JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

JG|U

Flavour at High-p_T (theory)

Admir Greljo

"**BEAUTY 2018**", 06 - 11 May 2018, La Biodola, Isola d'Elba

"**Flavour physics**" is a study of interactions that distinguish between flavours…

The Scope

(Flavour physics at the Energy Frontier)

This talk

- *Resonant effects*

  Direct production of a (hypothetical) flavour mediator ***X***

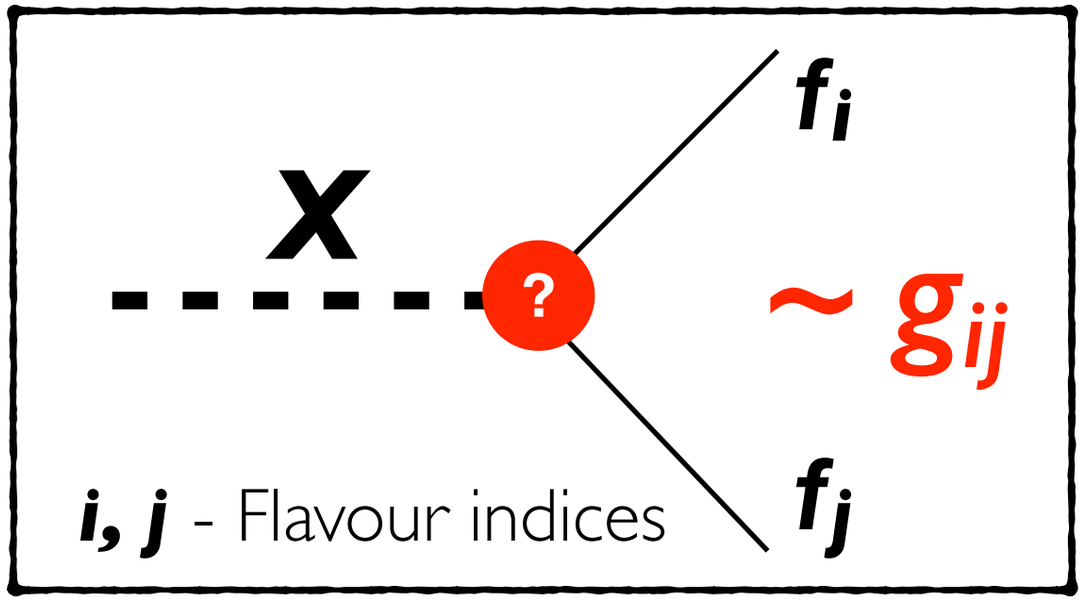
- *Non-resonant effects*

  Deviations in the high-p_T tails of distributions (due to ***X****)*

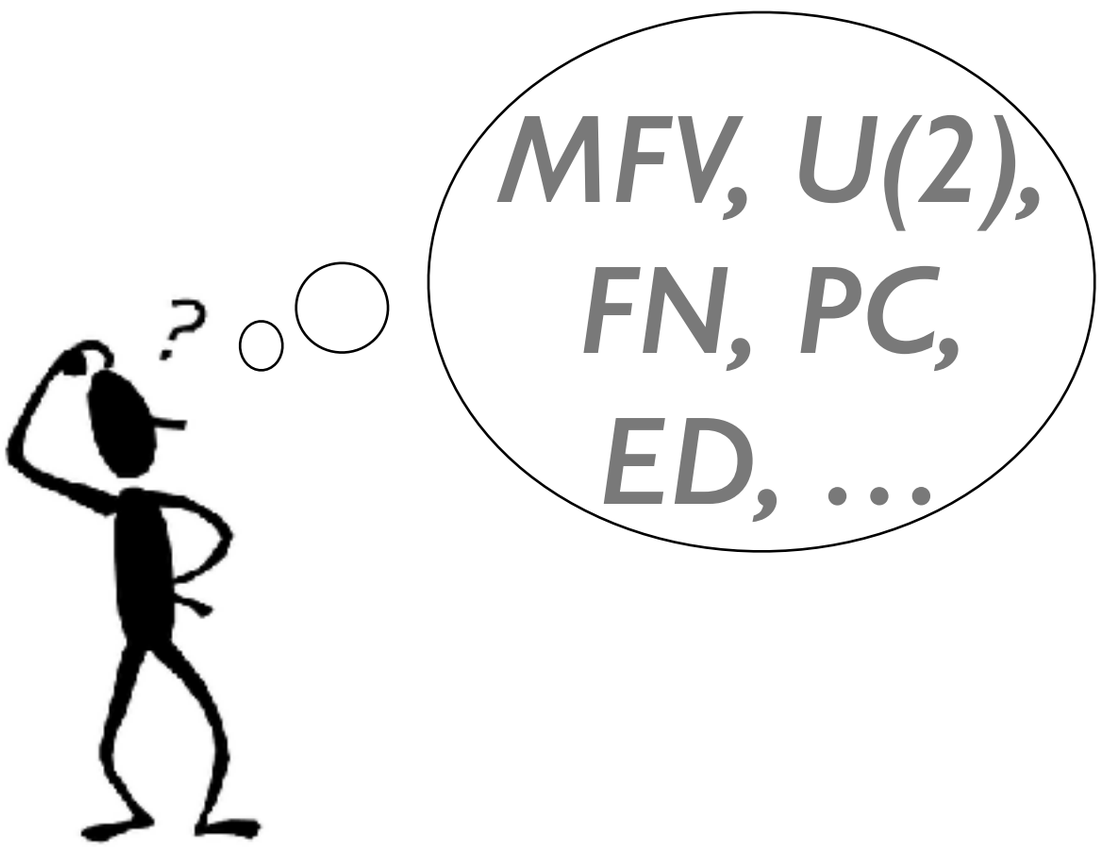
- *Flavour in Top and Higgs*

  Flavour violating Top and Higgs decays, etc…

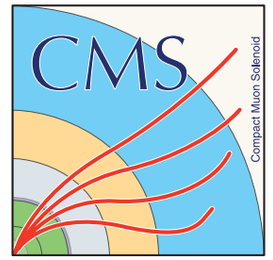
NP flavour structure?



Ideas



Approaches



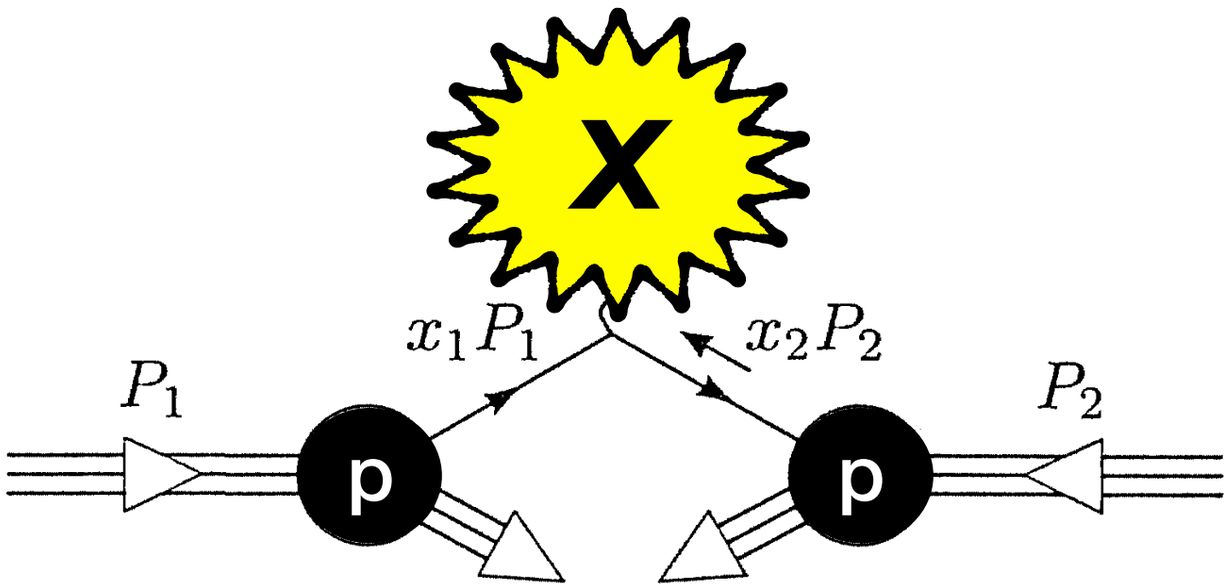
Energy f.

Intensity f.

Complementary

High-pT flavour toolbox

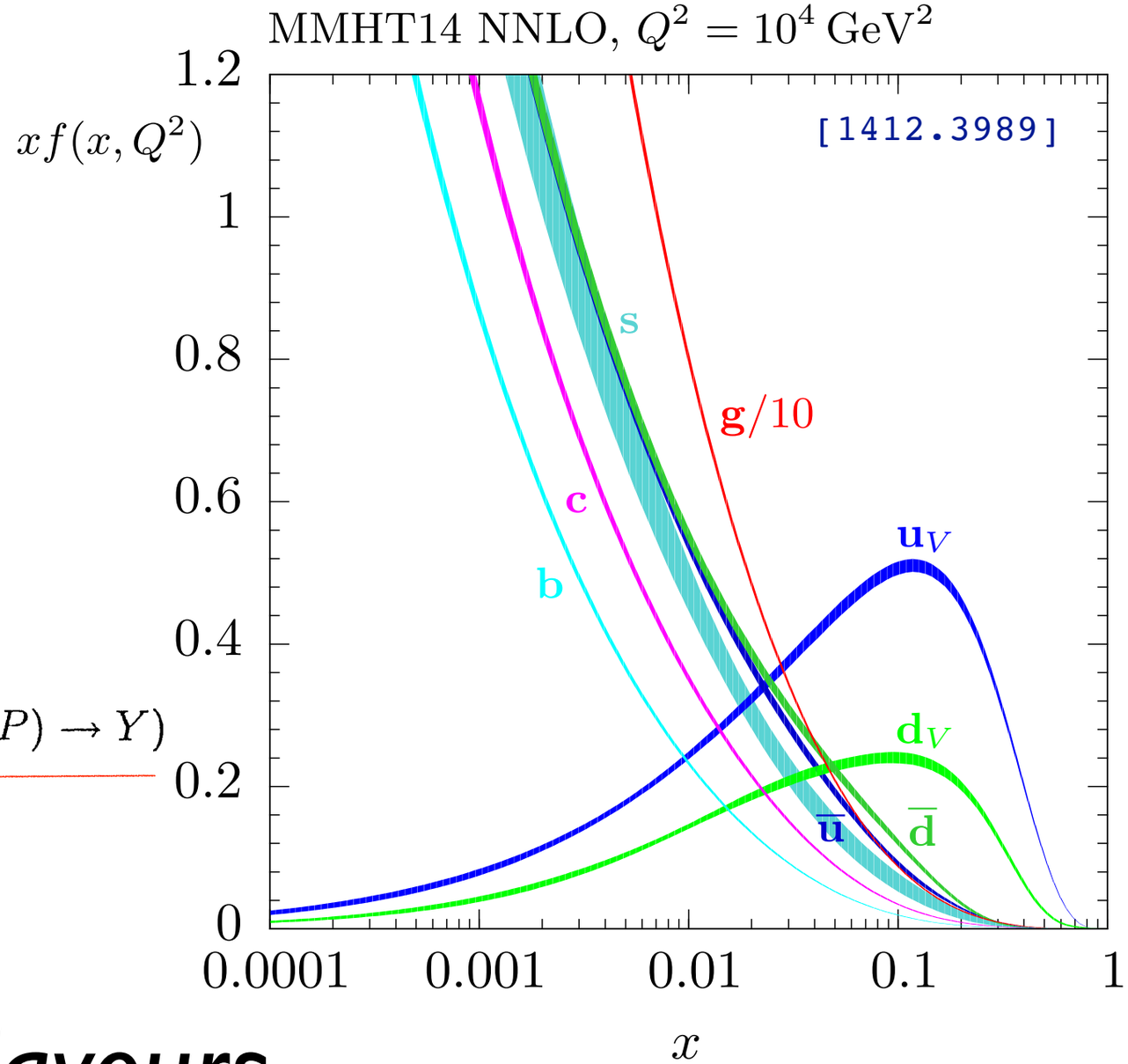
1 *In production*



$$\sigma(p(P_1)+p(P_2)\to Y+X)$$

$$=\int_0^1 dx_1\int_0^1 dx_2\sum_f f_f(x_1)f_{\bar f}(x_2)\cdot\sigma(q_f(x_1P)+\bar q_f(x_2P)\to Y)$$

Parton distribution functions



LHC is a …

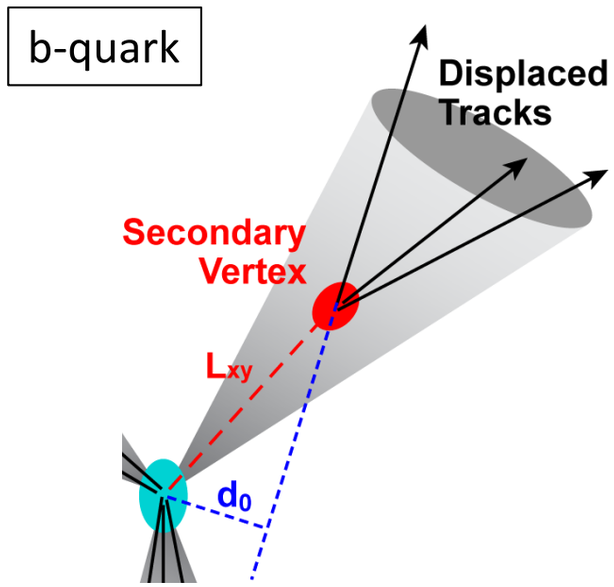
…collider of five quark flavours

See also
[1510.03865, 1410.8849, 1506.07443, …]

