Left-Right Symmetry: At the Edges of Phase Space and Beyond [1]

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[1] Based on several works: See slides for Refs. (*) = IPPP student.

Left-Right Symmetry...

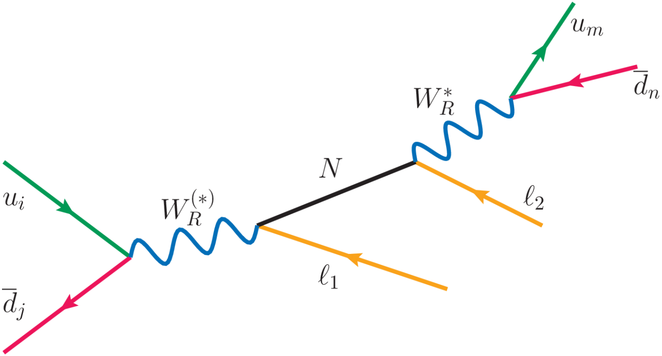
In general, the LHC has not yet ruled out edges and corners of BSM parameter space $\implies$ edges and corners of phase space

Question: How does collider pheno for neutrino mass models (Seesaws) qualitatively change for these regions of parameter and phase space?

... At the Edges of Phase Space and Beyond:

1. Left-Right Symmetric Model Primer
2. LRSM at the Edges of Phase Space
3. LRSM beyond the Edges of Phase Space
4. Redux I: Edges
5. Redux II: Beyond

Left-Right Symmetry at Hadron Colliders



Left-Right Symmetric Models (**LRSM**) postulate that the SM's $V - A$ structure originates from the spontaneous breakdown of parity:

$$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \underbrace{\mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}}$$

After scalar Δ_R acquires a vev $v_R \gg v_{SM}$: $\hookrightarrow \mathrm{U}(1)_Y$

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After scalar Δ_R acquires a vev $v_R \gg v_{SM}$: $\hookrightarrow \mathrm{U}(1)_Y$

Higgs field Φ then breaks down the EW group $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \rightarrow \mathrm{U}(1)_{EM}$

With N_R, all SM fermions can be grouped in $\mathrm{SU}(2)_L$ *and* $\mathrm{SU}(2)_R$ doublets. Dirac masses generated in (mostly) usual way with Φ, i.e., $\Delta\mathcal{L} \ni \overline{Q}_L \Phi Q_R$

Neutrinos obtain LH (RH) Majorana masses from triplet scalar Δ_L (Δ_R):

$$m^{\nu}_{\text{light}} = \underbrace{y_L \langle\Delta_L\rangle}_{\text{Type II}} - \underbrace{\left(y_D y_R^{-1} y_D^T\right) \langle\Phi\rangle^2 \langle\Delta_R\rangle^{-1}}_{\text{Type I a la Type II}} \sim \mathcal{O}(0) + \text{symm.-breaking}$$

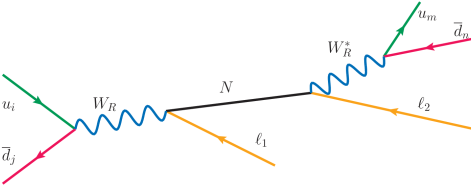
Major pheno: heavy N, W'/Z' ($\approx W_R/Z_R$), and $H_i^{\pm\pm},\ H_j^{\pm},\ H_k^0$

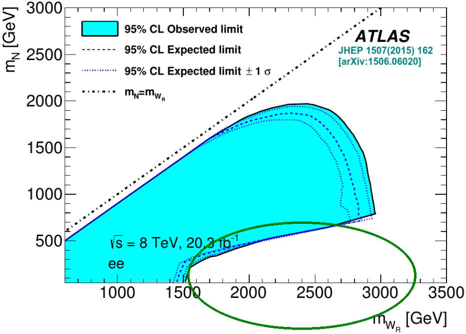
8 TeV LHC Exclusion with $\mathcal{L} \approx 20$ fb^{-1}

LHC expts have performed remarkably!

Plotted: excluded (m_{N_R}, M_{W_R}) from searches for resonant W_R, N

Signaure: $pp \to e^\pm e^\pm + nj + X$
$+\ p_T^\ell \gtrsim \mathcal{O}(M_{W_R})$ + no MET



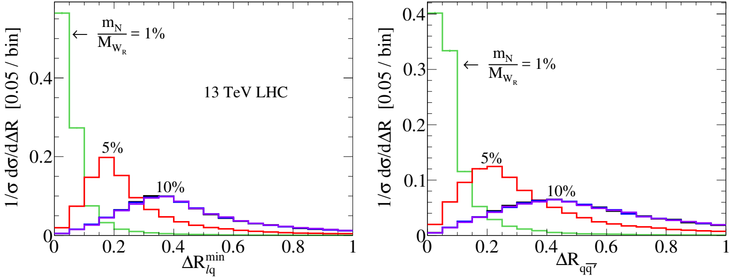


Similar sensitivity to searches for $pp \to Z_R \to NN \to e^\pm e^\pm + nj + X$

$\Longrightarrow$ For both W_R and Z_R, loss of sensitivity when $m_N \ll M_V$

(Lets see what is going on.)

