Phenomenological aspects of 2HDM

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BSM Models often involve extended Higgs sector :

- $U(1)_{B-L}$, Some DM models : SM Higgs + Scalar singlet
- MSSM : SM Higgs + Scalar doublet (2HDM)
- LR model, type-II seesaw : SM Higgs + Scalar triplet

Motivations for 2HDM:

- Explaining baryon asymmetry of the Universe
- PQ symmetry
- Neutrino mass generation, Dark matter etc.
- Muon anomalous magnetic moment.

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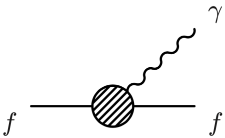
In this talk:

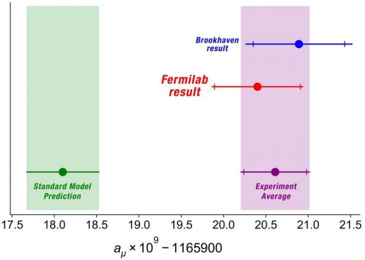
- Muon $g-2$ and light pseudoscalar: ILC prospect
- Is it possible to connect neutrino mass with $(g-2)_\mu$?

Muon anomalous magnetic moment



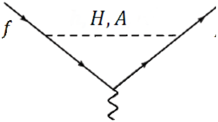
$$iM = -i\bar{u}_f e Q_f \left(F_1(q^2)\gamma^\mu + F_2(q^2) i \frac{\sigma^{\mu\nu} q_\nu}{2m_f} \right) u_f$$

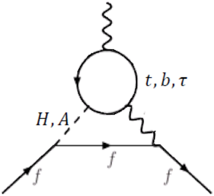
$$a_f = \frac{g_f - 2}{2} = F_2(0)$$



- $a_\mu^{\rm exp} = (11659206.1 \pm 4.1) \times 10^{-10}$
- $a_\mu^{\rm th} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had,VP} + a_\mu^{\rm had,LbL}$
- $\{(11658471.9 \pm 0.007) + (15.36 \pm 0.1)\} \times 10^{-10}$
- $\{(684.68 \pm 2.42) + (9.8 \pm 2.6)\} \times 10^{-10}$
- $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$

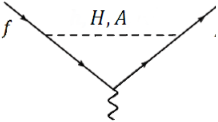
Scalar or Pseudoscalar Solutions to $(g-2)_\mu$

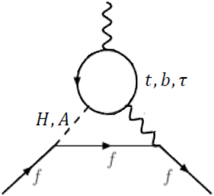




- One loop contribution :
  H is + ve & A is - ve
- Two loop contribution :
  H is - ve & A is + ve

Scalar or Pseudoscalar Solutions to $(g-2)_\mu$



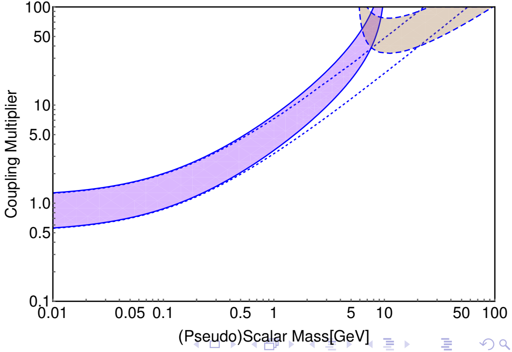


- One loop contribution : H is + ve & A is - ve
- Two loop contribution : H is - ve & A is + ve

Leptophilic Interactions

$$\mathcal{L}_S = -\xi_H \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} H \bar{\ell}\ell$$

$$\mathcal{L}_A = -\xi_A \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} A \bar{\ell} i\gamma^5 \ell$$



Experimental Constraints

- Strong constraint on light scalar comes from beam dump experiments.
- Limit from B and K decay (CHRAM, E949, NA62, LHCb)

$$\xi_H^q \lesssim \text{few} \times 10^{-4}$$

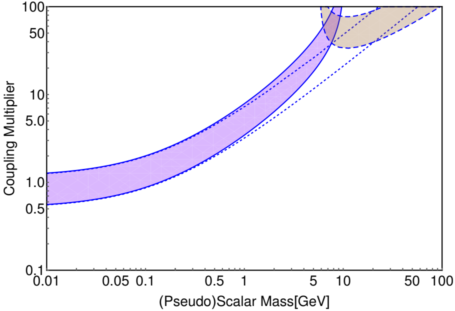
- Leptophilic scalars can evade hadronic constraints easily.
- Limit on leptophilic scalars come from BABAR:

$$e^+e^- \to \tau^+\tau^- H \;, \quad H \to e^+e^- \;\text{ or }\; \mu^+\mu^-$$

PRL 125 (2020) 18, 181801

- Also bremsstrahlung of light scalar at electron beam dump experiments, like Orsay, E137

Scalar or Pseudoscalar Solutions to $(g-2)_\mu$



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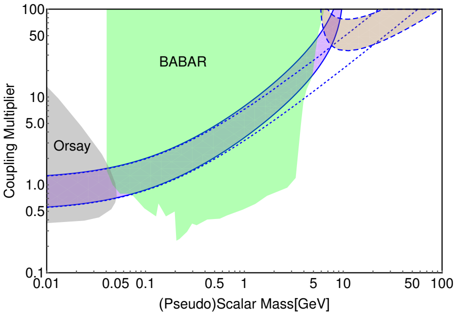

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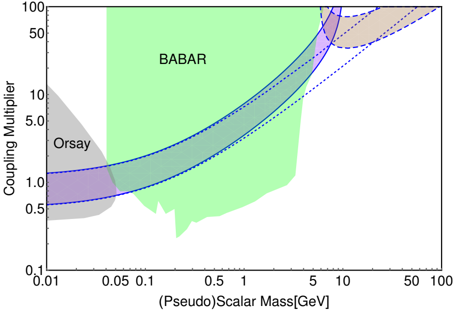

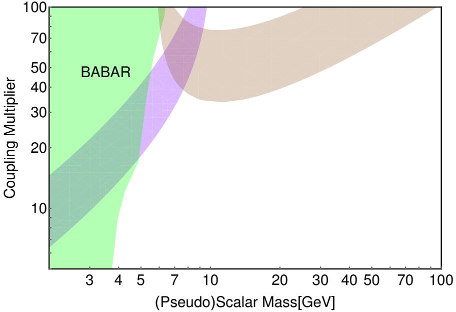

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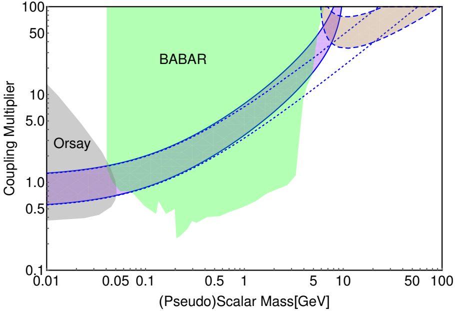

- 2HDM can be natural framework for leptophilic pseudoscalar
- Light leptophilic scalar can come from singlet extended 2HDM
- Mass of the light boson has to be $\gtrsim 5$ GeV
- Q. How much LHC or ILC can explore ?

