"Light" new physics at colliders

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based on work with

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

Rudjer Boskovic Institute

MITP Virtual Workshop:
Light New Physics: From Table-Top Experiments to the LHC
10.12.21

Disclaimer

- "Light" new physics: for me, refers to **DM masses** $\leq 1\,\mathrm{TeV}$

  [thanks to email exchange w Caterina in September...]

- obviously, **very large theory model space** $\Rightarrow$ impossible to cover all in a 15 minute talk

$\Rightarrow$ will try to make some general remarks, then discuss 2 specific models, then open questions

Lets get started...

General/ typical features of BSM scenarios with dark matter

- νs cannot correctly describe DM content of the universe

$\Rightarrow$ need **new particle content, aka BSM physics**

- typical setup: add **new scalar/ fermionic/ ... states**, which transform as singlets/ doublets/ ... under $SU(2) \otimes U(1)$

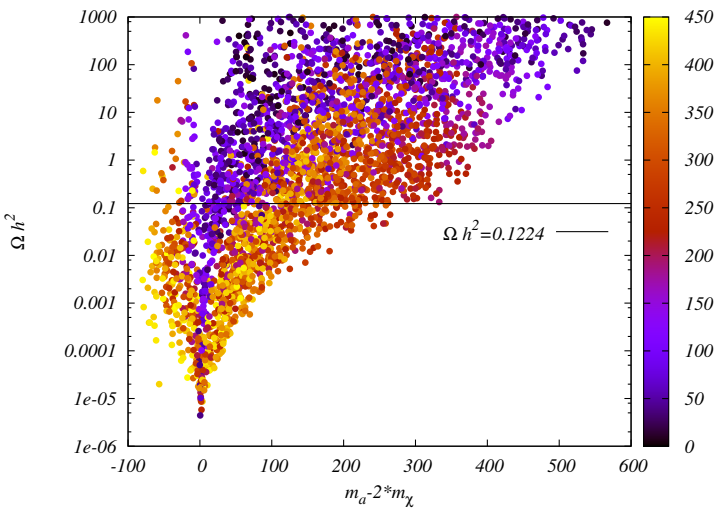
$\Rightarrow$ introduce **new unbroken symmetry**, which renders the lightest BSM particle(s) stable $\Rightarrow$ **dark matter candidate(s)**

- side remark: this typically also leads to **additional unstable new matter states !**

$\Longrightarrow$ **DM models constrained from various directions** $\Longleftarrow$

A "typical" plot

- in general: **strong constraints from relic density and direct detection**
- typical: **relic density annihilation mediated via s-channel resonance** (often: "Higgs funnel")



color coding: m_χ

$\Rightarrow$ **strong relation between mediator and dark matter mass !**

IDM and THDMa - mini-introduction

- both models **extend scalar sector of SM, lead to novel particle states and non-SM signatures**

IDM: Inert Doublet Model

Two-Higgs-Doublet Model with an exact Z_2 symmetry
$\Rightarrow$ $H, A, H^{\pm}$ **states**, one of these is dark matter

- **signatures: electroweak gauge bosons and $\not{E}_{\perp}$**

THDMa: Two-Higgs-Doublet Model + a

Two-Higgs-Doublet Model + pseudoscalar + fermionic dark matter, $\Rightarrow$ $H, a, A, H^{\pm}, \chi$ **states**, χ is dark matter

- **signatures: as in THDM, + many states with $\not{E}_{\perp}$ ($h/\ Z/\ t\bar{t}/\ ...$)**

Models with extended scalar sectors

Constraints

- **Theory**

  minimization of vacuum (tadpole equations), vacuum stability, positivity, perturbative unitarity, perturbativity of couplings

- **Experiment**

  provide viable candidate @ 125 GeV (coupling strength/ width/ ...);
  agree with null-results from additional searches and ew gauge boson measurements (widths);
  agree with electroweak precision tests (typically via S,T,U);
  agree with B-physics constraints (e.g. $B \to X_s \gamma, \ldots$);
  agree with astrophysical observations (if feasible)

tools used: `HiggsBounds`, `HiggsSignals`, `2HDMC`, `micrOMEGAs`, ...

Models with dark matter candidates: Inert Doublet Model

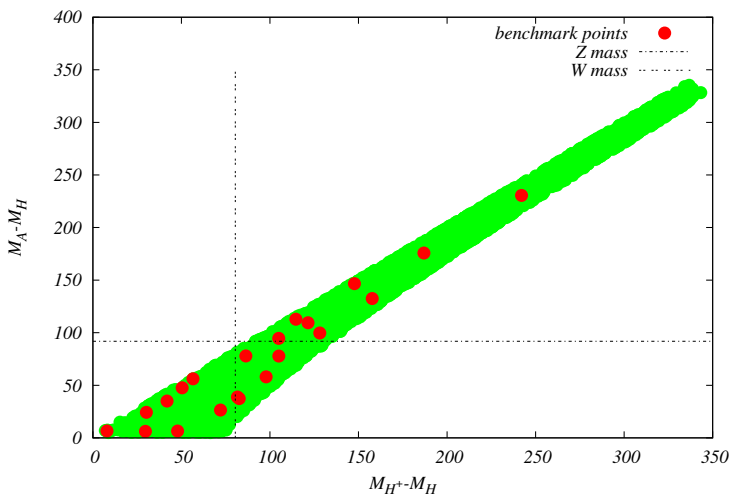
2 Higgs Doublet Model: 4 new scalars $H, A, H^{\pm}$

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

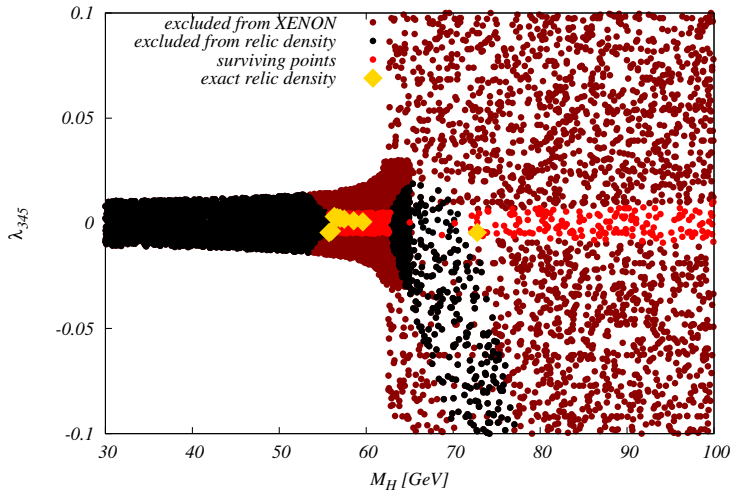
free parameters: **masses,** λ_2, λ_{345} (couplings in V)

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

Production and decay

- Z_2 symmetry:

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

- production modes:

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

$$\mathbf{e^{+}\,e^{-}} \to \mathbf{HA},\ \mathbf{H^{+}H^{-}}$$

- decays:

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

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

Parameters tested at colliders: mainly masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **relevant couplings follow from ew parameters (+ derivative couplings)**
- hXX **couplings:** determined by λ_{345} (constrained from direct detection), and **mass differences** $M_X^2 - M_H^2$ $\left(X \in \left[A,\, H^{\pm}\right]\right)$

