Constraining Extended Higgs Sectors at the LHC and beyond

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based on work with
A. Ilnicka, M. Krawczyk (Phys.Rev. D93 (2016) no.5, 055026)

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Physics Seminar

04/19/2017
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 !!
1 Introduction and Motivation

2 Singlet
   - Parameter space including bounds
   - $m_W$ at NLO
   - LHC
   - Renormalization
   - Summary

3 Inert Doublet Model
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

\[ m_H \sim 125 \text{ GeV} \]
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

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

⇒ Tasks at LHC ⇐

⇒ (re)discovery of the Standard Model of particle physics, especially Higgs
⇒ precision measurements of SM particles
⇒ discovery/ limit setting on BSM physics

⇒ Tasks for theorists ⇐

⇒ accurate predictions for SM processes
⇒ 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)

⇒ potential ($H$ doublet, $\chi$ real singlet)

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

- 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

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

- potential: 5 free parameters: 3 couplings, 2 VeVs
  \[ \lambda_1, \lambda_2, \lambda_3, v, x \]

- rewrite as
  \[ m_h, m_H, \sin \alpha, v, \tan \beta \]

- fixed, free
  \[ \sin \alpha: \text{mixing angle}, \tan \beta = \frac{v}{x} \]

- physical states \((m_h < m_H)\):
  \[ \begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix}, \]
Question 1: Modifcation 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:
  \[ \sigma_{\text{prod}} = \sin^2 \alpha \times \sigma_{\text{prod,SM}}, \text{BR}_{H \to ...} = \sin^2 \alpha \frac{\Gamma_{\text{tot,SM}}}{\Gamma_{\text{tot}}} \times \text{BR}_{H \to ...} \]

\[ \Rightarrow \text{ sufficient for tree level rescaling} \]
Bounds

G.M. Pruna, TR, PRD 88 (2013) 115012;
D. Lopez-Val, TR, PRD 90 (2014) 114018;
Theoretical and experimental constraints on the model

our studies: \( m_{h,H} = 125.09 \, \text{GeV} \), \( 0 \, \text{GeV} \leq m_{H,h} \leq 1 \, \text{TeV} \)

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

\(^*\): only for \( m_h = 125.09 \, \text{GeV} \)
**Results**

- **strongest constraints:**
  
  \[ m_H \gtrsim 800 \text{ GeV} : \text{perturbativity of couplings} \]
  \[ m_H \in [270; 800] \text{ GeV} : m_W \ @ \ NLO \]
  \[ m_H \in [175; 270] \text{ GeV} : \text{experimental searches} \]
  \[ m_H \in [120; 175] \text{ GeV} : \text{signal strength} \]
  \[ m_h \lesssim 120 \text{ GeV} : \text{SM-like Higgs coupling rates (+ LEP)} \]

⇒ \( \kappa \leq 0.25 \) for all masses considered here

\[ \Gamma_{\text{tot}} \lesssim 0.02 \, m_H \]

⇒ 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; ...]

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Higgs extended
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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 diagonalized system $\leq 0.5$
- "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:** \( 4\lambda_1\lambda_2 - \lambda_3^2 > 0 \)

\[ \Rightarrow \text{need (2), can debate about (1), (3) at all scales} \]
$m_W$ at NLO

**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 $\Rightarrow$ not relevant here)

$\Rightarrow$ **first step on the road to full renormalization** $\Leftarrow$
**NLO corrections to \( m_W \)**

**Contribution to \( m_W \) for different Higgs masses**

\[
\Delta m_W \quad [\text{MeV}] \quad \text{SM} \quad \text{Exp.}
\]

\[
m_h = 125.7 \text{ GeV}
\]

\[
m_H = 125.7 \text{ GeV}
\]

\[
\implies \text{low } m_h \text{ bring } m_W^{\text{NLO}} \text{ close to } m_W^{\text{exp}}
\]

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LHC

TR, T. Stefaniak,
EPJC75 (2015)3, 104; EPJC76 (2016)5, 268
Combined limits on $|\sin \alpha|$ 