The Model : Two Higgs Doublet Model

The scalar potential

$$
\begin{aligned}
V_{\mathrm{2HDM}} &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right] \\
&+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) \\
&+ \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{1}{2}\lambda_5 \left\{ \left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2 \right\}
\end{aligned}
$$

- The doublets contain 4 real fields each $\Rightarrow$ 8 total fields.

$$
\Phi_i = \begin{pmatrix} \phi_i^\pm \\ \frac{v_i}{\sqrt{2}} + \phi_i^r + i\phi_i^i \end{pmatrix}
$$

- After SSB we have 5 physical scalar fields : $H^\pm, h, H, A$.

The scalars of 2HDM

Masses of the scalars and quartic couplings

$$\lambda_1 = \frac{m_H^2 c_\alpha^2 + m_h^2 s_\alpha^2 - m_{12}^2 \tan\beta}{v^2 c_\beta^2},$$

$$\lambda_2 = \frac{m_H^2 s_\alpha^2 + m_h^2 c_\alpha^2 - m_{12}^2 \cot\beta}{v^2 s_\beta^2},$$

$$\lambda_3 = \frac{(m_H^2 - m_h^2) c_\alpha s_\alpha + 2 m_{H^\pm}^2 s_\beta c_\beta - m_{12}^2}{v^2 s_\beta c_\beta},$$

$$\lambda_4 = \frac{(m_A^2 - 2m_{H^\pm}^2) s_\beta c_\beta + m_{12}^2}{v^2 s_\beta c_\beta}, \quad \lambda_5 = \frac{m_{12}^2 - m_A^2 s_\beta c_\beta}{v^2 s_\beta c_\beta}.$$

$$m_H^2 \approx m_A^2 + \lambda_5 v^2, \quad m_{H^+}^2 \approx m_A^2 + \frac{1}{2}(\lambda_5 - \lambda_4) v^2.$$

If $\lambda_5 \approx -\lambda_4$ we will have $m_A \ll m_H \simeq m_{H^+}$

Yukawa Sector

Since we have two doublets the general Yukawa structure will be :

$$\mathcal{L} = y^1_{ij} \; \overline{\psi_i} \; \psi_j \; \Phi_1 + y^2_{ij} \, \overline{\psi_i} \; \psi_j \; \Phi_2$$
$$\Rightarrow m^f_{ij} = y^1_{ij} \frac{v_1}{\sqrt{2}} + y^2_{ij} \frac{v_2}{\sqrt{2}}$$

In general both y^1_{ij} and y^2_{ij} will not be simultaneously diagonalizable which leads to couplings like $(\bar{d} \; s \; \phi)$. FCNC

- Experimental limit on FCNC scalar mass $\sim$ 10 TeV.
- So we demand : No tree level FCNC.

Paschos-Glashow-Weinberg Theorem

A necessary and sufficient condition for the absence of FCNC at tree level is that all fermions of a given charge and helicity transform according to the same irreducible representation of SU(2), correspond to the same eigenvalue of T_3 and that a basis exists in which they receive their contributions in the mass matrix from a single source.

or

RH fields with same quantum number should couple to only one type of Higgs.

Paschos-Glashow-Weinberg Theorem

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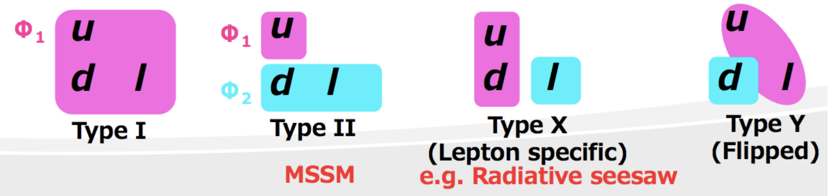

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Lets discuss type-X type coupling

2HDM X : Yukawa structure

$$\mathcal{L}_Y = -Y^u \bar{Q}_L \widetilde{\Phi}_2 u_R + Y^d \bar{Q}_L \Phi_2 d_R + Y^e \bar{\ell}_L \Phi_1 e_R + h.c.$$

2HDM X : Yukawa structure

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After symmetry breaking in terms of physical scalars the Yukawa couplings are

$$\begin{aligned}
\mathcal{L}_{\rm Yukawa}^{\rm Physical} &= -\sum_{f=u,d,\ell} \frac{m_f}{v} \left(\xi_h^f \overline{f} h f + \xi_H^f \overline{f} H f - i \xi_A^f \overline{f} \gamma_5 A f \right) \\
&\quad -\left\{ \frac{\sqrt{2} V_{ud}}{v} \overline{u} \left(m_u \xi_A^u P_L + m_d \xi_A^d P_R \right) H^+ d \right. \\
&\quad \left. + \frac{\sqrt{2} m_l}{v} \xi_A^l \overline{v}_L H^+ l_R + \text{h.c.} \right\},
\end{aligned}$$

ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{c_\alpha}{c_\beta}$	$\cot\beta$	$-\cot\beta$	$\tan\beta$

Table: The multiplicative factors of Yukawa interactions

A Framework for Light Leptophilic Scalars

2HDM type-X + Scalar

$$V_{Portal} \sim A_{12}(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1)s + A_{11}\ \Phi_1^\dagger \Phi_1 s + A_{22}\ \Phi_2^\dagger \Phi_2 s$$

- Mixing among the CP even scalars:

$$\begin{pmatrix} \Phi_1^{0R} \\ \Phi_2^{0R} \\ s \end{pmatrix} = \begin{pmatrix} -s_\alpha & c_\alpha & s_{\theta 1} \\ c_\alpha & s_\alpha & s_{\theta 2} \\ -s_{\theta 1} & -s_{\theta 2} & 1 \end{pmatrix} \begin{pmatrix} h_{125} \\ \Phi \\ H \end{pmatrix}$$

The Yukawa Lagrangian in mass eigenstates:

$$\mathcal{L} \supset -\frac{s_{\theta 2}}{\sin\beta} \sum_q \frac{m_q}{v} \bar{q} q H - \frac{s_{\theta 1}}{\cos\beta} \sum_\ell \frac{m_\ell}{v} \bar{\ell} \ell H$$

- $\tan\beta \gg 1 \implies H$ is leptophilic

PRD93, 035006 (2016), PRD 95, 075003 (2017), $\cdots$

A Framework for Light Leptophilic Pseudoscalars

2HDM type-X + Pseudoscalar

$$V_{\rm Portal} \sim$$
$$i\ B_{12}(\Phi_1^\dagger\Phi_2 - \Phi_2^\dagger\Phi_1)P + (\lambda_{P1}\Phi_1^\dagger\Phi_1 + \lambda_{P2}\Phi_2^\dagger\Phi_2 + \lambda_{P12}(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1))P^2$$

