Perspective of extended Higgs sectors in beyond Standard Model scenarios- Part II

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Plan

- Doublet Higgs boson: Type-I, II, III, IV
- Triplet Higgs boson: Real and complex
- Inert Higgs bosons: Singlet, Doublet and Triplet
- Left-Right Symmetric model

Two Higgs doublet model

Here we have two SU(2) Higgs doublets with same hyper charges

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_{1r} + i a_1 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_{2r} + i a_2 \end{pmatrix}$$

The general Higgs potential takes the form

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + H.c) + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$
$$+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + [\frac{\lambda_5}{2}((\Phi_1^\dagger \Phi_2)^2) + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + H.c]$$

The Yukawa part of the Lagrangian is

$$-\mathcal{L}_Y = Y^{ij}_{u\,1,2} \tilde{\Phi}_{1,2} Q_i u_j^c \, + \, Y^{ij}_{d\,1,2} \Phi_{1,2} Q_i d_j^c \, + \, Y^{ij}_{d\,1,2} \Phi_{1,2} L_i e_j^c \, + h.c.$$

2HDM

After EWSB:

$$\Phi_{1,2} = \begin{pmatrix} \phi^+_{1,2} \\ \frac{1}{\sqrt{2}}[v_{1,2} + h_{1,2} + i a_{1,2}] \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}, \quad \begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ s_\beta & -c_\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}, \quad \tan\beta = \frac{v_2}{v_1}$$

We have four massive Higgs bosons: $h(\simeq h_{125}), H, A, H^\pm$

2HDM and Flavour problem

Generic Yukawa coupling leads to FCNC:

$$-\mathcal{L}_Y = Y^{ij}_{u\,1,2}\tilde{\Phi}_{1,2}Q_i u^c_j + Y^{ij}_{d\,1,2}\Phi_{1,2}Q_i d^c_j + Y^{ij}_{d\,1,2}\Phi_{1,2}L_i e^c_j + h.c.$$

$$(Y^{ij}_{f_1}c_\beta + Y^{ij}_{f_2}s_\beta)\frac{v}{\sqrt{2}}f_i f^c_j \quad \mathrm{vs} \quad (\mathrm{Y^{ij}_{f_1}c_\alpha - Y^{ij}_{f_2}s_\alpha)hf_i f^c_j}$$

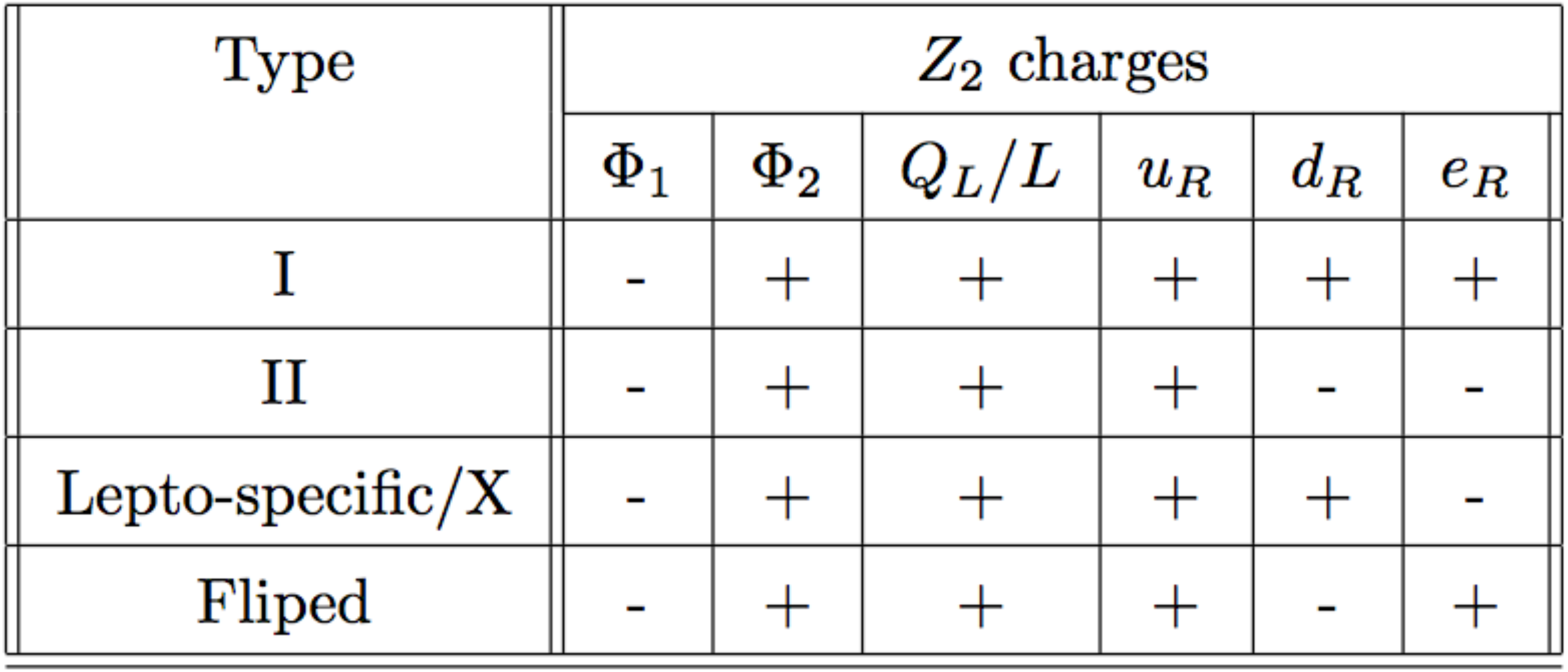
$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$m^{ij}_f \quad \mathrm{Mass} \neq \mathrm{Yukawa} \quad \mathrm{Y^{ij}_f}$$

- FCNC's arise because of the impossibility to simultaneously diagonalise two arbitrary complex matrices.

- One way to eliminate non-diagonal terms in the Lagrangian is by imposing flavour blind Z_2discrete symmetry

Types of 2HDM



Type	Z_2 charges					
	Φ_1	Φ_2	Q_L/L	u_R	d_R	e_R
I	-	+	+	+	+	+
II	-	+	+	+	-	-
Lepto-specific/X	-	+	+	+	+	-
Fliped	-	+	+	+	-	+

- Given a fermion couples only to one Higgs doublet

2HDM in SUSY and Non-SUSY: K.Ghosh et al., M. Mitra et al. B. Mukhopadhyay, S. Goswami , E. Chun et al, Rose et al., D. Das et al, D. Chaudhoury et al. and many

Yukawa structure in 2HDMs

- Type-I

Φ_1 does not couple to fermions

$$-\mathcal{L}_Y = Y_u \overline{Q}_L \widetilde{\Phi}_2 u_R + Y_d \overline{Q}_L \Phi_2 d_R + Y_l \overline{L}_L \Phi_2 l_R + \mathrm{H.c}$$

- Type-II

$$-\mathcal{L}_Y = Y_u \overline{Q}_L \widetilde{\Phi}_2 u_R + Y_d \overline{Q}_L \Phi_1 d_R + Y_l \overline{L}_L \Phi_1 l_R + \mathrm{H.c}$$

- Lepton specific(Type-X)

$$-\mathcal{L}_Y = Y_u \overline{Q}_L \widetilde{\Phi}_2 u_R + Y_d \overline{Q}_L \Phi_2 d_R + Y_l \overline{L}_L \Phi_1 l_R + \mathrm{H.c}$$

- Flipped(Type-Y)

$$-\mathcal{L}_Y = Y_u \overline{Q}_L \widetilde{\Phi}_2 u_R + Y_d \overline{Q}_L \Phi_1 d_R + Y_l \overline{L}_L \Phi_2 l_R + \mathrm{H.c}$$

2HDM Type II Status

- It is most popular one as natural to SUSY models
- Type II is excluded for low mass charged Higgs boson

$\bar{B} \to X_s\gamma$ puts a strong limit of $m_{H^\pm} > 480\ GeV$. Misiak, et.al., 1503.01789

$Br(B_s \to \mu^+\mu^-) \propto t_\beta^4/m_A^4$

→ Excludes $m_A/t_\beta \lesssim 10\ GeV$

- The main phenomenological searches at the LHC are

$$pp \to HA \quad hH \quad hA$$

$$pp \to H^+H^-$$

$$pp \to tH^\pm$$

$$pp \to tbH^\pm$$

Branco et al. Phys.Rept. 516 (2012) 1-102

Status of 2HDM Type X

- $\bar{B} \to X_s \gamma$ puts no bound on $m_{H^\pm}$ for $t_\beta > 2$.
- $B_s \to \mu^+ \mu^-$ not affected if $m_A \gtrsim 15\, GeV$.
- Type X at large t_β, being hadrophobic, is elusive at LHC.
- Being leptophilic, strong limits from precision leptonic observables like lepton universality in $Z \to ll\ \&\ l \to l' \nu \nu'$.

Slide courtesy EJC

Abe, et.al., 1504.07059
Cao, et.al., 0909.5146

- Can explain muon g-2 excess

- The light pseudoscalar and light charged Higgs boson is still allowed for Type X

Chun et al. PLB779 (2018) 201-205,PLB774 (2017) 20-25 ,
JHEP 1511 (2015) 099, JHEP 1411 (2014) 058

Scalar Dark Matter in Leptophilic Two-Higgs-Doublet

- Among four types of Z_2-symmetric 2HDMs, the type-X model is found to be a unique option for the explanation of the muon g – 2 anomaly
- A large parameter space allowed at 2σ favouring $\tan\beta > 30$ and $m_A \ll m_{H,H^\pm} \approx 200 - 400$ GeV
- A very light pseudo scalar is still allowed in this scenario

- Two Higgs doublets $\Phi_{1,2}$ and one singlet scalar S stabilized by the symmetry S → –S

$$\begin{aligned} V &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_1\Phi_2^\dagger) \\ &+ \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ &+ \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_1\Phi_2^\dagger)^2\right] \\ &+ \frac{1}{2}m_0^2S^2 + \frac{\lambda_S}{4}S^4 + S^2\left[\kappa_1|\Phi_1|^2 + \kappa_2|\Phi_2|^2\right], \quad (1) \end{aligned}$$

DM self Couplings

Higgs-DM couplings

- One is strongly constrained by direct detection experiments,
- Other remains free to be adjusted for the relic density

mainly through the process SS → AA

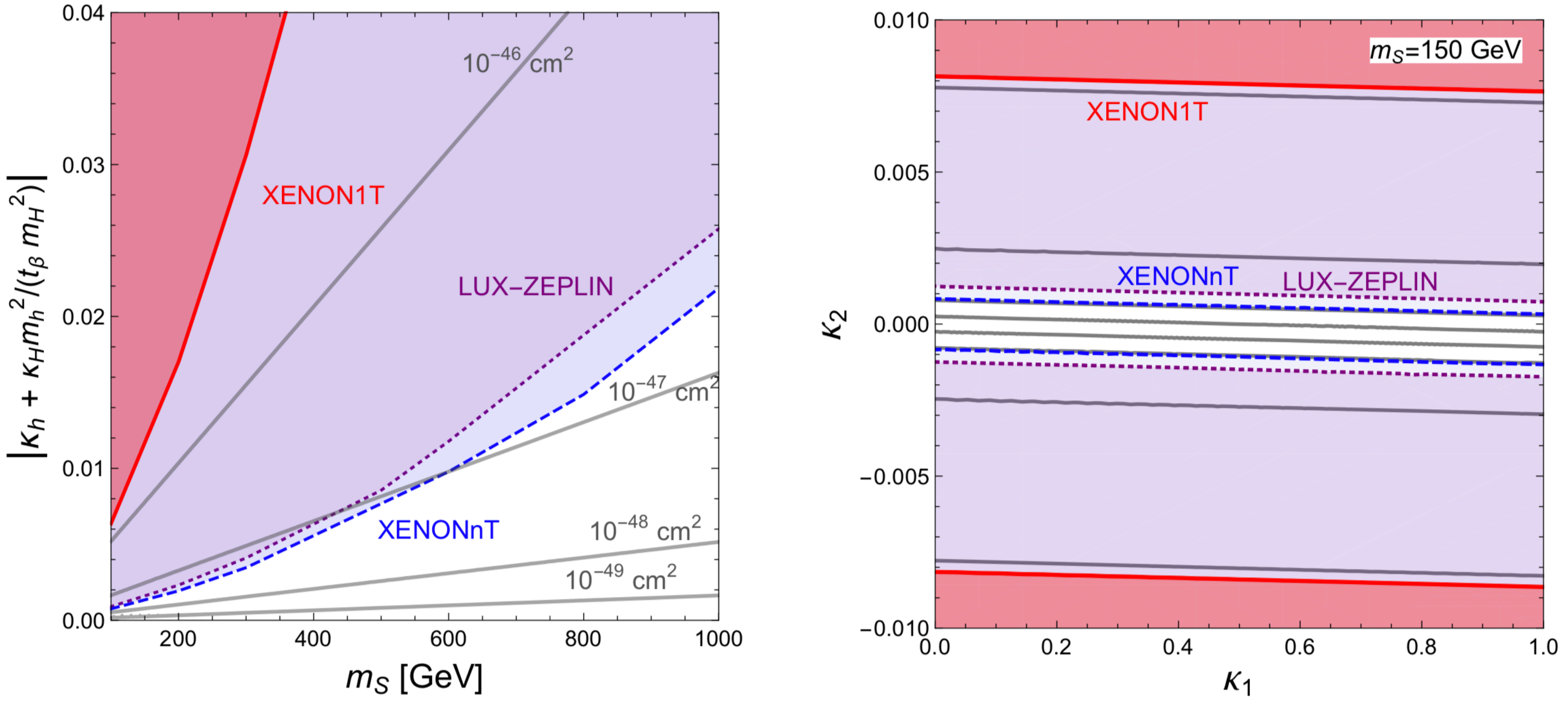
PB, Rusa Mandal, Eung Jin Chun
Phys.Lett. B779 (2018) 201-205

Sclar Dark matter in Leptophilic Two-Higgs-x

The spin-independent (SI) nucleonic cross section of the DM is given by

$$\sigma_N = \frac{m_N^2 v^2}{\pi(m_S + m_N)^2}\left(\frac{\kappa_h g_{NNh}}{m_h^2} + \frac{\kappa_H g_{NNH}}{m_H^2}\right)^2, \quad (9)$$

where $g_{NNh} \approx 0.0011$ [18] and $g_{NNH} \approx g_{NNh}/t_\beta$.

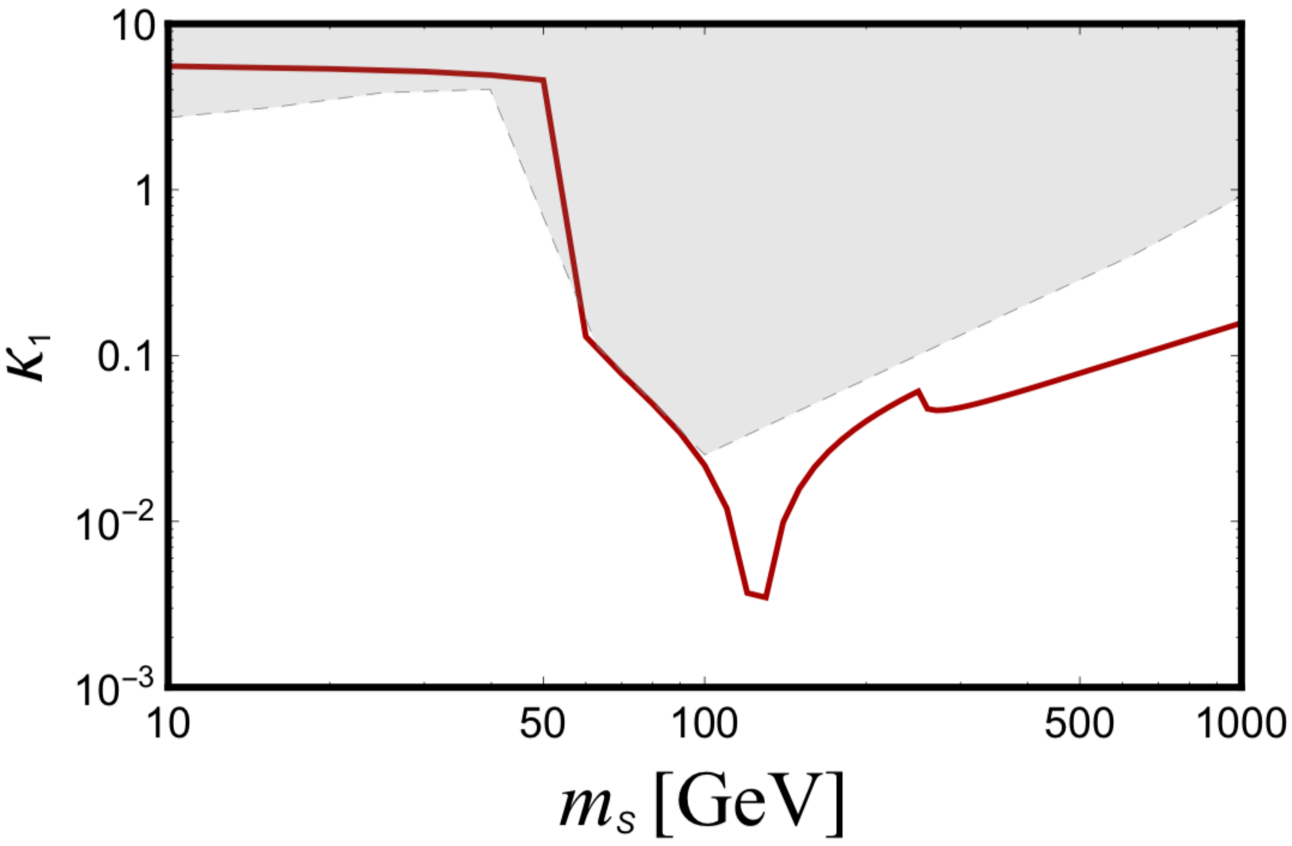


$$t_\beta >> 1,\ \kappa_h \simeq \kappa_2,\ \kappa_H \simeq 0$$

- Note that in the limit of tβ ≫ 1 and mH > mh, the combined coupling is dominated simply by κ2 and thus strongly constrained as in the SM Higgs portal scenario.

Scalar Dark Matter in Leptophilic Two-Higgs-Doublet

DM annihilation



- The right DM relic density is obtained by the red line through the DM annihilation channels SS → $\tau\tau$,AA, and HH/H^+H^-
- The gray shaded region is excluded by Fermi-LAT gamma ray detection in the 2τ and 4τ final states.
- The plot is obtained for $m_A = 50$ GeV, $m_{H,H^\pm} = 250$ GeV, and $t_\beta = 50$

PB, Rusa Mandal, Eung Jin Chun
Phys.Lett. B779 (2018) 201-205

Charged Higgs in Type-X 2HDM with inverse-Seesaw

$$
\begin{aligned}
-\mathcal{L} = &\left(Y_u \bar{Q}_L \tilde{\Phi}_2 u_R + Y_d \bar{Q}_L \Phi_2 d_R + Y_l \bar{\ell}_L \Phi_1 e_R + Y_N^{(\prime)} \bar{\ell}_L \tilde{\Phi}_{1,2} N_R \right.\\
&\left. + M_N \bar{N}_R^c S_2 + \text{h.c.}\right) + \mu \bar{S}_2^c S_2 + V(\Phi_1, \Phi_2).
\end{aligned}
$$

$$
\Phi_{1,2} = \begin{pmatrix} \phi_{1,2}^+ \\ \frac{1}{\sqrt{2}}\left(v_{1,2} + h_{1,2} + i a_{1,2}\right) \end{pmatrix}
$$

The neutrino mass terms in the Lagrangian can be written as

$$
-\mathcal{L}_m^\nu = \mu \bar{S}_2^c S_2 + m_D \bar{\nu}_L N_R + M_N \bar{N}_R^c S_2 + \text{h.c.}, \tag{2.3}
$$

where $m_D = Y_N^{(\prime)} v_{1,2}/\sqrt{2}$ for Type-X and Type-X′, respectively. In the basis of ν_L^c, N_R, S_2, the 9×9 neutrino mass matrix takes the form as

$$
m_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_N \\ 0 & M_N^T & \mu \end{pmatrix}. \tag{2.4}
$$

$$
\begin{aligned}
m_{\nu_\ell} &= m_D M_N^{-1} \mu (M_N^T) m_D^T, \\
m_{N_H}^2 &= m_{N_{H'}}^2 = M_N^2 + m_D^2.
\end{aligned}
$$

PB, Rusa Mandal, Eung Jin Chun
JHEP 1908 (2019) 169

Charged Higgs in Type-X 2HDM with inverse-Seesaw

Couplings for Type-X extensions

$$\begin{aligned}
\bar{\ell}_L H^- N_R : &\quad iY_N \sin\beta \big[\bar{\ell}_L H^- N_R + \text{h.c.}\big], \\
\bar{\nu}_L h N_R : &\quad \frac{iY_N \sin\alpha}{\sqrt{2}} \big[\bar{\nu}_L h N_R + \text{h.c.}\big], \\
\bar{\nu}_L H N_R : &\quad \frac{-iY_N \cos\alpha}{\sqrt{2}} \big[\bar{\nu}_L H N_R + \text{h.c.}\big], \\
\bar{\nu}_L A N_R : &\quad \frac{-Y_N \sin\beta}{\sqrt{2}} \big[\bar{\nu}_L A N_R + \text{h.c.}\big].
\end{aligned}$$

Enhanced at high tanβ

- At high tanβ region, the decay modes $H^{\pm} \to l_L N_R$ and $N_R \to A\nu_L$ are enhanced
- $H^{\pm} \to AW^{\pm}$ is governed only by the weak gauge coupling g_2 in all 2HDM scenarios and independent of tanβ
- Charged Higgs bosons are searched in $\nu\,\tau,\ t\,b$ modes
- Type-X charged Higgs production is down due to small coupling with quarks
- It has a very light pseudoscalar $m_A \sim 50\,\mathrm{GeV}$
- Dominant branchings are to $A\,W^{\pm}\,\text{and}\,\ell\,\mathrm{N_R}$
- Light charged Higgs is still a possibility

Final states at the LHC

$$\begin{aligned} pp &\to AH \to \tau\bar{\tau}N_i\nu_i \\ &\to \tau\bar{\tau}W^{\pm}\ell_i^{\mp}\nu_i \\ &\to \tau\bar{\tau}\ell_j^{\pm}\nu_j\ell_i^{\mp}\nu_i, \end{aligned}$$

$$\begin{aligned} pp &\to AH^{\pm} \to \tau\bar{\tau}N_i\ell_i^{\pm} \\ &\to \tau\bar{\tau}W^{\pm}\ell_i^{\mp}\ell_i^{\pm} \\ &\to \tau\bar{\tau}\ell_j^{\pm}\nu_j\ell_i^{\mp}\ell_i^{\pm} \end{aligned}$$

- $2\tau + 2\ell$ and $2\tau + 3\ell$ are looked into at the LHC

- For light pseudo scalar $4\tau + X$ final states are looked into

$$\begin{aligned} H^{\pm}H &\to Ne^{\pm}N\nu \\ &\to 2A + e^{\pm} + 3\nu \\ &\to 4\tau + e^{\pm} + \not{p}_T \\ H^{\pm}H^{\mp} &\to Ne^{+}Ne^{-} \\ &\to 4\tau + OSE + \not{p}_T \\ AH &\to \tau\tau N\nu \\ &\to 4\tau + \not{p}_T \\ AH^{\pm} &\to \tau\tau Ne^{\pm} \\ &\to 4\tau + e^{\pm} + \not{p}_T \end{aligned}$$

- The inverse seesaw Yukawa coupling is shown to be probed down to YN ~ 0.2 at HL LHC with 3000 fb^{-1}

PB, Rusa Mandal, Eung Jin Chun
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Inert Higgs doublet model (IHDM)

- What happens if one of the two Higgs doublets does not get vev ?
- You can say that it is inert or spectator Higgs doublet

- One of the Higgs doublet is odd under Z_2 symmetry and all the other SM particles are even under

$$\Phi_2 \to -\Phi_2, \quad \Psi_{SM} \to \Psi_{SM}$$

- It guarantees the absence of Yukawa couplings between fermions and the inert doublet

- This Higgs doublet does not get vev.

