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

PLB 774 (2017), PRD 98 (2018)
PLB 802 (2020), JHEP (2020)

Tanmoy Mondal

Korea Institute for Advanced Study
Seoul , South Korea

November 17th, 2020

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

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.

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 $\tan\beta$
- I will discuss some of the phenomenological aspects of a light pseudoscalar in Type-X 2HDM.

The Model : 2HDM Type X

The scalar potential

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

- 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 : $H^\pm, h, H, A$.

Masses of the scalars and quartic couplings

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

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

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

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

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

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

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 ~ 10 TeV.
- So we demand : No tree level FCNC.

Paschos-Glashow-Weinberg Theorem

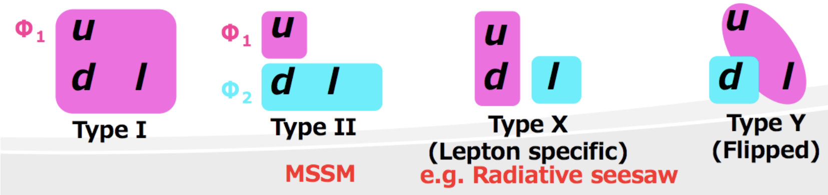
A necessary and sufficient condition for the absence of FCNC at tree level is that all fermions of a given charge and helicity transform according to the same irreducible representation of SU(2), correspond to the same eigenvalue of T_3 and that a basis exists in which they receive their contributions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

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



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

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

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

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

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

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

- Gauge-Higgs sector :

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

where $V = Z, W^\pm$.

- Relevant vertices

$$hAZ_\mu : \frac{g_Z}{2}\cos(\beta-\alpha)(p+p')_\mu, \quad HAZ_\mu : -\frac{g_Z}{2}\sin(\beta-\alpha)(p+p')_\mu,$$
$$H^\pm AW^\mp_\mu : \frac{g}{2}(p+p')_\mu$$

where p_μ (p'_μ) : outgoing four-momenta of the first (second) scalars.

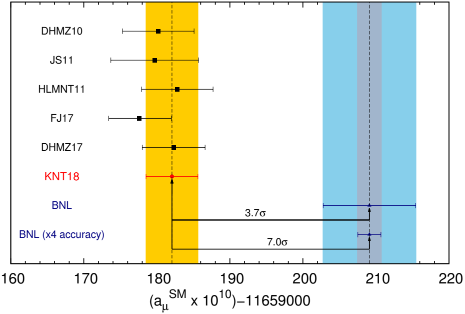
Interesting parameter space in 2HDM-X : Muon $(g-2)$ and other constraints

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

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

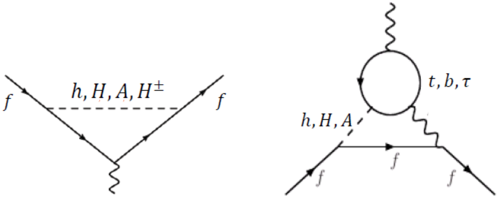
- $a_\mu^{\text{exp}} = (11659209.1 \pm 6.3) \times 10^{-10}$
- $a_\mu^{\text{th}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had,VP}} + a_\mu^{\text{had,LbL}}$
- $\{(11658471.9 \pm 0.007) + (15.36 \pm 0.1)\} \times 10^{-10}$
- $\{(684.68 \pm 2.42) + (9.8 \pm 2.6)\} \times 10^{-10}$
- $\Delta a_\mu = (27.06 \pm 7.26) \times 10^{-10}$ Ref: 1802.02995



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

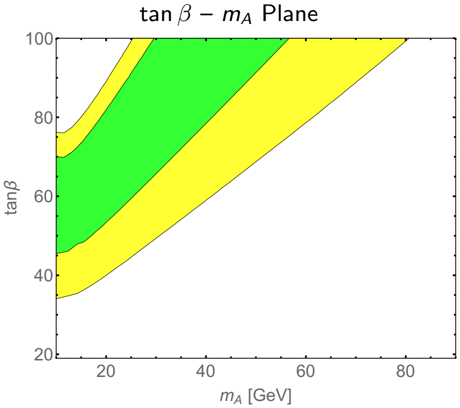
Muon $g-2$ in 2HDM



- 1loop: contribution from h, H are positive and A contributes negatively.
- $m_H < 5$ GeV to explain experimental data.
- Barr-Zee 2-Loop contribution with τ 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

