## The 3rd International Joint Workshop & The 11th KIAS Workshop on BSM and Cosmology

November 2023, Jeju Island

## Recent Progress in Minimal G2HDM Phenomenology



TC Yuan, IOP Academia Sinica, Taiwan Based on 2109.03185, 2208.10971, 2212.02333 & work in progress Collaborators: Raymundo Ramos (KIAS), Van Que Tran (TDLI), Thong T. Q. Nguyen (AS)





- Review of Minimal G2HDM
- Electroweak Precision Measurement of W Boson Mass
- Charged Lepton Flavor Violation Processes
- Gravitational Wave and First Order Electroweak Phase Transition
- Summary and Outlook

## Outline

## Gauged 2HDM (G2HDM)

- Novel idea is to lump  $H_1$  and  $H_2$  into a 2-dim irrep. of an hidden  $SU(2)_H$  gauge group
- Proposed a hidden SM-like gauge sector  $SU(2)_H \times U(1)_Y$
- A hidden Higgs doublet  $\Phi_H$  (augmented by a Stueckelburg  $U(1)_X$ scalar S) is also needed to break the hidden gauge group (to give masses to new gauge bosons  $\gamma', Z', \mathcal{W}'^{(p,m)}$ )
- No ad hoc discrete symmetry (like Z<sub>2</sub> in IHDM, R-parity in MSSM, T-parity in Littlest Higgs model, KK-parity in extra dim models ... for DM candidates). Instead a *b*-parity emerges naturally!

Huang, Tsai, TCY, 1512.00229 Ramos, Tran, TCY, 2109.03185



## Matter Content in Minimal G2HDM



Table II. Higgs scalars in the minimal G2HDM and their quantum number assignments.



Ramos, Tran, Yuan, 2101.07115, 2109.03185

$(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$	<i>h</i> -parity
	2	$\frac{1}{2}$	$\frac{1}{2}$	(+, -)
	2	0	$\frac{1}{2}$	(-,+)
	1	0	0	+



				/
$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$	<i>h</i> -parity
2	1	$\frac{1}{6}$	0	(+,+)
1	2	$\frac{2}{3}$	$\frac{1}{2}$	(+, -)
1	2	$-\frac{1}{3}$	$-\frac{1}{2}$	(-,+)
1	1	$\frac{2}{3}$	0	_
1	1	$-\frac{1}{3}$	0	_
2	1	$-\frac{1}{2}$	0	(+, +)
1	2	0	$\frac{1}{2}$	(+, -)
1	2	-1	$-\frac{1}{2}$	(-,+)
1	1	0	0	_
1	1	-1	0	_

Emerges naturally! No need to impose ad hoc by hand!

- All SM particles have even h-parity, while all new particles have odd.
- Free of gauge, gravitational and Witten's global SU(2) anomalies!

Table III. Fermions in the minimal G2HDM and their quantum number assignments.



### Scalar Potential in G2HDM

- The scalar potential is (no ad hoc  $Z_2$  imposed!)  $V = -\mu_H^2 \left( H^{\alpha i} H_{\alpha i} \right) + \lambda_H \left( H^{\alpha i} H_{\alpha i} \right)^2 + \frac{1}{2} \lambda'_H \epsilon_{\alpha\beta} \epsilon^{\gamma\delta} \left( H^{\alpha i} H_{\gamma i} \right) \left( H^{\beta j} H_{\delta j} \right)$
- Invariant under  $SU(2)_L \times U(1)_Y \times SU(2)_H \times U(1)_X$
- no CP violation in the scalar sector of G2HDM

 $-\mu_{\Phi}^{2}\Phi_{H}^{\dagger}\Phi_{H} + \lambda_{\Phi}\left(\Phi_{H}^{\dagger}\Phi_{H}\right)^{2} + \lambda_{H\Phi}\left(H^{\dagger}H\right)\left(\Phi_{H}^{\dagger}\Phi_{H}\right) + \lambda_{H\Phi}^{\prime}\left(H^{\dagger}\Phi_{H}\right)\left(\Phi_{H}^{\dagger}H\right),$ 

