Phenomenology of the Higgs Triplet Model with the mass difference at the LHC

Kei YAGYU (Univ. of Toyama)

M. Aoki, S. Kanemura, KY, arXiv: 1110.4625 [hep-ph]

18, November 2011 KIAS Phenomenology Workshop

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- Introduction
- Generation mechanisms for neutrino masses
- The Higgs Triplet Model
  - Decay
  - Production
  - LHC phenomenology
- Summary

Introduction

- **Higgs sector is unknown**
  - Minimal ? or Non minimal ?
  - Higgs boson search is starting at LHC

- **Some new physics models predict extended Higgs models**

Hierarchy problem

Neutrino mass

Dark matter

Baryon asymmetry of Universe

New physics at TeV scale

Predict

Determine the direction of NP

Extended Higgs models as a low energy effective theory

Two Higgs doublets

Higgs triplet

etc.

Generation mechanisms for neutrino masses

Majorana masses of neutrinos are given by the dimension 5 operator, where 2 units of lepton number are broken.

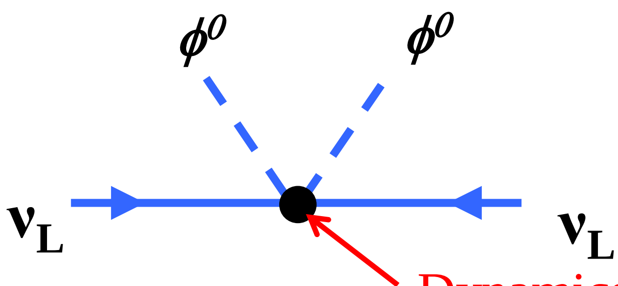
$$\mathcal{L}_{\text{eff}} = \frac{c}{M}\overline{\nu_L^c}\nu_L\phi^0\phi^0 \quad \Rightarrow \quad \underbrace{\frac{c\langle\phi^0\rangle^2}{M}}_{m_\nu}\overline{\nu_L^c}\nu_L$$

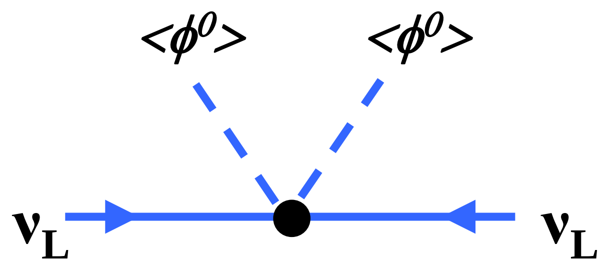
$<\phi^0>$ ~246 GeV

m_ν ~ 0.1 eV

$c/M \sim 10^{-14}$ GeV^{-1}

The Higgs boson acquires the VEV





Dynamics of extended Higgs model

There are scenarios, where neutrino masses generate through dynamics of **extended Higgs models.**

Ex. 1 The type II seesaw model (at the tree level)

Cheng, Li (1980); Schechter, Valle, (1980); Magg, Wetterich, (1980); Lazarides, Shafi, Wetterich, (1981); Mohapatra, Senjanovic, (1981).

Ex. 2 Radiative seesaw models (at the loop level)

Zee, (1980); Zee, (1986); Babu, (1988); Krauss, Nasri, Trodden, (2003); Ma, (2006); Aoki, Kanemura, Seto, (2009).

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$\langle\phi^0\rangle \sim 246$ GeV

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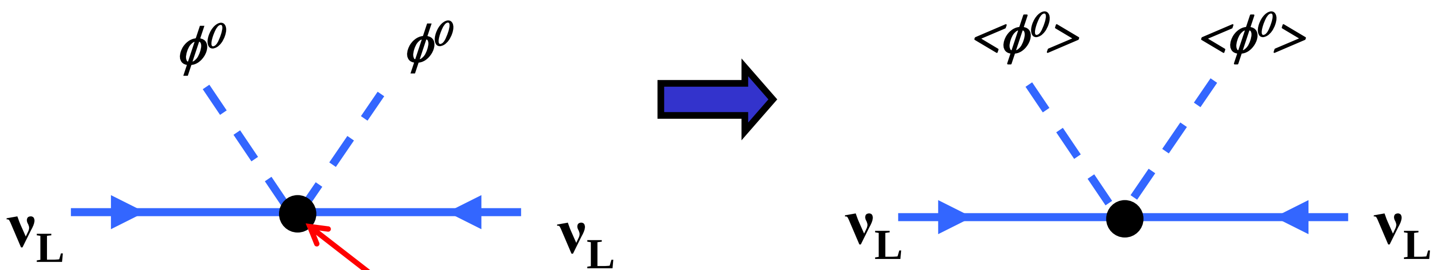

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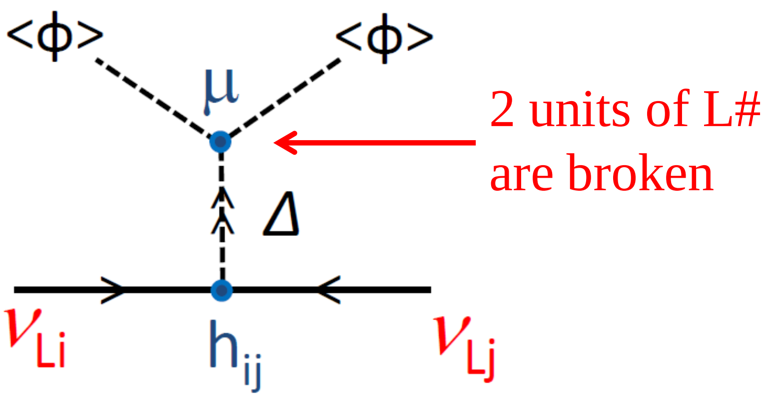
Type II seesaw model (Higgs Triplet Model)

The Higgs triplet field Δ (Y = 1) is added to the SM.

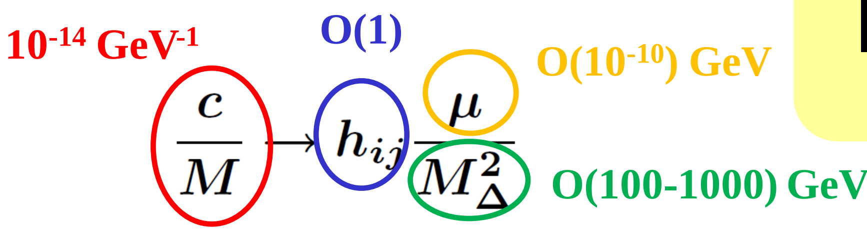
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$
Φ	1	2	+1/2	0
Δ	1	3	+1	2

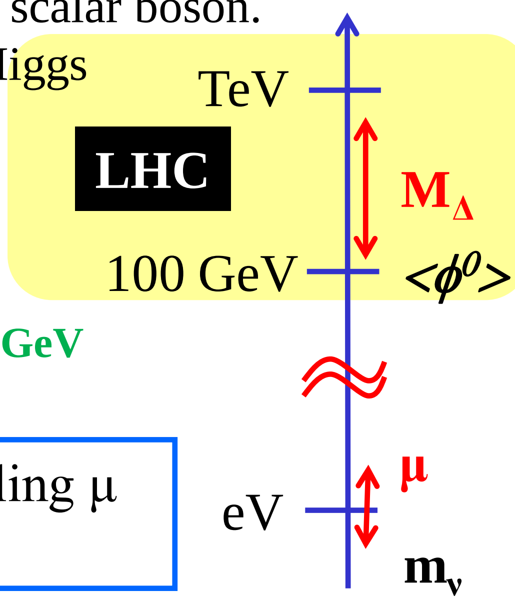
$$\mathcal{L}_{\rm typeII} = h_{ij}\overline{L_L^{ci}}\cdot\Delta L_L^j + \mu\Phi\cdot\Delta^\dagger\Phi + \cdots$$



$$(m_\nu)_{ij} = h_{ij}\frac{\mu\langle\phi^0\rangle^2}{M_\Delta^2} = h_{ij}v_\Delta$$

M_Δ : Mass of the Triplet scalar boson.
v_Δ : VEV of the triplet Higgs





When we consider the TeV scale M_Δ , the L# violating coupling μ has to be of O(10^{-10}) GeV.

