Constraining Extended Higgs Sectors at the LHC and beyond

Tania Robens
based on 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), F. Bojarski, G. Chalons, D. Lopez-Val (JHEP 1602 (2016) 147) , A. Ilnicka, M. Krawczyk (Phys.Rev. D93 (2016) no.5, 055026), A. Ilnicka, T. Stefaniak (arXiv:1803.03594)
MTA-DE Particle Physics Research Group, University of Debrecen

DESY
DESY Theory Seminar
03/12/2018

Introduction and motivation: Higgs discovery and the Nobel Prize

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

$\Rightarrow$ **Discovery of "a" Higgs boson** $\Leftarrow$

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

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

$\Rightarrow$ **!! Particle physics is more exciting than ever !!** $\Leftarrow$

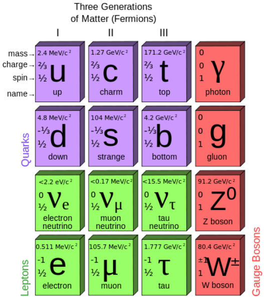
1. Introduction and Motivation
2. Singlet
   - Parameter space including bounds
   - m_W at NLO
   - LHC
   - Renormalization
   - Summary
3. Inert Doublet Model

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**

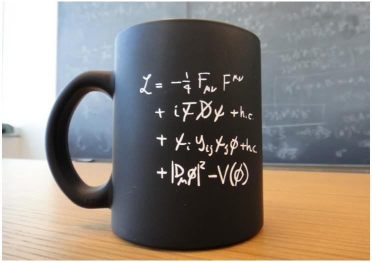
  [quarks: **building blocks of hadrons**]
- **forces which act on them**, coming with **gauge bosons**
- properties/ quantum numbers: **mass, spin, charges under gauge groups**



+ **Higgs**, $m_H \sim 125\,\text{GeV}$

Question: Is this all there is ??

SM Langrangian



[quantumdiaries.org]

with a SM Higgs

[particlezoo.net]

After Higgs discovery: Open questions

Higgs discovery in 2012 ⇒ last building block discovered

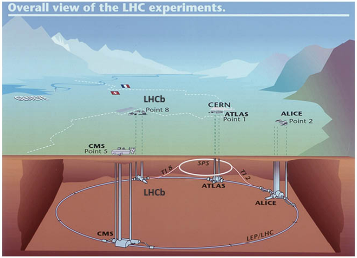
? Any remaining questions ?

- 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**

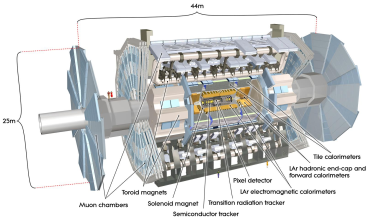
for all: **Search for Physics beyond the SM (BSM)**

⟹ **main test ground for this: particle colliders** ⟸

Current major focus: Physics at the LHC



[cern.ch]



ATLAS detector [atlas.ch]

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

second run: start in 2015, **13/ 14 TeV cm energy**

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

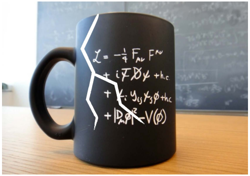
$\Longrightarrow$ Tasks for theorists $\Longleftarrow$

- $\Rightarrow$ **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]

Singlet extension: The model

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)

$\Rightarrow$ 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

$$\text{VeVs:}\;\; H \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix},\; \chi \equiv \frac{h'+x}{\sqrt{2}}.$$

- 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 ($m_h < m_H$):

$$\begin{pmatrix} \mathbf{h} \\ \mathbf{H} \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix},$$

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"** $\cos^4\alpha / \sin^4\alpha$ $\left(\cos^2\alpha / \sin^2\alpha\right)$ for full production and decay (production or decay)

- **BRs stay the same**

Tree-level rescaling (2)

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

$$H \rightarrow h\,h$$

- effect:

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

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:

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

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

Bounds

G.M. Pruna, TR, PRD 88 (2013) 115012;
D. Lopez-Val, TR, PRD 90 (2014) 114018;
TR, T. Stefaniak, EPJC75 (2015)3, 104; EPJC76 (2016)5, 268

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 and ATLAS-CONF-2015-044 [signal strength combination]

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

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

Results

- **strongest constraints:**

$$m_H \gtrsim 800\,\text{GeV} \quad : \quad \textbf{perturbativity of couplings}$$

$$m_H \in [270; 800]\text{GeV} \quad : \quad m_W \textbf{ @ NLO}$$

$$m_H \in [125; 800]\text{GeV} \quad : \quad \textbf{experimental searches/ signal strength}$$

$$m_h \lesssim 120\,\text{GeV} \quad : \quad \textbf{SM-like Higgs coupling rates } (+\text{ LEP})$$

$\Rightarrow\ \kappa \leq\ 0.25$ 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 (∼ 2015): cf. Maina ; Kauer, O'Brien; Kauer, O'Brien, Vryonidou; Ballestrero, Maina; Dawson, Lewis; ...]

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 $m_H \leq 1\,\mathrm{TeV}$!! for the model-builders...)

- arbitrary large m_H can cure this !! cf Lebedev; Elias-Miro ea. Out of collider range though ($\sim 10^8\,\mathrm{GeV}$) (...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)]

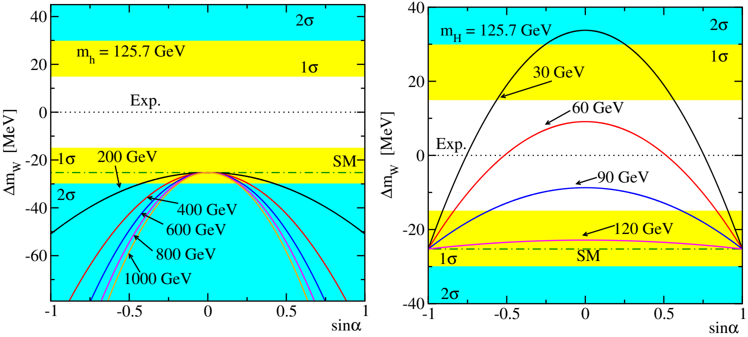
- electroweak fits: fit $\mathcal{O}\,(20)$ parameters, constraining S, T, U
- idea here: single out m_W, measured with error $\sim\,10^{-4}$
- **setup renormalization for Higgs and Gauge boson masses**
- EW gauge and matter sector: on-shell scheme
- Higgs sector: several choices, currently a mixture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



