Extended scalar sector and doubly charged Higgs bosons

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March 23, 2016

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Motivation

- Massless neutrinos in Standard Model. But neutrino oscillation discovered $\rightarrow$ neutrinos have mass.
- Fixed by type II seesaw by introducing a scalar triplet.
- If triplet hypercharge, Y $= 2$ ($Q = I_3 + \frac{Y}{2}$), doubly charged Higgs is a unique feature with clean decay channels.
- Rich scalar structure ($H^{\pm\pm}, H^{\pm}, A^0, H^0, h^0$).
- Naturally obtain a Standard Model-like Higgs.
- Unique event-topology.

The main reference can be found here.

Model Description

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,

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

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

$$\begin{aligned} V(H,\Delta) = & - m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + m_\Delta^2 Tr(\Delta^\dagger \Delta) + [\mu(H^\dagger i\sigma^2 \Delta^\dagger H) + h.c.] \\ & + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr \Delta^\dagger \Delta)^2 + \lambda_3 Tr\left(\Delta^\dagger \Delta\right)^2 \\ & + \lambda_4 H^\dagger \Delta \Delta^\dagger H. \end{aligned}$$

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,

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

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

Theoretical Constraints

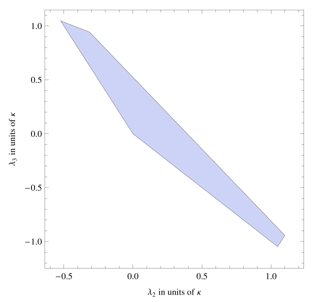


Figure 1: The largest $\lambda_2 - \lambda_3$ domain allowed by combined unitarity and BFB constraints for $\lambda_1 = \lambda_4 = 0$. Non-zero values give a subset of this domain.

Theoretical constrains such as absence of Tachyonic modes, stability of the vacuum, Boundedness from below (BFB), unitarity etc. are considered.
Putting these together, constraints on the parameters are obtained which are used in the simulations.

Constraints from precision measurements

Custodial symmetry: The fact that the potential $V = V(H^\dagger H)$ ensures $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \approx 1$ in the SM.
In the triplet model, modified ρ at tree level is given by,

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

where v_d is the vev of the doublet, and v_t is the vev of the triplet.
In the limit $v_d \ggg v_t$, $\rho \approx 1 - 2\frac{v_t^2}{v_d^2}$.
At 2σ level, measured $\rho_0 = 1.0004 \pm 0.00048 \Rightarrow$ upper bounds on v_t of about 1.6 GeV. [1]

[1] Radiative corrections from the BSM sector change ρ which can relax the constraints.

Production Modes

Possible production mechanisms of doubly charged Higgs include

- Pair production: $\gamma^*, Z^* \to H^{\pm\pm}H^{\mp\mp}$
- Associated production: $W^{\pm *} \to H^{\pm\pm}H^{\mp}$
- Single production: $W^{*+}W^{*+} \to H^{\pm\pm} \Rightarrow$ much smaller contribution.

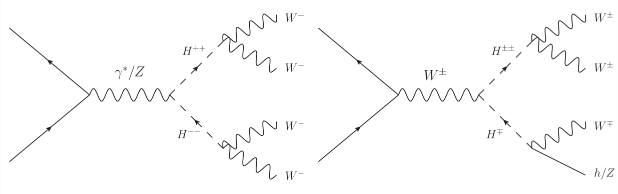


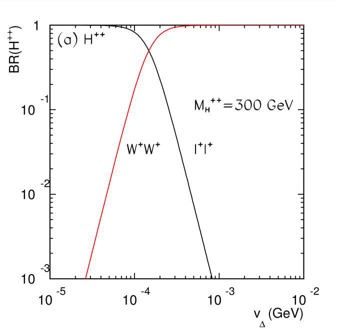
Figure 2: Pair-production and Associated-production

Decay Modes

Two main modes of decay to choose from:

- $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$. Searches for this mode have been performed at L3, OPAL, Delphi, CDF, ATLAS, CMS .. assuming 100% BR.
- $H^{\pm\pm} \to W^{\pm}W^{\pm} \to \ell^{\pm}\ell^{\pm}\nu\nu$.

