Higgs pair production at the LHC at NLO

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Scalar Search and Study in Belgium

Brussels 23/1/14

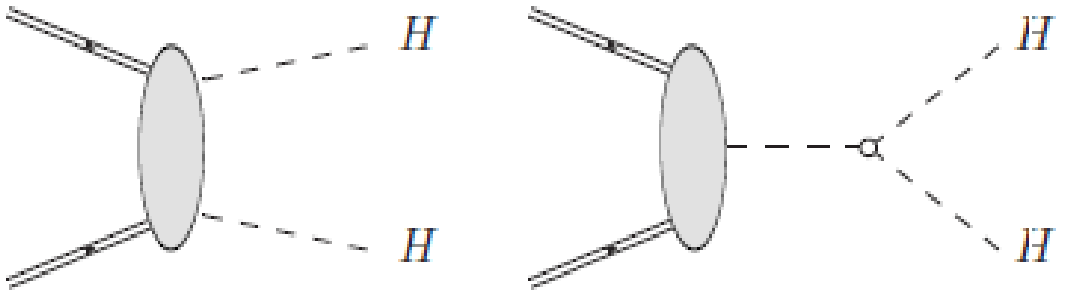
Outline

- Motivation
- Overview of HH results
- HH in gluon gluon fusion
- Outlook

Motivation

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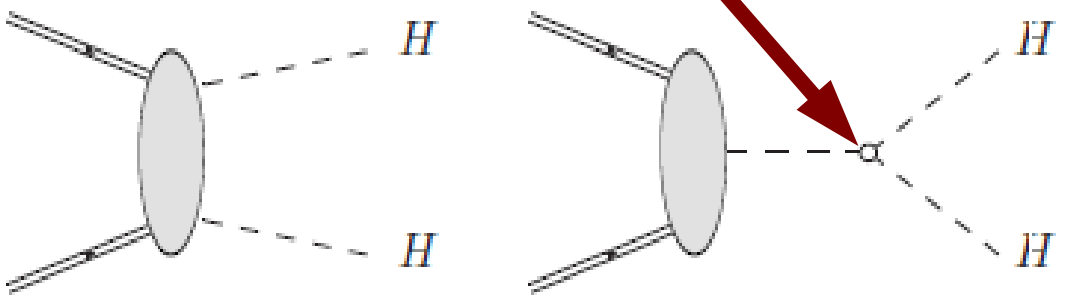

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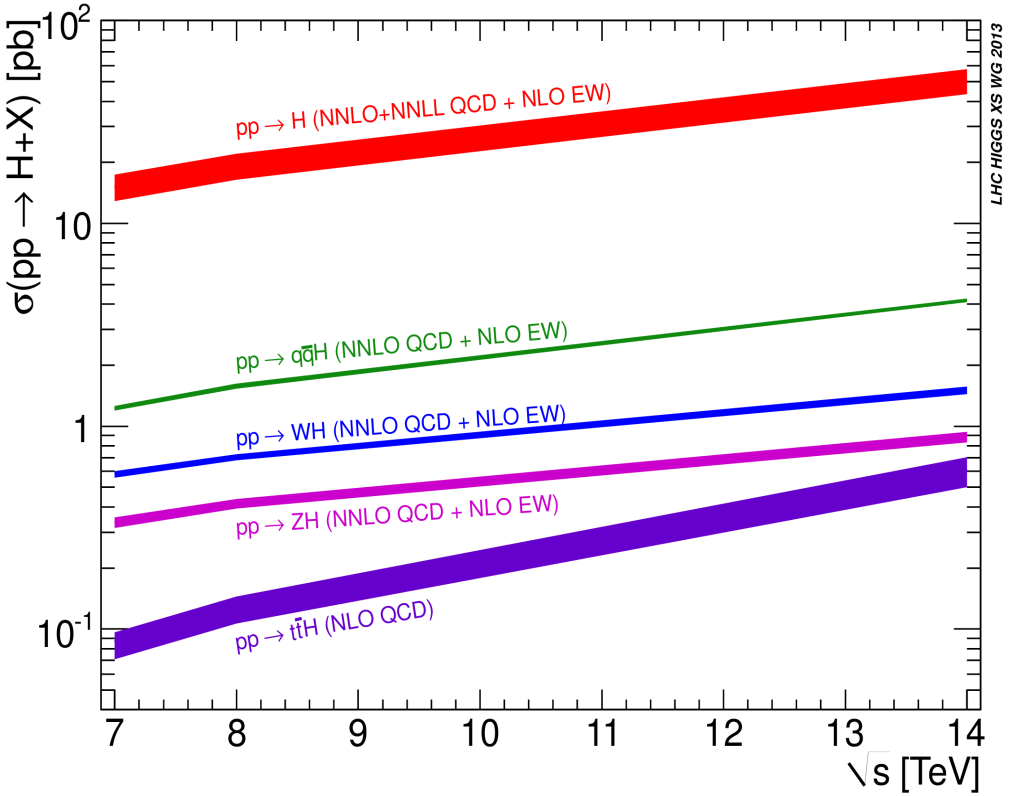
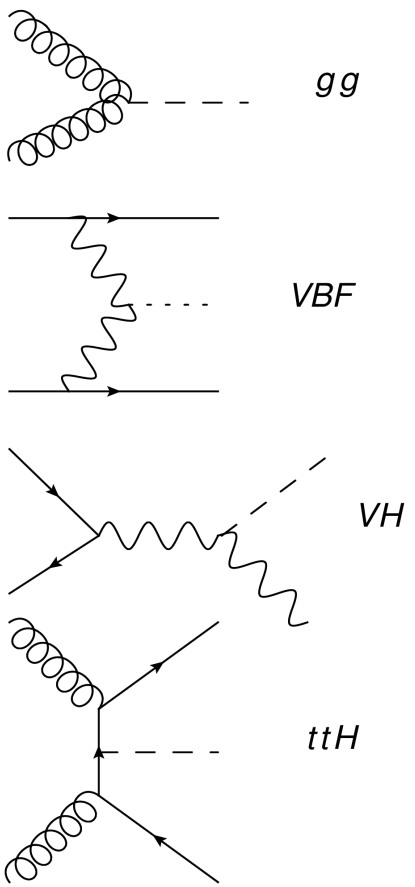
Higgs Pair Production channels

Similar to single Higgs production:

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



LHC Higgs Cross Sections Working Group



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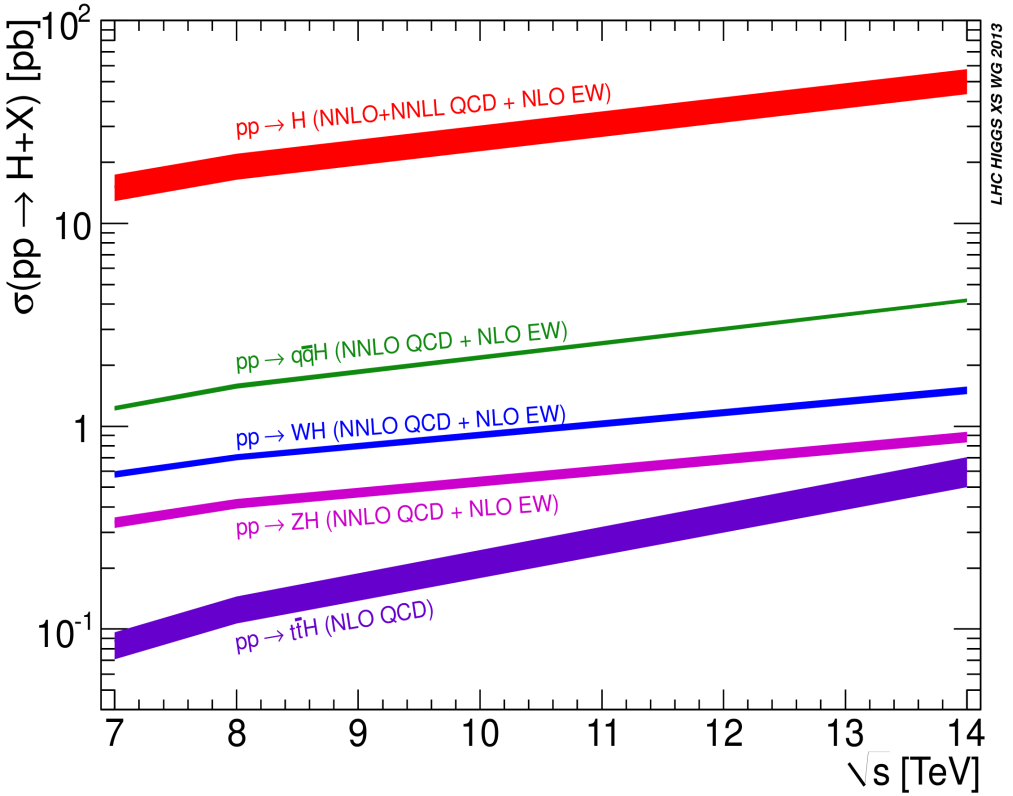

