Hunting for Leptoquarks

Felix Wilsch

Institute for Theoretical Particle Physics and Cosmology
RWTH Aachen University

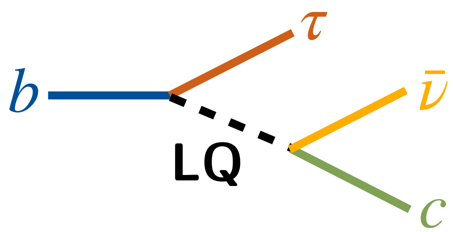
12th Edition of the Large Hadron Collider Physics Conference — BSM-1 TeV Scale Session
Northeastern University, Boston

June 4, 2024

Flavor anomalies hinting at leptoquarks (LQs)?

Hints for NP in $b \to c\tau\bar{\nu}$ transitions:

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

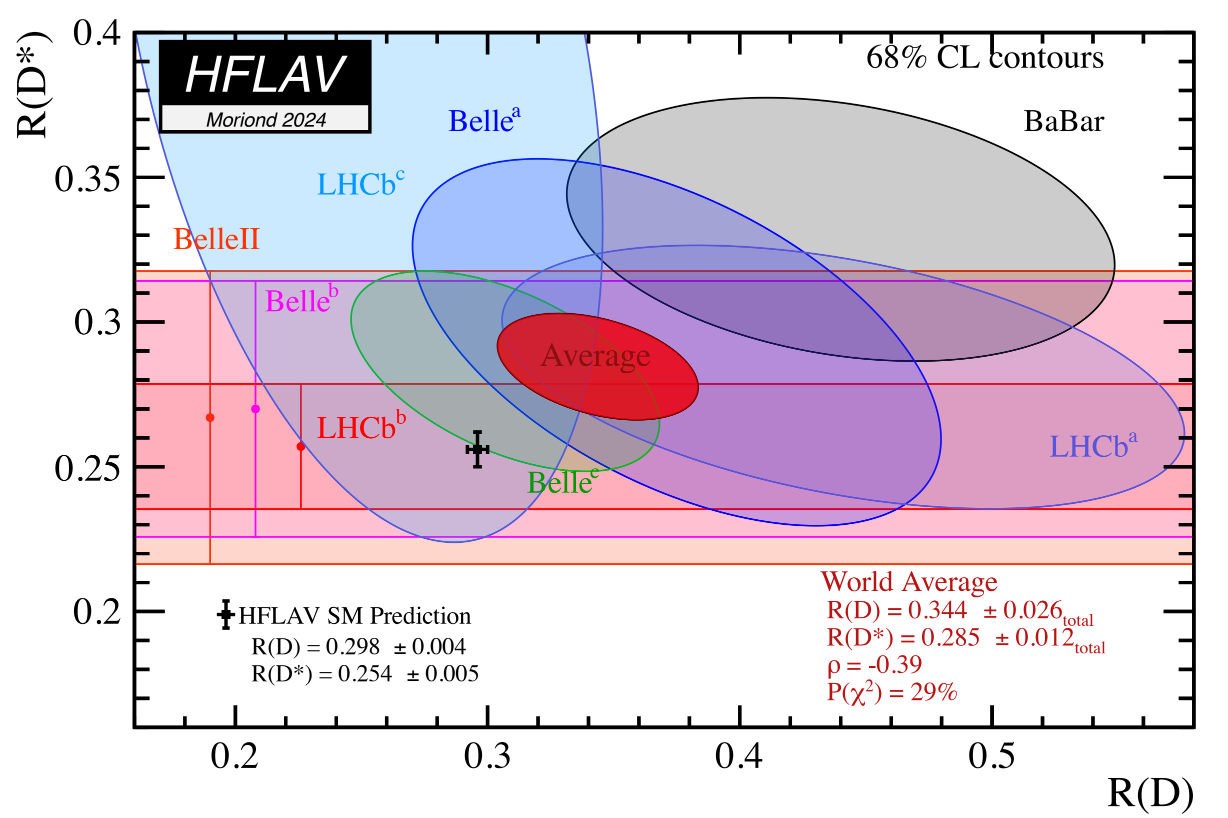


World average:

- $R_D = 0.344 \pm 0.026$
- $R_{D^*} = 0.285 \pm 0.012$

SM prediction:

- $R_D^{SM} = 0.298 \pm 0.004$
- $R_{D^*}^{SM} = 0.254 \pm 0.005$

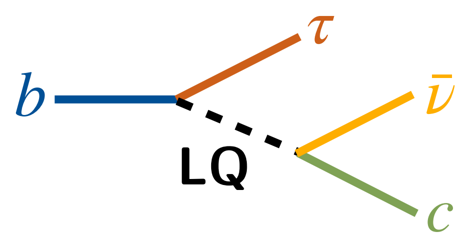


https://hflav-eos.web.cern.ch/hflav-eos/semi/moriond24/html/RDsDsstar/RDRDs.html

Flavor anomalies hinting at leptoquarks (LQs)?

Hints for NP in $b \to c\tau\bar{\nu}$ transitions:

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

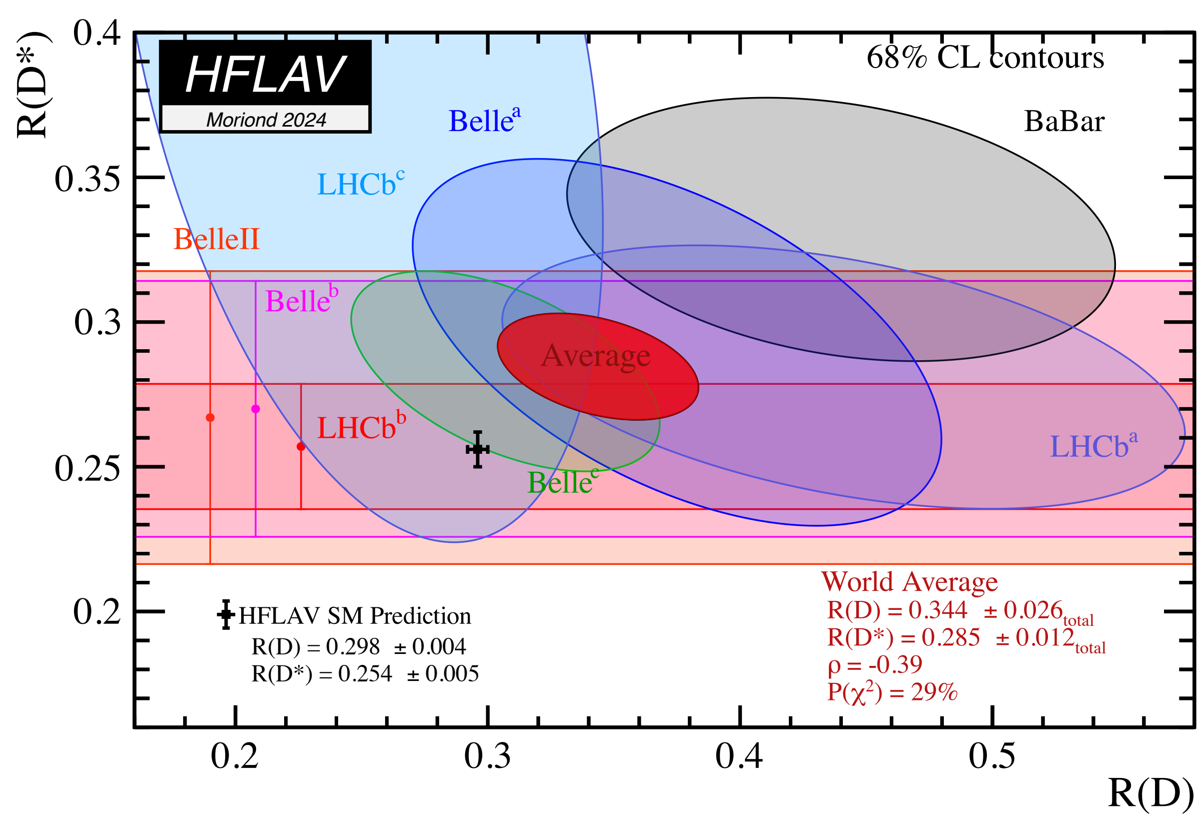


World average:

- $R_D = 0.344 \pm 0.026$
- $R_{D^*} = 0.285 \pm 0.012$

SM prediction:

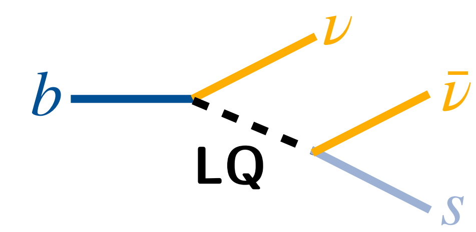
- $R_D^{\mathrm{SM}} = 0.298 \pm 0.004$
- $R_{D^*}^{\mathrm{SM}} = 0.254 \pm 0.005$



https://hflav-eos.web.cern.ch/hflav-eos/semi/moriond24/html/RDsDsstar/RDRDs.html

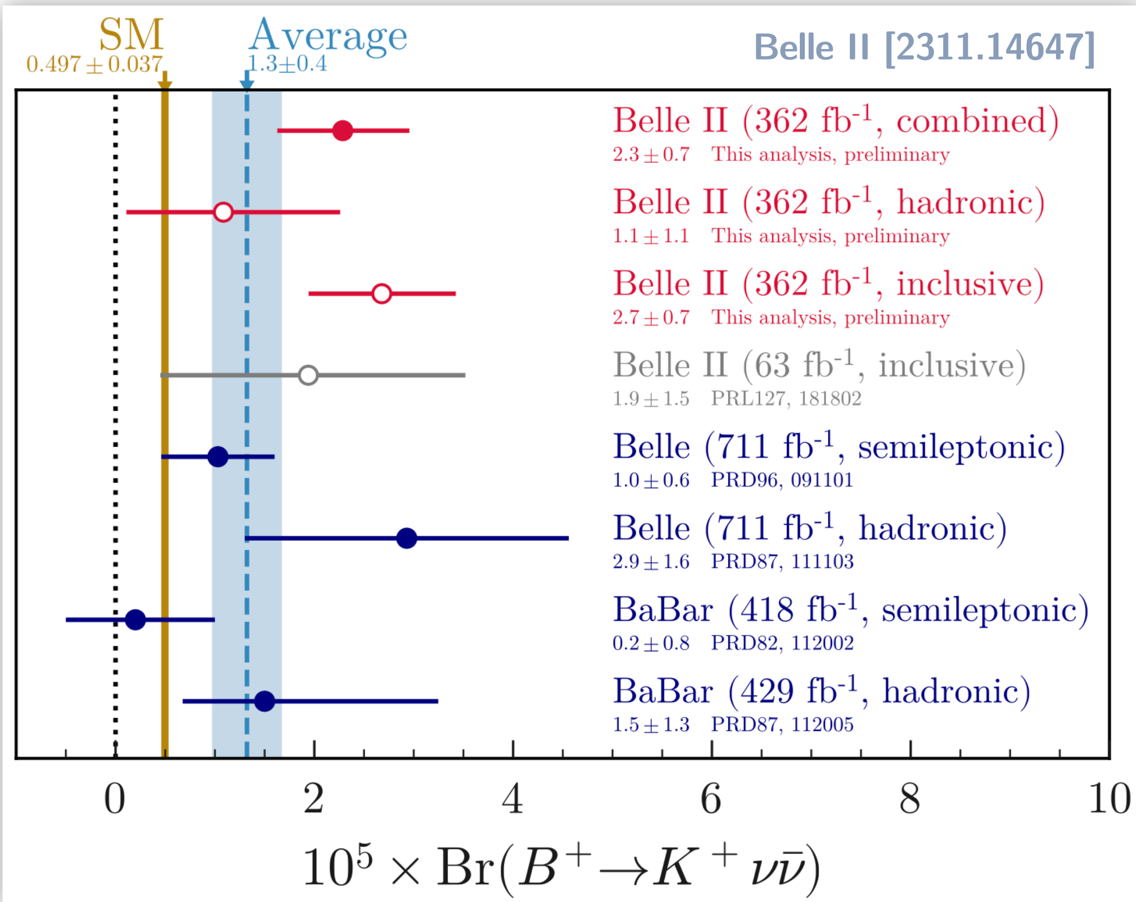
Hints for NP in $b \to s\nu\bar{\nu}$ transitions:

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$$



World average & SM prediction:

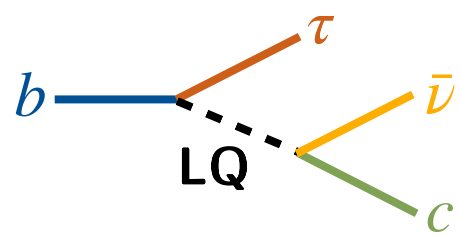
- $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = \left(2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$
- $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})^{\mathrm{SM}} = (5.58 \pm 0.37) \times 10^{-6}$



Flavor anomalies hinting at leptoquarks (LQs)?

Hints for NP in $b \to c\tau\bar{\nu}$ transitions:

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

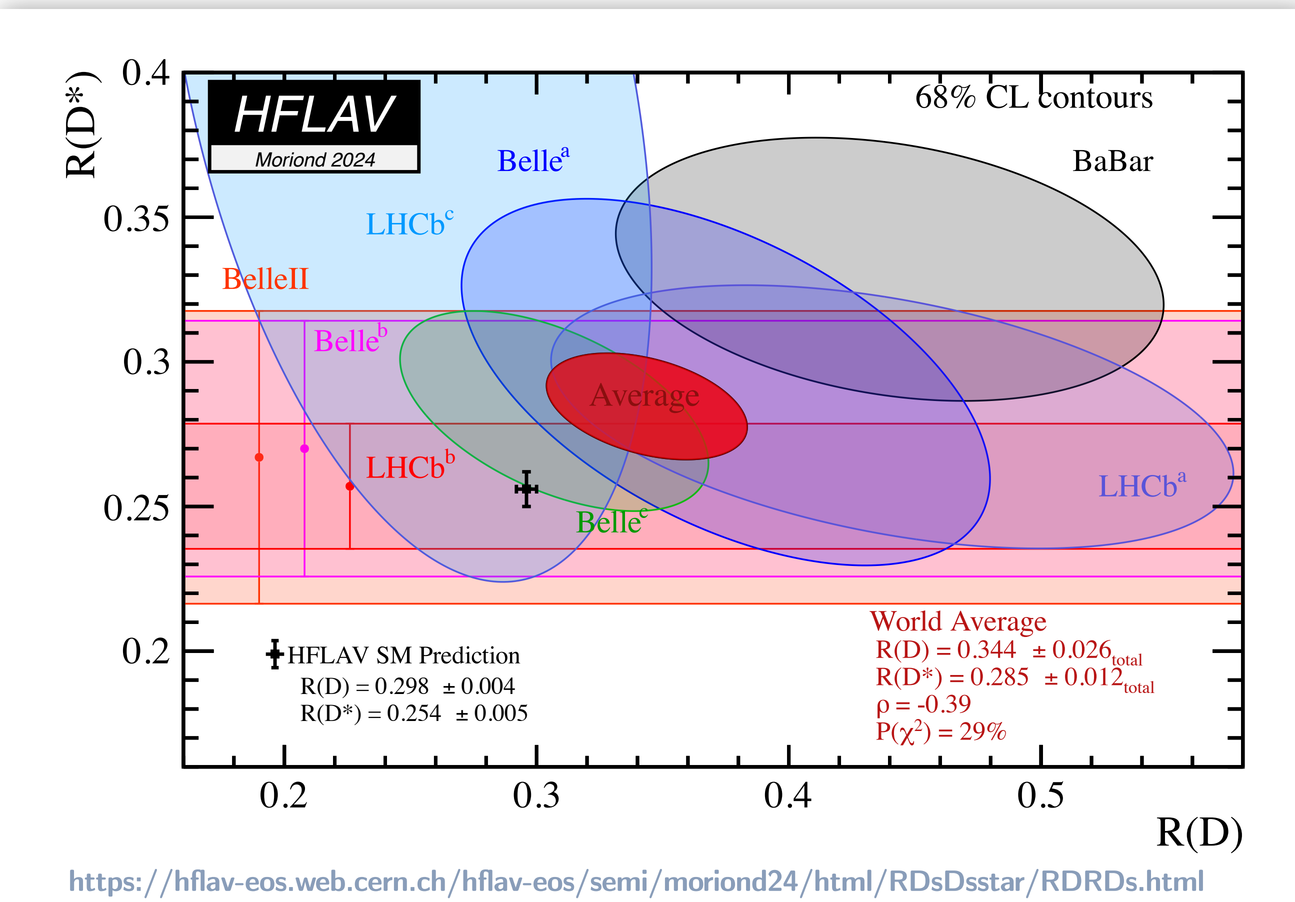


World average:

- $R_D = 0.344 \pm 0.026$
- $R_{D*} = 0.285 \pm 0.012$

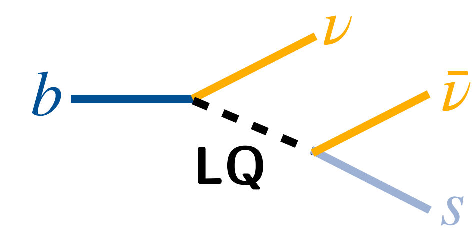
SM prediction:

- $R_D^{SM} = 0.298 \pm 0.004$
- $R_{D*}^{SM} = 0.254 \pm 0.005$



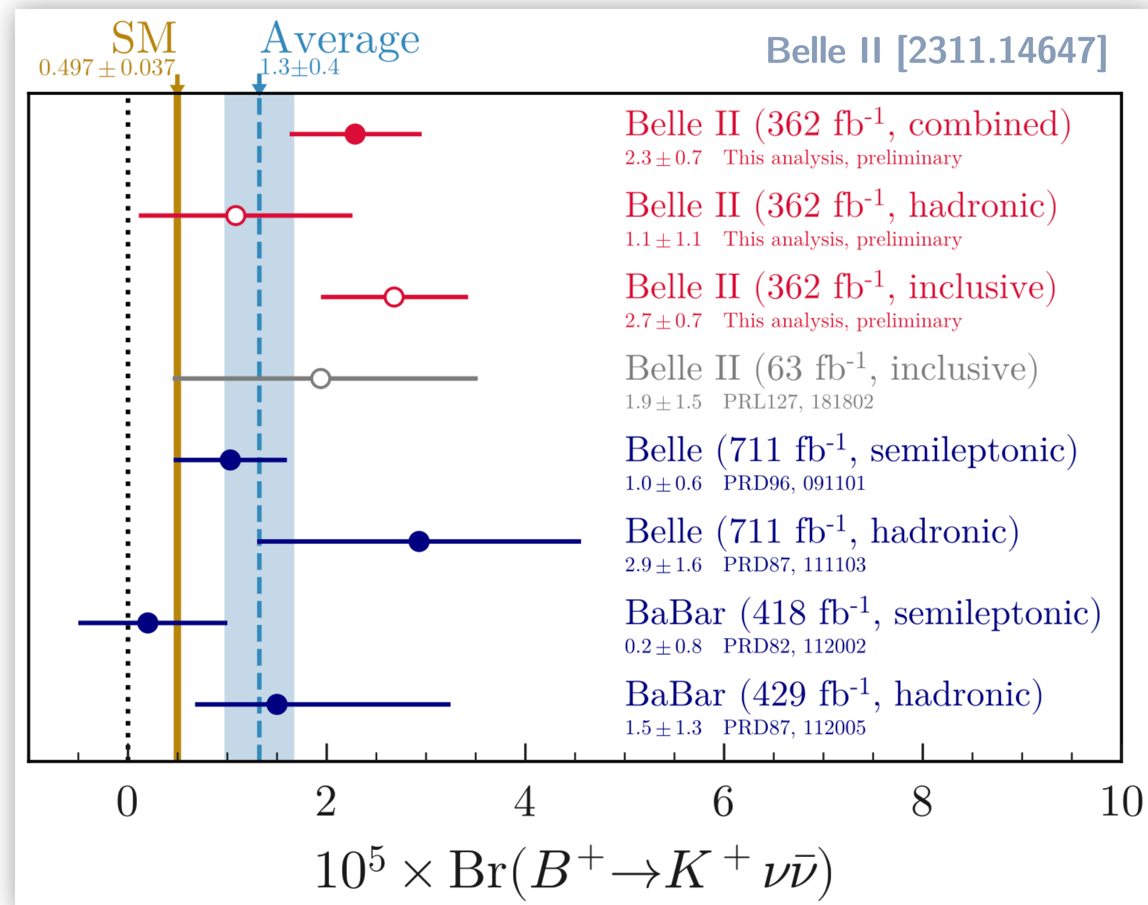
Hints for NP in $b \to s\nu\bar{\nu}$ transitions:

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$$



World average & SM prediction:

- $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = \left(2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right) \times 10^{-5}$
- $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})^{SM} = (5.58 \pm 0.37) \times 10^{-6}$



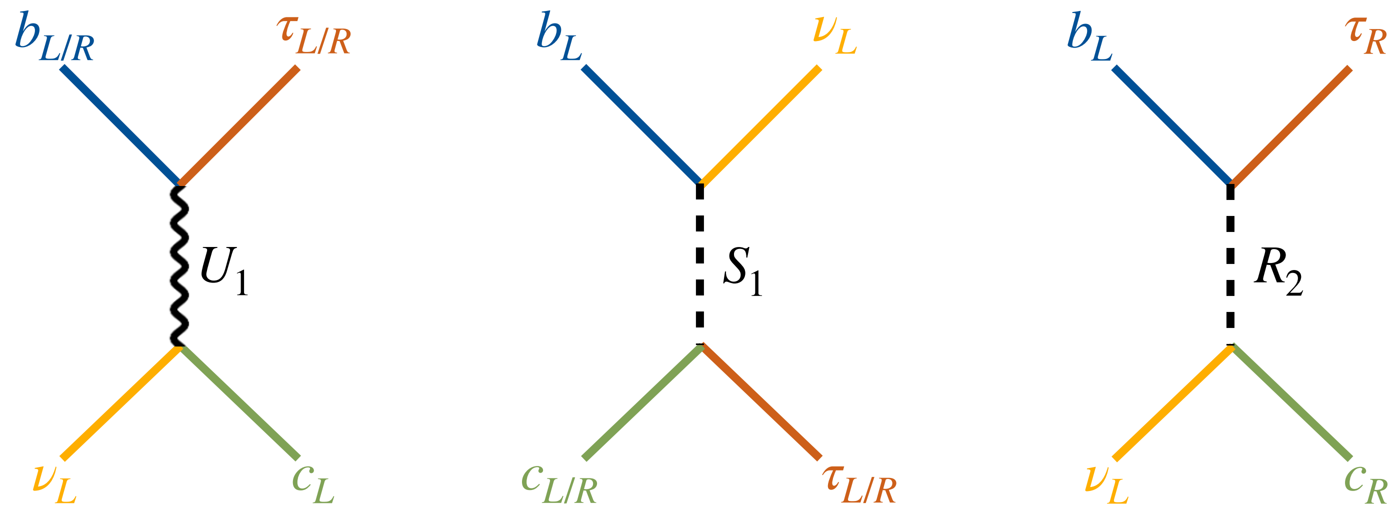
➡ **NP in semileptonic transitions of 3rd generation fermions? → leptoquarks?**

Leptoquark models with 3rd generation couplings

LQ explanations of $R_{D^{(*)}}$:

- Vector LQ: $U_1 \sim (\mathbf{3},\mathbf{1})_{2/3}$
- Scalar LQ: $S_1 \sim (\bar{\mathbf{3}},\mathbf{1})_{1/3}$
- Scalar LQ: $R_2 \sim (\mathbf{3},\mathbf{2})_{7/6}$

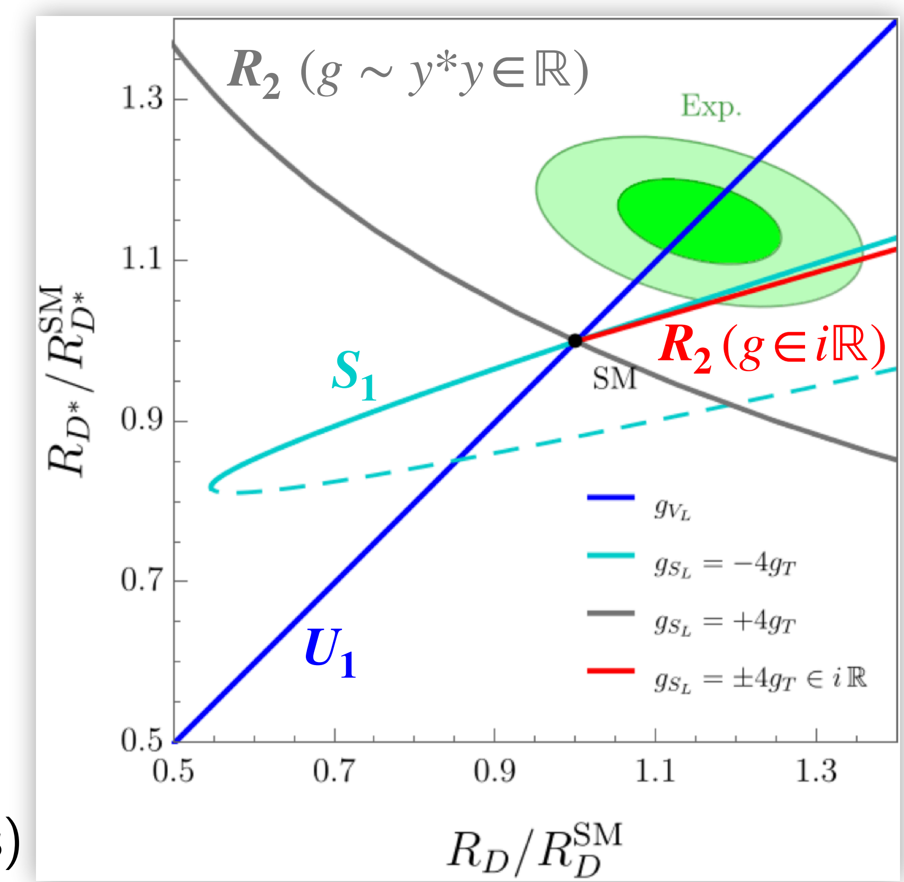
Angelescu, Becirević, Faroughy, Sumensari [1808.08179]



$Q = 2/3$ $\qquad$ $Q = 1/3$ $\qquad$ $Q = 2/3\ (5/3)$

$$\mathscr{L}_{\rm LQ} = y_{pr}\left(\bar{Q}_p \Gamma L_r\right)\phi_{\rm LQ} \quad \text{for} \quad Q \in \{q,d,u\}, \quad L \in \{\ell, e\}, \quad \phi_{\rm LQ} \in \{U_1, S_1, R_2, \dots\}$$

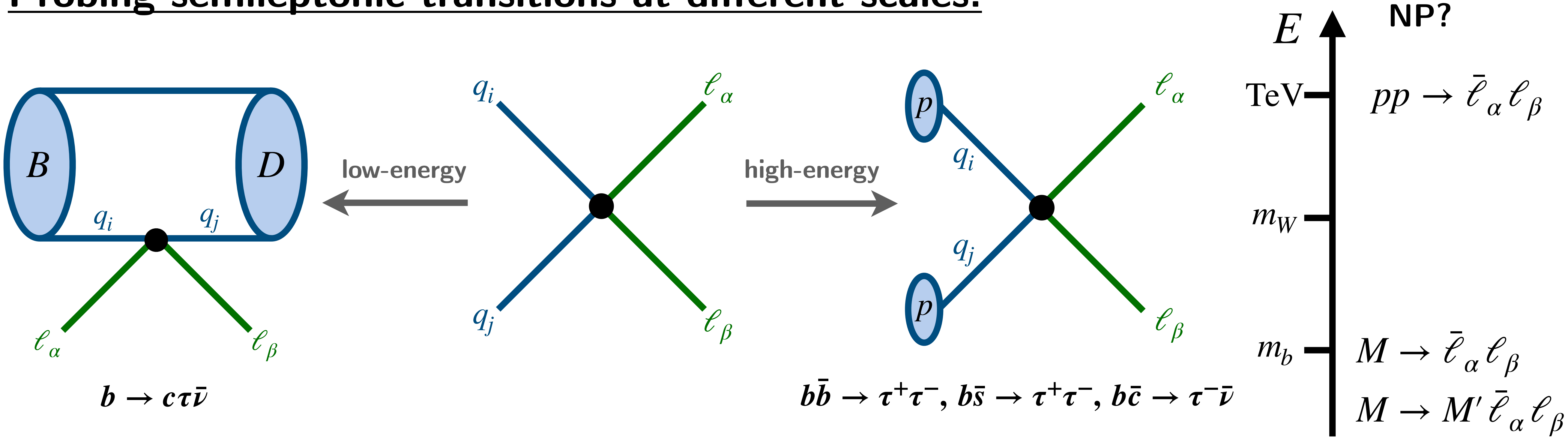
- Different Lorentz structures Γ depending on LQ state
- Only semi-leptonic interactions
  - No tree-level contribution to meson mixing
  - S_1 can have baryon-number violating interactions
  - S_1 only LQ of these 3 that can account for $B \to K\nu\bar{\nu}$
- LQ generally induce LFV (without imposing exact flavor symmetries)



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

Phenomenology of leptoquarks at LHC

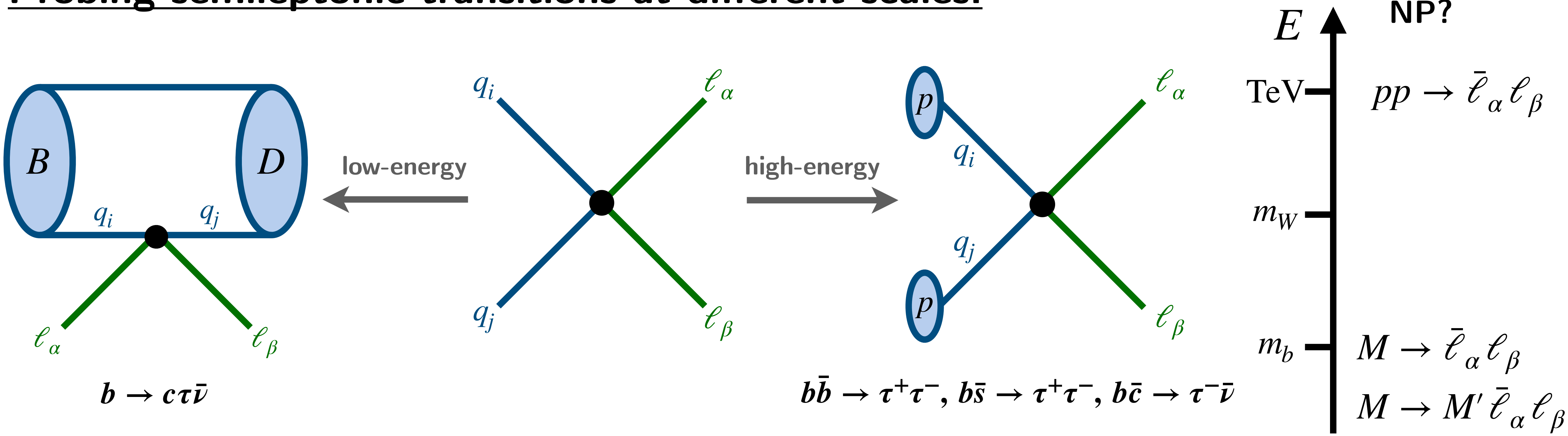
Probing semileptonic transitions at different scales:



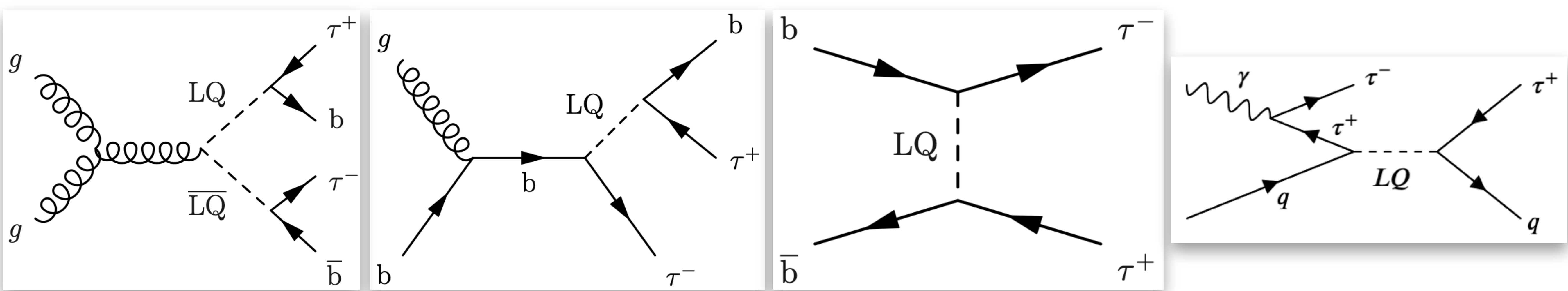
- Exploit complementarity of low- and high-energy measurements

Phenomenology of leptoquarks at LHC

Probing semileptonic transitions at different scales:



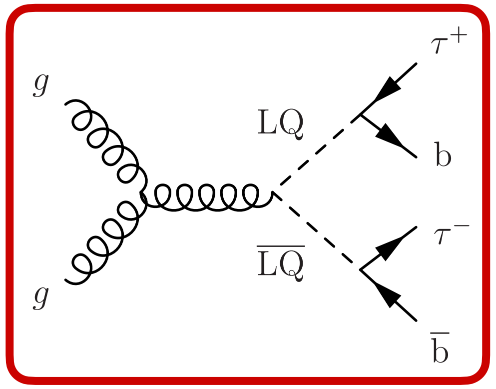
- Exploit complementarity of low- and high-energy measurements
- Various different channels for LQ searches:



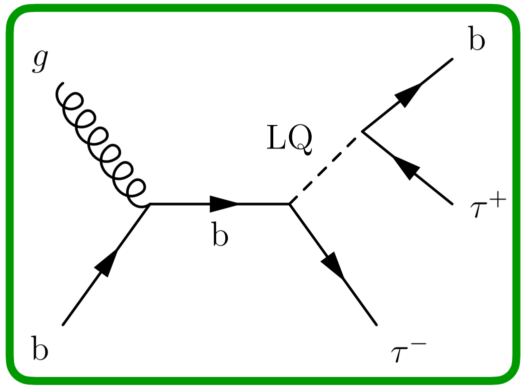
- Searches in different channels and different flavor combinations performed by ATLAS & CMS

