Phenomenological aspects of a light pseudoscalar in Type-X 2HDM

PLB 774 (2017), PRD 98 (2018)
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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
- Radiative neutrino mass generation, Dark matter etc.
- Muon anomalous magnetic moment.

Type-X 2HDM can explain Muon $g-2$ with a light pseudoscalar & large tan $\beta$
Introduction

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Type-X 2HDM

- Can explain Muon $g - 2$ with a light pseudoscalar & large $\tan \beta$
- I will discuss some of the phenomenological aspects of a light pseudoscalar in Type-X 2HDM.
The Model: 2HDM Type X
The 2HDM scalar potential

The scalar potential

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

- The doublets contain 4 real fields each ⇒ 8 total fields.

\[
\Phi_i = \left( \begin{array}{c} \phi_i^\pm \\ \frac{\nu_i}{\sqrt{2}} + \phi_i^r + i \phi_i^i \end{array} \right)
\]

- After SSB we have 5 physical scalar fields: \(H^\pm, h, H, A\).
The scalars of 2HDM

Masses of the scalars and quartic couplings

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

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

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

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

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

If \(\lambda_5 \approx -\lambda_4\) we will have \(m_A \ll m_H \approx m_{H^+}\).
Yukawa Sector

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

\[ \mathcal{L} = y^1_{ij} \bar{\psi}_i \psi_j \Phi_1 + y^2_{ij} \bar{\psi}_i \psi_j \Phi_2 \]

\[ \Rightarrow m^f_{ij} = y^1_{ij} \frac{v_1}{\sqrt{2}} + y^2_{ij} \frac{v_2}{\sqrt{2}} \]

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 \( \sim 10 \text{ TeV} \).

- 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

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

<table>
<thead>
<tr>
<th>Model</th>
<th>(u^i_R)</th>
<th>(d^i_R)</th>
<th>(e^i_R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>(\Phi_2)</td>
<td>(\Phi_2)</td>
<td>(\Phi_2)</td>
</tr>
<tr>
<td>Type II</td>
<td>(\Phi_2)</td>
<td>(\Phi_1)</td>
<td>(\Phi_1)</td>
</tr>
<tr>
<td>Lepton-specific</td>
<td>(\Phi_2)</td>
<td>(\Phi_2)</td>
<td>(\Phi_1)</td>
</tr>
<tr>
<td>Flipped</td>
<td>(\Phi_2)</td>
<td>(\Phi_1)</td>
<td>(\Phi_2)</td>
</tr>
</tbody>
</table>
2HDM X: Yukawa structure

\[ \mathcal{L}_Y = -Y^u \bar{Q}_L \phi_2 u_R + Y^d \bar{Q}_L \phi_2 d_R + Y^e \bar{\ell}_L \phi_1 e_R + h.c. \]
$\mathcal{L}_Y = -Y^u \bar{Q}_L \tilde{\Phi}_2 u_R + Y^d \bar{Q}_L \Phi_2 d_R + Y^e \bar{\ell}_L \Phi_1 e_R + h.c.$

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

$$\mathcal{L}_{\text{Physical Yukawa}}^{\text{Physical Yukawa}} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \left( \xi_f^f \bar{h} f h + \xi_f^f \bar{H} f H - i \xi_f^f \bar{\gamma}_5 A f \right)$$

$$- \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} \left( m_u \xi_A^u P_L + m_d \xi_A^d P_R \right) H^+ d$$

$$+ \frac{\sqrt{2} m_l}{v} \xi_A^l \bar{\nu}_L H^+ l_R + h.c. \right\},$$

<table>
<thead>
<tr>
<th>$\xi^u_h$</th>
<th>$\xi^d_h$</th>
<th>$\xi^l_h$</th>
<th>$\xi^u_H$</th>
<th>$\xi^d_H$</th>
<th>$\xi^l_H$</th>
<th>$\xi^u_A$</th>
<th>$\xi^d_A$</th>
<th>$\xi^l_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_\alpha$</td>
<td>$c_\alpha$</td>
<td>$-s_\alpha$</td>
<td>$s_\alpha$</td>
<td>$s_\alpha$</td>
<td>$c_\alpha$</td>
<td>$c_\alpha$</td>
<td>$-c_\alpha$</td>
<td>$\cot \beta$</td>
</tr>
<tr>
<td>$s_\beta$</td>
<td>$s_\beta$</td>
<td>$c_\beta$</td>
<td>$c_\beta$</td>
<td>$s_\beta$</td>
<td>$c_\beta$</td>
<td>$s_\beta$</td>
<td>$c_\beta$</td>
<td>$\tan \beta$</td>
</tr>
</tbody>
</table>

