Flavour anomaly inputs for high p_T measurements

Admir Greljo

1708.08450 - Luca Di Luzio, AG, Marco Nardecchia

1706.07808 - Dario Buttazzo, AG, Gino Isidori, David Marzocca

Eur.Phys.J. C77 (2017) no.8, 548 - AG, David Marzocca

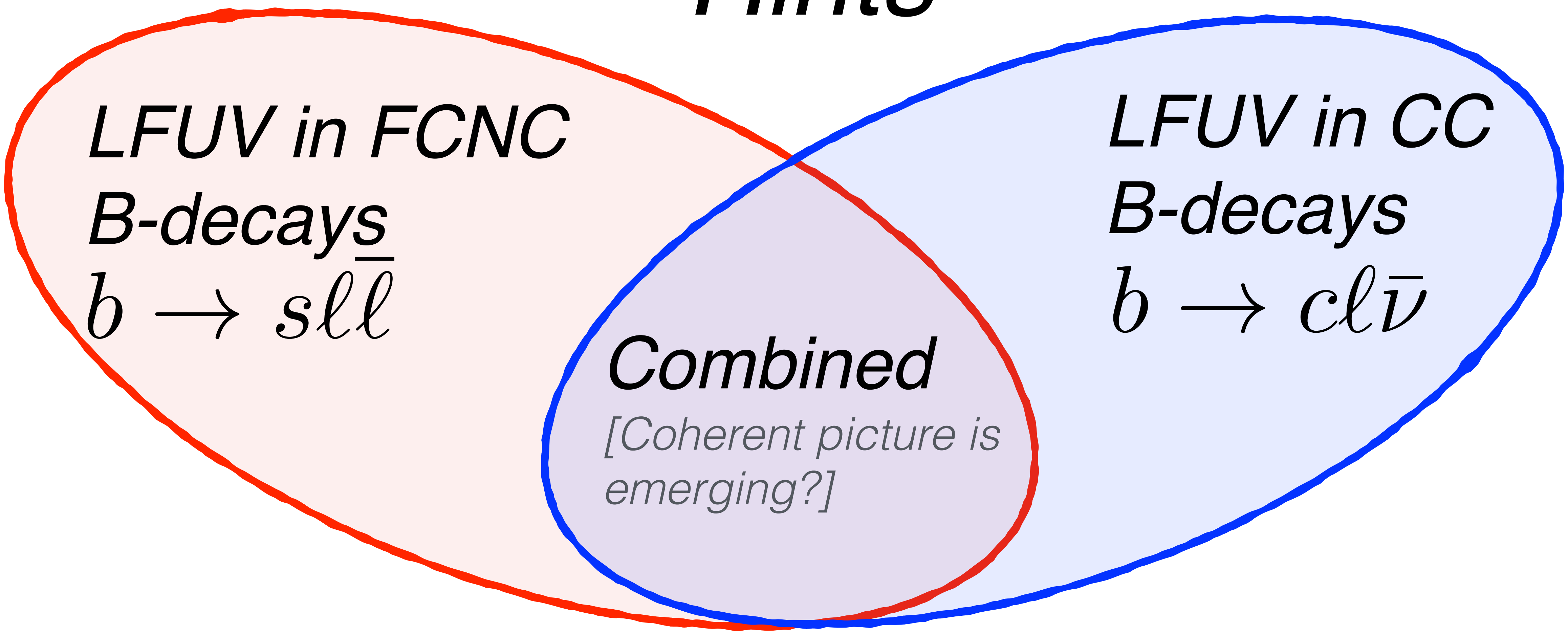
Phys.Lett. B766 (2017) 77-85 - Andreas Crivellin, Javier Fuentes-Martin, AG, Gino Isidori

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

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

"Workshop on the physics of HL-LHC, and perspectives at HE-LHC",
31/10/2017, CERN

Hints



LFUV in FCNC
B-decays
$b \to s\ell\bar{\ell}$

Combined
[Coherent picture is emerging?]

LFUV in CC
B-decays
$b \to c\ell\bar{\nu}$

Tools

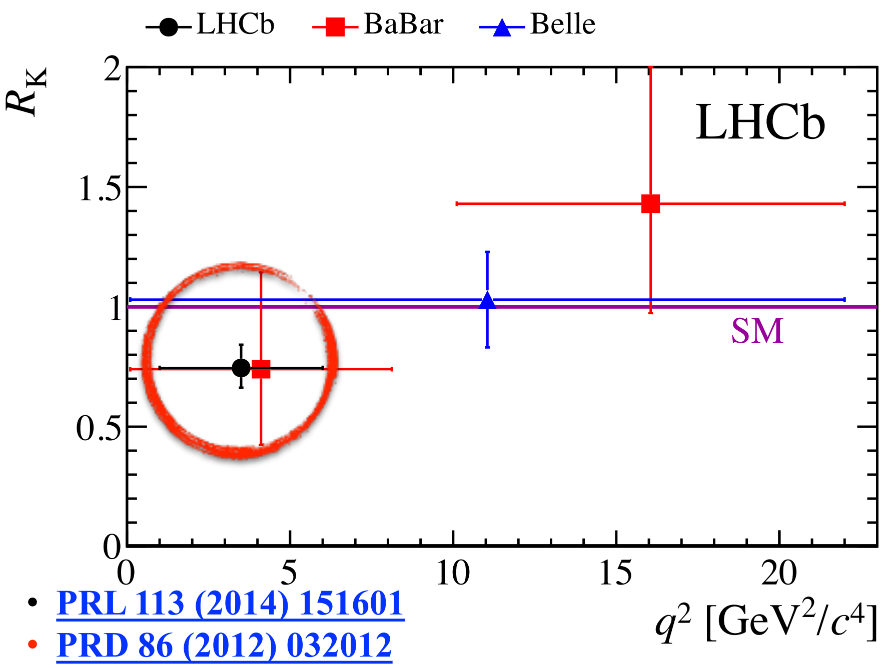
- Effective Hamiltonian
- SM EFT
- Dynamical models
- Flavour symmetry

Focus

If true, what is the physics case at high-p_T ?

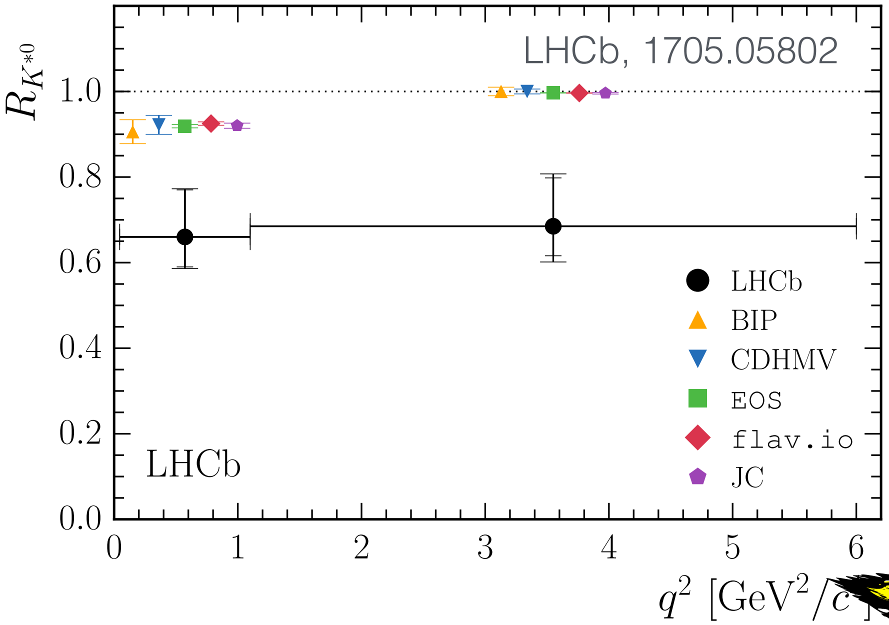
$b \to s\ell\bar{\ell}$

Lepton universality ratios μ/e



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

S. Bifani, CERN seminar

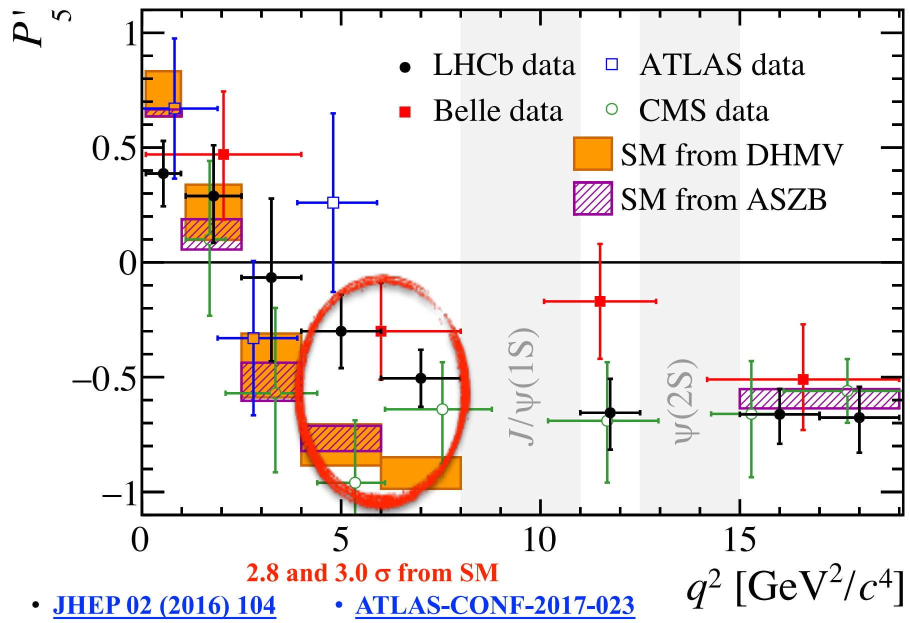


"Clean"

$$R_{K^+}[1.0,\ 6.0]^{\mathrm{SM}} = 1.00 \pm 0.01_{\mathrm{QED}}$$

[Bordone, Isidori, Pattori], 1605.07633

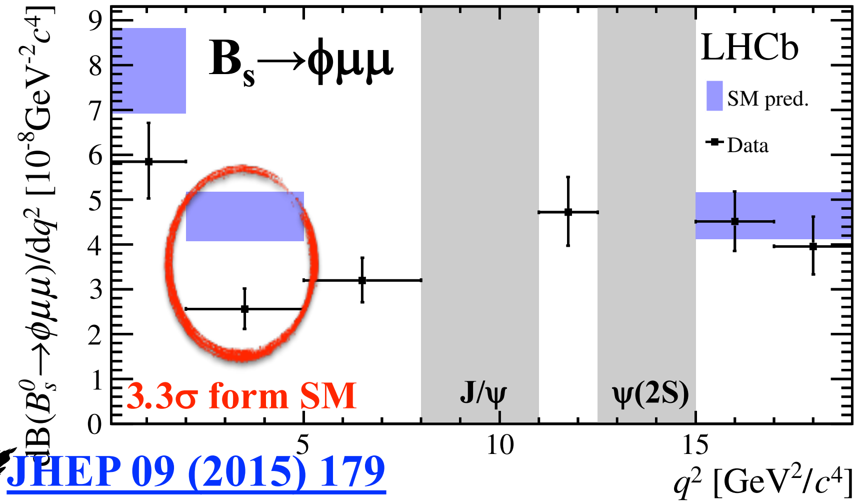
B → K*μμ angular analysis



2.8 and 3.0 σ from SM

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

Branching Fractions



3.3σ form SM

JHEP 09 (2015) 179

"Less clean"

Effective low-energy Hamiltonian

$$\mathcal{H}_{\rm eff} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\lambda_t^{sb}\sum_i \mathcal{C}_i\mathcal{O}_i\,,$$

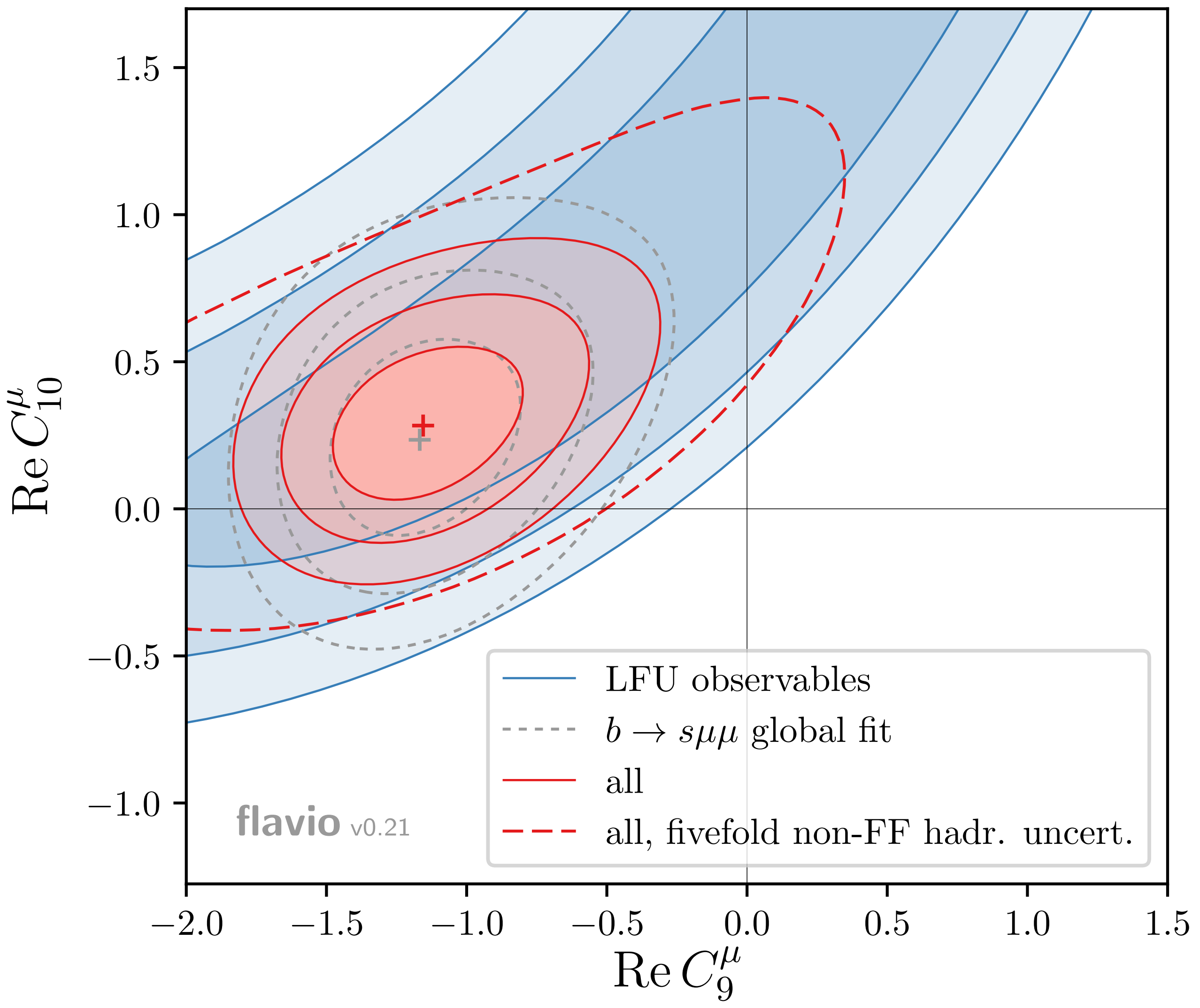
$$\mathcal{O}_9 = (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell)\,, \qquad \mathcal{O}_9' = (\bar{s}\gamma_\alpha P_R b)(\bar{\ell}\gamma^\alpha \ell)\,,$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha\gamma_5 \ell)\,, \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\alpha P_R b)(\bar{\ell}\gamma^\alpha\gamma_5 \ell)$$

$$\lambda_t^{ij} = V_{ti}^* V_{tj}$$

- *New physics contribution to muonic O_9 operator:* $(b_L\,\gamma_\mu\, s_L)(\mu\,\gamma^\mu\,\mu)$
- *Only LFU ratios* **~ 4σ**

