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Scrutinizing the G2HDM with the W mass measurement at the CDF II

V.Q. Tran

Tsung-Dao Lee Institute - SJTU

In collaboration with Thong T.Q. Nguyen (AS) and T.C. Yuan (AS)

Rapid Response Workshop on W Boson Mass Anomaly
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Outline

I. G2HDM – a brief review
II. W mass shift in G2HDM
III. Numerical result
IV. Summary

I. G2HDM - feature

Huang, Tsai, Yuan 2016

Interesting features of G2HDM:

- DM candidate is protected by a hidden discrete Z_2 symmetry (h-parity) arises naturally as an accidental symmetry rather than imposed by hand
- Unlike in Left-Right symmetric models, the complex vector fields $W'^{(p,m)}$ are **electrically neutral**
- It is anomaly free and no FCNC at tree level

I. G2HDM – particle content

Gauge group $\mathcal{G} = \underbrace{SU(3)_C \times SU(2)_L \times U(1)_Y}_{\text{SM gauge group}} \times \underbrace{SU(2)_H \times U(1)_X}_{\text{Extended}}$

Scalars

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$	h-parity
$H = (H_1 \ \ H_2)^T$	1	2	2	1/2	1	$+ \ -$
$\Phi_H = (\Phi_1 \ \ \Phi_2)^T$	1	1	2	0	1	$- \ +$

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i\frac{G^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix}$$

H_1 and H_2 are embedded into $SU(2)_H$

Accidental Z_2 symmetry

$SU(2)_H$ doublet gives mass to extra heavy fermions

I. G2HDM – particle content

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Fermions

Quarks

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$	h-parity
$Q_L = (u_L \;\; d_L)^{\rm T}$	3	2	1	1/6	0	$+\,+$
$U_R = \left(u_R \;\; u_R^H\right)^{\rm T}$	3	1	2	2/3	1	$+\,-$
$D_R = \left(d_R^H \;\; d_R\right)^{\rm T}$	3	1	2	$-1/3$	-1	$-\,+$
u_L^H	3	1	1	2/3	0	$-$
d_L^H	3	1	1	$-1/3$	0	$-$

Leptons

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$	h-parity
$L_L = (\nu_L \;\; e_L)^{\rm T}$	1	2	1	$-1/2$	0	$+\,+$
$N_R = \left(\nu_R \;\; \nu_R^H\right)^{\rm T}$	1	1	2	0	1	$+\,-$
$E_R = \left(e_R^H \;\; e_R\right)^{\rm T}$	1	1	2	-1	-1	$-\,+$
ν_L^H	1	1	1	0	0	$-$
e_L^H	1	1	1	-1	0	$-$

I. G2HDM- scalar potential

$$V = -\mu_H^2 \left(H^{\alpha i} H_{\alpha i} \right) + \lambda_H \left(H^{\alpha i} H_{\alpha i} \right)^2 + \frac{1}{2} \lambda'_H \epsilon_{\alpha\beta} \epsilon^{\gamma\delta} \left(H^{\alpha i} H_{\gamma i} \right) \left(H^{\beta j} H_{\delta j} \right)$$
$$- \mu_\Phi^2 \Phi_H^\dagger \Phi_H + \lambda_\Phi \left(\Phi_H^\dagger \Phi_H \right)^2 + \lambda_{H\Phi} \left(H^\dagger H \right) \left(\Phi_H^\dagger \Phi_H \right) + \lambda'_{H\Phi} \left(H^\dagger \Phi_H \right) \left(\Phi_H^\dagger H \right)$$

where $(\alpha, \beta, \gamma, \delta)$ and (i, j) refer to the $SU(2)_H$ and $SU(2)_L$ indices respectively, all of which run from 1 to 2, and $H^{\alpha i} = H^*_{\alpha i}$.

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i \frac{G^0}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix}, \quad \Phi_H = \begin{pmatrix} G_H^p \\ \frac{v_\Phi + \phi_2}{\sqrt{2}} + i \frac{G_H^0}{\sqrt{2}} \end{pmatrix}$$

- Goldstone bosons will be absorbed by W^+, W^3, W'^p, W'^3
- h and ϕ_2 are **h-parity even** scalars
- **h-parity odd** particles

I. G2HDM – scalar mixing

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❖ **Mixing between h-parity even scalars**

$$\begin{pmatrix} h \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & \sin\theta_1 \\ -\sin\theta_1 & \cos\theta_1 \end{pmatrix} \cdot \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

125 GeV SM-like Higgs (h_1)

Extra scalar boson (h_2)

$$\tan 2\theta_1 = \frac{\lambda_{H\Phi} v v_\Phi}{\lambda_\Phi v_\Phi^2 - \lambda_H v^2}$$

❖ **Mixing between h-parity odd scalars**

$$\begin{pmatrix} G_H^p \\ H_2^{0*} \end{pmatrix} = \begin{pmatrix} \cos\theta_2 & \sin\theta_2 \\ -\sin\theta_2 & \cos\theta_2 \end{pmatrix} \cdot \begin{pmatrix} \tilde{G}_H^p \\ D \end{pmatrix}$$

Nambu-Goldstone ($\tilde{G}_H^p$)

Dark Higgs (D)

$$\tan 2\theta_2 = \frac{2 v v_\Phi}{v_\Phi^2 - v^2}$$

I. G2HDM — gauge bosons

- $SU(2)_H$ gauge bosons $W'^{(p,m)}$ mass:

$$m_{W'} = \frac{1}{2} g_H \sqrt{v^2 + v_\Phi^2}$$

- $W'^{(p,m)}$ is **electrically neutral** and **odd** under **h-parity,** thus it can be a **DM candidate**!

