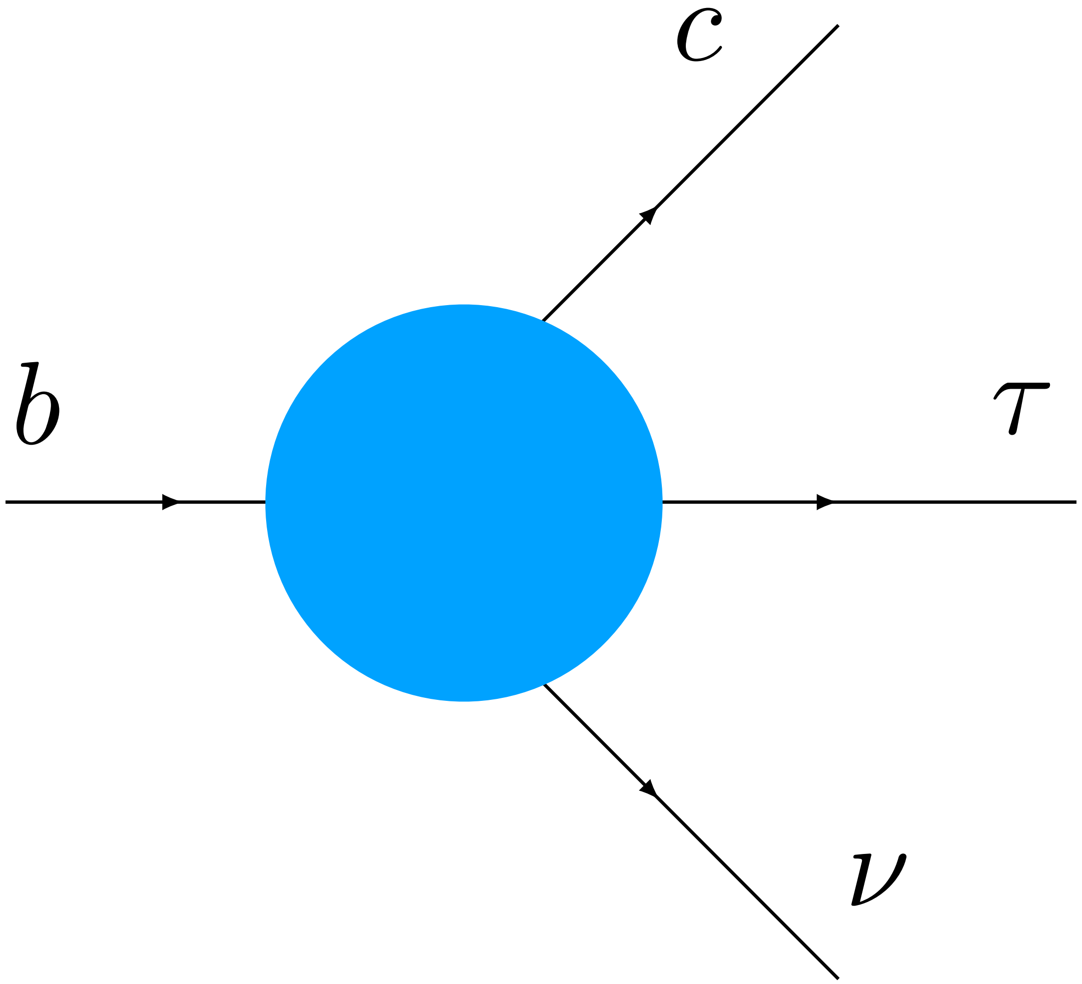
RD/RD* with RH neutrinos

David Shih
NHETC, Rutgers University

"High-Energy Implications of Flavor Anomalies"
CERN, October 2018

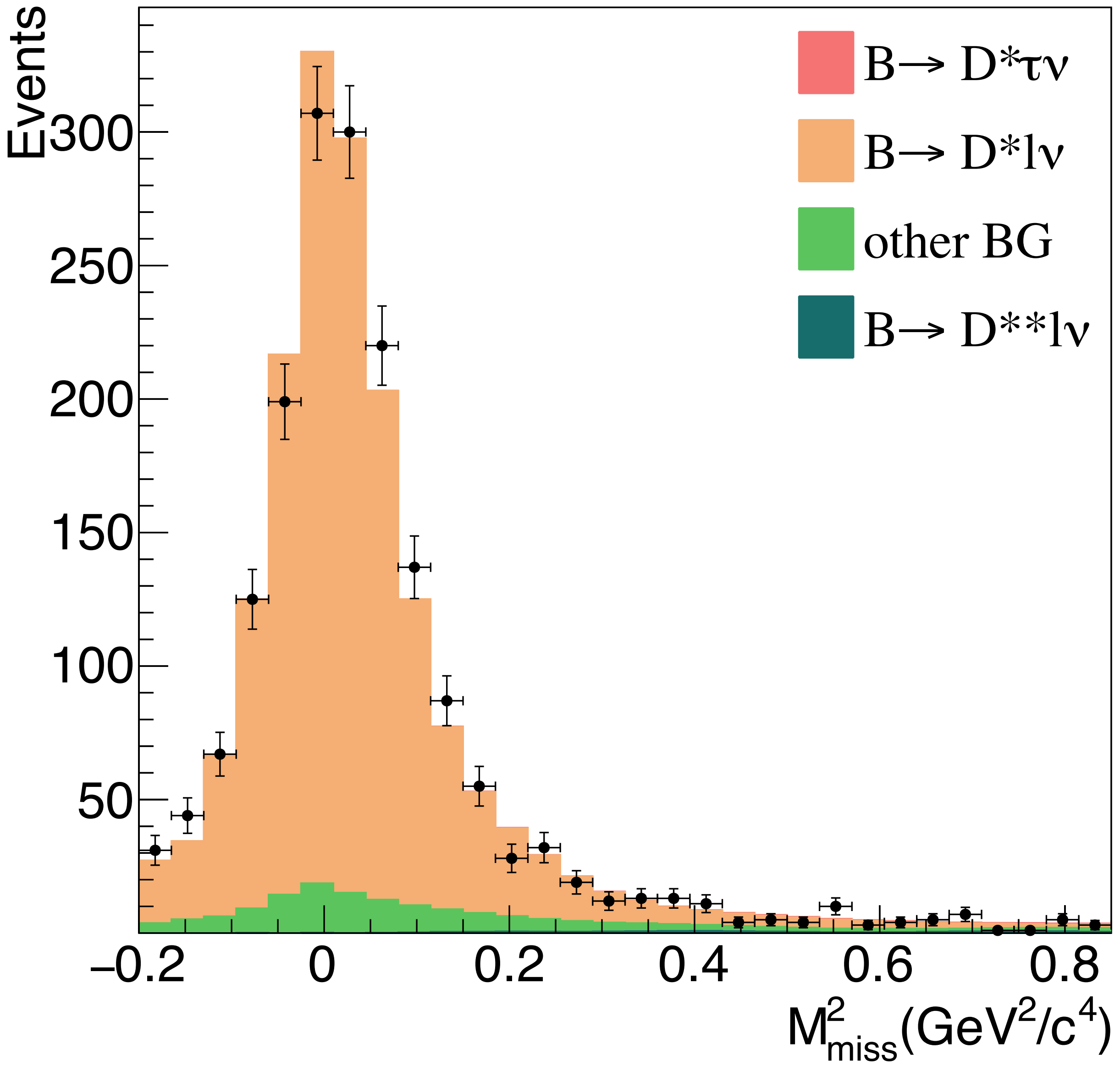
Based on Asadi, Buckley & DS 1804.04135, 1810.06597

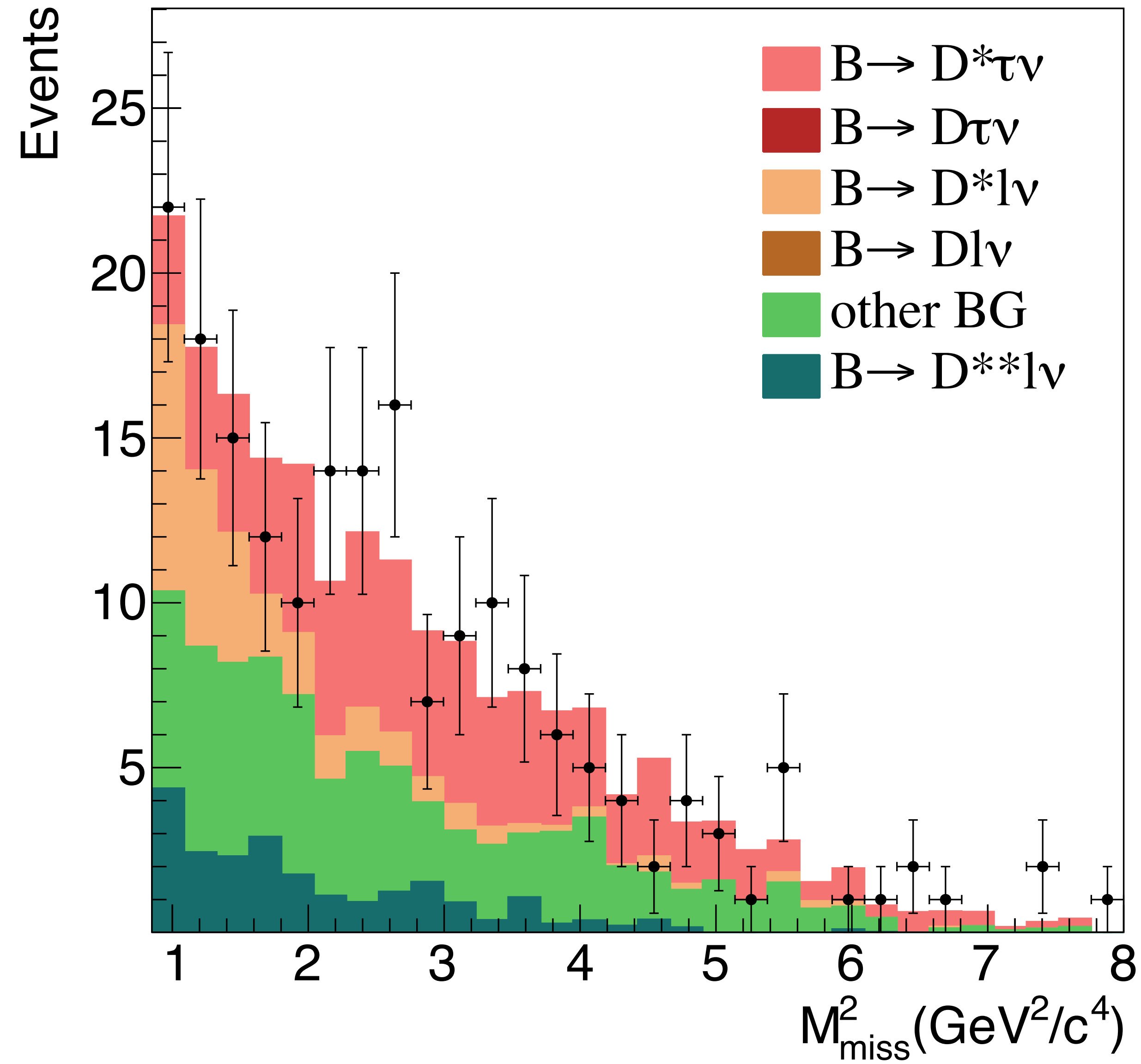
see also Robinson, Shakya, Zupan + Greljo 1804.04642, 1807.04753



ARE WE SURE THAT THESE ARE SM NEUTRINOS?