- Most generic Higgs potential can be written as:

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2) + +h.c.]$$

IHDM

- Higgs spectrum: $h(\simeq h_{125}), H, A, H^{\pm}$
- LEP-I exclude the possibility that massive SM gauge bosons decay into inert particles

$$m_{H^\pm} < m_{H/A} + m_{W^\pm}, \quad m_H < 2m_{W^\pm}, \quad m_H < m_A + m_Z$$

- The lighter of H, A is the lightest inert particle (ILP) and can be a DM candidate.

Annihilation channel: $HH/AA \to W^{\pm}W^{\mp}, ZZ$

Co-annihilation: $HA \xrightarrow{Z} SMSM$ and $\mathrm{HH}^{\pm} \xrightarrow{\mathrm{W}^{\pm}} \mathrm{SMSM}$

LHC searches: $p, p \xrightarrow{Z/\gamma} HA,\ H^+H^-$

$$pp \xrightarrow{W^{\pm}} H/A\,H^{\pm}$$

Decays: $H^{\pm} \to A/HW^{\pm}$

$$A \to HZ$$

PoS Charged 2010:030, 2010
Barbieri et al. PRD74,015007(2006),
Rajasekaran et al.PRD76:095011,2007
S. Chaubey JHEP 1711 (2017) 080

Vacuum Stability in IHDM with RHN

- Type-I seesaw Lagrangian

$$\mathcal{L}_{\rm I} = i\overline{N}_{R_i}\partial\!\!\!/ N_{R_i} - \left(Y_{N_{ij}}\overline{L}_i\widetilde{\Phi}_1 N_{R_j} + \frac{1}{2}\overline{N}^c_{R_i} M_{R_i} N_{R_i} + \text{H.c.}\right)$$

- Neutrino mass matrix:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^\intercal & M_R \end{pmatrix}$$

- Light neutrino mass

$$m_\nu \simeq -M_D M_R^{-1} M_D^\intercal$$

- Inverse-Seesaw Lagrangian

$$\mathcal{L}_{\rm ISS} = i\overline{N}_R\partial\!\!\!/ N_R + i\overline{S}\partial\!\!\!/ S - \left(Y_{N_{ij}}\overline{L}_i\widetilde{\Phi}_1 N_{R_j} + \overline{N}_{R_i} M_{R_{ij}} S_j + \frac{1}{2}\overline{S}^c_i \mu_{S_{ij}} S_j + \text{H.c.}\right)$$

- Neutrio mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^\intercal & 0 & M_R \\ 0 & M_R^\intercal & \mu_S \end{pmatrix}$$

- Light neutrino mass

$$m_\nu \simeq M_D M_R^{-1} \mu_S (M_R^\intercal)^{-1} M_D^\intercal$$

- Rest are almost degenerate around $M_R \pm \mu_S/2$

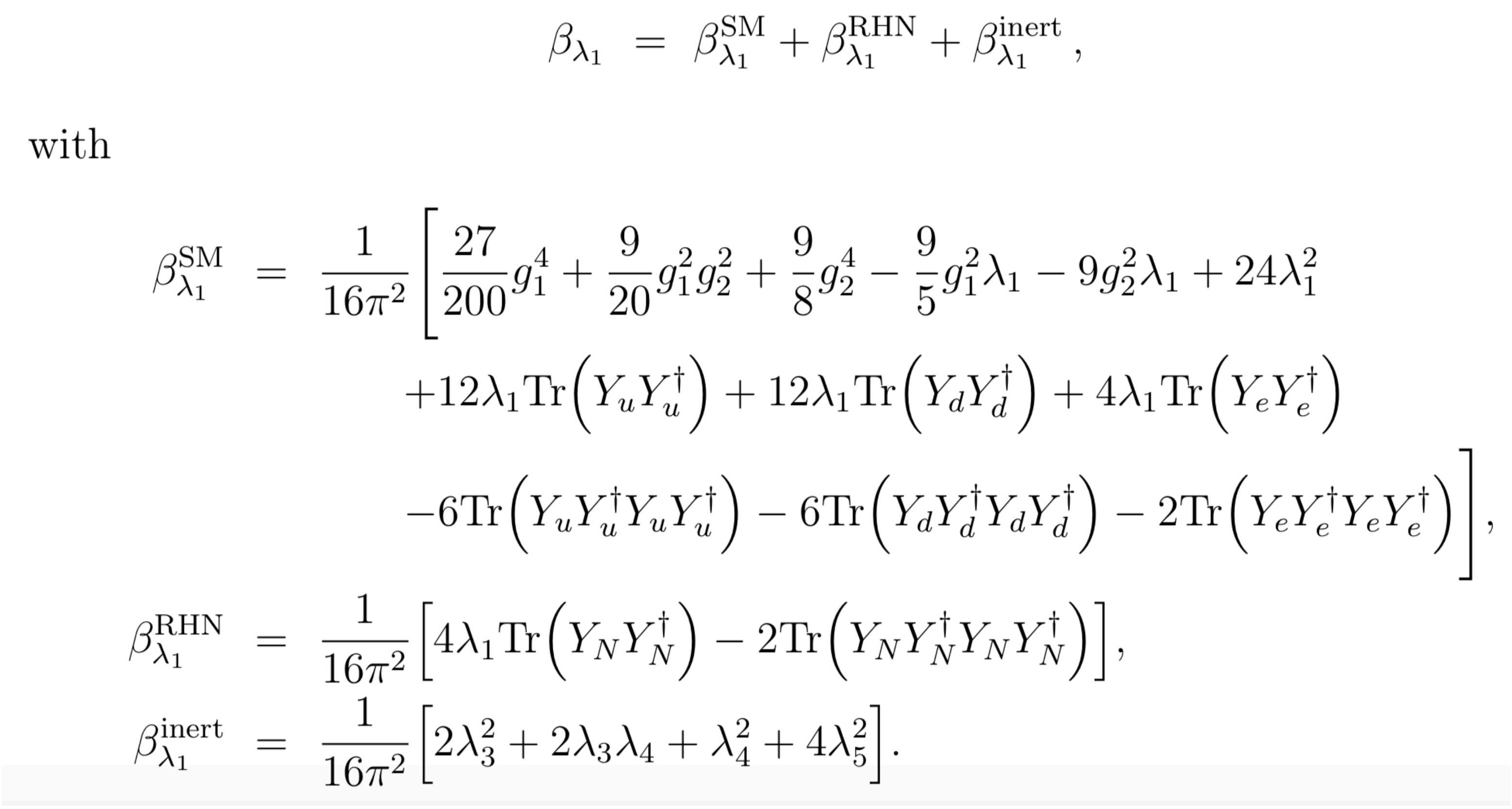
PB, Bhupal Dev, Arjun Kumar, Shilpa Jangid
arXiv:2001.01764 **[hep-ph]**

Vacuum Stability in IHDM with RHN

- Scalar Potential:

$$\begin{aligned} V_{\text{scalar}} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{H.c}) \\ &+ \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ \left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{H.c}\right], \end{aligned}$$

- Beta-functions corresponding



$$\beta_{\lambda_1} = \beta_{\lambda_1}^{\text{SM}} + \beta_{\lambda_1}^{\text{RHN}} + \beta_{\lambda_1}^{\text{inert}},$$

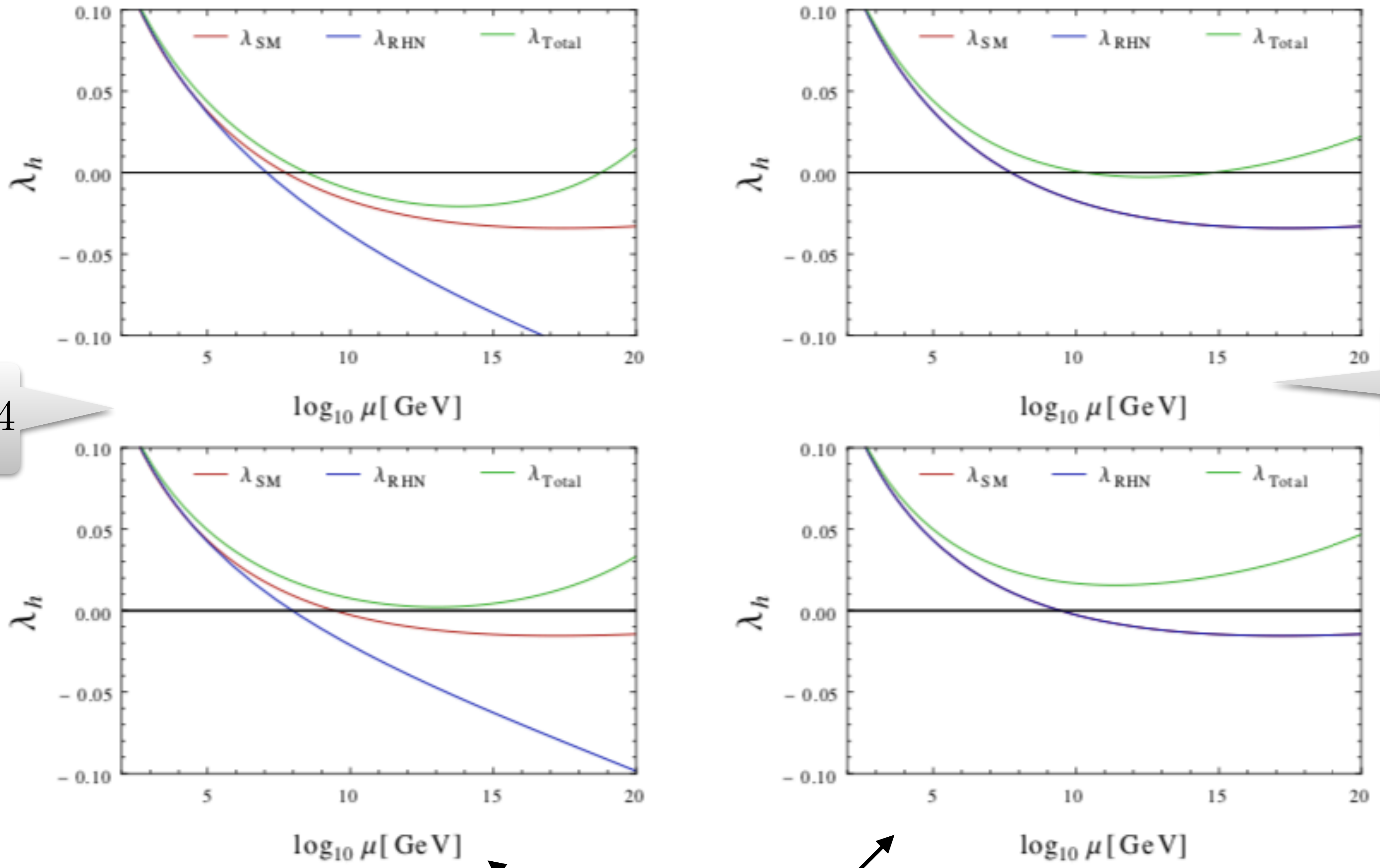
with

$$\begin{aligned} \beta_{\lambda_1}^{\text{SM}} &= \frac{1}{16\pi^2}\Bigg[\frac{27}{200}g_1^4 + \frac{9}{20}g_1^2g_2^2 + \frac{9}{8}g_2^4 - \frac{9}{5}g_1^2\lambda_1 - 9g_2^2\lambda_1 + 24\lambda_1^2 \\ &\quad +12\lambda_1\text{Tr}\Big(Y_uY_u^\dagger\Big) + 12\lambda_1\text{Tr}\Big(Y_dY_d^\dagger\Big) + 4\lambda_1\text{Tr}\Big(Y_eY_e^\dagger\Big) \\ &\quad -6\text{Tr}\Big(Y_uY_u^\dagger Y_uY_u^\dagger\Big) - 6\text{Tr}\Big(Y_dY_d^\dagger Y_dY_d^\dagger\Big) - 2\text{Tr}\Big(Y_eY_e^\dagger Y_eY_e^\dagger\Big)\Bigg], \\ \beta_{\lambda_1}^{\text{RHN}} &= \frac{1}{16\pi^2}\Big[4\lambda_1\text{Tr}\Big(Y_NY_N^\dagger\Big) - 2\text{Tr}\Big(Y_NY_N^\dagger Y_NY_N^\dagger\Big)\Big], \\ \beta_{\lambda_1}^{\text{inert}} &= \frac{1}{16\pi^2}\Big[2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + 4\lambda_5^2\Big]. \end{aligned}$$

Vacuum Stability in IHDM with RHN

One-loop

No effect of RHN



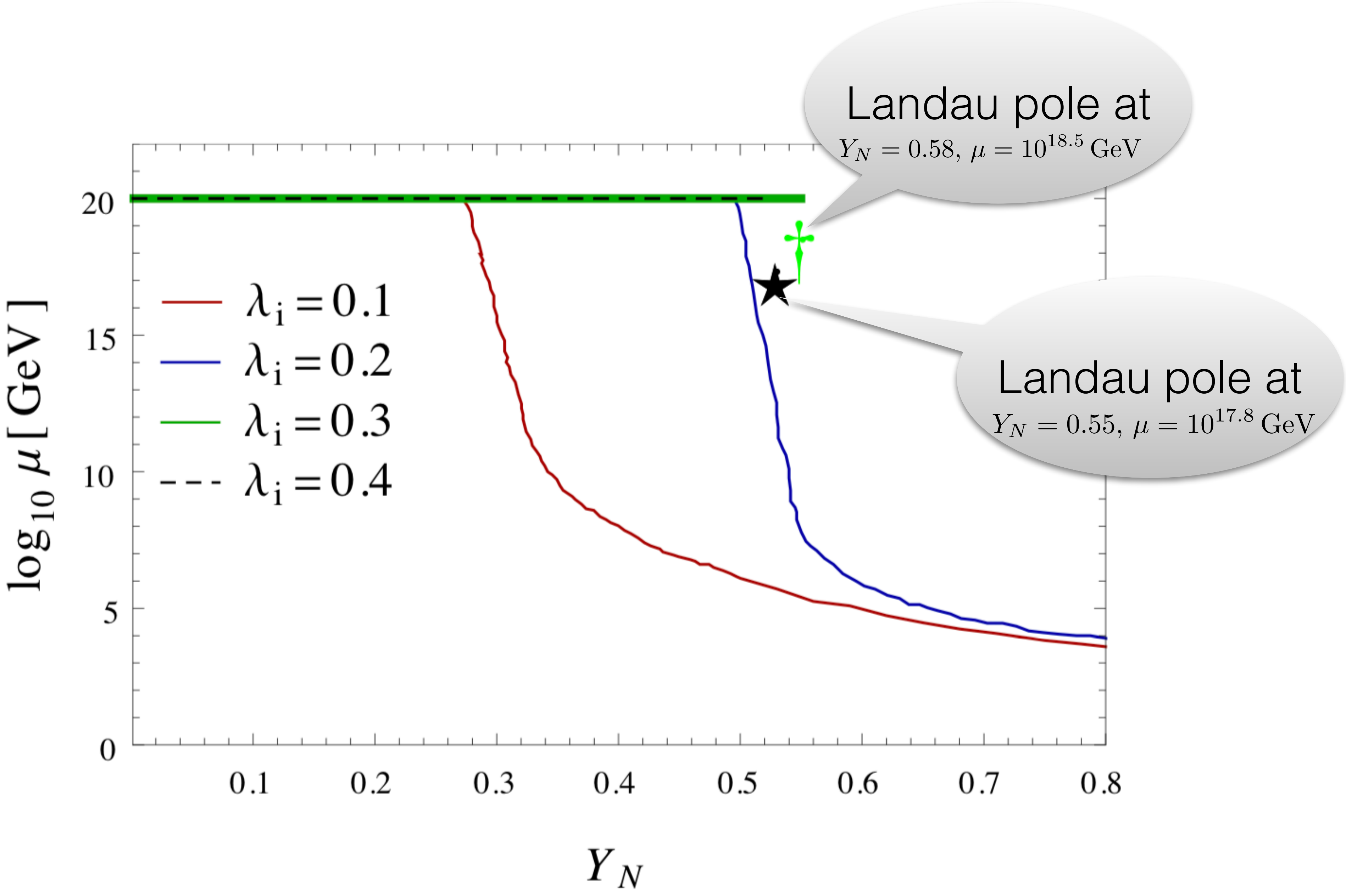
$Y_N = 0.4$

$Y_N = 0.01$

Two-loop

Vacuum Stability in IHDM with RHN

- Stability scale increases with higher values of λ_i for higher Y_N
- However, higher values of λ_i hits Landau pole at earlier scale

