Lepton Number Violation and W' Chiral Couplings at the LHC[1]

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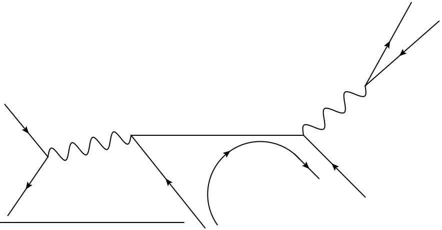

[1] With T. Han (Pitt.), I. Lewis (BNL), & Z. Si (Shandong)

The Standard Model (SM) of Particle Physics

- **SM**: A fantastically successful theory that describes the microscopic interactions of matter.

- Consists of 6 objects: $\ell, q; \overline{u}, \overline{d}, \overline{e}; \Phi$, with huge multiplicity.

- Impose local invariance, break with $\langle \Phi_0 \rangle = v$, and voilà! We have a universe!

- Quarks (g, γ, W, Z)
- Neutral leptons (neutrinos) (W, Z)
- Charged leptons (γ, W, Z)
- Gluon mediates $SU(3)_{Color}$
- Photon mediates $U(1)_{EM}$
- $W^{\pm}/Z^0$ mediate $SU(2)_{Left}$
- h dynamically generates masses
  - Only missing piece!

Even with SM Higgs, Questions Remain: Motivation for New Physics

- What is the origin of **neutrino masses**?
  - Dirac mass terms require N_R
  - N_R are SM singlets and may have Majorana mass terms, too.
- What is the origin of **Parity Asymmetry** in SM
  - Is there a $V + A$ structure, $SU(2)_R$, too? Is it from $SU(5)$?
  - Lots of different phenomenology.
- Are these even independent questions?

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- Are these even independent questions?

- Left-Right Symmetric theories, GUTS, SUSY GUTS, Extra Dim w/ KK, Little Higgs w/ new gauge sectors
  - Commonality 1: N_R (SM singlet) + heavy mass states
  - Commonality 2: Some charged vector boson $W'^{\pm}$.

3. Model Discrimination with W' and N

Issue: These are phenomenologically similar models.
- Measuring chiral couplings to W' is imperative.

[2] Keung & Senjanovic [PRL 50 (1983)]

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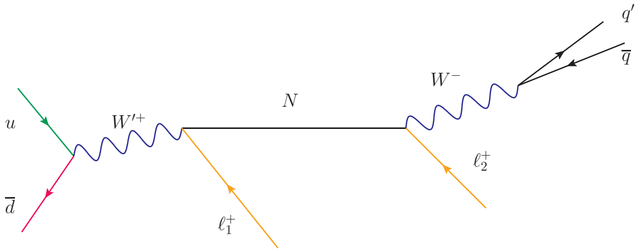
Issue: These are phenomenologically similar models.
- Measuring chiral couplings to W' is imperative.

Solution: Use model-independent parameterization.
- Parameters can then be measured with the spectacular L-Violating process[2]: $u\overline{d} \rightarrow W'^{+} \rightarrow N\ell^{+} \rightarrow \ell^{+}\ell^{+}q'\overline{q}$



[2] Keung & Senjanovic [PRL 50 (1983)]

3. Why $u\overline{d} \to W'^{+} \to N\ell^{+} \to \ell^{+}\ell^{+}q'\overline{q}$?

1. W' is heavy[3]. At the LHC, an $s-$channel $u\overline{d} \to W'^{+}$ annihilation provides the best opportunity to produce it.

2. N must also be heavy[4]. The $W'^{+} \to N\ell^{+}$ sub-process is the least constrained by phase space (v.s. t-channel N exchange).

3. $W^{-} \to q'\overline{q}(jj)$ allows for full reconstruction of kinematics; W-tagging is also a powerful background reducer.

4. $pp \to \ell^{+}\ell^{+}jj$ is a lepton number-violating process and a "smoking-gun" indication of Majorana behavior[5].

