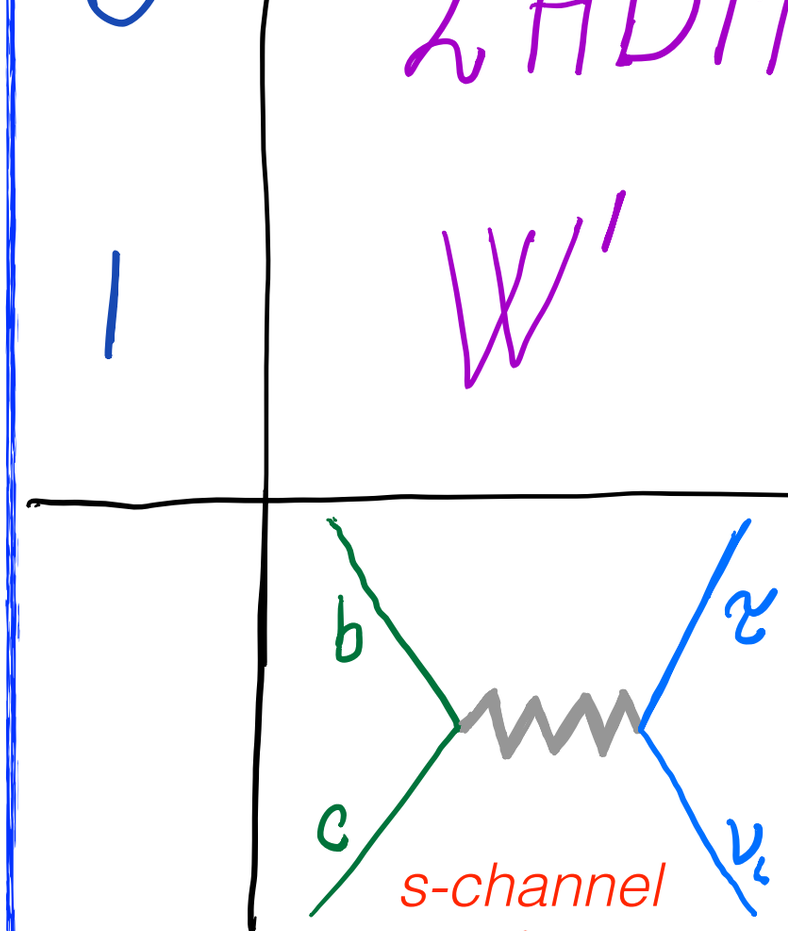


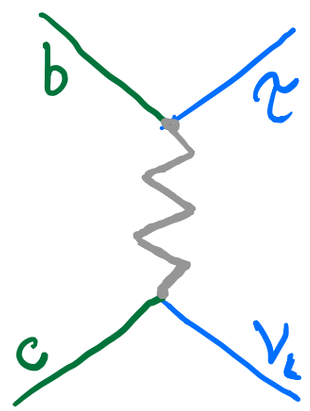
Single mediator models (8 options)

- Color: **0** or **3**
- Spin: **0**, **1**, ...

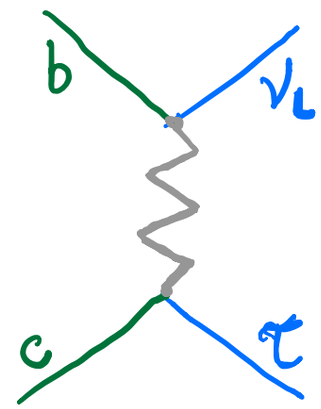
Spin \ Color	0	3
0	2 HDM	Scalar LQ
1	W'	Vector LQ



s-channel



t-channel



u-channel

Weak doublet scalar or triplet vector

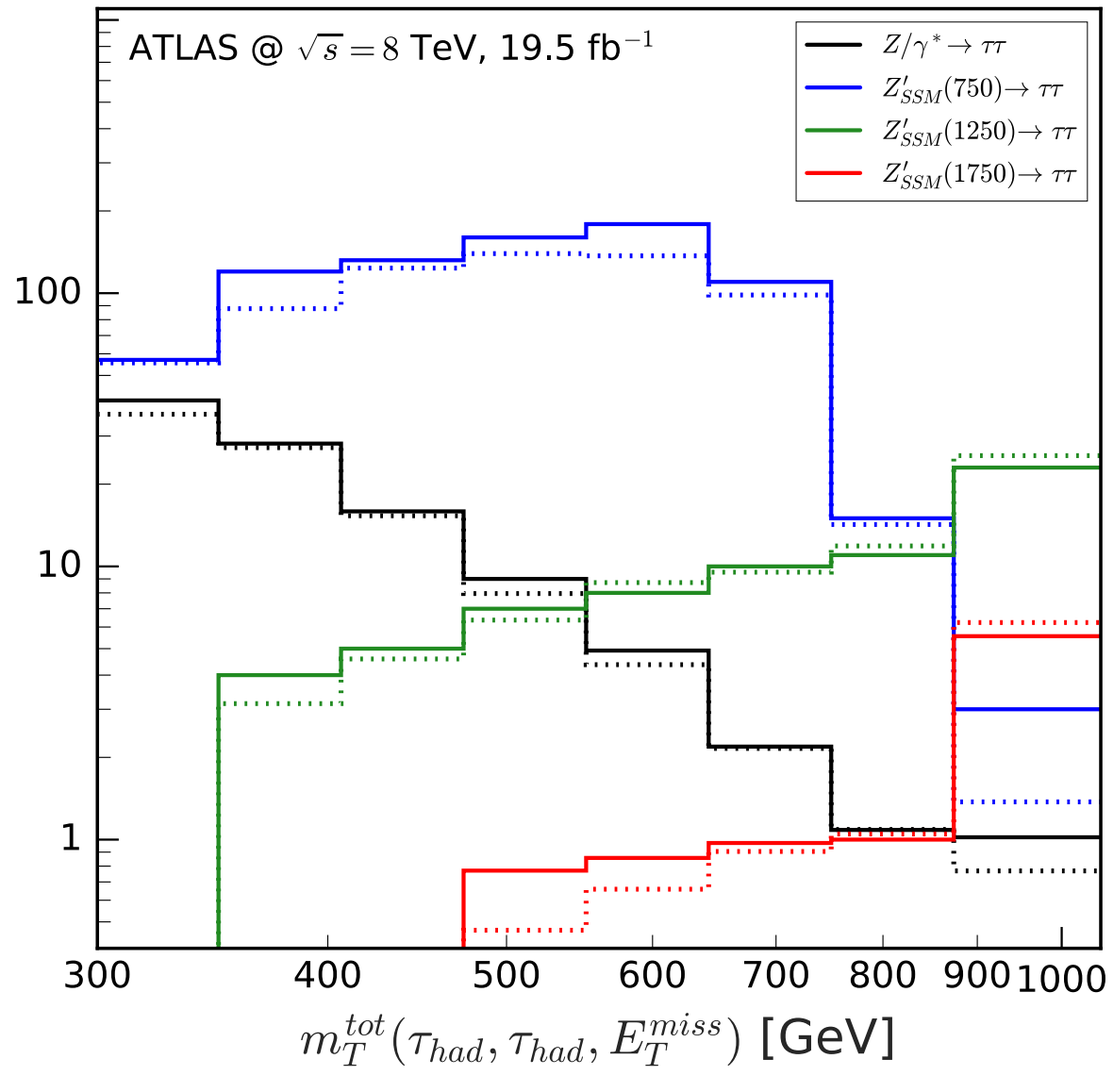
Weak singlet, doublet or triplet

[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

Recast of $\tau^+\tau^-$ resonance searches at the LHC

- Correlated high-p_T events have peculiar kinematics
- Full simulation pipeline:
  FeynRules>MadGraph>Pythia>Delphes
- Validated against the SM bkg, and the Sequential SM Z'
- Set limits on a model's parameter space by fitting the total transverse mass variable:

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



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

Warm-up exercise: **EFT**

[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

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

(1) ***Dominant couplings with the third generation***

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

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

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

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

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$$\left(2V_{cb}\bar{c}_L\gamma^\mu b_L\bar{\tau}_L\gamma_\mu\nu_L + \bar{b}_L\gamma^\mu b_L\bar{\tau}_L\gamma_\mu\tau_L\right)$$

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

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$$\to \left(2V_{cb}\bar{c}_L\gamma^\mu b_L\bar{\tau}_L\gamma_\mu\nu_L + \bar{b}_L\gamma^\mu b_L\bar{\tau}_L\gamma_\mu\tau_L\right)$$

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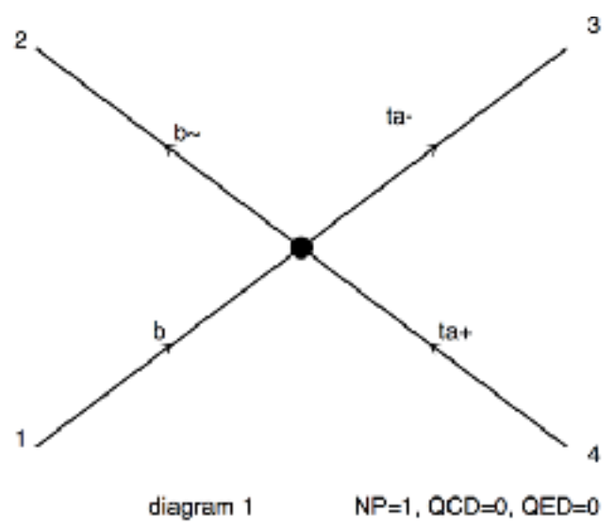
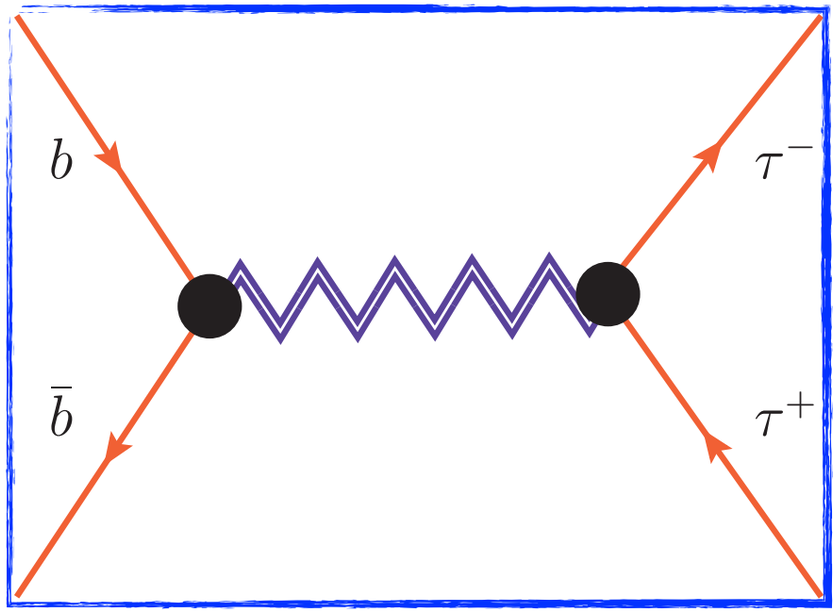