The Higgs Triplet Model (HTM)

The Higgs potential

$$V = m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^T i\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right]$$
$$+ \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[(\Delta^\dagger\Delta)^2]$$
$$+ \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi.$$

$$\Phi = \begin{bmatrix} \varphi^+ \\ \frac{1}{\sqrt{2}}(\varphi + v + i\chi) \end{bmatrix}$$

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

$$\Delta^0 = \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta)$$

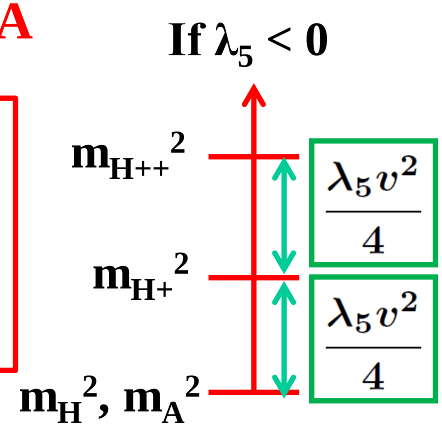
Mass eigenstates: (SM-like) **h**, (Triplet-like) **H^{++}, H^+, H, A**

Mass spectrum:

$$m_h^2 \simeq 2\lambda_1 v^2$$

$$M_\Delta^2 \equiv \frac{v^2\mu}{\sqrt{2}v_\Delta}$$

$$m_{H^{++}}^2 \simeq M_\Delta^2 - \frac{v^2}{2}\lambda_5$$
$$m_{H^+}^2 \simeq M_\Delta^2 - \frac{v^2}{4}\lambda_5$$
$$m_A^2 \simeq m_H^2 = M_\Delta^2$$



The characteristic mass spectrum: $m_{H^{++}}^2 - m_{H^+}^2 \simeq m_{H^+}^2 - m_{\phi^0}^2$ is predicted. Measuring this spectrum, the model can be tested !

The Higgs Triplet Model (HTM)

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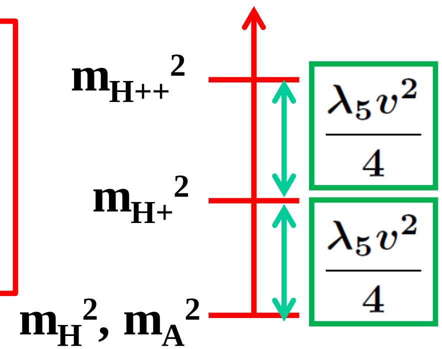
If $\lambda_5 < 0$

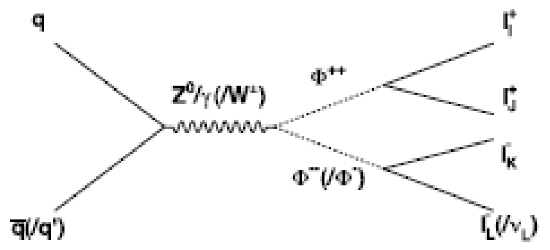


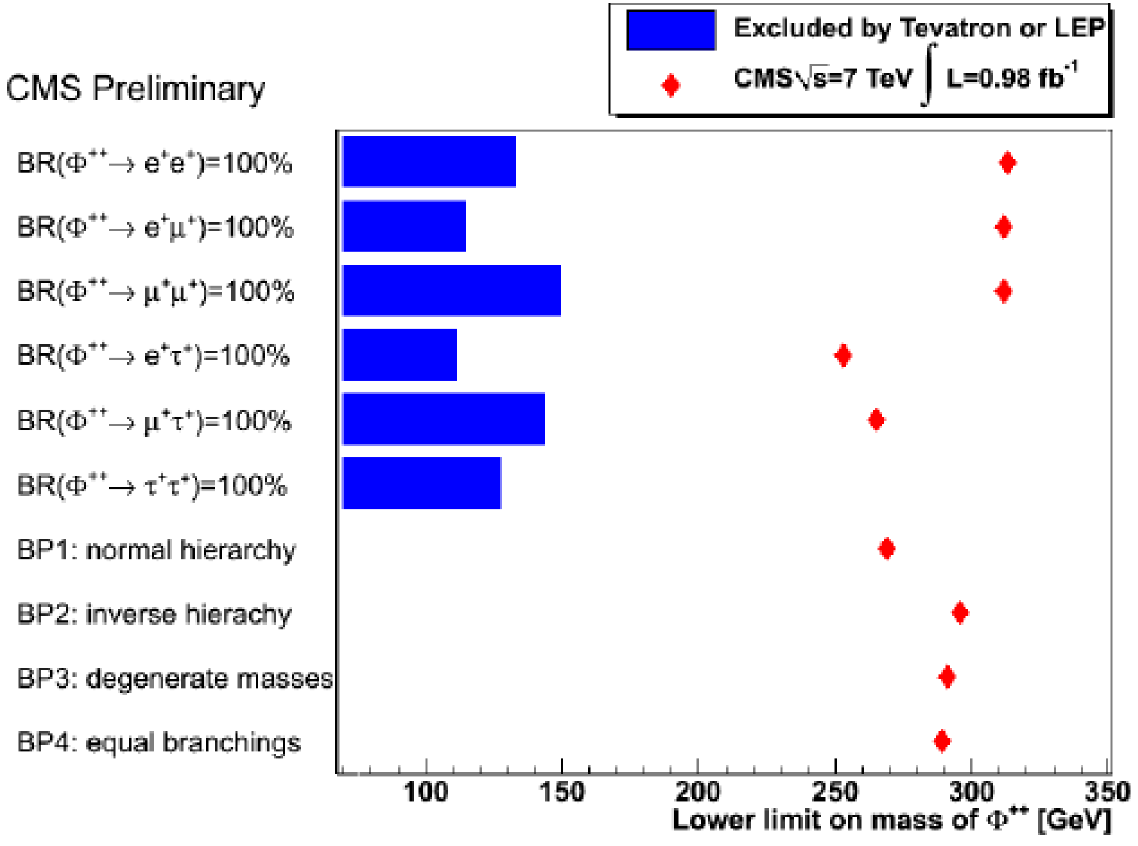
In this talk, we discuss **how we can test the HTM in the case with the mass difference** at the LHC.

Exotic Higgs Φ^{++}: EPS Results

V. Sharma, Lepton Photon 2011

- Arises in models with extra Higgs triplets
  - Φ^{++}, Φ^{+}, Φ^{0}
- Triplet responsible for small neutrino mass
- Unknown neutrino mass matrix
  → unknown branching ratios → broad search
- Below M ≈2M_W, only leptonic decays





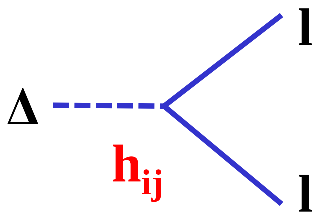
When $H^{++} \to l^+l^+$,
$m_{H++} > 250 – 300$ GeV.

This bound cannot be applied when H^{++} does not decay into the same sign dilepton.

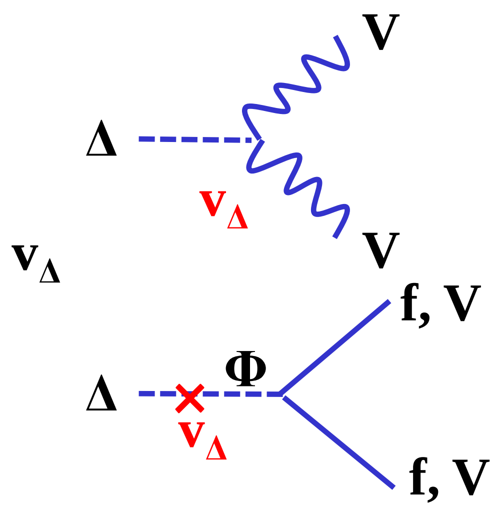
Decay

The decay of Δ-like scalar bosons can be classified into 3 modes.

