Signatures of new scalar particles at future e^+e^- colliders

EF/SNOWMASS21-EF9_EF2_Filip_Zarnecki-158

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(partially) based on

Phys.Rev. D93 (2016) no.5, 055026; Mod.Phys.Lett. A33 (2018) no.10n11, 1830007; JHEP 1812 (2018) 081 ;JHEP 1907 (2019) 053; CERN Yellow Rep. Monogr. Vol. 3 (2018); PoS CORFU2019 (2020) 047; work in progress

Ruder Boskovic Institute

EF02: LOIs
12.11.20

Inert doublet model: The model

2 Higgs Doublet Model, exact Z_2 symmetry

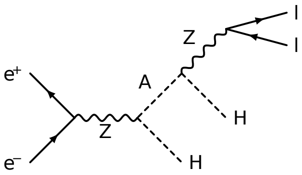
- scalar content: $h_{SM}, \underbrace{H, A, H^{\pm}}_{\text{dark}}$
- dark: no couplings to fermions, can only be pair-produced, DM candidate H
- many theorical and experimental constraints [see backup]
- in the end, depends on 7 free parameters

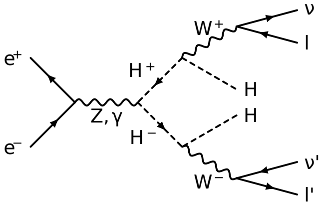
$$\mathbf{v},\ \mathbf{M_h},\ \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{345}\,[=\lambda_3+\lambda_4+\lambda_5]$$

v, M_h fixed [λs: couplings in potential]

Leptonic production modes

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



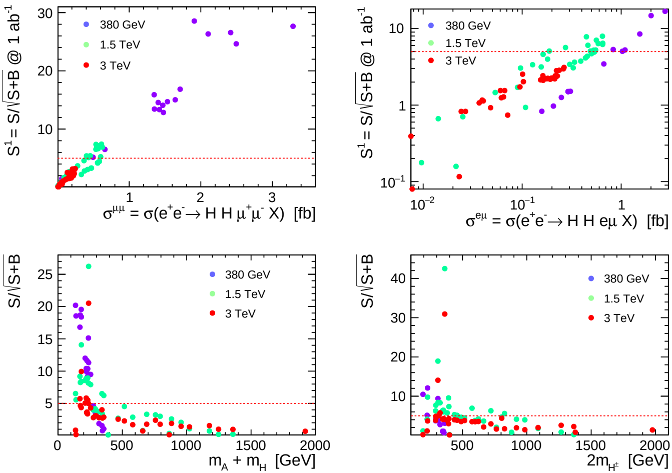


in reality: simulate ***everything* leading to** $\mu^+\mu^- + \not{E}, \mu^\pm e^\mp + \not{E}$

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

For selected benchmark points...

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



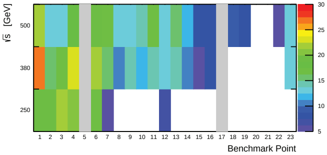
Results for ILC-type energies

[slides from A.F.Zarnecki, Snowmass meeting, 07/20]

Neutral IDM scalar production

Significance of observation scenario-independent approach

Summary of results for multivariate analysis of $\mu^+\mu^-$ final state
(generator level analysis, cuts reflecting detector acceptance)

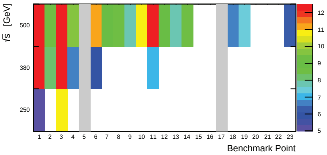


High significance of observation for scenarios accessible at given energy
Significance mainly related to the *AH* production cross section ⇒ scalar masses

Charged IDM scalar production

Significance of observation scenario-independent approach

Summary of results for multivariate analysis of $e^\pm\mu^\mp$ final state
(generator level analysis, cuts reflecting detector acceptance)



