Search of doubly-charged boson in the four-lepton channel at the LHC

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based on

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Introduction

A Higgs has been discovered at the first run of the LHC

However the Higgs sector is still unknown.

Minimal or non-minimal?

We already have various BSM phenomenon.

- Neutrino Oscillations
  $\Rightarrow$ confirms tiny neutrino mass
- Dark Matter $\Rightarrow \Omega_{DM} h^2 \sim 0.11$
- Matter-antimatter asymmetry
- etc.

To understand these, we need to extend the SM.

From Standard Model to New Physcis

- How can be the SM extended?

- Fundamental extensions:
  - Introduction of a larger symmetry like supersymmetry
  - Assumption of extra dimensions
  - Introducing a larger group encampassing SU(3)×SU(2)×U(1) like in GUT theories
  - etc.

- Particular extensions
  - Extension of single sector in the SM like scalar sector or fermion sector etc.

From Standard Model to New Physcis

- One major motivations for new physics smallness of neutrino masses
- Origin can be attributed to a new particle coupling to the lepton doublets of the SM.
- The type II seesaw mechanism introduces a Higgs triplet whose VEV generates the neutrino masses and mixing.
- The Higgs sector of the type II seesaw contains four more bosons, H^{++}, H^{+} and H^0/A^0, in addition to the SM Higgs boson, h.
- Higgs triplet couplings can change drastically the stability of the SM electroweak vacuum
  $\Rightarrow$ Hence are quite constrained.

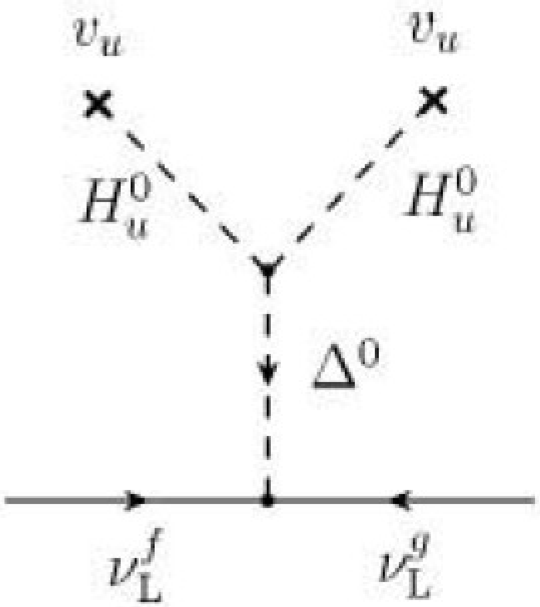
Type II seesaw Lagrangian

- One triplet scalar Δ with hypercharge $Y = 1$ is included.

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}.$$

- Important new interactions :

$$\mathcal{L} = f_{ij} L_i^T C i\tau_2 \Delta L_j + \mu \Phi \Delta^\dagger \Phi + h.c.$$



- When the neutral component acquires vev, the Neutrino mass matrix $(M_\nu)_{ij} = f_{ij} \frac{\mu v_u^2}{M_\Delta^2} = f_{ij} v_T$.

Scalar Potential of type II seesaw

The scalar potential is

$$
\begin{aligned}
V(\Phi,\Delta) &= m^2\Phi^\dagger\Phi+\lambda_1(\Phi^\dagger\Phi)^2+M^2\mathrm{Tr}(\Delta^\dagger\Delta)\\
&+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2+\lambda_3\mathrm{Det}(\Delta^\dagger\Delta)+\lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta)\\
&+ \lambda_5(\Phi^\dagger\tau_i\Phi)\mathrm{Tr}(\Delta^\dagger\tau_i\Delta)+\left[\frac{1}{\sqrt{2}}\mu(\Phi^T i\tau_2\Delta\Phi)+\mathrm{H.c.}\right].
\end{aligned}
$$

- Upon EWSB with $\langle\Phi^0\rangle = v_0/\sqrt{2}$,
- the μ term gives rise to the vev of the triplet $\langle\Delta^0\rangle = v_\Delta/\sqrt{2}$
- μ term violates lepton number by two units
- It also protects from the existence of majoron.
- small μ can be viewed as a soft breaking term for lepton number.

Particle content in type II seesaw

- Upon EWSB, there are seven physical massive scalar eigenstates denoted by $H^{\pm,\pm}$, $H^{\pm}$, H^0, A^0, h^0.

- For the neutral pseudoscalar and charged scalar parts,

$$\phi_I^0 = G^0 - 2\xi A^0 \,, \qquad \phi^+ = G^+ + \sqrt{2}\xi H^+$$
$$\Delta_I^0 = A^0 + 2\xi G^0 \,, \qquad \Delta^+ = H^+ - \sqrt{2}\xi G^+$$

- for the neutral scalar part,

$$\begin{aligned} \phi_R^0 &= h^0 - a\xi\, H^0 \,, \\ \Delta_R^0 &= H^0 + a\xi\, h^0 \end{aligned}$$

- Under the condition that $|\xi| \ll 1$ where $\xi \equiv v_\Delta / v_0$, the first five states are mainly from the triplet scalar and the last from the doublet scalar.

- For $v_\Delta << v$, the mixing between doublet and triplet is very small.

Masses of scalars

The masses of the Higgs bosons are

- $M^2_{H^{\pm\pm}} = M^2 + 2\frac{\lambda_4 - \lambda_5}{g^2} M^2_W$
- $M^2_{H^{\pm}} = M^2_{H^{\pm\pm}} + 2\frac{\lambda_5}{g^2} M^2_W$
- $M^2_{H^0, A^0} = M^2_{H^{\pm}} + 2\frac{\lambda_5}{g^2} M^2_W$.