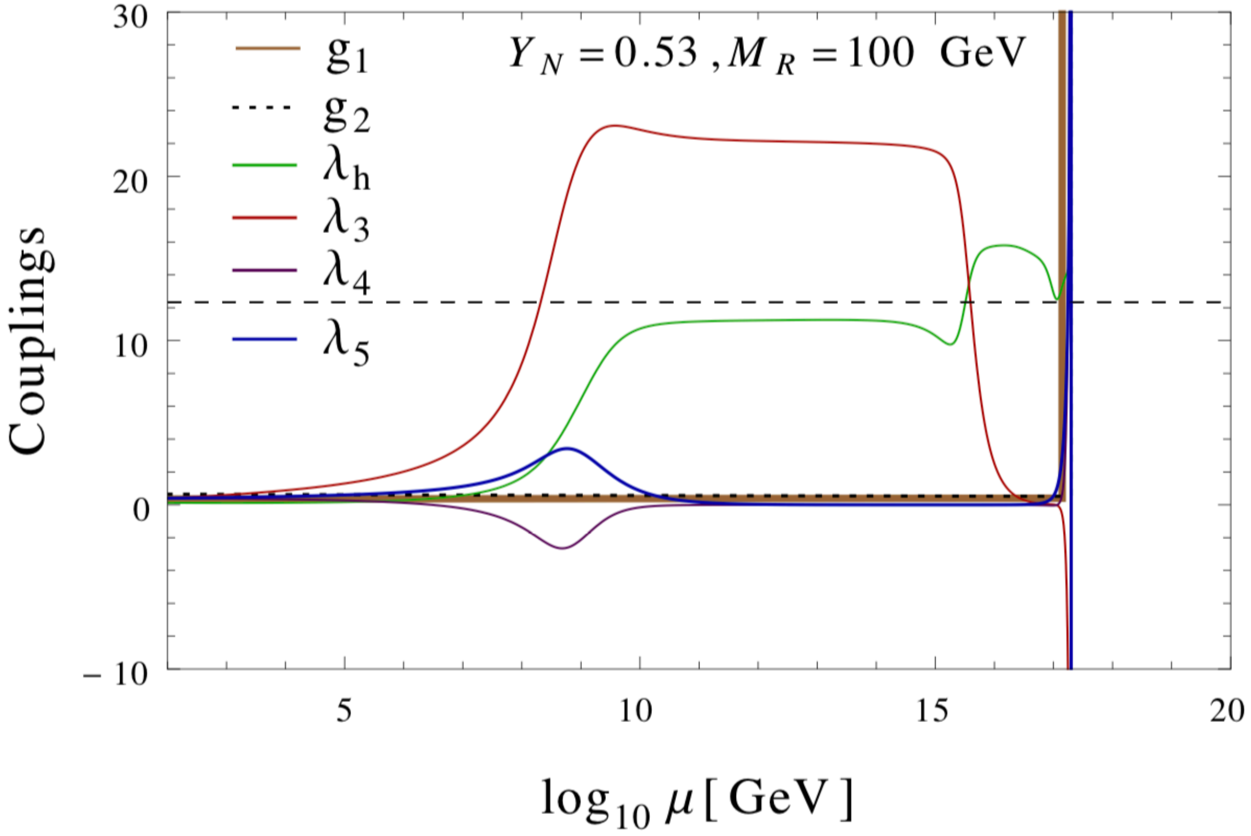


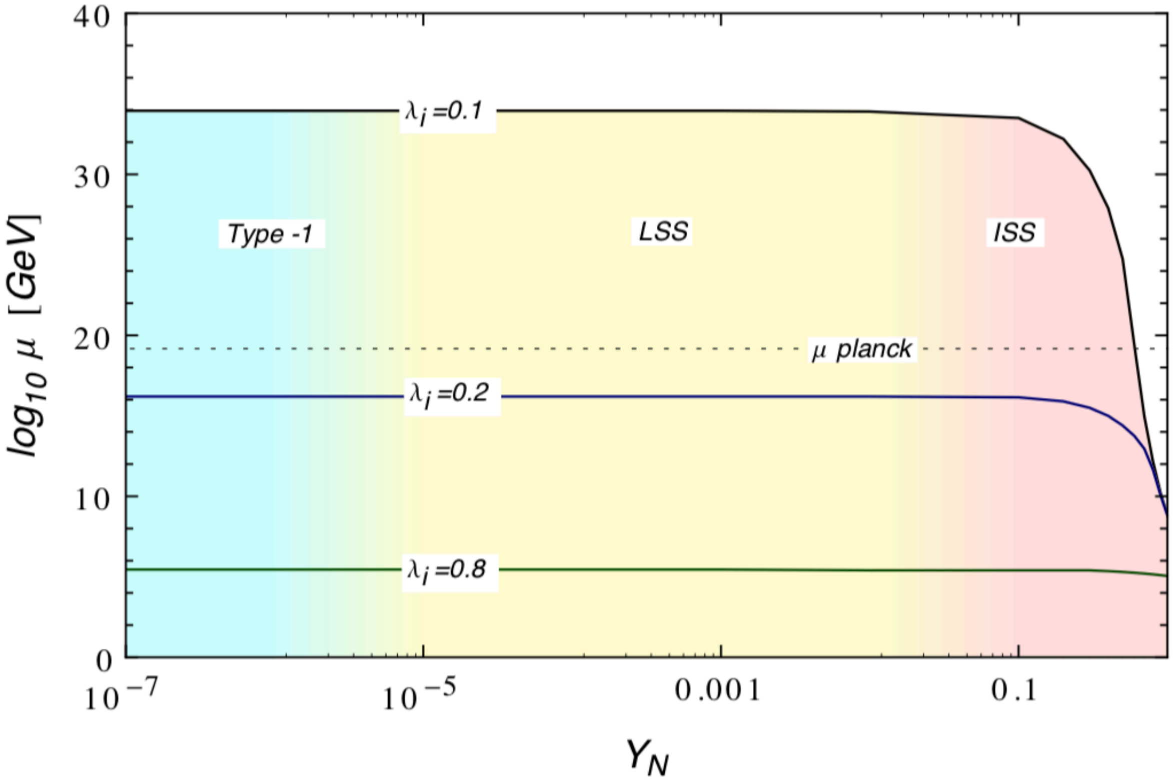
Landau pole at
$Y_N = 0.58,\ \mu = 10^{18.5}\,\mathrm{GeV}$

Landau pole at
$Y_N = 0.55,\ \mu = 10^{17.8}\,\mathrm{GeV}$

Vacuum Stability in IHDM with RHN

- Perturbative bounds on the couplings





- $Y_N = 0.53,\ \lambda_i = 0.4(\mu_{EW})\ M_R = 100\,\mathrm{GeV}$

- $Y_N \simeq 0.15$ perturbative scale gets affected via RHN

Vacuum Stability from RG-improved potential

- The effective potential in the h direction is given by

$$V_{\text{eff}}(h,\mu) \;\simeq\; \lambda_{\text{eff}}(h,\mu)\frac{h^4}{4}, \quad \text{with } h \gg v\,,$$

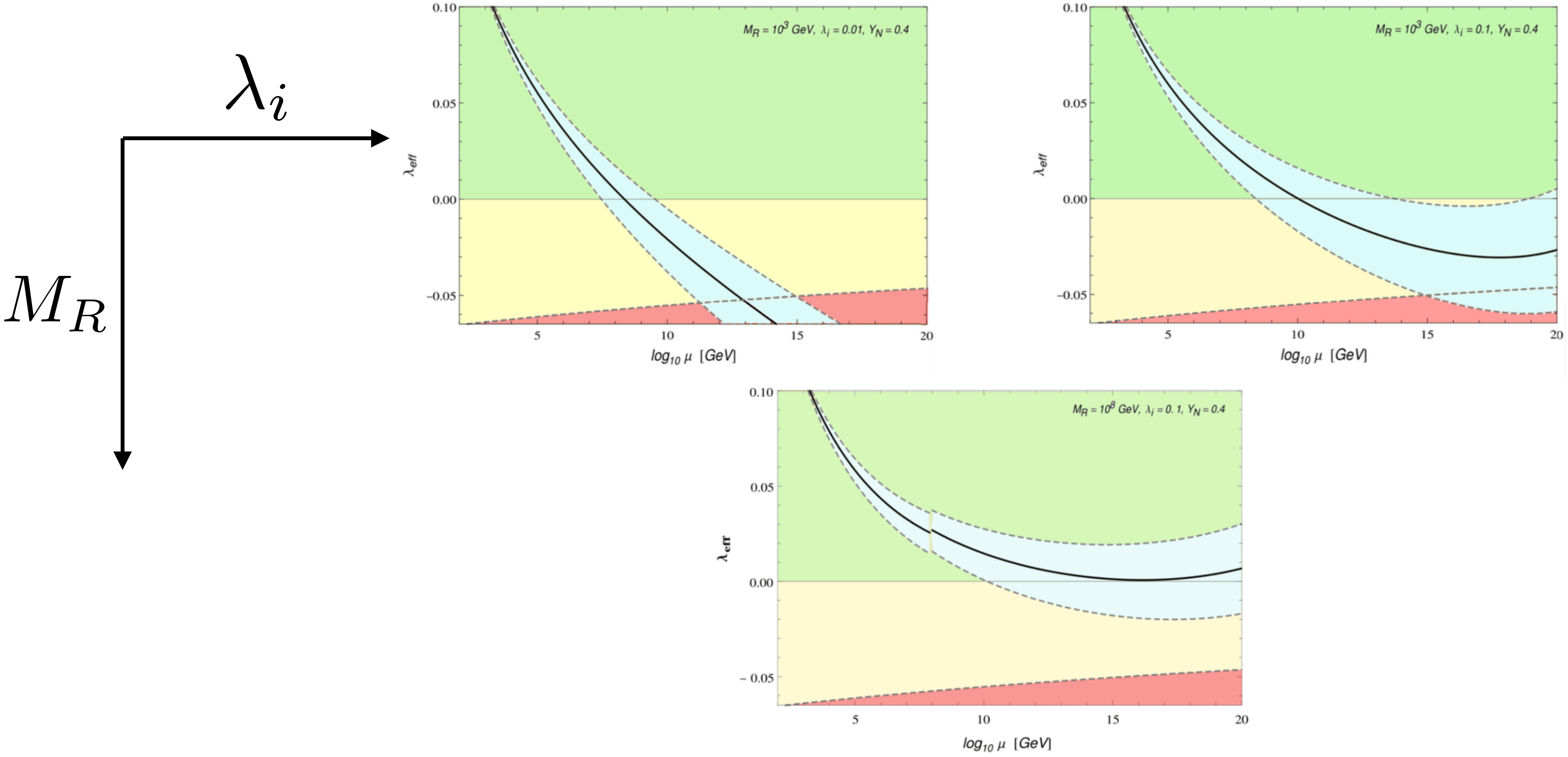
- Where λ_{eff} is given by

$$\begin{aligned}\lambda_{\text{eff}}\left(h,\mu\right) \;\simeq\; &\underbrace{\lambda_h\left(\mu\right)}_{\text{tree-level}} + \frac{1}{16\pi^2}\Bigg\{ \underbrace{\sum_{\substack{i=W^{\pm},Z,t,\\ h,G^{\pm},G^0}} n_i\kappa_i^2\Big[\log\frac{\kappa_i h^2}{\mu^2} - c_i\Big]}_{\text{Contribution from SM}} \\ &+ \underbrace{\sum_{i=H,A,H^{\pm}} n_i\kappa_i^2\Big[\log\frac{\kappa_i h^2}{\mu^2} - c_i\Big]}_{\text{Contribution from inert doublet}} + \underbrace{2\sum_{i=1,2,3} n_i\kappa_i^2\Big[\log\frac{\kappa_i h^2}{\mu^2} - c_i\Big]}_{\text{Contribution from RHN}} \Bigg\}\end{aligned}$$

Mestability and instability

- Condition of metastability

$$0 \;>\; \lambda_{\rm eff}(\mu) \;\gtrsim\; \frac{-0.065}{1-0.01\log\left(\frac{v}{\mu}\right)}$$

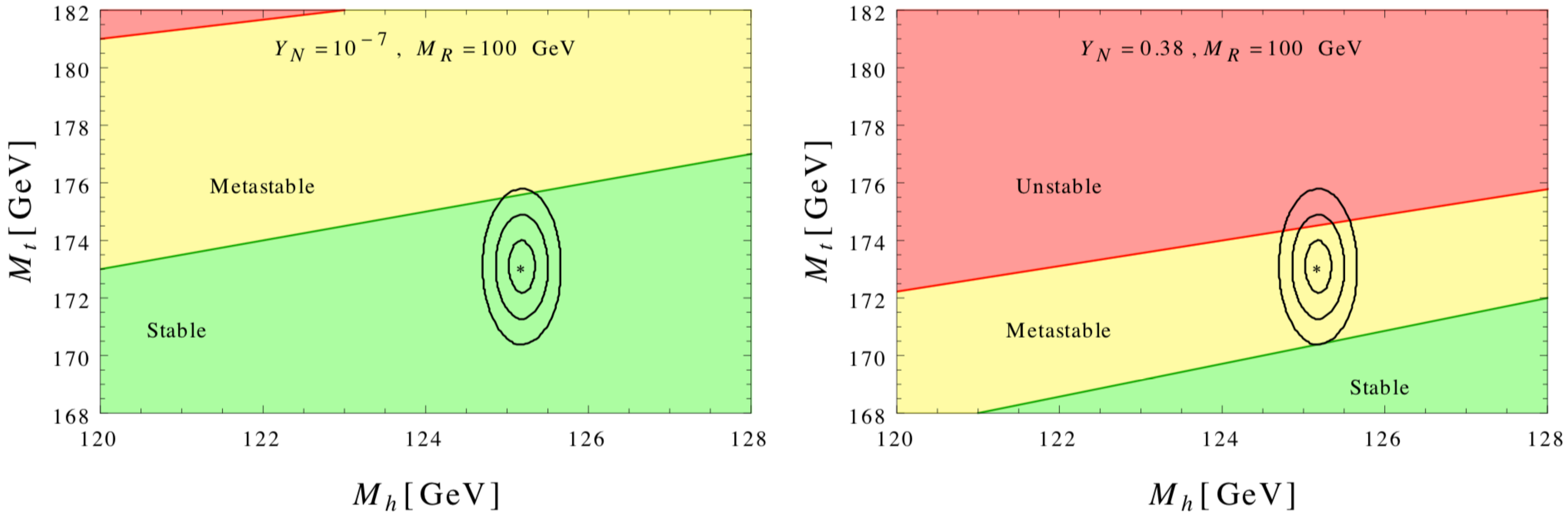


- λ_i are increased from 0.01 to 0.1 for the same value of $Y_N = 0.4$ and $M_R = 10^3$, $\lambda_{\rm eff}$ becomes unstable at 10^{15} GeV instead of 10^{11} GeV
- Stability also gets enhanced as we increase the RHN mass

Mestability and instability

- Condition of metastability

$$0 \; > \; \lambda_{\text{eff}}(\mu) \; \gtrsim \; \frac{-0.065}{1 - 0.01 \log\left(\frac{v}{\mu}\right)}$$



(a) $Y_N = 10^{-7}$

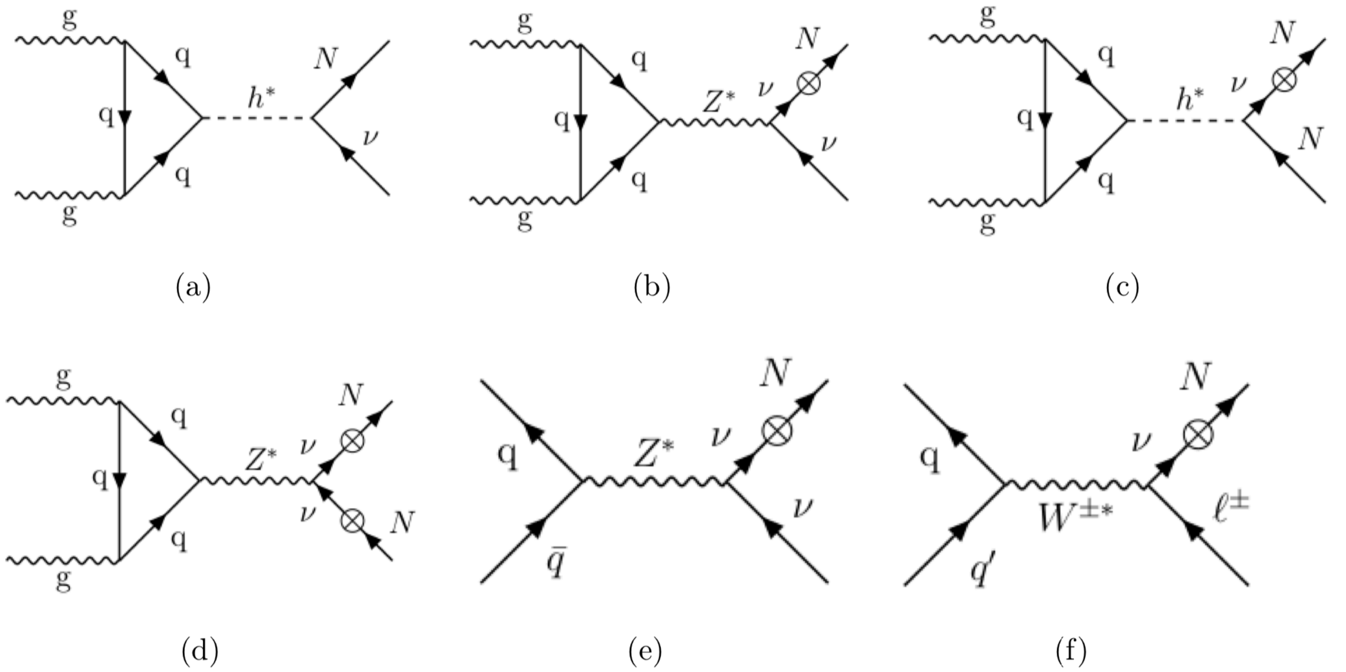
(b) $Y_N = 0.38$

- Lower Y_N corresponds to almost stable region
- Higher Y_N corresponds to some metastability and instability

PB, Bhupal Dev, Arjun Kumar, Shilpa Jangid
arXiv:2001.01764 [hep-ph]

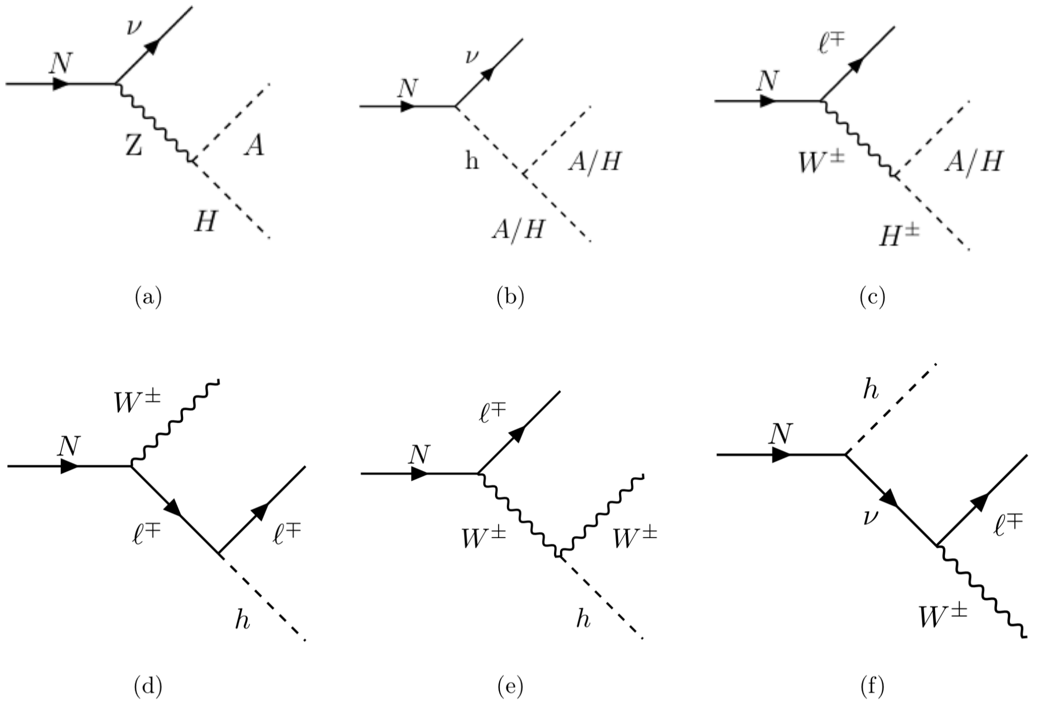
Phenomenology in IHDM with RHN

- RHN can be produced only via EW mixing



- At 14 TeV LHC, Drell-Yan is dominant and at 100 TeV it is gluon fusion

- RHN sectors connects to IDM only via three-body decays



PB, Bhupal Dev, Arjun Kumar, Shilpa Jangid
arXiv:2001.01764 [hep-ph]

Radiative neutrino mass with an IDM

$$\mathcal{L} \supset h_{ij}\bar{L}_i\epsilon\Phi N_j + \frac{1}{2}M_i\bar{N}_i^C N_i + \text{H.c.},$$

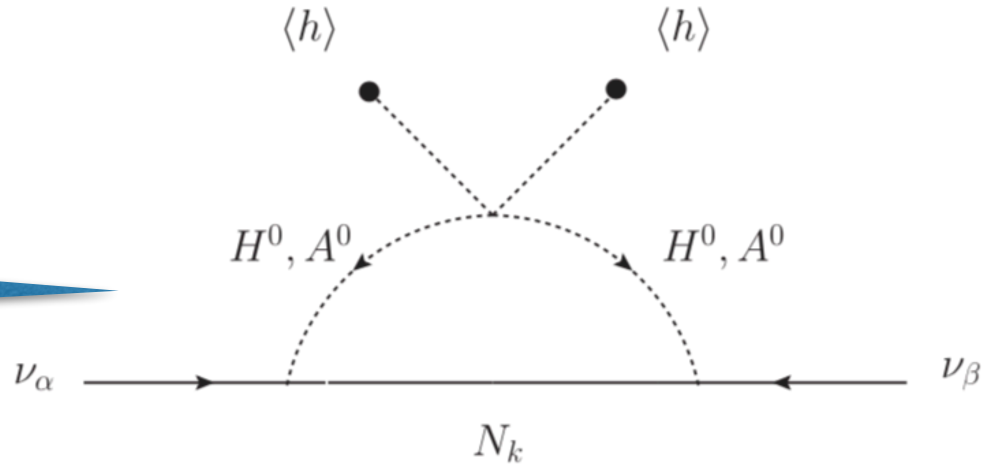
- Both RHN and IDM are odd under Z_2
- No Tree-level Dirac mass possible
- No Tree-level mixing between level left-right-handed Neutrinos
- Light neutrino mass is generated via one-loop

SM Higgs doublet

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

Inert Higgs doublet

Light neutrinos mass at one loop



Ahriche et al. :PRD 97, 095012, 2018

Heavy Higgs bounds

- H->WW: Combined upper limits at 95% confidence level on the product of the cross section and branching fraction exclude a heavy Higgs boson with SM-like couplings and decays up to 1870 GeV

CMS: arXiv:1912.01594 [hep-ex]

- H->ZZ: Bounds cross-section in ZZ decay modes are given till 3 TeV.

CMS:JHEP 06 (2018) 127

- $A \to b\bar{b}/\tau\bar{\tau}$: Bounds on cross-section give till 900 GeV in $2b + 2\tau$ mode

CMS:Phys. Lett. B 778 (2018) 101

Triplet extension

Possibilities ?

