Hidden Higgs boson in extended supersymmetric scenarios at the LHC

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Outline

1. Plan
   - Experimental constraints

2. TNSSM

3. Collider Phenomenology

4. Charged Higgs Phenomenology
   - Triplet charged Higgs boson
   - Charged Higgs boson in NMSSM
Plan

1. Standard Model Higgs boson
2. MSSM and its status
3. Triplet and Singlet extended Supersymmetric SM
4. Possibility of Hidden Higgs boson
5. Collider searches
6. Triplet like charged Higgs
The direct mass bound on SM Higgs is $m_H > 114.4$ GeV

Very low reduced couplings of $Z - Z - h$ and $h - f - f$ can bring down the lower bound.
CMS and ATLAS combined the results in $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$.

The combined measured mass of the Higgs boson is $m_H = 125.09 \pm 0.21\,\text{(stat)} + 0.11\,\text{(sys)}$ GeV.
Supersymmetry

- Standard Model Higgs mass is not protected by any symmetry!
- **Supersymmetry** protects the Higgs mass by giving possible cancellation.

\[
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\end{array}
\]

- **Price**: In the minimal extension, for each particle there is a super partner differing by spin 1/2.
Higgs sector in MSSM

- Minimal supersymmetric extension (MSSM) has five Higgs bosons,
  \( h, H \) the CP-even neutral Higgs bosons
  \( A \) the CP-odd neutral Higgs bosons
  \( H^\pm \) charged Higgs bosons

- Including \( R \)-parity, \( P_R = (-1)^{3(B-L)+2s} \) conservation leads to the lightest supersymmetric particle as Dark matter candidate.

Lightest Higgs in MSSM

- While in the SM the Higgs mass is essentially a free parameter the lightest CP–even Higgs particle in the MSSM is bounded from above.

- At tree level the lightest CP-even Higgs (\( h \)) mass, \( m_h \leq M_Z \)

- For desired Higgs mass around 125 GeV, one has to look for quantum correction.
Higgs sector in MSSM

Lightest Higgs in MSSM

- Depending on the SUSY parameters that enter the radiative corrections, it is restricted to values

\[
M_h^{\text{max}} \approx M_Z |\cos 2\beta| + \text{radiative corrections} \lesssim 110 - 135 \text{ GeV}
\]

- SUSY particles mass and other parameters enter in the radiative correction to the Higgs sector.

⇒ “Observed \( M_h \approx 125 \text{ GeV} \)” at the LHC, would place very strong constraints on the MSSM parameters through their contributions to the radiative corrections to the Higgs sector.
In MSSM, the main loop contributions come from the third generation strong sectors,

**push the mass scale** $\gtrsim 1$ TeV to up to 10 TeV depending on the models.

In most constrained SUSY scenarios viz mSUGRA, the required SUSY mass scale is $\gtrsim$ few TeV.

In pMSSM, $\lesssim$ TeV SUSY scale still a possibility but with large mixing in the stop mass matrix.

Fine tuning is necessary for MSSM to have lightest Higgs boson mass around $\sim 125$ GeV.

$\sim 125$ GeV Higgs $\Rightarrow$ very large SUSY mass scale or/and large mixings $\Rightarrow$ fine tuning.
Solution!

Extended Higgs sector!

- New scalars give additional contributions to the lightest Higgs mass
- so no large mixing and/or heavy sfermions needed
- Extended theory may solve the $\mu$ problem
- Possibility of spontaneous CP-violation.

Options?

Triplet and/or singlet extensions.
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The $\mu_D$ term in the superpotential can be generated spontaneously by the introduction of a gauge singlet superfield $S$.

The scale invariant superpotential with the $Y=0$ triplet $T$ and singlet $S$ is given by,

$$W_S = \lambda_T H_d \cdot TH_u + \lambda_S SH_d \cdot H_u + \lambda_{TS} S Tr[T^2] + \frac{\kappa}{3} S^3.$$ 

The complete Lagrangian with the soft SUSY breaking terms has an accidental $Z_3$ symmetry; $\phi_i \rightarrow e^{2\pi i/3} \phi_i$.

