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Comprehensive study of Type-X 2HDM in light of the muon g-2

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w/ A. Jueid, J. Kim, S. Lee, arXiv: 2104.10175

- 2. Type-X 2HDM
- 3. Muon g-2 in Type-X
- 4. Other constrains
- 5. Results
- 6. Implications
- 7. Conclusions

1. Motivation \mathcal{M} , the Positive Muon Anomalous Muon Anomalous Magnetic Moment to 0.4 ppm \mathcal{M}

Beautiful measurement of muon g-2 by BNL and Fermilab \rightarrow reduced error

1. Motivation \mathcal{M} , the Positive Muon Anomalous Muon Anomalous Magnetic Moment to 0.4 ppm \mathcal{M}

The SM prediction is still controversial.

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- **<u>2009</u>** • **TI WP20** prediction uses dispersive data-driven evaluations with **minimal model dependence HVP value and error** obtained **by merging** procedure ➠ accounts for tensions in input data and • Large spread between results
- rge sy digo oyotomatio difoortamento • Large systematic uncertainties
- Tension with EW precision data **[2003.04886]**

the measurement of a face value, the measurement of \mathbf{A}

We take the muon g-2 anomaly as a NP signal.

$$
\Delta a_{\mu} = a_{\mu}^{\exp} - a_{\mu}^{\rm SM} = 251(59) \times 10^{-11}.
$$

the connection of the connection of the connection fits NP some of the that some of the that some of the theorem of the theor **NP signal at 4.2**

Active studies of NP effects in a very short time

1. SUSY:

2104.07597, 2104.03839, 2104.03284, 2104.03262, 2104.03245, 2104.03274, 2104.03302, 2104.03491, 2104.03489, 2104.04458, 2104.03691, 2104.03259

- 2. two Higgs doublet model: 2104.03367, 2104.03227, 2104.03275, 2010.03590, 2103.10632, 2010.02799, 2003.03386, 2104.03249
- 3. leptophilic boson model: 2104.07680, 2104.03701
- 4. three Higgs doublet model: 2104.07047
- 5. leptoquark model: 2104.06656, 2104.05685
- 6. $L_{\mu} L_{\tau}$ model: 2104.05656, 2104.03340
- 7. $B L$ or $B 3L$ gauge model: 2104.03542, 2103.13991
- 8. flavorful scalar model: 2104.03238
- 9. 2HDM with a singlet scalar model: 1909.03969

Common factors of NP models

1. SUSY:

2104.07597, 2104.03839, 2104.03284, 2104.03262, 2104.03245, 2104.03274, 2104.03302, 2104.03491, 2104.03489, 2104.04458, 2104.03691, 2104.03259 SM prediction to 2013, 2104.0389, 2104.03264, 2104.03262, 210
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2 two Higgs doublet model:

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- 4. three Higgs doublet model: 2104.07047 \overline{a} . three Higgs doublet mo three Higgs doublet model:
2104.07047
- Loop-induced **.** MW
- 5. leptoquark model:

2104.06656, 2104.05685

• Loop-induced
• CP- and Flavor-conserving muuceu
M Flavor-conserviz

- 6. $L_{\mu} L_{\tau}$ model: 2104.05656, 2104.03340
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Research must go on! We have a vast amount of experimental data.

Beyond explaining the muon g-2. Whole parameter space of one model for all the data

The 2HDM accommodates two complex S Basic theory setup

2HDM

$$
\Phi_i = \left(\frac{w_i^+}{\sqrt{2}}\right), \quad i = 1, 2,
$$

where $v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}.$

² = 246 GeV. Using the simplified notation of *s^x* = sin *x*, *c^x* =

The 2HDM accommodates two complex S Basic theory setup

2HDM The 2HDM accommodates two complex *SU*(2)*^L* Higgs doublet scalar fields, ¹ and ² [78]:

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 Λ discrete Z symmetry for $x \circ \text{trace local FCMC}.$ 1 and 2 symmetry for ho tree fever flavor. n tree-level FCNC: A discrete Z_2 symmetry for no tree level FCNC:

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\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2
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$$
\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2
$$

$$
V_{\Phi} = m_{11}^{2} \Phi_{1}^{\dagger} \Phi_{1} + m_{22}^{2} \Phi_{2}^{\dagger} \Phi_{2} - m_{12}^{2} (\Phi_{1}^{\dagger} \Phi_{2} + \text{H.c.})
$$

