LEPTOQUARKS AND THEIR HIGH-PT SEARCHES

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In collaboration with
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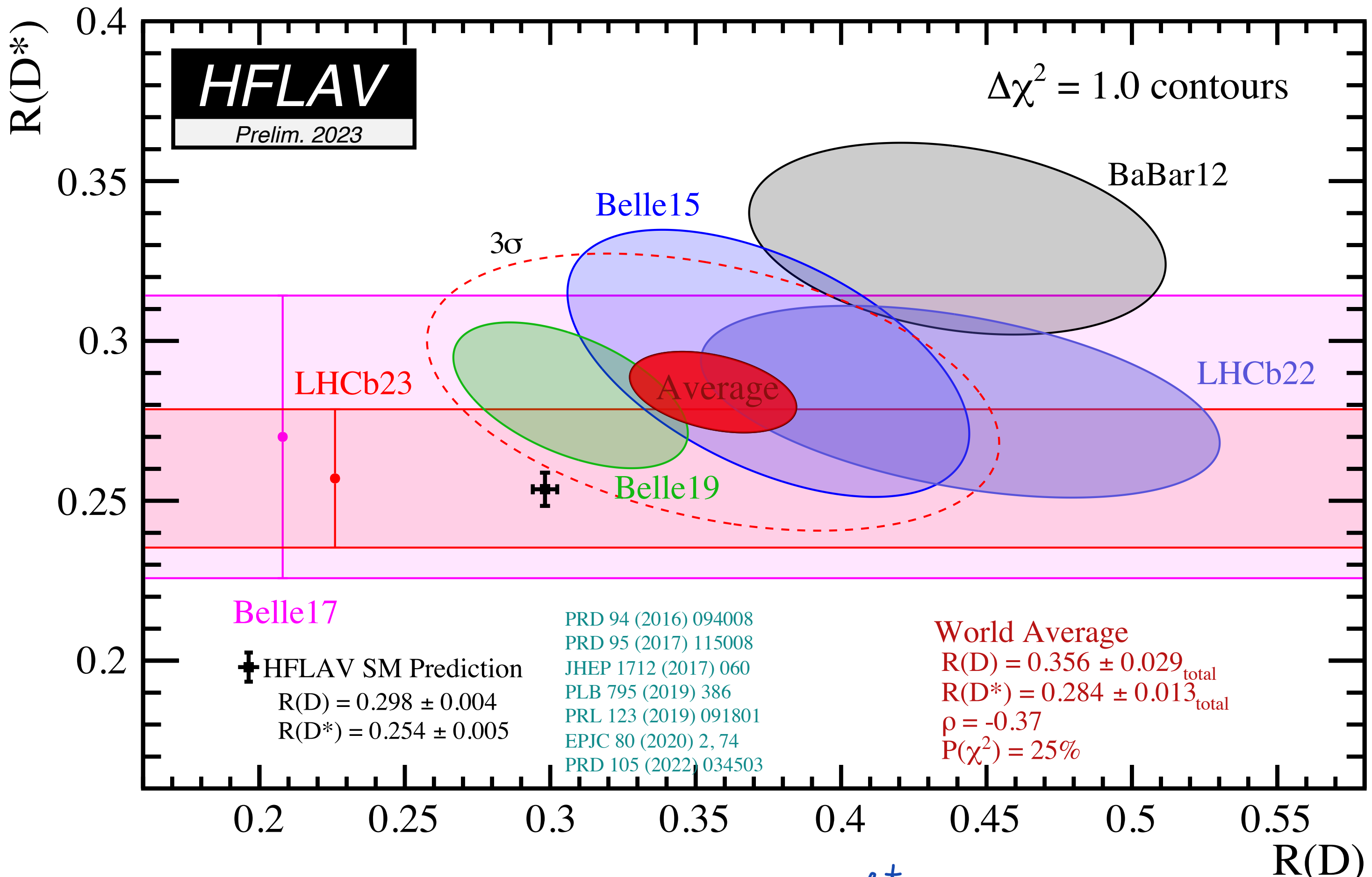
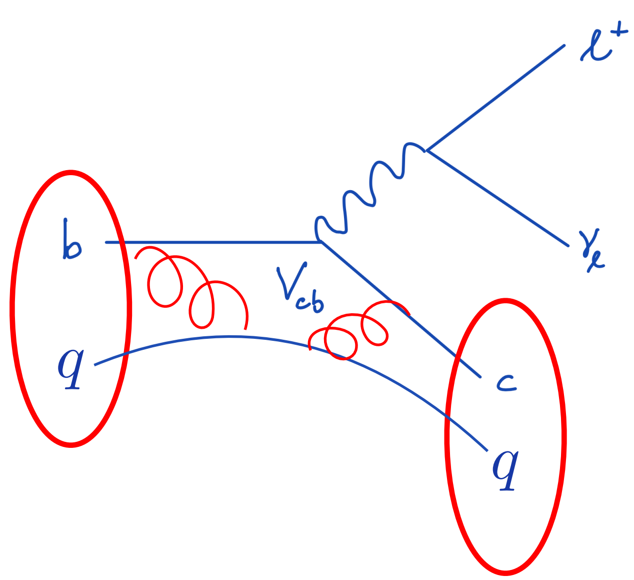
LEPTON FLAVOUR UNIVERSALITY



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}l\nu)}$$

- Semi-τ against semi-e, μ ($R_{D^{(*)}}^{(\mu/e)}$ consistent with 1)
- Crucial input by lattice QCD calculations
- Partial cancellation of form-factor uncertainties
- $R_{J/\psi}$ and R_{Λ_c} do not change the global picture

☞Talk by Florian Reiss



~3σ discrepancy between the SM prediction and WA by BaBar, Belle and LHCb*

Gauge couplings universality, $g_e = g_\mu = g_\tau$

Higgs couplings break LFU $m_e \ll m_\mu \ll m_\tau$

*Recent form factor calculation [Harrison, Davies 2304.03137] indicates tension with experimental spectra in $B \to D^* l\nu$

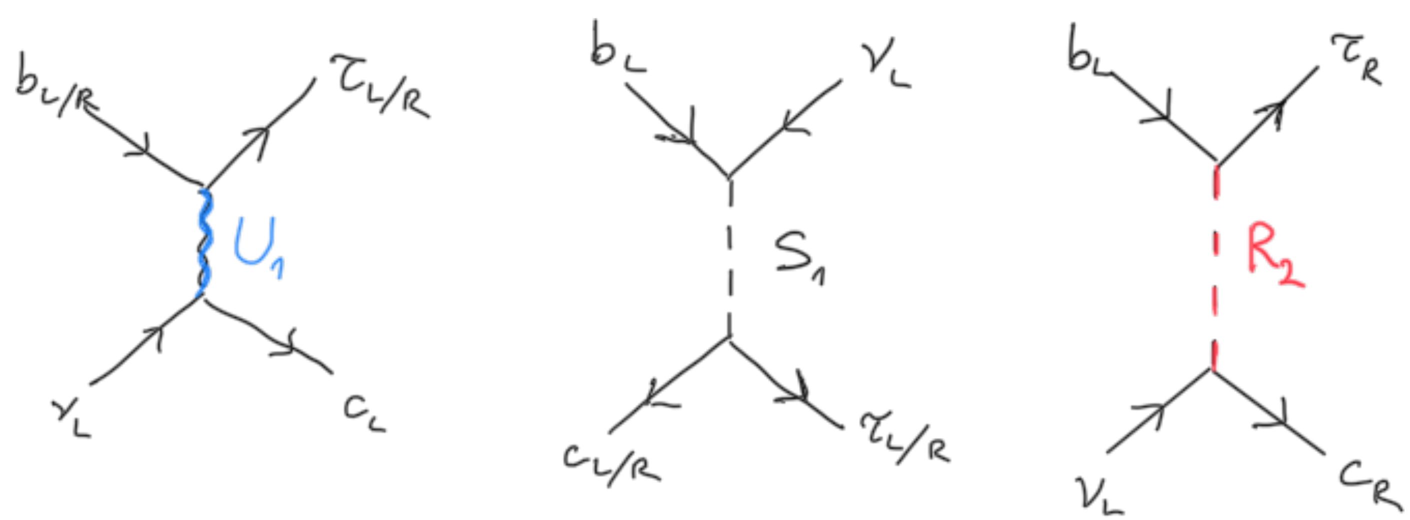
LEPTOQUARKS

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

[Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, 2103.12504]

