STERILE NEUTRINOS FOR FLAVOR ANOMALIES

NUTHEORIES: BEYOND THE 3×3 PARADIGM
PITTSBURGH, NOV 6, 2018

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BASED ON:
HEP-PH 1807.04753 WITH DEAN ROBINSON, JURE ZUPAN
HEP-PH 1804.04642 WITH ADMIR GRELJO, DEAN ROBINSON, JURE ZUPAN

NEUTRINOS ↔ NEW PHYSICS

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- THEORETICAL MOTIVATION
- EXPERIMENTAL OPPORTUNITIES
- ANOMALIES IN OBSERVATIONS

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anomalies in neutrino oscillation experiments (reactor/disappearance)

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anomalies in neutrino oscillation experiments (reactor/disappearance)

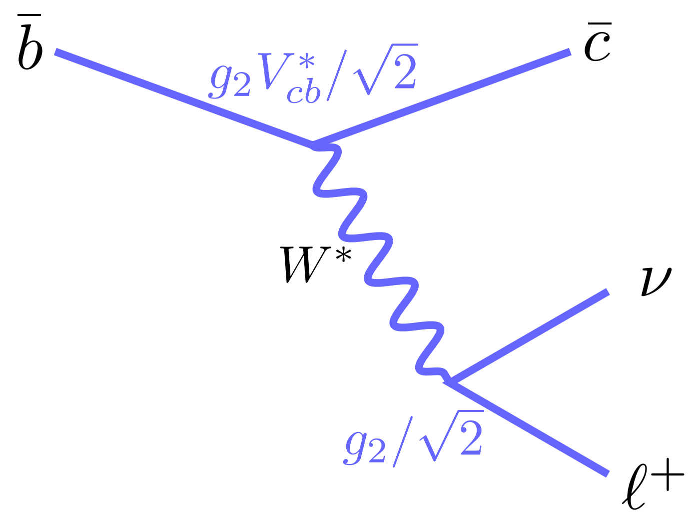
flavor anomalies (this talk)

$\mathbf{R(D^{(*)})}$

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

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

Semileptonic $b \to c\ell\nu$ processes are theoretically clean tests of lepton flavor universality



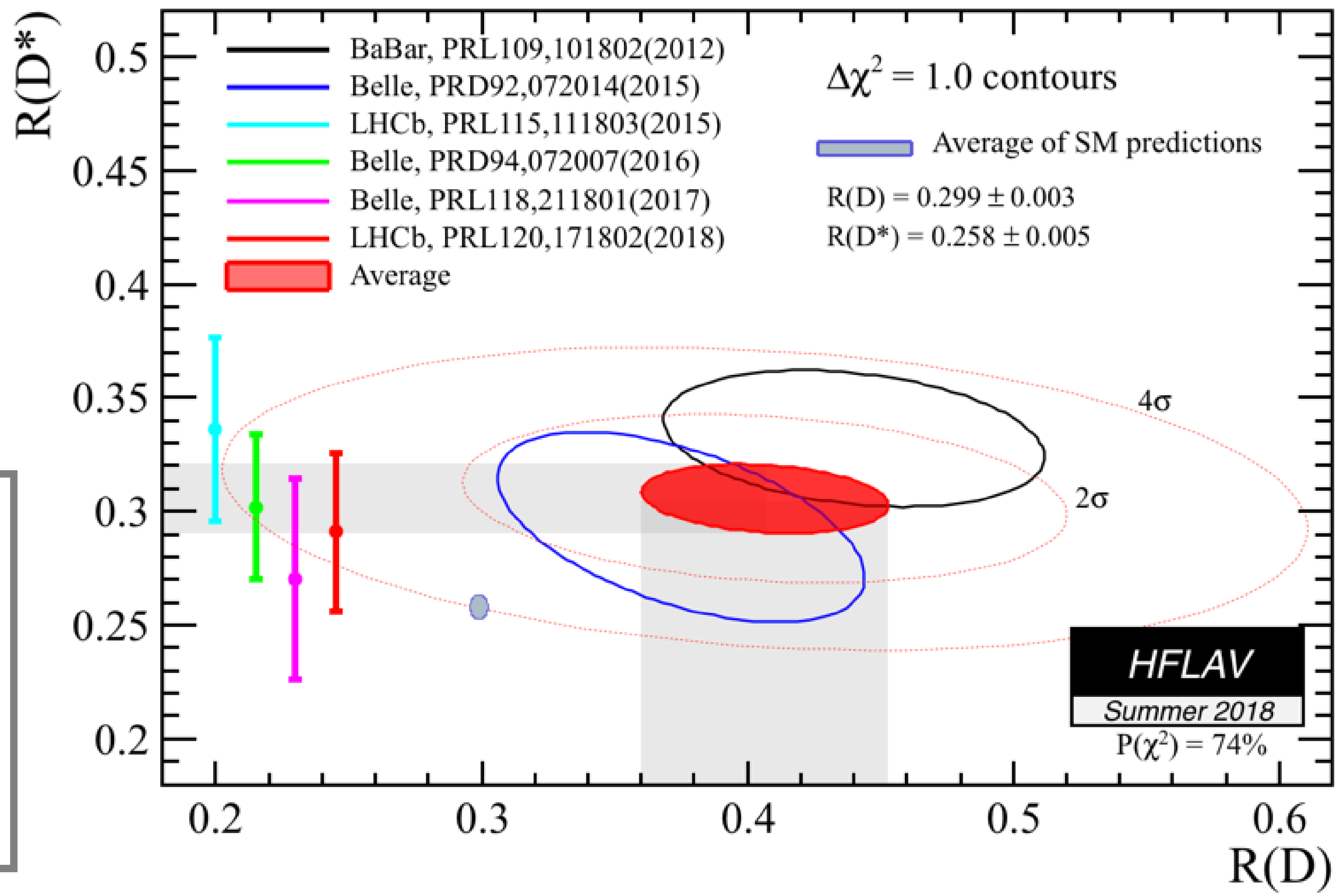
- Dominantly tree-level W exchange in the SM
- Lepton universal $\ell = e,\, \mu,\, \tau$, up to mass effects: PS & hadronic FFs

from D. Robinson

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

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

Experimental measurements disagree at almost 4σ level with SM predictions!



from D. Robinson

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

requires **new physics**

that couples $bc\tau\nu$ at a level comparable to SM

several constraints:

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

(in particular, very strong constraints from $pp \to \tau\,\tau$ from colliders)

[Faroughy,Greljo, Kamenik, 1609.07138]

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

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

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

THIS TALK

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

NP coupling to right-handed (sterile) neutrinos N_R

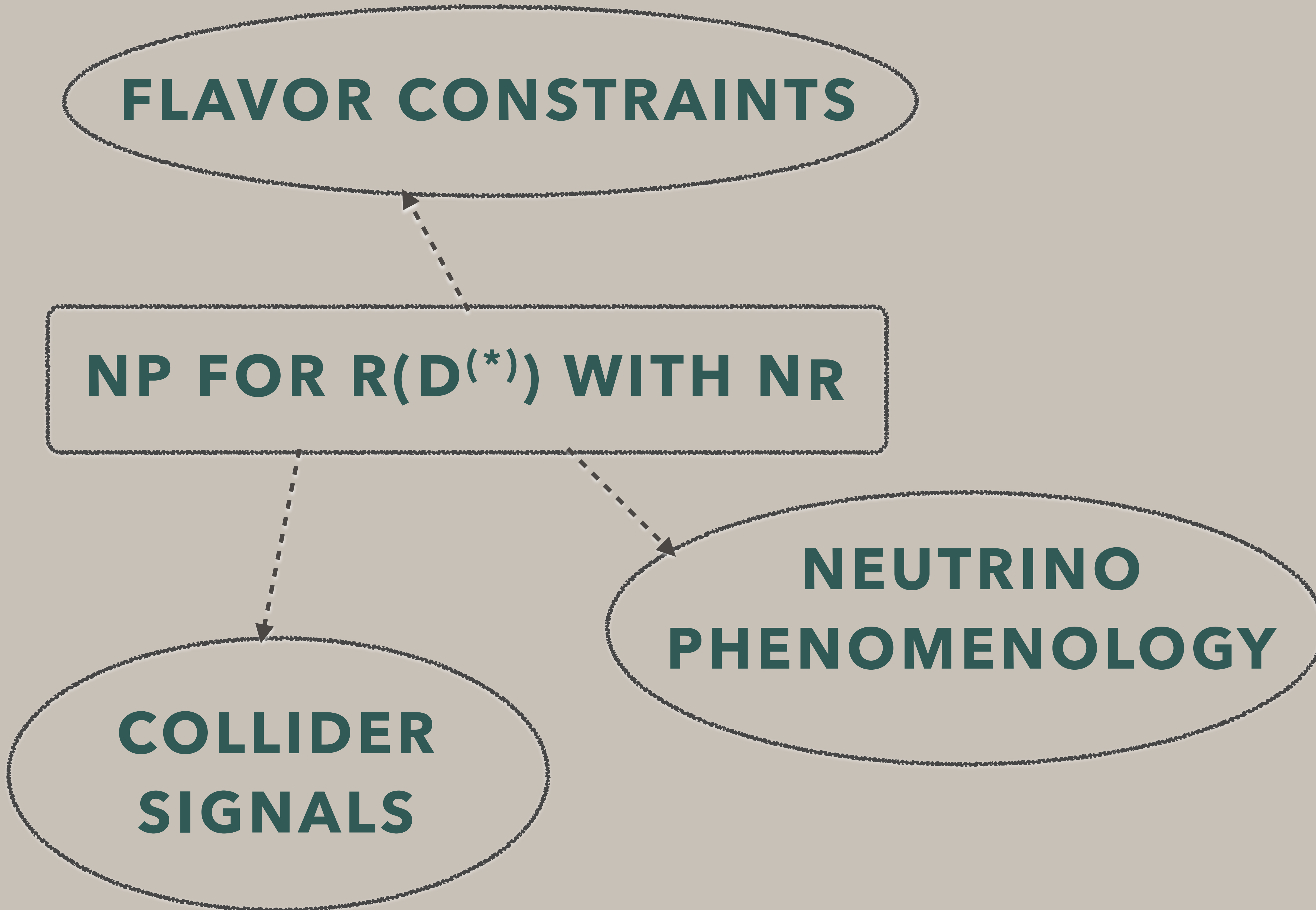
instead of the SM neutrinos

will consider right handed neutrinos to be separate Majorana particles

(easier to avoid constraints, richer phenomenology)

[aside: there are other flavor anomalies (R(K$^{(*)}$),

which do not directly involve neutrinos]


FLAVOR CONSTRAINTS
NP FOR R(D(*)) WITH NR
NEUTRINO PHENOMENOLOGY
COLLIDER SIGNALS

THE PLAN

- NEW PHYSICS FITS TO $R(D^{(*)})$
  - can do this with specific models or a general EFT language
  - take the EFT approach and talk about all possible operators (will come back to a specific UV complete model later)
  - flavor constraints/considerations
- STERILE NEUTRINO PHENOMENOLOGY
  - contributions to neutrino masses
  - sterile neutrino cosmology
  - direct search prospects
- COLLIDER PROBES OF HEAVY MEDIATORS

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

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

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

parametrize as

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

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

Dim-6 operators involving N_R

$$Q_{SR} = \epsilon_{ab}(\bar{Q}^a_L d_R)(\bar{L}^b_L N_R), \qquad Q_{SL} = (\bar{u}_R Q^a_L)(\bar{L}^a_L N_R),$$

$$Q_T = \epsilon_{ab}(\bar{Q}^a_L \sigma^{\mu\nu} d_R)(\bar{L}^b_L \sigma_{\mu\nu} N_R), \qquad Q_{VR} = (\bar{u}_R \gamma^\mu d_R)(\bar{\ell}_R \gamma_\mu N_R)$$

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parametrize as

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{\text{SM}}_{\text{eff}} \frac{1}{\Lambda^2_{\text{eff}}} \sum_i \alpha_i \mathcal{O}_i \ldots (2\sqrt{2} G_F V_{cb})^{-1/2} \ldots \left[\frac{40 \times 10^{-3}}{V_{cb}}\right]^{1/2} \text{TeV}$$

we will assume that these operators are completely aligned with the b, c, τ mass eigenstates, and no other corresponding couplings with other generations exist