The sign of the coupling $\lambda_5 \Rightarrow$ Two mass hierarchies:

- $M_{H^{\pm\pm}} > M_{H^{\pm}} > M_{H^0/A^0}$ for $\lambda_5 < 0$;
- $M_{H^{\pm\pm}} < M_{H^{\pm}} < M_{H^0/A^0}$ for $\lambda_5 > 0$.

Triplet production at LHC

At the LHC, the main production of triplets are:

- $q\bar{q} \to H^{++}H^{--}$: Pair production of doubly-charged Higgs,
- $q\bar{q}' \to H^{\pm\pm}H^{\mp}$: Associated production ,
- $q\bar{q} \to H^{+}H^{-}$: Pair production of singly-charged Higgs,
- $q\bar{q} \to H^{\pm}H^{0}/A^{0}$: Associated production,
- $q\bar{q} \to A^{0}H^{0}$: Neutral Higgs production,

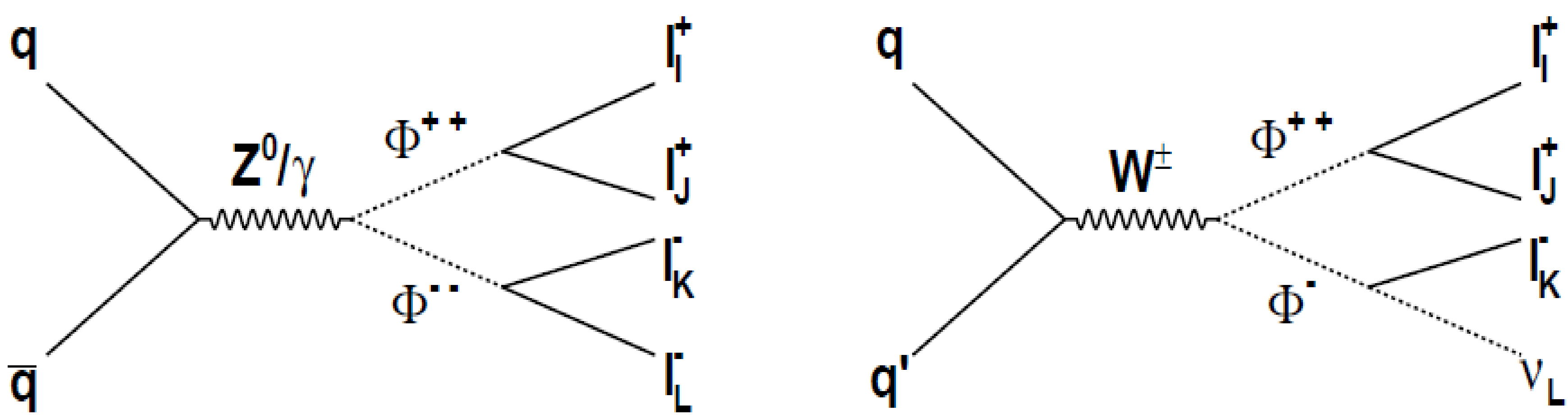
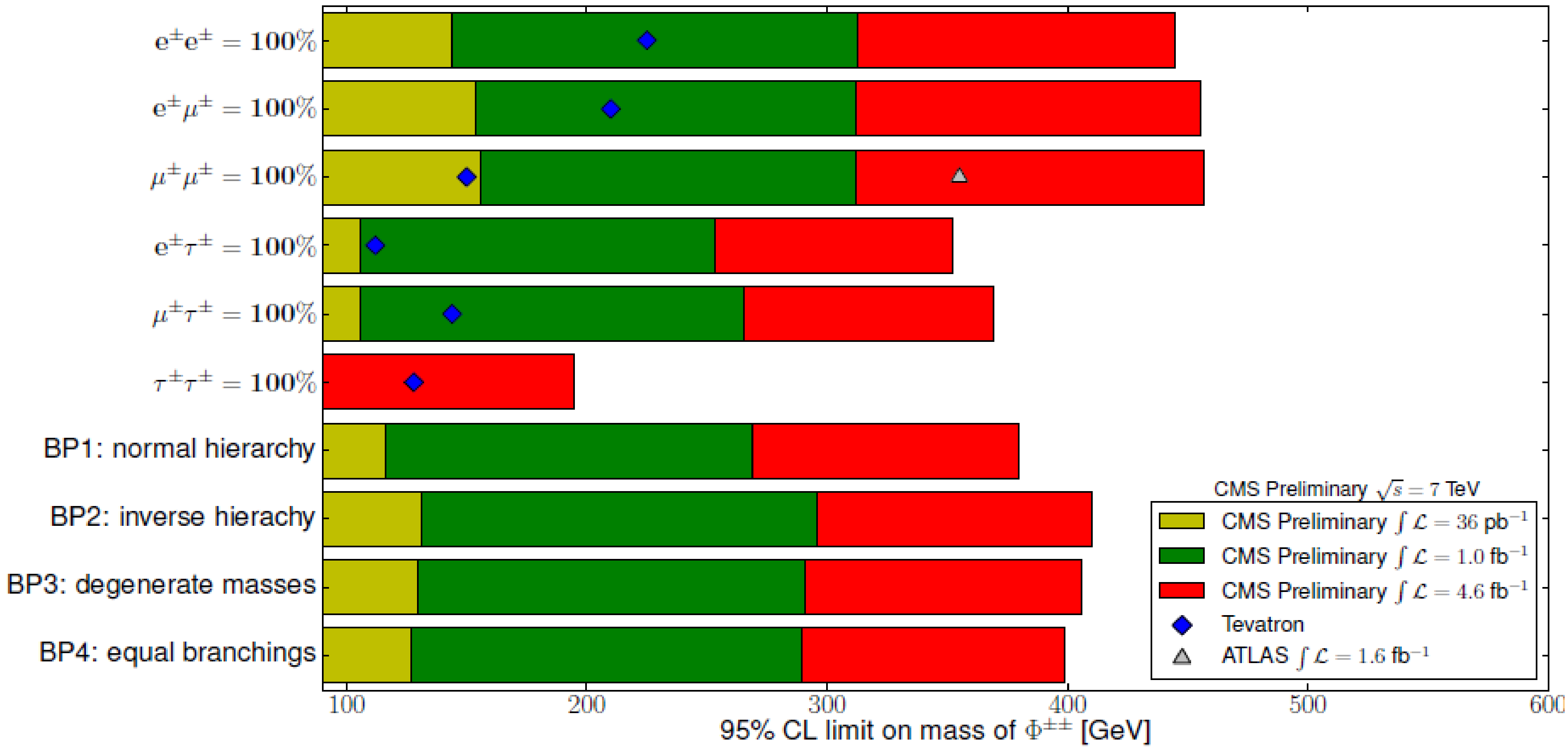