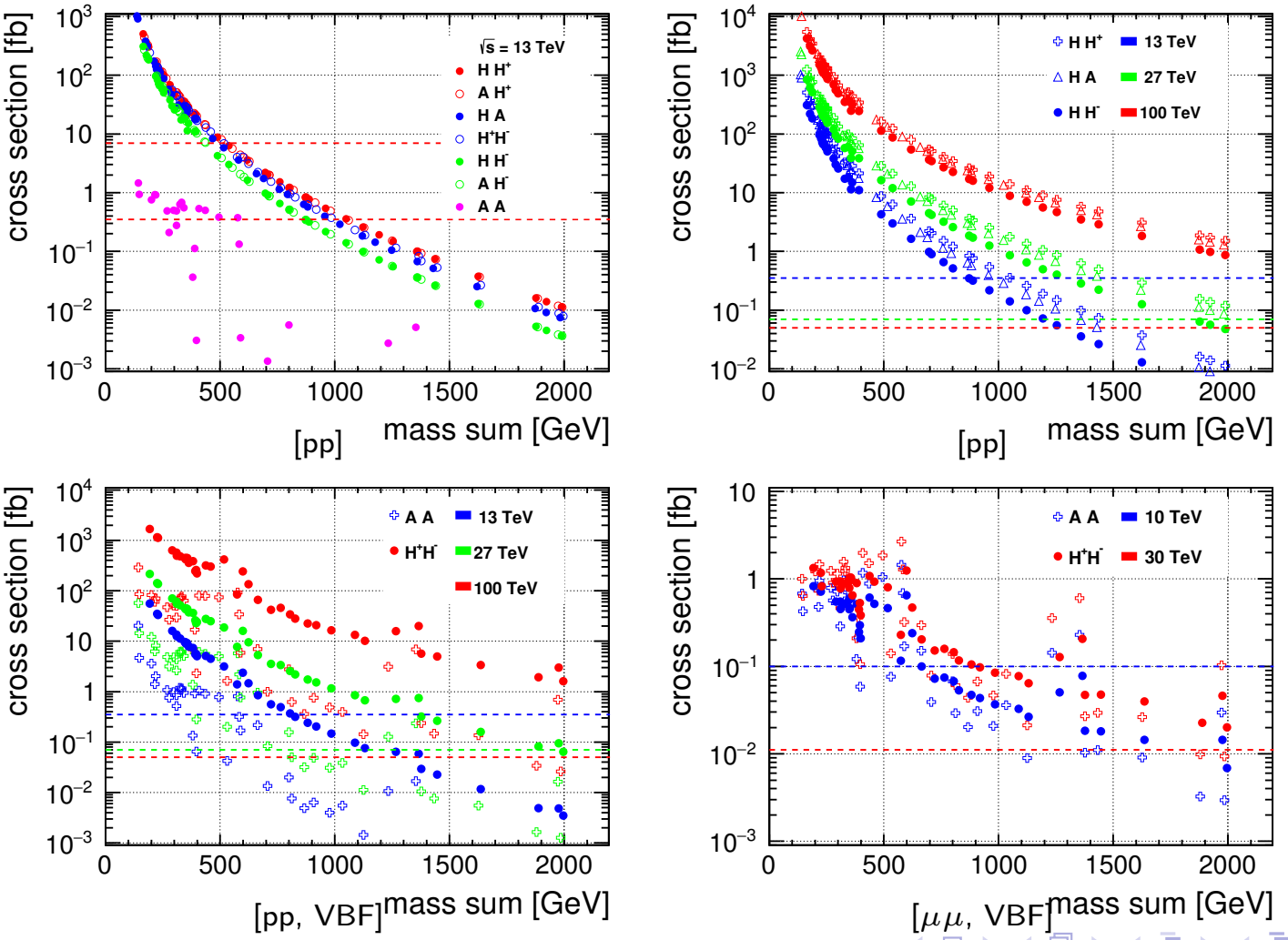
important interplay between astroparticle physics and collider searches

in the end kinematic test

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

Production cross sections [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

THDMa [arXiv:2105.06231, arXiv:2106.02962, arXiv:2110.07294]

setup: 2 Higgs Doublet Model (Type II), + **pseudoscalar** a (mixing with A), + **dark matter candidate** χ (fermionic)

- **DM couples to additional field in gauge-eigenstates**

$\Rightarrow$ promoted by LHC Dark Matter Working group in Phys.Dark Univ. 27 (2020) 100351

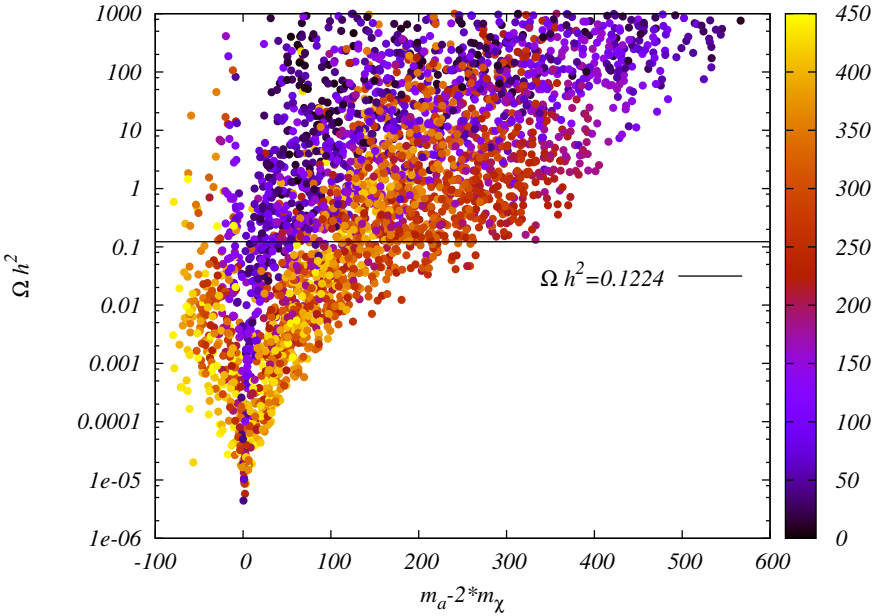
THDMa scalar sector particle content: h, H, $H^{\pm}$, a, A, χ

parameters:

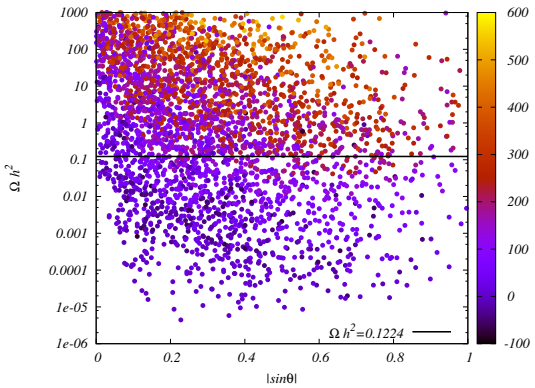
v, m_h, m_H, m_a, m_A, $m_{H^{\pm}}$, m_χ; $\cos(\beta-\alpha)$, $\tan\beta$, $\sin\theta$; y_χ, λ_3, λ_{P_1}, λ_{P_2}

Example: Dark matter constraints

using MadDM



color coding: m_χ



color coding: $m_a - 2\, m_\chi$

dominant channels: $\chi\,\bar{\chi} \to t\,\bar{t},\ b\,\bar{b}$, depending on m_a

