

# Light (Pseudo)Scalar at the ILC

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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

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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

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

Masses of the scalars and quartic couplings

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

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

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

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

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

## 2HDM X : Yukawa structure

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

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

After symmetry breaking,

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

$\xi_h^u$	$\xi_h^d$	$\xi_h^\ell$	$\xi_H^u$	$\xi_H^d$	$\xi_H^\ell$	$\xi_A^u$	$\xi_A^d$	$\xi_A^\ell$
$\frac{C_\alpha}{S_\beta}$	$\frac{C_\alpha}{S_\beta}$	$\frac{-S_\alpha}{C_\beta}$	$\frac{S_\alpha}{S_\beta}$	$\frac{S_\alpha}{S_\beta}$	$\frac{C_\alpha}{C_\beta}$	$\cot \beta$	$-\cot \beta$	$\tan \beta$

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

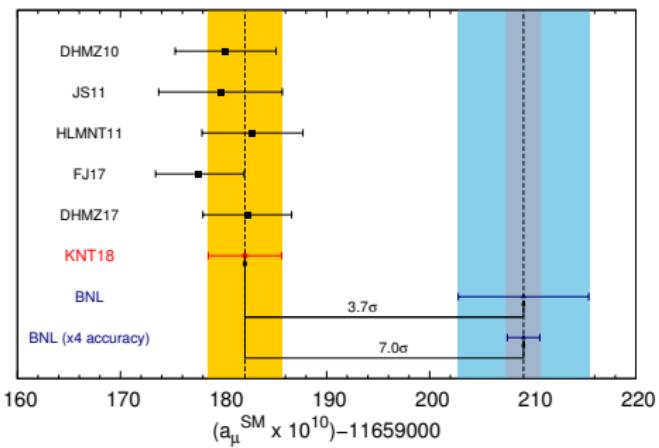
WS limit :  $t_\beta c_{\beta-\alpha} \simeq 2 \Rightarrow \xi_h^\tau \simeq -1$

## Constraints on 2HDMX Parameter space

- Muon  $g - 2$
- Lepton universality
- EWP<sup>D</sup>
- Higgs signal strength
- $B_s \rightarrow \mu^+ \mu^-$  or  $B_s \rightarrow X_s \gamma$

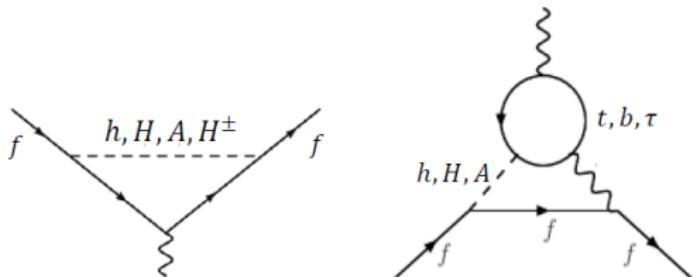
## 2HDM-X : Allowed parameter space

- $a_\mu^{\text{exp}} = (11659209.1 \pm 6.3) \times 10^{-10}$
- $a_\mu^{\text{th}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had,VP}} + a_\mu^{\text{had,LbL}}$
- $\{(11658471.9 \pm 0.007) + (15.36 \pm 0.1)\} \times 10^{-10}$
- $\{(684.68 \pm 2.42) + (9.8 \pm 2.6)\} \times 10^{-10}$
- $\Delta a_\mu = (27.06 \pm 7.26) \times 10^{-10}$  Ref: 1802.02995
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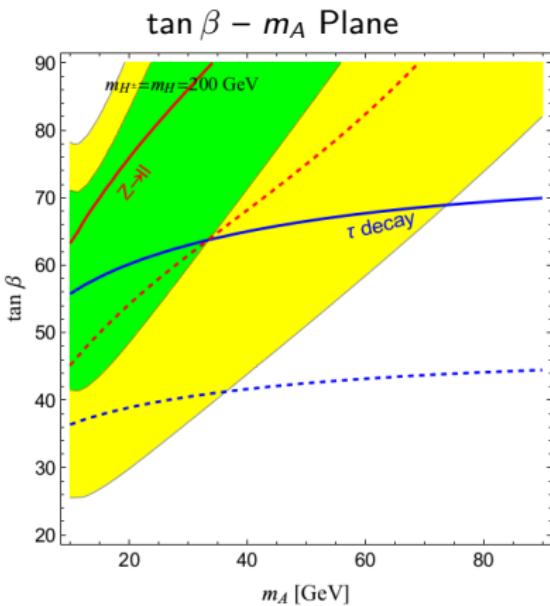
Muon  $g - 2$  in 2HDM