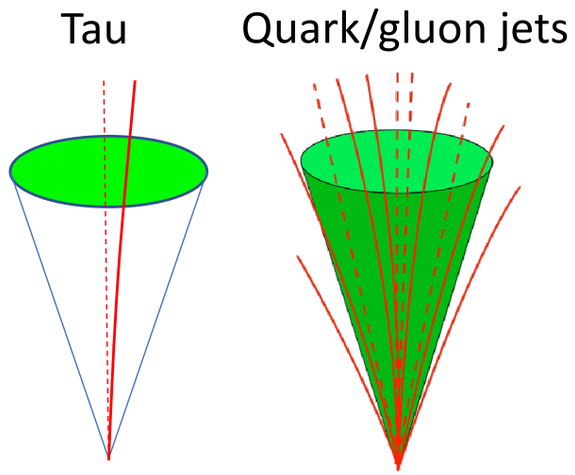
High-pT flavour toolbox

2 *In decay*

- *b-jet tagging*

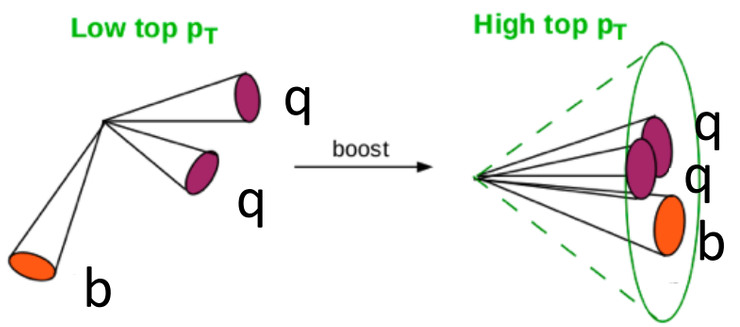


- *Hadronic Tau*



[Yuta Takahashi] @ ZPW2018

- *Boosted Top*

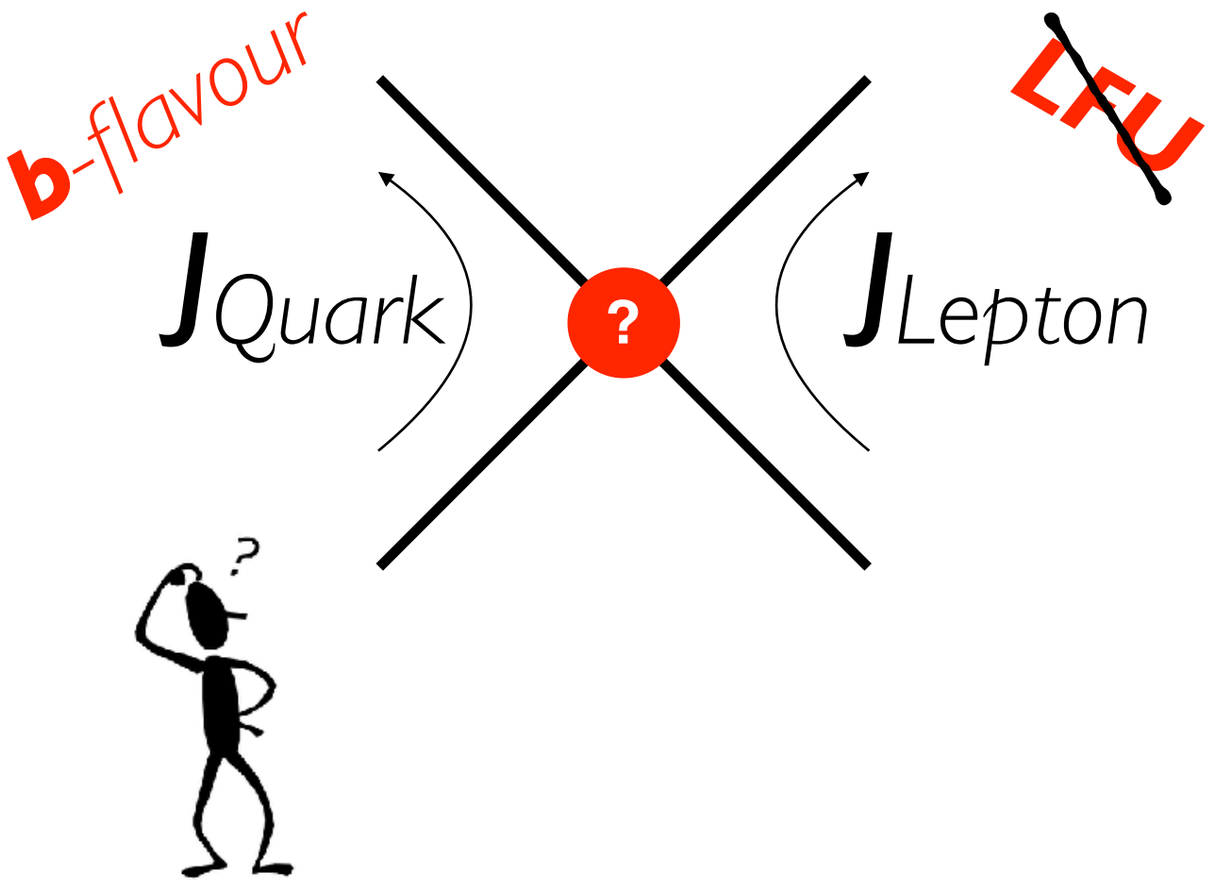


See also [ATL-PHYS-PUB-2017-003, CMS DP-2017/013, CMS-TAU-16-002, ATL-PHYS-PUB-2015-045]

CMS* & *ATLAS* *can…

…catch heavy flavours

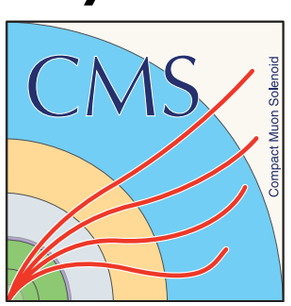
Imagine, for a moment, NP in



@

What is the physics case

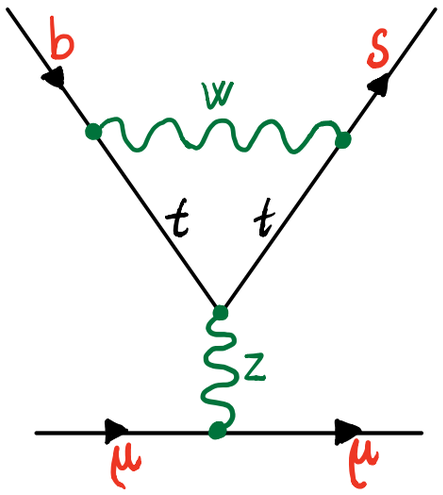
@ ATLAS EXPERIMENT



?

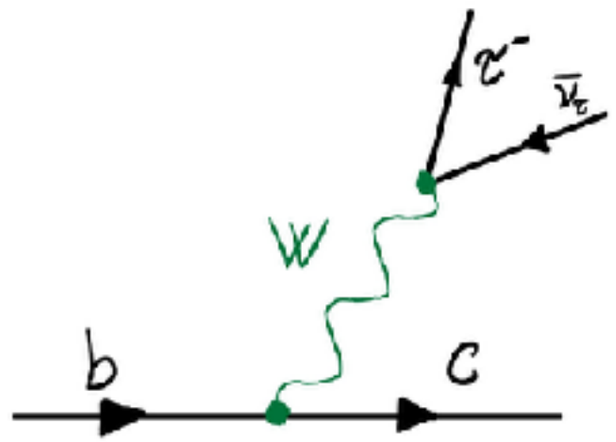
This talk

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



> 4σ

$$b \to c\tau\bar{\nu}_\tau$$



~ 4σ

Motivation?

(trends in the data)

B-anomalies

[1303.0571, 1612.00529, 1506.08614, 1406.6482, 1705.05802, 1308.1707, 1512.04442]

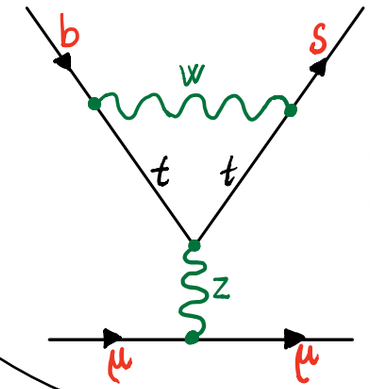
See theory talks:

Neubert, Sumensari, Tetlalmatzi-Xolocotzi, Mahmoudi, Feruglio, Ciuchini

Comment on NP in B-anomalies

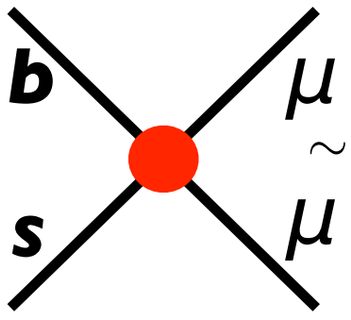
See talk by Feruglio

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



> 4σ

NP:

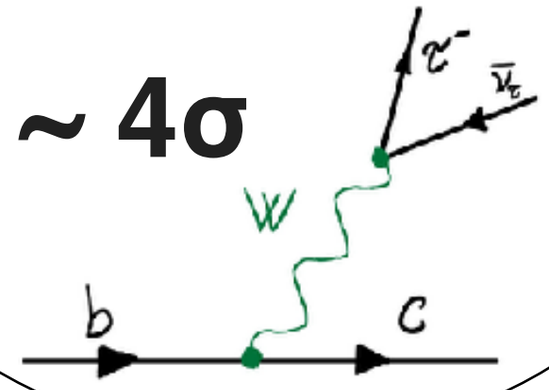


$\sim \frac{1}{(32\,\mathrm{TeV})^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma^\mu\mu_L)$

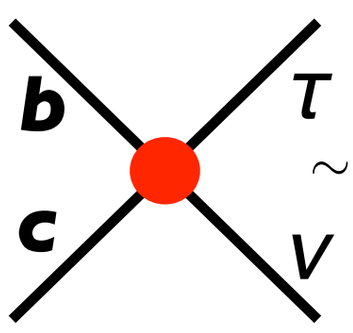
(tree-level or 1-loop)

$b \to c\tau\bar{\nu}_\tau$

~ 4σ



NP:



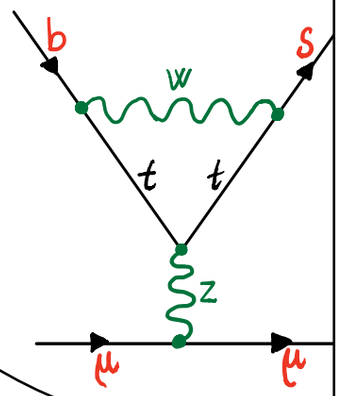
$\sim \frac{2}{(3.5\,\mathrm{TeV})^2}(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L)$

(tree-level)

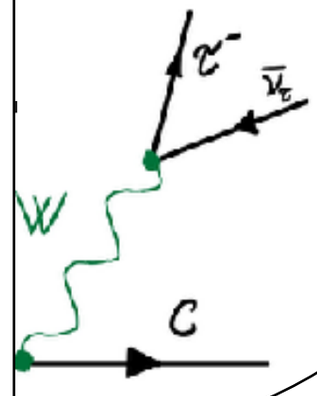
Comment on NP in B-anomalies

See talk by Feruglio

$b \to s$



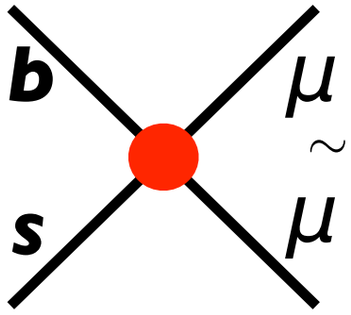
$c\tau\bar{\nu}_\tau$



Physics of LHC?

(or, at least, next generation c.)

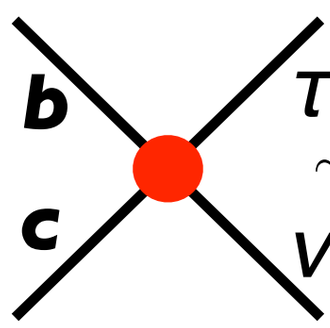
NP:



$$\sim \frac{1}{(32\,\mathrm{TeV})^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

(tree-level or 1-loop)

NP:



$$\sim \frac{2}{(3.5\,\mathrm{TeV})^2}(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L)$$

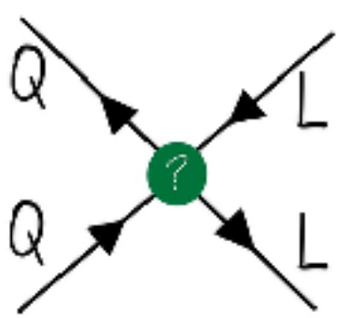
(tree-level)

From Low- to High-p_T

*Establishing correlations

Energy scale

SM EFT



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

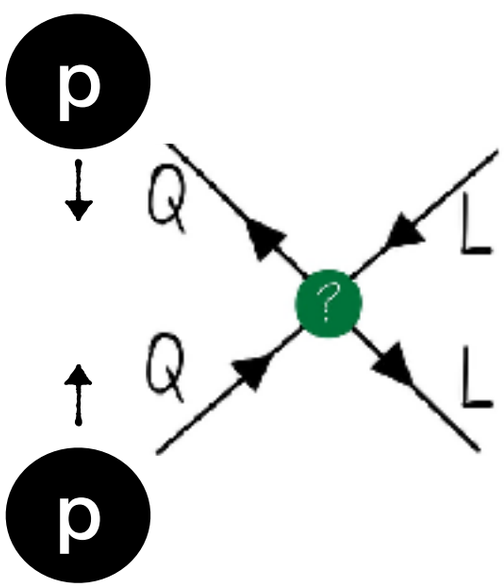
$$Q_i = (V^*_{ji}u^j_L, d^i_L)^T$$
$$L_i = (\nu^i_L, \ell^i_L)^T$$

