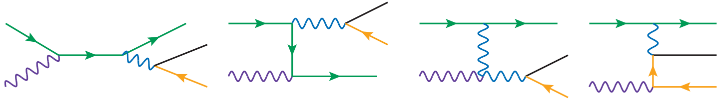
Lepton Number Violation with Jets: A Match Made at the Seesaw Scale[1]

Pheno 14

Richard Ruiz

Pitt-PACC, University of Pittsburgh

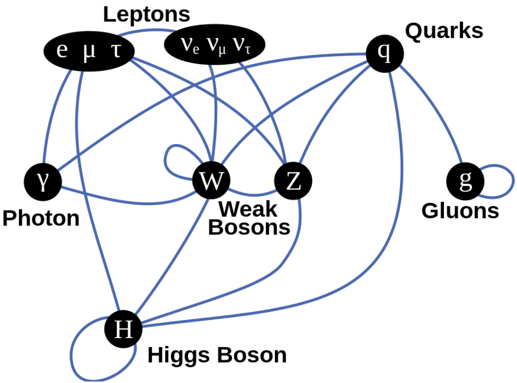
May 5, 2014



[1] w. T. Han (Pitt) and D. Alva (UFABC) [In Progress]

The Standard Model of Particle Physics

These are the ingredients of the Standard Model (SM) of Particle Physics (BEH '64, GWS 60s, 't Hooft-Veltman '72, etc.)



After electroweak (EW) symmetry breaking (EWSB), anything that touches (interacts with) the Higgs (field) gets a mass.

- No $y_\nu \implies$ No m_ν.

Disclaimer: Neutrinos have mass.

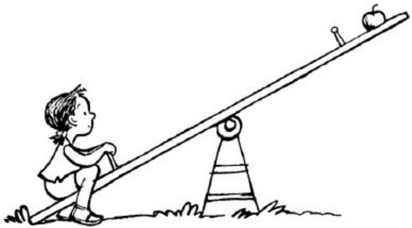
Massive Neutrinos is a Complicated Issue

- Massive neutrinos worsen the mass hierarchy of fermions
  - $\frac{m_e}{m_t} \sim \frac{10^5\mathrm{eV}}{10^{11}\mathrm{eV}} = 10^{-6}$, but $\frac{m_\nu}{m_t} \lesssim \frac{10^{-1}\mathrm{eV}}{10^{11}\mathrm{eV}} = 10^{-12}$
- The Universe is better off with massless neutrinos
  - Chiral symmetry in the neutrino sector is restored
- The Universe is better off with massive neutrinos
  - CP violation in lepton sector
  - With very heavy Majorana masses, we also get Leptogenesis
- Unless $B - L$ is promoted to a full symmetry, neutrino mass-generating mechanisms necessarily result in Lepton number violation at dimension-5 (Weinberg 1979)
  - $\mathcal{L} \in \frac{1}{\Lambda}\overline{L}\tilde{\Phi}\tilde{\Phi}^\dagger L$
- **Motivation:** Studying neutrino masses, the (spontaneous) generation of their masses, and their pheno is an investigation into new physics because neutrino masses is BSM physics.

Outline

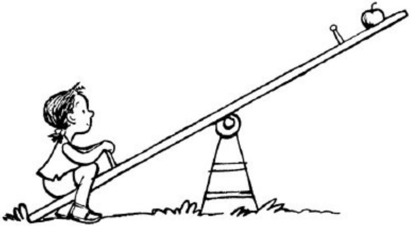
Lepton Number Violation with Jets **[PRELIMINARY]**

- Motivation for investigating neutrino masses✓
- The Seesaw Mechanism in a Nutshell
- Testing Seesaw Mechanisms with $pp \to N\ell^{\pm}$ at the LHC
- Testing Seesaw Mechanisms with $pp \to N\ell^{\pm} + nj$ at the LHC
  - Breaking things down
  - Results **[PRELIMINARY]**
- Summary



The Seesaw Mechanism[2] in a Nutshell

The seesaw mechanism is a device for simultaneously generating neutrino masses and explaining the smallness of their values compared to the EW scale.



