HiggsTools: A Toolbox for BSM Scalar Phenomenology

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In collaboration with Thomas Biekötter, Sven Heinemeyer, Cheng Li, Kateryna Radchenko Serdula, and Georg Weiglein

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HiggsDays 2024, 9.9.2024

Pheno workflow

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Theoretical model

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- Define field content + interactions.
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  - gauge invariance,
  - anomaly cancellation,
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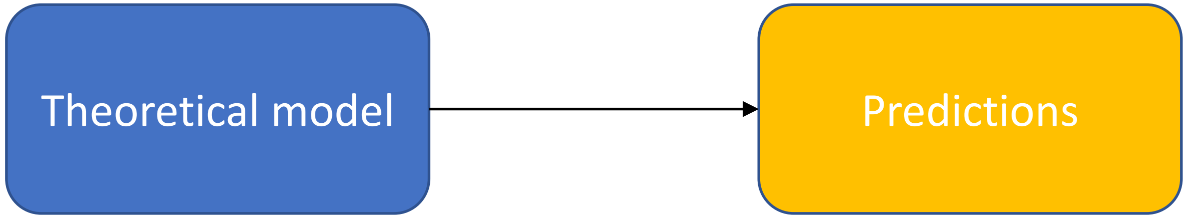

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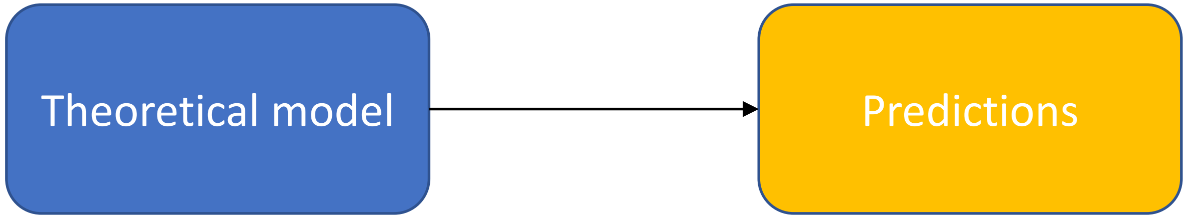

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- Electroweak precision observables.
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Some of these steps are easy, most are quite involved! → Automation.

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This talk

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Compatibility with experimental data:

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➡ Written in modern C++ for high performance; Python and Mathematica interfaces for ease of use.

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- Effective coupling input to set particle properties relative to these reference models.
- Automatically calculates XS and BRs in terms of effective couplings.

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For each particle, the most sensitive limit is selected based on the expected ratio. The parameter point is regarded as allowed if the observed ratio < 1 for all selected limits.

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- Limit database contains all types of limits:
  - Searches for neutral, charged, and doubly-charged scalars.
  - Chain decays pairs (e.g. $H \to ZA$) and pair decays (e.g. $h \to HH$).
  - Implementation of publicly available likelihoods (e.g. $H \to \tau\tau$).

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- Includes correlations correlations (experimental + theory).
- Also includes CP measurements (e.g. CMS $H \to \tau\tau$ CP measurement).

XS predictions

Easy access to predictions for Higgs XS and BRs

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cpls = Higgs.predictions.NeutralEffectiveCouplings()
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- Procedure:
  - Evaluate BSM XS $\sigma_{\mathrm{BSM}}(m)$ using parameterized XS fits.
  - Rescale to LHCHWG recommendations
    $\sigma_{BSM}(m) \rightarrow \sigma_{\mathrm{BSM}}(m) \cdot \frac{\sigma_{\mathrm{SM}}^{\mathrm{LHCHWG}}(m)}{\sigma_{\mathrm{SM}}(m)}$

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HiggsPredictions — parameterized XS's

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bbH	$c_b, \tilde{c}_b$	$10 - 3000$	resc. of SM result
VBF	c_Z, c_W	LHC8: $1 - 1050$, LHC13: $1 - 3050$	resc. of SM result
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$pp \to H^\pm \phi$	$c_{H^\pm \phi W^\mp}$	$m_\phi : 10 - 500$, $m_{H^\pm} : 100 - 500$	[HB et al.,2103.07484]

- Also $H \to \gamma\gamma, gg$ decay widths can be calculated in terms of effective couplings.

Example: $Z\phi$ production

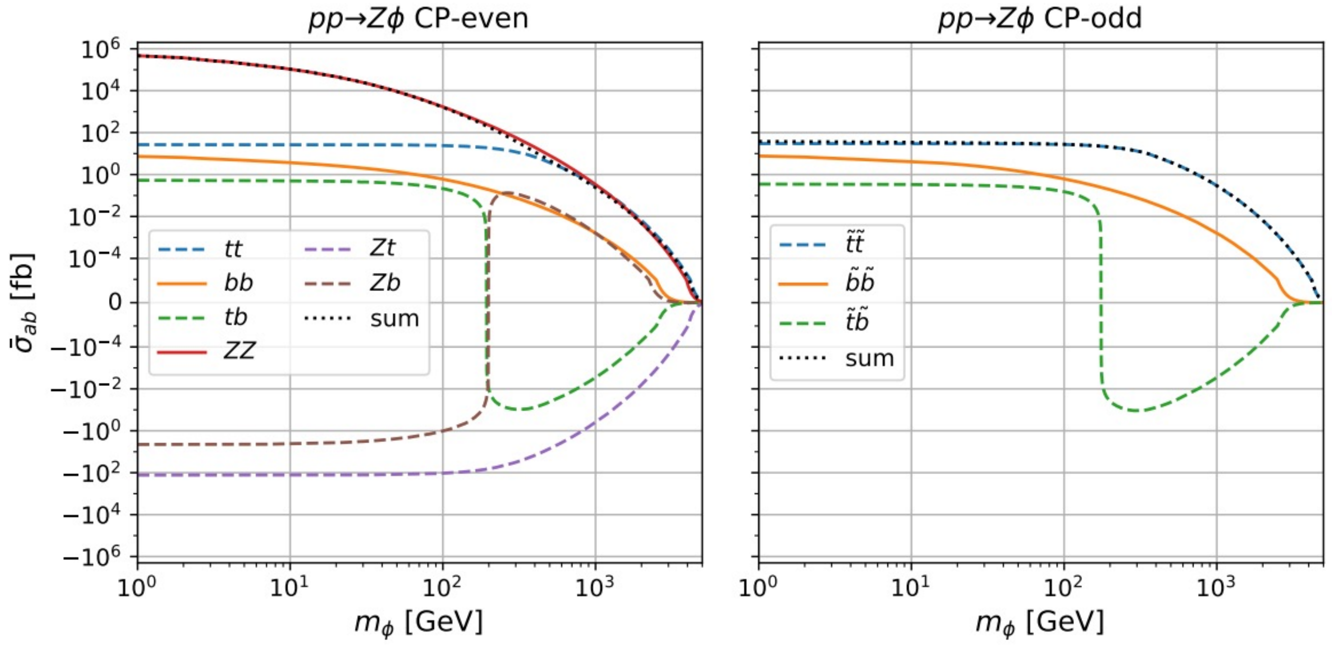
[Bechtle et al.,2006.06007]

- Split up cross-section such that coupling dependence is explicit:

$$\sigma^{Z\phi}[m_\phi] \approx \sum_{a,b\in\{Z,t,b,\tilde{t},\tilde{b}\}} \kappa_a \kappa_b \bar{\sigma}^{Z\phi}_{ab}[m_\phi]\,.$$

- Fit mass dependence of the various contributions individually using vh@nnlo.

- At run-time, take effective couplings to obtain total $Z\phi$ cross-section.