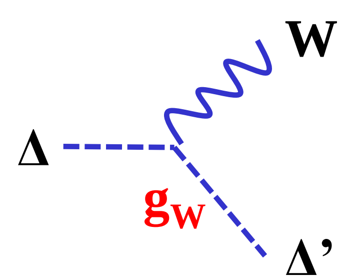
1. Decay via h_{ij}



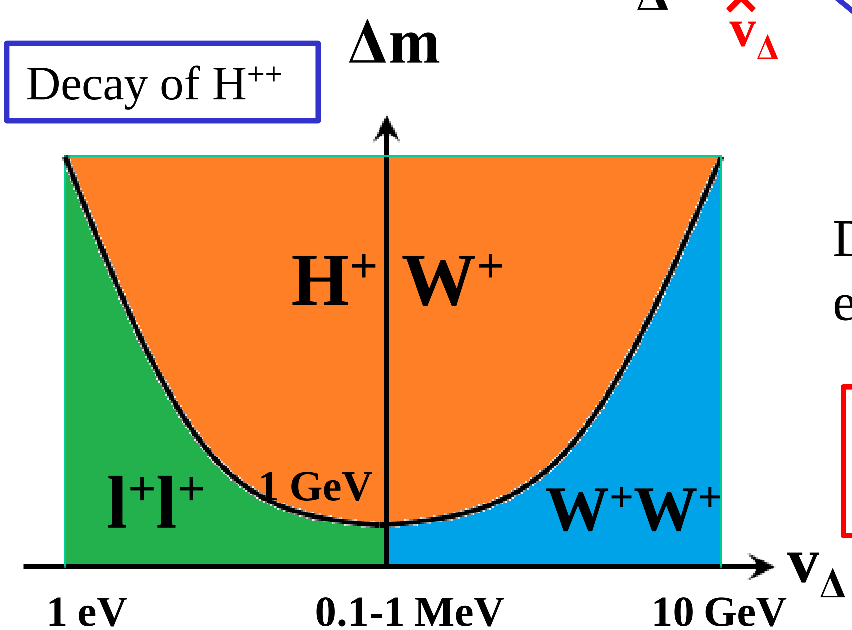
2. Decay via v_Δ



3. Decay via g_W



Decay of H^{++}

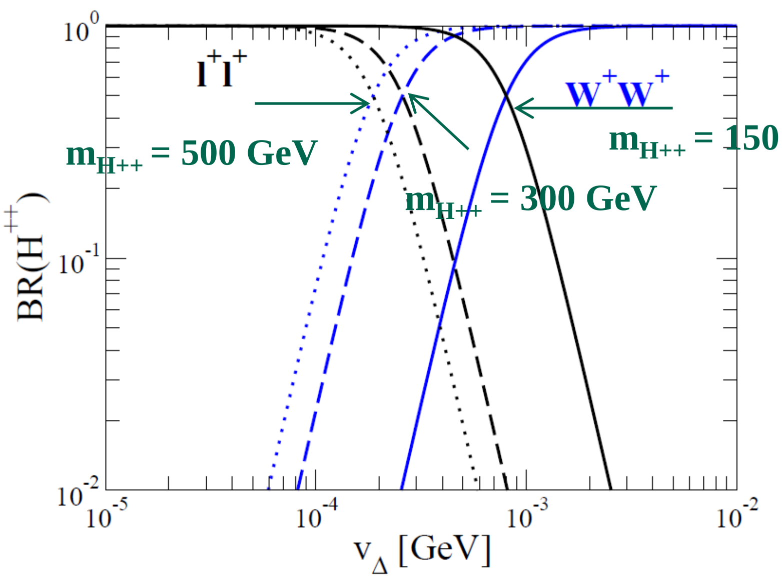


Decay modes of 1 and 2 are related to each other by the relation: $(m_\nu)_{ij} = h_{ij} v_\Delta$

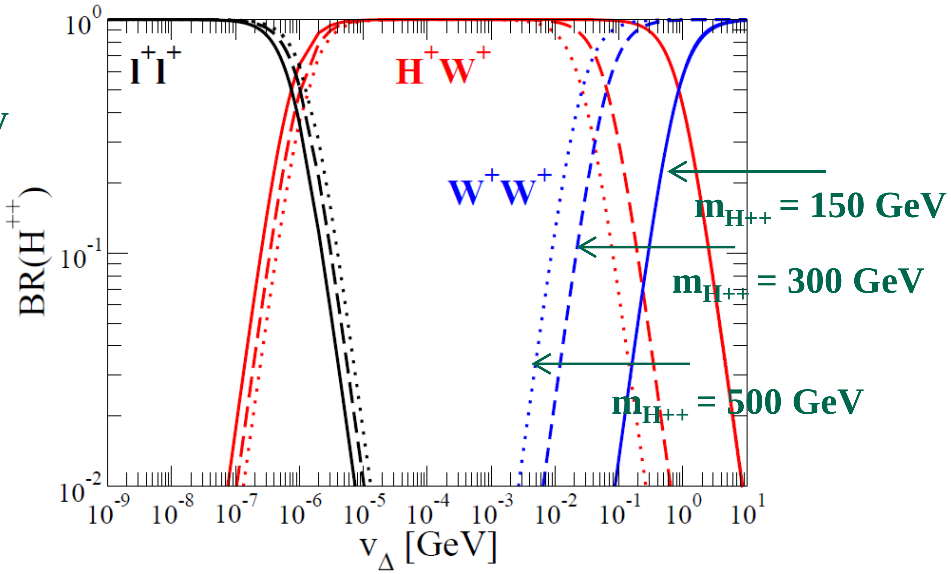
Decay of the triplet like scalar bosons strongly depend on v_Δ and Δm ($\equiv m_{H^{++}} - m_{H^+}$).

Branching ratio of H^{++}

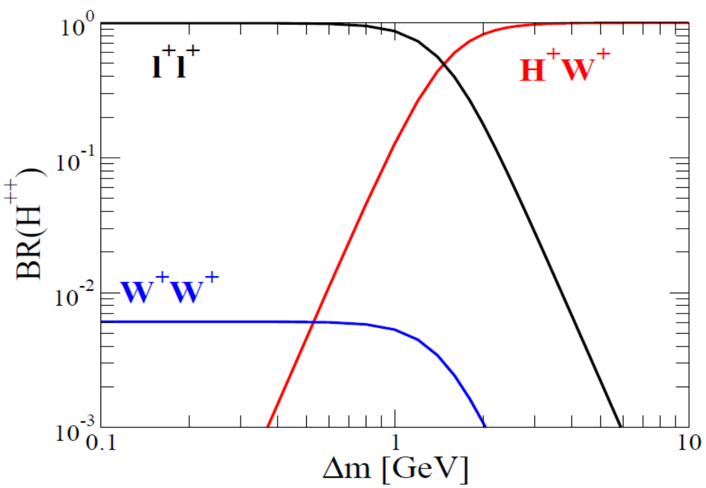
$\Delta m = 0$



$\Delta m = 10$ GeV



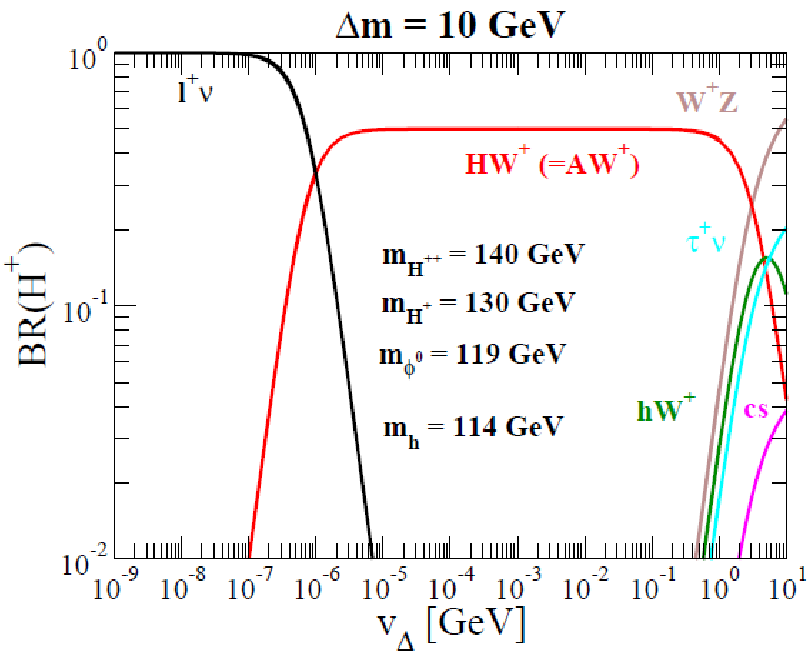
$v_\Delta = 0.1$ MeV, $m_{H++} = 200$ GeV

