

IDM benchmarks for the LHC at 13 and 27 TeV

Tania Robens

based on work with

A. Ilnicka, M. Krawczyk, (D. Sokolowska)

(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

(contribution to CLIC Yellow Report; arXiv:1809.07712)

[see also LHC Dark Matter Working Group, arXiv:1810.09420]

Ruder Boskovic Institute

WG3 extended scalars subgroup open meeting

24.10.18

Inert doublet model: The model

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

$$\phi_D \rightarrow -\phi_D, \phi_S \rightarrow \phi_S, \text{SM} \rightarrow \text{SM}$$

(\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

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

⇒ minimize potential

⇒ determine number of free parameters

Number of free parameters here: 7

- e.g.

$$\mathbf{v}, \mathbf{M}_h, \mathbf{M}_H, \mathbf{M}_A, \mathbf{M}_{H^\pm}, \lambda_2, \lambda_{345} [= \lambda_3 + \lambda_4 + \lambda_5]$$

- v, M_h fixed ⇒ left with **5 free parameters**

Constraints: Theory

⇒ **consider all current constraints on the model** ⇐

- Theory constraints: **vacuum stability, positivity, constraints to be in inert vacuum**
⇒ **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

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

- total width of M_h ($\Gamma_h < 13 \text{ MeV}$); \Rightarrow JHEP, 09:051, 2016^(*)
 - total width of W, Z
 - collider constraints from signal strength/ direct searches;
 $R_{\gamma\gamma}$ and $\text{BR}_{h \rightarrow \text{inv}}$ 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**

^(*) newest result: $\Gamma_h \leq 9 \text{ MeV}$ (CMS-PAS-HIG-18-002), not yet updated

Production and decay

- Z_2 symmetry:

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

- production modes:

$$pp \rightarrow HA, HH^\pm, AH^\pm, H^+H^-$$

- decays:

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

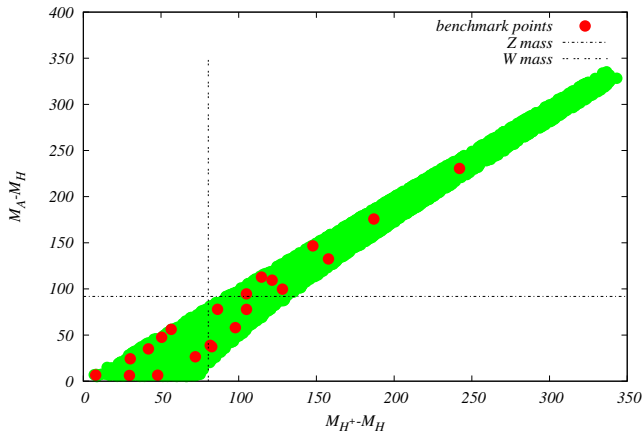
signature: **electroweak gauge boson(s) + MET**

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

Distribution in the mass plane [arXiv:1809.07712]



mainly from electroweak constraints

Low mass benchmark points [Points from arXiv:1809.07712]

No.	M_H	M_A	M_{H^\pm}	HA	HH^+	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

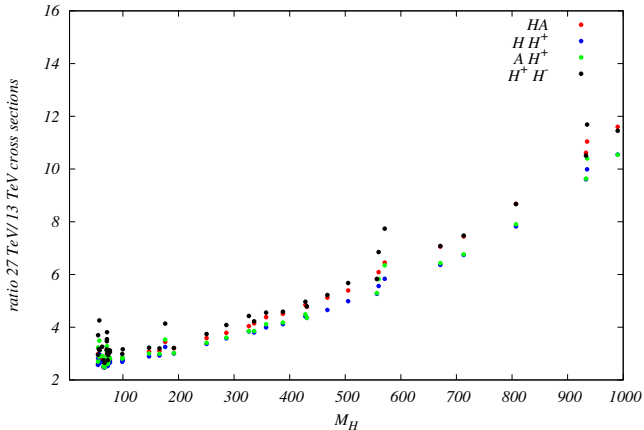
High mass benchmark points [Points from arXiv:1809.07712]

No.	M_H	M_A	M_{H^\pm}	HA	HH^+	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**

... and at 27 TeV... [15 ab⁻¹]



at high masses, **increase up to one order of magnitude**
all BPs and HPs more than 1000 events for total run

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	HH^+	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]

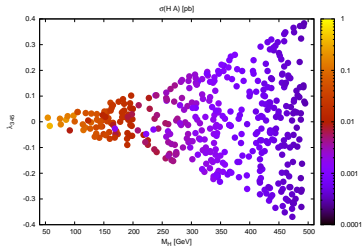
High mass benchmark points [Points from arXiv:1809.07712]