$m_h = 125.7\,\text{GeV}$ $\quad\quad$ $m_H = 125.7\,\text{GeV}$

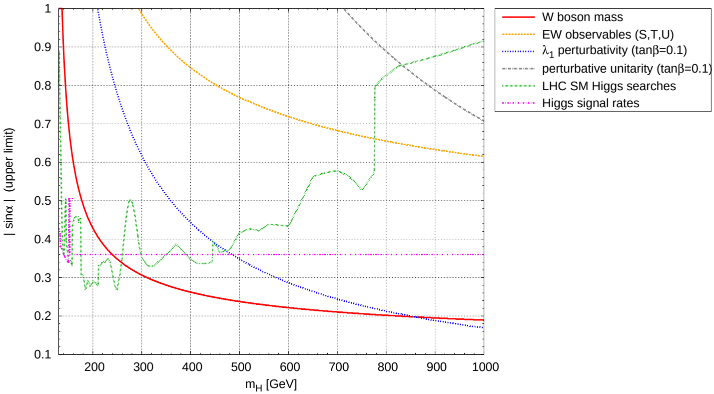
$\Longrightarrow$ low m_h bring m_W^{NLO} close to m_W^{exp} $\Longleftarrow$

LHC

TR, T. Stefaniak,
EPJC75 (2015)3, 104; EPJC76 (2016)5, 268

Combined limits on $|\sin\alpha|$

(TR, T. Stefaniak, Eur.Phys.J. C76 (2016) no.5, 268)

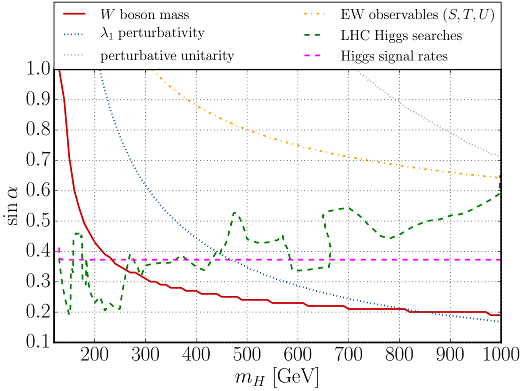


several bounds on $|\sin\alpha|$

m_W, perturbativity, LHC direct searches, Higgs Signal strength

Combined limits on $|\sin\alpha|$!! NEW !!

(A. Ilnicka, TR, T. Stefaniak, arXiv:1803.03594)



m_W still strongest constraint for $m_H \gtrsim 300\,\mathrm{GeV}$;

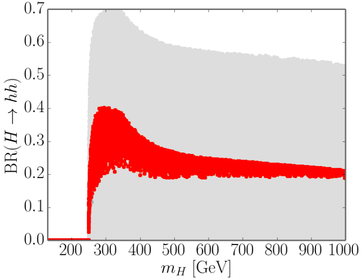
$\Rightarrow$ strong improvement: direct searches (ZZ @ 13 TeV) $\Leftarrow$

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

- **viable alternative:** search for

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

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



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

Results from generic scans and predictions for LHC 14

(TR, T. Stefaniak, Eur.Phys.J. C76 (2016) no.5, 268)

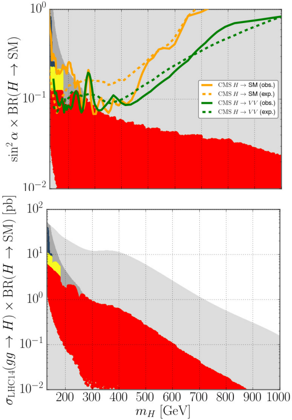
1 σ, 2 σ, allowed

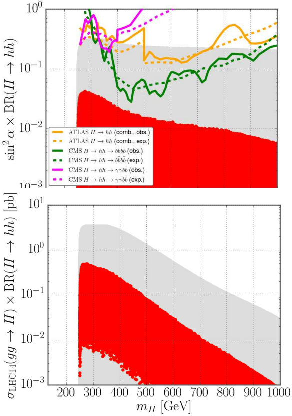
SM like decays

BSM decay to hh

limits

pred.





What about the "inverse" scenario, ie. $m_H = 125.1\,\mathrm{GeV}$

mainly ruled out by LEP and/ or χ^2 fit from HiggsSignals
however, *still* large number produced due to large $\sigma_{gg\to h}$

$m_h[\mathrm{GeV}]$	$\lvert\sin\alpha\rvert_{\text{min, exp}}$	$\lvert\sin\alpha\rvert_{\text{min, }2\sigma}$	$(\tan\beta)_{\max}$	$\#gg\sim$
110	0.82	0.94	9.3	10^5
100	0.85	0.90	10.1	10^5
90	0.90	$--$	11.2	10^5
80	0.97	$--$	12.6	10^4
70	0.99	$--$	14.4	10^4
60	0.98	$\gtrsim 0.99$	16.8	10^4
50	0.98	$\gtrsim 0.99$	20.2	10^4
40	0.99	$\gtrsim 0.99$	25.2	10^4

Table : Upper limit on $\tan\beta$ from perturbative unitarity. ($--$ means no additional constraint)

(side remark: for $m_h \gtrsim 60\,\mathrm{GeV}$, $\tan\beta$ irrelevant for collider observables)

Full Renormalization

F. Bojarski, G. Chalons, D. Lopez-Val, TR
JHEP 1602 (2016) 147

Full renormalization (1)

(F. Bojarski, G. Chalons, D. Lopez-Val, TR, JHEP 1602 (2016) 147)

- next topic: **full electroweak renormalization**
- many parts of ew sector: **follow SM prescriptions**
- **new:** renormalize

$$T_{h,H};\ v;\ x;\ m^2_{h,H};\ Z_{h,H,hH,Hh};\ m^2_{hH}$$

⇒ in total: **11 parameters in scalar sector**

⇒ need to be determined by **suitable renormalization conditions**

Full renormalization (2)

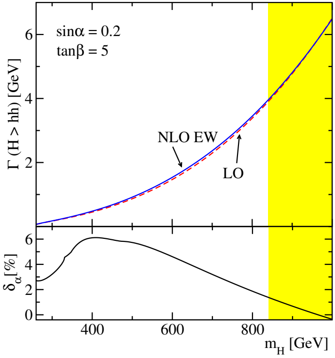
$\Longrightarrow$ **Our choices** $\Longleftarrow$

- Tadpoles: $\delta T = -T$ $[\hat{T}=0]$
- v: as in SM, on-shell (ie through ew gauge sector)
- $\delta x = 0$ (not fixed by any measurement) **!!! choice !!!**

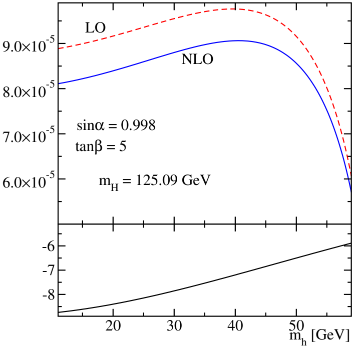
  [no UV-divergence ! ; Sperling ea, 2013]
- $\delta m_{h,H}$, $\delta Z_{H,h}$: on-shell
- difficult part **off-diagonal terms** m^2_{hH}, δZ_{hH} **!!**
- we choose: **'improved on-shell scheme' !!**
- for the experts: leads to gauge-invariant counterterms without resorting to physical measurements; tested via SloopS (Boudjema, Semenov, Temes 2005; Baro, Boudjema, Semenov 2007/ 2008;Baro, Boudjema 2009)
- based on 'Pinch Technique' (Cornwall 1982; Cornwall, Pappavassoliou 1989; Espinosa, Yamada, 2002; Binosi, Papavassiliou 2009;...)

