Double Higgs Production at Colliders Workshop

Fermilab

Summary of Theory Discussions

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Lot's of theory talks:

Latest SM predictions, Javier Mazzitelli
Trilinear Higgs self-coupling extraction from single Higgs measurements, Stefano Di Vita
Trilinear Higgs self-coupling determination from single-Higgs differential measurements, Ambresh Shivaji
Monte Carlo modelling of HH, Eleni Vryonidou
Full NLO QCD corrections to ggF HH production, Julien Baglio
Reinterpretation of non-resonant HH searches, Anamika Aggarwal
Beyond the Standard Model HH production, Ian Lewis
The least studied coupling in (double) Higgs physics, Ian Low
Di-Higgs, Gravitational Waves, and LHC, Tathagata Ghosh
A Dark Horse in Search for Non-Resonant Double Higgs, Jeong Han Kim
Exotic decays in HH production, Brian Batell
BSM multi Higgs, Nausheen Shah
Interferences in searches for heavy Higgs bosons, Stefan Liebler
ggHH generation and benchmarks, Alexandra Carvalho
Interference effects in the alignement scenario, Marcela Carena
Reflections on Double Higgs Production at the LHC, Carlos Wagner

Disclaimer: this is just a very brief summary of the results and discussions that I think have more overlap with the HXSWG activities

Many parallel discussion sessions:

1. ATLAS+CMS combination (Luca C., David W., Javier M., B. Di Micco) - Wednesday Room Ramsey
   - based on 2015+2016 in preparation of the Run-2 legacy
   - MC settings (NLO vs LO)
   - Single H+HH combination
   - Total cross section vs k_lambda + uncertainties

2) How to make results public (J. Allison, Max S., K. Leney) - Friday 1W (17:30 - 18:30)

- Tools to provide unfolded UL
  - How to handle bbb correlations?
- Resonant: Gamma vs Mx plot?
  - How to reweight different widths?
- cut based results
- differential results in m_HH (truth vs. reco)
- Special care for BDT-based results

3) EFT (S. Di Vita, M. Gouzevitch, J. Robinson) [17:30 - 18:30] 11th floor ROC

- Which framework? More operators beyond O6
- How to make EFT useful for model testing?
- Which inputs from H and HH?
- Which topology? ggF/VBF single H background?
- Usage of shape benchmarks

4) BSM (M. Carena, K. Tschann-Grimm, Ian Lewis, Lian-Tao Wang, X. Carvalho) Wednesday 11th floor ROC - Room One West

- Benchmark models : which one ?
  - Resonant: Is graviton still a good benchmark?
  - Interplay with VV
- Motivations for H1->H2 h
- Interference with SM HH (EWK-S, 2HDM) benchmark

5) ATLAS/CMS objects/analysis strategies (M.Kagan, F. Micheli, C.Vernieri) [Thursday 1W (5:00-5:45)]

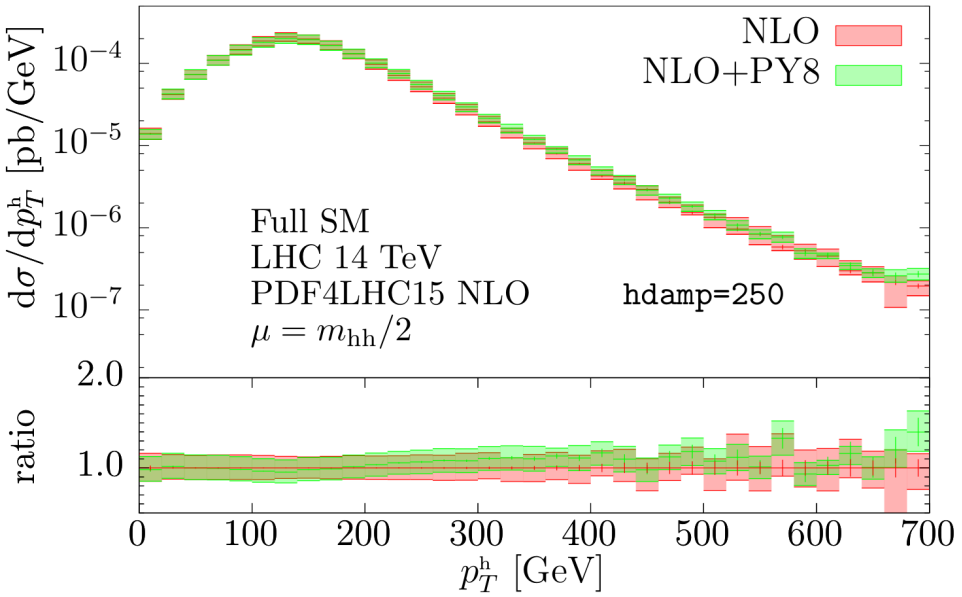
- Trigger strategies
- B-tagging and b-jets (regression)
- MET