When the neutral parts get vev,

$$< H^0_{u,d} > = \frac{v_{u,d}}{\sqrt{2}}, \quad < S > = \frac{v_S}{\sqrt{2}}, \quad < T^0 > = \frac{v_T}{\sqrt{2}}$$

generate the doublet mixing term $\mu_D = \frac{\lambda_S}{\sqrt{2}} v_S + \frac{\lambda_T}{2} v_T$ with $v_T \lesssim 5$ GeV from $\rho$ parameter.
Triplet-Singlet extended Supersymmetric scenarios

- Enhanced Higgs particle spectrum

  CP – even
  \[ h_1, h_2, h_3, h_4 \]

  CP – odd
  \[ a_1, a_2, a_3 \]

  charged
  \[ h_1^\pm, h_2^\pm, h_3^\pm \].

- The extra interaction terms also enhances the Higgs mass contribution at the tree-level thus reduces required SUSY the fine-tuning further.

\[
m_{h_1}^2 \leq m_Z^2 (\cos^2 2\beta + \frac{\lambda_T^2}{g_T^2 + g_Y^2} \sin^2 2\beta + \frac{2\lambda_S^2}{g_L^2 + g_Y^2} \sin^2 2\beta),
\]

\[
\tan \beta = \frac{v_u}{v_d}
\]
TNMSSM: Radiative corrections

- We follow Coleman-Weinberg effective potential approach for one-loop Higgs mass spectrum.

Parameter space scan

\[ |\lambda_{T,S,TS}| \leq 1, \quad |\kappa| \leq 3, \quad |v_s| \leq 1 \text{ TeV}, \quad 1 \leq \tan \beta \leq 10, \]
\[ |A_{T,S,TS,U,D}| \leq 500, \quad |A_\kappa| \leq 1500, \quad m^2_{Q_3, \bar{u}_3, \bar{d}_3} \leq 1000, \]
\[ 65 \leq |M_{1,2}| \leq 1000, \]

- The presence of more scalar enhances the Higgs self correction drastically.
TNMSSM: axion like pseudo-scalar

**In the limit of a continuous symmetry**

- In the limit when the $A_i$ parameters go to zero, the discrete $Z_3$ symmetry of the Lagrangian is promoted to a continuous $U(1)$ symmetry

\[
(\hat{\mathcal{H}}_u, \hat{\mathcal{H}}_d, \hat{T}, \hat{S}) \rightarrow e^{i\phi} (\hat{\mathcal{H}}_u, \hat{\mathcal{H}}_d, \hat{T}, \hat{S})
\]

- If this symmetry is softly broken by very small parameters $A_i$ of $\mathcal{O}(1)$ GeV, we get a very light pseudoscalar as pseudo-Nambu-Goldstone boson of the symmetry.

**Axion like pseudo-scalar**

- For $m_{a_1} < 2m_e$, the pseudo-scalar decays to diphotons only.

- If the decay life-time $\tau_a$ is greater than the age of the universe, it could be a potential dark matter candidate.

\[
\tau_a = \frac{64\pi}{g^2_{a\gamma\gamma} m_a^3}
\]

- Triplet and singlet part do not couple to fermions $\Rightarrow$ helps to evade the bounds from flavour physics and others.
We consider the discovered Higgs decay modes $WW$, $ZZ$ and $\gamma\gamma$ along with LEP data.

Possibilities of light pseudo-scalar and very light $m_{a_1} < 2m_e$ are still there.

Possibilities of two hidden Higgs are still alive.

