Universität Zürich[UZH]

Violation of Lepton Flavour Universality in *B*-decays: Interplay of low and high energy physics

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

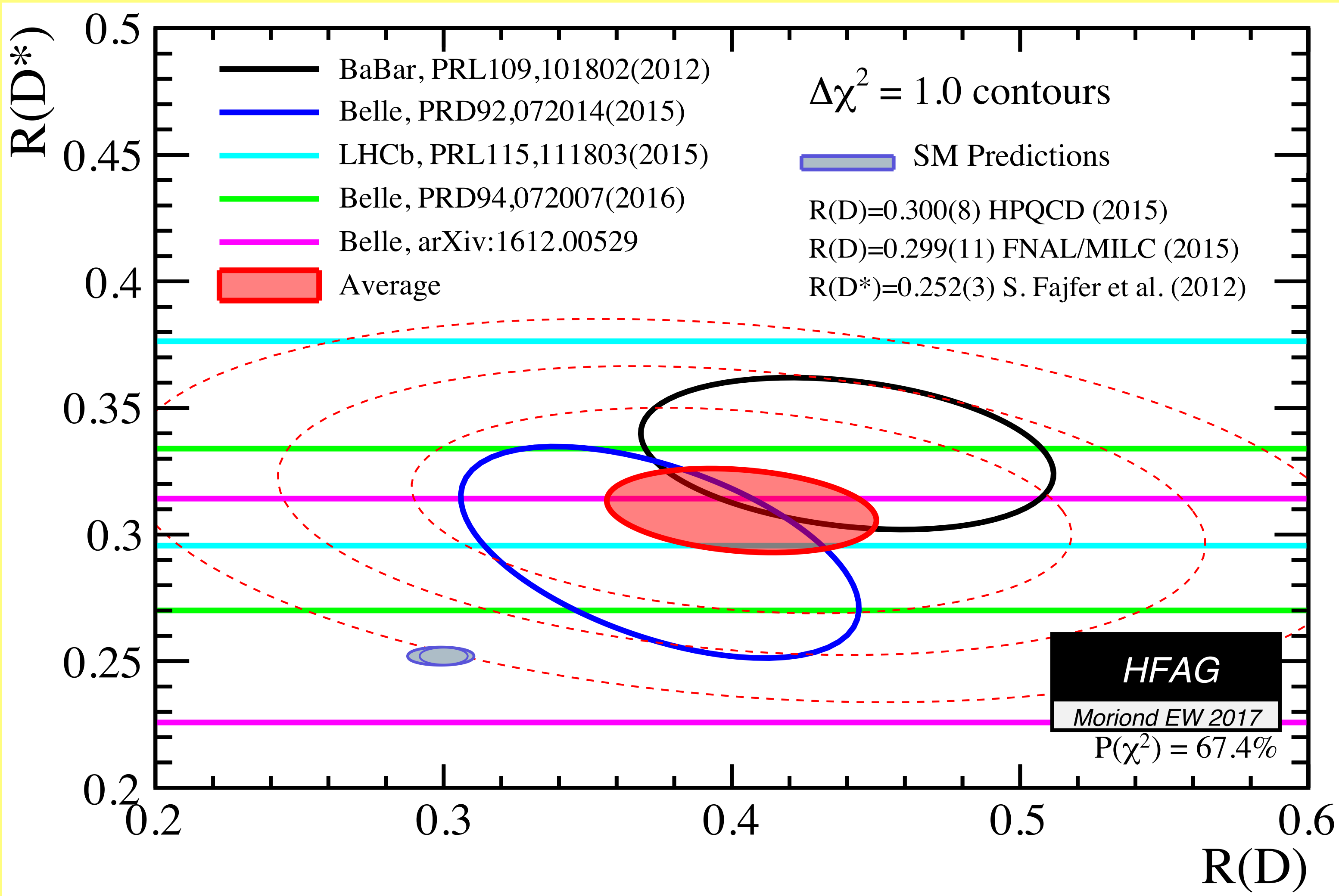
JHEP 1608 (2016) 035 - Dario Buttazzo, AG, Gino Isidori, David Marzocca

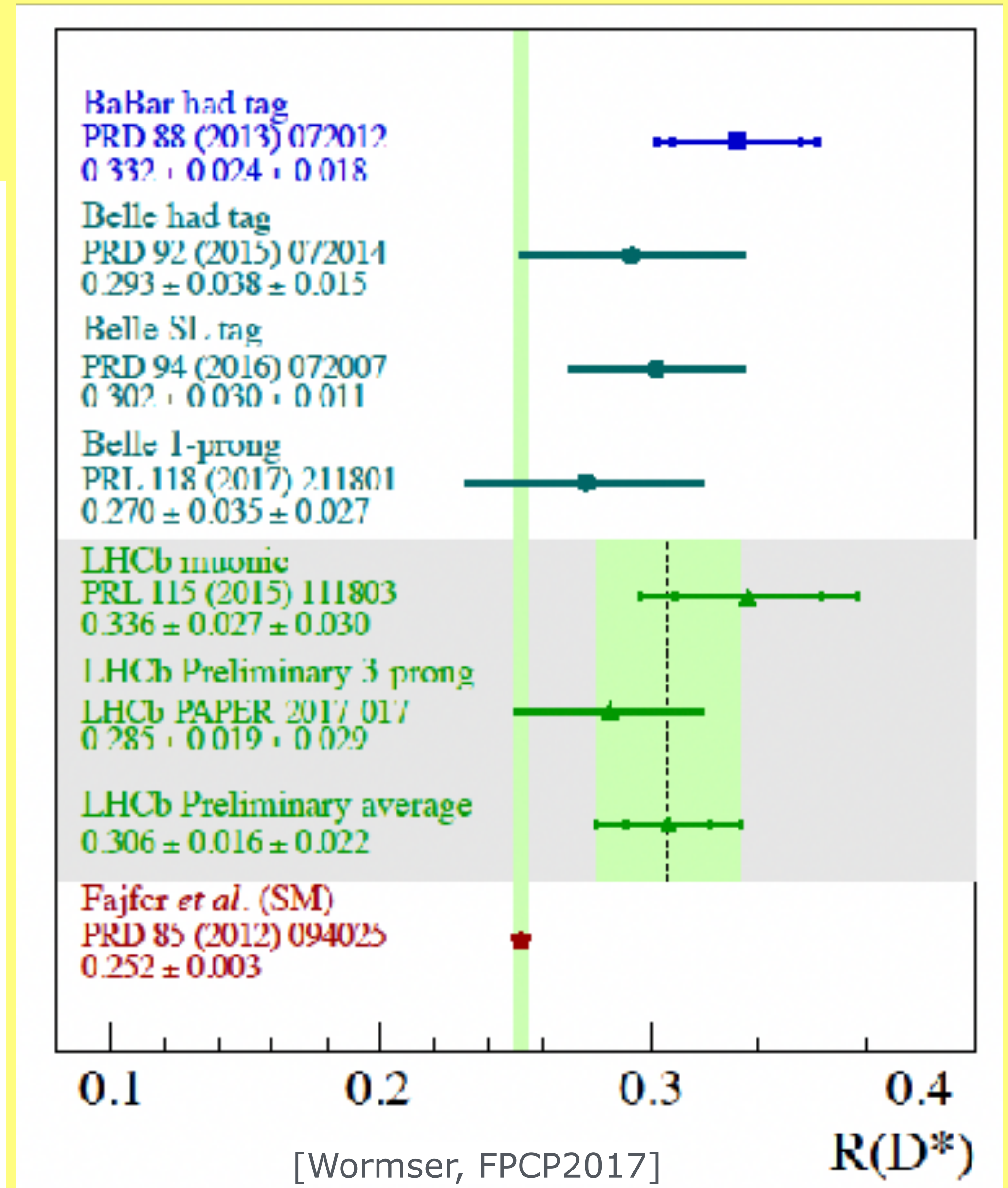
JHEP 1507 (2015) 142 - AG, Gino Isidori, David Marzocca

The Invisibles17 Workshop, 12 June 2017, Zurich

Motivation (a): Violation of LFU in charged currents

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





[Wormser, FPCP2017]

- **4σ excess** over the SM prediction
- Good agreement by <u>three (very) different</u> experiments

Motivation (b): Violation of LFU in neutral currents

μ/e universality ratios

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

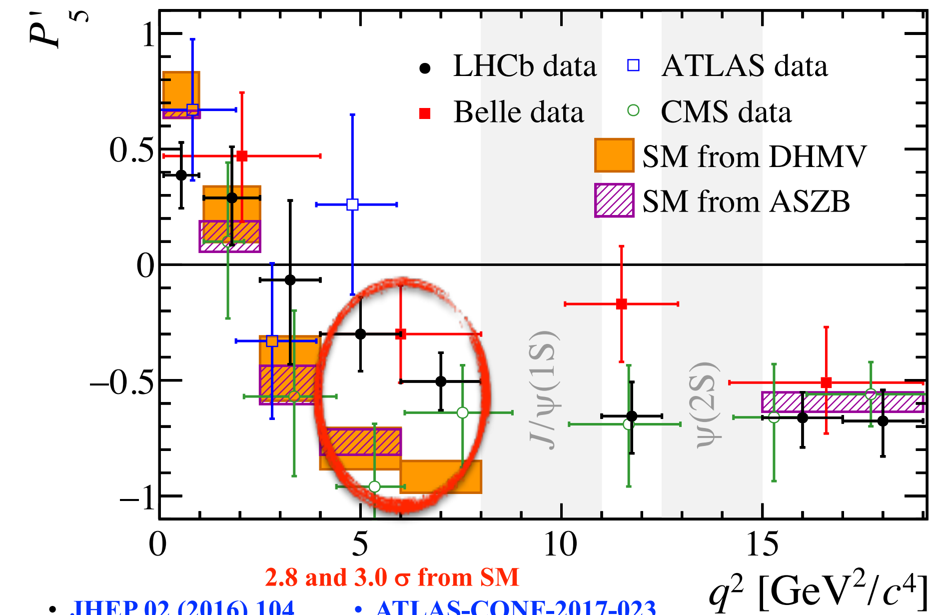
Phys. Rev. Lett. 113 (2014) 151601

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

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

S. Bifani, CERN seminar

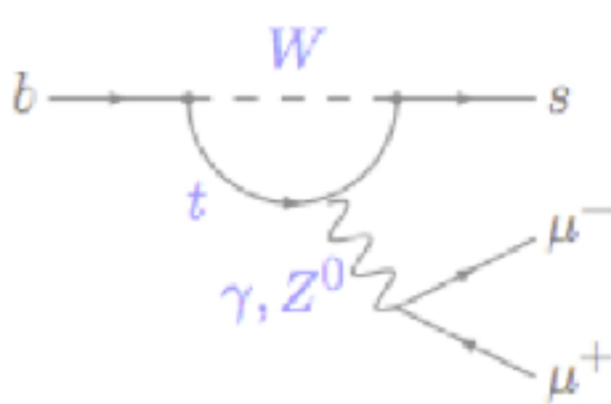
$B \to K^*\mu\mu$ angular distribution



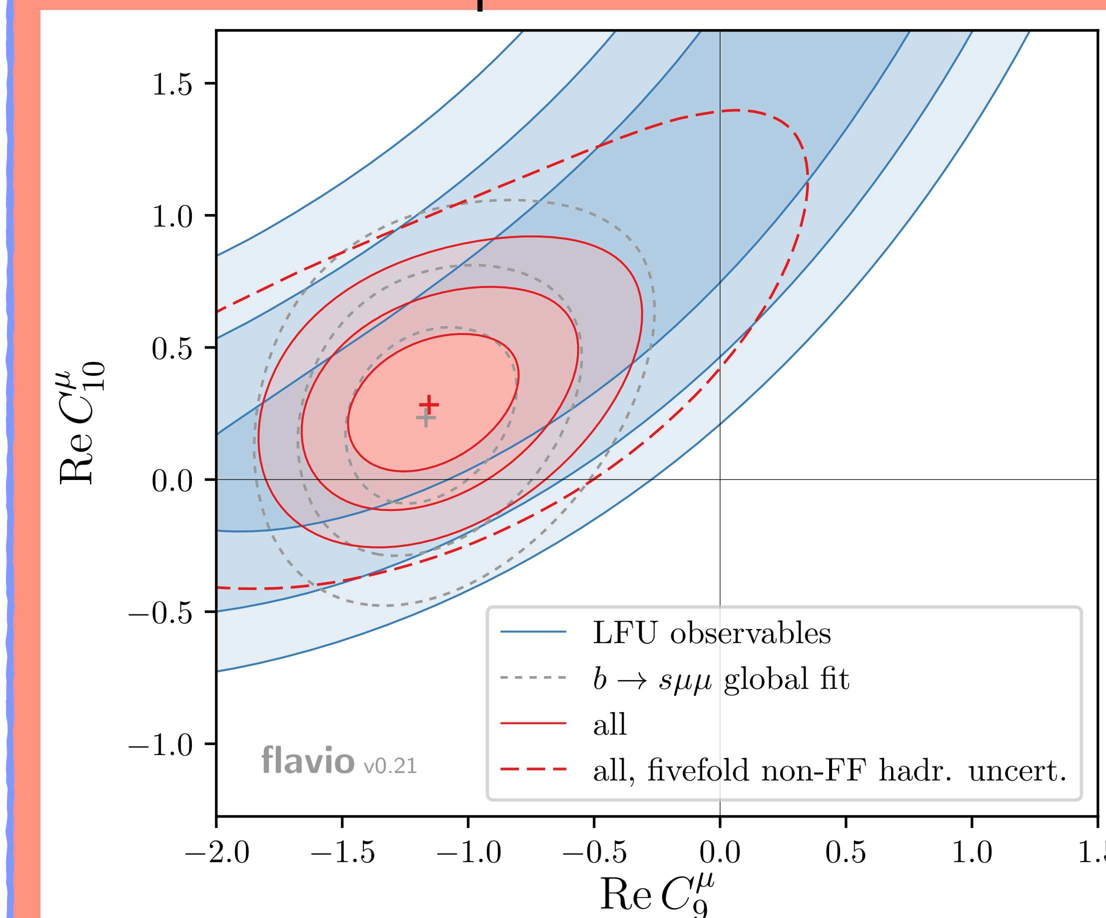
- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

S. Bifani

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



Consistent picture [1704.05435]



Good!

What to expect at the high-p_T LHC?

This talk

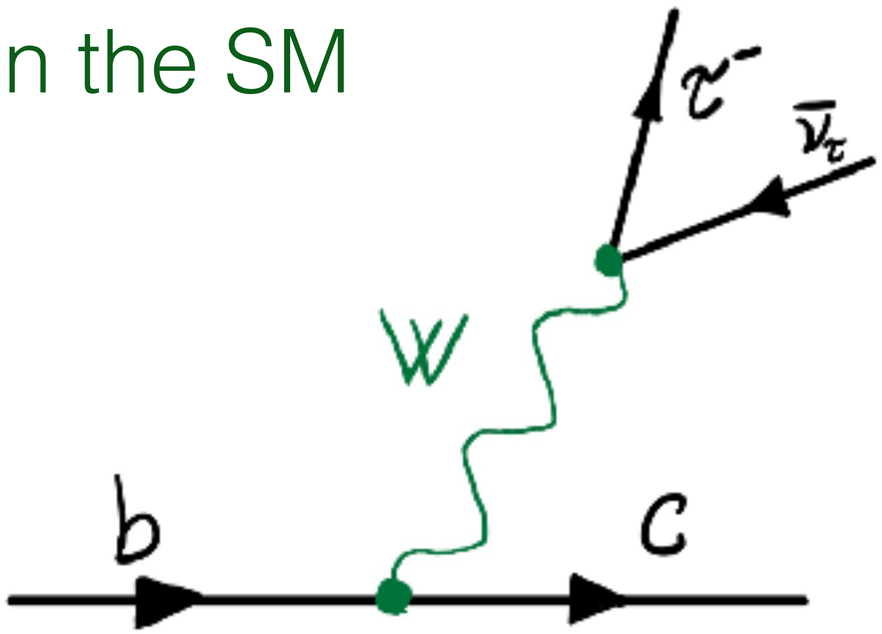
Part 1

R(D) & R(D)*

- General remarks:
  $SU(2)_L$ prediction, SM EFT,
  Flavour constraints
- Single mediator models
- Collider study:
  Di-tau searches