Figure 1: Feynman diagrams of both pair and associated production.

Constraints on H^{++} mass

- Recently, CMS also performed with 4.9 fb^{-1} luminosity a search for doubly charged Higgs decaying to a pair of leptons,

$$H^{++}H^{--} \to \ell^+\ell^+\ell^-\ell^- \text{ and } H^{++}H^- \to \ell^+\ell^+\ell^-\nu$$



Constraints on Mass-splitting

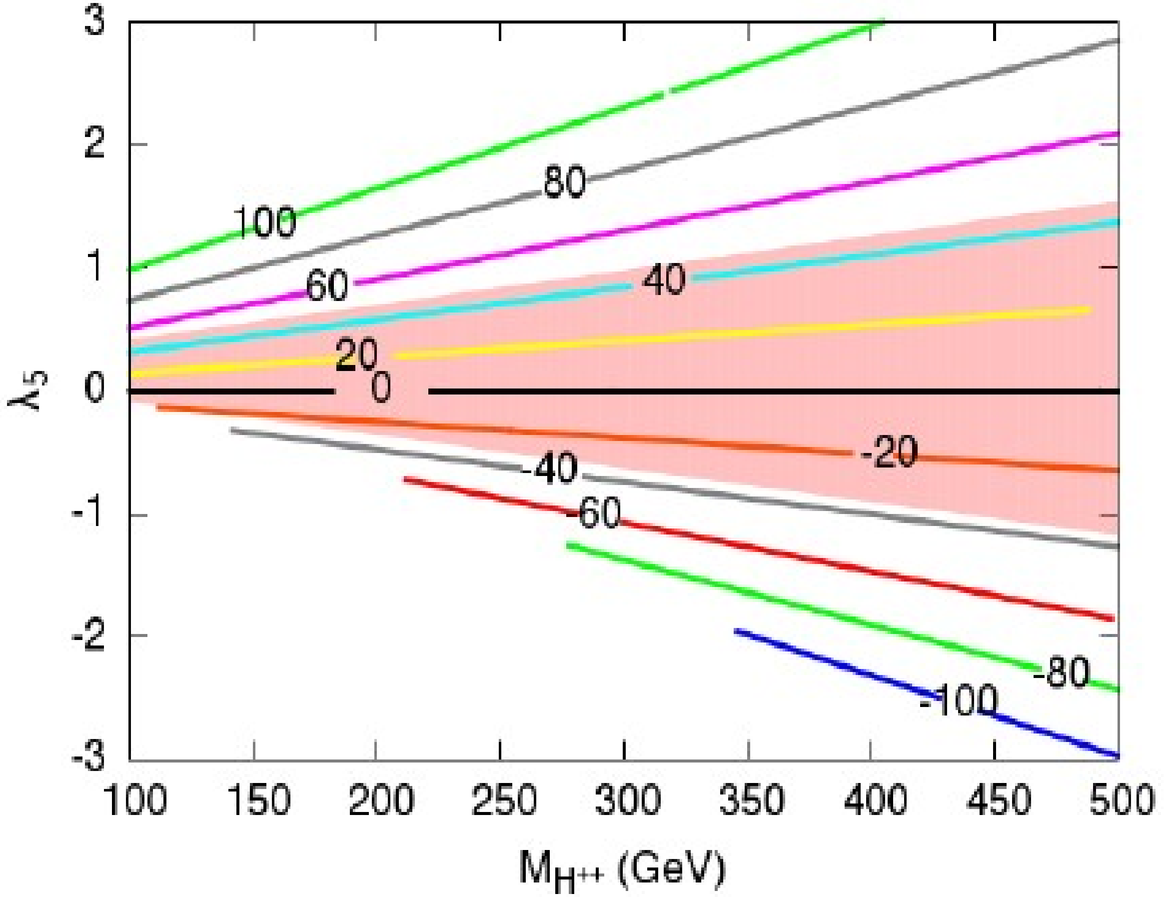
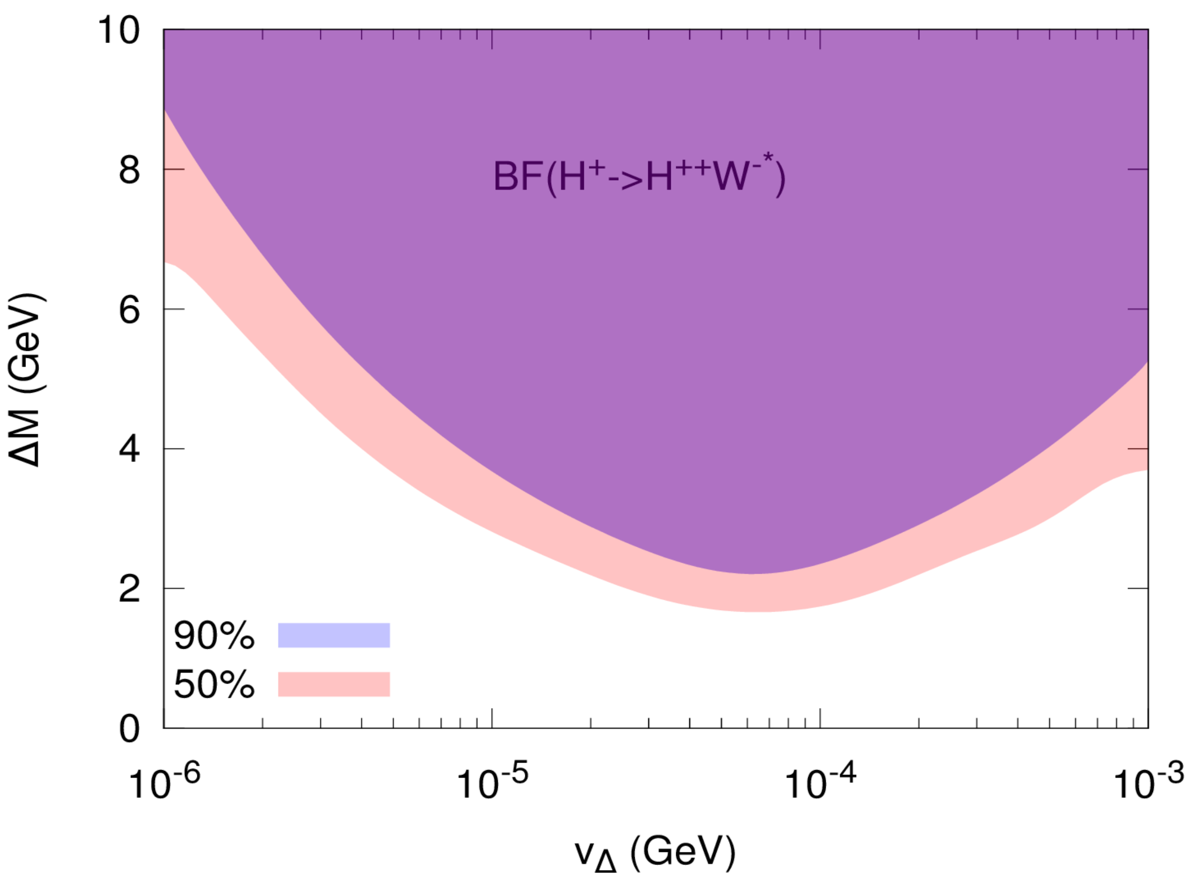
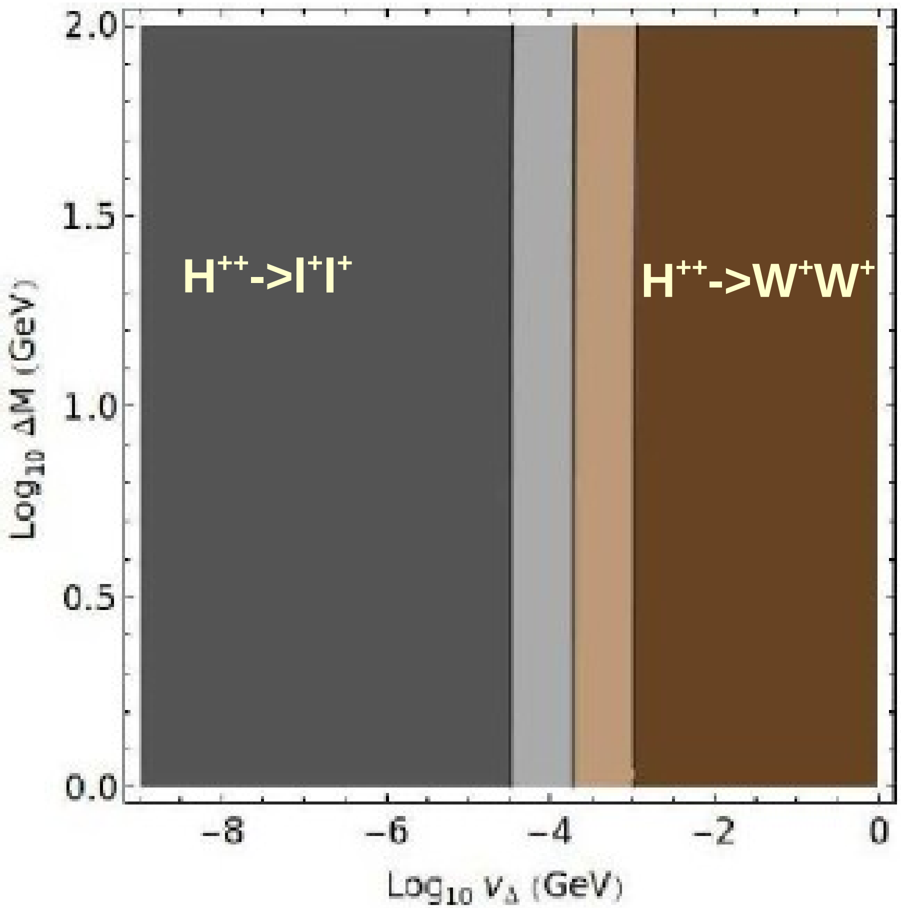


Figure 2. Allowed parameter space in the $M_{H^{++}}$–λ_5 plane. The contours represent the allowed values of mass splitting, $\Delta M \equiv M_{H^+} - M_{H^{++}}$, in the unit of GeV. The shaded band denotes the 99% CL region satisfying the EWPD constraint.

