Light (Pseudo)Scalar at the ILC

Tanmoy Mondal, KIAS

based on arXiv:1909.09515
In collaboration with Eung Jin Chun

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Introduction

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

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2HDM is one of the simplest scalar extensions of the Standard Model.

Type-X 2HDM :

- Possible to reconcile Muon $g-2$ with a light pseudoscalar
- I will discuss how to look for such light pseudoscalar at the ILC.

The Model : 2HDM Type X

The 2HDM scalar potential

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

Masses of the scalars and quartic couplings

$$
\lambda_1 = \frac{m_H^2 c_\alpha^2 + m_h^2 s_\alpha^2 - m_{12}^2\tan\beta}{v^2 c_\beta^2}, \quad \lambda_2 = \frac{m_H^2 s_\alpha^2 + m_h^2 c_\alpha^2 - m_{12}^2\cot\beta}{v^2 s_\beta^2},
$$

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

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

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

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

2HDM X : Yukawa structure

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

$\mathbb{Z}_2$ symmetry : $\Phi_2 \to \Phi_2$, $\Phi_1 \to -\Phi_1$ and $e_R \to -e_R$.

After symmetry breaking,

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

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
$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{c_\alpha}{c_\beta}$	$\cot\beta$	$-\cot\beta$	$\tan\beta$

Sign of Yukawa coupling: $\frac{-s_\alpha}{c_\beta} = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$. Now from Higgs data we know $|s_{\beta-\alpha}| \simeq 1$ and $|\xi_h^\tau| \simeq 1$.

RS limit : $t_\beta c_{\beta-\alpha} \simeq 0 \Rightarrow \xi_h^\tau \simeq +1$ WS limit : $t_\beta c_{\beta-\alpha} \simeq 2 \Rightarrow \xi_h^\tau \simeq -1$

Constraints on 2HDMX Parameter space

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

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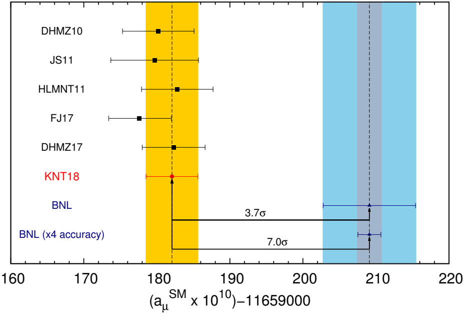
- $a_\mu^{\rm exp} = (11659209.1 \pm 6.3) \times 10^{-10}$
- $a_\mu^{\rm th} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had,VP} + a_\mu^{\rm had,LbL}$
- $\{(11658471.9 \pm 0.007) + (15.36 \pm 0.1)\} \times 10^{-10}$
- $\{(684.68 \pm 2.42) + (9.8 \pm 2.6)\} \times 10^{-10}$
- $\Delta\, a_\mu = (27.06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



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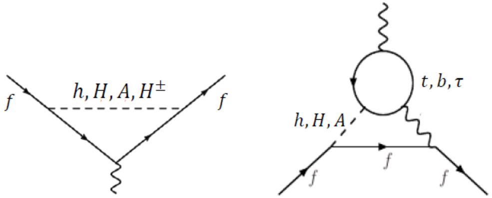
Muon $g-2$ in 2HDM



- 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.

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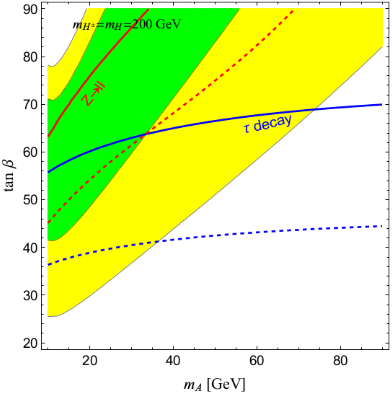
tan β – m_A Plane



E J Chun et al. JHEP 11 (2015) 099

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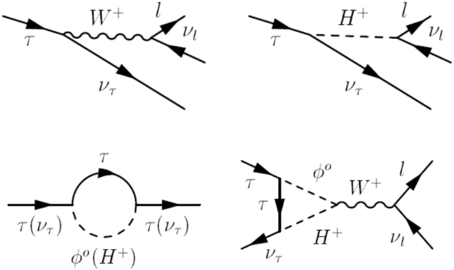