Leptoquark channels at high-p_T

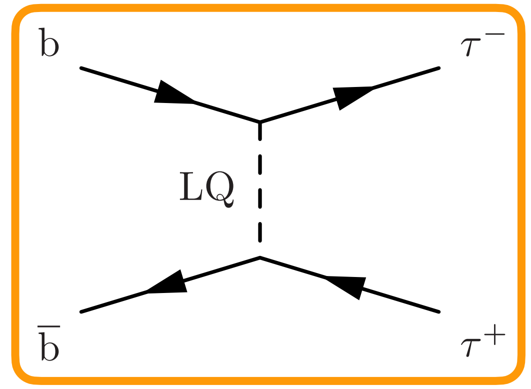
Leptoquark channel considered in analysis by CMS and ATLAS:



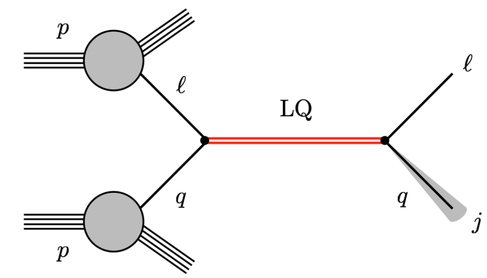
pair-production



single production



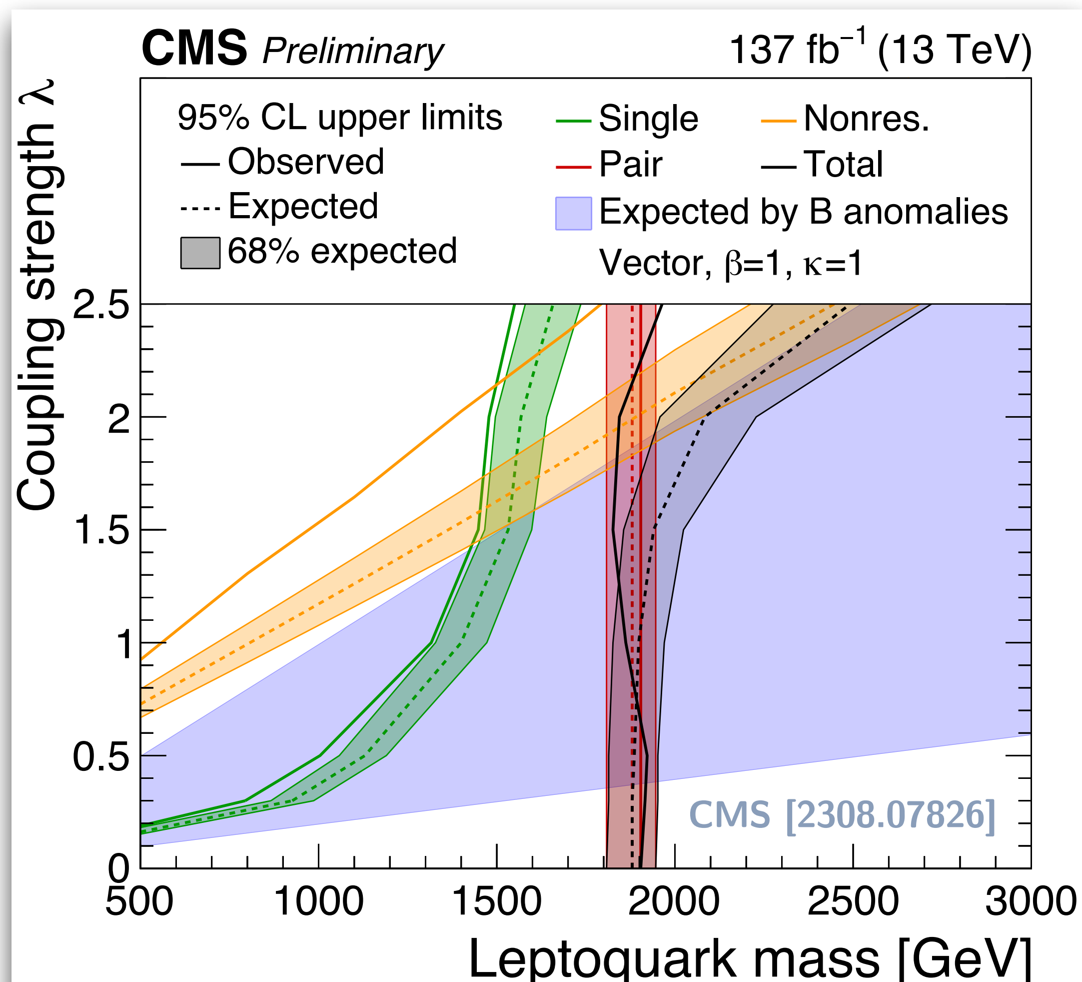
Drell-Yan

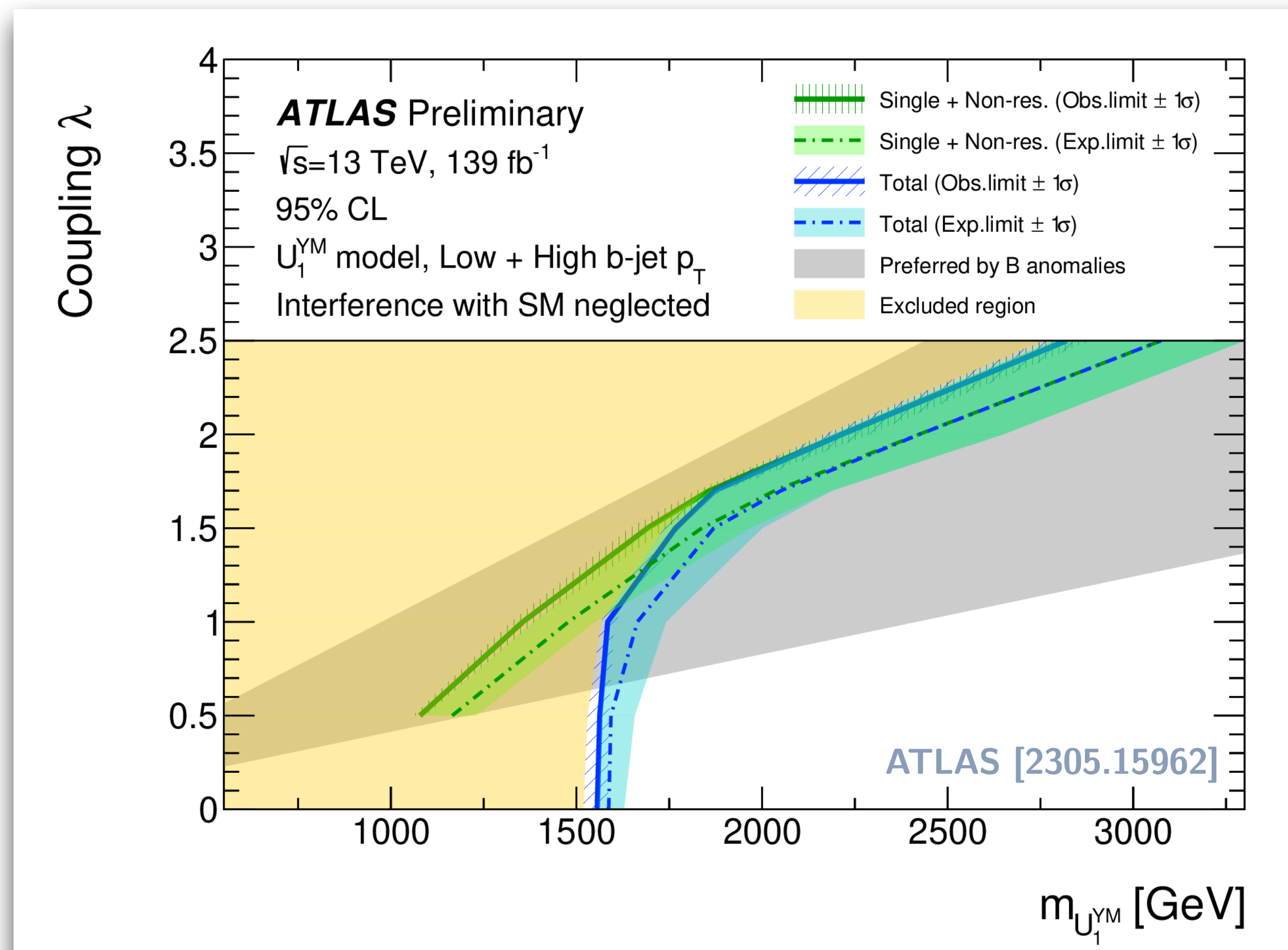


quark-lepton fusion / resonant production

See e.g.:
[hep-ph/9406235]
[hep-ph/9709319]
[2005.06475]
[2012.02092]
[2209.02599]
[2308.06143]

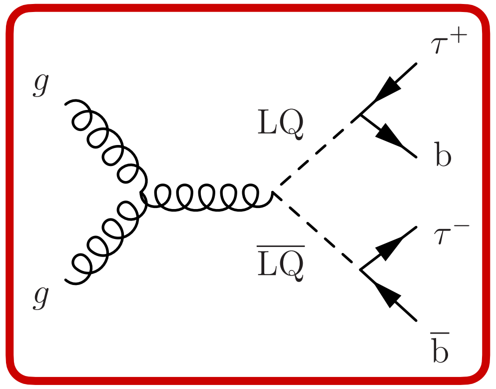
Example: constraints on U_1 vector leptoquark from various channels (quark-lepton fusion not yet included)



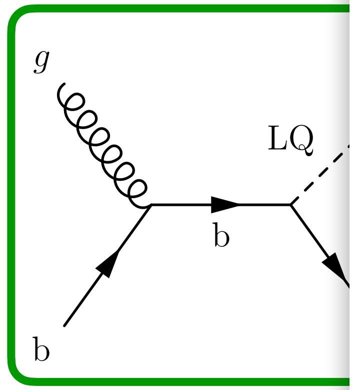


Leptoquark channels at high-p_T

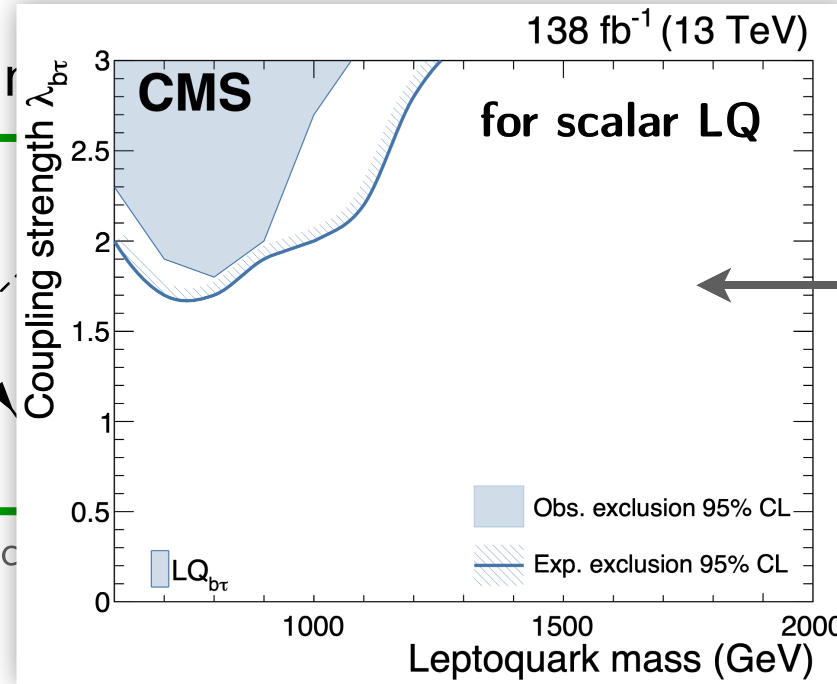
Leptoquark channel considered in

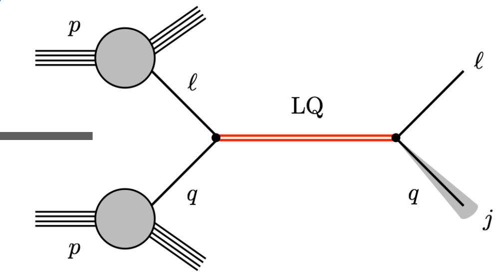


pair-production



single produc

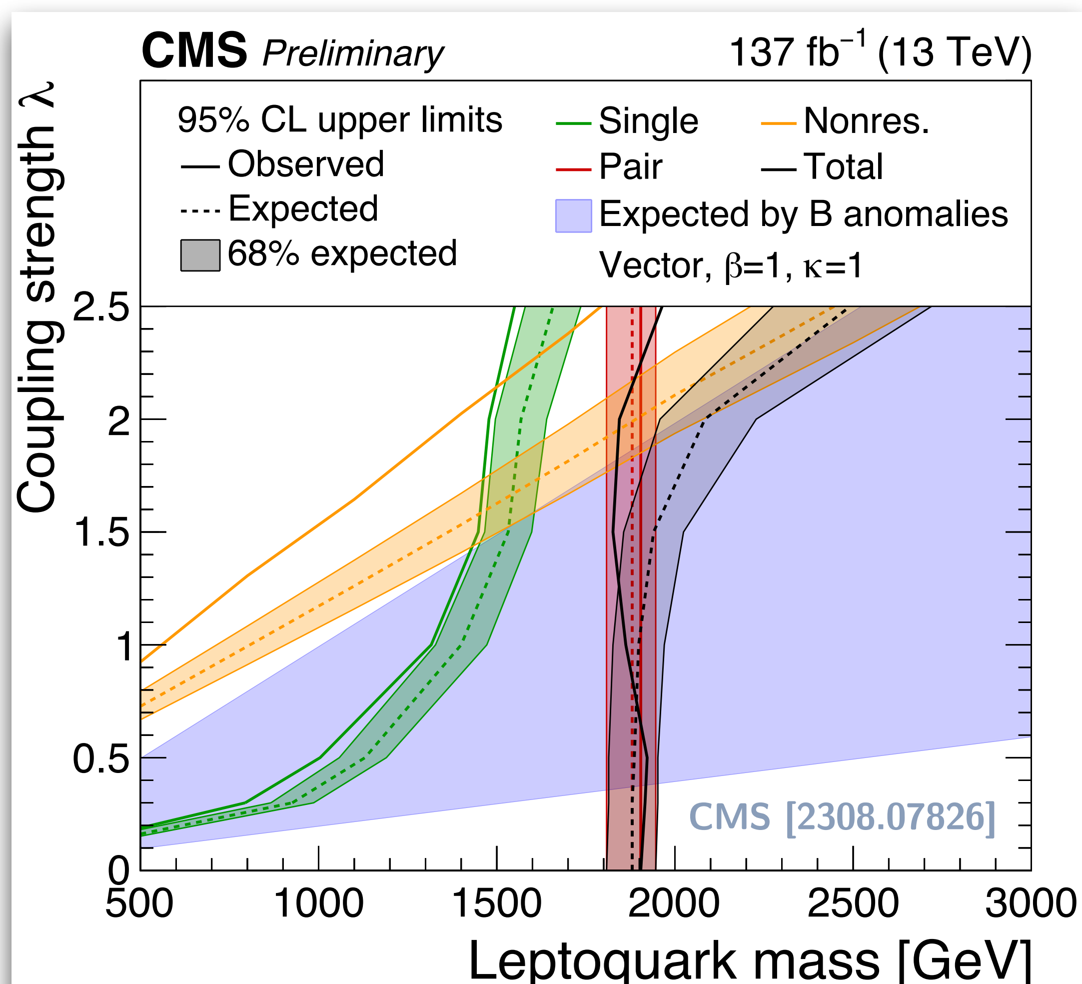


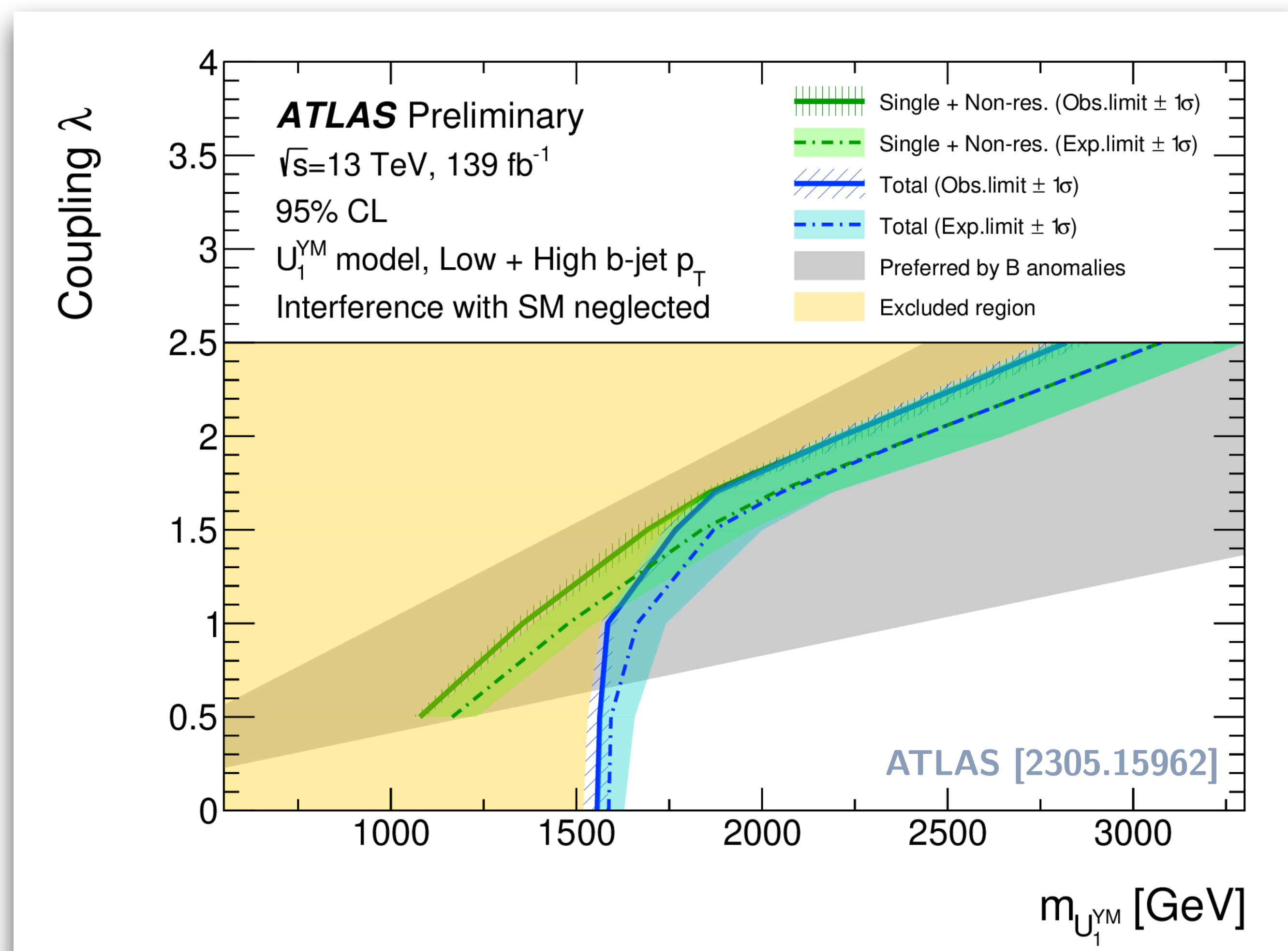


See e.g.:
[hep-ph/9406235]
[hep-ph/9709319]
[2005.06475]
[2012.02092]
[2209.02599]
[2308.06143]