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- 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  $\tau$  loop and low  $m_A$  comes to rescue.

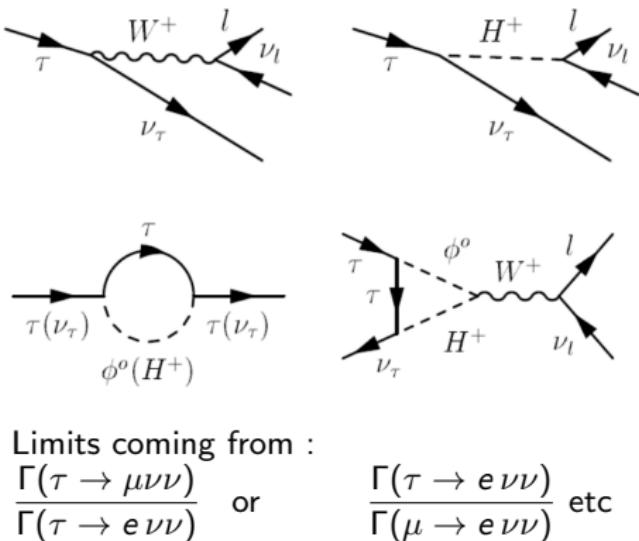
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E J Chun et al. JHEP 11 (2015) 099

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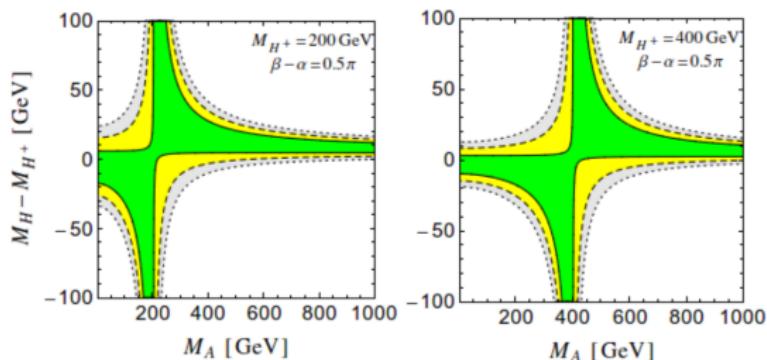


Limits coming from :

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

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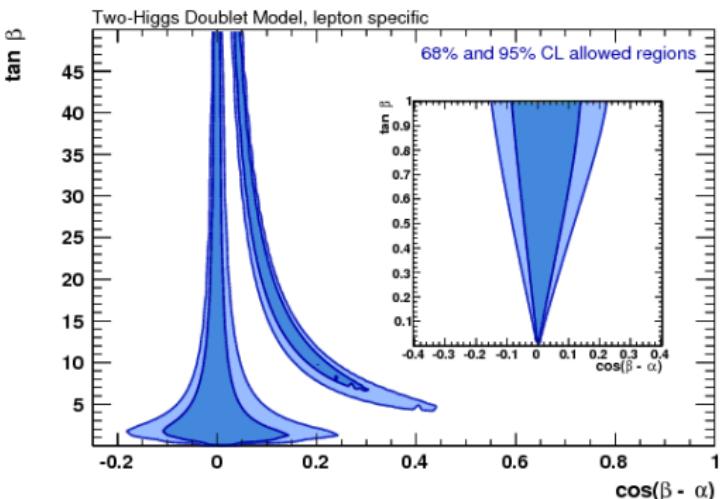
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Charged Higgs mass should be close to  $H$  or  $A$ .