main result: $|m_a - 2\, m_\chi| \leq 300\,\mathrm{GeV}$

Signatures at e^+e^- colliders

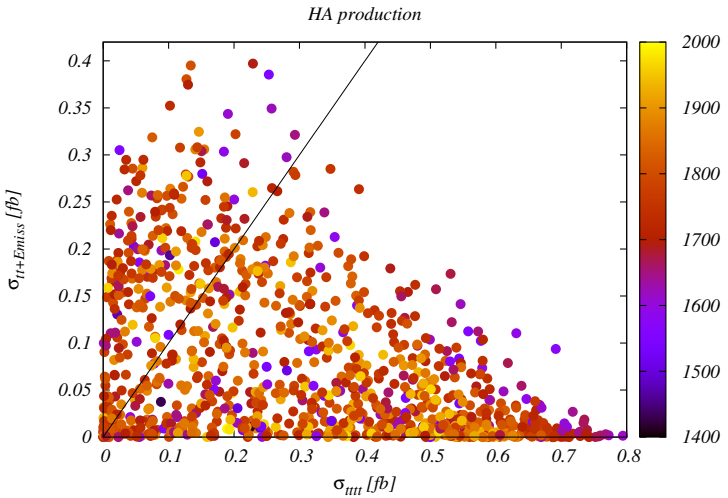
a priori: as standard THDM

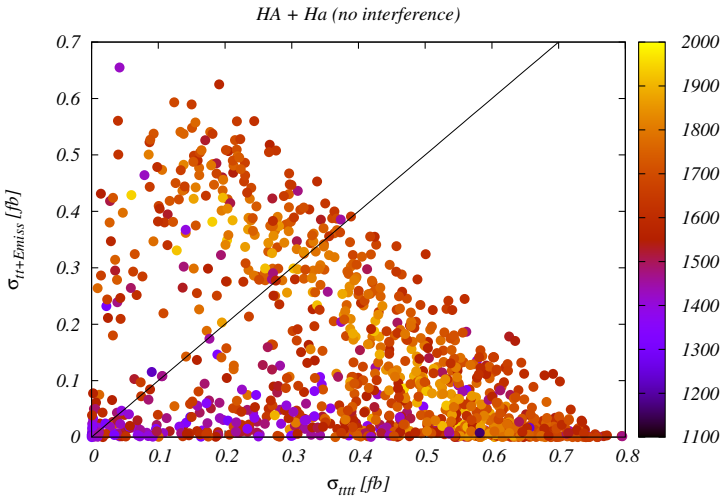
- new feature: **new scalar a; mixing: both a/A can decay invisibly**
- interesting channels: ha, hA, Ha, HA
- mass ranges: between $200\,\mathrm{GeV}$ and $2\,\mathrm{TeV}$
- most promising: HA, Ha **at 3 TeV**

$\Rightarrow$ **cross sections up to 1 fb**

$\Rightarrow$ **dominant final states:** $t\,\bar{t}\,t\,\bar{t}$; $t\bar{t} + \not{E}$

Can the $\not{E}$ channel ever be dominant ?





$t\bar{t}t\bar{t}$ and $t\,\bar{t} + \not{E}$ final states

[color coding $m_A + m_H$]

...including Ha channel

[color coding $0.5 \times (m_a + m_A) + m_H$]

bottom line: **can find regions where $t\bar{t} + \not{E}$ dominates**

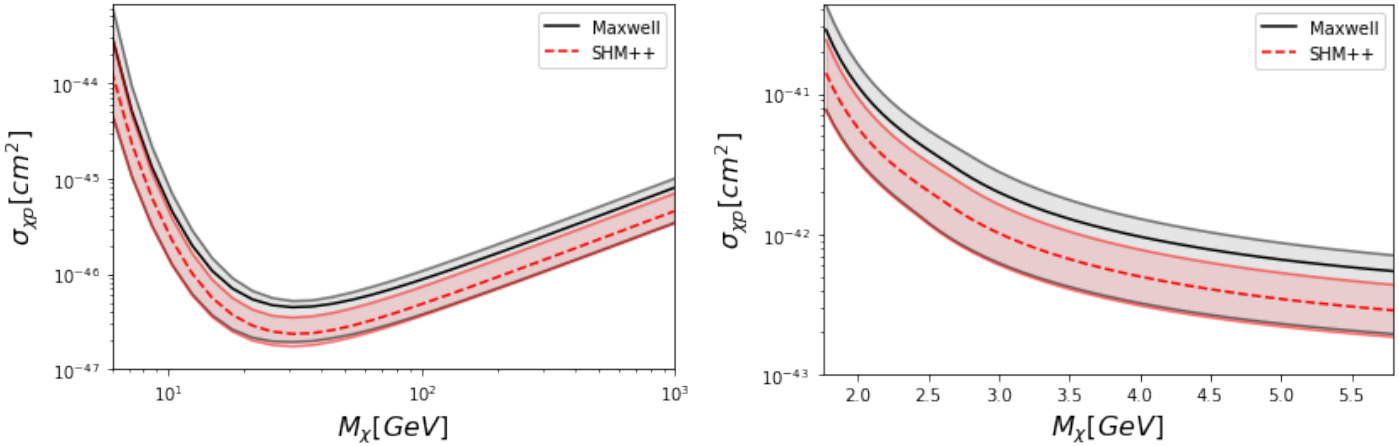
Open questions: general

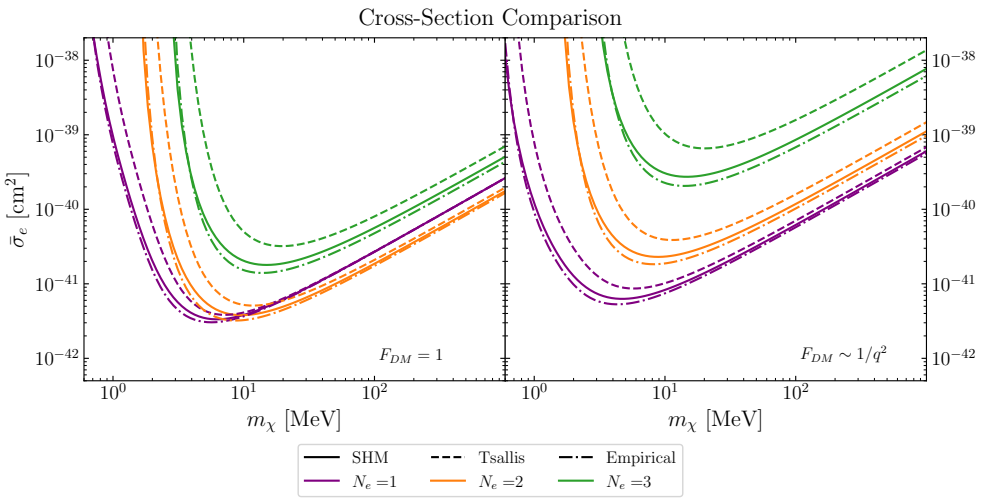
Questions one can ask...

- ask discussed, many BSM DM models have a **large number of additional signatures,** not necessarily containing DM candidates ⇒ **what can be learned from these ? Can there be a generic correlation, or is it model by model ?**
- due to large number of parameters, very often **many parameters fixed and only 2-d planes presented** ⇒ **might lead to many regions that are missed** (obvious solution: be recast-friendly ! LHC BSM reinterpretation forum)
- how well do "simplified models" work/ map to more complete ones ?
- **any other questions ?**

Open questions: astrophysical uncertainties for direct detection bounds

dependence on velocity distributions (including uncertainties) for Xenon1T and DarkSide-50;
dependence on different halo models for DM-electron scattering in semiconductors
(taken from G. Belanger, A. Mjallal, A. Pukhov, Eur.Phys.J.C 81 (2021) 3, 239; A. Radick, A.-M. Taki, T.-T. Yu, JCAP 02 (2021) 004)

