Nu Mass Models at Colliders: Worries and Hopes

Beyond 3×3 - Pittsburgh

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November 09, 2018

This is a talk where I will share my feelings

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Worry: Limitations and Robustness of Benchmarks

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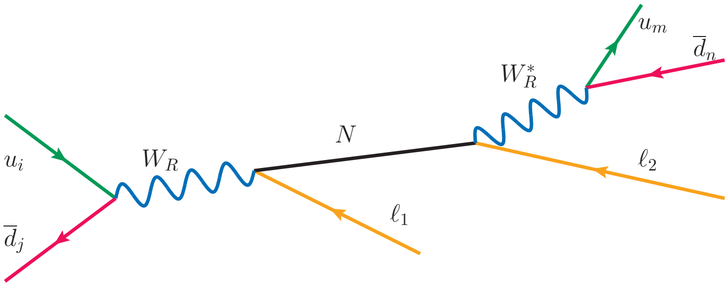
[1] See talks by Pavel (Sunday) and Miha (today)

Worry: Limitations and Robustness of Benchmarks



mass hierarchies in neutrino mass models with new gauge fields[1]

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Mass Hierarchies within Nu Mass Models

Majorana N can be produced through new gauge bosons, e.g., W_R, Z_{B-L}

- Canonical/simplified channels, e.g., $pp \to \ell_i^\pm \ell_k^\pm + nj$, very sensitive but **not designed** for mass hierarchies
  - E.g., $M_{WR} \sim g_L v_R \sim 5-6$ TeV $\gg m_N \sim y^N v_R \sim y^\tau v_R \sim 100$ GeV

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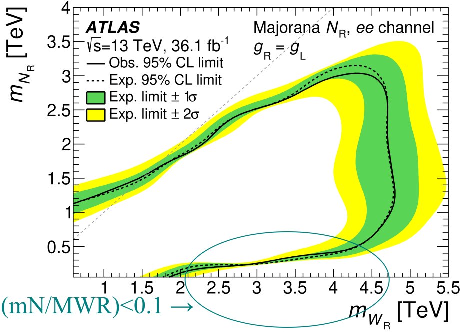
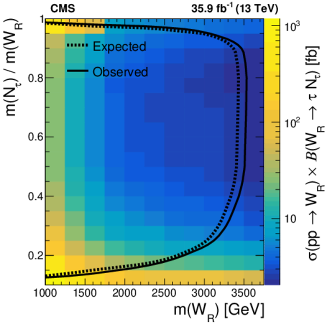
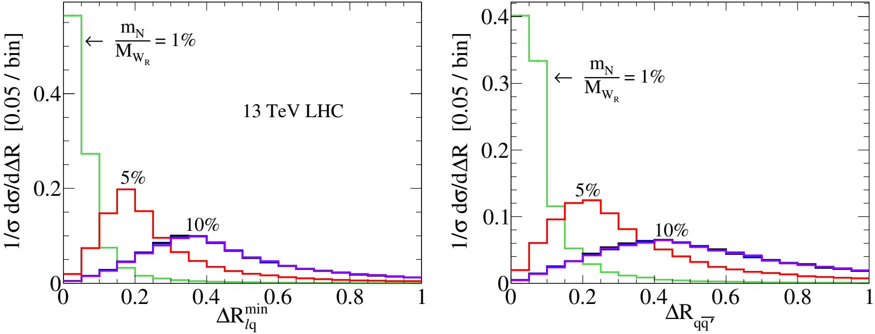


