Universität Zürich[UZH]

Flavour anomalies vs. high-p_T physics

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

10 March, La Thuile 2017

Universität Zürich[UZH]

Actually

Semitauonic *B* meson decays and $\tau^+\tau^-$ searches at high-p_T LHC

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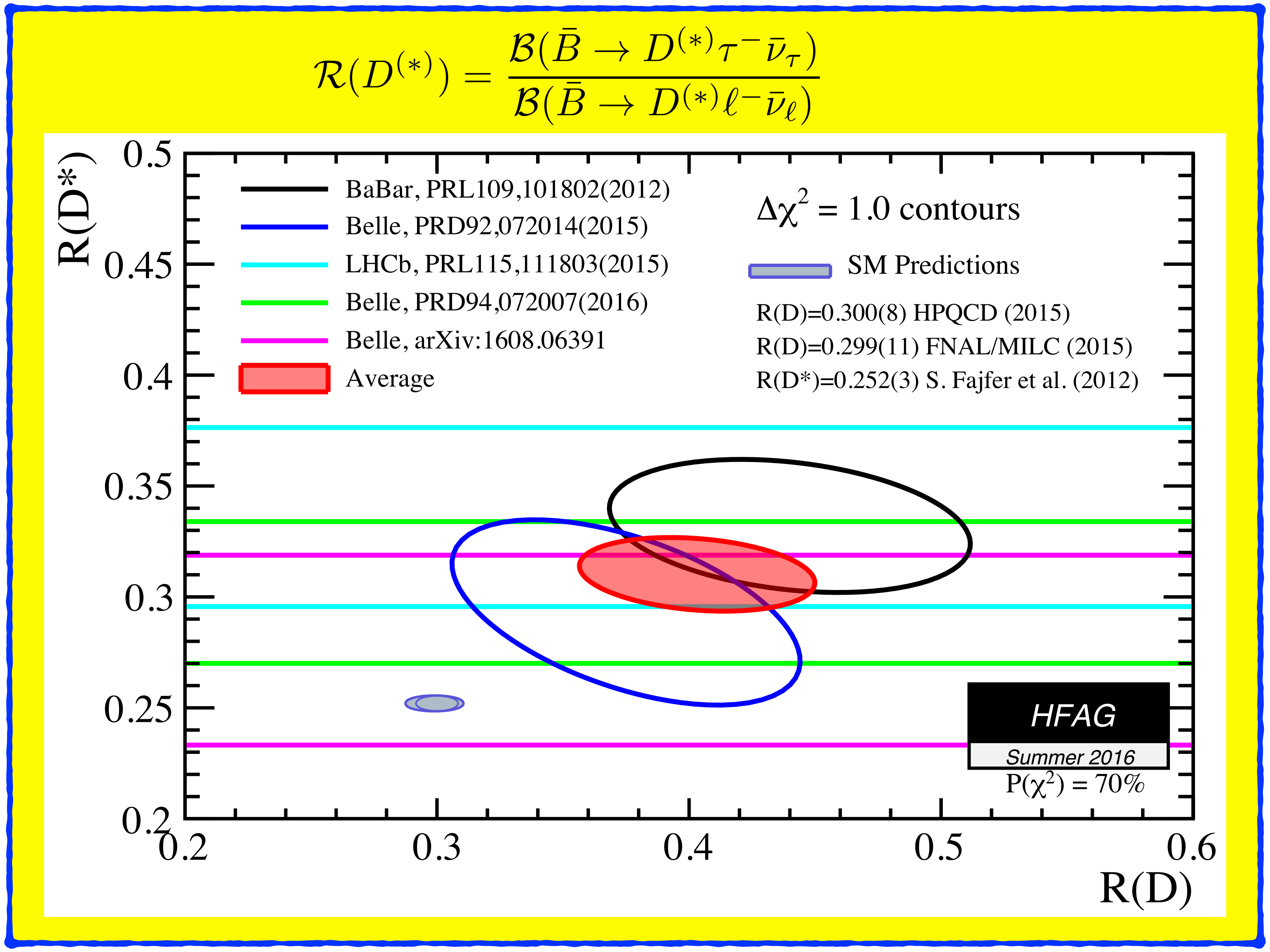
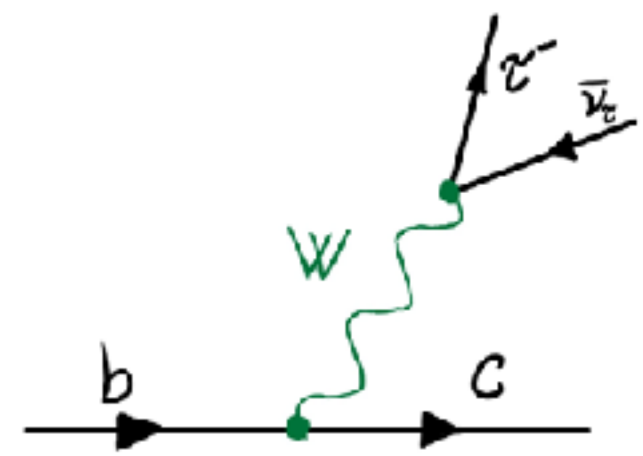
Motivation: Test of LFU in charged currents





For more details, see talk by: Stefanie Reichert

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

More experimental effort needed to be conclusive

(Theorist getting overly excited is not welcome)

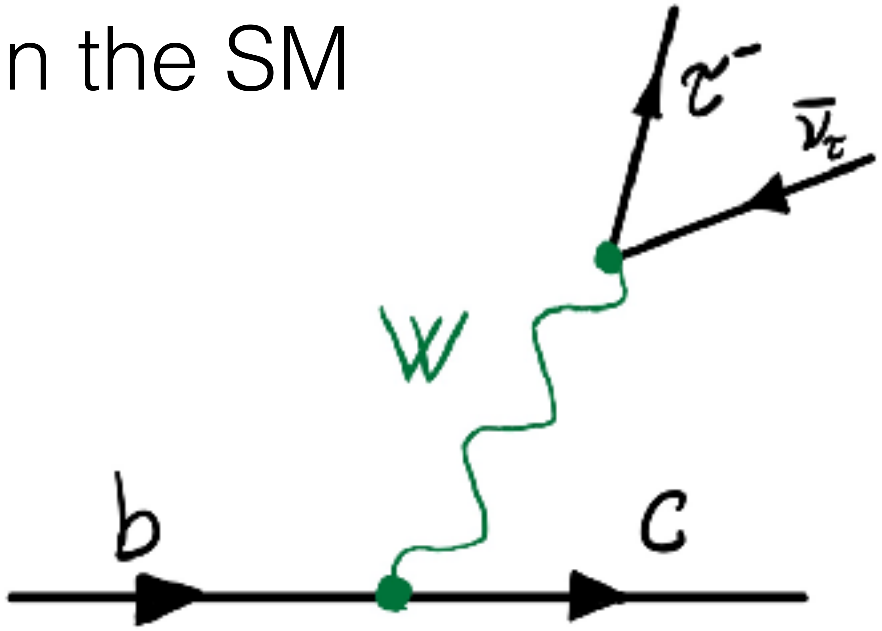
However, we could still be helpful by doing ***consistency checks****.*

For example, is the excess compatible with the high p_T LHC searches?

This talk

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

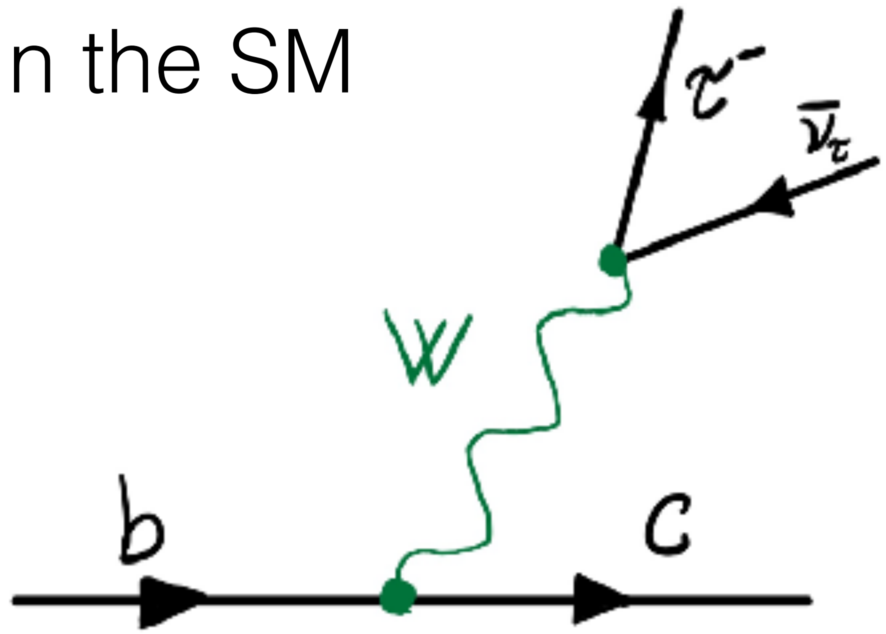
In the SM



- Tree-level process
- Only mild CKM suppression

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

In the SM



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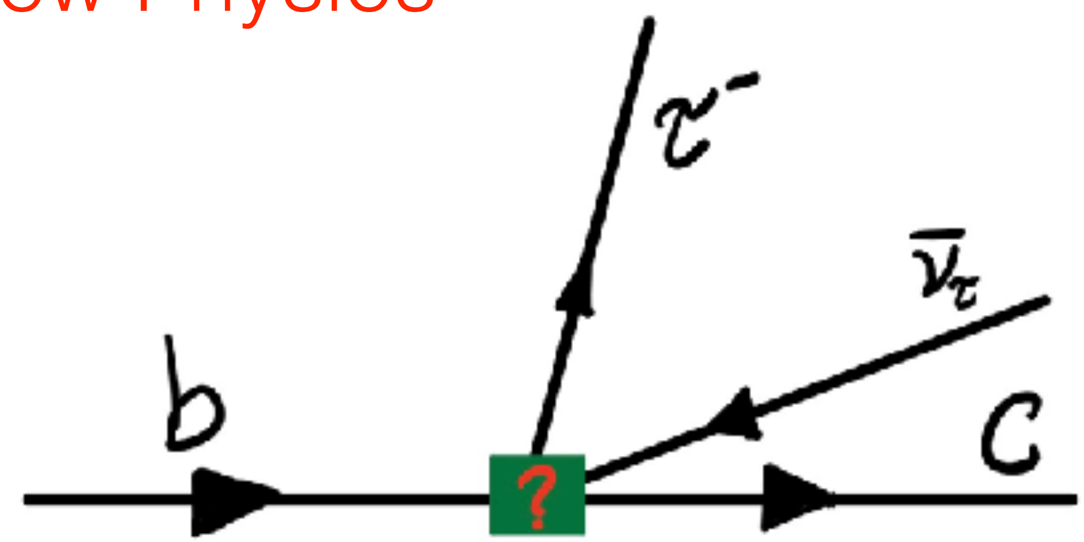
New Physics



- Large NP contribution required

<u>Mediator mass</u>:

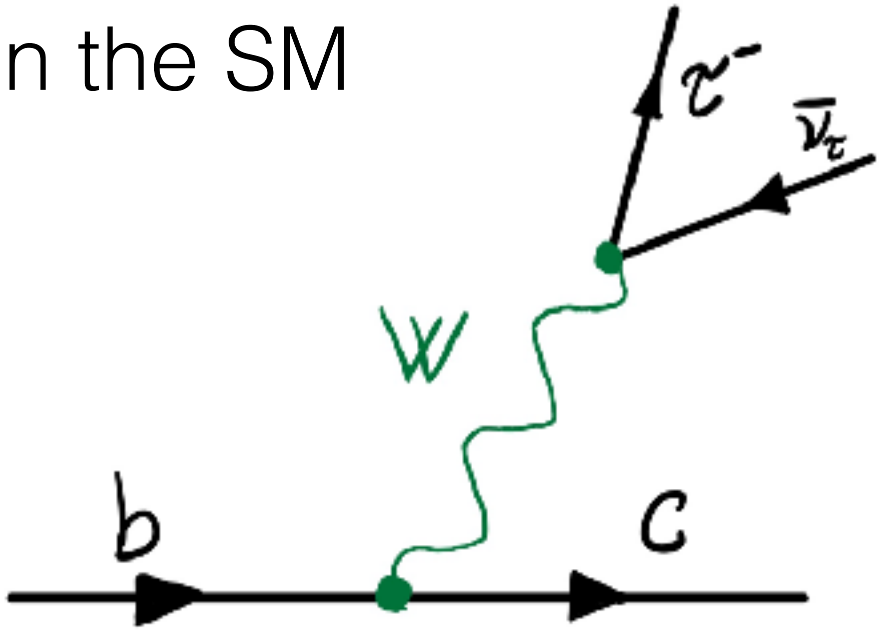
$\lesssim$ several TeV (to fit the anomaly)