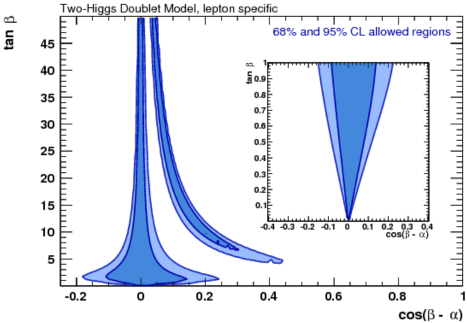


JHEP 11 (2014) 058, JHEP 05 (2015) 039, JHEP 07 (2015) 064, JHEP 11 (2015) 099, JHEP 02 (2016) 097, JHEP 01 (2017) 007

and many more

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

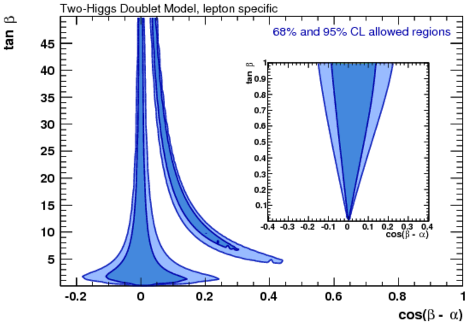
- Muon $g-2$
- **Higgs signal strength**
- $B_s \to \mu^+\mu^-$ or $B_s \to X_s\gamma$
- EWPD
- Lepton universality



GFitter : 1803.01853

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



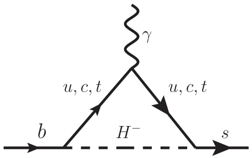
GFitter : 1803.01853

Wrong Sign Limit

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

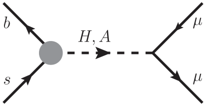
So, when $\tan\beta\cos(\beta-\alpha) \sim 2$ Higgs coupling to leptons flip sign.

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



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

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

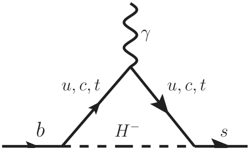


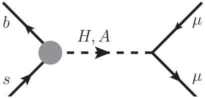
For type X : ~ 1
For type II : $(\tan\beta)^2$

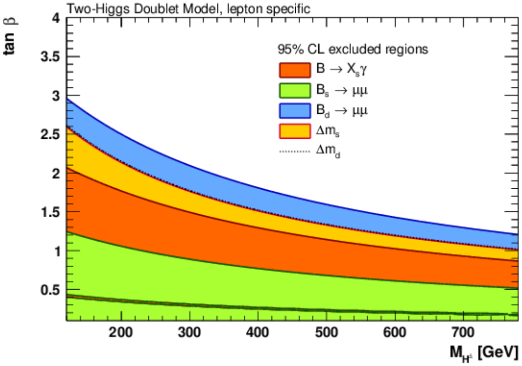
- 2HDM-II : $b \to s\,\gamma$: $m_{H^\pm} > 580$GeV. BELLE, 1608.02344
- $BR(B_s \to \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ LHCb, 1703.05747
- Limit on type-II 2HDM : $\tan\beta < 7$ for $m_A < 70$ GeV

