Higgs pair production at the LHC
SM and beyond

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Based on arxiv:1401.7340,1407.0281 and 1408.6542

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DESY Theory Workshop
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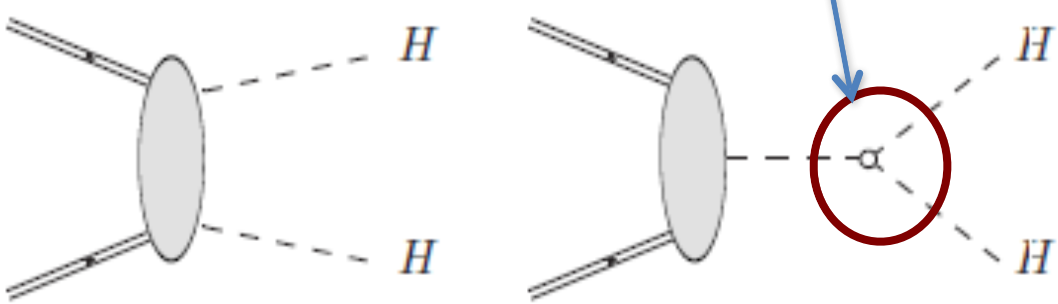
Outline

- Motivation
- HH in the SM
- HH in the 2HDM
- Outlook

Motivation

- ***Higgs self couplings: Not yet measured at the LHC***
  - Higgs potential:

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

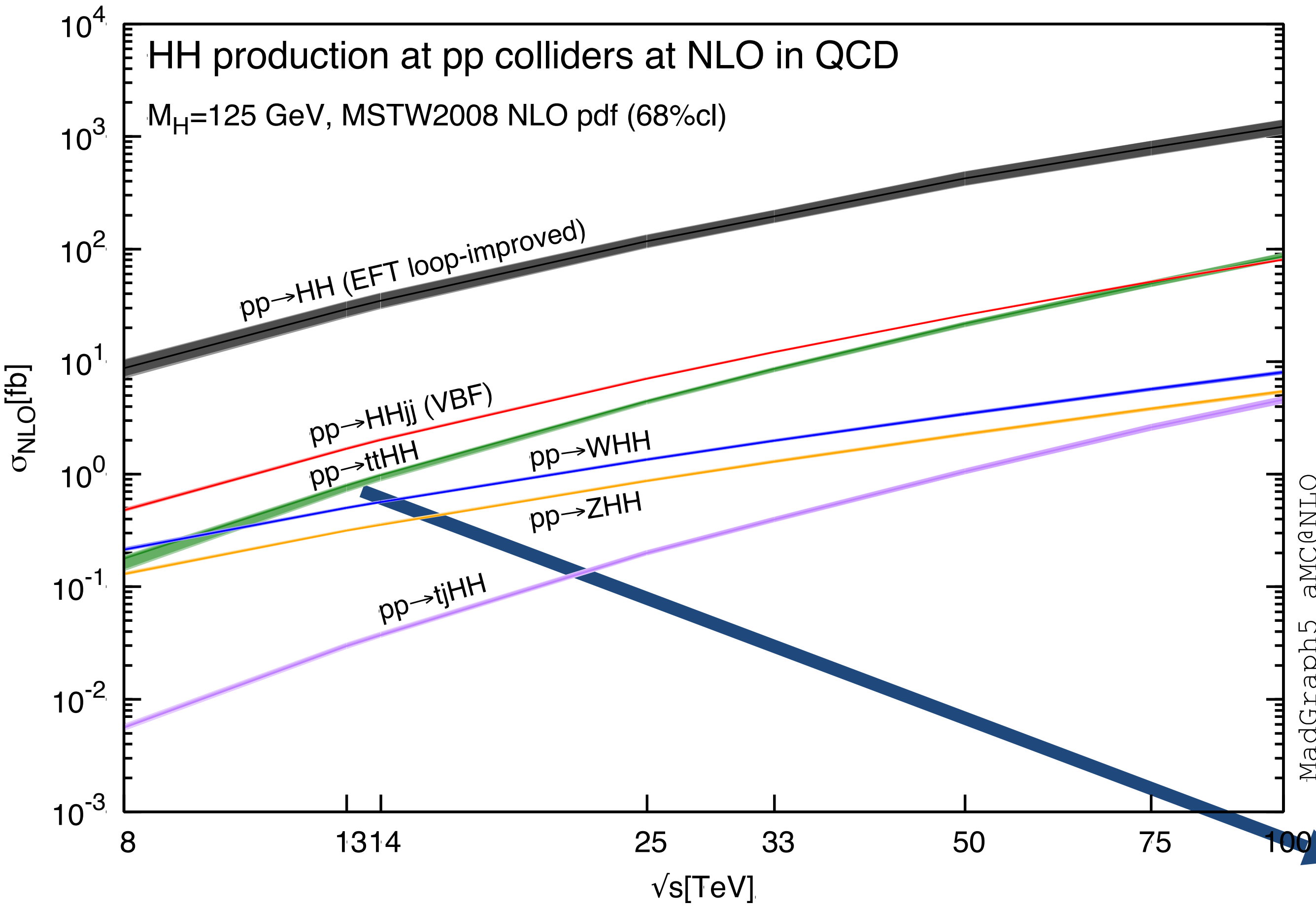


Triple Higgs production: σ<0.1fb at 14TeV

Fixed values in the SM

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

Higgs pair production at the LHC



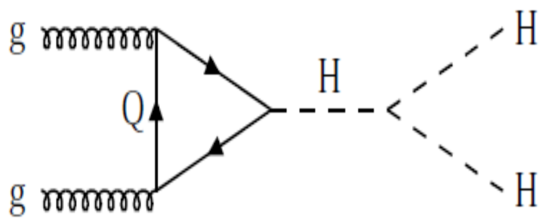
Gluon gluon fusion dominates
$\sigma \sim 35$fb at 14TeV

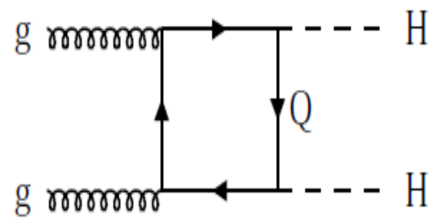
Vector boson associated production and ttHH hierarchy reversed compared to single Higgs production

Frederix et al. arxiv:1401.7340
Publicly available in MG5_aMC@NLO

See also Baglio et al. arxiv:1212.5581 for a survey of all channels

HH in gluon-gluon fusion

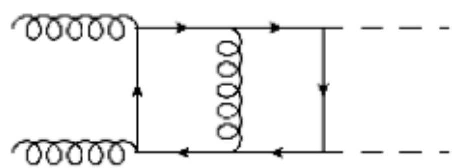




Biggest cross section
Loop-Induced

Glover, Van der Bij Nucl.Phys. B309 (1988) 282
Plehn, Spira, Zerwas, Nucl.Phys. B479 (1996) 46

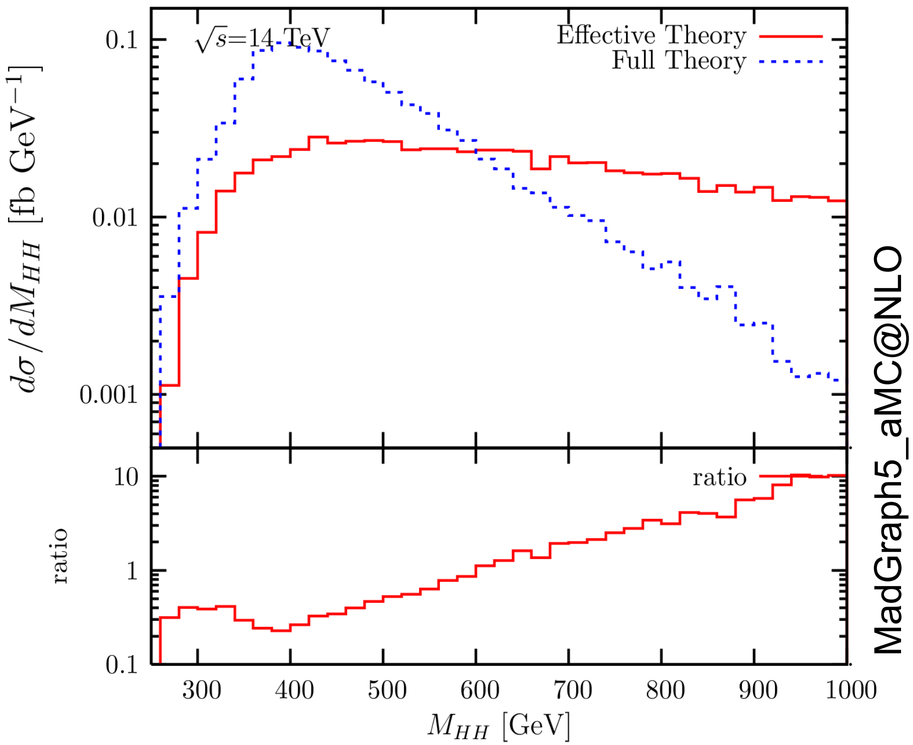
- Exact NLO computation requires:
  - Real emissions: HHj one loop ✔
  - Virtual corrections: Include 2-loop amplitudes ✗