- After EWSB, $\Phi_{1,2}$ mixes to generate Goldstone of Z and A_0
- Mixing among the CP odd scalars:

$$\begin{pmatrix} A_0 \\ P \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix}, \qquad \text{Mixing angle}: \tan 2\theta = \frac{2B_{12}v}{m_A^2 - m_a^2}$$

The Yukawa Lagrangian in mass eigenstates:

$$\mathcal{L} \supset -\left[\sum_{u(d)} \frac{m_q}{v}\frac{1(-1)}{\tan\beta}\, i\,\bar{q}\gamma^5 q \;-\; \sum_{\ell}\frac{m_\ell}{v}\tan\beta\; i\,\bar{\ell}\gamma^5\ell\right](\cos\theta\, A - \sin\theta\, a)$$

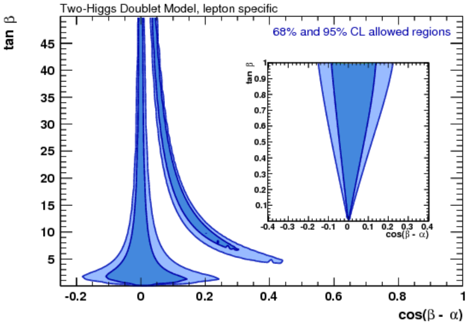
- $\tan\beta \gg 1$ and $\sin\theta \sim \mathcal{O}(0.1-1) \Longrightarrow a$ is leptophilic

PRD 90, 055021 (2014), JHEP 05 (2017) 138, $\cdots$

Interesting parameter space in 2HDM-X : Muon $(g-2)$ and other constraints

2HDM-X : Muon $(g-2)$ and other constraints

- Muon $g-2$
- **Higgs signal strength**
- $B_s \to \mu^+\mu^-$ or $B_s \to X_s\gamma$
- EWPD
- Lepton universality



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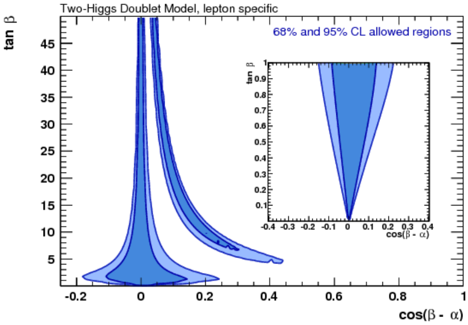

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Wrong Sign Limit

$h\ell\ell$ coupling : $\dfrac{-s_\alpha}{c_\beta} \simeq \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$

So, when $\tan\beta\cos(\beta-\alpha) \sim 2$ Higgs coupling to leptons flip sign.

2HDM-X : Muon $(g-2)$ and other constraints

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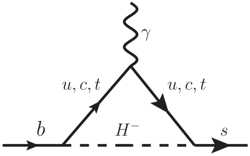

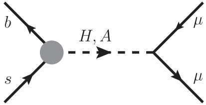

$$\frac{m_t}{t_\beta}P_L - \frac{m_b}{t_\beta}P_R \quad (X, I)$$

$$\frac{m_t}{t_\beta}P_L + m_b t_\beta P_R \; (II, Y)$$

For type X : ~ 1

For type II : $(\tan\beta)^2$

- 2HDM-II : $b \to s\gamma$: $m_{H^\pm} > 580$GeV. BELLE, 1608.02344
- $BR(B_s \to \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ LHCb, 1703.05747
- Limit on type-II 2HDM : $\tan\beta < 7$ for $m_A < 70$ GeV

2HDM-X : Muon $(g-2)$ and other constraints

- Muon $g-2$
- Higgs signal strength
- $B_s \to \mu^+\mu^-$ or $B_s \to X_s\gamma$
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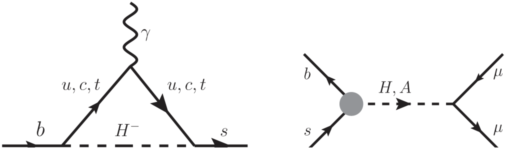

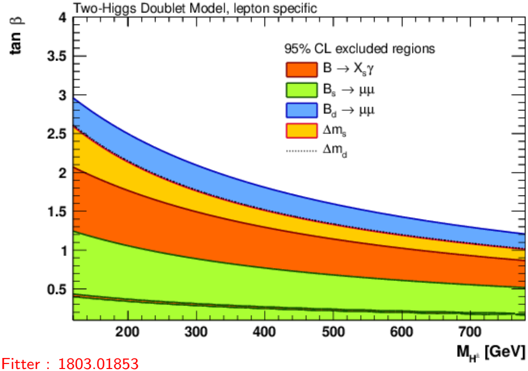

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2HDM-X : Allowed parameter space

- Muon $g-2$
- Higgs signal strength
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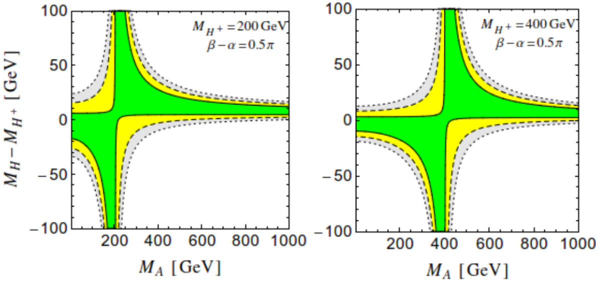
- **EWPD**
- Lepton universality



- $M_{H^\pm}$ should be very close to either M_H or M_A.

JHEP 11 (2014) 058

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2HDM-X : Muon $(g-2)$ and other constraints

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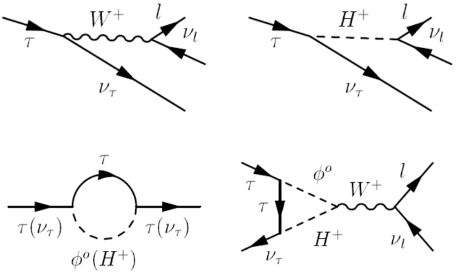
τ Decay



Limits coming from :

$$\frac{\Gamma(\tau \to \mu\nu\nu)}{\Gamma(\tau \to e\,\nu\nu)}, \quad \frac{\Gamma(\tau \to e\,\nu\nu)}{\Gamma(\mu \to e\,\nu\nu)} \text{ etc}$$

2HDM-X : Muon $(g-2)$ and other constraints

- Muon $g-2$
- Higgs signal strength
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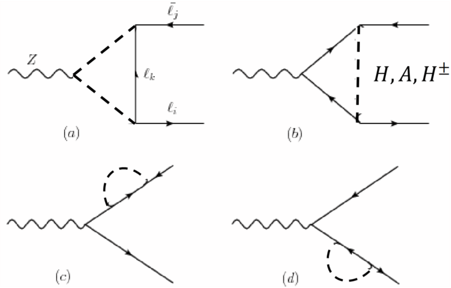
Z Decay