- Neutral gauge bosons: Mixing between Z^{SM}, W'^3, X

$$\mathcal{M}_Z^2 = \begin{pmatrix} m_{Z^{\rm SM}}^2 & -\frac{g_H v}{2} m_{Z^{\rm SM}} & -g_X v m_{Z^{\rm SM}} \\ -\frac{g_H v}{2} m_{Z^{\rm SM}} & m_{W'}^2 & \frac{g_X g_H \left(v^2 - v_\Phi^2\right)}{2} \\ -g_X v m_{Z^{\rm SM}} & \frac{g_X g_H \left(v^2 - v_\Phi^2\right)}{2} & g_X^2 (v^2 + v_\Phi^2) + M_X^2 \end{pmatrix}$$

R. Ramos, VQT, T.C. Yuan 2021

- **We require:** $0 \sim g_X \ll g_H \ll g, g'$ → To evade Z mass, Z', A' and DMDD constraints

II. W mass shift

❖ Peskin- Takeuchi oblique parameters

M. E. Peskin and T. Takeuchi 1992

$$\hat{\alpha} S = 4\hat{s}_W^2\hat{c}_W^2\left[\Pi'_{ZZ}(0) - \frac{\hat{c}_W^2 - \hat{s}_W^2}{\hat{s}_W\hat{c}_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] ,$$

$$\hat{\alpha} T = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2} ,$$

$$\hat{\alpha} U = 4\hat{s}_W^2\left[\Pi'_{WW}(0) - \hat{c}_W^2\Pi'_{ZZ}(0) - 2\hat{s}_W\hat{c}_W\Pi'_{Z\gamma}(0) - \hat{s}_W^2\Pi'_{\gamma\gamma}(0)\right]$$

$\Pi_{VV}(q^2) = \Pi_{VV}(0) + \Pi'_{VV}\, q^2 + \cdots$ is **vacuum polarization** of V boson

❖ W boson mass shift

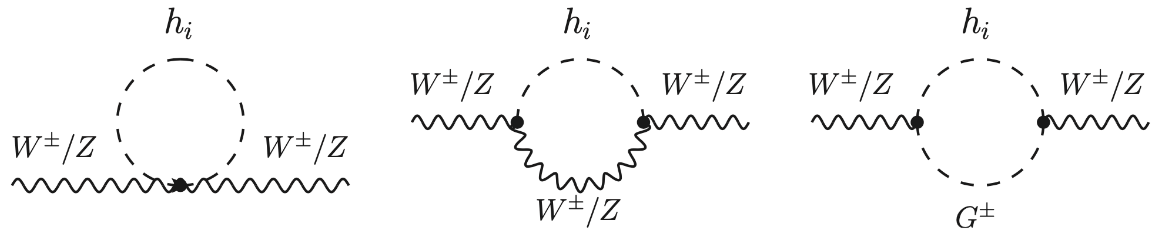
$$\frac{\Delta m_W^2}{m_Z^2} = \hat{\alpha}\frac{\hat{c}_W^2}{\hat{c}_W^2 - \hat{s}_W^2}\left[-\frac{S}{2} + \hat{c}_W^2 T + \frac{\hat{c}_W^2 - \hat{s}_W^2}{4\hat{s}_W^2}U\right] ,$$

$$= (-5.22\, S + 8.02\, T + 6.07\, U) \times 10^{-3} .$$

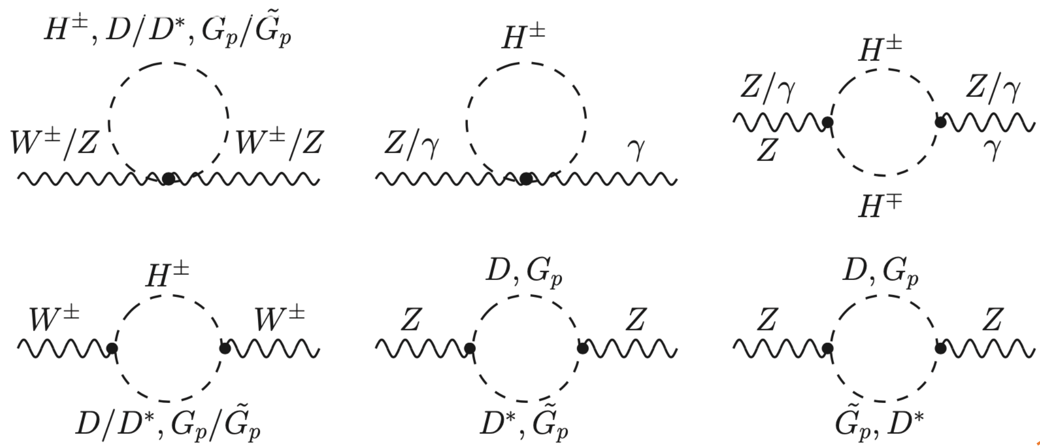
$m_W^2 - m_{W_{SM}}^2$

II. W mass shift in G2HDM

- ❖ **h-parity even scalars contribution**



- ❖ **h-parity odd scalars contribution**



- ❖ **New gauge bosons contribution**: **subdominant** due to the smallness of the new gauge couplings g_H and g_X
- ❖ **Heavy fermions contribution**: **Vanished!**