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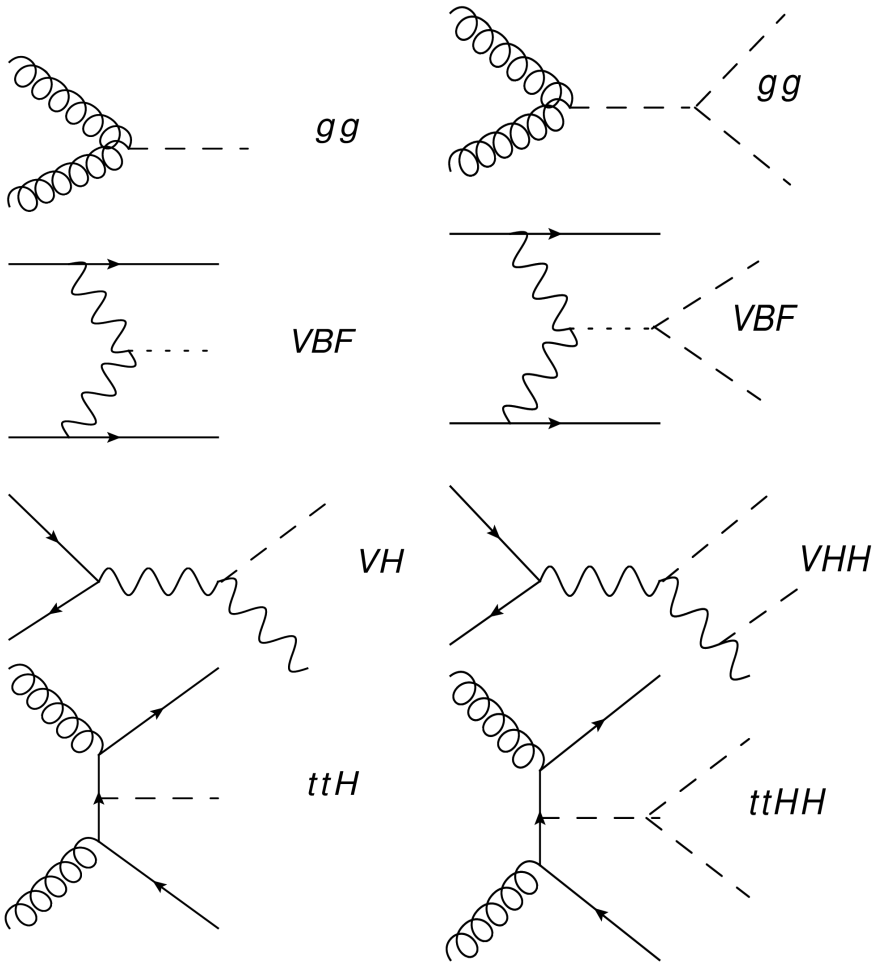

Schematically

Questions about HH?

- How does the hierarchy of the channels change for HH at 14TeV?
- How does the cross section change with the centre of mass energy?
- How do the results depend on the value of the trilinear Higgs coupling?
- Can we accurately obtain the results? Do we have NLO predictions?
- Do we have an efficient fully differential Monte Carlo implementation of the process?

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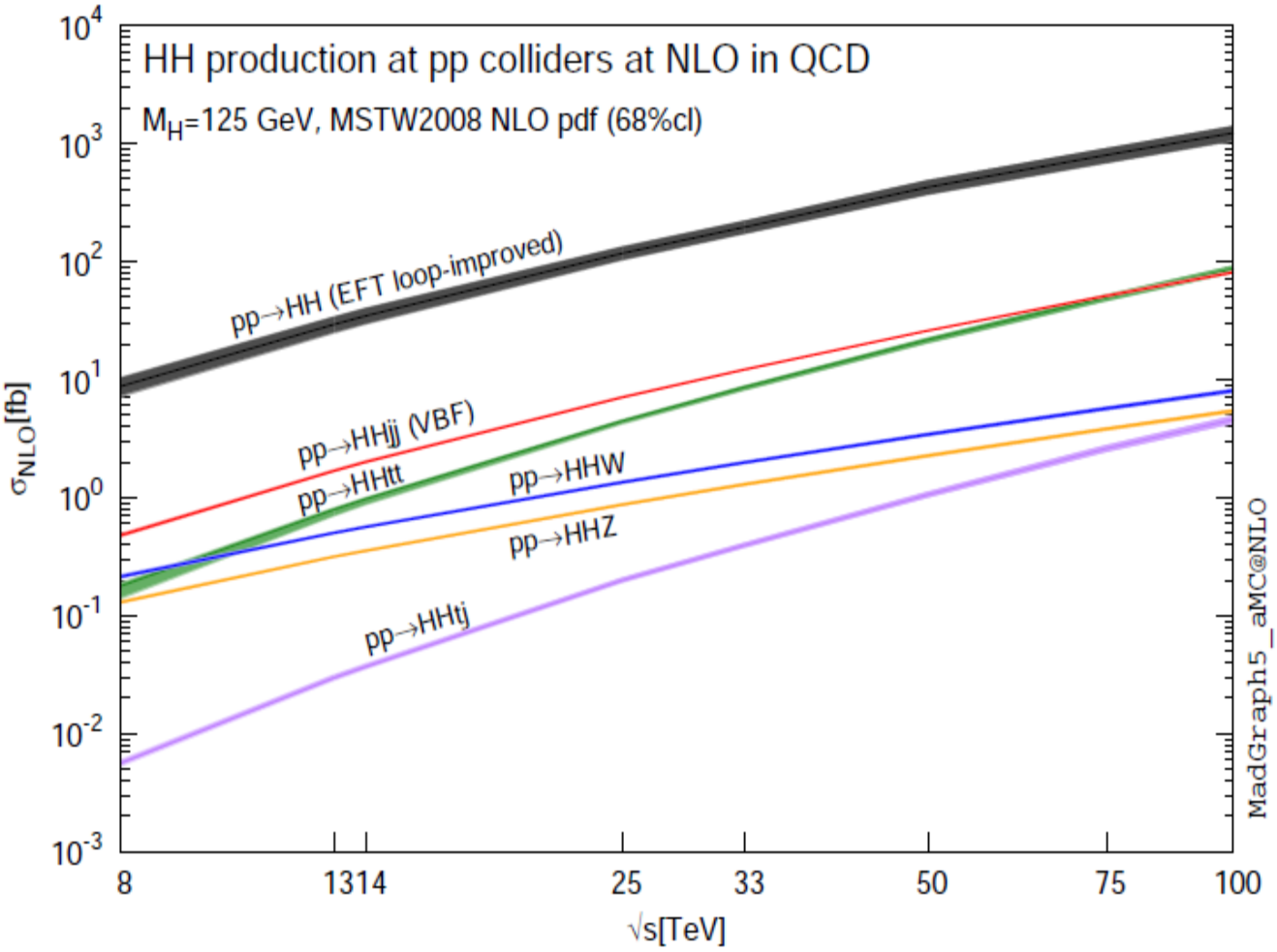
We have answers for all of these questions

aMC@NLO results



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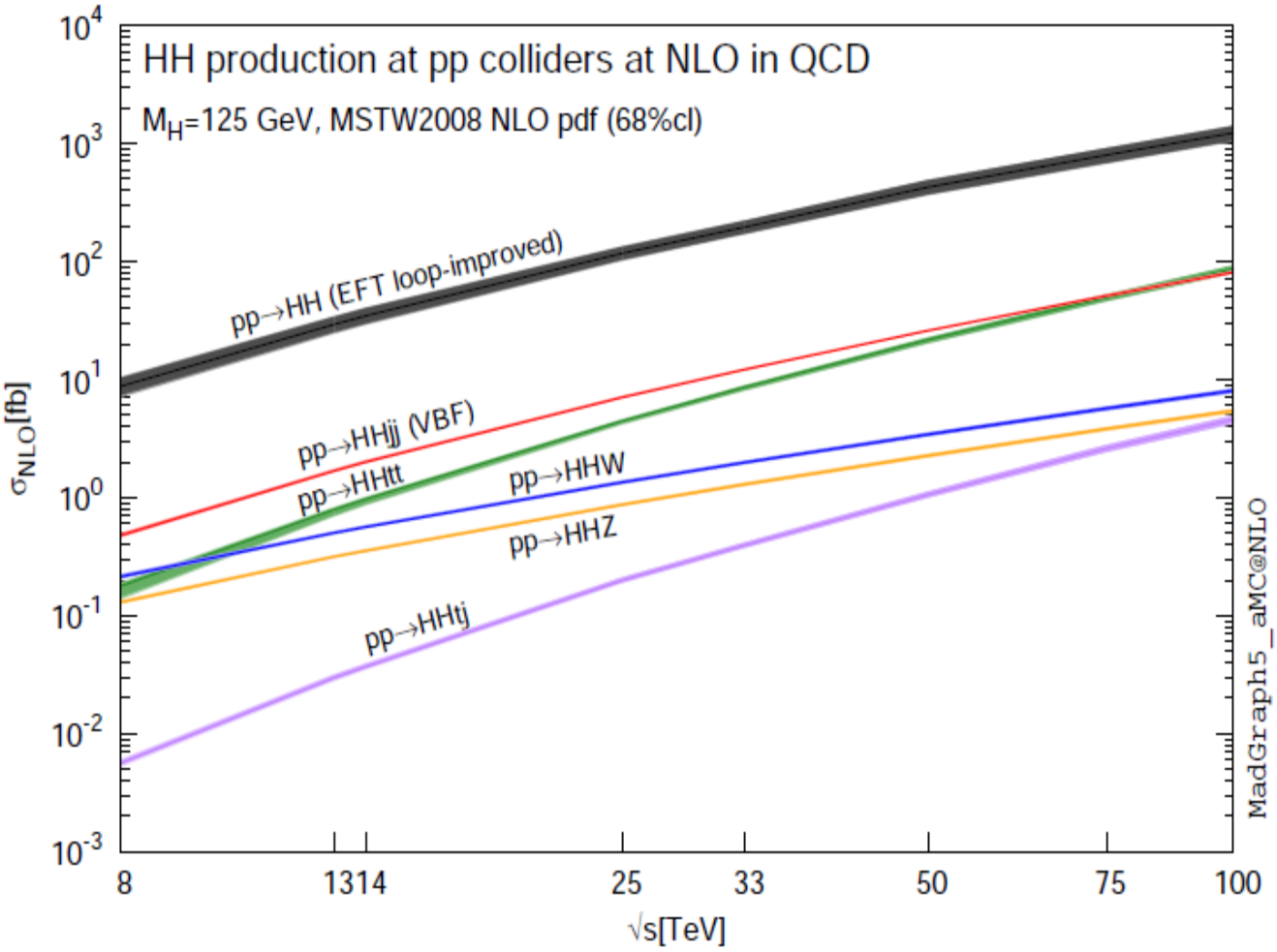