$W$ boson mass
EW observables (S,T,U)
$\lambda_1$ perturbativity ($\tan \beta = 0.1$)
perturbative unitarity ($\tan \beta = 0.1$)
LHC SM Higgs searches
Higgs signal rates

several bounds on $|\sin \alpha|$ 

$m_W$, perturbativity, LHC direct searches, Higgs Signal strength

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One more word about $H \rightarrow hh$

- **viable alternative:** search for
  
  $$H \rightarrow hh \rightarrow \ldots$$

- in our case: $\text{BR}(H \rightarrow hh) \lesssim 0.4$

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

- **$WW$ always dominant**
Introduction and Motivation

Singlet Inert Doublet Model Appendix

LHC

Results from generic scans and predictions for LHC 14

1 $\sigma$, 2 $\sigma$, allowed

SM like decays

limits

pred.

BSM decay to $hh$

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What about the “inverse” scenario, ie. $m_H = 125.1 \text{ GeV}$

mainly ruled out by LEP and/or $\chi^2$ fit from HiggsSignals

however, still large number produced due to large $\sigma_{gg \to h}$

| $m_h[\text{GeV}]$ | $|\sin \alpha|_{\text{min, exp}}$ | $|\sin \alpha|_{\text{min, } 2\sigma}$ | $(\tan \beta)_{\text{max}}$ | $\# gg \sim$ |
|-------------------|-----------------|-----------------|-----------------|----------------|
| 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 $m_h \gtrsim 60 \text{ GeV}$, $\tan \beta$ irrelevant for collider observables)

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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

\[ T_{h,H}; \nu; \chi; m_{h,H}^2; Z_{h,H,hH,Hh}; m_{hH}^2 \]

⇒ in total: **11 parameters in scalar sector**
⇒ need to be determined by **suitable renormalization conditions**
Full renormalization (2)

=⇒ Our choices ⇐=

- Tadpoles: $\delta T = -T$ [$\hat{T} = 0$]
- $\nu$: as in SM, on-shell (i.e. 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 $m_{hH}^2, \delta Z_{hH}$ !!
- 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, Pappavassiliou 1989; Espinosa, Yamada, 2002; Binosi, Papavassiliou 2009;...)

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Renormalization

Renormalization: numerical results

\begin{align*}
\Gamma(H \rightarrow hh) \text{ [GeV]} &\quad 400 \quad 600 \quad 800 \\
m_H \text{ [GeV]} &\quad 0 \quad 2 \quad 4 \quad 6
\end{align*}

\begin{align*}
\delta_\alpha \% &\quad 2 \quad 4 \quad 6 \\
tan\beta &\quad 5
\end{align*}

\begin{align*}
\sin\alpha &\quad 0.2 \\
tan\beta &\quad 5
\end{align*}

\begin{align*}
m_h &\quad 125 \text{ GeV}
\end{align*}

\begin{align*}
\sin\alpha &\quad 0.998 \\
tan\beta &\quad 5 \\
m_H &\quad 125.09 \text{ GeV}
\end{align*}

"typical" size of corrections

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Renormalization: numerical results, $m_h = 125$ GeV

**all results here for $\Gamma_{H \rightarrow hh}$**

exclusions (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 ($m_H \in [200 \text{ GeV}; 800 \text{ GeV}]$), *experimental searches and fits* ($m_{H,h} \leq 200 \text{ GeV}$) and/or *running couplings* ($m_H \geq 800 \text{ GeV}$)
- *Quite narrow widths wrt SM-like Higgses* in this mass range ⇒ *better theoretical handle*
- *Quite large suppression* from current experimental/theoretical constraints

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

⇒ STAY TUNED ⇐
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 \( \sim 125 \text{ GeV} \)
  - 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,...)