II. W mass shift in G2HDM

❖ **Heavy fermion contribution**

Dropped g_H, g_X terms

$$\mathcal{L}(f^H) = eQ_{f^H}\left(\bar{f}^H \gamma_\mu f^H\right)\left(A^\mu - \tan\theta_W Z^\mu\right) + \cdots ,$$

$$\Pi^{f^H}_{WW}(q^2) = 0 ,$$

$$\Pi^{f^H}_{\gamma\gamma}(q^2) = N_C e^2 Q^2_{f^H} \Pi_{QQ}(q^2) ,$$

$$\Pi^{f^H}_{\gamma Z}(q^2) = -N_C e^2 Q^2_{f^H} \tan\theta_W \Pi_{QQ}(q^2) ,$$

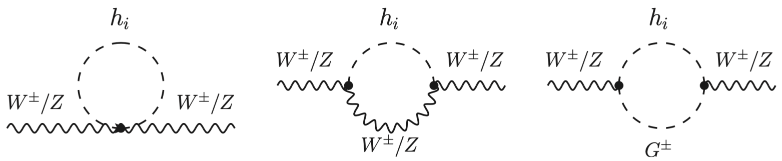
$$\Pi^{f^H}_{ZZ}(q^2) = N_C e^2 Q^2_{f^H} \tan^2\theta_W \Pi_{QQ}(q^2) ,$$

$\Delta S = \Delta T = \Delta U = 0$

$$\Pi_{QQ}(q^2) = \frac{1}{2\pi^2} q^2 \left(\frac{1}{6} E - \int_0^1 dx\, x(1-x) \log \frac{m^2_{f^H} - x(1-x)q^2}{\mu^2} \right)$$

II. W mass shift in G2HDM

❖ **h-parity even scalars contribution**



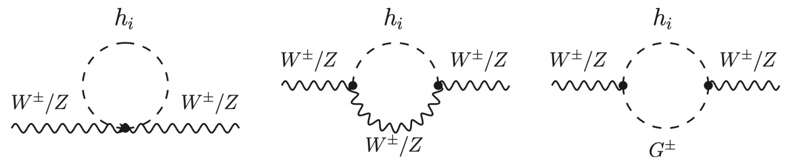
$$\Delta T(\Phi_H) = \frac{3\sin^2\theta_1}{16\pi \hat{s}_W^2}\left[\frac{m_{h_2}^2}{m_{h_2}^2 - m_W^2}\log\left(\frac{m_{h_2}^2}{m_W^2}\right) - \left(\frac{m_Z^2}{m_W^2}\right)\frac{m_{h_2}^2}{m_{h_2}^2 - m_Z^2}\log\left(\frac{m_{h_2}^2}{m_Z^2}\right) - (h_2 \to h_1)\right] .$$

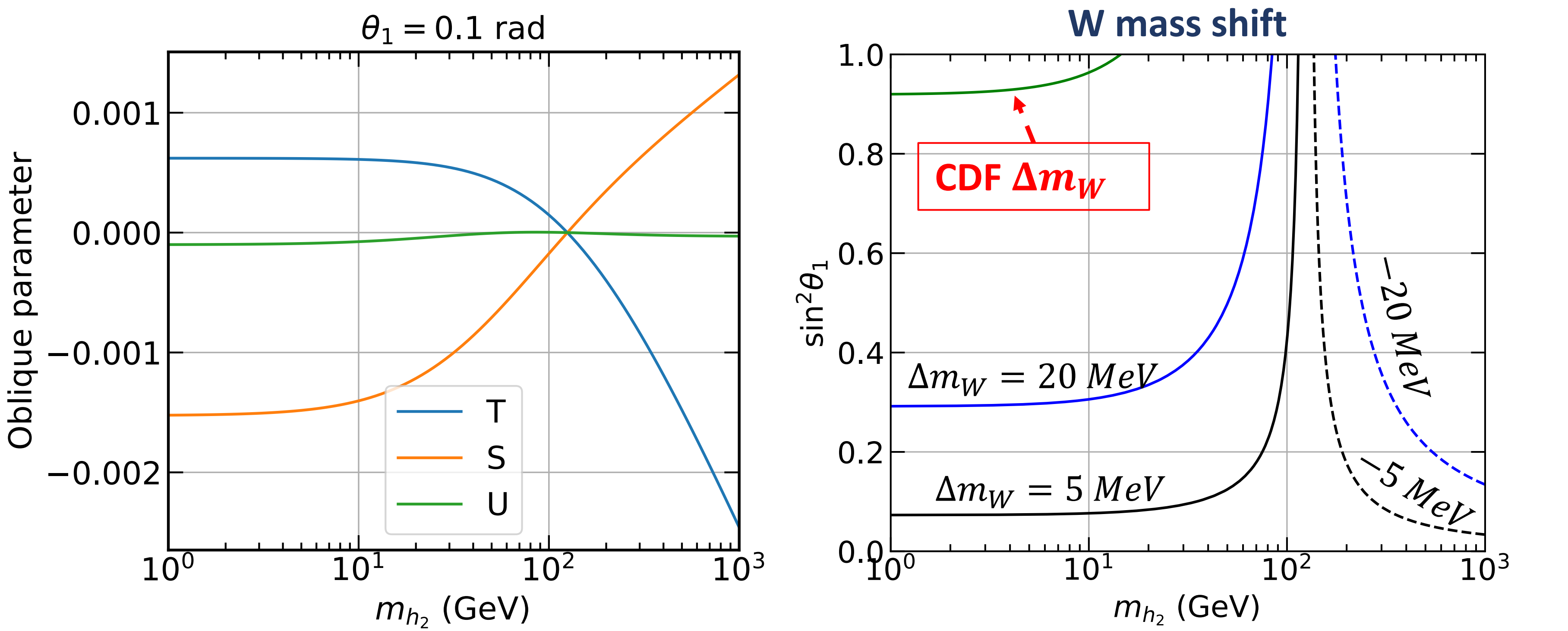
$$\Delta S(\Phi_H) = \frac{\sin^2\theta_1}{12\pi}\left\{-\frac{2\,m_Z^2\left(m_{h_1}^2 - m_{h_2}^2\right)\left(2m_{h_1}^2 m_{h_2}^2 + 3m_Z^2\left(m_{h_1}^2 + m_{h_2}^2\right) - 8m_Z^4\right)}{\left(m_{h_1}^2 - m_Z^2\right)^2\left(m_{h_2}^2 - m_Z^2\right)^2} + \left[\frac{m_{h_2}^2\left(m_{h_2}^4 - 3m_{h_2}^2 m_Z^2 + 12m_Z^4\right)}{\left(m_{h_2}^2 - m_Z^2\right)^3}\log\left(\frac{m_{h_2}^2}{m_Z^2}\right) - (m_{h_2} \to m_{h_1})\right]\right\} ;$$