quark-lepton fusion / resonant production

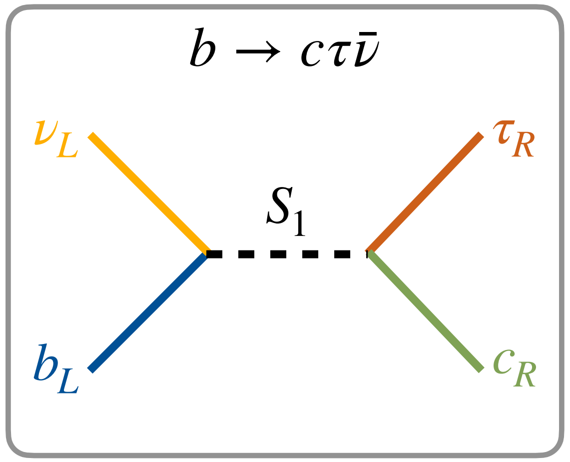
Example: constraints on U_1 vector leptoquark from various channels (quark-lepton fusion not yet included)

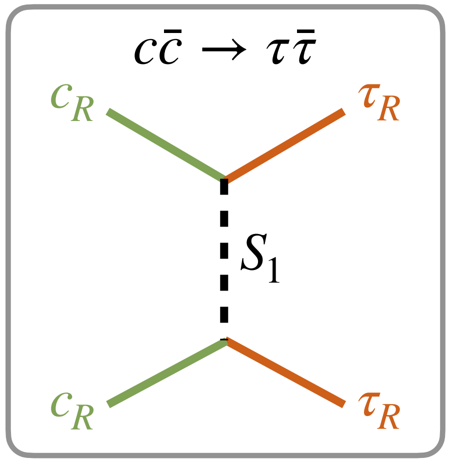


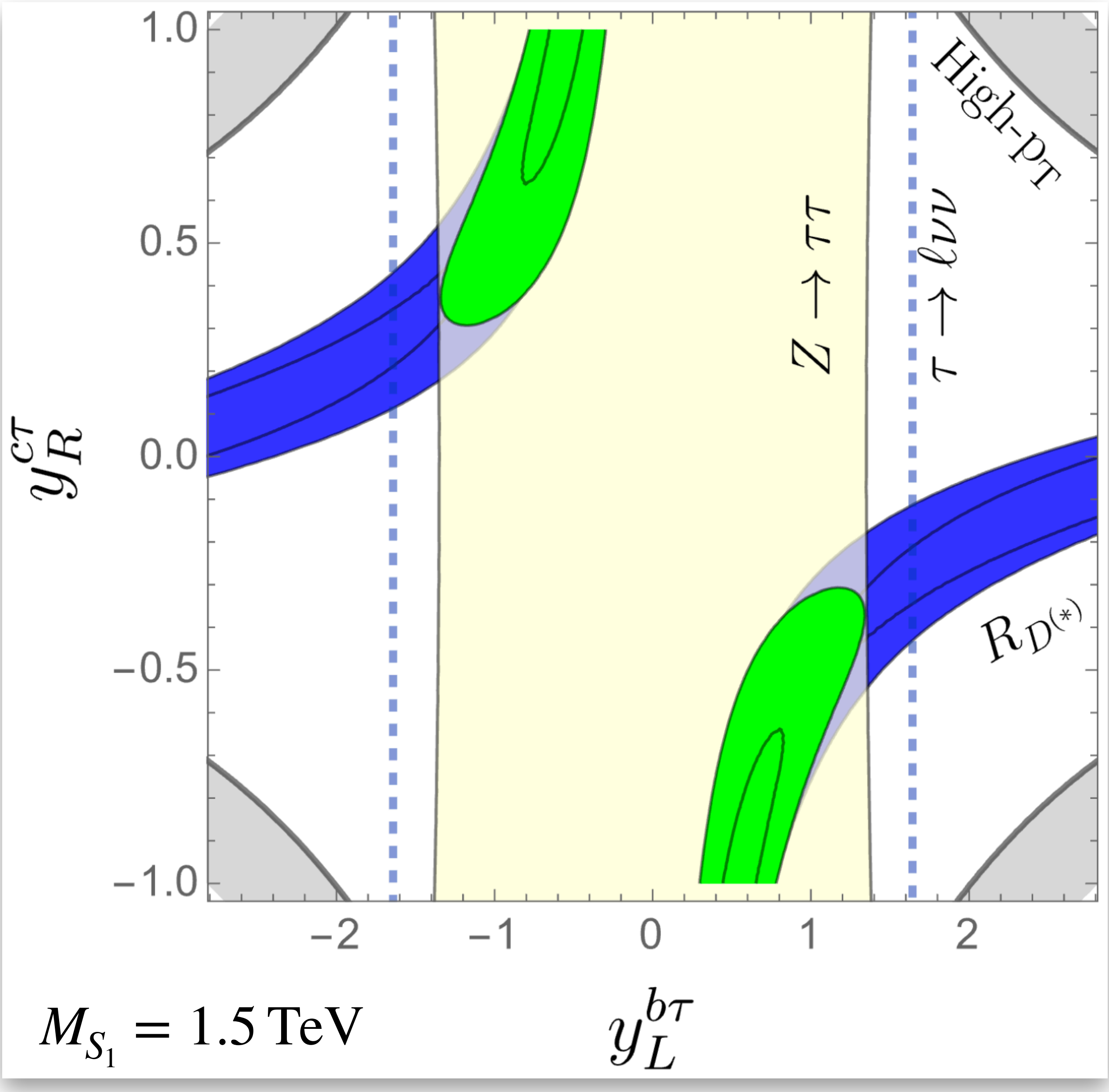


S_1 leptoquark explanation of $R_{D^{(*)}}$

- $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{1/6}$ interaction Lagrangian:
  - $\mathscr{L}_{S_1} = y_L^{pr} (\bar{q}_p^c \varepsilon \ell_r) S_1 + y_R^{pr} (\bar{u}_p^c e_r) S_1 + \text{h.c.}$
  - Minimal Yukawas required: $y_L^{b\tau}$, $y_R^{c\tau}$
  - Weak LHC bounds for $y_L^{b\tau}$:
    - Only $(\overline{b^c}\nu) S_1$ and $(\overline{t^c}\tau) S_1$ transitions
    - $b - \tau$ coupling CKM suppressed
  - Compatibility of measurements: $R_{D^{(*)}}$, Drell-Yan, $\Gamma(Z \to \tau\tau)$, $\mathscr{B}(\tau \to \mu\nu\bar{\nu})$
  - No tree-level contribution to $b \to s\nu\bar{\nu}$ in minimal setup → loop induced (can be enhanced by $y_L^{s\tau}$)



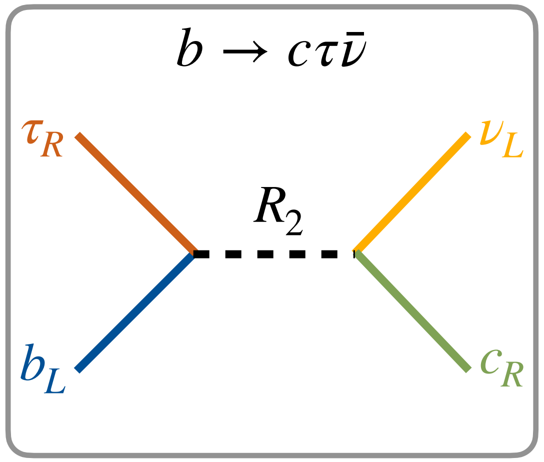


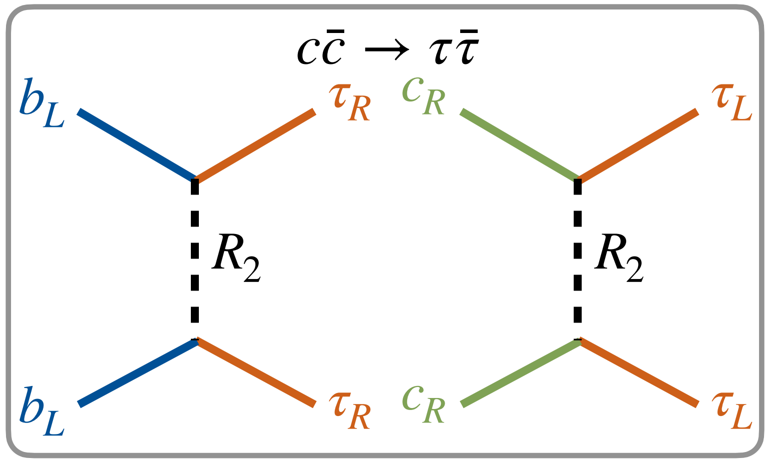


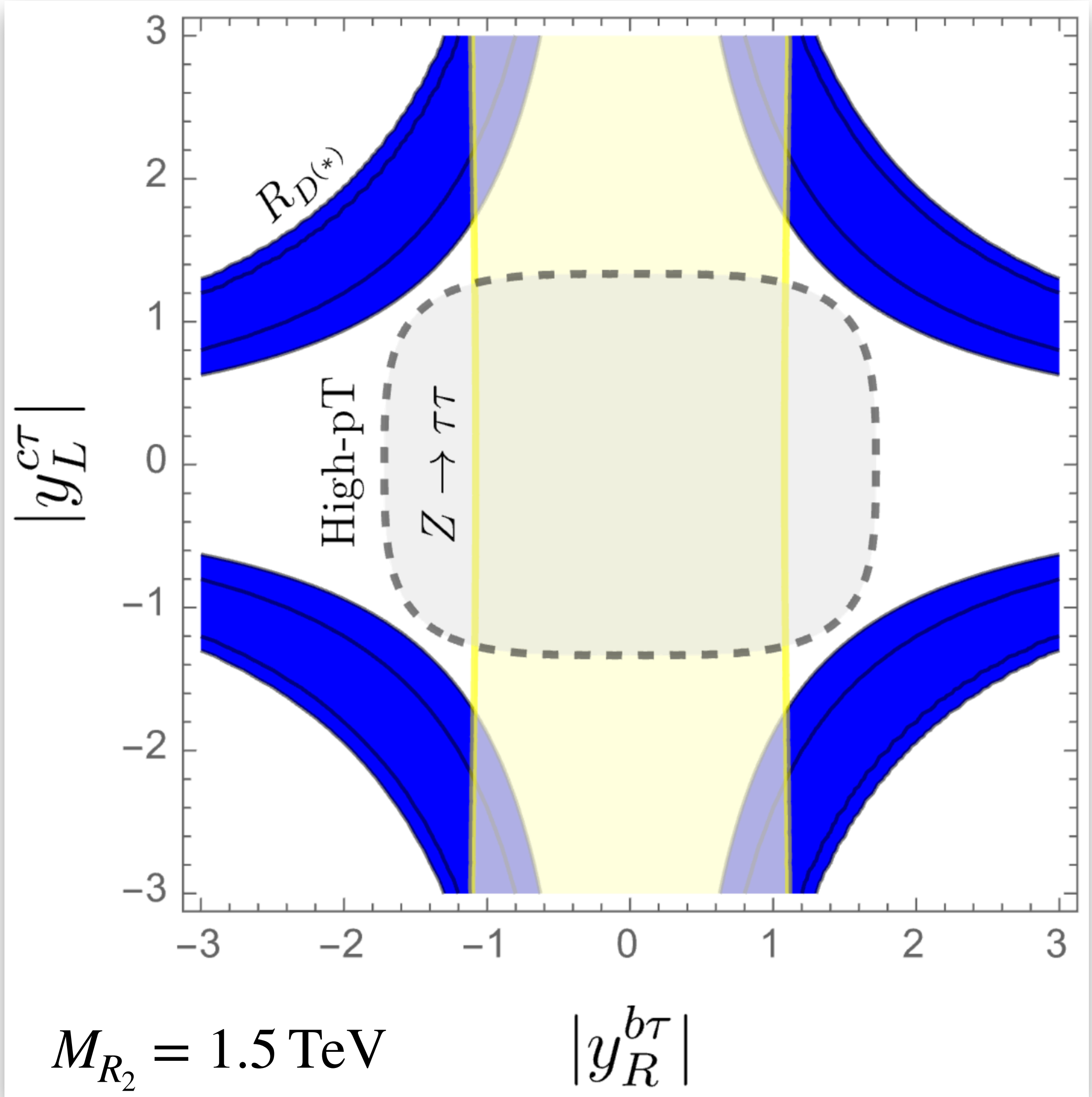
Becirevic, Fajfer, Kosnik, Pavicic [2404.16772]

R_2 leptoquark explanation of $R_{D^{(*)}}$

- $R_2 \sim (\mathbf{3}, \mathbf{2})_{7/6}$ interaction Lagrangian:
  - $\mathscr{L}_{R_2} = y_R^{pr}(\bar{q}_p e_r)R_2 + y_L^{pr}(\bar{u}_p R_2 \varepsilon \ell_r) + \mathrm{h.c.}$
  - Minimal Yukawas required: $y_R^{b\tau}$, $y_L^{c\tau}$
  - For $R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}}$ we need $\mathrm{Im}\left(y_R^{b\tau} y_L^{c\tau}\right) \neq 0$
    - No interference with SM
    - Larger couplings required (NP^2 effect)
    - Stronger LHC constraints
  - $R_{D^{(*)}}$, Drell-Yan, $\Gamma(Z \to \tau\tau)$ data shows $2\,\sigma$ tension in this model
  - No tree-level contribution to $b \to s\nu\bar{\nu}$