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

In the ballpark of high-p_T LHC searches

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

In the SM



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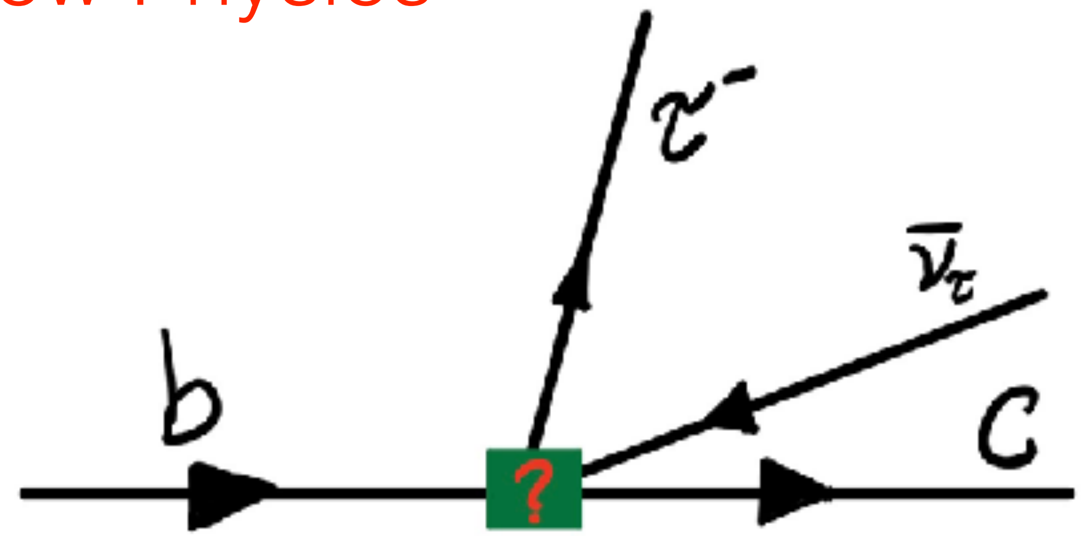

- Large NP contribution required

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

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

$\boxed{\mathcal{O}_{S_R}}$ $(\bar{d}^i_R Q_j)(\bar{L}_k \ell^l_R)$

$\boxed{\mathcal{O}_{S_L}}$ $(\bar{Q}_i u^j_R) i\sigma^2 (\bar{L}_k \ell^l_R)$

$\boxed{\mathcal{O}_T}$ $(\bar{Q}\,\sigma_{\mu\nu} u^j_R) i\sigma^2 (\bar{L}\sigma^{\mu\nu} \ell^l_R)$

SM EFT consideration & Implications for high-p$_T$ LHC

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

[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}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{V_L}$	$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
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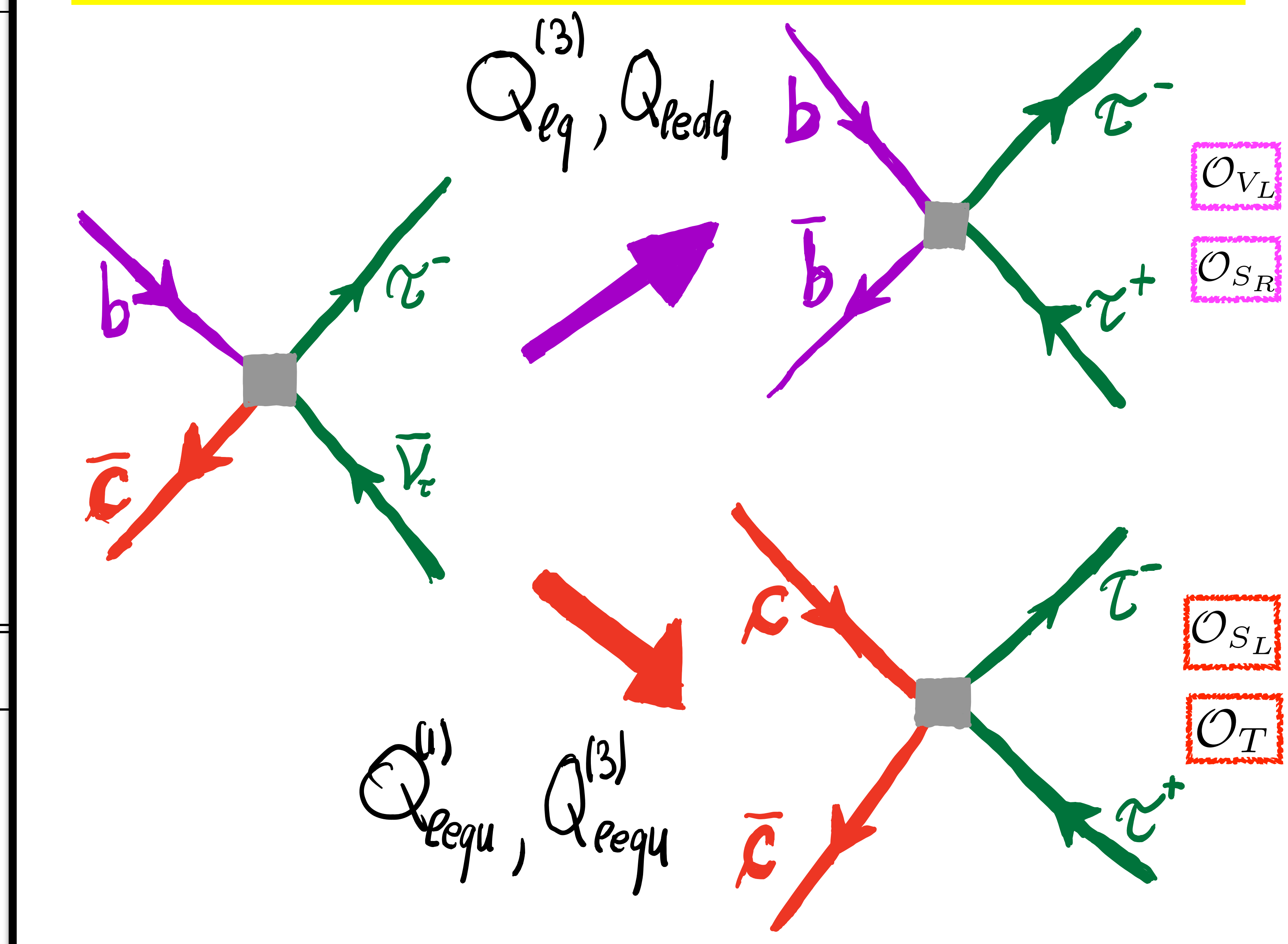
SU(2)$_L$ prediction: **Neutral currents**



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$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$\boxed{Q_{lq}^{(3)}}$	$\boxed{(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)}$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
$\boxed{Q_{ledq}}$	$\boxed{(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)}$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
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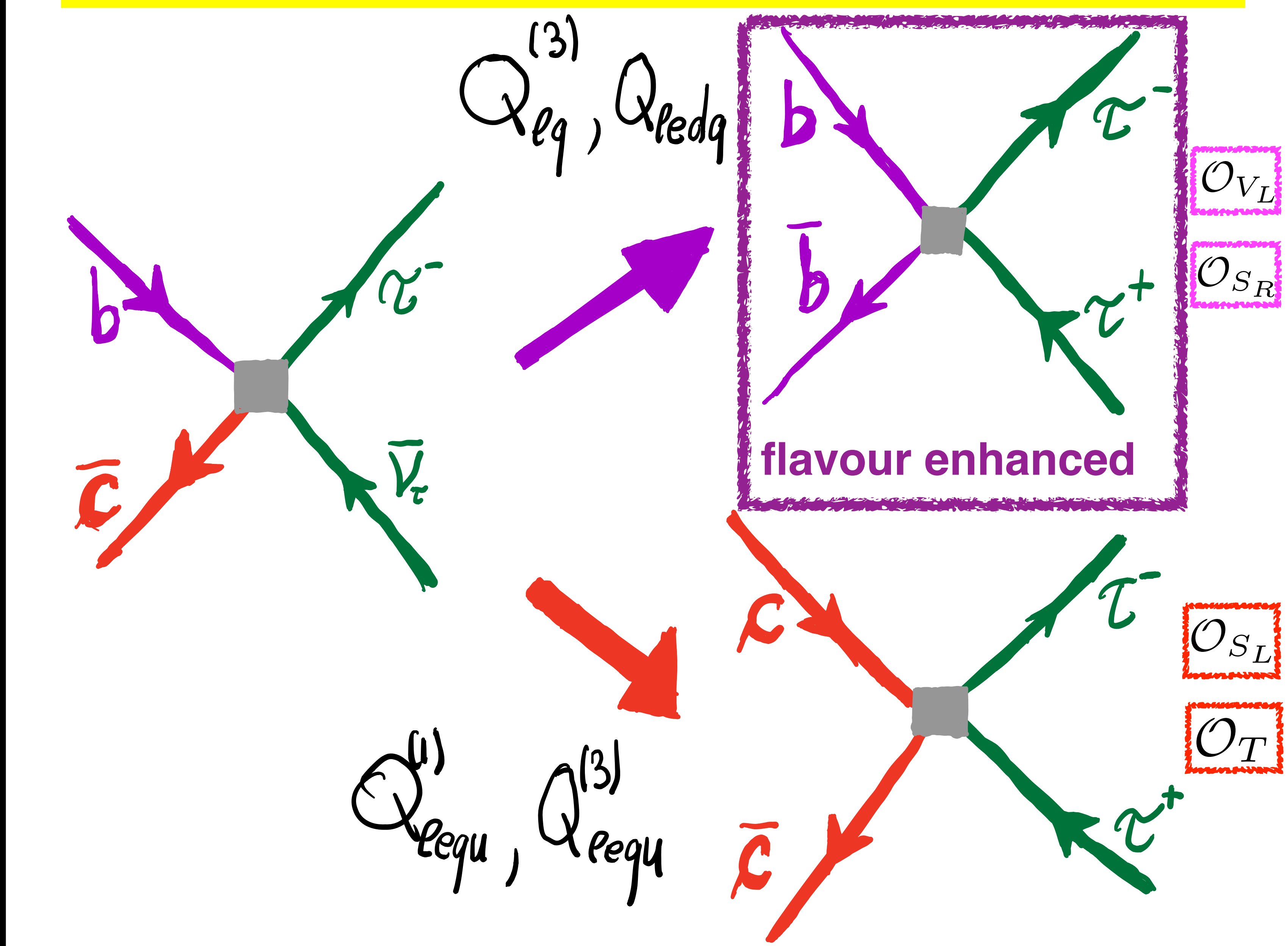
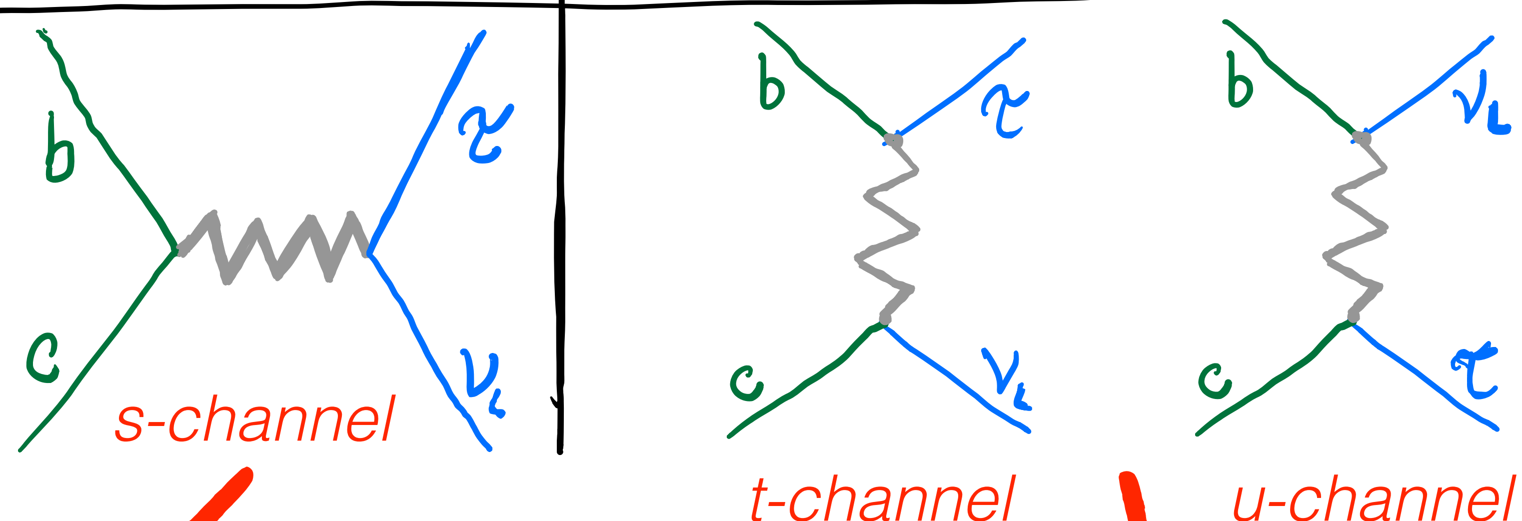


