TeV Scale Lepton Number Violation: Leptogenesis, $0\nu\beta\beta$ Decay, & the LHC

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- *UMass Amherst*

My pronouns: he/him/his

Collaborators:

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Nuc Theory Topical Collab
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Thanks

V. Cirigliano, J. de Vries, M. Graesser, W. Haxton, G. Li, E. Mereghetti, G. Prezeau, P. Vogel...

Outline

- *TeV Scale LNV: Context*
- *Implications:*
  - *Cosmology*
  - *Nuclear Physics*
  - *High Energy Physics*
- *Outlook*

Key Questions

- *Is total lepton number (LN) conserved at the classical (Lagrangian) level?*
- *If LN is violated classically, what is the associated mass scale?*
- *If LNV exists at the TeV scale, what are the implications?*

This talk

Implications

- *Cosmology: Matter-Antimatter Asymmetry*
- *High Energy Physics: LHC searches*
- *Nuclear Physics: $0\nu\beta\beta$ Decay*

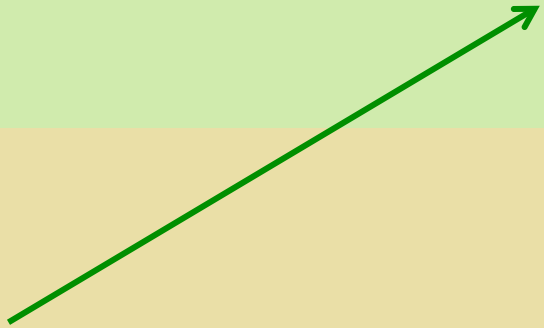
Lepton Number: ν Mass Term?

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

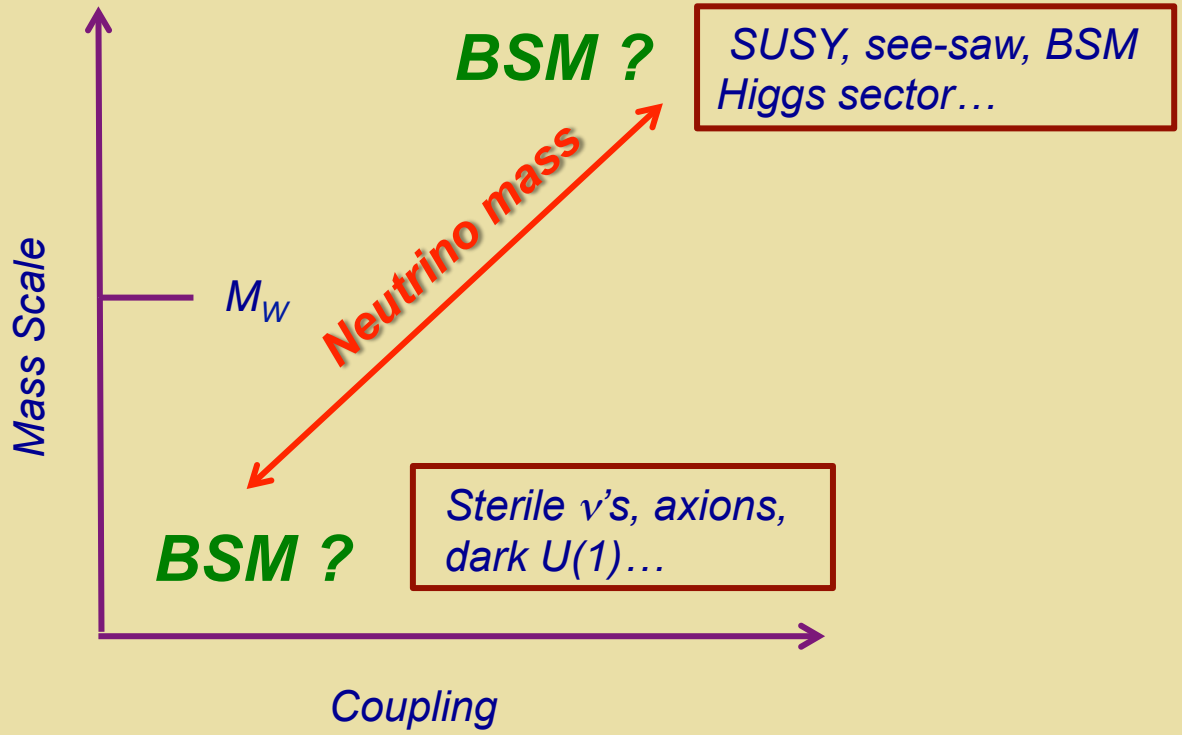
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana



Mass scale for LNV dynamics ?

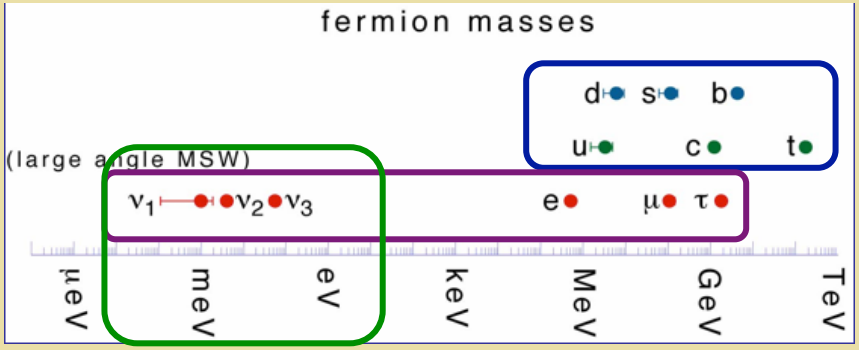
LNV Physics: Where Does it Live ?



Is the mass scale associated with m_ν far above M_W ? Near M_W ? Well below M_W ?