Recast of $\tau^+\tau^-$ ATLAS search:
$|c_{QQLL}| < 2.8\ \text{TeV}^{-2}$ at 95% CL

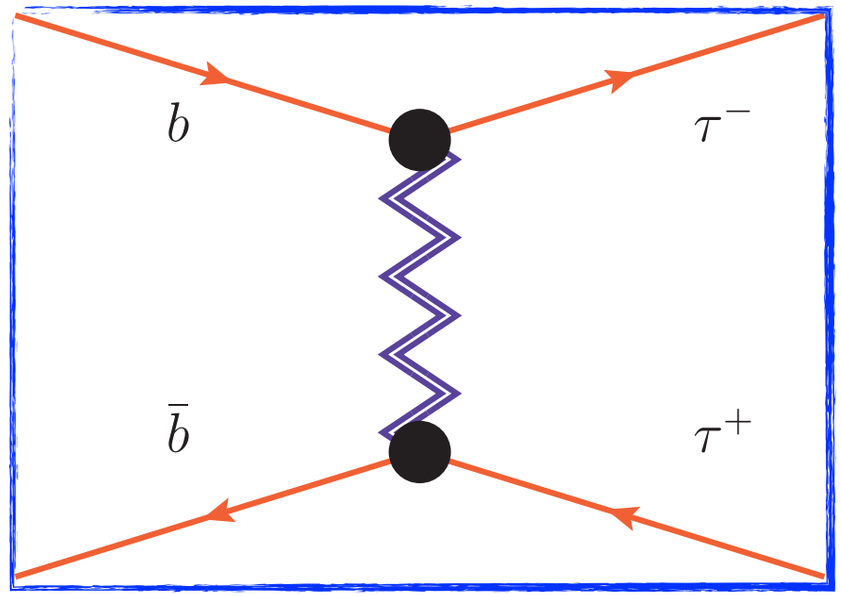
Fit to R(D*) anomaly:
$c_{QQLL} \simeq -(2.1 \pm 0.5)\ \text{TeV}^{-2}$

*Similar conclusions for $c^{ijkl}_{dQLe}(\bar{d}^i_R Q_j)(\bar{L}_k\ell^l_R)$

Single mediator models - LHC limits



- *W'*
- *2HDM*



- *Vector LQ*
- *Scalar LQ*

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

Vector Triplet Model - *W'*

- *Introduce a heavy spin-1 weak triplet*

$$\mathcal{L}_{W'} = -\frac{1}{4} W'^{a\mu\nu} W'^{a}_{\mu\nu} + \frac{M^2_{W'}}{2} W'^{a\mu} W'^{a}_{\mu} + W'^{a}_{\mu} J^{a\mu}_{W'}$$

$$J^{a\mu}_{W'} \equiv \lambda^{q}_{ij} \bar{Q}_i \gamma^\mu \sigma^a Q_j + \lambda^{\ell}_{ij} \bar{L}_i \gamma^\mu \sigma^a L_j \ .$$

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	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*μ(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	$\epsilon_q^2 \lvert\lambda^q_{bs}\rvert^2 (\lvert V^*_{tb} V_{ts}\rvert^2 R^{\rm loop}_{\rm SM})^{-1}$
4) b→s μ μ	ΔC^{μ}_9	-0.53 ± 0.18	$-(\pi/\alpha_{\rm em}) \lambda^{\ell}_{\mu\mu} \epsilon_\ell \epsilon_q \lambda^q_{bs} / \lvert V^*_{tb} V_{ts}\rvert$
5) τ → νν*μ(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 → 3*μ*	$\Lambda^{-2}_{\tau\mu}$	$(0.0 \pm 4.1) \times 10^{-9}$ [GeV^{-2}]	$(G_F/\sqrt{2}) \epsilon^2_\ell \lambda^{\ell}_{\mu\mu} \lambda^{\ell}_{\tau\mu}$
7) *D* mix	Λ^{-2}_{uc}	$(0.0 \pm 5.6) \times 10^{-14}$ [GeV^{-2}]	$(G_F/\sqrt{2}) \epsilon^2_q \lvert V_{ub} V^*_{cb}\rvert^2$

Flavour fit

Vector Triplet Model - *W'*

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

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

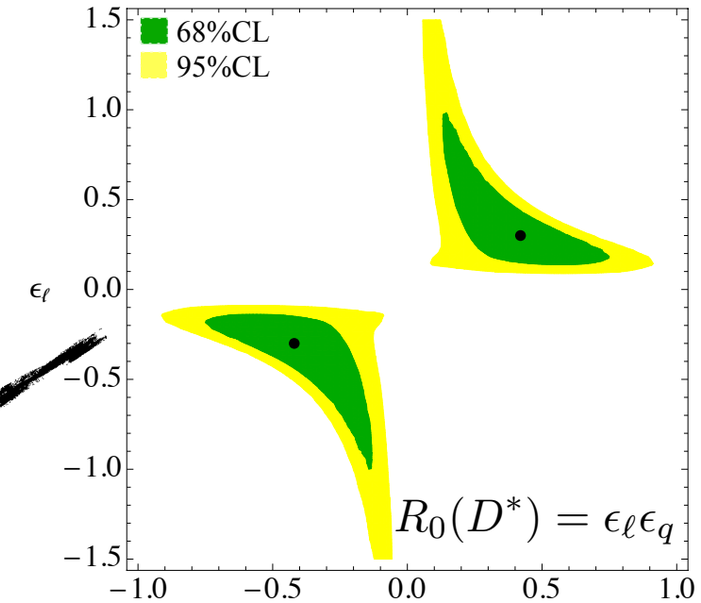
(1) *Dominant couplings with the third generation*

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

(2) Flavour alignment with down quarks and charged leptons (to avoid FCNC in the down sector)

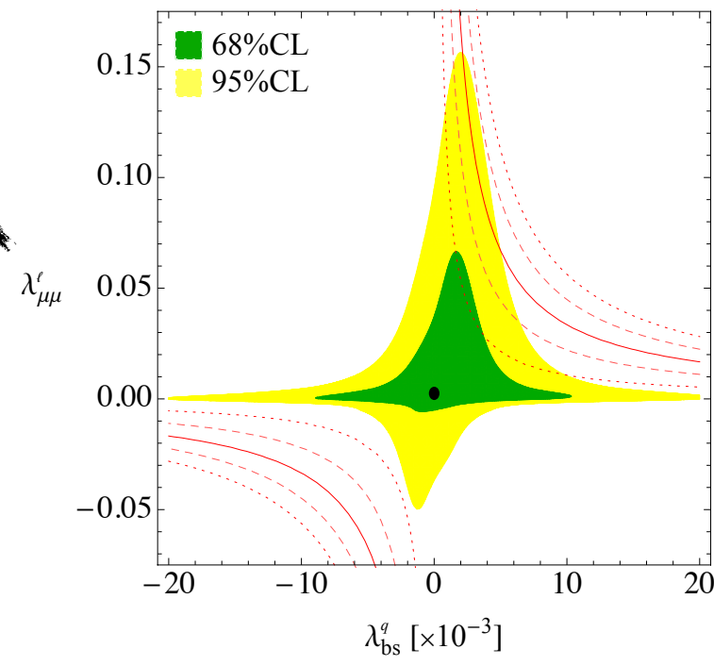
$$Q_i = (V^*_{ji}u^j_L, d^i_L)^T \text{ and } L_i = (U^*_{ji}\nu^j, \ell^i_L)^T$$

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



$$\epsilon_{q,\ell} \approx \lambda^{q,\ell}_{33} v/m_{Z'}$$

Flavour fit:
Conclusions



$$\lambda^q_{bs} \sim \epsilon_1 V_{ts}$$

Vector Triplet Model: **LHC phenomenology**

Low-energy flavour physics

$$-g_b g_\tau / M_{W'}^2 \simeq -(2.1 \pm 0.5) \, \mathrm{TeV}^{-2}$$

(1) Dominant decays to third generation SM fermions
(2) Production from the heavy quark flavour

Electroweak precision:

Small mass splitting in the multiplet

$M_{W'} \sim M_{Z'}$

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

Vector Triplet Model: **LHC phenomenology**

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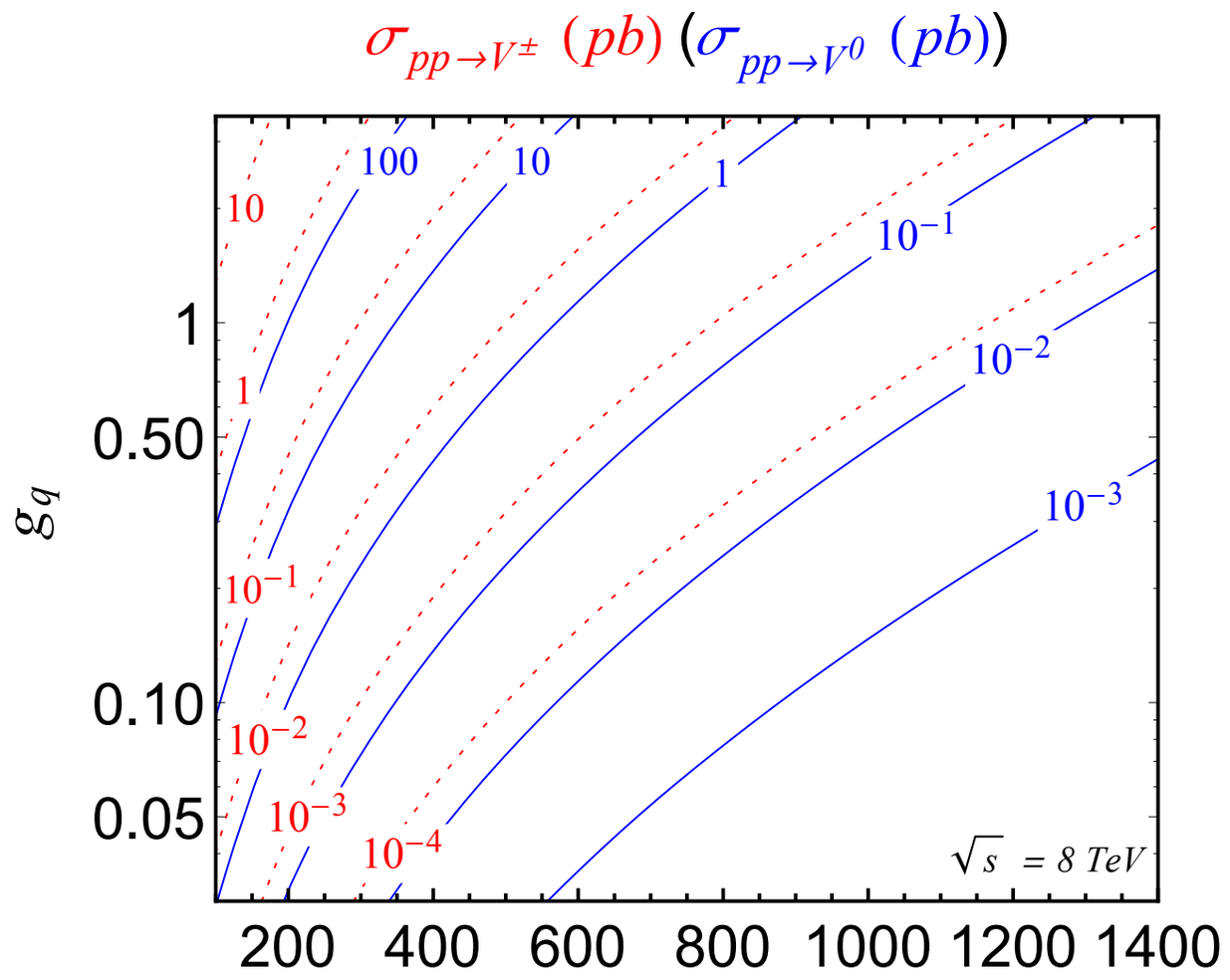
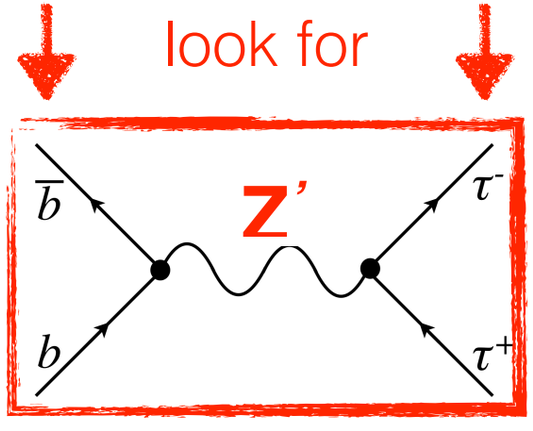




[AG, Isidori, Marzocca]
JHEP 1507 (2015) 142

Vector Triplet Model - *W'*

Z' production at NLO QCD

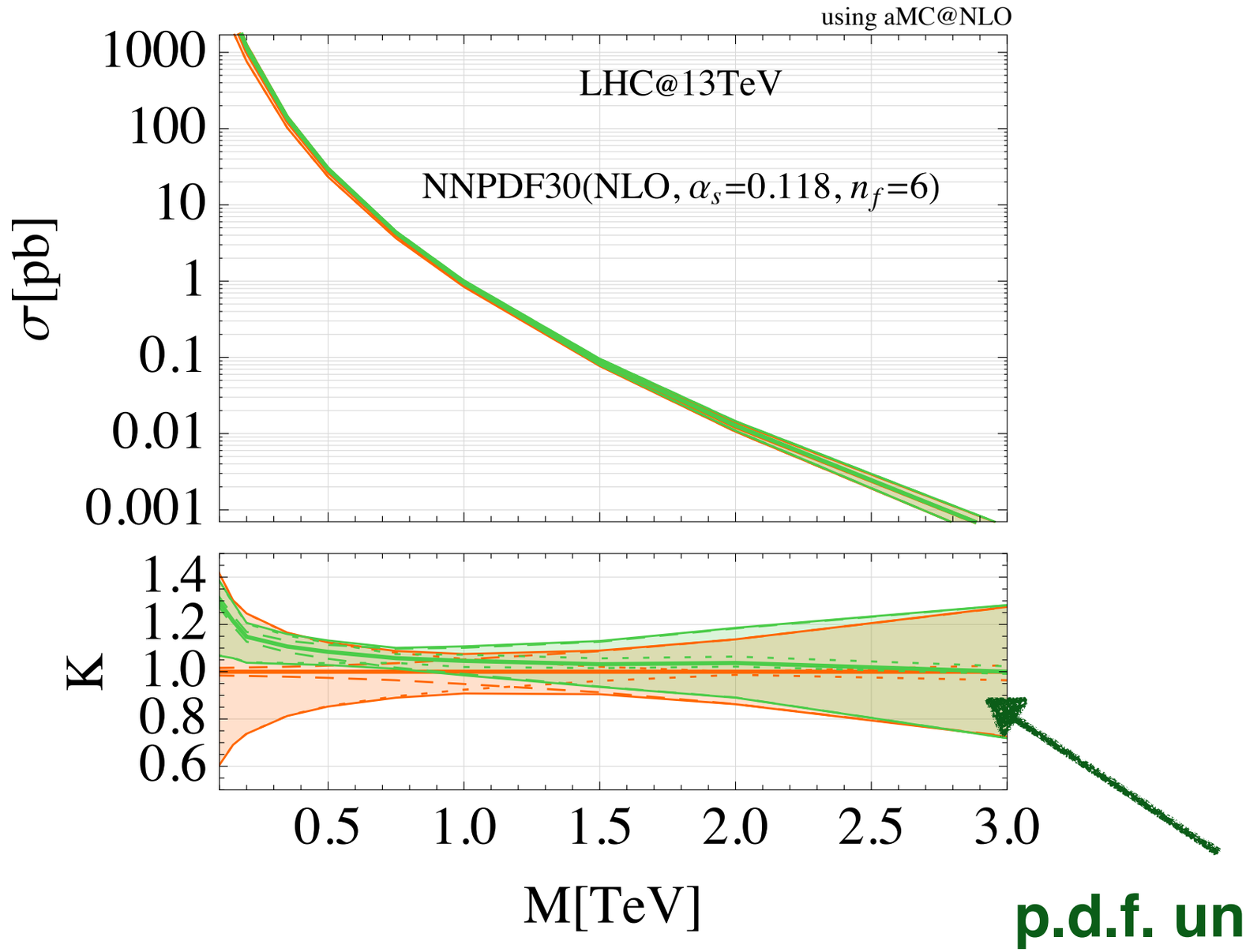
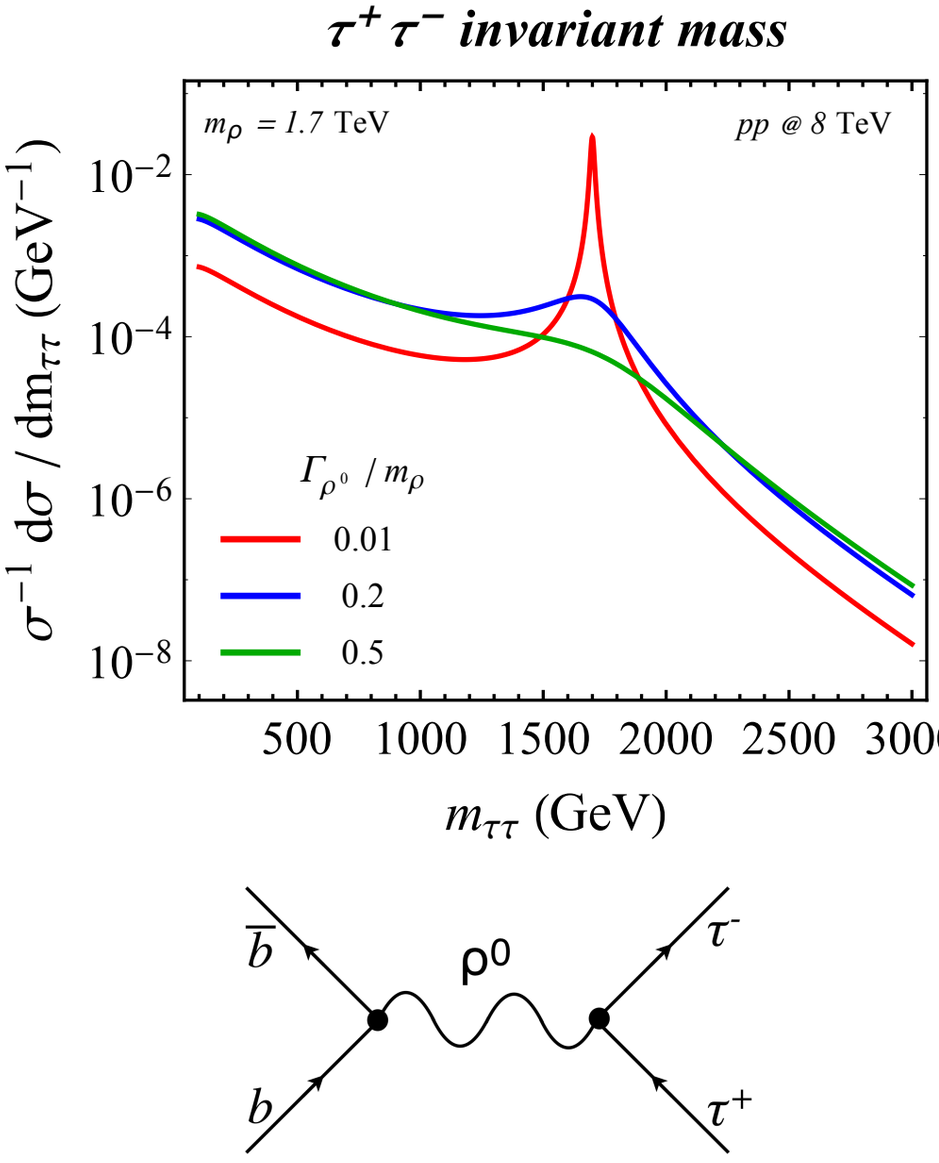


Figure 3: Next-to-leading order QCD corrections for a narrow Z' production via bottom-bottom fusion.