- Each LQ state generates particular Lorentz structure of the amplitude

- No tree-level meson mixing constraints



Q = 2/3 Q = 1/3 Q = 2/3

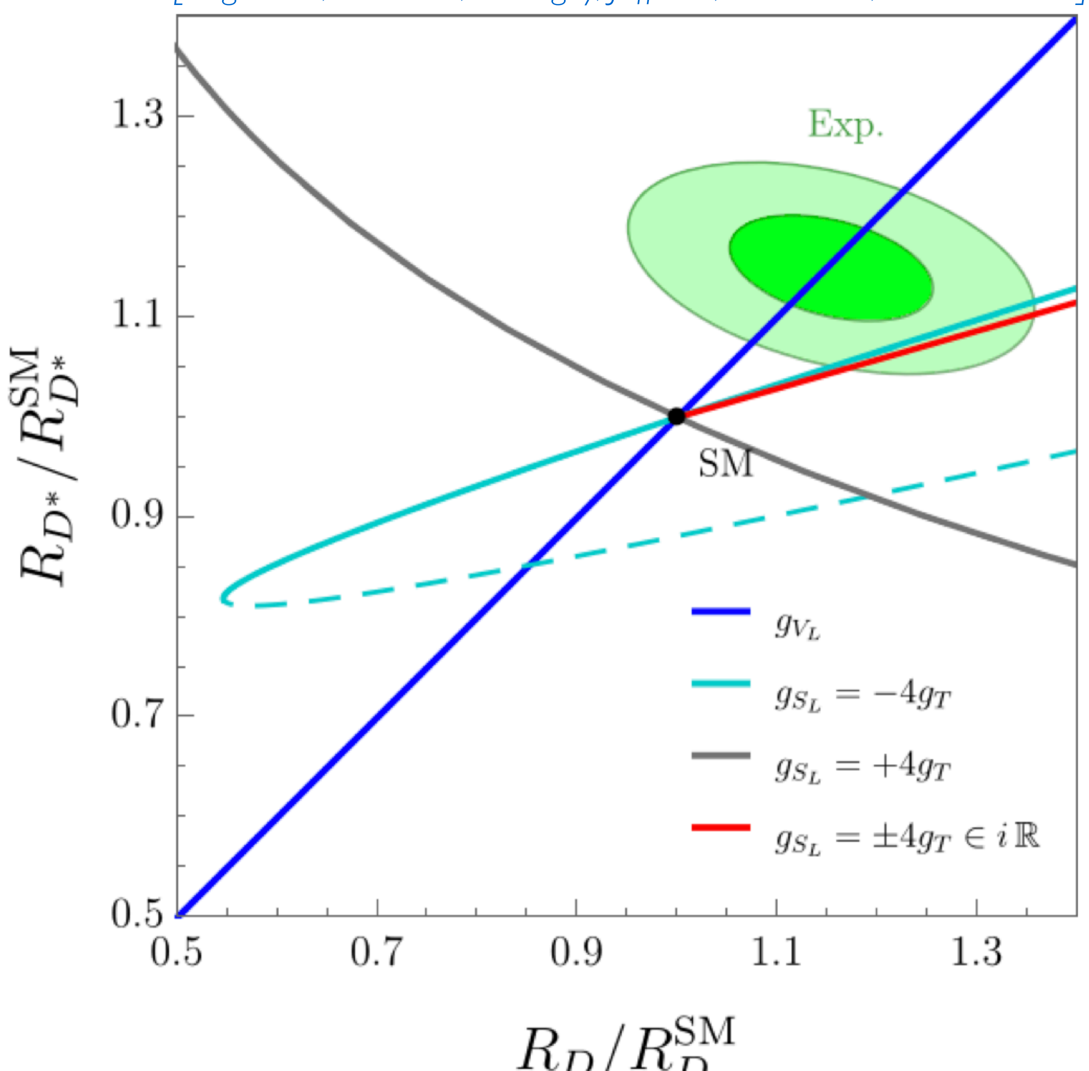
- Leptoquark charge Q = 2/3 or 1/3.
- Q = 1/3 can also couple as $S_1 \bar{u}\bar{d}$ and violate baryon and lepton number

LEPTON FLAVOUR UNIVERSALITY

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+g_{V_L})(\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu_L) + g_{V_R}(\bar{c}_R\gamma^\mu b_R)(\bar{\ell}_L\gamma_\mu\nu_L)$$
$$+g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L)$$
$$+g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)]$$

Weak effective theory

[Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, 2103.12504]



$R_{D(*)}$ may require a CPV phase of new couplings

- Effective couplings are naturally implemented by tree-level leptoquark exchanges

$U_1(3,1,2/3)$ vector LQ ☞Talk by Ben Stefanek

$S_1(\bar{3},1,1/3)$ scalar [Crivellin, Muller, Otai, 1703.09226] + …

$R_2(\bar{3},2,7/6)$ scalar [Becirevic et al, 2206.09717] …

- U_1 requires UV setting to provide its mass
- Scalar LQ models are renormalizable, can be embedded in GUT models

LEPTON FLAVOUR UNIVERSALITY

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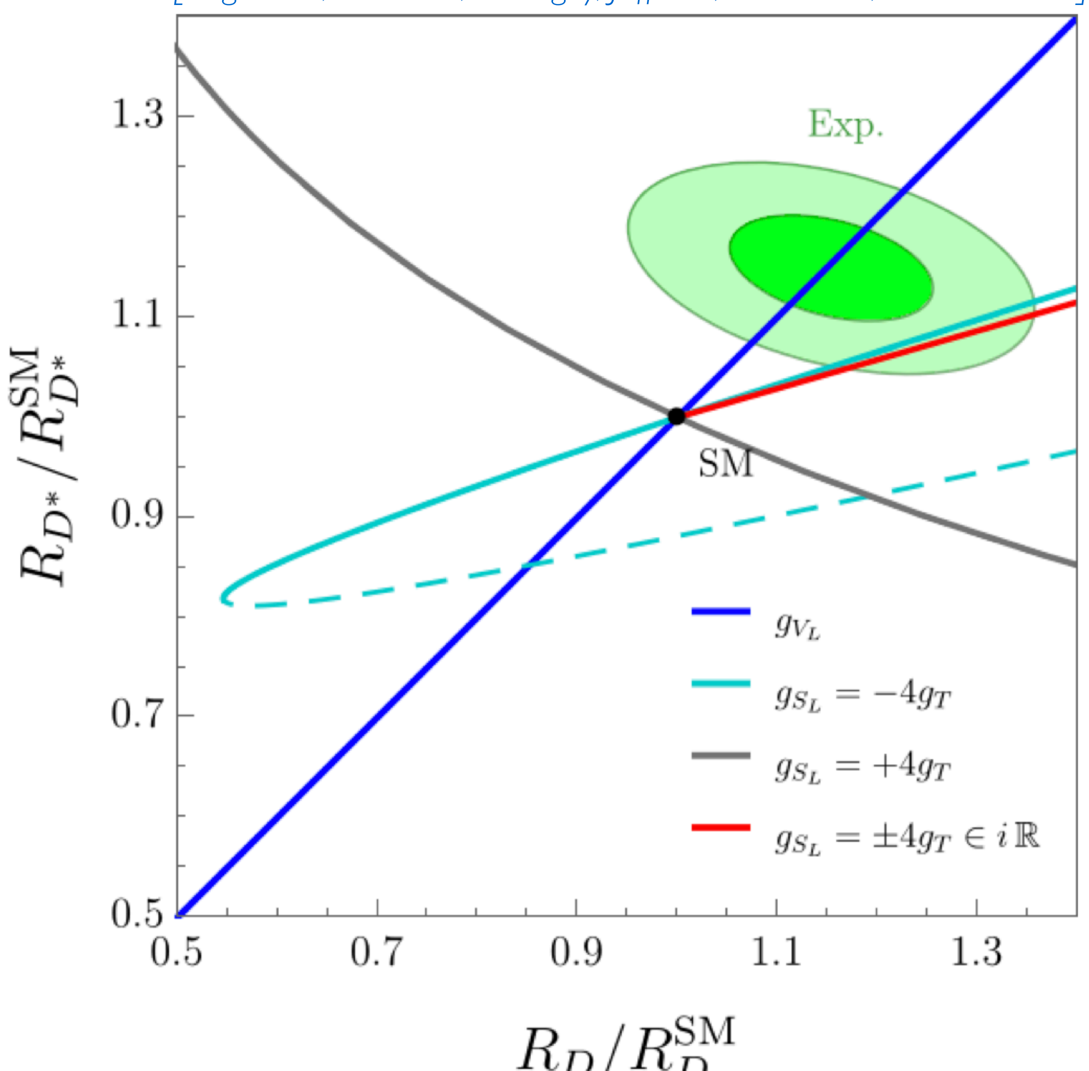

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THIS TALK

- U_1 requires UV setting to provide its mass
- Scalar LQ models are renormalizable, can be embedded in GUT models

MODEL WITH R_2 AND S_3

[Bečirević, Doršner, Fajfer, Faroughy, NK, O. Sumensari, 1806.05689]
[Becirevic, Doršner, Fajfer, Faroughy, Jaffredo, NK, Sumensari, 2206.09717]

$$\mathcal{L} \supset Y_R^{ij} \bar{Q}_i \ell_{Rj} R_2 + Y_L^{ij} \bar{u}_{Ri} R_2{}^T i\tau_2 L_j + \left(Y_L^{(S_3)}\right)^{ij} \bar{Q}_i^C i\tau_2 (\tau_k S_3^k) L_j$$

$$Y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix} \qquad Y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

d aligned

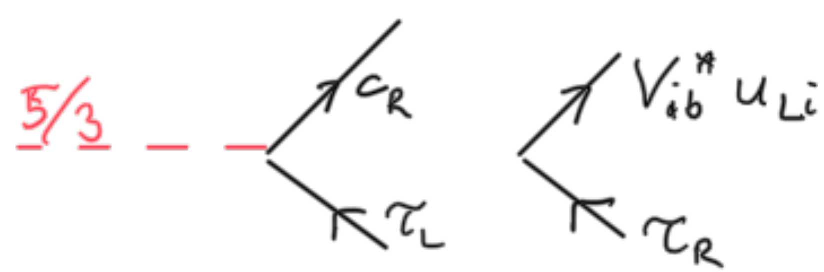
e aligned

$m_{S_3} \to m_{\mathrm{GUT}}$

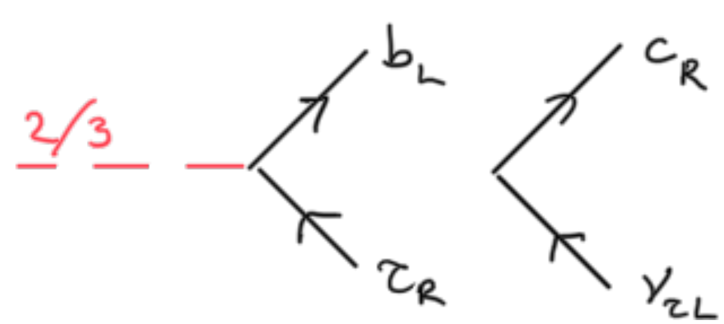
No longer needed after LHCb update of $R_{K^{(*)}}$

