Higgs pair production at the LHC in the SM and 2HDM

Eleni Vryonidou
Université catholique de Louvain

With B. Hespel, D. Lopez-Val, F. Maltoni, M. Zaro…

Based on arxiv:1401.7340 and 1407.0281

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Outline

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

Motivation

- Higgs discovery ⇒ SM Higgs?
- Higgs couplings measurements:
  - Couplings to fermions and gauge bosons

Good agreement with the SM

- ***Higgs self couplings***
  - Higgs potential:

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

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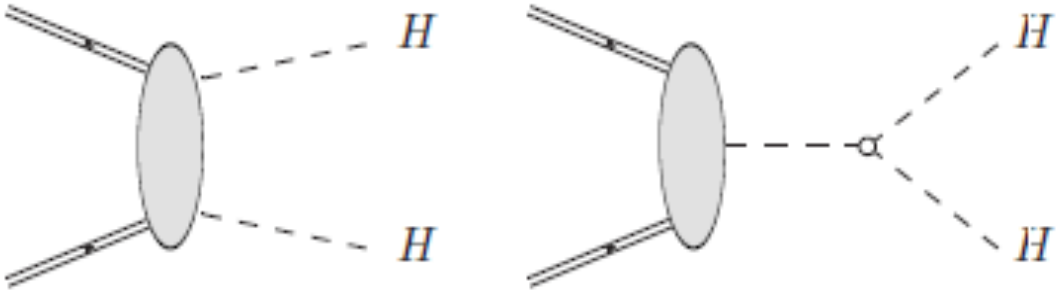

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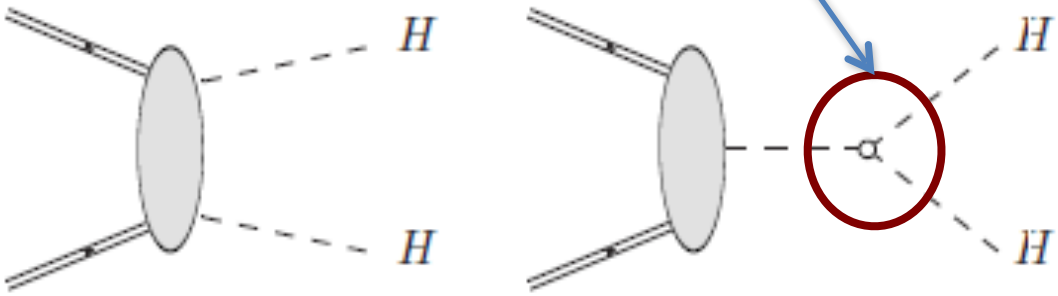

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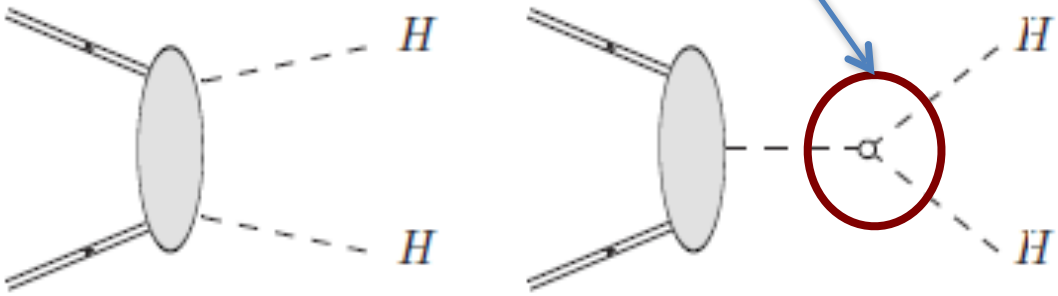

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

Fixed values in the SM

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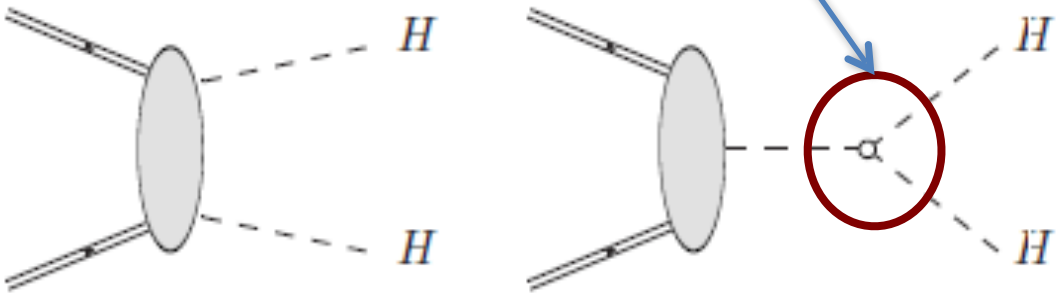


SM and similarly in extensions:
e.g. 2HDM

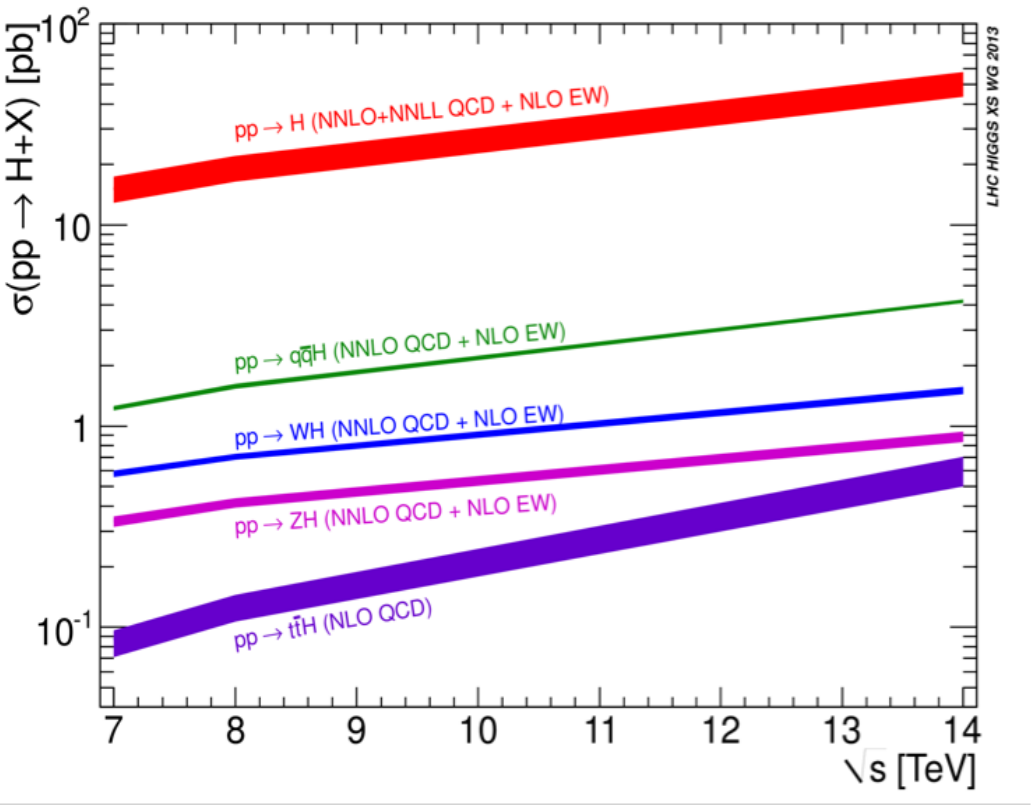
$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

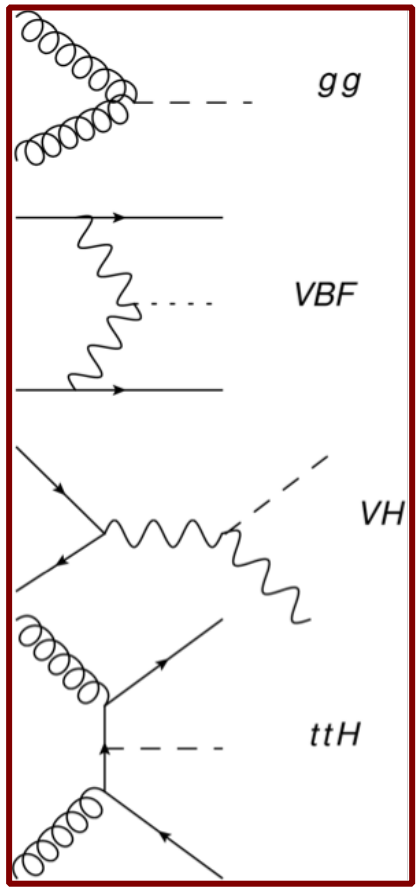
Fixed values in the SM

Higgs Pair Production channels

As in single Higgs production:

- Gluon-gluon fusion
- Vector boson fusion
- VHH associated production
- ttHH





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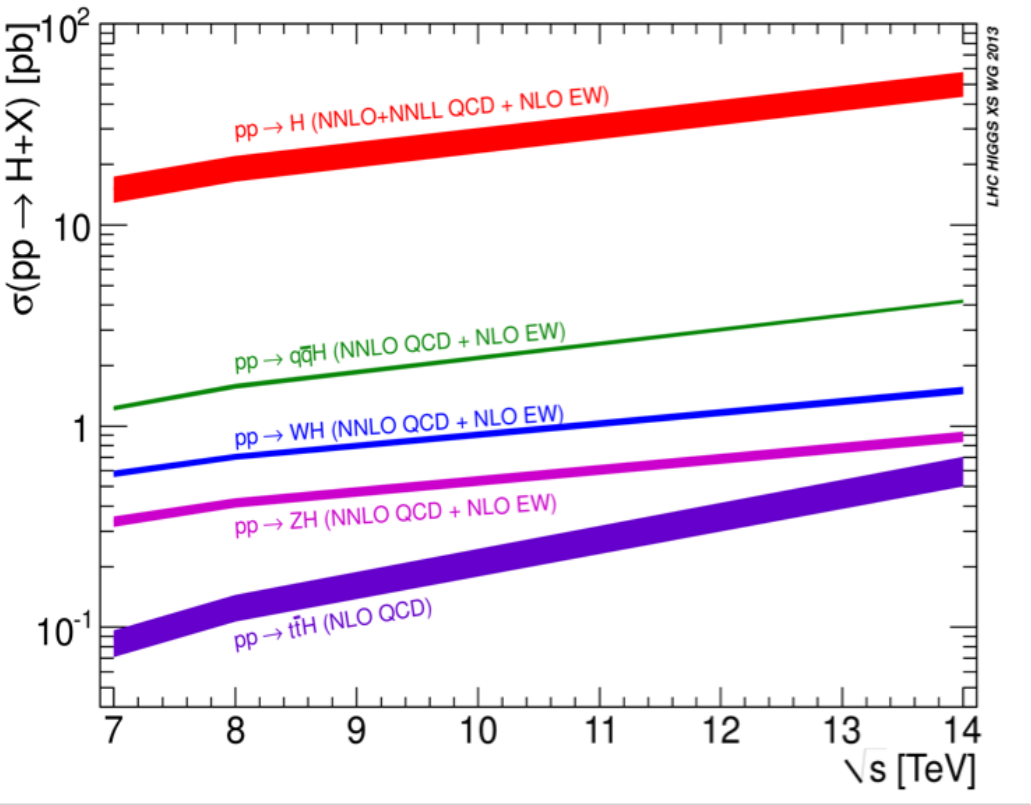
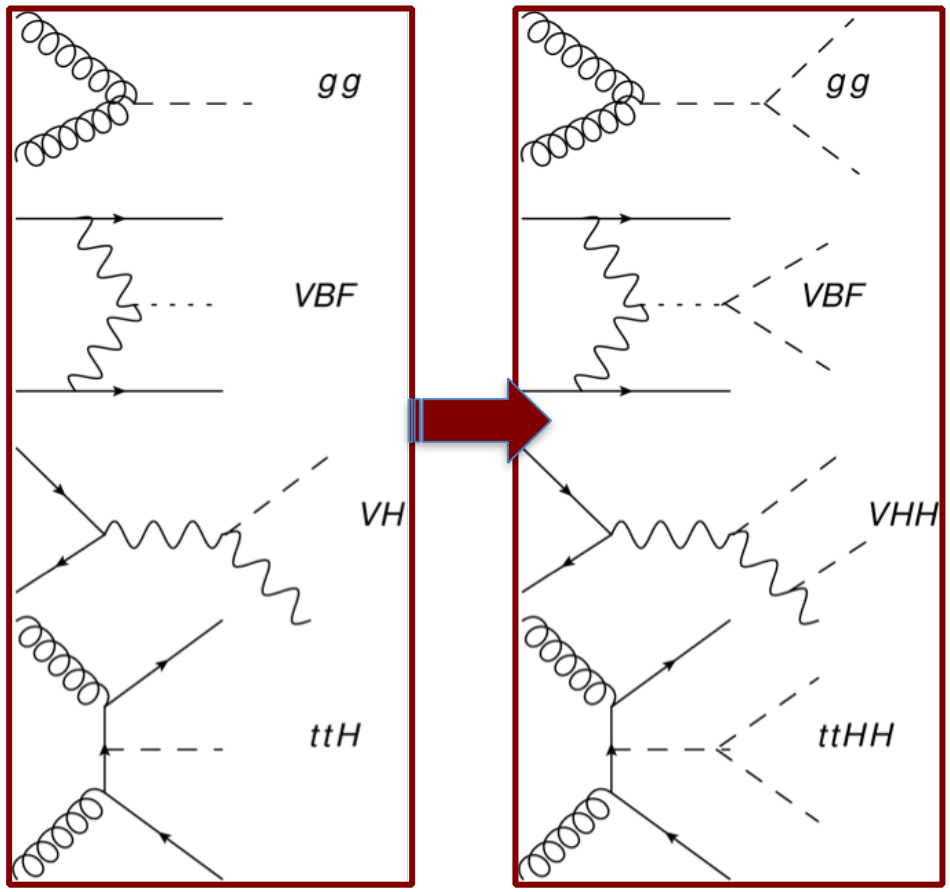


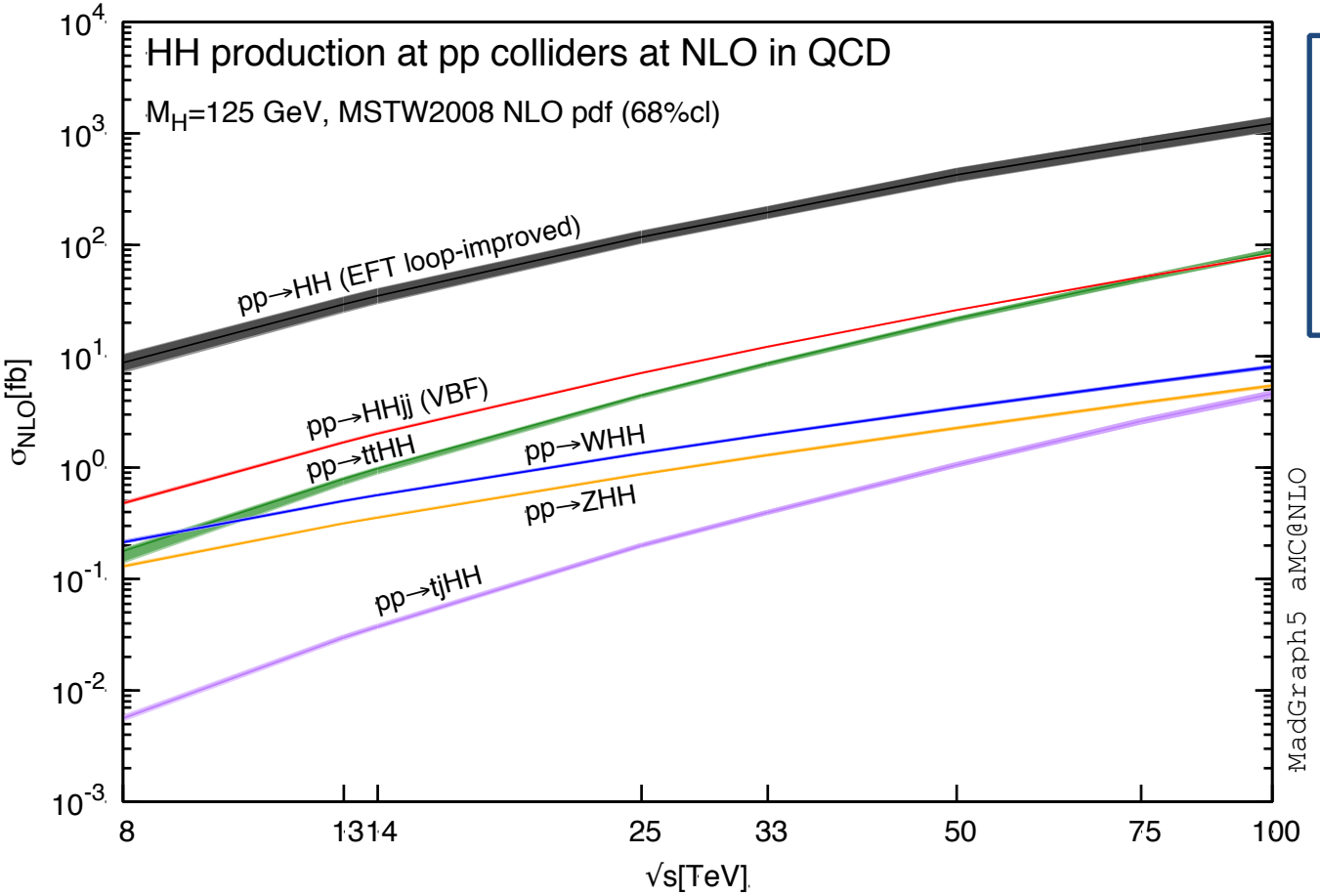


Schematically

Questions about HH

- How big is the HH cross section?
- How does the hierarchy of the channels change for HH at 14TeV? Is gluon fusion the dominant one?
- How does the cross section change with the centre of mass energy?
- How does the cross section depend on the value of the trilinear Higgs coupling?
- Do we have NLO predictions for all the channels?
- Do we have an efficient fully differential Monte Carlo implementation of the process?