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

In the SM



- Tree-level process
- Mild CKM suppression

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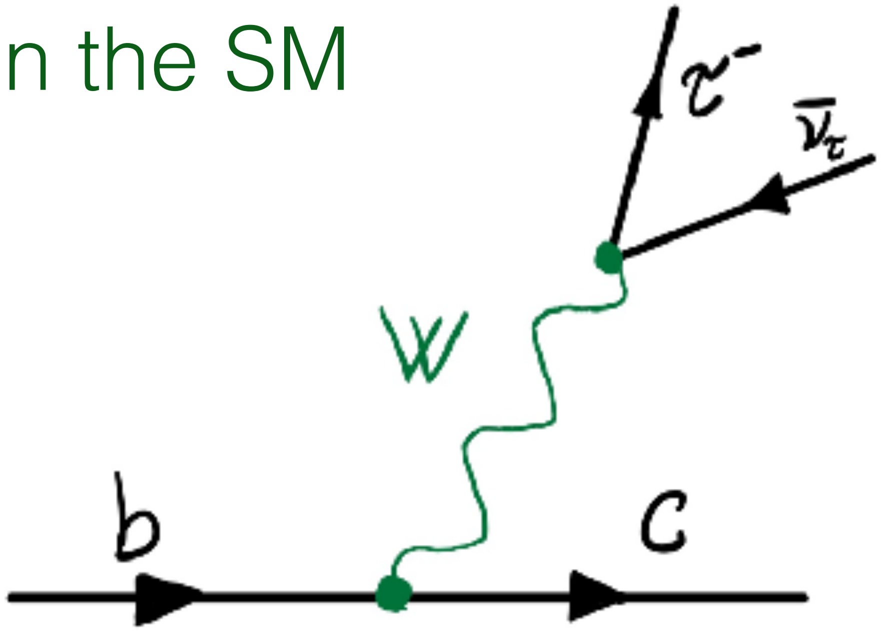
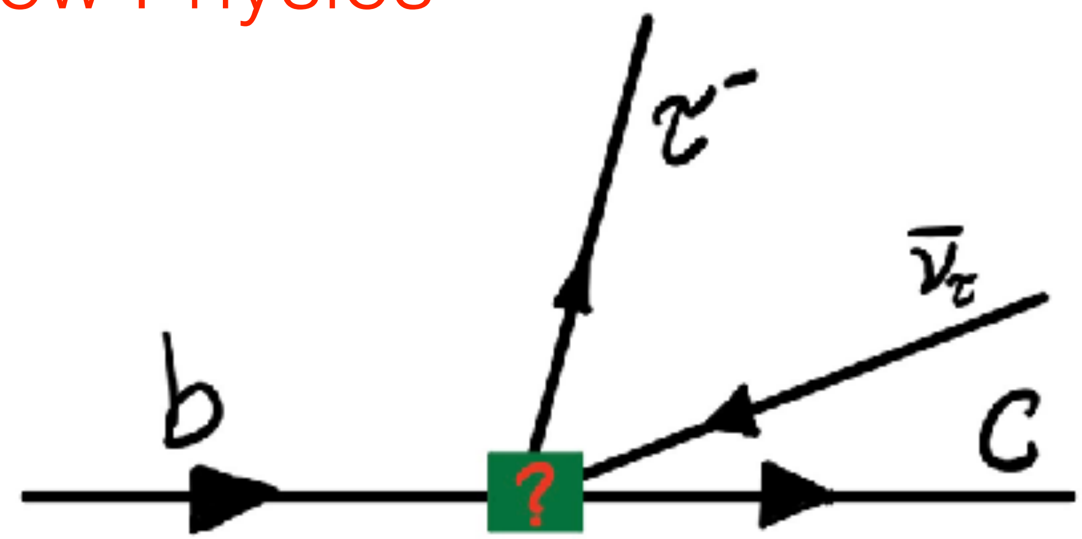


- Tree-level process
- Mild CKM suppression

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

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

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

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

- List of the relevant operators:

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

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

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

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

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

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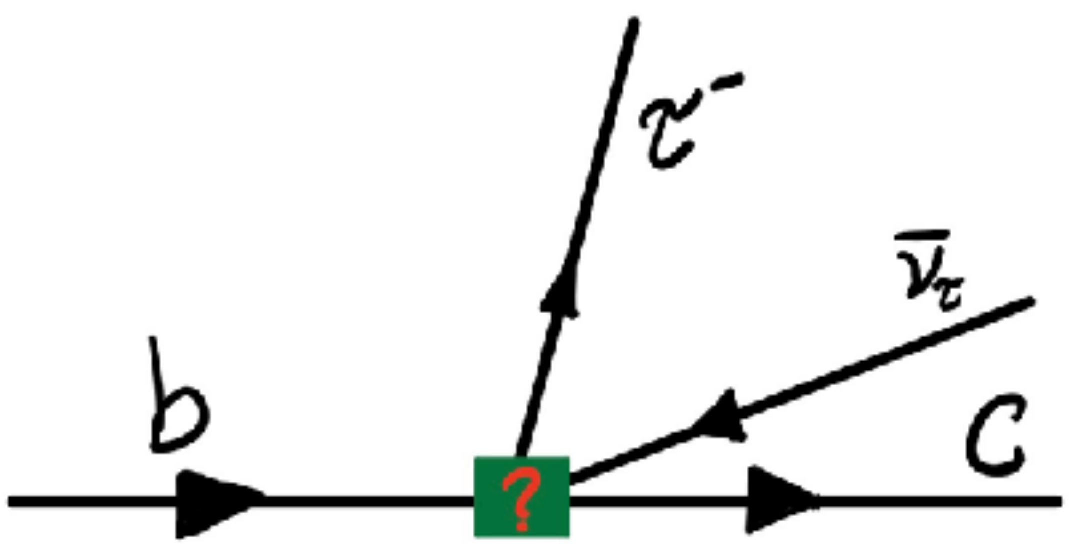

SM EFT: Violation of LFU in *B* → *D*$^{(*)}$ *τ ν* decays

- Leading effects - dim-6 operators
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$$\mathcal{L}_{eff}$$

- Only the four-ferm

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

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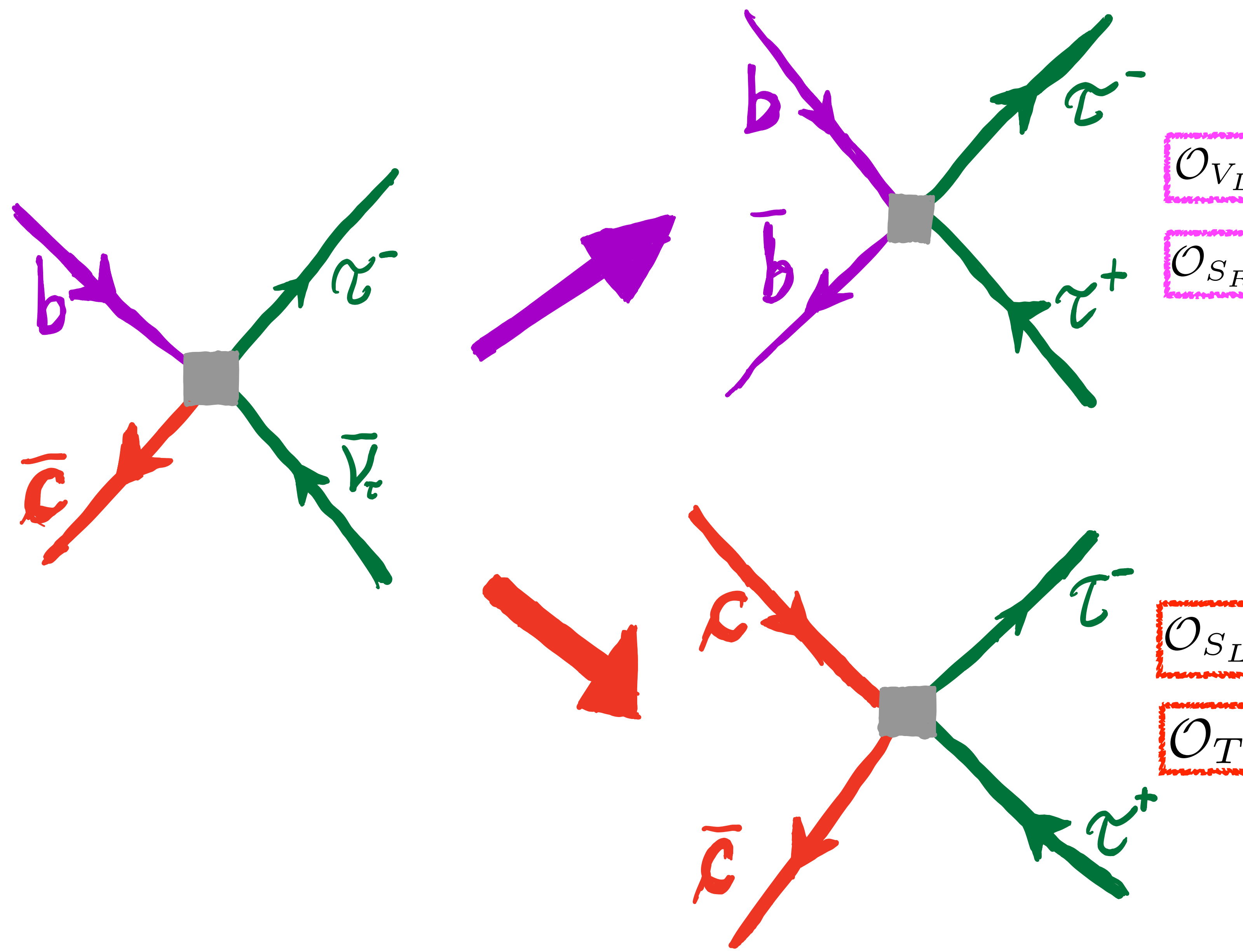
$\mathcal{O}_T$ $(\bar{Q}\, \sigma_{\mu\nu} u^j_R) i\sigma$

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



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

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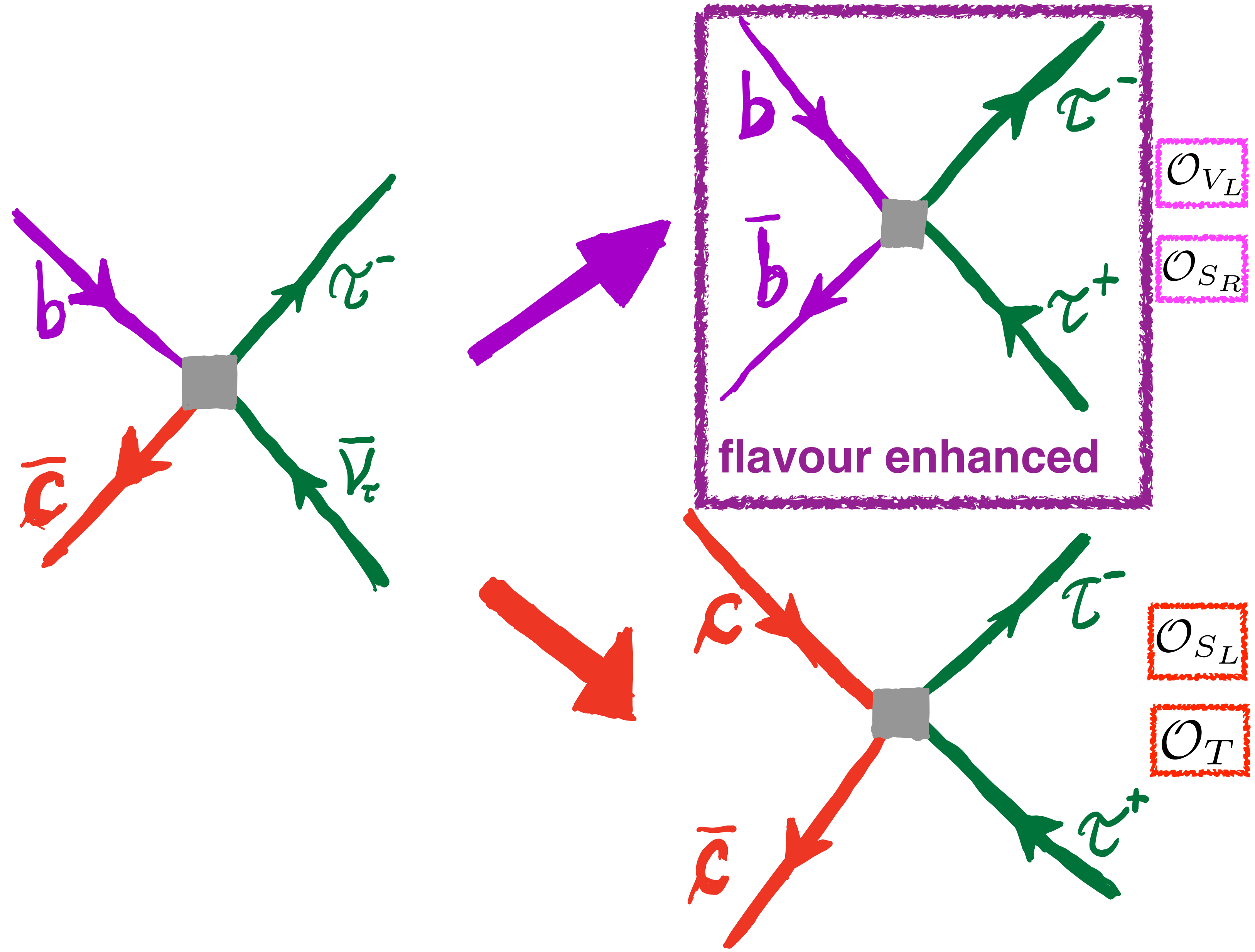
SU(2)$_L$ prediction: **Neutral currents**



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

Flavour structure

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

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

(1) ***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)

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

Consistent with the U(2) flavour symmetry

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

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Phys.Lett. B764 (2017) 126-134

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Consistent with the U(2) flavour symmetry

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

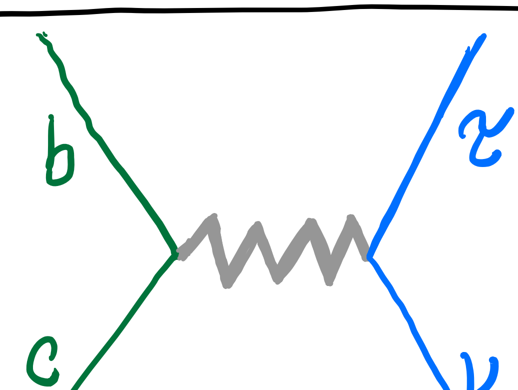
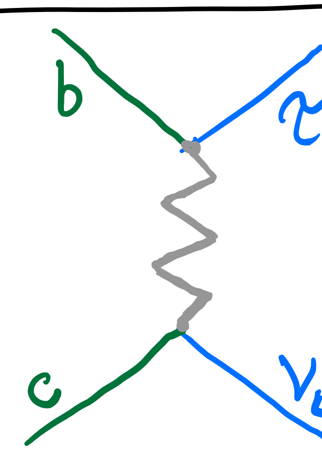
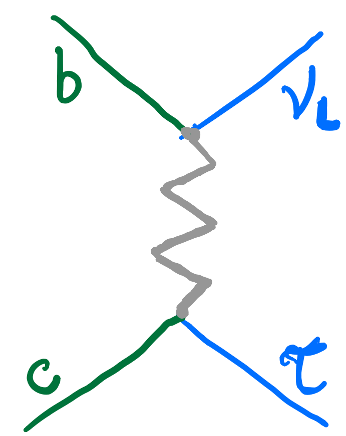
$$(2V_{cb}\bar{c}_L\gamma^\mu b_L \bar{\tau}_L \gamma_\mu \nu_L + \bar{b}_L \gamma^\mu b_L \bar{\tau}_L \gamma_\mu \tau_L)$$

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

Single mediator models (8 options)

No light ν_R

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

Color / Spin	1	3	
0	2HDM	Scalar LQ	
1	W'	Vector LQ	
	 s-channel	 t-channel	 u-channel

- Spin: **0**, **1**, …

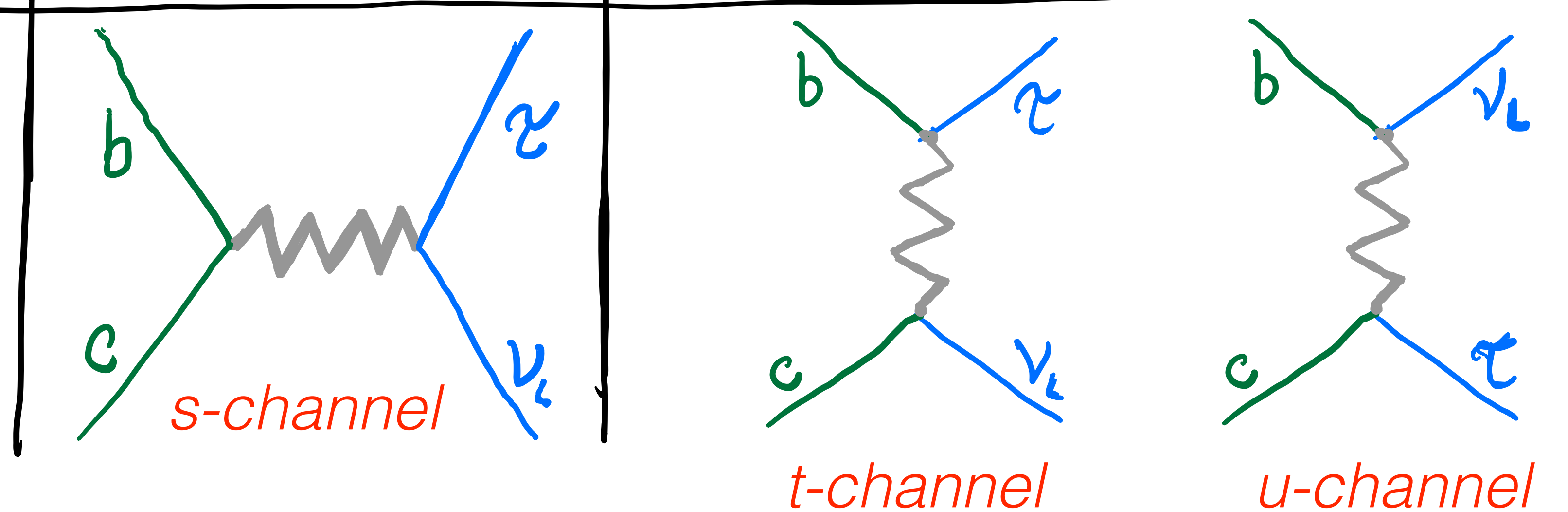
- SU(2) weak: **1**, **2** or **3**

Single mediator models (8 options)

