Renormalization of the Higgs sector in the triplet model

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Collaborators:

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The Higgs Triplet Model

The Higgs triplet field Δ is added to the SM.

	$SU(2)_I$	$U(1)_Y$	$U(1)_L$
Φ	2	1/2	0
Δ	3	1	-2

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

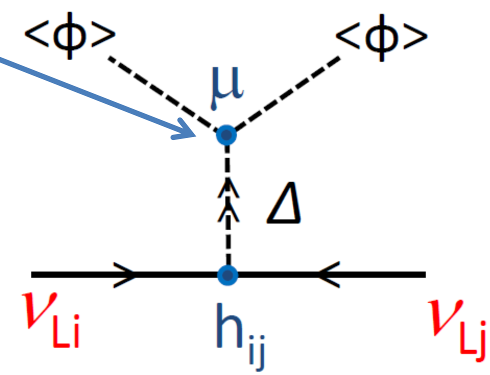
- **Neutrino Yukawa interaction:**

$$\mathcal{L}_Y = h_{ij}\overline{L_L^{ci}} \cdot \Delta L_L^j$$

- **Higgs Potential:**

Lepton number breaking parameter

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



- **Neutrino mass matrix**

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

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

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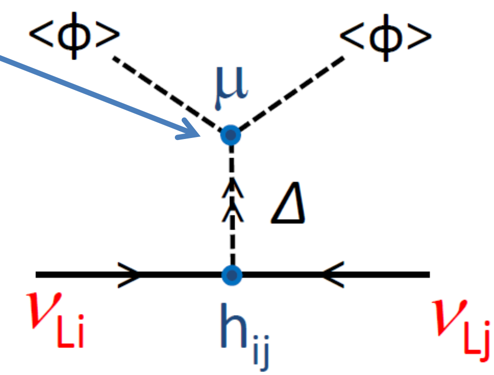


- **Neutrino mass matrix**

O(0.1) eV O(0.1) eV 246 GeV

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

O(1) O(100) GeV

The HTM can be tested at colliders !!

Important predictions

★ **Rho parameter deviates from unity.**

$$\rho_{\text{tree}} = \frac{1+\frac{2v_\Delta^2}{v_\Phi^2}}{1+\frac{4v_\Delta^2}{v_\Phi^2}} \simeq 1 - \frac{2v_\Delta^2}{v_\Phi^2}$$

★ **Extra Higgs bosons**

Doubly-charged $H^{\pm\pm}$, Singly-charged $H^{\pm}$, CP-odd A and **CP-even Higgs boson H**

★ **Characteristic mass relation is predicted.**

$$m_{H^{++}}{}^2 - m_{H^+}{}^2 \simeq m_{H^+}{}^2 - m_A{}^2$$

Under $v_\Delta \ll v_\Phi$ (From experimental data $\rho_{exp} \sim 1$)

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

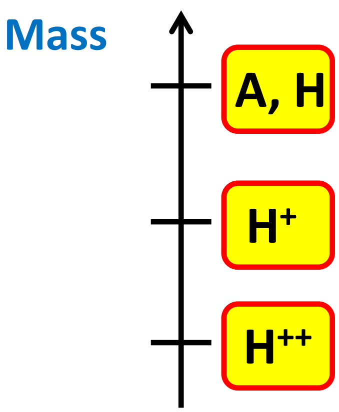
$$M_\Delta^2 \equiv \frac{v_\Phi^2 \mu}{\sqrt{2} v_\Delta}$$

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

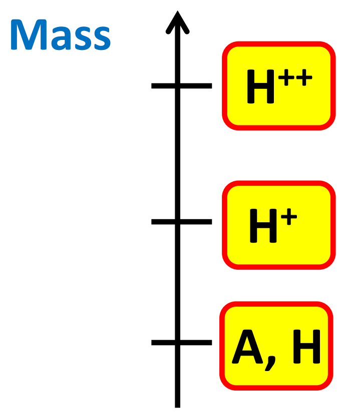
$$m_{H^+}^2 \simeq M_\Delta^2 - \frac{v^2}{4}\lambda_5$$

$$m_A^2 \simeq m_H^2 = M_\Delta^2$$

Case I ($\lambda_5 > 0$)



Case II ($\lambda_5 < 0$)



Theoretical bounds

- Vacuum stability bound (Bounded from below) *Arhrib, et al., PRD84, (2011)*

$$\lim_{r\to\infty} V(rv_1, rv_2, \ldots, rv_n) > 0$$

$$V^{(4)} = \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + \lambda_3\mathrm{Tr}[(\Delta^\dagger\Delta)^2] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

$$\lambda_2 = \lambda_3 = \lambda_\Delta$$

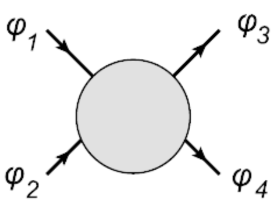
$$\lambda_1 > 0, \;\; \lambda_\Delta > 0,$$

$$2\sqrt{2\lambda_1\lambda_\Delta} + \lambda_4 + \mathrm{MIN}[0, \;\lambda_5] > 0$$

- Perturbative unitarity bound

Lee, Quigg, Thacker, PRD16, (1977)

Aoki, Kanemura, PRD77, (2008); Arhrib, et al., PRD84, (2011)



φ_i : Longitudinal modes of weak gauge bosons and physical Higgs bosons

$$|\langle\varphi_3\varphi_4|a^0|\varphi_1\varphi_2\rangle| < \frac{1}{2} \text{ or } 1$$

Eigenvalues of the matrix

$$x_1 = 3\lambda_1 + 7\lambda_\Delta + \sqrt{(3\lambda_1 - 7\lambda_\Delta)^2 + \frac{3}{2}(2\lambda_4 + \lambda_5)^2},$$

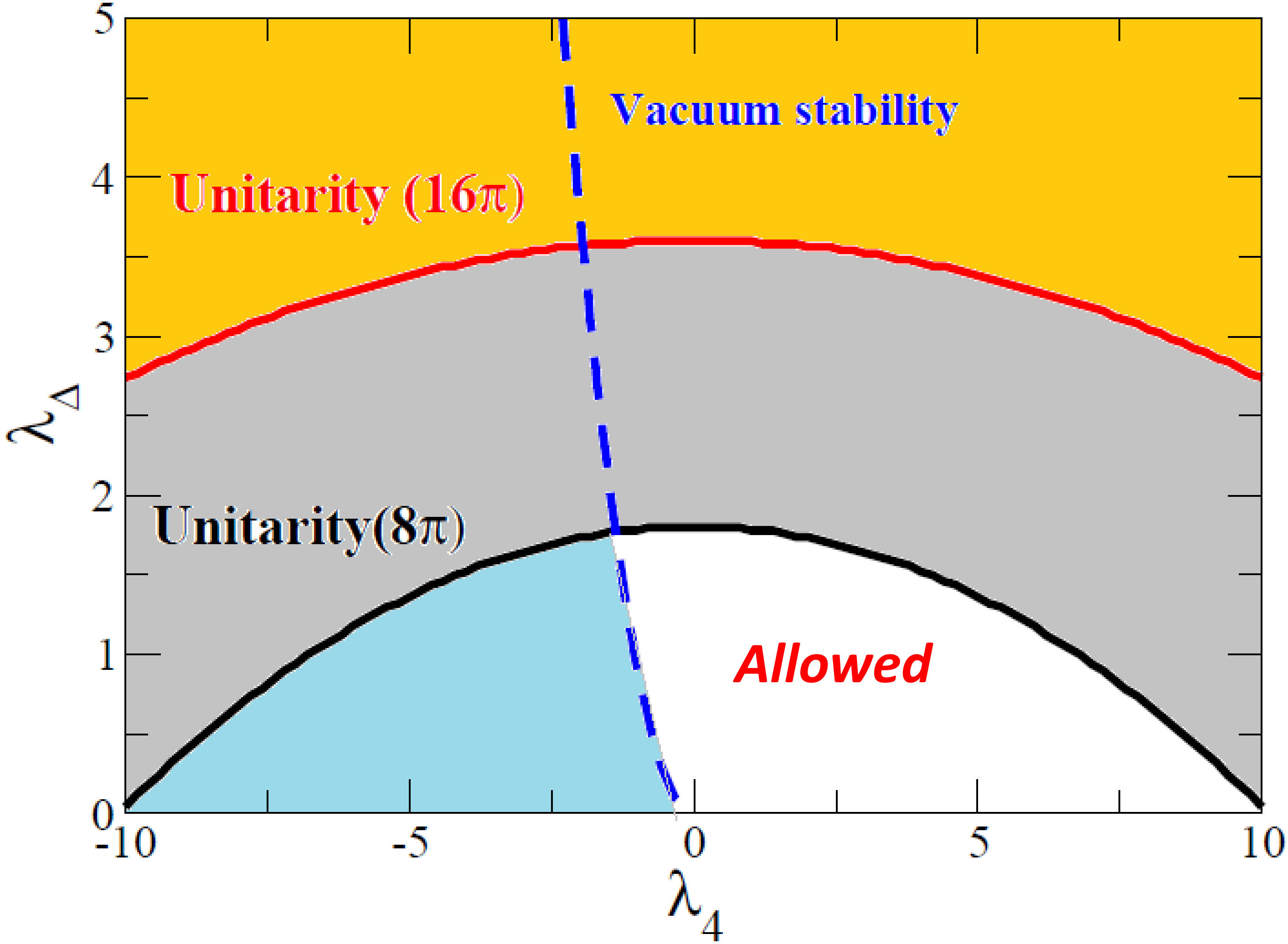
$$x_2 = \frac{1}{2}(2\lambda_4 + 3\lambda_5),$$

$$x_3 = \frac{1}{2}(2\lambda_4 - \lambda_5)$$

$$|x_i| < 8\pi \text{ or } 16\pi$$

Theoretical bounds

Case for $\lambda_5 = 0$ ($\Delta m = 0$)



