Constraining extended scalar sectors at current and future colliders

Tania Robens

based on work with

A. Ilnicka, M. Krawczyk, (D. Sokolowksa); A. Ilnicka, T. Stefaniak; J. Kalinowski, W. Kotlarski, D. Sokolowsa, A. F. Zarnecki; T. Stefaniak, J. Wittbrodt; A. Papaefstathiou, G. Tetlalmatzi Xolocotzi

Rudjer Boskovic Institute

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Workshop on the Standard Model and Beyond
1.9.21

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** $\Longleftarrow$

Current (large) collider landscape
[https://europeanstrategy.cern/home]

pp colliders: LHC, FCC-hh

LHC: center-of-mass energy: 8/ 13/ 14 TeV, since 2009/ ongoing
HL-LHC: 14 TeV, high luminosity (2027-2040)
FCC-hh: 100 TeV, under discussion

e^+e^- colliders: ILC/ CLIC/ FCC-ee, CePC

in plan, high priority in Europe, various center-of-mass energies discussed

$\mu^+\mu^-$ colliders

currently under discussion, early stages

Special role of the scalar sector

- **Higgs potential in the SM**

$$\mathbf{V} = -\mu^2\, \mathbf{\Phi}^\dagger\, \mathbf{\Phi} + \lambda\, \left(\mathbf{\Phi}^\dagger\, \mathbf{\Phi}\right)^2, \quad \mathbf{\Phi} = \frac{\mathbf{1}}{\sqrt{\mathbf{2}}} \begin{pmatrix} \mathbf{0} \\ \mathbf{v} + \mathbf{h(x)} \end{pmatrix}$$

$\Rightarrow$ **mass** for Higgs Boson and Gauge Bosons

$$\mathbf{m_h^2} = \mathbf{2}\,\lambda\,\mathbf{v^2},\ \mathbf{m_W} = \mathbf{g}\,\frac{\mathbf{v}}{\mathbf{2}},\ \mathbf{m_Z} = \sqrt{\mathbf{g^2} + (\mathbf{g'})^2}\,\frac{\mathbf{v}}{\mathbf{2}}$$

where v: Vacuum expectation value of the Higgs field, g, g': couplings in $SU(2) \times U(1)$

$\Rightarrow$ **everything determined in terms of gauge couplings, v, and λ**

form of potential determines minimum,
electroweak vacuum structure

$\Rightarrow$ stability of the Universe, electroweak phase transition, etc

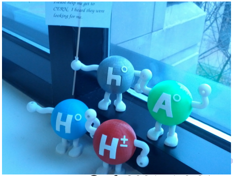
- **full test requires checks of *hhh*, *hhhh* couplings**

$\Rightarrow$ **so far: only limits; possible only at future machines** [HL-LHC: constraints on *hhhh*]

Other possible extensions

- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim 125\,\text{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add ons:**
  - can **push vacuum breakdown to higher scales**
  - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
  - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...

  $\Rightarrow$ **new scalar states** $\Leftarrow$



Models with extended scalar sectors

Constraints

- **Theory**

  minimization of vacuum (tadpole equations), vacuum stability, positivity, perturbative unitarity, perturbativity of couplings

- **Experiment**

  provide viable candidate @ 125 GeV (coupling strength/ width/ ...);
  agree with null-results from additional searches and ew gauge boson measurements (widths);
  agree with electroweak precision tests (typically via S,T,U);
  agree with astrophysical observations (if feasible)

Limited time ⇒ next slides highly selective...

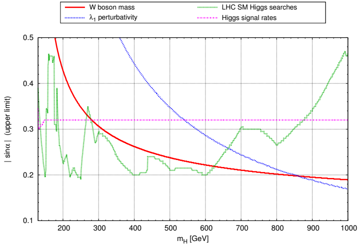
[long list of models, see e.g. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3]

tools used: `HiggsBounds`, `HiggsSignals`, `2HDMC`, `micrOMEGAs`, ...

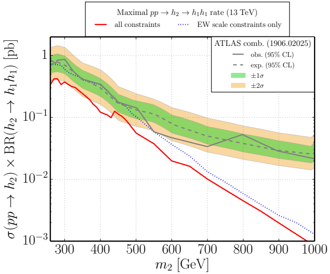
Examples for current constraints: Singlet extension, Z_2 symmetric: $+$ 1 scalar particle

$$\mathbf{V}(\mathbf{\Phi}, \mathbf{S}) = -\mathbf{m}^2\mathbf{\Phi}^\dagger\mathbf{\Phi} - \mu^2\mathbf{S}^2 + \lambda_1(\mathbf{\Phi}^\dagger\mathbf{\Phi})^2 + \lambda_2\mathbf{S}^4 + \lambda_3\mathbf{\Phi}^\dagger\mathbf{\Phi}\mathbf{S}^2$$

new parameters: $\mathbf{m_2}$, $\sin\alpha$ [$=$ 0 for SM], $\tan\beta$ [$=$ ratio of vevs]



(for fixed $\tan\beta$)



[update from Review in Physics (2020) 100045]

[see e.g. Pruna, TR, Phys. Rev. D 90, 114018;
(Bojarski, Chalons,) Lopez-Val, TR, Phys. Rev. D 90, 114018, JHEP 1602 (2016) 147;
(Ilnicka), TR, Stefaniak, EPJC (2015) 75:105, Eur.Phys.J. C76 (2016) no.5, 268, Mod.Phys.Lett. A33 (2018)]

Models with dark matter candidates: Inert Doublet Model

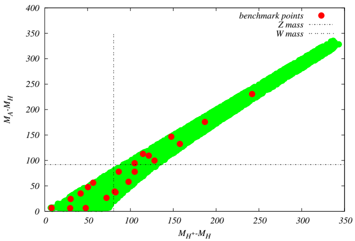
2 Higgs Doublet Model: 4 new scalars $H, A, H^{\pm}$

Z_2 symmetry $\rightarrow$ **DM candidate(s)** (here: choose H)

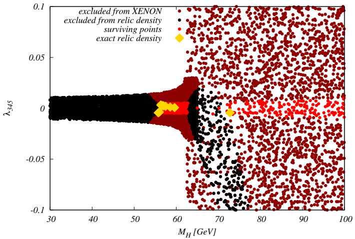
free parameters: **masses,** λ_2, λ_{345} (couplings in V)

signatures: EW gauge boson(s) + MET

$\Rightarrow$ **so far: no LHC analysis** $\Leftarrow$



Masses highly constrained from electroweak precision [Kalinowski, Kotlarski, TR, Sokolowska, Zarnecki, JHEP 1812 (2018)]



... and also from signal strength and astrophysical constraints ... [Ilnicka, TR, Stefaniak, Mod.Phys.Lett. A33 (2018) no.10n11, 1830007]