No light ν_R

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

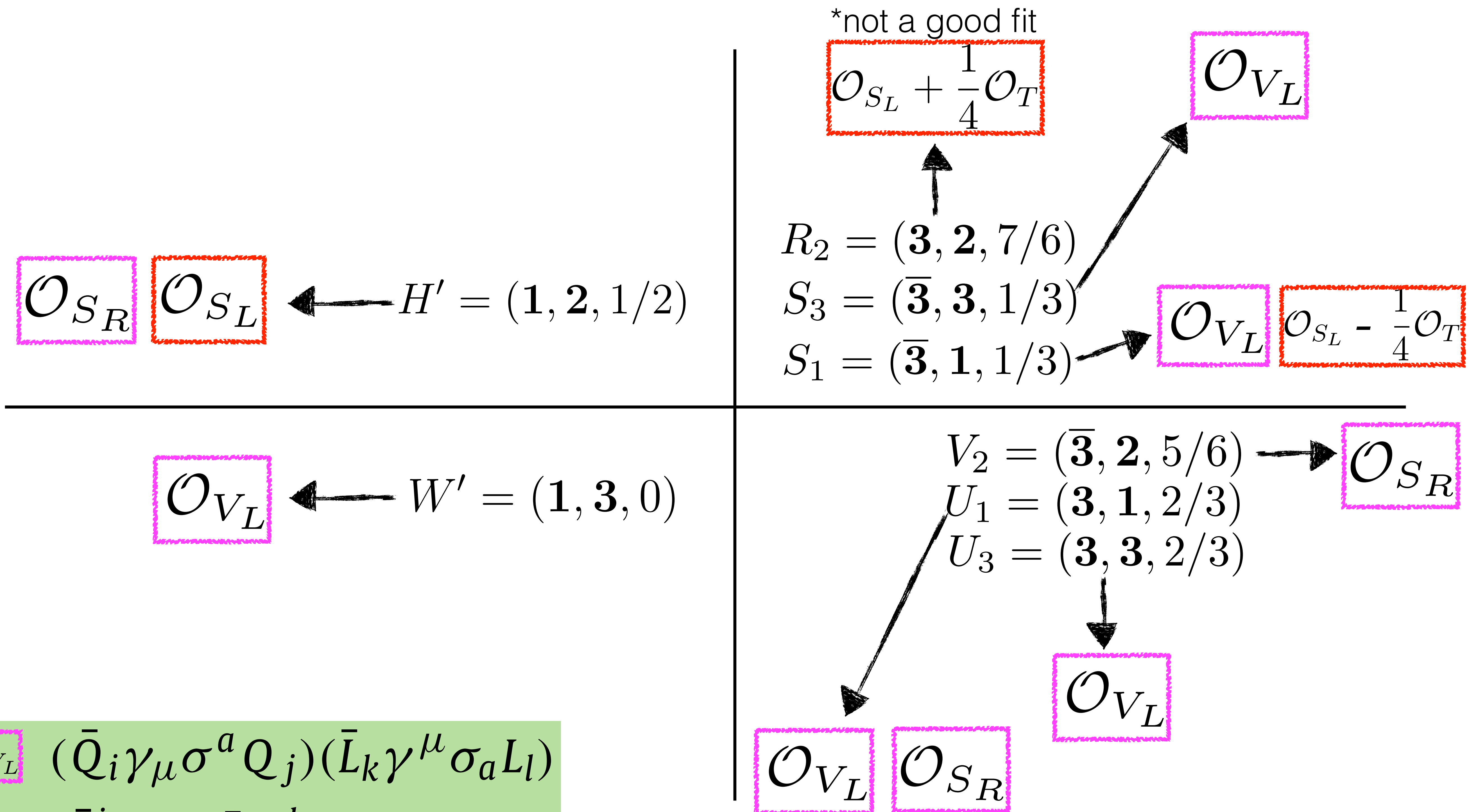
Spin \ Color	1	3
0	$H' = (\mathbf{1}, \mathbf{2}, 1/2)$	$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$ $S_3 = (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$ $S_1 = (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$
1	$W' = (\mathbf{1}, \mathbf{3}, 0)$	$V_2 = (\overline{\mathbf{3}}, \mathbf{2}, 5/6)$ $U_1 = (\mathbf{3}, \mathbf{1},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



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

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

Matching UV to the SM EFT



$\mathcal{O}_{V_L}$	$(\bar{Q}_i \gamma_\mu \sigma^a Q_j)(\bar{L}_k \gamma^\mu \sigma_a L_l)$
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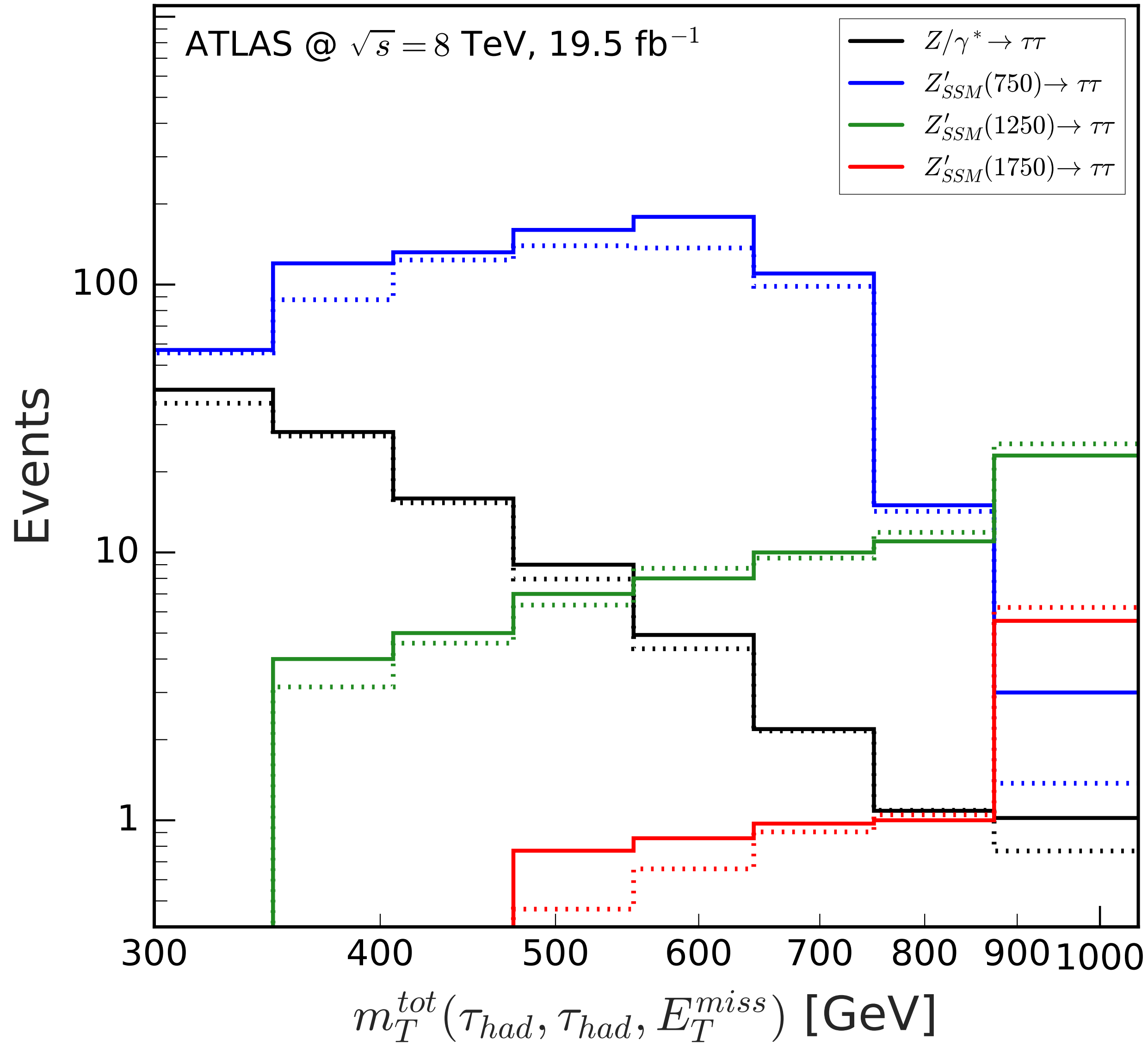
$\mathcal{O}_{S_L}$	$(\bar{Q}_i u^j_R) i\sigma^2 (\bar{L}_k \ell^l_R)$
$\mathcal{O}_T$	$(\bar{Q} \sigma_{\mu\nu} u^j_R) i\sigma^2 (\bar{L} \sigma^{\mu\nu} \ell^l_R)$

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:

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

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

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

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

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

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

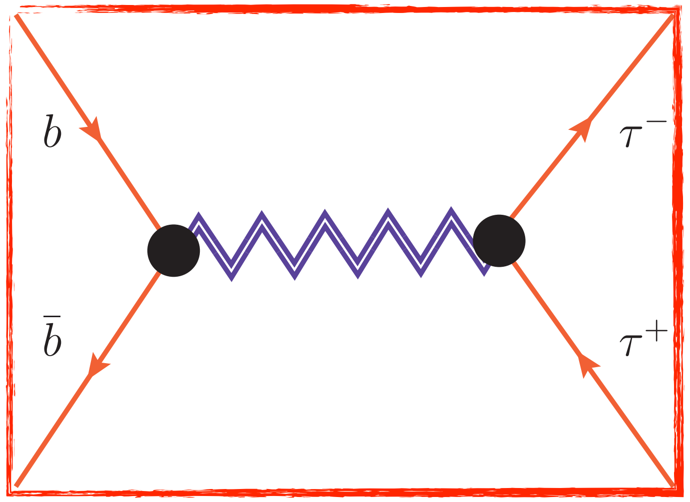
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ → NO $bb \to \tau\tau$

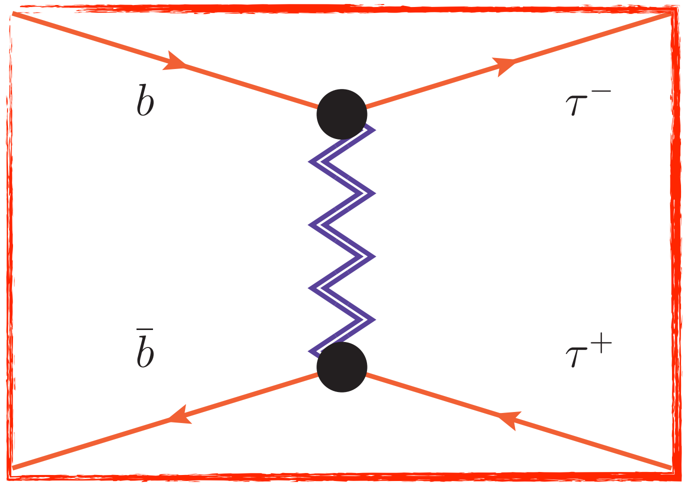
YES ← $W' = (\mathbf{1}, \mathbf{3}, 0)$

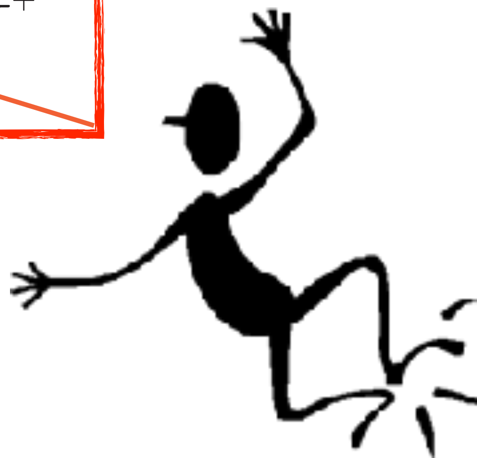
$V_2 = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$ → YES

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

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







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

Example

Vector Triplet Model (W')

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

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

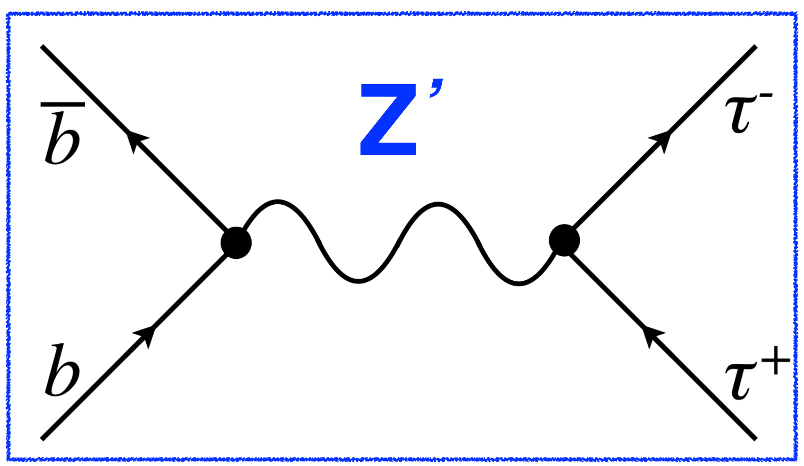
$$J^{a\mu}_{W'} \equiv \lambda^q_{ij} \bar{Q}_i \gamma^\mu \sigma^a Q_j + \lambda^\ell_{ij} \bar{L}_i \gamma^\mu \sigma^a L_j$$

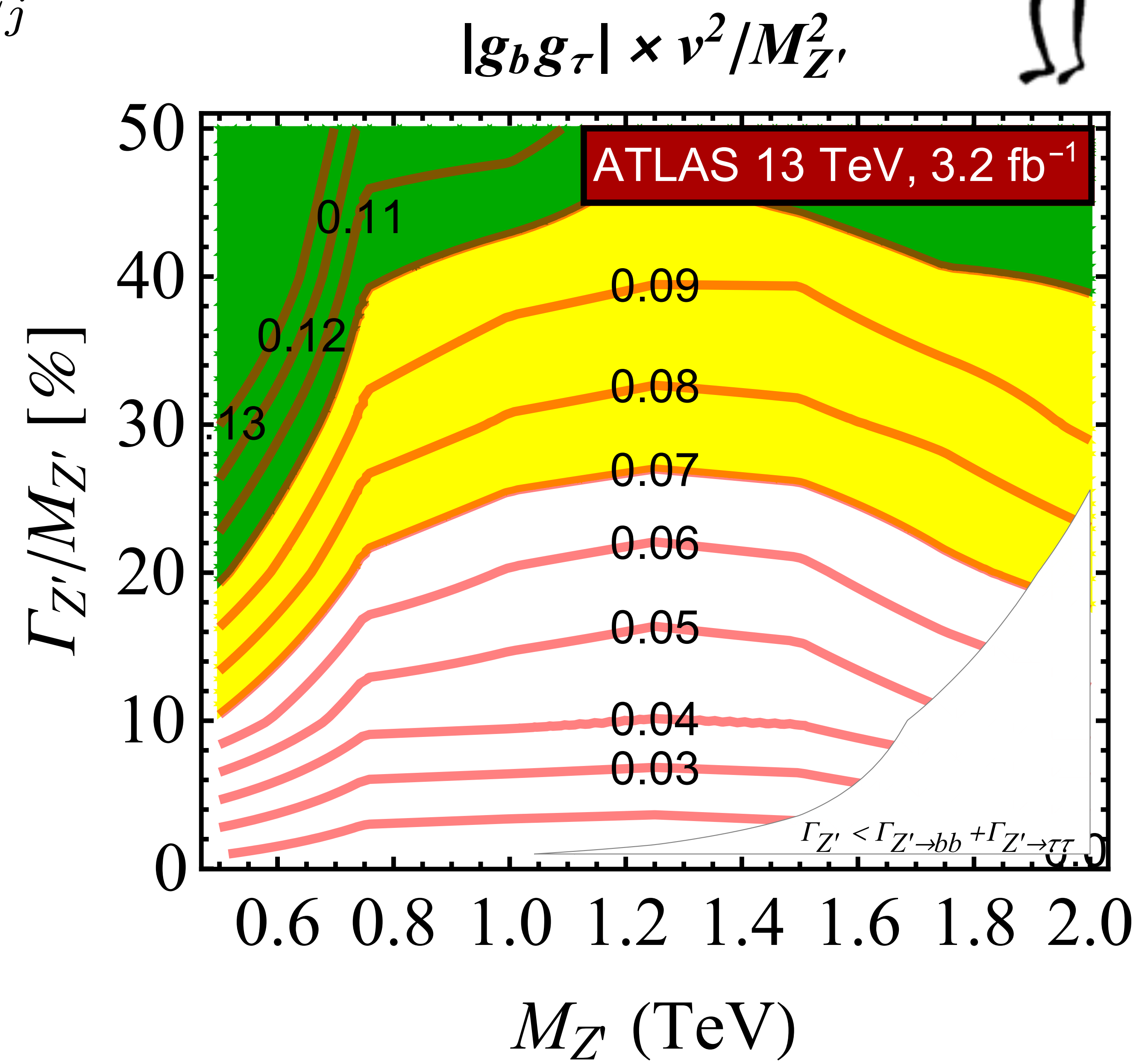
$$\lambda^{q(\ell)}_{ij} \simeq g_{b(\tau)} \delta_{i3} \delta_{j3}$$