- 3 parameters (mass and 2 Yukawa couplings)
- Small impact on 1st and 2nd generation flavour physics

$$R_2 = \begin{pmatrix} R_2^{5/3} \\ R_2^{2/3} \end{pmatrix}$$

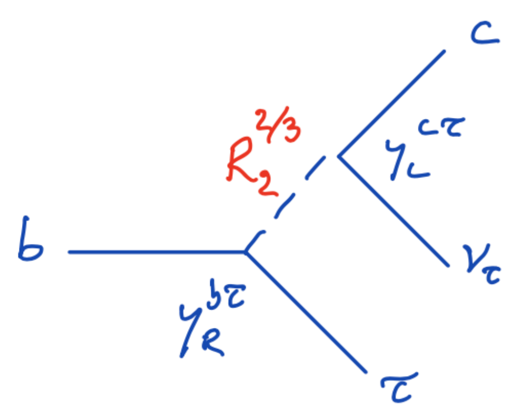


small up-quark FCNC (since Y_R is down-aligned)



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

MODEL WITH R_2 FOR $R_{D^{(*)}}$



$$g_{S_L}(\Lambda) = 4\, g_T(\Lambda) = \frac{y_L^{c\tau}\; y_R^{b\tau\,*}}{4\sqrt{2} G_F V_{cb}\, m_{R_2}^2}$$

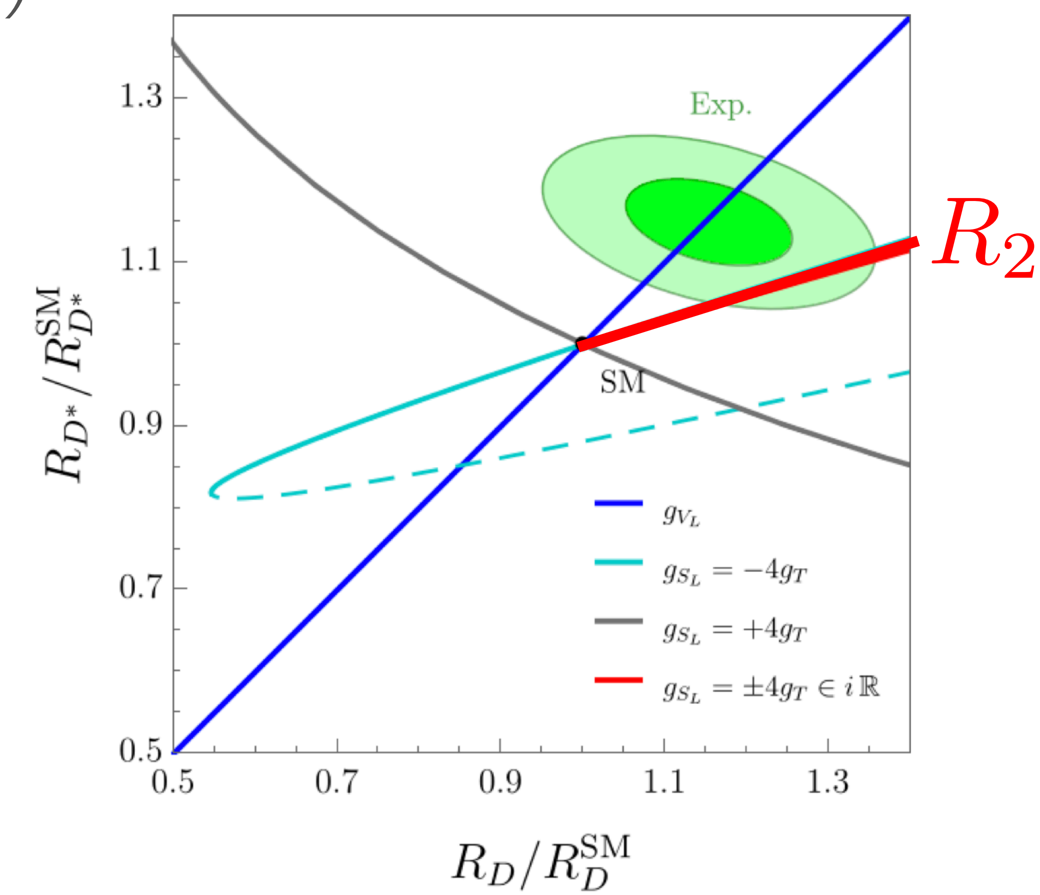
QCD running

$$\vec{g}(\mu_b) = U(\mu_b, m_{R_2})\vec{g}(\Lambda)$$

$$g_{S_L}(\mu_b) = 8.1 g_T(\mu_b)$$

$$\frac{R_D}{R_D^{\rm SM}} \approx 1 + 1.1|g_{S_L}|^2 + 0.83|g_T|^2 + 1.5\Re(g_{S_L}) + 1.1\Re(g_T)$$

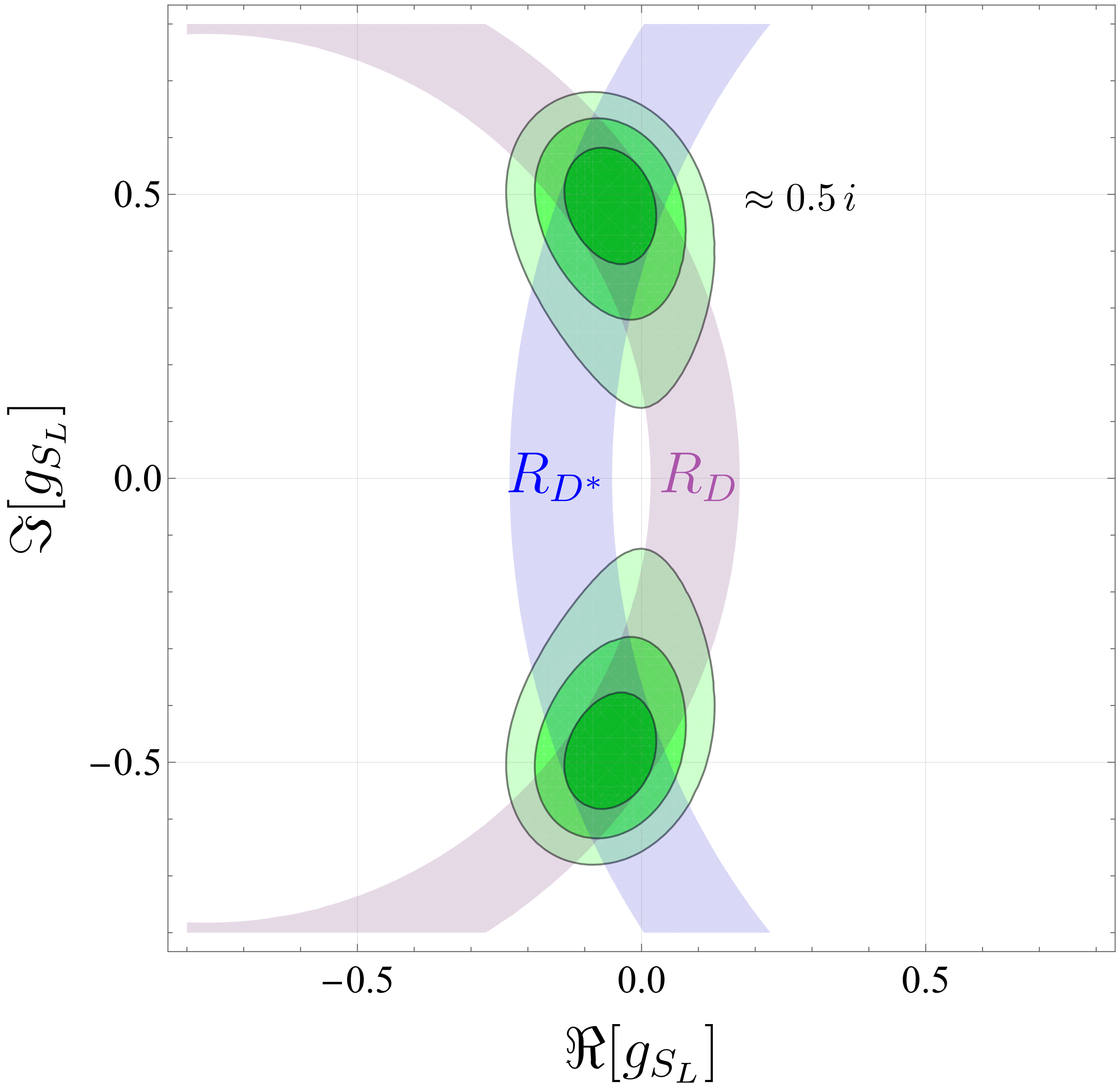
$$\frac{R_{D^*}}{R_{D^*}^{\rm SM}} \approx 1 + 0.047|g_{S_L}|^2 + 17|g_T|^2 - 0.14\Re(g_{S_L}) - 5.1\Re(g_T)$$



[Feruglio, Paradisi, Sumensari, 1806.10155]

- $g_{S_L}(\mu_b)$ is the only relevant parameter for $R_{D^{(*)}}$. It must be complex since the interference terms with the SM contribution have opposite signs for R_{D^*} and R_D
- Need large imaginary part of $g_{S_L}(\mu_b)$

