Higgs Triplet Models

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S. Kanemura, KY, PRD85 (2012),
M. Aoki, S. Kanemura, M. Kikuchi, KY, PLB714 (2012),
M. Aoki, S. Kanemura, M. Kikuchi, KY, PRD87 (2012),
S. Kanemura, M. Kikuchi, KY, 1301.7303

2013, Feb. 16th, HPNP2013, University of Toyama

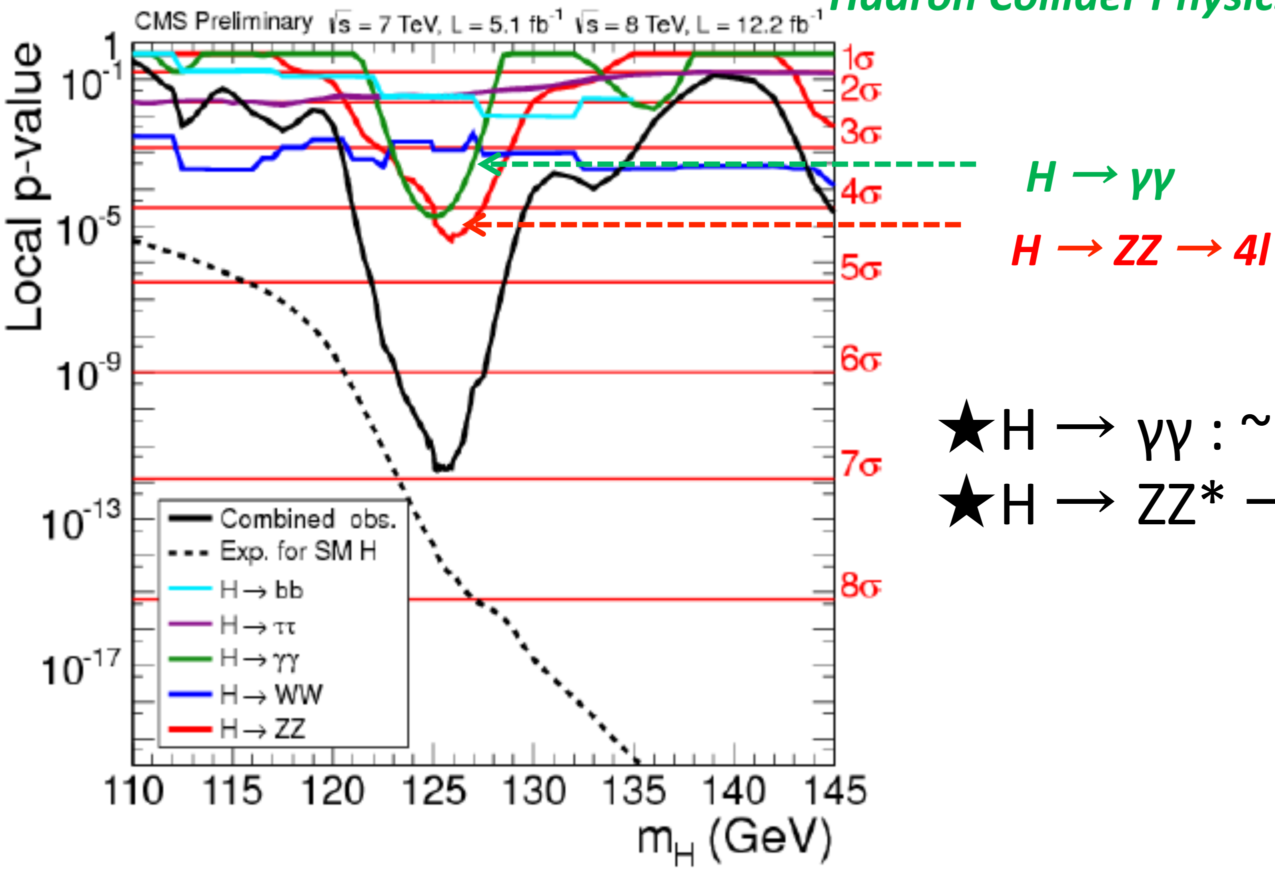
Contents

- Introduction
- Exotic Higgs sectors
- The Higgs triplet model
  - Direct test
  - Indirect test (Kikuchi's poster)
- Summary

Introduction

- A new particle has been found at around 126 GeV at the LHC.

Hadron Collider Physics Symposium, Nov. 2012



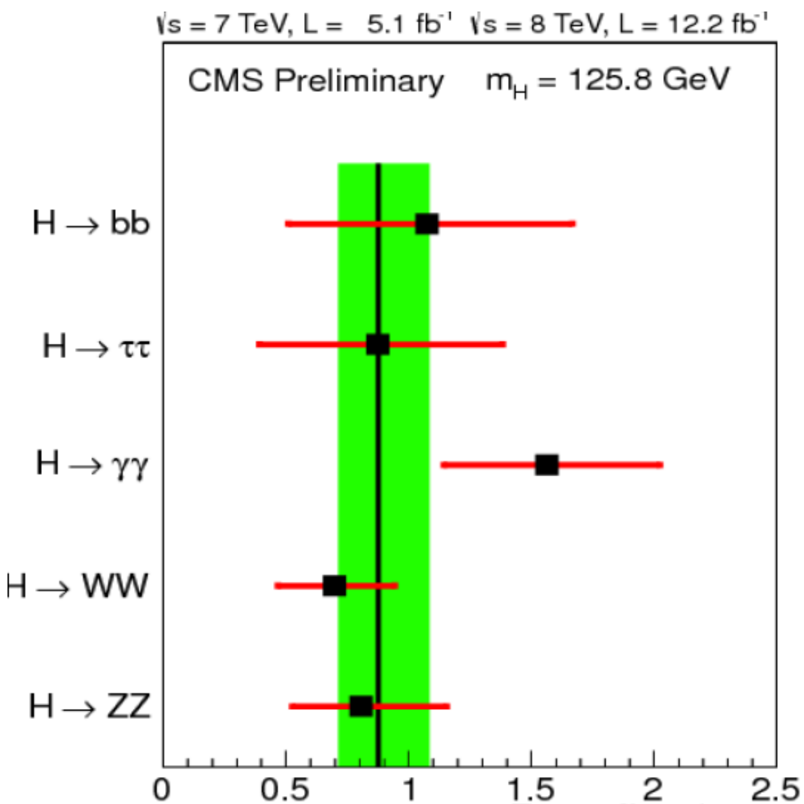
★H → γγ : ~ 4σ,
★H → ZZ* → 4-leptons : ~ 4σ

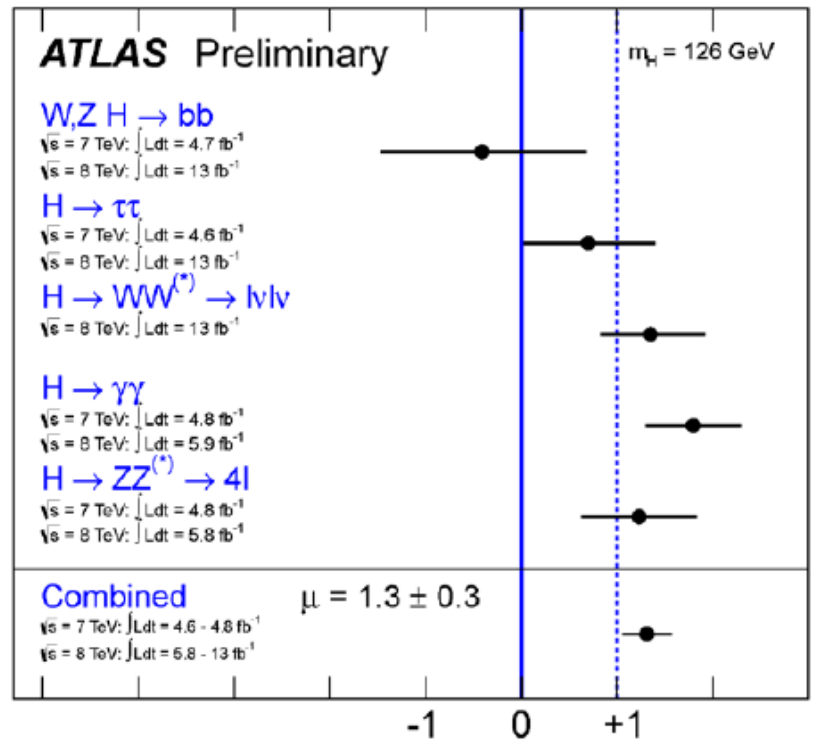
The combined significance is about 7σ at 126 GeV.

Introduction

- Signal strength (σ_{obs}/σ_{SM}) in each channel

Hadron Collider Physics Symposium, Nov. 2012





It is most likely the SM Higgs boson,
but it does not necessarily mean that SM is correct!

Introduction

Physics Beyond the SM

Neutrino masses

Dark matter

Baryon asymmetry

↓ **Introduce**

Extended Higgs Sectors

Minimal Higgs Sector

1 doublet: Φ

+

- **Singlets,**
- **Doublets,**
- **Triplets, …**

↑ **Test**

Experiments

EW precision obs.

126 GeV Boson

Extra Higgs, $H^{\pm}$, A, … ?

Higgs Coupling Measurents?

Introduction

Physics Beyond the SM

- *Neutrino masses*
- *Dark matter*
- *Baryon asymmetry*

↑ **Determine**

Higgs as a Probe of New Physics !!

↓ **Compare**

Experiments

- *EW precision obs.*
- *126 GeV Boson*
- *Extra Higgs, $H^{\pm}$, A, ... ?*
- *Higgs Coupling Measurents?*

Higgs sector with exotic fields

★In this talk, we focus on the Higgs sector with ***exotic scalar fields***.

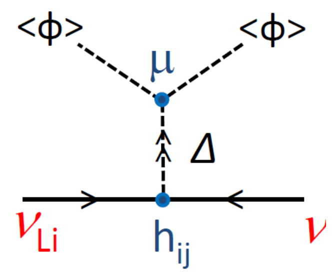
Higgs sectors with exotic fields

Normal extension

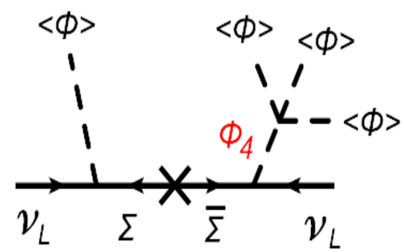
Minimal

Doublets and Singlets

Exotic Higgs field
→ isospin larger than 1/2 and having a non-zero VEV.



Cheng, Li (1980); Schechter, Valle (1980); Magg, Wetterich, (1980)

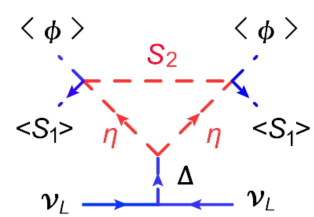


Babu, Nandi and Tavartkiladze (2009)

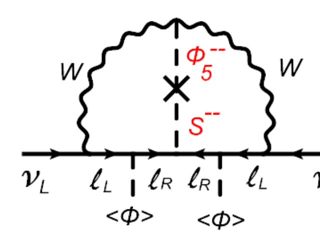
★Models with exotic scalar fields

- Type-II seesaw model [a comp. triplet]
- Georgi-Machacek (GM) model [a comp. and a real triplets]

- Model by Babu, Nandi and Tavartkiladze [a quadruplet]
- Radiative seesaw models
  - Model by Kanemura and Sugiyama [a comp. triplet]
  - Model by Chen, Geng and Tsai [a quintuplet]



Kanemura, Sugiyama (2012)



Chen, Geng, Tsai (2012)

Higgs sector with exotic fields

★There are striking features in Higgs sectors w/ exotic fields.

- **Electroweak rho parameter**
- **The $H^{\pm}W^{\mp}Z$ vertex**
- **The hZZ/hWW vertex**
- **Multi-charged Higgs bosons**

Higgs sector with exotic fields

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ρ_{exp} = 1.0004 $^{+0.0003}_{-0.0004}$

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

Y_i : hypercharge
T_i : isospin
v_i : VEV

Model with ρ_{tree} = 1

▪A Higgs field satisfying with the relation:

$$T = \frac{1}{2}(-1+\sqrt{1+12Y^2})$$

(T, Y) = (1, 0), (1/2, 1/2), (3, 2), (25/2, 15/2)

Model without ρ_{tree} = 1

▪Usually, exotic Higgs sectors predict rho ≠ 1 at the tree level except for some special cases.

▪Model w/ the Y=0 (Y=1) triplet

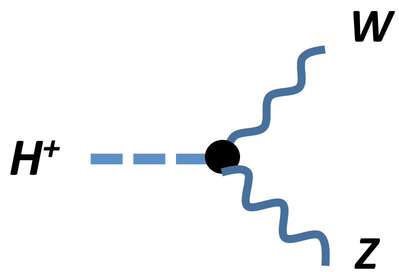
The other observables are necessary to discriminate exotic Higgs sectors.

CL

Higgs sector with exotic fields

★There are striking features in Higgs sectors w/ exotic fields.

- Electroweak rho parameter
- The $H^{\pm}W^{\mp}Z$ vertex
- The hZZ/hWW vertex



Grifols, Mendez (1980); Peyranere, Haber, Irulegui (1991); Mendez, Pomarol (1991); *Kanemura (2000)*

Effective HWZ vertex: $\mathcal{L}_{\rm eff} = g_Z m_W F H^+ W_\mu^- Z^\mu + \text{h.c.}$

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

Y_i : hypercharge
T_i : isospin
v_i : VEV

Model with multi-doublet structure

→ $|F|^2$ is **zero** at the tree level.
The $H^{\pm}W^{\mp}Z$ is induced at 1-loop level.

Model with exotic fields

→ $|F|^2$ is **non-zero** at the tree level.

In general, $|F|^2$ and ρ are independent quantities. Measuring $H^{\pm}W^{\mp}Z$ vertex can be a useful tool to the ρ to test triplet Higgs models.

