Universität Zürich[UZH]

Collider constraints on NP models aimed to address *B*-anomalies

Admir Greljo

Based on:

1704.09015 - AG, David Marzocca

Phys.Lett. B766 (2017) 77-85 - Andreas Crivellin, Javier Fuentes-Martin, AG, and Gino Isidori

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

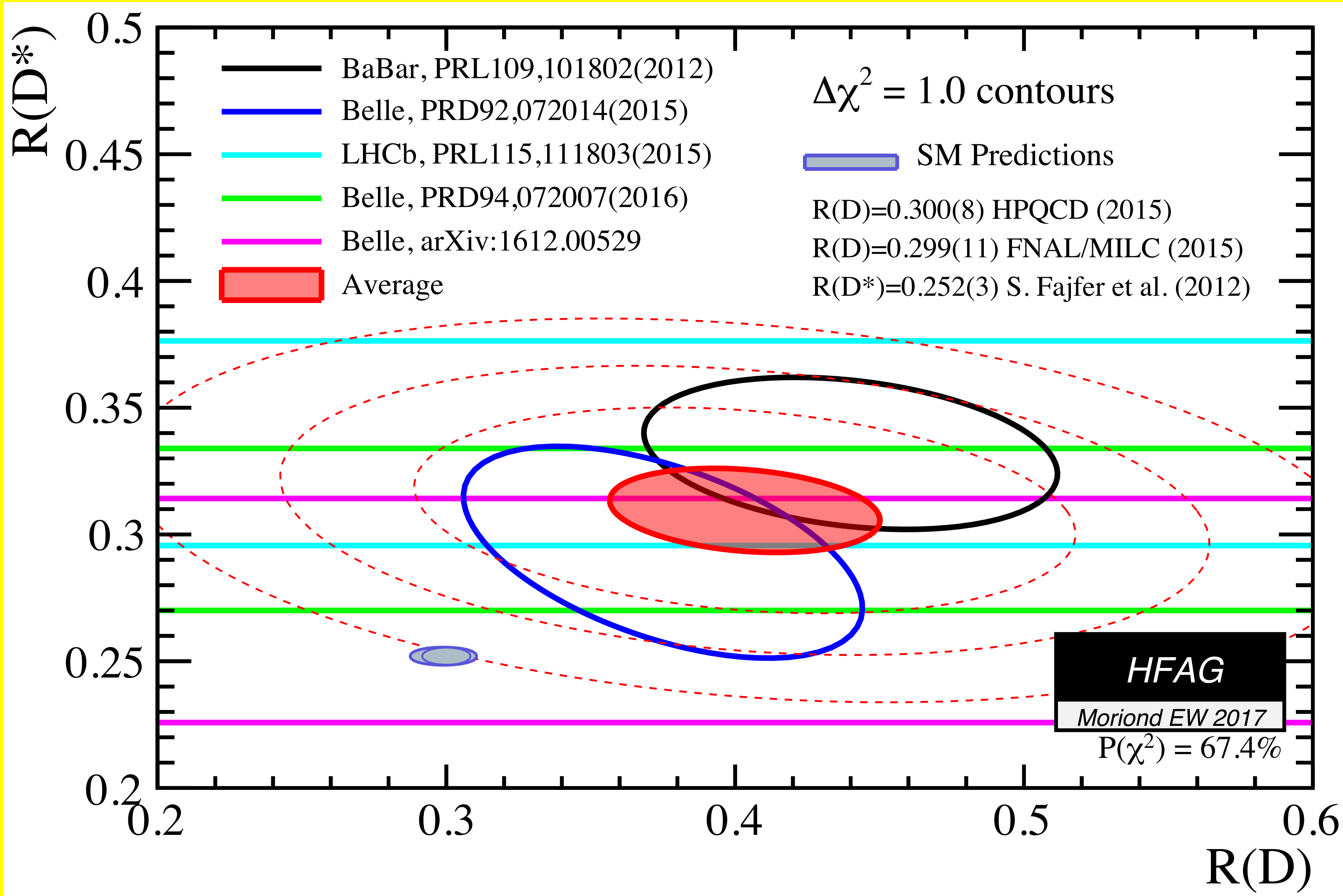
JHEP 1608 (2016) 035 - Dario Buttazzo, AG, Gino Isidori, David Marzocca

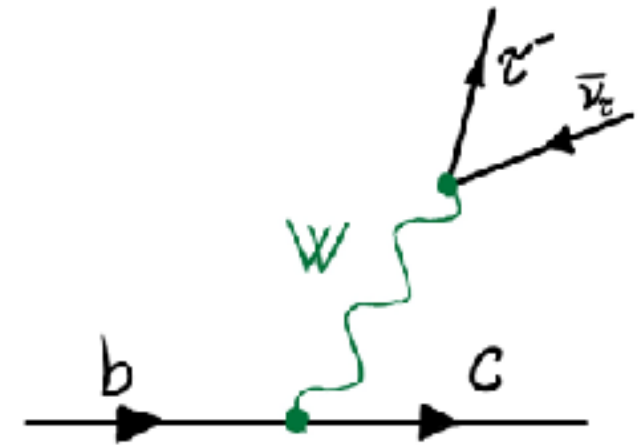
JHEP 1507 (2015) 142 - AG, Gino Isidori, David Marzocca

SM@LHC 2017, 04 May 2017 - Nikhef

Motivation (a): Violation 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 three (very) different experiments
- New results from LHCb expected soon [Federico Betti, Moriond 2017]

Motivation (b): Violation of LFU in neutral currents

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

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

Phys. Rev. Lett. 113 (2014) 151601

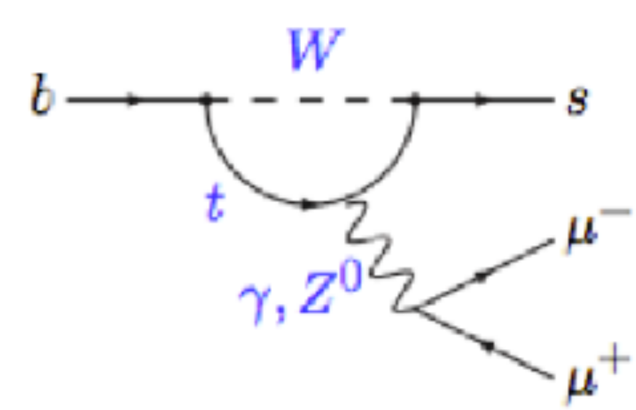
$$R_{K^*}^{[0.045,1.1]} = 0.660^{+0.110}_{-0.070}\pm 0.024$$

$$R_{K^*}^{[1.1,6]} = 0.685^{+0.113}_{-0.069}\pm 0.047$$

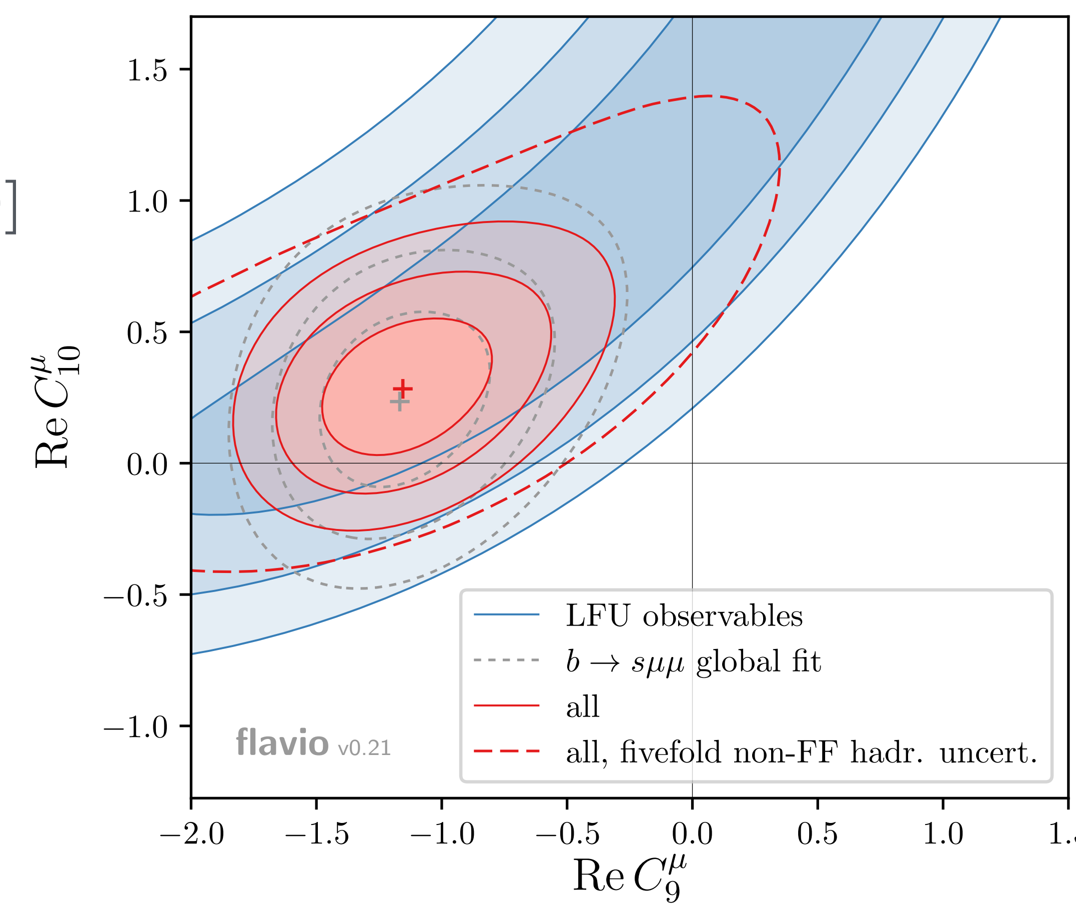
S. Bifani, CERN seminar

- *$B\to K^*\mu\mu$ angular distribution:* **P_5'**

JHEP 1602 (2016) 104



e.g. [Altmannshofer, Stangl, and Straub] 1704.05435



- Combined fit **(5.7σ)** [1704.05340]
- New physics contribution to muonic left-handed operator $(b_L\,\gamma_\mu\,s_L)(\mu\,\gamma^\mu\,\mu)$

Okey.

What to expect at the high-p_T LHC?

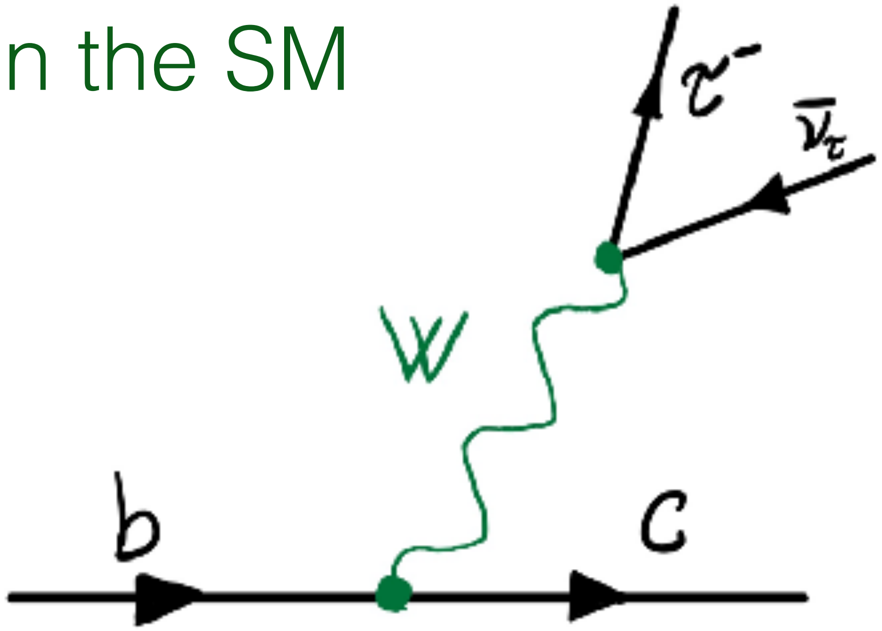
This talk

Part 1

R(D) & *R(D*)*

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

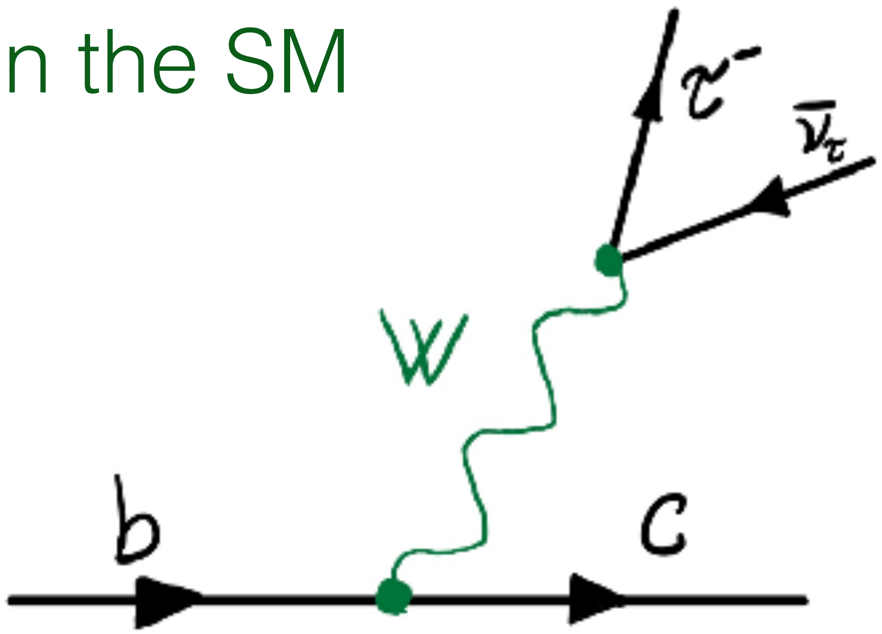
In the SM



- Tree-level process
- Mild CKM suppression

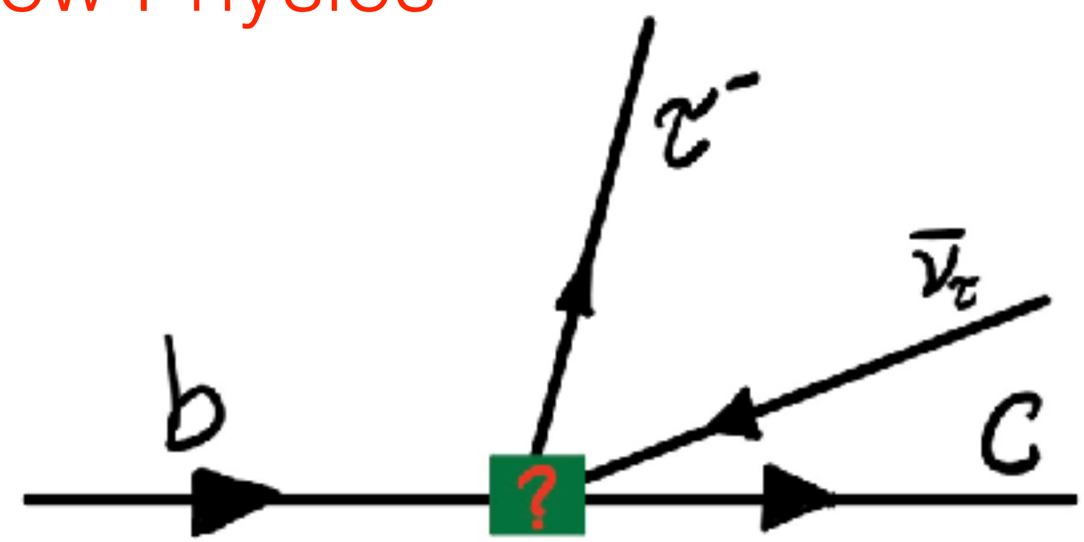
Prologue: Violation of LFU in $B \to D^{(*)} \tau \nu$ decays

