NEW PHYSICS MODELS GIVING RISE TO LFV (INVOLVING LEPTOQUARKS)

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OUTLINE

- Leptoquarks and flavour symmetries
- Radiative vs. leptonic vs. semileptonic LFV decays
- Examples: $\tau \to \mu$ transitions Vs. Higgs LFV decays / flavour anomalies
- Relation to lepton number violation
- Conclusions

LEPTOQUARKS

New scalar or vector states with renormalizable coupling to lepton and quark

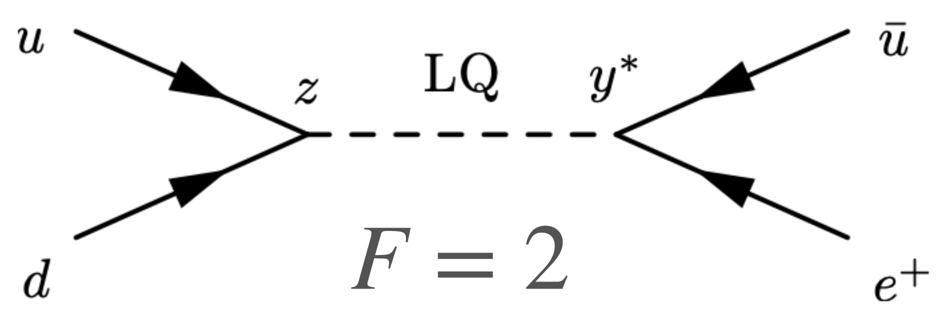
$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L)$, $LR\,(S_{1/2}^R)$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L)$, $\overline{LR}\,(\tilde{S}_{1/2}^{\overline{L}})$	0
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L)$, $RR\,(S_0^R)$, $\overline{RR}\,(S_0^{\overline{R}})$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^R)$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L)$, $LR\,(V_{1/2}^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L)$, $\overline{LR}\,(\tilde{V}_{1/2}^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V_0^L)$, $RR\,(V_0^R)$, $\overline{RR}\,(V_0^{\overline{R}})$	0
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^R)$	0

[Dorsner et al, 1603.04993]

Main features

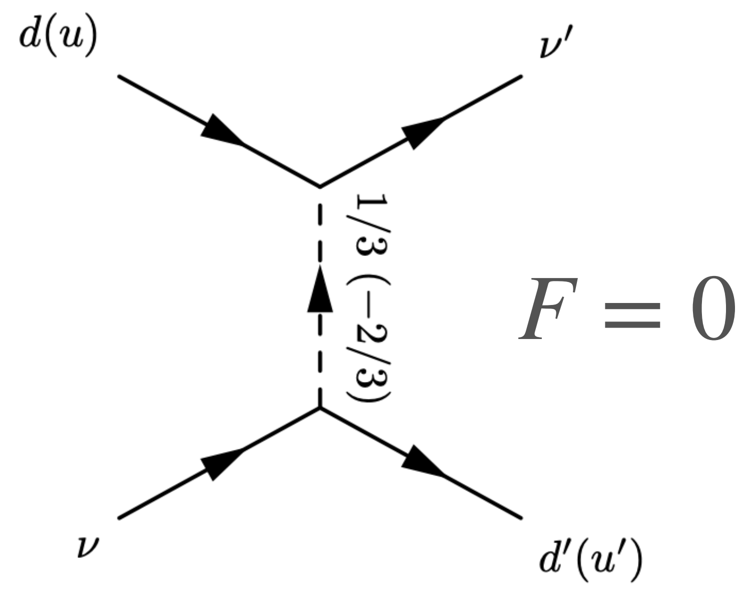
- LQs are color triplets - produced in pairs at the LHC
- F = 3B+L is a fermion number of LQ

- LQs with F=2 can couple also to two quarks and break baryon and lepton number, B and L



diquark coupling should be suppressed

- F = 0 states have well defined B and L - proton is stable*



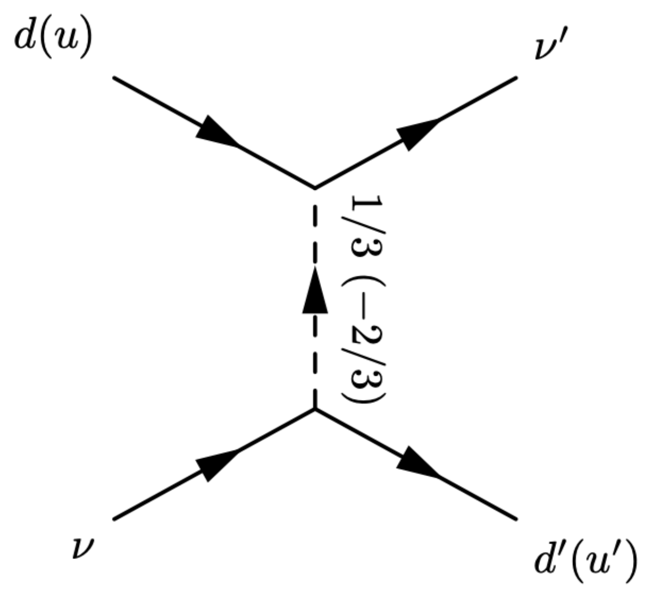
*in scenarios with several LQ states B and/or L can be broken by scalar potential terms

LEPTOQUARKS AND THEIR NUMBERS

- Scalar LQ Yukawa couplings

$$\mathscr{L}_{R_2-\text{Yuk}} = y_R^{ij}\, \bar{Q}_i^a e_j R_2^a + y_L^{ij}\, \bar{u}_{Ri} R_2^{T,a} \epsilon^{ab} L_j^b$$

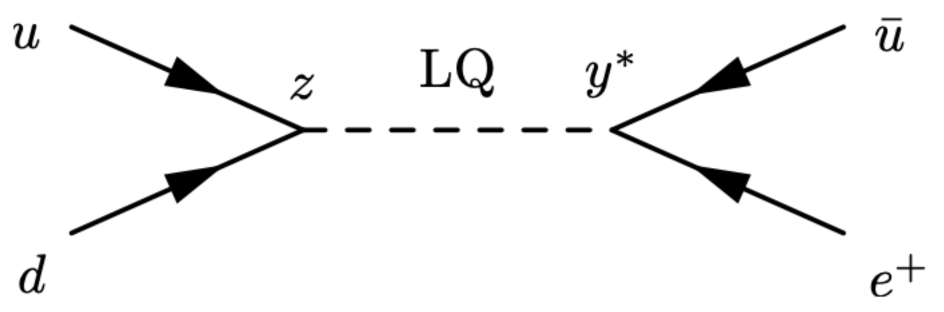
$F = 0$



baryon num. $= 1/3$, lepton num. $= -1$

$$\mathscr{L}_{S_1-\text{Yuk}} = y_R^{ij}\, \overline{u}_i^C e_j\, S_1 + z_R^{ij} \bar{u}_i^C d_j S_1^* + \cdots$$

$F = 2$



baryon num. $= 1/3$, lepton num. $= 1$

or

baryon num. $= 2/3$, lepton num. $= 0$?

$\Rightarrow B$ and L are broken,

$B - L$ still conserved*

* Since $q\ell$ and $\bar{q}\bar{q}$ both have equal $B - L = -2/3$

LEPTOQUARKS AND FLAVOR

Lepton flavour:

- kinetic and scalar parts enjoy
  $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm scalar} + \mathcal{L}_{\rm Yuk}$$

$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$

broken down to

$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$

$\mathcal{L}_{\rm LQ-Yuk}$

broken down to (in most general case)

$$\begin{cases} U(1)_B \times U(1)_L & ; \quad \text{LQ with } F = 0 \\ U(1)_{B-L} & ; \quad \text{LQ with } F = 2 \end{cases}$$

Lepton flavours can be partially conserved, depending on the ``texture'' of the LQ Yukawa matrices.

Lepton flavour symmetric example:

$$y_R^{ij}\, \bar{Q}_i^a e_j R_2^a = \left(\bar{d}, \bar{s}, \bar{b}\right) \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ y_R^{d\tau} & y_R^{s\tau} & y_R^{b\tau} \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} R_2^{2/3} + \cdots$$

… since for R_2 we can set $L_e = 0, L_\mu = 0, L_\tau(R_2) = -1$ and keep lepton flavour conserved.
Common (ad-hoc) choice when in addressing flavour anomalies.

