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

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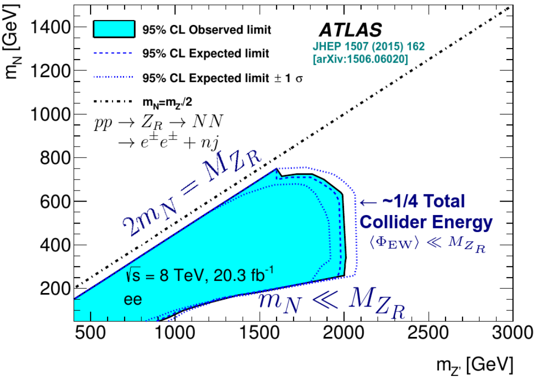
October 06, 2017

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

An Emerging Picture of New Physics Physics

The LHC is operating amazingly! $\mathcal{L} \sim 40$ fb^{-1} at 13 TeV (3-4x$\mathcal{L}_{\rm Tevatron}$)

Plotted: Excluded (m_N, M_{Z_R}) from $pp \to Z_R \to NN$ searches



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

- Remaining model space is hierarchical ⇒ extrema of phase space

Left-Right Symmetry...

When hierarchies are present, often a qualitatively different picture emerges. $\Rightarrow$ **Quantitatively**, difficult problems become simpler to solve.

- E.g., Effective Field Theory, Hadronization, Classical Mechanics

Question: Does collider pheno for neutrino mass models (Seesaws) qualitatively change for hierarchical regions of model parameter space?

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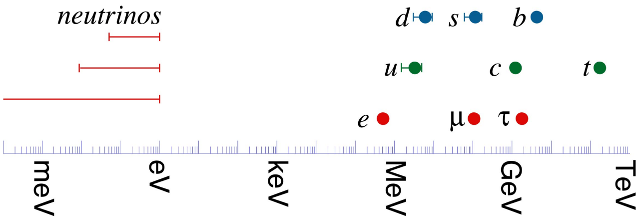
... At the Edges of Phase Space and Beyond:

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

Motivation for new physics from ν physics

Our Motivation

The SM, via the Higgs Mechanism, explains *how* elementary fermions obtain mass, i.e., the $m_f = y_f \langle \Phi \rangle$, **not** the values of m_f.



Spanning many orders of magnitudes, the relationship of fermion masses is still a mystery. Two observations:

1. Neutrinos have mass (BSM physics! !)
2. Neutrinos have unusually small mass (new physics? ?)

Collider Connection to Neutrino Mass Models (1/1)

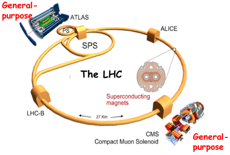
Seesaw models predict new Seesaw particles of all shapes, spins, and color:

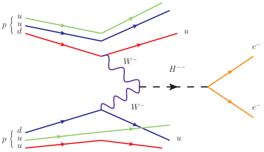
$$N \text{ (Type I)}, \ T^{0,\pm} \text{ (Type III)}, \ Z_{B-L}, \ H_R^{\pm,\pm\pm} \text{ (Type I+II)}, \ \ldots$$

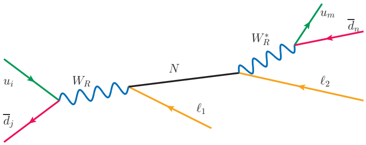
Through gauge couplings and mixing, production in *ee*/*ep*/*pp* collisions

$$\textbf{DY}: q\overline{q} \rightarrow \gamma^*/Z^* \rightarrow T^+T^- \quad \text{and} \quad q\overline{q'} \rightarrow W_R^\pm \rightarrow N\ell^\pm$$

$$\textbf{VBF}: W^\pm W^\pm \rightarrow H^{\pm\pm} \qquad \textbf{GF}: gg \rightarrow h^*/Z^* \rightarrow N\nu_\ell$$

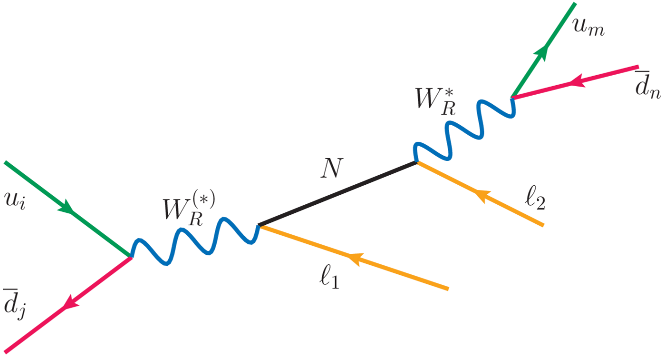






Identification of Seesaw partners is then inferred by their decays to SM particles and the associated final-state kinematics