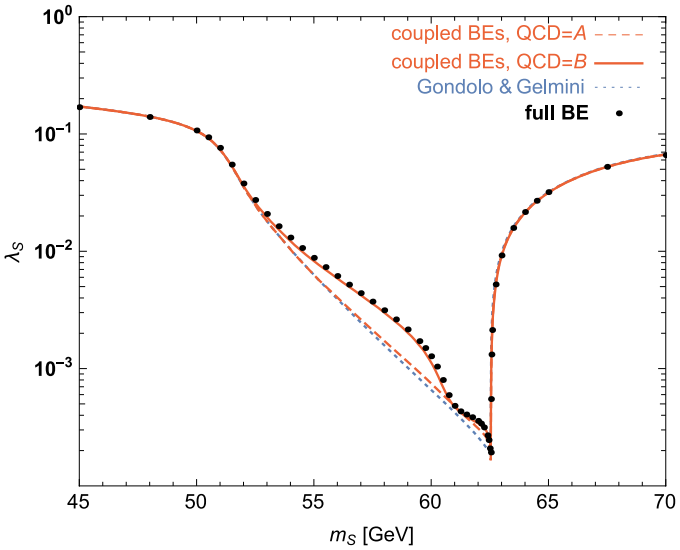


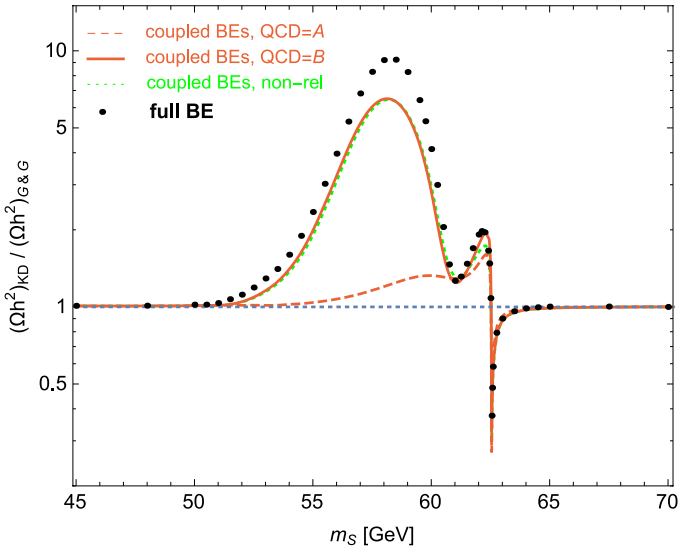


Open questions: Non-equilibrium freezout, relic density calculation

[taken from T. Binder, T. Bringmann, M. Gustaffson, A. Hryczuk, Phys.Rev.D 96 (2017) 11, 115010, Phys.Rev.D 101 (2020) 9, 099901 (erratum); see also Eur.Phys.J.C 81 (2021) 577]

case study: **chemical and kinematic departure from equilibrium happen "simultaneously"/ at similar scales**





singlet DM scenario

λ_S in various approaches that leads to Ω_h^{Planck}; Ω_h rescaled using that value in different calculations

Summary and Outlook

- DM at colliders: typically **signatures w SM + missing (transverse) energy**
- **interplay between astrophysical and collider bounds**, especially for models with large additional particle content

taking DM constraints at face value can lead to too strong constraints on BSM parameter spaces

Thanks for listening
Hope to see you in person soon

[copyright Landeshauptstadt Mainz]

Appendix

Inert doublet model: The model

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

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

(⇒ implies CP conservation)

⇒ 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
(⇒ 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: $M_H \leq M_A,\ M_{H^\pm}$

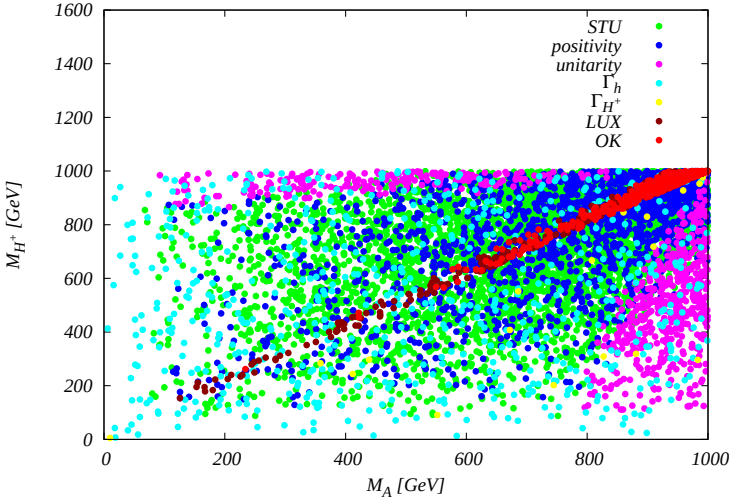
Constraints: Experiment

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

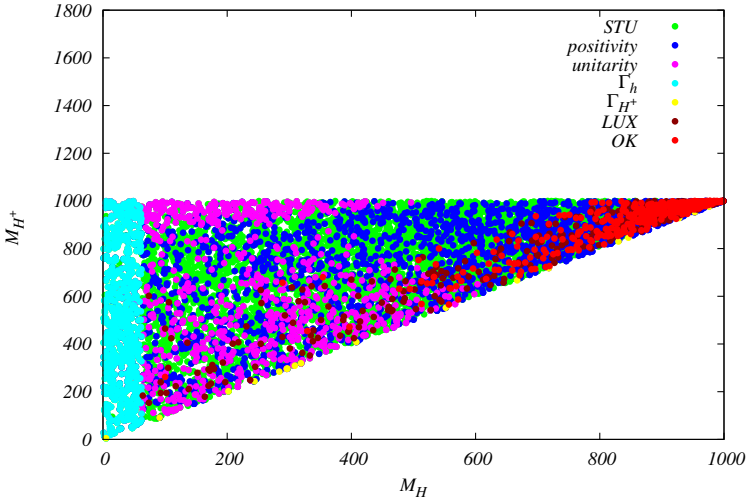
- total width of M_h ($\Gamma_h < 9\,\mathrm{MeV}$) (CMS, $80\,\mathrm{fb}^{-1}$) [Phys. Rev. D 99, 112003 (2019)]
- total width of W, Z
- collider constraints from signal strength/ direct searches;
- electroweak precision through S, T, U
- unstable $H^{\pm}$
- reinterpreted/ recastet LEP/ LHC SUSY searches (Lundstrom ea 2009; Belanger ea, 2015)
- dark matter relic density (upper bound)
- dark matter direct search limits (XENON1T)

$\Rightarrow$ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

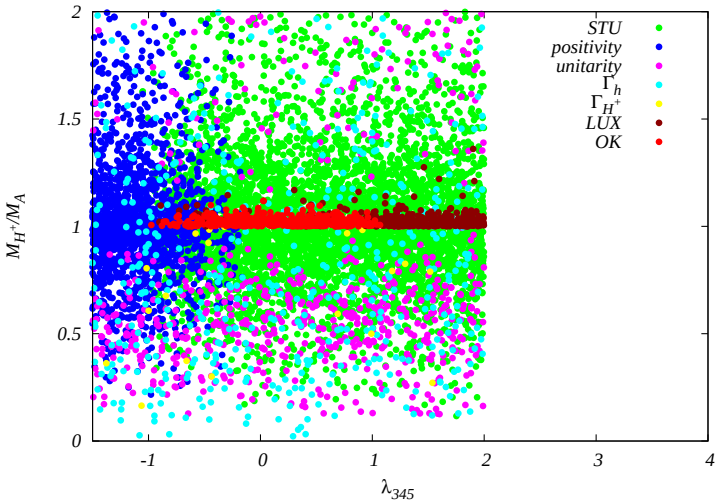
Results of generic scan [Phys.Rev.D 93 (2016) 5, 055026; JHEP 12 (2018) 081]



