Extended scalar sectors from all angles - Mostly at lepton colliders -

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Workshop on Standard Model and Beyond
Mon Repos, Corfu, Greece
27.8.2024

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After Higgs discovery: Open questions

Higgs discovery in 2012 ⇒ last building block discovered

? Any remaining questions ?

- Why is the SM the way it is ??
  ⇒ search for **underlying principles/ symmetries**
- find **explanations for observations not described by the SM**
  ⇒ e.g. dark matter, flavour structure, ...
- ad hoc approach: Test **which other models still comply with experimental and theoretical precision**

for all: **Search for Physics beyond the SM (BSM)**

⟹ main test ground for this: particle colliders ⟸

Special role of the scalar sector

- **Higgs potential in the SM**

$$\mathbf{V} = -\mu^2\,\mathbf{\Phi}^\dagger\,\mathbf{\Phi} + \lambda\,\left(\mathbf{\Phi}^\dagger\,\mathbf{\Phi}\right)^2, \quad \mathbf{\Phi} = \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}\begin{pmatrix} \mathbf{0} \\ \mathbf{v} + \mathbf{h(x)} \end{pmatrix}$$

⇒ **mass** for Higgs Boson and Gauge Bosons

$$\mathbf{m_h^2} = \mathbf{2}\,\lambda\,\mathbf{v^2},\ \mathbf{m_W} = \mathbf{g}\,\frac{\mathbf{v}}{\mathbf{2}},\ \mathbf{m_Z} = \sqrt{\mathbf{g^2} + (\mathbf{g'})^2}\,\frac{\mathbf{v}}{\mathbf{2}}$$

where v: Vacuum expectation value of the Higgs field, g, g': couplings in $SU(2) \times U(1)$

⇒ **everything determined in terms of gauge couplings, v, and λ**

> **form of potential determines minimum,**
> **electroweak vacuum structure**

⇒ stability of the Universe, electroweak phase transition, etc

- **full test requires checks of *hhh*, *hhhh* couplings**

⇒ **so far: only limits; possible only at future machines** [HL-LHC: constraints on *hhhh*]

How can we see new physics ?

Different ways to see new physics effects

- **Option 1:** see a **direct deviation**, in best of all cases a bump, and/ or something similar $\Rightarrow$ **clear enhanced rates for certain final states, mediated by new physics**
- **Option 2:** observe **signatures that do not exist in SM,** e.g. events with large missing energy (hint of model containting DM)
- **Option 3:** observe **deviations in SM-like quantities which are small(ish)**: $\Rightarrow$ loop-induced deviations, requiring precision measurements
- NB: these can in principle also be large !! $\Rightarrow$ all models floating around to explain m_W^{CDF}

In the following...

Discussion of

- **recasts of IDM using THDMa search** [w. J. Lahiri/ K. Rolbiecki]

  final state != topology

- **new scalars at lepton colliders** [ECFA effort/ w. A.F. Zarnecki ea]

  next machine: Higgs factory

- **searches for IDM at muon colliders** [w J. Braathen/ M. Gabelmann/ P. Stylianou]

  VBF-type enhancements at high energies

Recasting example: Inert Doublet Model

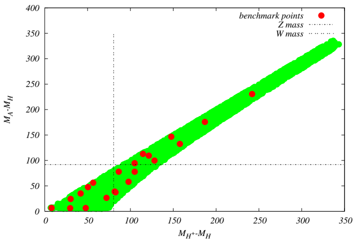
2 Higgs Doublet Model: 4 new scalars $H, A, H^{\pm}$

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

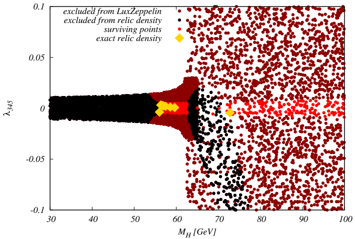
free parameters: **masses, λ_2, λ_{345}** (couplings in V)

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.