PB, Claudio Coriano and Antonio Costantini, JHEP 1509 (2015) 045
TNMSSM: Higgs mass hierarchy

- Doublet
- Triplet
- Singlet
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Hidden Higgs phenomenology

- We consider a light pseudo-scalar $\sim 20 - 50$ GeV, which is mostly singlet/triplet.
- These points are consistent with $\sim 125$ Higgs data in the discovered modes of $\gamma\gamma$, $ZZ$ and $WW$.
- The uncertainties of $2\sigma \Rightarrow B(h_{125} \rightarrow a_1a_1) \sim 20\%$.
- Being mostly singlet/triplet they cannot be produced directly at the LHC.
- Production via the decays of doublet scalar states is a possibility.
The light pseudo-scalars mostly decay to $b$ and $\tau$ pairs.
Hidden Higgs phenomenology

- We analysed the scenario in $2b + 2\tau$, $3\tau$, $2b + 2\mu$ and $2\tau + 2\mu$ final state topology.
- A PYTHIA based simulation has been conducted with taking into account the SM backgrounds.
- Earlier hints can be found around 25 fb$^{-1}$ of integrated luminosity of the LHC at 14 TeV.
- This mode can be very handy in measuring the Higgs cubic coupling.

PB, Claudio Coriano and Antonio Costantini, JHEP 1512 (2015) 127
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There are three charged Higgs bosons: \( h_1^\pm, h_2^\pm, h_3^\pm \). Two of them are triplet like. The triplet component does not couple to fermions.

Non-standard decay of charged Higgs

Non-zero triplet vev gives rise to non-zero tree-level \( Z - h_i^\pm - W^\mp \) coupling, which is absent in MSSM or 2HDM.

\[ h_i^\pm \rightarrow ZW^\pm \]

This decay mode can give us a smoking gun signal of triplet nature of the model.

Charged Higgs searches at the LHC

Charged Higgs was searched in \( H^\pm \rightarrow \tau \nu_\tau \) mode.

Main production mode searched is \( t \rightarrow bH^\pm \)

Upper bounds given on expected cross-sections.

Triplet charged Higgs

No coupling to fermions

\( \Rightarrow \) a triplet like light charged Higgs can evade the recent bounds

The light charged Higgs cloud be still allowed and unseen.
Among those charged Higgs production in vector boson fusion is unique to Triplet one which is absent in MSSM and 2HDM.

Tri-leptonic signature can probe the scenario with 72 fb$^{-1}$ data at the LHC.

PB, Claudio Coriano, Antonio Costantini, arXiv:1512.08651

P.B, Katri Huitu, Asli Sabanci, JHEP05(2015)026
Charged Higgs boson in NMSSM

NMSSM charged Higgs boson

- NMSSM with $Z_3$ symmetry only extra has extra singlet along with the two Higgs doublets of MSSM.
- We can have a light pseudo-scalar with mass $< 100$ GeV.
- Singlet does not contribute to charged Higgs.
- There is only one charged Higgs boson which is doublet type.

Searches at the LHC

- Final states with $1b + 2\tau + 2\ell, 3b + 2\ell$ can probe such possibility.
- A PYTHIA based simulation shows with early data $10 \text{ fb}^{-1}$ can probe some of the parameter space.

Non-standard decay

- Possibility of very light pseudo-scalar opens up $h^\pm \to a_1 W^\pm$.
- For healthy branching in this mode we need some doublet mixing in the light pseudo-scalar.

Distinguishing TNSSM, NMSSM, TESSM and MSSM

NMSSM and MSSM charged Higgs boson

- MSSM and NMSSM have one doublet like charged Higgs boson.
- In case of MSSM pseudo-scalar and charged Higgs boson are nearly degenerate \( \Rightarrow h^\pm \rightarrow aW^\pm \) is not kinematically allowed.
- NMSSM can have a light pseudo-scalar so \( h^\pm \rightarrow a_1 W^\pm \) is open.

TESSM and TNSSM

- TESSM and TNSSM have two additional triplet type charged Higgs bosons.
- The triplet charged Higgs does not couple to fermion but can decay to \( ZW^\pm \).
- In TESSM possibility of light pseudo-scalar is not so natural and \( h_1^\pm \rightarrow a_1 W^\pm \) is not kinematically open.
- In TNSSM we have a light pseudo-scalar so both \( h_1^\pm \rightarrow ZW^\pm \) and \( h_1^\pm \rightarrow a_1 W^\pm \) can be open.

