News about the Inert Doublet Model

[and Higgs $\rightarrow$ invisible (if time allows)]

Tania Robens

based on work with

A. Ilnicka, M. Krawczyk, (D. Sokolowksa)

(arXiv:1505.04734; arXiv:1508.01671; arXiv:1510.04159; arXiv: 1705.00225)

A. Ilnicka, T. Stefaniak

(arXiv:1803.03594)

J. Kalinowski, W. Kotlarski, D. Sokolowska, A. F. Zarnecki

(arXiv:1809.07712; arXiv:1811.06952; arXiv:1812.02093)

D. Dercks

(arXiv:1812.07913)

T. Stefaniak

(arXiv:1902.00134)

Ruder Boskovic Institute

Dark Matter Identification: Connecting Theory and Signature Space

MITP, Mainz, 2.4.19

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** $\Longleftarrow$

Inert doublet model: The model

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

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

($\Rightarrow$ implies CP conservation)

$\Rightarrow$ 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
  ($\Rightarrow$ 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**

Constraints: Theory

$\Longrightarrow$ **consider all current constraints on the model** $\Longleftarrow$

- Theory constraints: **vacuum stability, positivity, constraints to be in inert vacuum**
  $\Rightarrow$ **limits on (relations of) couplings**, e.g.

$$\lambda_1 > 0,\ \lambda_2 > 0,\ \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0,\ \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0$$

- **perturbative unitarity, perturbativity of couplings**
- **choosing** M_H as dark matter:

$$M_H \leq M_A,\ M_{H^\pm}$$

Constraints: Experiment

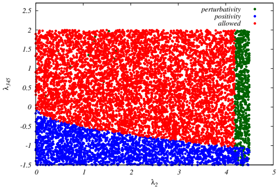
$$M_h = 125.1\,\mathrm{GeV},\; v = 246\,\mathrm{GeV}$$

- total width of M_h ($\Gamma_h < 9\,\mathrm{GeV}$); $\Rightarrow$ CMS-PAS-HIG-18-002
- total width of W, Z
- collider constraints from signal strength/ direct searches; $R_{\gamma\gamma}$ and $\mathrm{BR}_{h\to\mathrm{inv}}$ from JHEP, 08:045, 2016
- electroweak precision through S, T, U
- unstable $H^{\pm}$
- reinterpreted/ recastet LEP/ LHC SUSY searches (Lundstrom ea 2009; Belanger ea, 2015)
- dark matter relic density (upper bound)
- dark matter direct search limits (XENON1T)

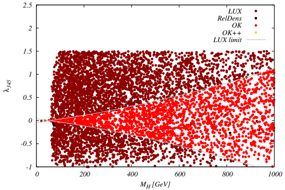
$\Rightarrow$ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

Obvious/ direct constraints on couplings and masses

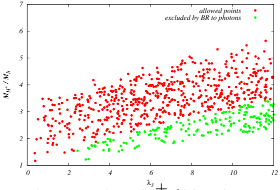
some constraints $\Rightarrow$ direct limits on couplings/ masses



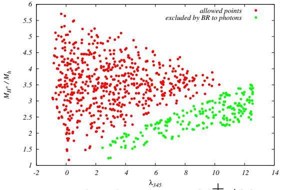
$\lambda_2,\ \lambda_{345}$ plane and limits from perturbativity, positivity



$M_H,\ \lambda_{345}$ plane, limits from LUX$^{(*)}$



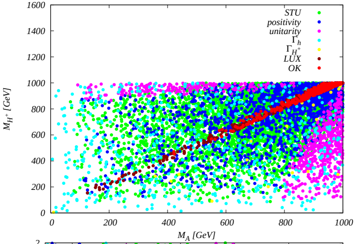
limits on $\lambda_3,\ M_H^{\pm}/M_h$, plane



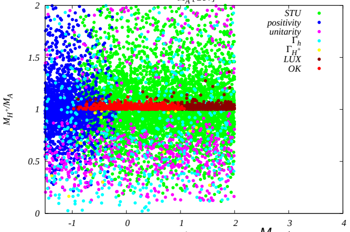
... translated to $\lambda_{345},\ M_H^{\pm}/M_h$

$^{(*)}$ updates not yet included

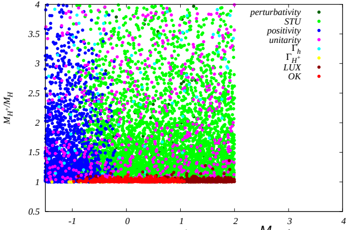
Other constraints less obvious (interplay); result $\Rightarrow$ mass degeneracies