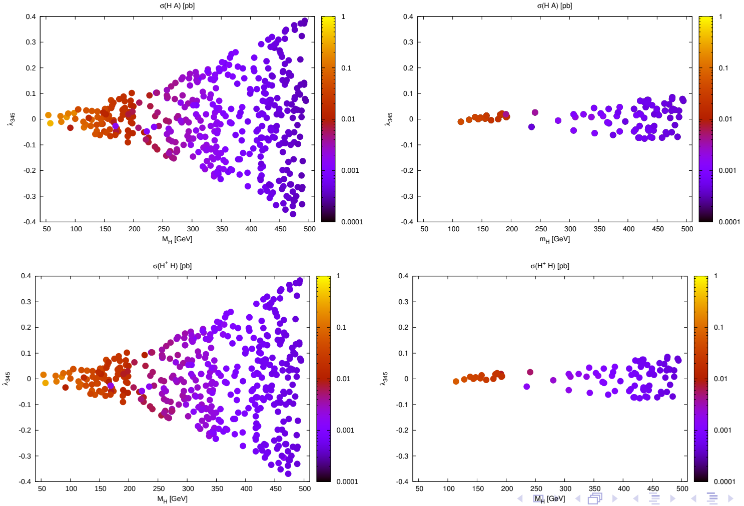
$$\underbrace{v,\ M_h,}_{\mathbf{246}\,\mathrm{GeV},\,\mathbf{125}\,\mathrm{GeV}}\quad \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{345}\ [=\lambda_3+\lambda_4+\lambda_5]$$

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] [arXiv:2207.03764]

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

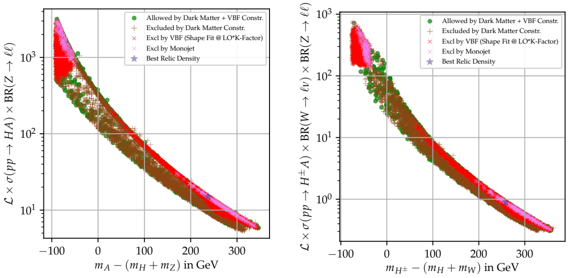
⇒ implemented in CheckMATE [currently: private version]

⇒ 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 ?**

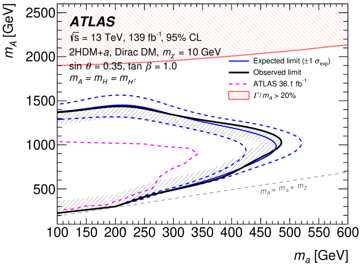
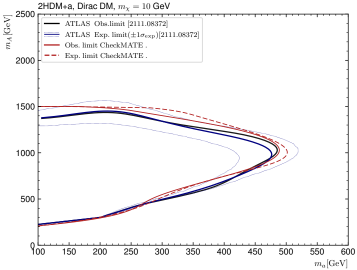


Fig from Phys. Lett. B 829 (2022) 137066



Validation within CheckMATE, thanks to I. Lara

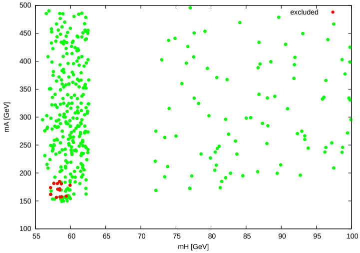
[1] Scan dependent statement

First results

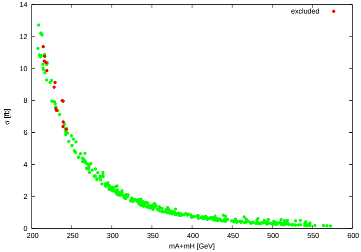
specific sample, concentrates on low $m_H \leq 100\,\mathrm{GeV}$

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

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

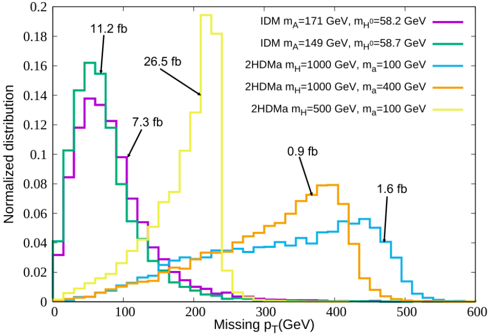
in practise:

contamination from $p\,p \rightarrow H^\pm\,A$ 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: $\not{E}_\perp \geq 90\,\mathrm{GeV}$

