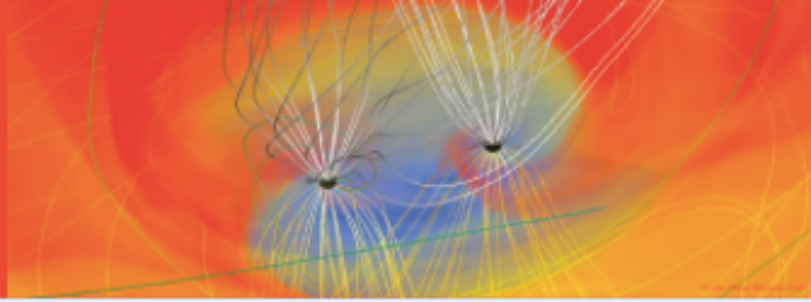

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The Inert Doublet Model:
confronting collider and dark matter searches

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Outline

- Motivation
- Inert Doublet Model
  - parameters
  - colliders and dark matter constraints
- Production and decay of IDM scalars
- IDM benchmark points
- IDM scalars at
  - LHC
  - e+e- colliders
- Conclusions

Based on papers with Wojtek Kotlarski, Tania Robens, Dorota Sokolowska and Filip Zarnecki

- JHEP 1812 (2018) 081,
- contribution to CLIC CERN Yellow Report arXiv:1812.02093
- arXiv:1811.06952, JHEP in press

Motivation

- July 4, 2012: Higgs-like particle discovered and its mass measured

  ➔ last building block of the SM discovered

Any remaining questions?

- why is the SM the way it is?

  ➔ search for underlying symmetries/principles, ···

- find explanation for observed deviations

  ➔ flavor physics, dark matter, ···

- explore different proposals for Beyond SM

  ➔ test against theoretical and experimental constraints,···

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- find explanation for observed deviations
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- explore different proposals for Beyond SM
  - ➔ test against theoretical and experimental constraints,⋯
- here Inert Doublet Model: a 2HDM with a dark matter candidate

Inert doublet model

take an additional doublet of scalars
i.e. a two Higgs doublet model $\Phi_S, \quad \Phi_D$

and impose a Z_2 symmetry under which

- the SM-like Higgs Φ_S and all SM fields are even
- the 'Inert' Higgs Φ_D is odd

- scalar potential

$$V = -\frac{1}{2}\left[m_{11}^2(\Phi_S^\dagger\Phi_S)+m_{22}^2(\Phi_D^\dagger\Phi_D)\right] + \frac{\lambda_1}{2}(\Phi_S^\dagger\Phi_S)^2+\frac{\lambda_2}{2}(\Phi_D^\dagger\Phi_D)^2$$
$$+\lambda_3(\Phi_S^\dagger\Phi_S)(\Phi_D^\dagger\Phi_D)+\lambda_4(\Phi_S^\dagger\Phi_D)(\Phi_D^\dagger\Phi_S) + \frac{\lambda_5}{2}\left[(\Phi_S^\dagger\Phi_D)^2+(\Phi_D^\dagger\Phi_S)^2\right]$$

- assume parameters real $m_{11},\ m_{22},\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5$

The model: parameters

- minimize the potential
  - due to Z_2 symmetry only the SM-like doublet aquires a vev

$$\Phi_S = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG) \end{pmatrix}, \qquad \Phi_D = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

  - fix $\quad v \sim 246 \text{ GeV}, \qquad M_h \sim 125 \text{ GeV}$

➔ left with 5 free parameters

  - can be traded for more physical ones

$$M_H,\ M_A,\ M_{H^\pm},\ \lambda_2, \lambda_{345} \ \ (= \lambda_3 + \lambda_4 + \lambda_5)$$

The model: parameters and couplings

- H or A are possible dark matter candidates

- their couplings to gauge bosons are controlled by SM couplings

$$\begin{array}{cccccc} & (H^+H^-\gamma, & H^+H^-Z, & HH^\pm W^\mp, & AH^\pm W^\mp, & AHZ) \\ \dfrac{ig}{2} & (2s_W, & c_{2W}/c_W, & \mp 1, & i, & i/c_W) \end{array}$$

- we choose H as a dark matter candidate,

$$M_H < M_A, \qquad M_H^2 - M_A^2 = \lambda_5 v^2$$

for opposite configuration, flip sign of λ_5

- $\lambda_3,\ \lambda_{345}$ determine SM-Higgs couplings to dark scalars

- λ_2 controls quartic couplings among dark scalars

Constraints

Theoretical:

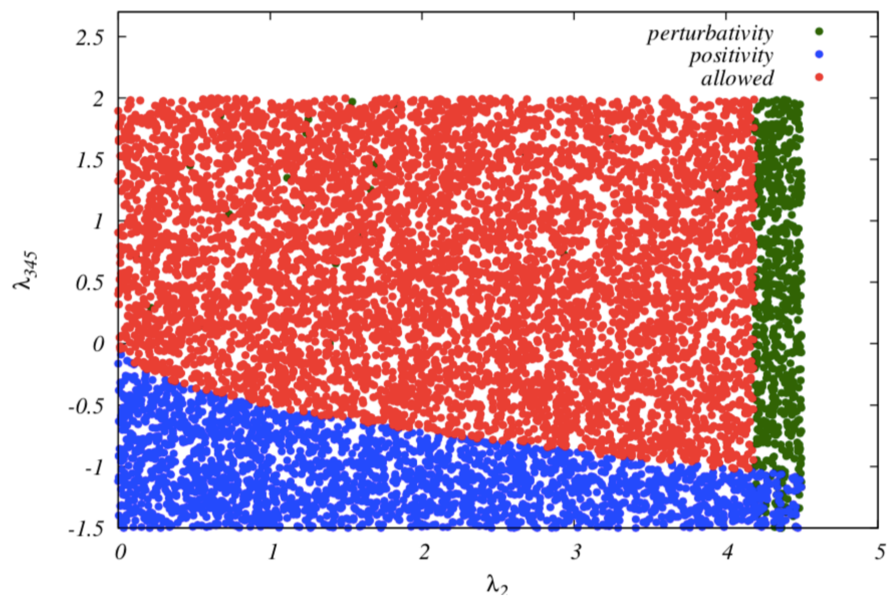
- vacuum stability, positivity, global minimum

➔ limits on couplings, e.g.

$$\lambda_1 > 0,\ \lambda_2 > 0,\ \lambda_3 + \sqrt{\lambda_1\lambda_2},\ \lambda_{345} + \sqrt{\lambda_1\lambda_2} > 0$$

- perturbative unitarity, perturbativity of couplings

e.g.



from Ilnicka, Krawczyk, Robens: PRD 93,055026

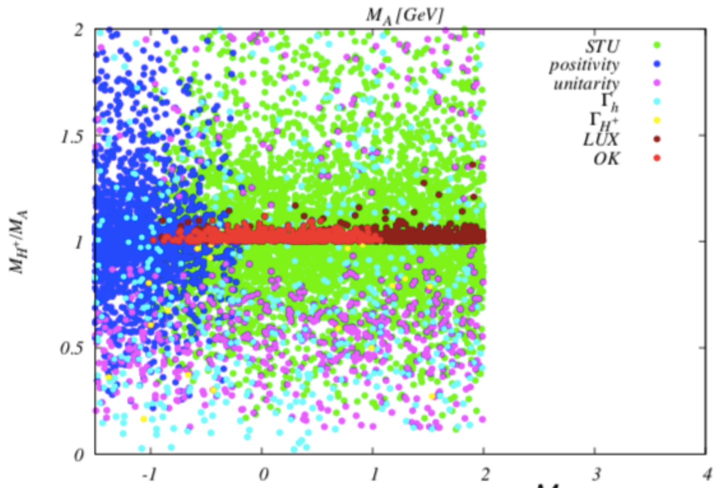
Constraints

Experimental:

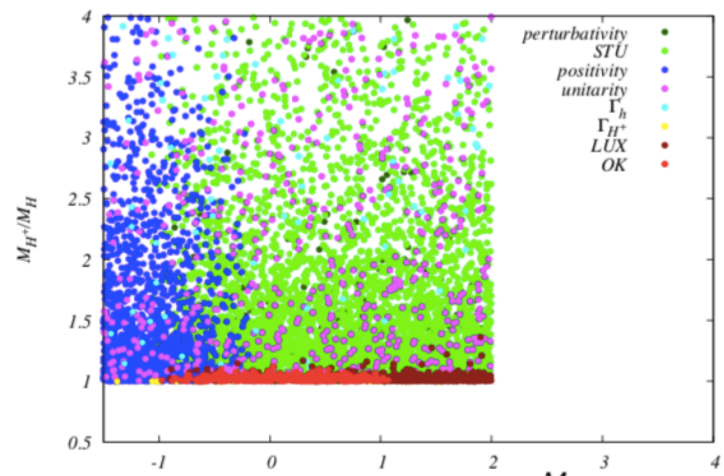
- total width of M_h ($\Gamma_h < 9\,\mathrm{GeV}$); $\Rightarrow$ CMS-PAS-HIG-18-002
- total width of W, Z
- collider constraints from signal strength/ direct searches; $R_{\gamma\gamma}$ and $\mathrm{BR}_{h\to \mathrm{inv}}$ from JHEP, 08:045, 2016
- electroweak precision through S, T, U
- unstable $H^{\pm}$
- 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**