Single mediator models (8 options)

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

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



Weak doublet scalar or triplet vector

Weak singlet, doublet or triplet

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

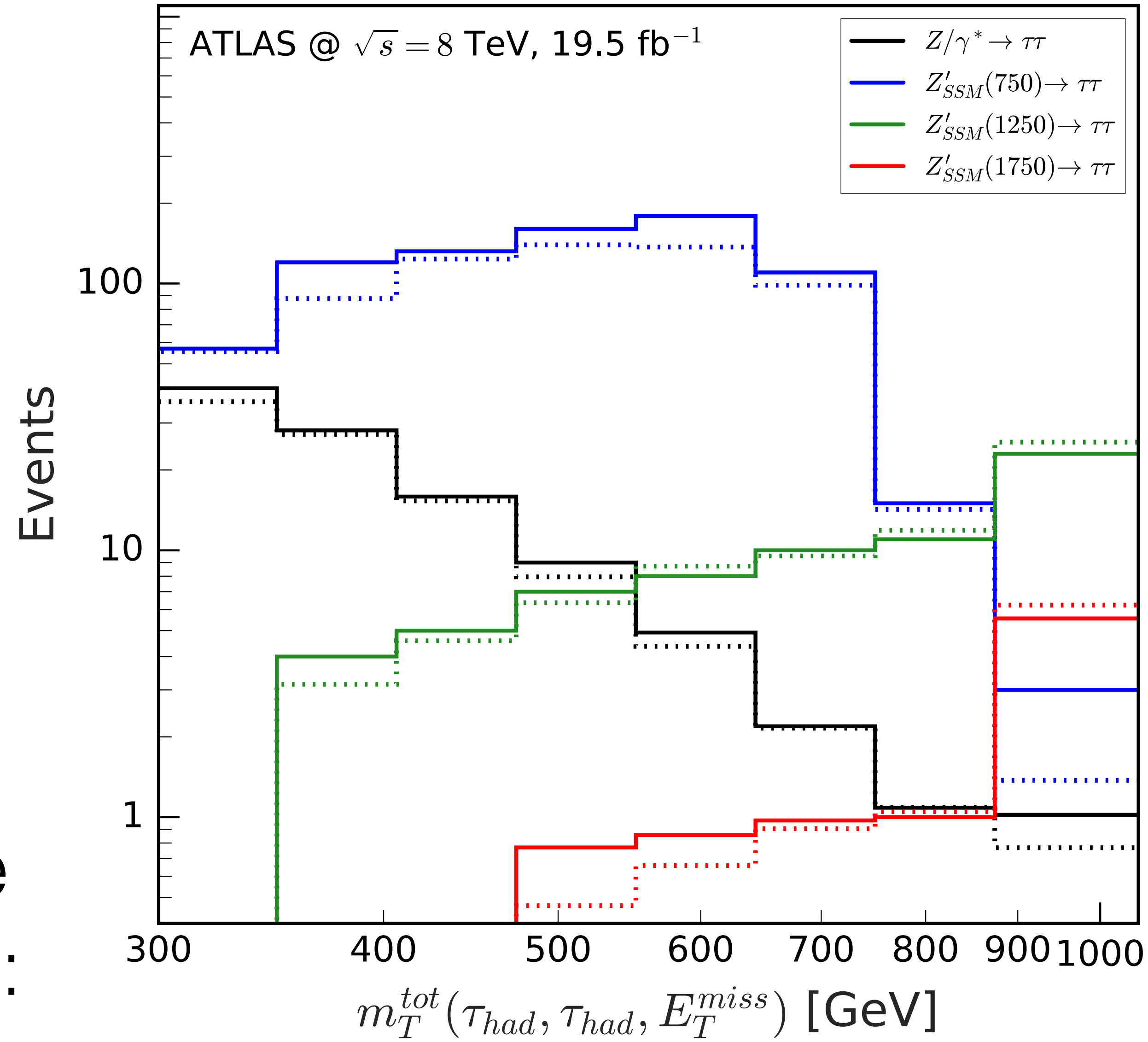
[ATLAS Collaboration], JHEP 1507, 157 (2015)

- Correlated high-p_T events have peculiar kinematics

- Full simulation pipeline:
  FeynRules>MadGraph>Pythia>Delphes

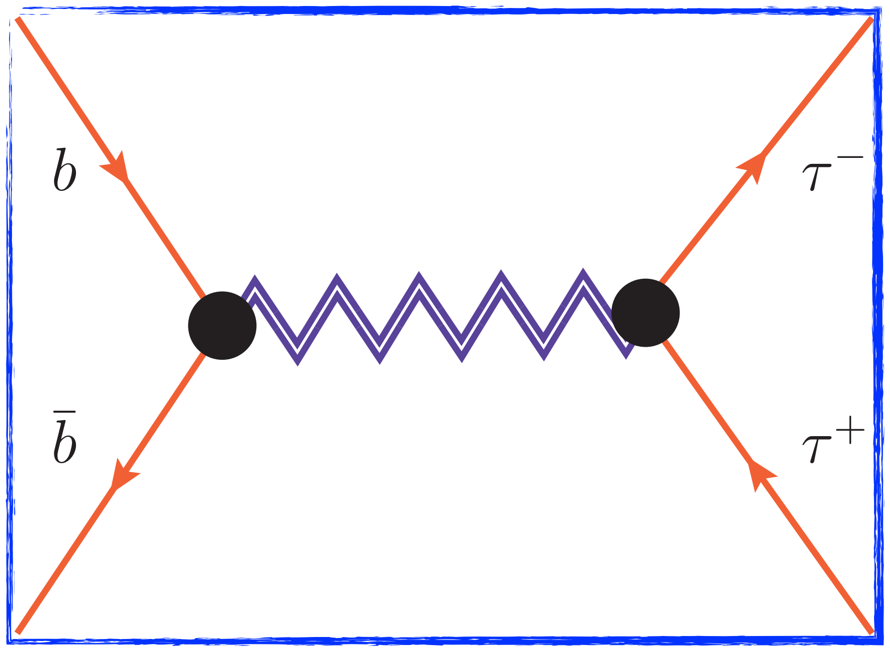
- Validated against the SM bkg, and the Sequential SM Z'

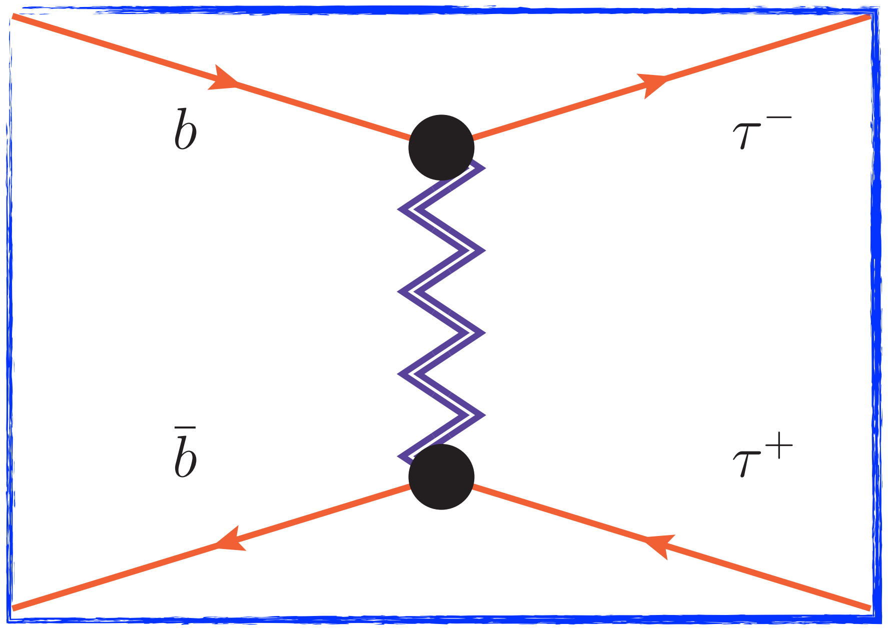
- Set limits on a model's parameter space by fitting the total transverse mass variable:



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

Single mediator models - LHC limits





Real Vector Triplet Model

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

- *Introduce heavy spin-1 triplet*

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

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

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Real Vector Triplet Model

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

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

Flavour fit

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

Real Vector Triplet Model

Flavour fit: Conclusions

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

(1)

(2)

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

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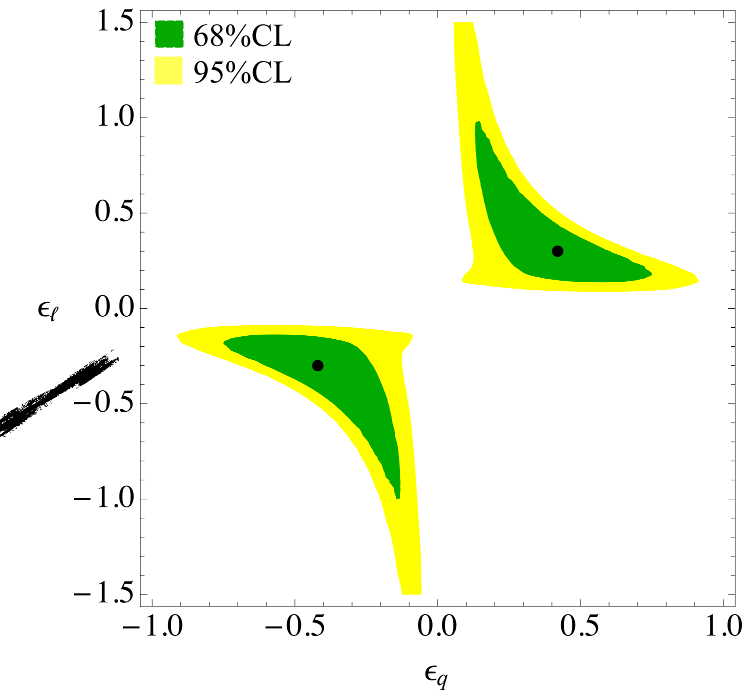
(1) *Dominant couplings with the third generation*