+ $\frac{1}{2} \lambda_{1} (\Phi_{1}^{\dagger} \Phi_{1})^{2} + \frac{1}{2} \lambda_{2} (\Phi_{2}^{\dagger} \Phi_{2})^{2} + \lambda_{3} (\Phi_{1}^{\dagger} \Phi_{1}) (\Phi_{2}^{\dagger} \Phi_{2}) + \lambda_{4} (\Phi_{1}^{\dagger} \Phi_{2}) (\Phi_{2}^{\dagger} \Phi_{1})$
+ $\frac{1}{2} \lambda_{5} \left[(\Phi_{1}^{\dagger} \Phi_{2})^{2} + \text{H.c.} \right],$

2. Type-X 2HDM where *^PR,L* = (1 *[±]* 5)*/*2 and ` ⁼ *µ,* ⌧ .

Minimal assumption from the Higgs precision data: alignment limit

 $\Delta a_{\mu} \implies$ huge t_{β} & light M_A

while the light one is the light one is highly separate the Higgs alignment is satisfied by $\frac{1}{8}$ ATLAS-CONF-2020-027

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2. Type-X 2HDM 0*.*2 for *m^A >* 30 GeV and 0*.*2-0*.*5 for 15 *< m^A <* 30 GeV. In the 2HDMs, the branching section 3.1.1. In ref. *A* \sim **A** \sim **A** \sim 47], the upper bound on Br(\sim 47], the about \sim **four the A + T and a + T t decay can be the main decay can be the main decay can be the main decay can be the m**

No arbitrary suppressions of h-A-A vertex in the alignment limit. of the *hAA* vertex in the Lagrangian; i.e., *L* = *v*λ*hAA hAA* + *···* which is given by section 3.1.1. In ref. [46, 47], the upper bound on Br(*h* → *AA* → 4τ) is given to be about No arbitrary suppressions of h-A-A vertex in the alignment limit.

$$
\lambda_{hAA} = \frac{1}{2v^2} \left[(2M^2 - 2m_A^2 - m_h^2)s_{\beta-\alpha} + (M^2 - m_h^2)(\cot \beta - \tan \beta)c_{\beta-\alpha} \right]
$$

- Γ*h*→*AA* = $\langle m_h/2,$ • If $M_A < m_h/2$,
	- $P(1 \tA 1) \tC 0 0 \tA$ $C \tA 10^{-3}$ 0*.*015%² $R(h_{\text{max}})$ $\mathcal{B}(h_{\rm SM} \to AA) < 0.2 \Longrightarrow \lambda_{hAA} \lesssim 6 \times 10^{-3}$

?

• Conspiracy of M_A , α , β , m_{12} to suppress λ_{hAA} ?

$$
\tan(\beta - \alpha) = \frac{M^2 - m_h^2}{2M^2 - 2m_A^2 - m_h^2} (\tan \beta - \cot \beta)
$$

can simply take λ_λ από το αρχαίο του από το αρχαίο του από το β − α β − α β − α παρατορικό αναφέρει το β − α f
Ο β − α from eq. (3.1) as a from extensive of β − α from eq. (3.1) as a from extensive of β − α from extens

• Stick to $s_{\beta-\alpha}=1$. $N¹$ 1, *m*² *^H[±]* & 1 and *^m*² • Stick to $s_{\beta-\alpha}=1$.

Two scenarios & model parameters Two-scanarios & model parameters

 $\{m_{\varphi^0}, M_A, M_{H^\pm}, M^2, t_\beta\}$ $\left.\right\}$

Two scenarios & model parameters Two-scanarios & model parameters

have a set of the contract of *m*² ¹²⁵ + *t* |
|
| *t*2 \sqrt{D} $\frac{1}{2}$ $\{m_{\varphi^0}, M_A, M_{H^\pm}, M^2, t_\beta\}$ $\left.\right\}$ ¹²*/*(*sc*) and '⁰ is the new *CP*-even neutral Higgs boson, i.e., '⁰ = *H* in the normal scenario and '⁰ = *h* in the inverted scenario. Two scenarios are summarized