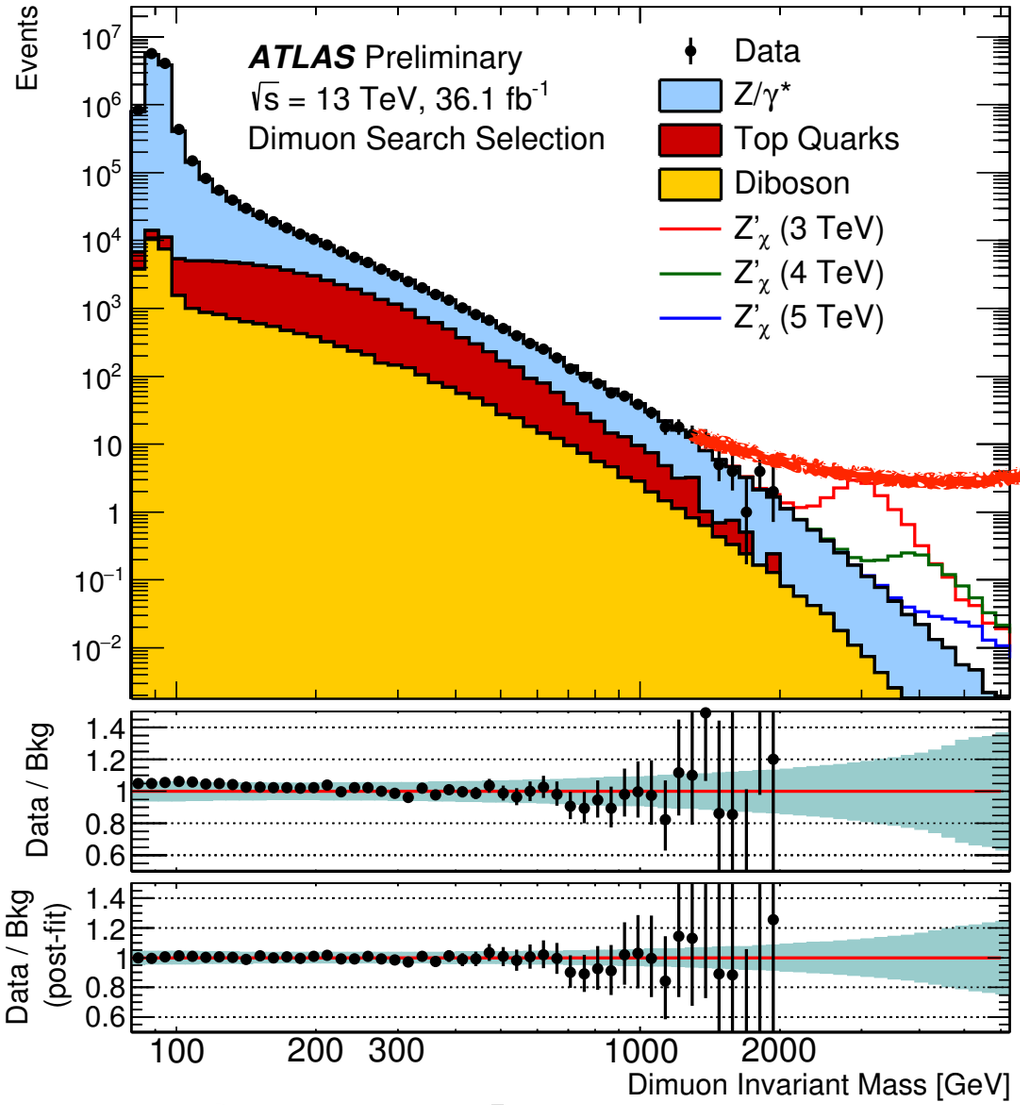
SM EFT @ High-pT

EFT validity

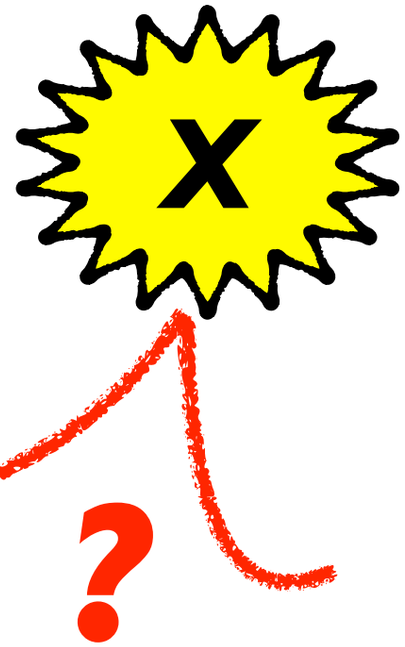
$q^2 << M_X$

$$p\ p \to \ell^+\ell^-$$





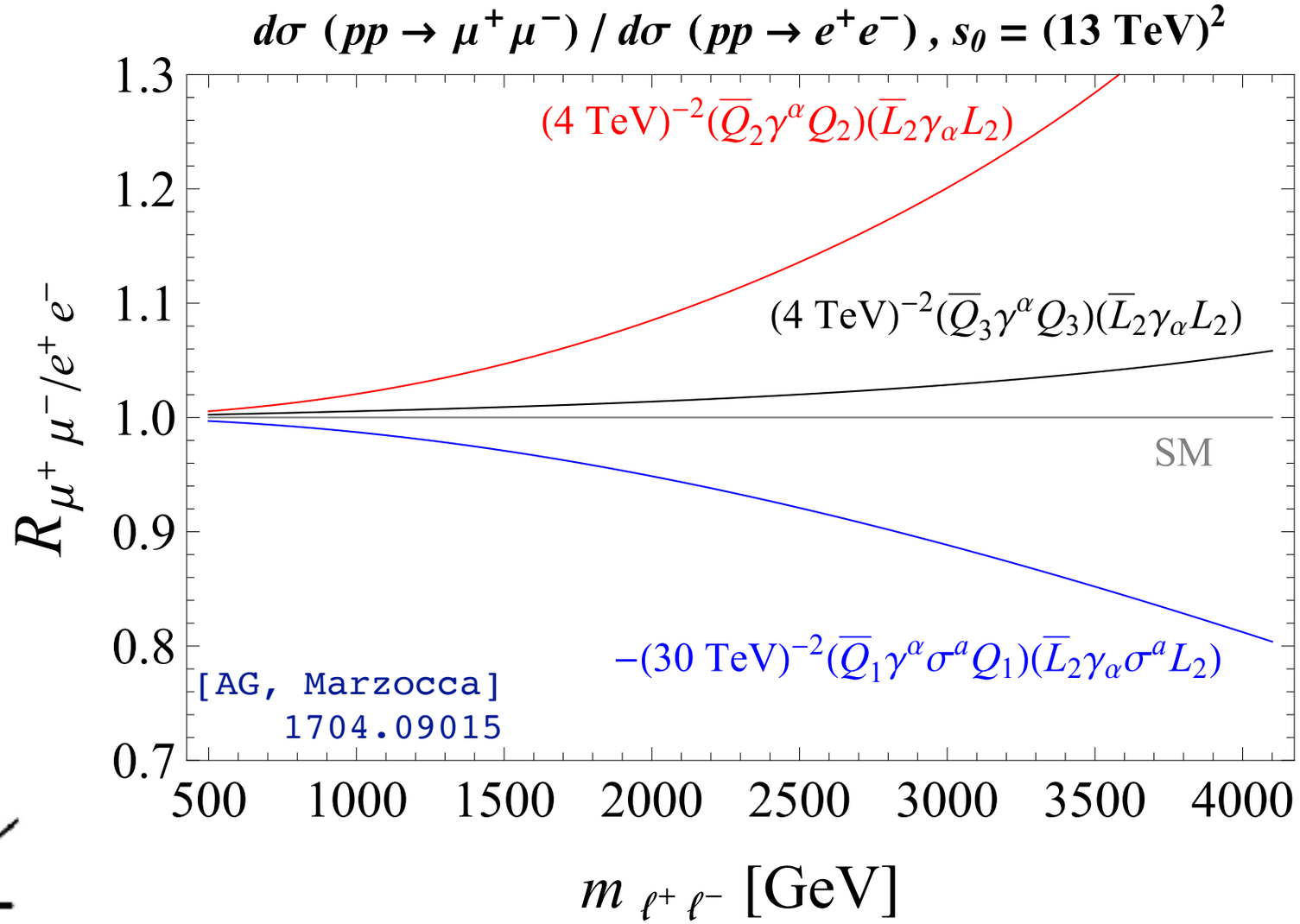
Dimuon Invariant Mass

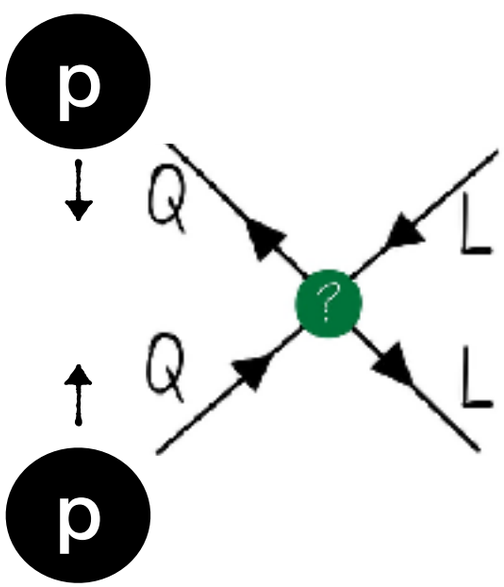


- *Dilepton tails at high-p_T*

Lepton flavour universality tests

R-ratios at high-p_T ?





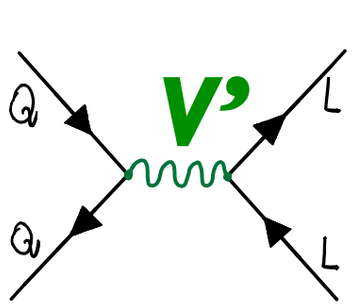
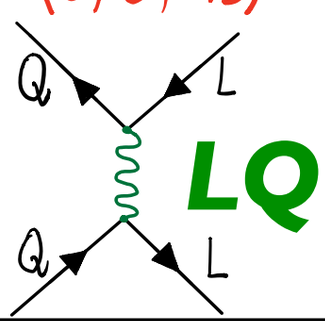
*SMEFT limits in the backup

From Low- to High-p_T

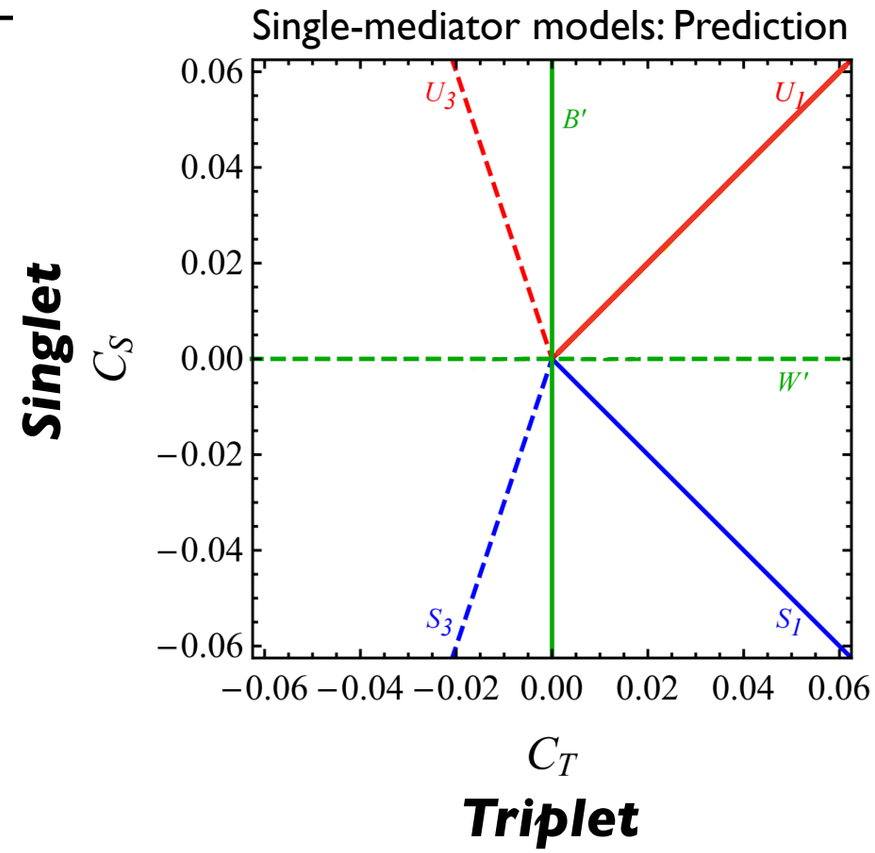
*Establishing correlations

Energy scale

Simplified models

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: $U_1^\mu \sim (3,1,2/3)$, $U_3^\mu \sim (3,3,2/3)$
	

SU(3)×SU(2)×U(1) representations



SM EFT

$$\mathcal{L}^{\text{SMEFT}} \supset \frac{c^{(3)}_{Q_iQ_jL_kL_l}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l) + \frac{c^{(1)}_{Q_iQ_jL_kL_l}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_k\gamma^\mu L_l)$$

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

MFV Z'

A class of Z' models

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

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

with MFV in the quark sector

$$g_Q^{(1),ij} \sim g^* \left(\mathbf{1} + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}$$

Let's talk models

<u>Example</u>:

$$g_Q^{(1),ii} = g^* \qquad g_L^{(1),22} = g^*$$

$$g_Q^{(1),23} = V_{ts} g^*$$

MFV Z'

A class of Z' models

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with MFV in the quark sector

$$g_Q^{(1),ij} \sim g^* \left(\mathbf{1} + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger\right)_{ij}$$

Example:

$$g_Q^{(1),ii} = g^* \qquad g_L^{(1),22} = g^*$$

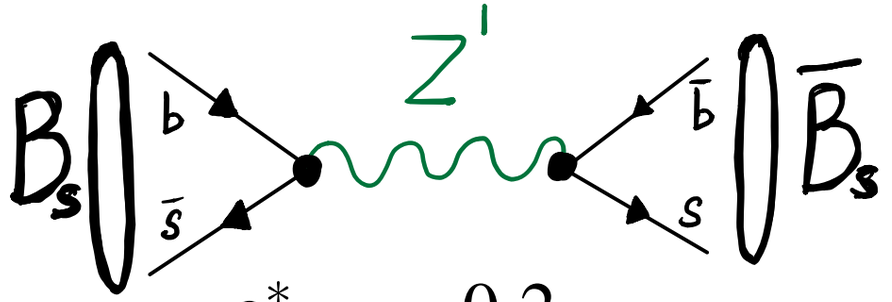
$$g_Q^{(1),23} = V_{ts} g^*$$

Low-p_T input

- *Rare decays* $b \to s\mu\bar{\mu}$

$$\frac{g^*}{M'_Z} \sim \frac{0.1}{1\ \text{TeV}}$$

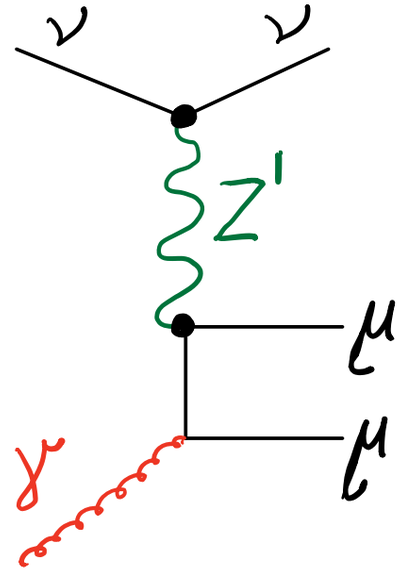
- *Neutral meson mixing*



$$\frac{g^*}{M'_Z} \lesssim \frac{0.2}{1\ \text{TeV}}$$

[Altmannshofer, Straub] 1308.1501

- *Neutrino trident production*



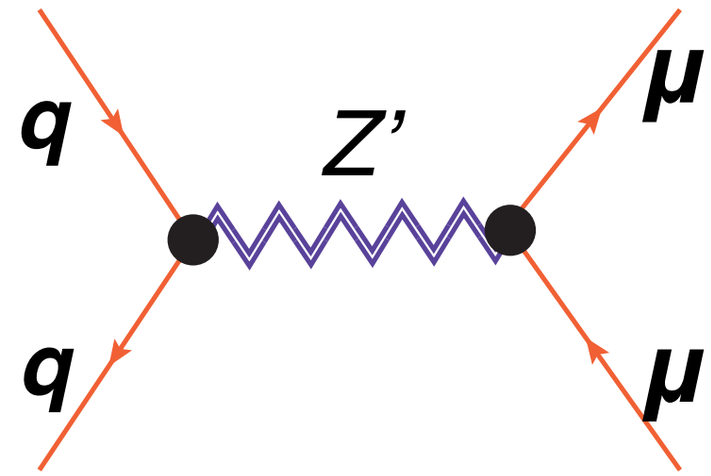
$$\frac{g^*}{M'_Z} \lesssim \frac{3}{1\ \text{TeV}}$$

