The THDMa and possible e^+e^- signatures

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based on arXiv: 2105.06231/ 2106.02962

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Higgs 2021 19. October '21

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THDMa [arXiv:2105.06231, arXiv:2106.02962]

setup: 2 Higgs Doublet Model (Type II), + pseudoscalar a (mixing with A), + dark matter candidate χ (fermionic)

- DM couples to additional field in gauge-eigenstates
- ⇒ promoted by LHC Dark Matter Working group in Phys.Dark Univ. 27 (2020) 100351

original literature: S. Ipek ea, [Phys. Rev. D90 (2014), no. 5 055021]; J. M. No, [Phys. Rev. D93 (2016), no. 3 031701]; D. Goncalves ea, [Phys. Rev. D95 (2017)]; M. Bauer ea, [JHEP 05 (2017) 138]; P. Tunney ea, [Phys. Rev. D96 (2017)]

⇒ highly scrutinized by LHC experiments

Interesting at e^+e^- colliders ??

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Image: A matching of the second se

$$\begin{split} \mathbf{V}_{\mathsf{THDM}} &= \mu_1 H_1^{\dagger} H_1 + \mu_2 H_2^{\dagger} H_2 + \lambda_1 (H_1^{\dagger} H_1)^2 + \lambda_2 (H_2^{\dagger} H_2)^2 \\ &+ \lambda_3 (H_1^{\dagger} H_1) (H_2^{\dagger} H_2) + \lambda_4 (H_1^{\dagger} H_2) (H_2^{\dagger} H_1) + \left[\mu_3 H_1^{\dagger} H_2 + \lambda_5 (H_1^{\dagger} H_2)^2 + h.c. \right] \\ \mathbf{V} &= \frac{1}{2} m_P^2 P^2 + \lambda_{P_1} H_1^{\dagger} H_1 P^2 + \lambda_{P_2} H_2^{\dagger} H_2 P^2 + (\imath b_P H_1^{\dagger} H_2 P + h.c.) \end{split}$$

$$V_{\chi} = \imath y_{\chi} P \bar{\chi} \gamma_5 \chi$$

THDMa scalar sector particle content: $h, H, H^{\pm}, a, A, \chi$

parameters:

 $v, m_h, m_H, m_a, m_A, m_{H^{\pm}}, m_{\chi}; \cos(\beta - \alpha), \tan\beta, \sin\theta; y_{\chi}, \lambda_3, \lambda_{P_1}, \lambda_{P_2}$

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THDMa: Implemented constraints

[see also Abe ea, JHEP, 01:114, 2020; Arcadi ea, JHEP, 06:098, 2020]

Theory

- boundedness of potential from below
- perturbativity of couplings
- perturbative unitarity

Experiment

- $v, m_{h/H}$: input
- electroweak precision through S, T, U
- $B \rightarrow X_s \gamma, \ B \rightarrow \mu^+ \mu^-, \ \Delta M_s$
- **Г**₁₂₅
- direct searches and 125 GeV signal strength through HiggsBounds/ HiggsSignals
- upper limit on relic density, direct detection [Phys. Rev., D90(5):055021]
- (pseudo) recast from current LHC searches

also using: own codes, Spheno, Sarah, MadDM, Madgraph

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Parameter ranges

WG recommendation:

$$m_H = m_A = m_{H^{\pm}}, m_{\chi} = 10 \,\text{GeV},$$

 $\cos(\beta - \alpha) = 0, \tan \beta = 1, \sin \theta = 0.35,$
 $y_{\chi} = 1, \lambda_3 = \lambda_{P_1} = \lambda_{P_2} = 3$

\Rightarrow effectively 2-d scan

• here; let everything float

Scan ranges:

$$\begin{split} &\sin \theta \, \in \, [-1; 0.8] \,, \, \cos \left(\beta - \alpha \right) \, \in \, [-0.08; 0.1] \,, \, \tan \beta \, \in \, [0.52; 9] \,, \\ & m_H \, \in \, [500; 1000] \, \text{GeV}, \, \, m_A \, \in \, [600; 1000] \, \text{GeV}, \\ & m_{H^{\pm}} \, \in \, [800; 1000] \, \text{GeV}, \, \, m_a \, \in \, [5 \, \text{GeV}; \, m_A] \,, \, m_\chi \, \in \, [0 \, \text{GeV}, \, m_a/2] \\ & y_\chi \, \in \, [-\pi; \pi] \,, \, \lambda_{P_1} \, \in \, [0; 10] \,, \, \lambda_{P_2} \, \in \, [0; 4 \, \pi] \,, \, \lambda_3 \, \in \, [-2; 4 \, \pi] \,. \end{split}$$

Example: B- physics constraints

Constraints from
$$B \rightarrow X_s \gamma, B_s \rightarrow \mu^+ \mu^-, \Delta M_s$$