MODEL WITH R_2 FOR $R_{D^{(*)}}$



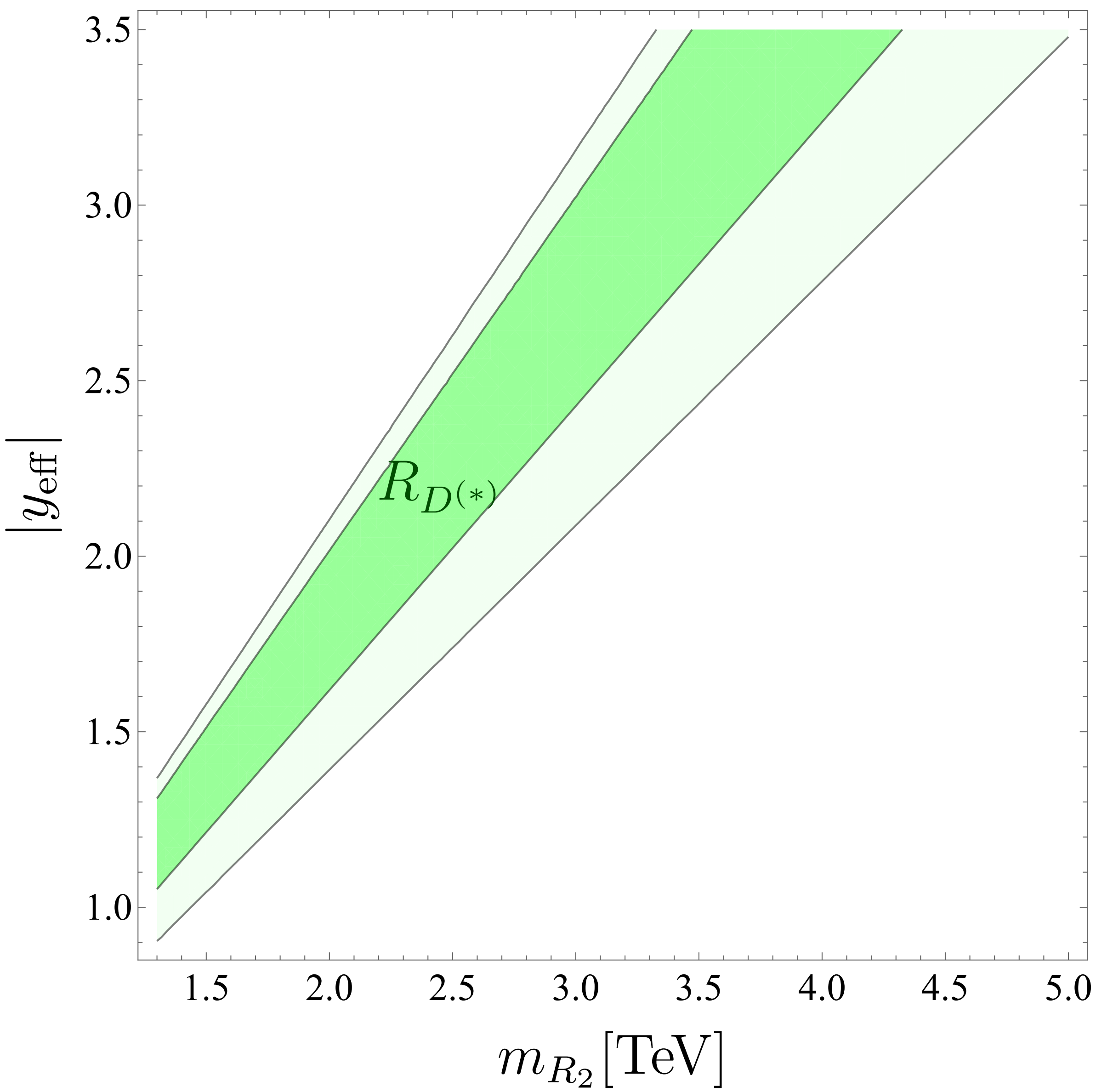
$$g_{S_L}(\mu_b) = 8.1 g_T(\mu_b) = 1.6|_{\rm RG} \times \frac{y_R^{b\tau *} y_L^{c\tau} v^2}{4 m_{R_2}^2 V_{cb}}$$

- Can we probe this in high pT processes or in precision observables?
- Useful phenomenological parameters

$$y_{\rm eff} \equiv \sqrt{y_R^{b\tau *} y_L^{c\tau}}, \qquad m_{R_2}$$

$$\frac{y_{\rm eff}^2}{m_{R_2}^2} \approx 0.8\, i/\mathrm{TeV}^2$$

MODEL WITH R_2 FOR $R_{D(*)}$

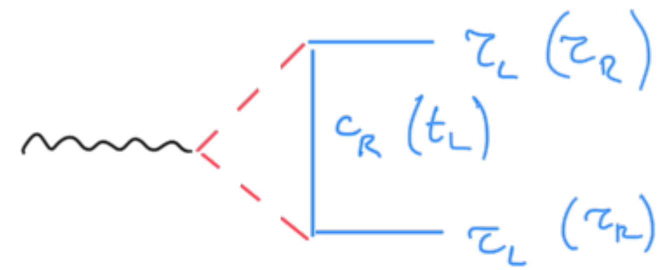


$$\frac{g_A^\tau}{g_A^e} = 1.0019 \pm 0.015$$

$$\frac{g_V^\tau}{g_V^e} = 0.959 \pm 0.029$$

[LEP EWWG, hep-ex/0509008]

LEP constraints on $Z \to \tau\tau$



[Arnan, Becirevic, Mescia, Sumensari 1901.06315]

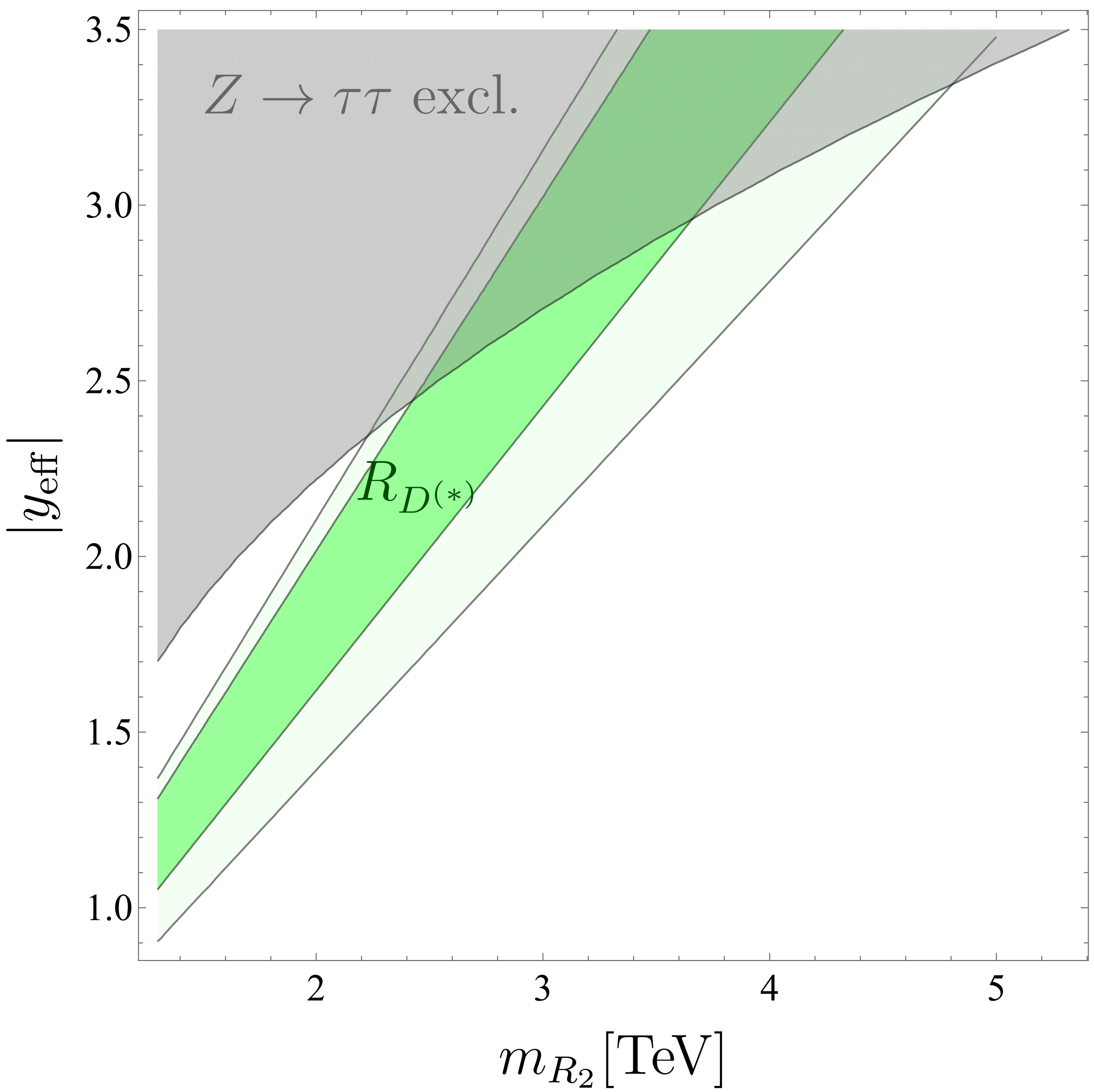
$Z \to \tau\tau$ and $R_{D^{(*)}}$ scale differently with Yukawa couplings and with mass.