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 symmetry:

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

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

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

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

W_R coupling to quarks is analogous to SM W_{SM} couplings:

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W^-_{R\mu} \sum_{q=u,d,...} [\overline{d_j}\ V^{CKM'}_{ij}\ \gamma^\mu P_R u_i] + \text{H.c.}$$

In **chiral/gauge** basis, couplings to leptons is given by:

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W^-_{R\mu} \sum_{a=1}^{3} [\bar{l}^a \gamma^\mu P_R \underbrace{N^a_R}_{Note:\ |N_R\rangle = X|\nu_m\rangle + Y|N_{m'}\rangle}] + \text{H.c.}$$

This is not a practical basis to use.

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In **mass** basis, coupling to leptons can be generically parametrized as[2]:

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W^-_{R\mu} \sum_{\ell=e}^{\tau}\ \overline{\ell}\gamma^\mu P_R \underbrace{\left[\sum_{m=1}^{3} \underbrace{X_{\ell m}}_{\mathcal{O}(m_\nu/m_N)}\ \nu_m + \sum_{m'=4}^{6} \underbrace{Y_{\ell m'}}_{\mathcal{O}(1)} N_{m'}\right]}_{Note:\ |N_R\rangle = X|\nu_m\rangle + Y|N_{m'}\rangle} + \text{H.c.}$$

[2] Atre, Han, Pascoli, Zhang [0901.3589]; Han, Lewis, **RR**, Si [1211.6447]

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Benchmark: Simply consider only the lightest $N \equiv N_{m'=4}$ and that the N mass state is aligned with $\ell = e$ flavor state, i.e., $|Y_{eN}| = 1$.

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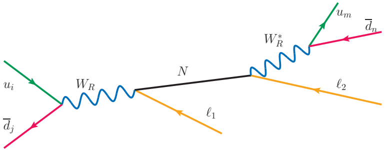
- $W_R \to Ne$ decay rate is BR $\approx 10\%$ for $M_{W_R} \gg m_N$ (90% to quarks)
- $N \to W_R^{*\pm}\ell^\mp \to \ell^\mp q\overline{q'}/tb$ are dominant decay channels with BR $\approx 100\%$



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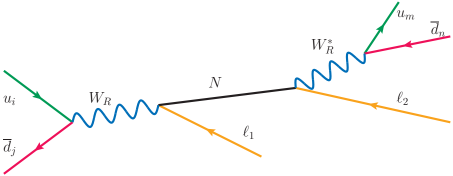
Hallmark LRSM collider signature is the spectacular same-sign lepton pairs:

$$q\overline{q'} \to W_R^\pm \to N\ell_1^\pm \to \ell_1^\pm \ell_2^\pm q'\overline{q}$$



Proposed by Keung & Senjanovic ('83) and basis for most Seesaw searches

- $W_R^\pm$ is heavy[4]. If kinematically accessible, s-channel $q\overline{q'} \to W_R^\pm$ production rate is largest at LHC
- *L*-**violating process**! $\Rightarrow$ Majorana nature of ν [Black Box Theorem]
- $W_R^* \to q'\overline{q}$ allows for full reconstruction of kinematics/properties
- High-p_T $\ell^\pm$ without light ν $\Rightarrow$ no transverse mom. imbalance (**MET**)

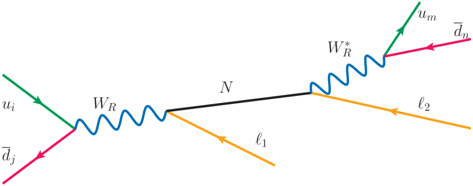
[4] ATLAS [1506.06020; 1512.01530] and CMS [1407.06020; 1512.01224]

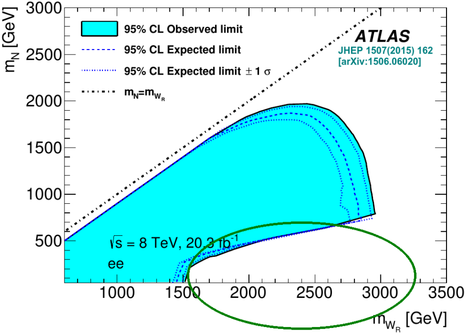
8 TeV LHC Exclusion with $\mathcal{L} \approx 20$ fb^{-1}

LHC expts have performed remarkably!