Best theoretical prediction for this process Gluon gluon fusion dominates

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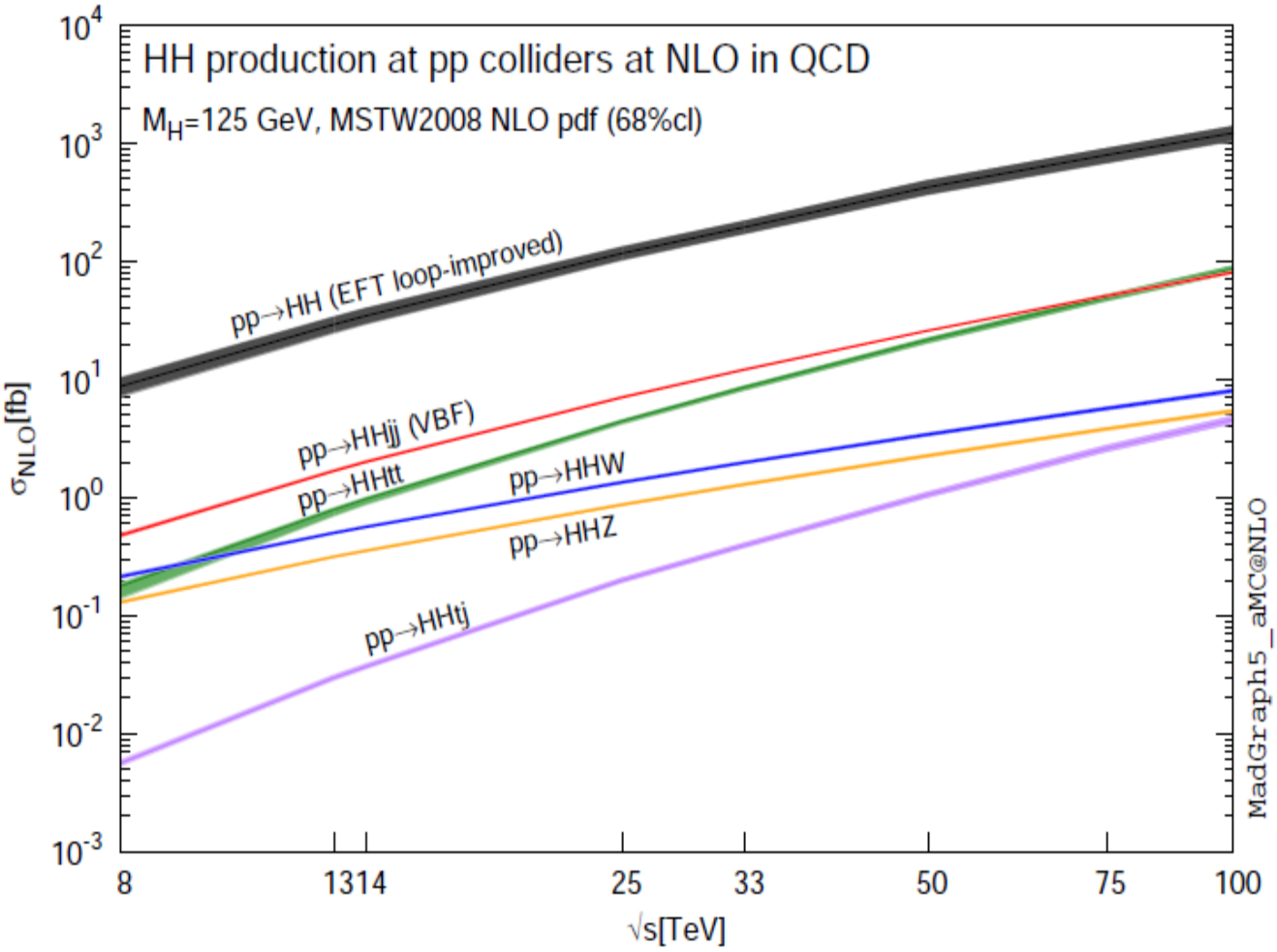

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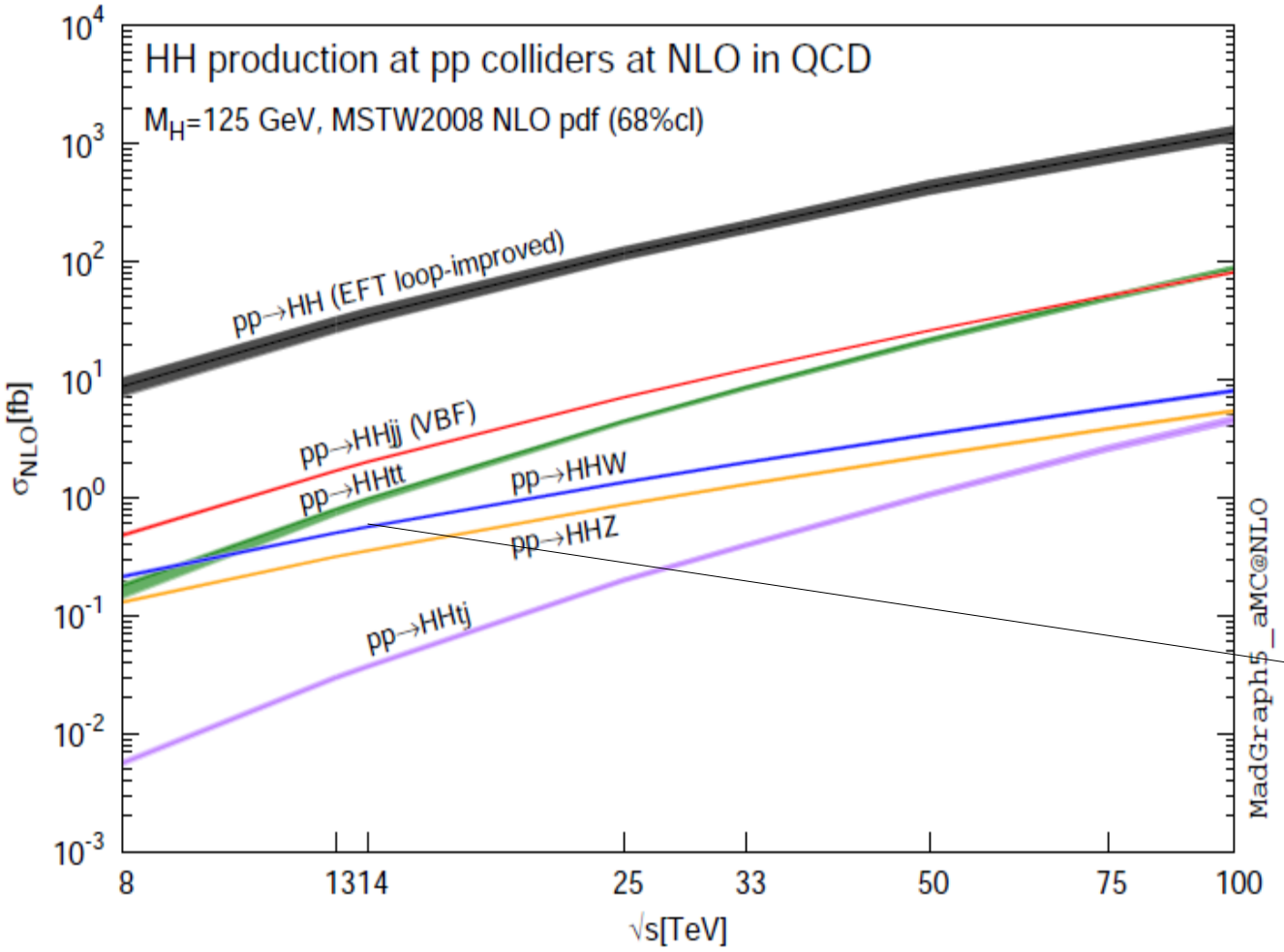