[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

LHC phenomenology: Vector Triplet Model



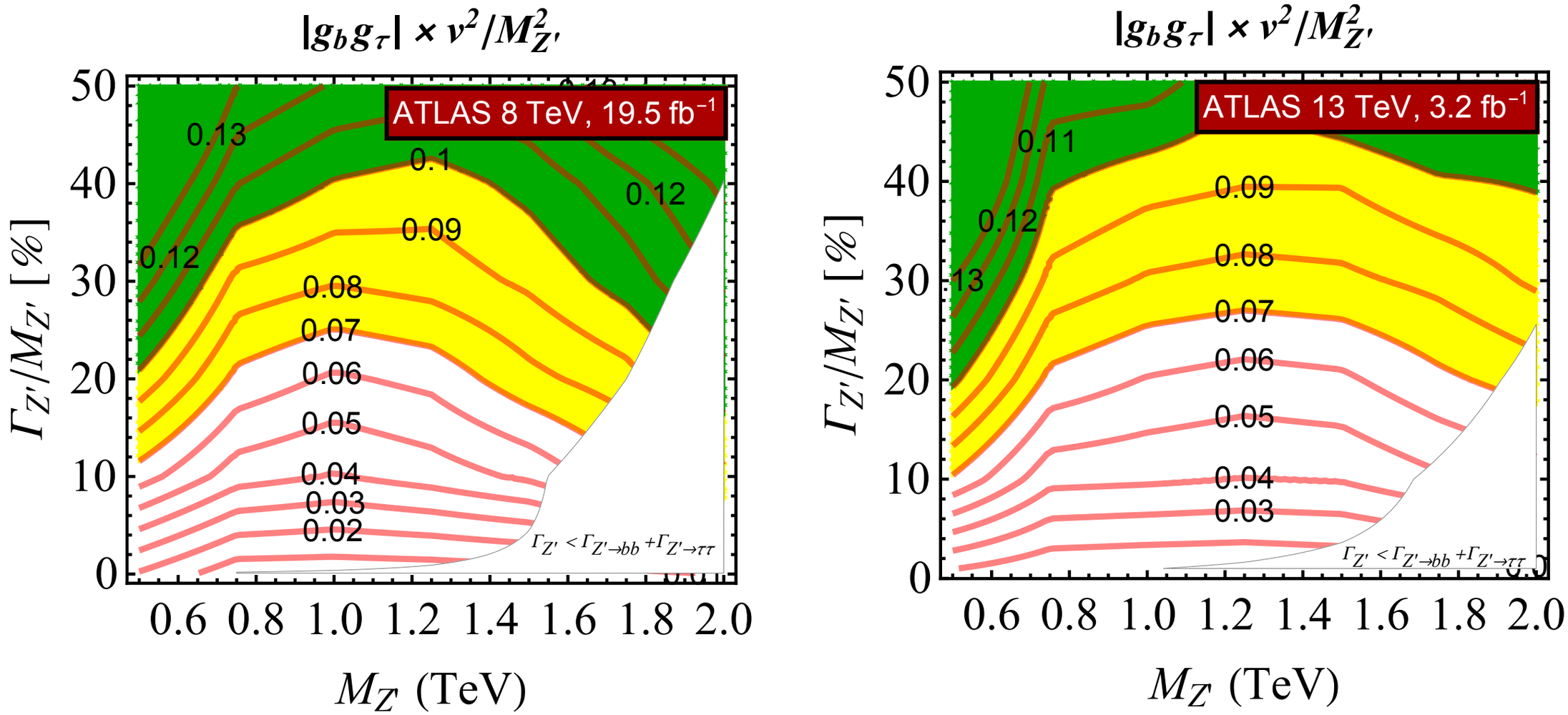
[Buttazzo, AG, Isidori, Marzocca]
JHEP 1608 (2016) 035

- Important to optimise searches for the broad resonances
- Careful extraction of the bounds is in order (recast)

[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

Set a limit on $|g_b g_\tau|$ as a function of the Z' mass and the total width

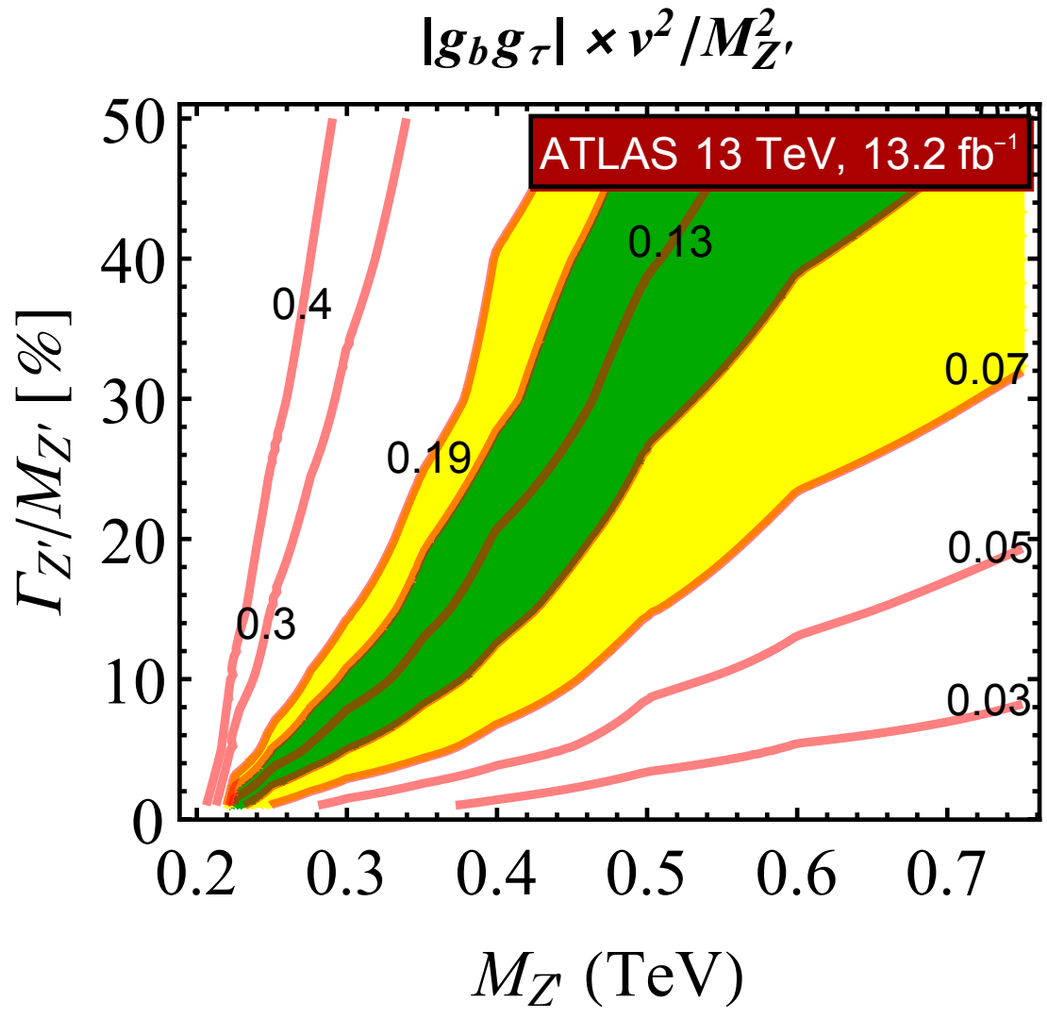
Vector triplet model: ***8 & 13 TeV recast bounds***



- 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]
Phys.Lett. B764 (2017) 126-134

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



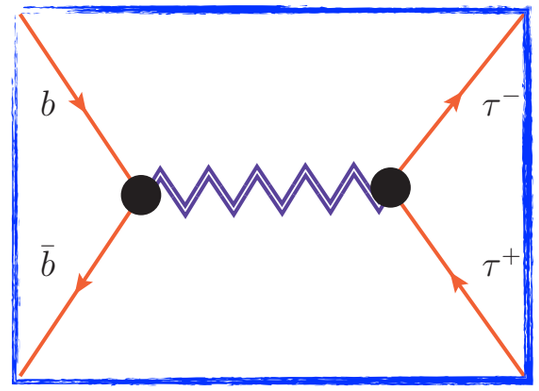
- Need for improvements in the low mass region!

