Inert Doublet Model

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)

Ruder Boskovic Institute

Spring 2020 LHC DM WG meeting:
DM models with t-channel mediators (Wildcard Session)

28.04.20

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

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

- total width of M_h ($\Gamma_h < 9\,\text{MeV}$) (CMS, $80\,\text{fb}^{-1}$) [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:

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

- decays:

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

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

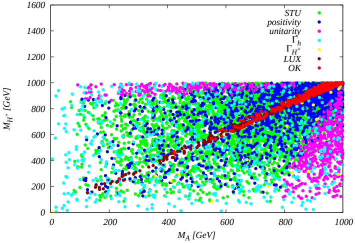
Parameters tested at colliders: mainly masses

- 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

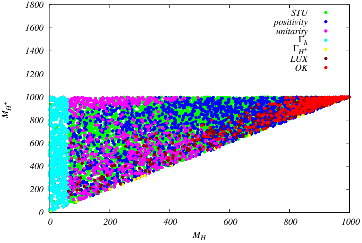
$\Rightarrow$ **high complementarity between astroparticle physics and collider searches**

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

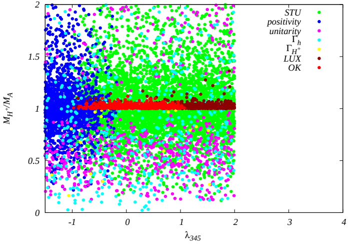
Results of generic scan [arXiv:1508.01671,arXiv:1809.07712]



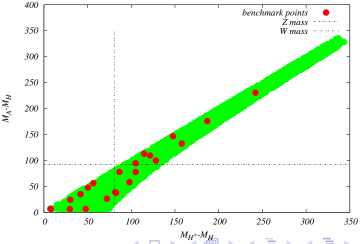
M_A vs $M_{H\pm}$



M_H vs $M_{H\pm}$



λ_{345} vs $M_{H\pm}\,/\,M_A$

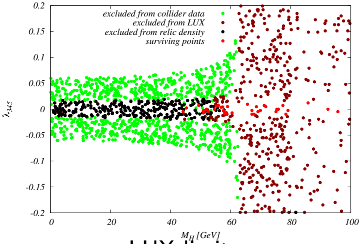


mass differences

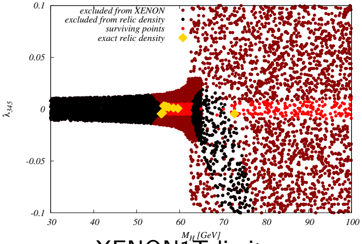
Cases where $M_H \leq M_h/2$

- **discussion so far:** decay $h \to H\,H$ 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 $M_H \sim 50\,\mathrm{GeV}$

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

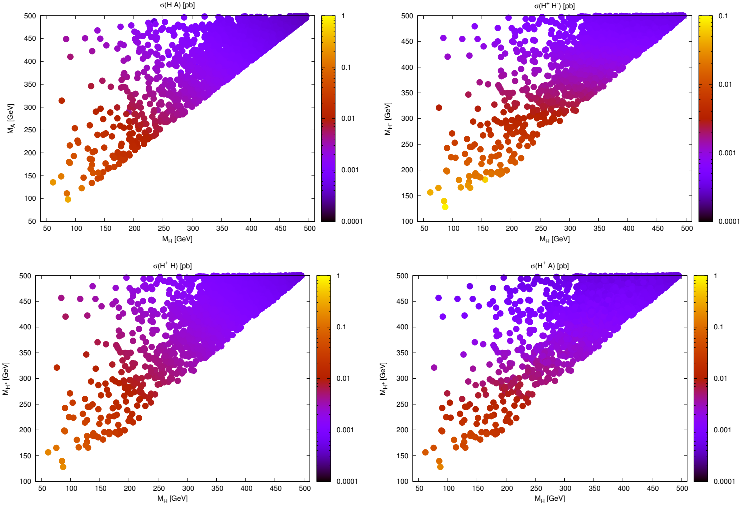


Figure : Production cross sections in pb at a 13 TeV LHC

IDM recast (in collaboration w D. Dercks, arXiv:1812.07913)

