FLAVOR ANOMALIES AND STERILE NEUTRINOS

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BASED ON:
HEP-PH 1804.04642 WITH ADMIR GRELJO, DEAN ROBINSON, JURE ZUPAN
HEP-PH 1806.XXXXX WITH DEAN ROBINSON, JURE ZUPAN

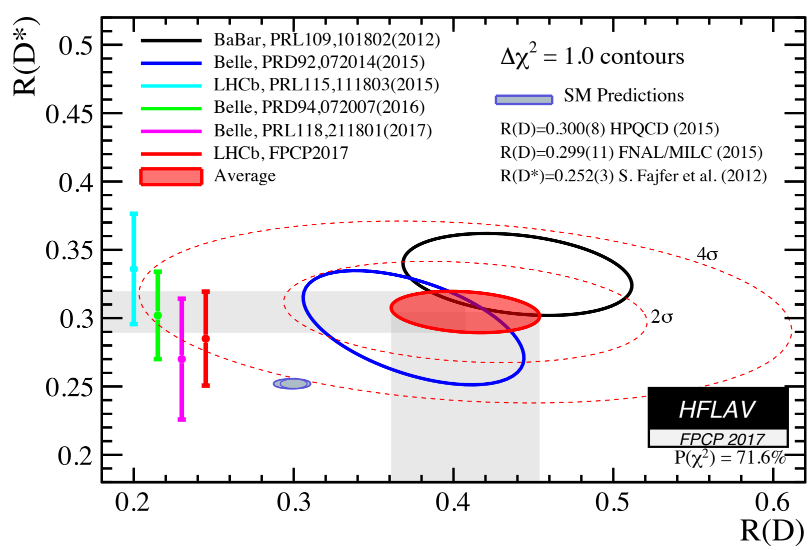
R(D$^{(*)}$) ANOMALY

For the past 5 years, persistent, signals of lepton flavor universality violation in the ratios

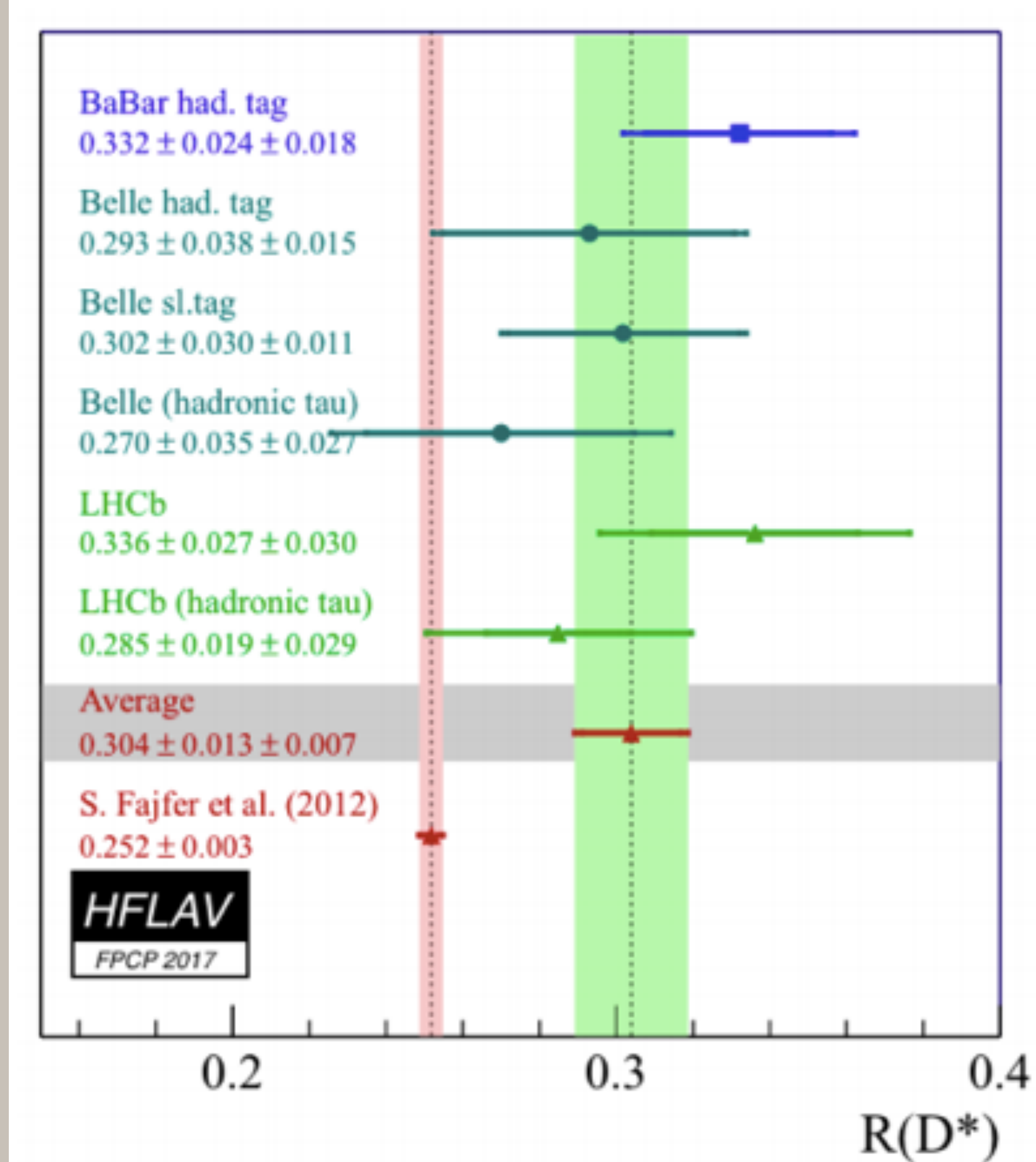
$$R(D^{(*)}) \equiv \frac{\Gamma[B \to D^{(*)}\tau\nu_\tau]}{\Gamma[B \to D^{(*)} l\nu]}\,, \qquad l = \mu,\, e\,.$$

$[D^{(*)} = \bar{c}q$ is a scalar (vector) meson$]$

Experimental measurements disagree at almost 4σ level with SM predictions! A signal of NP?