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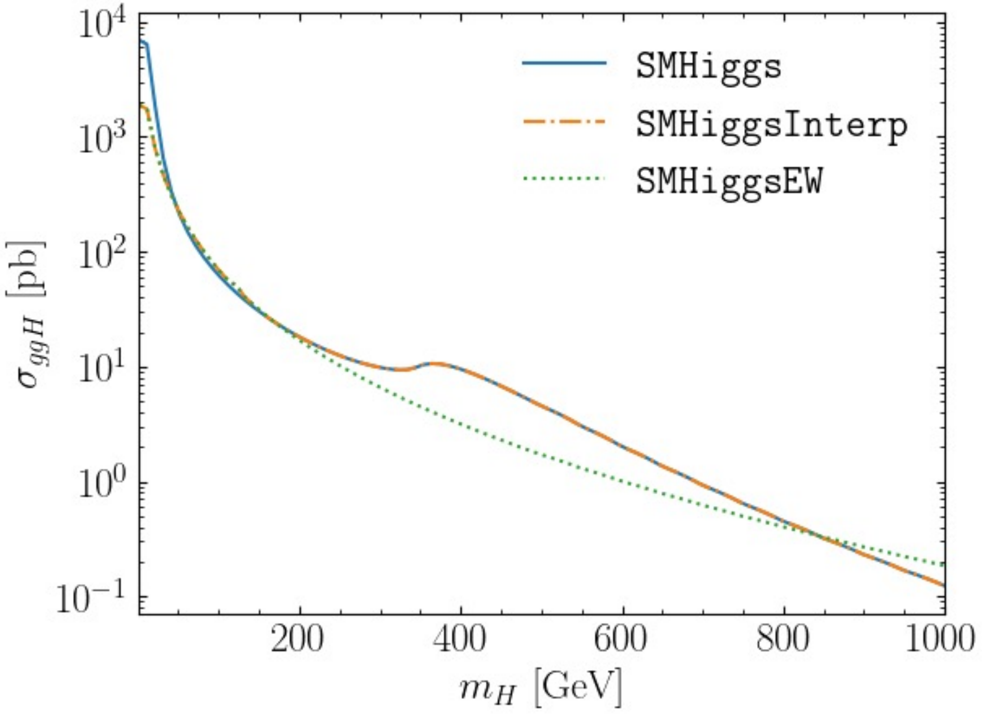
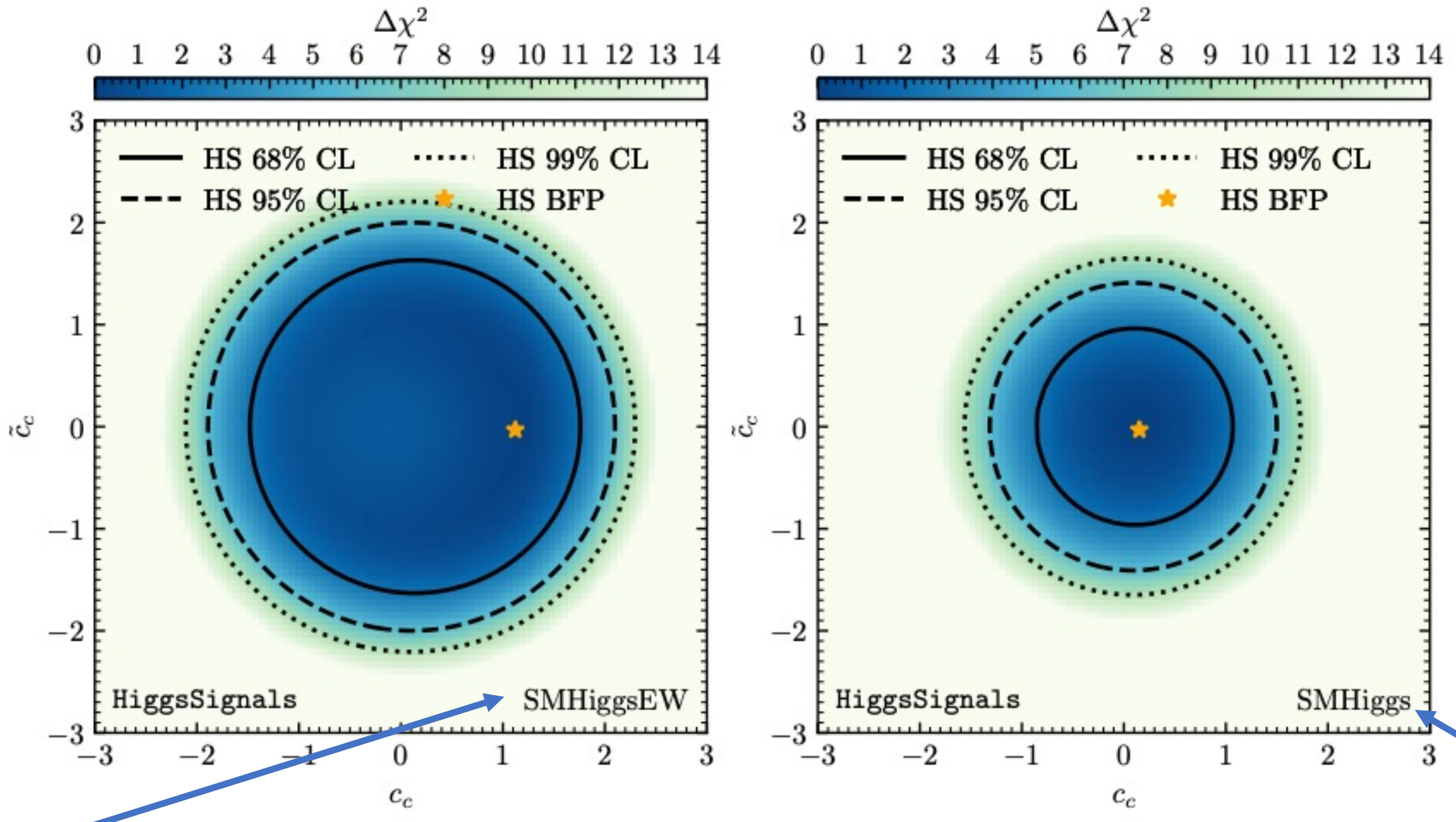
- New feature: SMHiggsInterp reference model interpolating between SMHiggs and SMHiggsEW



Using the most precise XS predictions matters

Example: charm-Yukawa fit $\mathcal{L}_{c\,\text{Yuk}} = \frac{y_c^{SM}}{\sqrt{2}}\bar{c}(c_c + i\gamma_5\,\tilde{c}_c)c\,H$



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Preparing for Run-3

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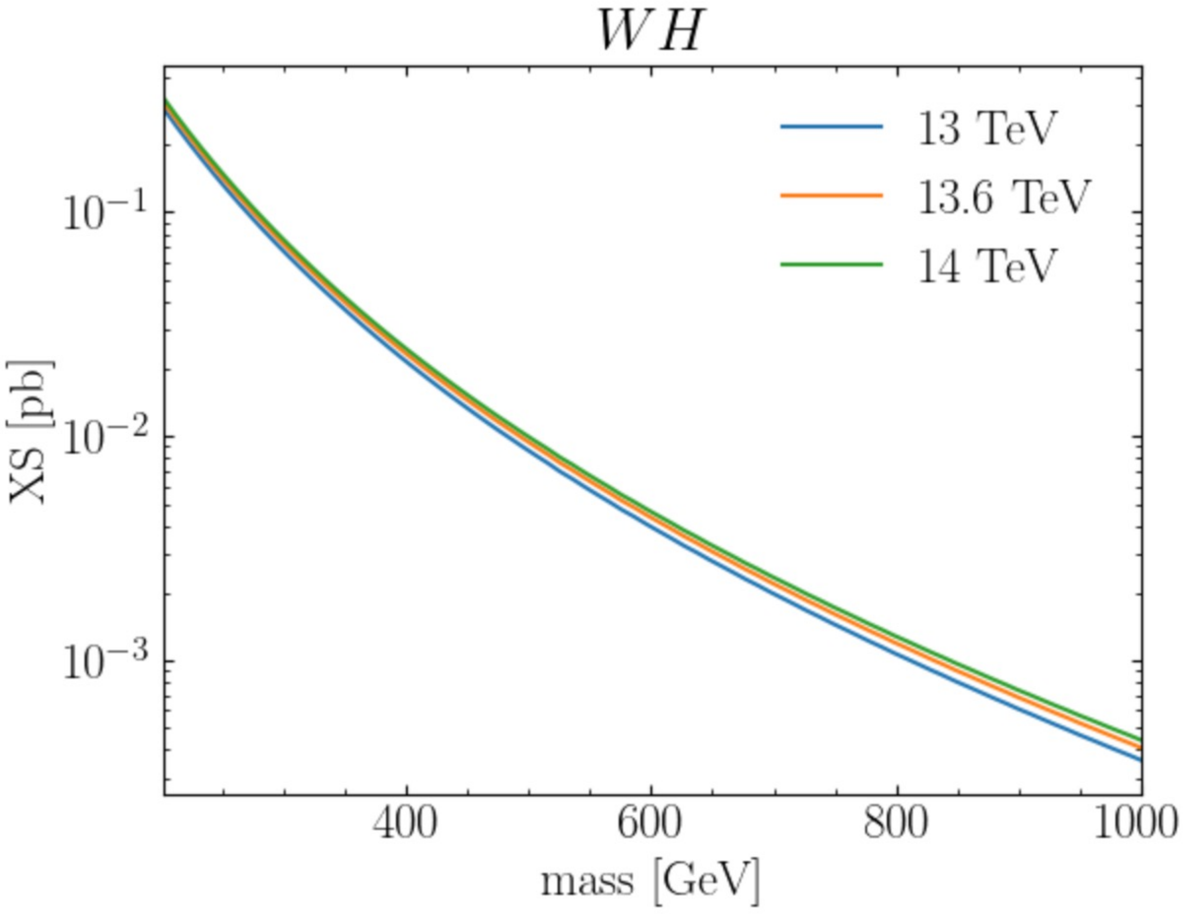
Now also available for 13.6 TeV and 14 TeV! (rows ggH through $q_i q_j \to H$)

Preparing for Run-3 – WH example



$h_{125}h_{125}$ pair production XS I

[work in progress]

- Goal: Easy application of resonant and non-resonant di-Higgs searches.
- Split $h_{125}h_{125}$ XS into various pieces:

$$\sigma_{h_{125}h_{125}} = \sigma_{\mathrm{non-res}} + \sigma_{\mathrm{res}} + \sigma_{\mathrm{int}} = |\mathrm{box} + \mathrm{triangle}|^2 + |\mathrm{res}|^2 + 2\,\mathrm{Re}[(\mathrm{box} + \mathrm{triangle}) \cdot \mathrm{res}^*]$$

- Include dependence on resonance mass, width, Yukawas, and trilinear couplings.

$h_{125}h_{125}$ pair production XS II

[work in progress]

- Fit each of these pieces individually (using anyHH for XS calculation) [HB et al., to appear]

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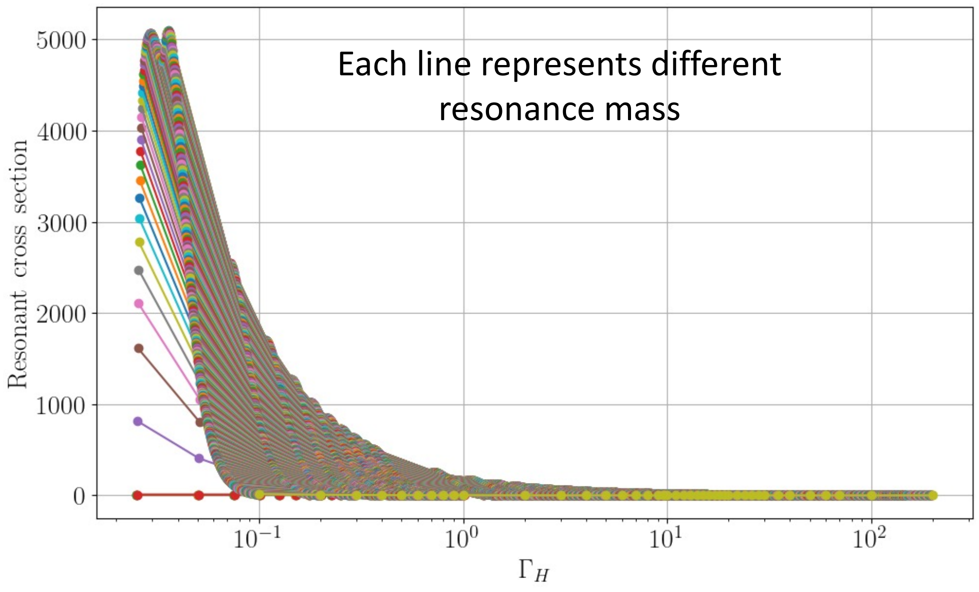