**Table:** The multiplicative factors of Yukawa interactions
Gauge-Higgs sector:

\[ g_{hVV} = \sin(\beta - \alpha)g_{hVV}^{\text{SM}}, \quad g_{HVV} = \cos(\beta - \alpha)g_{hVV}^{\text{SM}}, \quad g_{AVV} = 0, \]

where \( V = Z, W^\pm \).

Relevant vertices

\[ hAZ_\mu : \frac{g_Z}{2} \cos(\beta - \alpha)(p + p'_\mu), \quad HAZ_\mu : -\frac{g_Z}{2} \sin(\beta - \alpha)(p + p'_\mu), \]

\[ H^\pm A W^\mp_\mu : \frac{g}{2} (p + p'_\mu) \]

where \( p_\mu (p'_\mu) \): outgoing four-momenta of the first (second) scalars.
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
2HDM-X: Muon \((g-2)\) and other constraints

- **Muon \(g-2\)**
  - \(a_{\mu}^{\exp} = (11659209.1 \pm 6.3) \times 10^{-10}\)
  - \(a_{\mu}^{\text{th}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{had,VP}} + a_{\mu}^{\text{had,LbL}}\)
  - \(\{(11658471.9 \pm 0.007) + (15.36 \pm 0.1)\} \times 10^{-10}\)
  - \(\{(684.68 \pm 2.42) + (9.8 \pm 2.6)\} \times 10^{-10}\)
  - \(\Delta a_{\mu} = (27.06 \pm 7.26) \times 10^{-10}\)  
    

- **Higgs signal strength**

- **\(B_s \rightarrow \mu^+\mu^-\) or \(B_s \rightarrow X_s\gamma\)**

- **EWPD**

- **Lepton universality**

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Osaka University, Osaka  
Light Pseudoscalar Phenomenology in 2HDM - X
2HDM-X : Muon \((g - 2)\) and other constraints

- **Muon \(g - 2\)**
- Higgs signal strength
- \(B_s \rightarrow \mu^+ \mu^-\) or \(B_s \rightarrow X_s \gamma\)
- EWPD
- Lepton universality

1-loop: contribution from \(h, H\) are positive and \(A\) contributes negatively.

- \(m_H < 5\) GeV to explain experimental data.
- Barr-Zee 2-Loop contribution with \(\tau\) loop and low \(m_A\) comes to rescue.
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

\[
\begin{align*}
\tan \beta - m_A \text{ Plane} \\
\end{align*}
\]


and many more
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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Wrong Sign Limit

\[ \ell \ell \ell \text{ coupling} : \frac{-s_\alpha}{c_\beta} \simeq \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha) \]

So, when \(\tan \beta \cos(\beta - \alpha) \sim 2\) Higgs coupling to leptons flip sign.
2HDM-X : Muon \((g - 2)\) and other constraints

- Muon \(g - 2\)
- Higgs signal strength
  - \(B_s \rightarrow \mu^+ \mu^-\) or \(B_s \rightarrow X_s \gamma\)
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\[
\frac{m_t}{t_\beta} P_L \frac{m_b}{t_\beta} P_R \quad (X, I)
\]

\[
\frac{m_t}{t_\beta} P_L + m_b t_\beta P_R \quad (II, Y)
\]

- For type X : \(\sim 1\)
- For type II : \((\tan \beta)^2\)

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

- Muon \(g - 2\)
- Higgs signal strength
  - \(B_s \rightarrow \mu^+ \mu^-\) or \(B_s \rightarrow X_s \gamma\)
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\[\tan \beta < 7 \text{ for } m_A < 70 \text{ GeV}\]

**GFitter**: 1803.01853
2HDM-X : Allowed parameter space

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

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

JHEP 11 (2014) 058
GFitter : 1803.01853
2HDM-X: Muon \( (g - 2) \) and other constraints