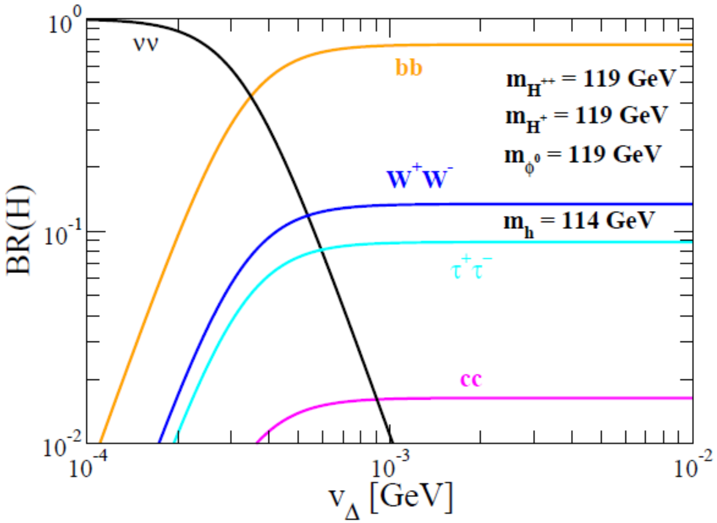


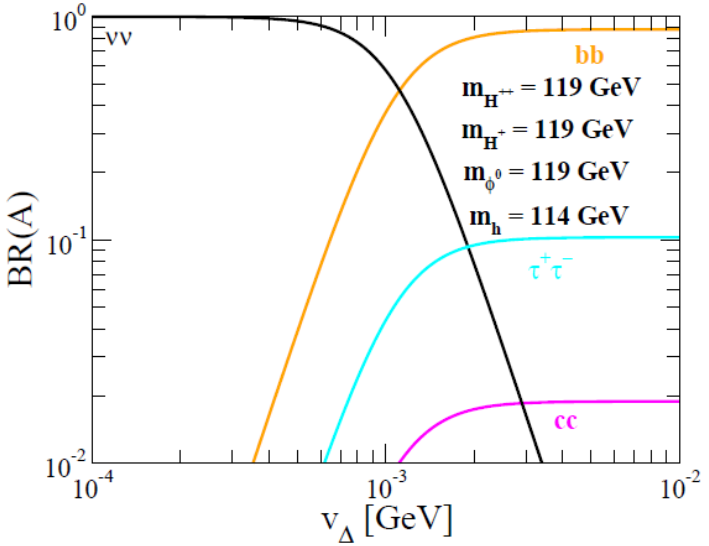
Chakrabarti, Choudhury, Godbole, Mukhopadhyaya, (1998);
Chun, Lee, Park, (2003);
Perez, Han, Huang, Li, Wang, (2008);
Melfo, Nemevsek, Nesti, Senjanovic, (2011)

Phenomenology of $\Delta m \neq 0$ is drastically different from that of $\Delta m = 0$.

Branching ratios of H^+, H and A



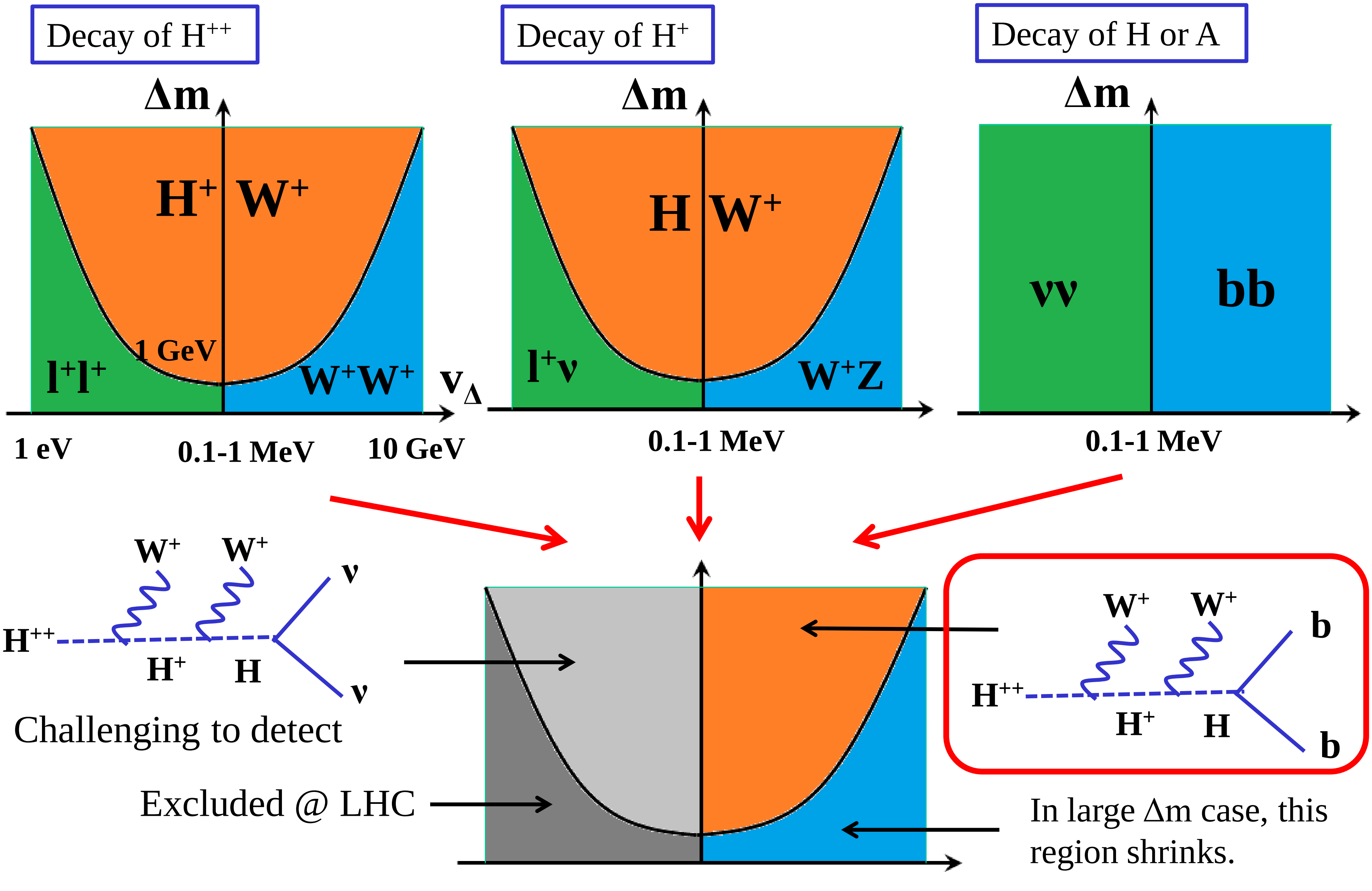




★ The $H^+ \to \phi^0 W^+$ mode can be dominant in the case of $\Delta m \neq 0$.