M_A vs $M_{H\pm}$ after all constraints



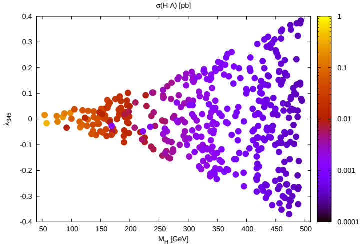
λ_{345} vs $\frac{M_{H\pm}}{M_A}$



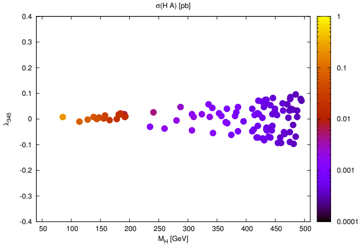
λ_{345} vs $\frac{M_{H\pm}}{M_H}$

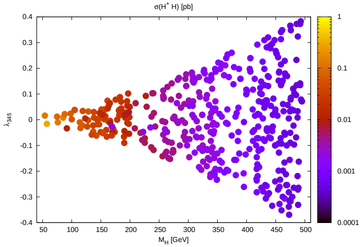
Updated constraints [XENON1T] [Phys.Rev.Lett. 121 (2018) no.11, 111302]

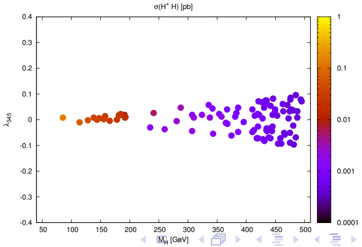
LUX



XENON



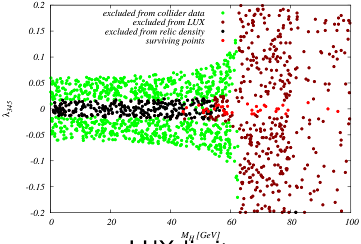




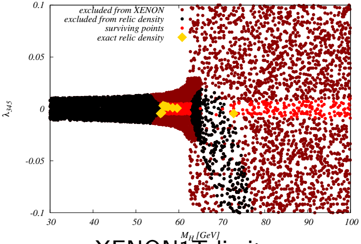
Cases where $M_H \leq M_h/2$

- **discussion so far:** decay $h \rightarrow H\,H$ kinematically not accessible
- for these cases, discussion along different lines

$\Rightarrow$ **extremely strong constraints from signal strength, and dark matter requirements**



LUX limits



XENON1T limits

- additional constraints from combination of W, Z decays and recasted analysis at LEP

lower limit $M_H \sim 50\,\mathrm{GeV}$

Production and decay

- Z_2 symmetry:

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

- production modes:

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

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

- decays:

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

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

Parameters tested at colliders: mainly masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **e.g. predictions for LHC@13 TeV do not depend on λ_2, only marginally on λ_{345}**
- all **relevant couplings follow from ew parameters (+ derivative couplings)** $\Rightarrow$ in the end a kinematic test
- only in exceptional cases λ_{345} important

$\Rightarrow$ **high complementarity between astroparticle physics and collider searches**

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

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

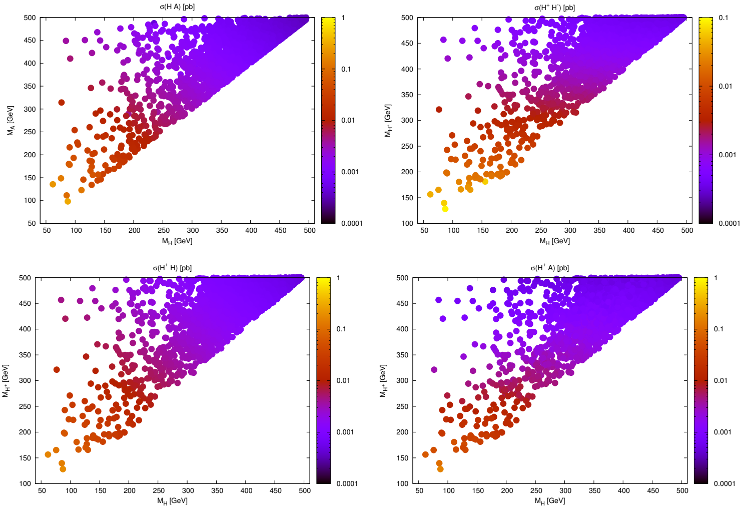


Figure : Production cross sections in pb at a 13 TeV LHC

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

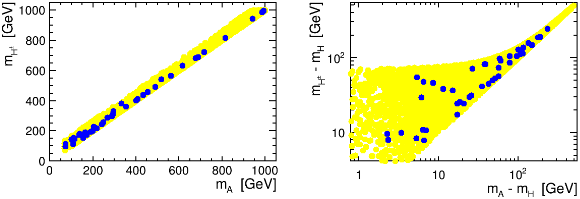
Benchmark points: JHEP 1812 (2018) 081; Analysis: arXiv:1811.06952

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

IDM benchmark points

FACULTY OF PHYSICS WARSAW UNIVERSITY

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

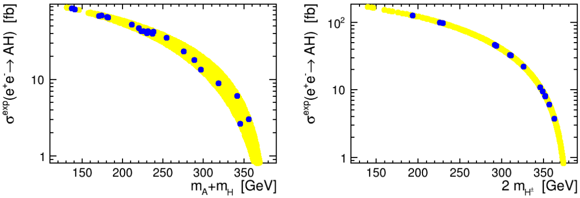
IDM at CLIC [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

Analysis strategy

Production of IDM scalars at CLIC dominated by two processes:

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

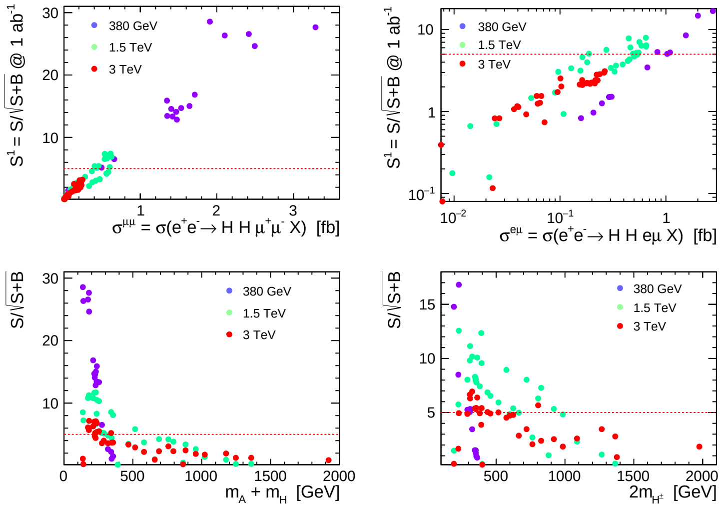
Leading-order cross sections for inert scalar production processes at 380 GeV:



Beam luminosity spectra not taken into account

Results for CLIC studies [using boosted decision trees]

HA **production** | H^+H^- **production**



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 recast in more detail (VBF)

- considered final states:

$$p\,p \,\rightarrow\, jj + \not{E}_\perp$$

($\not{E}_\perp$ = HH in Madgraph syntax)

- **can come from a number of processes:**

$$p\,p \,\rightarrow\, h\,j\,j, h \,\rightarrow\, H\,H, (*)$$
$$p\,p \,\rightarrow\, H\,A,\; A \,\rightarrow\, Z\,H,\; Z \,\rightarrow\, jj,$$
$$p\,p \,\rightarrow\, H\,H\,j\,j \text{ (via t-channel A)},$$
$$\ldots$$

(*) most prominent after applying experimental VBF cuts
(tested by explicit exclusion in production mode)

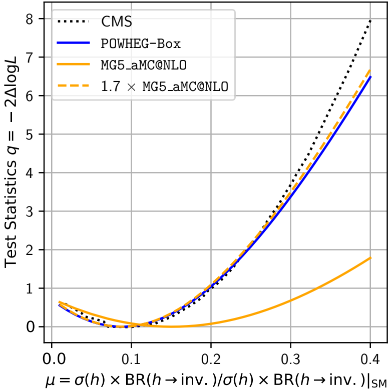
IDM recast: validation

- recover original paper results:
  number of events in m_{jj} bins, after application of all cuts

  $\Rightarrow$ VBF production of h, which is considered invisible
  $\Rightarrow$ ggF production of hj at NLO

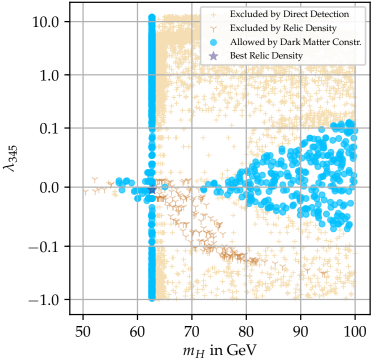
- tools: Powheg Box interfaced with Pythia;
  reproduced results ✓
- **BSM signal: Madgraph5 at leading order**
- numbers lower by factor 1.7: **LO results conservative**

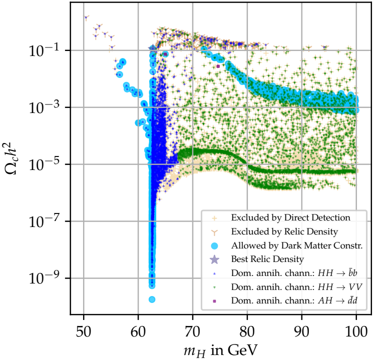
Validation: Profile Likelihood



IDM recast: Results

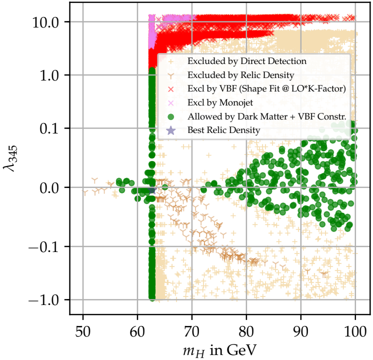
before recast

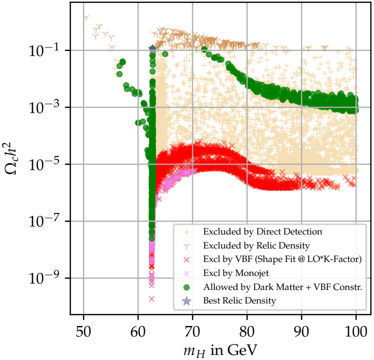




IDM recast: Results

after recast





What about other channels ?