[2] Yanagita (1979); Gell-Mann, Ramond, Slansky (1979); S.L. Glashow (1980); Mohapatra, Senjanovic (1980) + Type II + Type III + Inverse + Radiative + many others

The Seesaw Mechanism[3] in a Nutshell

Massive, left-handed neutrinos exist. Suppose y_ν exist and that L is not a good symmetry at low energies. Below the EW scale we get

$$\mathcal{L} \ni -m_D \overline{\nu_R} \nu_L + h.c.$$

Suppose also some spin-1/2 fermion with zero charge under any exact symmetry below EW scale (singlet!). We are allowed to write

$$-m_M \overline{S^c} S$$

However, below the EW scale, ν and S have the same spacetime (LN?) and good, internal q numbers, so they mix.
The mass eigenvalues are

$$m_1 \approx m_D \frac{m_D}{m_M}, \quad m_2 \approx m_M \qquad (m_D \ll m_M)$$

For $m_D \sim 100$ GeV and $\nu_1 \sim 0.1$ eV, $M_N \sim 10^{14}$ GeV

[3] Yanagita (1979); Gell-Mann, Ramond, Slansky (1979); S.L. Glashow (1980); Mohapatra, Senjanovic (1980)

Many Ways to Generate EW Scale m_D and TeV Scale m_M

Type(I)[4]: Add a spin-$1/2$ singlet with a Majorana mass term:

- $\mathcal{L} \ni \; m_M \overline{S^c} S \implies \; m_\nu^{ij} \propto m_D^i m_D^j / m_M$
- N_R can be the singlet

Type(II)[5]: Add Higgs $SU(2)_L$ triplet $(H^{0,\pm,\pm\pm})$ but no N_R

- $\mathcal{L} \ni \; y\overline{L^c}(i\sigma_2)\Delta L \implies \; m_M \overline{\nu^c}\nu$

Type(III)[6]: Introduce fermion $SU(2)_L$ triplet $(T^{0,\pm})$

- $m_\nu^{ij} \propto m_D^i m_D^j / M_T$

Inverse and **Radiative**[7]: Facilitate low-energy Seesaw Mechanisms

Lepton number violation (LNV) is present in all these mechanisms.

Punchline: There are many different ways to generate $m_{D/M}$, and each results in rich collider phenomenology.

---

[4] Minkowski ('77); Gell-Mann, Ramond, Slansky ('79); etc...

[5] Mohapatra,Senjanovic (80,81); Magg,Wetterich (80); Lazarides,Shafi (81)

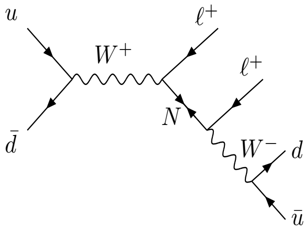
[6] Foot, Lew, He, Joshi (1989); G. Senjanovic et al. ...

[7] Mohapatra (1986); Mohapatra, Valle (1986). Zee (1985), Babu (1988)

Testing Seesaw Mechanisms with $pp \to N\ell^\pm$ at the LHC

Seesaw Mechanisms with N are tested with cool L-Violating processes:

$$u\overline{d} \to W^+ \to N\ell^+ \to \ell^+\ell^+ q'\overline{q}$$

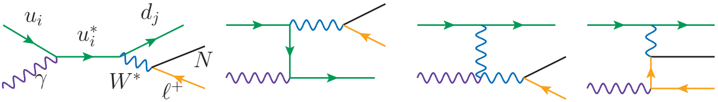


- First proposed by Keung & Senjanovic (1983) in the context of W_R and N_R
- Many, many good papers since then and lots left to study
  - e.g., See talks by De La Puente, Das, Lewis, MC Chen
- Expt limits on m_N are tough... as is building new colliders
  - We must be more clever to test higher seesaw scales at 14 TeV