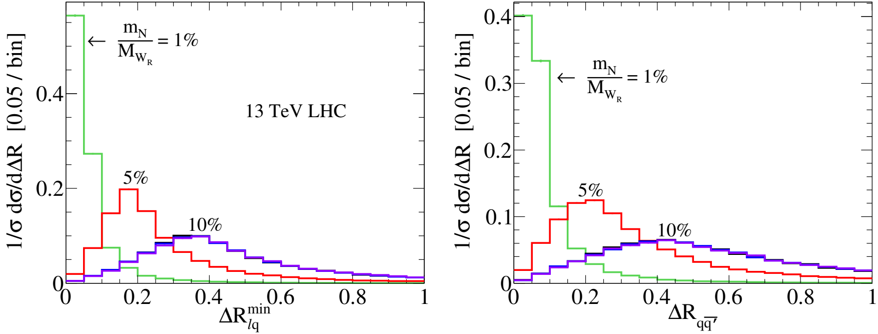
(mN/MWR)<0.1 →



For $(m_N/M_{W_R}) \ll 1$, i.e., boosted N, searches losing sensitivity!



For a $1 \rightarrow 2$ process, $m_{ij}^2 = (p_i + p_j)^2 \approx 2E_iE_j(1 - \cos\theta_{ij}) \approx E_iE_j\theta_{ij}^2$



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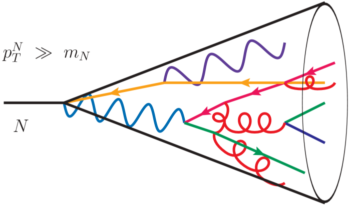
$$\Rightarrow \Delta R_{ij} \sim \frac{m_N}{\sqrt{E_iE_j}} \sim \frac{4m_N}{M_{W_R}} \Rightarrow \text{For } \left(\frac{m_N}{M_{W_R}}\right) < 0.1, \Delta R_{\ell X}^{\min} = 0.4 \text{ iso. req. fails}$$

K&S process $pp \to \ell^\pm \ell^\pm jj + X$ contains two same-sign charged leptons

- S/B power comes from high-p_T leptons + little/no MET
- **Subtle**: 2 jets (composite/dressed) vs quarks (elementary/undressed)

Question: Is it necessary to identify the second lepton or jet multiplicity?

Merged topologies impact both hadronic and lepton observables



The formation of "neutrino jets" is a bit funny [1607.03504; 1610.08985]

- Seeded by a 1 → 3 splitting: the charged lepton disappears
- Driven by kinematics: $m_N \ll M_{WR}$
- Little to do with nature of W_R, e.g., "lepton jets" [Izaguirre and Shuve, 1504.02470]

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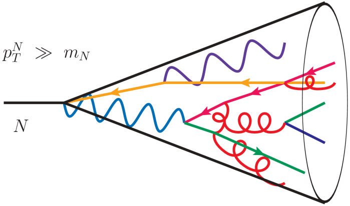

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Worry: Applicable to searches for long-lived / displaced N

- For $m_N \lesssim 10$ GeV, then in $W/Z \to NX$ decays, $N \to \ell q\overline{q}$ decays are actually neutrino jet at detector level
- No collider study to date has taken this into account for low-scale Type I seesaw (SM+N). Ditto for Type I+III seesaw.

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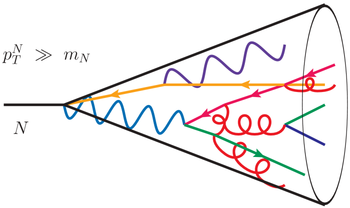

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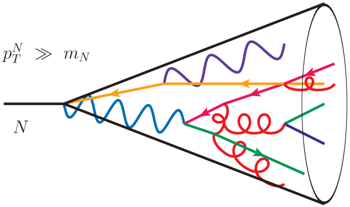
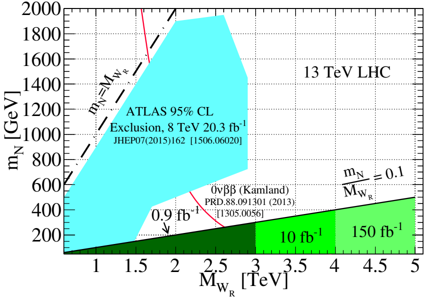
Hope: There is a language and have tools, and they work!