Dependence of branching ratio into leptons and W's on the vev of the triplet shown below. Source: Testing type II seesaw



Previous ATLAS searches

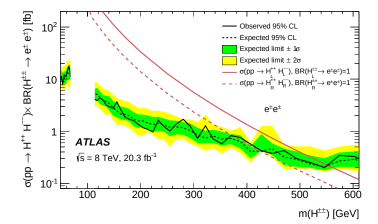
Model and event selection

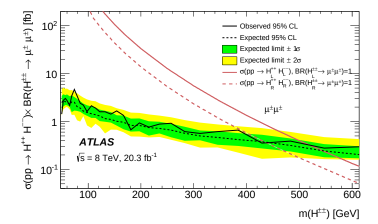
Model: Type II Seesaw as a LRSM with $\sigma_{H_L^{++}H_L^{--}} \sim 2.5\sigma_{H_R^{++}H_R^{--}}$ because of the coupling with Z-bosons.

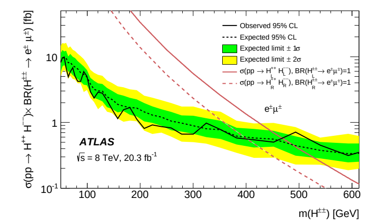
- $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}; (e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm})$
- 100% BR assumed. Mass limits depend on such assumptions.
- Search for narrow resonances at invariant mass of interest.
- Event selection:
  - $e_{P_T} > 20$ GeV; $\mu_{P_T} > 18$ GeV;
  - Isolated leptons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

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**:



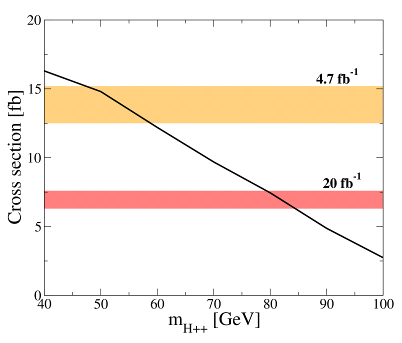




Phenomenological motivations

Kanemura et al studied a region in parameter space where $H^{++} \to W^{\pm *}W^{\pm *}$ is dominant i.e. $v_t > 0.1$ MeV. **Lower limit reduced to 85 GeV from about 400 GeV**(set by ATLAS and CMS in leptonic decay modes).

- Production: $pp \to \gamma^*/Z^* \to H^{\pm\pm}H^{\mp\mp}$ and $pp \to W^{\pm *} \to H^{\pm\pm}H^{\mp}$.
- Decay: $H^{++}H^{--} \to W^{+}W^{+}W^{-}W^{-} \to \ell^{\pm}\ell^{\pm}\not{E}_T + X$
  $H^{\pm\pm}H^{\mp} \to W^{\pm}W^{\pm} + X \to \ell^{\pm}\ell^{\pm}\not{E}_T + X$
- Assumption: $H^{\pm\pm}$ and $H^{\pm}$ have the same mass.



Simulation

Simulation

- CalcHEP used for the simulation of the parton level events.
- $\sqrt{s} = 13$ TeV; $v_t = 0.1$ GeV
- Pair-production of doubly charged Higgs and $m_{H^{\pm\pm}} = m_{H^{\pm}} = m_{A^0/H^0}$. Single production will also be generated.
- A scan of allowed parameters is on-going.
- $s_\alpha = 10^{-4}$, where α is the mixing angle of the neutral $\mathcal{CP}_{even}$ Higgs.
- Mass points: 100, 200, 300, 400 GeV. Focus on low mass points to test the phenomenology predictions.

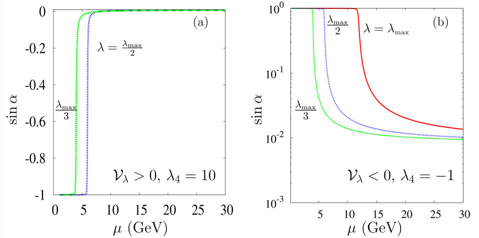


Figure 3: Example of the relation between $\sin\alpha$ and μ

Naturally allowed parameters

$\sin\alpha$	$m_{H^{\pm\pm}}$	$m_{H^{\pm}}$	m_{H^0}	m_{A^0}
0.	100.	100.	100.00031399061868	100.
0.	100.	200.	264.5752488305759	264.5751311064591
0.	100.	300.	412.3106354531287	412.31056256176606
0.	100.	400.	556.776484976137	556.7764362830021
0.	200.	200.	200.0001557343423	200.
0.	200.	300.	374.16581899976217	374.16573867739413
0.	200.	400.	529.1503134482512	529.1502622129182
0.	300.	300.	300.0001001795879	300.
0.	300.	400.	479.58320886201017	479.5831523312719
0.	400.	300.	141.42156875018287	141.4213562373095
0.	400.	400.	400.0000677779723	400.

