Towards testing multi-scalar models at colliders

Dorota Sokołowska

IIP UFRN, Natal

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based on
IDM benchmarks for the LHC at 13 and 27 TeV with J. Kalinowski, W. Kotlarski, T. Robens, A. F. Żarnecki
and
work in progress with A. Cordero-Cid, J. Hernandez-Sanchez, V. Keus, S. Moretti, D. Rojas

Motivation

- **Standard Model:**
  - Higgs particle found at the LHC in 2012
  - no signal for New Physics as of 2018

- **Dark Matter:**
  - if Standard Cosmological Model correct: 85% of mass missing
  - only gravitational interaction observed
  - no (in)direct detection signal
  - nature of DM unknown – here we assume it is a WIMP

- **Models:**
  - the IDM
  - the 3HDM with two Inert and one Higgs doublets

Inert Doublet Model

2-Higgs Doublet Model with an exact Z_2 symmetry

$$\Phi_S = \begin{pmatrix} G^\pm \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}, \Phi_D = \begin{pmatrix} H^\pm \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

- Φ_S is the SM–like Higgs doublet, gives us SM-like Higgs
- Φ_D (inert doublet) has four additional scalars H, A, $H^\pm$,
- a discrete Z_2 symmetry:
  Φ_S is *even*: $\Phi_S \to \Phi_S$ (also SM→SM)
  Φ_D is *odd*: $\Phi_D \to -\Phi_D$,
- Yukawa-type interactions only for Higgs doublet (Φ_S):
  Φ_D does not interact with the SM fermions
- the lightest inert particle is stable: a natural candidate for DM
- we assume H is the DM particle

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

Parameters

- After EWSB, the model contains seven free parameters

$$\lambda_{1,2,3,4,5}, m_{11}^2, m_{22}^2$$

- λ_1, m_{11}^2 fixed from the SM (v, M_h)
- left with five free parameters, which we take as:
  - three inert scalar masses: M_H, M_A, $M_{H^\pm}$
  - two couplings, λ_2 and $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$
- inert scalars' couplings to γ, $W^\pm$ and Z determined by SM parameters

Constraints on parameters

All relevant experimental and theoretical constraints lead to:

- STU: $M_A < M_{H^\pm}$ and $M_{H^\pm} - M_A \lesssim 100\,\text{GeV}$
- $M_H < M_A < M_{H^\pm}$
- relic density & W, Z widths & Higgs invisible decays: $45\,\text{GeV} \lesssim M_H$
- exact relic density: 55 GeV $\lesssim M_H \lesssim$ 75 GeV and $M_H \gtrsim$ 525 GeV
- λ_2: no influence on tree-level DM annihilation, LHC physics
- λ_{345}: very strong constraints from LHC & DD & relic density
  $\rightarrow \lambda_{345} \sim \mathcal{O}(10^{-3})$ if 100% DM
  $\rightarrow$ after that almost no influence on collider physics
- 20 low mass BPs and 20 high mass BPs
- see details in: *Benchmarking the IDM, arXiv:1809.07712*

Testing IDM at DM experiments

Direct detection experiments (LUX, XENON, ...):

sensitive only to M_H and λ_{345}

No information about other masses!

We may be completely blind to the rest of the dark sector:

M_H	M_A	$M_{H\pm}$	λ_{345}	$\Omega_{DM}h^2$	$\sigma_{DM,N}$ [pb]
71.21	228.436	229.358	0.0023	0.11639	9.108e-12
71.24	289.42	305.317	-0.00238	0.12259	9.745e-12
71.33	354.408	366.476	-0.00234	0.11821	9.396e-12

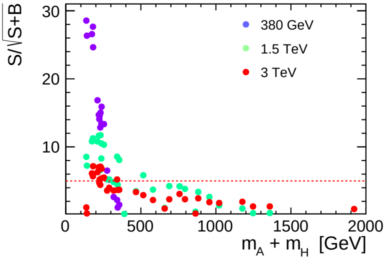
from Tania's scans

collider physics is sensitive to dark masses – complimentary approach

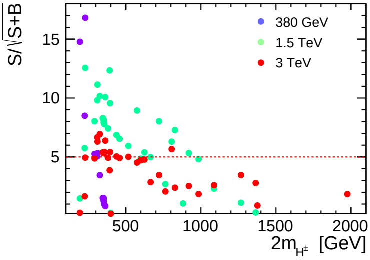
IDM Benchmarks at CLIC

See Wojtek's talk for details:

AH signature $(\mu^+\mu^-)$



H^+H^- signature $(\mu^\pm e^\mp)$



Relevant papers:
scan and constraints: Benchmarking the IDM, arXiv:1809.07712
CLIC analysis: Exploring Inert Scalars at CLIC, arXiv:1811.06952