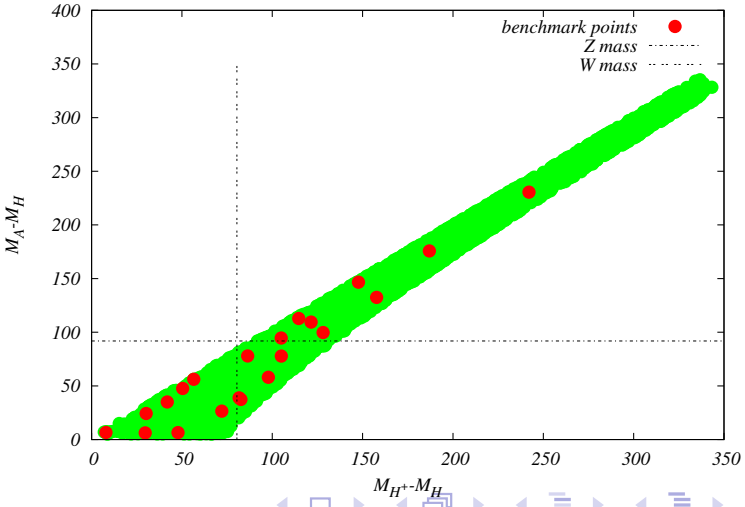
M_A vs $M_{H\pm}$



M_H vs $M_{H\pm}$



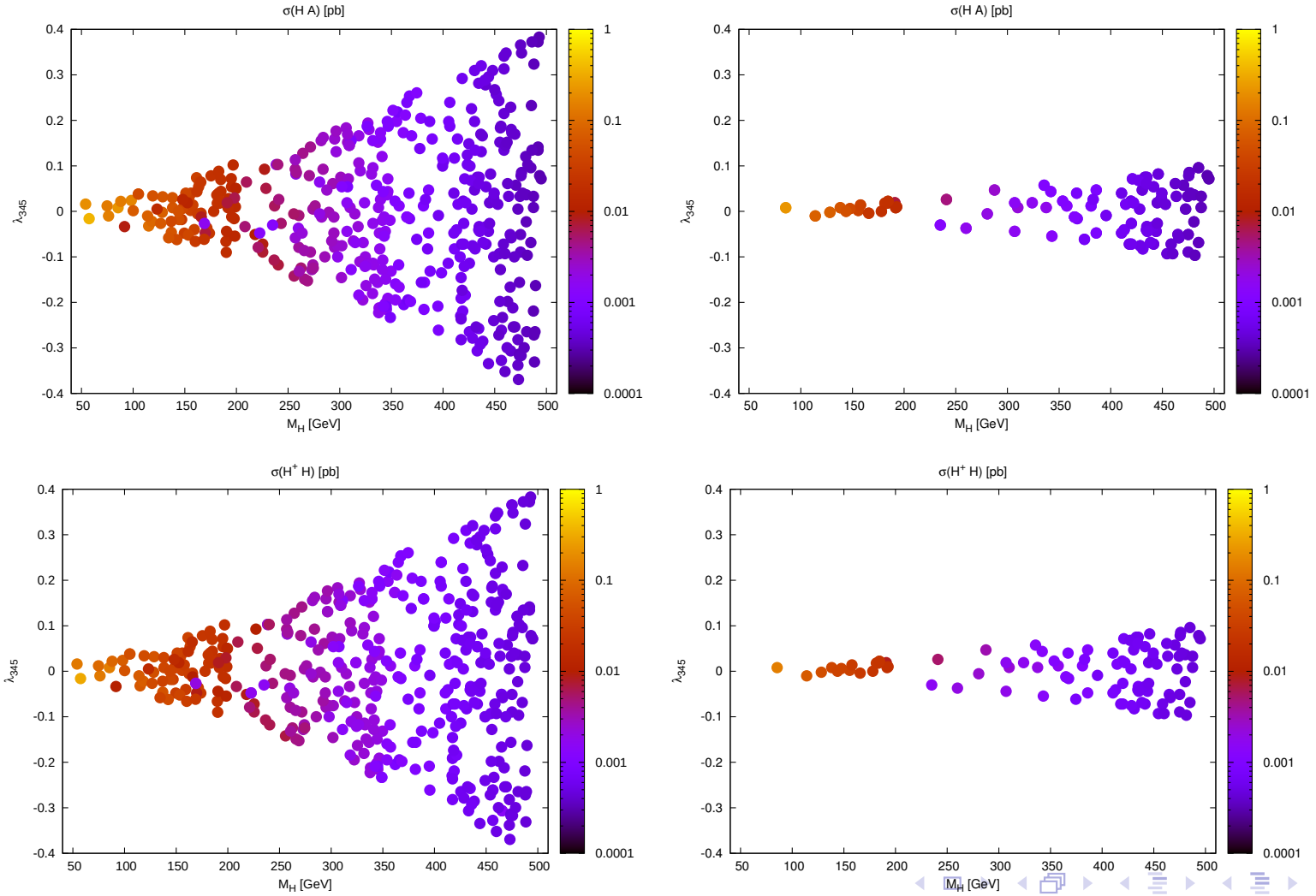
λ_{345} vs $M_{H\pm}/M_A$



mass differences

Updated constraints [XENON1T] [Phys.Rev.Lett. 121 (2018) no.11, 111302]

LUX **XENON**



Exact relic density ??

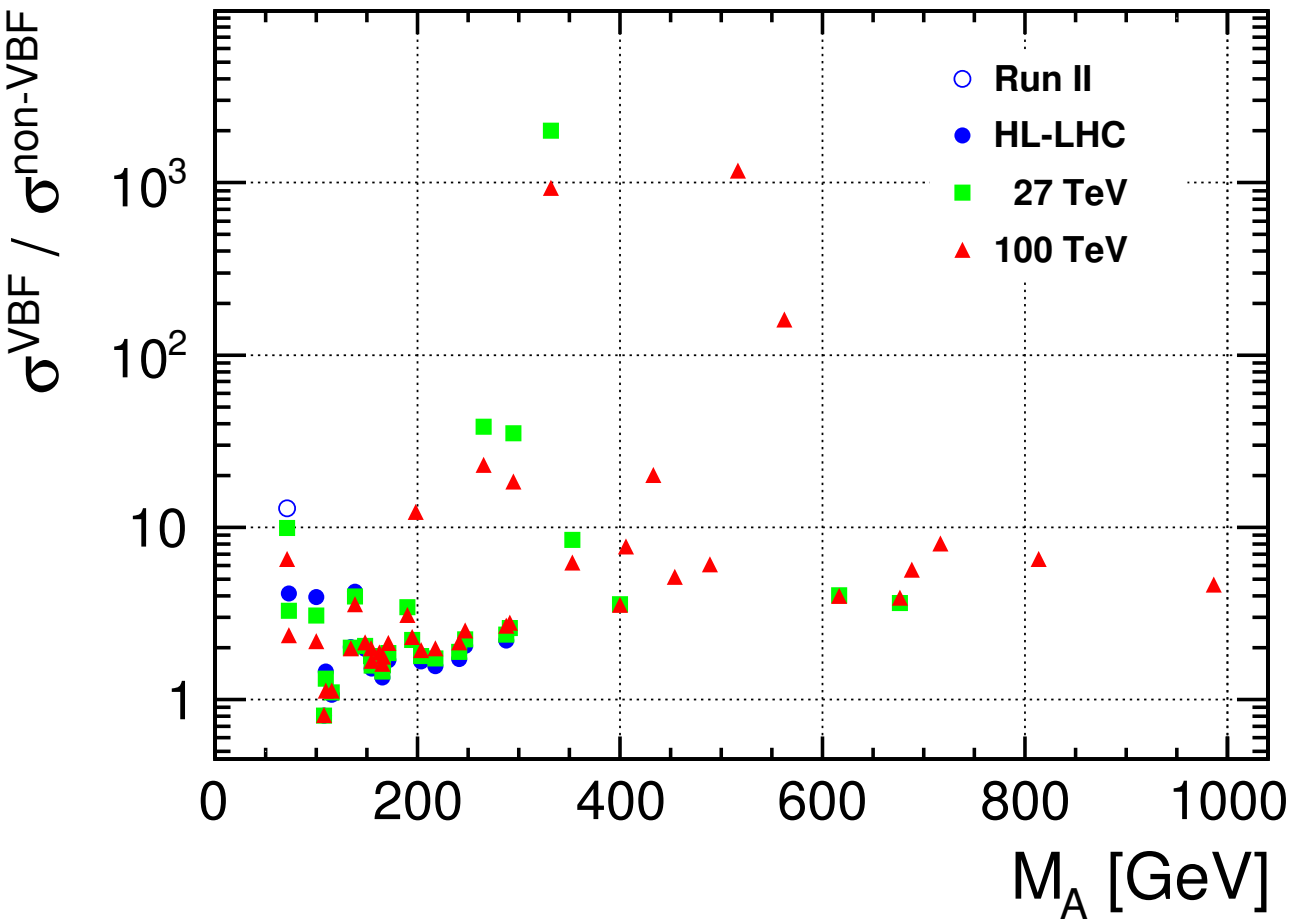
Depends on dark matter mass

- **lower mass bound:** $m_H \leq 55\,\mathrm{GeV}$ excluded by combination of signal strength and relic density
- $m_H \sim M_h/2$**: exact relic density possible**, $b\,\bar{b}$ and WW final states, $|\lambda_{345}| \lesssim 0.006$
- $m_H \in [65\,;\,500\,\mathrm{GeV}]$ **no points with exact relic density**
- **above** $m_H = 500\,\mathrm{GeV}$**: possible for small mass splittings** $\Delta\,m \leq 10\,\mathrm{GeV}$, dominantly into $W^+\,W^-$ final states