Searches at the LHC

\[
pp \rightarrow h_1^\pm h_1^{\mp} \\
\rightarrow a_1 W^\pm ZW^{\mp} \\
\rightarrow 2\tau(2b) + 2j + 3\ell + E_T \\
\rightarrow 2\tau(2b) + 4\ell + E_T.
\]

- Extracting both \( a_1 \) and \( ZW^\pm \) can be proof of existence of both triplet and singlet.

P.B, Claudio Coriano, Antonio Costaniti (work in progress)
Conclusions

- So far we have discovered a CP-even Higgs boson around $\sim 125$ GeV.
- All possible Standard Model modes are yet to be discovered.
- Possibility of hidden Higgs bosons still exists.
- Observation of Charged Higgs would be a direct proof of extended Higgs sector.
- In the extended Higgs SUSY scenarios, lighter SUSY mass scale is still a possibility.
- $h_1^\pm \rightarrow ZW^\pm$ could be a smoking gun signature for the triplet scenario.
- A very light pseudo-scalar is still a possibility with extended Higgs sector.
- We expect that LHC at 14 TeV will unveil few more and surprise more.
Thank you
MSSM Higgs sector

- In the large $m_A$ limit, the lightest CP-even neutral Higgs mass at tree-level is $m_h^2 \approx m_Z^2 \cos^2 2\beta$
  $\Rightarrow m_h$ cannot be greater than $m_Z$.

- With the radiative correction at one-loop the lightest Higgs mass becomes,

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12M_S^2} \right) \right]$$

where $M_S = \sqrt{m_{\tilde{t}_1}m_{\tilde{t}_2}}$, the stop mixing parameter is $X_t = A_t - \mu \cot \beta$
and for maximal mixing scenario: $X_t^{max} = \sqrt{6}M_S$. 

\[\text{back}\]
After $\sim 125$ GeV Higgs boson discovery, the parameter spaces of MSSM like theories are stringently constrained. Let’s consider two well known theories: mSUGRA/cMSSM, pMSSM.

mSUGRA/cMSSM Soft SUSY breaking parameters are unified at the high scale (GUT). Parameter space of the theory contains only sign($\mu$), $\tan \beta$, $A_0$, $m_0$, $m_{1/2}$.

Phenomenological MSSM: CP conservation, flavor diagonal mass and coupling matrices, universality of the 1st and 2nd generations are imposed. Parameter space of the model (22 parameters) : $\tan \beta$, $\mu$, $M_A$, gaugino Masses: $M_1, M_2, M_3$ $A_f$ (3 for the 3rd generation+3 for 1st and 2nd generations) $m_{\tilde{f}_L}$ and $m_{\tilde{f}_R}$ (5 $\oplus$ 5)
**125 GeV Higgs in MSSM**

*\( M^\text{max}_h \) in pMSSM, Djouadi et al. PLB708 (2012) 162-169*

- Only the scenarios with large \( X_t / M_S \) values and, in particular, those close to the maximal mixing scenario \( A_t / M_S \approx \sqrt{6} \) survive.
- The no–mixing scenario is ruled out for \( M_S \lesssim 3 \) TeV.
- The typical mixing scenario needs large \( M_S \) and moderate to large \( \tan \beta \) values.
- \( M^\text{max}_h = 136, 123 \) and 126 GeV have been obtained in, the maximal, zero and typical mixing scenarios.

*\( M^\text{max}_h \) in pMSSM, Carena et al. JHEP 1203 (2012) 014*

- With the significant splitting of the stop soft masses, the mass of the heaviest stop is of the order of the largest soft stop mass, and the lightest stop mass can be as low as \( \sim 100 \) GeV.
- \( \sim 125 \) GeV Higgs does not imply a hard lower bound on the squark masses.
- \( A_t \) larger than \( \sim 2 \) TeV are required to achieve \( \sim 125 \) GeV Higgs.
- In the case of no splitting between the two stop soft masses, values of \( A_t \) above \( \sim 1.5 \) TeV are needed to achieve Higgs masses in the region of interest.
- In this case the mass of the lightest stop is naturally above a few hundred GeV.
With $\sim 125$ GeV Higgs

- For $A_0 = 0$, $m_0$ versus $m_{1/2}$ planes are excluded (only possible $\sim 125$ GeV solutions with $m_{1/2} \sim m_0 \sim 10$ TeV; corresponding squark/gaugino masses $\sim 20$ TeV).
- For $A_0 = \pm 2m_0$ and $m_0 \sim 4 - 10$ TeV: Possible to get desired Higgs mass. Result: heavy scalars but light gauginos are still possible.
- $|A_0| < 1.8m_0$ is excluded for $m_0 < 5$ TeV
- $|A_0| < 0.3m_0$ is excluded for $m_0$ up to 20 TeV

Conclusion: High $m_0$ and $A_0$ are required!