[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

Two Higgs doublet model

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

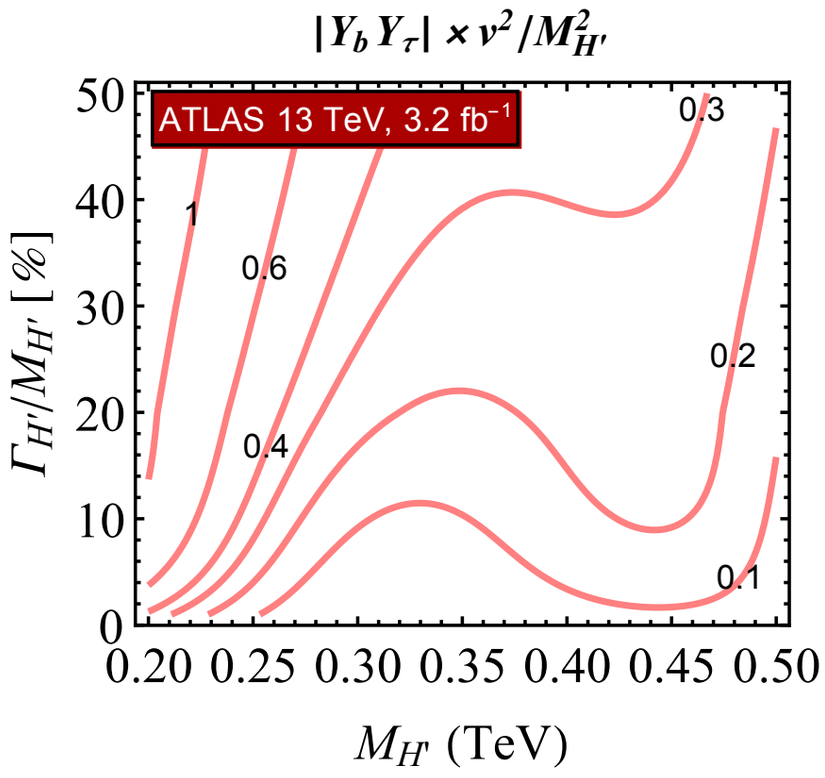
$$\mathcal{L}_{H'} = |D^\mu H'|^2 - M^2_{H'}|H'|^2 - \lambda_{H'}|H'|^4 - \delta V(H', H)$$
$$- Y_b \bar{Q}_3 H' b_R - Y_c \bar{Q}_3 \tilde{H}' c_R - Y_\tau \bar{L}_3 H' \tau_R + \text{h.c.},$$

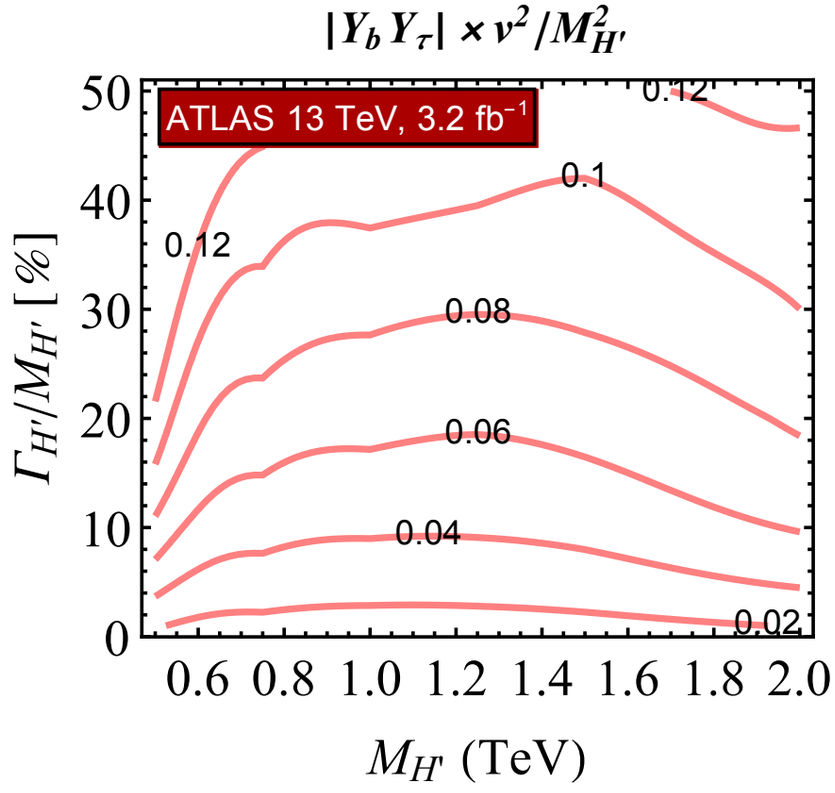


Fit to R(D*) anomaly

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

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





[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

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

[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

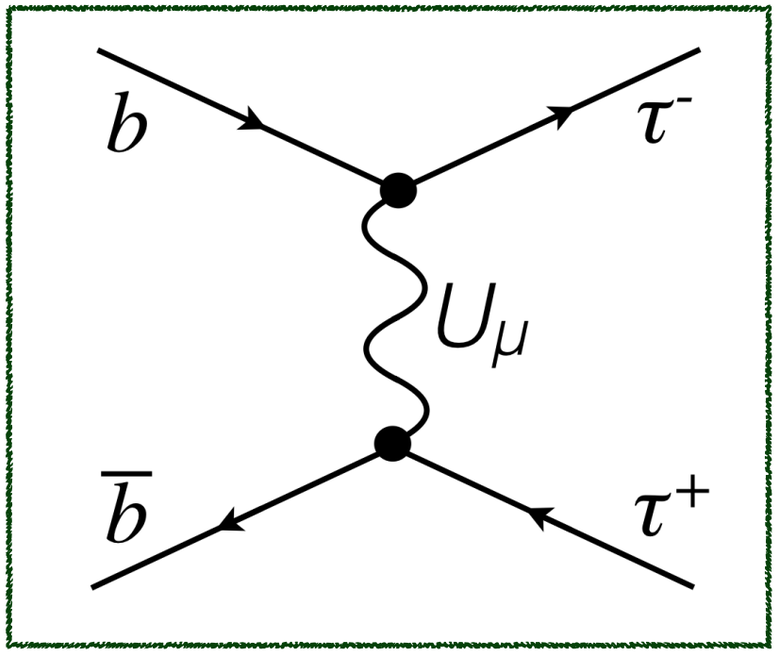
$$\mathcal{L}_U \supset -\frac{1}{2} U^\dagger_{\mu\nu} U^{\mu\nu} + m_U^2 U^\dagger_\mu U^\mu + (J^\mu_U U_\mu + \text{h.c.}),$$

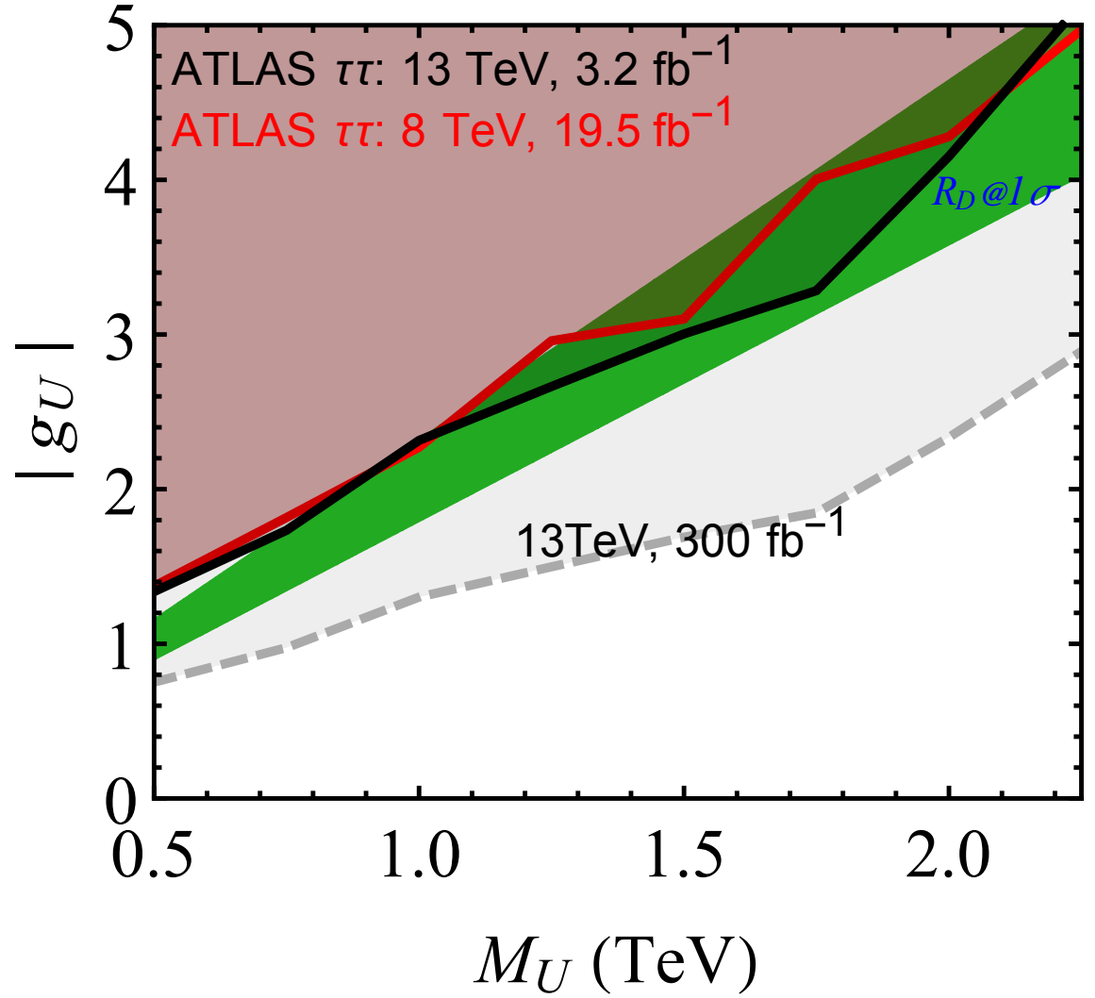
$$J^\mu_U \equiv g_U \; \beta_{ij} \; \bar{Q}_i \gamma^\mu L_j \; .$$

[Barbieri, Isidori, Pattori, Senia]
Eur.Phys.J. C76 (2016) no.2, 67

Integrating out the LQ

$$\mathcal{L}_U^{\text{eff}} \supset -\frac{|g_U|^2}{M_U^2} \left[V_{cb} (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) + (\bar{b}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \tau_L) \right]$$