In the SM



- Tree-level process
- Mild CKM suppression

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

Step I

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

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

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

- Only the four-fermion operators

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$ ⟶ corrections to *W* decays

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$ ⟶ no LFU violation

- List of the relevant operators:

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

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

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

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

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

Step I

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

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

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

- Only the four-fermion operators

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$ ⟶ corrections to *W* decays

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$ ⟶ no LFU violation

- List of the relevant operators:

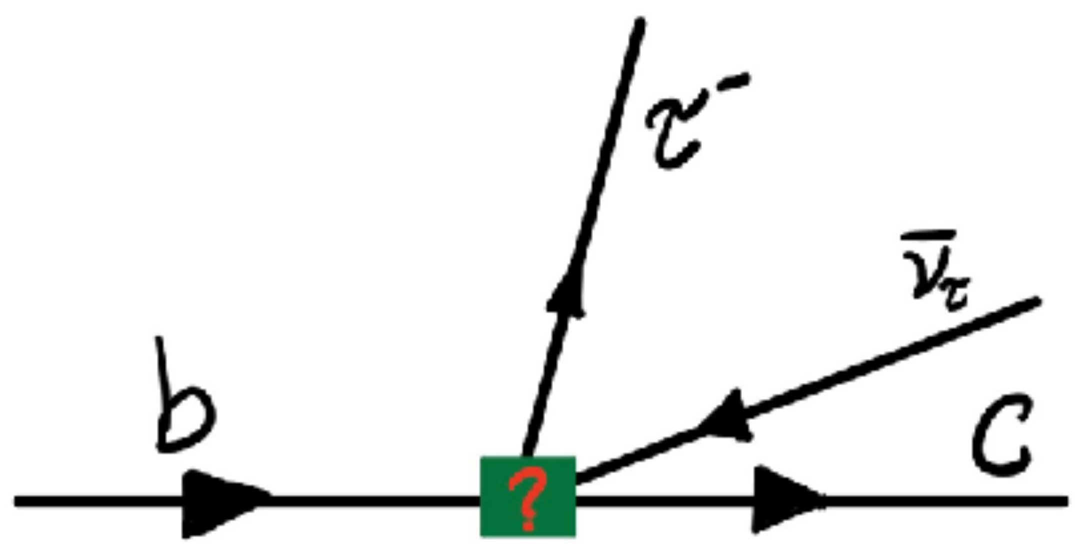
[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

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

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

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

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



Step I

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

- Leading effects - dim-6 operators
  (Presumably tree-level

$\mathcal{L}_{eff}$

- Only the four-ferm

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu$

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu$

- List of the releva

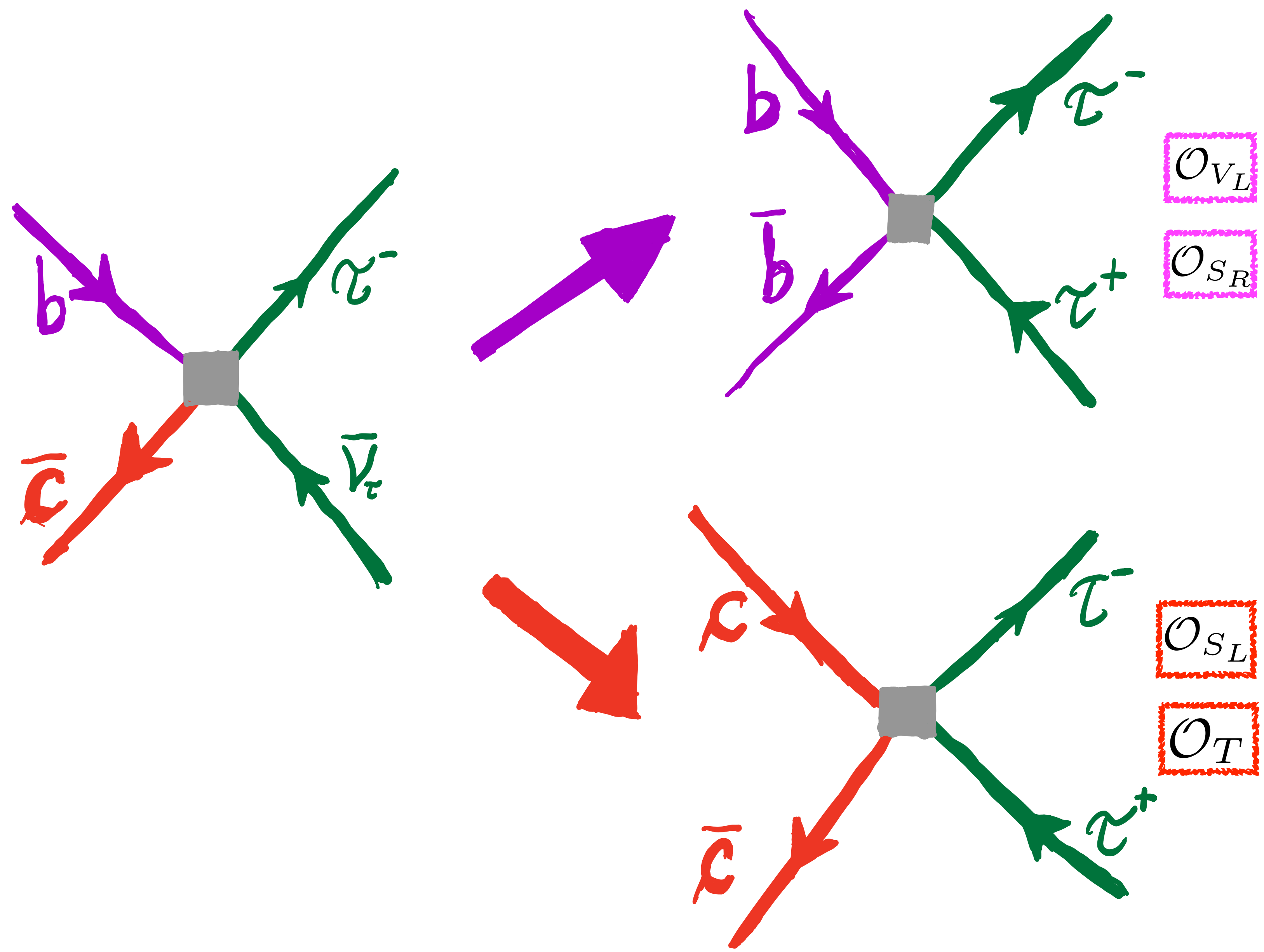
$\mathcal{O}_{V_L}$ $(\bar{Q}_i \gamma_\mu \sigma^a Q_j$

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

$\mathcal{O}_{S_L}$ $(\bar{Q}_i u^j_R) i\sigma^2 ($

$\mathcal{O}_T$ $(\bar{Q} \sigma_{\mu\nu} u^j_R) i\sigma$

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



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

Step I

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

- Leading effects - dim-6 operators
  (Presumably tree-level

$\mathcal{L}_{eff}$

- Only the four-ferm

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu$

$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu$

- List of the releva

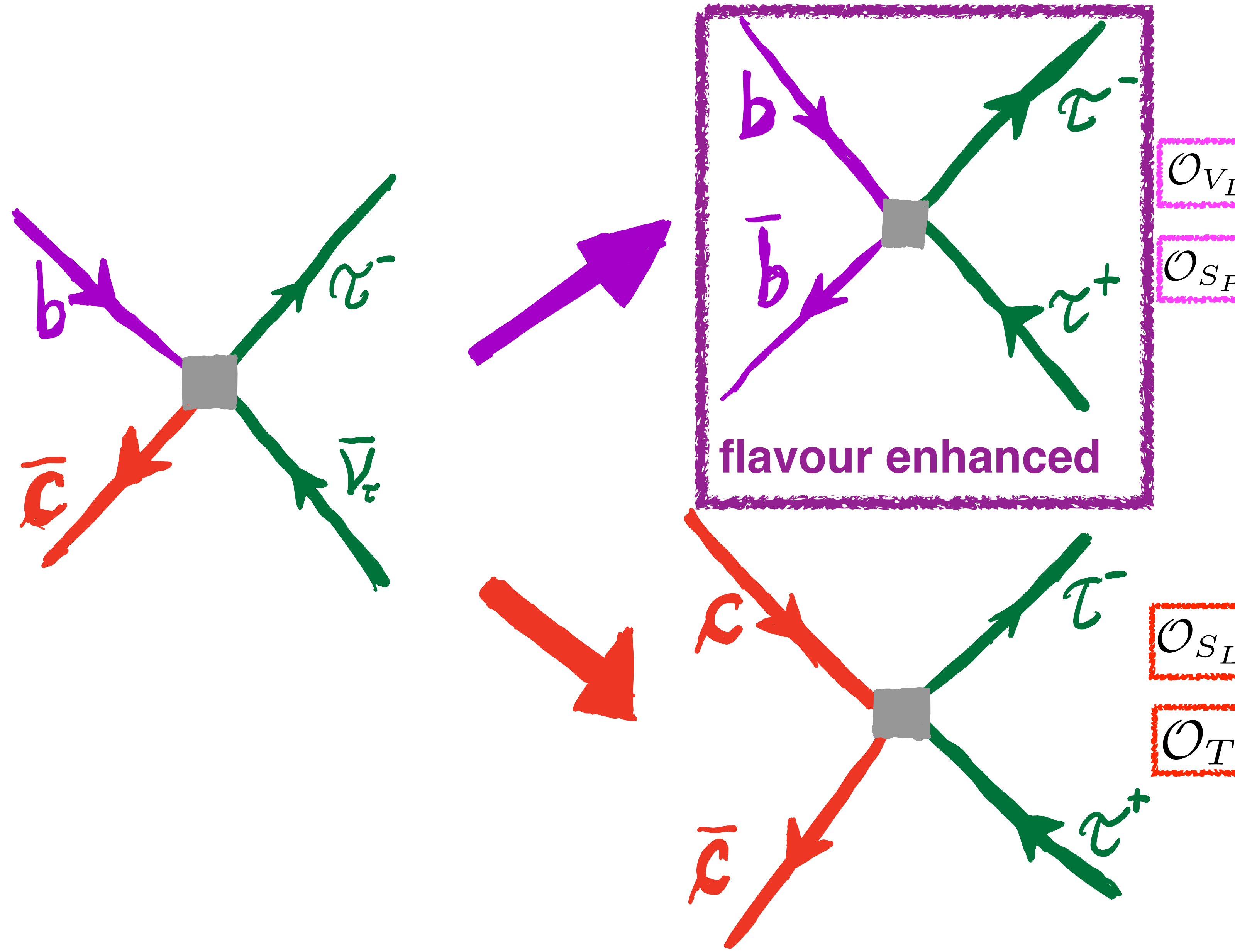
$\mathcal{O}_{V_L}$ $(\bar{Q}_i \gamma_\mu \sigma^a Q_j$

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

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

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

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



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

Flavour structure

[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)

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

Consistent with the U(2) flavour symmetry

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

Flavour structure

[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)

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

Consistent with the U(2) flavour symmetry

[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

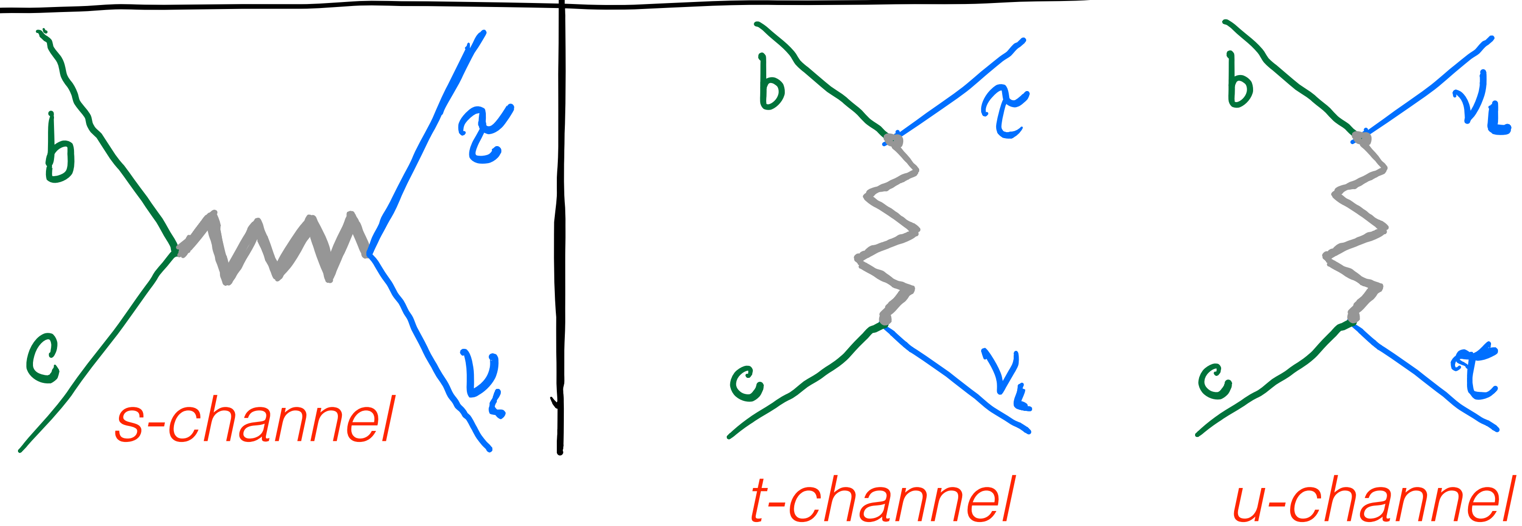
Single mediator models (8 options)

No light ν_R

Step II

- Color: **1** or **3**

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



- Spin: **0**, **1**, …
- SU(2) weak: **1**, **2** or **3**

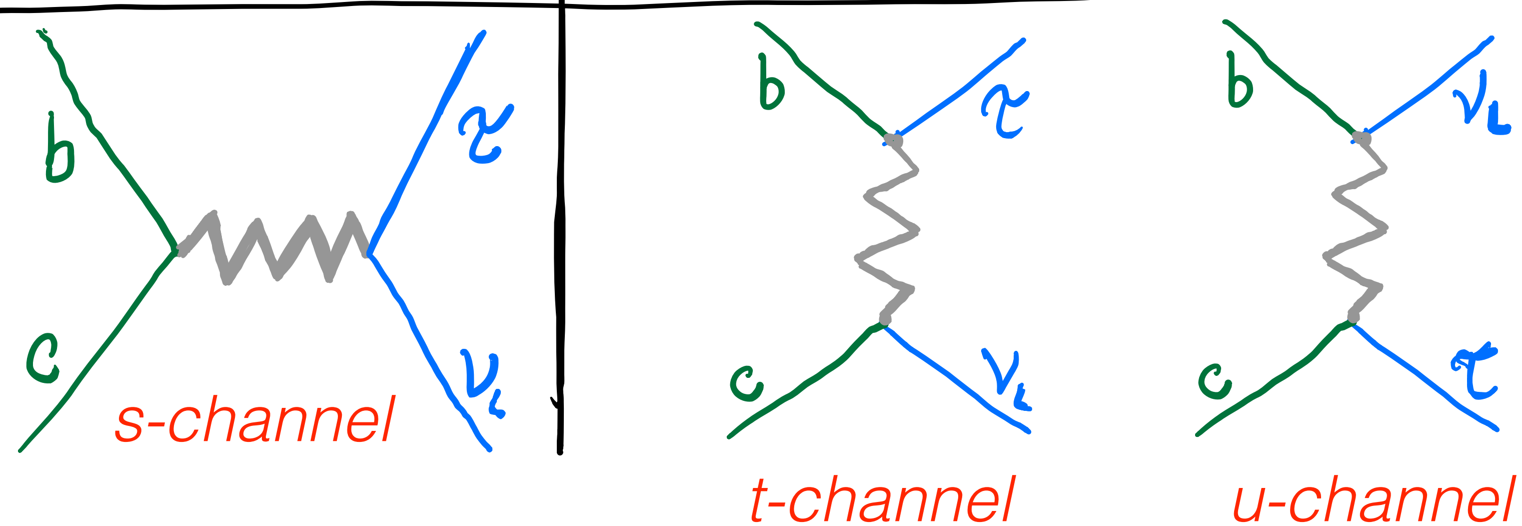
Single mediator models (8 options)