Consistency! [1704.05435]



Global fits by several groups [1704.05435,1704.05340, 1704.05438, 1704.05447, 1704.05446, 1705.06274]

Effective low-energy Hamiltonian

$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\lambda_t^{sb}\sum_i \mathcal{C}_i\mathcal{O}_i\,,$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha\ell)\,, \qquad \mathcal{O}_9' = (\bar{s}\gamma_\alpha P_R b)(\bar{\ell}\gamma^\alpha\ell)\,,$$

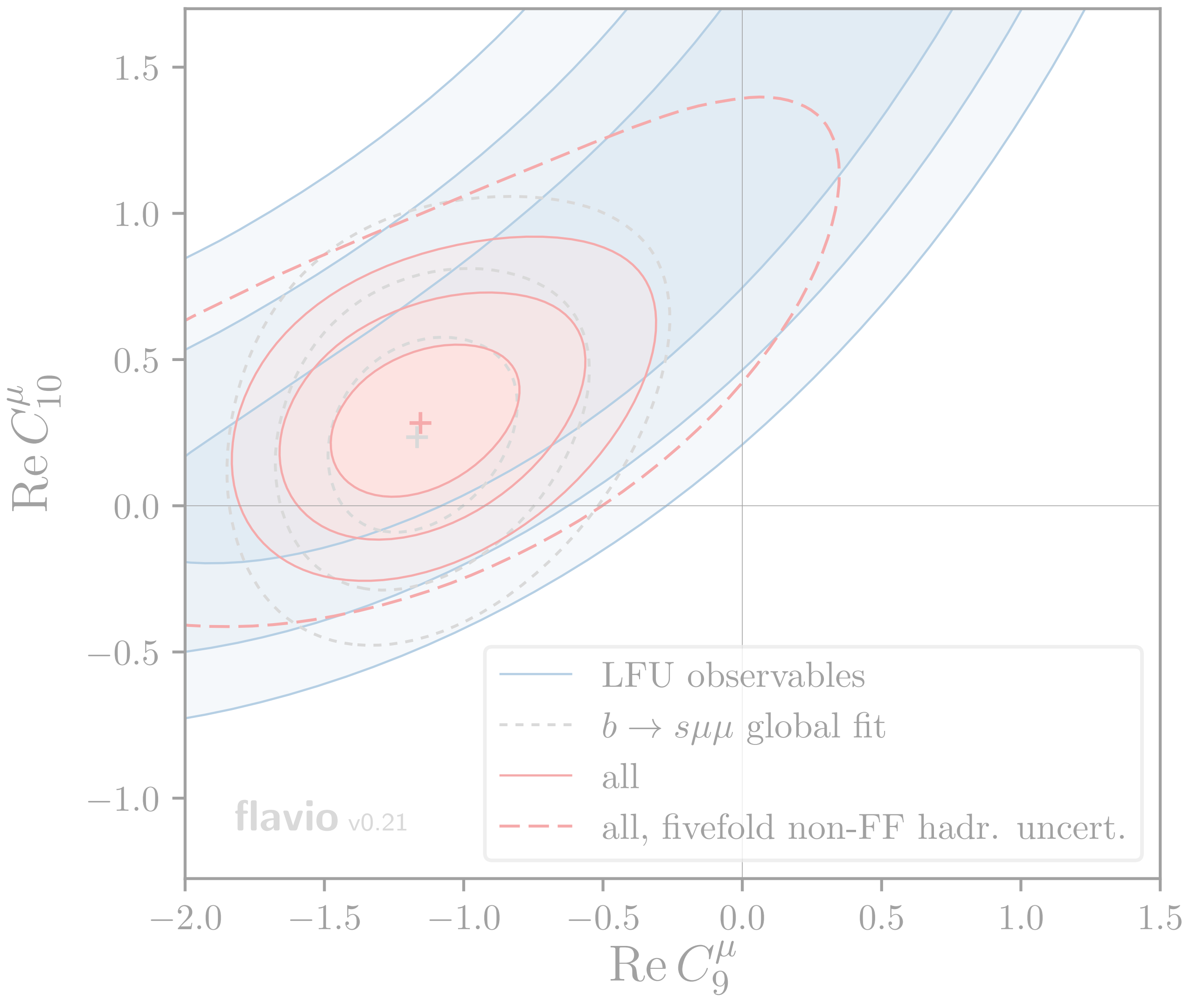
$$\mathcal{O}_{10} = (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha\gamma_5\ell)\,, \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\alpha P_R b)(\bar{\ell}\gamma^\alpha\gamma_5\ell)$$

$$\lambda_t^{ij} = V_{ti}^* V_{tj}$$

- New physics contribution to muonic O_9 operator:
  $(b_L\,\gamma_\mu\, s_L)(\mu\,\gamma^\mu\,\mu)$

Consistency!

[1704.05435]



Global fits by several groups [1704.05435,1704.05340, 1704.05438, 1704.05447, 1704.05446, 1705.06274]

What do we learn when matching two EFTs at the EW scale?

SM EFT

- $\Lambda > v$
- SU(3)×SU(2)$_L$×U(1)
- Linear EWSB
- Dim-6 operators

NP in (at least) one of the operators (involving muons)

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

$$\mathcal{L}^{\text{SMEFT}} \supset$$

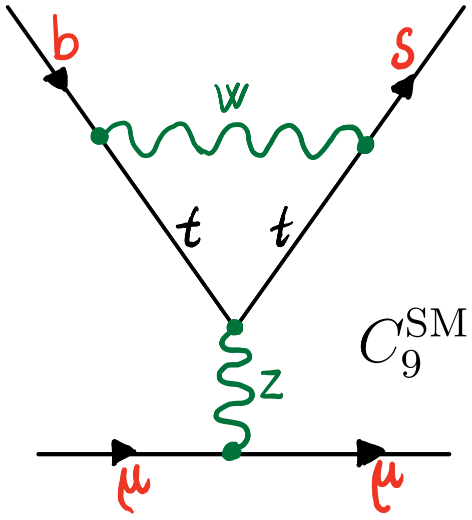
$$\frac{C^{(3)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l) + \frac{C^{(1)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_k\gamma^\mu L_l)$$

e.g. [1704.05672]

Disclaimer: I do not consider sizeable NP in electrons. Possible, but only for LFU ratios.

Where is the scale of *NP in b → s ℓ ℓ?*

In the SM



$$C_9^{\rm SM} \approx -C_{10}^{\rm SM} \approx 4.2$$

- Loop, CKM, and GIM suppression

New Physics

e.g. pure V-A scenario:

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

[1704.05340]

implies ↘

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

$$c_{QL}^{(1)} \sim g_*^2$$

[1704.09015]

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

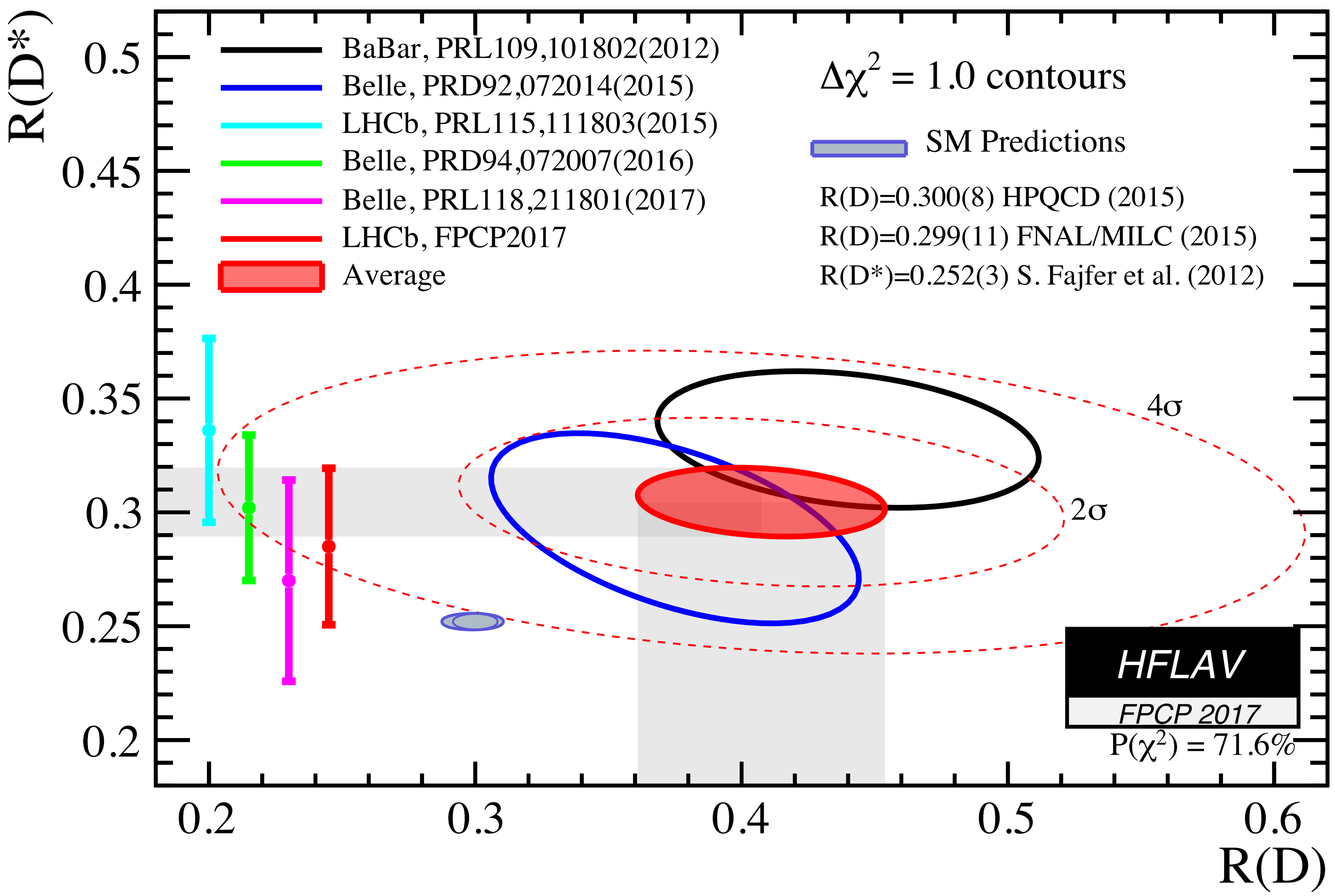
Potentially relevant slide for the future collider planners…

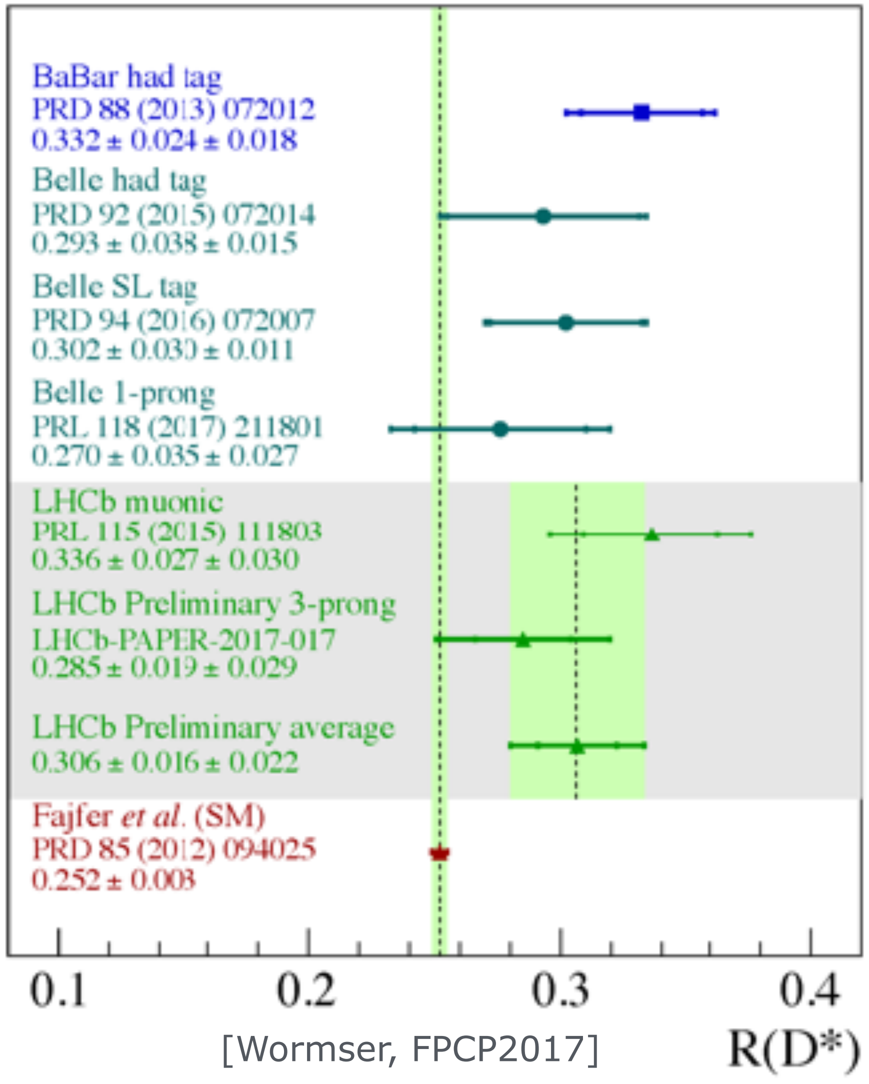
Perturbative unitarity constraint: NP scale ≲ 80 TeV

[Di Luzio and Nardecchia], 1706.01868

$b \to c\ell\bar{\nu}$

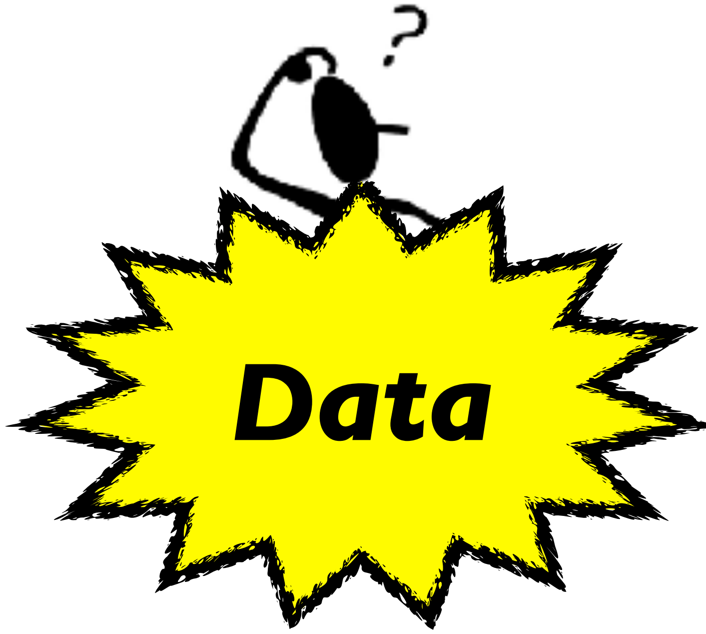
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$