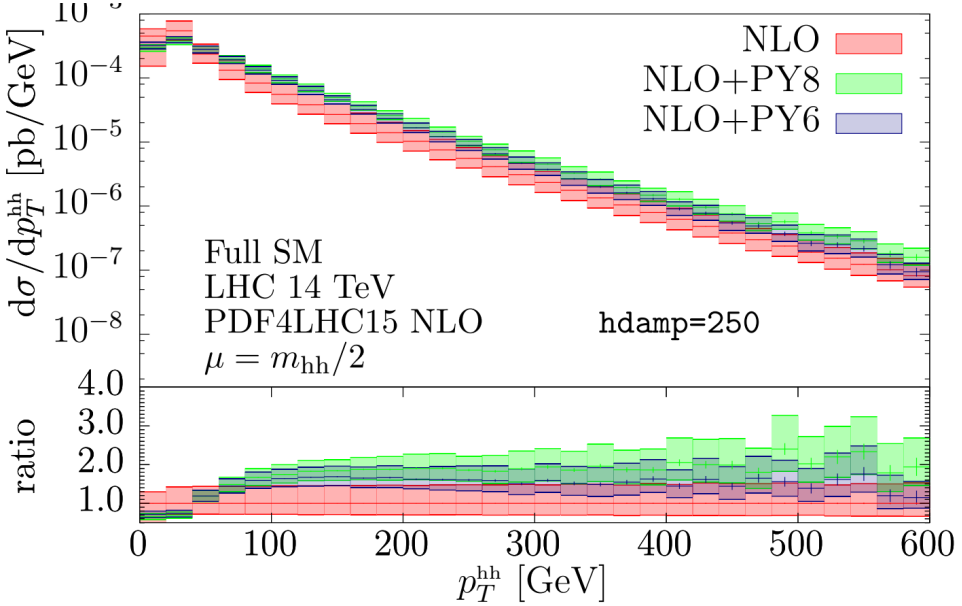
6) How to improve WWbb (W off-shell) [S. Shrestha, N. De Filippis - Thursday 11 ROC]

MC settings: talk by Eleni Vryonidou, latest full NLO + PS results presented

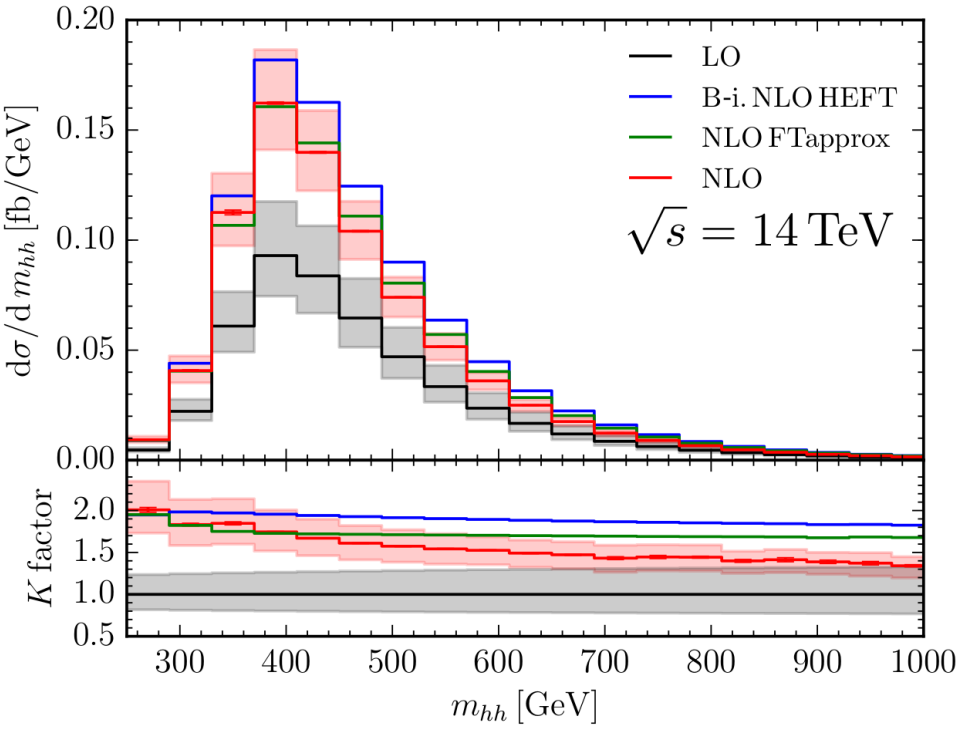
Available implementations: POWHEG-BOX VS: User-Processes-V2/ggHH/
MG5_aMC@NLO (contact Eleni)

NLO two-loop virtuals: 2D grid+interpolation (necessary to ensure reasonable running times)





- Small PS effects in NLO-accurate observables
- Very large effects for effectively LO-accurate distributions
- Also larger matching uncertainties
- Reliable predictions at low pT_{hh}, where FO fails
- Full NLO crucial to get accurate description of m_{hh} distribution



- **Currently:** CMS using LO+Pythia8, ATLAS $NLO_{FTapprox}$ with MC@NLO+Herwig++

- **Plan:** move to a full NLO generator (at latest for the ATLAS+CMS combination)
  Still no decision about Powheg or MC@NLO and Pythia or Herwig