No light ν_R

Step II

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

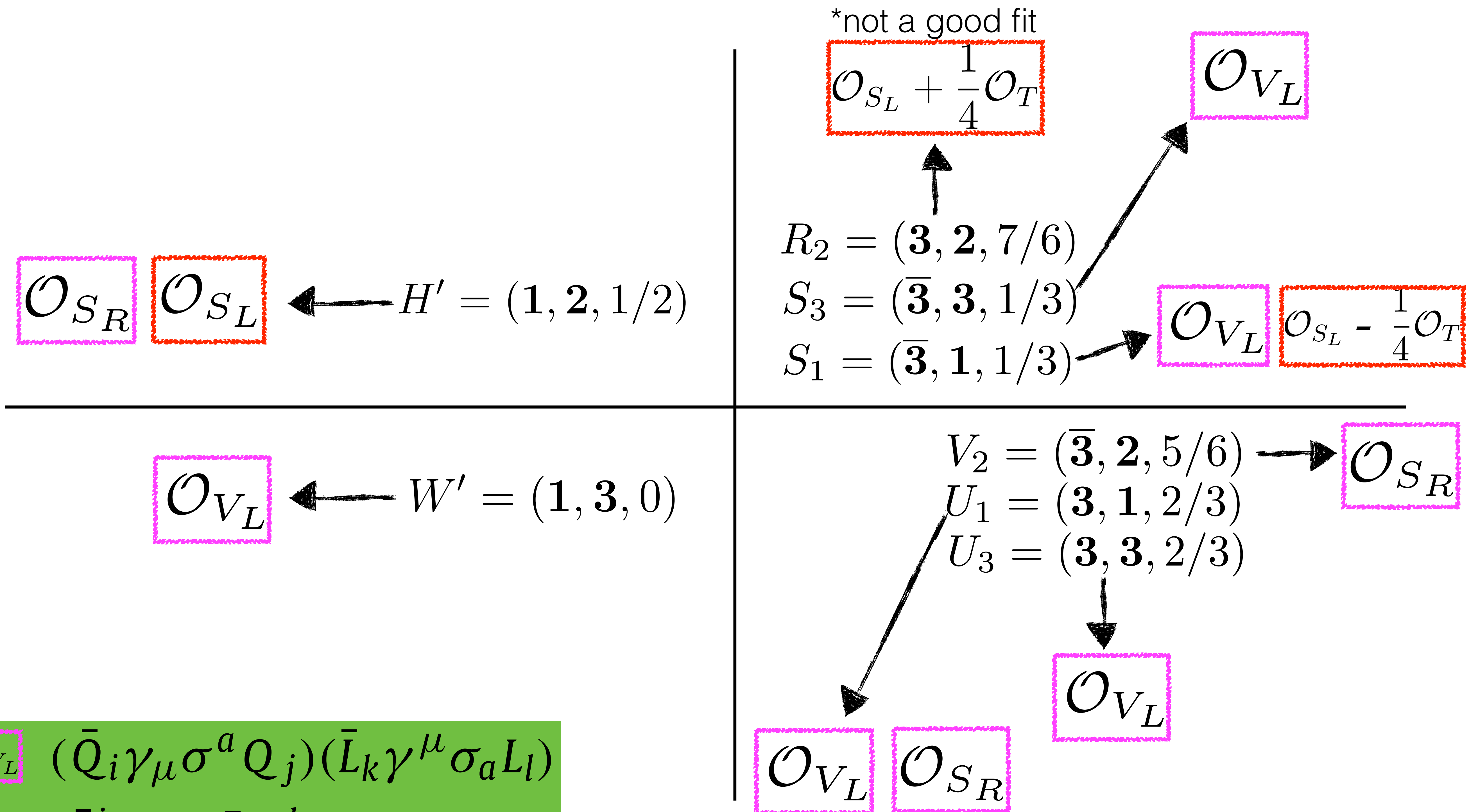
Spin \ Color	1	3
0	$H' = (\mathbf{1}, \mathbf{2}, 1/2)$	$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$ $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
1	$W' = (\mathbf{1}, \mathbf{3}, 0)$	$V_2 = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$ $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$ $U_3 = (\mathbf{3}, \mathbf{3}, 2/3)$



See Table 3 in [Doršner, Fajfer, AG, Košnik, F. Kamenik] Phys.Rept. 641 (2016) 1-68

- SU(2) weak: **1**, **2** or **3**

Single mediator models & SM EFT



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

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

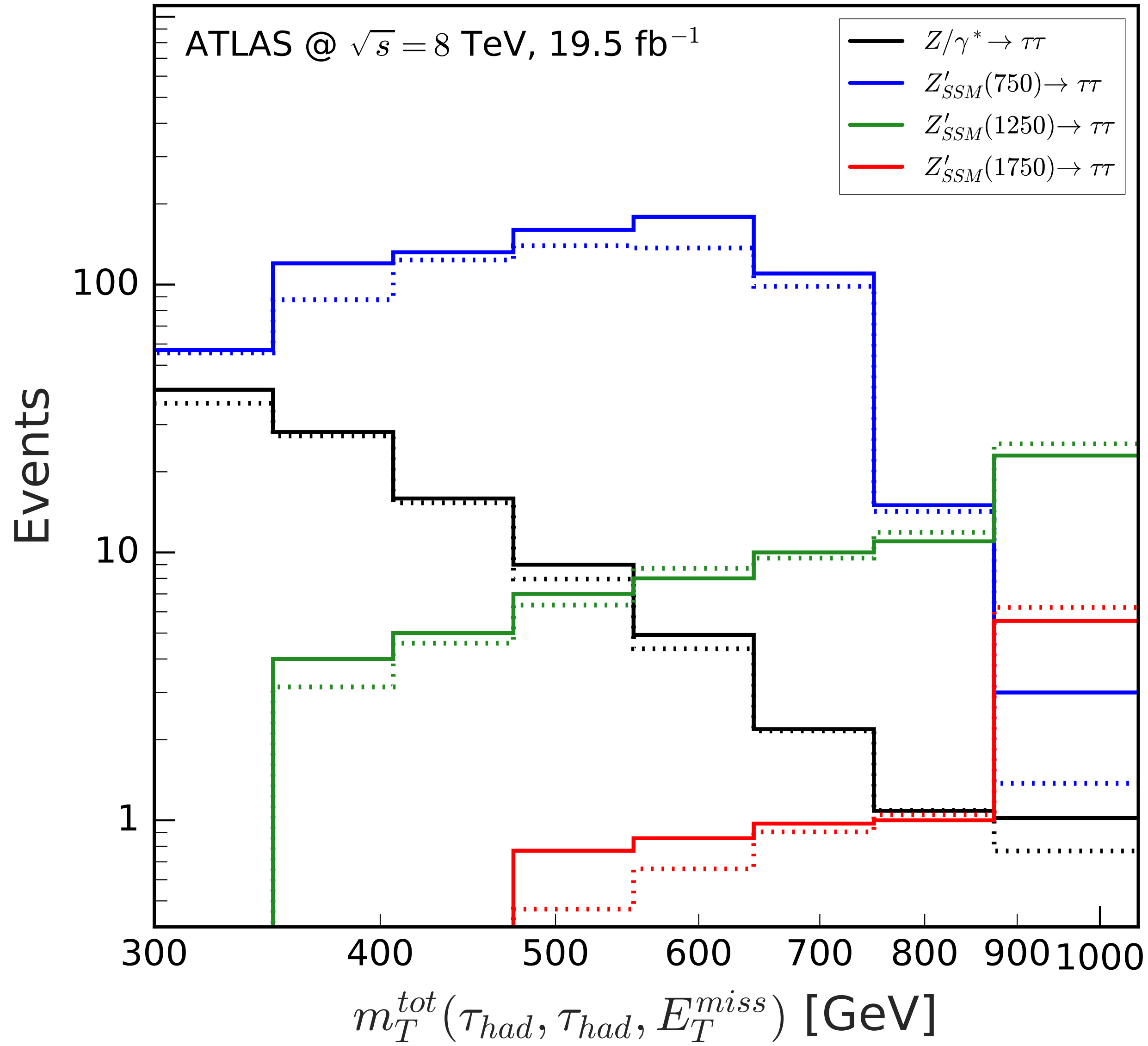
$\mathcal{O}_{S_L}$ $\quad (\bar{Q}_i u^j_R) i\sigma^2 (\bar{L}_k \ell^l_R)$

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

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

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

- Predicted high-p_T events have a peculiar kinematics
- Full simulation pipeline:
  FeynRules>MadGraph>Pythia>Delphes
- Validated against the SM bckg, and the sequential Z'
- Set limits by fitting the total transverse mass variable:



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

Single mediator models subject to $\tau^+\tau^-$ search limits

- With V_{cb} suppression in $b\,c \to \tau\,\nu$

YES ← $H' = (\mathbf{1}, \mathbf{2}, 1/2)$

Not a good fit ← $R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$

YES ← $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

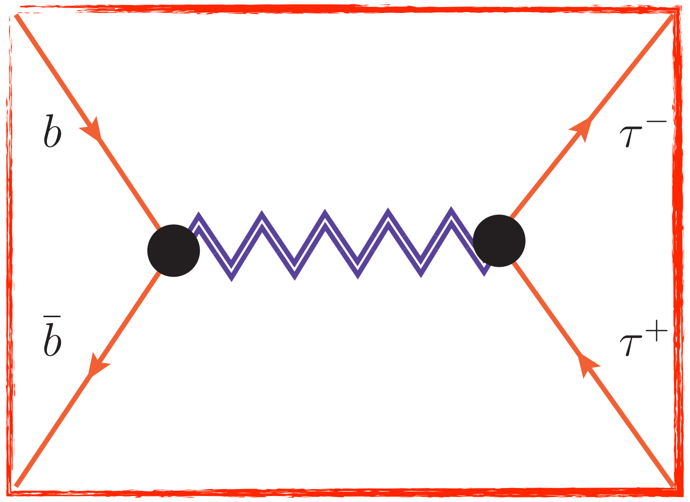
NO $bb \to \tau\tau$ ← $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

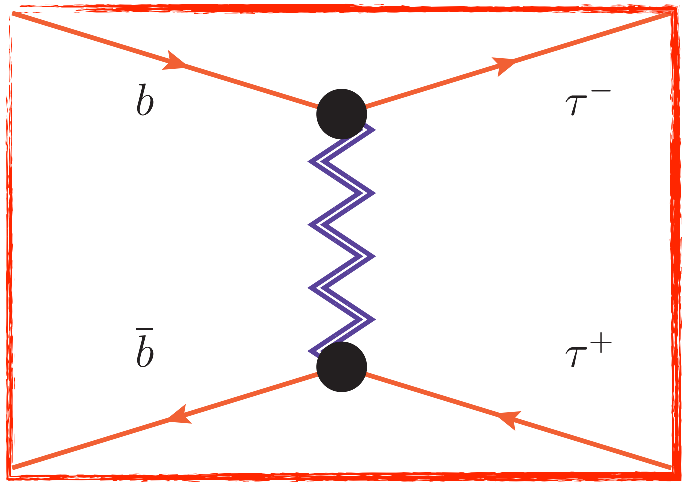
YES ← $W' = (\mathbf{1}, \mathbf{3}, 0)$

$V_2 = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$ → **YES**

YES ← $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

$U_3 = (\mathbf{3}, \mathbf{3}, 2/3)$ → **YES**





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

Vector Triplet Model - W'

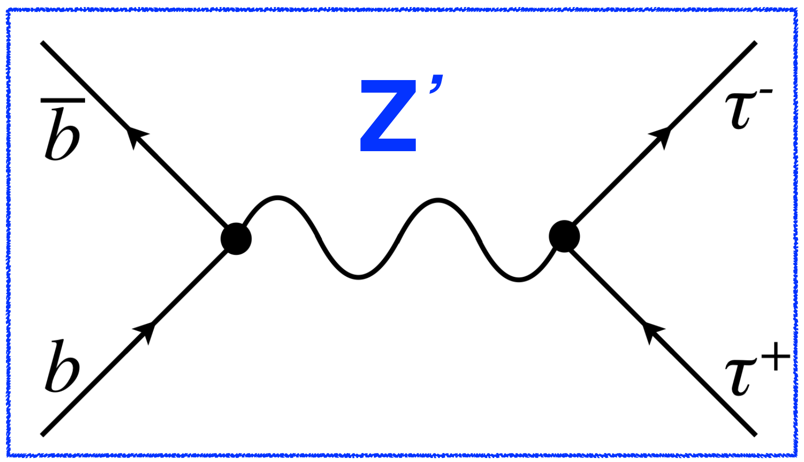
Example

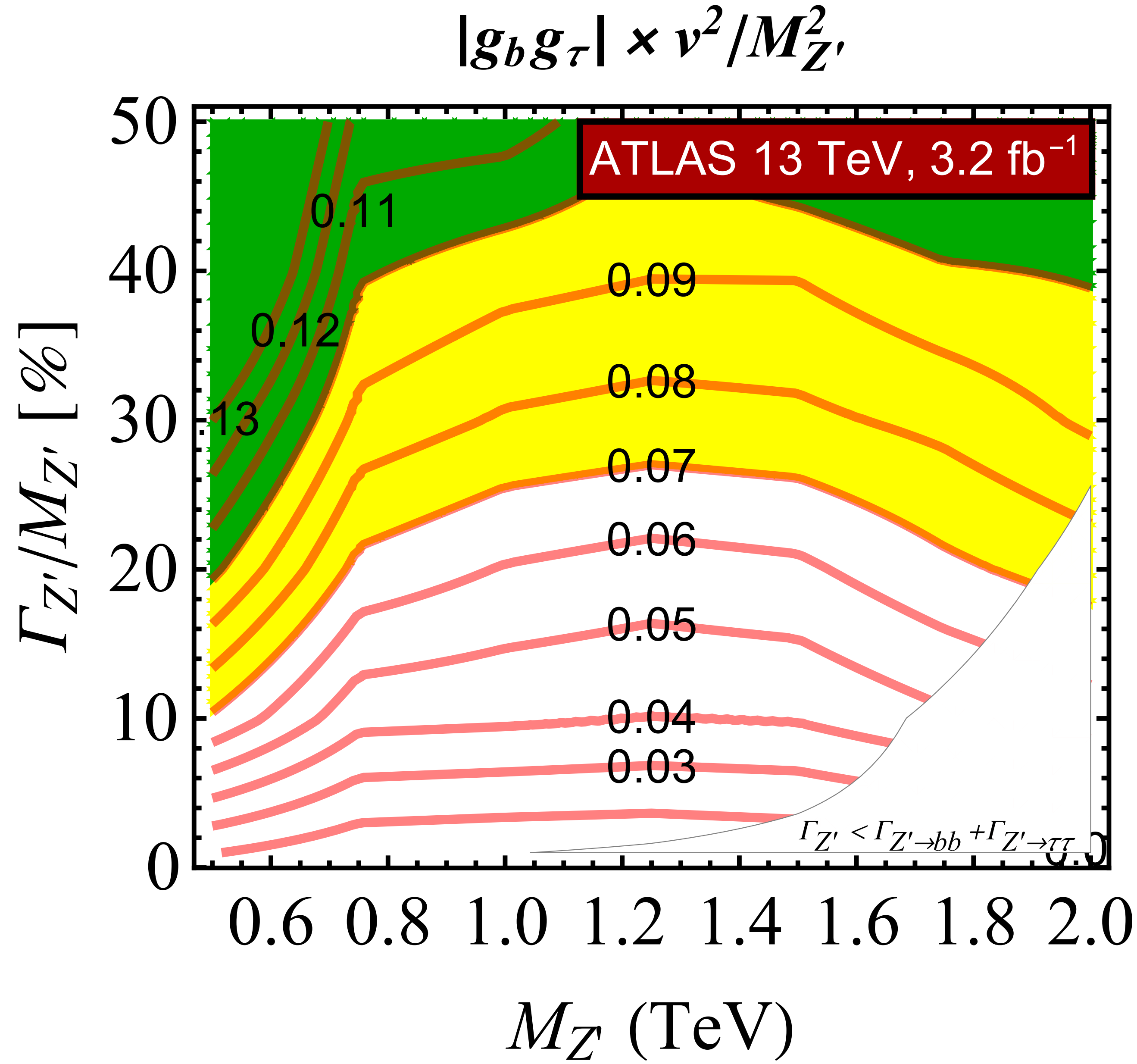
[AG, Isidori, Marzocca] JHEP 1507 (2015) 142

$$W' = (\mathbf{1}, \mathbf{3}, 0)$$

Fit to R(D*) anomaly
$|g_b g_\tau| \times v^2/M_{Z'}^2 = (0.13 \pm 0.03)$

Look for





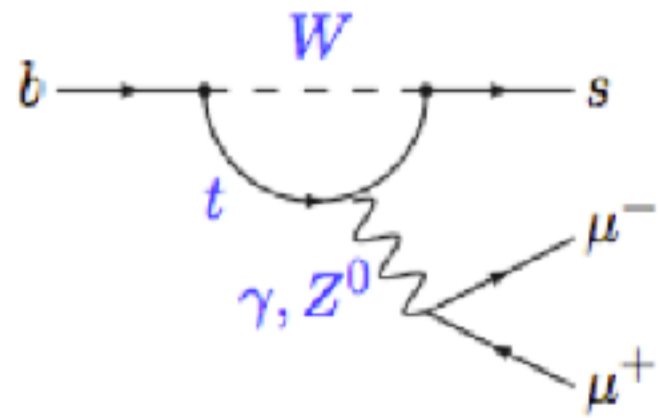
We set a limit on $|g_b g_\tau|$ as a function of the Z' mass and the total width