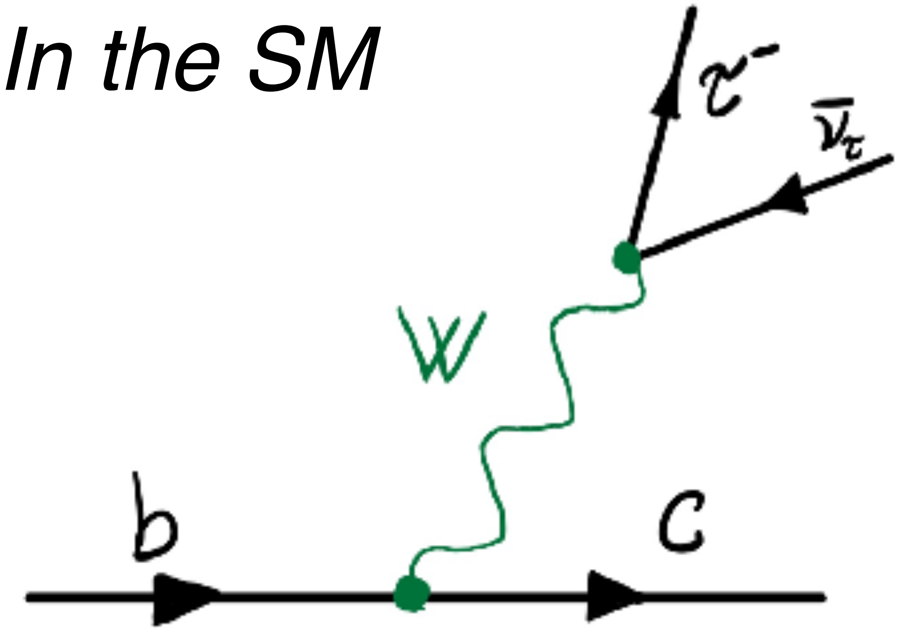
[Wormser, FPCP2017]

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



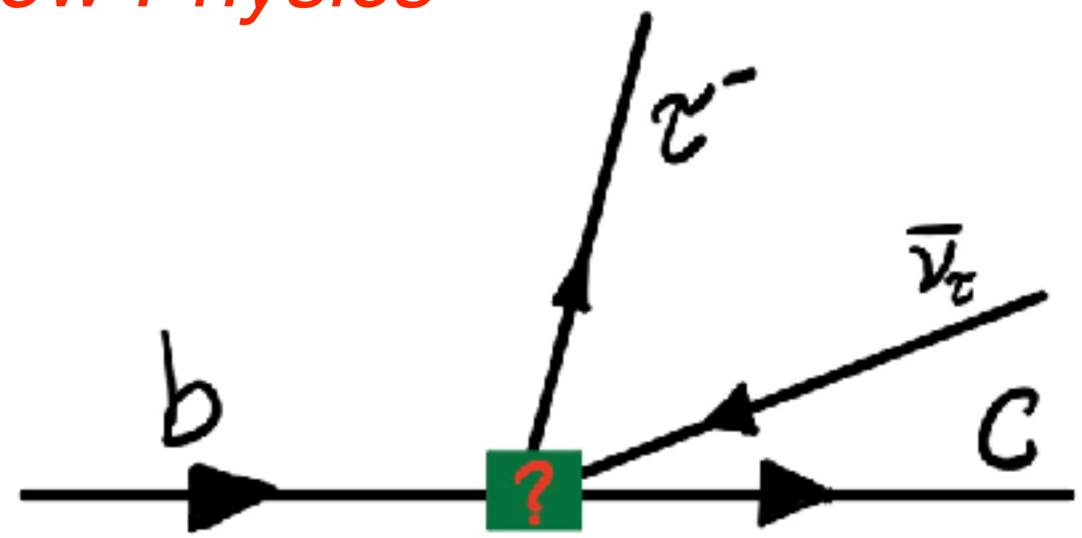
Where is the scale of NP in $b \to c\,\tau\,\nu$?

In the SM



- Tree-level process
- Mild CKM suppression

New Physics



- Large NP contribution required
  [Presumably tree-level generated]

<u>Tree-level, unsuppressed</u> ($g_* \sim 1$)	<u>Tree-level, MFV</u> ($g_*^2 = V_{cb}$)
~ 3.5 TeV	~ 0.7 TeV

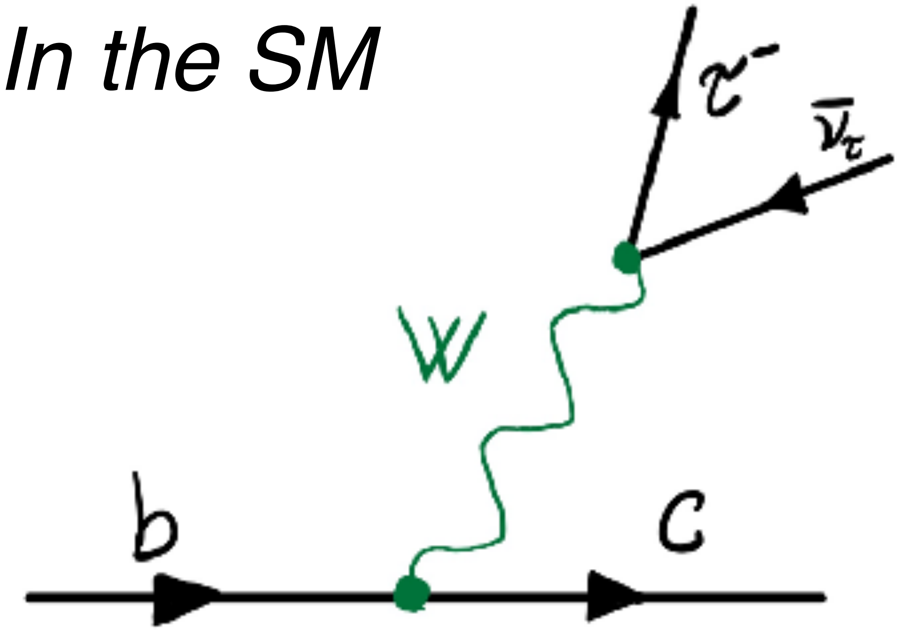
<u>Perturbative unitarity constraint</u>: NP scale $\lesssim$ 9 TeV

[Di Luzio and Nardecchia], 1706.01868

Potentially relevant
slide for the future
collider planners…

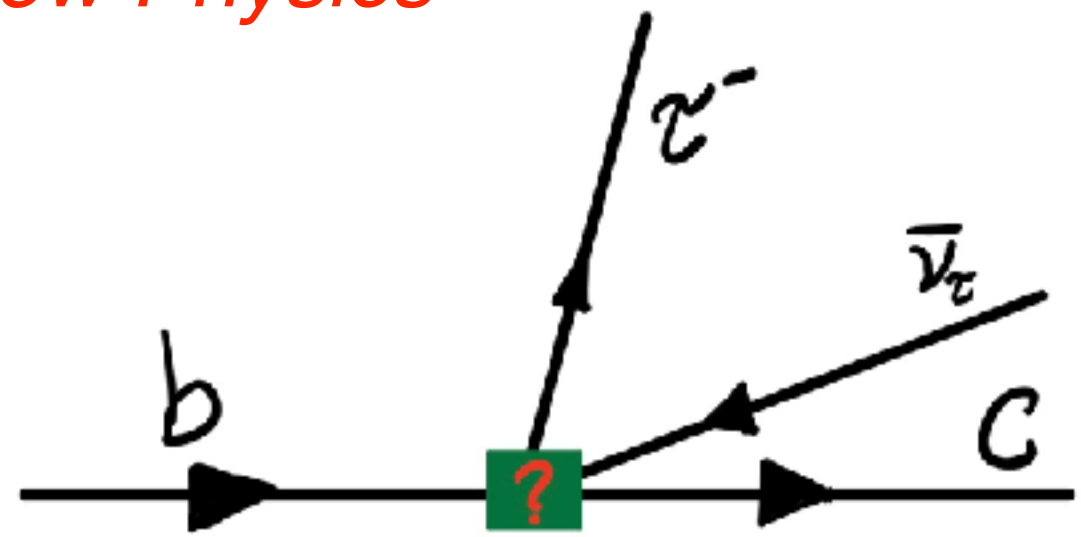
Where is the scale of NP in b → c τ ν?

In the SM

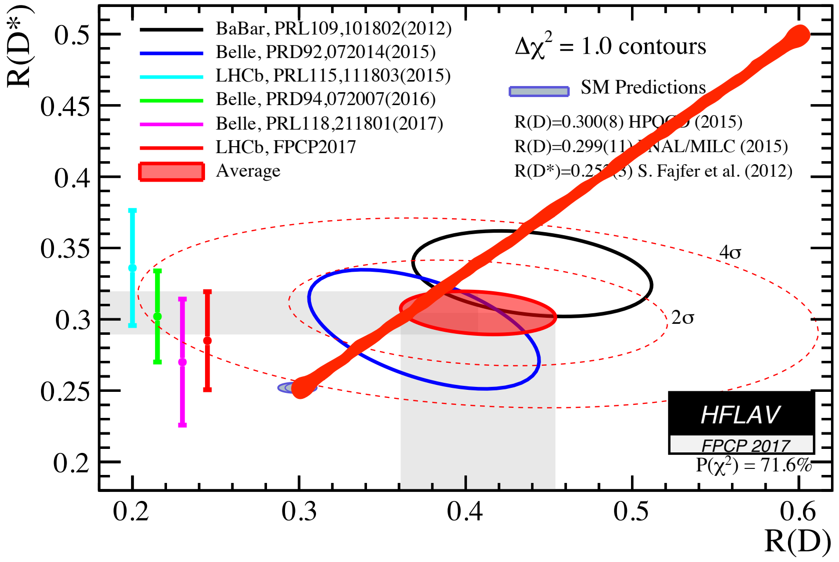


- Tree-level process
- Mild CKM suppression

New Physics



- Large NP contribution required
  [Presumably tree-level generated]



SM EFT

The most elegant solution:

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

- SM-like contribution, *~15% universal enhancement* in $b_L \to c_L\, \tau_L\, \nu_L$ amplitude
- Unlike tensor and scalar operators, points to larger NP scale
- No problems with B_c lifetime [1611.06676]

Related references: [1206.1872, 1505.05164, 1506.01705, 1506.08896, …]

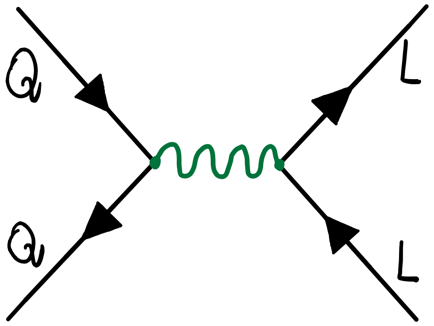
Slide relevant to both anomalies

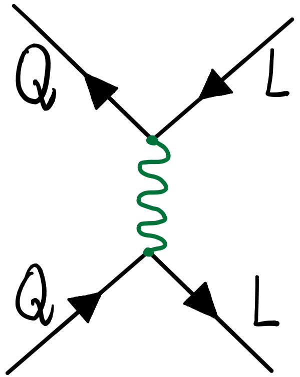
Tree-level models

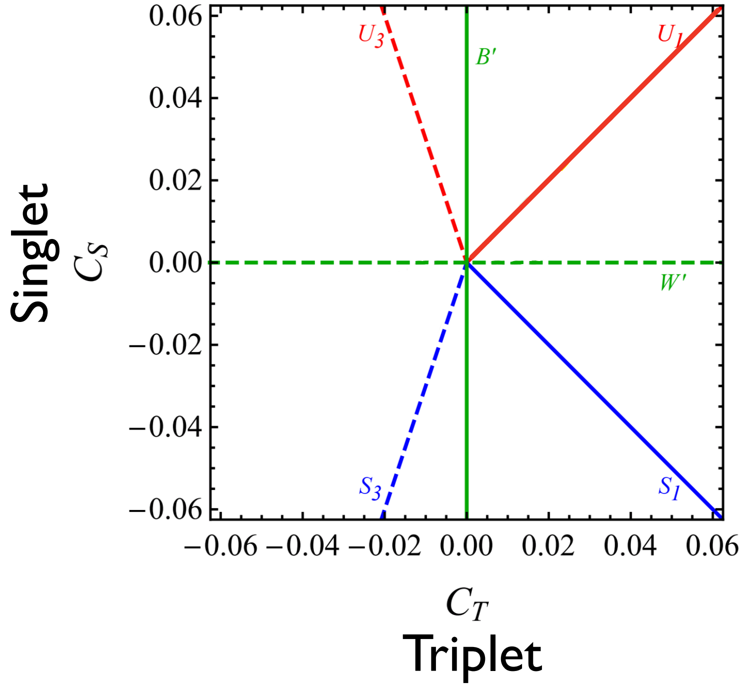
Classify single-mediator models matching to the relevant SM EFT operators:

$$(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)$$
$$(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)$$

Colour singlet	Colour triplet
Vectors:	Scalar LQ:
$W'_\mu \sim (1, 3, 0)$	$S_1 \sim (\bar{3}, 1, 1/3)$ *no (dd)(ℓℓ)
$B'_\mu \sim (1, 1, 0)$	$S_3 \sim (\bar{3}, 3, 1/3)$
	Vector LQ:
	$U_1^\mu \sim (3, 1, 2/3)$
	$U_3^\mu \sim (3, 3, 2/3)$







Colorless vectors

[1308.1501, 1310.1082, 1403.1269, 1411.3161, 1501.00993, 1503.03477, 1505.03079, 1506.01705, 1509.01249, 1604.03088, 1611.02703, 1511.07447, 1601.07328, 1510.07658, 1706.08510, 1706.06575, 1706.06100, 1710.02140 …]

Leptoquarks

LQ review: [Doršner, Fajfer, AG, Košnik, F. Kamenik], Phys.Rept. 641 (2016) 1-68

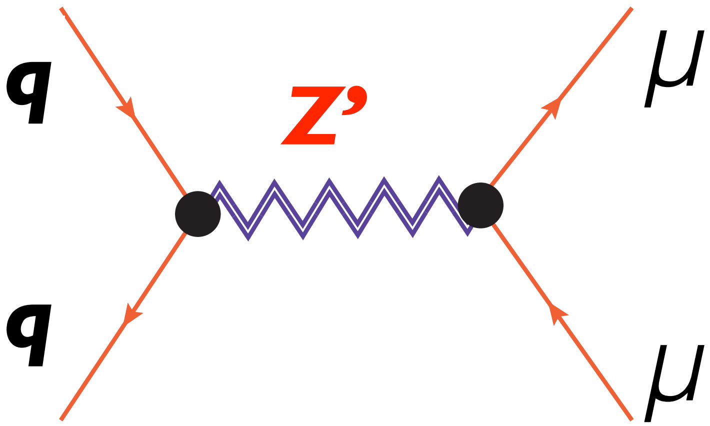
[1411.4773, 1503.01084, 1505.05164, 1510.08757, 1511.06024, 1511.01900, 1512.01560, 1608.07583, 1604.03940, 1611.04930, 1703.09226, 1704.05444, 1704.05849, 1706.07779, 1708.08450…]

Lesson for high p_T searches at the LHC and beyond

This is what we used to call "Exotica"

Did not fit our prejudice. To be reconsidered if *B*-anomalies turn out to be true.

