Introduction to HiggsBounds and HiggsSignals

+ tutorial on 2HDM studies

Tim Stefaniak

Deutsches Elektronen-Synchrotron DESY
Email: tim.stefaniak@desy.de

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

2HDM working group

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6. Interpret your result (95% C.L. allowed/excluded or χ^2).

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Run HiggsBounds and HiggsSignals.

6. Interpret your result (95% C.L. allowed/excluded or χ^2).

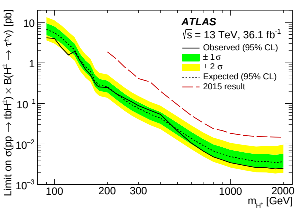
HiggsBounds AND HiggsSignals

Team: P. Bechtle, S. Heinemeyer, T. Klingl, TS, G. Weiglein, J. Wittbrodt

HiggsBounds

Confronts BSM Higgs sectors with exclusion limits from LEP, Tevatron and LHC Higgs searches.

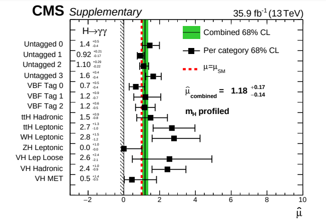
$\Rightarrow$ excluded/allowed at 95% C.L.



HiggsSignals

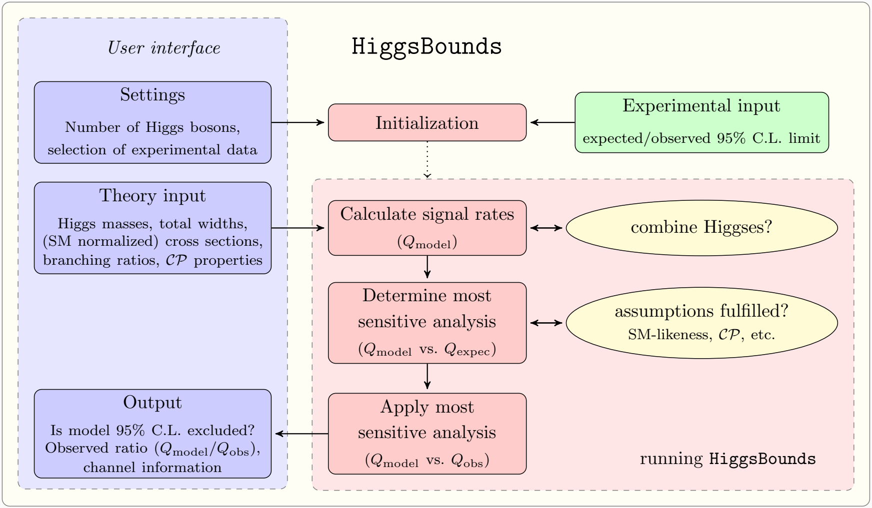
Confronts BSM Higgs sectors with LHC Higgs signal rate and mass measurements.

$\Rightarrow \chi^2$ (sep. for rates and mass)



Codes available at `GitLab` (*more later in tutorial*).

HiggsBounds: basic structure



Main input

M_i, Γ_i^{tot}, XS's and BR's for all neutral and charged Higgs bosons.

Theoretical input

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Per default assume factorization of XS and BR for signal rate calculation,

$$\sigma(P[h_i], D[h_i]) = \sigma(P[h_i]) \times \mathrm{BR}(D[h_i])$$

($P[h_i]$: production mode of h_i; $D[h_i]$: decay mode of h_i)

Channel rates $\sigma(P[h_i], D[h_i])$ can be set directly, if needed.

Example: CPV MSSM with destructive interference in $pp \to h_{2,3} \to \tau^+\tau^-$.

[Fuchs, Weiglein, 1705.05757]

HiggsBounds: Experimental input

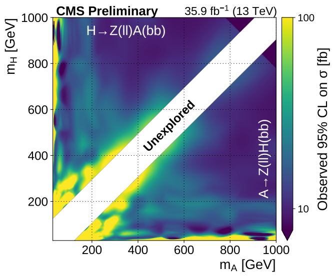
= "model-independent" 95% C.L. limits from LEP, Tevatron, LHC7/8/13.