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

Part 2

R(K)* & *R(K*)

b → s μ μ anomaly & SM EFT

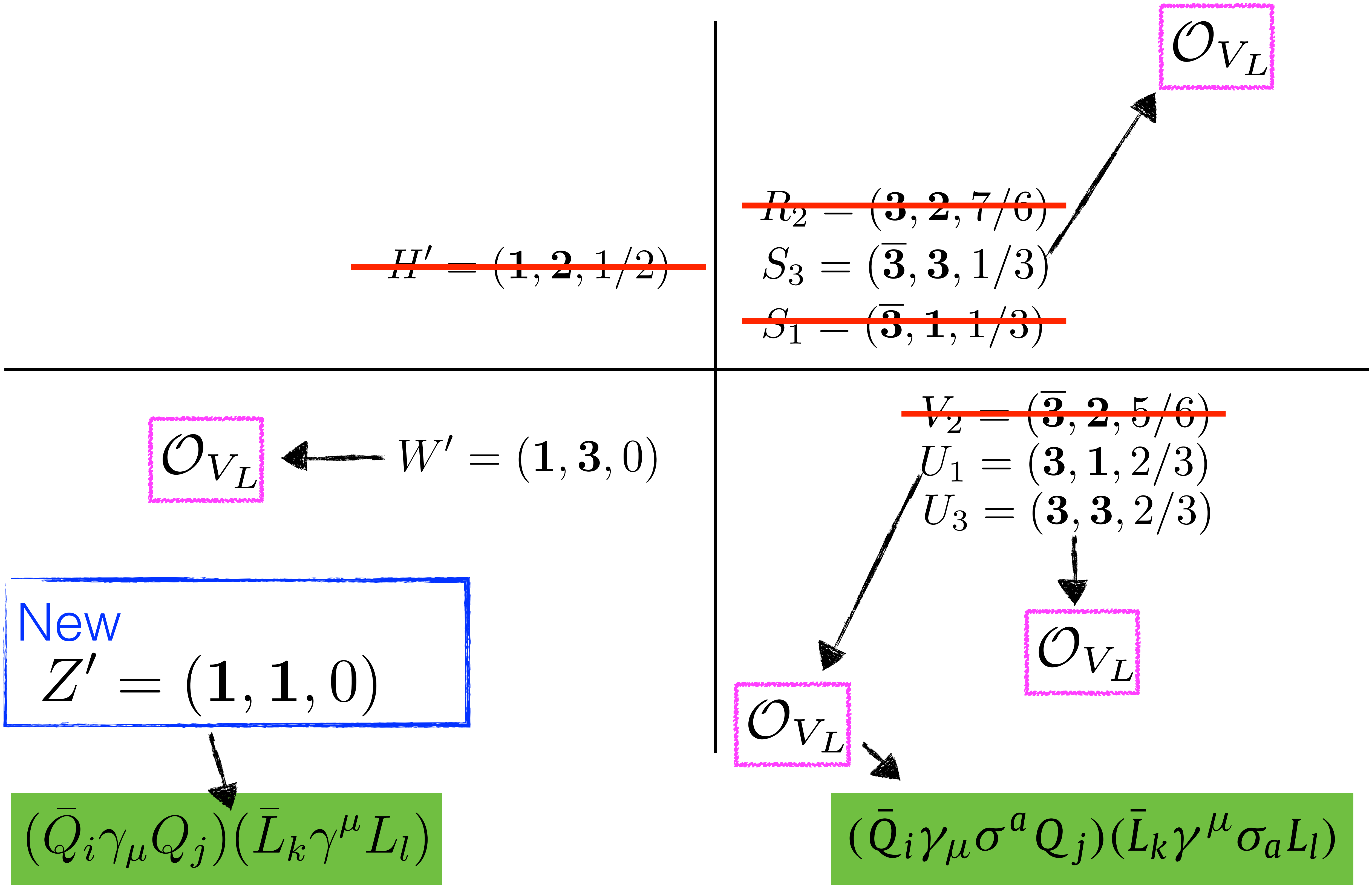


$$\Delta C_9^\mu = -\Delta C_{10}^\mu = -0.61 \pm 0.12 \longrightarrow \Lambda / g_* \approx 32^{+4}_{-3}\ \text{TeV}$$

- *New physics within or beyond the LHC threshold production*
- *Data points towards*

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

b → s μ μ anomaly & Single mediator models



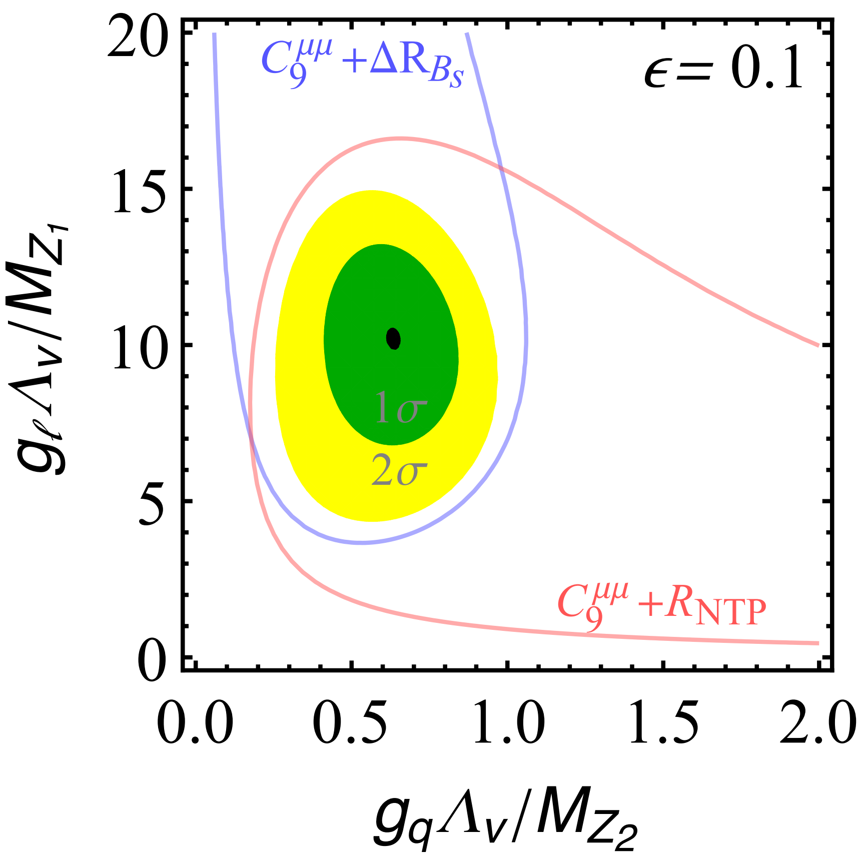
- *b → s μ μ at tree level*

Resonance searches

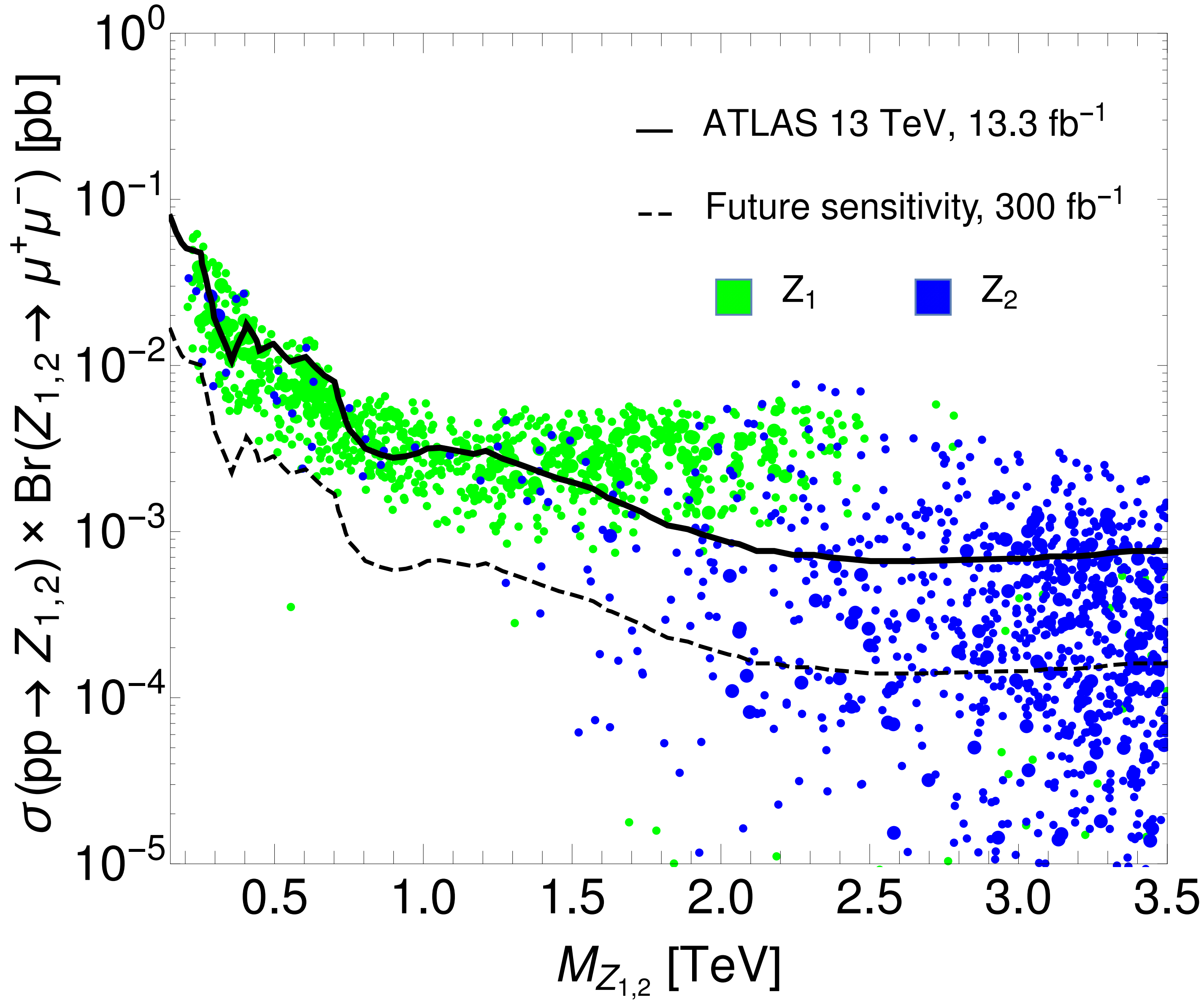
[Crivellin, Fuentes-Martin, AG, and Isidori]
Phys.Lett. B766 (2017) 77-85

Model example:

- Gauged $U(1)_q \times U(1)_{\mu-\tau}$
- Two Z' bosons
- Mass mixing
$$\delta\hat{M}^2 = \hat{M}_{Z_q}\hat{M}_{Z_\ell}\epsilon$$