• Each term is self-hermitian, all couplings are real, hence

## Symmetry Breaking

• As in I2HDM, we assume *b*-parity is *not* spontaneously broken

$$H_{1} = \begin{pmatrix} G^{+} \\ \frac{v + h_{\rm SM}}{\sqrt{2}} + i \frac{G^{0}}{\sqrt{2}} \end{pmatrix}, \ H_{2} = \begin{pmatrix} H^{+} \\ H_{2}^{0} \end{pmatrix}, \ \Phi_{H} = \begin{pmatrix} G_{H}^{p} \\ \frac{v_{\Phi} + \phi_{H}}{\sqrt{2}} + i \frac{G_{H}^{0}}{\sqrt{2}} \end{pmatrix}$$

SM Higgs doublet

- $(h_{\text{SM}}, \phi_H) \rightarrow (h_1, h_2)$  with mixing angle  $\theta_1$ .
- $(H_2^0, G_H^m) \to (D, \tilde{G})$  with mixing angle  $\theta_2$  (not constraint!)

Inert Higgs doublet

Hidden Higgs doublet

 $\langle H_2 \rangle = 0$ 

 $h(125) = h_1 \text{ or } h_2 \text{ is very much SM-like} \implies \text{Small effect to } \Delta M_W$  $\implies$  Sizable effect to  $\Delta M_W!$ 

## DM Candidate (*b*-parity odd)

(depends on parameter space)

- spin 0 from inert doublet In G2HDM reality,  $H_{2} = \begin{pmatrix} H^{+} \\ H_{2}^{0} \end{pmatrix} \qquad \begin{pmatrix} G_{H}^{m} \\ H_{2}^{0} \end{pmatrix} = \begin{pmatrix} \cos \theta_{2} & \sin \theta_{2} \\ -\sin \theta_{2} & \cos \theta_{2} \end{pmatrix} \begin{pmatrix} \tilde{G} \\ D \end{pmatrix}$  $-2 - (H_2^0)$  (r. 2208.109/165 - spin 1 hidden vector gauge bosons 212.02332, 2208.109/165 - spin 1 hidden vector gauge bosons

- spin 1/2 hidden neutrino Not study yet.

• Lightest *b*-parity *odd* electrically *neutral* particle

Doesn't mix with SM  $W^{\pm}$ ! Different from Left-Right model!

Dirac or Majorana

### CDF II New High Precision Measurement of $M_W$ [Science 376, no. 6589, 170-176 (2022)]

 $8.8 \text{ fb}^{-1}$  data collected from 2002—2011:

 $m_W({
m CDF~II}) = 80,433.5 \pm 9.4 \;{
m MeV}/c^2$ 

- CDF ~  $3\sigma$  away from ATLAS and LHCb
- CDF ~  $6 7\sigma$  away from best fits (de Blas et al, 2112.07274)

 $m_W(\text{SM} - \text{Global Fits}) = 80,359.1 \pm 5.2 \text{ MeV}/c^2$ .

 $\Delta M_W \approx 75 \,\mathrm{MeV}$ 

- BSM physics? Or Systematic? (CDF data collected 2002-2011, Best people left, ...)
- Exp. data not yet combined with LEP and LHC!

#### **RESEARCH** | RESEARCH ARTICLE

Fig. 5. Comparison of this CDF II measurement and past  $M_W$ measurements with the SM expectation. The latter includes the published estimates of the uncertainty (4 MeV) due to missing higher-order quantum corrections, as well as the uncertainty (4 MeV) from other global measurements used as input to the calculation, such as  $m_t$ . c, speed of light in a vacuum.



#### Neutral Gauge Boson Mass Mixing vs Z Mass Shift

- $M_7^{\text{BestFit}-\text{PDG}-2022} = 91.1876 \pm 0.0021 \,\text{GeV}$
- In the basis of  $\{Z^{SM}, W'^3, X\}$

$$\mathcal{M}_{Z}^{2} = \begin{pmatrix} m_{Z^{\text{SM}}}^{2} & -\frac{g_{H}v}{2}m_{Z^{\text{SM}}} & -g_{X}vm_{Z^{\text{SM}}} \\ -\frac{g_{H}v}{2}m_{Z^{\text{SM}}} & m_{W'}^{2} & \frac{g_{X}g_{H}\left(v^{2}-v_{\Phi}^{2}\right)}{2} \\ -g_{X}vm_{Z^{\text{SM}}} & \frac{g_{X}g_{H}\left(v^{2}-v_{\Phi}^{2}\right)}{2} & g_{X}^{2}\left(v^{2}+v_{\Phi}^{2}\right)+M_{X}^{2} \end{pmatrix}, \qquad \Longrightarrow \quad \{Z, \gamma', Z'\}$$