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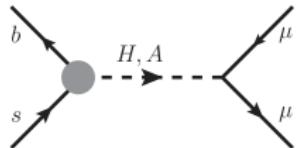
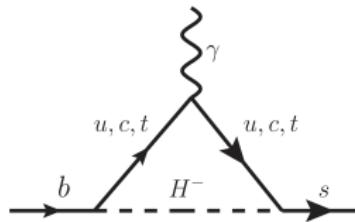
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GFitter : 1803.01853.

## 2HDM-X : Allowed parameter space

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

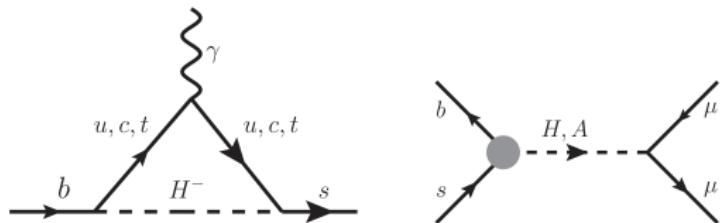
$$\frac{m_t}{t_\beta} P_L + m_b t_\beta P_R \quad (II, Y)$$

For type X :  $\sim 1$

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

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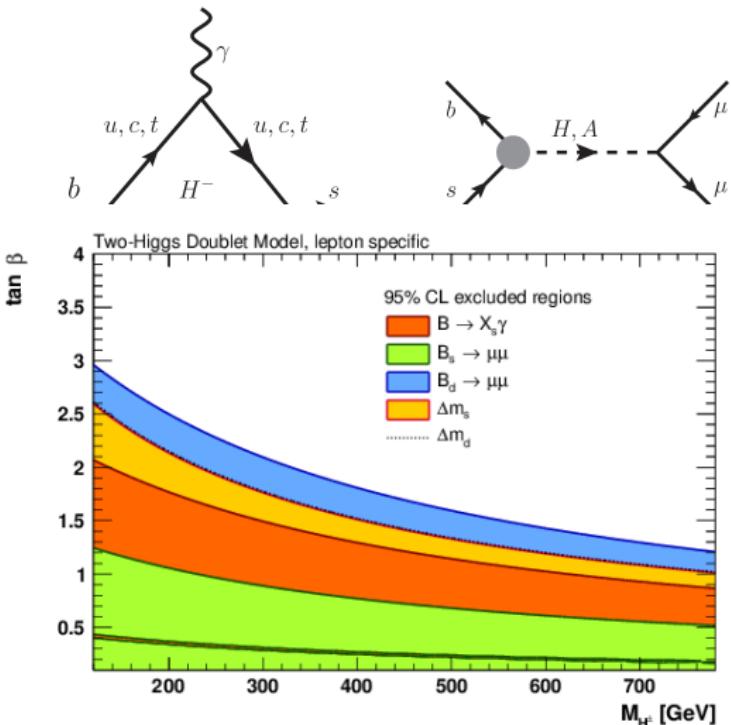
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- $b \rightarrow s \gamma$  :  $m_{H^\pm} > 580$  GeV. [BELLE, 1608.02344](#)
- $BR(B_s \rightarrow \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$  [LHCb, 1703.05747](#)
- Limit on type-II 2HDM :  $\tan \beta < 7$  for  $m_A < 70$  GeV

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GFitter : 1803.01853.