from D. Robinson



see talk this morning by C. Fitzpatrick

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

requires **new physics that couples bcτν at a level comparable to SM**

several constraints:

- enhanced $B_c \to \tau\nu$ decay rate
- modified differential distributions due to interference effects
- additional interactions due to SU(2) nature of ν

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THIS TALK

consider the possibility that the $R(D^{(*)})$ signal arises due to

NP coupling to right-handed (sterile) neutrinos N_R

instead of the SM neutrinos

N_R OPERATORS FOR R(D$^{(*)}$)

Dim-6 operators involving N_R

$$Q_{\rm SR} = \epsilon_{ab}\big(\bar{Q}_L^a d_R\big)\big(\bar{L}_L^b N_R\big), \qquad Q_{\rm SL} = \big(\bar{u}_R Q_L^a\big)\big(\bar{L}_L^a N_R\big),$$

$$Q_{\rm T} = \epsilon_{ab}\big(\bar{Q}_L^a \sigma^{\mu\nu} d_R\big)\big(\bar{L}_L^b \sigma_{\mu\nu} N_R\big), \qquad Q_{\rm VR} = \big(\bar{u}_R \gamma^\mu d_R\big)\big(\bar{\ell}_R \gamma_\mu N_R\big)$$

After electroweak symmetry breaking

$$\mathcal{O}_{\rm SR} = \big(\bar{c}_L b_R\big)\big(\bar{\tau}_L N_R\big), \qquad \mathcal{O}_{\rm SL} = \big(\bar{c}_R b_L\big)\big(\bar{\tau}_L N_R\big),$$

$$\mathcal{O}_{\rm VR} = \big(\bar{c}_R \gamma^\mu b_R\big)\big(\bar{\tau}_R \gamma_\mu N_R\big), \qquad \mathcal{O}_{\rm T} = \big(\bar{c}_L \sigma^{\mu\nu} b_R\big)\big(\bar{\tau}_L \sigma_{\mu\nu} N_R\big)$$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm eff}^{\rm SM} + \frac{1}{\Lambda_{\rm eff}^2}\sum_i c_i \mathcal{O}_i. \qquad \Lambda_{\rm eff} = \big(2\sqrt{2}G_F V_{cb}\big)^{-1/2} \simeq 0.87\left[\frac{40\times 10^{-3}}{V_{cb}}\right]^{1/2} \text{TeV}$$

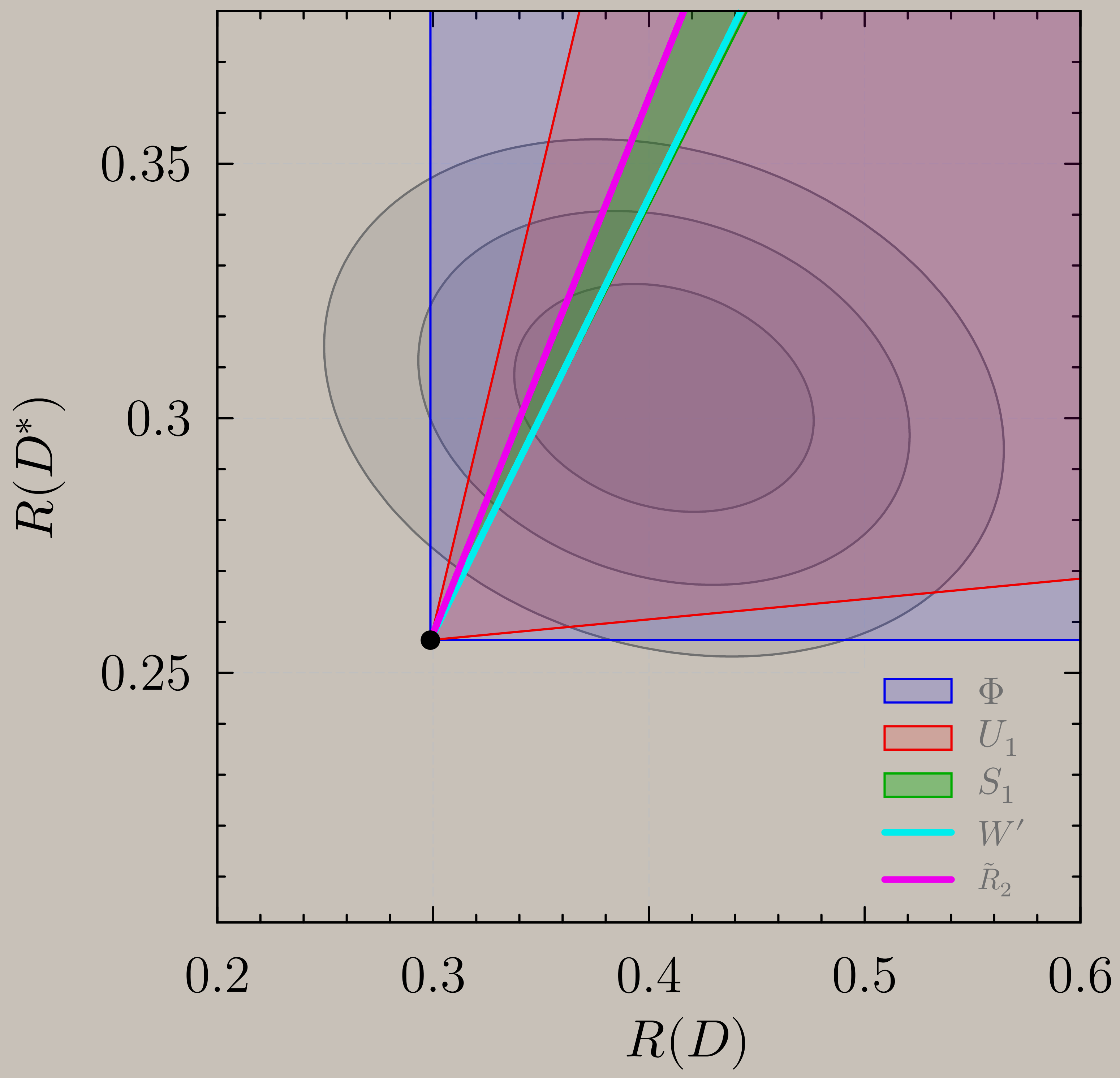
UV COMPLETIONS

$$\mathcal{O}_{\mathrm{SR}} = \left(\bar{c}_L b_R\right)\left(\bar{\tau}_L N_R\right), \qquad \mathcal{O}_{\mathrm{SL}} = \left(\bar{c}_R b_L\right)\left(\bar{\tau}_L N_R\right),$$

$$\mathcal{O}_{\mathrm{VR}} = \left(\bar{c}_R \gamma^\mu b_R\right)\left(\bar{\tau}_R \gamma_\mu N_R\right), \qquad \mathcal{O}_{\mathrm{T}} = \left(\bar{c}_L \sigma^{\mu\nu} b_R\right)\left(\bar{\tau}_L \sigma_{\mu\nu} N_R\right)$$