New CP-even scalar boson

Two scenarios & model parameters

2. Type-X 2HDM 2. Type-X 2HDM

 $t_{\beta} \simeq 100$

Theoretical stabilities require strong constraints due to chain reaction. where *^PR,L* = (1 *[±]* 5)*/*2 and ` ⁼ *µ,* ⌧ .

$$
t_{\beta} \simeq 100
$$
\n
$$
\lambda_1 = \frac{1}{v^2} \left[m_{125}^2 + \frac{t_{\beta}^2}{2} \left(m_{\varphi^0}^2 - M^2 \right) \right],
$$
\n
$$
\lambda_2 = \frac{1}{v^2} \left[m_{125}^2 + \frac{1}{t_{\beta}^2} \left(m_{\varphi^0}^2 - M^2 \right) \right],
$$
\n
$$
\lambda_3 = \frac{1}{v^2} \left[m_{125}^2 - m_{\varphi^0}^2 - M^2 + 2M_{H^{\pm}}^2 \right],
$$
\n
$$
\lambda_4 = \frac{1}{v^2} \left[M^2 + M_A^2 - 2M_{H^{\pm}}^2 \right],
$$
\n
$$
\lambda_5 = \frac{1}{v^2} \left[M^2 - M_A^2 \right],
$$

$$
M^2=m_{12}^2/(s_\beta c_\beta)
$$

the normal scenario and '⁰ = *h* in the inverted scenario. Two scenarios are summarized

2. Type-X 2HDM 2. Type-X 2HDM

Theoretical stabilities require strong constraints due to chain reaction.

$$
\begin{split} \lambda_1 &= \frac{1}{v^2} \left[m_{125}^2 + \frac{t_\beta^2}{t_\beta^2} \left(m_{\varphi^0}^2 - M^2 \right) \right], \\ \lambda_2 &= \frac{1}{v^2} \left[m_{125}^2 + \frac{1}{t_\beta^2} \left(m_{\varphi^0}^2 - M^2 \right) \right], \\ \lambda_3 &= \frac{1}{v^2} \left[m_{125}^2 - m_{\varphi^0}^2 - M^2 + 2M_{H^\pm}^2 \right], \\ \lambda_4 &= \frac{1}{v^2} \left[M^2 + M_A^2 - 2M_{H^\pm}^2 \right], \\ \lambda_5 &= \frac{1}{v^2} \left[M^2 - M_A^2 \right], \end{split}
$$

2. Type-X 2HDM 2. Type-X 2HDM

Theoretical stabilities require strong constraints due to chain reaction.

$$
\begin{aligned}\n\lambda_1 &= \frac{1}{v^2} \left[m_{125}^2 + \frac{t_\beta^2}{t_\beta^2} \left(m_{\varphi^0}^2 - M^2 \right) \right], \\
\lambda_2 &= \frac{1}{v^2} \left[m_{125}^2 + \frac{1}{t_\beta^2} \left(m_{\varphi^0}^2 - M^2 \right) \right], \\
\lambda_3 &= \frac{1}{v^2} \left[m_{125}^2 - m_{\varphi^0}^2 - M^2 + 2M_{H^\pm}^2 \right], \\
\lambda_4 &= \frac{1}{v^2} \left[M^2 + M_A^2 - 2M_{H^\pm}^2 \right], \\
\lambda_5 &= \frac{1}{v^2} \left[M^2 - M_A^2 \right],\n\end{aligned}
$$

2. Type-X 2HDM 2. Type-X 2HDM $\overline{\mathbf{M}}$

Theoretical stabilities require strong constraints due to chain reaction.

$$
\lambda_1 = \frac{1}{v^2} \left[m_{125}^2 + \frac{t_B^2}{t_B^2} \left(m_{\varphi^0}^2 - M^2 \right) \right],
$$

\n
$$
\lambda_2 = \frac{1}{v^2} \left[m_{125}^2 + \frac{1}{t_B^2} \left(m_{\varphi^0}^2 - M^2 \right) \right],
$$

\n
$$
\lambda_3 = \frac{1}{v^2} \left[m_{125}^2 - m_{\varphi^0}^2 - M^2 + 2M_{H^\pm}^2 \right],
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\n
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\lambda_4 = \frac{1}{v^2} \left[M^2 + M_A^2 - 2M_{H^\pm}^2 \right],
$$