Belle 1507.03233





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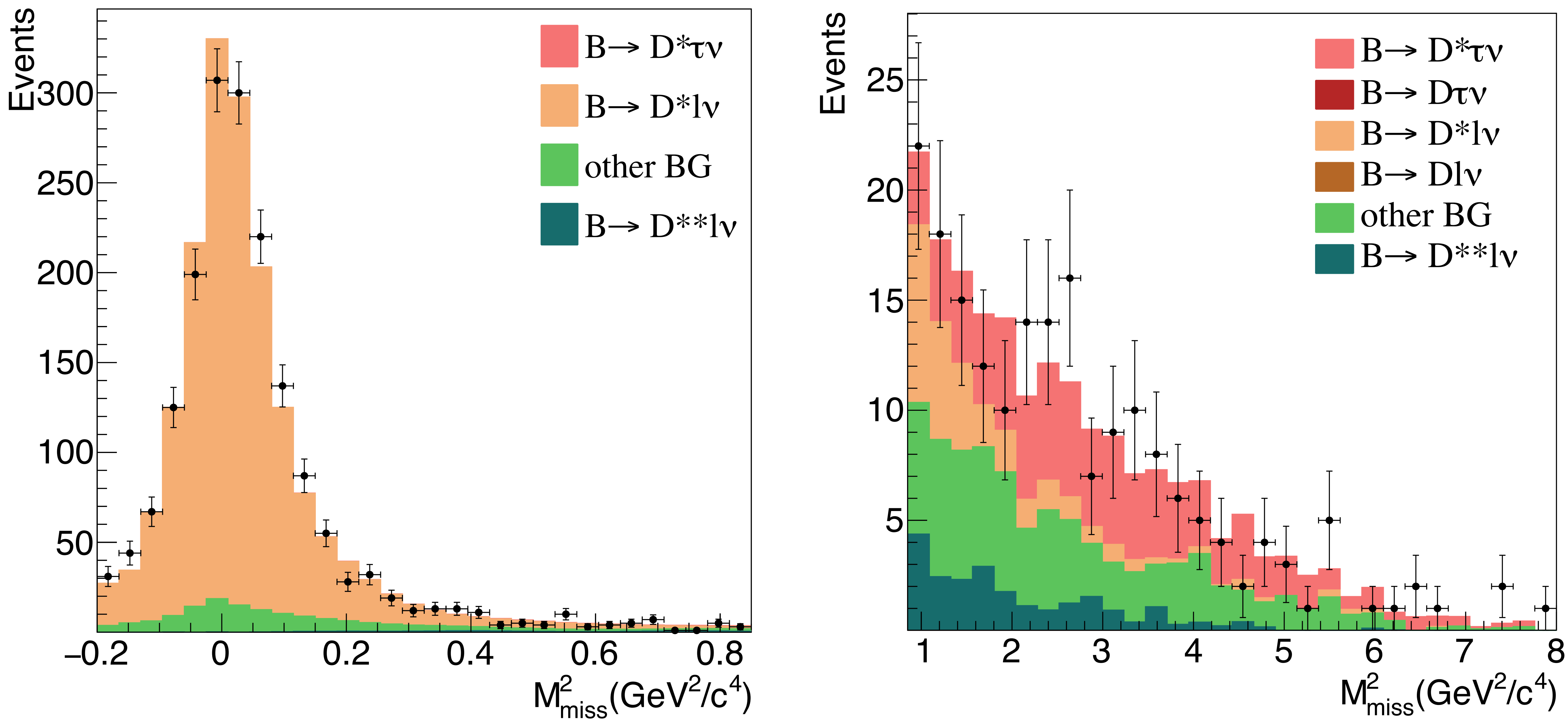
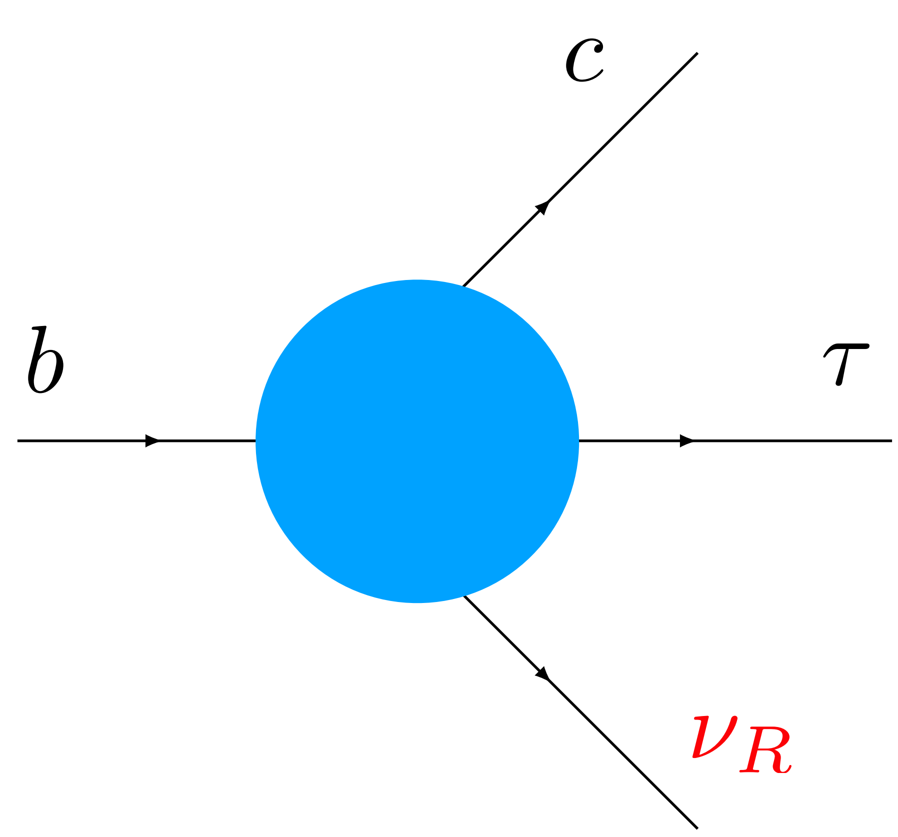


ARE WE SURE THAT THESE ARE SM NEUTRINOS?

➡ Could be a light, weakly-interacting BSM particle instead?

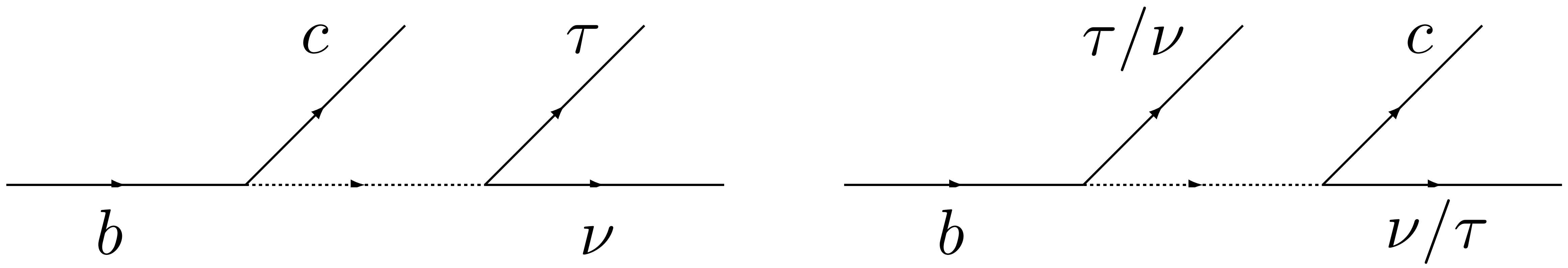


Allowing for RH neutrinos opens up new avenues for model building and phenomenology.

He & Valencia 1211.0348
Dutta et al 1307.6653
Cline 1512.02210
Becirevic et al 1608.08501
Bardhan et al 1610.03038
Dutta & Bhol 1611.00231
Iguro & Omura 1802.01732
Asadi et al 1804.04135
Greljo et al 1804.04642
Abdullah et al 1805.01869
Robinson et al 1807.04753
Azatov et al 1807.10745
Heeck et al 1808.07492
Carena et al 1809.01107
Iguro et al 1810.05843
Asadi et al 1810.06597

How will we be able to tell LH from RH neutrinos experimentally?