Fewer scenarios can be observed, clear need for 500 GeV
Significance mainly related to the H^+H^- production cross section ⇒ scalar mass

lesson: **sum of masses determine reach !** roughly:

$$230\,\text{GeV}@250\text{GeV},\ \sim\ 300\,\text{GeV}@380\,\text{GeV},\ \sim\ 380\text{GeV}@500\,\text{GeV}$$

[for points we considered]

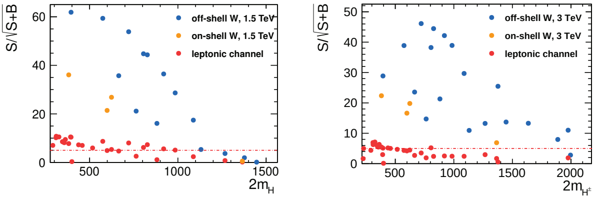
Semi-leptonic channel at CLIC

[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

2HDMa model

[slide from A.F.Zarnecki, CLICdp WG Analysis Meeting, 11/20]

Introduction

2HDM+a

Simplified model: two Higgs doublets (h, H, A, $H^{\pm}$)
+ scalar mediator (a) + fermion DM (χ)

Proposed for studies at LHC, but interesting signatures also for e^+e^-

Masses below TeV scale still not excluded by LHC…

[1] M.Bauer, U.Haisch, F.Kahlhoefer, *Simplified dark matter models with two Higgs doublets: I. Pseudoscalar mediators*, JHEP (2017) 05, arXiv:1701.07427.

[2] T.Abe et al. (LHC Dark Matter Working Group), *Next-generation spin-0 dark matter models*, arXiv:1810.09420.

Benchmark point

[slide from A.F.Zarnecki, CLICdp WG Analysis Meeting, 11/20]

Introduction

Benchmark scenario Tania Robens, private communication

We consider benchmark scenario with:

- m_H = 752.9 GeV
- m_a = 310.88 GeV
- m_A = 905.3 GeV
- $m_{H\pm}$ = 749.78 GeV
- m_χ = 112.28 GeV

Considered production channel:

$$e^+e^- \rightarrow H\,a$$

a is invisible (decays to $\chi\chi$), but H has ~33% chance to decay in $t\bar{t}$

Channels considered

[slide from A.F.Zarnecki, CLICdp WG Analysis Meeting, 11/20; Results from M. Giza]

Simulation

Software framework

- signal and background events were simulated with WHIZARD 2.7.0
  - CLIC luminosity spectra included with CIRCE2
- Detector response simulated with DELPHES
  - Jet energy smearing due to overlay events NOT taken into account (DELPHES problem)

Cross section estimates (for 3 TeV, negative polarisation):

- qW qW 141.86 fb
- qW qW νν 10.44 fb
- qW qW a 1.40 fb

Results

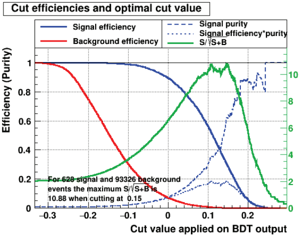
[slide from A.F.Zarnecki, CLICdp WG Analysis Meeting, 11/20; Results from M. Giza]

Results

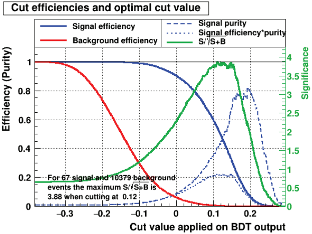
BDT training results for 3 TeV CLIC

Expected significance
for the expected integrated luminosity of 4000/1000 fb^{-1}

Negative electron polarisation



Positive electron polarisation



2HDMa study: conclusions
[slide from A.F.Zarnecki, CLICdp WG Analysis Meeting, 11/20]

Conclusions

- Production of 2HDM+a scalars at high energy CLIC considered for the process:

  $e^+e^- \rightarrow H\,a \rightarrow t\bar{t}\,\chi\chi$

- Only top-related background channels considered
- Most simplified analysis approach, based on “fat jet” reconstruction
- Final signal selection efficiency on 6-8% level
- Still, signal significance of ~10 σ very promising
- Significance of only about 1.2 σ at 1.5 TeV CLIC – too close to the production threshold