Limits coming from :

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

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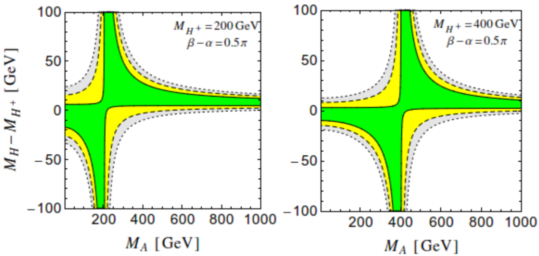

Charged Higgs mass should be close to H or A.

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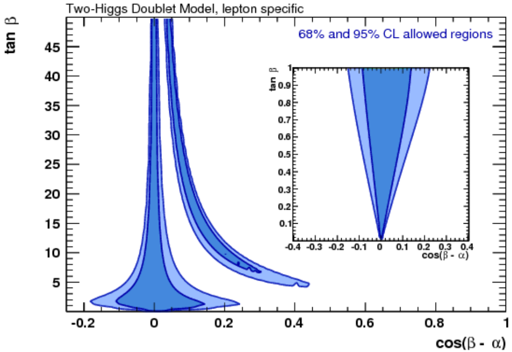

GFitter : 1803.01853.

2HDM-X : Allowed parameter space

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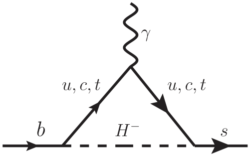
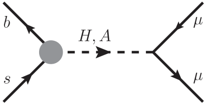


$$\frac{m_t}{t_\beta} P_L - \frac{m_b}{t_\beta} P_R \quad (X, I)$$

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



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

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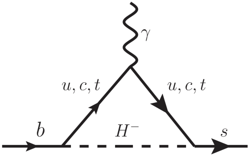

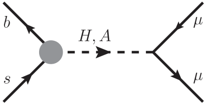

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For type X : ~ 1
For type II : $(\tan\beta)^2$

- $b \to s\,\gamma$: $m_{H^\pm} > 580$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

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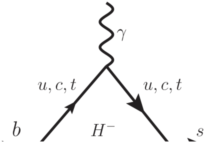

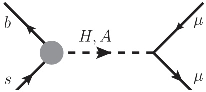

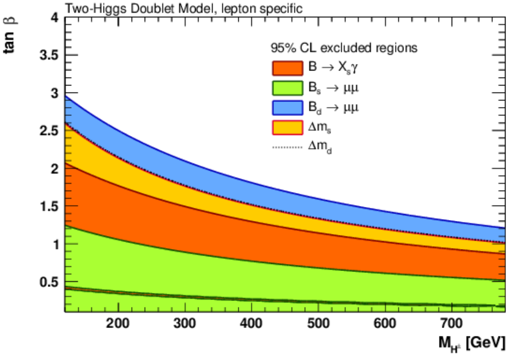

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Light A of 2HDMX at LHC

LHC phenomenology of light A

- Hadrophobic scalars. No direct production. Tau rich signals.
- Different multi tau signal has been studied :

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

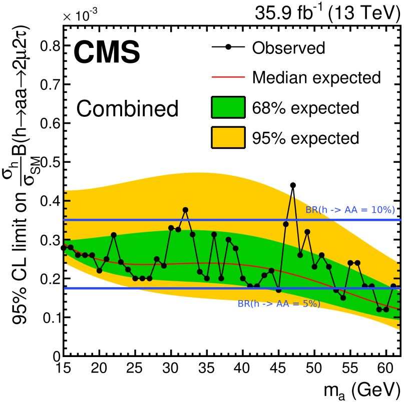
Kanemura et.al. (1111.6089), E.J.Chun et.al. (1507.08067)

- However, it is not possible to reconstruct the masses of the scalars from tau only final states.
- To reconstruct the mass of the A :
  - $h \to AA \to 2\mu 2\tau$
  - $W^{*}(Z^{*}) \to H^{\pm}(H)A \to W^{\pm}A(ZA)\ A \to j\, j\, 2\mu\ \ 2\tau$

TM et.al. (PLB 774, 2017), TM et.al. (PRD 98, 2018)

LHC phenomenology of light A

CMS Search for light A : 13 TeV, 36 fb^{-1} Ref:JHEP 11 (2018) 018



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

It can be very small in WS limit due to cancellation when $m_H \gg m_h/m_A$.
Does not necessarily limit the light A large tan β scenario.

