Light (pseudo)scalars lurking undetected? Some suggestions on mass reconstruction

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- **Q2:** *If so, how well can the high-luminosity run reveal them?*
- *We consider a sample scenario*

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- *A common new physics option:*
  two Higs doublet models (2HDM)

- *Low-energy 2HDM can retain vacuum stability upto the Planck scale*

  N. Chakrabarty, U. K. Dey, BM (2014),
  N. Chakrabarty (2016), N. Chakrabarty, BM (2017)

2HDM...

$$\Phi_1 = (\phi_1^+, \phi_1^0), \quad \Phi_2 = (\phi_2^+, \phi_2^0)$$
$$\longrightarrow h, H, A, H^\pm$$

Suppression of tree-level flavour violation

$\Rightarrow$ *Z_2 symmetry hypotheses*

$\Rightarrow$ *Type 1 / Type 2 / Type X / Type Y......*

Type X: One doublet couples to all quarks, the other to leptons

$$\mathcal{L} = -y_u \bar{Q}_L u_R \tilde{\Phi}_2 + y_d \bar{Q}_L d_R \Phi_2 + y_\ell \bar{L}_L e_R \Phi_1 + h.c.$$

Suppressed quark coupling for $H, A, H^\pm$ close to the 'alignment limit': $(\beta - \alpha) = \pi/2$

$\tan\beta = v_2/v_1$, $\alpha = h - H$ *mixing angle*

For large tan β....

$\mathcal{L}_{\bar{u}uH} \sim \cot\beta$
$\mathcal{L}_{\bar{d}dH} \sim \cot\beta$
$\mathcal{L}_{udH^{\pm}} \sim \cot\beta$
$\mathcal{L}_{\bar{\ell}\ell H} \sim \tan\beta$
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$H, H^{\pm}, A$: suppressed interaction with the quark sector

Also, $\mathcal{L}_{VVH} \sim \cos(\beta - \alpha)$

Production suppressed at LHC:

A potential challenge for the high-luminosity run

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- *Bottomline: substantial positive contributions may serve to reduce the persistent discrepancy*
  A. Keshavarzi et al. (2018)

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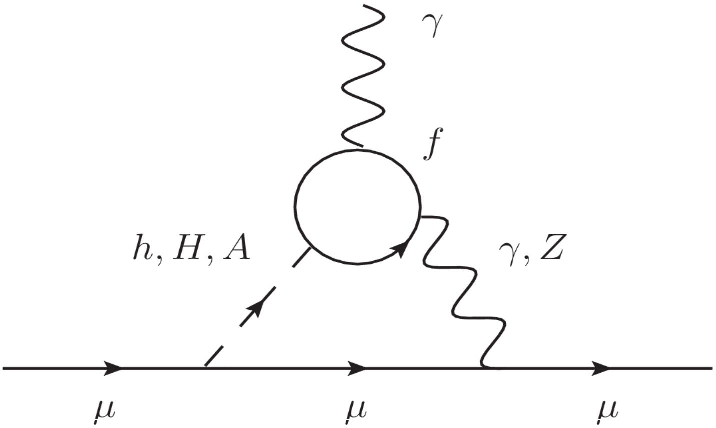
- *Negative contributions from* h, H
  Positive contributions from A
  D. Chang (2001)

The Bar-Zee diagrams....



Type-X 2HDM helps for $m_A \lesssim 60\,GeV, \tan\beta \simeq 40 - 50\,GeV$

EW precision data ($m_W, \sin\theta_W, Z\ell\bar{\ell}$ coupling at Z-peak)

$\Rightarrow m_A \simeq 40 - 60\,GeV$ *requires*
$|m_H - m_{H^\pm}| \lesssim 25\,GeV$

Vacuum stability:
$m_A \simeq 40 - 60\,GeV \Rightarrow m_{H^\pm} \lesssim 200\,GeV$

A. Broggio et al. (2014)

Signals at the LHC....