2HDM-X : Muon $(g-2)$ and other constraints

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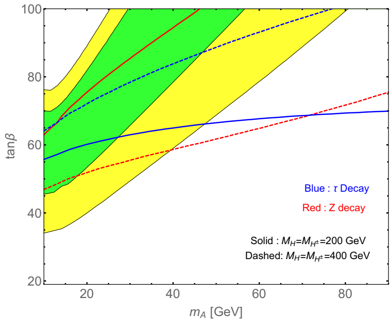
Allowed space



Z Phys. C 51 (1991) 695
JHEP 1507 (2015) 064

JHEP 07 (2016) 110

LHC phenomenology of 2HDM-X

- No direct production of the new scalars since the coupling to quarks are suppressed.
- Different multi tau signal has been studied

$$\begin{aligned} pp &\to W^\pm \to H^\pm H/A \to (\tau^\pm \nu)(\tau^+\tau^-) \\ pp &\to Z/\gamma \to HA \to (\tau^+\tau^-)(\tau^+\tau^-) \\ pp &\to Z/\gamma \to H^+H^- \to (\tau^+\nu)(\tau^-\nu) \end{aligned}$$

S.Kanemura et.al. (1111.6089), Chun et.al. (1507.08067) TM et.al. PRD(2018)

- However, it is not possible to reconstruct the masses of the scalars from tau only final states.
- For mass reconstruction we proposed: $pp \to h \to AA \to 2\mu\, 2\tau$

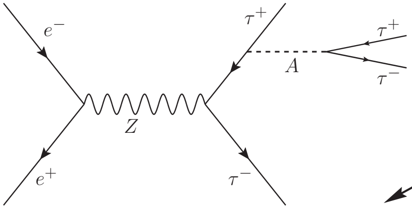
Chun,Dwivedi,TM,Mukhopadhyaya PLB 774 (2017)

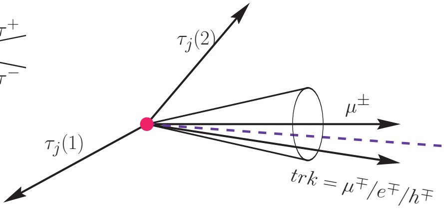
- No direct search for light scalar @ LHC
- What about lepton collider like ILC?

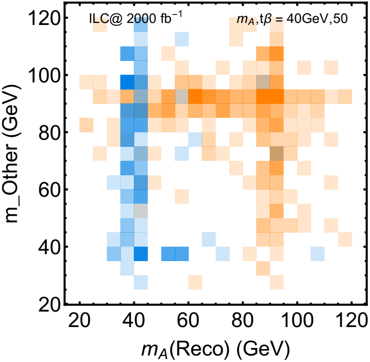
Search at lepton collider

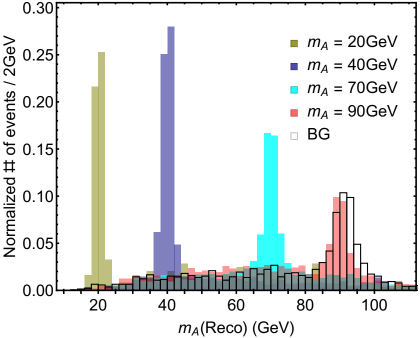
- Yukawa production : $\boldsymbol{Z \to \tau\tau \to \tau\tau A \to 4\tau}$
- Equivalent to ttH searches at LHC. Independent probe of Yukawa.
- Based on mass of A different signal topology is possible.
- **When A is relatively heavy :**
  - We can see 4 separated tau leptons.
  - It is possible to reconstruct mass of A using collinear approximation.
  - Use reconstructed invariant mass to minmize background.
- **When A is light :**
  - A will be boosted and taus coming from boosted A will merge.
  - Four distinguished tau lepton search is not feasible.
  - Utilize the large one-prong BR of tau to look $A \to \tau_\mu \tau_{\text{one-prong}}$ decay

ILC search of light (pseudo)scalar









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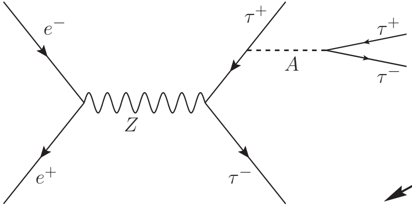
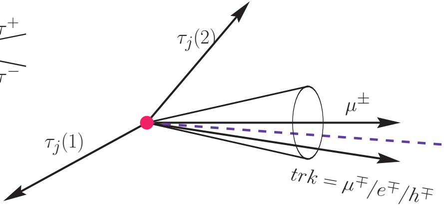
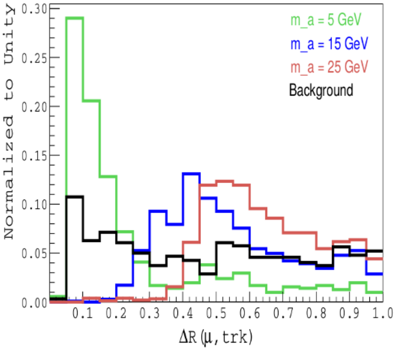
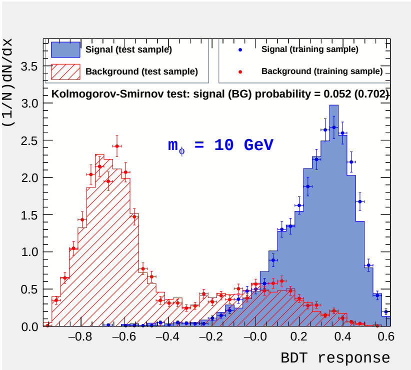
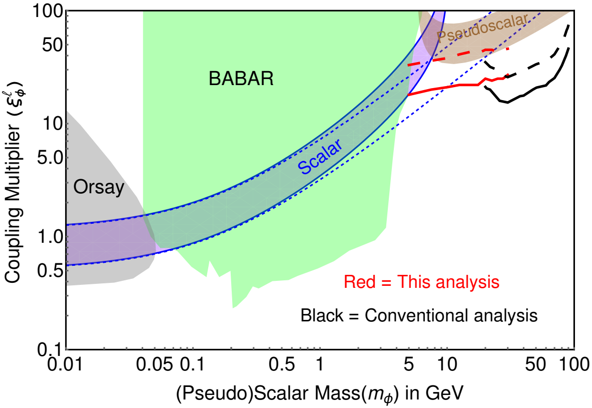






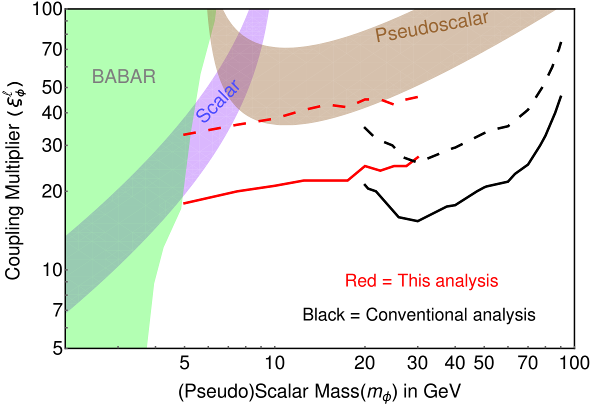


The big picture



Results

The big picture



TM & E.J.Chun, Phys.Lett.B 802 (2020) 135190, JHEP 07 (2021) 044

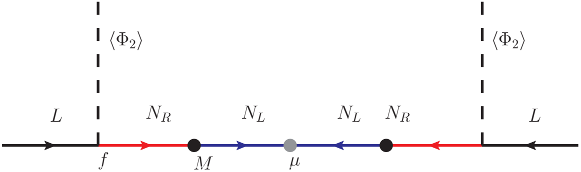
Can we connect neutrino mass with muon $(g-2)$?

