Neutrino Jets from High-Mass W_R Bosons [1]

IHEP

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[1] with Manimala Mitra, Darren Scott, and Michael Spannowsky [1607.03504]

The Plan

I would like to...

- motivate Beyond Standard Model physics from a neutrino perspective
- introduce the Left-Right Symmetric Model and demonstrate the breakdown of current search strategies
- introduce neutrino jets
- address threshold corrections to inclusive W_R production at (V)LHC
- present (V)LHC discovery potential, summarize, and then conclude

The Standard Model of Particle Physics

SM: A successful and complete theory that describes how matter and energy function at scales where $\hbar c \sim 200$ MeV-fm is sizable.

Consists of several spacetime and internal symmetries:

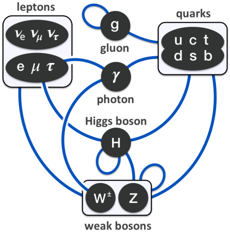
Lorentz, color, weak isospin, and weak hypercharge,

and several fields possessing these symmetric transformations:

$$L^i, Q^{i\alpha}; u_R{}^{i\alpha}, d_R{}^{i\alpha}, e_R{}^i; \Phi.$$

Impose local invariance ($\partial_\mu \to \partial_\mu + igA_\mu$), break with $\langle\Phi\rangle = v/\sqrt{2}$.

During electroweak (EW) symmetry breaking (EWSB), anything coupling directly to the Higgs field acquires a spontaneously generated mass proportional to this interaction strength.



Note: In SM, ν are massless

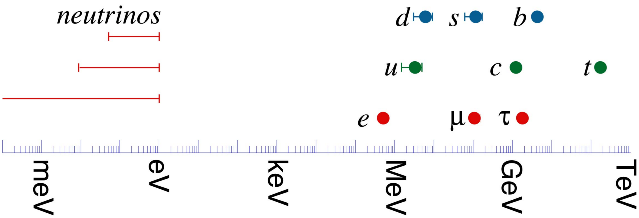
So, neutrinos have masses $\lesssim \mathcal{O}(0.1)$ eV.

Is this a problem?

Maybe.

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?)

Seesaw Mechanisms: pathways to naturally small m_ν

Seesaw Mechanisms: Pathways to Naturally Small m_ν

Spinor/gauge algebra + renormalizability restrict ways to construct m_ν [Ma'98]

"Type 0": Add N_R with $y_\nu \sim 10^{-12}$ and forbid Majorana mass

- Certainly possible but such small y_ν is theoretically unsatisfying

Type I: Add N_R and allow a Majorana mass term

- $\mathcal{L} \ni \ -y_\nu \overline{L}\tilde{\Phi}N_R \ - \ \frac{m_R}{2}\overline{N_R{}^c}N_R \implies \ m_\nu \propto m_D^2/m_R, \quad m_D = y_\nu\langle\Phi\rangle$

Type II: Add scalar $SU(2)_L$ triplet ($\Delta^{0,\pm,\pm\pm}$) - **No N_R required**

- $\mathcal{L} \ni \ y_\Delta \overline{L}(i\sigma_2)\Delta L^c \implies \ m_\nu \propto y_\Delta\langle\Delta\rangle\overline{\nu^c}\nu, \quad \langle\Delta\rangle <$ few GeV

Type III: Add fermion $SU(2)_L$ triplet ($T^{0,\pm}$)

- $\mathcal{L} \ni y_T \overline{L} T^a \sigma^a (i\sigma^2)\Phi \ + \ \frac{m_T}{2}\overline{T^{0c}}T^0 \implies \ m_\nu \propto m_D^2/m_T$

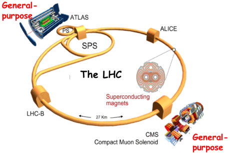
Less Minimal Models: Hybrid, Inverse, Radiative, ..., all with rich pheno

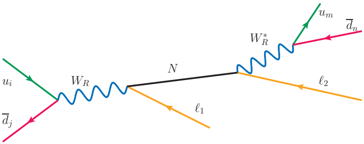
Collider Connection to Seesaw Models

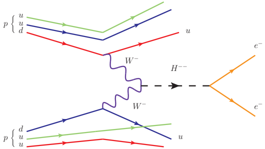
Through SM interactions and mixing, Seesaw models *predict* production of Seesaw partners, e.g., N_R, Z_{B-L}, in $ee/ep/pp$ collisions[2]