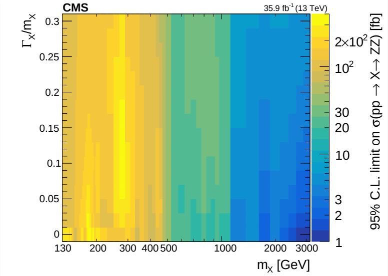
current version: more than 200 experimental limits are implemented.

"Combination" procedure:

Each Higgs boson h_i is *only* confronted with the observed limit of the experimental analysis that's *most sensitive* to it (judged by expected limit).

Some limits are two-dimensional, e.g. in (M_A, M_H) or $(M_h, \Gamma^{\text{tot}})$ plane:





⇒ Underlying data files are needed for a proper implementation.

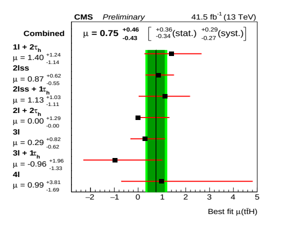
HiggsSignals: χ^2 calculation from Higgs signal rates

$$\chi^2_\mu = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})\, \mathsf{C}_{\boldsymbol{\mu}}{}^{-1}\, (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

$$\chi^2_\mu = (\hat{\mu} - \mu)\, C_\mu^{-1}\, (\hat{\mu} - \mu)$$

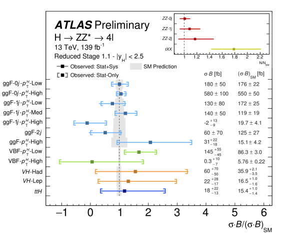
Measured signal strengths (in various forms):

(analysis assumes a SM-like Higgs signal)

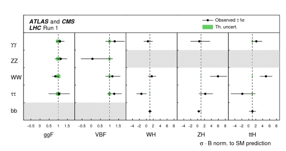


Signal strengths (μ) in exp. categories

(SM normalized rate)



STXS (absolute rate)



Signal strengths (μ) in pure channels

(SM normalized rate)

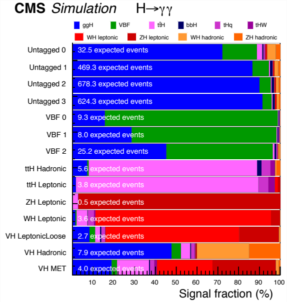
current version: 27 traditional μ obs. + 39 STXS obs. + 20 LHC-Run-1 obs.

HiggsSignals: χ^2 calculation from Higgs signal rates

$$\chi^2_\mu = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})\, \mathbf{C}_\mu^{\;-1}\, (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

Predicted signal strength:

$$\mu = \frac{\sum_i \epsilon_i \, [\sigma \times \mathrm{BR}]_i}{\sum_j \epsilon_{\mathrm{SM},j} \, [\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_j}$$



$\epsilon_{\mathrm{SM},i}$: signal efficiency of channel i in SM.

ϵ_i: signal efficiency of channel i in model.

default assumption: $\epsilon_i = \epsilon_{\mathrm{SM},i}$

$\epsilon_i \neq \epsilon_{\mathrm{SM},i}$ requires external MC simulation:

$\Rightarrow$ ϵ_i can then be set as additional input.

HiggsSignals: χ^2 calculation from Higgs signal rates

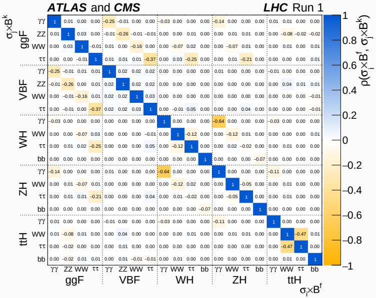
$$\chi^2_\mu = (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})\, \mathbf{C}_{\boldsymbol{\mu}}^{-1}\, (\hat{\boldsymbol{\mu}} - \boldsymbol{\mu})$$

Covariance matrix

correlation matrices sometimes given by ATLAS/CMS (for subset of observables).

$\Rightarrow$ included in HiggsSignals.