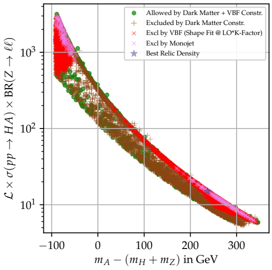
- largest production cross sections:

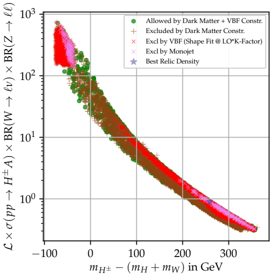
$$\boxed{pp \;\rightarrow\; H\,A,\; H\,H^{\pm}}$$

- lead to **single- or dilepton final states + $\not{E}_{\perp}$**
  [previous study: G. Belanger, B. Dumont, A. Goudelis, B. Herrmann, S. Kraml, D. Sengupta, arXiv:1503.07367]
- we tested:
  - M. Aaboud et al. *Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.*, Phys. Lett., B776:318-337, 2018, 1708.09624.
  - *Search for electroweak production of supersymmetric particles in the two and three lepton final state at $\sqrt{s} = 13$ TeV with the ATLAS detector.* Technical Report ATLAS-CONF-2017-039, CERN, Geneva, Jun 2017

no constraints !! why ?

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)

Topics for discussion

- ⇒ (How) can we convince the LHC experiments to look for this model ? No dedicated searches
- ⇒ How wrong are we when projecting more involved models into the IDM ?

  (this also concerns theory constraints (e.g. special vacuum conditions, etc))
- ⇒ can/ should new approaches be applied ? "hot" topic: machine learning...
- ⇒ what about alternative methods for searches ? "bump" hunting via generalized mass variables ? a lot of work has been done that one might have to rediscover

  Determining SUSY model parameters and masses at the LHC using cross-sections, kinematic edges and other observables, C. Lester, M. Parker, M. J. White, arXiv:0508143

Very briefly: the collider connection

[w. T. Stefaniak, arXiv:1902.00134 (HL-LHC Higgs Yellow Report)]

Higgs portal models

- In the context of **dark matter**:
- models where **SM Higgs mediates to dark sector**
- **collider signature:** $h_{125} \rightarrow$ **invisible**

$\Rightarrow$ either **direct constraint on BR**, or **modification of SM branching ratios**

High luminosity LHC

- LHC with current (or 14 TeV) cm energy, $\mathcal{L}^{\text{int}} = 300\,(3000)\,\mathrm{ab}^{-1}$
- one of possible future LHC directions

$\Rightarrow$ important: **good physics case !!**

Our study for Yellow Report

A) for **simple parametrization of Higgs couplings in κ framework** (rescaled couplings):

complementarity of SM decays and invisible BR

B) for **different DM candidates** (scalar, vector, fermion):

comparison with direct detection limits

C) for a **specific model** (singlet with additional scalar dark matter candidate):

complementarity of different constraints

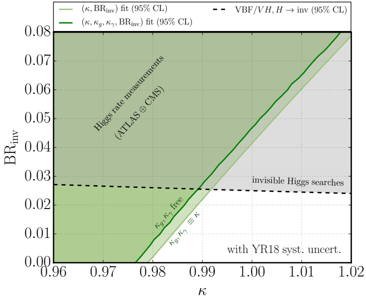
In all cases, $m_{DM} \leq m_h/2$!!

A) SM decays vs invisible branching ratio

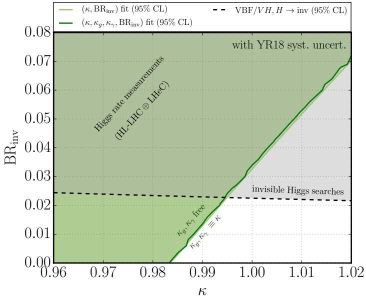
κ fit only:

HL-LHC only, SM couplings: $\mathrm{BR_{inv}} \leq$ **4.2%**

HL-LHC and LHeC, SM couplings: $\mathrm{BR_{inv}} \leq$ **3.3%**



HL-LHC, S2 scenario



...combined with LHeC

More details on Higgs portal model

Minimal Higgs portal [Kanemura, Matsumoto, Nabeshima, Okada '10], [Djouadi, Lebedev, Mambrini, Quevillon '11]

Impose *portal interaction* between SM Higgs field H and the DM field:

(scalar DM) (vector DM) (fermion DM)

$$\mathcal{L} \supset \quad -\frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \quad \text{or} \quad +\frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu \quad \text{or} \quad -\frac{1}{4}\frac{\lambda_{h\chi\chi}}{\Lambda} H^\dagger H \bar{\chi}\chi.$$

- If $M_{\mathrm{DM}} < M_h/2 \Rightarrow$ invisible Higgs decays;
- Higgs couplings to SM fields unaffected ($\kappa = 1$).