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

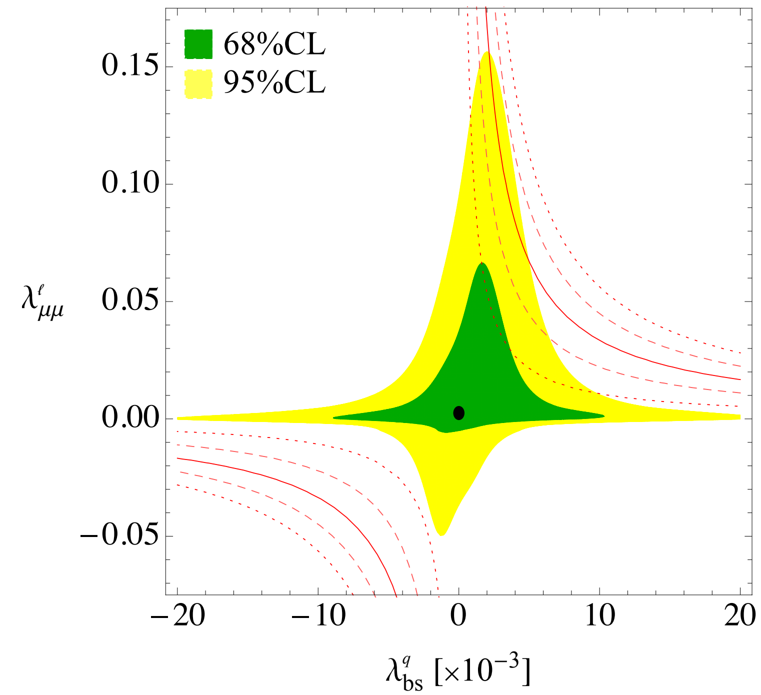
(2) Flavour alignment with down quarks and charged leptons (to avoid FCNC in the down sector)

$$Q_i = (V_{ji}^* u_L^j, d_L^i)^T \text{ and } L_i = (U_{ji}^* \nu^j, \ell_L^i)^T$$

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



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



$$\lambda_{bs}^q \sim \epsilon_1 V_{ts}$$

Real Vector Triplet Model

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

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

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

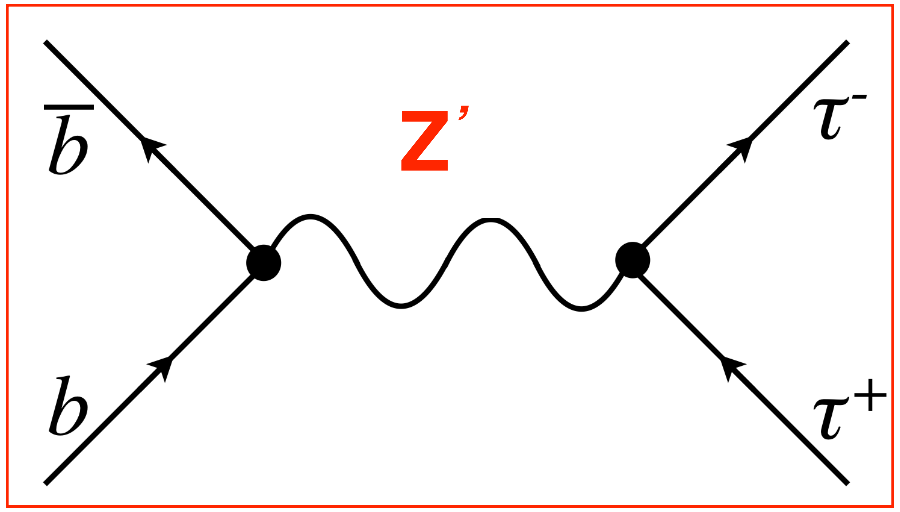
LHC phenomenology: Vector Triplet Model

Low-energy flavour physics

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

(1) Decays to third generation SM fermions

(2) Production from the heavy quark flavour



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

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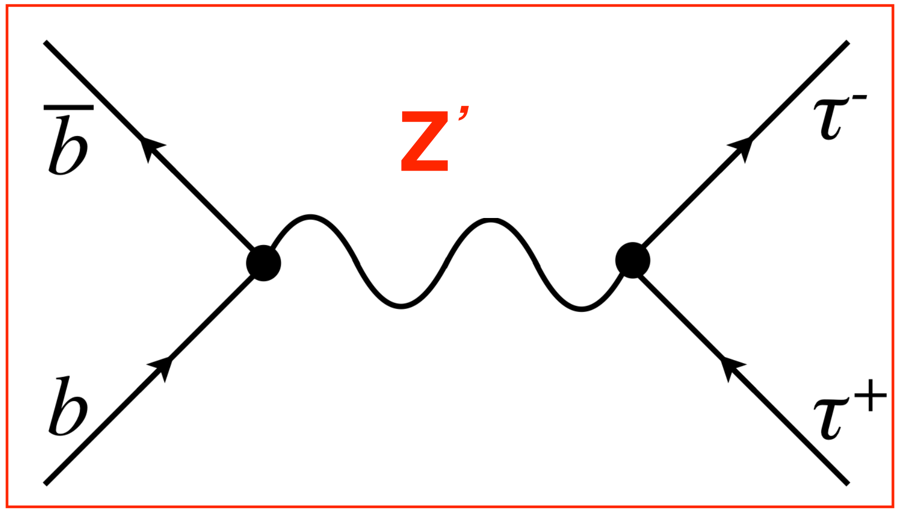

Electroweak precision:

Small mass splitting in the multiplet

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

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

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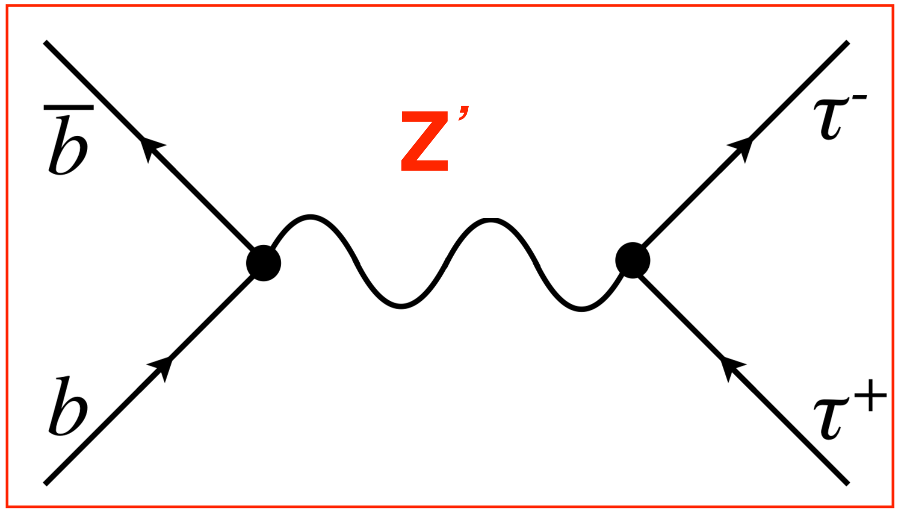

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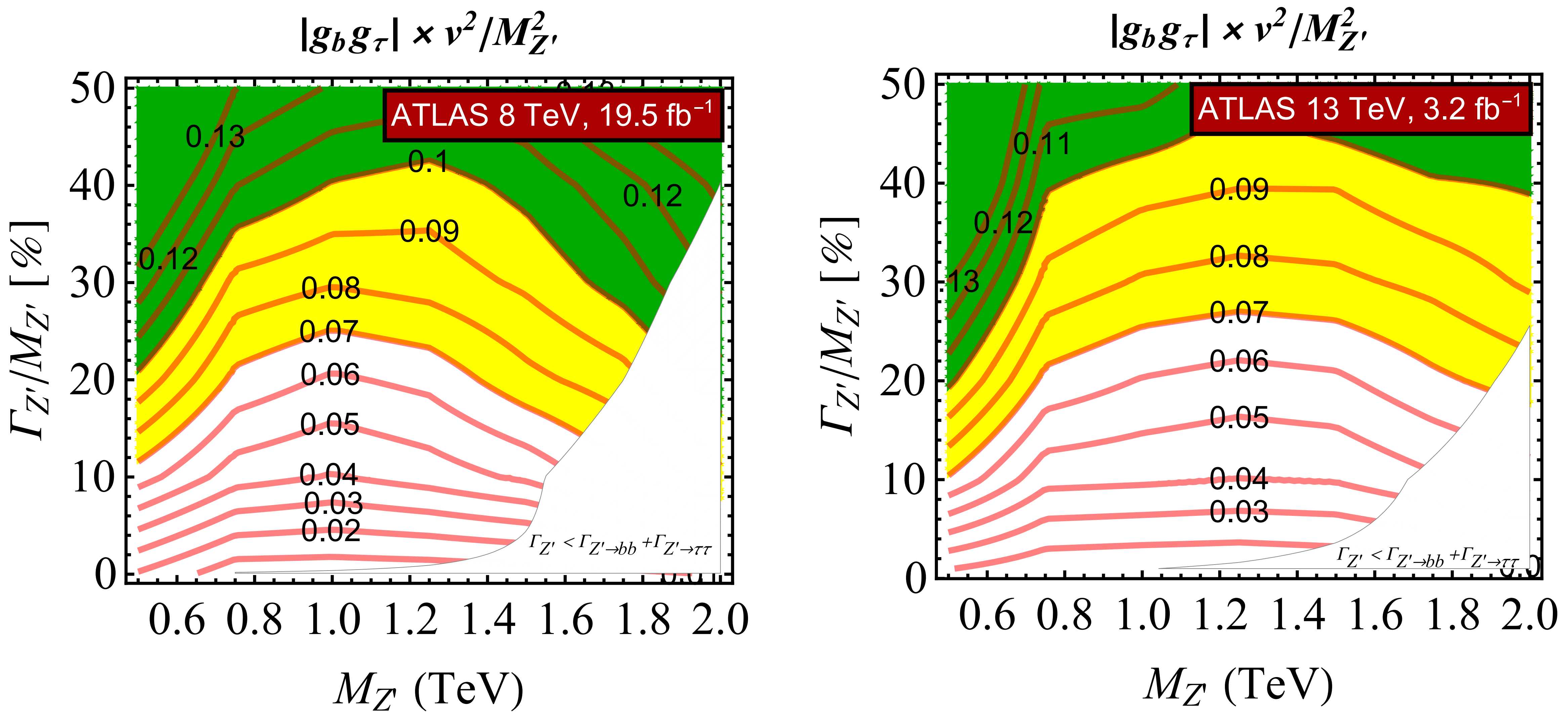
[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

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

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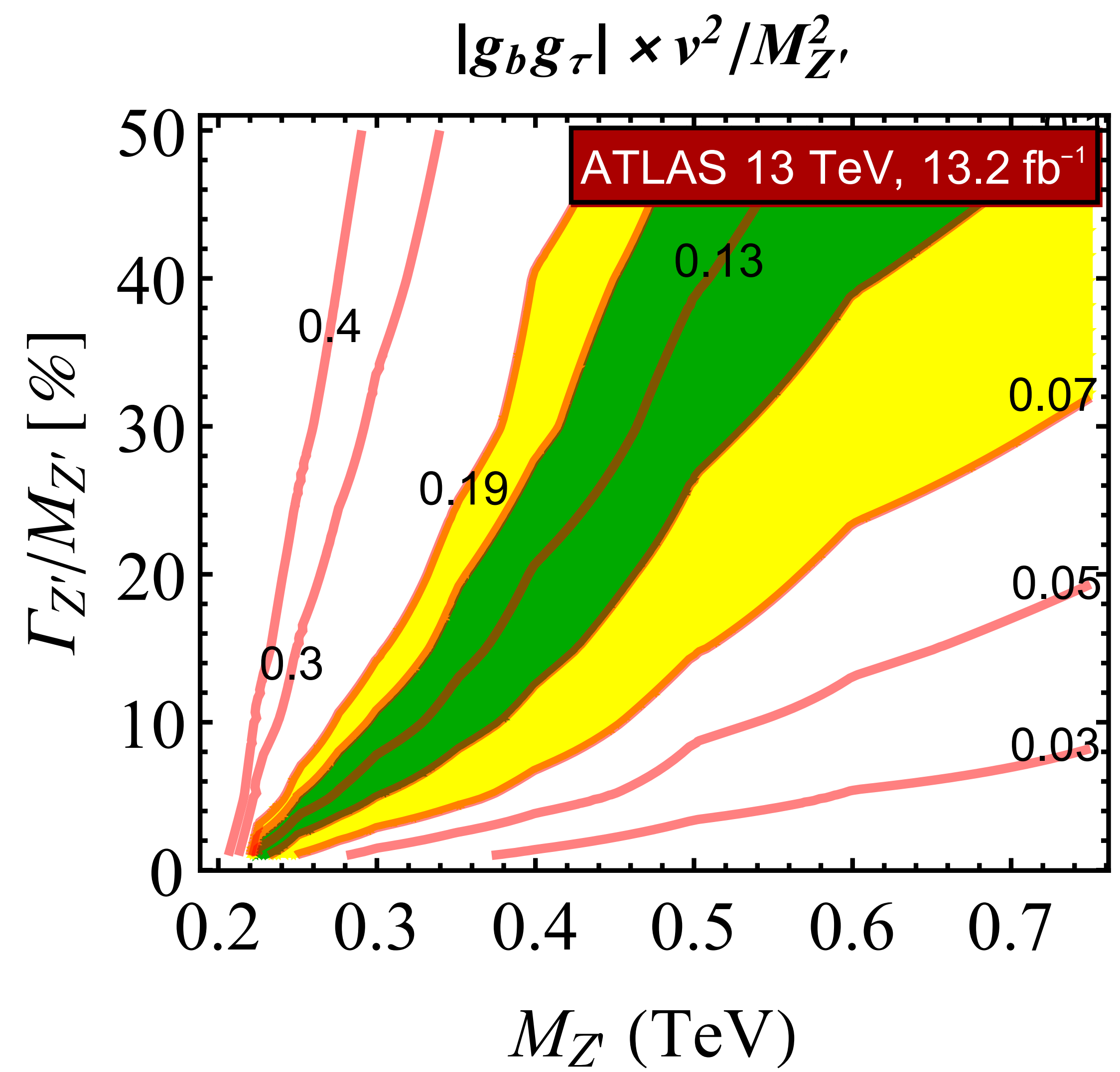


