News from the Inert Doublet Model

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Recasting example: Inert Doublet Model

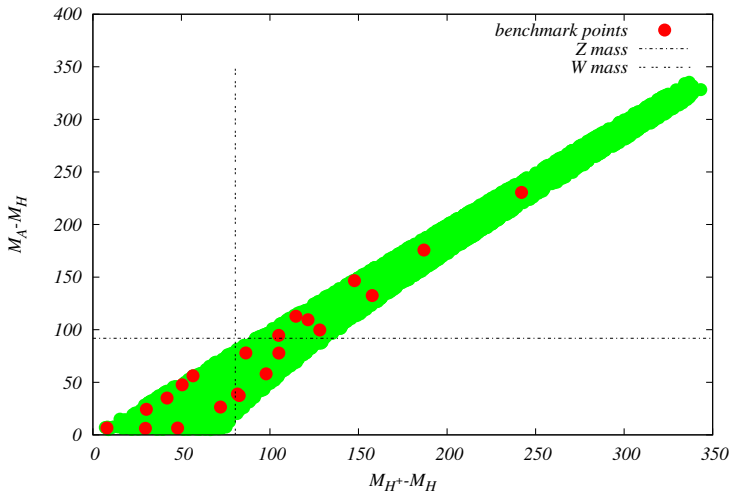
2 Higgs Doublet Model: 4 new scalars $H, A, H^{\pm}$

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

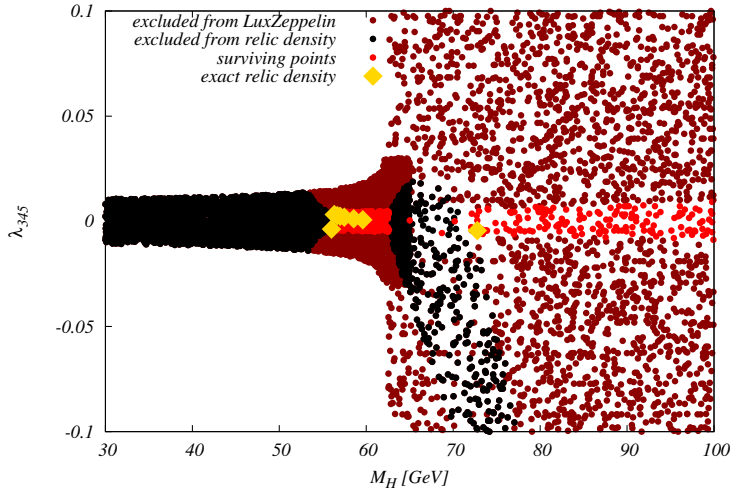
free parameters: **masses,** λ_2, λ_{345} (couplings in V)

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.

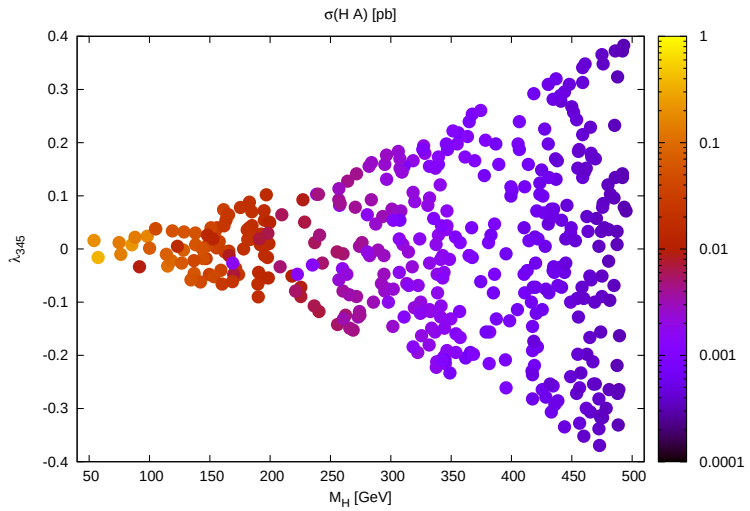
$$\underbrace{v,\ M_h,}_{\mathbf{246}\,\mathrm{GeV},\,\mathbf{125}\,\mathrm{GeV}} \quad \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{345}\,[=\lambda_3+\lambda_4+\lambda_5]$$

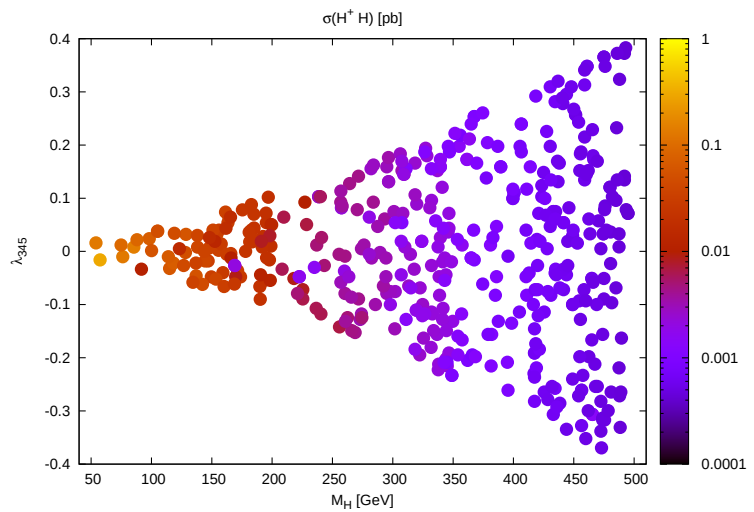
Constraints

- **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)

