Probing the nature of Electroweak Symmetry breaking at the LHC with the ATLAS detector

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Type II Seesaw: Motivation

- Massless neutrinos in Standard Model.
- Neutrino oscillation discovered. Implication: Neutrinos have mass.
- Fixed by type II seesaw by introducing a scalar triplet.
- Model naturally gives a SM-like Higgs and a rich scalar structure $(H^{\pm}, H^{\pm}, A^0, H^0, h^0)$.
- Easy to find/rule out this model. It has very unique experimental signatures.
- If triplet hypercharge, Y = 2 ($Q = I_3 + \frac{Y}{2}$), doubly charged Higgs is a unique feature with clean decay channels.
- Light and heavy doubly charged Higgs possible. Direct searches at LHC for light Higgs are possible.

The main reference can be found here: arxiv 1105.1925

The potential (1)

A scalar triplet, Δ, with a hypercharge, $Y_\Delta = 2$, is included along with the SM doublet. $H \sim (1,2,1)\,, \Delta \sim (1,3,2)$ under the SM gauge group, $SU(3) \times SU(2) \times U(1)$. The most general Lagrangian in the scalar sector can then be written as,

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H,\Delta) + \mathcal{L}_{Yukawa} \tag{1}$$

where $V(H,\Delta)$ is given by,

$$V(H,\Delta) = -\, m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + m_\Delta^2 Tr(\Delta^\dagger \Delta) + [\mu(H^\dagger i\sigma^2 \Delta^\dagger H) + h.c.] \\ + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H$$

The potential (2)

$\mathcal{L}_{Yukawa}$ contains all terms from the SM. In addition, it also contains the term which gives mass to the neutrinos,

$$\mathcal{L}_{Yukawa} \supset -Y_\nu L^T C \otimes i\sigma^2 \Delta L \quad (2)$$

where L: $SU(2)_L$ lepton doublets; Y_ν: neutrino Yukawa couplings.
The fields Δ and H are given by

$$\Delta = \begin{pmatrix} \delta^+/\sqrt(2) & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}; H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Some extra comments:

- Δ has a **lepton number of -2** as seen from the yukawa term for neutrinos.
- The μ term **violates lepton number** by two units.
- Parameters: 5 independent couplings $\lambda_i's$, 3 mass parameters- m_H^2, M_Δ^2, and μ

Masses after EWSB: Charged Higgs

EWSB can be broken if the neutral components of H and Δ acquire vevs of v_d and v_t respectively at the minimum of the potential. Collecting quadratic terms (for eg: terms like $\delta^{++}\delta^{--}$) gives the mass,

$$m_{H^{\pm\pm}} = \frac{\sqrt{2}\mu v_d^2 - \lambda_4 v_d^2 v_t - 2\lambda_3 v_t^3}{2v_t} \tag{3}$$

$$m_{H^{\pm}} = \frac{(v_d^2 + v_t^2)[2\sqrt{2}\mu - \lambda_4 v_t]}{4v_t} \tag{4}$$

Already clear that large μ correspond to large masses for the doubly charged Higgs. The rest of the masses/mass mixing matrices are summarized in the back up slides and in the main reference.

Theoretical Constraints

Custodial symmetry: The fact the potential $V = V(H^\dagger H)$ ensures $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$ at tree level and measurements put upper bounds on v_t. At tree level, modified ρ is given by,

$$\rho = \frac{v_d^2 + 2v_t^2}{v_d^2 + 4v_t^2} (< 1)$$

In the limit $v_d \ggg v_t$, $\rho \approx 1 - 2\frac{v_t^2}{v_d^2}$. At 2σ level, $\rho_0 = 1.0004 \pm 0.00048$. This puts an upper bound on v_t of about 1.6 GeV. A little more leeway can be obtained by considering radiative corrections.
No Tachyonic modes: Result in an allowed range for μ i.e. $\mu_- < \mu < \mu_+$. μ_+ provides upper bounds on the six Higgs masses. Other constraints arise from requiring the vacuum to be stable, the potential to be bounded from below (BFB), and the scattering matrices to be unitary.