$$\Delta U(\Phi_H) = \frac{\sin^2\theta_1}{12\pi}\left\{\left[\frac{2\,m_Z^2\left(m_{h_1}^2 - m_{h_2}^2\right)\left(2m_{h_1}^2 m_{h_2}^2 + 3m_Z^2\left(m_{h_1}^2 + m_{h_2}^2\right) - 8m_Z^4\right)}{\left(m_{h_1}^2 - m_Z^2\right)^2\left(m_{h_2}^2 - m_Z^2\right)^2} - \frac{m_Z^4\left(9m_{h_2}^2 + m_Z^2\right)}{\left(m_{h_2}^2 - m_Z^2\right)^3}\log\left(\frac{m_{h_2}^2}{m_Z^2}\right) + \frac{m_Z^4\left(9m_{h_1}^2 + m_Z^2\right)}{\left(m_{h_1}^2 - m_Z^2\right)^3}\log\left(\frac{m_{h_1}^2}{m_Z^2}\right)\right] - \left[(m_Z \to m_W)\right]\right\} .$$

II. W mass shift in G2HDM

❖ **h-parity even scalars contribution**

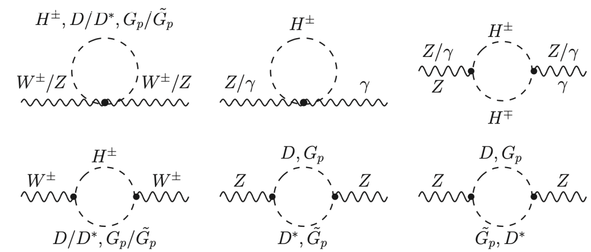




❖ This contribution to W mass shift cannot explain CDF II anomaly due to the Higgs signal strength measurement at the LHC

II. W mass shift in G2HDM

❖ **h-parity odd scalars contribution**



$$\Delta T(H_2) = \frac{1}{8\pi^2 \hat{\alpha} v^2}\Big[F(m_{H^\pm}, m_D)\cos^2\theta_2 + F(m_{H^\pm}, m_{W'})\sin^2\theta_2 - \frac{1}{4}F(m_D, m_{W'})\,\sin^2 2\theta_2\Big]\,.$$

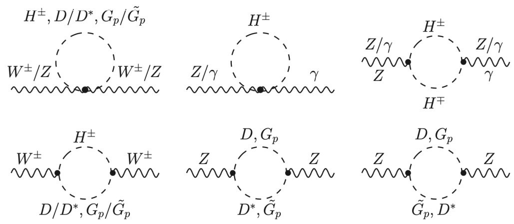
Where $m_{W'}$ is the mass of $\tilde{G}_p$ which is absorbed by the longitudinal component of W'

And

$$F(m_1, m_2) = \begin{cases} \frac{m_1^2+m_2^2}{2} - \frac{m_1^2 m_2^2}{m_1^2-m_2^2}\log\left(\frac{m_1^2}{m_2^2}\right) & \text{for } m_1 \neq m_2\,, \\ 0 & \text{for } m_1 = m_2\,. \end{cases}$$

