News from the Inert Doublet Model

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Workshop on Multi-Higgs Models 2026
Instituto Superior Tecnico, Lisbon, Portugal
26.8.2026

Recasting example: Inert Doublet Model

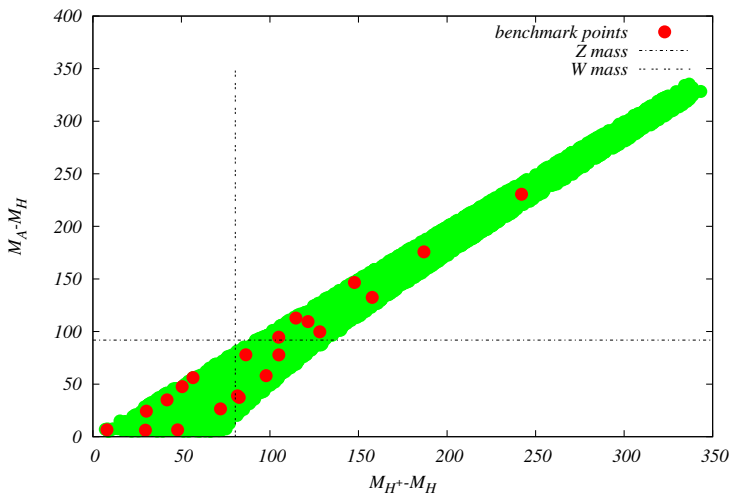
2 Higgs Doublet Model: 4 new scalars $H, A, H^{\pm}$

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

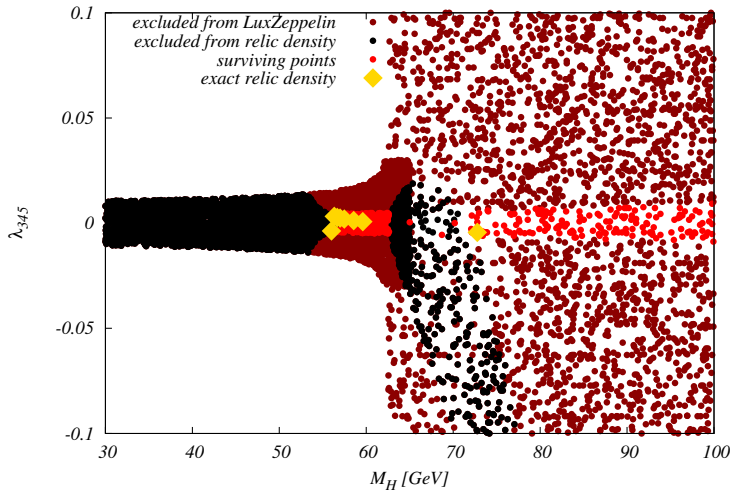
free parameters: **masses,** λ_2, λ_{345} (couplings in V)

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

Number of free parameters and constraints

Model has 7 free parameters

- choose e.g.

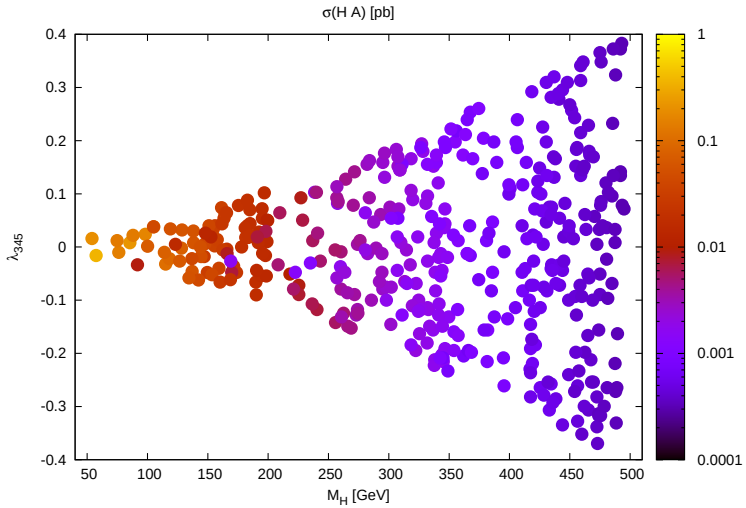
$$\underbrace{v,\ M_h,}_{246\,\mathrm{GeV},\,125\,\mathrm{GeV}} \quad \mathrm{M_H},\ \mathrm{M_A},\ \mathrm{M_{H^\pm}},\ \lambda_2,\ \lambda_{345}\,[=\ \lambda_3+\lambda_4+\lambda_5]$$

Constraints

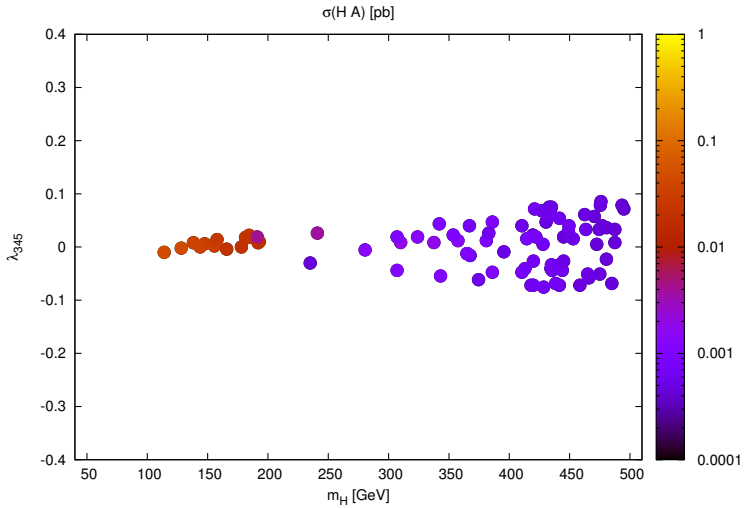
- **Theory constraints:** vacuum stability, positivity, constraints to be in inert vacuum, perturbative unitarity, perturbativity of couplings, choosing M_H as dark matter: $M_H \leq M_A,\ M_{H^\pm}$
- **Experimental constraints:** total width of $h\,W,\ Z$; collider constraints from signal strength/ 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 (LUX-ZEPLIN)

