Type-III see-saw at the LHC

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arXiv:0805.1613 with T.Hambye and A. Strumia

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Outline

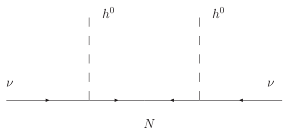
1. **introduction**
   - see-saw type III
   - overview of LHC
2. **TypeIII@LHC**
   - interactions
   - production
   - decay
   - handles on neutrino spectrum
   - signals@partonic level
   - displaced vertexes
3. **Conclusions**

neutrino mass with type-III see-saw

Within the SM only left-handed neutrinos exists $L_i = \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \sim (\mathbf{2}, -\frac{1}{2})$

Adding a fermionic SU(2) triplet N^a

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \bar{N}_i i \not{D} N_i + \left[\lambda^{ij}\, N_i^a (L_j \cdot \varepsilon \cdot \tau^a \cdot H) + \frac{M_{ij}}{2} N_i^a N_j^a + \text{h.c.} \right]$$



- Each N^a is coupled to one combination of flavours $\ell \equiv c_i \cdot l_i$
- neutrino oscillations require at least 2 triplets, $N^a_{i=1,2,\dots}$

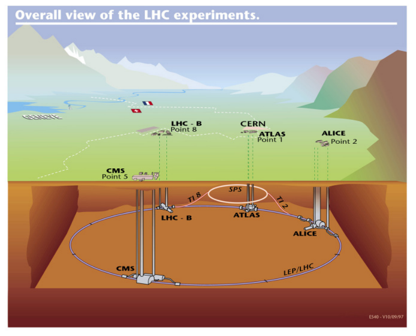
neutrino masses m_i defined as $0 < m_1 < m_2 < m_3$

constraints on the spectrum:

$$\tilde{m}_i \equiv \frac{v^2 (\lambda^\dagger \lambda)_{ii}}{M_i}$$

- $\tilde{m}_1 \geqslant m_1$
- $\Sigma_i \tilde{m}_i \geqslant \Sigma_i m_i$

overview of LHC



pp collisions at design regime

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

operation just started !!!

Press Release

First beam in the LHC - accelerating science

PR08.08
10.09.2008

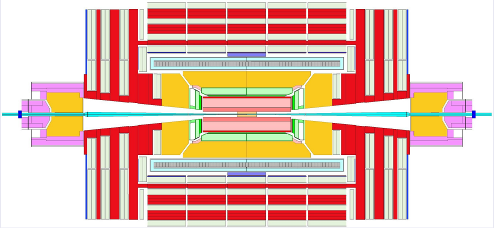
Geneva, 10 September 2008. The first beam in the Large Hadron Collider at CERN[1] was successfully steered around the full 27 kilometres of the world's most powerful particle accelerator at 10h28 this morning. This historic event marks a key moment in the transition from over two decades of preparation 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.

A historic moment in the CERN Control Centre: the beam was successfully steered around the accelerator.

General Purpose Detector (CMS)

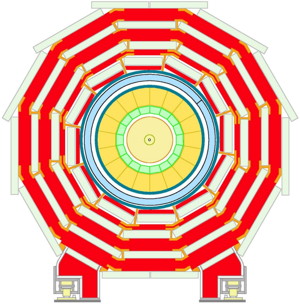


$\vec{p} = (p_T, \eta, \phi)$

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

$$\eta = \ln\cot\frac{\theta}{2}$$

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



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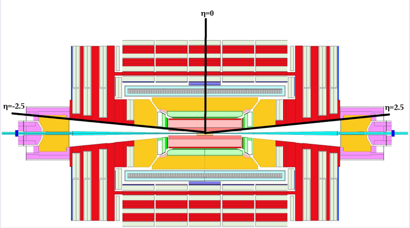

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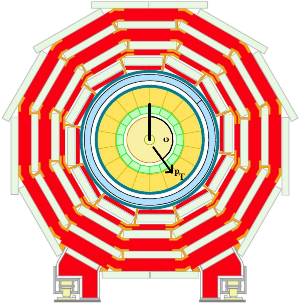