- Inverse seesaw is a low energy seesaw mechanism with additional singlet fermions
- In this scenario the smallness of neutrino mass comes from lepton number violating μ term.
- The chirality flipping Dirac mass term can be large.
- We try to exploit the large Dirac mass term to explain $(g-2)_\mu$

Neutrino Mass

2HDM + Inverse seesaw

- Model contents: SM + Φ_2, N_L, N_R
- $\mathcal{L} \supset f\ \bar{L}_L \tilde{\Phi}_2^* N_R + y_N \bar{N}_L N_R \varphi + \frac{\lambda_L}{\Lambda} \bar{N}_L^C N_L \varphi^2$, $\quad \varphi$ breaks $U(1)_{B-L}$



- Neutrino mass matrix:

$$M_N = \begin{bmatrix} 0 & m_D^* & 0 \\ m_D^\dagger & 0 & M^\dagger \\ 0 & M^* & \mu_L \end{bmatrix}, m_D \equiv \frac{f v_{H_1}}{\sqrt{2}},\ M \equiv \frac{y_N v_\varphi}{\sqrt{2}}, \mu_L \equiv \frac{\lambda_L v_\varphi^2}{2\Lambda}$$

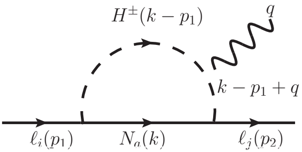
- We get $m_\nu \approx m_D^* (M^*)^{-1} \mu_L (M^\dagger)^{-1} m_D^\dagger$.
- Both NH and IH can be accommodated.

Anomalous magnetic moment

- SM+ISS can not explain $(g-2)_\mu$ due to strong constraints from non unitarity EPJC (2012) 72:2108

- 2HDM contains additional charged Higgs which gives additional contribution

- Unfortuately the charged Higgs contribution does not contain chiral enhancement



$$\int d^q k\{\cdots\}(f_{aj}P_R)\frac{i\ \not{k}+M_a}{k^2-M_a^2}\ (f^\dagger_{ai}P_L)\{\cdots\}$$

- To bypass this we introduce a singlet charged scalar $\chi^\pm$

Charged Scalar sector

$$V = V_{2HDM} + \left\{\lambda(H_1^T i\sigma_2 H_2)\chi^- \varphi + h.c.\right\} + \{\cdots\}$$

Which gives the charged scalar mass matrix:

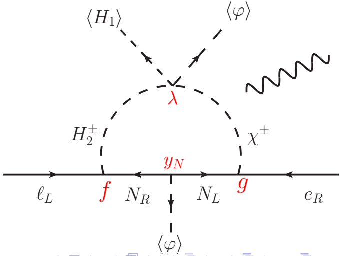
$$M_C^2 = \frac{1}{2}\begin{bmatrix} 2m_{12}^2\frac{v_1}{v_2} - (\lambda_4+\lambda_5)v_1^2 & -2m_{12}^2 + (\lambda_4+\lambda_5)v_1 v_2 & -\lambda v_1 v_\varphi \\ * & 2m_{12}^2\frac{v_2}{v_1} - (\lambda_4+\lambda_5)v_2^2 & \lambda v_2 v_\varphi \\ * & * & 2\mu_\chi^2 + (\lambda_{H_1\chi}v_1^2 + \lambda_{H_2\chi}v_2^2 + \lambda_{\varphi\chi}v_\varphi^2) \end{bmatrix}$$

Anomalous magnetic moment

$$\mathcal{L} \supset f\bar{L}_L\tilde{H}_2^* N_R + g\bar{N}_L e_R \chi^+ + y_N \bar{N}_L N_R \varphi$$

$$-\mathcal{L}_{\Delta a_\ell} = f_{ij}\ \bar{\ell}_i P_R N_j (O_C^T)_{2,a+1} H_a^- + g_{ij}\ \bar{N}_i P_R \ell_j (O_C^T)_{3,a+1} H_a^+ + \text{h.c.}$$

- Dominant contribution($\propto M_a$) comes from combination of $f\,g$ and $g^\dagger f^\dagger$



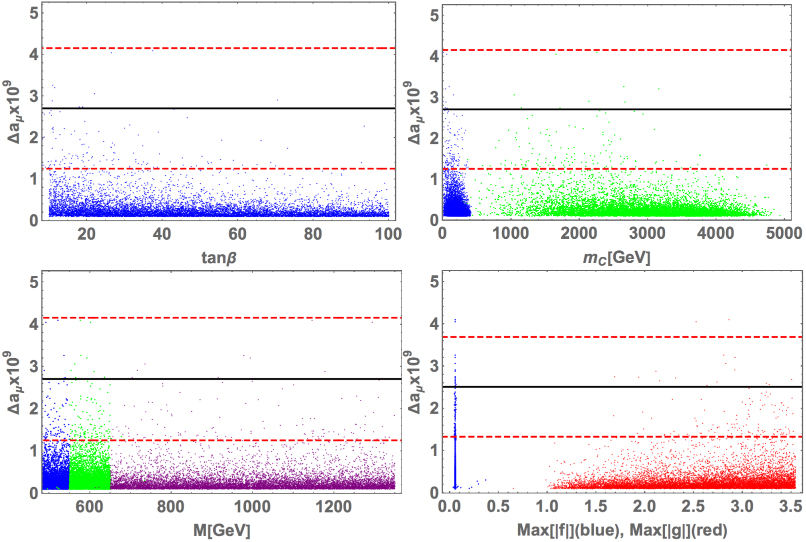
Constraints on the parameter comes from:

- Neutrino oscillation data, non-unitarity
- Oblique parameters : S,T, U
- Flavor conserving Z decay: $Z \to \bar{\ell}_i \ell_i$
- LFV : $\mu \to e\gamma$
- LHC constraints on $H^{\pm}, Z'$ etc