PRD85(2012)075010
$\sim 125$ GeV Higgs boson in the TESSM

(a) $\mu/\mu$ (GeV)

(b) $\mu/\beta$ (GeV)
Constraints from $B \rightarrow X_S \gamma$

**$B \rightarrow X_S \gamma$ in TESSM**

- TESSM has two more charged Higgses and one more chargino than in the MSSM.
- The difference compared to the MSSM is that the triplet part of the charged Higgses and charginos does not couple to quarks.

$$W = \lambda H_d \Sigma H_u + \mu_D H_d H_u + \mu_T \text{Tr}(\Sigma^2),$$

- For this purpose we check the doublet content in both the lightest Charged Higgs and lightest chargino.
TNMSSM potential

\[ V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 \]
\[ + m_T^2 |T|^2 + m_Q^2 |Q|^2 + m_U^2 |U|^2 + m_D^2 |D|^2 \]
\[ + (A_S S H_d \cdot H_u + A_\kappa S^3 + A_T H_d \cdot T \cdot H_u + A_{TS} S \text{Tr}(T^2) \]
\[ + A_U U H_U \cdot Q + A_D D H_D \cdot Q + h.c.), \]

while the D-terms are given by

\[ V_D = \frac{1}{2} \sum_k g_k^2 (\phi_i^\dagger t_{ij}^a \phi_j)^2. \]
TNMSSM perturbativity

\[ \lambda_T = \lambda_S = 0.8 \]
Fine-tuning

\[ M_Z^2 = \mu_{\text{soft}}^2 - \mu_{\text{eff}}^2 \]
\[ \mu_{\text{eff}} = v_S \lambda_S - \frac{1}{\sqrt{2}} v_T \lambda_T, \]
\[ \mu_{\text{soft}}^2 = 2 m_{H_d}^2 - \tan^2 \beta m_{H_u}^2 \frac{\tan^2 \beta - 1}{\tan^2 \beta - 1}. \]

It is also convenient to introduce the additional parameter

\[ F = 1 - \frac{\mu_{\text{soft}}^2 - \mu_{\text{eff}}^2}{\mu_{\text{soft}}^2}, \]

characterizing the ratio between \( M_Z^2 \) and \( \mu_{\text{soft}}^2 \), which can be considered a measure of the fine-tuning.
Non-standard decay of charged Higgs

- For $Y = 0$, ±2 triplet extended models, $h_i^{\pm} Z W^\mp$ coupling is not zero at tree-level for non vanishing triplet VEV.

\[
g_{h_i^{\pm} W^\mp Z} = -\frac{1}{2} i g_2 \left( g_1 \sin \theta_W (v_u R(i+1)_1 - v_d R(i+1)_2) \right)
- \frac{1}{2} i g_2 \left( \sqrt{2} g_2 v_T \cos \theta_W (R(i+1)_3 + R(i+1)_4) \right)
\]

where $\theta_W$ is the Weinberg angle, $R_{ij}$ is the rotation matrix, $h_i = R_{ij} H_j$.

- The $h_i^{\pm} W^\mp Z$ coupling goes to zero for $v_T = 0$ to preserve $U(1)_{em}$ gauge symmetry.
- Similarly when the charged Higgs is completely doublet like i.e., $R_{(i+1)3,4} = 0$, $h_i^{\pm} W^\mp Z$ again zero giving rise to MSSM like scenario.