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

Enhancement AA using VBF type topologies, pp colliders

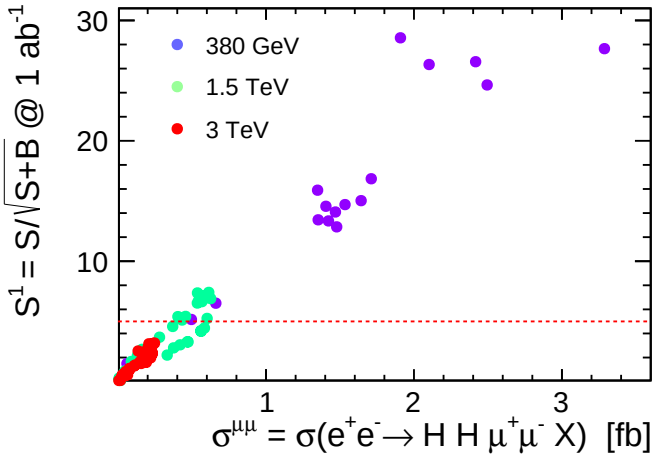


Dominant enhancements e.g. from H^+A production (offshell) / WW fusion diagrams

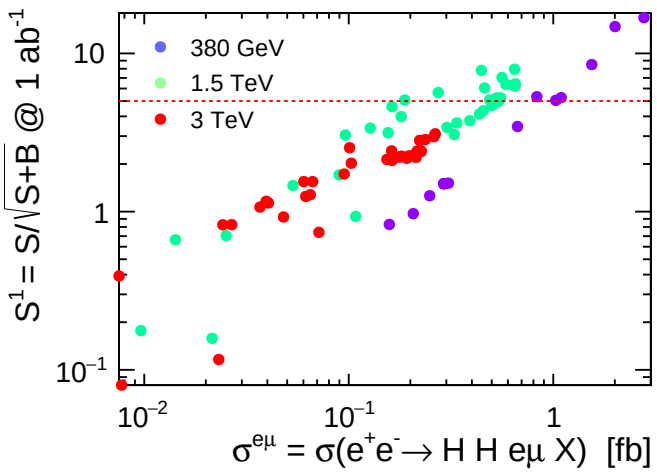
Results for CLIC studies [JHEP 1812 (2018) 081; JHEP 1907 (2019) 053]

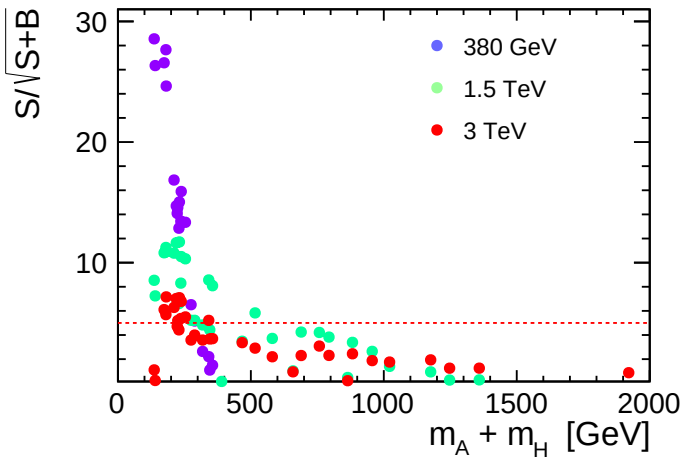
For selected benchmark points...

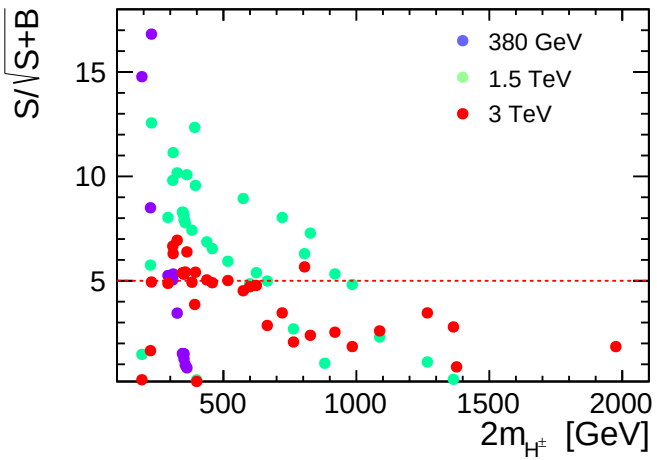
HA **production**



H^+H^- **production**







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

⇒ 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 [$35.9\mathrm{fb}^{-1}$]

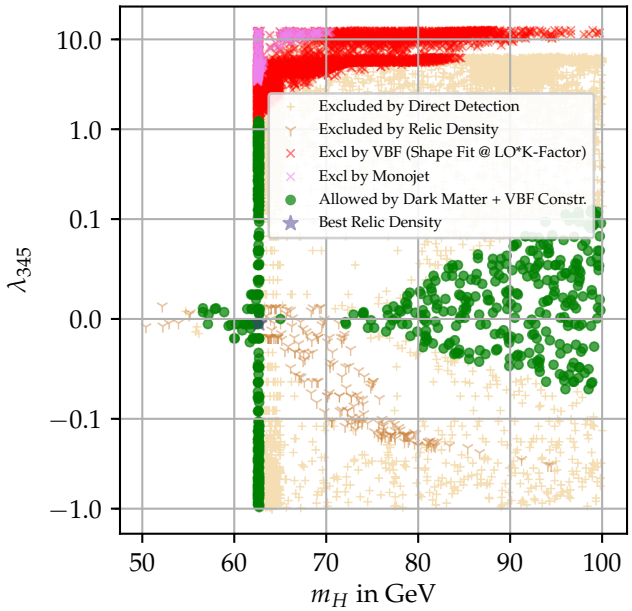
Monojet: *Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector*, ATLAS, ATLAS-CONF-2017-060 [$36.1\mathrm{fb}^{-1}$]

IDM at LHC

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

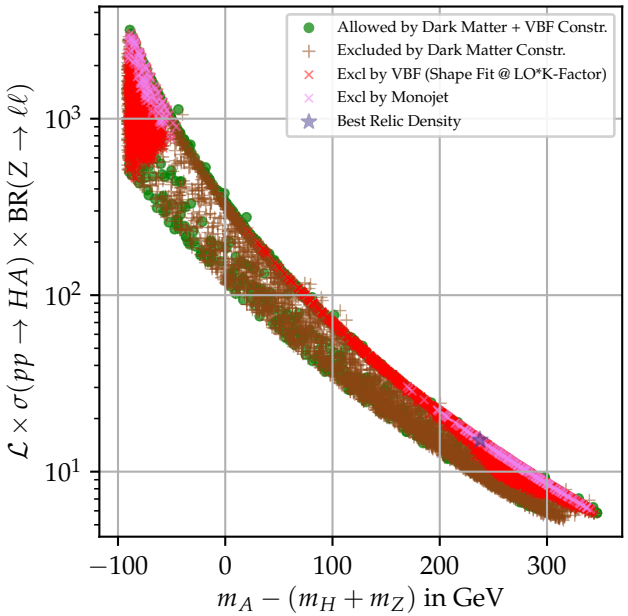
VBF recast; test of dilepton sensitivity

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 [$35.9\mathrm{fb}^{-1}$]



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

important constraints in offshell regime !