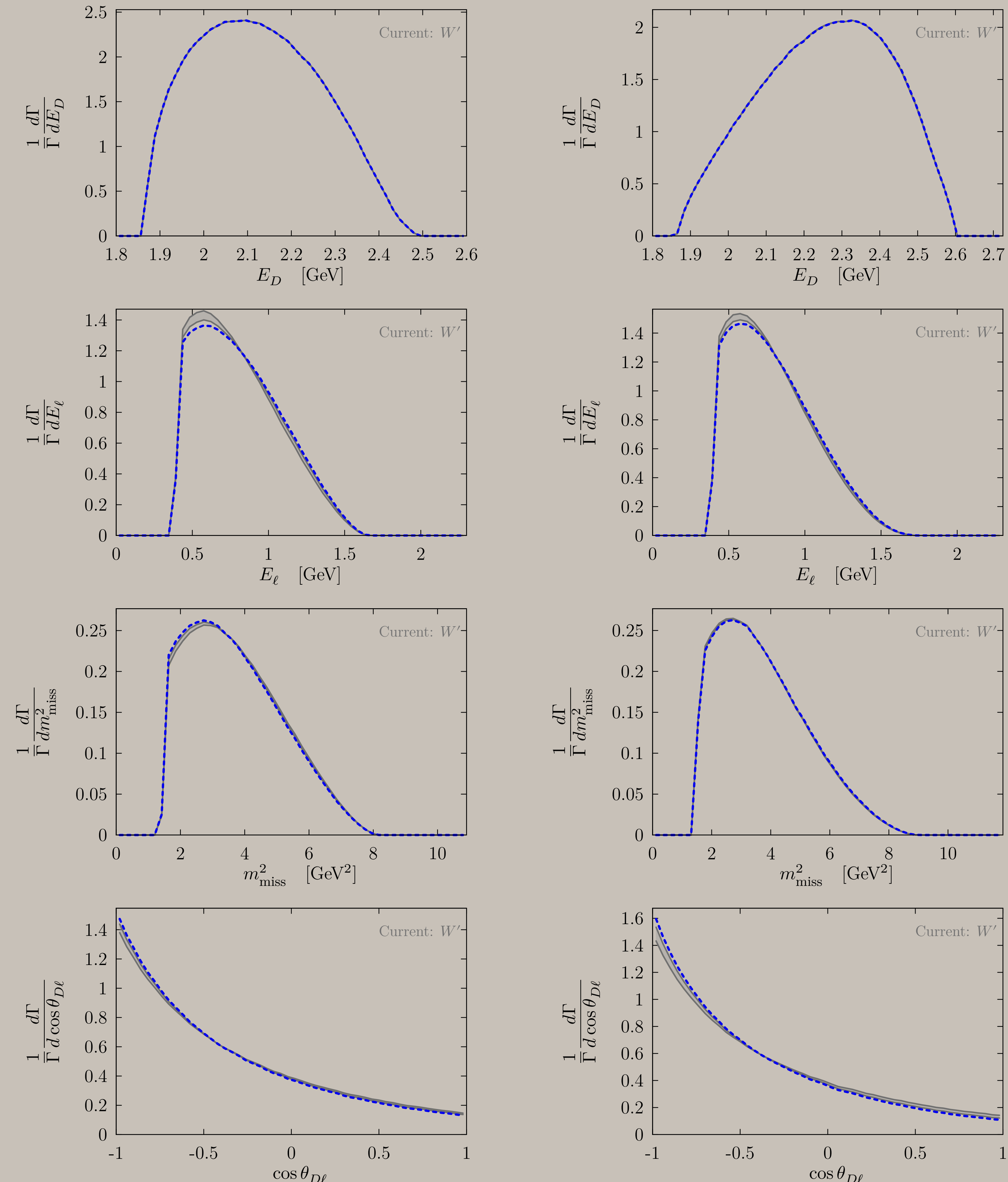
	mediator	irrep	$\delta\mathcal{L}_{\mathrm{int}}$	WCs
vector	W'_μ	$(1,1)_1$	$g'\left(c_q \bar{u}_R \not{W}' d_R + c_N \bar{\ell}_R \not{W}' N_R\right)$	c_{VR}
scalar	Φ	$(1,2)_{1/2}$	$y_u \bar{u}_R Q_L \epsilon \Phi + y_d \bar{d}_R Q_L \Phi^\dagger + y_N \bar{N}_R L_L \epsilon \Phi$	$c_{\mathrm{SL}}, \quad c_{\mathrm{SR}}$
leptoquarks	U_1^μ	$(3,1)_{2/3}$	$\left(\alpha_{LQ} \bar{L}_L \gamma_\mu Q_L + \alpha_{\ell d} \bar{\ell}_R \gamma_\mu d_R\right) U_1^{\mu\dagger} + \alpha_{uN}\left(\bar{u}_R \gamma_\mu N_R\right) U_1^\mu$	$c_{\mathrm{SL}}, \quad c_{\mathrm{VR}}$
	$\tilde{R}_2$	$(3,2)_{1/6}$	$\alpha_{Ld}\left(\bar{L}_L d_R\right)\epsilon \tilde{R}_2^\dagger + \alpha_{QN}\left(\bar{Q}_L N_R\right)\tilde{R}_2$	$c_{\mathrm{SR}} = 4 c_{\mathrm{T}}$
	S_1	$(\bar{3},1)_{1/3}$	$z_u(\bar{U}_R^c \ell_R) S_1 + z_d(\bar{d}_R^c N_R) S_1 + z_Q(\bar{Q}_L^c \epsilon L_L) S_1$	c_{VR}, $c_{\mathrm{SR}} = -4 c_{\mathrm{T}}$