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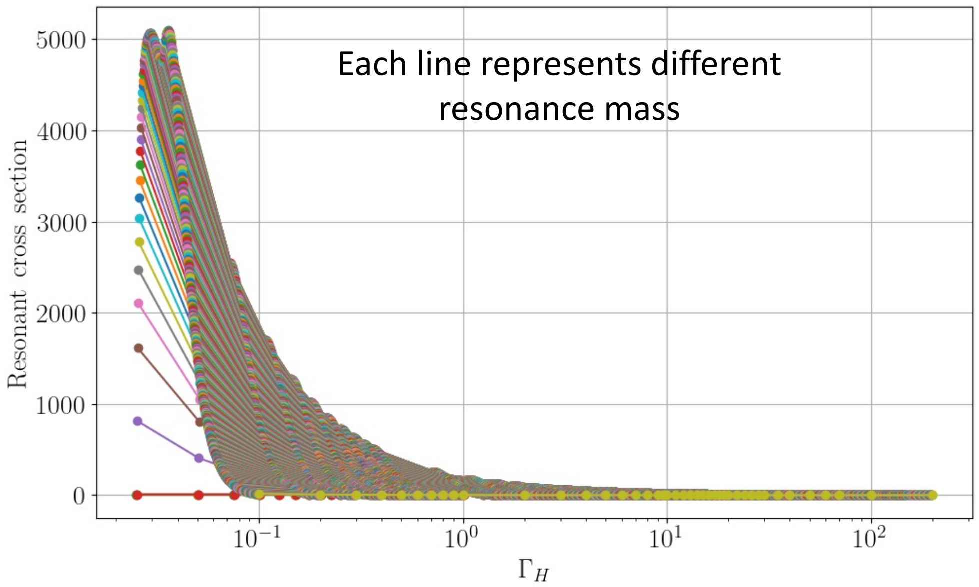
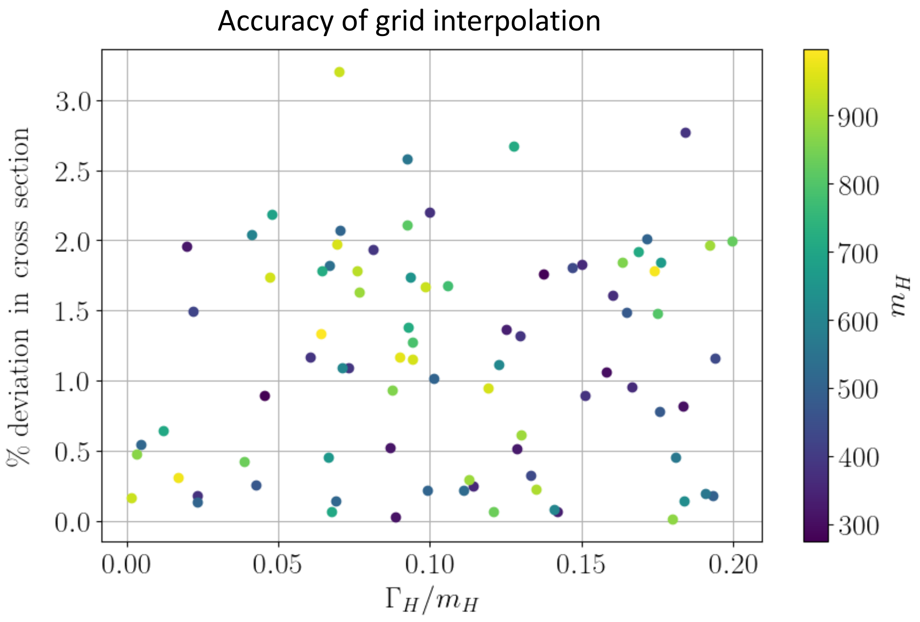
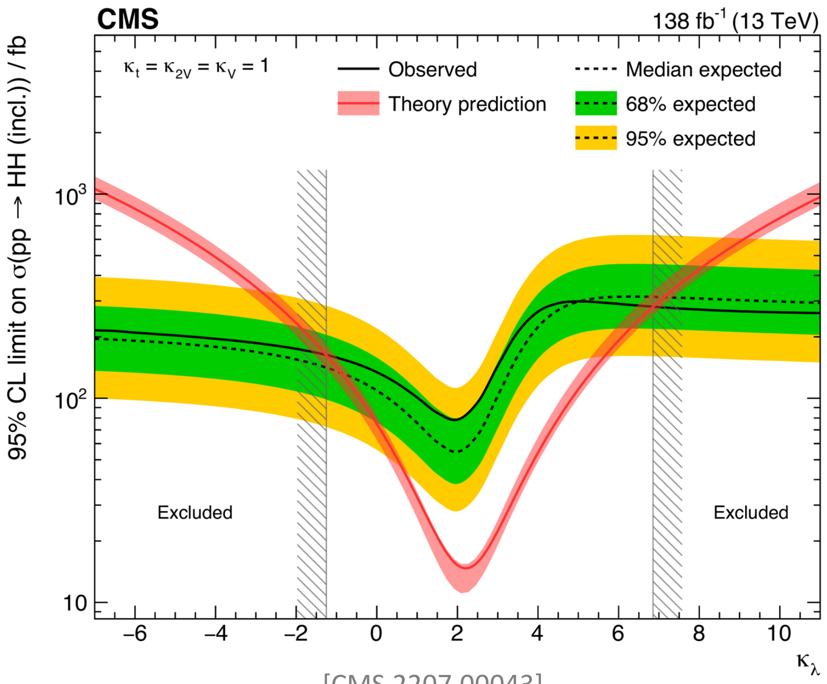




Implementation of new searches

Non-resonant HH limits

- New feature: implementation of λ dependence of non-resonant HH limits (via acceptance).
- Provide κ_λ via effective coupling input.



[CMS,2207.00043]

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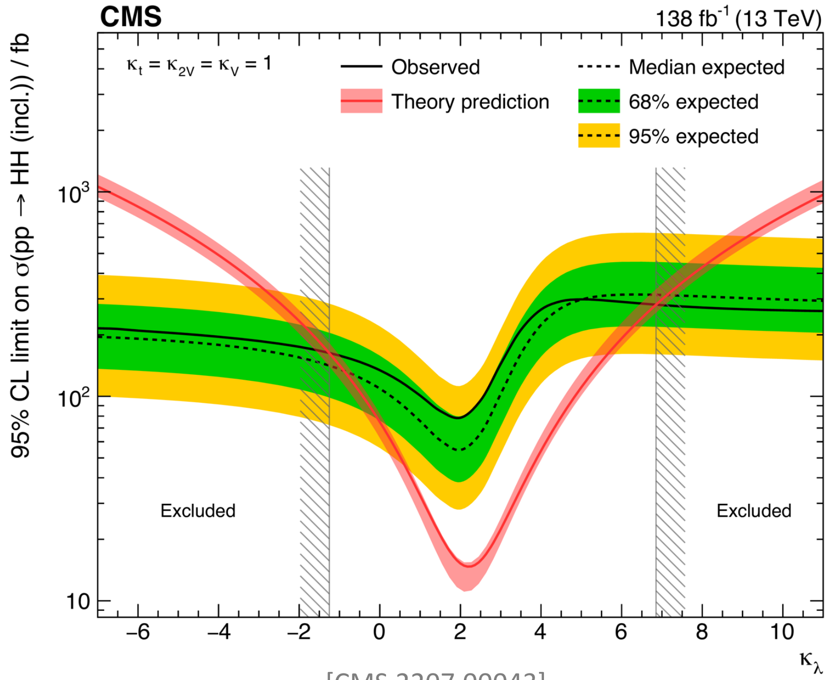
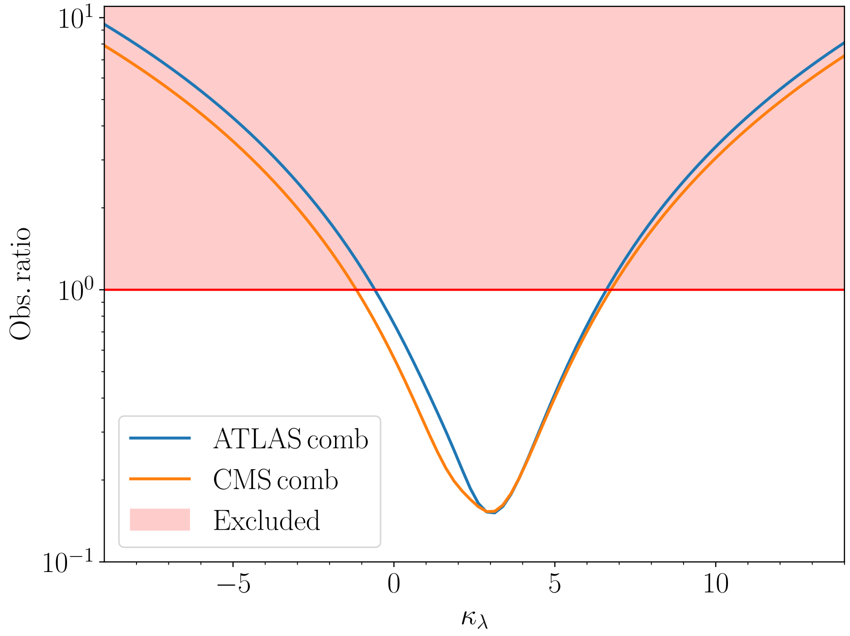
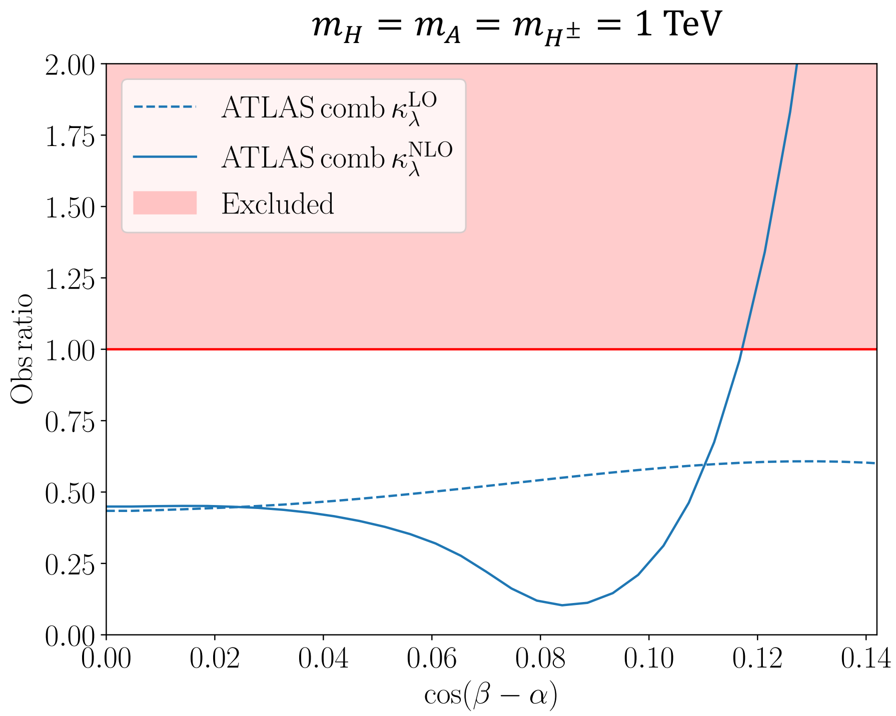