The "Standard" Picture: High-Scale LNV

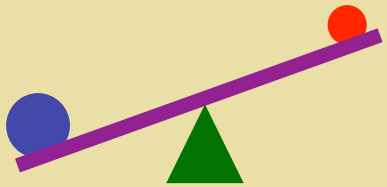
Neutrino Masses



Partners

Partners

"See saw mechanism"



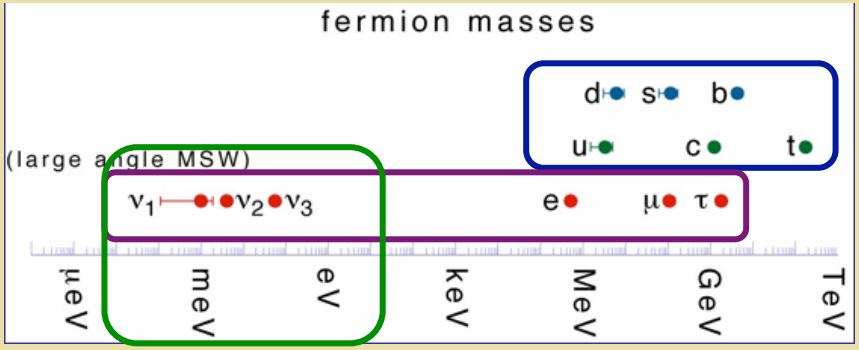
Physical state masses

$$m_1 \approx \frac{m_D^2}{M_N} \qquad \sim eV$$

$$m_2 \approx M_N \qquad \sim 10^{12} - 10^{15}\ GeV$$

New heavy neutrino-like particle = its own anti-particle

Neutrino Masses



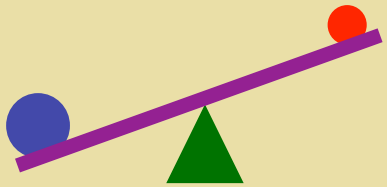
Partners

Partners

"See saw mechanism"

"Leptogenesis"

Fukugita & Yanagida '87



Heavy neutrino decays in early universe generate baryon asym

New heavy neutrino-like particle = its own anti-particle

Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*
- *Majorana neutrinos can decay to particles and antiparticles*
- *Rates can be slightly different (CP violation)*

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \bar{\ell} H^*)$$

- *Resulting excess of leptons over anti-leptons partially converted into excess of quarks over anti-quarks by Standard Model sphalerons*

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TeV-Scale LNV ?

Implications

- *Cosmology*
- *High Energy physics*
- *Nuclear Physics*

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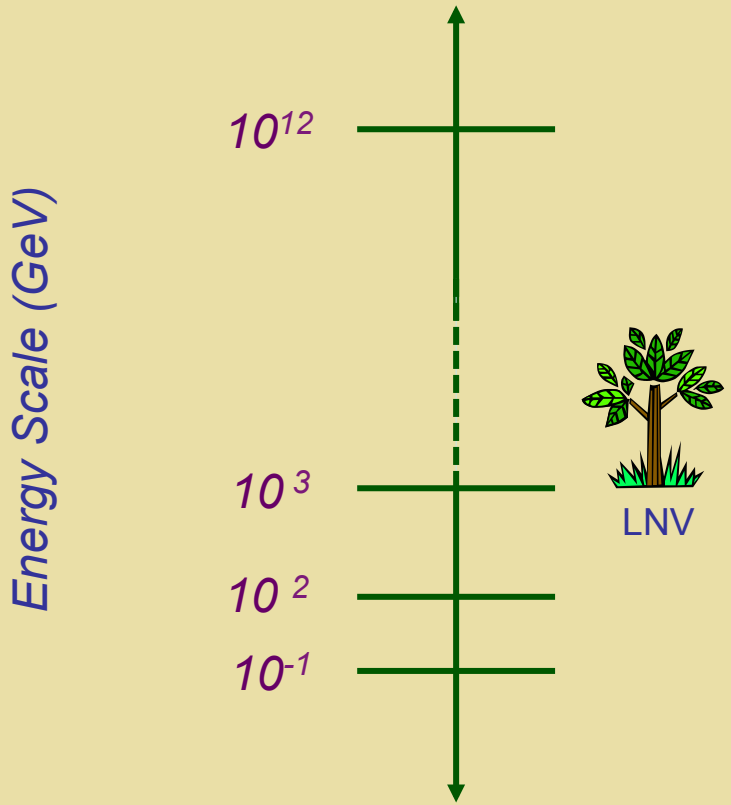
TeV LNV & Leptogenesis



Standard thermal lepto

Fast $\Delta L = 2$ int: erase L

Deppisch et al '14, '15

Our work: concrete model realizations to link cosmological effects with experiment

Boltzmann: N_R & B-L

Basic equations: decays & inverse decays

$$\frac{dY_N}{dz} = -(D+S)\left(Y_N - Y_N^{\rm EQ}\right)$$

$$\frac{dY_{B-L}}{dz} = -\epsilon D\left(Y_N - Y_N^{\rm EQ}\right) - W\, Y_{B-L}$$

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Decay

Scattering

Boltzmann: N_R & B-L

Basic equations: decays & inverse decays

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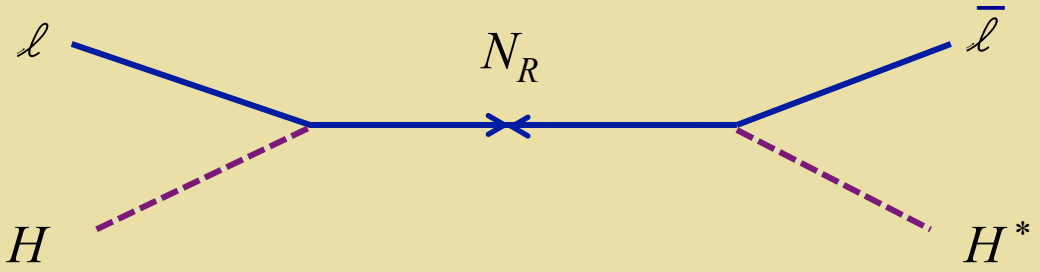
CPV Decay Asymmetry: source