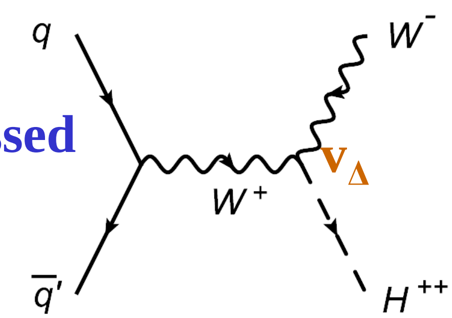
★ The $\phi^0 \to bb$ mode can be dominant when $v_\Delta >$ MeV.

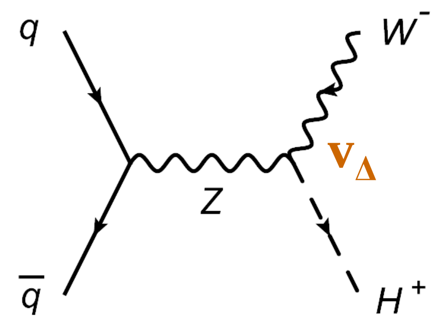
Light Δ [O(100) GeV] Scenario



Production mechanisms at LHC

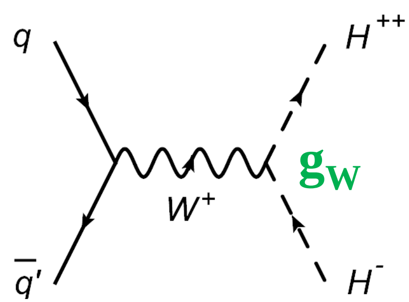
W associate
- depends on $v_\Delta \rightarrow$ **Suppressed**

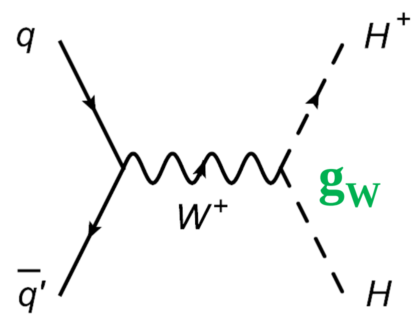


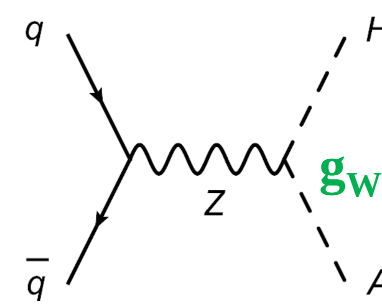


Main production process

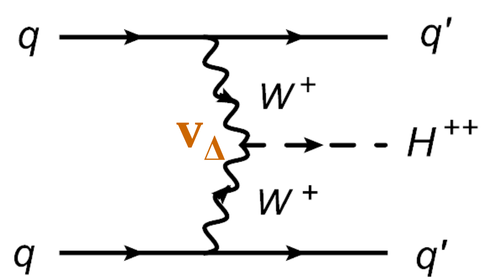
Drell-Yan
- depends on g_W

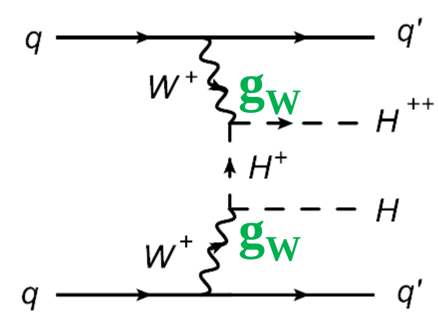






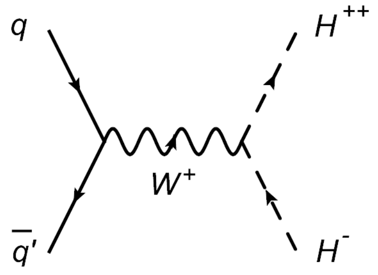
Vector Boson Fusion
- depends on $v_\Delta \rightarrow$ **Suppressed**
- depends on $g_{W,}$
  but unitary cancellation works
  $\rightarrow$ **Suppressed**

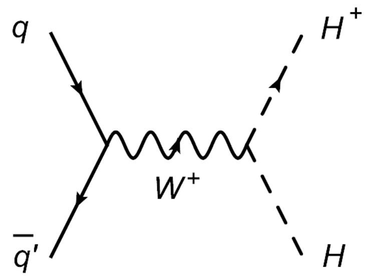


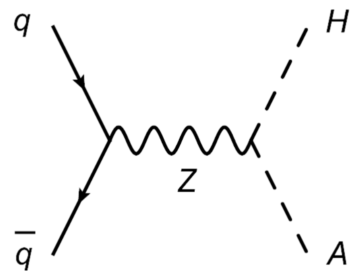


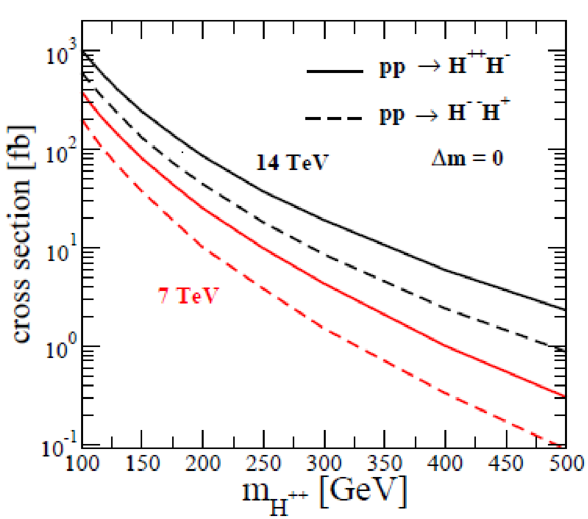
Production cross sections

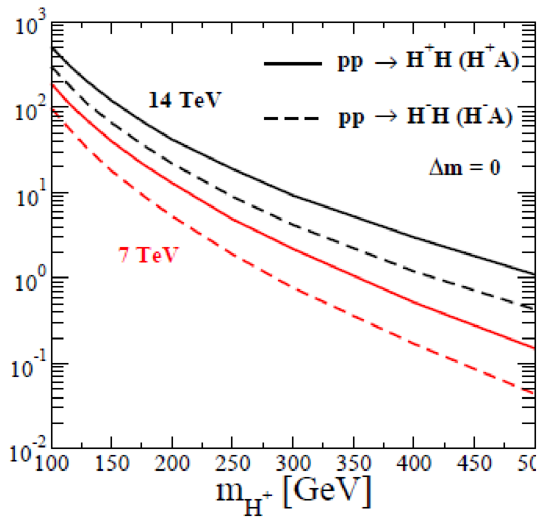
Akeroyd, Aoki, PRD72 (2005);
Perez, Han, Huang, Li, Wang, PRD78 (2008).