# 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 :

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

[Kanemura et.al. \(1111.6089\)](#), [E.J.Chun et.al. \(1507.08067\)](#)

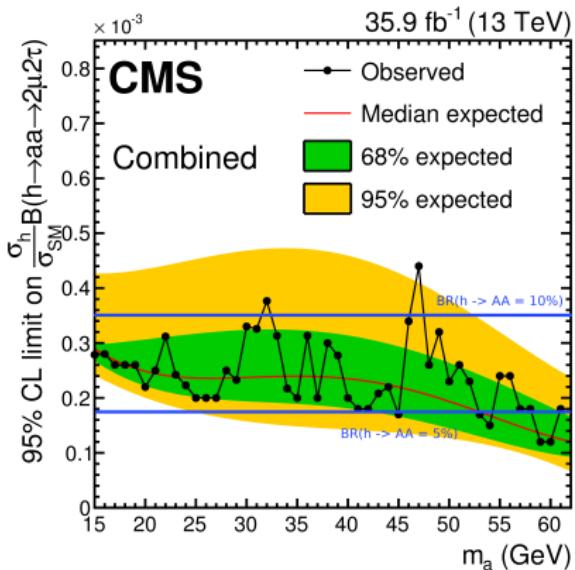
- However, it is not possible to reconstruct the masses of the scalars from tau only final states.
- To reconstruct the mass of the  $A$  :
  - $h \rightarrow AA \rightarrow 2\mu 2\tau$
  - $W^*(Z^*) \rightarrow H^\pm(H)A \rightarrow W^\pm A(ZA) A \rightarrow jj 2\mu 2\tau$

[TM et.al. \(PLB 774, 2017\)](#), [TM et.al. \(PRD 98, 2018\)](#)

# LHC phenomenology of light A

CMS Search for light A : 13 TeV,  $36 \text{ fb}^{-1}$

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  $\tan \beta$  scenario.

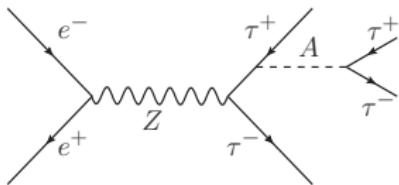
# Light $A$ of 2HDMX at ILC

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

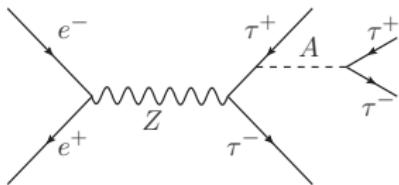
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- Possible search option :  $Z \rightarrow \tau\tau \rightarrow \tau\tau A \rightarrow 4\tau$ . So called Yukawa production.

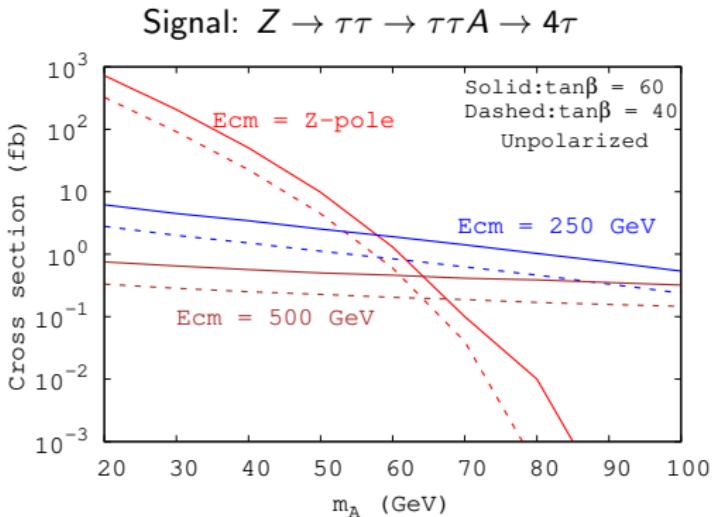


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- This is the equivalent to  $t\bar{t}H$  searches at LHC. Independent probe of Yukawa structure.
- At the ILC all the  $4\tau$  s can be reconstructed using collinear approximation.
- This enables to measure mass of the light particle.

# Searches for light A in 2HDMX at ILC250



- 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  $\simeq 6.6 \text{ fb}$ .  $2\tau 2j \simeq 100 \text{ fb}$ .

- 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  $z_i$ .

