Extended scalar sector in DTHM

$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$

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Motivation and model description

Motivation

- Massless neutrinos in Standard Model. But neutrino oscillation discovered $\rightarrow$ neutrinos have mass.
- One of the ways to obtain neutrino masses is via the type II seesaw by introducing a scalar triplet.
- Since 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.
- The main reference is The Higgs potential in Type II Seesaw models.

Focus of this talk is on charged Higgses, in particular $H^{\pm\pm}$.

The potential

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,

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

Besides the yukawa terms in SM, an additional term for the neutrinos is added. if Y_ν denotes the neutrino yukawa, this term is:

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

where L: $SU(2)_L$ lepton doublets.

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.

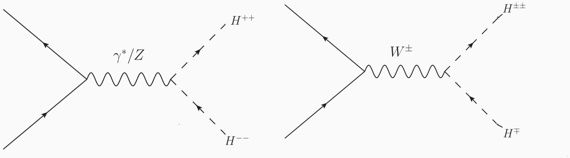


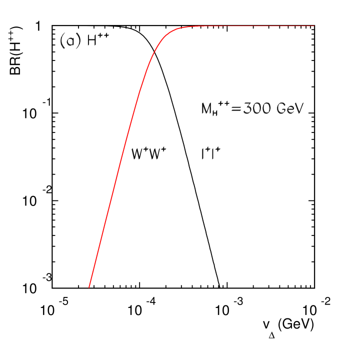
Figure 1: Pair-production and Associated-production

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 (v_t) shown below.
Source: Testing type II seesaw



Arbitrarily high values of v_t are not allowed.

- Custodial symmetry in the SM forces $\rho \sim 1$.
- In DTHM, modified ρ at tree level is given by,

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

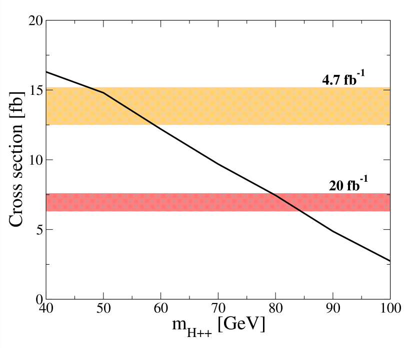
- At 2σ level, experimentally measured $\rho_0 = 1.0004 \pm 0.00048$
- Upper bound on v_t of about 1.6 GeV.

Phenomenology

Type 2 Seesaw with dominant WW decay mode

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.

- 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.



- Triplet Higgses have fermiophobic couplings (couplings proportional to neutrino masses).
- The existing limits on $H^\pm$ or the other Higgses don't apply because of the triplet coupling.
- **Lower limit reduced to 85 GeV from about 400 GeV**(set by ATLAS (included in the backup) and CMS in leptonic decay modes).

Parameter and Cross-sections

Different processes can have the same final states in this model. For example:

$$pp \to \gamma^*, Z^* \to H^{\pm\pm}H^{\mp\mp} \to 4W \to 3\ell + 2j + E_T^{miss} \text{ and}$$
$$pp \to W^{*\pm} \to H^{\pm\pm}H^{\mp} \to 3W + Z \to 3\ell + 2j + E_T^{miss}$$

Cross-sections of other processes giving the same final states need to be evaluated to estimate the contributions.

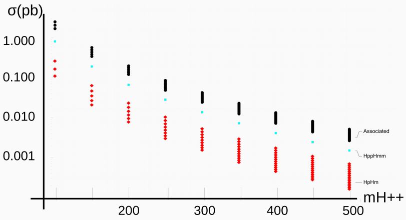


Figure 2: Cross-sections as a function of the mass of $H^{\pm\pm}$

We implemented the model in CalcHEP and MadGraph5.