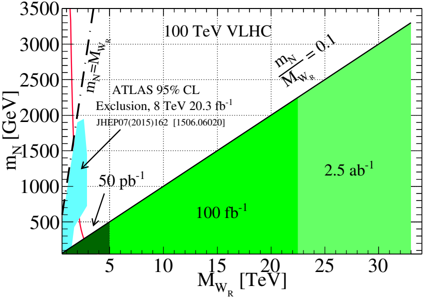
Like boosted t, treat decays of boosted N as a single ***neutrino jet*** (j_N)



$pp \to \ell + j_N$ sensitivity (green) is precisely where $\ell\ell jj$ searches exclusion (blue) stop [1607.03504; 1610.08985]

W_R sensitivity recovered and can reach $5 - 6$ ($35 - 45$) TeV at $\sqrt{s} = 14$ (100) TeV





Worry: Feasibility of Lepton Number Violation at Colliders

Canonical Type I Seesaw Mechanism

... extends the Standard Model (**SM**) field content with N_R, and supposes the existence of Dirac and RH Majorana masses:

$$\mathcal{L}_{\text{Type I}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{N~Kin.} - \underbrace{y_\nu \overline{L}\tilde{\Phi} N_R + H.c.}_{\text{Dirac mass}} - \underbrace{\mu_R \overline{N_R^c} N_R}_{\text{Majorana mass}}$$

Combining the mass terms makes manifest neutrino mass-mixing

$$\mathcal{L}_{D+M} = -\frac{1}{2}\overline{\tilde{N}}\tilde{M}\tilde{N} = \begin{pmatrix} \overline{\nu_L} & \overline{N_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & \mu_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

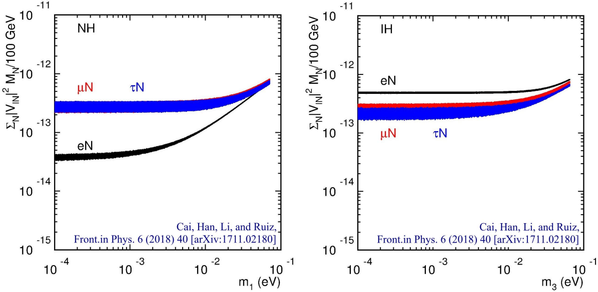
which gives in the following mass eigenvalues when $\mu_R \gg m_D$:

$$m_1 \approx -m_D |V|^2 = -m_D \frac{m_D}{\mu_R}, \quad m_2 \approx \mu_R$$

Realistic ***models*** have large and messy mass matrix $\tilde{M}$, where

$$\tilde{m}_\nu = -\tilde{M}_D \tilde{M}_R^{-1} \tilde{M}_D^T \text{ with active-sterile mixing } \tilde{V} = \tilde{M}_D \tilde{M}_R^{-1}$$

Plugging in measured ν mass splittings and solving for mixing reveals very small $|V_{\ell N}|$ for *three* EW/TeV-scale N



Cai, Han, Li, and Ruiz, Front.in Phys. 6 (2018) 40 [arXiv:1711.02180]

This suggests that N *might decouple from colliders experiments*[2]

- For MeV N, rate okay if can be produced from meson decays
- Many attempts to invoke flavor symmetries to obtain sizable mixing
- Exception[3] when (lots) more N added with ***small*** Majorana mass $\mu_X \ll m_D, \mu_R$, leading to $\tilde{m}_\nu = -\tilde{M}_D^T \tilde{M}_R^{T\,-1} \mu_X \tilde{M}_R^{-1} \tilde{M}_D$

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[2] Pilaftsis [hep-ph/9901206] and Kersten & Smirnov [0705.3221]

[3] Inverse and Linear Seesaw mechs. in literature, and N is Dirac-like/pseudo-Dirac

Clarity on Lepton Number Violation vs Colliders

Whether or not N_i decouple from collider experiments has been clarified

- Theorem[4]: In SM + arbitrary number of gauge singlet/sterile fermions, $\tilde{m}_\nu = 0 \Leftrightarrow$ lepton number (L) conservation

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[4] Moffat, et al [1712.07611]

[5] See Yuber's and Brian's talks tomorrow!