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

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





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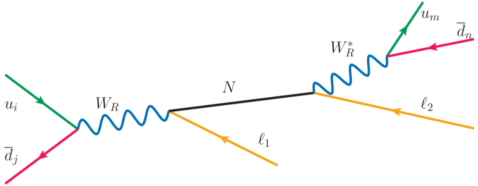
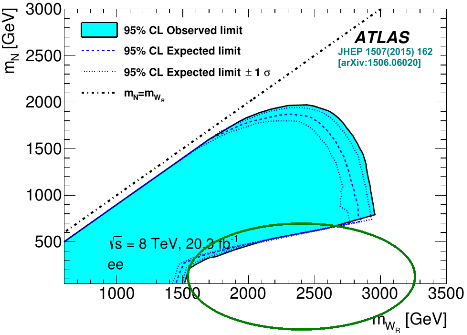


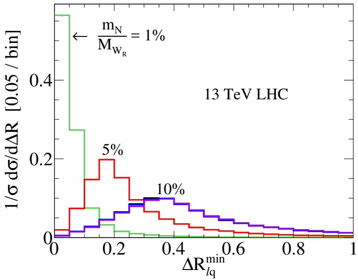


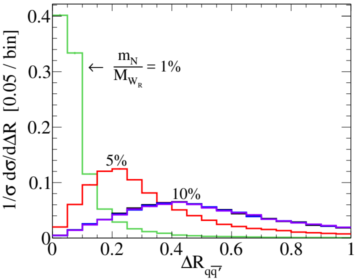
Similar sensitivity to searches for $pp \to Z_R \to NN \to e^{\pm}e^{\pm} + nj + X$

$\Longrightarrow$ 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 $pp \to W_R \to \ell^\pm N(\to \ell^\pm q\overline{q'})$





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

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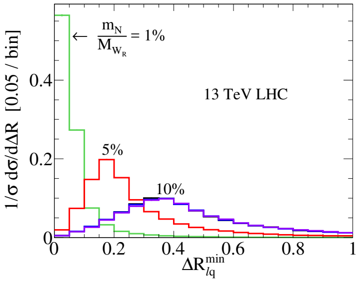

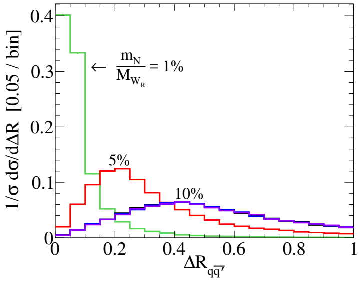

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$\Rightarrow \Delta R_{ij} \sim \frac{m_N}{\sqrt{E_iE_j}} \sim \frac{4m_N}{M_{W_R}} \Rightarrow$ For $\left(\frac{m_N}{M_{W_R}}\right) < 0.1, \Delta R_{\ell X}^{\min} = 0.4$ iso. req. fails

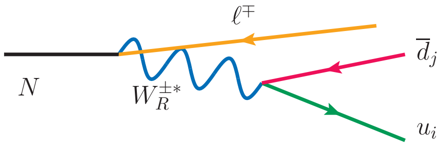
K&S process $pp \to \ell^\pm\ell^\pm jj + X$ contains two same-sign charged leptons
- S/B power comes from high-p_T leptons without accompanying MET

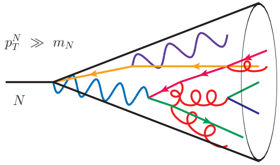
Question: Is it necessary to identify the second lepton or jet multiplicity?

Neutrino Jets[5] (n):

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

(ii) a fat jet originating from a heavy neutrino

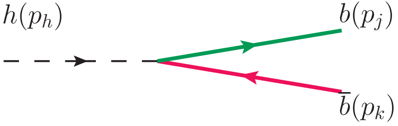




[5] A. Ferrari, et, al, PRD ('00); Mitra, **RR**, Scott*, Spannowsky, PRD ('16) [1607.03504]; Mattelaer, Mitra, **RR** [1610.08985]

Jet Structure and Substructure

Consider the Higgs decay $h \to b\overline{b}$ with $p_h = p_j + p_k$ and $z = E_j/E_h$.



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$$\to \Delta R_{jk} \sim \theta_{jk} = \frac{m_h}{\sqrt{z(1-z)}E_h} = \frac{2m_h}{E_h}$$

In $1 \to 2$ *decays* we have $z = (1-z) = 0.5 \implies \frac{1}{\sqrt{z(1-z)}} = 2.$

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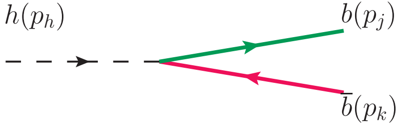

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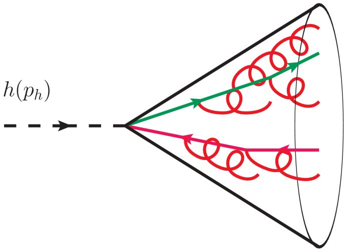
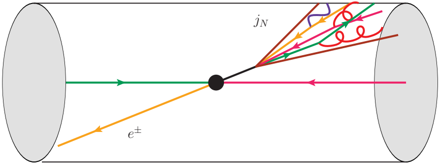


Collimated objects are difficult to resolve.