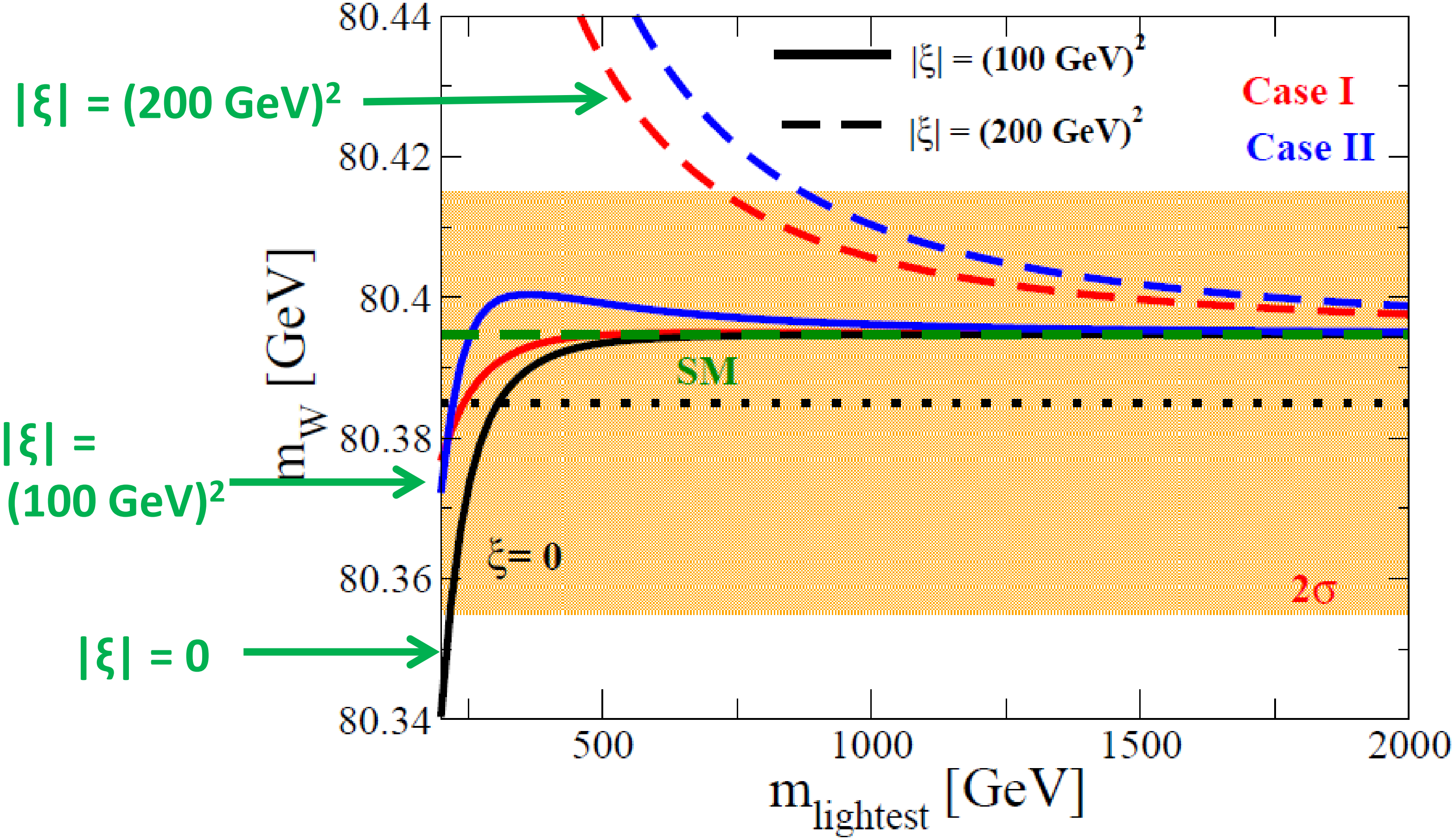
1-loop corrected W mass

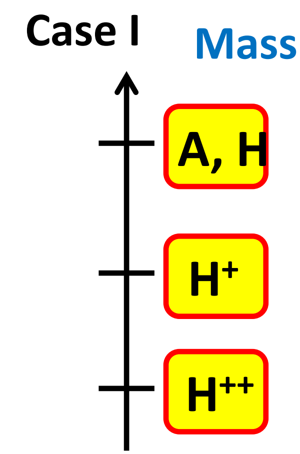
$\xi = m_{H^{++}}^2 - m_{H^+}^2$

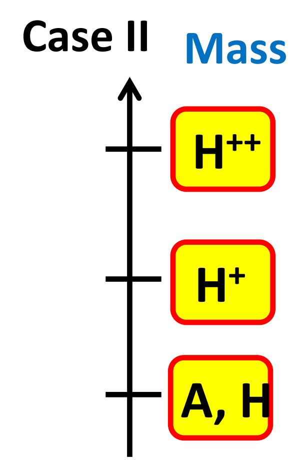
mh = 126 GeV, mt = 173 GeV

$$v_\Delta \simeq \mu \frac{v^2}{m_A^2}$$

μ = 5 GeV





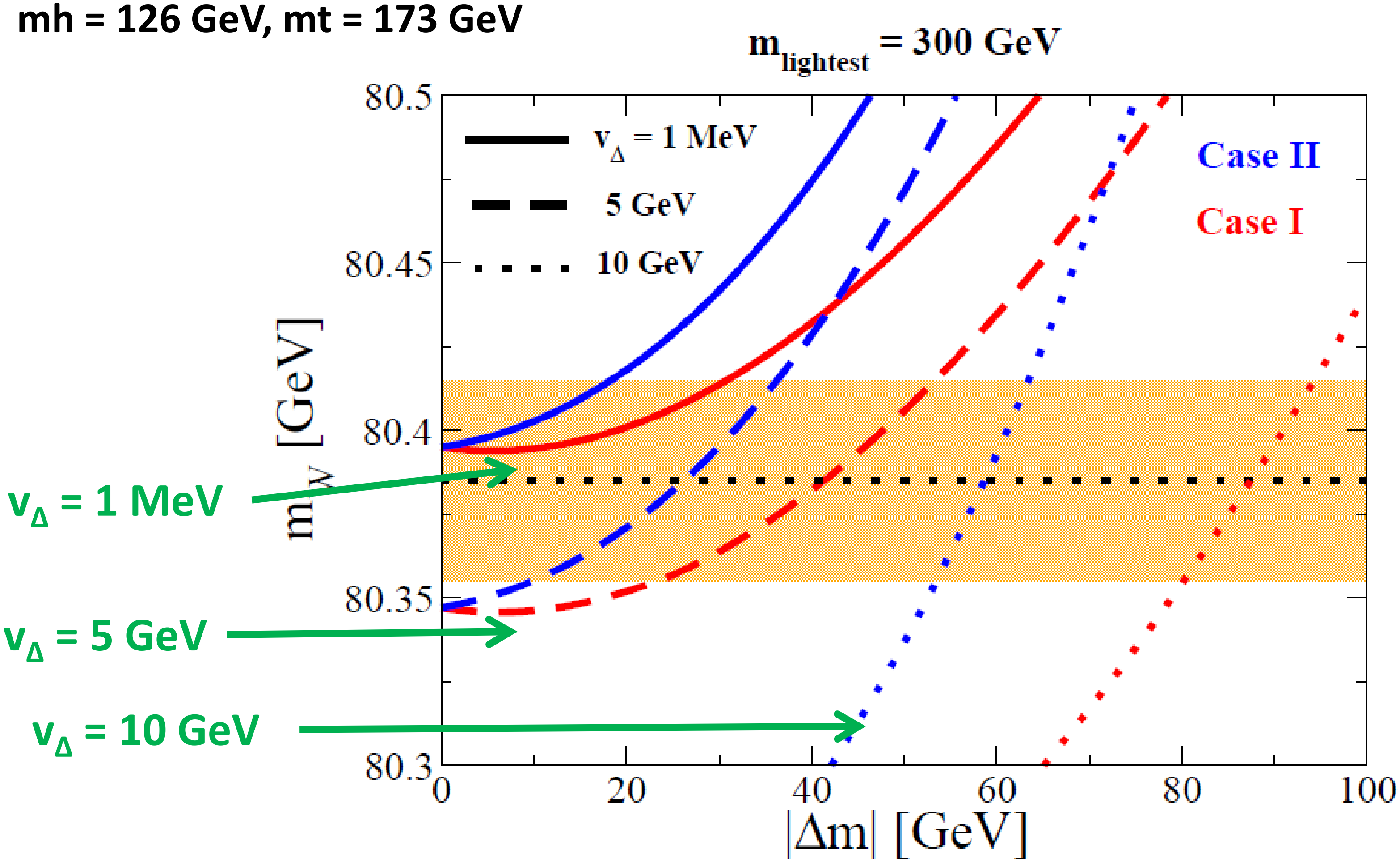


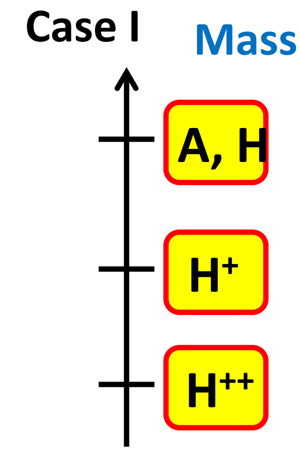
In the large mass limit, the HTM can be decoupled to the SM.

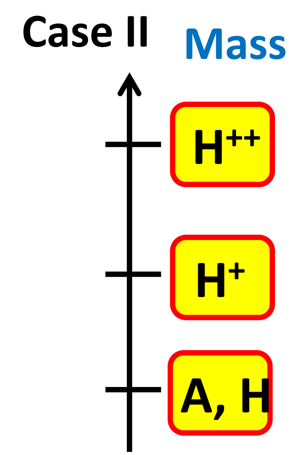
1-loop corrected W mass

$\Delta m = m_{H++} - m_{H+}$

mh = 126 GeV, mt = 173 GeV







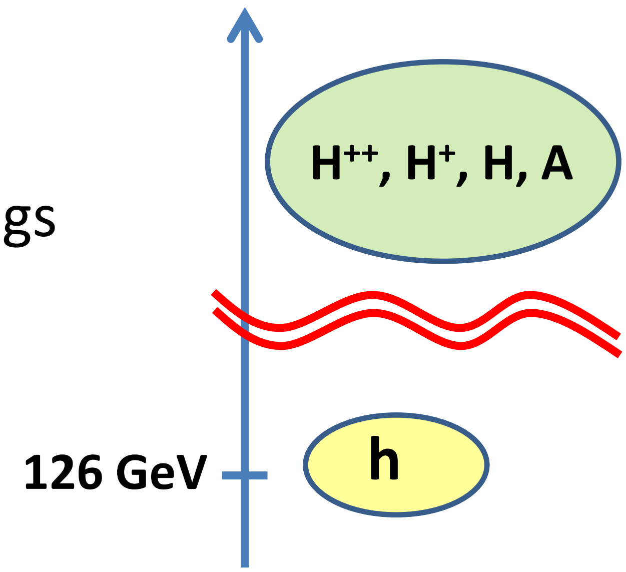
For large triplet VEV case, large mass difference is favored.

Testing the Higgs Triplet Model at colliders

- Indirect way (Decoupling case)

  -Precise measurement for the Higgs couplings

  Ex. hγγ, hhh, hWW, hZZ, …



- Direct way

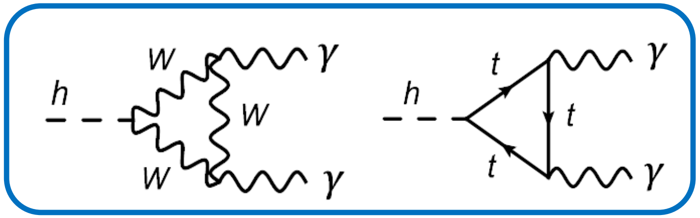
  -Discovery of extra Higgs bosons

  Ex. Doubly-charged Higgs boson, Singly-charged Higgs boson, …

  - Testing the mass spectrum among the triplet like Higgs bosons.

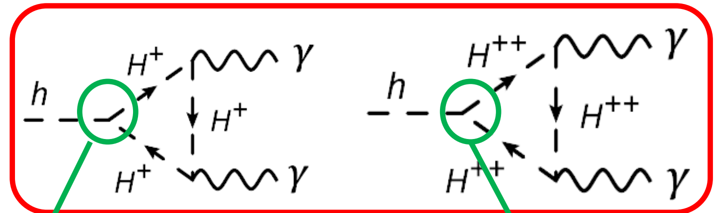
Higgs → γγ

Arhrib, et al. JHEP04 (2012); Kanemura, KY, PRD85 (2012); Akeroyd, Moretti PRD86 (2012)



SM contribution

+



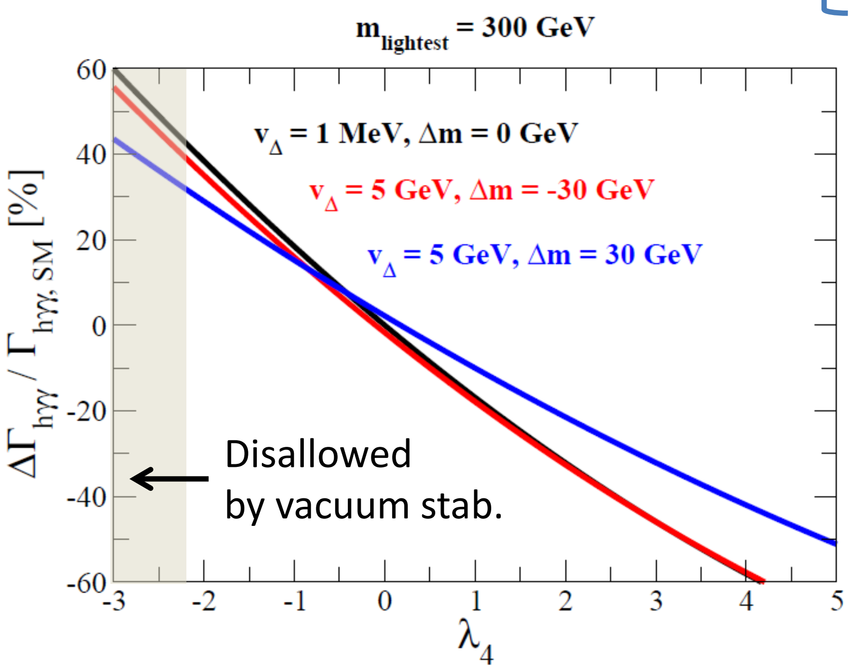
Triplet-like Higgs loop contribution

$$\lambda_{hH^+H^-} \approx -(\lambda_4 + \lambda_5/2)v$$

$$\lambda_{hH^{++}H^{--}} \simeq -\lambda_4 v$$

Sign of λ_4 is quite important!

- If $\lambda_4 < 0$ → Constructive contribution
- If $\lambda_4 > 0$ → Destructive contribution

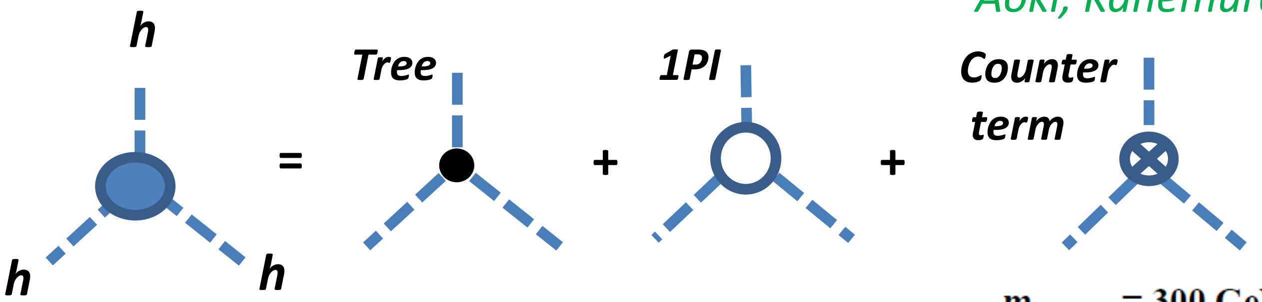


Signal strength (σ_{obs}/σ_{SM}) is 1.56± 0.43 (CMS) and 1.9±0.5 (ATLAS).

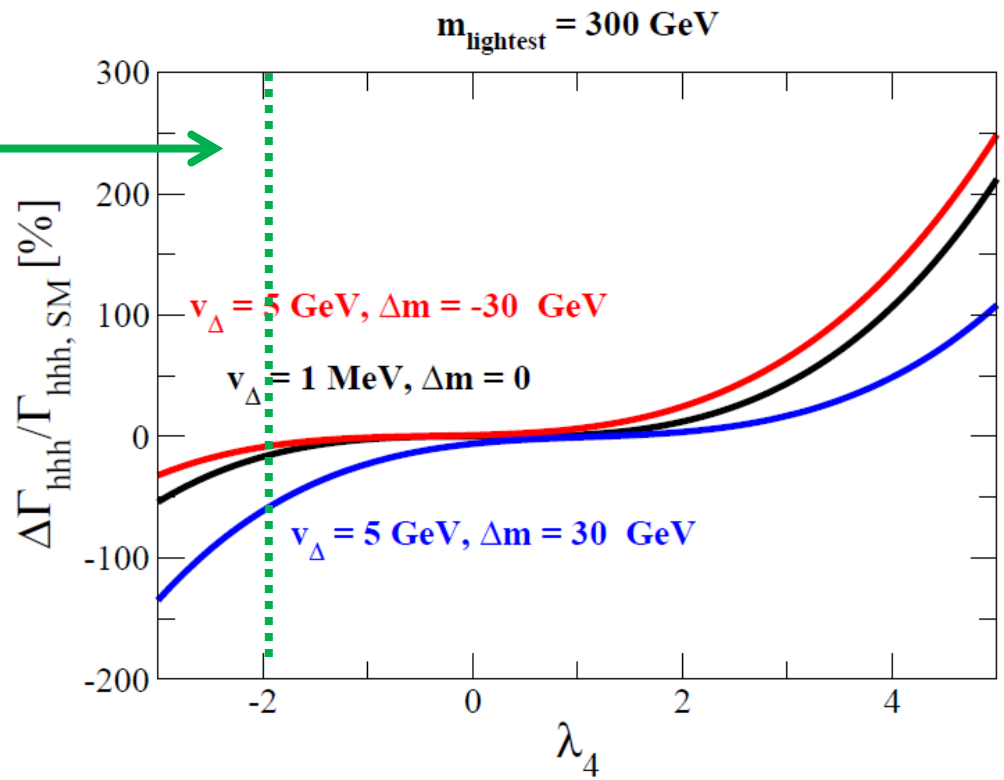
When triplet Higgs mass ~ 300 GeV, hγγ can be enhanced by ~ +40 % ~ +50% .

