Radiative corrections to electroweak parameters in the Higgs Triplet Model and implication with the recent Higgs boson searches at LHC

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S. Kanemura, K. Yagyu, arXiv: 1201.6287 [hep-ph]

Physics Opportunities with LHC at 7 TeV, KEK, Feb. 17th 2012

Introduction

- **The Higgs sector is unknown.**
  - Minimal? or Non-minimal?
  - The Higgs boson search is underway at the LHC.
    The Higgs boson mass is constrained to be
    115 GeV < mh < 127 GeV or mh > 600 GeV.
  - By the combination with electroweak precision data at the LEP,
    we may expect that a light Higgs boson exists.

- **There are phenomena which cannot explain in the SM.**
  - Tiny neutrino masses
  - Existence of dark matter
  - Baryon asymmetry of the Universe

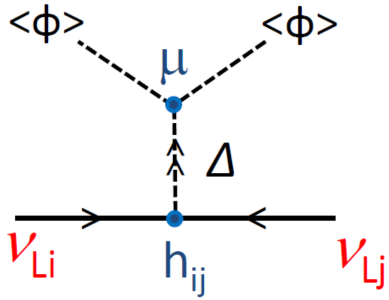
- **New physics may explain these phenomena above the TeV scale.**
  - Extended Higgs sectors are often introduced.

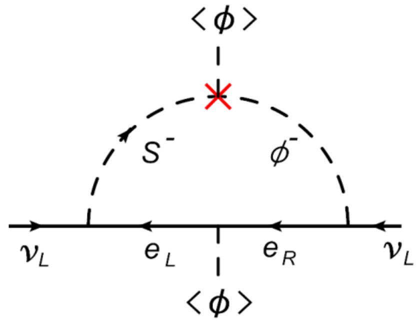
Physics of the Higgs sector ⟺ **New physics beyond the SM**

Explanation by extended Higgs sectors

- Tiny neutrino masses
  - The type II seesaw model
  - Radiative seesaw models

    (e.g. Zee model)





- Dark matter
  - Higgs sector with the discrete symmetry
- Baryon asymmetry of the Universe
  - Electroweak baryogenesis

Introduce extended Higgs sectors

SU(2) doublet Higgs + Singlet [$U(1)_{B-L}$ model]
+ Doublet [Inert doublet model]
+ Triplet [Type II seesaw model], etc…

How we can constrain these possibilities?

Constraint from the rho parameter

★ The experimental value of the rho parameter is quite close to unity.

★ Prediction of the rho parameter strongly depends on the structure of the extended Higgs sector.

$\rho_{exp} \sim 1$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i \left[T_i(T_i+1) - Y_i^2\right] v_i^2}{\sum_i 2Y_i^2 v_i^2}$$

Y_i : hypercharge

T_i : isospin

v_i : VEV

Model with ρ = 1 at the tree level

- **The Standard Model**
- **Models with Multi-doublet fields (with singlets)**

The **custodial SU(2) symmetry** exists in the kinetic term.

Model with ρ ≠ 1 at the tree level

- **Model with a Y=0 Triplet field**
- **Model with a Y=1 Triplet field**
- **Models with larger isospin rep.**

The **custodial SU(2) symmetry** does not exist in the kinetic term.

How the ρ parameter is calculated in both classes of models at the loop level.

Models with ρ = 1 at the tree level

The electroweak parameters are described by the 3 (+2) input parameters.

➡ $g, g', v + (Z_B, Z_W)$

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

$\alpha_{em}(mz) = 128.903 \pm 0.0015$
$G_F = 1.16637 \pm 0.00001\ \mathrm{GeV}^{-2}$
$m_z = 91.1876 \pm 0.0021\ \mathrm{GeV}$

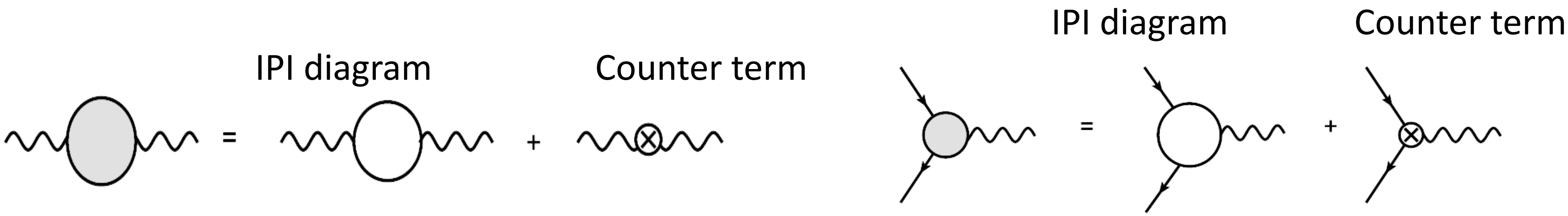
The other parameters can be written in terms of the above 3 inputs.

$$v^2 = \frac{1}{\sqrt{2}G_F}$$

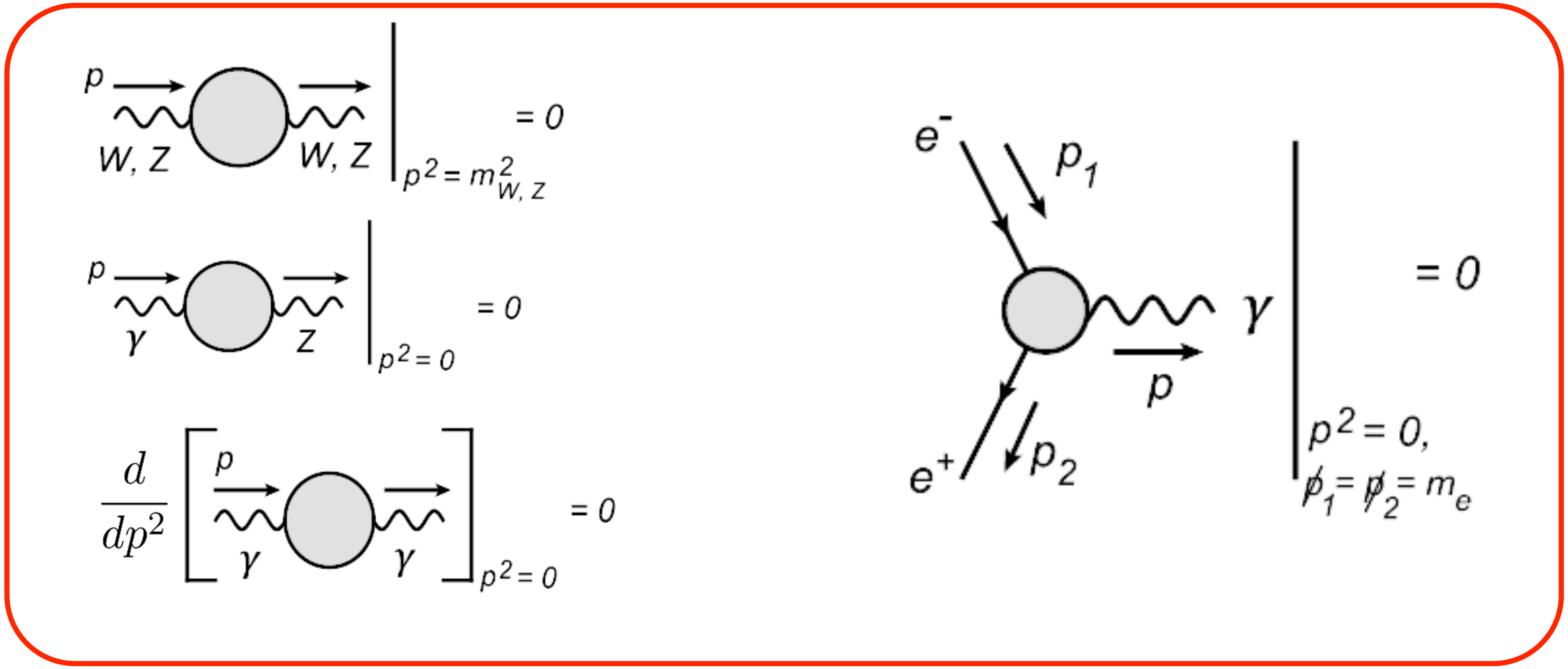
$$m_W^2 s_W^2 = \frac{\pi\alpha_{\rm em}}{\sqrt{2}G_F}$$

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

On-shell renormalization scheme



On-shell renormalization conditions



From these 5 conditions, 5 counter terms (δg, $\delta g'$, δv, δZ_B, δZ_W) are determined.

Radiative corrections to the EW parameters

The deviation form $m_W^2 s_W^2 = \frac{\pi \alpha_{\rm em}}{\sqrt{2} G_F}$ can be parametrized as:

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

$$\Delta r = -\frac{\delta G_F}{G_F} + \frac{\delta \alpha_{\rm em}}{\alpha_{\rm em}} - \frac{\delta s_W^2}{s_W^2} - \frac{\delta m_W^2}{m_W^2}$$

From the renormalization conditions;

$$\frac{\delta \alpha_{\rm em}}{\alpha_{\rm em}} = \frac{d}{dp^2}\Pi_T^{\gamma\gamma}(p^2)\Big|_{p^2=0} + \frac{2 s_W}{c_W}\frac{\Pi_T^{\gamma Z}(0)}{m_Z^2}$$

$$\frac{\delta G_F}{G_F} = -\frac{\Pi_T^{WW}(0)}{m_W^2} - \delta_{VB}$$

$$\frac{\delta m_W^2}{m_W^2} = \frac{\Pi_T^{WW}(m_W^2)}{m_W^2}$$

In models with ρ = 1 at the tree level, s_W^2 is the dependent parameter.
Therefore, the counter term for δs_W^2 is given by the other conditions.

$$s_W^2 = 1 - \frac{m_W^2}{m_Z^2} \quad \Rightarrow \quad \frac{\delta s_W^2}{s_W^2} = \frac{c_W^2}{s_W^2}\left[\frac{\Pi_T^{ZZ}(m_Z^2)}{m_Z^2} - \frac{\Pi_T^{WW}(m_W^2)}{m_W^2}\right]$$

This part represents the violation of the custodial symmetry by the sector which is running in the loop.