Renormalization: numerical results

all results here for $\Gamma_{H\to h\,h}$



$m_h = 125\,\text{GeV}$

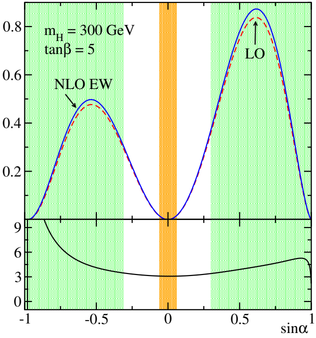


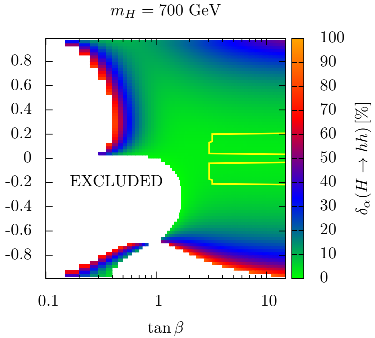
$m_H = 125\,\text{GeV}$

"typical" size of corrections

Renormalization: numerical results, $m_h = 125\,\mathrm{GeV}$

all results here for $\Gamma_{H\to h\,h}$





exlusions (left): m_W, vacuum stability ;
white space (right): corrections $> 100\,\%$

Summary and Outlook: Singlet

Summary

- Singlet extension: **simplest extension of the SM Higgs sector**, easily identified with one of the benchmark scenarios of the HHXWG (cf. also YR3, Snowmass report, YR4)
- constraints on **maximal mixing** from **m_W at NLO** ($m_H \in [200\,\mathrm{GeV}; 800\,\mathrm{GeV}]$), **experimental searches and fits** ($m_{H,h} \leq 200\,\mathrm{GeV}$) and/ or **running couplings** ($m_H \geq 800\,\mathrm{GeV}$)
- **quite narrow widths wrt SM-like Higgses** in this mass range $\Rightarrow$ **better theoretical handle**
- quite large suppression from current experimental/ theoretical constraints

!!! still, large numbers could have been produced already !!!

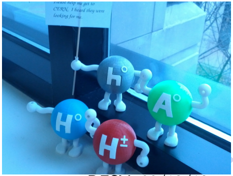
$\Longrightarrow$ **STAY TUNED** $\Longleftarrow$

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 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

Inert doublet model: The model

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

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

$\Rightarrow$ 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
  ($\Rightarrow$ implies analogous EWSB)

Number of free parameters

$\Rightarrow$ then, **go through standard procedure...**

$\Rightarrow$ minimize potential

$\Rightarrow$ determine number of free parameters

Number of free parameters here: 7

- e.g.

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

- v, M_h fixed $\Rightarrow$ left with **5 free parameters**

Constraints: Theory

- As before: need to consider all current constraints on the model
- Theory constraints: **vacuum stability, positivity, constraints to be in inert vacuum**
  $\Rightarrow$ **limits on (relations of) couplings**
- **perturbative unitarity, perturbativity of couplings**
- **choosing** M_H as dark matter:

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

Constraints: Experiment

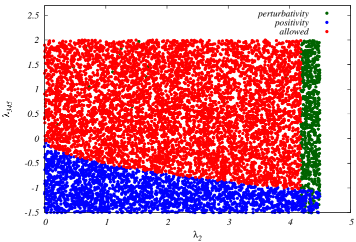
$$M_h = 125.1\,\mathrm{GeV},\; v = 246\,\mathrm{GeV}$$

- total width of M_h
- total width of W, Z
- collider constraints from signal strength/ direct searches
- electroweak precision through S, T, U
- unstable $H^{\pm}$
- reinterpreted/ recastet LEP/ LHC SUSY searches (Lundstrom ea 2009; Belanger ea, 2015)
- dark matter relic density (upper bound)
- dark matter direct search limits (before: LUX; now: XENON1T)

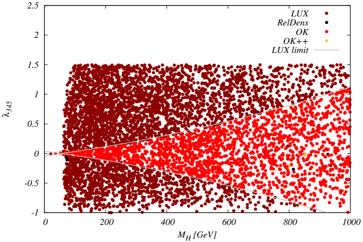
$\Rightarrow$ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

Obvious/ direct constraints on couplings

- some constraints $\Rightarrow$ direct limits on couplings
- examples: limit on λ_2 from $HHHH$ coupling, limit on $\lambda_{345}(M_H)$ from direct detection

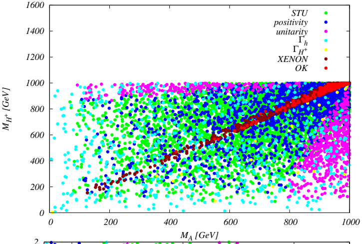


λ_2, λ_{345} plane and limits from perturbativity, positivity

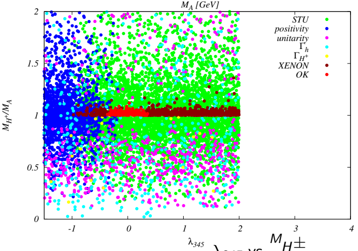


M_H, λ_{345} plane, limits from LUX

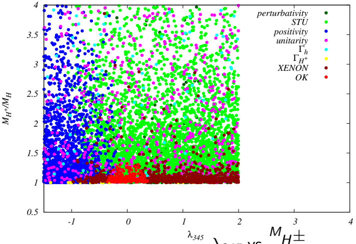
Other constraints less obvious (interplay); result $\Rightarrow$ mass degeneracies



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



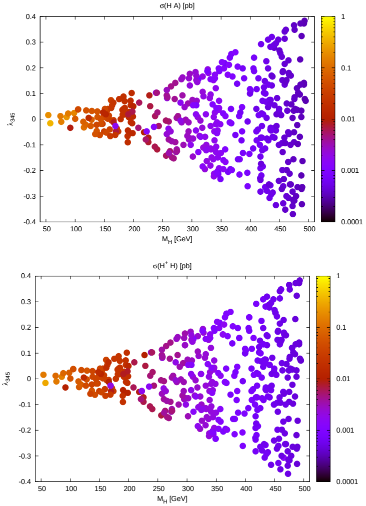
λ_{345} vs $\frac{M_{H^\pm}}{M_A}$



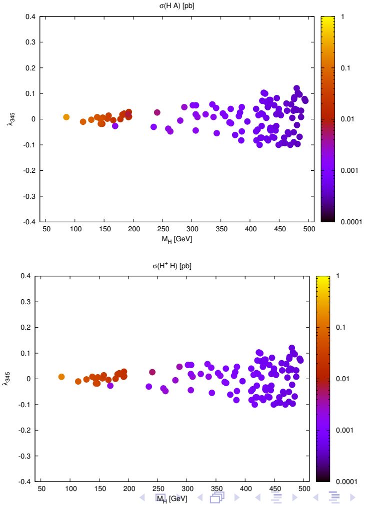
λ_{345} vs $\frac{M_{H^\pm}}{M_H}$

Effect of updated constraints [especially: XENON1T] [1705.06655]