- considered a long list of processes at 13 TeV
- most sensitive:

VBF + invisible Higgs decay (by far), Monojet

⇒ implemented in CheckMATE [currently: private version]

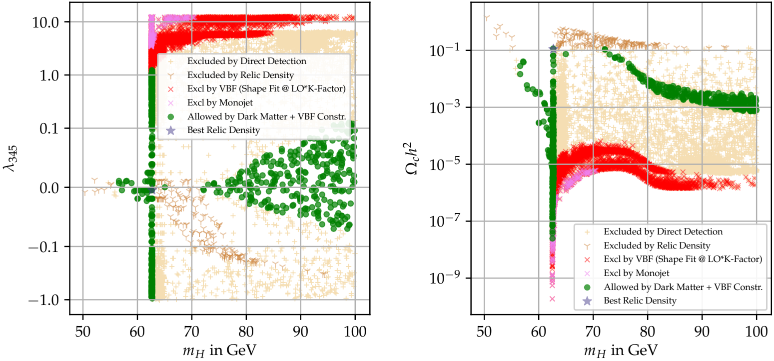
⇒ applied to IDM

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: Results

after recast



What about other channels ?

- largest production cross sections:

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

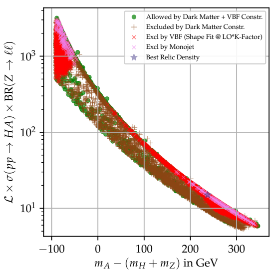
- lead to **single- or dilepton final states + $\not{E}_{\perp}$**

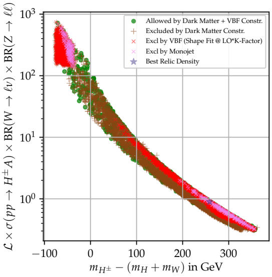
  [previous study: G. Belanger, B. Dumont, A. Goudelis, B. Herrmann, S. Kraml, D. Sengupta, arXiv:1503.07367]

- 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)

$^{(*)}(m_H - m_A > x\,\mathrm{GeV}$, lower bound on $m_H \sim 50\,\mathrm{GeV} \Rightarrow m_H + m_A \gtrsim (100 + x)\,\mathrm{GeV})$

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

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

Summary

Inert Doublet Model

- **intriguing new physics model with a scalar dark matter candidate**
- signature: **electroweak gauge boson(s) + MET**, and/ or Higgs $\to$ invisible
- pair-production of dark scalars can reach pb **regime at 13 TeV**

$\Rightarrow$ typically **2 dimensional scan in masses** (couplings from SM electroweak sector)

- recast for dilepton searches:

need to venture into low MET region

$\Rightarrow$ already nice results for e^+e^- colliders [arXiv:1811.06952, arXiv:1812.02093, arXiv:2002.11716, ongoing work]

so far no dedicated public results from LHC

LHC pheno studies [I am aware of]