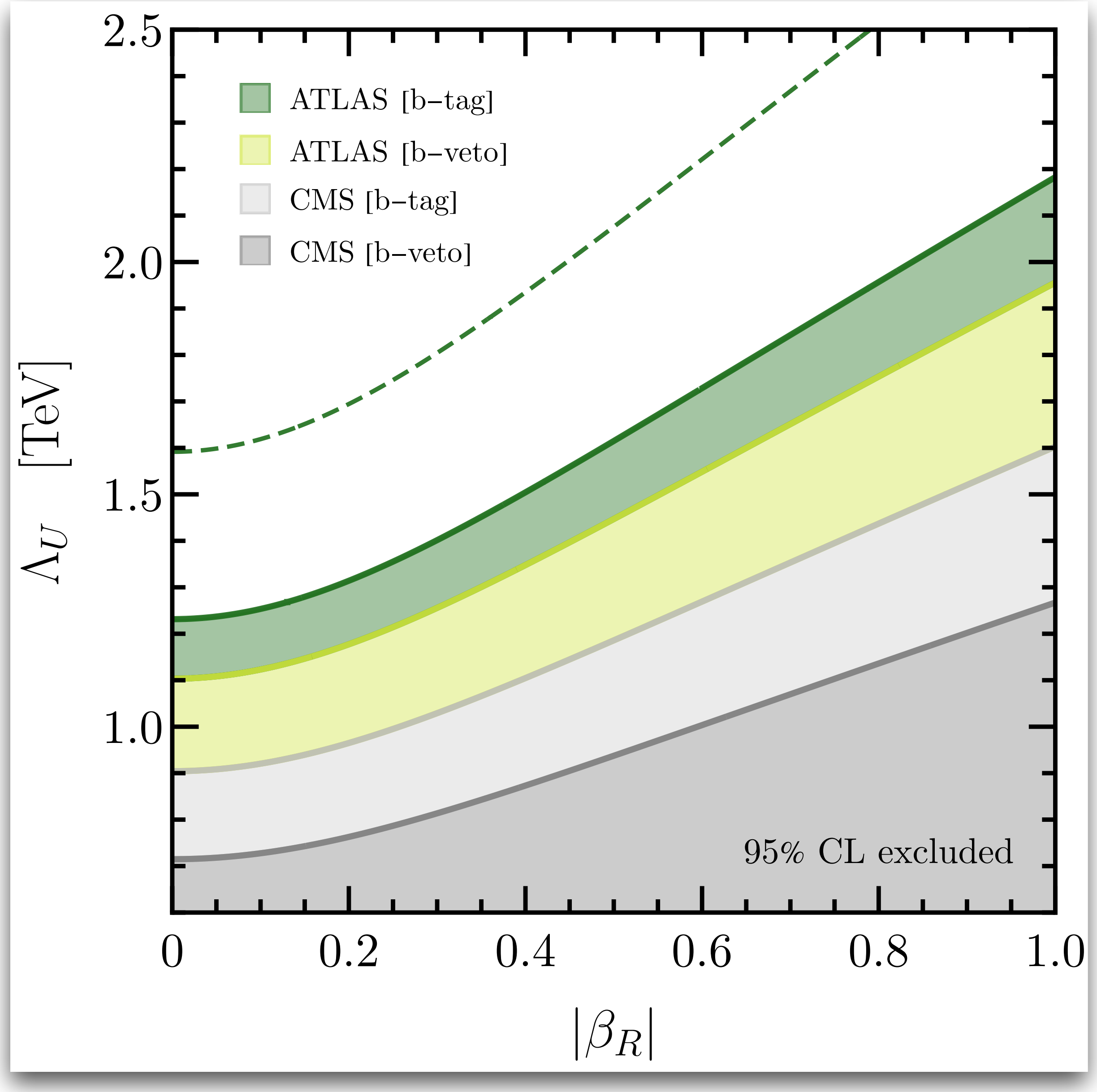
Becirevic, Fajfer, Kosnik, Pavicic [2404.16772]

U_1 vector leptoquark and b-jet tagging

U_1 leptoquark Lagrangian: $$\mathscr{L}_{U_1} = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3\gamma_\mu\ell_L^3 + \beta_R\,\bar{d}_R^3\gamma_\mu e_R^3 + \sum_{k=1,2}\epsilon_{q_k}\bar{q}_L^k\gamma_\mu\ell_L^3\right]U_1^\mu + \mathrm{h.c.}$$

- High-p_T constraints
  - from: $b\bar{b} \to \tau^+\tau^-$
  - on: effective scale $\Lambda_U = \sqrt{2}M_U/g_U$
  - Obtained with HighPT Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10756]
- Resonant searches for $pp \to \tau\tau$
  - **ATLAS** *(no excess)* [2002.12223]
  - **CMS** *($\sim 3\sigma$ excess)* [2208.02717]

Constraints on right-handed coupling scenarios



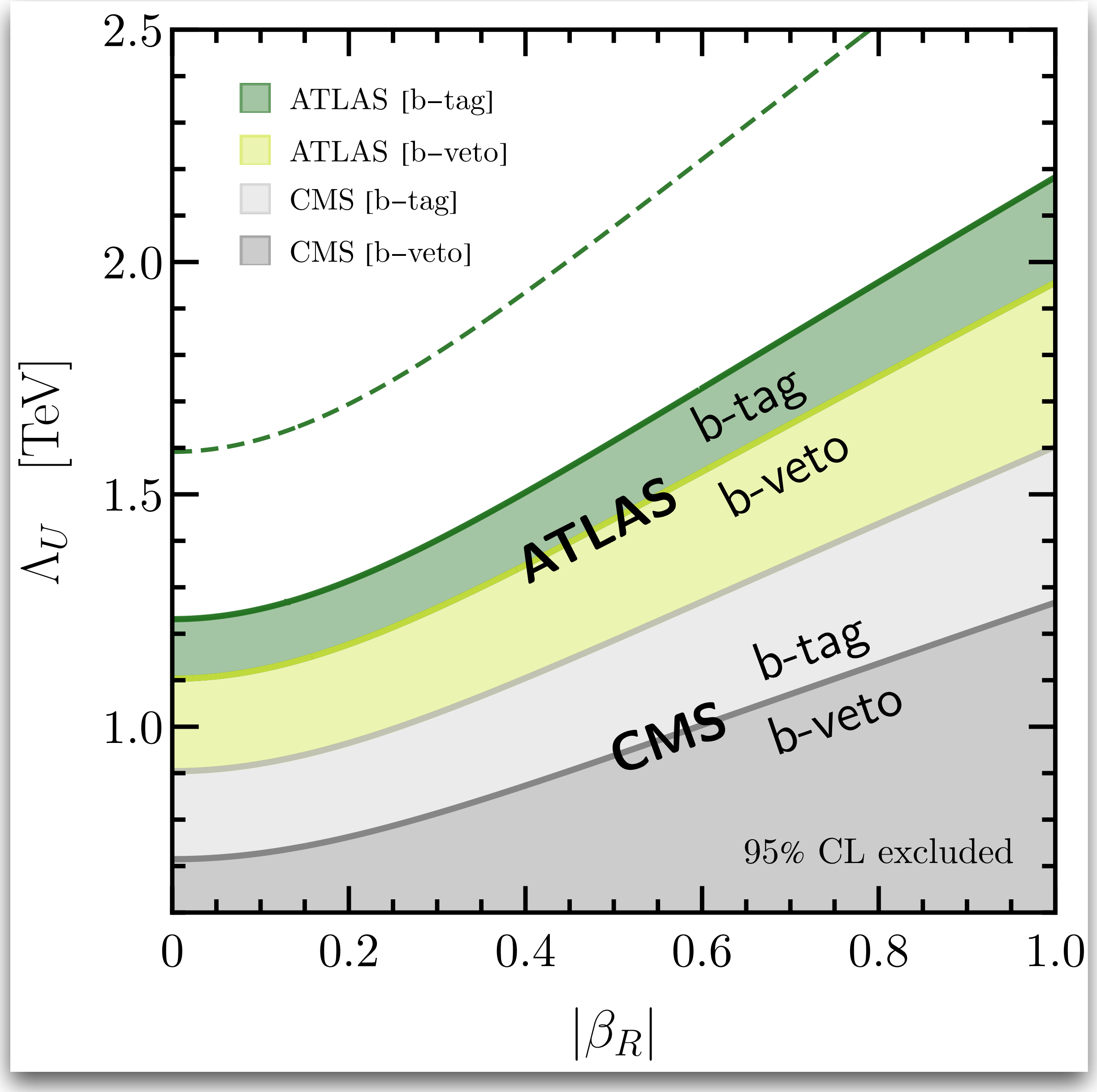
Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]

U_1 vector leptoquark and b-jet tagging

U_1 leptoquark Lagrangian: $$\mathscr{L}_{U_1} = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3\gamma_\mu\ell_L^3 + \beta_R\,\bar{d}_R^3\gamma_\mu e_R^3 + \sum_{k=1,2}\epsilon_{q_k}\bar{q}_L^k\gamma_\mu\ell_L^3\right]U_1^\mu + \mathrm{h.c.}$$

- High-p_T constraints
  - from: $b\bar{b} \to \tau^+\tau^-$
  - on: effective scale $\Lambda_U = \sqrt{2}M_U/g_U$
  - Obtained with **HighPT** Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10756]
- Resonant searches for $pp \to \tau\tau$
  - **ATLAS** *(no excess)* [2002.12223]
  - **CMS** *($\sim 3\sigma$ excess)* [2208.02717]
- Initial state gluon splitting: $g \to b\bar{b}$
  - Expect soft associated b jet
  - Requiring associated b jets reduces background and improves performance

Constraints on right-handed coupling scenarios



Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]

- Rescaled likelihood to account for b tagging and including NLO corrections

Haisch, Schnell, Schulte [2207.00356], [2209.12780]

U_1 vector leptoquark at low energies

U_1 leptoquark Lagrangian: $\mathscr{L}_{U_1} = \frac{g_U}{\sqrt{2}}\left[\bar{q}^3_L\gamma_\mu\ell^3_L + \beta_R\,\bar{d}^3_R\gamma_\mu e^3_R + \sum_{k=1,2}\epsilon_{q_k}\bar{q}^k_L\gamma_\mu\ell^3_L\right]U_1^\mu + \mathrm{h.c.}$

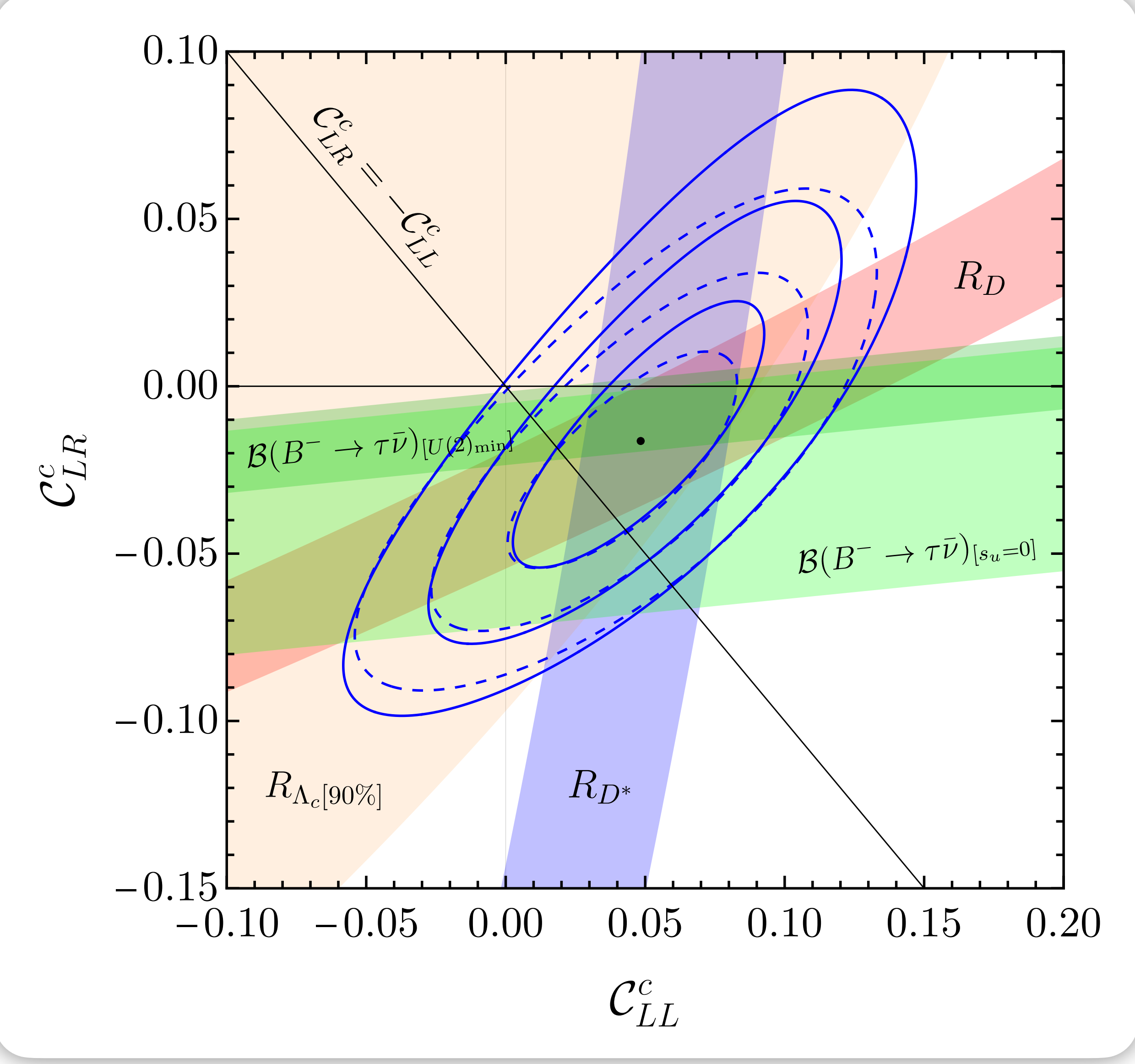
- EFT Lagrangian for $b \to c\tau\nu$

$$\mathscr{L}_{b\to c} = -\frac{G_F}{\sqrt{2}}V_{cb}\Big[\left(1+\mathscr{C}^c_{LL}\right)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) \\ -2\mathscr{C}^c_{LR}(\bar{c}_L b_R)(\bar{\tau}_R\nu_L)\Big]$$

where $\mathscr{C}^c_{LR} = \beta_R^*\mathscr{C}^c_{LL}$

  - Left-handed couplings only: $\mathscr{C}_{LR} = 0$
  - Equal magnitude: $\mathscr{C}^c_{LR} = -\mathscr{C}^c_{LL}$

- Observables relevant to low-energy fit:
  - $R_D\,,\quad R_{D^*}\,,\quad R_{\Lambda_c}\,,\quad \mathscr{B}(B_u^- \to \tau\bar{\nu})$
- Combined fit shows $3\,\sigma$ discrepancy with SM
- Compatible with both $\beta_R = 0$ and $\beta_R = -1$



Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]

See, e.g. also:
Cornella, Faroughy, Fuentes-Martín, Isidori, Neubert [2103.16558]
Bhaskar, Das, Mandal, Mitra, Neeraj [2101.12069]

U_1 vector leptoquark at high-p_T

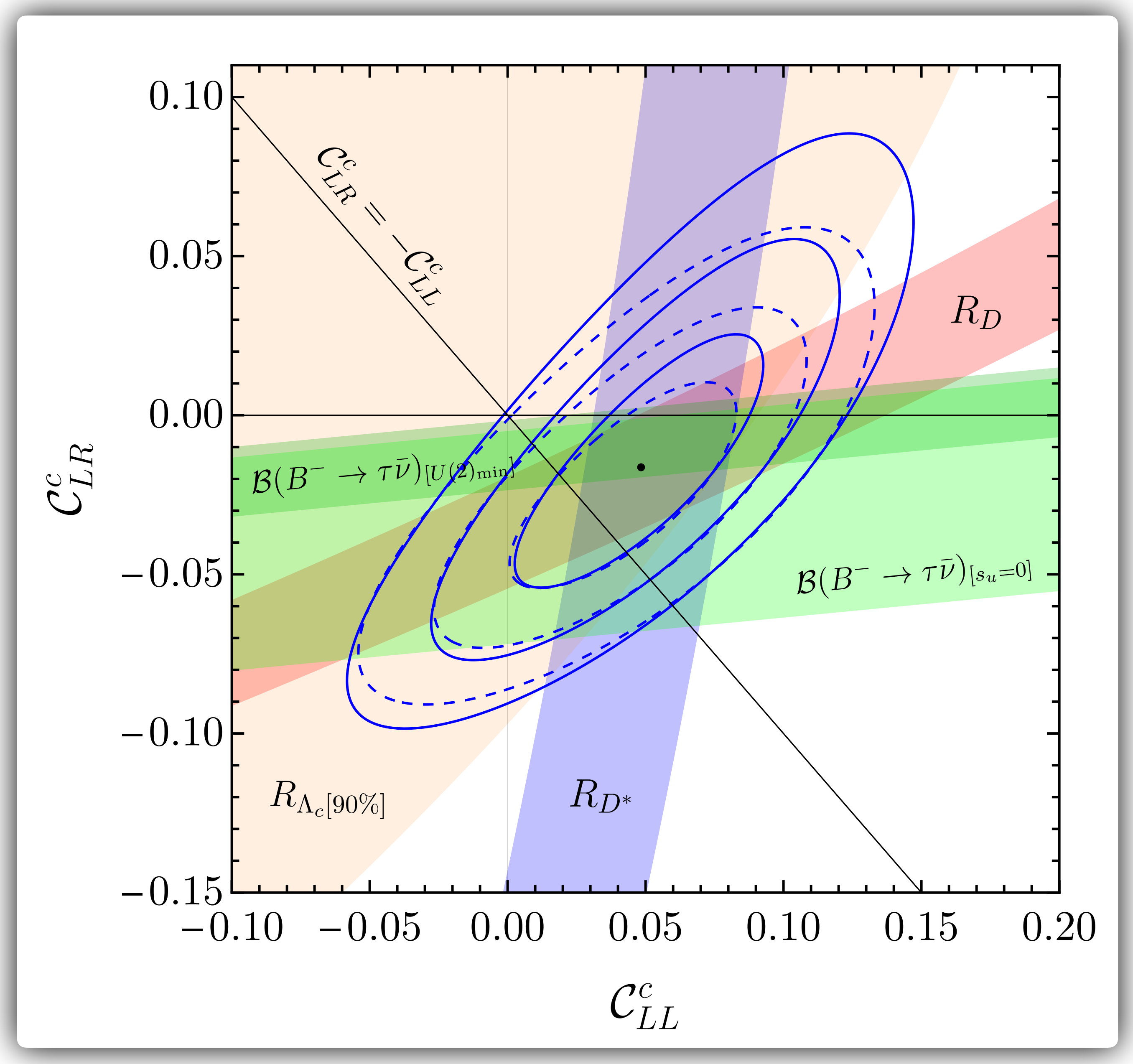
- Effective Lagrangian for $b \to c$ transitions:

$$\mathscr{L}_{b\to c} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(1 + \mathscr{C}^c_{LL}\right)(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) - 2\mathscr{C}^c_{LR}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) \right]$$