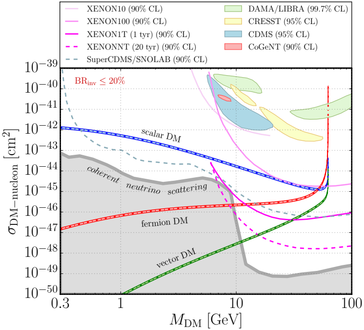
The Higgs portal coupling λ relates

invisible Higgs decay width ($\Gamma_{\mathrm{inv}} \propto \lambda^2 v^2$)	$\longleftrightarrow$	DM-nucleon scattering cross section ($\sigma_{\mathrm{DM-nucleon}} \propto \lambda^2$)

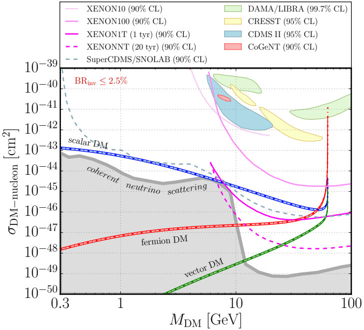
$\Rightarrow$ Complementarity: invisible Higgs searches $\leftrightarrow$ DM direct detection (DD).

B) Collider measurements vs direct detection experiments

idea: **measure BR_{inv} at collider, translate to DM nucleon scattering cross section** (dependence on same coupling), for different DM candidates



now



future

Example: Scalar singlet portal

[TR, T. Stefaniak, arXiv:1902.00134; TR, T. Stefaniak, J. Wittbrodt, in preparation]

$\Rightarrow$ study a more involved model to investigate complementarity

$\Rightarrow$ here: Higgs singlet:

$$\boxed{\textbf{2 scalar states } h, H \textbf{ with mixing angle } \alpha}$$

with singlet coupling to **scalar dark matter candidate** X

- important parameters

$$\underbrace{M_h,\ \cos\alpha,\ v_s}_{\text{visible sector}},\ \underbrace{M_X,\ \lambda_{SXX}}_{\text{dark sector}}$$

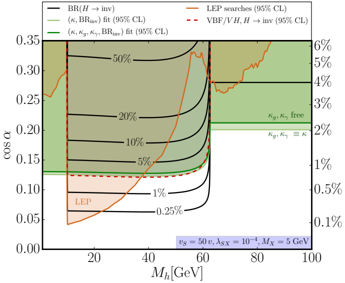
M_i: new masses, λ: new coupling, v_s: singlet vev

(e.g. Englert, Plehn, Zerwas^2, Phys.Lett. B703 (2011))

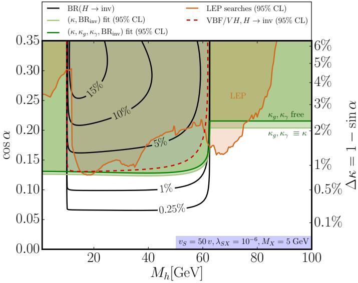
(Singlet: e.g. TR, T. Stefaniak, Eur.Phys.J. C75 (2015), Eur.Phys.J. C76 (2016))

C) Complementarity of different limits for singlet + scalar DM

parameters: $\underbrace{M_h,\ \cos\alpha,\ v_s}_{\text{as in singlet}},\ \underbrace{M_X,\ \lambda_{SXX}}_{\text{new}}$



invisible decays enhanced



invisible decays suppressed

Open questions II

- what about complementarity between collider measurements and dark matter searches
  - constraining the same parameters (Higgs portals)
  - constraining different parameters (IDM)
- can we identify regions in parameter spaces that are hard/ easy to investigate via dm/ collider measurements/ can this be categorized (or is it already...)
- how generic would this be ?
- ...

Appendix

Last comments: publications where scan has been used

- **Production of Inert Scalars at the high energy e^+e^- colliders**, M. Hashemi ea, **JHEP 1602 (2016) 187**
  use Yellow Report benchmarks
- **Exploring the Inert Doublet Model through the dijet plus missing transverse energy channel at the LHC**, P. Poulose ea, **Phys.Lett. B765 (2017) 300-306**
  use benchmarks with $m_H = 65\,\mathrm{GeV}$
- **Yellow Report IV of the Higgs Cross Section Working Group, arXiv:1610.07922**
- **Benchmarking the Inert Doublet Model for e^+e^- colliders**, J. Kalinowski ea, **arXiv:1809.07712**
- CLIC Yellow Report, *to appear*

Very brief: parameters determining couplings (production and decay)

dominant production modes: through Z; Z, γ, h for AH; $H^+ H^-$

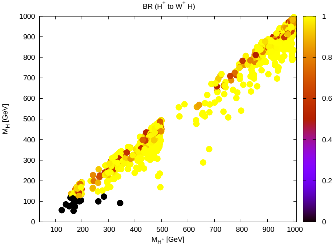
important couplings:

- $Z\,H\,A$: $\sim\ \frac{e}{s_W\,c_w}$
- $Z\,H^+\,H^-$: $\sim\ e\,\coth\,(2\,\theta_w)$
- $\gamma\,H^+\,H^-$: $\sim\ e$
- $h\,H^+\,H^-$: $\lambda_3\,v$
- $H^+\,W^+\,H$: $\sim\ \frac{e}{s_w}$
- $H^+\,W^+\,A$: $\sim\ \frac{e}{s_w}$

!! mainly determined by electroweak SM parameters !!