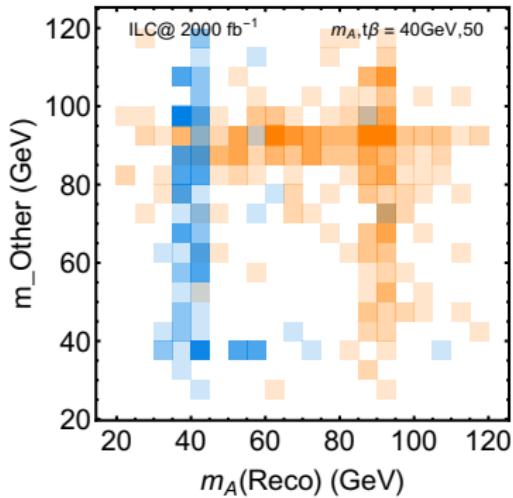
## Reconstruction of the pseudoscalar

- 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  $125 \text{ GeV}$ .
- 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  $m\_Other$ .

## Reconstruction of the pseudoscalar

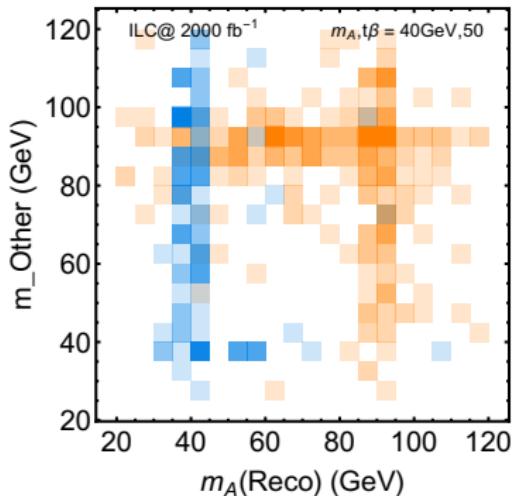
$m_A = 40 \text{ GeV}$  and  $\tan \beta = 50$

For different  $m_A$

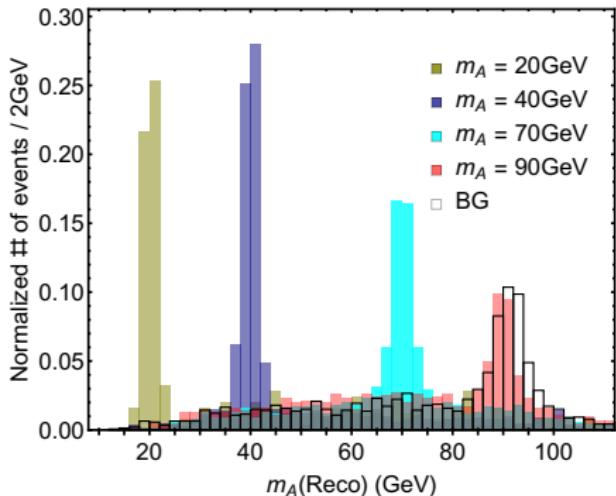


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# Searches for light A in 2HDMX at ILC250 : Result

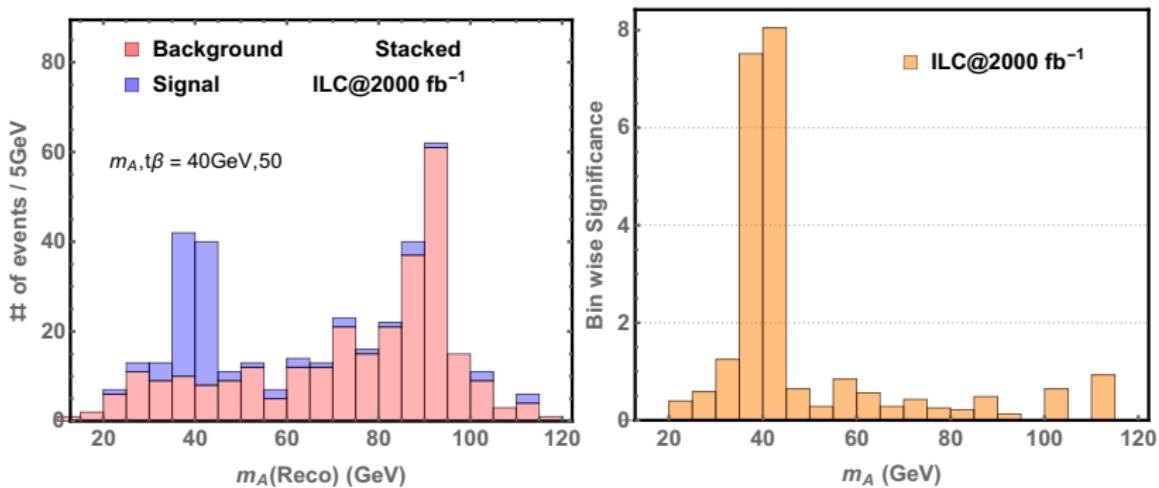
Cut-flow table for  $m_A = 40, \tan \beta = 50$  @ ILC250 with  $\mathcal{L} = 2 ab^{-1}$