- Match $\mathscr{C}^c_{LL(LR)}$ to the U_1 model
  - $\mathscr{C}^c_{LL} \sim g_U^2$
  - $\mathscr{C}^c_{LR} \sim \beta_R \, g_U^2$

U_1 Lagrangian:

$$\mathscr{L}_{U_1} = \frac{g_U}{\sqrt{2}} \left[\bar{q}^3_L \gamma_\mu \ell^3_L + \beta_R \, \bar{d}^3_R \gamma_\mu e^3_R + \sum_{k=1,2} \epsilon_{q_k} \bar{q}^k_L \gamma_\mu \ell^3_L \right] U_1^\mu + \mathrm{h.c.}$$



Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]

U_1 vector leptoquark at high-p_T

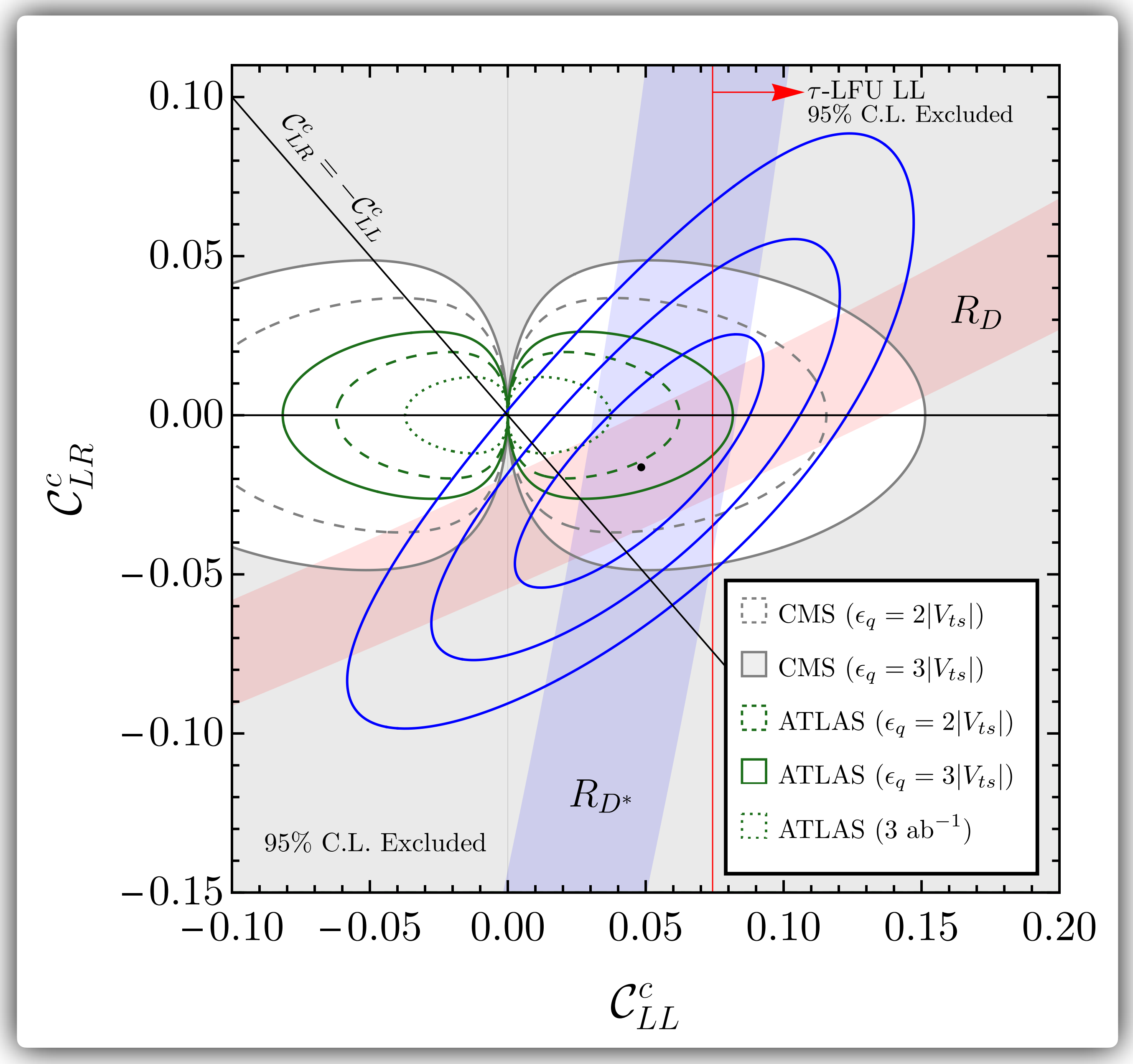
U_1 Lagrangian:

$$\mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}}\Big[\bar{q}_L^3\gamma_\mu\ell_L^3 + \beta_R\,\bar{d}_R^3\gamma_\mu e_R^3 + \sum_{k=1,2}\epsilon_{q_k}\bar{q}_L^k\gamma_\mu\ell_L^3\Big]U_1^\mu + \mathrm{h.c.}$$

- Effective Lagrangian for $b \to c$ transitions:

$$\mathcal{L}_{b\to c} = -\frac{4G_F}{\sqrt{2}}V_{cb}\left[\left(1+\mathcal{C}_{LL}^c\right)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) - 2\mathcal{C}_{LR}^c(\bar{c}_L b_R)(\bar{\tau}_R\nu_L)\right]$$

- Match $\mathcal{C}_{LL(LR)}^c$ to the U_1 model
  - $\mathcal{C}_{LL}^c \sim g_U^2$
  - $\mathcal{C}_{LR}^c \sim \beta_R\,g_U^2$
- Details of the fit:
  - $\mathcal{C}_{LL}^c \to 0$ corresponds to $|\beta_R| \to \infty$
  - More model dependence
    - Depends on 2nd gen. coupling ϵ_q
    - Small ϵ_q requires lower scale Λ_U
- Currently good compatibility of constraints
- CMS excess favors scenario with large β_R



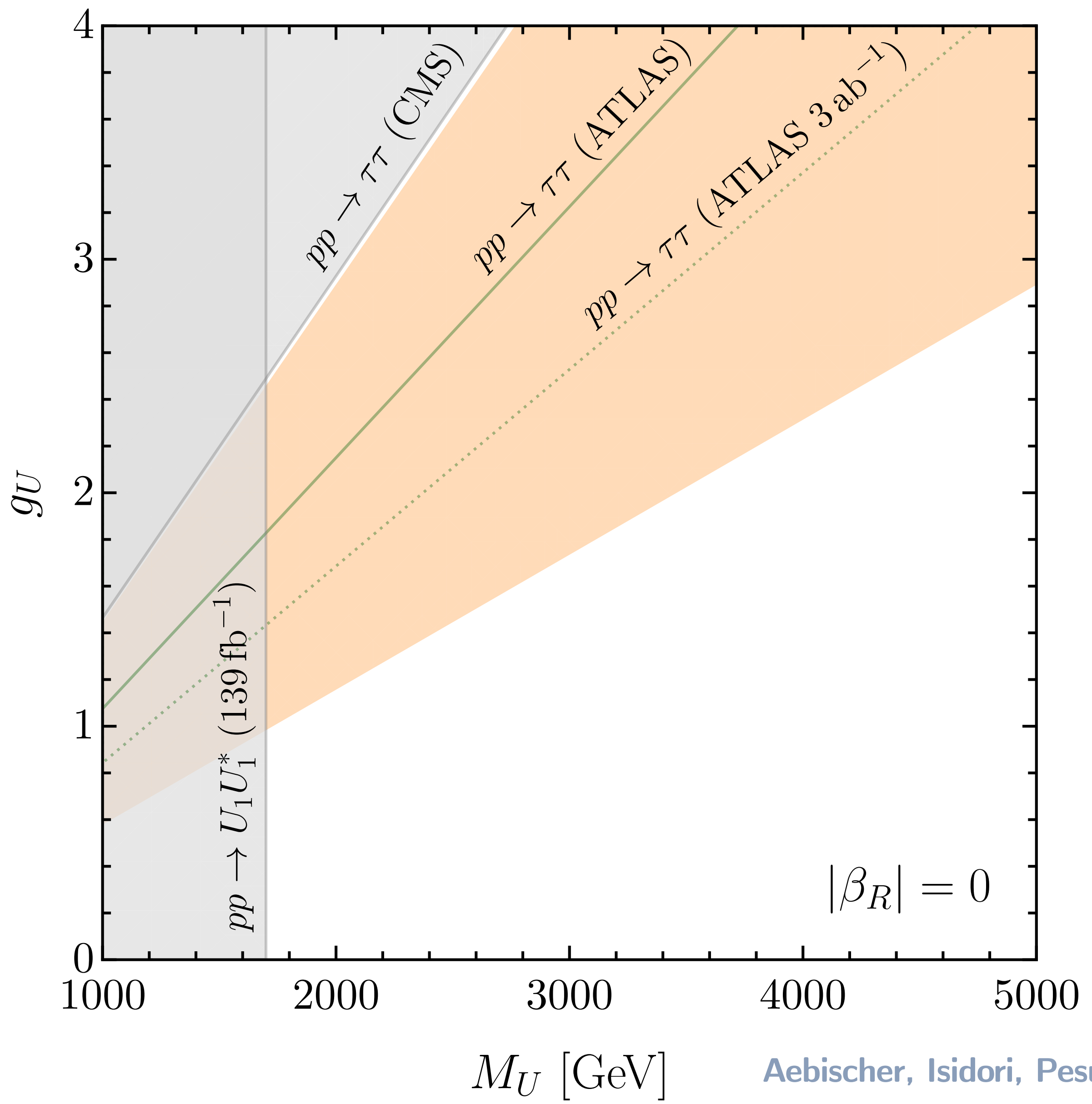
Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]

Comparison of different searches

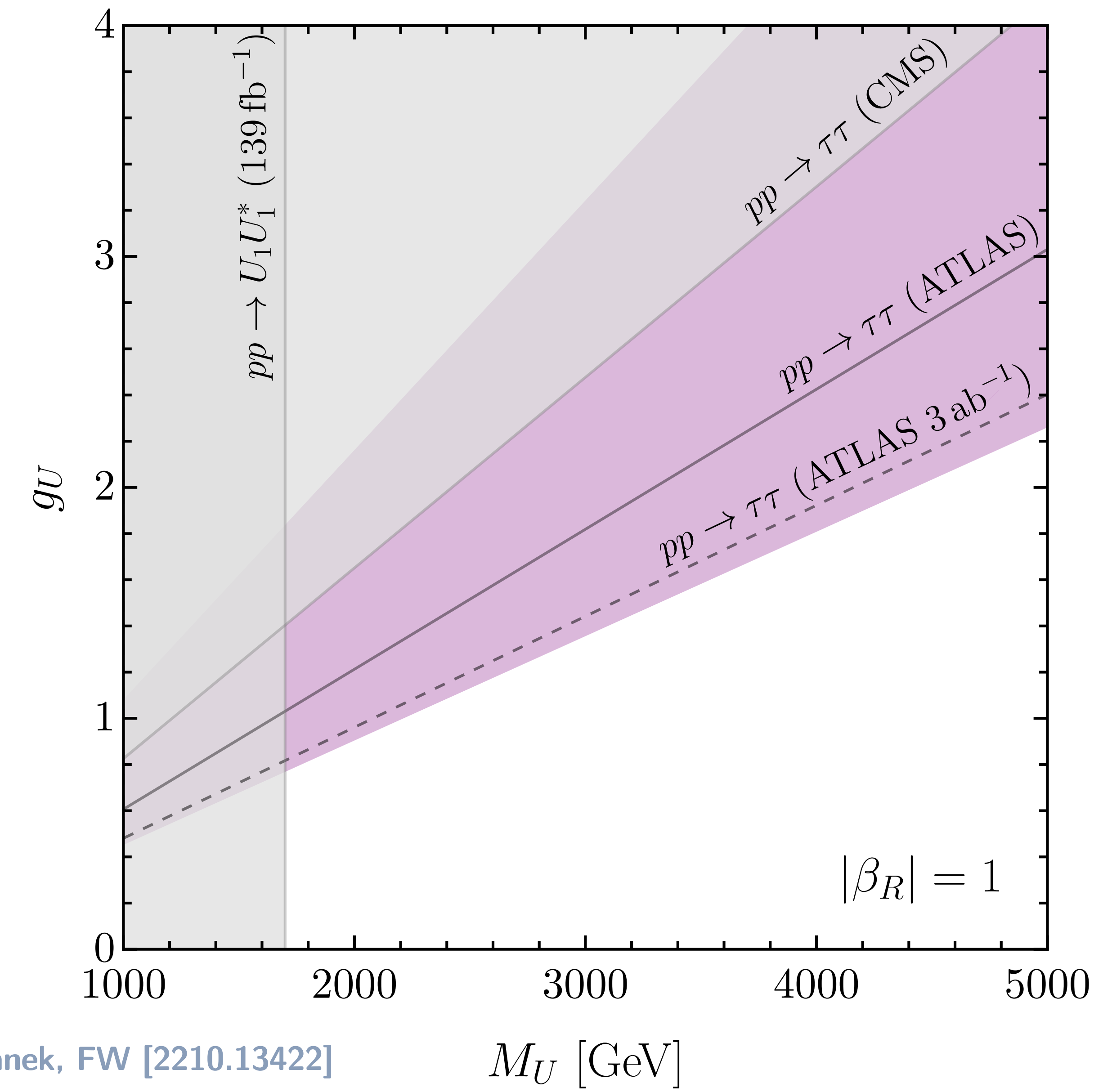
- Constraints on the U_1 leptoquark in the coupling g_U vs. mass M_U plane
  - Preferred regions from low-energy fit **[only left-handed couplings]** **[equal size left- & right-handed couplings]**
  - Excluded from high-p_T Drell-Yan tails

$$\mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3 \gamma_\mu \ell_L^3 + \beta_R \, \bar{d}_R^3 \gamma_\mu e_R^3\right] U_1^\mu + \mathrm{h.c.}$$

$|\beta_R| = 0$



$|\beta_R| = 1$



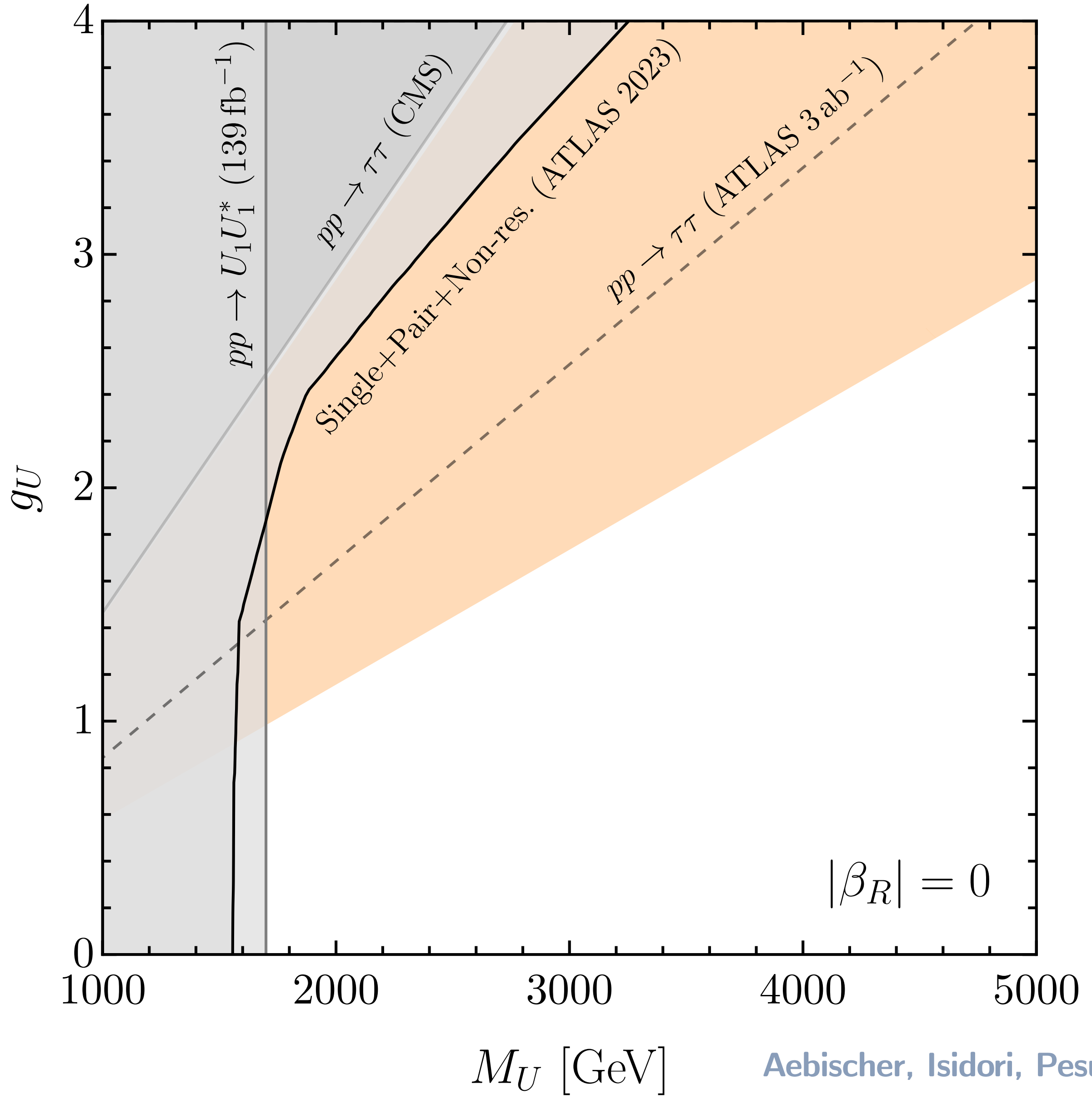
Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]