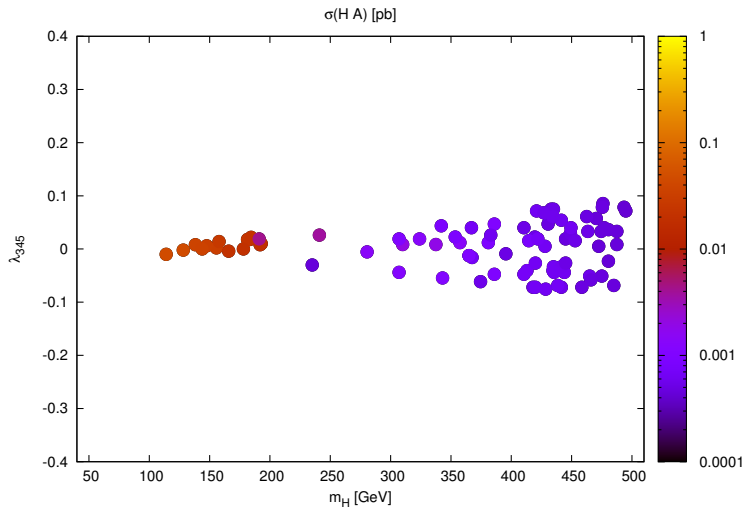
Updated constraints [LUX-ZEPLIN] [Phys.Rev.Lett. 131 (2023) 4, 041002]

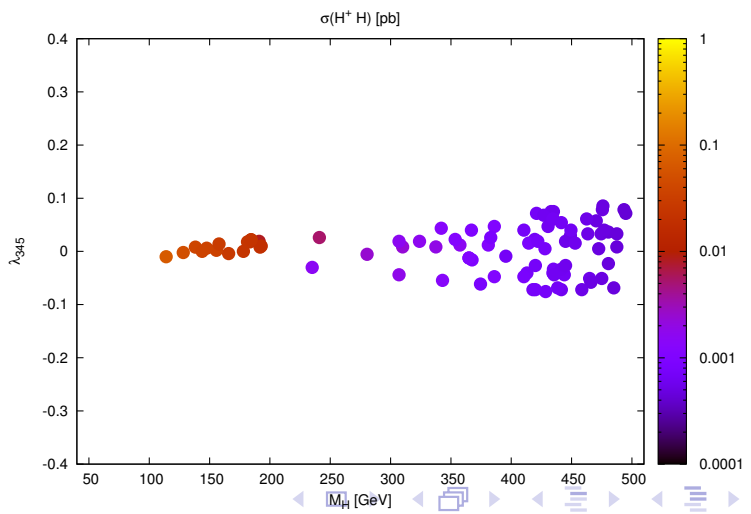
LUX





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

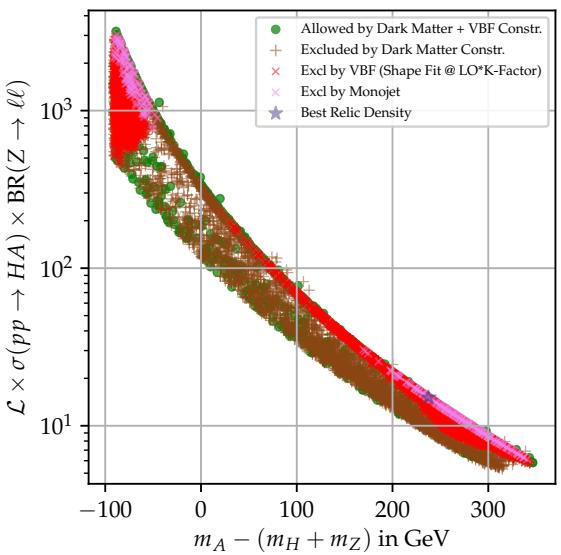
⇒ implemented in CheckMATE [currently: private version]

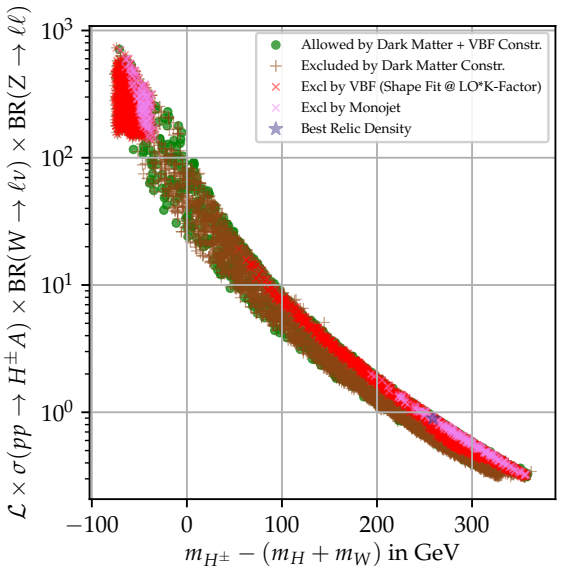
⇒ applied to IDM

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, 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)

