Constraining Extended Scalar Sectors at the LHC and beyond

Tania Robens

based on [recent] work with

G.M. Pruna (PRD 88 (2013) 115012); D. Lopez-Val (PRD 90 (2014) 114018);

T. Stefaniak (EPJC 75 (2015) 3,105, Eur.Phys.J. C76 (2016) no.5, 268);

A. Ilnicka, M. Krawczyk (Phys.Rev. D93 (2016) no.5, 055026);

J. Kalinowski, W. Kotlarski, D. Sokolowska, A.F.Zarnecki

(JHEP 1812 (2018) 081, JHEP 1907 (2019) 053), CERN Yellow Rep. Monogr. Vol. 3 (2018);

D.Dercks (Eur.Phys.J. C79 (2019) no.11, 924);

T. Stefaniak, J. Wittbrodt (arXiv:1908.08554)

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Introduction and motivation: Higgs discovery and the Nobel Prize

As you all know, **extraordinary success** of particle physics in recent years

⇒ **Discovery of "a" Higgs boson** ⇐

(by ATLAS and CMS, Phys.Lett. B716 (2012))

... leading to the **Nobel Prize** for Higgs/ Englert

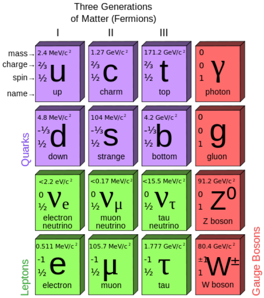
⇒ **!! Particle physics is more exciting than ever !!** ⇐

The Standard Model (SM) of particle physics

The Standard Model of particle physics: a brief introduction

- **SM of particle physics**: describes **known particle content of the universe**
- quarks/ leptons: **fundamental constituents of matter**

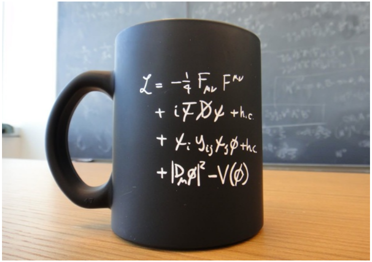
  [quarks: **building blocks of hadrons**]
- **forces which act on them**, coming with **gauge bosons**
- properties/ quantum numbers: **mass, spin, charges under gauge groups**



+ Higgs, $m_H \sim 125\,\mathrm{GeV}$

Question: Is this all there is ??

SM Lagrangian



[quantumdiaries.org]

with a SM Higgs

[particlezoo.net]

After Higgs discovery: Open questions

Higgs discovery in 2012 $\Rightarrow$ last building block discovered

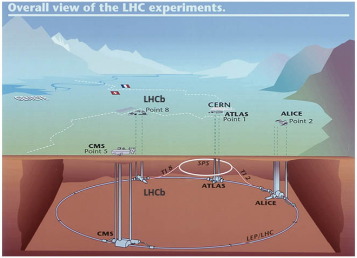
? Any remaining questions ?

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

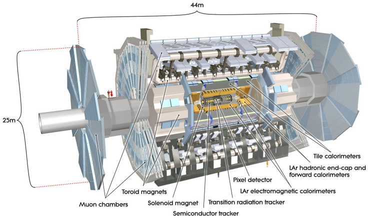
for all: **Search for Physics beyond the SM (BSM)**

$\Longrightarrow$ **main test ground for this: particle colliders** $\Longleftarrow$

Current major focus: Physics at the LHC



[cern.ch]



ATLAS detector [atlas.ch]

first run: 2009-2014, **7/8 TeV cm energy**

second run: 2015-2018, **13 TeV cm energy**

now waiting for upgrade; run III scheduled to start in 2021 (14 TeV)

Theorists tasks in the LHC era

$\Longrightarrow$ Tasks at LHC $\Longleftarrow$

- $\Rightarrow$ **(re)discovery of the Standard Model** of particle physics, especially **Higgs**
- $\Rightarrow$ **precision measurements** of SM particles
- $\Rightarrow$ **discovery/ limit setting** on BSM physics

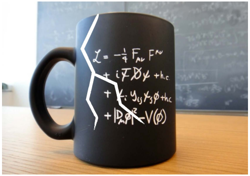
$\Longrightarrow$ Tasks for theorists $\Longleftarrow$

- $\Rightarrow$ **accurate predictions for SM processes**
- $\Rightarrow$ rendering ideas/ insight **where and how to look for new physics**

A first example of Higgs sector extension: Electroweak singlet

(in other words: **what else can be out there...**)

a crack in the SM



[quantumdiaries.org]

⇒ see whether I can extend Higgs sector ⇐

- … accomodating for all **limits from theory and experiment**
- … and how I would **look for this at present or future colliders**

  (or elsewhere)

introduce physics beyond the SM (BSM)

take minimal approach

add 1 additional scalar

obtain theory with 3 additional free parameters

Higgs Singlet extension (aka The Higgs portal)

The model

- Singlet extension:

  simplest extension of the SM Higgs sector
- add an **additional scalar**, singlet under SM gauge groups

  (further reduction of terms: impose additional symmetries)

⇒ potential (H doublet, χ real singlet)

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

- collider phenomenology studied by many authors: Schabinger, Wells; Patt, Wilzcek; Barger ea; Bhattacharyya ea; Bock ea; Fox ea; Englert ea; Batell ea; Bertolini/ McCullough; ...
- our approach: **minimal:** no hidden sector interactions
- equally: **Singlet acquires VeV**

Singlet extension: free parameters in the potential

$$\text{VeVs:}\ \ H \equiv \left(\begin{array}{c} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{array} \right),\ \chi \equiv \frac{h'+x}{\sqrt{2}}.$$

- potential: 5 free parameters: 3 couplings, 2 VeVs

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ v,\ x$$

- rewrite as

$$\mathbf{m_h},\ \mathbf{m_H},\ \sin\alpha,\ \mathbf{v},\ \tan\beta$$

- **fixed**, **free**

$$\sin\alpha\text{: mixing angle, } \tan\beta = \frac{v}{x}$$

- physical states ($m_h < m_H$):

$$\left(\begin{array}{c} \mathbf{h} \\ \mathbf{H} \end{array} \right) = \left(\begin{array}{cc} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{array} \right) \left(\begin{array}{c} \tilde{h} \\ h' \end{array} \right),$$

SM phenomenology in three lines

Question 1:
Modfication for SM-like final states at tree level ?