Updated constraints [LUX-ZEPLIN] [Phys.Rev.Lett. 131 (2023) 4, 041002]

LUX



LUX-ZEPLIN



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 (yet)

- 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

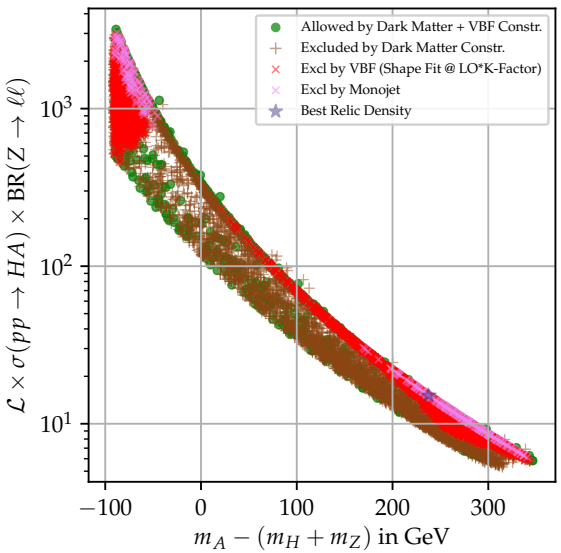
$\Rightarrow$ implemented in CheckMATE [currently: private version]

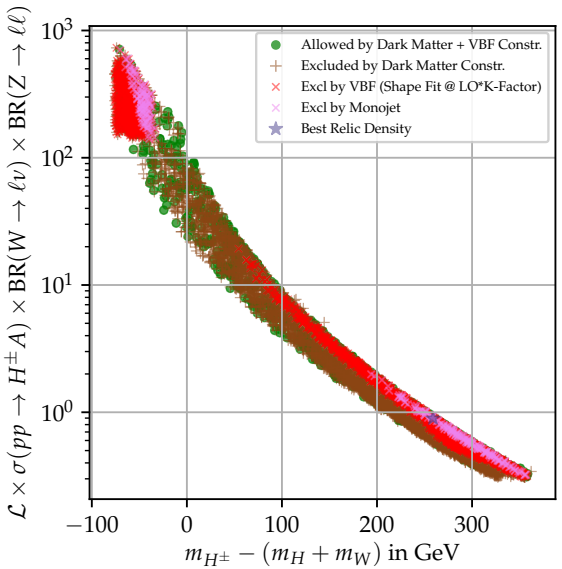
$\Rightarrow$ applied to IDM

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, Phys.Lett.B 793 (2019) 520-551, [$35.9\mathrm{fb}^{-1}$]

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, JHEP 01 (2018) 126, [$36.1\mathrm{fb}^{-1}$]

Brief comments on null-results for dilepton final states





- **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)

Recasting $\ell\ell + \not{E}_\perp$ using full Run 2 results

(w. J. Lahiri/ K. Rolbiecki, arXiV:2511.23133)

- recently: **a lot of interest has gone into the THDMa**
  [THDM+ additional pseudoscalar + fermionic dm candidate]

  [see Ipek ea, Phys. Rev., D90(5):055021, 2014; No, Phys. Rev., D93(3):031701, 2016; Goncalves ea, Phys. Rev. D95(5):055027, 2017; Bauer ea, JHEP, 05:138, 2017; Tunney ea, Phys. Rev., D96(9):095020, 2017; also TR, Symmetry 13 (2021) 12, 2341]

  shares $Z + \not{E}_\perp$ as a dominant channel

- **what about a recast there ??**
- tool of choice: **CheckMATE**

  [Drees ea, Comput.Phys.Commun. 187 (2015) 227-265; Dercks ea, Comput.Phys.Commun. 221 (2017) 383-418]

Search for associated production of a Z boson with an invisibly decaying Higgs boson or dark matter candidates at $\sqrt{s} = 13\text{TeV}$ with the ATLAS detector, Phys. Lett. B 829 (2022) 137066

- used in TR, Symmetry 13 (2021) 12, 2341 to constrain $Z + \not{E}_{\perp}$ channel
- cut out 9% **of the THDMa parameter space**[1]
- **maybe also useful for IDM ?**