- Muon \( g - 2 \)
- Higgs signal strength
- \( B_s \rightarrow \mu^+ \mu^- \) or \( B_s \rightarrow X_s \gamma \)
- EWPD
- Lepton universality

Limits coming from:
\[
\frac{\Gamma(\tau \rightarrow \mu \nu \nu)}{\Gamma(\tau \rightarrow e \nu \nu)}, \quad \frac{\Gamma(\tau \rightarrow e \nu \nu)}{\Gamma(\mu \rightarrow e \nu \nu)} \text{ etc}
\]
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Allowed space

- Blue : $\tau$ Decay
- Red : Z decay
- Solid : $M_H = M_{H'} = 200$ GeV
- Dashed : $M_H = M_{H'} = 400$ GeV

References:
- JHEP 1507 (2015) 064
- JHEP 07 (2016) 110
2HDMX at LHC
LHC phenomenology of 2HDM-X

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

\[ pp \rightarrow W^{\pm} \rightarrow H^{\pm} H / A \rightarrow (\tau^{\pm}\nu)(\tau^{+}\tau^{-}) \]
\[ pp \rightarrow Z / \gamma \rightarrow HA \rightarrow (\tau^{+}\tau^{-})(\tau^{+}\tau^{-}) \]
\[ pp \rightarrow Z / \gamma \rightarrow H^{+} H^{-} \rightarrow (\tau^{+}\nu)(\tau^{-}\nu) \]

S.Kanemura et.al. (1111.6089), E.J.Chun et.al. (1507.08067)

- However, it is not possible to reconstruct the masses of the scalars from tau only final states.
- Also for light A only tau-rich final state is hard to trigger.
- We proposed to look for 2HDM-X signal at the LHC and reconstruct the light pseudoscalar in \(2\mu2\tau\) final state.
- Also we have shown how to reconstruct the heavy charged/neutral scalars.

Chun,Dwivedi,TM,Mukhopadhyaya PLB 774 (2017)
Chun,Dwivedi,TM,Mukhopadhyaya,Rai PRD 98 (2018) 7
We can produce a pair of pseudoscalars from Higgs decay.

Since coupling of $A$ to leptons is proportional to mass of the leptons, $A$ will predominantly decay to a pair of taus leading to $4\tau$ signal.

As argued, we can't reconstruct mass of $A$ from this final state.

However a very small portion of $A$ decays to muons with $\text{BR}(A \to \mu\mu) \approx 0.35\%$

This channel can be used to estimate mass of the pseudoscalar.
Signal of a light A : An analysis for the LHC

<table>
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<tr>
<th>Parameters</th>
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<th>$\cos(\beta - \alpha)$</th>
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<tr>
<td>BP1</td>
<td>50</td>
<td>60</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>BP2</td>
<td>60</td>
<td>60</td>
<td>0.03</td>
<td>0.03</td>
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$p p \rightarrow h \rightarrow A A \rightarrow \mu^+\mu^- \tau^+\tau^- \rightarrow \mu^+\mu^- j_{\tau} j_{\tau} + \text{MET}$

$\sigma \sim 0.021 \text{ pb}$
Signal of a light A : An analysis for the LHC

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$$pp \rightarrow h \rightarrow AA \rightarrow \mu^+\mu^- \tau^+\tau^- \rightarrow \mu^+\mu^- j_\tau j_\tau + MET$$

$$\sigma \sim 0.021 \text{ pb}$$

Backgrounds:

- $pp \rightarrow \mu^+\mu^- + jets \quad \sigma \sim 2100 \text{ pb}$
- $pp \rightarrow VV + jets (V = Z, W, \gamma^*) \quad \sigma \sim 6.2 \text{ pb}$
- $pp \rightarrow t\bar{t} + jets. \quad \sigma \sim 0.03 \text{ pb}$
Collider signature of light $A$

- We have a light $A$ (mass $< 60$ GeV) decaying to two tau which further decays hadronically.

- If minimum $p_T$ for the tau tagged jets is close to $M_A/2$ then the neutrinos can not take large amount of tau momentum.