- \( h, H \) CP-even, neutral
- \( A \) CP-odd, neutral
- \( H^\pm \) 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

\[
\phi_D \to -\phi_D, \phi_S \to \phi_S, \text{SM} \to \text{SM}
\]

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

⇒ minimize potential

⇒ determine number of free parameters

**Number of free parameters here:** 7

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

- $v, M_h$ fixed ⇒ 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
  \[ \Rightarrow \text{limits on (relations of) couplings} \]
- perturbative unitarity, perturbativity of couplings
- choosing \( M_H \) as dark matter:
  \[ M_H \leq M_A, \; M_{H^\pm} \]
Constraints: Experiment

\[ M_h = 125.1 \text{ GeV}, \, \nu = 246 \text{ GeV} \]

- 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 \((*)\) (LUX)

\[ \Rightarrow \text{ tools used: } 2\text{HDMC, HiggsBounds, HiggsSignals, MicrOmegas} \]

\((*)\) updates not yet included

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Obvious/ direct constraints on couplings

- some constraints ⇒ direct limits on couplings
- examples: limit on $\lambda_2$ from $HHHH$ coupling, limit on $\lambda_{345}(M_H)$ from direct detection

\[
\begin{align*}
\lambda_2, \lambda_{345} \text{ plane and limits from perturbativity, positivity}
\end{align*}
\]

\[
\begin{align*}
M_H, \lambda_{345} \text{ plane, limits from LUX}
\end{align*}
\]
Other constraints less obvious (interplay); result $\Rightarrow$ mass degeneracies

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

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

[preliminary results]

E.g. this means

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

sample plot, $M_H$ vs. $M_{H^\pm}$
Benchmark selection for current LHC run

⇒ points need to have passed all bounds
⇒ total cross sections calculated using Madgraph5, IDM model file from Goudelis ea, 2013 (LO)
⇒ effective ggH vertex implemented by hand
  • highest production cross sections: $HA; H^\pm H; H^\pm A; H^+ H^-$
  • decay $A \to HZ$ always 100 %
  • decay $H^\pm \to HW^\pm$ usually dominant

\[
pp \to HA : \leq 0.03 \text{ pb}, \\
pp \to H^\pm H : \leq 0.03 \text{ pb}, \\
pp \to H^\pm A : \leq 0.015 \text{ pb}, \\
pp \to H^+ H^- : \leq 0.01 \text{ pb}.
\]
Benchmark planes

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

- side remark: all couplings involving gauge bosons determined by electroweak SM parameters

- LHC@13 TeV does not depend on $\lambda_2$, only marginally on $\lambda_{345}$

- all relevant couplings follow from ew parameters (+ derivative couplings) ⇒ in the end a kinematic test

- only in exceptional cases $\lambda_{345}$ important; did not find such points

⇒ high complementarity between astroparticle physics and collider searches

(holds for $M_H \geq \frac{M_{h/2}}{2}$)
Last comment: 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
  ⇒ extremely strong constraints from signal strength, and dark matter requirements

- additional constraints from combination of $W, Z$ decays and recasted analysis at LEP
  no allowed point with $M_H < 45$ GeV
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

- **Exploring the Inert Doublet Model through the dijet plus missing transverse energy channel at the LHC**, P. Poulouse ea, *arXiv:1604.03045*

- **Yellow Report IV of the Higgs Cross Section Working Group**, *to appear*

- S. Moretti ea, *to appear*
Summary

- **LHC run II just started** ⇒ **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: 2 models: **2HDM with dark matter (IDM)**
- **identified viable regions in parameter space**
- from these: **predictions for current LHC run**
  
  [A. Ilnicka, M. Krawzyk, TR, ”**IDM benchmarks for the 13 TeV run of the LHC**”, for CERN Yellow Report]

!! stay tuned, and thanks for listening !!
Appendix
... and discovery

[ATLAS collaboration, 2 e 2 \mu Higgs candidate]

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**

**ATLAS Prelim.**

\[ m_H = 125.36 \text{ GeV} \]