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[3] CMS Collaboration [arXiv:1204.4764]
[4] ATLAS Collaboration [arXiv:1203.5420]
[5] T. Han, et. al. [arXiv:hep-ph/0505260]

Outline

Synopsis: *We have investigated the production of a heavy Majorana N in association with a heavy W', and have determined* an efficient way to measure the couplings associated with a model-independent parameterization of W' *at the LHC.*

1. The Standard Model
2. Motivation
   - For New Physics
   - For Lepton No. Violation in association with Chiral Couplings
3. Model Discrimination with W' and N
   - Utility of the $pp \to \ell^+ \ell^+ jj$ collider signature
4. Model-Independent Parameterization
5. Analytic Results
6. Numerical Results
7. Summary & Conclusion

4. Model-Independent Parameterization (1/1.5)

- W' coupling to quarks:

$$\mathcal{L} = -\frac{1}{\sqrt{2}} W'^{+}_{\mu} \overline{u_i} V^{CKM'}_{ij} \gamma^{\mu} \left[g^q_R P_R + g^q_L P_L \right] d_j + h.c.$$

- W' coupling to leptons.

$$\mathcal{L} = -\frac{g^{\ell}_R}{\sqrt{2}} W'^{+}_{\mu} \left[\sum_{m=1}^{3} \overline{\nu^c_m} C^R_{m\ell} + \overline{N} D^R_{N\ell} \right] \gamma^{\mu} P_R \ell^-$$

$$-\frac{g^{\ell}_L}{\sqrt{2}} W'^{+}_{\mu} \left[\sum_{m=1}^{3} \overline{\nu_m} C^{L*}_{m\ell} + \overline{N^c} D^{L*}_{N\ell} \right] \gamma^{\mu} P_L \ell^- + h.c.$$

- E.g., Left-Right Symmetric W'_R
  - Light mass mixing is small and heavy mass mixing is large:

$$g_L \equiv 0, \quad |C^R_{m\ell}| \sim \mathcal{O}\left(\frac{m_m}{m_N}\right) \text{ for } m \leq 3, \quad \text{and} \quad |D^R_{N\ell}| \sim \mathcal{O}(1)$$

4. Model-Independent Parameterization (1.5/1.5)

- SM W coupling to leptons:

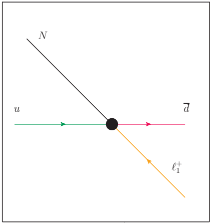
$$\mathcal{L} = -\frac{g}{\sqrt{2}} W_{\mu}^{\prime +} \left[\sum_{m=1}^{3} \overline{\nu_m} U_{m\ell}^{*} + \overline{N^c} V_{N\ell}^{*} \right] \gamma^{\mu} P_L \ell^{-} + h.c.$$

- Light mass mixing is large and heavy mass mixing is small:

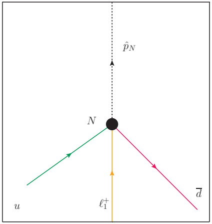
$$|U_{m\ell}| \sim \mathcal{O}(1), \quad \text{and} \quad |V_{m\ell}| \sim \mathcal{O}\left(\frac{m_m}{m_N}\right) \text{ for } m \leq 3$$

5. Pre-Results: Definition of Observables θ_{ℓ_2} and Φ

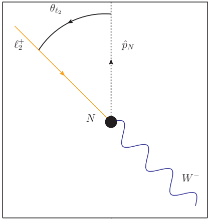
Production Plane: Take initial $2 \to 2$ process in CM frame, then rotate and boost into N's rest frame



$\curvearrowright$ Rotate + $\upuparrows$ Boost



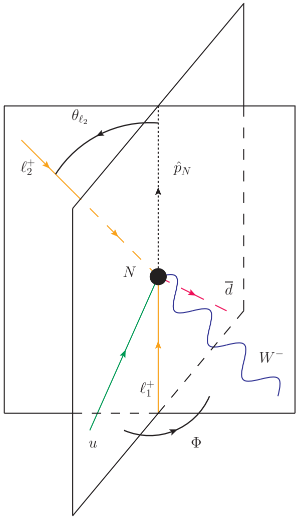
Decay Plane: N's products relative to $\hat{p}_N$ (Direction of N in CM)