Failure of Electron ID in $pp \to W_R \to \ell^{\pm} N(\to e^{\pm} q\overline{q'})$



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

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

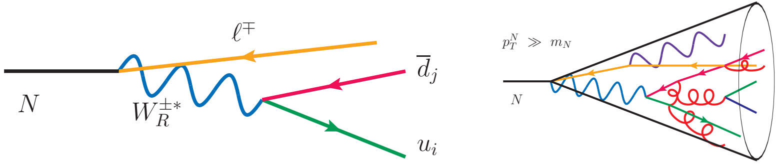
Standard isolation criteria for electrons is failing in boosted configurations

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

Neutrino Jets[2] (n):

(i) hadronically decaying, high-p_T heavy neutrinos;

(ii) a fat jet originating from a heavy neutrino



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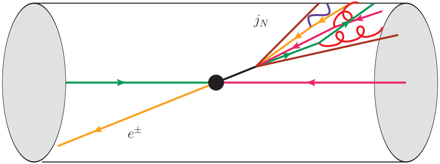
[2] A. Ferrari, et, al, PRD ('00); Mitra, **RR**, Scott*, Spannowsky, PRD ('16) [1607.03504]; Mattelaer, Mitra, **RR** [1610.08985]

Neutrino Jets in LRSM

Change the scale of our problem: treat $\ell_2^{\pm}$ like any other poorly isolated parton bathed in QCD radiation and cluster via a sequential jet algorithm[3]



Changing scales simplifies the problem, a lot:

For $m_N \ll M_{W_R}$, one has a different collider topology:

$$pp \rightarrow W_R \rightarrow e^{\pm} N \rightarrow e^{\pm} j_{\rm Fat} \ (+ \text{ no MET!})$$

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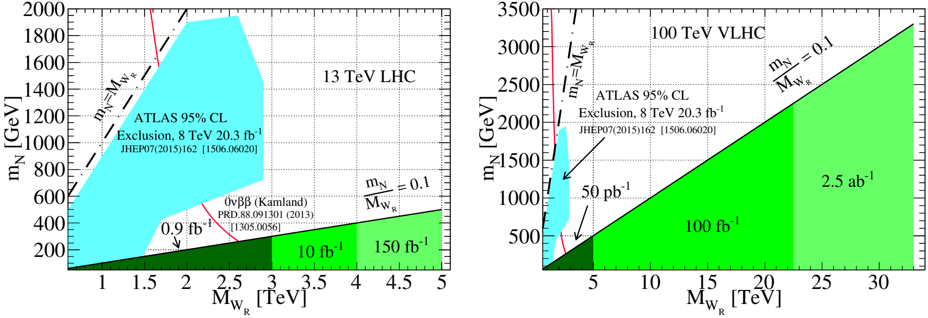
[3] Sequential jet algorithm ≈ definition of collimated, clusters of partons that is meaningful at all orders of perturbation theory, i.e., Infrared-Collinear (IRC)-safe

Discovery Potential at the Edge of Phase Space

For $m_N/M_{W_R} \leq 0.1$, the region where ATLAS/CMS searches breakdown, neutrino jet searches recovers lost sensitivity



Signature: $pp \rightarrow \ell^{\pm} + j_{\text{Fat}} + X$ [MET$<$ 100 GeV, $p_T^{\ell,j} \gtrsim 1$ TeV, $M_{\ell j}$ Cut]

- 13 TeV: $M_{W_R} \approx 3$ (4) [5] TeV discovery after 10 (100) [2000] fb^{-1}
- 100 TeV: $M_{W_R} \approx 15$ (30) TeV discovery after 100 fb^{-1} (10 ab^{-1})

Left-Right Symmetry Beyond the Edge of Phase Space:

A pathological but plausible scenario.

Ignoring UV completions, limits[4] on neutral flavor changing transitions require Δ_R sector to be $\langle\Delta_R\rangle \gtrsim \mathcal{O}(10)$ TeV

What if LR gauge and Yukawa couplings have similar values as in the SM?

- What if $M_{W_R} \sim g_L\langle\Delta_R\rangle \sim 6.5$ TeV and $m_N \sim y^{\tau}_{\rm SM}\langle\Delta_R\rangle \sim 100$ GeV?