Summary

- **discussed several models and discovery potential at future e^+e^- colliders**
- **Inert Doublet Model at CLIC: reachability mainly determined by cross section/ mass scales**
- leptonic channel:
  up to $\sum_i M_i \sim 800\,\mathrm{GeV}$ can be reached at 1.5 TeV
  [can be enhanced up to $\sim 2\,\mathrm{TeV}$ for semi-leptonic decay]
- **IDM at ILC-like energies:**
  mass scales up to $380\,\mathrm{GeV}$ reachable at 500 GeV
- **2HDMa: study reveals high sensitivity at 3 TeV for mass scales around 1 TeV, for $t\bar{t} + \not{E}$ final states**

more to come

[did not mention Higgs portal model studies ⇒ maybe another talk ?]

Appendix

Number of free parameters and theory constraints

Model has 7 free parameters

- choose e.g.

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

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

Constraints: Theory

- **vacuum stability, positivity, constraints to be in inert vacuum**
- **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 ($\Gamma_h < 9\,\mathrm{MeV}$) (CMS, $80\,\mathrm{fb}^{-1}$) [Phys. Rev. D 99, 112003 (2019)]
- total width of W, Z
- collider constraints from signal strength/ direct searches;
- 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**

Production and decay

- Z_2 symmetry:

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

- production modes:

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

- decays:

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

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

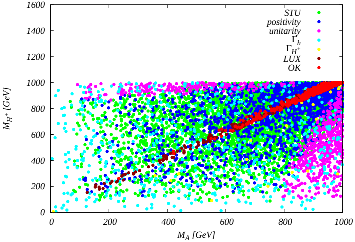
Parameters tested at colliders: mainly masses

- 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

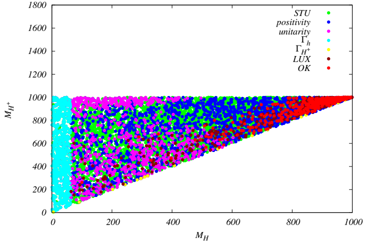
$\Rightarrow$ **high complementarity between astroparticle physics and collider searches**

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

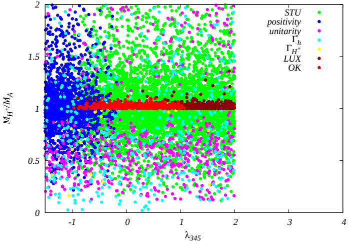
Results of generic scan [arXiv:1508.01671,arXiv:1809.07712]



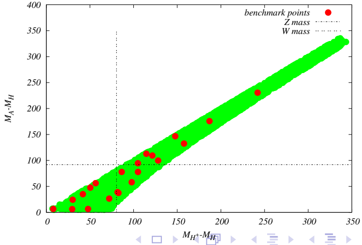
M_A vs $M_{H\pm}$



M_H vs $M_{H\pm}$



λ_{345} vs $M_{H\pm}/M_A$

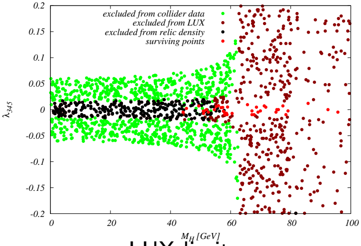


mass differences

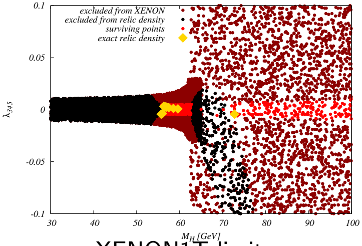
Cases where $M_H \leq M_h/2$

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

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

Benchmark points: JHEP 1812 (2018) 081; Analysis: JHEP 1907 (2019) 053 [J. Kalinowski, W. Kotlarski, TR, D. Sokolowska, A.F. Zarnecki]

