Heavy Majorana Neutrino and Chiral Rules

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Majorana Neutrinos at Colliders

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Majorana Neutrinos and the Production of the Right-Handed Charged Gauge Boson

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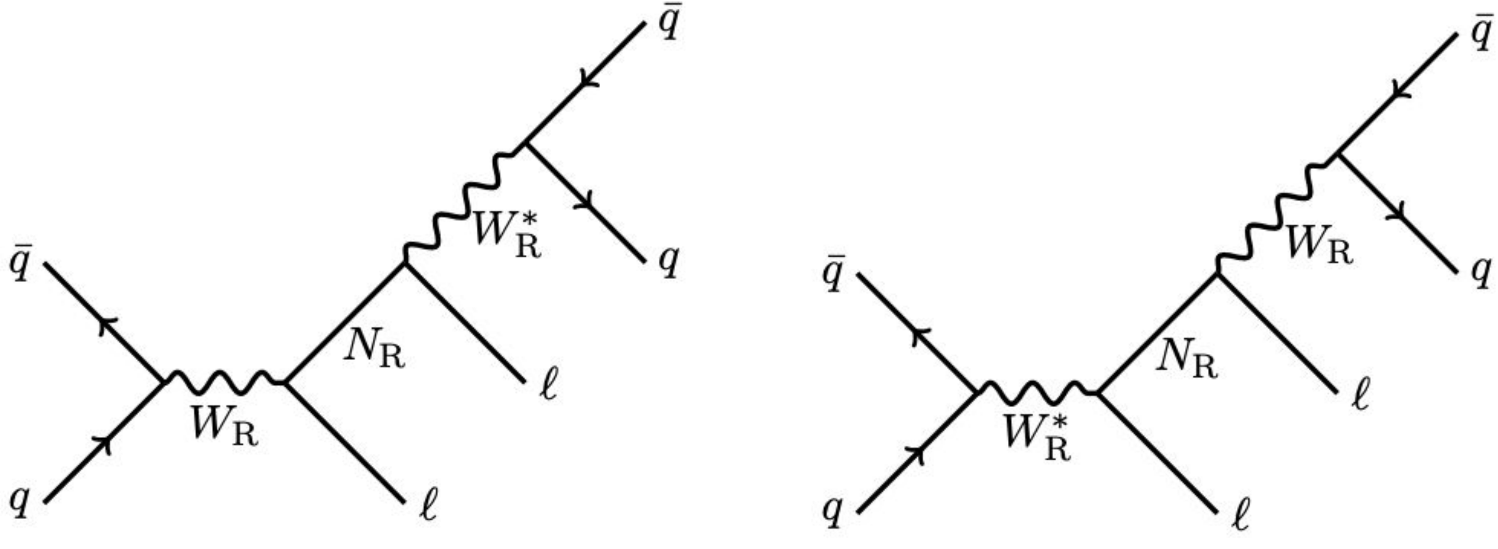
A possibility of a very clean signature for the production of $W_R^{\pm}$ is pointed out. If the right-handed neutrino is lighter than $W_R^{\pm}$, left-right symmetric gauge theory predicts the decay $W_R^+ \to \mu^+\mu^+ + 2$ hadronic jets, with the branching ratio $\simeq 3\%$. The lack of neutrinos in the final state and the absence of a sizable background make $W_R^{\pm}$ rather easy to detect (if it exists). Detailed predictions regarding the production and decay rates of W_R^+ are presented.

PACS numbers: 14.80.Er, 12.10.Ck, 13.85.Qk, 14.60.Gh

We would like to thank . . . Larry Trueman for getting us involved with the physics study for the future CBA at the Brookhaven National Laboratory that led to this work.

Inverse process of the neutrinoless double beta decay at very high energy.



(a) (b)

Figure 1. The KS process, for (a) the $m_{W_R} > m_{N_R}$ case and (b) the $m_{N_R} > m_{W_R}$ case.