Experimental Signatures and Searches

- Production and decay modes
- Background possibilities
- Previous ATLAS searches: arxiv 1412.0237
- Previous CMS searches: arxiv 1207.2666v2
- Phenomenological paper considering the di-boson channel: arxiv 1305.2383v3

Production Modes

Possible production mechanisms include

- $p\bar{p}/pp \to \gamma^*, Z^* \to H^{\pm\pm}H^{\mp\mp}X$
- $p\bar{p}/pp \to W^{\pm *}W^{\pm *} \to H^{\pm\pm}X$ (depends on $H^{\pm\pm}W^{\pm}W^{\pm}$ coupling which is proportional to the v_t as $-i\sqrt{2}g^2 v_t g_{\mu\nu}$. This could be compensated by the fact that VV fusion can be substantial at high energies?)

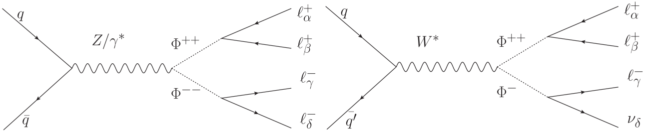
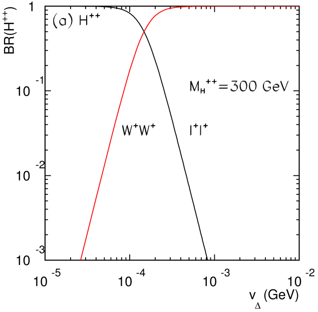


Figure 1: Feynman diagrams for pair and associated production of Φ^{++}.

Decay Modes

Two main modes of decay to choose from:

- $H^{\pm\pm} \to l^{\pm} l^{\pm}$. Searches for this mode have been performed at L3, OPAL, Delphi, CDF, ATLAS, CMS .. assuming 100% BR. Some results from ATLAS and CMS later!
- $H^{\pm\pm} \to W^{\pm} W^{\pm} \to l^{\pm} l^{\pm} \nu\nu$. In some part of the parameter space, this is substantial and the previous mode is suppressed.



- If H^{++} and H^{--} are produced in pairs, there would be 4 leptons in the final state. Of these, how many can be detected depends on the production mechanism of the $H^{\pm\pm}$
- If $H^{\pm\pm}$ is produce in association with a $H^{\mp}/W^{\mp}$, the final state would have 3 leptons.
- So, the final state can have 2, 3, or 4 leptons with/without missing E_T.
- Some of the other decay modes could be $H^{\pm\pm} \rightarrow W^{\pm}H^{\pm}$ or $H^{\pm\pm} \rightarrow H^{\pm}H^{\pm}$

Background sources

Plus-point: Both final states have similar background sources and are reasonably clean to test!
Two types of background sources - prompt and $t\bar{t}$.

- Prompt sources: WZ, ZZ, WW, ttW, ttZ
- Non-prompt: $t\bar{t}$

Other issues at the level of identification like $\pi^{\pm}$ as fake electrons, $\pi^0 \to e^+e^-$ with the charge of one of the leptons being misidentified etc.

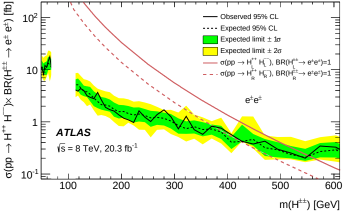
Experimental Searches: ATLAS

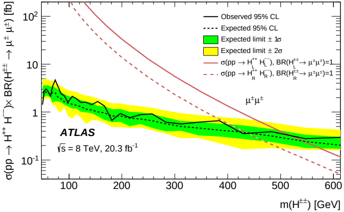
Claim: Type II Seesaw as a LRSM with $\sigma_{H_L^{++}H_L^{--}} \sim 2.5\sigma_{H_R^{++}H_R^{--}}$ because of the coupling with Z-bosons.