Production and decay

- Z_2 symmetry:

only pair-production of dark scalars $H, A, H^{\pm}$

- production modes:

$$\mathbf{p\,p \rightarrow HA, HH^{\pm}, AH^{\pm}, H^{+}H^{-}}$$

$$\mathbf{e^{+}e^{-} \rightarrow HA, H^{+}H^{-}}$$

- decays:

$$\mathbf{A \rightarrow Z\,H:\ 100\%,\ H^{\pm} \rightarrow W^{\pm}H:}\ \text{dominant}$$

signature: **electroweak gauge boson(s) + MET**

"Sensitivity" comparison, based on simple criterium

production cross sections for BPs at 13, 27, 100 TeV for *pp* collisions, $10, 30\,\mathrm{TeV}$ for $\mu\mu$

- simple counting criterium: **1000 events with design luminosity, comparison of mass reach**

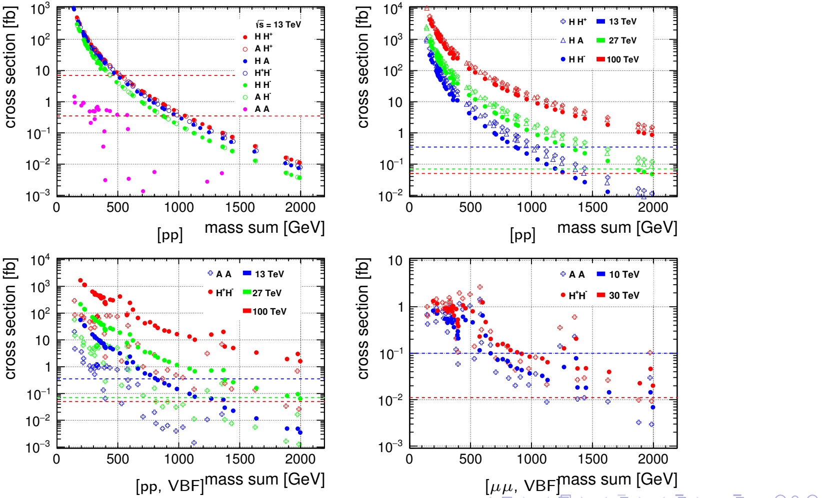
! **processes differ:** pair-production for all but *AA* final states from electroweak processes (Drell-Yan)

- *AA*: mediated via coupling $\bar{\lambda}_{345} = \lambda_{345} - 2\frac{M_H^2 - M_A^2}{v^2}$
  $\Rightarrow$ **strong constraints from direct detection and electroweak precision observables**

$\Rightarrow$ **include VBF-type topologies: VBF starts playing role**, especially at $\mu\mu$ colliders

Sensitivity in figures [Symmetry 13 (2021) 6, 991]

lines: 1000 events for design luminosity



Sensitivity in numbers

after HL-LHC: in general **mass scales** ($\sum M_i$ for pair-production) **up to 1 TeV**, in AA **channel 200-600 GeV** (500-600 including VBF)

collider	all others	AA	AA +VBF
HE-LHC	2 TeV	400-1400 GeV	800-1400 GeV
FCC-hh	2 TeV	600-2000 GeV	1600-2000 GeV
CLIC, 3 TeV	2 TeV$^{1),2)}$	- $^{3)}$	300-600 GeV
$\mu\mu$, 10 TeV	2 TeV$^{1)}$	-	400-1400 GeV
$\mu\mu$, 30 TeV	2 TeV$^{1)}$	-	1800-2000 GeV

1) only HA, H^+H^-;
2) detailed investigation including background, beam strahlung, etc [JHEP 07 (2019) 053, CERN Yellow Rep. Monogr. Vol. 3 (2018)]
3) also including Zh mediation

LHC: Multi scalar production modes

[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151]

ADDING TWO REAL SCALAR SINGLETS

Scalar potential (Φ: $SU(2)_L$ doublet, S, X: $SU(2)_L$ singlets)

$$\mathcal{V} = \mu_\Phi^2 \Phi^\dagger \Phi + \mu_S^2 S^2 + \mu_X^2 X^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_S S^4 + + \lambda_X X^4 + \\ \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2.$$

Imposed $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetry, which is spontaneously broken by singlet vevs.

$\Rightarrow$ three $\mathcal{CP}$-even neutral Higgs bosons: h_1, h_2, h_3

Two interesting cases:

Case (a): $\langle S \rangle \neq 0, \langle X \rangle = 0 \Rightarrow X$ is DM candidate;

Case (b): $\langle S \rangle \neq 0, \langle X \rangle \neq 0 \Rightarrow$ all scalar fields mix.

Again, Higgs couplings to SM fermions and bosons are *universally reduced by mixing*.

[some material stolen from T. Stefaniak, Talk at ALPS 2019, April '19]

Exploration of $h_1 h_1 h_1$ final state at HL-LHC

[A. Papaefstathiou, TR, G. Tetlalmatzi-Xolocotzi, JHEP 05 (2021) 193]

- 3 scalar states h_1, h_2, h_3 that mix

concentrate on

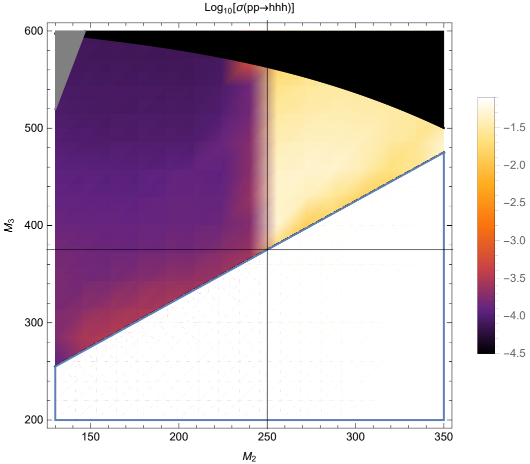
$$p\,p \to h_3 \to h_2\,h_1 \to h_1\,h_1\,h_1 \to b\,\bar{b}\,b\,\bar{b}\,b\,\bar{b}$$

$\Rightarrow$ **select points** on BP3 which might be **accessible at HL-LHC**

$\Rightarrow$ perform detailed analysis including SM background, hadronization, ...