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

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







- If heavy states are kinematically accessible at a given collider energy
- Sizable interactions strength (coupling might be suppressed by mixing)

Then direct, on-shell production of Seesaw particles at colliders is possible

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[2] Many processes cataloged and compared in [hep-ph/9311257] and [1602.06957]

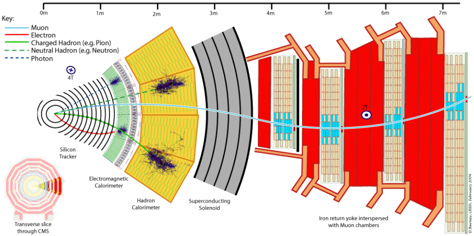
Collider Connection to Seesaw Models

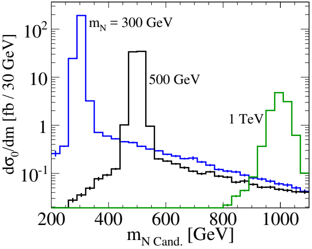
Seesaw partners then decay via charged and neutral currents, etc., to SM particles that are observed/inferred by detector subsystems

$$T^{\pm} \to W^{\pm}\nu,\ Z\ell^{\pm},\ h\ell^{\pm},$$

$$N/T^{0} \to W^{\pm}\ell^{\mp},\ Z\nu,\ h\nu,$$

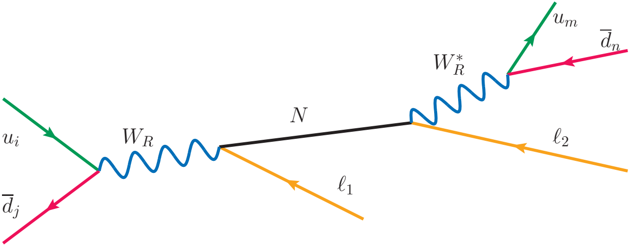
Identification of Seesaw partners is possible through reconstruction of final-state kinematics, e.g., invariant mass peaks and angular distributions





Left-Right Symmetric Models

at Hadron Colliders



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

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

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

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

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

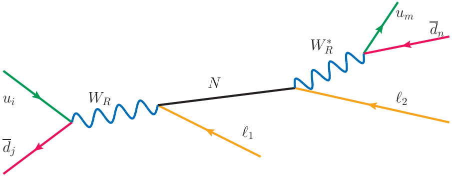
Neutrinos obtain LH (RH) Majorana masses from triplet scalar Δ_L (Δ_R):

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

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

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[3]. If kinematically accessible, s-channel $q\overline{q'} \to W_R^{\pm}$ production is the best/largest LHC mechanism
- N must also be heavy to trigger Seesaw. $W_R^{\pm} \to N\ell^{\pm}$ is least constrained by phase space (v.s. t-channel N exchange).
- $W_R^{*} \to q'\overline{q}(jj)$ allows for full reconstruction of kinematics.
- Violates L! "Smoking-gun" for Majorana behavior and $m^{\nu}_{\ell_1\ell_2} \neq 0$!

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

Properties of W_R and N when $M_{W_R} \gg m_N$

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

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

Coupling/mixing to leptons can be parametrized generally[4] as:

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

For simplicity, we consider only the lightest N and assume maximal mixing with $\ell = e$ (equally applicable to μ or nontrivial $e - \mu$ mixing).

- $W_R \to Ne$ branching fraction is 10% for $M_{W_R} \gg m_N$
- $N \to W_R^{*\pm} \ell^\mp \to \ell^\mp q\overline{q'}/tb$ are the dominant decay modes, so $\approx 100\%$

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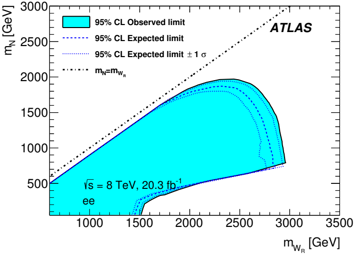
[4] Atre, Han, Pascoli, Zhang [0901.3589]; Han, Lewis, RR, Si [1211.6447]