Effective Hamiltonian



Integrate out heavy mediator

$$\mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \left(\mathcal{O}^V_{LL} + \sum_{\substack{X=S,V,T \\ M,N=L,R}} C^X_{MN} \mathcal{O}^X_{MN} \right)$$

$$\begin{aligned} \mathcal{O}^S_{MN} &\equiv (\bar{c} P_M b)(\bar{\tau} P_N \nu) \\ \mathcal{O}^V_{MN} &\equiv (\bar{c} \gamma^\mu P_M b)(\bar{\tau} \gamma_\mu P_N \nu) \qquad M,N = L,R \\ \mathcal{O}^T_{MN} &\equiv (\bar{c} \sigma^{\mu\nu} P_M b)(\bar{\tau} \sigma_{\mu\nu} P_N \nu) \end{aligned}$$

Viable mediators for RD/RD*

Mediator	Operator Combination	Viability
Colorless Scalars	$\mathcal{O}^S_{XL}$	✗ $(Br\,(B_c \to \tau\nu))$
W'^μ (LH fermions)	$\mathcal{O}^V_{LL}$	✗ (collider bounds)
S_1 LQ $(\bar{3},1,1/3)$ (LH fermions)	$\mathcal{O}^S_{LL} - x\mathcal{O}^T_{LL},\ \ \mathcal{O}^V_{LL}$	✓
U_1^μ LQ $(3,1,2/3)$ (LH fermions)	$\mathcal{O}^S_{RL},\ \ \mathcal{O}^V_{LL}$	✓
R_2 LQ $(3,2,7/6)$	$\mathcal{O}^S_{LL} + x\mathcal{O}^T_{LL}$	✓
S_3 LQ $(\bar{3},3,1/3)$	$\mathcal{O}^V_{LL}$	✗ $(Br\,(B \to X_s\nu\nu))$
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V_2^μ LQ $(\bar{3},2,5/6)$	$\mathcal{O}^S_{RL}$	✗ ($R_{D^{(*)}}$ value)
Colorless Scalars	$\mathcal{O}^S_{XR}$	✗ $(Br\,(B_c \to \tau\nu))$
W'^μ (RH fermions)	$\mathcal{O}^V_{RR}$	✓
$\tilde{R}_2$ LQ $(3,2,1/6)$	$\mathcal{O}^S_{RR} + x\mathcal{O}^T_{RR}$	✓
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see also Robinson et al 1807.04753

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Only leptoquarks are viable with SM neutrinos

see also Robinson et al 1807.04753

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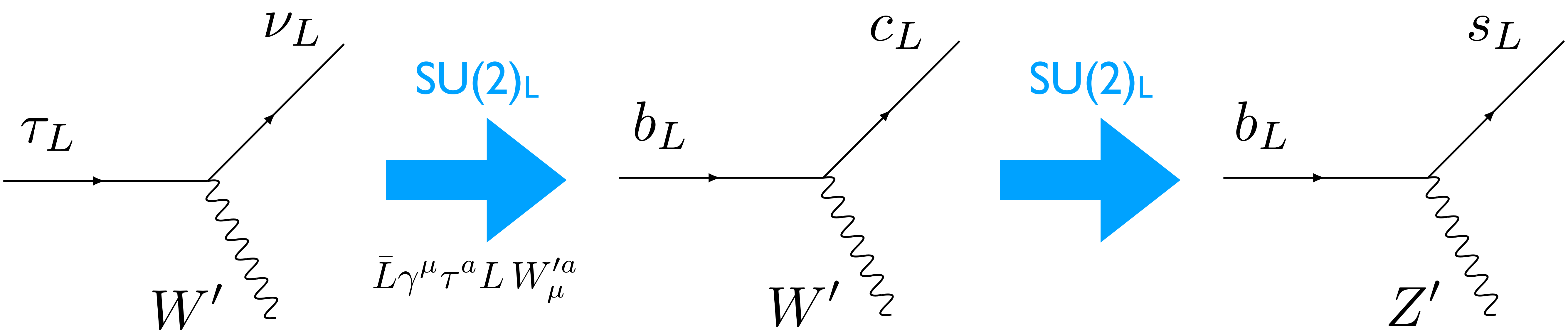
Only leptoquarks are viable with SM neutrinos

W' and leptoquarks are both viable with RH neutrinos!

see also Robinson et al 1807.04753

W' with LH neutrinos: problems



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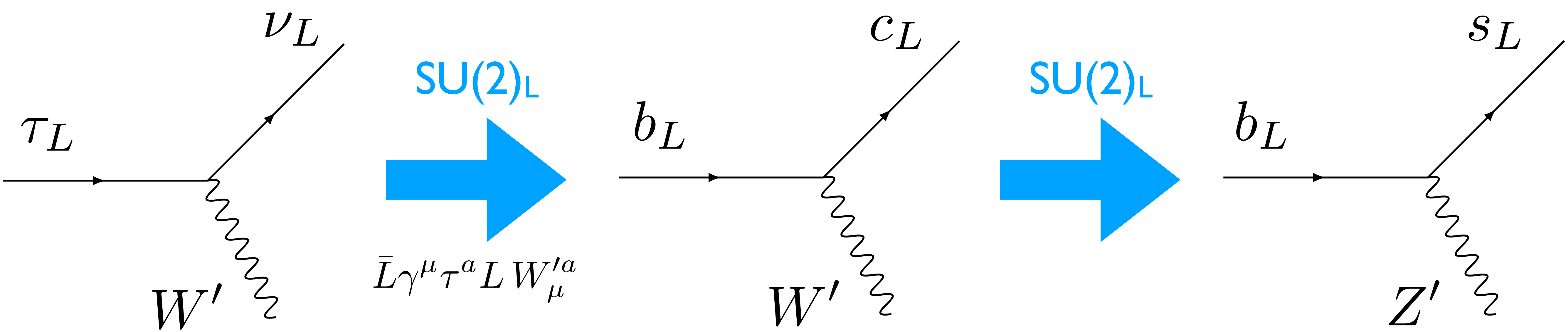

Tree-level FCNCs!

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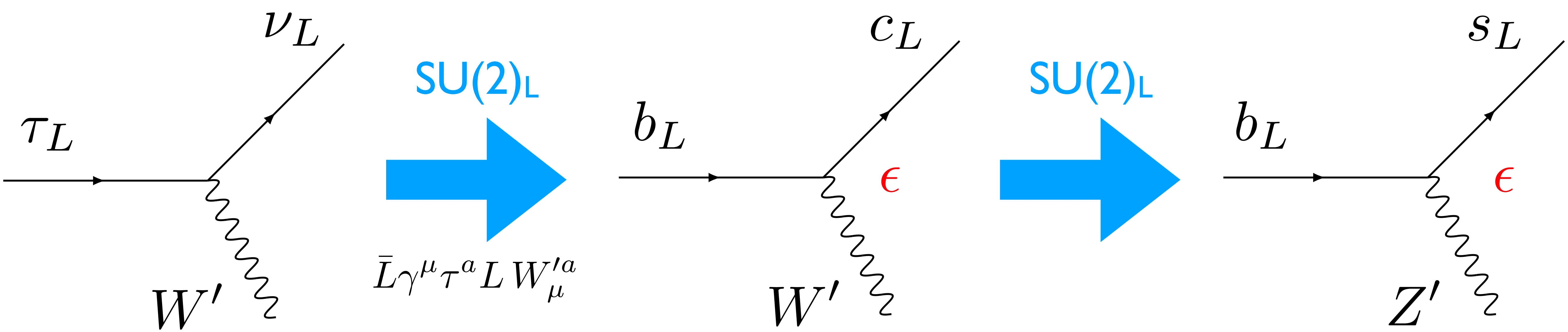

Tree-level FCNCs!

Need 3rd generation dominance

$\epsilon \sim V_{cb}$

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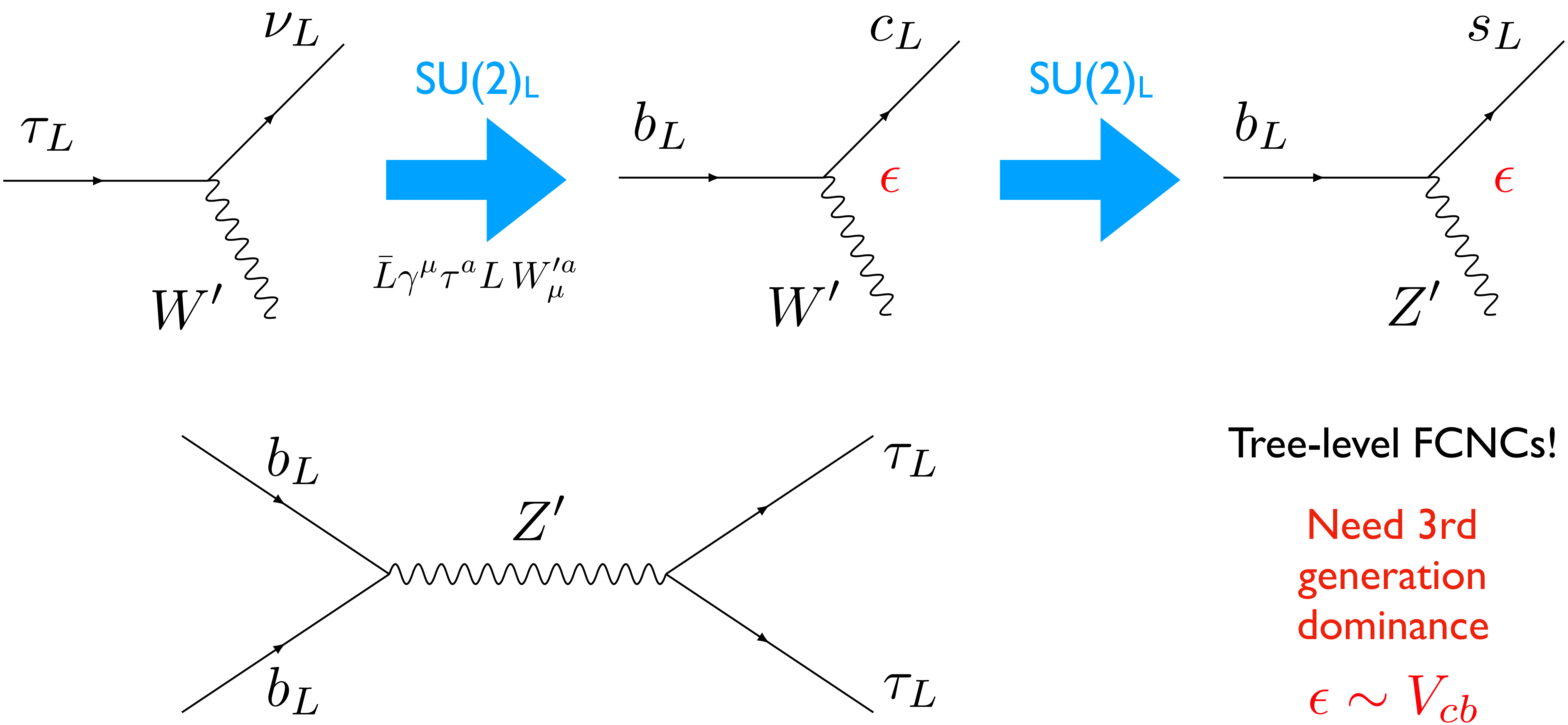