- tools: implementation using **full** t, b **mass dependence, leading order** [UFO/ Madgraph/ Herwig] [analysis: use K-factors]

$h_1 h_1 h_1$ production cross sections, leading order [pb]



[using interpolation]

highest values: $\sim$ 50fb **for** $M_2 \sim 250\,\mathrm{GeV}$, $M_3 \sim 400 - 450\mathrm{GeV}$

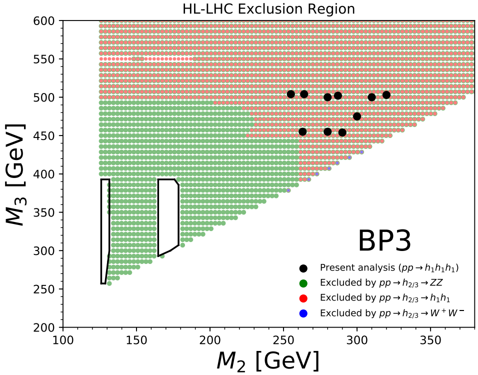
Benchmark points and results

(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	$\text{sig}\vert_{300\text{fb}^{-1}}$	$\text{sig}\vert_{3000\text{fb}^{-1}}$
$(255, 504)$	32.40	6.40	2.92	9.23
$(263, 455)$	50.36	9.95	4.78	15.11
$(287, 502)$	39.61	7.82	4.01	12.68
$(290, 454)$	49.00	9.68	5.02	15.86
$(320, 503)$	35.88	7.09	3.76	11.88
$(264, 504)$	37.67	7.44	3.56	11.27
$(280, 455)$	51.00	10.07	5.18	16.39
$(300, 475)$	43.92	8.68	4.64	14.68
$(310, 500)$	37.90	7.49	4.09	12.94
$(280, 500)$	40.26	7.95	4.00	12.65

discovery, exclusion

$\Rightarrow$ at HL-LHC, all points within reach $\Leftarrow$

What about other channels ?



[extrapolation of $36\,\mathrm{fb}^{-1}$ and HL projections]

$\Rightarrow$ model can be tested from various angles $\Leftarrow$

[Phys. Rev. Lett. 122 (2019) 121803; Phys. Lett. B800 (2020) 135103; JHEP 06 (2018) 127; CERN Yellow Rep. Monogr. 7 (2019) 221; Eur. Phys. J. C78 (2018) 24; ATL-PHYS-PUB-2018-022]

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**

$\Rightarrow$ promoted by LHC Dark Matter Working group in Phys.Dark Univ. 27 (2020) 100351

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

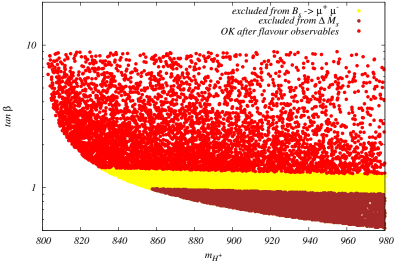
- v, $m_{h/H}$: input
- **electroweak precision** through S, T, U
- $B \to X_s \gamma$, $B \to \mu^+ \mu^-$, ΔM_s
- Γ_{125}
- **direct searches and 125 GeV signal strength** through HiggsBounds/ HiggsSignals
- upper limit on **relic density**, direct detection [Phys. Rev., D90(5):055021]
- **(pseudo)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

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

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], $\Rightarrow \tan\beta_{\textbf{min}}\,(m_{H^\pm})$
- $B_s \to \mu^+\mu^-$, ΔM_s: via SPheno, compare to LHC combination [ATLAS-CONF-2020-049], HFLAV value [arXiv:1909.12524]



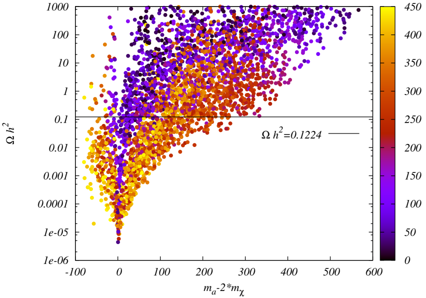
$$R_\gamma^{\text{exp}} \equiv \frac{\mathcal{B}_{(s+d)\gamma}}{\mathcal{B}_{c\ell\nu}} = (3.22 \pm 0.15) \times 10^3,$$

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

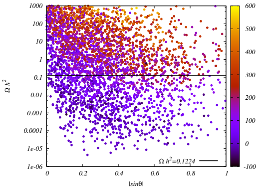
$$\left(B_s \to \mu^+\mu^-\right)^{\text{comb}} = \left[2.69^{+0.37}_{-0.35}\right] \times 10^{-9}$$

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

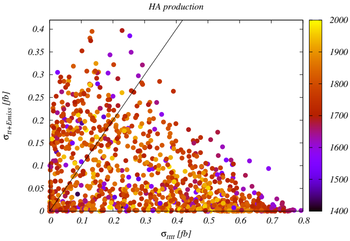
a priori: as standard THDM

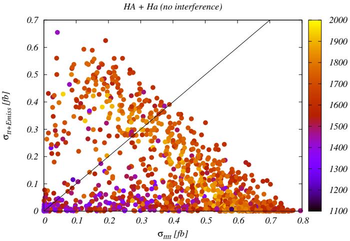
- new feature: **new scalar a; mixing: both a/A can decay invisibly**
- interesting channels: ha, hA, Ha, HA
- mass ranges: between $200\,\mathrm{GeV}$ and $2\,\mathrm{TeV}$
- most promising: HA, Ha **at 3 TeV**

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

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

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 $0.5 \times (m_a + m_A) + m_H$]

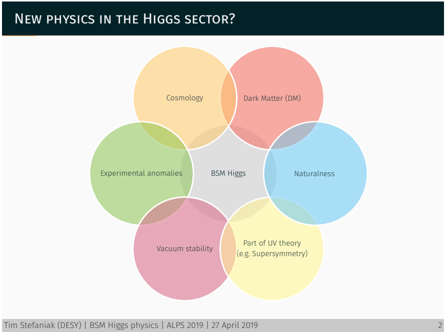
bottom line: **can find regions where $t\bar{t} + \not\!\!E$ dominates**

Summary/ Outlook

⇒ **LHC already strongly constrains (some) models**

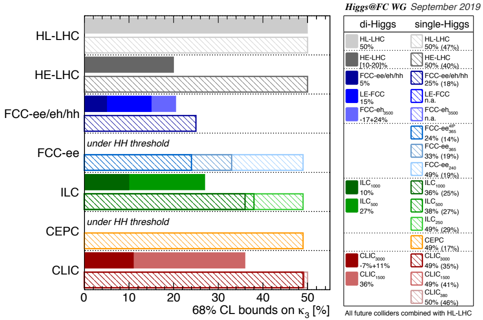
⇒ **others are not investigated so far....** (but should)

⇒ **role of future colliders equally important**

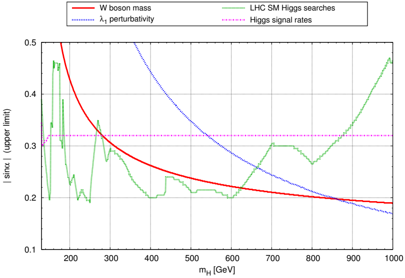


(figure stolen from T. Stefaniak)