[CMS,2207.00043]



Non-resonant HH limits: 2HDM example result

- $h_{125}h_{125}$ XS calculated using HPair [Gröber et al.,1705.05314;…]
- Optionally include NLO corrections to κ_λ via BSMPT. [Basler et al., 1803.02846;…]



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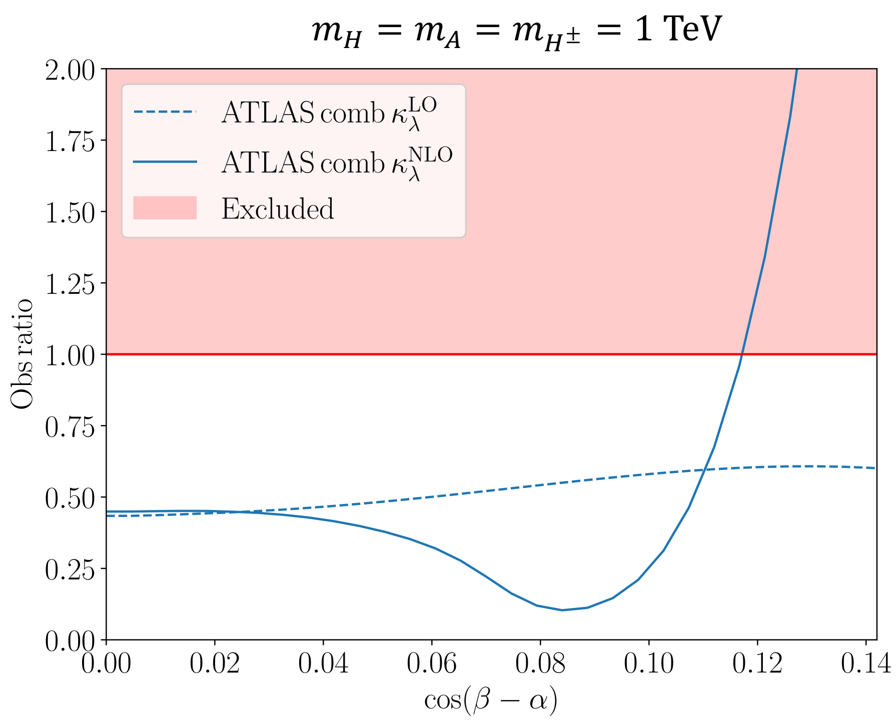

Unresolved issue: which limit should be applied how in presence of large resonant/non-resonant interference?

Multi-top final states

- BSM scalars with large top-Yukawa couplings well motivated $\rightarrow$ searches for multi-top final states.

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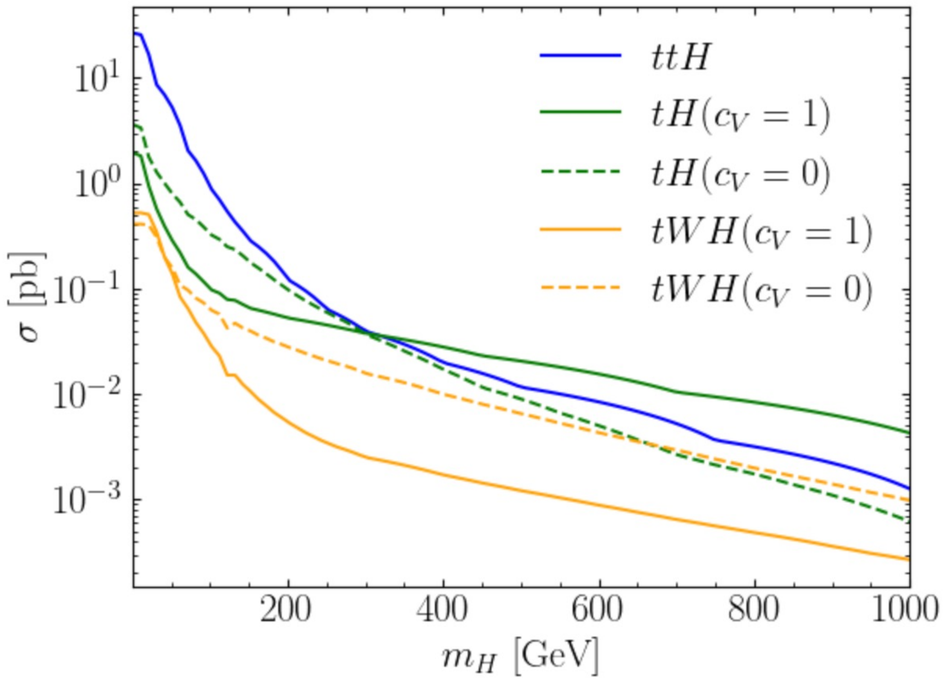

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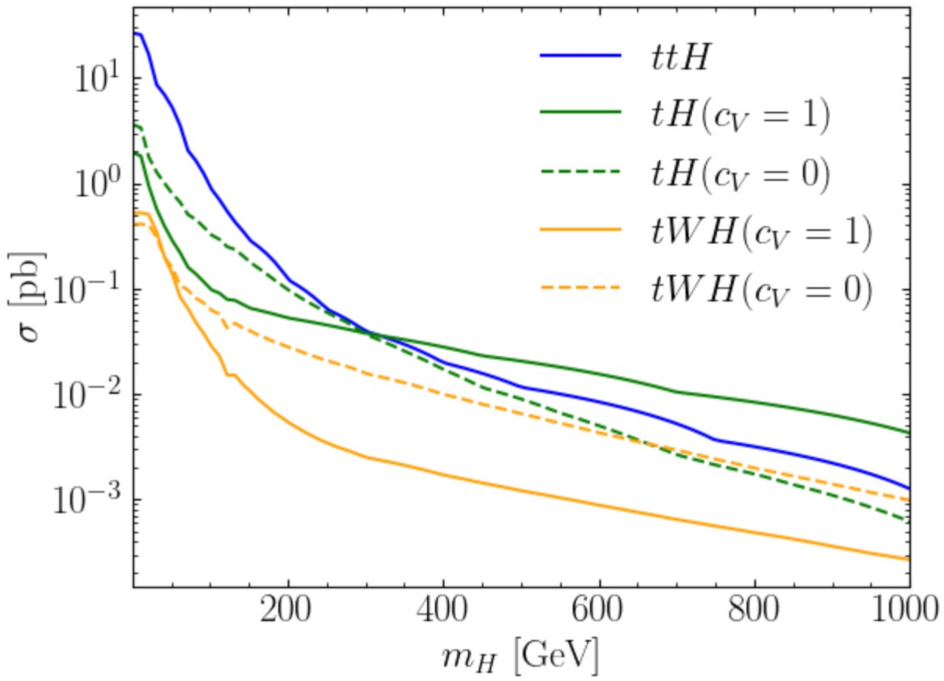
- $t\bar{t}t\bar{t}$:
  - Much smaller signal-background interference.
  - Easier to reinterpret.



Reinterpretation of CMS $t\bar{t}t\bar{t}$ search

[CMS,1908.06463]

- Use existing MadAnalysis implementation [Darme et al.,2104.09512] to fit signal efficiencies.

$$\epsilon = \frac{\sigma}{\sigma_{\rm tot}} = \frac{c_1^\sigma c_V^2 c_t^2 + c_2^\sigma c_V^2 \tilde{c}_t^2 + c_3^\sigma c_V c_t^3 + c_4^\sigma c_V c_t \tilde{c}_t^2 + c_5^\sigma c_t^4 + c_6^\sigma c_t^2 \tilde{c}_t^2 + c_7^\sigma \tilde{c}_t^4}{c_1^{\sigma_{\rm tot}} c_V^2 c_t^2 + c_2^{\sigma_{\rm tot}} c_V^2 \tilde{c}_t^2 + c_3^{\sigma_{\rm tot}} c_V c_t^3 + c_4^{\sigma_{\rm tot}} c_V c_t \tilde{c}_t^2 + c_5^{\sigma_{\rm tot}} c_t^4 + c_6^{\sigma_{\rm tot}} c_t^2 \tilde{c}_t^2 + c_7^{\sigma_{\rm tot}} \tilde{c}_t^4}.$$

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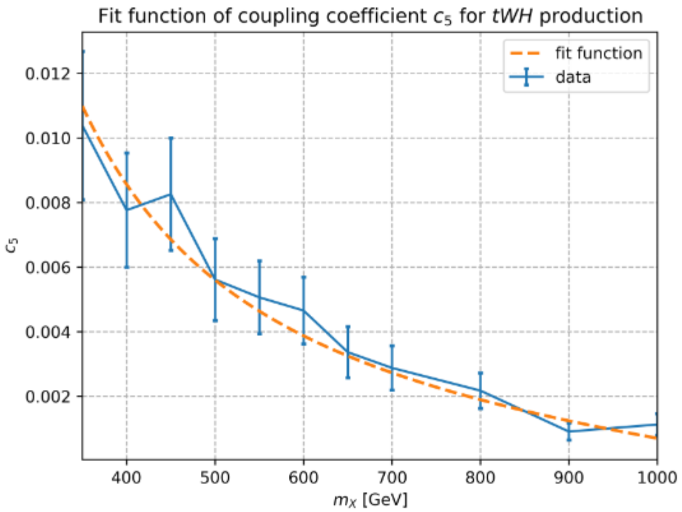