Parameters for simulation:

- $\sin\alpha = 10^{-4} \Rightarrow$ mixing between netural $\mathcal{CP}_{even}$ Higgses is negligible.
- $m_{h^0} = 126$ GeV
- $m_{H^{\pm\pm}} = 200$ GeV, $m_{H^{\pm}} = 193$ GeV
- $m_{H^0} = m_{A^0} = 163$ GeV

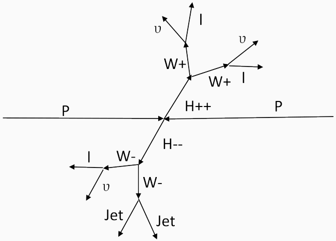
These are parameters allowed by all the theoretical constraints put together.

Experimental analysis

Signal + Backgrounds

Signal Region

$H^{\pm\pm}H^{\mp\mp} \to 4W \to 3\ell + E_T^{miss} + 2j$



The current benchmark point of the analysis is $M_{H^{\pm\pm}}200$ GeV. Signal optimzation available for:300, 400, 500, 600, 700 GeV. 2ℓ final state to be presented by **Ruiqi**.

Dominant backgrounds

- **Prompt**: WZ, ZZ. These are estimated **from MC**.
- **Non-prompt**: $t\bar{t}$, Z+jets. These are estimated using **data-driven methods**.

Cuts in preselection (a.k.a XR):

- b-jet veto to reduce $t\bar{t}$
- Z-veto to reduce WZ, ZZ, and Z+jets
- Isolation and lepton ID

Both regions employ some more event level cuts such as triggers, p_T cuts, E_T^{miss}, $M_{\ell\ell}$. The analysis further exploits some discriminating variables such as angular correlations etc.

Discriminating variables

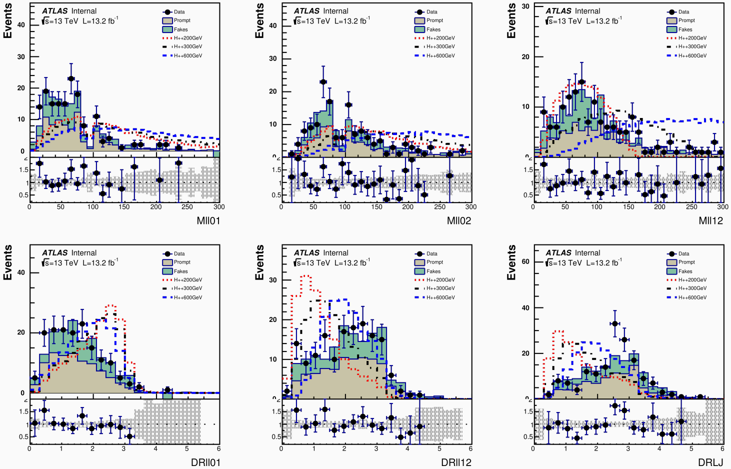
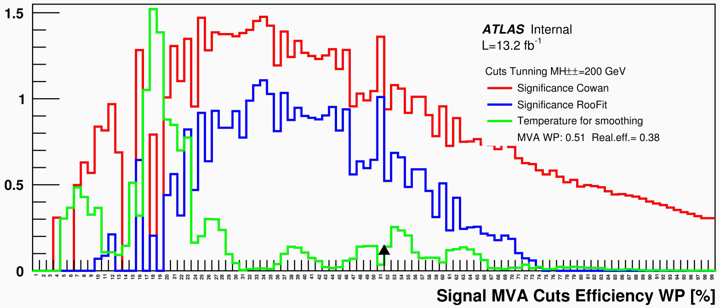


Figure 3: Angular correlations between different leptons, and between leptons and jets provide a good discrimination between signal and background

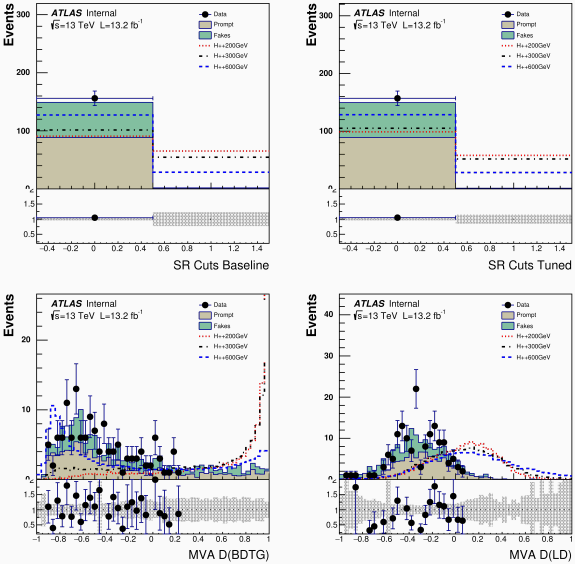
Details of background estimation can be found in the backup!