Appendix



JHEP 2001 (2020) 139

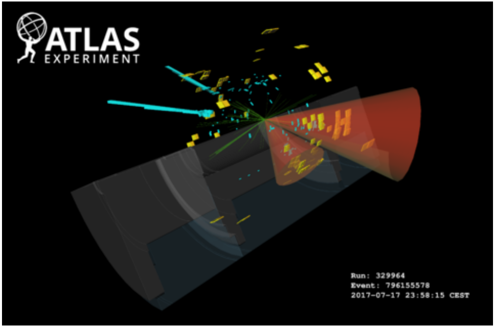


- $\leq$ 153 GeV : $h_2 \rightarrow ZZ$ Run II [arXiv:1804.01939]
- [153 − 183 GeV] : SM-like decays to VV, Run I [CMS-PAS-HIG-13-003], Run II [1712.06386], Run I combination [CMS-PAS-HIG-17-045]
- [183 − 438 GeV] : $h_2 \rightarrow ZZ$ Run II [arXiv:1804.01939]
- [438 − 990 GeV] : $h_2 \rightarrow VV$, combination Run II [arXiv:1808.02380]
- $>$ 990 GeV: VBF mode to VV, combination Run II [arXiv:1808.02380]

Examples for current constraints: Singlet extension, Z_2 symmetric: + 1 scalar particle

$$H \to h\,h \to b\bar{b}\gamma\gamma$$

[example event display]



[ATLAS-CONF-2021-016]

Constraints

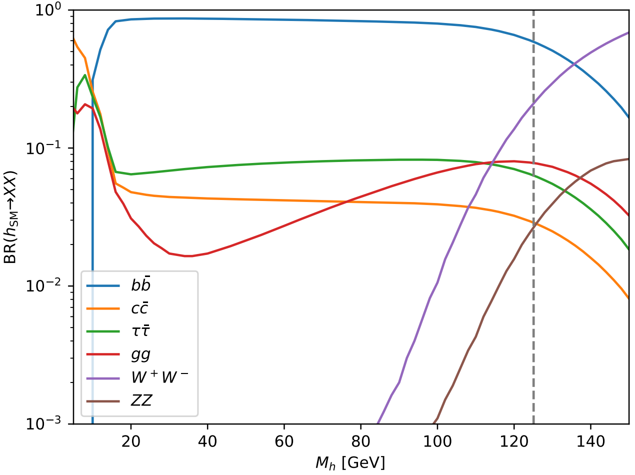
- **Theory**:
  boundedness from below for potential,
  perturbative unitarity;
- **Experiment:**
  electroweak precision via S, T, U;
  agreement with measurements of 125 GeV scalar;
  agreement with null-results for additional searches;
  also tested: $W-$mass as precision observable [à la Lopez-Val, TR, Phys. Rev. D 90, 114018]

Tools which were used:

HiggsBounds*, HiggsSignals, ScannerS*

[*: private updated version]

Decays of light SM-like scalars



[from YREP 4/ HDecay]

Inert doublet model: The model

- idea: take **two Higgs doublet model, add additional Z_2 symmetry**

$$\phi_D \;\rightarrow\; -\phi_D, \phi_S \;\rightarrow\; \phi_S, \text{SM} \;\rightarrow\; \text{SM}$$

(⇒ implies CP conservation)

⇒ obtain a **2HDM with (a) dark matter candidate(s)**

- potential

$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2$$
$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right],$$

- only one doublet acquires VeV v, as in SM
  (⇒ implies analogous EWSB)

Number of free parameters

$\Rightarrow$ then, **go through standard procedure...**

$\Rightarrow$ minimize potential

$\Rightarrow$ determine number of free parameters

Number of free parameters here: 7

- e.g.

$$\mathbf{v},\ \mathbf{M_h},\ \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{\mathbf{345}}\ [=\ \lambda_3+\lambda_4+\lambda_5]$$

- v, M_h fixed $\Rightarrow$ left with **5 free parameters**

Parameters tested at colliders: mainly masses

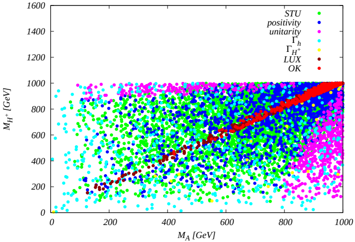
- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **relevant couplings follow from ew parameters (+ derivative couplings)**
- hXX **couplings:** determined by λ_{345} (constrained from direct detection), and **mass differences** $M_X^2 - M_H^2$ $\left(X \in \left[A,\, H^\pm\right]\right)$

important interplay between astroparticle physics and collider searches

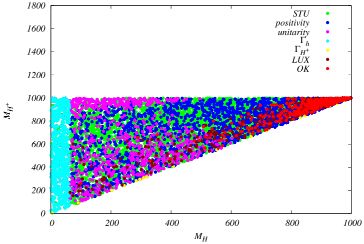
in the end kinematic test

(holds for $M_H \geq \frac{M_h}{2}$)

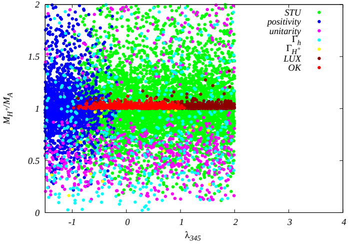
Results of generic scan [arXiv:1508.01671,arXiv:1809.07712]



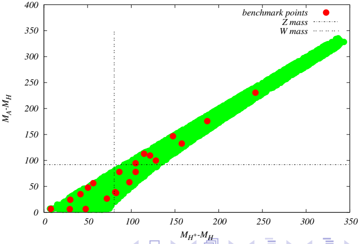
M_A vs $M_{H\pm}$



M_H vs $M_{H\pm}$



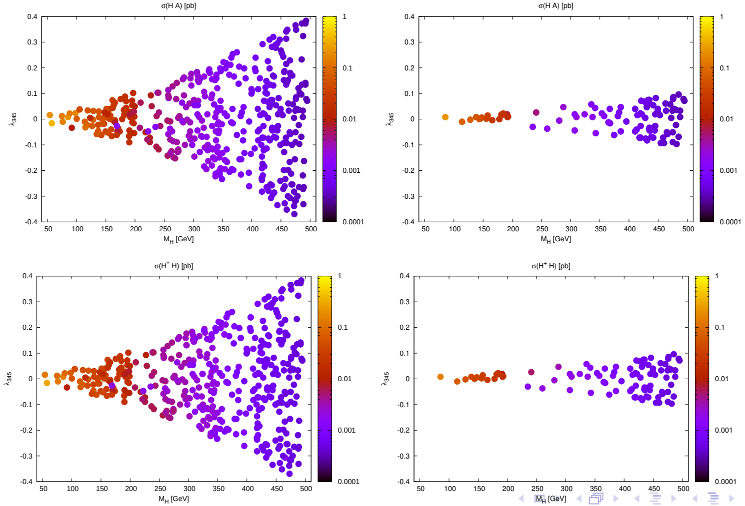
λ_{345} vs $M_{H\pm}\,/\,M_A$



mass differences

Updated constraints [XENON1T] [Phys.Rev.Lett. 121 (2018) no.11, 111302]

LUX **XENON**



Benchmark planes for LHC [XENON/ Signal rates improved] [YREP 4]