In case we neglect the new *Hhh* coupling:

- light/ heavy Higgs non-singlet component $\sim \cos\alpha / \sin\alpha$

$\Rightarrow$ for light/ heavy Higgs: every SM-like coupling is **rescaled by** $\cos\alpha/ \sin\alpha$

$\Rightarrow$ this alone would lead to **"global"** $\cos^4\alpha/\sin^4\alpha$ $(\cos^2\alpha/\sin^2\alpha)$ for full production and decay (production or decay)

- **BRs stay the same**

Tree-level rescaling (2)

- in addition: **new physics channel:**

$$H \to h\,h$$

- effect:

$$\Gamma_{\text{tot}}(H) = \sin^2\alpha\,\Gamma_{\text{SM}}(H) + \Gamma_{H\to h\,h},$$

needs to be included for SM like decays

$$\kappa \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{\text{BSM}}}{\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}} = \frac{\sin^4\alpha\,\Gamma_{\text{tot,SM}}}{\Gamma_{\text{tot}}}$$

- breakdown:

$$\sigma_{\text{prod}} = \sin^2\alpha \times \sigma_{\text{prod,SM}},\ \text{BR}_{H\to\ldots} = \sin^2\alpha\,\frac{\Gamma_{\text{tot, SM}}}{\Gamma_{\text{tot}}} \times \text{BR}^{\text{SM}}_{H\to\ldots}$$

$\Rightarrow$ **sufficient for tree level rescaling** $\Leftarrow$

Theoretical and experimental constraints on the model

our studies: $m_{h,H} = 125.09\,\mathrm{GeV},\ 0\,\mathrm{GeV} \leq m_{H,h} \leq 1\,\mathrm{TeV}$

1. limits from **perturbative unitarity**
2. limits from EW precision observables through $S,\ T,\ U$
3. special: **limits from W-boson mass** as precision observable
4. **perturbativity** of the couplings (up to certain scales*)
5. **vacuum stability and minimum condition** (up to certain scales*)
6. **collider limits** using HiggsBounds
7. measurement of **light Higgs signal rates** using HiggsSignals

(debatable: minimization up to arbitrary scales, $\Rightarrow$ perturbative unitarity to arbitrary high scales [these are common procedures though in the SM case])

(*): only for $m_h = 125.09\,\mathrm{GeV}$

Comments on constraints (1) - Perturbativity issues

Perturbative unitarity:

- tests combined system of all (relevant) $2 \rightarrow 2$ scattering amplitudes for $s \rightarrow \infty$
- we considered:

$$WW,\, ZZ,\, HH,\, Hh,\, hh \rightarrow WW,\, ZZ,\, HH,\, Hh,\, hh$$

- makes sure that the largest eigenvalue for the "0"-mode partial wave of the diagnolized system ≤ 0.5
- "crude" check that unitarity is not violated

  (Literature: Lee/ Quigg/ Thacker, Phys. Rev. D 16, 1519 (1977))

  (in the end: all "beaten" by perturbativity of running couplings)

Comments on constraints (2) - running couplings and vacuum

Vacuum stability and perturbativity of couplings at arbitrary scales

- clear: vacuum should be stable for large scales
- unclear: do we need ew-like breaking everywhere ? perturbativity ?

⇒ check at relative low scale

⇒ bottom line: small mixings excluded from stability for larger scales (for $m_H \leq 1\,\text{TeV}$!! for the model-builders...)

- arbitrary large m_H can cure this !! cf Lebedev; Elias-Miro ea. Out of collider range though ($\sim 10^8\,\text{GeV}$) (...like SUSY, this model can never be excluded...)
- perturbativity of couplings severely restricts parameter space, even for low scales

Comments on constraints (2) - running couplings and vacuum

1. **perturbativity:** $|\lambda_{1,2,3}(\mu_{\text{run}})| \leq 4\,\pi$
2. **potential bounded from below:** $\lambda_1, \lambda_2 > 0$
3. **potential has local minimum:** $4\lambda_1\lambda_2 - \lambda_3^2 > 0$

$\Longrightarrow$ need (2), can debate about (1), (3) at all scales $\Longleftarrow$

NLO corrections to m_W

[D. Lopez-Val, TR, (PRD 90 (2014) 114018)]

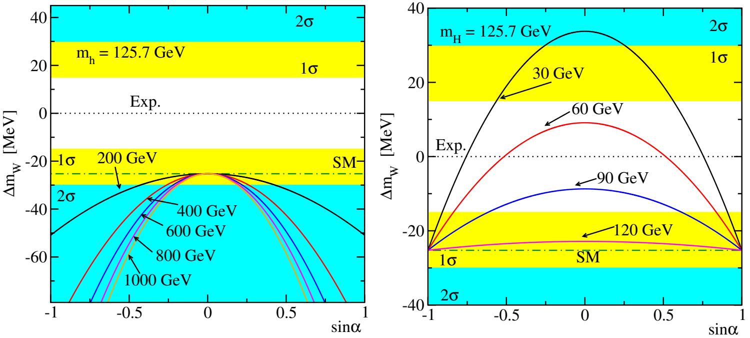
- electroweak fits: fit $\mathcal{O}(20)$ parameters, constraining S, T, U
- idea here: single out m_W, measured with error $\sim 10^{-4}$
- **setup renormalization for Higgs and Gauge boson masses**
- EW gauge and matter sector: on-shell scheme
- Higgs sector: several choices, currently a mixture of onshell/ $\overline{MS}$

  (in this case: $\delta\lambda$ only enter at 2-loop $\Longrightarrow$ not relevant here)

$\Longrightarrow$ **first step on the road to full renormalization** $\Longleftarrow$

NLO corrections to m_W

Contribution to m_W for different Higgs masses

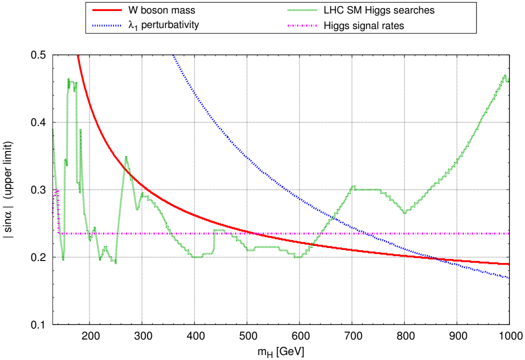


$m_h = 125.7\,\mathrm{GeV}$ $\qquad$ $m_H = 125.7\,\mathrm{GeV}$

$\Longrightarrow$ low m_h bring m_W^{NLO} close to m_W^{exp} $\Longleftarrow$

Combined limits on $|\sin\alpha|$

(TR, arXiv:1908.10809 [LHCP19 proceedings])