II. W mass shift in G2HDM

❖ **h-parity odd scalars contribution**



$$\Delta S(H_2) = \frac{1}{36\pi}\left\{-3\log\left(\frac{m_{H^\pm}^2}{m_D^2}\right) + 6\left(\cos^4\theta_2 - 1\right) + 3\left(2 - \log\left(\frac{m_D^2}{m_{W'}^2}\right)\right)\sin^4\theta_2 + \frac{1}{4}G(m_D, m_{W'})\sin^2 2\theta_2\right\}$$

$$\Delta U(H_2) = \frac{1}{36\pi}\left\{-3\log\left(\frac{m_{H^\pm}^2}{m_D^2}\right) - 6\left(\cos^4\theta_2 + 1\right) + G\left(m_D, m_{H^\pm}\right)\cos^2\theta_2 - 3\left(2 - \log\left(\frac{m_D^2}{m_{W'}^2}\right)\right)\sin^4\theta_2 - \left(6\log\left(\frac{m_D^2}{m_{W'}^2}\right) - G(m_{W'}, m_{H^\pm})\right)\sin^2\theta_2 - \frac{1}{4}G\left(m_D, m_{W'}\right)\sin^2 2\theta_2\right\},$$

Where:

$$G\left(m_1, m_2\right) = \frac{(7m_1^4 - 2m_1^2 m_2^2 + 7m_2^4)}{\left(m_1^2 - m_2^2\right)^2} - 6\,\frac{m_2^4\left(3\,m_1^2 - m_2^2\right)}{\left(m_1^2 - m_2^2\right)^3}\log\left(\frac{m_1^2}{m_2^2}\right)$$

in the limit of $m_2 \to m_1$, $G(m_1, m_1) = 12$.

II. W mass shift in G2HDM

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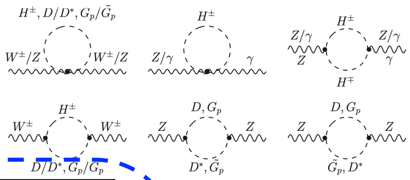
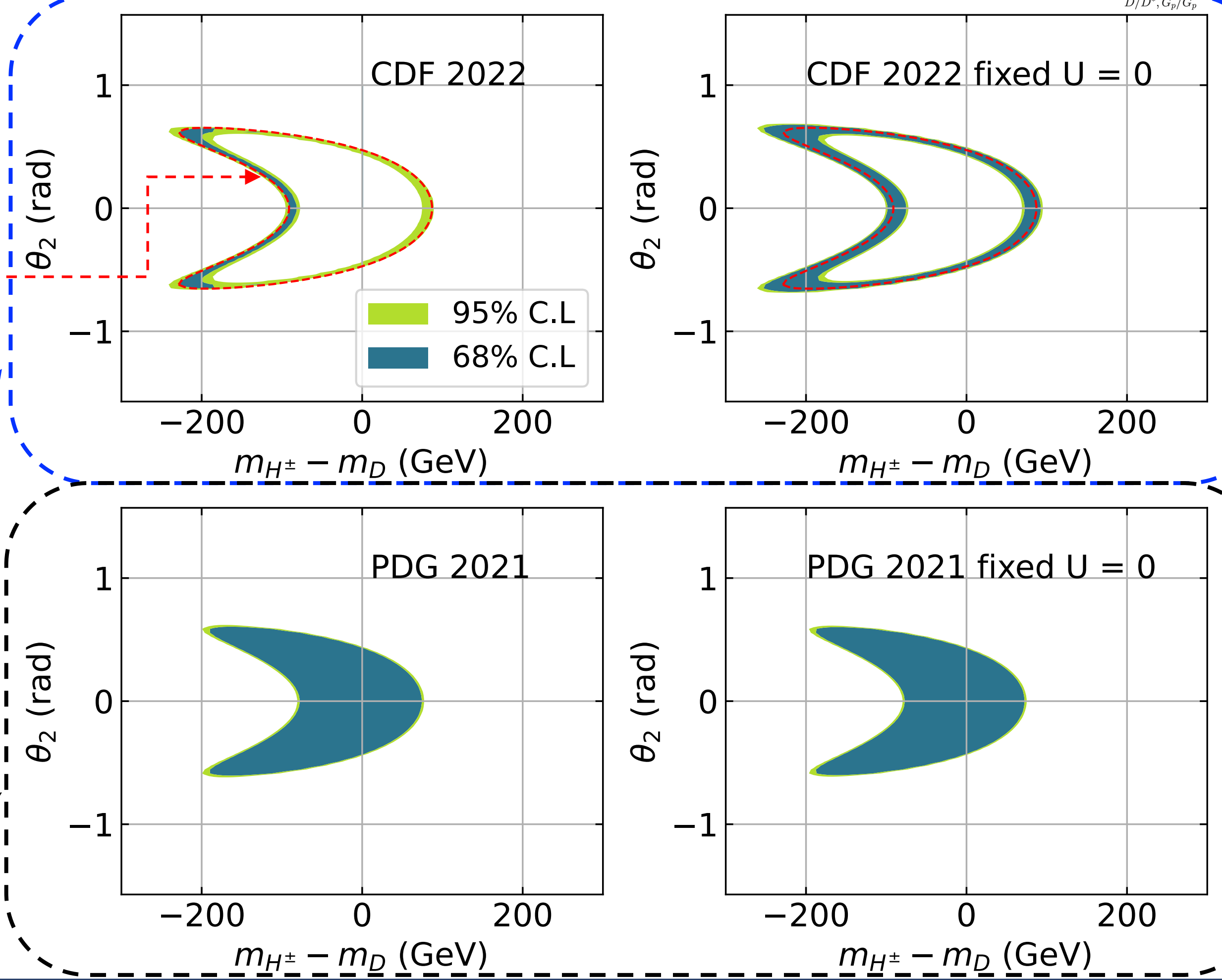
❖ h-parity **odd** scalars contribution