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[4] Bertonlini, et al [1403.7112, + others]; Zhang, et al. [0704.1662; + others]

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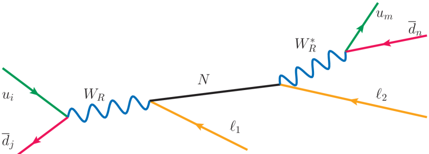
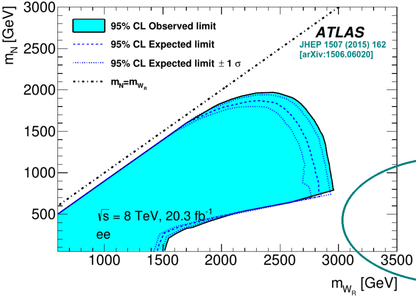
Data may be suggesting EW-scale N but kinematically inaccessible W_R, Z_R





Searches follow Keung & Senjanovic ('83), and assume resonant W_R, N

- No sensitivity to $M_{W_R} > 6-7$ TeV due to finite data set
- **Naive Question**: is an on-shell W_R necessary for discovery of N?

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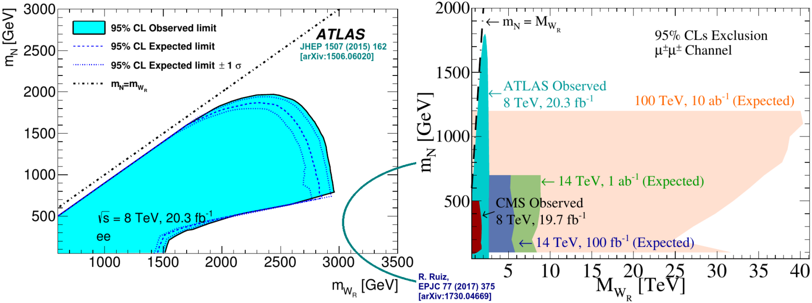
[4] Bertonlini, et al [1403.7112, + others]; Zhang, et al. [0704.1662; + others]

L Violation from Beyond the Edges of Phase Space[5]

Of course $pp \to W_R^* \to N\ell + X$ can occur via an off-shell mediator.

- LR analog of Fermi interaction $\mathcal{L} = G_F[\overline{\mathcal{N}}\gamma^\mu\mathcal{P}][\overline{\nu}\gamma_\mu\ell]$

“Type I” searches and projected sensitivities for can be reinterpreted for LRSM in the limit that $M_{W_R} \sim \sqrt{s} \gg \sqrt{\hat{s}}$



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

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

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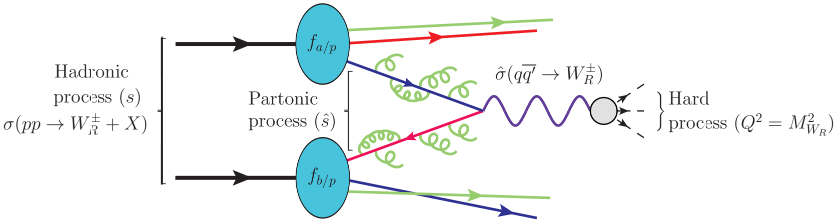
[5] First concrete example of Seesaw mimicry! **RR**, EPJC ('17) [1703.04669]

Redux I: Back to Edges of the LHC Phase Space

Can you see $M_{W_R} \gtrsim 5$ TeV?

Recall: W_R production is analogous to $W_{\rm SM}$, except $M_{W_R} \gtrsim 3-5$ TeV



Away from phase space boundaries, QCD corrections are 20-30%.

Near boundaries, i.e., for $M_{W_R} \lesssim \sqrt{s}$, the case is different:

- Initial-state gluon radiation is soft by momentum conservation
- Soft or **threshold** logs must be resummed to keep track of gluons

For Drell-Yan[6], threshold resummation is important for $M_{W_R}/\sqrt{s} \gtrsim 0.3$

- For gluon fusion, always important for SM and BSM[7]

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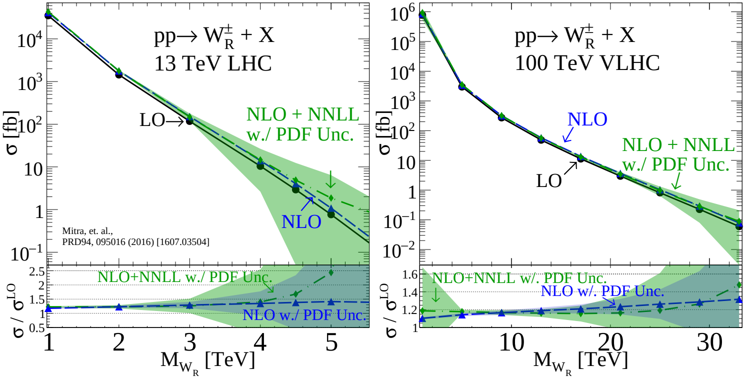
[6] See, e.g., Appell, Sterman, Mackenzie ('88); Forte and Ridolffi ('03)

