Neutrino Jets from High-Mass W_R Bosons [1]

DESY

Richard Ruiz

Institute for Particle Physics Phenomenology,
University of Durham

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[1] with M. Mitra, D. Scott, and M. Spannowsky + O. Mattelaer [1607.03504; 1610.08985; 17XX.YYZZZ]

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 for inclusive W_R production at (V)LHC
- present (V)LHC discovery potential, summarize, and then conclude

Situation: It appears we may be entering a regime at LHC13 where

$$\Lambda_{BSM} \gg \langle \Phi_{EW} \rangle \gg \Lambda_{QCD}$$

At LEP, Tevatron, and LHC7/8, we were largely exploring a regime where

$$\langle \Phi_{EW} \rangle \gtrsim \Lambda_{BSM} > \Lambda_{QCD}$$

Problem: Terms from radiative processes, e.g., VBF & $+nj$, that scale as

$$\sigma(pp \to X) \sim \log \Lambda_{BSM}/\langle \Phi_{EW} \rangle \text{ and } \sim \log \Lambda_{BSM}/\Lambda_{QCD}$$

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Solution: These are issues long-understood by the pQCD community: exploit soft/collinear factorization, resummation, and IRC-safety.
From this perspective, BSM collider pheno looks **qualitatively different**.

Results focus on Seesaw partners (N, W_R) but are applicable/ necessary for other high-mass, colorless systems, e.g., $W^\pm h$, $\tilde{\ell}\tilde{\nu}_\ell$

Motivation for new physics

The Standard Model of Particle Physics

SM: A successful and complete theory that describes how matter and energy function at scales where $\hbar c \sim 0.2$ GeV-fm is sizable.

Consists of several spacetime and internal symmetries:

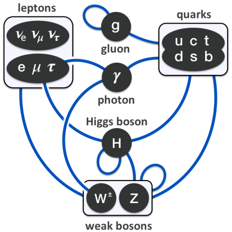
Lorentz, color, weak isospin, and weak hypercharge,

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 mass proportional to the coupling strength.



Note: In SM, ν are massless since no N_R

Nonzero Neutrino Masses is BSM Physics

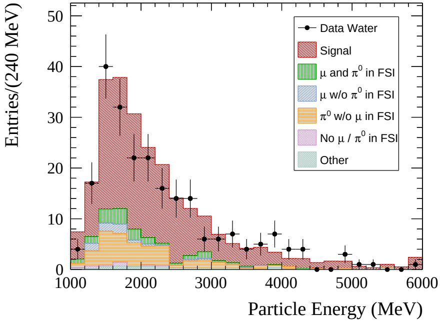
To generate ν masses similar to other SM fermions, we need N_R

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \left(\overline{\nu_L} \quad \overline{\ell_L} \right) \begin{pmatrix} 0 \\ \langle \Phi \rangle + h \end{pmatrix} N_R + H.c. \implies -m_D \overline{\nu_L} N_R + H.c.$$

$m_D = y_\nu \langle \Phi \rangle$, and y_ν is the neutrino's Higgs Yukawa coupling.

Since ${N_R}^i$ do not exist in the SM, massless neutrinos are predicted.

However, we have learned through neutrino oscillations that massless neutrinos is not an accurate description. [T2K ν_e appearance, 1503.08815v3] **[2015 Nobel Physics Prize]**



Neutrino masses is evidence of physics beyond the SM.

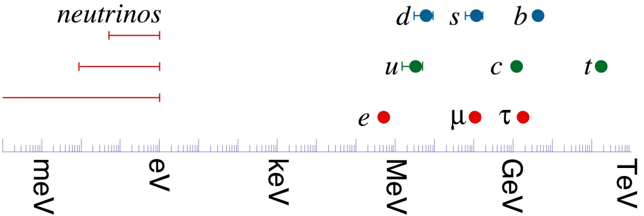
So, neutrinos have masses $\lesssim \mathcal{O}(0.1)$ eV.