\n
$$
\lambda_5 = \frac{1}{v^2} \left[M^2 - M_A^2 \right],
$$

\n
$$
M_A \sim M_{H^\pm} \sim M \approx m_{\varphi^0}.
$$

controls the theoretical constraints in the limit of large *t*. Therefore, we need the condition

3. Muon g-2 in Type-X 2HDM

Two kinds of contributions

3. Muon g-2 in Type-X 2HDM

Apidir the Observed H Large tanβ is required. CP-even scalar cannot explain the observed muon g-2. as follows:
as follows:

3. Muon g-2 in Type-X 2HDM

A light pseudo scalar A helps, but a light CP-even scalar doesn't.

Scan strategy in three steps

Step I: Δa_{μ} at 2σ .

Step II: Theory+EWPD after Step I

1. Theoretical stabilities:

Higgs potential being bounded from below, unitarity of scalar-scalar scatterings, perturbativity, vacuum stability.

- 2. Peskin-Takeuchi electroweak oblique parameters.
- Step III: Collider bounds after Step II
	- 1. Higgs precision data by using HiggsSignals.
	- 2. Direct searches for new scalars at the LEP, Tevatron, and LHC, by using HiggsBounds.

References for the analyses currently implemented in 4. Other constrains

HiggsBounds provide powerful checkup. HiggsBounds

HiggsBounds currently incorporates results from LEP $[1-15]$, the Tevatron $[16-50]$, and the ATLAS $[51-123]$ and CMS $[124-194]$ experiments at the LHC. \mathbf{H}

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HiggsBounds provide powerful checkup.

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The inverted scenario survived harder, from the collider data.

- For each scenario, we obtained 5×10^5 parameter sets satisfying Step II.
- *•* After Step III,
	- $-$ Normal scenario: $\sim 80\%$ survived.
	- $-$ Inverted scenario: $\sim 1.8\%$ parameter sets survived.

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The inverted scenario is not dead. straints. After a position the Step III constraints, about 105 parameter survive in the Step III constraints, a
In the Step III constraints in the Step III constraints, and in the Step III constraints in the Step III const

5. Results in the normal scenario \sim ts . Direct searches for new scalars at the LEP, Tevatron, Tevatron, Tevatron, Tevatron, Tevatron, Teva

and LHC, by using HiggsBown and LHC, by using HiggsBown and LHC, by using HiggsBown and 4.2 Results in the normal scenario (1) In the normal scenario, collider data are crucial.

$$
\Delta a_\mu
$$

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Step II (Step I+Theory+EWPD), and Step III (Step II+Collider), with the color code indicating Δa_μ

 Δa_{μ} Step I+Theory+EWPD

5. (1) Results in the normal scenario that the SM Higgs boson is a linear combination of *h* and *H*, as Results ts . Direct searches for new scalars at the LEP, Tevatron, Tevatron, Tevatron, Tevatron, Tevatron, Teva

and LHC, by using HiggsBown and LHC, by using HiggsBown and LHC, by using HiggsBown and 4.2 Results in the normal scenario *h*SM = $\frac{1}{2}$ + $\frac{1}{2}$ (1) In the normal scenario, collider data are crucial.

Step II (Step I+Theory+EWPD), and Step III (Step II+Collider), with the color code indicating Δa_μ

• Type-X is better in explaining the LFU violation.

 Δa_{μ} Step I+Theory+EWPD Step II+Collider \overline{D} \overline{D} \overline{D} \overline{D} \overline{D} \overline{D} \overline{D} \overline{D}

Step II+Collider

We show the allowed (*MA, t*) of the normal scenario in Fig. 2, following the sequence of

 $t_{\beta} \gtrsim 100, \quad \text{ intermediate-mass } A^0$ Step II+Collider $\epsilon \epsilon \Delta^0$ only the *a*obs

three steps in the previous subsection. At $\mathcal{L}_{\mathcal{A}}$ (the left panel), which demands to explain demand

5. (1) Results in the normal scenario Results *h*SM = *h,* '⁰ = *H h*SM = *H,* '⁰ = *h ^f* = 1*, s*↵ = 1 *y*