Fit to R(D*) anomaly

$|g_b g_\tau| \times v^2/M^2_{Z'} = (0.13 \pm 0.03)$

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

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

Example

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

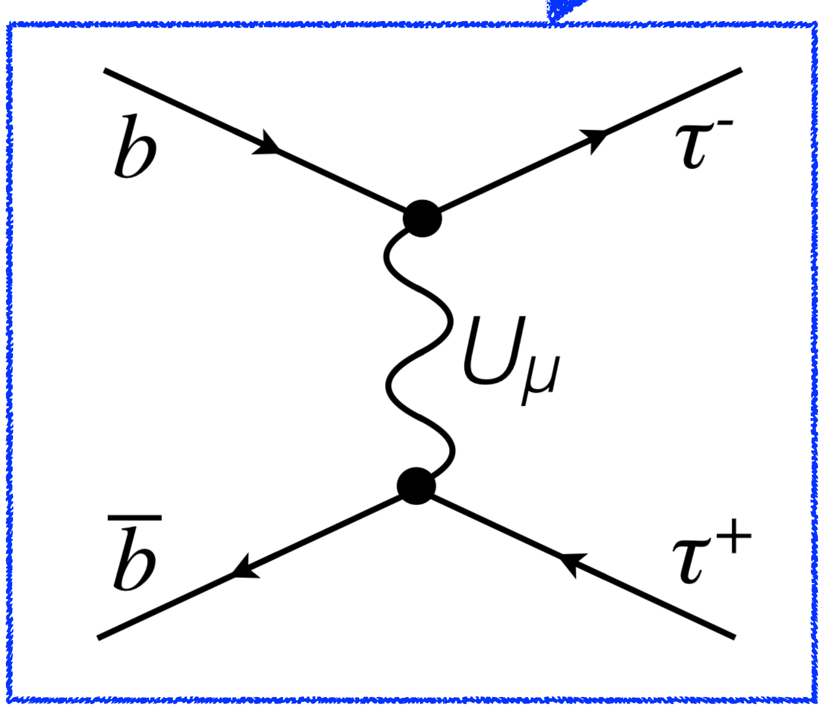
$$J^{\mu}_U \equiv g_U \; \beta_{ij} \; \bar{Q}_i \gamma^{\mu} L_j \; .$$

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

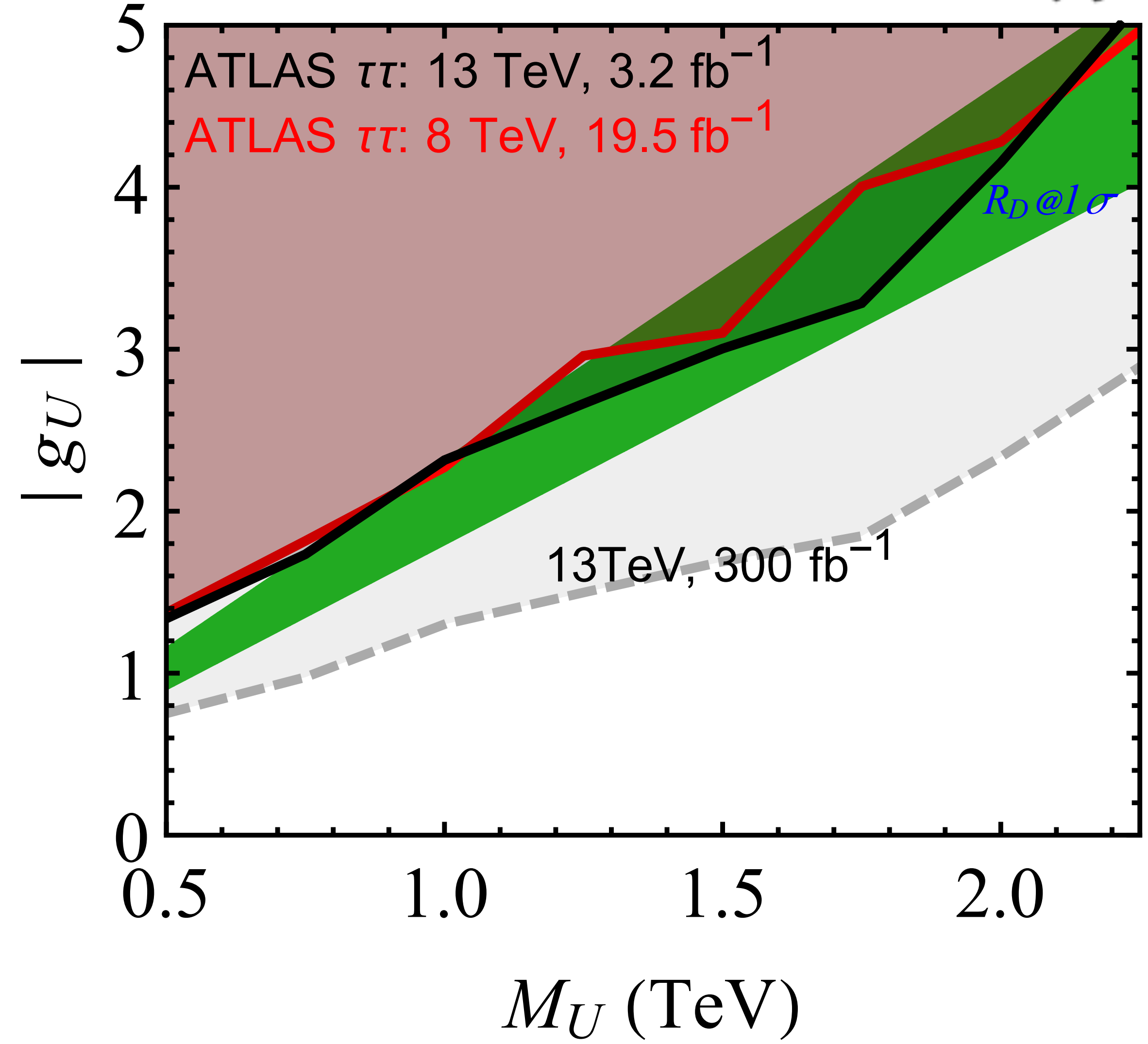
- Integrating out the LQ: $\beta_{ij} \simeq g_U \delta_{3i} \delta_{3j}$

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

Look for



Vector LQ exclusion



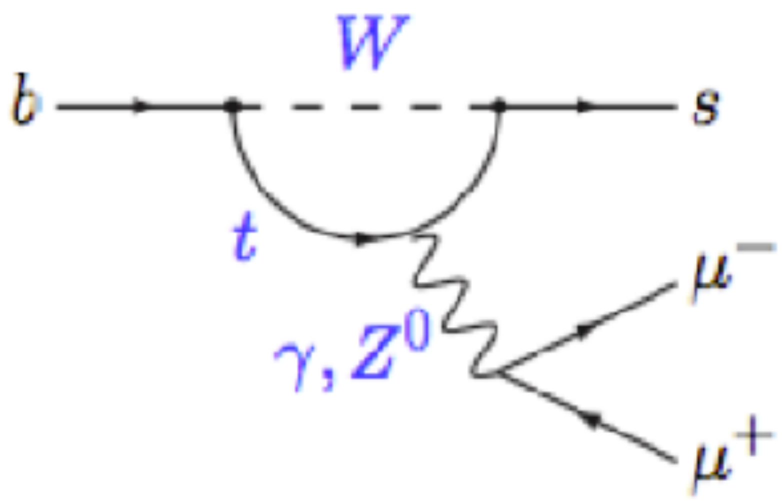
[Faroughy, AG, F. Kamenik]
Phys.Lett. B764 (2017) 126-134

Part 2
R(K)* & *R(K*)

- General remarks:
  SM EFT, Simplified models
- Collider signatures:
  Resonances
  Di-lepton tails

Prologue: *New physics in b → s μ μ*

In the SM



- Loop, CKM, and GIM suppression

Prologue: *New physics in b → s μ μ*

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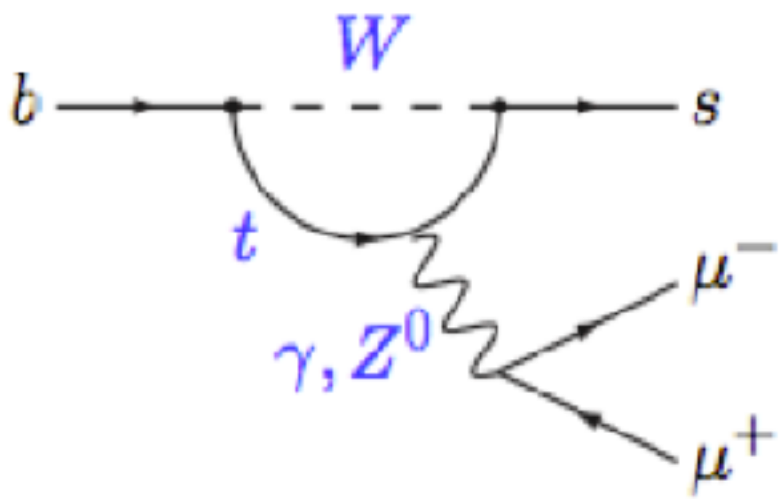


- Loop, CKM, and GIM suppression

New Physics

Left-handed currents

$$\Delta C_9^\mu = -\Delta C_{10}^\mu = -0.61 \pm 0.12$$

$$\Lambda / g_* \approx 32^{+4}_{-3}\ \text{TeV}$$

Tree-level, unsuppressed ($g^* \sim 1$)	Loop-generated ($g^* = 1/4\pi$)
~ 30 TeV	~ 2.5 TeV
Tree-level, MFV ($g^{*2} = V_{ts}$)	Loop-generated, MFV
~ 6 TeV	~ 0.5 TeV

→ *New physics within or beyond the LHC threshold production*

Single mediator models

Need to generate one of the operators at the EW scale:

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

- ***b → s μ μ at tree level***

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

~~$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$~~

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

~~$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$~~

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

New

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

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

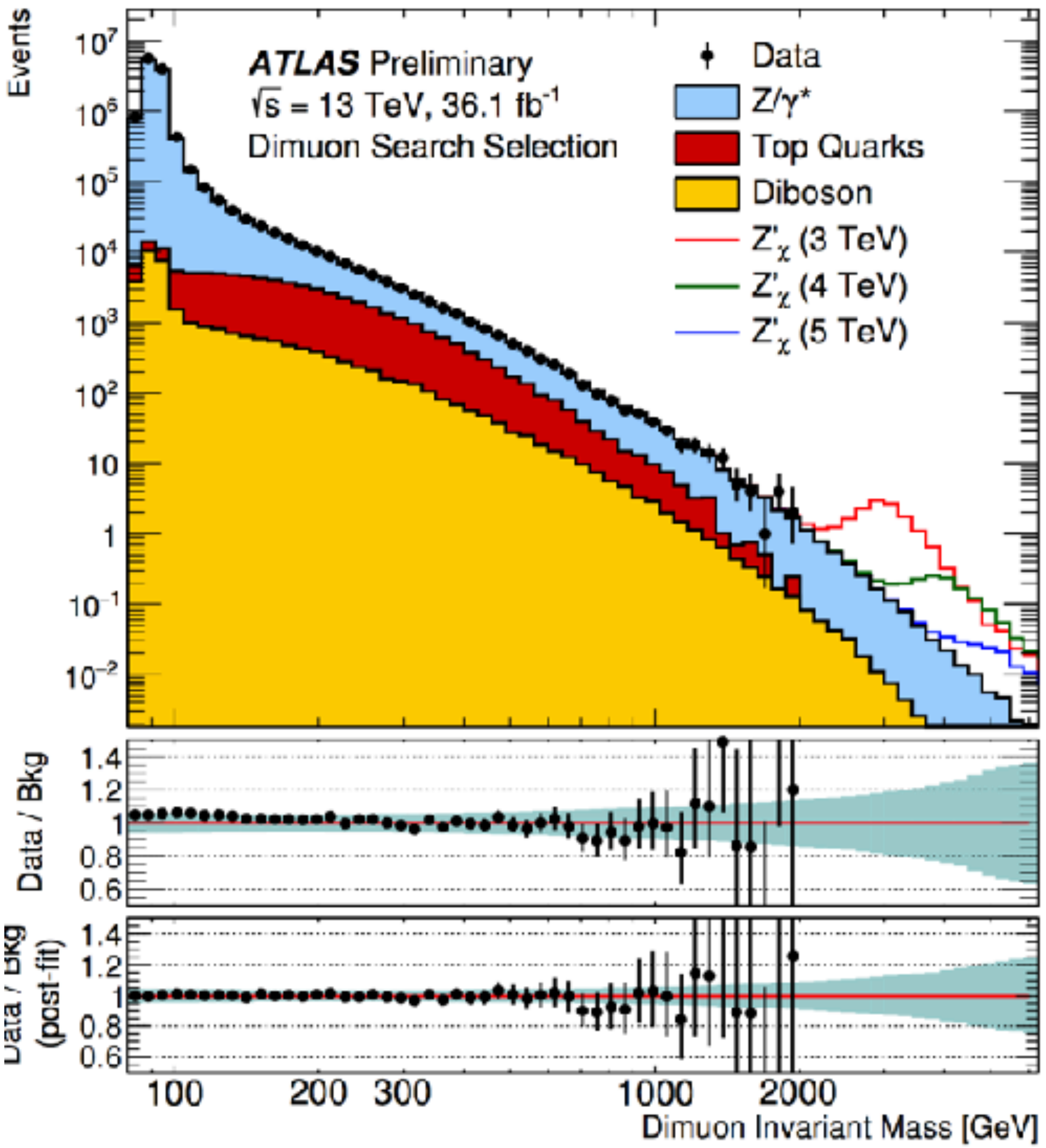
$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

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

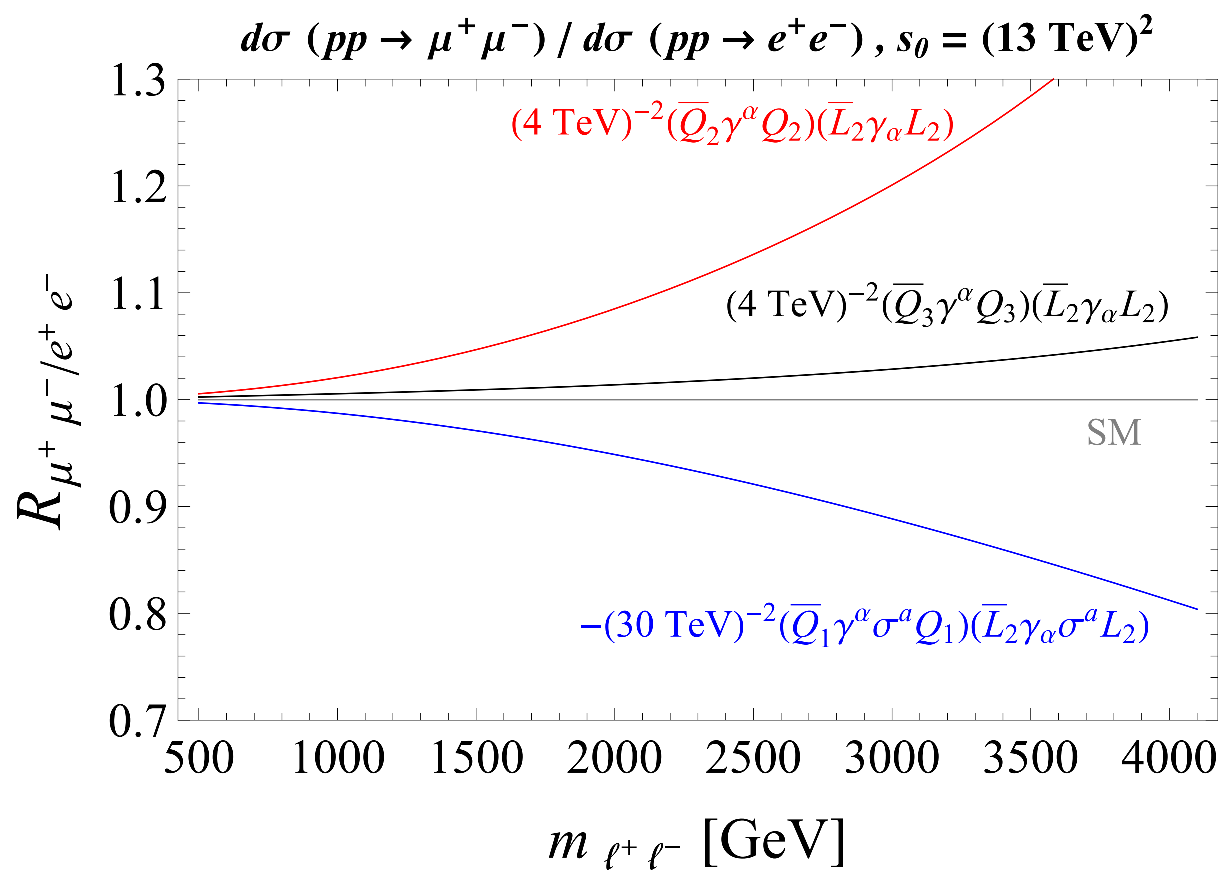
- Coherent picture of *B*-anomalies is emerging?