- $B \rightarrow X_s \gamma$: use fit from updated calculation of Misiak ea, [JHEP 2006 (2020) 175, Eur.Phys.J. C77 (2017) no.3, 201], $\Rightarrow \tan \beta_{\min} (m_{H^{\pm}})$
- $B_s \rightarrow \mu^+ \mu^-$, ΔM_s : via SPheno, compare to LHC combination [ATLAS-CONF-2020-049], HFLAV value [arXiv:1909.12524]



$$\begin{split} R_{\gamma}^{\text{exp}} &\equiv \frac{\mathcal{B}_{(s+d)\gamma}}{\mathcal{B}_{c\ell\nu}} = (3.22 \pm 0.15) \times 10^{3}, \\ \Delta M_{s} \, (\text{ps}^{-1}) &= 17.757 \pm 0.020 \pm 0.007, \\ \left(\mathcal{B}_{s} \to \mu^{+}\mu^{-}\right)^{\text{comb}} &= \left[2.69^{+0.37}_{-0.35}\right] \times 10^{-9} \end{split}$$

Image: A math a math

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Oblique parameters via SPheno, compare to GFitter [Eur. Phys. J., C78(8):675]



Direct searches and signal strength

Via HiggsBounds/ HiggsSignals



Relevant BSM searches:

LHC searches

Model widely promoted by LHC Dark matter working group

- \Rightarrow searches considered:
 - $h + \not{\!\! E}_{\perp}$: ATLAS, Run II dataset [ATLAS-CONF-2021-006]
 - 2 $\ell\ell + \not{\!\!\!E}_{\perp}$: CMS, Run II dataset [Eur. Phys. J. C 81 (2021) 13]
 - **(3)** $W^+\bar{t}/W^-t + \not\models_{\perp}$: ATLAS, Run II dataset [arXiv:2011.09308]
 - $H^+ \bar{t}b, H^+ \rightarrow t \bar{b}$: ATLAS, Run II dataset [JHEP, 06:151; arXiv:2102.10076]
 - **◎** $t \bar{t}, b\bar{b} + \not{\!\!\!E}_{\perp}$: ATLAS, Run II dataset [Eur.Phys.J. C78 (2018) no.1, 18; JHEP 2104 (2021) 174; JHEP 2105 (2021) 093; JHEP, 04:165, 2021]
 - 6 $A \rightarrow Z H$: ATLAS, Run II dataset [Eur. Phys. J., C81(5):396, 2021]
 - (4), (5) not relevant due to tan β \gtrsim 1, m_b small
 - (6) also not relevant (large masses $m_A, \ m_H \gtrsim \ m_a)$

 - **but:** all parameter float \Rightarrow no 2-dim clear distinction

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Example: Dark matter constraints



color coding: m_{χ}

dominant channels: $\chi \bar{\chi} \to t \bar{t}, b \bar{b}$, depending on m_a main result: $|m_a - 2 m_{\chi}| \le 300 \,\text{GeV}$

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a priori: as standard THDM

- new feature: new scalar *a*; mixing: both *a*/*A* can decay invisibly
- interesting channels: ha, hA, Ha, HA
- $\bullet\,$ mass ranges: between 200 ${\rm GeV}$ and $2\,{\rm TeV}$
- most promising: HA, Ha at 3 TeV
- \Rightarrow cross sections up to 1 fb

BRs and rates, HA, 3 TeV



BR for HA final states

...convoluted with production cross sections

[color coding $t \,\overline{t} \, t \,\overline{t}$ final states]

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Can the $\not\models$ channel ever be dominant ?



bottom line: can find regions where $t\bar{t} + \not\in$ dominates

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"Best" point

$$\begin{split} m_{H} &= \, 643 \, {\rm GeV}, \qquad m_{A} \,= \, 907 \, {\rm GeV}, \qquad m_{a} \,= \, 653 \, {\rm GeV}, \\ \sin \theta \,= \, -0.626, \quad \cos \left(\beta - \alpha\right) \,= \, 0.0027, \quad \tan \beta \,= \, 3.55, \\ \Gamma_{H} \,= \, 2.41 \, {\rm GeV}, \qquad \Gamma_{A} \,= \, 52.5 \, {\rm GeV}, \qquad \Gamma_{a} \,= \, 26.5 {\rm GeV} \end{split}$$

 $\mathsf{BR}(H \to t\,\overline{t}) \sim 0.94, \, \mathsf{BR}(A \to \chi\overline{\chi}) \sim 0.63, \, \mathsf{BR}(a \to \chi\overline{\chi}) \sim 0.95$

 $\sigma_{HA} = 0.51 \,\mathrm{fb}, \, \sigma_{Ha} = 0.39 \,\mathrm{fb} \implies \sigma_{t\bar{t}+\not\!\!\!E} \sim 0.66 \,\mathrm{fb}$

$$[m_{\chi} = 277 \, \text{GeV}, \, y_{\chi} = -1.73]$$

$$[m_{H^{\pm}} = 814\,{\rm GeV},\, \Gamma_{H^{\pm}} = 12.1\,{\rm GeV};\,\,\lambda_3 = 8.63,\,\lambda_{P_1} = 0.18,\,\lambda_{P_2} = 2.98]$$

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THDMa: Summary

First scan of THDMa that combines all bounds in a consistent way, letting all unknown parameters float

- if B-physics as strict bound: all heavy scalars have masses $\gtrsim\,500\,{\rm GeV}$! $_{\rm [might be different in fit]}$
- DM set bound on $|m_a-2\,m_\chi|$
- for e⁺e[−]: new signatures X + ∉ [new wrt THDM]
- presented here: *HA*/*a* production at 3 TeV
- \Rightarrow regions in parameter space where $t \, \overline{t} + \not E$ dominant
 - a lot to be done ...: simulation including background,