Type-III see-saw at the LHC

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Outline

1. introduction
   - see-saw type III
   - overview of LHC

2. TypeIII@LHC
   - interactions
   - production
   - decay
   - handles on neutrino spectrum
   - signals@partonic level
   - displaced vertexes

3. Conclusions
neutrino mass with type-III see-saw

Within the SM only left-handed neutrinos exists \( L_i = \left( \nu_i, \ell_i \right) \sim (2, -\frac{1}{2}) \)

Adding a fermionic SU(2) triplet \( N^a \)

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{N}_i i \partial \mathcal{D} N_i + \left[ \lambda^{ij} N^a_i (L_j \cdot \varepsilon \cdot \tau^a \cdot H) + \frac{M_{ij}}{2} N^a_i N^a_j + \text{h.c.} \right]
\]

Each \( N^a \) is coupled to one combination of flavours \( \ell \equiv c_i \cdot l_i \)
neutrino oscillations require at least 2 triplets, \( N^a_i = 1, 2, \ldots \)
neutrino masses \( m_i \) defined as
\( 0 < m_1 < m_2 < m_3 \)

constraints on the spectrum:
\[
\tilde{m}_i \equiv \frac{v^2 (\lambda^\dagger \lambda)_{ii}}{M_i}
\]
\( \tilde{m}_1 \geq m_1 \)
\( \sum_i \tilde{m}_i \geq \sum_i m_i \)
**PP collisions at design regime**

- **C.o.M. Energy** = 14 TeV
- \[ \mathcal{L} = 10^{34} \cdot cm^{-2}s^{-1} \]
- \(~ 10^4\) protons per bunch
- \(~ 25\) *pp* interactions per crossing
- bunch crossed each 25 ns

**Press Release**

First beam in the LHC - accelerating science

Geneva, 10 September 2008. The first beam in the Large Hadron Collider at CERN was successfully steered around the full 27 kilometres of the world’s most powerful particle accelerator at 10h28 this morning. This historic event marks a key moment in the transition from over two decades of preparation to a new era of scientific discovery.

“It’s a fantastic moment,” said LHC project leader Lyn Evans, “we can now look forward to a new era of understanding about the origins and evolution of the universe.”

Starting up a major new particle accelerator takes much more than flipping a switch. Thousands of individual elements have to work in harmony, timings have to be synchronized to under a billionth of a second, and beams finer than a human hair have to be brought into head-on collision. Today’s success puts a tick next to the first of those steps, and over the next few weeks, as the LHC’s operators gain experience and confidence with the new machine, the machine’s acceleration systems will be brought into play, and the beams will be brought into collision to allow the research programme to begin.
General Purpose Detector (CMS)

\[ \vec{p} = (p_T, \eta, \phi) \]

\[ p_T = \sqrt{p_x^2 + p_y^2} = p \cdot \sin \theta \]

\[ \eta = \ln \cot \frac{\theta}{2} \]

\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]
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\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]
\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{N}_i i \mathcal{D} N_i + \left[ \chi^{ij} N_i^a \left( L_j \cdot \varepsilon \cdot \tau^a \cdot H \right) + \frac{M_{ij}}{2} N_i^a N_j^a + \text{h.c.} \right] \]
**Drell-Yan**: $pp \rightarrow V \rightarrow N^a N^b$

Take only one triplet light enough for direct production

- Production dominated by gauge couplings
- $W^\pm NL$ and $Z^0 NL$ couplings is suppressed as $\frac{\lambda v}{M} \Rightarrow$ difficult to extract information about neutrino masses
- Due to spin of N, cross section is higher compared to type-II (scalar triplet) $\Rightarrow$ rough discrimination between type-II and type-I

![Graph showing cross section vs. mass](image-url)
Gauge decays: \( N^\pm \rightarrow N^0 W^\pm \)

As \( \Delta M \simeq 166 \text{ MeV} \):

- \( N^\pm \rightarrow N^0 \pi^\pm \)
- \( N^\pm \rightarrow N^0 l^\pm \nu_l (\bar{\nu}_l) \)