[built-in assumption for us, but can be accomplished in flavor-locked models (S. Knapen and D. J. Robinson, 1507.00009)]

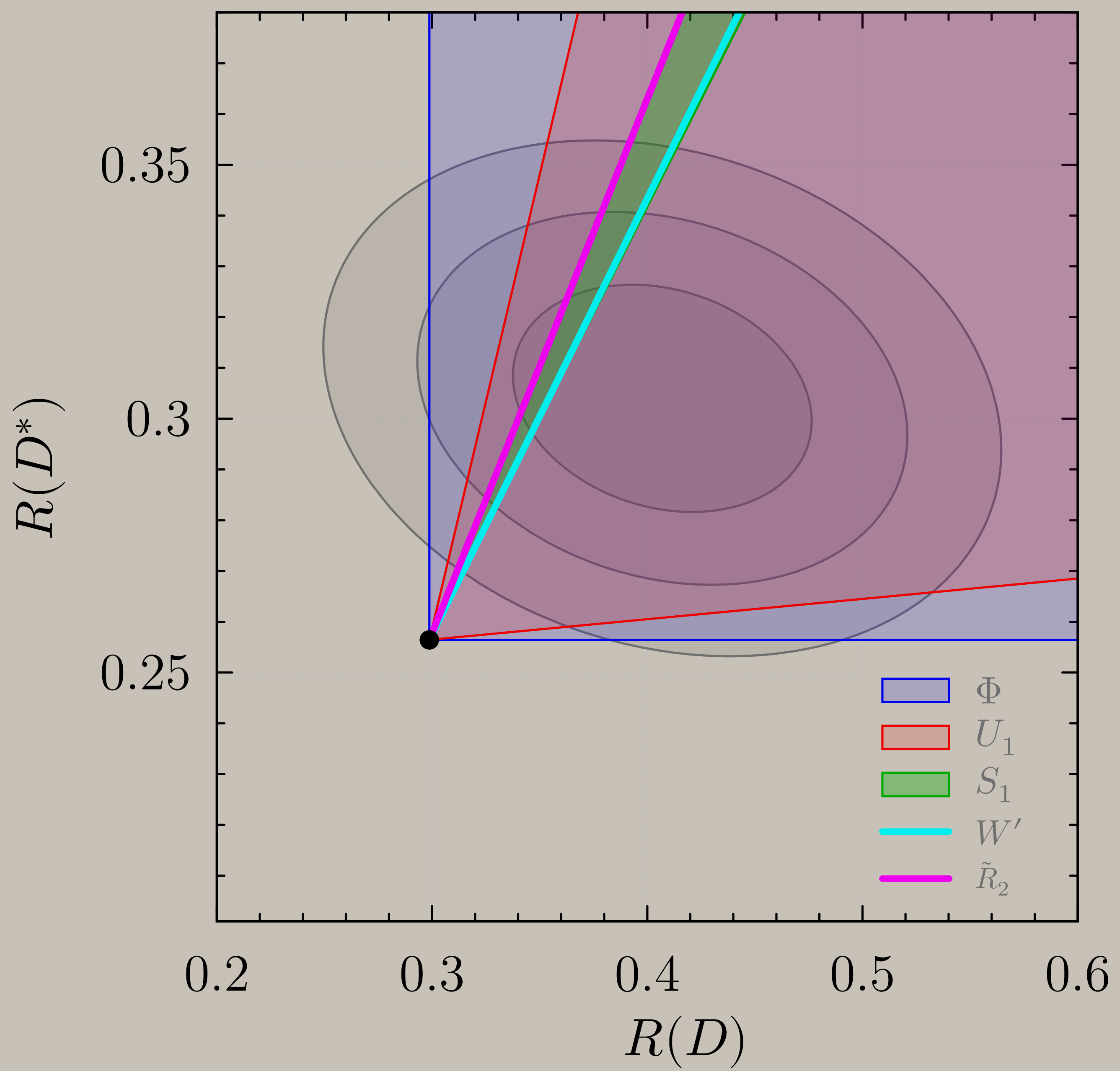
have to be careful about running effects when comparing physics at different scales

UV COMPLETIONS

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

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

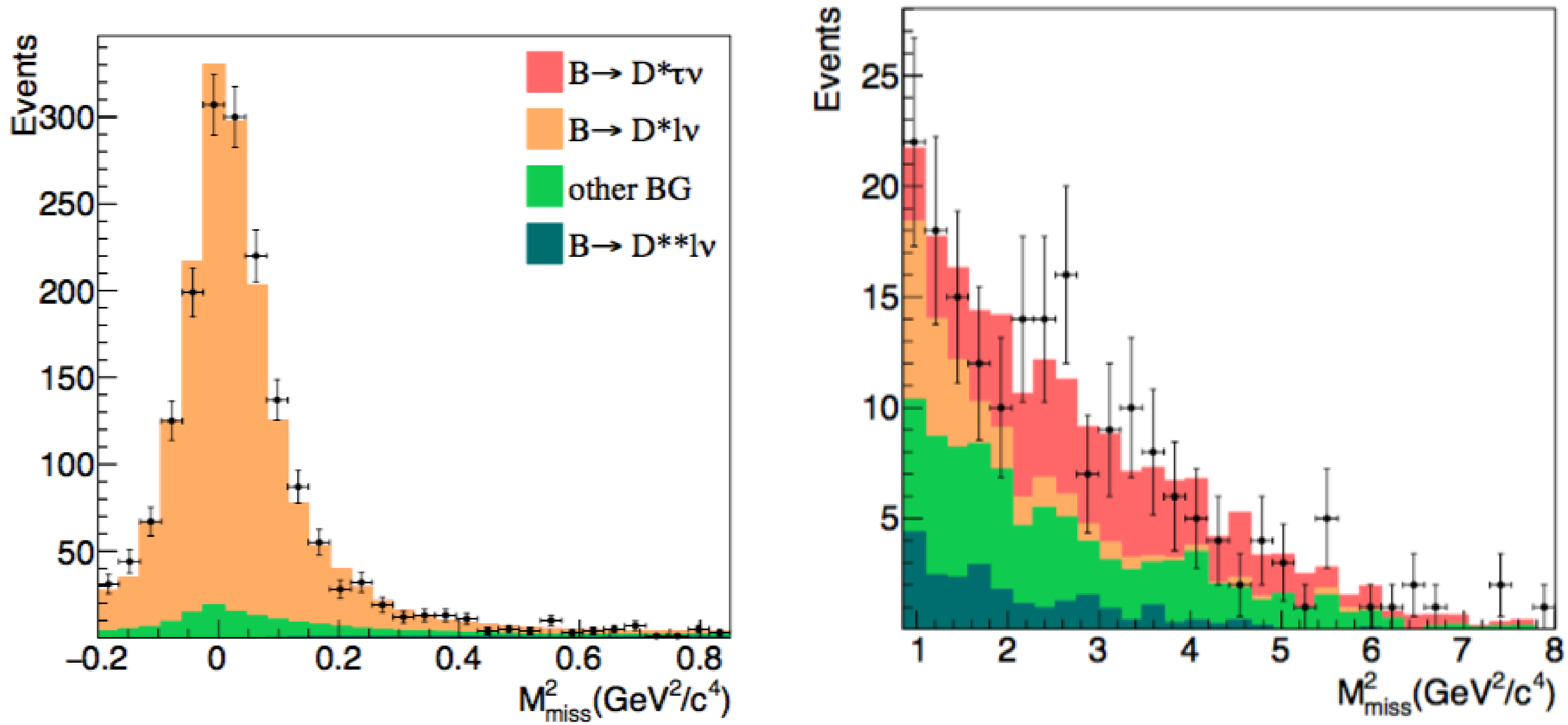
$R(D^{(*)})$ CONTRIBUTIONS



NP contributions add INCOHERENTLY to the SM effect.

Can only increase $R(D^{(*)})$, as the measurements demand!

HOW HEAVY CAN N_R BE?



1507.03233 [Belle]

- Migration in m^2_{miss} can be large
- Existing analyses can probably tolerate $m_{N_R} \lesssim \mathcal{O}(100)$ MeV

from D. Robinson

MAIN CONSTRAINT

from D. Robinson

Introducing $b \to c\tau N_R$ operator $\implies$ contribution to $B_c \to \tau N_R$ decays

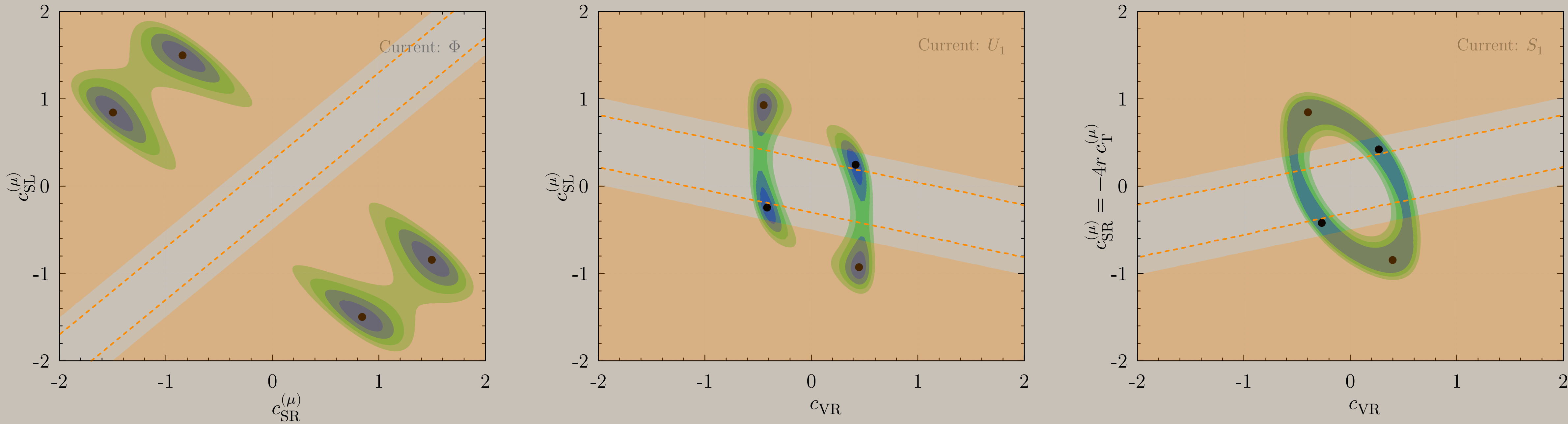
$$\mathrm{Br}[B_c \to \tau\nu_{\mathrm{SM}}] = \mathrm{Br}_{\mathrm{SM}}\left[1 + \left|c_{\mathrm{VR}} + \frac{m_{B_c}^2}{m_\tau(\overline{m}_b + \overline{m}_c)}[c_{\mathrm{SL}}(\mu) - c_{\mathrm{SR}}(\mu)]\right|^2\right]$$