LEPTOQUARKS AND FLAVOR

Lepton flavour violating (LFV) example:

$$y_R^{ij}\,\bar{Q}_i^a e_j R_2^a = (\bar{d},\bar{s},\bar{b})\begin{pmatrix} 0 & 0 & 0 \\ y_R^{d\mu} & y_R^{s\mu} & y_R^{b\mu} \\ y_R^{d\tau} & y_R^{s\tau} & y_R^{b\tau} \end{pmatrix}\begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} R_2^{2/3}$$

$L_e = 0$ and L_e conserved ✅

However, there is a conflict between

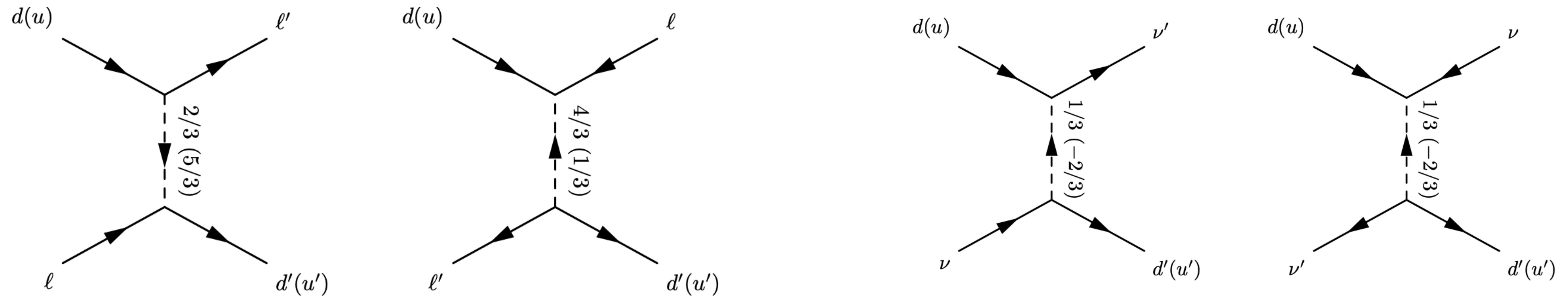
$L_\mu = 0, L_\tau = -1$

and

$L_\mu = -1, L_\tau = 0$

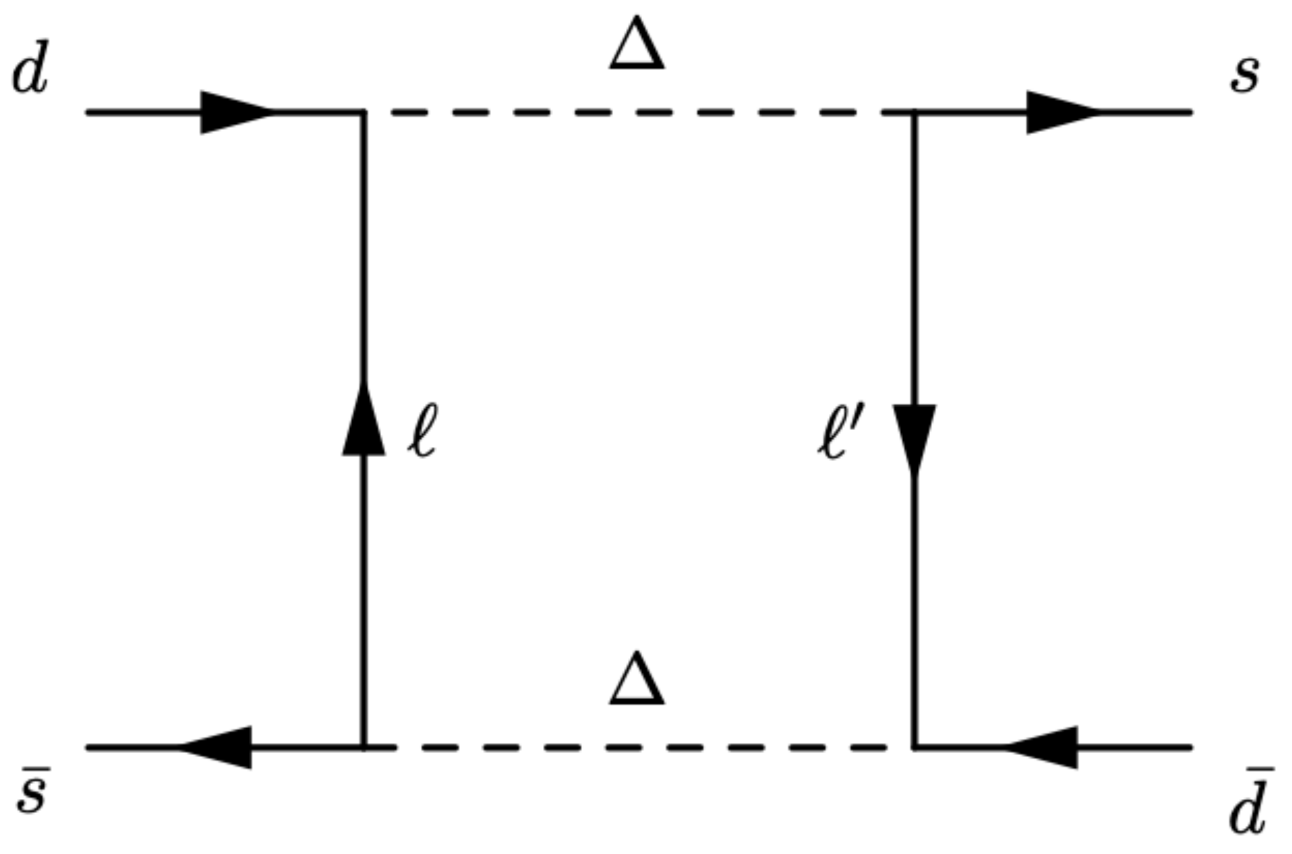
$\Rightarrow L_\mu, L_\tau$ are broken ❌

Natural processes for LFV and quark flavour violation are semileptonic operators

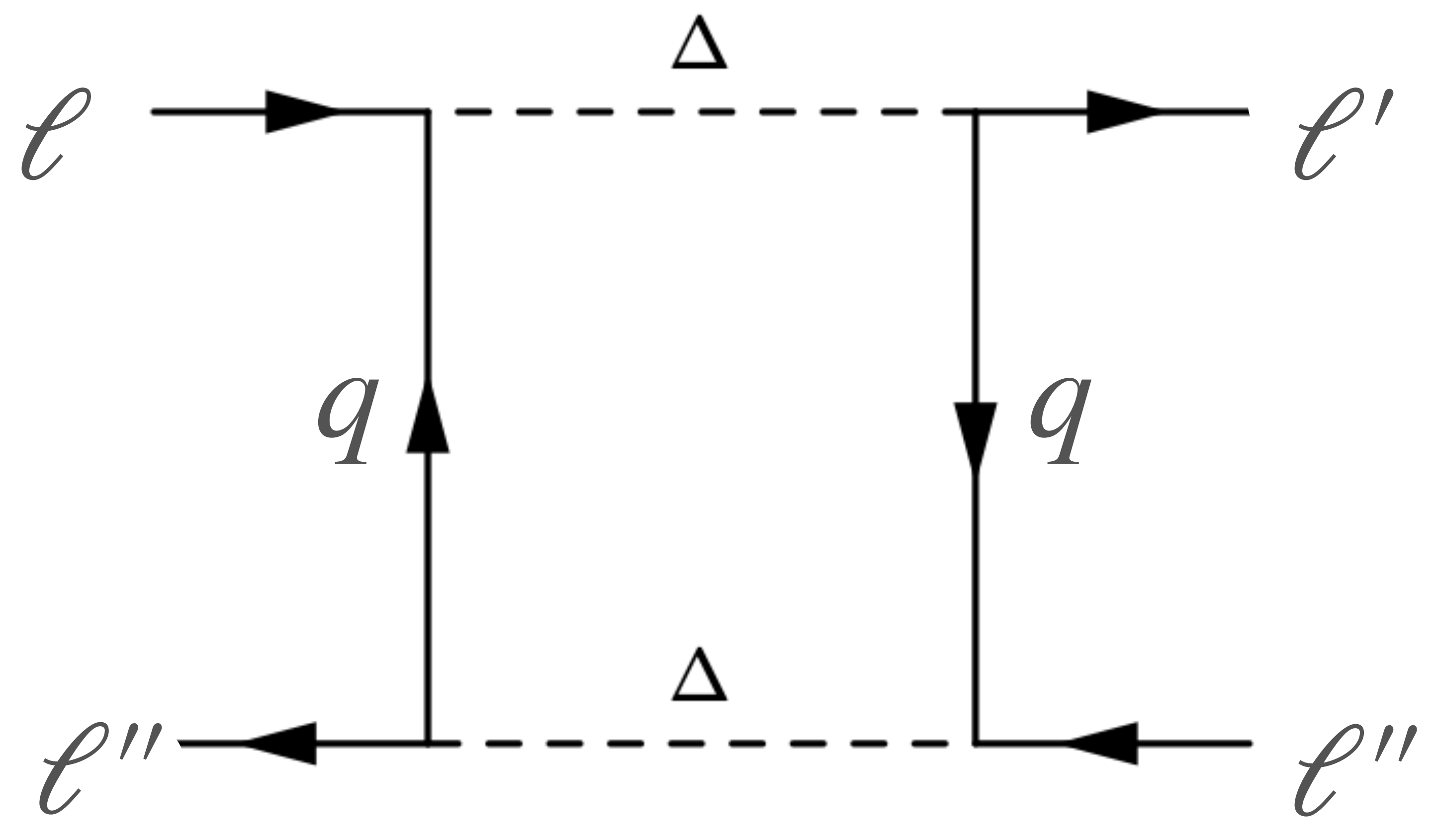


LEPTOQUARKS AND FLAVOR

Hadronic and leptonic processes with flavor violation are always loop-suppressed.