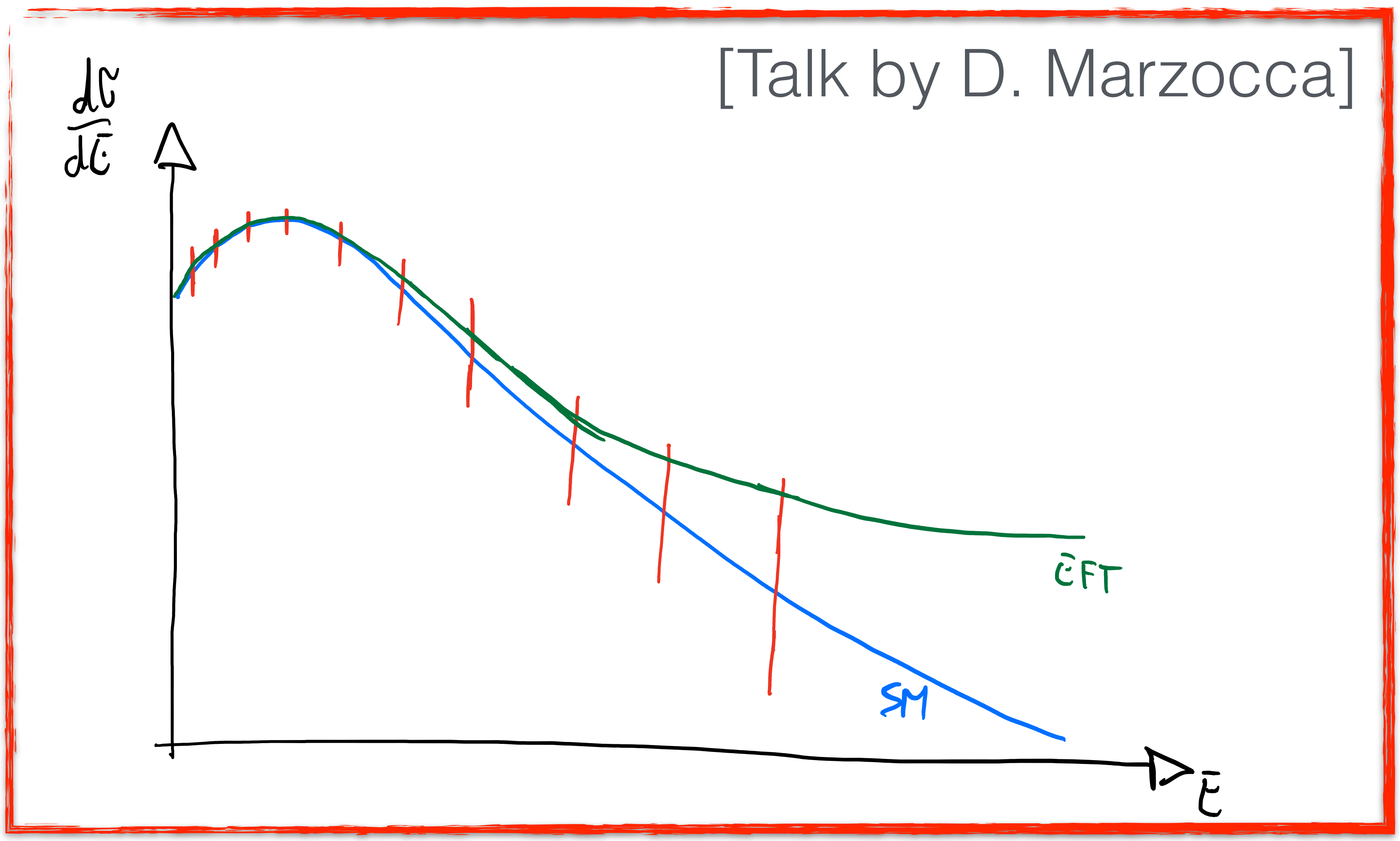
Two dimuon resonances



Drell-Yan tails

[AG, and D. Marzocca]
1704.09015

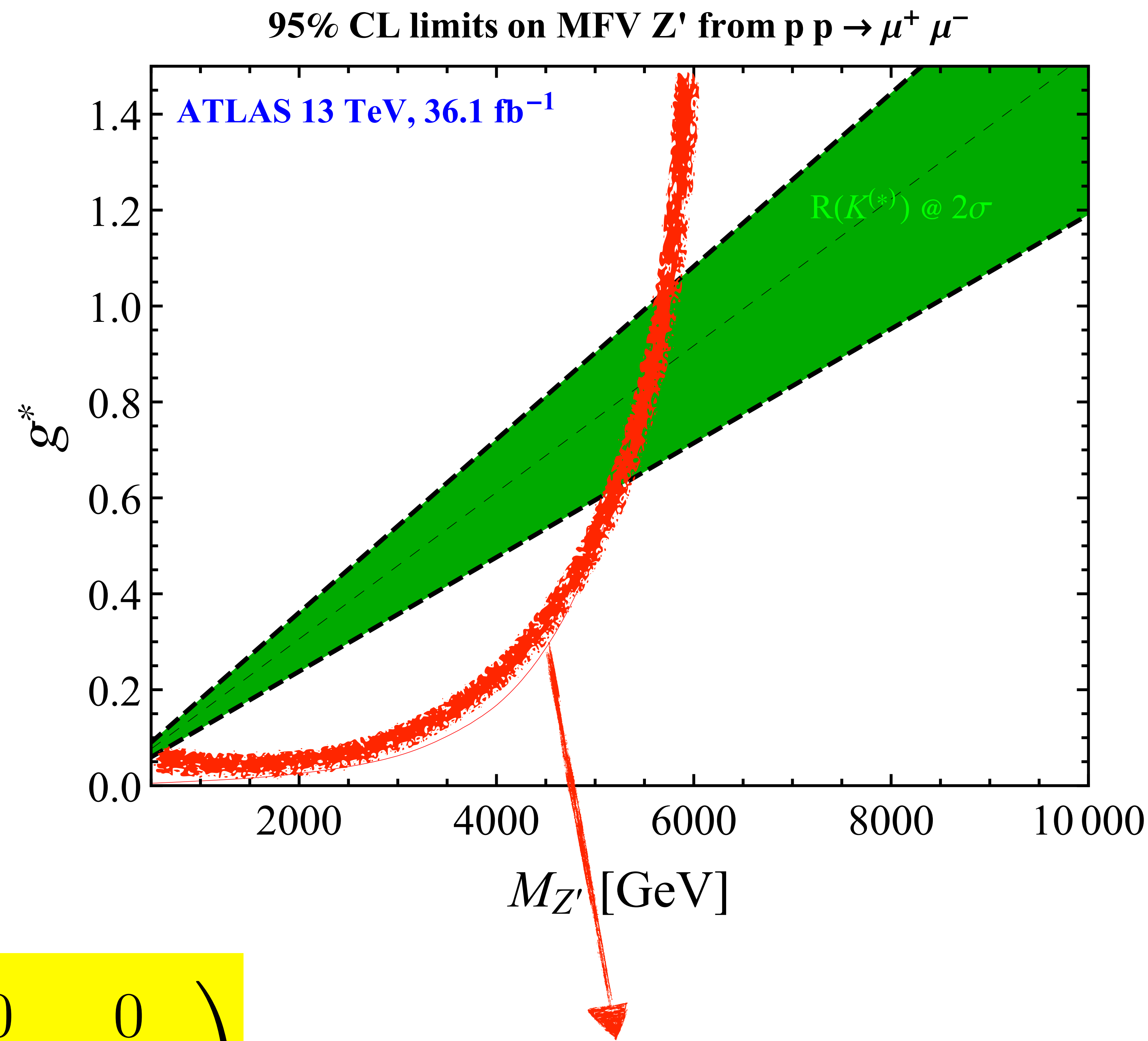
- High-energy tails in the dimuon spectrum
- Strong limits on the flavour-conserving operators (no flat directions)
- Complementary info on the NP flavour structure



Drell-Yan tails

[AG, and D. Marzocca]
1704.09015

Model example:
MFV Z' boson



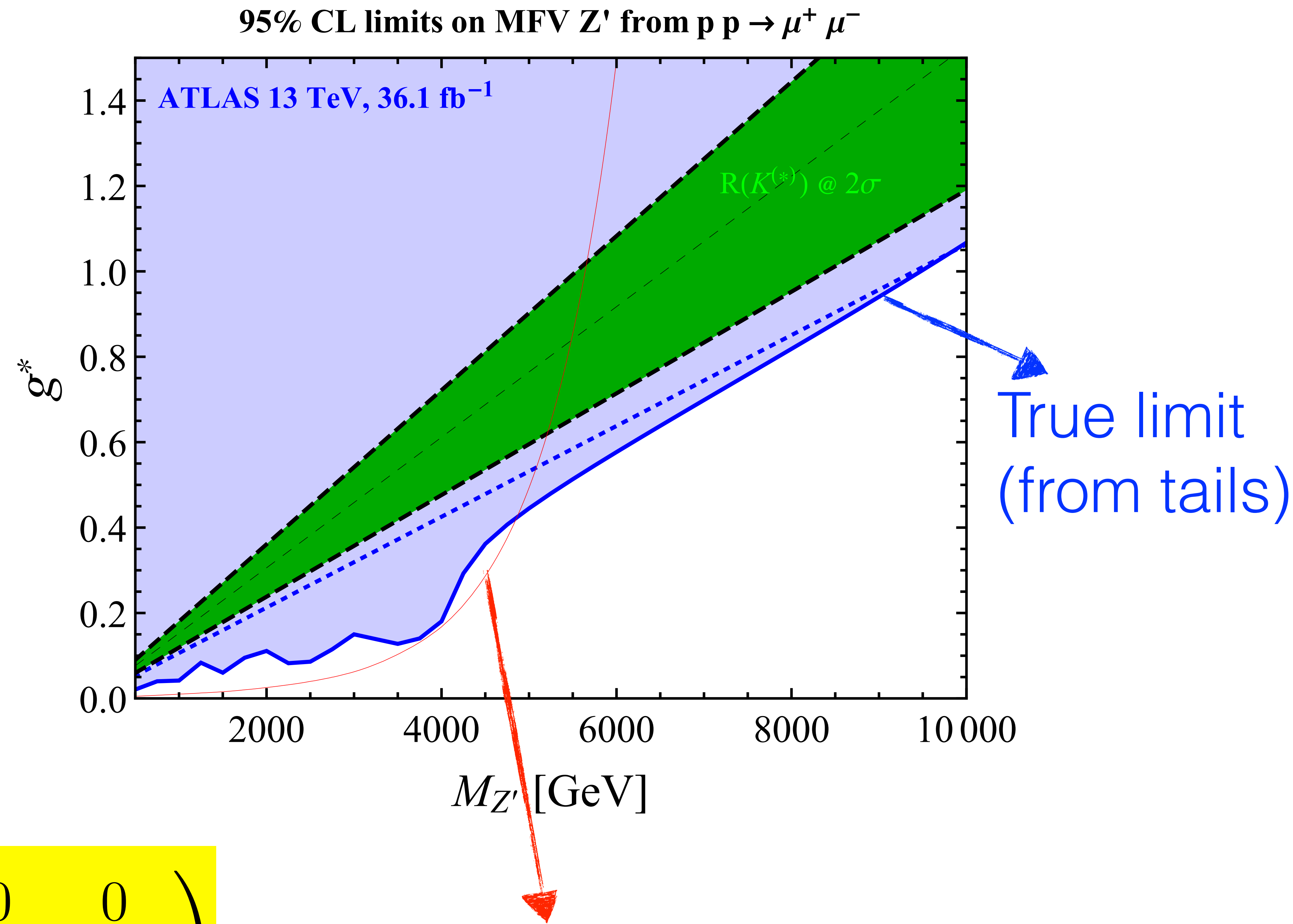
$$(Z'\bar{q}q)_{ij} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & V_{ts}^* \\ 0 & V_{ts} & 1 \end{pmatrix}$$

Resonance search limit stops here

Drell-Yan tails

[AG, and D. Marzocca]
1704.09015

Model example:
MFV Z' boson



$$(Z'\bar{q}q)_{ij} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & V_{ts}^* \\ 0 & V_{ts} & 1 \end{pmatrix}$$

Conclusions

- *$R(D^{(*)})$: Di-Tau signal at the high-p_T!*
- *$R(K^{(*)})$: Even if the mass scale of New Physics is well beyond the kinematical reach for on-shell production, the signal in the high-p_T dilepton tail might still be observed*

Stay tuned…

… for the interplay of flavour and collider physics in years to come…

Backup slides

EFT approach: Matching to the simplified models

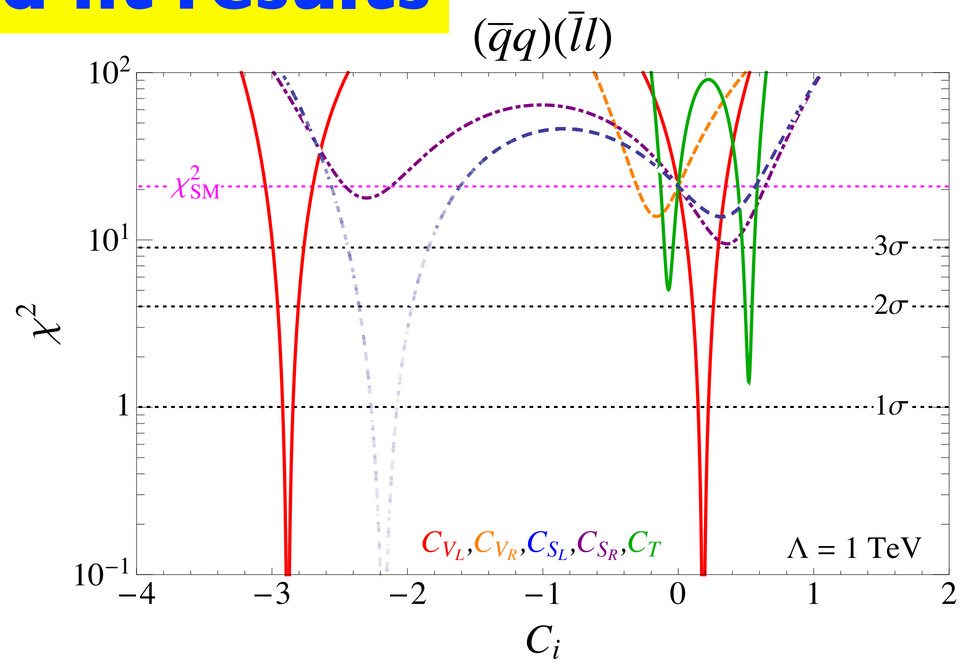
Three operator bases | **Simplified models**

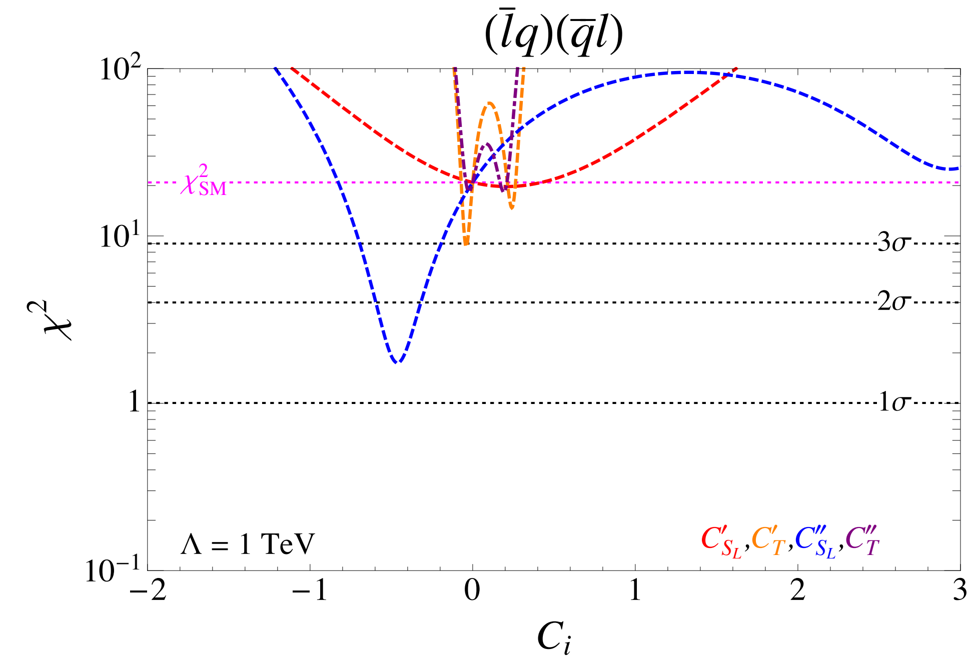
	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\rm int}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L) W'_\mu$
$\mathcal{O}_{V_R}$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

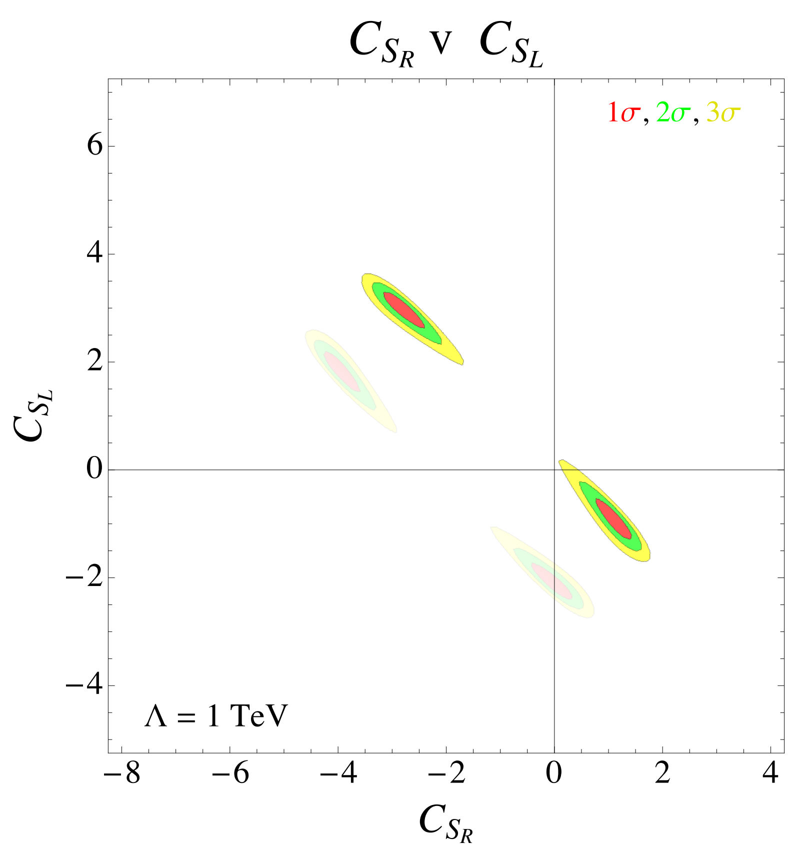
[Freytsis, Ligeti, Ruderman]
Phys.Rev. D92 (2015) no.5, 054018