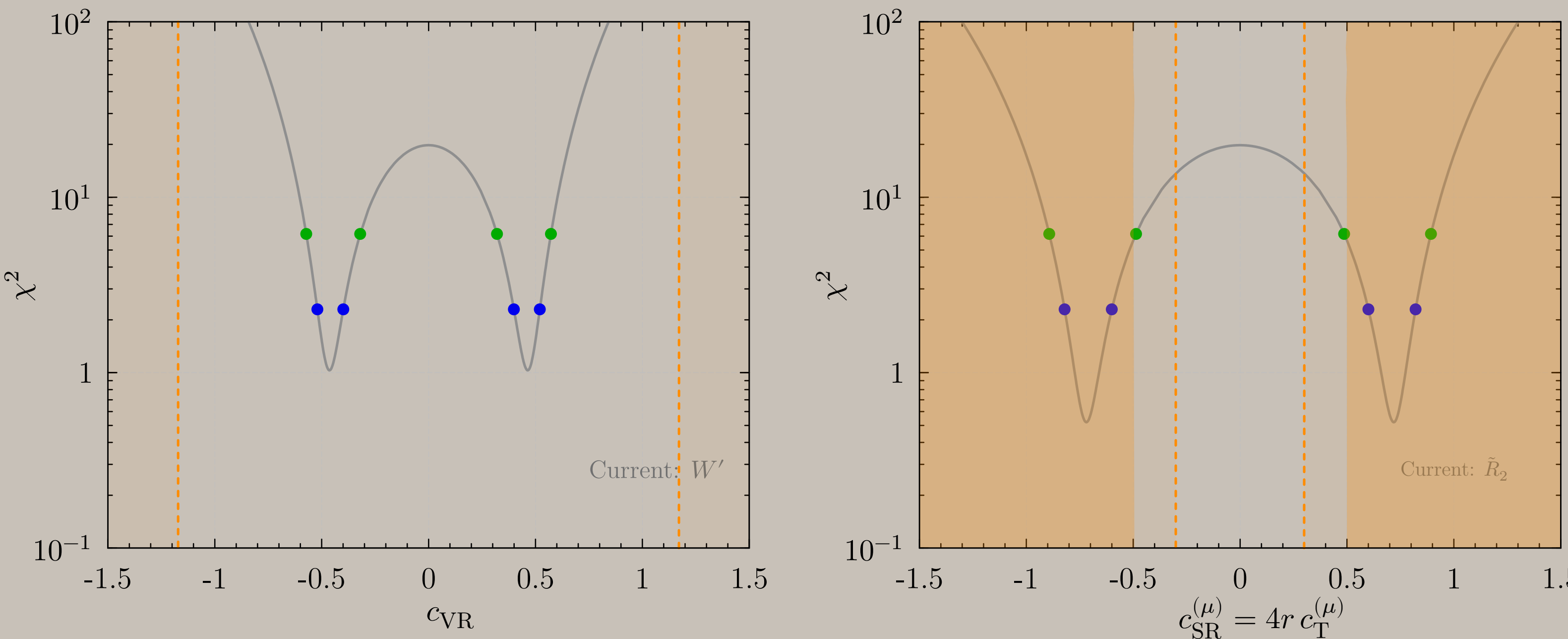
- A huge enhancement for scalar operators $\sim m_{B_c}/m_\tau$
- $B_c \to \tau\nu$ is not measured, but the B_c lifetime time and exclusive BRs to hadrons *are*

We will impose $\mathrm{Br}(B_c \to \tau\nu) < 10\%$ (reasonable) or $< 5\%$ (aggressive)

FITS AND CONSTRAINTS

(assuming all couplings real)





Orange:

excluded region from requiring $Br(B_c \to \tau\nu) < 10\%$ (dotted: 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

(assuming all couplings real)

		Real
Model	WCs	Best fit
W'	$c_{\rm VR}$	± 0.46
$\tilde{R}_2$	$c_{\rm SR}^{(\mu)} = 4r\, c_{\rm T}^{(\mu)}$	± 0.72
Φ	$\{c_{\rm SR}^{(\mu)}, c_{\rm SL}^{(\mu)}\}$	$\{\pm 1.50, \mp 0.84\}$ $\{\pm 0.84, \mp 1.50\}$
U_1	$\{c_{\rm VR}, c_{\rm SL}^{(\mu)}\}$	$\{\pm 0.45, \mp 0.93\}$ $\{\pm 0.42, \pm 0.24\}$
S_1	$\{c_{\rm VR}, c_{\rm SR}^{(\mu)} = -4r\, c_{\rm T}^{(\mu)}\}$	$\{\pm 0.40, \mp 0.85\}$ $\{\pm 0.27, \pm 0.42\}$

on the verge of exclusion

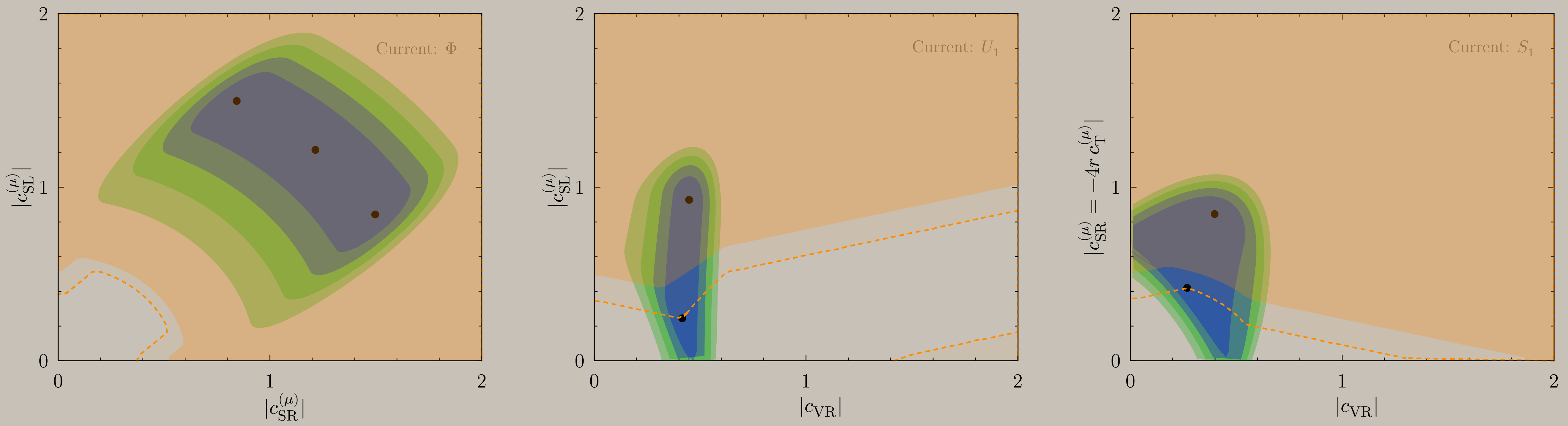
excluded by $\mathrm{Br}(B_c \to \tau\nu)$

Take away message: best fit couplings are ~1

New physics interactions must be comparable in strength to SM weak interactions!

FITS AND CONSTRAINTS

(with complex parameters)



Orange: excluded region from requiring Br($B_c \to \tau\nu$) < 10% (dotted: 5%)

More parameter space for leptoquarks, scalar remains excluded

BEST FIT VALUES

(with complex parameters)

		Real	Phase-optimized
Model	WCs	Best fit	Best fit
W'	c_{VR}	± 0.46	–
$\tilde{R}_2$	$c_{\mathrm{SR}}^{(\mu)} = 4r\, c_{\mathrm{T}}^{(\mu)}$	± 0.72	–
Φ	$\{c_{\mathrm{SR}}^{(\mu)}, c_{\mathrm{SL}}^{(\mu)}\}$	$\{\pm 1.50, \mp 0.84\}$	$\{1.50, -0.84\}$
			$\{1.21, \pm 1.21 e^{\pm i 0.17\pi}\}$
		$\{\pm 0.84, \mp 1.50\}$	$\{0.84, -1.50\}$
U_1	$\{c_{\mathrm{VR}}, c_{\mathrm{SL}}^{(\mu)}\}$	$\{\pm 0.45, \mp 0.93\}$	$\{0.45, -0.93\}$
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		$\{\pm 0.27, \pm 0.42\}$	$\{0.27, 0.42\}$

new best fit, but remains excluded

New best fit point for scalar mediator, still excluded.

For other mediators, best fit points do not change.

BEST FIT VALUES

(with complex parameters)

Model	WCs	Real: Best fit	Phase-optimized: Best fit
W'	c_{VR}	± 0.46	–
$\tilde{R}_2$	$c_{\mathrm{SR}}^{(\mu)} = 4r\, c_{\mathrm{T}}^{(\mu)}$	± 0.72	–
[illegible]	[illegible]	$\{\pm 1.50, \mp 0.84\}$	$\{1.50, -0.84\}$
			[illegible]
		$\{\pm 0.84, \mp 1.50\}$	$\{0.84, -1.50\}$
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IGNORE FROM HEREON

new best fit, but remains excluded

New best fit point for scalar mediator, still excluded.

For other mediators, best fit points do not change.

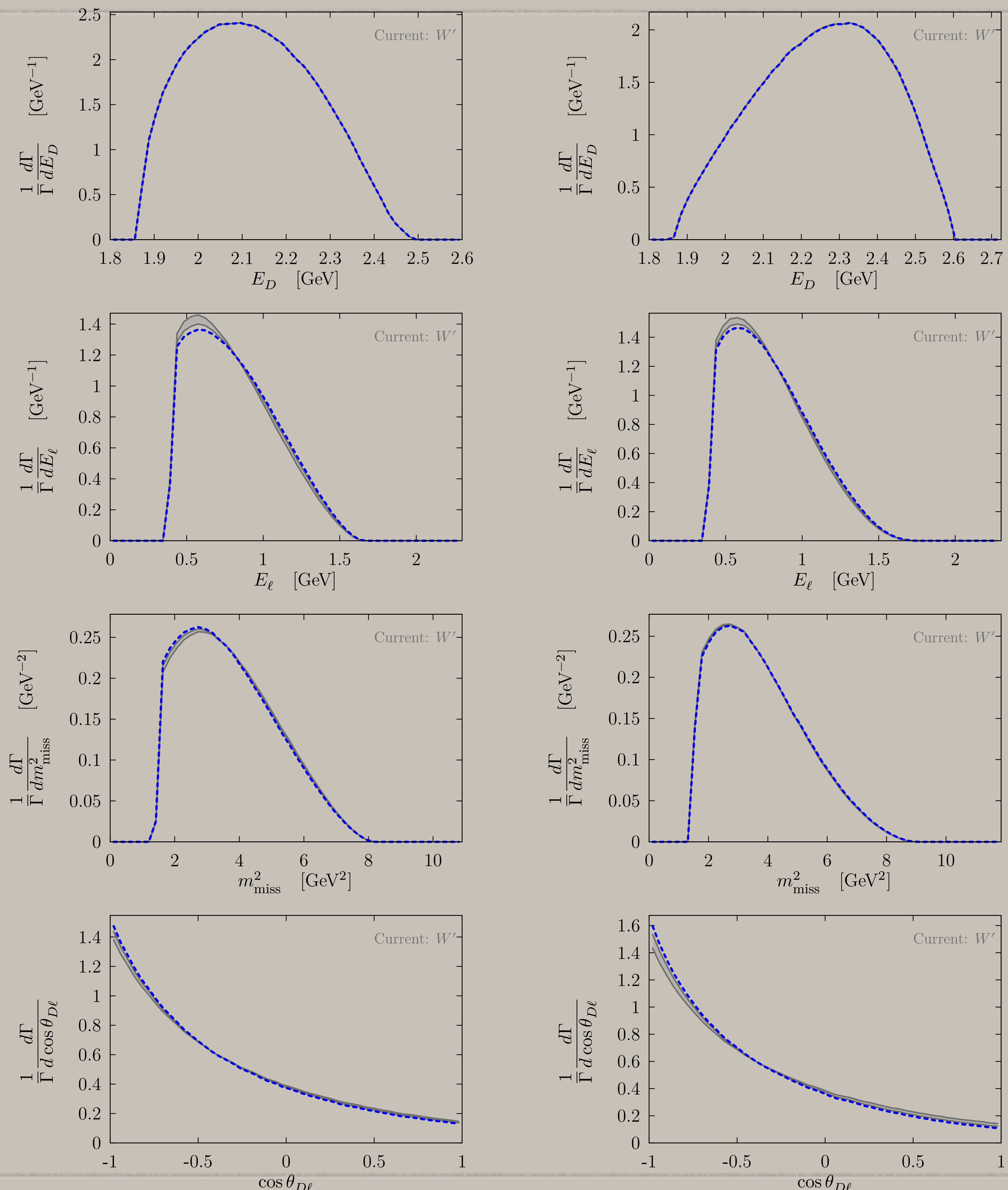
effects on kinematic distributions

(here: W’ mediator, massless N_R)

blue: SM only.