1. Inert
2. Real Triplet
3. Complex triplet with zero hypercharge
4. Triplets with non-zero hypercharge
5. Left-right Symmetric Model
6. Georgi-Machacek Model

Gain?

1. Dark matter
2. New Higgs bosons
3. Solving neutrino mass generation
4. Invisible Higgs boson!(?)

Constraints

- Due to SU(2) charged they couple to W boson and can contribute to W mass

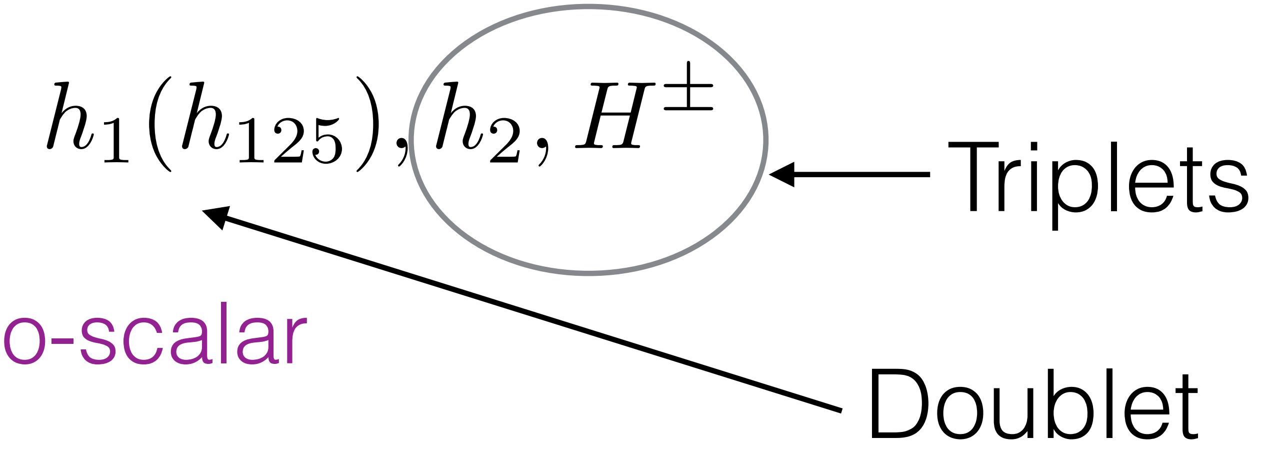
SM+Real Triplet

- SM with a Y=0 real SU(2) triplet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad T = \begin{bmatrix} \frac{T^0}{\sqrt{2}} & T^+ \\ T^- & -\frac{T^0}{\sqrt{2}} \end{bmatrix}$$

$$\begin{aligned} V(\Phi, T) &= m_\Phi^2 \Phi^\dagger \Phi + m_T^2 Tr(T^\dagger T) + \lambda_1 |\Phi^\dagger \Phi|^2 \\ &+ \lambda_2 (Tr|T^\dagger T|)^2 + \lambda_3 \Phi^\dagger \Phi Tr(T^\dagger T) + A(\Phi^\dagger T \Phi) \end{aligned}$$

- EWSB condition: $\phi^0 = v_1 + \phi_r^0 + iG^0 \text{ and } \mathrm{T}^0 = \mathrm{v_T} + \mathrm{T_r^0}$



- Particle spectrum: $h_1(h_{125}), h_2, H^\pm$

Triplets

Doublet

- There is no pseudo-scalar
- h_2 Does not couple to ZZ

SM+Real Triplet

- Triplets do not couple to fermions: as no right-handed SU(2) fermonic doublet present

$\bar{L}TL$ Identically zero

- We will come to the possibility later

- However, doublet-triplet mixing via $\lambda_3 \,\mathrm{and}\, \mathrm{A}$ opens up such couplings

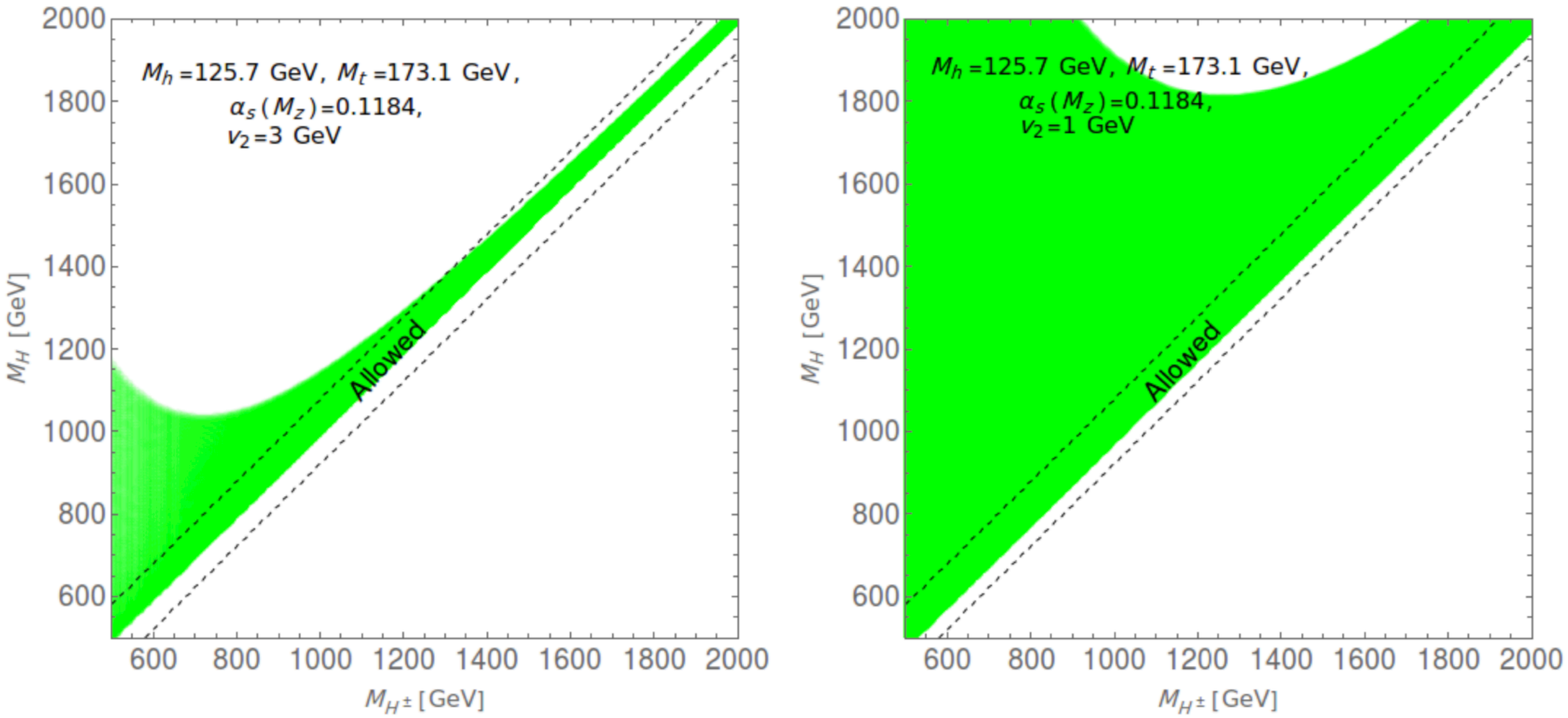
- Such mixings are constrained by Higgs data from LHC

- $\mathcal{B}(h_{125} \to A\,A) \lesssim 18\%$ as constrainted from Higgs data

PB,Claudio Coriano,Antonio Costantini: JHEP 1512 (2015) 127
Chabab et al.: 10.1140/epjc/s10052-018-6339-2

SM+Real Triplet

Stability and perturbativity bounds



(a) (b)

FIG. 1. *The allowed region (green) from the unitarity, perturbativity and absolute stability which is valid up to the Planck mass* $M_{\rm Pl}$. *The region between the black-dashed line is allowed from the EWPT data at* 2σ.

Najimuddin Khan
Eur.Phys.J. C78 (2018) no.4, 341

Inert Triplet

- If the triplet field is odd under Z_2: $T \rightarrow -T$, the potential

$$V(\Phi, T) = m_\Phi^2 \Phi^\dagger \Phi + m_T^2 Tr(T^\dagger T) + \lambda_1 |\Phi^\dagger \Phi|^2 + \lambda_2 (Tr|T^\dagger T|)^2 + \lambda_3 \Phi^\dagger \Phi Tr(T^\dagger T$$

- Triplet does not get vev

- Neutral component T^0 can become lightest inert particle (ITP) and a candidate dark matter.

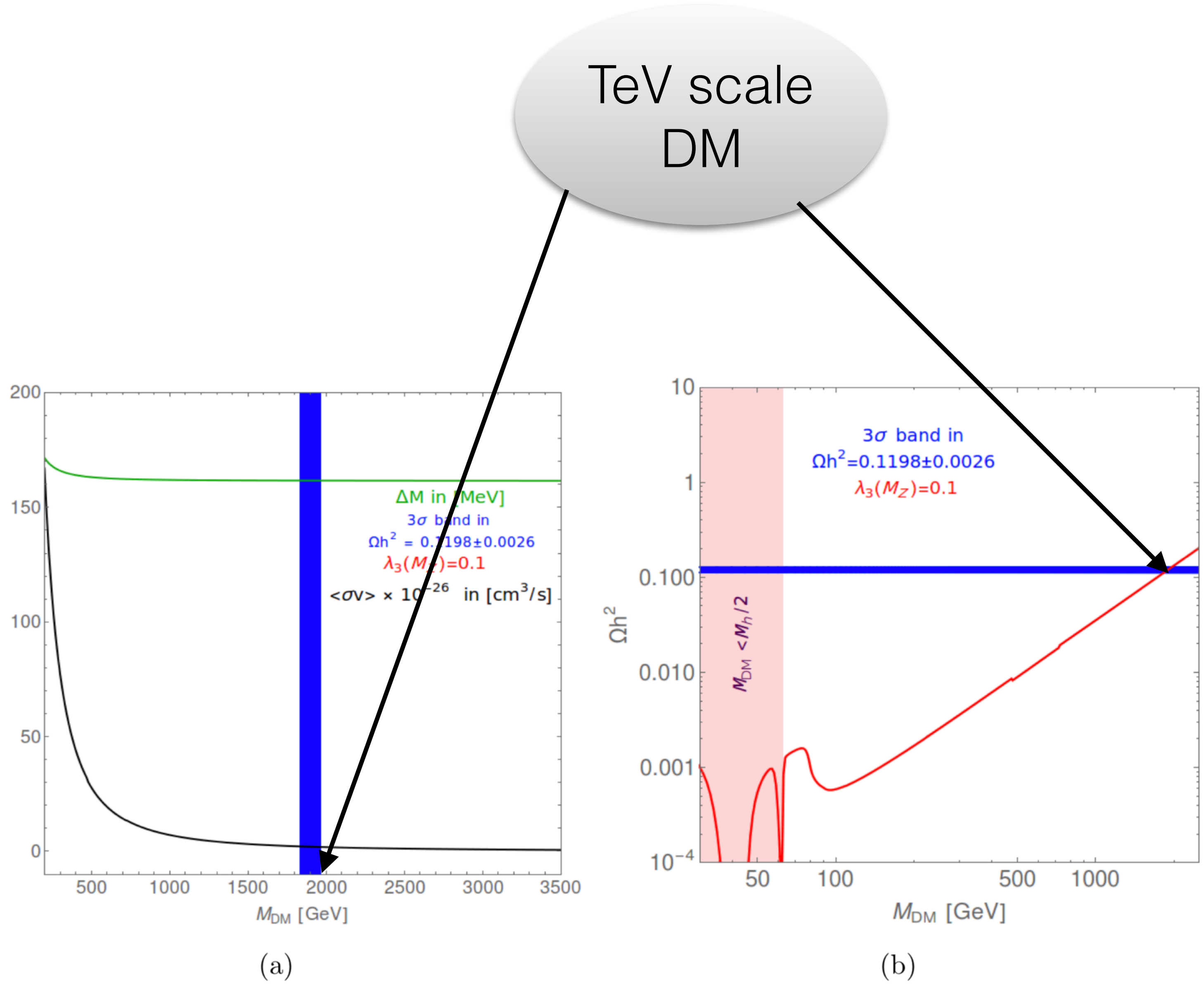
- In this case triplet and doublet does not mix at all.

- Tree-level mass values

$$m_h^2 = 2\lambda_1 v^2$$
$$m_{T^0}^2 = 2m_T^2 + \lambda_3 v^2$$
$$m_{T^\pm}^2 = 2m_T^2 + \lambda_3 v^2$$

- Loop level mass difference is

$$\Delta m_{T^\pm - T^0} \sim 150\,\mathrm{MeV} \sim \mathrm{m}_\pi$$

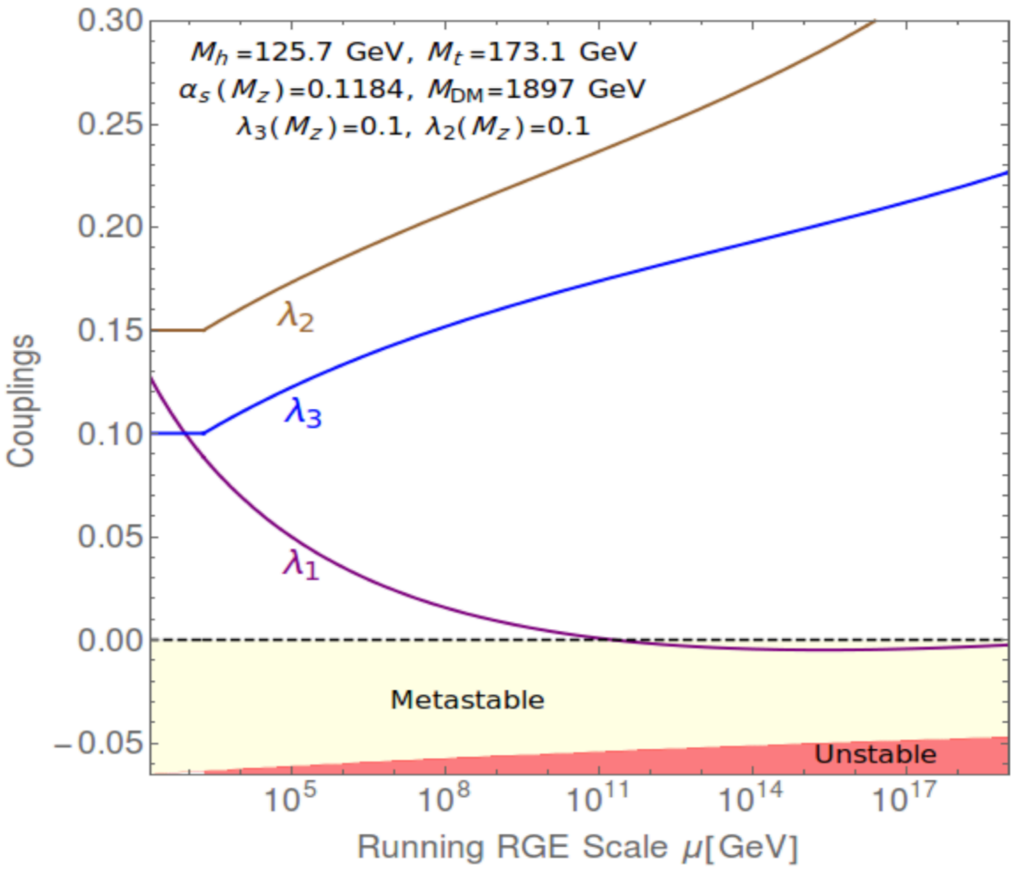


TeV scale DM

(a)

(b)

FIG. 2. The thin blue band corresponds the relic density, $\Omega h^2 = 0.1198 \pm 0.0026$ (3σ) from the com data of WMAP and Planck [61]. (*a*) The mass difference ΔM (green line) and the effective annihi cross-section (black line) as function of dark matter mass for the portal coupling $\lambda_3(M_Z) = 0.10$. (*b*) The relic density Ωh^2 as a function of the DM mass $M_{DM}(\equiv M_H)$ (red line) for $\lambda_3(M_Z) = 0.10$.



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Y=0 complex triplet

- Here a complex triplet with Y=0 given as

$$T = T^a \sigma^a,\, T^a \in \mathbb{C} \qquad T = \begin{bmatrix} \frac{T^0}{\sqrt{2}} & T^+ \\ T^- & -\frac{T^0}{\sqrt{2}} \end{bmatrix}$$

Complex field

- The Higgs spectrum: $h_1 (\simeq h_{125}), h_2, A, T^+, T^-$ ⟵ Triplets

Not charged conjugate

- The Triplet does not couple to fermions
- In this case we have a pure triplet pseduosclar
- Two pure triplet charged Higgs bosons
- CP-even doublet and triplet can mix

Triplet with Y=2

- A hypercharge non-zero triplet is manily motivated for Type-II Seesaw

$$\frac{M_\nu^{ij}}{v_\Delta} L_i^T\, C i\sigma_2 \Delta L_j + \mathrm{h.c.}\,,$$

Melfo et al. PRD85 (2012) 055018,
EJC et al. PL B728 (2014) 256-261, PLB722 (2013) 86-93
B.Mukhopadhyaya, D Chaudhury, T Han, S. Rai, M. Mitra
S.Niyogi, Anirban Kundu, Paramita Dey
JHEP 1402 (2014) 060
PLB434 (1998) 347-353, PLB633 (2006) 519-525
PRD76 (2007) 075013, PRD95(2017) no.3, 035042
J.Phys.G36:025002,2009

$$T = \begin{bmatrix} \frac{T^+}{\sqrt{2}} & T^{++} \\ T_r^0 + iT_i^0 & -\frac{T^-}{\sqrt{2}} \end{bmatrix}$$

- Mass spectrum: $h_1(\simeq h_{125}), h_2, A, T^\pm, T^{\pm\pm}$

Triplet like doubly charge Higgs bosons

- Doubly charged Higgs boson is the main signature

- Z_2 odd triplet can give a inert triplet and a candidate DM.

Araki et al. PRD83, 075014 (2011)

Constrains

- N Higgs multiplets $\Phi_i (i = 1, ..N)$ with isospin charge T_i and hypercharge Y_i

$$\mathcal{L}_{Kin} = \sum C_i |D^i_\mu \Phi^i|^2$$

$$m_W^2 = \frac{g_2^2}{2} \sum v_i^2 [T_i(T_i + 1) - Y_i^2]$$

$$m_Z^2 = g_1^2 \sum v_i^2 Y_i^2, \quad v_i = \sqrt{2C_i} < \phi_i^0 >$$

- This leads to tree-level contribution to,

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

- For Y=0 triplet $m_W^2 = g_2^2(v^2 + 4v_T^2)/2$, $\rho = 1 + 4v_T^2/v^2$

$\rho = 1.0004^{+0.0003}_{-0.0004}$ → $v_T \leq 5\,\mathrm{GeV}$

Georgi-Machacek Model

- In SM $\rho = 1$ due to custodial symmetry
- One SU(2) doublet, one real and one complex triplet

Y=1 Y=0 Y=2

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad T = \begin{bmatrix} \frac{T^0}{\sqrt{2}} & T^+ \\ T^- & -\frac{T^0}{\sqrt{2}} \end{bmatrix} \quad \xi = \begin{bmatrix} \frac{\xi^+}{\sqrt{2}} & \xi^{++} \\ \xi_r^0 + i\xi_i^0 & -\frac{\xi^-}{\sqrt{2}} \end{bmatrix}$$

$$\rho_{tree} = \frac{m_W^2}{m_Z^2 cos^2\theta_W} = 1 + \frac{4v_T^2 - 2v_\xi^2}{v_\phi^2 + 4v_\xi^2}$$

- A choice of $v_T^2 = \frac{v_\xi^2}{2}$ leads to $\rho = 1$ at the tree level.