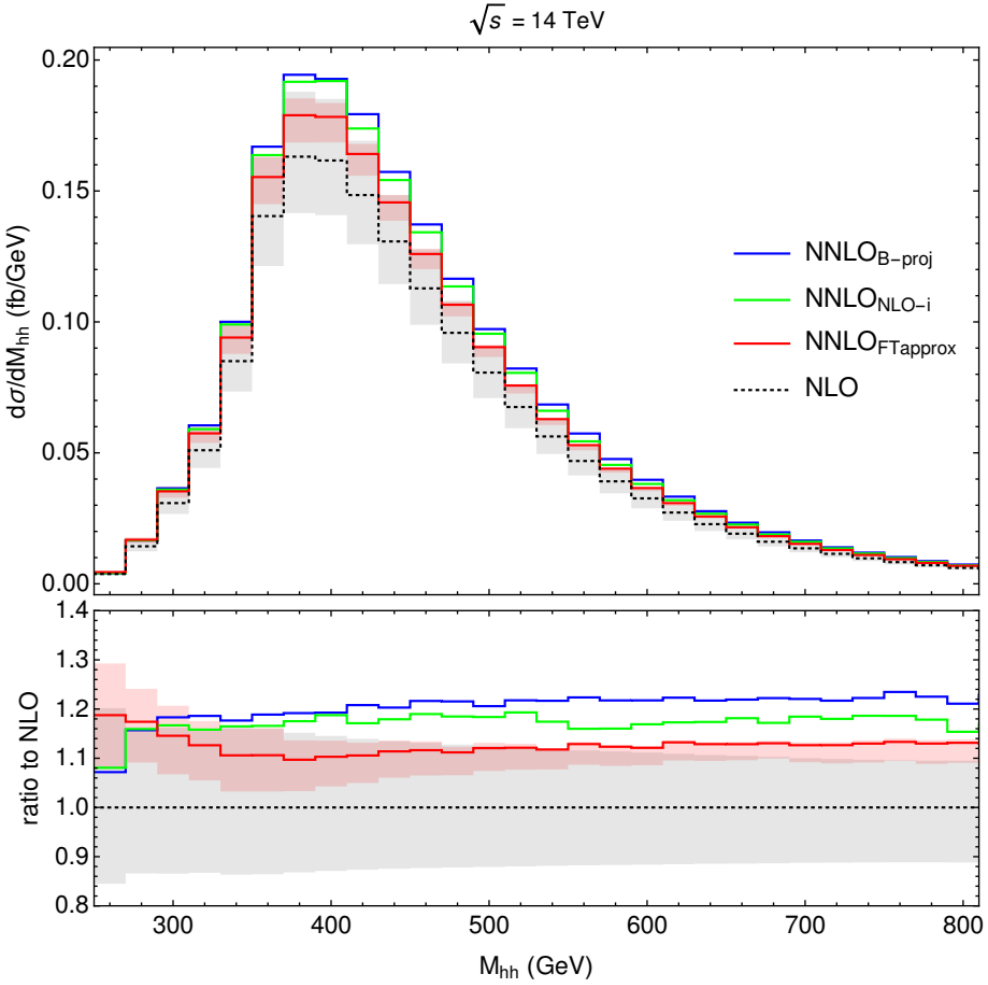
  Obs: ATLAS+CMS combination not before end of Run2, realistic time ~2020, after individual channels legacy papers are out

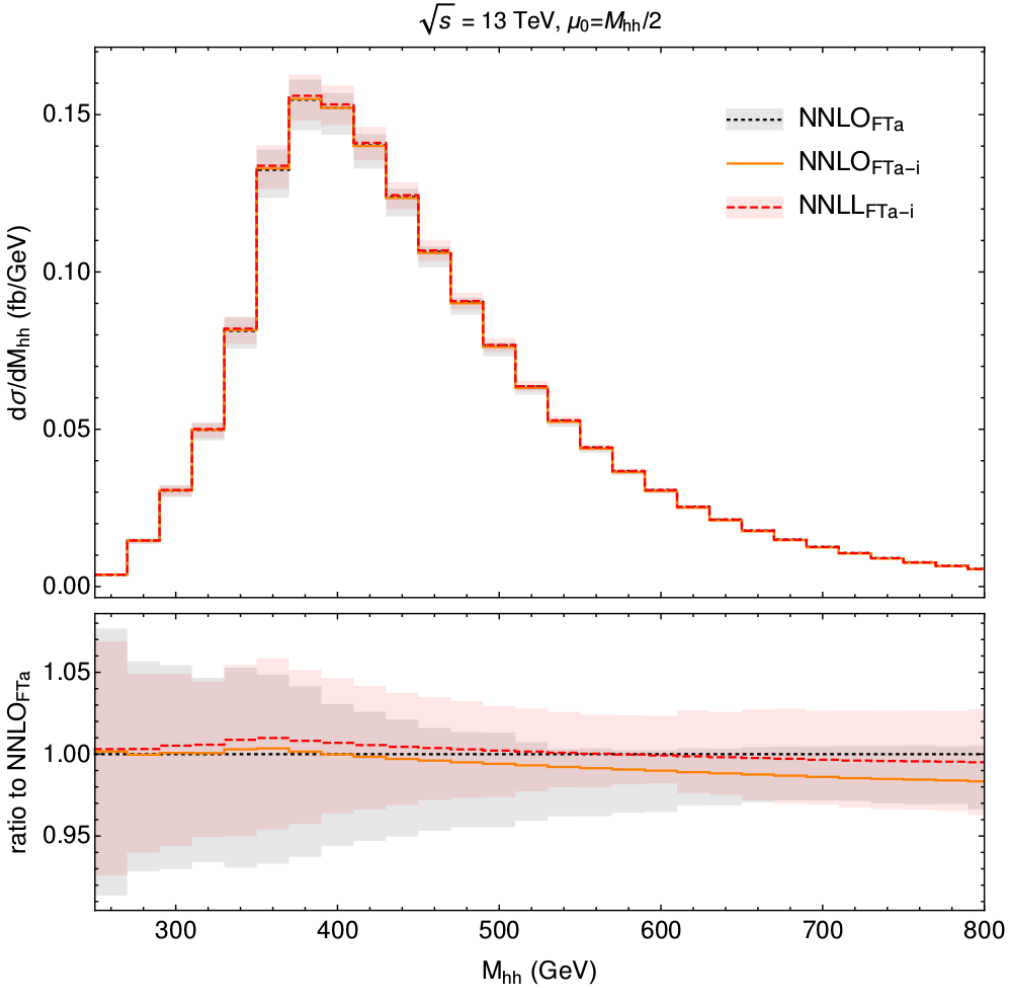
- Developments needed from the theory side:

  Full NLO MC generator allowing κ_λ variations

  → Needs κ_λ in virtuals (Gudrun et al.), probably available soon?