Optimization procedure for the cut-based method



- TMVA CutsSA is used to evaluate cuts as a function of signal efficiency.
- Significance is then evaluated as a function of signal efficiency.
- A measure called the temperature is defined to asses the fluctuation around every point in the plot. This avoids catching statistical fluctuations in the background.
- An optimum point is then chosen such that the significance is maximized.
- The cut values are given in the backup for reference.

Cuts, LD, and BDT responses



Cuts on variables are optimized using TMVA CutsSA method. The cuts, their efficiencies, and the effect of changing the benchmark points can be seen in the backup.

Yields in SR

Backup includes details on all estimates, optimization etc.

	Channel	Data	Prompt	Fakes	H++200GeV
1	eee	–	0.057 ± 0.087	0.022 ± 0.001	0.218 ± 0.010
2	$ee\mu$	–	0.260 ± 0.120	0.051 ± 0.001	0.513 ± 0.015
3	$e\mu\mu$	–	0.062 ± 0.014	0.121 ± 0.004	0.311 ± 0.011
4	μee	–	0.102 ± 0.019	0.095 ± 0.004	0.244 ± 0.010
5	$\mu e\mu$	–	0.174 ± 0.060	0.050 ± 0.001	0.501 ± 0.014
6	$\mu\mu\mu$	–	0.211 ± 0.093	0.026 ± 0.001	0.262 ± 0.010
7	Total	–	0.865 ± 0.186	0.364 ± 0.006	2.049 ± 0.029

Table 1: Signal and background yields in SR for the $M_{H^{\pm\pm}} = 200$ GeV with $\int \mathcal{L} = 13.2 fb^{-1}$. The yields are split into six channels since some backgrounds like WZ dominate in all channels except channels 3 and 4. No yields are shown in data since the analysis is still blind.

The yields show a good ratio b/w signal and background at 13.2 fb^{-1} of data. Will significantly improve by the end of 2016 with roughly 40 fb^{-1} of data.

Conclusion

- The model with the triplet extension of the SM was implemented in CalcHEP and MadGraph5.
- Analysis in place with background estimation and SR optimzation.
  - Combined sensitivity in $2\ell, 3\ell$ final states will be shown by Ruiqi this afternoon.
- The first draft of the conf note is available within ATLAS and was reviewed by the editorial board.
- Unblinding in 2 weeks; systematics to be included.
- Plan to publish by the end of the year including full 2015/2016 data of about 40 fb^{-1}.
- Lots of possible variations.
  - New final states in pair-production as an experimental analysis.
  - Experimental analysis of associated production mode.
  - Generalized parameters etc. for event generation such as non-negligible mixing between the h^0, and H^0.
    - Targeting a phenomenology paper with these studies.

Backup

Event Selection

Step	Selection Criteria	*Data*	Signal $M_{\mathrm{H}^{\pm\pm}} = 200$
A	Three leptons with $P_T^{0,1,2} > 10, 20, 20 GeV$	7108	11.60 ± 0.10
B	$\lvert M_{01} - M_Z \rvert > 10$ GeV and $\lvert M_{02} - M_Z \rvert > 10$ GeV	2835	10.30 ± 0.10
	$M_{01} > 15$ GeV and $M_{02} > 15$ GeV	2535	10.20 ± 0.10
	$MET > 30$ GeV	1146	9.28 ± 0.06
	$N_{\mathrm{jet}} >= 2$	485	5.94 ± 0.05
C	$N_{\mathrm{b-jet}} = 0$	245	5.62 ± 0.05
D	$0.1 < \Delta R_{12} < 1.5$ and $38.1 GeV < MET < 353.7 GeV$	–	–
	$153 GeV < M_{\ell\ell\ell} < 1867 GeV$ and $0.4 < \Delta R_{\ell j} < 1.5$	–	–
	$32.6 GeV < P_T^{leadjet} < 1365 GeV$ and $46.1 GeV < (P_T^0 + P_T^1 + P_T^2)/3 < 2087 GeV$	–	–

Table 2: Cut flow: 3ℓ

The set of cuts in section D are optimized for 200 GeV; these cuts vary as a function of mass.