Wash out: Inverse decays, ΔL = 1, 2 processes…

Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

Washout processes



$\Delta L = 2$

Converts leptons into anti-leptons

Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

Washout processes

$\Delta L = 2$

Converts leptons into anti-leptons

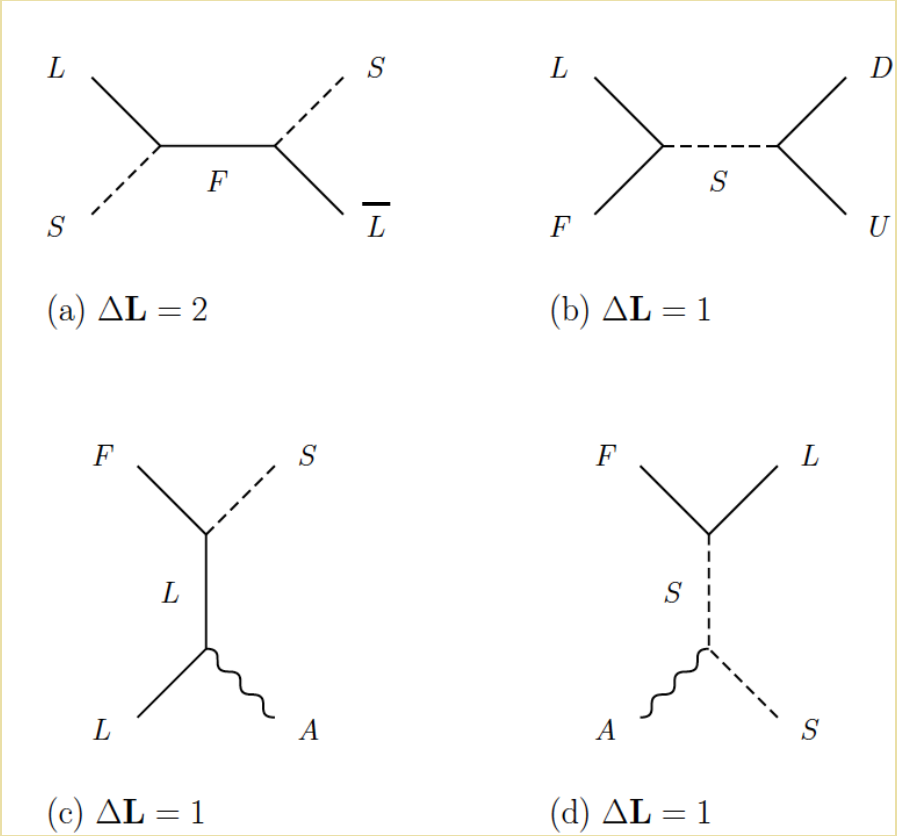
Simplified Models: Illustrative Case

$$\mathcal{L}_{\rm INT} = g_1 \bar{Q}_i^a d^a S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + {\rm H.c.}$$

S: *(1, 2, ½)*
F: *(1, 0, 0)* *Majorana*

Similar ingredients as in scotogenic neutrino mass models (but no Z_2 symmetry)

Leptogenesis: Washout Processes



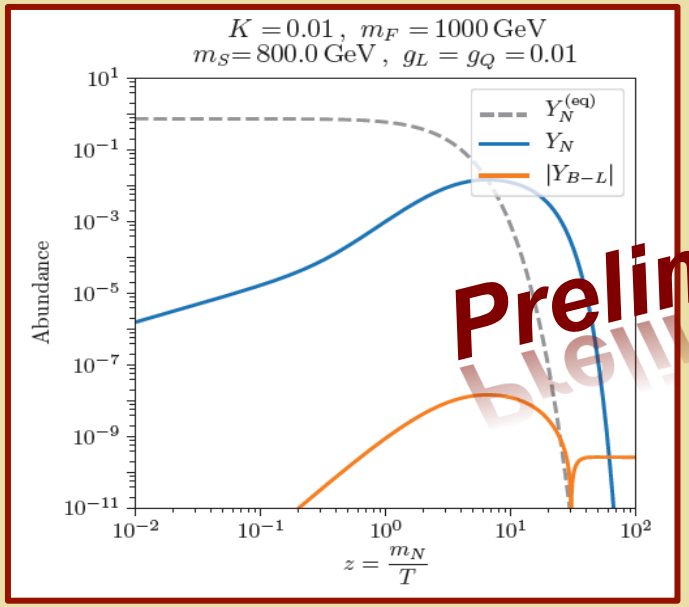
Thanks! S. Urrutia Quiroga

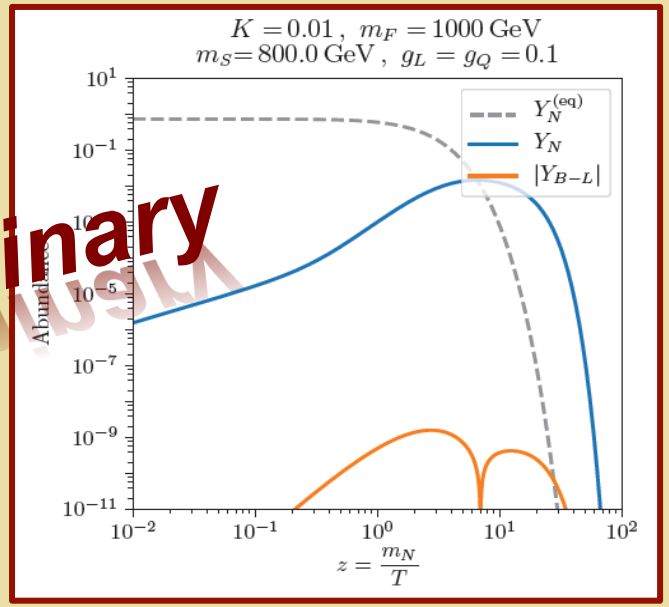
Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