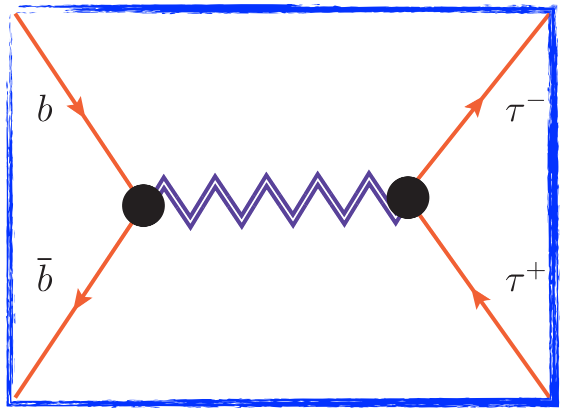
- Need for improvements in the low mass region!

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

Two Higgs doublet model

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

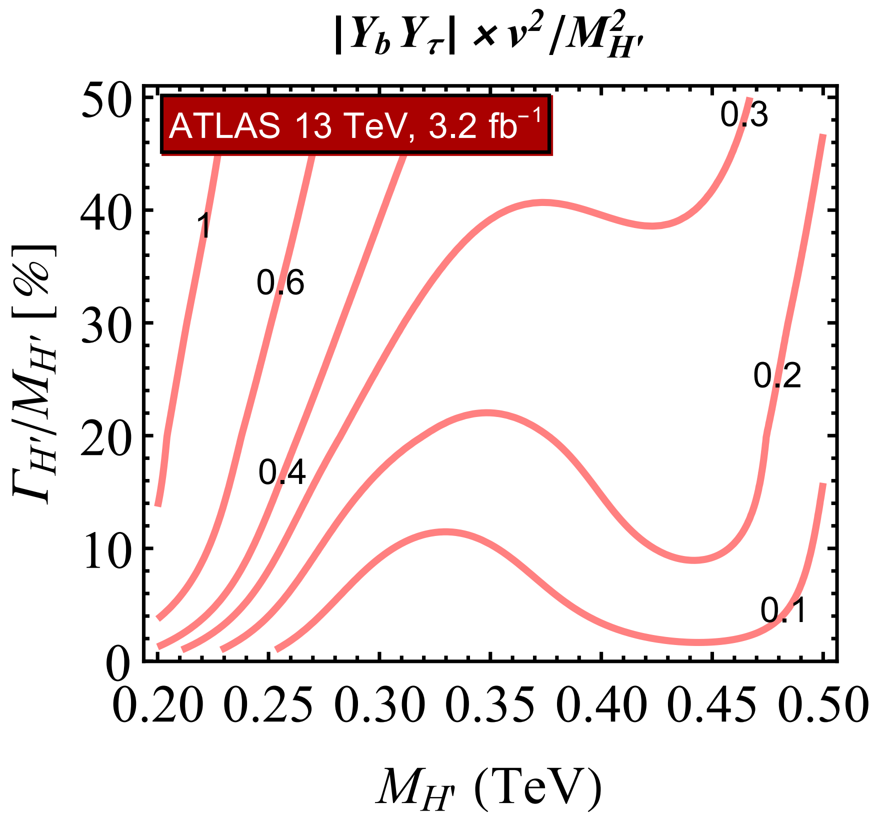
$$\mathcal{L}_{H'} = |D^\mu H'|^2 - M_{H'}^2 |H'|^2 - \lambda_{H'} |H'|^4 - \delta V(H', H)$$
$$- Y_b \bar{Q}_3 H' b_R - Y_c \bar{Q}_3 \tilde{H}' c_R - Y_\tau \bar{L}_3 H' \tau_R + \text{h.c.} \,,$$

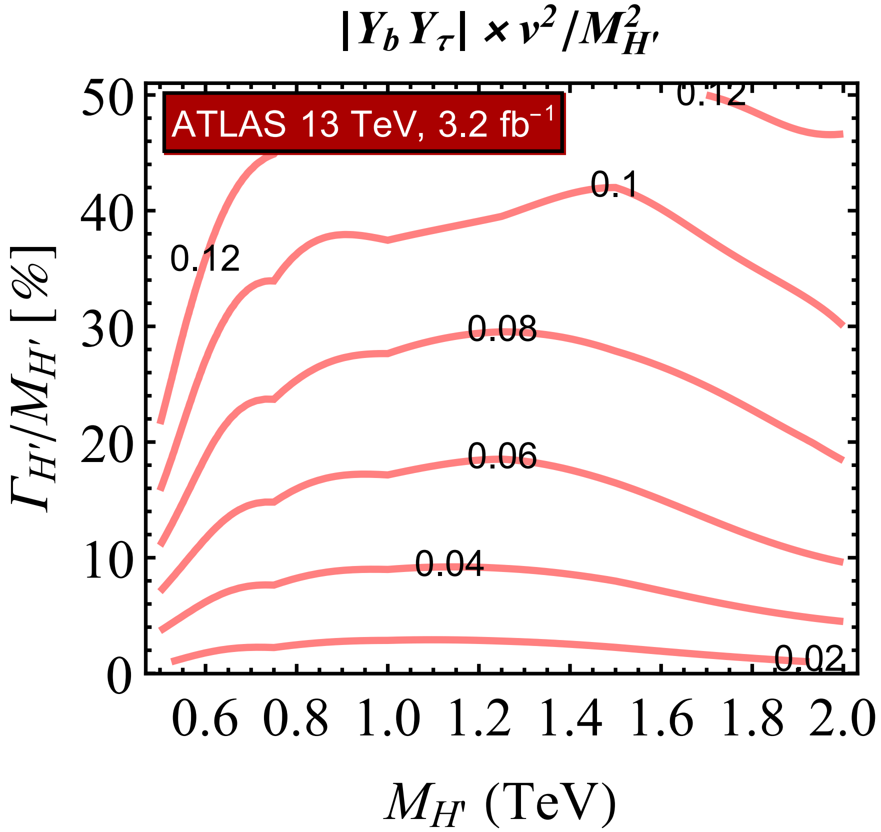


Fit to R(D*) anomaly

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

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





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

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

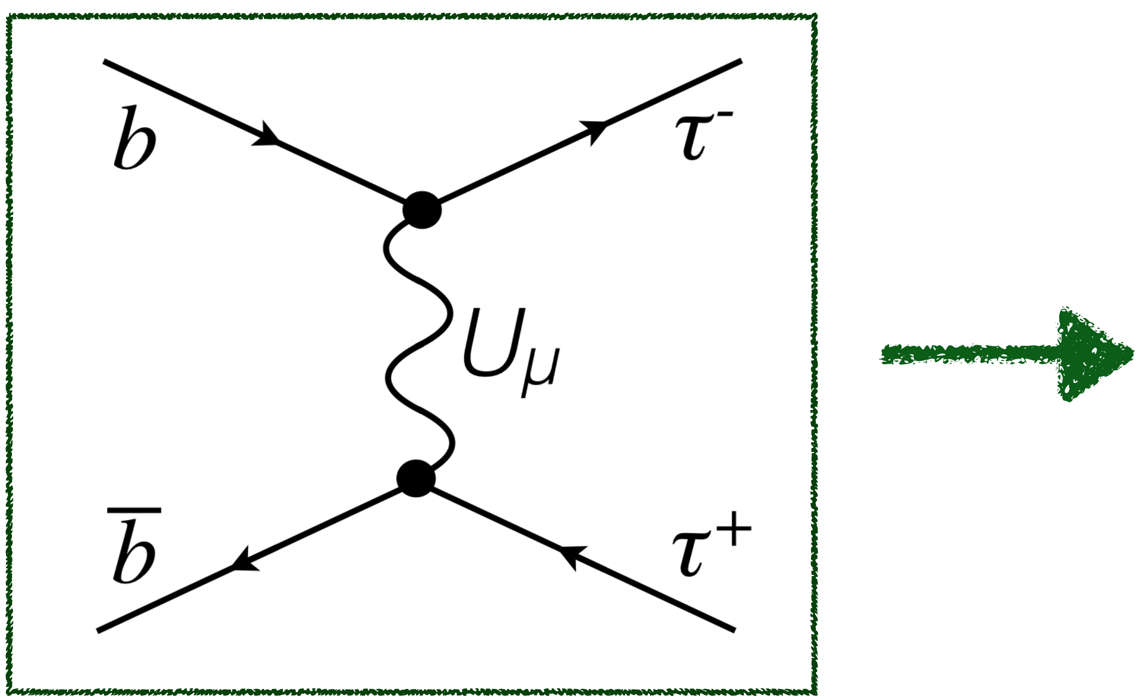
Vector Leptoquark: (**3**,**1**,2/3)