Higgs sector with exotic fields

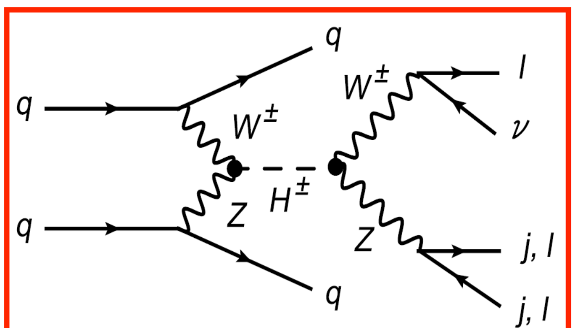
★There are striking features in Higgs sectors w/ exotic fields.

- **Electroweak rho parameter**
- **The $H^{\pm}W^{\mp}Z$ vertex**
- **The hZZ/hWW vertex**

★ Measuring the HWZ vertex at the collider experiments

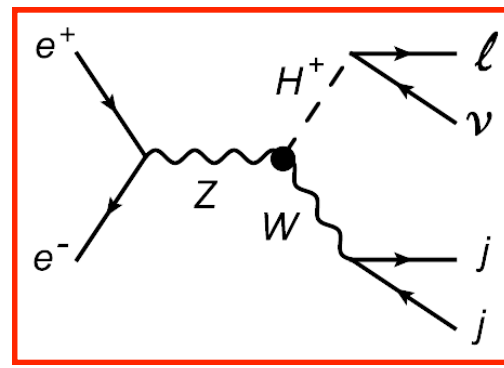
LHC

Asakawa, Kanemura, Kanzaki (2007)



ILC

Kanemura, KY, Yanase (2011)



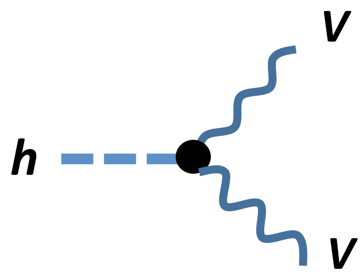
|F|^2 > 0.036 is required to reach S/Root(B)=2 with Root(s) = 14 TeV, Int. luminosity = 600 fb-1, mH+ = 200 GeV.

|F|^2 > 0.001 is required to reach S/Root(B)=2 with Root(s) = 300 GeV, Int. luminosity = 1000 fb-1 mH+ = 150 GeV.

Higgs sector with exotic fields

★There are striking features in Higgs sectors w/ exotic fields.

- **Electroweak rho parameter**
- **The $H^{\pm}W^{\mp}Z$ vertex**
- **The hZZ/hWW vertex**



$$g_{hVV} = g_{hVV}^{\rm SM} \times c_{hVV}$$

The deviation in the hVV coupling:

$$c_{hWW} = \frac{\sum_i 2v_i[T_i(T_i+1)-Y_i^2]R_{ih}}{v_{\rm SM}} \qquad c_{hZZ} = \sum_i \frac{2Y_i^2 v_i R_{ih}}{\sqrt{\sum_j Y_j^2 v_j^2}}$$

Y_i : hypercharge
T_i : isospin
v_i : VEV

$v_{\rm SM}^2 = \sum_i 2v_i^2[T_i(T_i+1) - Y_i^2]$ = (246 GeV)^2

R_{ih} : Mixing angle among CP-even Higgs bosons

Logan (2006)

Model with multi-doublet structure

→ c_{hVV} is **smaller** than 1

Model with exotic fields

→ c_{hVV} **can be larger** than 1

This is because the Clebsh-Gordan coefficient 2[T(T+1)-Y^2]v and the factor 4Y^2v from exotic fields are larger than those from the doublet.

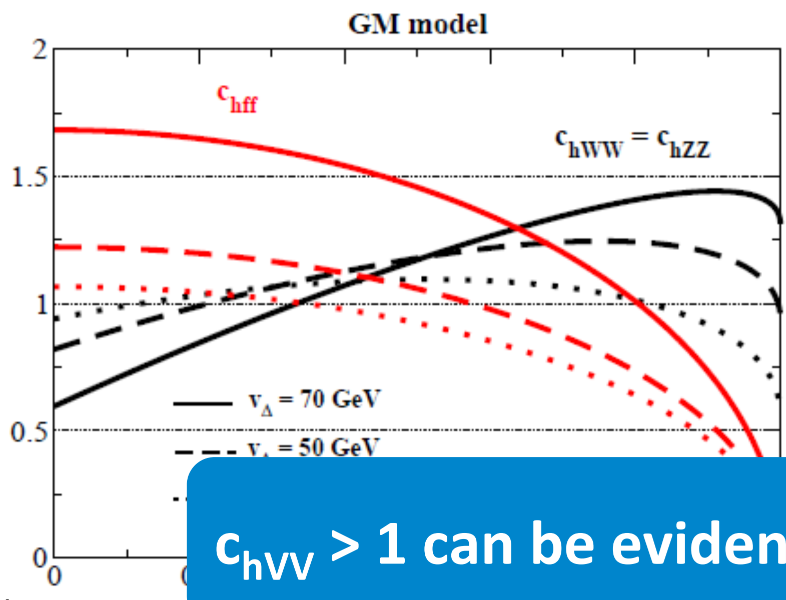
Higgs sector with exotic fields

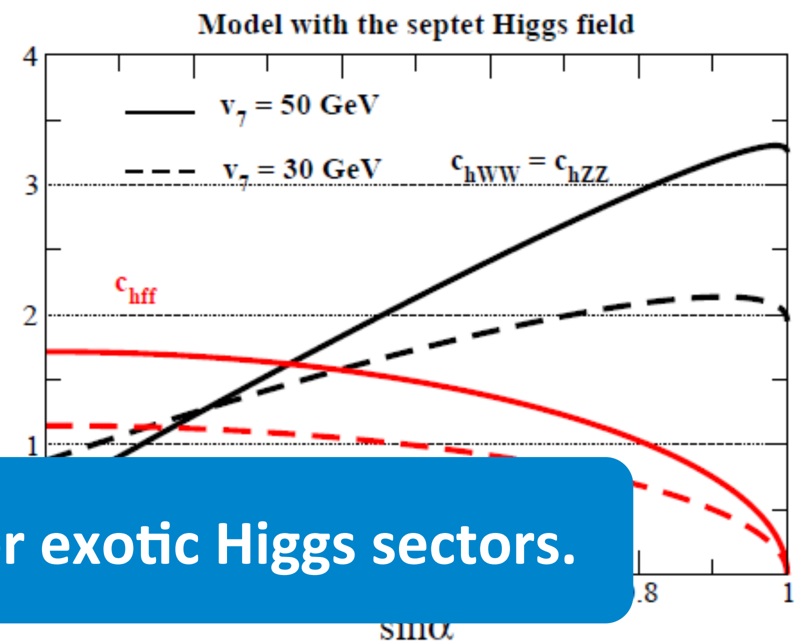
α, **β** and **β'** are mixing angles for **CP-even**, **singly-charged** and **CP –odd** Higgs bosons.

Model	$\tan\beta$	$\tan\beta'$	c_{hWW}	c_{hZZ}
$\phi_1+\phi_2$ (THDM)	v_{ϕ_2}/v_{ϕ_1}	v_{ϕ_2}/v_{ϕ_1}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$\phi+\chi$ (cHTM)	$\sqrt{2}v_\chi/v_\phi$	$2v_\chi/v_\phi$	$\cos\beta\cos\alpha+\sqrt{2}\sin\beta\sin\alpha$	$\cos\beta'\cos\alpha+2\sin\beta'\sin\alpha$
$\phi+\xi$ (rHTM)	$2v_\xi/v_\phi$	-	$\cos\beta\cos\alpha+2\sin\beta\sin\alpha$	$\cos\alpha$
$\phi+\chi+\xi$ (GM model)	$2\sqrt{2}v_\Delta/v_\phi$	$2\sqrt{2}v_\Delta/v_\phi$	$\cos\beta\cos\alpha+\frac{2\sqrt{6}}{3}\sin\beta\sin\alpha$	$\cos\beta\cos\alpha+\frac{2\sqrt{6}}{3}\sin\beta\sin\alpha$
$\phi+\varphi_7$	$4v_{\varphi_7}/v_\phi$	$4v_{\varphi_7}/v_\phi$	$\cos\beta\cos\alpha+4\sin\beta\sin\alpha$	$\cos\beta\cos\alpha+4\sin\beta\sin\alpha$

Kanemura, Kikuchi, KY (2013)

(T, Y)
ϕ: (1/2, 1/2)
χ: (1, 1)
ξ: (1, 0)
ϕ_7: (3, 2)





c_{hVV} > 1 can be evidence for exotic Higgs sectors.

Higgs sector with exotic fields

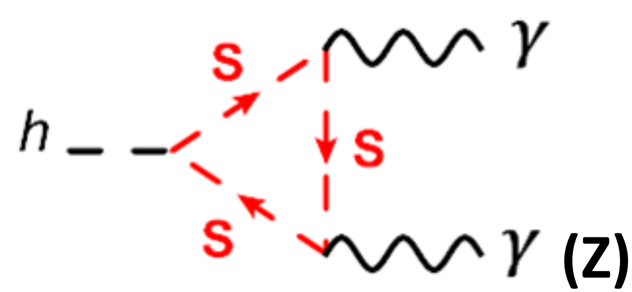
★There are striking features in Higgs sectors w/ exotic fields.

- **Electroweak rho parameter**
- **The $H^{\pm}W^{\mp}Z$ vertex**
- **The hZZ/hWW vertex**
- **Multi-charged Higgs bosons**

- From the relation $Q = T_3 + Y$, the EM charge of component scalar fields can be expressed as: $\Phi = [\phi^{Q=T+Y}, \ldots, \phi^{++}, \phi^{+}, \phi^{0}, \phi^{-}, \phi^{--}, \ldots, \phi^{Q=-T+Y}]^T$.

- Discovery of multi-charged Higgs bosons is direct evidence for the exotic Higgs sectors.

- Multi-charged Higgs bosons can affect the **h→γγ** decay via the loop effect.
In addition to h→γγ, measuring the **h→ Zγ** mode is also important to know the isospin of the multi-charged Higgs bosons.



Carena, Wagner, Low (2012), Chiang, KY (2012)

The Higgs Triplet Model (HTM)

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

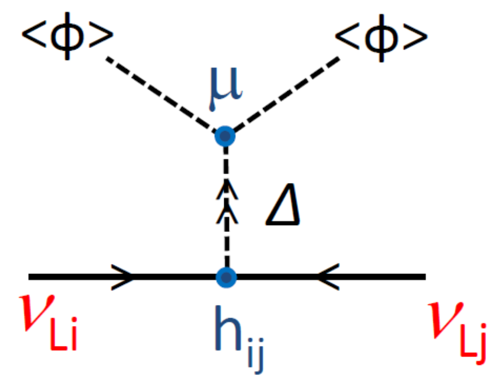
The Higgs triplet field Δ is added to the SM.

	SU(2)I	U(1)Y	U(1)L
Φ	2	1/2	0
Δ	3	1	-2

- **Important new interaction terms:**

Lepton number breaking parameter

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



- **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 : Triplet Higgs VEV

- **Electroweak rho parameter**

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

The HTM can be tested at colliders !!

Higgs potential

- **The Higgs potential**

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

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

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

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

- **7 physical scalar states.**

$$\Delta^{\pm\pm} = H^{\pm\pm}$$ Doubly-charged Higgs

$$R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

NG bosons

$$\begin{pmatrix} \varphi^0 \\ \delta^0 \end{pmatrix} = R(\alpha)\begin{pmatrix} h^0 \\ H^0 \end{pmatrix},\quad \begin{pmatrix} \varphi^\pm \\ \Delta^\pm \end{pmatrix} = R(\beta)\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix},\quad \begin{pmatrix} \chi^0 \\ \eta^0 \end{pmatrix} = R(\beta')\begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

CP-even Higgs — Singly-charged Higgs — CP-odd Higgs

$$\tan 2\alpha \simeq \frac{v_\Delta}{v_\Phi}\frac{2v_\Phi^2(\lambda_4+\lambda_5) - 4M_\Delta^2}{2v_\Phi^2\lambda_1 - M_\Delta^2}$$

$$\tan\beta = \frac{\sqrt{2}v_\Delta}{v_\Phi} \qquad \tan\beta' = \frac{2v_\Delta}{v_\Phi}$$

- **Mass formulae ($v_\Delta/v_\phi \ll 1$)**

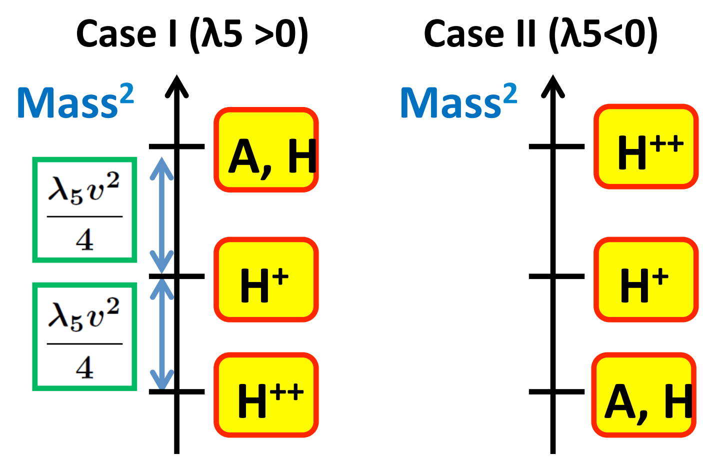
Triplet-like

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

SM-like

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

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

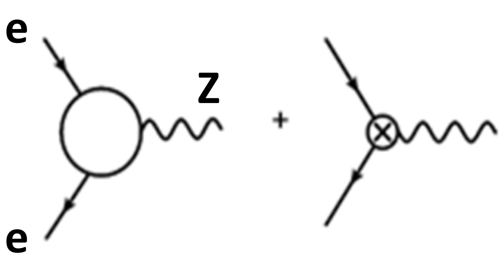
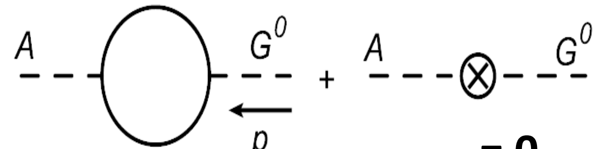


Constraint from EW precision data

- Renormalization in models with $\rho_{tree} \neq 1$ is different from that in models with $\rho_{tree} = 1$.
- We need ***four*** (not **three** such as α_{em}, G_F and mz) input parameters to describe the EW parameters.