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

Flavour structure

[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)

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

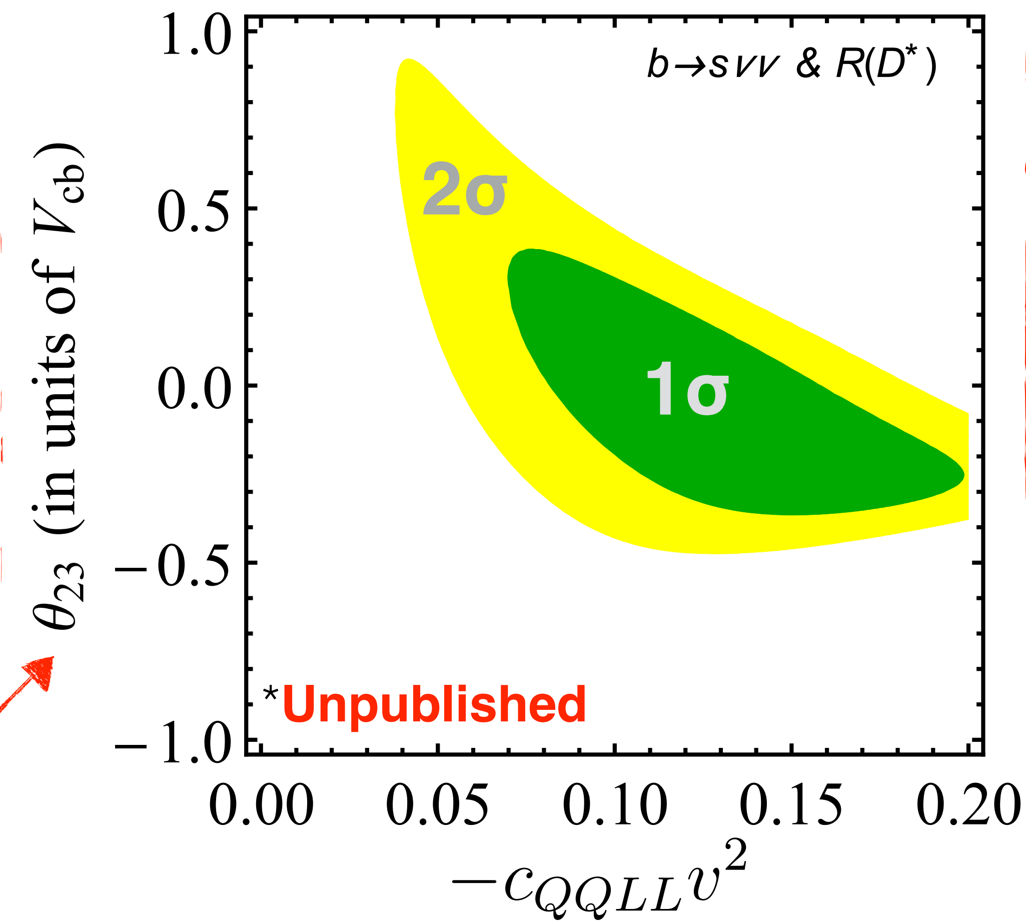
Consistent with the U(2) flavour symmetry
[AG, Isidori, Marzocca, JHEP 1507 (2015) 142]

Departure from this picture:

- Large cancelations in FCNC required

2 - 3 mixing down quarks

$R_{K^{(*)}\nu}$



$\Delta R^{\Delta F=2}_{B_s}$

*Tree level (stronger)
*One-loop (similar)

Warm-up exercise: **SM EFT**

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

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

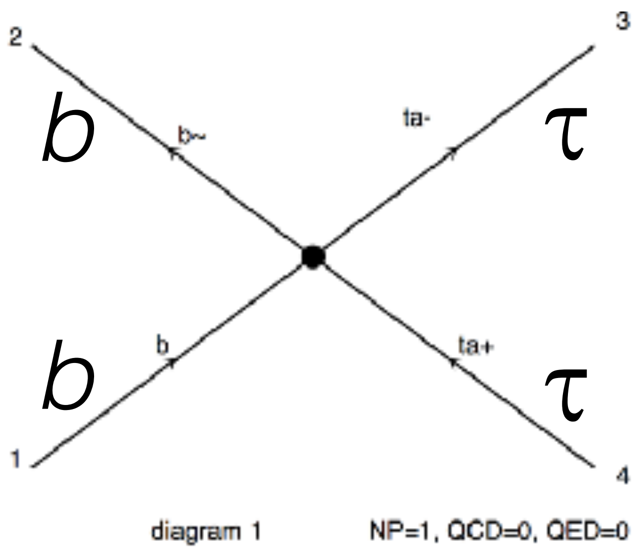
(1) ***Dominant couplings with the third generation***

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

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

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

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



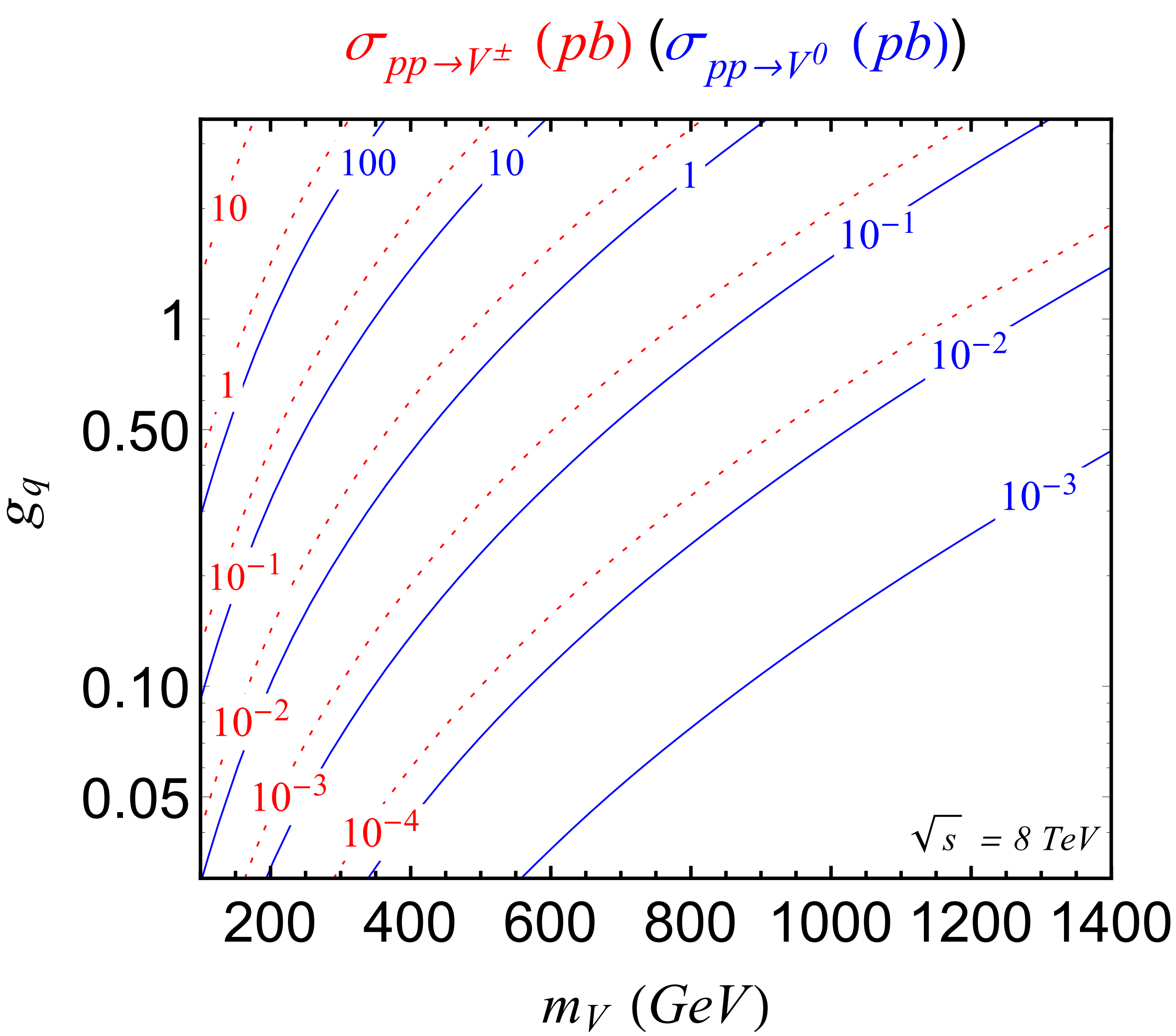
Recast of $\tau^+\tau^-$ ATLAS search:
$|c_{QQLL}| < 2.8\ \text{TeV}^{-2}$ at 95% CL

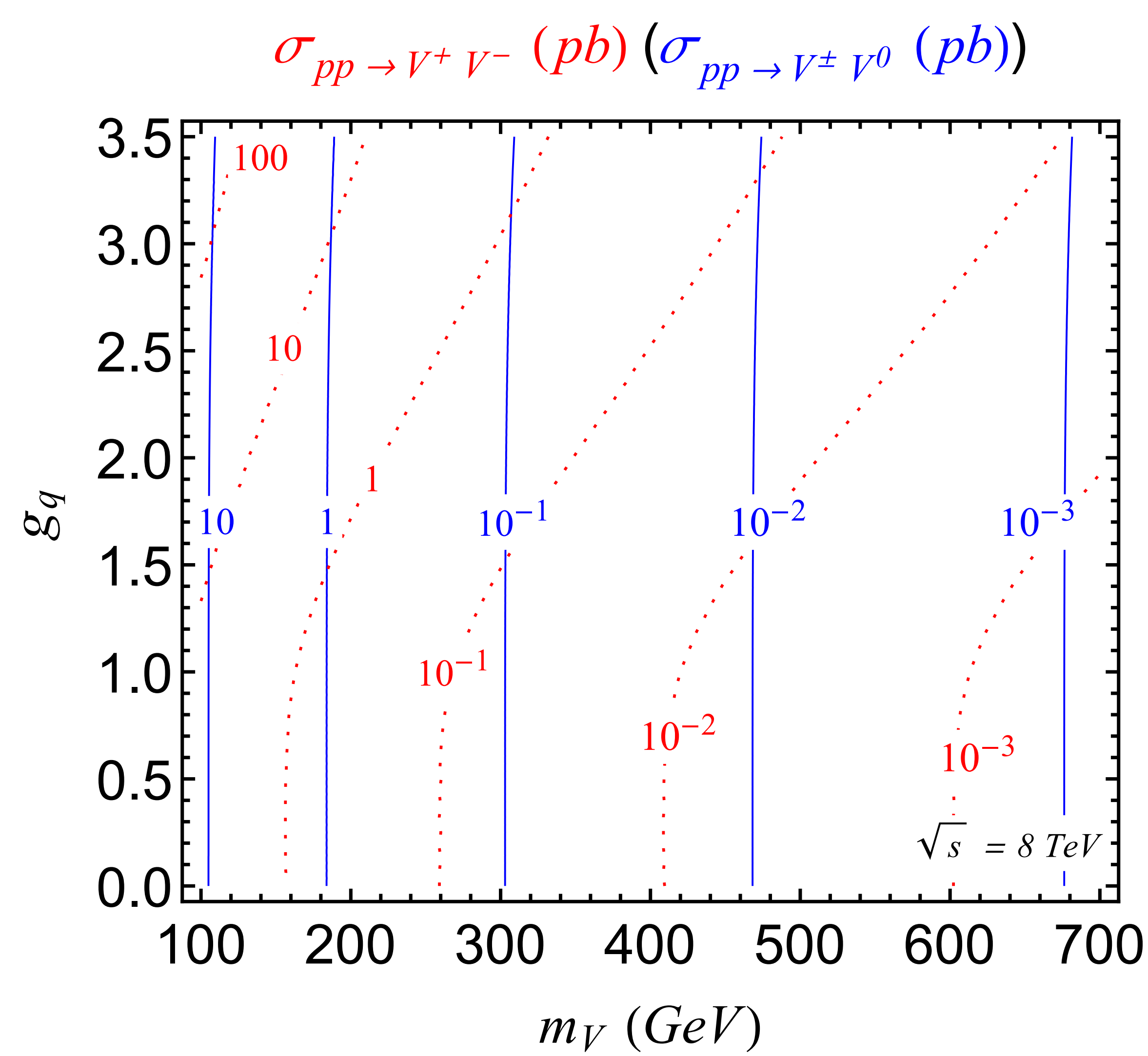
Fit to R(D*) anomaly:
$c_{QQLL} \simeq -(2.1 \pm 0.5)\ \text{TeV}^{-2}$

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

LHC phenomenology: Vector Triplet Model

Production cross sections:

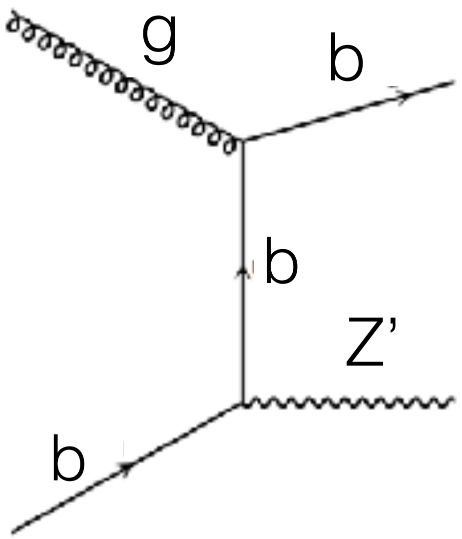




- Left: single V production ($bb \to V^0$, $b\,c \to V^+$)
- Right: pair production

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

Z' production at NLO QCD



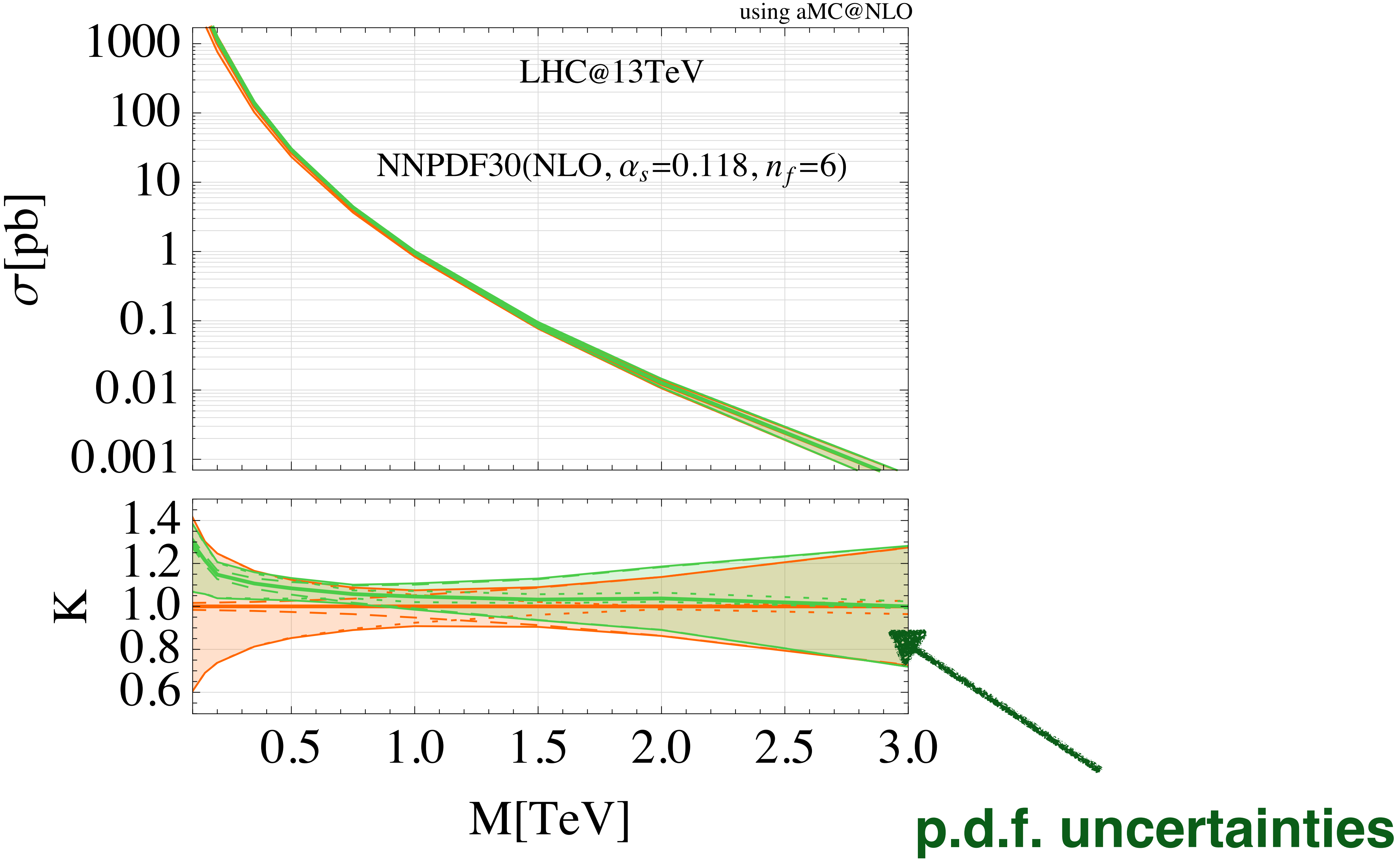


Figure 3: Next-to-leading order QCD corrections for a narrow Z' production via bottom-bottom fusion.