- 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 ?**

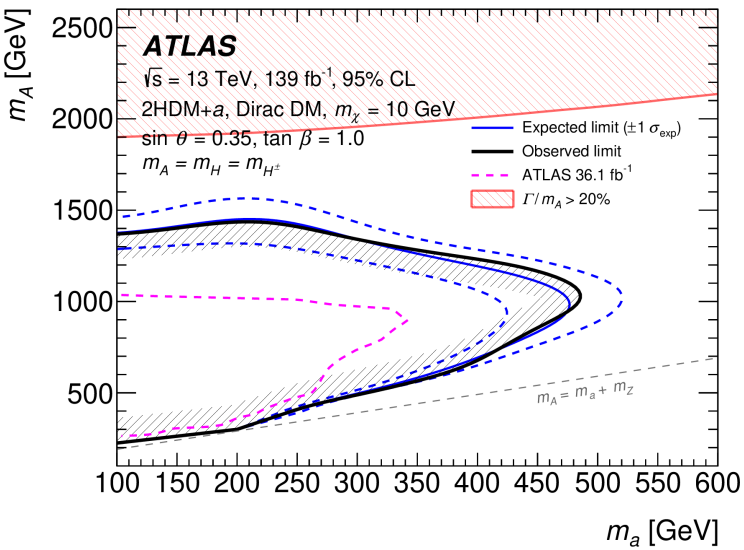
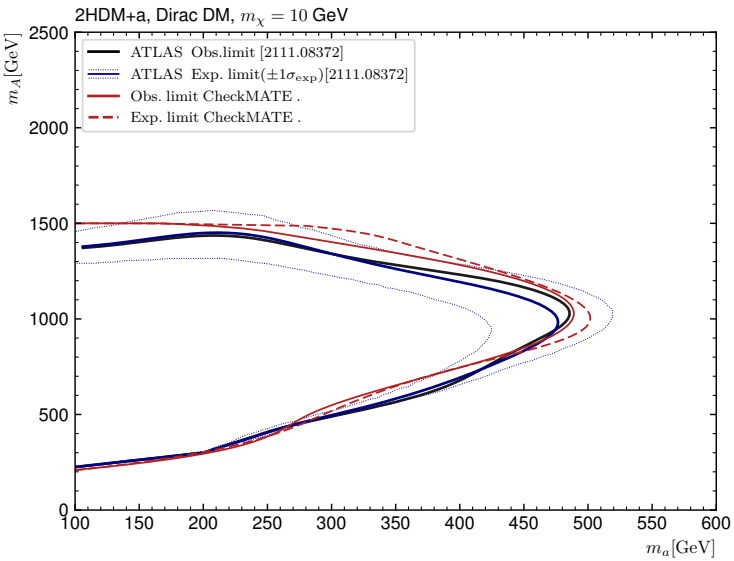


Fig from Phys. Lett. B 829 (2022) 137066



Validation within CheckMATE, thanks to I. Lara

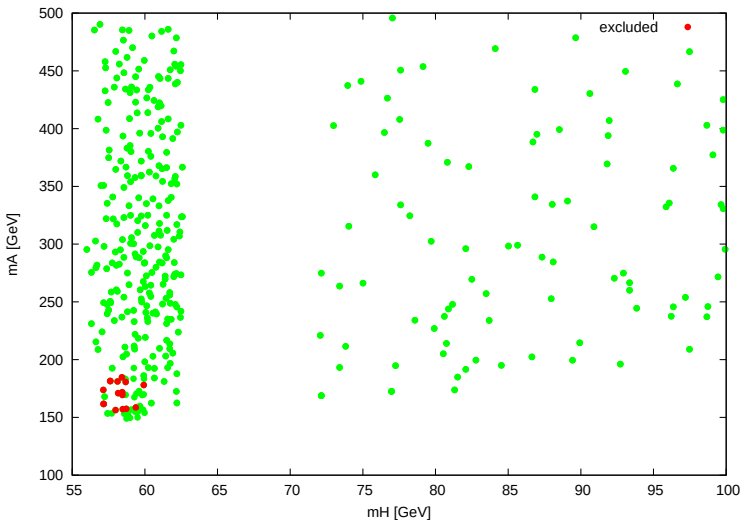
[1] Scan dependent statement

First results

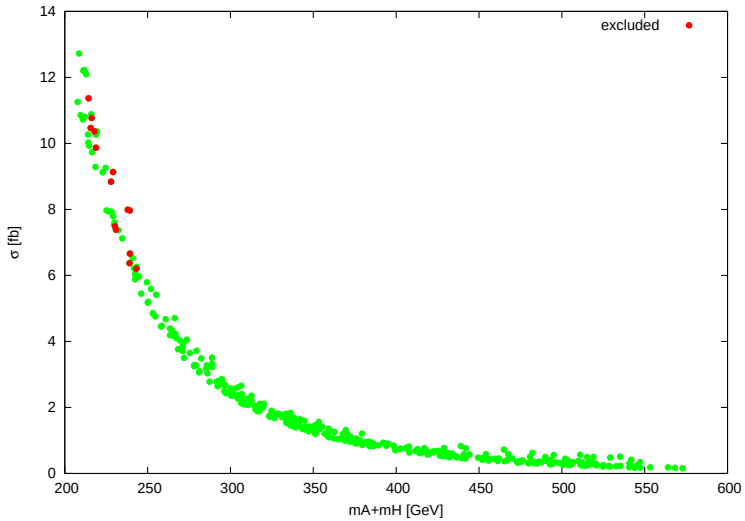
specific sample, concentrates on low $m_H \leq 100\,\mathrm{GeV}$

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 $\left(m_H + m_A, \sigma_{HA}^{\mathrm{cuts}}\right)$ plane