Blanck, Hollik (1997); Kanemura, KY (2012)

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

	Scheme I	**Scheme II**
Inputs:	α_{em}, G_F, mz and $\sin\theta_{eff}$	α_{em}, G_F, mz and β'
Reno. condition:	 **= 0** **at $p^2 = m_Z^2$**	 **= 0** **at $p^2 = m_A^2$**
Reno. Scale:	Electroweak	Decoupling parameter

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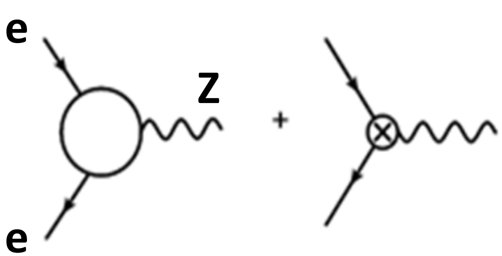
Scheme I

Inputs: α_{em}, G_F, mz and **$\sin\theta_{eff}$**

Reno. condition:



= 0

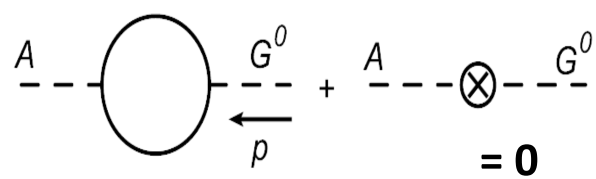
at $p^2 = m_Z^2$

Reno. Scale: Electroweak

Scheme II

Inputs: α_{em}, G_F, mz and **β’**

Reno. condition:



= 0

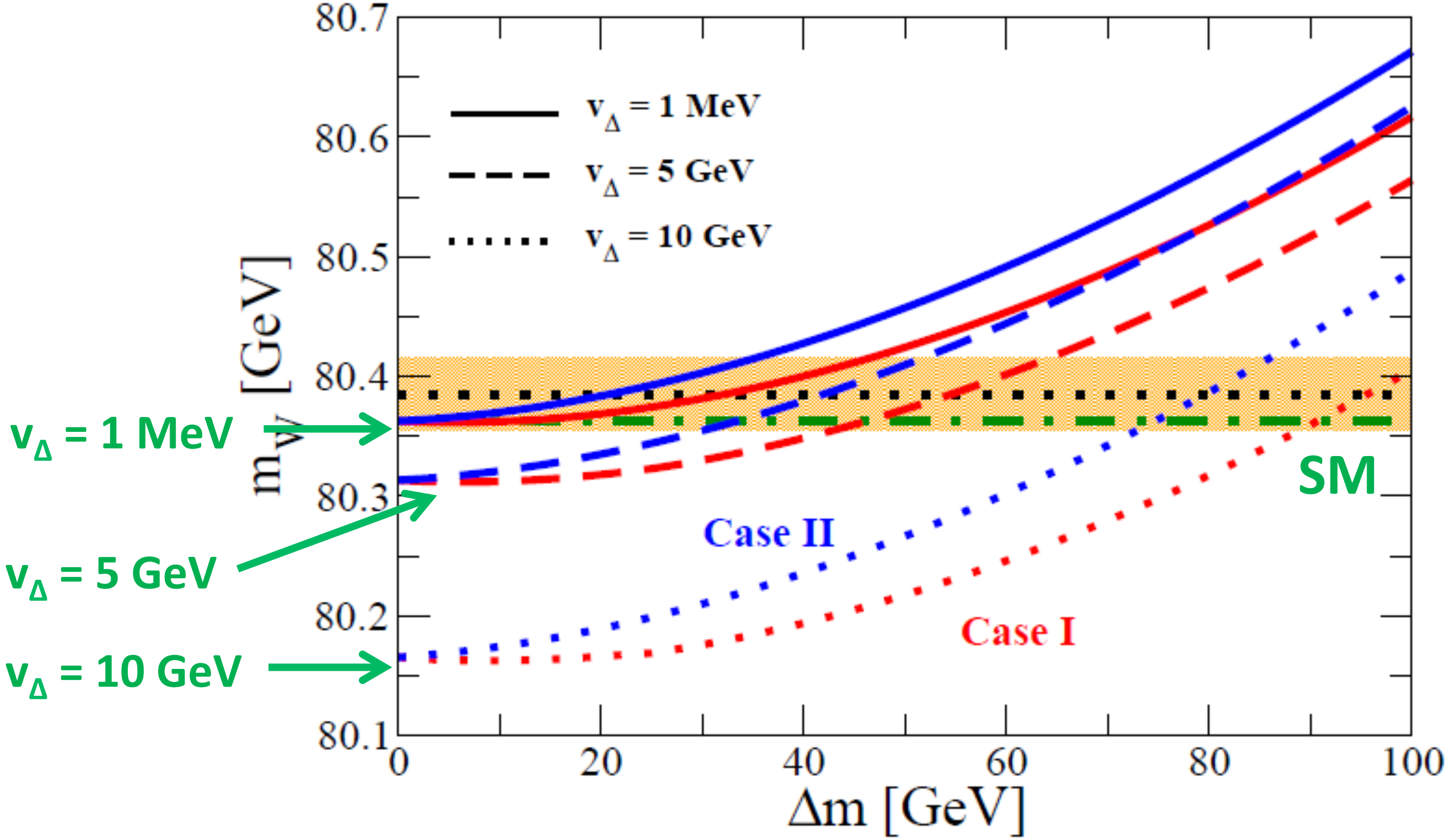
at $p^2 = m_A^2$

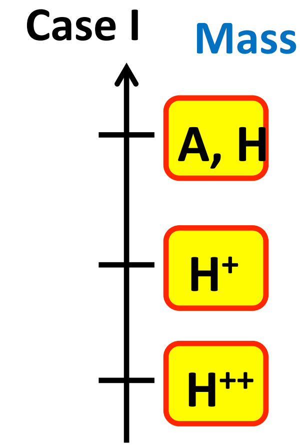
Reno. Scale: Decoupling parameter

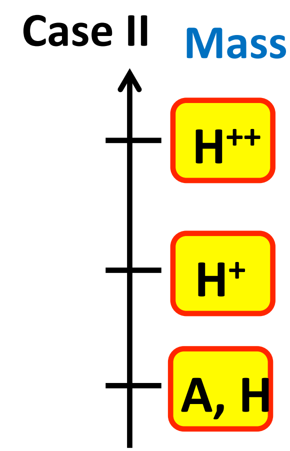
1-loop corrected W mass

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

Kanemura, Kikuchi, KY, PRD87 (2012)



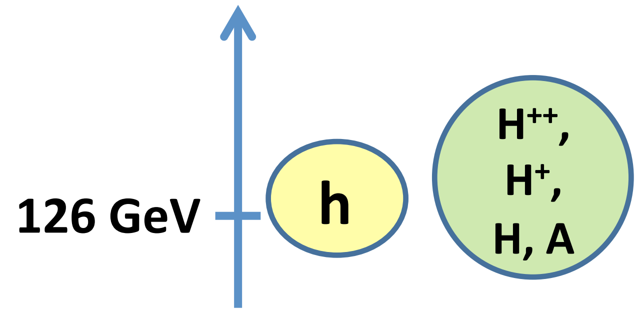




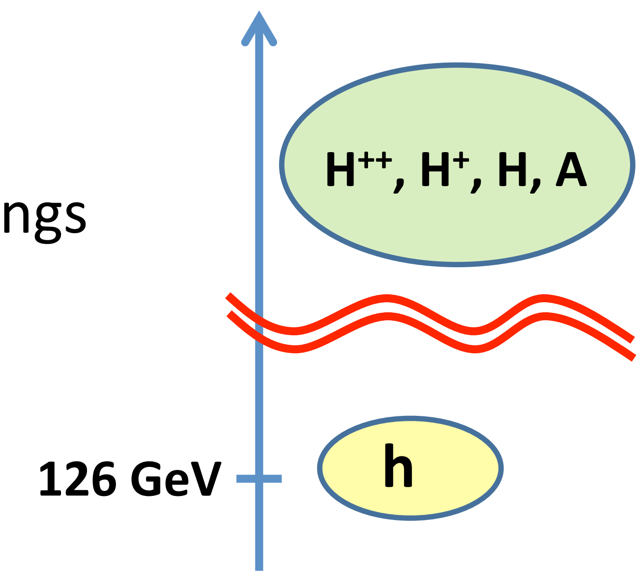
For large triplet VEV case, large mass difference is favored.

Testing the Higgs Triplet Model at colliders

- Direct way
  - Discovery of extra Higgs bosons, e.g., $H^{\pm\pm}$, $H^{\pm}$, …
  - Testing the mass spectrum among the triplet like Higgs bosons.



- Indirect way
  - Precise measurement for the Higgs couplings
    Ex. $h\gamma\gamma$, hWW, hZZ, hhh



Testing the Higgs Triplet Model at colliders

- ***Direct way***

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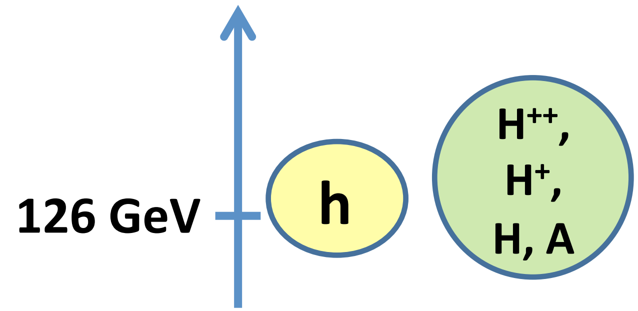

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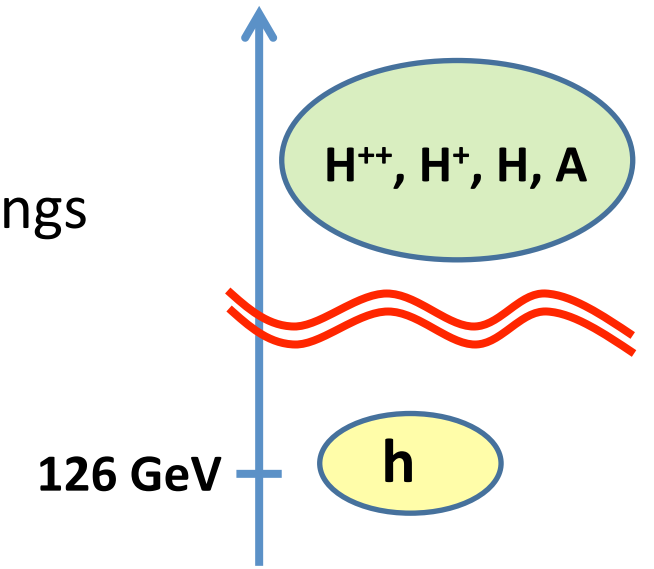
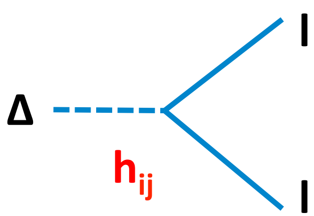


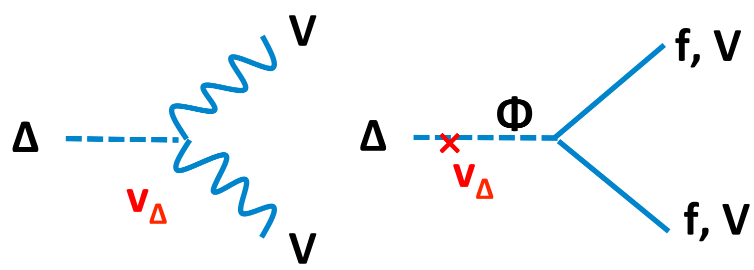
Decay of the triplet-like Higgs bosons

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

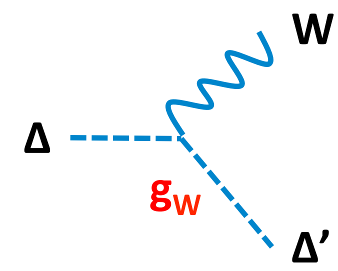
1. Decay via h_{ij}



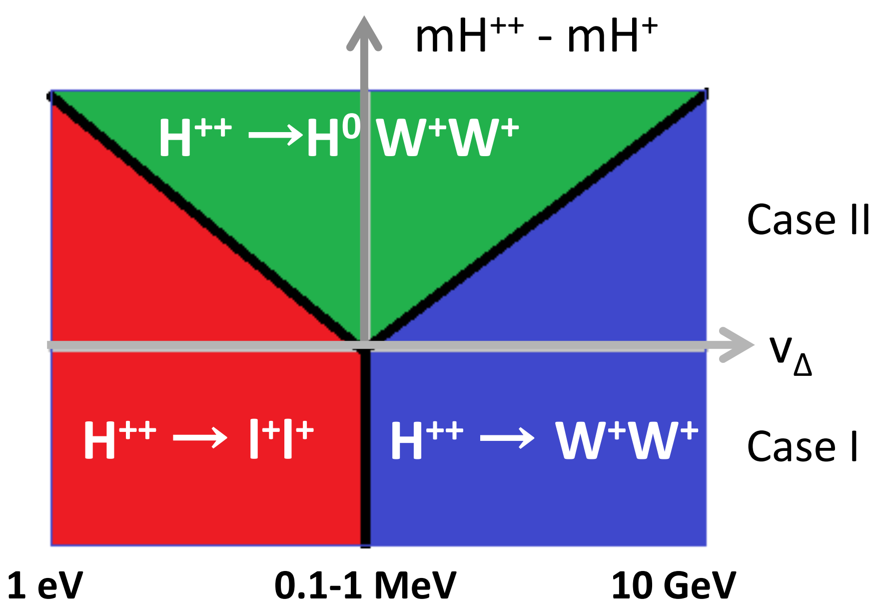
2. Decay via v_Δ



3. Decay via g



Decay of H^{++}

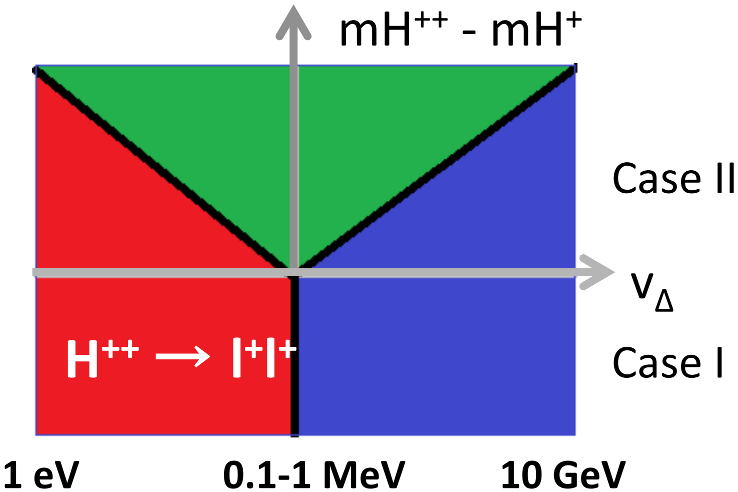


Decay modes of 1 and 2 are related to each other by the relation:

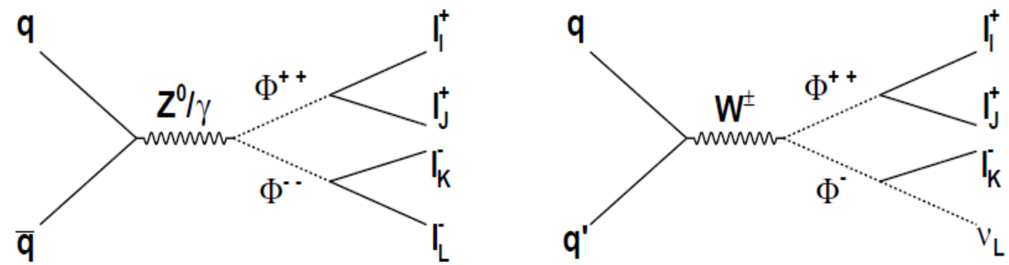
$$(m_\nu)_{ij} = h_{ij} v_\Delta$$

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

Dilepton decay scenario

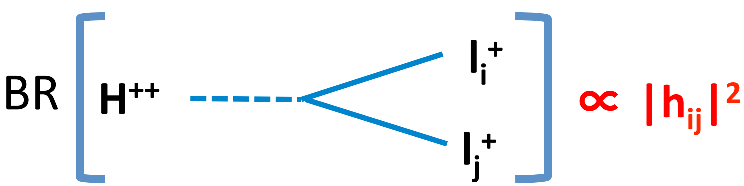


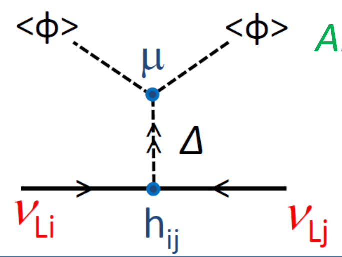
- Signal: Same-sign dilepton



mH++ >~ 400 GeV by the LHC data

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



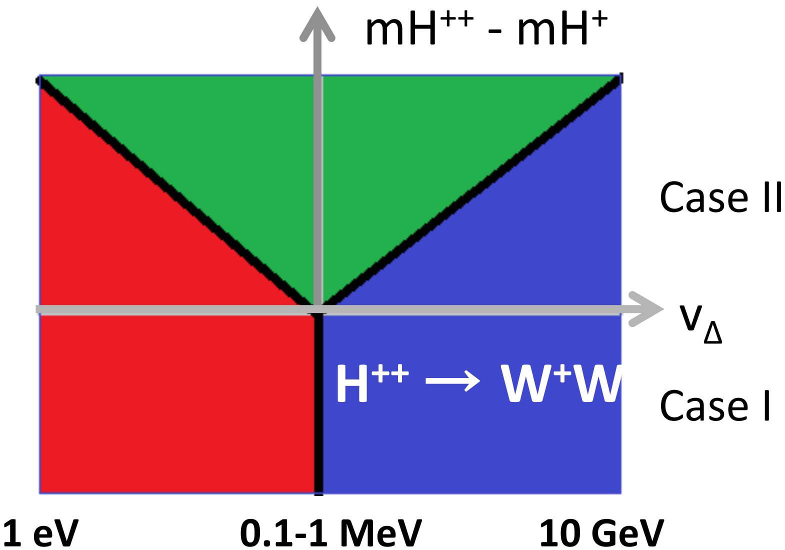


Akeroyd, Aoki, Sugiyama, 2008

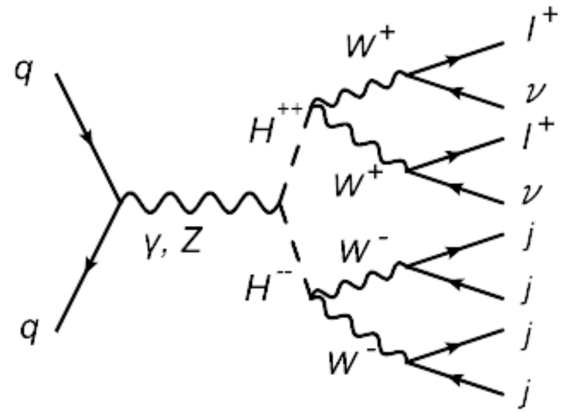
$h_{ij} v_\Delta$

- LHC phenomenology
  - -4 lepton , 3 lepton signature *Perez, Han, Huang, Li, 2008 ; Akeroyd, Chiang, Gaur, 2010, …*
  - -Using tau polarization *Sugiyama, Tsumura, Yokoya (2012)*
    - Discrimination of chiral structure of the Yukawa coupling
  - -Same sign tetra-lepton signature *Chun, Sharma (2012)*

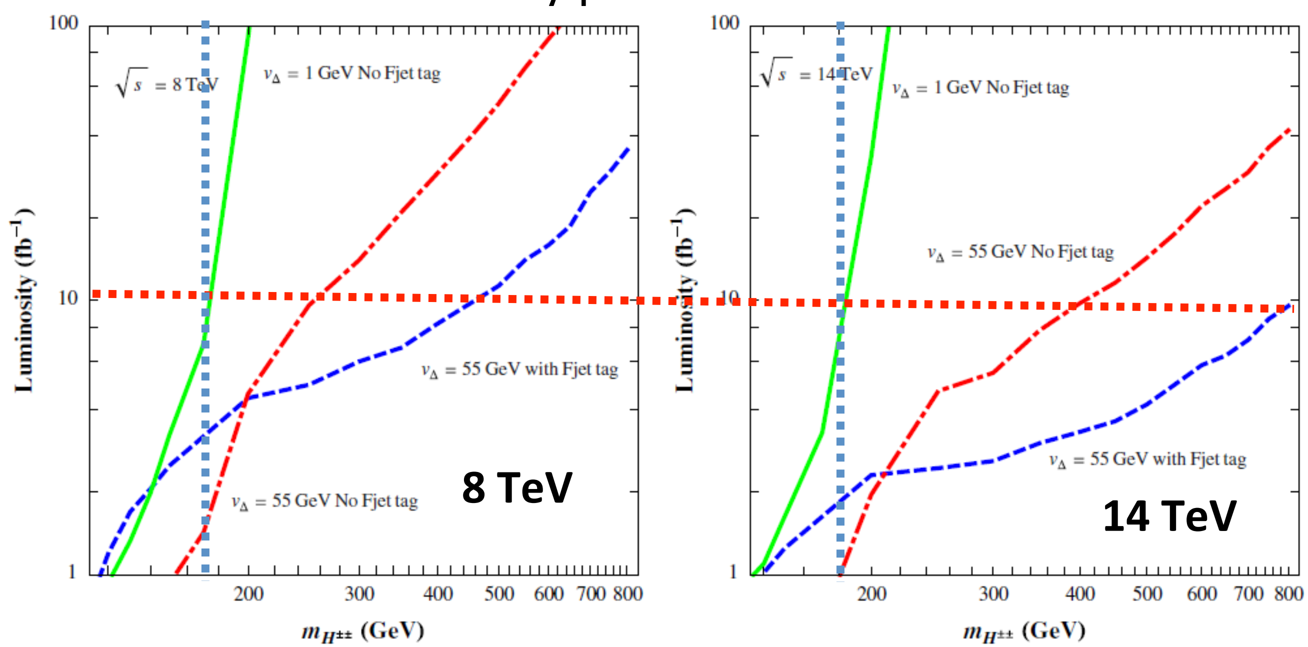
Diboson decay scenario



- Signal: Same-sign dilepton + Jets + Missing

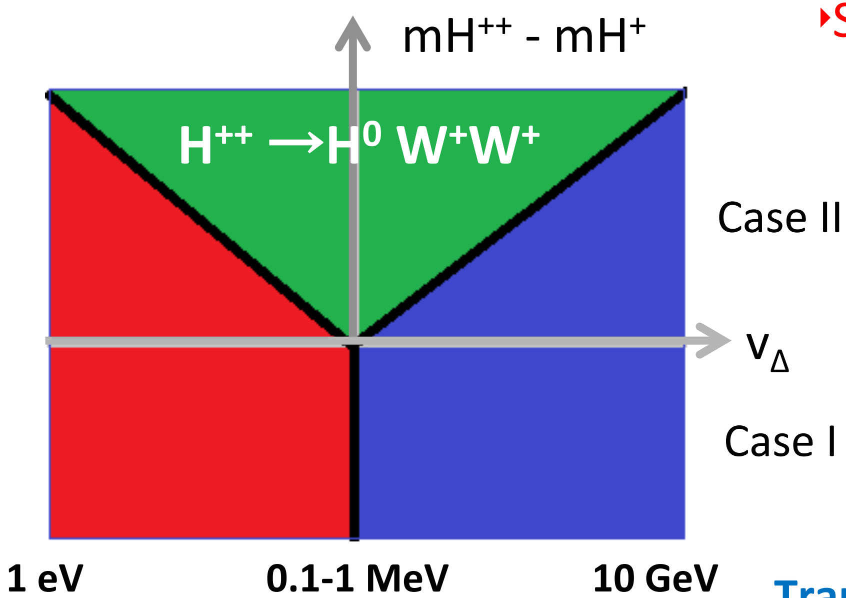


5σ discovery potential of H++

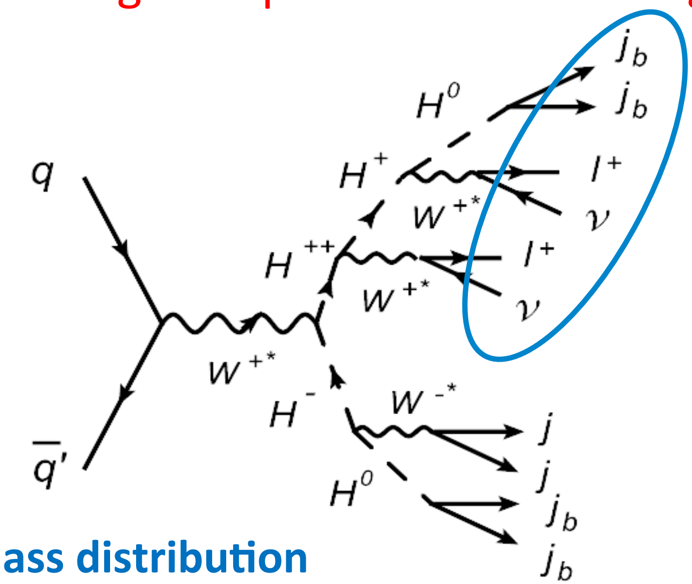


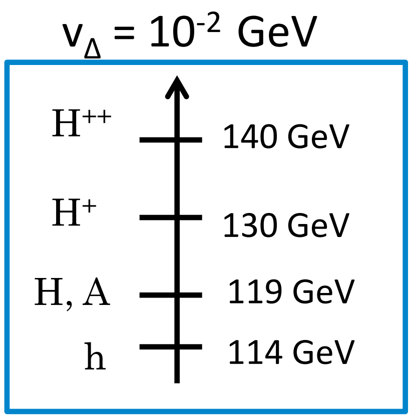
Chiang, Nomura, Tsumura, PRD85 (2012)

Cascade decay scenario

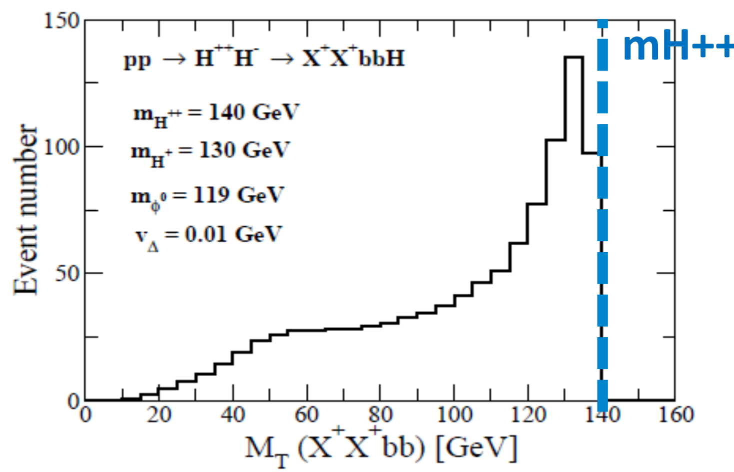


‣Signal: Same-sign dilepton + Jets + Missing





Transverse mass distribution



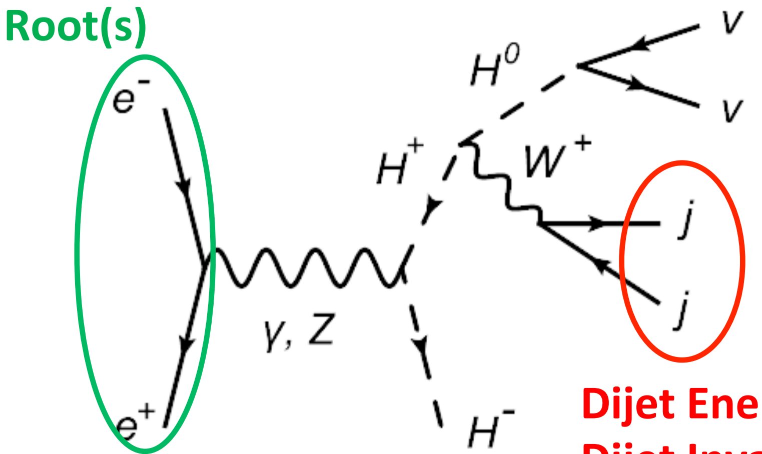
Aoki, Kanemura, KY, PRD85 (2012)