- In that case invariant mass of tau-jets will peak at parent mass(!!)
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$\tau_j \tau_j \ M_{10} \ 20 \ 30 \ 40 \ 50 \ 60 \ 70 \ 80 \ 90 \ \tau_j \tau_j /dM \ \sigma \ d\sigma \ 1/0 \ 0.02 \ 0.04 \ 0.06 \ 0.08 \ 0.1 \ = 50$ GeV

$\tau_j \tau_j (jT\ P) > 25$ GeV

$\tau_j \tau_j \ M_{10} \ 20 \ 30 \ 40 \ 50 \ 60 \ 70 \ 80 \ 90 \ \tau_j \tau_j /dM \ \sigma \ d\sigma \ 1/0 \ 0.02 \ 0.04 \ 0.06 \ 0.08 \ 0.1 \ = 60$ GeV

$\tau_j \tau_j (jT\ P) > 25$ GeV

Chun, Dwivedi, TM, Mukhopadhyaya PLB 774 (2017)
Collider signature of light $A$

The same argument holds if we construct invariant mass using $2\mu$ and 2 $\tau$-tagged jet.

\[
M_{2\mu 2\tau}, \ M_A = 50 \text{ GeV}
\]

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

- Signal contains 2 isolated muons and 2 tau-tagged jets.
- Preselection:
  - $p_T(\mu) > 10$ GeV and $|\eta| < 2.5$.
  - $p_T(j_\tau) > 20/25$ GeV $|\eta(j_\tau)| < 2.5$.
- The invariant mass of the di-muon system ($M_{\mu\mu}$) satisfies the window: $|M_{\mu\mu} - M_A| < 7.5$ GeV.
- The invariant mass of the two tau-tagged jets ($M_{j_\tau j_\tau}$) satisfies:
  - for $p_T(j_\tau) > 20$ GeV: $(M_A - 20) < M_{j_\tau j_\tau} < (M_A + 10)$ GeV
  - for $p_T(j_\tau) > 25$ GeV: $|M_{j_\tau j_\tau} - M_A| < 15$ GeV.
- The invariant mass of two muons and two tau jets ($M_{2\mu2j_\tau}$) lies within the range:
  - for $p_T(j_\tau) > 20$ GeV: $(M_h - 20) < M_{2\mu2j_\tau} < (M_h + 10)$ GeV.
  - for $p_T(j_\tau) > 25$ GeV: $|M_{2\mu2j_\tau} - M_h| < 15$ GeV.
- Asymmetric cuts for low $p_T$ since the distribution peaks at lower value.
Result

Significance = \( S = \sqrt{2 \left[ (S + B) \ln \left( 1 + \frac{S}{B} \right) - S \right]} \)

- Large \( p_T(j) \) results in better invariant mass peaks but provides fewer number of events which decreases the discovery prospect.
- At 3 \( ab^{-1} \) it is possible to rule out \( \text{BR}(h \rightarrow aa) < 1\% \).

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

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Light Pseudoscalar Phenomenology in 2HDM - X
CMS limit
Collider searches for $H$ and $H^\pm$
Branching fraction of $H^\pm$

There are two possible decay modes for the charged Higgs

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

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

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

![Graph showing branching ratio as a function of $M_{H^+}$ for different values of $M_A$ and $\tan \beta$.]
Branching fraction of $H^\pm$

There are two possible decay modes for the charged Higgs

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

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

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

Same is true for neutral heavy Higgs and $BR(H \rightarrow ZA)$ is substantial.
Collider searches for $H$ and $H^\pm$

- EWPD forces the heavy scalars to be almost degenerate.

- Signal at LHC

$$p\ p \rightarrow (H^\pm)A \rightarrow (W^\pm A) \ A \rightarrow (jj\ 2\mu)\ 2\tau$$

- Added contribution from heavy Higgs $H$

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

- Signal: 2 light jets, 2 muon and at least one $\tau$ 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 $jj\ 2\mu$ 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**:
  - $p\ p \rightarrow \mu^+\mu^- + jets$
  - $p\ p \rightarrow t\bar{t} + jets$

- **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 $|M_{\mu\mu} - M_A| < 2.5$ GeV.

- Other cuts from kinematic distributions.
Collider searches for $H$ and $H^\pm$

**Kinematic distributions - I**

The $2\mu$ system originates from a light $A$ which in turn comes from heavy $H/H^\pm$ decay. Expected to be boosted.
Collider searches for $H$ and $H^\pm$

**Kinematic distributions - I**

The $2\mu$ 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 $\tau$-jet.