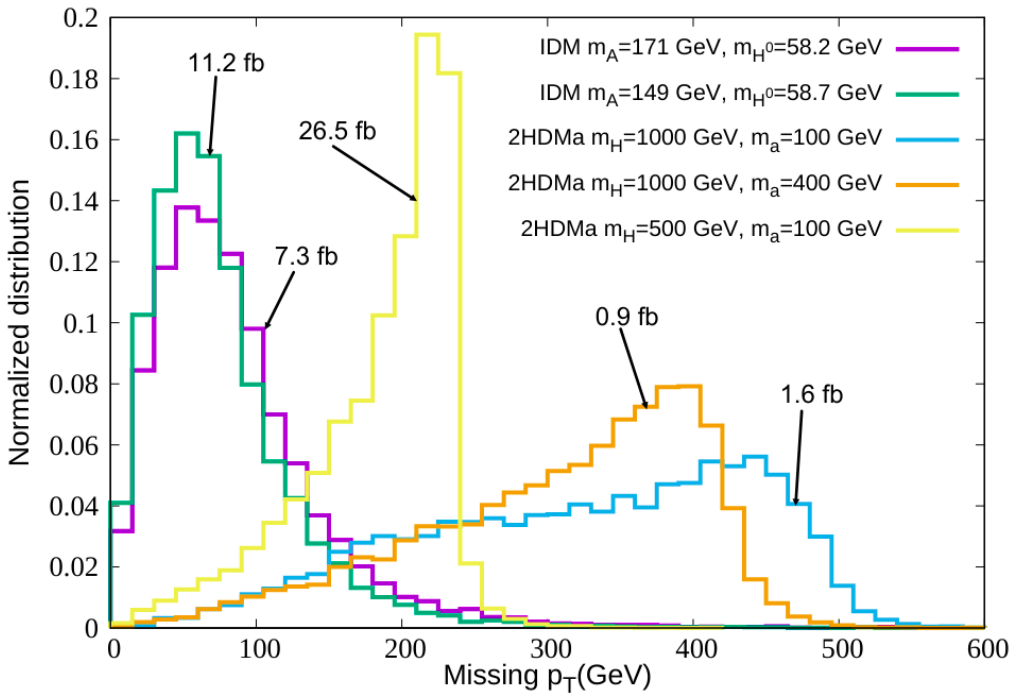
in practise:

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

Investigate VBF-type production of AA at muon collider (10 TeV) (w. J. Braathen, M. Gabelmann, P. Stylianou; arXiv:2411.13729)

- main target

$$\mu^+ \mu^- \to A A \nu_\mu \bar{\nu}_\mu$$

  with $A \to H Z$ and semileptonic decay modes for Zs.

- typical cross sections [after some basic cuts]
  $\lesssim 0.05\,\mathrm{fb}$ **at 10 TeV center of mass energy**

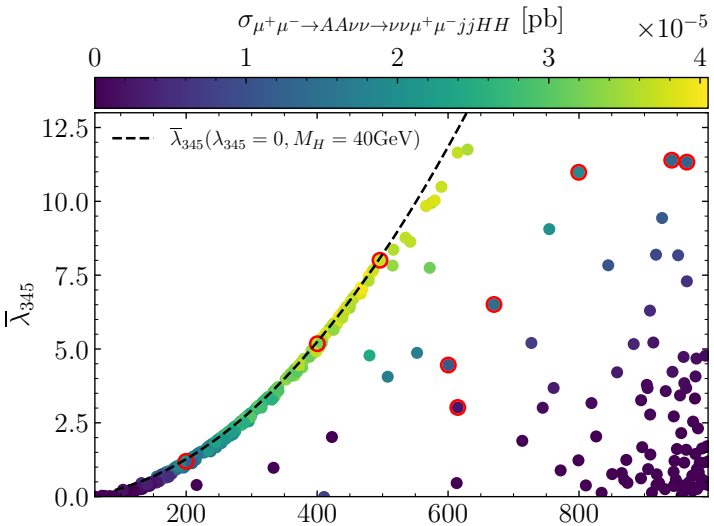
Why muon collider ?

- AA **production only mediated via** h_{125}
- coupling

$$\bar{\lambda}_{345} = \lambda_{345} + \frac{2(m_A^2 - m_H^2)}{v^2}$$

- λ_{345} **typically small from DM constraints**
- **mass difference can also not be too large**

  [although we found counterexamples]
- large com energies $\Rightarrow$ **log-enhanced VBF type production**