$\Delta S = 2$



LFV

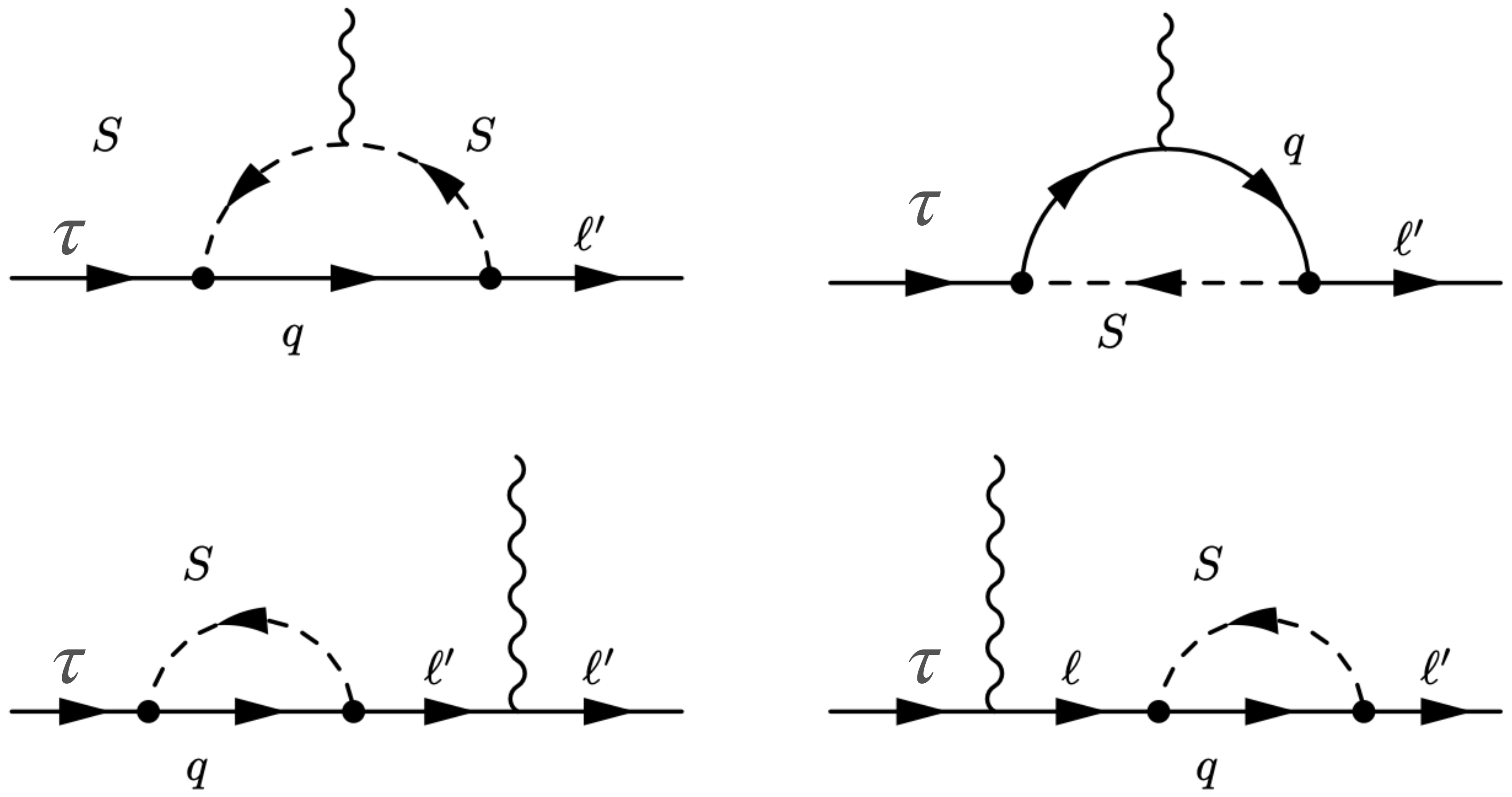
One of the reasons LQs have been so successful in targeting precisely semileptonic processes without usurping (too much) neutral meson mixing or LFV observables.

If we want to modify a single lepton flavor, LFV can be avoided with suitable choice of LQ couplings.

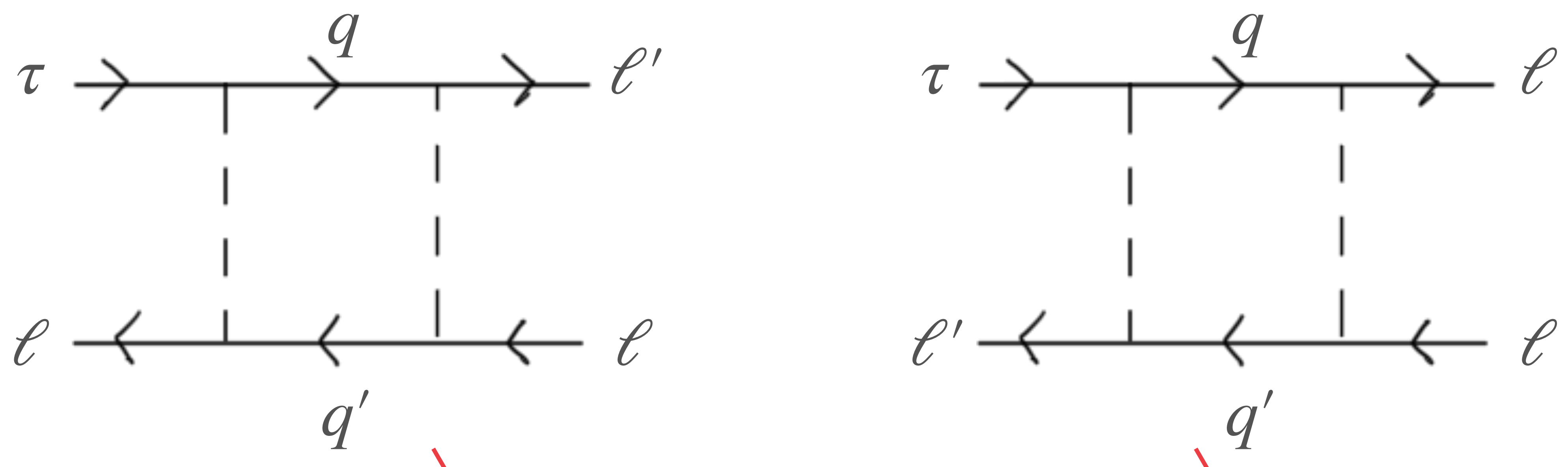
LFV IN LEPTONIC DECAYS

Short-distance penguins and/or boxes

$\tau \to \ell' \gamma$



$\tau \to \ell' \ell^+ \ell^-$



$$\mathcal{A}_{\tau\to\ell'\gamma} \sim \frac{\sum_q y_{q\tau} y^*_{q\ell'}}{(4\pi)^2 m^2_{\rm LQ}}$$

$$\mathcal{A}_{\tau\to\ell'\ell^+\ell^-} \sim \frac{1}{(4\pi)^2 m^2_{\rm LQ}} \left[\sum_q y_{q\tau} y^*_{q\ell'} \sum_{q'} |y_{q'\ell}|^2 + \sum_q y_{q\tau} y^*_{q\ell} \sum_{q'} y_{q'\ell} y^*_{q'\ell'} \right]$$

like "rescaled" $\mathscr{A}_{\tau\to\ell'\gamma}$

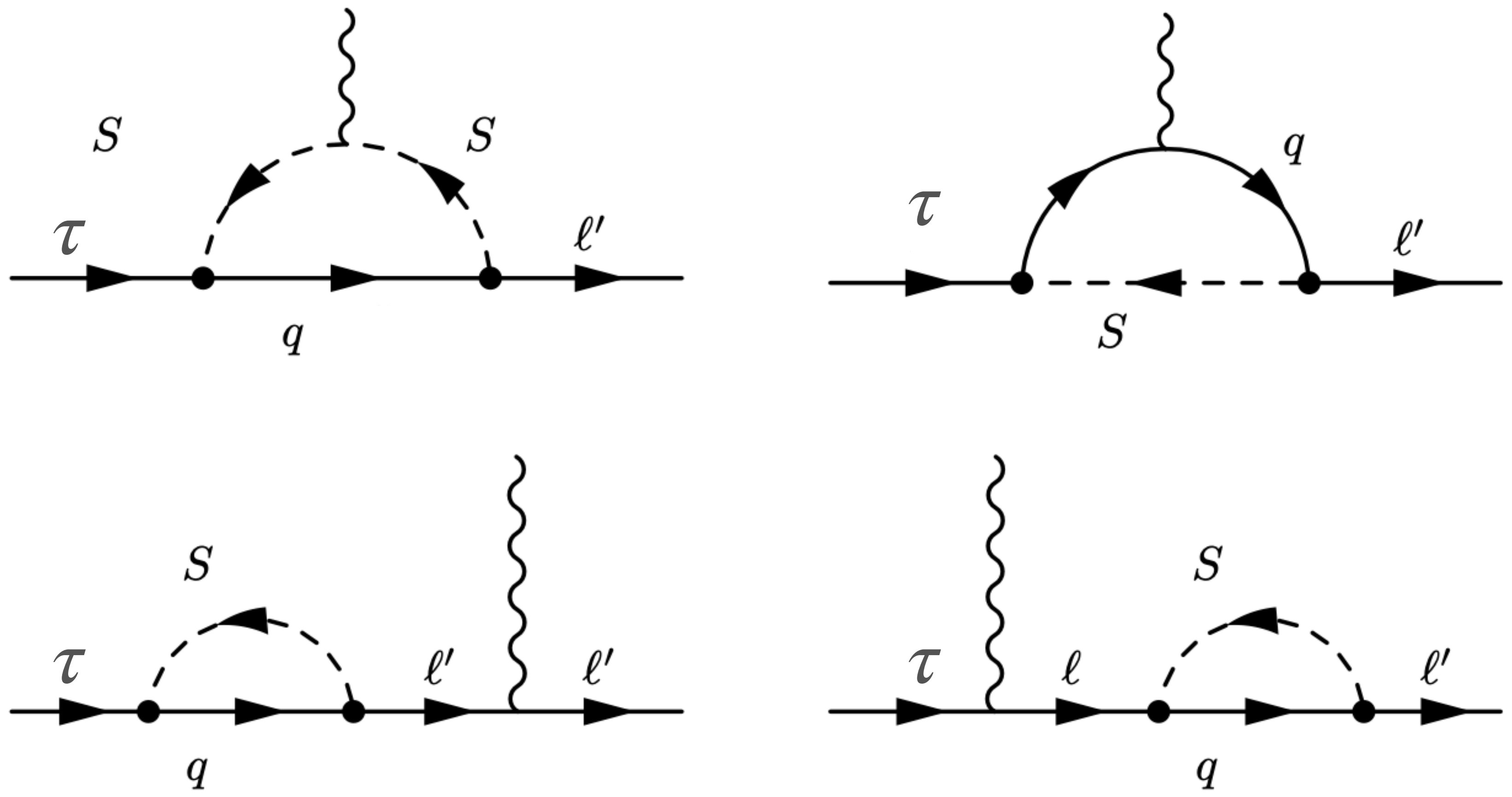
crossed

Radiative mode scales as $\dfrac{y}{m_{\rm LQ}}$, opposed to scaling of leptonic mode: $\dfrac{y}{\sqrt{m_{\rm LQ}}}$. Leptonic decays is more sensitive to larger leptoquark masses. However there are additional long-distance LFV effects + additional semileptonic constraints.