$m_{H^\pm} = 500$ GeV, $m_{W'} = 50$ GeV

W-boson mass measurement at CDF

CDF W-mass

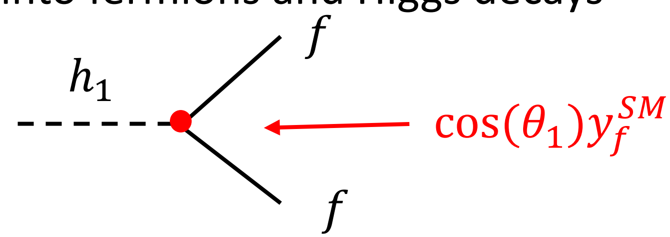


old W-mass

III. Numerical result – constraint

❖ Constraints

1. Vaccuum stability and perturbative unitarity   R. Ramos, VQT, T.C. Yuan 2021
2. Higgs data at LHC including Higgs decays into fermions and Higgs decays into diphoton



- Higgs decays into $\tau^+ \tau^-$

$$\mu_{ggH}^{\tau^+\tau^-} = 1.05_{-0.47}^{+0.53}$$ **CMS**

- Higgs decays into diphoton

$$\mu_{ggH}^{\gamma\gamma} = 0.96 \pm 0.14.$$ **ATLAS**

3. Global fit values for **S, T** and **U** oblique parameters which have been included the new high-precision W-boson mass measurement at CDF II:

$$\Delta S = 0.005 \pm 0.096$$
$$\Delta \mathrm{T} = 0.040 \pm 0.120$$
$$\Delta U = 0.134 \pm 0.087$$
$$\delta_{ST} = 0.91, \delta_{SU} = -0.65, \delta_{TU} = -0.88$$

J. de Blas, M. Pierini, L. Reina, and L. Silvestrini 2204.04204

III. Numerical result - scanning

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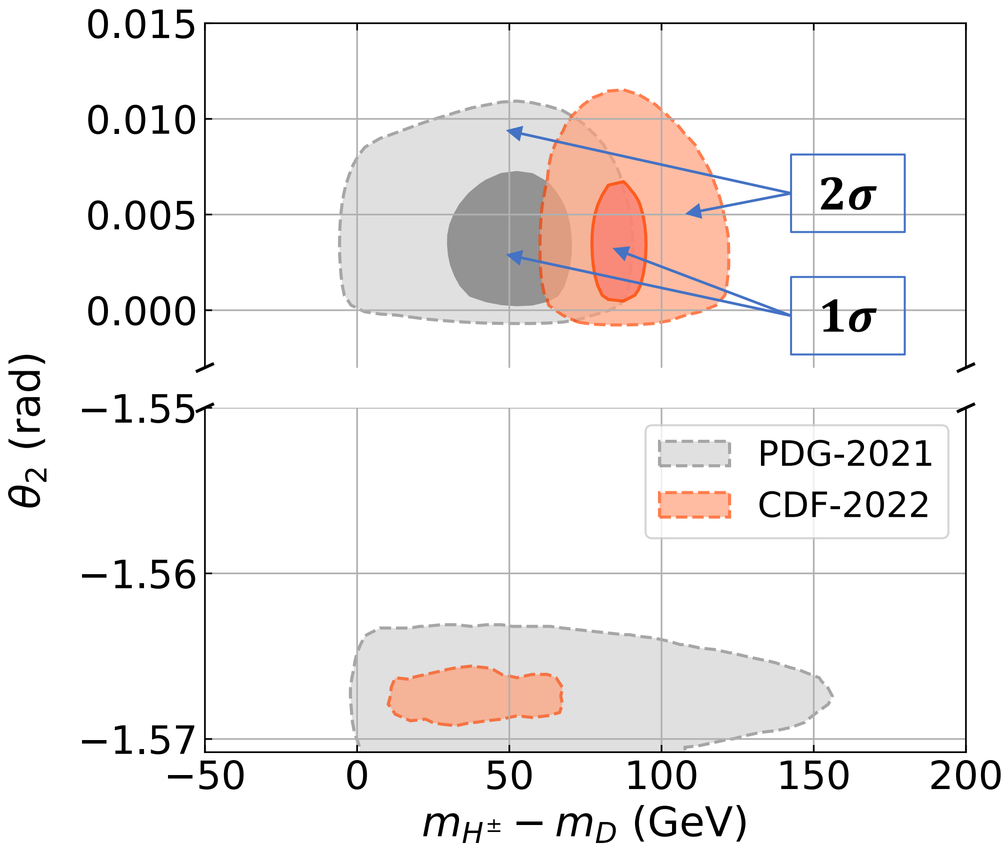
❖ **Parameter scanning range**

$$m_{h_2} = [125, 5000]\ \text{GeV}$$
$$m_{H^\pm} = [100, 5000]\ \text{GeV}$$
$$m_{H^\pm} - m_D = [-500, 500]\ \text{GeV}$$
$$m_{W'} = [0.1, 5000]\ \text{GeV}$$
$$\theta_1 = \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]\ \text{rad}$$
$$\theta_2 = \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]\ \text{rad}$$