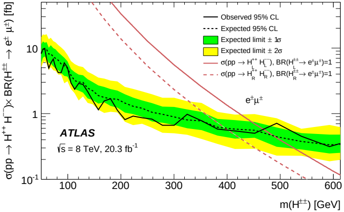
- $H^{\pm\pm} \to l^{\pm}l^{\pm}; (e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm})$
- 100% BR assumed. Mass limits depend on such assumptions.
- Search for narrow resonances at invariant mass of interest.
- Event selection:
  - $e_{P_T} > 20/22$ GeV; $\mu_{P_T} > 18$ GeV;
  - Isolated leptons
  - All pairs considered, so multiple pairs per event
  - $m_{ll} > 15$ GeV
  - veto over Z for electrons to avoid background dure to charge misID
- Windows in m_{ll} defined to ensure signal sensitivity. These are compared to expected signal and background yields.
- Resonance width dominated by detector resolution. Windows defined take this into account.

Experimental Searches: ATLAS - Results

Lower bounds on the mass of the doubly charged Higgs in the LRSM using the channels $e^{\pm}e^{\pm}, and \mu^{\pm}\mu^{\pm}$ were set to be 550 GeV and 430 GeV respectively. Constraints on the $\sigma \times BR$ are shown:







Experimental Searches: CMS

Search for doubly charged Higgs in type II Seesaw model with a Y=2 scalar triplet. $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ are assumed to be suppressed.

- Study split into 4 Benchmark points (BP): BP1 - normal neutrino mass hierarchy, BP2 - inverted hierarchy, BP3 - degenerate masses, BP4 - H^{++} has equal BR to all lepton generations.
- Signal processes simulated at 16 mass points ranging from 130-70) GeV.
- Mass windows are defined for good signal sensitivities. The lower bounds of the window depend on the final state.
- Special distinction made while analyzing light leptons and heavy leptons.
- A few additional cuts are used compared to ATLAS. Details can be found in http://arxiv.org/abs/1207.2666 .

Experimental Searches: CMS Results

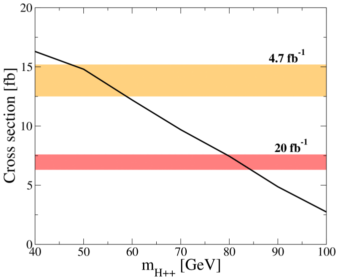
These bounds were obtained with $\sqrt{s} = 7$ TeV data. Combined results imply results from considering the pair-production of the doubly charged Higgs and results from the associated production of $H^{\pm\pm}$ with $H^{\pm}$.

Benchmark point	Combined 95% CL limit [GeV]	95% CL limit for pair production only [GeV]
$\mathcal{B}(\Phi^{++} \to e^+e^+) = 100\%$	444	382
$\mathcal{B}(\Phi^{++} \to e^+\mu^+) = 100\%$	453	391
$\mathcal{B}(\Phi^{++} \to e^+\tau^+) = 100\%$	373	293
$\mathcal{B}(\Phi^{++} \to \mu^+\mu^+) = 100\%$	459	395
$\mathcal{B}(\Phi^{++} \to \mu^+\tau^+) = 100\%$	375	300
$\mathcal{B}(\Phi^{++} \to \tau^+\tau^+) = 100\%$	204	169
BP1	383	333
BP2	408	359
BP3	403	355
BP4	400	353

Phenomenological bounds: Paper by S. Kanemura et al

Study region in parameter space where $H^{++} \rightarrow W^{\pm *} W^{\pm *}$ is dominant i.e. $v_t > 0.1$ MeV. **Lower limit set to 85 GeV.**

- Production: $pp \rightarrow \gamma^* / Z^* \rightarrow H^{\pm\pm} H^{\mp\mp}$ and $pp \rightarrow W^{\pm *} \rightarrow H^{\pm\pm} H^{\mp}$. Production modes with low cross-sections were not considered.
- Decay: $H^{++} H^{--} \rightarrow W^+ W^+ W^- W^- \rightarrow l^\pm l^\pm \not{E}_T + X$
  $H^{\pm\pm} H^{\mp} \rightarrow W^\pm W^\pm + X \rightarrow l^\pm l^\pm \not{E}_T + X$
- Assumption: $H^{\pm\pm}$ and $H^\pm$ have the same mass.
- Results extrapolated to 20 fb^{-1} of data.