**Signal strength (µ)**

<table>
<thead>
<tr>
<th>Process</th>
<th>( \mu )</th>
<th>Total uncertainty</th>
<th>±1σ on µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow γγ )</td>
<td>1.17 ± 0.27</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* \rightarrow 4l )</td>
<td>1.44 ± 0.30</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow WW^* \rightarrow ℓνℓν )</td>
<td>1.08 ± 0.20</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>( W,Z H \rightarrow b\bar{b} )</td>
<td>0.5 ± 0.4</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow ℓ\bar{ℓ} )</td>
<td>1.4 ± 0.3</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

\( \sigma_{(stat.)} \)

**95% CL limit on \( \sigma/\sigma_{SM} \)**

![Graph showing 95% CL limit on \( \sigma/\sigma_{SM} \) vs. \( m_H \) in GeV](image)

(CMS-PAS-HIG-13-002)

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

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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:** $\mu_{SM,\text{break}} \sim 2.5 \times 10^{10}$ GeV  
  (remark: just simple NLO running)
- **we took:** $\mu_R \sim 4.0 \times 10^{10}$ GeV  
  (higher scales $\iff$ stronger constraints)

- **obvious:** for $m_H \sim 125$ GeV, breakdown “immediate”
  when going to $\mu_{\text{run}} > \nu$
  $\Rightarrow$ 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 $\sigma$ around central values
- main impact: on vacuum stability, ie $\lambda_1 > 0$ condition
- no significant change in $\kappa_{\text{max}}(m_H)$, ...

⇒ not relevant for collider studies (at this stage...)
Interim comment on total width

- Total width greatly reduced

- width over mass
- suppression factor of width
we tested: maximal $m_H$ from PU

$\Rightarrow$ strongest constraints from $H H \rightarrow H H \leftrightharpoons$

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

Maximally allowed heavy Higgs masses from perturbative unitarity

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

$\Rightarrow$ for realistic $\sin \alpha$ and our $m_H$ range, $\tan \beta \lesssim 8$
Comments on constraints (1) - Perturbativity issues

However...

- For the scenario $m_H = 125.7 \text{ GeV}$, $m_h \leq m_H$:
  - $\Rightarrow$ strongest theory limit on $\tan \beta_{\text{max}}$ 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 only relevant for an open $H \rightarrow hh$ channel!!

Tania Robens  Higgs extended  Wichita State, 04/19/17
Could we have seen them ??

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

<table>
<thead>
<tr>
<th>( m_H ) [GeV]</th>
<th>( \kappa_{\text{max}} )</th>
<th>#gg ( \sim )</th>
<th>( \kappa'_{\text{max}} )</th>
<th>#gg ( \sim )</th>
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<tbody>
<tr>
<td>200</td>
<td>0.19</td>
<td>( 3 \times 10^4 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>300</td>
<td>0.076</td>
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<tr>
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<td>510</td>
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<tr>
<td>700</td>
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<td>180</td>
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<td>50</td>
</tr>
<tr>
<td>800</td>
<td>0.035</td>
<td>90</td>
<td>0.010</td>
<td>25</td>
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</tr>
<tr>
<td>1000</td>
<td>0.023</td>
<td>17</td>
<td>0.006</td>
<td>4</td>
</tr>
</tbody>
</table>

[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 !!

Tania Robens

Higgs extended

Wichita State, 04/19/17
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

\[ \mathcal{L}_{\text{xSM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{fermions}} + \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{ghost}} \]

\[ \mathcal{L}_{\text{scalar}} = (D^\mu \Phi)^\dagger D_\mu \Phi + \partial^\mu S \partial_\mu S - \mathcal{V}(\Phi, S) \]
\[ \mathcal{V}(\Phi, S) = \mu^2 \Phi^\dagger \Phi + \lambda_1 |\Phi^\dagger \Phi|^2 + \mu_s^2 S^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2. \]