Definitions of various regions

Various regions defined for fake estimations, ttbar (TR+TR') and Z+jets(ZR +ZR') enriched regions etc. The fake estimates are estimate from YR (low jet multiplicity) and used in XR/SR.

	Selection Criteria	YR+YR'	XR+XR'	ZR+ZR'	TR+TR'
A	Three leptons with $P_T^{0,1,2} > 10, 20, 20 GeV$	√	√	√	√
B	$\lvert M_{01} - M_Z \rvert > 10$ GeV and $\lvert M_{02} - M_Z \rvert > 10$ GeV	√	√		√
*	$\lvert M_{01} - M_Z \rvert \leq 10$ GeV or $\lvert M_{02} - M_Z \rvert \leq 10$ GeV			√	
	$M_{01} > 15$ GeV and $M_{02} > 15$ GeV	√	√		√
	$MET > 30$ GeV		√		√
	$N_{\text{jet}} >= 2$		√		√
*	$N_{\text{jet}} == 1$	√			
*	$N_{\text{jet}} >= 1$			√	√
C	$N_{\text{b-jet}} = 0$		√	√	
*	$N_{\text{b-jet}} >= 0$				√

Figure 4: Definitions of various regions. * indicates variations of the baseline signal region

All regions with a prime (YR', XR', TR', ZR') are obtained by requiring one of the same sign leptons to be loose and not-tight; and without primes imply both same-sign leptons to be tight.

Fake Factor

Fake factors are estimated in YR+YR' because of the lack of statistics in the signal region.
The fake factor is given by,

$$\theta_{\mathrm{e}/\mu} = \frac{(Data - MC^{prompt})_{\mathrm{xee}/\mathrm{x}\mu\mu}}{(Data - MC^{prompt})_{\mathrm{xee_f}/\mathrm{x}\mu\mu_\mathrm{f}}} \tag{3}$$

Here the index f indicate the lepton in YR' region that is not tight.
The fake-enriched YR' region can be used to estimate the fake contribution in the signal enriched region YR, using the "fake factors" for electrons θ_e and muons θ_μ as follows:

$$N_{\mathrm{xe}\mu} = \theta_\mathrm{e} \times N_{\mathrm{x}\mu\mathrm{e_f}} + \theta_\mu \times N_{\mathrm{xe}\mu_\mathrm{f}} \tag{4}$$

$$N_{\mathrm{xee}} = \theta_\mathrm{e} \times N_{\mathrm{xee_f}} \tag{5}$$

$$N_{\mathrm{x}\mu\mu} = \theta_\mu \times N_{\mathrm{x}\mu\mu_\mathrm{f}} \tag{6}$$

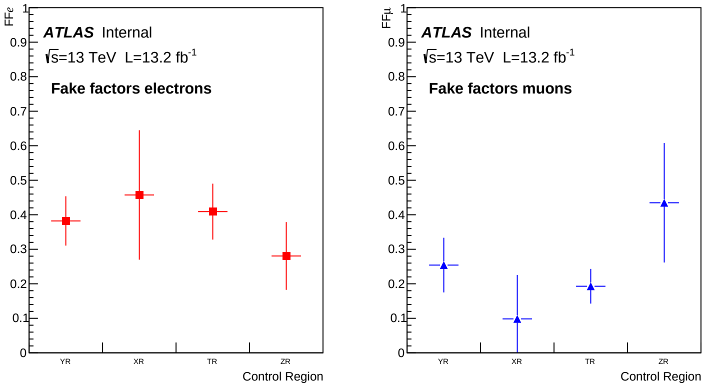
Fake estimation using YR+YR'