Decays of triplet Higgs can be classified into 3 modes

- Decay via f_{ij} i.e., $\Delta \to \ell\ell$
- Decay via v_T i.e., $\Delta \to VV$
- Gauge decay g_W i.e., $\Delta \to \Delta' W$





Event selection

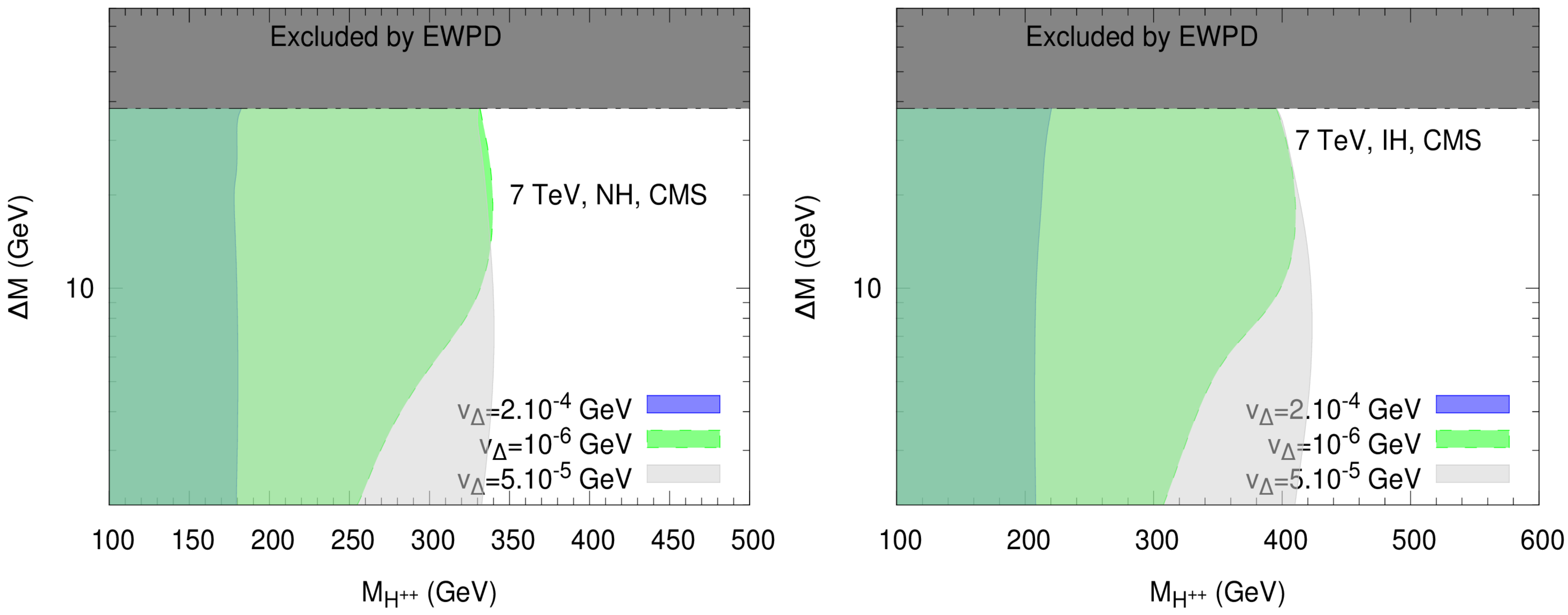
CMS : Selections applied for four-lepton final states

Variable	ee, $e\mu$, $\mu\mu$
$\sum p_{\mathrm{T}}$	$> 0.6 \cdot m_{\Phi^{++}} + 130\,\mathrm{GeV}$
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	none
Mass window	$[0.9 \cdot m_{\Phi^{++}}; 1.1 \cdot m_{\Phi^{++}}]$