Renormalized hhh coupling

Aoki, Kanemura, Kikuchi, KY, PLB714 (2012)



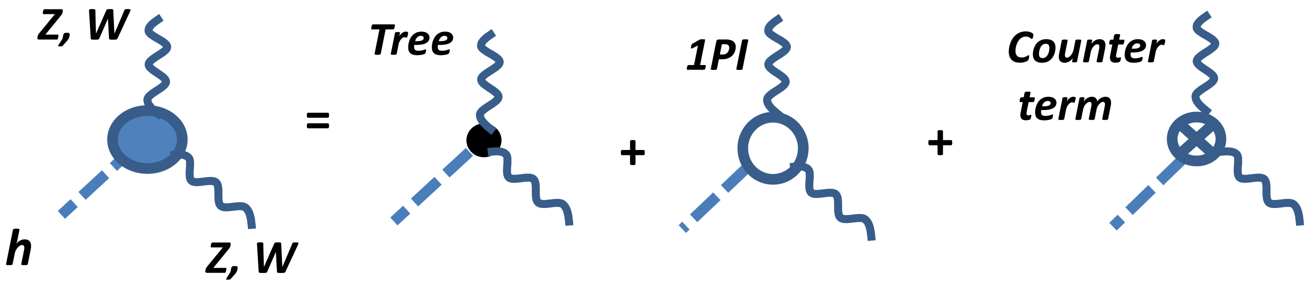
Corresponds to Δhγγ ~ +50 %

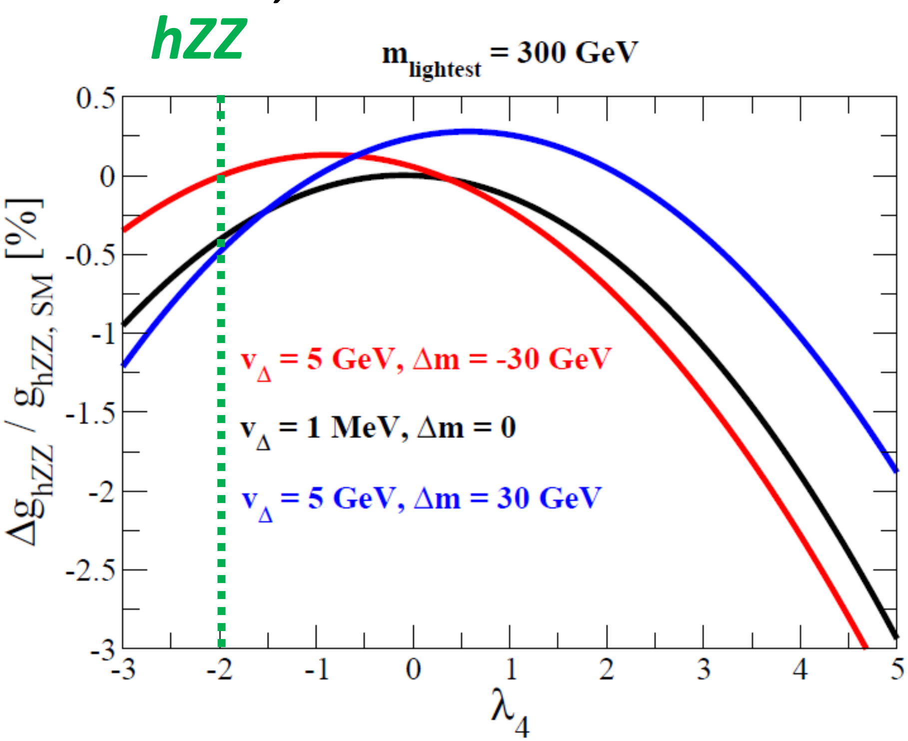


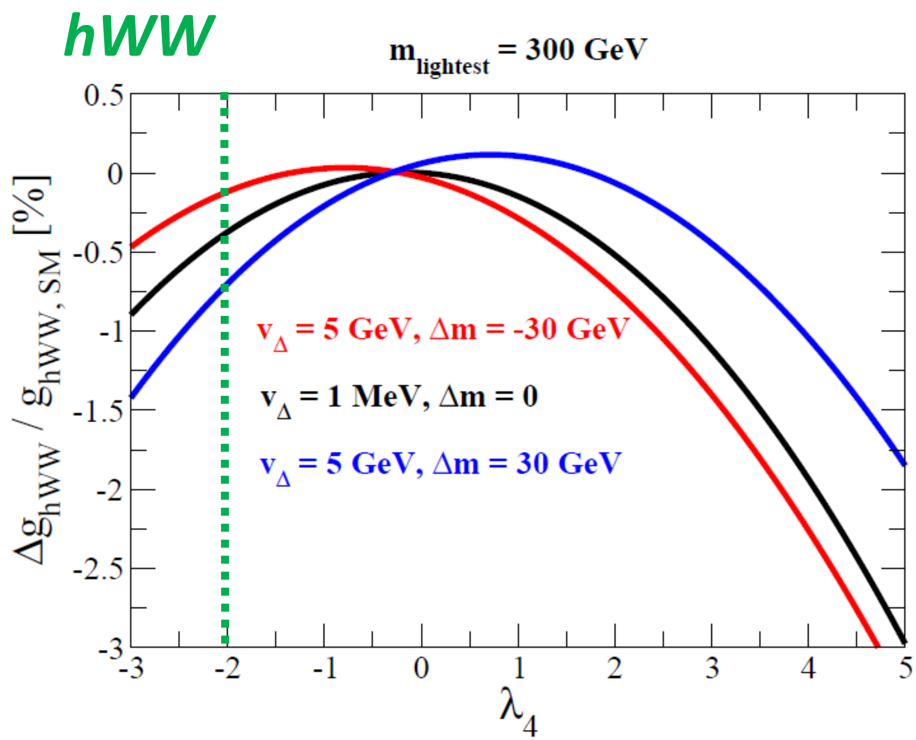
When hγγ (HTM) > hγγ (SM) [λ_4 <0], hhh (HTM) < hhh (SM).

In the case of λ_4 ~ -2, deviation of the hhh coupling is -10 ~ -60 %.

Renormalized hZZ and hWW coupling







In the case of λ_4 ~ -2,
deviation of the hZZ (hWW) coupling is 0 ~ -0.5% (-0.1 ~ -0.7)%.

Testing the Higgs Triplet Model at colliders

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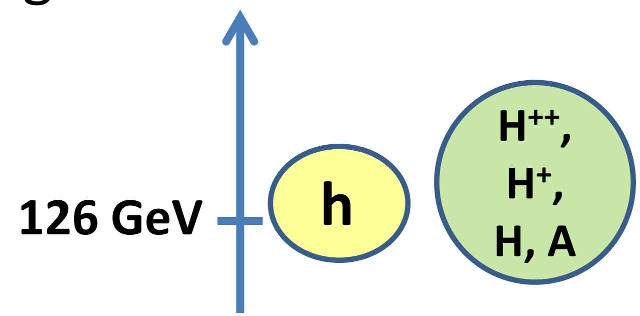

- Direct way

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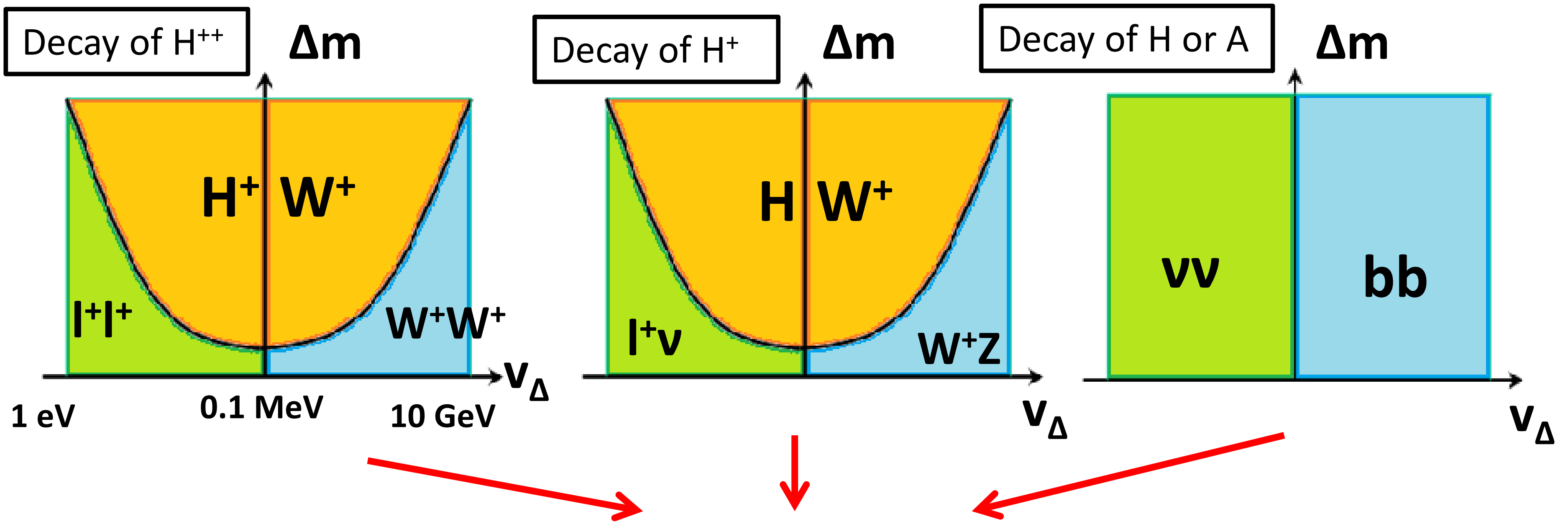
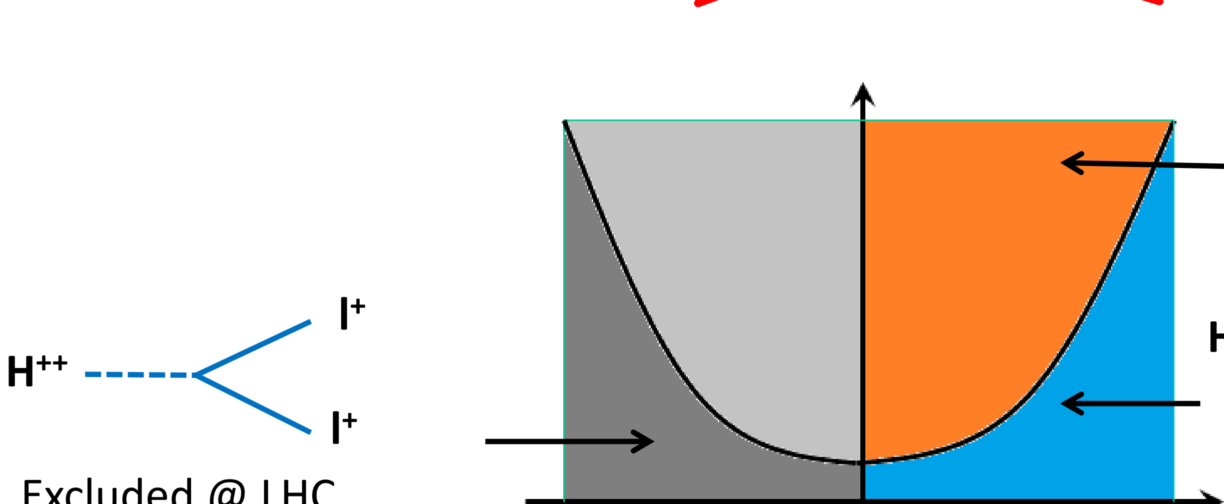
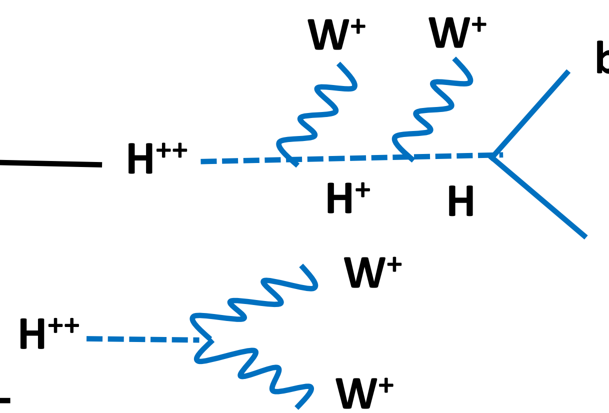
Decay property of the triplet-like Higgs bosons [O(100) GeV case]