- Fully reconstructed kinematics w/o $\not{p}$
- Majorana rules

Tao Han et al., Phys. Rev. Lett. 97, (2006)

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Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with two charged leptons and two jets at $\sqrt{s} = 13\,\text{TeV}$ with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: A search for heavy right-handed Majorana or Dirac neutrinos N_{R} and heavy right-handed gauge bosons W_{R} is performed in events with a pair of energetic electrons or muons, with the same or opposite electric charge, and two energetic jets. The events

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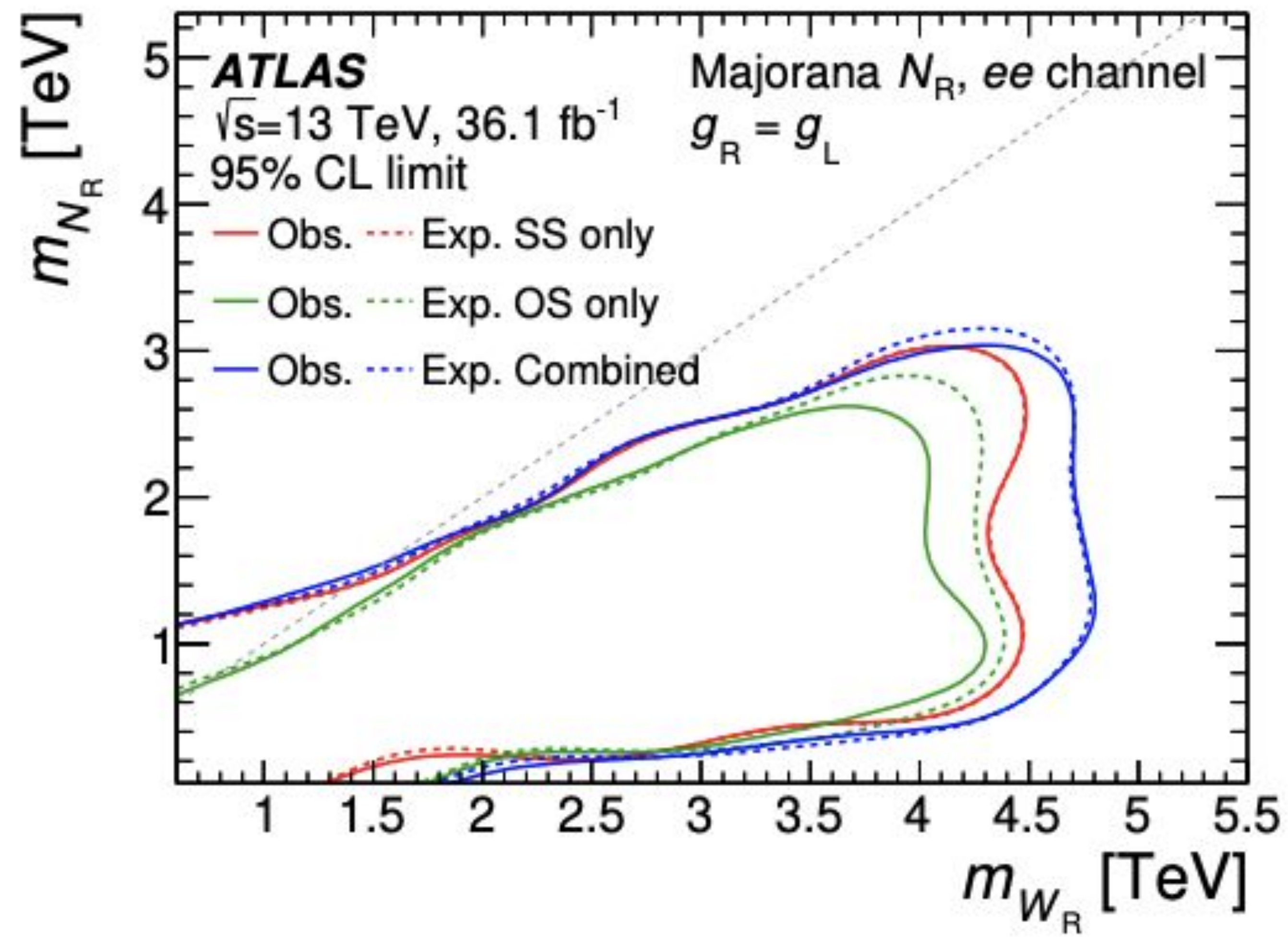

ATLAS
√s=13 TeV, 36.1 fb-1
95% CL limit
Majorana N_R, ee channel
$g_R = g_L$
Obs.
Exp. SS only
Obs.
Exp. OS only
Obs.
Exp. Combined
m_{N_R} [TeV]
m_{W_R} [TeV]
1
2
3
4
5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5

For the opposite sign process $\bar{u}d \to W_R^- \to e^- N$ plus $N \to e^+ jj$

$$\cdots \gamma^\mu \tfrac{1}{2}(1+\gamma_5) \frac{\not p + M}{p^2 - M^2 + i\Gamma_N M} \gamma^\nu \tfrac{1}{2}(1+\gamma_5) \cdots$$

if we look at the same sign process, $\bar{u}d \to W_R^- \to e^- N$ plus $N \to e^- j'j'$,

$$\cdots \gamma^\mu \tfrac{1}{2}(1+\gamma_5) \frac{\not p + M}{p^2 - M^2 + i\Gamma_N M} \gamma^\nu \tfrac{1}{2}(1-\gamma_5)(-1) \cdots$$