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

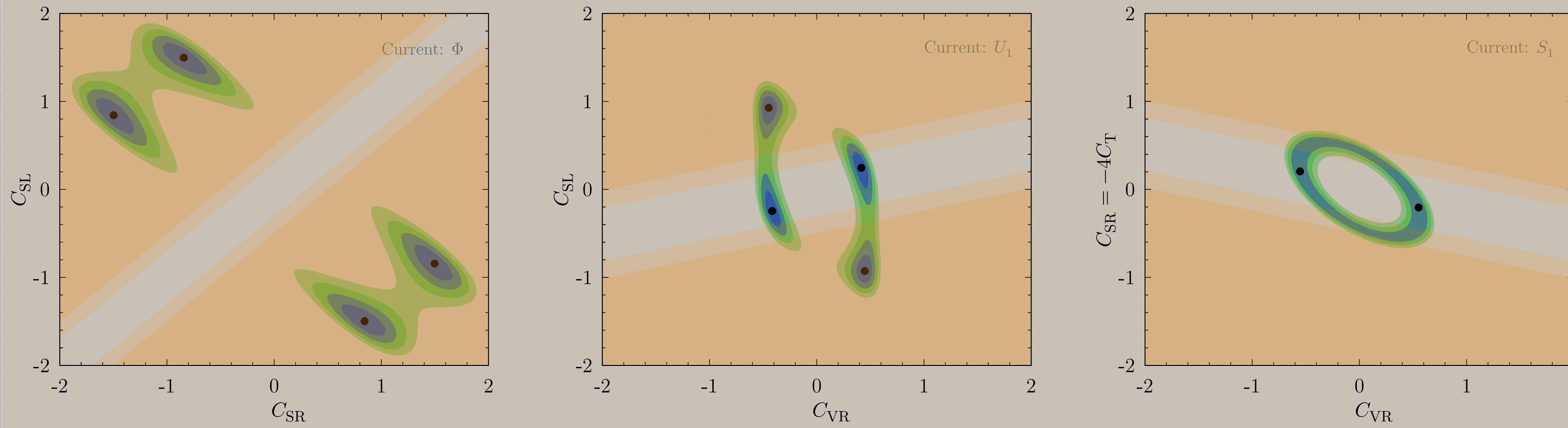


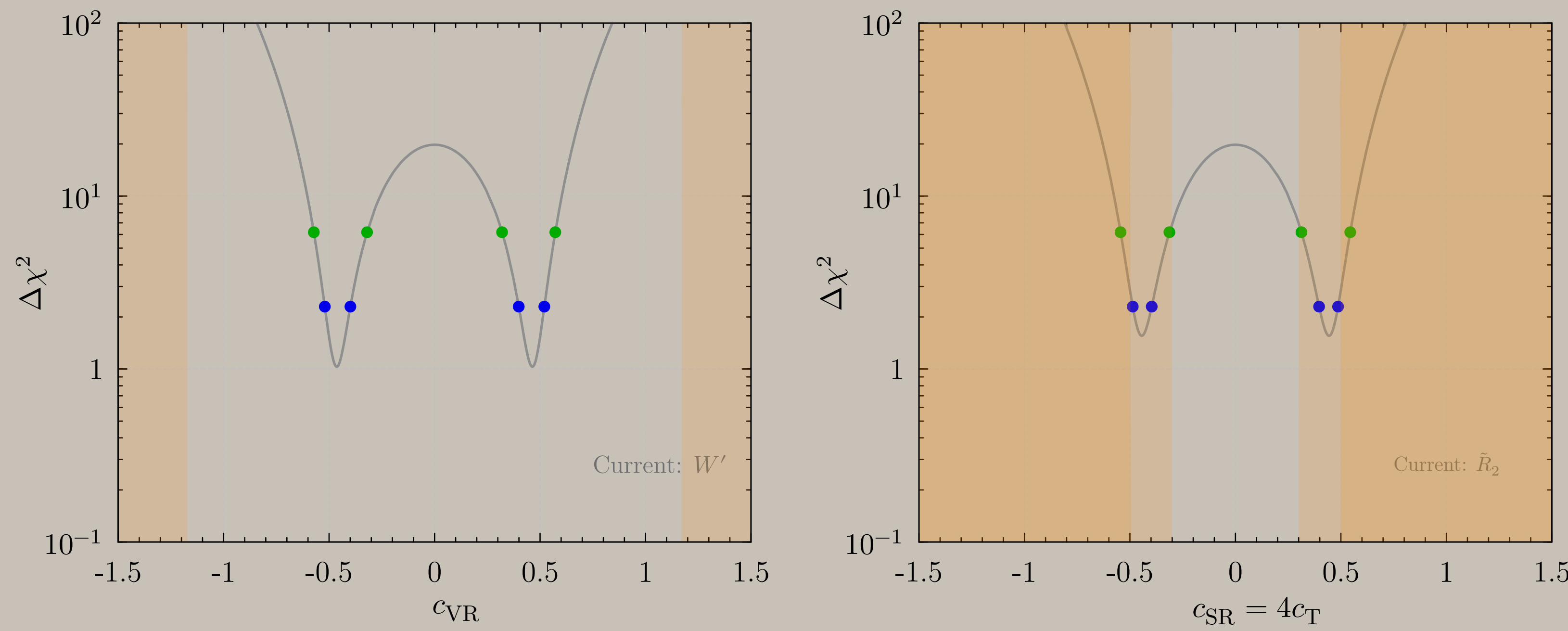
effects on kinematic distributions

(here: W' mediator, massless N_R. similar observations for other mediators)



FITS AND CONSTRAINTS





Orange:

excluded region from requiring $Br(B_C \to \tau\nu) < 5\%$

- NP corrections and form factor fits based on

  Z. Ligeti, M. Papucci, and D. J. Robinson, JHEP 01, 083 (2017), 1610.02045

- F. U. Bernlochner, Z. Ligeti, M. Papucci, and D. J. Robinson, Phys. Rev. D95, 115008 (2017), 1703.05330