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

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

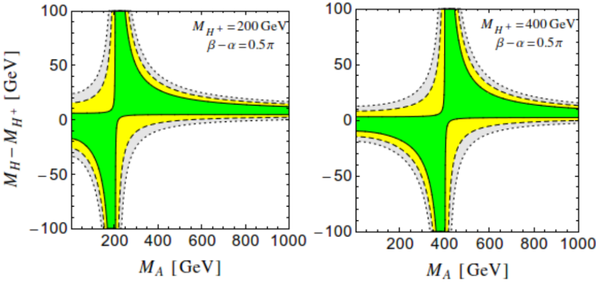






GFitter : 1803.01853

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



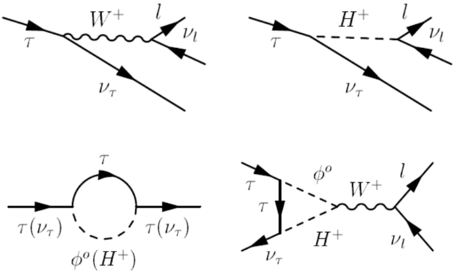
- $M_{H^\pm}$ should be very close to either M_H or M_A.

JHEP 11 (2014) 058

GFitter : 1803.01853

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

τ Decay



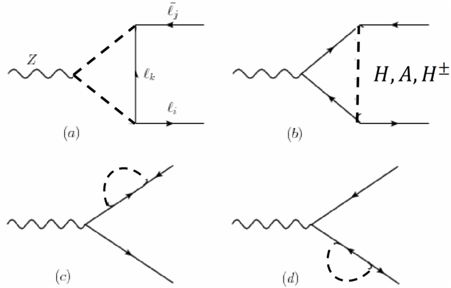
Limits coming from :

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

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

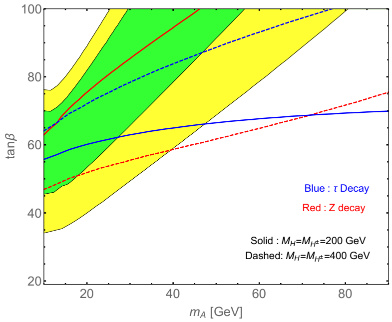
- Muon $g-2$
- Higgs signal strength
- $B_s \to \mu^+\mu^-$ or $B_s \to X_s\gamma$
- EWPD
- **Lepton universality**

Z Decay



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

Allowed space



Z Phys. C 51 (1991) 695
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

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

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 $2\mu 2\tau$ 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

Production of light pseudoscalar at the LHC

- 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 4τ 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 $\text{BR}(A \to \mu\mu) \simeq 0.35\%$
- This channel can be used to estimate mass of the pseudoscalar.

Parameters	M_A (GeV)	$\tan\beta$	$\cos(\beta-\alpha)$	λ_{hAA}/v
BP1	50	60	0.03	0.02
BP2	60	60	0.03	0.03

$$p\,p \to h \to A\,A \to \mu^+\mu^- \;\; \tau^+\tau^- \to \mu^+\mu^- \;\; j_\tau\, j_\tau + MET$$

$$\sigma \sim 0.021\ pb$$

Parameters	M_A (GeV)	$\tan\beta$	$\cos(\beta-\alpha)$	λ_{hAA}/v
BP1	50	60	0.03	0.02
BP2	60	60	0.03	0.03

$$p\,p \to h \to A\,A \to \mu^+\mu^- \;\; \tau^+\tau^- \to \mu^+\mu^- \;\; j_\tau\, j_\tau + MET$$

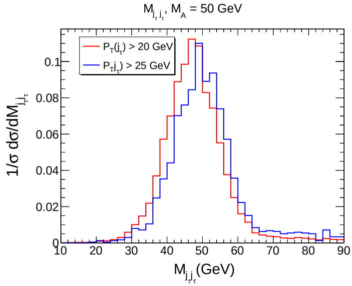
$$\sigma \sim 0.021\ pb$$

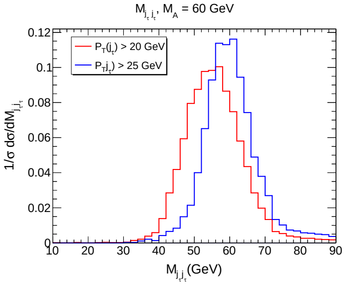
Backgrounds:

- $pp \to \mu^+\mu^- + jets$ $\sigma \sim 2100$ pb
- $pp \to VV + jets(V = Z, W, \gamma^*)$ $\sigma \sim 6.2$ pb
- $pp \to t\bar{t} + jets.$ $\sigma \sim 0.03$ pb

- 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(!!)