Table 1: Parameters allowed by simplified theoretical constraints

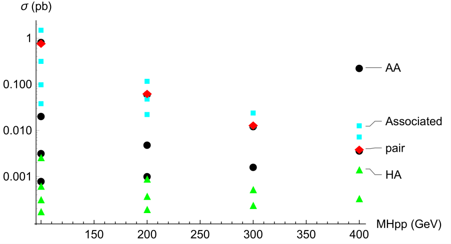
Production cross-section for all scalars

The associated production, $H^{\pm\pm}H^{\mp}$, can have comparable cross-section depending on the masses.

$$pp \to H^{++}H^{--} \to W^+W^+W^-W^- \quad \to \quad \begin{cases} 2\ell^+ + 2\ell^- + \not{E}_T \\ 3\ell + 2j + \not{E}_T \\ 2\ell^\pm + 4j + \not{E}_T \end{cases}$$

$$pp \to H^{\pm\pm}H^{\mp} + h.c. \to W^{\pm}W^{\pm} \quad + \quad \begin{cases} \overbrace{if(m_{H^{\mp}} \lesssim 150\text{ GeV})}^{H^{\mp}\to\bar{c}s} & \to \quad 2\ell^\pm + 2j + \not{E}_T \\ \underbrace{if(m_{H^{\mp}} \gtrsim 150\text{ GeV})}_{H^{\mp}\to W^{\mp}h/Z} & \to \quad \begin{cases} 3\ell + 2b + \not{E}_T \\ 2\ell^\pm + 2b + 2j + \not{E}_T \\ 3\ell + 2j + \not{E}_T \\ 2\ell^\pm + 4j + \not{E}_T \end{cases} \end{cases}$$

The cross-sections for all the scalars in the model need to be taken into consideration.



Mass dependence of kinematics

The aim is to understand the process,
$pp \to H^{++}H^{--} \to W^+W^+W^-W^- \to \ell^\pm\ell^\pm + X + E_T^{miss}$ and how the kinematics changes as a function of mass.

- Only $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$, and $e^\pm e^\pm$ events were selected.
- $p_T > 20 GeV$
- $|\eta| < 2.5$

$2\ell^{ss}, 3\ell, 4\ell$ final states are used for the following plots.

Kinematics

The following plots were generated using true electrons and muons.

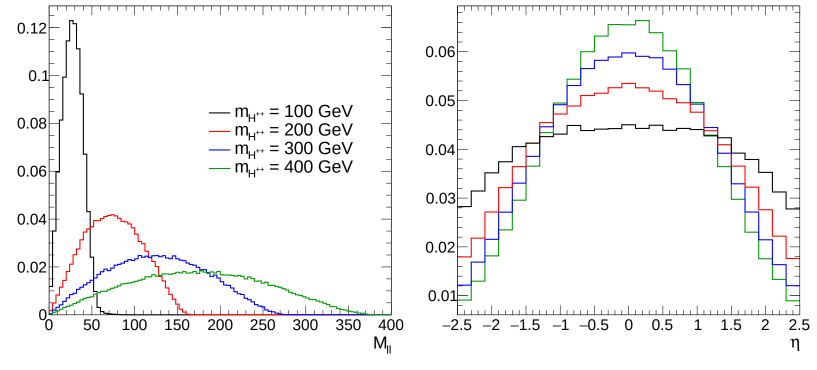


Figure 4: Left : Missing E_T in GeV; Right: η of the same sign leptons

Angular Observables

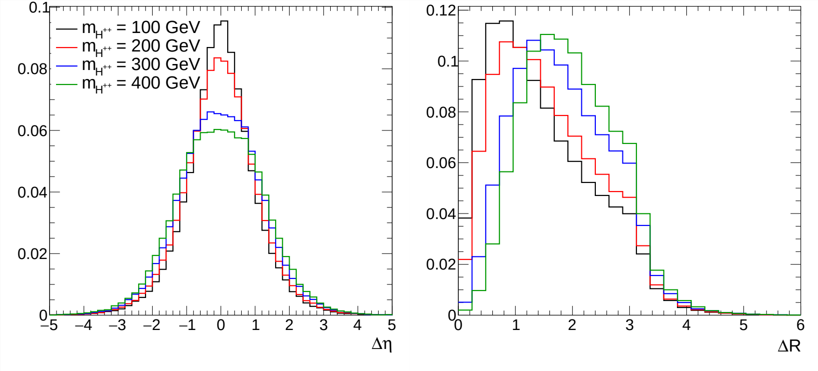


Figure 5: $\Delta\eta$ and ΔR between the two same sign leptons originating from the same $H^{\pm\pm}$.