The $H^\pm$ and $A$ are expected to be almost back-to-back.
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.
CMS reported $2\mu 2\tau$ search in 2018

$$\lambda_{hAA} = \frac{-1}{\nu} \left[ 2m_A^2 + \xi^\ell m_h^2 - (s_\beta^2 m_h - \alpha + \xi_h s_\beta m_h) m_H^2 \right].$$

$\lambda_{hAA}$ can be very small in Wrong Sign limit due to cancellation when $m_H \gg m_h / m_A$.

- Can not restrict the light A – large $\tan \beta$ scenario.
- Q. Can we explore light pseudiscalar without any additional information?

JHEP 11 (2018) 018
CMS reported $2\mu2\tau$ search in 2018

\[ \lambda_{hAA} = \frac{-1}{v} \left[ 2m_A^2 + \xi^\ell m_h^2 - (s_\beta^2 - \alpha + \xi^\ell s_\beta - \alpha)m_H^2 \right]. \]

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\[ \text{A. ILC} \]
Searches for light A in 2HDMX at ILC250

- The channel $Z \rightarrow h_{125}A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.

- At ILC250 $Z \rightarrow HA$ may not be feasible when $H$ is heavier than 200 GeV.

- Possible search option: $Z \rightarrow \tau\tau \rightarrow \tau\tau A \rightarrow 4\tau$. So called Yukawa production.

This is the equivalent to $ttH$ searches at LHC. Independent probe of Yukawa structure. At the ILC all the 4 $\tau$s can be reconstructed using collinear approximation.

This enables to measure mass of the light particle.
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Searches for light A in 2HDMX at ILC250

Signal: \( Z \rightarrow \tau\tau \rightarrow \tau\tau A \rightarrow 4\tau \)

- Dominant Backgrounds: \( e^+e^- \rightarrow Z(\gamma^*) \ Z(\gamma^*) \rightarrow 4\tau \)
- Also \( e^+e^- \rightarrow Z(\gamma^*) \ Z(\gamma^*) \rightarrow 2\tau 2j \) with mis-identified jets
- Other background: \( e^+e^- \rightarrow Zh \rightarrow 4\tau \)
- Parton level total \( 4\tau \) BG cross-section \( \simeq 6.6 \text{ fb} \). \( 2\tau 2j \simeq 100 \text{ fb} \).
Searches for light A in 2HDMX at ILC250

- MadGraph → aMC@NLO → PYTHIA8 → Delphes3 + ILD card
- Signal: 3 $\tau$-tagged jets + X (= $\tau$-jet/untagged jet/lepton) so that total number of object = 4.
- Jets and leptons should have minimum energy of 20 GeV and should be in the central region with $|\eta| < 2.3$ i.e. $\cos \theta < 0.98$.
- $\tau$-tagging efficiency: 60% (From LHC) or 90% (Hopefully at ILC).
- Mis-identification of jets: 0.5%

Collinear approximation: Reconstruction of the taus

- The collinear approximation: Assume that the missing energy in the decay of a tau lepton is collinear to the visible part of the decay.
- Energy momentum equations are,

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

- 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 $z_i$. 
Reconstruction of the pseudoscalar

- We have 4 tau jets. However, the highest energy $\tau$ out of the four is unlikely to come from the pseudoscalar since the maximum available energy for $A$ is $125 \text{ GeV}(\sqrt{s}/2)$, whereas energy of highest $\tau$ can also be 125 GeV.

- It is reasonable to assume that the highest energy tau is coming from the decay of $Z$ and did not radiate an $A$.

- From the remaining 3 taus there are two possible OS combinations.

- Choose the combination which gives highest transverse momentum($p_T$) since they are likely to come from the decay of $A$. The invariant mass calculated from this combination is denoted as $m_A(\text{Reco})$.