Total cross section: $NNLO_{FTapprox}$ presented, including threshold resummation





Large reduction of scale uncertainties w.r.t. NLO

Good overlap with NLO uncertainty band, ~12% increase for total cross section

Much smaller Mt uncertainties than other approximations, at the few percent level

Threshold resummation effects below 1% for $\mu=m_{hh}/2$

Strongest effect in the shape of scale uncertainties

- **Currently:** NNLO+NNLL in the BI-HTL --including full NLO effects-- is used (YR4)

- **Plan:** move to the $NNLO_{FTapprox}$ (current recommendation on the twiki, -8% difference from YR4)
  NNLL effect very small for $\mu=m_{hh}/2$, we can stick with the fixed order prediction

- Also here **κ_λ variations** would be welcome

  In the meantime results for the full NLO for different κ_λ values including theory uncertainties would be useful (for instance for κ_λ=0,1,20), probably available in a short time scale (essentially available in arXiv:1806.05162, just no uncertainties in the paper)

- Scans on κ_λ are very welcome, but more general deviations from the SM need to be included

EFTs are the best way to address anomalous couplings

- EFT model independent, but validity assumptions should be clearly recalled in WhP
- Both linear and non-linear approaches should be considered
- Consider both *Dim6*SM* and *Dim6*SM+Dim6^2* (latter justified if Dim8*SM suppresed)

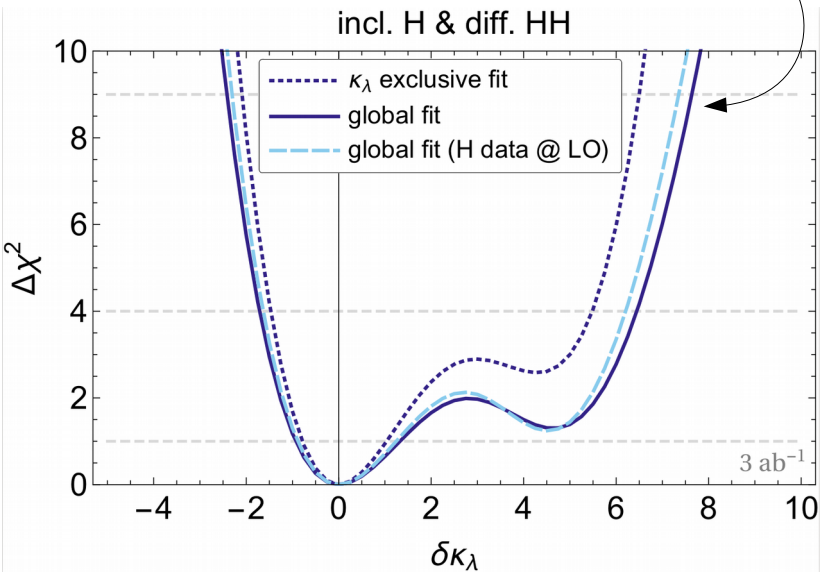
Suggested to define classes of models and operators to include for each of them

- Operators affecting only Higgs observables at LO to be included at least
- Chromomagnetic or 4 fermions (with tops) operators not considered until now (expected to be small in some class of models) but can also be considered in future analyses
- Of course, independently of including or not κ_λ loop effects on H production, single H observables need to be included in the fit to constrain the other operators affecting HH

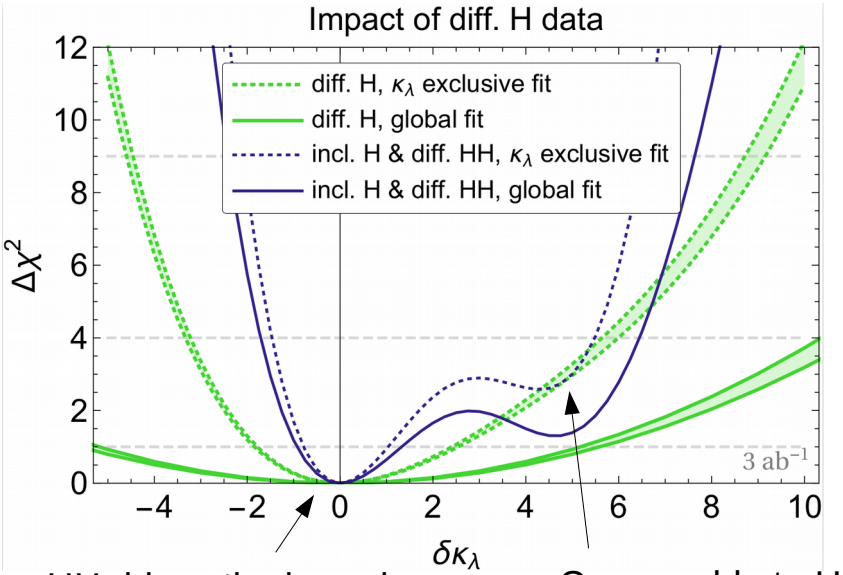
What about κ_λ constraints from single H?

Talks by Stefano Di Vita, Ambresh Shivaji

Using only inclusive single H data, κ_λ effects in single H are not relevant in a global fit



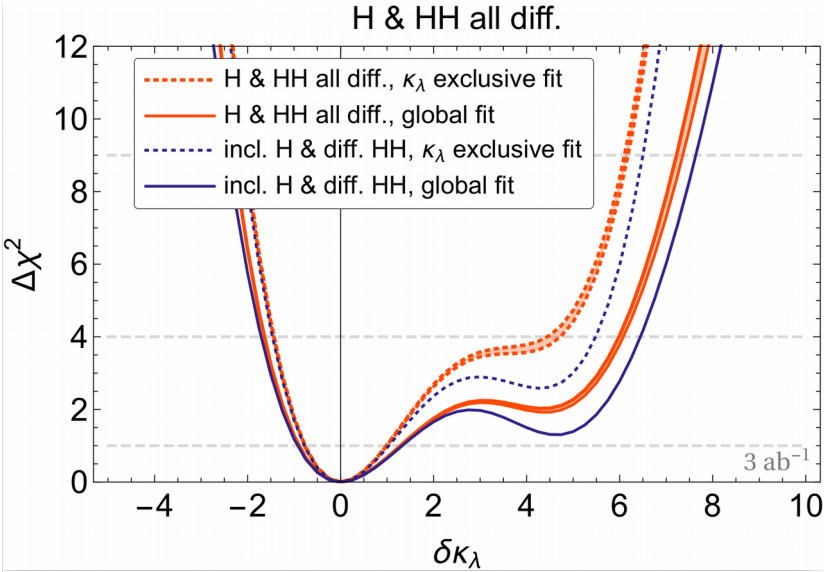
Including differential H data improves a lot the situation