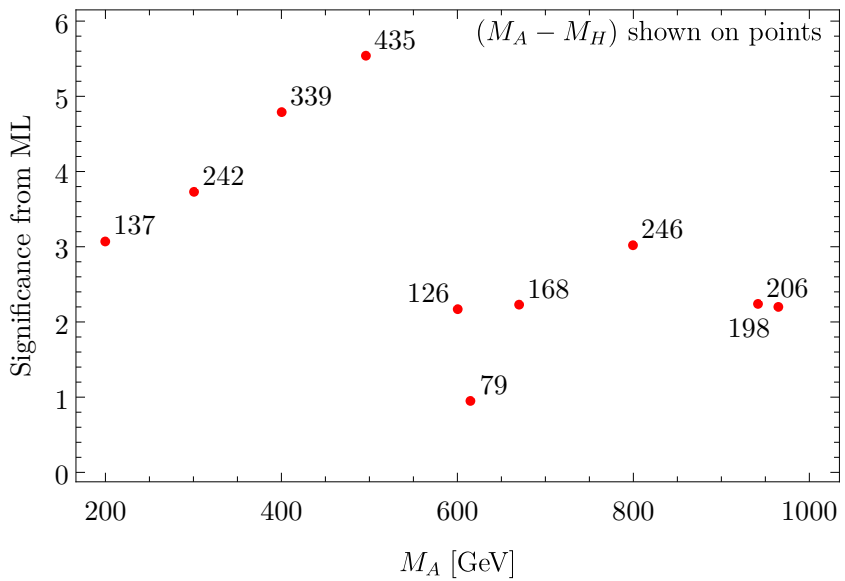


upper limit on $\bar{\lambda}_{345}$
pert. limit at 4 π

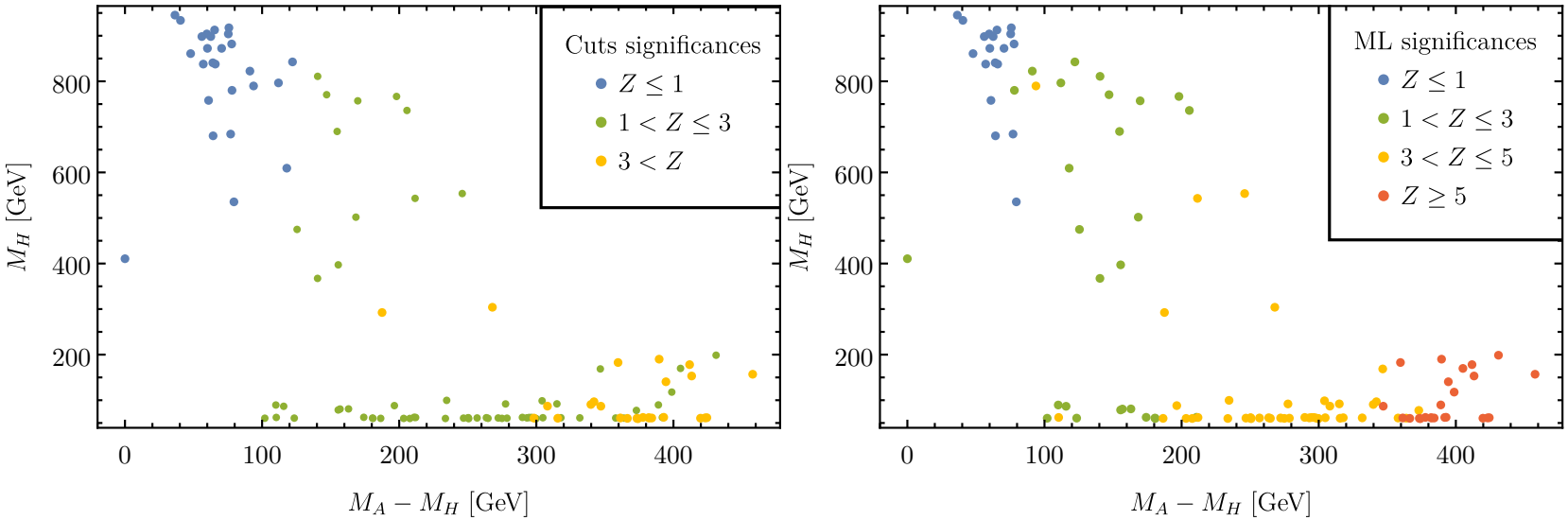
benchmark points (red circles)

Strategy

- generate $\mu^+ \mu^- \to A A \nu_\mu \bar{\nu}_\mu$ with $A \to H \ell^+ \ell^-$, $A \to H j j$
- 2 approaches: **cut based vs machine learning** (XGBoost)
- main result: **ML supersedes the cut based method, significances $\geq 3/5$ possible**



Results



$$Z = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right) - S\right]}$$

- IDM should be **testable at 10 TeV muon collider**, using ML analysis (similar to ours)
- **lower limit on cross sections** (w precuts) **of about** $0.07\,(0.05)\mathrm{fb}$ **for exclusion (discovery)**
- **systematic uncertainties need to be well under control**; best $\leq$ 5% for systematic uncertainties

Summary

- **Inert Doublet Model: interesting scenario for new physics containing DM candidate**
- so far: **no direct search at collider experiments** [FCC-ee analysis: see e.g. Bal ea, arXiv:2504.12178]
- discussed here:

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

Search at muon collider:
evasive channels accessible

! Thanks for listening !

Appendix

Models

- new scalars $\Rightarrow$ **models with scalar extensions**
- many possibilites: introduce new $SU(2) \times U(1)$ **singlets, doublets, triplets, ...**
- unitarity $\Rightarrow$ important **sum rule***

$$\sum_i g_i^2 (h_i) = g_{SM}^2$$

for coupling g to vector bosons

- many scenarios $\Rightarrow$ **signal strength poses strong constraints**

* modified in presence e.g. of doubly charged scalars, see Gunion, Haber, Wudka, PRD 43 (1991) 904-912.

What about extensions ?

- in principle: **no limit**

> **can add more singlets/ doublets/ triplets/ ...**

$\Rightarrow$ consequence: **will enhance particle content**

> **additional (pseudo)scalar neutral, additional charged, doubly charged, etc particles**

- common feature:

> **new scalar states, which can now also be produced/ decay into each other/ etc**

Particle content

typical content:
singlet extensions ⇒ additional CP-even/ odd mass eigenstates
2HDMs, 3HDMs: add additional charged scalars

- e.g. 2 real scalars ⇒ **3 CP-even neutral scalars**
- 2HDM → **2 CP-even, one CP odd neutral scalar, and charged scalars**
- ...

Current (large) collider landscape [https://europeanstrategy.cern/home]

pp colliders: LHC, FCC-hh

LHC: center-of-mass energy: 8/ 13/ 13.6 TeV, since 2009/ ongoing

HL-LHC: 14 TeV, high luminosity (2027-2040)

FCC-hh: 100 TeV, under discussion

e^+e^- colliders: ILC/ CLIC/ FCC-ee, CePC

in plan, high priority in Europe, various center-of-mass energies discussed, priority $\sim 240-250\,\mathrm{GeV}$ "Higgs factories"

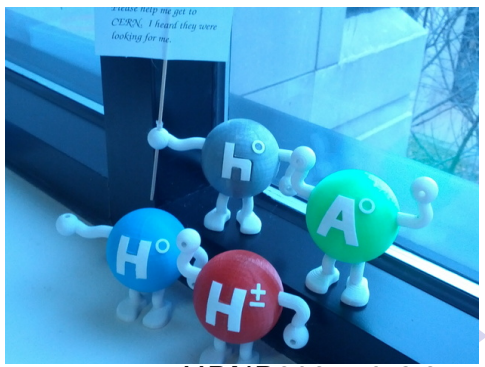
$\mu^+\mu^-$ colliders

under discussion, early stages [EU-funded design study MuCol started 1.3.23]

Other possible extensions

- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim 125\,\mathrm{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add ons:**
  - can **push vacuum breakdown to higher scales**
  - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
  - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...