BEST FIT VALUES

Model	WCs	Best Fit
W'	c_{VR}	± 0.46
$\tilde{R}_2$	$c_{\mathrm{SR}} = 4c_{\mathrm{T}}$	± 0.44
Φ	$\{c_{\mathrm{SR}}, c_{\mathrm{SL}}\}$	$\{\pm 1.50, \mp 0.84\}$ $\{\pm 0.84, \mp 1.50\}$
U_1	$\{c_{\mathrm{VR}}, c_{\mathrm{SL}}\}$	$\{\pm 0.45, \mp 0.93\}$ $\{\pm 0.42, \pm 0.24\}$
S_1	$\{c_{\mathrm{VR}}, c_{\mathrm{SR}} = -4c_{\mathrm{T}}\}$	$\{\pm 0.55, \mp 0.21\}$

excluded by

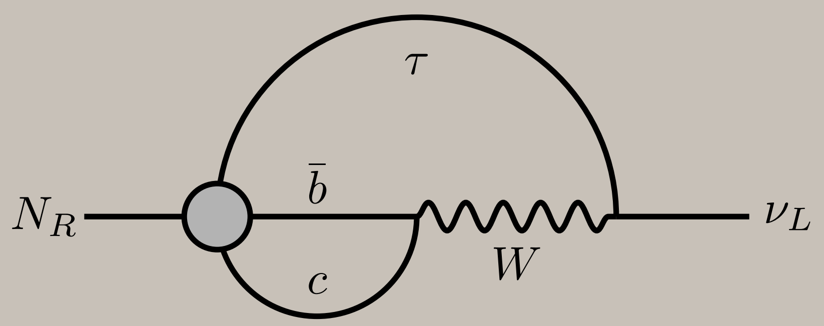
$\mathrm{Br}(B_c \to \tau\nu)$

NEW PHYSICS

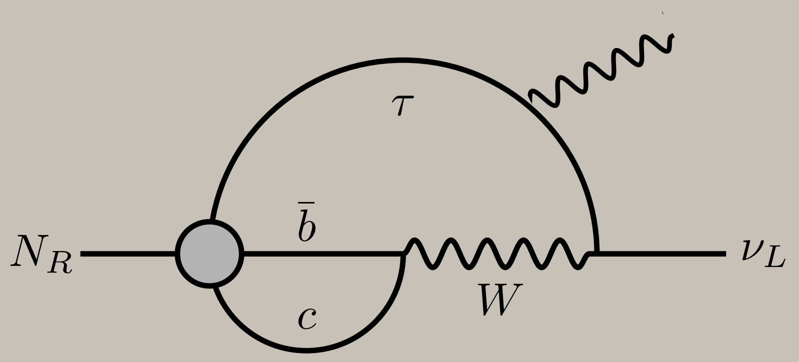
- new mediators (W', R_2, U_1, S_1):

look for other (more direct) evidence at the LHC - can couple to other SM particles and carry other signatures

- sterile neutrino N_R effects and signals



neutrino mass contribution at 2 loop



sterile neutrino decay

[Note: NO free parameters once $R(D^{(*)})$ fixed!]

- flavor structure of the underlying theory crucial:

determines couplings to other SM particles, controls constraints/signatures

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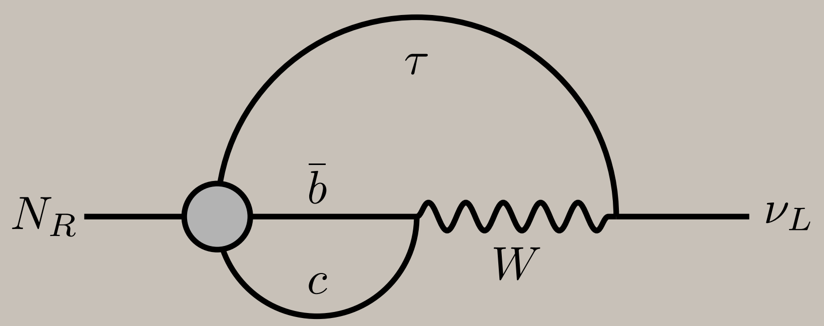

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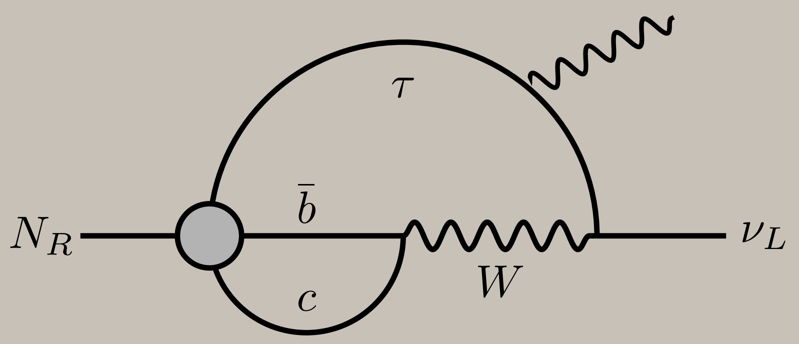

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NEXT: study these in more detail in the W' model

THE W' (3221) MODEL

gauge group $\mathcal{G} = SU(3)_c \times SU(2)_L \times SU(2)_V \times U(1)'$ $\quad SU(2)_V \times U(1)' \to U(1)_Y$

Field	$SU(3)_c$	$SU(2)_L$	$SU(2)_V$	$U(1)'$
		SM-like chiral fermions		
$q_L'^i$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	1/6
$\ell_L'^i$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	-1/2
$u_R'^i$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	2/3
$d_R'^i$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	-1/3
$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
$\nu_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0
		Extra vector-like fermions		
$Q_{L,R}'^i$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	1/6
$L_{L,R}'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	-1/2
		Scalars		
H	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	1/2
H_V	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	1/2

W' talks to SM fermions only via mixing with vector-like fermions. Can appropriately engineer this mixing so that W' talks significantly only to (right-handed) b,c,τ