MadGraph5_aMC@NLO results



Gluon gluon fusion dominates
σ~35fb at 14TeV

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

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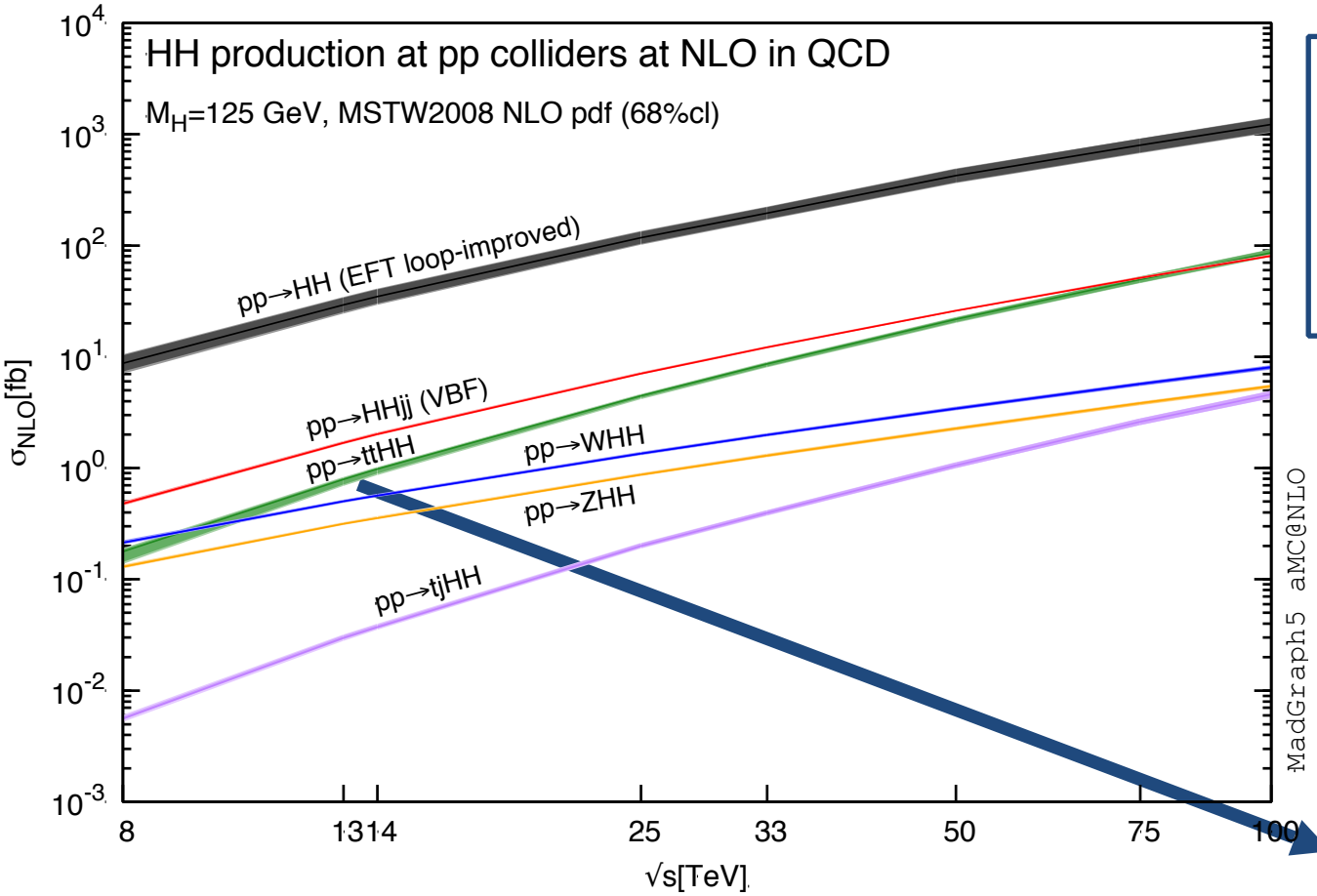

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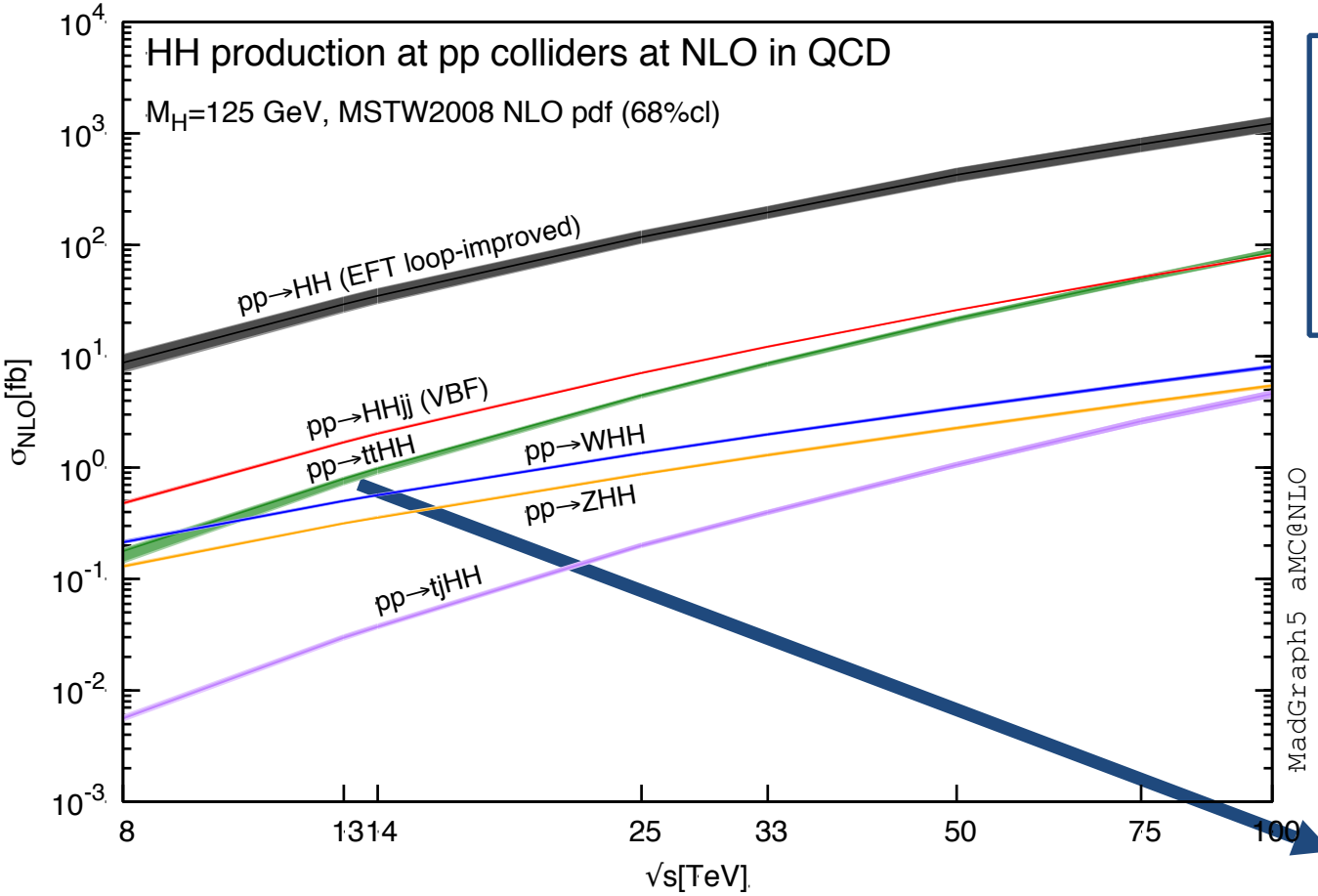

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- **Automatic calculation of the scale and PDF uncertainties**

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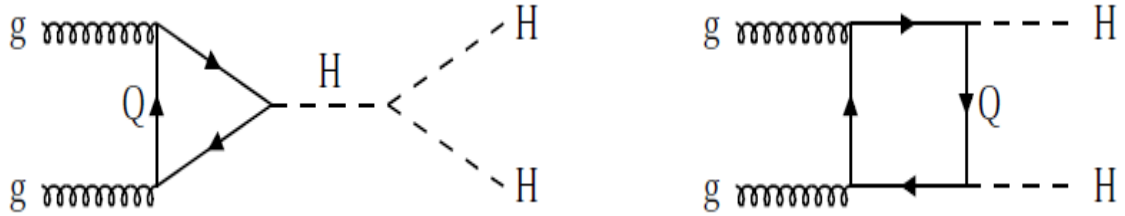
Focussing on gluon-gluon fusion...

At LO...