HH drives the bound for small or negative κ_λ

Comparable to HH for large κ_λ

Specially for studies with large κ_λ, important to include κ_λ effects in (differential) single Higgs



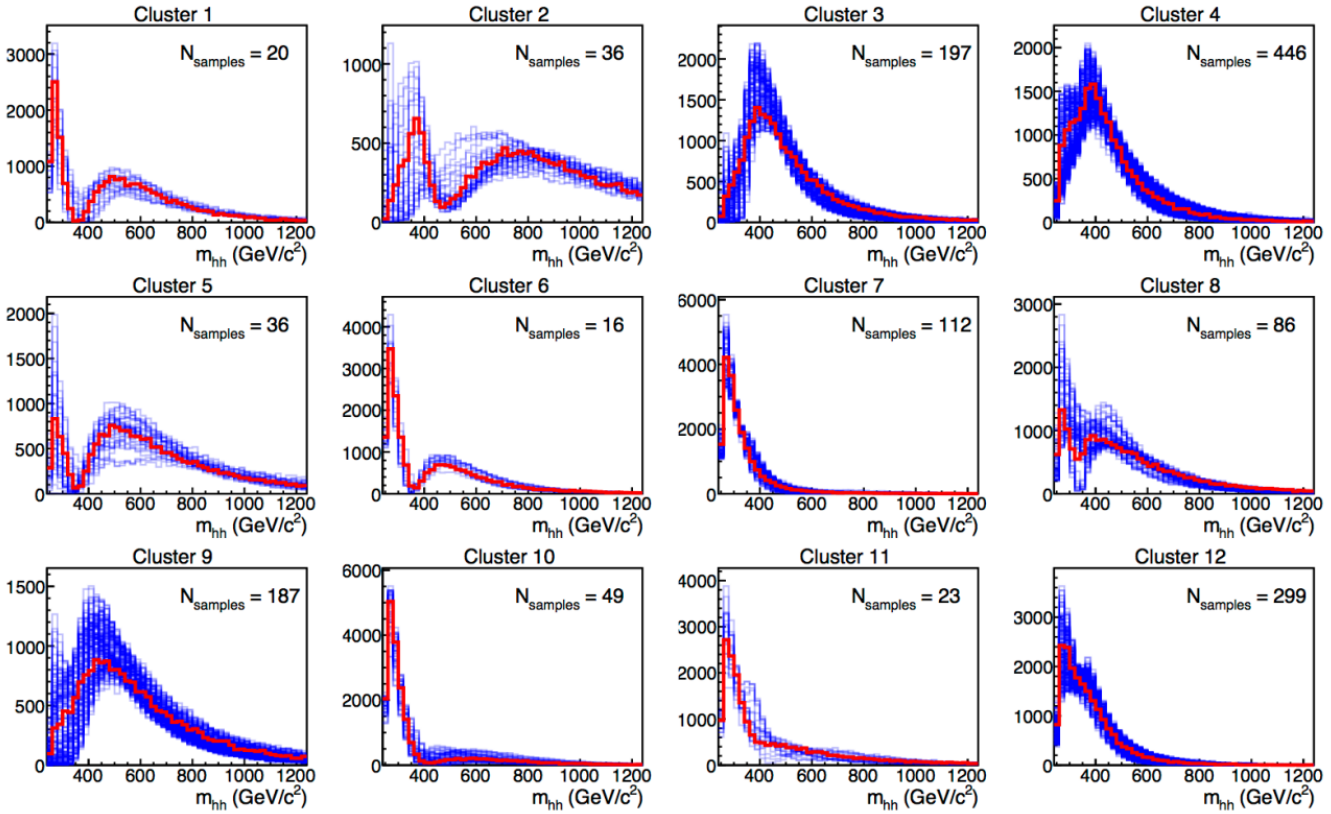
Ultimately a global fit will be needed:
HH+H+aTGC

First (training) step:
Consider HH+ttH, let κ_λ and κ_t float for a combined fit including EW corrections

Warning:
Bounds on κ_λ from simplifed fits have a physical interpretation only in very non-generic scenarios!

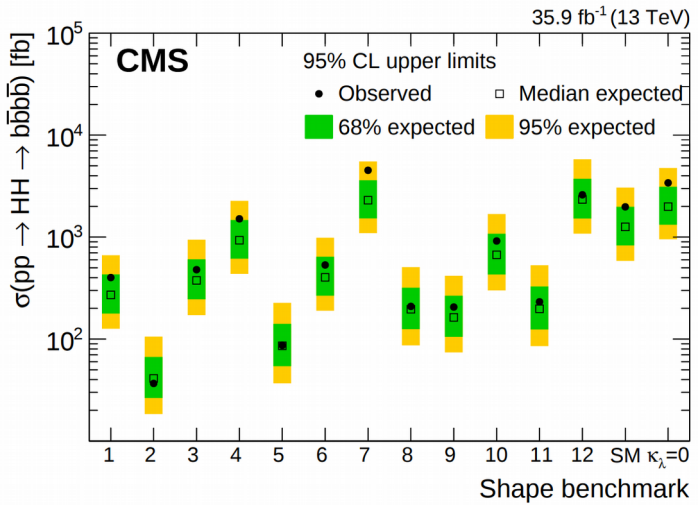
Presentation of the results

- Shape benchmarks Talk by Alexandra Carvalho



12 benchmarks clustering the possible shapes of the m_{hh} distribution for different EFT Wilson coefficients (κ_λ, κ_t, c_{tthh}, c_{ggh}, c_{gghh})