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 and **2015** !)
2. Neutrinos have unusually small mass (new physics?)

Seesaw Mechanisms: pathways to naturally small m_ν

Nonzero neutrino masses implies new degrees of freedom exist:

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

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

$$m_\nu^L = y\langle\Delta\rangle \text{ or strong dynamics} \qquad m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$$

New dof might be new scalars and/or right-handed (RH) fermions

- New particles might also be charged under new gauge symmetries, e.g., (e_R, N_R) form $\text{SU}(2)_R$ doublet

Seesaw Mechanisms: Pathways to Naturally Small m_ν

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

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

- Possible, but tiny y_ν is theoretically unsatisfying

Type I: Add N_R and keep the 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 ($T^{0,\pm}$)

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

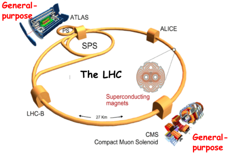
Less Minimal Models: Hybrid, Inverse, Radiative, ..., all with rich pheno

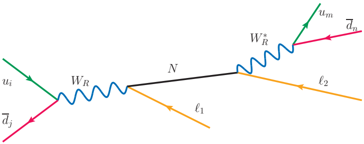
Collider Connection to Seesaw Models

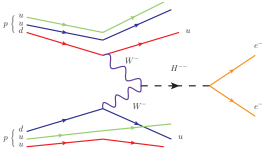
Through SM gauge couplings and mixing, Seesaw models *predict* production of Seesaw partners, e.g., N, Z_{B-L}, in $ee/ep/pp$ collisions[2]

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

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







- 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

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

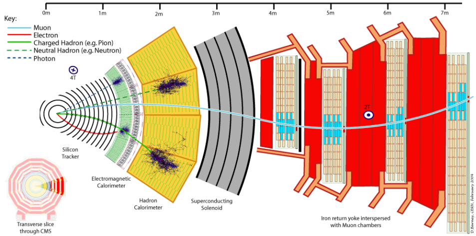
Collider Connection to Seesaw Models

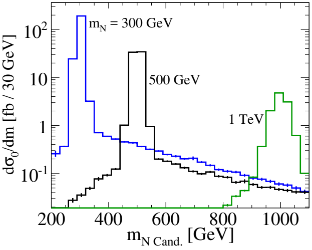
Seesaw partners then decay via charged and neutral currents, etc., to SM particles that are observed/inferred by detector subsystems

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

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

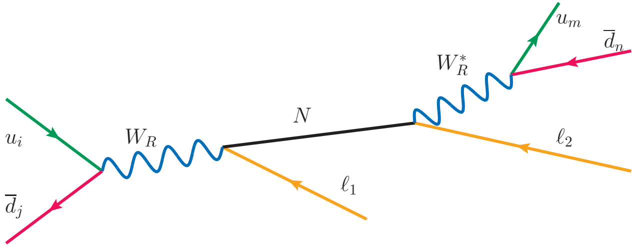
Identification of Seesaw partners is possible through reconstruction of final-state kinematics, e.g., invariant mass peaks and angular distributions





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:

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

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

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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 $H_i^{\pm\pm},\ H_j^{\pm},\ H_k^0$

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

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

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

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

However, this is not a practical basis to use.

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

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

In **mass** basis, coupling to leptons can be generically parametrized as[3]:

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

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

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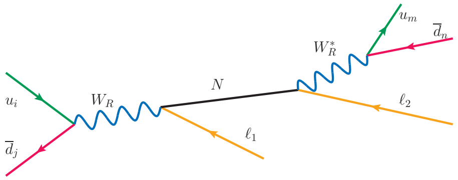
For simplicity, consider only the lightest $N \equiv N_{m'=4}$ and assume maximal $\ell = e$ mixing, i.e., $|Y_{eN}| = 1$.