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

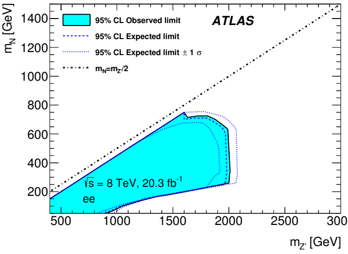
LHC experiments have performed remarkably!
Limits on on LRSM in SS channel reach up to [1506.06020]

$$M_{W_R} \gtrsim 3\ \text{TeV and } m_N \gtrsim 2.4\ \text{TeV}$$

Complimentary dijet searches give comparable M_{W_R} limits [1512.01530].
CMS SS [1407.06020] and dijet [1512.01224] results similar.



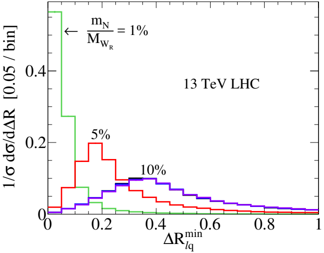
$$pp \to W_R \to N e^\pm \to e^\pm e^\pm 2j$$



$$pp \to Z_R \to NN \to e^\pm e^\pm 4j$$

Note the gapping holes for $m_N \ll M_{W_R},\ M_{Z_R}$.

Failure of Isolation Criterion in $pp \to W_R \to \ell^\pm N(\to \ell^\pm q\overline{q'})$



$$\Delta R_{ij} \sim \frac{2p_T^{\perp(ij)}}{p_T^N} \sim \frac{2m_N}{(M_{W_R}/2)} \implies \left(\frac{m_N}{M_{W_R}}\right) < 0.1 \quad \text{iso. fails for } \Delta R^{\min}_{\ell X} = 0.4$$

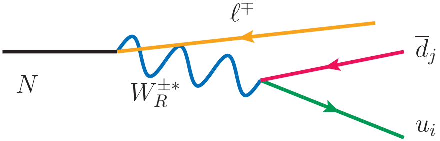
K&S process $pp \to \ell^\pm\ell^\pm jj + X$ contains two same-sign charged leptons
- SS selects types of background, e.g., $W^\pm W^\pm jj$ and $t\bar{t}W^\pm$
- S/B power comes from high-p_T leptons without accompanying MET

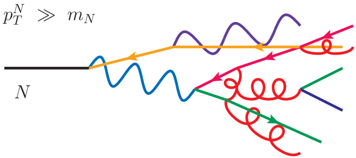
Question: Is it necessary to identify the second lepton or jet multiplicity?
- For properties, yes! For discovery? ... maybe not.

Neutrino Jets (n):

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

(ii) a fat jet originating from a heavy neutrino

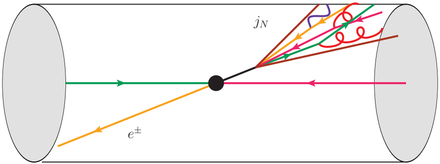




Neutrino Jets in LRSM

Lets treat $\ell_2^\pm$ as we would any other poorly separated parton bathed in radiation: cluster it via a sequential jet algorithm (Cambridge/Aachen)

- For partons ij, calculate their "distance" measure[5] $d_{ij} = \min(p_T^i, p_T^j)^{(2p)} \Delta R_{ij}^2 / R^2$, where $p = \pm 1, 0$ for (anti-)k_T, or C/A
- For parton i, calculate distance measure w.r.t. to beam $d_{iB} = {p_T^i}^{(2p)}$
- If d_{iB} is smallest, call a jet; else, merge (i,j) momenta and restart