Scalar boson and fermion loop contributions to Δr

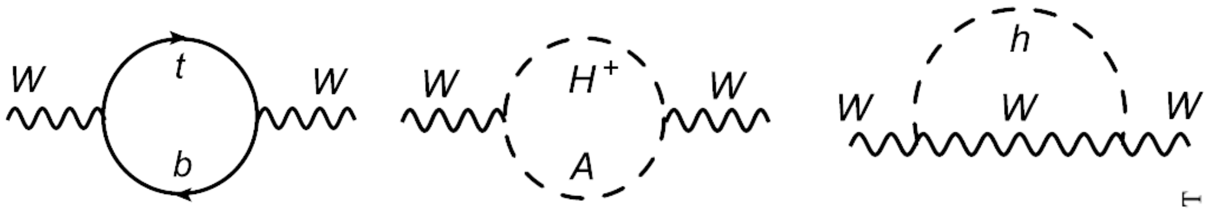
$$\Delta r_{\rho=1} = \frac{\Pi_T^{WW}(0) - \Pi_T^{WW}(m_W^2)}{m_W^2} + \frac{d}{dp^2}\Pi_T^{\gamma\gamma}(p^2)\Big|_{p^2=0} + \frac{2s_W}{c_W}\frac{\Pi_T^{\gamma Z}(0)}{m_Z^2} + \delta_{VB}$$
$$- \frac{c_W^2}{s_W^2}\left[\frac{\Pi_T^{ZZ}(m_Z^2)}{m_Z^2} - \frac{\Pi_T^{WW}(m_W^2)}{m_W^2}\right]$$

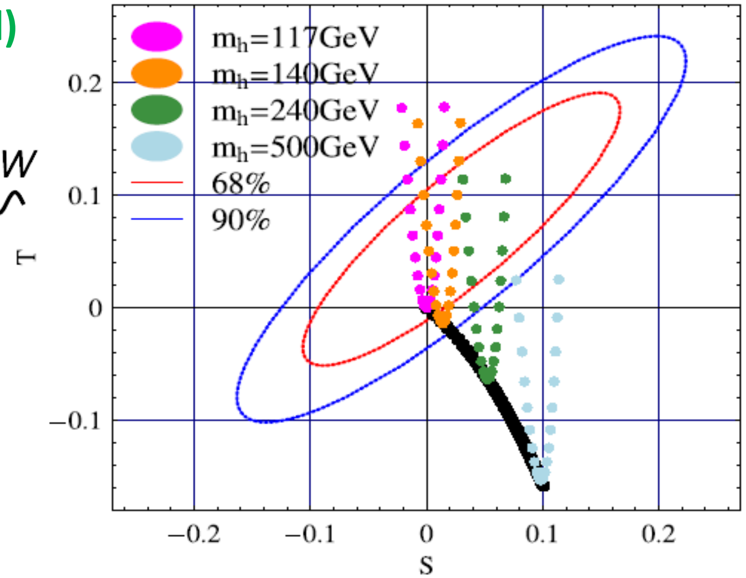
~ ρ-1 = α_{em} T

$$\simeq \frac{1}{16\pi^2}\left[\frac{(m_t - m_b)^2}{m_W^2} + \frac{(m_{H^+} - m_A)^2}{m_W^2} - \ln m_h^2\right]$$

Peskin, Wells (2001);
Grimus, Lavoura, Ogreid, Osland (2008);
Kanemura, Okada, Taniguchi, Tsumura (2011).

(In the case of the two Higgs doublet model)





Dependence of the **quadratic mass splitting** among particles in the same isospin multiplet appears in the T (rho) parameter.

Previous works and motivation of our work

- In models with $\rho \neq 1$ at the tree level, the renormalization scheme is different from that in models with ρ=1 at the tree level.

- In the model with the Y=0 Higgs triplet field, one-loop corrections to the electroweak parameters have been studied in Blank, Hollik (1997), Chen, Dawson (2004) etc.

NEW

- **We first study one-loop corrections to the electroweak precision parameters in the Y = 1 Higgs Triplet Model which is introduced in the type II seesaw mechanism. We then discuss how the model can be constrained by the data.**

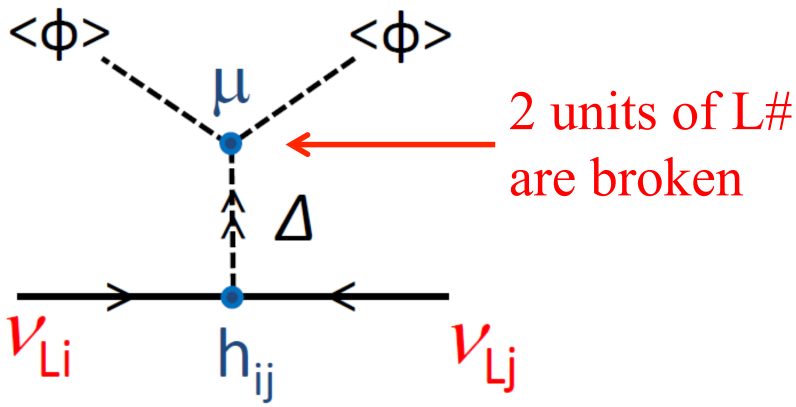
- **Under this constraint, we discuss the implication with the recent Higgs boson searches at the LHC.**

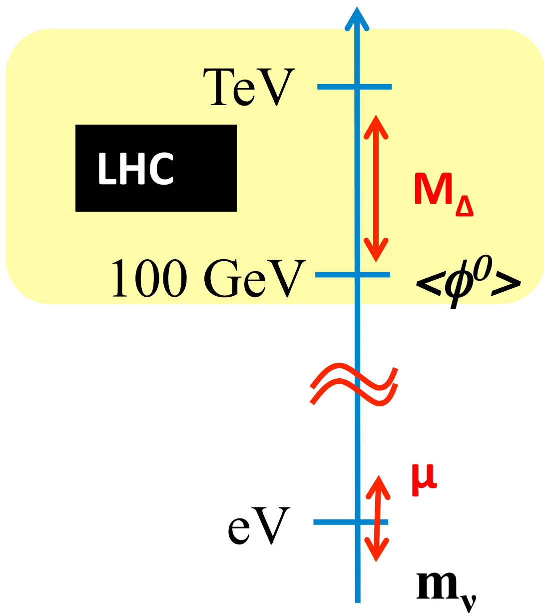
The type II seesaw model (The Y=1 Higgs Triplet Model)

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

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

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





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

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

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

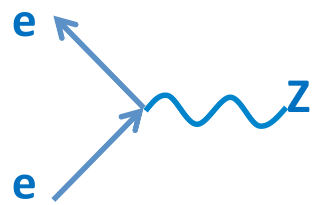
Models with ρ ≠ 1 at the tree level

The electroweak parameters are described by the **4** (+2) input parameters.

$g, g', v_\Phi, v_\Delta + (Z_B, Z_W)$

Blank, Hollik (1997)

We can choose α_{em}, G_F, m_Z and $\hat{s}_W^2$ as the input parameters.



$\hat{s}_W^2$ is defined by the effective Zee vertex:

$$\mathcal{L} = \bar{e}\frac{g}{2\hat{c}_W}(v_e\gamma_\mu - a_e\gamma_\mu\gamma_5)eZ^\mu$$

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

$\hat{s}_W^2 = 0.23146 \pm 0.00012$

The other parameters are determined as:

$$v^2 = v_\Phi^2 + 2v_\Delta^2 = \frac{1}{\sqrt{2}G_F}$$

$$m_W^2 = \frac{\pi\alpha_{\rm em}}{\sqrt{2}G_F\hat{s}_W^2}$$

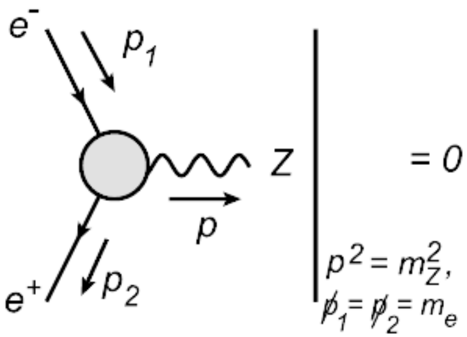
$$v_\Delta^2 = \frac{\hat{s}_W^2(1-\hat{s}_W^2)}{2\pi\alpha_{\rm em}}m_Z^2 - \frac{\sqrt{2}}{4G_F}$$

Radiative corrections to EW parameters in models with ρ ≠ 1 at the tree level

In the model with $\rho \neq 1$: $\mathbf{s_W^2}$ is **an independent parameter.**

→ **Additional renormalization condition is necessary.**

Blank, Hollik (1997)



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

$$\Delta r_{\rho\neq 1} = \frac{\Pi_T^{WW}(0) - \Pi_T^{WW}(m_W^2)}{m_W^2} + \frac{d}{dp^2}\Pi_T^{\gamma\gamma}(p^2)\Big|_{p^2=0} + \frac{2\hat{s}_W}{\hat{c}_W}\frac{\Pi_T^{\gamma Z}(0)}{m_Z^2} + \delta_{VB} + \frac{\hat{c}_W}{\hat{s}_W}\frac{\Pi_T^{\gamma Z}(m_Z^2)}{m_Z^2} + \delta_V'$$

$$\simeq \frac{1}{16\pi^2}\left[\ln m_t^2 + \ln m_{\Delta\text{-like}}^2 + \ln m_h^2\right]$$

By the renormalization of δs_W^2, quadratic depndence of the mass splitting disappear.

$$\rho = \frac{\pi\alpha_{\rm em}}{\sqrt{2}G_F m_Z^2 \hat{s}_W^2 \hat{c}_W^2}(1+\Delta r) \qquad m_W^2 = \frac{\pi\alpha_{\rm em}}{\sqrt{2}G_F \hat{s}_W^2}(1+\Delta r)$$

Higgs potential in the HTM

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) **$H^{\pm\pm}$, $H^\pm$, H, A**

Mass spectrum:

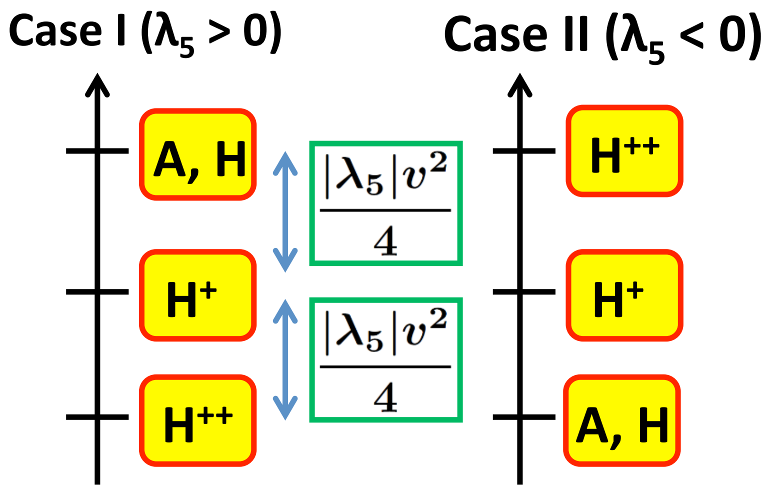
$$m_h^2 \simeq 2\lambda_1 v^2$$

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

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

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

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



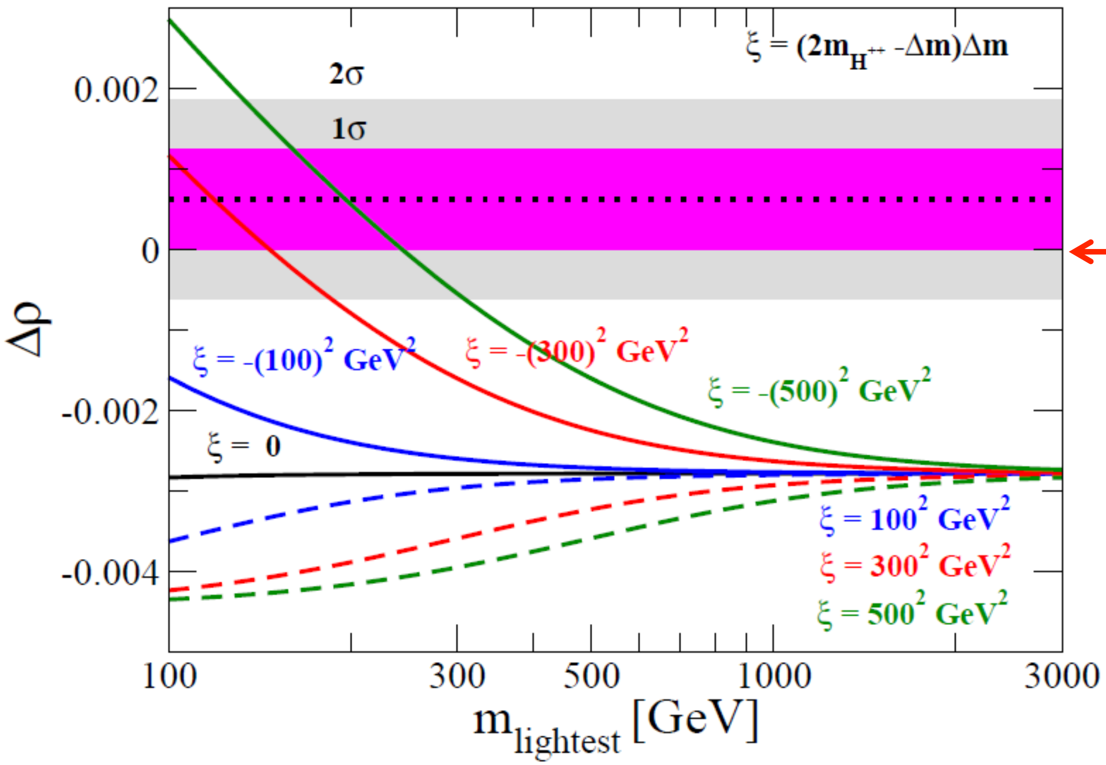
We discuss the constraint from the electroweak precision data In both Case I and Case II.

Heavy mass limit

$$\Delta\rho \equiv \rho - \rho_{\rm SM}(m_h^{\rm ref} = 125\ {\rm GeV})$$

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

$$\Delta\rho^{\rm exp} = 0.000632 \pm 0.000621$$



SM prediction

Case I

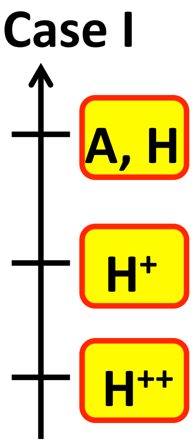
Case II

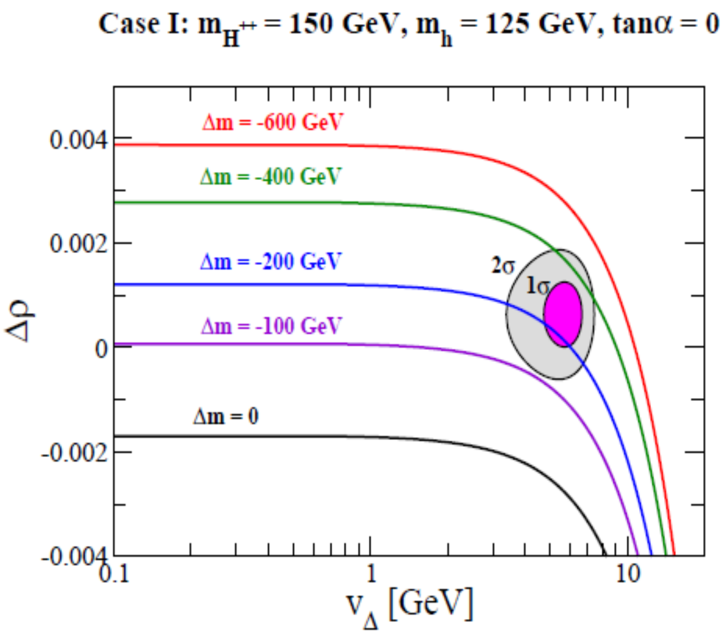
When we take heavy mass limit, loop effects of the triplet-like scalar bosons disappear. Even in such a case, the prediction does not coincide with the SM prediction.

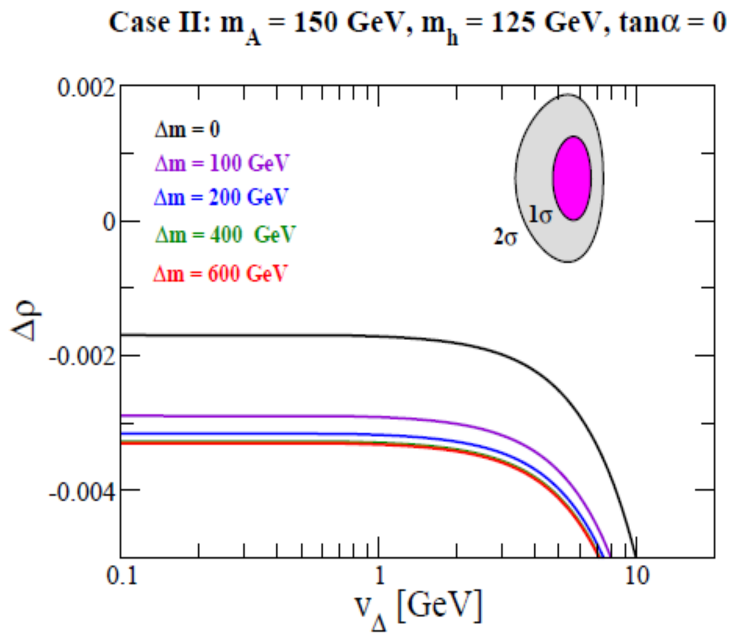
Prediction to the rho parameter at the 1-loop level

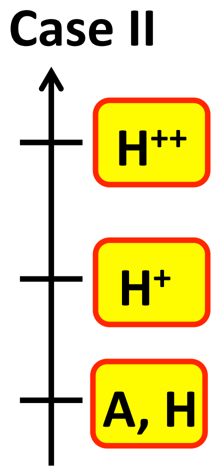
Kanemura, Yagyu, arXiv: 1201.6287 [hep-ph]

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









$\mathbf{v_\Delta}$ is calculated according to the tree level relation:

$$v_\Delta^2 = \frac{\hat{s}_W^2(1-\hat{s}_W^2)}{2\pi\alpha_{\rm em}} m_Z^2 - \frac{\sqrt{2}}{4G_F}$$

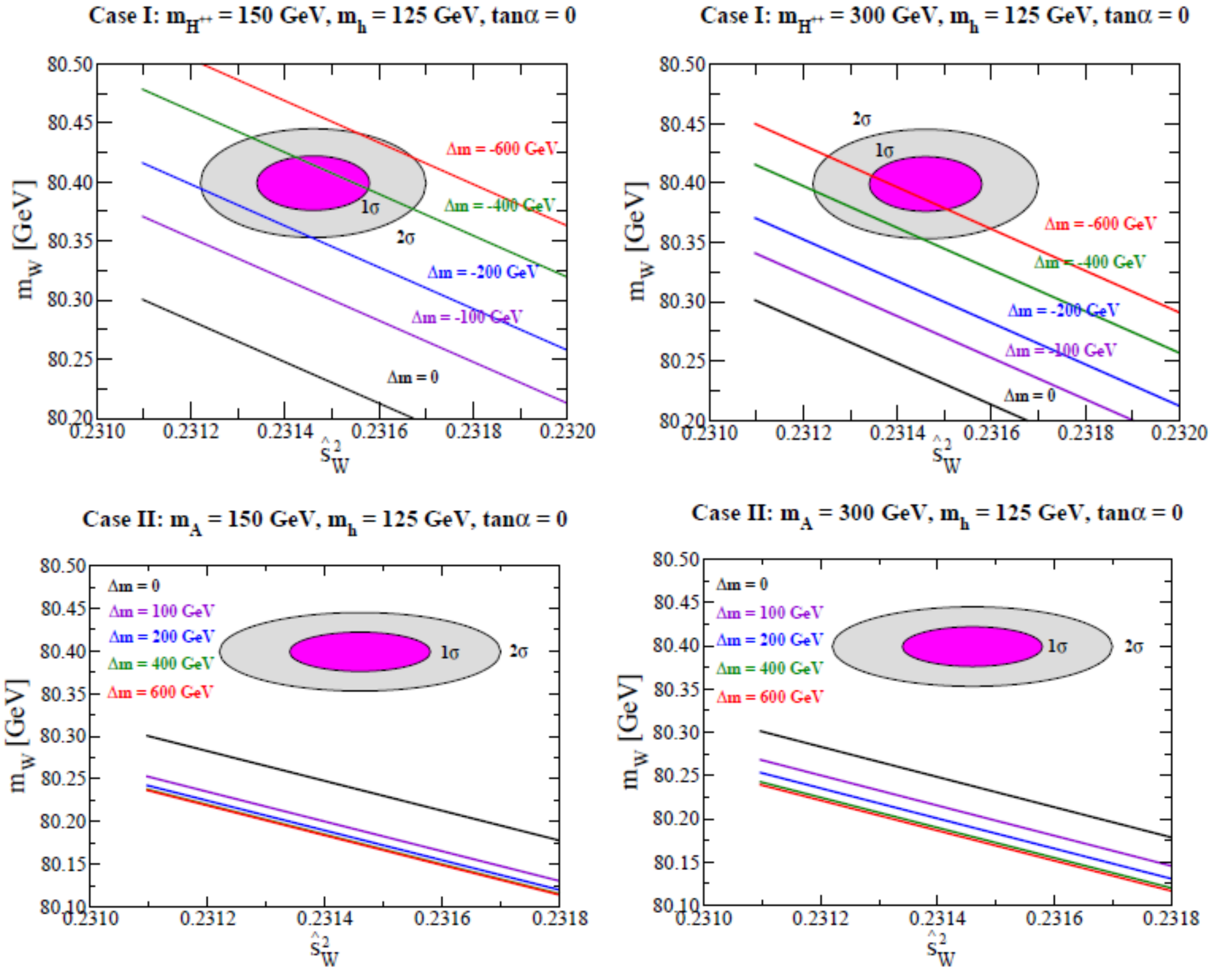
In Case I with mH^{++} = 150 GeV, 100 GeV < |Δm| < 400 GeV and 3 GeV < vΔ < 8 GeV is allowed.
Case II is highly constrained by the rho parameter data.