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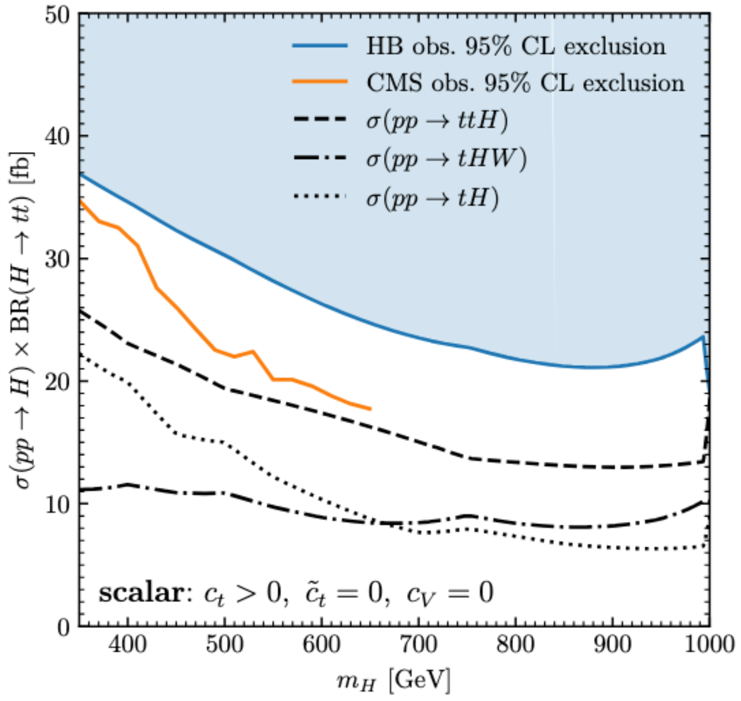

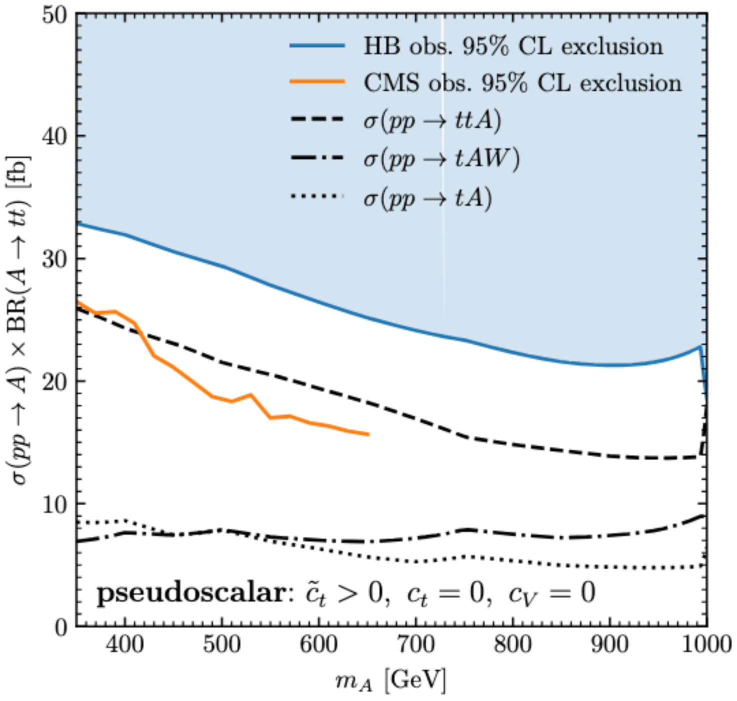

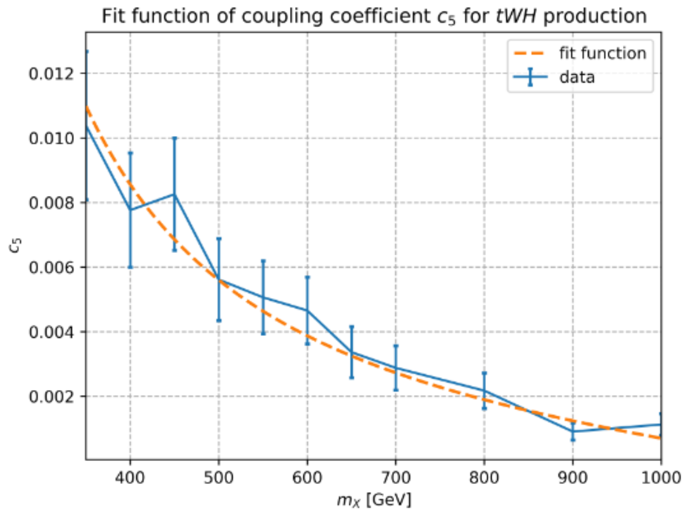

Bringing everything together

2HDM benchmark planes

2HDM type I scans

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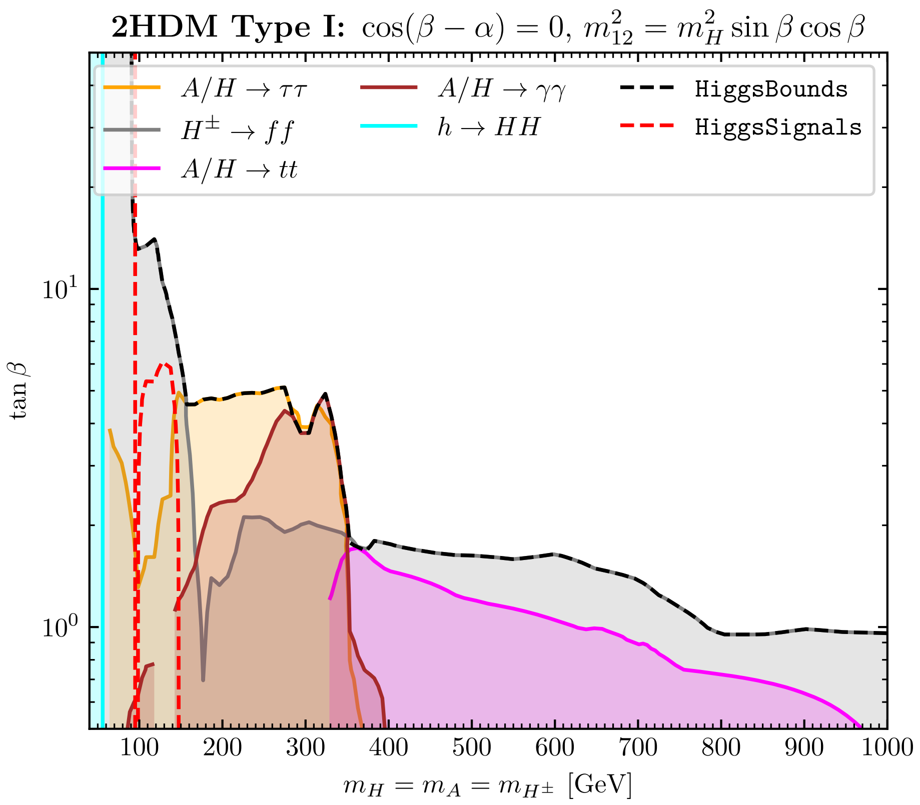
alignment limit



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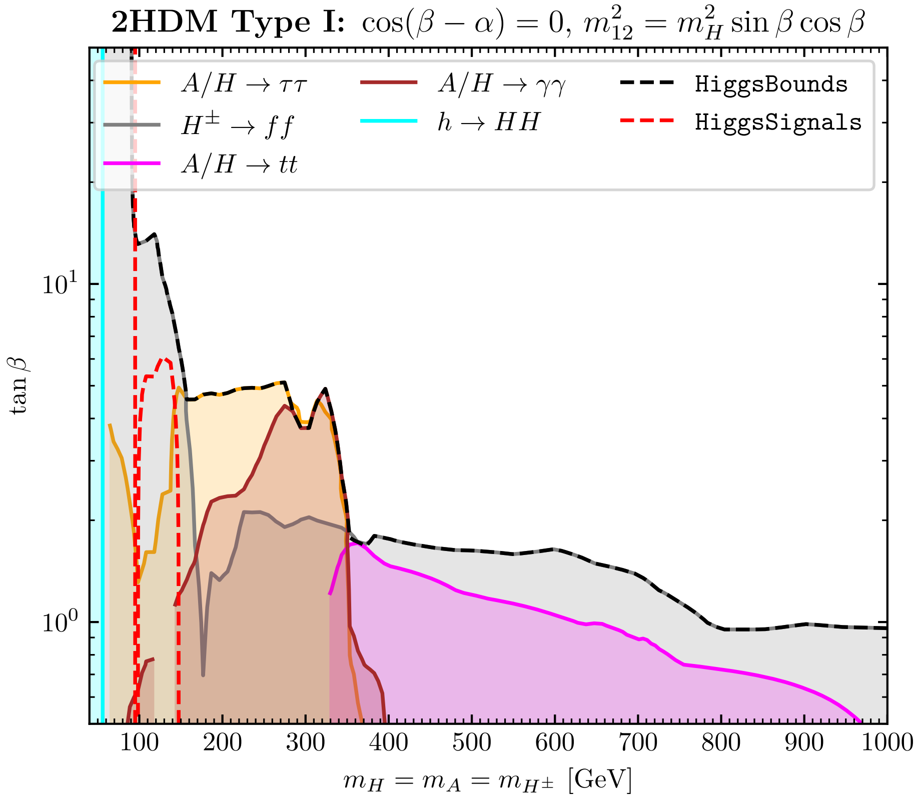
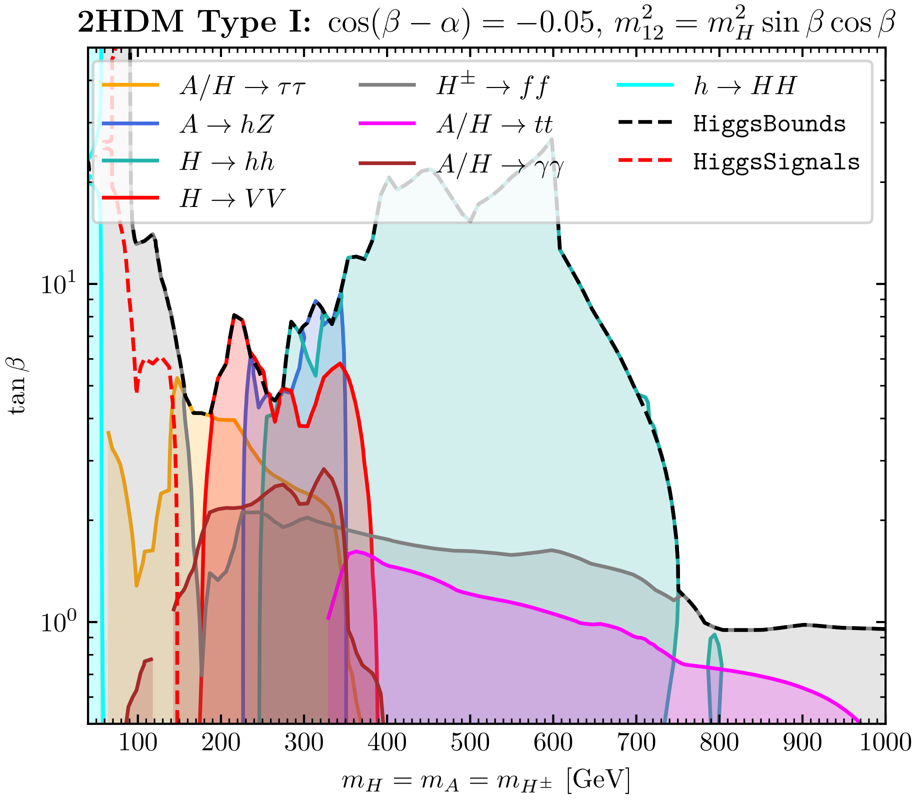