[Buttazzo, AG, Isidori, Marzocca] to appear soon

Di-lepton searches at high p_T



- Peak hunt
- Deviation in the tail

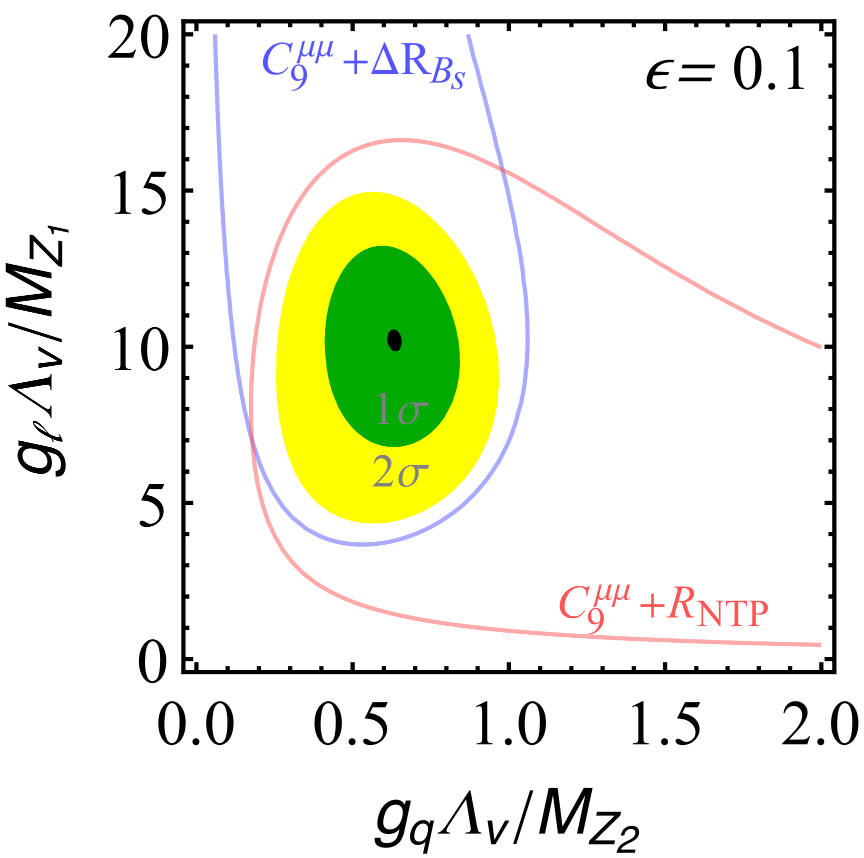


[AG, and D. Marzocca]
1704.09015

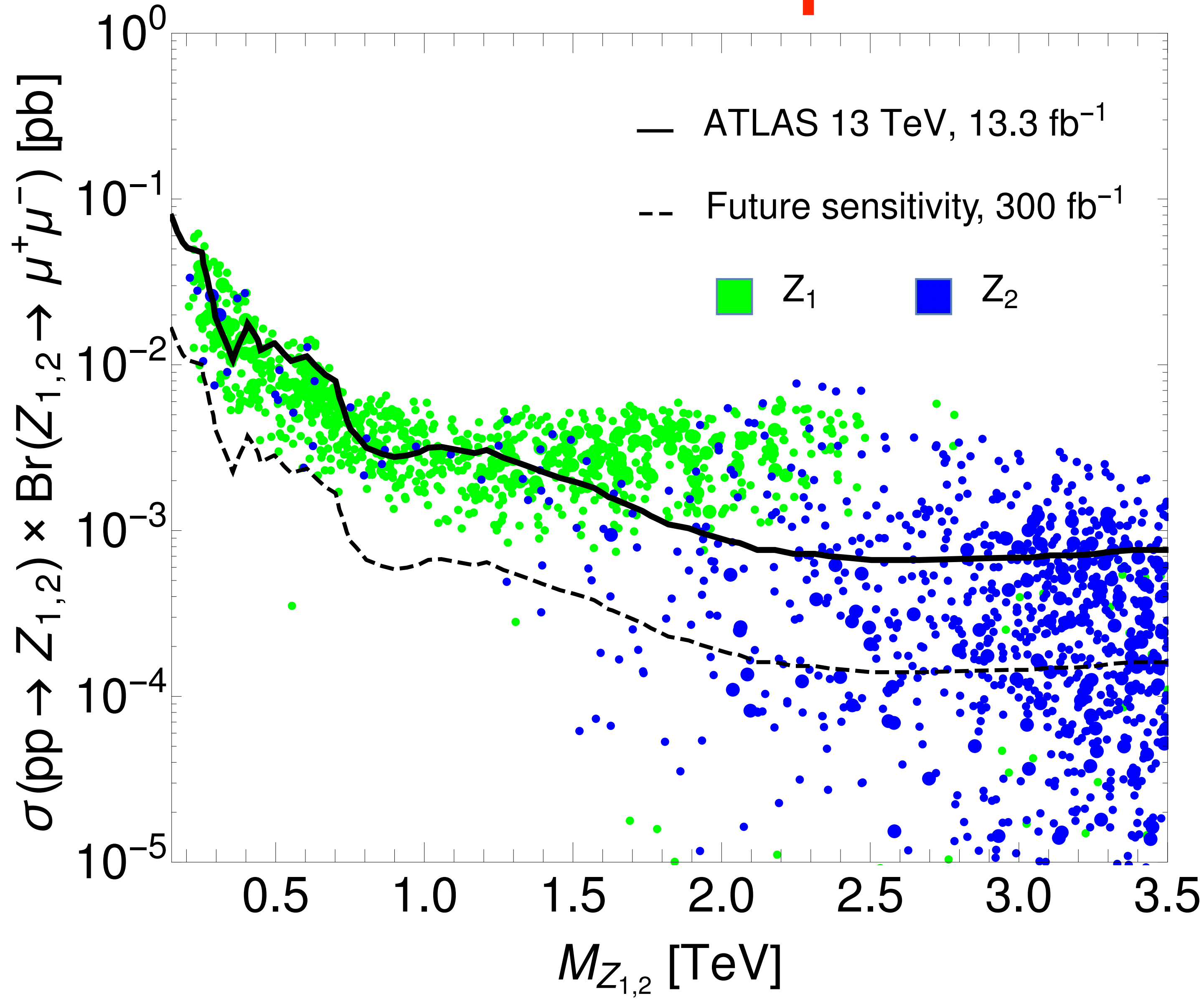
Resonance searches

- 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 "peaks"



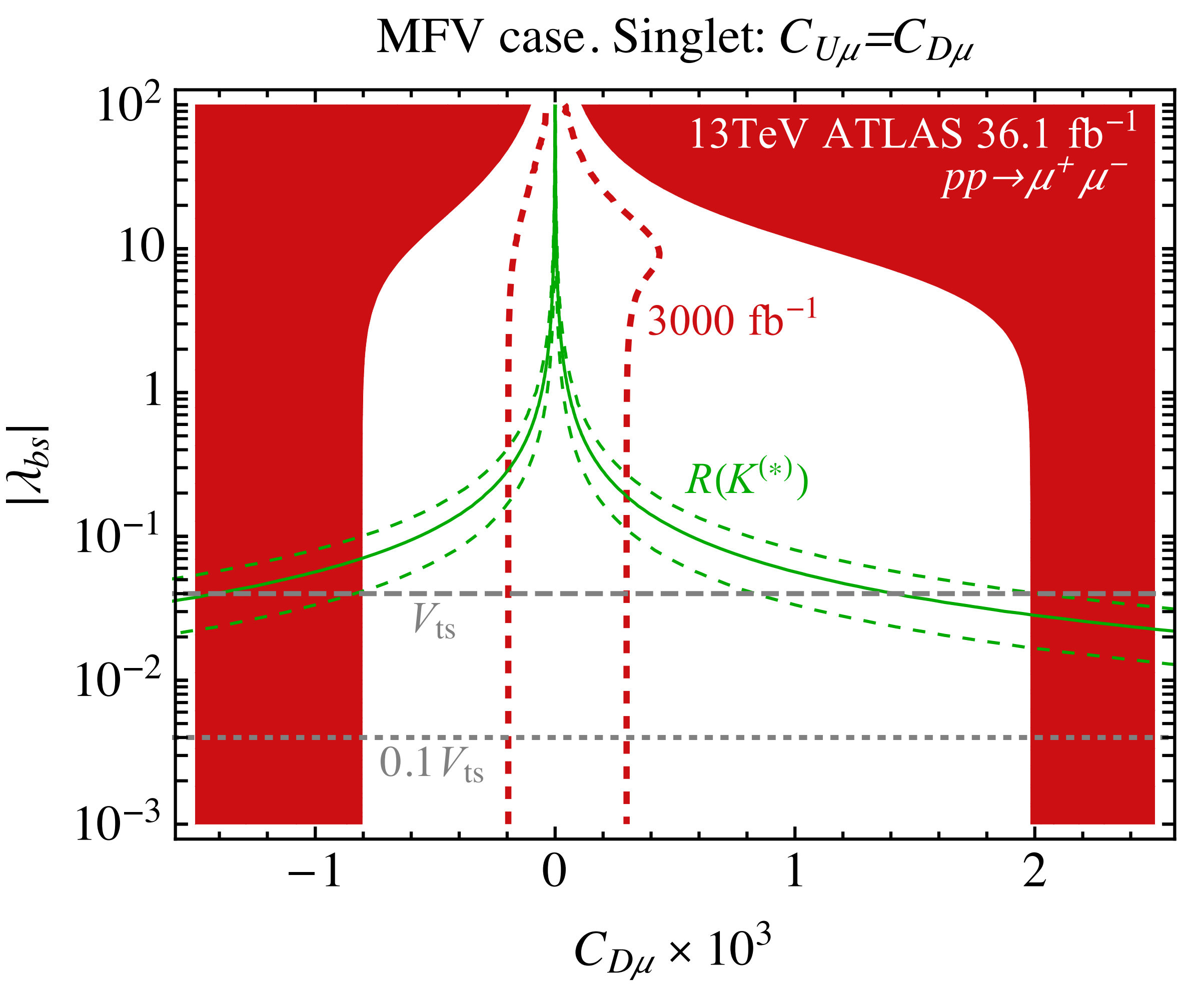
[Crivellin, Fuentes-Martin, AG, and Isidori]
Phys.Lett. B766 (2017) 77-85

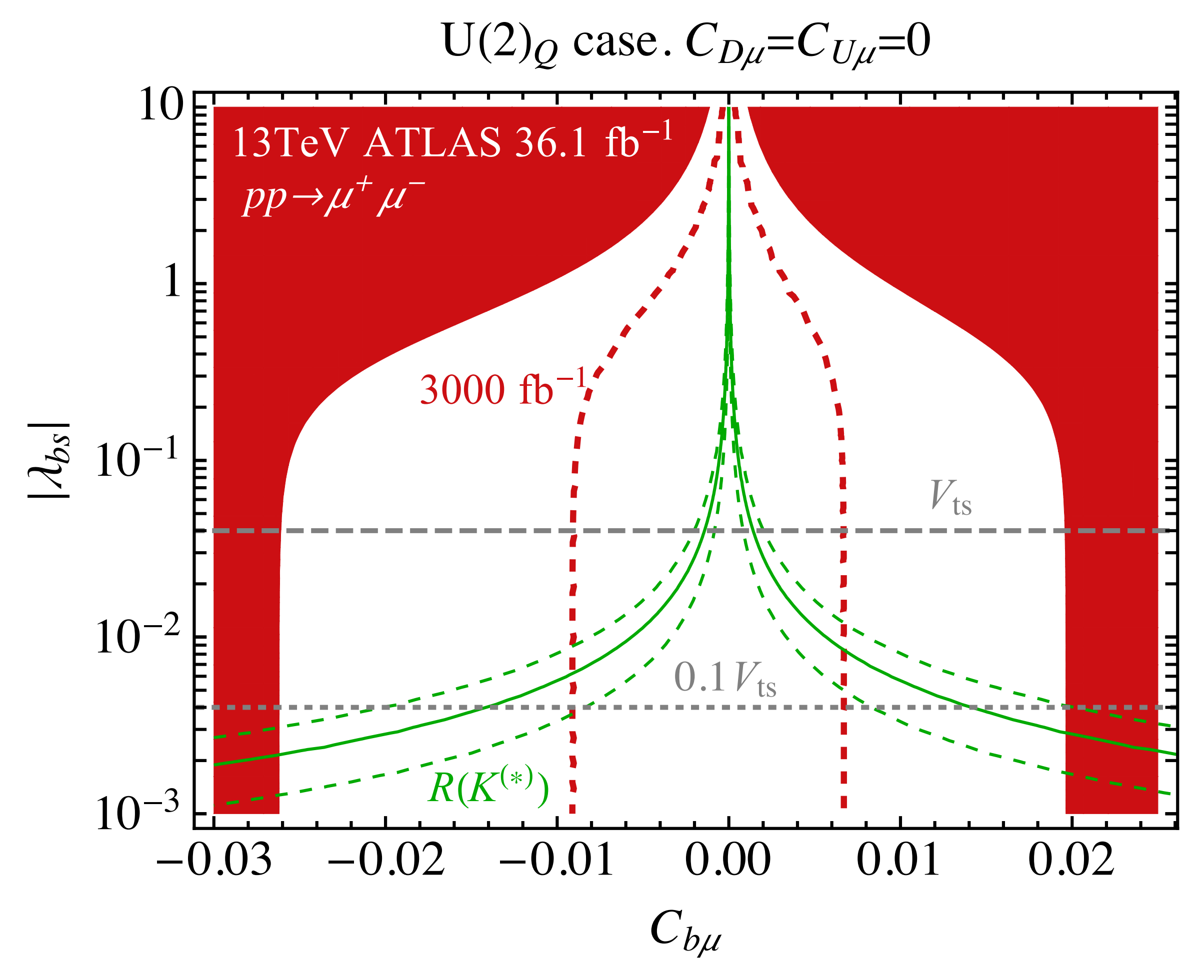
Drell-Yan tails

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

$$\mathscr{L}^{\text{eff}} \supset \frac{\mathbf{C}_{ij}^{U\mu}}{v^2}(\bar{u}_L^i \gamma_\mu u_L^j)(\bar{\mu}_L \gamma^\mu \mu_L) + \frac{\mathbf{C}_{ij}^{D\mu}}{v^2}(\bar{d}_L^i \gamma_\mu d_L^j)(\bar{\mu}_L \gamma^\mu \mu_L)$$

- Complementary info on the NP flavour structure





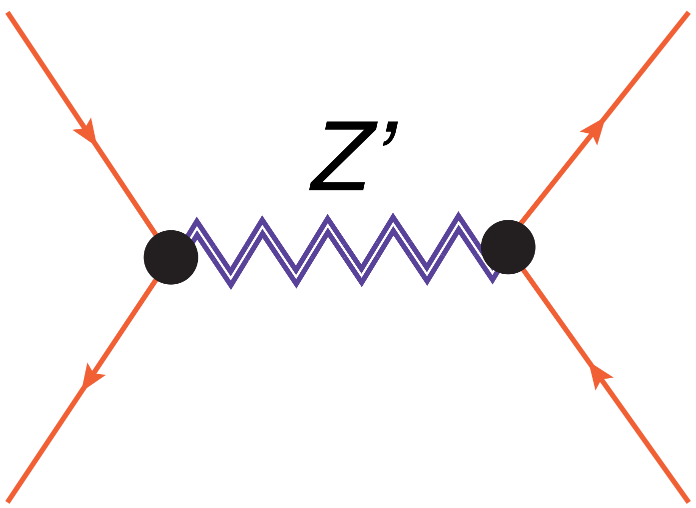
$$\lambda_{bs}^q \equiv C_{bs\mu}/C_{q\mu}$$