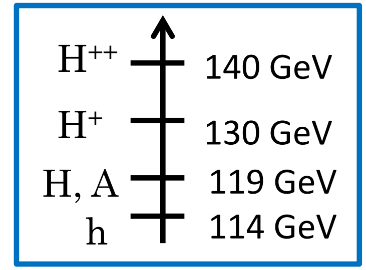




Discussed by *Chiang, Nomura, Tsumura, PRD85, 2012*

Mass reconstruction at LHC

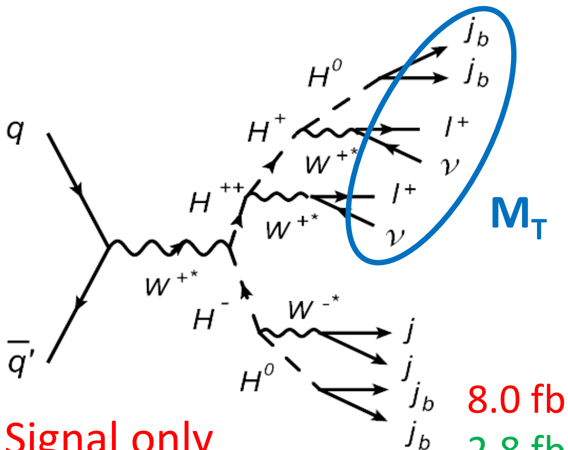
Aoki, Kanemura, KY, PRD85(2012)



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

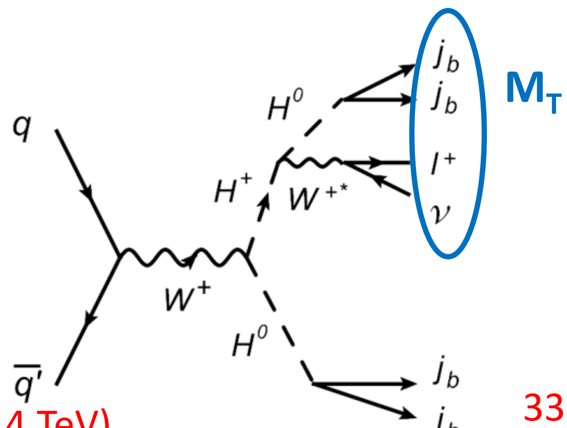
qq' → $H^{+}H$ → ($l^+\nu bb$)(bb)

qq → HA → (bb)(bb)

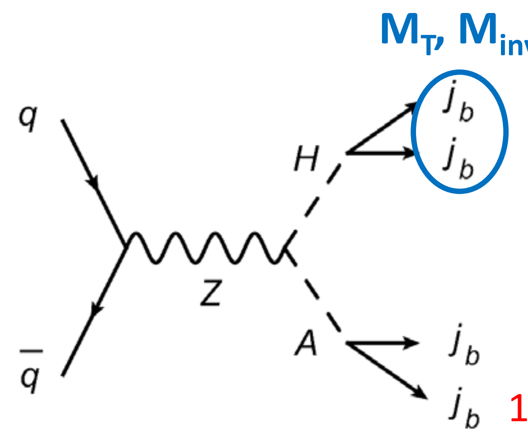


Signal only

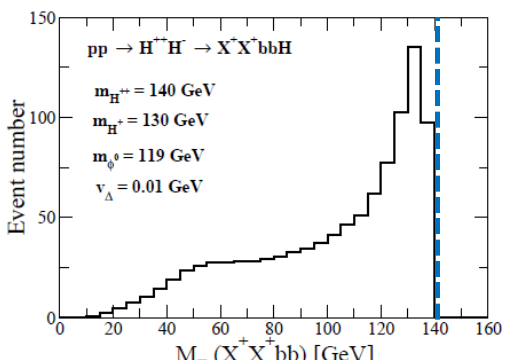
8.0 fb (14 TeV)
2.8 fb (7 TeV)



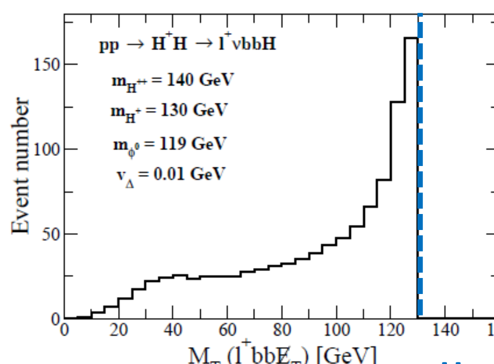
33 fb
12 fb



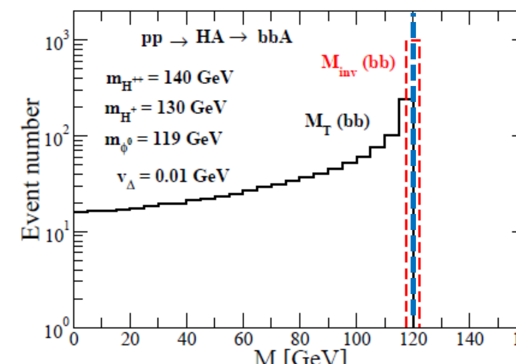
130 fb
42 fb



mH++



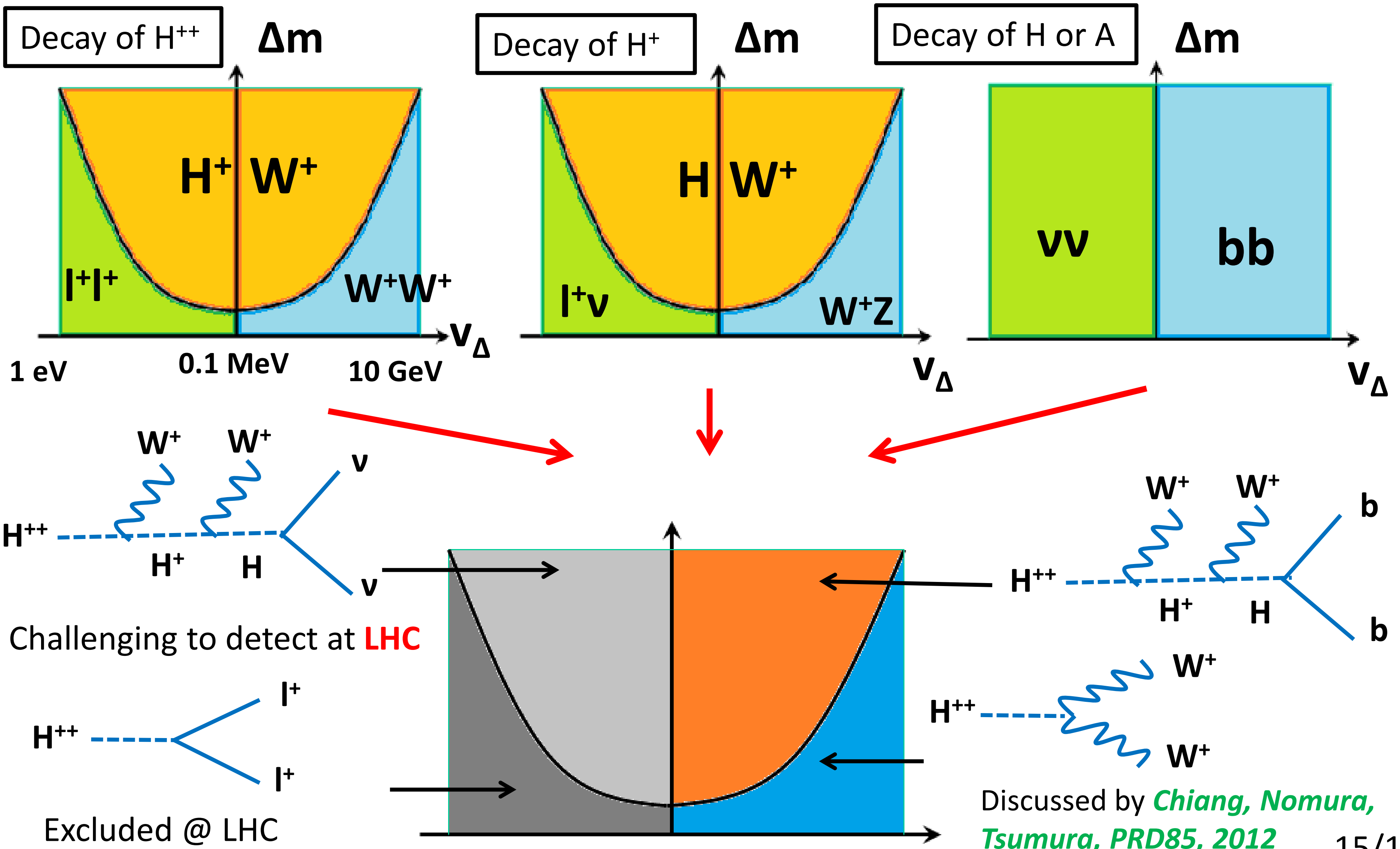
mH+



mH, mA

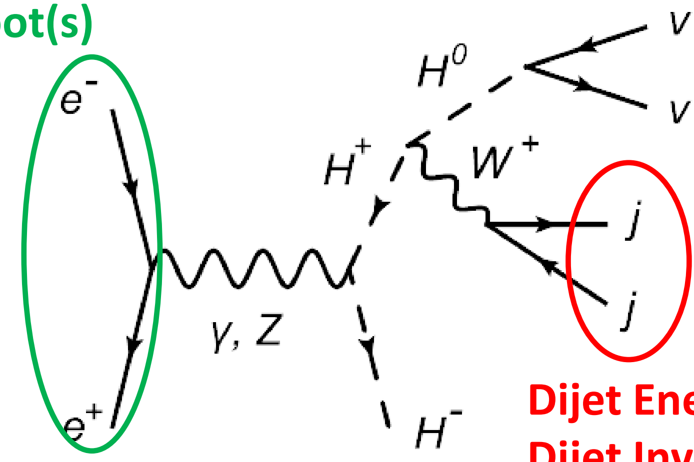
All the masses of the Δ-like scalar bosons may be reconstructed.

Decay property of the triplet-like Higgs bosons [O(100) GeV case]



Mass reconstruction at ILC

Root(s)



σ ~ 20 fb

Dijet Energy E_{jj}

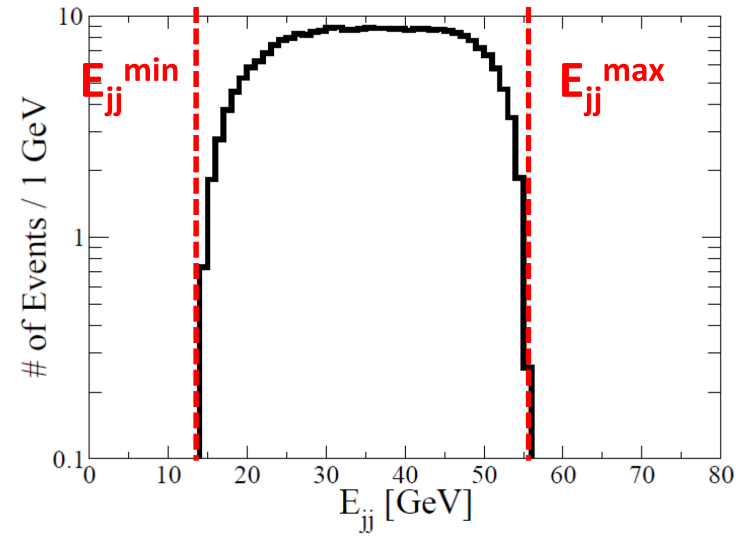
Dijet Invariant mass M_{jj}

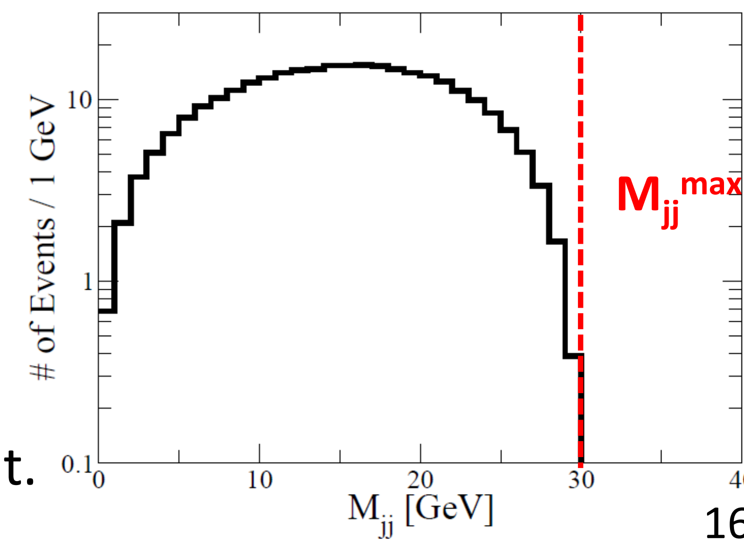
$$m^2_{H+} \simeq \frac{s}{4}\left[1-\left(\frac{E_{jj}^{\max}-E_{jj}^{\min}}{E_{jj}^{\max}+E_{jj}^{\min}}\right)^2\right]$$

$$m^2_{H^0} \simeq \frac{s}{4}\left[1-\left(\frac{E_{jj}^{\max}-E_{jj}^{\min}}{E_{jj}^{\max}+E_{jj}^{\min}}\right)^2\right]-\frac{2\sqrt{s}E_{jj}^{\max}E_{jj}^{\min}}{E_{jj}^{\max}+E_{jj}^{\min}}$$

$$M_{jj}^{\max} \simeq m_{H+}-m_H$$

mH+ = 200 GeV, mH = 170 GeV,
Root(s) = 500 GeV, 100 fb^{-1}





H^{++} can be measured by looking at the excess of the SS dilepton + jets + missing event.

Summary

The Higgs Triplet Model (HTM) :

Tiny neutrino masses can be explained.

Indirect way to test the HTM at colliders (Decoupling case):

Measuring the deviation of the Higgs coupling from the SM prediction.