Region	Data	Prompt	Data-Prompt	MC fakes
YR' xeef	169	18.16 $\pm$ 1.62	150.84 $\pm$ 13.10	105.80 $\pm$ 24.53
YR' xemf	92	8.82 $\pm$ 1.31	83.18 $\pm$ 9.68	75.76 $\pm$ 5.79
YR' xmef	282	21.41 $\pm$ 1.81	260.59 $\pm$ 16.89	109.40 $\pm$ 19.67
YR' xmmf	132	9.34 $\pm$ 1.29	122.66 $\pm$ 11.56	87.60 $\pm$ 7.63

Region	Data	Prompt	Data-Prompt	MC fakes	DD fakes	in-situ DD fakes
YR xee	87	29.36 $\pm$ 2.06	57.64 $\pm$ 9.55	27.16 $\pm$ 10.44	57.64 $\pm$ 11.89	57.64 $\pm$ 11.89
YR xem	186	92.99 $\pm$ 4.01	93.01 $\pm$ 14.21	42.00 $\pm$ 27.74	120.72 $\pm$ 20.93	120.72 $\pm$ 20.93
YR xmm	79	47.82 $\pm$ 2.57	31.18 $\pm$ 9.25	11.42 $\pm$ 1.21	31.18 $\pm$ 10.14	31.18 $\pm$ 10.14
θ_e in-situ	0.3821 $\pm$ 0.0715					
θ_μ in-situ	0.2542 $\pm$ 0.0791					

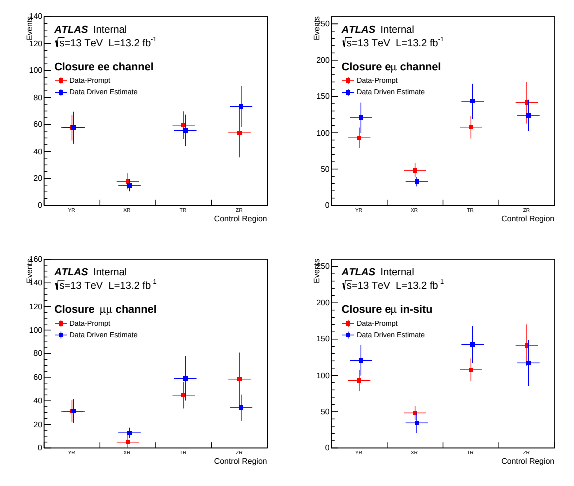
Table 3: YR+YR' samples. Note that the column "Data Driven Fakes" contains the fake lepton contribution estimated using the fake factors. The numbers in that column are directly comparable to the column "Data-Prompt". A trivial agreement is expected in the first and third line of the bottom table. The middle (xem) line provides however a non-trivial test, since sample is disjoint from xee and xmm samples, used to calculate the fake factors. A good agreement is observed.

Closure test per region



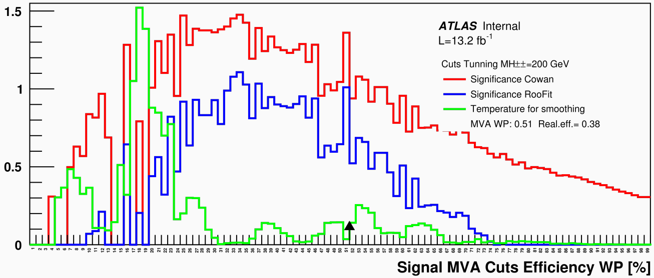
The fake factors are stable within errors across all regions considered.

Summary of fake factors per channel



Good agreement between Data−prompt and data-driven estimates across all channels

Optimization procedure for the cut-based method



- TMVA CutsSA is used to evaluate cuts as a function of signal efficiency.
- Significance is then evaluated as a function of signal efficiency.
- Very low values of signal efficiencies are avoided. The scan begins from 40% efficiency
- A measure called the temperature is defined to asses the fluctuation around every point in the plot. This avoids catching statistical fluctuations in the background.
- An optimum point is then chosen such that the significance is maximized.
- The cut values are given in the backup for reference.