Solution: Instead of treating decay products as individual objects, consider them as a single object, a *Higgs jet*.

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[6]



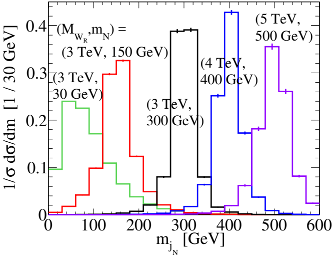
Changing scales *simplifies* the problem, a lot:

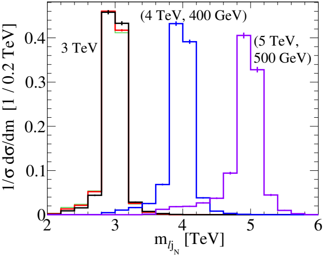
For $m_N \ll M_{W_R}$, one has a different collider topology:

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

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

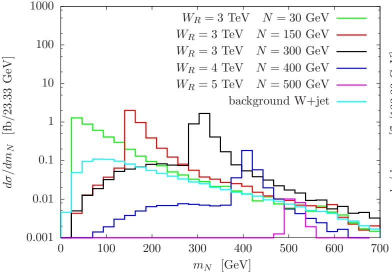
At parton-level + smearing, expected invariant mass peaks are visible:

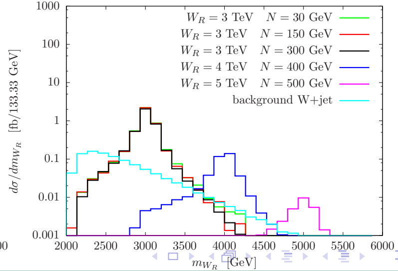




QCD corrections do not change this; oddly, exhibits “ideal” jet behavior

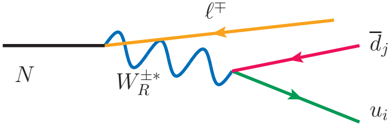
With parton shower + P.U. + detector simulation, structures are retained:

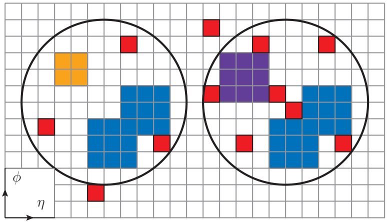




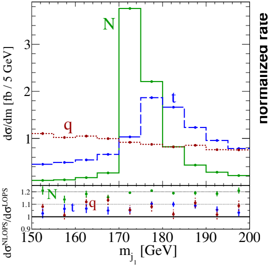
Neutrino jets inherently contain less QCD radiation than top jets

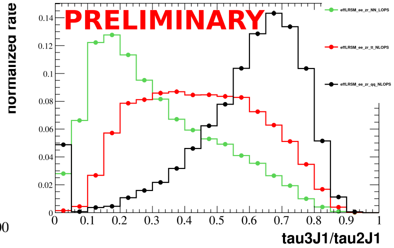
- Prongs within a jet are more likely to be resolved





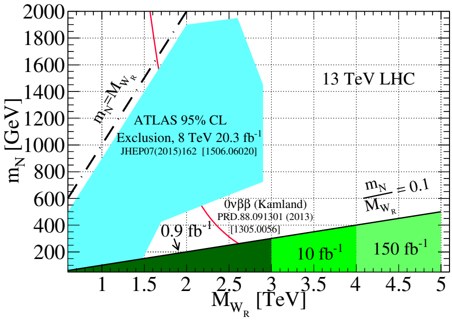
Retain resonant structure and substructure more ideally than top jets:

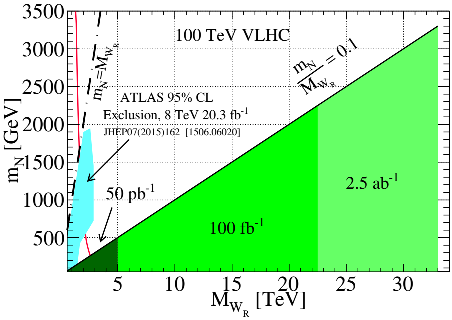




Discovery Potential at the Edge of Phase Space

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





Signature: $pp \to \ell^{\pm} + j_{\rm Fat} + X$ [no MET, $p_T^{\ell,j} \gtrsim 1$ 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:

Left-Right Symmetry Beyond the Edge of Phase Space:

A pathological but plausible scenario.