5. Pre-Results: Definition of Observables θ_{ℓ_2} and Φ

Production Plane and **Decay Plane** share same axis, so angle between two can be defined

- Algebraically: dot products of cross products of 3-momenta



5. Analytical Result I: Coupling to Final-State Leptons

- Analytical calculation of angular distributions leads to fascinating results!

$$\frac{d\hat{\sigma}}{d\cos\theta_{\ell_2}} = \frac{\hat{\sigma}_0}{2}\left[1 + \mathcal{A}\cdot\left(\frac{g_R^{\ell\,2} - g_L^{\ell\,2}}{g_R^{\ell\,2} + g_L^{\ell\,2}}\right)\cdot\cos\theta_{\ell_2}\right],$$

where $\mathcal{A}$ contains a few mass ratios, etc., and

$$\hat{\sigma}_0 = \hat{\sigma}_{Tot.}(u\overline{d} \to \ell^+\ell^+W^-) \times \mathcal{BR}(W \to q\overline{q}').$$

- **This is a measurement of W' coupling to leptons.**
- Slope of angular distribution is sensitive to handedness of W'.
- $\mathcal{A} \to -\mathcal{A}$ for Dirac neutrino case ($\ell^+\ell^- jj$).

5. Analytical Result II: Coupling to Initial-State Quarks

- We see some surprising results, too!

$$\frac{d\hat{\sigma}}{d\Phi} = \frac{\hat{\sigma}_0}{2\pi}\left[1 + \mathcal{B}\cdot\left(\frac{{g_R^q}^2 - {g_L^q}^2}{{g_R^q}^2 + {g_L^q}^2}\right)\cdot\cos\Phi\right],$$

where $\mathcal{B}$ contains a few mass ratios, etc., and

$$\hat{\sigma}_0 = \hat{\sigma}_{Tot.}(u\overline{d} \to \ell^+\ell^+W^-) \times \mathcal{BR}(W \to q\overline{q}').$$

- **This is a measurement of W' couplings to quarks.**
- Slope of angular distribution is sensitive to handedness of W'.
- $\mathcal{B} \to -\mathcal{B}$ for Dirac neutrino case ($\ell^+\ell^-jj$).
  - **Majorana nature of N can be verified with angular distributions!**

6. Running the Numbers: Monte Carlo Input

To demonstrate usefulness of the $W'^{+} \rightarrow \ell^{+}\ell^{+}jj$ signal for measuring model parameters, we assume the following input:

- $pp \rightarrow W'^{+} \rightarrow \mu^{+}\mu^{+}\overline{q}q'$
  - $\sqrt{s}$ =14 TeV pp Collisions
- W'^{+}:
  - $M_{W'}$ =2.5 TeV
  - $g_R^{\ell,q} = 1,\ g_L^{\ell,q} = 0$, i.e., pure gauge state W'_R.
  - $g_R^{\ell,q} = 0,\ g_L^{\ell,q} = 1$, i.e., pure gauge state W'_L.
  - $|V_{u\overline{d}}^{CKM'}|^2 = 1$ for the $u\overline{d}W'^{+}$ vertex.
- N:
  - m_N =500 GeV (only one heavy mass state)
  - $|V_{\mu N}|^2 = 5.0 \times 10^{-4}$ for the $N \rightarrow W^{-}\mu^{+}$ vertex[6]
  - $|D_{\mu N}^{L}|^2 = |D_{\mu N}^{R}|^2 = 1$ for the $W'^{+} \rightarrow N\mu^{+}$ vertex

[6] $G.Belanger, et.al.,$ [hep − ph/9508317]; $D.London,$ [hep − ph/9907419]; $delAguila, et.al$[arXiv : 0803.4008].