Kanemura, Yagyu, arXiv: 1201.6287 [hep-ph]

Prediction to the W boson mass at the 1-loop level

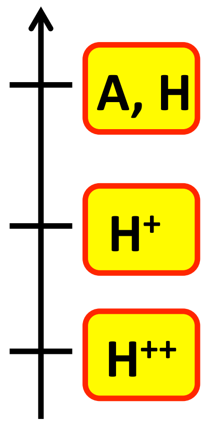
mH++ = 150 GeV   mH++ = 300 GeV

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

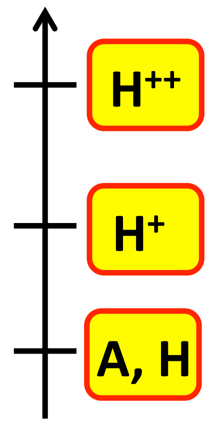


mA = 150 GeV   mA = 300 GeV

Case I



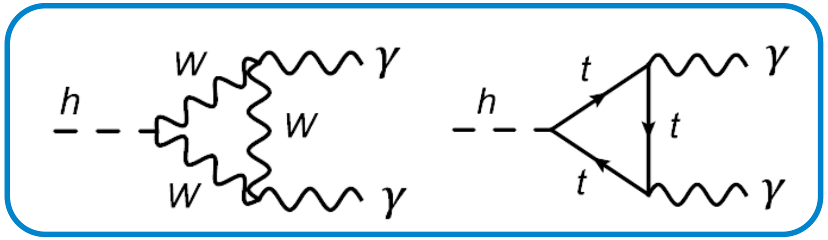
Case II

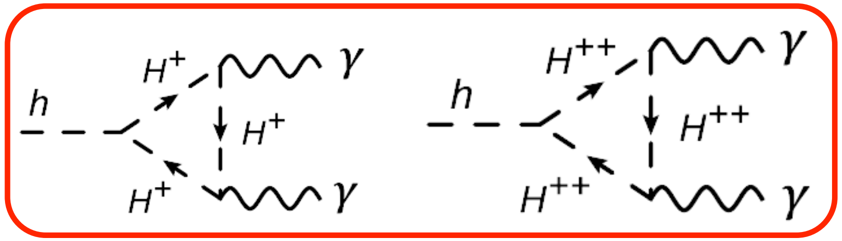


In Case I, by the effect of the mass splitting, there are allowed regions .
Case II is highly constrained by the data.

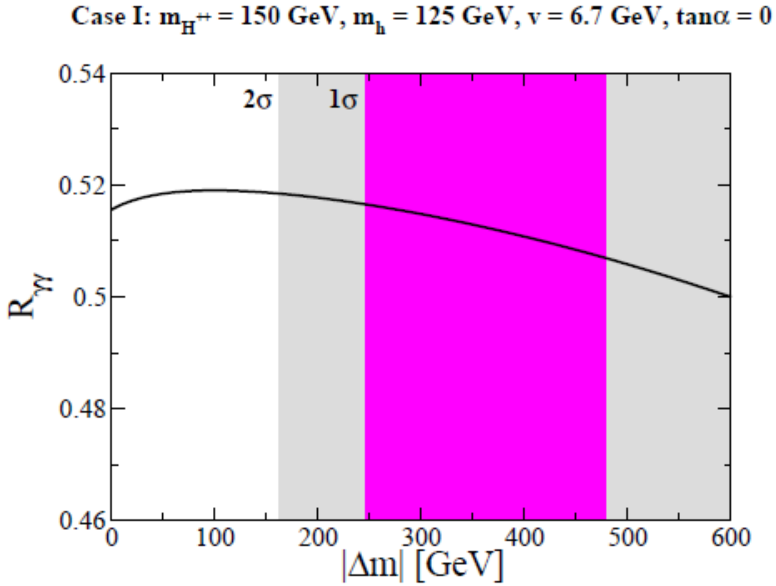
Kanemura, Yagyu, arXiv: 1201.6287 [hep-ph]

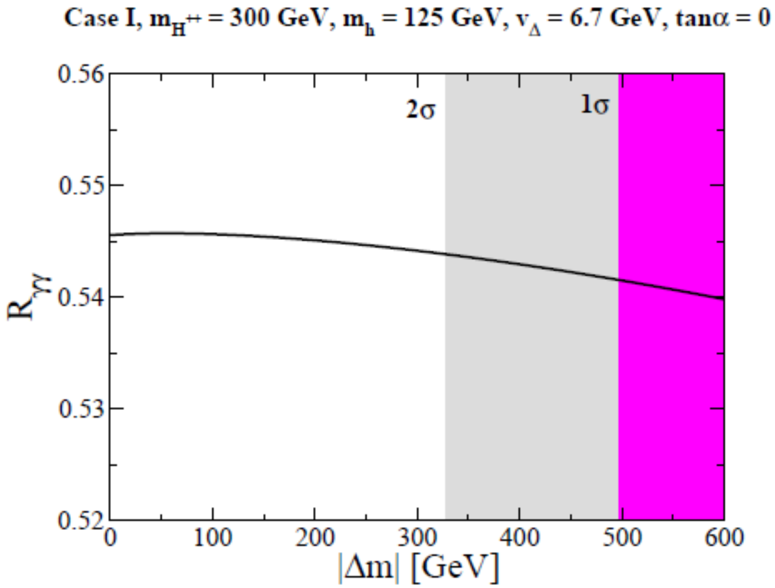
Higgs → two photon decay

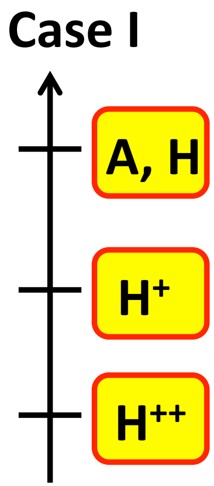




SM contribution + **Triplet-like scalar loop contribution**







$$R_{\gamma\gamma} \equiv \frac{\Gamma(h \to \gamma\gamma)_{\rm HTM}}{\Gamma(\phi_{\rm SM} \to \gamma\gamma)_{\rm SM}}$$

The decay rate of h → γγ is around half in the HTM compared with that in the SM.

Summary

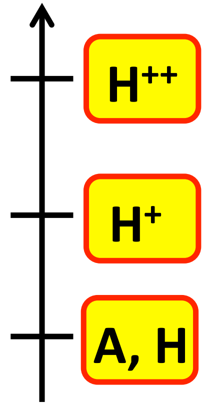
- Electroweak precision data (rho, m_W , …) can be constrained to the structure of extended Higgs sectors.
- In models with $\rho \neq 1$ at the tree level, **4 input parameters** are necessary to describe the electroweak parameters. → An additional renormalization condition is required to renormalize the electroweak parameters.
- Case II is strongly constrained by the electroweak precision data.
- In Case I with **mH^{++} ~ 150 GeV, |Δm|~ several 100 GeV and v_Δ~ O(1) GeV is favored by the data.**
- In the allowed parameter regions by the data, the decay rate of $h \to \gamma\gamma$ is around 50% in the HTM compared to that in the SM.
- In the case with the mass splitting, **cascade decays** of the triplet-like scalar bosons can be important. By measuring the **transverse mass distributions** of such decay products, the mass spectrum may be reconstructed, and we may be able to test the HTM at the LHC.

Phenomenology of HTM with the mass splitting at the LHC

Aoki, Kanemura, Yagyu , Phys. Rev. D, in press (2011)

Cascade decays of the Δ-like scalar bosons become important.

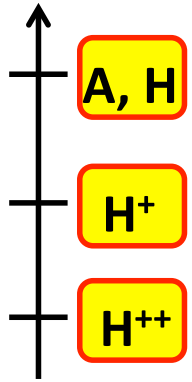
Case II

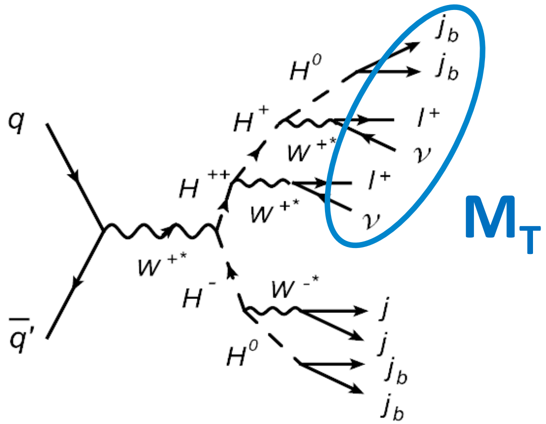


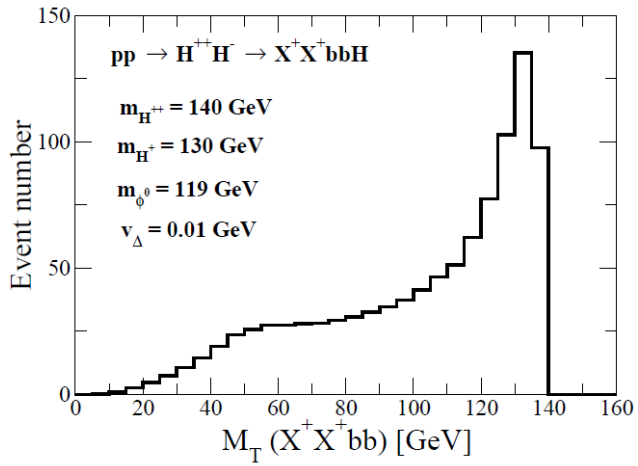
$H^{++} \to H^{+} W^{+} \to A\,(H) W^{+} W^{+}$
$H^{+} \to A\,(H) W^{-}$
$A\,(H) \to \nu\nu$ or bb
(mA~100 GeV case)

Case I

$A\,(H) \to H^{+} W^{-} \to H^{++} W^{-} W^{-}$
$H^{+} \to H^{++} W^{-}$
$H^{++} \to l^{+} l^{+}$ or $W^{+} W^{+}$







Transvers mass

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

By using the M_T distribution, we may reconstruct the mass spectrum of Δ-like scalar bosons.
→ We would test the Higgs potential in the HTM.