LFV IN LEPTONIC DECAYS

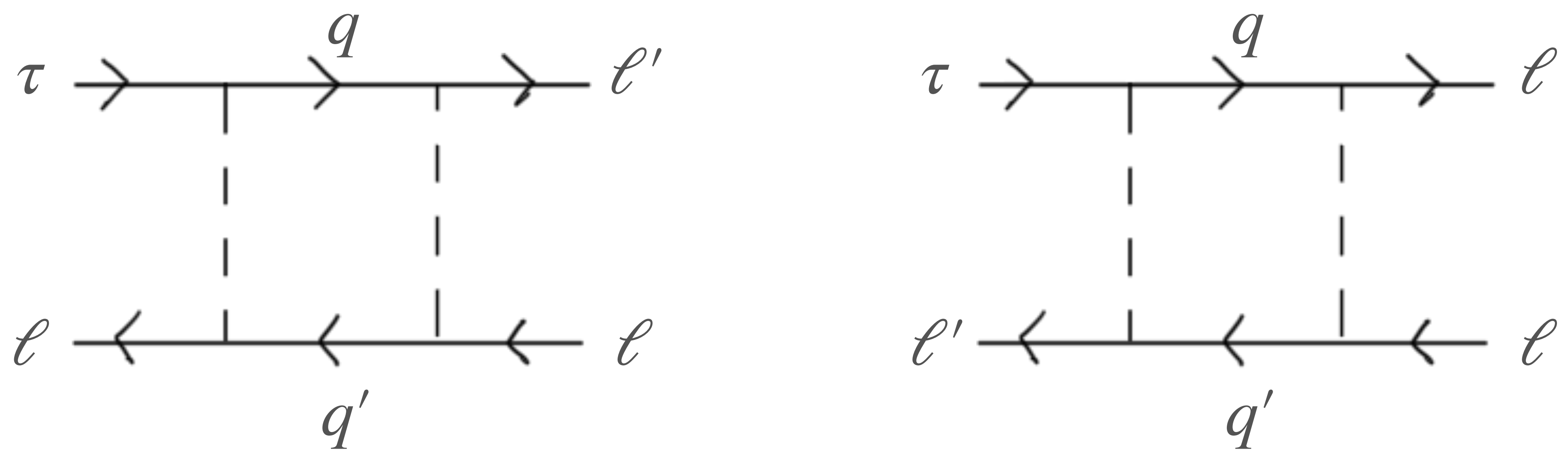
Short-distance penguins and/or boxes

$\tau \to \ell' \gamma$



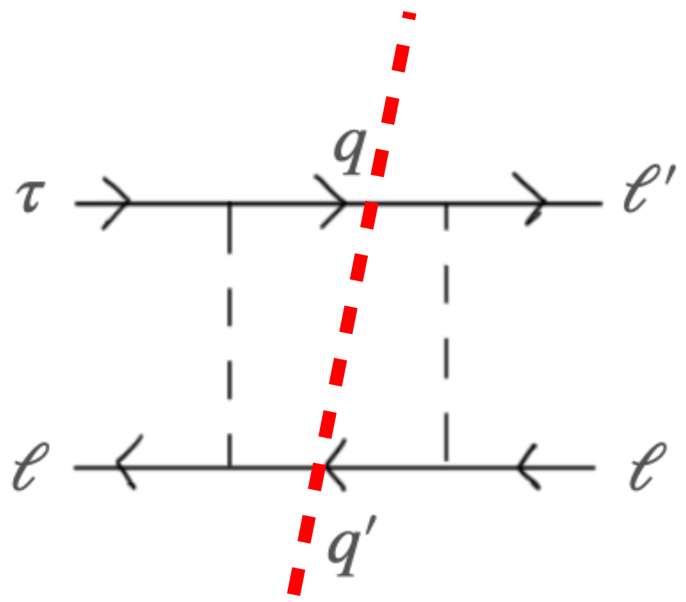
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$

$\tau \to \ell' \ell^+ \ell^-$



Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$

Both decay modes should be interpreted together with related tree-level processes



$\tau \to \text{hadrons}(q\bar{q}')\ell'$

$pp \to \tau\ell'$ at LHC [L. Allwicher et al (HighPT))

$B \to \tau\ell'(H)$

- [Plakias, Sumensari, 2312.14070]

SENSITIVITIES OF LFV PROCESSES

Tree-level contributions of effective operators at low energies

$$\frac{1}{\Lambda^2} \mathrm{C}_{\mathrm{SLL}} \, (\bar{\mu} P_L \tau)\, (\bar{\mu} P_L \mu)$$

$$\frac{1}{\Lambda^2} \mathrm{C}_{\mathrm{VLL}} \, (\bar{\mu} \gamma^\mu P_L \tau)\, (\bar{\mu} \gamma_\mu P_L \mu)$$

4-lepton operators: $\mathrm{C}_{\mathrm{SLL,RR}}$, $\mathrm{C}_{\mathrm{VLL,RR}}$, $\mathrm{C}_{\mathrm{VLR,RL}}$

EM dipole: $\mathrm{C}_{\mathrm{DL,R}}$

semileptonic operators: $\mathrm{C}^q_{\mathrm{VL,R}}$, $\mathrm{C}^q_{\mathrm{SL,R}}$, $\mathrm{C}_{\mathrm{GL,R}}$, $\mathrm{C}^q_{\mathrm{AL,R}}$, $\mathrm{C}^q_{\mathrm{PL,R}}$

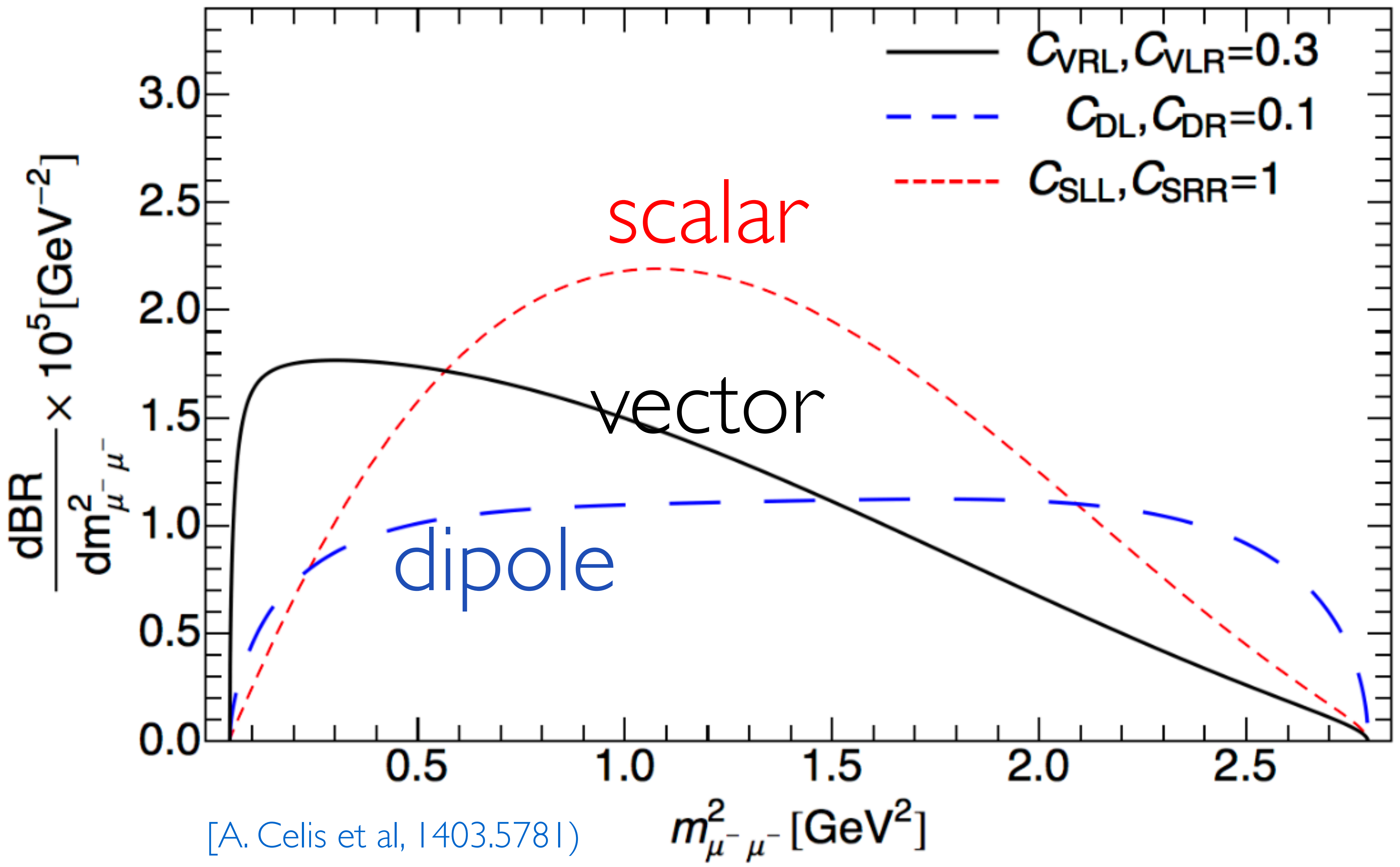
	$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$\mathrm{C}_{\mathrm{SLL,RR}}$	✓	–	–	–	–	–
$\mathrm{C}_{\mathrm{VLL,RR}}$	✓	–	–	–	–	–
$\mathrm{C}_{\mathrm{VLR,RL}}$	✓	–	–	–	–	–
$\mathrm{C}_{\mathrm{DL,R}}$	✓	✓	✓	✓	–	–
$\mathrm{C}^q_{\mathrm{VL,R}}$	–	–	✓ (I=1)	✓(I=0,1)	–	–
$\mathrm{C}^q_{\mathrm{SL,R}}$	–	–	✓ (I=0)	✓(I=0,1)	–	–
$\mathrm{C}_{\mathrm{GL,R}}$	–	–	✓	✓	–	–
$\mathrm{C}^q_{\mathrm{AL,R}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
$\mathrm{C}^q_{\mathrm{PL,R}}$	–	–	–	–	✓ (I=1)	✓ (I=0)
$\mathrm{C}_{\tilde{\mathrm{G}}\mathrm{L,R}}$	–	–	–	–	–	✓

In LQ models semileptonic operators come at tree-level, while 4-lepton interaction are loop suppressed.