Perfect opportunity for high-pT searches

- mass bounded from above, $m_{R_2} < 4\,\mathrm{TeV}$
- large coupling, perturbativity breaking is prevented by $Z \to \tau\tau$

? CP violation

MODEL WITH R_2 FOR $R_{D^{(*)}}$



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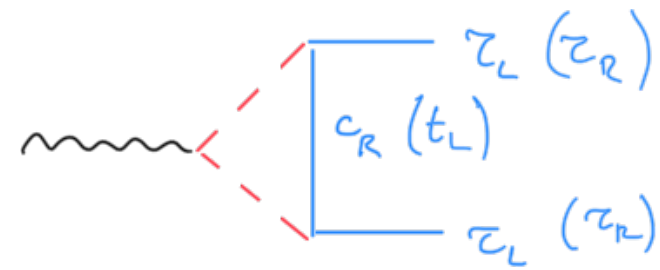

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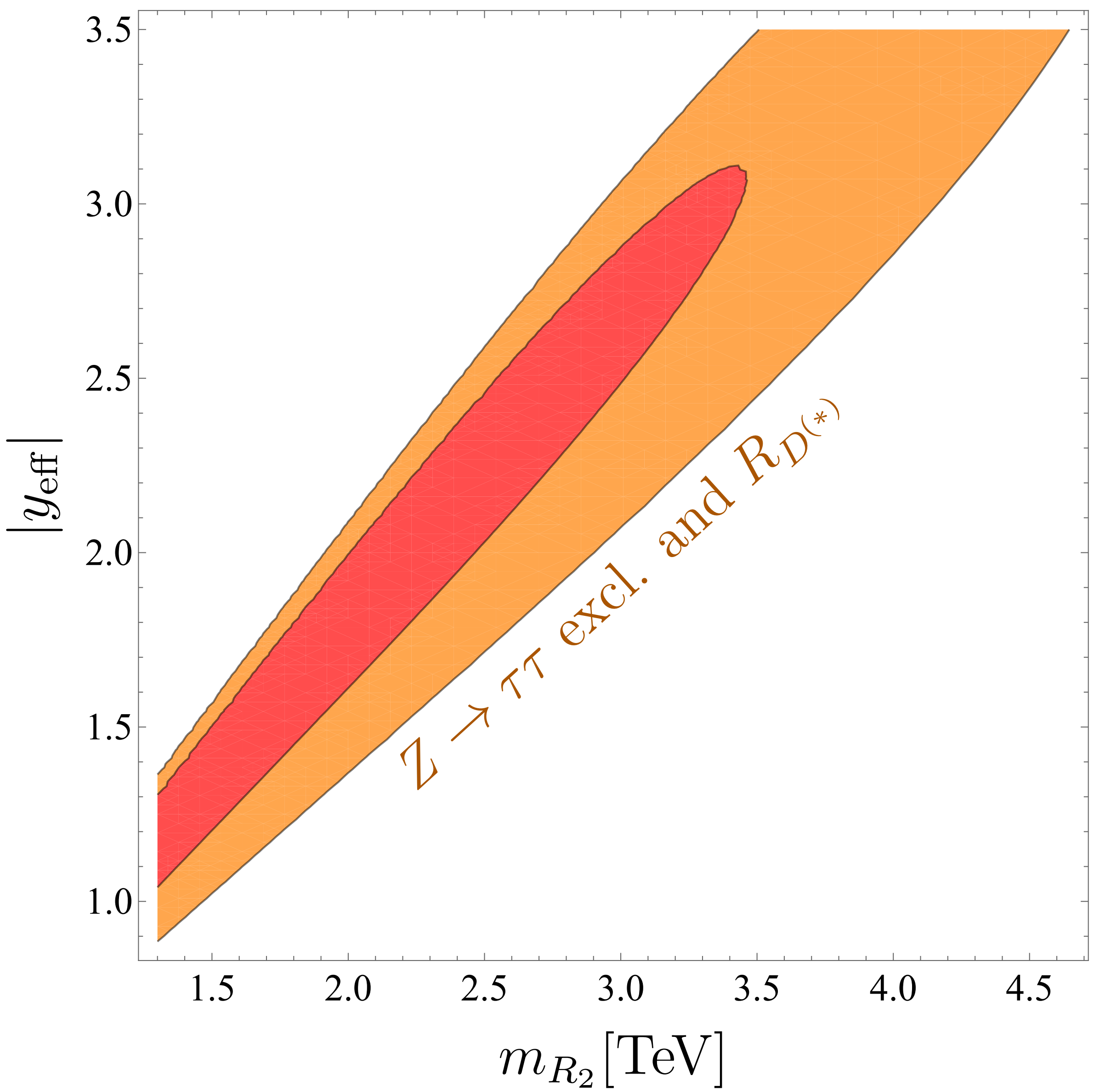

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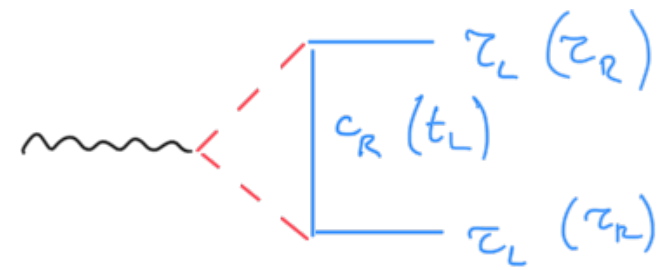

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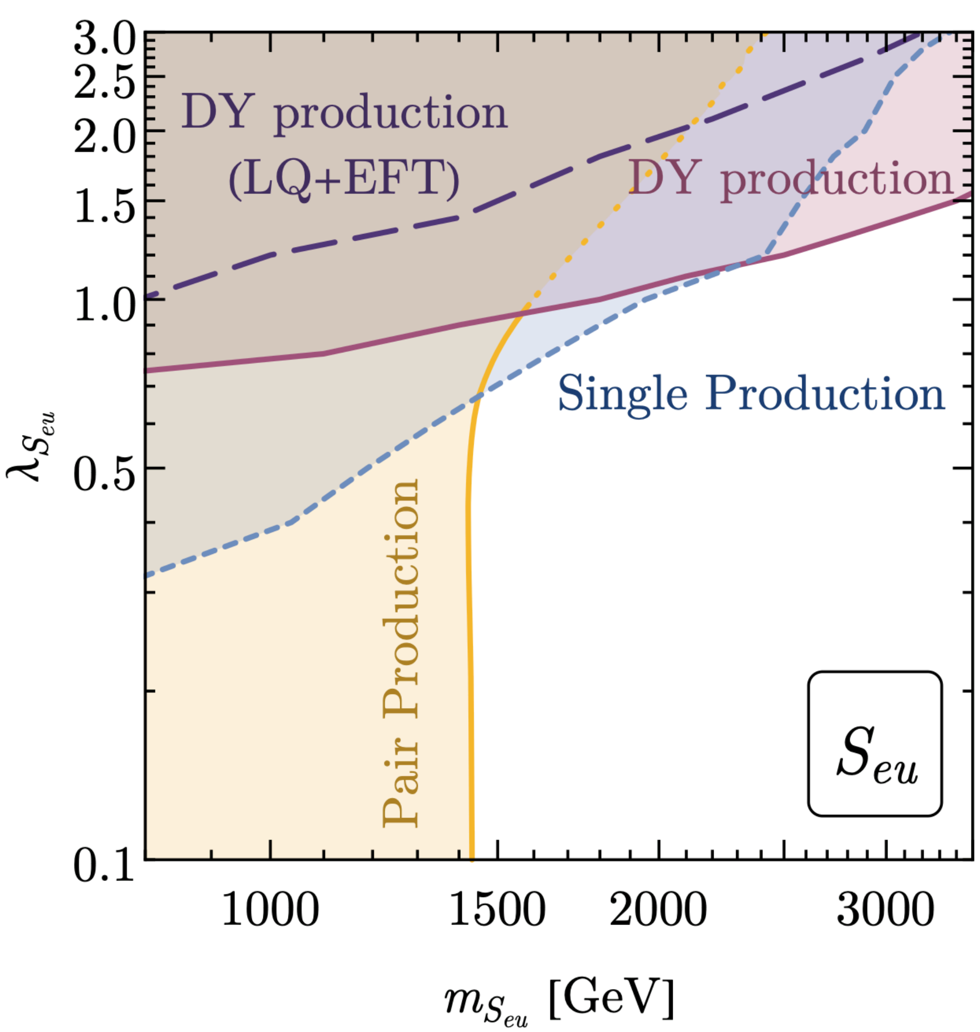
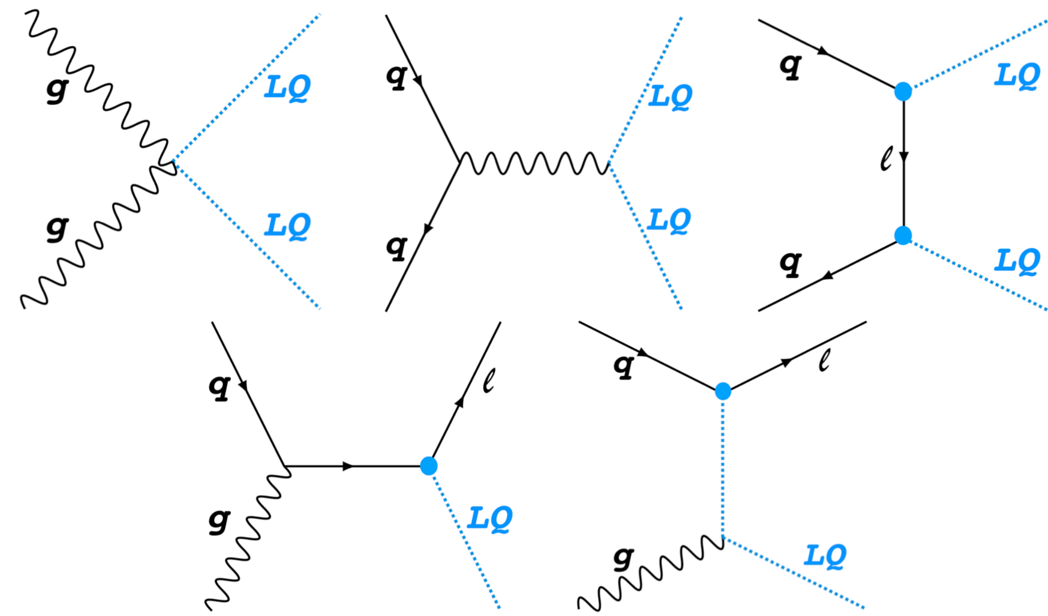
HIGH-PT SEARCHES FOR LQS