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$\implies$ In pure Type I scenarios, L violation decouples one of two ways:

1. **High-scale seesaw**: $\mu_M \gg \langle \Phi_{SM} \rangle \implies m_\nu \sim m_D \left(\frac{m_D}{\mu_M}\right), \quad m_N \sim \mu_M$
2. **Low-scale seesaw**: $\mu_M \ll \langle \Phi_{SM} \rangle \implies m_\nu \sim \mu_M \left(\frac{m_D}{m_R}\right)^2, \quad m_N \sim m_R$

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② **Low-scale seesaw**: $\mu_M \ll \langle \Phi_{SM} \rangle \implies m_\nu \sim \mu_M \left(\frac{m_D}{m_R}\right)^2, \quad m_N \sim m_R$

$\implies$ In Type I scenarios, EW/TeV-scale Dirac-like N_i do not decouple[5]

Collider observation of $N_i + L$-violation $\implies$ *more new particles!*

- Important since concrete example of a realistic Type II Seesaw mimicking the canonical Type I collider signature

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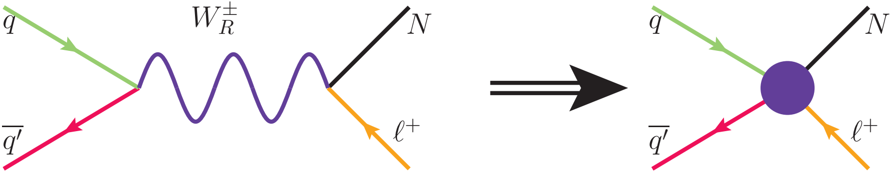
Mimicking Type I Seesaw

If gauge mediators are too heavy, light *N* are still accessible



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[6] Han, Lewis, **RR**, Si, PRD ('12) [1211.6447]; **RR**, EPJC ('17) [1703.04669]

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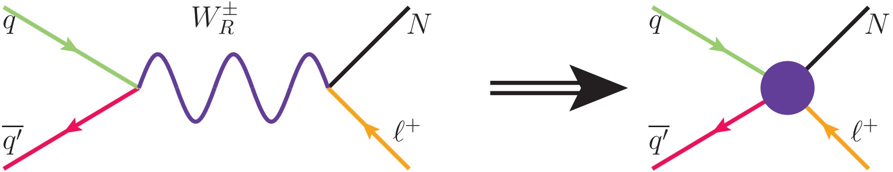

When $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV, $pp \to N\ell + X$ production in the LRSM and minimal Type I Seesaw are not discernible[6]

- Occurs near threshold $\sqrt{\hat{s}} \sim m_N$ and same $\ell_1^\pm$ polarization
- Differentiation requires polar and azimuthal polarization measurements of the full $pp \to \ell^\pm\ell^\pm + nj + X$ final state

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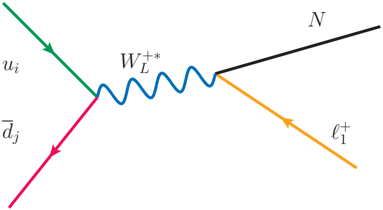
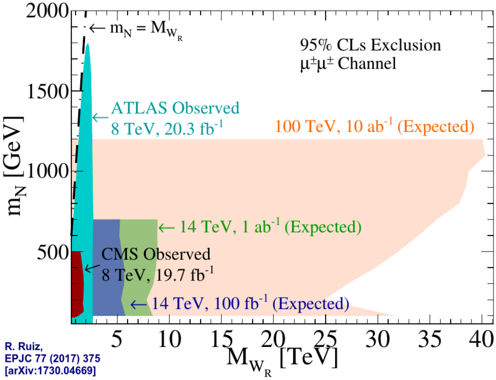
"Type I" searches and sensitivities for Majorana N can be reinterpreted[7] in the context of LRSM when $M_{W_R} \gtrsim \sqrt{s} \gg \sqrt{\hat{s}}$