LUX



XENON



Benchmark planes [old]

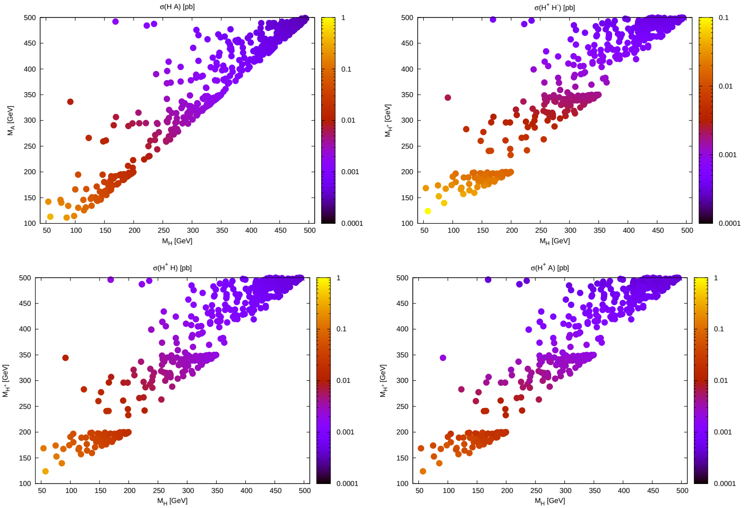


Figure : Production cross sections in pb at a 13 TeV LHC

Benchmark planes [new; XENON/ Signal rates improved]

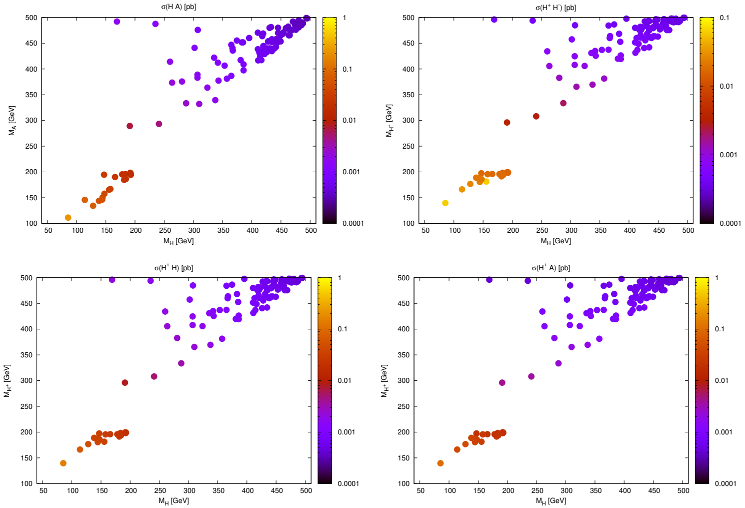


Figure : Production cross sections in pb at a 13 TeV LHC

Benchmark selection for current LHC run

$\Rightarrow$ points need to **have passed all bounds**

$\Rightarrow$ total cross sections calculated using **Madgraph5, IDM model file from Goudelis ea**, 2013 (LO)

$\Rightarrow$ **effective ggH vertex implemented by hand**

- highest production cross sections: $H\,A;\ H^\pm\,H;\ H^\pm\,A;\ H^+\,H^-$
- decay $A\,\rightarrow\,H\,Z$ always 100 %
- decay $H^\pm\,\rightarrow\,H\,W^\pm$ usually dominant

$$\begin{aligned} p\,p\,\rightarrow\,H\,A &:\quad \leq\,0.03\,\mathrm{pb},\\ p\,p\,\rightarrow\,H^\pm\,H &:\quad \leq\,0.03\,\mathrm{pb},\\ p\,p\,\rightarrow\,H^\pm\,A &:\quad \leq\,0.015\,\mathrm{pb},\\ p\,p\,\rightarrow\,H^+\,H^- &:\quad \leq\,0.01\,\mathrm{pb}. \end{aligned}$$

Parameters tested at LHC: masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **LHC@13 TeV** **does 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 expectional cases λ_{345} important; did not find such points

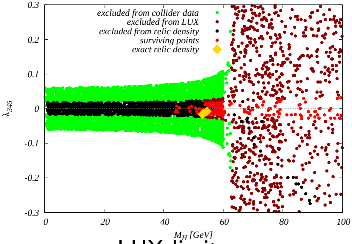
$\Rightarrow$ **high complementarity between astroparticle physics and collider searches**

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

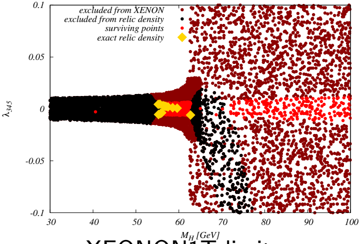
Last comment: cases where $M_H \leq M_h/2$

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

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



LUX limits



XEONON1T limits

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

lower limit $M_H \sim 40\,\mathrm{GeV}$

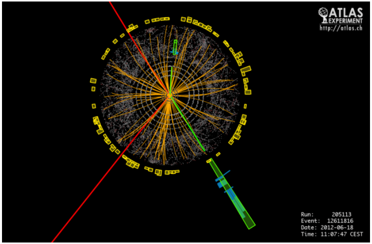
Summary

- **LHC run II in full swing** ⇒ **exciting times ahead of us**
- one important question: **test Higgs sector**, especially wrt **extensions/ additional matter content**
- from current **LHC and astrophysical data: models already highly constrained**
- discussion here: **2HDM with dark matter (IDM)**
- **identified viable regions in parameter space**
- from these: **predictions for current LHC run**
  [A. Ilnicka, M. Krawzyk, TR, CERN Yellow Report]

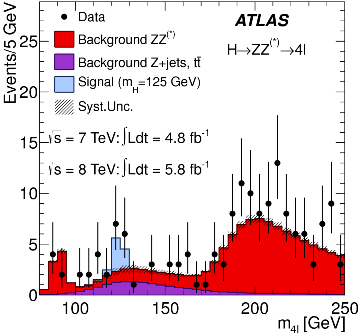
!! stay tuned, and thanks for listening !!