Light A of 2HDMX at ILC

Searches for light A in 2HDMX at ILC250

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

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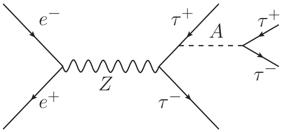
- Possible search option : $Z \to \tau\tau \to \tau\tau A \to 4\tau$. So called Yukawa production.



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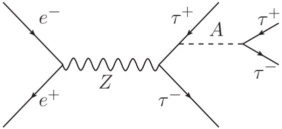
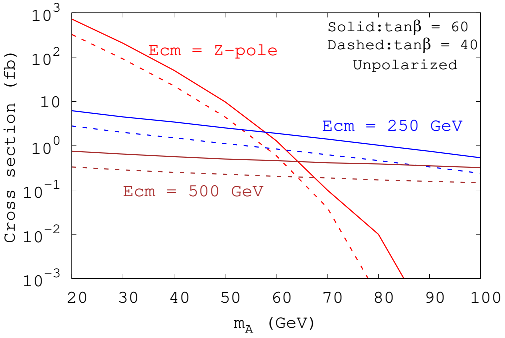


- This is the equivalent to ttH searches at LHC. Independent probe of Yukawa structure.
- At the ILC all the 4τ s can be reconstructed using collinear approximation.
- This enables to measure mass of the light particle.

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.

Searches for light A in 2HDMX at ILC250

- `MadGraph_aMC@NLO` $\rightarrow$ `PYTHIA8` $\rightarrow$ `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,

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

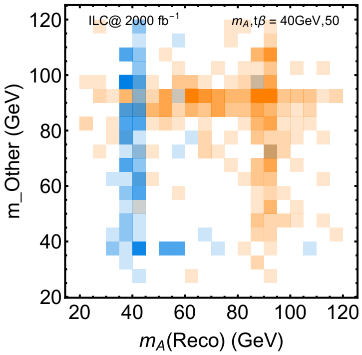
- Visible part of the tau decay take z_i fraction of the tau momentum : $p^\mu(j_i) = z_i \; p^\mu(\tau_i)$
- Solve for z_i where we should have $0 < z_i < 1$. However to account for the detector resolution etc we assume 10% relaxation in the upper limit of z_i.

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

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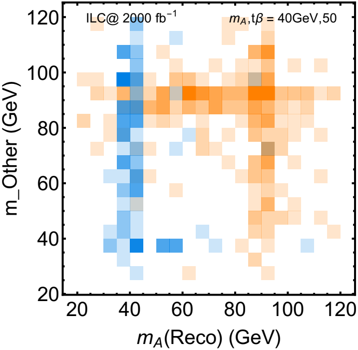

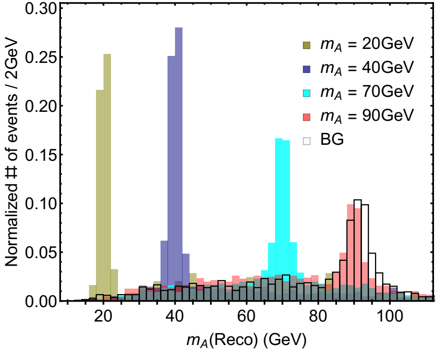

Searches for light A in 2HDMX at ILC250 : Result

Cut-flow table for $m_A = 40, \tan\beta = 50$ @ ILC250 with $\mathcal{L} = 2\ ab^{-1}$

Pre-selection cut : Energy > 20 GeV. $\|\eta\| < 2.3$				
$\mathcal{L} = 2000\ fb^{-1}$	Signal	Background		Significance
		4τ	2τ 2 j	
Pre-selection cut	106 [100%]	242 [100%]	98[100%]	5.5
Collinear approx $0 < z_i < 1.1$	91 [86.0%]	217[89.7%]	69[70.4%]	5.1
$m_A \pm 10$GeV	66 [62.3%]	32 [14.9%]	10[10.2%]	8.5