Testing Seesaw Mechs. with $pp \to N\ell^{\pm} + nj$ at the LHC

An interesting study by Bhupal Dev, Pilaftsis, and Yang (BPY) appeared in August[8] considering a new heavy N production mechanism via the $U(1)_{\rm EM}$ corrections to the DY process:

The inclusive $pp \to N\ \ell^+\ j$

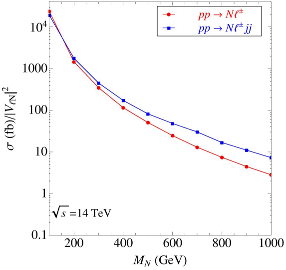


Two types of diagrams:

- Compton scattering
- Vector Boson Scattering (VBS)

Includes contributions from

- Exclusive $pp \to N\ \ell^+\ jj$
- Semi-elastic $p\gamma \to N\ \ell^+\ j(p)$



BPY Claim: $\sigma(2j) > \sigma_{DY}$ for $m_N \gtrsim 200$ GeV

[8] arXiv:1308.2209, PRL112, 081801 (2014)

$pp \to N\ell^\pm + nj$ at the LHC

Inclusive $pp \to N\ \ell^+\ j$ is *very* interesting because

(i) LHC detectors were designed with forward jet tagging capabilities for vector boson scattering

(ii) Includes a diffractive process, which can be sizable at the LHC

- $p \to p\gamma$ means collinear, initial-state γ and proton escapes detector undetected
- Elastic, Semi-Elastic, and Inelastic $\gamma\gamma \to X$ processes have been extensively studied, e.g.,[9] $\gamma\gamma \to \tilde{\ell}^+\tilde{\ell}^-, H^+H^-, H^{++}H^{--}$

(iii) Despite $\mathcal{O}(\alpha_{\rm EM}^2)$ suppression over DY, IR, collinear (log), and (longitudinal) polarizations enhancements are present.

(iv) Existence of new dominant mechanism is a big deal.

[9] Drees, Godbole, et., al., (1994); Khoze, Martin, et al (2004); Han, Mukhopadhyaya, et al (2007)

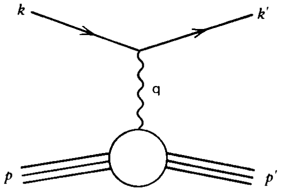
pp Scattering with Collinear Photons

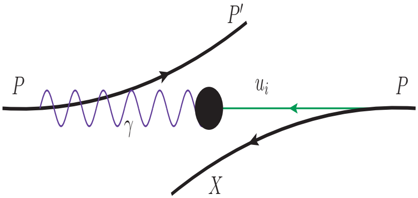
For small photon virtualities $\left(\sqrt{q^2} < \Lambda_{\text{Cutoff}} \sim \mathcal{O}(m_p)\right)$ and small $p \to p\gamma$ emission angles, diffractive processes are factorizable

$$d\sigma(pp \to N\ell^+ j + Y) =$$
$$\int d\xi_1 d\xi_2 \ \sum_q [f_{q/p}(\xi_1) f_{\gamma/p}(\xi_2) + (1 \leftrightarrow 2)] \times d\hat{\sigma}(q\gamma \to N\ell^+ j),$$

Modified Williams-Weizsäcker Equivalent Photon Approximation (EPA)

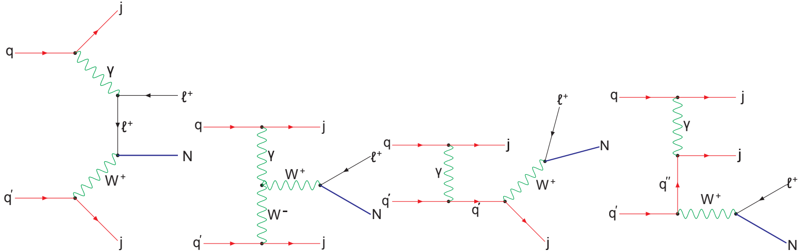
Several good descriptions exist, e.g. Budnev, et. al. (1975) [MG5, CalcHEP], Drees-Zeppenfeld (1989)





Exclusive $pp \to N\ell^{\pm}jj$

For large photon virtualities $\left(\sqrt{q^2} > \mathcal{O}(m_p)\right)$ and careful cuts, the $2j$ process is perfectly perturbative and can be modeled with MG5, CalcHEP, etc.