Analysis for 3-lepton final state

Simulation Part II

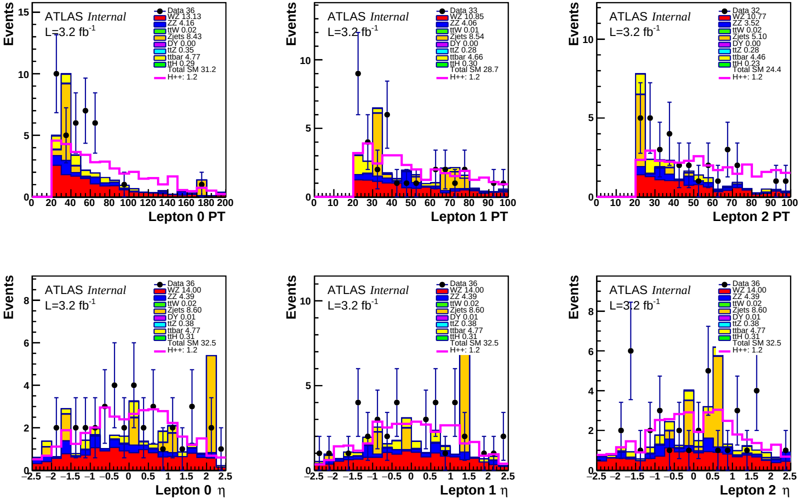
- EVNT:AtlasProduction,19.2.4.5,A14 tune, di-lepton filter with efficiency $\approx 28\%$
- HITS: AtlasProduction,19.2.4.9
- DIGI+RECO: AtlasProduction,20.1.4.7, no pile-up
- HIGG8D1: AtlasDerivation20.1.9.1
- NTUP: tag ttHMultiAna-00-01-04 $\Rightarrow$ ttHMultiLepton framework in ATLAS.
- Full sim of 40000 events available for benchmark mass of 200 GeV with an inclusive cross-section $\sigma_{pp \to H^{\pm\pm} H^{\mp\mp} \to 4W} = 64.58 fb^{-1}$.

Event selection: Control Region

- Only $e^{\pm}, \mu^{\pm}$ considered, no τs
- Lepton $p_T > 20$ GeV
- 3ℓ with a total charge of ±1
- nJets > 1
- bJet veto
- $E_T^{miss} > 30$ GeV
- Z-veto
- Isolation: GradientLoose

In all control plots, signal is normalized to the 3.2 fb^{-1} of data. Lepton 1 and lepton 2 are by construction always same sign, and lepton 0 is opposite sign.

Kinematics


ATLAS Internal
L=3.2 fb^{-1}
Data 36
WZ 13.13
ZZ 4.16
ttW 0.02
Zjets 8.43
DY 0.00
ttZ 0.35
ttbar 4.77
ttH 0.29
Total SM 31.2
H++: 1.2
Events
Lepton 0 PT
ATLAS Internal
L=3.2 fb^{-1}
Data 33
WZ 10.85
ZZ 4.06
ttW 0.01
Zjets 8.54
DY 0.00
ttZ 0.28
ttbar 4.66
ttH 0.30
Total SM 28.7
H++: 1.2
Events
Lepton 1 PT
ATLAS Internal
L=3.2 fb^{-1}
Data 32
WZ 10.77
ZZ 3.52
ttW 0.02
Zjets 5.10
DY 0.00
ttZ 0.28
ttbar 4.46
ttH 0.23
Total SM 24.4
H++: 1.2
Events
Lepton 2 PT
ATLAS Internal
L=3.2 fb^{-1}
Data 36
WZ 14.00
ZZ 4.39
ttW 0.02
Zjets 8.60
DY 0.01
ttZ 0.38
ttbar 4.77
ttH 0.31
Total SM 32.5
H++: 1.2
Events
Lepton 0 η
ATLAS Internal
L=3.2 fb^{-1}
Data 36
WZ 14.00
ZZ 4.39
ttW 0.02
Zjets 8.60
DY 0.01
ttZ 0.38
ttbar 4.77
ttH 0.31
Total SM 32.5
H++: 1.2
Events
Lepton 1 η
ATLAS Internal
L=3.2 fb^{-1}
Data 36
WZ 14.00
ZZ 4.39
ttW 0.02
Zjets 8.60
DY 0.01
ttZ 0.38
ttbar 4.77
ttH 0.31
Total SM 32.5
H++: 1.2
Events
Lepton 2 η