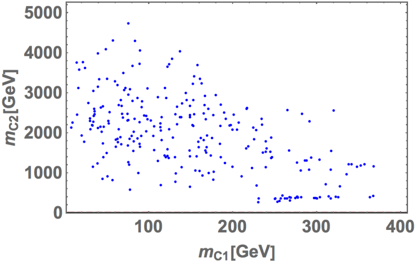
And then we scanned the parameter space

- $\tan\beta \in [10, 100]$
- $v_{\varphi} \in [1, 5]\mathrm{TeV}$
- $[|f|_{ii}, |g|_{ii}] \in [0.01, \sqrt{4\pi}]$
- $|f|_{i\neq j} = 0$
- $|g|_{i\neq j} \in [10^{-5}, 10^{-2}]$
- $|\lambda' s| \in [10^{-3}, 1]$
- $M_1 \leq M_2 \leq M_3 = [10, 1500]\mathrm{GeV}$
- $m_{c_1} \leq m_{c_2} = [100, 5000]\mathrm{GeV}$

Results



Charged Higgs remains light and can be explored at the LHC



- Leotophilic scalar/pseudoscalar can explain muon anomalous magnetic momen
- 2HDM provides a natual framework for such boson
- The leptophilic nature makes it difficult to study at the LHC
- ILC can be very crucial to explore light boson explanation
- Complete parameter space will be covered
- In a bottom up approach we studied 2HDM with inverse seesaw mechanism
- The model is capable of explaining $(g-2)_\mu$ and neutrino mass generation
- The most dominant processs contains a light scalar which can be explored at the expleriments.

Conclusion

- Leotophilic scalar/pseudoscalar can explain muon anomalous magnetic momen
- 2HDM provides a natual framework for such boson
- The leptophilic nature makes it difficult to study at the LHC
- ILC can be very crucial to explore light boson explanation
- Complete parameter space will be covered
- In a bottom up approach we studied 2HDM with inverse seesaw mechanism
- The model is capable of explaining $(g-2)_\mu$ and neutrino mass generation
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Thank You

BACK UP SLIDES

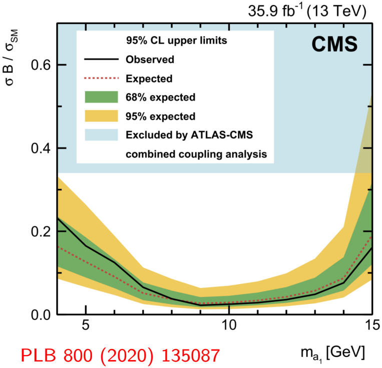
LHC search

- Higgs decay to *aa*

$$\lambda_{haa}\, v \simeq \begin{cases} \cos^2\theta \left(v^2 \left(\lambda_{P1}\cos^2\beta + \lambda_{P2}\sin^2\beta + \lambda_{P12}\sin 2\beta \right) - m_A^2 \sin^2\theta \right) \\ \cos^2\theta \left(\left(\lambda_{P2}\sin^2\beta - \lambda_{P1}\cos^2\beta \right) v^2 + m_A^2 \cos 2\beta \sin^2\theta \right) \end{cases}$$

- Quartic couplings makes this parameter free
- At the LHC only feasible channel is via Higgs decay:

$$pp \to h_{125} \to HH/AA \to 4\tau/2\tau 2\mu/4\mu$$



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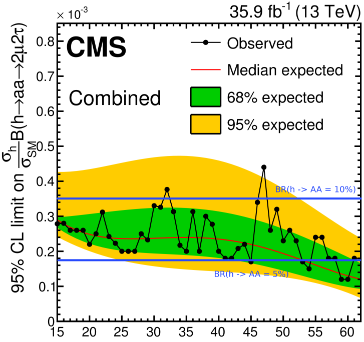

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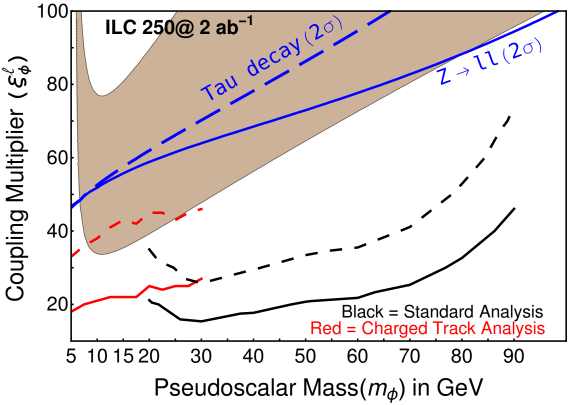
Additional constraints may come from UV completion



- `MadGraph_aMC@NLO` → `PYTHIA8` → `Delphes3 + ILD card`
- Signal : 3 τ-tagged jets + X (= τ-jet/untagged jet/lepton)
- Jets and leptons should have minimum energy of 20 GeV and should be in the central region with $|\eta| < 2.3$ i.e. $\cos\theta < 0.98$.

Collinear approximation : Reconstruction of the taus

- Energy momentum equations are,

$$\begin{aligned} \vec{p}(\tau_1) + \vec{p}(\tau_2) + \vec{p}(\tau_3) + \vec{p}(\tau_4) &= \vec{0}, \\ E(\tau_1) + E(\tau_2) + E(\tau_3) + E(\tau_4) &= \sqrt{s}. \end{aligned}$$

- Assumption: The missing energy in the decay of a tau lepton is collinear to the visible part of the decay.
- Visible part of the tau decay take z_i fraction of the tau momentum :

$$p^\mu(j_i) = z_i \; p^\mu(\tau_i)$$

- Solve for z_i where we should have $0 < z_i < 1$. However to account for the detector resolution etc we assume 10% relaxation in the upper limit of z_i.

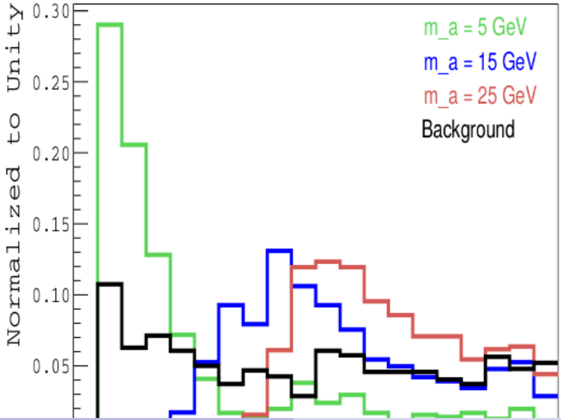
ILC search of light (pseudo)scalar

Background

- $e^+e^- \to Z(\gamma^*)\ Z(\gamma^*) \to 2\tau\ 2\mu$
- $e^+e^- \to Z(\gamma^*)\ Z(\gamma^*) \to 4\tau$
- $e^+e^- \to Z\ h_{125} \to 4\tau/2\mu 2\tau$

Background

- $e^+e^- \to Z(\gamma^*)\ Z(\gamma^*) \to 2\tau\ 2\mu$
- $e^+e^- \to Z(\gamma^*)\ Z(\gamma^*) \to 4\tau$
- $e^+e^- \to Z\ h_{125} \to 4\tau/2\mu2\tau$