Z' bosons

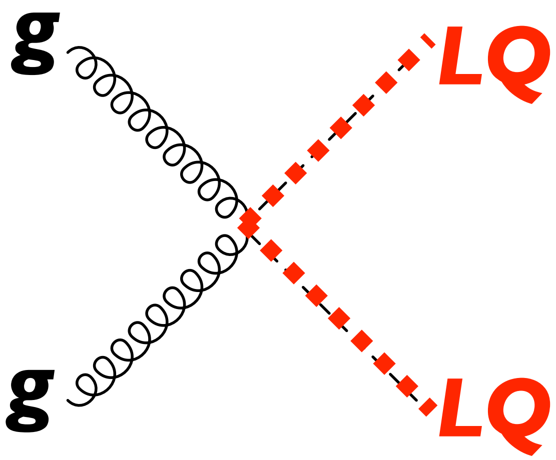


- *Resonance searches*
- *Deviations in the tails*

Final states:

ττ, μμ, *tt*, *bb*, *jj*, …

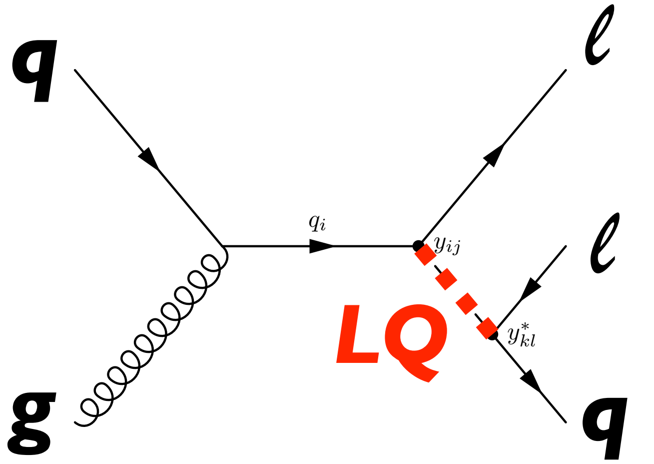
Leptoquarks



QCD pair production

Final states:

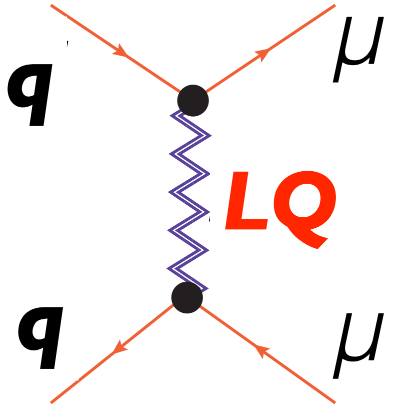
bτbτ, tνbτ, bτbμ, bμbμ, …



Single LQ + lepton production

Final states:

bττ, tντ, bμτ, …



Dilepton production

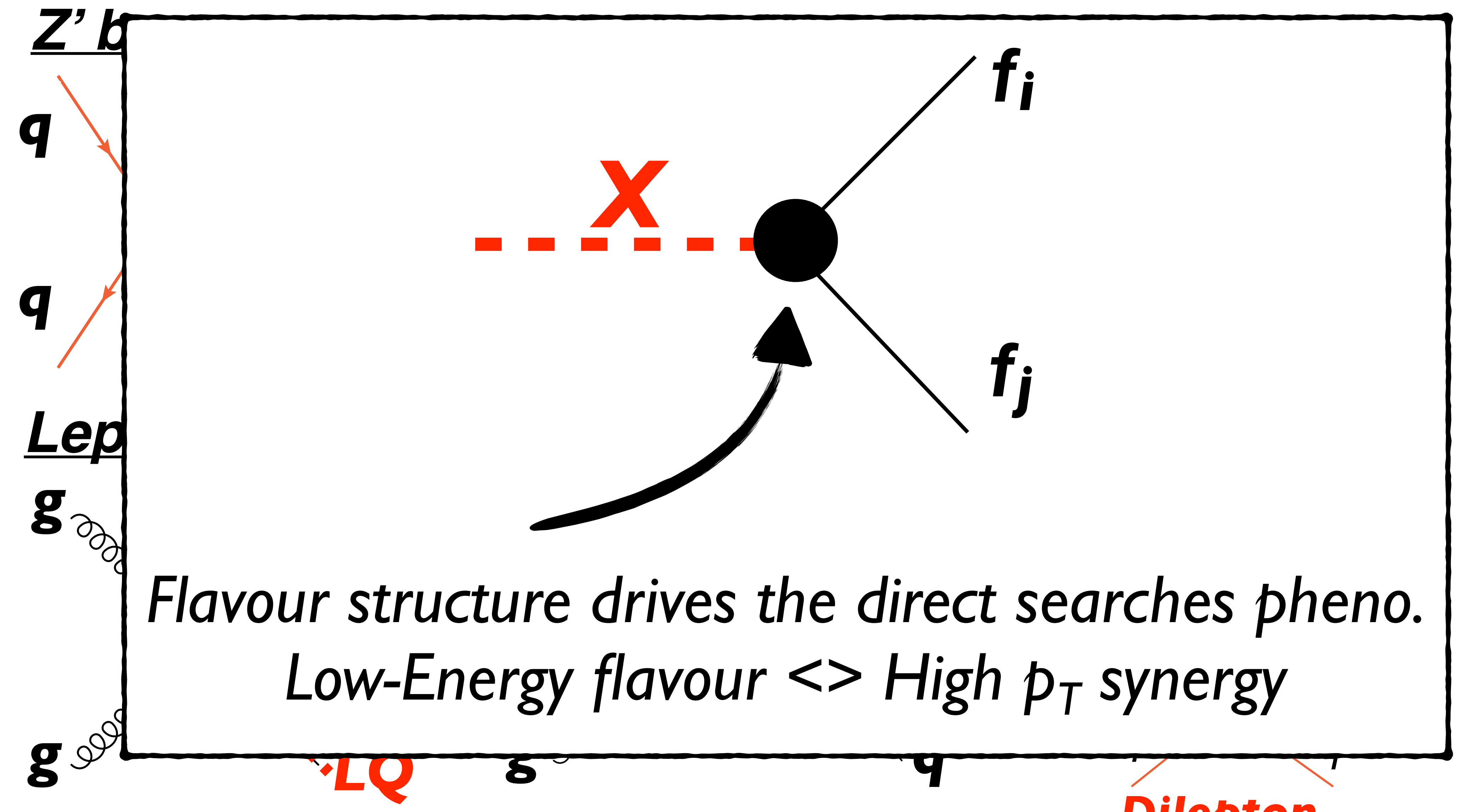
Final states:

ττ, μμ

Lesson for high p_T searches at the LHC and beyond

This is what we used to call “Exotica”

Did not fit our prejudice. To be reconsidered if *B*-anomalies turn out to be true.



Flavour structure drives the direct searches pheno.

Low-Energy flavour <> High p_T synergy

QCD pair production

Final states:

bτbτ, tνbτ, bτbμ, bμbμ, …

Single LQ + lepton production

Final states:

bττ, tντ, bμτ, …

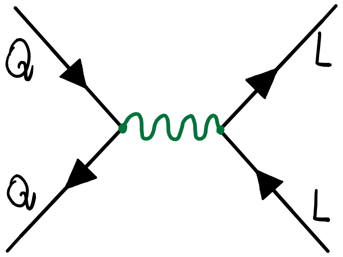
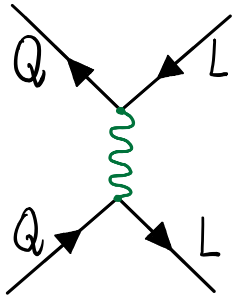
Dilepton production

Final states:

ττ, μμ

Flavour lesson I

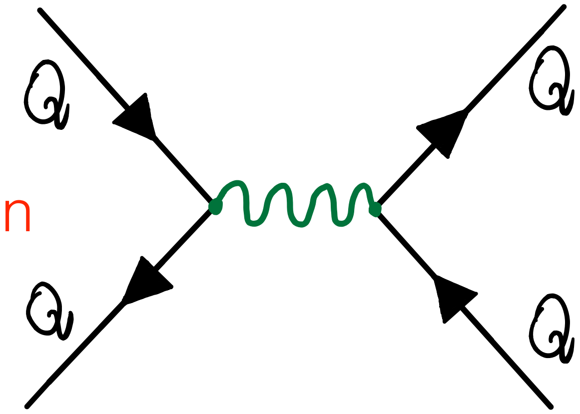
Classify UV dynamics based on the relative size of semi-leptonic vs. 4-quark operators.

Colour singlet	Colour triplet
Vectors: $W'_\mu \sim (1, 3, 0)$ $B'_\mu \sim (1, 1, 0)$	Scalar LQ: $S_1 \sim (\bar{3}, 1, 1/3)$ $S_3 \sim (\bar{3}, 3, 1/3)$ Vector LQ: $U_1^\mu \sim (3, 1, 2/3)$ $U_3^\mu \sim (3, 3, 2/3)$
	

Colorless vectors

$\Delta F = 2$

Tree-level



Flavour suppression needed (e.g. MFV)

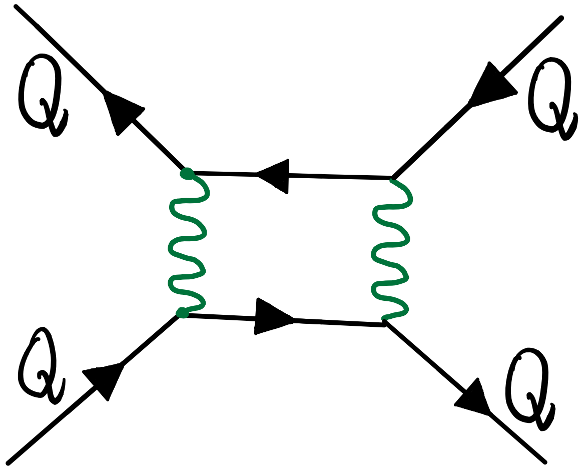
Lower NP scale!

Important!

Leptoquarks

$\Delta F = 2$

One-level



[Altmannshofer, Straub], 1411.3161
[AG, Isidori, Marzocca], 1506.01705

[Hiller, Nisandzic], 1704.05444
Talk by Jure Zupan

$$\Delta F = 2$$

Implications for

$$b \to c\ell\bar{\nu}$$

Vector Triplet Model

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

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

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

$$\lambda^{q(\ell)}_{ij} \simeq g_{b(\tau)} \delta_{i3} \delta_{j3} \quad Q_i = (V^*_{ji} u^j_L, d^i_L)^T$$

$$|\lambda^q_{sb}| \lesssim 0.1 |V_{ts}|$$

Tree-level B_s mixing

Fit to R(D*) anomaly

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

$$\Delta F = 2$$

Implications for

$$b \to c\ell\bar{\nu}$$

Vector Triplet Model

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

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

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

$$\lambda^{q(\ell)}_{ij} \simeq g_{b(\tau)}\delta_{i3}\delta_{j3} \quad Q_i = (V^*_{ji}u^j_L, d^i_L)^T$$

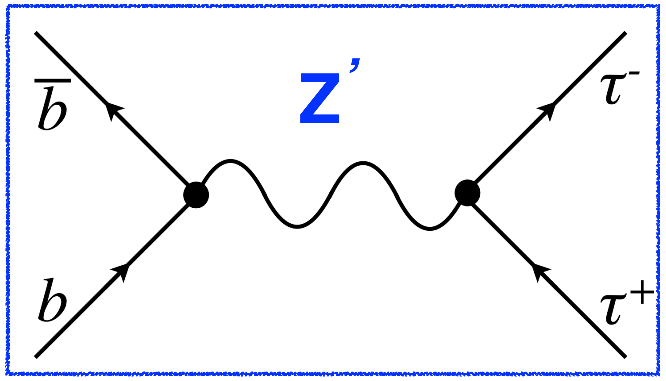
$$|\lambda^q_{sb}| \lesssim 0.1|V_{ts}|$$

Tree-level B_s mixing

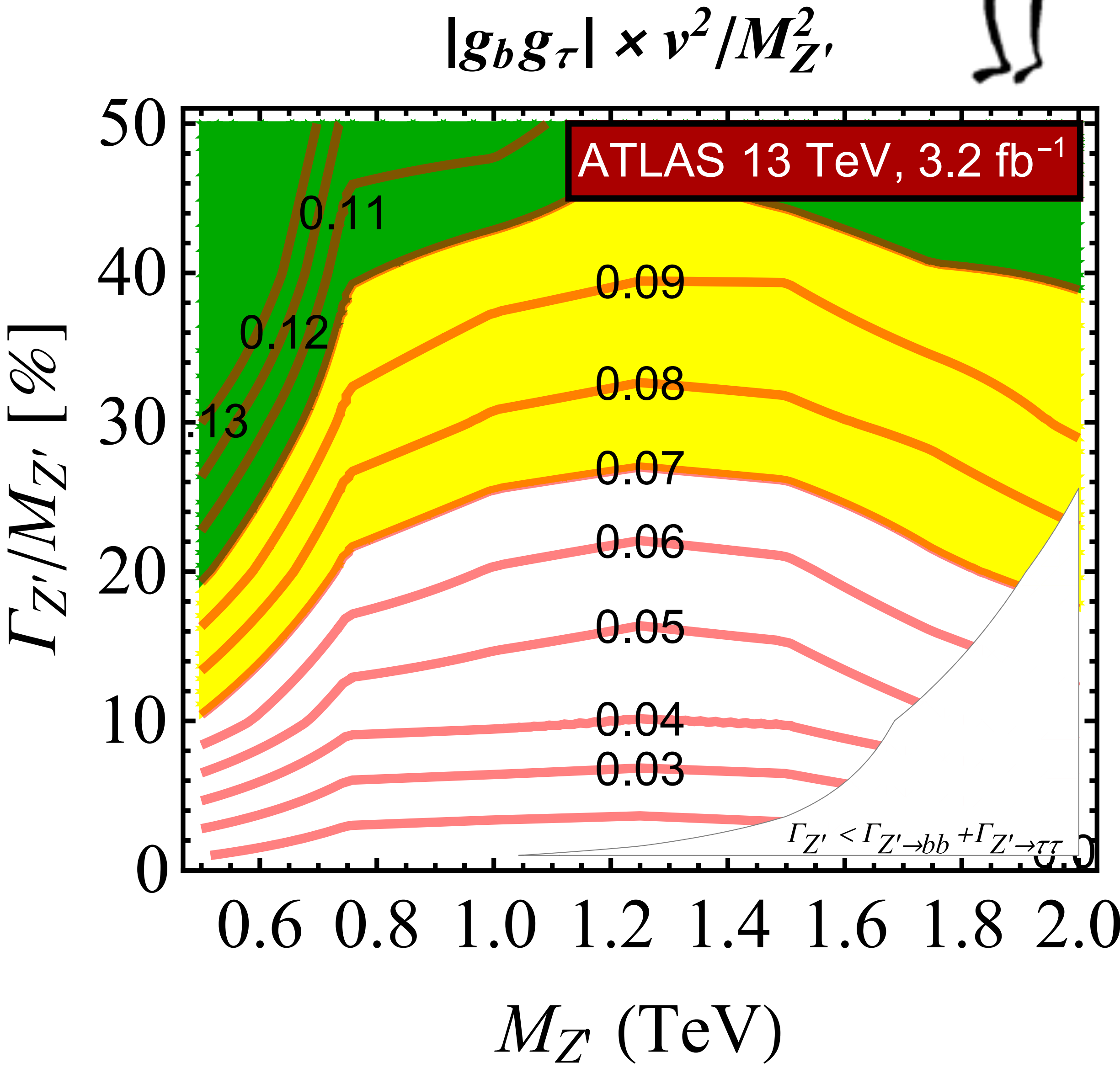
Fit to R(D*) anomaly

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

Large signal



$pp \to \tau^+\tau^-$



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

$$\Delta F = 2$$

Implications for

$$b \to c\ell\bar{\nu}$$

Vector Triplet Model

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

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

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

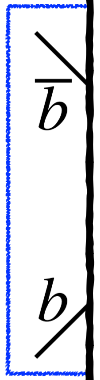
$$\lambda^{q(\ell)}_{ij}$$

$|\lambda^q_{sb}$

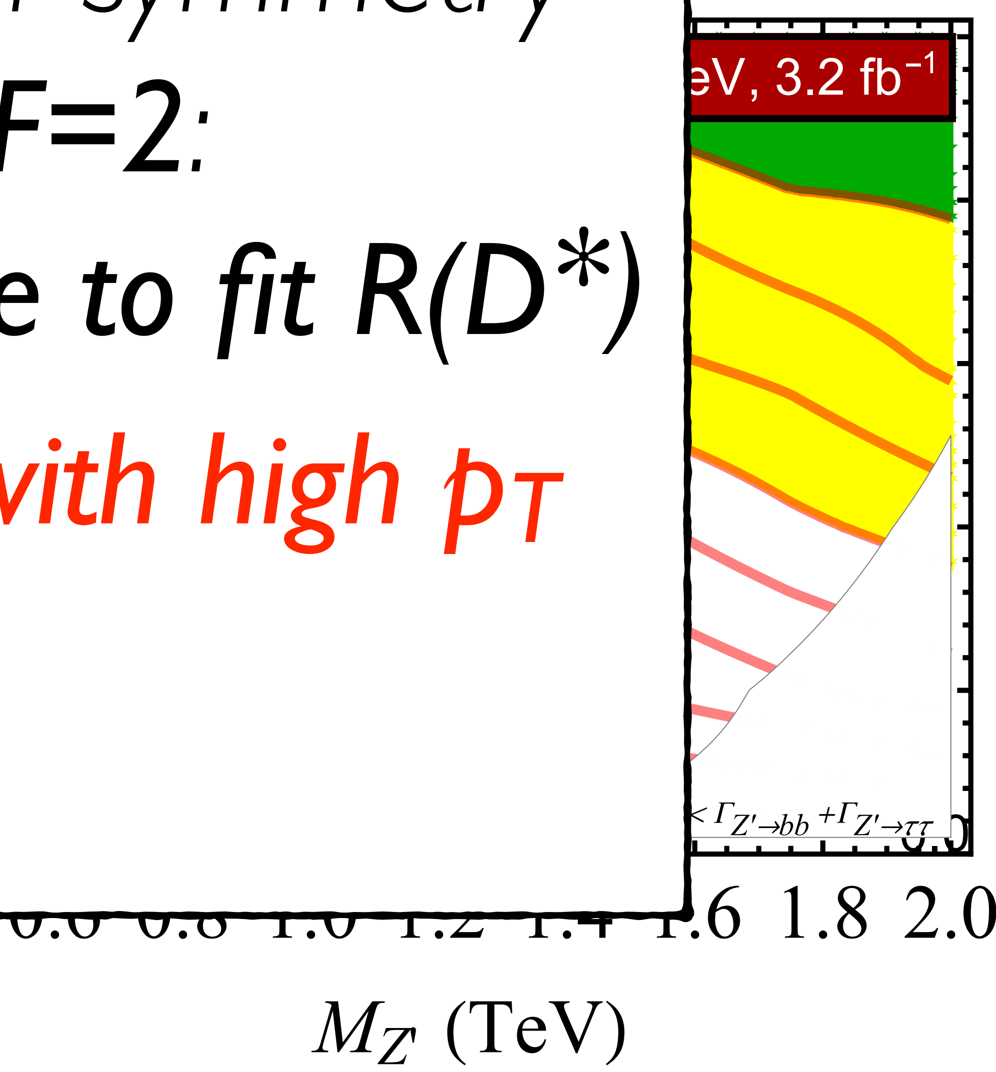
Tree-

Fit to

$|g_b g_\tau|$



- *If no dynamical or symmetry suppression in* **ΔF=2***:*
  Very low NP scale to fit R(D*)
- ***Already tension with high p_T***