[A. Celis et al, 1403.5781]

LEPTOQUARKS AND LFV IN LEPTONIC DECAYS

How to disentangle the information that's hidden in $\tau \to \ell' \ell^+ \ell^-$ Dalitz plot?



[A. Celis et al, 1403.5781)

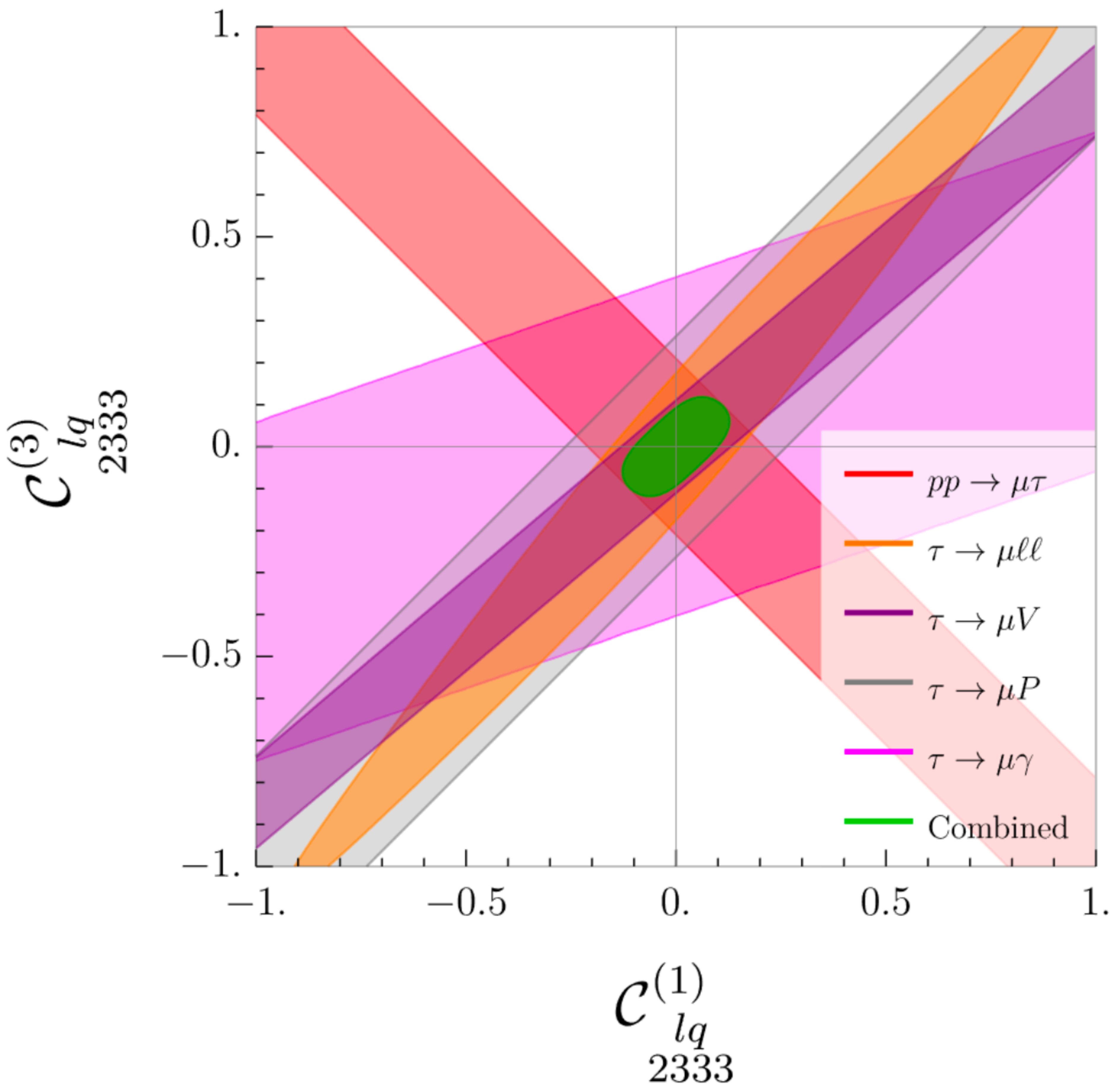
- if $\tau \to \ell' \ell^+ \ell^-$ is observed, dimuon spectrum differentiates between low energy operators
- scalar arises only at dim-8 in SMEFT
- LQs contribute to both vector and dipole ops.

[Giffels et al, 0802.0049]
[Matsuzaki, Sanda, 0711.0792]
[Kuno,Okada, hep-ph/9909265]

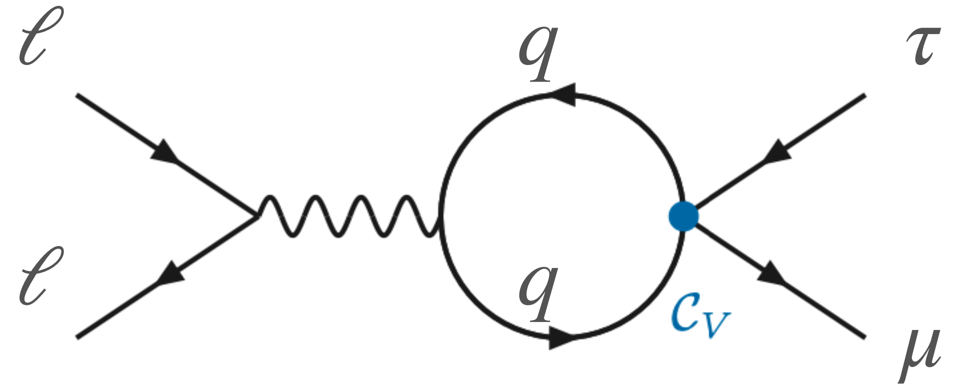
- In LQ model one has to incorporate LFV resonant ``backgrounds'' e.g. $\tau \to (\phi, \rho)\ell'$
- Just a first estimate - in a complete picture all operators are correlated

SM-EFT ANALYSIS

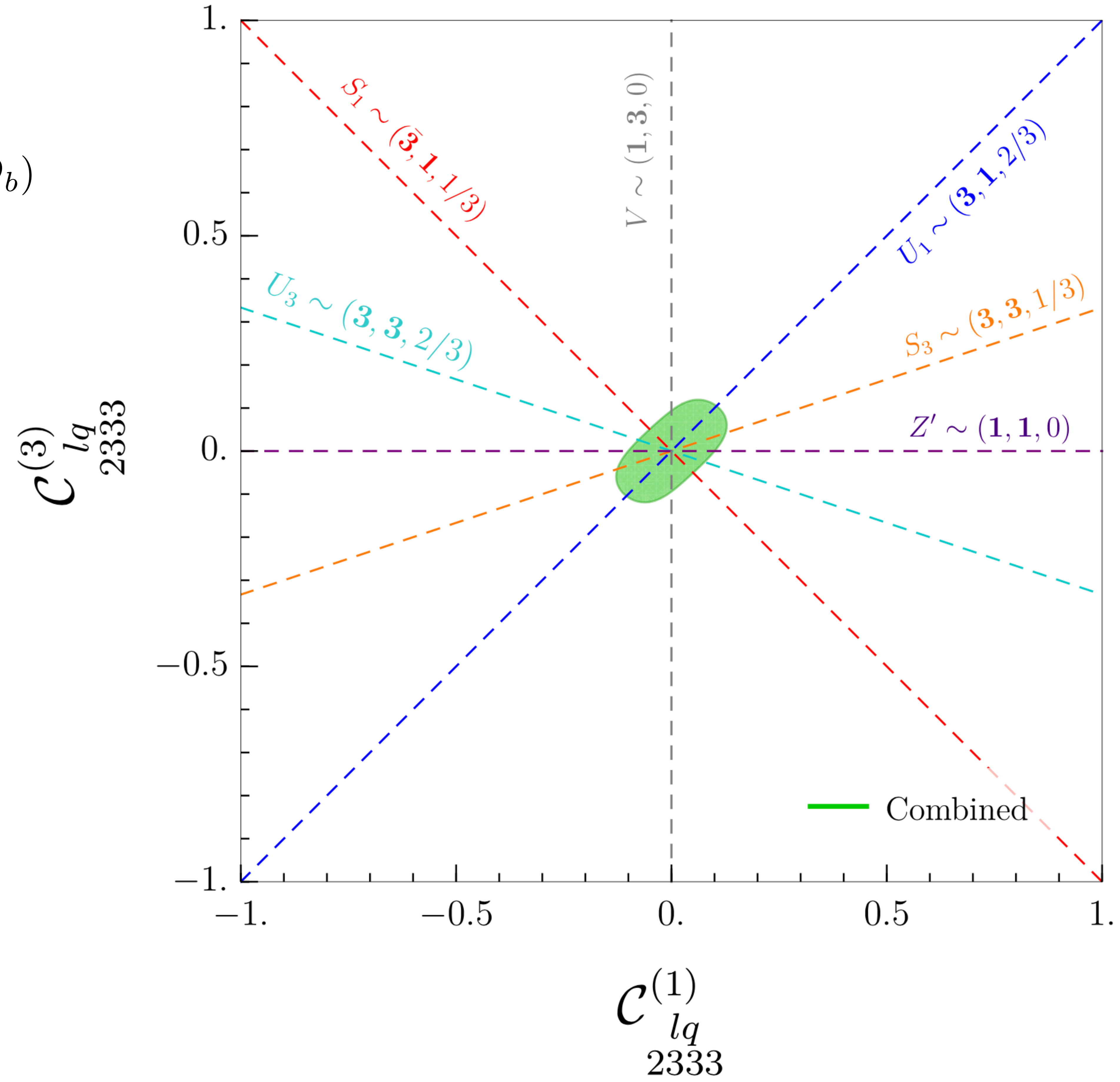
- SM effective field theory, suited for heavy new physics mediators, defined at energy scale $\gg m_t$
- Streamlined approach of matching and RG evolution to lower energy scales [e.g. Matchete, MatchmakerEFT, wilson, flavio, + many more]
- $2.5\,k$ parameters in full generality
- LFV due to only a small subset of parameters