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- *Difficulty: precise mass reconstruction...*
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- *A solution: utilise* $A \longrightarrow \mu^+\mu^-$
  E. J. Chun, S. Dwivedi, T. Mondal, BM, PLB 774, 20 (2017)

Signals at the LHC....

In the region of interest,
$B(A \longrightarrow \tau^+\tau^-) \gtrsim 99\%$, $B(A \longrightarrow \mu^+\mu^-) \simeq 0.35\%$

Preferred channel :
$pp \longrightarrow hX, h \longrightarrow AA \longrightarrow (\mu^+\mu^-)(\tau^+\tau^-)$

Constraint on the Type-X 2HDM parameter space:

$\mu\mu\tau\tau$ *search,....* $\Rightarrow B(\longrightarrow AA) \leq 3-4\%$

Higgs coupling studies $\Rightarrow \cos(\beta-\alpha) \lesssim 0.1$ *for large* $\tan\beta$
(Excepting a narrow strip allowing $\cos(\beta-\alpha) \simeq 0.2-0.3$*.)*

CMS, JHEP11(2018)018 (Nov, 2018),
ATLAS-CONF-2019-005,
D. Taylor, Talk at Moriond, 2019

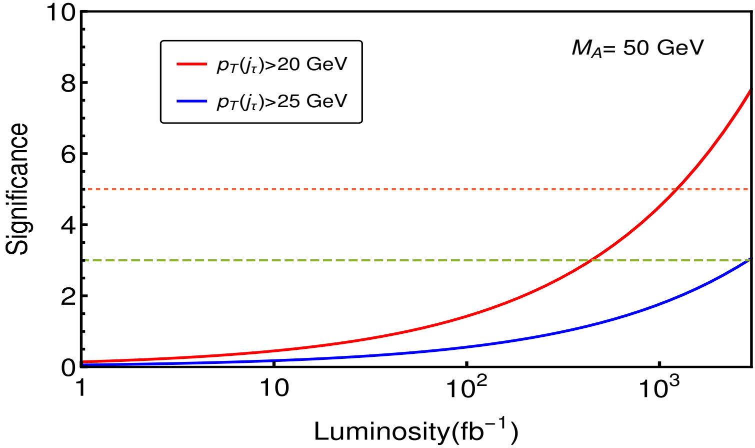
Signal to look for:
a $\mu^+\mu^-$ peak + two jets including one tagged τ

Jet-$p_T \geq 20 - 25 GeV$ leads to the jj-and $\mu^+\mu^-$-peaks close together (within $\lesssim 15$ GeV)

Major SM backgrounds:

- $\mu^+\mu^- + jets$
- $VV \rightarrow \mu^+\mu^- + jets$
- $t\bar{t}$

The key feature in background reduction:
Closeness of the $m_{inv}(\mu\mu)$, $m_{inv}(jj)$ peaks



$m_A = 50 GeV, \; B(h \longrightarrow AA) = 3\%$

$Significance = \sqrt{2[(S+B)ln(1+S/B) - S]}$

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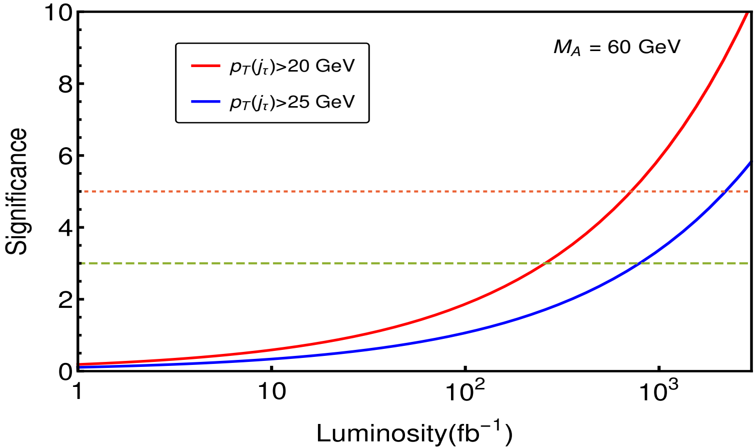

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Reconstruction of $H, H^{\pm}$....