Appendix

… and discovery



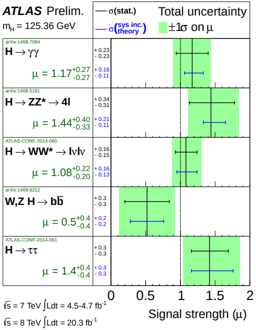
[ATLAS collaboration, 2 e 2 μ Higgs candidate]

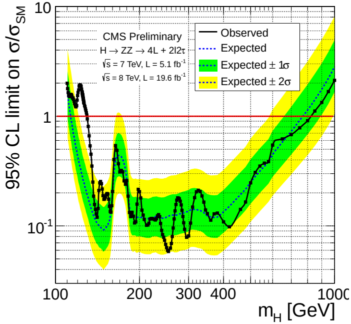


[ATLAS collaboration, Phys.Lett. B716 (2012) 1-29]

Finally: collider results

- Incorporation of **collider bounds**: in principle many things need to be considered: Limits from **LEP, Tevatron, LHC, ...**
- same: agreement with **observed coupling strengths**





(CMS-PAS-HIG-13-002)

approach here: let **HiggsBounds/ HiggsSignals** (Bechtle ea, Bechtle ea*) do this for you

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

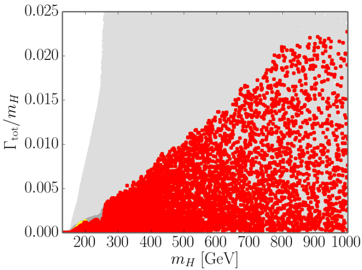
RGE running: variation of input parameters

- 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 $\kappa_{max}(m_H)$, ...**

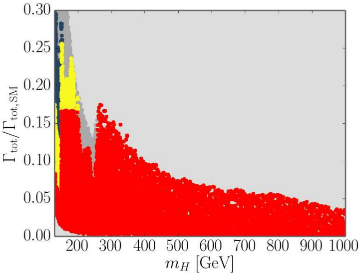
$\Rightarrow$ **not relevant for collider studies** (at this stage...)

Interim comment on total width

- Total width greatly reduced



width over mass



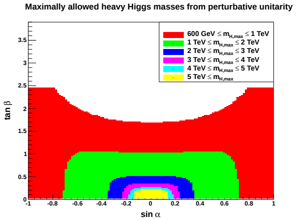
suppression factor of width

Comments on constraints (1) - Perturbativity issues

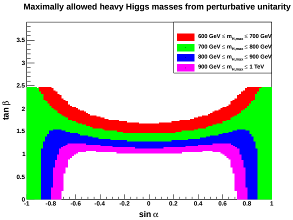
- we tested: **maximal m_H** from PU

  $\Longrightarrow$ **strongest constraints from $H\,H \to H\,H$** $\Longleftarrow$

- rule of thumb (exact for $\alpha = 0$): $\tan^2\beta \leq \frac{16\,\pi\,v^2}{3\,m_H^2}$



Limits in $\sin\alpha$, $\tan\beta$ plane, maximally allowed m_H from PU



Limits in $\sin\alpha$, $\tan\beta$ plane, maximally allowed $m_H \leq 1\,\mathrm{TeV}$ from PU

$\Longrightarrow$ **for realistic $\sin\alpha$ and our m_H range, $\tan\beta \lesssim 8$**

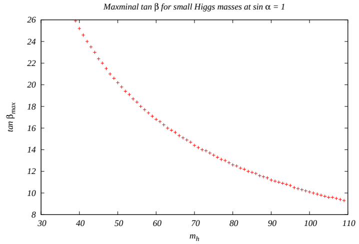
Comments on constraints (1) - Perturbativity issues

However...

- For the scenario $m_H = 125.7\,\mathrm{GeV},\ m_h \leq m_H$:

$\Rightarrow$ **strongest** ***theory*** **limit** on $\tan\beta_{\max}$ **from PU**
(will comment on this later in more detail)

- then: $\tan\beta \lesssim 20$



- **remember:** $\tan\beta$ only appears in Higgs self-couplings

$\Rightarrow$ **currently only relevant for an open $H \rightarrow h\,h$ channel !!**

Could we have seen them ??

all numbers below: $\sqrt{S_{\text{hadr}}} = 8\,\text{TeV},\ \int \mathcal{L} = 23\,\text{fb}^{-1}$

m_H [GeV]	κ_{max}	#gg ∼	κ'_{max}	#gg ∼
200	0.19	**3×10^4**	0	0
300	0.076	**6×10^3**	0.039	**3×10^3**
400	0.058	**4×10^3**	0.019	**1×10^3**
500	0.046	**1×10^3**	0.013	**380**
600	0.042	**510**	0.013	160
700	0.035	180	0.010	50
800	0.035	90	0.010	25
900	0.029	40	0.007	10
1000	0.023	17	0.006	4

[for specific final state, multiply with SM-like BR (LO approx)]

for $m_H \lesssim 600\,\text{GeV}$, may could already have been produced which are not excluded by current searches !!

Tools which can do it ?? (incomplete list)

("it"=LO,NLO,...)

- LO: **any tool talking to FeynRules** (in principle)/ **LanHep** (in practice)
- implemented (and run): **CompHep** (M. Pruna), **Whizard** (J. Reuter), **Sherpa** (±) (would need some modification, T. Figy), privately modified codes (??)
- NLO: (mb) a modified version of **aMC@NLO** (R. Frederix) ?? (production only; might be important for VBF)
- higher orders: would need to be implemented in respective tools (I am not aware of any at the moment)

Singlet Extension: Classical Lagrangian

$$\mathscr{L}_{\mathbf{xSM}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{fermions}} + \mathscr{L}_{\text{Yukawa}} + \mathscr{L}_{\text{scalar}} + \mathscr{L}_{\mathbf{GF}} + \mathscr{L}_{\mathbf{ghost}}$$

$$\mathscr{L}_{\text{scalar}} = (\mathcal{D}^{\mu}\Phi)^{\dagger}\,\mathcal{D}_{\mu}\Phi + \partial^{\mu}S\partial_{\mu}S - \mathcal{V}(\Phi, S)$$

$$\mathcal{V}(\boldsymbol{\Phi}, \mathbf{S}) = \mu^2\,\Phi^{\dagger}\,\Phi + \lambda_1\,|\Phi^{\dagger}\Phi|^2 + \mu_s^2\,S^2 + \lambda_2\,S^4 + \lambda_3\,\Phi^{\dagger}\,\Phi S^2\ .$$

- $\mathscr{L}_{\text{gauge}}$, $\mathscr{L}_{\text{fermions}}$, $\mathscr{L}_{\text{Yukawa}}$ as in SM
- BRST invariance $\Rightarrow$ $\delta_{\text{BRST}}\mathscr{L}_{GF} = -\delta_{\text{BRST}}\mathscr{L}_{ghost}$
- more later...