- **Signature**: $pp \to \ell^\pm \ell^\pm + nj + X + p_T^\ell \gtrsim \mathcal{O}(m_N) + \text{no MET}$





R. Ruiz,
EPJC 77 (2017) 375
[arXiv:1730.04669]

At 14 (100) TeV with $\mathcal{L} = 1\ (10)\ \text{ab}^{-1}$, $M_{W_R} \lesssim 9\ (40)$ TeV can be probed

- **DO NOT STOP SEARCHING FOR TYPE I LNV**

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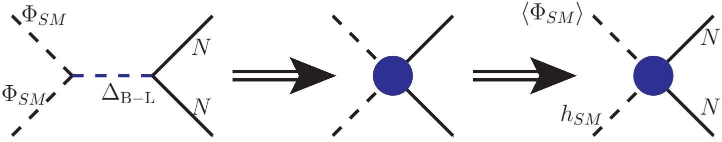
[7] **RR** [1703.04669]

Collider LNV from Inaccessible Mediators

If other mediators are too heavy, light *N* are still accessible[8]



SM-invariant effective field theories with sterile neutrinos exist![9]

- Heavy Neutrinos EFT (NEFT) [Aparici, 0904.3244]

$$\mathcal{L}_{\mathrm{NEFT}} = \mathcal{L}_{\mathrm{Type\ I}} + \sum_5 \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)}, \qquad \mathcal{O}_V^{(6)} = \left(\overline{d}\gamma^\mu P_R u\right)\left(\overline{e}\gamma_\mu P_R N_R\right)$$

---

[8] For Higgs-Neutrino relationship, see afternoon talks!

[9] See Mike's talk Wednesday and [1703.04415] for relevant (SM)EFT details; and Bibhushan's talk Wednesday for example!

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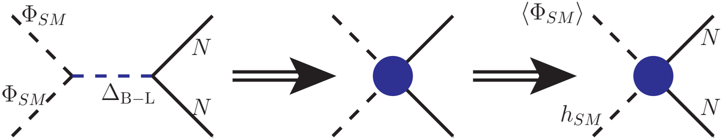

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One subtlety [**RR**, 1703.04669]: N_R here is *chiral/interaction* state

- Must decompose into mass basis: $N_R = \sum X_{\ell m}\nu_m + \sum Y_{\ell m'} N_{m'}$
- After EWSB, maps onto light neutrino NSI operators!

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Worry: Monte Carlo Resources

Collider Monte Carlo for Seesaws

Until 2015-16, few public codes existed to simulate Seesaws colliders:

	Pythia	ALPGEN	FeynRules[10]
Dirac N			
Majorana N	✓	✓	✓
Drell-Yan: LH Current		✓	
Drell-Yan: RH Current	✓		✓
Vector Boson Fusion			
Gluon Fusion			
Triplet Leptons/Scalars DY	✓	✓	✓
Triplet Leptons/Scalars VBF	✓		✓
Triplet Leptons/Scalars GF			

No Monte Carlo $\Longrightarrow$ no experimental interpretation

Lack of tests tied to lack of tools!

