Inert Doublet Model

Tania Robens

based on work with

A. Ilnicka, M. Krawczyk, (D. Sokolowksa); A. Ilnicka, T. Stefaniak; D. Dercks; J. Kalinowski, W. Kotlarski, D. Sokolowsa, A. F. Zarnecki

Rudjer Boskovic Institute

Extended scalars group seminar
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Models with dark matter candidates: Inert Doublet Model

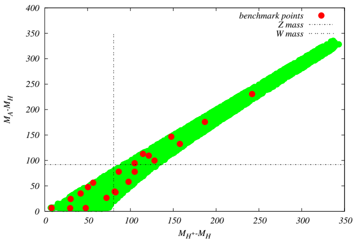
2 Higgs Doublet Model: 4 new scalars $H, A, H^\pm$

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

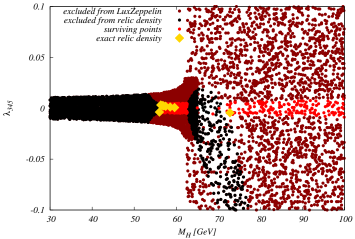
free parameters: **masses,** λ_2, λ_{345} (couplings in V)

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 ...
[update of Ilnicka, TR, Stefaniak, Mod.Phys.Lett. A33 (2018) no.10n11, 1830007]

Inert doublet model: The model

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

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

  ($\Rightarrow$ 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 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

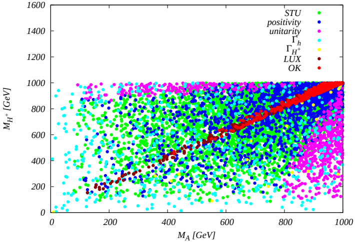
$$M_h = 125.1\,\mathrm{GeV},\; v = 246\,\mathrm{GeV}$$

- 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

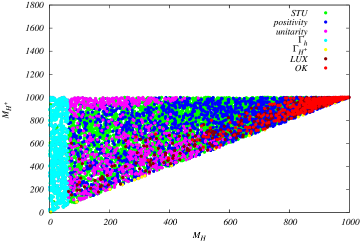
  (Lundstrom ea 2009; Belanger ea, 2015)
- dark matter relic density (upper bound)
- dark matter direct search limits (LUX-ZEPLIN)

⇒ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

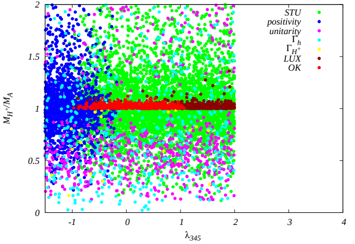
Results of generic scan [Phys.Rev.D 93 (2016) 5, 055026, JHEP 12 (2018) 081]



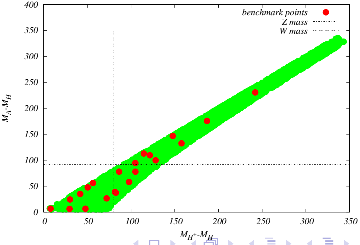
M_A vs $M_{H^\pm}$



M_H vs $M_{H^\pm}$



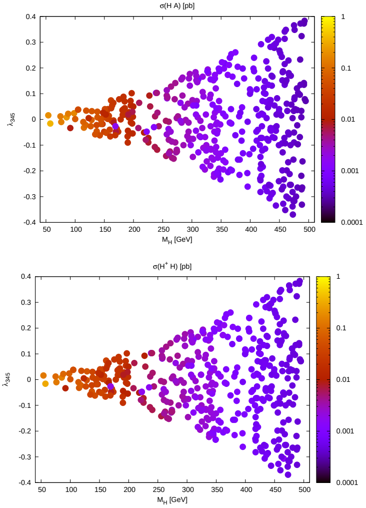
λ_{345} vs $M_{H^\pm}/M_A$



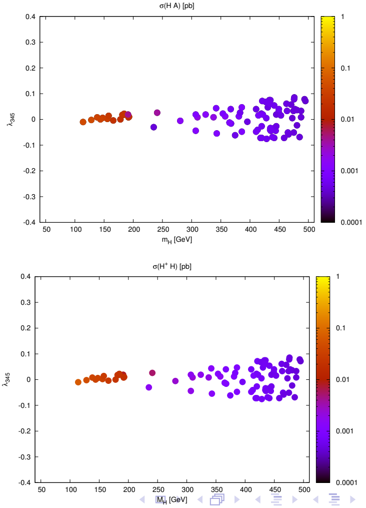
mass differences

Updated constraints [LUX-ZEPLIN] [arXiv:2207.03764]

LUX



LUX-ZEPLIN



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 $M_H \geq \frac{M_h}{2}$)

Recast of LHC Run II results

(in collaboration w D. Dercks, Eur.Phys.J.C 79 (2019) 11, 924))

- 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

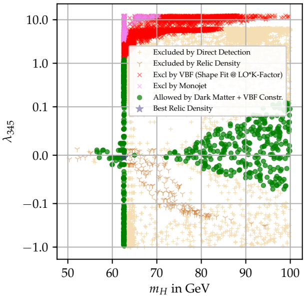
$\Rightarrow$ implemented in CheckMATE [currently: private version]

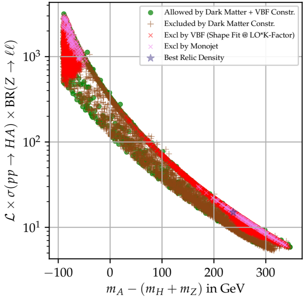
$\Rightarrow$ applied to IDM

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, Phys.Lett.B 793 (2019) 520-551, [$35.9\mathrm{fb}^{-1}$]

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, JHEP 01 (2018) 126, [$36.1\mathrm{fb}^{-1}$]

IDM at LHC





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

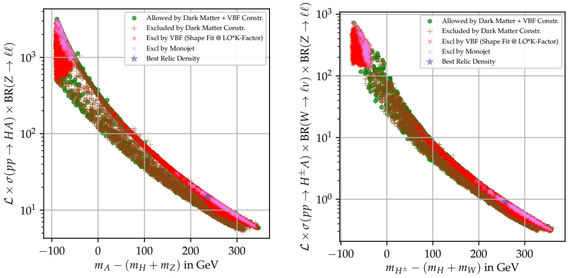
important constraints in offshell regime !