Experiments can provide limits on these benchmarks:



Keep providing these benchmarks, maintain a **tool** to easily convert **limits on benchmarks** to limit for combination of **Wilson coefficients**

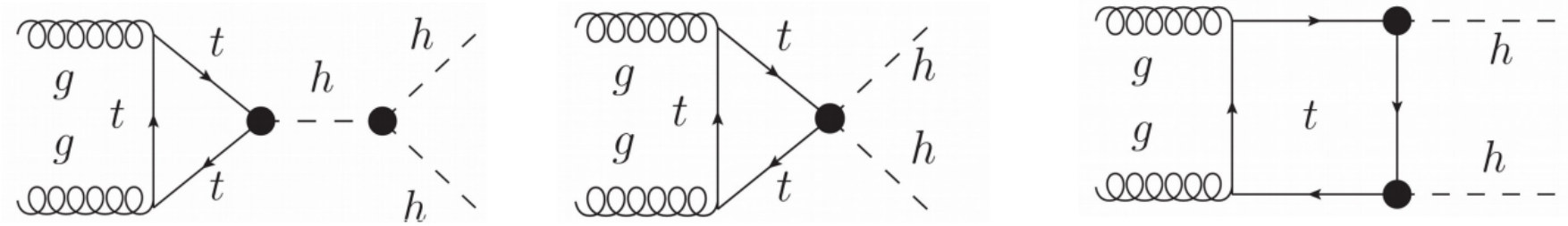
Check if Chromomagnetic shape is covered by one of the benchmarks

- Theorists would like experiments to provide information on m_{hh}, something like limit/bin
  Dedicated discussion session on this topic

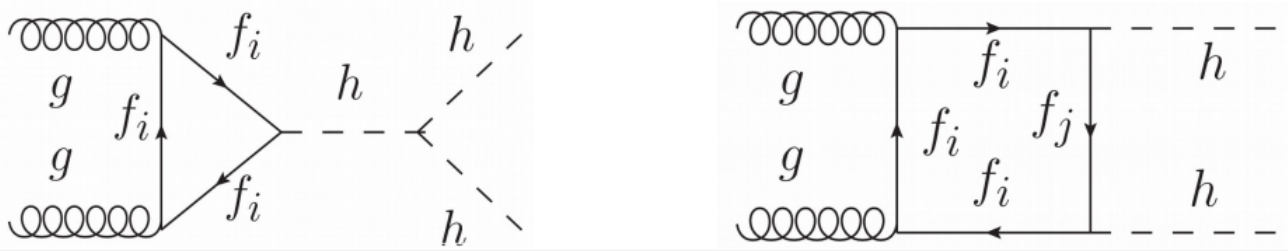
BSM in double Higgs

[Talk by Ian Lewis]

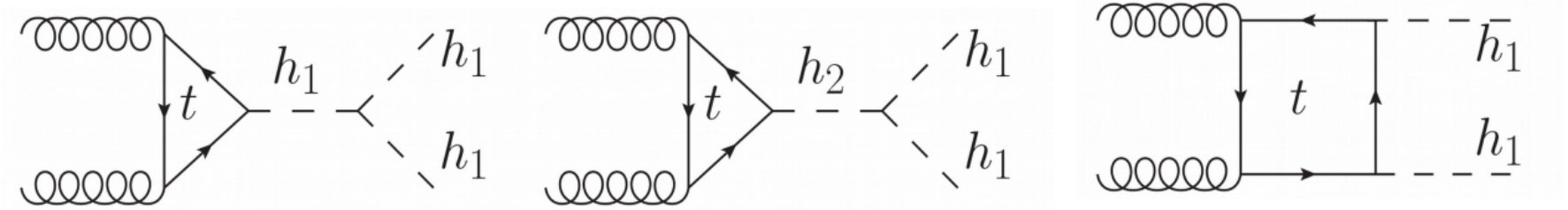
- Couplings different from the SM and/or EFT



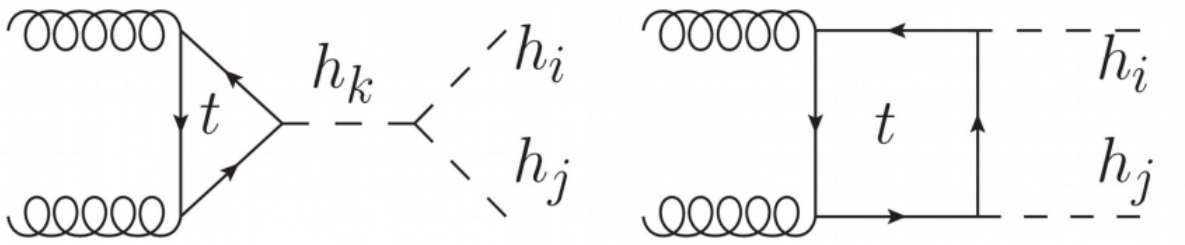
- New physics in the loop.



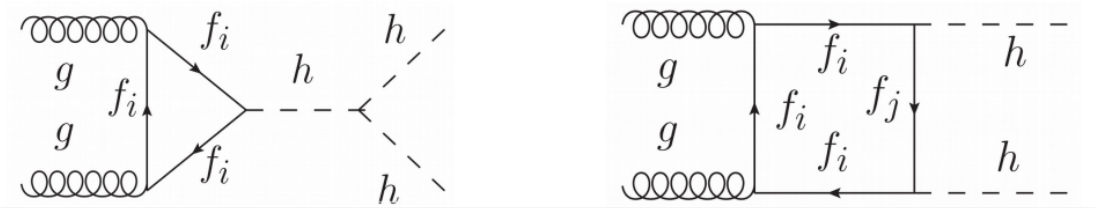
- New resonances.