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

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

We may test the characteristic mass spectrum of Δ-like Higgs bosons

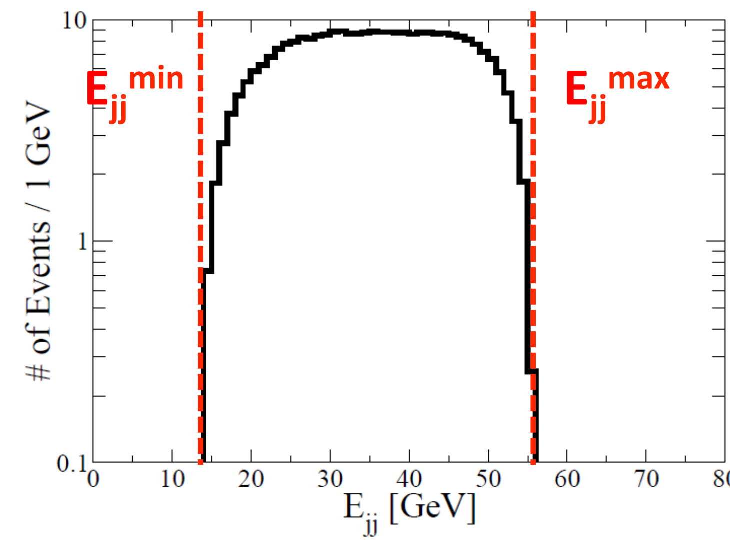
Mass reconstruction at ILC



σ ~ 20 fb

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

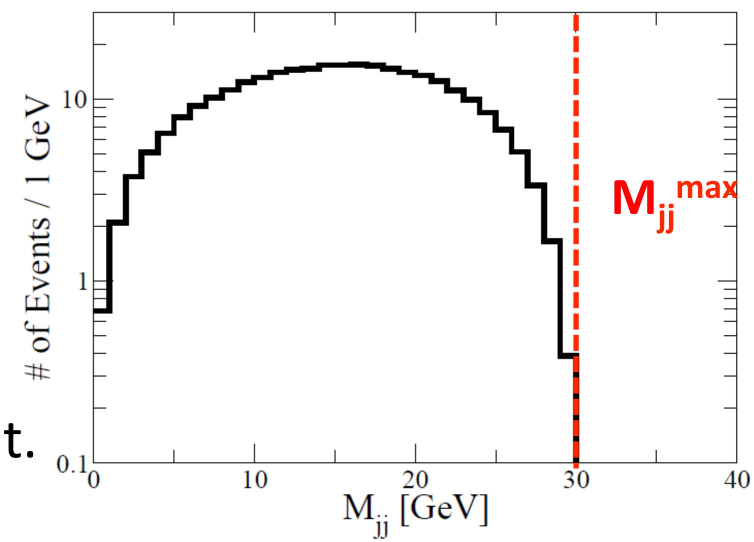
Dijet Energy E_{jj}
Dijet Invariant mass M_{jj}



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

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

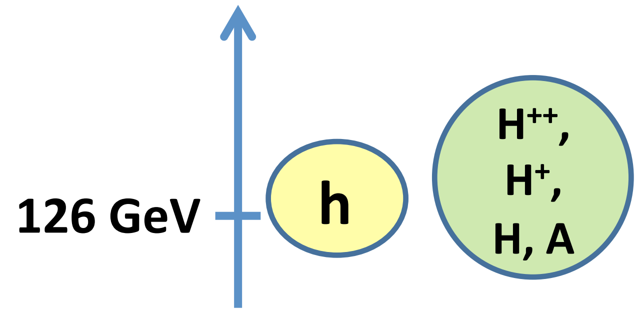
$$M_{jj}^{\max} \simeq m_{H+}-m_H$$



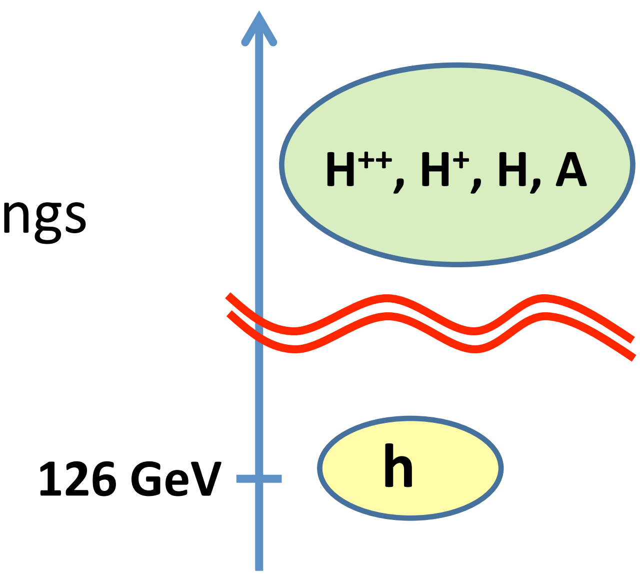
H^{++} can be measured by looking at the excess of the SS dilepton + jets + missing event.

Testing the Higgs Triplet Model at colliders

- Direct way
  - Discovery of extra Higgs bosons,
    e.g., $H^{\pm\pm}$, $H^{\pm}$, …
  - Testing the mass spectrum among the triplet like Higgs bosons.

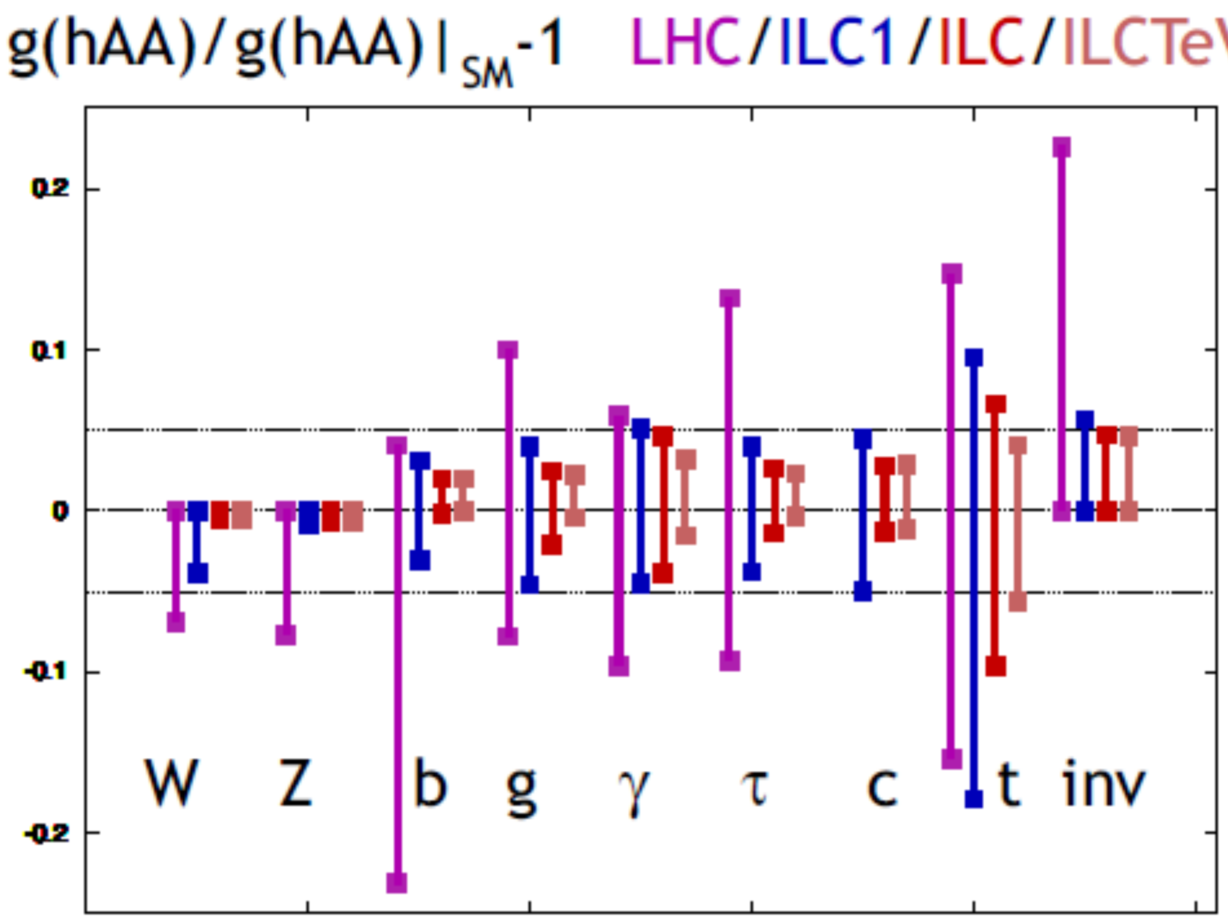


- ***<u>Indirect way</u>***
  -Precise measurement for the Higgs couplings
  Ex. hγγ, hWW, hZZ, hhh



Higgs coupling measurements

Peskin, arXiv: 1207.2516



LHC: 14 TeV, 300 fb^{-1},

ILC1: 250 GeV, 250 fb^{-1},

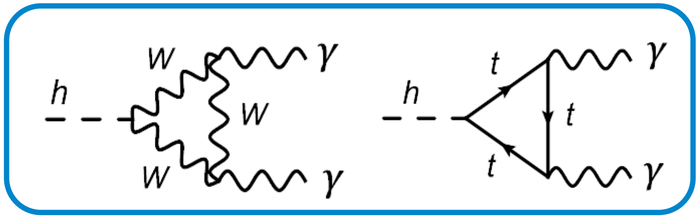
ILC: 500 GeV, 500 fb^{-1},

ILCTeV: 1 TeV, 1000 fb^{-1}

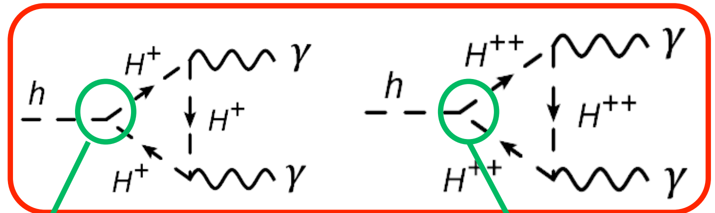
Higgs boson couplings can be measured accurately at future colliders.

Higgs → diphoton

Arhrib, et al. JHEP1204; Kanemura, KY, PRD85; Akeroyd, Moretti PRD86; Chun, Lee, Sharma JHEP1211



+



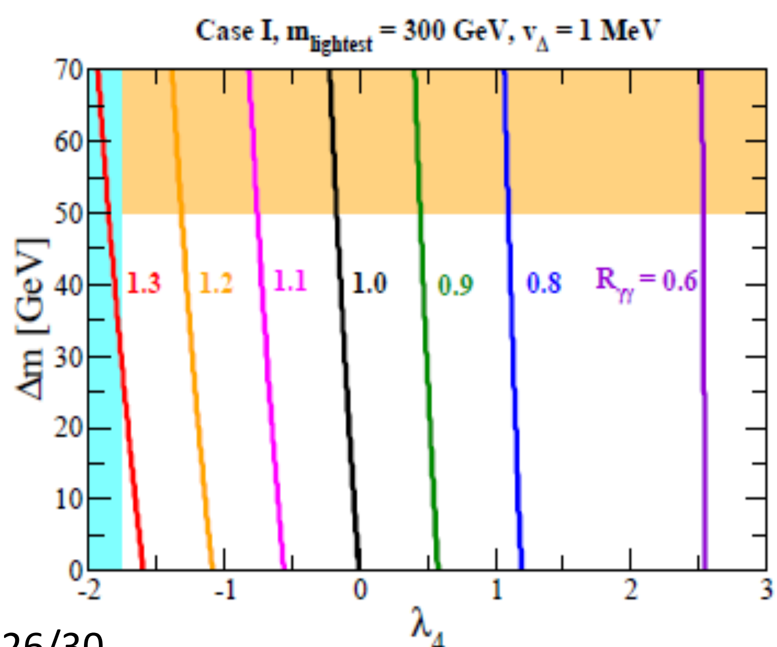
SM contribution + **Triplet-like Higgs loop contribution**

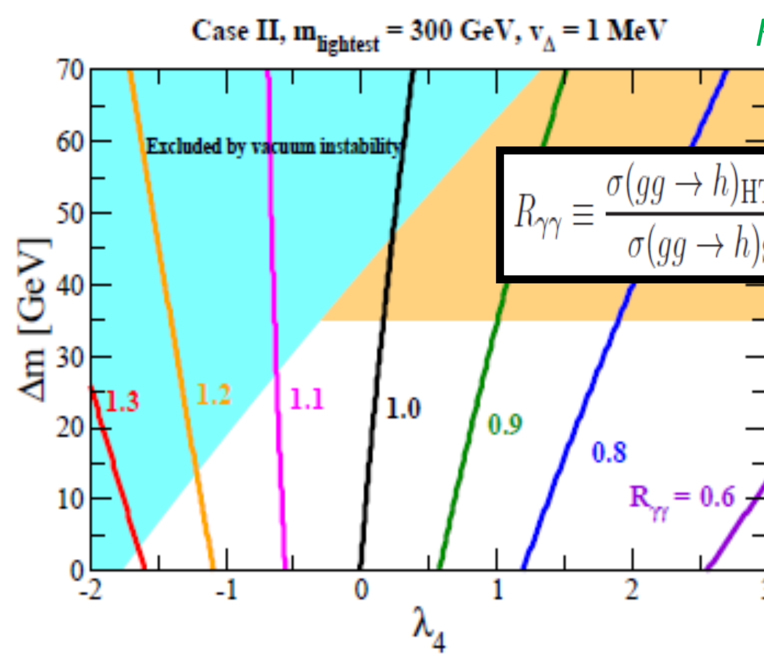
$$\lambda_{hH^+H^-} \approx -(\lambda_4+\lambda_5/2)v \qquad \lambda_{hH^{++}H^{--}} \simeq -\lambda_4 v$$

★Sign of λ_4 is quite important! If $\lambda_4 < 0$ → Constructive (Destructive) contribution.