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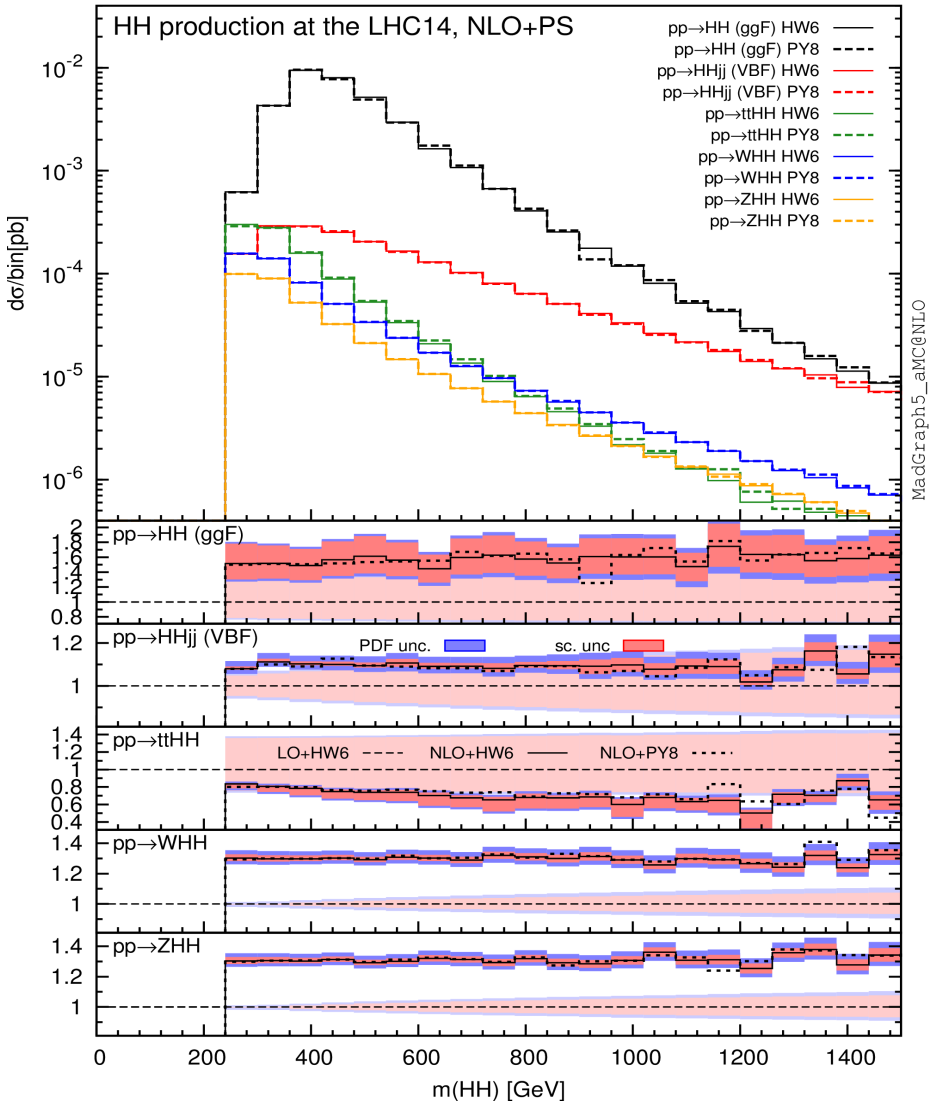
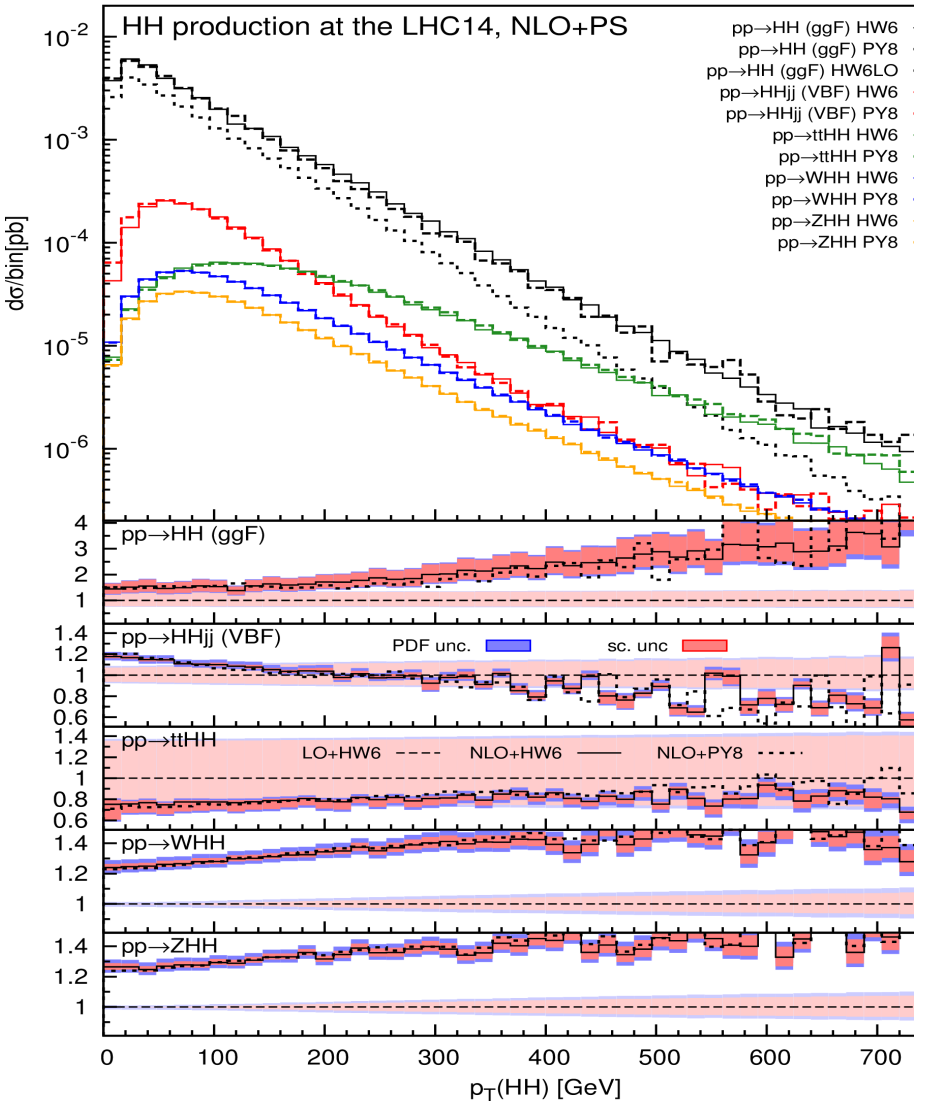
Difference from single Higgs at 14 TeV:
Vector boson associated production and ttHH hierarchy reversed