$$\mathcal{O}^{(1)}_{\substack{lq\\2333}} = (\bar{L}_\mu \gamma^\mu L_\tau)(\bar{Q}_b \gamma_\mu Q_b)$$
$$\mathcal{O}^{(3)}_{\substack{lq\\2333}} = (\bar{L}_\mu \sigma^A \gamma^\mu L_\tau)(\bar{Q}_b \sigma^A \gamma_\mu Q_b)$$



- [Plakias, Sumensari, 2312.14070]

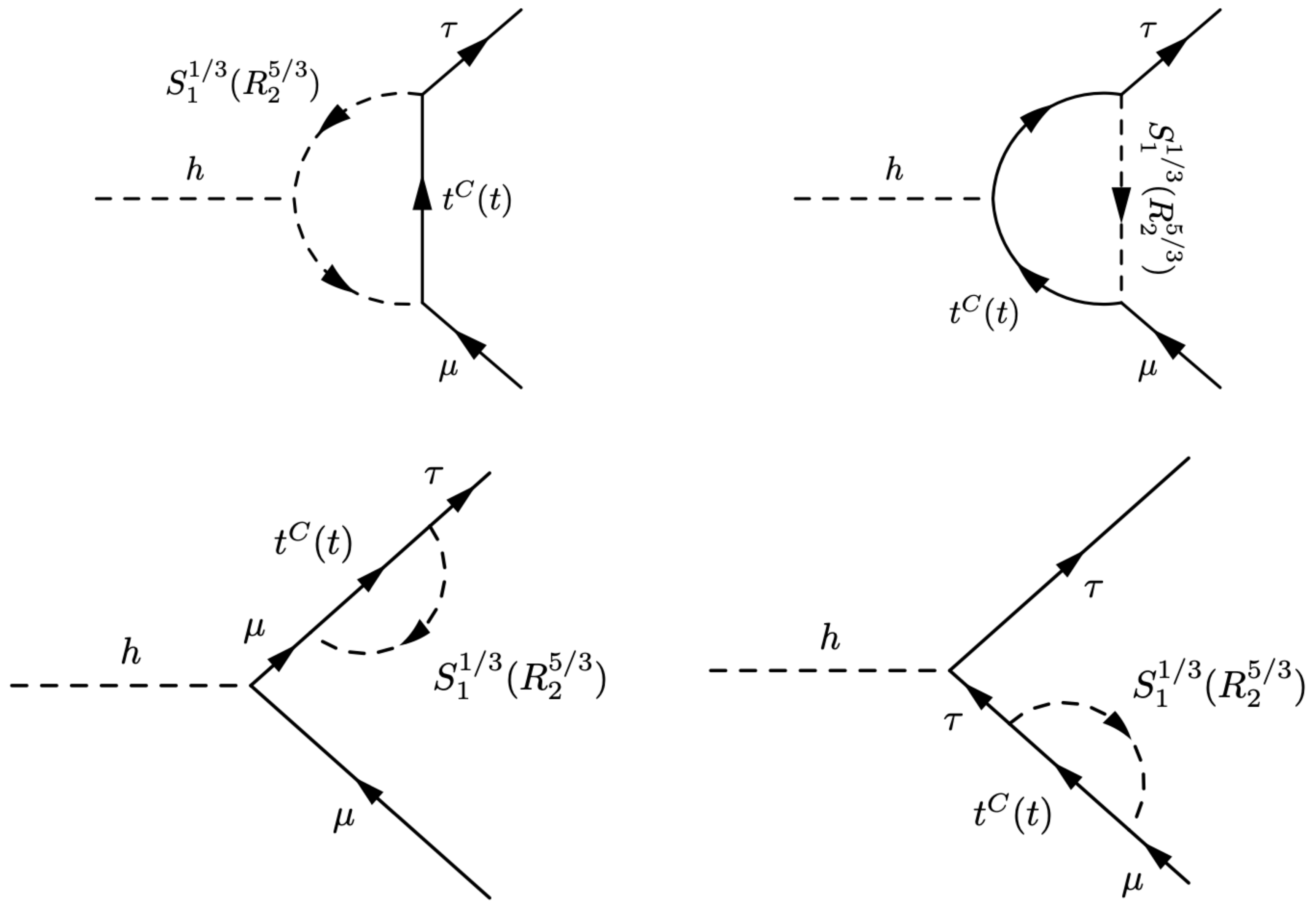


EXAMPLE: CAN HIGGS DECAY INTO A LEPTON FLAVORED STATE?

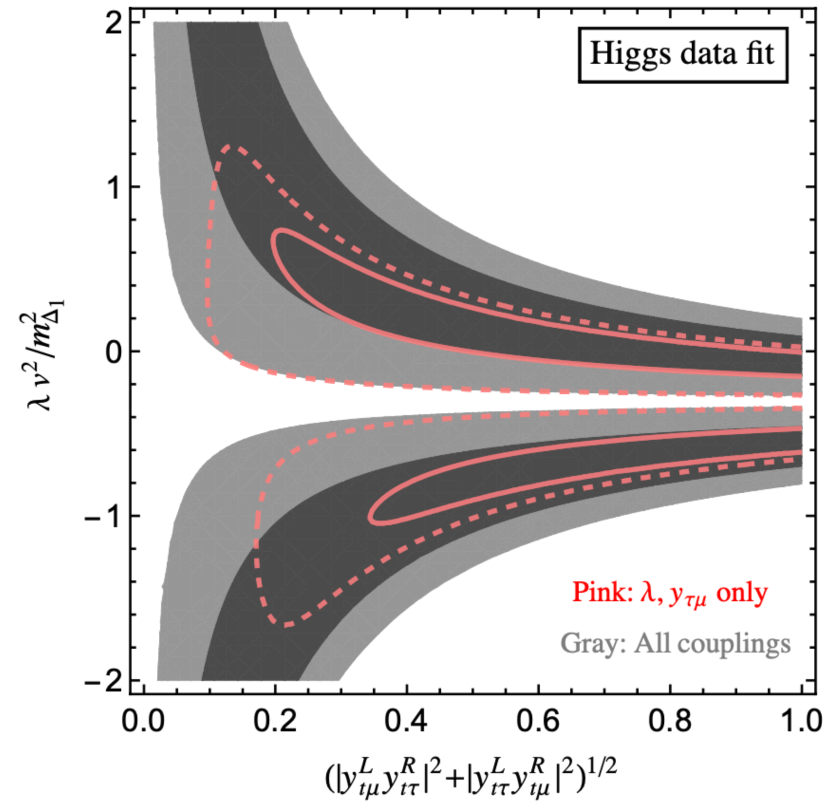
Γ_{22}	$e\mu$	LF	$< 6.1 \times 10^{-5}$	CL=95%
Γ_{23}	$e\tau$	LF	$< 2.2 \times 10^{-3}$	CL=95%
Γ_{24}	$\mu\tau$	LF	$< 1.5 \times 10^{-3}$	CL=95%

Current bounds on $h \to \ell\ell'$
by ATLAS & CMS

How much Higgs LFV is allowed in a model with a single LQ mediator?