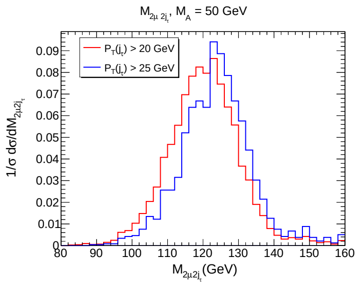
- We have a light A (mass < 60 GeV) decaying to two tau which further decays hadronically.
- If minimum p_T for the tau tagged jets is close to $M_A/2$ then the neutrinos can not take large amount of tau momentum.
- In that case invariant mass of tau-jets will peak at parent mass(!!)

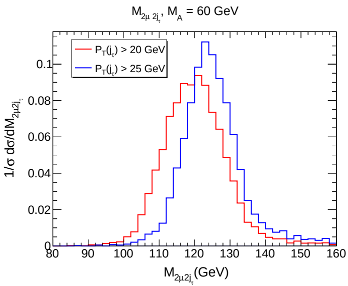




Chun,Dwivedi,TM,Mukhopadhyaya PLB 774 (2017)

The same argument holds if we construct invariant mass using 2μ and 2 τ-tagged jet.



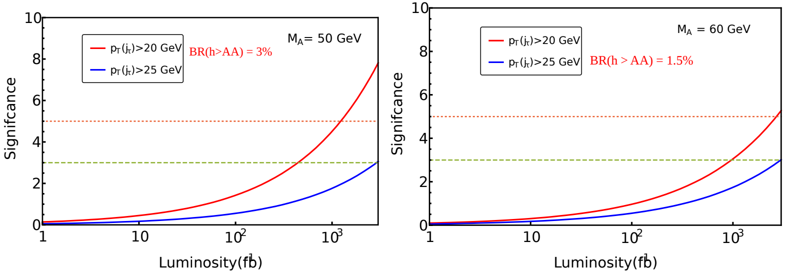


Chun,Dwivedi,TM,Mukhopadhyaya PLB 774 (2017)

- 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: $|M_{\mu\mu} - M_A| < 7.5\,\mathrm{GeV}$.
- 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 taujets ($M_{2\mu 2j_\tau}$)lies within the range :
  - for $p_T(j_\tau) > 20$ GeV : $(M_h - 20) < M_{2\mu 2j_\tau} < (M_h + 10)$ GeV.
  - for $p_T(j_\tau) > 25$ GeV : $|M_{2\mu 2j_\tau} - M_h| < 15$ GeV.
- Asymmetric cuts for low p_T since the distribution peaks at lower value.

Result

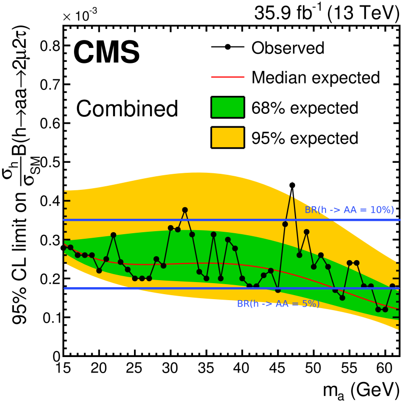
$$\text{Significance} = \mathcal{S} = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right)-S\right]}$$



- 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 $\text{BR}(h \to aa) < 1\%$.