After LHC: Higgs factory next (?)

various production modes possible

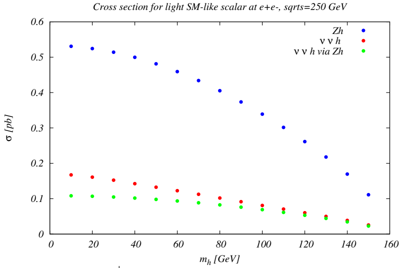
1) **easiest example:** $e^+ e^- \rightarrow Z\, h_1$, onshell production interesting up to $m_1 \sim 160\,\mathrm{GeV}$
2) in **models with various scalars:** e.g. also $e^+ e^- \rightarrow h_1\, h_2$ (e.g. from 2HDMs); example processes and bounds from LEP in Eur.Phys.J.C 47 (2006) 547-587

   again: for onshell production, $\sum_i m_i \leq 250\,\mathrm{GeV}$
3) another (final) option: **look at** $e^+ e^- \rightarrow h_i\, Z,\, h_i \rightarrow h_j\, h_k$

already quite a few studies for 1), 3) available

Possible production modes and rates
[TR, Universe 2022, 8(5), 286, updated]

$$e^+ e^- \rightarrow Z^* \rightarrow Zh,\ e^+ e^- \rightarrow \nu\bar{\nu}h\ \textbf{(VBF)}$$



[cross sections for $e^+ e^-$ at $\sqrt{s} = 250\,\text{GeV}$ using Madgraph5;

LO analytic expressions e.g. in Kilian ea, Phys.Lett.B 373 (1996) 135-140]

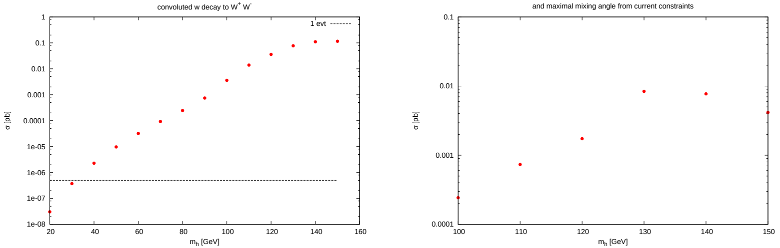
- rule of thumb: **rescaling** $\lesssim 0.1$
- $\Rightarrow$ maximal production **cross sections around 50 fb**
- $\sim 10^5$ **events using full luminosity**

ECFA effort: novel final states

- already mentioned by Filip: what about hZ **with** $h \to WW$?

$\Rightarrow$ **define points that are still allowed** (singlet extension)

$\Rightarrow$ **convolute w decay rate and branching ratios**



"Best" points for masses $\geq 130\,\mathrm{GeV}$

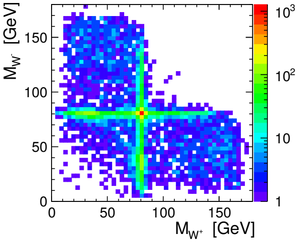
simulation study ongoing... stay tuned

$S \to W^+W^-$

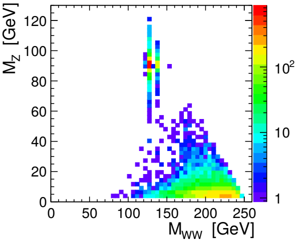
Simulation study with Tania Robens, Yang Ma, Mohamed Ouchemhou

Correlation of reconstructed boson masses on generator level
TRSM model with additional 140 GeV scalar at $\sqrt{s}$ =250 GeV