Washout processes

Example: weak washout, $m_N = 10^{10}$ TeV, $M_F = 1$ TeV, $M_S = 0.8$ TeV

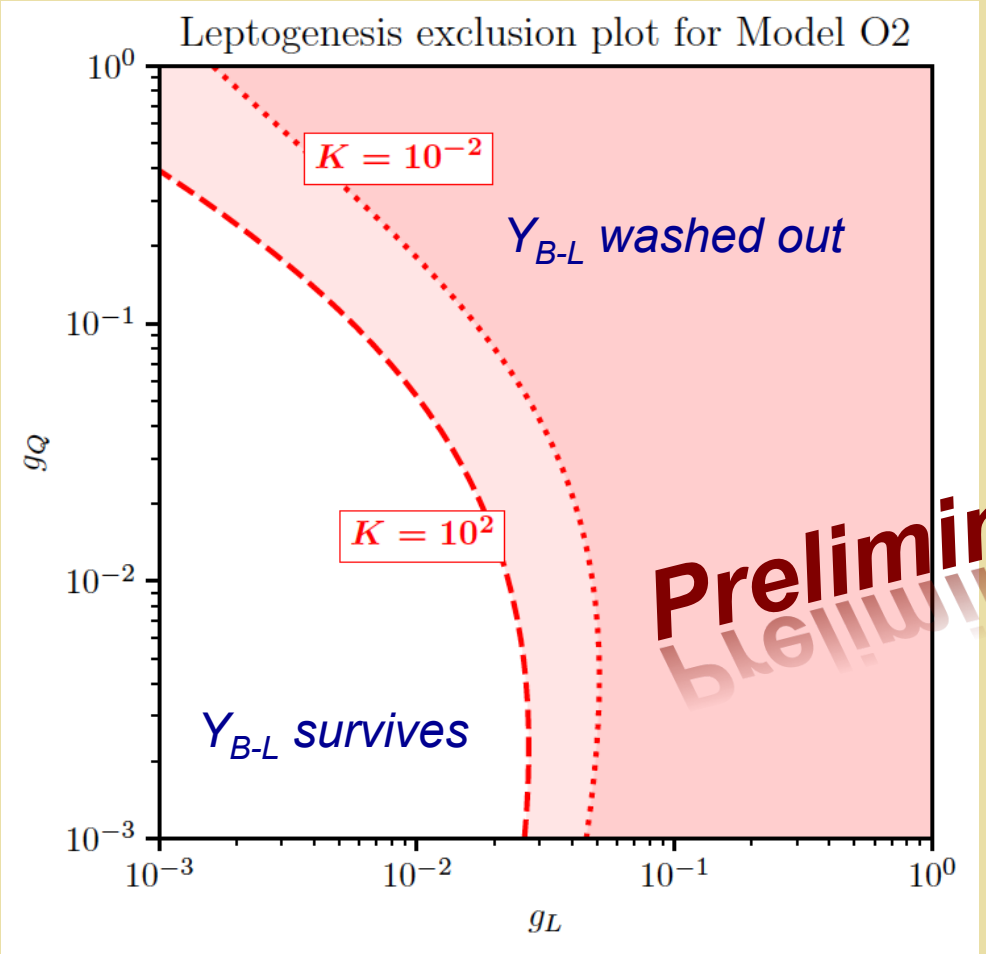




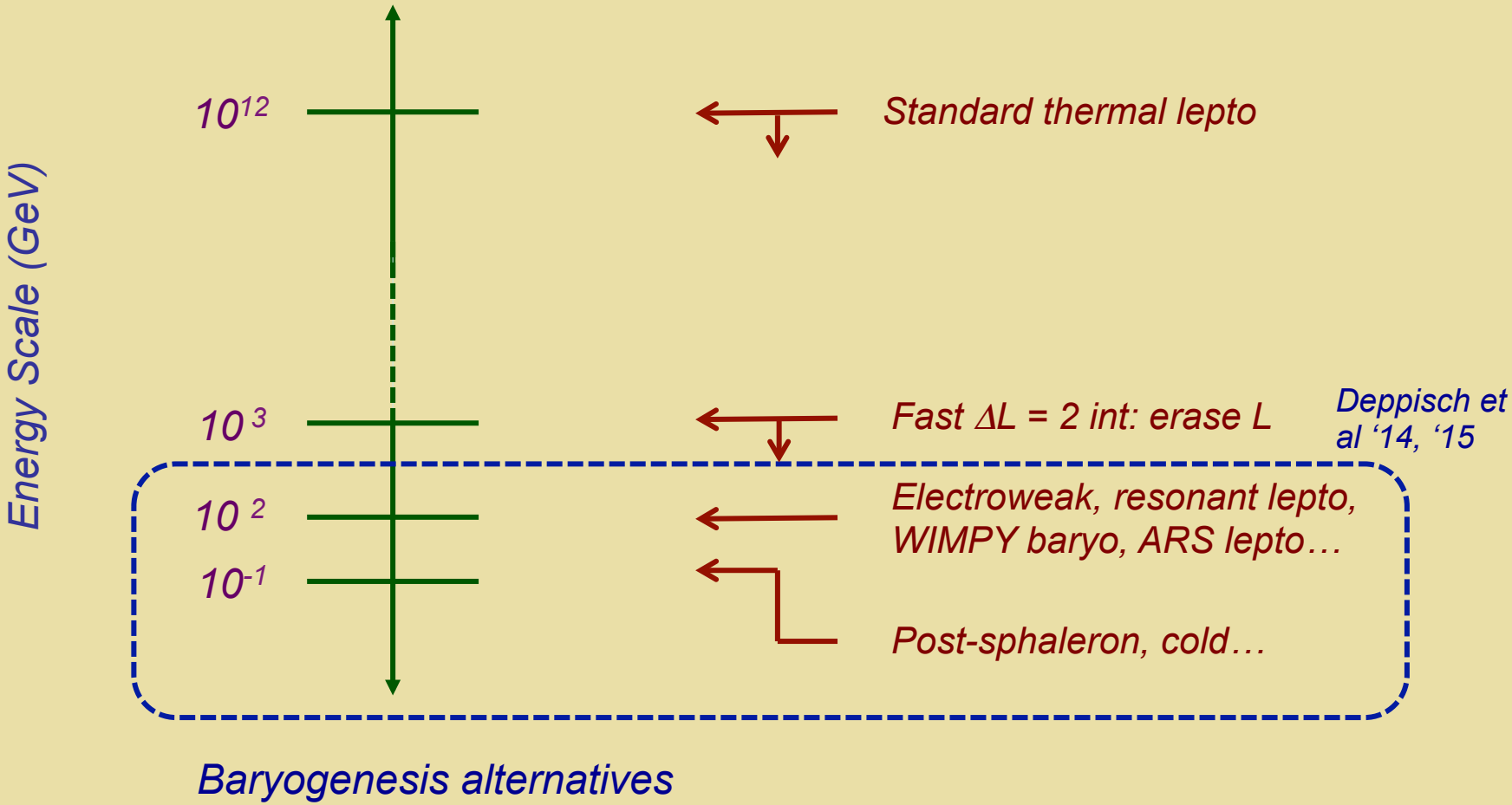
Preliminary

Thanks! S. Urrutia Quiroga

Results: Leptogenesis



TeV LNV & Leptogenesis



Implications

- *Cosmology*
- *High Energy physics*
- *Nuclear Physics*

TeV Scale LNV: $0\nu\beta\beta$-Decay & Colliders

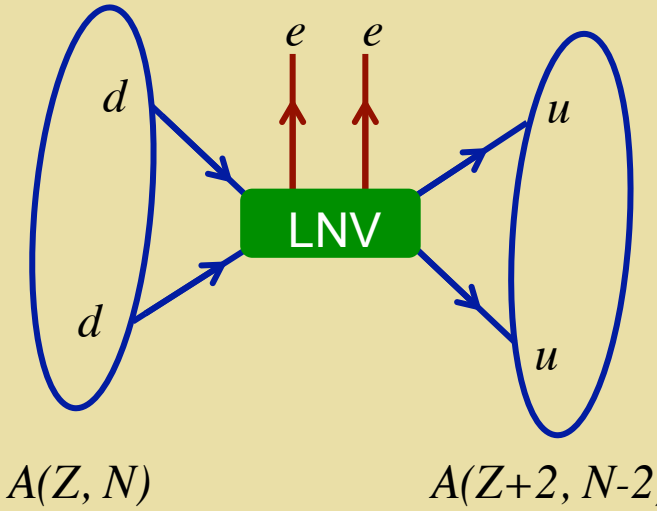
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

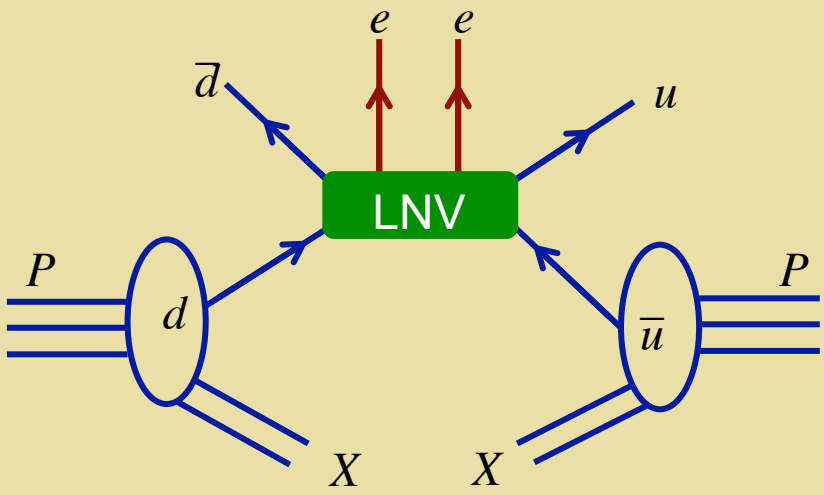
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