- E. Dolle, X. Miao, S. Su, and B. Thomas. *Dilepton Signals in the Inert Doublet Model*, Phys.Rev., D81:035003, 2010, 0909.3094 X. Miao, S. Su, and B. Thomas, *Trilepton Signals in the Inert Doublet Model*, Phys. Rev.D82 (2010) 035009, 1005.0090
- M. Gustafsson, S. Rydbeck, L. Lopez-Honorez, and E. Lundstrom. *Status of the Inert Doublet Model and the Role of multileptons at the LHC.* Phys. Rev., D86:075019, 2012, 1206.6316.
- P. Poulose, S. Sahoo, and K. Sridhar. *Exploring the Inert Doublet Model through the dijet plus missing transverse energy channel at the LHC*, Phys. Lett., B765:300-306, 2017, 1604.03045.
- A. Datta, N. Ganguly, N. Khan, and S. Rakshit. *Exploring collider signatures of the inert Higgs doublet model*, Phys. Rev., D95(1):015017, 2017, 1610.00648
- B. Dutta, G. Palacio, J. D. Ruiz-Alvarez, and D. Restrepo, *Vector Boson Fusion in the Inert Doublet Model*, Phys. Rev. D97 (2018), no. 5 055045, 1709.09796
- N. Wan, N. Li, B. Zhang, H. Yang, M.-F. Zhao, M. Song, G. Li, and J.-Y. Guo. *Searches for Dark Matter via Mono-W Production in Inert Doublet Model at the LHC*, Commun. Theor. Phys., 69(5):617, 2018.
- A. Belyaev, T. R. Fernandez Perez Tomei, P. G. Mercadante, C. S. Moon, S. Moretti, S. F. Novaes, L. Panizzi, F. Rojas, and M. Thomas. *Advancing LHC probes of dark matter from the inert two-Higgs-doublet model with the monojet signal*,Phys. Rev., D99(1):015011, 2019, 1809.00933
- A. Bhardwaj, P. Konar, T. Mandal, and S. Sadhukhan, *Probing the inert doublet model using jet substructure with a multivariate analysis*, Phys.Rev. D100 (2019) no.5, 055040, 1905.04195

Appendix

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

Low mass benchmark points [Points from arXiv:1809.07712]

No.	M_H	M_A	$M_{H^\pm}$	HA	$H\,H^+$	AH^+	H^+H^-	AA
BP1	72.77	107.803	114.639	846	770	440	364	1.5
BP2	65	71.525	112.85	2535	909	813	384	0.5
BP3	67.07	73.222	96.73	2268	1245	1102	642	0.5
BP4	73.68	100.112	145.728	982	432	307	165	1.1
BP6	72.14	109.548	154.761	824	379	241	135	1.6
BP7	76.55	134.563	174.367	470	266	143	91	1.9
BP8	70.91	148.664	175.89	395	276	122	89	2.3
BP9	56.78	166.22	178.24	347	308	100	86	2.8
BP10	76.69	154.579	163.045	332	315	131	114	2.2
BP11	98.88	155.037	155.438	249	271	142	131	1.0
BP12	58.31	171.148	172.96	313	330	100	95	2.8
BP13	99.65	138.484	181.321	317	189	127	80	1.3
BP14	71.03	165.604	175.971	297	275	102	89	2.4
BP15	71.03	217.656	218.738	138	152	44	44	2.4
BP16	71.33	203.796	229.092	167	133	45	38	2.4
BP18	147	194.647	197.403	90	98	64	58	0.5
BP19	165.8	190.082	195.999	78	84	67	58	0.02
BP20	191.8	198.376	199.721	57	64	61	54	0.002
BP21	57.475	288.031	299.536	65	66	15	17	2.2
BP22	71.42	247.224	258.382	95	95	26	26	2.2
BP23	62.69	162.397	190.822	346	240	91	69	2.6

Production cross sections in fb, at 27 TeV [UFO+Madgraph]

High mass benchmark points [Points from arXiv:1809.07712]