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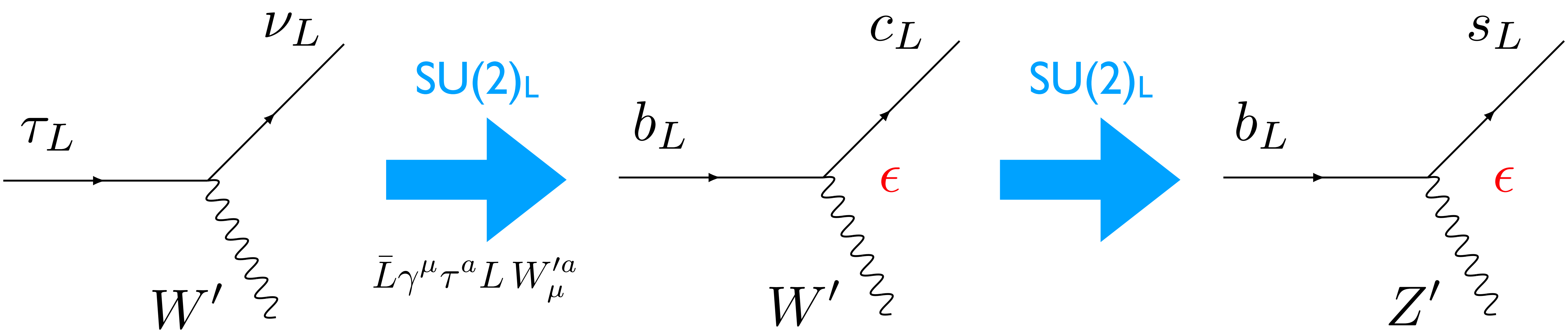

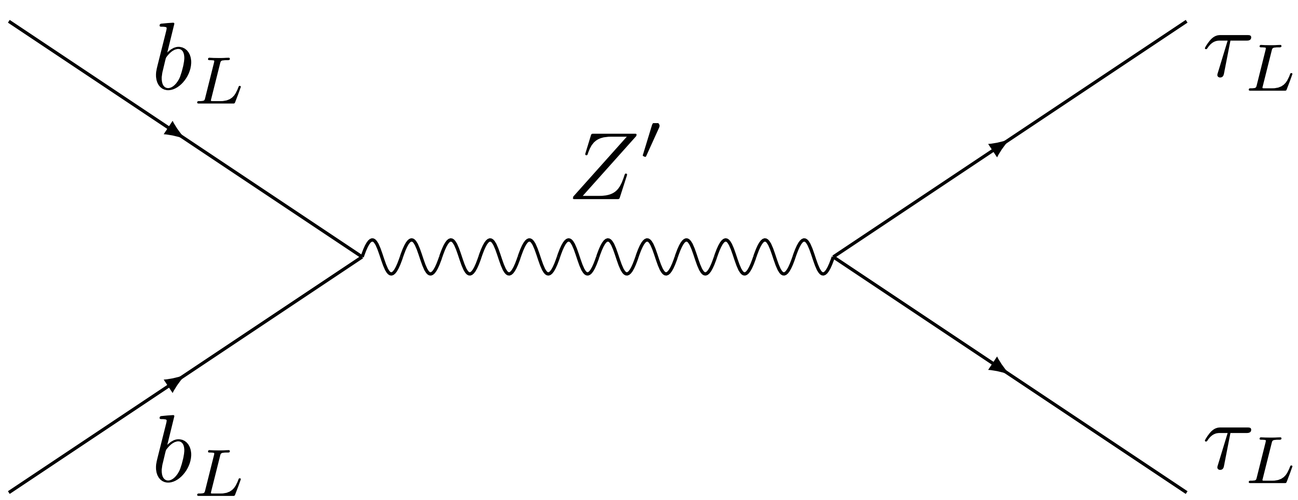

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Need 3rd generation dominance

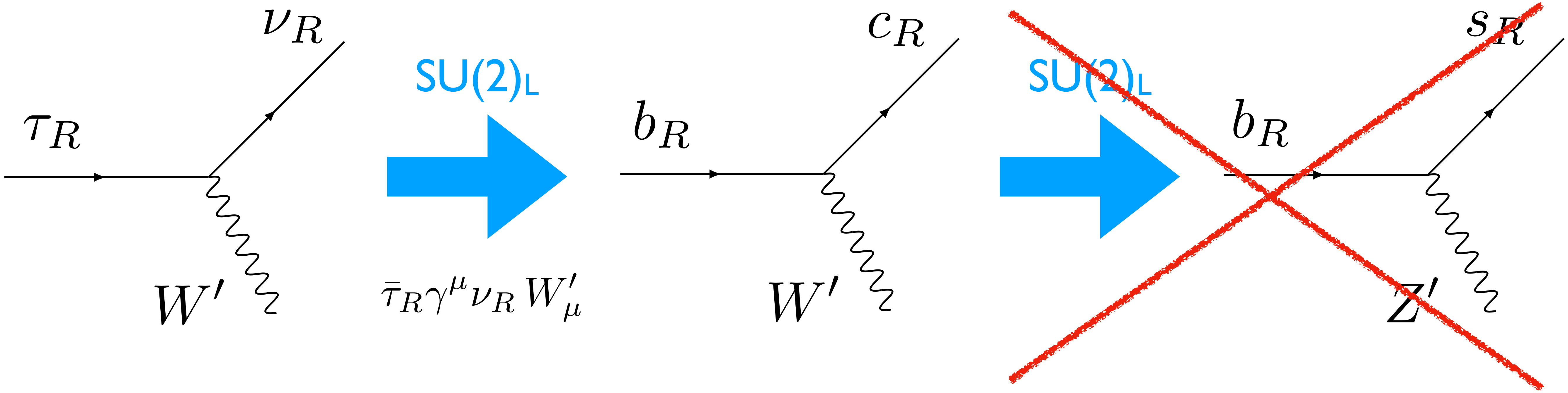
$\epsilon \sim V_{cb}$

Strong constraints from Z'→ττ resonance searches rule out these models!

Faroughy et al 1609.07138, Crivellin et al 1703.09226

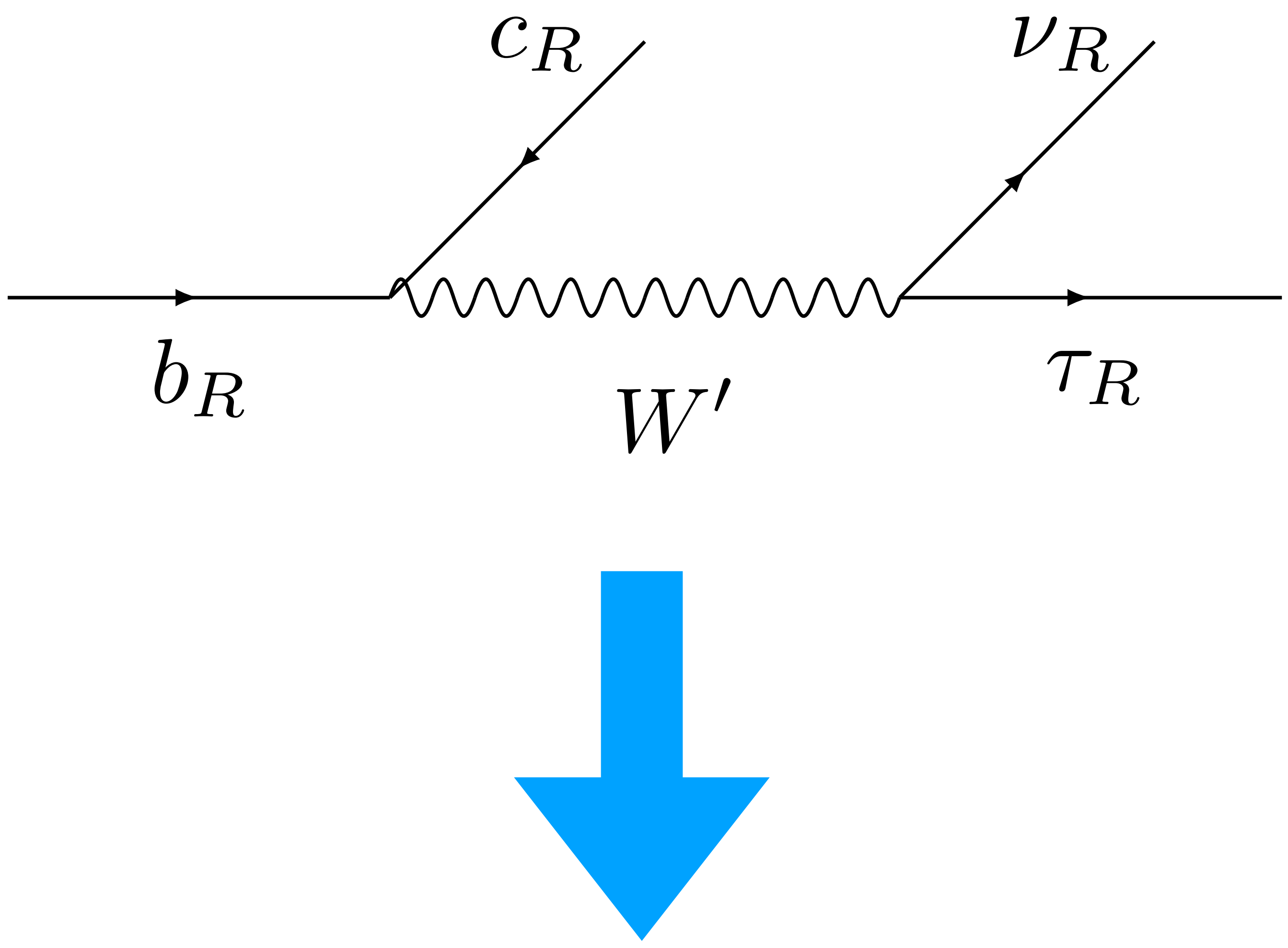
W’ with RH neutrinos: no problem!