- However one can have  $m_{Z'} \approx 2m_{W'}$  to achieve resonant scenario. For heavy DM mass, we need coannihilation mechanism with  $H^{\pm}$ , which is *b*-parity odd in G2HDM.

Z Mass Shift (LEP) 2.1 MeV

[See also talk by Kazuki Enomoto]

• EWPT gives strong constraints on new gauge couplings  $g_H, g_X!$ 

 $|g_X| \sim |g_H| \lesssim 0.006 \times \sqrt{1 - \frac{7}{5} \frac{m_{W'}^2}{m_{Z^{SM}}^2} + \frac{4}{5} \frac{M_X^2}{m_{Z^{SM}}^2}} \cdot \frac{1}{2021} \cdot \frac{1}{12}$ Ramos, Tran, and TCY, JHEP11 (2021) 112  $\implies \text{Small effect to } \Delta M_W$ 

• Small  $g_{H,X}$  implies W DM overabundance! (: annihilation cross section too small)

annihilation to get the correct relic density in *light* DM mass





### Contributions from heavy fermions $f^{H}$

 $f^{H}$ s couple to the SM  $\gamma$ , Z are very close to *vector-like*!

$$\begin{split} \Pi_{WW}^{f^{H}}(q^{2}) &= 0 , \\ \Pi_{\gamma\gamma}^{f^{H}}(q^{2}) &= N_{C}e^{2}Q_{f^{H}}^{2}\Pi_{QQ}(q^{2}) , \\ \Pi_{\gamma Z}^{f^{H}}(q^{2}) &= -N_{C}e^{2}Q_{f^{H}}^{2}\tan\theta_{W}\Pi_{QQ}(q^{2}) , \\ \Pi_{ZZ}^{f^{H}}(q^{2}) &= N_{C}e^{2}Q_{f^{H}}^{2}\tan^{2}\theta_{W}\Pi_{QQ}(q^{2}) , \end{split}$$

• This implies,  $\Delta S(f^H) = \Delta T$ 

• Thus  $\Delta m_{W_f^H}^2 = 0!$ 

• From our previous analysis, we know  $g_H, g_X \ll g, g'$ . This implies

$$U(f^H) = \Delta U(f^H) = 0$$
.

### Contributions from Inert Doublet $H_2$

Only significant contributions from G2HDM (Feynman-'t Hooft gauge,  $m_{\tilde{G}^{(*)}} = m_{\mathcal{W}^{'}(p,m)}$ )

$$\begin{pmatrix} G_H^m \\ H_2^0 \end{pmatrix} = \mathcal{O}^D \cdot \begin{pmatrix} \tilde{G} \\ D \end{pmatrix} = \begin{pmatrix} \cos \theta_2 & \sin \theta_2 \\ -\sin \theta_2 & \cos \theta_2 \end{pmatrix} \cdot \begin{pmatrix} \tilde{G} \\ D \end{pmatrix}$$



Mass splitting  $(m_{H^{\pm}} - m_D)$  can be sensitively probed by T parameter

### S, T, U (New Physics Only) - Global Fits

- PDG-2021[PTEP 2020, no.8, 083C01 (2020)] •

- Correlation coefficients are 0.92(S, T), -0.8(S, U), -0.93(T, U)• CDF-2022 [de Blas *et al*, 2204.04204]

- $S = -0.01 \pm 0.1$ ,
- $T = 0.03 \pm 0.12$ ,
- $U = 0.02 \pm 0.11$ ,

- $S = 0.005 \pm 0.096$ ,
- $T = 0.04 \pm 0.12$ ,
- $U = 0.134 \pm 0.087$ ,  $\leftarrow$  A much larger U!!
- Correlation coefficients are 0.91(S, T), -0.65(S, U), -0.88(T, U)