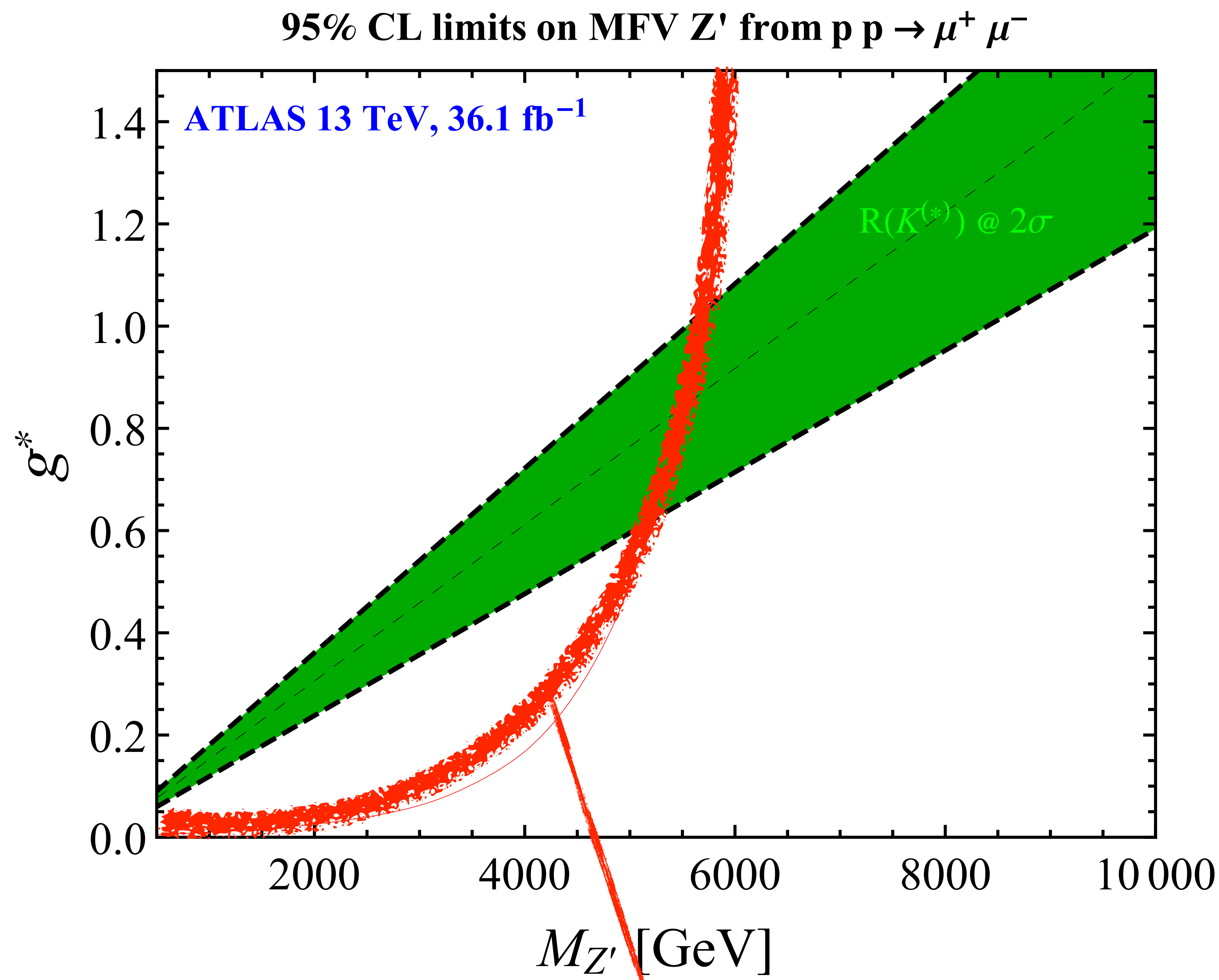
[AG, and D. Marzocca]
1704.09015

Example

MFV Z' boson

[AG, and D. Marzocca]
1704.09015





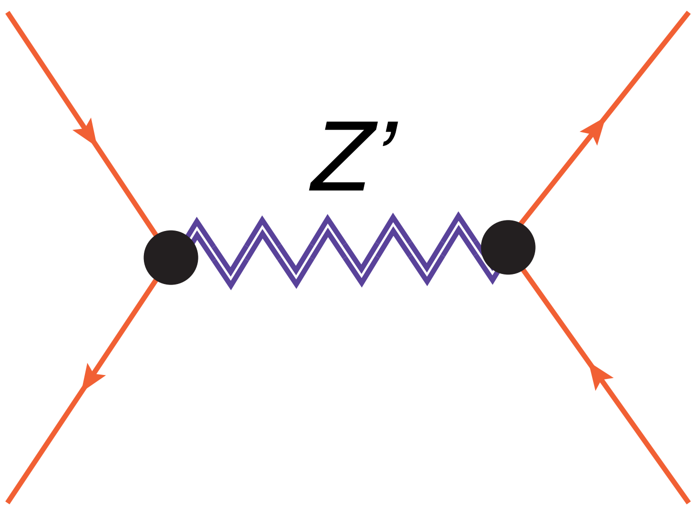
$$(Z'\bar{q}q)_{ij} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & V_{ts}^* \\ 0 & V_{ts} & 1 \end{pmatrix}$$

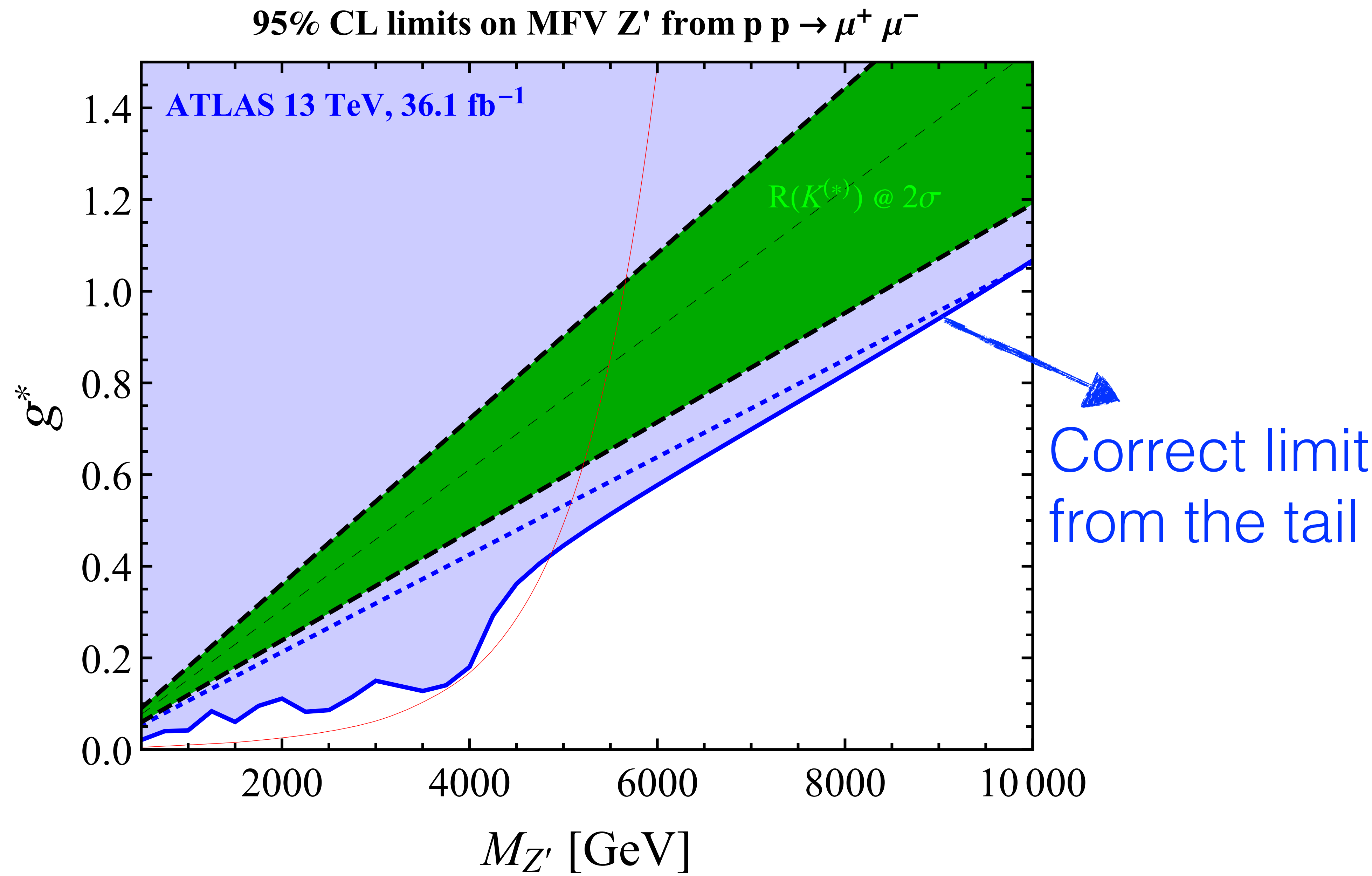
Resonance search limit stops here

Example

MFV Z' boson

[AG, and D. Marzocca]
1704.09015





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

Conclusions

- *$R(D^{(*)})$: Di-Tau signal at the high-p_T!*

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

- *$R(K^{(*)})$: Even if the NP scale is beyond the LHC collision energies, deviation in the high-p_T dilepton tail might still be observed.*

  [AG, and D. Marzocca] 1704.09015

Conclusions

- *$R(D^{(*)})$: Di-Tau signal at the high-p_T!*
  [Faroughy, AG, F. Kamenik] Phys.Lett. B764 (2017) 126-134

- *$R(K^{(*)})$: Even if the NP scale is beyond the LHC collision energies, deviation in the high-p_T dilepton tail might still be observed.*
  [AG, and D. Marzocca] 1704.09015

Stay tuned…

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

Backup slides

Flavour structure

[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)

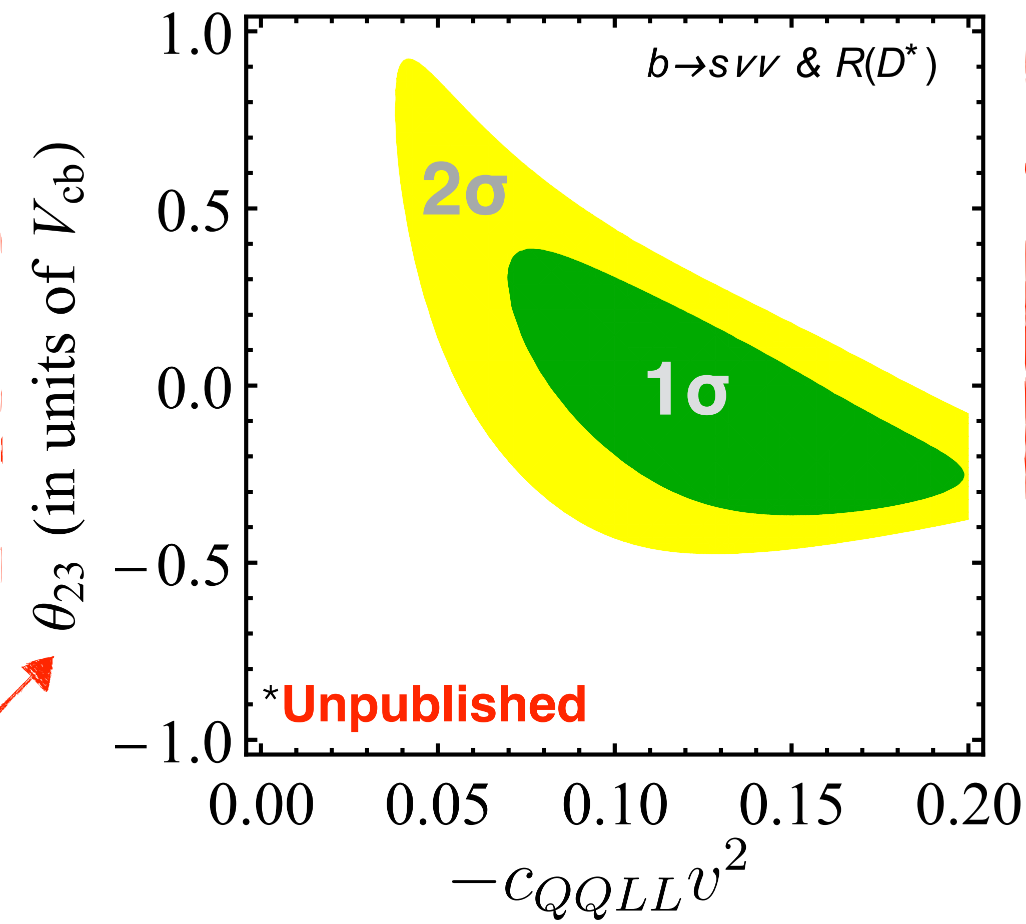
$$Q_i = (V_{ji}^* u_L^j, d_L^i)^T \text{ and } L_i = (U_{ji}^* \nu^j, \ell_L^i)^T$$

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

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



$\Delta R_{B_s}^{\Delta F=2}$

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

Collider limits: **SM EFT**

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

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

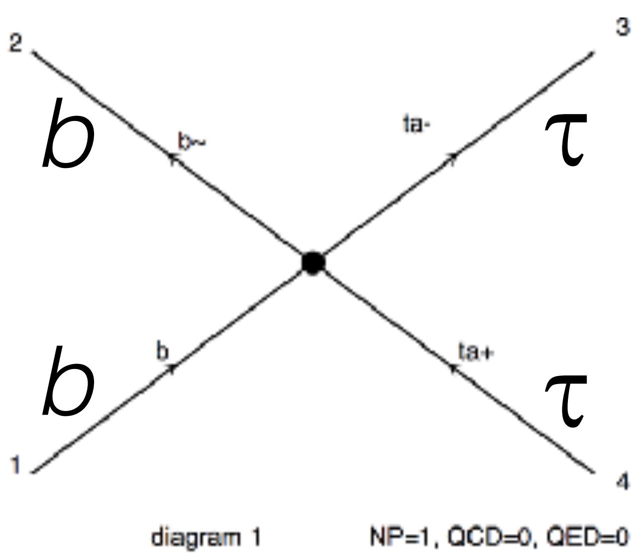
(1) *Dominant couplings with the third generation*

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

(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



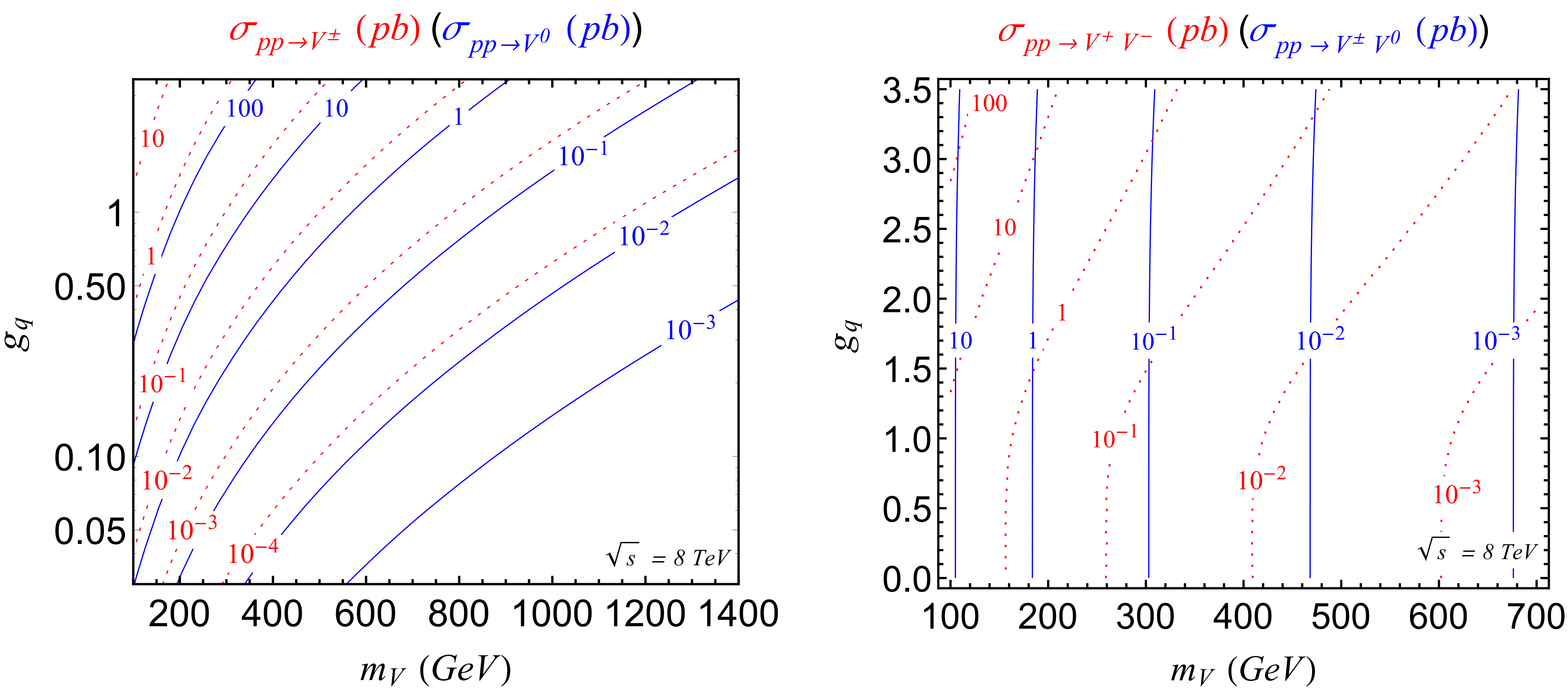
Recast of $\tau^+\tau^-$ ATLAS search:
$|c_{QQLL}| < 2.8\ \text{TeV}^{-2}$ at 95% CL

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

*Similar conclusions for: $\mathcal{O}_{S_R}$ $(\bar{d}^i_R Q_j)(\bar{L}_k \ell^l_R)$