- $W_R \to Ne$ 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 $\approx 100\%$

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

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:

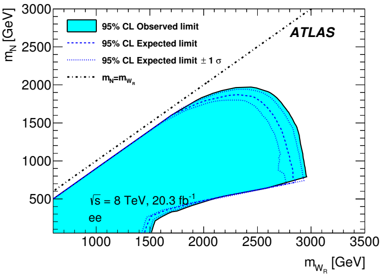
- $W_R^\pm$ is heavy[5]. If kinematically accessible, s-channel $q\overline{q'} \to W_R^\pm$ production is the best mechanism at LHC
- N decays **violate** L! "Smoking-gun" for Majorana nature/mass
- $W_R^* \to q'\overline{q}(jj)$ allows for full reconstruction of kinematics; **no MET**(!)

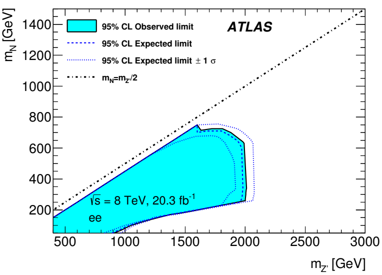
[5]ATLAS [1506.06020; 1512.01530] and CMS [1407.06020; 1512.01224]

LHC expts have performed remarkably! Limits from SS channel[6]

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

Plotted: Excluded (L) $m_{N_R} - M_{W_R}$ and (R) $m_{N_R} - M_{Z_R}$ spaces.



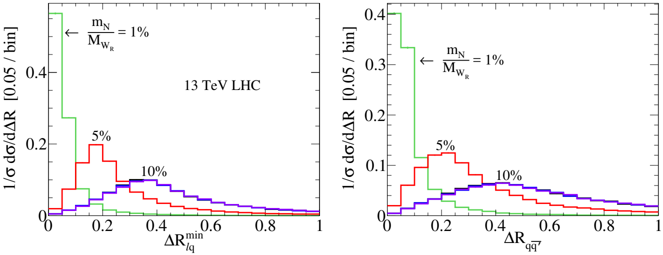


$pp \to W_R \to Ne^\pm \to e^\pm e^\pm 2j$ $\qquad$ $pp \to Z_R \to NN \to e^\pm e^\pm 4j$

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

[6] [1506.06020; 1407.06020]. Comparable limits from dijet [1512.01530; 1512.01224]

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



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

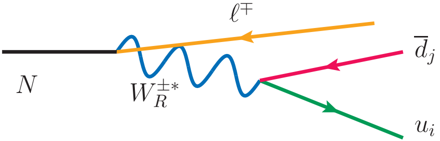
K&S process $pp \to \ell^\pm \ell^\pm jj + X$ contains two same-sign charged leptons
- SS criterion selects types of background, e.g., $W^\pm W^\pm jj$ and $t\bar{t}W^\pm$
- S/B power comes from high-p_T leptons without accompanying MET

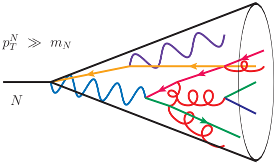
Question: Is it necessary to identify the second lepton or jet multiplicity?
- For properties, yes! For discovery? ... maybe not.

Neutrino Jets (n):

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

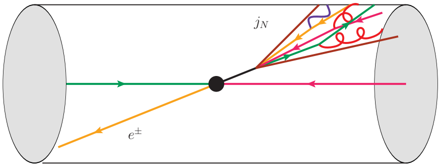
(ii) a fat jet originating from a heavy neutrino





Neutrino Jets in LRSM

Lets change scale of problem. Treat $\ell_2^\pm$ like any other poorly separated parton bathed in radiation: cluster it via a sequential jet algorithm[7]



For $m_N \ll M_{W_R}$, we consider a different collider search

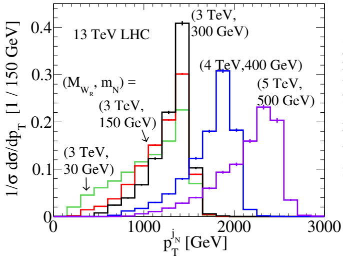
$$pp \ \rightarrow \ W_R \ \rightarrow \ e^\pm \ N \ \rightarrow \ e^\pm \ j_{\rm Fat}$$