$h_1^{\pm} - W^\mp - Z$
Decay Modes of charged Higgs

Decay modes of charged Higgs

\[ h_i^\pm \rightarrow tb \]
\[ \rightarrow ZW^\pm \]
\[ \rightarrow \tau\nu \]
\[ \rightarrow h_j W^\pm \]

Triplet nature

- The triplet part does not couple to fermions, so normal decays to \( tb \) or \( \tau\nu \) is suppressed.
- The triplet can decay to \( ZW^\pm \) which is absent in MSSM or 2HDM.
  \[ \Rightarrow \text{this decay mode can give us smoking gun signal of triplet nature of the model.} \]
- If kinematically allowed, \( ZW^\pm \) mode gets tough competition from \( tb \).
Production of charged Higgs

Production modes of charged Higgs

- As the triplet part does not couple to fermions the dominant mode $pp \rightarrow t\bar{t}$ for light charged Higgs is no longer the most important one for $m_{h_i^\pm} < m_t$.
- For $m_t > m_{h_i^\pm}$, $gg \rightarrow h_1^\pm tb$ and $bg \rightarrow h_1^\pm t$ are also suppressed.
- Due to non-zero $h_i^\mp - Z - W^\pm$ coupling there are now few more additional production processes.
- Among those charged Higgs production in vector boson fusion is unique to Triplet one which is absent in MSSM and 2HDM.

Final state studies

- We mainly focus on the multi-leptonic final states coming from charged Higgs decays to $ZW^\pm$.
- Additional modes like $\tau\nu$ and $tb$ enrich the final states with more jets: $b$ or $\tau$.
- We found that the charged Higgs production in association with neutral Higgses, i.e. $h_i/ A_i h_j^\pm$ is quite interesting.
Benchmark point for collider study at the LHC

To select to few benchmark points with a light charged Higgs to see the prospect at the LHC.

Given points have a SM like Higgs bosons around $\sim 125$ GeV.

The other heavy and charged Higgs constraints have also been checked.

We can see the light charged Higgs is quite non-standard due to its decay to $ZW^\pm$.

It is this non-standard decay that evade the recent bounds from LHC on the light charged Higgs.

It also decays to $tb$ and $\tau \nu$

This prompts us to look for different final states constitute of lepton, tau, jets and $b$-jets.

<table>
<thead>
<tr>
<th>Benchmark Points</th>
<th>$\tan \beta$</th>
<th>$m_{h_2}$ (GeV)</th>
<th>$m_{A_1}$ (GeV)</th>
<th>$m_{H_1^\pm}$ (GeV)</th>
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<td>BP1</td>
<td>8.63</td>
<td>182.898</td>
<td>610.91</td>
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<td>BP2</td>
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<td>216.94</td>
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<th>Branching fractions</th>
<th>$ZW^\pm$</th>
<th>$h_1 W^\pm$</th>
<th>$t\bar{b}$</th>
<th>$\tau \nu\tau$</th>
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<td>56.3</td>
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<td>12.8</td>
<td>48.4</td>
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**Searches for charged Higgs in TESSM at the LHC**

### Production modes of charged Higgs

- \( h_i^\pm h_1^\mp, h_i^\pm W^\mp \) and \( h_1^\pm \phi \) give the dominant contributions for the light charged Higgs production in TESSM at the LHC.
- Considering different leptonic decays we focus on multi-leptonic final states: \( 3\ell, 4\ell \) and \( 5\ell \) final states.
- Due to other decay modes we also looked for \( 3\ell + 2j + p_T, 3\ell + 2b + p_T, 3\ell + 1\tau + p_T \) final states.

### Basic Cuts

- The calorimeter coverage is \(|\eta| < 4.5\).
- As we are looking for leptonic final state we demanded hard jets, \( p_{jet}^{T, min} = 20 \) GeV and jets are ordered in \( p_T \).
- Leptons (\( \ell = e, \mu \)) are selected with \( p_T \geq 10 \) GeV and \(|\eta| \leq 2.5\).
- \( \Delta R_{lj} \geq 0.4 \) and \( \Delta R_{ll} \geq 0.2 \).