$\Sigma^{abs} = A \not p + B$

$$\cdots \not p (A \not p + B) \not p \cdots = \cdots p^2 (A \not p + B) \cdots$$

$$\cdots M (A \not p + B) M \cdots = \cdots M^2 (A \not p + B) \cdots$$

$$\frac{\text{Opposite sign}}{\text{Same sign}} = \frac{p^2}{M^2}$$

Helicity Method a la Barger et el.

The overall amplitude accounting both the production and the decay is

$$\mathcal{M}_{(V+A)^2} = \underbrace{(\cdots d_\mu \gamma^\mu R)}_{\text{decay}}(\not{N} + \cancel{M_N})\underbrace{(\gamma^\nu R p_\nu \cdots)}_{\text{prod.}} \ ,$$

$$\sum |\mathcal{M}|^2_{(V+A)^2} = \mathrm{Tr}\left(\cdots p_\beta \gamma^\beta R \times \not{N}\gamma^\alpha R d_\alpha \cdots \cdots d_\mu \gamma^\mu R \times \not{N}\gamma^\nu R p_\nu \cdots\right) \ .$$

$$\sum |\mathcal{M}|^2_{(V+A)^2} = \tfrac{1}{4}\mathrm{Tr}\underbrace{\left(\Gamma^i \ \not{N}\gamma^\nu R p_\nu \cdots\cdots p_\beta \gamma^\beta R\right)}_{N\cdot\mathcal{P}} \mathrm{Tr}\underbrace{(\Gamma_i \ \not{N}\gamma^\alpha R d_\alpha \cdots\cdots d_\mu \gamma^\mu R)}_{N\cdot\mathcal{D}} \ .$$

$\Gamma \in \{1, \gamma_5, \frac{1}{\sqrt{2!}}\sigma_{\rho\eta}, \gamma_\rho, i\gamma_\rho\gamma_5\}$

for $\Gamma_i = 1$ and γ_5,

$$\sum |\mathcal{M}|^2_{(V+A)^2} = \tfrac{1}{4}\left(2\mathcal{P}\cdot N \ \mathcal{D}\cdot N\right) \quad + \quad \cdots\cdot$$

tensor matrix $\Gamma_i = \frac{1}{\sqrt{2!}}\sigma_{\rho\eta}$.

$$\gamma^\rho\gamma^\eta \not{N} = g^{\rho\eta} \not{N} - N^\rho\gamma^\eta + N^\eta\gamma^\rho - i\epsilon^{\rho\eta N\xi}\gamma_\xi\gamma_5 \ .$$

$$\sigma_{\rho\eta} \not{N} = \tfrac{1}{i}(-N^\rho\gamma^\eta + N^\eta\gamma^\rho) - \epsilon^{\rho\eta N\xi}\gamma_\xi\gamma_5 \ .$$

After some algebra, we obtain the correlated probability,

$$\tfrac{1}{4}\left[2\mathcal{P}\cdot N \ \mathcal{D}\cdot N + (2\mathcal{P}\cdot N \ \mathcal{D}\cdot N - 2N\cdot N\mathcal{P}\cdot\mathcal{D})\right] \ .$$

The same result applies for $(V-A)^2$.

$$\boxed{\sum|\mathcal{M}|^2_{(V+A)^2} = \mathcal{P}\cdot N \ \mathcal{D}\cdot N - \tfrac{1}{2}N\cdot N\mathcal{P}\cdot\mathcal{D} \ .}$$

$$\boxed{\sum|\mathcal{M}|^2_{(V\pm A)\otimes(V\mp A)} = +\tfrac{1}{2}M_N^2\mathcal{P}\cdot\mathcal{D} \ .}$$

$$\int d(\mathrm{PS})\sum|\mathcal{M}|^2_{(V\pm A)\otimes(V\mp A)} = \int d(\mathrm{PS})\sum|\mathcal{M}|^2_{(V\pm A)^2} \ .$$