non-alignment



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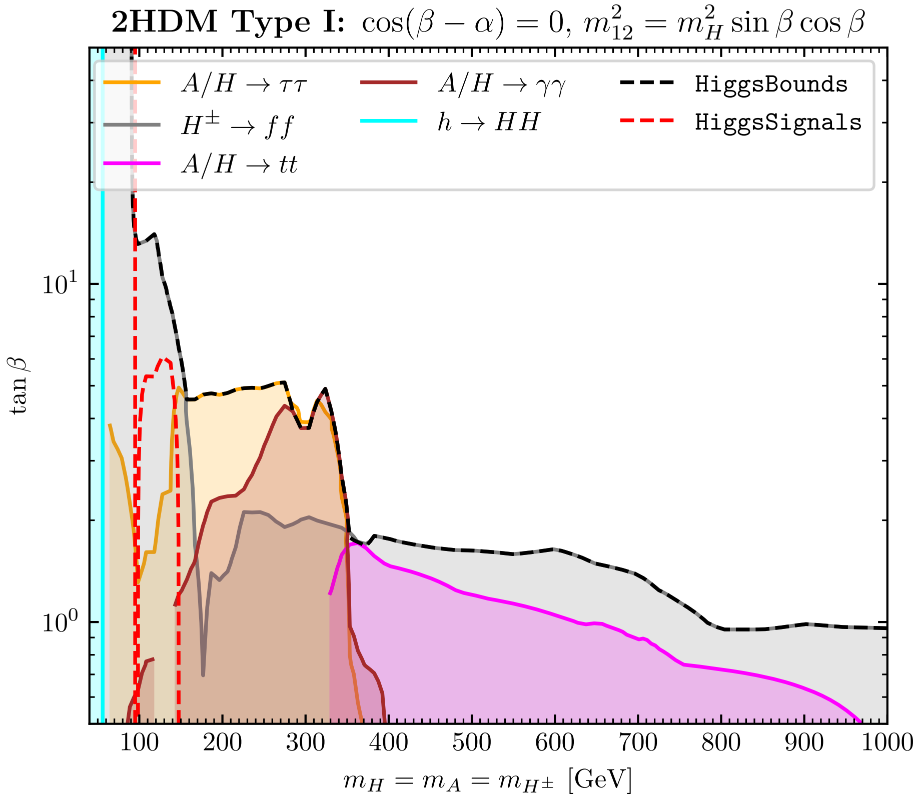
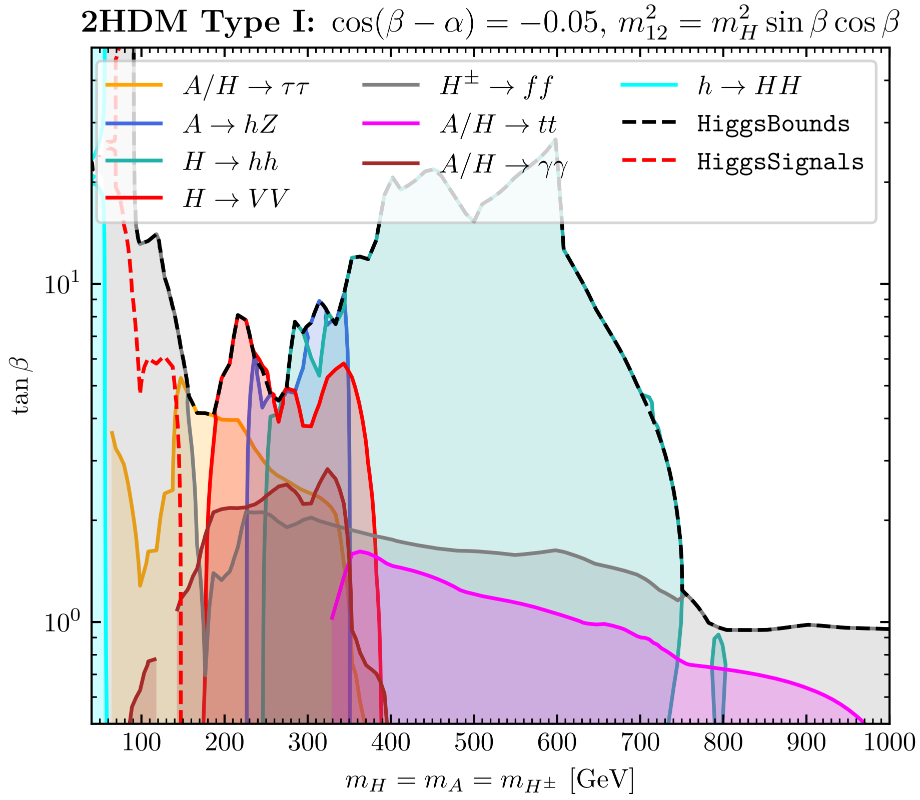


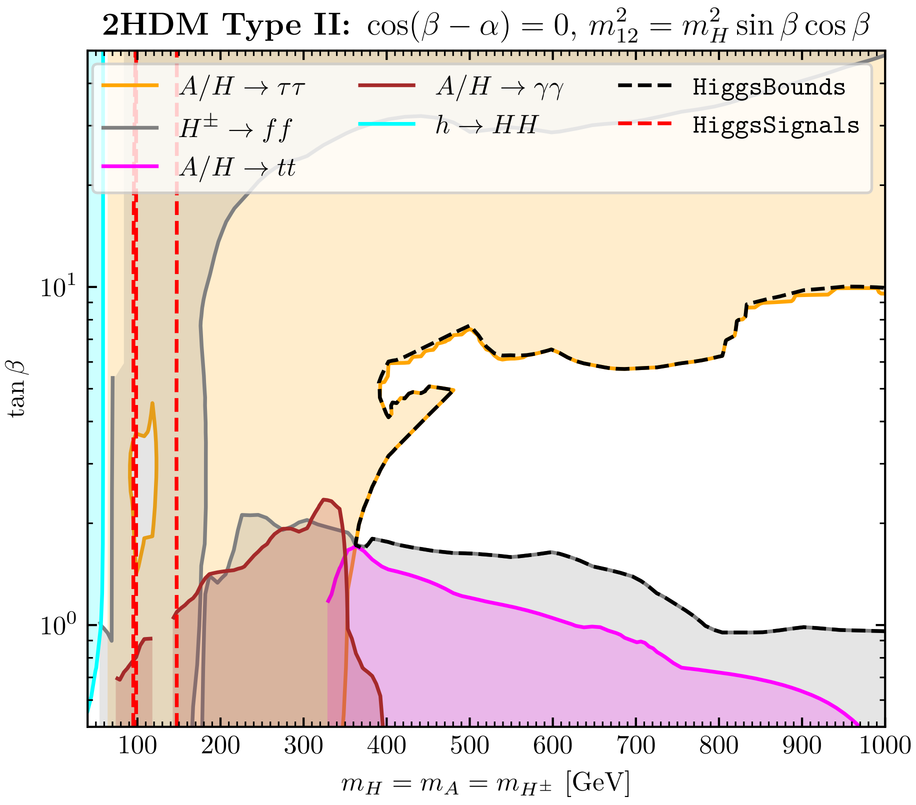
non-alignment



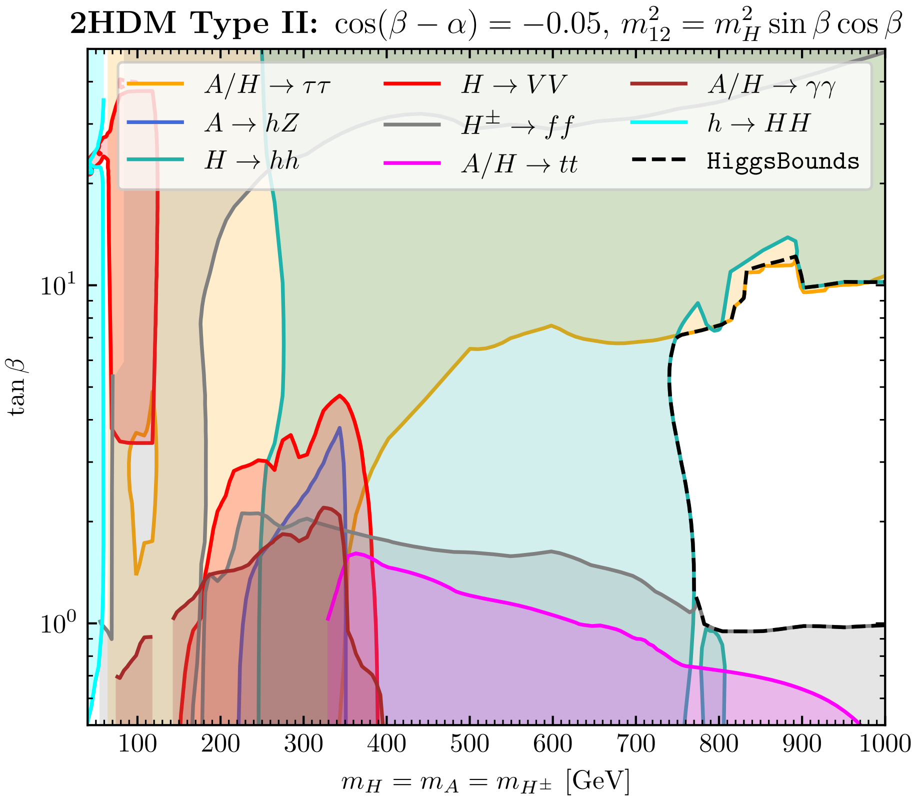
→ HiggsTools enables phenomenologists to make use of all the searches and measurements!

2HDM type II scans

alignment limit



non-alignment



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Thanks for your attention!