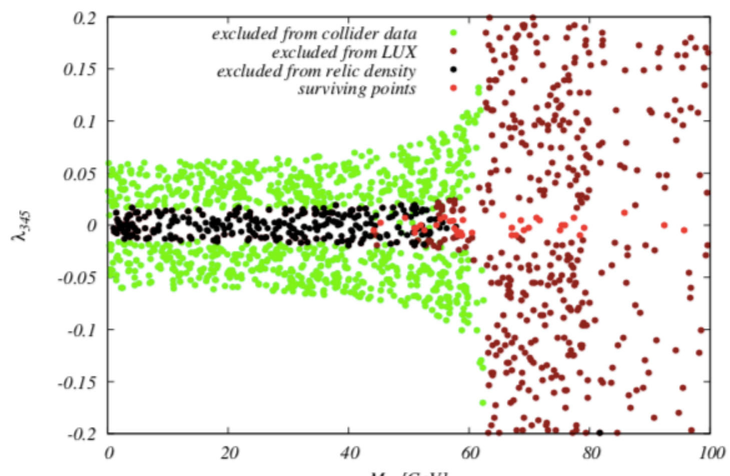
Constraints: combined



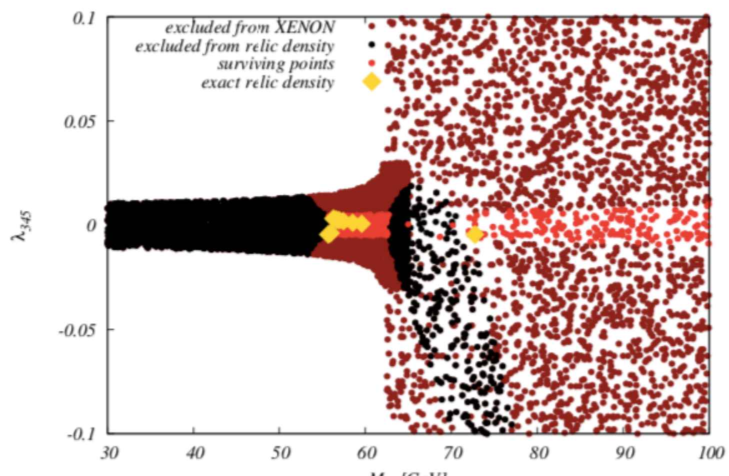
λ_{345} vs $\frac{M_{H^\pm}}{M_A}$



λ_{345} vs $\frac{M_{H^\pm}}{M_H}$



LUX limits



XENON1T limits

high complementarity of astroparticle and collider physics

Production and decay of H, A and H^+,H^-

- Z_2 symmetry ➔ only pair-production of dark scalars
  - production modes at colliders

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

$$e^+e^- \to HA,\ H^+H^-$$

  - decays

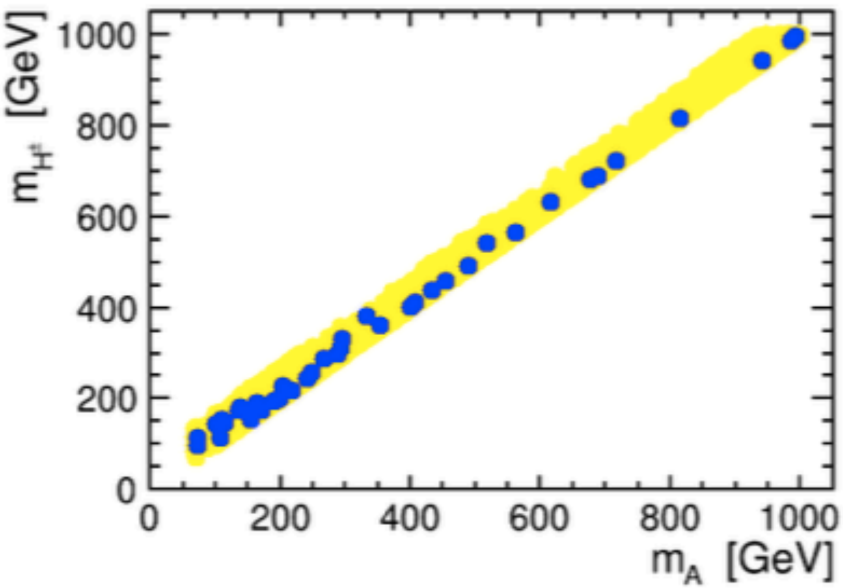
$$A \to ZH:\ 100\%,\ H^\pm \to W^\pm H:\ \text{dominant}$$