Limits on neutral flavor changing transitions require[7] 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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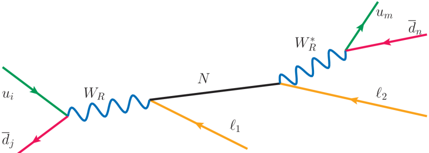
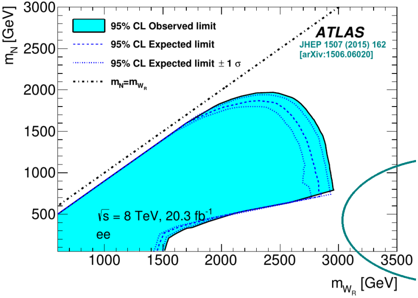
Data may be suggesting EW-scale N but kinematically inaccessible W_R, Z_R





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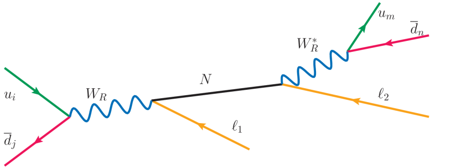

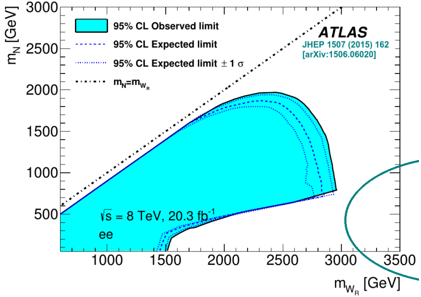

Searches follow Keung & Senjanovic ('83), and assume resonant W_R, N

- Zero 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?

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

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

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

Interestingly, in the limit that $M_{W_R} \gg \sqrt{\hat{s}}$ but $m_N \lesssim \mathcal{O}(1)$ TeV,
$pp \to N\ell + X$ production in the LRSM and "Type I" are indistinguishable[8]

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

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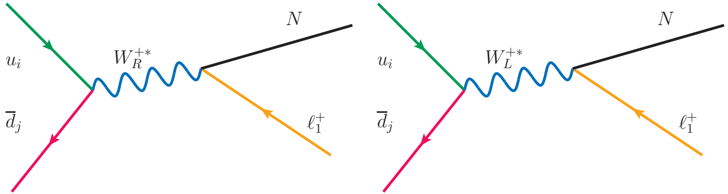

- Occurs near threshold $\sqrt{\hat{s}} \sim m_N$ and same $\ell_1^\pm$ polarization
- Differentiation requires polar and azimuthal polarization measurements of the full $pp \to \ell^\pm \ell^\pm + nj + X$ final state

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L Violation from Beyond the Edges of Phase Space[9]

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

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

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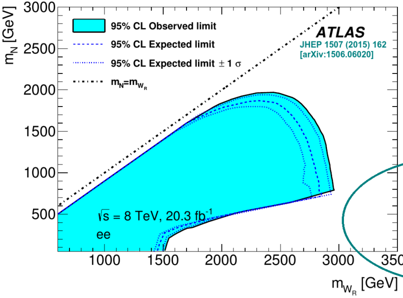

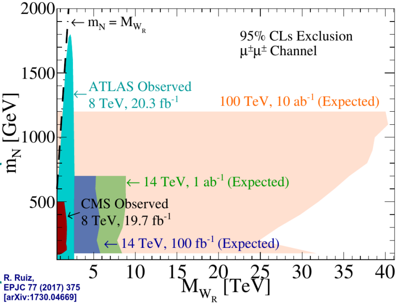

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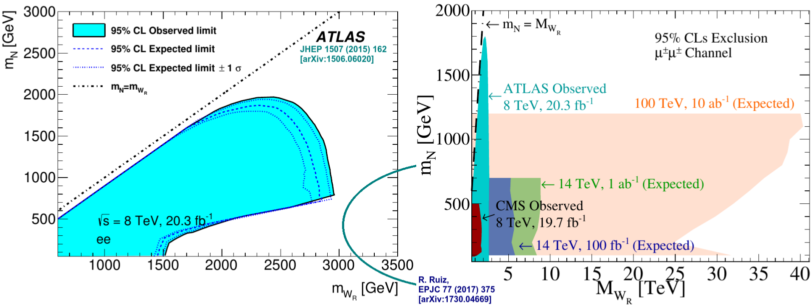

At 14 (100) TeV with $\mathcal{L} = 1$ (10) ab^{-1}, $M_{W_R} \lesssim 9$ (40) TeV can be probed

- Caveat: Numbers can be improved with (a) dedicated analysis (not reinterpretation) and (b) knowledge of 100 TeV detector definition

[9] **RR**, EPJC ('17) [1703.04669]

Redux I: Back to Edges of the LHC Phase Space

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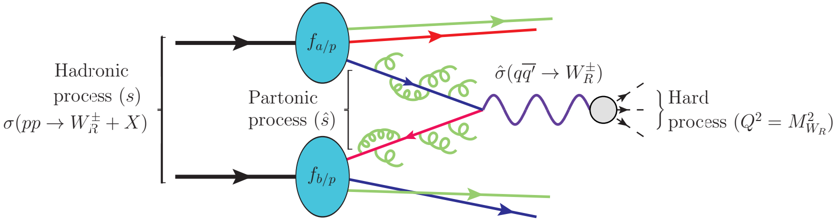
Can you see $M_{W_R} \gtrsim 5$ TeV?