[Altmannshofer, Gori, Pospelov, Itay] 1406.2332

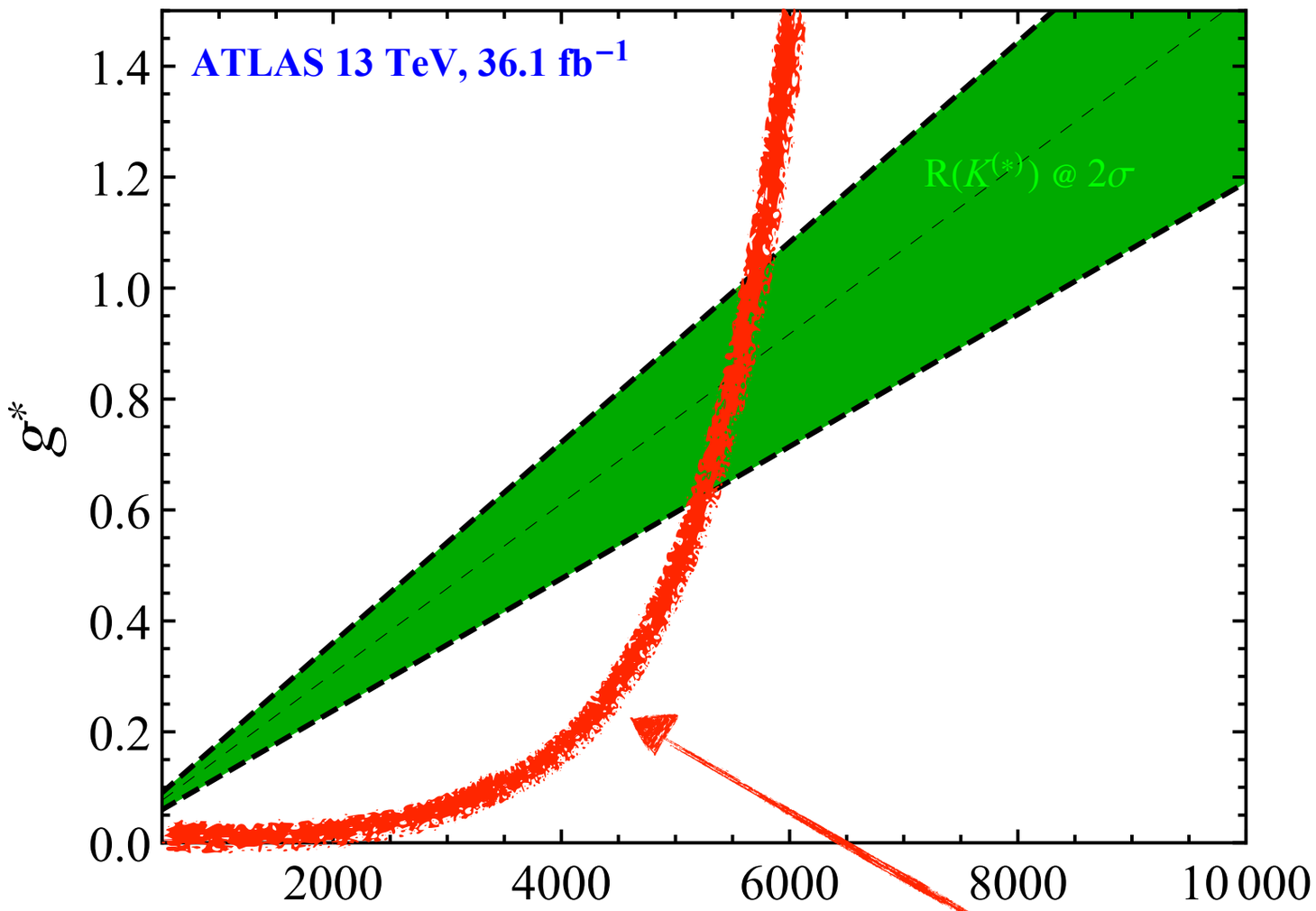
MFV Z'

[AG, Marzocca] 1704.09015

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



$$\Gamma_{Z'}/M_{Z'} \approx 5g_*^2/(6\pi)$$



Z' couplings

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

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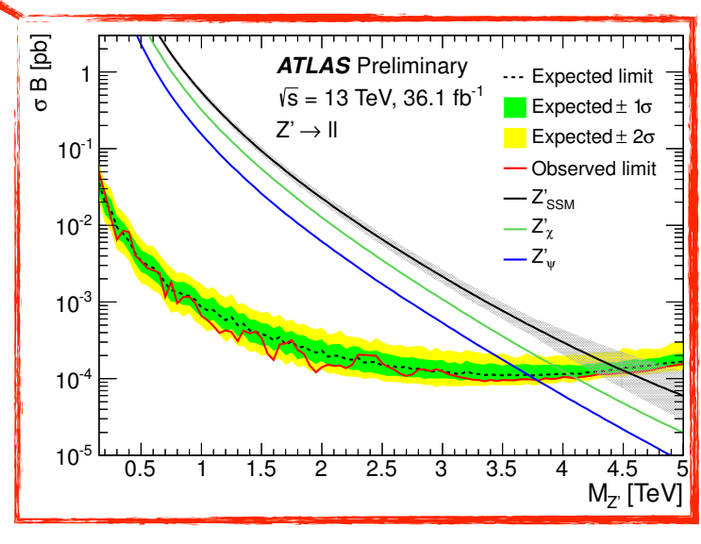
$$g_Q^{(1),ii} = g_L^{(1),22} = g_* \qquad g_Q^{(1),23} = V_{ts}g_*$$

$$\Delta F = 2$$

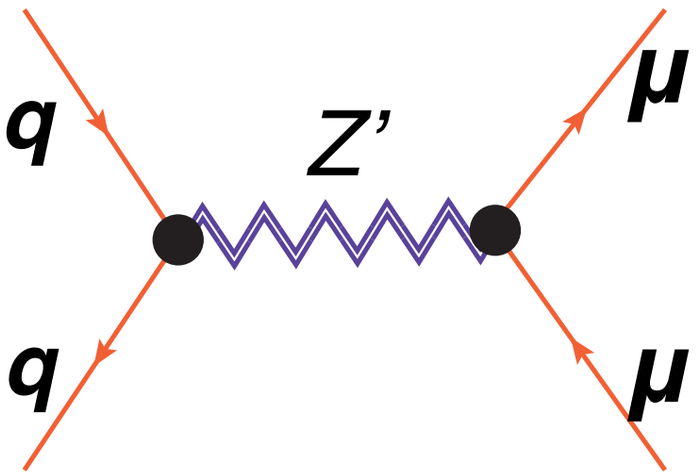
Narrow resonance search limits



MFV Z'

[AG, Marzocca]
1704.09015

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



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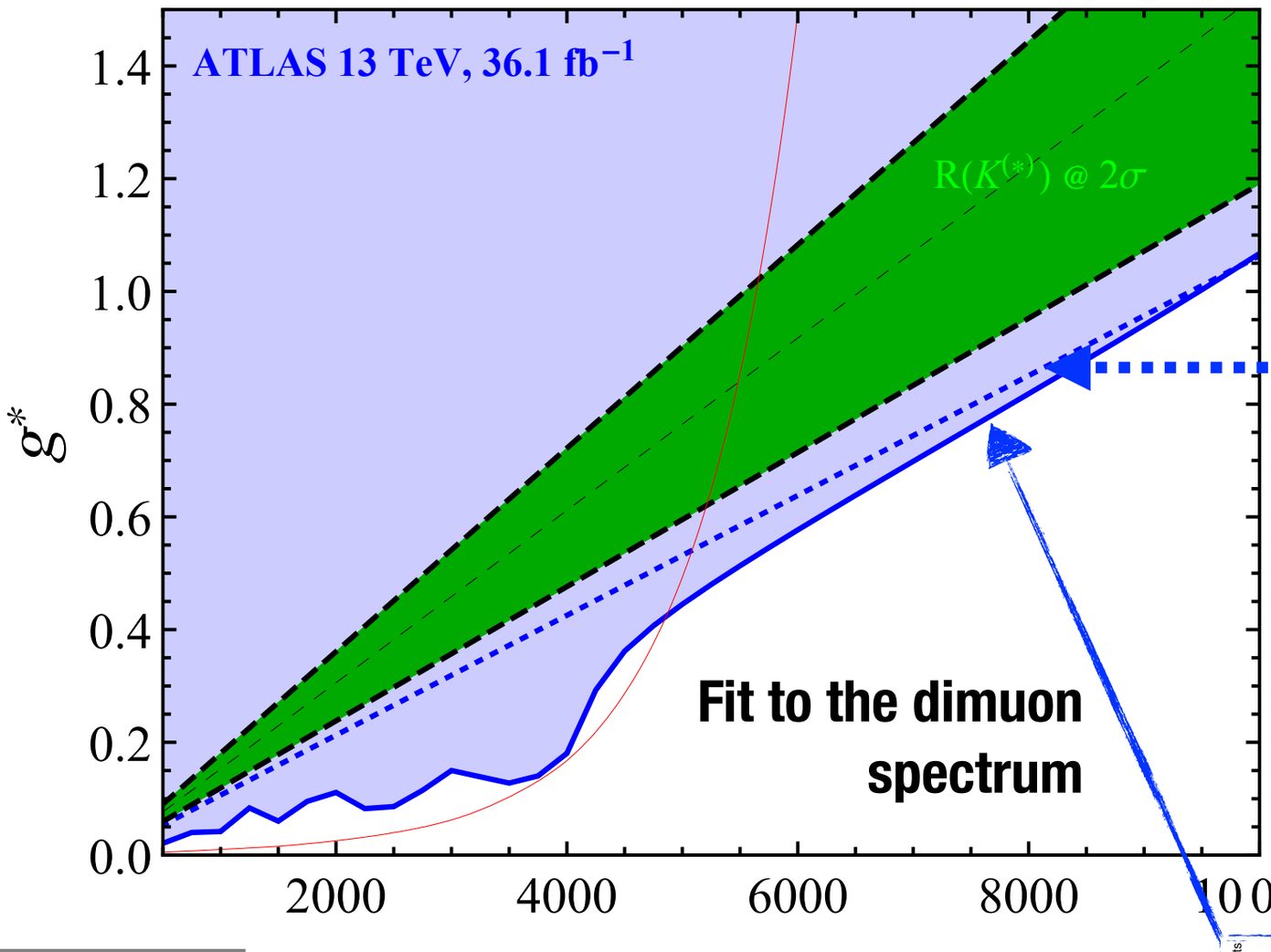

Z' couplings

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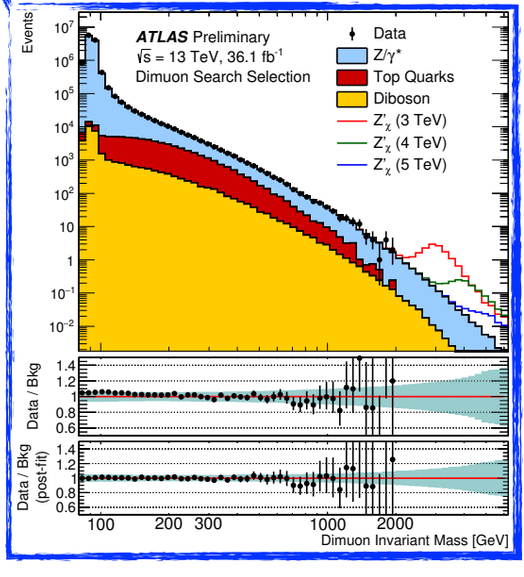
$$g_Q^{(1),ii} = g_L^{(1),22} = g_* \qquad g_Q^{(1),23} = V_{ts}g_*$$

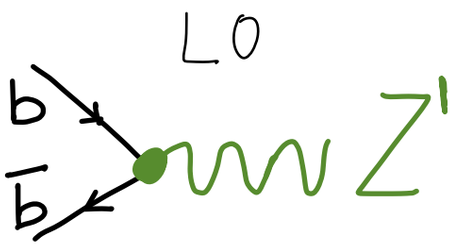
$$\Delta F = 2$$

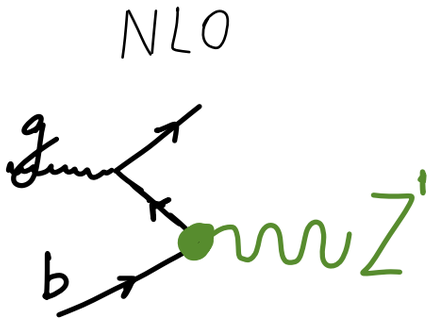
The correct limit!



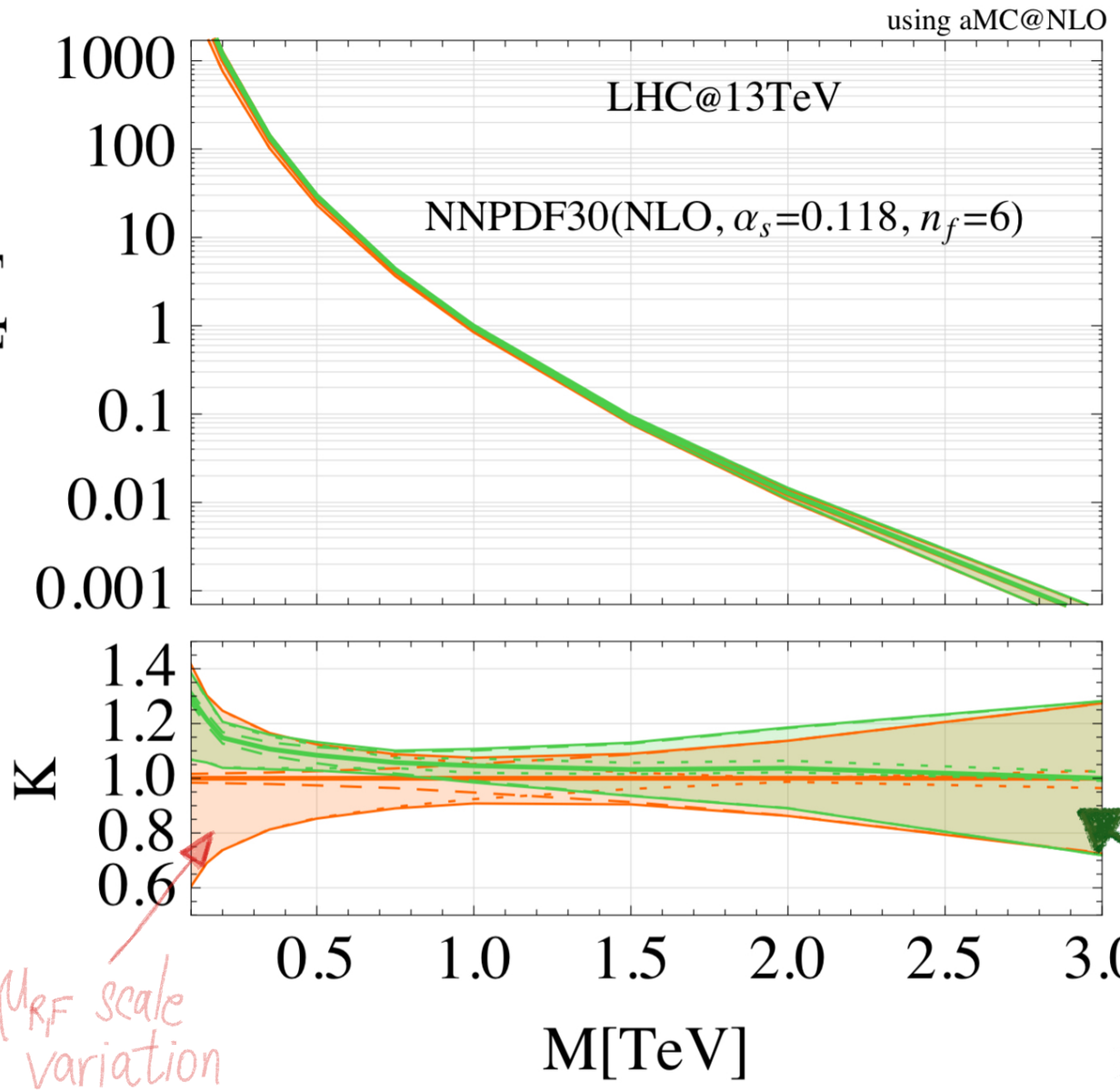
$bb \to Z'$ @ NLO QCD

5FS:





+ etc.