No.	M_H	M_A	$M_{H^\pm}$	HA	HH^+	AH^+	H^+H^-	AA
HP1	176	291.36	311.96	29	28	14	13	0.8
HP2	557	562.316	565.417	1.1	1.4	1.4	1.1	-
HP3	560	616.32	633.48	0.9	1.1	0.9	0.8	0.03
HP4	571	676.534	682.54	0.7	0.9	0.6	0.6	0.06
HP5	671	688.108	688.437	0.5	0.6	0.6	0.5	0.002
HP6	713	716.444	723.045	0.4	0.5	0.5	0.4	-
HP7	807	813.369	818.001	0.2	0.3	0.3	0.2	-
HP8	933	939.968	943.787	0.1	0.2	0.2	0.1	-
HP9	935	986.22	987.975	0.1	0.1	0.1	0.1	0.004
HP10	990	992.36	998.12	0.09	0.1	0.1	0.09	-
HP11	250.5	265.49	287.226	21	21	20	15	0.005
HP12	286.05	294.617	332.457	14	13	12	9.1	0.02
HP13	336	353.264	360.568	7.2	8.4	7.8	6.5	0.01
HP14	326.55	331.938	381.773	8.5	7.9	7.8	5.4	-
HP15	357.6	399.998	402.568	5.0	6.1	5.0	4.3	0.04
HP16	387.75	406.118	413.464	4.2	5.0	4.7	3.9	0.004
HP17	430.95	433.226	440.624	3.0	3.6	3.7	3.0	-
HP18	428.25	453.979	459.696	2.8	3.4	3.1	2.6	0.008
HP19	467.85	488.604	492.329	2.0	2.5	2.4	2.0	0.004
HP20	505.2	516.58	543.794	1.6	1.8	1.7	1.3	-

Production cross sections in fb, at 27 TeV [UFO+Madgraph]

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:**

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

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

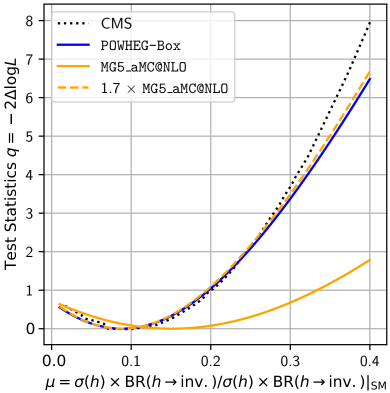
IDM recast: validation

- 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



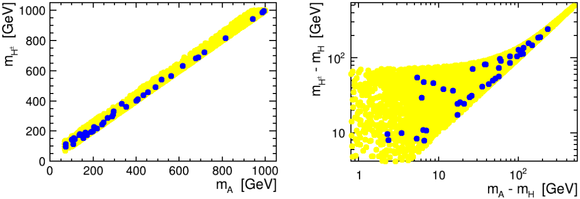
IDM at CLIC [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

Benchmark points: JHEP 1812 (2018) 081; Analysis: JHEP 1907 (2019) 053

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

IDM benchmark points

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

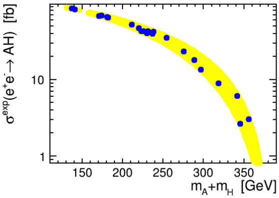
IDM at CLIC [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

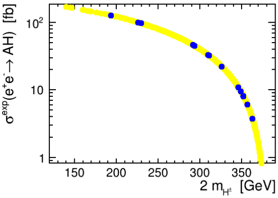
Analysis strategy

Production of IDM scalars at CLIC dominated by two processes:

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

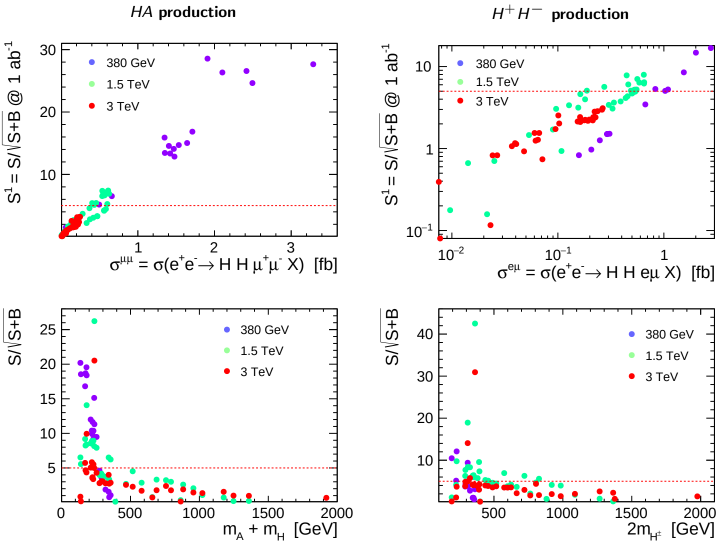
Leading-order cross sections for inert scalar production processes at 380 GeV:





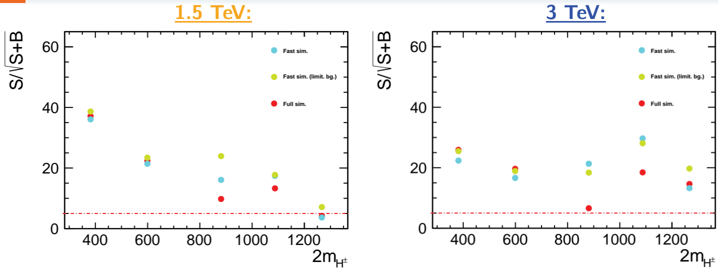
Beam luminosity spectra not taken into account

Results for CLIC studies [using boosted decision trees]



Most recent results [from J. Klamka, talk at CLICdp WG Analysis Meeting, 27.4.20]

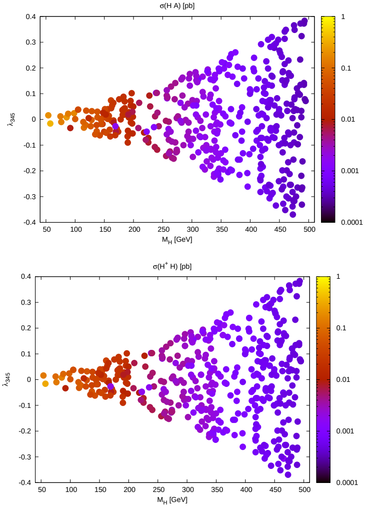
Results (fast vs. full simulation)



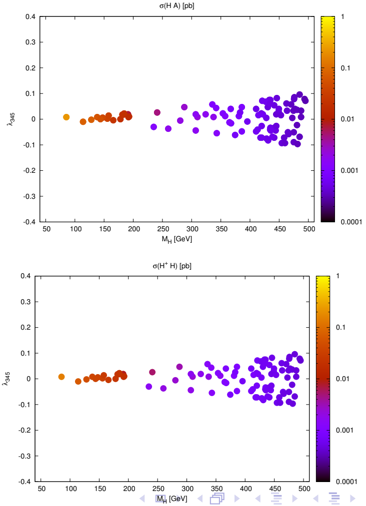
- Good results at **1.5 TeV**, a little bit worse at **3 TeV**
- **Small gap** for scenarios with **on-shell W**
- Higher decrease in significance for scenarios with smaller $m_{H^\pm} - m_H$

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

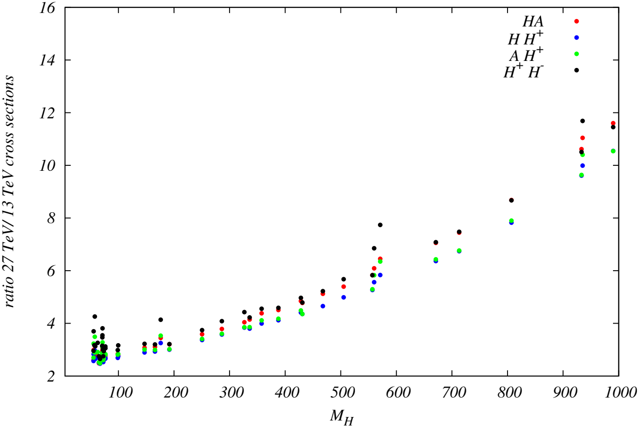
LUX



XENON



... 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

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 !! ⟸**

Very brief: parameters determining couplings (production and decay)

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

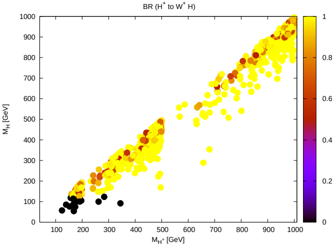
important couplings:

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

!! mainly determined by electroweak SM parameters !!