Biggest cross section
Only loop induced channel

Glover, Van der Bij Nucl.Phys. B309 (1988) 282
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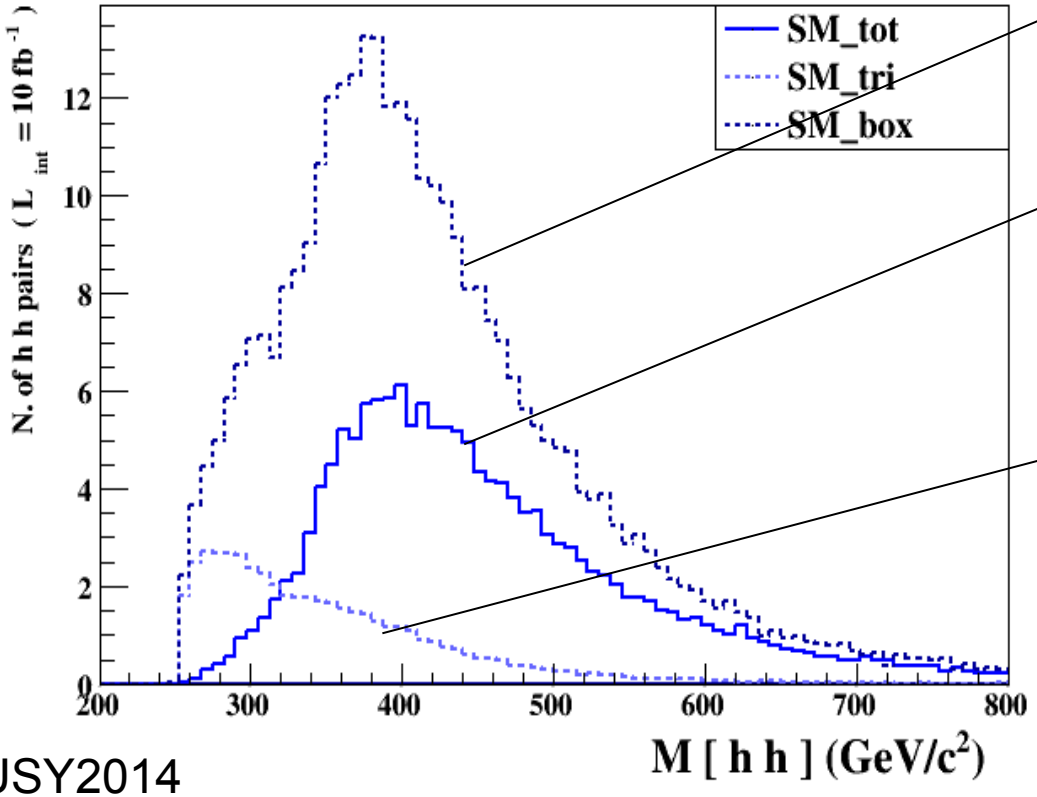
How much does each diagram contribute?



Box

Total

Triangle

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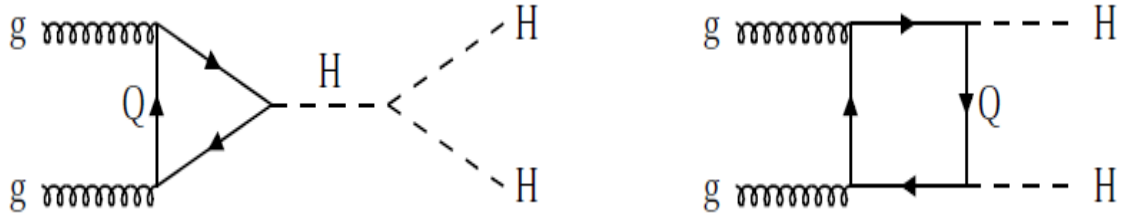

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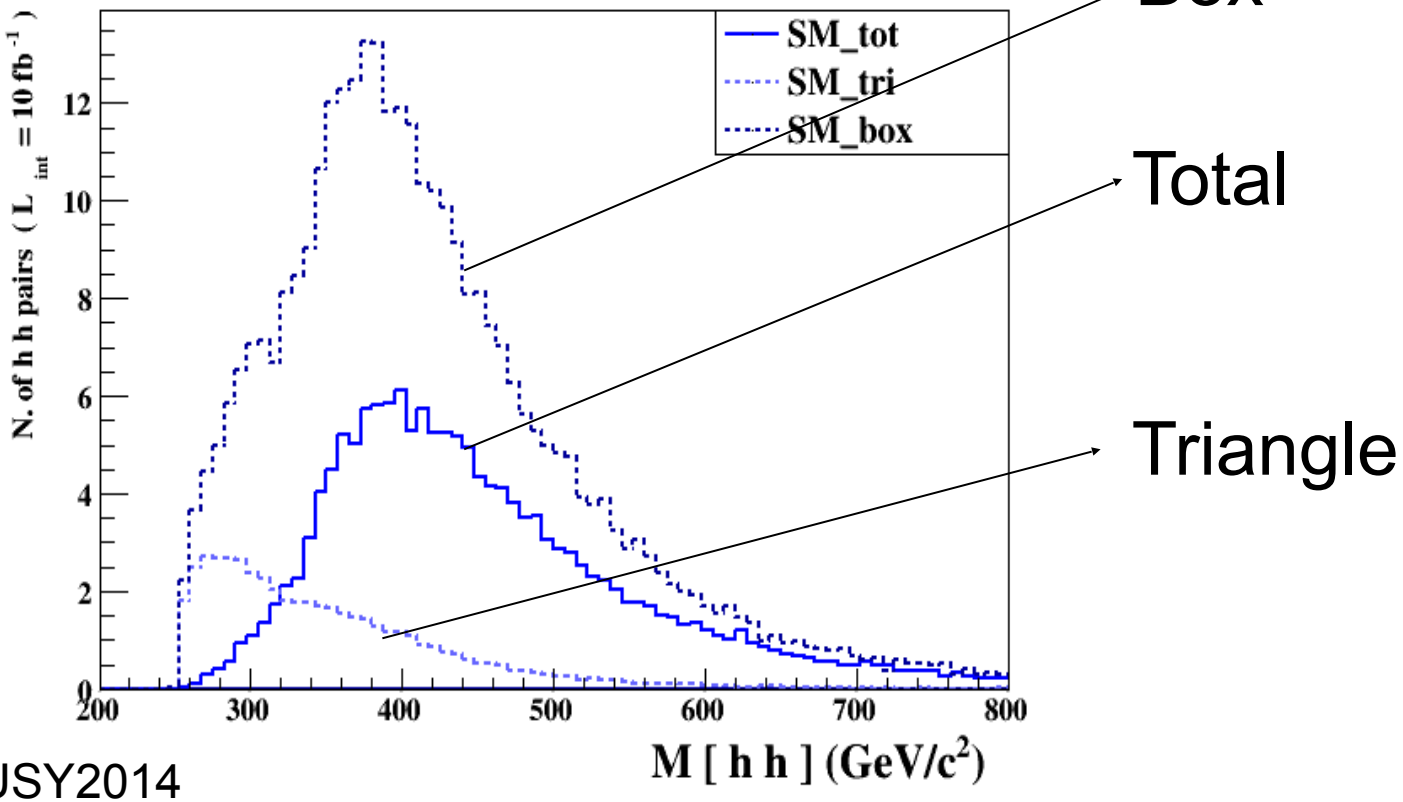
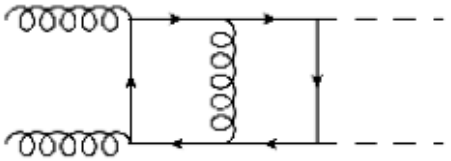


Significant cancellation between the two diagrams
Sensitive to value and sign of λ_{HHH}

HH in gluon-gluon fusion beyond LO

- Exact NLO computation requires:
  - Real emissions: HHj one loop (not easy but doable)
  - Virtual corrections: Include 2-loop amplitudes



Beyond current loop technology

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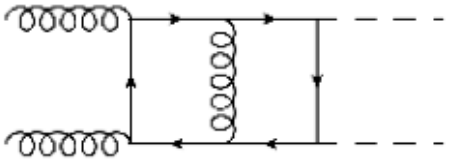

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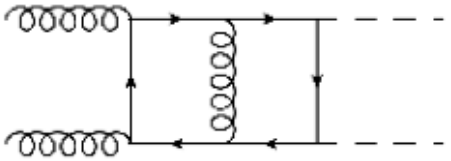

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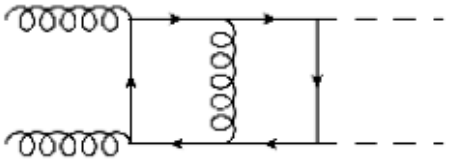