- Double exotic Higgs production.

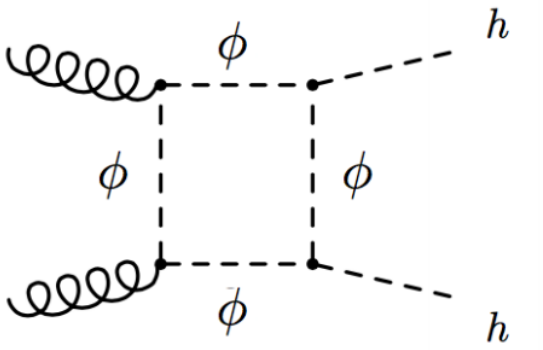


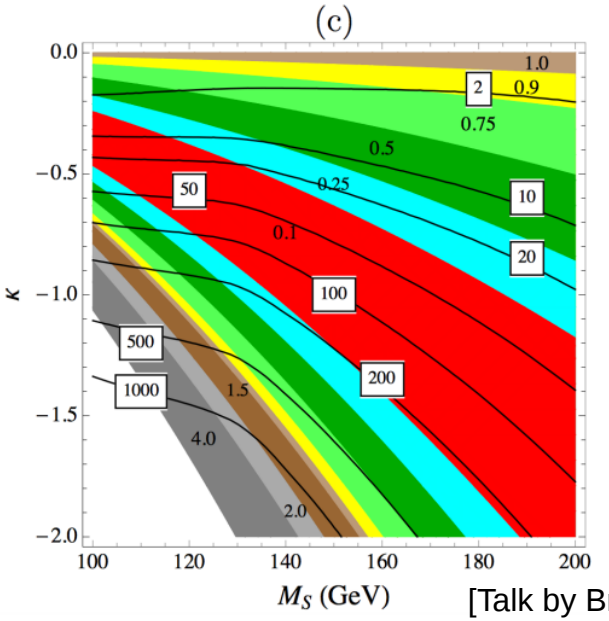
New physics in the loop



New colored scalars can dramatically enhance HH production

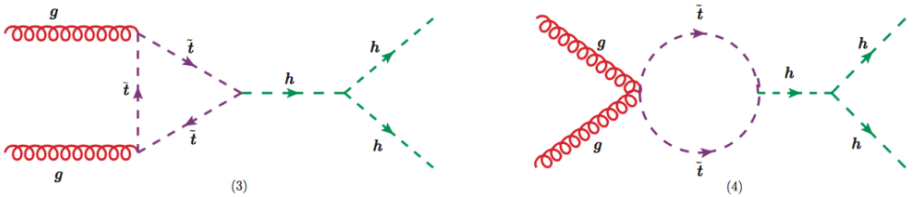
However it's hard to remain consistent with single H limits



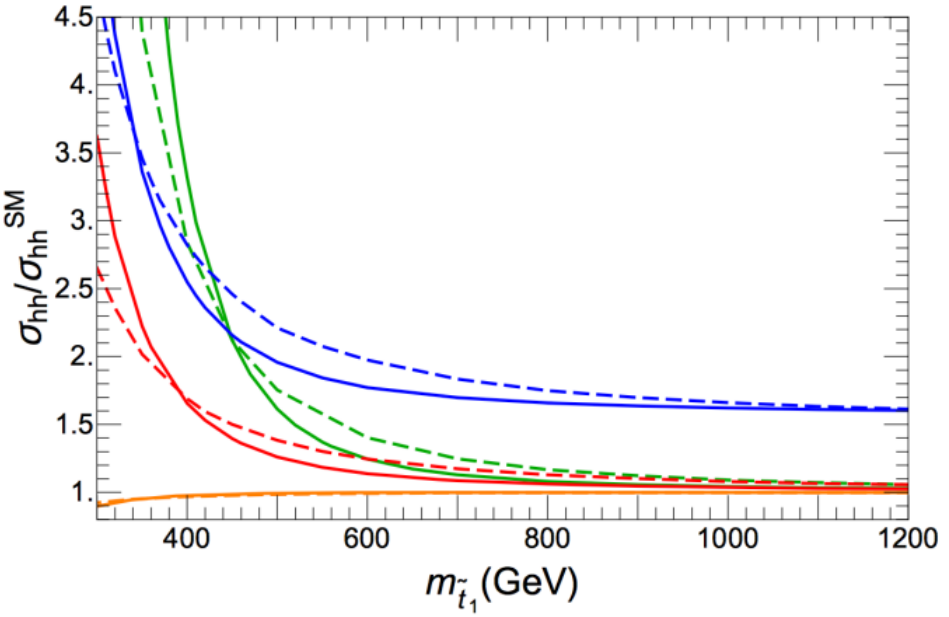


[Talk by Brian Batell]

Stops are colored and couple strongly to Higgs, can have important contribution to HH production

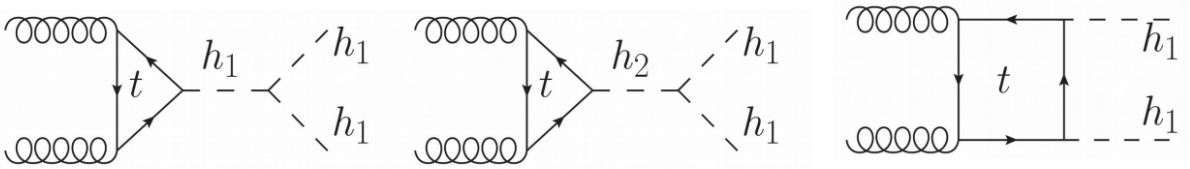


Stops loops can produce an O(1) enhancement, particularly if top Yukawa is enhanced