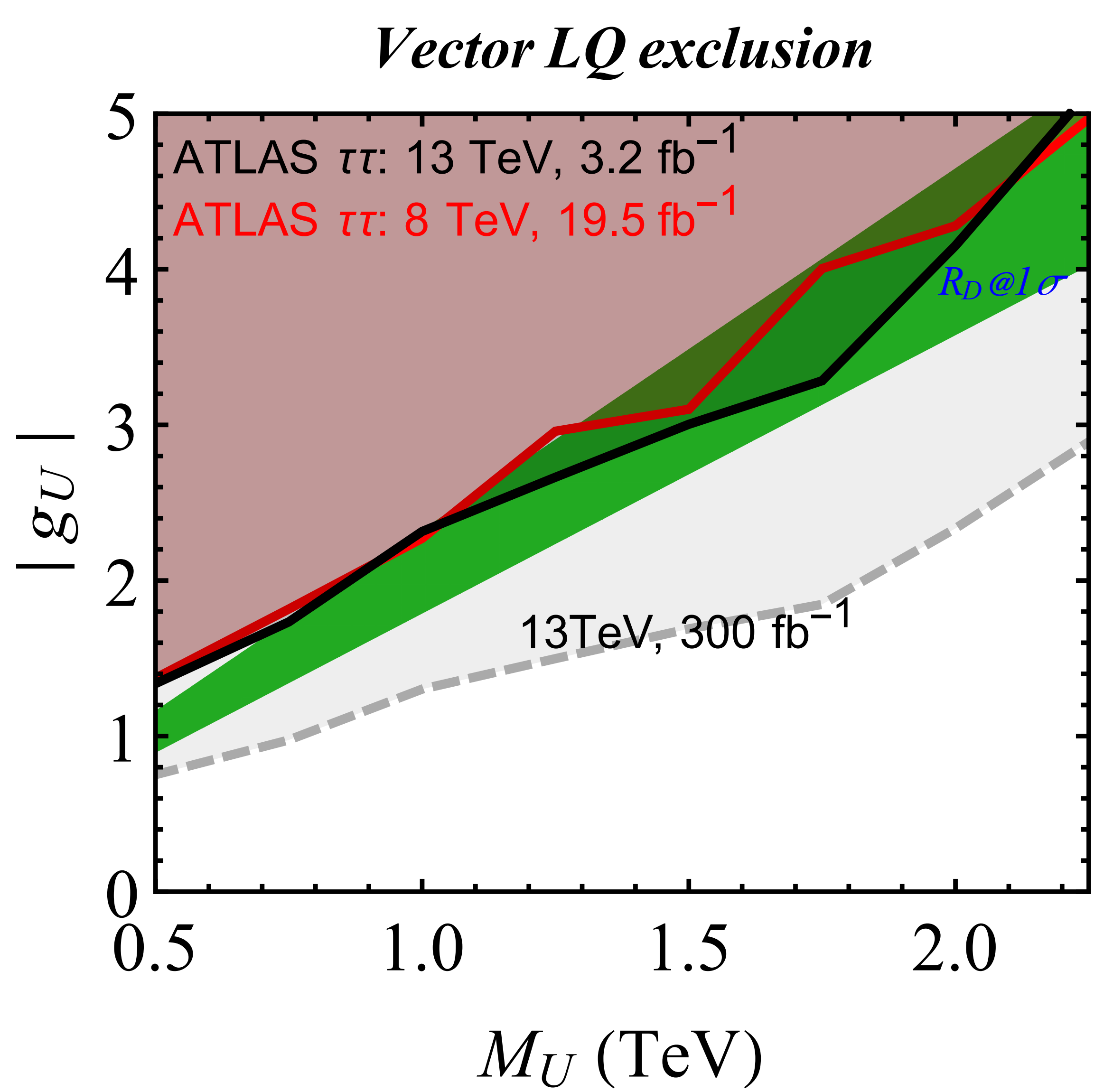
$$\mathcal{L}_U \supset -\frac{1}{2} U^\dagger_{\mu\nu} U^{\mu\nu} + m_U^2 U^\dagger_\mu U^\mu + (J^\mu_U U_\mu + \text{h.c.}),$$
$$J^\mu_U \equiv g_U \; \beta_{ij} \; \bar{Q}_i \gamma^\mu L_j \; .$$

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

Integrating out LQ

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





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

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

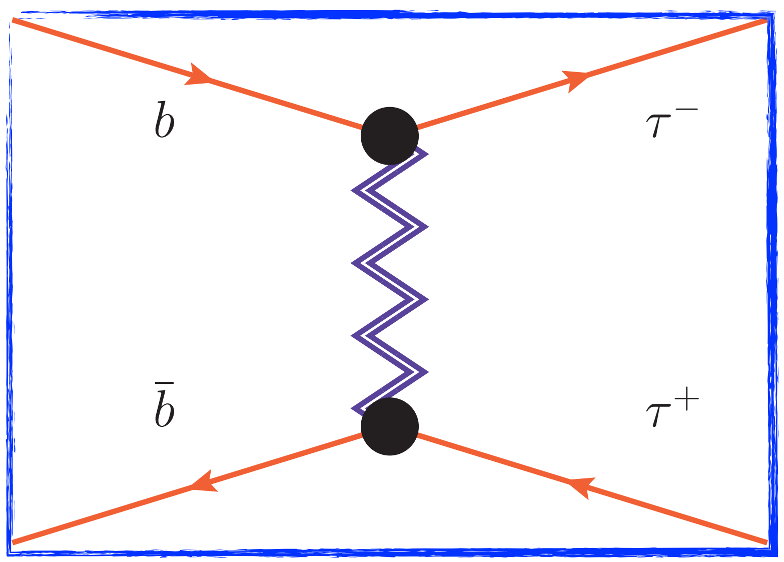
*with the right-handed neutrino

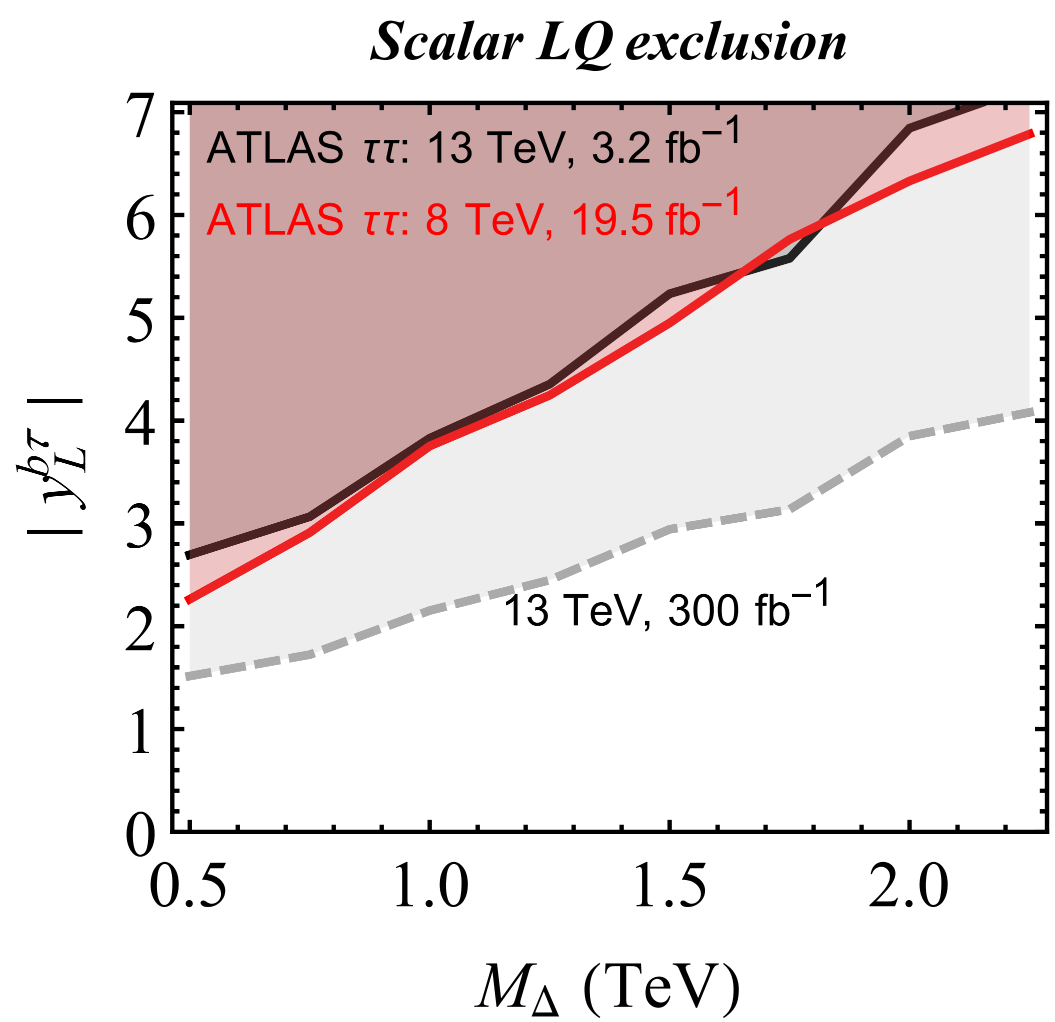
$$\mathcal{L}_\Delta \supset Y_L^{ij} \bar{d}_i (i\sigma_2 \Delta^*)^\dagger L_j + Y_R^{i\nu} \bar{Q}_i \Delta \nu_R + \text{h.c.}\ .$$

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

Fit to R(D*) anomaly

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





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

- ***QCD LQ pair production*** limits are getting stronger ($\gtrsim$1 TeV)
- Third generation LQ searches - ***Important***

Summary: *Models subject to τ+τ- search limits*

	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$	
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L) W'_\mu$	**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**
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)(\bar{\tau}P_L \nu)$				
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L \nu)$				
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \mathcal{O}_{V_L}$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda \bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$	**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*

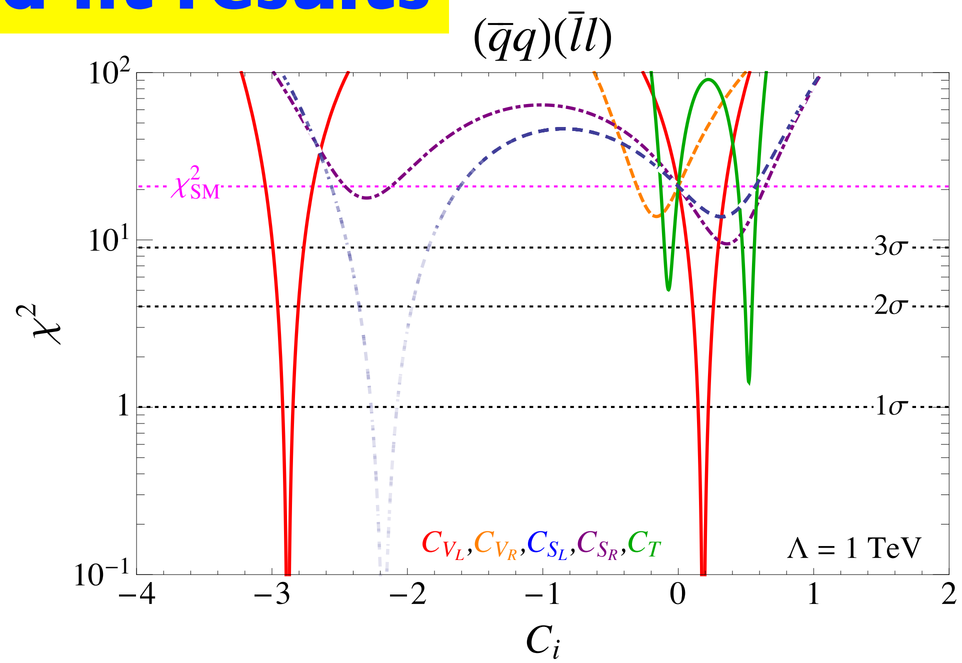
Alternative conclusions

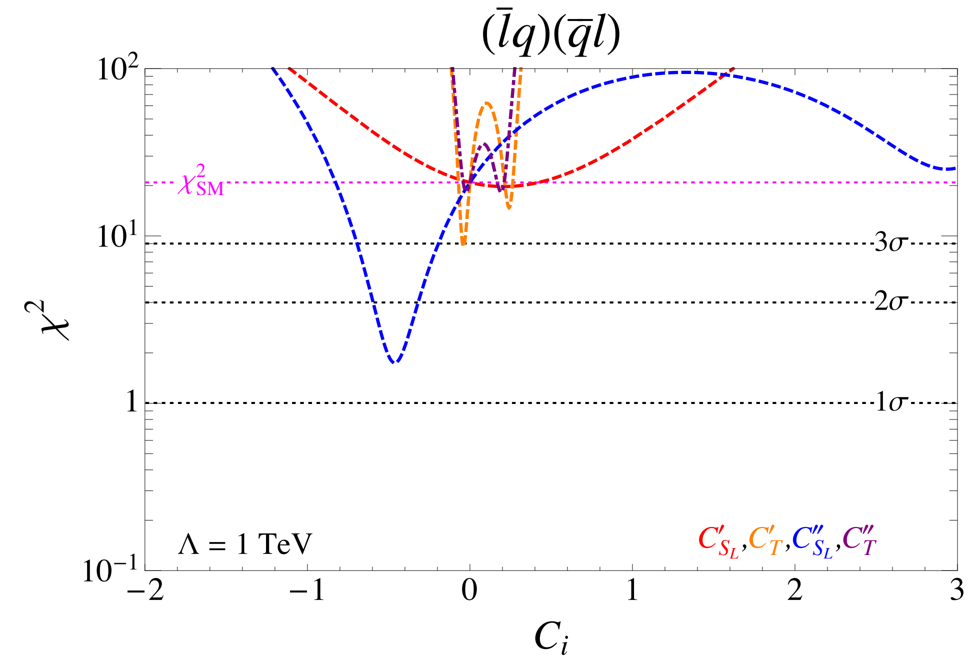
- *Something is wrong either with the low or high p_T Taus*
- *Let's hope it's the high p_T ones*