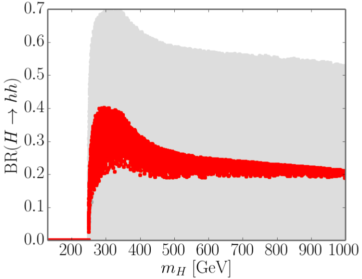
direct searches, m_W, and **perturbativity** strongest constraints

One more word about $H \to h\,h$

- **viable alternative:** search for

$$H \to h\,h \to \ldots$$

- in our case: $\text{BR}(H \to h\,h) \lesssim 0.4$



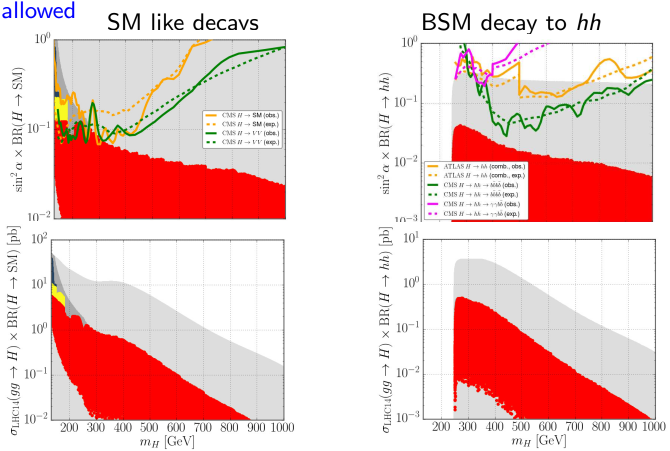
- **widely discussed in the literature**
(for recent work, cf Gouzevitch, Oliveira, Rojo, Rosenfeld, Salam, Sanz; Cooper, Konstantinidis, Lambourne, Wardrope; ...)
- ***WW* always dominant**

Example for results from generic scans and predictions for LHC 14 (TR, T. Stefaniak, Eur.Phys.J. C76 (2016) no.5, 268)

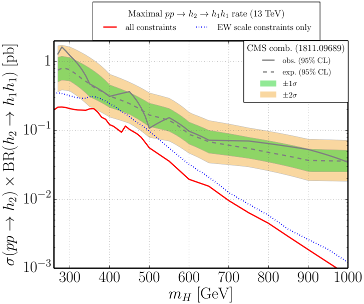
1 σ, 2 σ, allowed

limits

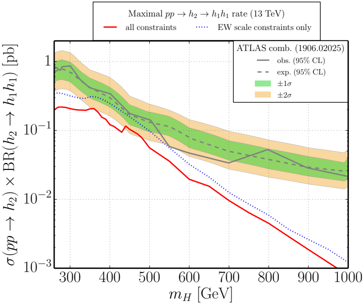
pred.



... and for Dihiggs final states



(CMS Dihiggs combination, 36 fb^{-1})



(ATLAS Dihiggs combination, 36 fb^{-1})

from TR, arXiv:1908.10809 (see also Di Micco ea, arXiv:1910.00012)

2 real scalar extension

TR, T. Stefaniak, J. Wittbrodt,

arXiv:1908.08554

2 real scalar extension

Motivation

- already (largely) investigated at LHC:

$$\mathbf{h_{125}} \rightarrow \mathrm{SM},\ \mathbf{H} \rightarrow \mathbf{h_{125} h_{125}},\ \mathbf{h_{125}} \rightarrow \mathbf{a\,a}$$

- so far one search: $H \rightarrow a\,a$
- not investigated at all so far: $h_1 \rightarrow h_2,\ h_3$ (one $h_i \equiv h_{125}$)

easiest model to realize this:

extend scalar sector by 2 real singlets

Adding two real scalar singlets

Scalar potential (Φ: $SU(2)_L$ doublet, S, X: $SU(2)_L$ singlets)

$$\mathcal{V} = \mu_\Phi^2 \Phi^\dagger\Phi + \mu_S^2 S^2 + \mu_X^2 X^2 + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda_S S^4 + +\lambda_X X^4 + \lambda_{\Phi S}\Phi^\dagger\Phi S^2 + \lambda_{\Phi X}\Phi^\dagger\Phi X^2 + \lambda_{SX} S^2 X^2.$$

Imposed $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetry, which is spontaneously broken by singlet vevs.

$\Rightarrow$ three $\mathcal{CP}$-even neutral Higgs bosons: h_1, h_2, h_3

Two interesting cases:

Case (a): $\langle S\rangle \neq 0, \langle X\rangle = 0 \Rightarrow X$ is DM candidate;

Case (b): $\langle S\rangle \neq 0, \langle X\rangle \neq 0 \Rightarrow$ all scalar fields mix.

Again, Higgs couplings to SM fermions and bosons are *universally reduced by mixing*.

Tim Stefaniak (DESY) | BSM Higgs physics | ALPS 2019 | 27 April 2019 10

[some material stolen from T. Stefaniak, Talk at ALPS 2019, April '19]

singlet = singlet under SM gauge group

Input parameters/ Constraints

- **Input parameters** (our choice):

masses, mixing angles, vevs

[⇒ all other parameters derived from these]

- **Theory**:
  boundedness from below for potential,
  perturbative unitarity;
- **Experiment:**
  electroweak precision via S, T, U;
  agreement with measurements of 125 GeV scalar;
  agreement with null-results for additional searches;

  also tested: $W-$mass as precision observable [à la Lopez-Val, TR, Phys. Rev. D 90, 114018]

Tools which were used:

HiggsBounds*, HiggsSignals, ScannerS* [*: private updated version]

Possible production and decay patterns

$$M_1 \leq M_2 \leq M_3$$

Production modes at *pp* and decays

$$pp \to h_3 \to h_1\, h_1; \qquad pp \to h_3 \to h_2\, h_2;$$
$$pp \to h_2 \to h_1\, h_1; \qquad pp \to h_3 \to h_1\, h_2$$

$$h_2 \to \text{SM};\ h_2 \to h_1\, h_1;\ h_1 \to \text{SM}$$

⇒ two scalars with same or different mass decaying directly to SM, or $h_1\, h_1\, h_1$, or $h_1 h_1 h_1 h_1$

[h_1 decays further into SM particles]

[BRs of h_i into $X_{\text{SM}} = \frac{\kappa_i \Gamma^{\text{SM}}_{h_i \to X}(M_i)}{\kappa_i \Gamma^{\text{SM}}_{\text{tot}}(M_i) + \sum_{j,k} \Gamma_{h_i \to h_j h_k}}$; κ_i: rescaling for h_i]

Benchmark points/ planes [ASymmetric/ Symmetric]