Y=1 Higgs Triplet Model:Kinetic term

$$\mathcal{L}_{\rm kin} = (D_\mu\Phi)^\dagger(D^\mu\Phi) + {\rm Tr}[(D_\mu\Delta)^\dagger(D^\mu\Delta)]$$

共変微分

$$D_\mu\Phi = \left(\partial_\mu + i\frac{g}{2}\tau^a W_\mu^a + i\frac{g'}{2}B_\mu\right)\Phi$$

$$D_\mu\Delta = \partial_\mu\Delta + i\frac{g}{2}[\tau^a W_\mu^a, \Delta] + ig'B_\mu\Delta$$

真空期待値

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_\Phi \end{pmatrix}$$

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

ゲージボソン
質量

$$m_W^2 = \frac{g^2}{4}(v_\Phi^2 + 2v_\Delta^2)$$

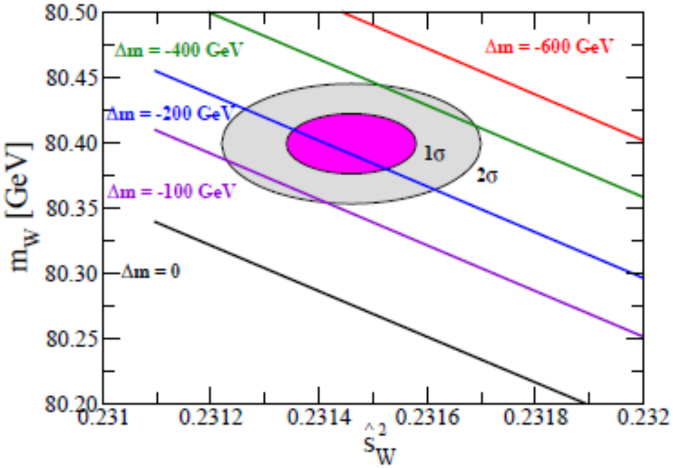
$$m_Z^2 = \frac{g^2}{4\cos^2\theta_W}(v_\Phi^2 + 4v_\Delta^2)$$

ρパラメータ

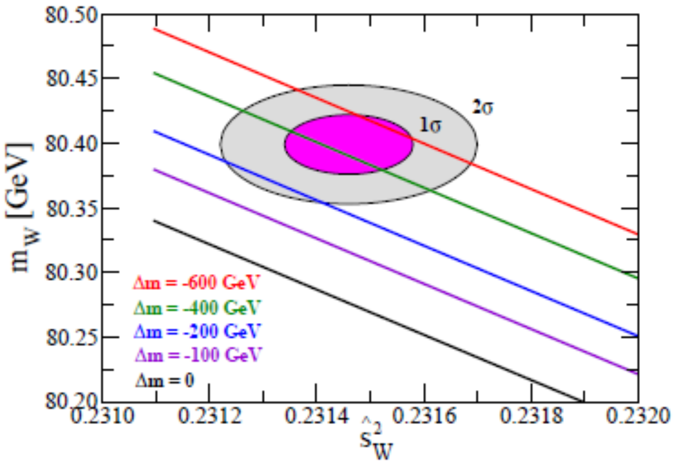
$$\rho \equiv \frac{m_W^2}{m_Z^2\cos^2\theta_W} = \frac{1+\frac{2v_\Delta^2}{v_\Phi^2}}{1+\frac{4v_\Delta^2}{v_\Phi^2}} \simeq 1 - \frac{2v_\Delta^2}{v_\Phi^2}$$

mh = 700 GeV case

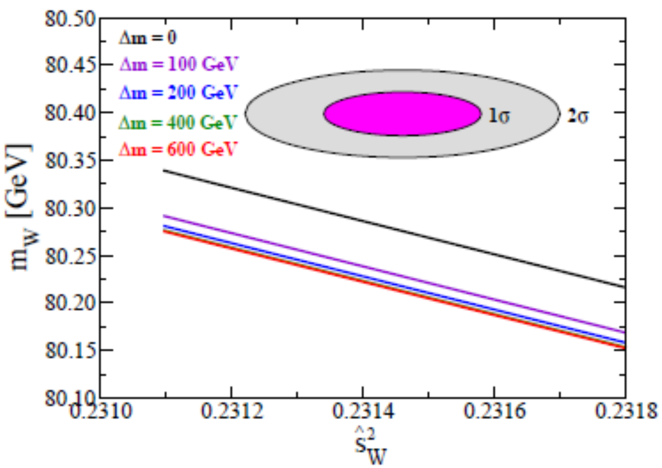
Case I: $m_{H^{++}}$ = 150 GeV, m_h = 700 GeV, tanα = 0



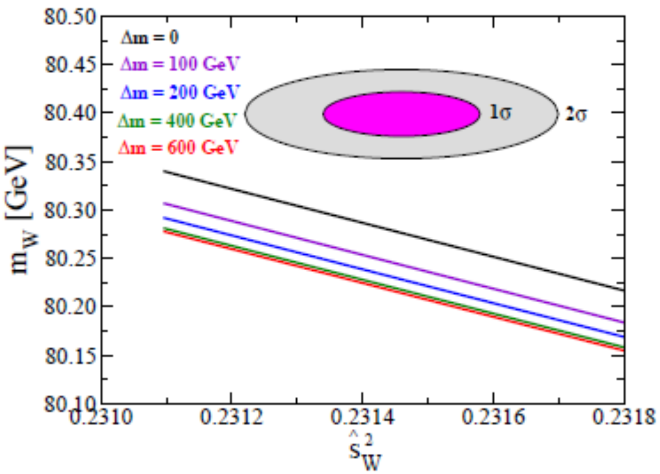
Case I: $m_{H^{++}}$ = 300 GeV, m_h = 700 GeV, tanα = 0

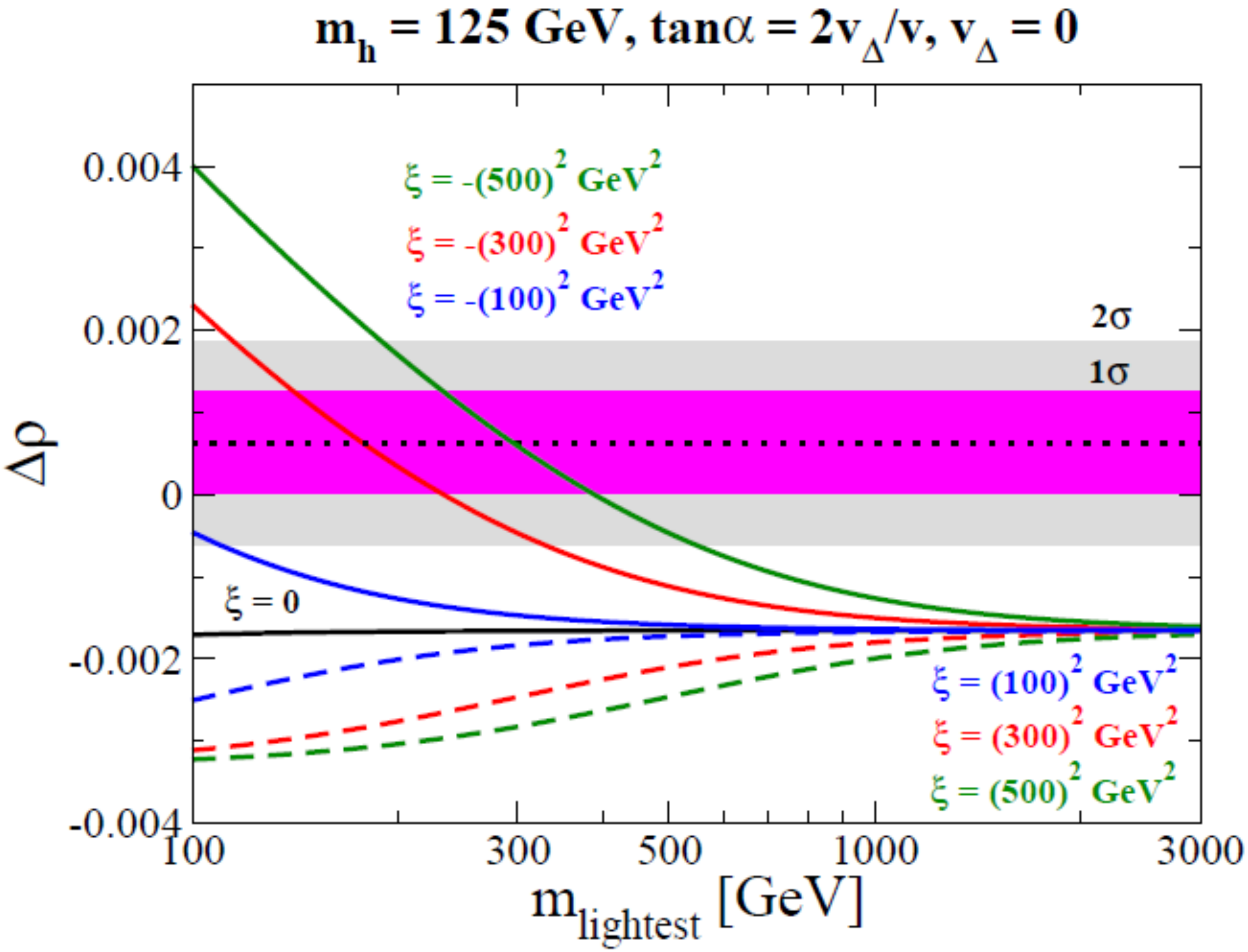


Case II: m_A = 150 GeV, m_h = 700 GeV, tanα = 0



Case II: m_A = 300 GeV, m_h = 700 GeV, tanα = 0





m_h = 125 GeV, tanα = 2v_Δ/v, v_Δ = 0
ξ = -(500)^2 GeV^2
ξ = -(300)^2 GeV^2
ξ = -(100)^2 GeV^2
2σ
1σ
ξ = 0
ξ = (100)^2 GeV^2
ξ = (300)^2 GeV^2
ξ = (500)^2 GeV^2
Δρ
0.004
0.002
0
-0.002
-0.004
100
300
500
1000
3000
m_lightest [GeV]

Custrodial Symmetry

The Higgs doublet can be written by the 2×2 matrix form

$$\Sigma \equiv (\widetilde{\Phi}, \Phi) = \begin{pmatrix} -\phi_0^\star & \phi^+ \\ \phi^- & \phi_0 \end{pmatrix}$$

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

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

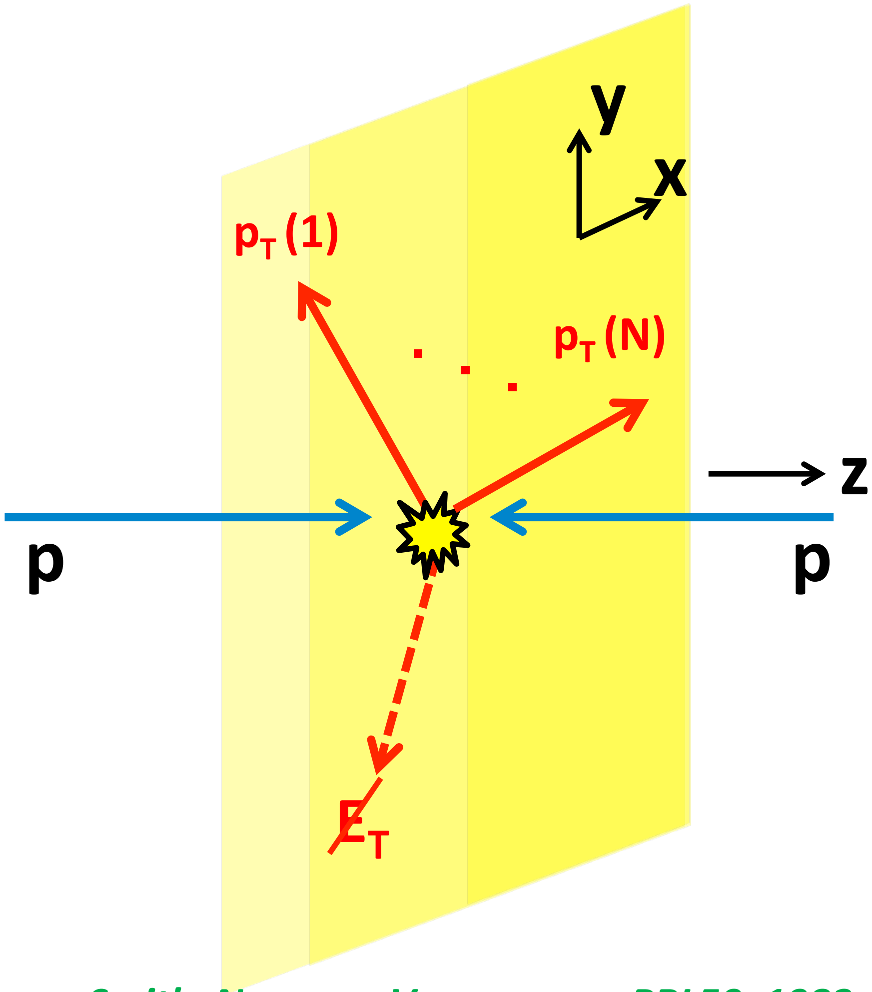
g’ → 0のリミットで運動項は、
完全に$SU(2)_L \times SU(2)_R$対称性を持つ

$$\Sigma \to \Sigma' = U_L \Sigma U_R^\dagger$$

ヒッグス場が真空期待値を持つと、 $\Sigma \to \langle \Sigma \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