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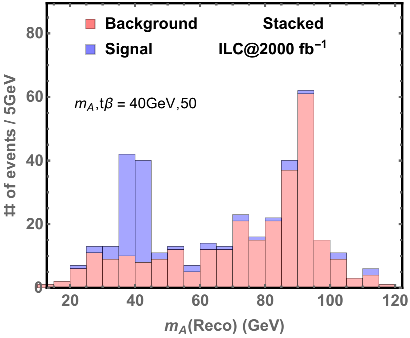

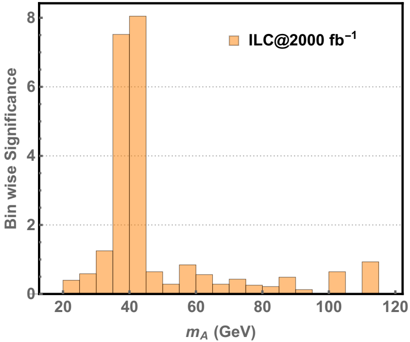

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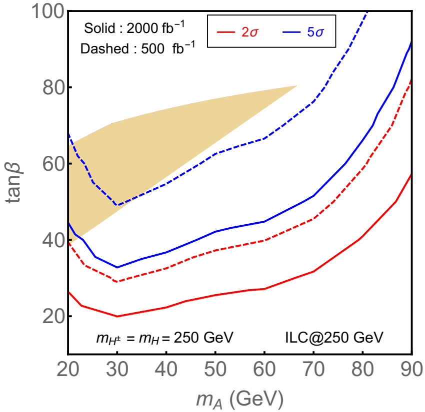
Reach of ILC250. $\epsilon_\tau = 60\%$



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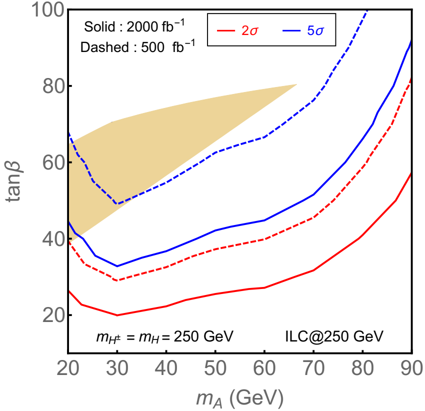

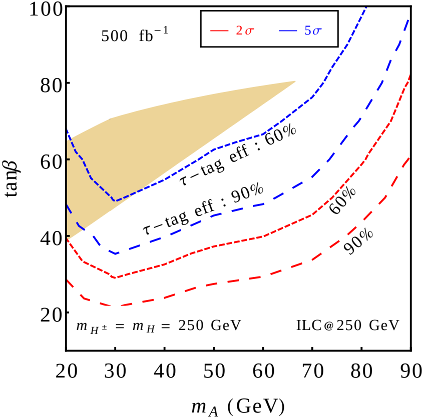

Conclusion

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- Due to hadrophobic nature it is hard to test at 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.
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Thank You

back up

- 1-Loop contribution :

$$\Delta a_\mu^{\rm 2HDM}(1{\rm loop}) = \frac{G_F\, m_\mu^2}{4\pi^2\sqrt{2}} \sum_j \left(y_\mu^j\right)^2 r_\mu^j\, f_j(r_\mu^j)$$

$$\begin{aligned} f_{h,H}(r) &= -\ln r - 7/6 + O(r), \\ f_A(r) &= +\ln r + 11/6 + O(r), \\ f_{H^\pm}(r) &= -1/6 + O(r), \end{aligned}$$

- $r_\mu^j = \frac{m_\mu^2}{m_j^2}$ i.e. $ln(r) \Rightarrow$ large negative. H(A) contribution is +ve(-ve).
- 2-Loop contribution

$$\Delta a_\mu^{\rm 2HDM}(2{\rm loop}-{\rm BZ}) = \frac{G_F\, m_\mu^2}{4\pi^2\sqrt{2}}\, \frac{\alpha_{\rm em}}{\pi} \sum_{i,f} N_f^c\, Q_f^2\, y_\mu^i\, y_f^i\, r_f^i\, g_i(r_f^i)$$