- \( \mathcal{L}_{\text{gauge}}, \mathcal{L}_{\text{fermions}}, \mathcal{L}_{\text{Yukawa}} \) as in SM
- BRST invariance \( \Rightarrow \delta_{\text{BRST}} \mathcal{L}_{\text{GF}} = -\delta_{\text{BRST}} \mathcal{L}_{\text{ghost}} \)
- 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]

\[
\mathcal{L}_{GF} = -\frac{1}{\xi_W} F^+ F^- - \frac{1}{2\xi_Z} |F^Z|^2 - \frac{1}{2\xi_A} |F^A|^2
\]

\[
F^\pm = \left( \partial_\mu \mp ie\tilde{\alpha}_A \mp ig \cos\theta_W \tilde{\beta} Z_\mu \right) W^\mu +
\]

\[
\pm i\xi_W g \left( \nu + \delta_1 h + \delta_2 H \pm i\kappa G^0 \right) G^+ 
\]

\[
F^Z = \partial_\mu Z^\mu + \xi_Z g \frac{2}{2\cos\theta_W} \left( \nu + \tilde{\epsilon}_1 h + \tilde{\epsilon}_2 H \right) G^0
\]

\[
F^A = \partial_\mu A^\mu .
\]

- \(\tilde{\alpha}, \tilde{\beta}, \ldots: \text{non-linear gauge-fixing parameters}\)
- \(\tilde{\alpha} = \tilde{\beta} = \ldots = 0, \xi = 1 \Rightarrow \text{back to t’Hooft-Feynman gauge}\)
Renormalization: SM inheritance

- \( S \): singlet under SM gauge group

- in the electroweak gauge sector: follow SM prescriptions

- parameter count in the scalar sector: 11 counterterms

- renormalize

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

- need to be determined by suitable renormalization conditions

* performed in 2 different electroweak schemes:

\( \alpha_{em} : \alpha_{em}(0), \, m_W, \, m_Z \) as input;

\( G_F : \alpha_{em}(0), \, G_F, \, m_Z \) as input, related via \( \Delta r \)
... and in more detail...

\[
\begin{align*}
\nu_i^0 & \rightarrow \nu_i + \delta \nu_i, \\
T_i^0 & \rightarrow T_i + \delta T_i, \\
M_\phi^2 & \rightarrow M_\phi^2 + \delta M_\phi^2
\end{align*}
\]

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

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

**NO mixing angle renormalization**
Different choices for mixed terms $\delta Z_{Hh,hH}$, $\delta m^2_{hH}$

Always: $\text{Re} \hat{\Sigma}_{hH}(m^2_h) = 0$; $\text{Re} \hat{\Sigma}_{hH}(m^2_H) = 0$

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

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

- **Mixed $\overline{\text{MS}}$/on-shell**: fix $\delta m^2_{hH}$ through UV-divergence of $\lambda_2$

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

- **improved onshell**

  $\delta m^2_{hH} = \text{Re} \Sigma_{hH}(p^2) \big|_{\xi_W=\xi_Z=1, \tilde{\delta}_i=0, \ p^2_* = \frac{m^2_h + m^2_H}{2}}$

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

  $\Rightarrow$ **drawback**: NONE !!
### NLO corrections to $H \rightarrow hh$ decay, gauge-parameter dependence

<table>
<thead>
<tr>
<th>Scheme</th>
<th>$\Delta = 0, {\text{nlgs}} = 0$</th>
<th>$\Delta = 10^7, {\text{nlgs}} = 0$</th>
<th>$\Delta = 10^7, {\text{nlgs}} = 10$</th>
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<tbody>
<tr>
<td>OS</td>
<td>$+4.26334888 \times 10^{-3}$</td>
<td>$+4.26334886 \times 10^{-3}$</td>
<td>$-5.27015844 \times 10^{3}$</td>
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<tr>
<td>Mixed $\overline{\text{MS}}$/OS</td>
<td>$+6.8467506 \times 10^{-3}$</td>
<td>$+6.8467504 \times 10^{-3}$</td>
<td>$+6.8467500 \times 10^{-3}$</td>
</tr>
<tr>
<td>Improved OS</td>
<td>$+3.9393569 \times 10^{-3}$</td>
<td>$+3.9393568 \times 10^{-3}$</td>
<td>$+3.9393556 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Δ : UV-divergence; \{ngls\} : non-linear gauge fixing parameters
Renormalization: numerical results, $m_h = 125$ GeV