Logan, Roy: Phys.Rev.D82:115011,2010

Left-right Symmetric Model

- GSM ≡ SU(3)c × SU(2)L × U(1)Y ⇨ GLR ≡ SU(3)c × SU(2)L × SU(2)R × U(1)B−L
- The field contains are exchanged under left-right symmetry such that the largangian is symmetric

$$Q_L^i \leftrightarrow Q_R^i,\ \ell_L^i \leftrightarrow \ell_R^i,\ \Delta_L \leftrightarrow \Delta_R,\ \Phi \leftrightarrow$$

$$\begin{aligned} SU(2)_L \otimes SU(2)_R: \quad & \phi \to U_L \phi U_R^\dagger, \quad \Delta_L \to U_L \Delta_L U_L^\dagger, \quad \Delta_R \to U_R \Delta_R U_R^\dagger, \\ U(1)_{B-L}: \quad & \phi \to \phi, \quad \Delta_L \to e^{i\theta_{B-L}} \Delta_L, \quad \Delta_R \to e^{i\theta_{B-L}} \Delta_R, \end{aligned}$$

$$\Delta_{L/R} = \begin{pmatrix} \frac{\delta_{L/R}}{\sqrt{2}} & \delta^{++}_{L/R} \\ \delta^0_{L/R} & -\frac{\delta_{L/R}}{\sqrt{2}} \end{pmatrix}^{+}, \quad \Phi = \begin{pmatrix} \phi_1^+ & \phi_1^0 \\ \phi_2^0 & \phi_2^- \end{pmatrix}$$

Type-II.
Seesaw

- Additional Yukawa couplings:

$$-\mathcal{L}_M = \lambda^{ij}\, \overline{\ell_L^{i\,c}}\, i\sigma_2 \Delta_L\, \ell_L^j + \lambda^{ij}\, \overline{\ell_R^{i\,c}}\, i\sigma_2 \Delta_R \ell_R^j + h.c..$$

- One possible breaking: SU(2)R × U(1)B−L ⇨ U(1)Y
- W_R, Z_R are heavy: above few TeV
- WL – WR mixing is allowed and is very small, ξ ≤ 0.05
- Unlike 2HDM, there is no solution to tree-level FCNC
- There are two singly and two doubly charged Higgs bosons
- Doubly charged Higgs leads to four lepton signature
- Four CP-even Higgs bosons
- Two pseudoscalar Higgs bosons

P.S. Bhupal Dev et al. :arXiv:1811.06869v1

J. Chakrabortty et al. :JHEP05(2014)033

S Awagrwala, K, Ghosh, A. Patra: arXiv:1607.03878
Fr`ere et al: Phys.Rev.D75:085017,2007

Pospelov: Phys.Rev. D56 (1997) 259-264

Deshpande et al.: PRD44.837
R. Mohapatra and J. C. Pati: Phys.Rev. D11 (1975) 2558

Left-right symmetric Model

- Gauge and Physical states

$$\begin{aligned}
\phi_1^0 &\simeq \frac{1}{\sqrt{2}}\left[H_0^0 + i\tilde{G}_1^0\right], \\
\phi_2^0 &\simeq \frac{1}{\sqrt{2}}\left[H_1^0 - iA_1^0\right], \\
\delta_R^0 &= \frac{1}{\sqrt{2}}\left(H_2^0 + iG_2^0\right), \;\; \delta_L^0 = \frac{1}{\sqrt{2}}\left(H_3^0 + iA_2^0\right), \\
\delta_L^+ &= H_1^+, \quad \delta_R^+ \simeq G_R^+, \\
\phi_1^+ &\simeq H_2^+, \quad \phi_2^+ \simeq G_L^+, \\
\delta_R^{\pm\pm} &= H_1^{\pm\pm}, \quad \delta_L^{\pm\pm} = H_2^{\pm\pm}.
\end{aligned}$$

Heavy Higgs bounds

- H->WW: Combined upper limits at 95% confidence level on the product of the cross section and branching fraction exclude a heavy Higgs boson with SM-like couplings and decays up to 1870 GeV

CMS: arXiv:1912.01594 [hep-ex]

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CMS:JHEP 06 (2018) 127

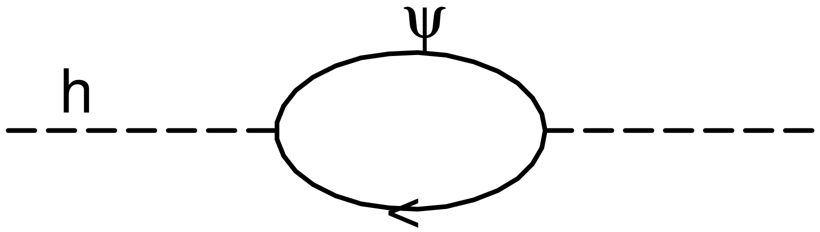
- $A \to b\bar{b}/\tau\bar{\tau}$: Bounds on cross-section give till 900 GeV in $2b + 2\tau$ mode

CMS:Phys. Lett. B 778 (2018) 101

Supersymmetric extensions

Higgs mass in Standard Model

- Higgs mass is a free parameter not predicted by SM

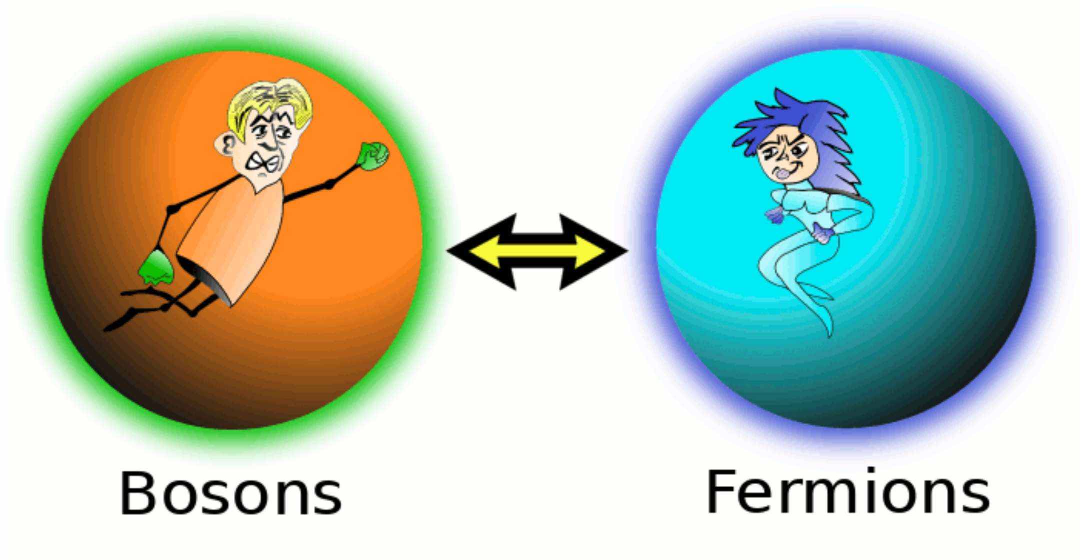


$\sim \Lambda^2$

Cut off scale of the theory

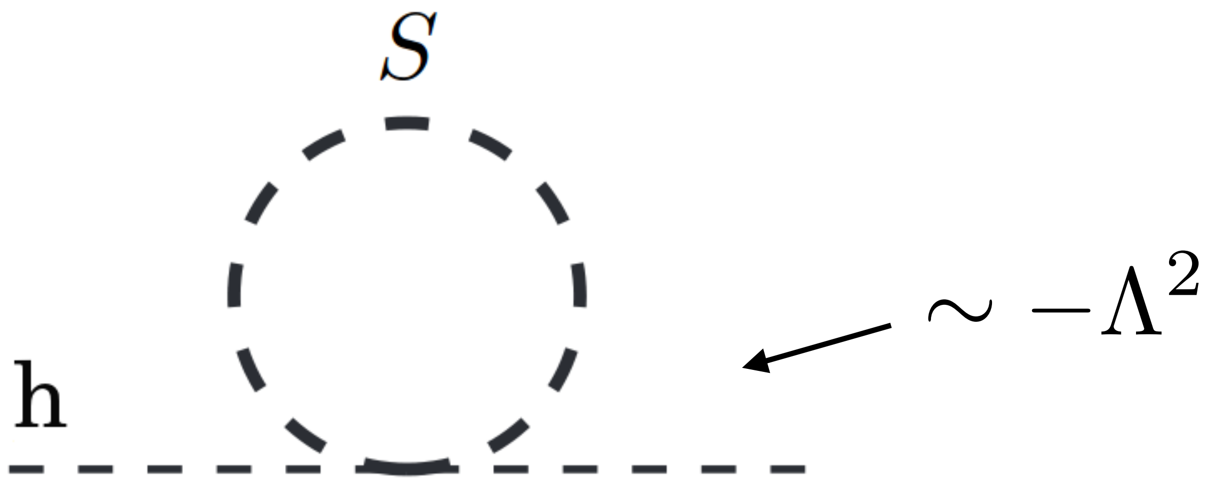
- Quantum correction to Higgs mass is divergent

We need additional symmetry to cancel the quadratic divergence



Supersymmetry !!

- Supersymmetry protects the Higgs mass with additional contributions

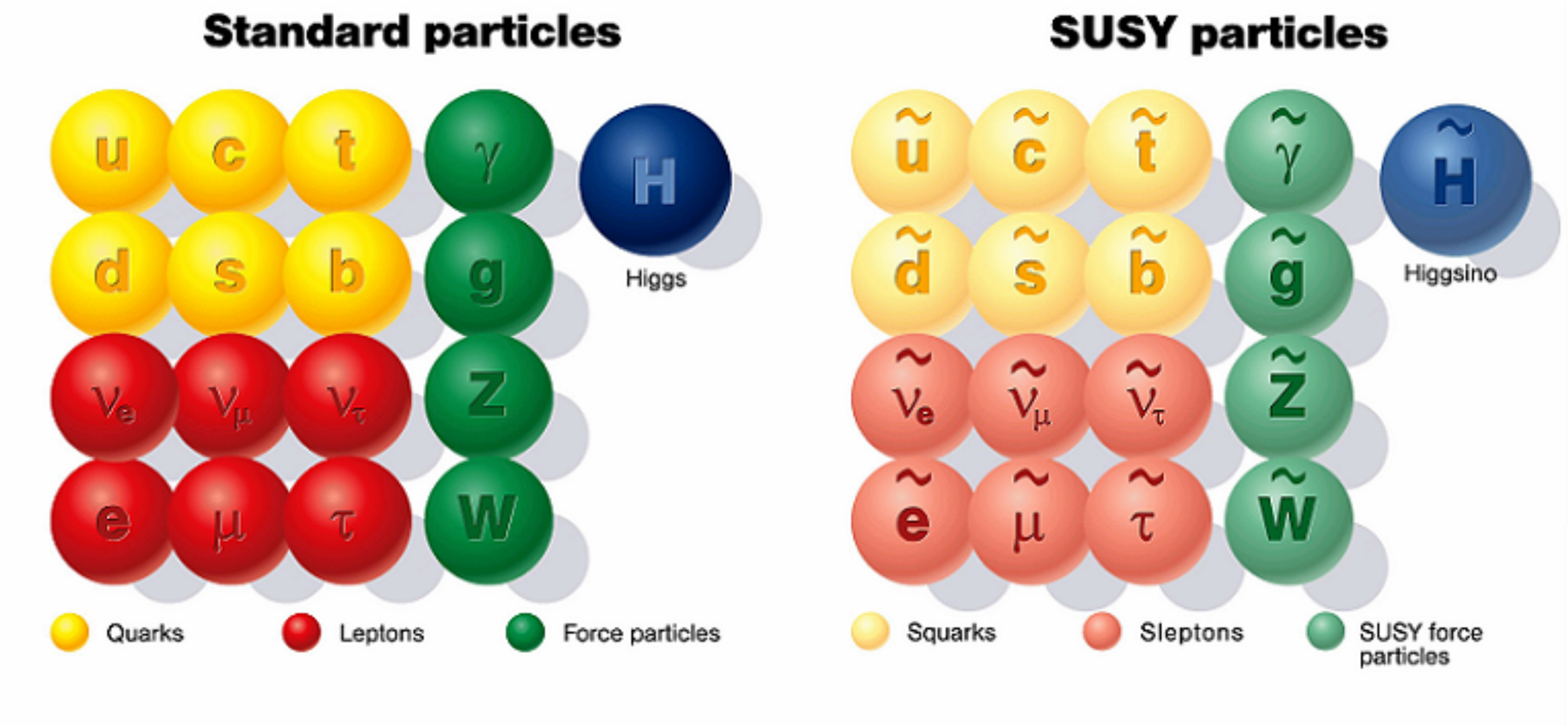


- Radiative correction to the Higgs mass is no longer divergent

- With and extra discrete symmetry R-parity, it can have dark matter candidate.

See Prof. EJC’s talk

Even in the Minimal sector particle spectrum is enhanced



How many Higgs bosons ?

- Minimal sector has two Higgs doublets with hyper charges +1 and -1

$$H_u = \left(\begin{array}{c} H_u^+ \\ H_u^0 \end{array} \right), \quad H_d = \left(\begin{array}{c} H_d^0 \\ H_d^- \end{array} \right),$$

- Physical mass basis: two CP even Higgs boson: h, H
- One CP odd: A
- One charged Higgs boson: $H^{\pm}$

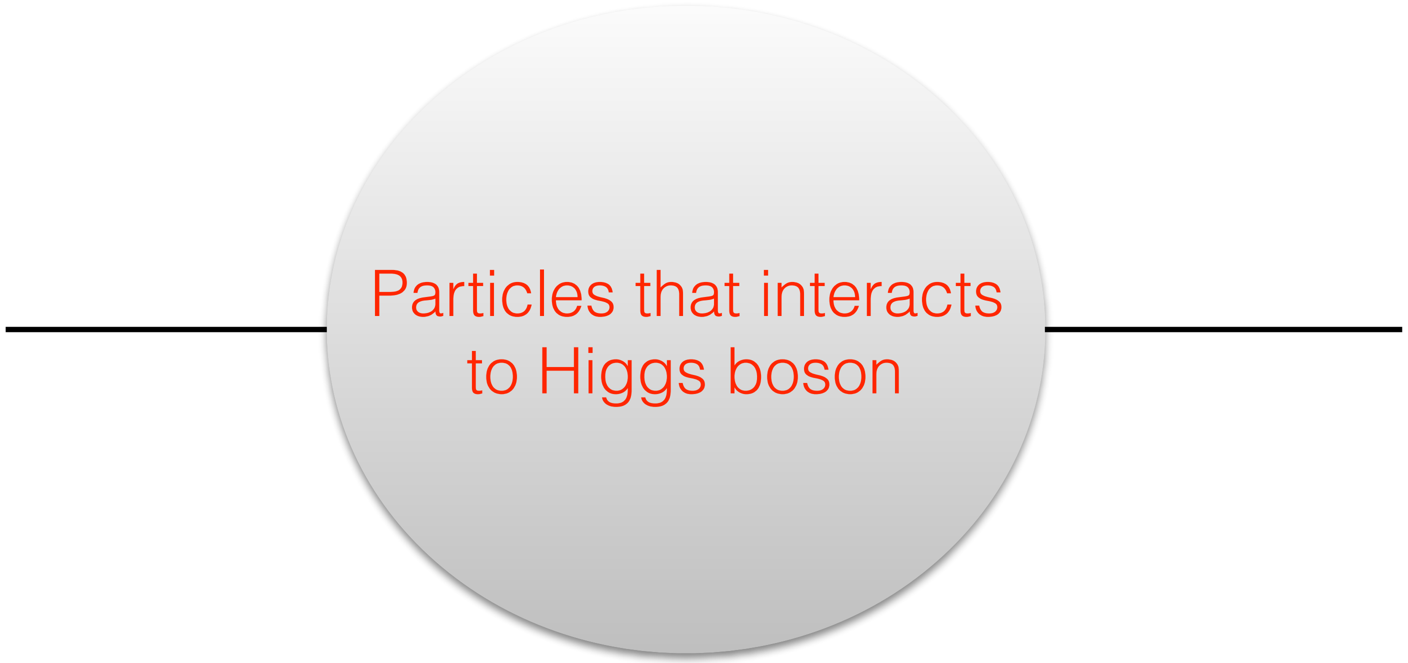
So far we have observed only one Higgs boson !

Lightest CP even Higgs boson

- Unlike Standard Model, here light Higgs mass bounded from above
- At tree-level $m_h < m_Z$
- For desired Higgs mass around 125 GeV, one has to look for quantum correction

Quantum correction is important

$$\Delta m_h \sim$$



Particles that interacts to Higgs boson

$$h_{125} = m_h + \Delta m_h$$

- Particles in the loop get indirect bounds

Status of minimal supersymmetric scenarios

- Trivial solution: Very large mass for super-partners

$\gtrsim$ few TeV

- Or large mass splitting between the super-partners

  - Fine tuning is necessary

- There are possibilities in different SU(2) representations

Singlet

and/or

Triplets

$S = s_r + i s_i$

Y=0 $T = \begin{pmatrix} \frac{T^0}{\sqrt{2}} & T_2^+ \\ T_1^- & -\frac{T^0}{\sqrt{2}} \end{pmatrix}$

Espinosa, Quiros, Agashe, ..

What is the gain?

$\Delta m_h \simeq$

Other
Higgs bosons
contribute
at tree-level

$+$

Contribute
at
quantum
level

Do not need much help from ‘super partners’

Supersymmetry can still exists below TeV !

Are there are other theoretical motivation ?

1. Spontaneous CP-violation
2. Solution of the μ_D in supersymmetry
3. Possibility of hidden Higgs bosons

…

How exotic are they ?

Triplet

Do not couple to fermions

Singlet

Singlet does not couple to gauge bosons

Neutral part of Y=0 Triplet does not couple to Z boson

Triplet extension

- Model I: Y=0 Triplet extension

$$W_T = \lambda H_d.T.H_u + \mu_D H_d.H_u + \mu_T Tr(T^2)$$

- It gives two additional triplet-like charged Higgs bosons

- Extra CP even and CP odd neutral Higgs bosons

- None of them couple to fermions

- Model II: A scale invariant superpotential with Y=0 SU(2) triplet and a singlet

Triplet

Singlet

$$W_S = \lambda_T H_d . T H_u \; + \lambda_S S H_d \cdot H_u \; + \; \lambda_{TS} S Tr[T^2] + \; \frac{\kappa}{3} S^3$$

- The complete Lagrangian with the soft SUSY breaking terms has an Z_3 symmetry

- During electro-weak symmetry breaking neutral parts get vev

$$< H^0_{u,d} >= \frac{v_{u,d}}{\sqrt{2}}, \quad < S >= \frac{v_S}{\sqrt{2}} \quad < T^0 >= \frac{v_T}{\sqrt{2}}$$

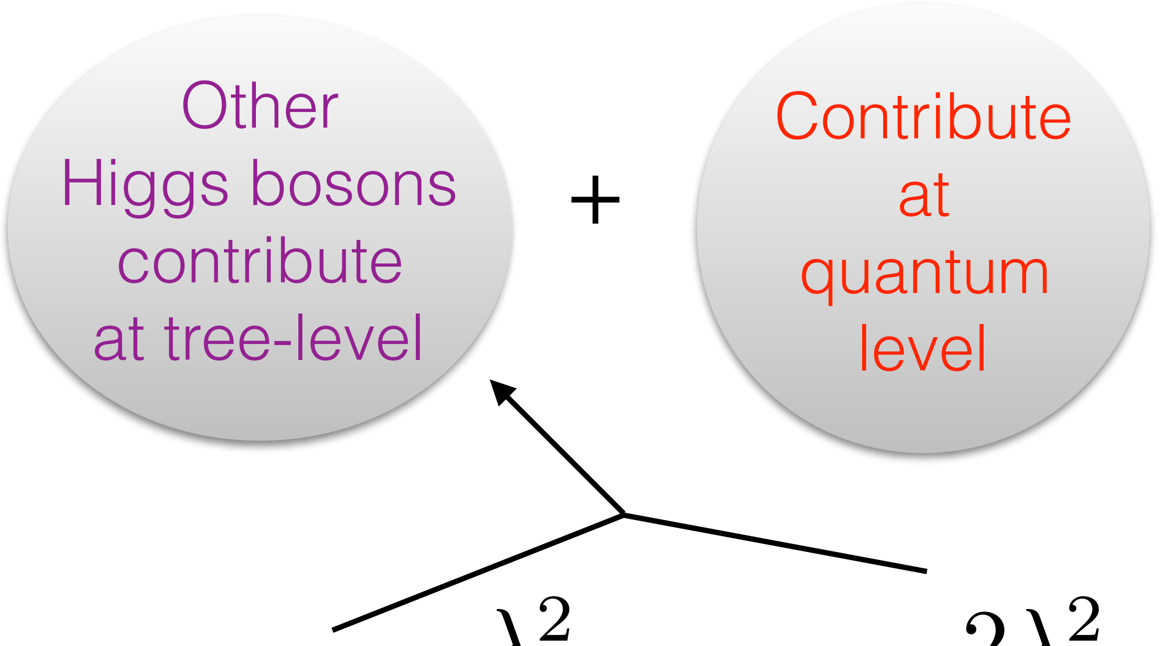
- Triplet vev contributes to the W mass but not the Z mass

$$m_W^2 = g_2^2 (v^2 + 4 v_T^2)/2 \qquad \rho = 1 + 4 v_T^2 / v^2$$

$$v_T \leq 5 \, \mathrm{GeV}$$

Restricted from
ρ parameter

What is the gain?



$$\Delta m_h \simeq$$

Other Higgs bosons contribute at tree-level

$+$

Contribute at quantum level

$$m_{h_1}^2 \leq m_Z^2\left(\cos^2 2\beta + \frac{\lambda_T^2}{g_L^2 + g_Y^2} + \frac{2\lambda_S^2}{g_L^2 + g_Y^2}\sin^2 2\beta\right)$$

Do not need much help from ‘super partners’

Supersymmetry can still exists below TeV !

$$V_{soft} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2$$
$$+ m^2_T|T|^2 + m^2_Q|Q|^2 + m^2_U|U|^2 + m^2_D|D|^2$$
$$+(A_S S H_d.H_u + A_T H_d.T.H_u + A_{TS} S Tr(T^2)$$
$$+ A_\kappa S^3 + A_U U H_U.Q + A_D D H_D.Q + h.c),$$