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

A coherent picture…

[Buttazzo, AG, Isidori, Marzocca], 1706.07808

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

Gauge

Leading NP effects: Semi-leptonic operators built from left-handed doublets **Q** and **L**

Flavour

Minimally broken U(2)$_q$ x U(2)$_\ell$ flavour symmetry:

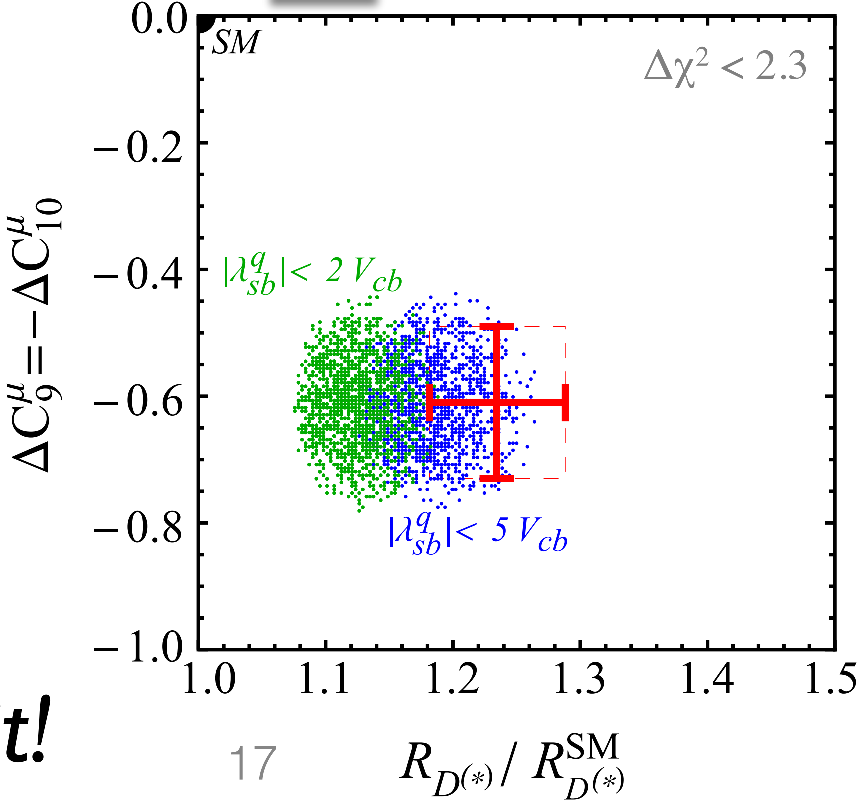
$V_q \sim (\mathbf{2},\mathbf{1})$ and $V_\ell \sim (\mathbf{1},\mathbf{2})$

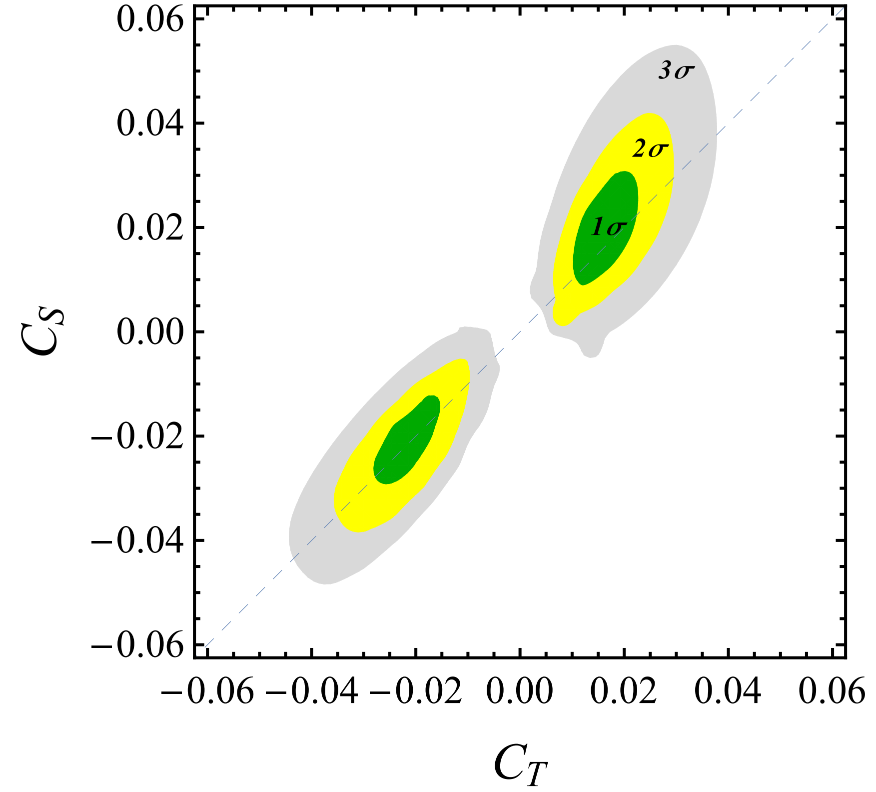
$\lambda^q_{bb} = \lambda^\ell_{\tau\tau} = 1$

$\lambda^q_{sb} = \mathcal{O}(|V_{cb}|)\ , \quad \lambda^\ell_{\tau\mu} = \mathcal{O}(|V_{\tau\mu}|)\ , \quad \lambda^\ell_{\mu\mu} = \mathcal{O}(|V_{\tau\mu}|^2)\ .$

Observable
$R^{\tau\ell}_{D^{(*)}}$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$
$R^{\mu e}_{b\to c} - 1$
$B_{K^{(*)}\nu\bar\nu}$
$\delta g^Z_{\tau_L}$
$\delta g^Z_{\nu_\tau}$
$\lvert g^W_\tau / g^W_\ell \rvert$
$\mathcal{B}(\tau\to 3\mu)$

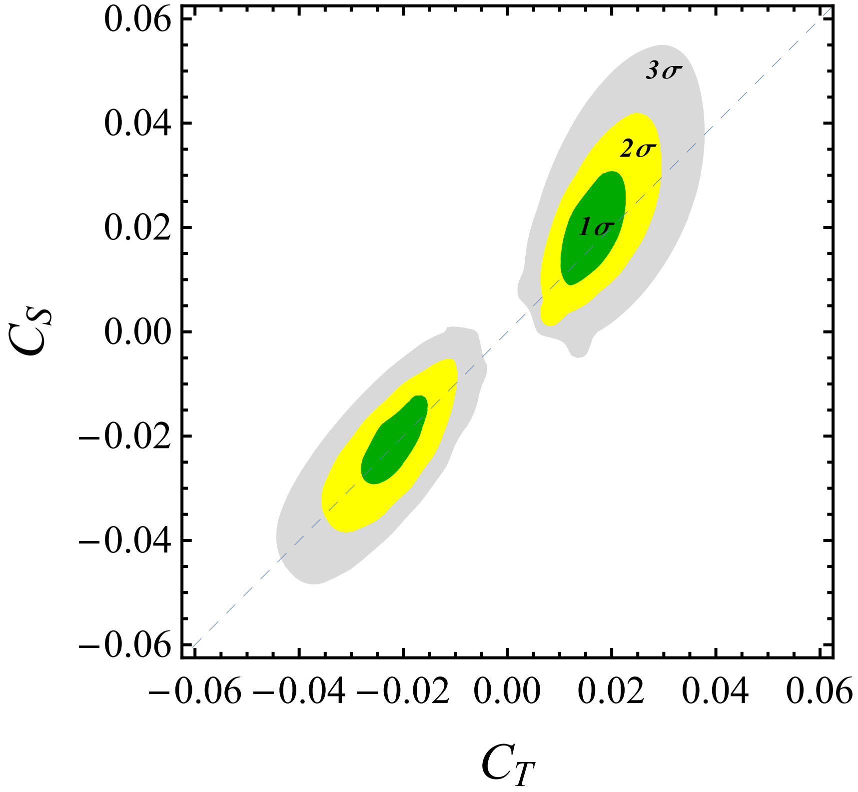
Good fit!



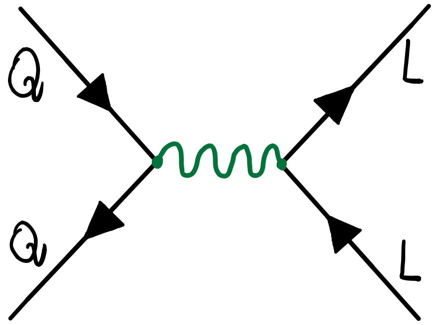
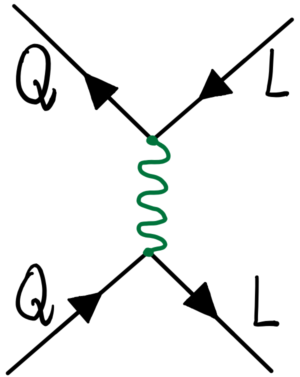


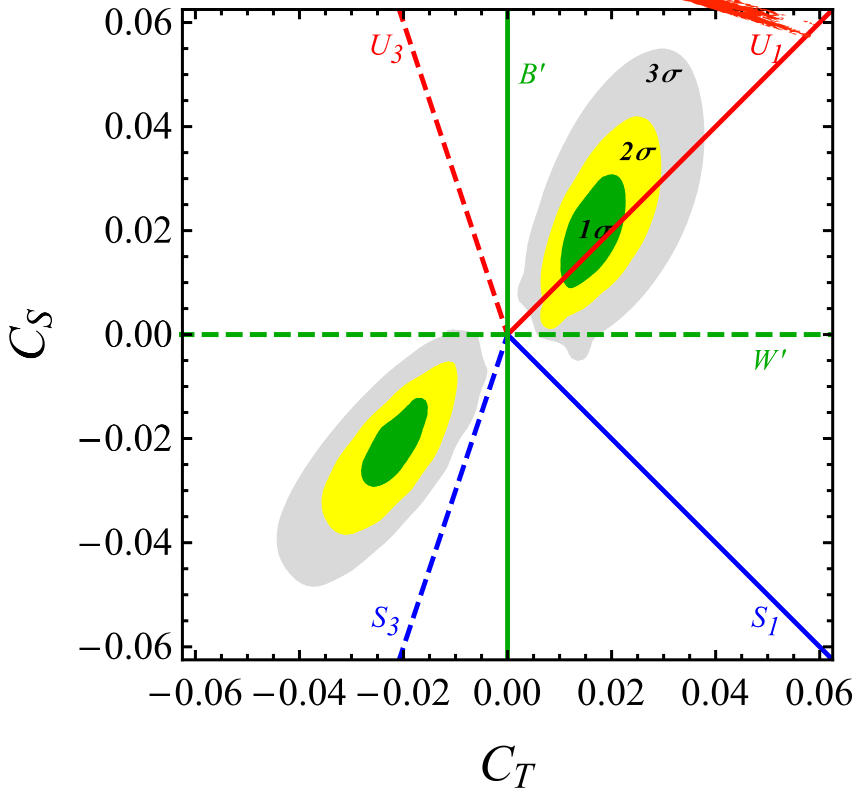
[Buttazzo, AG, Isidori, Marzocca],
1706.07808

- *So which (simplified) UV model?*



[Buttazzo, AG, Isidori, Marzocca], 1706.07808

Colour singlet	Colour triplet
Vectors: $W'_\mu \sim (1, 3, 0)$ $B'_\mu \sim (1, 1, 0)$	**Scalar LQ:** $S_1 \sim (\bar{3}, 1, 1/3)$ $S_3 \sim (\bar{3}, 3, 1/3)$ **Vector LQ:** $U_1^\mu \sim (3, 1, 2/3)$ $U_3^\mu \sim (3, 3, 2/3)$
	



- *U_1 alone works well*
- *Combinations are possible, e.g. $S_1 + S_3$*

Vector Leptoquark

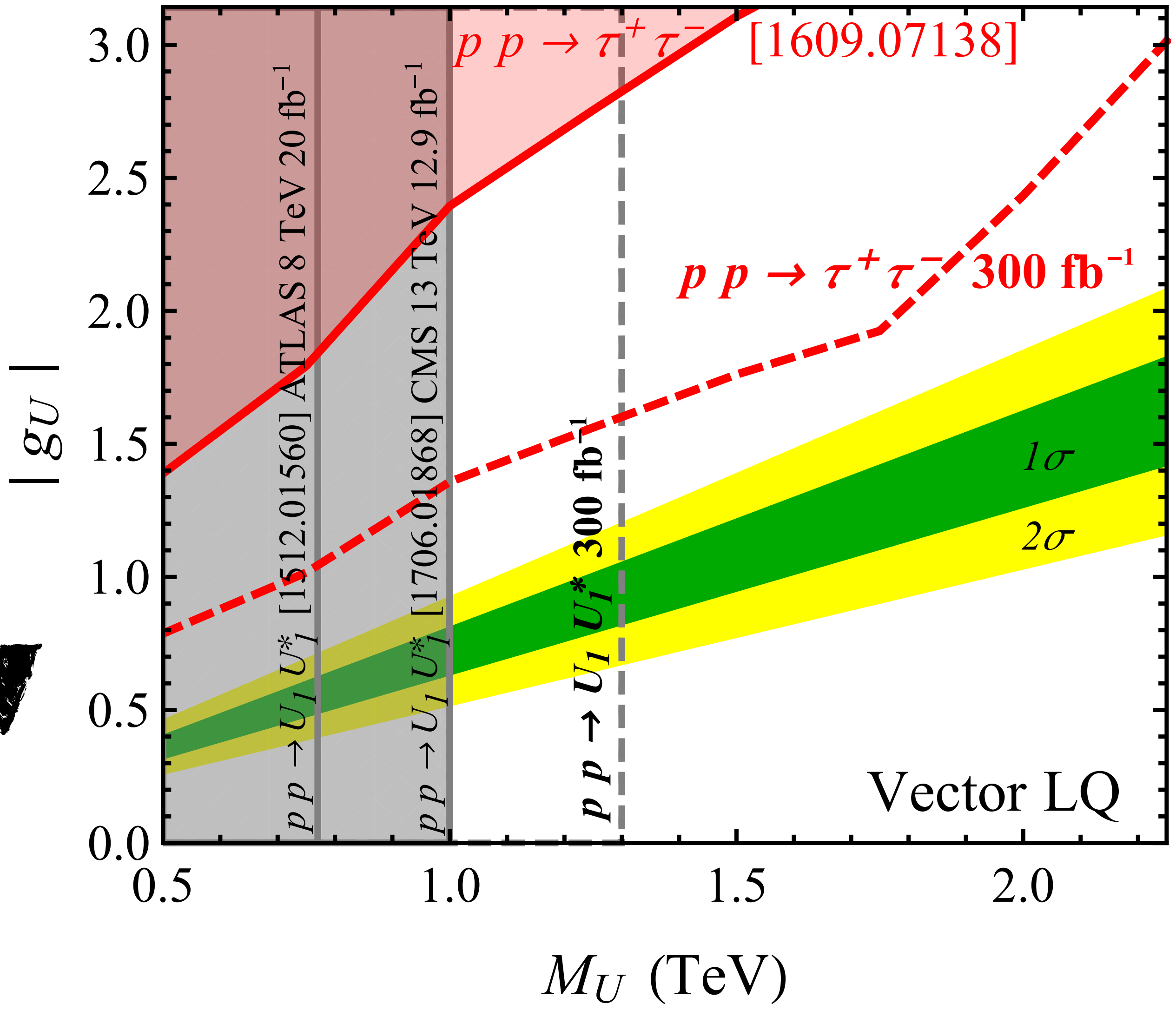
$$U_1^\mu \equiv (\mathbf{3},\mathbf{1},2/3)$$

$$\begin{aligned}\mathcal{L}_U &= -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M_U^2 U^\dagger_{1,\mu}U_1^\mu + g_U(J_U^\mu U_{1,\mu} + \text{h.c.})\\ J_U^\mu &\equiv \beta_{i\alpha}\,\bar{Q}_i\gamma^\mu L_\alpha \;.\end{aligned}$$

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

We need HL- or even HE- LHC!