❖ We sample the parameter space using ***emcee*** package

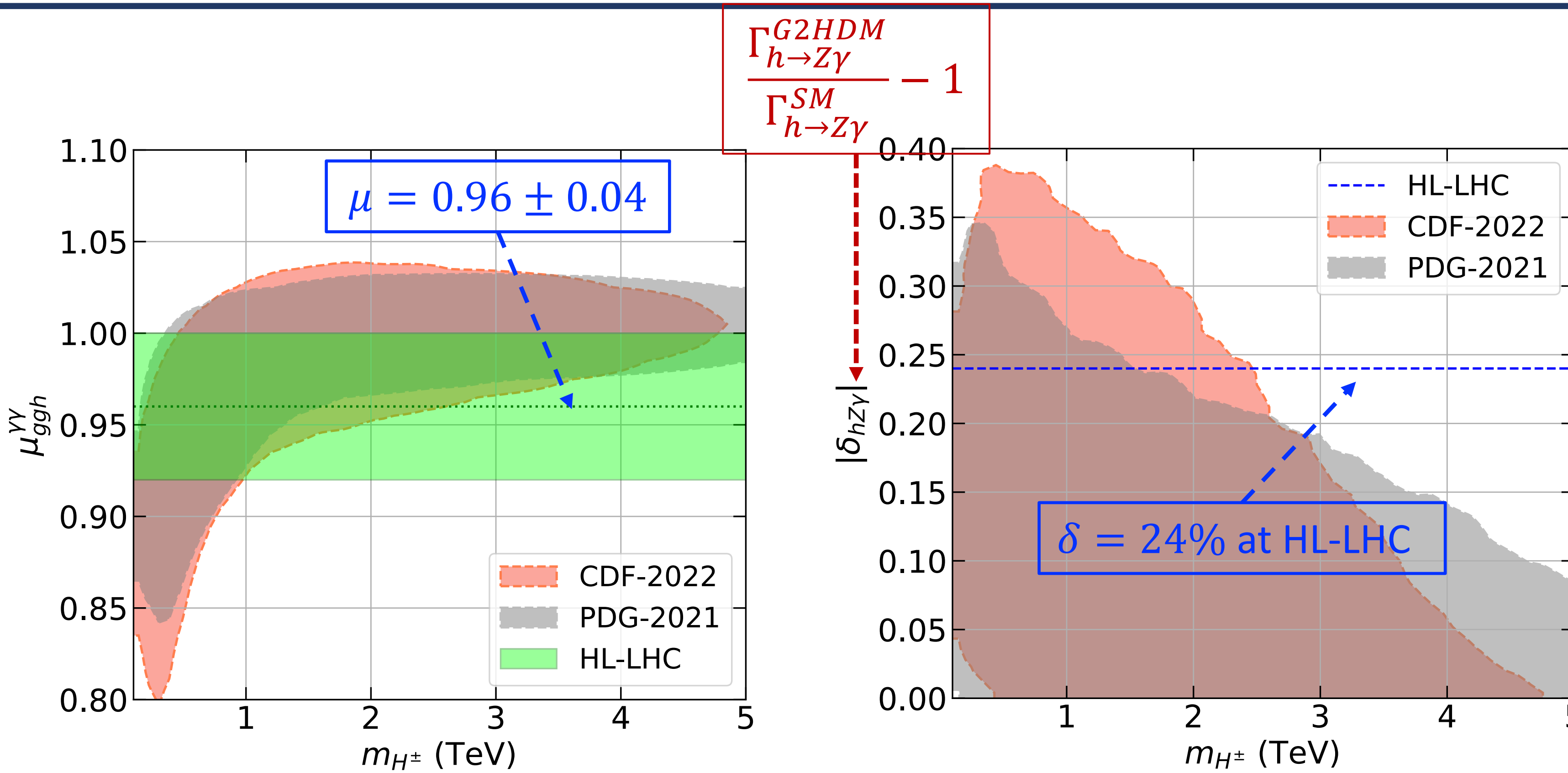
❖ We employ two sets of scanning: one using the **new** global fit values for the oblique parameters (**CDF-2022**) and one using the **old** global fit values (**PDG-2021**)

III. Numerical result



❖ CDF region preferred a **non-degenerate** mass between charged Higgs and dark Higgs

Di-photon and $Z\gamma$ production



- Effects from the mixing between the SM-like Higgs h_1 and extra scalar h_2
- New contributions from the **charged Higgs** and **heavy fermions** in the loop
- CDF region prefers to a larger deviation as compared with PDG region