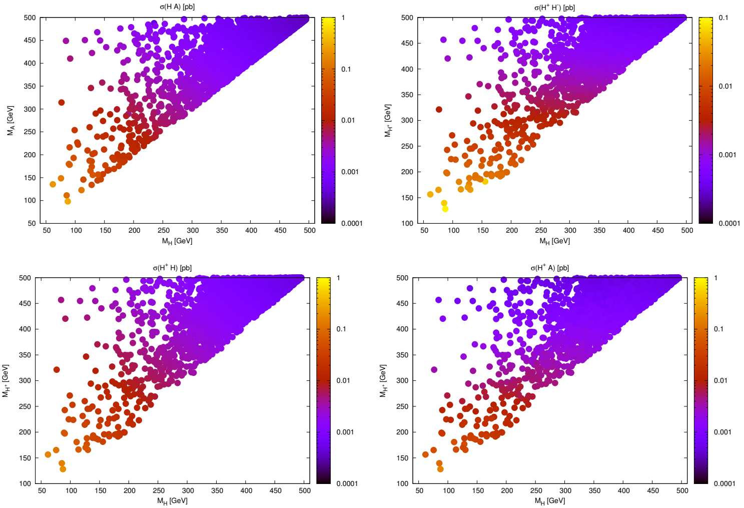


Figure : Production cross sections in pb at a 13 TeV LHC

IDM at CLIC [slide from A.F.Zarnecki]

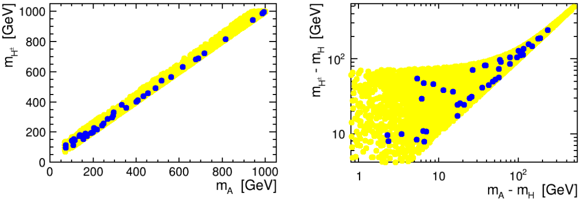
["13.67/ 15" (ECFA meeting Granada 05/19)]

Benchmark points: JHEP 1812 (2018) 081; Analysis: arXiv:1811.06952

[J. Kalinowski, W. Kotlarski, TR, D. Sokolowska, A.F. Zarnecki]

IDM benchmark points

Out of about 15'000 points consistent with all considered constraints, we chose 43 benchmark points (23 accessible at 380 GeV) for detailed studies:



The selection was arbitrary, but we tried to

- cover wide range of scalar masses and the mass splittings
- get significant contribution to the relic density

For list of benchmark point parameters, see backup slides

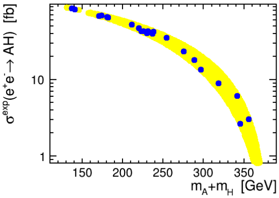
IDM at CLIC [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

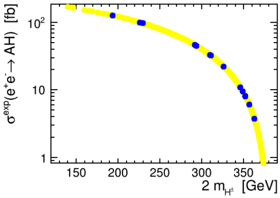
Analysis strategy

Production of IDM scalars at CLIC dominated by two processes:

$$e^+e^- \to A\ \ H \qquad\qquad e^+e^- \to H^+H^-$$

Leading-order cross sections for inert scalar production processes at 380 GeV:

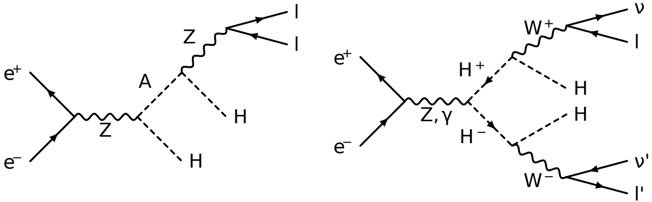




Beam luminosity spectra not taken into account

Leptonic production modes

$$e^+ e^- \rightarrow HA^{(*)} \rightarrow HZ^{(*)}H \rightarrow HH\mu^+\mu^-,$$
$$e^+ e^- \rightarrow H^{+(*)}H^{-(*)} \rightarrow W^{+(*)}W^{-(*)}\,H\,H$$
$$\rightarrow HH\mu^+e^-\nu_\mu\bar{\nu}_e, \qquad (+e \longleftrightarrow \mu)$$

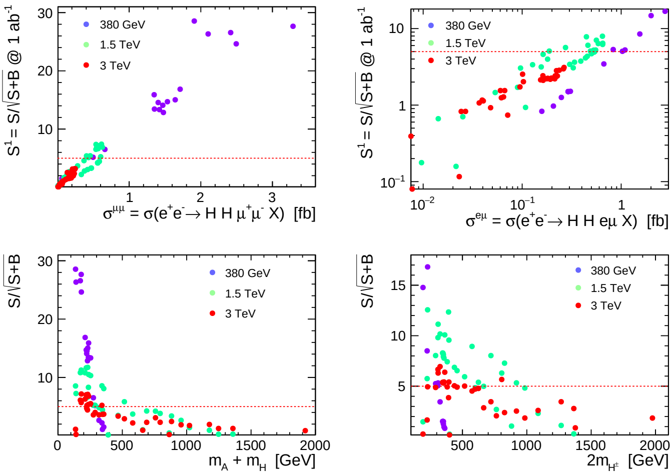


in reality: simulate ***everything* leading to** $\mu^+\mu^- + \not{E}, \mu^\pm e^\mp + \not{E}$

Results for CLIC studies [JHEP 1812 (2018) 081; JHEP 1907 (2019) 053]

For selected benchmark points...

HA **production** $\qquad$ H^+H^- **production**

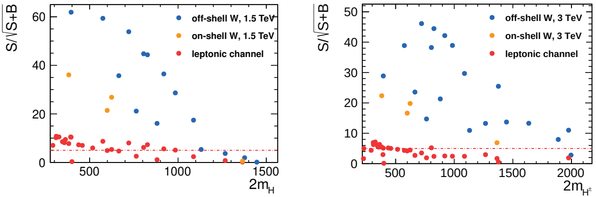


Semi-leptonic channel at CLIC
[slide from A.F.Zarnecki, Snowmass meeting, 07/20]

IDM scalars: semi-leptonic analysis

Results

Summary of results obtained for the semi-leptonic channel
compared with leptonic channel results for high mass benchmarks @ CLIC



Huge increase of signal significance!

