News from the Inert Doublet Model

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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)
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(contribution to CLIC Yellow Report; in preparation)
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Workshop on Multi-Higgs Models
IST
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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

⇒ then, **go through standard procedure...**

⇒ minimize potential

⇒ 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 ⇒ 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

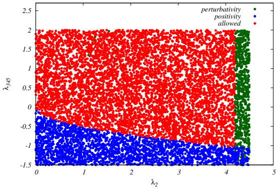
$$M_h = 125.1\,\mathrm{GeV},\; v = 246\,\mathrm{GeV}$$

- total width of M_h ($\Gamma_h < 13\,\mathrm{GeV}$); $\Rightarrow$ JHEP, 09:051, 2016
- 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**

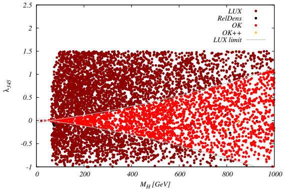
Obvious/ direct constraints on couplings and masses

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

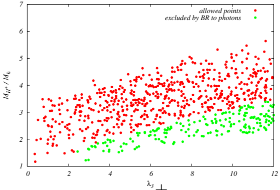


λ_2, λ_{345} plane and limits from

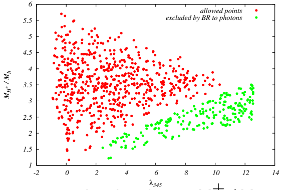
perturbativity, positivity



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



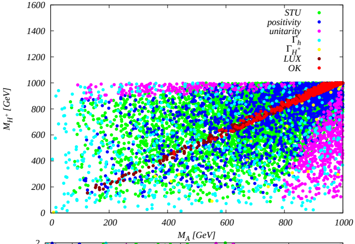
limits on λ_3, $M_H^{\pm}/M_h$, plane



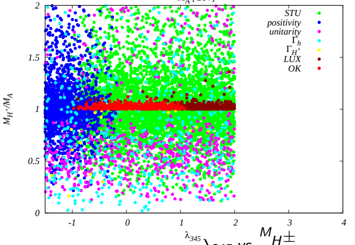
... translated to λ_{345}, $M_H^{\pm}/M_h$

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

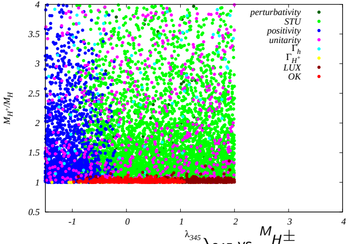
Other constraints less obvious (interplay); result $\Rightarrow$ mass degeneracies



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



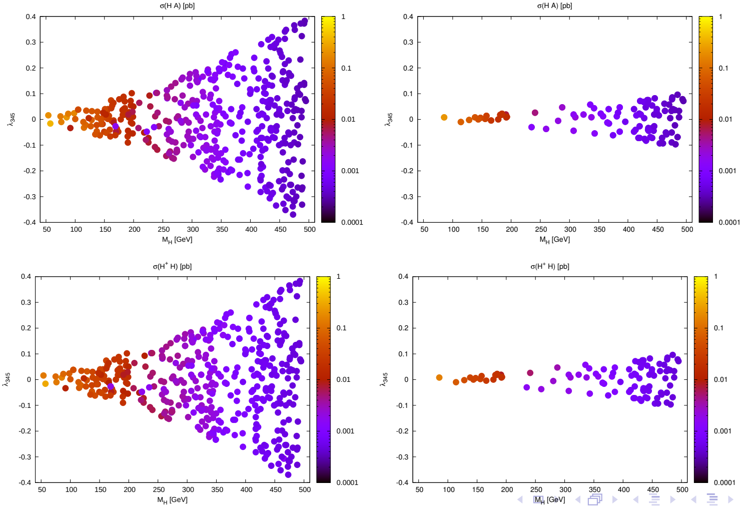
λ_{345} vs $\frac{M_{H\pm}}{M_A}$



λ_{345} vs $\frac{M_{H\pm}}{M_H}$

Effect of updated constraints [especially: XENON1T] [1805.12562]

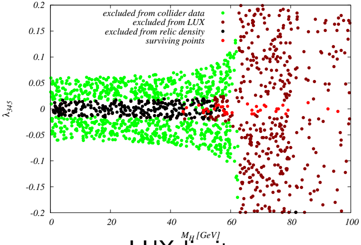
LUX **XENON**



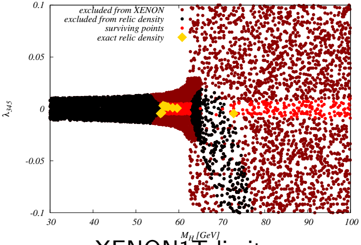
Cases where $M_H \leq M_h/2$

- **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 $M_H \sim 50\,\mathrm{GeV}$