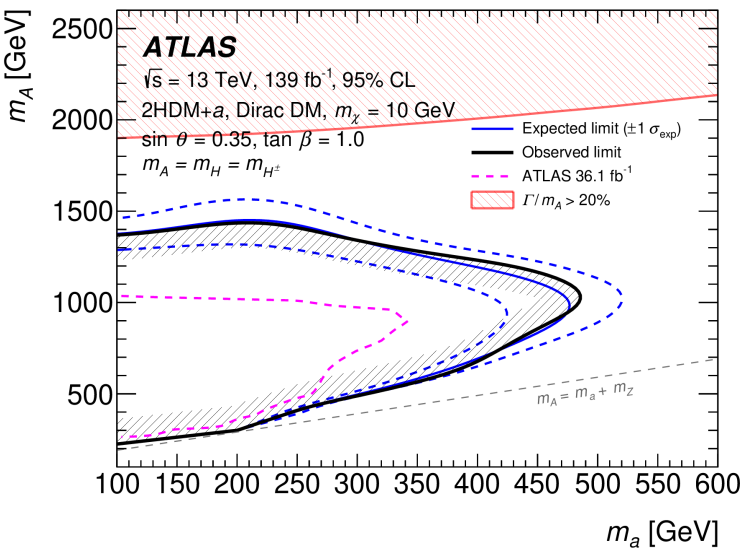
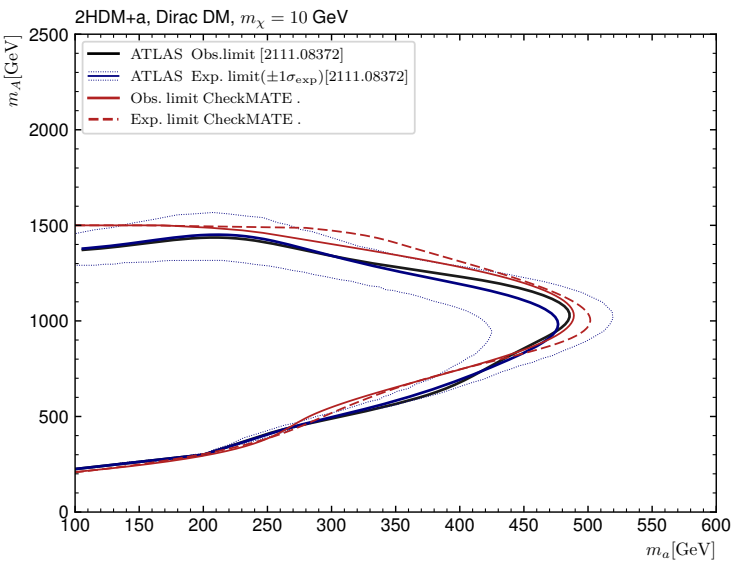


Fig from Phys. Lett. B 829 (2022) 137066



Validation within CheckMATE, thanks to I. Lara

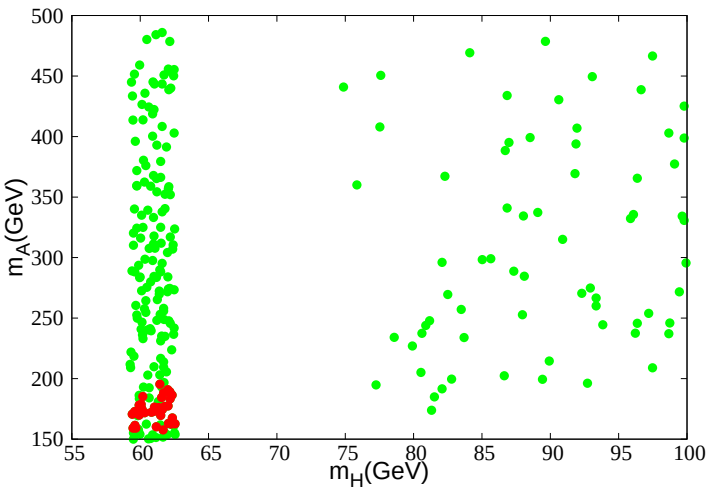
[1] Scan dependent statement

Results

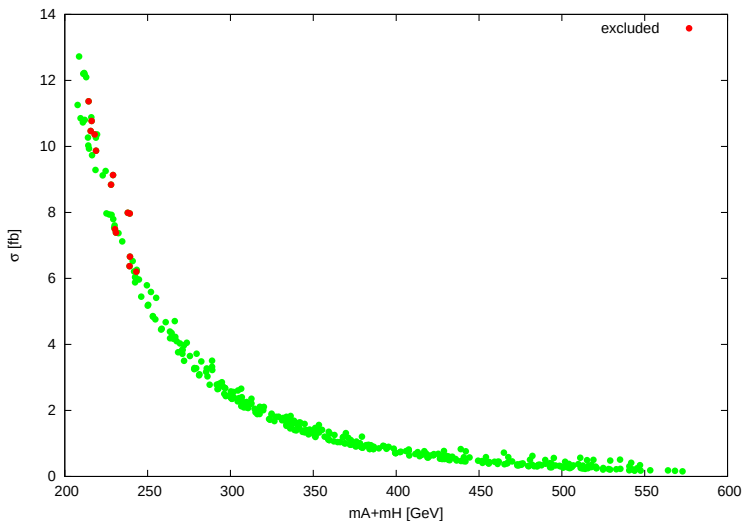
specific sample, concentrates on low $m_H \leq 100\,\mathrm{GeV}$

dominant production: $p\,p \to Z^* \to H\,A,\ A \to H\,\ell^+\,\ell^-$

In principle: only m_A, m_H should matter



allowed and excluded points, $(m_H,\ m_A)$ plane



allowed and excluded points $\left(m_H + m_A, \sigma_{HA}^{\text{cuts}}\right)$ plane