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

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

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

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

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:*

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

- 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_9^μ	-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*	$\Lambda^{-2}_{\tau\mu}$	$(0.0 \pm 4.1) \times 10^{-9}$ [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}]	$(G_F/\sqrt{2}) \epsilon_q^2 \lvert V_{ub} V_{cb}^*\rvert^2$

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

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

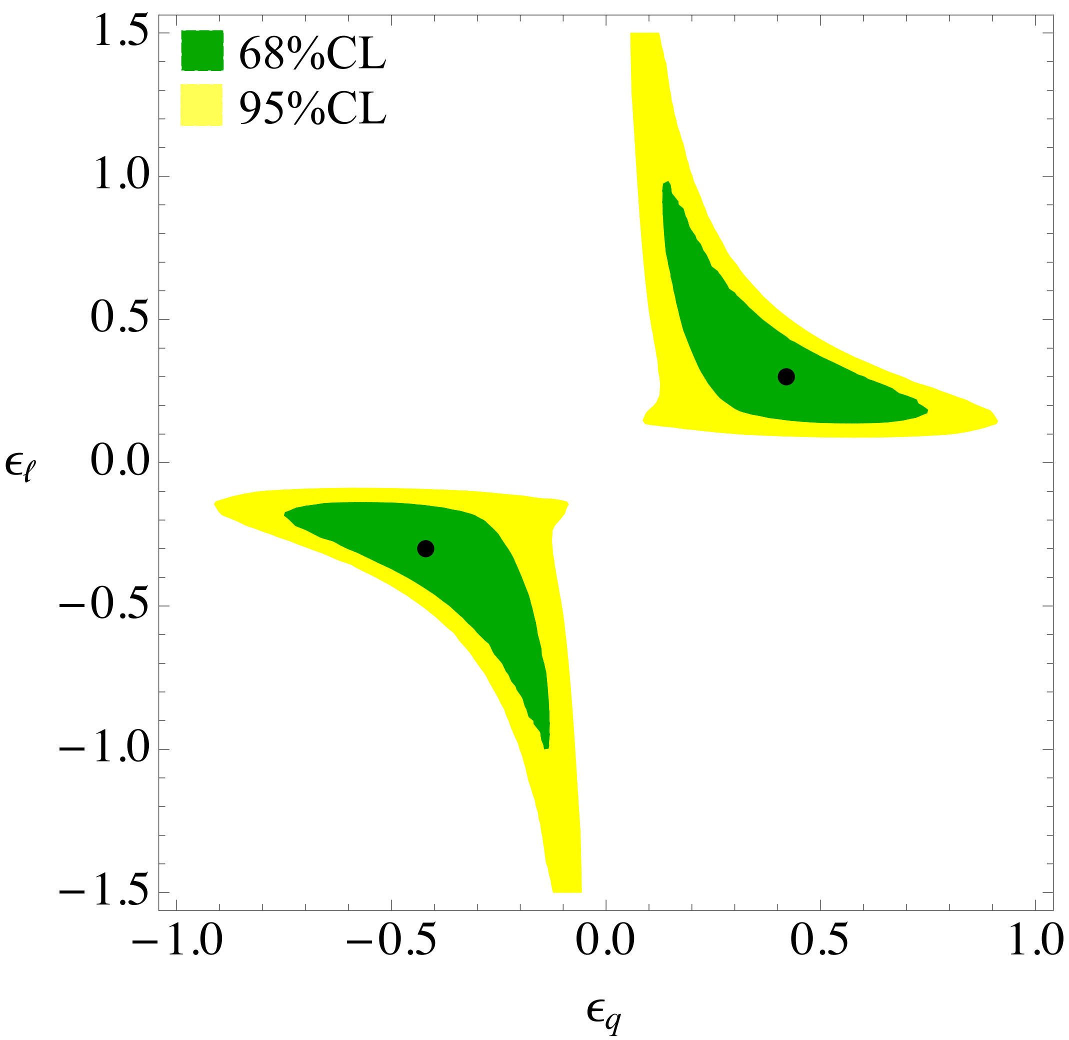
VTM: *Combined fit to low-energy data*

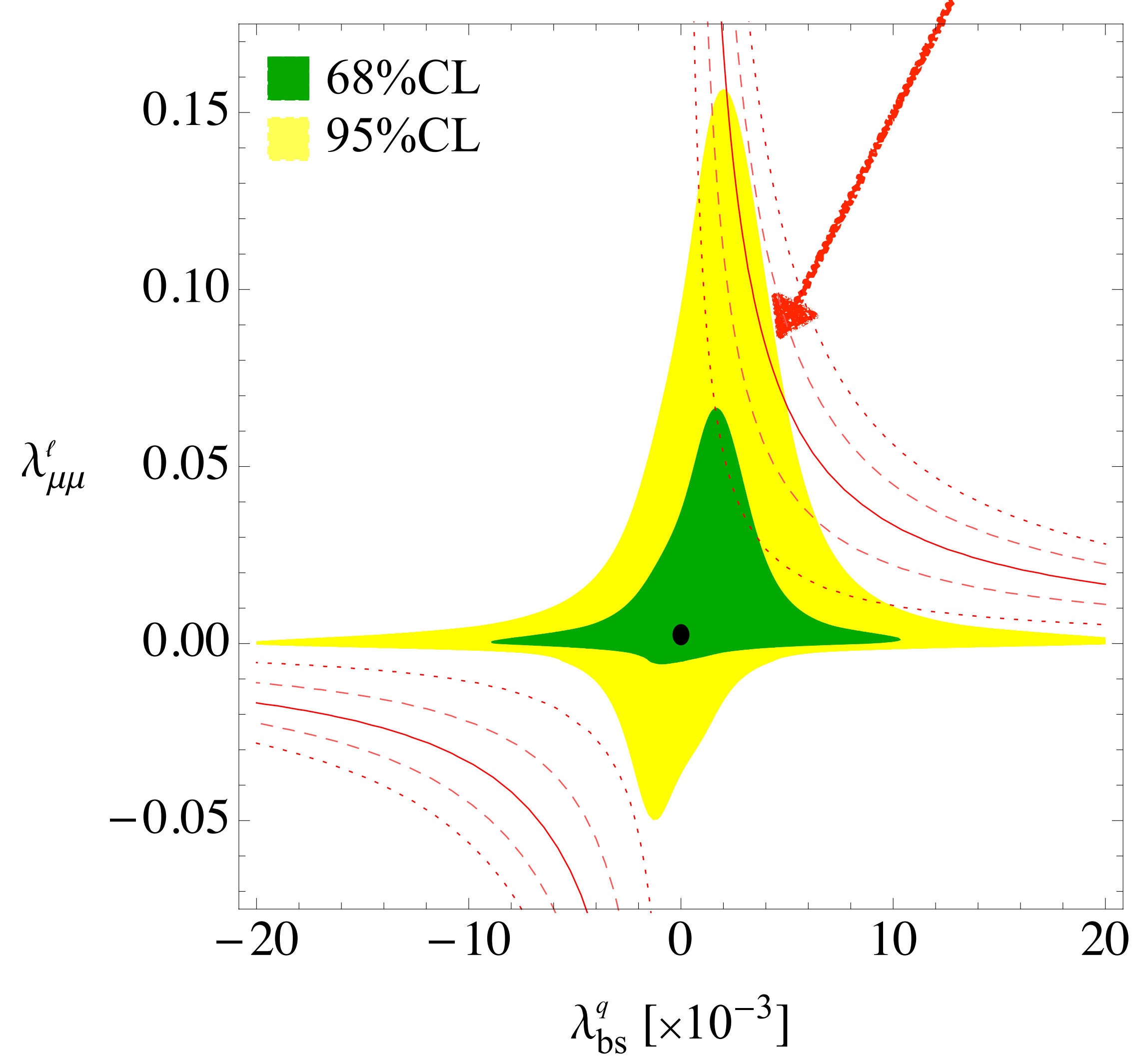
- The fit is driven by

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

- Some tension with

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





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

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

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

Two Higgs doublet model

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

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

$\mathcal{O}_{S_R}$ $Y_b Y_\tau^* / M_{H^+}^2$ $\mathcal{O}_{S_L}$ $Y_c Y_\tau / M_{H^+}^2$

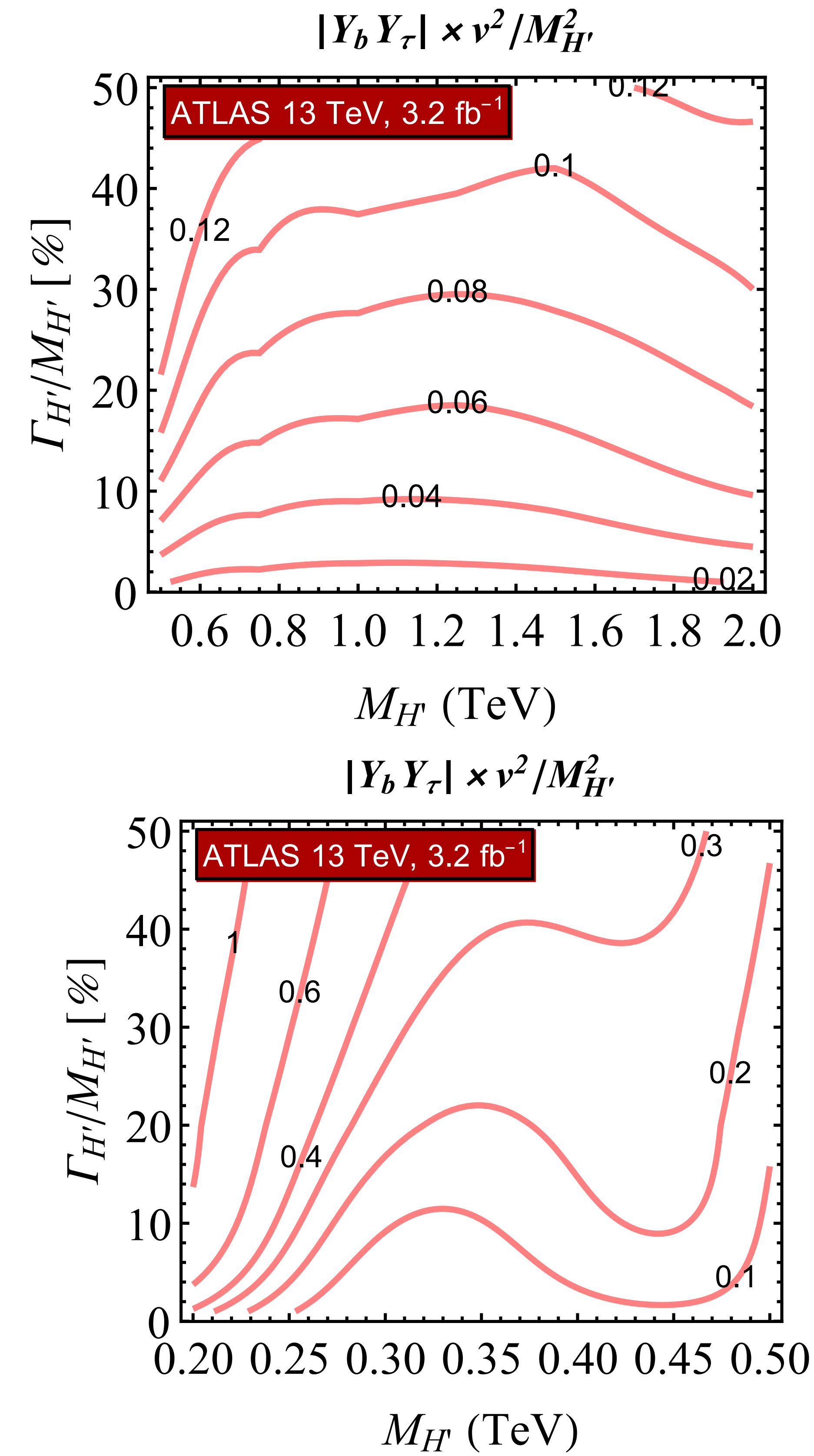
- Both non-zero to fit the anomaly

*V_{cb} suppression in $b\, c \to \tau\, \nu$

Fit to R(D*) anomaly

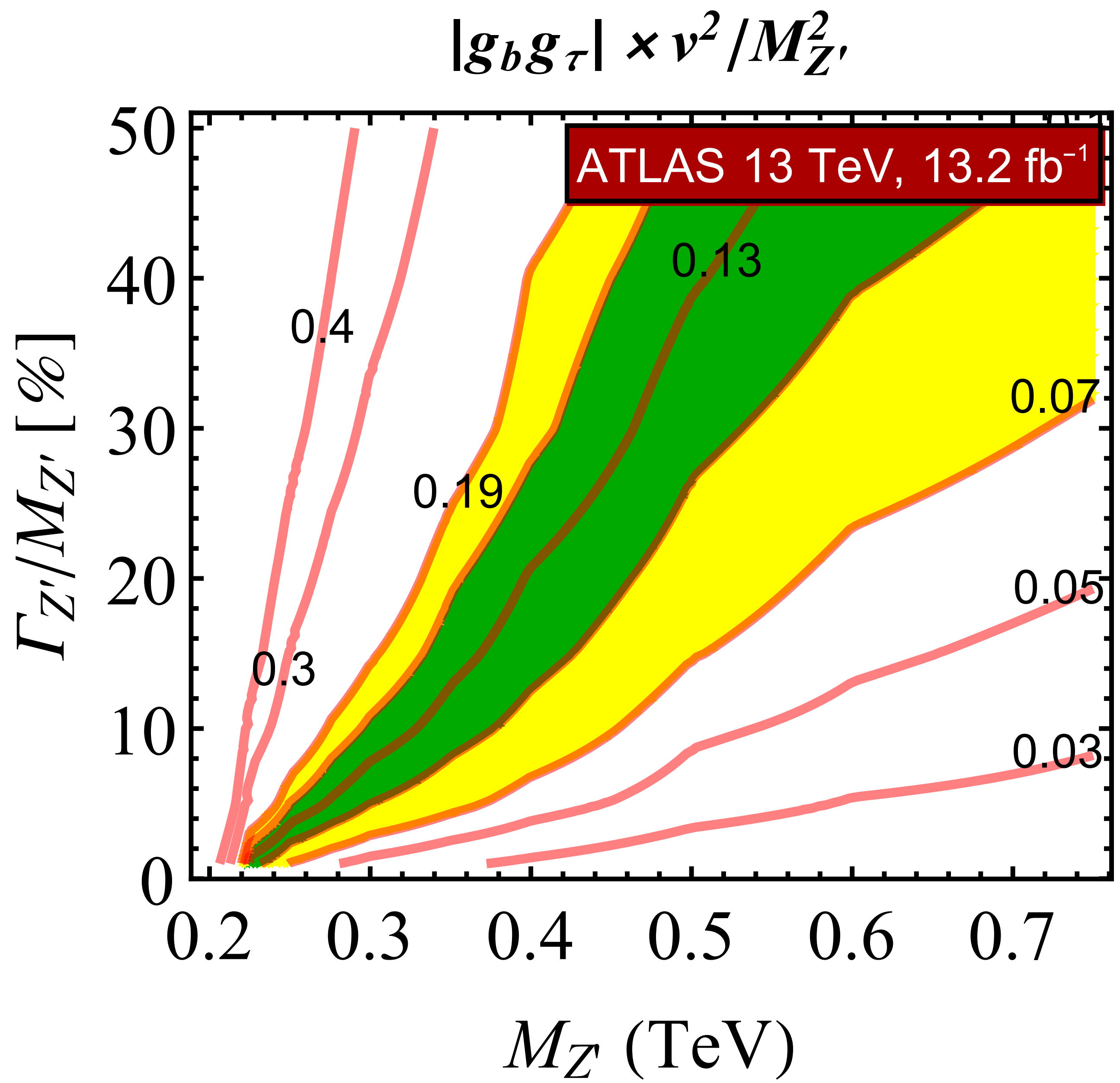
$$Y_b Y_\tau^* \times v^2 / M_{H^+}^2 = (2.9 \pm 0.8)$$

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



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

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



- Improvements needed in the low mass region!