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	-

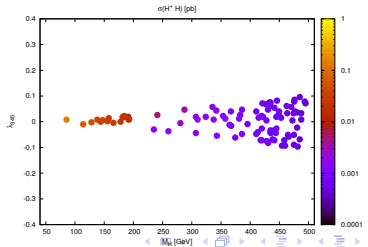
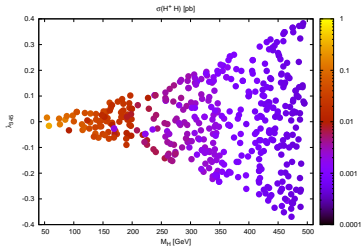
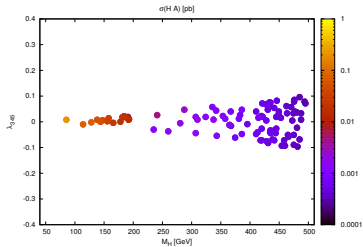
Production cross sections in fb, at 27 TeV [UFO+Madgraph]

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

LUX

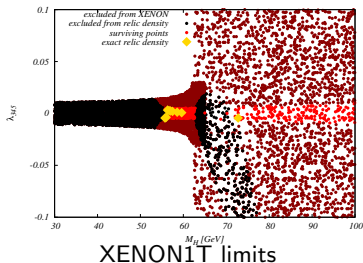
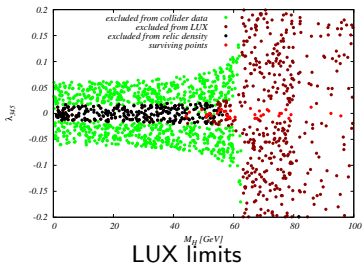


XENON



Cases where $M_H \leq M_h/2$

- **discussion so far:** decay $h \rightarrow HH$ kinematically not accessible
 - for these cases, **discussion along different lines**
- ⇒ **extremely strong constraints from signal strength, and dark matter requirements**



- additional constraints from combination of W, Z decays and recasted analysis at LEP

lower limit $M_H \sim 50$ GeV

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

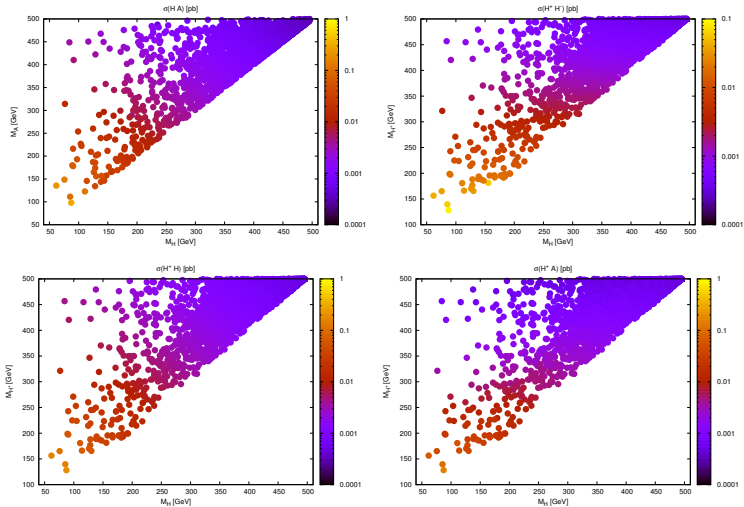


Figure : Production cross sections in pb at a 13 TeV LHC
Tania Robens IDM WG3 subgroup, 24.10.18

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)

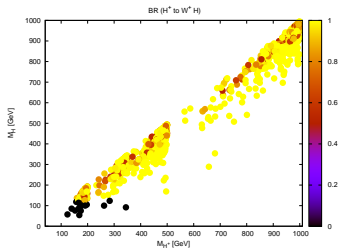
dominant production modes: through Z ; Z, γ, h for AH ; H^+H^-
important couplings:

- ZHA : $\sim \frac{e}{s_W c_W}$
- ZH^+H^- : $\sim e \coth(2\theta_w)$
- γH^+H^- : $\sim e$
- hH^+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 $A \rightarrow HZ$ always 100 %
- decay $H^\pm \rightarrow HW^\pm$



second channel $H^\pm \rightarrow A W^\pm$

⇒ collider signature: SM particles and MET ⇐

Total widths in IDM scenario [old]