[7] Cluster "nearest neighbors", where proximity is measured by "distance" d_{ij}

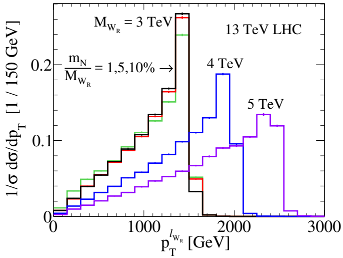
- For partons ij, calculate $d_{ij} = \min(p_T^i, p_T^j)^{(2p)} \Delta R_{ij}^2 / R^2$, where $p = \pm 1, 0$ for (anti-)k_T, or *Cambridge/Aachen* algorithms. R is desired jet radius/size
- For parton i, calculate distance measure w.r.t. to beam $d_{iB} = {p_T^i}^{(2p)}$
- If d_{iB} is smallest, call a jet; else, merge (i, j) momenta and restart

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

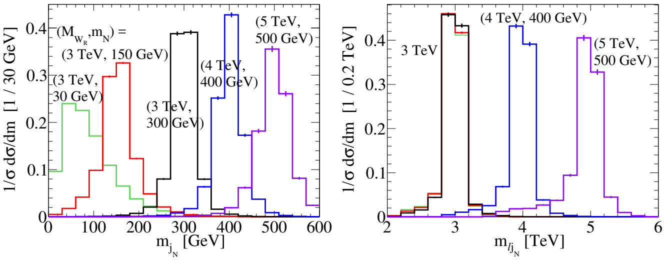
First sanity check: Up to mass effects, kinematics of j_N:



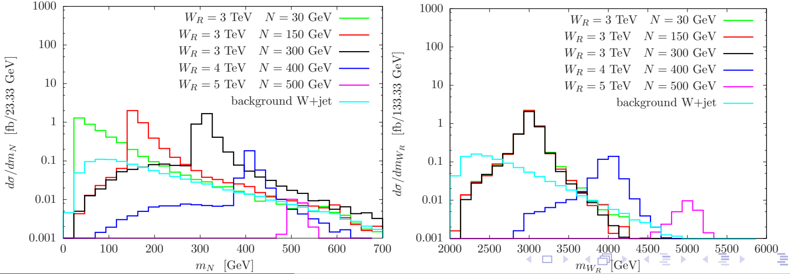
match the kinematics of $\ell^{\pm}_{W_R}$ (the charged lepton from the W_R decay):



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

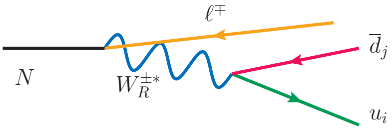


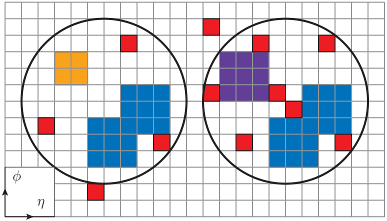
QCD corrections do not change this picture [OM,MM,**RR**; 1610.08985].
With parton shower + P.U. + detector simulation, structures are retained:



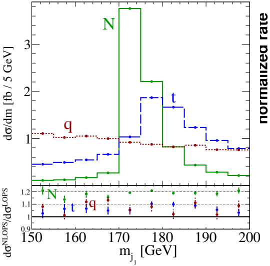
Neutrino jets inherently contain less QCD radiation than top jets

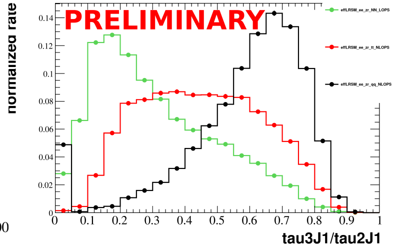
- Prongs within a jet are more likely to be resolved





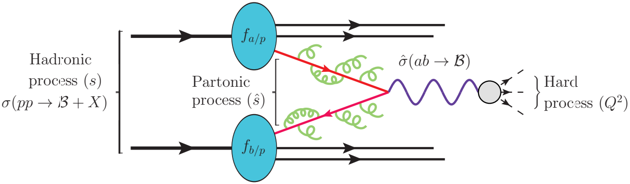
Retain resonant structure and substructure more ideally than top jets:





Production of super heavy W_R at Hadron Colliders

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



Away from phase space boundaries, QCD corrections for high-mass DY-systems are 20-40% (total and differential[8]).