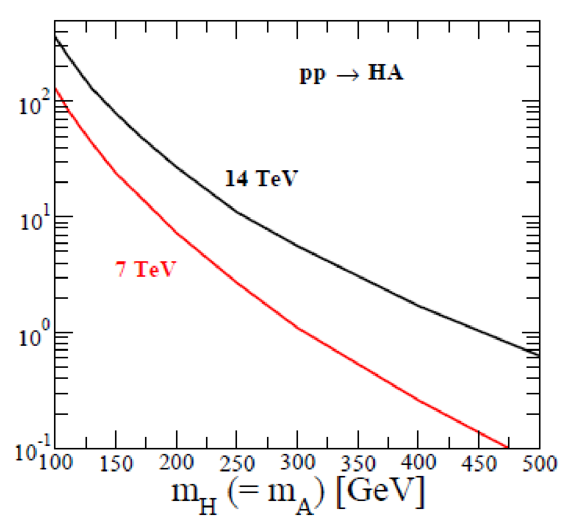






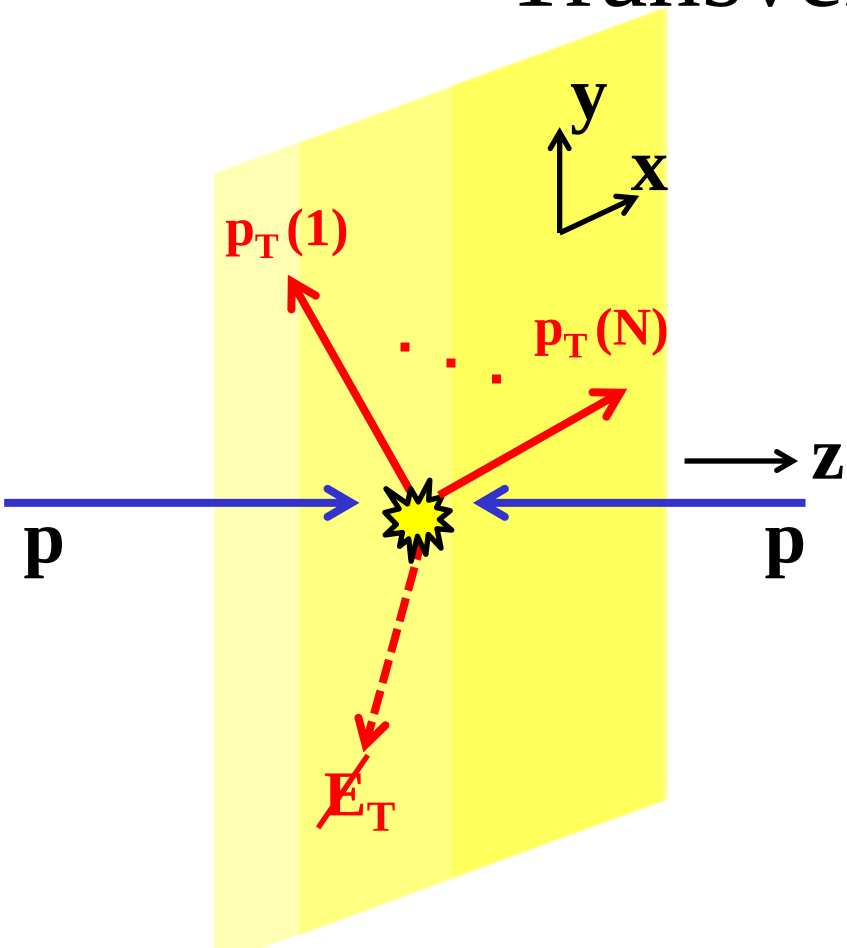






The magnitude of these production cross sections is around 1-100 fb.

Transverse mass



Missing transverse energy:

$$\not{E}_T = -\sum_{i}^{N} p_T(i)$$

φ : azimuthal angle

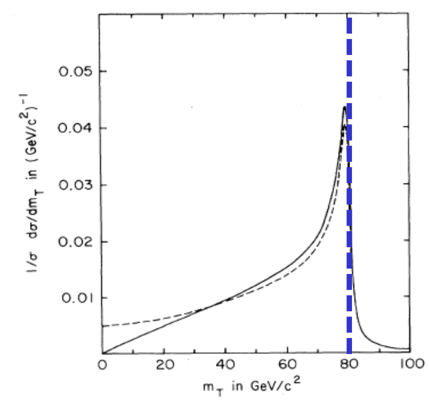
$$p_T = p_T(a) + p_T(b) + \cdots$$

Transverse mass:

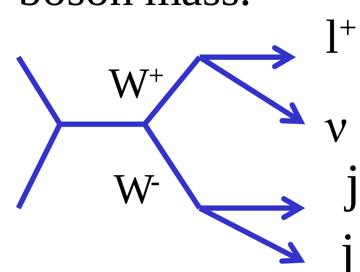
$$M_T^2 = (\not{E}_T + p_T)^2 \simeq 2|\not{E}_T||p_T|(1 - \cos\varphi)$$

Smith, Neerven, Vermaseren, PRL50, 1983

Ex. The W boson mass reconstruction

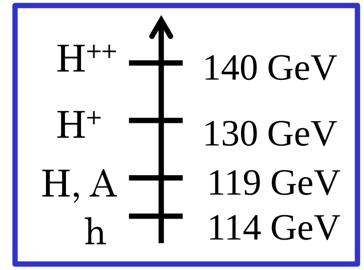


This endpoint shows the W boson mass.



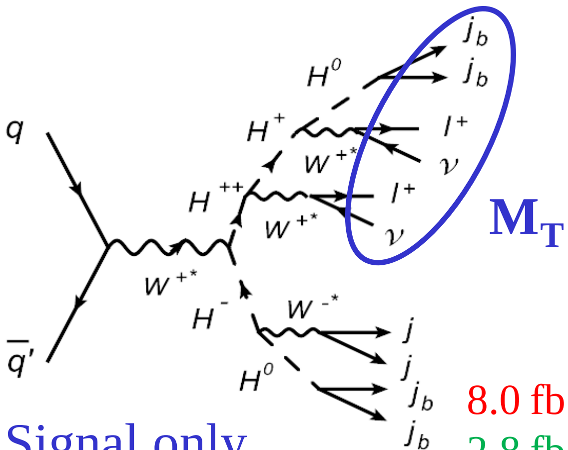
By using transverse mass distribution,
the masses of Δ-like scalar bosons can be reconstructed.

Mass reconstruction



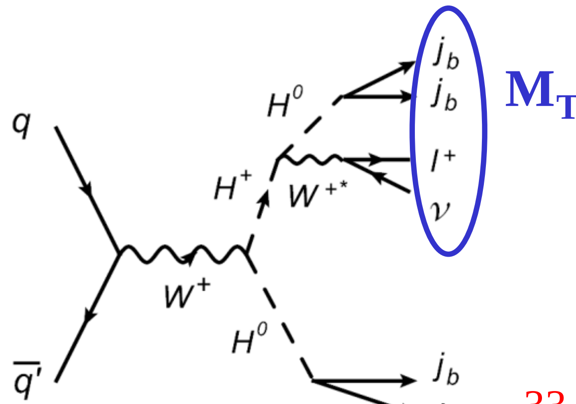
$v_\Delta = 10^{-2}$ GeV

$qq' \to H^{++}H^{-} \to (l^+l^+\nu\nu bb)(jjbb)$ $qq' \to H^{+}H \to (l^+\nu bb)(bb)$ $qq \to HA \to (bb)(bb)$

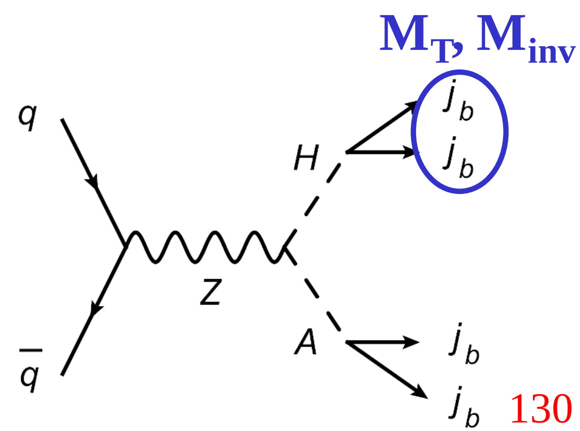


8.0 fb (14 TeV)
2.8 fb (7 TeV)