THE NEUTRINO SECTOR

basis $(\nu'_L, \nu'^c_R, N'_L, N'^c_R)$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \frac{y_\nu v_{\rm EW}}{\sqrt{2}} & 0 & 0 \\ \frac{y_\nu v_{\rm EW}}{\sqrt{2}} & \mu & \frac{\lambda_\nu v_V}{\sqrt{2}} & 0 \\ 0 & \frac{\lambda_\nu v_V}{\sqrt{2}} & 0 & M_L \\ 0 & 0 & M_L & 0 \end{pmatrix}$$

$$N^c_R = \cos\theta_N \nu'^c_R - \sin\theta_N N'^c_R$$

responsible for anomaly

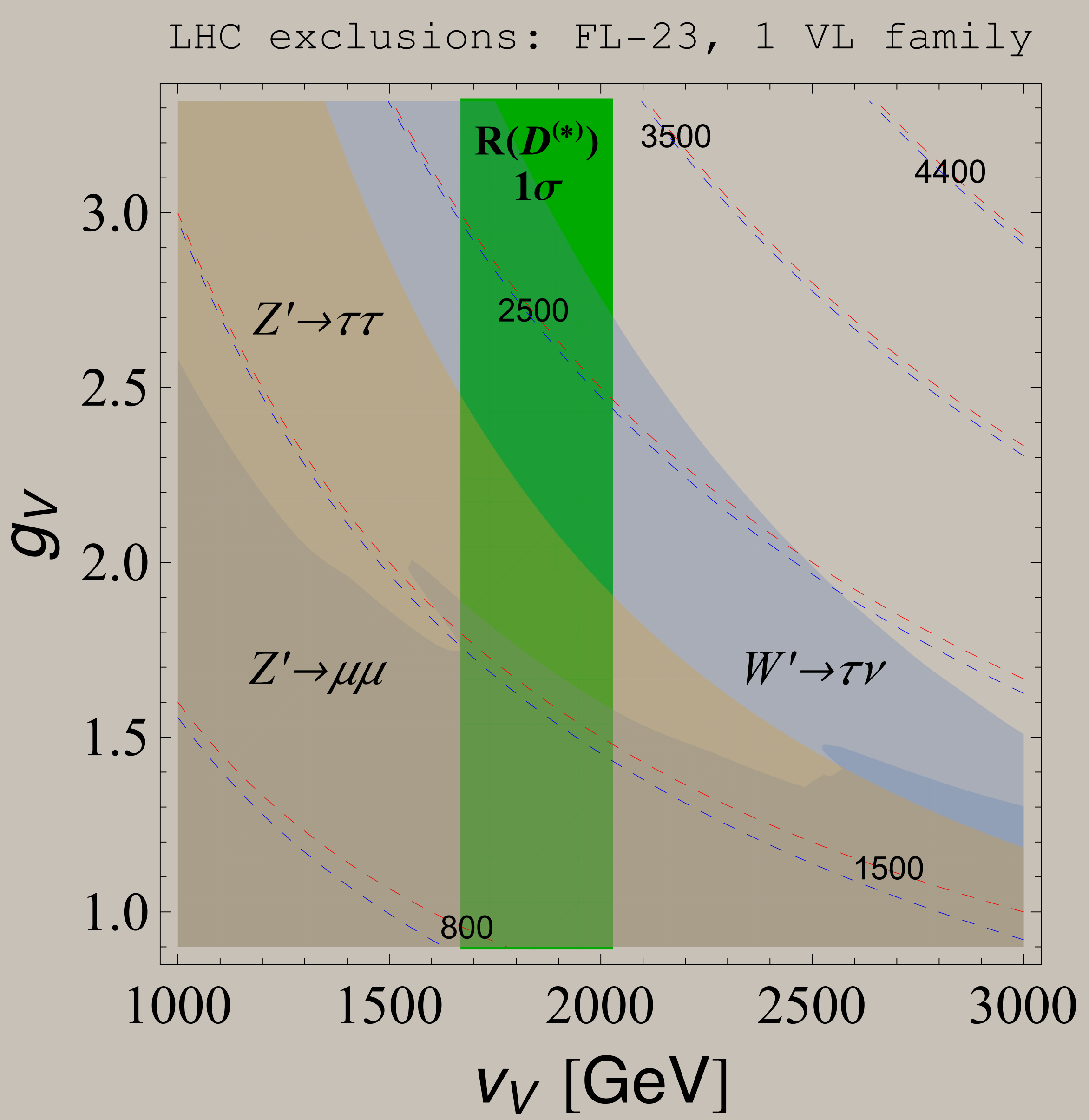
$$\tan\theta_N = (\lambda_\nu v_V)/(\sqrt{2} M_L)$$