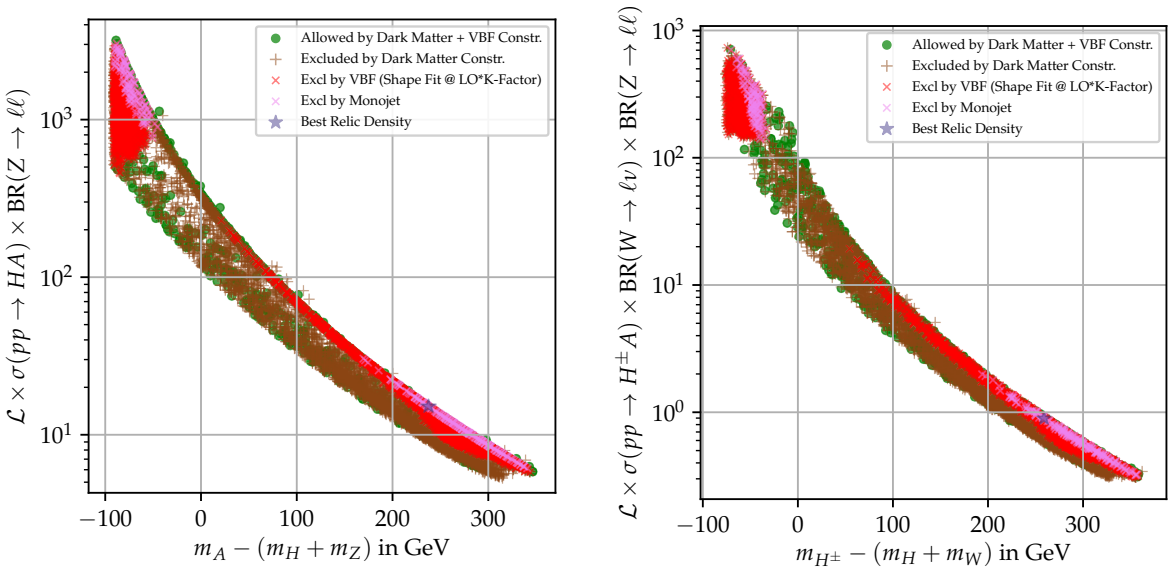


example for $\not{E}_\perp$ vs rate

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)

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

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

THDMa

setup: 2 Higgs Doublet Model (Type II), + **pseudoscalar** a (mixing with A), + **dark matter candidate** χ (fermionic)

- **DM couples to additional field in gauge-eigenstates**

⇒ promoted by LHC Dark Matter Working group in Phys.Dark Univ. 27 (2020) 100351

original literature: S. Ipek ea, [Phys. Rev. D90 (2014), no. 5 055021]; J. M. No, [Phys. Rev. D93 (2016), no. 3 031701]; D. Goncalves ea, [Phys. Rev. D95 (2017)]; M. Bauer ea, [JHEP 05 (2017) 138]; P. Tunney ea, [Phys. Rev. D96 (2017)]

⇒ **highly scrutinized by LHC experiments**

THDMa: Lagrangian/ parameters

$$V_{\text{THDM}} = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2$$
$$+\lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left[\mu_3 H_1^\dagger H_2 + \lambda_5 (H_1^\dagger H_2)^2 + h.c.\right]$$

$$V = \frac{1}{2} m_P^2 P^2 + \lambda_{P_1} H_1^\dagger H_1 P^2 + \lambda_{P_2} H_2^\dagger H_2 P^2 + (\imath b_P H_1^\dagger H_2 P + h.c.)$$

$$V_\chi = \imath y_\chi P \bar{\chi} \gamma_5 \chi$$

THDMa scalar sector particle content: h, H, $H^\pm$, a, A, χ

parameters:

v, m_h, m_H, m_a, m_A, $m_{H^\pm}$, m_χ; $\cos(\beta - \alpha)$, $\tan\beta$, $\sin\theta$; y_χ, λ_3, λ_{P_1}, λ_{P_2}

THDMa: Implemented constraints

[see also Abe ea, JHEP, 01:114, 2020; Arcadi ea, JHEP, 06:098, 2020]

Theory

- **boundedness of potential** from below
- **perturbativity of couplings**
- **perturbative unitarity**

Experiment

- v, $m_{h/H}$: input
- **electroweak precision** through S, T, U
- $B \to X_s \gamma$, $B \to \mu^+\mu^-$, ΔM_s
- Γ_{125}
- **direct searches and 125 GeV signal strength** through HiggsBounds/ HiggsSignals
- upper limit on **relic density**, direct detection [Phys. Rev., D90(5):055021]
- **(pseudo) recast from current LHC searches**

also using: own codes, Spheno, Sarah, MadDM, Madgraph

Parameter ranges

WG recommendation:

$$m_H = m_A = m_{H^\pm},\ m_\chi = 10\,\mathrm{GeV},$$
$$\cos(\beta-\alpha) = 0,\ \tan\beta = 1,\ \sin\theta = 0.35,$$
$$y_\chi = 1,\ \lambda_3 = \lambda_{P_1} = \lambda_{P_2} = 3$$

$\Rightarrow$ **effectively 2-d scan**

- here; let everything float

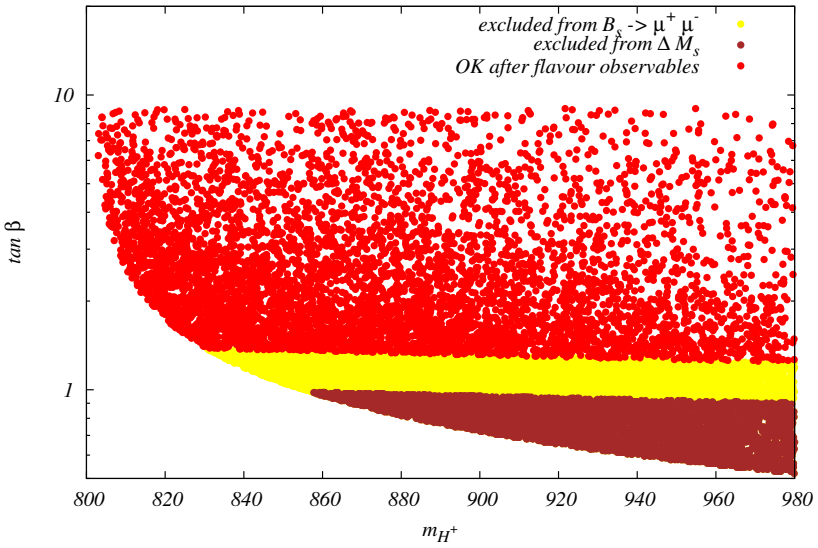
Scan ranges:

$$\sin\theta \in [-1; 0.8]\,,\ \cos(\beta-\alpha) \in [-0.08; 0.1]\,,\ \tan\beta \in [0.52; 9]\,,$$
$$m_H \in [500; 1000]\,\mathrm{GeV},\ m_A \in [600; 1000]\,\mathrm{GeV},$$
$$m_{H^\pm} \in [800; 1000]\,\mathrm{GeV},\ m_a \in [5\,\mathrm{GeV}; m_A]\,,\ m_\chi \in [0\,\mathrm{GeV}, m_a/2]\,,$$
$$y_\chi \in [-\pi; \pi]\,,\ \lambda_{P_1} \in [0; 10],\ \lambda_{P_2} \in [0; 4\pi]\,,\ \lambda_3 \in [-2; 4\pi]\,.$$