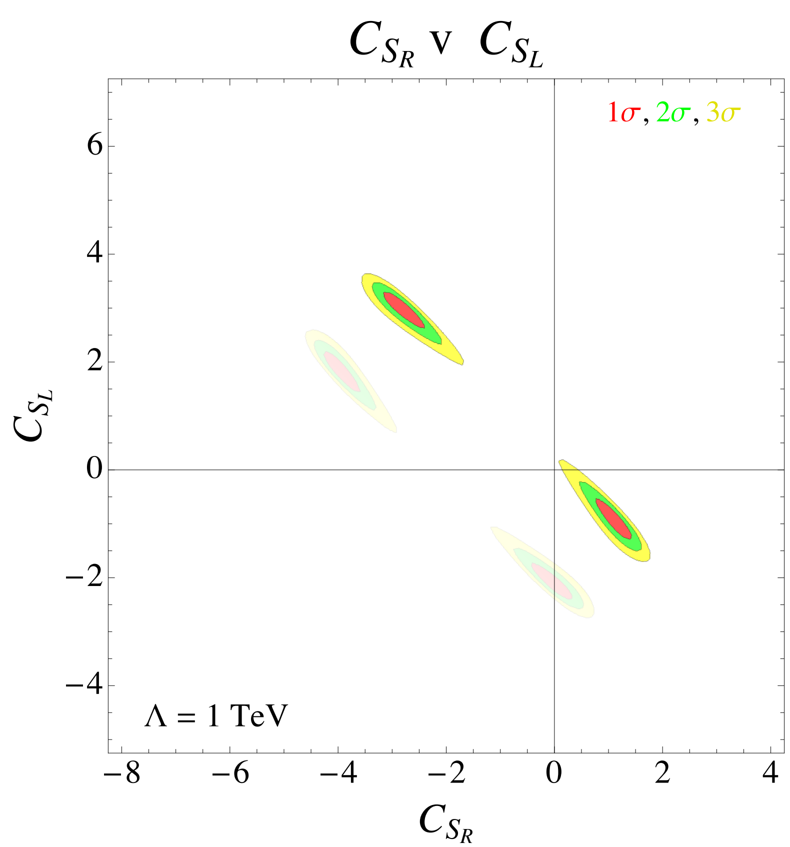
Backup slides

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

Warm-up exercise: **EFT**

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

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

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

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

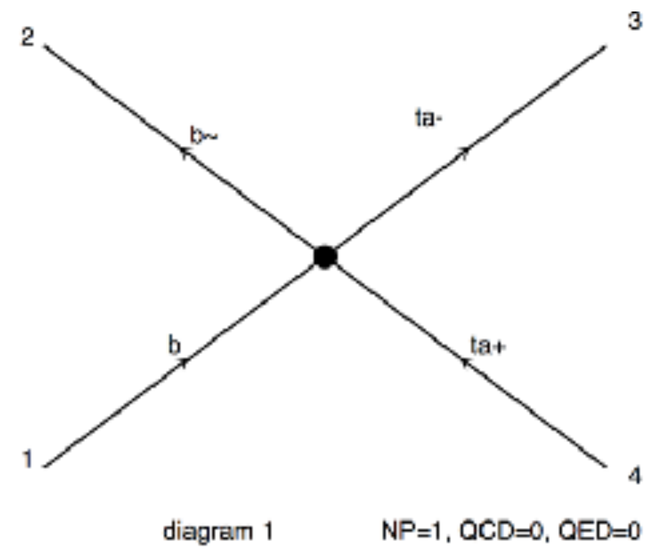
(2) Flavor alignment with down quarks and charged leptons (to avoid FCNC in the down sector)

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

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

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

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



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

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

SU(2)$_L$ triplet current:

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

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

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

quark x lepton

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

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

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

- *Fit parameters:* $\boxed{\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \approx g_{\ell,q} \frac{122\,\mathrm{GeV}}{m_V}}$ $\boxed{\lambda^q_{bs},\ \lambda^\ell_{\mu\mu},\ \lambda^\ell_{\tau\mu}}$
  - 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*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	$\epsilon_q^2 \lvert\lambda^q_{bs}\rvert^2 (\lvert V^*_{tb} V_{ts}\rvert^2 R^{\mathrm{loop}}_{\mathrm{SM}})^{-1}$
4) b→s μ μ	ΔC^μ_9	-0.53 ± 0.18	$-(\pi/\alpha_{\mathrm{em}})\lambda^\ell_{\mu\mu}\epsilon_\ell\epsilon_q\lambda^q_{bs}/\lvert V^*_{tb}V_{ts}\rvert$
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*	$\Lambda^{-2}_{\tau\mu}$	$(0.0 \pm 4.1) \times 10^{-9}$ $[\mathrm{GeV}^{-2}]$	$(G_F/\sqrt{2})\epsilon_\ell^2 \lambda^\ell_{\mu\mu}\lambda^\ell_{\tau\mu}$
7) *D* mix	Λ^{-2}_{uc}	$(0.0 \pm 5.6) \times 10^{-14}$ $[\mathrm{GeV}^{-2}]$	$(G_F/\sqrt{2})\epsilon_q^2 \lvert V_{ub}V^*_{cb}\rvert^2$

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

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

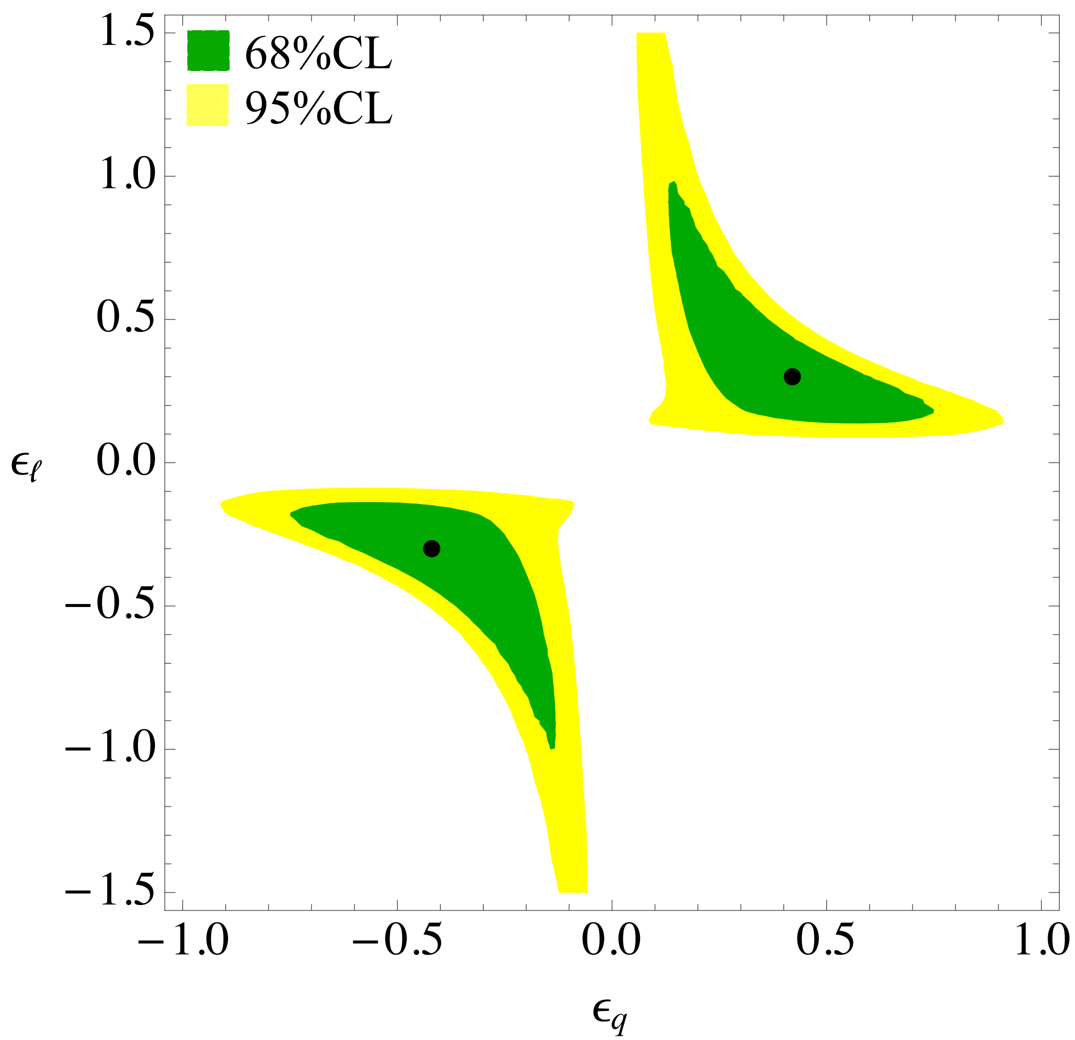
VTM: ***Combined fit to low-energy data***