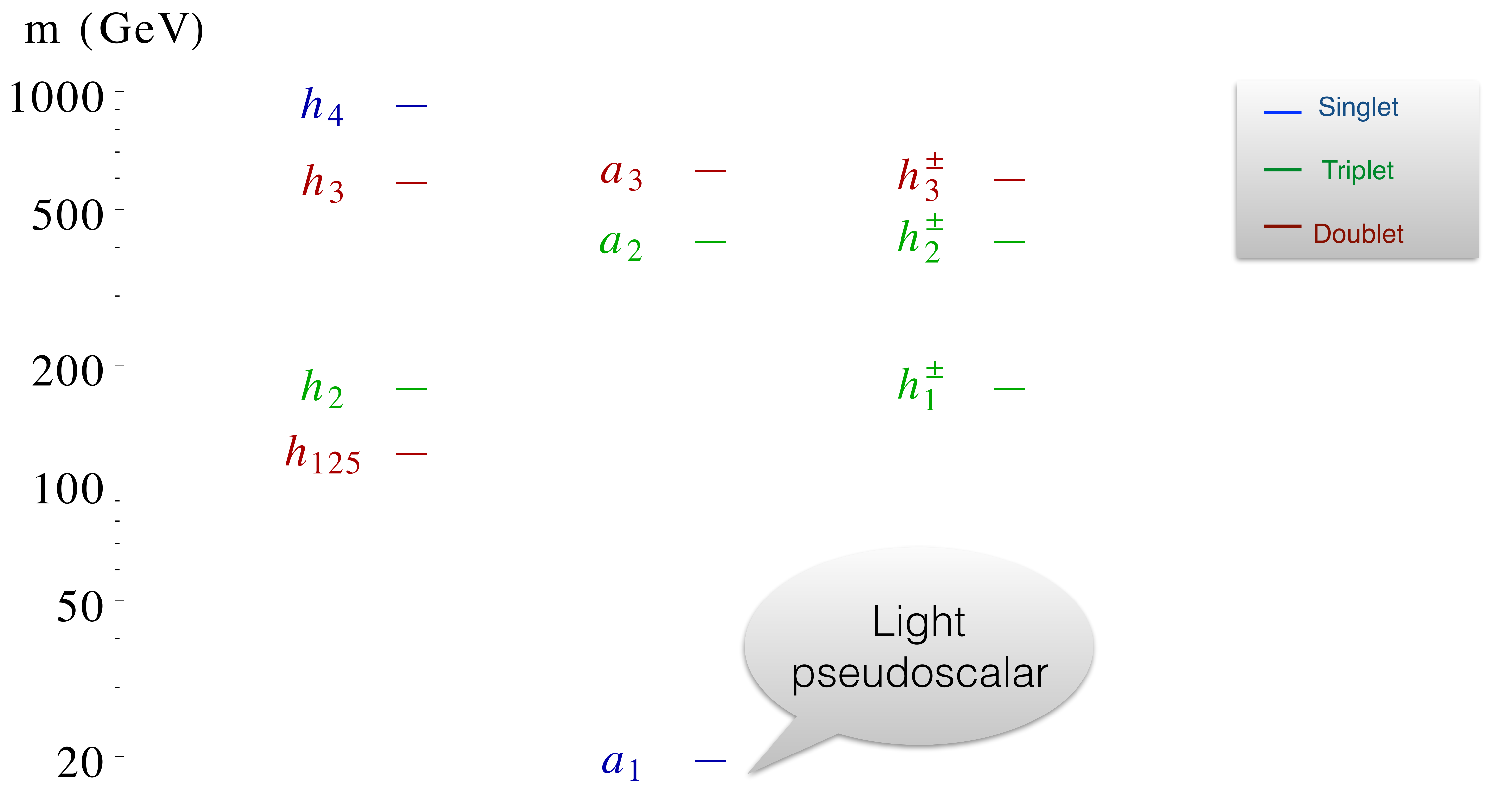
- In the limit where all the A parameters vanish the scalar potential accrues an enhanced U(1) symmetry

$$(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S}) \rightarrow e^{i\phi}(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S})$$

- If this symmetry is softly broken by very small A parameters $\mathcal{O}(1)\mathrm{GeV}$,

- We get a very light pseudoscalaras pseudo-Nambu-Goldstone boson of the symmetry.

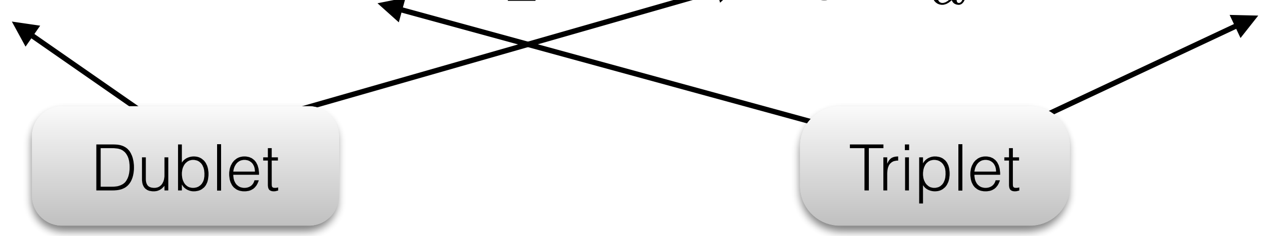
Correlation of gauge-mass hierarchy and possibility of hidden scalars



PB, Claudio Coriano and Antonio Costantini, JHEP 1509 (2015) 045,
JHEP 1512 (2015) 127

Gauge structure

$$h_i^{\pm} = \mathcal{R}^C_{i1} H_u^+ + \mathcal{R}^C_{i2} T_2^+ + \mathcal{R}^C_{i3} H_d^{-*} + \mathcal{R}^C_{i4} T_1^{-*}$$



Dublet

Triplet

$$\mathcal{R}^C_{ij} = f^C_{ij}\left(v_u, v_d, v_T, v_S, \lambda_T, \lambda_{TS}, \lambda_S, A_i\right)$$

- In particular the charged Goldstone has contribution from triplets

$$h_0^{\pm} = \pm N_T \left(\sin\beta H_u^+ - \cos\beta H_d^{-*} \mp \sqrt{2}\, \frac{v_T}{v} (T_2^+ + T_1^{-*}) \right)$$

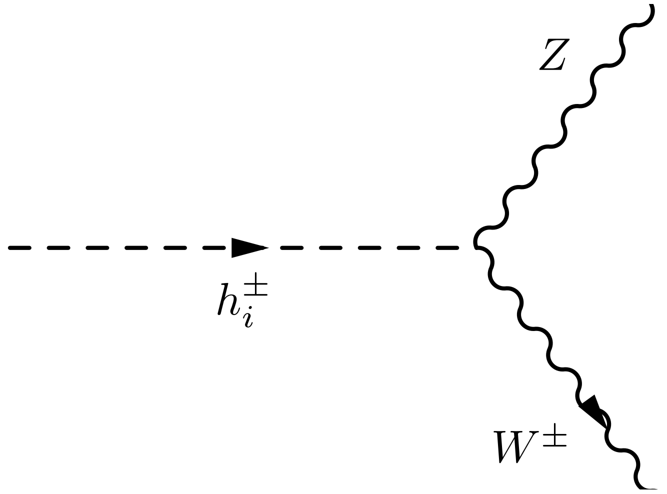
$$N_T = \frac{1}{\sqrt{1 + 4\frac{v_T^2}{v^2}}}$$

has
a triplet
contribution

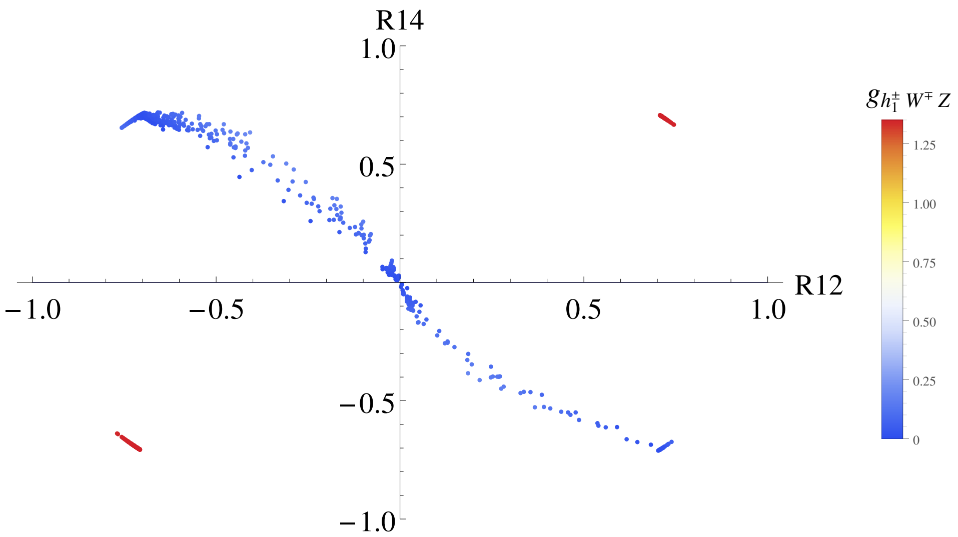
No λ_i

Non-standard decay modes

$$g_{h_i^\pm W^\mp Z} = -\frac{i}{2}\left(g_L\, g_Y\, (v_u \sin\beta\, \mathcal{R}^C_{i1} - v_d \cos\beta\, \mathcal{R}^C_{i3}) + \sqrt{2}\, g_L^2 v_T\, (\mathcal{R}^C_{i2} + \mathcal{R}^C_{i4})\right)$$



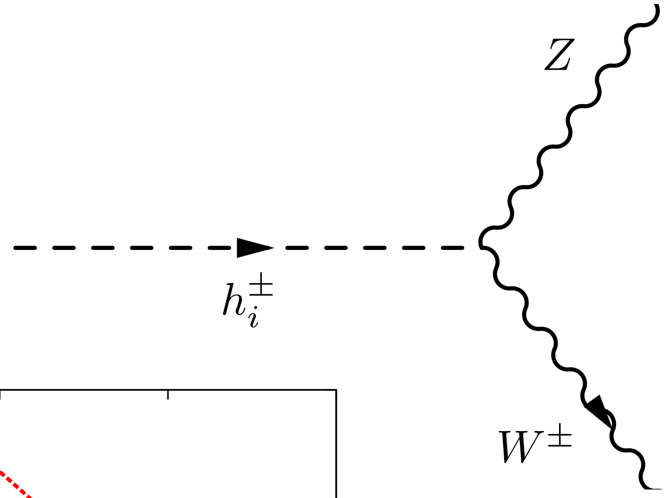
- For $\lambda_T \sim 0$, $\mathcal{R}^C_{12}$ and $\mathcal{R}^C_{14}$ take the same sign
- Hence, $h_1^\pm - W^\mp - Z$ coupling is enhanced
- Non-zero triplet vev, initiates this vertex



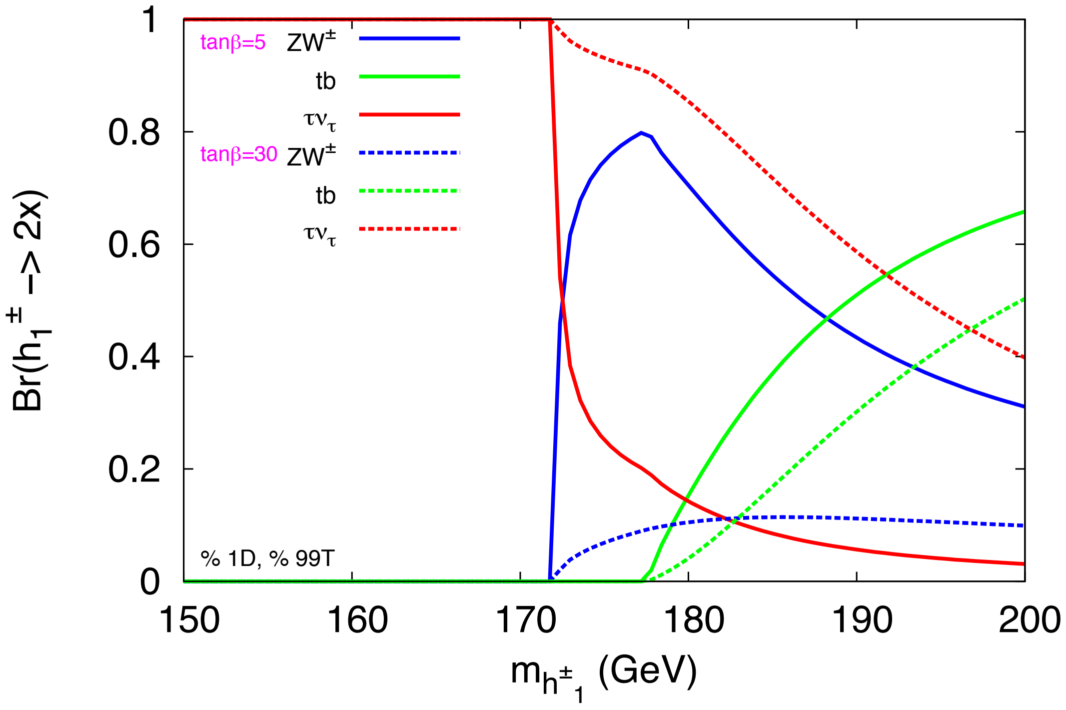
Triplet signature

Non-standard decay modes

$$g_{h_i^\pm W^\mp Z} = -\frac{i}{2}\left(g_L\, g_Y\,\left(v_u \sin\beta\,\mathcal{R}^C_{i1} - v_d\cos\beta\,\mathcal{R}^C_{i3}\right) + \sqrt{2}\,g_L^2 v_T\left(\mathcal{R}^C_{i2} + \mathcal{R}^C_{i4}\right)\right)$$



$$h_i^\pm \to tb$$
$$\to ZW^\pm$$
$$\to \tau\nu$$
$$\to h_j W^\pm$$
$$\to a_j\, W^\mp$$



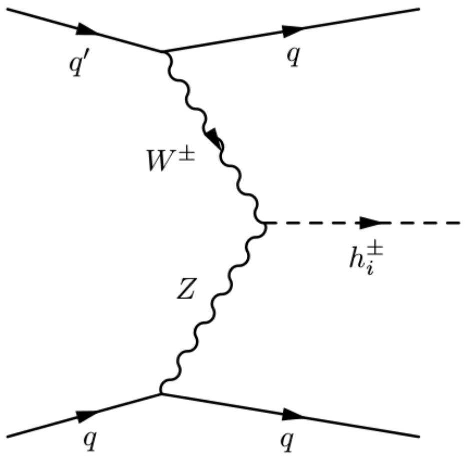
- Mixing with the doublets is crucial for the decays as well as production channels
- $h_1^\pm \to a_1 W^\pm$ opens up due to the presence of light pseudo scalar

P.B, Katri Huitu, Asli Sabanci, JHEP05(2015)026

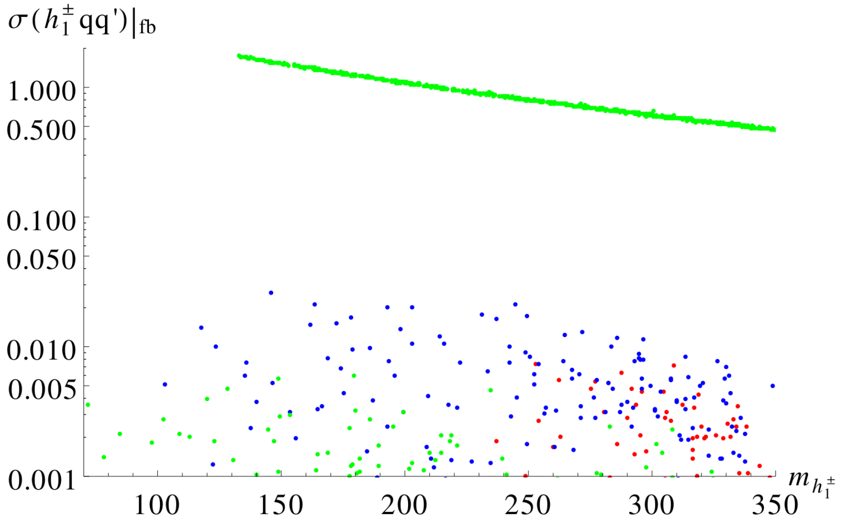
PB, Claudio Coriano, Antonio Costantini, PRD94 (2016) no.5, 055030

Vector boson fusion to charged Higgs boson

- $h_1^{\pm} - W^{\mp} - Z$ coupling creates additional tree-level production mode for the charged Higgs boson

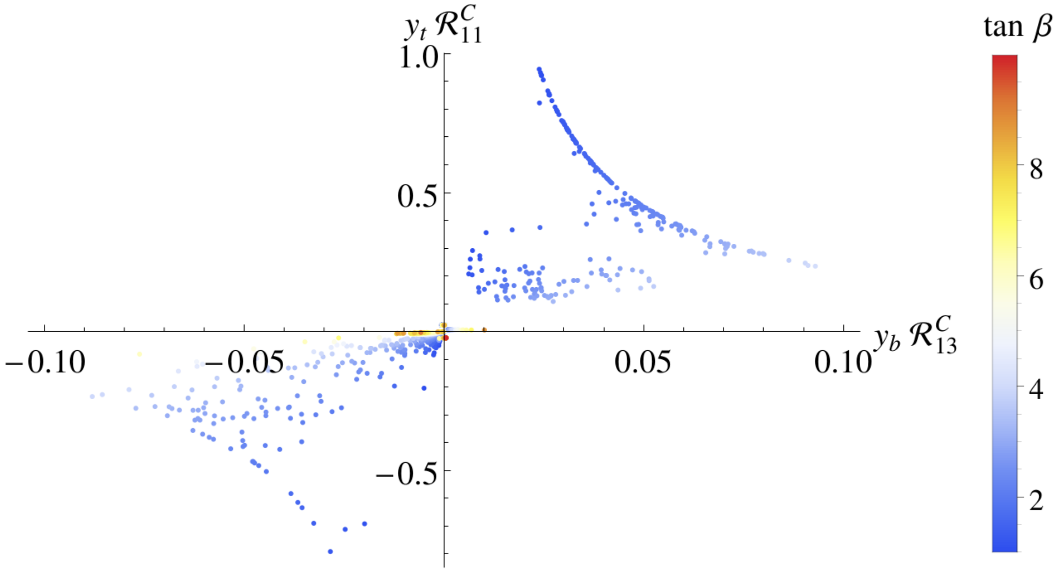


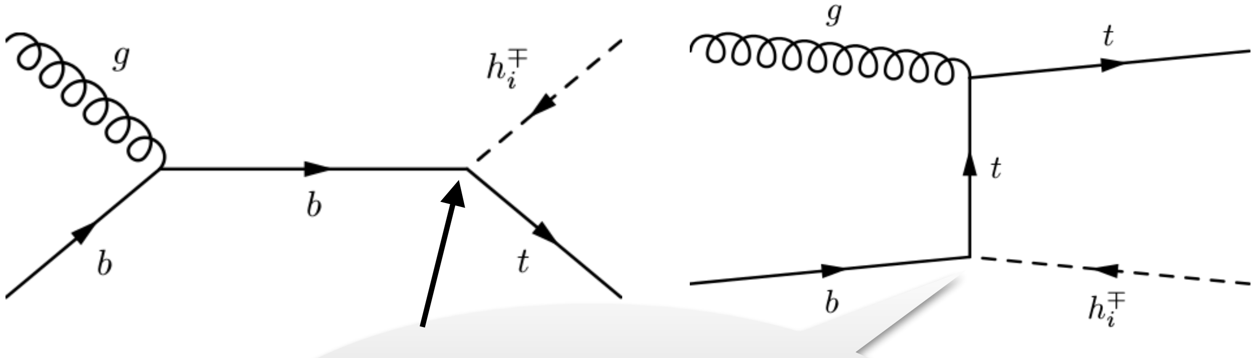
- This process is absent for doublet-like charged Higgs boson



What happens to standard single charged Higgs production mechanism ?

$$g_{h_i^+\bar{u}d} = i\left(y_u\,\mathcal{R}^C_{i1}\,\mathrm{P_L} + y_d\,\mathcal{R}^C_{i3}\,\mathrm{P_R}\right)$$