[8]See, e.g., Altarelli, et al ('79); Sullivan ('02); Harris and Owens ('02); **RR** ('15)
[9]See, e.g., Sterman ('87); Catani, et al ('89,'91,'96); Forte and Ridolffi ('03)

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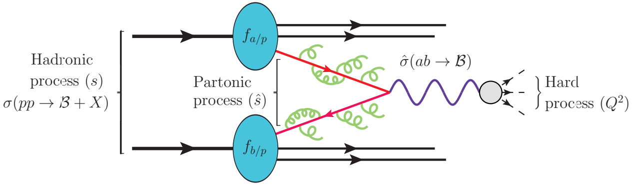

Away from phase space boundaries, QCD corrections for high-mass DY-systems are 20-40% (total and differential[8]). In $E_g \ll E_q$ limit,

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

[8] See, e.g., Altarelli, et al ('79); Sullivan ('02); Harris and Owens ('02); **RR** ('15)

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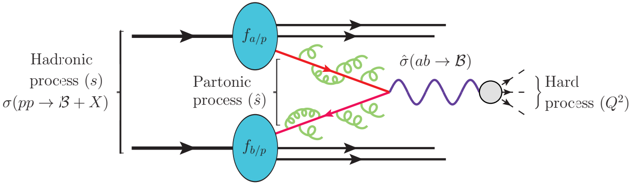

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$$= \left(1 - \frac{M_{W_R}^2}{\hat{s}}\right)^{1-2\varepsilon} \sim 2\varepsilon \log\left(1 - \frac{M_{W_R}^2}{\hat{s}}\right),$$

As $M_{W_R}^2 \to s$, logs explode since $M_{W_R}^2 \to \hat{s} < s$ forces additional ***threshold*** radiation g to be soft. Inclusive **FO** prediction not reliable.

In this limit, **soft factorization** is justified and logs can be **resummed**![9]

[8] See, e.g., Altarelli, et al ('79); Sullivan ('02); Harris and Owens ('02); **RR** ('15)

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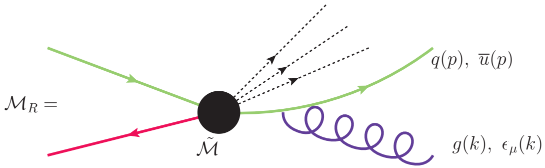
Soft Factorization in Gauge Theories

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

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

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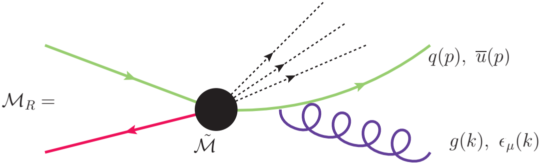

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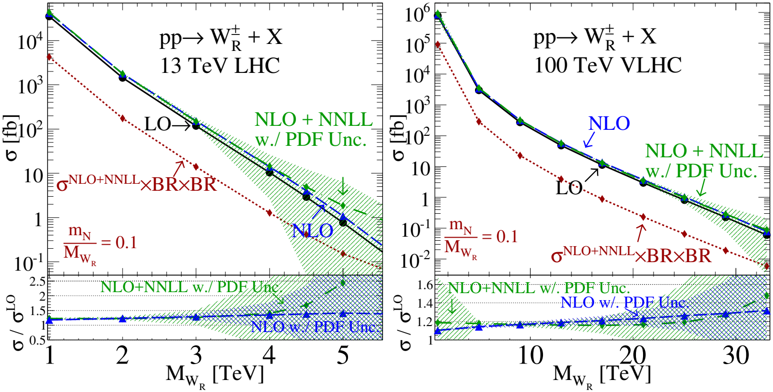
Anti-commute and applying Dirac Eq. gives us