grey: 95% CL region

left: D*; right: D



effects on kinematic distributions

(here: U_1 mediator, massless N_R)

blue: SM only.
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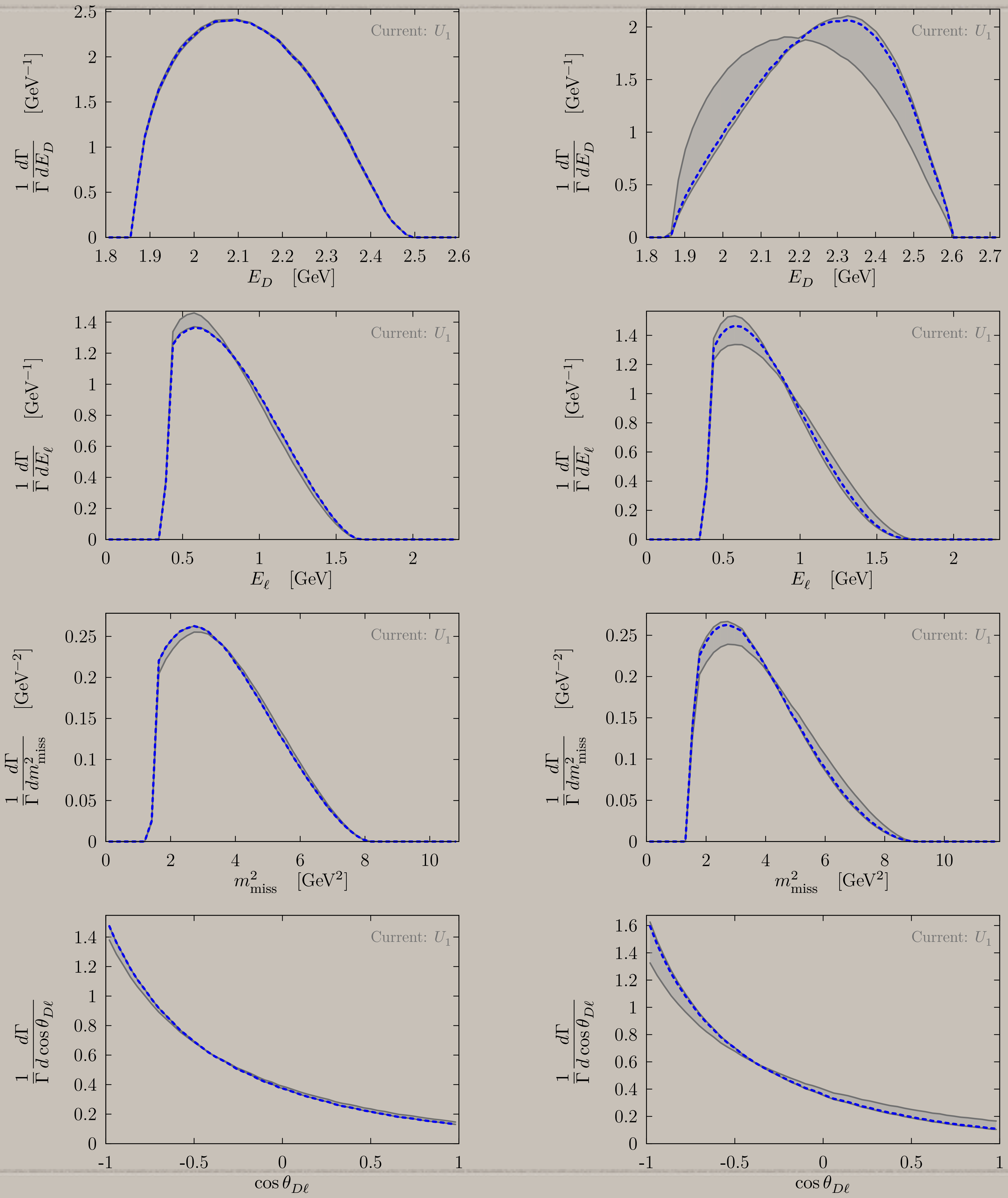


ADDITIONAL FLAVOR CONSTRAINTS

$$\mathcal{O}_{\rm SR} = (\bar{c}_L b_R)(\bar{\tau}_L N_R) \qquad \mathcal{O}^s_{\rm SR} = (\bar{s}_L b_R)(\bar{\nu}_\tau N_R)$$

SU(2)

$$\mathcal{O}_{\rm T} = (\bar{c}_L \sigma^{\mu\nu} b_R)(\bar{\tau}_L \sigma_{\mu\nu} N_R) \qquad \mathcal{O}^s_{\rm T} = (\bar{s}_L \sigma^{\mu\nu} b_R)(\bar{\nu}_\tau \sigma_{\mu\nu} N_R)$$

generating $b \to s\nu\nu$

- $c^s_{\rm SR,T} \simeq c_{\rm SR,T}$

$$\frac{d\Gamma_{B\to K\nu\bar{\nu}}}{d\hat{q}^2} \bigg/ \frac{d\Gamma_{B\to K\nu\bar{\nu}}}{d\hat{q}^2}\bigg|_{\rm SM} \simeq 1+5\times 10^4\,\hat{q}^2\left[\frac{3}{8}\left(c^s_{\rm SR}\right)^2\frac{f_0^2}{f_+^2}+(1-\hat{q}^2)\left(c^s_{\rm T}\right)^2\frac{f_T^2}{f_+^2}\right]$$

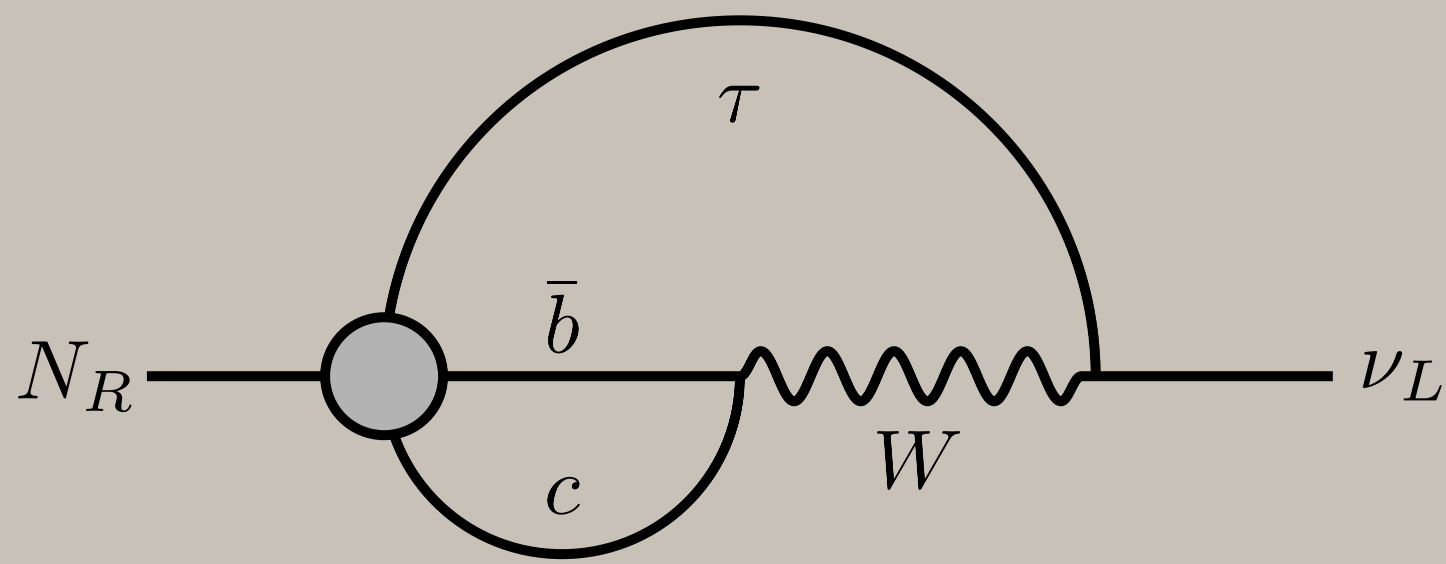
- Current bound $\text{Br}(B^+ \to K^+\nu\bar{\nu}) < 1.6 \times 10^{-5}$ vs SM prediction, $\text{Br}(B^+ \to K^+\nu\bar{\nu})|_{\rm SM} \simeq 4 \times 10^{-6}$: $c_{\rm SR,T}$ highly constrained [Or a tuning is required]
- Requires $\alpha_{Ld}\alpha_{QN} \ll 1$ for $\widetilde{R}_2$, and $z_d z_Q \ll 1$ for S_1.

from D. Robinson

STERILE NEUTRINO PHENOMENOLOGY

NEUTRINO MASSES

(Dirac) neutrino mass contribution at two loops



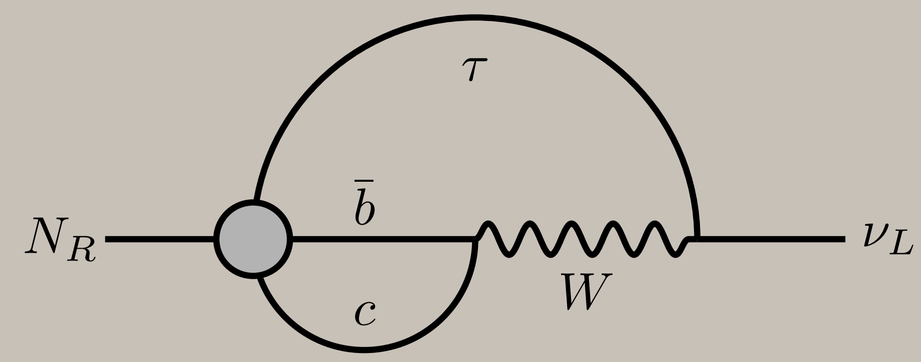
[Note 1: NO free parameters once $R(D^{(*)})$ contribution is fixed.

Note 2: only gives a mass contribution with tau neutrino]

NEUTRINO MASSES

NDA estimate

(ignore O(1) prefactors, loop integral factors)



$$W': \qquad m_D \sim \frac{c_{\mathrm{VR}}}{\Lambda^2_{\mathrm{eff}}} \frac{g_2^2}{2} \frac{V_{cb}}{(16\pi^2)^2} m_b m_c m_\tau \sim c_{\mathrm{VR}} 10^{-3}\,\mathrm{eV},$$

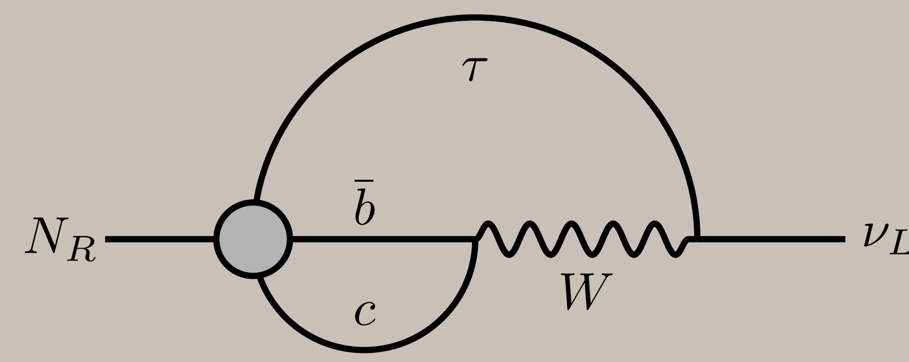
$$\tilde{R}_2: \qquad m_D \sim c_{\mathrm{SR}} m_b \frac{g_2^2}{2} \frac{V_{cb}}{(16\pi^2)^2} \sim c_{\mathrm{SR}} 10^{2}\,\mathrm{eV},$$

$$U_1: \qquad m_D \sim \left[c_{\mathrm{SL}} m_c + \frac{c_{\mathrm{VR}}}{\Lambda^2_{\mathrm{eff}}} m_b m_c m_\tau \right] \frac{g_2^2}{2} \frac{V_{cb}}{(16\pi^2)^2} \sim (c_{\mathrm{SL}} 10^2 + c_{\mathrm{VR}} 10^{-3})\,\mathrm{eV}$$

$$S_1: \qquad m_D \sim \left[c_{\mathrm{SR}} m_b + \frac{c_{\mathrm{VR}}}{\Lambda^2_{\mathrm{eff}}} m_b m_c m_\tau \right] \frac{g_2^2}{2} \frac{V_{cb}}{(16\pi^2)^2} \sim (c_{\mathrm{SR}} 10^2 + c_{\mathrm{VR}} 10^{-3})\,\mathrm{eV}$$

most important factor: number of mass insertions in the loops

NEUTRINO MASSES



$$W' : \qquad m_D \sim \frac{c_{\rm VR}}{\Lambda^2_{\rm eff}} \frac{g_2^2}{2} \frac{V_{cb}}{(16\pi^2)^2} m_b m_c m_\tau \sim c_{\rm VR} 10^{-3}\,{\rm eV},$$