Renormalization: gauge fixing

Our choice: **non-linear gauge fixing !!**

- reason: want to check **gauge-parameter dependence for physical processes**
- implementation: **SLOOPS** [Boudjema ea, '05; Baro ea, '07-'09]

$$\boxed{\mathscr{L}_{GF} = -\frac{1}{\xi_W} F^+ F^- - \frac{1}{2\xi_Z} |F^Z|^2 - \frac{1}{2\xi_A} |F^A|^2}$$

$$\begin{aligned}
F^\pm &= \left(\partial_\mu \mp ie\tilde{\alpha} A_\mu \mp ig \cos\theta_W \tilde{\beta} Z_\mu\right) W^{\mu\,+} \\
&\quad \pm i\xi_W \frac{g}{2}\left(v + \tilde{\delta}_1 h + \tilde{\delta}_2 H \pm i\tilde{\kappa} G^0\right) G^+ \\
F^Z &= \partial_\mu Z^\mu + \xi_Z \frac{g}{2\cos\theta_W}\left(v + \tilde{\epsilon}_1 h + \tilde{\epsilon}_2 H\right) G^0 \\
F^A &= \partial_\mu A^\mu \,.
\end{aligned}$$

- $\tilde{\alpha}, \tilde{\beta}, \ldots$: **non-linear gauge-fixing parameters**
- $\tilde{\alpha} = \tilde{\beta} = \ldots = 0, \xi = 1 \Rightarrow$ back to t'Hooft-Feynman gauge

Renormalization: SM inheritance

- S: **singlet under SM gauge group**

$\Rightarrow$ in the electroweak gauge sector: **follow SM prescriptions***

- parameter count in the scalar sector: **11 counterterms**

$\Rightarrow$ renormalize

$$T_{h,H};\ v;\ v_s;\ m^2_{h,H};\ Z_{h,H,hH,Hh};\ m^2_{hH}$$

$\Rightarrow$ need to be determined by **suitable renormalization conditions**

* performed in **2 different electroweak schemes:**
α_{em} : $\alpha_{em}(0)$, m_W, m_z as input;
G_F : $\alpha_{em}(0)$, G_F, m_z as input, related via Δr

... and in more detail...

$$\begin{aligned} v_i^0 &\longrightarrow v_i + \delta v_i, \\ T_i^0 &\longrightarrow T_i + \delta T_i, \\ \mathcal{M}_\phi^2 &\longrightarrow \mathcal{M}_\phi^2 + \delta \mathcal{M}_\phi^2 \end{aligned}$$

where $\delta \mathcal{M}_{hH}^2 = U(\alpha) \cdot \delta \mathcal{M}_{\phi_h,\phi_s}^2 \cdot U(-\alpha) = \begin{pmatrix} \delta m_h^2 & \delta m_{hH}^2 \\ \delta m_{hH}^2 & \delta m_H^2 \end{pmatrix}$

$$\begin{pmatrix} h \\ H \end{pmatrix}^0 \longrightarrow \begin{pmatrix} 1 + \frac{1}{2}\delta Z_h & \frac{1}{2}\delta Z_{hH} \\ \frac{1}{2}\delta Z_{Hh} & 1 + \frac{1}{2}\delta Z_H \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

NO mixing angle renormalization

Different choices for mixed terms $\delta Z_{Hh,hH}$, δm^2_{hH}

Always: $\boxed{\textbf{Re}\,\hat{\Sigma}_{hH}(m_h^2) = 0;\, \textbf{Re}\,\hat{\Sigma}_{hH}(m_H^2) = 0}$

- **Onshell scheme**: $\delta Z_{hH} = \delta Z_{Hh}$

$\Rightarrow$ **drawback:** predictions remain **gauge-parameter dependent !!**

- **Mixed $\overline{\text{MS}}$/on-shell:** fix δm^2_{hH} through **UV-divergence of** λ_2

$\Rightarrow$ **drawback:** corrections $\sim \sin^{-1}\alpha,\ \cos^{-1}\alpha$, **can get large !!**

- **improved onshell**

$$\delta m^2_{hH} = \textbf{Re}\,\Sigma_{hH}(p_*^2)\big|_{\xi_W=\xi_Z=1,\tilde{\delta}_i=0},\ p_*^2 = \frac{m_h^2 + m_H^2}{2}$$

[similar result e.g. in Baro, Boudjema, Phys. Rev. D80 (2009) 076010; ...]

$\Rightarrow$ **drawback: NONE !!**

... and in numbers...

NLO corrections to $H \to h\,h$ decay, gauge-parameter dependence

	$\delta\Gamma^{\text{1-loop}}_{H\to hh}$ [GeV]		
Scheme	$\Delta = 0$, $\{\text{nlgs}\} = 0$	$\Delta = 10^7$, $\{\text{nlgs}\} = 0$	$\Delta = 10^7$, $\{\text{nlgs}\} = 10$
OS	$+4.2633488\mathbf{8} \times 10^{-3}$	$+4.2633488\mathbf{6} \times 10^{-3}$	$-5.27015844 \times 10^{3}$
Mixed $\overline{\text{MS}}$/OS	$+6.846750\mathbf{6} \times 10^{-3}$	$+6.846750\mathbf{4} \times 10^{-3}$	$+6.846750\mathbf{0} \times 10^{-3}$
Improved OS	$+3.939356\mathbf{9} \times 10^{-3}$	$+3.939356\mathbf{8} \times 10^{-3}$	$+3.93935\mathbf{56} \times 10^{-3}$

$\delta\Gamma^{\text{1-loop}}_{H\to hh}$

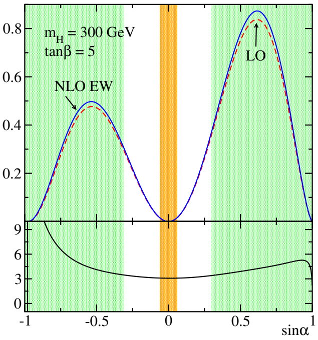
$\delta m^2_{hH}\vert^{\infty}$	$\{\text{nlgs}\} = 0$	$\{\text{nlgs}\} = 10$	$\delta m^2_{hH}\vert^{\text{fin}}$	$\{\text{nlgs}\} = 0$	$\{\text{nlgs}\} = 10$
OS	-5.80×10^2	-9.44×10^2	OS	$+5.75 \times 10^3$	$+8.80 \times 10^3$
Mixed $\overline{\text{MS}}$/OS	-5.80×10^2	-5.80×10^2	Mixed $\overline{\text{MS}}$/OS	-2.48×10^2	-2.48×10^2
Improved OS	-5.80×10^2	-5.80×10^2	Improved OS	$+5.72 \times 10^3$	$+5.72 \times 10^3$

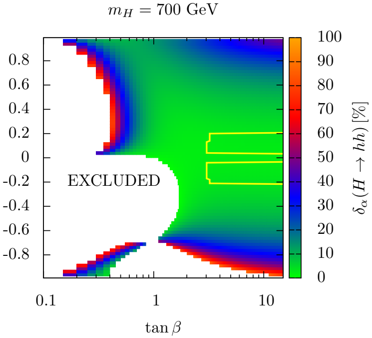
δm^2_{hH}

Δ : UV-divergence; $\{\text{ngls}\}$: non-linear gauge fixing parameters

Renormalization: numerical results, $m_h = 125\,\mathrm{GeV}$

all results here for $\Gamma_{H \to h\,h}$





exlusions (left): m_W, vacuum stability ;

white space (right): corrections $> 100\,\%$

Results for benchmarks (BR max)