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

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



First W_R calculation to match threshold ME with thresh.-PDFs![10]

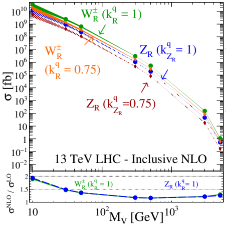
- Threshold region $M_{W_R}/\sqrt{s} \gtrsim 0.3$ at both colliders [Sterman ('88)]
- At 13 TeV, resummation larger impact than NNLO for $M_{W_R} > 4.5$ TeV

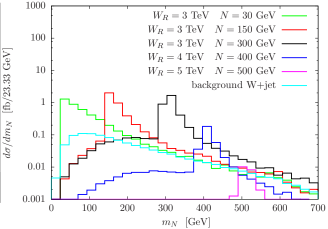
[10] NNPDF30-Thresh. [1507.01006] and case study by Beenakker, et al [1510.00375]

Discovery Potential and Sensitivity

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

- LRSM FeynRules model file [1401.3345][11]
- 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

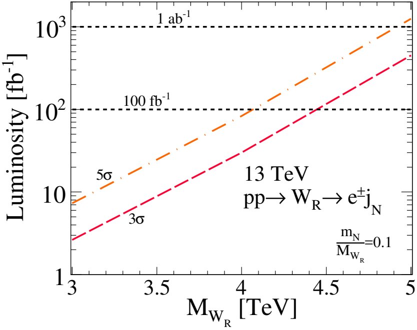


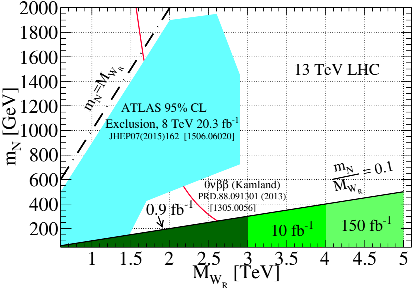


[11] New simplified NLO model file [1610.08985]: feynrules.irmp.ucl.ac.be/wiki/EffLRSM

Discovery Potential

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





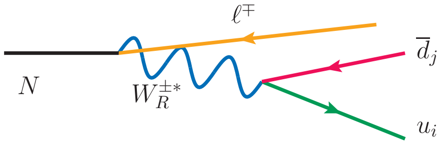
- 13 TeV: $M_{W_R} \approx 3$ (4) [5] TeV discovery after 10 (100) [2000] fb^{-1}
- 100 TeV: $M_{W_R} \approx 15$ (30) TeV discovery after 100 fb^{-1} (10 ab^{-1})

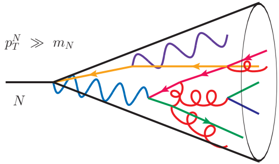
As BRs and signal definition remain largely same for (relatively) lighter *N*, discovery potential extends also to (relatively) lighter *N*

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, $e^+e^- \to Z_R \to NN \to j_N\, j_N$ 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
- Works are in the pipeline to study this new class of jets.

... 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.

LHC is now probing such large scales that pheno is qualitatively different. This requires reassessing validity of standard BSM collider signatures[12]

- We have studied an alternative search strategy for $W_R - N$ production at hadron colliders when $m_N \ll M_{W_R}$ and recover **huge** sensitivity precisely where current methodologies breakdown

- We have updated predictions (NLO+NNLL w/ **thresh-PDF**) and Scale+PDF unc. for $pp \to W_R$ in threshold regime $(M_{W_R}/\sqrt{s} \gtrsim 0.3)$. Threshold corrections as/more important than NLO corrections.

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

Thank you.