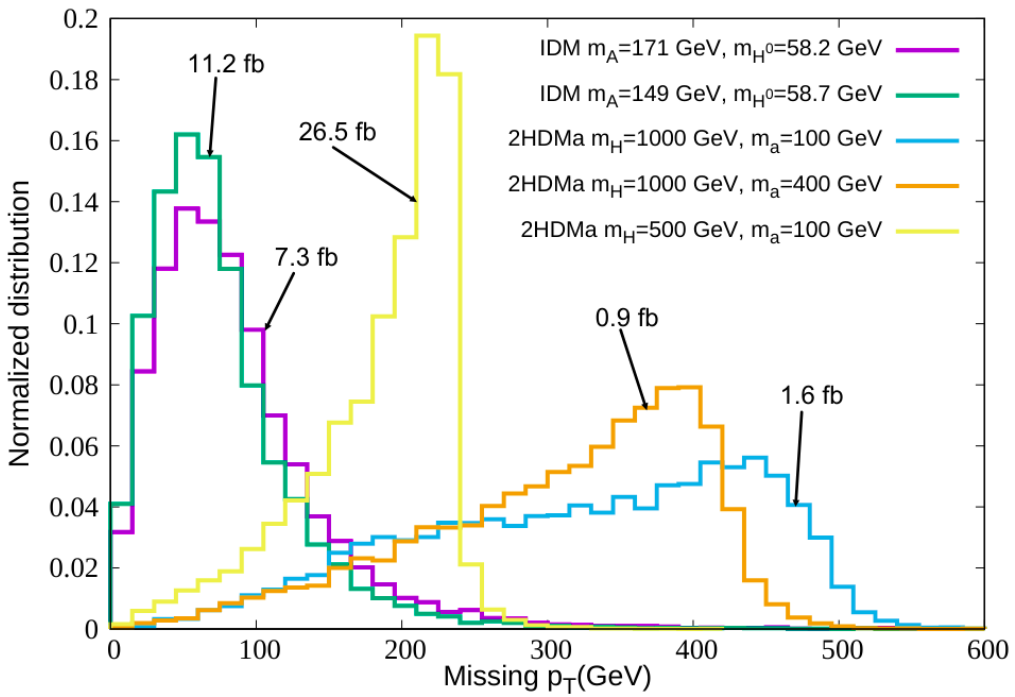
in practise:

contamination from $p\,p \to H^{\pm}\,A$ with hadronic W decays

Kinematic distributions

nota bene: **cross sections for THDMa typically much smaller, still excluded !**

reason: **differences in kinematic distributions**; here:**missing $\not{p}_\perp$**

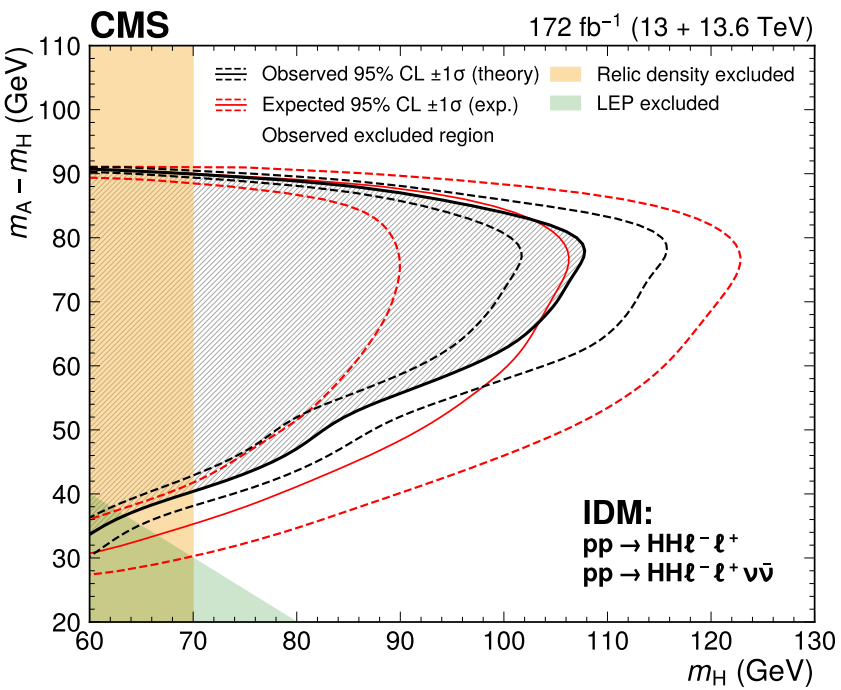


Cut in analysis: $\not{E}_\perp \geq 90\,\mathrm{GeV}$

In the meantime...

CMS collaboration,
Search for pair production of additional neutral scalars within the Inert Doublet Model in a final state with two electrons or two muons in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ and $13.6\,\mathrm{TeV}$,
CMS-NPS-25-002, CERN-EP-2026-098, arXiV:2605.13614