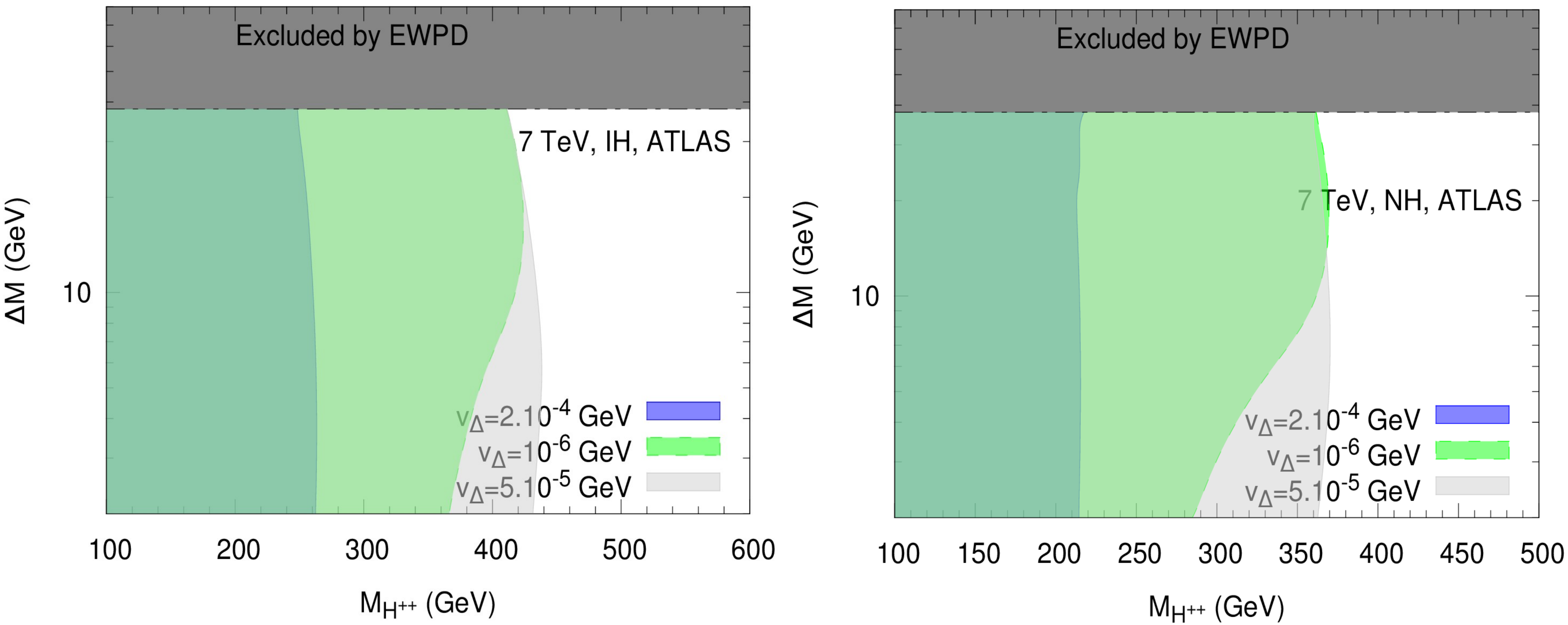
ATLAS: Selection strategy

$$\sigma(pp \to H^{\pm\pm}H^{\mp\mp}) \times BR(H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = \frac{N^{\mathrm{rec}}(\ell^{\pm}\ell'^{\pm})}{2 \times A \times \varepsilon \times \mathscr{L}}$$

Constraints from CMS data



Constraints from ATLAS data



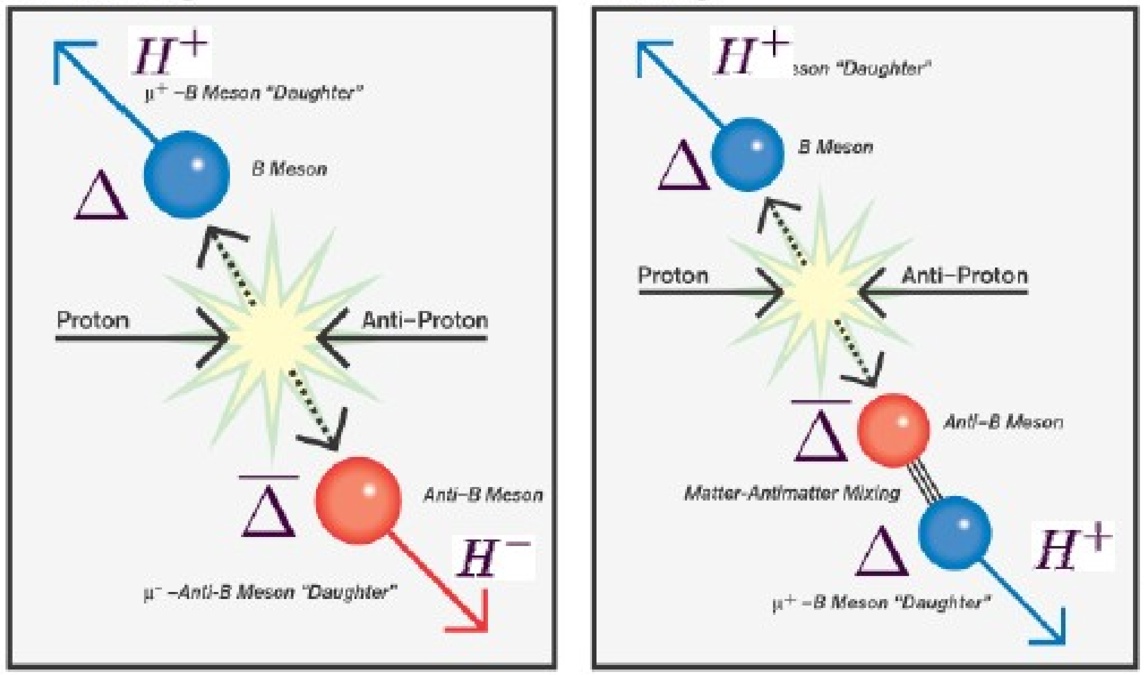
Same-sign tetra-lepton (SS4L)

$$\mathcal{L}_{\not\Delta} = \frac{1}{\sqrt{2}}\mu\Phi^T i\tau_2\Delta^\dagger\Phi + h.c. \Rightarrow -\mu v_0 h^0 H^0$$