Otherwise: treat luminosity uncertainty, theoretical σ and BR uncertainties as fully correlated.



How to *not* interpret the χ^2

Always keep in mind (as a theorist):

All statistical interpretation of LHC results *we can do* is *approximate*!

Frequentist meaning of $p(\chi^2, ndf = n_{\rm obs})$: "Assuming model is realized in Nature, p is probability that the observed distribution is due to chance."

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Although we calculate χ^2, the true probability $p \neq p(\chi^2, ndf = n_{\rm obs})$:

- Observables are not purely Gaussian (syst. uncertainties, limited stats., etc.),
- f: model parameters $\mapsto$ observables is often highly non-linear,
- Many observables cannot be independently predicted by the model (i.e., effective number of statistical degrees of freedom is smaller than number of observables).

$\Rightarrow$ Do *not* (blindly) use probability $p(\chi^2, ndf = n_{\rm obs})$ for interpretation!

How to interpret the χ^2

Instead, perform a statistical *model comparison*:

Hypothesis

How much better/worse does *model A* describe the data than *model B*?

In the literature, this is a "log-likelihood ratio (LLR) test":

$$-2\ln\frac{\mathcal{L}(\vec{p}_\mathrm{A}|\vec{x})}{\mathcal{L}(\vec{p}_\mathrm{B}|\vec{x})} = -2(\ln\mathcal{L}(\vec{p}_\mathrm{A}|\vec{x}) - \ln\mathcal{L}(\vec{p}_\mathrm{B}|\vec{x})) \approx \chi^2(\vec{p}_\mathrm{A}|\vec{x})) - \chi^2(\vec{p}_\mathrm{B}|\vec{x})) \equiv \Delta\chi^2.$$

Typical choices for reference model B: SM, parameter point with minimal χ^2.

In the ratio, many of the "problems" (prev. slide) cancel out.

Determine of confidence intervals/regions by cutting on $\Delta\chi^2$:

C.L.	1D	2D
68% (1σ)	1	2.3
95%	3.84	5.99
95.45% (2σ)	4	6.18

Note: C.L. values again rely on the Gaussian approximation!

Complications with extended Higgs sectors

If $N > 1$ neutral Higgs bosons in model $\Rightarrow$ identify the Higgs candidate(s)!

- Higgs boson h_i is *assigned* to the observable α, if its mass is close enough to observed signal position:

$$|m_i - \hat{m}_\alpha| \leq \Lambda\sqrt{(\Delta m_i)^2 + (\Delta \hat{m}_\alpha)^2} \quad \Rightarrow \quad \text{Higgs } h_i \text{ assigned.}$$

Λ: "assignment range" (tuning parameter $\sim \mathcal{O}(1)$)

$\Delta \hat{m}_\alpha$: experimental mass resolution of observable α

Δm_i: theoretical mass uncertainty of Higgs boson h_i

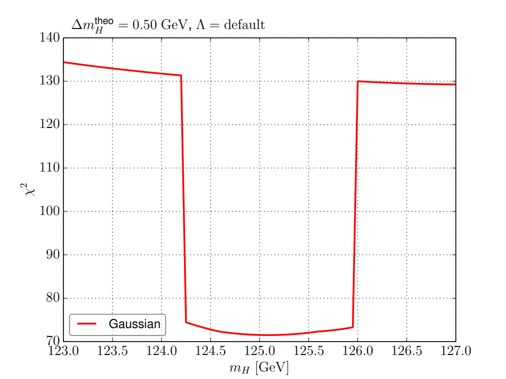
- If $N > 1$ Higgs bosons assigned $\Rightarrow \mu_\alpha = \sum_i \mu_{\alpha,i}$.
  A signal-strength weighted mass average $\overline{m}$ then enters the χ^2_m evaluation.

- If no Higgs boson is assigned to observable α, its χ^2 contribution is evaluated for zero predicted signal strength, $\mu_\alpha = 0$.

Mass dependence of total χ^2 for a SM-like Higgs boson

HiggsSignals provides three different probability distribution functions (pdfs) for the Higgs box-shaped, Gaussian, box-theo.+Gaussian-exp.