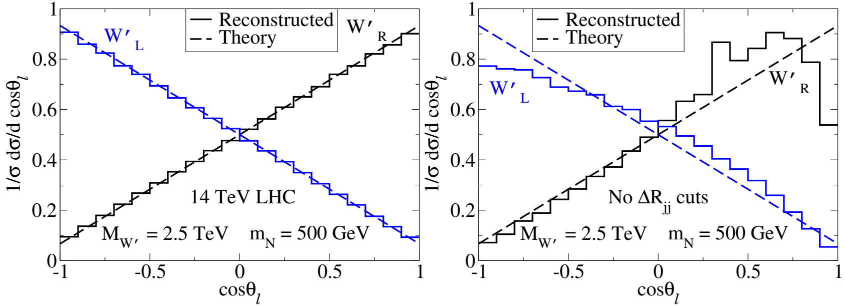
6. Numerical Results I: Cross Section

- Cross section (fb) for $pp \to W'^{+} \to \mu^{+}\mu^{+}\overline{q}q'$
- Reconstruction/selection details in "Backup Slides"
- Irreducible background < 0.1 fb

σ(fb)	7 TeV	7 TeV	14 TeV	14 TeV
Cuts	W'_L	W'_R	W'_L	W'_R
Event Reco.	0.095	0.12	2.7	3.6
Smear + Kinematics	0.083	0.088	2.4	2.6
+ Isolation	0.049	0.071	1.2	2.0
$+ M_{W'}^{Cand} + m_N^{Cand}$ Cuts	0.026	0.048	0.95	1.8
$+ \not{E}_T + m_{jj}$ Cut	0.022	0.042	0.77	1.5
$\mathcal{A} = \sigma_{AllCuts}/\sigma_{Reco}$	23%	35%	29%	42%

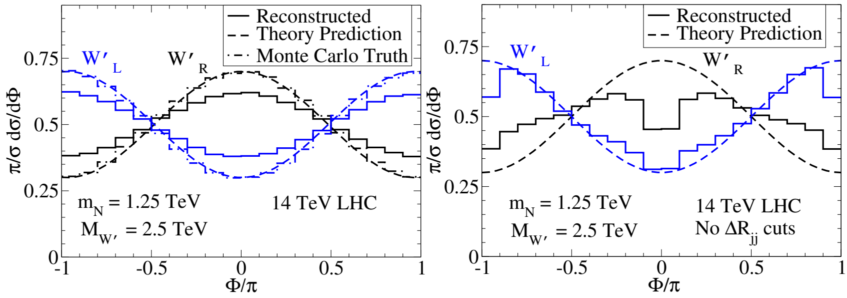
6. Numerical Results II: Polar Distribution (g^ℓ)

- (L) No smearing or cuts; (R) smearing and full selection cuts
- Great Agreement!
  - Jet-isolation cut not applied (Jets are very collinear).



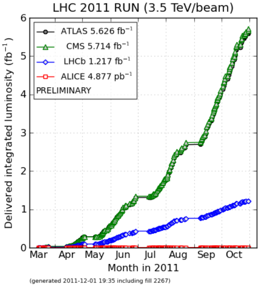
6. Numerical Results III: Azimuthal Distribution (g^q)

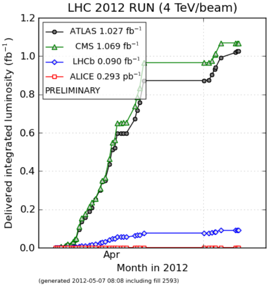
- Dependent on $(m_N/M_{W'})^2$, so set m_N =1.25 TeV for clarity.
- (L) No smearing or cuts; (R) smearing and full selection cuts
- Great Agreement!
  - Jet-isolation cut not applied (Jets are very collinear).