$SU(2)_L$＝$SU(2)_R$ =$SU(2)_V$の対称性が残る。これをカストディアル対称性という。

Transverse mass analysis



Missing transverse energy:

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

ϕ : azimuthal angle

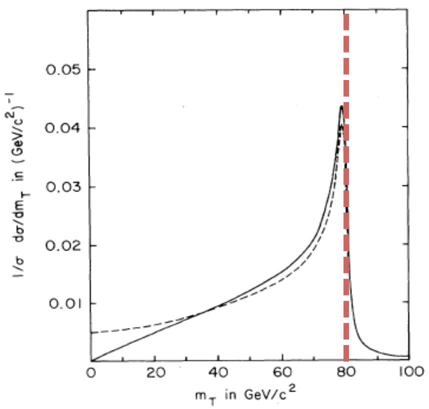
Transverse mass:

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

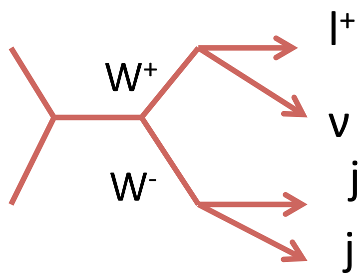
$$M_T^2 = (\not{E}_T + p_T)^2 \simeq 2|\not{E}_T||p_T|(1-\cos\varphi)$$

Smith, Neerven, Vermaseren, PRL50, 1983

Ex. The W boson mass reconstruction



The endpoint shows the W boson mass.

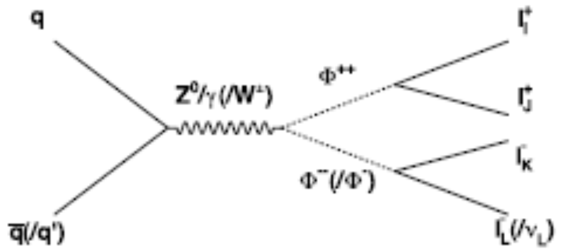


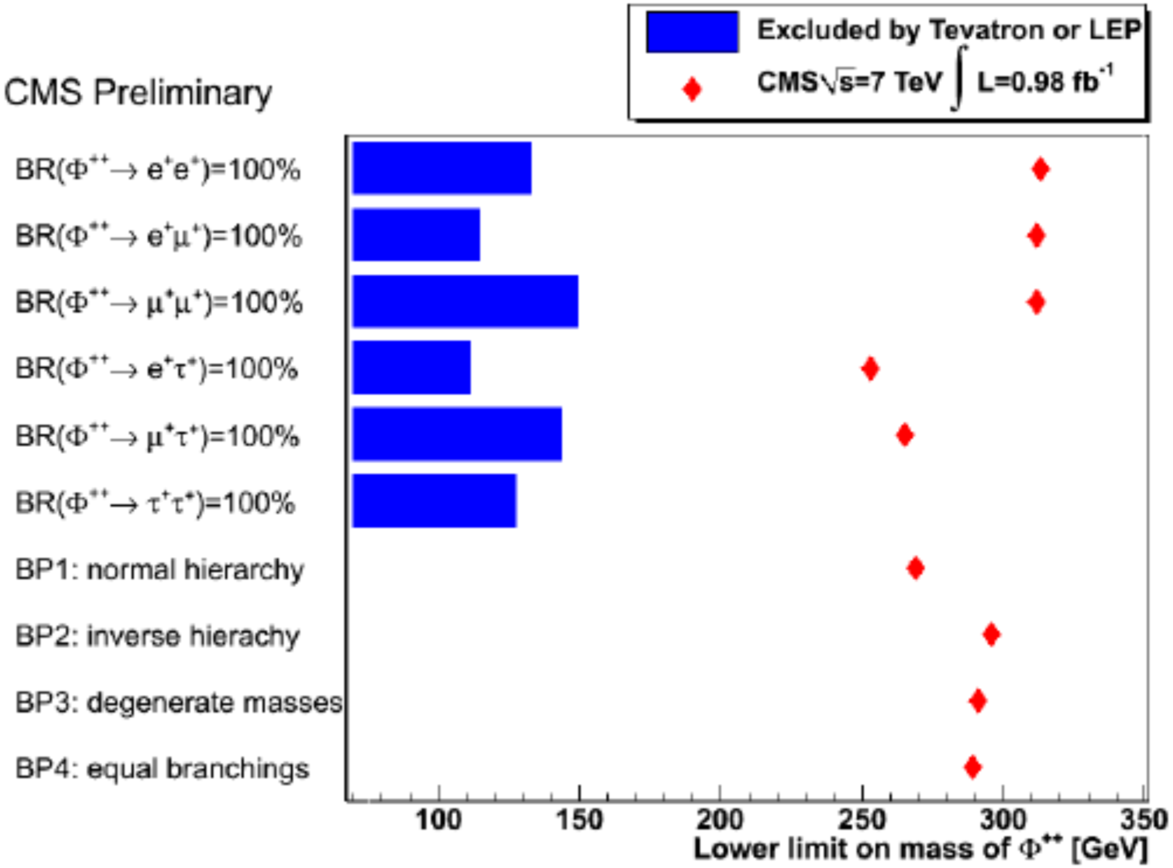
By using transverse mass distribution, the masses of Δ-like scalar bosons can be reconstructed.

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



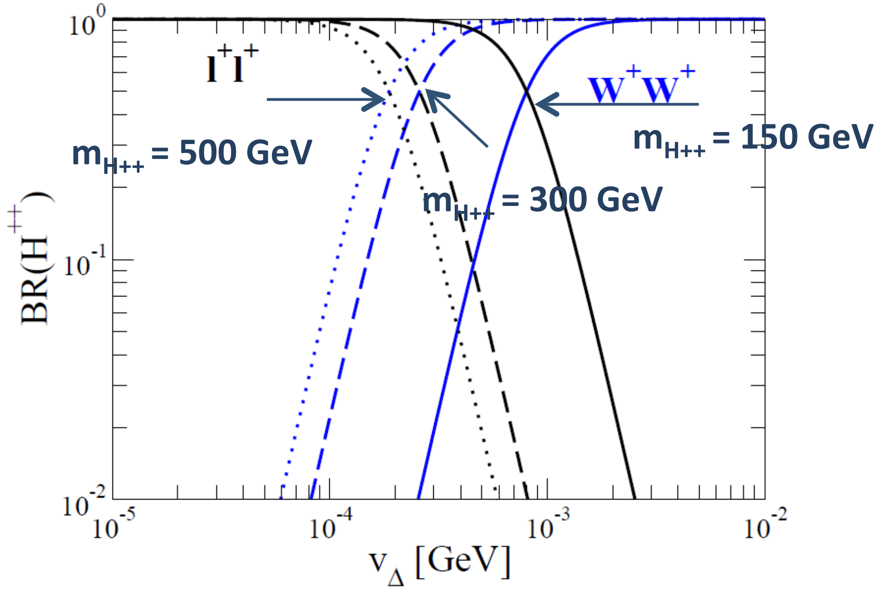


When **H^{++} → l^{+}l^{+}**,
m_{H++} > 250 – 300 GeV.

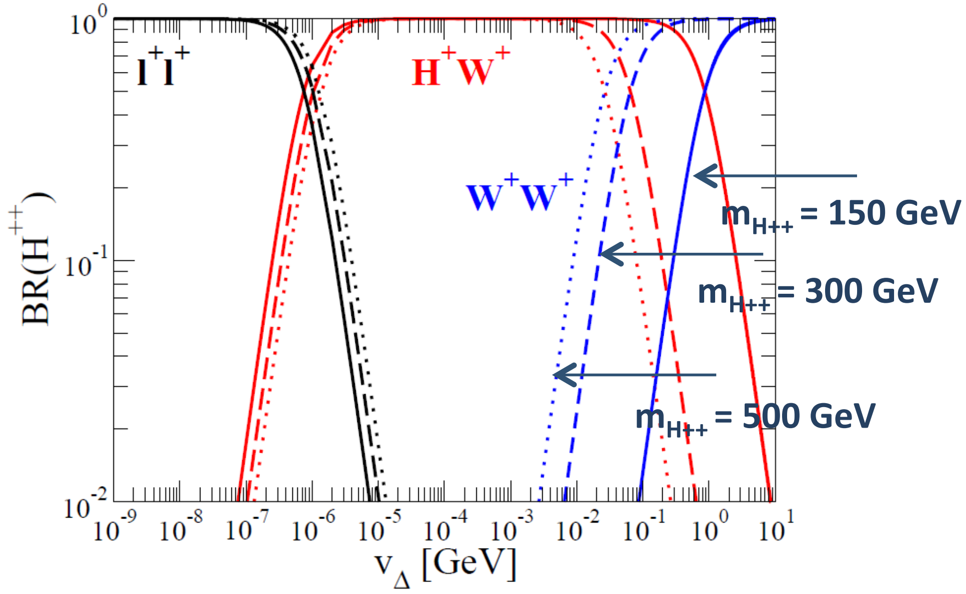
This bound cannot be applied when H^{++} does not decay into the same sign dilepton.

