Majorana Neutrino and W' Couplings at the LHC

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Outline

1. Introduction
2. Theoretical Framework
3. Signal Reconstruction and Selection at the LHC
4. Measuring $W'N\ell$ Chiral Couplings
5. W' and initial state quark chiral couplings
6. Conclusions

Motivation

- Over the last decade, neutrino oscillation experiments have shown that neutrinos are massive.
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- Massive neutrinos can be accomodated by introducing heavy right-handed SM singlet neutrinos, N_R.
- Many models with heavy massive right-handed neutrinos also contain new charged gauge bosons, W's
- If new heavy states at the TeV scale, the LHC has potential to discover the states.
- In particular, if $M_{W'} > M_{N_R}$ then it may be possible to observe the spectacular lepton-number-violating process $pp \to W' \to \ell^\pm \ell^\pm jj$
- If such particles are discovered, it will be imperative to measure their properties, such as mass, spin, and chiral couplings.

Interaction Lagrangian

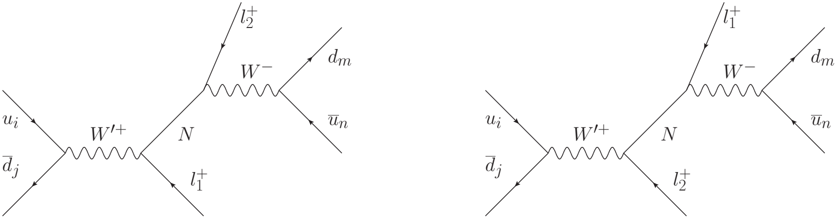
Charged current interactions of Majorana neutrinos, and W' interactions:

$$\begin{aligned}\mathcal{L} &= \frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \sum_{m'=4}^{n+3} V_{m'\ell}^* \overline{N_{m'}^c} \gamma^\mu P_L \ell \\ &\quad + \sum_{\alpha=L,R} \frac{g_\alpha}{\sqrt{2}} W_\alpha'^{+\mu} \sum_{\ell=e}^{\tau} \sum_{m'=4}^{n+3} \overline{N_{m'}^c} V_{\ell m'}^{\alpha *} \gamma^\mu P_\alpha \ell + \text{h.c.}\end{aligned}$$

- V and V^α are neutrino mixing matrices.
- W_L' will denote a W' with purely left-handed couplings, and W_R' a W' with purely right-handed couplings.

Signal

- We consider the lepton number violating process:



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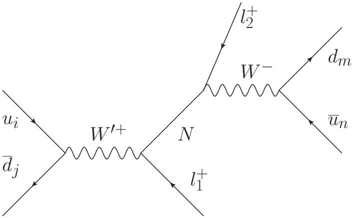

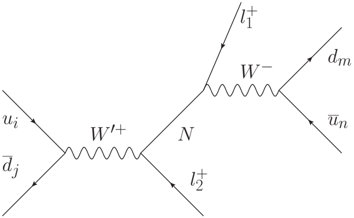

- To fully reconstruct the event, the origin of each charged lepton must be determined.
- There are two possible solutions to the neutrino mass: $m_N^2 = (p_{\ell_1} + p_{j_1} + p_{j_2})^2$ or $m_N^2 = (p_{\ell_2} + p_{j_1} + p_{j_2})^2$
- The lepton that most closely reconstructs the majorana neutrino mass is identified as the lepton originating from the neutrino.

Event Selection

- Energy resolution is simulated according to a Gaussian distribution, and is parameterized according to
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$$
where for leptons $a = 5\%,\ b = 0.55\%$ and for jets $a = 100\%,\ b = 5\%$.
- The basic detector acceptance cuts are applied:
$$p_T^j > 30\,\text{GeV},\ p_T^\ell > 20\,\text{GeV},\ \eta_j < 3.0,\ \eta_\ell < 2.5$$
- Signal consists of two leptons and two jets that are required to be well separated:
$$\Delta R_{\ell j}^{\text{min}} \geq 0.4,\ \Delta R_{jj} \geq 0.3$$
- Finally, apply the missing energy and invariant mass cuts:
$$\begin{aligned} |m_N^{\text{rec}} - m_N| &\leq 0.1 m_N, \qquad & |\sqrt{\hat{s}} - M_{W'}| &\leq 0.1 M_{W'} \\ \not{E}_T &< 30\text{ GeV}, \qquad & 60\text{ GeV} \leq m_{jj} &\leq 100\text{ GeV} \end{aligned}$$

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- Define θ^* to be the angle between $\hat{a}$ and the motion of the lepton in the neutrino's rest frame:

  $$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*}(N \to \ell^\pm jj) = \frac{1}{2}\left(1 + 2A\cos\theta^*\right),$$

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- Choose $\hat{a}$ as the direction of the neutrino in the partonic c.m.