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



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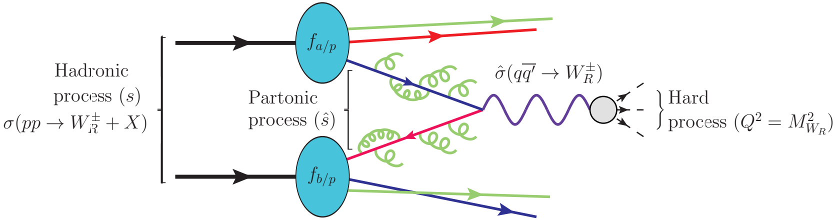

Away from phase space boundaries,

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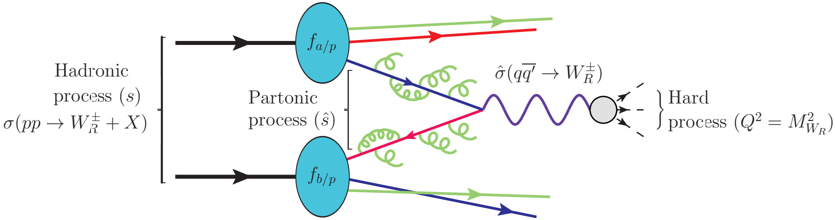

Away from phase space boundaries,QCD corrections are 20-30%.

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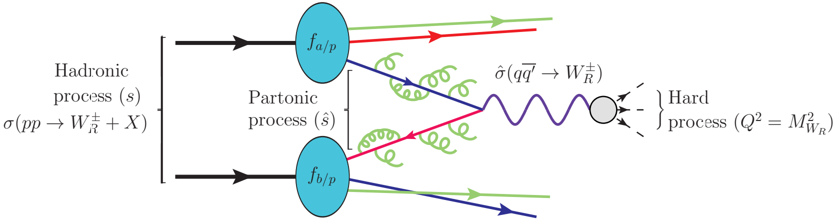

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However, ***near*** boundaries, where $E_g \ll E_q$,

$$\sigma(pp \to W_R + g) \sim \int d^{4-2\varepsilon} PS_2 \sim \lambda^{\frac{1-2\varepsilon}{2}} \left(1, \frac{Q^2{=}M_{W_R}^2}{\hat{s}}, \frac{k_g^2{=}0}{\hat{s}}\right)$$

$$= \left(1 - \frac{M_{W_R}^2}{\hat{s}}\right)^{1-2\varepsilon} \sim 2\varepsilon \log\left(1 - \frac{M_{W_R}^2}{\hat{s}}\right)$$

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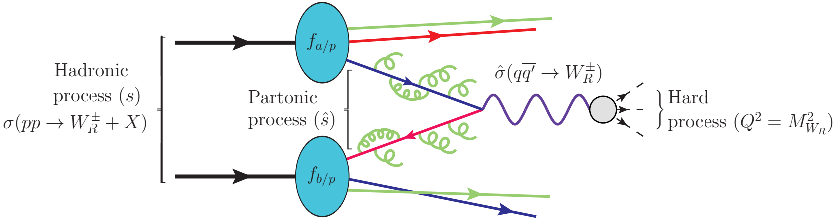

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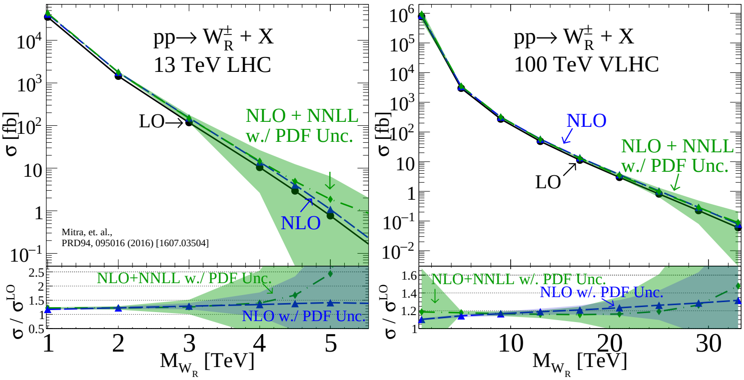
As $M_{W_R}^2 \to s$, logs diverge since $M_{W_R}^2 \to \hat{s} < s$ forces ${\color{red}g}$ to be soft.
In this limit, **soft factorization** & **exponentiation** possible!
$\Rightarrow$ All-orders (re)summation of $\alpha_s \log(1 - M^2/\hat{s})$