LHC phenomenology: Vector Triplet Model

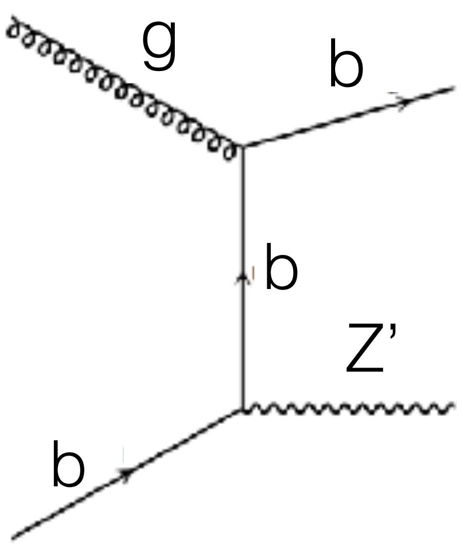
Production cross sections:



- 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



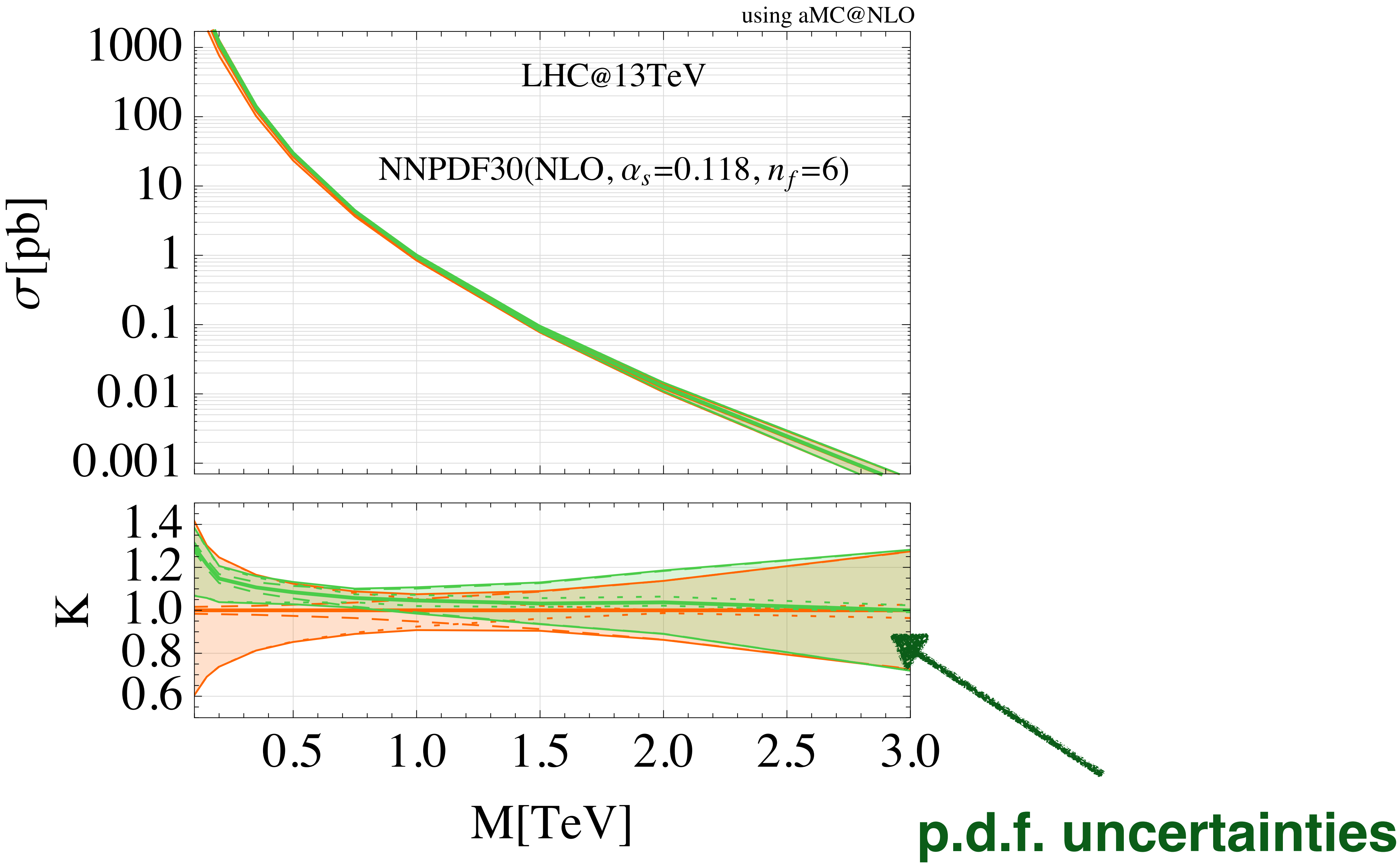
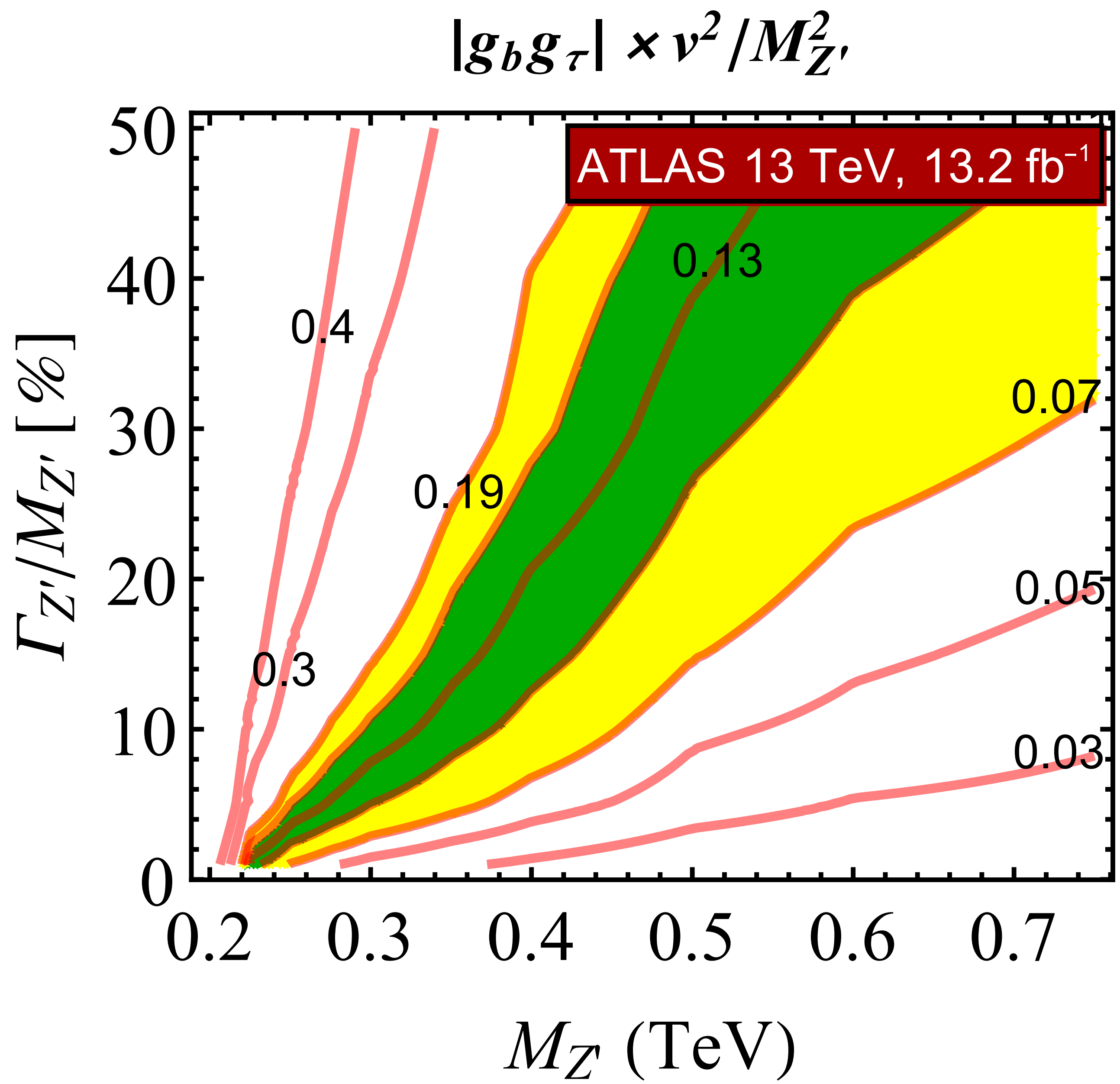


Figure 3: Next-to-leading order QCD corrections for a narrow Z' production via bottom-bottom fusion.

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

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



- Improvements needed in the low mass region!

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

Two Higgs doublet model

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

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

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

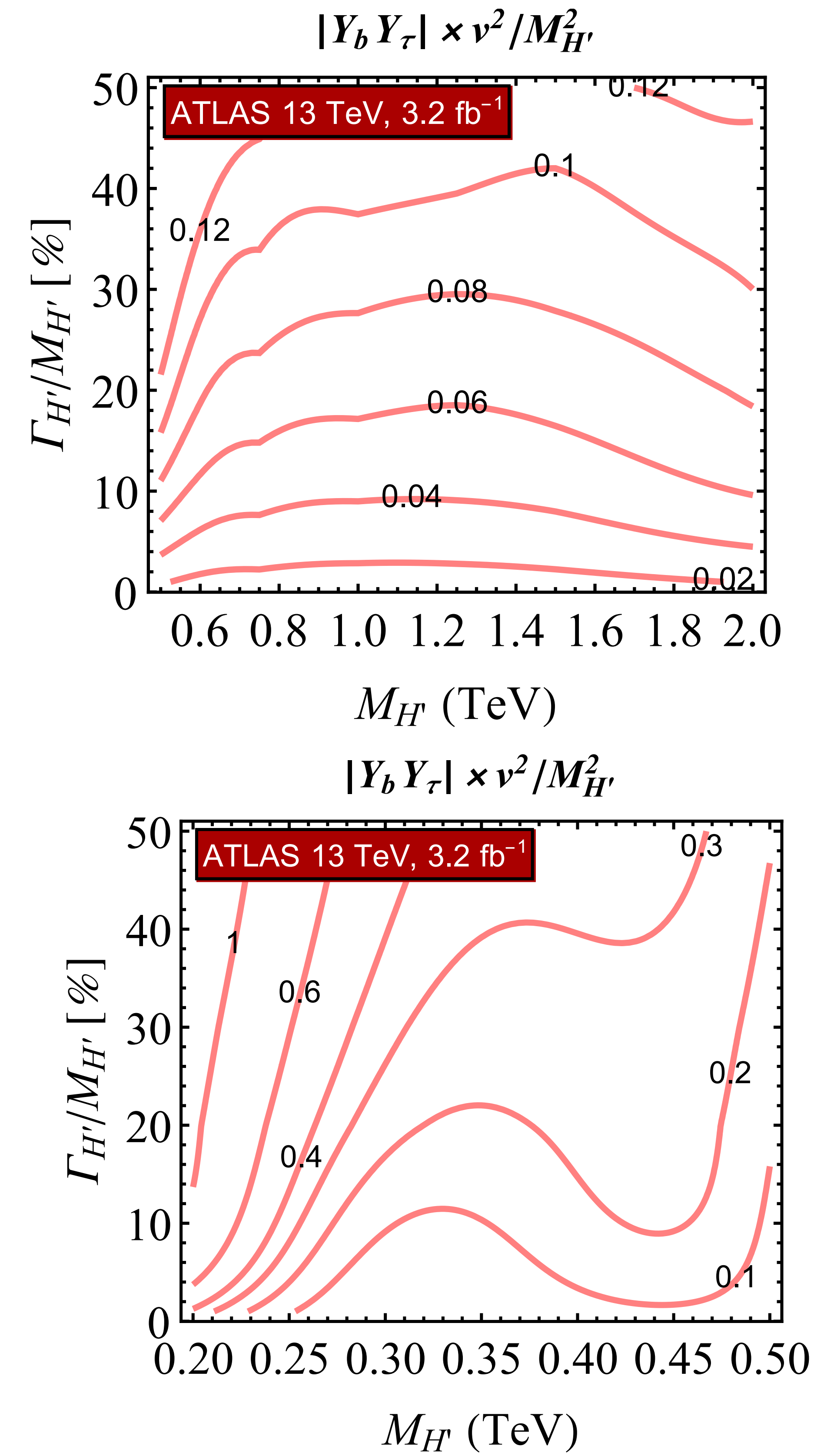
- Both non-zero to fit the anomaly

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

Fit to R(D*) anomaly

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

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



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

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

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

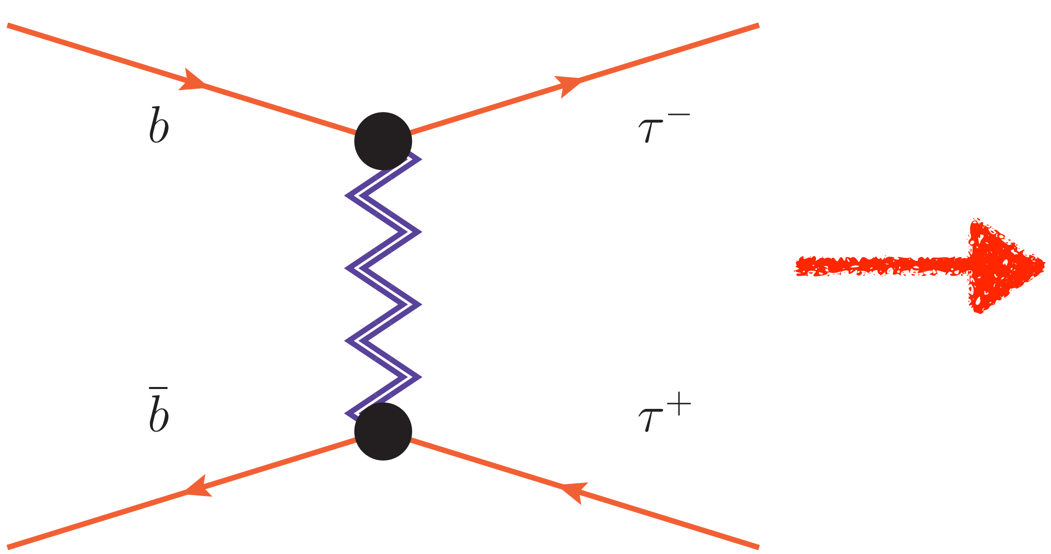
- With the right-handed neutrino

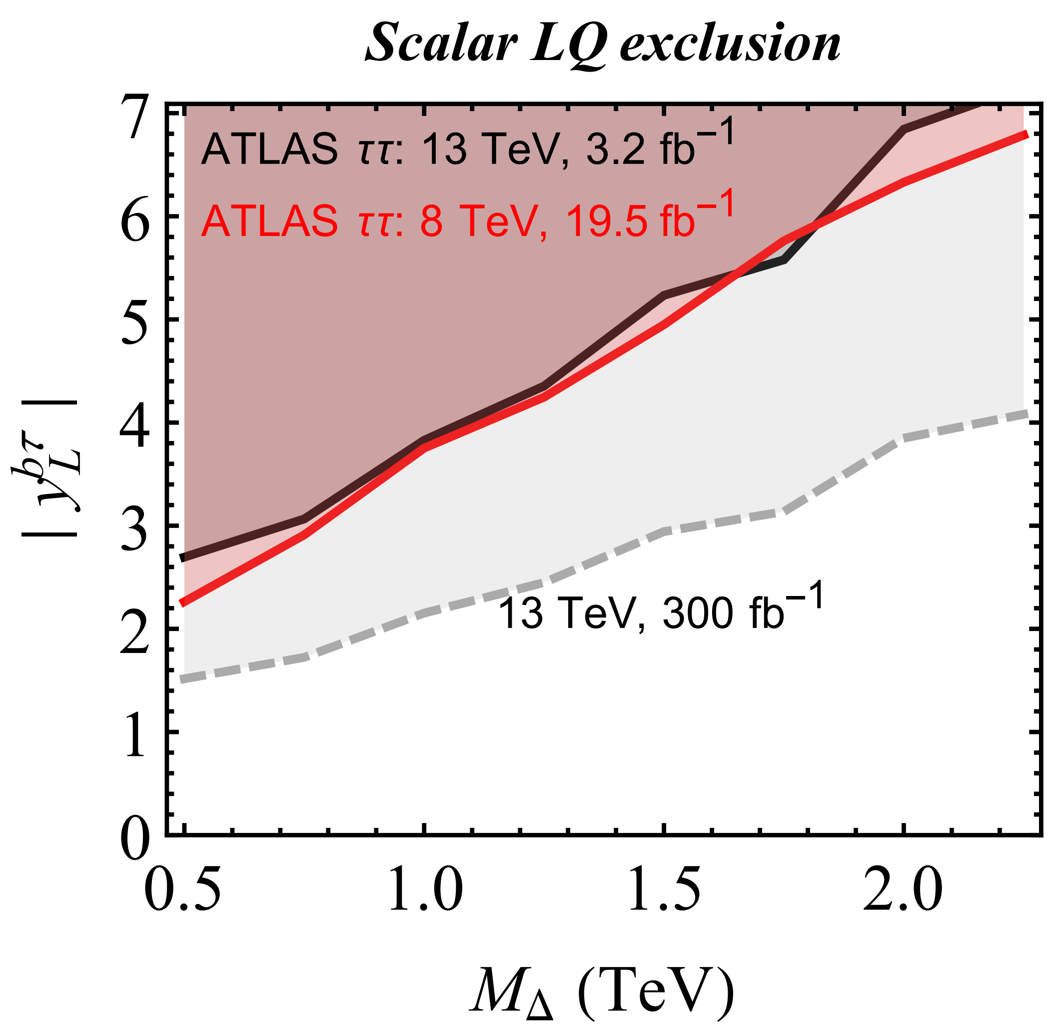
$$\mathcal{L}_\Delta \supset Y_L^{ij} \bar{d}_i (i\sigma_2 \Delta^*)^\dagger L_j + Y_R^{i\nu} \bar{Q}_i \Delta \nu_R + \text{h.c.}\ .$$