### Collider Set up

- We analyse the signals and SM backgrounds via Pythia+Fastjet simulation at the LHC with 14 TeV.
- \( t\bar{t}, t\bar{t}Z, t\bar{t}W^\pm \) and \( VV \ (V : Z, W^\pm) \) have been considered as dominant SM backgrounds.
Tri-lepton final states at the LHC

### $3\ell + 2j$ final state

- When the charged Higgs decays to $Z W^\pm \rightarrow 3\ell$ other associated particles decay hadronically.
- For the final state we choose: $3\ell (|M_{\ell\ell} - M_Z| \leq 5 \text{ GeV}) + 2j + p_T \geq 30 \text{ GeV}
- For BP1 $5\sigma$ signal significance reaches in around 70 fb$^{-1}$ of integrated luminosity at the LHC with 14 TeV.
- At 1000 fb$^{-1}$ of luminosity, rest of the benchmark points reach around $10\sigma$.

### $3\ell + 2b$ final state

- This $h^\pm \phi$ process can have additional $b$-jets from $\phi$.
- To find out we choose $3\ell (|M_{\ell\ell} - M_Z| \leq 5 \text{ GeV}) + 2b - \text{jets} + p_T \geq 30 \text{ GeV}$ as our final state.
- For BP1 and BP2 $h^\pm h_2$ contributes due low masses of $h_2$.
- For BP3 and BP4, $h^\pm A_1$ contributes.
- The highest reach is for BP1, reaches $5\sigma$ in 100 fb$^{-1}$ of integrated luminosity at the LHC with 14 TeV.
- whereas BP2 has the lowest reach takes 1000 fb$^{-1}$ to reach $5\sigma$ due to triplet nature of $h_2$, $\text{Br}(h_2 \rightarrow b\bar{b})$ is very small.

### $3\ell + 1 - \tau$

- $h_i^\pm$ can also decay to $\tau\nu$, so also search $3\ell (|M_{\ell\ell} - M_Z| \leq 5 \text{ GeV}) + 1\tau - \text{jet} + p_T \geq 30 \text{ GeV}$ final state.
- The extra $\tau$-jet reduces the backgrounds substantially.
- Highest reach is again for BP1, reaches $5\sigma$ in around 146 fb$^{-1}$ of integrated luminosity.
4ℓ and 5ℓ final states at the LHC

4ℓ final state

- When the associate particle to the light charged Higgs also contribute leptonically we can have ≥ 4ℓ final state.
- We look for 4ℓ + pT ≥ 30 GeV final state.
- t̄t̄ and VV are still dominant backgrounds.
- For BP1 & BP2 5σ signal significance reaches in around 200 fb−1 of integrated luminosity at the LHC with 14 TeV.
- At 1000 fb−1 of luminosity, rest of the benchmark points reach around 5σ.

5ℓ final state

- In h±h∓ if both the charged Higgs decay to ZW± then we can have 5ℓ and 6ℓ final states.
- We look for 5ℓ + pT ≥ 30 GeV final state.
- In BP2 h±φ also contributes as Br(h2 → ZZ ∼ 44%).
- The highest reach is for BP2, ∼ 10σ at 1000 fb−1 of integrated luminosity at the LHC with 14 TeV.

5ℓ + 2 − jet, 6ℓ

- Mainly charged Higgs pair-production contributes.
- 5ℓ + 2 − jet and 6ℓ final states are almost background free.
- These are important at higher luminosities.

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Mass reconstruction of the charged Higgs at LHC

$h_1^{±}$ mass reconstruction

- When one of the $h_1^{±}$ decays to full visible particle via
  \[ h_i^{±} \rightarrow Z, W^{±} \rightarrow ℓℓqq' \]

- It is possible to reconstruct $M_{ℓℓjj}$ invariant mass distribution.

Probing triplet decay mode

- This is one of the direct way to probe the triplet nature of the charged Higgs.
- Reconstruction of the peak can lead to a discovery of the light charged Higgs in TESSM.
- The edge at the end part of the distribution also carries information about the higher Higgs masses contributing to the production processes.
- Requirements of multiple leptons ($≥3$) and $b$-jets ($≥2$) make this almost background free.