[Buttazzo, AG, Isidori, Marzocca], 1706.07808



Technical note:

Massive vector requires UV completion, otherwise ambiguities in predictions…

e.g.* B_s *mixing at one-loop, LQ pair production, etc.

Vector Leptoquark

$$U_1^\mu \equiv (\mathbf{3}, \mathbf{1}, 2/3)$$

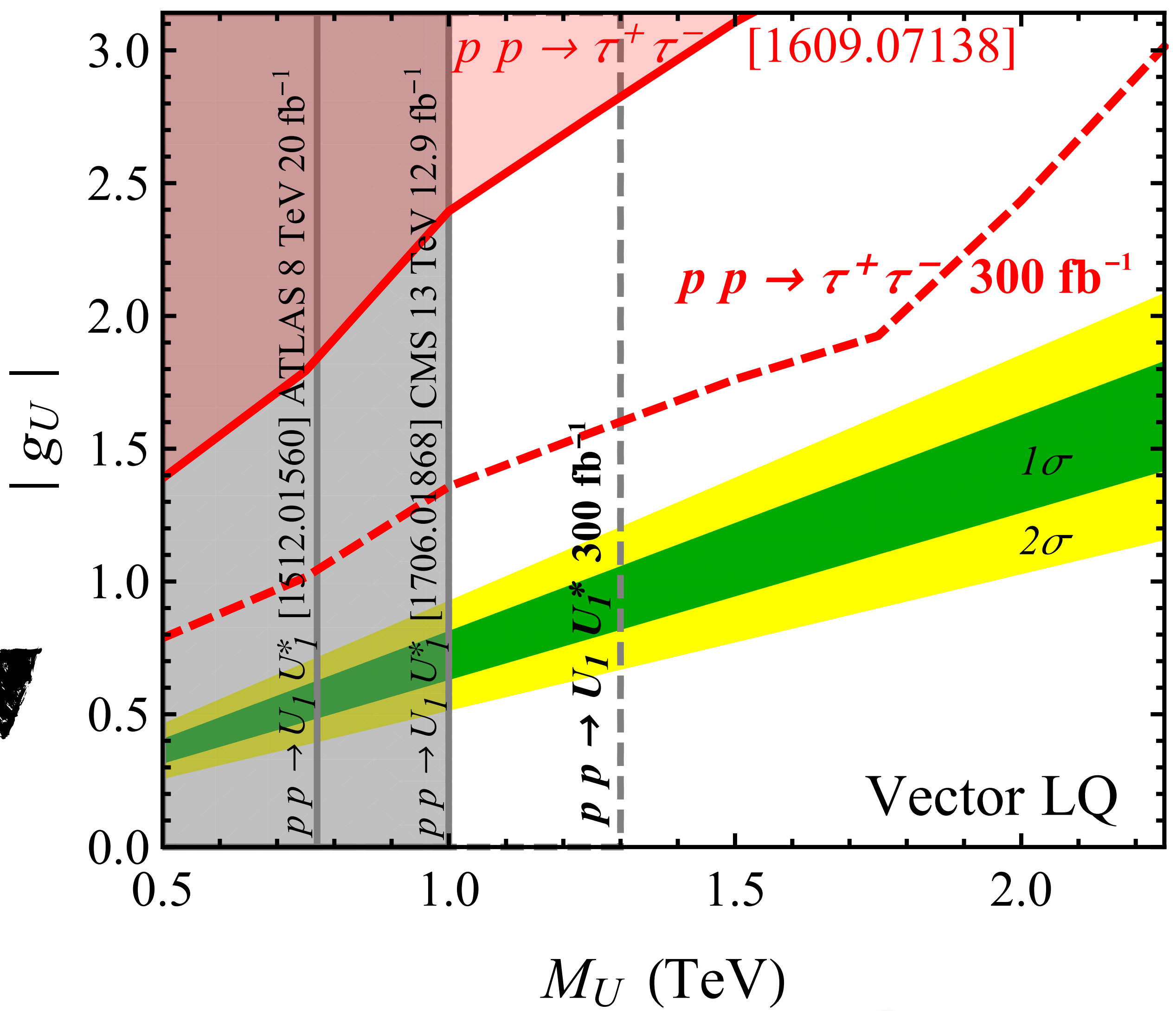
$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M_U^2 U^\dagger_{1,\mu}U_1^\mu + g_U(J_U^\mu U_{1,\mu} + \text{h.c.})$$

$$J_U^\mu \equiv \beta_{i\alpha}\,\bar{Q}_i\gamma^\mu L_\alpha \ .$$

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

We need HL- or even HE- LHC!

[Buttazzo, AG, Isidori, Marzocca], 1706.07808



UV completion

Gauge leptoquark model

[Di Luzio, AG, Nardecchia], 1708.08450

- *Extended gauge symmetry*

$$G = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$$\Big\downarrow \ \langle\Omega_3\rangle, \langle\Omega_1\rangle$$

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$SU(3)_C = [SU(3)_4 \times SU(3)']_{diag}$$

$$Y = X + Y'$$

Massive gauge bosons:

1) **Leptoquark**

2) *Coloron*

3) *Z'*

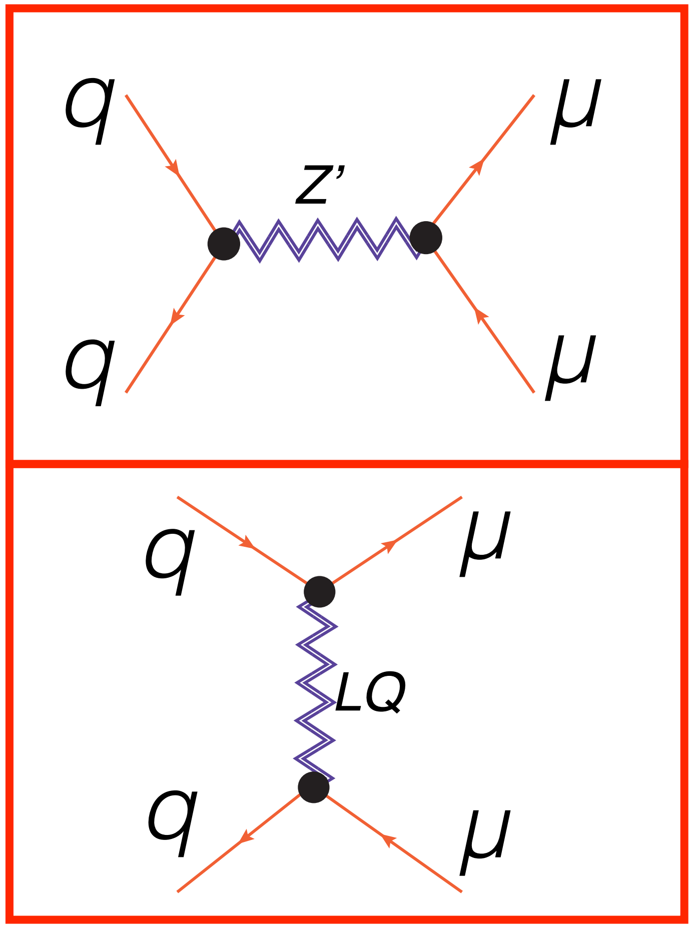
Calculable!

$pp \to \mu^+\mu^-$

Let us focus on $R(K^{(*)})$ alone…

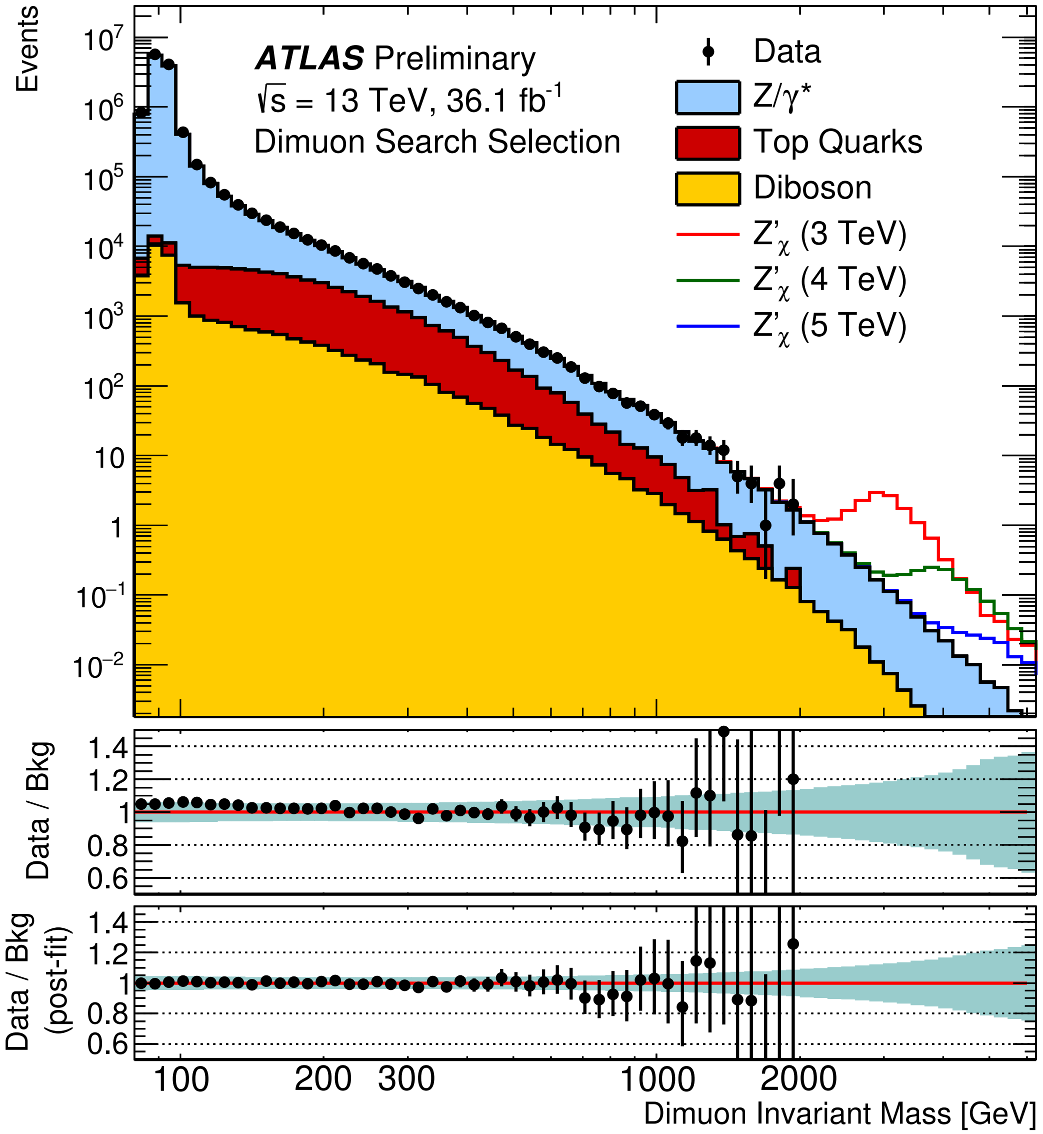
$b \to s\ell\bar{\ell}$

Example diagrams:



[AG, and D. Marzocca]
1704.09015

Dimuon invariant mass spectrum



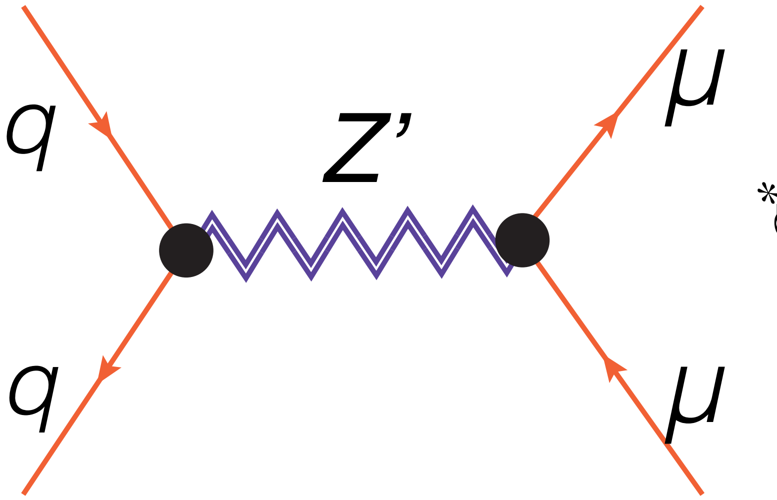
[ATLAS-CONF-2017-027]