IDM benchmark points

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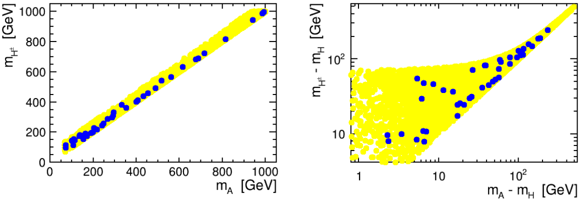
Out of about 15'000 points consistent with all considered constraints, we chose 43 benchmark points (23 accessible at 380 GeV) for detailed studies:



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

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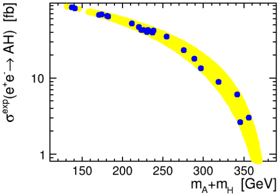
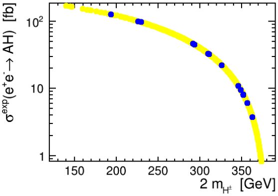
Production of IDM scalars at CLIC dominated by two processes:

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

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





Beam luminosity spectra not taken into account

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

Everything

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

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

BDT variables

- leptonic final states

$$E_{\ell\ell},\, M_{\ell\ell},\, P_\perp^{\ell\ell},\, \Theta_{\ell\ell},\, \beta_{\ell\ell},\; M_{\text{miss}} \tag{1}$$

  and lepton angles with respect to beam and dilepton boost directions.

- semi leptonc final states

$$M_{jj},\, E_{jj},\, \theta_{W^\pm},\, E_\ell,\, p_\perp^\ell,\, \not{E}_\perp,\, M_{\text{miss}},\, E_{\text{flow}}^{\text{sum}},\, \Delta\theta_{jW^\pm},\, \Delta\Phi_{jW^\pm} \tag{2}$$

Low mass benchmark points [arXiv:1809.07712]

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

High mass benchmark points [arXiv:1809.07712]

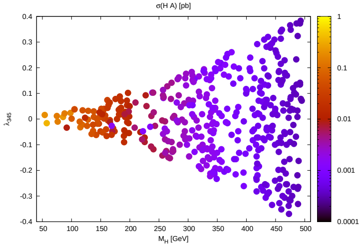
Backup slide

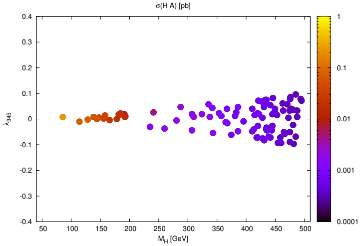
High mass IDM benchmark points

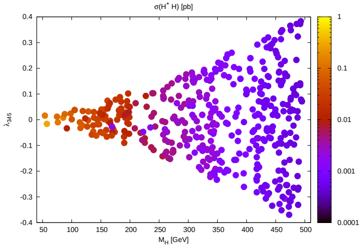
No.	M_H	M_A	$M_{H^\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
HP1	176	291.4	312	1.49	-0.1035	0.0007216
HP2	557	562.3	565.4	4.045	-0.1385	0.07209
HP3	560	616.3	633.5	3.38	-0.0895	0.001129
HP4	571	676.5	682.5	1.98	-0.471	0.0005635
HP5	671	688.1	688.4	1.377	-0.1455	0.02447
HP6	713	716.4	723	2.88	0.2885	0.03515
HP7	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

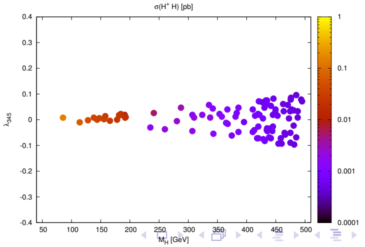
Effect of updated constraints [especially: XENON1T] [1805.12562]

LUX **XENON**









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]

$\Longrightarrow$ **should/ could be turned around to devise optimized search strategies** $\Longleftarrow$

so far, $\Longrightarrow$ **no (!) experimental study is publicly available interpreting in the IDM framework !!** $\Longleftarrow$

Very brief: parameters determining couplings (production and decay)