Ex) Triplet Higgs mass = 300 GeV case

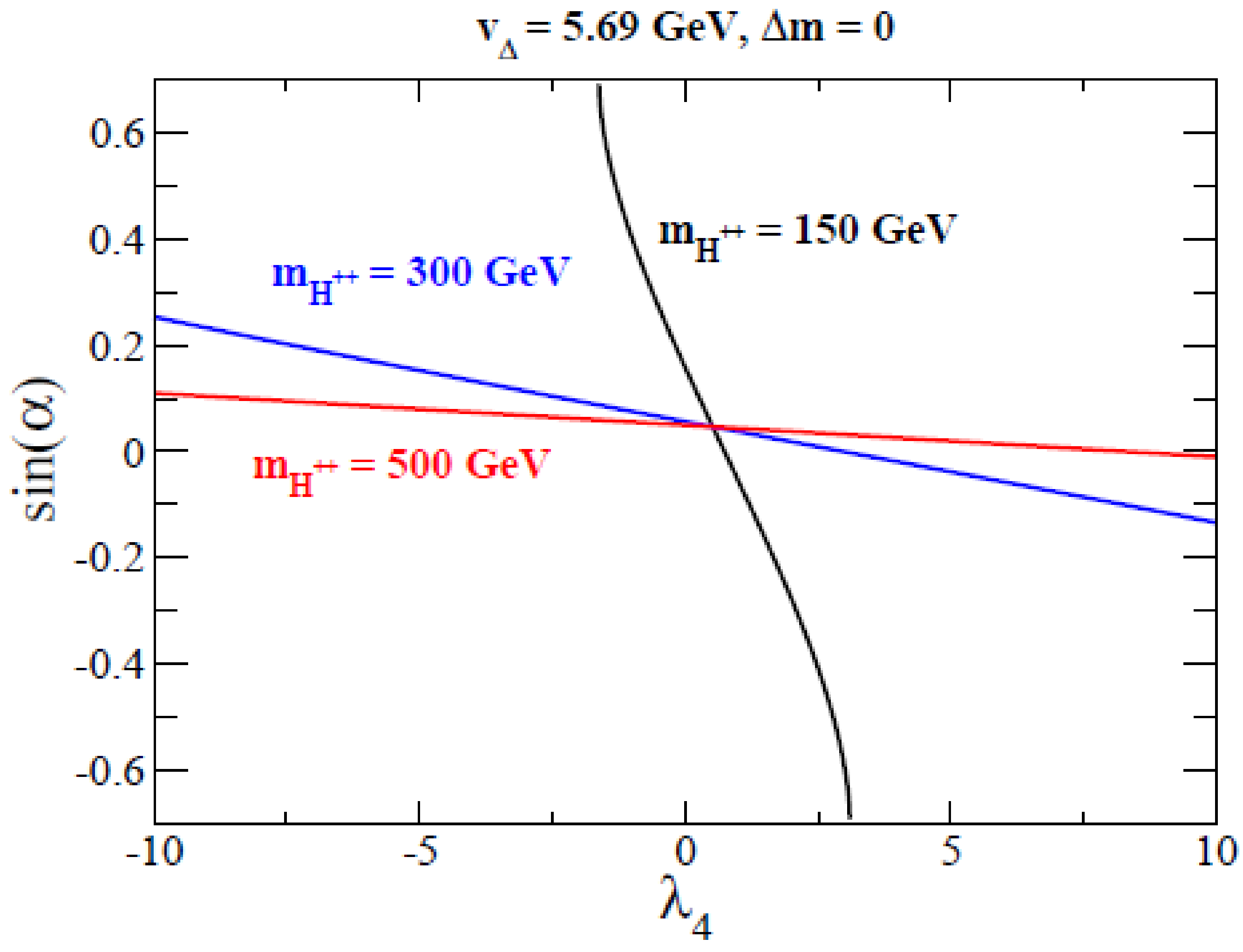
- $h\gamma\gamma \rightarrow$ +50% Current LHC data can be reproduced.
- $hhh \rightarrow$ -60 % ~ +100 % Direction of the correction is opposite to $h\gamma\gamma$.
- hZZ, hWW $\rightarrow$ ~-1 % O(1%) deviation of hVV can be measured at the ILC.

Direct way to test the HTM at colliders (Light triplet Higgs case):

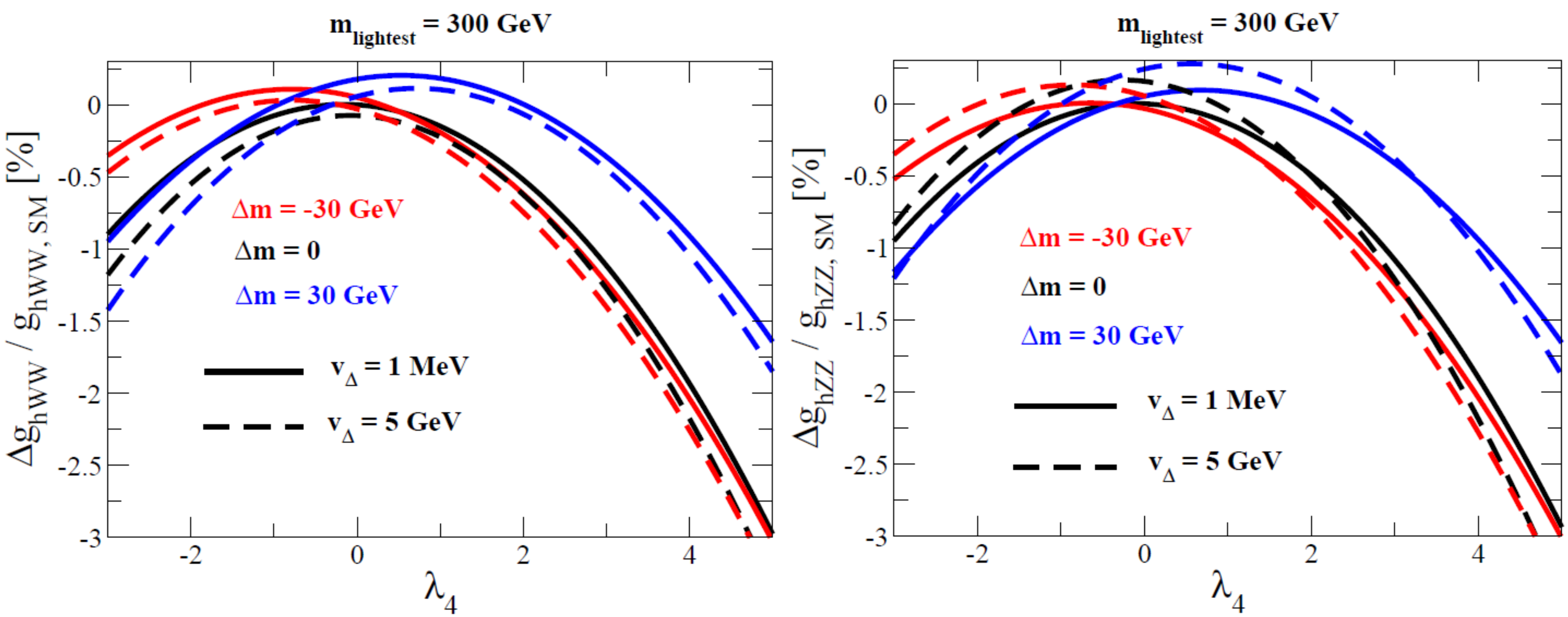
At the LHC, mH > mH+ > mH++ with small v_Δ case is challenging to test the model.

At the ILC, even if this scenario is realized, triplet-like Higgs bosons may be detectable by using the dijet energy and invariant mass distribution.

ILC is necessary to test the HTM in both indirect way and direct way!!

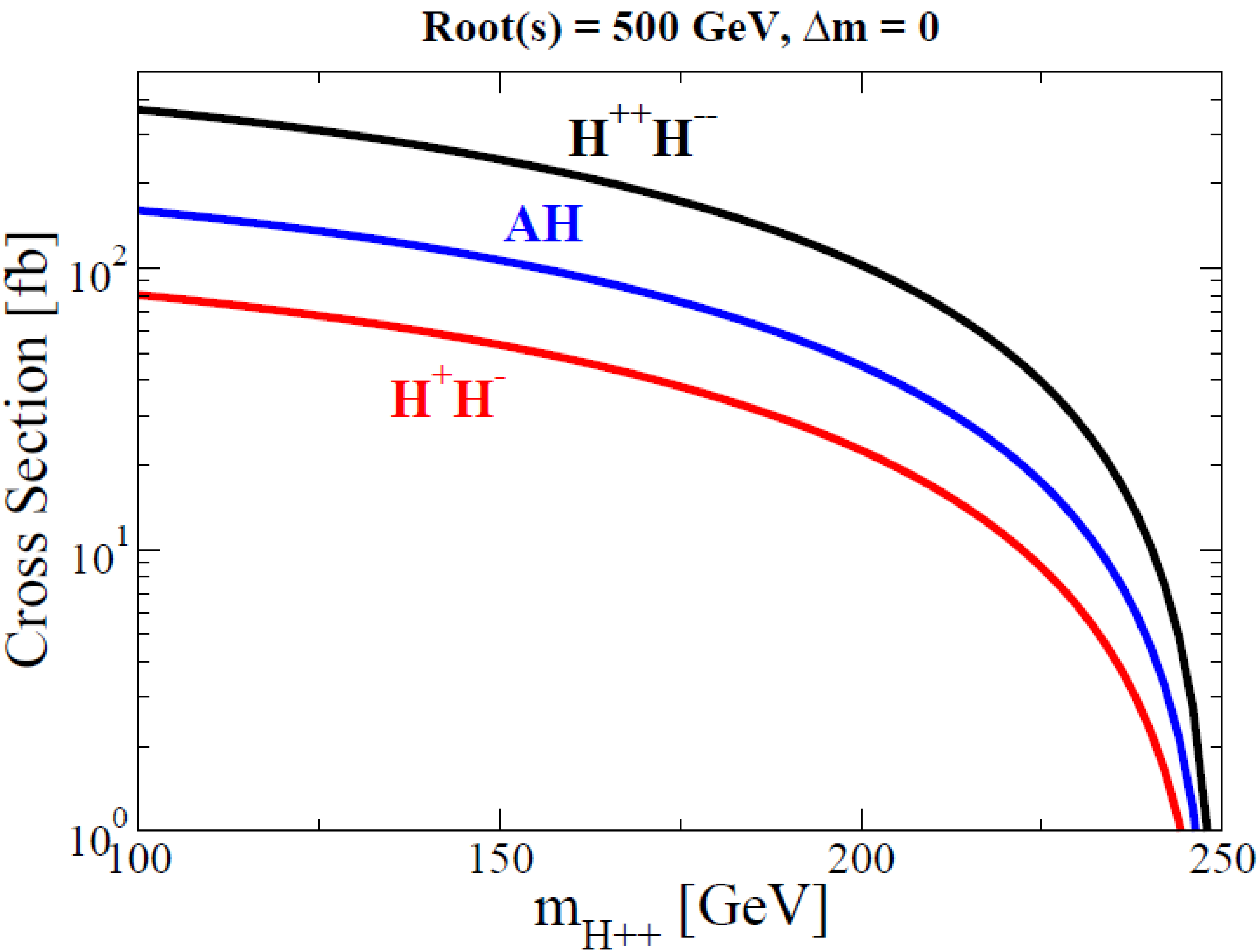


v_Δ = 5.69 GeV, Δm = 0
$m_{H^{++}}$ = 150 GeV
$m_{H^{++}}$ = 300 GeV
$m_{H^{++}}$ = 500 GeV
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
sin(α)
-10
-5
0
5
10
λ_4



$m_{lightest}$ = 300 GeV
$\Delta g_{hWW} / g_{hWW, SM}$ [%]
λ_4
Δm = -30 GeV
Δm = 0
Δm = 30 GeV
v_Δ = 1 MeV
v_Δ = 5 GeV
$m_{lightest}$ = 300 GeV
$\Delta g_{hZZ} / g_{hZZ, SM}$ [%]
λ_4
Δm = -30 GeV
Δm = 0
Δm = 30 GeV
v_Δ = 1 MeV
v_Δ = 5 GeV

Cross section



Renormalization of the Higgs potential

Aoki, Kanemura, Kikuchi, KY, PLB714

8 parameters in the potential
$\mu, m, M, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$

→

8 physical parameters
$v, m_{H++}, m_{H+}, m_A, m_h, m_H, \alpha, \beta'\ (v\Delta)$

Counter terms

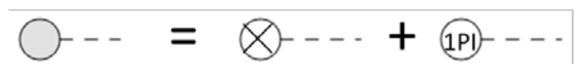
δv, $\delta m_{H++}^2, \delta m_{H+}^2, \delta m_A^2, \delta m_h^2, \delta m_H^2, \delta\alpha, \delta\beta'$

Tadpole : $\delta T_\varphi, \delta T_\Delta,$

Wave function renormalization : $\delta Z_{H++}, \delta Z_{H+}, \delta Z_A, \delta Z_H, \delta Z_h$

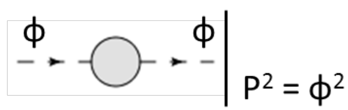
Reno. of EW parameters → δv

Vanishing 1-point function

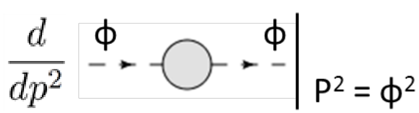


= 0 → $\delta T_\varphi, \delta T_\Delta$

On-shell condition

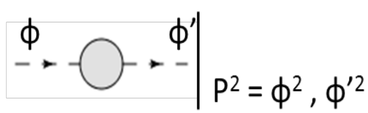


= 0 → $\delta m_{H++}^2, \delta m_{H+}^2, \delta m_A^2, \delta m_H^2, \delta m_h^2$



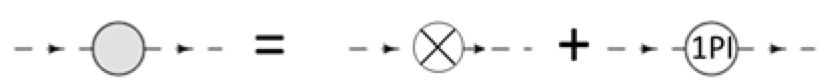
= 0 → $\delta Z_{H++}, \delta Z_{H+}, \delta Z_A, \delta Z_H, \delta Z_h$

No-mixing condition



= 0 → $\delta\alpha, \delta\beta'$

where 2-point function is defined by



Constraints from EW precision data

There are 3 parameters: g, g' and v in the kinetic term of Higgs fields.

➡ The electroweak observables are described by the 3 input parameters.

We can choose α_{em}, m_W and m_Z as the 3 input parameters.