Lepton Angular Distribution

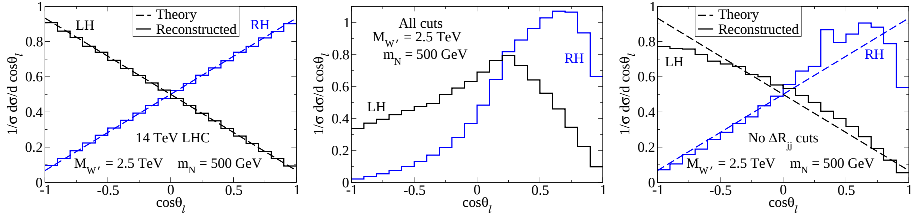
At partonic level, the angular distribution of the lepton originating from neutrino decay is

$$\frac{d\hat{\sigma}}{d\cos\theta_{\ell_2}}(u\bar{d}\to\ell_1^+N\to\ell_1^+\ell_2^+W^-)=\frac{\hat{\sigma}_0}{2}\left(1+\left(\frac{\hat{\sigma}(W_0)-\hat{\sigma}(W_T)}{\hat{\sigma}(W_0)+\hat{\sigma}(W_T)}\right)\frac{g_R^{N\ell^2}-g_L^{N\ell^2}}{g_R^{N\ell^2}+g_L^{N\ell^2}}\frac{2-x_N^2}{2+x_N^2}\cos\theta_{\ell_2}\right)$$

- $\theta_{\ell 2}$ is the angle between the lepton in the neutrino rest frame and the direction of motion of the neutrino in the partonic c.m.
- $\hat{\sigma}(W_0)$ and $\hat{\sigma}(W_T)$ are the cross sections for neutrino decay into longitudinally and transversely polarized W's, respectively.
- $x_N=m_N/\sqrt{\hat{s}}$ and $x_W=m_W/m_N$.

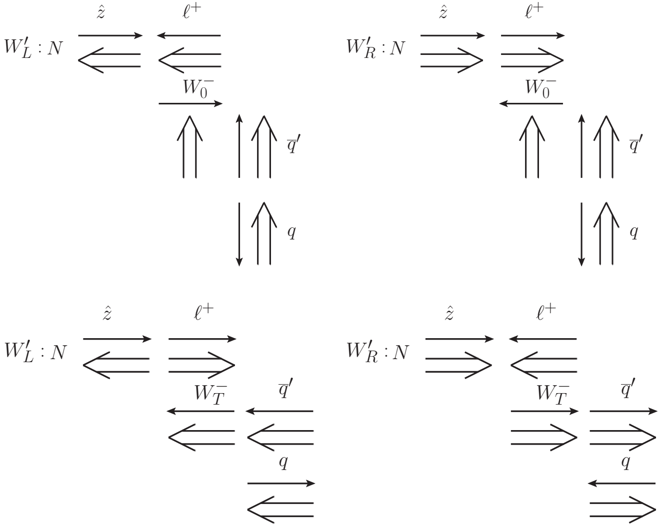
For an on-shell W', the analyzing power is $A=\hat{A}=\frac{1}{2}\frac{1-2x_W^2}{1+2x_W^2}\frac{2-x_N^2}{2+x_N^2}\frac{g_R^{N\ell^2}-g_L^{N\ell^2}}{g_R^{N\ell^2}+g_L^{N\ell^2}}$

Lepton Angular Distribution



$$\frac{d\hat{\sigma}}{d\cos\theta_{\ell_2}}(u\bar{d}\to\ell_1^+N\to\ell_1^+\ell_2^+W^-) = \frac{\hat{\sigma}_0}{2}\left(1+\left(\frac{\hat{\sigma}(W_0)-\hat{\sigma}(W_T)}{\hat{\sigma}(W_0)+\hat{\sigma}(W_T)}\right)\frac{{g_R^{N\ell}}^2-{g_L^{N\ell}}^2}{{g_R^{N\ell}}^2+{g_L^{N\ell}}^2}\,\frac{2-x_N^2}{2+x_N^2}\cos\theta_{\ell_2}\right)$$

Spin Correlations



Lepton Forward Backward Asymmetry

- Without cuts:

$$A = \mathcal{A} = \frac{\sigma(\cos\theta_{\ell 2} \geq 0) - \sigma(\cos\theta_{\ell 2} < 0)}{\sigma(\cos\theta_{\ell 2} \geq 0) + \sigma(\cos\theta_{\ell 2} < 0)}$$