- The invariant mass from the other opposite sign tau pair is denoted as $m_{\text{Other}}$. 
Searches for light $A$ in 2HDMX at ILC250

Reconstruction of the pseudoscalar $m_A = 40$ GeV and $\tan\beta = 50$

For different $m_A$

Ilion@2000 fb$^{-1}$ $m_A, t\beta = 40$ GeV, 50

Normalized # of events / 2 GeV

Tanmoy Mondal, KIAS, Seoul
Osaka University, Osaka

Light Pseudoscalar Phenomenology in 2HDM - X
Searches for light $A$ in 2HDMX at ILC250

Reconstruction of the pseudoscalar

$m_A = 40$ GeV and $\tan \beta = 50$

For different $m_A$

Chun, TM PLB 802 (2020) 135190
Searches for light A in 2HDMX at ILC250: Result

Reach of ILC250. $\epsilon_T = 60\%$

- Solid: 2000 fb$^{-1}$
- Dashed: 500 fb$^{-1}$

$\tan\beta$

$m_A$ (GeV)

$m_{H^\pm} = m_H = 250$ GeV

ILC@250 GeV
Reach of ILC250. $\epsilon_\tau = 60\%$

Chun, TM PLB 802 (2020) 135190
Explaining electron and muon anomalous magnetic moment in 2HDM-X
Electron and muon $g - 2$ anomalies

Electron anomalous magnetic moment:

$$\delta a_e = a_e^{\text{EXP}} - a_e^{\text{SM}} = -(8.8 \pm 3.6) \times 10^{-13}$$

Muon anomalous magnetic moment:

$$\delta a_\mu = a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = (2.706 \pm 0.726) \times 10^{-9}$$

- Deviations are in opposite directions
- Also $$\frac{\delta a_\mu}{\delta a_e} \neq \frac{m_\mu^2}{m_e^2}$$
- Possibly of different origin $\Rightarrow$ light $A$ in 2HDM-X can not explain both.
- Q. What minimal modification in 2HDM-X can explain both $\delta a_e/\mu$ ?
Electron and muon $g - 2$ anomalies

2HDM + Vector-like leptons ($L_{L,R}$ and $E_{L,R}$)

\[-\mathcal{L} \supset y_e \bar{\ell}_L e_R \Phi_1 + \lambda_L \bar{\ell}_L e_R \Phi_1 + \lambda_E \bar{\ell}_L E_R \Phi_1 + \lambda \bar{\ell}_L E_R \Phi_1 + \bar{\lambda} \Phi_1^\dagger \bar{E}_L L_R + M_L \bar{\ell}_L L_R + M_E \bar{E}_L E_R + \text{h.c.}\]

Mass matrix for charged leptons:

\[
\mathcal{L}_{mass} = (\bar{\ell}_L, \bar{\ell}_L^-, \bar{E}_L) \mathcal{M}_E \begin{pmatrix} \ell_{Rj} \\ L_R^- \\ E_R \end{pmatrix} + \text{h.c.}
\]

\[
\mathcal{M}_E = \begin{pmatrix}
\frac{1}{\sqrt{2}} y_{e,ij} v_1 & 0 & \frac{1}{\sqrt{2}} \lambda_{E_i} v_1 \\
\frac{1}{\sqrt{2}} \lambda_{L_j} v_1 & M_L & \frac{1}{\sqrt{2}} \lambda v_1 \\
0 & \frac{1}{\sqrt{2}} \bar{\lambda} v_1 & M_E
\end{pmatrix},
\]

- Mass diagonalization: $\tilde{U}_L^\dagger \mathcal{M}_E \tilde{U}_R = \text{diag}(m_e, m_\mu, m_\tau, m_1, m_2)$
- We assume $\lambda_{E_2}, \lambda_{E_3}, \lambda_{L_2}, \lambda_{L_3} = 0$
Electron and muon $g-2$ anomalies

- Electron $g-2$ diagrams mediated by W and Z bosons is small.
- When VLL is heavier than $H/A$, then $H$ and $A$ contribution will cancel partially.

<table>
<thead>
<tr>
<th>$v_1 [\lambda_{L/E}]/M_{L/E}$</th>
<th>$\lambda, \bar{\lambda}$</th>
<th>$M_L(\text{GeV})$</th>
<th>$\Delta M = \frac{M_E - M_L}{M_E + M_L}$</th>
<th>$M_A(\text{GeV})$</th>
<th>$\tan \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(10^{-1}, 10^{-5})$</td>
<td>$(-\sqrt{4\pi}, \sqrt{4\pi})$</td>
<td>(500, 1000)</td>
<td>(0.01, 0.10)</td>
<td>(30, 150)</td>
<td>(30, 100)</td>
</tr>
</tbody>
</table>
Electron and muon $g - 2$ anomalies

Log10 $\frac{|\lambda_L v_1|}{M_L}$ vs Log10 $\frac{|\lambda_E v_1|}{M_E}$

Red: $m_A = m_{H^±} = 250$ GeV
Blue: $m_A = m_{H^±} = 1$ TeV

The dashed lines in the left plot are constraints coming from $Z$ pole observables:

$v_1 |\lambda_E| \leq 0.04$ and $v_1 |\lambda_L| \leq 0.02$.