#### Phenomenological and Theoretical Constraints

- Vacuum stability Scalar potential is bounded from below 🤗
- Perturbative unitarity constraints via  $(S_1S_2 \rightarrow S_3S_4)$  $\bullet$
- Signal strengths for  $h_{\rm SM} \to \gamma \gamma$ ,  $h_{\rm SM} \to VV^*(V = W, Z)$ ,  $h_{\rm SM} \to \tau^+ \tau^-$  from LHC  $\oslash$  $\bullet$

- Higgs invisible width (*light* dark matter scenario): ullet $Br(h \rightarrow invisible) < 0.13 (ATLAS 2020) \oslash$
- Electroweak precision data from LEP: Z mass shift *I*  $\bullet$
- Dark photon  $\gamma'$  searches (beam dump, BelleII, ...)  $\bullet$
- Z' searches (High invariant mass dilepton searches)  $\oslash$
- Monojet searches 🔗
- Dark matter relic density:  $\Omega_{\gamma}h^2 = 0.120 \pm 0.001 (PLANCK 2018) \oslash$
- Dark matter direct searches ( $\sigma_{\chi p}^{SI}$ ) from CRESST III, DarkSide-50, XENON1T, PandaX-4T, LZ, CDEX, NEWS-G, SuperCDMS etc.
- New  $m_W$  measurement from CDF-II (2022)  $\oslash$

- $\mu_{ggh}^{\gamma\gamma} = 0.96 \pm 0.14 \,(\text{ATLAS 2020}), \,\mu_{ggh}^{\tau\tau} = 1.05^{+0.53}_{-0.47} \,(\text{CMS 2019})$ 
  - $\mu_{ggh}^{WW*} = 1.13^{+0.13}_{-0.12}, \ \mu_{ggh}^{ZZ*} = 0.95^{+0.11}_{-0.11} (ATLAS 2022)$

#### $1\sigma$ and $2\sigma$ Flavored Regions of Masses and Mixing Angles V.Q. Tran, T. T. Q. Nguyễn and TCY, arXiv:2208:10971



### DM Direct Detection



Light DM mass scenario

Spin independent DM-proton elastic cross section  $\sigma_{\mathcal{W}'p}^{SI}$  versus DM mass  $m_{\mathcal{W}'}$ HeRALD — Superfuild He<sup>4</sup> as target with roton and phonon quasiparticle signals



V.Q. Tran, T. T. Q. Nguyễn and TCY, arXiv:2208:10971



### Charged Lepton Flavor Violation Radiative Decays

- $l_i \rightarrow l_j \gamma$ , MDM  $a_{i_i}$ , EDM  $d_{l_i}$  are closely related
- $\mu \to e\gamma, \mu \to e\phi, \dots; \mu e$  conversion etc.

$$\mathscr{B}(\mu \to e\gamma)_{\rm SM} = \frac{3\alpha}{32\pi} \left( \sum_{i} U_{ei}^* U_{\mu i} \frac{m_{\nu_i}^2}{M_W^2} \right)^2 < 10^{-55} \text{ Exceedingly small}!!$$

	From tion	Observable	Experimental Result/Limit	Future Goal
		$a_{\mu}(\text{BNL})$	$(11659208.9\pm5.4_{\rm stat}\pm3.3_{\rm sys}) \times 10^{-10}$ [15–17]	
1.0		$a_{\mu}(\mathrm{FNAL})$	$(11659204.0\pm5.4) imes10^{-10}$ [18]	Uncertainty ${\sim}1/4$ of BNL
4.2 $\sigma$ away from SM prediction		$a_{\mu}(BNL + FNAL)$	$(11659206.1\pm 4.1) \times 10^{-10}$ [18]	Uncertainty ${\sim}1/4$ of BNL
om prediction		$\mathcal{B}(\mu^+ \to e^+ \gamma)$ (MEG)	$< 4.2 \times 10^{-13} (90\% C.L.)$ [4]	$\sim 6 \times 10^{-14}~({\rm MEG~II}~[5])$
		$\left \frac{d_{\mu}}{e}\right $ [cm]	$< 1.8 \times 10^{-19} (95\% C.L.)$ [21]	$\sim 6\times 10^{-23}~(\mathrm{PSI}~[22])$
		$\left \frac{d_e}{e}\right $ [cm] (ACME)	$< 1.1 \times 10^{-29} (90\% C.L.)$ [23]	(Advanced ACME [24])