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

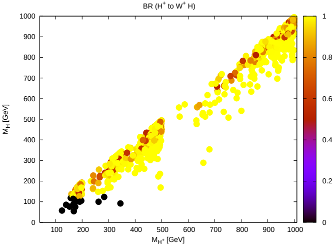
important couplings:

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

!! 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]

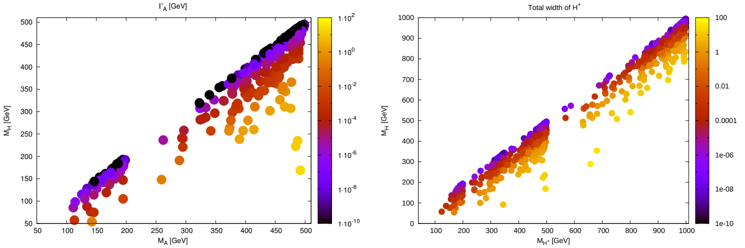
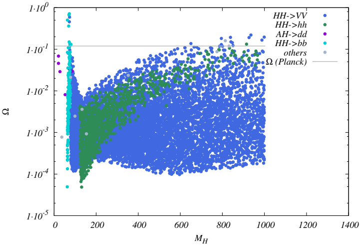
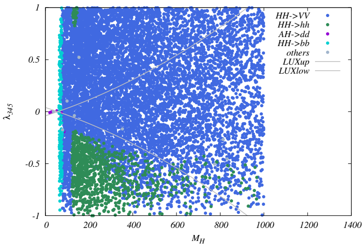


Figure : Total widths of unstable dark particles: A and $H^{\pm}$ in plane of their and dark matter masses.

Dark matter relic density

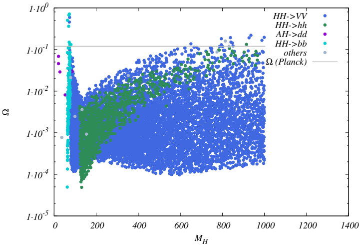


all but DM constraints

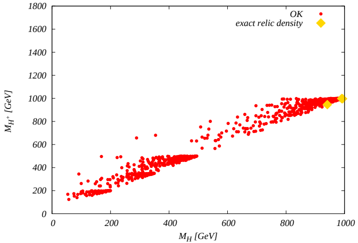


all but DM constraints

Dark matter relic density: exact limit vs upper bound



Ω vs m_H, all but DM constraints



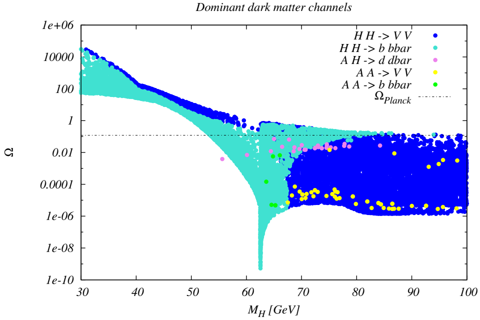
sample plot, M_H vs. $M_{H\pm}$

General scan results

⇒ 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

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 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**

Which other models are interesting/ similar/ ... ?

- prominent example: **2HDMa**

  [Ipek, McKeen, Nelson, '14; No, '15; Goncalves, Machado, No, '16; Bauer, Haisch, Kahlhoefer, '17; Tunney, No, Fairbairn, '17] [also: LHC DM Working Group, '18]

- **2 Higgs Doublet Model** (Type II), + **pseudoscalar** a (mixing with A), + **dark matter candidate** χ (fermionic)

$\Rightarrow$ currently a "prime" model of LHC DM working group !