- NLO results in the HEFT:
  - Dawson, Dittmaier, Spira hep-ph/9805244
  - Improved by exact LO contribution
- NNLO results in the HEFT : De Florian and Mazzitelli, arXiv:1309.6594, Grigo et al, arXiv:1408.2422

HEFT approach in HH production

How well does the HEFT work for HH?



10-20% difference for the total cross section

HEFT fails to reproduce the differential distributions

Top mass effects are important and need to be included

Higher order HEFT computations use the exact LO contribution: using the EFT k-factor

$$\sigma^{NLO}_{HEFT}/\sigma^{LO}_{HEFT} \times \sigma^{LO}_{FT}$$

at the differential level: matrix elements ratio

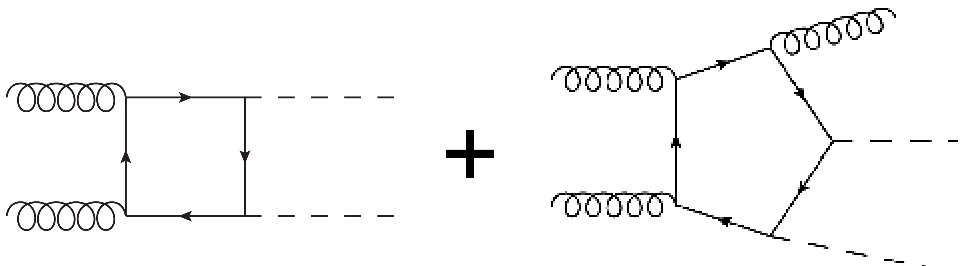
$$\mathcal{B}_{FT}/\mathcal{B}_{HEFT}$$

NLO HH production: A step further

Available information:

Exact real emission matrix elements
Virtual corrections in the HEFT-rescaled by the exact born