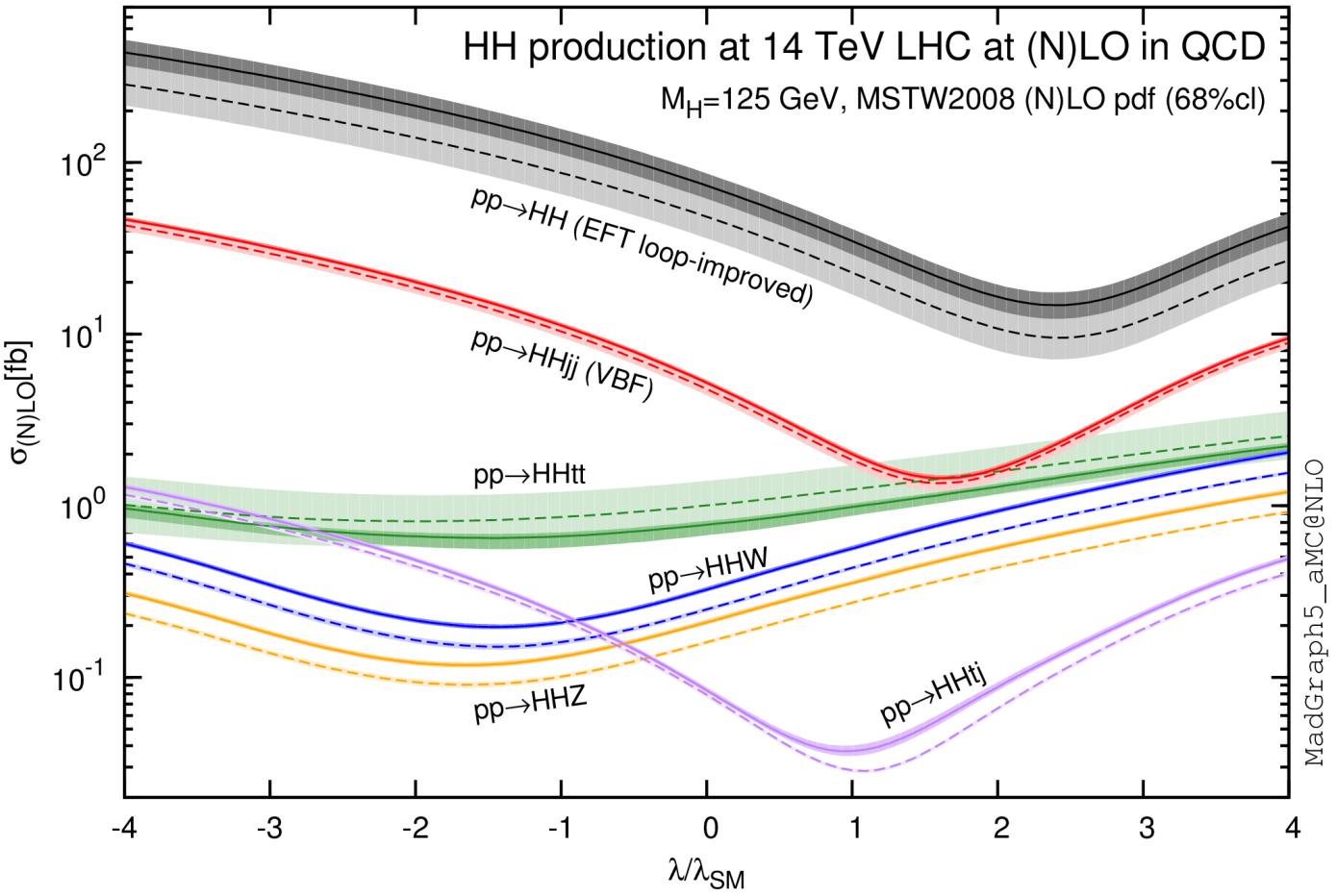
Differential distributions





Including NLO and PS effects: best available predictions

Dependence on the trilinear Higgs coupling



Sensitivity of different channels to λ

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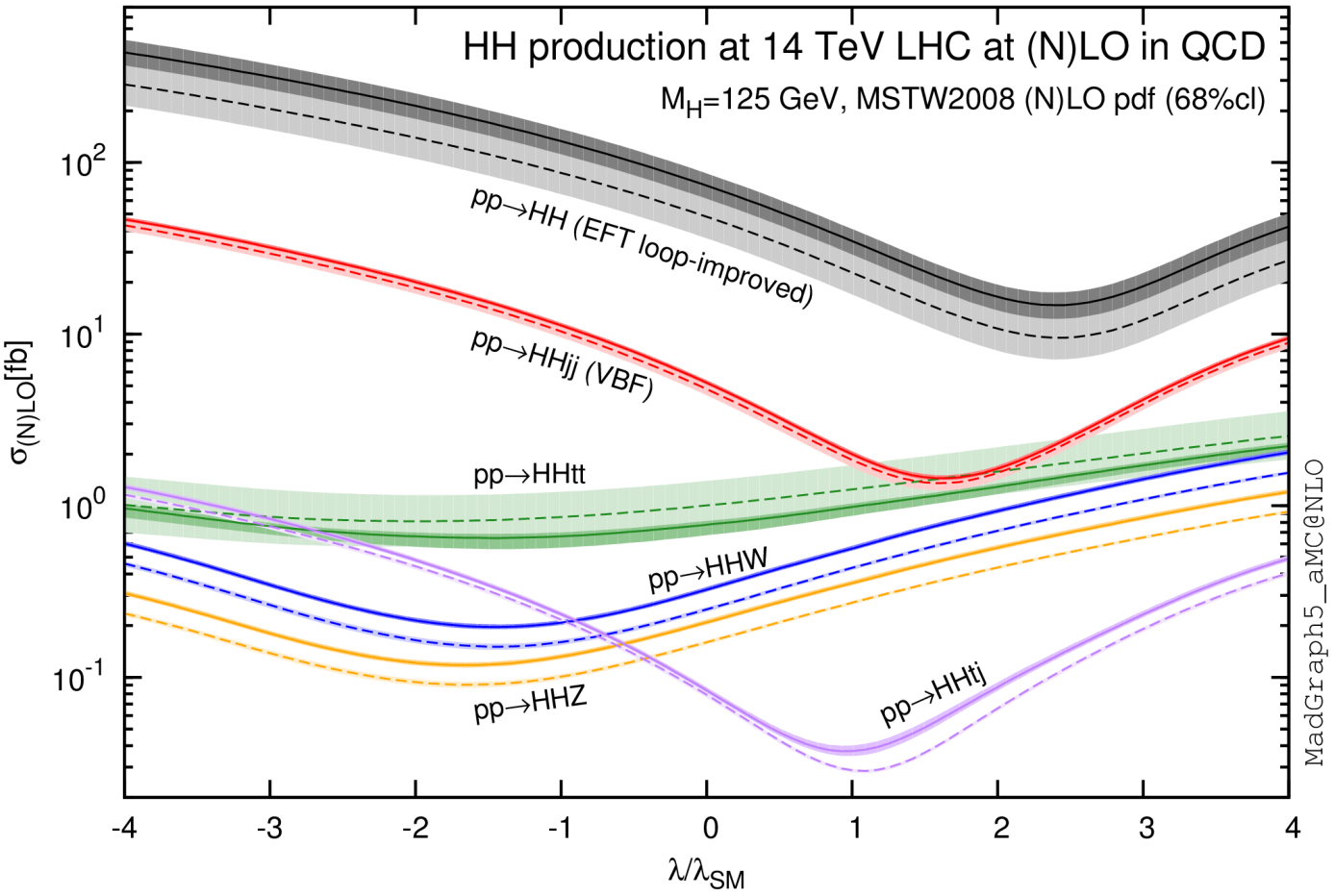


Sensitivity of different channels to λ

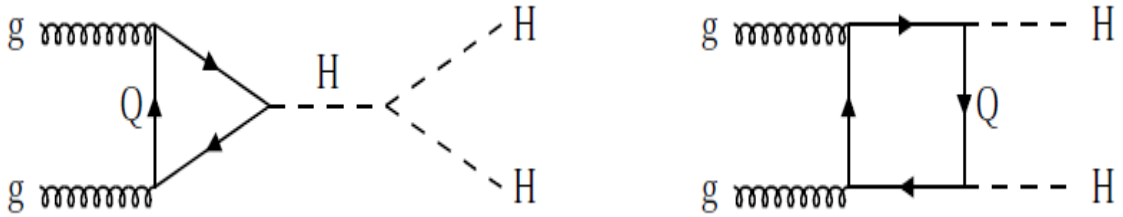
Significant reduction of the scale uncertainty at NLO, especially for gg and ttHH

This could be the end of the story...

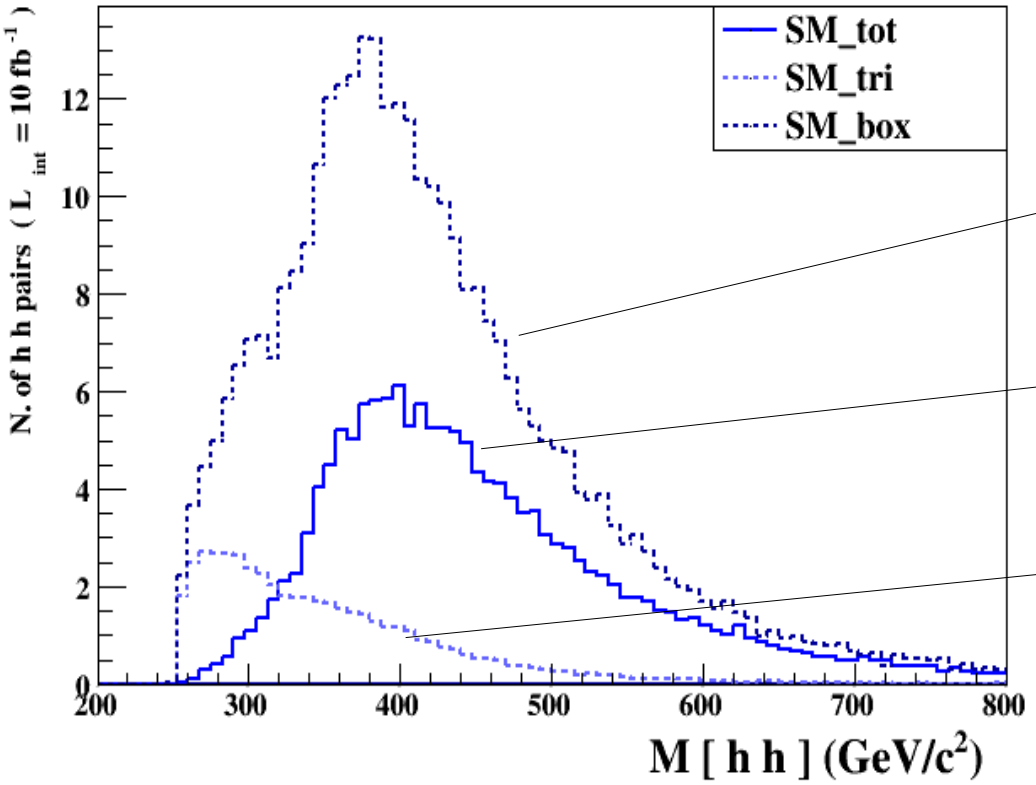
But what does EFT-loop improved really mean for gluon fusion?

Focussing on gluon-gluon fusion...

- At LO...



How much does each diagram contribute?