All events



Clear separation of scalar production



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**

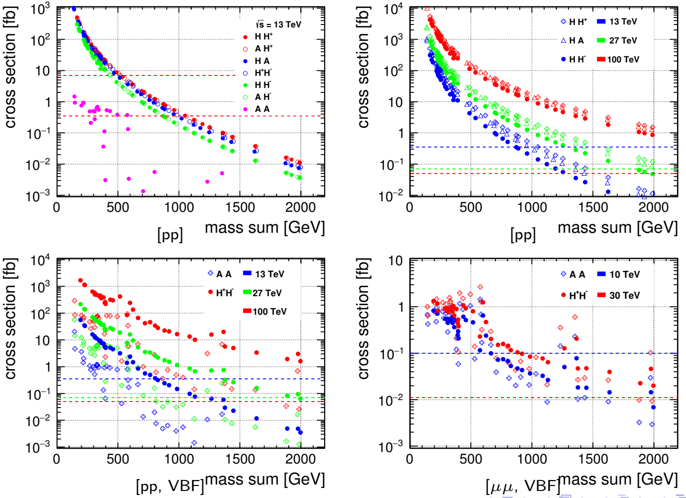
! **processes differ:** pair-production for all but AA final states from electroweak processes (Drell-Yan)

- 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

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

lines: 1000 events for design luminosity



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

- sensitivity study last slide: based on cross sections only

How does it look in real life ??

- main target

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

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

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

Why muon collider ?

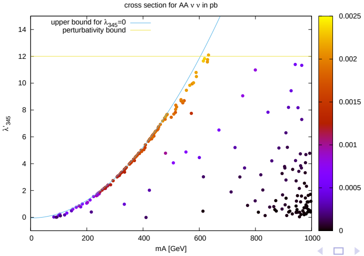
- ***AA* production only mediated via h_{125}**
- coupling

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

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

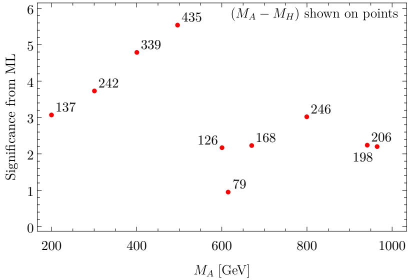
  [although we found counterexamples]

- large com energies $\Rightarrow$ **log-enhanced VBF type production**

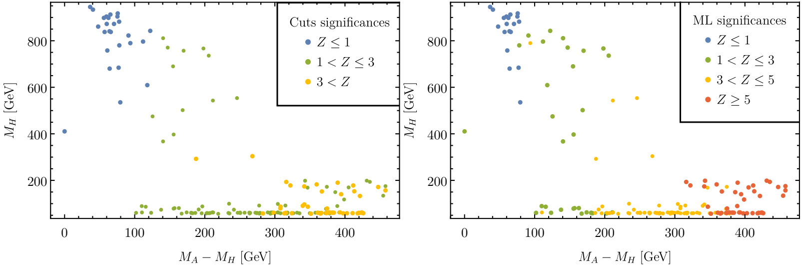


Strategy

- 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**



Preliminary results



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

Open points

- analyze more points
- add additional signal contributions
- ...

Summary

Models with extended scalar sectors provide an interesting setup to introduce new scalar particles, with different CP/ charge quantum numbers

$\Rightarrow$ leads to many **new interesting signatures**, some of which are not yet covered by current searches

some of these: also interesting connections of electroweak phase transitions/ gravitational waves/ etc

Next steps

- **(re) investigate models with extended scalar sectors at e^+e^- colliders** [ECFA effort ongoing]

Many things to do

Do not miss

Extended Scalars from all angles, CERN, 21.-25.10.24

https://indico.cern.ch/e/scalars2024

next HHH workshop in Dubrovnik, 09/25

⇒ stay tuned ⇐

Appendix

Models

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

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

for coupling g to vector bosons

- many scenarios ⇒ **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

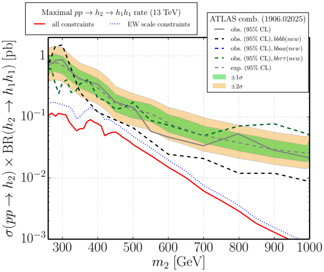
e^+e^- colliders: ILC/ CLIC/ FCC-ee, CePC