$\Delta = 2$

No Mixing $H^{++}H^{--}$

Mixing $H^{\pm\pm}H^{\mp\mp}$



SS4L Signal

- Effect of oscillation is controlled by parameter

$$x \equiv \frac{\delta M_{HA}}{\Gamma_{\Delta^0}} \gtrsim 1$$

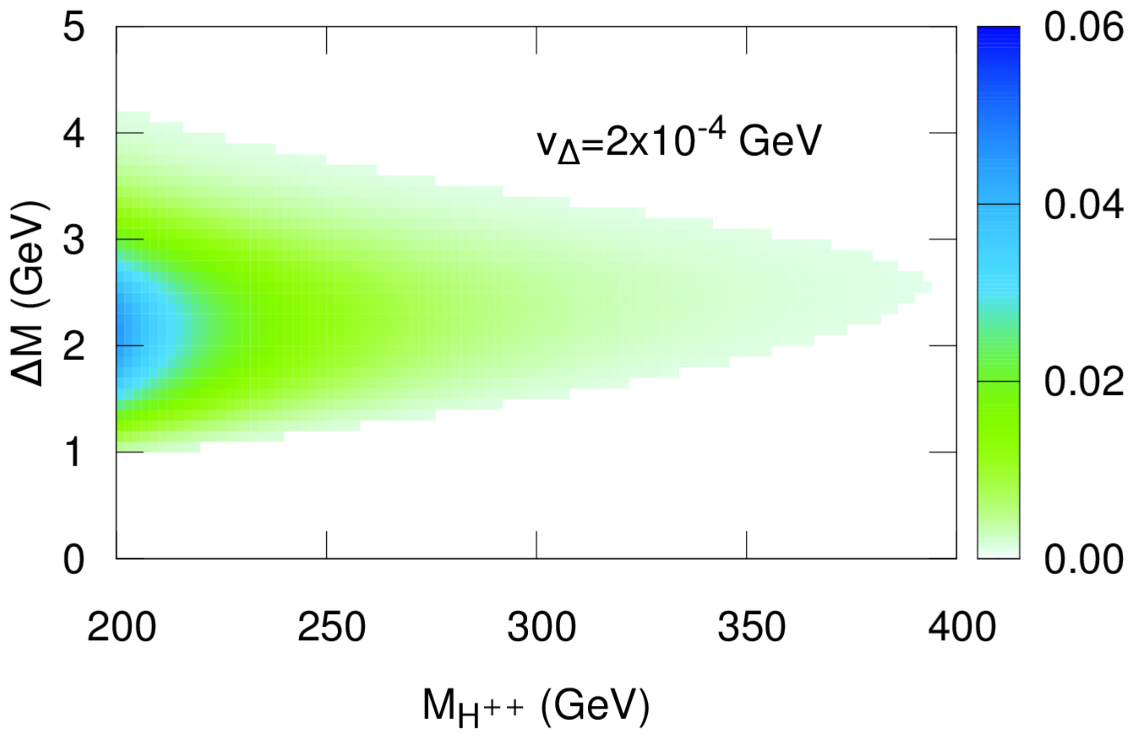
- Using NWA, cross section for SS4L signal can be written as:

$$\begin{aligned}\sigma\left(4\ell^{\pm} + nW^{\mp^*}\right) \; = & \left\{\sigma\left(pp \to H^{\pm}\Delta^{0(\dagger)}\right)\left[\frac{x^2}{2(1+x^2)}\right] \mathrm{BF}(\Delta^{0(\dagger)} \to H^{\pm}W^{\mp^*})\right. \\ & \left. + \; \sigma\left(pp \to \Delta^0\Delta^{0\dagger}\right)\left[\frac{2+x^2}{2(1+x^2)}\frac{x^2}{2(1+x^2)}\right]\left[\mathrm{BF}(\Delta^{0(\dagger)} \to H^{\pm}W^{\mp^*})\right]^2\right\} \\ & \times \; \left[\mathrm{BF}(H^{\pm} \to H^{\pm\pm}W^{\mp^*})\right]^2 \left[\mathrm{BF}(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm})\right]^2 . \qquad (1\end{aligned}$$