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

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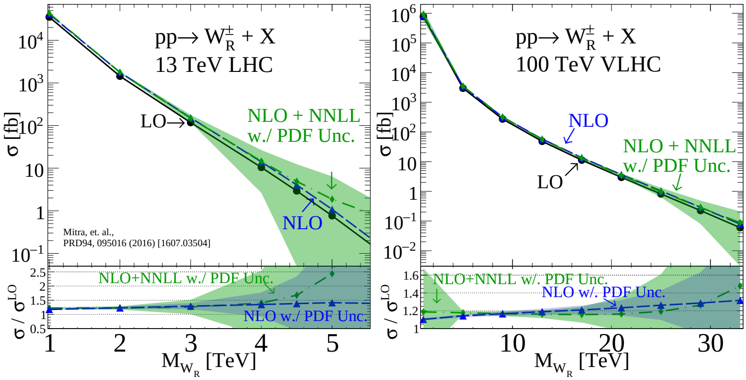
W_R Numerology at the Edge of Collider Phase Space[10]



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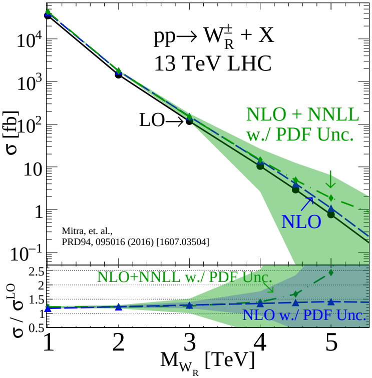

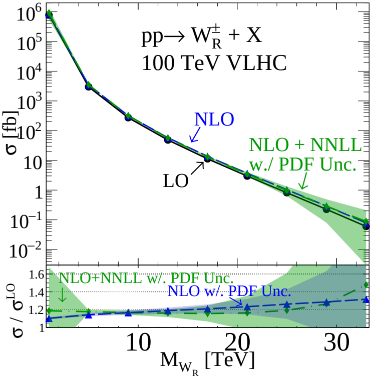

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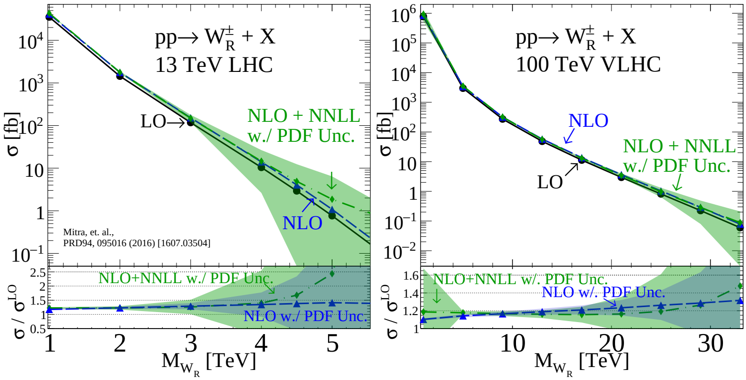

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Assuming $\text{BR} \times \varepsilon \times \mathcal{A} = 2\% \implies N \approx 34$ events ($\sim 6\sigma$ *vs* $\sim 4\sigma$)

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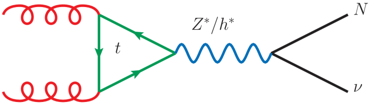
Q: Are high-mass $W_R,\ Z_R$ unique in this respect?

Heavy N at the Edge of Partonic Phase Space[11]

For $gg \to N\nu$, large loops and radiation near "partonic threshold" drives $Q^2 \to \hat{s}$ dynamically
$\Rightarrow$ large increase $(2-3\times)$ in production rate



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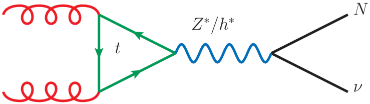