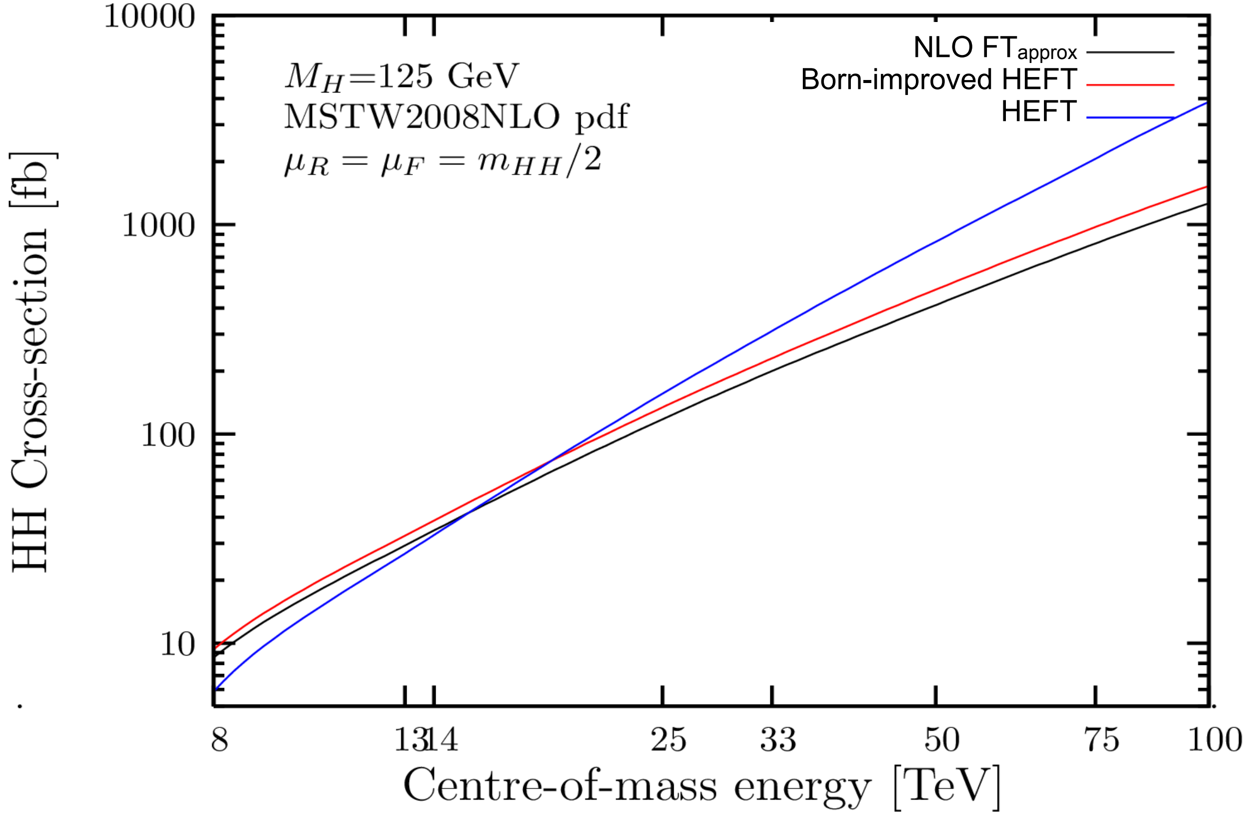
- Within the MG5_aMC@NLO framework:
  - HEFT UFO model allows us to generate events at NLO
  - MadLoop can perform the computation of the exact one-loop matrix elements: born and real-emission



- Event by event basis reweighting: Fully differential
- Better description of hard emissions
- Matching to parton showers with the MC@NLO method

arxiv:1401.7340 and 1408.6542

Results: Total cross section for HH



Comparing:

- NLO FT$_{approx}$ (exact real-approximate virtuals)
- Born-improved HEFT
- NLO HEFT

▹ Reduction of the cross section by about 10% compared to the Born-improved results at 14 TeV

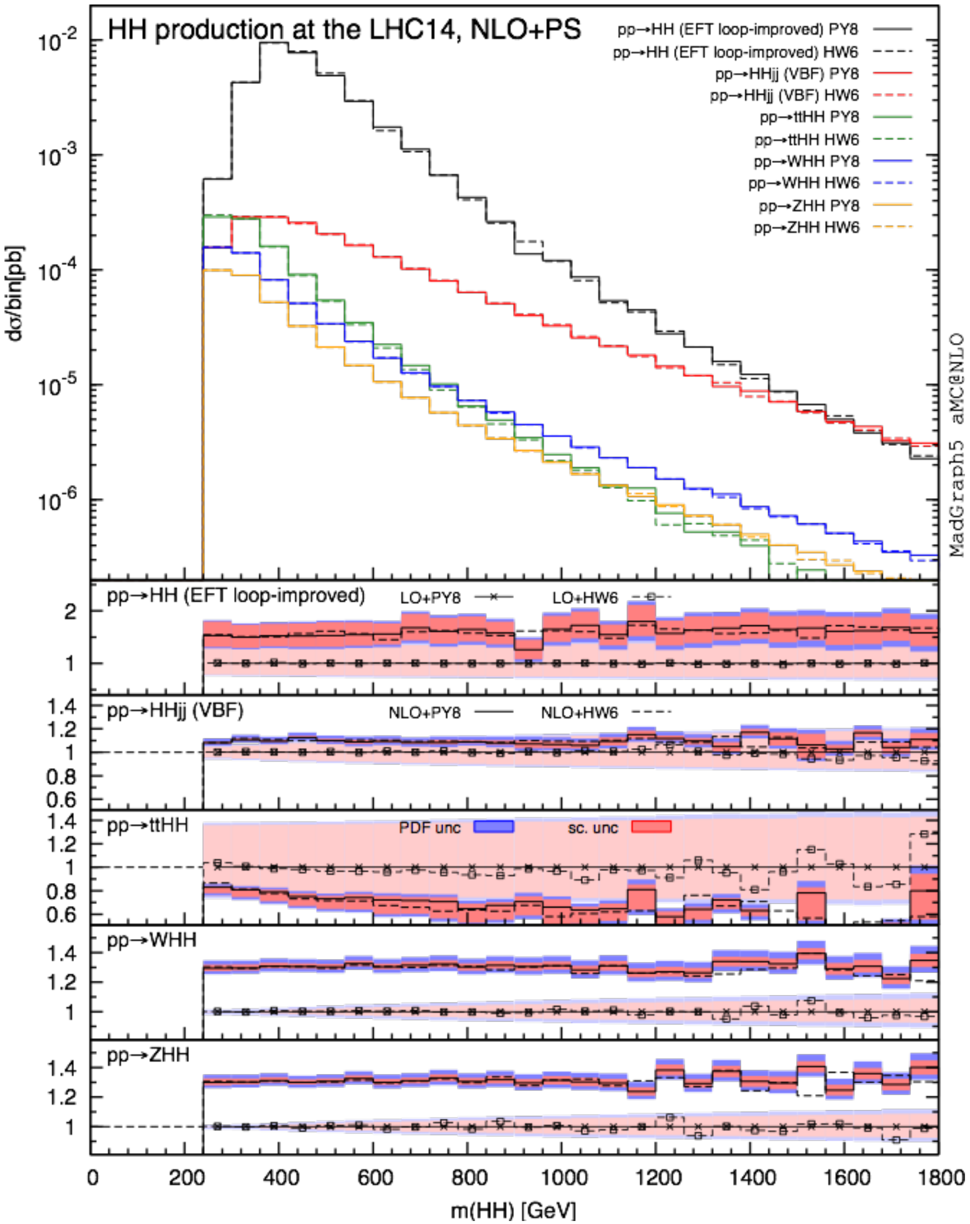
Results at 14 TeV [fb]