AS **BP1:** $h_3 \to h_1 h_2$ $(h_3 = h_{125})$

SM-like decays for both scalars: $\sim$ 3 pb; h_1^3 final states: $\sim$ 3pb

AS **BP2:** $h_3 \to h_1 h_2$ $(h_2 = h_{125})$

SM-like decays for both scalars: $\sim$ 0.6 pb

AS **BP3:** $h_3 \to h_1 h_2$ $(h_1 = h_{125})$

(a) SM-like decays for both scalars $\sim$ 0.3 pb; **(b)** h_1^3 **final states:** $\sim$ 0.14 pb

S **BP4:** $h_2 \to h_1 h_1$ $(h_3 = h_{125})$

up to 60 pb

S **BP5:** $h_3 \to h_1 h_1$ $(h_2 = h_{125})$

up to 2.5 pb

S **BP6:** $h_3 \to h_2 h_2$ $(h_1 = h_{125})$

SM-like decays: up to 0.5 pb; h_1^4 **final states: around 14 fb**

Decay patterns

- **SM couplings inherited through mixing**, $\propto \kappa_i$, such that

$$g_{h_i \to X\,Y} \,=\, \kappa_i\, g^{\rm SM}_{h_i \to X\,Y}.$$

- **additional onshell decays**

$$h_3 \,\to\, h_1\, h_2,\; h_3 \,\to\, h_1\, h_1,\; h_3 \,\to\, h_2\, h_2,\; h_2 \,\to\, h_1\, h_1$$

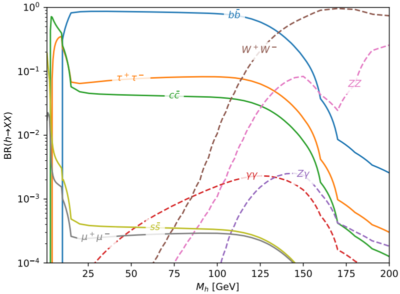
(whenever kinematically feasible)

$\Rightarrow$

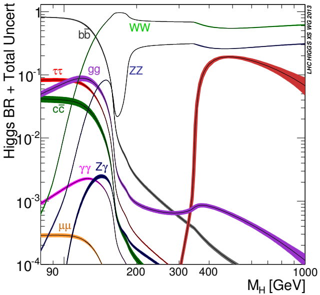
$$\text{BR}_{h_i \to \text{SM}}(M_i) \,=\, \frac{\kappa_i^2\,\Gamma^{\rm SM}_{h_i \to \rm SM}(M_i)}{\kappa_i^2\,\Gamma^{\rm SM}_{h_i \to \rm SM}(M_i) + \sum_{j,k}\Gamma_{h_i \to h_j\,h_k}}$$

$\Rightarrow$ **relative ratio for SM final states as in SM at mass M_i**

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



(using HDecay, courtesy J.Wittbrodt)



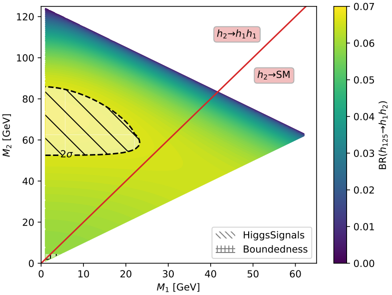
(https://twiki.cern.ch/twiki/bin/view/LHCPhysics

/LHCHXSWGCrossSectionsFigures)

BP1: $h_3 \to h_1 h_2$ ($h_3 = h_{125}$) [up to 3 pb]

BP1

$\sigma(pp \to h_3) \simeq \sigma(pp \to h_{SM}) \sim 50$ pb,
$\mathrm{BR}(h_3 \to h_1 h_2)$ up to 7%, if
$M_2 > 2M_1$
$\Rightarrow \mathrm{BR}(h_2 \to h_1 h_1) \approx 100\%$,
($\to$ e.g., three pairings $m_{bb} \simeq M_1$)
if $M_2 < 2M_1 \Rightarrow h_2 \to$ SM particles.
($\to$ e.g., $m_{bb}^{(1)} \simeq M_1$ and $m_{bb}^{(2)} \simeq M_2$)

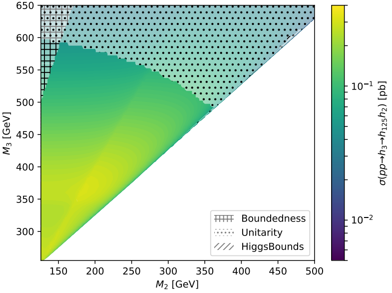


$\Rightarrow$ $h_1 h_1 h_1$ final states: reconstructing to M_3, with one pair reconstructing to M_2

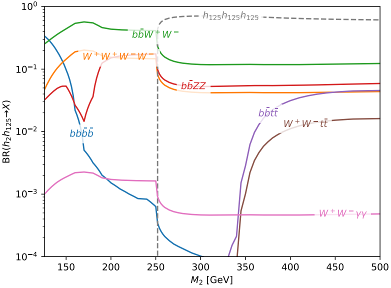
$\Rightarrow$ both scalars as in SM: 2 light scalars reconstructing to M_3

[$|\kappa_3| = 0.9965$]

BP3: $h_3 \rightarrow h_1 h_2 \; (h_1 = h_{125})$ [up to 0.3 pb]



production cross sections; $|\kappa_3| \sim 0.24$

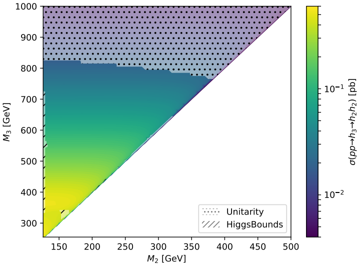


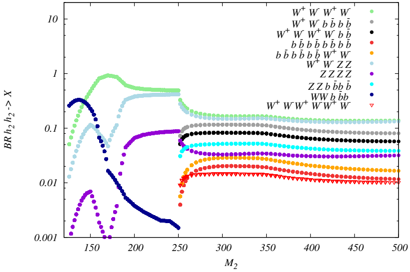
BRs

$h_{125} h_{125} h_{125}$ final states (up to 140 fb)

[exclusions above: 36 fb^{-1} searches for $h_3 \rightarrow V V$]

BP6: $h_3 \to h_2 h_2 \; (h_1 = h_{125})$ [up to 0.5 pb]





- $|\kappa_3| \sim 0.25$

$$\sigma_{gg \to h_3}(M_3) \sim 0.06\, \sigma^{SM}_{gg \to h_3}(M_3)$$

$h_{125} h_{125} h_{125} h_{125}$ **up to 14 fb**

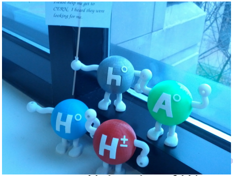
! $36\,\mathrm{fb}^{-1}$ searches start being sensitive in *WWWW* final state [1811.11028] !