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[10] Input libraries for MadGraph, Herwig, Sherpa, WHIZARD

Collider Monte Carlo for Seesaws

Now

	Pythia	ALPGEN	FeynRules[11]
Dirac *N*			✓
Majorana *N*	✓	✓	✓
Drell-Yan: LH Current		✓	NLO
Drell-Yan: RH Current	✓		NLO
Vector Boson Fusion			NLO
Gluon Fusion			LO
Triplet Leptons/Scalars DY	✓	✓	✓/NLO
Triplet Leptons/Scalars VBF	✓		✓/NLO
Triplet Leptons/Scalars GF			/LO

New Monte Carlo tools $\Longrightarrow$ experimental test possible

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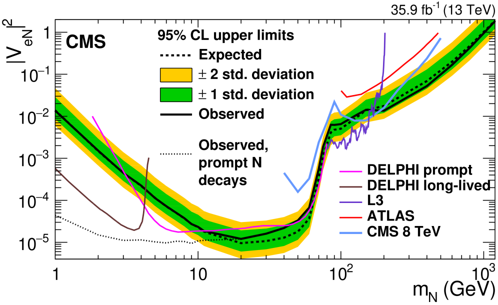
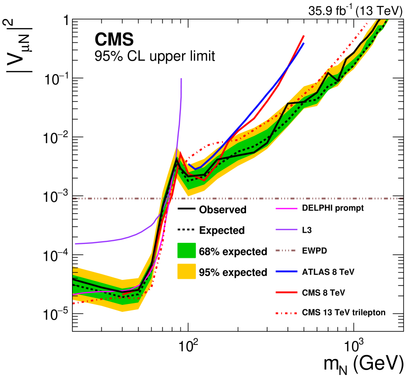
[11] Input libraries for MadGraph, Herwig, Sherpa, WHIZARD

These tools now standard for LHC experiments!





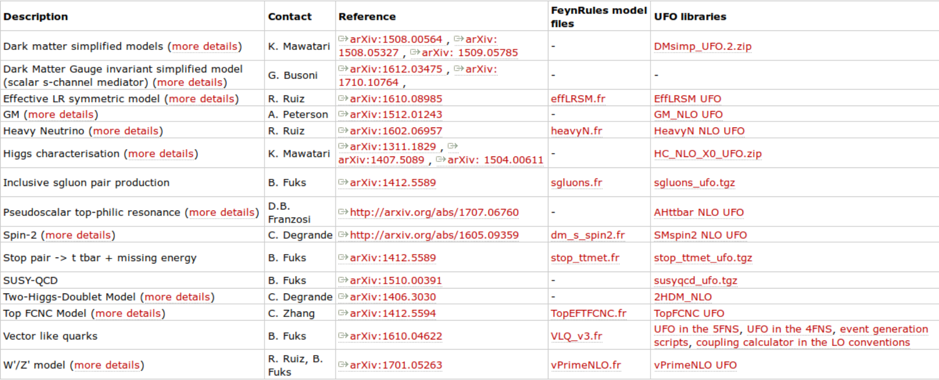
Plotted: Exclusion on mixing $|V_{\ell N}|^2$ vs heavy N mass (m_N)

- (L) Search for $pp \to N\ell \to 3\ell + X$ [1802.02965]
- (R) Search for $pp \to N\ell \to \ell^\pm\ell^\pm + nj + X$ [1806.10905]

Public Libraries

Models files are being (re)written based on need / interest [*feynrules.irmp.ucl.ac.be/wiki/NLOModels*]