Comparison between CutsSA and BDTG/LD

Selection	Data	SM Background	Signal
All input MVA	147	132.47 ± 5.50	3.933 ± 0.040
Cuts fixed eff 0.55	1	1.81 ± 0.44	1.678 ± 0.027
Cuts best sig eff 0.51	0	0.50 ± 0.16	1.492 ± 0.025
Tuned Cuts	0	0.60 ± 0.19	1.494 ± 0.025
BDTG method $D > 0.985$ Sig. $=$ Cuts Tuned	0	0.70 ± 0.24	1.497 ± 0.025
LD method $D > 0.602$ Sig. $=$ Cuts Tuned	0	2.70 ± 0.75	1.491 ± 0.025
BDTG method $D > 0.965$ Bg$=$ Cuts Tuned	0	1.88 ± 0.58	1.917 ± 0.028
LD method $D > 0.633$ Bg$=$ Cuts Tuned	0	1.85 ± 0.63	1.110 ± 0.021
BDTG method $D > 0.976$ Best Signif.	0	1.05 ± 0.40	1.740 ± 0.027
LD method $D > 0.581$ Best Signif.	0	3.38 ± 0.80	1.738 ± 0.027

Table 4: Various options to select the signal region, using cuts and multivariate discriminants. In selecting the signal region with a cut on the discriminat (D) value, various options are tested: the cut is made such that the signal rate is close to cut-based baseline selection(SiLikeCut), the background rate is similar to cut-based (BgLikeCut), the best significance is achieved (calculated using Cowan prescription ($\sqrt{2 * ((s+b) * log(1+s/b) - s})$) and signal rate equal to the background rate. The comparison is shown only for channel 2 as an example.

Extrapolation of fake estimates to the SR

Once the SR cuts are defined, it is found that the SR lacks statistics for fake estimation. The following method is used for the extrapolation:

- Group variables that have strong linear correlation together.
- Evaluate the efficiency of each group ($\epsilon_1, \epsilon_2, ..$ corresponding to groups, $g_1, g_2, ..$)
- The factorized efficiency is defined as the product of these efficiencies ($\epsilon_1 \times \epsilon_2 \times ...$).
- Fakes in the SR are then given by the product of fakes in XR and the factorized efficiency.

Efficiencies for extrapolation

	Channel 1	Channel 2	Prompt	Fakes	H++200GeV
1	$0.2 < \Delta R_{12} < 1.7$ and MET> 56.2	$0.2 < \Delta R_{12} < 1.5$ and MET> 43	0.204 ± 0.042	0.153 ± 0.046	0.636 ± 0.205
2	$M_{3\ell} > 122$ and $0.4 < \Delta R_{\ell j} < 2.5$	$M_{3\ell} > 139$ and $0.3 < \Delta R_{\ell j} < 1.6$	0.150 ± 0.038	0.144 ± 0.045	0.607 ± 0.208
3	$P_T^{\text{leading jet}} > 75$ and $\frac{\left(p^T_{\ell_0}+p^T_{\ell_1}+p^T_{\ell_2}\right)}{3} > 46$	$P_T^{\text{leading jet}} > 28.4$ and $\frac{\left(p^T_{\ell_0}+p^T_{\ell_1}+p^T_{\ell_2}\right)}{3} > 55.5$	0.536 ± 0.053	0.261 ± 0.056	0.720 ± 0.191
4		All cuts	0.010 ± 0.010	0.006 ± 0.009	0.370 ± 0.205
5		Factorised efficiency	0.016 ± 0.000	0.006 ± 0.000	0.278 ± 0.000

Table 5: The cuts applied at the signal region level ("tuned cuts" criteria) and their individual efficiencies.The cuts are optimized in two channels, Channel 1 corresponds to events with no same flavour opposite sign events, while Channel 2 corresponds to only those events which consist of same flavour opposite sign leptons. The cuts on correlated variables are grouped. The "All cuts" line displays the nominal efficiency when all cuts are applied while the last line "Factorised efficiency" shows the product of the individual efficiencies (no intrinsic error is calculated for these values).