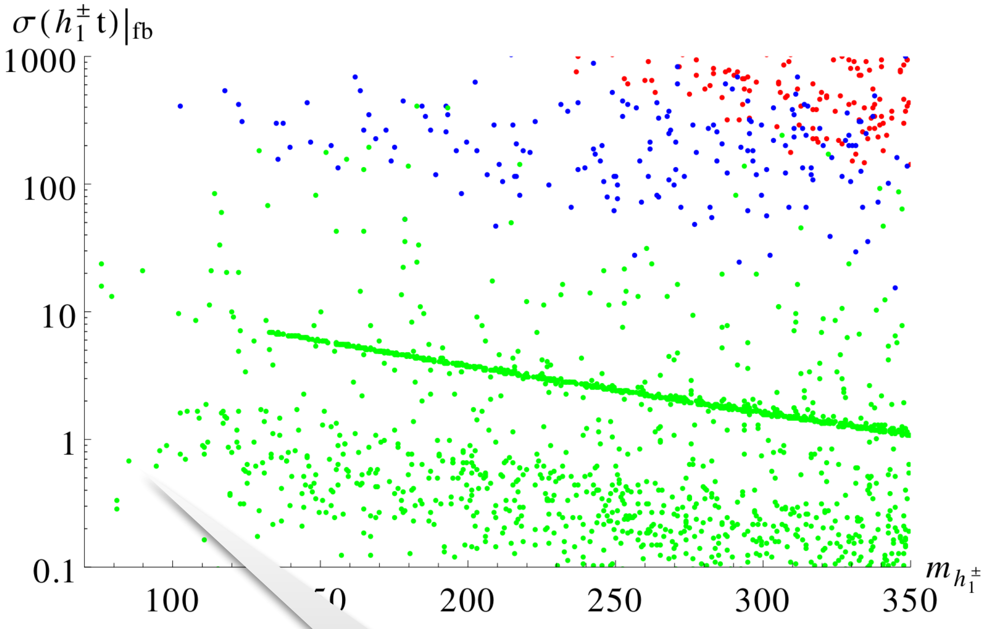


Suppressed for triplet-like Higgs

- Triplets do not couple to fermions

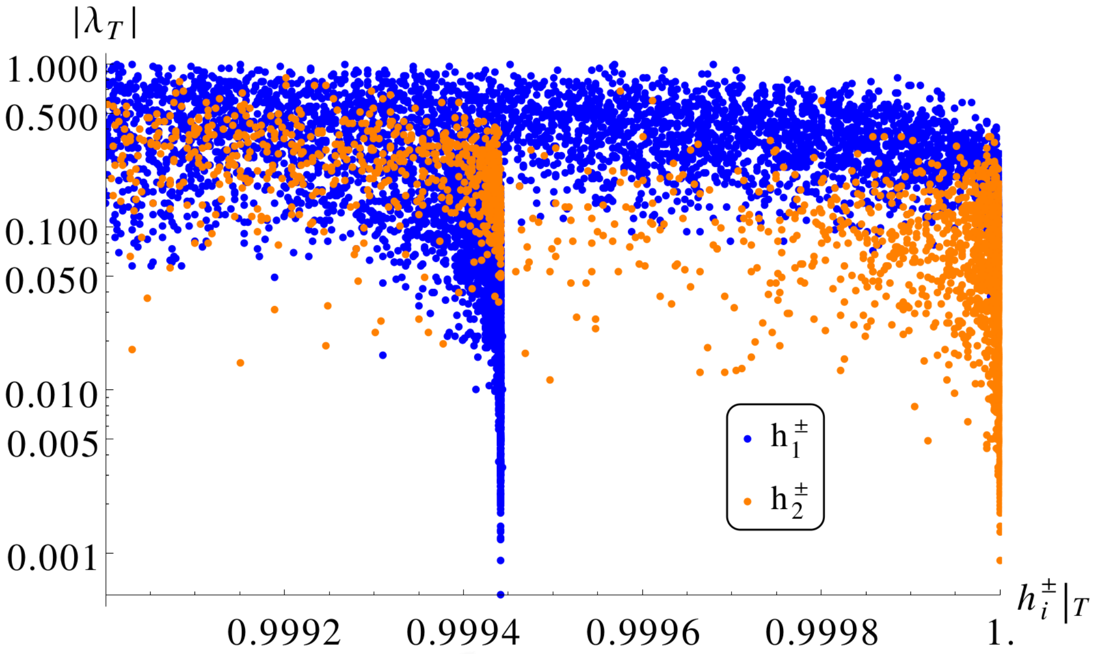
bg fusion is really suppressed

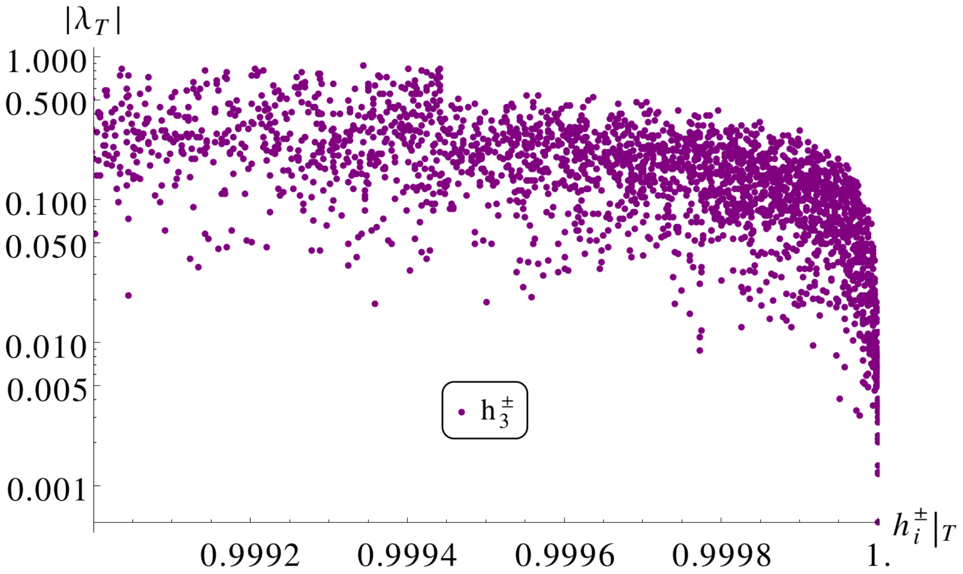
- Even if $\lambda_T = 0$, lightest charged Higgs boson still has some doublet component!



For pure triplet the coss-section goes to zero.

$\boxed{\lambda_T \simeq 0}$ limit



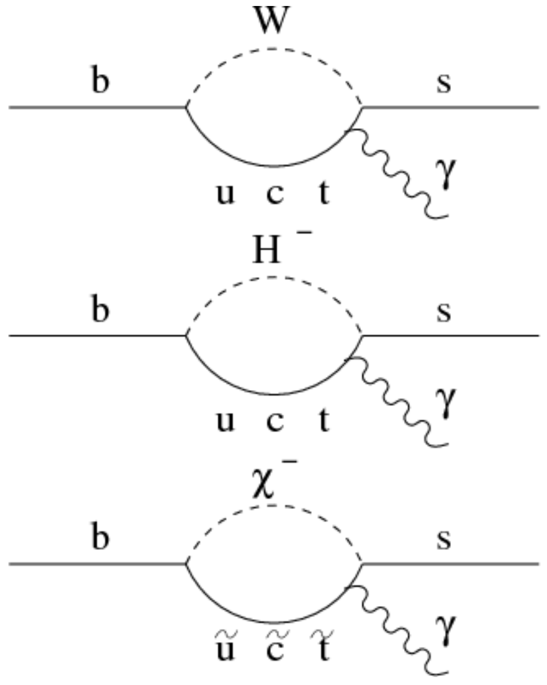


Not 100%

$$\lambda_T = 0$$

- $h_{2,3}^\pm$ only can be pure triplets
- $h_1^\pm$ has some doublet parts as perpendicular mode of the charged Goldstone

Rare decay



- The triplet type charged Higgs bosons, charginos and neutralinos do not couple to fermions

- This affect the indirect bounds coming from rare fermionic decays

- We calculated $\mathcal{B}(B \to X_s\gamma)$at NLO and showed that

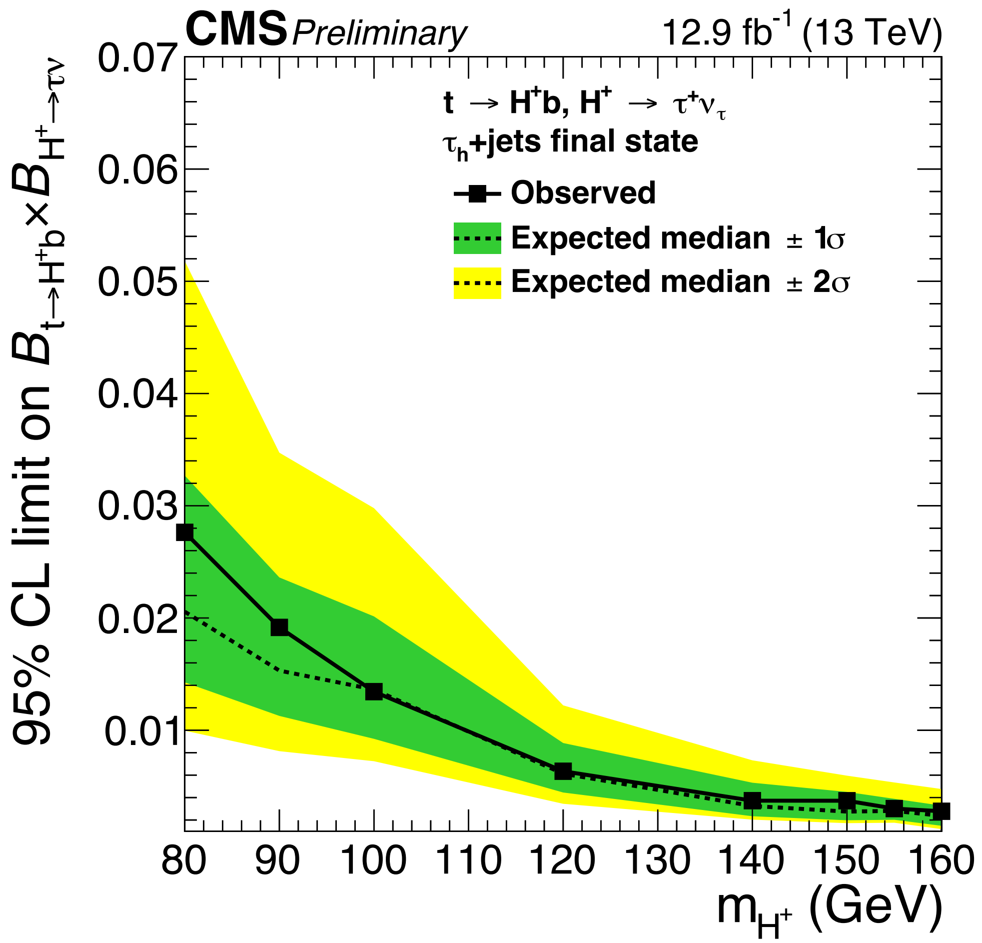
- Allowed 2σ region constrains the high λ_T region of parameter space preferred by naturalness.

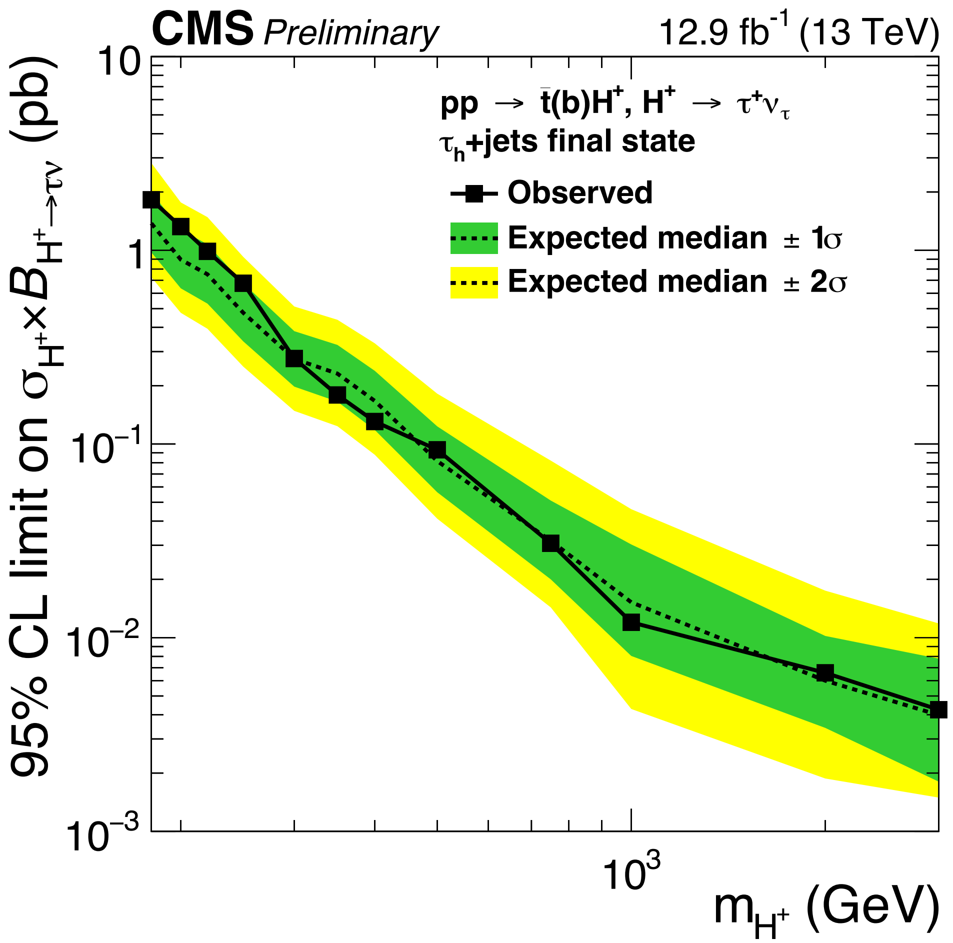
PB, Katri Huitu, Asli Sabanci, JHEP 1310 (2013) 091
PB, Stefano Di Chiara, Katri Huitu, Asli Sabanci, JHEP 1411 (2014) 062

Experimental searches of the charged Higgs boson

- LHC looked for this doublet type charged Higgs bosons via mainly its couplings to fermions
- Light charged Higgs boson: $pp \to t\bar{t} \to bW^+\bar{b}H^-$
- Heavy charged Higgs boson: $pp \to tbH^{\pm}$
- Where charged Higgs boson is search in decay modes $\tau + \nu \,\text{and}\, t + b$

Experimental bounds on the charged Higgs





- CMS puts 95% Cl upper limits as: $E_{cm} = 13\,\mathrm{TeV\ and\ }12.9\,\mathrm{fb}^{-1}$

$$\mathcal{B}(t \to bH^\pm) \times \mathcal{B}(H^\pm \to \tau\nu) = 0.004 - 0.05\,\mathrm{for\ m_{H^\pm}} \sim 80 - 160\,\mathrm{GeV}$$

$$\sigma(pp \to H^\pm W^\pm b\bar{b}) \times \mathcal{B}(H^\pm \to \tau\nu) = 2 - 0.01\,\mathrm{pb\ for\ m_{H^\pm}} \sim 180\,\mathrm{GeV} - 3\,\mathrm{TeV}$$

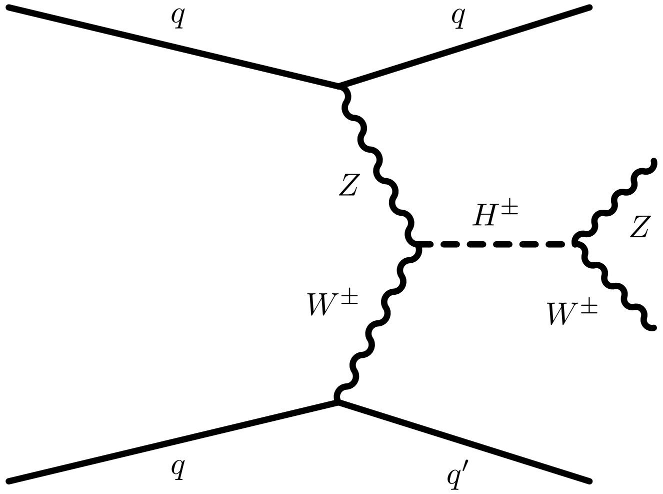
CMS-PAS-HIG-16-031

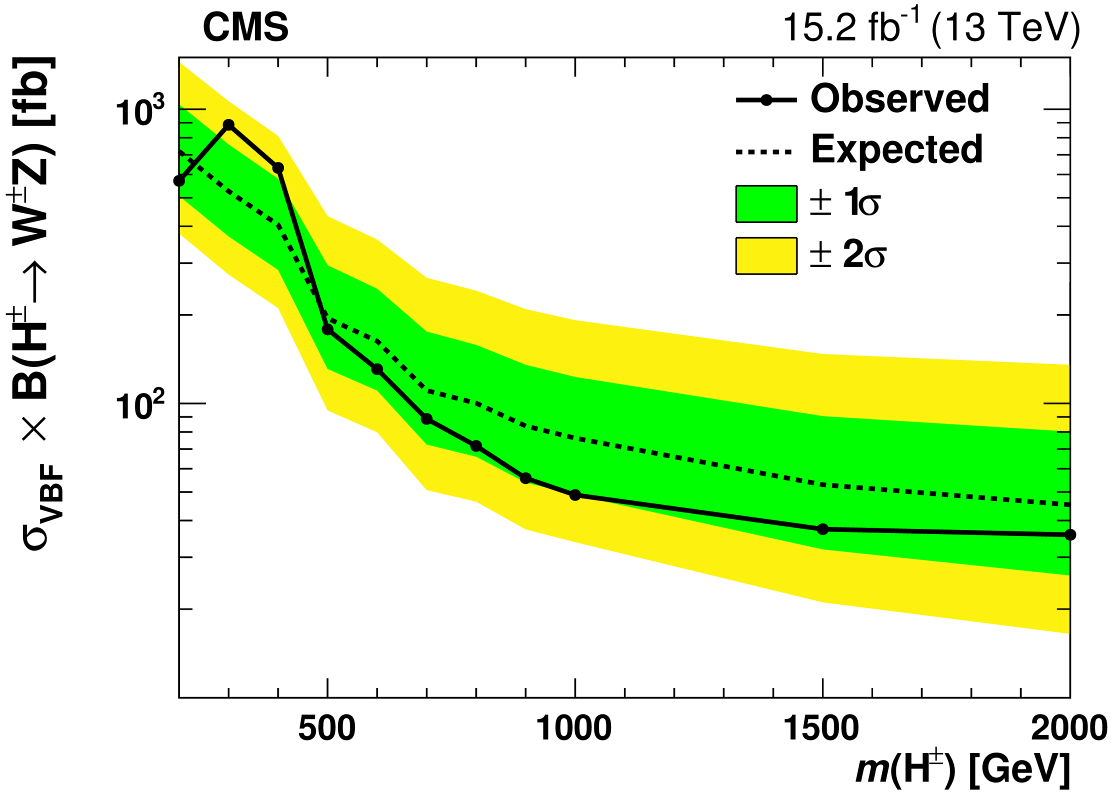
- ATLAS puts 95% Cl upper limits as: $E_{cm} = 13\,\mathrm{TeV\ and\ }3.2\,\mathrm{fb}^{-1}$

$$\sigma(pp \to tbH^\pm) \times \mathcal{B}(H^\pm \to \tau\nu) = 1.9\,\mathrm{pb} - 15\,\mathrm{fb\ for\ m_{H^\pm}} \sim 200 - 2000\,\mathrm{GeV}$$

PLB 759(2016)555-574

Experimental bounds on the Triplet charged Higgs





- CMS puts 95% Cl upper limits on $\sigma_{VBF} \times (H^\pm \to W^\pm Z)$ for $200 \leq m_{H^\pm} \leq 2000\,\mathrm{GeV}$

  CMS-PAS-HIG-16-027/PRL119(2017)14180

- ATLAS puts 95% Cl upper limits at $E_{cm} = 8\,\mathrm{TeV}$ with $20.3\,\mathrm{fb}^{-1}$

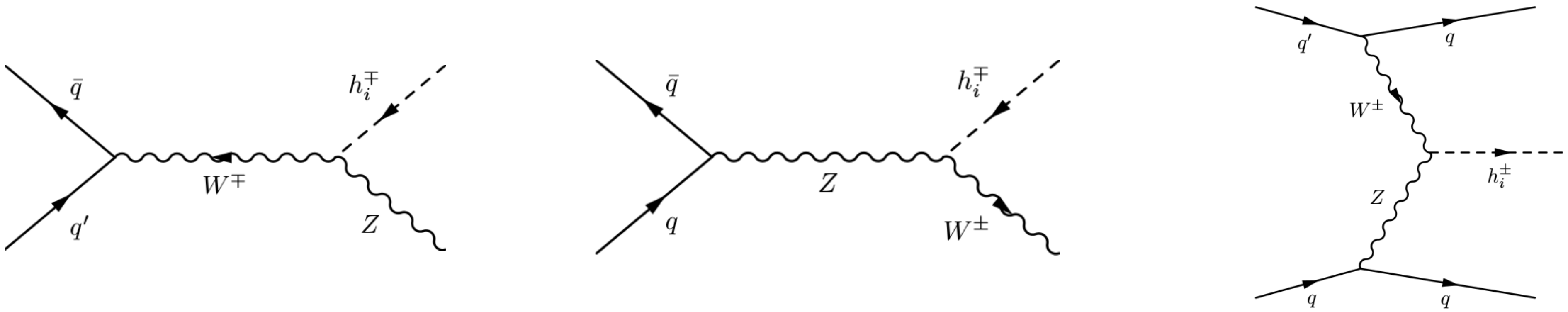
$$\sigma_{VBF} \times \mathcal{B}(H^\pm \to ZW^\pm) \sim 31 - 1020\,\mathrm{fb}\ \mathrm{for}\ 200 \leq \mathrm{m_{H^\pm}} \leq 2000\,\mathrm{GeV}$$

PRL 114,23801(2015)

- Doubly charged Higgs boson: $E_{cm} = 13\,\mathrm{TeV}$ with $36.1\,\mathrm{fb}^{-1}$

$$m_{H^{++}} > 770 - 870\,\mathrm{GeV}$$

Look for new production modes



- Multi-leptonic final states can probe the triplet mode

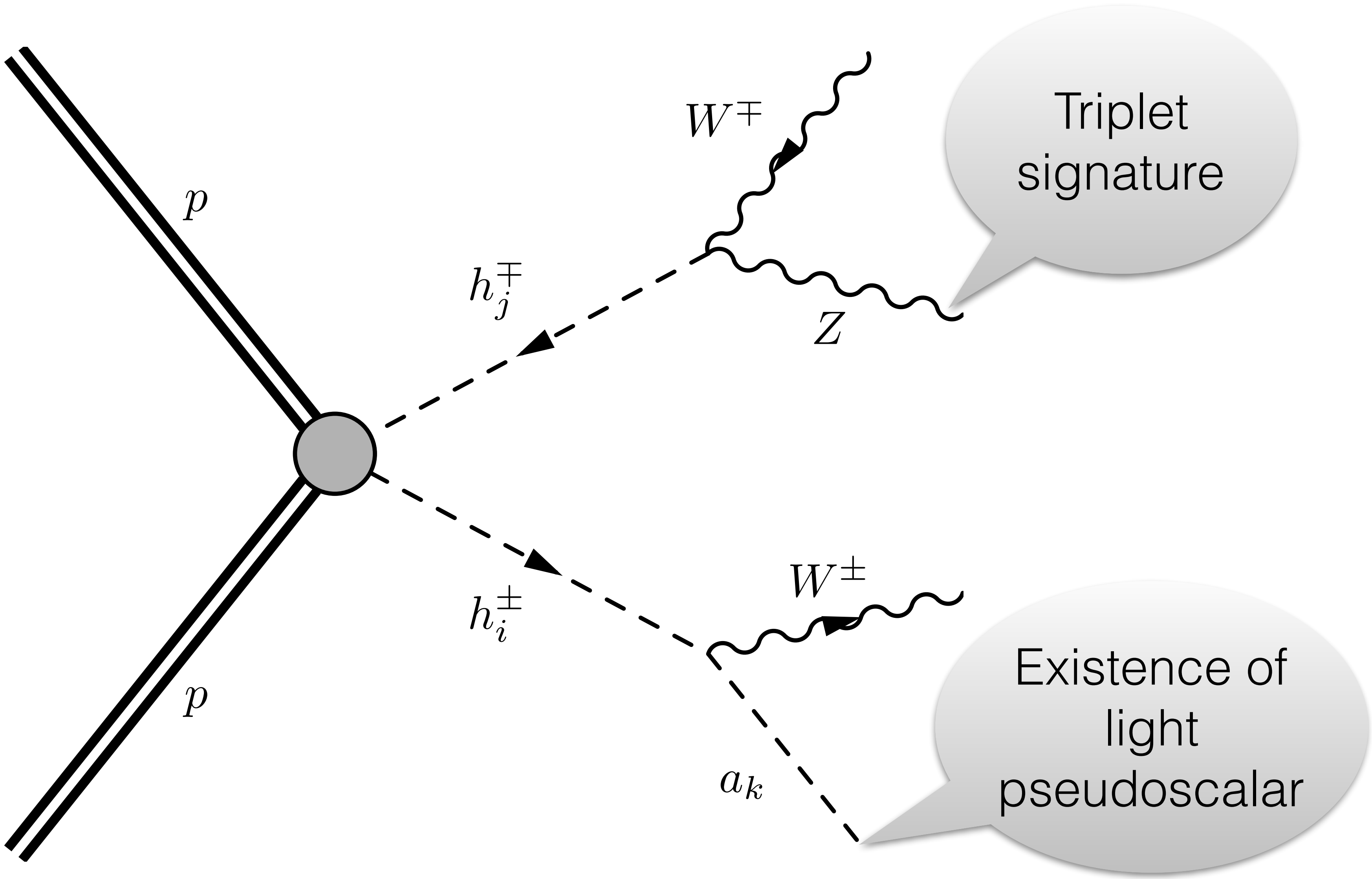
- $3\ell + 2j,\ 3\ell + 2b$ final states can probe such triplet signature by $\sim 100\,\mathrm{fb}^{-1}$ of integrated luminosity at the LHC@14 TeV

- Higher lepton multiplicities can be probed at further higher luminosities.