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

*with the right-handed neutrino

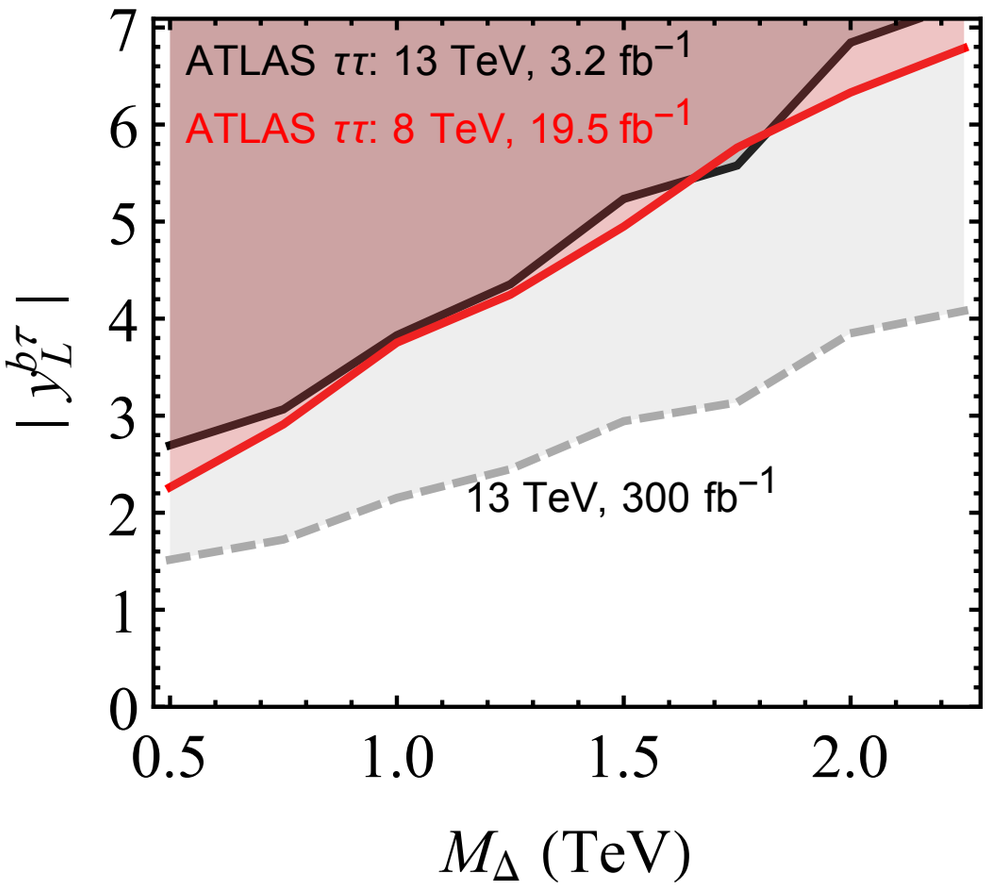
[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

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

[Becirevic, Fajfer, Sumensari, Kosnik]
Phys.Rev. D94 (2016) no.11, 115021

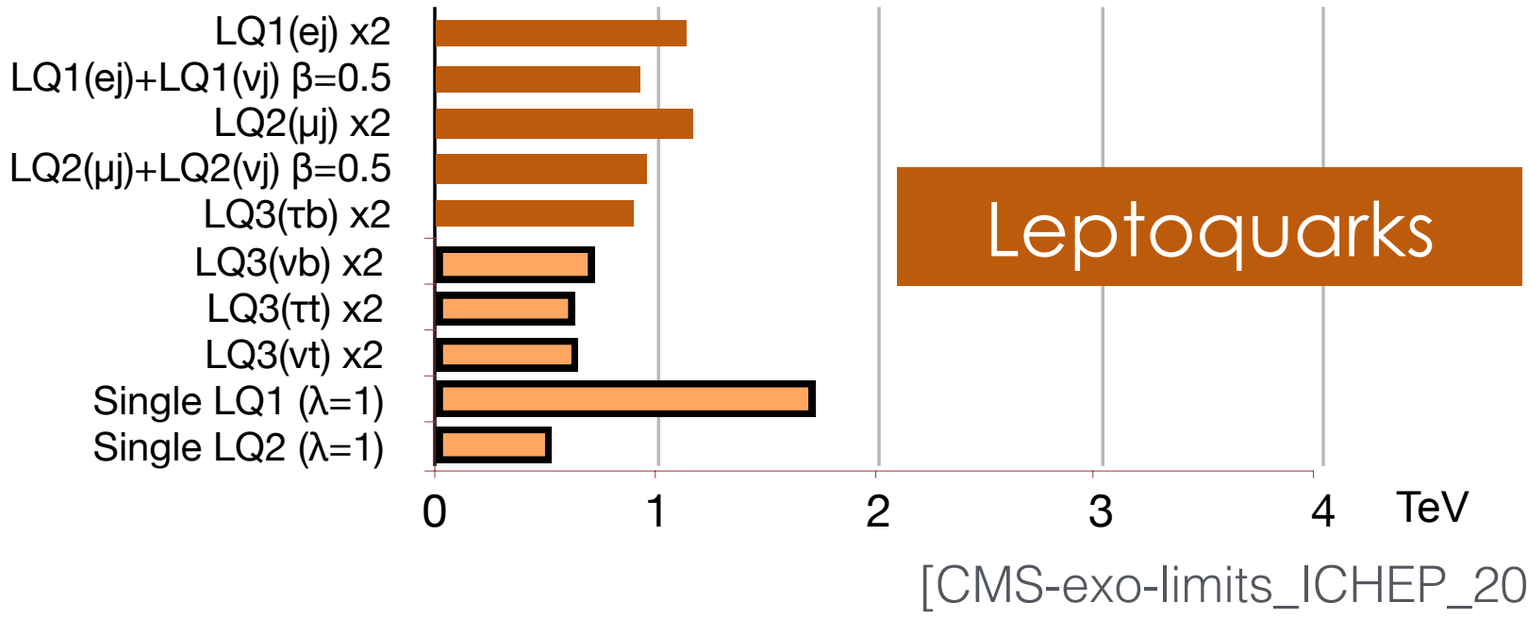
Fit to R(D*) anomaly

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



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

Other signatures at the LHC



[CMS-exo-limits_ICHEP_2016]

- *QCD induced LQ pair production is large*
- Limits are getting stronger (≳1 TeV)
- Focus is on the **third generation LQ searches**

Summary: *Models subject to $\tau^+\tau^-$ search limits*

	Operator		Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$	
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \tau \gamma^\mu q_L + g_\ell \bar{\ell}_L \tau \gamma^\mu \ell_L) W'_\mu$	YES
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$					
$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)\,(\bar{\tau}P_L \nu)$			$(\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$	YES
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)\,(\bar{\tau}P_L \nu)$					
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$					
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow$	$\mathcal{O}_{V_L}$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda\, \bar{q}_L \tau \gamma_\mu \ell_L U^\mu$	YES
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow$	$-2\mathcal{O}_{S_R}$	$(\mathbf{3},\mathbf{1})_{2/3}$	$(\lambda\, \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{d}_R \gamma_\mu e_R) U^\mu$	YES
$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)\,(\bar{c}P_L \nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{V_R}$			
$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)\,(\bar{c}P_L \nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(\mathbf{3},\mathbf{2})_{7/6}$	$(\lambda\, \bar{u}_R \ell_L + \tilde{\lambda}\, \bar{q}_L i\tau_2 e_R) R$	not a good fit
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow$	$-6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$			
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow$	$-\mathcal{O}_{V_R}$			
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow$	$-2\mathcal{O}_{S_R}$	$(\bar{\mathbf{3}},\mathbf{2})_{5/6}$	$(\lambda\, \bar{d}^c_R \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{q}^c_L \gamma_\mu e_R) V^\mu$	YES
$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow$	$\frac{1}{2}\mathcal{O}_{V_L}$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$	$\lambda\, \bar{q}^c_L i\tau_2 \boldsymbol{\tau} \ell_L \boldsymbol{S}$	YES
$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$	$(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$(\lambda\, \bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda}\, \bar{u}^c_R e_R) S$	No
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c \sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow$	$-6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$			

Table taken from [Freytsis, Ligeti, Ruderman]
Phys.Rev. D92 (2015) no.5, 054018

For the last model, see [Bauer, Neubert]
Phys.Rev.Lett. 116 (2016) no.14, 141802

Conclusions

- *R(D$^{(*)}$) excess implies signal in the Tau-Tau searches at high p_T*
- *Do not miss wide (or light) resonances, nor tails*

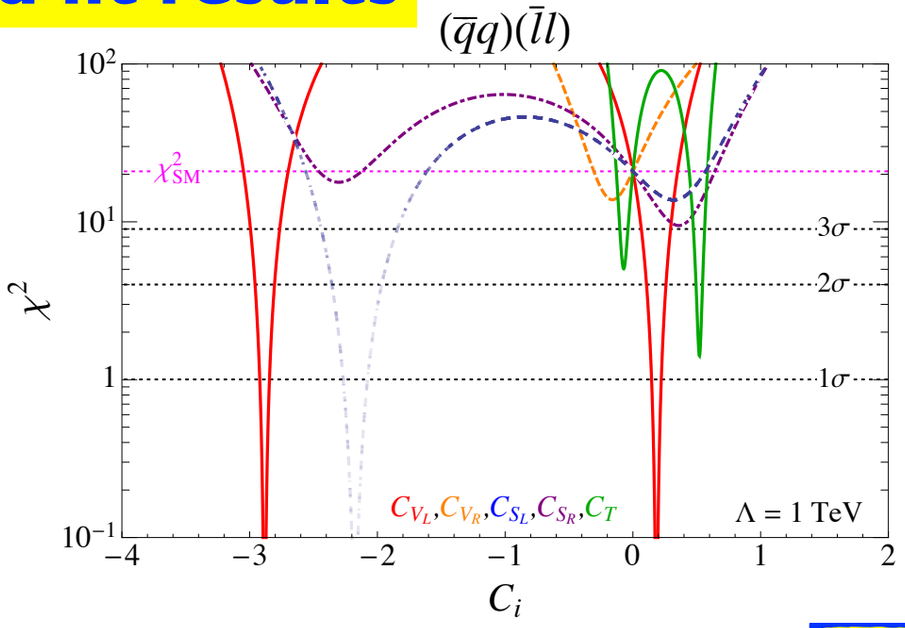
Final talk's optimism

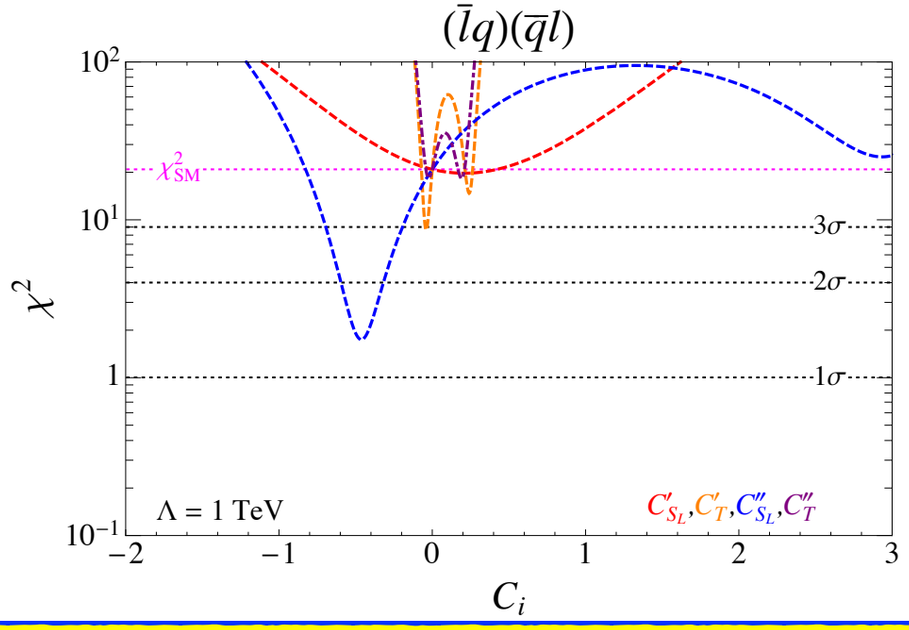
- *Maybe BSM in the interplay of flavour and collider physics in years to come…*