Example: SM Higgs boson with $\Delta m = 0.5$ GeV



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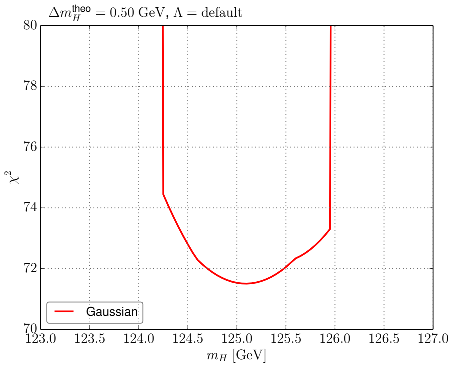


Tutorial

2HDMC= 2HDM Calculator

[D. Eriksson, J. Rathsman, O. Stål, 0902.0851] latest version (2015): 1.7.0

Calculates for the CP-conserving 2HDM:

- tree-level Higgs masses and couplings,
- Higgs (and non-SM top) decay rates,
- tree-level theoretical constraints (unitarity, perturbativity, stability),
- EW precision observables (oblique parameters).
- ...

It features

- various parametrizations,
- all possible Yukawa types (including a “general” Yukawa structure),
- LesHouches-style output,
- `MadGraph/MadEvent (v4)` model,
- interface to `HiggsBounds-4`/`HiggsSignals-1`. → outdated!
- many example programs (have a look!)

Private version of a new interface available at

`https://gitlab.com/higgsbounds/additional_tools`.

New interface necessary due to extended theoretical input in `HiggsBounds-5` (LHC 13 TeV quantities).

This includes a small program (`xsecHptb.F90`) to obtain the 13 TeV cross section for $pp \to H^{\pm}tb$ (at NLO) from numerical grids provided by the LHC Higgs Cross Section workgroup.

Setting up the codes

1. Download and install `HiggsBounds` and `HiggsSignals` from `https://gitlab.com/higgsbounds`.
2. Download and extract `2HDMC` from `https://2hdmc.hepforge.org`.

   (`libHB.a` and `libHS.a` have to be copied into `/2HDMC-1.7.0/lib/` folder)
3. Download and install updated `2HDMC-HB/HS` interface from `https://gitlab.com/higgsbounds/additional_tools`.
4. Compile `2HDMC`.

   (Maybe need to add `-fpermissive` to `CFLAGS`)

(All codes need `gcc` *(including* `gfortran`*),* `2HDMC` *also needs* `gsl`*)*

"EXERCISES"

First steps in 2HDMC:

1. Let's try one point in the 2HDM in Type 1 and 2:

```
./CalcPhys 125.1 250. 500. 500. 0.9995 0. 0. 20000. 5 1 point1.slha
./CalcPhys 125.1 250. 500. 500. 0.9995 0. 0. 20000. 5 2 point2.slha
```

   Look up the relevant Higgs searches in `Key.dat`.

Invisible Higgs decay and $H \to \gamma\gamma$ in the inert doublet model

Use the provided `ScanInert.cpp` program to study

2. Direct and indirect constraints on $\mathrm{BR}(H \to \text{invisible})$ and, in turn, the relevant IDM parameters (m_H, λ_L).
3. Constraints on the $H \to \gamma\gamma$ rate and, in turn, the relevant IDM parameters $(m_{H^\pm}, \lambda_3)$.

(*Note*: For the SM, `HiggsSignals` gives $\chi^2_{\text{SM}} = 71.64$.)

Recap: Inert Doublet Model

useful reference: [Goudelis, Herrmann, Stål 1303.3010]

Lightest neutral inert Higgs boson is stable (i.e. dark matter candidate).
Assume $m_H < m_A$ here.

$$V = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\phi)^2 + \text{h.c.}\right].$$

Tree-level Higgs masses:

$$\begin{aligned} m_h^2 &= \mu_1^2 + 3\lambda_1 v^2 \\ m_H^2 &= \mu_2^2 + \lambda_L v^2 \\ m_A^2 &= \mu_2^2 + \lambda_S v^2 \\ m_{H\pm}^2 &= \mu_2^2 + \tfrac{1}{2}\lambda_3 v^2 \end{aligned}$$

with

$$\begin{aligned} \lambda_L &= \tfrac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) \\ \lambda_S &= \tfrac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5) \end{aligned}$$