Dark matter

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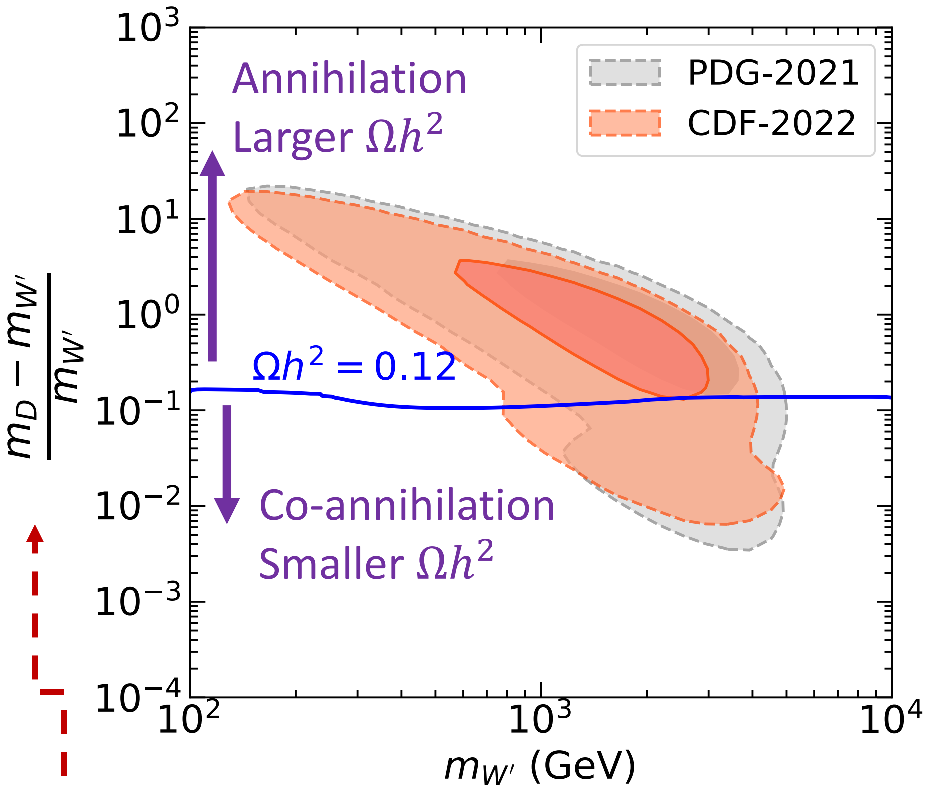

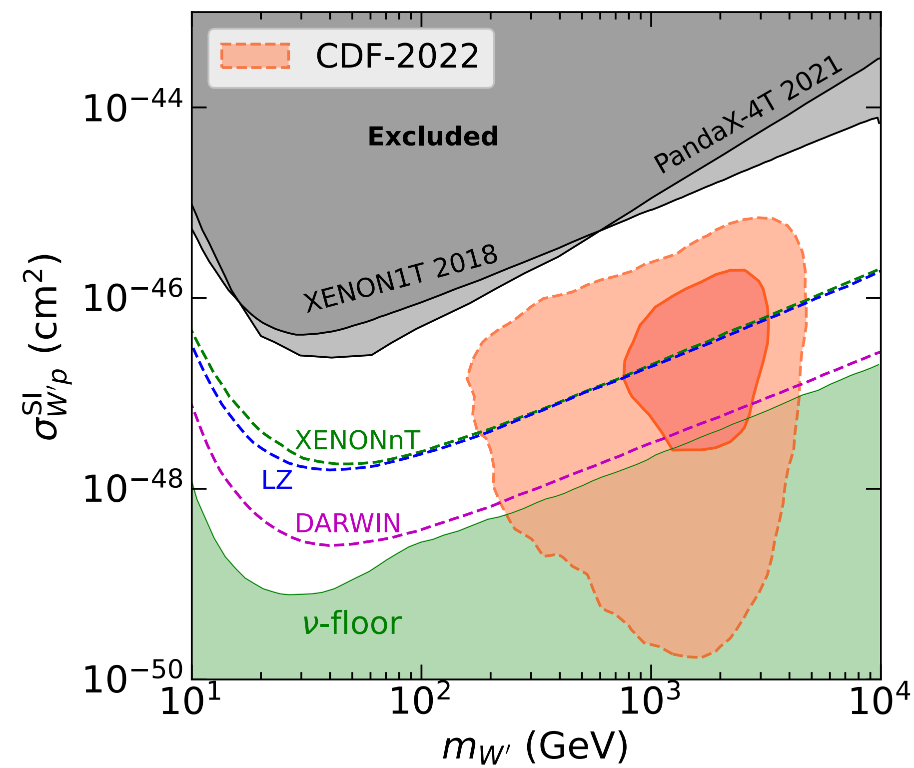

Mass splitting between h-parity odd particles W' and D

✓ Most part of the favored region can be probed at future DMDD searches

IV. Summary

- ✓ We computed the contributions to the Peskin-Takeuchi oblique parameters **S, T** and **U** from additional Higgs doublets (**h-parity even** and **odd**) and extra heavy fermions in G2HDM

- ✓ We found out the effects from the **h-parity even** scalars and the extra heavy fermions are **small**, while the **h-parity odd** scalars can give a **sizable** effect.

- ✓ The new W mass measurement at CDF II can give discernible impacts on the mass splitting and mixing effect among the **h-parity odd** scalars

- ✓ We show the **impact** on the collider searches for **di-photon** and γZ **productions**, and **DM physics** in the model

Thank You