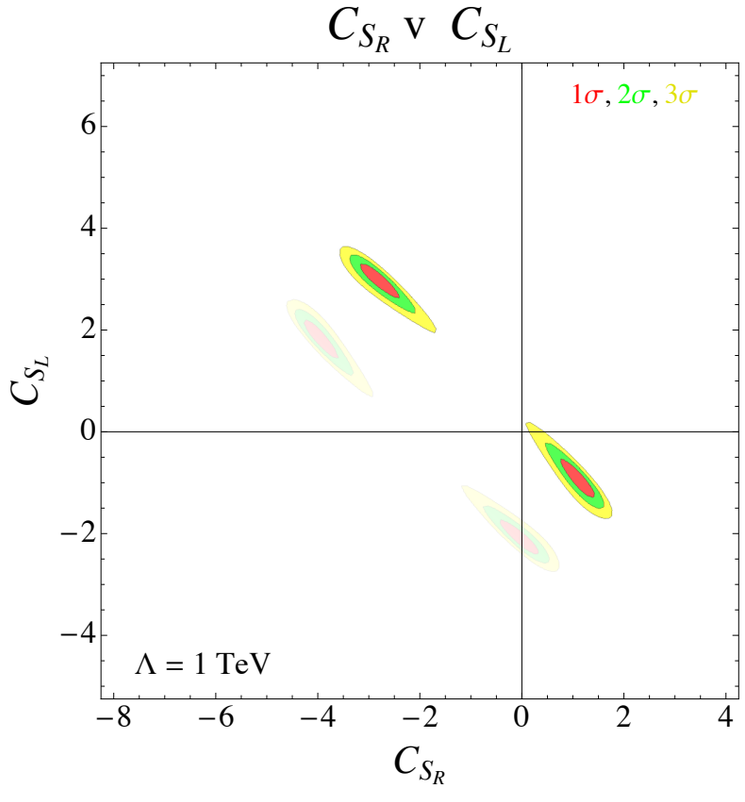
Backup slides

Fitting the anomaly

Selected fit results







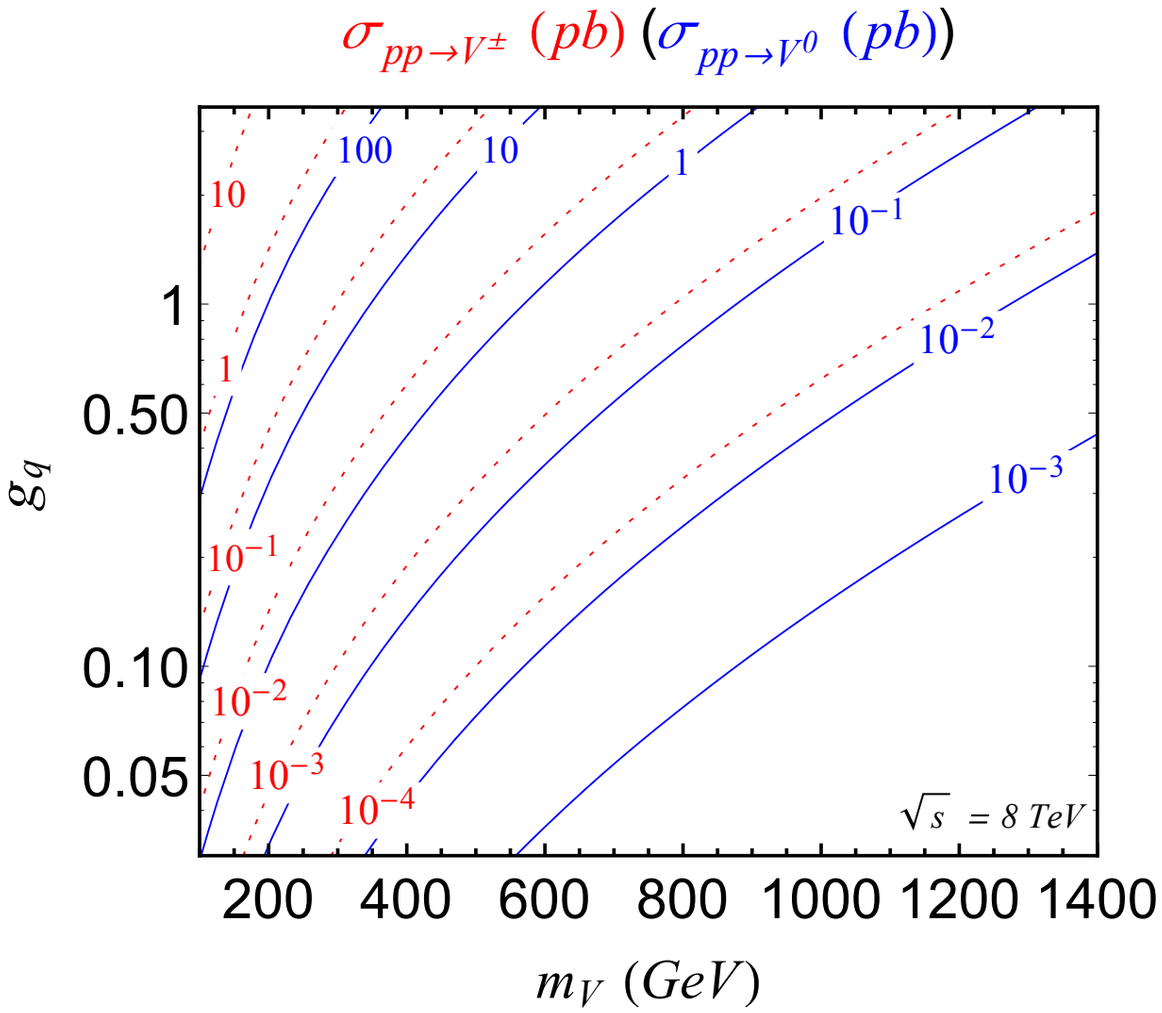
Coefficient(s)	Best fit value(s) ($\Lambda = 1$ TeV)	
C_{V_L}	0.18 ± 0.04,	-2.88 ± 0.04
C_T	0.52 ± 0.02,	-0.07 ± 0.02
C''_{S_L}	-0.46 ± 0.09	
(C_R, C_L)	$(1.25, -1.02)$,	$(-2.84, 3.08)$
(C'_{V_R}, C'_{V_L})	$(-0.01, 0.18)$,	$(0.01, -2.88)$
(C''_{S_R}, C''_{S_L})	$(0.35, -0.03)$,	$(0.96, 2.41)$,
	$(-5.74,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

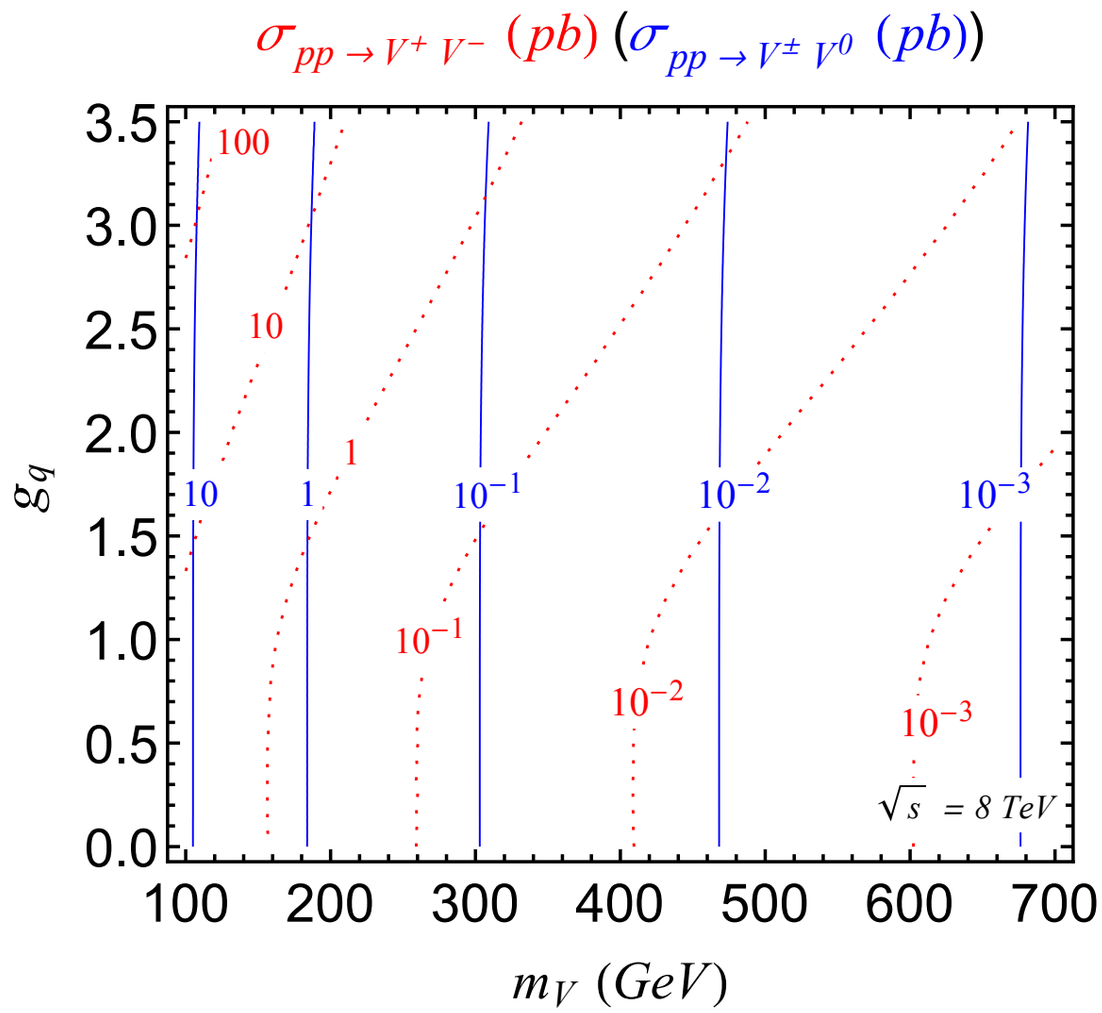
TABLE III. Best-fit operator coefficients with acceptable q^2 spectra and $\chi^2_{\rm min} < 5$.