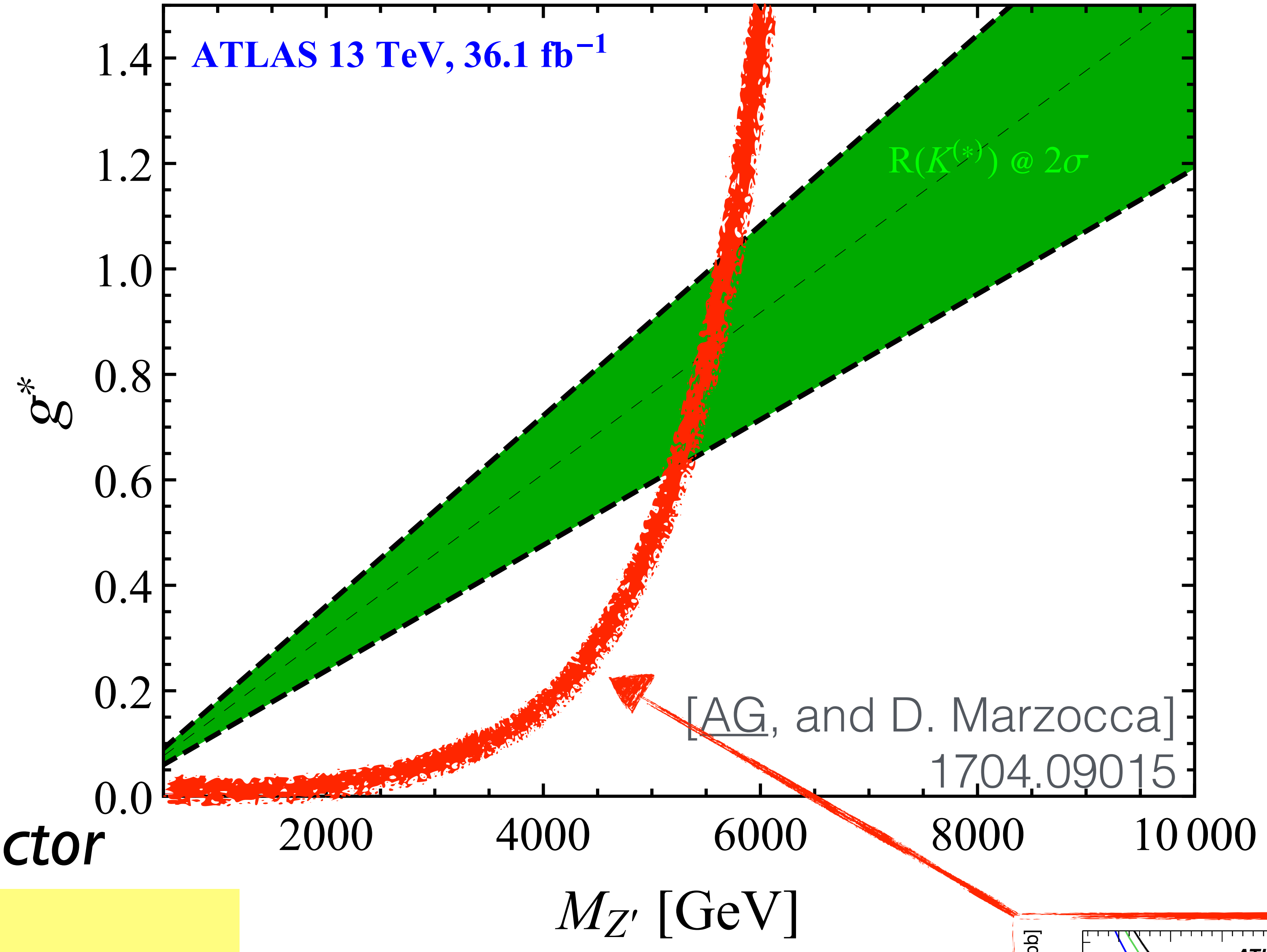
- *Bump hunt* e.g. [1706.06575]
- *Non-resonant deviations in the tail*

"Bump hunt" projections at HL-LHC and HE-LHC in the *pessimistic scenario* [1710.06363].
Talk by Tevong You

Example

Z' model





95% CL limits on MFV Z' from p p → $\mu^+ \mu^-$

[AG, and D. Marzocca] 1704.09015

MFV in the quark sector

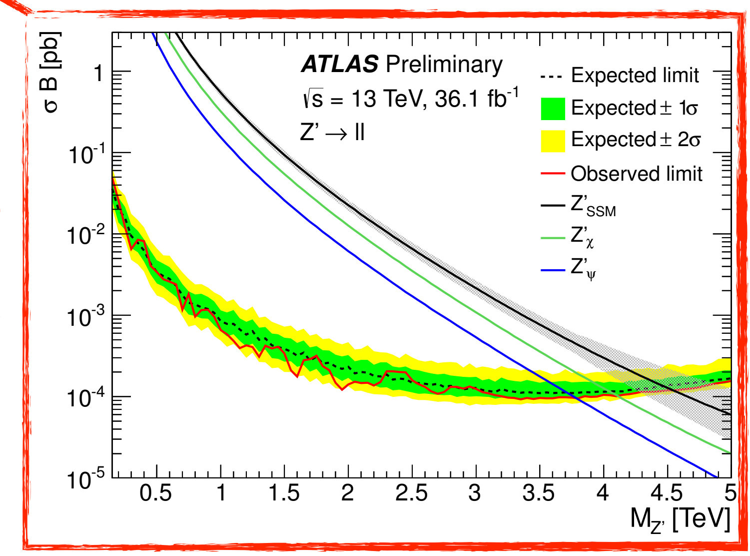
$$\mathscr{L} \supset Z'_\mu J_\mu$$

$$J_\mu = g_Q^{(1),ij}(\bar{Q}_i \gamma_\mu Q_j) + g_L^{(1),kl}(\bar{L}_k \gamma^\mu L_l)$$

$$g_Q^{(1),ii} = g_L^{(1),22} = g_* \qquad \boxed{g_Q^{(1),23} = V_{ts} g_*}$$

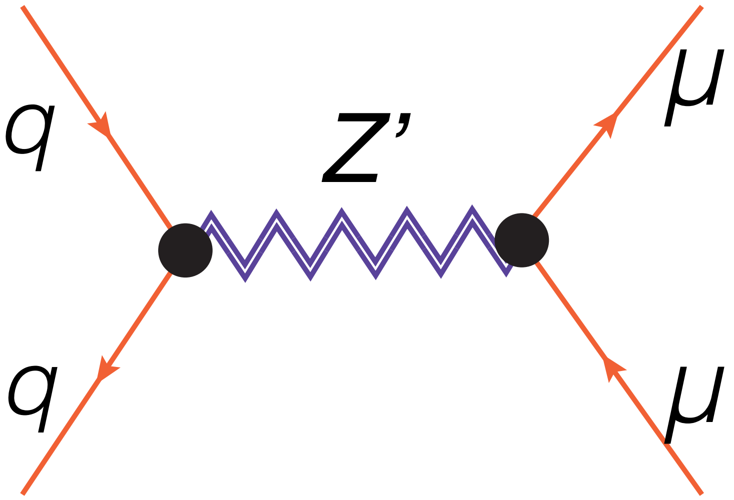
$$\Delta F = 2$$

Resonance search limits

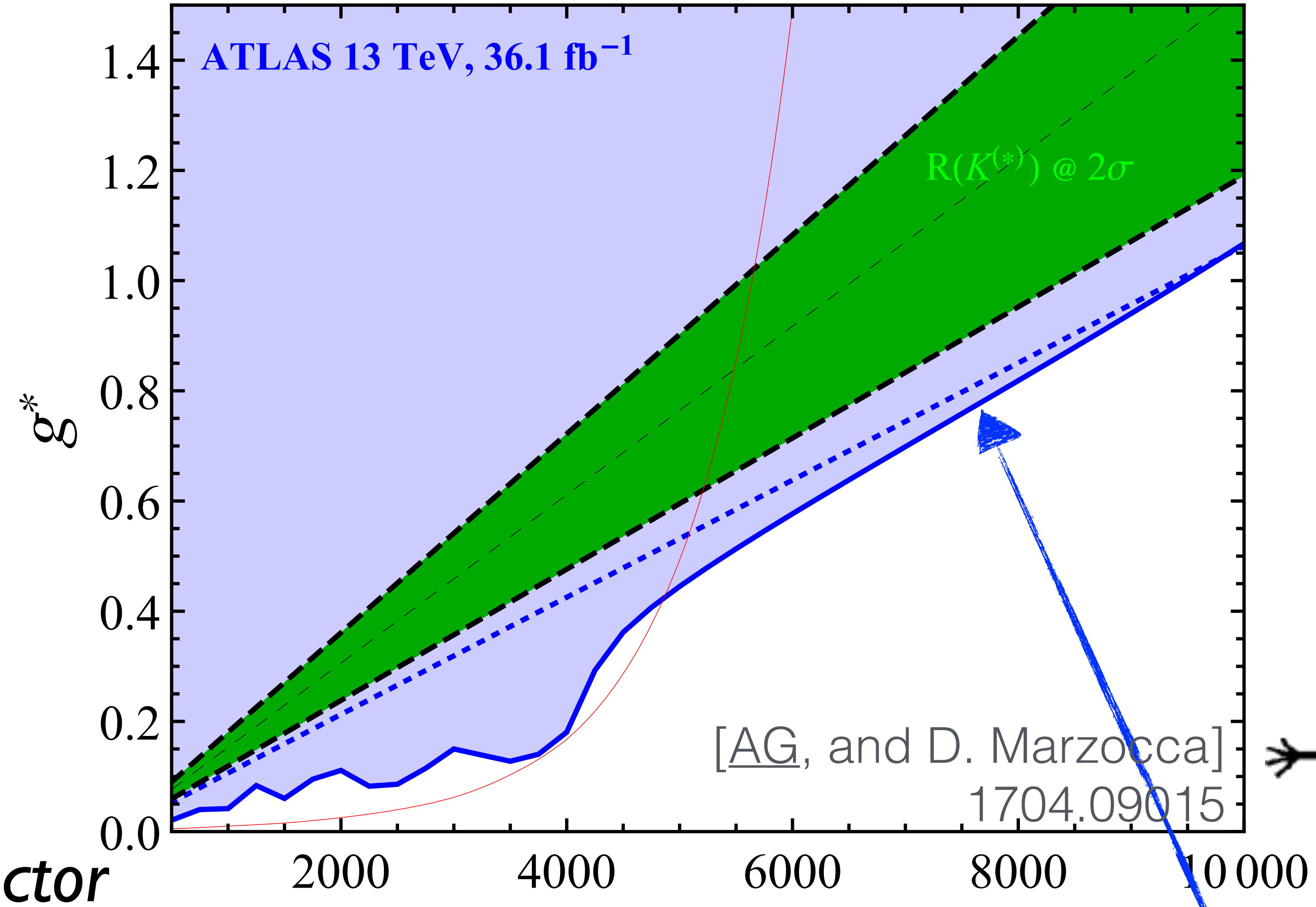


Example

Z' model



95% CL limits on MFV Z' from p p → $\mu^+ \mu^-$



[AG, and D. Marzocca]
1704.09015

MFV in the quark sector

$$\mathscr{L} \supset Z'_\mu J_\mu$$

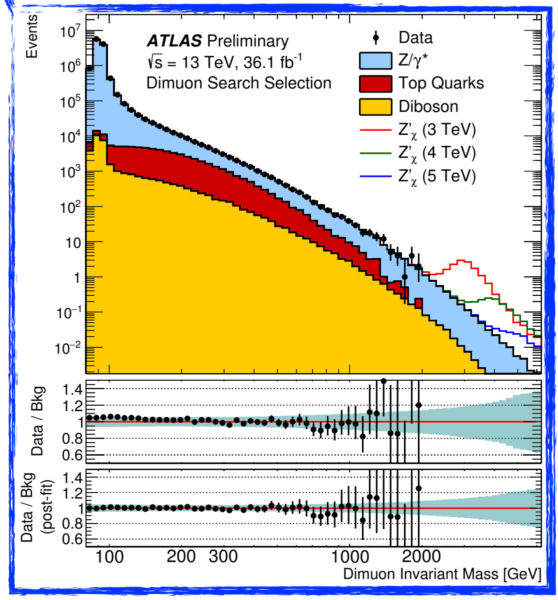
$$J_\mu = g_Q^{(1),ij}(\bar{Q}_i \gamma_\mu Q_j) + g_L^{(1),kl}(\bar{L}_k \gamma^\mu L_l)$$

$$g_Q^{(1),ii} = g_L^{(1),22} = g_* \qquad \boxed{g_Q^{(1),23} = V_{ts} g_*}$$

$$\Delta F = 2$$

Correct limit

(from the tail)