Yukawa decays

The lightest triplet \( N \) is coupled to the unknown combination of flavors

\[ \ell = c_1 e + c_2 \mu + c_3 \tau \]

\( N^0 \) Yukawa decays (c.c. final states left understood):

\[
\Gamma(N^0 \rightarrow h \nu_\ell) = \frac{1}{8} \frac{\lambda^2 M}{8\pi} (1 - \frac{m_h^2}{M^2})^2 \\
\Gamma(N^0 \rightarrow Z^0 \nu_\ell) = \frac{1}{8} \frac{\lambda^2 M}{8\pi} (1 - \frac{M_Z^2}{M^2})^2 (1 + 2 \frac{M_Z^2}{M^2}) \\
\Gamma(N^0 \rightarrow W^+ \ell^-) = \frac{1}{4} \frac{\lambda^2 M}{8\pi} (1 - \frac{M_W^2}{M^2})^2 (1 + 2 \frac{M_W^2}{M^2}) 
\]

\( N^\pm \) Yukawa decays (c.c. final states left understood):

\[
\Gamma(N^\pm \rightarrow \ell^\pm h) = \frac{1}{4} \frac{\lambda^2 M}{8\pi} (1 - \frac{m_h^2}{M^2})^2 \\
\Gamma(N^\pm \rightarrow \ell^\pm Z^0) = \frac{1}{4} \frac{\lambda^2 M}{8\pi} (1 - \frac{M_Z^2}{M^2})^2 (1 + 2 \frac{M_Z^2}{M^2}) \\
\Gamma(N^\pm \rightarrow \nu_\ell W^\pm) = \frac{1}{2} \frac{\lambda^2 M}{8\pi} (1 - \frac{M_W^2}{M^2})^2 (1 + 2 \frac{M_W^2}{M^2}) 
\]
introduction

**TypeIII@LHC Conclusions**

handles on neutrino spectrum

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**Yukawa dominates when** $\tilde{m}_1 \gtrsim 10^{-4}$ eV

![Graph showing Yukawa dominance](graph.png)

- $N_0 \rightarrow vh$, $N^\pm \rightarrow f^\pm h$
- $N_0 \rightarrow Zv$, $N^\pm \rightarrow Zf^\pm$
- $N_0 \rightarrow W^\mp f^\pm$, $N^\pm \rightarrow W^\pm \nu$
- $N^\pm \rightarrow N_0 f^\pm$
- $N^\pm \rightarrow N_0 f^\mp \nu$

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**Constraints on the spectrum**

- $\Gamma(Yukawa)/\Gamma(Gauge)$ depends on $\tilde{m}_1$
- $\Gamma_{tot}$ (vertex displacement) depends on $\tilde{m}_1$

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**N can have a displaced decay vertex**

![Graph showing displaced decay](graph.png)

- $\tau_{N_0}$
- $\tau_{N_0}$
- $\tilde{m}_1$ in eV
- $M$ in GeV
- $0.1$ mm
- mm
- cm
- dm
- m

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**Introduction**

**Signals at partonic level**

**LFV:** \( pp \rightarrow N^+ N^{(-,0)} \rightarrow (\ell_1^+ Z)(\ell_2^- V) \)

- \( pp \rightarrow \ell_1 \bar{\ell}_2 4j \)
  - no missing transverse energy
  - \( p_T^l \sim M \)
  - \( 4j \sim ZV \)
  - central production at large \( M \)

- LFV with LNC
- not available in type II

**Low \( M \)**
- low \( \mathcal{L} \) in principle
- use of \( E_T \) risky
- just using \( p_T^l \) cut \( S/\sqrt{B} \sim 1 \)

At \( M=250 \text{ GeV}, p_T^l > 70 \text{ GeV} \)
- \( S=8 \text{ fb}, B=36 \text{ fb} \)