$0\nu\beta\beta$-Decay



pp Collisions



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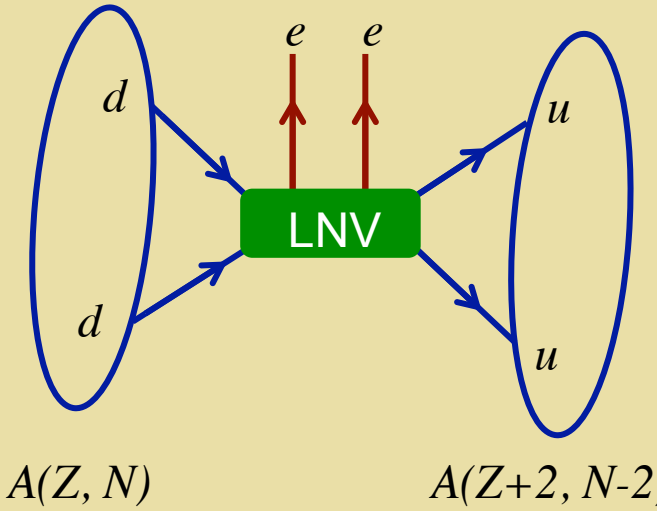
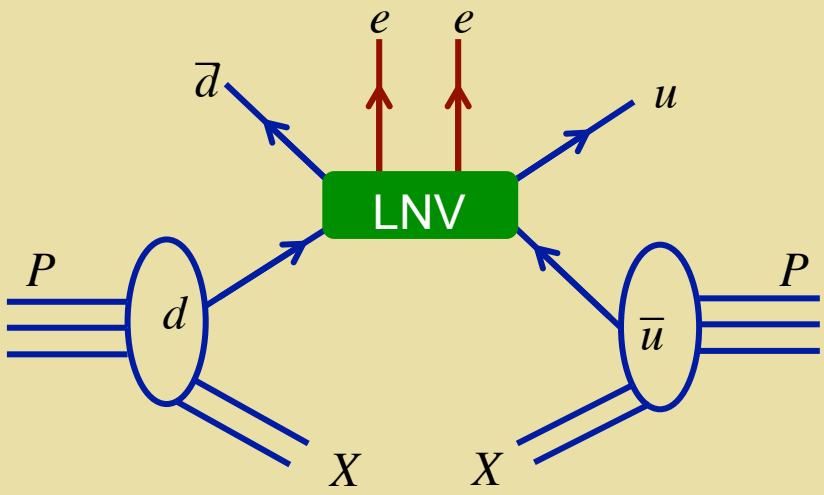
Majorana

LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



pp Collisions



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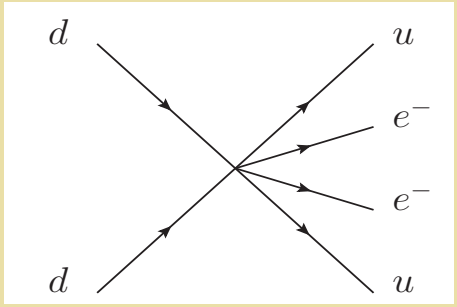
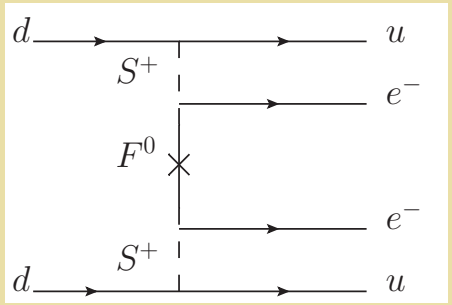
Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay



LHC: pp → jj e⁻e⁻



Can it be discovered with combination of $0\nu\beta\beta$ & LHC searches ?