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

LHC phenomenology: Vector Triplet Model

Production cross sections:





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

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

VTM: ***Low-energy flavour physics***

SU(2)$_L$ triplet current:

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

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

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

quark x lepton

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

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

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

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

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

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

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

- *Fit parameters:*

$$\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \approx g_{\ell,q} \frac{122\,\text{GeV}}{m_V}$$

- 2 flavour universal

$$\lambda^q_{bs},\ \lambda^\ell_{\mu\mu},\ \lambda^\ell_{\tau\mu}$$

- 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*μ(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*μ(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 → 3*μ*	$\Lambda^{-2}_{\tau\mu}$	$(0.0 \pm 4.1) \times 10^{-9}\ \ [\text{GeV}^{-2}]$	$(G_F/\sqrt{2}) \epsilon_\ell^2 \lambda^\ell_{\mu\mu} \lambda^\ell_{\tau\mu}$
7) *D* mix	Λ^{-2}_{uc}	$(0.0 \pm 5.6) \times 10^{-14}\,[\text{GeV}^{-2}]$	$(G_F/\sqrt{2}) \epsilon_q^2 \lvert V_{ub} V^*_{cb}\rvert^2$

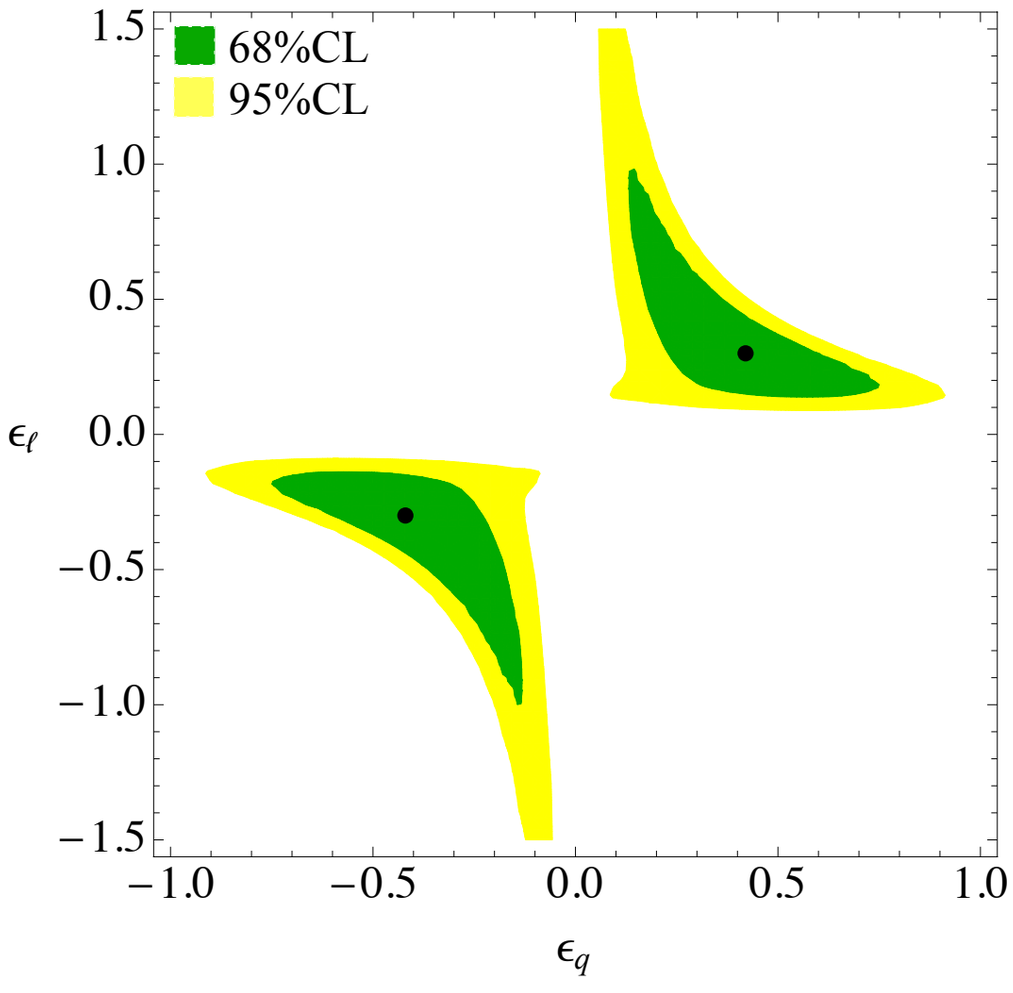
$$\chi^2(x_\alpha) = \sum_i \frac{(\mathcal{O}_i(x_\alpha) - \mu_i)^2}{\sigma_i^2} \quad \longrightarrow \quad \chi^2(x_{\text{SM}}) - \chi^2(x_{\text{BF}}) = 18.6$$

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

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

- The fit is driven by

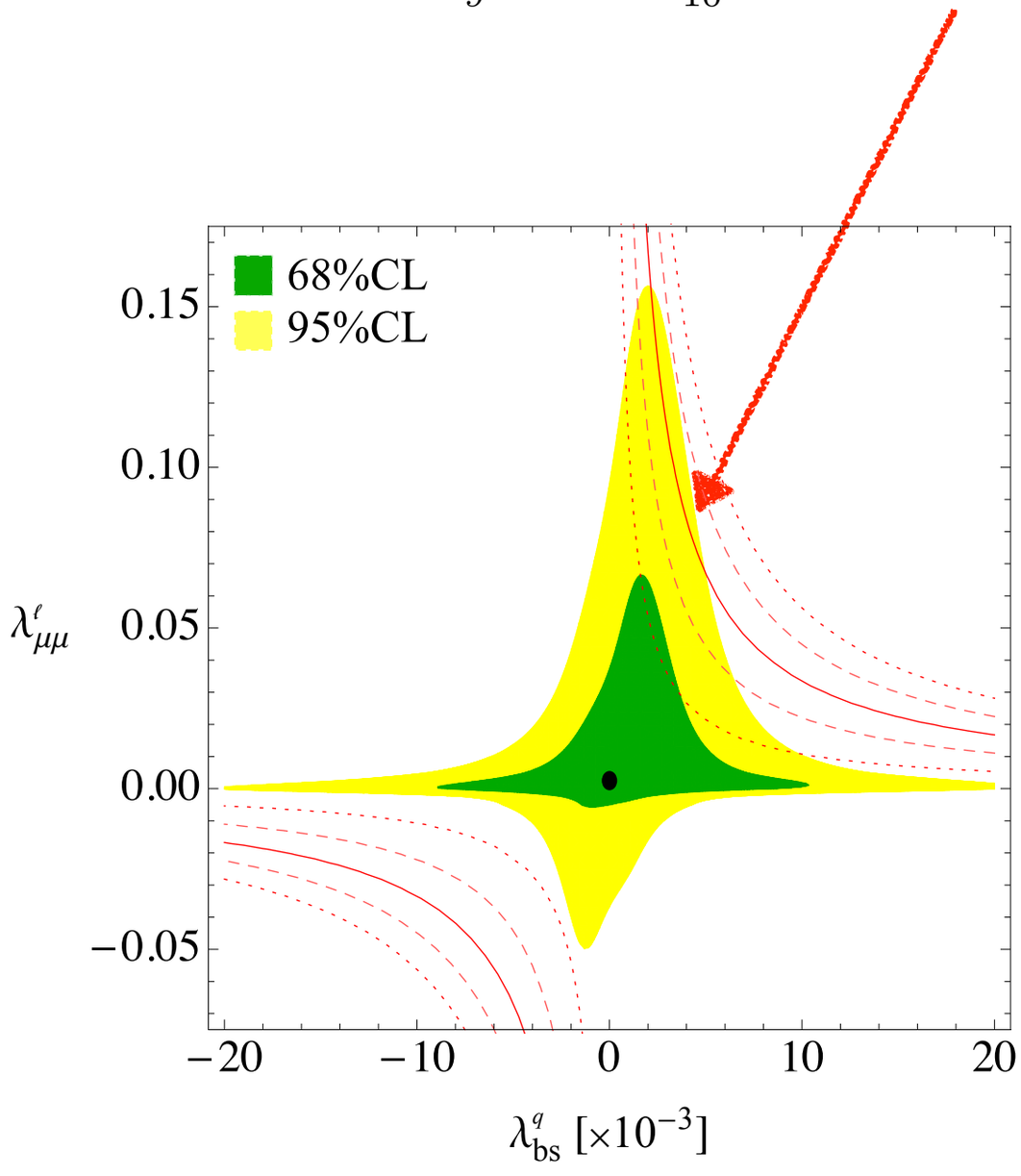
$$R_0(D^*) = \epsilon_\ell \epsilon_q$$



$$\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \approx g_{\ell,q} \frac{122\,\text{GeV}}{m_V}$$

- Some tension with

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



$$\lambda^q_{bs} \sim \epsilon_1 V_{ts}$$

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