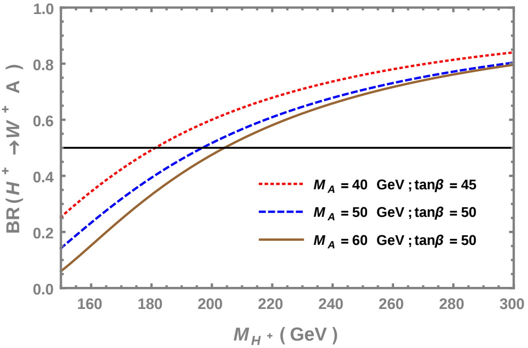
Branching fraction of $H^\pm$

There are two possible decay modes for the charged Higgs

$$\Gamma(H^\pm \to W^\pm A) \sim \frac{m_{H^\pm}}{16\pi}\left(\frac{m_{H^\pm}}{v}\right)^2$$

$$\Gamma(H^\pm \to \tau^+\nu_\tau) \sim \frac{m_{H^\pm}}{16\pi}\left(\frac{\sqrt{2}m_\tau}{v}\tan\beta\right)^2$$

WA channel dominates when $m_{H^\pm} > \sqrt{2}\, m_\tau \tan\beta$



Same is true for neutral heavy Higgs and $BR(H \to ZA)$ is substantial.

Collider searches for H and $H^{\pm}$

- EWPD forces the heavy scalars to be almost degenerate.
- Signal at LHC

$$p\ p \rightarrow (H^{\pm})A \rightarrow (W^{\pm}A)\ \ A \rightarrow (j\ j\ 2\mu)\ \ 2\tau$$

- Added contribution from heavy Higgs H

$$p\ p \rightarrow (H)A \rightarrow (ZA)\ \ A \rightarrow (j\ j\ 2\mu)\ \ 2\tau$$

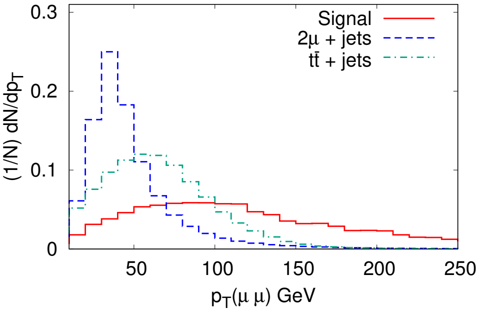
- Signal : 2 light jets, 2 muon and at least one τ tagged jet
- Benchmark the signal for $m_A = 40, 50$ and 60 GeV. For each, $m_{H^{\pm}}$ and m_H lies in 150 – 300 GeV.
- Invariant mass distribution of $j\,j\ 2\mu$ system will peak at the parent particle mass.

Collider searches for H and $H^{\pm}$

- Signal : $2\ j + 2\ \mu + \geq 1\ j_\tau$
- Dominant Backgrounds :
  - $p\,p \to \mu^+\mu^- + jets$
  - $p\,p \to t\bar{t} + jets$
- Preselection Cuts (a) : Two oppositely charged muons with $p_T > 10$ GeV accompanied with two light jets and at least one tau-tagged jet of $p_T > 20$ GeV.
- Preselection Cuts (b) : b-veto on the final state to suppress the $t\bar{t} + jets$ and $tW + jets$ background.
- The invariant mass of the di-muon system $(M_{\mu\mu})$ satisfies $|M_{\mu\mu}\ -\ M_A| < 2.5\ \mathrm{GeV}$.
- Other cuts from kinematic distributions.

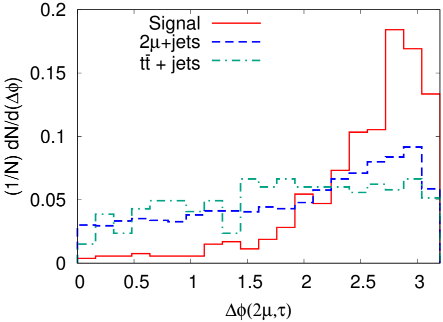
Kinematic distributions - I

The 2μ system is originates from a light A which in turn comes form heavy $H/H^{\pm}$ decay. Expected to be boosted.

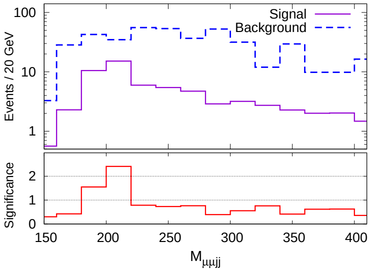


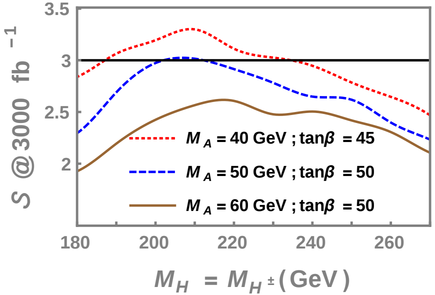
Kinematic distributions - II

Azimuthal separation between the $\mu\mu$ & the τ-jet. The $H^{\pm}$ and A are expected to be almost back-to-back.



Mass of the Heavy Scalar





- Low $M_{H\pm}$: Significance decreases as not enough branching to $W^\pm A$.
- Also low boost for the $\mu\mu$ system.
- High $M_{H\pm}$: Low production cross-section.

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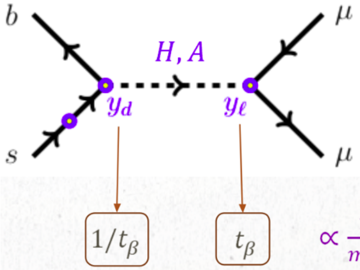

$$\propto \frac{1}{m_A^2} \Rightarrow m_A \gtrsim 10 \text{ GeV}$$

Type-X + ISS

	Fermions							Bosons			
Symmetry	Q_L	u_R	d_R	L_L	e_R	$N_L(N'_L)$	N_R	H_1	H_2	φ	χ^-
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**2**	**2**	**1**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$	-1	0	0	$\frac{1}{2}$	$\frac{1}{2}$	0	-1
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	$-\frac{1}{2}(\frac{1}{2})$	-1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
$\mathbb{Z}_2$	$+$	$+$	$+$	$+$	$-$	$+(-)$	$+$	$-$	$+$	$+$	$-$

$$-\mathcal{L}_Y = y_u \bar{Q}_L \tilde{H}_2^* u_R + y_d \bar{Q}_L H_2 d_R + f \bar{L}_L \tilde{H}_2^* N_R + y_\ell \bar{L}_L H_1 e_R + g \bar{N}_L e_R \chi^+$$
$$+ y_N \bar{N}_L N_R \varphi + \frac{\lambda_L}{\Lambda} \bar{N}_L^C N_L \varphi^2 + \frac{\lambda_{L'}}{\Lambda} \bar{N}_L'^C N'_L \varphi^{*2} + \text{h.c.},$$