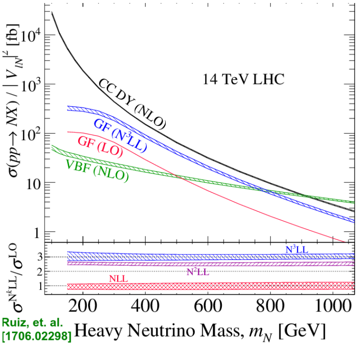

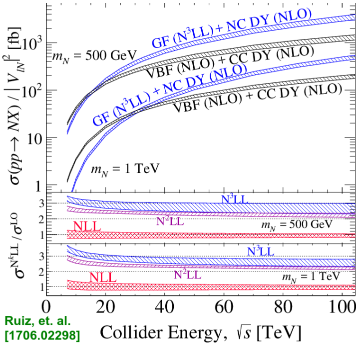

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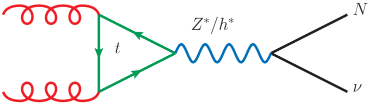

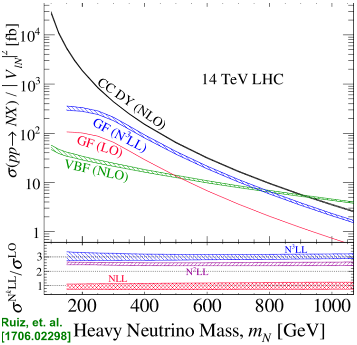

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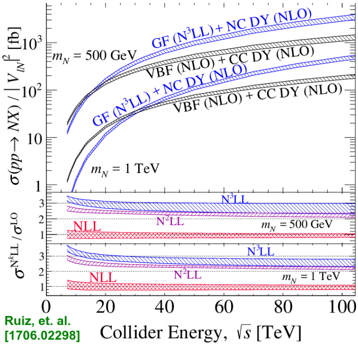

Ruiz, et. al. [1706.02298]

- At LHC, $\sigma^{\rm GF} \sim \sigma^{\rm DY} \gg \sigma^{\rm VBF} \implies \mathcal{O}(1)$ improvement in sensitivity
- For any (proposed) future pp collider, $\sigma(N\nu) > \sigma(N\ell)$!

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Redux II: Beyond

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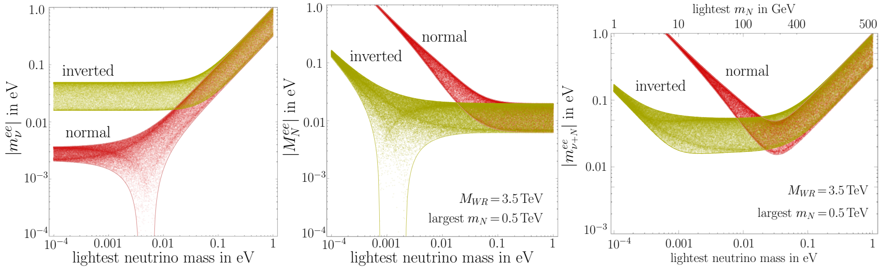
An outlook of Left-Right Symmetry beyond LHC Run II

Complementarity to Low Energy Expts

LRSM extremely far reaching in its impact:

- Eg. flavor-changing neutral transitions via Higgs mediation[12]
- Counterexample of naive picture of neutrinoless double beta decay[13]



(L) Canonical description, (C) RH currents, (R) LH+RH currents

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[12] Chakrabortty, et al [1204.0736]; Bertolini, et al [1403.7112]; Maiezza et al [1407.3678]

[13] E.g., Tello, Nemevsek , Nesti, Senjanovic, Vissani [1011.3522]

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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)

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[14] **RR**, Neutrino Platform Kickoff Mtg [CERN, 27-31 March]

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- **Long-term**:$\mathcal{L} = 3 - 5$ ab^{-1} of LHC + 50 ab^{-1} of Belle 2 data
  - Discovery?
- **Long-long-term**:

[14] **RR**, Neutrino Platform Kickoff Mtg [CERN, 27-31 March]
[15] K. Fuji, Linear Collider '17 Mtg [CERN, 7-9 June]

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  - ILC-250/380: Expected update[15] Sept '17 at JPS + summer '18
  - European Strategy for Particle Physics '19-'20
  - Chinese Five-Year Plan '20-'25
- **Long-term**:$\mathcal{L} = 3 - 5$ ab^{-1} of LHC + 50 ab^{-1} of Belle 2 data
  - Discovery?
- **Long-long-term**:Outcome of **near-term** choices. Many discoveries?

[14] **RR**, Neutrino Platform Kickoff Mtg [CERN, 27-31 March]

[15] K. Fuji, Linear Collider '17 Mtg [CERN, 7-9 June]

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[16] Meizza, et al [1503.06834]; Gluza, et al [1604.01388]; **IPPP** [many]

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Remember: "The LHC is planned to run over the next 20 years, with several stops scheduled for upgrades and maintenance work." [press.cern]

- High-Luminosity LHC and Belle II goals: 1-5 ab^{-1} and 50 ab^{-1}
- Premature to claim "nightmare scenario" (SM Higgs + nothing else)

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Thank you.