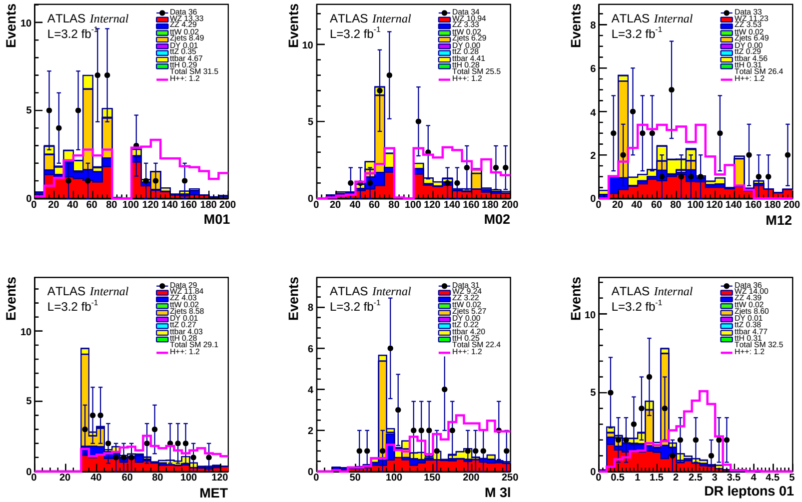


Figure 6: Top row, left to right: $M_{\ell 0 \ell 1}$, $M_{\ell 0 \ell 2}$, $M_{\ell 1 \ell 2}$
Bottom row, left to right: E_T^{miss}, $M_{3\ell}$, $\Delta R(\ell 0 \ell 1)$

Few more variables..

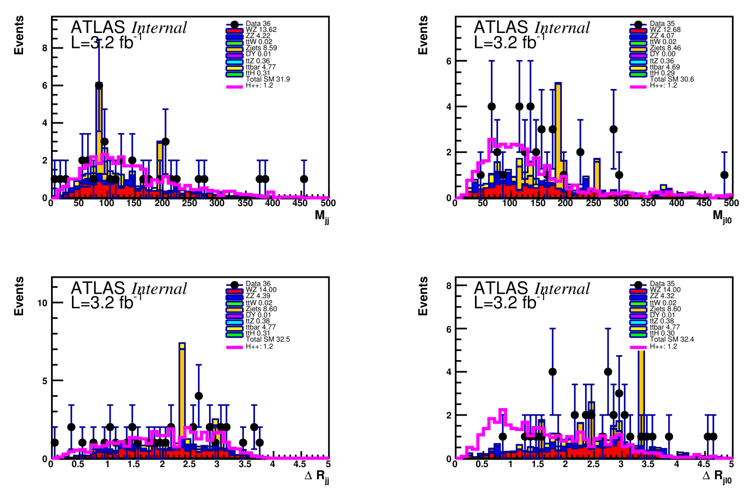


Figure 7: Top left: Leading-subleading jet Invariant mass,
Top right: leading jet-ℓ_0 invariant mass,
Bottom left: ΔR-leading and subleading jets, Bottom right: ΔR-leading jet-ℓ_0

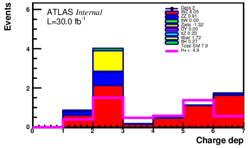
Cuts for the signal region

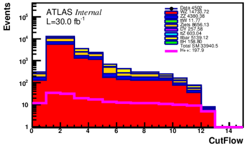
- $P_T > 25$ GeV for leading lepton in the same-sign pair
- $M_{\ell\ell^{ss}} > 25$ GeV
- $\Delta R(\ell^+\ell^-) > 1.0$
- $\Delta R(\ell^\pm\ell^\pm) < 2.3$
- ΔR(leading jet - opposite sign lepton) > 1.5

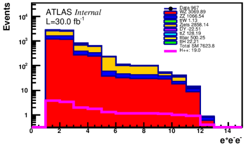
The cuts are sub-optimal. A TMVA optimization is foreseen, besides addition of new variables.