Discovery reach extended up to $m_{H^\pm} \sim 1$ TeV for CLIC @ 3 TeV

Collider parameters

collider	cm energy [TeV]	$\int \mathcal{L}$	1000 events [fb]
HL-LHC	13/ 14	$3\,\text{ab}^{-1}$	0.33
HE-LHC	27	$15\,\text{ab}^{-1}$	0.07
FCC-hh	100	$20\,\text{ab}^{-1}$	0.05
ee	3	$5\,\text{ab}^{-1}$	0.2
$\mu\mu$	10	$10\,\text{ab}^{-1}$	0.1
$\mu\mu$	30	$90\,\text{ab}^{-1}$	0.01

Recast of LHC Run II results
(in collaboration w D. Dercks, arXiv:1812.07913)

- so far:

  no dedicated searches at the LHC

- however, dominant final states:

  jet(s) + MET, EW gauge boson(s) + MET

  $\Rightarrow$ same final states appear in other BSM searches $\Leftarrow$

- idea: **use recasting methods** to give (preliminary) exclusion limits if feasible
- many tools around; here: **CheckMATE**
  [Drees ea '13, Dercks ea '16]

IDM recast

- considered a long list of processes at 13 TeV
- most sensitive:

VBF + invisible Higgs decay (by far), Monojet

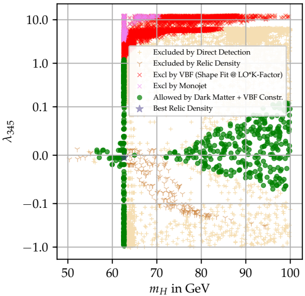
$\Rightarrow$ implemented in CheckMATE [currently: private version]

$\Rightarrow$ applied to IDM

VBF: *Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at* $\sqrt{s} = 13\,\mathrm{TeV}$, CMS, arXiv:1809.05937 [$35.9\mathrm{fb}^{-1}$]

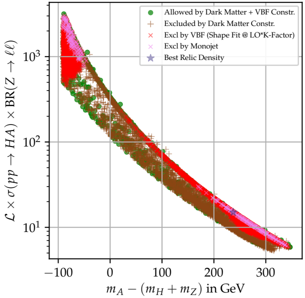
Monojet: *Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector*, ATLAS, ATLAS-CONF-2017-060 [$36.1\mathrm{fb}^{-1}$]

IDM at LHC



Recast of 13 TeV VBF $h \to$ invisible search

important constraints in offshell regime !

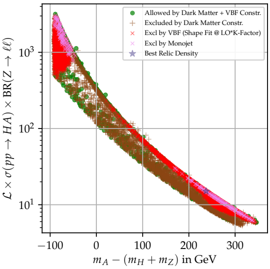


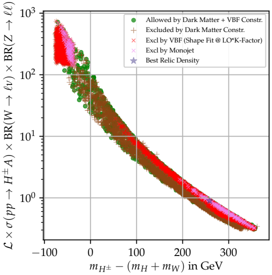
example for $\not{E}_\perp$ vs rate

high rates $\Longleftrightarrow$ low $\not{E}_\perp$ cuts

current searches at LHC need to be modified

Brief comments on null-results for other channels





- **high** $\not{E}_\perp \Rightarrow$ **low** σ and vice versa

experiments need to venture into low $\not{E}_\perp$ region

(first discussions: The 15th Workshop of the LHC Higgs Cross Section Working Group, CERN, 12/18; cf e.g. summary talk by D. Sperka)

Total widths in IDM scenario [old]

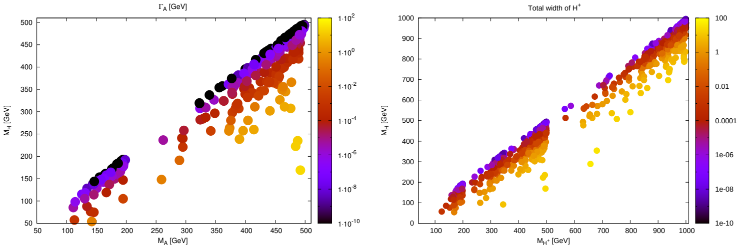
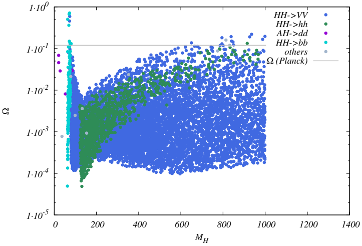
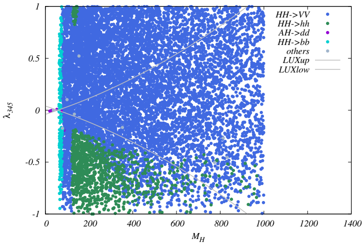


Figure : Total widths of unstable dark particles: A and $H^{\pm}$ in plane of their and dark matter masses.

Dark matter relic density

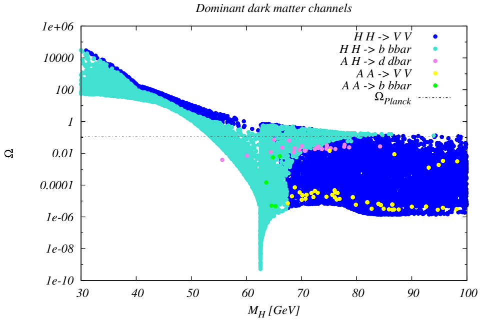


all but DM constraints



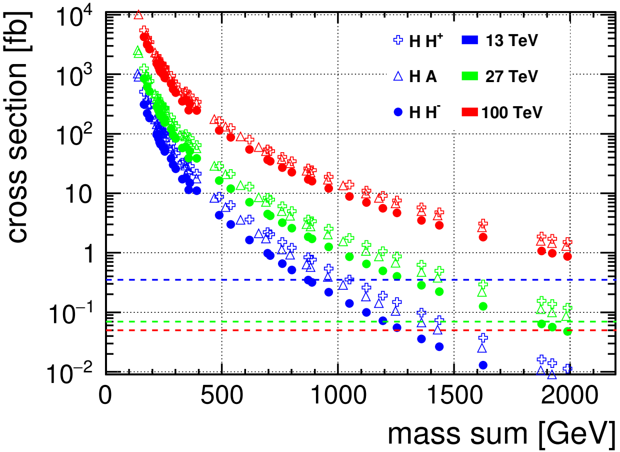
all but DM constraints

Dominant annihilation channels for the IDM



- dominant = **largest contribution** can be 51 % vs 49 %...
- as obtained from **MicroMegas 4.3.5**
- interesting/ promising: $A\,H \to d\,\bar{d}$;
  needs further investigation

pp production cross sections at various com energies



Backup slide

High mass IDM benchmark points

No.	M_H	M_A	$M_{H\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
HP1	176	291.4	312	1.49	-0.1035	0.0007216
HP2	557	562.3	565.4	4.045	-0.1385	0.07209
HP3	560	616.3	633.5	3.38	-0.0895	0.001129
HP4	571	676.5	682.5	1.98	-0.471	0.0005635
HP5	671	688.1	688.4	1.377	-0.1455	0.02447
HP6	713	716.4	723	2.88	0.2885	0.03515
HP7	807	813.4	818	3.667	0.299	0.03239
HP8	933	940	943.8	2.974	-0.2435	0.09639
HP9	935	986.2	988	2.484	-0.5795	0.002796
HP10	990	992.4	998.1	3.334	-0.051	0.1248
HP11	250.5	265.5	287.2	3.908	-0.1501	0.00535
HP12	286.1	294.6	332.5	3.292	0.1121	0.00277
HP13	336	353.3	360.6	2.488	-0.1064	0.00937
HP14	326.6	331.9	381.8	0.02513	-0.06267	0.00356
HP15	357.6	400	402.6	2.061	-0.2375	0.00346
HP16	387.8	406.1	413.5	0.8168	-0.2083	0.0116
HP17	430.9	433.2	440.6	3.003	0.08299	0.0327
HP18	428.2	454	459.7	3.87	-0.2812	0.00858
HP19	467.9	488.6	492.3	4.122	-0.252	0.0139
HP20	505.2	516.6	543.8	2.538	-0.354	0.00887