Example: B-physics constraints

Constraints from $B \to X_s \gamma$, $B_s \to \mu^+ \mu^-$, ΔM_s

- $B \to X_s \gamma$: use fit from updated calculation of Misiak ea, [JHEP 2006 (2020) 175, Eur.Phys.J. C77 (2017) no.3, 201], $\Rightarrow \tan\beta_{\mathbf{min}}(m_{H^\pm})$
- $B_s \to \mu^+ \mu^-$, ΔM_s: via SPheno, compare to LHC combination [ATLAS-CONF-2020-049], HFLAV value [arXiv:1909.12524]



$$R_\gamma^{\text{exp}} \equiv \frac{\mathcal{B}_{(s+d)\gamma}}{\mathcal{B}_{c\ell\nu}} = (3.22 \pm 0.15) \times 10^3,$$

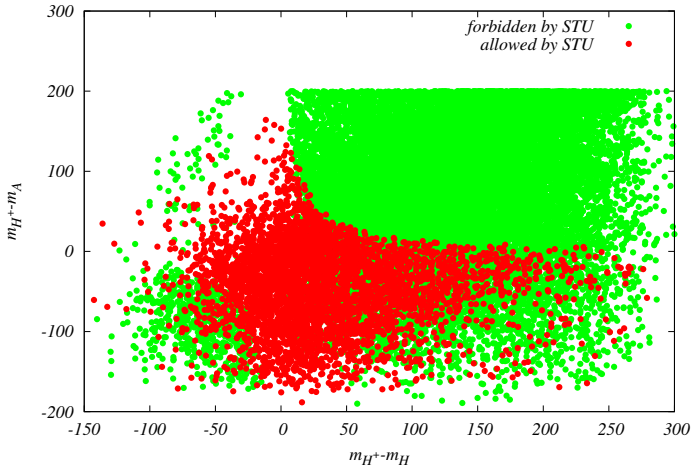
$$\Delta M_s\,(\text{ps}^{-1}) = 17.757 \pm 0.020 \pm 0.007,$$

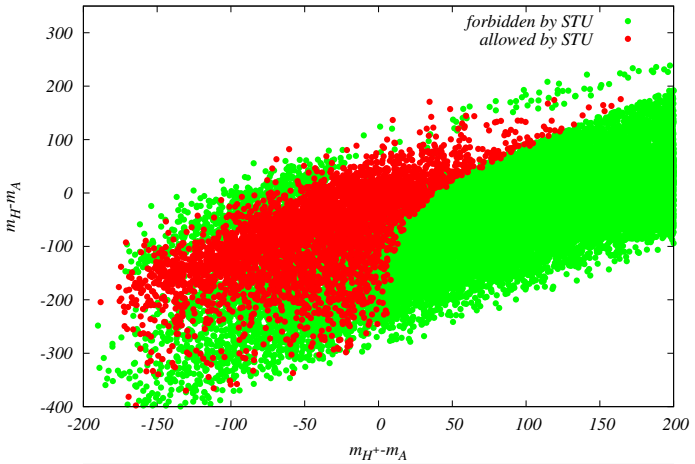
$$\left(B_s \to \mu^+\mu^-\right)^{\text{comb}} = \left[2.69^{+0.37}_{-0.35}\right] \times 10^{-9}$$

Oblique parameters via SPheno, compare to GFitter [Eur. Phys. J., C78(8):675]

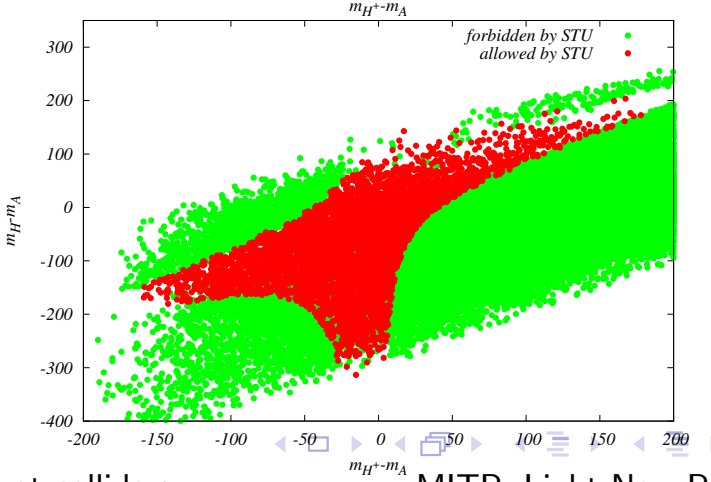
Constraints on mass differences

$$m_{H^\pm} - m_H,\ m_{H^\pm} - m_A,\ m_A - m_H$$



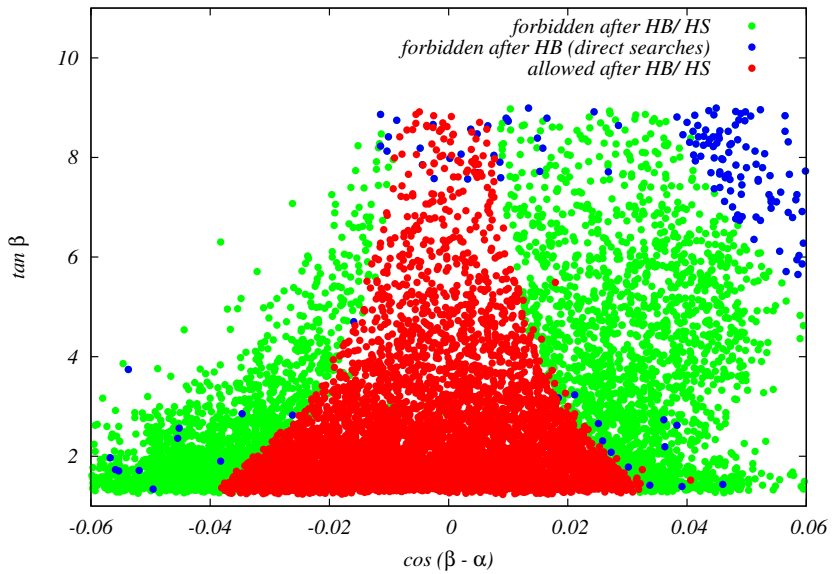


compare to THDM ⇒



Direct searches and signal strength

Via HiggsBounds/ HiggsSignals



$\cos(\beta - \alpha) > 0.04$:

$h_{125} \to Z\,Z$

[CMS Run I, Phys. Rev. D 89 (2014) 092007]

Relevant BSM searches:

$H/A \to \tau\,\tau$ [ATLAS Run II, Phys.Rev.Lett. 125 (2020) no.5, 051801],

$H \to h_{125} h_{125}$ [ATLAS 2018 data, JHEP 1901 (2019) 030],

$A \to H/h_{125} Z$ [ATLAS 2018/ full Run 2 data, Phys.Lett. B783 (2018) 392-414, ATLAS-CONF-2020-043]

LHC searches

Model widely promoted by LHC Dark matter working group

$\Rightarrow$ searches considered:

1. $h + \not{E}_\perp$: ATLAS, Run II dataset [ATLAS-CONF-2021-006]
2. $\ell\ell + \not{E}_\perp$: CMS, Run II dataset [Eur. Phys. J. C 81 (2021) 13]
3. $W^+\bar{t}/W^-t + \not{E}_\perp$: ATLAS, Run II dataset [arXiv:2011.09308]
4. $H^+\bar{t}b$, $H^+ \to t\bar{b}$: ATLAS, Run II dataset [JHEP, 06:151; arXiv:2102.10076]
5. $t\bar{t}$, $b\bar{b} + \not{E}_\perp$: ATLAS, Run II dataset [Eur.Phys.J. C78 (2018) no.1, 18; JHEP 2104 (2021) 174; JHEP 2105 (2021) 093;JHEP, 04:165, 2021]
6. $A \to Z\,H$: ATLAS, Run II dataset [Eur. Phys. J., C81(5):396, 2021]

- (4), (5) not relevant due to $\tan\beta \gtrsim 1$, m_b small
- (6) also not relevant (large masses m_A, $m_H \gtrsim m_a$)
- others: cut out some part, dominantly via $h + \not{E}_\perp$
- **but:** all parameter float $\Rightarrow$ no 2-dim clear distinction