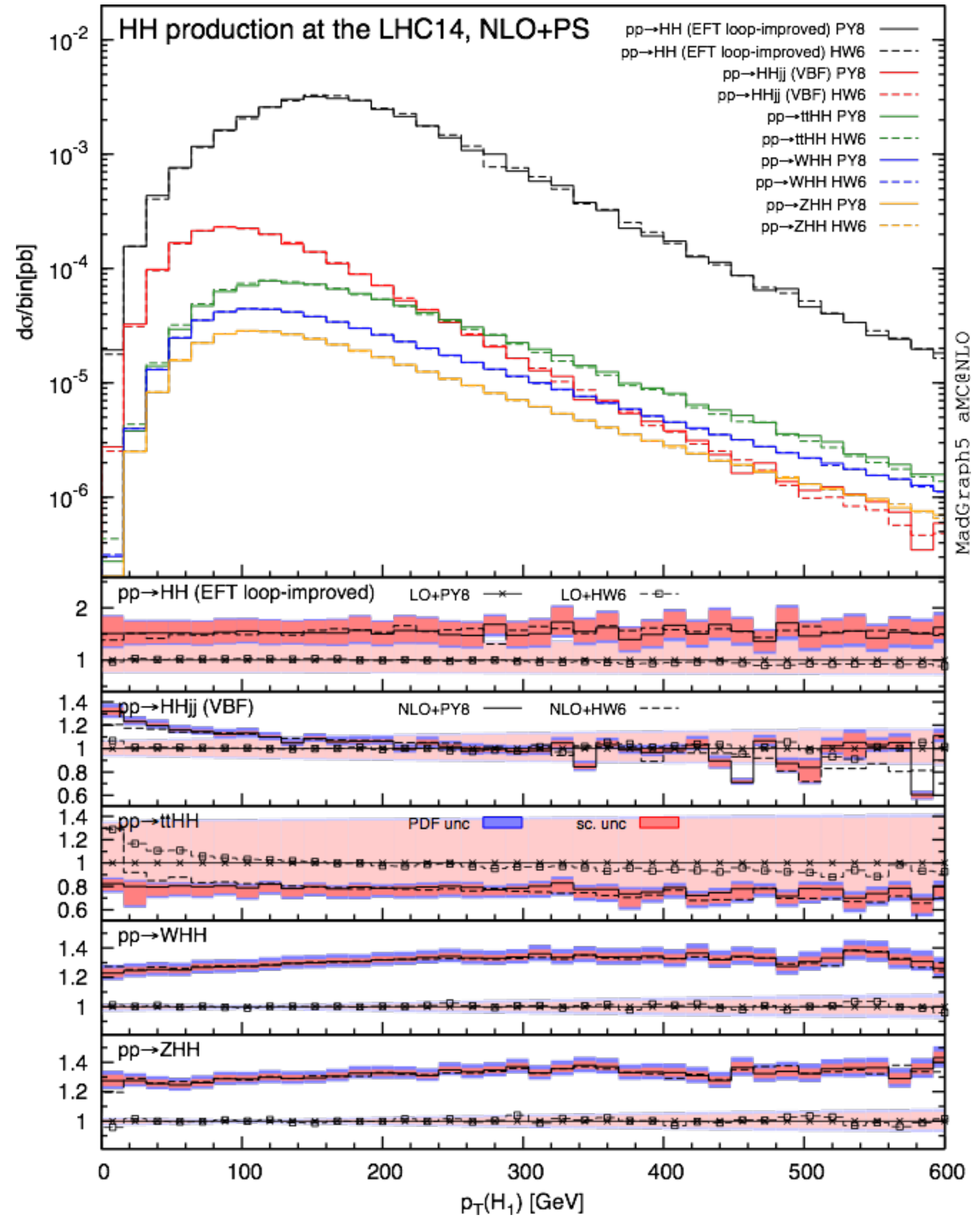
LO	FT, $\Gamma_t = 0$ GeV	$23.2^{+32.3+2.0\%}_{-22.9-2.3\%}$
LO	FT, $\Gamma_t = 1.5$ GeV	$22.7^{+32.3+2.0\%}_{-22.9-2.3\%}$
NLO	HEFT	$32.9^{+18.1+2.9\%}_{-15.5-3.7\%}$
NLO	HEFT Born-improved	$38.5^{+18.4+2.0\%}_{-15.1-2.4\%}$
NLO	FT$_{approx}$ (virtuals: Born-rescaled HEFT)	$34.3^{+15.0+1.5\%}_{-13.4-2.4\%}$