Chain reaction \rightarrow Not too heavy MH and charged Higgs

5. (1) Results in the normal scenario Results *h*SM = *h,* '⁰ = *H h*SM = *H,* '⁰ = *h ^f* = 1*, s*↵ = 1 *y*

Chain reaction \rightarrow Not too heavy MH and charged Higgs

3 *a^µ* in the Type-X 2HDM

200

250

The condition in Eq. (2.8) makes it dicult to have a vanishing *h*SM*AA*. Since the Higgs precision measurement puts a strong bound on the exotic Higgs decay as *B*(*h*SM ! *XX*) . **Combounds on MH and MH+**

150 M_H [GeV]

5. Results in the normal scenario \sim

Exotic Higgs decay removes light A.

5. Results in the normal scenario that the SM Higgs boson is a linear combination of \mathbf{H} III (the right panel of Fig. 2) implies that the observed *a^µ* can be explained by *t* & 90 and *M^A* 2 [62*.*5*,* 145] GeV when scanning *t* up to 200.

*h*SM = *n* α *scenario, collider data are more crucial.* (2) In the inverted scenario, collider data are more crucial. \mathcal{A} . Since the intervals in the inverted scenario scen Step I: *a^µ* at 2.

5. (1) Results in the normal scenario Results *h*SM = *h,* '⁰ = *H h*SM = *H,* '⁰ = *h ^f* = 1*, s*↵ = 1 *y*

Chain reaction \rightarrow Not too heavy MH and charged Higgs

that the normal scenario colors in the allowed parameter points at Step I and S

Exotic Higgs decay & LEP search for Ah are crucial.

What do the surviving parameters imply?

- (1) Electron anomalous magnetic moment
- (2) Lepton Flavor Universality in Z and τ decays
- (3) Phenomenological signatures at the HL-LHC

6. Implications in the normal scenario contractor of the normal scenario contractor of the normal scenario con As a flavor-universal theory, the Type-X 2HDM has the same contributions to the electron 5 Implications on the electron *g* 2 and the LHC collider signatures

(1) Electron anomalous magnetic moment: *g* and the muon of the muon muon control of the distribution of the distribution of the electron and muon masses. If $\frac{1}{2}$ 5.1 Electron anomalous magnetic moment

the same contributions to the muon/electron *g*-2 except for mass. And Sanid Continuutions to the Thuori diectron g-Z except for mass.

 Δa_e is sensitive to the value of the fine structure constant α

$$
\Delta a_e^{\rm Cs} = -8.8(3.6) \times 10^{-13}, \qquad \text{Science 360 (2018)}
$$

, (5.1) Science 360 (2018)

 $\Delta a_e^{\rm Rb} = 4.8(3.0) \times 10^{-13}$. *a*Cs ⁼ 8*.*8(3*.*6) ⇥ ¹⁰¹³ Nature 588 (2020)

(1) Electron anomalous magnetic moment is consistent with Type-X. euc moment is consistent with Type-X.

(2-1) Lepton Flavor Universality in Z decays:

$$
\frac{\Gamma(Z \to \mu^+ \mu^-)}{\Gamma(Z \to e^+ e^-)} \equiv 1 + \delta_{\mu\mu}^Z = 1.0009 \pm 0.0028,
$$
\n[hep-ex/0509008]
\n
$$
\frac{\Gamma(Z \to \tau^+ \tau^-)}{\Gamma(Z \to e^+ e^-)} \equiv 1 + \delta_{\tau\tau}^Z = 1.0019 \pm 0.0032,
$$

[hep-ex/0509008]

With the correlation of $+0.63$ ⌧ ⌧ = 1*.*0019 *±* 0*.*0032*,*

$$
\boxed{\ \ \delta^Z_{\tau\tau} \ \propto \ m_\tau^2 t_\beta^2 \ \ }
$$

(2-2) Lepton Flavor Universality in τ decays:

(2-3) χ 2 analysis of LFU in Z and τ decays:

• Type-X is better in explaining the LFU violation.

$$
\chi^2_{\rm min} = 6.6, \quad \chi^2_{\rm SM} = 13.4
$$

• $\chi^2_{\rm min}$ happens when

NS:
$$
t_{\beta} = 195
$$
, $M_A = 108.7 \text{ GeV}$,
\n $M_H = 130.4 \text{ GeV}$, $M_{H^{\pm}} = 121.7 \text{ GeV}$, $M^2 = (130.4 \text{ GeV})^2$,
\nIS: $t_{\beta} = 186$, $M_A = 75.6 \text{ GeV}$,
\n $m_h = 116.7 \text{ GeV}$, $M_{H^{\pm}} = 116.3 \text{ GeV}$, $M^2 = (116.5 \text{ GeV})^2$.