$\Delta m^2_{\rm sol}$ $[10^{-5}\ {\rm eV}^2]$	$\Delta m^2_{\rm atm}$ $[10^{-3}\ {\rm eV}^2]$	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}
7.42	2.514	0.304	0.570	0.02221	195°
7.42	2.497	0.304	0.575	0.02240	286°

$$|FF^\dagger| \leq \begin{bmatrix} 2.5\times10^{-3} & 2.4\times10^{-5} & 2.7\times10^{-3} \\ 2.4\times10^{-5} & 4.0\times10^{-4} & 1.2\times10^{-3} \\ 2.7\times10^{-3} & 1.2\times10^{-3} & 5.6\times10^{-3} \end{bmatrix}$$

Type-X + ISS

$$\mathrm{BR}(\ell_i \to \ell_j \gamma) = \frac{48\pi^3 \alpha_{\rm em} C_{ij}}{(4\pi)^4 m_{\ell_i}^2 G_F^2} \left(|A_{L_{ij}}|^2 + |A_{R_{ij}}|^2\right)$$

$$\begin{aligned}
A_{L_{ij}} &= g^\dagger_{ja} M_a f^\dagger_{ai} \left[(O_C^T)_{22}(O_C^T)_{32} I_1(M_a, m_{c_1}) + (O_C^T)_{23}(O_C^T)_{33} I_1(M_a, m_{c_2})\right] \\
&+ f_{ja} f^\dagger_{ai} m_{\ell_j} \left[(O_C^T)^2_{22} I_1(M_a, m_{c_1}) + (O_C^T)^2_{23} I_1(M_a, m_{c_2})\right] \\
&+ g^\dagger_{ja} g_{ai} m_{\ell_i} \left[(O_C^T)^2_{32} I_2(M_a, m_{c_1}) + (O_C^T)^2_{33} I_2(M_a, m_{c_2})\right], \\
A_{R_{ij}} &= f_{ja} M_a g_{ai} \left[(O_C^T)_{22}(O_C^T)_{32} I_1(M_a, m_{c_1}) + (O_C^T)_{23}(O_C^T)_{33} I_1(M_a, m_{c_2})\right] \\
&+ f_{ja} f^\dagger_{ai} m_{\ell_i} \left[(O_C^T)^2_{22} I_2(M_a, m_{c_1}) + (O_C^T)^2_{23} I_2(M_a, m_{c_2})\right] \\
&+ g^\dagger_{ja} g_{ai} m_{\ell_j} \left[(O_C^T)^2_{32} I_1(M_a, m_{c_1}) + (O_C^T)^2_{33} I_1(M_a, m_{c_2})\right], \\
I_1(m_1, m_2) &= \int [dx]_3 \frac{y}{(x^2 - x) m_{\ell_i}^2 + x m_1^2 + (y+z) m_2^2}, \\
I_2(m_1, m_2) &= \int [dx]_3 \frac{z}{(x^2 - x) m_{\ell_i}^2 + x m_1^2 + (y+z) m_2^2},
\end{aligned}$$

$$\Delta a_\mu \approx -\frac{m_\ell^2}{(4\pi)^2} (A_{L_{\mu\mu}} + A_{R_{\mu\mu}}).$$

- The muon $g-2$ is written by $f_{21} g_{12} + f_{22} g_{22} + f_{31} g_{32}$
- $\mathrm{BR}(\mu \to e\gamma)$ is $f_{11} g_{12} + f_{12} g_{22} + f_{11} g_{32}$.

Type-X + ISS

$$\Delta\Gamma(Z \to f_i\bar{f}_i)_{\rm new} \approx \Gamma(Z \to f_i\bar{f}_i)_{\rm SM+new} - \Gamma(Z \to f_i\bar{f}_i)_{\rm SM},$$

New contribution:

$$\Delta\Gamma(Z \to \ell_i\bar{\ell}_i)_{\rm new}$$
$$\approx \frac{m_Z}{12(4\pi)^2}\frac{g_2^2}{c_w^2}\left[s_w^4 {\rm Re}[(O_C{}^T_{2,a+1})^2 f_{i\alpha} f^\dagger_{\alpha i} I_3(M_\alpha, m_{c_a})] + \left(s_w^2 - \frac{1}{2}\right)^2 {\rm Re}[(O_C{}^T_{3,a+1})^2 g^\dagger_{i\alpha} g_{\alpha i} I_3(M_\alpha, m_{c_a})]\right],$$

$$\Delta\Gamma(Z \to \nu_i\bar{\nu}_i)_{\rm new} \approx \frac{m_Z}{24(4\pi)^2}\frac{g_2^2 s_w^4}{c_w^2}{\rm Re}\left[(U^\dagger_{MNS_{ai}} U_{MNS_{ia}}) f_{ia} f^\dagger_{ai} (c_\alpha^2 I_3(M_a, m_h) + s_\alpha^2 I_3(M_a, m_H)\right],$$

where

$$I_3(m_1, m_2) = \int_0^1 dx(1-x)\ln[xm_1^2 + (1-x)m_2^2] - \int_0^1 dx \int_0^{1-x} dy \ln[(x+y)m_2^2 + (1-x-y)m_1^2].$$

Type-X + ISS : One Benchmark

Input Parameter	Value
$\tan\beta$	28.89
$[\frac{M_1}{\mathrm{GeV}}, \frac{M_2}{\mathrm{GeV}}, \frac{M_3}{\mathrm{GeV}}]$	$[377.8, 558.2, 1377]$
$[\frac{m_{C_1}}{\mathrm{GeV}}, \frac{m_{C_2}}{\mathrm{GeV}}]$	$[253.1, 283.8]$
$\frac{v_\varphi}{\mathrm{GeV}}$	2854

$$f = \begin{bmatrix} 0.03160 & 0 & 0 \\ 0 & 0.05278 & 0 \\ 0 & 0 & -0.02328 \end{bmatrix}, \quad g = \begin{bmatrix} -1.06494 & -0.0000385 & 0.0002324 \\ 0.0000235 & 3.19761 & -0.0041557 \\ -0.0000839 & -0.0006508 & 0.00345861 \end{bmatrix}$$

$$O_C \approx \begin{bmatrix} 0.999402 & 0.034591 & 0 \\ 0.029247 & -0.845007 & 0.533954 \\ -0.018470 & 0.533635 & 0.845513 \end{bmatrix}$$

	Value
Δa_μ	2.36×10^{-9}
Δa_e	-3.67×10^{-13}
$[\mathrm{BR}(\mu \to e\gamma), \mathrm{BR}(\tau \to e\gamma), \mathrm{BR}(\tau \to \mu\gamma)]$	$[1.31 \times 10^{-13}, 6.81 \times 10^{-13}, 1.11 \times 10^{-9}]$
$[\mathrm{BR}(Z \to \mu\bar{\mu}), \mathrm{BR}(Z \to e\bar{e}), \mathrm{BR}(Z \to \nu\bar{\nu})]$	$[2.87 \times 10^{-11}, 4.77 \times 10^{-11}, 7.64 \times 10^{-11}]$

Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8