2%: Use of Complex-Mass-Scheme Finite top width

10% : Exact real emission amplitudes

Differential distributions





NLO plus PS: all channels

SM HH Outlook

- Top mass effects are important: ~10% uncertainty due to missing top mass effects (see also previous talk and results in arXiv:1305.7340, arXiv:1508.00909)

Exact NLO calculation computation needed

Ongoing work to extract the 2-loop amplitudes both analytically and numerically

Next step:

- Phenomenology with a ~40fb (gluon fusion) cross-section
- Which are the promising decay channels to observe the process?
  - $bb\gamma\gamma$ (1212.5581), $bb\tau\tau$ (1206.5001,1212.5581), bbWW (1209.1489,1212.5581), bbbb (1404.7139)
- Recent progress achieved with boosted techniques
- Prospects for the measurement of the trilinear Higgs coupling at the LHC?
  - Optimistic estimate of 30% accuracy with 3000 fb^{-1} at 14 TeV (arxiv:1404.7139)
- Prospects in other channels? ttHH: 1409.8074, VBF: 1506.08008

Higgs pair production beyond the SM

BSM physics enhancements

New particles
Resonances

Higher dimension operators

- Non SM Yukawa couplings (1205.5444, 1206.6663)
- ttHH interactions (1205.5444)
- Resonances from extra dimensions (1303.6636)
- Vector-like quarks (1009.4670, 1206.6663)
- Light coloured scalars (1207.4496,1504.05596)
- Dimension-6 operators (hep-ph/0609049, 1410.3471, 1502.00539, 1504.06577)
- Higgs Singlet Model (1508.05397)