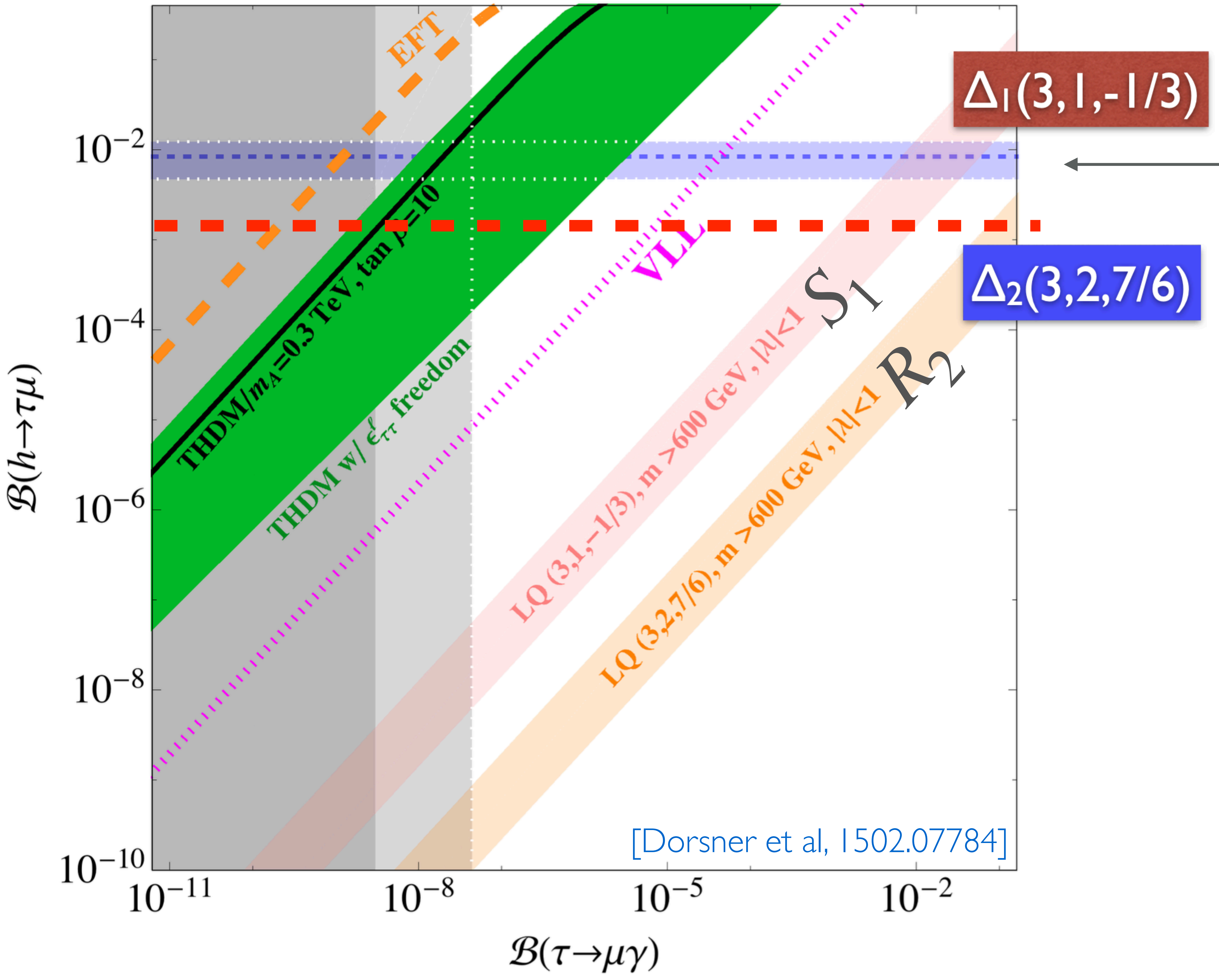
Higgs portal coupling
is constrained



EXAMPLE: CAN HIGGS HAVE LFV DECAYS?

Current bounds on $h \to \ell\ell'$
by ATLAS & CMS

Γ_{22}	$e\mu$	LF	$< 6.1 \times 10^{-5}$	CL=95%
Γ_{23}	$e\tau$	LF	$< 2.2 \times 10^{-3}$	CL=95%
Γ_{24}	$\mu\tau$	LF	$< 1.5 \times 10^{-3}$	CL=95%

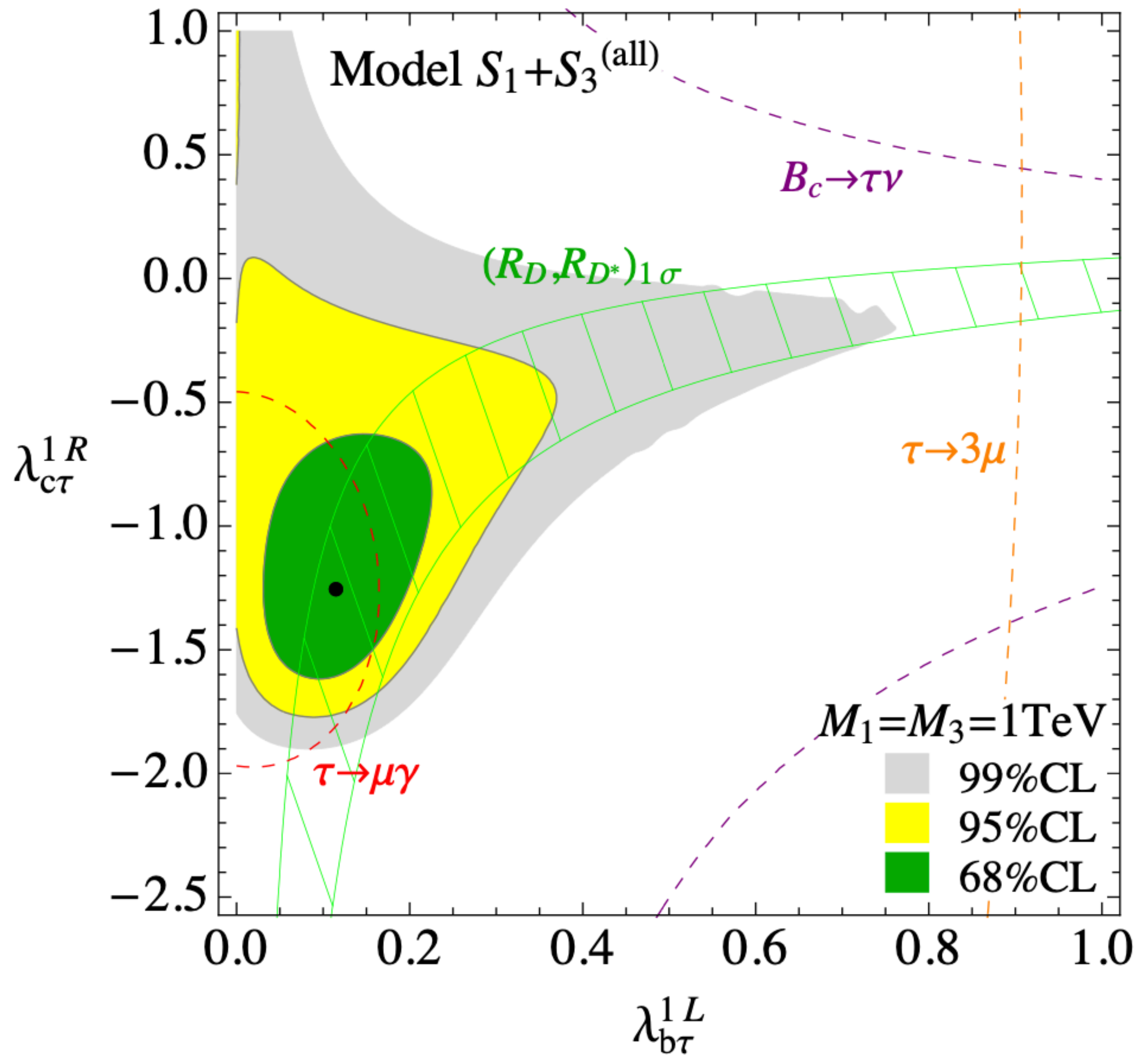


$\mathcal{B}(h \to \tau\mu) = \left(0.84^{+0.39}_{-0.37}\right)\,\%$ (CMS anomaly long passed)

In LQ models also $h \to \tau\mu$ should be below $\lesssim 10^{-8}$.

NECESSITY OF LEPTOQUARKS WITH LFV?

If a LQ has to couple to different lepton flavors.