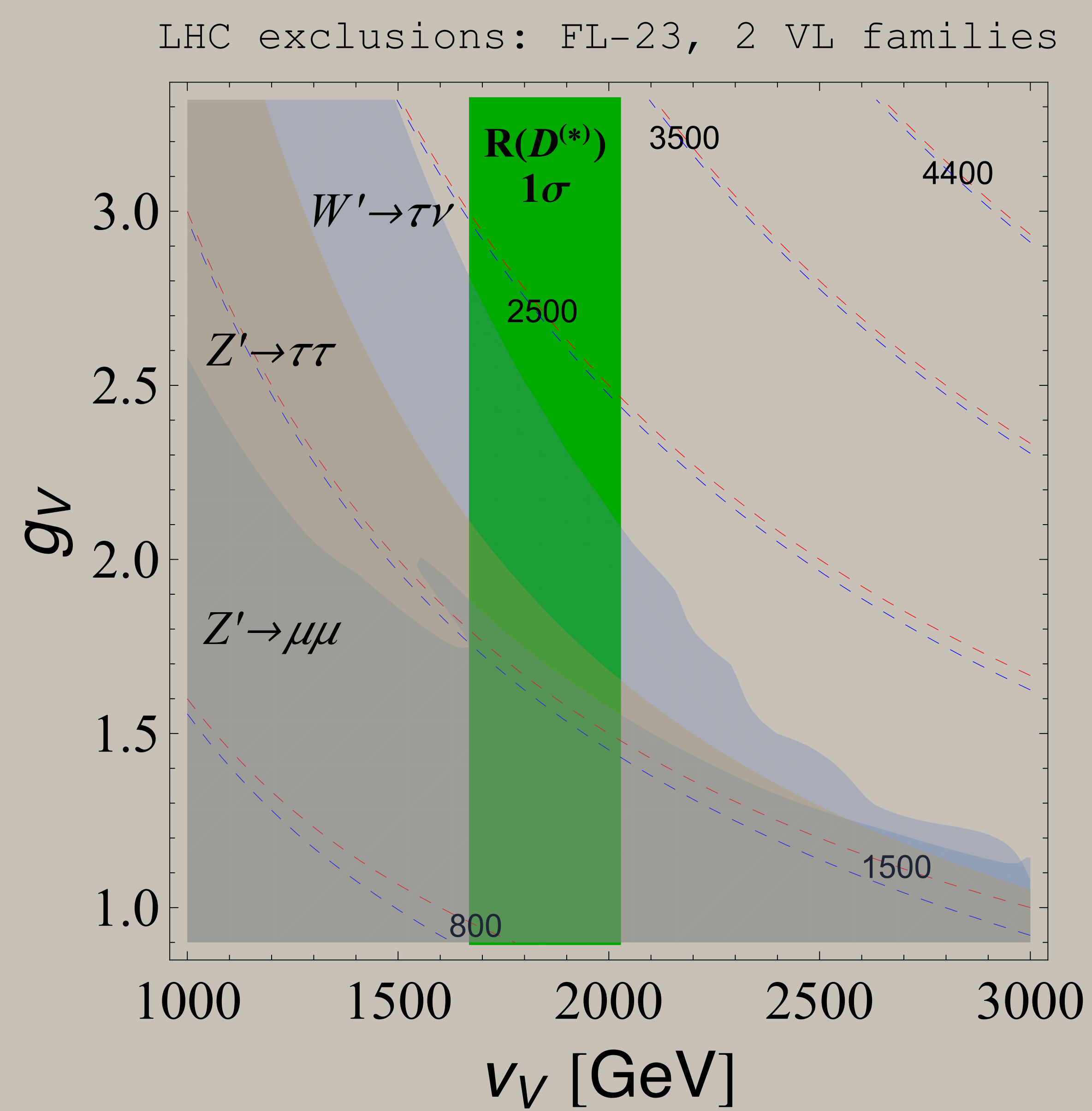
$$M_{N_R} \approx \mu \, (M_L/M_{N'})^2 \qquad (\mu \ll M_L, \lambda_\nu v_V)$$

vectorlike states give pseudo-Dirac state of mass $M_{N'} \equiv M_L \sqrt{1 + \tan^2\theta_N}$ split by O(μ)

The Yukawa couplings y_ν can be appropriately chosen such that $y_\nu v_{EW} << \mu$ and the SM neutrinos get the right masses via a low scale type-I seesaw

GAUGE BOSON (W',Z') CONSTRAINTS

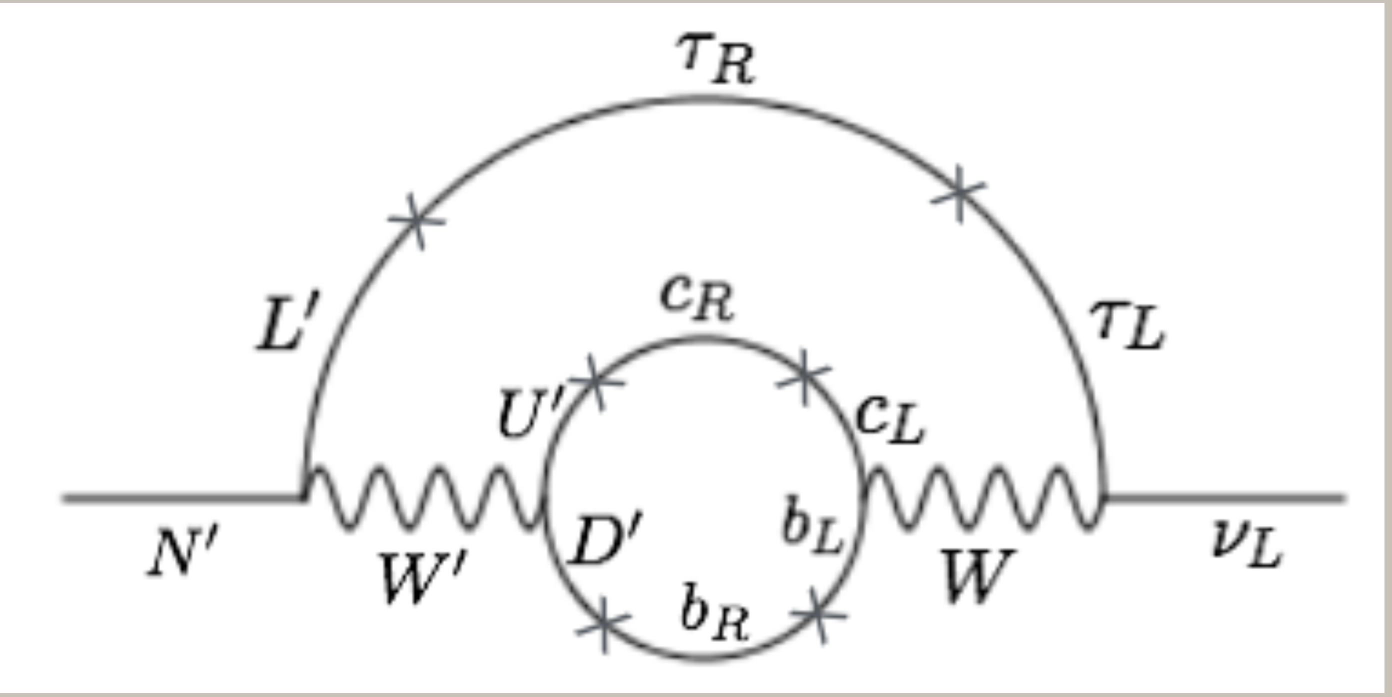




dashed blue (red): contours of Z'(W') masses

NEUTRINO MASSES

Dirac mass at 2 loops



$$m_D \sim \frac{g^2\, V_{cb}}{512\pi^4}\, \frac{C_{23,3}}{\Lambda_{\text{eff}}^2}\, m_b\, m_c\, m_\tau \approx \mathcal{O}(10^{-3})\,\text{eV}$$

[For other mediators that couple to left-handed instead of right-handed SM fermions, this contribution can be big and requires cancellations with tree-level Yukawa mass terms for consistency]

STERILE NEUTRINO COSMOLOGY

produced in the early Universe via the same interaction that gives $R(D^{(*)})$

relativistic freezeout: unsuppressed relic density

STERILE NEUTRINO … DARK MATTER?