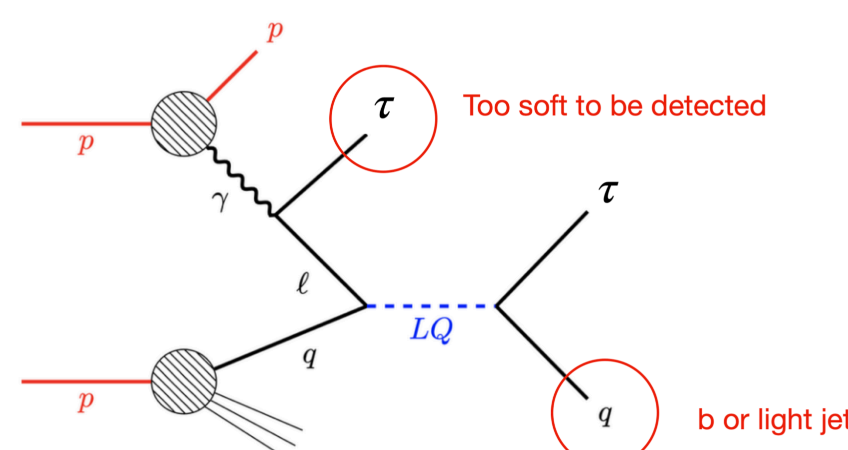
- Different mass vs. Yukawa sensitivities:
  - LQ pair production (2j 2l final state)
  - single LQ production (2l j final state, also s-channel)
  - Drell-Yann dilepton and mono-tau (2l)



[Schmaltz, Zhong, 1810.10017.]



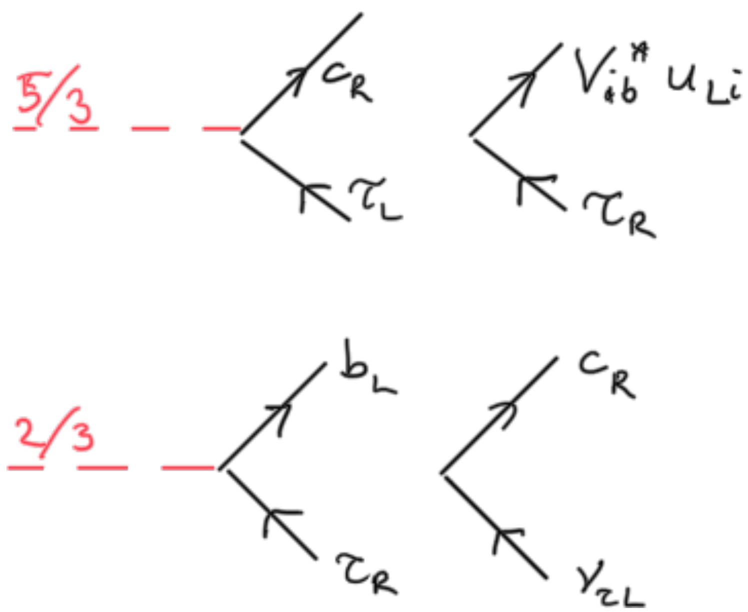
[Dorsner, Greljo, 1801.07641]



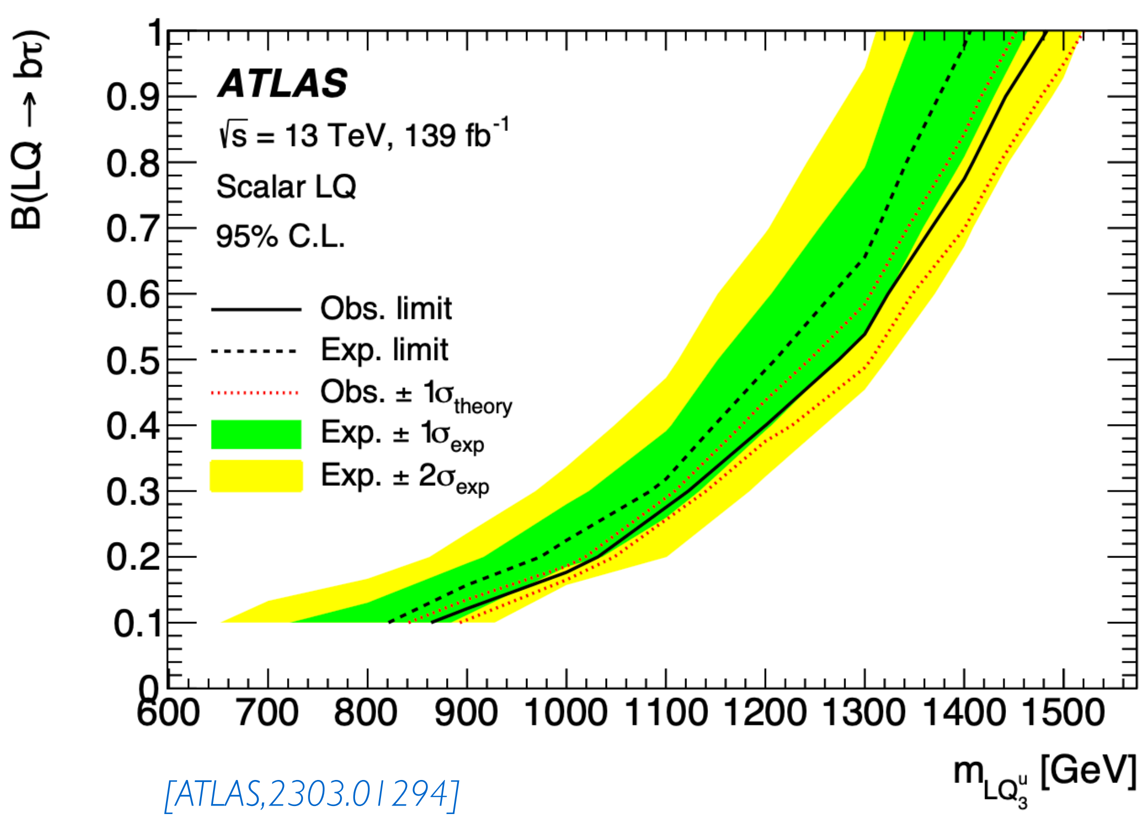
☞Talks by Halil Saka, Giovanni Padovano

HIGH-PT SEARCHES FOR R_2

- Pair production
  - LQ pair production (2j 2l final state)



> - doublet nature of R_2 implies
>
> $$\mathcal{B}(R_2 \to c\tau) = \mathcal{B}(R_2 \to c\nu) \propto |y_L^{c\tau}|^2$$
> $$\mathcal{B}(R_2 \to b\tau) = \mathcal{B}(R_2 \to t\tau) \propto |y_R^{b\tau}|^2$$
>
> - distinct feature from other LQ representations



[ATLAS,2303.01294]

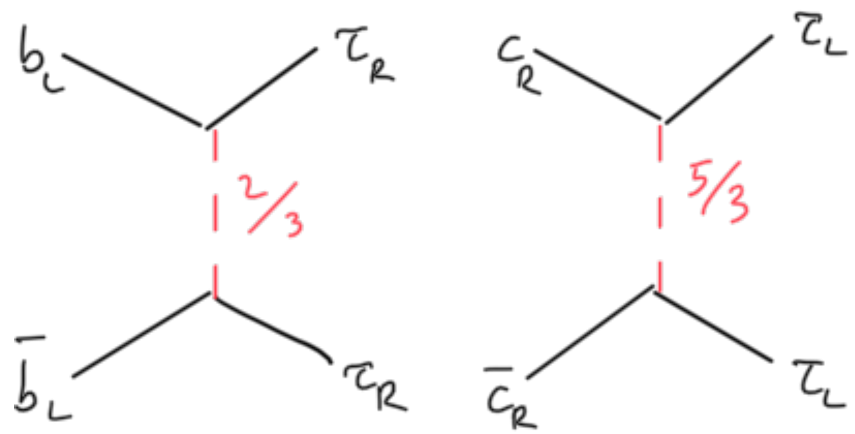
> - in our case we have to consider $m_{R_2} > 1.3\,\text{TeV}$ to be safe from pair production constraints
> - most important constraints are from Drell-Yann dileptons: $\tau\tau$ and $\tau\nu$ final states