dedicated search for $\ell\ell$ + MET

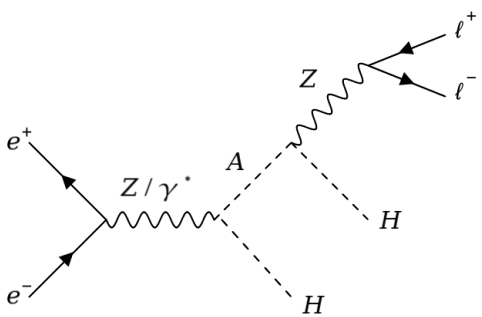


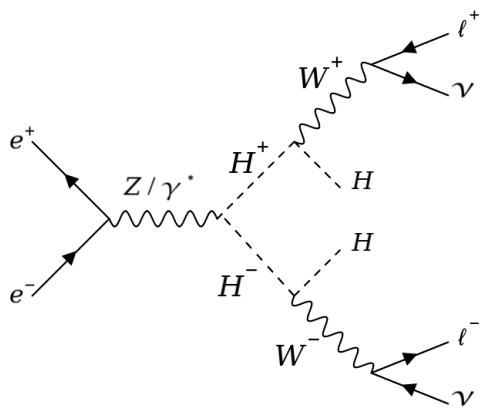
sensitive in different parameter space

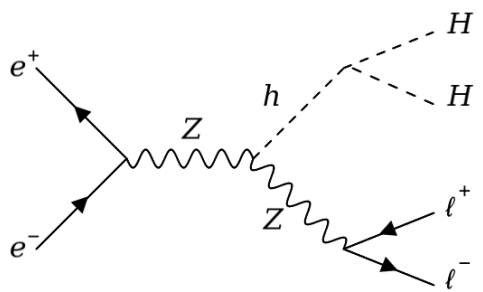
IDM: Leptonic production modes

(M. Benedikt ea., Eur. Phys. J. C (2025) 85:891)

$$
\begin{aligned}
e^+ e^- &\to HA^{(*)} \to HZ^{(*)}H \to HH\ell^+\ell^-, \\
e^+ e^- &\to H^{+(*)}H^{-(*)} \to W^{+(*)}W^{-(*)}\,H\,H \\
&\to HH\ell^+\ell^-\,\nu_\ell\,\bar{\nu}_\ell,
\end{aligned}
$$







in reality: simulate ***everything* leading to** $\ell^+\ell^- + \not{E}$

Search strategy

- consider **3 scenarios**

$$
\begin{aligned}
(S1) \quad & M_{H^\pm} = M_A,\ \lambda_{345} = 0; \\
(S2) \quad & M_{H^\pm} = M_A,\ \lambda_{345} = \lambda_{345}^{\max}; \\
(S3) \quad & M_{H^\pm} = M_{H^\pm}^{\max},\ \lambda_{345} = \lambda_{345}^{\max}
\end{aligned}
$$

- idea: **switch on/ off various contributions**
- other parameters: M_H **free,** $\lambda_2 = 0.1$

Setup

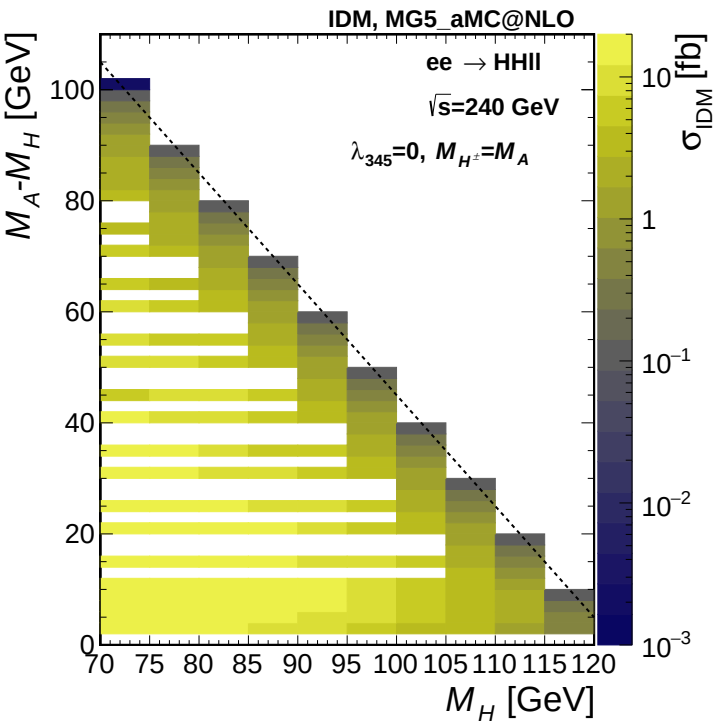
Signal generation

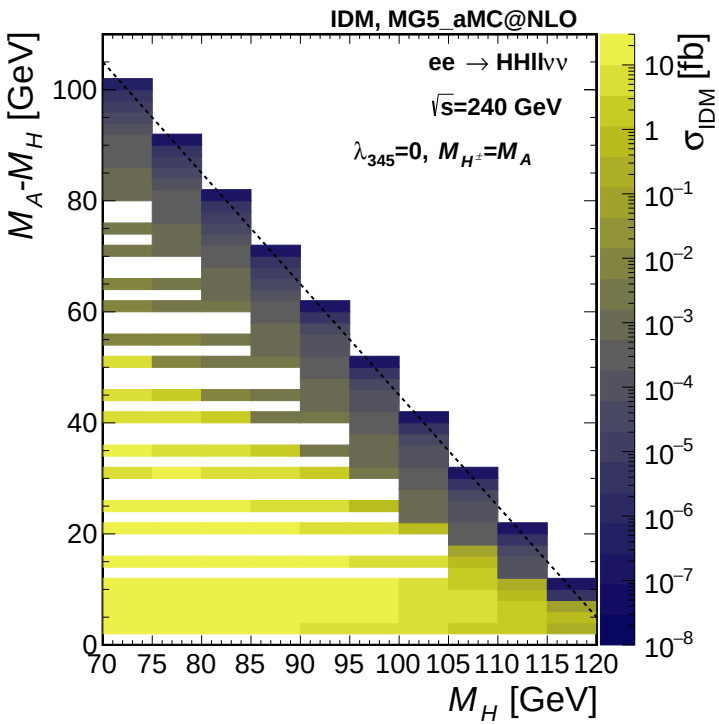
- Generate Madgraph5_aMC@NLO cards for all benchmark points, see https://github.com/amagnan/FCC
- Generated 500k events per points, for FCC-ee @ $\sqrt{s} = 240$ and 365 GeV.
- Directly by final state: ee$\rightarrow$llHH or ll$\nu\nu$HH, with l=e, μ, τ.
- Use Pythia8 for hadronisation and τ decays.
- Finally, run through Delphes using FCC IDEA cards from official FCC-ee repository, Winter2023 production.