Comparison of different searches

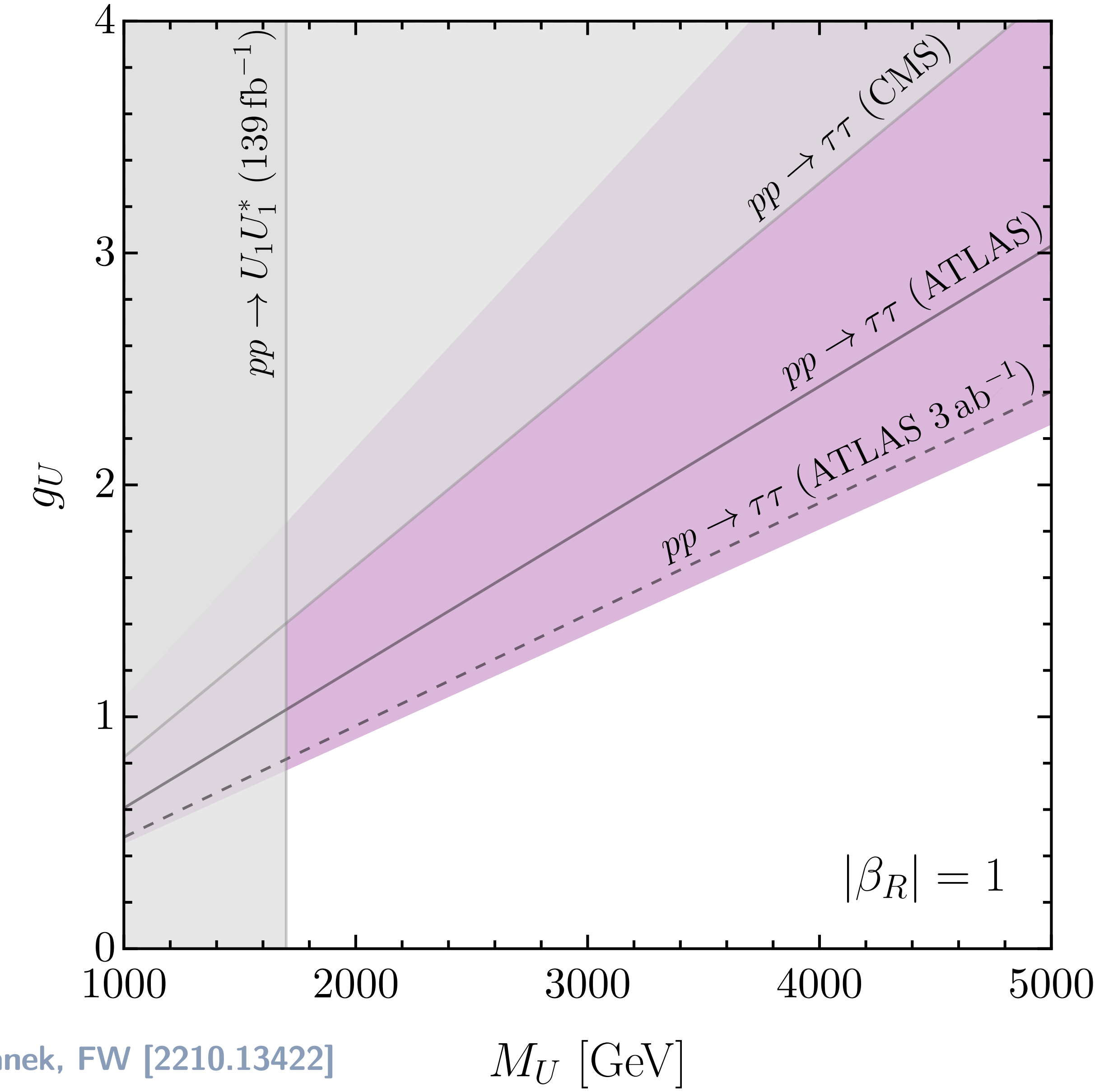
- Constraints on the U_1 leptoquark in the coupling g_U vs. mass M_U plane
  - Preferred regions from low-energy fit **[only left-handed couplings]** **[equal size left- & right-handed couplings]**
  - Excluded from high-p_T Drell-Yan tails

$$\mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3 \gamma_\mu \ell_L^3 + \beta_R \, \bar{d}_R^3 \gamma_\mu e_R^3\right] U_1^\mu + \mathrm{h.c.}$$

$|\beta_R| = 0$



$|\beta_R| = 1$



Aebischer, Isidori, Pesut, Stefanek, FW [2210.13422]

Conclusions

- Leptoquark models well motivated in light of $R_{D^{(*)}}$ anomalies and $\mathscr{B}(B \to K\nu\bar{\nu})$
- To explain anomalies and, at the same time, be compatible with further low-energy data dominant couplings to 3rd generation required
  - LQ models possibly linked to explanations of SM Yukawa structure?
- LQ models can be well tested at LHC:
  - Pair production, single production, Drell-Yan, quark-lepton fusion
  - Sensitivity improvements for 3rd generation LQs by requiring associated b-tagged jets
- Different LQ models viable:
  - U_1 vector leptoquark: large parts of parameter space will be covered by HL-LHC
  - S_1 scalar leptoquark: improvements expected by HL-LHC
  - R_2 scalar leptoquark: already at $2\,\sigma$ tension with current data
- Overall: important complementarity of low- and high-energy data

Backup

$$\mathscr{L}_{U_1} = [x_1^L]_{i\alpha} U_1^\mu (\bar{q}_i \gamma_\mu \ell_\alpha) + [x_1^R]_{i\alpha} U_1^\mu (\bar{d}_i \gamma_\mu e_\alpha) + \mathrm{h.c.} \quad \rightarrow \quad [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$$

- Consider couplings to left-handed fields only $q^L_{3,2}$ and ℓ^L_3 $\rightarrow$ $[C_{lq}^{(1,3)}]_{3333(3323)}$
- Relevant processes: $b\bar{b} \rightarrow \tau^+\tau^-$, $b\bar{s} \rightarrow \tau^+\tau^-$, $b\bar{c} \rightarrow \tau^-\bar{\nu}$ … (+ c.c.)

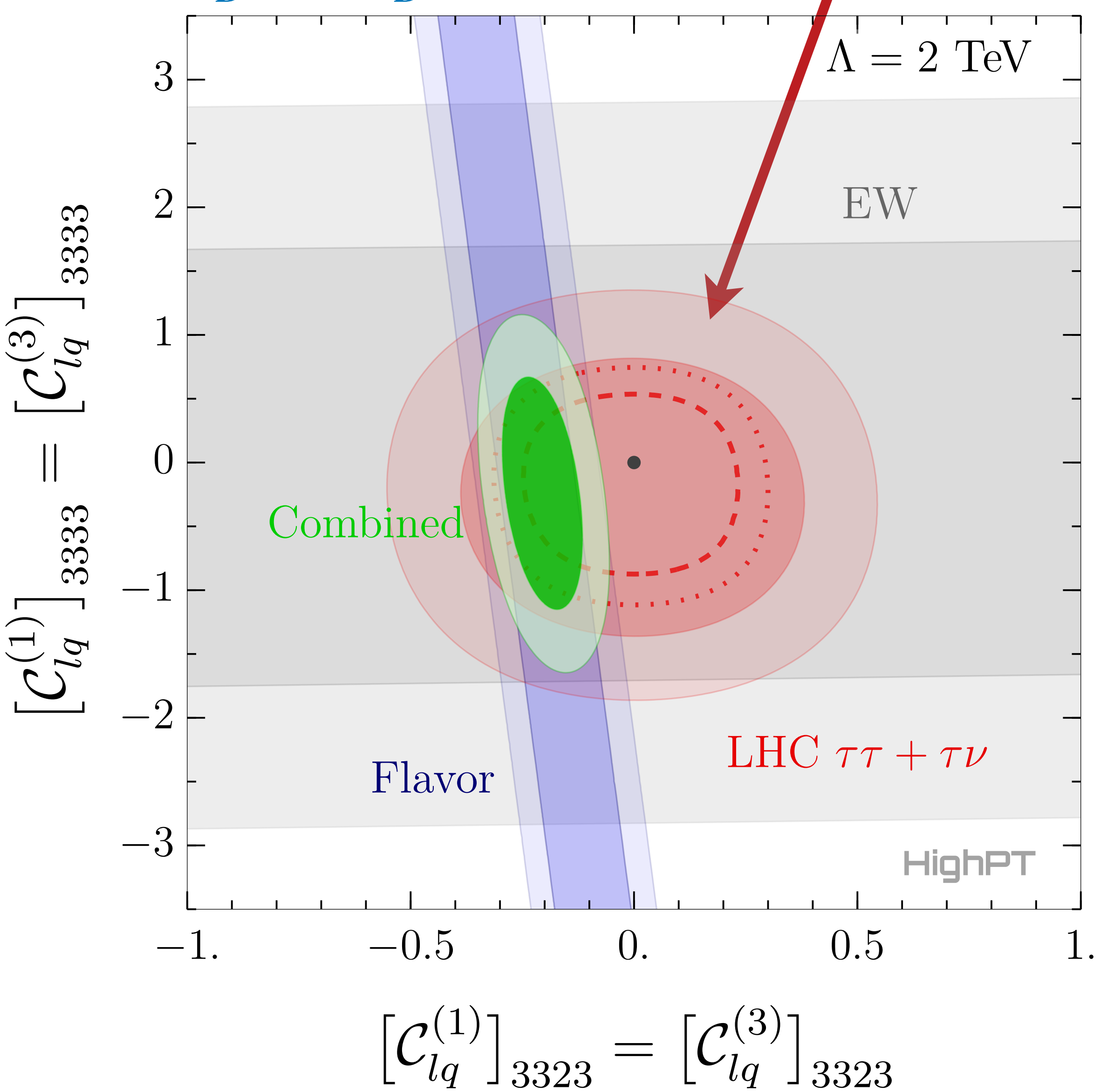
Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714, 2207.10756]

SMEFT fit

EW: $W \rightarrow \tau\nu$

Flavor: R_D and R_{D^*}

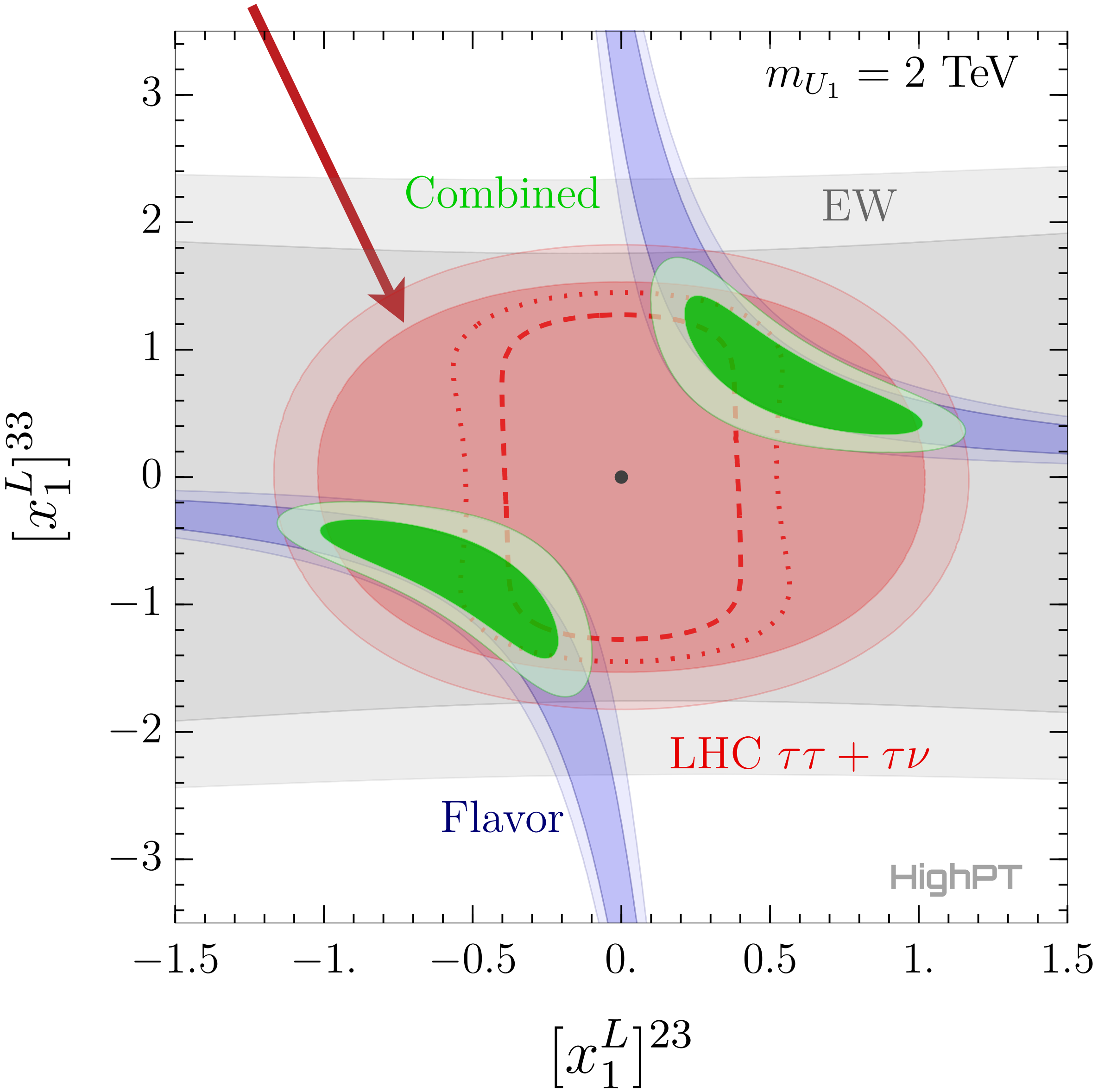
HighPT SMEFT mode



LQ mediator fit

HighPT mediator mode

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



Drell-Yan in light of the $R_{D^{(*)}}$ anomalies: S_1 leptoquark

$$\mathscr{L}_{S_1} = [y_1^L]_{i\alpha} S_1 (\bar{q}_i^c \varepsilon \ell_\alpha) + [y_1^R]_{i\alpha} S_1 (\bar{u}_i^c e_\alpha) + \mathrm{h.c.} \quad \rightarrow$$

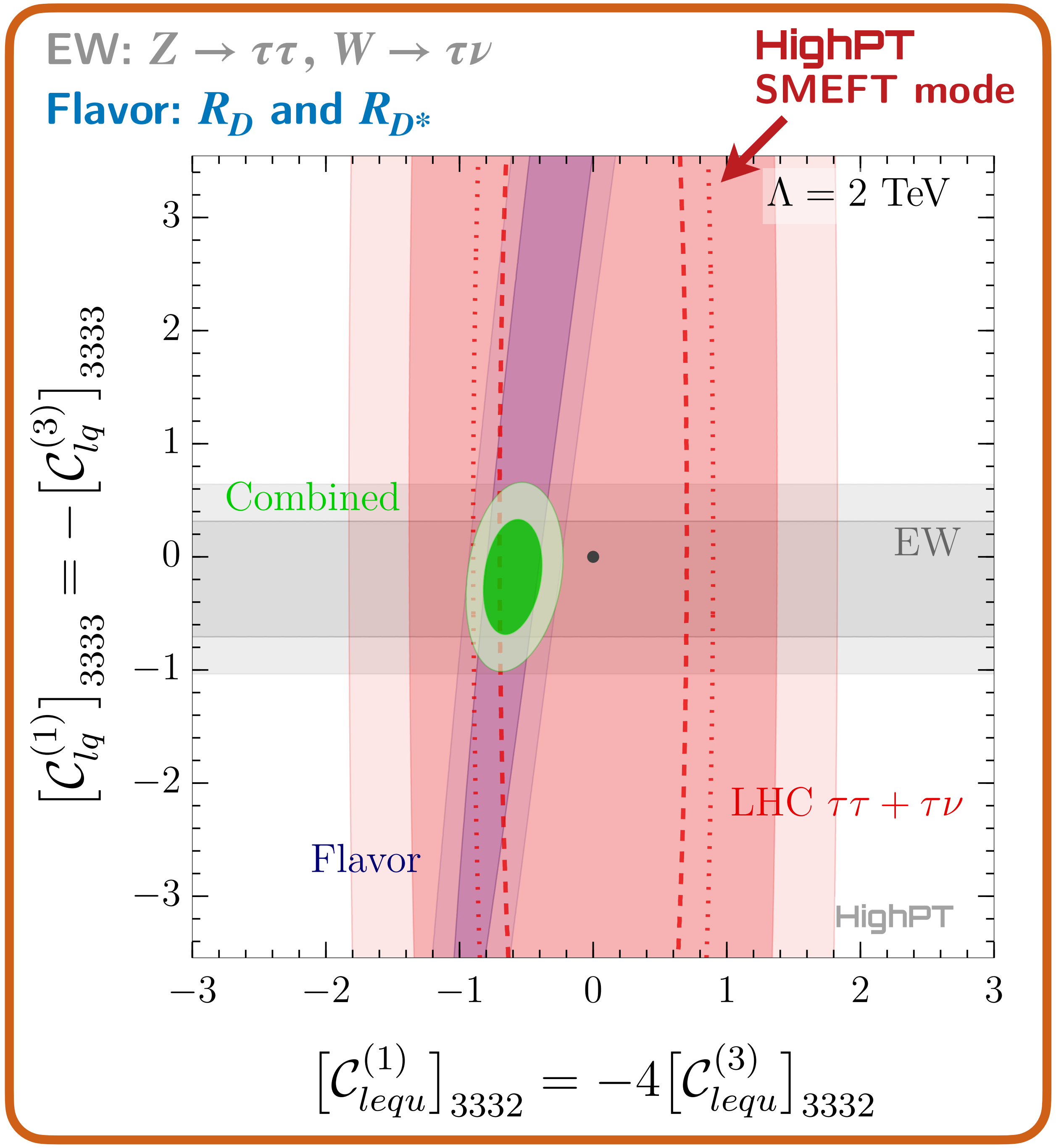
$$[C_{lequ}^{(1)}]_{\alpha\beta ij} = -4[C_{lequ}^{(3)}]_{\alpha\beta ij} = \frac{1}{2}[y_1^L]^*_{i\alpha}[y_1^R]_{j\beta}$$

$$[C_{lq}^{(1)}]_{\alpha\beta ij} = -[C_{lq}^{(3)}]_{\alpha\beta ij} = \frac{1}{4}[y_1^L]_{j\beta}[y_1^L]^*_{i\alpha}$$