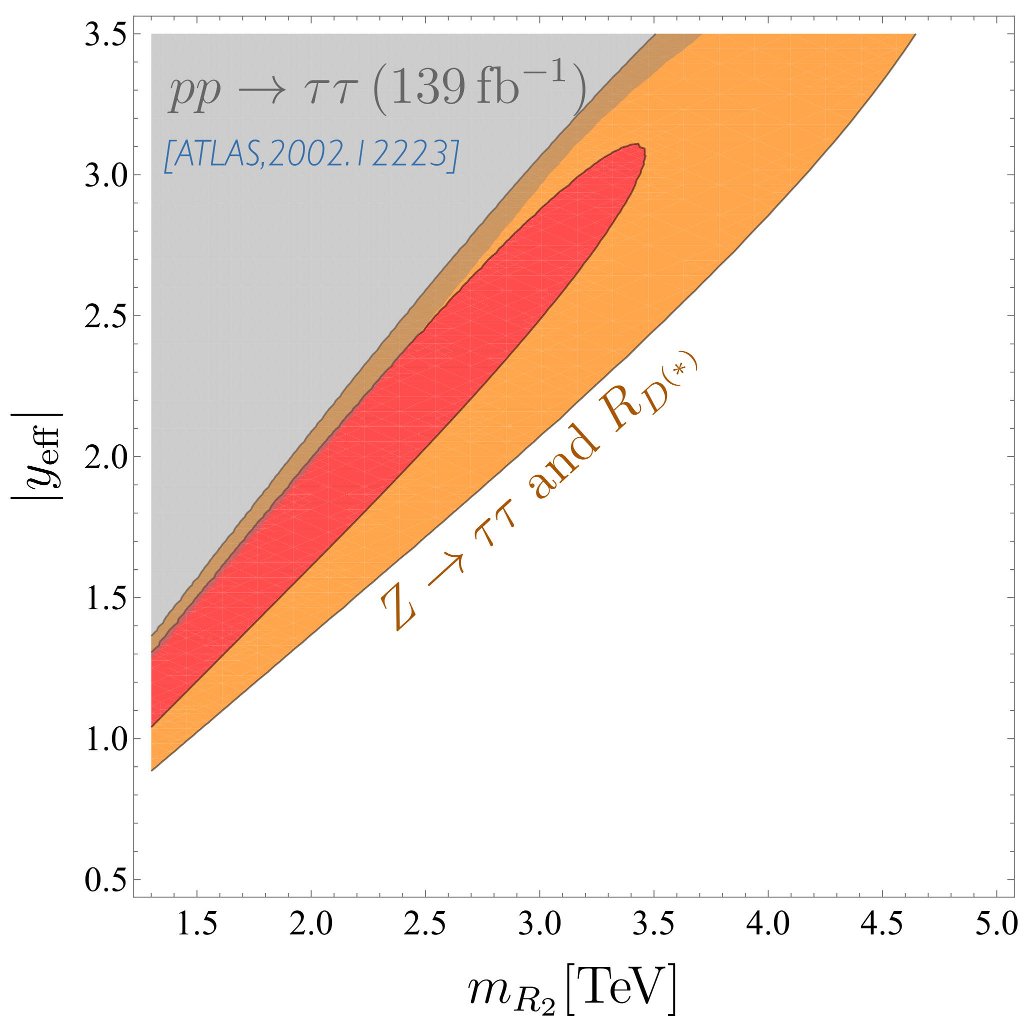
HIGH-PT SEARCHES FOR R_2

- Di-τ constraints ($pp \to \tau^+\tau^-$)

[Faroughy, Kamenik, Greljo, 1609.07138]

[Bečirević, Doršner, Fajfer, Faroughy, NK, O. Sumensari, 1806.05689]

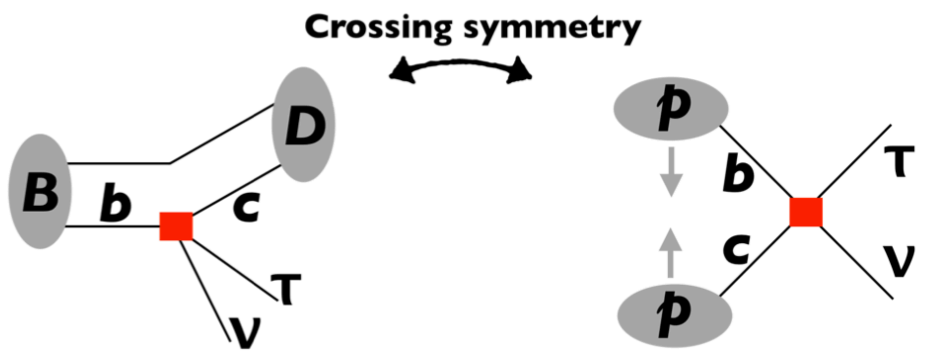




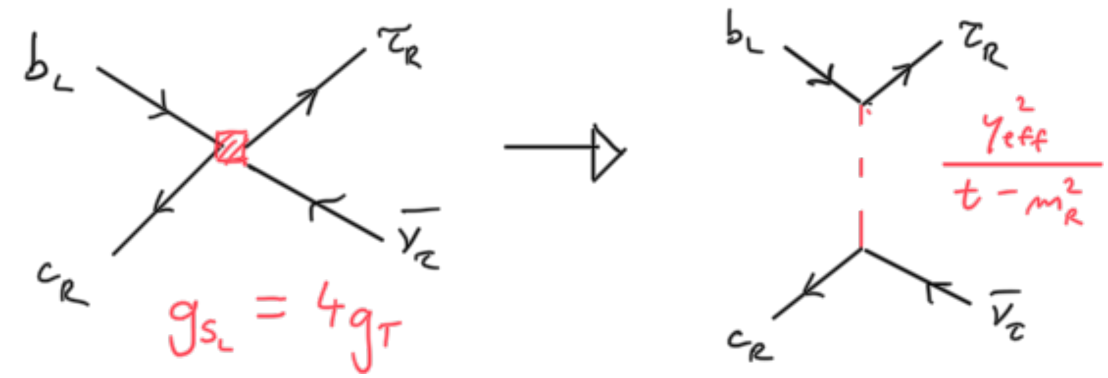
- from low energies $\frac{y_{\rm eff}^2}{m_{R_2}^2} \approx 0.8\, i/\mathrm{TeV}^2$
- at least one of the diagrams will have coupling O(1)
- no sensitivity to CPV phase - tiny interference effects
- Recast of $\tau\tau$ resonance search

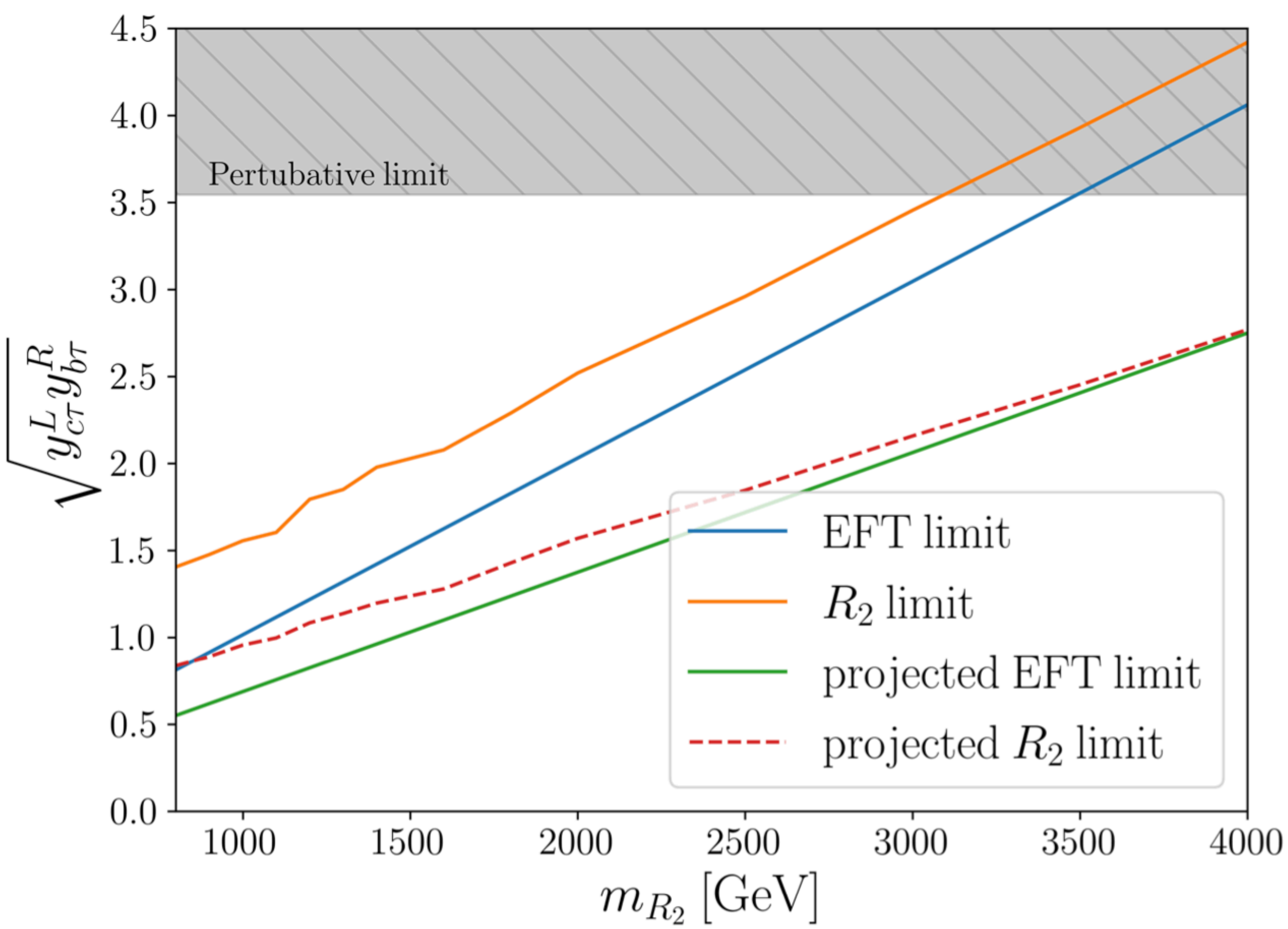
HIGH-PT SEARCHES FOR R_2

- Mono-τ constraints ($pp \to \tau^+\nu$)



[Greljo,Camalich,Ruiz-Alvarez,1811.07920]





[F. Jaffredo,2112.14604]

based on [ATLAS-CONF-2021-025]