Other possible extensions

- A priori: **no limit to extend Higgs 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
  - ...

Another option: **Two Higgs Doublet models: 5 Higgses** (as eg realized in the MSSM,...)

$$\underbrace{h, H}_{\text{CP -even, neutral}}, \quad \underbrace{A}_{\text{CP-odd, neutral}}, \quad \underbrace{H^{\pm}}_{\text{charged}}$$



Inert Doublet Model

A. Ilnicka, M. Kracwzyk, TR,
Phys.Rev. D93 (2016) no.5, 055026

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

J. Kalinowski, W. Kotlarski, TR, D. Sokolowska, A.F.Zarnecki,
JHEP 1812 (2018) 081, JHEP 1907 (2019) 053, CERN Yellow Rep. Monogr. Vol. 3 (2018)

D. Dercks, TR,
Eur.Phys.J. C79 (2019) no.11, 924

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)

Number of free parameters

⇒ then, **go through standard procedure...**

⇒ minimize potential

⇒ determine number of free parameters

Number of free parameters here: 7

- e.g.

$$\mathbf{v},\ \mathbf{M_h},\ \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{\mathbf{345}}\ [= \lambda_3 + \lambda_4 + \lambda_5]$$

- v, M_h fixed ⇒ left with **5 free parameters**

Constraints: Theory

$\Longrightarrow$ **consider all current constraints on the model** $\Longleftarrow$

- Theory constraints: **vacuum stability, positivity, constraints to be in inert vacuum**
  $\Rightarrow$ **limits on (relations of) couplings**, e.g.

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

- **perturbative unitarity, perturbativity of couplings**
- **choosing** M_H as dark matter:

$$M_H \leq M_A,\ M_{H^\pm}$$

Constraints: Experiment

$$M_h = 125.1\,\text{GeV},\; v = 246\,\text{GeV}$$

- total width of M_h ($\Gamma_h < 9\,\text{MeV}$) (CMS, $80\,\text{fb}^{-1}$) [Phys. Rev. D 99, 112003 (2019)]
- total width of W, Z
- collider constraints from signal strength/ direct searches; $R_{\gamma\gamma}$ from JHEP, 08:045, 2016 (Run I combination), $\text{BR}_{h\to\text{inv}}$ from Phys.Lett. B793 (2019) 520-551 (CMS, VBF, $40\,\text{fb}^{-1}$)
- 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**

Production and decay

- Z_2 symmetry:

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

- production modes:

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

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

- decays:

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

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

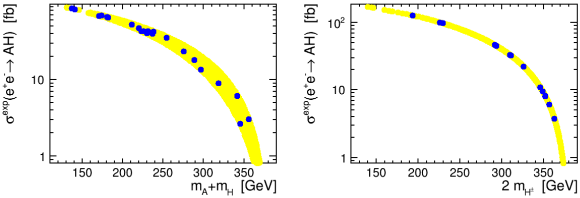
IDM at CLIC [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

Analysis strategy

Production of IDM scalars at CLIC dominated by two processes:

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

Leading-order cross sections for inert scalar production processes at 380 GeV:

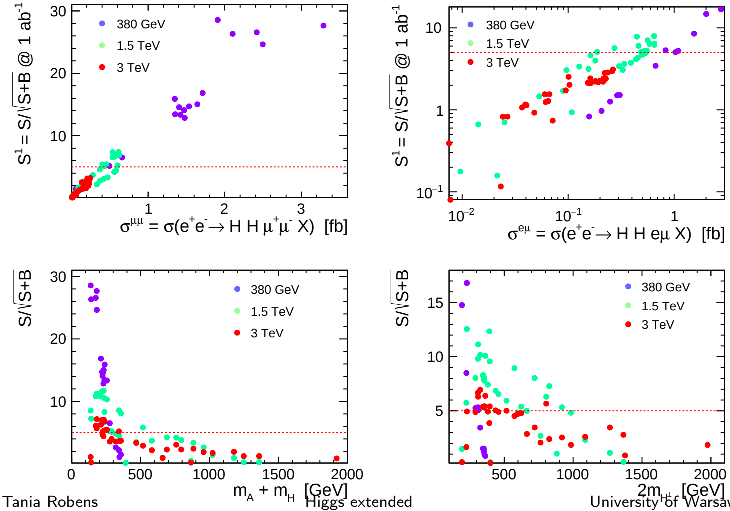


Beam luminosity spectra not taken into account

Results for CLIC studies [using boosted decision trees]

$(i)\ e^+e^-\ (\to\ H\,A)\ \to\ \mu^+\mu^- + \not{E}_\perp;\quad (ii)\ e^+e^-\ \left(\to\ H^+H^-\right)\ \to\ \ell^+\ell'^- + \not{E}_\perp\quad (\ell = e,\ \mu)$

HA **production** | H^+H^- **production**



Recast of LHC Run II results

- 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

- considered final states:

$$p\,p \rightarrow jj + \not{E}_\perp$$

($\not{E}_\perp$ = HH in Madgraph syntax)

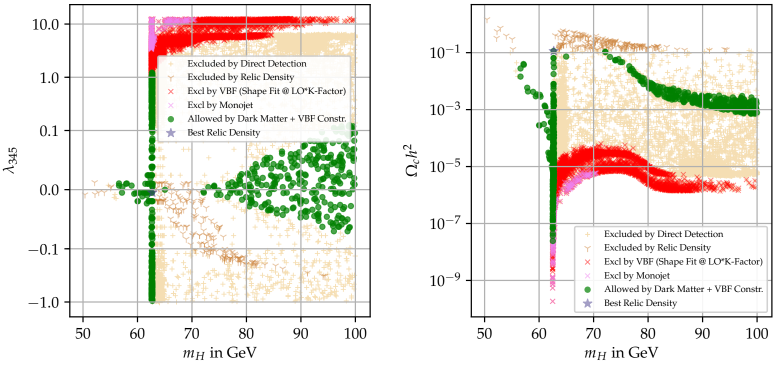
⇒ implemented in CheckMATE [currently: private version]

⇒ 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 recast: Results

after recast



most important constraints: $m_H \gtrsim m_h/2$

What about other channels ?