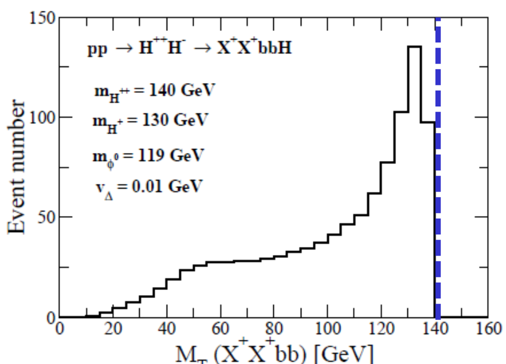
Signal only



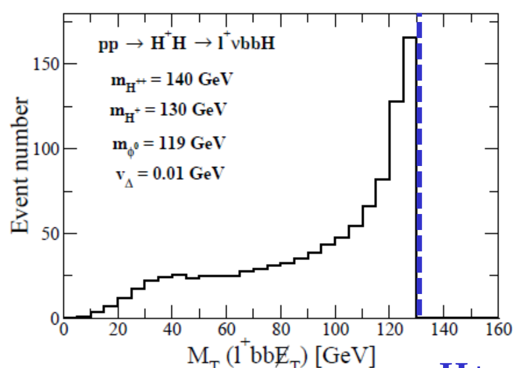
33 fb
12 fb



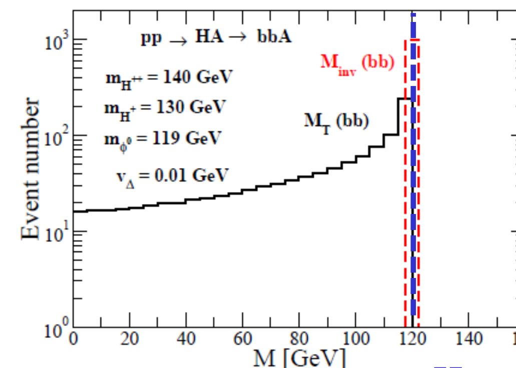
130 fb
42 fb



mH++



mH+



mH, mA

All the masses of the Δ-like scalar bosons may be reconstructed.

Summary

- The type II seesaw model can be explained neutrino masses, which deduces the extended Higgs model (The Higgs triplet model).
- In the Higgs triplet model, a characteristic mass spectrum appears :

$$m_{H^{++}}^2 - m_{H^+}^2 \simeq m_{H^+}^2 - m_{\phi^0}^2$$

- Phenomenology of the HTM in the case with $\Delta m \neq 0$ is drastically different from that in the case with $\Delta m = 0$ (**$H^{++} \to H^+W^+ \to HW^+W^+$**).

NEW

- **In our work, we focus on the characteristic mass spectrum, and we outline how the HTM can be tested in the case with $\Delta m \neq 0$ at the LHC.**
- **By measuring the transverse mass distribution and the invariant mass distribution, the masses of the Δ-like scalar bosons may be reconstructed.**

- Background simulation is the future work to clarify the feasibility.

Back up slides

Backgrounds

Signal: $pp \to H^{++}H^{-} \to (\phi^0 W^+ W^+)(\phi^0 W^-) \to \underline{(\ell^+\ell^+ b\bar{b} \not{E}_T)(b\bar{b}jj)}$

8 fb

Backgrounds:

(A): $pp \to t\bar{t}W^+W^- \to (bW^+)(\bar{b}W^-)W^+W^- \to \underline{(b\ell^+\nu)(\bar{b}jj)(\ell^+\nu)(jj)}$ O(10) fb

(B): $pp \to t\bar{t}W^+W^- \to (bW^+)(\bar{b}W^-)W^+W^- \to \underline{(b\ell^+\nu)(\bar{b}\ell^-\nu)(jj)(jj)}$ O(10) fb

For (A), top reconstruction by the M_T and M_{inv} distributions may be used.
For (B), charge identification for leptons may be used.

Signal: $pp \to H^+\phi^0 \to (\phi^0 W^+)(b\bar{b}) \to \underline{(\ell^+ b\bar{b} \not{E}_T)(b\bar{b})}$

33 fb

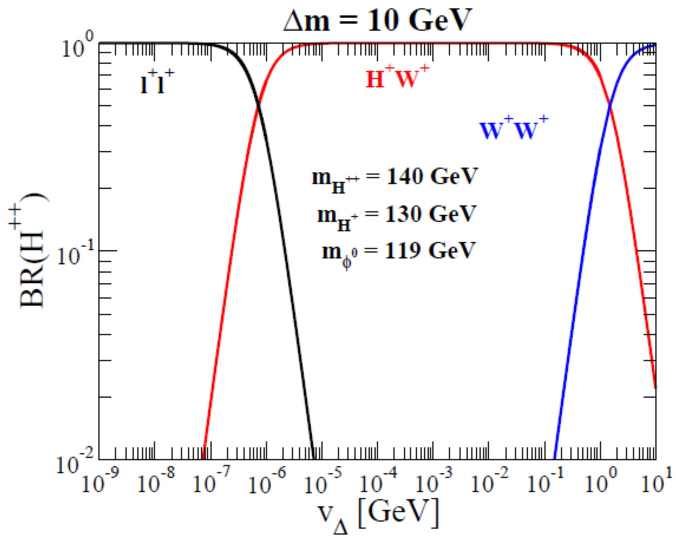
Backgrounds:

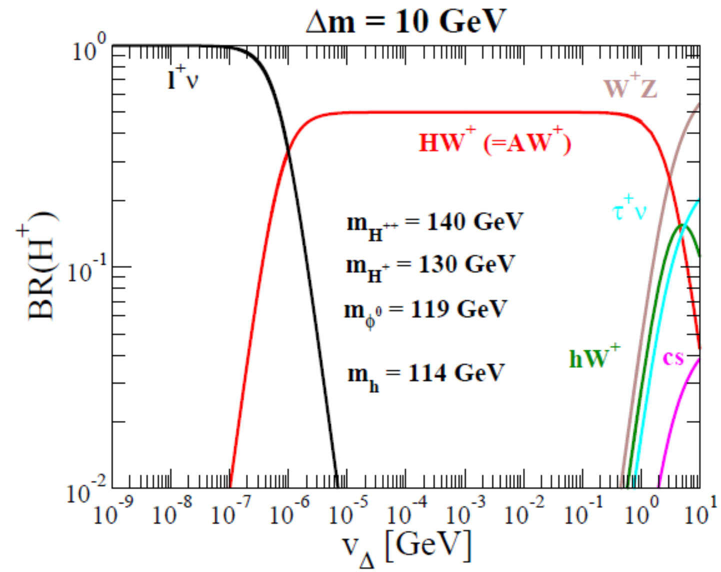
(C): $pp \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to \underline{(b\ell^+\nu)(\bar{b}jj)}$ O(1) pb

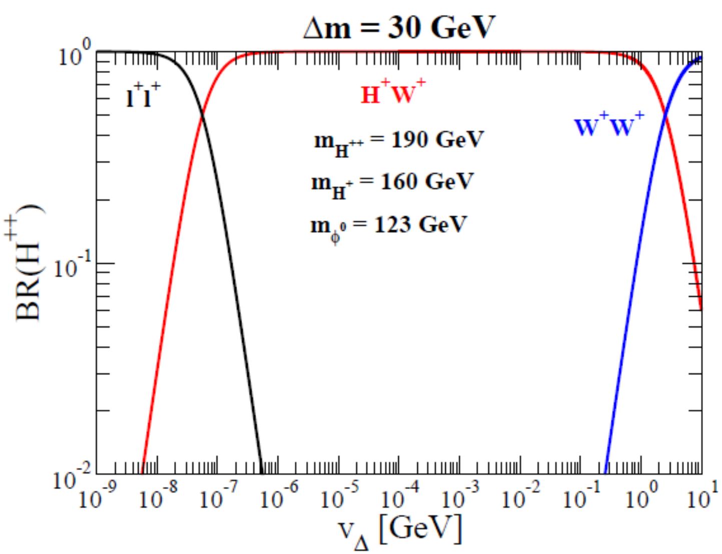
(D): $pp \to t\bar{t}\gamma^*/g^* \to (bW^+)(\bar{b}W^-)(jj) \to \underline{(b\ell^+\nu)(\bar{b}\not{\ell}^-\nu)(jj)}$ O(10) fb