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

CMS limit



JHEP 11 (2018) 018

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

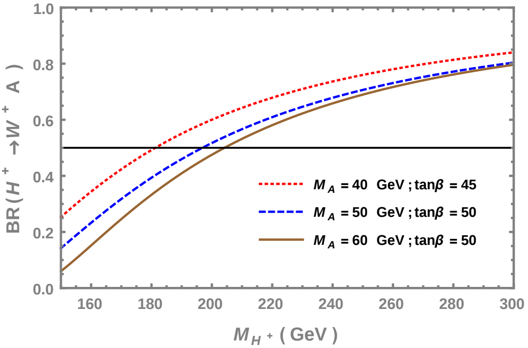
Branching fraction of $H^{\pm}$

There are two possible decay modes for the charged Higgs

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

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

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



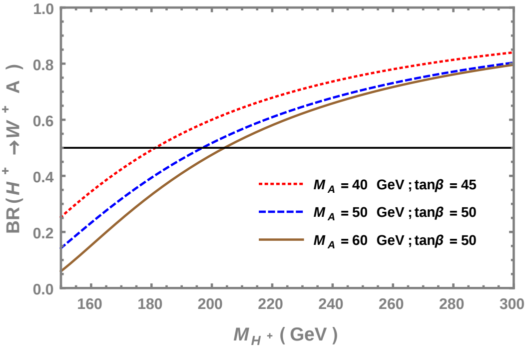
Branching fraction of $H^{\pm}$

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

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

- Added contribution from heavy Higgs H

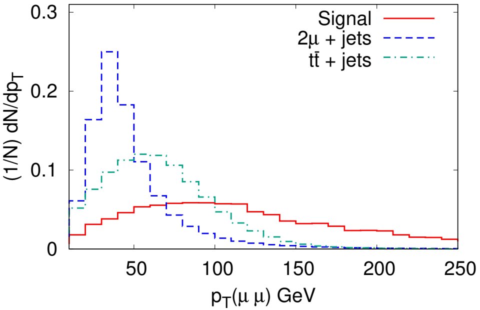
$$p\ p \to (H)A \to (ZA)\ \ A \to (j\ j\ 2\mu)\ \ 2\tau$$

- 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.

- 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.

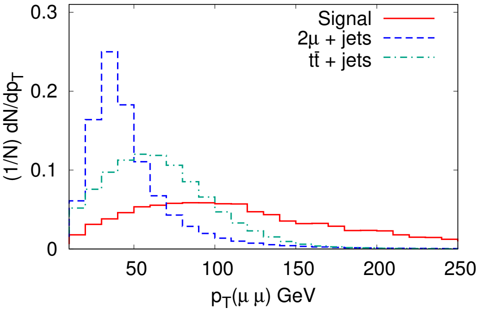
Kinematic distributions - I

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



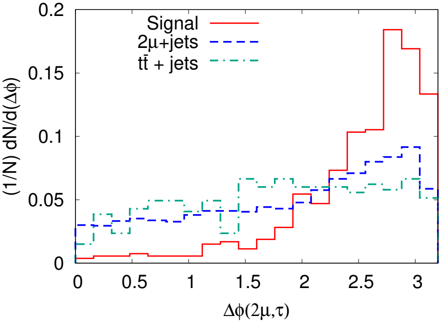
Kinematic distributions - I

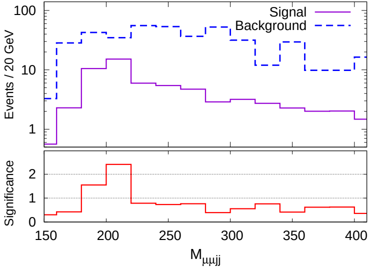
The 2μ system is originates from a light A which in turn comes form heavy $H/H^{\pm}$ decay. Expected to be boosted.

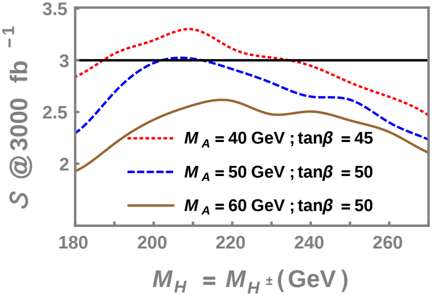


Kinematic distributions - II

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

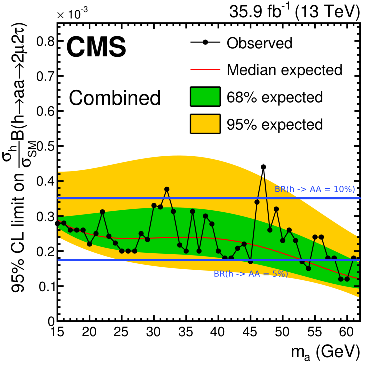






- Low $M_{H^\pm}$: Significance decreases as not enough branching to $W^\pm A$.
- Also low boost for the $\mu\mu$ system.
- High $M_{H^\pm}$: Low production cross-section.