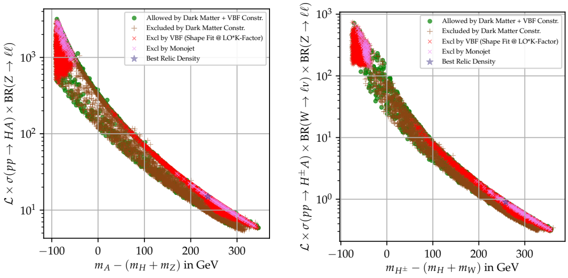
- largest production cross sections:

$$pp \rightarrow H\,A,\; H\,H^{\pm}$$

- lead to **single- or dilepton final states + $\not{E}_\perp$**
  [previous study: G. Belanger, B. Dumont, A. Goudelis, B. Herrmann, S. Kraml, D. Sengupta, arXiv:1503.07367]
- we tested:
  - M. Aaboud et al. *Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.*, Phys. Lett., B776:318-337, 2018, 1708.09624.
  - *Search for electroweak production of supersymmetric particles in the two and three lepton final state at $\sqrt{s}$ = 13 TeV with the ATLAS detector.* Technical Report ATLAS-CONF-2017-039, CERN, Geneva, Jun 2017

no constraints !! why ?

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)

Summary

Models with scalar extensions

"Next thing" to investigate after Higgs discovery

$\Rightarrow$ lead to "known" final states (W^+W^-, $b\bar{b}, \ldots$) as well as **new signatures**

- some models already quite well constrained (scalar resonances, ...)
- other models/ signatures not yet investigated
- e.g. $Z + \not{E}_\perp$: **investigated, but not interpreted all models**
- or $h_i \rightarrow h_j\, h_k$: **not yet investigated**

$\Longrightarrow$ STAY TUNED $\Longleftarrow$

Appendix

Constraints on the model [1908.10809]

- **strongest constraints:**

$$m_H \gtrsim 850\,\text{GeV} \quad : \quad \textbf{perturbativity of couplings}$$
$$m_H \in [650;850]\,\text{GeV} \quad : \quad m_W \textbf{ @ NLO}$$
$$m_H \in [125;650]\,\text{GeV} \quad : \quad \textbf{experimental searches/signal strength}$$
$$m_h \lesssim 120\,\text{GeV} \quad : \quad \textbf{SM-like Higgs coupling rates} \text{ (+ LEP)}$$

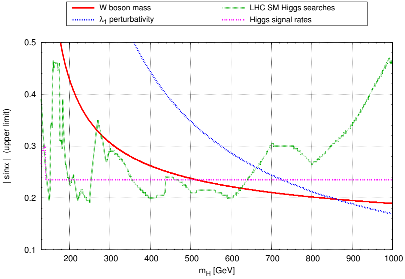
$\Rightarrow \kappa \leq 0.06$ for all masses considered here

$$\Gamma_{\textbf{tot}} \lesssim 0.02\, m_H$$

⇒ Highly (??) suppressed, narrow(er) heavy scalars ⇐

⇒ new (easier ?) strategies needed wrt searches for SM-like Higgs bosons in this mass range ⇐

[width studies (from ∼ 2015): cf. Maina ; Kauer, O'Brien; Kauer, O'Brien, Vryonidou; Ballestrero, Maina; Dawson, Lewis; Martin; Jung, Yoon, Song; Djouadi, Ellis, [Popov], Quevillon; Carena, Liu, Riembau; Kauer, Lind, Maierhöfer, Song; ...]



- $\leq 153\,\text{GeV}$: $h_2 \rightarrow ZZ$ Run II [arXiv:1804.01939] (CMS, $35.9\ \text{fb}^{-1}$)
- $[153 - 183\,\text{GeV}]$: SM-like decays to VV, Run I [CMS-PAS-HIG-13-003], Run II [1712.06386] (ATLAS, $36.1\ \text{fb}^{-1}$), Run I combination [CMS-PAS-HIG-12-045]
- $[183 - 438\,\text{GeV}]$: $h_2 \rightarrow ZZ$ Run II
- $[438 - 990\,\text{GeV}]$: $h_2 \rightarrow VV$, combination Run II [arXiv:1808.02380] (ATLAS, $36\ \text{fb}^{-1}$)
- $> 990\,\text{GeV}$: VBF mode to VV, combination Run II [arXiv:1808.02380]

Coupling and mass relations

$$m_h^2 = \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \quad (1)$$

$$m_H^2 = \lambda_1 v^2 + \lambda_2 x^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \quad (2)$$

$$\sin 2\alpha = \frac{\lambda_3 x v}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}, \quad (3)$$

$$\cos 2\alpha = \frac{\lambda_2 x^2 - \lambda_1 v^2}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}. \quad (4)$$

RGE running in more detail (1)

Question: at which scale did we require perturbativity ?

Answer: "just above" the SM breakdown

(other answers equally valid...)

- RGEs for this model well-known (cf eg Lerner, McDonald)
- decoupling ($\lambda_3 = 0$): recover SM case
- in our setup: $\mu_{\text{SM,break}} \sim 2.5 \times 10^{10}\,\mathrm{GeV}$
  (remark: just simple NLO running)
- **we took:** $\mu_R \sim 4.0 \times 10^{10}\,\mathrm{GeV}$

  (higher scales $\Longleftrightarrow$ stronger constraints)

- **obvious: for $m_H \sim 125\,\mathrm{GeV}$, breakdown "immediate"** when going to $\mu_{\text{run}} > v$

$\Rightarrow$ disregard constraints from running in this case

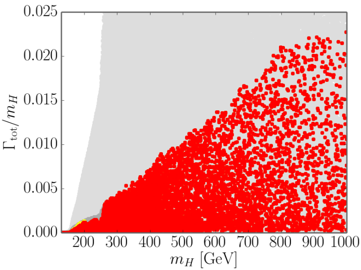
RGE running: variation of input parameters

- especially in sensitive cases, but also otherwise:
  check robustness against input parameters
- here: especially important in decoupling (ie SM-like) case
  (cf. various discussions in the literature...)
- our check:
  vary $\alpha_s(m_Z)$, $y_t(m_t)$ for 1 σ around central values
- main impact: **on vacuum stability,** ie $\lambda_1 > 0$ condition
- **no significant change in $\kappa_{\mathrm{max}}(\mathrm{m_H})$, ...**

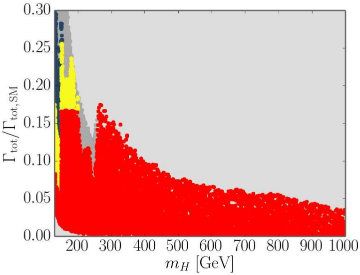
$\Rightarrow$ **not relevant for collider studies** (at this stage...)