Beyond current loop technology

- NLO results in the HEFT:
  - Dawson, Dittmaier, Spira hep-ph/9805244
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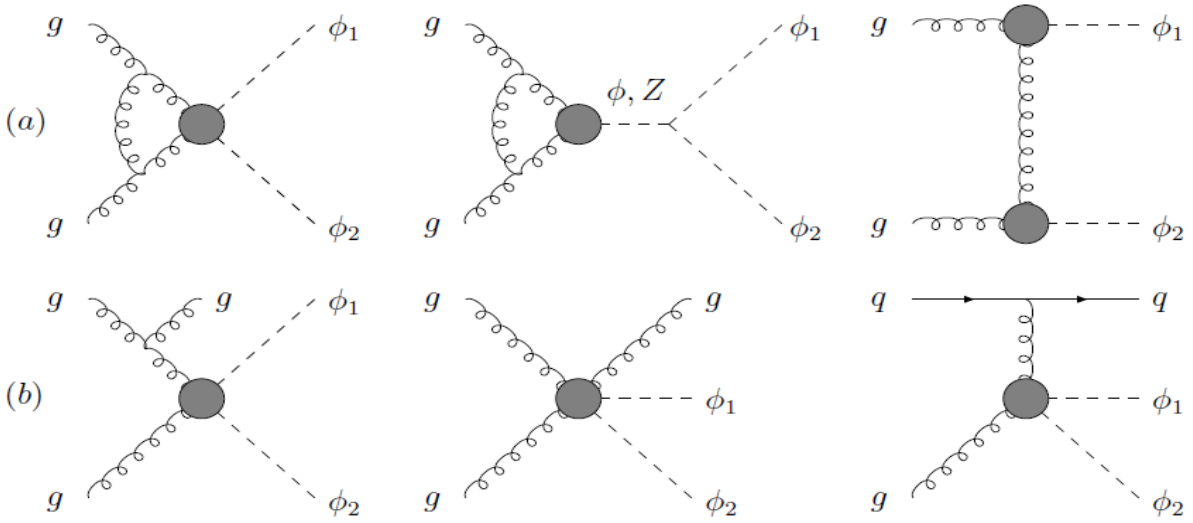

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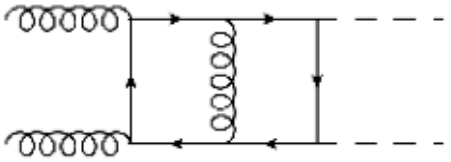

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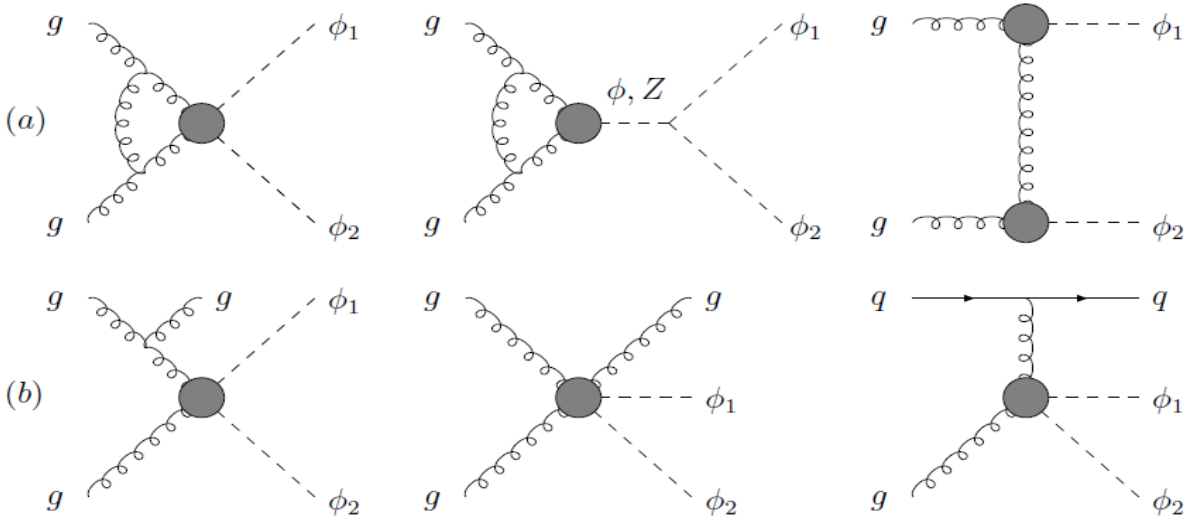
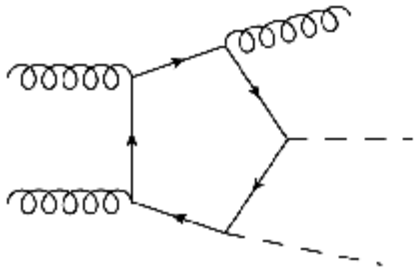


HEFT does not describe the kinematics of HH:
Mass effects are important and need to be included

HH in gluon-gluon fusion beyond LO

arxiv:1401.7340

- Inclusion of the exact real emission matrix elements
  - NLO HEFT event generation within MG5_aMC@NLO
  - Reweigh on an event by event basis using the results of the exact loop matrix elements
  - Loop matrix elements obtained by MadLoop for both Born and real emission



- When done consistently improves previous results, because of better description of hard emissions
- Matching to parton showers with the MC@NLO method

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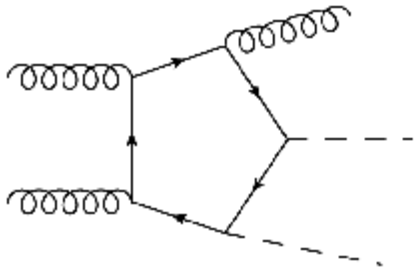

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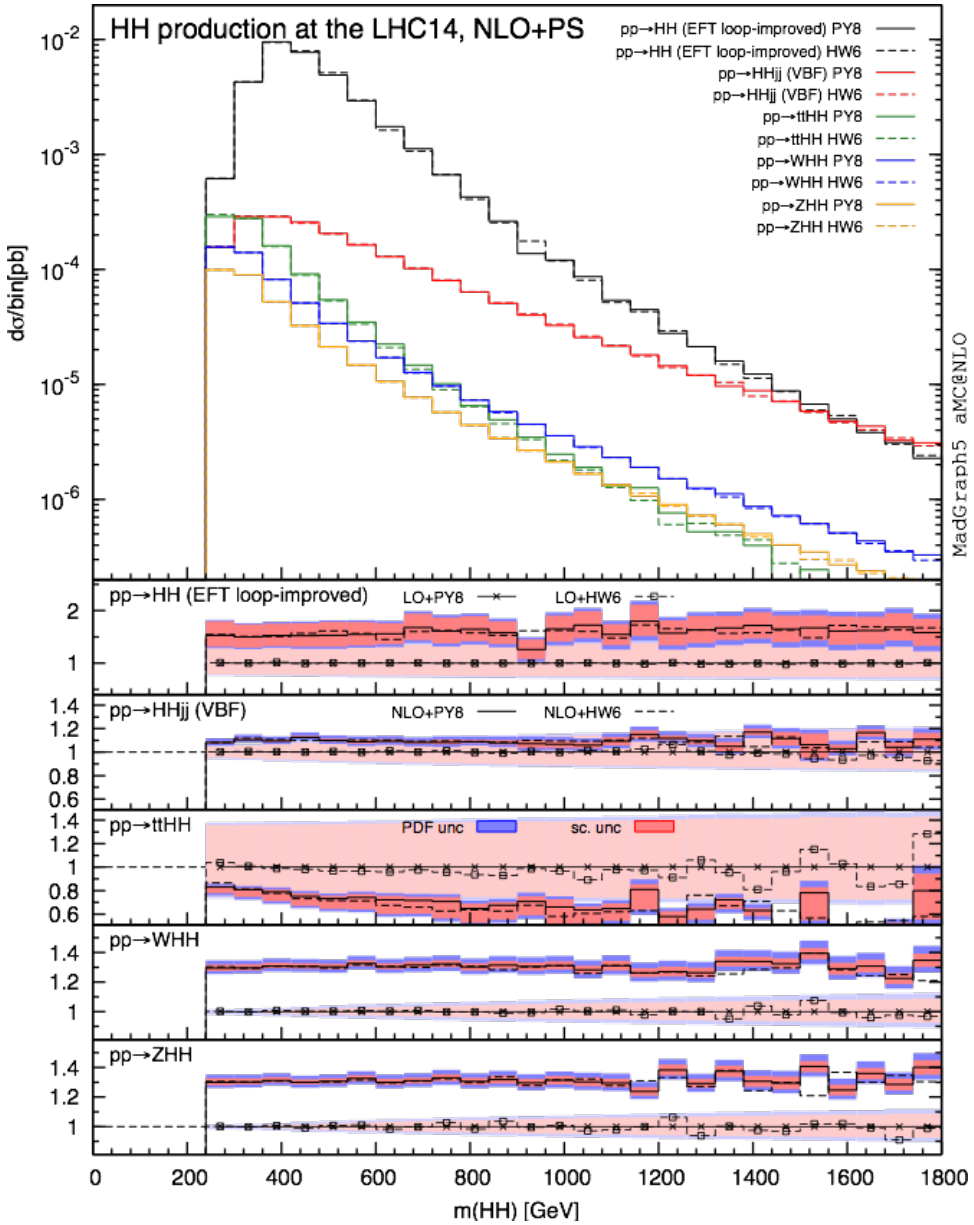
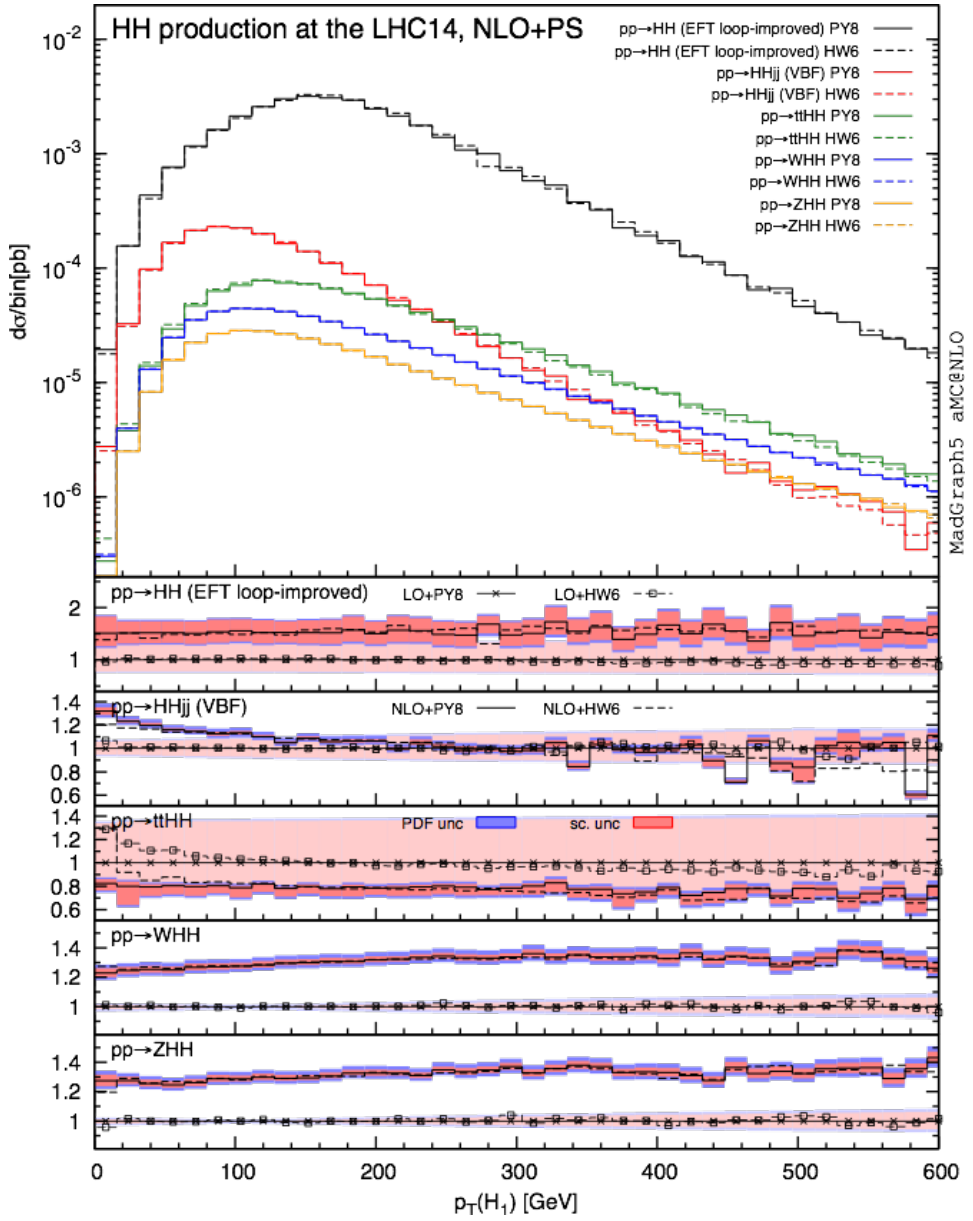
Other recent gluon fusion results:

- ❖ Merged samples: Li, Yan, Zhao arXiv:1312.3830
  Maierhofer, Papaefstathiou arXiv:1401.0007
  Exact one-loop born and real emission matrix elements but LO accuracy
- ❖ Resummation: Shao et al. arXiv:1301.1245
- ❖ NNLO EFT corrected by full LO, De Florian and Mazzitelli, arxiv:1309.6594
  Total cross section K-factor ~2.3 at 14TeV
- ❖ Expansion in 1/mt at NLO, Grigo et al. arXiv:1305.7340

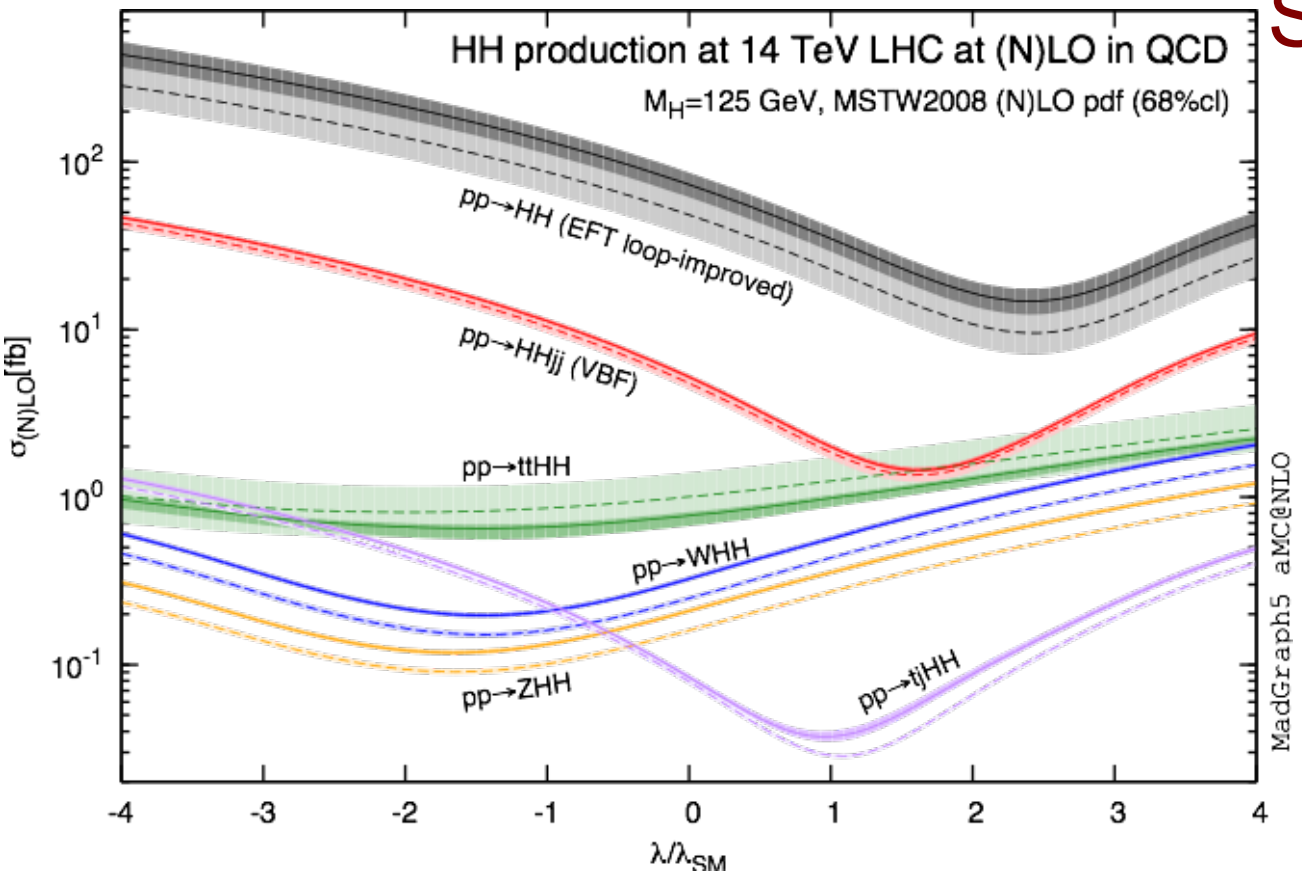
Differential distributions for the LHC





Best available predictions: NLO plus PS

Dependence on the trilinear Higgs coupling



Sensitivity of different channels on λ

Reduction of the theoretical uncertainties at NLO

All channels apart from gg obtained automatically within MG5_aMC@NLO

MadGraph5_aMC@NLO gluon fusion
Dedicated codes can be downloaded from:
https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsPairProduction

Higgs pair production beyond the SM

- SM rates are small 35fb at 14TeV

BSM physics enhancements

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Resonances

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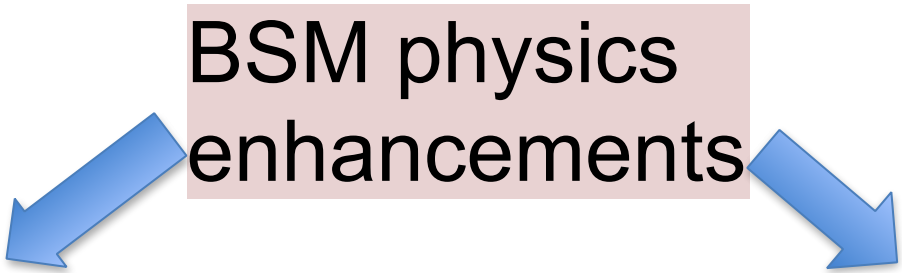