Pre-selection cut : Energy > 20 GeV. $ \eta  < 2.3$				
$\mathcal{L} = 2000 fb^{-1}$	Signal	Background		Significance
		$4\tau$	$2\tau 2 j$	
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
$m_A \pm 10\text{GeV}$	66 [62.3%]	32 [14.9%]	10[10.2%]	8.5

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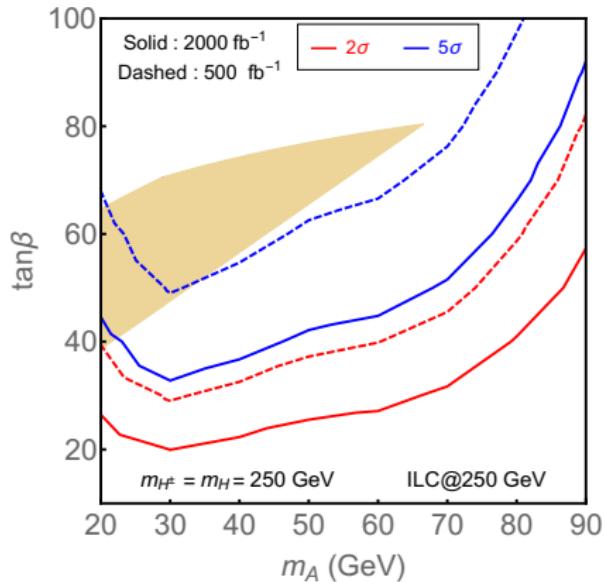
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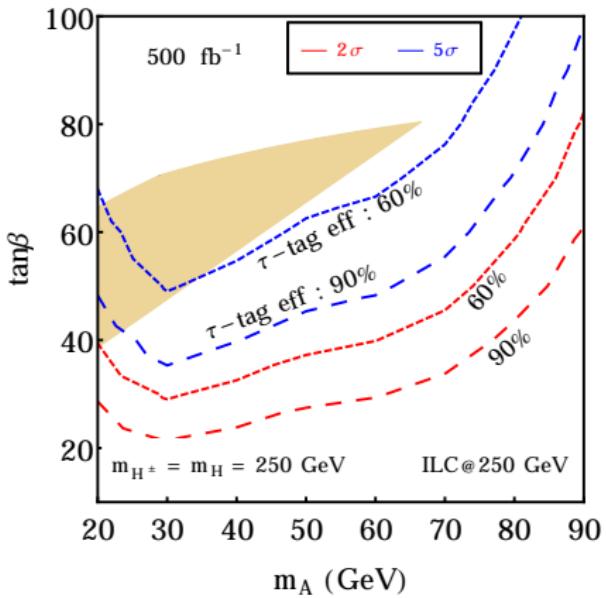
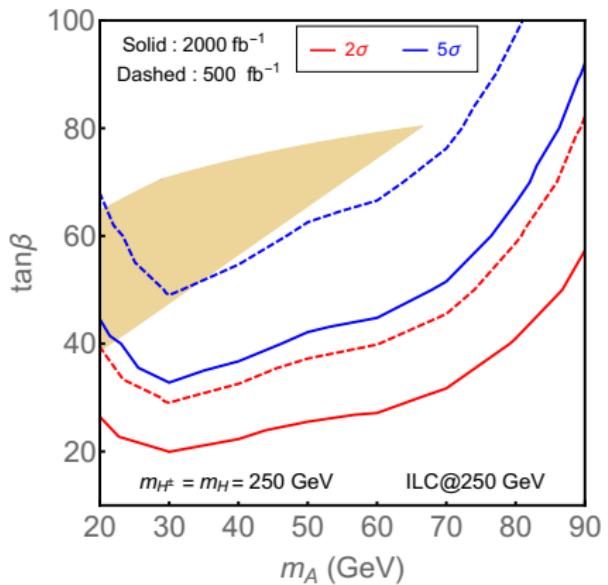
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# Conclusion