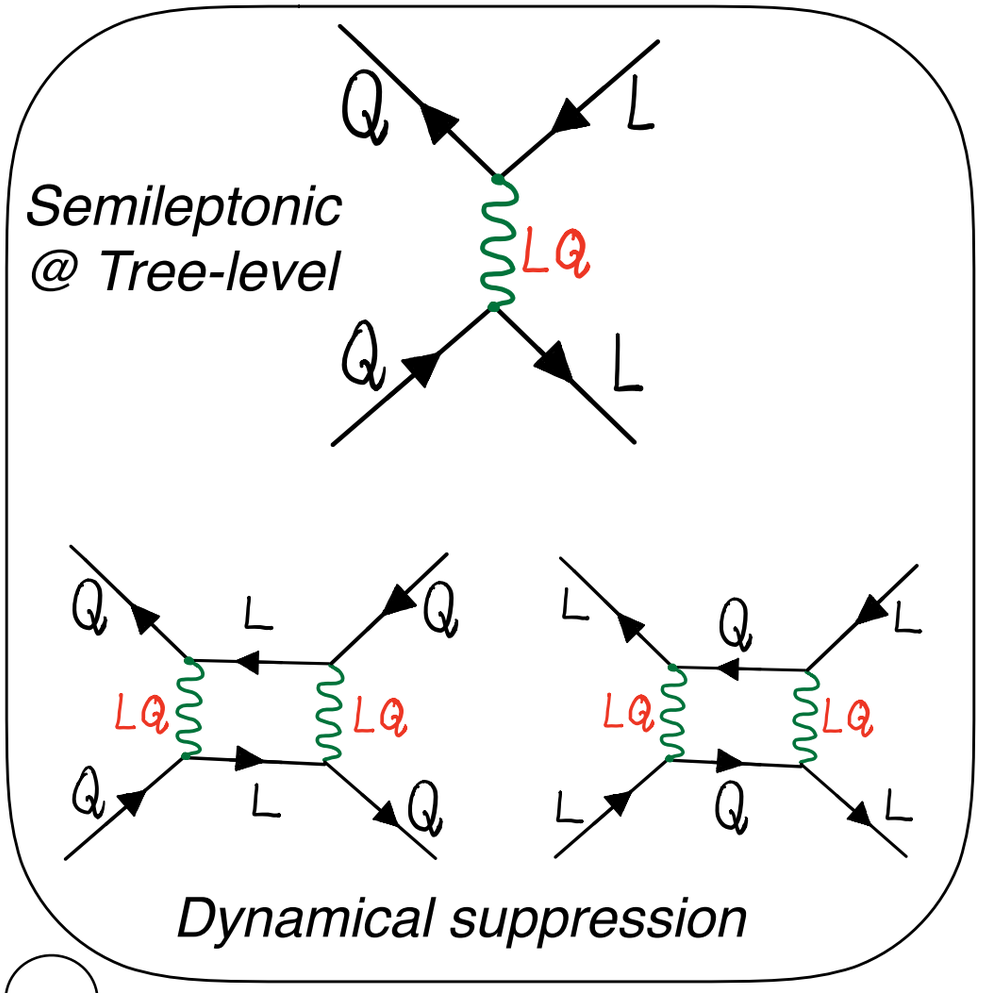
[Faroughy, AG, F. Kamenik] 1609.07138

Improve PDF at large x...

More Z' models in the backup

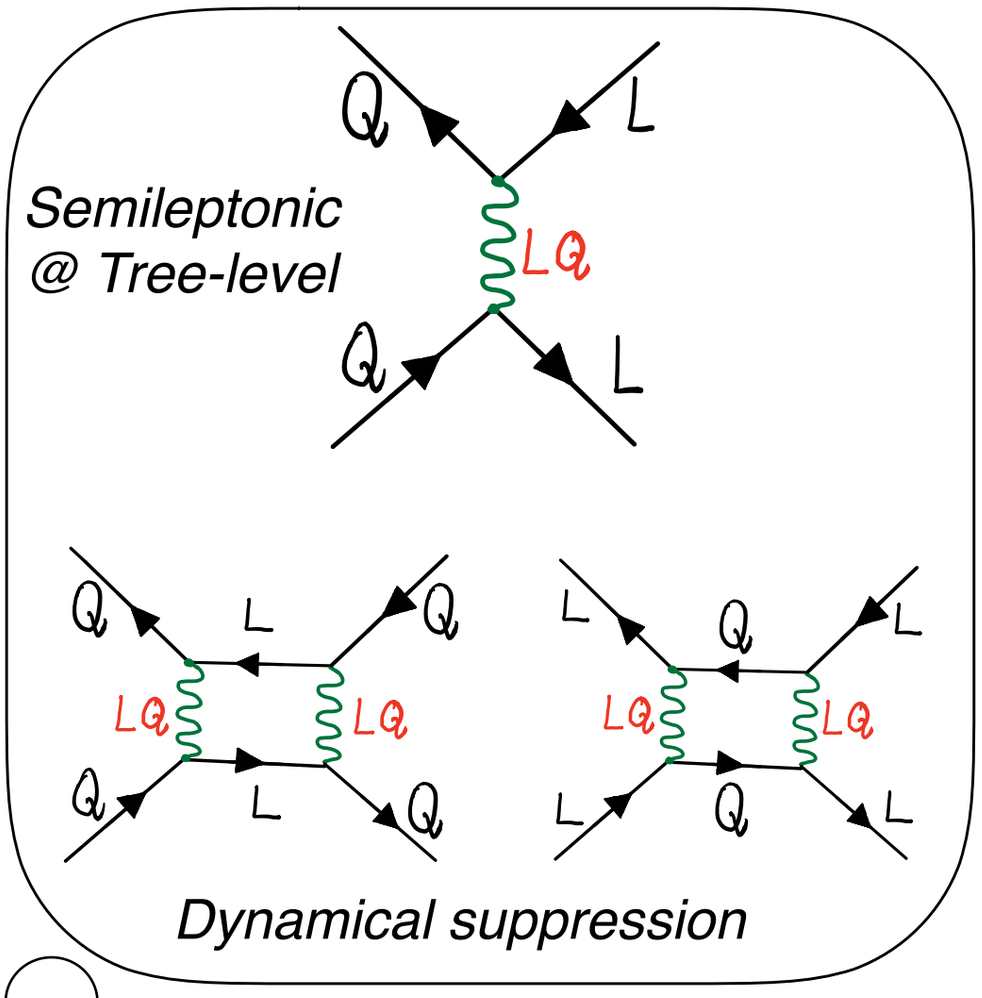
*Weaker limits compared to the MFV case, e.g.
[Falkowski, King, Perdomo, Pierre] 1803.04430
[Allanach, Gripaios, You] 1710.06363

Leptoquark @ Low-p_T



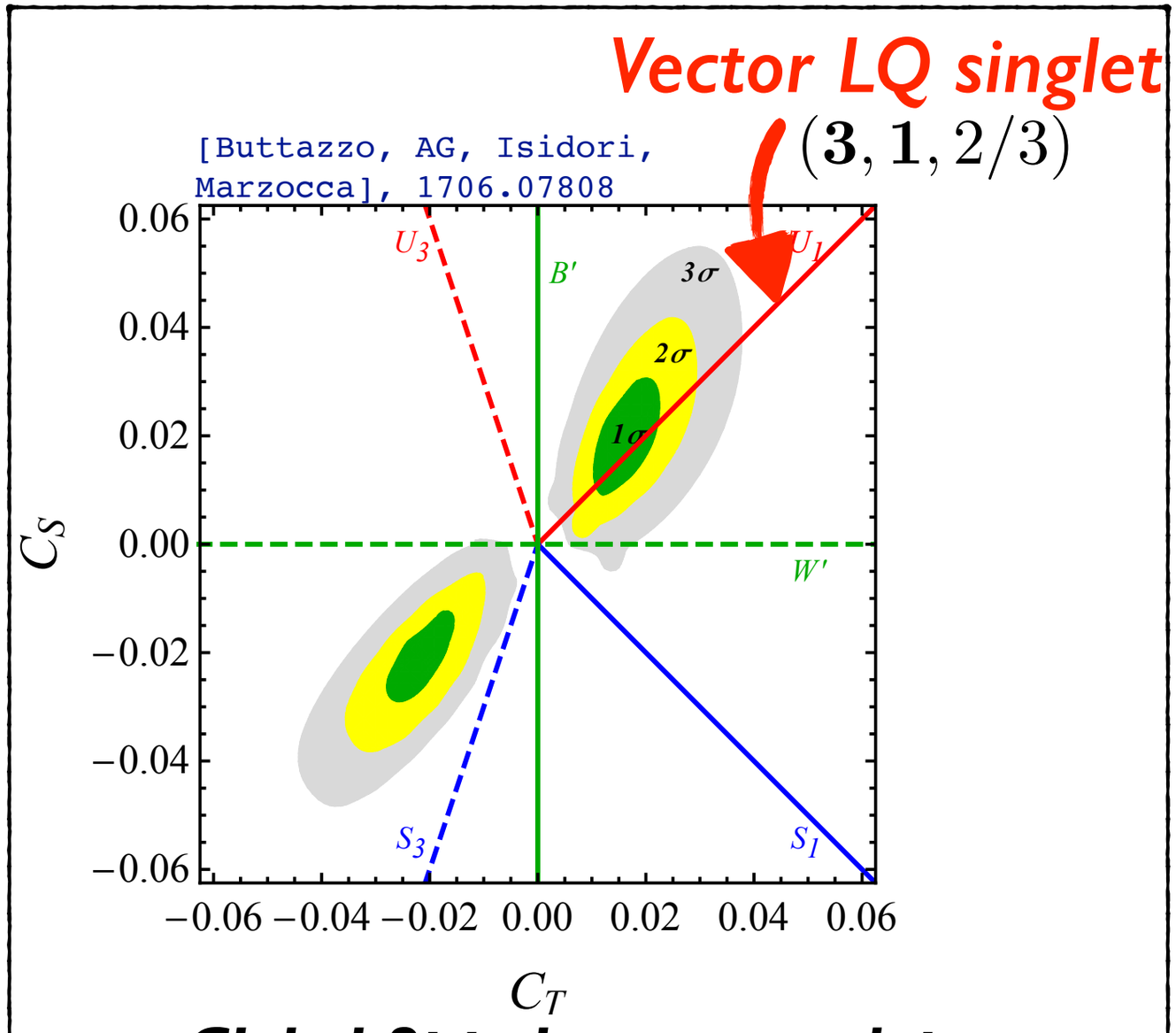
LQ physics review:
[Doršner, Fajfer, AG, Košnik, F. Kamenik]
Phys.Rept. 641 (2016) 1-68

Leptoquark @ Low-p_T



Vector LQ singlet $(\mathbf{3},\mathbf{1},2/3)$

[Buttazzo, AG, Isidori, Marzocca], 1706.07808



Global fit to low-energy data

(RGE effects included)

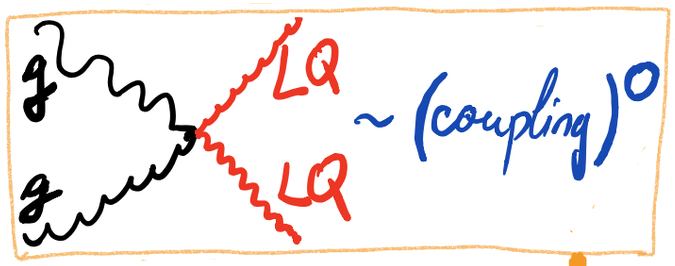
$R^{\tau\ell}_{D^{(*)}}$ $\Delta C_9^\mu = -\Delta C_{10}^\mu$

$B_{K^{(*)}\nu\bar{\nu}}$ $\delta g^Z_{\tau_L}$ $\delta g^Z_{\nu_\tau}$ $|g^W_\tau / g^W_\ell|$

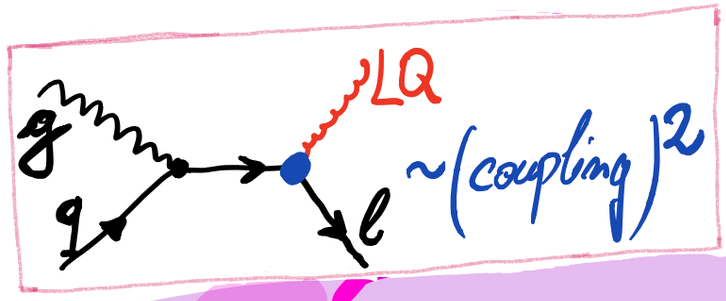
See also talk by Sumensari

Leptoquark @ High-p_T

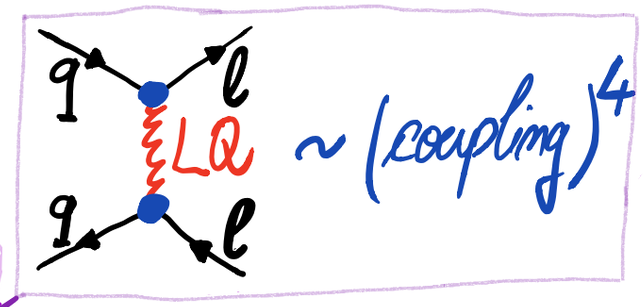
Pair prod.

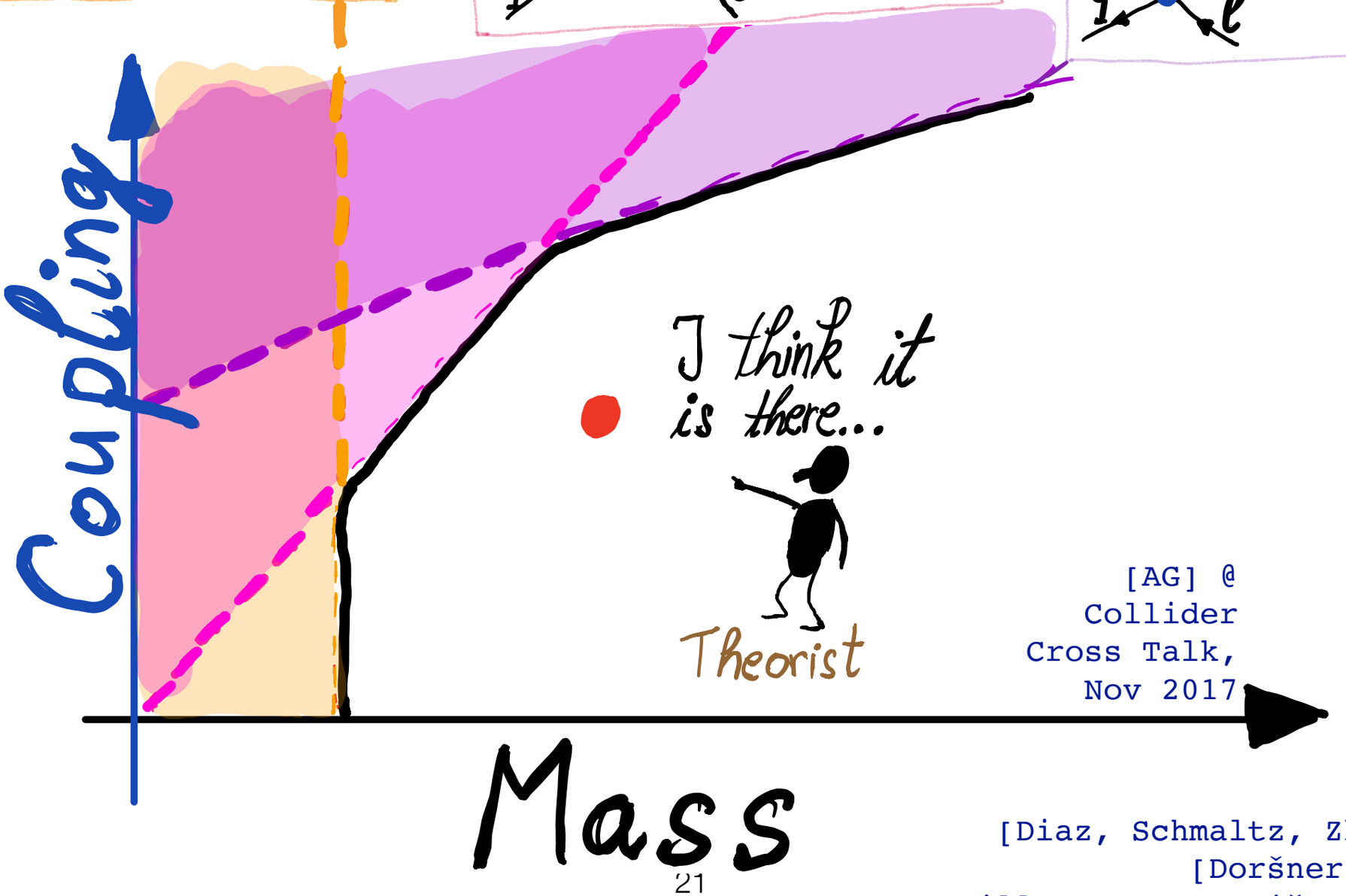


Single prod.