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Higher dimensional operators

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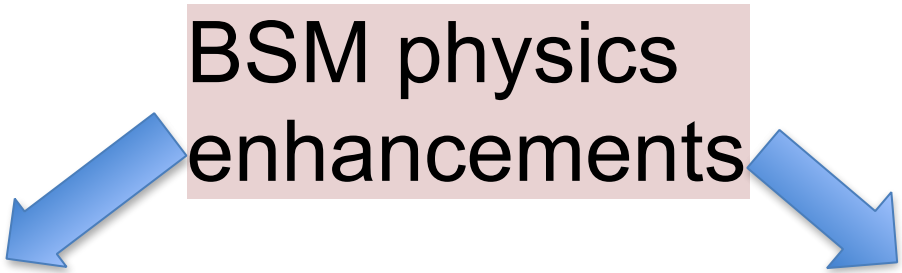

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- Non SM Yukawa couplings (1205.5444, 1206.6663)
- ttHH interactions (1205.5444)
- Resonances from extra dimensions (1303.6636)
- Vector-like quarks (1009.4670, 1206.6663)
- Light coloured scalars (1207.4496)
- Dimension-6 gluon Higgs operators (0609.049)
- many more BSM scenarios….

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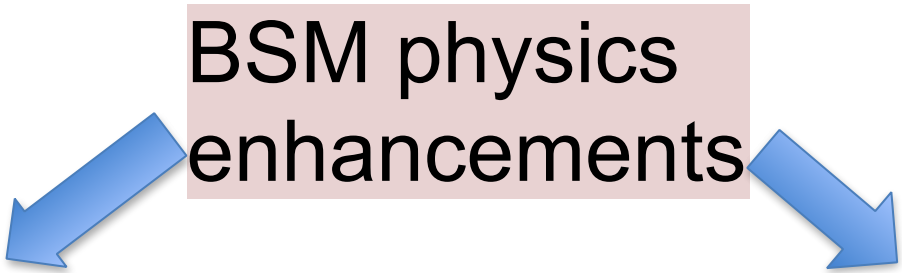

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RICH PHENOMENOLOGY

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

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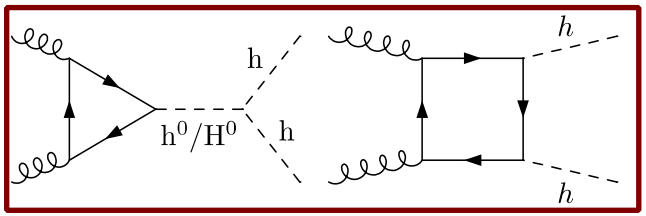

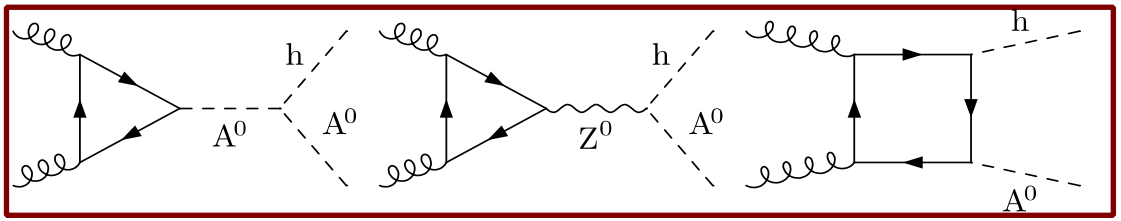

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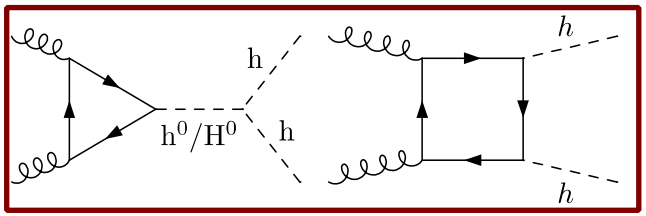
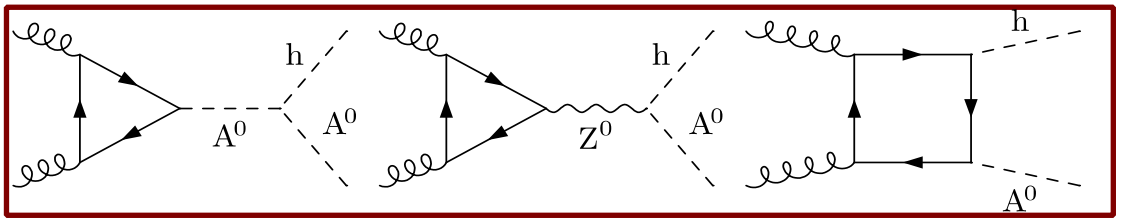




qq for hA, HA, H^+H^-

Higgs pair production in gluon fusion in the 2HDM

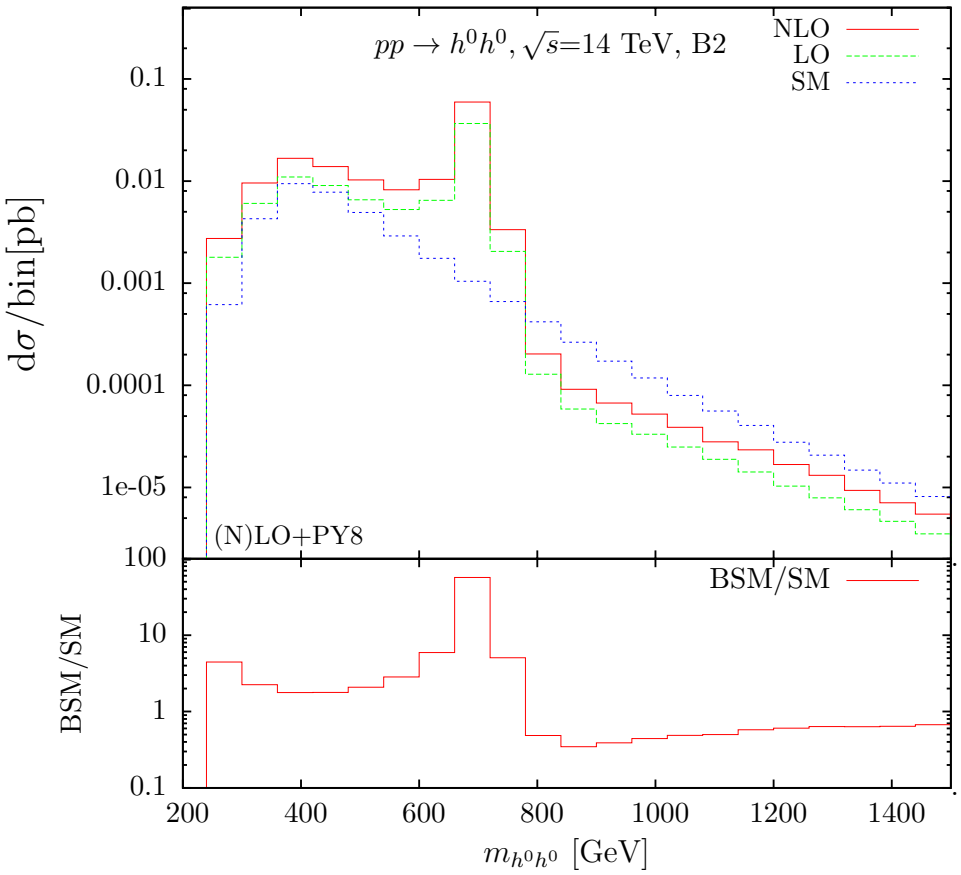
- Calculation of all seven combinations at LO and approximate NLO (similar to SM)
- Calculation within the MG5_aMC@NLO framework using the CTNLO package (Degrande arxiv:1406.3030)
- Results matched to parton shower
- Codes available:

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsPairProduction

- Results presented for a series of 2HDM benchmarks, in agreement with all up-to-date constraints (including the recent direct heavy Higgs searches: CMS-PAS-HIG-13-025, ATLAS: arXiv:1406.5053)
- Cross sections strongly depend on the parameter input, heavy pair production heavily suppressed