  $\Rightarrow$ **new scalar states** $\Leftarrow$



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 astrophysical observations (if feasible)

Limited time $\Rightarrow$ next slides highly selective...

[long list of models, see e.g. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3]

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

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

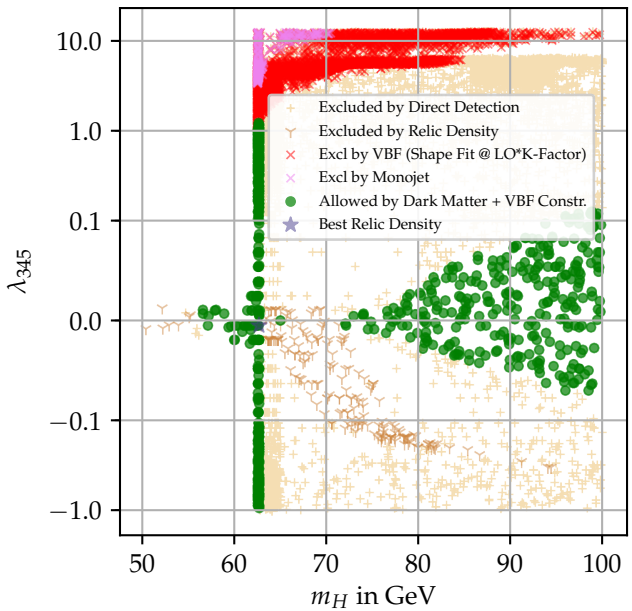
- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **relevant couplings follow from ew parameters (+ derivative couplings)**
- hXX **couplings:** determined by λ_{345} (constrained from direct detection), and **mass differences** $M_X^2 - M_H^2$ $\left(X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

important interplay between astroparticle physics and collider searches

in the end kinematic test

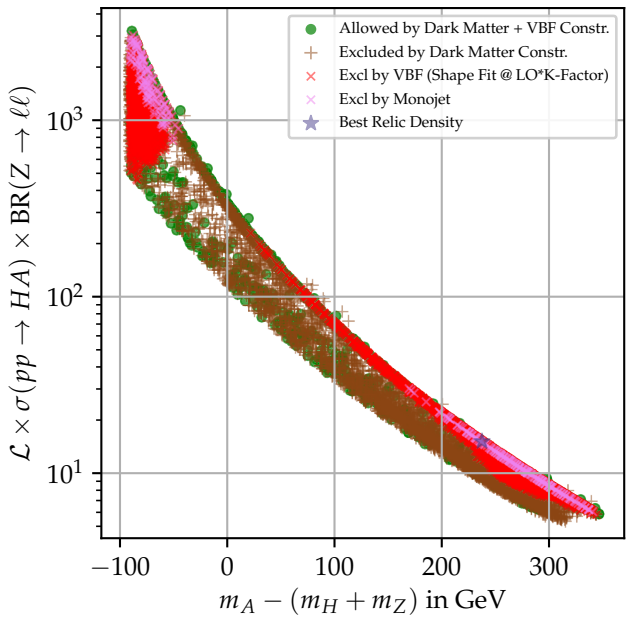
(holds for $M_H \geq \frac{M_h}{2}$)

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

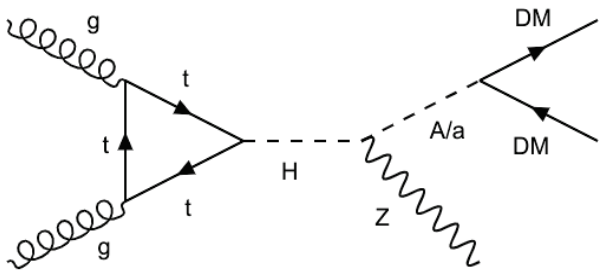
current searches at LHC need to be modified

Different production topologies...

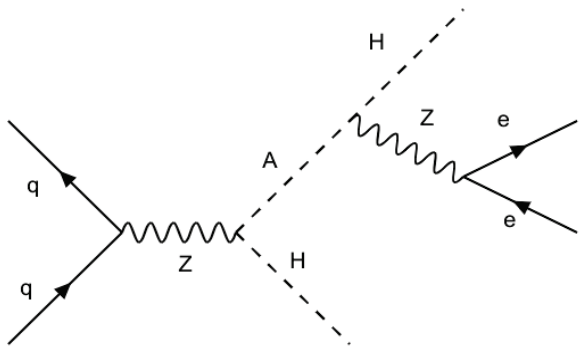
[slide from J. Lahiri, Talk at "Roadmap of Dark Matter models at LHC Run 3", 05/24]

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

2HDMa:



Inert Doublet Model:

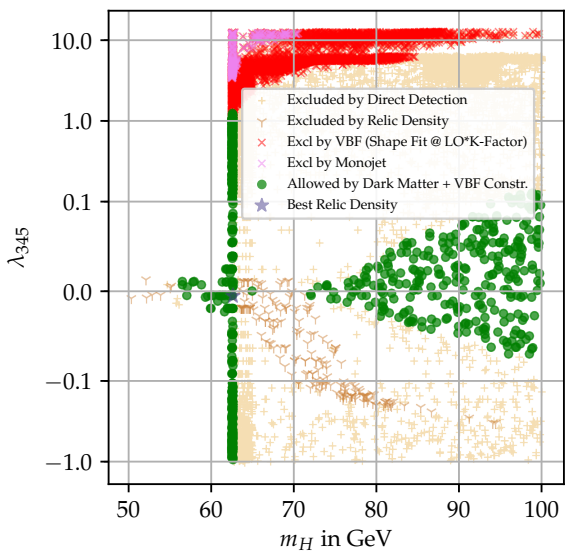


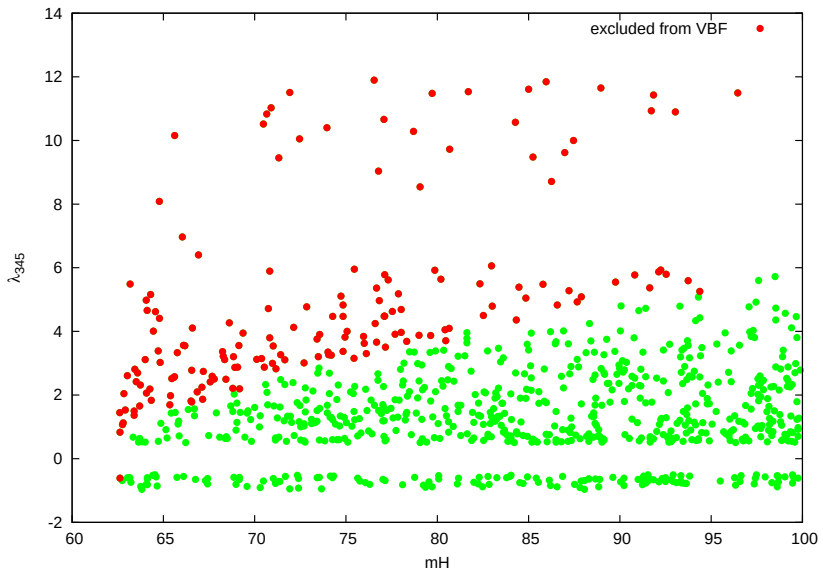
Other ongoing work: also reinvestigate VBF with Higgs to invisible

- 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$)$



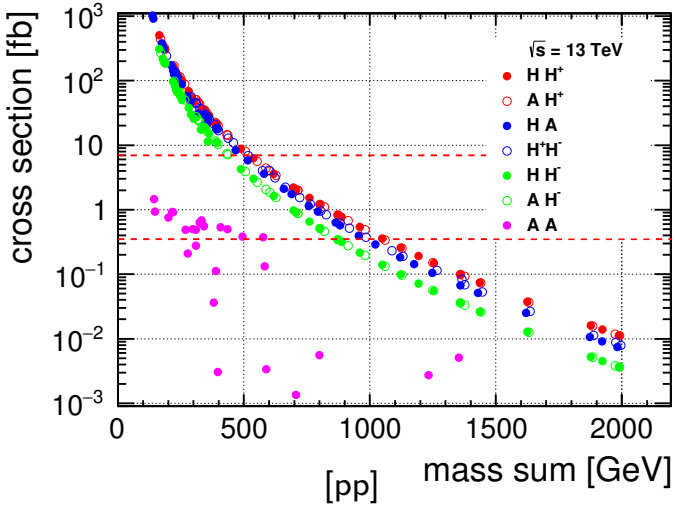


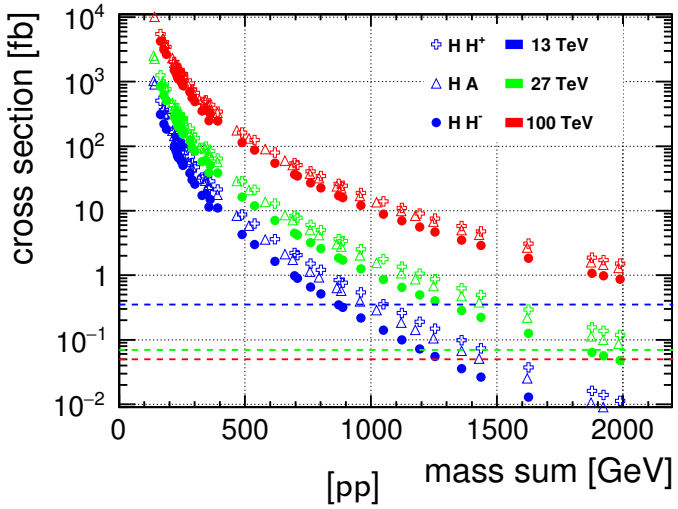
Collider parameters

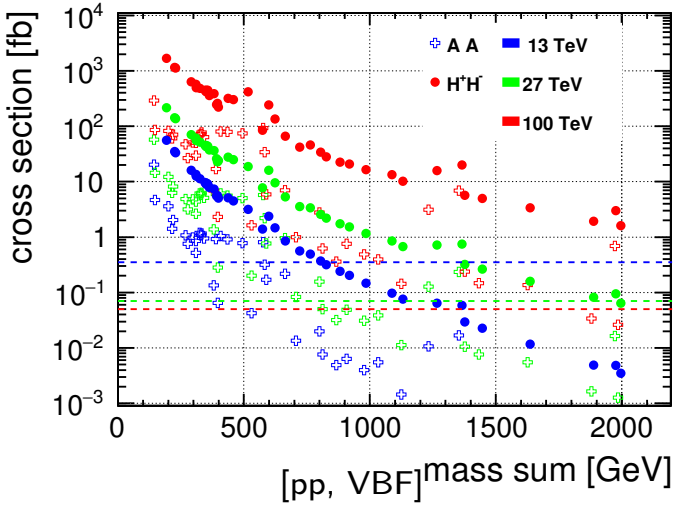
collider	cm energy [TeV]	$\int \mathcal{L}$	1000 events [fb]
HL-LHC	13/ 14	$3\,\mathrm{ab}^{-1}$	0.33
HE-LHC	27	$15\,\mathrm{ab}^{-1}$	0.07
FCC-hh	100	$20\,\mathrm{ab}^{-1}$	0.05
ee	3	$5\,\mathrm{ab}^{-1}$	0.2
$\mu\mu$	10	$10\,\mathrm{ab}^{-1}$	0.1
$\mu\mu$	30	$90\,\mathrm{ab}^{-1}$	0.01