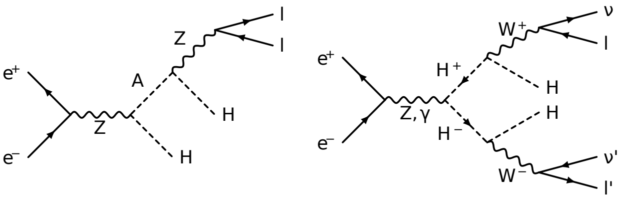
Analysis strategy

Lepton pair production can be a signature of the AH production process followed by the A decay:

$$e^+e^- \rightarrow HA \rightarrow HHZ^{(\star)} \rightarrow HH\mu^+\mu^-$$

while the production of the different flavour lepton pair is the expected signature for H^+H^- production:

$$e^+e^- \rightarrow H^+H^- \rightarrow HHW^{+(*)}W^{-(*)} \rightarrow HH\ell^+\ell'^-\nu\bar{\nu}'$$



Backup slide

Signal processes for $\mu^+\mu^-$ final state

$$
\begin{aligned}
e^+e^- &\rightarrow \mu^+\mu^- \, HH, \\
&\rightarrow \mu^+\mu^-\nu_\mu\bar{\nu}_\mu \, HH, \\
&\rightarrow \tau^+\mu^-\nu_\tau\bar{\nu}_\mu \, HH, \;\; \mu^+\tau^-\nu_\mu\bar{\nu}_\tau \, HH, \\
&\rightarrow \tau^+\tau^- \, HH, \;\; \tau^+\tau^-\nu_\tau\bar{\nu}_\tau \, HH. \\
&\quad \text{with} \tau^\pm \rightarrow \mu^\pm\nu\nu
\end{aligned}
$$

Signal processes for $e^\pm\mu^\mp$ final state

$$
\begin{aligned}
e^+e^- &\rightarrow \mu^+\nu_\mu \, e^-\bar{\nu}_e \, HH, \;\; e^+\nu_e \, \mu^-\bar{\nu}_\mu \, HH, \\
&\rightarrow \mu^+\nu_\mu \, \tau^-\bar{\nu}_\tau \, HH, \;\; \tau^+\nu_\tau \, \mu^-\bar{\nu}_\mu \, HH, \\
&\rightarrow e^+\nu_e \, \tau^-\bar{\nu}_\tau \, HH, \;\; \tau^+\nu_\tau \, e^-\bar{\nu}_e \, HH, \\
&\rightarrow \tau^+ \, \tau^- \, HH, \;\; \tau^+\nu_\tau \, \tau^-\bar{\nu}_\tau \, HH,
\end{aligned}
$$

Analysis strategy

We consider two possible final state signatures:

- moun pair production, $\mu^+\mu^-$, for AH production
- electron-muon pair production, μ^+e^- or $e^+\mu^-$, for H^+H^- production

Both channels include contributions from AH and H^+H^- production!
In particular due to leptonic tau decays.

Signal and background samples were generator with WHizard 2.2.8
based on the dedicated IDM model implementation in SARAH,
parameter files for benchmark scenarios were prepared using SPheno 4.0.3

CLIC luminosity spectra taken into account (1.4 TeV scaled to 1.5 TeV)

Generator level cuts reflecting detector acceptance:

- require lepton energy $E_l > 5\,\mathrm{GeV}$ and lepton angle $\Theta_l > 100\,\mathrm{mrad}$
- no ISR photon with $E_\gamma > 10\,\mathrm{GeV}$ and $\Theta_\gamma > 100\,\mathrm{mrad}$

Possible production and decay patterns

$$M_1 \leq M_2 \leq M_3$$

Production modes at pp and decays

$$pp \to h_3 \to h_1\,h_1; \qquad pp \to h_3 \to h_2\,h_2;$$
$$pp \to h_2 \to h_1\,h_1; \qquad pp \to h_3 \to h_1\,h_2$$

$$h_2 \to \text{SM};\; h_2 \to h_1\,h_1;\; h_1 \to \text{SM}$$

$\Rightarrow$ two scalars with same or different mass decaying directly to SM, or $h_1\,h_1\,h_1$, or $h_1 h_1 h_1 h_1$

[h_1 decays further into SM particles]

[BRs of h_i into $X_{\text{SM}} = \frac{\kappa_i \Gamma^{\text{SM}}_{h_i \to X}(M_i)}{\kappa_i \Gamma^{\text{SM}}_{\text{tot}}(M_i) + \sum_{j,k} \Gamma_{h_i \to h_j h_k}}$; κ_i: rescaling for h_i]

Benchmark points/ planes [ASymmetric/ Symmetric]

AS **BP1:** $h_3 \to h_1 h_2 \; (h_3 = h_{125})$

SM-like decays for both scalars: $\sim$ 3 pb; h_1^3 final states: $\sim$ 3pb

AS **BP2:** $h_3 \to h_1 h_2 \; (h_2 = h_{125})$

SM-like decays for both scalars: $\sim$ 0.6 pb

AS **BP3:** $h_3 \to h_1 h_2 \; (h_1 = h_{125})$

(a) SM-like decays for both scalars $\sim$ 0.3 pb; **(b)** h_1^3 **final states:** $\sim$ 0.14 pb

S **BP4:** $h_2 \to h_1 h_1 \; (h_3 = h_{125})$

up to 60 pb

S **BP5:** $h_3 \to h_1 h_1 \; (h_2 = h_{125})$

up to 2.5 pb

S **BP6:** $h_3 \to h_2 h_2 \; (h_1 = h_{125})$

SM-like decays: up to 0.5 pb; h_1^4 **final states: around 14 fb**

LHC: Multi scalar production modes

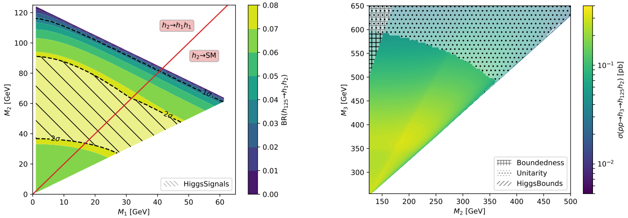
[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151]

2 real singlet extension ⇒ 2 additional scalars $(M_1 \le M_2 \le M_3;\ M_i \in [0; 1\text{TeV}])$

[1 mass always at 125 GeV, others free]