- For $M_{W'} = 2.5$ TeV and $m_N = 500$ GeV:
  $A = \pm 0.43$ for ${W'}_R$ and ${W'}_L$, respectively.
- Results for $\mathcal{A}$ from signal simulation and reconstruction:

$\mathcal{A}$	14 TeV	
	${W'}_L$	${W'}_R$
No cuts or smearing	-0.43	0.43
All cuts and smearing	0.063	0.71
Without ΔR_{jj} cuts	-0.36	0.46

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- Distribution of angle between neutrino production and decay planes, Φ, is sensitive to W' coupling to initial state quarks.
- The angular distribution is then

$$\frac{d\hat{\sigma}}{d\Phi} = \frac{\sigma_0}{2\pi}\left(1 + \frac{3\pi^2}{16}\frac{x_N}{2+x_N^2}\frac{\hat{\sigma}(W_0)-\hat{\sigma}(W_T)}{\hat{\sigma}(W_0)+\hat{\sigma}(W_T)}\frac{{g_R^{qq'}}^2-{g_L^{qq'}}^2}{{g_R^{qq'}}^2+{g_L^{qq'}}^2}\cos\Phi\right)$$

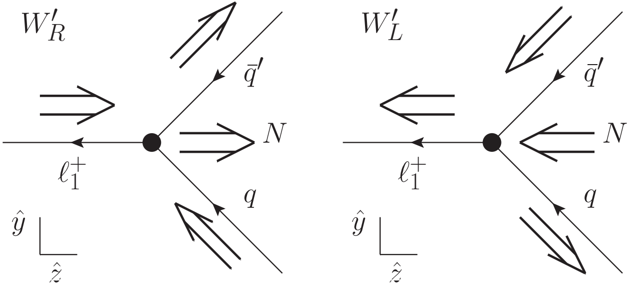
- Where Φ is measured in the partonic c.m.:

$$\Phi = \mathrm{sign}\left((\hat{\mathbf{p}}_N \times \mathbf{p}_\ell)\cdot\mathbf{p}_q\right)\cos^{-1}\left(\frac{\hat{\mathbf{p}}_N \times \mathbf{p}_\ell}{|\hat{\mathbf{p}}_N \times \mathbf{p}_\ell|}\cdot\frac{\hat{\mathbf{p}}_N \times \mathbf{p}_q}{|\hat{\mathbf{p}}_N \times \mathbf{p}_q|}\right)$$

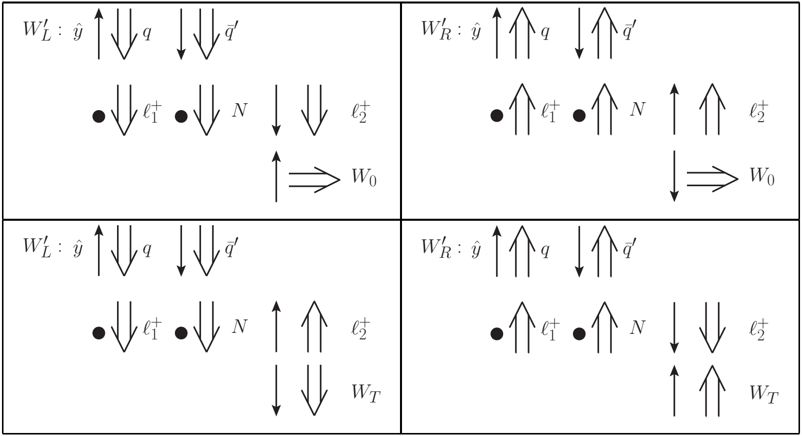
- The W'_L and W'_R distributions are 180° out of phase.

To explain this results, choose frame and orientation carefully:

- Work in the neutrino's rest frame.
- Define $\hat{z}$ direction to be the neutrino's direction in the partonic c.m.
- Define $\hat{y}$ direction to be the quark momentum component perpindicular to $\hat{z}$



- In this frame and with this orientation $\Phi = \phi_q - \phi_\ell$.
- Analyze spin correlations with $\hat{y}$ as the quantization axis.



$$\frac{d\hat{\sigma}}{d\Phi} = \frac{\sigma_0}{2\pi}\left(1 + \frac{3\pi^2}{16}\frac{x_N}{2+x_N^2}\frac{\hat{\sigma}(W_0)-\hat{\sigma}(W_T)}{\hat{\sigma}(W_0)+\hat{\sigma}(W_T)}\frac{{g_R^{qq'}}^2-{g_L^{qq'}}^2}{{g_R^{qq'}}^2+{g_L^{qq'}}^2}\cos(\phi_q-\phi_\ell)\right)$$

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To measure Φ, associate the system direction in the lab frame with the intitial state quark direction.