W’ coupling to RH neutrinos avoids these problems



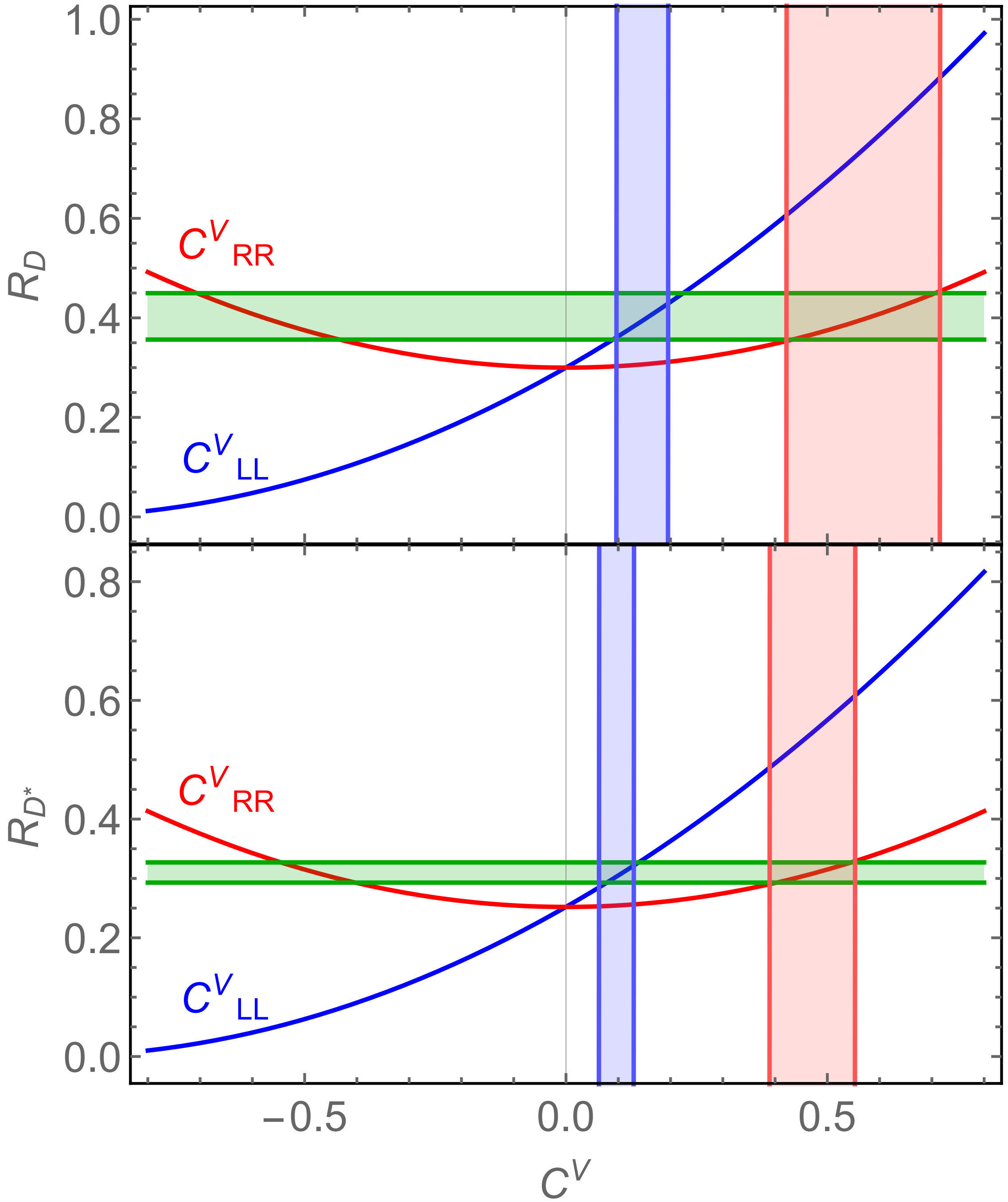
No FCNCs. Don’t need 3rd generation dominance —
no enhancement of Z’→ττ production!

W' with RH neutrinos



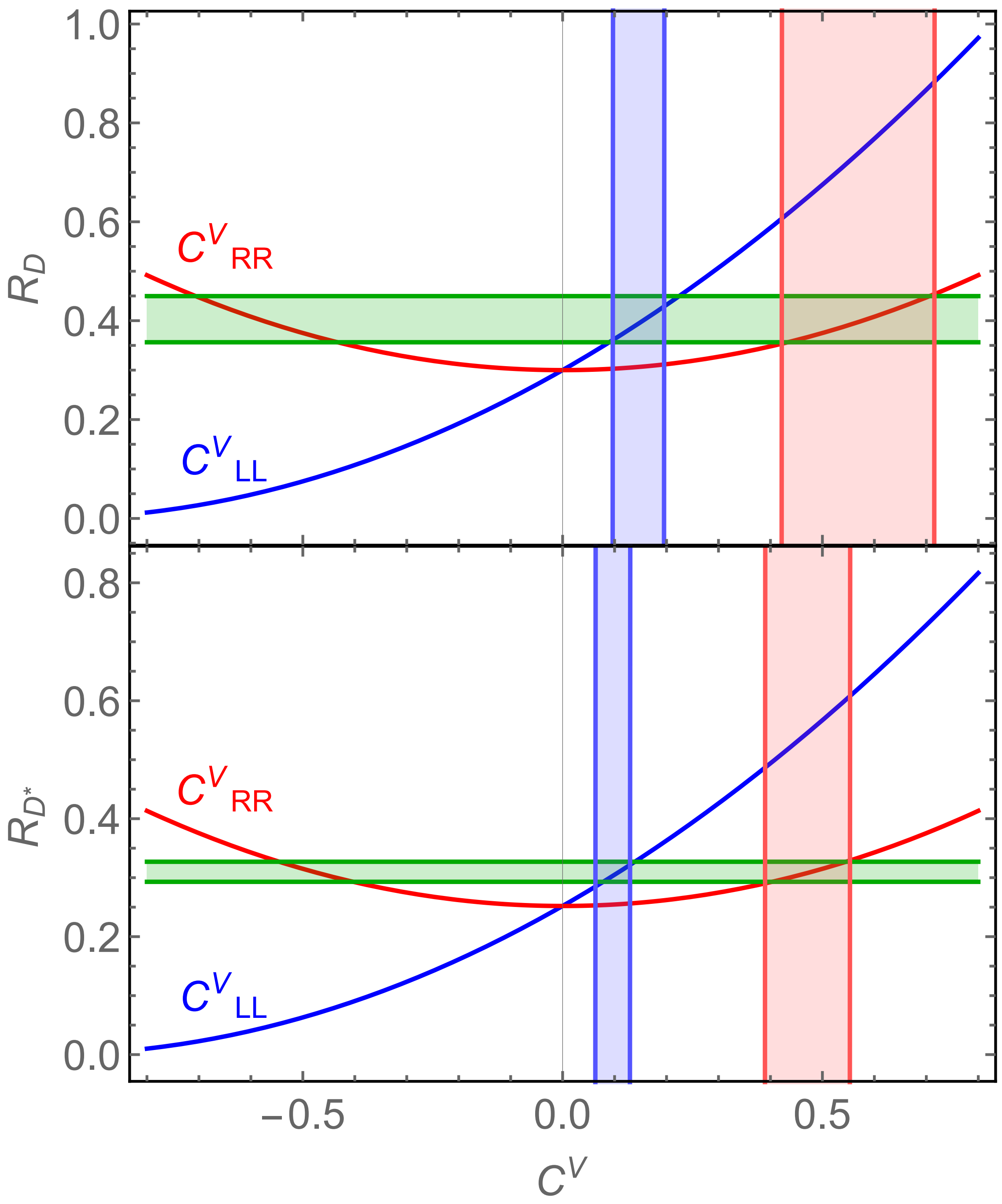
$$C_{RR}^{V}\mathcal{O}_{RR}^{V} = C_{RR}^{V}(\bar{c}_R\gamma^{\mu}b_R)(\bar{\tau}_R\gamma_{\mu}\nu_R)$$

W' with RH neutrinos



$$R_{D^{(*)}} = R_{D^{(*)}}^{SM} \left(|1 + C_{LL}^V|^2 + |C_{RR}^V|^2 \right)$$

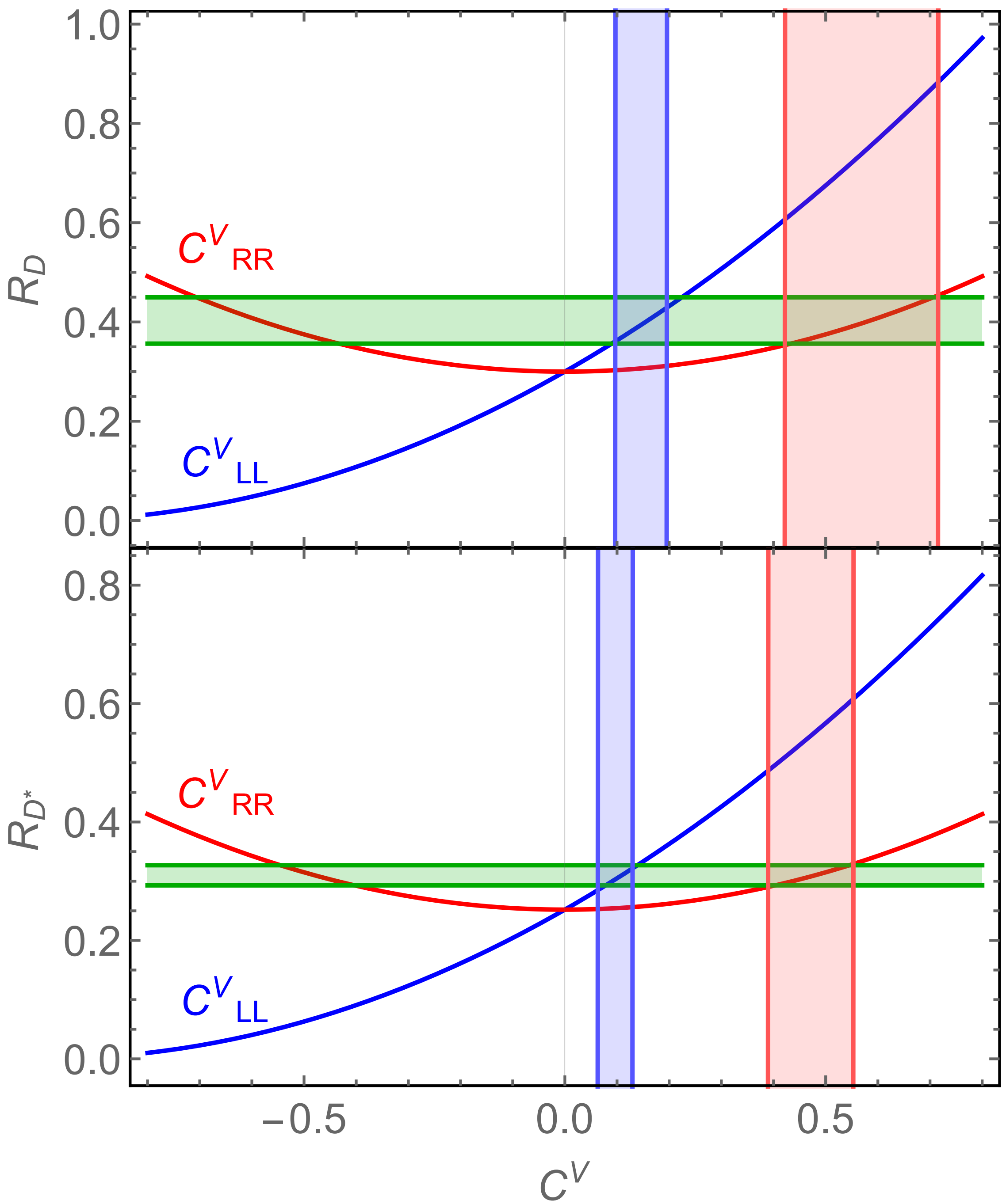
W' with RH neutrinos



$$R_{D^{(*)}} = R_{D^{(*)}}^{SM} \left(|1 + C_{LL}^V|^2 + |C_{RR}^V|^2 \right)$$

Just like for $C^V{}_{LL}$, automatically explain both anomalies simultaneously with a single Wilson coefficient.