- Light  $A$  in 2HDMX can explain muon anomaly
- 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.
- It is possible to reconstruct the mass of the resonance using collinear approximation.
- $500 \text{ fb}^{-1}$  is enough to explore the relevant parameter space.

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Thank You

back up

- 1-Loop contribution :

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

$$f_{h,H}(r) = -\ln r - 7/6 + O(r),$$

$$f_A(r) = +\ln r + 11/6 + O(r),$$

$$f_{H^\pm}(r) = -1/6 + O(r),$$

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

- 2-Loop contribution

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

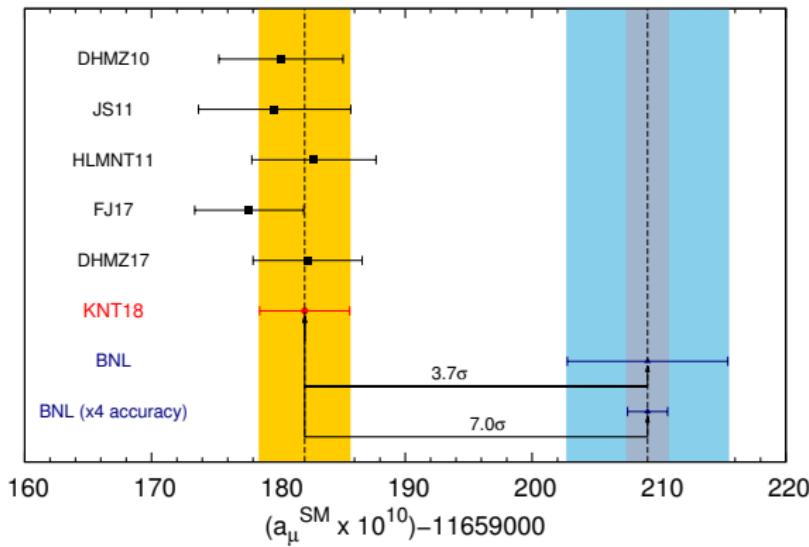
$$g_i(r) = \int_0^1 dx \frac{\mathcal{N}_i(x)}{x(1-x)-r} \ln \frac{x(1-x)}{r} \quad \mathcal{N}_{h,H}(x) = 2x(1-x) - 1 \text{ and } \mathcal{N}_A(x) = 1$$

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

	Type I	Type II	Lepton-specific	Flipped
$\xi_h^u$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$
$\xi_h^d$	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$
$\xi_h^\ell$	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$	$-\sin \alpha / \cos \beta$	$\cos \alpha / \sin \beta$
$\xi_H^u$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$
$\xi_H^d$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$
$\xi_H^\ell$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$	$\cos \alpha / \cos \beta$	$\sin \alpha / \sin \beta$
$\xi_A^u$	$\cot \beta$	$\cot \beta$	$\cot \beta$	$\cot \beta$
$\xi_A^d$	$-\cot \beta$	$\tan \beta$	$-\cot \beta$	$\tan \beta$
$\xi_A^\ell$	$-\cot \beta$	$\tan \beta$	$\tan \beta$	$-\cot \beta$