The weak angle $\sin^2\theta_W = s_W^2$ can be described in terms of the gauge boson masses.

$$s_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

The counter term of δs_W^2 is derived as

$\sim \delta\rho = \rho - 1 = \alpha_{em} T$

$$\frac{\delta s_W^2}{s_W^2} = \frac{s_W^2}{c_W^2}\left[\frac{\delta m_Z^2}{m_Z^2} - \frac{\delta m_W^2}{m_W^2}\right] = \frac{s_W^2}{c_W^2}\left[\frac{\Pi^{ZZ}(m_Z^2)}{m_Z^2} - \frac{\Pi^{WW}(m_W^2)}{m_W^2}\right]$$

The quantity $\delta\rho$ (or T) measures the violation of the custodial symmetry.

Constraints from EW precision data

There are **4** parameters (instead of 3 in the SM):
g, g', v and v_Δ in the kinetic term of Higgs fields.

The electroweak observables are described by the **4** input parameters.

The weak angle $\sin^2\theta_W = s_W^2$ cannot be given in terms of the gauge boson masses.

$$s_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

Scheme 1 *Blank, Hollik (1997)*

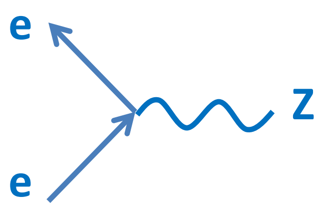
Input parameters:

m_W, m_Z, α_{em}, $\mathbf{s_W^2}$

Scheme 2 *Chankowski, Pokorski, Wagner (2007); Chen, Dawson, Jackson (2008)*

Input parameters:

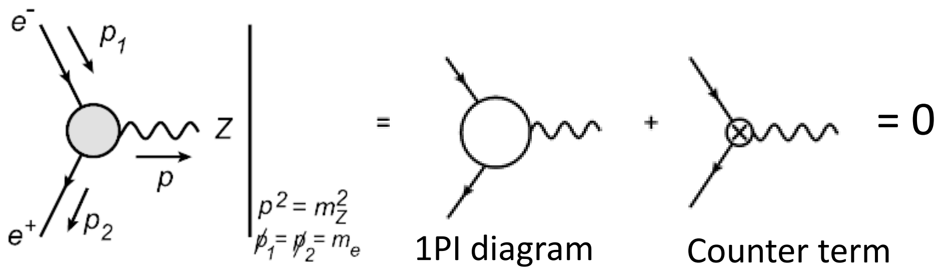
m_W, m_Z, α_{em}, $\mathbf{v_\Delta}$



$$1 - 4\hat{s}_W^2(m_Z) = \frac{\mathrm{Re}(v_e)}{\mathrm{Re}(a_e)}$$

Additional renormalization condition

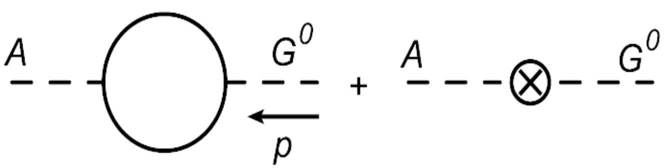
Scheme 1



$$\frac{\delta \hat{s}_W^2}{\hat{s}_W^2} = \frac{\hat{c}_W}{\hat{s}_W} \frac{\Pi_T^{\gamma Z}(m_Z^2)}{m_Z^2} - \delta'_V$$

$$\delta\rho \simeq \frac{1}{16\pi^2} \ln \frac{m_t}{m_b} + \cdots$$

Scheme 2



$$\delta\beta' = -\frac{1}{2m_A^2}\left[\Pi_{GA}^{\rm 1PI}(0) + \Pi_{GA}^{\rm 1PI}(m_A^2) - \frac{4}{v^2+2v_\Delta^2}(v_\Delta \delta T_\Phi - v_\phi \delta T_\Delta)\right]$$

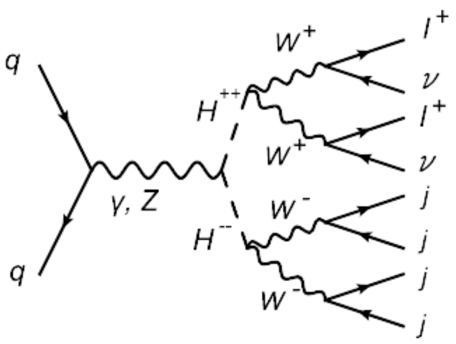
$$\frac{\delta v_\Delta}{v_\Delta} = \frac{(v^2+2v_\Delta^2)v_\phi}{2v_\Delta v^2}\delta\beta' + \frac{\delta v}{v}$$

$$\delta\rho \simeq \frac{1}{16\pi^2} \frac{(m_t - m_b)^2}{m_W^2} + \cdots$$

Diboson decay scenario

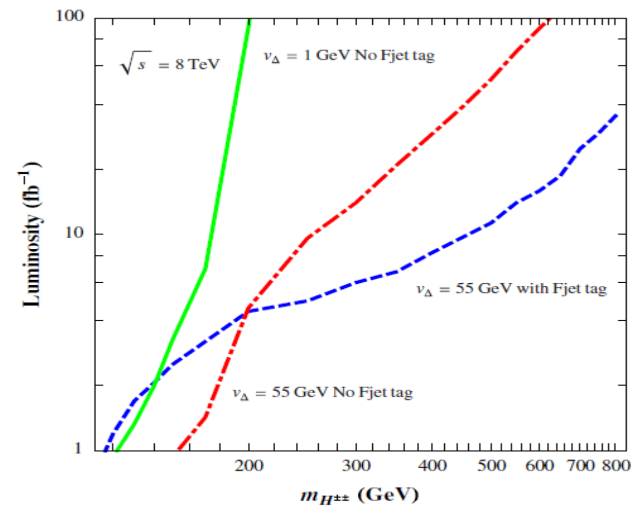
Realizing $v_\Delta > 0.1$ MeV with Case I

- Signal: Same-sign dilepton + Jets + Missing



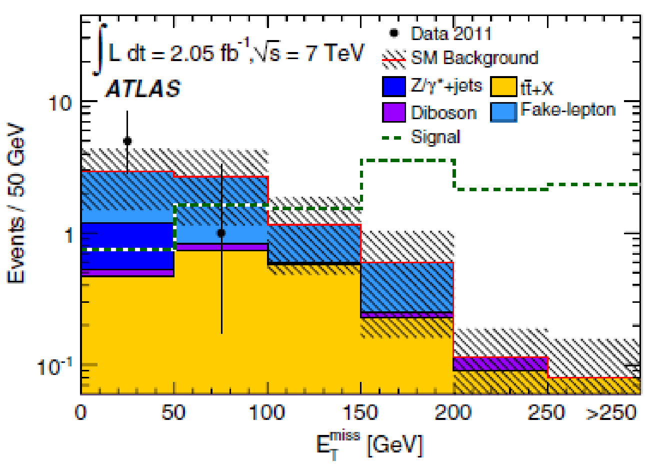
When mH++ = 100 GeV, root(s) = 7 TeV the signal cross section is ~ 3 fb.

Chiang, Nomura, Tsumura, 2012



- Chiang, Nomura and Tsumura studied discovery potential for this scenario at the LHC.

ATLAS, data 2011



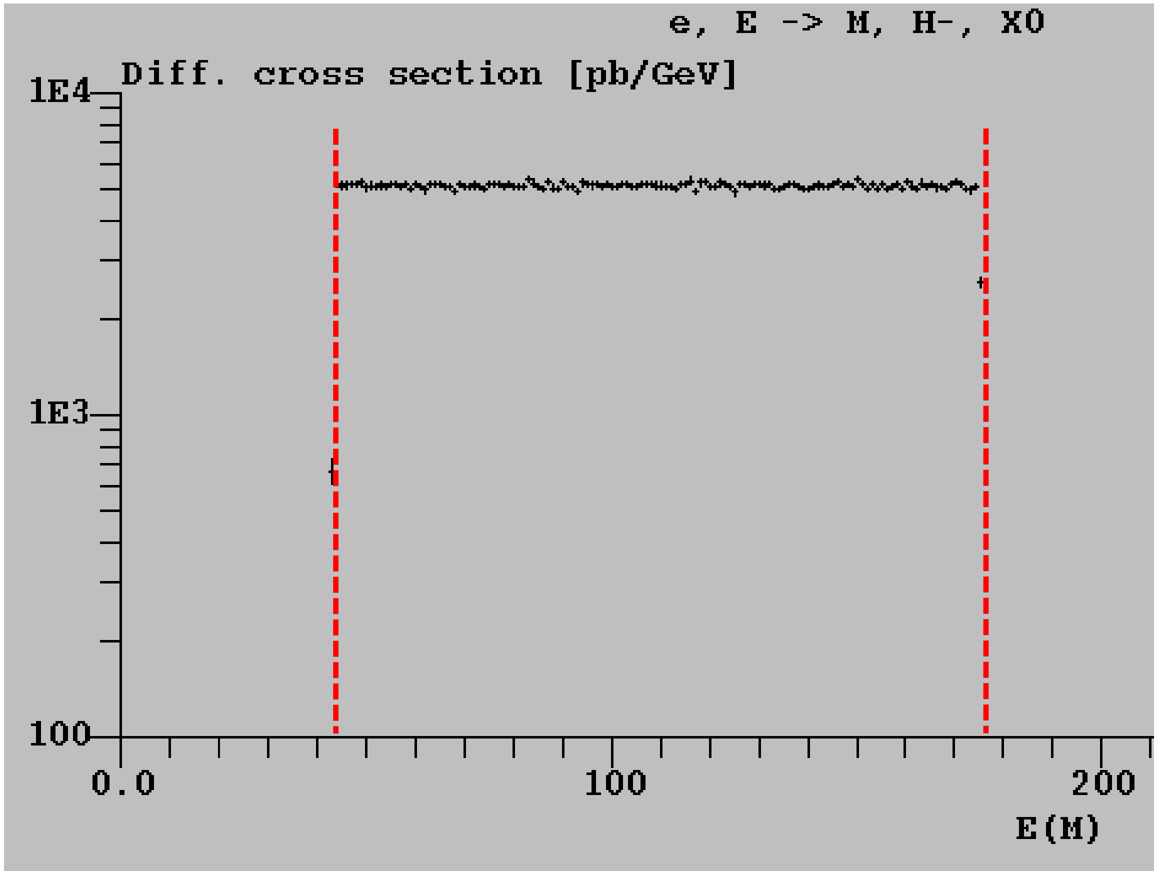
- Data: L~2 fb^{-1}, root(s) = 7 TeV at ATLAS

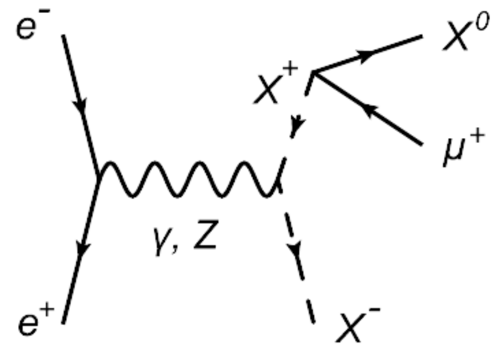
6 events have been discovered, which is consistent with the SM prediction.

Can we set a lower bound for the mass of H^{++} in the case of H^{++} decays into diboson?

Mass reconstruction at ILC

Ex. mX+ = 200 GeV, mX0 = 70 GeV





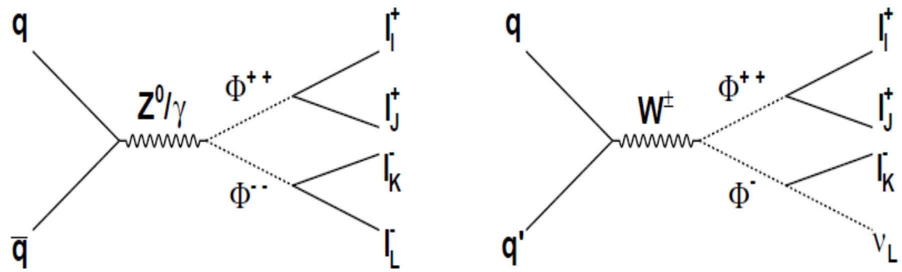
$$m_{X^0}^2 = \frac{s}{4}\left[1 - \left(\frac{E_\mu^{\max} - E_\mu^{\min}}{E_\mu^{\max} + E_\mu^{\min}}\right)^2\right] - \frac{2\sqrt{s}E_\mu^{\max}E_\mu^{\min}}{E_\mu^{\max} + E_\mu^{\min}}$$