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)

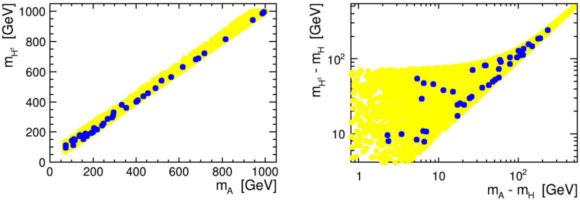
IDM at CLIC [slide from A.F.Zarnecki]

Benchmark points: JHEP 1812 (2018) 081; Analysis: JHEP 07 (2019) 053

[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

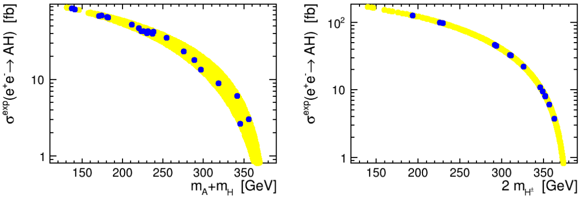
IDM at CLIC [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

Analysis strategy

Production of IDM scalars at CLIC dominated by two processes:

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

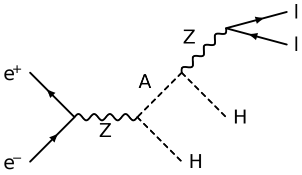
Leading-order cross sections for inert scalar production processes at 380 GeV:

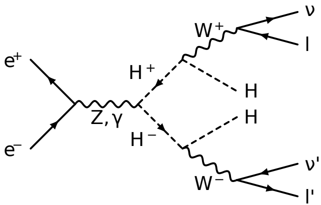


Beam luminosity spectra not taken into account

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** $\mu^+\mu^- + \not{E}, \mu^\pm e^\mp + \not{E}$

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)

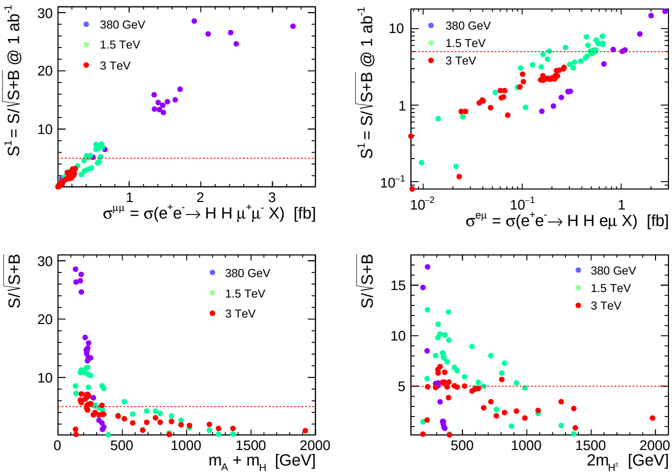
Generator level cuts reflecting detector acceptance:

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

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

For selected benchmark points...

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



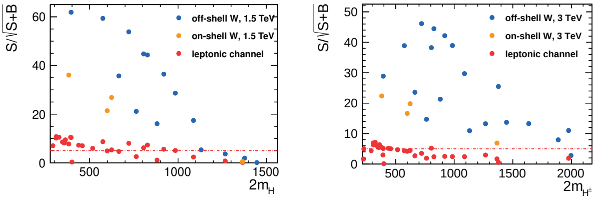
Semi-leptonic channel at CLIC

[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

"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**

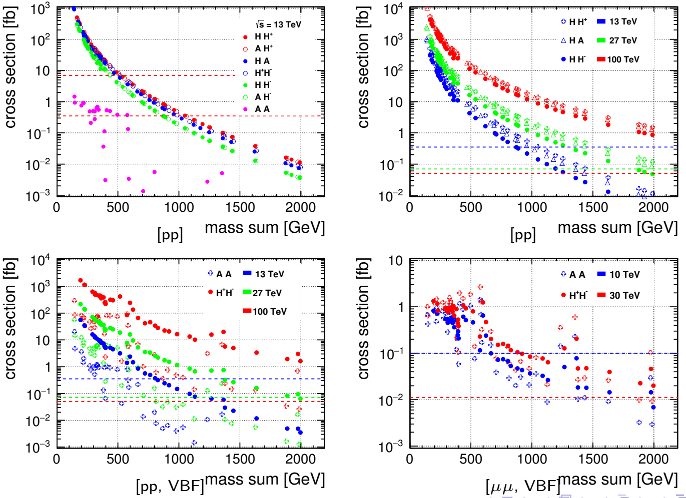
$\Rightarrow$ **include VBF-type topologies: VBF starts playing role**, especially at $\mu\mu$ colliders

Collider parameters

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

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

Commercial: *HHH* workshop in Dubrovnik, 14.-16.7.23

- Organizers:
  V. Brigljevic, D. Ferencek, G. Landsberg, TR, M. Stamenkovic [IRB, Croatia and Brown University, US]
- **https://indico.cern.ch/e/hhh2023**