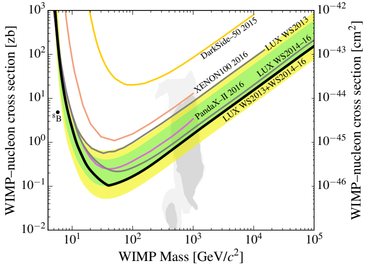
high mass region					low mass region				
	m_H[GeV]	$\vert \sin\alpha \vert$	$BR^{H\to h\,h}$	$\tan\beta$		m_h[GeV]	$\vert \sin\alpha \vert$	$BR^{H\to h\,h}$	$\tan\beta$
BHM1	300	0.31	0.34	3.71	BLM1	60	0.9997	0.26	0.29
BHM2	400	0.27	0.32	1.72	BLM2	50	0.9998	0.26	0.31
BHM3	500	0.24	0.27	2.17	BLM3	40	0.9998	0.26	0.32
BHM4	600	0.23	0.25	2.70	BLM4	30	0.9998	0.26	0.32
BHM5	700	0.21	0.24	3.23	BLM5	20	0.9998	0.26	0.31
BHM6	800	0.21	0.23	4.00	BLM6	10	0.9998	0.26	0.30

	$\Gamma^{LO}_{H\to hh}$	$\Gamma^{NLO}_{H\to hh}$	δ_α [%]	δ_{G_F} [%]	Γ_H		$\Gamma^{LO}_{H\to hh}$	$\Gamma^{NLO}_{H\to hh}$	δ_α [%]	δ_{G_F} [%]	Γ_H
BHM1	0.399	0.413	3.411	3.291	1.210	BLM1	1.426	1.536	7.765	7.763	5.506
BHM2	0.963	1.026	6.485	6.272	3.092	BLM2	1.439	1.472	2.305	2.304	5.520
BHM3	1.383	1.463	5.803	5.604	5.299	BLM3	1.423	1.432	0.586	0.586	5.504
BHM4	2.067	2.161	4.520	4.361	8.574	BLM4	1.419	1.415	-0.272	-0.272	5.500
BHM5	2.637	2.717	3.027	2.918	11.413	BLM5	1.431	1.425	-0.445	-0.445	5.512
BHM6	3.798	3.867	1.826	1.759	17.204	BLM6	1.427	1.421	-0.438	-0.438	5.508

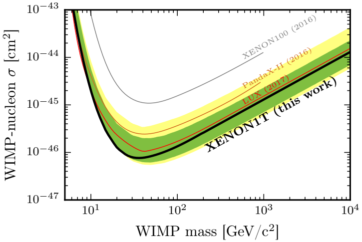
$\Longrightarrow$ **"typical" corrections between .2 and 20 %** $\Longleftarrow$

Newest results for indirect detection [1705.06655]

- newest results: **XENON1T**



[1608.07648]



[1705.06655]

Very brief: parameters determining couplings (production and decay)

dominant production modes: through Z; Z, γ, h for AH; H^+H^-

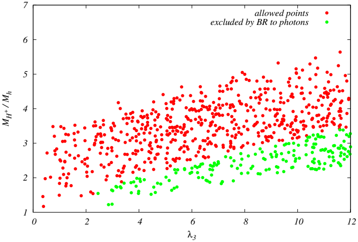
important couplings:

- $Z\,H\,A$: $\sim\ \frac{e}{s_W\, c_w}$
- $Z\,H^+\,H^-$: $\sim\ e\,\coth\,(2\,\theta_w)$
- $\gamma\,H^+\,H^-$: $\sim\ e$
- $h\,H^+\,H^-$: $\lambda_3\,v$
- $H^+\,W^+\,H$: $\sim\ \frac{e}{s_w}$
- $H^+\,W^+\,A$: $\sim\ \frac{e}{s_w}$

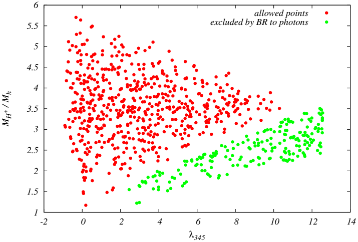
!! mainly determined by electroweak SM parameters !!

More direct constraints on couplings

- constraints on **combination of $M_H^{\pm}/M_h$ and λ_3** from one-loop corrected rate of $h \to \gamma\gamma$ (constraints: ratio too low !!)



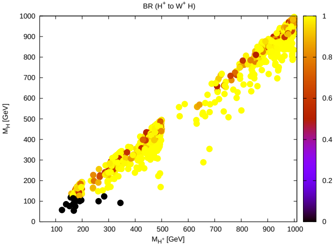
limits on λ_3, $M_H^{\pm}/M_h$, plane



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

Aside: typical BRs

- decay $A \rightarrow H\,Z$ always 100 %
- decay $H^{\pm} \rightarrow H\,W^{\pm}$



second channel $H^{\pm} \rightarrow A\,W^{\pm}$

$\Longrightarrow$ collider signature: SM particles and MET $\Longleftarrow$

Total widths in IDM scenario

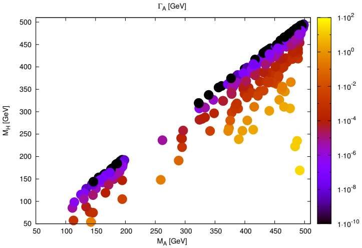
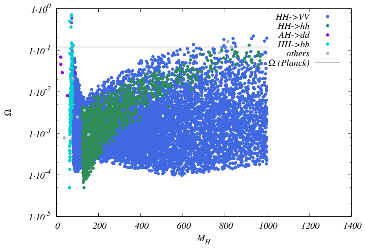
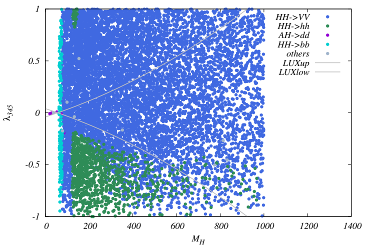


Figure : Total widths of unstable dark particles: A and $H^{\pm}$ in plane of their and dark matter masses.

Dark matter relic density



all but DM constraints



all but DM constraints

Combination of ew gauge boson total widths and LEP recast

- decays widths W, Z: **kinematic regions**

$$M_{A,H} + M_H^{\pm} \geq m_W,\ M_A + M_H \geq m_Z,\ 2\,M_H^{\pm} \geq m_Z.$$

- **LEP recast** (Lundstrom 2008)

$$M_A \leq 100\,\mathrm{GeV},\ M_H \leq 80\,\mathrm{GeV}, \Delta M \geq 8\,\mathrm{GeV}$$

- **combination leads to**
  - $M_H \in [0; 41\,\mathrm{GeV}]$: $M_A \geq 100\,\mathrm{GeV}$,
  - $M_H \in [41; 45\mathrm{GeV}]$: $M_A \in [m_Z - M_H; M_H + 8\,\mathrm{GeV}]$ or $M_A \geq 100\,\mathrm{GeV}$
  - $M_H \in [45; 80\mathrm{GeV}]$: $M_A \in [M_H; M_H + 8\,\mathrm{GeV}]$ or $M_A \geq 100\,\mathrm{GeV}$

Last topic: multicomponent dark matter

If $\Omega < \Omega_{\text{DM}}^{\text{Planck}}$: what does it mean ?