Branching ratio of H^{++}

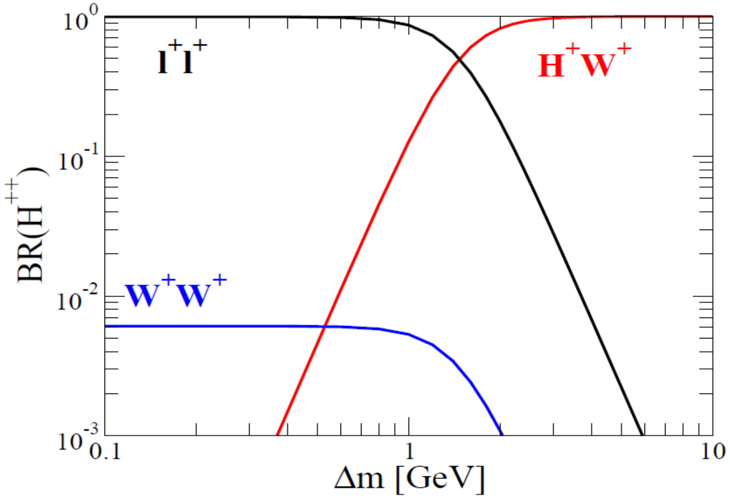
$\Delta m = 0$



$\Delta m = 10$ GeV



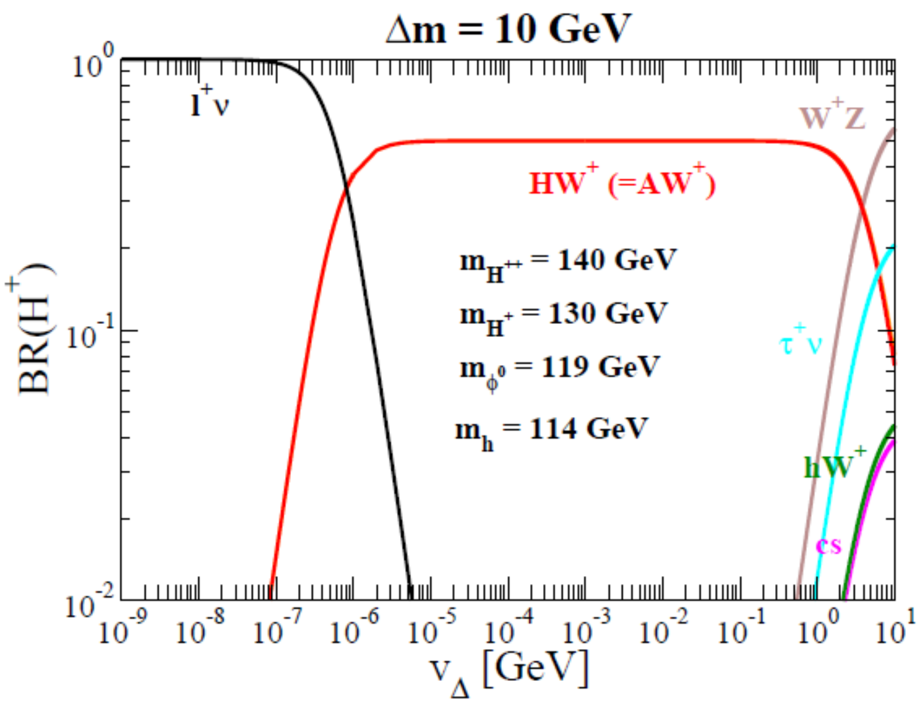
$v_\Delta = 0.1$ MeV, $m_{H^{++}} = 200$ GeV

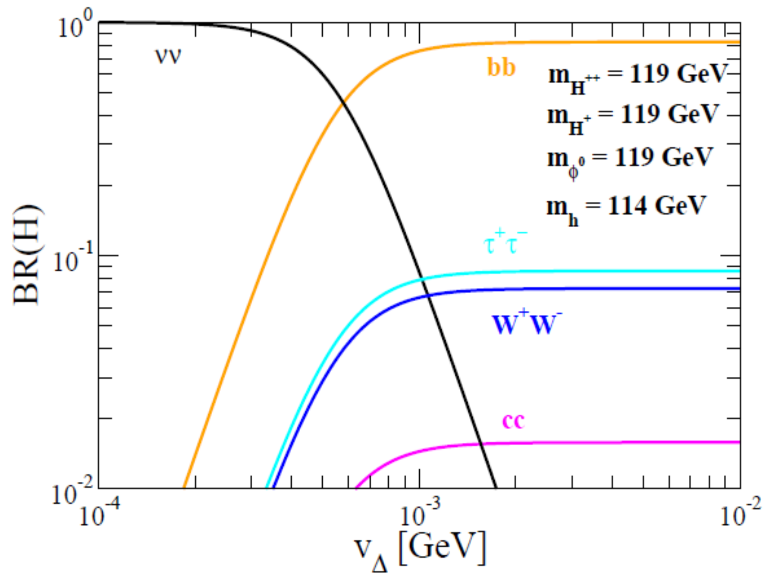


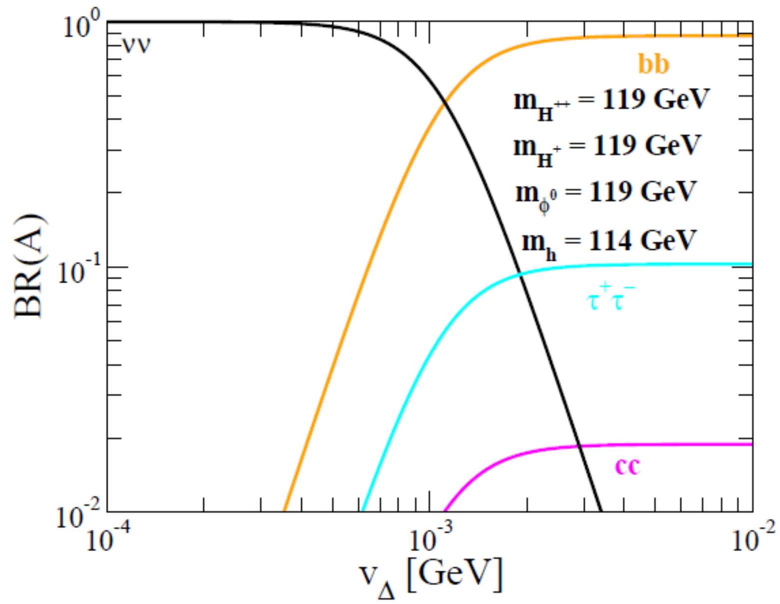
Chakrabarti, Choudhury, Godbole, Mukhopadhyaya, (1998);
Chun, Lee, Park, (2003);
Perez, Han, Huang, Li, Wang, (2008);
Melfo, Nemevsek, Nesti, Senjanovic, (2011)

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_Δ > MeV.

Constraints to extended Higgs sectors

- Non-minimal Higgs sectors

SU(2) doublet + [**SU(2) singlets** / **SU(2) doublets** / **SU(2) triplets**] Etc…

Ex. MSSM → 2HDM
Radiative seesaw models → 2HDM + singlets
Type II seesaw model → triplet

There are many possibilities of non-minimal Higgs sectors.

- Constraints to extended Higgs sectors

★ Electroweak precision observables
- The rho parameter
- The W boson mass, …

★ Flavor experiments
- Lepton flavor violation experiments ($\mu \to e\gamma$, $\mu \to eee$, …)
- Quark flavor violation experiments ($b \to s\gamma$, K0-K0 mixing, …)

In this talk, we focus on the constraint from the electroweak precision data.

Generation mechanisms for neutrino masses

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

$$\mathcal{L}_{\rm eff} = \frac{c}{M}\overline{\nu_L^c}\nu_L\phi^0\phi^0$$

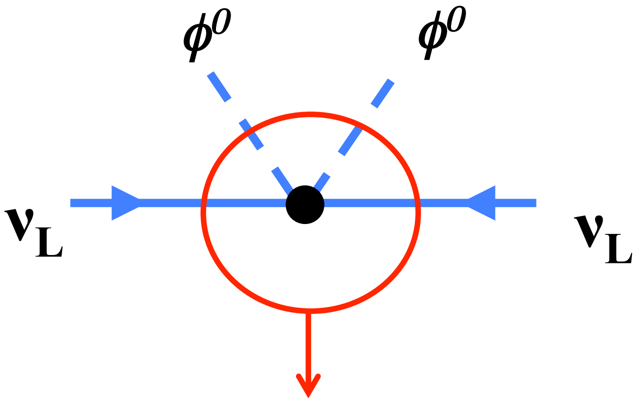
The Higgs boson gets the VEV.

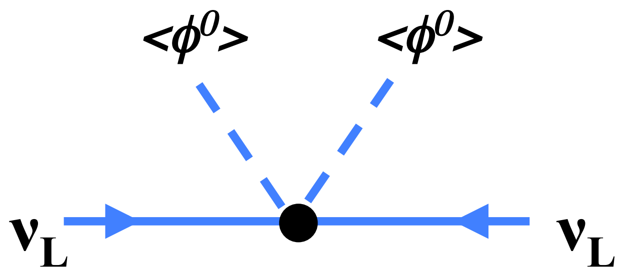
$$\frac{c\langle\phi^0\rangle^2}{M}\overline{\nu_L^c}\nu_L$$

$<\phi^0>$ ~ 246 GeV

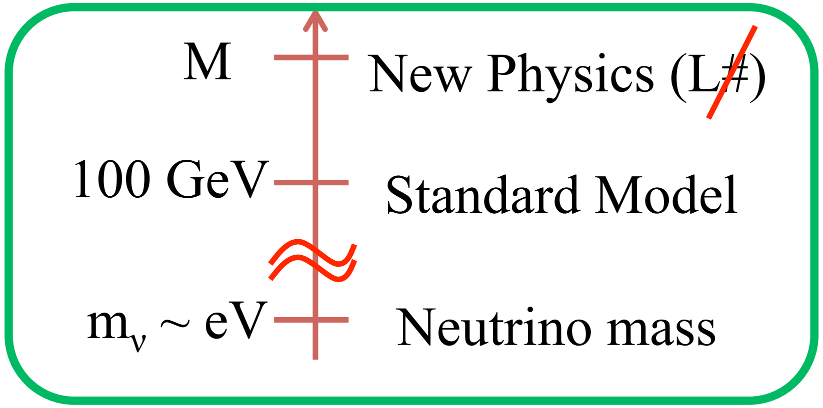
m_ν ~ 0.1 eV

c/M ~ 10^{-14} GeV^{-1}



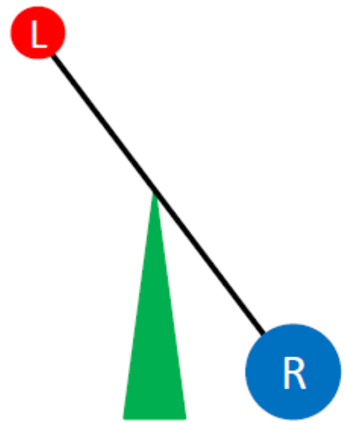


Dynamics of new physics models is mediated in the vertex.



What kind of NP models for generating neutrino masses are there ?