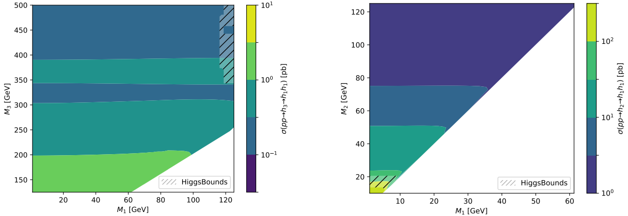
asymmetric, triple h_1

(3.5/ 0.25 pb)



symmetric, no h_{125} involved

(2.5/ 60 pb)



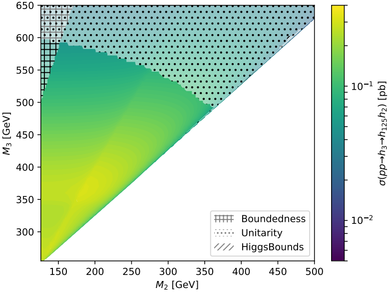
BP3: $h_3 \to h_1 h_2$ $(h_1 = h_{125})$ [up to 0.3 pb]

BP3

$\sigma(pp \to h_3) \simeq 0.06 \cdot \sigma(pp \to h_{SM})|_{m=M_3}$
$\mathrm{BR}(h_3 \to h_{125} h_2)$ mostly $\sim 50\%$.
if $M_2 < 250\,\mathrm{GeV}$: $\Rightarrow h_2 \to$ SM particles.
if $M_2 > 250\,\mathrm{GeV}$:
$\Rightarrow \mathrm{BR}(h_2 \to h_{125} h_{125}) \sim 70\%$,

$\Rightarrow$ **spectacular triple-Higgs signature**

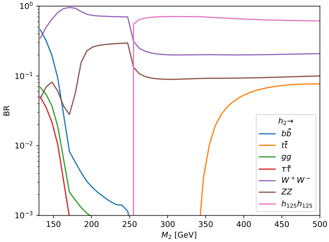
[up to 140 fb; maximal close to thresholds]

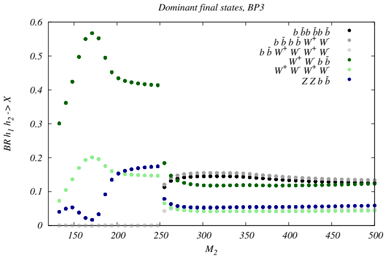


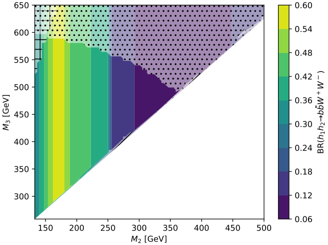
$[\kappa_3 = 0.24]$ $[\Gamma_3/M_3 \leq 0.05]$

[relevant searches: $36\,\mathrm{fb}^{-1}$ searches for $h_3 \to V\,V$]

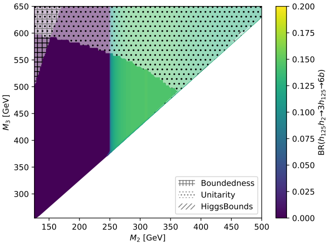
BP3: $h_3 \to h_1 h_2 \; (h_1 = h_{125})$ [up to 0.3 pb]







up to 0.18 pb



up to 30 fb

Cut selection

Label	(M_2, M_3) [GeV]	$< P_{T,b}$ [GeV]	$\chi^{2,(4)} <$ [GeV^2]	$\chi^{2,(6)} <$ [GeV^2]	$m^{\rm inv}_{4b} <$ [GeV]	$m^{\rm inv}_{6b} <$ [GeV]
A	(255, 504)	34.0	10	20	-	525
B	(263, 455)	34.0	10	20	450	470
C	(287, 502)	34.0	10	50	454	525
D	(290, 454)	27.25	25	20	369	475
E	(320, 503)	27.25	10	20	403	525
F	(264, 504)	34.0	10	40	454	525
G	(280, 455)	26.5	25	20	335	475
H	(300, 475)	26.5	15	20	352	500
I	(310, 500)	26.5	15	20	386	525
J	(280, 500)	34.0	10	40	454	525

Table : $|\eta|_b < 2.35$, $\Delta m_{\rm min,\ med,\ max} < [15, 14, 20]$ GeV, $p_T(h_1^i) > [50, 50, 0]$ GeV, $\Delta R(h_1^i, h_1^j) < 3.5$ and $\Delta R_{bb}(h_1) < 3.5$.

χ^2s: variables used in h_1 reconstruction

THDMa

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:

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

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

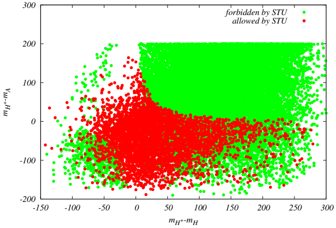
Scan ranges:

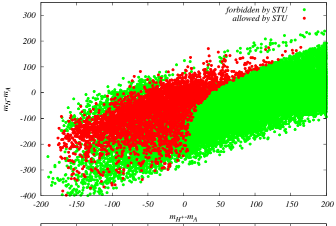
$$\sin\theta \in [-1; 0.8],\ \cos(\beta-\alpha) \in [-0.08; 0.1],\ \tan\beta \in [0.52; 9],$$
$$m_H \in [500; 1000]\,\mathrm{GeV},\ m_A \in [600; 1000]\,\mathrm{GeV},$$
$$m_{H^\pm} \in [800; 1000]\,\mathrm{GeV},\ m_a \in [5\,\mathrm{GeV}; m_A],\ m_\chi \in [0\,\mathrm{GeV}, m_a/2],$$
$$y_\chi \in [-\pi;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

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

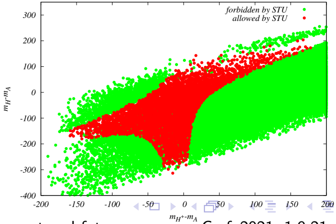
Constraints on mass differences

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



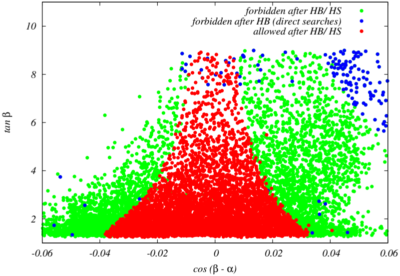


compare to THDM ⇒



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/ CMS 2018 data, Phys.Lett. B783 (2018) 392-414, Eur. Phys. J. C 79 (2019) 564]

LHC searches

Model widely promoted by LHC Dark matter working group

$\Rightarrow$ searches considered:

1. $h + \not{E}_\perp$: 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. $W^+\bar{t}/W^-t + \not{E}_\perp$: 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. $t\,\bar{t},\ b\bar{b} + \not{E}_\perp$: 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

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**

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

- a lot to be done...: *ha* at small center of mass energies, simulation including background, ...

Thanks for listening