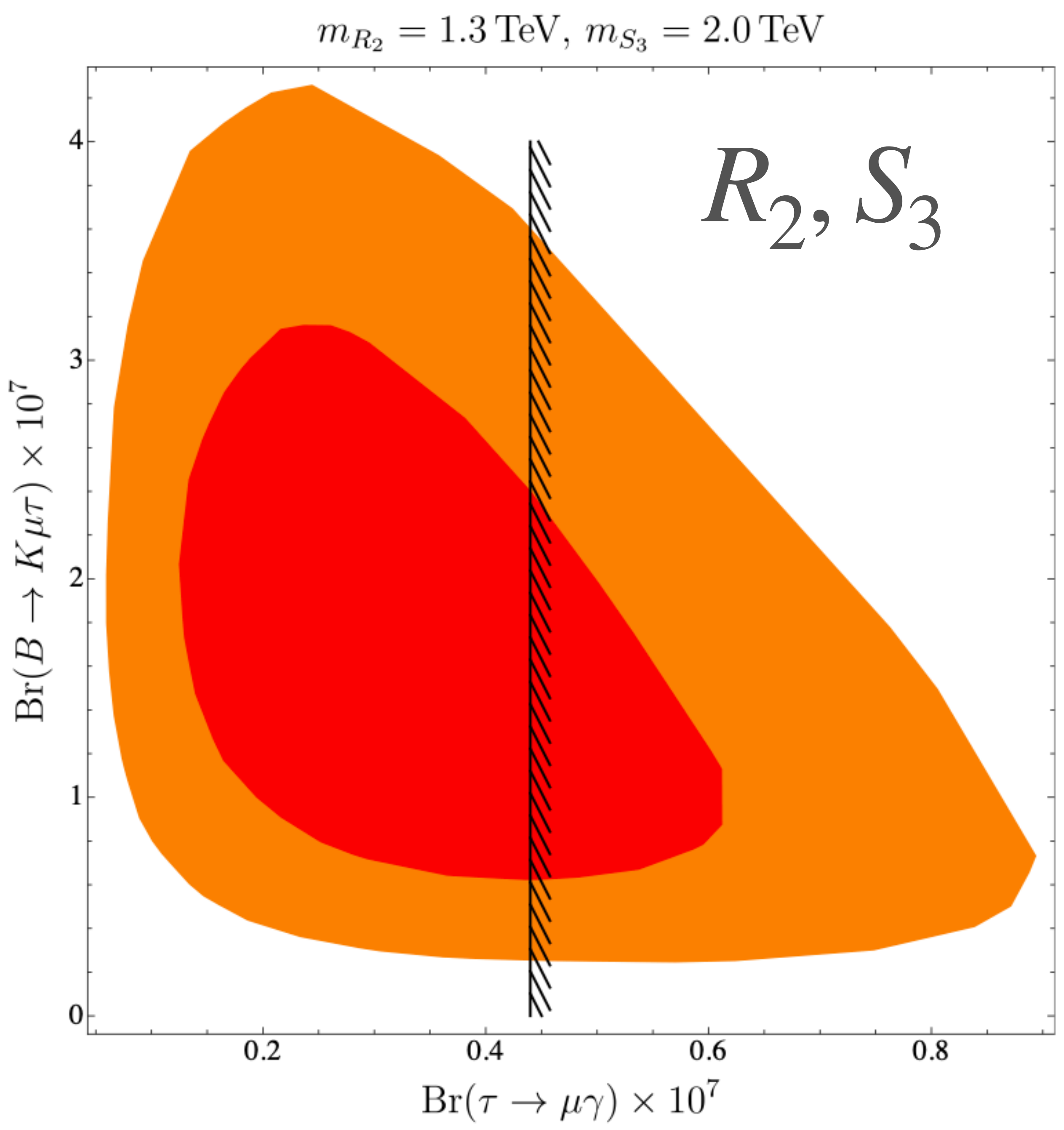


[Gherardi et al, 2008.09548]

This is a scenario with $S_1 + S_3$ or R_2, S_3 leptoquarks

When coupling to μ was required by $R_K^{(*)}$.

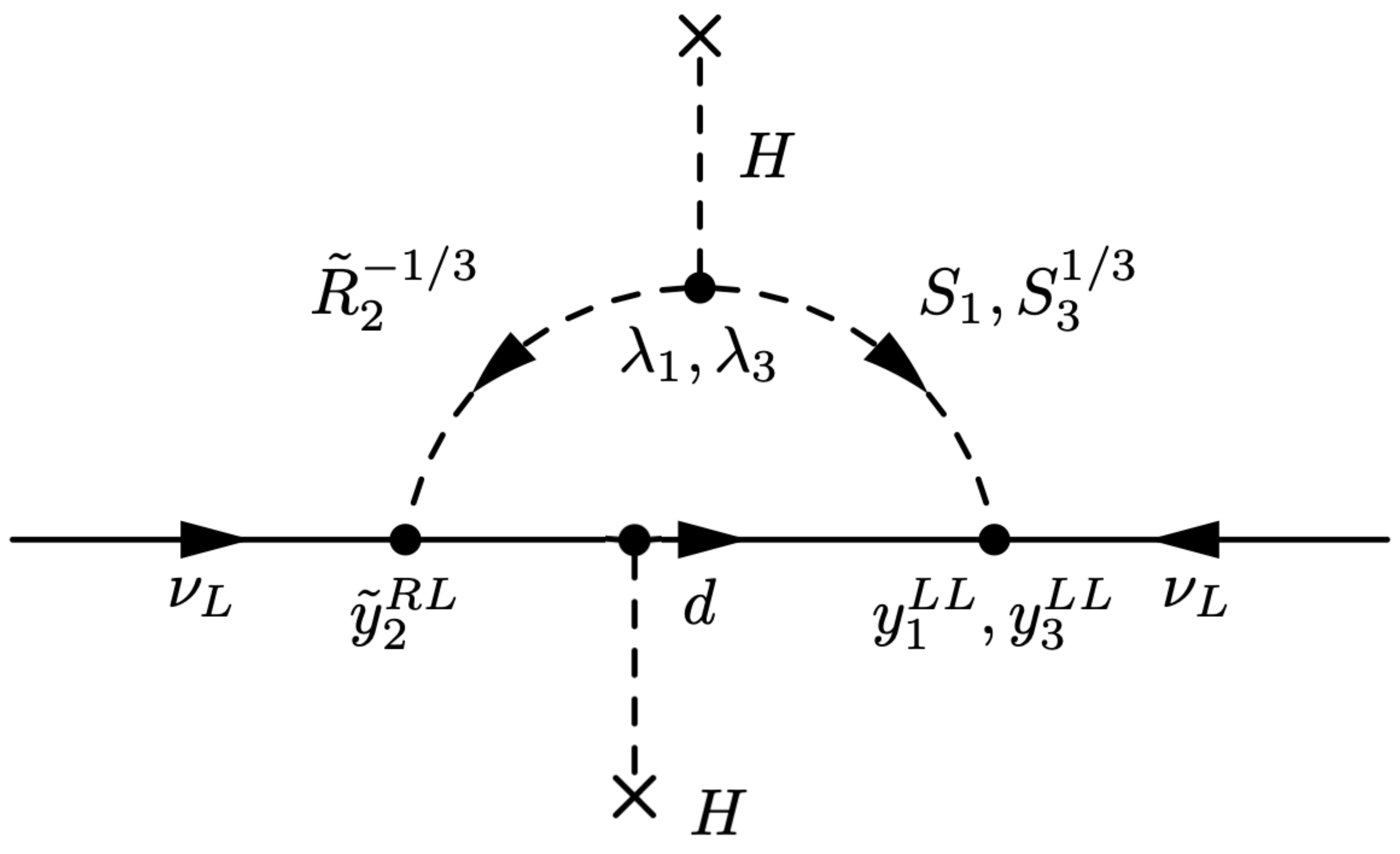
For illustrative purposes - these plots are now outdated.



[Becirevic et al, 2206.09717]

NECESSITY OF LEPTOQUARKS WITH LFV?

Weinberg operator for Majorana neutrino terms can be (partially or fully) accommodated by a 2-LQ loop



A gem in the scalar potential

$$-\lambda_1 \tilde{R}_2^{\dagger\, a} H^a S_1^\dagger$$

$$B(\tilde{R}_2) = 1/3, L(\tilde{R}_2) = -1$$
$$B(S_1) = -1/3, L(S_1) = -1$$
$$\sum B = 0, \sum L = -2$$

[Dorsner et al, 1701.08322]

In order to accommodate neutrino masses and mixings, the Yukawa matrices $\tilde{y}_2^{RL}$ and y_1^{LL} violate LFV across all generations.

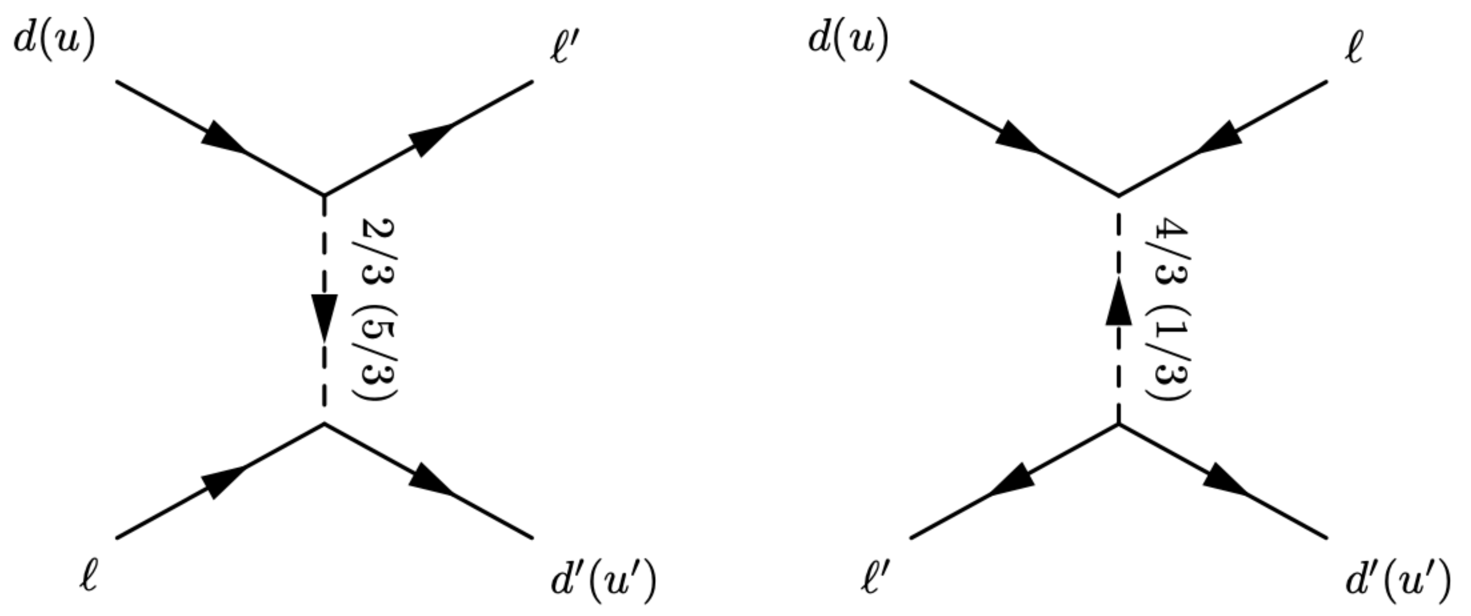
Mass of the LQ states Vs. Yukawa texture should be pinned down by neutrino physics, lepton number violating constrants ***and charged LFV.***

… generalizations to 2-loop exist, where mass scale of LQ's could be even lower.

SUMMARY AND CONCLUSIONS

Leptoquarks naturally introduce quark and lepton FV

Leptonic LFV is correlated with semileptonic processes



Possibly rich structure of $\tau \to 3\ell$ due to semileptonic operators

Relation between LFV and lepton number violation