The THDMa and possible e^+e^- signatures

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based on arXiv: 2105.06231/ Symmetry 13 (2021) 12, 2341

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After Higgs discovery: Open questions

Higgs discovery in 2012 $\Rightarrow$ last building block discovered

? Any remaining questions ?

- Why is the SM the way it is ??
  $\Rightarrow$ search for **underlying principles/ symmetries**
- find **explanations for observations not described by the SM**
  $\Rightarrow$ e.g. dark matter, flavour structure, ...
- ad hoc approach: Test **which other models still comply with experimental and theoretical precision**

for all: **Search for Physics beyond the SM (BSM)**

$\Longrightarrow$ **main test ground for this: particle colliders** $\Longleftarrow$

THDMa [arXiv:2105.06231, Symmetry 13 (2021) 12, 2341]

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**

$\Rightarrow$ 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)]

$\Rightarrow$ **highly scrutinized by LHC experiments**

Interesting at e^+e^- colliders ??

THDMa: Lagrangian/ parameters

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

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

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

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

parameters:

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

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 $S,\ T,\ U$
- $B \rightarrow X_s \gamma,\ B \rightarrow \mu^+\mu^-,\ \Delta M_s$
- 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

Parameter ranges

WG recommendation:

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

$\Rightarrow$ **effectively 2-d scan**

- here; let everything float

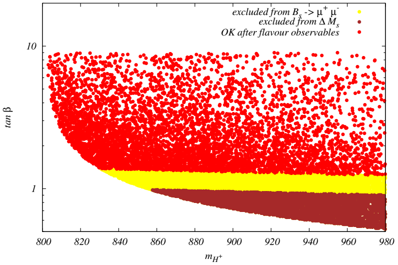
Scan ranges:

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

Example: B- physics constraints

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

- $B \to X_s \gamma$: use fit from updated calculation of Misiak ea, [JHEP 2006 (2020) 175, Eur.Phys.J. C77 (2017) no.3, 201], $\Rightarrow \tan \beta_{\mathbf{min}} \left(m_{H^\pm}\right)$
- $B_s \to \mu^+ \mu^-$, ΔM_s: via SPheno, compare to LHC combination [ATLAS-CONF-2020-049], HFLAV value [Eur.Phys.J.C 81 (2021) 3, 226]



$$R_\gamma^{\mathrm{exp}} \equiv \frac{\mathcal{B}_{(s+d)\gamma}}{\mathcal{B}_{c\ell\nu}} = (3.22 \pm 0.15) \times 10^3,$$

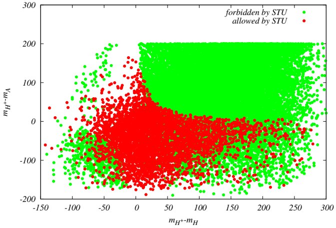
$$\Delta M_s \; (\mathrm{ps}^{-1}) = 17.757 \pm 0.020 \pm 0.007,$$

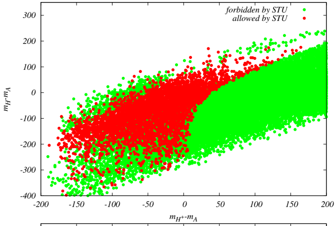
$$\left(B_s \to \mu^+ \mu^-\right)^{\mathrm{comb}} = \left[2.69^{+0.37}_{-0.35}\right] \times 10^{-9}$$

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

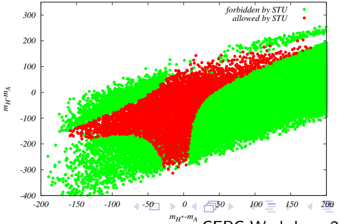
Constraints on mass differences

$$m_{H^\pm} - m_H,\ m_{H^\pm} - m_A,\ m_A - m_H$$



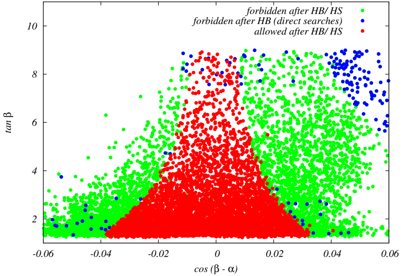


compare to THDM ⇒



Direct searches and signal strength

Via HiggsBounds/ HiggsSignals



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

$h_{125} \to Z\,Z$

[CMS Run I, Phys. Rev. D 89 (2014) 092007]

Relevant BSM searches:

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

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

$A \to H/h_{125}Z$ [ATLAS 2018/ full Run 2 data, Phys.Lett. B783 (2018) 392-414, ATLAS-CONF-2020-043]

LHC searches

Model widely promoted by LHC Dark matter working group

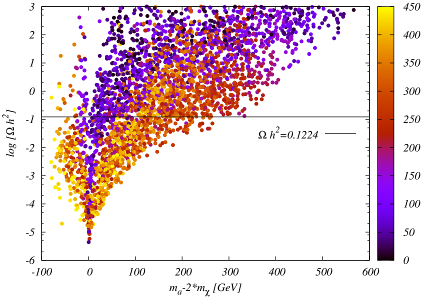
$\Rightarrow$ searches considered:

1. $h + \not{E}_\perp$: ATLAS, Run II dataset [JHEP 11 (2021) 209]
2. $\ell\ell + \not{E}_\perp$: CMS, Run II dataset [Eur. Phys. J. C 81 (2021) 13]
3. $W^+\bar{t}/W^-t + \not{E}_\perp$: ATLAS, Run II dataset [Eur.Phys.J.C 81 (2021) 860]
4. $H^+\bar{t}b$, $H^+ \rightarrow t\,\bar{b}$: ATLAS, Run II dataset [JHEP, 06:151; JHEP 06 (2021) 145]
5. $t\,\bar{t}$, $b\bar{b} + \not{E}_\perp$: 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]

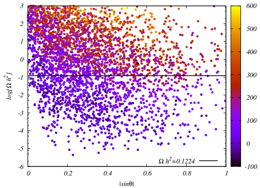
- (4), (5) not relevant due to $\tan\beta \gtrsim 1$, m_b small
- (6) also not relevant (large masses m_A, $m_H \gtrsim m_a$)
- others: cut out some part, dominantly via $h + \not{E}_\perp$
- **but:** all parameter float $\Rightarrow$ no 2-dim clear distinction

Example: Dark matter constraints

using MadDM



color coding: m_χ



color coding: $m_a - 2\, m_\chi$

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

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

Signatures at e^+e^- colliders

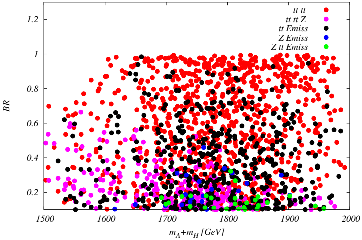
a priori: as standard THDM

- new feature: **new scalar a; mixing: both a/A can decay invisibly**
- interesting channels: ha, hA, Ha, HA
- mass ranges: between $200\,\mathrm{GeV}$ and $2\,\mathrm{TeV}$
- most promising: HA, Ha **at 3 TeV**

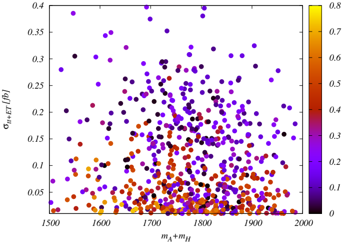
$\Rightarrow$ **cross sections up to 1 fb**

$\Rightarrow$ **dominant final states:** $t\,\bar{t}\,t\,\bar{t}$; $t\bar{t} + \not{E}$

BRs and rates, *HA*, 3 TeV



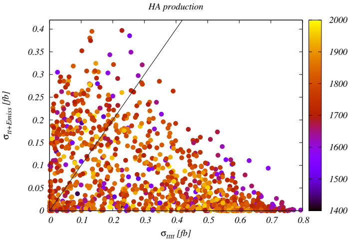
BR for *HA* final states

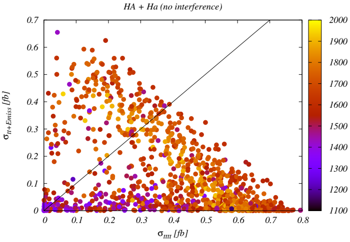


...convoluted with production cross sections

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

Can the $\not{E}$ channel ever be dominant ?





$t\bar{t}t\bar{t}$ and $t\,\bar{t} + \not{E}$ 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 $t\bar{t} + \not{E}$ dominates**

"Best" point

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

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

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

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

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

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 $\gtrsim 500\,\mathrm{GeV}$! [might be different in fit]
- DM set bound on $|m_a - 2\,m_\chi|$
- **for e^+e^-: new signatures $X + \not{E}$** [new wrt THDM]
- presented here: HA/a **production at 3 TeV**

⇒ **regions in parameter space where $t\,\bar{t} + \not{E}$ dominant**

- a lot to be done...: simulation including background, ...