Can choose as input parameters:

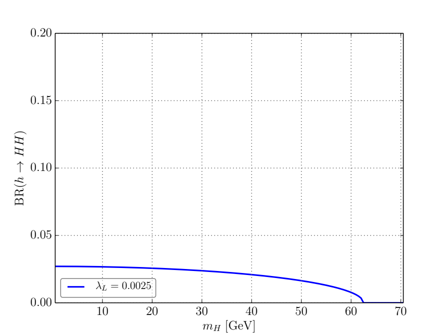
$$\{m_h, m_H, m_A, m_{H\pm}, \lambda_2, \lambda_3\}$$

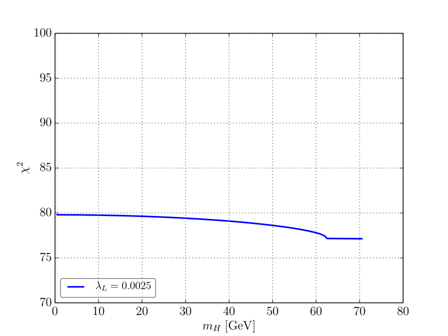
We can further replace λ_3 by λ_L via

$$\lambda_3 = \frac{2}{v^2}(m_{H\pm}^2 - m_H^2) + 2\lambda_L.$$

hHH coupling $\sim \lambda_L$,
hH^+H^- coupling $\sim \lambda_3$.

1-dimensional scan over m_H (for fixed λ_L)





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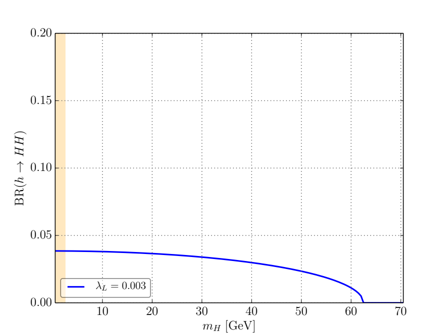

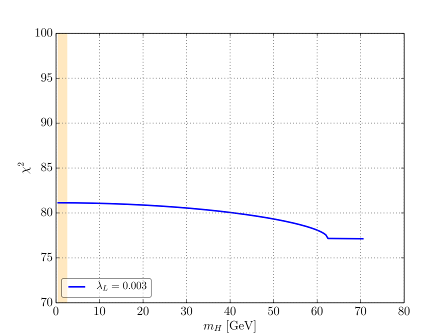

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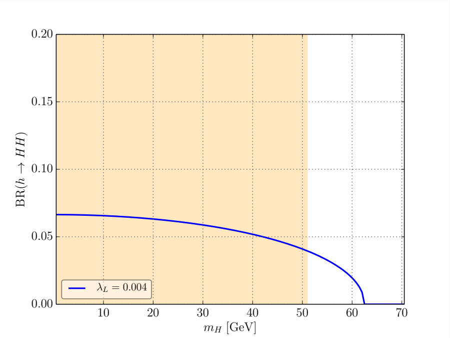

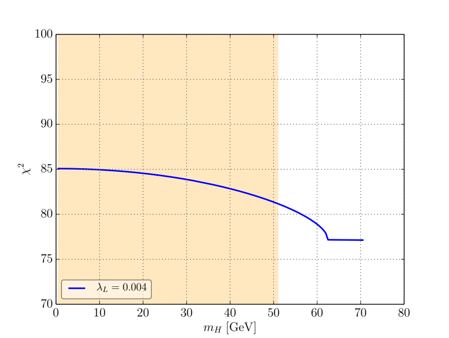

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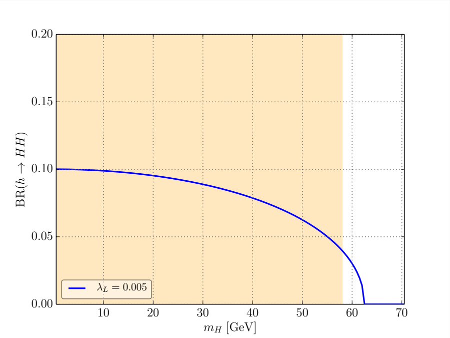