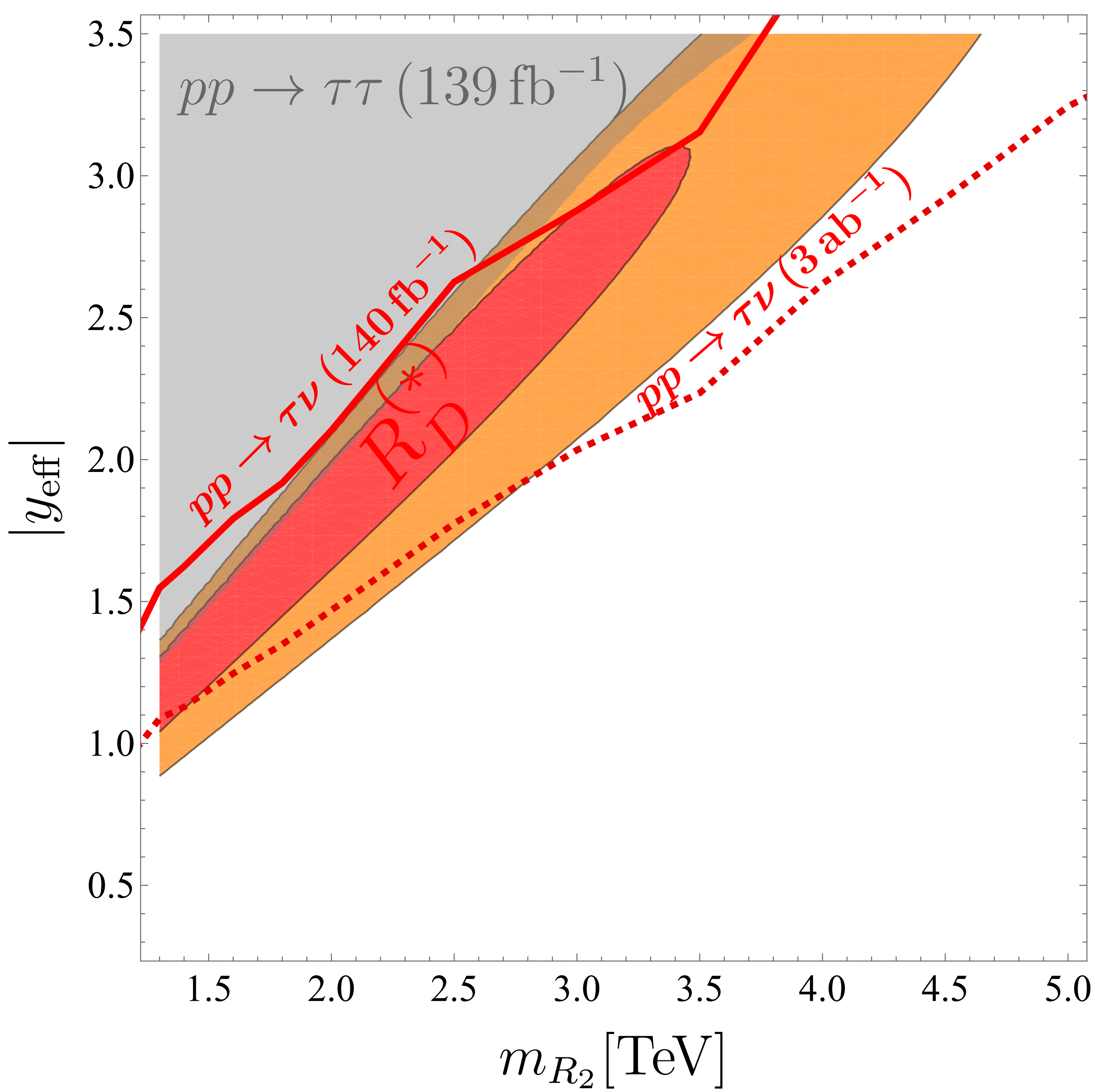
$$\hat{\sigma}(\hat{s}) \simeq \frac{|y^R_{b\tau}|^2 |y^L_{c\tau}|^2}{192\pi m^2_{R_2}} \left[\frac{x+2}{x(1+x)} - \frac{2\log(1+x)}{x^2} \right],$$

- the EFT description is not valid at the LHC for masses of few TeV
- full model (dynamic LQ) results in weaker bounds

$$|g_{S_L}|_{\text{EFT}} < 0.51$$

$$|g_{S_L}|_{\text{full}} < 0.88$$

HIGH-PT SEARCHES FOR R_2



based on [ATLAS-CONF-2021-025]

- Mono-τ constraints and di-τ constraints effectively probe R_2 leptoquark

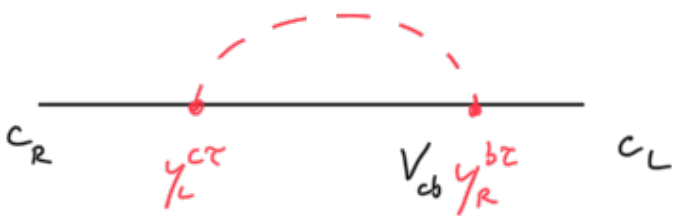
- What about large CPV?

$$\arg y_{\text{eff}} \approx \pi/4$$

CPV OBSERVABLES

- How to test large CPV phase ?

  - Charm quark electric dipole moment induces neutron EDM [Dekens, de Vries, Jung, Vos, 1809.09114]



$$d_c = 0.1 \times Q_c\, e\, m_c \frac{1}{m_{R_2}^2} \mathrm{Im}\left[V_{cb}^* \, y_R^{b\tau\,*}\, y_L^{c\tau}\right]$$

$$\longrightarrow \mathcal{L}_{\text{dipole}} = -\frac{i d_f}{2} \bar{c}\sigma^{\mu\nu}\gamma_5 c\, F_{\mu\nu}$$

(neutron charm tensor charge)

$$\longrightarrow \langle N|\bar{c}\sigma^{\mu\nu}\gamma_5 c|N\rangle = g_T^c\, \bar{u}_N \sigma^{\mu\nu}\gamma_5 u_N$$

[C. Alexandrou, et al, 1909.00485]

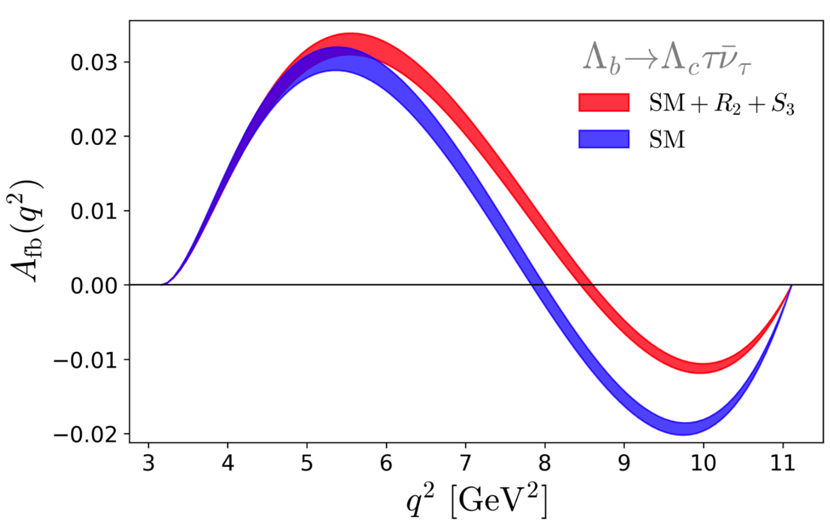
$$\longrightarrow d_n = g_T^c\, d_c$$

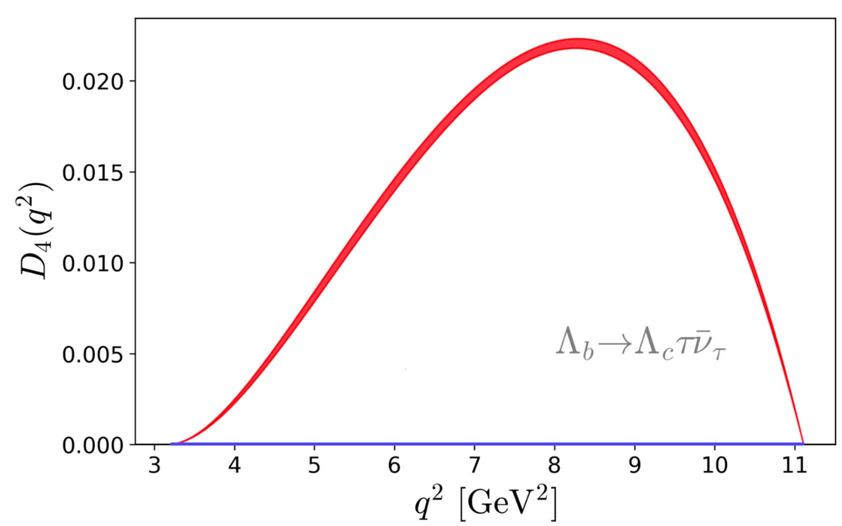
$$d_n < 1.8 \times 10^{-26}\, e\,\text{cm} \qquad \Longrightarrow |\Im(g_{S_L})| < 0.76$$

[PSI, 2001.11966]

Improving precision of the lattice result could probe relevant range $|\Im(g_{S_L})| \approx 0.5$

  - Angular spectra of $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\nu$





- That is in contrast to U_1 LQ, where these features are absent.

[Becirevic et al, 2206.09717]

SUMMARY

- Leptoquarks are most suitable candidates to address the LFU anomalies observed in $b \to c\ell\nu$ transitions
- Among S_1, U_1, R_2 states R_2 leptoquark stands out since it lives in the non-interfering CPV region of parameters
- Large couplings are sitting in $b\tau, t\tau$ and $c\tau$ flavours and do not show in down-quark FCNCs
- LQ pair production constraints sets the lower bound $m_{R_2} > 1.3\,\text{TeV}$ whereas LEPZ $\to \ell\ell$ studies require $m_{R_2} \lesssim 4\,\text{TeV}$
- Mono-τ and di-τ measurements in the future (HL)LHC will efficiently probe the relevant parameter space. Future high-pT searches have discriminating power between LQ states.
- CPV effects are dominated by neutron electric dipole moment.

Thanks for your attention!