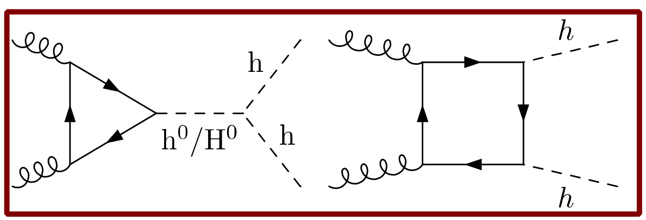
Higgs pair production in the 2HDM

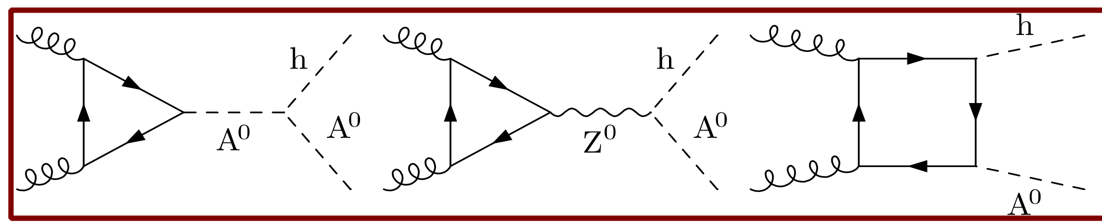
2HDM: Additional Higgs doublet

h light CP even
H heavy CP even
A CP odd
H^+ H^- Charged

Type-I and Type-II setups
2HDM input:
$\tan\beta$, $\sin\alpha$, m_h, m_H, m_A, m_{H+}, m_{12}^2

Pair production in gluon fusion

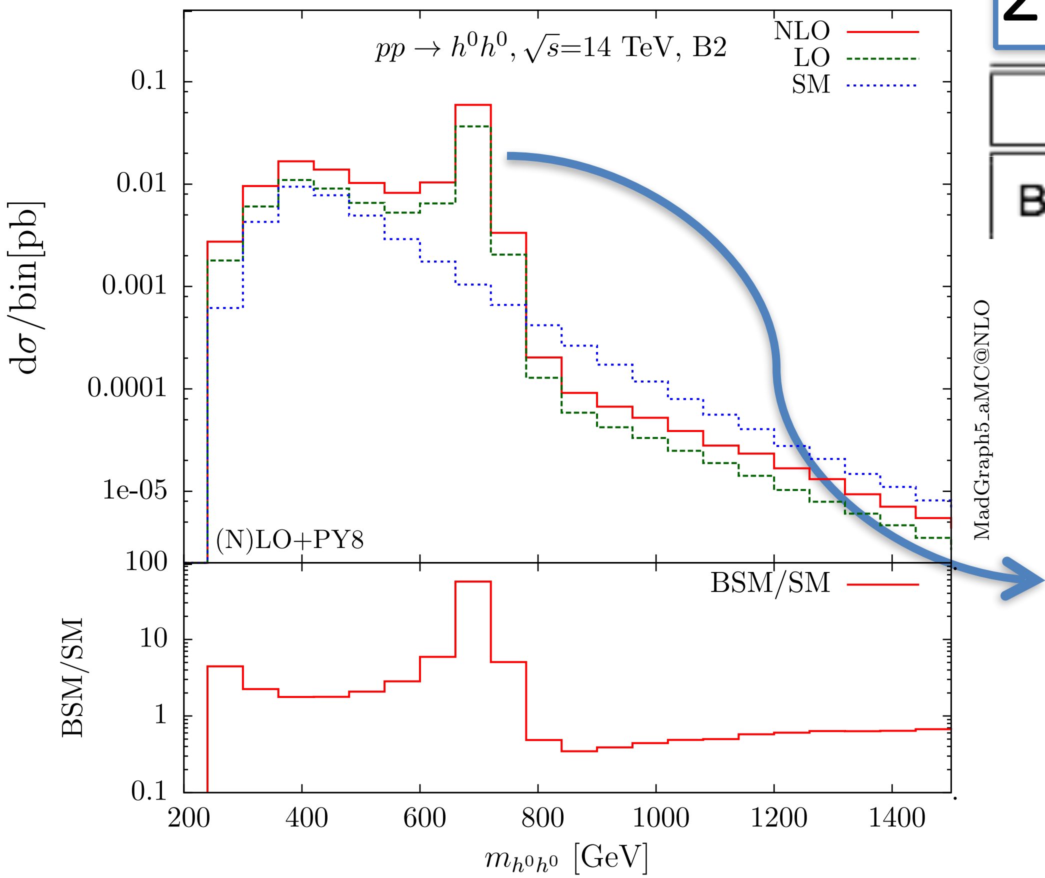




hh hH HH hA HA AA H^+H^-

Computation within the MG5_aMC@NLO framework arxiv:1407.0281
2HDM implementation using NLOCT arxiv:1406.3030