Aside: typical BRs [old values]

- decay $A \to H\,Z$ 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]

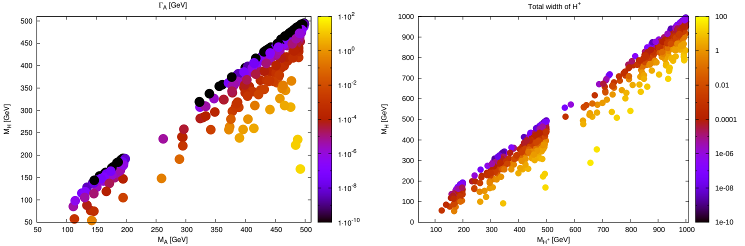
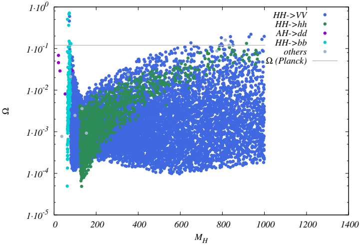
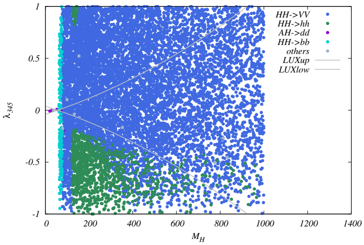


Figure : Total widths of unstable dark particles: A and $H^\pm$ in plane of their and dark matter masses.

Dark matter relic density

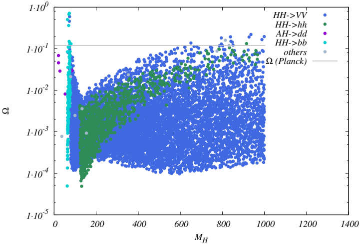


all but DM constraints

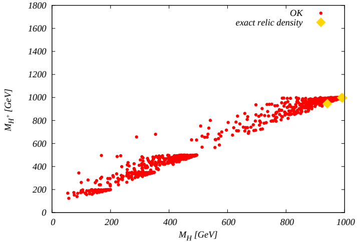


all but DM constraints

Dark matter relic density: exact limit vs upper bound



Ω vs m_H, all but DM constraints



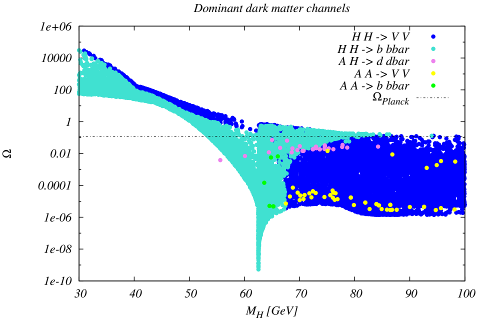
sample plot, M_H vs. $M_{H^\pm}$

General scan results

$\Rightarrow$ window with $m_H \in [100\,\text{GeV}; 600\text{GeV}]$ **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

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

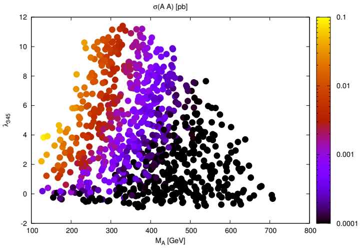
$$\sigma\,(M_H)\,\leq\,\sigma^{\text{LUX}}(M_H)\times\,\frac{\Omega^{\text{Planck}}}{\Omega(M_H)}$$

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

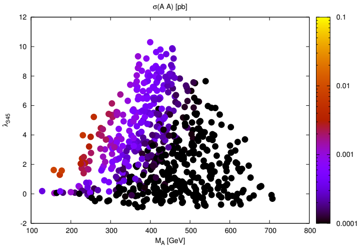
$\Rightarrow$ **influences especially AA production**

AA production with rescaled dark matter

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



[old]



[new]

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