FCC software

- Produce events in the EDM4Hep format, root-based.
- Analyse with FCCAnalyses package, forked here: https://github.com/amagnan/FCCAnalyses
- Python-based config files to create branches with analysis variables in 2 stages,
- then python-based config files to define selection in 2 steps also: output separate histograms for each sample and selection, then plot together signal and backgrounds.

Sample cross sections





Background samples

- Using FCC officially generated samples.
- Winter 2023 production.
- ee collisions at $\sqrt{s} = 240$ and 365 GeV.
- Inclusive W, Z and Higgs decays.
- ee to ee,$\mu\mu$,$\tau\tau$ production via t- and s-channel.
- Generators: Pythia8 and Whizard+Pythia6.

Ecm	Process	N Gen	xs (pb)	Eq. L (ab^{-1})
240	ZZ	56162093	1.359	41
	WW	373375386	16.4385	23
	eeH	1200000	0.00716	168
	mumuH	1200000	0.00676	178
	tautauH	1200000	0.00675	178
	nunuH	3500000	0.0462	76
	ee M30-150	85400000	8.305	10
	mumu	53400000	5.288	10
	tautau	52400000	4.668	11
365	ZZ	11470944	0.6428	18
	WW	11754213	10.7165	1.1
	eeH	1000000	0.00739	135
	mumuH	1200000	0.004185	287
	tautauH	1100000	0.004172	264
	nunuH	2200000	0.05394	41
	ee M30-150	3000000	1.527	2.0
	mumu	6600000	2.2858	2.9
	tautau	12800000	2.01656	6.3
	ttbar	2700000	0.8	3.4

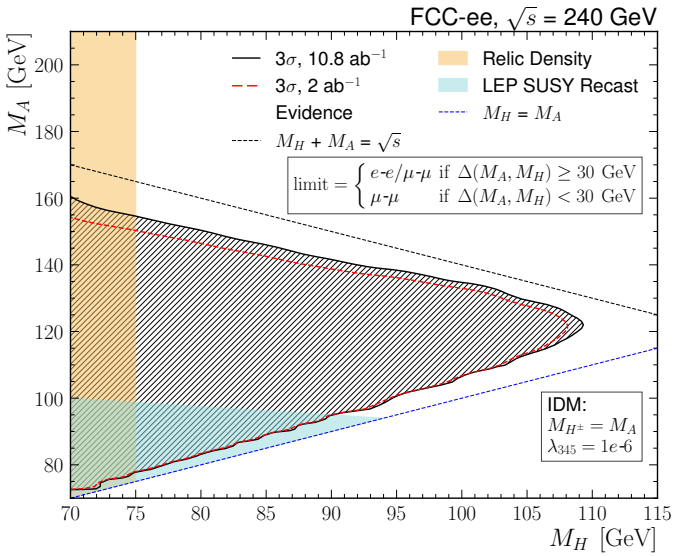
PS: contribution from Noor as CERN Summer Student: addition of the $\sqrt{s}$ =365 GeV samples.