IDM at the LHC

Production mechanism at the LHC:

- gauge channels (electroweak parameters)

$$pp \to HA,\ H^{\pm}H^{\mp},\ AH^{+},\ HH^{+}$$

- Higgs channel (Higgs-inert coupling, much smaller unless large λ_{345})

$$pp \to AA$$

Decays of heavy scalars:

- mass order $M_H < M_A < M_{H^\pm}$
- $A \to ZH$ – basically 100%
- $H^\pm \to W^\pm H$ – dominant; for most benchmarks BR > 0.99
- $H^\pm \to W^\pm A$ – subdominant, relevant for BP2,3

1000 events expected for:

$$13\ \text{TeV}\ (150\ \text{fb}^{-1}):\ \sigma = 7\ \text{fb}, \quad \text{HL}\ (3\ \text{ab}^{-1}):\ \sigma = 0.35\ \text{fb},$$
$$27\ \text{TeV}\ (15\ \text{ab}^{-1}):\ \sigma = 0.07\ \text{fb}$$

Low mass benchmark points [Points from arXiv:1809.07712]

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

from T. Robens, IDM benchmarks for the LHC at 13 and 27 TeV, WG3 extended scalars subgroup open meeting

High mass benchmark points [Points from arXiv:1809.07712]

No.	M_H	M_A	$M_{H^\pm}$	HA	$H\,H^+$	AH^+	H^+H^-	AA	onshell
HP1	176	291.36	311.96	8.3	8.8	4.0	3.1	0.1	W,Z
HP2	557	562.316	565.417	0.2	0.3	0.3	0.2	-	
HP3	560	616.32	633.48	0.1	0.2	0.2	0.1	0.003	
HP4	571	676.534	682.54	0.1	0.1	0.1	0.08	0.005	W,Z
HP5	671	688.108	688.437	0.07	0.1	0.09	0.07	-	
HP6	713	716.444	723.045	0.05	0.07	0.07	0.05	-	
HP7	807	813.369	818.001	0.03	0.04	0.04	0.03	-	
HP8	933	939.968	943.787	0.01	0.02	0.02	0.01	-	
HP9	935	986.22	987.975	0.009	0.01	0.01	0.009	-	
HP10	990	992.36	998.12	0.07	0.01	0.01	0.008	-	
HP11	250.5	265.49	287.226	5.8	6.3	5.7	4.0	-	
HP12	286.05	294.617	332.457	3.6	3.6	3.4	2.2	0.003	
HP13	336	353.264	360.568	1.7	2.2	2.0	1.5	0.001	
HP14	326.55	331.938	381.773	2.1	2.0	2.0	1.2	-	
HP15	357.6	399.998	402.568	1.1	1.5	1.2	1.0	0.006	
HP16	387.75	406.118	413.464	0.9	1.2	1.1	0.8	-	
HP17	430.95	433.226	440.624	0.6	0.8	0.8	0.6	-	
HP18	428.25	453.979	459.696	0.6	0.8	0.7	0.5	-	
HP19	467.85	488.604	492.329	0.4	0.5	0.5	0.4	-	
HP20	505.2	516.58	543.794	0.3	0.4	0.3	0.2	-	

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

$>$ 1000 events at HL-LHC for each process: HP1, HP11-19

from T. Robens, IDM benchmarks for the LHC at 13 and 27 TeV, WG3 extended scalars subgroup open meeting

27 TeV vs 13 TeV

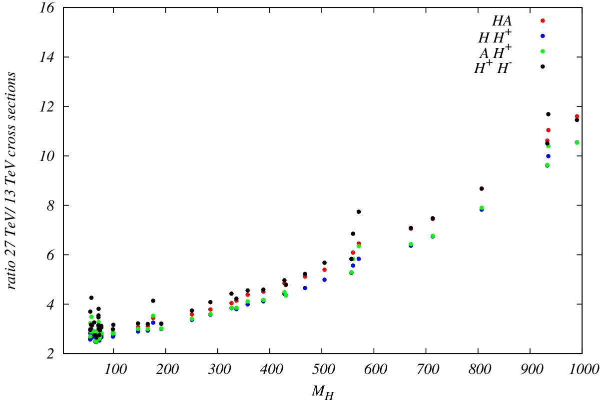


Figure : Ratio of production cross sections for the four dominant production channels at the 27 TeV HE-LHC and current center-of-mass energy of 13 TeV. While in the low energy range, cross sections are enhanced roughly by a factor $\lesssim 3$, for higher masses they can change by an order of magnitude.