The resultant fake estimate in SR is 0.23 events.

Cuts and yields for $M_{H^{\pm\pm}} = 200$ GeV

	Channel 1	Channel 2	Data	Prompt	Fakes	H++200GeV
0		All XR level	157.000 ± 12.530	89.948 ± 3.299	61.429 ± 5.387	5.534 ± 0.048
1	$0.2 < \Delta R_{\ell\ell}(12) < 1.7$	$0.2 < \Delta R_{\ell\ell}(12) < 1.5$	51.000 ± 7.141	24.783 ± 1.593	16.732 ± 2.595	3.967 ± 0.041
2	MET> 56.2	MET> 43	32.000 ± 5.657	18.353 ± 1.278	9.286 ± 1.935	3.520 ± 0.039
3	$M_{3\ell} > 121.8$	$M_{3\ell} > 139$	14.000 ± 3.742	6.656 ± 0.770	1.955 ± 0.900	2.934 ± 0.035
4	$0.4 < \Delta R_{\ell j} < 2.5$	$0.3 < \Delta R_{\ell j} < 1.6$	1.000 ± 1.000	1.542 ± 0.410	0.268 ± 0.077	2.314 ± 0.031
5	$P_T^{\text{leading jet}} > 75$	$P_T^{\text{leading jet}} > 28.4$	1.000 ± 1.000	1.489 ± 0.410	0.273 ± 0.077	2.131 ± 0.030
6	$\frac{\left(p^T_{\ell_0}+p^T_{\ell_1}+p^T_{\ell_2}\right)}{3} > 46$	$\frac{\left(p^T_{\ell_0}+p^T_{\ell_1}+p^T_{\ell_2}\right)}{3} > 55.5$	0.000 ± 0.000	0.865 ± 0.186	0.364 ± 0.006	2.049 ± 0.029

Table 6: The cuts applied at the signal region level. Channel 1 corresponds to events w/o same-flavour opposite sign leptons. Channel 2 is !Channel1

Cuts and yields for $M_{H^{\pm\pm}} = 400$ GeV

	Channel 1	Channel 2	Data	Prompt	Fakes	H++400GeV
0		All XR level	157.000 ± 12.530	89.948 ± 3.299	60.863 ± 5.392	0.656 ± 0.004
1	$0.1 < \Delta R_{12} < 2.3$	$0.1 < \Delta R_{12} < 2.4$	92.000 ± 9.592	52.353 ± 2.685	31.819 ± 3.598	0.502 ± 0.004
2	MET64.3	MET$>$ 90.9	17.000 ± 4.123	14.634 ± 1.142	10.032 ± 1.919	0.426 ± 0.004
3	$M_{3\ell} > 285$	$274.4 < M_{3\ell}$	0.000 ± 0.000	1.754 ± 0.293	0.663 ± 0.462	0.325 ± 0.003
4	$0.8 < \Delta R_{\ell j} < 2.4$	$0.3 < \Delta R_{\ell j} < 2.2$	0.000 ± 0.000	0.585 ± 0.109	0.069 ± 0.005	0.263 ± 0.003
5	$P_T^{\text{leading jet}} > 25$	$46.4 < P_T^{\text{leading jet}}$	0.000 ± 0.000	0.565 ± 0.109	0.068 ± 0.005	0.260 ± 0.003
6	$\frac{\left(p^T_{\ell_0}+p^T_{\ell_1}+p^T_{\ell_2}\right)}{3} > 103.5$	$\frac{\left(p^T_{\ell_0}+p^T_{\ell_1}+p^T_{\ell_2}\right)}{3} >> 109.4$	0.000 ± 0.000	0.249 ± 0.058	0.050 ± 0.004	0.229 ± 0.003

Table 7: The cuts applied at the signal region level ("tuned cuts" criteria) for 400 GeV. The cuts are optimized in two channels, Channel 1 corresponds to events with no same flavour opposite sign events, while Channel 2 corresponds to only those events which consist of same flavour opposite sign leptons