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

Kanemura, Kikuchi, KY (2012)





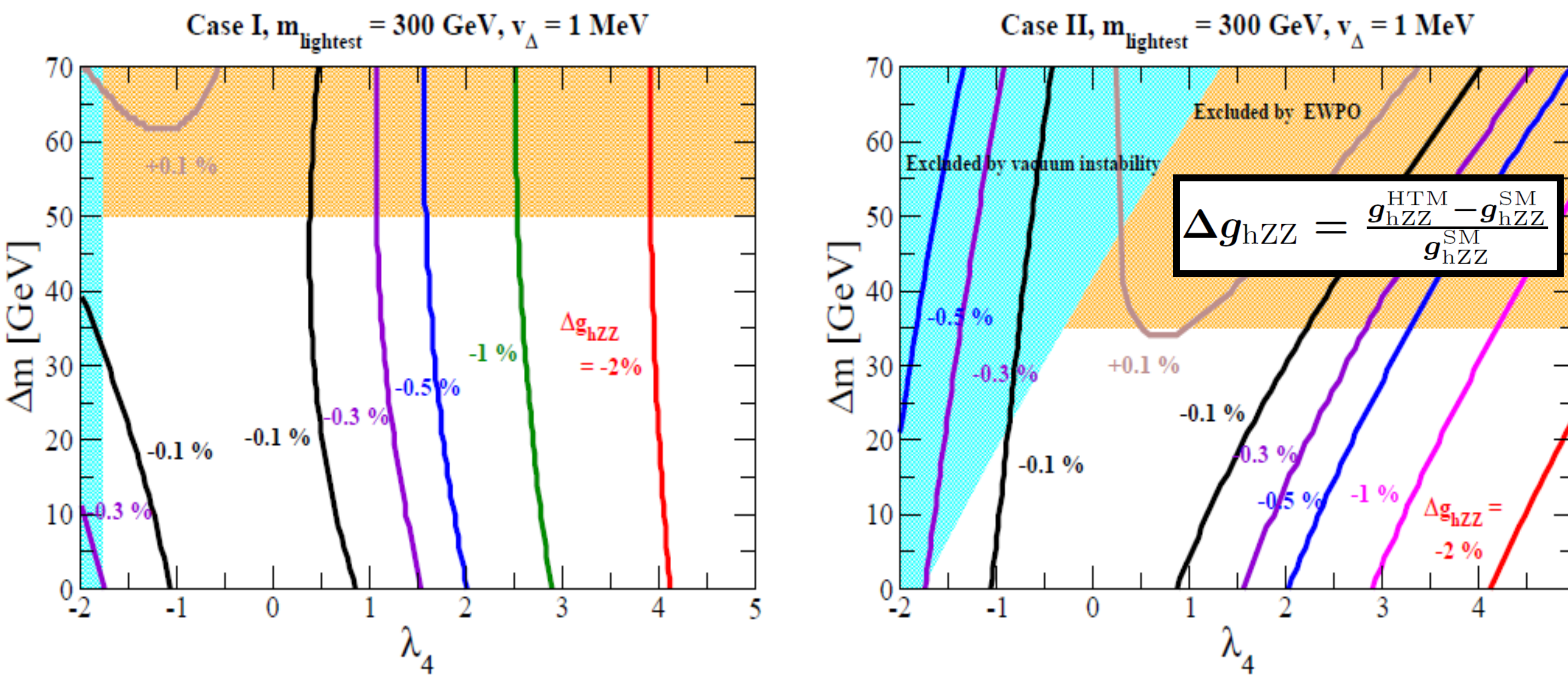
$$R_{\gamma\gamma} \equiv \frac{\sigma(gg\to h)_{\rm HTM}\times {\rm BR}(h\to\gamma\gamma)_{\rm HTM}}{\sigma(gg\to h)_{\rm SM}\times {\rm BR}(h\to\gamma\gamma)_{\rm SM}}$$

Renormalized hZZ

Kanemura, Kikuchi, KY, PRD87 (2012)

$$g_{\rm hVV} \simeq \frac{2m_V^2}{v}\left[1-\frac{1}{32\pi^2}\left(\frac{\lambda^2_{H^{++}H^{--}h}}{6m^2_{H^{++}}}+\frac{\lambda^2_{H^{+}H^{-}h}}{6m^2_{H^{+}}}+\frac{\lambda^2_{AAh}}{3m^2_{A}}+\frac{\lambda^2_{HHh}}{3m^2_{H}}\right)+\frac{1}{4\pi^2}\frac{c_W^2-s_W^2}{s_W^2}\left(\frac{F_5(m_{H^{++}},m_{H^+})}{v^2}+\frac{F_5(m_{H^+},m_A)}{v^2}\right)\right]$$

$$\simeq \frac{2m_V^2}{v}\left[1-\frac{1}{32\pi^2}\left(\frac{\lambda_4^2}{6m^2_{H^{++}}}+\frac{(\lambda_4+\frac{\lambda_5}{2})^2}{6m^2_{H^{+}}}+\frac{(\lambda_4+\lambda_5)^2}{12m^2_{A}}+\frac{(\lambda_4+\lambda_5)^2}{12m^2_{H}}\right)+\frac{1}{4\pi^2}\frac{2(c_W^2-s_W^2)}{3s_W^2}\left(\frac{(m_{H^{++}}-m_{H^+})^2}{v^2}+\frac{(m_{H^+}-m_A)^2}{v^2}\right)\right]$$



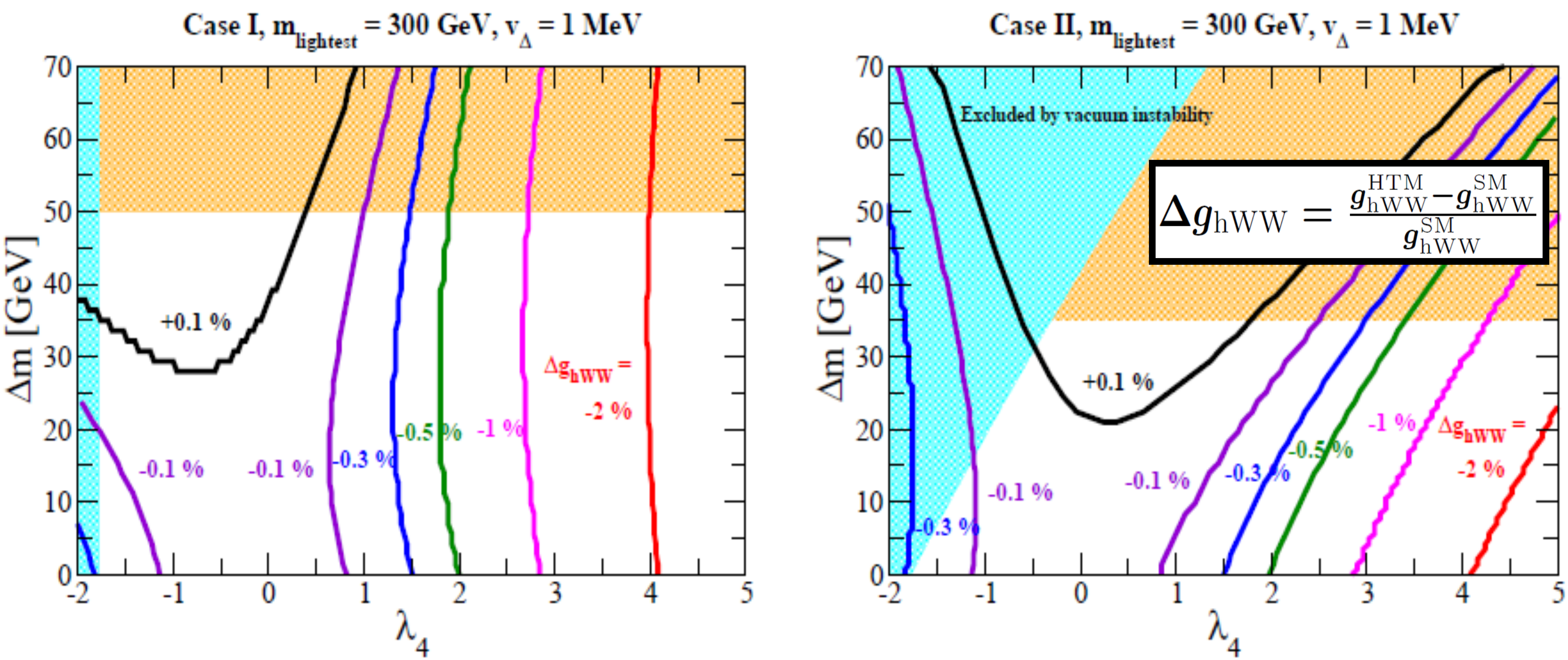
Δg_{hZZ} is predicted -0.3 % ~ -2 % when Rγγ is +30% ~ -40%

Renormalized hWW

Kanemura, Kikuchi, KY, PRD87 (2012)

$$g_{hVV} \simeq \frac{2m_V^2}{v}\left[1-\frac{1}{32\pi^2}\left(\frac{\lambda^2_{H^{++}H^{--}h}}{6m^2_{H^{++}}}+\frac{\lambda^2_{H^+H^-h}}{6m^2_{H^+}}+\frac{\lambda^2_{AAh}}{3m_A^2}+\frac{\lambda^2_{HHh}}{3m_H^2}\right) + \frac{1}{4\pi^2}\frac{c_W^2-s_W^2}{s_W^2}\left(\frac{F_5(m_{H^{++}},m_{H^+})}{v^2}+\frac{F_5(m_{H^+},m_A)}{v^2}\right)\right]$$

$$\simeq \frac{2m_V^2}{v}\left[1-\frac{1}{32\pi^2}\left(\frac{\lambda_4^2}{6m^2_{H^{++}}}+\frac{(\lambda_4+\frac{\lambda_5}{2})^2}{6m^2_{H^+}}+\frac{(\lambda_4+\lambda_5)^2}{12m_A^2}+\frac{(\lambda_4+\lambda_5)^2}{12m_H^2}\right) + \frac{1}{4\pi^2}\frac{2(c_W^2-s_W^2)}{3s_W^2}\left(\frac{(m_{H^{++}}-m_{H^+})^2}{v^2}+\frac{(m_{H^+}-m_A)^2}{v^2}\right)\right]$$

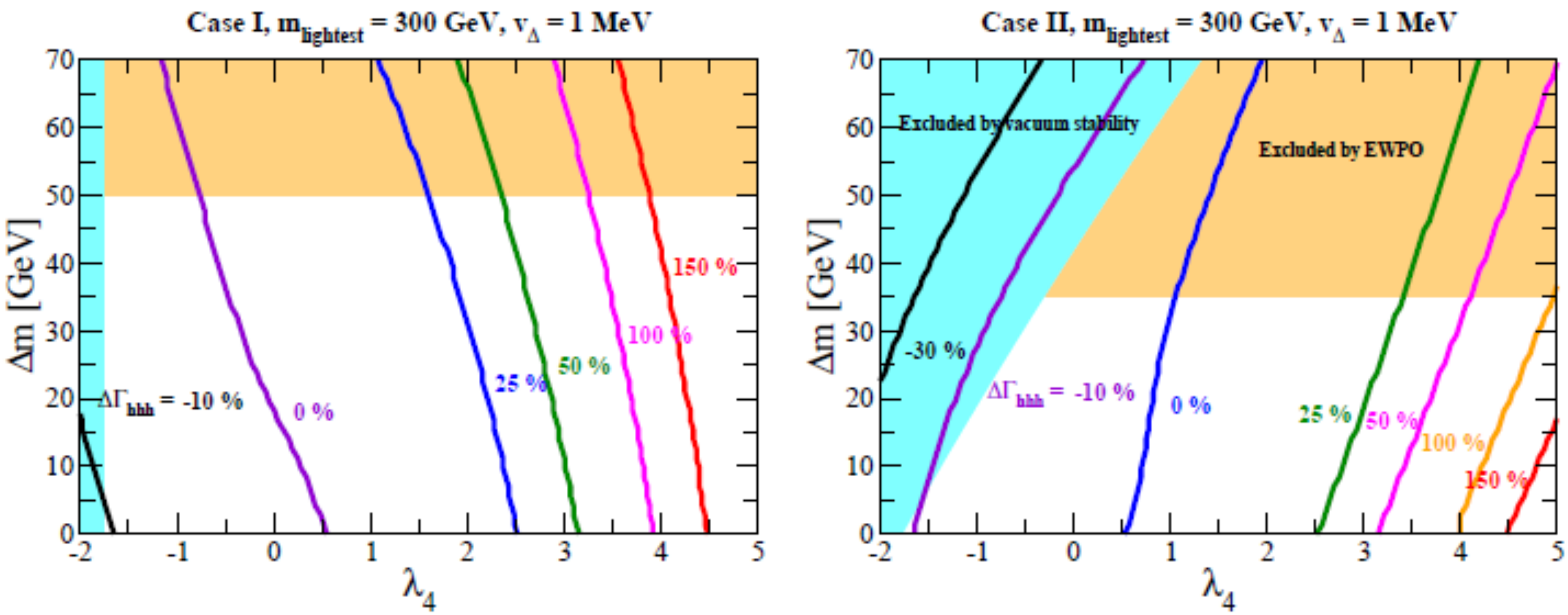


Δg_{hWW} is predicted -0.3 % ~ -2 % when Rγγ is +30% ~ -40%

Renormalized hhh coupling

Kanemura, Kikuchi, KY, PRD87 (2012)