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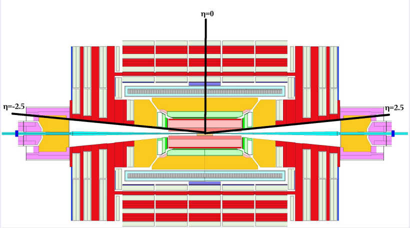

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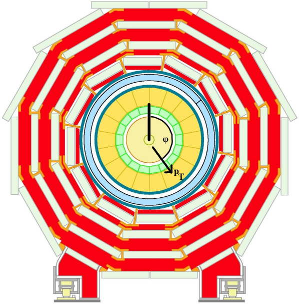
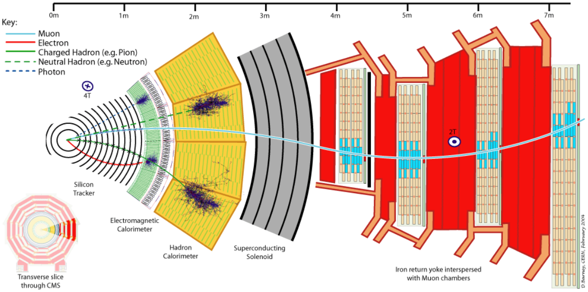
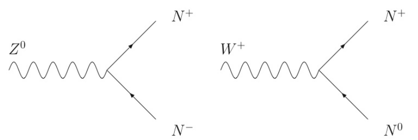




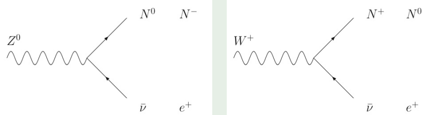
interactions

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \bar{N}_i i \not{D} N_i + \left[\lambda^{ij}\, N_i^a (L_j \cdot \varepsilon \cdot \tau^a \cdot H) + \frac{M_{ij}}{2} N_i^a N_j^a + \text{h.c.}\right]$$

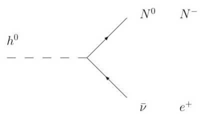
gauge interactions (production)



new interactions after SSB (decay)



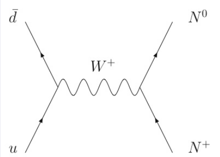
$N^0 - \nu$ and $N^- - e^-$ mixing

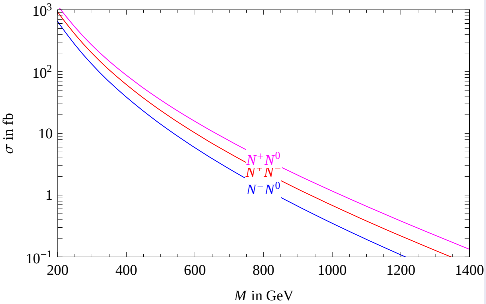


all the new vertexes have been added to MADGRAPH

Drell-Yan: $pp \to V \to N^a N^b$

Take only one triplet light enough for direct production





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

Gauge decays: $N^\pm \to N^0 W^{\pm *}$

As $\Delta M \simeq 166$ MeV:

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

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)

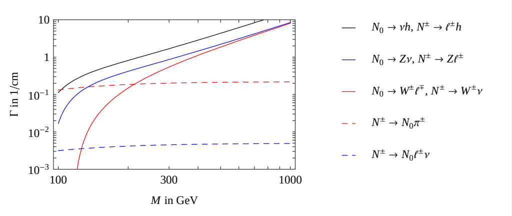
$$\Gamma(N^0 \to h\nu_\ell) = \frac{1}{8}\frac{\lambda^2 M}{8\pi}(1 - \frac{m_h^2}{M^2})^2$$
$$\Gamma(N^0 \to Z^0\nu_\ell) = \frac{1}{8}\frac{\lambda^2 M}{8\pi}(1 - \frac{M_Z^2}{M^2})^2(1 + 2\frac{M_Z^2}{M^2})$$
$$\Gamma(N^0 \to W^+\ell^-) = \frac{1}{4}\frac{\lambda^2 M}{8\pi}(1 - \frac{M_W^2}{M^2})^2(1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