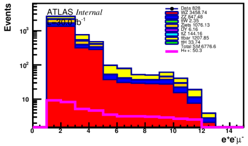
Extrapolation to 30 fb^{-1}

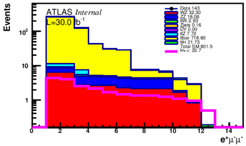
CutFlow

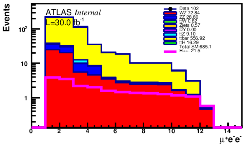


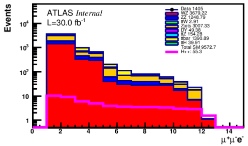


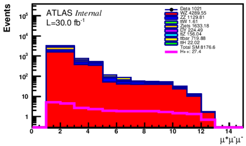












1: Lep PT
2: Charge
3: nJets
4: bJet veto
5: Z veto
6: MET
7: Isolation
8: Lep PT
9: Mll ss
10: DR os
11: DR ss
12: DR j-l0

Signal and Background Yields in different channels

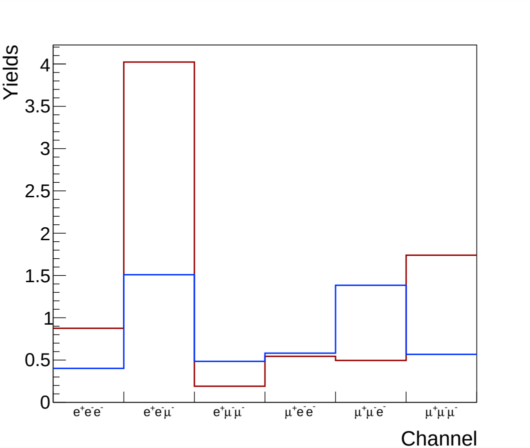


Figure 8: Signal and background yields in different channels.

Some channels give better yields compared to others for the same set of cuts. Channel-dependent optimization of the cuts is required.

Summary

- The .lhe events for 4 benchmark mass points are ready with only pair production.
- Parameter selection for associated production is on-going.
- Full-simulation for one benchmark point is available.
- Even with sub-optimal cuts, background is under control. Further optimization using TMVA is foreseen.
- Analysis strategy would be to separate the final state into charge and flavour dependent final states and perform optimization.
- The exclusion limits using the above mentioned yields are shown in the next talk.

Backup

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.

The masses

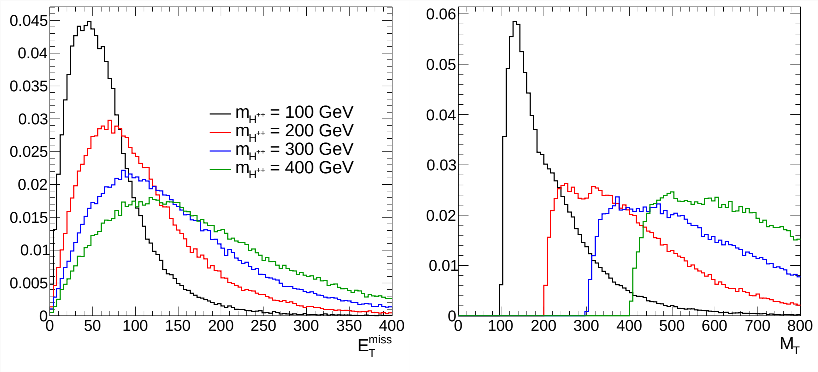


Figure 9: Left : Invariant mass of same sign leptons in GeV; Right: Transverse mass in GeV.

Ignore the transverse mass plot– still trying to find a sensible way to construct this.

Event Selection

The aim is to understand the process,
$pp \to H^{++}H^{--} \to W^+W^+W^-W^- \to \ell^\pm\ell^\pm + X + E_T^{miss}$.

- Only $\mu^\pm\mu^\pm$, $e^\pm\mu^\pm$, and $e^\pm e^\pm$ events were selected.
- $p_T > 20 GeV$
- $|\eta| < 2.5$

The acceptance is then calculated as $\frac{\text{Number of events selected}}{\text{Total number of events}}$.

The product of σ_{th} and the acceptance is called the fiducial cross-section. On the following slide, 2ℓ refers to files where two W's from the same Higgs decay leptonically while the other two decay hadronically.

Fiducial cross-sections

Theoretical cross-sections ($\sigma_{WW} \times BR(finalstate)$) are shown below:
The estimated fiducial cross-sections are shown below:

Final State	200 GeV (in fb)	300 GeV (in fb)	400 GeV (in fb)
$2\ell^{ss}$	2.808	0.625	0.193
3ℓ	1.256	0.292	0.095

Topology