Dilepton tails



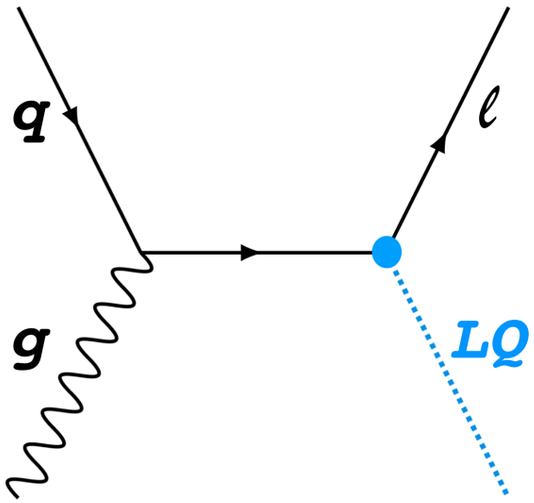


[AG] @ Collider Cross Talk, Nov 2017

See e.g.
[Diaz, Schmaltz, Zhong] 1706.05033
[Doršner, AG] 1801.07641
[Hiller, Loose, Nišandžić] 1801.09399

LQ toolbox

Single prod.



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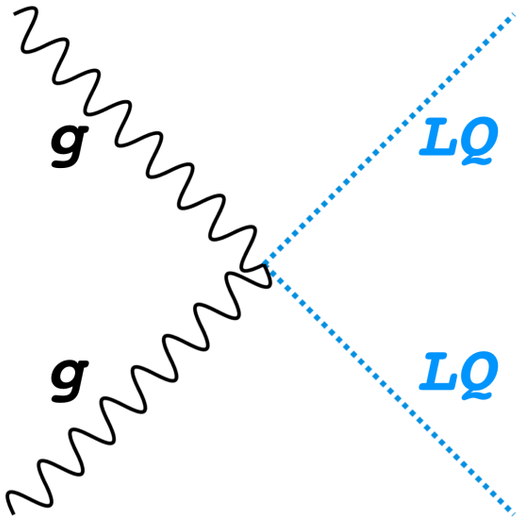
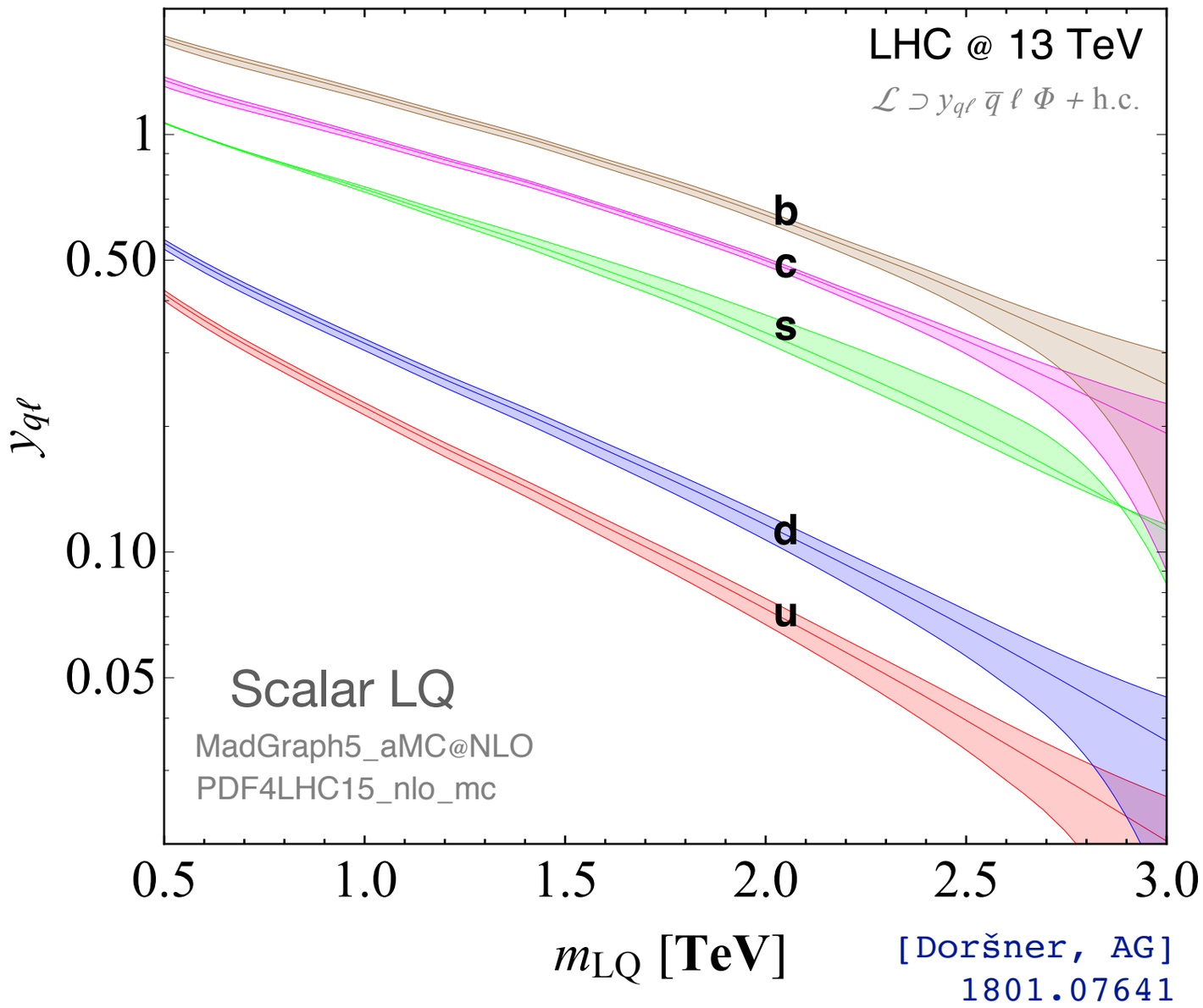


Pair prod.

$\sigma_{\text{single}} = \sigma_{\text{pair}}$ @NLO QCD

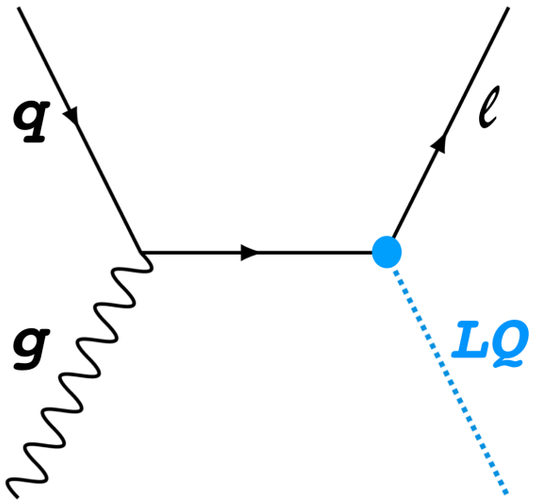


[Doršner, AG] 1801.07641

LQ MC tool at NLO QCD:
http://lqnlo.hepforge.org

LQ toolbox

Single prod.



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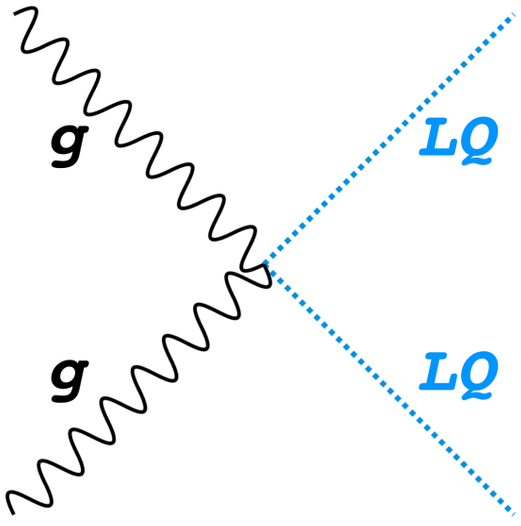
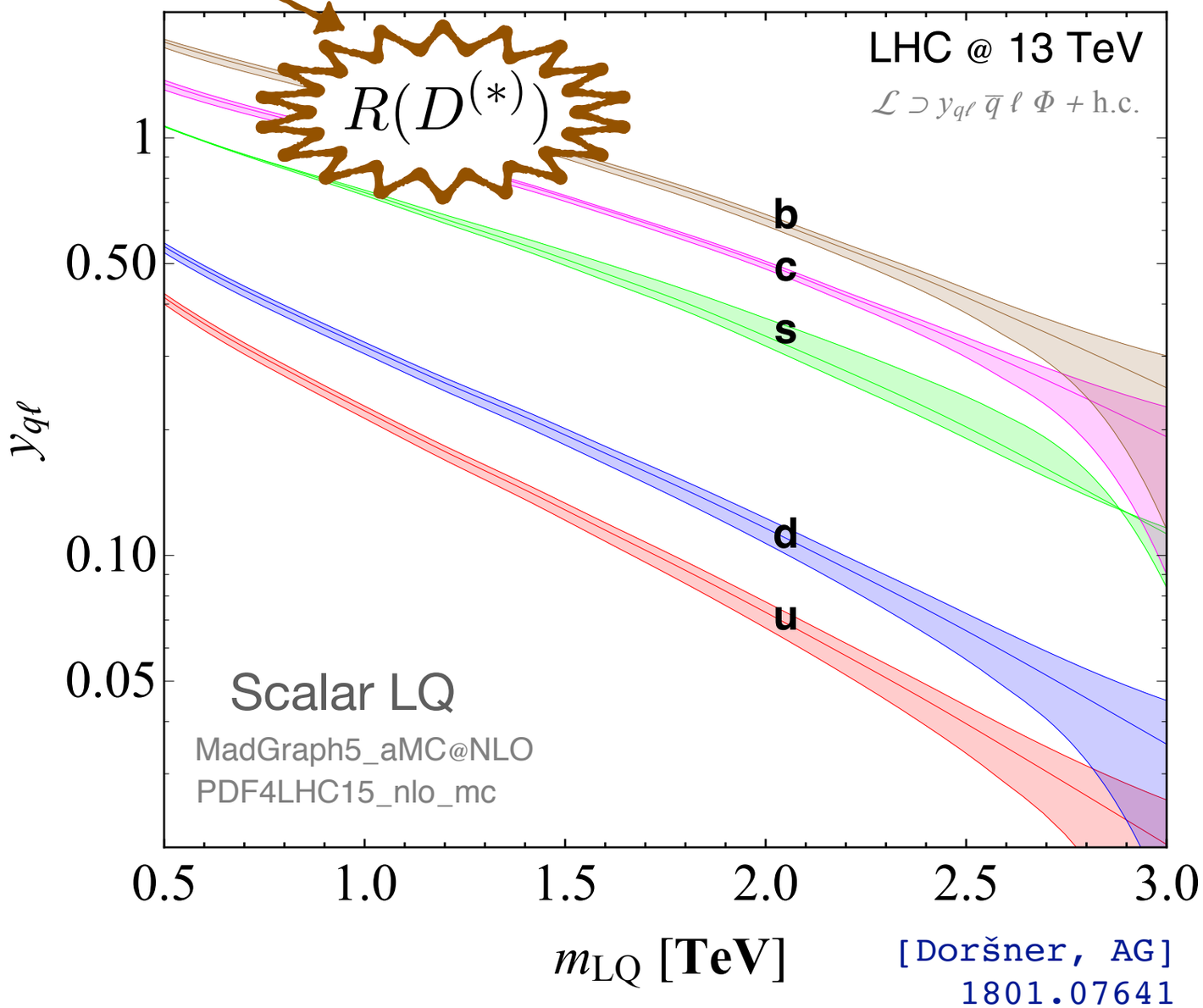


Pair prod.

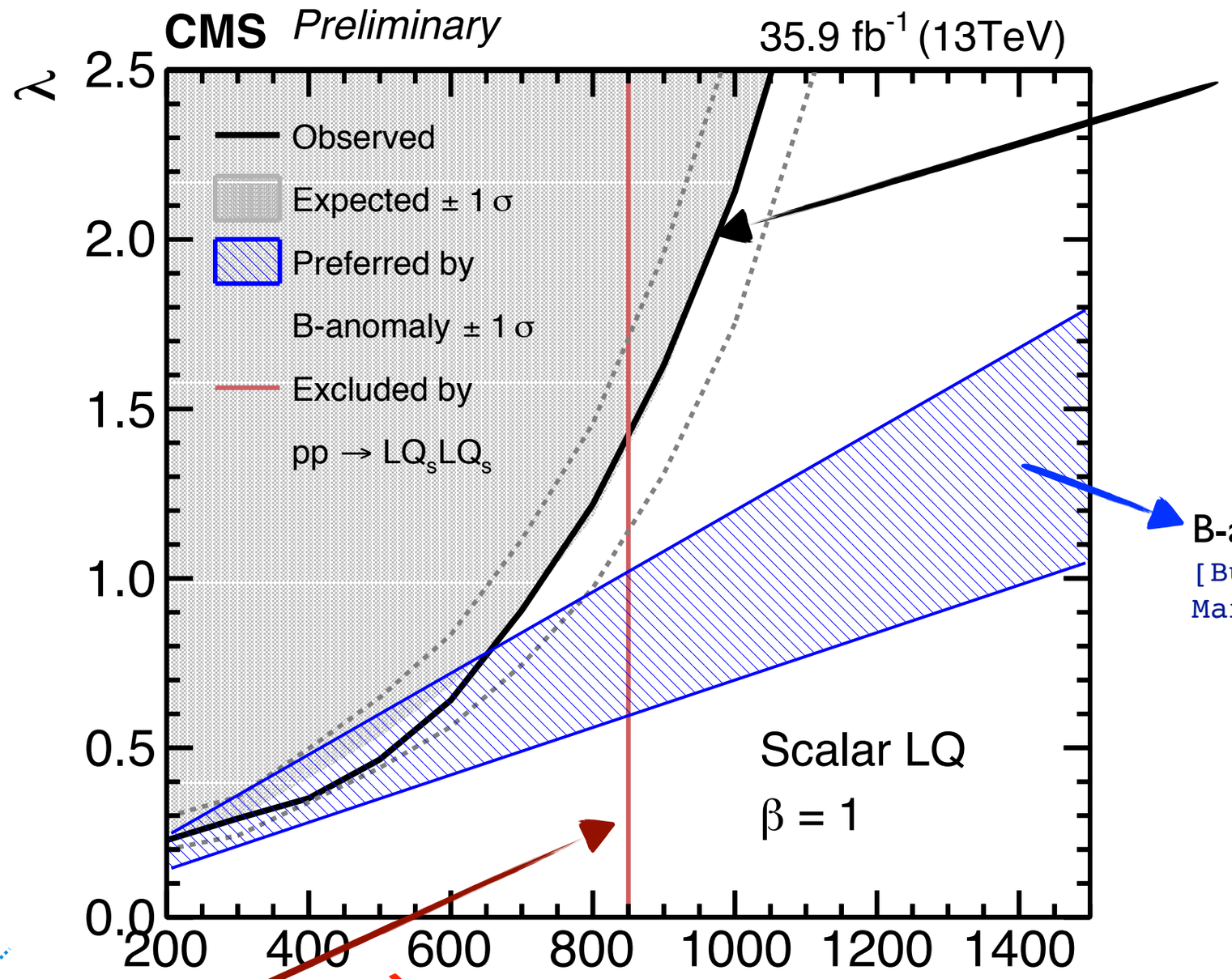
Suggested range for y_{bT}

$\sigma_{\text{single}} = \sigma_{\text{pair}}$ @NLO QCD



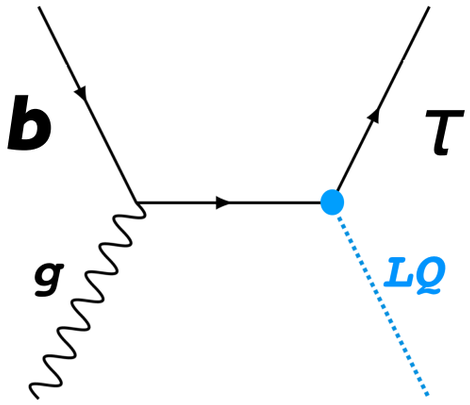
[Doršner, AG] 1801.07641

LQ MC tool at NLO QCD:
http://lqnlo.hepforge.org



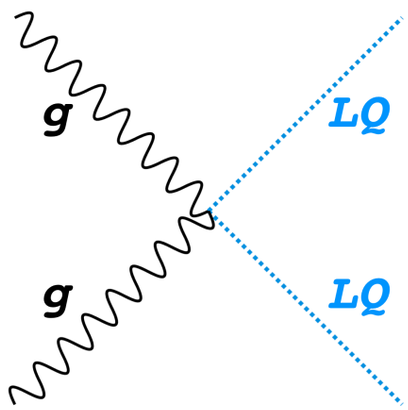
[CMS-PAS-EXO-17-029]