3HDM

Z_2-symmetric 3HDM:

$$\phi_1 = \left(\begin{array}{c} H_1^+ \\ \frac{H_1+iA_1}{\sqrt{2}} \end{array} \right), \quad \phi_2 = \left(\begin{array}{c} H_2^+ \\ \frac{H_2+iA_2}{\sqrt{2}} \end{array} \right), \quad \phi_3 = \left(\begin{array}{c} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{array} \right),$$

$$\phi_1 \to -\phi_1, \phi_2 \to -\phi_1, \phi_3 \to \phi_3$$

Potential (many free parameters):

$$\begin{aligned}
V_{3HDM} &= V_0 + V_{Z_2}, \\
V_0 &= -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) - \mu_3^2(\phi_3^\dagger\phi_3) \\
&\quad +\lambda_{11}(\phi_1^\dagger\phi_1)^2 + \lambda_{22}(\phi_2^\dagger\phi_2)^2 + \lambda_{33}(\phi_3^\dagger\phi_3)^2 \\
&\quad +\lambda_{12}(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_{23}(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) + \lambda_{31}(\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1) \\
&\quad +\lambda'_{12}(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda'_{23}(\phi_2^\dagger\phi_3)(\phi_3^\dagger\phi_2) + \lambda'_{31}(\phi_3^\dagger\phi_1)(\phi_1^\dagger\phi_3), \\
V_{Z_2} &= -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c.
\end{aligned}$$

Certain parameters can be complex even with Z_2 symmetry.

Physical states

- SM-like Higgs particle from ϕ_3:

$$M_h = 125.1\,\mathrm{GeV}$$

- **4 charged inert scalars** $S_1^\pm, S_2^\pm$

$$\begin{pmatrix} S_1^\pm \\ S_2^\pm \end{pmatrix} = \begin{pmatrix} \cos\alpha_c & \sin\alpha_c \\ -\sin\alpha_c & \cos\alpha_c \end{pmatrix} \begin{pmatrix} H_1^\pm \\ H_2^\pm \end{pmatrix}$$

- **4 neutral scalars**

  → complex parameters in V: $\lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c.$

  → neutral states with mixed CP:

$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix} = R_{ij} \begin{pmatrix} H_1 \\ H_2 \\ A_1 \\ A_2 \end{pmatrix}$$

Production of inert scalars at the LHC

- gauge channels (EW parameters + rotation matrix)

$$pp \to S_1 S_2,\ S_1 S_3,\ S_1 S_4,\ S_2 S_3,\ S_2 S_4,\ S_3 S_4$$

$$pp \to S^+_{1,2} S^-_{1,2},\ S^+_{1,2} S_{1,2,3,4}$$

- **more channels than in the IDM**

$$pp \to HA, H^\pm H^\mp, AH^+, HH^+$$

- **more channels than in the CPC 3HDM**

$$pp \to H_1 A_1, H_2 A_2, H_1 A_2, H_2 A_1$$

$$pp \to H^\pm_{1,2} H^\mp_{1,2}, A_{1,2} H^+_{1,2}, H_{1,2} H^+_{1,2}$$

- Higgs channels (Higgs-inert couplings)

$$pp \to h \to S_i S_i, i = 2, 3, 4$$

$$pp \to h \to S_i S_j, i \neq j$$

Example – Benchmark A

- agreement with all constraints
- relatively uniform distribution of masses with medium ΔM:

$$M_{S_1}=72.33 \text{ GeV}, \quad M_{S_2}=103.31 \text{ GeV}, \quad M_{S_3}=129.467 \text{ GeV},$$
$$M_{S_4}=155.178 \text{ GeV}, \quad M_{S_1^\pm}=106.235 \text{ GeV}, \quad M_{S_2^\pm}=157.588 \text{ GeV}$$

- **Higgs-inert couplings:**

$g_{hS_1S_1} = -0.002,\ g_{hS_1S_2} = 0.0012,\ g_{hS_1S_3} = 0.0011,\ g_{hS_1S_4} = 0.012$

$\rightarrow$ definitely not negligible wrt to $g_{hS_1S_1}$

- **Z-inert couplings:**

$$g_{ZS_1S_2} = 0.366, \quad g_{ZS_1S_3} = 0.0397, \quad g_{ZS_1S_4} = -0.04$$
$$g_{ZS_2S_3} = -0.04, \quad g_{ZS_2S_4} = -0.0397, \quad g_{ZS_3S_4} = 0.366$$

- expected change in cross-section wrt to the IDM/CPC 3HDM
- other features?

Conclusions

for the IDM:

- promising production cross-sections for inert scalars in the IDM for future runs
- 19 BPs can be properly investigated at the current LHC run
- HL-LHC (3 ab^{-1}) – access to masses up to 500 GeV
- HE-LHC – all BPs and HPs accessible
- can we really identify it as the IDM signal?

for the 3HDM:

- many more channels – different signatures?
- work in progress – but can we see any CP effects?