Box

Total

Triangle

Significant cancellation between the two diagrams

High energies: Box dominates
Triangle decouples

HH in gluon-gluon fusion

Loop induced process: not yet automated in MC

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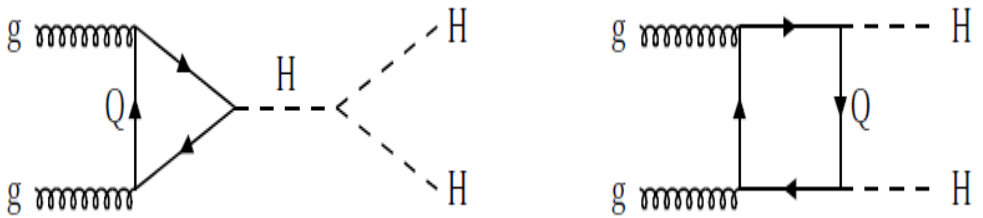

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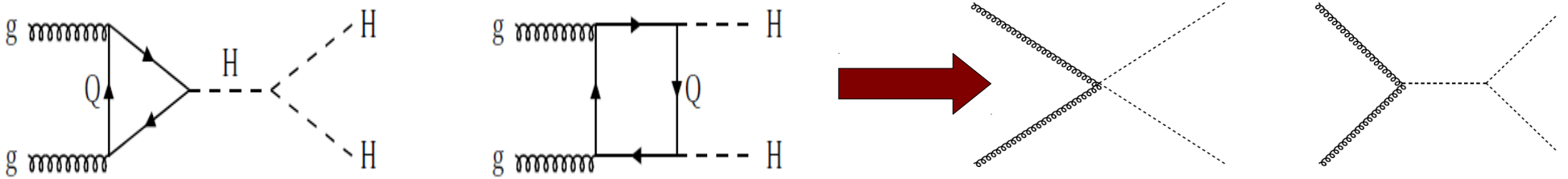
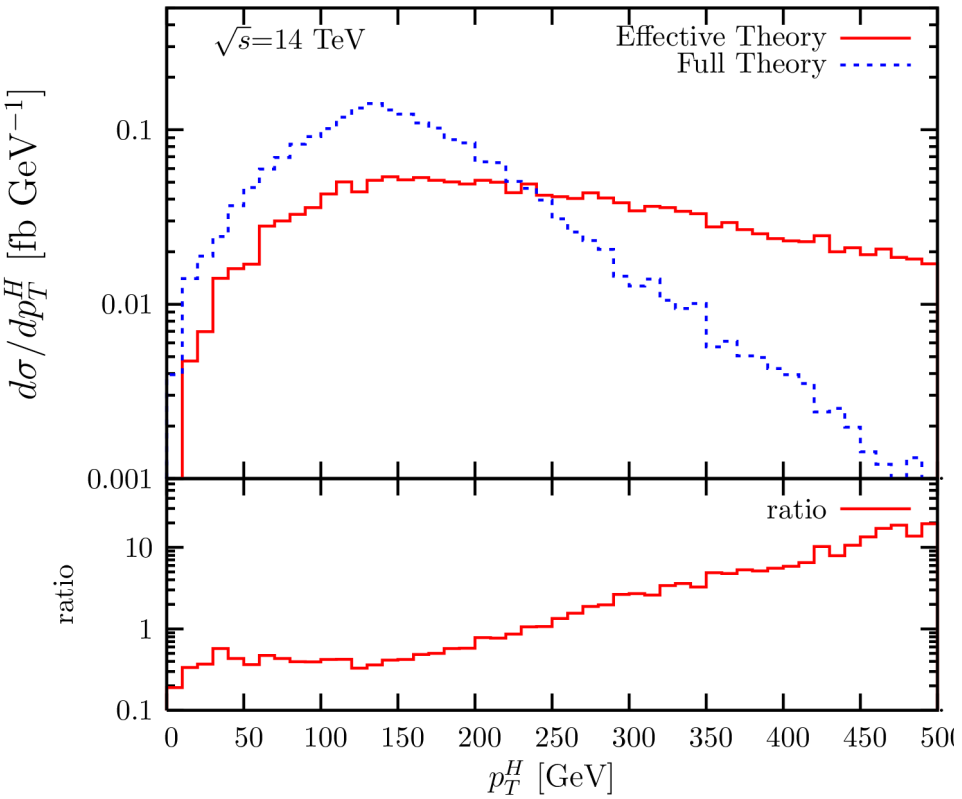
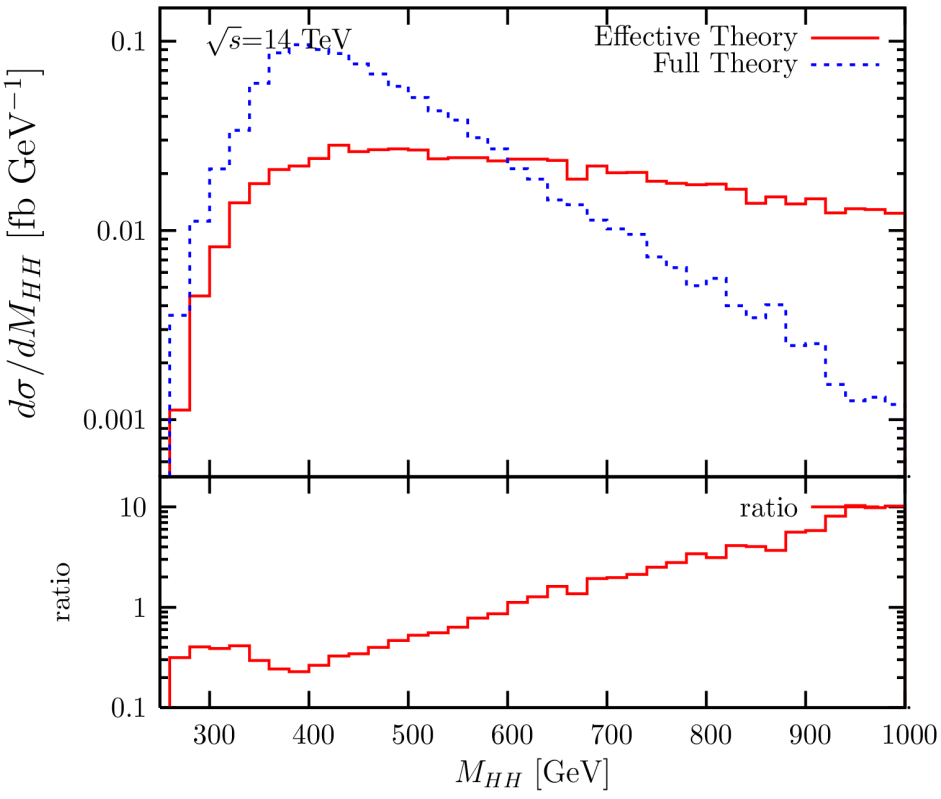


How well does LET do?

- Differential distributions p_T and m_{HH}





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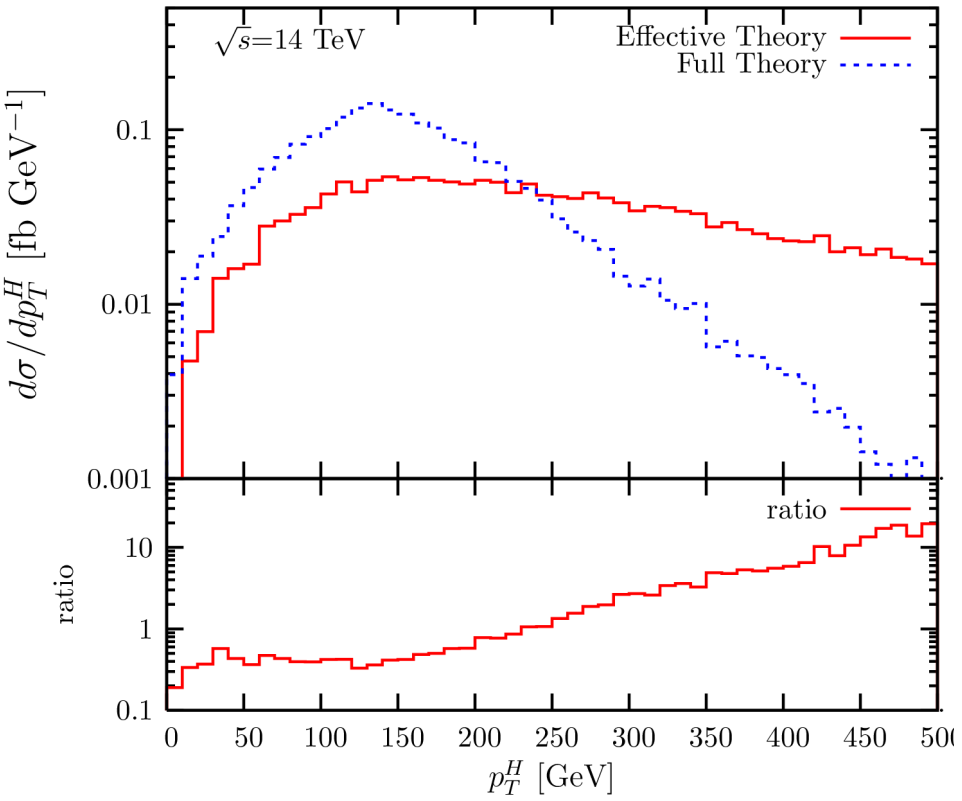