Seesaw Mechanism (Type-I)



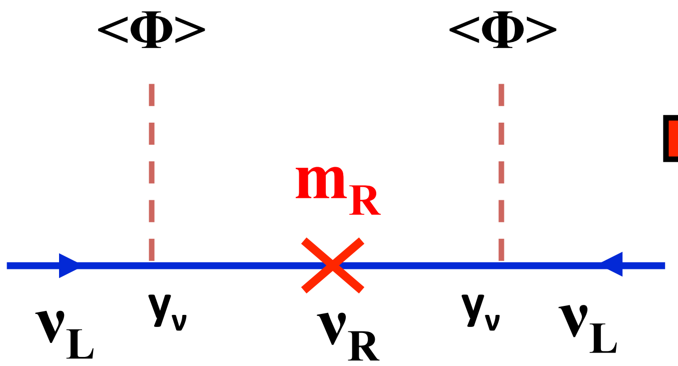
Introducing right-handed neutrinos ν_R into the SM

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \underline{y_\nu \bar{L}_L \tilde{\Phi} \nu_R} - \frac{1}{2}\underline{m_R \overline{\nu_R^c} \nu_R} + {\rm h.c.}$$

Dirac mass term **Majorana mass term**

$$\frac{c\langle\phi^0\rangle^2}{M}\ \overline{\nu_L^c}\nu_L$$

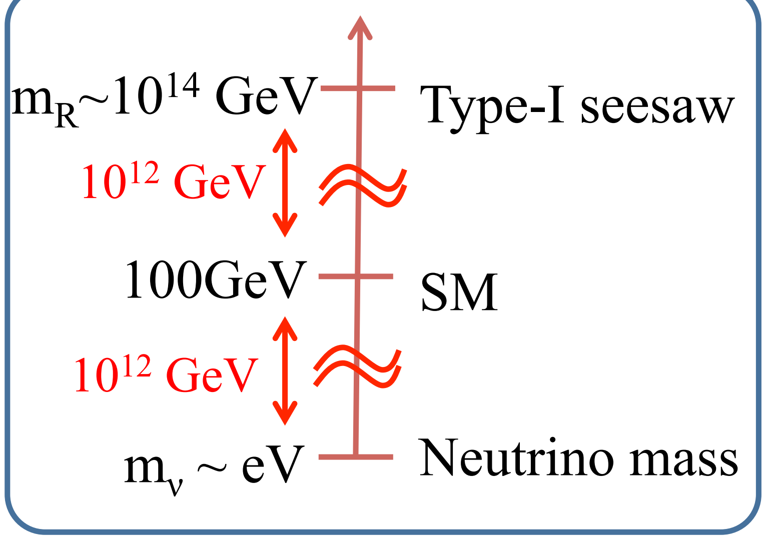
M → m_R



$$m_\nu = \frac{(y_\nu v)^2}{m_R}$$

m_ν ~ O (0.1) eV ⇒ $\mathbf{m_R \sim O(10^{14})\ GeV}$

[In the case of y_ν= O(1)]



This model is simple but difficult to test.

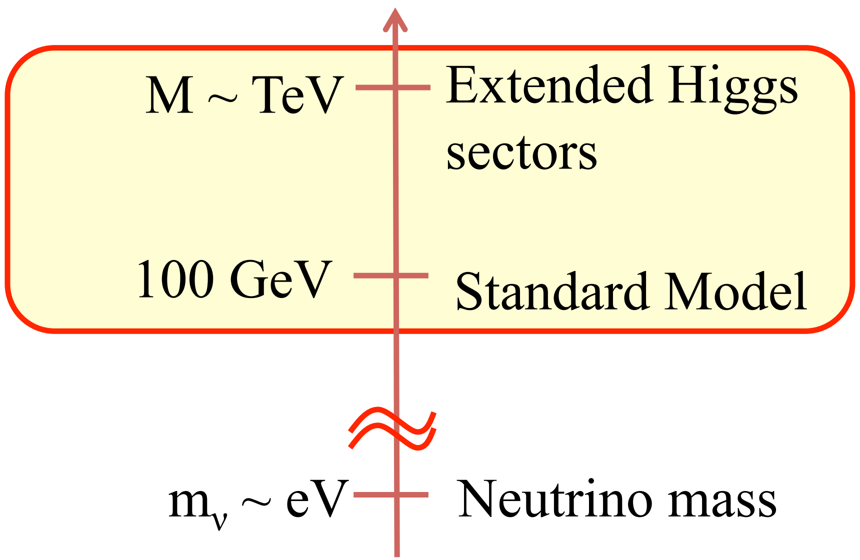
Extended Higgs sectors and neutrino masses

Tiny neutrino masses can be generated through dynamics of extended Higgs sectors at the TeV scale .

★ Radiative seesaw models : Neutrino masses can be generated at the loop level, where additional scalar bosons are running in the loop.

★ Type-II seesaw model : The Higgs triplet field is added to the SM.

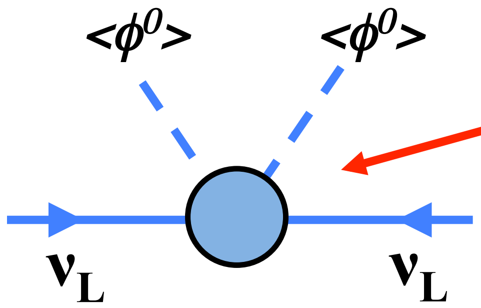
This region will be surveyed at the LHC.



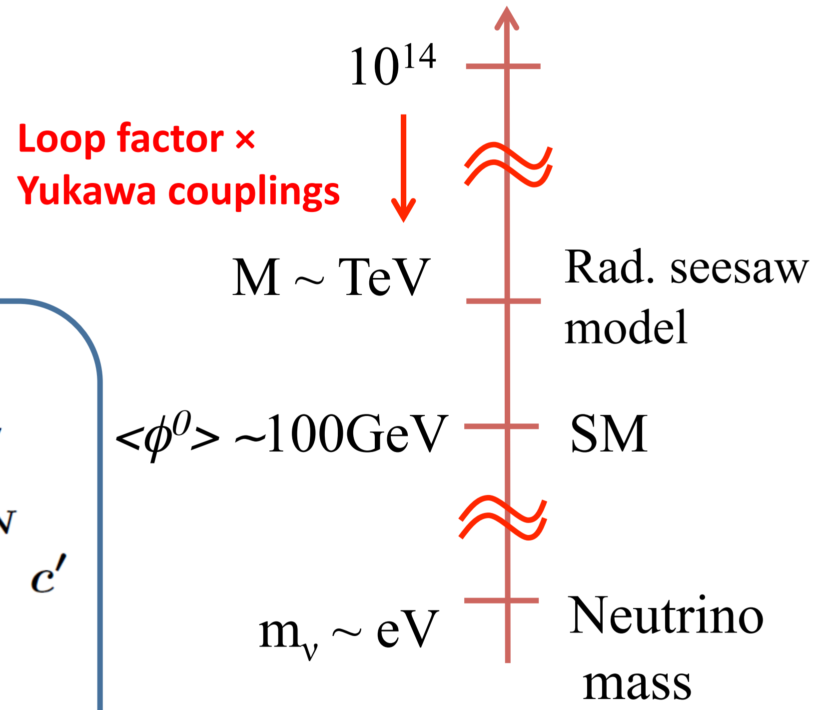
These models are testable at the LHC

Radiative seesaw models

Neutrino masses are generated at the loop level.



Additional scalar bosons are running in the loop.



Neutrino mass

$$m_\nu = \left(\frac{1}{16\pi^2}\right)^N \frac{c'\langle\phi^0\rangle^2}{M_\Phi}$$

Loop Factor

$$\frac{c\langle\phi^0\rangle^2}{M}\ \overline{\nu_L^c}\nu_L$$

$$c \to \left(\frac{1}{16\pi^2}\right)^N c'$$

$$M \to M_\Phi$$

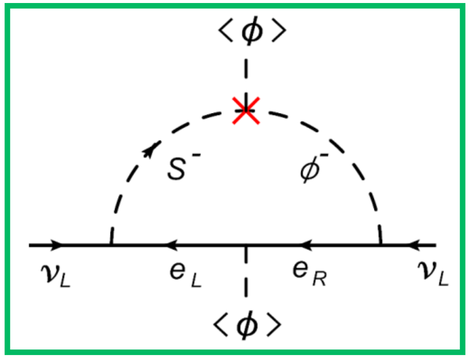
Thanks for the loop factor, M_Φ (e.g., charged Higgs mass) can be taken to be TeV scale without finetuning in Yukawa couplings.

Variation for radiative seesaw models

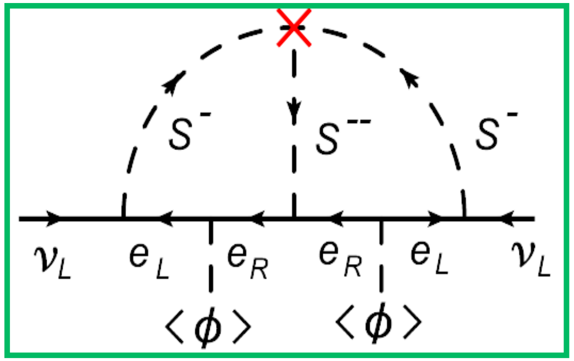
Source of L# violation

Scalar interaction

Zee Model (1980)

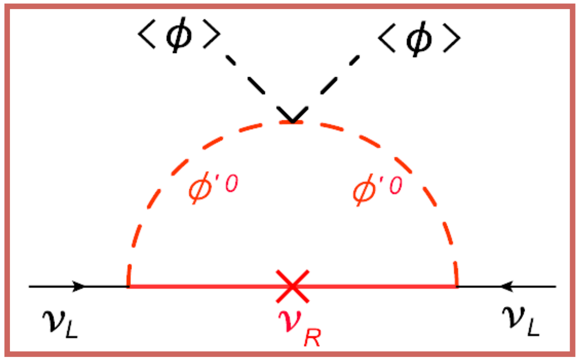


Zee-Babu Model (1986)

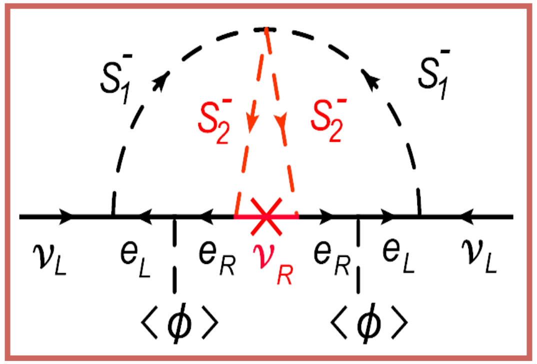


Majorana mass

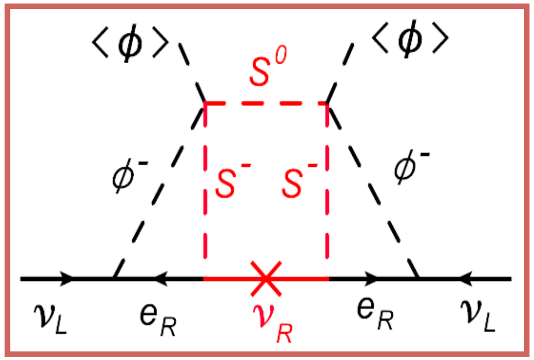
Ma Model (2006)



Krauss, Nasri, Trodden Model (2003)



Aoki, Kanemura, Seto Model (2009)



In the latter three models, a lightest Z_2-odd particle can be a dark matter candidate.

Constraint to extended Higgs sectors

- There are two important experimental results.
  1. The electroweak rho parameter is quite close to unity.
  2. FCNC processes are suppressed.

SU(2) doublet Higgs
+ Singlet [Both 1 and 2 are satisfied.]
+ Doublet [To satisfy 2, Z_2 symmetry is imposed]
+ Triplet [To satisfy both 1 and 2, parameter tuning is necessary.]

In this talk, we focus on the constraint from the electroweak precision measurement.