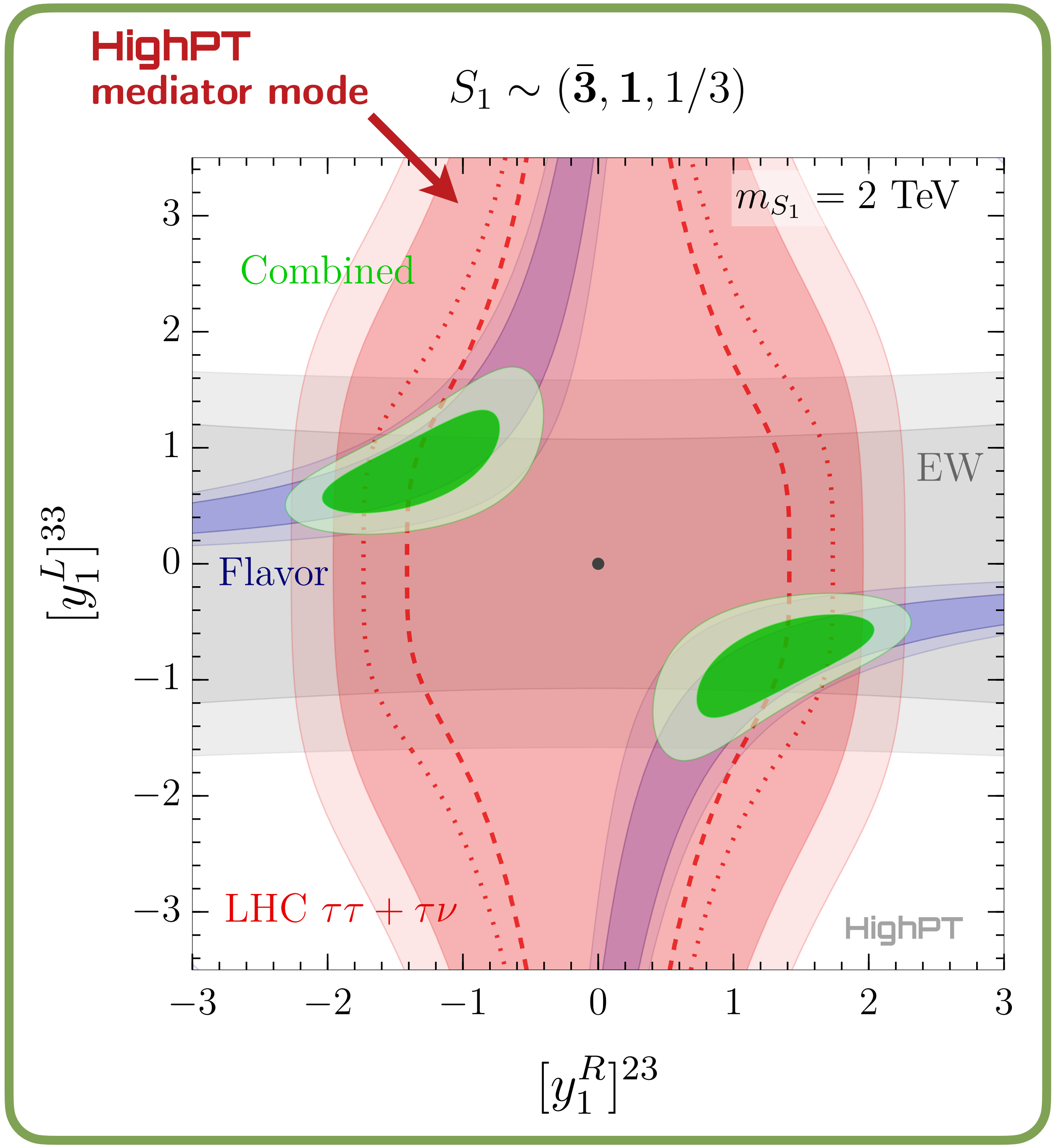
- Consider couplings to 3rd (and 2nd) generation fermions only
- Relevant processes: $b\bar{c} \to \tau^- \bar{\nu}$ ... (+ c.c.)

Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714, 2207.10756]

SMEFT fit



LQ mediator fit



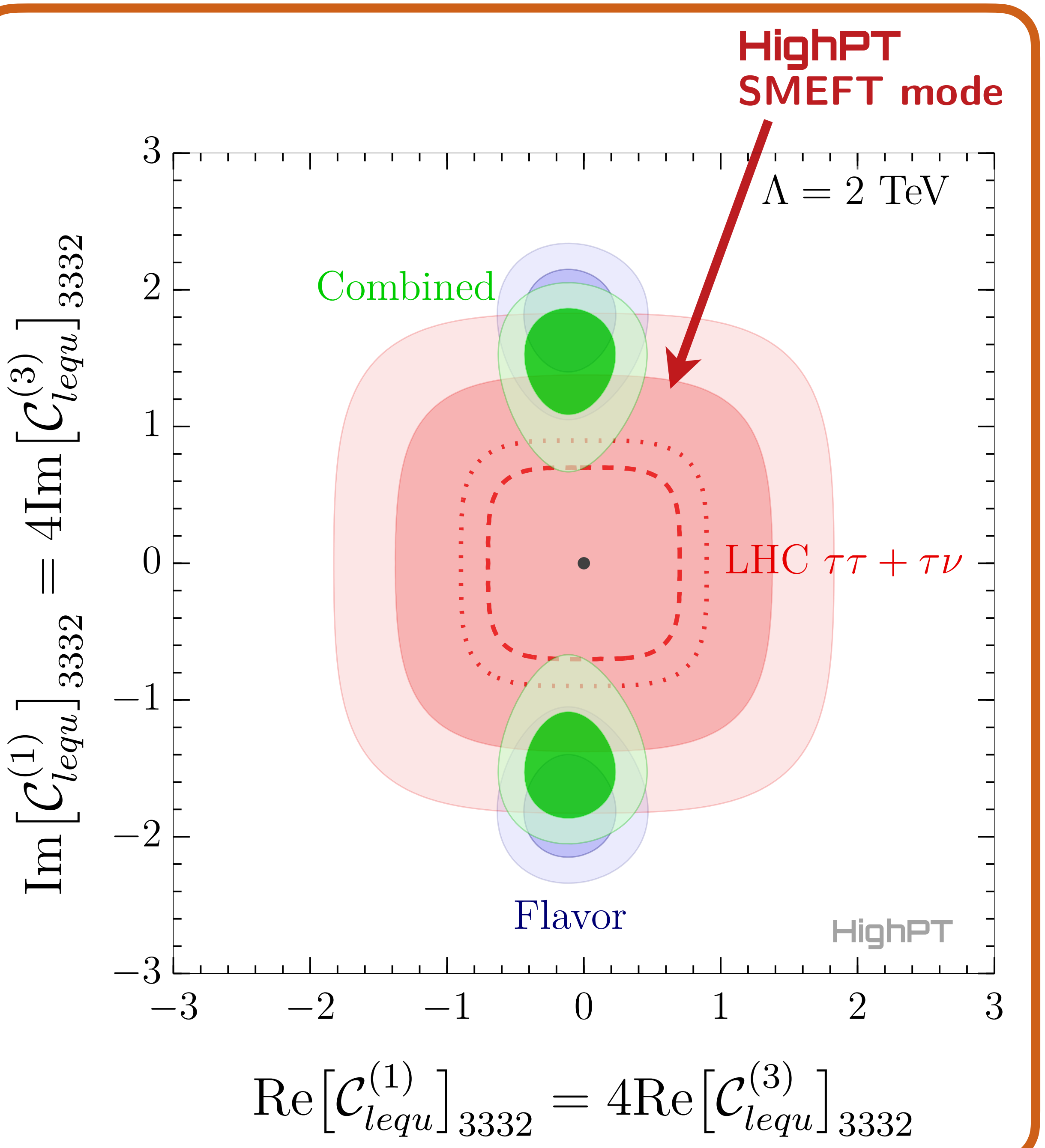
Drell-Yan in light of the $R_{D^{(*)}}$ anomalies: R_2 leptoquark

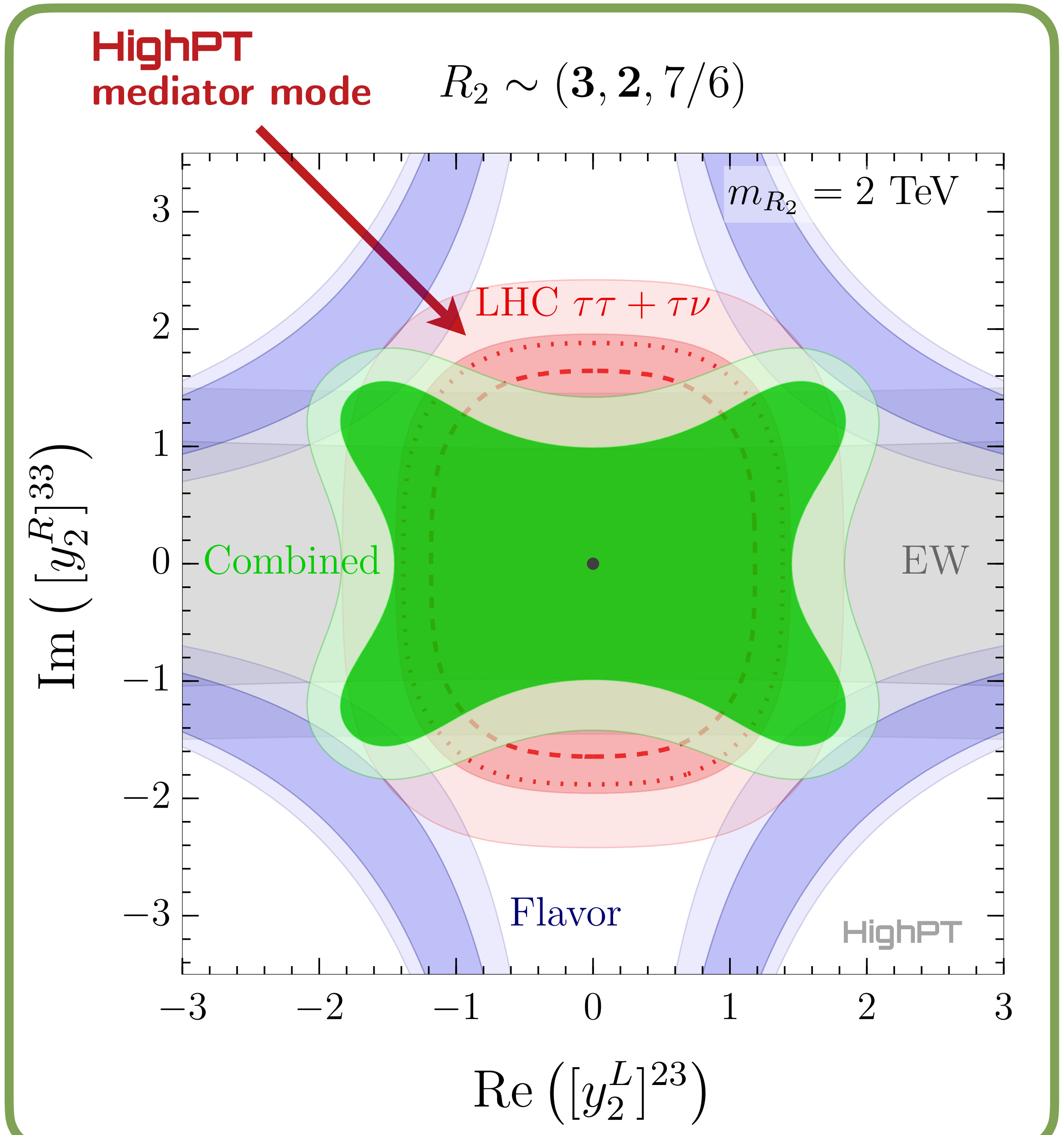
$$\mathscr{L}_{R_2} = -[y_2^L]_{i\alpha}(\bar{u}_i R_2 \varepsilon \ell_\alpha) + [y_2^R]_{i\alpha}(\bar{q}_i e_\alpha) R_2 + \mathrm{h.c.} \quad \rightarrow \quad [C_{lequ}^{(1)}]_{\alpha\beta ij} = 4[C_{lequ}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2}[y_2^R]_{i\beta}[y_2^L]^*_{j\alpha}$$

SMEFT fit

LQ mediator fit

Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714, 2207.10756]

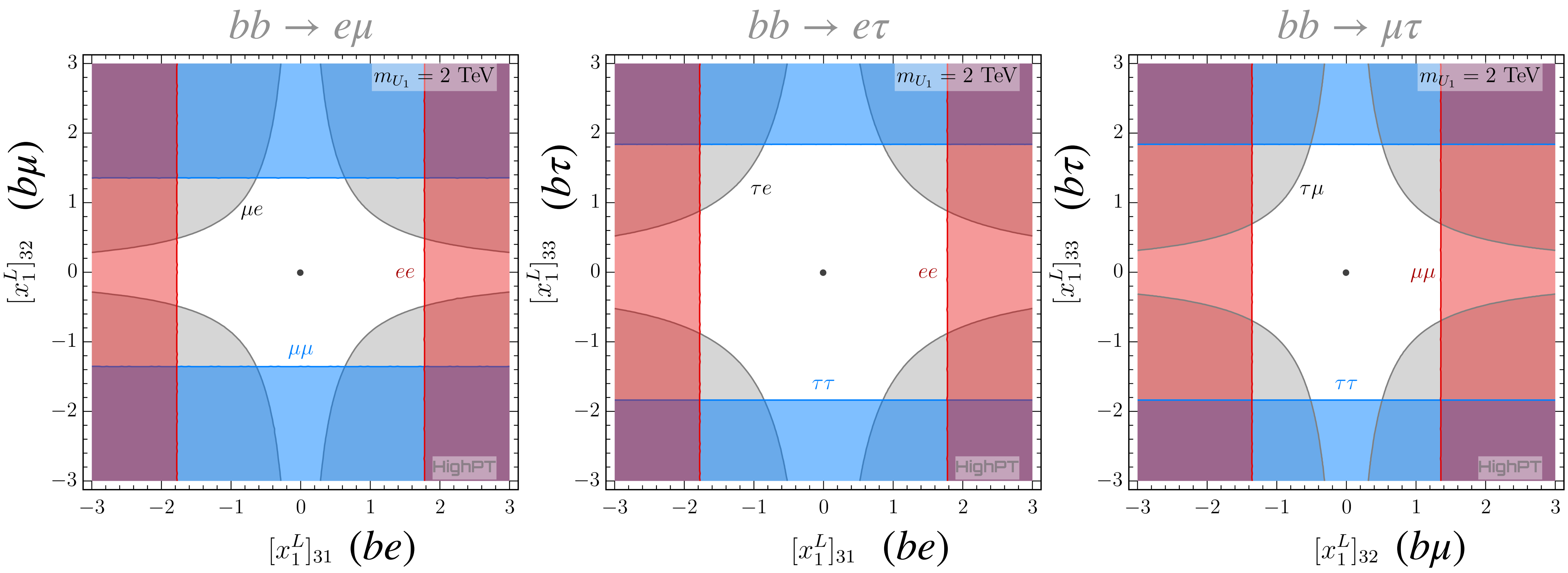




Lepton-Flavor Violation in the U_1 model

Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714, 2207.10756]

- $U_1 \sim (\mathbf{3}, \mathbf{1})_{2/3}$ leptoquark model:
- LFV requires 2 couplings turned on
  - LFV can be constrained by $pp \to \ell\bar{\ell}$ and $pp \to \ell\bar{\ell}'$
- Example: consider only 3rd generation quarks



⇒ LFV searches $pp \to \ell\bar{\ell}'$ can yield complementary information to flavor conserving searches