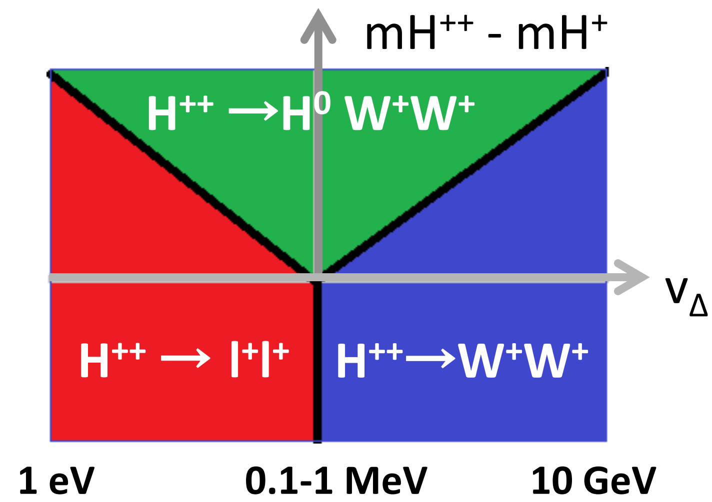
$$\Gamma_{hhh} \simeq -\frac{3m_h^2}{v}\left[1-\frac{v}{48\pi^2 m_h^2}\left(\frac{\lambda^3_{H^{++}H^{--}h}}{m^2_{H^{++}}}+\frac{\lambda^3_{H^+H^-h}}{m^2_{H^+}}+\frac{4\lambda^3_{AAh}}{m_A^2}+\frac{4\lambda^3_{HHh}}{m_H^2}\right)+\cdots\right]$$
$$\simeq -\frac{3m_h^2}{v}\left\{1+\frac{v^4}{48\pi^2 m_h^2}\left[\frac{\lambda_4^3}{m^2_{H^{++}}}+\frac{(\lambda_4+\frac{\lambda_5}{2})^3}{m^2_{H^+}}+\frac{(\lambda_4+\lambda_5)^3}{2m_A^2}+\frac{(\lambda_4+\lambda_5)^3}{2m_H^2}\right]+\cdots\right\},$$



hhh coupling can deviate about -10% ~ +150 %, when Rγγ is +30% ~ -40%.

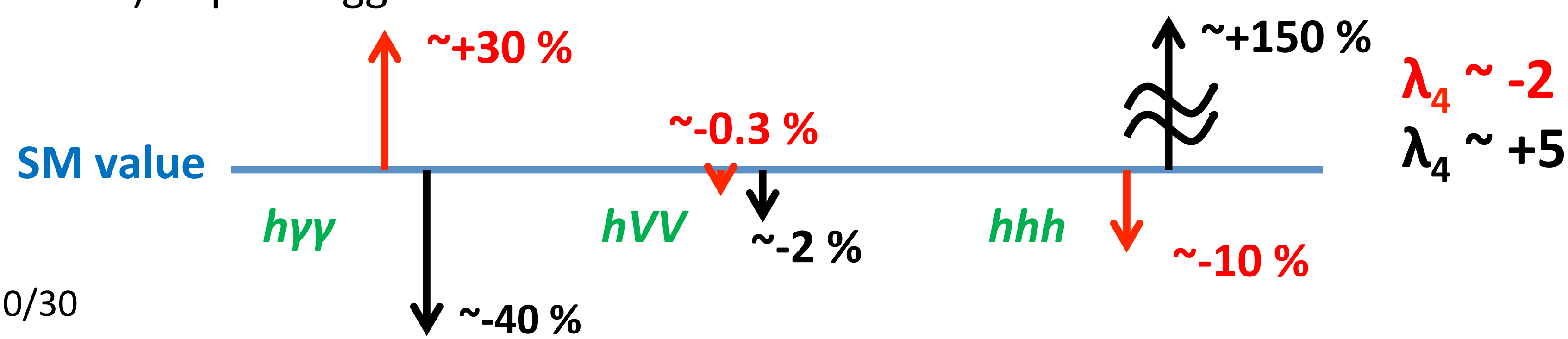
Summary

- **Probing exotic Higgs sectors** :
  There are several characteristic natures in exotic Higgs sectors,
  e.g., rho parameter, $H^{\pm}W^{\mp}Z$ vertex, hVV vertex
  and multi-charged scalar bosons.



- **Direct way of testing the HTM** :
  -Decay of H++ can be classified into 4 regions
  in the vΔ – Δm plane.
  If small vΔ and large mH++ - mH+ is realized,
  we need ILC to identify H++.

- **Indirect way of testing the HTM** :
  -Precise measurements of the Higgs couplings
  -Precise calculations of the deviation in the Higgs couplings from the SM prediction.
  Ex) Triplet Higgs masses = 300 GeV case



Back up slides

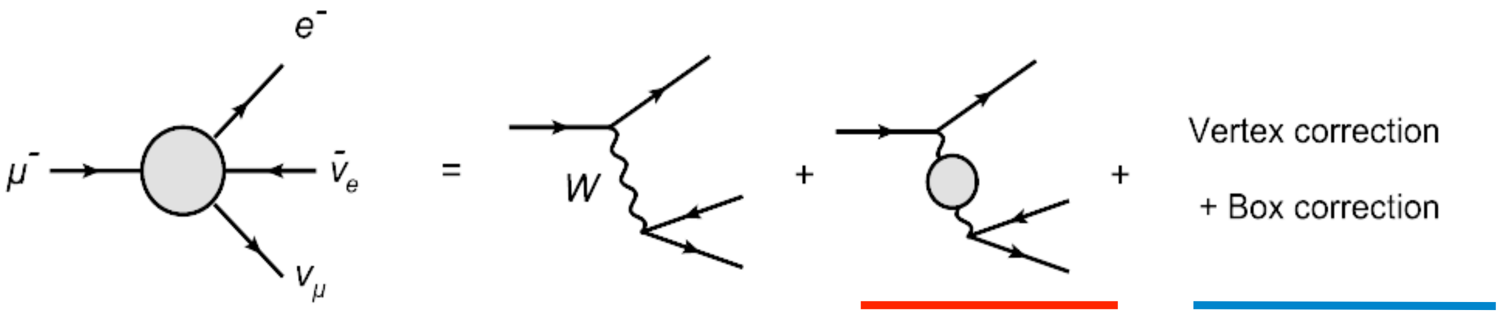
Radiative corrections to the EW parameters

Hollik, Fortsch, Phys. (1990)

★One-loop corrections to the W boson mass can be calculated via Δr:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2(1-\Delta r)} = \frac{\pi\alpha_{\rm em}}{2m_W^2 s_W^2(1-\Delta r)}$$

Muon decay



$$\Delta r = \frac{\hat{\Pi}_{WW}(0)}{m_W^2} + \delta_{VB}$$

$$= \Delta\alpha_{\rm em} - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\rm rem}$$

[ρ_{tree} = 1]

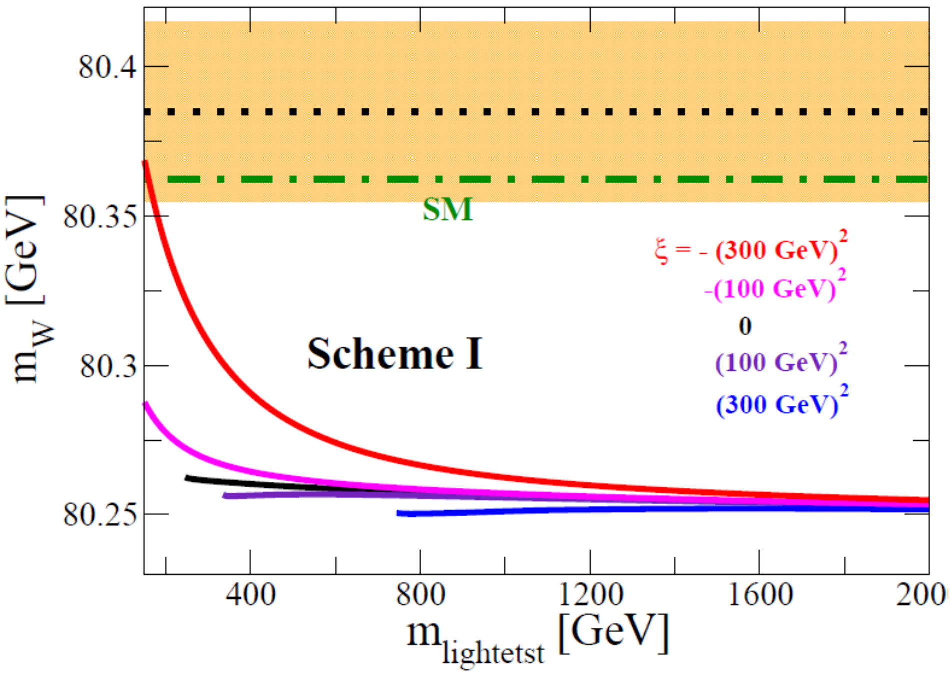
$\Delta\alpha_{em}$: shift of αem from 0 to mZ.
Δρ : corrections to the rho parameter
Δr_{rem}: The other terms

Decoupling

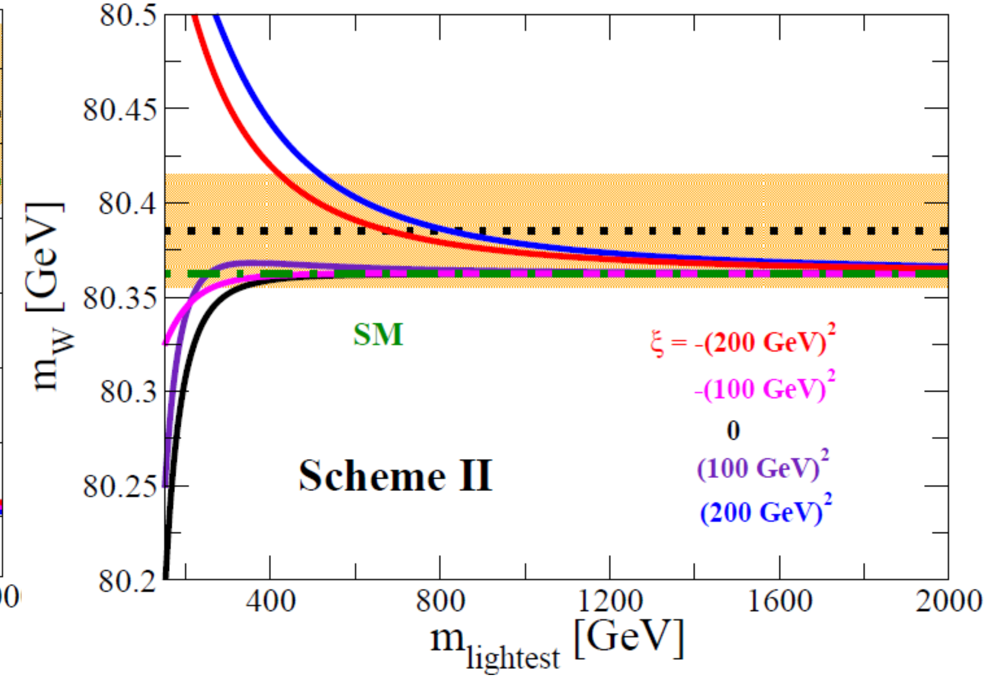
$\xi = m_{H++}^2 - m_{H+}^2 \; (= m_{H+}^2 - m_A^2)$

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

Sw^2 = 0.23146



μ = 5 GeV



In Scheme II, we can take the decoupling limit.

Theoretical bounds

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

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

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

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

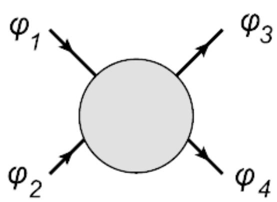
$$\lambda_1 > 0, \ \lambda_\Delta > 0,$$

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

Lee, Quigg, Thacker, PRD16, (1977)