Aside: typical BRs [old values]

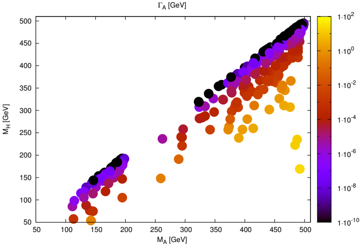
- decay $A \rightarrow H\,Z$ always 100 %
- decay $H^{\pm} \rightarrow H\,W^{\pm}$



second channel $H^{\pm} \rightarrow A\,W^{\pm}$

$\Longrightarrow$ **collider signature: SM particles and MET** $\Longleftarrow$

Total widths in IDM scenario [old]



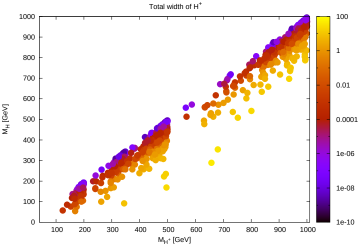
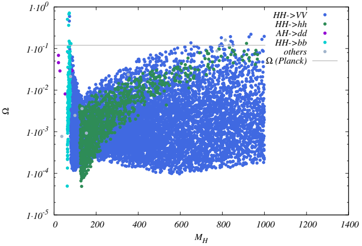
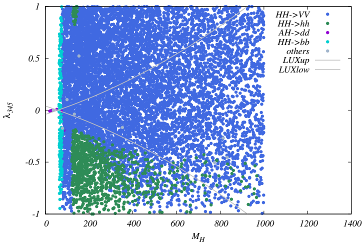


Figure : Total widths of unstable dark particles: A and $H^{\pm}$ in plane of their and dark matter masses.

Dark matter relic density

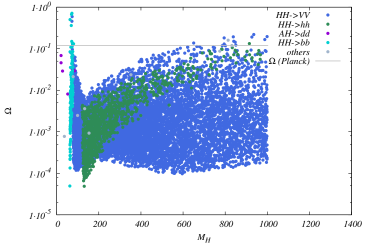


all but DM constraints

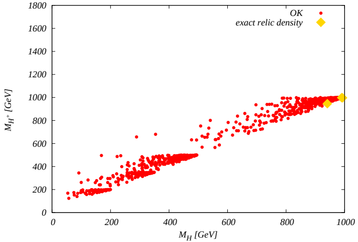


all but DM constraints

Dark matter relic density: exact limit vs upper bound



Ω vs m_H, all but DM constraints



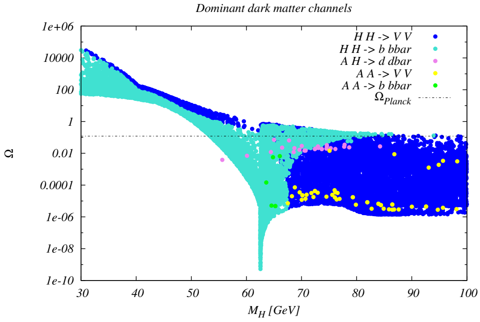
sample plot, M_H vs. $M_{H\pm}$

General scan results

$\Rightarrow$ window with $m_H \in [100\,\mathrm{GeV}; 600\mathrm{GeV}]$ **which cannot provide exact DM**

$\Rightarrow$ **only few points in a general scan** [more can be found using finetuned scans]

Dominant annihilation channels for the IDM



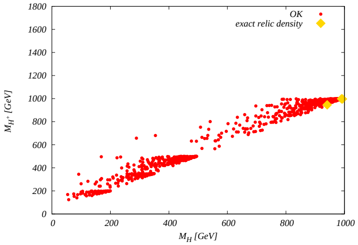
- dominant = **largest contribution** can be 51 % vs 49 %...
- as obtained from **MicroMegas 4.3.5**
- interesting/ promising: $A\,H \rightarrow d\,\bar{d}$;
  needs further investigation

... and what if I want exact DM relic density ??

[preliminary results]

E.g. **this means**

- $m_{H^\pm} \in [100\,\mathrm{GeV}; 620\,\mathrm{GeV}]$ or $> 840\,\mathrm{GeV}$
- $m_H \notin [75\,\mathrm{GeV}; 120\,\mathrm{GeV}]$ or $\sim 54\,\mathrm{GeV}$
- ...



sample plot, M_H vs. $M_{H^\pm}$

Benchmark selection for current LHC run for YREP 4

⇒ points need to **have passed all bounds**

⇒ total cross sections calculated using **Madgraph5, IDM model file from Goudelis ea**, 2013 (LO)

⇒ **effective ggH vertex implemented by hand**

- highest production cross sections: $H\,A$; $H^{\pm}\,H$; $H^{\pm}\,A$; $H^{+}\,H^{-}$
- decay $A \to H\,Z$ always 100 %
- decay $H^{\pm} \to H\,W^{\pm}$ usually dominant

$$\begin{aligned} p\,p \to H\,A &: \quad \leq 0.03\,\mathrm{pb}, \\ p\,p \to H^{\pm}\,H &: \quad \leq 0.03\,\mathrm{pb}, \\ p\,p \to H^{\pm}\,A &: \quad \leq 0.015\,\mathrm{pb}, \\ p\,p \to H^{+}\,H^{-} &: \quad \leq 0.01\,\mathrm{pb}. \end{aligned}$$

And what about LHC ?