OK

$$\tilde{R}_2 : \qquad m_D \sim c_{\rm SR} m_b \frac{g_2^2}{2} \frac{V_{cb}}{(16\pi^2)^2} \sim c_{\rm SR} 10^2\,{\rm eV},$$

OK with N_R mass > 100 keV

$$U_1 : \qquad m_D \sim \left[c_{\rm SL} m_c + \frac{c_{\rm VR}}{\Lambda^2_{\rm eff}} m_b m_c m_\tau \right] \frac{g_2^2}{2} \frac{V_{cb}}{(16\pi^2)^2} \sim (c_{\rm SL} 10^2 + c_{\rm VR} 10^{-3})\,{\rm eV}$$

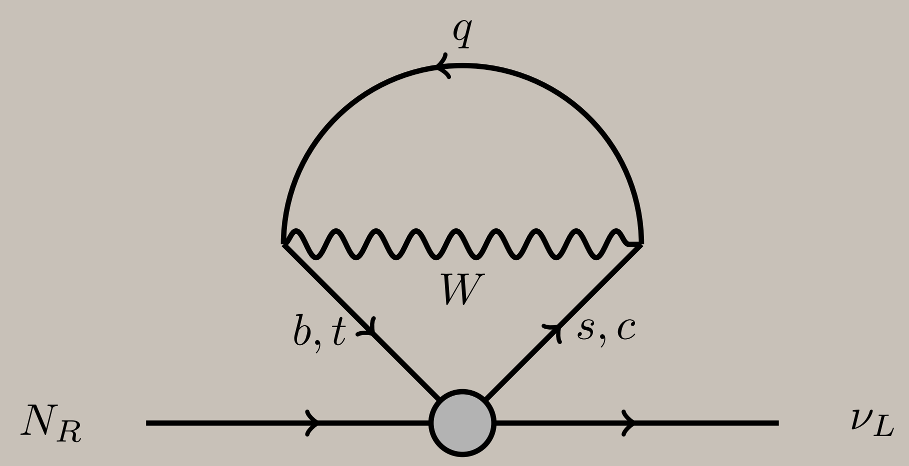
$$S_1 : \qquad m_D \sim \left[c_{\rm SR} m_b + \frac{c_{\rm VR}}{\Lambda^2_{\rm eff}} m_b m_c m_\tau \right] \frac{g_2^2}{2} \frac{V_{cb}}{(16\pi^2)^2} \sim (c_{\rm SR} 10^2 + c_{\rm VR} 10^{-3})\,{\rm eV}$$

OK with N_R mass > 100 keV

or small c_{SL}, c_{SR}

OTHER MASS CONTRIBUTIONS

from SU(2) counterparts

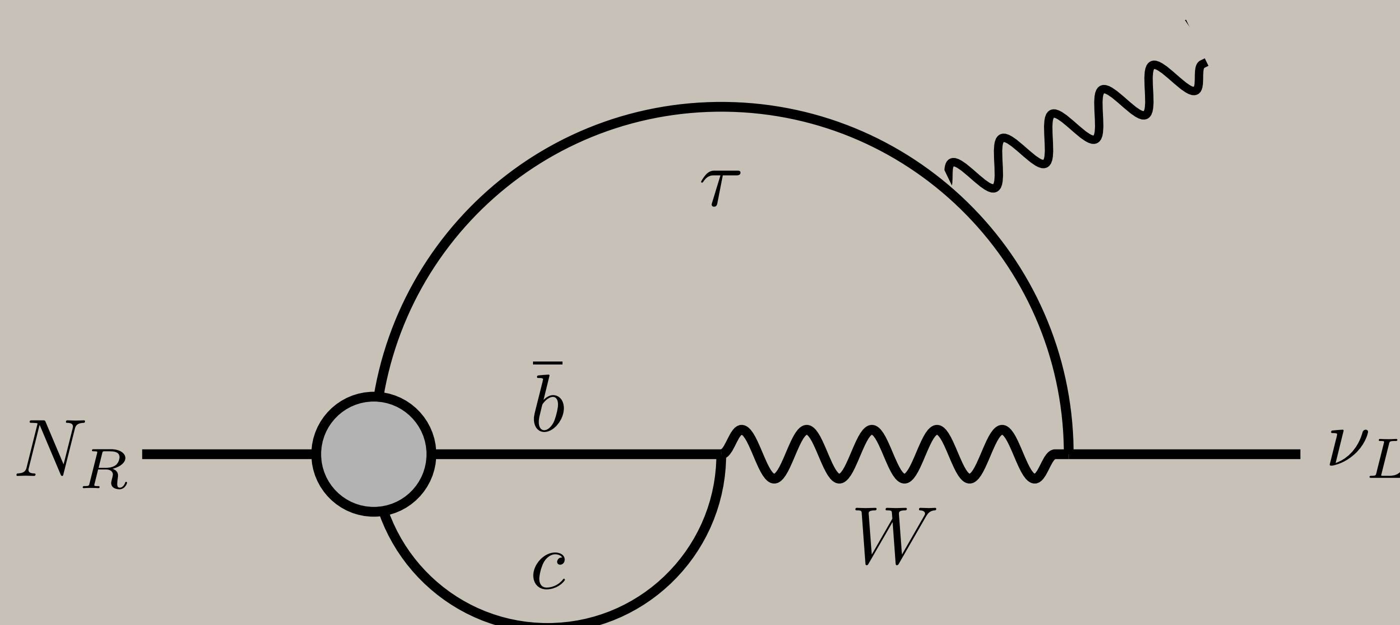


(same size as previous from NDA, GIM suppressed)

adding other operators might result in (unacceptably) large contributions to neutrino masses. e.g. operators that lead to diagrams with mass insertion on a top quark line, or one loop diagrams for neutrino masses. Need to be careful while adding operators!

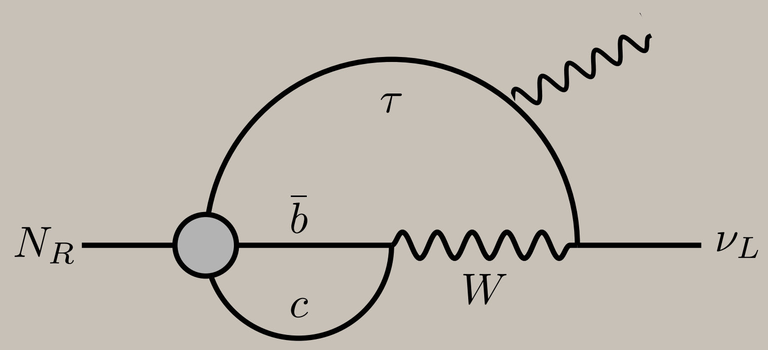
STERILE NEUTRINO DECAY

the above loop diagrams also give rise to the decay $N_R \to \nu\gamma$



STERILE NEUTRINO DECAY

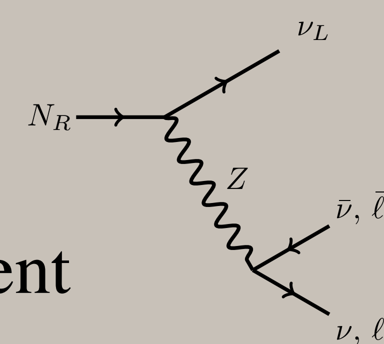
NDA estimate of decay width and lifetime

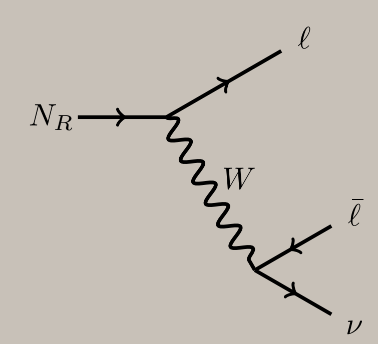


Model	$\Gamma_{N_R \to \nu\gamma}$	lifetime (s)
W'	$\frac{c_{\rm VR}^2}{\Lambda_{\rm eff}^4} \frac{\alpha}{32\,\pi^8} V_{cb}^2\, G_F^2\, m_\tau^2\, m_b^2\, m_c^2\, m_{N_R}^3$	$c_{\rm VR}^{-2}\, 10^{24}\ (m_{N_R}/{\rm keV})^{-3}$
$\tilde{R}_2$	$c_{\rm SR}^2 \frac{\alpha}{32\,\pi^8} V_{cb}^2\, G_F^2\, m_b^2\, m_{N_R}^3$	$c_{\rm SR}^{-2}\, 10^{13}\ (m_{N_R}/{\rm keV})^{-3}$
U_1	$c_{\rm SL}^2 \frac{\alpha}{32\,\pi^8} V_{cb}^2\, G_F^2\, m_c^2\, m_{N_R}^3$	$c_{\rm SL}^{-2}\, 10^{14}\ (m_{N_R}/{\rm keV})^{-3}$
S_1	$c_{\rm SR}^2 \frac{\alpha}{32\,\pi^8} V_{cb}^2\, G_F^2\, m_b^2\, m_{N_R}^3$	$c_{\rm SR}^{-2}\, 10^{13}\ (m_{N_R}/{\rm keV})^{-3}$

Tends to dominate over standard channels such as

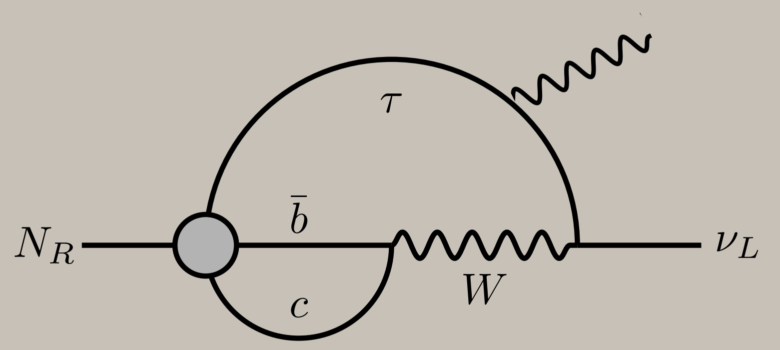
as long as mixing remains below seesaw requirement





STERILE NEUTRINO DECAY

NDA estimate of decay width and lifetime



Model	$\Gamma_{N_R \to \nu\gamma}$	lifetime (s)
W'	$\frac{c_{\rm VR}^2}{\Lambda_{\rm eff}^4} \frac{\alpha}{32\,\pi^8} V_{cb}^2\, G_F^2\, m_\tau^2\, m_b^2\, m_c^2\, m_{N_R}^3$	$c_{\rm VR}^{-2}\, 10^{24}\ (m_{N_R}/{\rm keV})^{-3}$
$\tilde{R}_2$	$c_{\rm SR}^2 \frac{\alpha}{32\,\pi^8} V_{cb}^2\, G_F^2\, m_b^2\, m_{N_R}^3$	$c_{\rm SR}^{-2}\, 10^{13}\ (m_{N_R}/{\rm keV})^{-3}$
U_1	$c_{\rm SL}^2 \frac{\alpha}{32\,\pi^8} V_{cb}^2\, G_F^2\, m_c^2\, m_{N_R}^3$	$c_{\rm SL}^{-2}\, 10^{14}\ (m_{N_R}/{\rm keV})^{-3}$
S_1	$c_{\rm SR}^2 \frac{\alpha}{32\,\pi^8} V_{cb}^2\, G_F^2\, m_b^2\, m_{N_R}^3$	$c_{\rm SR}^{-2}\, 10^{13}\ (m_{N_R}/{\rm keV})^{-3}$

Lifetimes over a large range possible: < 1s (for heavy N_R) to ~10^{30} s (light N_R)

Cosmologically interesting?

STERILE NEUTRINO COSMOLOGY

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

kept in equilibrium while the involved SM fermions are in the thermal bath (ie down to GeV scale temperatures)

DARK MATTER?