Simplified models

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

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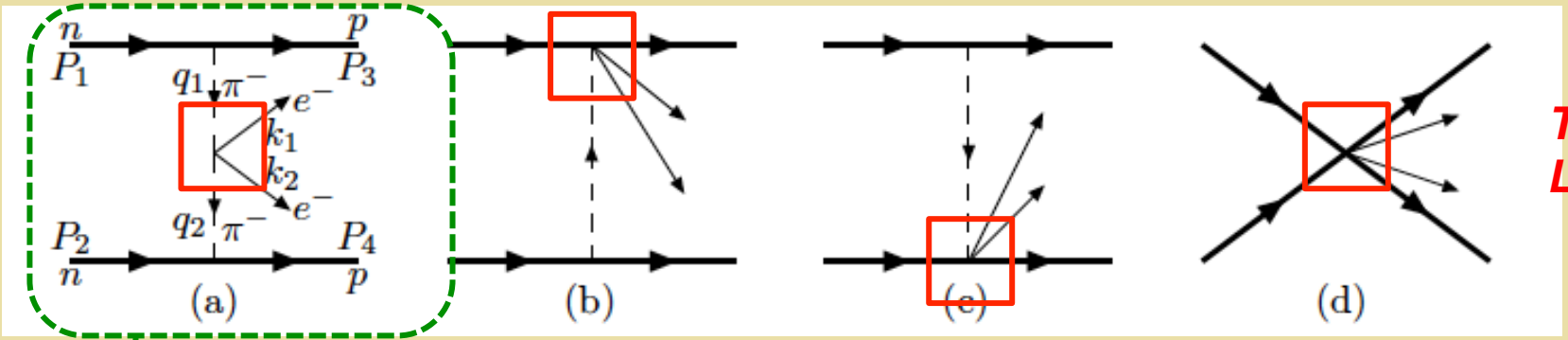
Majorana

Low energy: *Nuclear Matrix Elements: Long Range Effects*

*Prezeau, R-M, Vogel '03 **



TeV LNV

This model: LO + counterterm

Exploit Chiral Symmetry & EFT ideas

** Other recent → this collaboration*

$0\nu\beta\beta$-Decay: Our Earlier Study

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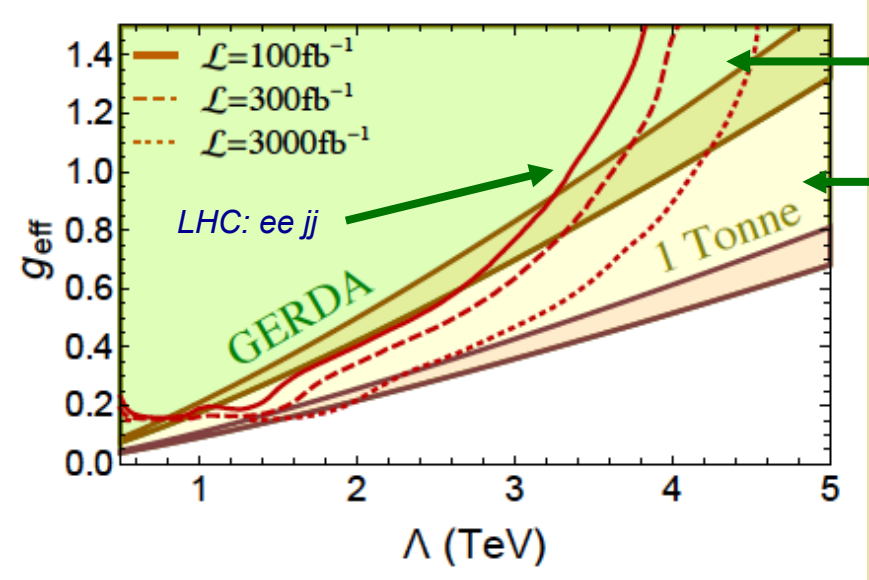
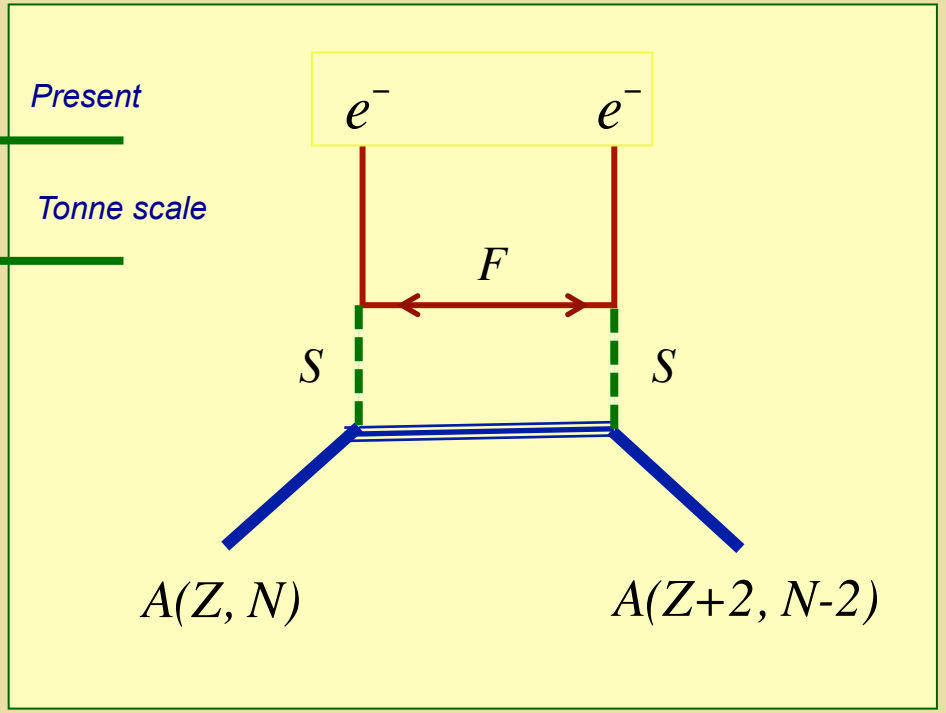
Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