Appendix

HiggsTools — quick start guide

Extensive online documentation: higgsbounds.gitlab.io/higgstools/index.html

C++ library:

1. Make sure you have the right dependencies (gcc >= 9, clang >= 5, CMake >= 3.17, Python >=3.5).
2. Download HiggsTools code and data repositories from gitlab.com/higgsbounds.
3. In the code directory, type

```
mkdir build && cd build
cmake ..
make
```

Python interface: In the code directory, type

```
pip install .
```

Mathematica interface:

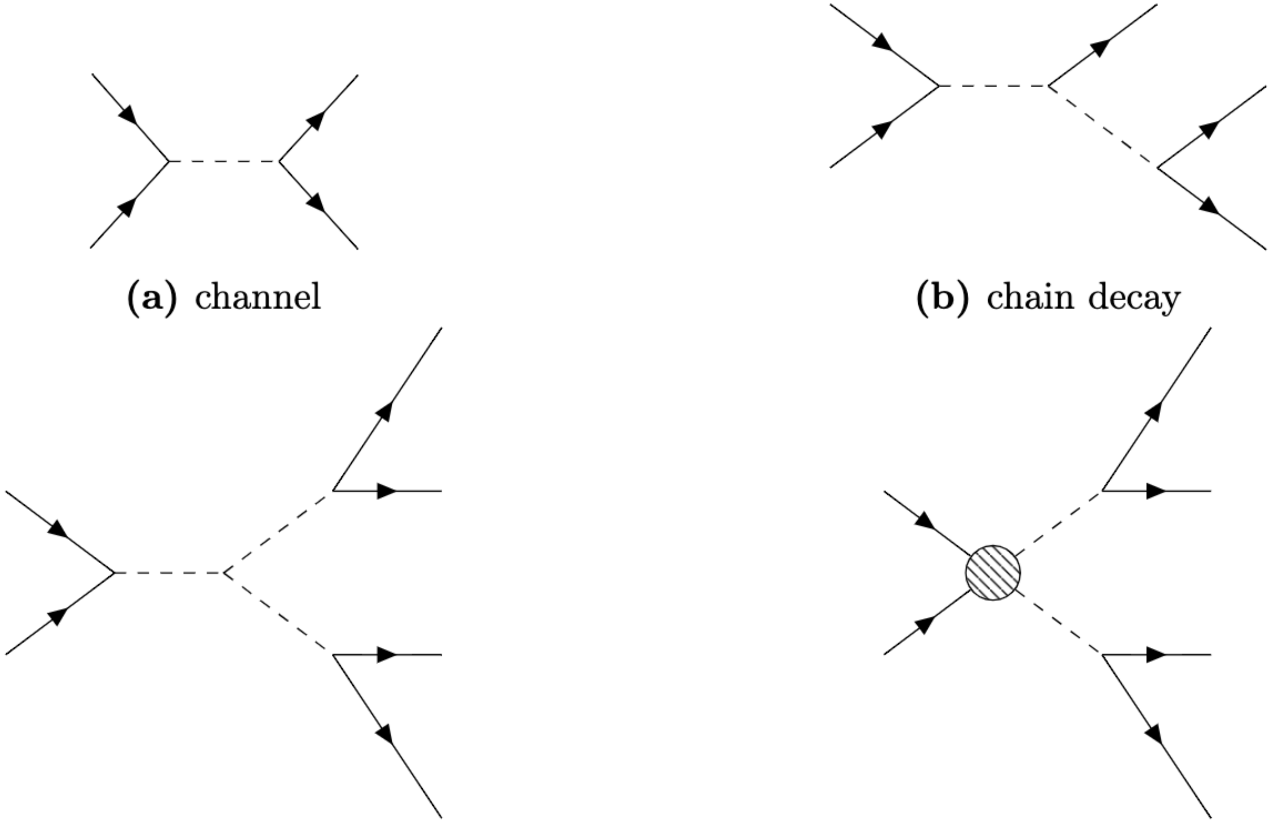
```
cmake -DHiggsTools_BUILD_MATHEMATICA_INTERFACE=ON ..
```

SLHA and datafile input still available via Python interface.

HiggsPredictions — process types

All processes used in HiggsBounds and HiggsSignals are now consistently defined as one of four process types:

a) Channel (1 BSM particles).
b) Chain decay (2 BSM particles).
c) Pair decay (3 BSM particles).
d) Pair production (2 BSM particles).



(a) channel (b) chain decay (c) pair decay (d) pair production

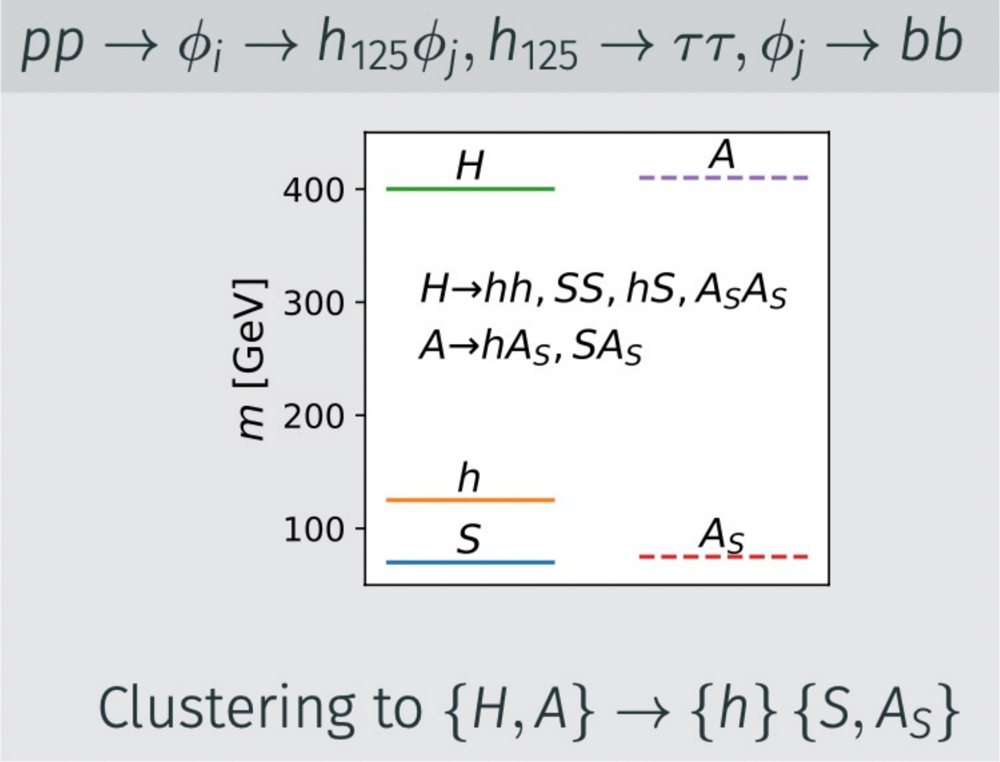
HiggsBounds — clustering

Multiple particles of similar mass can remain unresolved.

→ Define clusters of particles with masses m_i fulfilling

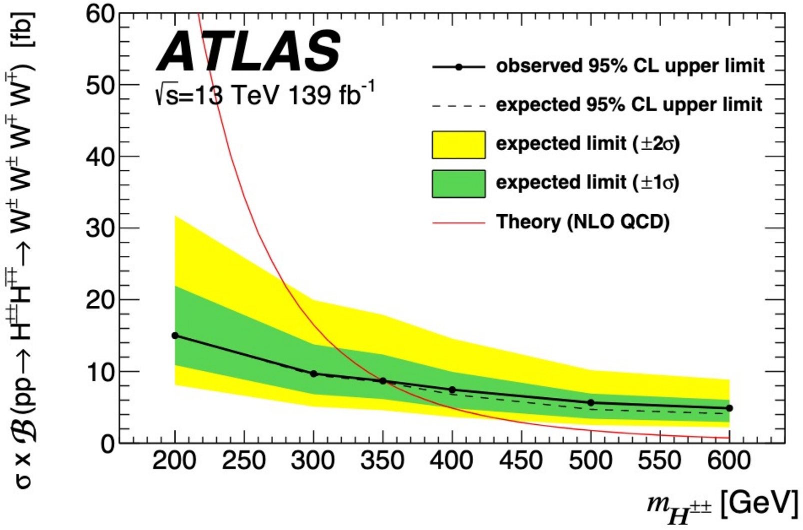
$$\max(m_i) - \min(m_i) \leq r_{\text{abs}} + r_{\text{rel}} \cdot \text{mean}(m_i)$$

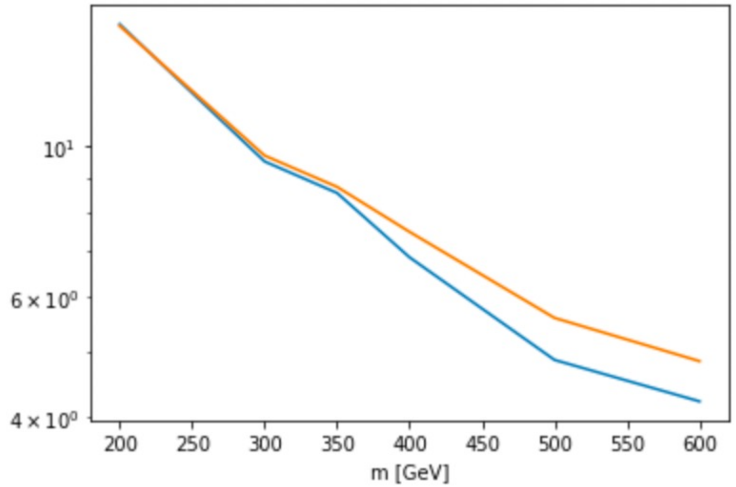
- Mass resolutions given by experiment or estimated.
- Can also account for theoretical mass uncertainties Δm_i:
  - Cautious: only if entire $\pm\Delta m_i$ regions overlap.
  - Eager: as soon as $\Delta m + r$ regions touch.
  - Ignore: ignore Δm_i for clustering.
- Clustering for all particle roles in all search topologies.
- Consistent treatment of all implemented searches.