[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

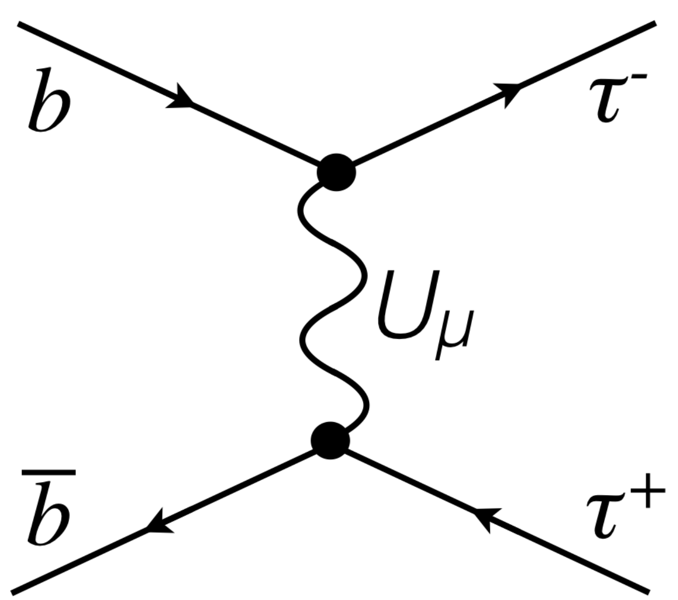
$$\mathcal{L}_U \supset -\frac{1}{2}U^{\dagger}_{\mu\nu}U^{\mu\nu} + m_U^2 U^{\dagger}_{\mu}U^{\mu} + (J^{\mu}_U U_{\mu} + \mathrm{h.c.}),$$

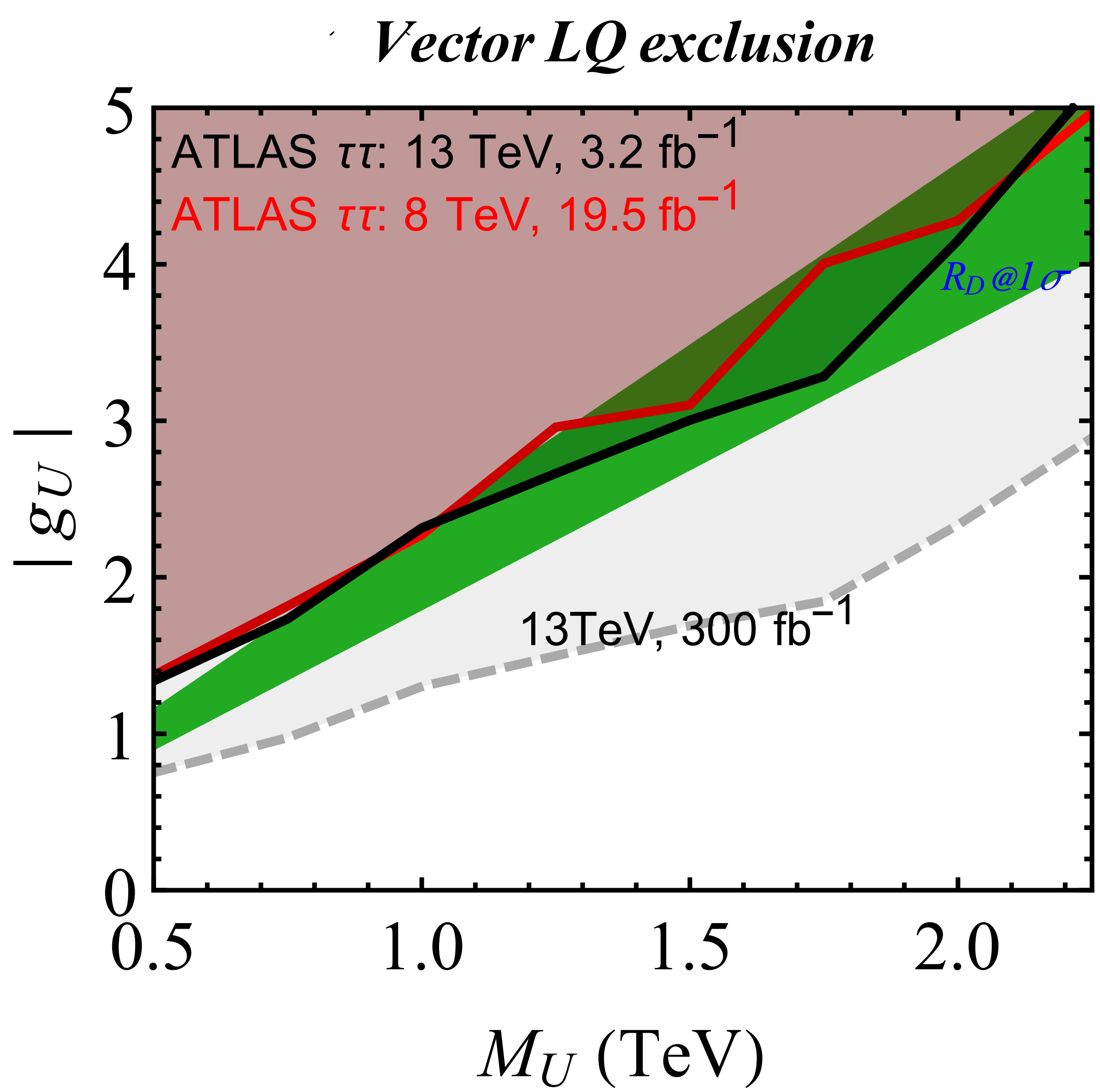
$$J^{\mu}_U \equiv g_U \; \beta_{ij} \; \bar{Q}_i \gamma^{\mu} L_j \; .$$

[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)

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

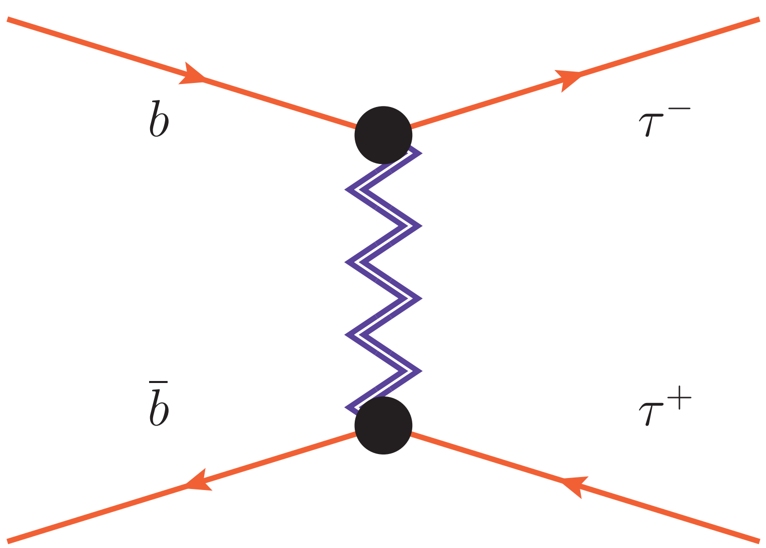
- With the right-handed neutrino

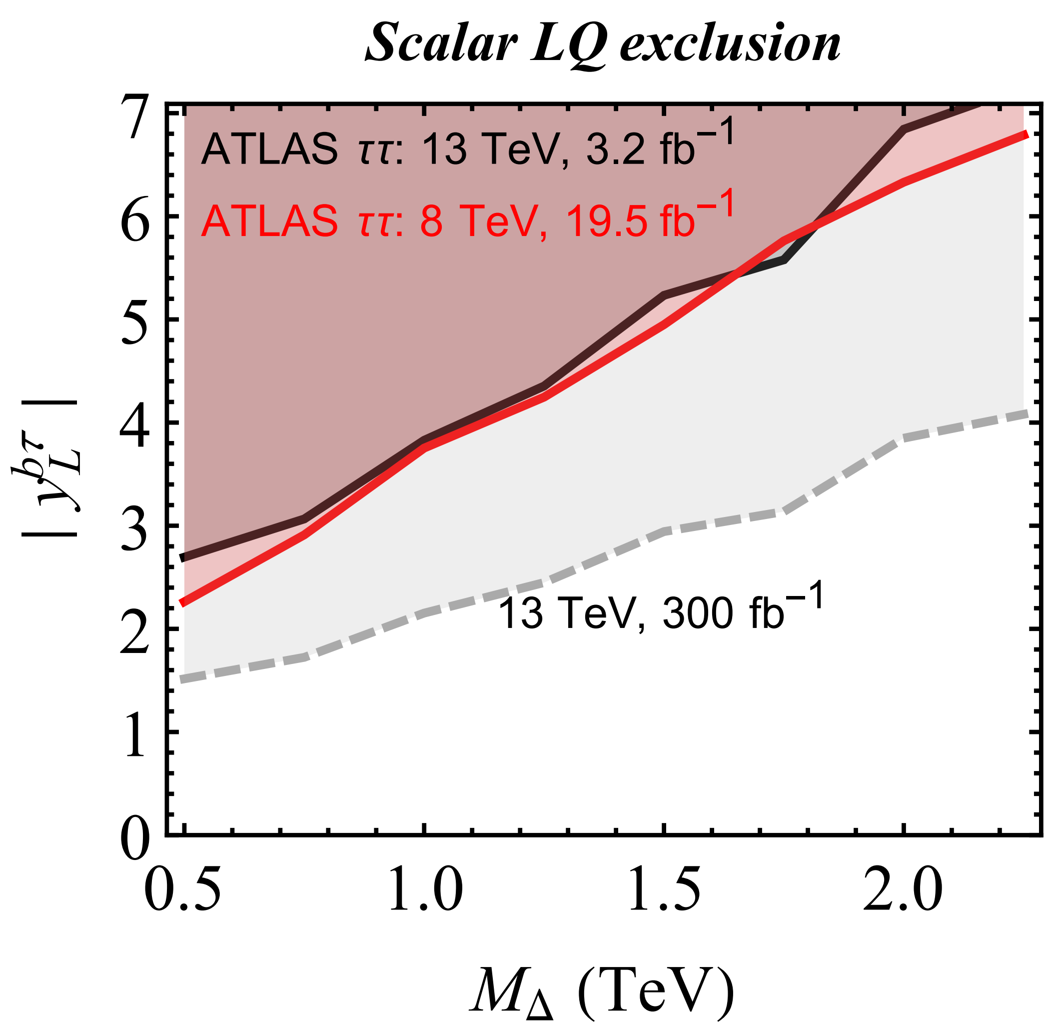
$$\mathcal{L}_\Delta \supset Y_L^{ij} \bar{d}_i (i\sigma_2 \Delta^*)^\dagger L_j + Y_R^{i\nu} \bar{Q}_i \Delta \nu_R + \text{h.c.} \; .$$

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

Fit to R(D*) anomaly

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

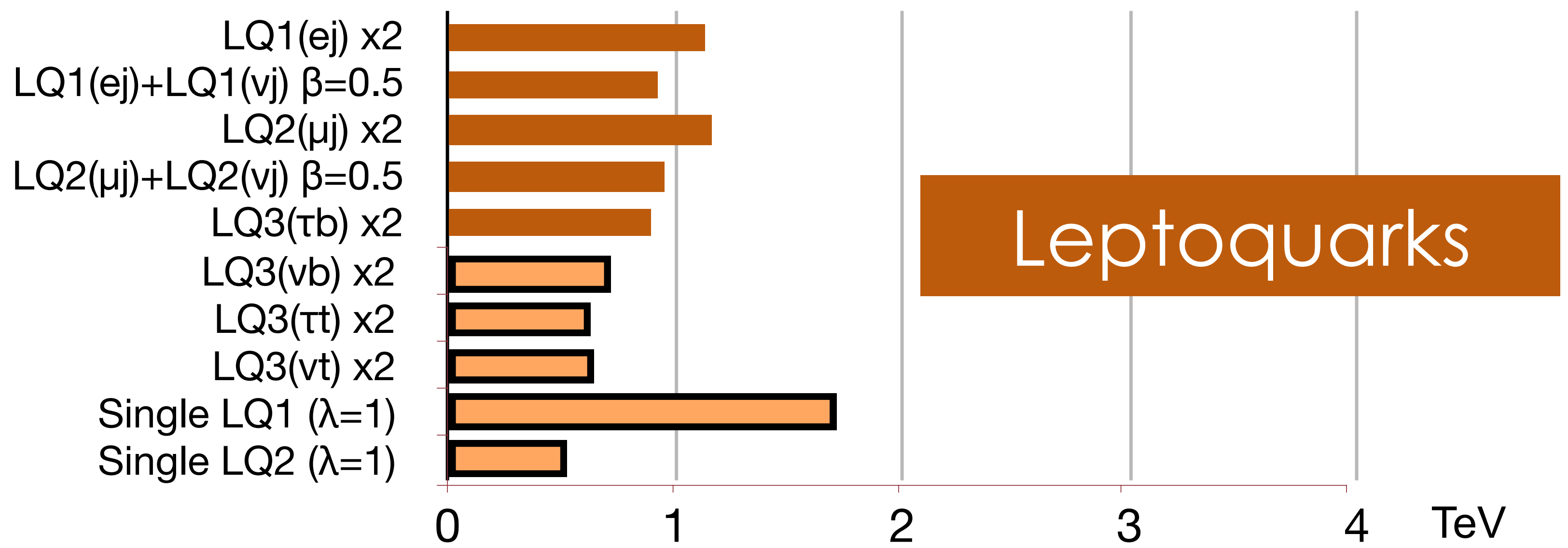




$Y_R^{b\tau}$ is pushed to non-perturbative values

- QCD induced **third generation LQ** searches provide additional limits

Other signatures at the LHC



[CMS-exo-limits_ICHEP_2016]

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