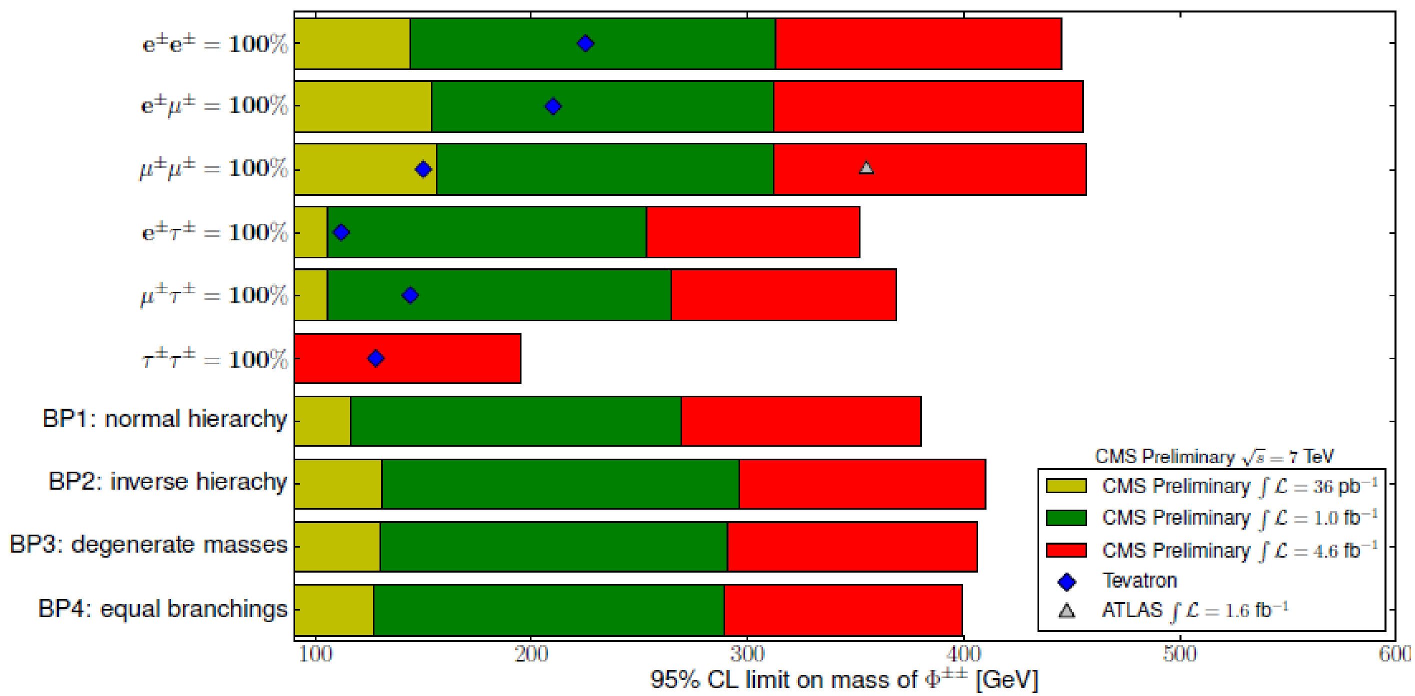
$$m_{X+}^2 = \frac{s}{4}\left[1 - \left(\frac{E_\mu^{\max} - E_\mu^{\min}}{E_\mu^{\max} + E_\mu^{\min}}\right)^2\right]$$

Experimental bounds (Direct)

Assuming 100% same-sign leptonic decay of the doubly-charged Higgs boson

CMS PAS HIG-12-005, 7TeV, 4.6 fb^{-1}



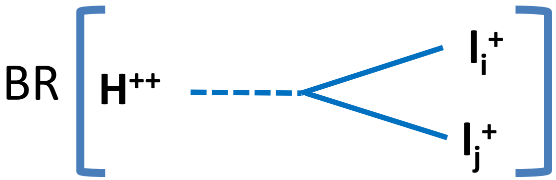


$mH^{++} \gtrsim 400$ GeV

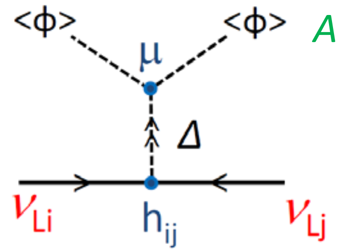
Dilepton decay scenario

Realizing $v_\Delta < 0.1$ MeV with Case I.

- By measuring the pattern of leptonic decay, we can direct test the neutrino mass matrix.



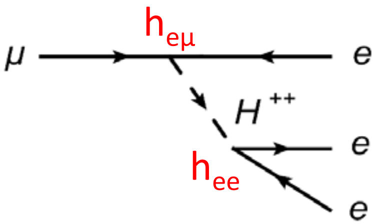
$\propto |h_{ij}|^2$



Akeroyd, Aoki, Sugiyama, 2008

$h_{ij} v_\Delta$

- Lepton flavor violation (μ → 3e, μ-e conversion, etc)



Chun, Lee, Park, 2003; Kakizaki, Ogura, Shima, 2003; Abada, Biggio, Bonnet, Gavela, Hambey, 2007, …

$$BR(\mu \to 3e) \simeq \frac{\Gamma(\mu \to 3e)}{\Gamma(\mu \to e\nu\bar{\nu})} \simeq \frac{|h_{ee}h_{e\mu}|^2}{4m_{H^{++}}^4 G_F^2} < 10^{-12} \Rightarrow |h_{ee}h_{e\mu}| \lesssim 10^{-5} \times \left(\frac{m_{H^{++}}}{1\ \mathrm{TeV}}\right)^2$$

- LHC phenomenology

-4 lepton , 3 lepton signature *Perez, Han, Huang, Li, 2008 ; Akeroyd, Chiang, Gaur, 2010, …*

-Using tau polarization *Sugiyama, Tsumura, Yokoya, arXiv:1207.0179*

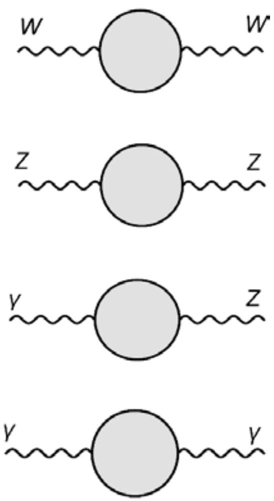
Discrimination of chiral structure of the Yukawa coupling

-Same sign tetra-lepton signature *Chun, Sharma, arXiv:1206.6278*

Experimental bounds (Indirect)

Gauge boson self-energies

6 nondec. d.o.f.



$$= M_{\rm New}^2 + p^2 \ln \frac{M_{\rm New}^2}{p^2} + \cdots$$

$$= M_{\rm New}^2 + p^2 \ln \frac{M_{\rm New}^2}{p^2} + \cdots$$

$$= p^2 \ln \frac{M_{\rm New}^2}{p^2} + \cdots$$

$$= p^2 \ln \frac{M_{\rm New}^2}{p^2} + \cdots$$

Model w/ $\rho_{\rm tree} = 1$

3 input parameters

→ 6-3 (Ren. conditions) = 3 nondec. d.o.f.

= S, T, U *Peskin, Takeuchi, PRL65, (1990)*

$$\delta\rho \simeq \frac{1}{16\pi^2}\frac{(m_t - m_b)^2}{m_W^2} + \cdots$$

Model w/o $\rho_{\rm tree} = 1$

4 input parameters *Blank, Hollik, NPB514, (1998)*

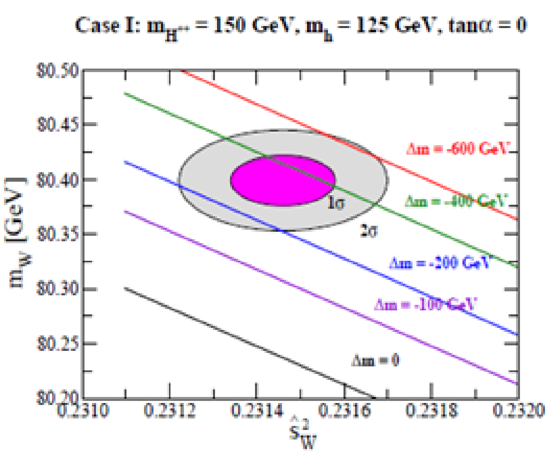
→ 6-4 (Ren. conditions) = 2 nondec. d.o.f.

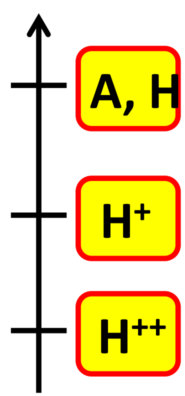
$$\delta\rho \simeq \frac{1}{16\pi^2}\ln\frac{m_t}{m_b} + \cdots$$

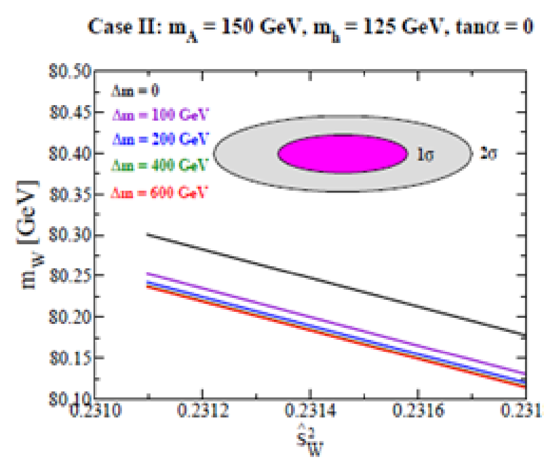
1-loop corrected W mass

Kanemura, KY, PRD85 (2012)

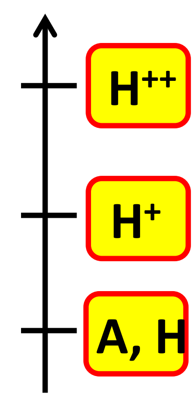
Case I







Case II



Radiative corrections to the mass spectrum

Aoki, Kanemura, Kikuchi, KY, arXiv: 1204.1951

Ratio of the squared mass difference *R*

$$R \equiv \frac{m_{H^{++}}^2 - m_{H^+}^2}{m_{H^+}^2 - m_A^2}$$

Tree level: $$R^{\text{tree}} = 1 + \left(\frac{v_\Delta^2}{v^2}\right) \simeq 1$$

Less than 10^{-3}

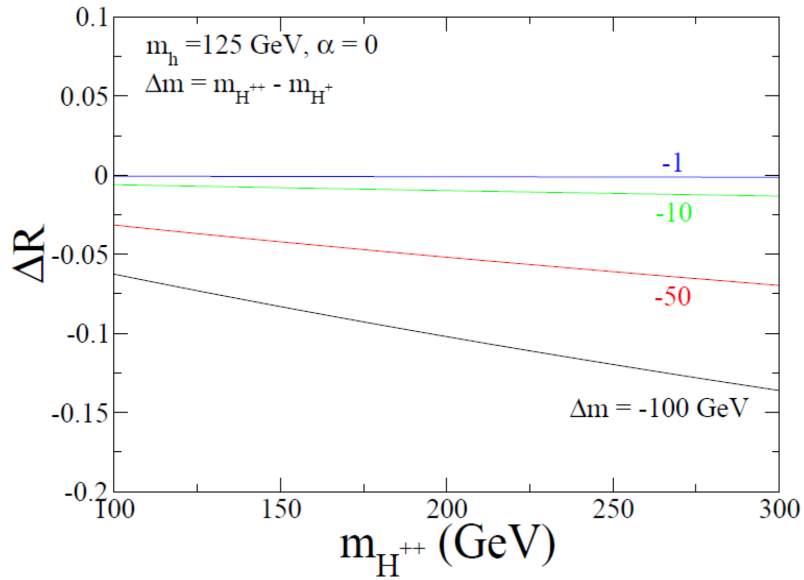
Loop level: $$R^{\text{loop}} = 1 + \Delta R + \left(\frac{v_\Delta^2}{v^2}\right)$$

Loop correction

$$\Delta R = \frac{\Pi^{1PI}_{H^{++}H^{--}}[m_{H^{++}}^2] - 2\Pi^{1PI}_{H^+H^-}[m_{H^+}^2] + \Pi^{1PI}_{AA}[(m_A^2)_{\text{tree}}]}{m_{H^{++}}^2 - m_{H^+}^2}$$

$(m_A^2)_{tree}$ is determined by $m_{H^{++}}^2$ and $m_{H^+}^2$: $$(m_A^2)_{\text{tree}} = 2m_{H^+}^2 - m_{H^{++}}^2$$

Case I



In favored parameter sets by EW precision data: $m_{H^{++}}$ = O(100)GeV, $|\Delta m| \sim$ 100GeV, ΔR can be as large as **O(10)%**.

Custodial Symmetry

The SM Lagrangian can be written by the 2 × 2 matrix form of the Higgs doublet:

$$\Sigma = (\tilde{\Phi}, \Phi) = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{-} & \phi^{0} \end{pmatrix}$$

★ **Kinetic term**

$$\mathcal{L}_{\rm kin} = \frac{1}{2}{\rm Tr}\left[(\tilde{D}_\mu \Sigma)^\dagger (\tilde{D}^\mu \Sigma)\right]$$

$$\tilde{D}_\mu \Sigma = \partial_\mu \Sigma + i\frac{g}{2}\tau \cdot W_\mu \Sigma - i\frac{g'}{2}B_\mu \Sigma \tau_3$$

★ **Higgs potential**

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$

$$= -\frac{\mu^2}{2}{\rm Tr}(\Sigma^\dagger \Sigma) + \frac{\lambda}{4}{\rm Tr}(\Sigma^\dagger \Sigma)^2$$

★ **Yukawa interaction (top-bottom sector)**

$$\mathcal{L}_Y = y_t \bar{Q}_L \tilde{\Phi} t_R + y_b \bar{Q}_L \Phi b_R + {\rm h.c.}$$

$$= y_V \bar{Q}_L \Sigma Q_R + y_A \bar{Q}_L \Sigma \tau_3 Q_R + {\rm h.c.}$$

When we take g' and $y_A \to 0$,
Lagrangian is invariant under $SU(2)_L \times SU(2)_R$

$$\boldsymbol{\Sigma \to U_L \Sigma U_R^\dagger \;,\; Q_{L,R} \to U_{L,R} Q_{L,R}}$$

After the Higgs field gets the VEV:

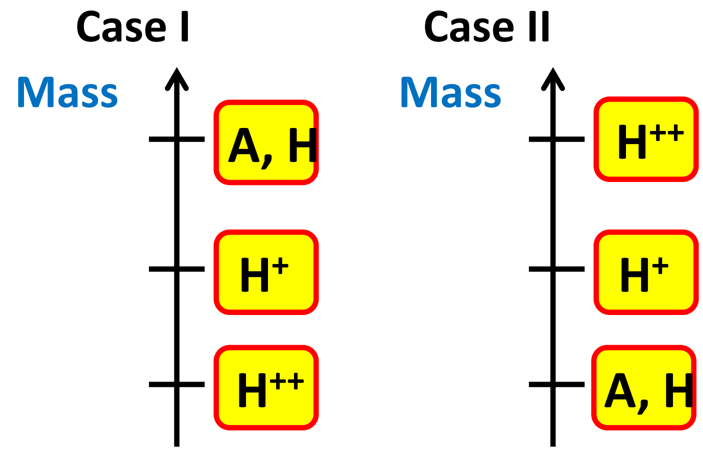
$$\Sigma \to \langle \Sigma \rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \langle \Delta \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix}$$

this symmetry is reduced to
$SU(2)_L = SU(2)_R = SU(2)_V$ (custodial symmetry).