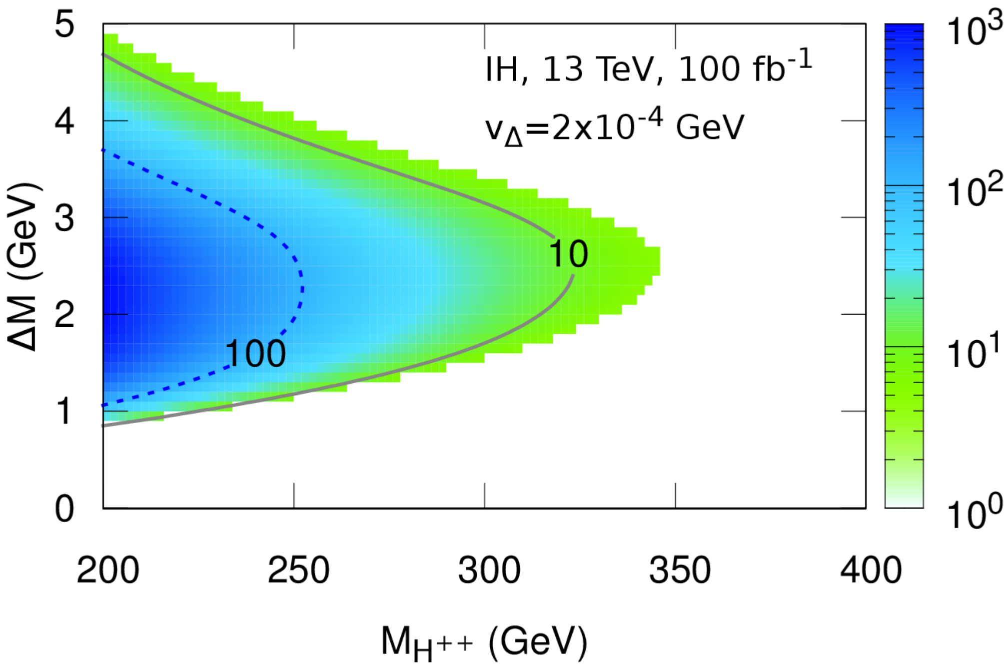
SS4L Signal

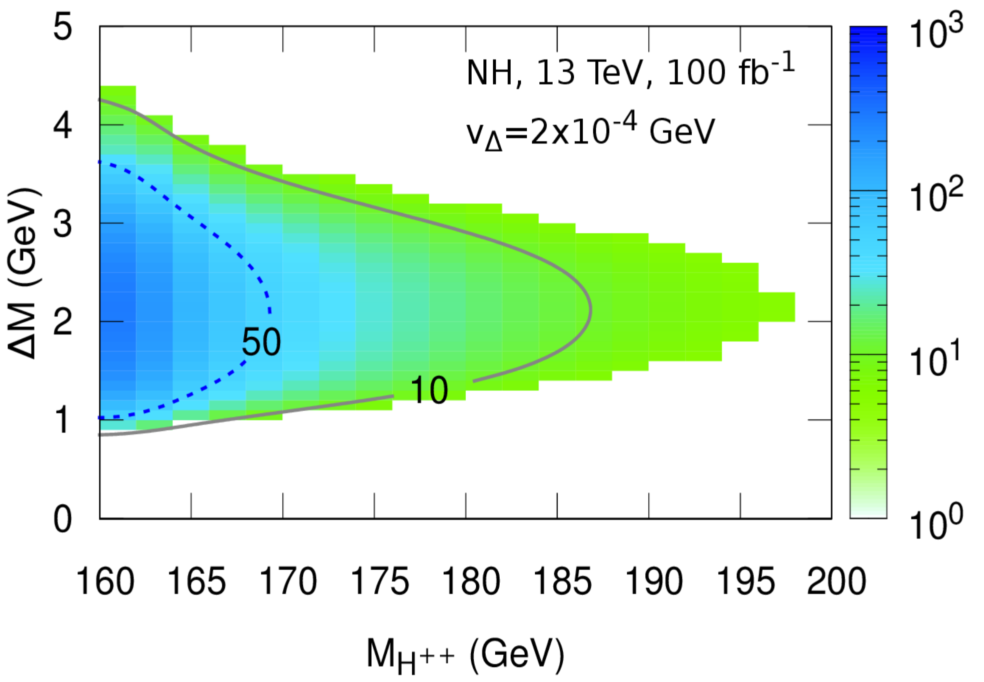
Defining a parameter to analyse the viability of SS4L signal :

$$\chi_B \equiv \left[\frac{x^2}{2(1+x^2)}\right] \mathrm{BF}(\Delta^{0(\dagger)} \to H^{\pm}W^{\mp^*}) \left[\mathrm{BF}(H^{\pm} \to H^{\pm\pm}W^{\mp^*})\right]^2 \left[\mathrm{BF}(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm})\right]^2 \quad (17)$$

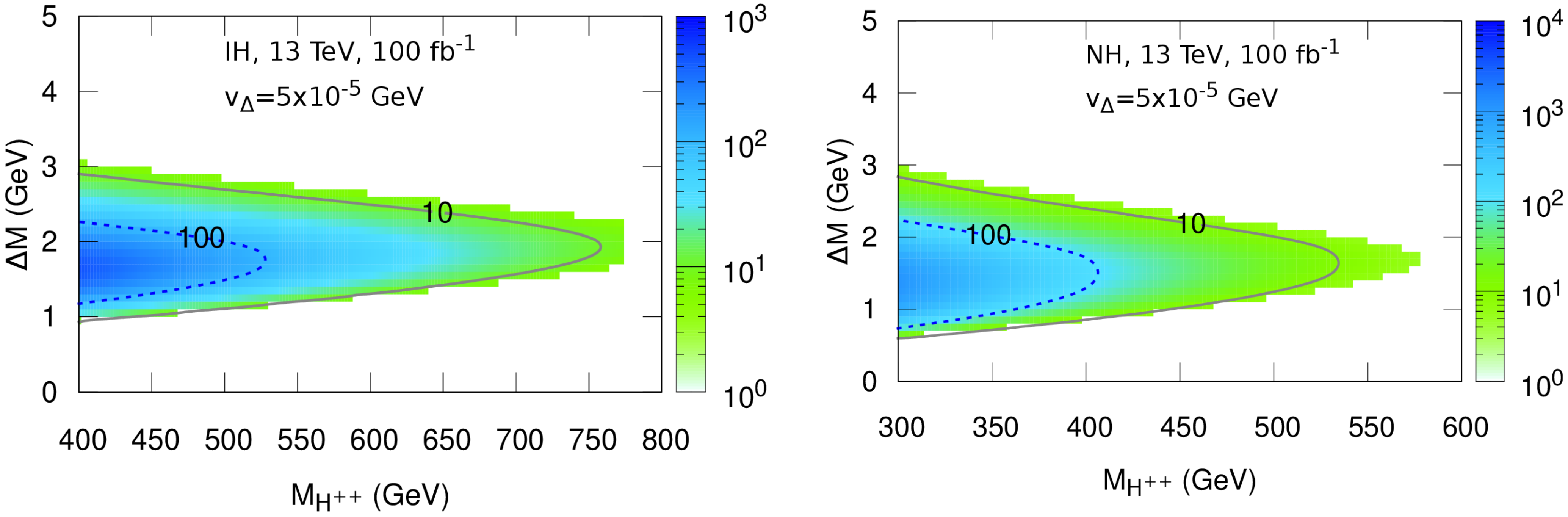


Constraints from SS4L signal





Constraints from SS4L signal



Conclusions

- Constraints on H^{++} mass has been revised in the case where μ is non-zero

- ATLAS and CMS data have been utilized to put constraints in the $\Delta M - M_{H++}$ plane of the type II seesaw model

- SS4L signals have been studied in $\Delta M - M_{H++}$ plane

- Doubly-charged Higgs can be probed upto mass of 700 GeV in a specific part of parameter space

THANKS