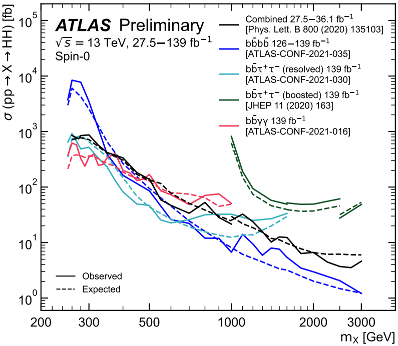
in plan, high priority in Europe, various center-of-mass energies discussed, priority $\sim$ 240 $-$ 250 GeV "Higgs factories"

$\mu^+\mu^-$ colliders

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

ATLAS-PHYS-PUB-2021-031

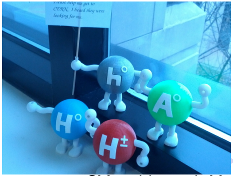




Other possible extensions

- 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]

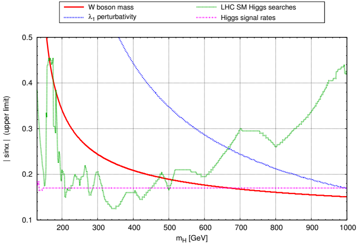
tools used: `HiggsBounds`, `HiggsSignals`, `2HDMC`, `micrOMEGAs`, ...

Examples for current constraints: Singlet extension, Z_2 symmetric: + 1 scalar particle

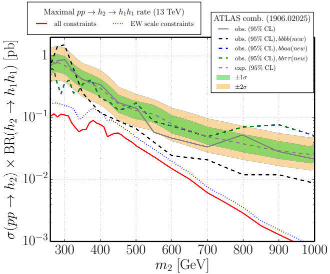
[TR, arXiv:2209.15544; updated using HiggsTools]

$$\mathbf{V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger\Phi S^2}$$

new parameters: m_2, $\sin\alpha$ [= 0 for SM], $\tan\beta$ [= ratio of vevs]



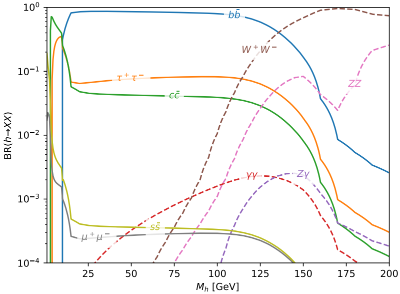
(for fixed $\tan\beta$)



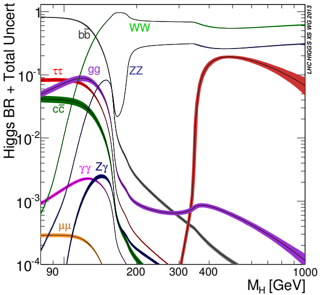
[update from Review in Physics (2020) 100045]

[see e.g. Pruna, TR, Phys. Rev. D 90, 114018;
(Bojarski, Chalons,) Lopez-Val, TR, Phys. Rev. D 90, 114018, JHEP 1602 (2016) 147;
(Ilnicka), TR, Stefaniak, EPJC (2015) 75:105, Eur.Phys.J. C76 (2016) no.5, 268, Mod.Phys.Lett. A33 (2018)]

Reminder: decays of a SM-like Higgs of mass $M \neq 125\,\mathrm{GeV}$



(using HDecay, courtesy J.Wittbrodt)



(https://twiki.cern.ch/twiki/bin/view/LHCPhysics /LHCHXSWGCrossSectionsFigures)

Testing the Higgs potential

- remember:

$$\mathbf{V} = -\mu^2\,\mathbf{\Phi}^\dagger\,\mathbf{\Phi} + \lambda\,\left(\mathbf{\Phi}^\dagger\,\mathbf{\Phi}\right)^2, \quad \mathbf{\Phi} = \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}\begin{pmatrix}\mathbf{0}\\ \mathbf{v}+\mathbf{h(x)}\end{pmatrix}$$