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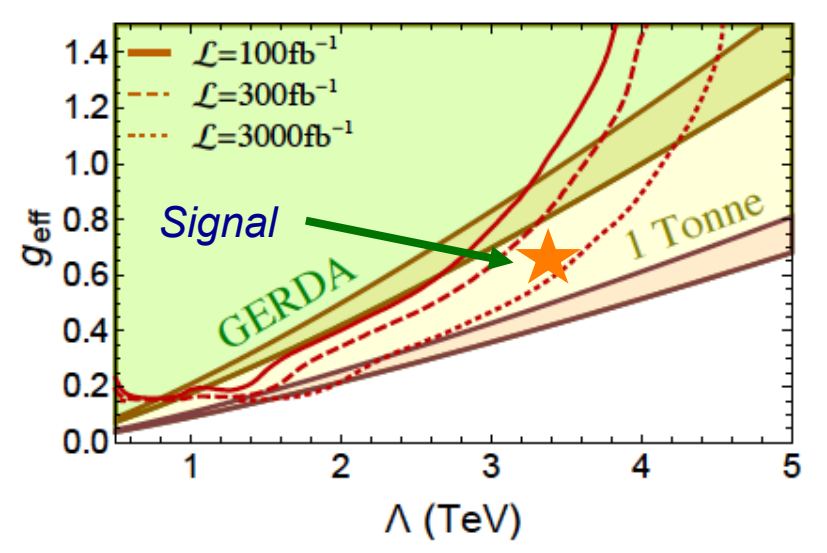
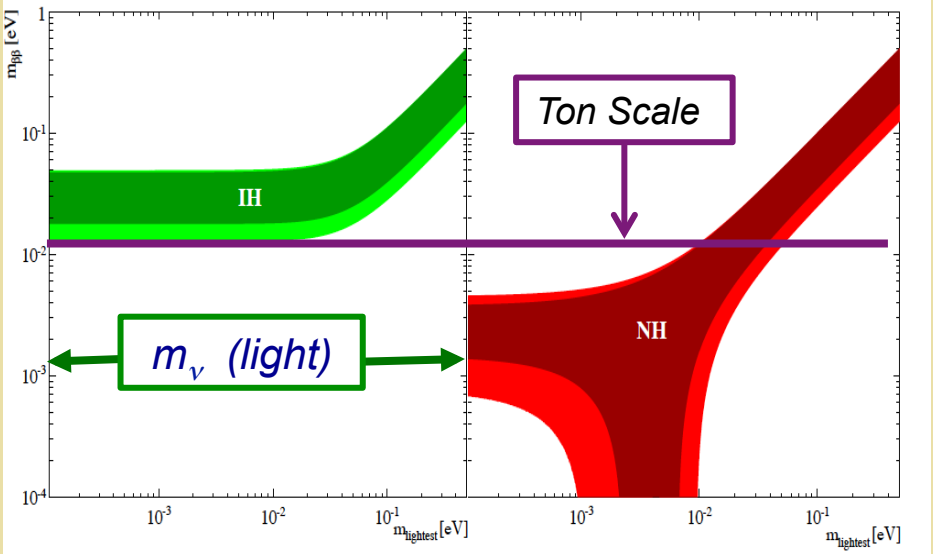
Majorana

Implications for m_ν:





A hypothetical scenario

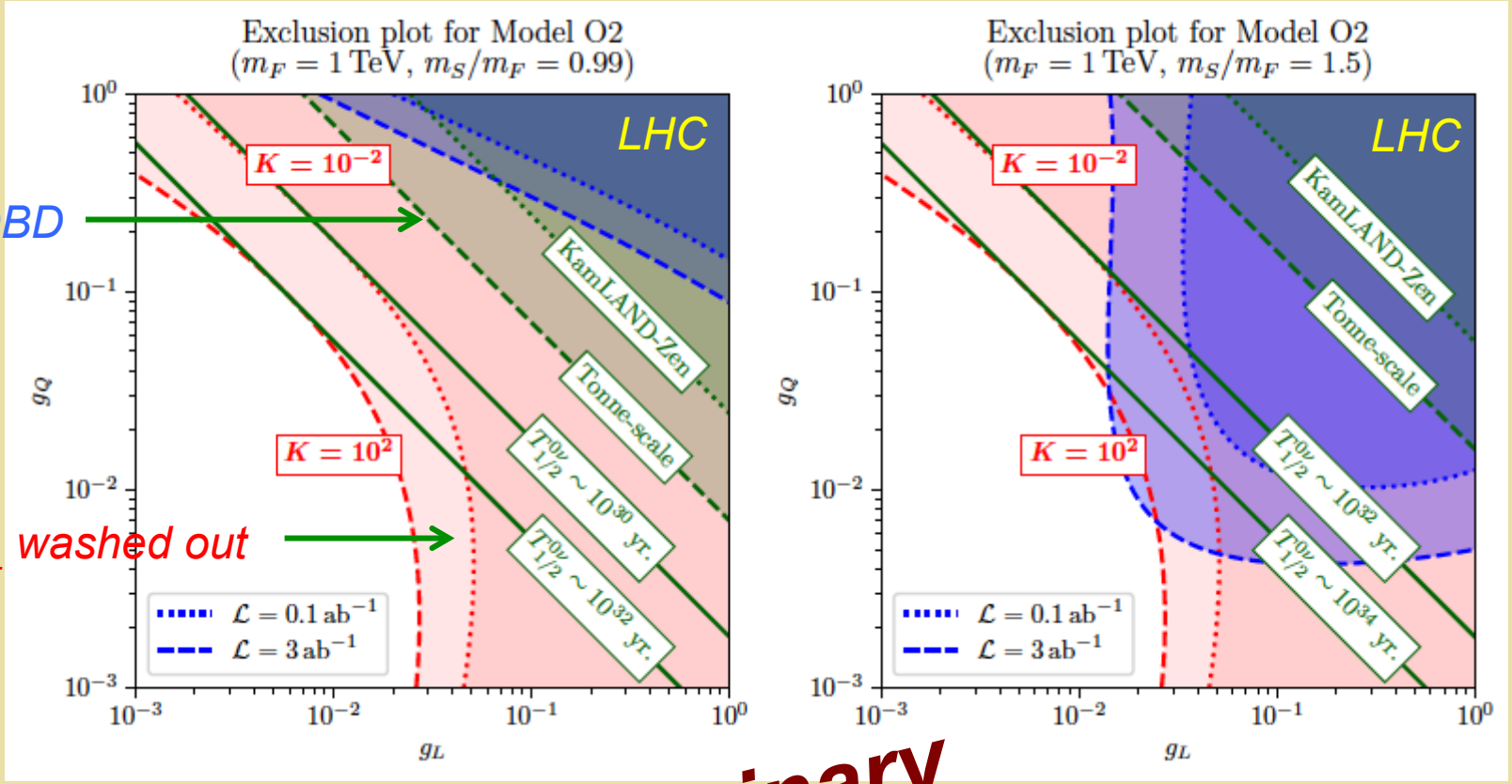
LHC Update: Signal & Background

	$g_L = 1.0\,,\ g_Q = 0.1$	$g_L = 0.1\,,\ g_Q = 1.0$
$\sigma(pp \to jje^+e^+)$ (pb)	9.701×10^{-3}	1.811×10^{-3}
$\sigma_{(b)}(pp \to S^+)$ (pb)	2.614×10^{-2}	2.614
$\mathrm{Br}(S^+ \to e^+F)$	9.494×10^{-1}	1.871×10^{-3}
$\mathrm{Br}(F \to e^+jj)$	0.5	0.5

(a) $\sqrt{s} = 14$ TeV, $m_F = 1$ TeV, and $m_S = 2$ TeV.