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

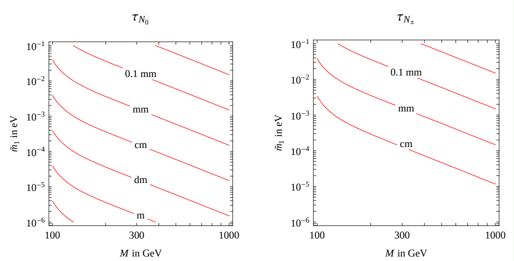
$$\Gamma(N^\pm \to \ell^\pm h) = \frac{1}{4}\frac{\lambda^2 M}{8\pi}(1 - \frac{m_h^2}{M^2})^2$$
$$\Gamma(N^\pm \to \ell^\pm Z^0) = \frac{1}{4}\frac{\lambda^2 M}{8\pi}(1 - \frac{M_Z^2}{M^2})^2(1 + 2\frac{M_Z^2}{M^2})$$
$$\Gamma(N^\pm \to \nu_\ell W^\pm) = \frac{1}{2}\frac{\lambda^2 M}{8\pi}(1 - \frac{M_W^2}{M^2})^2(1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

handles on neutrino spectrum

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



N can have a *displaced decay* vertex



constraints on the spectrum

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

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

$pp \to \ell_1 \bar{\ell}_2 4j$

- 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

$pp \to t\bar{t}2j \to 2j2b\ell_1\bar{\ell}_2 \not{E}_T$ (Madgraph)

- 7.2 pb after $p_T^j > 20 GeV, p_T^l > 10 GeV, \eta < 5, \Delta R > 0.4$
- $2b2j \sim ZV$ lessen to 250 fb

low M

- low $\mathcal{L}$ in principle
- use of $\not{E}_T$ risky
- just using p_T^l cut $S/\sqrt{B} \sim 1$

At M=250 GeV, with $p_T^l > 70 GeV$
S=8 fb, B=36 fb

F. del Aguila, J. A. Aguilar-Saavedra
arXiv:0808.2468

at M=300 GeV finds that detector level effects shift the discovery at $\mathcal{L} \simeq 80/fb$

LNV: $pp \longrightarrow (N^{+} \longrightarrow \ell_1^{+} Z^{0})(N^{0} \longrightarrow \ell_2^{+} W^{-})$

$pp \longrightarrow 4j\ell_1\ell_2$

- no missing transverse energy
- $p_T^l \sim M$
- $4j \sim ZW$

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

$pp \longrightarrow 4jW^{+}W^{+} \longrightarrow 4j\ell_1^{+}\ell_2^{+}\not{E}_T$

- Alpgen yields O(20 fb) with $p_T^j > 20 GeV, \eta < 5, \Delta R_{jj} > 0.4$
- BG can be reduced as in LFV

$pp \longrightarrow \bar{t}tnj$

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

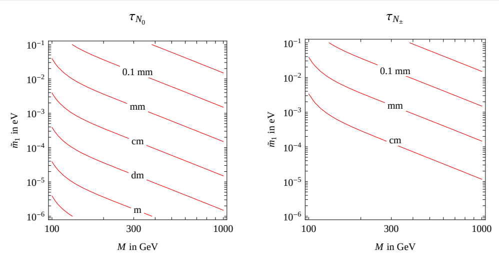
$M = 300$ GeV

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

vertex displacement and neutrino mass

Vertex measurement

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



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

features of the spectrum

- $c\tau \gtrsim 0.1\ \mathrm{mm}$ 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
$$\Sigma_k \tilde{m}_k \geqslant \Sigma_i m_i$$
($\sim 10^{-1}$eV for IH or $\sim 5 \cdot 10^{-2}$eV for NH)

detection issues

Detector size is $\sim$ 10m 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 ℓ determines detectors performance

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

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

gauge decays are not detectable

- $c\tau(N^+) \lesssim 6\mathrm{cm}$

far decays are difficult to see

- $c\tau(N^0)$ is unbounded

- reconstruction worsen as distance from IP increase: $\tau \lesssim 0.5\mathrm{m},\ e \lesssim 1\mathrm{m},\ \mu \lesssim 10\mathrm{m}$
- $\tilde{m}_1 \lesssim 10^{-6}$ eV has no signatures

- *full detector response* has to be simulated to assess the potential in vertex measurement

Conclusions

if TeV type-III see-saw is relevant for neutrino masses

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