The right plot shows solid (dashed) lines as upper limits on $\tan \beta$ from $Z \rightarrow \ell \ell$ for $M_H = 250(1000)$ GeV.

Contribution $\propto \left( \frac{\lambda}{\bar{\lambda}} \frac{v_1}{M_L} \right)$.

Tanmoy Mondal, KIAS, Seoul Osaka University, Osaka
The dashed lines in left plot are constraints coming from $Z$ pole observables:

$$\frac{\nu_1 |\lambda_E|}{M_E} \leq 0.04 \quad \text{and} \quad \frac{\nu_1 |\lambda_L|}{M_L} \leq 0.02.$$ 

Right plot: Solid(dashed) lines are upper limit on $\tan \beta$ from $Z \rightarrow \ell \ell$ for $M_H = 250(1000)\text{GeV}$.

The VLL loop contribution for $(g - 2)_\mu$ is small due to chiral mass insertion in the fermion loop in BZ diagram. Contribution $\propto \left( \frac{\lambda/\bar{\lambda} \nu_1}{M_L/E} \right)$. 

E J Chun, TM JHEP 2020
Electron and muon $g-2$ anomalies

The model has interesting signature at the LHC

- VLL couples dominantly to new scalars ($A/H/H^{\pm}$) as gauge boson couplings are proportional to small vev $v_1$

- Hence the doublet VLL ($\equiv (L^0, L^-)^T$) signature at the LHC:
  
  $$p \ p \rightarrow W^{*+} \rightarrow L^0 \ L^+ \rightarrow (H^+ e^-)(H/A \ e^+ ) \rightarrow e^+e^- H^+ H/A.$$ 

- Depending on $M_A$ and $\tan \beta$, $H(H^{\pm})$ decays to $\tau \tau (\tau \nu)$ or $ZA(WA)$

- Since $M_L \gg M_A \Rightarrow L^+ \rightarrow e^+ A$ will produce a highly boosted $A$:
  
  $$p_T(A) \sim \frac{m_{L^+}^2 - m_A^2}{2 \ m_{L^+}}$$

- The tau pair from the $A$ will be collimated and appear as merged jet

- ‘di-$\tau$’ tagger by ATLAS can be used to look for such light boosted pseudoscalar

- Another signature will be a lepton in the close proximity of a tau-jet.
2HDM : one of the simplest BSM scalar structure.
Type-X 2HDM : Can explain muon $g - 2$ anomaly. Constrained by lepton universality.
The allowed parameter space can be explored at the LHC.
Conventional signature at LHC : multi $\tau$-tagged jets.
Can’t reconstruct the mass of mediator. Hard to trigger for low mass pseudoscalar.
One needs to look for $\mu\mu\tau\tau$ final state.
Due to light $A$, the tau-tagged jets takes almost all the momentum from the taus.
This enables us to reconstruct $M_{j\tau j\tau}$ and $M_{2\mu 2j\tau}$. We can restrict $h \rightarrow AA$ branching ratio.
Using the associated production the heavy scalar/charged higgs can be reconstructed.
Sweet spot : $M_{H^\pm} \sim [200 - 240]$ GeV with $M_A \sim [40 - 50]$ GeV.
Conclusion - II

- Due to hadrophobic nature it is hard to probe light $A$ at the LHC.
- Lepton collider can be ideal to test the model.
- We can utilize ILC *Higgs Factory* for testing the light $A$ scenario independent of the mass scale of the other scalars ($H/H^\pm$).
- It is possible to reconstruct the mass of the resonance using collinear approximation.
- 500 $fb^{-1}$ is enough to explore the relevant parameter space.
- Recent measurement of electron $g - 2$ can not be explained the pure Type-X 2HDM.
- A family of vector-like lepton doublet and singlet can explain both the anomalies.
- The model has interesting collider signature which can explore the model independently.
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Thank You