W' with RH neutrinos



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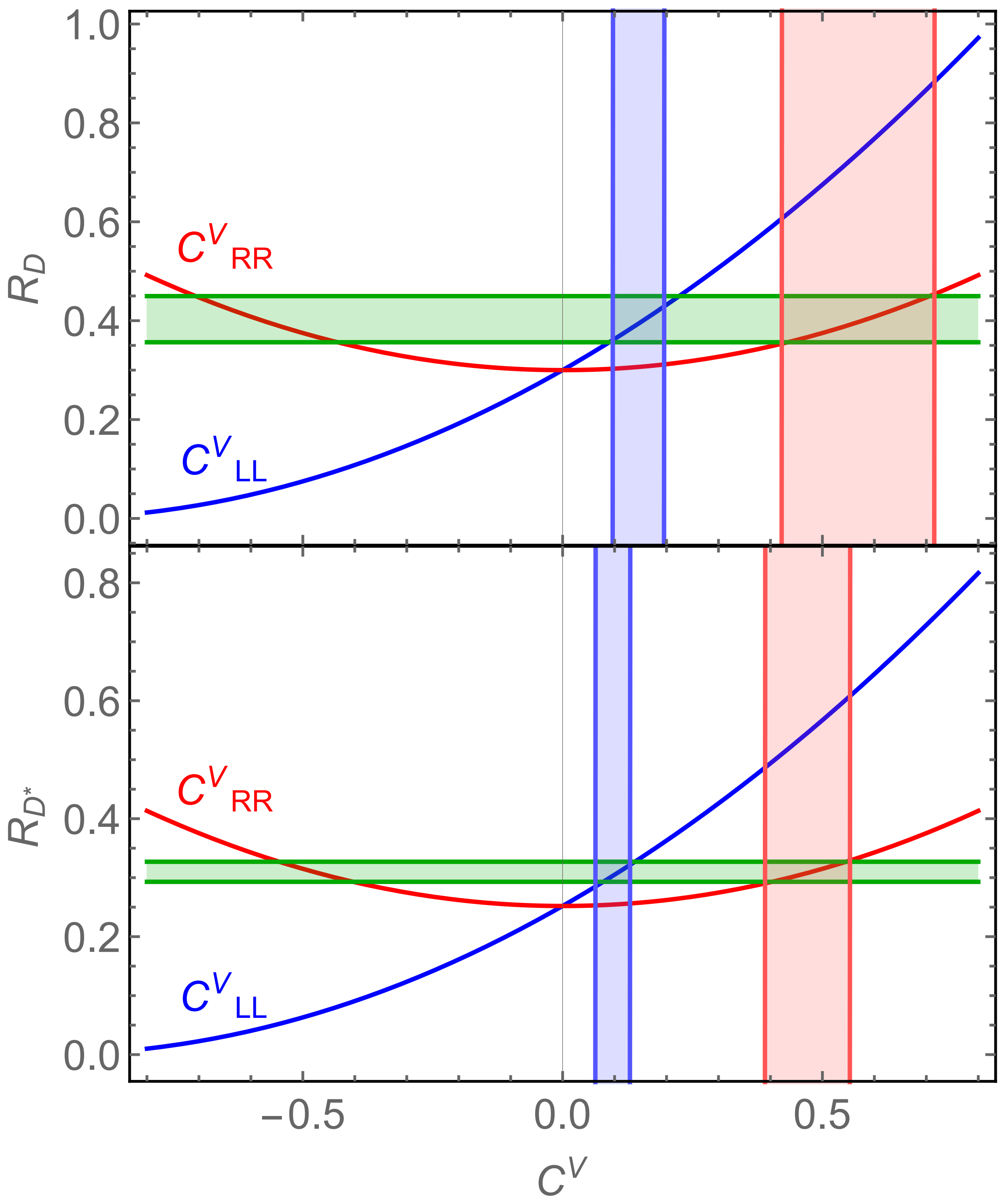
Unlike $C^V{}_{LL}$, lack of interference with SM means a larger Wilson coefficient is required.

W’ with RH neutrinos



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Just like for C^V_{LL}, automatically explain both anomalies simultaneously with a single Wilson coefficient.

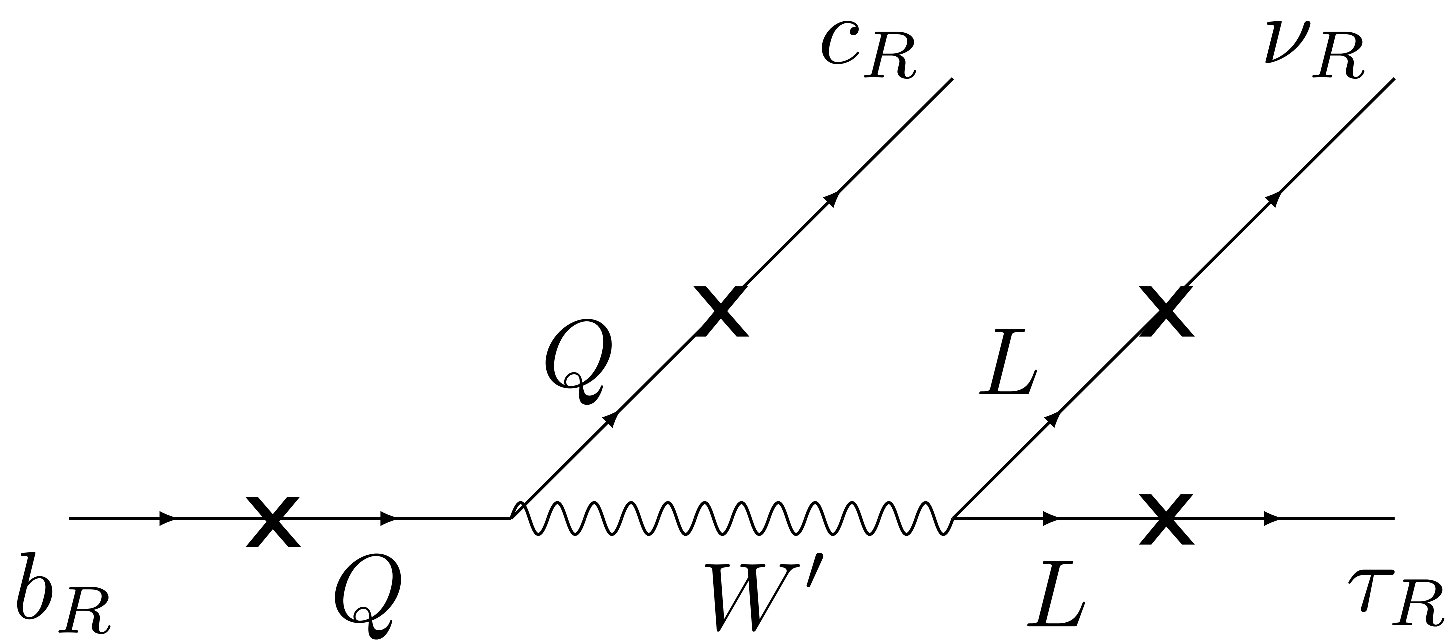
Unlike C^V_{LL}, lack of interference with SM means a larger Wilson coefficient is required.

➡ Collider constraints are still not negligible.

UV model

Basic idea: $SU(2)_V \times U(1)_X \to U(1)_Y$ $\langle \phi' \rangle \sim \mathcal{O}(\mathrm{TeV})$

W' couples to RH fermions through mixing with additional vector-like fermions charged under $SU(2)_V \times U(1)_X$



$$C_{RR}^V \sim \frac{g_V^2 U_{Qb} U_{Qc} U_{L\tau} U_{L\nu}}{m_{W'}^2 G_F V_{cb}} \sim \frac{v_L^2}{v_V^2} \frac{U^4}{V_{cb}}$$

UV model

	Generations	$SU(3)$	$SU(2)_L$	$SU(2)_V$	$U(1)_X$
ϕ	1	1	2	1	1/2
q_L	3	3	2	1	1/6
u_R	3	3	1	1	2/3
d_R	3	3	1	1	-1/3
ℓ_L	3	1	2	1	-1/2
e_R	3	1	1	1	-1
ν_R	1	1	1	1	0
ϕ'	1	1	1	2	1/2
Q	N_V	3	1	2	1/6
L	N_V	1	1	2	-1/2

$$-\mathcal{L} \supset M_Q \bar{Q}_L Q_R + M_L \bar{L}_L L_R + m_{\nu_R} \nu_R \nu_R$$
$$+ \tilde{y}^d \bar{Q}_L \phi' b_R - \tilde{y}^u \bar{Q}_L \phi'^* c_R + \tilde{y}^e \bar{L}_L \phi' \tau_R - \tilde{y}^n \bar{L}_L \phi'^* \nu_R + \text{h.c.}$$

Constraints on the model

FCNCs:

- eliminated at tree-level and one-loop order — no coupling of W',Z' to s or d quarks!

Precision EW:

- Use most stringent EW constraints (G_F, α_{EM}, m_Z) to fix parameters of the model. Then no longer have freedom to fix m_W and fermion couplings.