B-anomalies model from
[Buttazzo, AG, Isidori, Marzocca] 1706.07808



Single prod.

pp → τ(bτ)

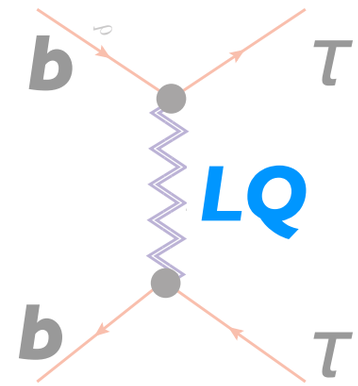


pp → (bτ)(bτ)

Pair prod.

Dilepton

pp → ττ



(Missing)
Please do it

Summary

Signatures

$p\,p \to$ **$b\tau b\tau$, $t\nu t\nu$, $t\tau t\tau$, $t\nu b\tau$, ...** **$b\tau\tau$, $t\nu\tau$, $t\tau\tau$, ...** **$\tau\nu$, $\tau\tau$,** **bb, tt,**

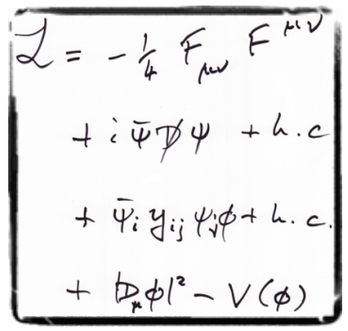
$b\tau b\mu$, $t\nu b\mu$, ... **$b\mu\tau$, ...** **$\mu\mu$** ***jj***

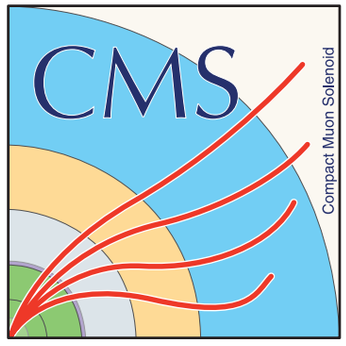
$b\mu b\mu$, ...

To do list

- Improve heavy flavour PDF / tagging
- Explore the tails
- Test lepton flavour universality
- Go beyond the narrow-width resonance hypothesis
- Expand the scope of LQ searches

NP in **beauty**





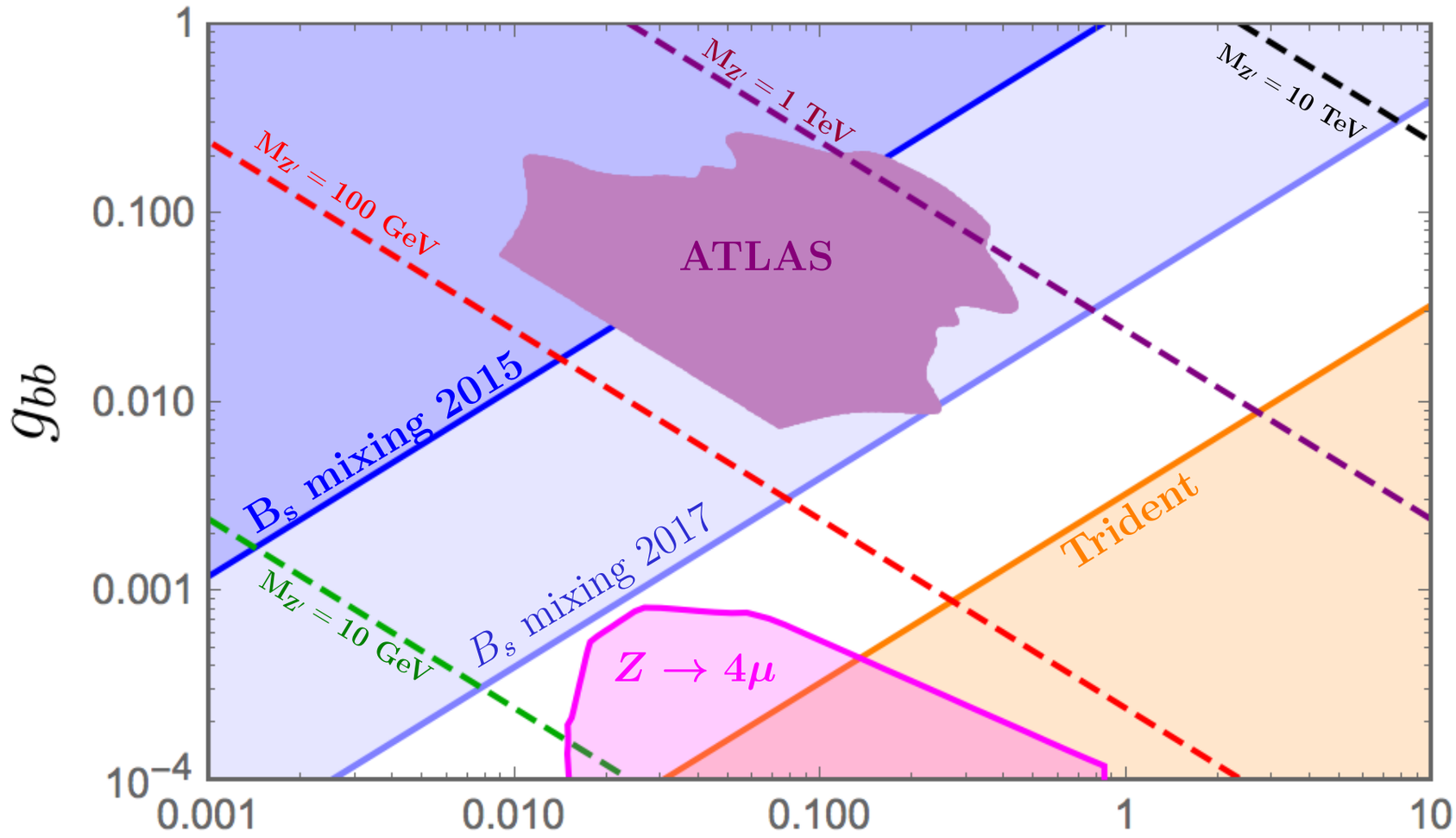
is bringing us all together

Backup

$bb \to Z'$

$$\mathcal{L} \supset Z'_\mu \left(g_{bb} \bar{q}_L \gamma^\mu q_L + g_{bs} \bar{b}_L \gamma^\mu s_L + g_{\mu\mu} \bar{\ell}_L \gamma^\mu \ell_L \right)$$

$$g_{bs} = V_{ts} g_{bb}$$



[Falkowski, King, Perdomo, Pierre] 1803.04430

$$\Gamma_{Z' \to \mu\bar{\mu}} = \frac{1}{24\pi} g_{\mu\mu}^2 M_{Z'} = \Gamma_{Z' \to \nu_\mu \bar{\nu}_\mu},$$

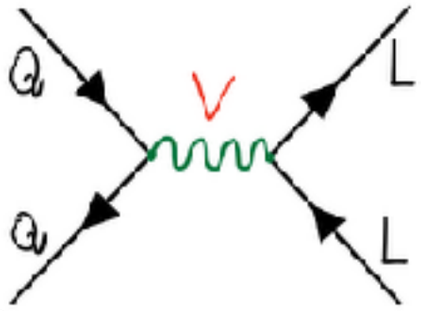
$$\Gamma_{Z' \to b\bar{b}} = \frac{1}{8\pi} g_{bb}^2 M_{Z'}, \qquad \Gamma_{Z' \to b\bar{s}} = \frac{1}{8\pi} g_{bb}^2 V_{ts}^2 M_{Z'},$$

$$\Gamma_{Z' \to t\bar{t}} = \frac{1}{8\pi} g_{bb}^2 M_{Z'} \left(1 - \frac{m_t^2}{M_{Z'}^2}\right) \sqrt{1 - \frac{4m_t^2}{M_{Z'}^2}},$$

- *Bottom fusion @ NLO QCD*
- *Narrow-width resonance hypothesis*

[AG, Isidori, Marzocca]
1506.01705

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



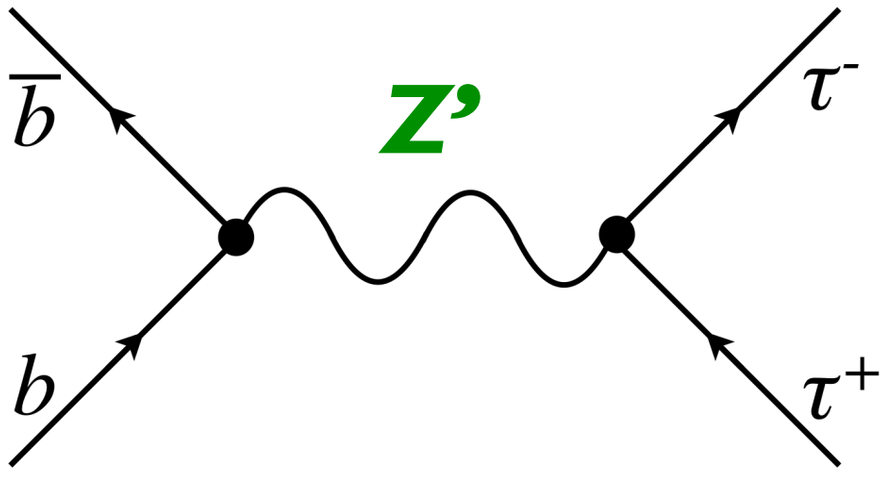
$b \to c\tau\bar{\nu}$ ***charged***

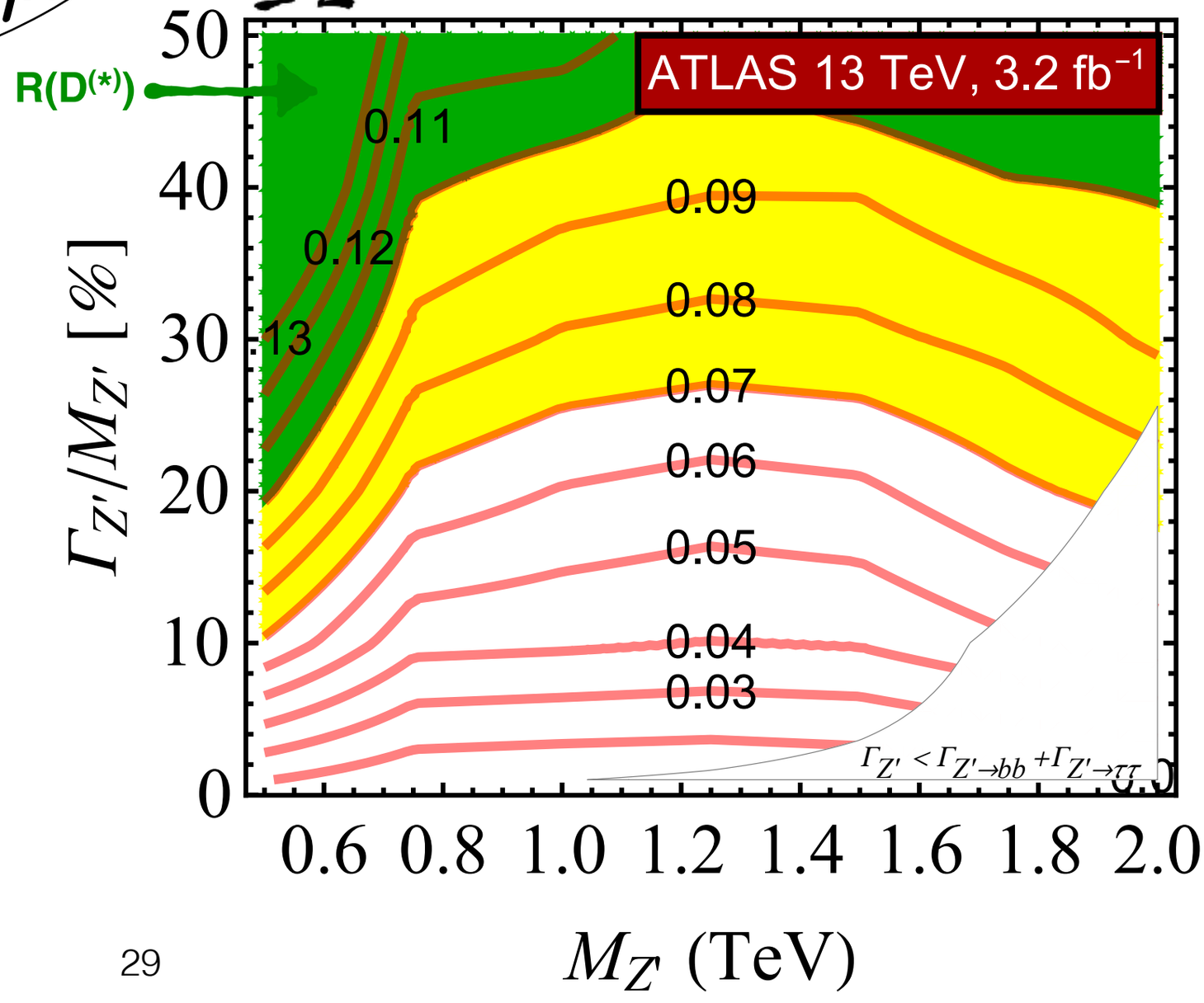
$b \to s\mu\bar{\mu}$ ***neutral***

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

[Faroughy, AG, F. Kamenik]
1609.07138

$|g_b g_\tau| \times v^2/M_{Z'}^2$





$B_s \leftrightarrow \bar{B}_s$ important

'3221' model

~TeV

Extended gauge symmetry

[AG, Robinson, Shakya, Zupan] 1804.04642

$$\mathcal{G} \equiv SU(3)_c \times SU(2)_L \times SU(2)_V \times U(1)'$$

SSB: $\langle H_V \rangle$

$$G_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

3 broken generators

$(1,1,+1)$

W'