- Lots more work still to do! **(happy to collaborate)**



Description	**Contact**	**Reference**	**FeynRules model files**	**UFO libraries**
Dark matter simplified models (more details)	K. Mawatari	arXiv:1508.00564 , arXiv: 1508.05327 , arXiv: 1509.05785	-	DMsimp_UFO.2.zip
Dark Matter Gauge invariant simplified model (scalar s-channel mediator) (more details)	G. Busoni	arXiv:1612.03475 , arXiv: 1710.10764 ,	-	-
Effective LR symmetric model (more details)	R. Ruiz	arXiv:1610.08985	effLRSM.fr	EffLRSM UFO
GM (more details)	A. Peterson	arXiv:1512.01243	-	GM_NLO UFO
Heavy Neutrino (more details)	R. Ruiz	arXiv:1602.06957	heavyN.fr	HeavyN NLO UFO
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089 , arXiv: 1504.00611	-	HC_NLO_X0_UFO.zip
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz
Pseudoscalar top-philic resonance (more details)	D.B. Franzosi	http://arxiv.org/abs/1707.06760	-	AHttbar NLO UFO
Spin-2 (more details)	C. Degrande	http://arxiv.org/abs/1605.09359	dm_s_spin2.fr	SMspin2 NLO UFO
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz
SUSY-QCD	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO
Top FCNC Model (more details)	C. Zhang	arXiv:1412.5594	TopEFTFCNC.fr	TopFCNC UFO
Vector like quarks	B. Fuks	arXiv:1610.04622	VLQ_v3.fr	UFO in the 5FNS, UFO in the 4FNS, event generation scripts, coupling calculator in the LO conventions
W'/Z' model (more details)	R. Ruiz, B. Fuks	arXiv:1701.05263	vPrimeNLO.fr	vPrimeNLO UFO

Worry: Modeling hard *pp* scattering

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BSM@NLO?

Precision of Normalization $\neq$ Precision of Distribution

Not all observables $\hat{\mathcal{O}}$ are well-defined (physically meaningful) when total cross section σ is known only at Born/leading order (**LO**)

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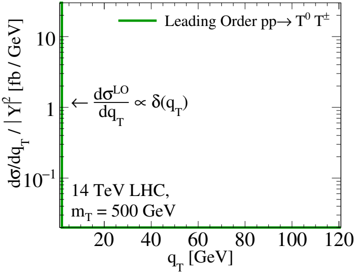
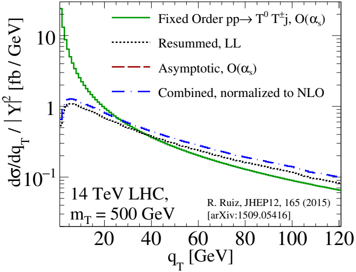
Ex: transverse momentum (q_T) of W/Z system in $pp \to V + X$

- $q_T = 0$ at Born-level and singular at $\mathcal{O}(\alpha_s)$
- Lowest order q_T physical is when σ is known at NLO w/ leading log. (**LL**) resummation (**or +PS**) $\implies d\sigma/dq_T$ is LO+LL accurate

Due to color structure, also true for heavy leptons and dark γ_D/Z'





R. Ruiz, JHEP12, 165 (2015) [arXiv:1509.05416]

Collider Monte Carlo for Seesaws

BSM at 1-loop systematically possible [Degrande, 1406.3030]

- Follows OPP expansion and R_2 term expressed as Feynman rule

	Pythia	ALPGEN	FeynRules[12]
Dirac N			✓
Majorana N	✓	✓	✓
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BSM@NLO in QCD $\Longrightarrow$ jet observables at least LO+LL accurate!

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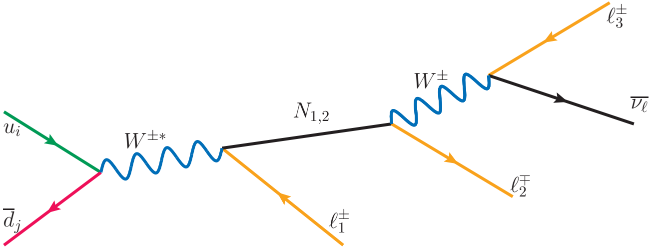
[12] Input libraries for MadGraph, Herwig, Sherpa, WHIZARD

Heavy Neutrinos and Jet Vetoes[13]



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[13] w/ collaborators [1805.09335, 1811.????? (I worry about this, too...)]