  Find that only the former sets a significant bound:

$$m_{W'} g_V \gtrsim 0.97 \text{ TeV}$$

Collider searches:

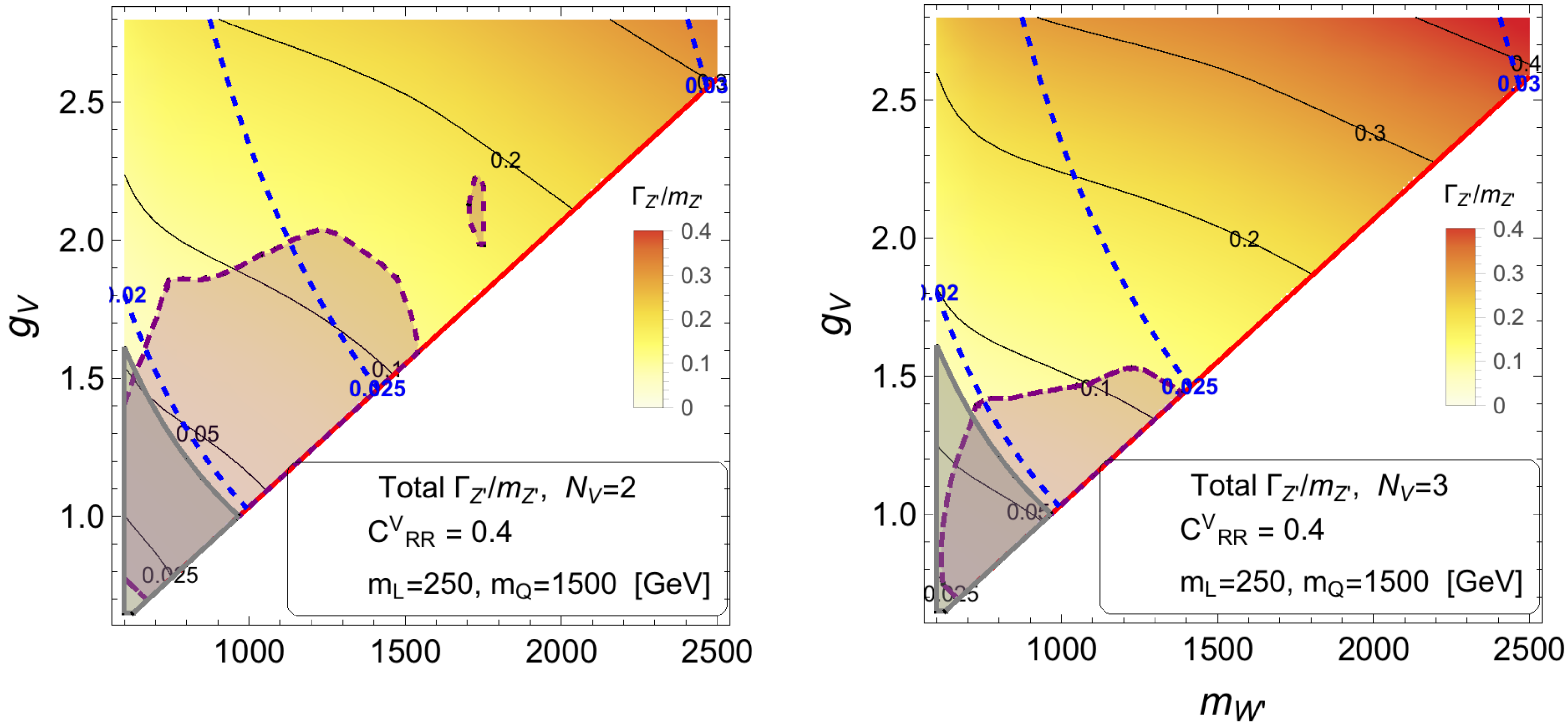
- Significant constraints from searches for $Z' \to \tau\tau$

  $W' \to \tau\nu$

see Admir's talk tomorrow for an update

Need light VL-leptons to broaden Z' resonance and dilute Z' BR…

Collider constraints



gray: mW EWP constraint

purple: ATLAS 36/fb Z'→ττ (estimated)

[Slightly stronger limits from ATLAS 36/fb W'→τν (Greljo et al 1804.04642)]

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How can we tell all these models apart?

Signatures of LH vs RH neutrinos

Recent work: tau asymmetries at Belle II! Asadi, Buckley & DS 1810.06597

Large literature on this…

Tanaka 9411405
Tanaka & Watanabe 1005.4306, 1212.1878
Fajfer et al 1203.2654
Sakaki & Tanaka 1205.4908

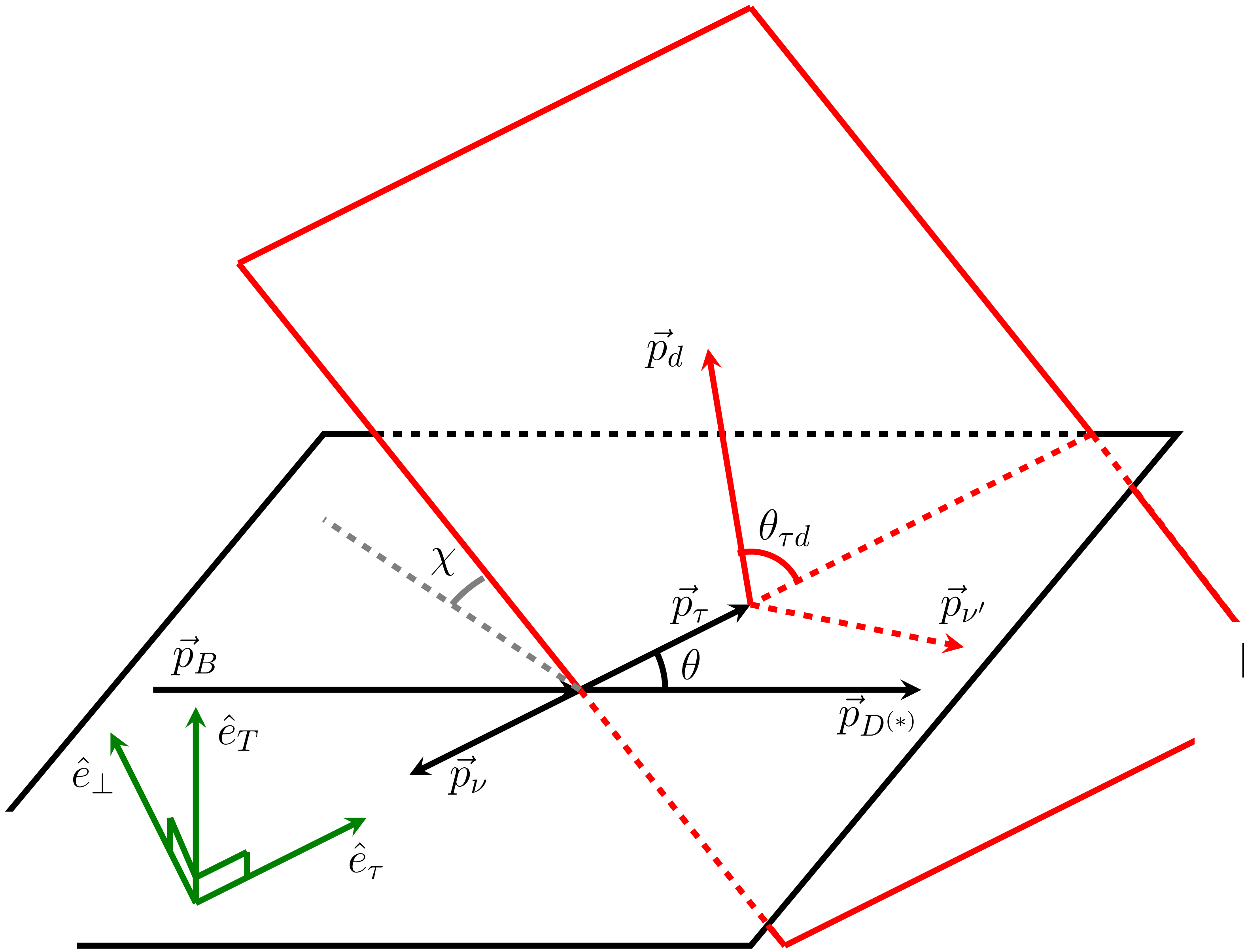
Datta et al 1206.3760
Duraisamy & Datta 1302.7031
Ivanov et al 1508.02678,1701.02937
Becirevic et al 1602.03030

Alonso et al 1602.07671, 1702.02773
Alok et al 1606.03164, 1804.08078
Bardhan et al 1610.03038
Celis et al 1612.07757
Huang et al 1808.03565
………

Our work

- Includes RH neutrinos
- Focuses on mediators, not effective operators
- Takes into account experimental feasibility and projected sensitivity

Tau asymmetries



$\mathcal{P}_{\hat{e}}^{(*)}$

polarization asymmetry wrt arbitrary direction e

$\mathcal{A}_{FB}^{(*)}$

Forward-backward asymmetry wrt $D^{(*)}$ direction

leptonic center of mass frame

Tau asymmetries

One measurement of P_τ^* by Belle (2016):

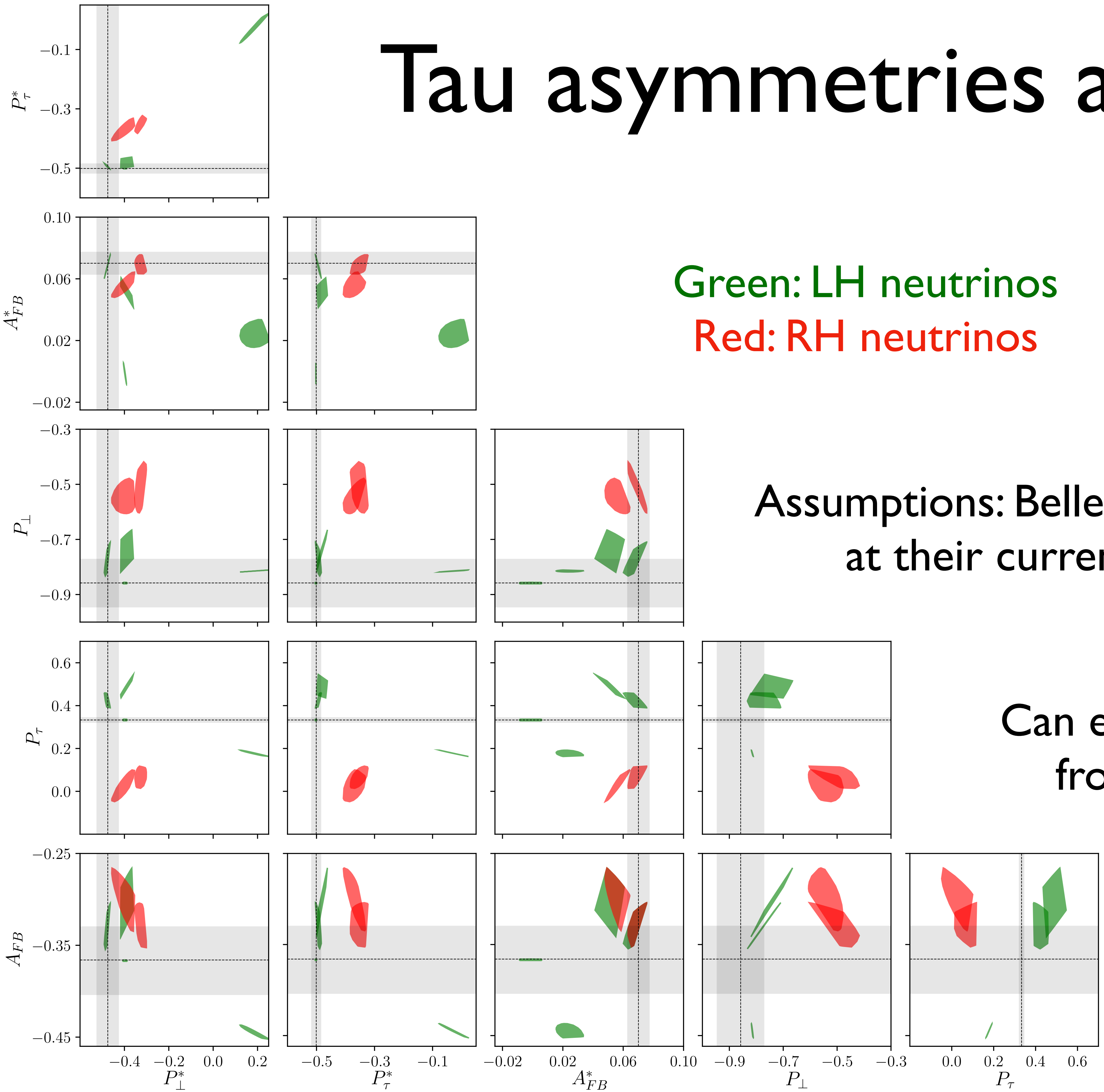
$P_\tau^* = -0.38 \pm 0.51 \pm 0.2$

Huge error bars.