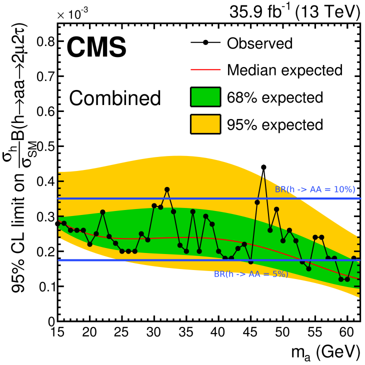
Chun,Dwivedi,TM,Mukhopadhyaya,Rai PRD 98 (2018) 7



JHEP 11 (2018) 018

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

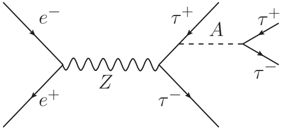
CMS reported $2\mu 2\tau$ search in 2018



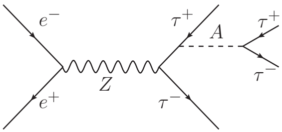
JHEP 11 (2018) 018

- $\lambda_{hAA} = \frac{-1}{v}\left[2m_A^2 + \xi_h^\ell m_h^2 - (s_{\beta-\alpha}^2 + \xi_h^\ell s_{\beta-\alpha})m_H^2\right].$
- λ_{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 ?
- A. **ILC**

- The channel $Z \to h_{125} A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.
- At ILC250 $Z \to HA$ may not be feasible when H is heavier than 200 GeV.
- Possible search option : $Z \to \tau\tau \to \tau\tau A \to 4\tau$. So called Yukawa production.

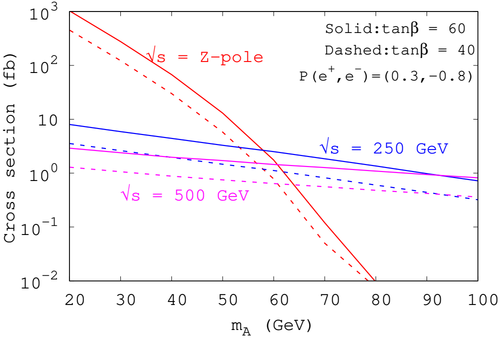


- The channel $Z \to h_{125} A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.
- At ILC250 $Z \to HA$ may not be feasible when H is heavier than 200 GeV.
- Possible search option : $Z \to \tau\tau \to \tau\tau A \to 4\tau$. So called Yukawa production.



- This is the equivalent to ttH searches at LHC. Independent probe of Yukawa structure.
- At the ILC all the 4τ s can be reconstructed using collinear approximation.
- This enables to measure mass of the light particle.

Signal: $Z \to \tau\tau \to \tau\tau A \to 4\tau$



- Dominant Backgrounds : $e^+e^- \to Z(\gamma^*)\ \ Z(\gamma^*) \to 4\tau$
- Also $e^+e^- \to Z(\gamma^*)\ \ Z(\gamma^*) \to 2\tau 2j$ with mis-identified jets
- Other background : $e^+e^- \to Zh \to 4\tau$
- Parton level total 4τ BG cross-section $\simeq$ 6.6 fb. $2\tau 2j$ $\simeq$100 fb.

- MadGraph_aMC@NLO → PYTHIA8 → Delphes3 + ILD card
- Signal : 3 τ-tagged jets + X (= τ-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. $\cos\theta < 0.98$.
- τ-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,

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

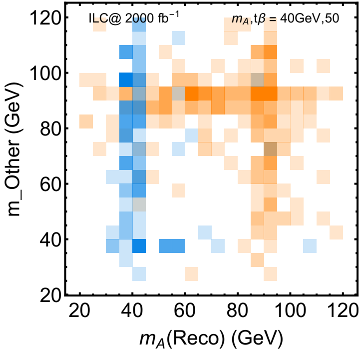
- Visible part of the tau decay take z_i fraction of the tau momentum : $p^\mu(j_i) = z_i \; p^\mu(\tau_i)$
- Solve for z_i where we should have $0 < z_i < 1$. However to account for the detector resolution etc we assume 10% relaxation in the upper limit of z_i.