Light Higgs pair production
Resonant 2HDM scenario



σ_{hh}~ 4 times the SM prediction

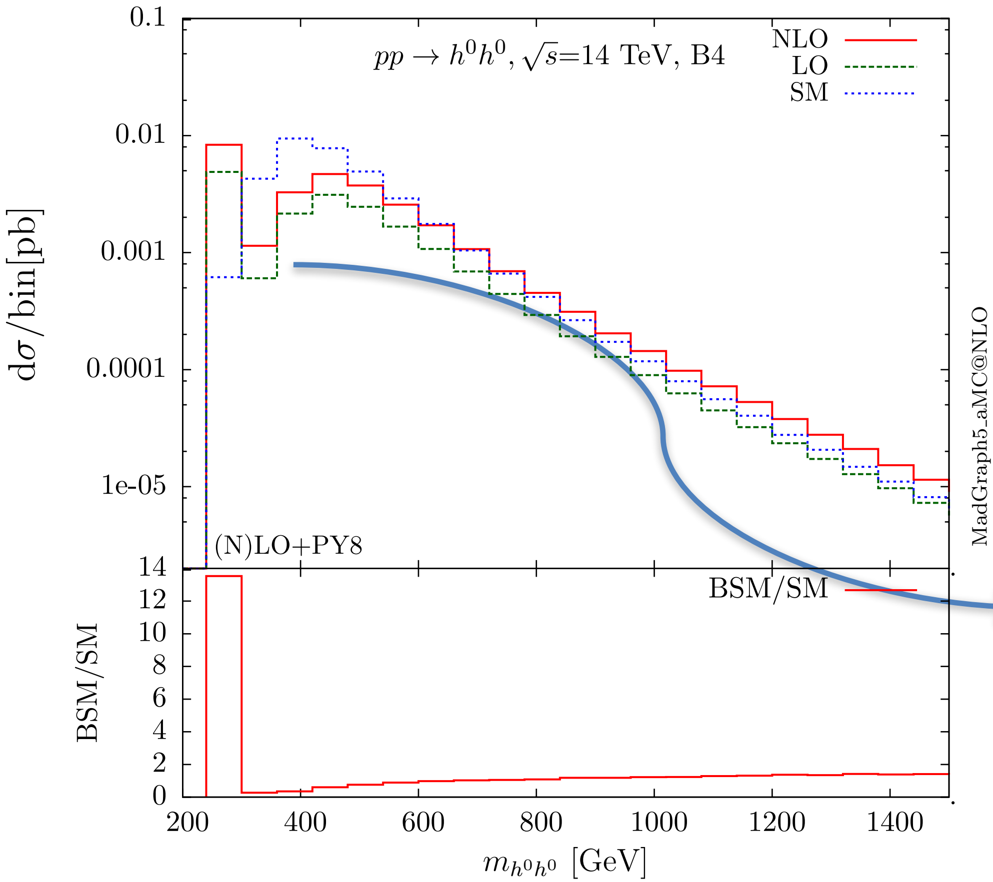
2HDM input: Type-ii

	tan β	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m^2_{12}
B2	1.50	-0.2162	700	701	670	180000

- Slightly reduced top Yukawa
- Reduced hhh coupling
- Enhanced Hhh coupling

- Significant resonant enhancement from H➔hh
- Distinctive resonance peak
- Bigger enhancements can be achieved with smaller H masses
- See also Baglio et al. arxiv: 1403.1264

Light Higgs pair production
Non-resonant 2HDM scenario



σ_{hh}~ 30% reduction of the SM prediction

2HDM input: Type-i

	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m^2_{12}
B4	1.20	-0.1760	200	500	500	-60000

- Slightly enhanced top Yukawa
- Enhaced hhh coupling
- Enhanced Hhh coupling

- Heavy Higgs mass below the hh threshold: No resonant enhancement
- Interference between different contributions leads to a different shape compared to the SM
- Important to study the distributions

Conclusions

- Higgs pair production key to the measurement of triple Higgs coupling
- MC implementation of the process at approximate NLO using the exact real emission amplitudes, provided in MG5_aMC@NLO
- Results can now be used for phenomenological studies including decays to identify the most promising channels
- HH can be a window to New Physics
- 2HDM an attractive framework to study the process: Computation for all pair of Higgs bosons in gluon fusion
- Light Higgs pair production can receive significant total rate enhancements due to resonant heavy Higgs production

Thanks for your attention...