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 expectional cases λ_{345} important; did not find such points

$\Rightarrow$ **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]

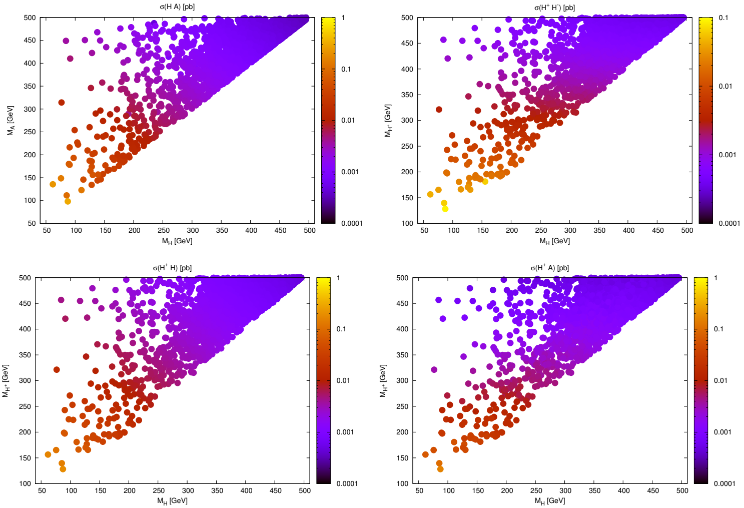


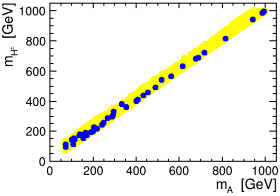
Figure : Production cross sections in pb at a 13 TeV LHC

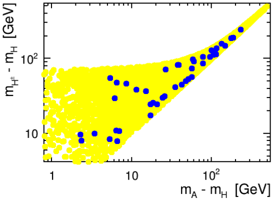
IDM at CLIC (new !!)

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

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 (new !!)

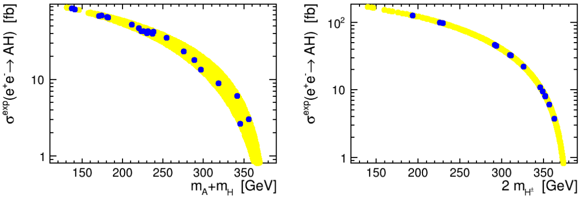
[slide from A.F.Zarnecki, CLICdp meeting, 08/18]

Analysis strategy

Production of IDM scalars at CLIC dominated by two processes:

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

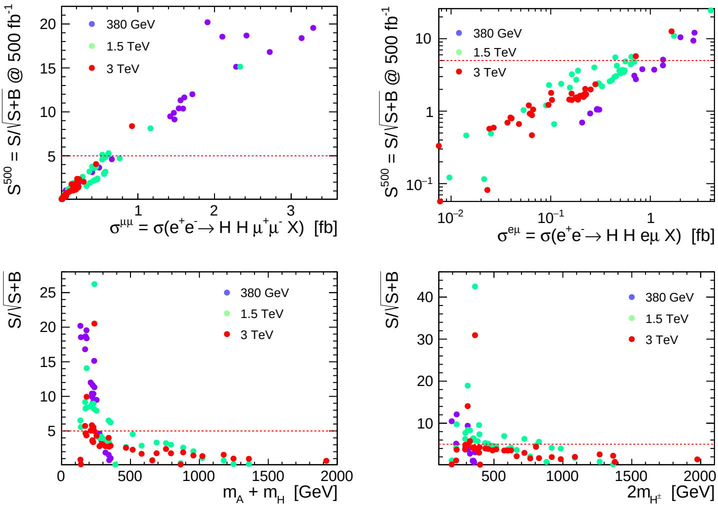
Leading-order cross sections for inert scalar production processes at 380 GeV:



Beam luminosity spectra not taken into account

Results for CLIC studies [using boosted decision trees]

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



Things I did not talk about

- **similar scan**, with focus on low mass regime: A. Belyaev ea [arXiv:1612.00511]

⇒ **results agree**, but more explicit plots for low mass range

⇒ **more parameter points in the low-m_H region**

⇒ find **same lowest mass for dark matter candidate**

- also important: **recasts for LHC**, e.g. Belanger ea [Phys.Rev. D91 (2015) no.11, 115011]; A. Belyaev ea [arXiv:1612.00511]