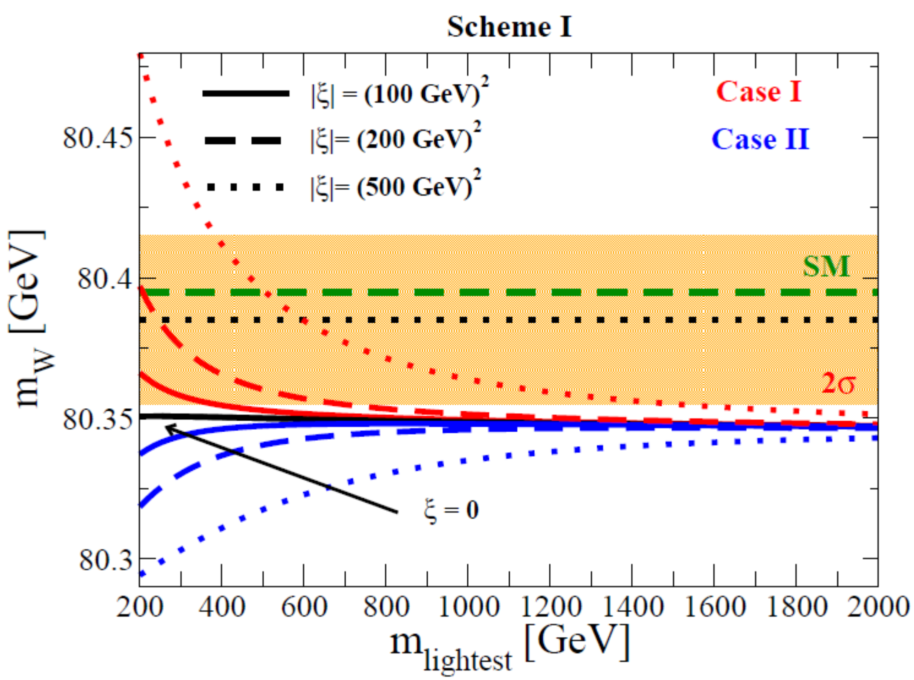
$SU(2)_V$ breaking by g' is included in the definition of the rho parameter, while that by y_A is not.
There is a significant contribution to the deviation of rho = 1 from the top-bottom sector by the loop effect.

1-loop corrected W mass

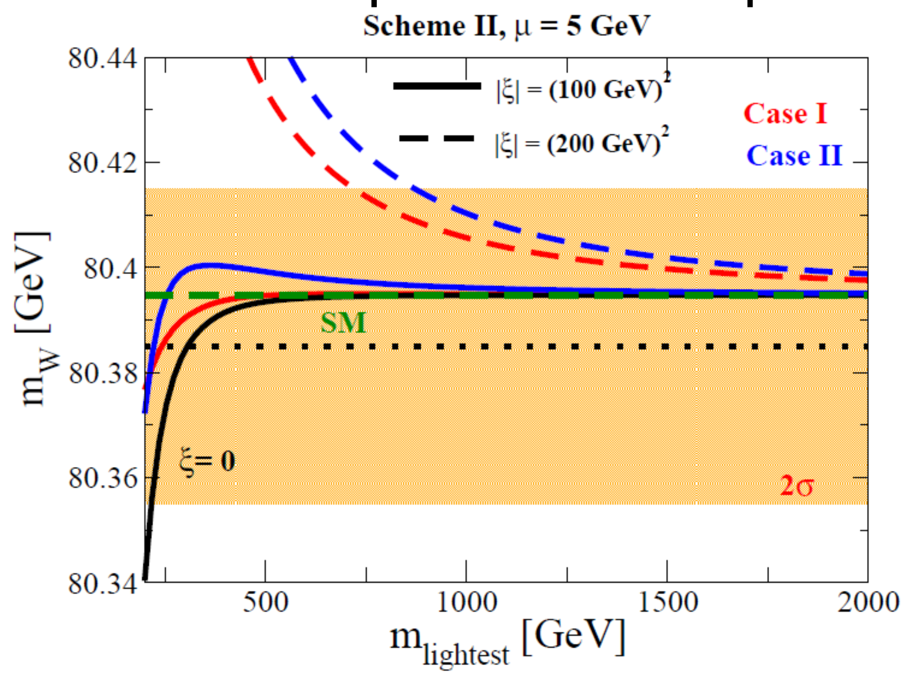
$\xi = m_{H++}^2 - m_{H+}^2$



Scheme 1



Scheme 2

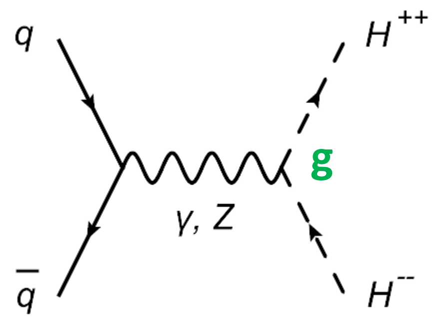


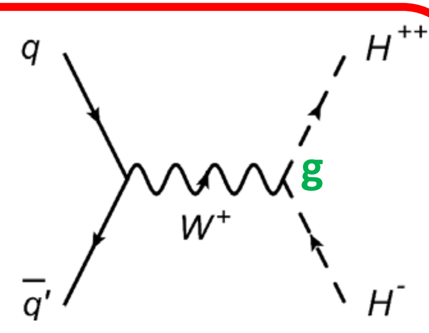
In Scheme II, decoupling limit can be taken in the heavy mass limit.

Production mechanisms at LHC

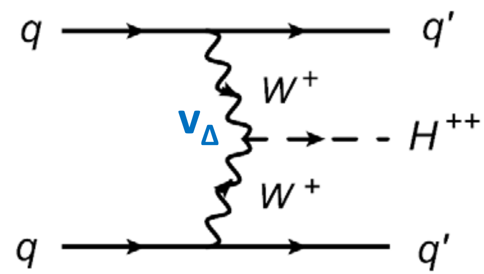
Main production process

Drell-Yan
- depends on the gauge coupling

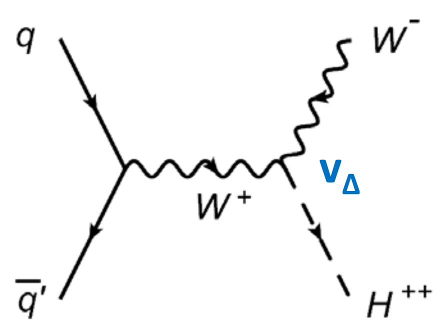


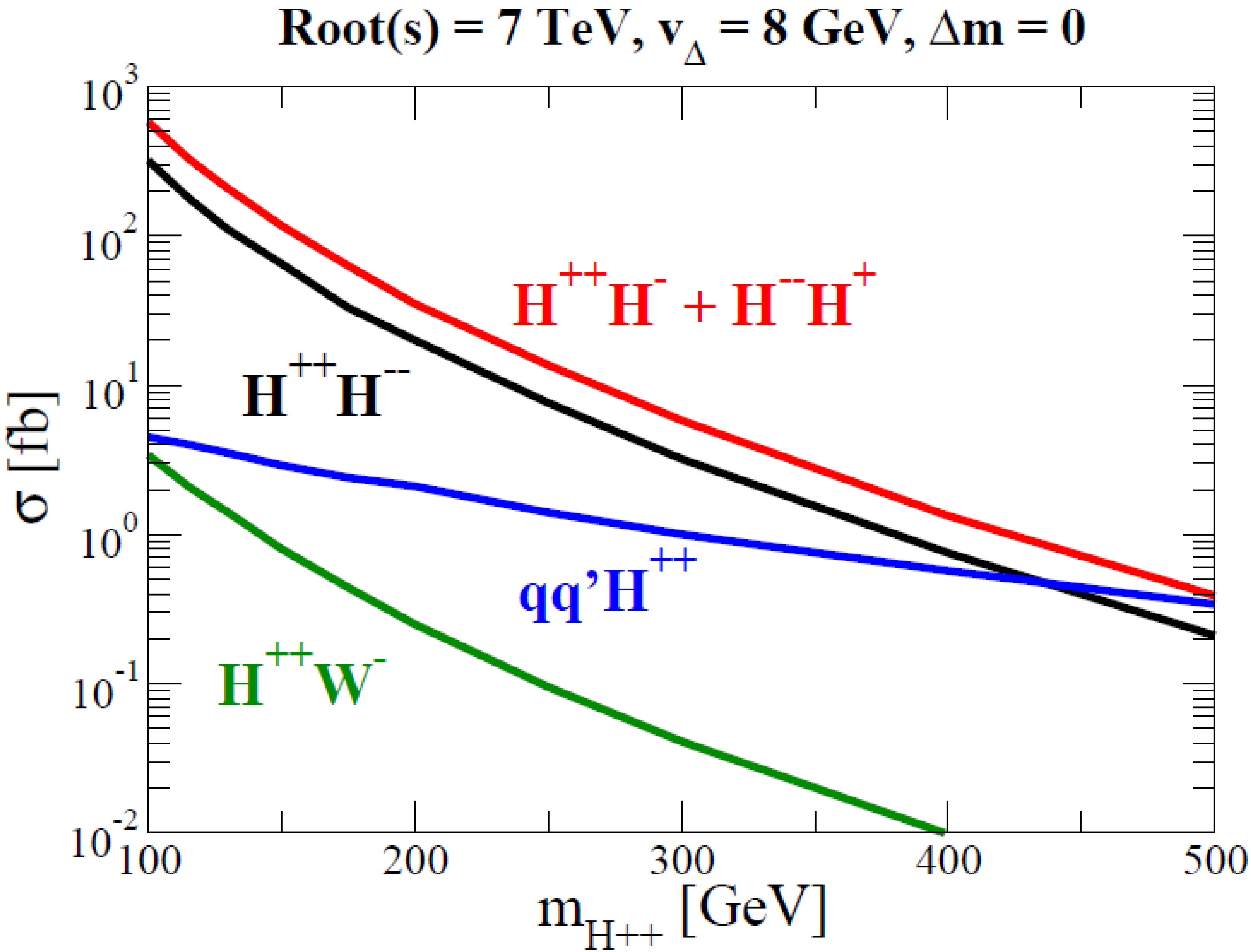


Vector Boson Fusion
- depends on v_Δ → **Suppressed**



W associate
- depends on v_Δ → **Suppressed**



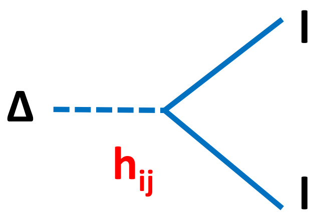


Root(s) = 7 TeV, v_Δ = 8 GeV, Δm = 0
σ [fb]
m_H++ [GeV]
H++H- + H--H+
H++H--
qq'H++
H++W-
10^3
10^2
10^1
10^0
10^-1
10^-2
100
200
300
400
500

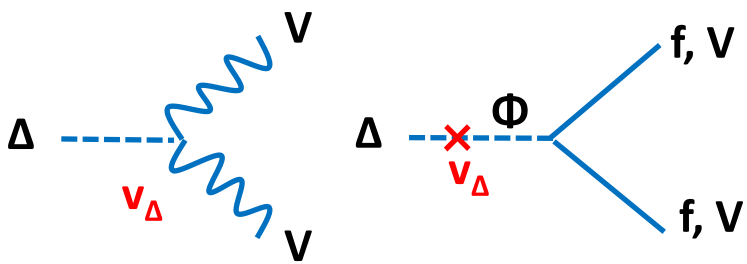
Decay

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

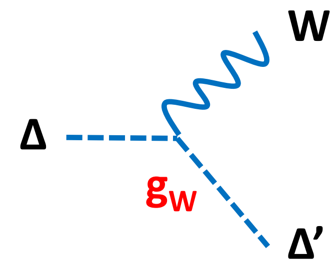
1. Decay via h_{ij}



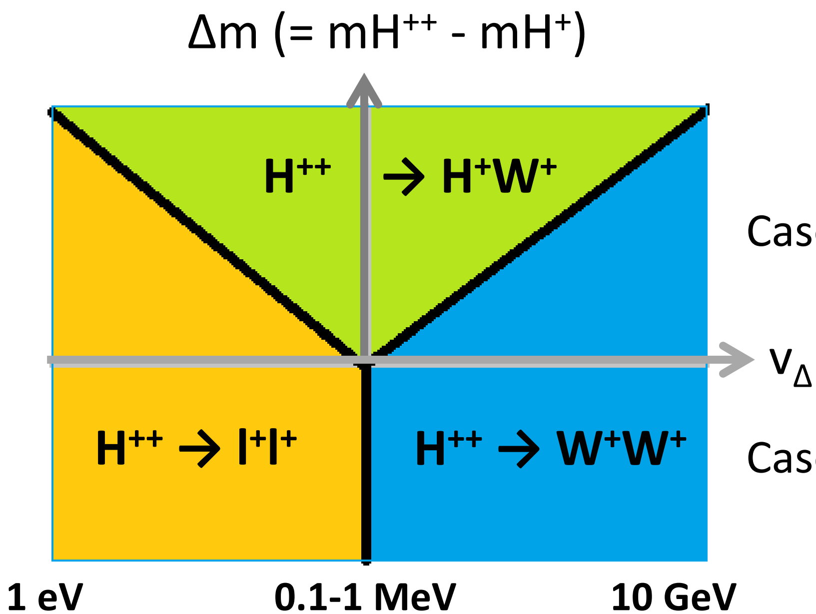
2. Decay via v_Δ



3. Decay via g



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 ($\equiv m_{H++} - m_{H+}$).