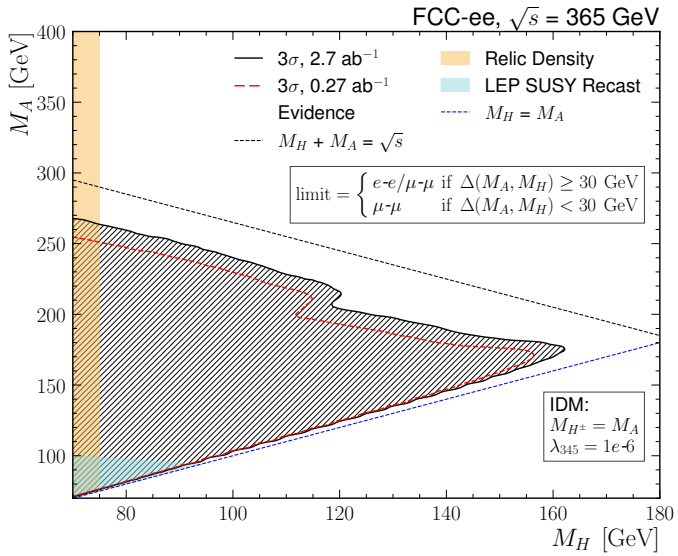
Selection

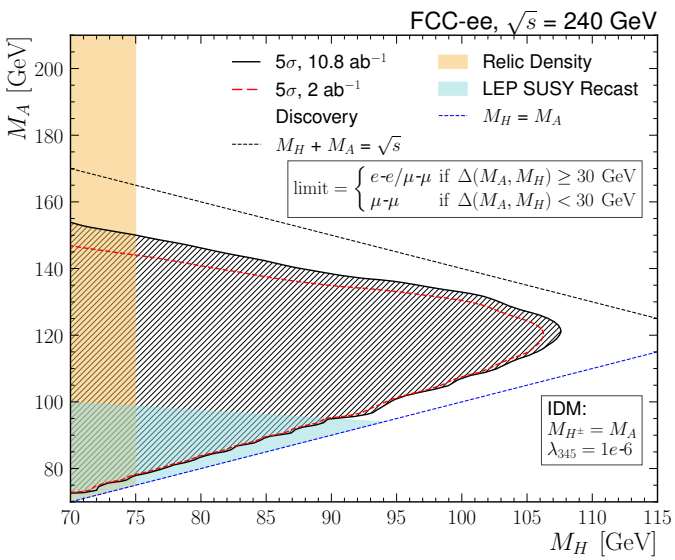
- Largely inspired from arXiv:2002.11716 with adaptation to new $\sqrt{s}$ scenarios, and addition of ee channel.
- Final state: exactly 2e (2μ) with $p > 5$ GeV [including $\tau \to e, \mu$], no other μ (e) or γ, jets.
- Some transverse missing energy to further reject inclusive ee ($\mu\mu$) production.
- Note: for ee production, missing $M_{ee} < 30$ GeV contribution ! Combining channels only for mass splitting $m_A - m_H > 30$ GeV.

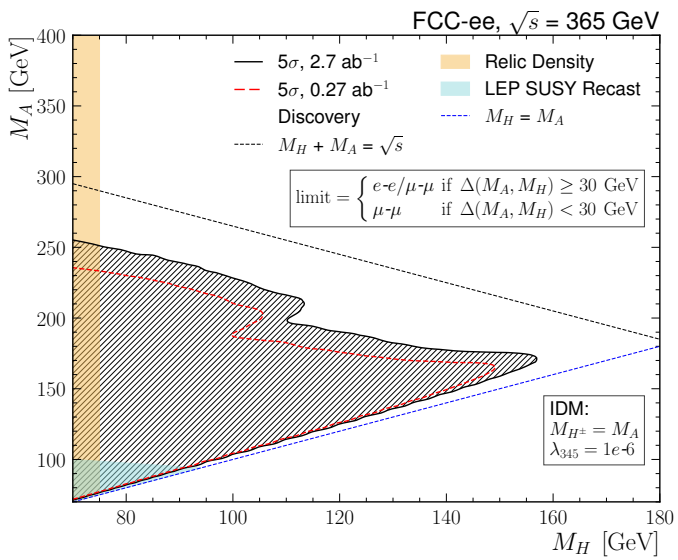
Step	Selection at $\sqrt{s}$ =240 GeV	Selection at $\sqrt{s}$ =365 GeV	target background
Preselection	$\lvert p_z(\ell\ell)\rvert < 70$ GeV	$\lvert p_z(\ell\ell)\rvert < 140$ GeV	ZZ, ee$\to ee, \mu\mu$
	$M_{\ell\ell} < 120$ GeV	$M_{\ell\ell} < (-9.0/14.0 \times \lvert p_z(\ell\ell)\rvert + 200)$	WW, ee$\to ee, \mu\mu$
	$E_T^{\text{miss}} > 5$ GeV		ZZ, ee$\to ee, \mu\mu$
Object veto	3$^{\text{rd}}$ lepton E$>$ 5 GeV, jet, photon E$>$ 5 GeV		WW, ZZ, ee$\to \ell\ell$
Leptons p_T	$p_T < 80, 60$ GeV	$p_T < 140, 80$ GeV	WW, ZZ, ee$\to \tau\tau$
E/p	$p_{ll}/E_{ll} > 0.1$		ee$\to \ell\ell$

Results [exclusion and discovery], scen 1, including pNN









IDM at ee: summary

- investigated **dilepton+ missing energy signal for IDM** at FCC-ee, 240 and 365 GeV center of mass energies

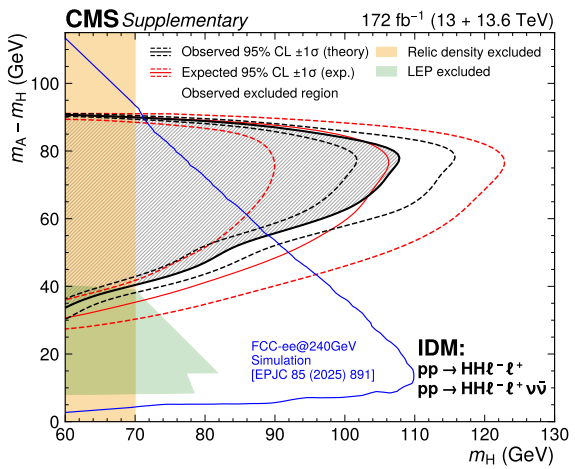
$\Rightarrow$ **main contribution comes from HA production and decay**

- nearly **all the mass range that is kinematically accessible can be covered in exclusion**
- highest mass reach for M_H (M_A) **around 110/ 160 GeV**$(160/270\,\mathrm{GeV})$

And together....

Conclusion

- For the first time, a dedicated search for extra scalars within the IDM is performed on collider data from CMS.
- Limits are complementary to those expected at a future collider, and will remain competitive for a long time !
- Explored only the same-flavour option here, sensitive to m_A and m_H, a dedicated analysis using e.g. opposite flavour or single-lepton final state would allow to test further the bounds on $m_{H^\pm}$.