also predicts *hhh* and *hhhh* interactions

- so far: only constraints

$\Longrightarrow$ **future accessibility ?** $\Longleftarrow$

Start with resonance enhanced BSM scenarios for *hhh*

Inert doublet model: The model

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

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

(⇒ 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

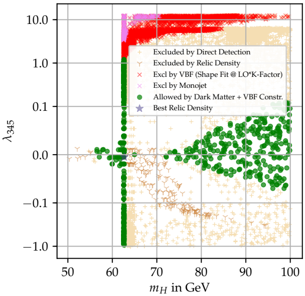
- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **relevant couplings follow from ew parameters (+ derivative couplings)**
- hXX **couplings:** determined by λ_{345} (constrained from direct detection), and **mass differences** $M_X^2 - M_H^2$ $\left(X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

important interplay between astroparticle physics and collider searches

in the end kinematic test

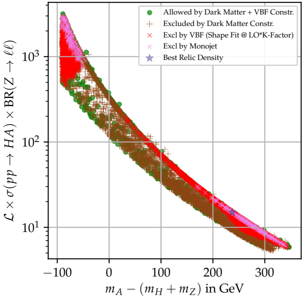
(holds for $M_H \geq \frac{M_h}{2}$)

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

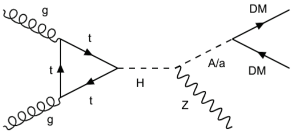
current searches at LHC need to be modified

Different production topologies...

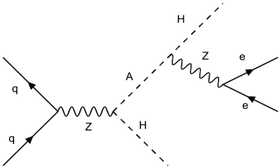
[slide from J. Lahiri, Talk at "Roadmap of Dark Matter models at LHC Run 3", 05/24]

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

2HDMa:



Inert Doublet Model:

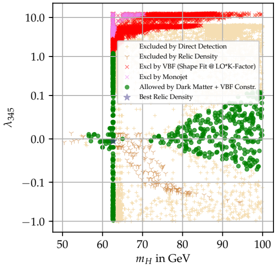


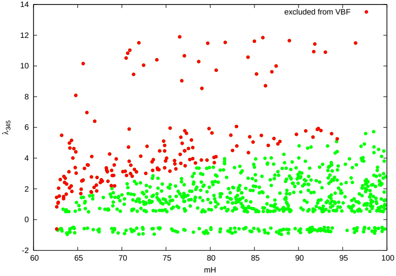
Other ongoing work: also reinvestigate VBF with Higgs to invisible

- 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 $(h \rightarrow$ inv$)$





Collider parameters

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

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

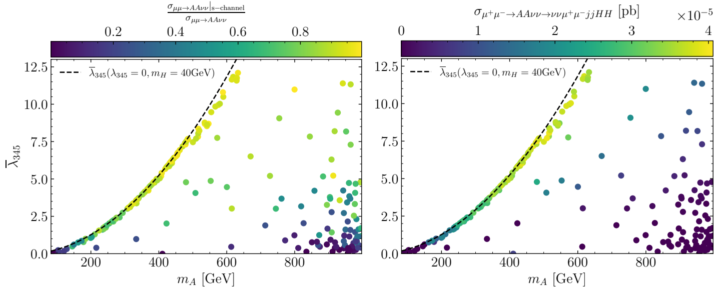
Why muon collider

- at muon colliders at higher com energies:

  ***WW* fusion processes enhanced**

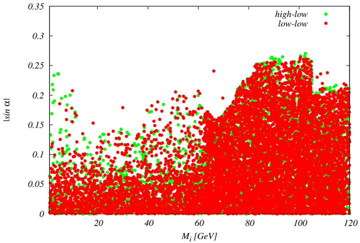
⇒ can become dominant

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

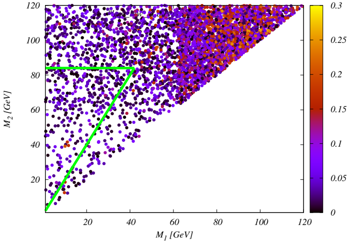


Singlet extensions [TR, arXiv:2203.08210 and Symmetry 2023, 15(1), 27]

TRSM: 2 real singlets [TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151]



mass and mixing angle



case with two light scalars;
color coding: h_1 rescaling

- **low-low:** both additional scalars below 125 GeV; **high-low:** one new scalar above 125 GeV