P.B, Katri Huitu, Asli Sabanci, JHEP05(2015)026

- Is it possible to distinguish different possible extensions ?

$$W_S = \lambda_T H_d . T H_u \; + \lambda_S S H_d \cdot H_u \; + \lambda_{TS} S Tr[T^2] + \frac{\kappa}{3} S^3$$

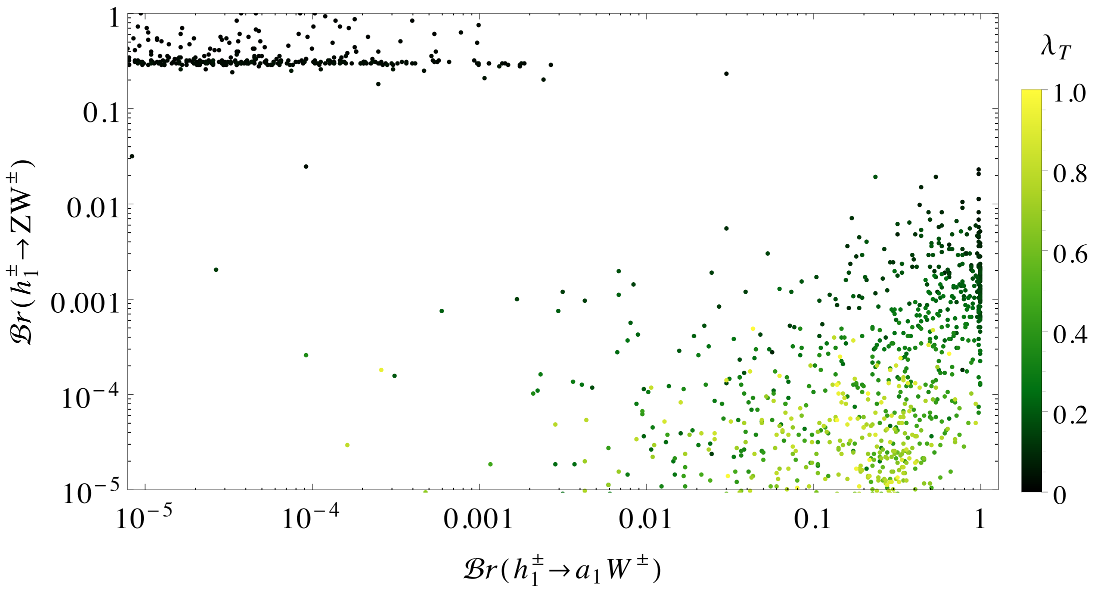


Triplet signature

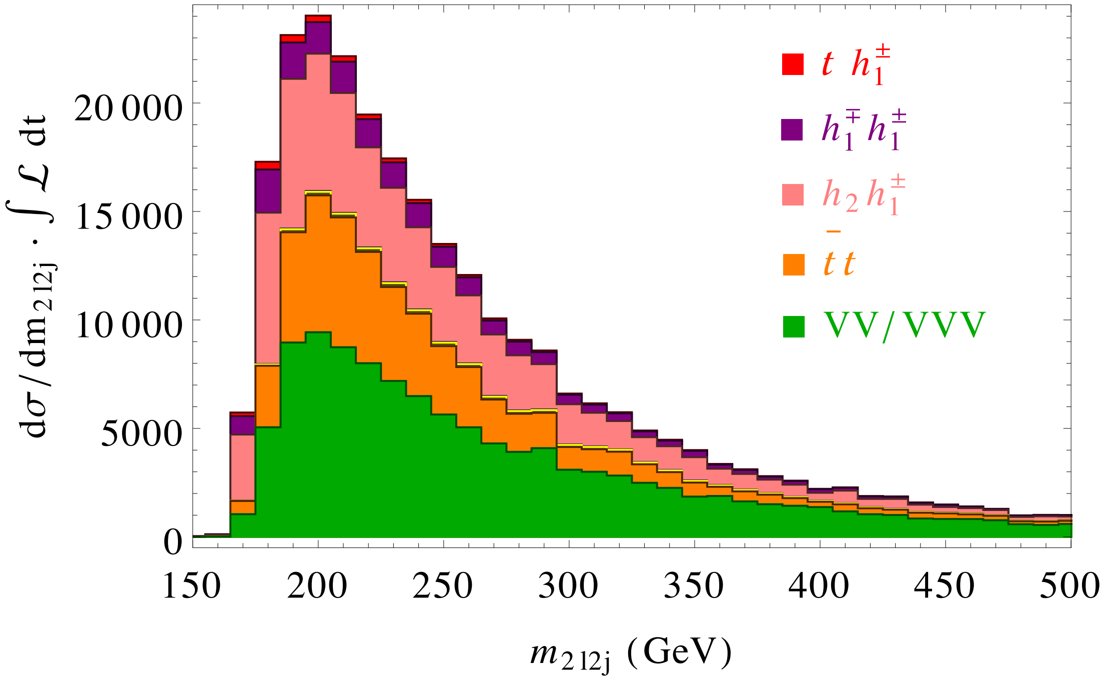
Existence of light pseudoscalar

PB, Claudio Coriano, Antonio Costantini, Phys.Rev. D94 (2016) no.5, 055030

Status of triplet Y=0 charged Higgs boson



- Probing $a_1 W^\pm$ and $\mathrm{ZW}^\pm$ together is challenging
- $a_1 W^\pm$ can be probed via $2b + 2\tau + 1\ell + m_{jj} \sim m_W$ at the LHC with $43\,\mathrm{fb}^{-1}$
- ZW mode can be probed via $3\ell + 1\tau$ with $54\,\mathrm{fb}^{-1}$



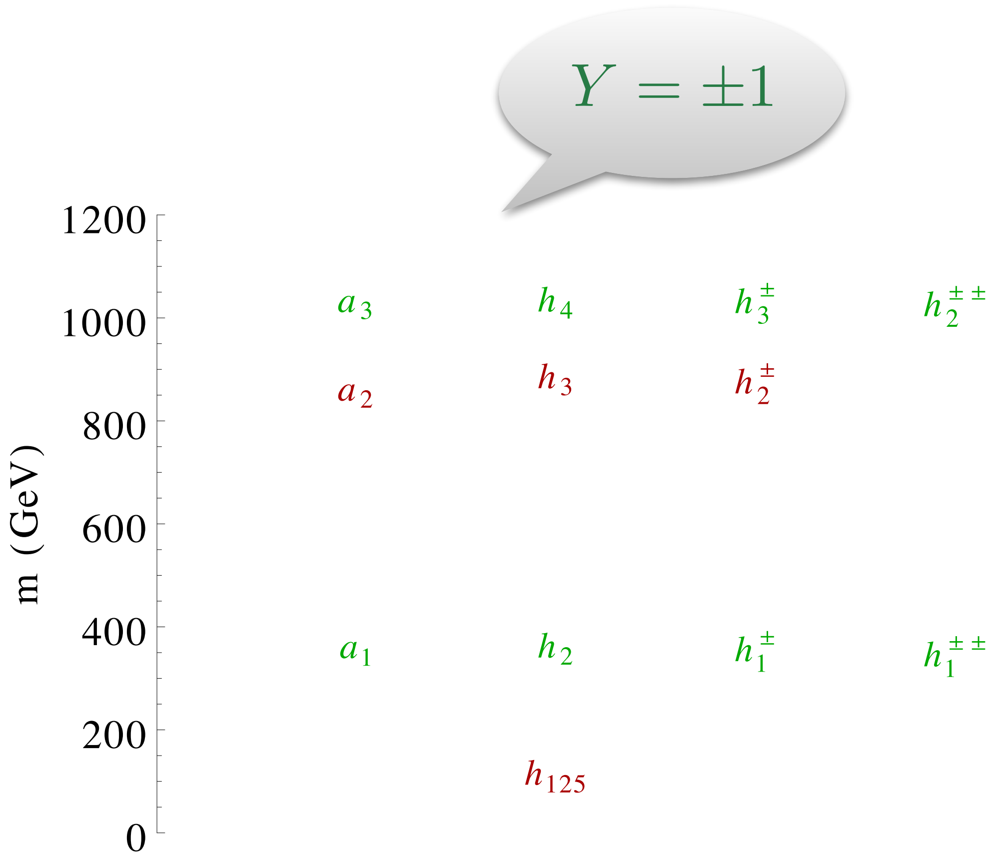
- Light pseudo scalar mass can probed with early data of $55\,\mathrm{fb}^{-1}$
- Probing charged Higgs mass via reconstruction of Z and W will take around $712\,\mathrm{fb}^{-1}$ of integrated luminosity

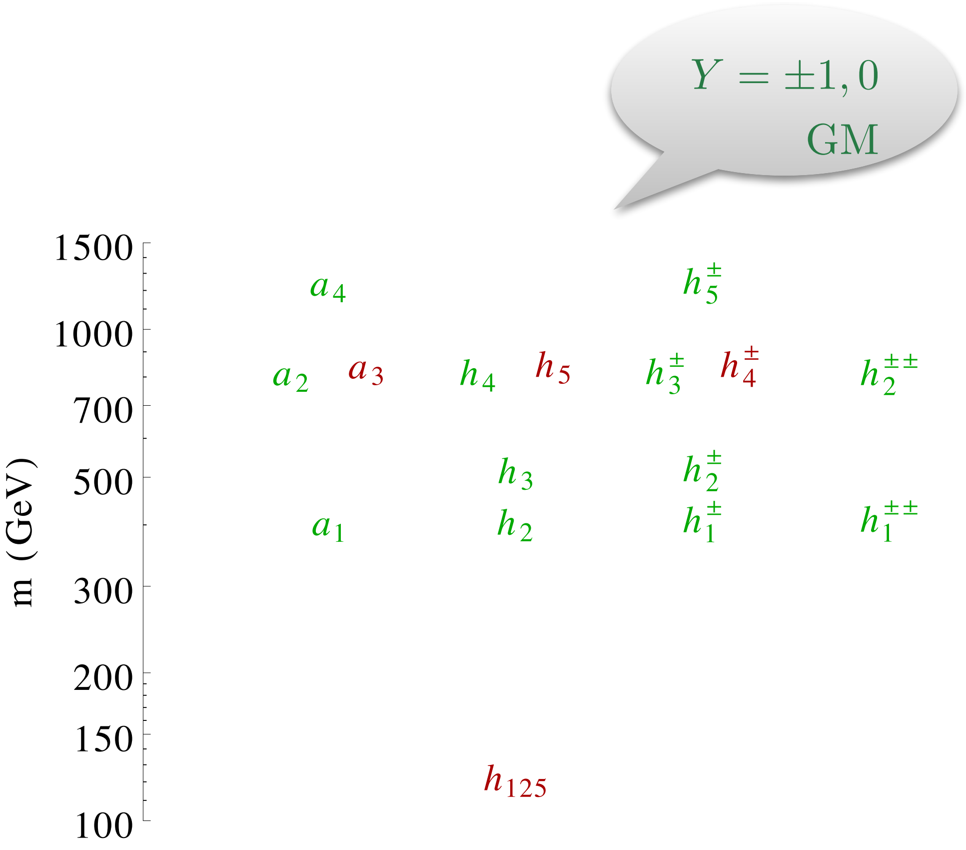
- It is possible to distinguish charged Higgs bosons from different representations of SU(2)

PB, Antonio Costantini, JHEP 1801 (2018) 067

Status of non-zero Hyper-charged triplets charged Higgs bosons

- $Y = \pm 1 \,\text{invokes}\, \mathrm{H}^{\pm\pm}$ in the spectrum but constrained from ρ parameter
- $Y = \pm 1, 0$ can form custodial triplets known as Georgi-Machacek triplets which can evade the constraints from ρ parameter





- For these cases one needs to find out the doubly charged states with the given hierarchy

Conclusions

- So far we have observed one Higgs boson at 125 GeV
- All standard and non-standard modes are yet to be explored
- Observation of Charged Higgs would be a direct proof of extended Higgs sector.
- Non-standard decay modes $h^\pm \to a_1 W^\pm$ and $h^\pm \to ZW^\pm$ are direct proofs of higher representations of Higgs sectors.
- $t - b - h_1^\pm$ coupling will also be good measure
- Indirect searches can also give us some hints
- We hope LHC bring some more discoveries

THANK YOU!

Some of them can evade detection for earlier searches

Searches of the Higgs bosons

- Higgs bosons are searched via their decay modes

$$\left.\begin{array}{l} h \to b\bar{b} \\ \quad \to \tau\bar{\tau} \end{array}\right\} \textbf{Lepton and quark modes}$$

$$\left.\begin{array}{l} \to ZZ^* \\ \to WW^* \end{array}\right\} \textbf{Gauge bosons}$$

$$\to \gamma\bar{\gamma} \text{ (di-photon)} \Big\} \textbf{Loop decay}$$

- Add-mixture or possibility of other Higgs bosons are not ruled out

  - But other Higgs bosons may not be seen in normal decay modes!

  - Triplets or Singlet type Higgs bosons are hard to produce and find

  - There is possibility of lighter Higgs bosons but not observed yet

Still longer run at the LHC has a good chance

- How about charged Higgs boson ?

- Is there a charged Higgs boson in nature ?

- Do we really need them?

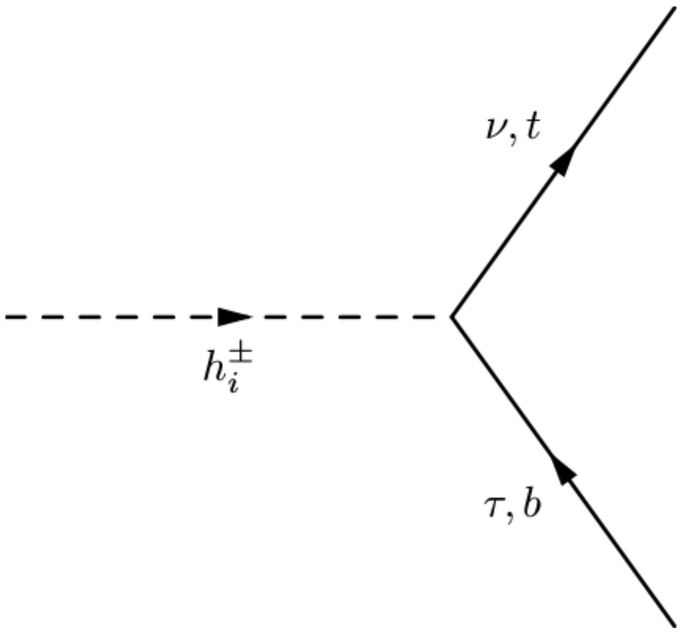
- In the current form of Standard Model we do not have any charged Higgs boson

- It is certainly a beyond Standard Model physics

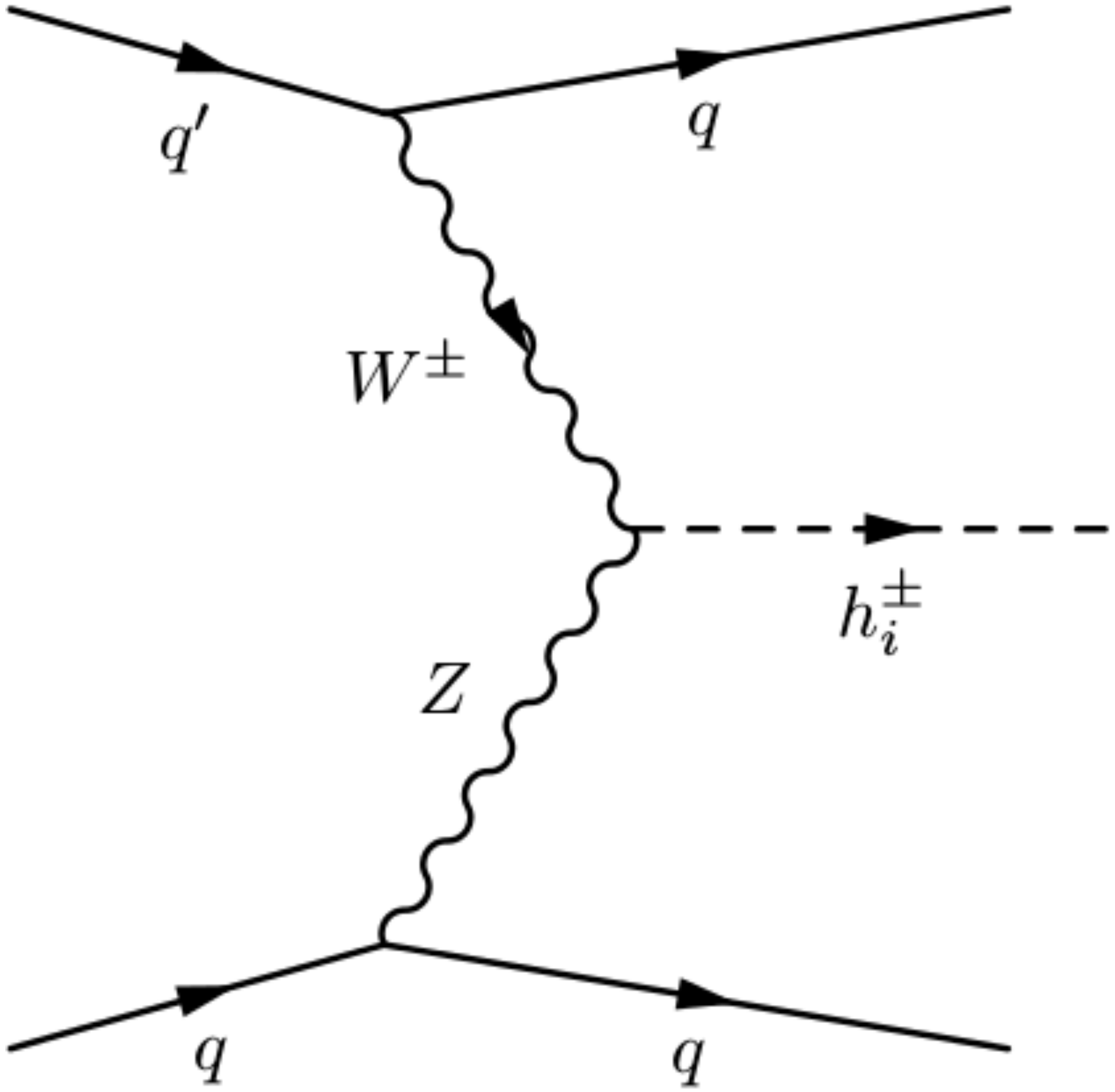
- Necessary for Supersymmetric theories

  - If they are there, how do we see them?

  - They will leave charged track as their signature



Look for new production modes



Prospects at the LHC

- More data
- New resonance !
- New Discoveries !