⟹ should/ could be turned around to devise optimized search strategies ⟸

so far, ⟹ **no (!) experimental study is publicly available interpreting in the IDM framework !! ⟸**

Summary

- **LHC run II in full swing** $\Rightarrow$ **exciting times ahead of us**
- one important question: **test Higgs sector**, especially wrt **extensions/ additional matter content**
- from current **LHC and astrophysical data: models already highly constrained**
- discussion here: **2HDM with dark matter (IDM)**
- **identified viable regions in parameter space**
- from these: **predictions for current LHC run**
  [A. Ilnicka, M. Krawzyk, TR, CERN Yellow Report]

$\Rightarrow$ **new : benchmarks for e^+e^- colliders**, and **first results**

!! stay tuned, and thanks for listening !!

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**
- CLIC Yellow Report, *to appear*

Very brief: parameters determining couplings (production and decay)

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

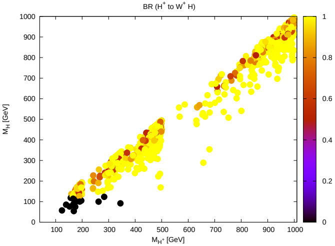
important couplings:

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

!! mainly determined by electroweak SM parameters !!

Aside: typical BRs [old values]

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



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

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

Total widths in IDM scenario [old]

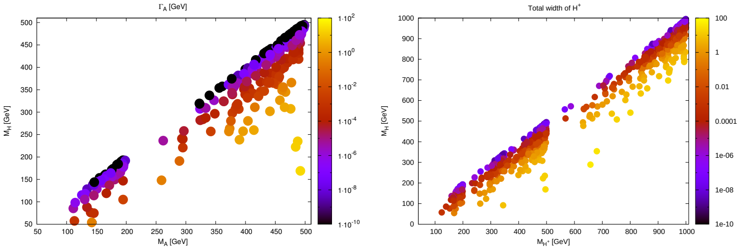
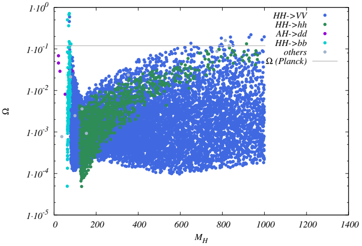
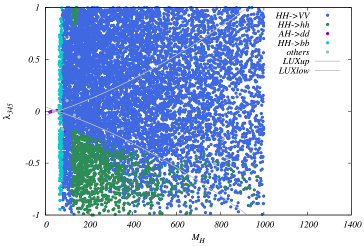


Figure : Total widths of unstable dark particles: A and $H^{\pm}$ in plane of their and dark matter masses.

Dark matter relic density

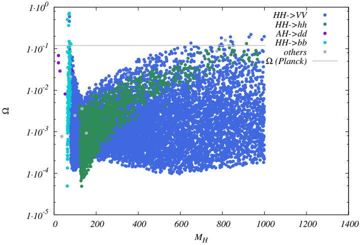


all but DM constraints

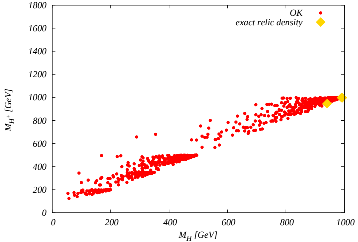


all but DM constraints

Dark matter relic density: exact limit vs upper bound



Ω vs m_H, all but DM constraints



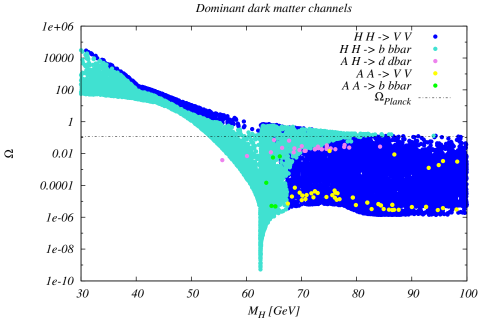
sample plot, M_H vs. $M_{H^\pm}$

General scan results

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

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

Dominant annihilation channels for the IDM



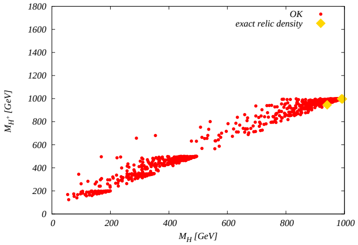
- dominant = **largest contribution** can be 51 % vs 49 %...
- as obtained from **MicroMegas 4.3.5**
- interesting/ promising: $A\,H \rightarrow d\,\bar{d}$;
  needs further investigation