RELIC ABUNDANCE:

- relativistic freezeout: relic density not Boltzmann suppressed
- overcloses the Universe for masses > keV
- need to dilute relic density: e.g. entropy dilution from additional (heavier) sterile neutrinos (~GeV) that decay late (before BBN) can do this

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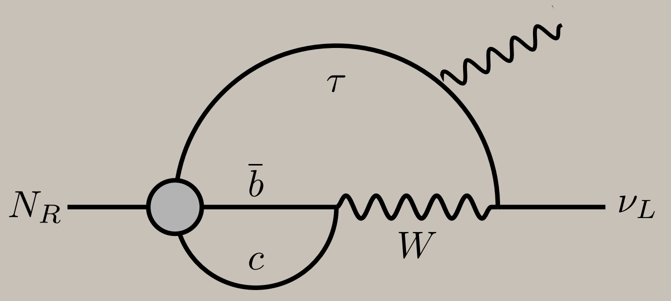
LIFETIME:

- In W', U1, S1 mediator models, can get lifetime

$$c_{\rm VR}^{-2}\, 10^{24}\, (m_{N_R}/{\rm keV})^{-3}$$



- gamma ray constraint on DM lifetime: $\mathcal{O}(10^{26-28})s$ in the keV-MeV window

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- cannot simultaneously satisfy gamma ray and warm DM constraints if all of DM
- can be a small fraction of DM, with detectable gamma ray signals in the future

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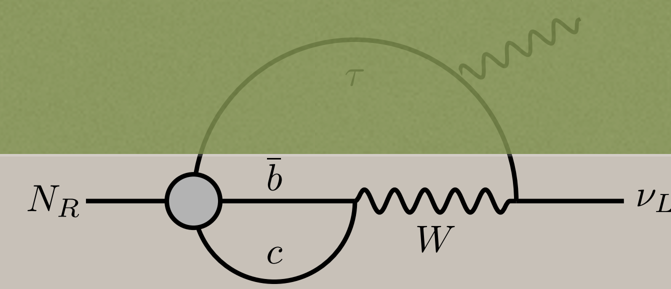

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DARK RADIATION

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

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

- detectable e.g. with CMB-S4

DISPLACED DECAYS AT DIRECT SEARCHES

The other end of lifetime possibility: $c_{\rm SL}^{-2}\, 10^{14}\ (m_{N_R}/{\rm keV})^{-3}$

For masses close to 100 MeV, lifetime < 1s. Decay before BBN.

No cosmological signatures.

Can look for displaced decays from direct production:

challenging final state ($N_R \to \nu\gamma$), but might still be possible?

ADDITIONAL STERILE NEUTRINOS

The underlying theory could contain additional light ν_R (multiple generations, entropy dilution, low scale seesaw…), with new physics couplings similar to N_R

do not contribute to $R(D^{(*)})$ due to reduced couplings / too heavy to be produced

but could be produced via other processes at colliders / neutrino experiments

similar displaced decay signals

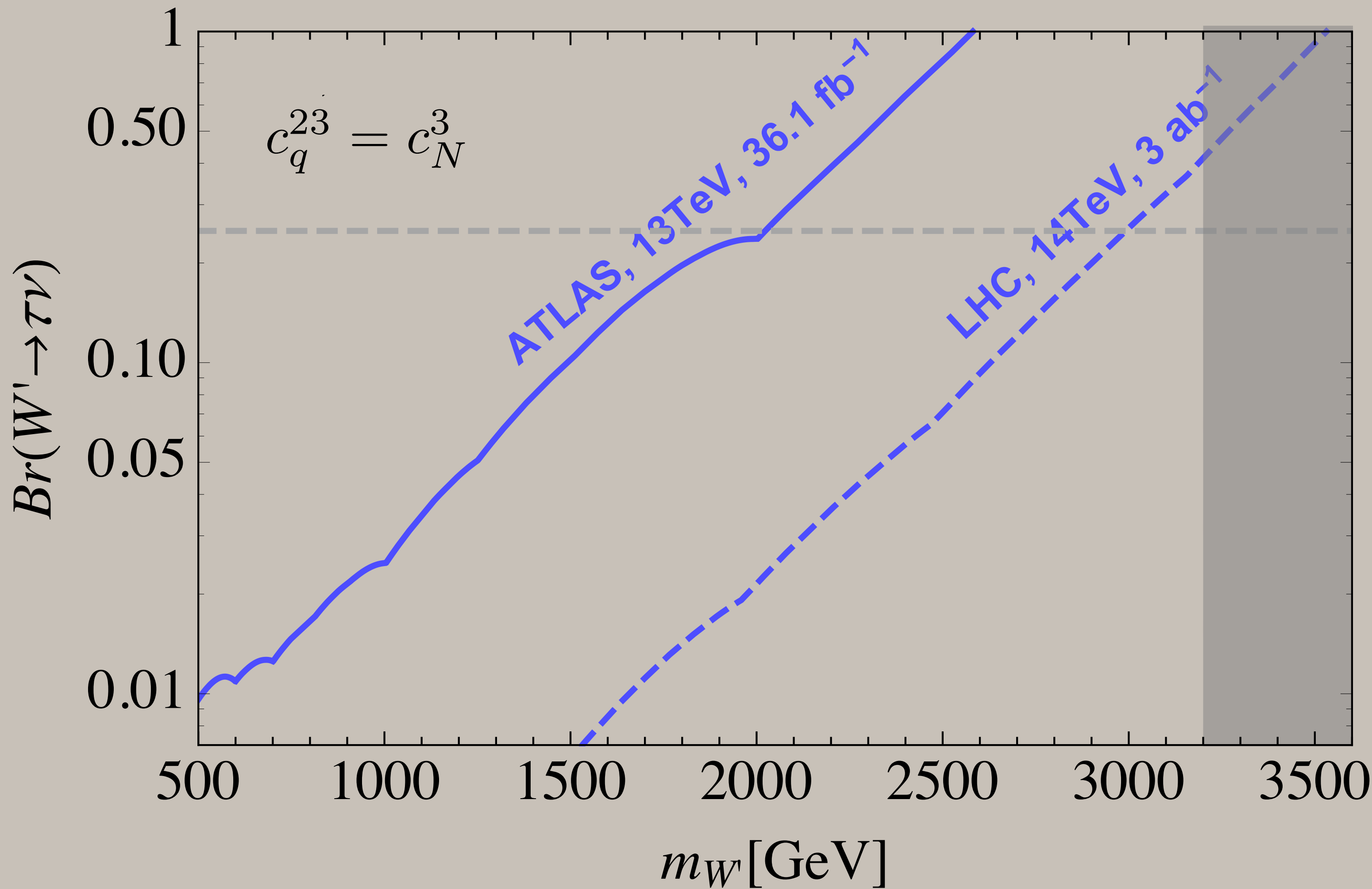
if sufficiently heavy (GeV scale or above), could even have tree level decay channels from NP couplings: instantaneous decays to exotic final states!

COLLIDER CONSTRAINTS ON HEAVY MEDIATORS

charged vector boson W'_μ

$$\mathcal{L} = \frac{g_V}{\sqrt{2}} c_q^{ij} \bar{u}_R^i \slashed{W}' d_R^j + \frac{g_V}{\sqrt{2}} c_N^i \bar{\ell}_R^i \slashed{W}' N_R + \text{h.c.} \qquad \frac{c_{\text{VR}}}{\Lambda_{\text{eff}}^2} = -\frac{g_V^2 c_q^{23} c_N^3}{2 m_{W'}^2}$$

$$m_{W'} \simeq 540 \left| c_q^{23} c_N^3 \right|^{1/2} \left[\frac{g_V}{0.6} \right] \left[\frac{40 \times 10^{-3}}{V_{cb}} \right]^{1/2} \text{GeV}$$



From searches for

W' → τν

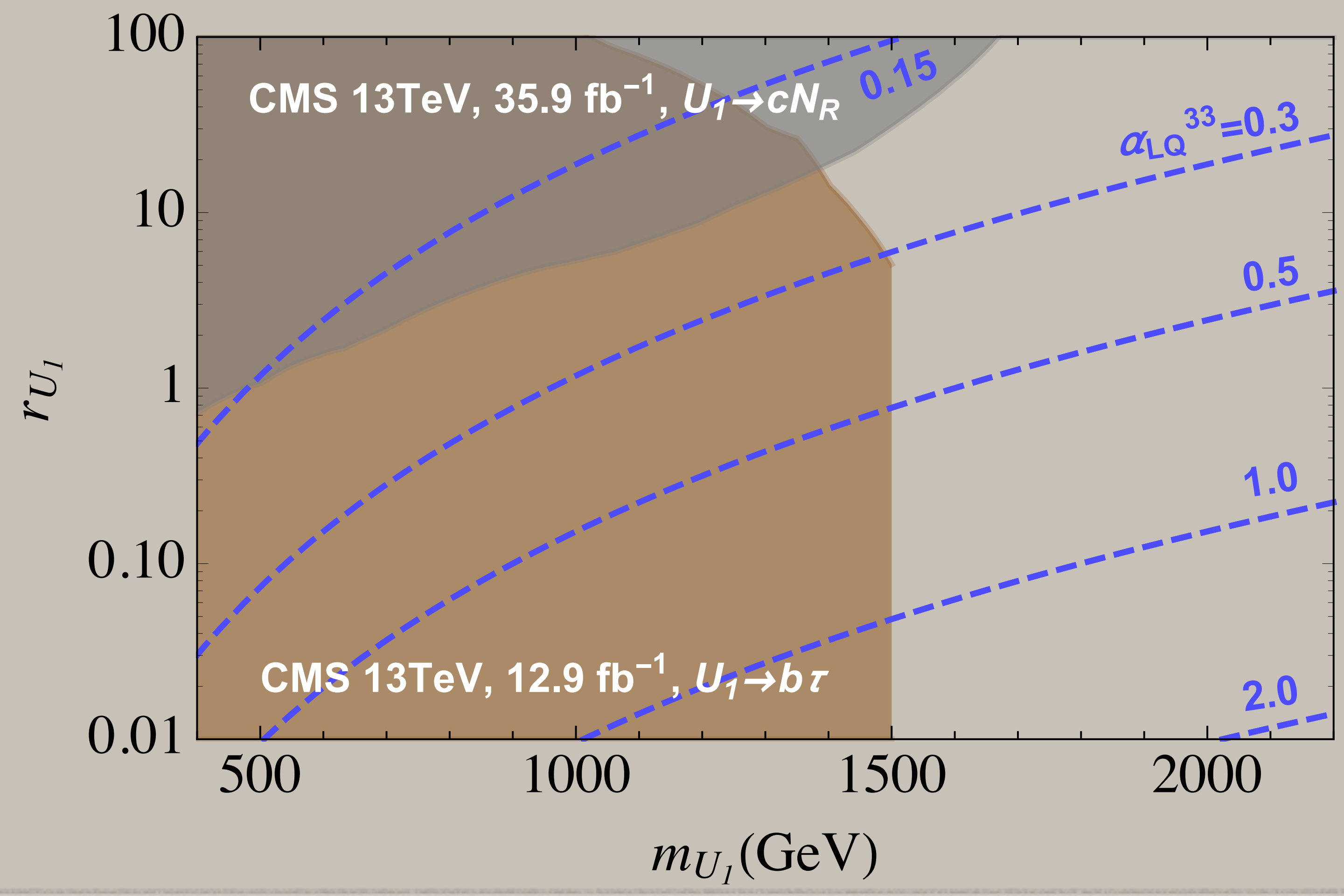
Reach from dijet search is weaker

Vector leptoquark U_1^μ

$$\mathcal{L} \supset \alpha_{LQ}^{ij}\left(\bar{L}_L^i \gamma_\mu Q_L^j\right) U_1^{\mu\dagger} + \alpha_{\ell d}^{ij}\left(\bar{\ell}_R^i \gamma_\mu d_R^j\right) U_1^{\mu\dagger} + \alpha_{uN}^{i}\left(\bar{u}_R^i \gamma_\mu N_R\right) U_1^{\mu}$$

$$\frac{c_{\rm SL}^{(\mu)}}{\rho_{\rm SL}\Lambda_{\rm eff}^2} = 2\frac{\alpha_{LQ}^{33}\alpha_{uN}^2}{m_{U_1}^2}, \qquad \frac{c_{\rm VR}}{\Lambda_{\rm eff}^2} = -\frac{\alpha_{\ell d}^{33}\alpha_{uN}^2}{m_{U_1}^2}$$