Refs: Too many, not enough room to cite!! [Cheung, ..., Chun, ..., Ko, ..., Ramos, ..., Song, ..., Tseng, ... ]

[See also talk by Gabriela Lima Lichtenstein]

**Table 1.** Experimental results for  $a_{\mu}$  and upper limits for  $\mathcal{B}(\mu \to e\gamma)$ ,  $|d_{\mu}/e|$  and  $|d_e/e|$ .



## One loop contributions in Minimal (with V.Q. Tran, JHEP 02 (2023) 117) G2HDM

#### **SM Contributions** are recalculated!

Figure 1. The one-loop SM-like contribution to  $l_i - l_j - \gamma$  vertex from the SM W boson diagram (left panel), and contributions to  $l_i - l_i - \gamma$  vertex from  $\{Z_n\}$  diagram (center panel) and  $\{h_n\}$ diagram (right panel) in G2HDM.

W

N

 $\nu_k$ 

 $l_j$ 







Figure 2. Three new contributions of  $\mathcal{D}$ ,  $\mathcal{H}^+$  and  $\mathcal{W}'$  to  $l_i - l_j - \gamma$  vertex in G2HDM.



#### Viable Parameter Space $(2\sigma)$ For sub GeV DM



Figure 6. Viable DM parameter points spanned in the plane of the total branching ratio of  $\mu \to e\gamma$  and muon anomalous magnetic dipole moment  $\Delta a_{\mu}$ . Here we fixed  $m_{l^{H}} = 1$  TeV and  $\Delta m_{l^{H}} = 50 \,\text{GeV}$ . The solid red and dashed blue lines are the current limit from MEG [4] and future sensitivity from MEG II [5], respectively. The shaded light blue band represents the  $2\sigma$  region of  $\Delta a_{\mu}$  measured at BNL [15–17] and FNAL [18].



#### MEG II Sensitivity

Figure 7. Favored data projected on the plane of the DM mass and spin independent DM-proton scattering cross section. Here we fixed  $m_{l^{H}} = 1$  TeV and  $\Delta m_{l^{H}} = 50$  GeV. The crossed purple points indicate the data satisfied the MEG constraint [4], while the circle green points indicate the data that can be probed by future experiment from MEG II [5]. The gray regions are the exclusion from CRESST-III [45], DarkSide-50 [46] and XENON1T [47] experiments. The dashed blue, red and light blue lines represent the future sensitivities from DM direct detection experiments at NEWS-G [51], SuperCDMS [52] and CDEX [53], respectively. Orange region is the neutrino floor background.









# GW Signals & Strong FOEWPT in Minimal G2HDM

With Michael Ramsey-Musolf and VQ Tran, in preparation.

[See also talk by Ryusuke Jinno]

**BM** : { $m_{(h_2,H^{\pm},m_D,m_{W'},m_X,m_{fH})} = (290,350,288,0.105,0.219,10^3)$  GeV; ( $\theta_1, \theta_2$ ) = (0.26,0.32) rad;  $g_X = 4 \times 10^{-5}$  }







 $\xi = \frac{v_C}{T_C}$ 

$$v_C \equiv \phi_{\min}(T_C) = \sqrt{2}$$



PhaseTracer

star represents the benchmark point **BM**.

#### FOPT Viable Parameter Space $(2\sigma)$

Figure 4. Viable model parameter region for the two-step phase transition. The color legend on the top indicates the value of  $\xi = v_C/T_C$  for the second transition. The red

### Nucleation Viable Parameter Space $(2\sigma)$



CosmoTransitions + PTPlot packages





PTPlot package  $\rightarrow$  GW spectrum and SNR

## GW Signals and DM Direct Detection





- Minimal G2HDM has rich phenomenological implications •  $\mathcal{W}^{'(p,m)}$  as SIDM (Small scale issues in WIMP paradigm)
- Matter antimatter asymmetry

## Summary and Outlook