B. Hespel, D. Lopez-Val, E.V. arxiv:1407.0281

Light Higgs pair production
Resonant 2HDM scenario



2HDM input: Type-ii

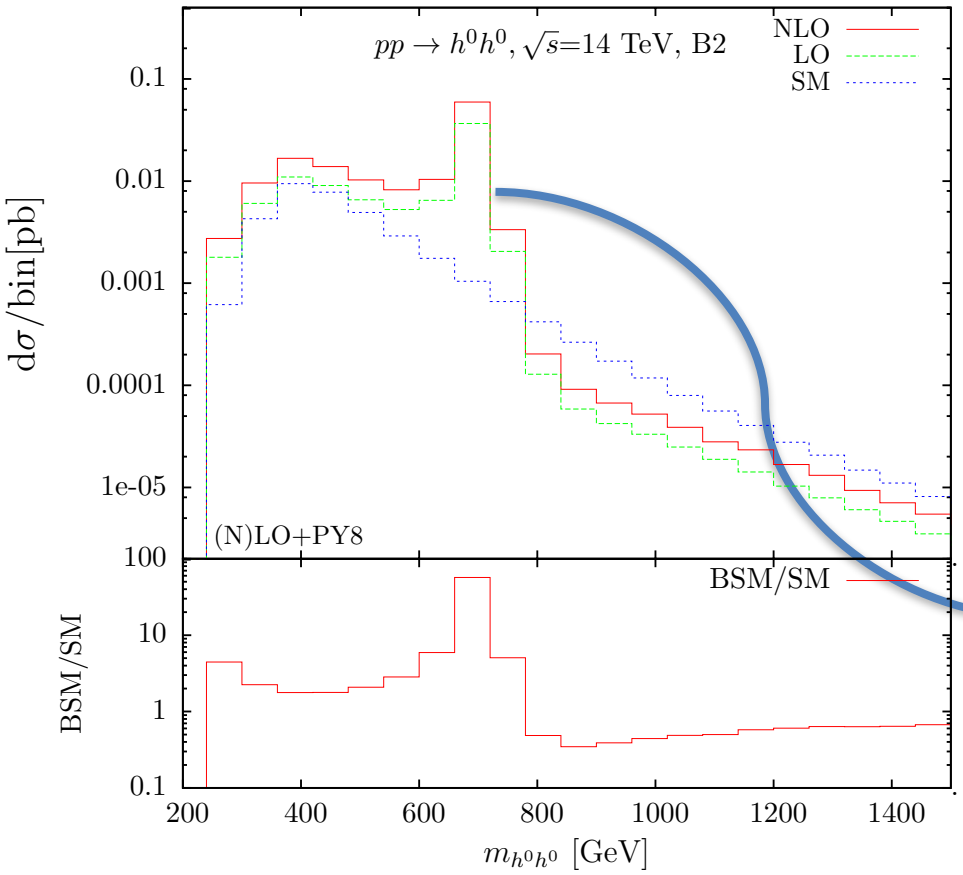
	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m^2_{12}
B2	1.50	-0.2162	700	701	670	180000

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

σ_{hh}~ 4 times the SM prediction

arxiv:1407.0281

Light Higgs pair production
Resonant 2HDM scenario



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

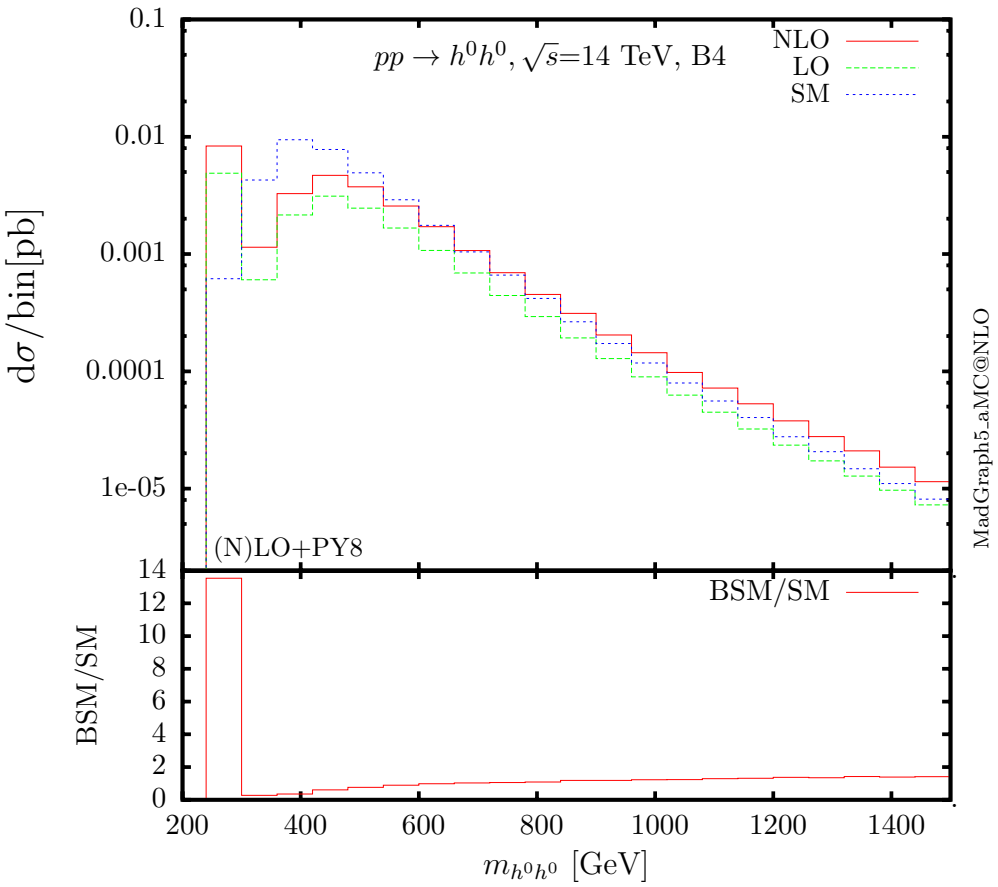
- **Slightly reduced top Yukawa**
- **Reduced hhh coupling**
- **Enhanced Hhh coupling**

- Significant resonant enhancement from H→hh
- Distinctive resonance peak
- Bigger enhancements can be achieved with smaller H masses (60 times the SM for a 300GeV H)
- See also Baglio et al. arxiv: 1403.1264

σ_{hh}~ 4 times the SM prediction

arxiv:1407.0281

Light Higgs pair production
Non-resonant 2HDM scenario



2HDM input: Type-i

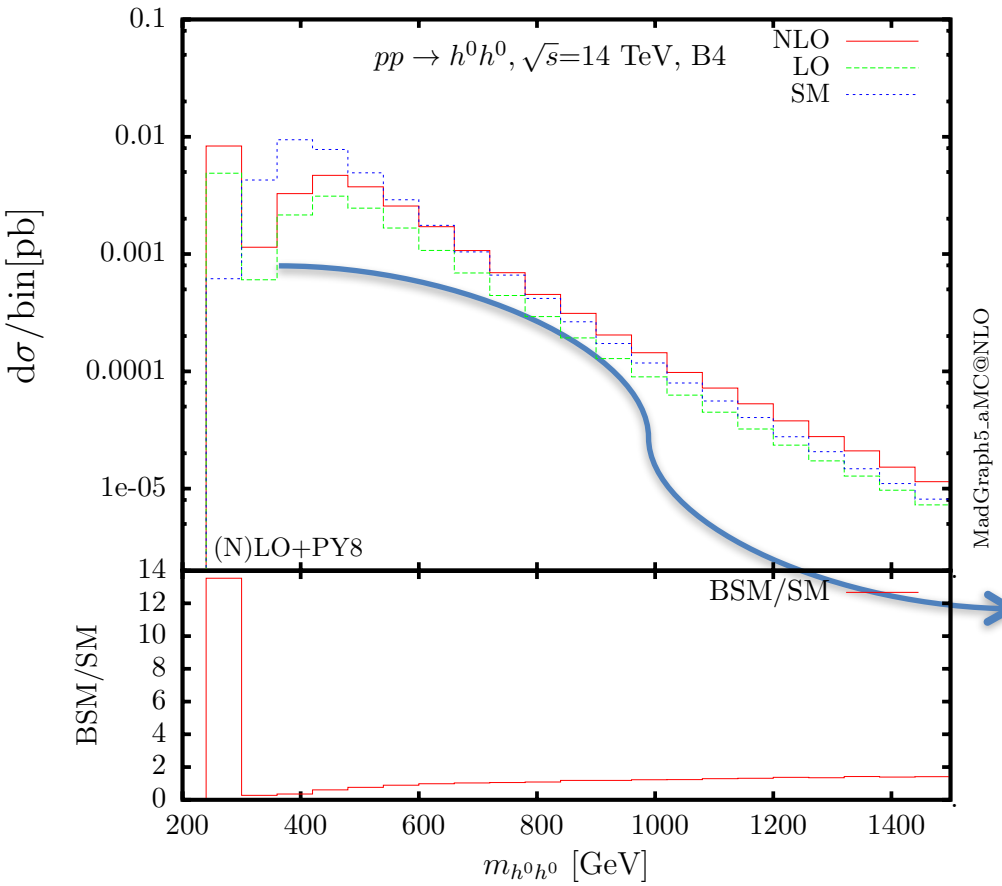
	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m^2_{12}
B4	1.20	-0.1760	200	500	500	-60000

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

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

arxiv:1407.0281

Light Higgs pair production
Non-resonant 2HDM scenario



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

arxiv:1407.0281

2HDM input: Type-i

	tan β	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, key to explore the Higgs potential
- Presented results of a MC implementation of the process at NLO, provided in an automated way by MG5_aMC@NLO for the SM
- Results can now be used for phenomenological studies including decays, acceptance cuts and detector effects
- HH production is 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 but also changes in the distribution shapes

Thanks for your attention...