Best fit: $m_{U_1} \simeq 3.2\left|\alpha_{LQ}^{33}\alpha_{uN}^2\right|^{1/2}\left[\frac{40\times10^{-3}}{V_{cb}}\right]^{1/2}$ TeV $\qquad \alpha_{\ell d}^{33} \simeq -5.8\,\alpha_{LQ}^{33}$



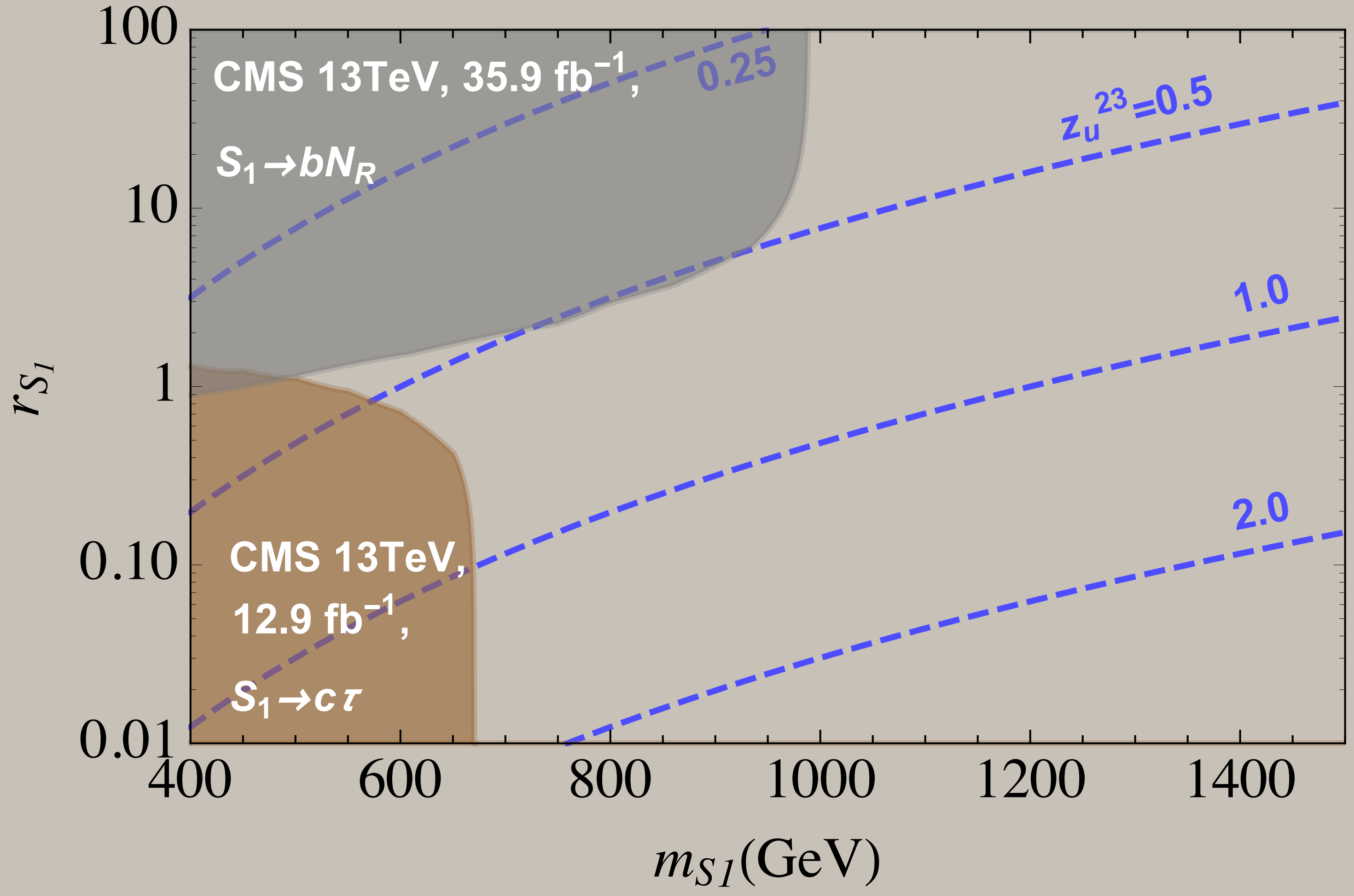
$$r_{U_1} = \left(\frac{\alpha_{uN}^2}{\alpha_{LQ}^{33}}\right)^2$$

Scalar leptoquark S_1

$$z_u(\bar{U}^c_R \ell_R)S_1 + z_d(\bar{d}^c_R N_R)S_1 + z_Q(\bar{Q}^c_L \epsilon L_L)S_1$$

$$\frac{c_{\rm VR}}{\Lambda^2_{\rm eff}} = -\frac{z_u^{23*} z_d^3}{2m^2_{S_1}}, \qquad \frac{c^{(\mu)}_{\rm SR}}{\rho_{\rm SR}\Lambda^2_{\rm eff}} = -4\frac{c^{(\mu)}_{\rm T}}{\rho_{\rm T}\Lambda^2_{\rm eff}} = -\frac{z_Q^{23*} z_d^3}{2m^2_{S_1}}$$

Best fit: $m_{S_1} \simeq 1.2 |z_u^{23} z_d^3|^{1/2} \left[\frac{40\times 10^{-3}}{V_{cb}}\right]^{1/2}$ TeV $\qquad z_u^{23} \simeq 1.1 z_Q^{23}$



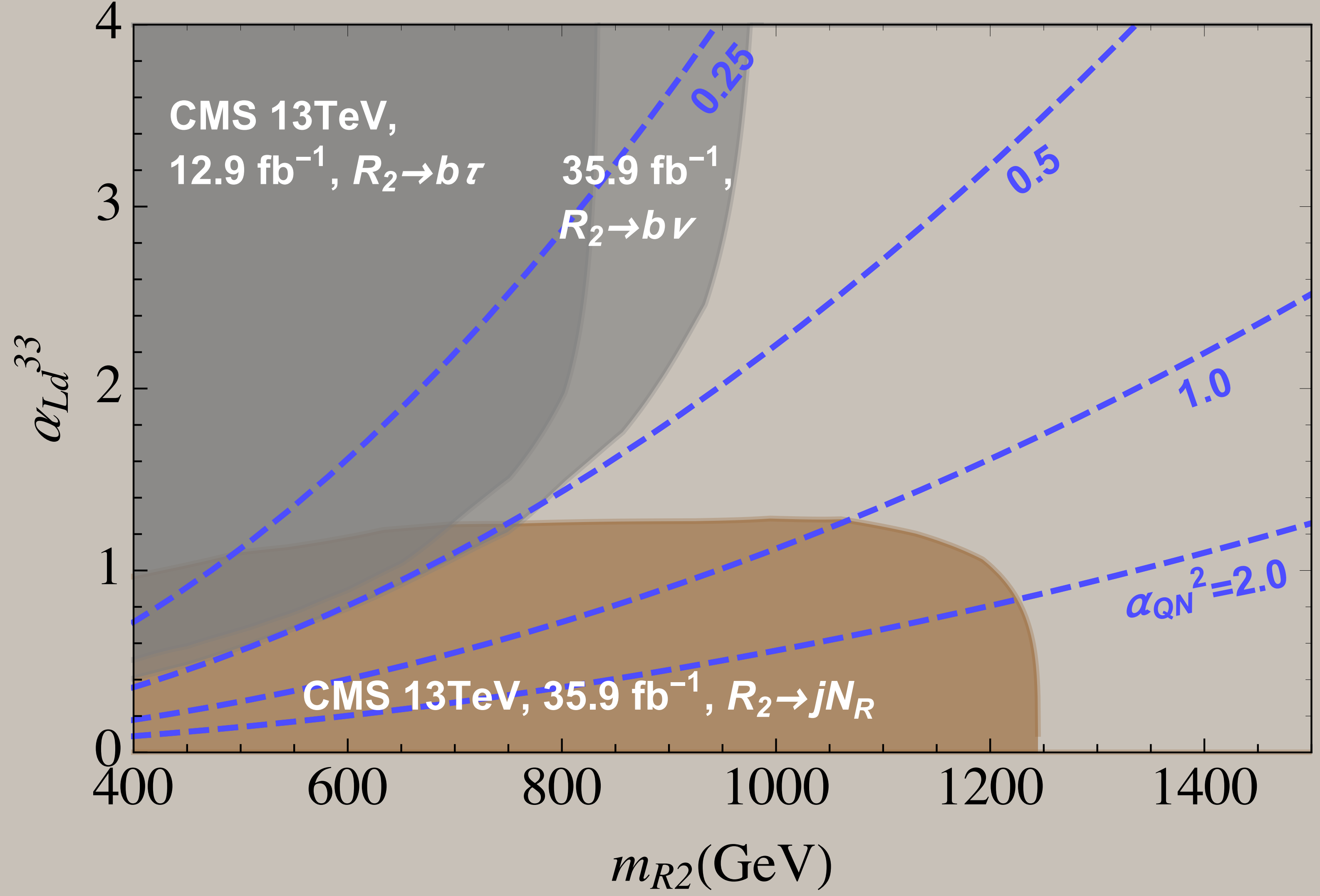
$$r_{S_1} = \left(\frac{z_d^3}{z_u^{23}}\right)^2.$$

Scalar leptoquark $\tilde{R}_2$

$$\mathcal{L} \supset \alpha_{Ld}\left(\bar{L}_L d_R\right)\epsilon \tilde{R}_2^\dagger + \alpha_{QN}\left(\bar{Q}_L N_R\right)\tilde{R}_2 + \text{h.c}$$

$$\frac{c_{\rm SR}^{(\mu)}}{\rho_{\rm SR}\Lambda_{\rm eff}^2} = 4\frac{c_{\rm T}^{(\mu)}}{\rho_{\rm T}\Lambda_{\rm eff}^2} = \frac{\alpha_{Ld}^{33}\alpha_{QN}^2}{2m_{\tilde{R}_2}^2}$$

$$m_{\tilde{R}_2} \simeq 0.95\left|\alpha_{Ld}^{33}\alpha_{QN}^2\right|^{1/2}\left[\frac{40\times 10^{-3}}{V_{cb}}\right]^{1/2}\text{TeV}$$



FROM EFT TO COMPLETE MODELS

the details can be important:

additional particles / constraints / opportunities

case study: a UV complete model for the W’ mediator

Asadi, Buckley, Shih 1804.04135; Greljo, Robinson, Shakya, Zupan 1804.04642

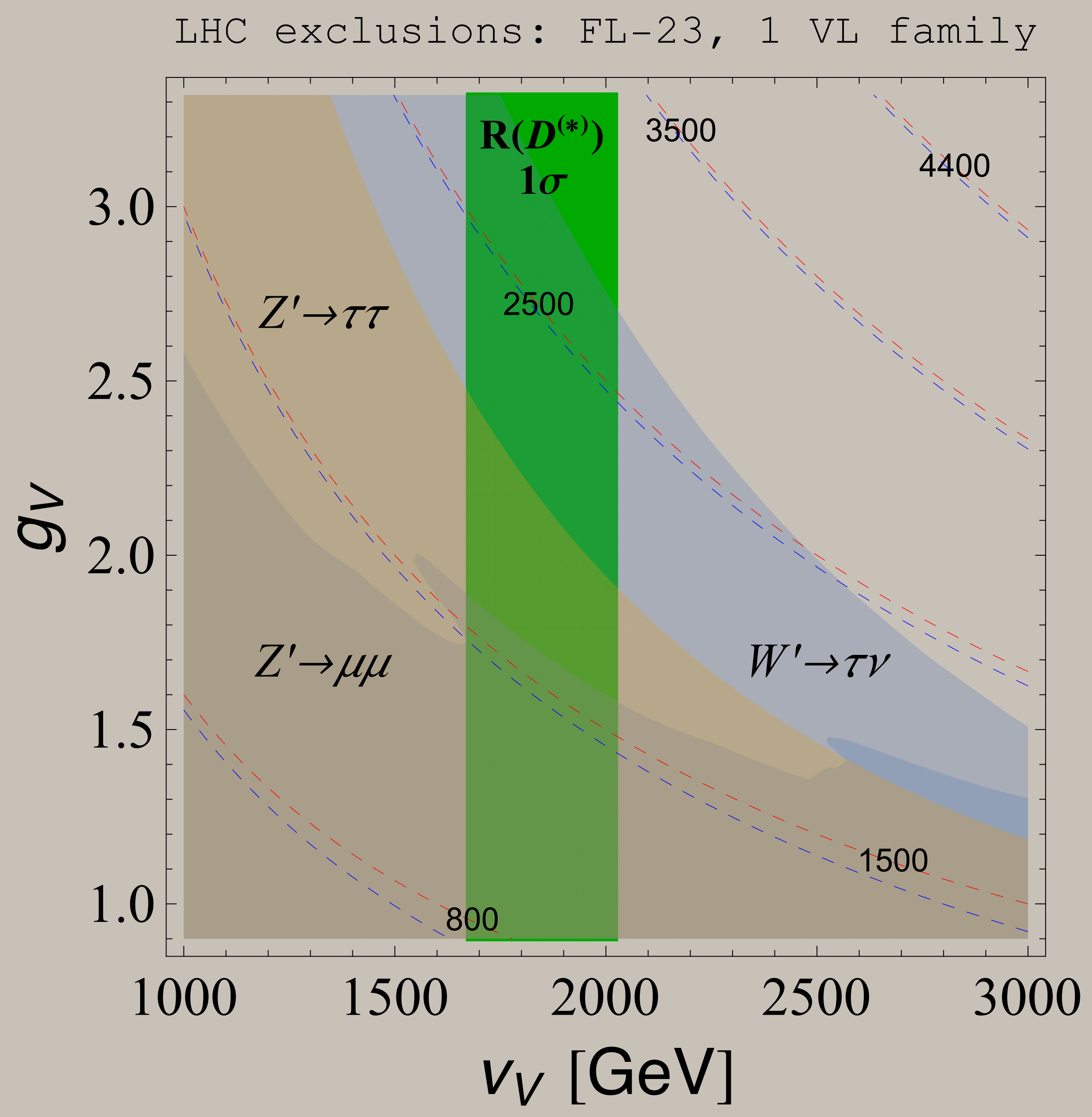
THE W' (3221) MODEL

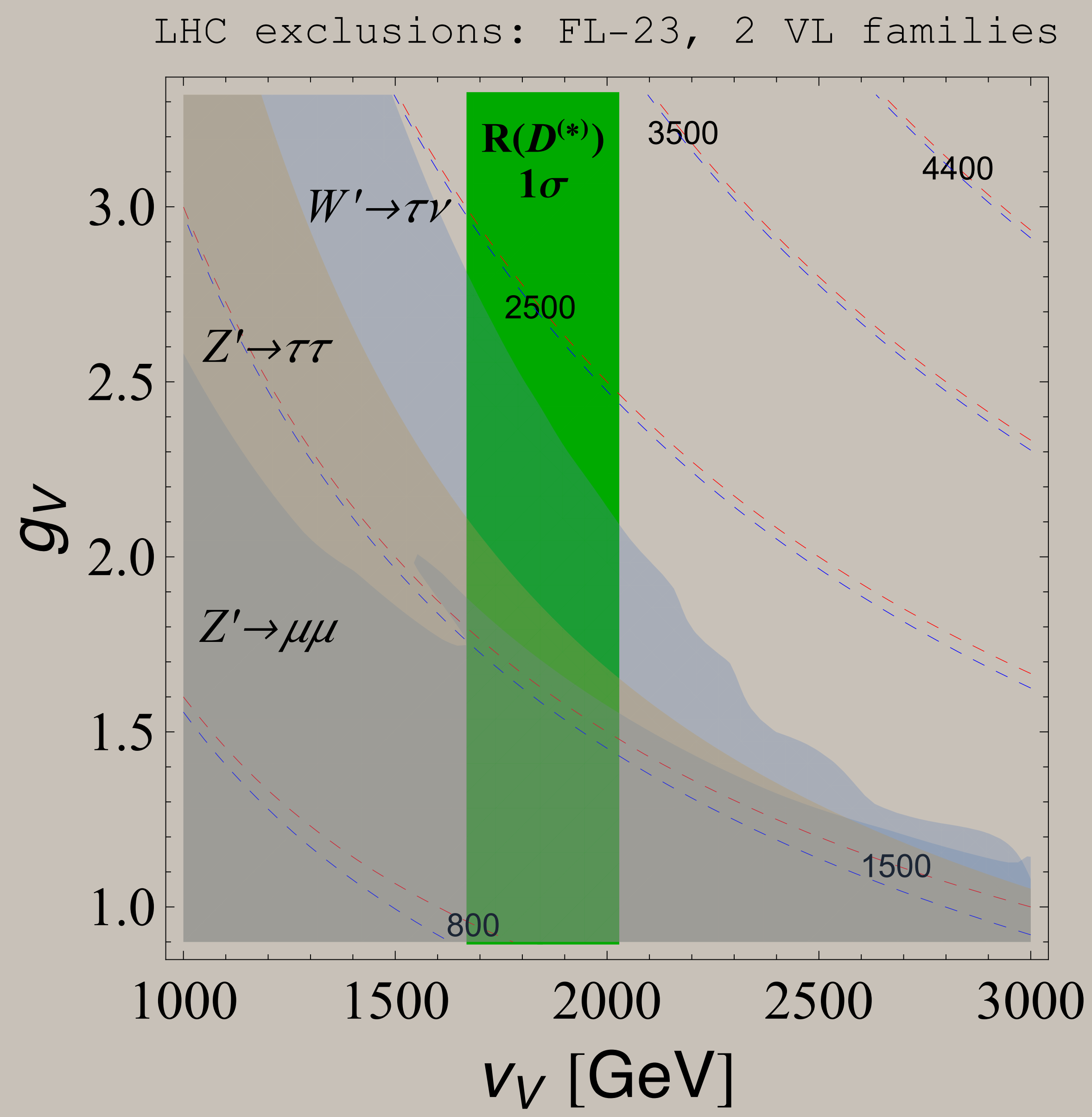
gauge group $\mathcal{G} = SU(3)_c \times SU(2)_L \times SU(2)_V \times U(1)'$ $\quad SU(2)_V \times U(1)' \to U(1)_Y$

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

GAUGE BOSON (W',Z') CONSTRAINTS





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

additional content can reduce relevant branching ratios, alleviate collider constraints

THE NEUTRINO SECTOR

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

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

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

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

responsible for anomaly

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

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 $y_\nu v_{\rm EW} << \mu$ and the SM neutrinos get the right masses via a low scale type-I seesaw

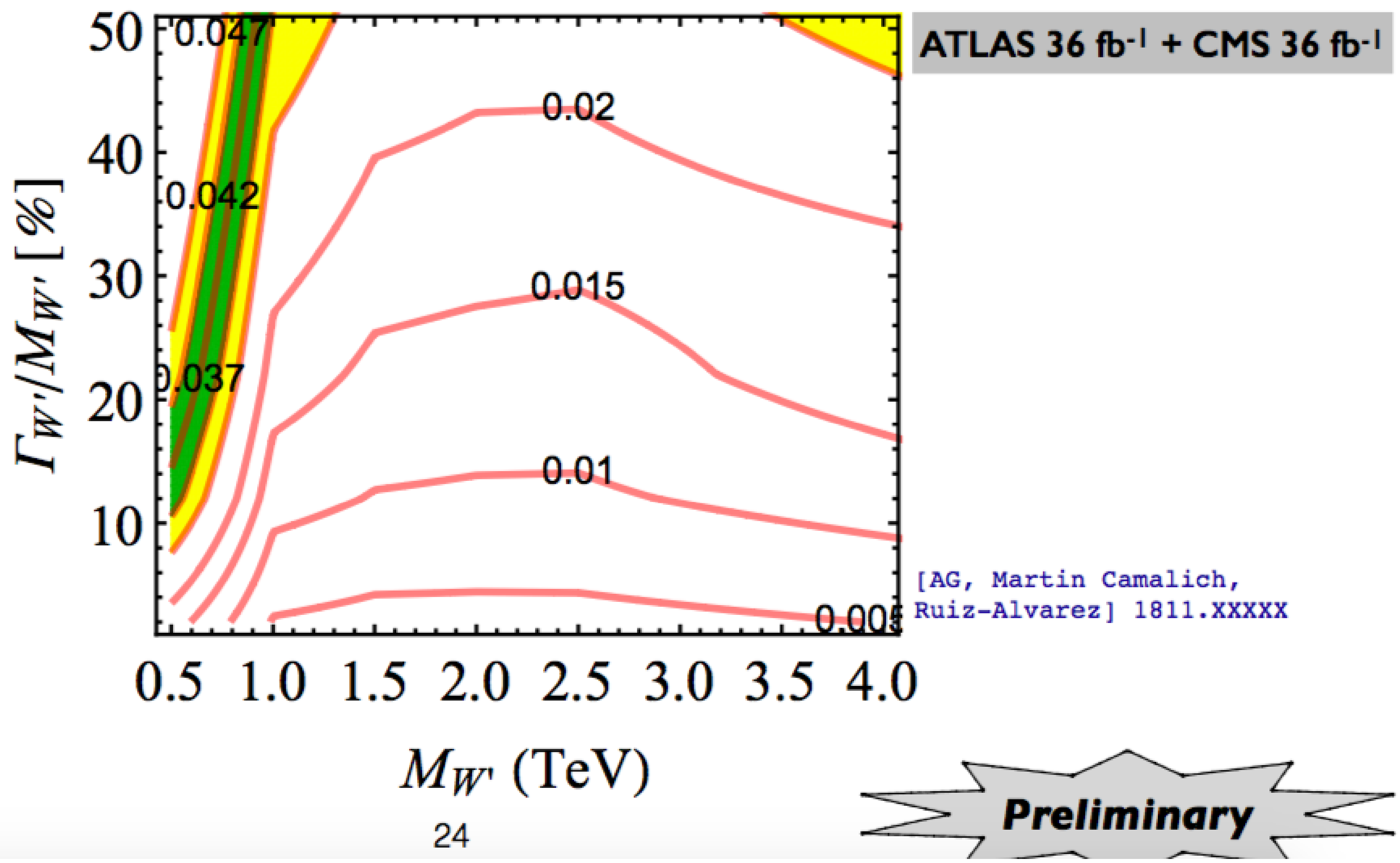
MEDIATORS RECAP

	mediator	irrep	$\delta\mathcal{L}_{\text{int}}$	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	$(1,2)_{1/2}$	$y_u \bar{u}_R Q_L \epsilon \Phi + y_d \bar{d}_R Q_L \Phi^\dagger +$ $y_N \bar{N}_R L_L \epsilon \Phi$	$c_{\text{SL}}, \quad c_{\text{SR}}$	excluded by Br($B_c \to \tau\nu$)
leptoquarks	U_1^μ	$(3,1)_{2/3}$	$(\alpha_{LQ} \bar{L}_L \gamma_\mu Q_L + \alpha_{\ell d} \bar{\ell}_R \gamma_\mu d_R) U_1^{\mu\dagger} +$ $\alpha_{uN}\left(\bar{u}_R \gamma_\mu N_R\right) U_1^\mu$	$c_{\text{SL}}, \quad c_{\text{VR}}$	
	$\tilde{R}_2$	$(3,2)_{1/6}$	$\alpha_{Ld}\left(\bar{L}_L d_R\right) \epsilon \tilde{R}_2^\dagger + \alpha_{QN}\left(\bar{Q}_L N_R\right) \tilde{R}_2$	$c_{\text{SR}} = 4 c_{\text{T}}$	borderline consistent w/ Br($B_c \to \tau\nu$)
	S_1	$(\bar{3},1)_{1/3}$	$z_u (\bar{U}_R^c \ell_R) S_1 + z_d (\bar{d}_R^c N_R) S_1 +$ $z_Q (\bar{Q}_L^c \epsilon L_L) S_1$	$c_{\text{VR}},$ $c_{\text{SR}} = -4 c_{\text{T}}$	$b \to s\nu\nu$ requires cSR to be small

Latest collider results are already turning the crank...

LHC bounds $pp \to \tau\nu$

Including recent $W' \to \tau\nu$ CMS search, model can only survive if W' is broad



Prepared by Admir Greljo

SUMMARY

persistent anomalies in measurements of $\mathbf{R(D^{(*)})}$ 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**.

short lifetimes / additional sterile neutrinos: **displaced decays** at direct searches