For $m_N \ll M_{W_R}$, we propose a new collider search

$$pp \rightarrow W_R \rightarrow e^\pm N \rightarrow e^\pm j_{\rm Fat}$$

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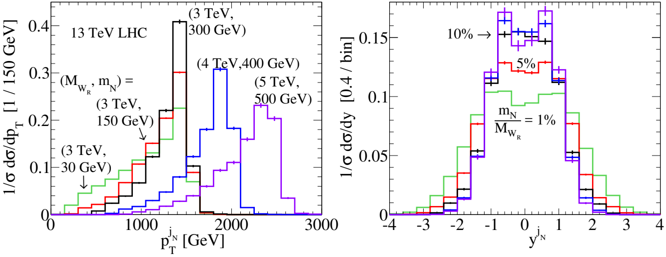
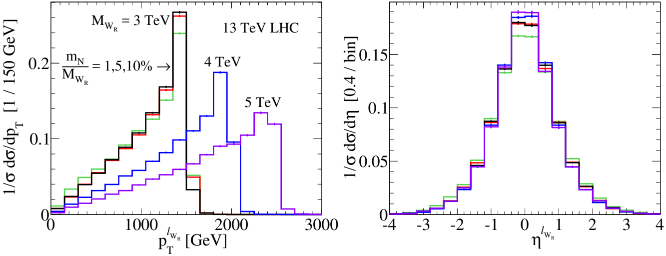
[5] Origin of d_{ij}: for $p = 1$ (k_T), d_{ij} approximates inv. mass of parent near poles

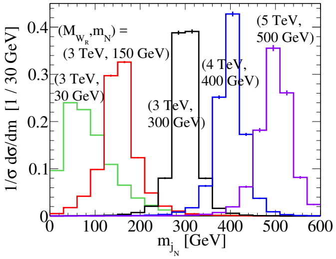
First sanity check: Up to mass effects, kinematics of j_N:



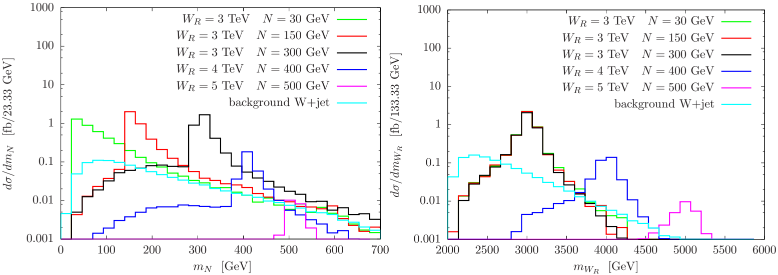
match the kinematics of $\ell^{\pm}_{W_R}$ (the charged lepton from the W_R decay):



At parton-level + smearing, expected resonant structures are visible:

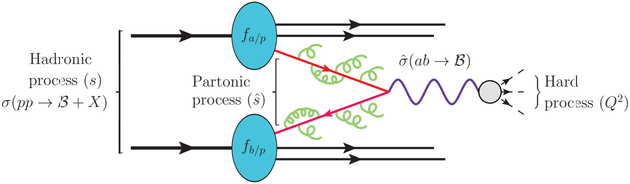


With parton shower + P.U. + detector simulation, structures are retained:



W_R Production at Hadron Colliders

Inclusive W_R production is identical to $W_{\rm SM}$, except $M_{W_R} \gtrsim 3-4$ TeV.



Away from phase space boundaries, QCD corrections for DY-systems are 20-40% (and somewhat trivial[6]). However, each radiation gives new logs

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

In particular, for hard process scale $Q^2 = M_{W_R}^2$, as $M_{W_R}^2 \to s$, logs explode since $M_{W_R}^2 \to \hat{s} < s$ forces radiation g to be *soft*.

In this limit, **soft factorization** is justified and logs can be **resummed**!

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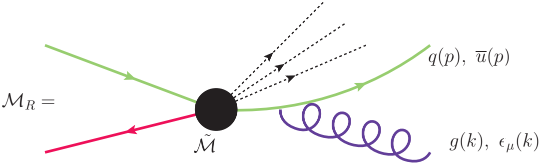
[6] See e.g., Z. Sullivan ('02)

Soft Factorization in Gauge Theories

Factorization in gauge theories is where a radiation amplitude $\mathcal{M}_R$ in certain kinematic limits can be written as the no-radiation amplitude $\mathcal{M}_B$ and a **universal**, i.e., process-independent, piece:



For radiation $q^*(p+k_g) \to q(p) + g(k_g),\ E_g \ll E_q$, the amplitude is

$$\mathcal{M}_R \equiv \overline{u}(p)\epsilon^*_\mu(k)(ig_s T^A)\gamma^\mu \frac{(\not{p}+\not{k}_g)}{(p+k_g)^2}\cdot\tilde{\mathcal{M}} \approx (ig_s T^A)\overline{u}(p)\frac{\epsilon^*_\mu\gamma^\mu\not{p}}{(2p\cdot k_g)}\cdot\tilde{\mathcal{M}}$$

Anti-commute and applying Dirac Eq. gives us

$$\mathcal{M}_R = (ig_s T^A)\ \overline{u}(p)\cdot\frac{(p^\mu\epsilon^*_\mu)}{(p\cdot k_g)}\cdot\tilde{\mathcal{M}} = \underbrace{(ig_s T^A)\frac{p^\mu\epsilon^*_\mu}{(p\cdot k_g)}}_{\text{Process independent}}\cdot\mathcal{M}_B$$

Soft Threshold Resummation and Sudakov Factors

Exploiting *inclusivity*, it is possible to safely account for threshold radiation.

$$\mathcal{M}^{\rm FO}_{\rm DY+1\ soft\ radiation} = \underbrace{(ig_s T^A)\frac{p_g\cdot\varepsilon^*}{(p\cdot k_g)}}_{\rm universal\ factor} \times \mathcal{M}^{\rm FO}_{\rm DY}$$

The squaring, averaging, looping, and phase space decomposition-ing gives

$$\sigma^{\rm FO}_{\rm DY+1\ thresh.} = \int dPS_2(\text{universal piece})\Big|_{\rm thresh.} \times \sigma^{\rm FO}_{\rm DY}$$

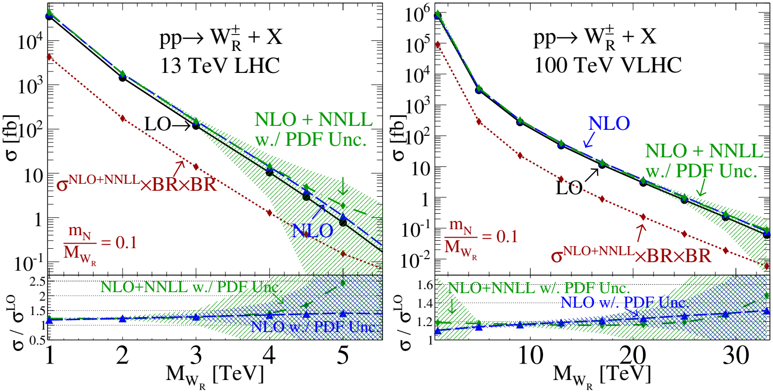
Keeping track of symmetry factors lets us do this for *k*-emissions:

$$\sigma^{\rm FO}_{\rm DY+k\ thresh.} = \frac{1}{k!}[\underbrace{\int dPS_2(\text{universal piece})}_{\equiv\,\mathcal{S}}]^k_{\rm thresh.} \times \sigma^{\rm FO}_{\rm DY}$$

Summing over ***all*** soft emissions gives us a closed result:

$$\sigma^{\rm Res}_{\rm DY} \ \equiv\ \sigma_{\rm DY+any\ soft} \ =\ \exp[\mathcal{S}] \times \sigma^{\rm FO}_{\rm DY}$$

$pp \to W_R^\pm + X$ at NLO+NNLL(Thresh.)



First W_R calculation to match thresh. ME with thresh.-improved PDFs[7]!

- Threshold region $M_{W_R}/\sqrt{s} \gtrsim 0.3$ at both colliders
- At 13 TeV, resummation larger impact than NNLO for $M_{W_R} > 4.5$ TeV

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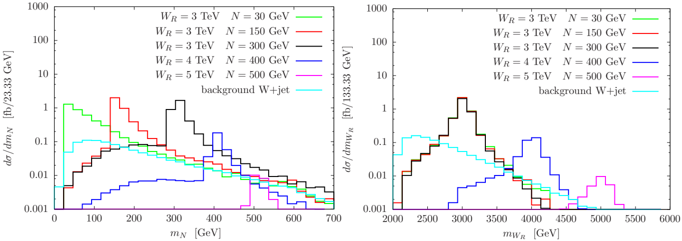
[7] NNPDF30-Thresh. [1507.01006] and case study by Beenakker, et al [1510.00375]