Proposal by Alonso, Camalich & Westhoff 1702.02773 for how to measure asymmetries in D mode with improved precision

Observable	$\mathcal{A}_{FB}$	$\mathcal{A}_{FB}^*$	$\mathcal{P}_\tau$	$\mathcal{P}_\tau^*$	$\mathcal{P}_\perp$	$\mathcal{P}_\perp^*$	$\mathcal{P}_T$	$\mathcal{P}_T^*$
SM value	-0.366	0.0701	0.333	-0.501	-0.858	-0.475	0	0
Projected Precision [36]	10%	–	3%	–	10%	–	–	–

Tau asymmetries at Belle II

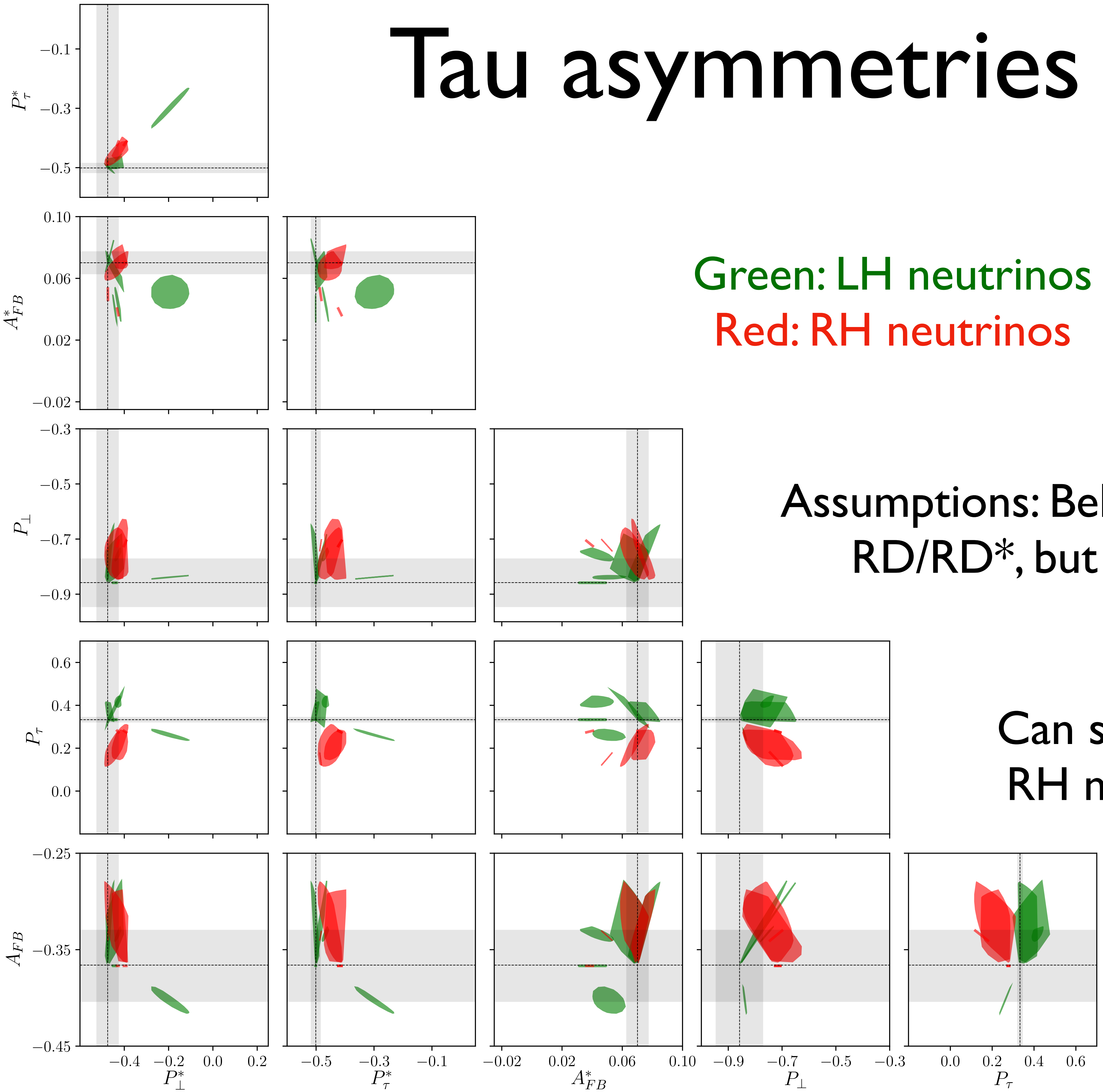


Green: LH neutrinos
Red: RH neutrinos

Assumptions: Belle II measures RD/RD* at their current global average

Can easily tell apart LH from RH models!

Tau asymmetries at Belle II



Green: LH neutrinos
Red: RH neutrinos

Assumptions: Belle II measures reduced RD/RD*, but still 5σ significance

Can still tell apart LH from RH models in most cases!

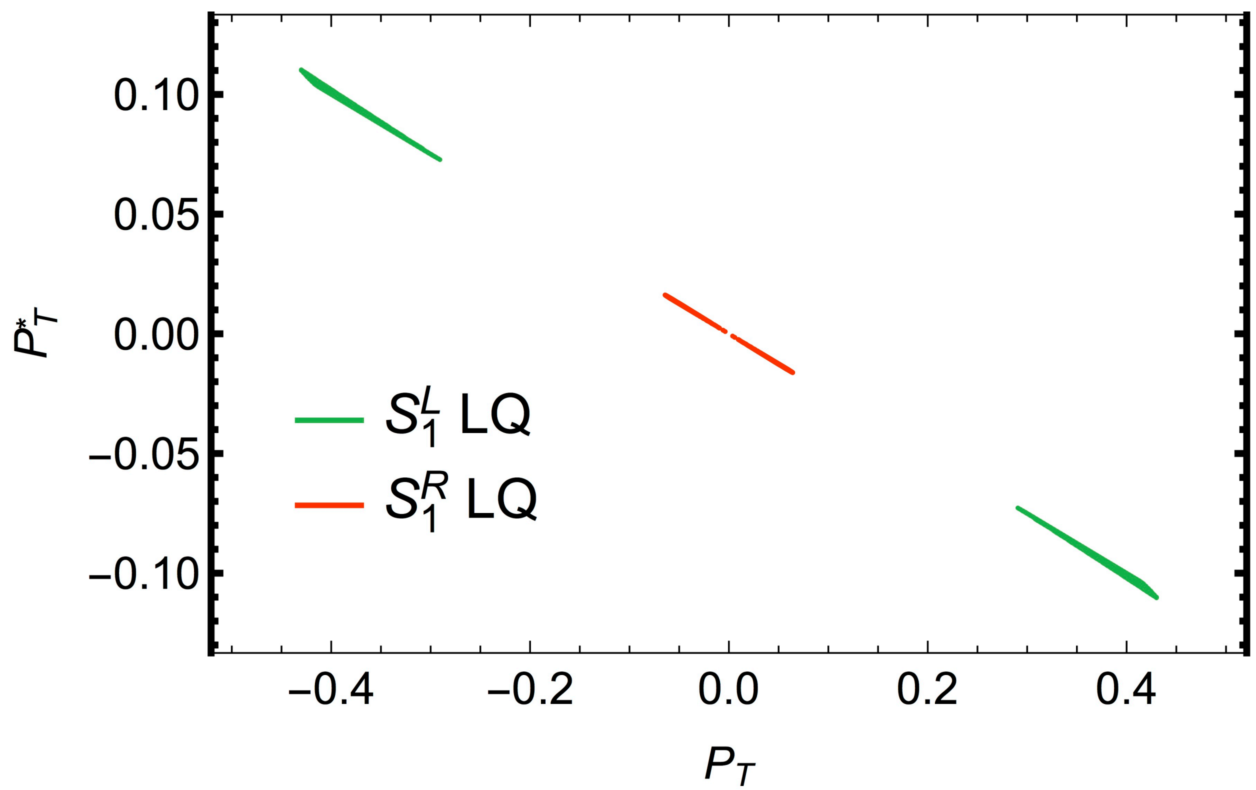


Figure 9: The $\mathcal{P}_T$ and $\mathcal{P}_T^*$ observables for the points from Fig. 8 that are less than 1σ apart according to our χ^2 constructed from all the CP-even observables. The green (red) points correspond to S_1 LQs coupled to LH (RH) neutrinos. Notice the identical slope of the lines, which is a consequence of the symmetry outlined in (3.1)–(3.2). If these CP-odd asymmetries can even be measured, and with enough experimental precision, then they will be able to distinguish between the LH and RH neutrino cases.

CP-odd asymmetries may play a crucial role in resolving the most difficult degeneracies.

Currently no substantiative proposal for how to measure these at Belle II.

Summary and Outlook

The invisible energy in the B decays of the RD/RD* anomalies might not be entirely from SM neutrinos.

Allowing for light, sterile RH neutrinos in the B decays opens up new avenues for model building and phenomenology.

- In particular, it allows for models with W' mediators which would otherwise be ruled out by direct collider searches.

Various tau asymmetries (FB, polarization) are measurable at Belle II and should allow us to distinguish between models with LH and RH neutrinos.

- tau asymmetries in the D* mode?
- D* polarization asymmetries?
- prospects at LHCb?
- CP-odd asymmetries?

Thanks for your attention!