**F. del Aguila, J. A. Aguilar-Saavedra**

- \( pp \rightarrow t\bar{t}2j \rightarrow 2j2b\ell_1 \bar{\ell}_2 E_T (\text{Madgraph}) \)
  - 7.2 pb after \( p_T^j > 20 \text{ GeV}, p_T^l > 10 \text{ GeV}, \eta < 5, \Delta R > 0.4 \)
  - \( 2b2j \sim ZV \) lessen to 250 fb

- \( pp \rightarrow \) at \( M=300 \text{ GeV} \) finds that detector level effects shift the discovery at \( \mathcal{L} \sim 80/\text{fb} \)
**signals@partonic level**

**LNV:** $pp \rightarrow (N^+ \rightarrow \ell_1^+ Z^0)(N^0 \rightarrow \ell_2^+ W^-)$

- $pp \rightarrow 4j \ell_1 \ell_2$
  - no missing transverse energy
  - $p_T^\ell \sim M$
  - $4j \sim ZW$

- same-sign leptons $\Rightarrow$ lower BG
- LNV and LFV
- $\frac{\Gamma(WW)}{\Gamma(WZ)}$ is sensitive to
- $BR(N^+ \rightarrow N^0 \pi^+) \sim O(1)$
- $BR(N^+ \rightarrow N^0 \pi^+) \Rightarrow \tilde{m}_1$

- $pp \rightarrow 4j W^+ W^- \rightarrow 4j \ell_1^+ \ell_2^+ E_T$
  - Alpgen yields $O(20 \text{ fb})$ with $p_T^\ell > 20 \text{GeV}, \eta < 5, \Delta R_{jj} > 0.4$
  - BG can be reduced as in LFV

- $pp \rightarrow \bar{t}tnj$
  - in principle no same-sign pairs
  - $t \rightarrow cW^+ W^-$ cannot be entirely removed because of detector effects

- $M = 300 \text{ GeV}$

arXiv:0808.2468 includes detector effects and finds $5\sigma$ discovery for $\mathcal{L} = 2/\text{fb}$
displaced vertexes

vertex displacement and neutrino mass

**Vertex measurement**
- check of $\Gamma(Gauge)/\Gamma(Yukawa)$
- only possible direct measurement when Yukawa dominates

**features of the spectrum**
- $c_T \gtrsim 0.1\,\text{mm}$ gives
  $\tilde{m}_1 \lesssim \sqrt{\Delta^2_{atm}}$
  and points towards hierarchy

- if all the involved triplets are discovered one can try to unfold the hierarchy using
  $$\Sigma_k \tilde{m}_k \geq \Sigma_i m_i$$
  ($\sim 10^{-1}\,\text{eV}$ for IH or
  $\sim 5 \cdot 10^{-2}\,\text{eV}$ for NH)

displacement above few cm is not possible in see-saw-II
displaced vertexes

detection issues

Detector size is $\sim 10\text{m}$ and not all parts can see all particles:

- displaced vertex can provide further *discrimination* against the background or be an *obstacle* to detect decay products of $N$.

unknown flavor composition of $\ell$ determines detectors performance

$\tilde{m}_1$ controls $\tau(N^{\pm,0})$

- a bonus rejection criterion for $c\tau \gtrsim 0.1\ \text{mm}$

- reconstruction worsen as distance from IP increase:
  $\tau \lesssim 0.5\text{m}$, $e \lesssim 1\text{m}$, $\mu \lesssim 10\text{m}$

- $\tilde{m}_1 \lesssim 10^{-6}\ \text{eV}$ has no signatures

- gauge decays are not detectable
  - $c\tau(N^+) \lesssim 6\text{cm}$

- far decays are difficult to see
  - $c\tau(N^0)$ is unbounded

- full detector response has to be simulated to assess the potential in vertex measurement
if TeV type-III see-saw is relevant for neutrino masses

- LFV and LNV discoverable at the LHC
- measurement of $\text{BR}(N^+ \to N^0 \pi^+)$ and vertex displacement tell about light neutrino spectrum degeneracy
- the type of spectrum hierarchy can potentially be determined
- determination of the flavour composition of $\ell$ gives insights into neutrino Yukawas couplings