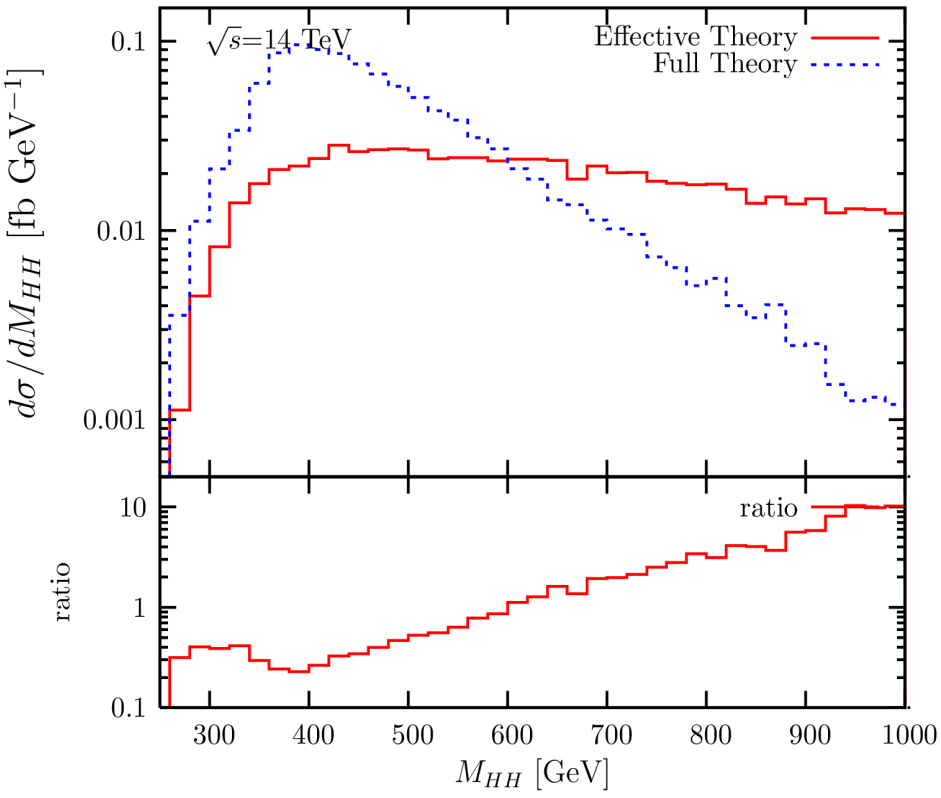

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Low energy theory fails to reproduce kinematic distributions

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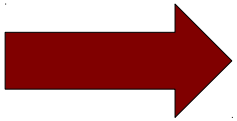

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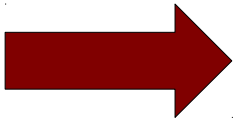

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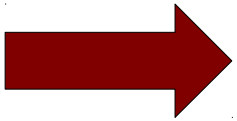

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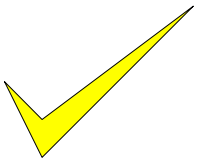

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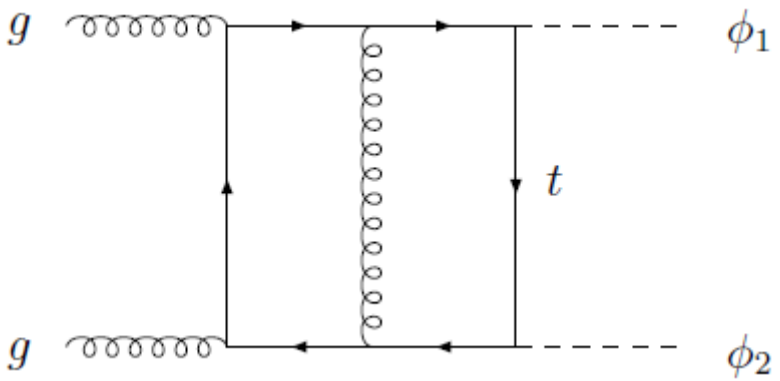

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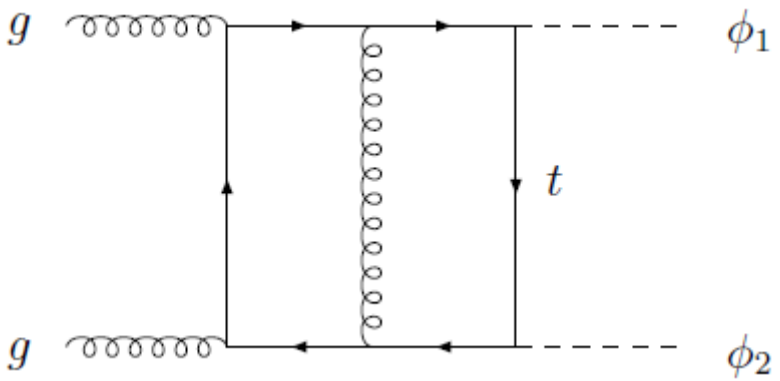
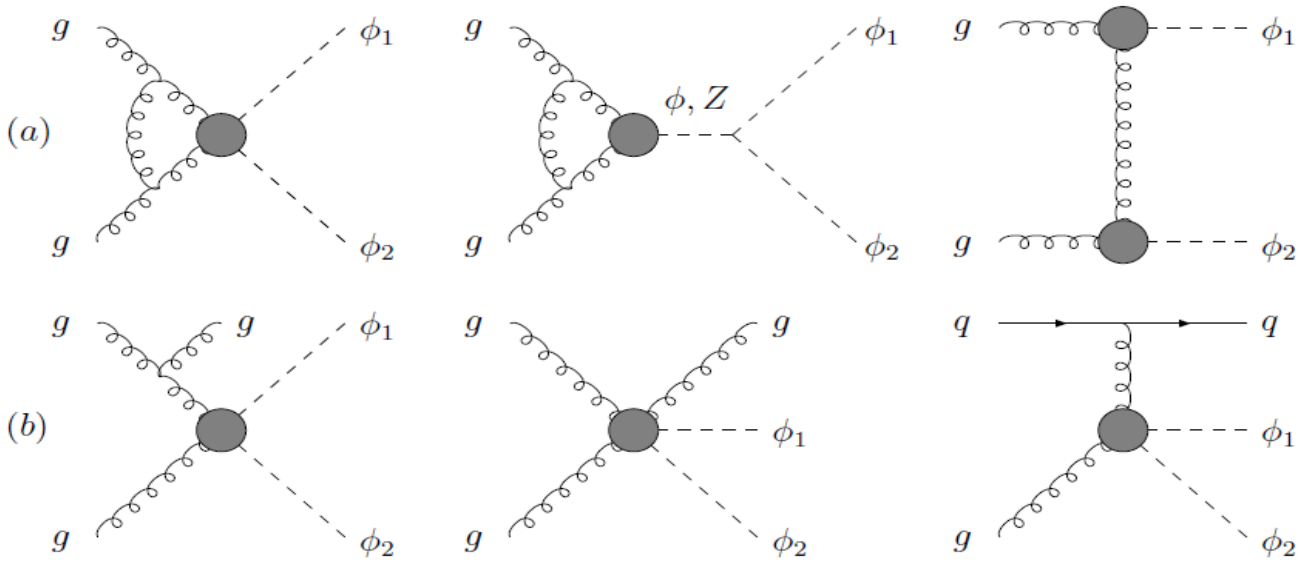


Beyond current loop technology

NLO corrections

- What did we have instead of the full NLO corrections?
- Corrections in the low energy theory:
  Dawson et al. Hep-ph/9805244



- Improved by using the full loop results for the Born cross section and available in Hpair code (total cross section)

How did we improve this?

- What we have done:
  - Implementation of gluon fusion channel in aMC@NLO
  - Use LET to generate events
  - Reweigh on an event by event basis using the results of loop matrix elements, obtained from MadLoop for both Born and real emission kinematics
- When done consistently improves current results, because of better description of real emission processes not included in previous results

This approximate NLO result combined with PS effects give the best current theoretical prediction for HH production in gluon fusion

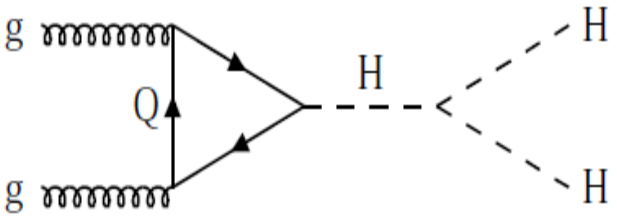
Conclusions and future plans

- Higgs pair production key to the measurement of triple Higgs coupling
- For the phenomenological analyses we need an efficient MC implementation of the process at NLO provided in an automated way by aMC@NLO
- Future:
  - Use of results for phenomenological studies
  - Use for feasibility studies including decays of H
  - Implementation of BSM scenarios-rich phenomenology

ADDITIONAL SLIDES

Gluon-gluon fusion

- What do these form factors mean? Why do we have 3?