- The fit is driven by

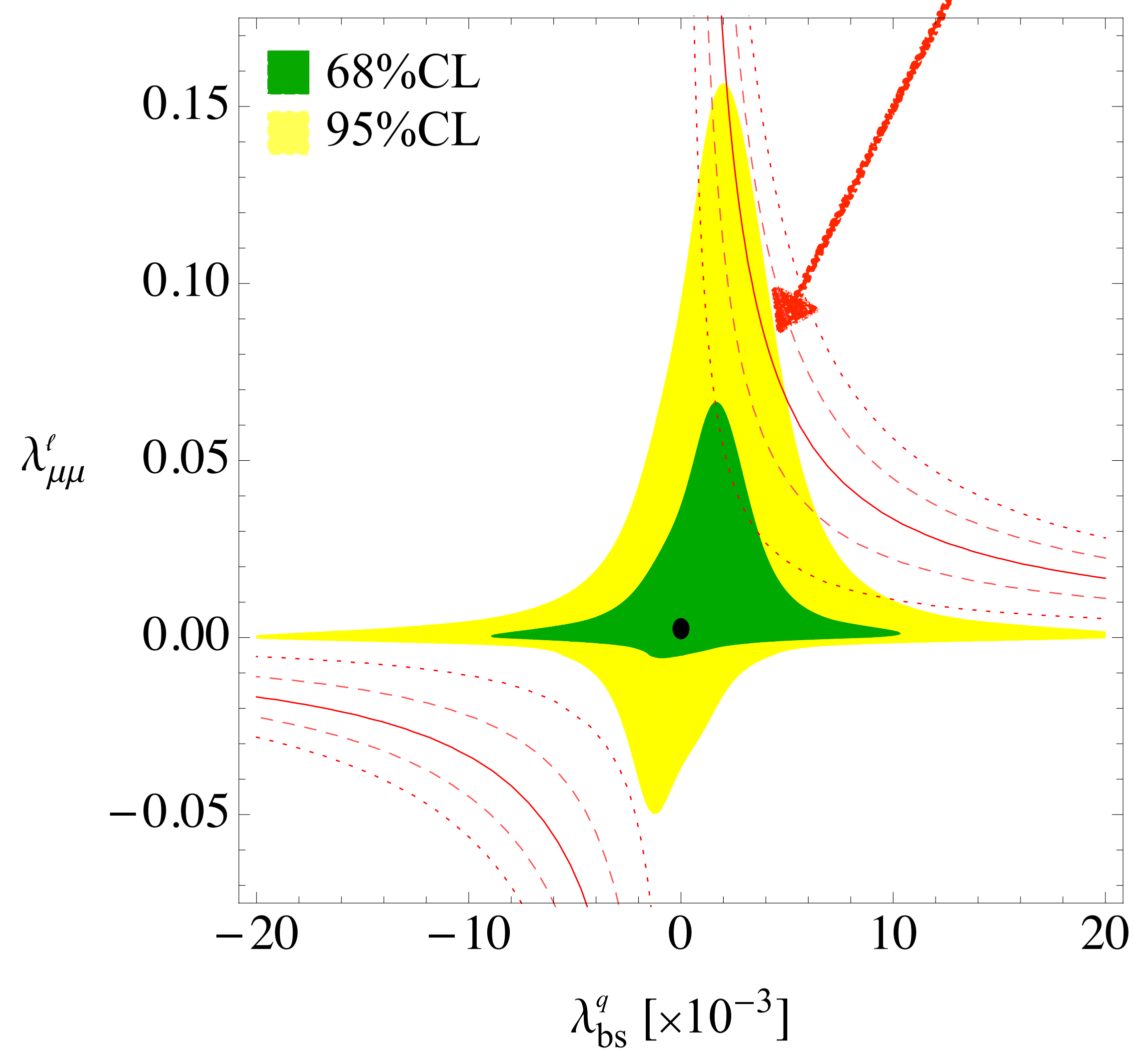
$$R_0(D^*) = \epsilon_\ell \epsilon_q$$

- Some tension with

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



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

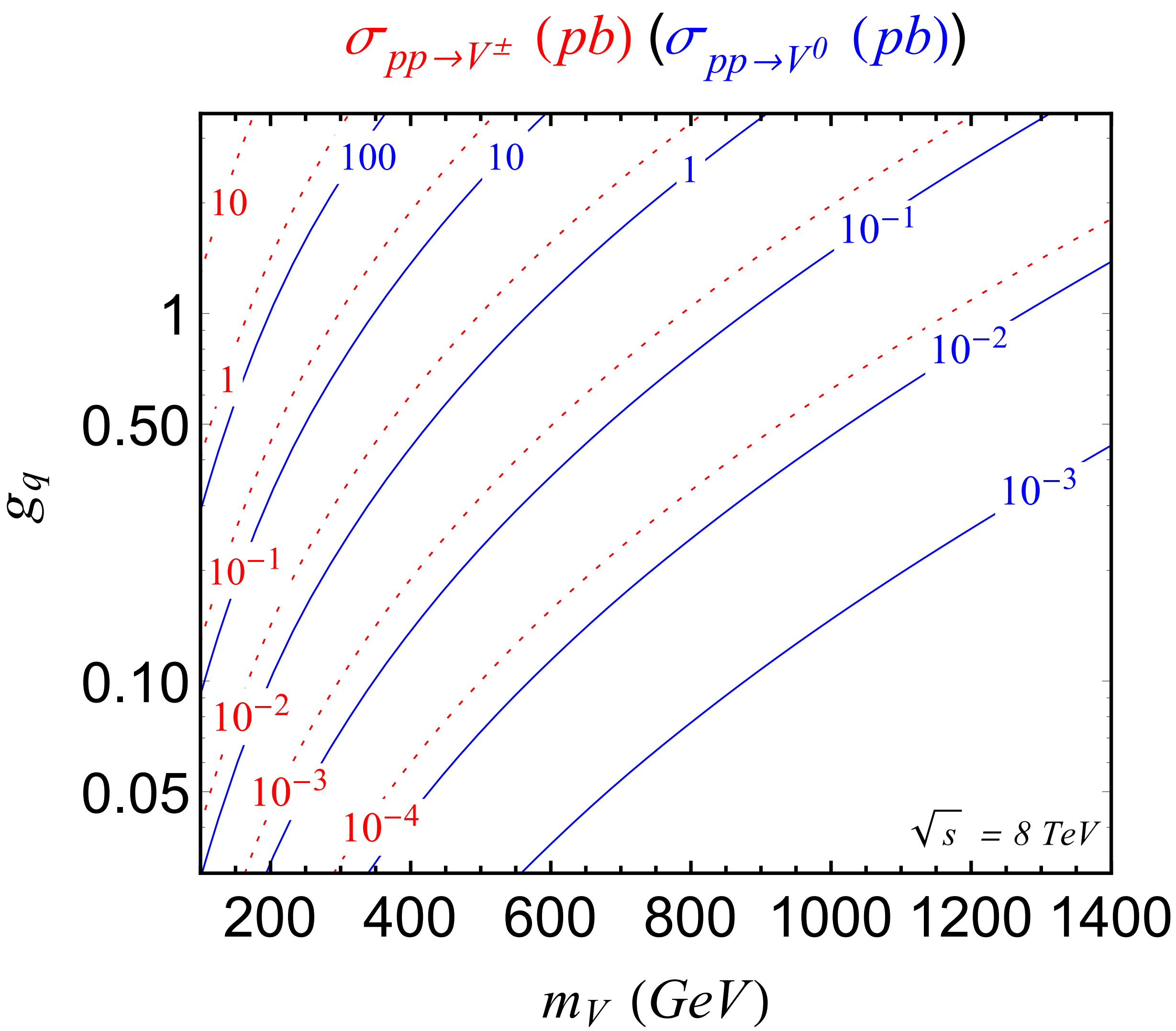


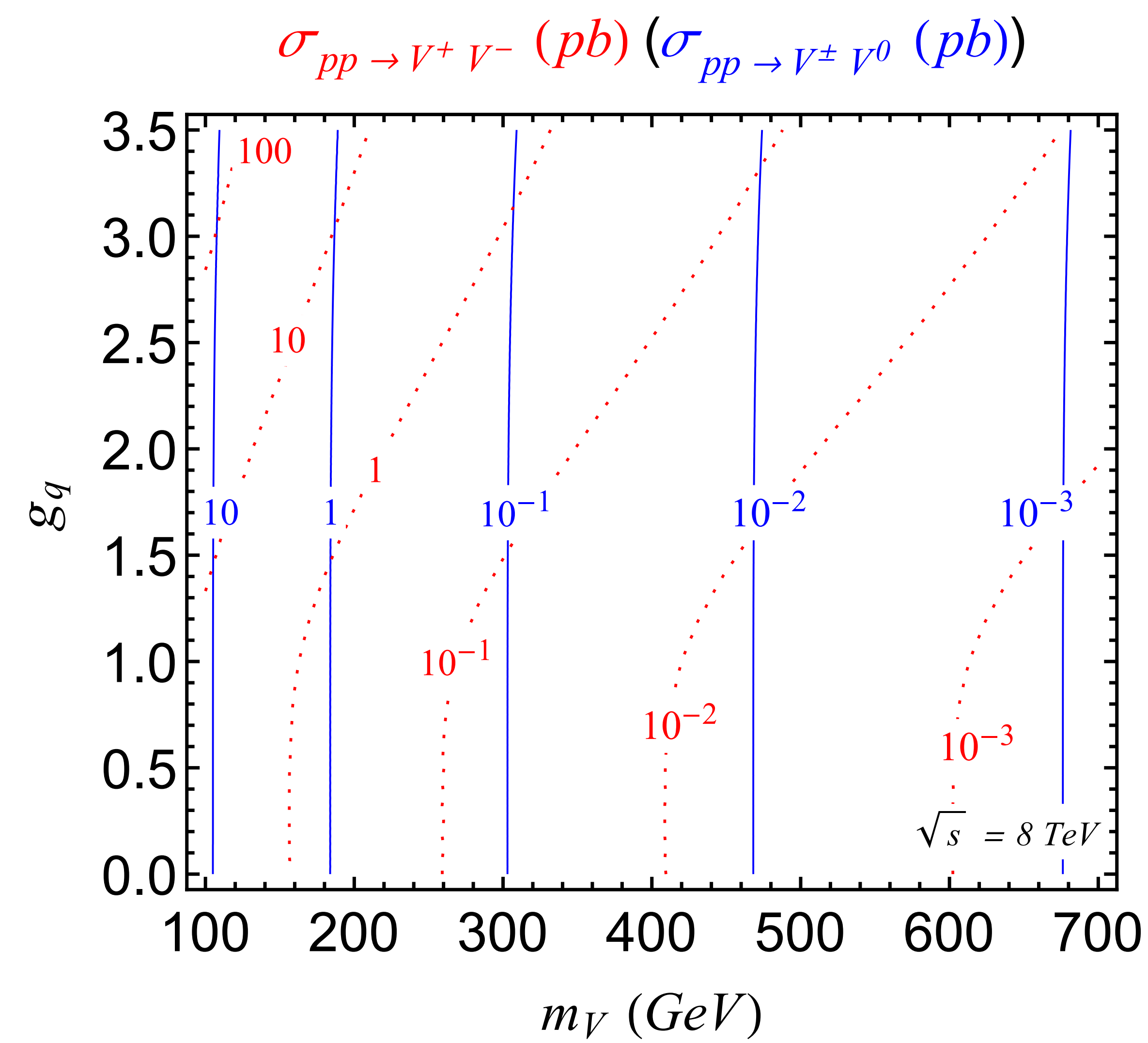
$$\boxed{\lambda^q_{bs} \sim \epsilon_1 V_{ts}}$$

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

VTM: *LHC phenomenology*

Production cross sections:





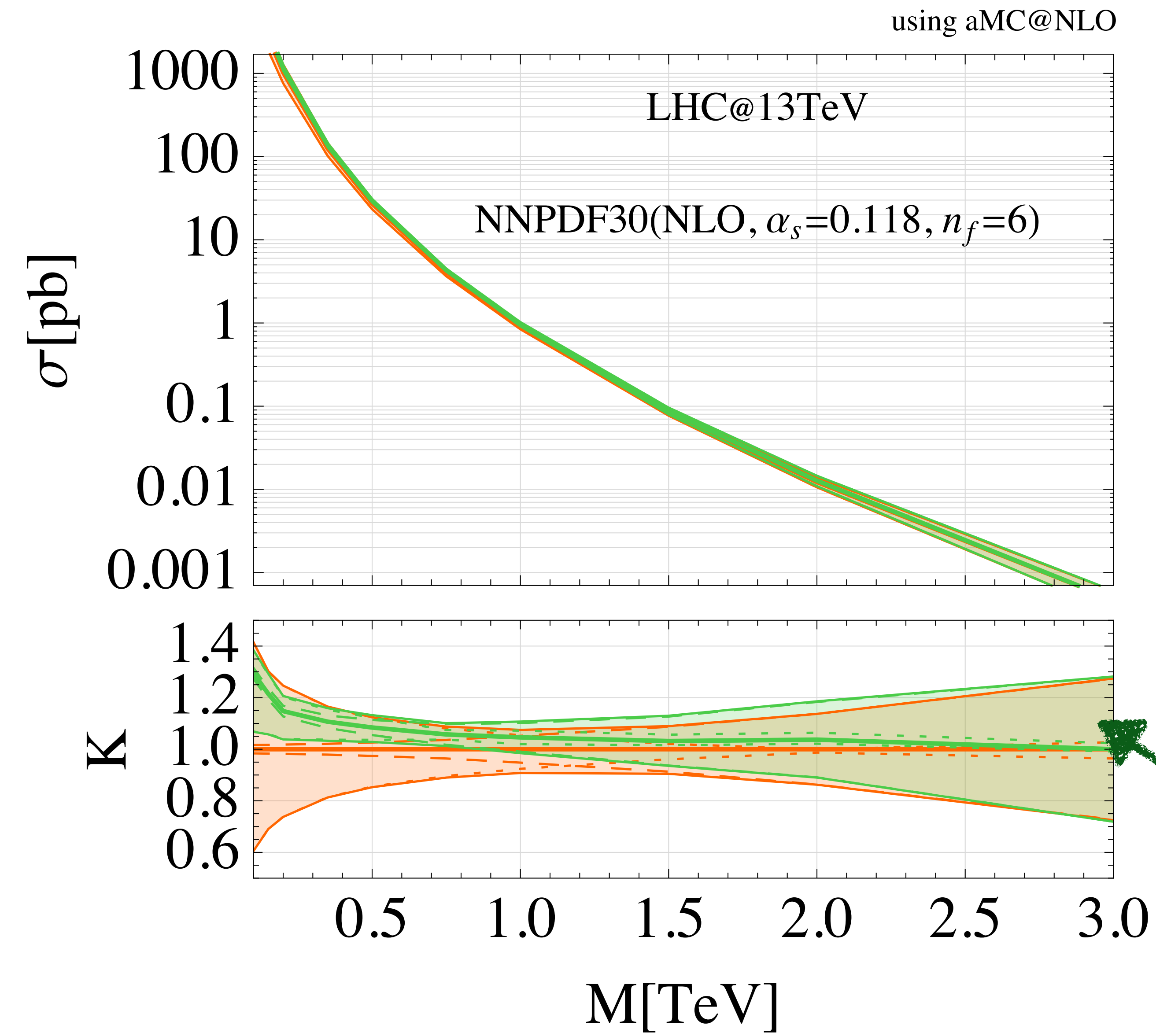
- Left: single V production ($bb \to V^0$, $b\,c \to V^+$)
- Right: pair production

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

VTM: LHC phenomenology

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

Z' production @ NLO QCD



pdf uncertainties

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