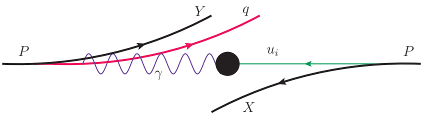
$+$ other diagrams (Z and internal ν_ℓ)

pp Scattering with Collinear Photons (Part II)

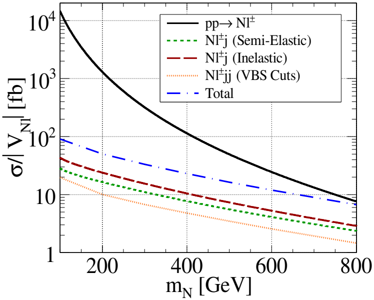
New contribution: For intermediate photon virtualities $\left(\mathcal{O}(m_p) < \sqrt{q^2} \sim E_\gamma\right)$ and small $q \to q\gamma$ emission angles, diffractive processes still are factorizable

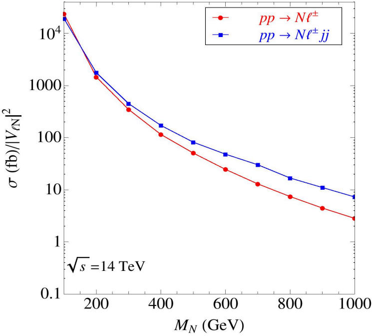
$$d\sigma(pp \to N\ell^+ j + Y) = \int d\xi_1 d\xi_2 dz \sum_{q,q'} \left[f_{q/p}(\xi_1) f_{q'/p}(\xi_2) f_{\gamma/q'}(z) e_{q'}^2 + (1 \leftrightarrow 2)\right] d\hat{\sigma}(q\gamma), \quad \hat{s} = \xi_1 \xi_2 z s$$

The Williams-Weizsäcker Approximation enjoys both the same parton luminosity as the $2j$ process and log enhancements of semi-elastic processes.



Results (Preliminary!)





- Inelastic $N\ell^+1j$ rate is **larger** than both semi-elastic $N\ell^+1j$ and $N\ell^+2j$
- However, even with new contribution, we do **not** observe a rate larger than the DY rate

Summary

- A new mechanism for generating heavy neutrinos at the LHC has been proposed
  - Consists of radiative EW corrections to DY
  - Claim: $\sigma(2j) > \sigma_{DY}$ for $m_N \gtrsim 200$ GeV
- We have considered a previously unconsidered contribution (inelastic $p\gamma$ scattering) and find that it is dominant over other contributions (semi-elastic $p\gamma$, $2j$)
- We have verified that the inclusive $pp \to N\ell^+ j$ rate is much larger than naive expectations
  - However, we do not observe a rate that is larger than the DY rate

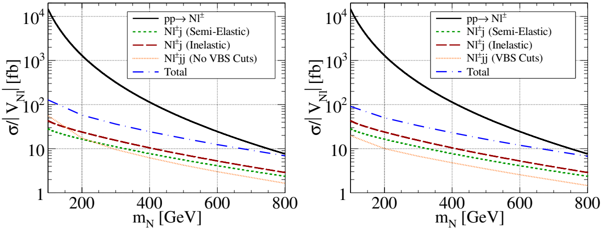
"*Hadron colliders may serve as the discovery machine for the mysterious 'sterile Majorana neutrinos'*"[10]

"Observing neutrinos at the LHC"... I think that is really cool.

Thank you.

[10] arXiv:hep-ph/0604064, PRL97, 171804 (2006)

Backup 1/1 (Preliminary!)



Minimalistic VBS Cuts added to remove prompt $W/Z/\gamma$ + GI contributions, and quantify contribution from VBS diagrams.