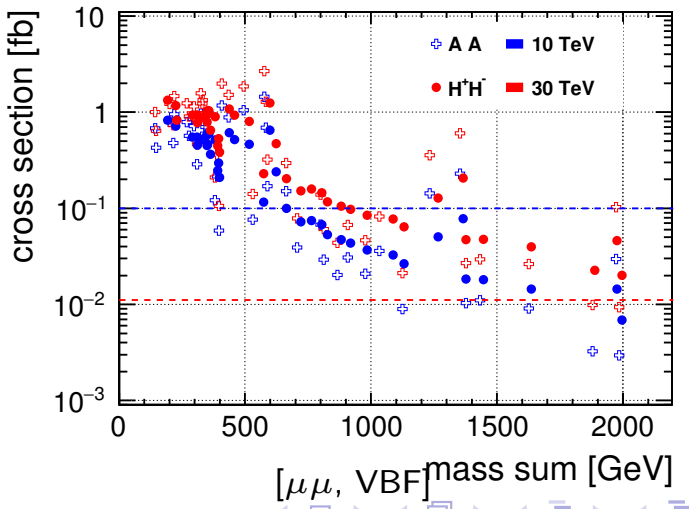
Sensitivity in figures [Symmetry 13 (2021) 6, 991]

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

Next^n colliders: muons

"Sensitivity study" for IDM: production cross sections for BPs at 13, 27, 100 TeV for pp collisions, $10, 30\,\mathrm{TeV}$ for $\mu\mu$

- simple counting criterium: **1000 events with design luminosity, comparison of mass reach**

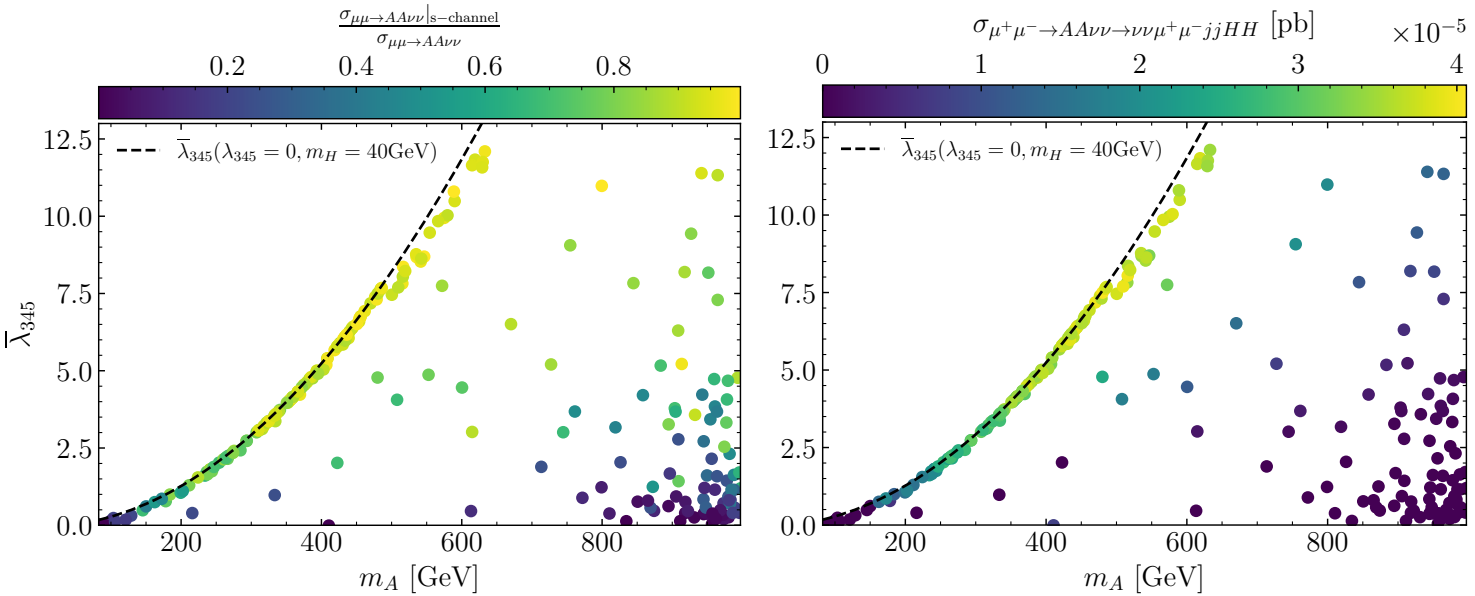
! **processes differ:** pair-production for all but AA final states from electroweak processes (Drell-Yan)

- AA**:** mediated via coupling $\bar{\lambda}_{345} = \lambda_{345} - 2\frac{M_H^2 - M_A^2}{v^2}$
  $\Rightarrow$ **strong constraints from direct detection and electroweak precision observables**

$\Rightarrow$ **include VBF-type topologies: VBF starts playing role**, especially at $\mu\mu$ colliders

Why muon collider

- at muon colliders at higher com energies:
  WW **fusion processes enhanced**

$\Rightarrow$ can become dominant

- supersedes this process at hadron colliders
- **crucial: high center of mass energy**