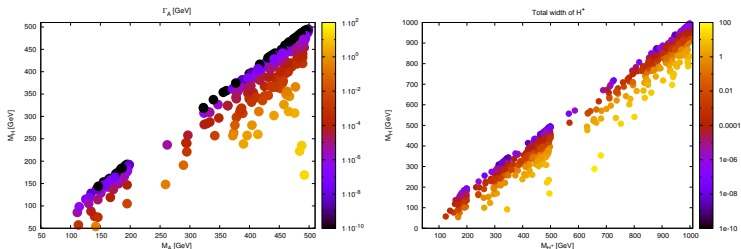
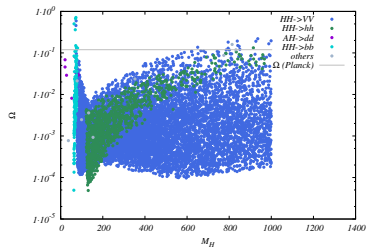
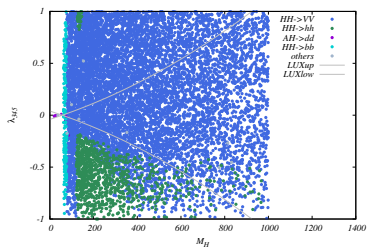


Figure : Total widths of unstable dark particles: A and H^\pm in plane of their and dark matter masses.

Dark matter relic density

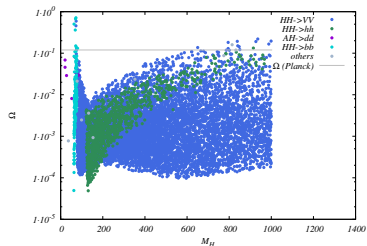


all but DM constraints

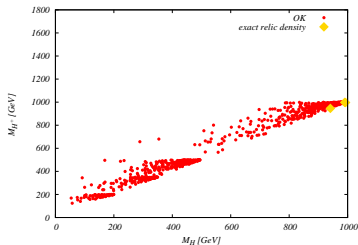


all but DM constraints

Dark matter relic density: exact limit vs upper bound



Ω vs m_H , all but DM constraints



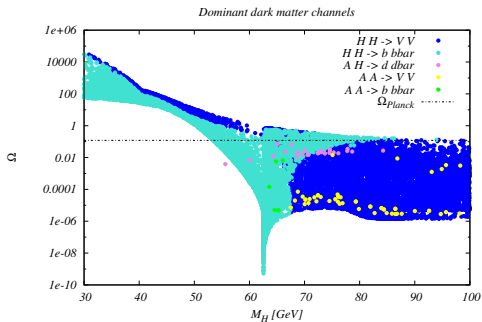
sample plot, M_H vs. M_{H^\pm}

General scan results

⇒ window with $m_H \in [100 \text{ GeV}; 600 \text{ GeV}]$ **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: $AH \rightarrow d\bar{d}$;
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)

$$M_A \leq 100 \text{ GeV}, M_H \leq 80 \text{ GeV}, \Delta M \geq 8 \text{ GeV}$$

- **combination leads to**

- $M_H \in [0; 41 \text{ GeV}]$: $M_A \geq 100 \text{ GeV}$,
- $M_H \in [41; 45 \text{ GeV}]$: $M_A \in [m_Z - M_H; M_H + 8 \text{ GeV}]$ or $M_A \geq 100 \text{ GeV}$
- $M_H \in [45; 80 \text{ GeV}]$: $M_A \in [M_H; M_H + 8 \text{ GeV}]$ or $M_A \geq 100 \text{ GeV}$

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 ?

⇒ one possible understanding:

Multi-component dark matter

- **in practise: direct detection limits relaxed**, according to

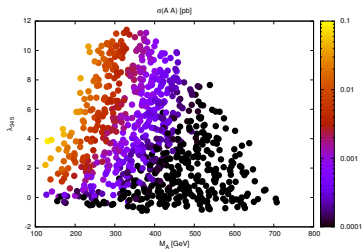
$$\sigma(M_H) \leq \sigma^{\text{LUX}}(M_H) \times \frac{\Omega^{\text{Planck}}}{\Omega(M_H)}$$

⇒ **in practise**: larger parameter space for λ_{345}

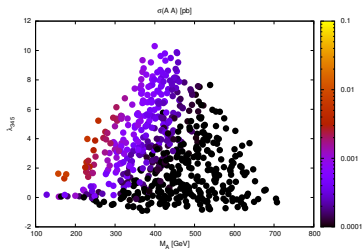
⇒ **influences especially AA production**

AA production with rescaled dark matter

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



[old]



[new]

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