Benchmark flavor mixing scenario:

$$|V_{e4}| = |V_{\tau 4}| \neq 0 \quad \text{and} \quad |V_{\mu 4}| = 0$$

Two complementary signal processes ($\ell_X = e, \mu, \tau_h$):

Signal I: $pp \to \tau^+\tau^-\ell_X$+MET and **Signal II:** $pp \to \tau^\pm e^\mp \ell_X$+MET

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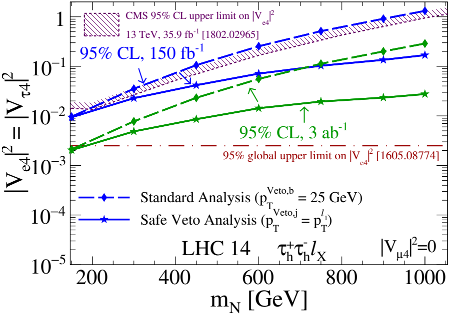
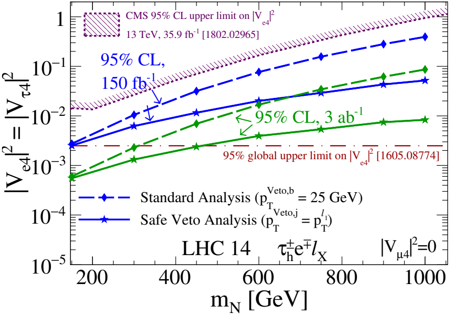




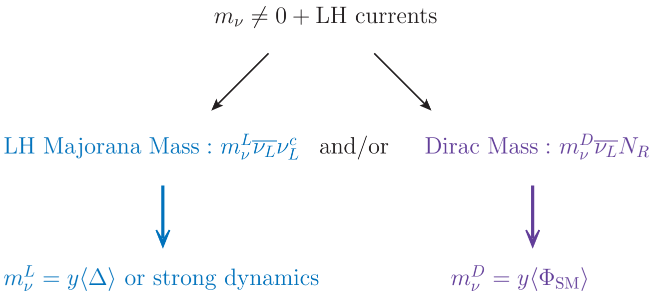
- Dash = standard search with *b*-jet veto (13 TeV CMS for e/μ)
- Solid = "improved" analysis with special type of jet veto

Improved sensitivity up to $10 - 11\times$ **with** $\mathcal{L} = 3$ ab^{-1} **at LHC 14**

Hope: New Particles Must Exists!

Keeping an Open Mind on Origin of Neutrinos Masses

Nonzero neutrino masses implies new degrees of freedom exist [Ma'98]:



$m_\nu \neq 0 + \text{LH currents}$

LH Majorana Mass : $m_\nu^L \overline{\nu_L} \nu_L^c$ and/or Dirac Mass : $m_\nu^D \overline{\nu_L} N_R$

$m_\nu^L = y\langle\Delta\rangle$ or strong dynamics

$m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$

$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\implies$ **new particles!**

- New particles might be charged under new or old gauge symm., e.g., (N_R, e_R) form $\text{SU}(2)_R$ doublet and Δ_L is scalar $\text{SU}(2)_L$ triplet
- *Exciting* since long "to do" list in case of discovery!

I worry, a lot:

- Language we use to describe phenomena matches reality
  - Partons vs jets picture has qualitative impact
- Limitations of benchmark signatures
  - Benchmarks not designed for all parameter space regions
- Do we have the necessary tools?

Lack of clear guidance from data and theory means we must take a broad, open approach to uncovering the origin of tiny ν masses.

Hope: a community effort is working to address this

1. Review on Nu Mass Models at Colliders [arXiv:1711.02180], Y. Cai, T. Han, T. Li, **RR**
2. HL/HE-LHC Yellow Book Chapter on Nu Mass Modes, T. Han, T. Li, X. Marcano, S. Pascoli, **RR**, C. Weiland
3. Other community documents, both "*public*" and "*in preparation*"

Be encouraged! More data soon!


ν
PITTPACC
HOPE
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Thank you.