[1810.09420]

- final states:

$$h + \not{E}_\perp,\; Z + \not{E}_\perp,\; Wt + \not{E}_\perp,\; t\bar{t} + \not{E}_\perp,\; g + \not{E}_\perp$$

$Z + \not{E}_\perp$: **similar to IDM ! comparable ?**

2HDMa: Lagrangian/ parameters

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

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

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

2HDMa scalar sector particle content: h, H, a, A, χ

parameters:

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

2HDMa (TR; work in progress)

- **started scan, including all relevant bounds**

  [boundedness and minimum of potential, perturbativity of couplings, perturbative unitarity; constraints from B-physics (mainly on $H^{\pm}$), direct searches, signal strength; dark matter relic density]

- results (preliminary): $B \to X_s\,\gamma\,:\; m_{H^\pm} \gtrsim 800\,\mathrm{GeV}$

$\Rightarrow$ similar range for H, A (STU/ perturbative unitarity/ ...)

- "standard" 2HDM constraints from signal strength in $\cos(\beta-\alpha)$, $\tan\beta$ plane
- can find viable points
- need to check: **recasts of current bounds in $h+\not{E}_\perp, Z+\not{E}_\perp$ searches** [CMS: Eur.Phys.J. C79 (2019) no.3, 280; ATLAS: JHEP 1905 (2019) 142, $36/37\mathrm{fb}^{-1}$]

work in progress $\Rightarrow$ stay tuned !

[Tools: Spheno/ Sarah/ HiggsBounds/ HiggsSignals/ MadDM/ Madgraph/ own codes]

2HDMa: Implemented constraints [see also 2001.10540]

Theory

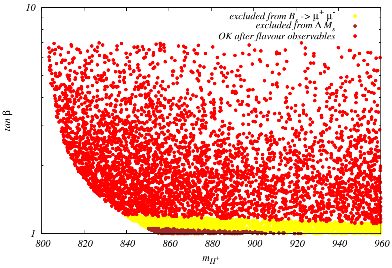
- boundedness of potential from below
- perturbativity of couplings
- perturbative unitarity

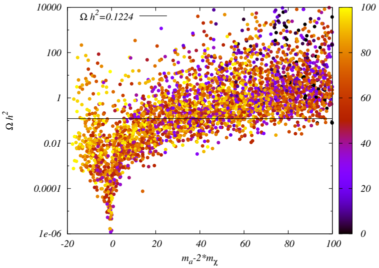
Experiment

- v, $m_{h/H}$: input
- electroweak precision through S, T, U
- $B \to X_s \gamma$, $B \to \mu^+\mu^-$, $Z \to b\,\bar{b}$
- Γ_{125}
- direct searches and signal strength through HiggsBounds/ HiggsSignals
- upper limit on relic density

also using: own codes, Spheno, Sarah, MadDM

Example results (TR; work in progress)





2HDMa Simulation

[slide from A.F.Zarnecki, CLICdp WG Analysis Meeting, 11/20]

Simulation

Top-quark pair-production events are expected to be selected with little background. Consider only two related background channels:

$$e^+e^- \rightarrow qW\,qW$$

consistent with $t\bar{t}$ production and decay
+ nonresonant contributions

$$e^+e^- \rightarrow qW\,qW\,\nu\nu$$

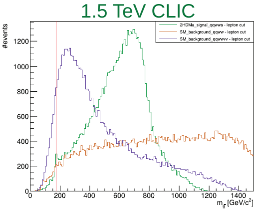
consistent with $t\bar{t}$ production in WW fusion process
+ nonresonant contributions

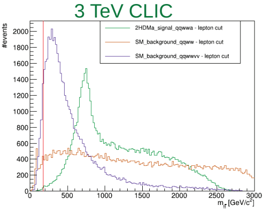
Distributions

[slide from A.F.Zarnecki, CLICdp WG Analysis Meeting, 11/20; Results from M. Giza]

Simulation

Comparison of the kinematic distributions for the produced top-quark pairs





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Analysis

[slide from A.F.Zarnecki, CLICdp WG Analysis Meeting, 11/20; Results from M. Giza]

Analysis

Signal-background discrimination and significance estimate with TMVA

Following variables were used as input to BDT:

- jet parameters: mass, transverse momenta, energy, polar angle (x 2)
- angles between two jets
- reconstructed H mass, energy, angle and boost
- reconstructed a mass

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