Interim comment on total width

- Total width greatly reduced

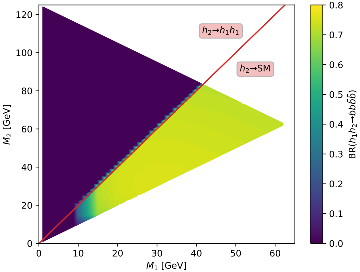


width over mass

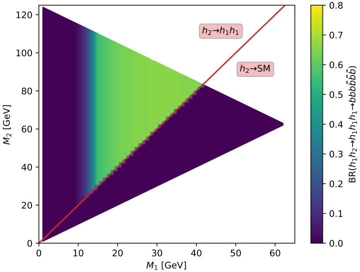


suppression factor of width

BP1: $h_3 \to h_1 h_2$ $(h_3 = h_{125})$ [up to 3 pb]



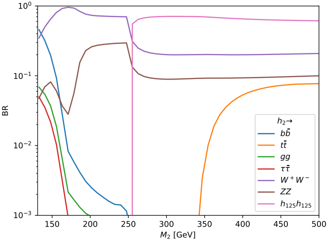
$h_3 \to h_1\ h_2 \to b\bar{b}b\bar{b}$

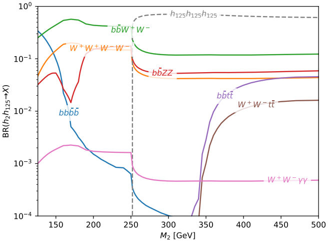


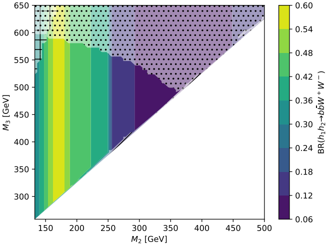
$h_3 \to h_1\ h_2 \to h_1\ h_1\ h_1 \to b\bar{b}b\bar{b}b\bar{b}$

reaching $\sim 2\,\mathrm{pb}$, depending on masses

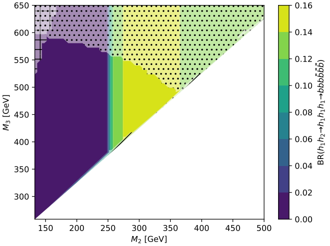
BP3: $h_3 \to h_1 h_2$ $(h_1 = h_{125})$ [up to 0.3 pb]





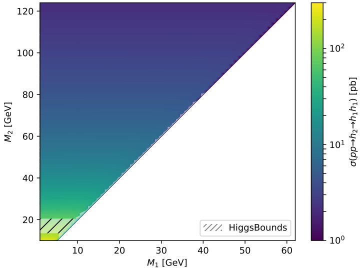


up to 0.18 pb



up to 50 fb

BP4: $h_2 \to h_1 h_1$ ($h_3 = h_{125}$) [up to 60 pb]



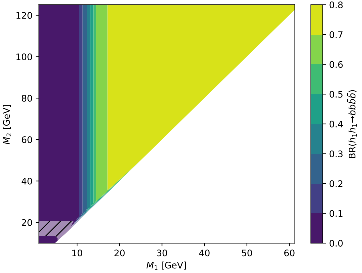
- $|\kappa_2| \sim 0.2$

$$\sigma_{gg \to h_2}(M_2) \sim 0.04\, \sigma^{SM}_{gg \to h_2}(M_2)$$

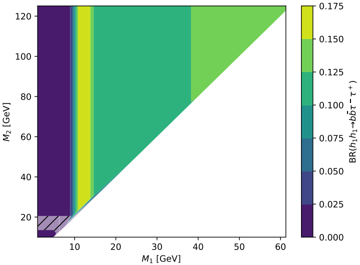
[$\text{BR}_{h_2 \to h_1 h_1} \gtrsim 0.9$ for $M_1 \gtrsim 40\,\text{GeV}$]

dominant decays to $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$

BP4: $h_2 \to h_1 h_1$ $(h_3 = h_{125})$ [up to 60 pb]



$h_2 \to h_1\, h_1 \to b\bar{b}b\bar{b}$

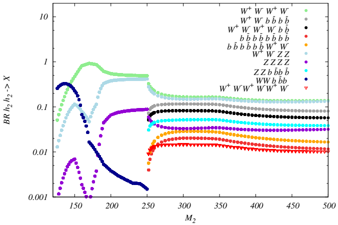


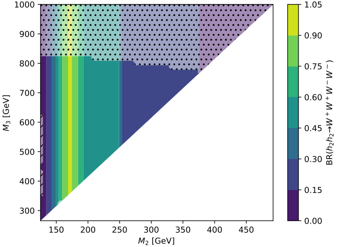
$h_2 \to h_1\, h_1 \to b\bar{b}\tau^+\tau^-$

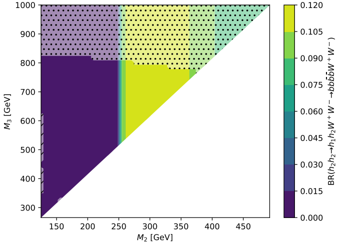
reaching $\sim 15/8\,\mathrm{pb}$, **max for** $M_1 \sim 15/10\,\mathrm{GeV}$, $M_2 \sim 2\,M_1$

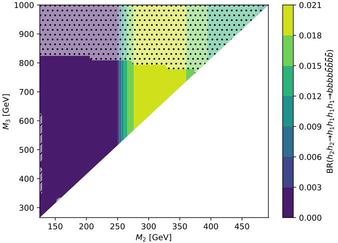
[for lower masses: $c\bar{c}c\bar{c}$, $c\bar{c}\tau^+\tau^+$ also become sizeable]

BP6: $h_3 \to h_2 h_2$ $(h_1 = h_{125})$ [up to 0.5 pb]





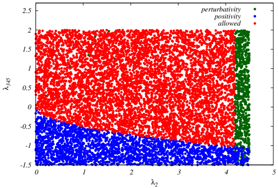




$W^+W^-W^+W^-$: 0.45 pb for $M_2 \sim M_{top}$/ others: 14 fb; 2 fb

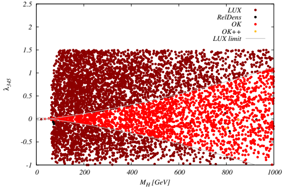
Obvious/ direct constraints on couplings and masses

some constraints ⇒ direct limits on couplings/ masses

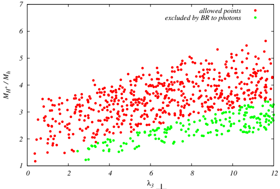


$\lambda_2,\ \lambda_{345}$ plane and limits from

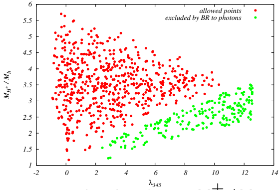
perturbativity, positivity



$M_H,\ \lambda_{345}$ plane, limits from LUX$^{(*)}$



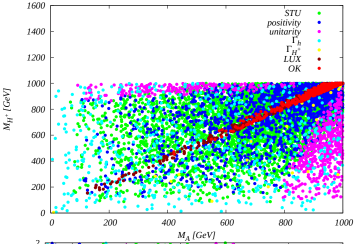
limits on $\lambda_3,\ M_H^{\pm}/M_h$, plane