BKG type		σ before signal selection (pb)	σ after signal selection (pb)	σ after NN (pb)
Diboson	WW	3.28×10^{-3}	6.40×10^{-4}	6.87×10^{-5}
	WZ	2.59×10^{-2}	6.65×10^{-3}	2.10×10^{-4}
	ZZ	1.32×10^{-3}	5.62×10^{-4}	1.14×10^{-5}
Jet-fake	$W + 3j$	1.79×10^{-1}	4.34×10^{-2}	1.78×10^{-4}
	$t\bar{t}$	9.11×10^{-2}	2.64×10^{-2}	6.10×10^{-5}
Charge misidentification	$t\bar{t}$	3.33×10^{-2}	1.54×10^{-2}	4.45×10^{-4}
	Z/γ^*	2.54×10^{-1}	1.37×10^{-1}	4.89×10^{-3}
		5.88×10^{-1}	2.30×10^{-1}	5.86×10^{-3}

Results: $0\nu\beta\beta$ Decay & LHC



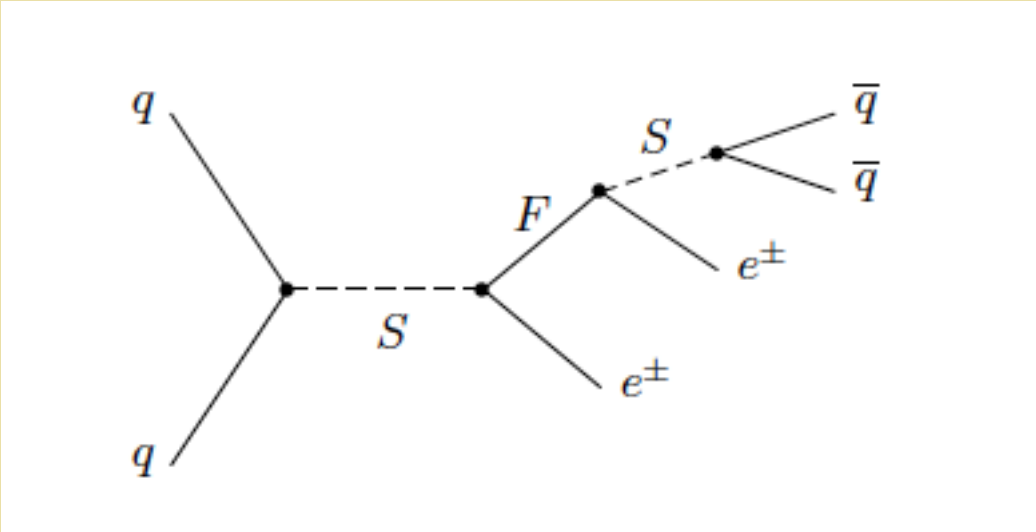
DBD

Y_{B-L} washed out

Preliminary

Thanks! S. Urrutia Quiroga

Results: LHC Cross Section



- *Largest σ for $m_S > m_F$*
- *Off-shell S suppression for $m_F > m_S$*

Thanks! S. Urrutia Quiroga

$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

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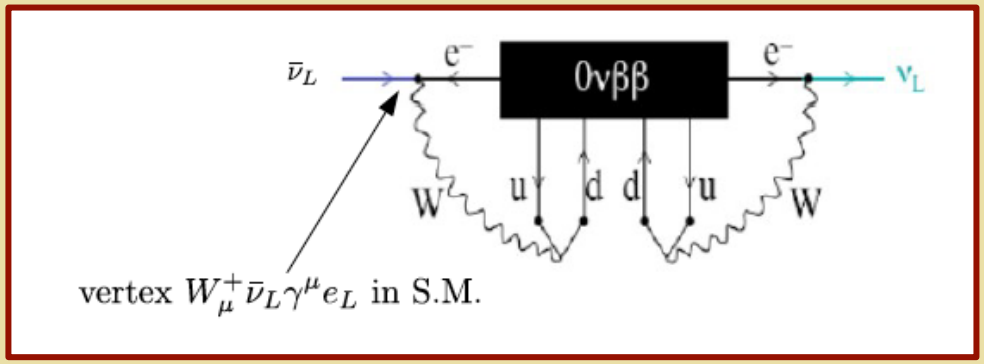

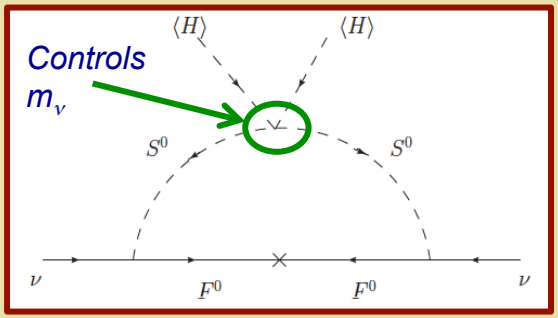

Schecter-Valle: non-vanishing Majorana mass at (multi) loop level

Simplified model: possible (larger) one loop Majorana mass

Next Steps

- *Analyze flavor effects:**
  - *LHC: pp → $\mu\mu$, eμ , $\tau\tau$, … ; prompt vs DV*
  - *Flavored leptogenesis*
  - *Low-energy: μ → e γ , …*
- *Other simplified models & UV completions*

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V. Outlook

- *The observation of TeV scale LNV would have profound implications for our understanding of the origin of m_ν & the cosmic baryon asymmetry*
- *There exists a rich interplay between $0\nu\beta\beta$ and collider searches*
- *Exciting opportunities ahead for exploring model realizations, flavor effects in the early universe, and connections to other experimental tests*