Reconstruction of the pseudoscalar

- We have 4 tau jets. However, the highest energy τ out of the four is unlikely to come from the pseudoscalar since the maximum available energy for A is 125 GeV($\sqrt{s}/2$), whereas energy of highest τ 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 $m_A(Reco)$.
- The invariant mass from the other opposite sign tau pair is denoted as m_Other.

Reconstruction of the pseudoscalar

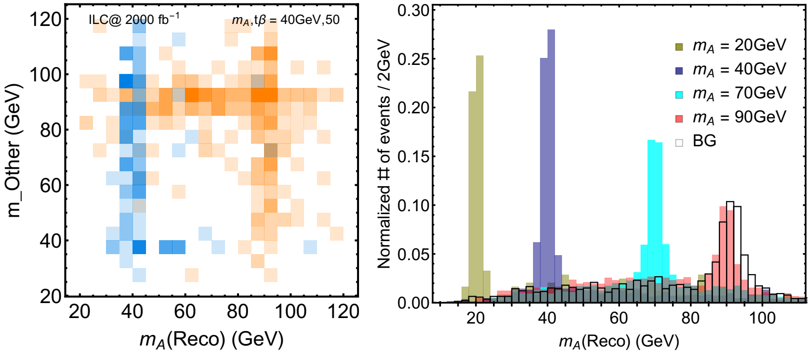
$m_A = 40$ GeV and $\tan\beta = 50$



For different m_A

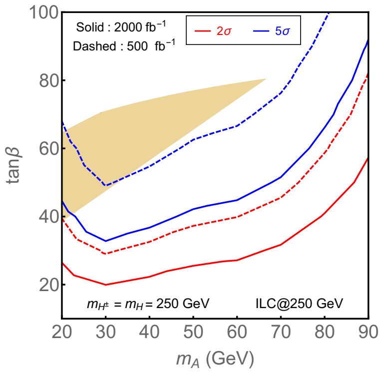
Reconstruction of the pseudoscalar

$m_A = 40$ GeV and $\tan\beta = 50$ — For different m_A

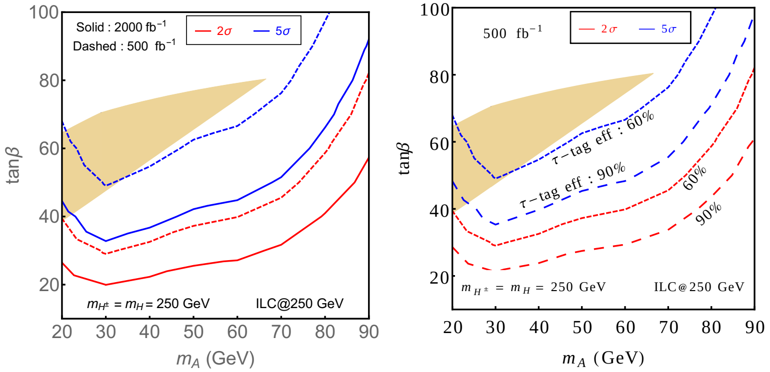


Chun,TM PLB 802 (2020) 135190

Reach of ILC250. $\epsilon_\tau = 60\%$



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: Science 360 (2018) 191

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

Muon anomalous magnetic moment:

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

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

imagine the impossible KIAS KOREA INSTITUTE FOR ADVANCED STUDY

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

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

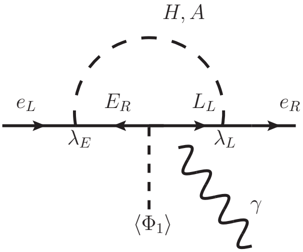
Mass matrix for charged leptons:

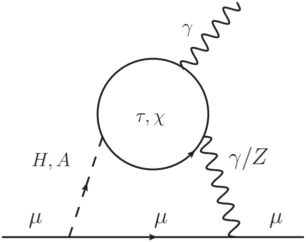
$$\mathcal{L}_{mass} = (\bar{\ell}_{Li}, \bar{L}_L^-, \bar{E}_L)\,\mathcal{M}_E \begin{pmatrix} \ell_{Rj} \\ L_R^- \\ E_R \end{pmatrix} + h.c..$$

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

- Mass diagonalization : $\widetilde{U}_L^\dagger\,\mathcal{M}_E\,\widetilde{U}_R = diag(m_e, m_\mu, m_\tau, m_1, m_2)$
- We assume $\lambda_{E_2}, \lambda_{E_3}, \lambda_{L_2}, \lambda_{L_3} = 0$

Electron and muon $g-2$ anomalies

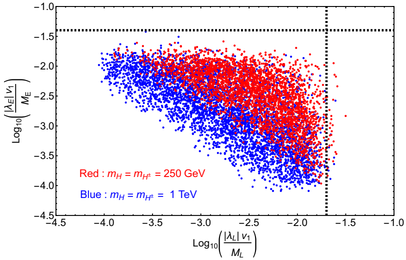




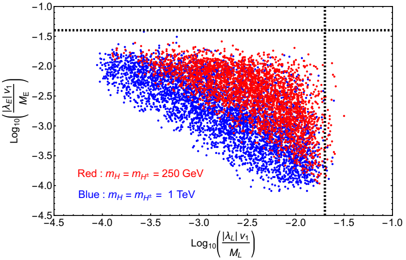
- Electron $g-2$ diagrams mediated by W and Z bosons is small.
- When VLL is heavier than H/A, then H and A contribution will cancel partially.

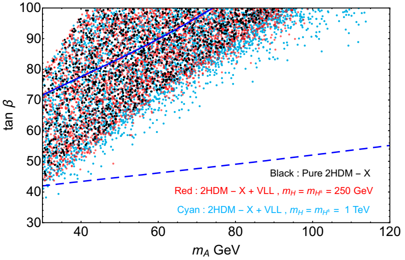
$v_1 \frac{\|\lambda_{L/E}\|}{M_{L/E}}$	$\lambda, \bar{\lambda}$	M_L(GeV)	$\Delta M = \frac{M_E - M_L}{M_E + M_L}$	M_A(GeV)	$\tan\beta$
$(10^{-1}\ ,\ 10^{-5})$	$(-\sqrt{4\pi}, \sqrt{4\pi})$	(500 , 1000)	(0.01 , 0.10)	(30 , 150)	(30 , 100)

Electron and muon $g-2$ anomalies



Electron and muon $g-2$ anomalies





E J Chun, TM JHEP 2020

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

$$\frac{v_1\ |\lambda_E|}{M_E} \leq 0.04 \quad \text{and} \quad \frac{v_1\ |\lambda_L|}{M_L} \leq 0.02.$$

- Right plot : Solid(dashed) lines are upper limit on $\tan\beta$ from $Z \to \ell\ell$ for $M_H = 250(1000)$GeV.
- The VLL loop contribution for $(g-2)_\mu$ is small due to chiral mass insertion in the fermion loop in BZ diagram. Contribution $\propto \left(\frac{\lambda/\bar{\lambda}\ v_1}{M_{L/E}}\right)$.

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$\left(\equiv (L^0, L^-)^T\right)$ signature at the LHC:

$$p\ p \to W^{*+} \to L^0\ L^+ \to (H^+ e^-)(H/A\ e^+) \to e^+ e^-\ \ H^+\ H/A.$$

- Depending on M_A and $\tan\beta$, $H(H^{\pm})$ decays to $\tau\tau(\tau\nu)$ or $ZA(WA)$
- Since $M_L \gg M_A \Rightarrow L^+ \to e^+ A$ 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-τ' 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 τ-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 $h \to AA$ 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.

- 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.

imagine the impossible KIAS KOREA INSTITUTE FOR ADVANCED STUDY

- 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.

Thank You