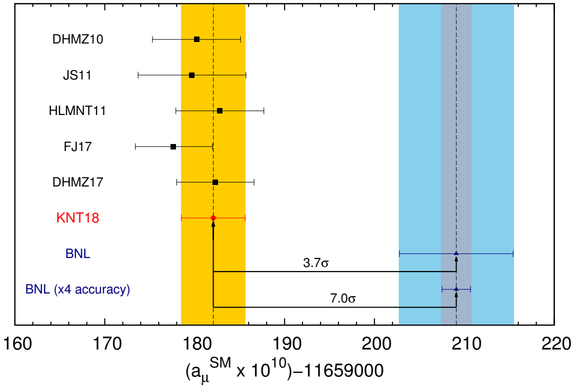
$$g_i(r) = \int_0^1 dx\, \frac{\mathcal{N}_i(x)}{x(1-x)-r} \ln\frac{x(1-x)}{r} \qquad \mathcal{N}_{h,H}(x) = 2x(1-x)-1 \text{ and } \mathcal{N}_A(x) = 1$$

- Enhancement factor in $r_i^f = \frac{m_f^2}{m_i^2}$. τ-loop dominates.
- H(A) contribution is -ve(+ve).

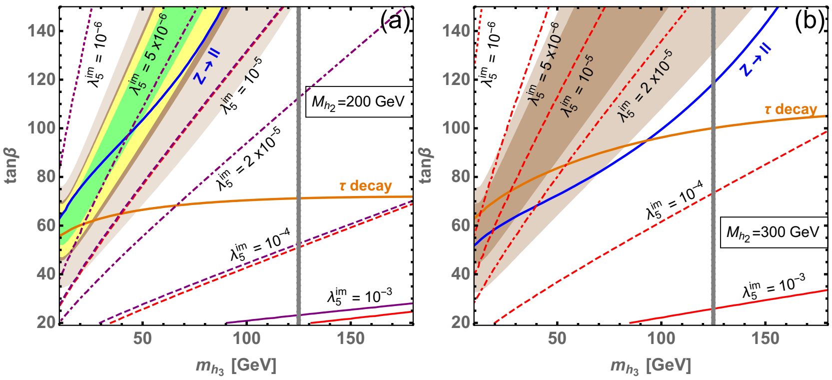
	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Back-up : Present Status of Muon $g-2$

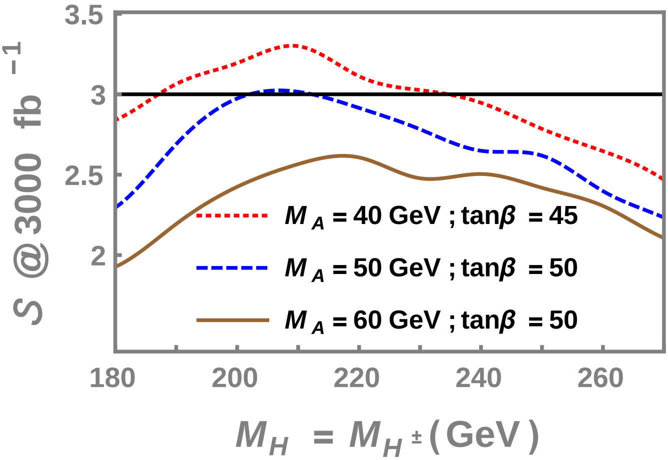
- $a_\mu^{\rm exp} = (11659209.1 \pm 6.3) \times 10^{-10}$
- $a_\mu^{\rm th} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had,VP} + a_\mu^{\rm had,LbL}$
- $a_\mu^{\rm QED} + a_\mu^{\rm EW} = \{(11658471.9 \pm 0.007) + (15.36 \pm 0.1)\} \times 10^{-10}$
- $a_\mu^{\rm had,VP} + a_\mu^{\rm had,LbL} =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



EDM


(a)
$\lambda_5^{im} = 10^{-6}$
$\lambda_5^{im} = 5\times10^{-6}$
$Z \to ll$
$\lambda_5^{im} = 10^{-5}$
$\lambda_5^{im} = 2\times10^{-5}$
M_{h_2}=200 GeV
τ decay
$\lambda_5^{im} = 10^{-4}$
$\lambda_5^{im} = 10^{-3}$
tanβ
m_{h_3} [GeV]
(b)
M_{h_2}=300 GeV

Reach of HL-LHC for Mass Reconstruction



- 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.