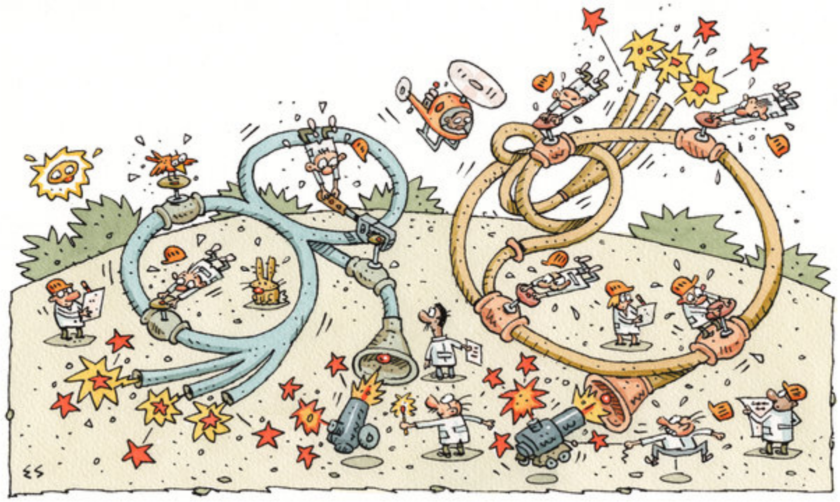
Summary & Conclusion

- If new physics appears in the form of W' & N, we are ready to exploit it for whatever it is worth.
  - Chiral couplings to leptons
  - Chiral couplings to quarks
  - Discriminating power between Dirac and Majorana behavior
- The LHC Experiments' Mantra: Be ready for new physics.
  - With so much data, we better be!





Thank You! Questions?



[Credit: NYTimes *nyti.ms/oPvA0a*]

Backup

6. Event Reconstruction (1/2)

- In order to make our events more realistic, we apply a **Gaussian smearing** to the reconstructed μ and j energies:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b,$$

with $a(a) = 5(100)\%$ and $b(b) = 0.55(5)\%$;

- Followed by basic **fiducial** + **kinematic** cuts:

$$p_T^j \geq 30 \text{ GeV}, \; p_T^\ell \geq 20 \text{ GeV}, \; |\eta_j| \leq 3.0 \; |\eta_\ell| \leq 2.5;$$

- For particles i and j, we define the **isolation** parameter $\Delta R_{ij} = \sqrt{(\Delta\phi_{ij})^2 + (\Delta\eta_{ij})^2}$, and **require**

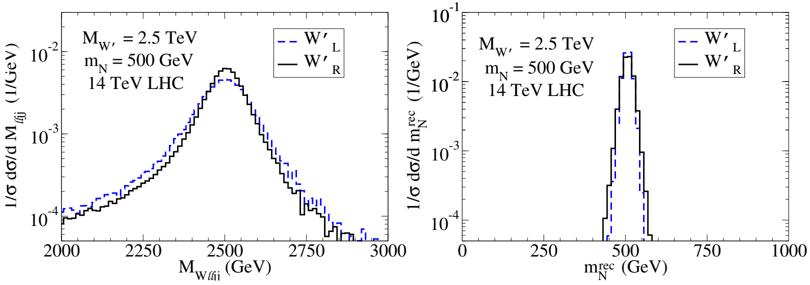
$$\Delta R_{jj} \geq 0.3, \; \Delta R_{\ell j}^{min} \geq 0.4,$$

where $\Delta R_{\ell j}^{min}$ represents the smallest $\Delta R_{\ell j}$ amongst $\mu_1^+ \& \mu_2^+$

6. Event Reconstruction (2/2)

The invariant mass distributions from reconstructed pseudo-experiment events:

- $m_{W'}^{Reco.} = m_{\ell\ell jj}$ and $m_N^{Reco.} = \min_{\ell=\mu_1,\mu_2} [m_N - m_{\ell jj}]$



6. LHC Monte Carlo: Event Selection (1/1)

- Apply standard **smearing**, **kinematic** cuts, and **isolation** cuts.
- Impose cuts on the **reconstructed candidate mass** m_N^{Reco} and $m_{W'}^{Reco}$:

$$\frac{|m_N^{Reco.} - m_N|}{m_N} \leq 0.1, \& \quad \frac{|\sqrt{\hat{s}} - M_{W'}^{Reco.}|}{M_{W'}} \leq 0.1;$$

- To reduce background from $\bar{t}t \to W^- b\bar{c}\ell^+\ell^+\nu_\ell\bar{\nu}_\ell$ decays, we add $\not{E}_T$ & $m_W^{Reco.}$ **cuts**:

$$\not{E}_T < 30 \text{ GeV}, \quad 60 \text{ GeV} < M_W^{Reco} < 100 \text{ GeV}.$$

- The **irreducible background** comprises rare SM processes, e.g., $pp \to W^\pm W^\pm W^\mp$, and contribute at most 0.085 fb.