$u\overline{d} \to W_R^+ \to \overline{\ell} N$ $\qquad \sum |\mathcal{M}_{\text{prod}}|^2 = (N \cdot \overline{d})(u \cdot \overline{\ell})(\ldots)$

decaying $N \to \ell' u' \overline{d}'$. $\sum |\mathcal{M}^{\text{op}}_{\text{deca}}|^2 = (N \cdot \overline{d}')(u' \cdot \ell')(\cdots)$

$$\sum |\mathcal{M}^{\text{op}}|^2 = (u \cdot \overline{\ell})(u' \cdot \ell') \left[(N \cdot \overline{d})(N \cdot \overline{d}') - \tfrac{1}{2} N^2 (\overline{d} \cdot \overline{d}') \right] (\cdots)(\cdots)$$

$N \to \overline{\ell}' \overline{u}' d'$

$$\sum |\mathcal{M}^{\text{ss}}_{\text{deca}}|^2 = (N \cdot d')(\overline{u}' \cdot \overline{\ell}')(\cdots)$$

$$\sum |\mathcal{M}^{\text{ss}}|^2 = (u \cdot \overline{\ell})(\overline{u}' \cdot \overline{\ell}') \left[\tfrac{1}{2} m_N^2 (\overline{d} \cdot d') \right] (\cdots)(\cdots)$$

Conclusion

Lepton Number Violation and Majorana Heavy Neutrino at Colliders has outstanding signal.

Charge-conjugated channels (OS/SS) have the same rate when the decay PS integrated.

But they have different event distributions, which provide good test of Majorana Feynman rules.

V. Barger (1974 IHEP, London)

As a parting comment, Figure 34 illustrates the real art of phenomenology. Theoretical interpretations at times depend on how the data are plotted. Unfortunately more than one interpretation is sometimes possible as is the case here.

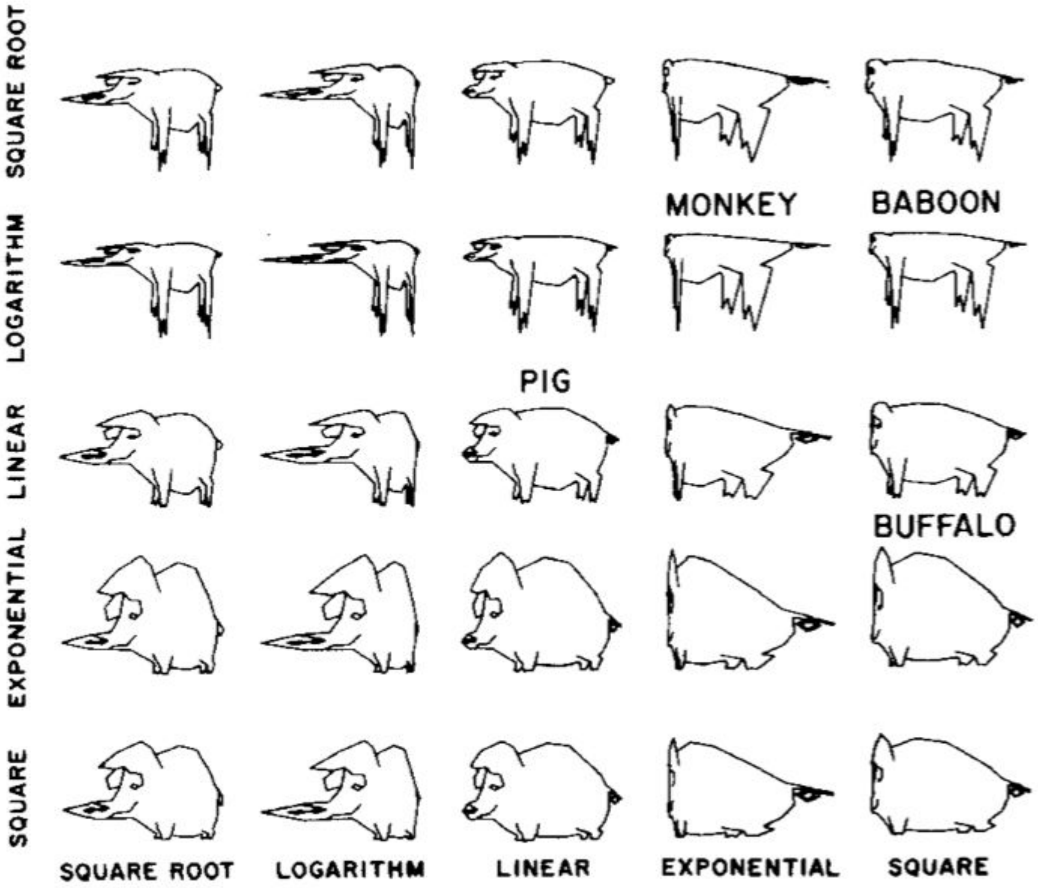

Figure 34: The art of phenomenology.