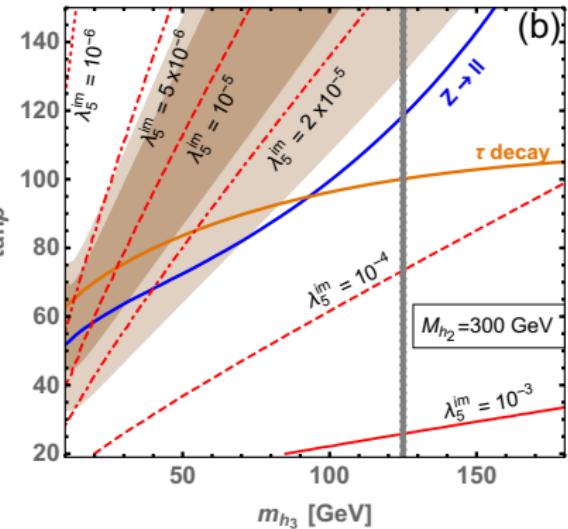
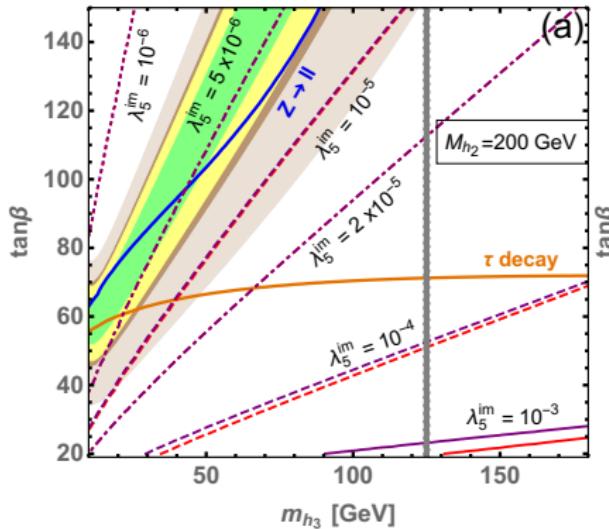
## Back-up : Present Status of Muon $g - 2$

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

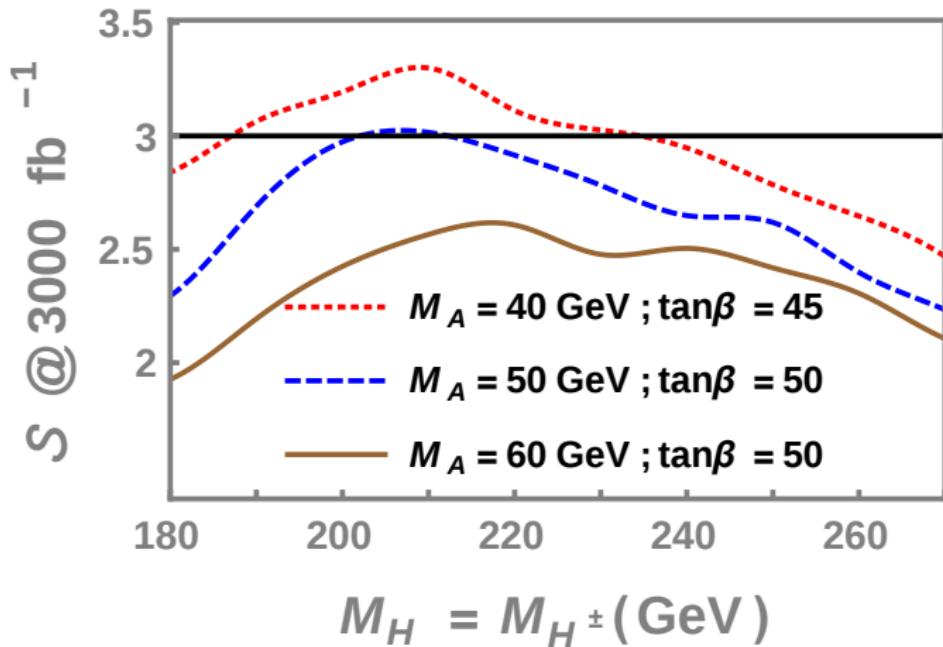


## Back-up

EDM



# 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.