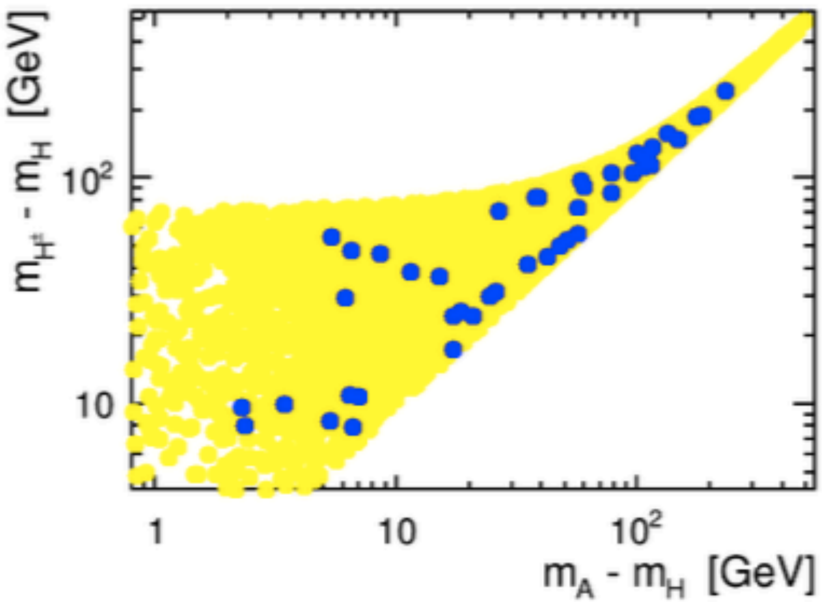
➔ signature: EW gauge bosons + MET

- predictions do not depend on λ_2 , and only marginally on λ_{345}
- parameters tested at colliders: mainly masses