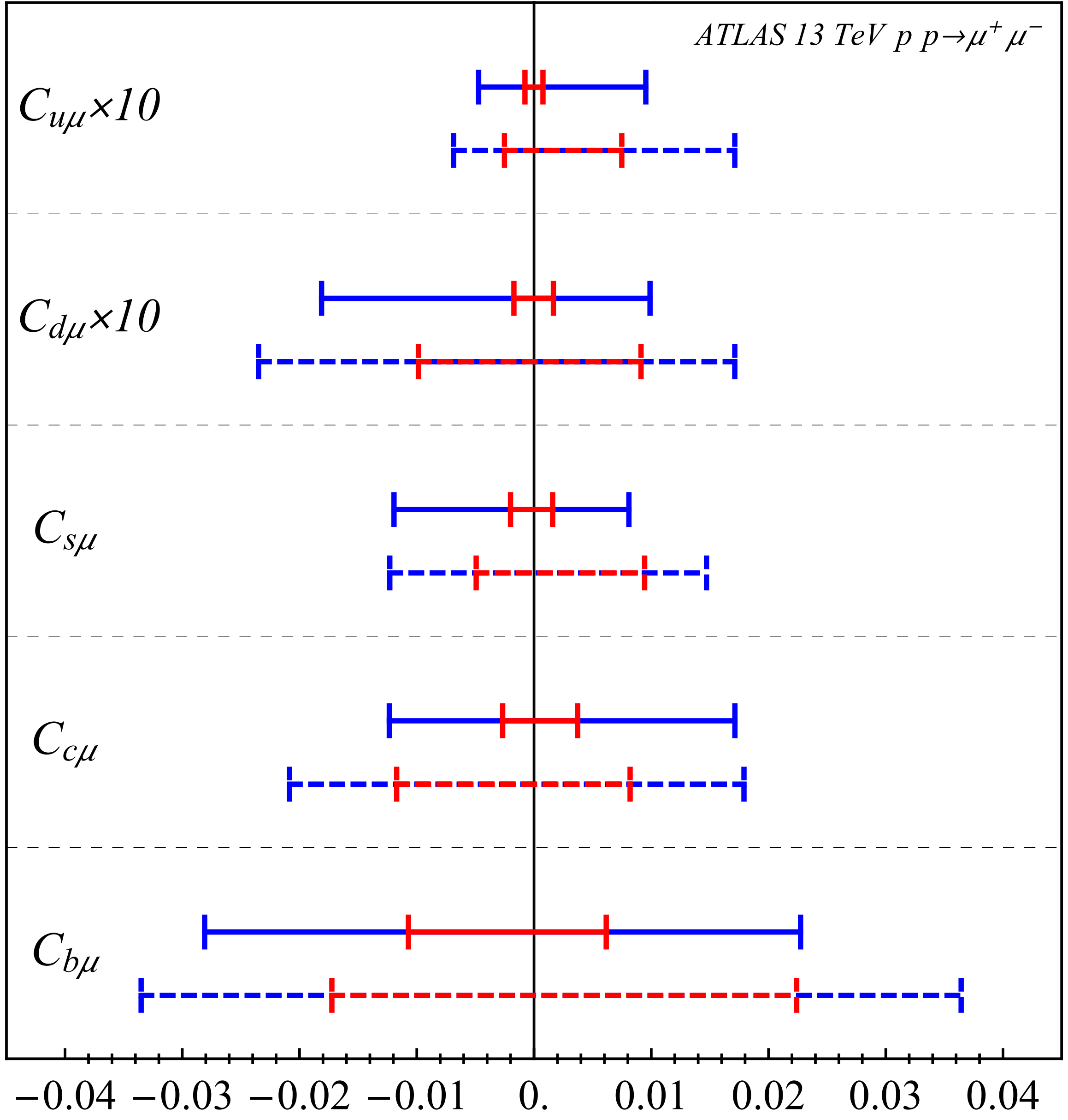
Drell-Yan tails

$$pp \to \mu^+ \mu^-$$

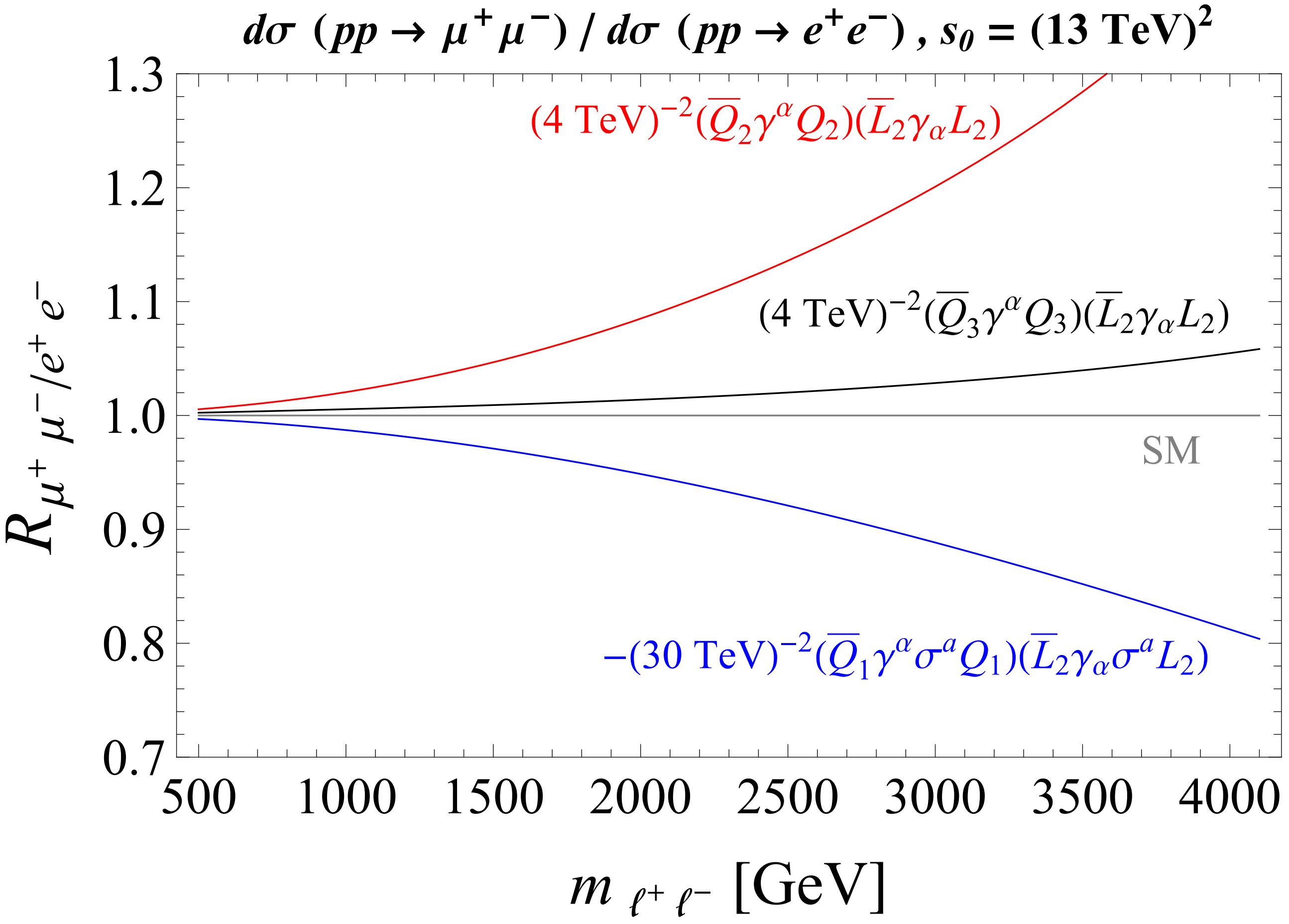
*See also talk by
Marco Farina

$$\mathscr{L}^{\rm eff} \supset \frac{\mathbf{C}^{U\mu}_{ij}}{v^2}(\bar u^i_L \gamma_\mu u^j_L)(\bar\mu_L \gamma^\mu \mu_L) + \frac{\mathbf{C}^{D\mu}_{ij}}{v^2}(\bar d^i_L \gamma_\mu d^j_L)(\bar\mu_L \gamma^\mu \mu_L)$$

2σ observed: 36.1 fb^{-1} (blue), 2σ expected: 3000 fb^{-1} (red)



- ***R ratios at high-p_T?***



Great improvement at HL-LHC, how about HE-LHC?

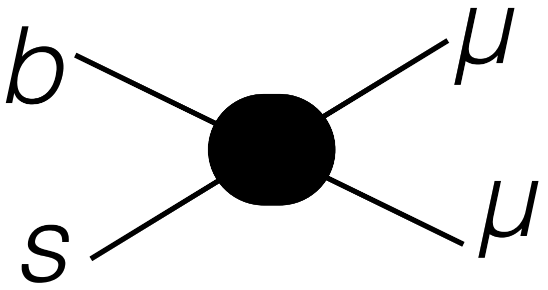
[AG, and D. Marzocca]
1704.09015

Drell-Yan tails

$$pp \to \mu^+\mu^-$$

[AG, and D. Marzocca],
1704.09015

1)"Pessimistic" scenario



O(1) from R(K)

Now

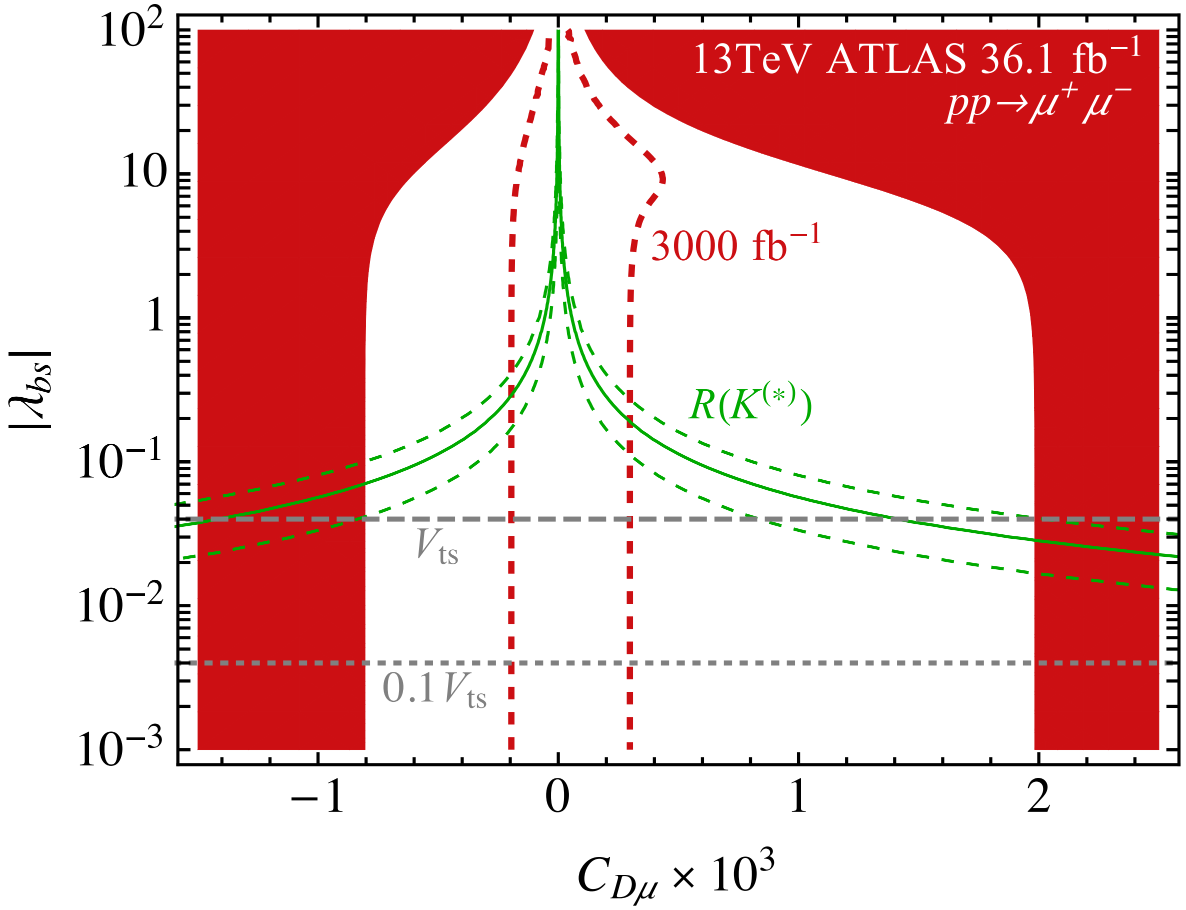
$$\boxed{\left|\frac{\pi}{\alpha V_{tb}V_{ts}^*}C_{bs\mu}\right| < 100\ (39)}$$

HL-LHC

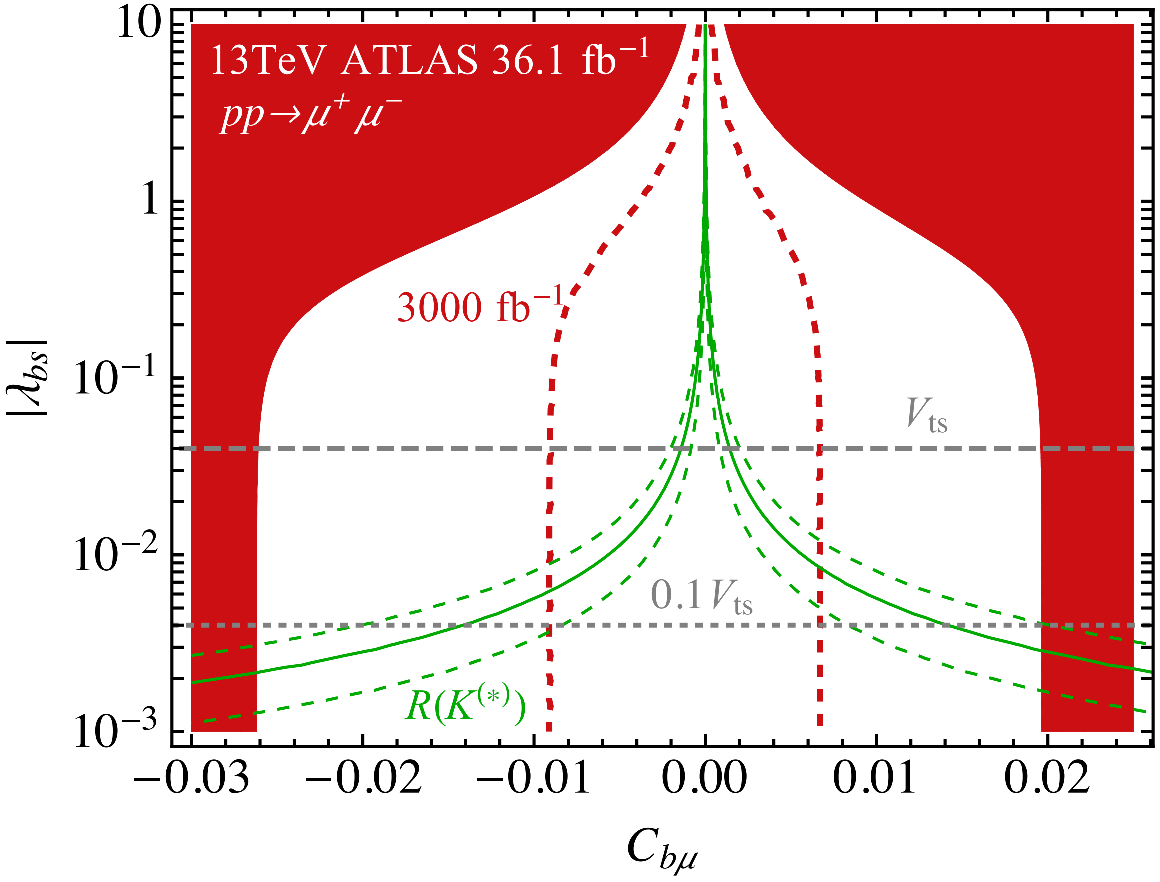
2) Two motivated flavour structures

$$\lambda^q_{bs} \equiv C_{bs\mu}/C_{q\mu}$$

MFV case. Singlet: $C_{U\mu}$=$C_{D\mu}$



U(2)$_Q$ case. $C_{D\mu}$=$C_{U\mu}$=0

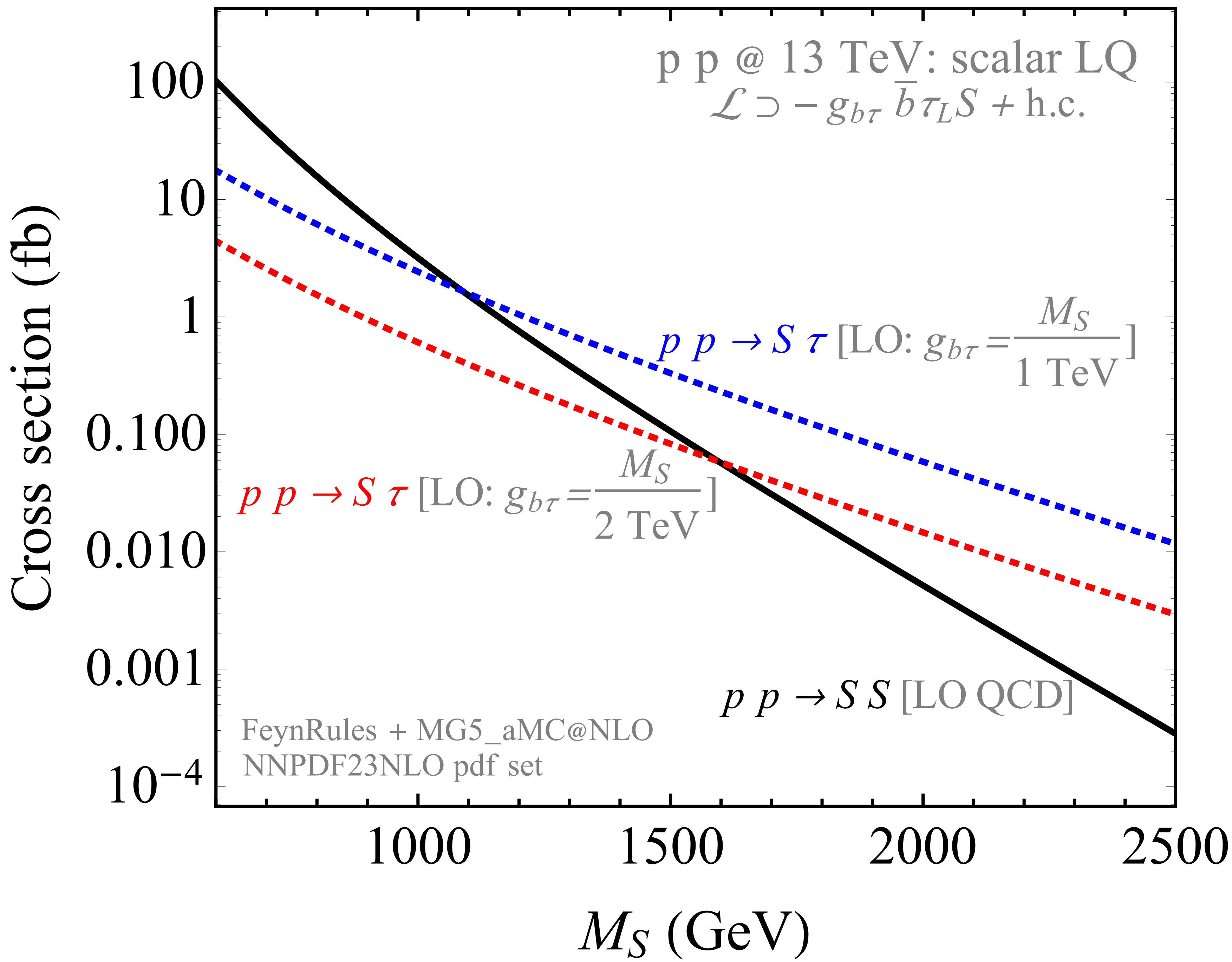


Conclusions

- *Standard model might be cracking down in the semi-leptonic B-decays*
- *If true, clear indication of the NP scale*
  [$\lesssim$ 80 TeV (NC) and $\lesssim$ 9 TeV (CC)] [Di Luzio and Nardecchia]
- *Signatures at high p_T:*
  ***Z'*, Leptoquark**
- *Can we formulate a "no-lose" theorem?*
  [Requires a dedicated study: non-resonant deviations, wide resonances, etc.]

Backup slides

Pair vs. single LQ production



Single LQ + lepton process is dominant at high LQ masses

[Buttazzo, AG, Isidori and Marzocca], 1706.07808