E. J. Chun, S. Dwivedi, T. Mondal, BM, S. K Rai, PRD 98, 075008 (2018)

- *The region of interest:* $m_H, m_{H^\pm} \approx 200\,GeV$, *with* $|m_H - m_{H^\pm}| \lesssim 25\,GeV$.

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- *The region of interest:* $m_H, m_{H^\pm} \approx 200\, GeV$, *with* $|m_H - m_{H^\pm}| \lesssim 25\, GeV$.
- $pp \longrightarrow H^{\pm}A, HA$

  $H^{\pm} \longrightarrow WA, H \longrightarrow ZA$

  $BR \approx 50\,\%$ *for decays*

  A-reconstruction information via the $\mu^{\pm}$ *mode*
  $\Rightarrow$ *The heavier scalars reconstructed*

- $\mu\mu + jj$ *with one tagged* τ*-jet*

  Various cuts reduce combinatorial backgrounds:
  - $m_{\mu\mu} \geq 90$ *GeV: to utilise the boost*
  - *Geometry of chosen events* $\Rightarrow \Delta\phi_{(\mu\mu),j_\tau} \geq 1.6$

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- $3.0 - 3.5\sigma$ *with* $3000 fb^{-1}$

  Excess in a bin covering a broad peak ($\simeq 25 - 30$ *GeV*)

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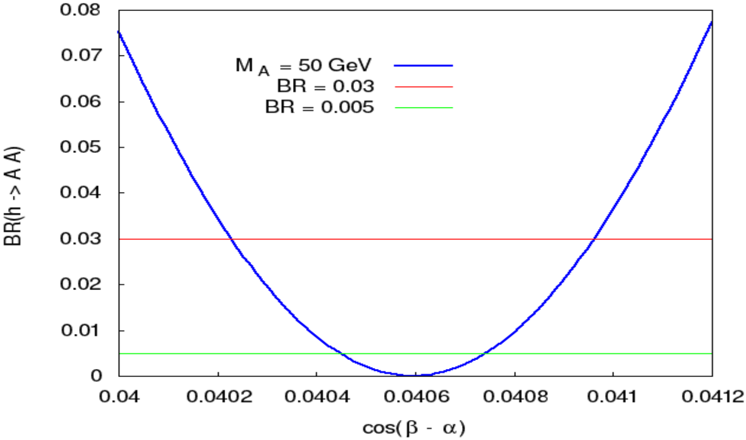
- *The light pseudoscalar mass can be reconstructed precisely using the* $\mu^+\mu^-$ *decay modes, to 4-6* σ *significance, for a few hundred to 3000* fb^{-1}.
- *The H and the* $H^\pm$ *are also reconstructible, and their closeness in mass established, to about 25-30 GeV.*



Branching ratio against $\cos(\beta - \alpha)$

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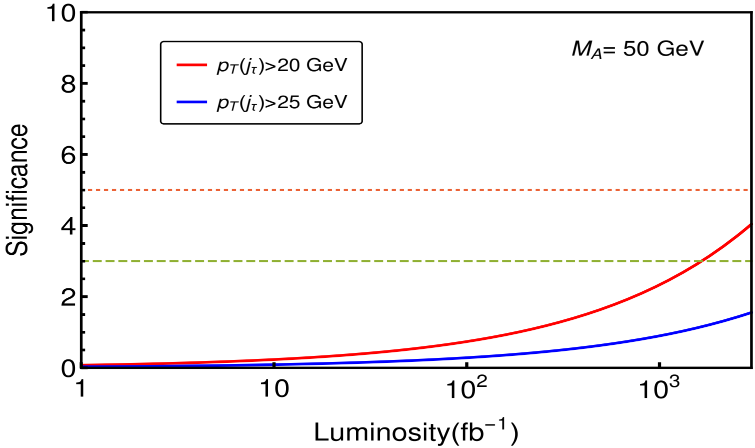

$$m_A = 50 GeV, \; B(h \longrightarrow AA) = 1.5\%$$