**all results here for $\Gamma_{H \rightarrow hh}$**

Exclusions (left): $m_W$, vacuum stability; white space (right): corrections $> 100\%$
## Results for benchmarks (BR max)

<table>
<thead>
<tr>
<th>high mass region</th>
<th>low mass region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>$m_H$ [GeV]</td>
<td>$m_H$ [GeV]</td>
</tr>
<tr>
<td>$</td>
<td>\sin \alpha</td>
</tr>
<tr>
<td>$BR^{H \rightarrow hh}$</td>
<td>$BR^{H \rightarrow hh}$</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>$\tan \beta$</td>
</tr>
</tbody>
</table>

<p>| | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>BHM1</td>
<td>300</td>
<td>0.31</td>
<td>0.34</td>
<td>3.71</td>
<td>BLM1</td>
<td>60</td>
<td>0.9997</td>
<td>0.26</td>
<td>0.29</td>
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<tr>
<td>BHM2</td>
<td>400</td>
<td>0.27</td>
<td>0.32</td>
<td>1.72</td>
<td>BLM2</td>
<td>50</td>
<td>0.9998</td>
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<td>0.31</td>
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<tr>
<td>BHM3</td>
<td>500</td>
<td>0.24</td>
<td>0.27</td>
<td>2.17</td>
<td>BLM3</td>
<td>40</td>
<td>0.9998</td>
<td>0.26</td>
<td>0.32</td>
<td></td>
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<tr>
<td>BHM4</td>
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<td>0.25</td>
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<td>BHM5</td>
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<td>0.21</td>
<td>0.24</td>
<td>3.23</td>
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<tr>
<td>BHM6</td>
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<td>0.21</td>
<td>0.23</td>
<td>4.00</td>
<td>BLM6</td>
<td>10</td>
<td>0.9998</td>
<td>0.26</td>
<td>0.30</td>
<td></td>
</tr>
</tbody>
</table>

$$\Gamma_{LO}^{H \rightarrow hh} \, \Gamma_{NLO}^{H \rightarrow hh} \, \delta_{\alpha} \, \% \, \delta_{GF} \, \% \, \Gamma_H$$

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>BHM1</td>
<td>0.399</td>
<td>0.413</td>
<td>3.411</td>
<td>3.291</td>
<td>1.210</td>
<td>BLM1</td>
</tr>
<tr>
<td>BHM2</td>
<td>0.963</td>
<td>1.026</td>
<td>6.485</td>
<td>6.272</td>
<td>3.092</td>
<td>BLM2</td>
</tr>
<tr>
<td>BHM3</td>
<td>1.383</td>
<td>1.463</td>
<td>5.803</td>
<td>5.604</td>
<td>5.299</td>
<td>BLM3</td>
</tr>
<tr>
<td>BHM4</td>
<td>2.067</td>
<td>2.161</td>
<td>4.520</td>
<td>4.361</td>
<td>8.574</td>
<td>BLM4</td>
</tr>
<tr>
<td>BHM5</td>
<td>2.637</td>
<td>2.717</td>
<td>3.027</td>
<td>2.918</td>
<td>11.413</td>
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<td>3.798</td>
<td>3.867</td>
<td>1.826</td>
<td>1.759</td>
<td>17.204</td>
<td>BLM6</td>
</tr>
</tbody>
</table>

$$\rightarrow \, "\text{typical}" \, \text{corrections between .2 and 20 \%} \, \leftarrow$$

Tania Robens
Higgs extended
Kansas State, 04/19/17
Very brief: parameters determining couplings (production and decay)

dominant production modes: through $Z$; $Z$, $\gamma$, $h$ 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** $\lambda_3$ from one-loop corrected rate of $h \rightarrow \gamma\gamma$ (constraints: ratio too low !!)