[7] E.g., heavy neutrino production, **RR**, Spannowsky, Waite*, PRD ('17) [1706.02298]

W_R Numerology at the Edge of Collider Phase Space[8]



At 13 TeV, corrections to production rate $> +100\%$ for $M_{W_R} \gtrsim 4.5$ TeV

- $\sigma^{LO}(M_{W_R} = 5\ \text{TeV}) \sim 0.7$ fb $\implies \sigma \times (1\ \text{ab}^{-1}) = 700$ events
- $\sigma^{NLO+NNLL} \sim 1.7$ fb $\implies \sigma \times (1\ \text{ab}^{-1}) = 1.7$k events

Assuming $\text{BR} \times \varepsilon \times \mathcal{A} = 2\% \implies N \approx 34$ events ($\sim 6\sigma$ *vs* $\sim 4\sigma$)

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[8] Mitra, **RR**, Scott*, Spannowsky, PRD ('16) [1607.03504]

Redux II: LRSM at the LHC and Beyond

Outlook

- Discovery at Run II or elsewhere?
- **Need**: more pheno analyses for “PS boundary” LRSM parameter space and also other models
- **Need**: “What is the dominant production mode for a sub-TeV N_R?”
- Standardization of pheno tools: adoption of robust, public software

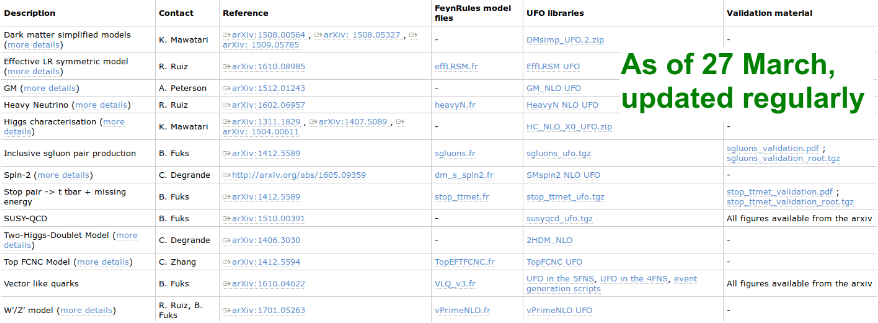
State-of-Art Event Generators

NLO+PS automated in MadGraph5aMC@NLO, Herwig, Sherpa

- All one needs NLO-accurate FeynRules input model file

Explosion past two years: [*feynrules.irmp.ucl.ac.be/wiki/NLOModels*]

- Most neutrino mass models available (just “import” and cite!)



Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	arXiv:1508.00564 , arXiv: 1508.05327 , arXiv: 1509.05785	-	DMsimp_UFO.2.zip	-
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	sgluons_validation.pdf ; sgluons_validation_root.tgz
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	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
SUSY-QCD	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
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	All figures available from the arxiv
W'/Z' model (more details)	R. Ruiz, B. Fuks	arXiv:1701.05263	vPrimeNLO.fr	vPrimeNLO UFO	-

As of 27 March, updated regularly

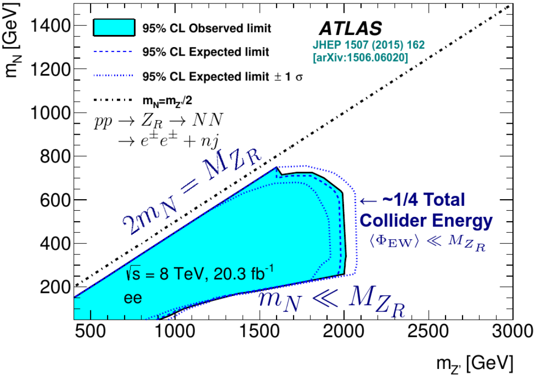
Modern general purpose MC packages are *very* sophisticated

"With great power there must also come - great responsibility"- S. Lee ('62)

Summary: An Emerging Picture of New Physics

While no confirmed **BSM** discoveries at colliders, certainly still possible

- Remaining model space is hierarchical ⇒ extrema of phase space



- Pheno for ν mass models is being *systematically rewritten*
- Sensitivity "at the edge" is pretty good; likely true for other BSM, too