[Talk by Carlos Wagner]

New resonances



- Simplest model: add a real singlet scalar

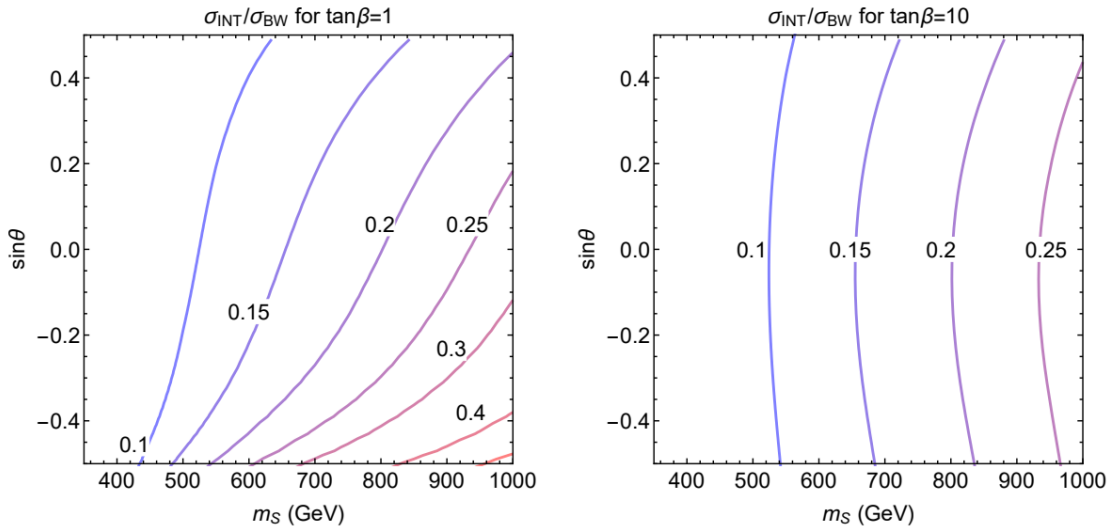
$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + \frac{a_1}{2} \Phi^\dagger \Phi S + \frac{a_2}{2} \Phi^\dagger \Phi S^2$$
$$+ b_1 S + \frac{b}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

[Talk by Ian Lewis]

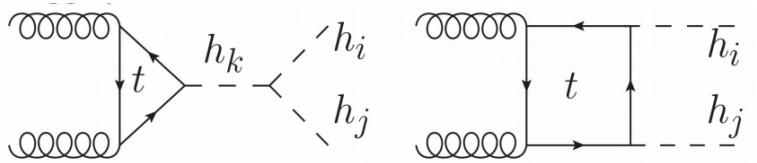
- Free parameters: two masses, mixing angle, potential parameters
  In regions of parameter space HH can be its dominant decay mode

- Interference effects between SM and new resonances can be significant [Talk by Marcela Carena]

  If there is a phase shift between SM and new physics amplitudes → on-shell interference effect affecting total rate



Double exotic Higgs production

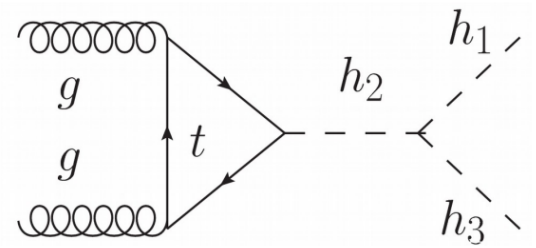


Production of exotic Higgs bosons also deserves attention

Well motivated from the theoretical point of view, more difficult experimentally

Simple model: complex singlet → three physical scalar bosons $h_1(125)$, h_2, h_3 [Talk by Ian Lewis]

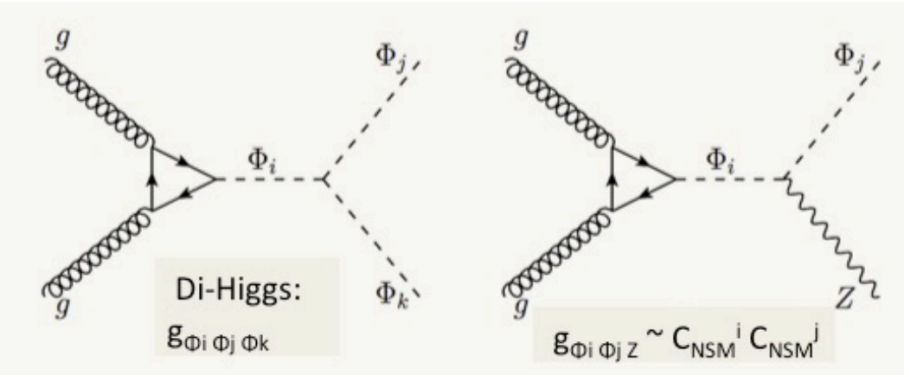
Possible to have $h_2 \rightarrow h_1 h_3$ (in fact it's the only way to produce h_3 in the limit in which it does not mix)



Also: 2HDM+S well motivated extended Higgs sector [Talk by Mausheen Shah]

H decays to $h_{125}h_{125}$, $h_{125}Z$, ZZ suppressed due to alignement

H decays to h h_{125} and hZ final states NOT supressed



BSM in double Higgs

Some items in the summary of the discussion session:

- Simple models that could be included in searches:

  S-channel resonances: 1) spin-0, 2) spin-2
  higgsino → hh+MET or higgsino → hh+jets
  Also $X \rightarrow h_1 h_2$ or $X \rightarrow V h_2$, with h_2 not the 125GeV boson

- Move away from RS models, which were firstly introduced to have sizeable cross sections to be probed

- **Action item: go for simplified models**


Thanks!