HiggsBounds — limit example

- Publicly available iPython notebooks for every limit.
- If possible, data is pulled from HEPdata.
- Outputs json limit file containing all information about a limit.
- Validation plots are generated automatically.






```
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    "collider": "LHC13",
    "experiment": "ATLAS",
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        "secondDecay": [
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        ]
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                350.0,
                400.0,
                500.0,
                600.0
            ]
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                7.4858,
                5.5951,
                4.8339
            ],
            "expected": [
                15.111,
                9.4993,
```

HiggsSignals —meas. example

- Publicly available iPython notebooks for every measurement.
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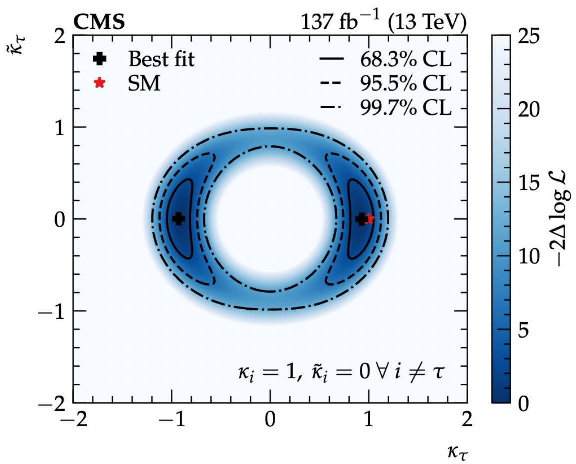
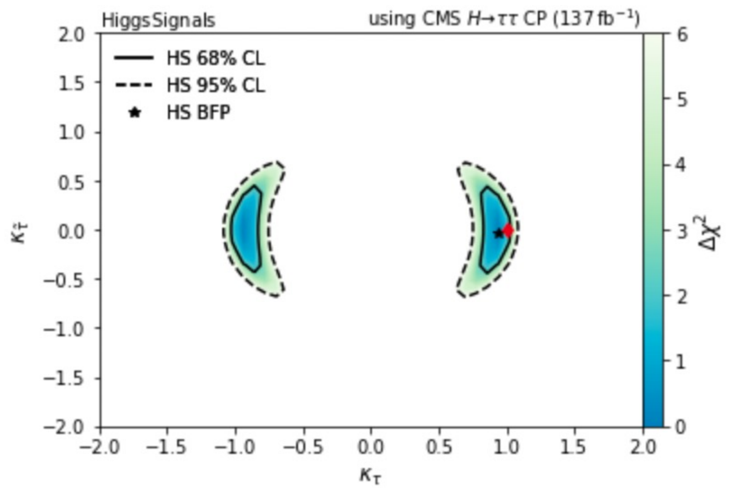
- Outputs json limit file containing all information about a measurement.
- Validation plots are generated automatically.






```
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                    ],
                    [
                        "vbfH",
                        "tautau"
                    ]
                ]
            }
        },
```
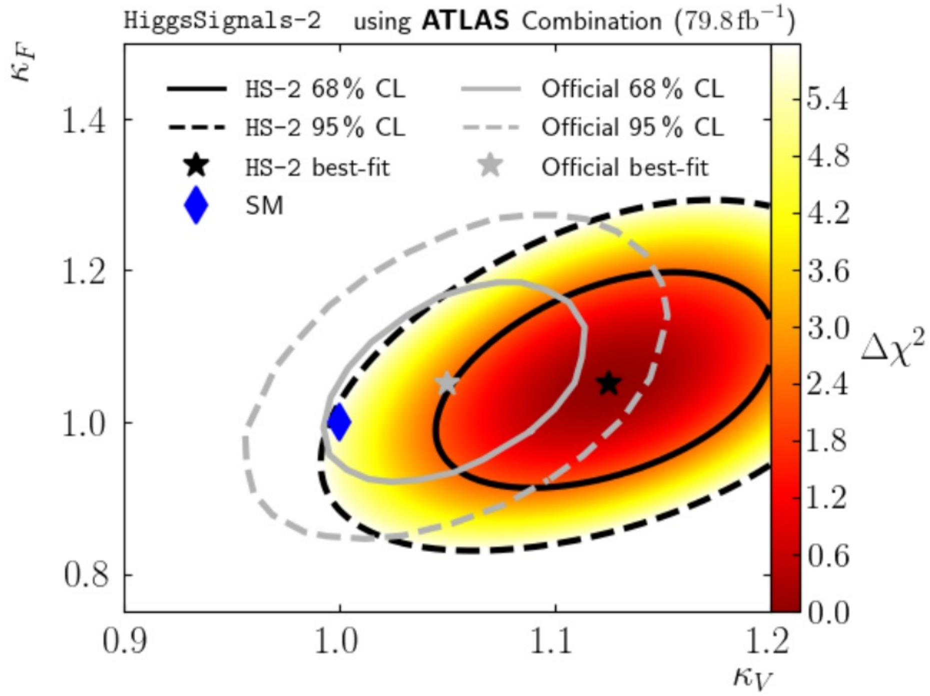
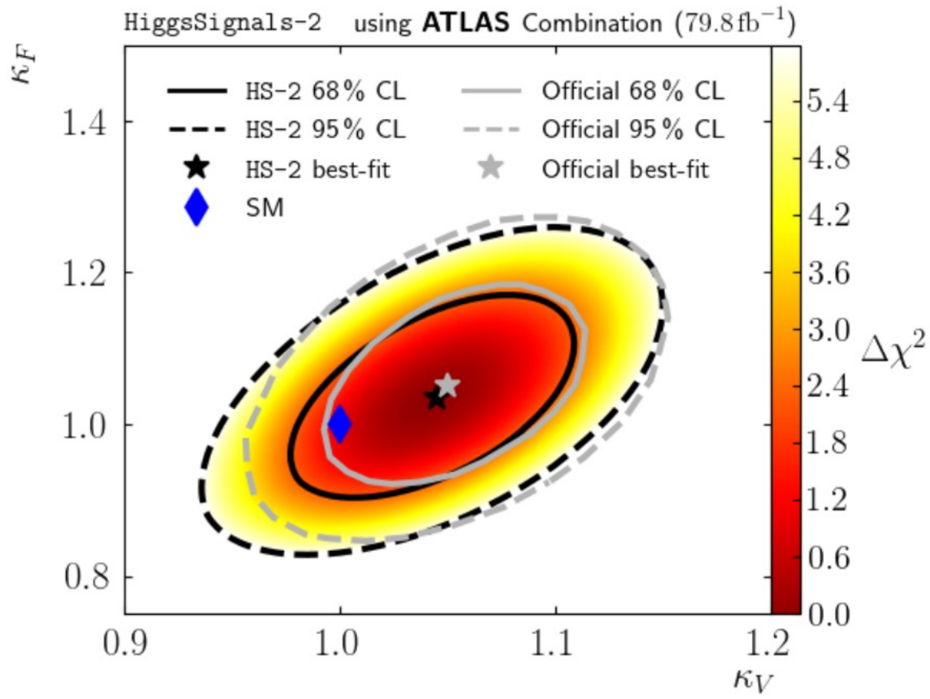

HiggsSignals correlations

[Bechtle et al., 2012.09197]





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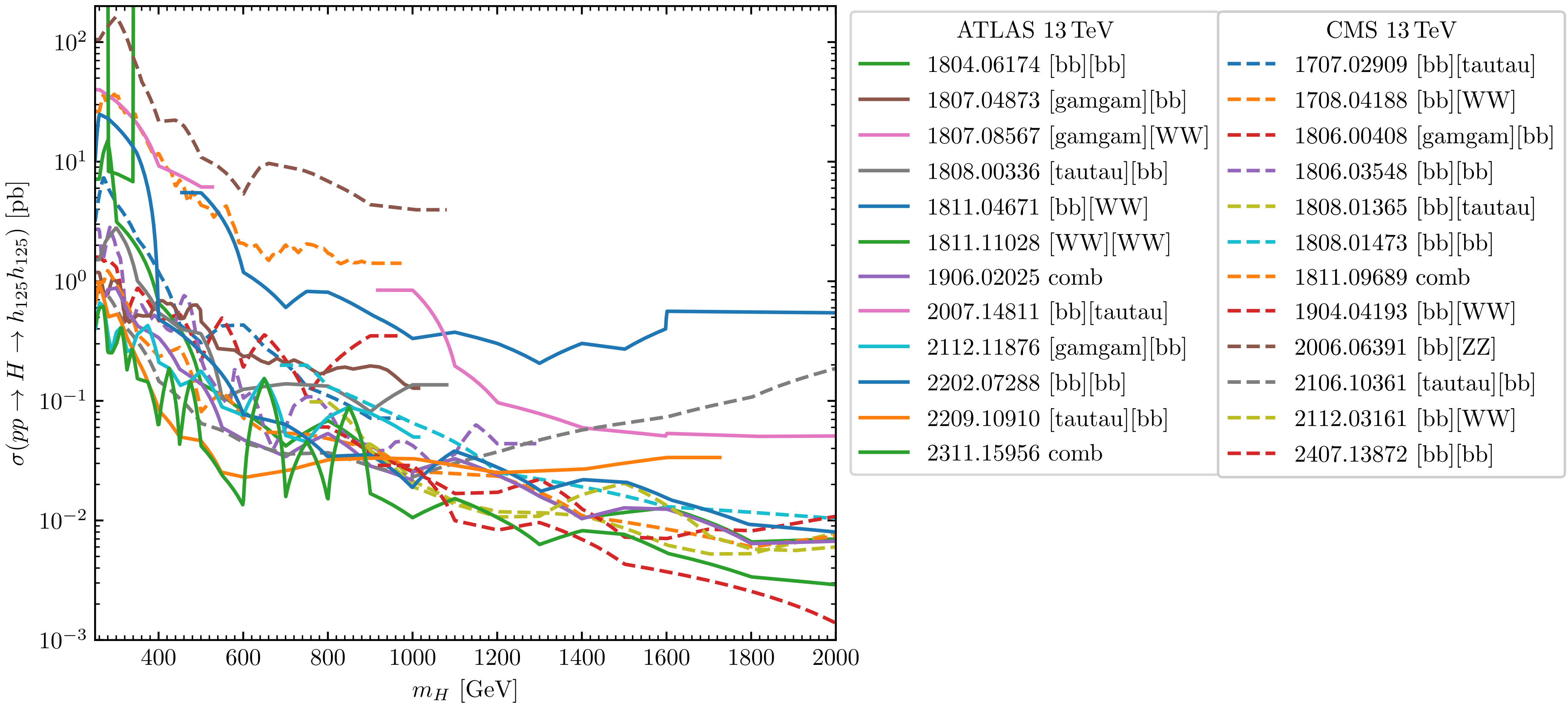

$t\bar{t}t\bar{t}$ validation