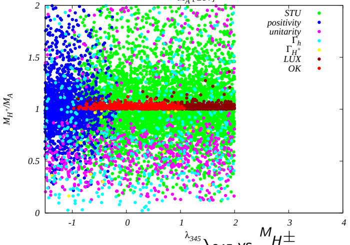
... translated to $\lambda_{345},\ M_H^{\pm}/M_h$

$^{(*)}$ updates not yet included

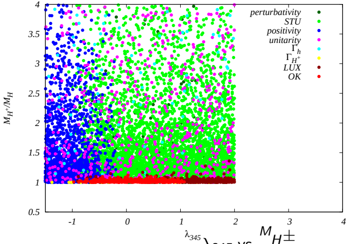
Other constraints less obvious (interplay); result ⇒ mass degeneracies



M_A vs $M_{H^\pm}$ after all constraints



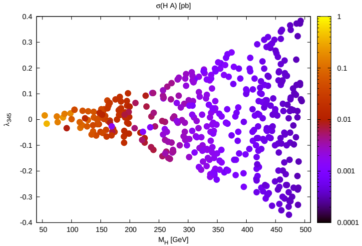
λ_{345} vs $\frac{M_{H^\pm}}{M_A}$

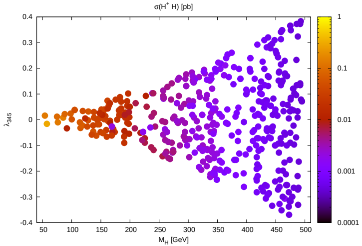


λ_{345} vs $\frac{M_{H^\pm}}{M_H}$

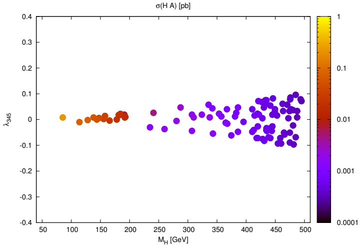
Updated constraints [XENON1T] [Phys.Rev.Lett. 121 (2018) no.11, 111302]

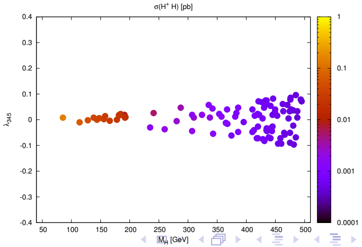
LUX





XENON

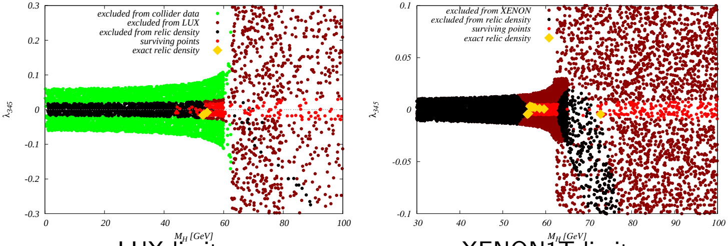




Cases where $M_H \leq M_h/2$

- **discussion so far:** decay $h \rightarrow H\,H$ kinematically not accessible
- for these cases, discussion along different lines

$\Rightarrow$ **extremely strong constraints from signal strength, and dark matter requirements**



LUX limits XENON1T limits

- additional constraints from combination of W, Z decays and recasted analysis at LEP

lower limit $M_H \sim 50\,\mathrm{GeV}$

Parameters tested at colliders: mainly masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **e.g. predictions for LHC@13 TeV do not depend on λ_2, only marginally on λ_{345}**
- all **relevant couplings follow from ew parameters (+ derivative couplings)** $\Rightarrow$ in the end a kinematic test
- only in exceptional cases λ_{345} important

$\Rightarrow$ **high complementarity between astroparticle physics and collider searches**

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

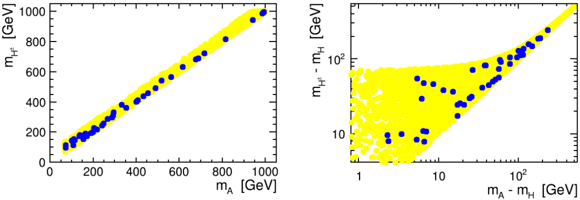
IDM at CLIC [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

Benchmark points: JHEP 1812 (2018) 081; Analysis: JHEP 1907 (2019) 053

[J. Kalinowski, W. Kotlarski, TR, D. Sokolowska, A.F. Zarnecki]

IDM benchmark points

Out of about 15'000 points consistent with all considered constraints, we chose 43 benchmark points (23 accessible at 380 GeV) for detailed studies:



The selection was arbitrary, but we tried to

- cover wide range of scalar masses and the mass splittings
- get significant contribution to the relic density

For list of benchmark point parameters, see backup slides

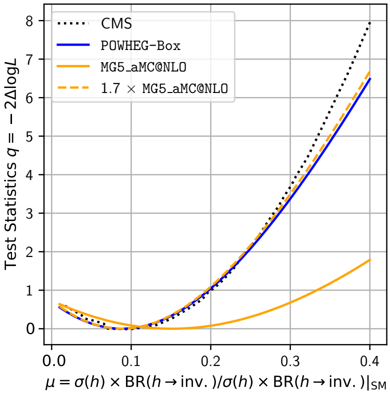
IDM recast: validation

- recover original paper results:
  number of events in m_{jj} bins, after application of all cuts

> $\Rightarrow$ VBF production of h, which is considered invisible
> $\Rightarrow$ ggF production of hj at NLO

- tools: Powheg Box interfaced with Pythia;
  reproduced results ✓
- **BSM signal: Madgraph5 at leading order**
- numbers lower by factor 1.7: **LO results conservative**

Validation: Profile Likelihood



Topics for discussion

⇒ (How) can we convince the LHC experiments to look for this model ? No dedicated searches

⇒ How wrong are we when projecting more involved models into the IDM ?

(this also concerns theory constraints (e.g. special vacuum conditions, etc))

⇒ can/ should new approaches be applied ? "hot" topic: machine learning...

⇒ what about alternative methods for searches ? "bump" hunting via generalized mass variables ? a lot of work has been done that one might have to rediscover

Determining SUSY model parameters and masses at the LHC using cross-sections, kinematic edges and other observables, C. Lester, M. Parker, M. J. White, arXiv:0508143