RELIC ABUNDANCE:

- overabundant due to relativistic freezeout: need to dilute relic density.
- entropy dilution from additional (heavier) sterile neutrinos (~GeV) that decay late (just before BBN) can do this

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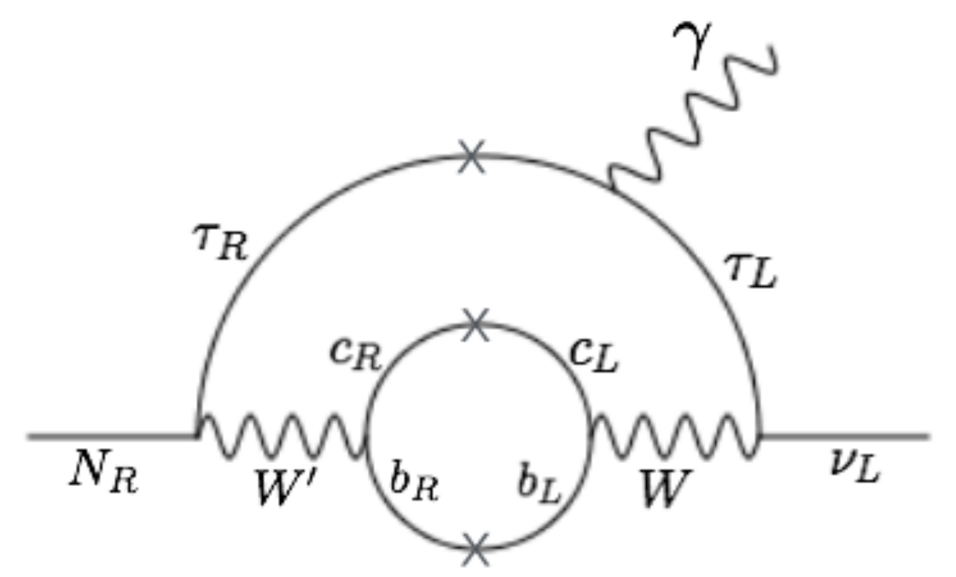
LIFETIME:

$$\Gamma_{N_R\to\nu\gamma} \simeq \frac{\alpha}{32\,\pi^8}\,V_{cb}^2\,\frac{G_F^2\,m_\tau^2\,m_b^2\,m_c^2\,m_{N_R}^3}{(\Lambda_{\rm eff}^2/C_{23,3})^2}$$
$$\simeq 10^{-49}\left(\frac{m_{N_R}}{\rm keV}\right)^3 \rm GeV.$$



- lifetime $\sim 10^{25}\,(m_{N_R}/\mathrm{keV})^{-3}$ s
- gamma ray constraint on DM lifetime: $\mathcal{O}(10^{26-28})s$ in the keV-MeV window

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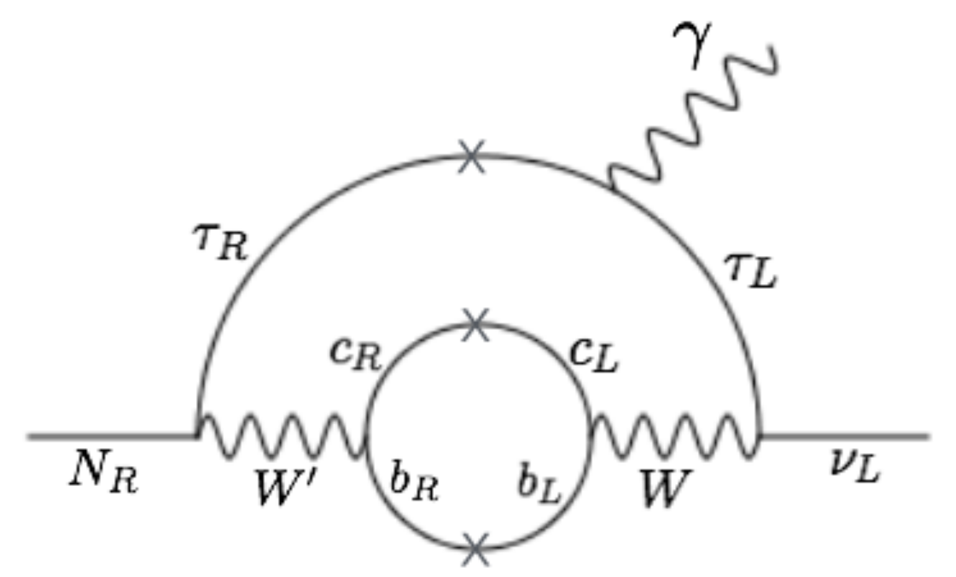

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- longer lifetime than age of Universe, but cannot be all of DM
- can be a small fraction of DM, with detectable gamma ray signals

STERILE NEUTRINO AS DARK RADIATION

If light (~ eV), N_R is relativistic at BBN/CMB decoupling, and can contribute

$$\Delta N_{\rm eff} \approx \mathcal{O}(0.1).$$

- detectable with CMB-S4

ADDITIONAL STERILE NEUTRINOS

The theory potentially contains additional light ν_R (multiple generations, entropy dilution, low scale seesaw…)

not as strongly coupled to W_R, but can still be produced at experiments

cosmology requires short (< 1s) lifetime: displaced vertices! signal for MATHUSLA / FASER / CODEX-b

SUMMARY

persistent anomalies in measurements of **$R(D^{(*)})$** at **several experiments**

could arise from couplings to **sterile neutrinos**. **many UV completions** possible

measurable deviations in kinematic distributions of events possible

predicts heavier mediator particles - LHC can look for them!

exotic sterile neutrino phenomenology:

relic sterile neutrinos can give **measurable dark radiation** or **small fraction of dark matter** that can possibly give **gamma ray signals**.

additional sterile neutrinos in the sector can give more exotic direct signals **(displaced decays)**