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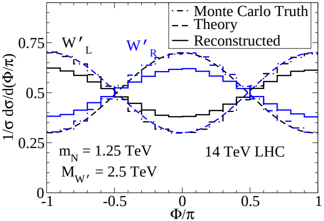

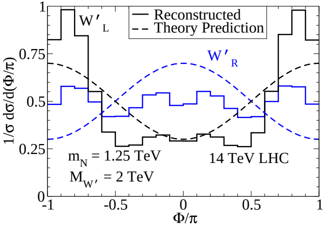

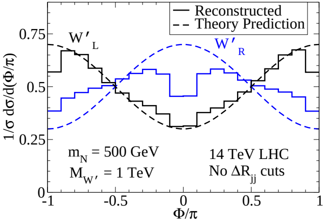

Conclusions

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- Many models with heavy massive right-handed neutrinos also contain new charged gauge bosons, W's
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- We analyzed the signal $pp \to W' \to \ell^+\ell^+jj$
- Through analytical results, intuitive understanding, and monte carlo simulation we showed that
  - (a) the $W'N\ell$ chiral couplings can be measured by observing the angular distribution of the lepton as originating from the neutrino in the neutrino's rest frame.
  - (b) The chiral couplings of the W' and initial state quarks can be measured by observing the angular distribution of the neutrino production and decay planes.

Extra Slides

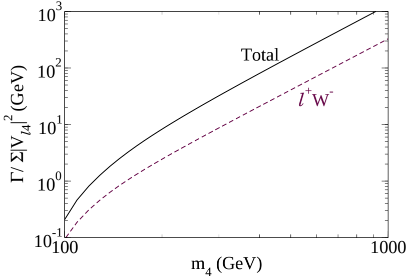
Majorana Neutrino Decay

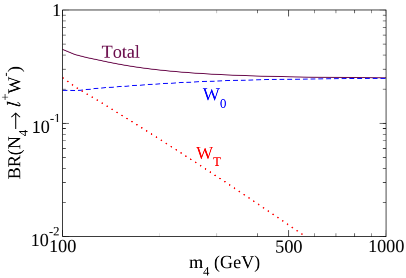
Majorana neutrino may decay to $W^\pm$, Z and higgs:

$$\Gamma_N(\ell^\pm W_0^\mp) = \frac{g_2^2}{64\pi M_W^2}|V_{\ell 4}|^2 m_N^3 (1-x_W^2)^2, \qquad \Gamma_N(\ell^\pm W_T^\mp) = \frac{g_2^2}{32\pi}|V_{\ell 4}|^2 m_N \left(1-x_W^2\right)^2$$

$$\Gamma_N(\nu_\ell Z) = \frac{g_2^2}{32\pi\cos^2\theta_W}|V_{\ell 4}|^2 m_N \left(1+\frac{m_N^2}{2M_Z^2}\right)(1-x_Z^2)^2 \qquad \Gamma_N(\nu_\ell H) = \frac{g_2^2}{64\pi M_W^2}|V_{\ell 4}|^2 m_N^3 (1-x_H^2)^2$$

where $x_i = M_i/m_N$.





Signal and Background

For $M_{W'} = 2.5$ TeV and $m_N = 500$ GeV, the signal cross section with consecutive cuts is:

σ(fb)	14 TeV	
	W'_L	W'_R
No cuts or smearing	2.7	3.6
+Smearing+Acceptance Cuts	2.4	2.6
+ΔR cuts	1.2	2.0
+m_N^{rec} and $\hat{s}$ cuts	0.95	1.8
+$\not{E}_T$ and m_{jj} cuts	0.77	1.5

The largest backgrounds are $t\bar{t}$ with

$$t \to W^+ b \to \ell^+ \nu_l b, \quad \bar{t} \to W^- \bar{b} \to W^- \bar{c} \nu_l \ell^+.$$

Other backgrounds include

$$pp \to W^\pm W^\pm W^\mp, \qquad pp \to W^\pm W^\pm jj$$
$$pp \to jjZZ, \qquad pp \to jjZW$$

At the 14 TeV, with all cuts except m_N^{rec} and $\hat{s}$, the total background cross section is 0.085 fb.