$(1,1,0)$

Z'

v_{EW}

R(D$^{(*)}$)

$$\mathcal{L}_{\rm VR} = \frac{C_{ij,k}}{\Lambda^2_{\rm eff}} \left(\bar{u}^i_R \gamma^\mu d^j_R\right) \left(\bar{e}^k_R \gamma_\mu N_R\right)$$

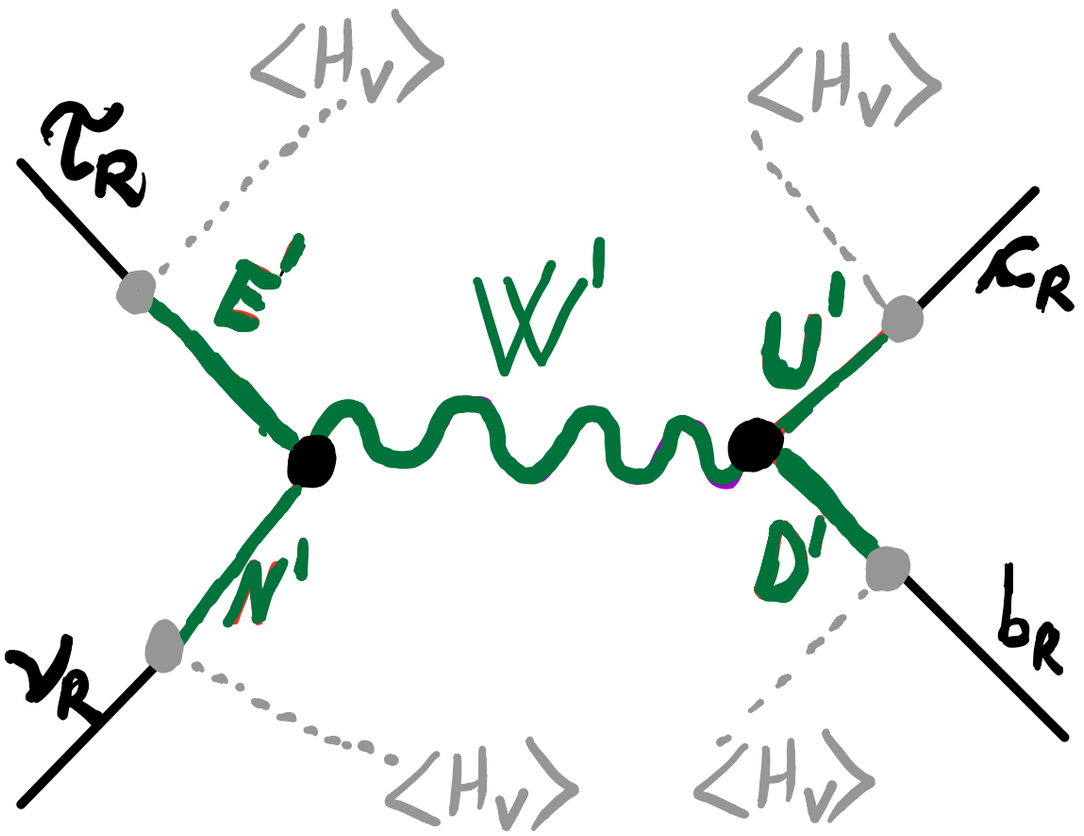
'3221' model

[AG, Robinson, Shakya, Zupan]
1804.04642

Matter content

Field	$SU(3)_c$	$SU(2)_L$	$SU(2)_V$	$U(1)'$
SM-like chiral fermions				
q'^i_L	**3**	**2**	**1**	1/6
ℓ'^i_L	**1**	**2**	**1**	-1/2
u'^i_R	**3**	**1**	**1**	2/3
d'^i_R	**3**	**1**	**1**	-1/3
e'^i_R	**1**	**1**	**1**	-1
ν'^i_R	**1**	**1**	**1**	0
Extra vector-like fermions				
$Q'_{L,R}$	**3**	**1**	**2**	1/6
$L'_{L,R}$	**1**	**1**	**2**	-1/2
Scalars				
H	**1**	**2**	**1**	1/2
H_V	**1**	**1**	**2**	1/2

$$\mathcal{L} \supset \mathcal{L}^{\rm SM}_{\rm Yuk} - \lambda^i_d \bar{Q}'_L H_V d'^i_R - \lambda^i_u \bar{Q}'_L \tilde{H}_V u'^i_R - \lambda^i_e \bar{L}'_L H_V e'^i_R - \lambda^i_\nu \bar{L}'_L \tilde{H}_V \nu'^i_R - M_Q \bar{Q}'_L Q'_R - M_L \bar{L}'_L L'_R + \text{h.c.}$$



FL-23 case:

$$\lambda^i_d \sim (0,0,1) \quad \lambda^i_u \sim (0,1,0)$$

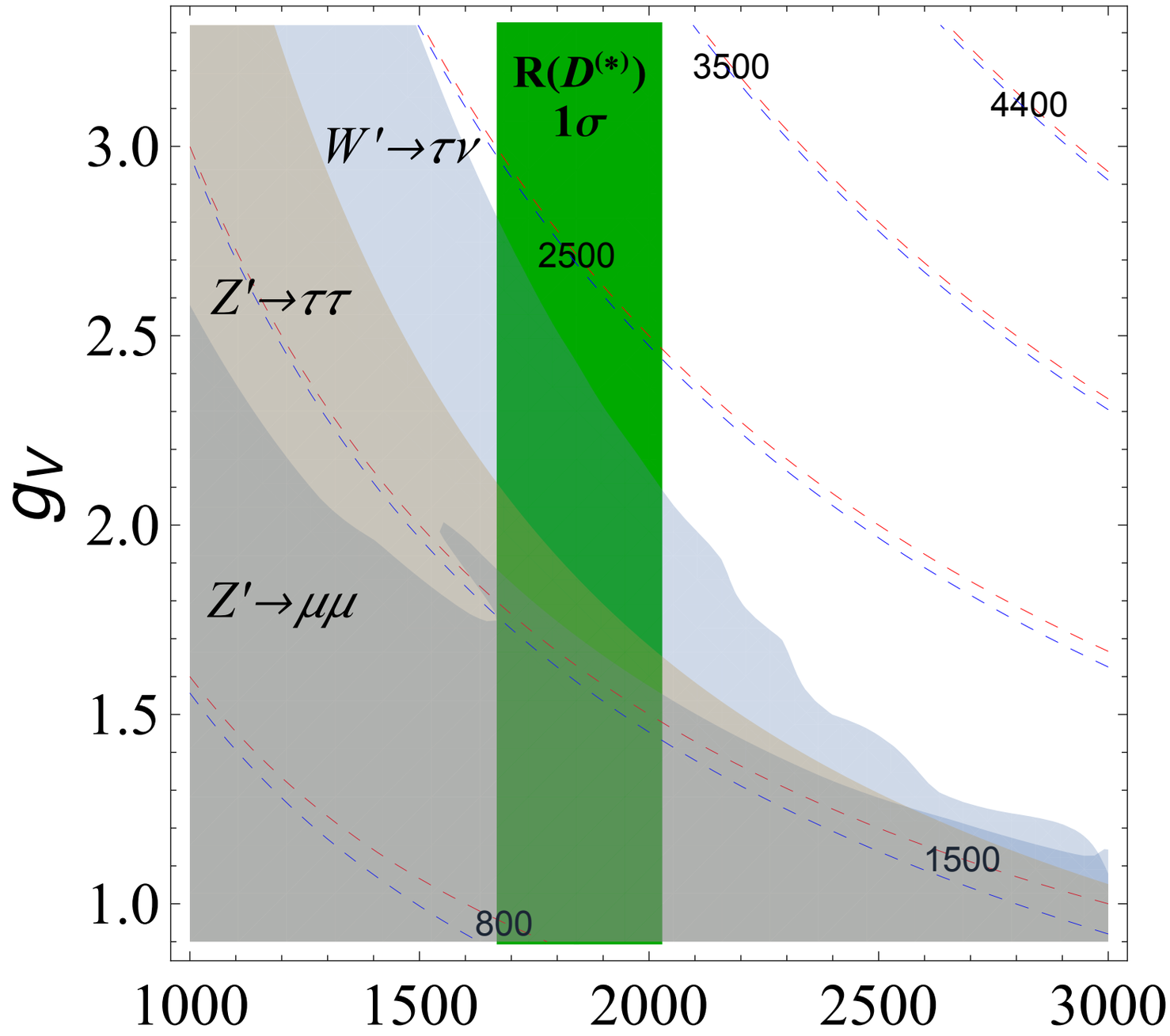
:) *FV Z' couplings uncorrelated!*

:(*Connection to R(K(*))?*
[work in progress]

'3221' model

[AG, Robinson, Shakya, Zupan]
1804.04642

LHC exclusions: FL-23, 2 VL families



Direct searches at the LHC are marching in

SM EFT limits

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

$$\mathcal{L}_{\text{eff}} \supset -\frac{C_{b\tau}}{v^2}(\bar{Q}_3\gamma_\mu\sigma^a Q_3)(\bar{L}_3\gamma^\mu\sigma^a L_3)$$

$$|C_{b\tau}| < 0.15(0.03)$$

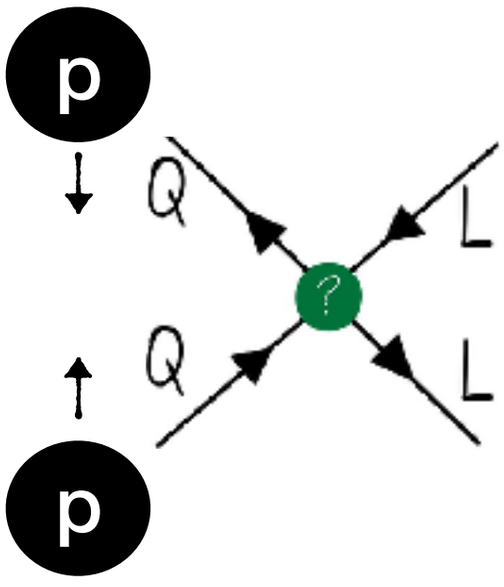
3.2 fb^{-1}(3000 fb^{-1})

[Faroughy, AG, F. Kamenik]

1609.07138

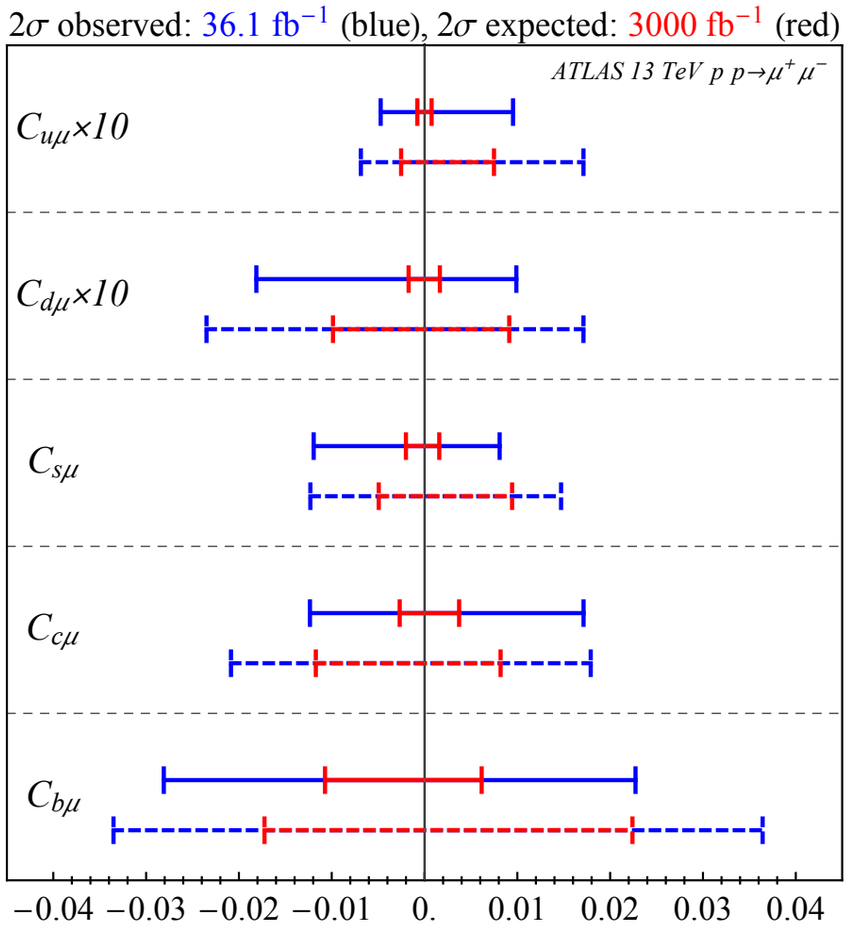
Fit to R(D$^{(*)}$): $C_{b\tau} \sim 0.1$

$$Q_L^i = \begin{pmatrix} V_{ji}^* u_L^j \\ d_L^i \end{pmatrix}$$



SM EFT limits

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



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

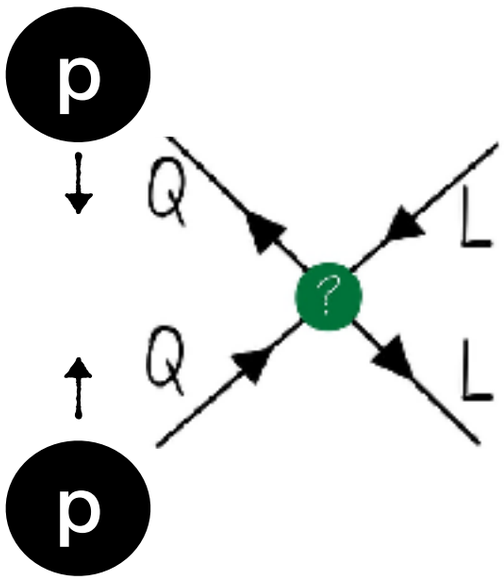
$$\mathbf{C}^{U\mu}_{ij} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad \mathbf{C}^{D\mu}_{ij} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C^*_{bs\mu} \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}.$$

$$\left|\frac{\pi}{\alpha V_{tb}V^*_{ts}} C_{bs\mu}\right| < 100\ (39)$$
$$36.1\ \text{fb}^{-1}\ (3000\ \text{fb}^{-1})$$

Fit R(K$^{(*)}$), set limits on:

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

$$\lambda^u_{bs} > 0.072\ (0.77),\ \ \lambda^u_{bs} < -0.097\ (-0.76)\ ,$$
$$\lambda^d_{bs} > 0.049\ (0.36),\ \ \lambda^d_{bs} < -0.032\ (-0.34)\ ,$$
$$\lambda^s_{bs} > 0.007\ (0.04),\ \ \lambda^s_{bs} < -0.004\ (-0.03)\ ,$$
$$\lambda^c_{bs} > 0.003\ (0.02),\ \ \lambda^c_{bs} < -0.004\ (-0.02)\ ,$$
$$\lambda^b_{bs} > 0.002\ (0.01),\ \ \lambda^b_{bs} < -0.002\ (-0.006)\ .$$



[AG, Marzocca] 1704.09015