Discovery Potential

Setup for $pp \to e^{\pm} + j_{\rm Fat} + X$

- Manifest LRSM FeynRules model file[8] of Roitgrund, et al [1401.3345]
- Event Generation via MG5amc@NLO
  - Signal: LO$\times K^{NLO+NNLL}$ + PS(Herwig) + Detector Sim.
  - Background: NLO + PS + Det. Sim.
- After identification + fiducial + etc. criteria, apply:
  - $p_T^{\ell, j_N} > 1$ TeV
  - MET < 100 GeV (no intrinsic MET, inherited from $\ell\ell jj$)
  - $|m_{\ell, j_N} - M_{W_R}| < 200$ GeV



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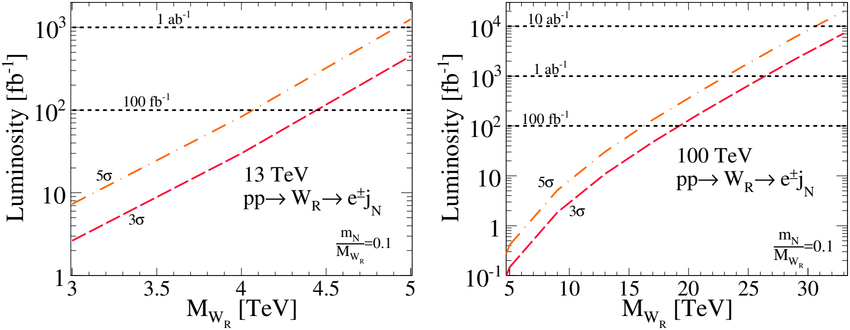
[8] See App. B of [1607.03504] and arXiv .tar.gz file for our reconfiguration files

Discovery Potential

For $m_N/M_{W_R} = 0.1$, the region where ATLAS/CMS searches breakdown:



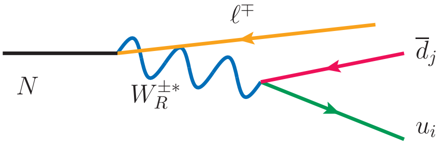
- 13 TeV: $M_{W_R} \approx 3$ (4) [5] TeV discovery after 10 (100) [2000] fb^{-1}
- 100 TeV: $M_{W_R} \approx 15$ (30) TeV discovery after 100 fb^{-1} (10 ab^{-1})

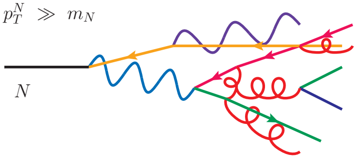
As BRs and signal definition remain largely same for (relatively) lighter N, discovery potential extends also to (relatively) lighter N

Outlook

We have introduced the concept of ***neutrino jets***:

hadronically decaying, high-p_T heavy neutrinos





They have widespread application to other processes:

- In LRSM, $pp \to Z_R \to NN \to j_N\, j_N$ possible since $M_{Z_R} > M_{W_R}$
- In other models, e.g., Inverse Seesaw, $pp \to W_{\rm SM} \to N\ell \to j_N \ell$ for $\mathcal{O}(1-5)$ GeV pseudo-Dirac neutrino
- Majorana nature may be observable via μ from t decays in $N \to \ell t b$

... and are necessary for searches of Seesaw scenarios at 13 and 100 TeV

Summary and Conclusion

The origin of tiny neutrino masses is still a puzzle and may manifest at collider experiments via the production of Seesaw partners, e.g., $W_R^{\pm}$, N.

However, LHC is now probing such large scales that pheno is qualitatively different, and requires reassessing validity of BSM collider signatures[9]

- We have introduced a new search strategy for $W_R - N$ production at hadron colliders when $m_N \ll M_{W_R}$ and find **huge** sensitivity precisely where current methodologies breakdown
- We have updated predictions (NLO+NNLL+thresh-PDF) and Scale+PDF unc. for $pp \to W_R$ in threshold regime ($M_{W_R}/\sqrt{s} \gtrsim 0.3$). Corrections and uncertainties are **large**.

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[9] See e.g., VBF in Alva, Han, RR [1411.7305] or DY+nj in RR [1509.05416]

Thank you.