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

JK, Kotlarski, Robens, Sokolowska, Zarnecki JHEP 1812 (2018) 081

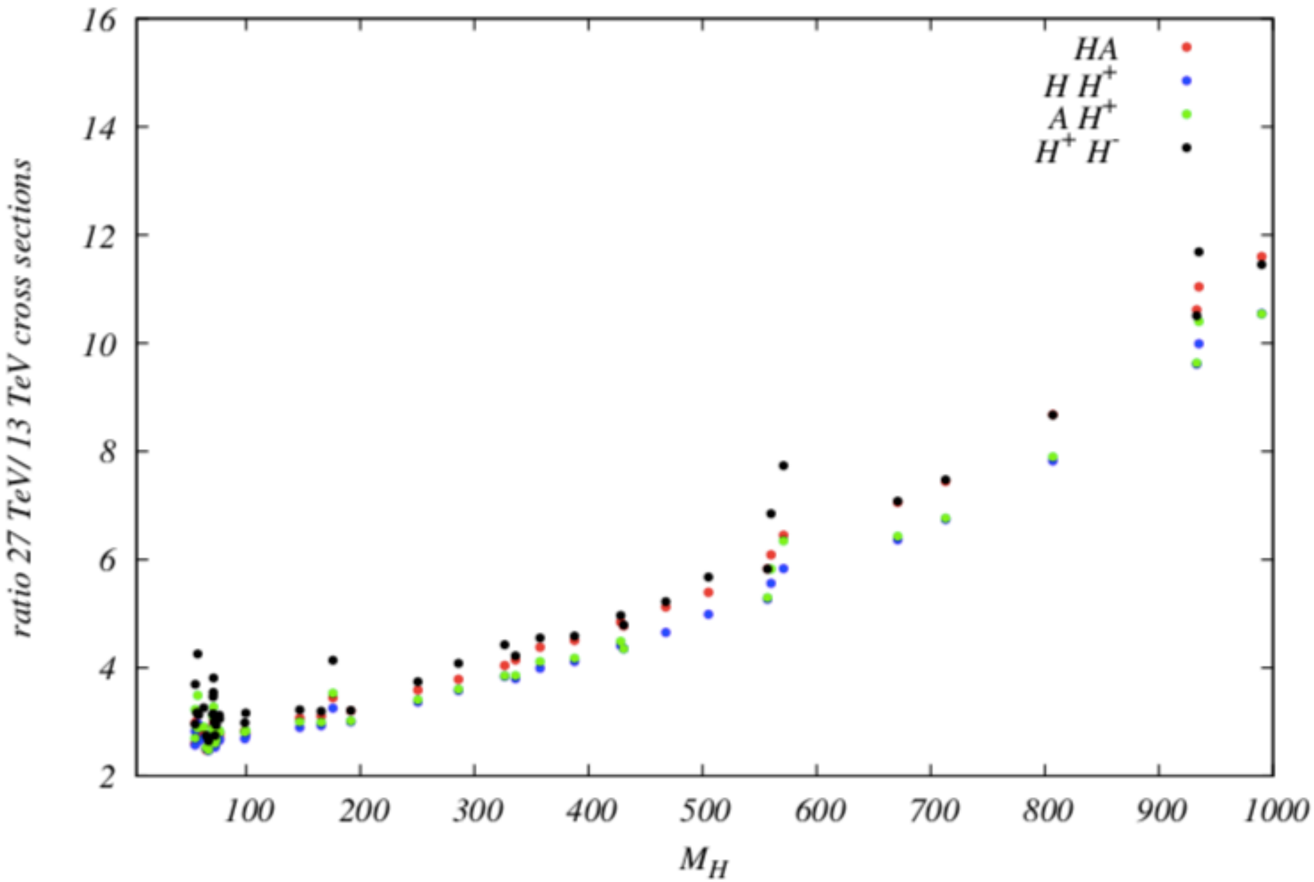
Low mass benchmarks at the LHC

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

and at 27 TeV LHC



at high masses, **increase up to one order of magnitude**

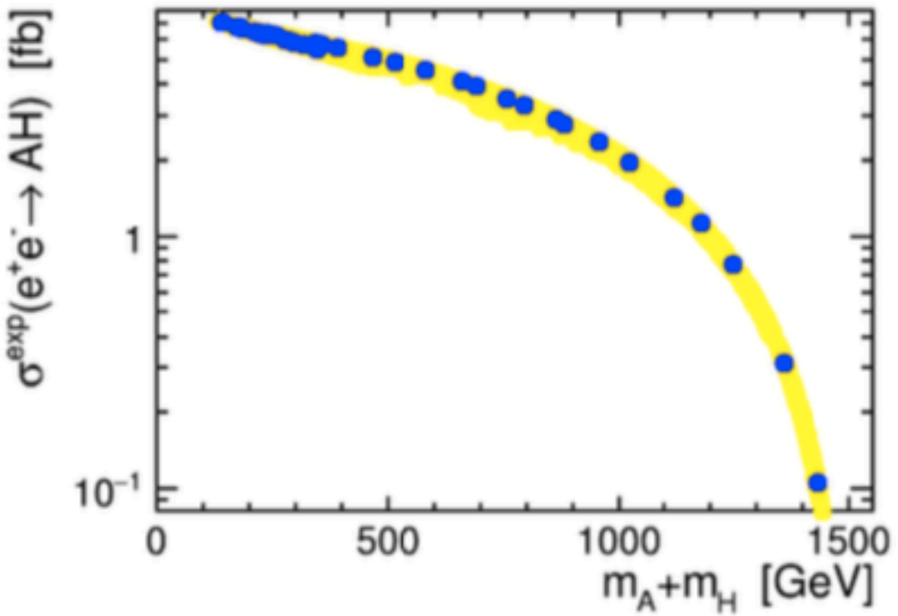
all BPs and HPs more than 1000 events for total run

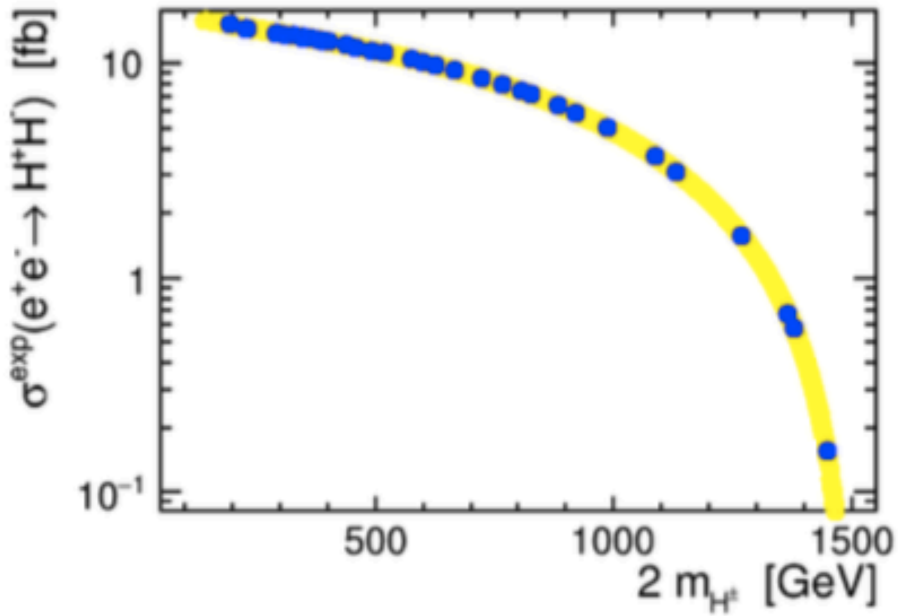
IDM at linear e+e- colliders

production of dark scalars dominated by two processes

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

Leading-order cross sections for inert scalar production processes at 1.5 TeV:





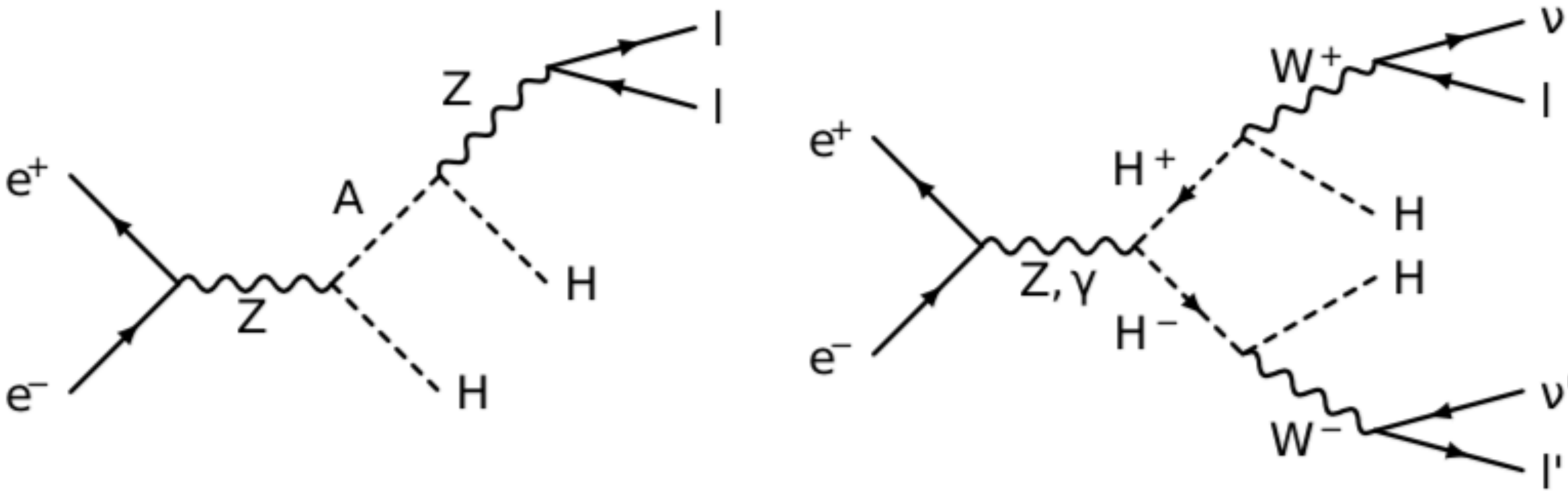
Analysis strategy

Lepton pair production can be a signature of the AH production process followed by the A decay:

$$e^+e^- \quad\rightarrow\quad HA \rightarrow HHZ^{(\star)} \rightarrow HH\mu^+\mu^-$$

while the production of the different flavour lepton pair is the expected signature for H^+H^- production:

$$e^+e^- \quad\rightarrow\quad H^+H^- \rightarrow HHW^{+(*)}W^{-(*)} \rightarrow HH\ell^+\ell'^-\nu\bar{\nu}'$$



IDM scalars at CLIC

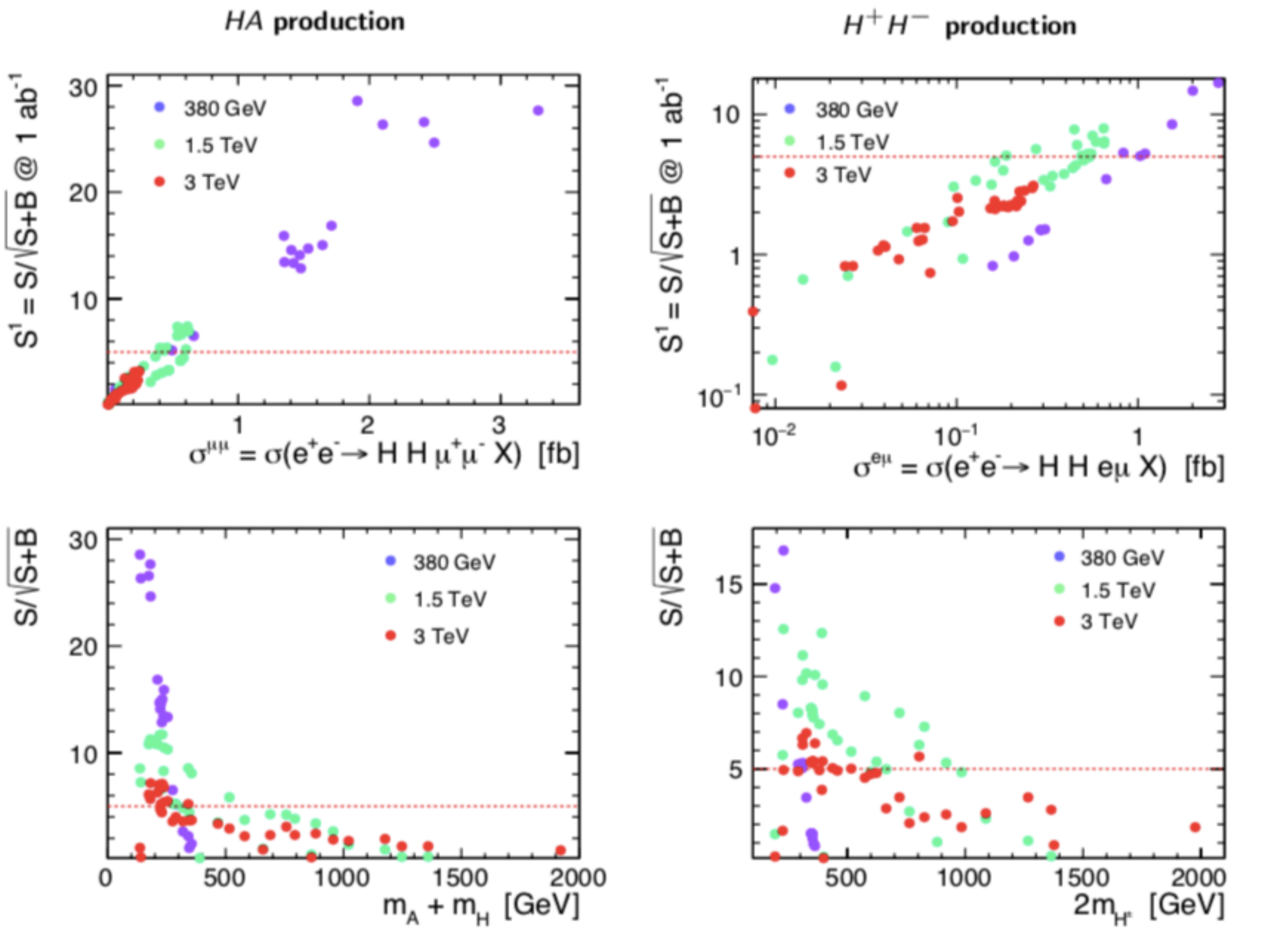
Signal processes for $\mu^+\mu^-$ final state