Towards the analysis..

Start by looking at all possible branching ratios for the doubly charged Higgs produced in pairs, and then produced singly. If we restrict ourselves to the regime for WW decay mode dominates and ll-mode is suppressed, we assume $H^{\pm\pm} \to W^{\pm}W^{\pm}$ to be 100%.

$H^{\pm\pm}H^{\mp\mp} \to 4W$	BR (in %)
$\to 0l + 8$ jets	20.1
$\to 1l + \not{E}_T + 6$ jets	39.7
$\to 2l + \not{E}_T + 4$ jets	29.3
$\to 3l + \not{E}_T + 2$ jets	9.6
$\to 4l + \not{E}_T +$ no jets	1.2

Frameworks available at CPPM to 2l and 3l final states. A possible starting point would be to use these on the DCH MC available in ATLAS already.

Backup

Masses after EWSB: Neutral Higgs

Mass matrices for neutral scalar and pseudo-scalar Higgs,

$$\mathcal{M}^2_{\mathcal{CP}_{even}} = \begin{pmatrix} \frac{\lambda v_d^2}{2} & v_d(-\sqrt{2}\mu + (\lambda_1 + \lambda_4)v_t \\ v_d(-\sqrt{2}\mu + (\lambda_1 + \lambda_4)v_t & \frac{\sqrt{2}\mu v_d^2 + 4(\lambda_2 + \lambda_3)v_t^3)}{2v_t} \end{pmatrix} \tag{5}$$

$$\mathcal{M}^2_{\mathcal{CP}_{odd}} = \begin{pmatrix} 2v_t & -v_d \\ -v_d & v_d^2/2v_t \end{pmatrix} \tag{6}$$

The masses are then given by,

$$m^2_{h^0} = 1/2[A + C - \sqrt{(A - C)^2 + 4B^2}],$$
$$m^2_{H^0} = 1/2[A + C + \sqrt{(A - C)^2 + 4B^2}]$$

Notation: $\mathcal{M}_{CP_{even}}[11] = A$, $\mathcal{M}_{CP_{even}}[12] = B$, $\mathcal{M}_{CP_{even}}[22] = C$

Mass mixing for neutral Higgs

Diagonalizing (by applying rotation) the matrices give the masses and the corresponding Mass eigenstates. If the rotation angles are α and β for the $\mathcal{CP}_{even}$ and $\mathcal{CP}_{odd}$ matrices respectively, then the massive neutral physical states with even parity are given by,

$$h^0 = c_\alpha h + s_\alpha \xi^0 ; H^0 = s_\alpha h + c_\alpha \xi^0 \tag{7}$$

$$A^0 = -s_\beta Z_1 + c_\beta Z_2 ; G^0 = c_\beta Z_1 + s_\beta Z_2 \tag{8}$$

where h and ξ^0 are $Re(\phi^0)$ and $Re(\delta^0)$. Z_1 and Z_2 are $Im(\phi^0)$ and $Im(\delta^0)$ respectively. G^0 is the massless Goldstone boson, while A^0 is massive with a mass of

$$m_A^2 = \frac{\mu(v_d^2 + 4v_t^2)}{\sqrt{2}v_t}$$

Theoretical Constraints (2)

Other constraints arise from requiring the vacuum to be stable, the potential to be bounded from below (BFB), and the scattering matrices to be unitary. For example, BFB, in all directions and the most general case, imposes these constraints -

$$\lambda > 0; \lambda_2 + \lambda_3 > 0; \lambda_2 + \frac{\lambda_3}{2} > 0;$$
$$\lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} > 0; \lambda_1 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} > 0;$$
$$\lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \lambda_3)} > 0; \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} > 0.$$

Note: These are only tree-level constraints.

Georgi-Machacek Model

Similar Analysis in ATLAS, and CPPM

Parameters in the Lagrangian