6. Implications

(2-3) Many parameters have χ 2 less than χ 2sm

6. Implications ations We study the branching ratios of *A*, '0, and *H[±]* in the finally allowed parameter space including *aµ*. We found that both

(3) LHC signatures? For the final surviving points, new scalar bosons are hadro-phobic. *pp* ! *AH* ! 4⌧ *do* : I be the inter*^e*+*e* ! *Ah*

$$
{\cal B}(A/\varphi^0\to\tau^+\tau^-)\sim 1
$$

6. Implications *the branching rations the inverted scenario (right)* *****n*

(3) Two golden modes at the HL-LHC

 $q\bar{q} \to Z^* \to A\varphi^0 \to \tau^+\tau^-\tau^+\tau^-,$ $pp \rightarrow H^+H^- \rightarrow \tau^+\nu\tau^-\nu$,

6. Implications whole allowed parameter space are beyond the scope of this paper, we calculate the scope of th *gg* ! *^H*+*H* ! ⌧⌫⌧⌫

(3) Four tau lepton channel: very promising cross sections of new signals at the parton-level and compare them with the irreducible (b) Four tau repton channe **very promising** *qq*¯ ! *^H*+*H* ! ⌧⌫⌧⌫

Figure 10 shows total cross section at the 14 TeV LHC for the process *pp* ! *Z*⇤ ! $\sigma(pp \to ZZ \to 4\tau) \sim 17~{\rm fb} \,\, {\rm at \,\, the}\,\, 13 \,\, {\rm TeV} \,\,{\rm LHC}$ t_0 to the normal (international terms) scheme t_0

4 tau mode has a high potential. [1507.06257] [1512.05314] at the 13 Tev 20 Apple 20
A has a high potential potential to probe the whole allowed parameters space of the whole allowed parameter space of the Type-X 2HDM.

al. 2007.06257] [1507.06257] [1512.05314]

6. Implications

(3) Two tau lepton plus missing ET channel *^e*+*e* ! *Ah gg* ! *^H*+*H* ! ⌧⌫⌧⌫ 180 \vert (**Fwo tau lepton plus missing ET chare** i.
Sedan

 $arXiv:1905.04242,$ $\sigma_{\text{tot}}^{\text{SM}}(pp \to W^{+}W^{-} \to \tau \nu \tau \nu) \simeq 1.7 \text{ pb} \text{ arXiv:1905.04242},$ SM_{ℓ} σ σ $+$ σ σ σ σ σ σ σ $\sigma_{\rm tot}$ (pp \rightarrow $ZZ \rightarrow$ τ τ $\sigma_{\text{tot}}^{\text{SM}}(pp \to ZZ \to \tau^+ \tau^- \nu \nu) \simeq 0.1 \text{ pb} \quad \text{arXiv:1507.06257}$

6. Conclusions exclude a large portion of the parameter space. In the normal scenario, *h*SM ! *AA* at the

scenario, the most crucial one is the LEP search for *^e*+*e* ! *^Z*⇤ ! *Ah*. For the full picture of the model parameters in the allowed parameters of the allowed parameters in the allowed parame as follows: Type-X 2HDM is a viable model for the muon g-2 and other data.

- *•* In the normal scenario
	- $\mathbf{t}_{\beta} \gtrsim 90$ and $\mathbf{M}_{\mathbf{A}} \in [\mathbf{m}_{125}/2, 145] \text{ GeV};$
	- $-$ M_H \in [130, 245] GeV and M_{H^{±}} \in [95, 285] GeV.</sub>
- *•* In the inverted scenario
	- $-$ t_{β} \gtrsim 120 and M_A \in [70, 105] GeV;
	- $-$ M_H \in [100, 120] GeV and M_{H^{±}} \in [95, 185] GeV;</sub>
	- $M_A + M_h \gtrsim 190 \text{ GeV}.$