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

Fit to R(D*) anomaly

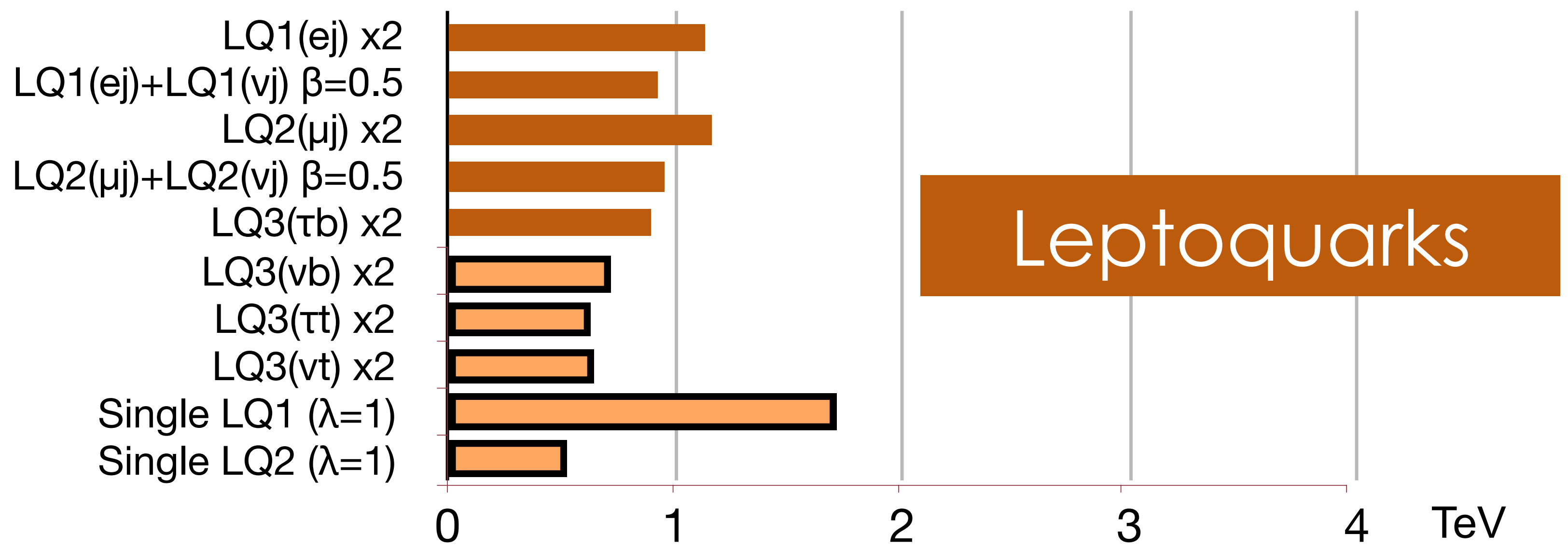
$$\left(\frac{Y_R^{b\nu}\ Y_L^{b\tau *}}{g_w^2}\right)\left(\frac{M_W}{M_\Delta}\right)^2 = 1.2 \pm 0.3$$





- 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 (≳1 TeV)
- Focus is on the **third generation LQ searches**

Limits from Drell-Yan tails

C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^2}$	[-5.73, 14.2] $\times 10^{-4}$	[-1.30, 1.51] $\times 10^{-4}$
$C^{(3)}_{Q^1L^2}$	[-7.11, 2.84] $\times 10^{-4}$	[-5.25, 5.25] $\times 10^{-5}$
$C_{u_RL^2}$	[-0.84, 1.61] $\times 10^{-3}$	[-2.00, 2.66] $\times 10^{-4}$
$C_{u_R\mu_R}$	[-0.52, 1.36] $\times 10^{-3}$	[-1.04, 1.08] $\times 10^{-4}$
$C_{Q^1\mu_R}$	[-0.82, 1.27] $\times 10^{-3}$	[-2.25, 4.10] $\times 10^{-4}$
$C_{d_RL^2}$	[-2.13, 1.61] $\times 10^{-3}$	[-8.98, 5.11] $\times 10^{-4}$
$C_{d_R\mu_R}$	[-2.31, 1.34] $\times 10^{-3}$	[-4.89, 3.33] $\times 10^{-4}$
$C^{(1)}_{Q^2L^2}$	[-8.84, 7.35] $\times 10^{-3}$	[-3.83, 2.39] $\times 10^{-3}$
$C^{(3)}_{Q^2L^2}$	[-9.75, 5.56] $\times 10^{-3}$	[-1.43, 1.15] $\times 10^{-3}$
$C_{Q^2\mu_R}$	[-7.53, 8.67] $\times 10^{-3}$	[-2.58, 3.73] $\times 10^{-3}$
$C_{s_RL^2}$	[-1.04 , 0.93] $\times 10^{-2}$	[-4.42, 3.33] $\times 10^{-3}$
$C_{s_R\mu_R}$	[-1.09 , 0.87] $\times 10^{-2}$	[-4.67, 2.73] $\times 10^{-3}$
$C_{c_RL^2}$	[-1.33, 1.52] $\times 10^{-2}$	[-4.58, 6.54] $\times 10^{-3}$
$C_{c_R\mu_R}$	[-1.21, 1.62] $\times 10^{-2}$	[-3.48, 6.32] $\times 10^{-3}$
$C_{b_LL^2}$	[-2.61, 2.07] $\times 10^{-2}$	[-11.1, 6.33] $\times 10^{-3}$
$C_{b_L\mu_R}$	[-2.28, 2.42] $\times 10^{-2}$	[-8.53, 10.0] $\times 10^{-3}$
$C_{b_RL^2}$	[-2.41, 2.29] $\times 10^{-2}$	[-9.90, 8.68] $\times 10^{-3}$
$C_{b_R\mu_R}$	[-2.47, 2.23] $\times 10^{-2}$	[-10.5, 7.97] $\times 10^{-3}$

C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^1}$	[-0.0, 1.75] $\times 10^{-3}$	[-1.01, 1.13] $\times 10^{-4}$
$C^{(3)}_{Q^1L^1}$	[-8.92, -0.54] $\times 10^{-4}$	[-3.99, 3.93] $\times 10^{-5}$
$C_{u_RL^1}$	[-0.19, 1.92] $\times 10^{-3}$	[-1.56, 1.92] $\times 10^{-4}$
$C_{u_Re_R}$	[0.15, 2.06] $\times 10^{-3}$	[-7.89, 8.23] $\times 10^{-5}$
$C_{Q^1e_R}$	[-0.40, 1.37] $\times 10^{-3}$	[-1.8, 2.85] $\times 10^{-4}$
$C_{d_RL^1}$	[-2.1, 1.04] $\times 10^{-3}$	[-7.59, 4.23] $\times 10^{-4}$
$C_{d_Re_R}$	[-2.55, 0.46] $\times 10^{-3}$	[-3.37, 2.59] $\times 10^{-4}$
$C^{(1)}_{Q^2L^1}$	[-6.62, 4.36] $\times 10^{-3}$	[-3.31, 1.92] $\times 10^{-3}$
$C^{(3)}_{Q^2L^1}$	[-8.24, 2.05] $\times 10^{-3}$	[-8.87, 7.90] $\times 10^{-4}$
$C_{Q^2e_R}$	[-4.67, 6.34] $\times 10^{-3}$	[-2.11, 3.30] $\times 10^{-3}$
$C_{s_RL^1}$	[-7.4 , 5.9] $\times 10^{-3}$	[-3.96, 2.8] $\times 10^{-3}$
$C_{s_Re_R}$	[-8.17, 5.06] $\times 10^{-3}$	[-3.82, 2.13] $\times 10^{-3}$
$C_{c_RL^1}$	[-0.83, 1.13] $\times 10^{-2}$	[-3.74, 5.77] $\times 10^{-3}$
$C_{c_Re_R}$	[-0.67, 1.27] $\times 10^{-2}$	[-2.59, 4.17] $\times 10^{-3}$
$C_{b_LL^1}$	[-1.93, 1.19] $\times 10^{-2}$	[-8.62, 4.82] $\times 10^{-3}$
$C_{b_Le_R}$	[-1.47, 1.67] $\times 10^{-2}$	[-7.29, 8.99] $\times 10^{-3}$
$C_{b_RL^1}$	[-1.65, 1.49] $\times 10^{-2}$	[-8.86, 7.48] $\times 10^{-3}$
$C_{b_Re_R}$	[-1.73, 1.40] $\times 10^{-2}$	[-9.38, 6.63] $\times 10^{-3}$

[AG, and D. Marzocca]
1704.09015

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:*

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

- 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	$\epsilon_q^2 \lvert\lambda^q_{bs}\rvert^2 (\lvert V^*_{tb}V_{ts}\rvert^2 R^{\rm loop}_{\rm SM})^{-1}$
4) b→s μ μ	ΔC_9^μ	-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}]	$(G_F/\sqrt{2})\epsilon_q^2 \lvert V_{ub}V^*_{cb}\rvert^2$

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

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

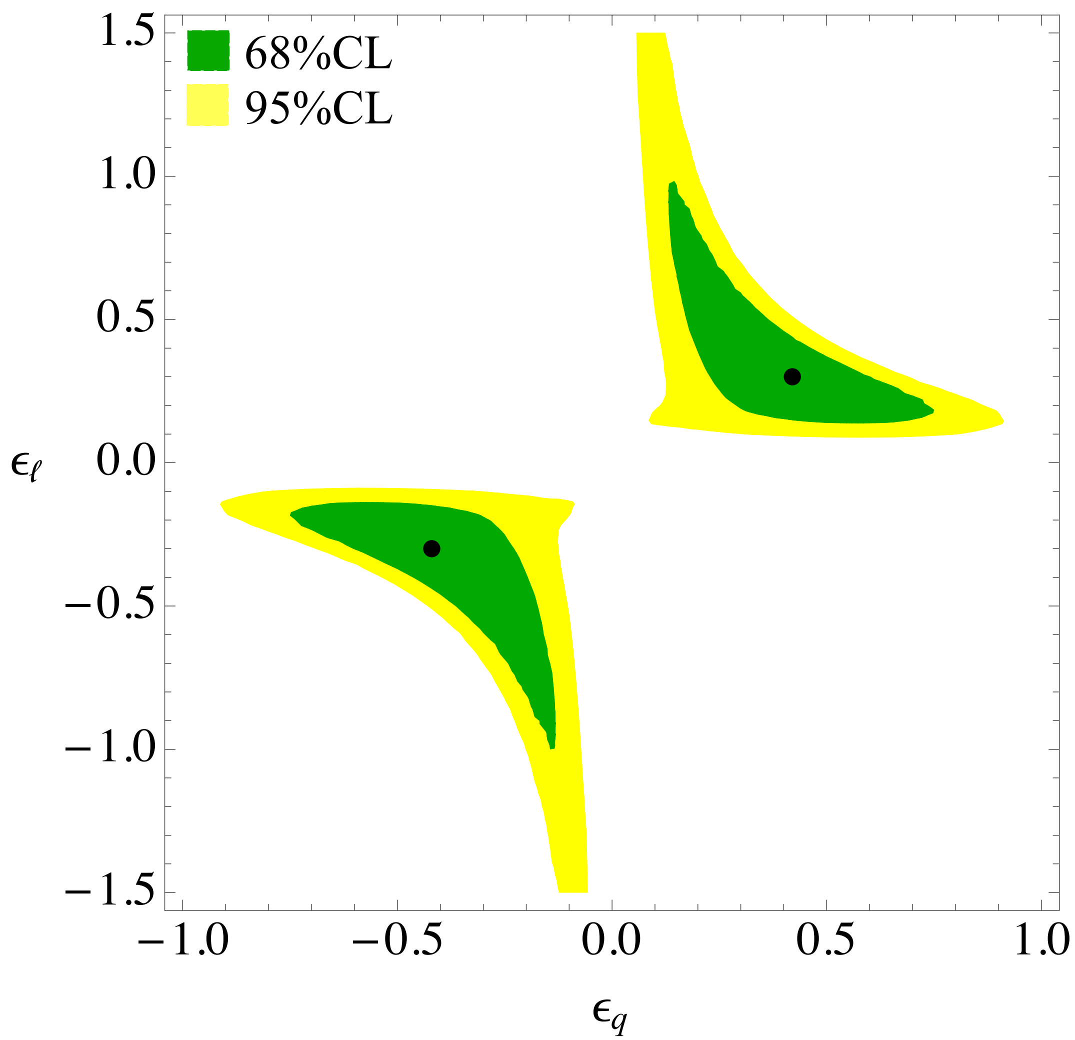
***VTM**: Combined fit to low-energy data*

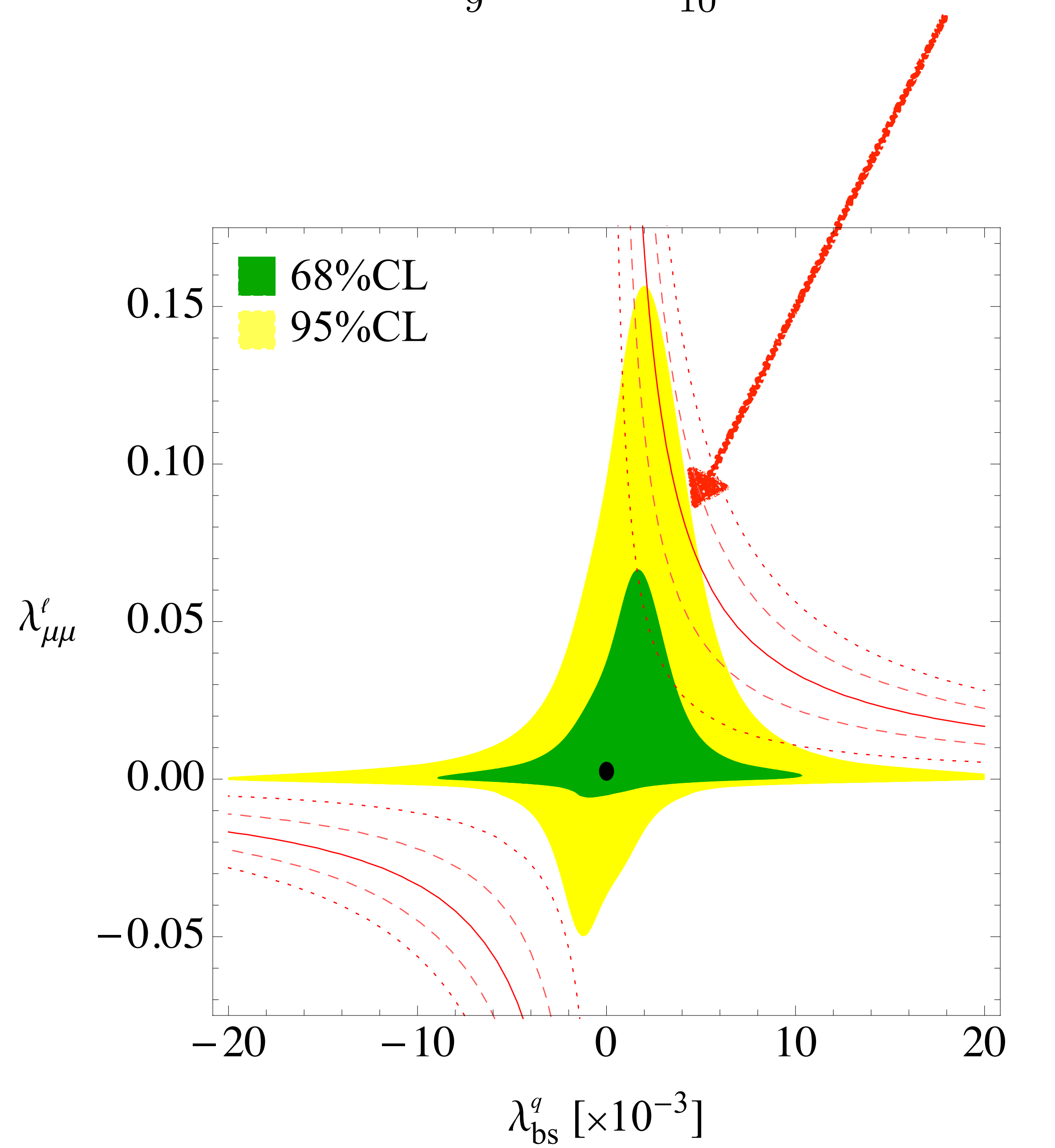
- The fit is driven by

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

- Some tension with

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





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

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

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