Limits on $\lambda_3$, $M_{H^\pm}/M_h$, plane

... translated to $\lambda_{345}$, $M_{H^\pm}/M_h$
Aside: typical BRs

- decay $A \rightarrow HZ$ always 100 %
- decay $H^\pm \rightarrow HW^\pm$

second channel $H^\pm \rightarrow AW^\pm$

$\Rightarrow$ collider signature: SM particles and MET
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

- $1 \cdot 10^{-5}$
- $1 \cdot 10^{-4}$
- $1 \cdot 10^{-3}$
- $1 \cdot 10^{-2}$
- $1 \cdot 10^{-1}$
- $1 \cdot 10^0$

$\Omega$ (Planck)

all but DM constraints

Tania Robens

Higgs extended

Wichita State, 04/19/17
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)

$$M_{A} \leq 100 \text{ GeV}, \ M_{H} \leq 80 \text{ GeV}, \ \Delta M \geq 8 \text{ GeV}$$

- combination leads to
  - $M_H \in [0; 41 \text{ GeV}]: M_A \geq 100 \text{ GeV},$
  - $M_H \in [41; 45\text{GeV}]: M_A \in [m_Z - M_H; M_H + 8 \text{ GeV}]$ or $M_A \geq 100 \text{ GeV}$
  - $M_H \in [45; 80\text{GeV}]: M_A \in [M_H; M_H + 8 \text{ GeV}]$ or $M_A \geq 100 \text{ GeV}$
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
Benchmarks submitted to Higgs Cross Section Working Group

all benchmarks: $A \rightarrow ZH = 100\%$

- **Benchmark I: low scalar mass**
  
  $M_H = 57.5$ GeV, $M_A = 113.0$ GeV, $M_{H\pm} = 123$ GeV
  
  $\Gamma_H = 4.8$ MeV, $\Gamma_A = 1.5 \times 10^{-1}$ MeV, $\Gamma_{H\pm} = 1.0$ MeV
  
  $HA : 0.371(4) \text{pb}, H^+H^- : 0.097(1) \text{pb}$

- **Benchmark II: low scalar mass**
  
  $M_H = 85.5$ GeV, $M_A = 111.0$ GeV, $M_{H\pm} = 140$, GeV
  
  $\Gamma_H = 4.4$ MeV, $\Gamma_A = 1.5 \times 10^{-1}$ MeV, $\Gamma_{H\pm} = 4.6 \times 10^{-1}$ MeV
  
  $HA : 0.226(2) \text{pb}, H^+H^- : 0.0605(9) \text{pb}$

- **Benchmark III: intermediate scalar mass**
  
  $M_H = 128.0$ GeV, $M_A = 134.0$ GeV, $M_{H\pm} = 176.0$, GeV
  
  $\Gamma_H = 4.4$ MeV, $\Gamma_A = 3.9 \times 10^{-6}$ MeV, $\Gamma_{H\pm} = 4.1 \times 10^{-1}$ MeV
Benchmark: high masses

- **Benchmark IV: high scalar mass, mass degeneracy**
  
  \[ M_H = 363.0 \text{ GeV}, \quad M_A = 374.0 \text{ GeV}, \quad M_{H^\pm} = 374.0 \text{ GeV} \]
  
  \[ \Gamma_H = 4.4 \text{ MeV}, \quad \Gamma_A = 8.4 \times 10^{-5} \text{ MeV}, \quad \Gamma_{H^\pm} = 2.0 \times 10^{-4} \text{ MeV} \]
  
  \( H, A : 0.00122(1) \text{ pb}, \quad H^+ H^- : 0.00124(1) \text{ pb} \)

- **Benchmark V: high scalar mass, no mass degeneracy**
  
  \[ M_H = 311.0 \text{ GeV}, \quad M_A = 415.0 \text{ GeV}, \quad M_{H^\pm} = 447.0 \text{ GeV} \]
  
  \[ \Gamma_H = 4.4 \text{ MeV}, \quad \Gamma_A = 220 \text{ MeV}, \quad \Gamma_{H^\pm} = 2.1 \text{ GeV} \]
  
  \( H, A : 0.00129(1) \text{ pb}, \quad H^+ H^- : 0.000553(7) \text{ pb} \)