(slide from A.M. Magnan, Extended Scalars from All Angles 2026)

Summary

- **Inert Doublet Model: interesting scenario for new physics containing DM candidate**

Recast of THDMa search within IDM
$\Rightarrow$ need topology-specific cuts

Current and future collider searches:
high sensitivity

! Thanks for listening !

Appendix

Inert doublet model: The model

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

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

(⇒ 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)

Parameters tested at colliders: mainly masses

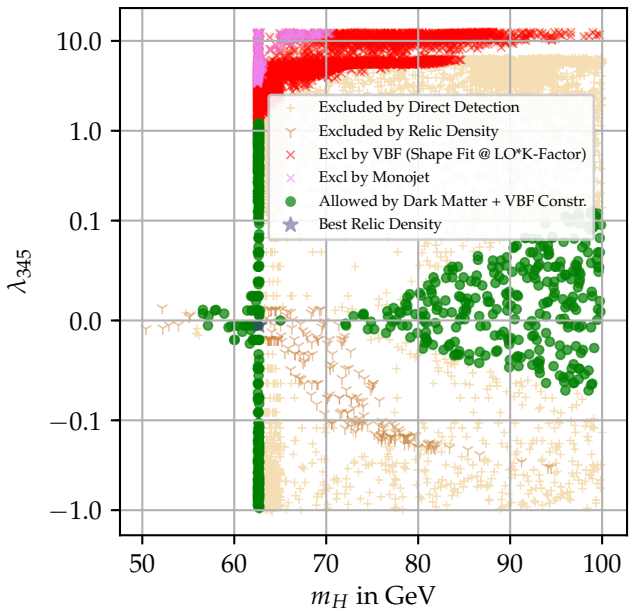
- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **relevant couplings follow from ew parameters (+ derivative couplings)**
- hXX **couplings:** determined by λ_{345} (constrained from direct detection), and **mass differences** $M_X^2 - M_H^2$ $\left(X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

important interplay between astroparticle physics and collider searches

in the end kinematic test

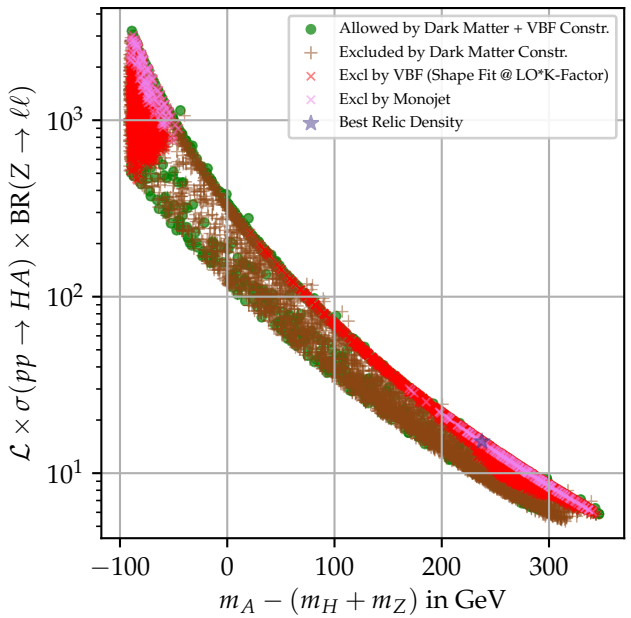
(holds for $M_H \geq \frac{M_h}{2}$)

IDM at LHC



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

important constraints in offshell regime !



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

high rates $\Longleftrightarrow$ low $\not{E}_\perp$ cuts

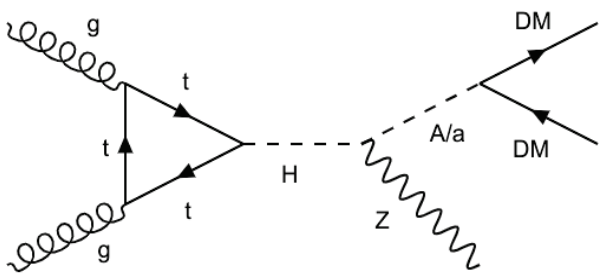
current searches at LHC need to be modified

Different production topologies...

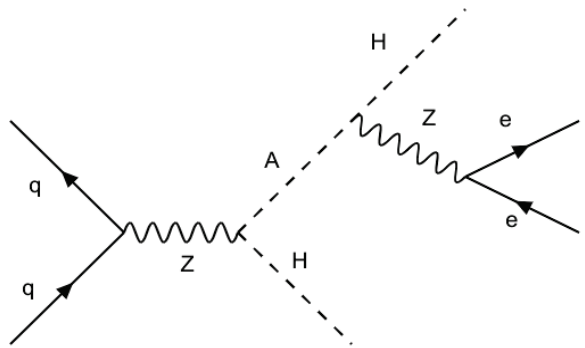
[slide from J. Lahiri, Talk at "Roadmap of Dark Matter models at LHC Run 3", 05/24]

Recasting $\ell^+\ell^- + \not{E}_T$ using full run-2 data (139 fb^{-1})

2HDMa:



Inert Doublet Model:



Other ongoing work: also reinvestigate VBF with Higgs to invisible

- take full run 2 result from ATLAS [JHEP 08 (2022) 104]

$\Rightarrow$ **should extend full search range of previous paper**

- important parameters now: m_H, λ_{345}
- main emphasis:
  off-shell range not covered by BR$(h \to$ inv$)$