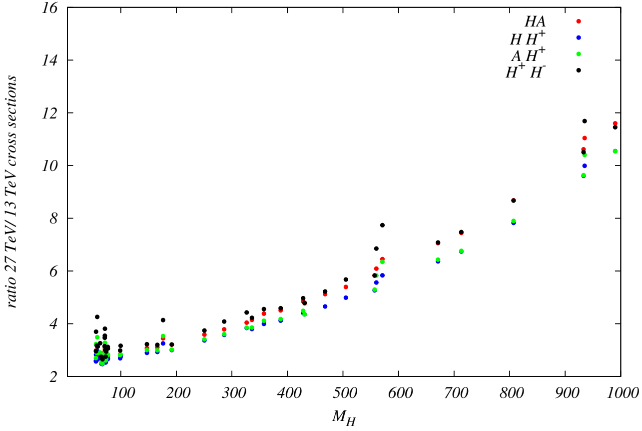
[TR, *IDM benchmarks for the LHC at 13 and 27 TeV*, Talk at Higgs Cross Section Working group WG3 submeeting, 24.10.18]

No.	M_H	M_A	$M_{H^\pm}$	HA	$H\,H^+$	AH^+	H^+H^-	AA	onshell
BP1	72.77	107.803	114.639	322	304	169	132	0.4	
BP2	65	71.525	112.85	1022	363	322	140	0.1	
BP3	67.07	73.222	96.73	909	504	444	242	0.1	
BP4	73.68	100.112	145.728	377	165	115	55.1	0.3	
BP6	72.14	109.548	154.761	314	144	88.9	45.1	0.4	W
BP7	76.55	134.563	174.367	173	99.0	50.8	29.2	0.4	W
BP8	70.91	148.664	175.89	144	103	42.7	28.3	0.5	W
BP9	56.78	166.22	178.24	125	116	34.4	27.1	0.6	W, Z
BP10	76.69	154.579	163.045	120	119	46.4	37.3	0.5	W
BP11	98.88	155.037	155.438	87.7	101	50.4	43.8	0.2	
BP12	58.31	171.148	172.96	113	125	34.5	30.3	0.6	W, Z
BP13	99.65	138.484	181.321	113	68.8	44.7	25.2	0.3	W
BP14	71.03	165.604	175.971	106	103	35.5	28.3	0.5	W, Z
BP15	71.03	217.656	218.738	46.9	54.6	14.2	12.8	0.4	W, Z
BP16	71.33	203.796	229.092	57.3	47.3	14.6	10.8	0.4	W, Z
BP18	147	194.647	197.403	29.6	34.0	21.3	17.9	0.1	
BP19	165.8	190.082	195.999	25.5	28.6	22.5	18.3	0.03	
BP20	191.8	198.376	199.721	17.9	21.4	20.1	16.9	0.03	
BP21	57.475	288.031	299.536	20.6	21.8	4.02	4.04	0.3	W, Z
BP22	71.42	247.224	258.382	31.3	32.5	8.05	6.90	0.4	W, Z
BP23	62.69	162.397	190.822	125	88.9	31.3	21.1	0.5	W, Z

Production cross sections in fb, at 13 TeV [UFO+Madgraph]

$>$ 1000 events in Run II for each process: all but BPs 21 and 22

... and at 27 TeV... $[15\,\mathrm{ab}^{-1}]$



at high masses, **increase up to one order of magnitude**

all BPs and HPs more than 1000 events for total run

Combination of ew gauge boson total widths and LEP recast

- decays widths W, Z: **kinematic regions**

$$M_{A,H} + M_H^{\pm} \geq m_W,\ M_A + M_H \geq m_Z,\ 2\,M_H^{\pm} \geq m_Z.$$

- **LEP recast** (Lundstrom 2008)

$$M_A \leq 100\,\mathrm{GeV},\ M_H \leq 80\,\mathrm{GeV}, \Delta M \geq 8\,\mathrm{GeV}$$

- **combination leads to**
  - $M_H \in [0; 41\,\mathrm{GeV}]$: $M_A \geq 100\,\mathrm{GeV}$,
  - $M_H \in [41; 45\mathrm{GeV}]$: $M_A \in [m_Z - M_H; M_H + 8\,\mathrm{GeV}]$ or $M_A \geq 100\,\mathrm{GeV}$
  - $M_H \in [45; 80\mathrm{GeV}]$: $M_A \in [M_H; M_H + 8\,\mathrm{GeV}]$ or $M_A \geq 100\,\mathrm{GeV}$

Last comment: IDM tools for LHC phenomenology

- leading order production and decay: Madgraph5, + (currently) private version for ggh (top loop in $m_{\text{top}} \to \infty$ limit)
- in principle available: gg @ NLO, MG5 (needs however modification of current codes, not straightforward)
- IMHO: **currently LO sufficient**

Last topic: multicomponent dark matter

If $\Omega < \Omega_{\text{DM}}^{\text{Planck}}$: what does it mean ?