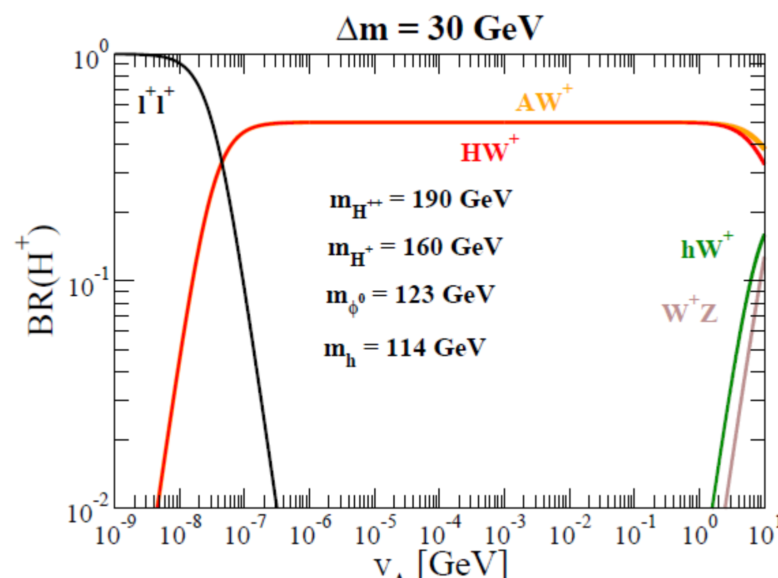
For (C), top reconstruction by the M_T and M_{inv} distributions may be used.
For (D), b-tagging and cut for the low E jet would be useful to reduce the BG.

Large Δm case

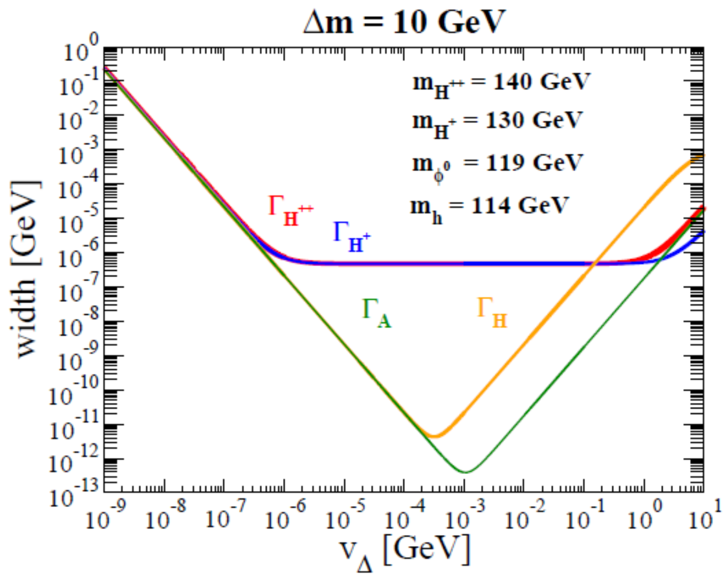


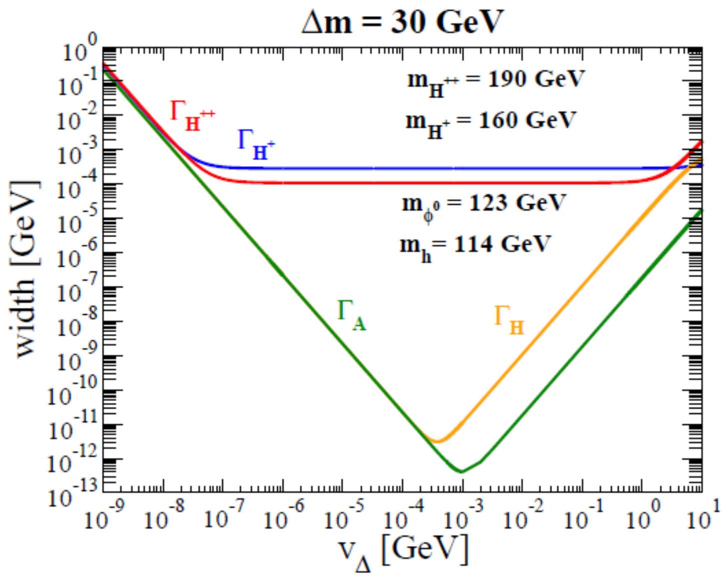






Decay widths for Δ-like scalar bosons





In the wide parameter regions, the decay width of the Δ-like scalar bosons is much smaller than that of top quark and massive gauge bosons.

Constraint from the rho parameter

Experimental value of rho parameter is quite close to unity: $\rho_{exp} \sim 1$

Theoretical prediction of rho parameter strongly depends on structure of Higgs sectors.

$$\rho_{\rm tree} = \frac{\sum_i v_i^2 [T_i(T_i+1) - Y_i^2]}{\sum_i 2Y_i^2 v_i^2}$$

Y_i : hypercharge
T_i : isospin
v_i : VEV

- **Multi-doublet models**
  → Custodial SU(2) symmetry exists in the kinetic term of Higgs fields.
  → $\rho_{tree} = 1$ is predicted.
  ★ Rho parameter deviates from unity at the 1-loop level.

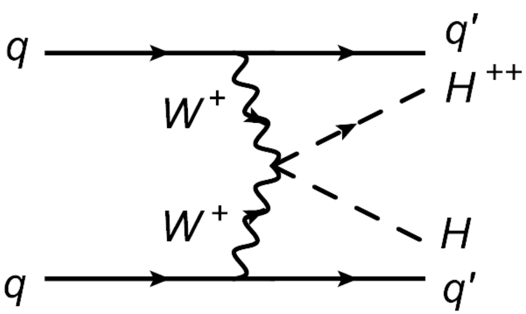
- **Models with Higgs triplets**
  → Custodial SU(2) symmetry is broken in the kinetic term of Higgs fields
  → $\rho_{tree} \neq 1$ is predicted.

1. Triplet VEV is small compared with doublet VEV.
2. Imposing alignment among triplet VEVs, custodial SU(2) symmetry is restored.

Triplet VEV is constrained from rho parameter

$$\begin{pmatrix} \varphi^{\pm} \\ \Delta^{\pm} \end{pmatrix} = R(\beta_{\pm}) \begin{pmatrix} w^{\pm} \\ H^{\pm} \end{pmatrix}, \quad \begin{pmatrix} \chi \\ \eta \end{pmatrix} = R(\beta_0) \begin{pmatrix} z \\ A \end{pmatrix}, \quad \begin{pmatrix} \varphi \\ \delta \end{pmatrix} = R(\alpha) \begin{pmatrix} h \\ H \end{pmatrix}, \quad R(\theta) \equiv \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

$$\cos\beta_{\pm} = \frac{v}{\sqrt{v^2 + 2v_\Delta^2}}, \quad \cos\beta_0 = \frac{v}{\sqrt{v^2 + 4v_\Delta^2}}, \quad \tan 2\alpha \simeq \frac{v_\Delta}{v} \frac{4M_\Delta^2 - 2v^2(\lambda_4 + \lambda_5)}{M_\Delta^2 - 2v^2\lambda_1}.$$



Model	SM with η $(Y = 0)$	SM with Δ $(Y = 1)$	SM with η and Δ
$\lvert F\rvert^2 =$	$\frac{4v^2 v_\eta^2}{\cos^2\theta_W (v^2+4v_\eta^2)^2}$	$\frac{2v^2 v_\Delta^2}{\cos^2\theta_W (v^2+2v_\Delta^2)^2}$	$\frac{4v_\Delta^2}{\cos^2\theta_W (v^2+4v_\Delta^2)}$
$\rho_{\rm tree} =$	$1 + \frac{4v_\eta^2}{v^2}$	$1 - \frac{2v_\Delta^2}{v^2+4v_\Delta^2}$	1

$v_\eta = v_\Delta/\sqrt{2}$