... 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

$\Rightarrow$ points need to **have passed all bounds**

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

$\Rightarrow$ **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

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

Benchmarks submitted to Higgs Cross Section Working Group

all benchmarks: $A \to Z\,H = 100\,\%$

- **Benchmark I: low scalar mass**

$$M_H = 57.5\,\mathrm{GeV},\; M_A = 113.0\,\mathrm{GeV},\, M_{H^\pm} = 123\,\mathrm{GeV}$$

$HA : 0.371(4)\mathrm{pb},\; H^+\,H^- : 0.097(1)\mathrm{pb}$

- **Benchmark II: low scalar mass**

$$M_H = 85.5\,\mathrm{GeV},\; M_A = 111.0\,\mathrm{GeV},\, M_{H^\pm} = 140,\; \mathrm{GeV}$$

$HA : 0.226(2)\mathrm{pb},\, H^+H^- : 0.0605(9)\mathrm{pb}$

- **Benchmark III: intermediate scalar mass**

$$M_H = 128.0\,\mathrm{GeV},\; M_A = 134.0\,\mathrm{GeV},\, M_{H^\pm} = 176.0,\; \mathrm{GeV}$$

$H\,A : 0.0765(7)\mathrm{pb},\; H^+\,H^- : 0.0259(3)\mathrm{pb};$

Benchmark: high masses

- **Benchmark IV: high scalar mass, mass degeneracy**

$$M_H = 363.0\,\mathrm{GeV},\, M_A = 374.0\,\mathrm{GeV},\, M_{H^\pm} = 374.0\,\mathrm{GeV}$$

$H, A : 0.00122(1)\mathrm{pb},\ H^+H^- : 0.00124(1)\mathrm{pb}$

- **Benchmark V: high scalar mass, no mass degeneracy**

$$M_H = 311.0\,\mathrm{GeV},\, M_A = 415.0\,\mathrm{GeV},\, M_{H^\pm} = 447.0\,\mathrm{GeV}$$

$H, A : 0.00129(1)\mathrm{pb},\ H^+H^- : 0.000553(7)\mathrm{pb}$

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 $m_{\text{top}} \rightarrow \infty$ 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

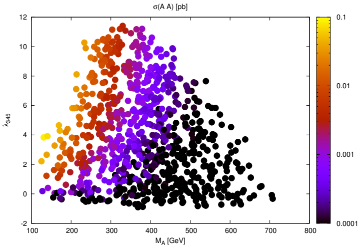
$$\sigma\,(M_H)\,\leq\,\sigma^{\text{LUX}}(M_H)\times\,\frac{\Omega^{\text{Planck}}}{\Omega(M_H)}$$

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

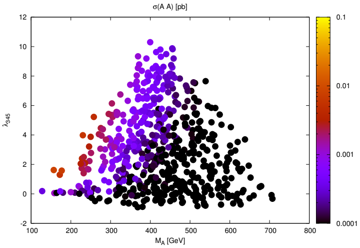
$\Rightarrow$ **influences especially AA production**

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

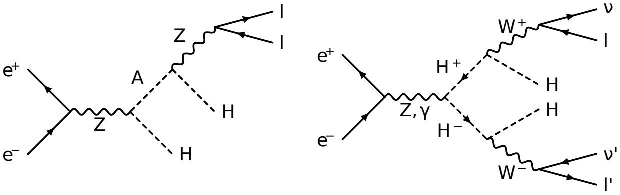
Analysis strategy

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

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

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

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

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)

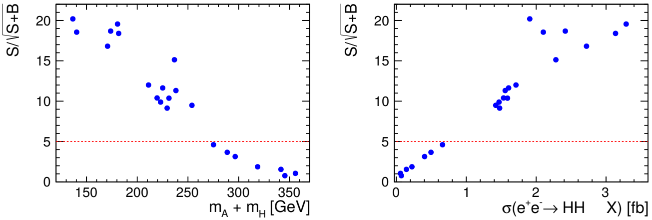
Generator level cuts reflecting detector acceptance:

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

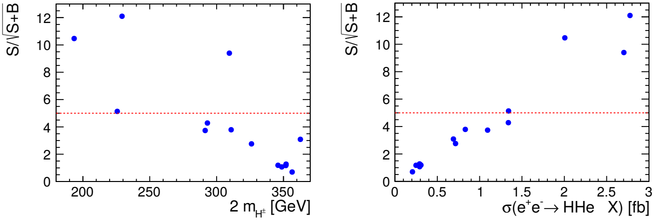
$5\,\sigma$ observation possible for signal cross section above about 1 fb (in the $\mu^+\mu^-$ channel)

$\Rightarrow$ 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