

The THDMa and possible e^+e^- signatures

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based on arXiv: 2105.06231/ 2106.02962

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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 ??

THDMa: Lagrangian/ parameters

$$V_{\text{THDM}} = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 \\ + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left[\mu_3 H_1^\dagger H_2 + \lambda_5 (H_1^\dagger H_2)^2 + h.c. \right]$$

$$V = \frac{1}{2} m_P^2 P^2 + \lambda_{P_1} H_1^\dagger H_1 P^2 + \lambda_{P_2} H_2^\dagger H_2 P^2 + (i b_P H_1^\dagger H_2 P + h.c.)$$

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

THDMa scalar sector particle content: h, H, H^\pm, a, A, χ

parameters:

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

THDMa: Implemented constraints

[see also Abe et al., JHEP, 01:114, 2020; Arcadi et al., 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
- $B \rightarrow X_s \gamma$, $B \rightarrow \mu^+ \mu^-$, ΔM_s
- Γ_{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

WG recommendation:

$$\begin{aligned} m_H = m_A = m_{H^\pm}, m_\chi &= 10 \text{ GeV}, \\ \cos(\beta - \alpha) &= 0, \tan \beta = 1, \sin \theta = 0.35, \\ y_\chi &= 1, \lambda_3 = \lambda_{P_1} = \lambda_{P_2} = 3 \end{aligned}$$

⇒ **effectively 2-d scan**

- here; let everything float

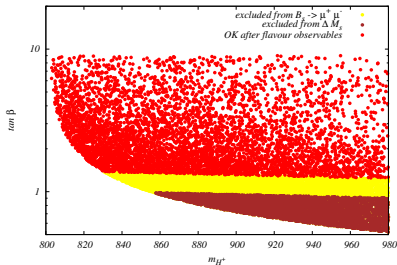
Scan ranges:

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

B- physics constraints

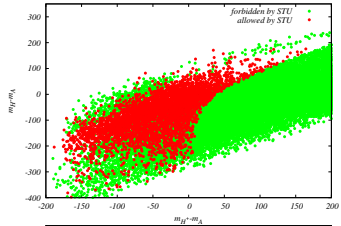
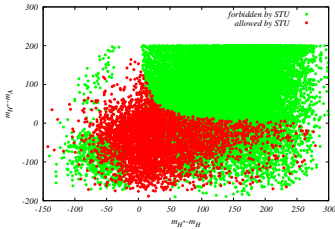
Constraints from $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, ΔM_s

- $B \rightarrow X_s \gamma$: 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]

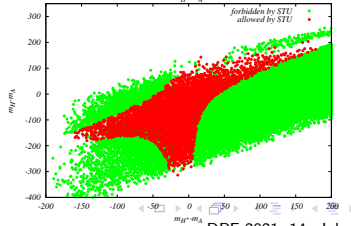


$$R_\gamma^{\text{exp}} \equiv \frac{\mathcal{B}(s+d)\gamma}{\mathcal{B}_{\text{clv}}} = (3.22 \pm 0.15) \times 10^3,$$
$$\Delta M_s (\text{ps}^{-1}) = 17.757 \pm 0.020 \pm 0.007,$$
$$(B_s \rightarrow \mu^+ \mu^-)^{\text{comb}} = [2.69_{-0.35}^{+0.37}] \times 10^{-9}$$

Constraints on mass differences
 $m_{H^\pm} - m_H, m_{H^\pm} - m_A, m_A - m_H$

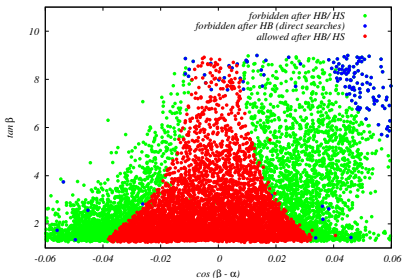


compare to THDM \Rightarrow



Direct searches and signal strength

Via HiggsBounds/ HiggsSignals



$\cos(\beta - \alpha) > 0.04$:

$h_{125} \rightarrow ZZ$

[CMS Run I, Phys. Rev. D

89 (2014) 092007]

Relevant BSM searches:

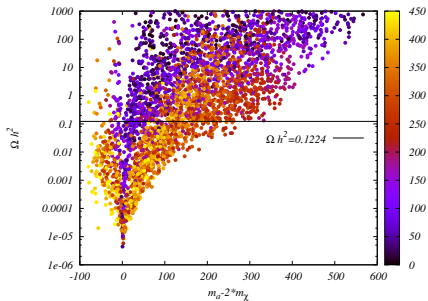
$H/A \rightarrow \tau\tau$ [ATLAS Run II, Phys.Rev.Lett. 125 (2020) no.5, 051801],

$H \rightarrow h_{125}h_{125}$ [ATLAS 2018 data, JHEP 1901 (2019) 030],

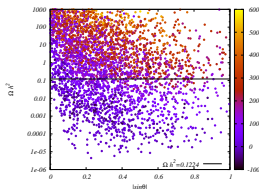
$A \rightarrow H/h_{125}Z$ [ATLAS/ CMS 2018 data, Phys.Lett. B783 (2018) 392-414, Eur. Phys. J. C 79 (2019)

Dark matter constraints

using MadDM



color coding: m_χ



color coding: $m_a - 2m_\chi$

dominant channels: $\chi \bar{\chi} \rightarrow t \bar{t}, b \bar{b}$, depending on m_a

main result: $|m_a - 2m_\chi| \leq 300 \text{ GeV}$

Model widely promoted by LHC Dark matter working group

⇒ searches considered:

- 1 $h + \cancel{E}_\perp$: ATLAS, Run II dataset [ATLAS-CONF-2021-006]
- 2 $ll + \cancel{E}_\perp$: CMS, Run II dataset [Eur. Phys. J. C 81 (2021) 13]
- 3 $W^+\bar{t}/W^-t + \cancel{E}_\perp$: ATLAS, Run II dataset [arXiv:2011.09308]
- 4 $H^+\bar{t}b, H^+ \rightarrow t\bar{b}$: ATLAS, Run II dataset [JHEP, 06:151; arXiv:2102.10076]
- 5 $t\bar{t}, b\bar{b} + \cancel{E}_\perp$: 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 $A \rightarrow ZH$: ATLAS, Run II dataset [Eur. Phys. J., C81(5):396, 2021]

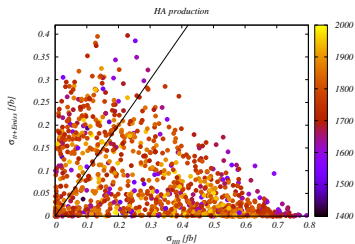
- (4), (5) not relevant due to $\tan\beta \gtrsim 1$, m_b small
- (6) also not relevant (large masses $m_A, m_H \gtrsim m_a$)
- others: cut out some part, dominantly via $h + \cancel{E}_\perp$
- **but:** all parameter float ⇒ no 2-dim clear distinction

Signatures at e^+e^- colliders

a priori: as standard THDM

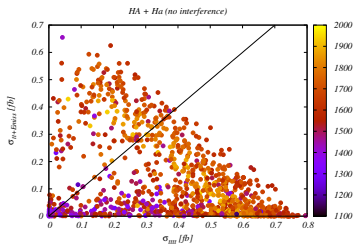
- new feature: **new scalar a ; mixing: both a/A can decay invisibly**
 - interesting channels: ha, hA, Ha, HA
 - mass ranges: between 200GeV and 2 TeV
 - most promising: **HA, Ha at 3 TeV**
- ⇒ **cross sections up to 1 fb**
- ⇒ **dominant final states: $t\bar{t}t\bar{t}; t\bar{t} + \cancel{E}$**

Can the \cancel{E} channel ever be dominant ?



$t\bar{t}t\bar{t}$ and $t\bar{t} + \cancel{E}$ final states

[color coding $m_A + m_H$]



...including Ha channel

[color coding $0.5 \times (m_a + m_A) + m_H$]

bottom line: **can find regions where $t\bar{t} + \cancel{E}$ dominates**

Summary and outlook

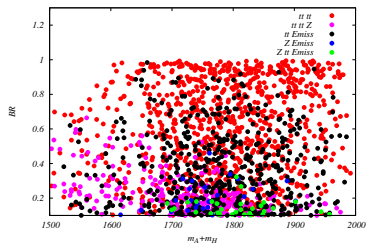
First scan of THDMa that combines all bounds in a consistent way, letting all unknown parameters float

- if B-physics as strict bound:
all heavy scalars have masses $\gtrsim 500$ GeV ! [might be different in fit]
 - DM set bound on $|m_a - 2 m_\chi|$
 - **for e^+e^- : new signatures $X + \cancel{E}$** [new wrt THDM]
 - presented here: **HA/a production at 3 TeV**
- \Rightarrow **regions in parameter space where $t\bar{t} + \cancel{E}$ dominant**
- a lot to be done...: ha at small center of mass energies, simulation including background,

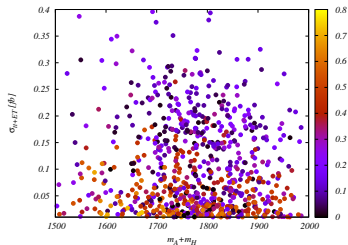
Thanks for listening

Appendix

BRs and rates, HA , 3 TeV



BR for HA final states



...convoluted with production
cross sections

[color coding $t\bar{t}\tau\bar{\tau}$ final states]

"Best" point

$$\begin{aligned} m_H &= 643 \text{ GeV}, & m_A &= 907 \text{ GeV}, & m_a &= 653 \text{ GeV}, \\ \sin \theta &= -0.626, & \cos(\beta - \alpha) &= 0.0027, & \tan \beta &= 3.55, \\ \Gamma_H &= 2.41 \text{ GeV}, & \Gamma_A &= 52.5 \text{ GeV}, & \Gamma_a &= 26.5 \text{ GeV} \end{aligned}$$

$$\text{BR}(H \rightarrow t\bar{t}) \sim 0.94, \quad \text{BR}(A \rightarrow \chi\bar{\chi}) \sim 0.63, \quad \text{BR}(a \rightarrow \chi\bar{\chi}) \sim 0.95$$

$$\sigma_{HA} = 0.51 \text{ fb}, \quad \sigma_{Ha} = 0.39 \text{ fb} \implies \sigma_{t\bar{t}+\cancel{E}} \sim 0.66 \text{ fb}$$

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

$$[m_{H^\pm} = 814 \text{ GeV}, \Gamma_{H^\pm} = 12.1 \text{ GeV}; \lambda_3 = 8.63, \lambda_{p_1} = 0.18, \lambda_{p_2} = 2.98]$$