$\Rightarrow$ one possible understanding:

Multi-component dark matter

- **in practise: direct detection limits relaxed**, according to

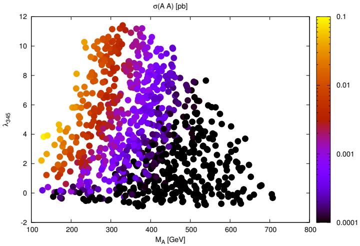
$$\sigma\left(M_H\right) \leq \sigma^{\text{LUX}}(M_H) \times \frac{\Omega^{\text{Planck}}}{\Omega(M_H)}$$

$\Rightarrow$ **in practise**: larger parameter space for λ_{345}

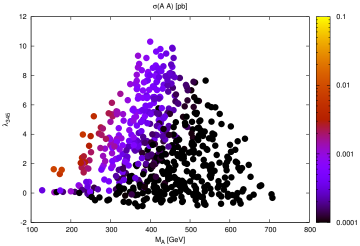
$\Rightarrow$ **influences especially AA production**

AA production with rescaled dark matter

before: $\sigma_{AA}^{13\,\mathrm{TeV}} \leq 0.0015\,\mathrm{pb}$



[old]



[new]

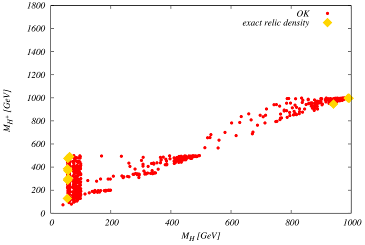
strongest constraint now : $\mathrm{BR}_{h\to\gamma\gamma}$

… and what if I want exact DM relic density ??

[preliminary results]

E.g. **this means**

- $m_{H^\pm} \in [100\,\mathrm{GeV}; 620\,\mathrm{GeV}]$ or $> 840\,\mathrm{GeV}$
- $m_H \notin [75\,\mathrm{GeV}; 120\,\mathrm{GeV}]$ or $\sim 54\,\mathrm{GeV}$
- …



sample plot, M_H vs. $M_{H\pm}$

Last comment: IDM tools for LHC phenomenology

- leading order production and decay: Madgraph5, + (currently) private version for ggh (top loop in $m_{\text{top}} \to \infty$ limit)
- in principle available: gg @ NLO, MG5 (needs however modification of current codes, not straightforward)
- IMHO: **currently LO sufficient**

Last comments: publications where scan has been used

- **Production of Inert Scalars at the high energy e^+e^- colliders**, M. Hashemi ea, **JHEP 1602 (2016) 187**
  use Yellow Report benchmarks
- **Exploring the Inert Doublet Model through the dijet plus missing transverse energy channel at the LHC**, P. Poulose ea, **Phys.Lett. B765 (2017) 300-306**
  use benchmarks with $m_H = 65\,\mathrm{GeV}$
- **Yellow Report IV of the Higgs Cross Section Working Group, arXiv:1610.07922**
- S. Moretti ea, *to appear*

Benchmarks submitted to Higgs Cross Section Working Group

all benchmarks: $A \to Z\,H = 100\,\%$

- **Benchmark I: low scalar mass**

$$M_H = 57.5\,\mathrm{GeV},\; M_A = 113.0\,\mathrm{GeV}, M_{H^\pm} = 123\,\mathrm{GeV}$$
$$\Gamma_H = 4.8\,\mathrm{MeV},\; \Gamma_A = 1.5\times 10^{-1}\,\mathrm{MeV},\; \Gamma_{H^\pm} = 1.0\,\mathrm{MeV}$$

$HA : 0.371(4)\mathrm{pb},\; H^+H^- : 0.097(1)\mathrm{pb}$

- **Benchmark II: low scalar mass**

$$M_H = 85.5\,\mathrm{GeV},\; M_A = 111.0\,\mathrm{GeV}, M_{H^\pm} = 140,\; \mathrm{GeV}$$
$$\Gamma_H = 4.4\,\mathrm{MeV},\; \Gamma_A = 1.5\times 10^{-1}\,\mathrm{MeV},\; \Gamma_{H^\pm} = 4.6\times 10^{-1}\,\mathrm{M}$$

$HA : 0.226(2)\mathrm{pb}, H^+H^- : 0.0605(9)\mathrm{pb}$

- **Benchmark III: intermediate scalar mass**

$$M_H = 128.0\,\mathrm{GeV},\; M_A = 134.0\,\mathrm{GeV}, M_{H^\pm} = 176.0,\; \mathrm{GeV}$$
$$\Gamma_H = 4.4\,\mathrm{MeV},\; \Gamma_A = 3.9\times 10^{-6}\,\mathrm{MeV},\; \Gamma_{H^\pm} = 4.1\times 10^{-1}\,\mathrm{M}$$

Benchmark: high masses

- **Benchmark IV: high scalar mass, mass degeneracy**

$$M_H = 363.0\,\mathrm{GeV}, M_A = 374.0\,\mathrm{GeV}, M_{H^\pm} = 374.0\,\mathrm{GeV}$$
$$\Gamma_H = 4.4\,\mathrm{MeV},\ \Gamma_A = 8.4 \times 10^{-5}\,\mathrm{MeV},\ \Gamma_{H^\pm} = 2.0 \times 10^{-4}\,\mathrm{M}$$

$$H, A : 0.00122(1)\mathrm{pb},\ H^+H^- : 0.00124(1)\mathrm{pb}$$

- **Benchmark V: high scalar mass, no mass degeneracy**

$$M_H = 311.0\,\mathrm{GeV}, M_A = 415.0\,\mathrm{GeV}, M_{H^\pm} = 447.0\,\mathrm{GeV}$$
$$\Gamma_H = 4.4\,\mathrm{MeV},\ \Gamma_A = 220\,\mathrm{MeV},\ \Gamma_{H^\pm} = 2.1\,\mathrm{GeV}$$

$$H, A : 0.00129(1)\mathrm{pb},\ H^+H^- : 0.000553(7)\mathrm{pb}$$

Things I did not talk about

- **similar scan**, with focus on low mass regime: A. Belyaev ea [arXiv:1612.00511]

$\Rightarrow$ **results agree**, but more explicit plots for low mass range

$\Rightarrow$ **more parameter points in the low-m_H region**

$\Rightarrow$ find **same lowest mass for dark matter candidate**

- also important: **recasts for LHC**, e.g. Belanger ea [Phys.Rev. D91 (2015) no.11, 115011]; A. Belyaev ea [arXiv:1612.00511]

$\Longrightarrow$ **should/ could be turned around to devise optimized search strategies** $\Longleftarrow$

so far, $\Longrightarrow$ **no (!) experimental study is publicly available interpreting in the IDM framework !!** $\Longleftarrow$