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

‣Unitarity bound



j_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

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

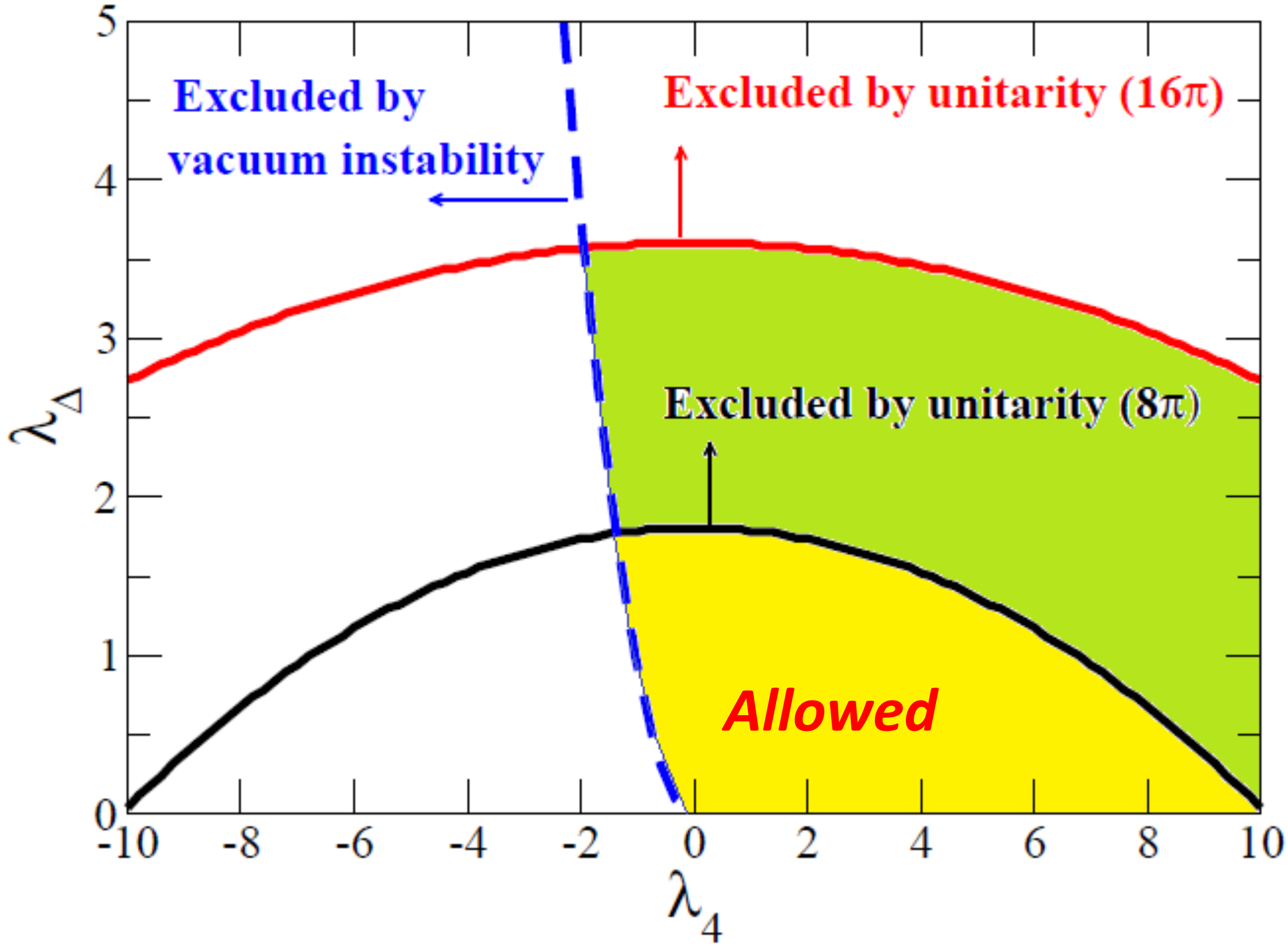
$$x_2 = \frac{1}{2}(2\lambda_4 + 3\lambda_5),$$

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

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

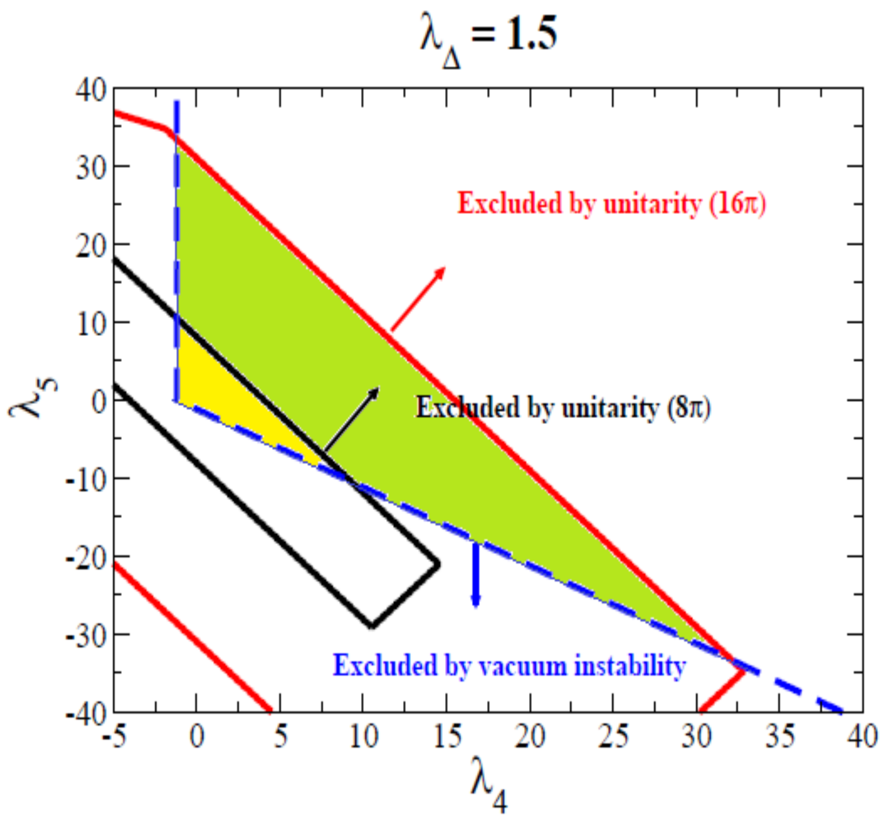
Theoretical bounds

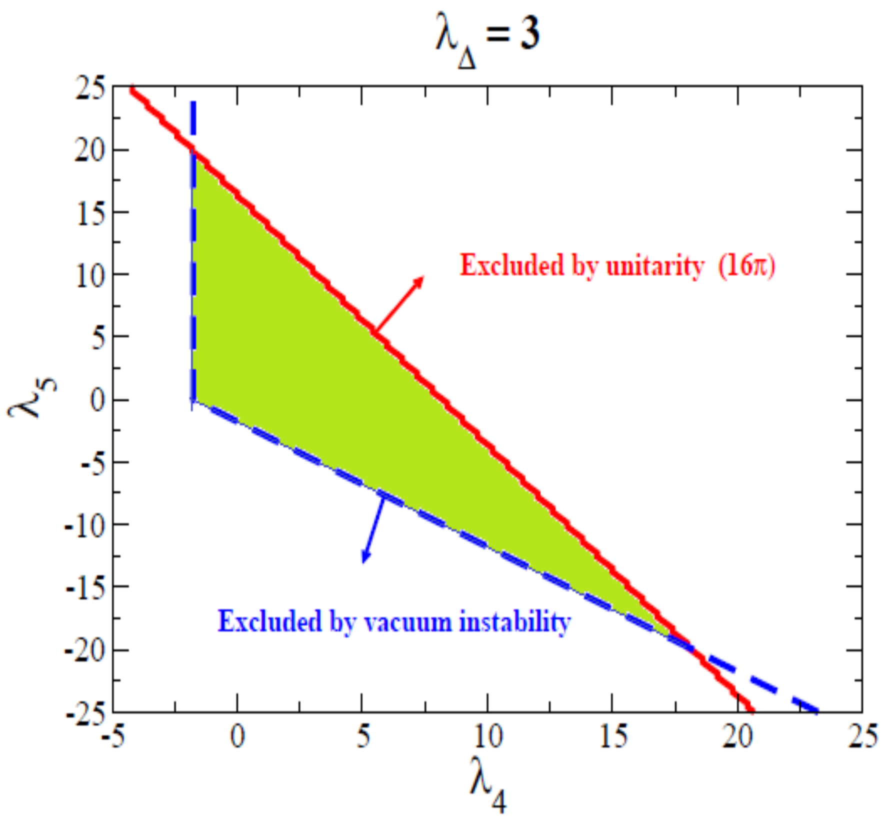
Case for $\lambda_5 = 0$ ($\Delta m = 0$)



Negative values of λ4 are constrained by the vacuum stability.

Theoretical bounds





When λ4 < 0, negative values of λ5（Case of mH++ > mH+ > mA) is highly constrained by the vacuum stability bound.

Custodial Symmetry

- The kinetic term can be written by the 2×2 matrix form of the Higgs doublet:

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

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

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

- When g' is zero,
  L_{kin} is invariant under the $SU(2)_L \times SU(2)_R$ transformation: $\boldsymbol{\Sigma \to U_L \Sigma U_R^\dagger}$

- After the EWSB: $\Sigma \to \langle\Sigma\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

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

- Rho parameter: **$\rho = m_W^2 / m_Z^2 \cos^2\theta_W = 1$**

$\rho_{exp} = 1.0008^{+0.0017}_{-0.0007}$

Custodial symmetry in the kinetic term
maintains the electroweak rho parameter to be unity at the tree level.

Custodial Symmetry

- The kinetic term can be written by the 2×2 matrix form of the Higgs doublet:

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

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

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

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

- Rho parameter: $\rho = m_W^2 / m_Z^2 \cos^2\theta_W = 1$

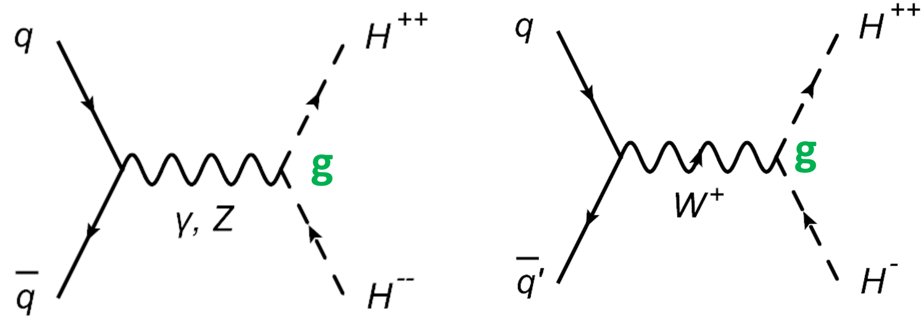
  $\rho_{exp} = 1.0008^{+0.0017}_{-0.0007}$

The data suggests that the Higgs sector should be custodial symmetric!

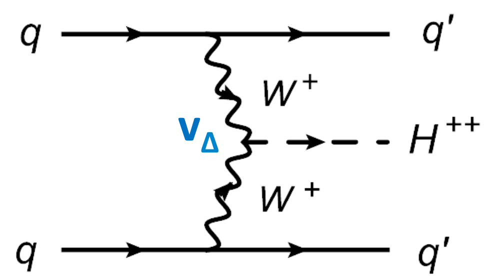
Production processes for H^{++}

Main production process

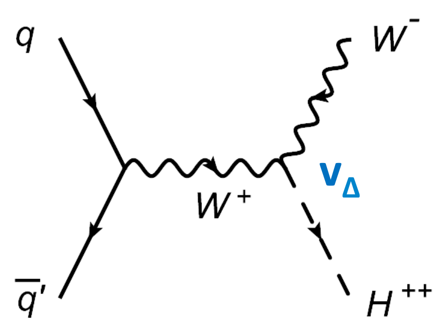
Drell-Yan
- depends on the gauge coupling

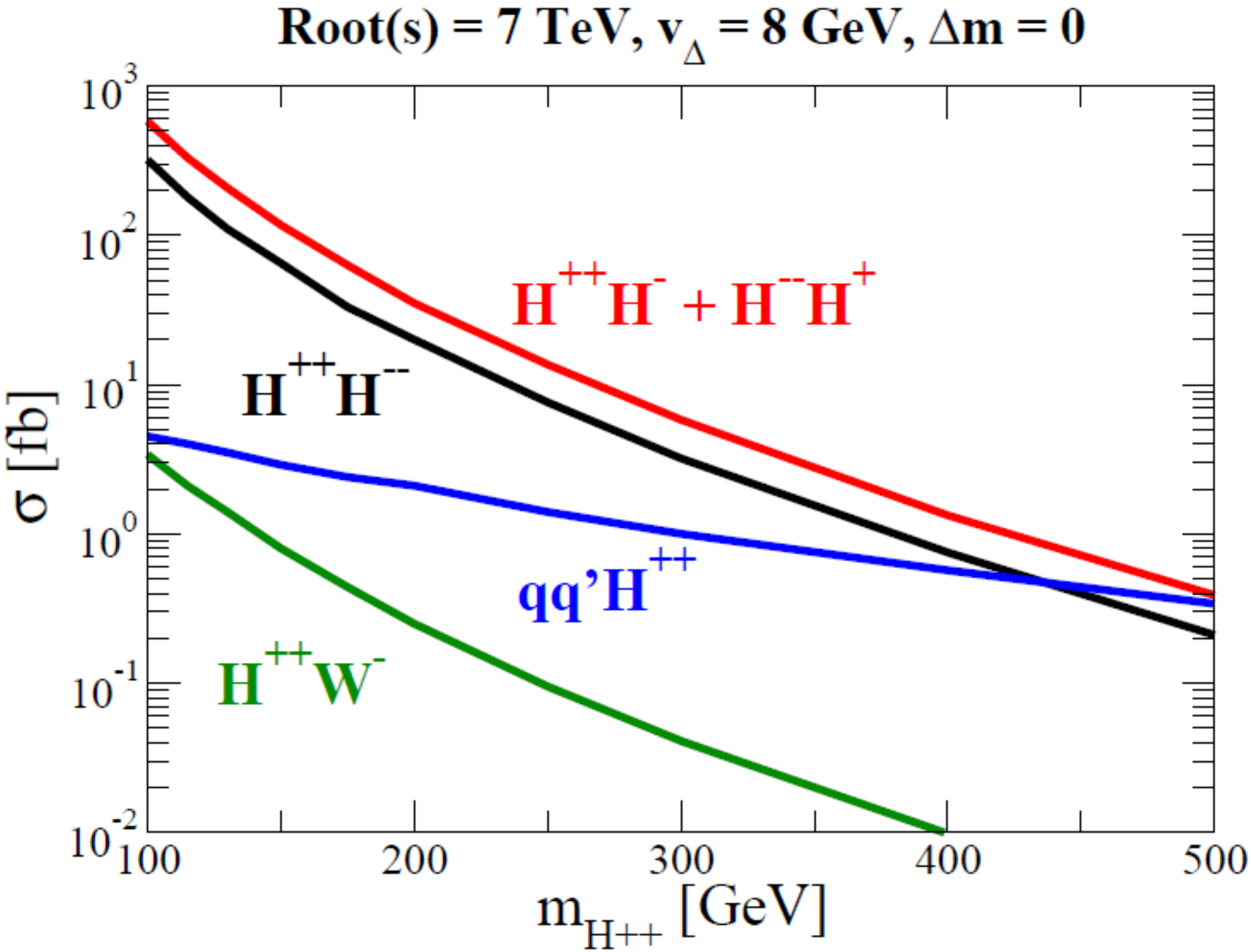


Vector Boson Fusion
- depends on v_Δ → **Suppressed**



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




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