$$
\begin{aligned}
e^+e^- &\rightarrow \mu^+\mu^- \, HH, \\
&\rightarrow \mu^+\mu^-\nu_\mu\bar{\nu}_\mu \, HH, \\
&\rightarrow \tau^+\mu^-\nu_\tau\bar{\nu}_\mu \, HH, \;\; \mu^+\tau^-\nu_\mu\bar{\nu}_\tau \, HH, \\
&\rightarrow \tau^+\tau^- \, HH, \;\; \tau^+\tau^-\nu_\tau\bar{\nu}_\tau \, HH. \\
&\quad \text{with} \tau^\pm \rightarrow \mu^\pm\nu\nu
\end{aligned}
$$

Signal processes for $e^\pm\mu^\mp$ final state

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

Results for CLIC studies (using BDT)



JK, Kotlarski, Robens, Sokolowska, Zarnecki JHEP in press

Conclusions

- LHC run III in full preparation ➔ exciting times ahead
- Higgs sector special: wrt extensions, additional matter content,
- Inert doublet model: simple and interesting
- Current collider and dark matter searches highly constraining
- Viable benchmarks with with low and high mass scalars
  - predictions for current and future LHC runs
  - detailed analyses for e+e- colliders

Conclusions

- LHC run III in full preparation → exciting times ahead
- Higgs sector special: wrt extensions, additional matter content,
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- Current collider and dark matter searches highly constraining
- Viable benchmarks with with low and high mass scalars
  - predictions for current and future LHC runs
  - detailed analyses for e+e- colliders
  - stay tuned!

backup:

Benchmarks:

Low mass IDM benchmark points

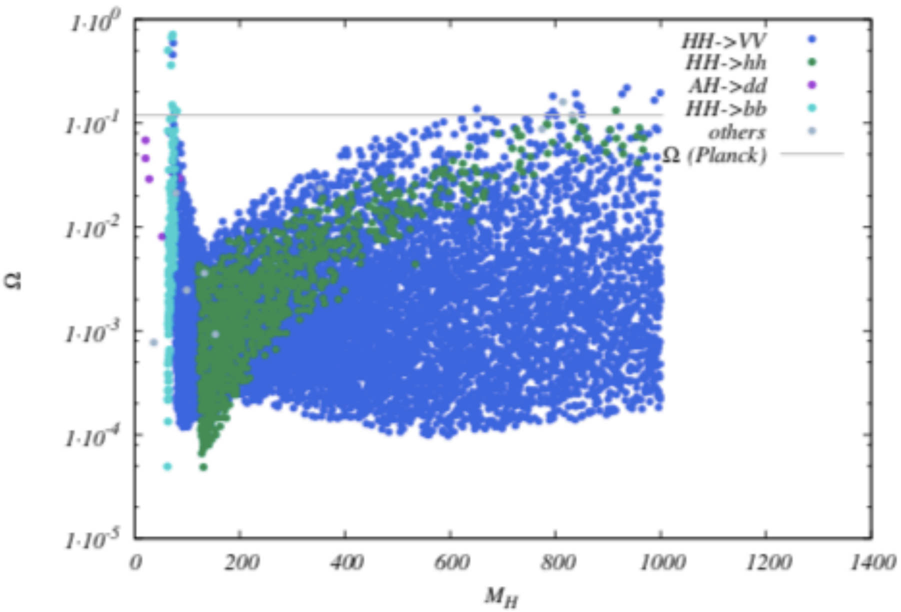
No.	M_H	M_A	$M_{H^\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
BP1	72.77	107.8	114.6	1.445	-0.004407	0.1201
BP2	65	71.53	112.8	0.7791	0.0004	0.07081
BP3	67.07	73.22	96.73	0	0.00738	0.06162
BP4	73.68	100.1	145.7	2.086	-0.004407	0.08925
BP5	55.34	115.4	146.6	0.01257	0.0052	0.1196
BP6	72.14	109.5	154.8	0.01257	-0.00234	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

Benchmarks:

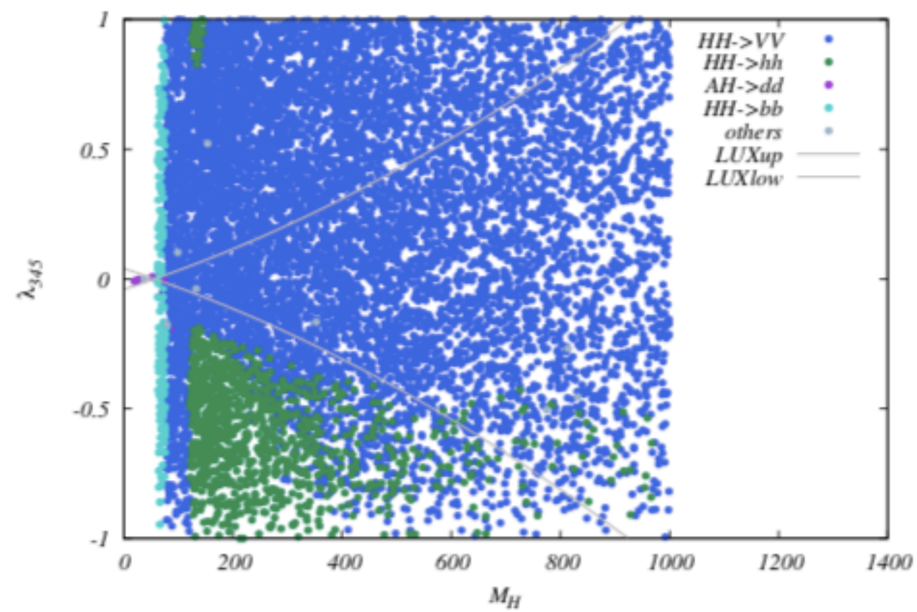
High mass IDM benchmark points

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

dark matter relic density:



all but DM constraints



all but DM constraints

for 100 GeV <~ M_H <~ 600 GeV no exact DM

Boosted decision trees

BDT input variables

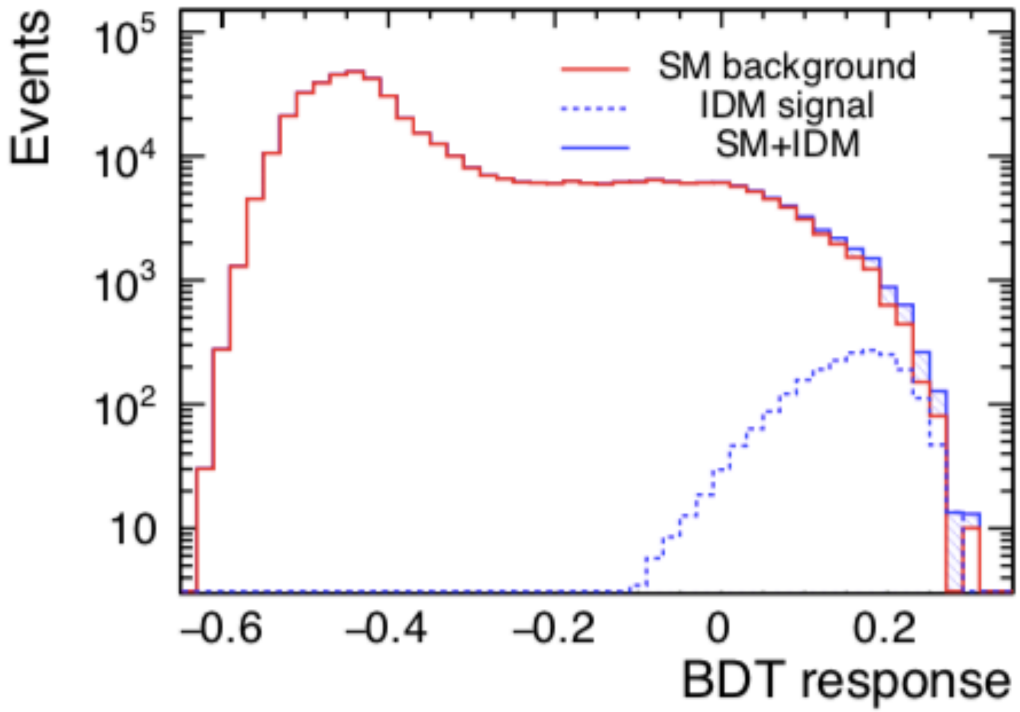
Input variables describing the kinematics of the dilepton final state:

- total energy of the muon pair, E_{ll};
- dilepton invariant mass, M_{ll};
- dilepton transverse momentum, p_T^{ll};
- polar angle of the dilepton pair, Θ_{ll} ;
- Lorentz boost of the dilepton pair, $\beta_{ll} = p_{ll}/E_{ll}$;
- ℓ^- production angle with respect to the beam direction, calculated in the dilepton center-of-mass frame, $\Theta_l^\star$
- ℓ^- production angle with respect to the dilepton pair momentum direction, calculated in the dilepton center-of-mass frame, $\angle^\star(\ell, \ell\ell)$,
- reconstructed missing (recoil) mass M_{miss} (calculated assuming nominal e^+e^- collision energy),

Boosted decision trees

Charged scalar production @ 380 GeV

BDT classifier response distribution for $e\mu$ channel:
BP1 scenario and SM background $1000\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 380$ GeV



$\Rightarrow$ signal significance of about 17 σ for BDT> 0.12