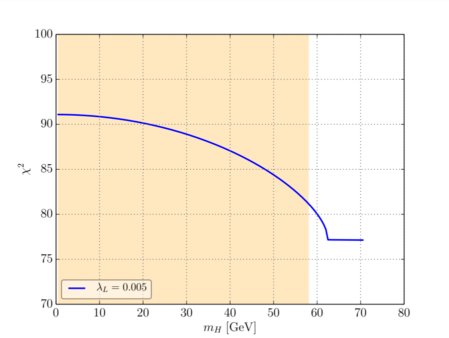

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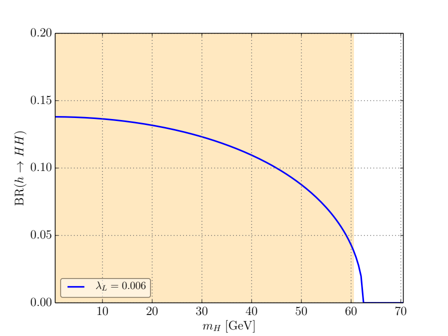

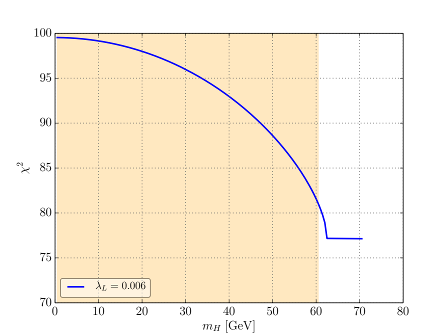

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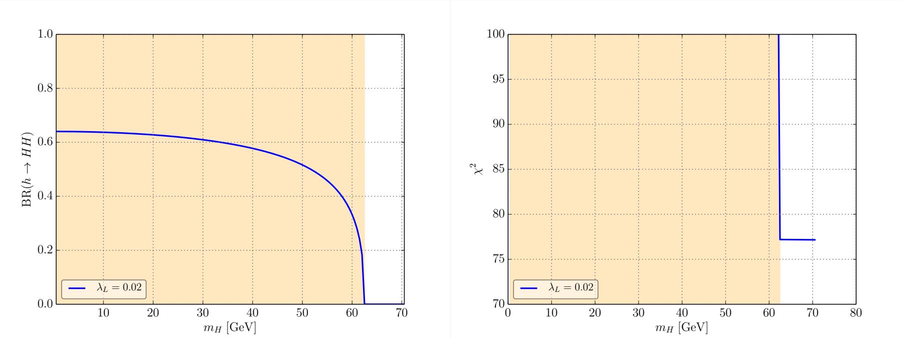
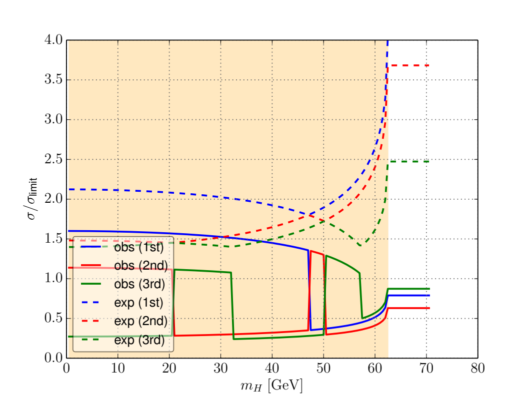


Invisible Higgs decays

1-dimensional scan over m_H (for fixed λ_L)



HiggsBounds: $\sigma/\sigma_{\text{limit}} > 1 \Rightarrow$ model excluded at 95% C.L..

Problem: pre-discovery SM Higgs search limits compete against invisible Higgs searches.

Charged Higgs contribution to $H \to \gamma\gamma$

1-dimensional scan over $m_{H^\pm}$ (for fixed $\lambda_3 = 0.5$)