$\Rightarrow$ one possible understanding:

Multi-component dark matter

- **in practise: direct detection limits relaxed**, according to

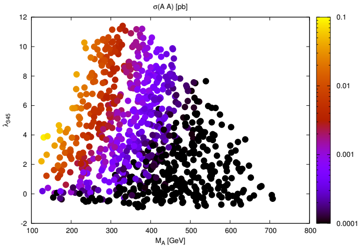
$$\sigma\,(M_H) \,\leq\, \sigma^{\text{LUX}}(M_H) \times \frac{\Omega^{\text{Planck}}}{\Omega(M_H)}$$

$\Rightarrow$ **in practise**: larger parameter space for λ_{345}

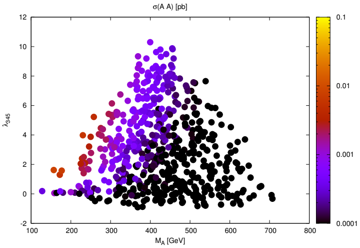
$\Rightarrow$ **influences especially AA production**

AA production with rescaled dark matter

before: $\sigma_{AA}^{13\,\mathrm{TeV}} \leq 0.0015\,\mathrm{pb}$



[old]



[new]

strongest constraint now : BR$_{h\to\gamma\gamma}$

Backup slide

Low mass IDM benchmark points

No.	M_H	M_A	$M_{H\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
BP1	72.77	107.8	114.6	1.445	-0.004407	0.1201
BP2	65	71.53	112.8	0.7791	0.0004	0.07081
BP3	67.07	73.22	96.73	0	0.00738	0.06162
BP4	73.68	100.1	145.7	2.086	-0.004407	0.08925
BP5	55.34	115.4	146.6	0.01257	0.0052	0.1196
BP6	72.14	109.5	154.8	0.01257	-0.00234	0.1171
BP7	76.55	134.6	174.4	1.948	0.0044	0.0314
BP8	70.91	148.7	175.9	0.4398	0.0051	0.124
BP9	56.78	166.2	178.2	0.5027	0.00338	0.08127
BP10	76.69	154.6	163	3.921	0.0096	0.02814
BP11	98.88	155	155.4	1.181	-0.0628	0.002737
BP12	58.31	171.1	173	0.5404	0.00762	0.00641
BP13	99.65	138.5	181.3	2.463	0.0532	0.001255
BP14	71.03	165.6	176	0.3393	0.00596	0.1184
BP15	71.03	217.7	218.7	0.7665	0.00214	0.1222
BP16	71.33	203.8	229.1	1.03	-0.00122	0.1221
BP17	55.46	241.1	244.9	0.289	-0.00484	0.1202
BP18	147	194.6	197.4	0.387	-0.018	0.001772
BP19	165.8	190.1	196	2.768	-0.004	0.002841
BP20	191.8	198.4	199.7	1.508	0.008	0.008494
BP21	57.48	288	299.5	0.9299	0.00192	0.1195
BP22	71.42	247.2	258.4	1.043	-0.00406	0.1243
BP23	62.69	162.4	190.8	2.639	0.0056	0.06404

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

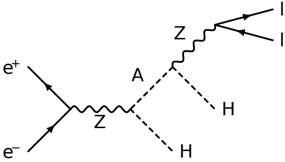
Analysis strategy

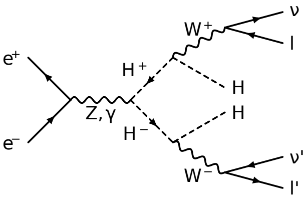
Lepton pair production can be a signature of the AH production process followed by the A decay:

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

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

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

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

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

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)

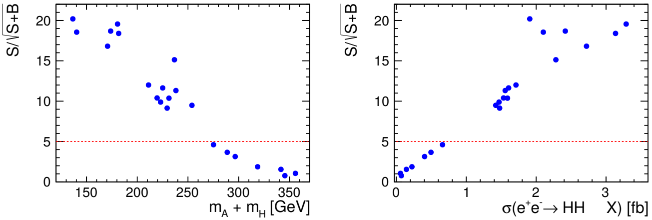
Generator level cuts reflecting detector acceptance:

- 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 $\Theta_\gamma > 100\,\mathrm{mrad}$

Neutral scalar production @ 380 GeV

Multivariate analysis

Summary of results for the considered benchmark scenarios



Expected significance mainly related to the *AH* production cross section

$5\,\sigma$ observation possible for signal cross section above about 1 fb

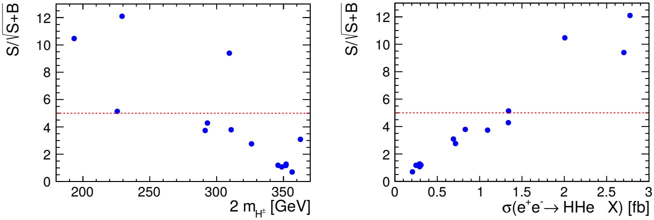
(in the $\mu^+\mu^-$ channel)

$\Rightarrow$ neutral inert scalar mass sum below about 260 GeV

Charged scalar production @ 380 GeV

Multivariate analysis

Summary of results for the considered benchmark scenarios



Expected significance mainly related to the H^+H^- production cross section

$5\,\sigma$ observation possible for signal cross section above about 1.5 fb

$\Rightarrow$ charged scalar masses up to about 140 GeV

significant differences are visible between different benchmark scenarios, mainly depending on the mass difference between charged and neutral inert scalar