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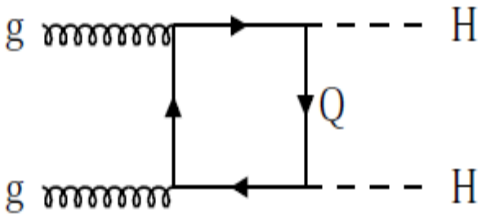

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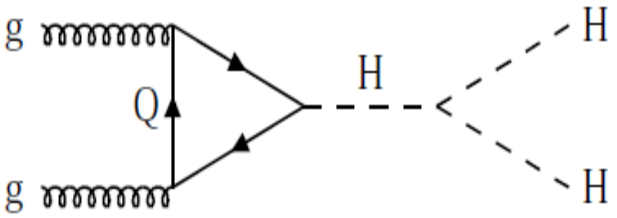

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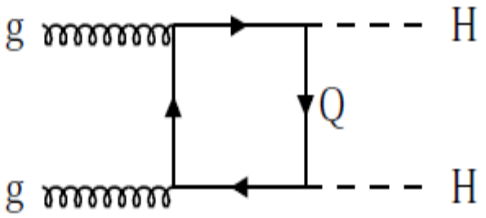

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- Main contribution comes from top quark loop (b-quark contribution ~0.1%)

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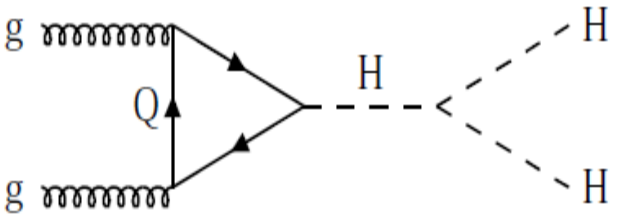

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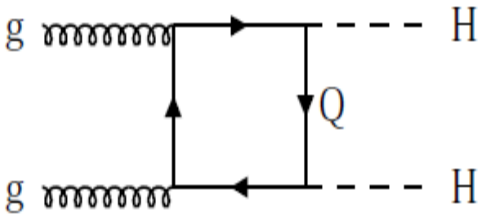

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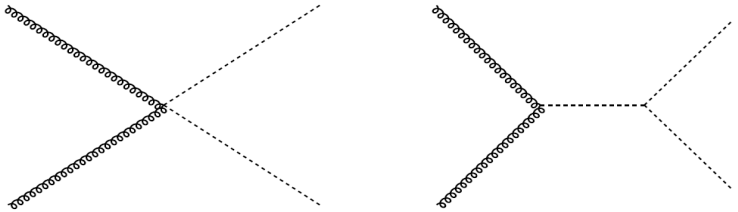

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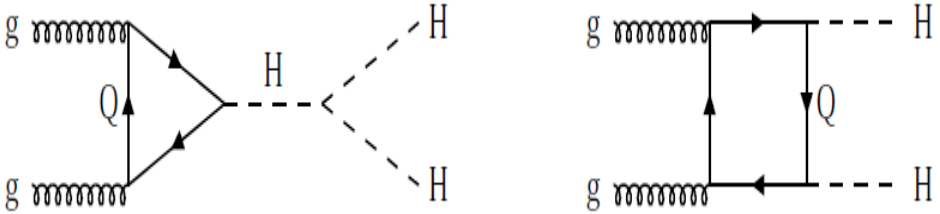

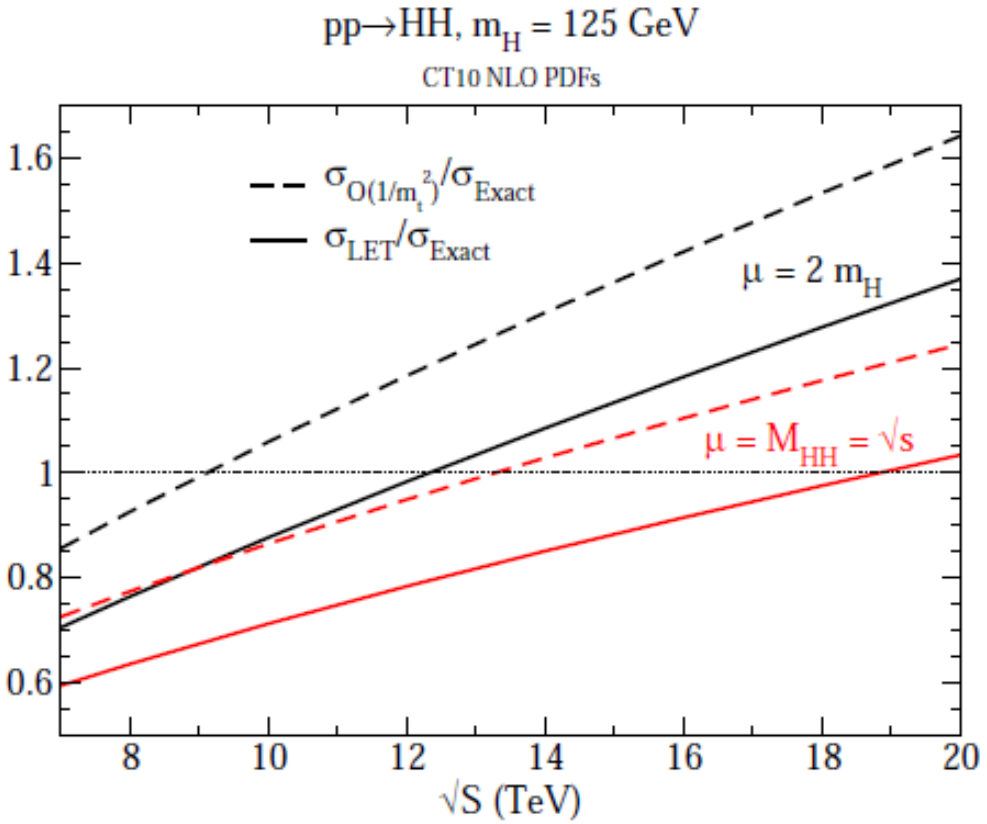

Dawson et al 1206.6663

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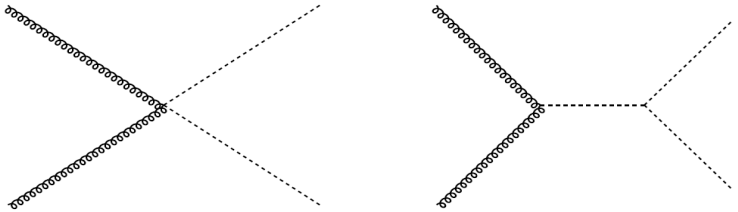

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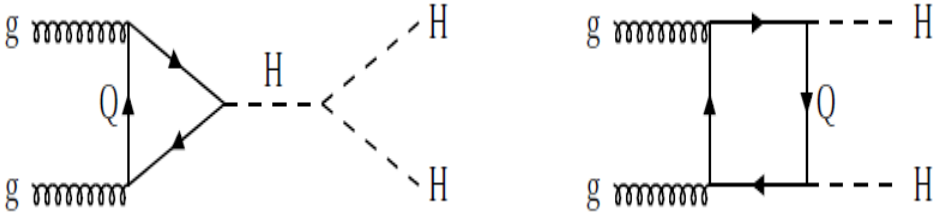

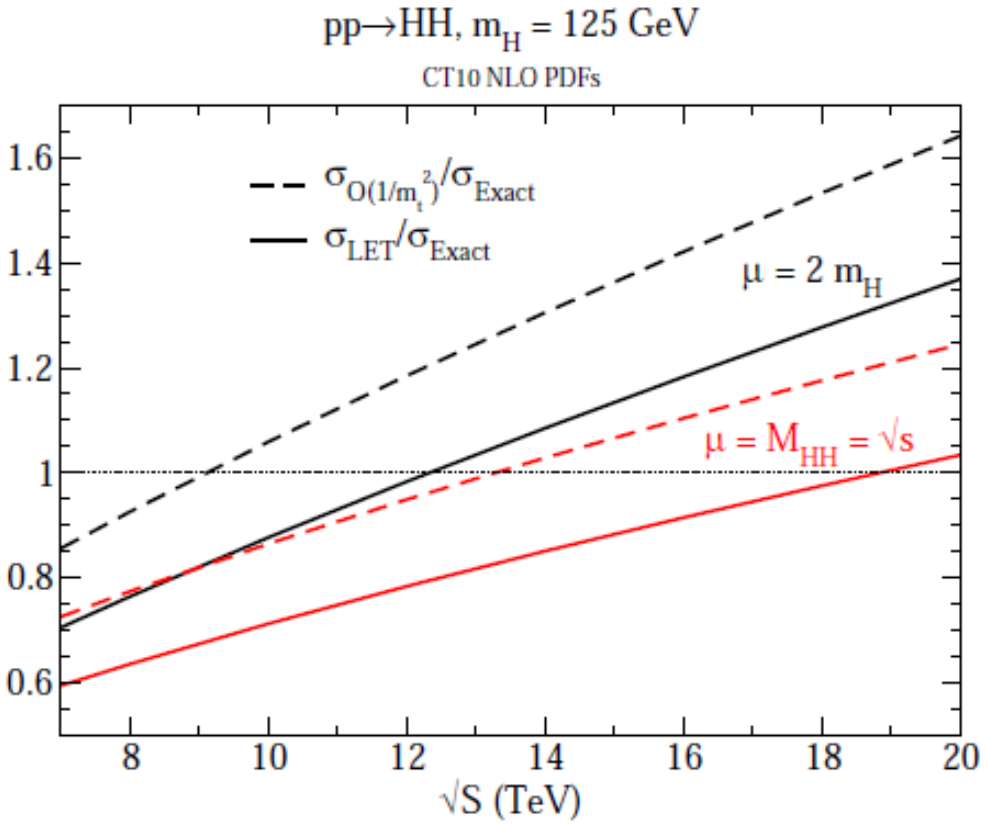

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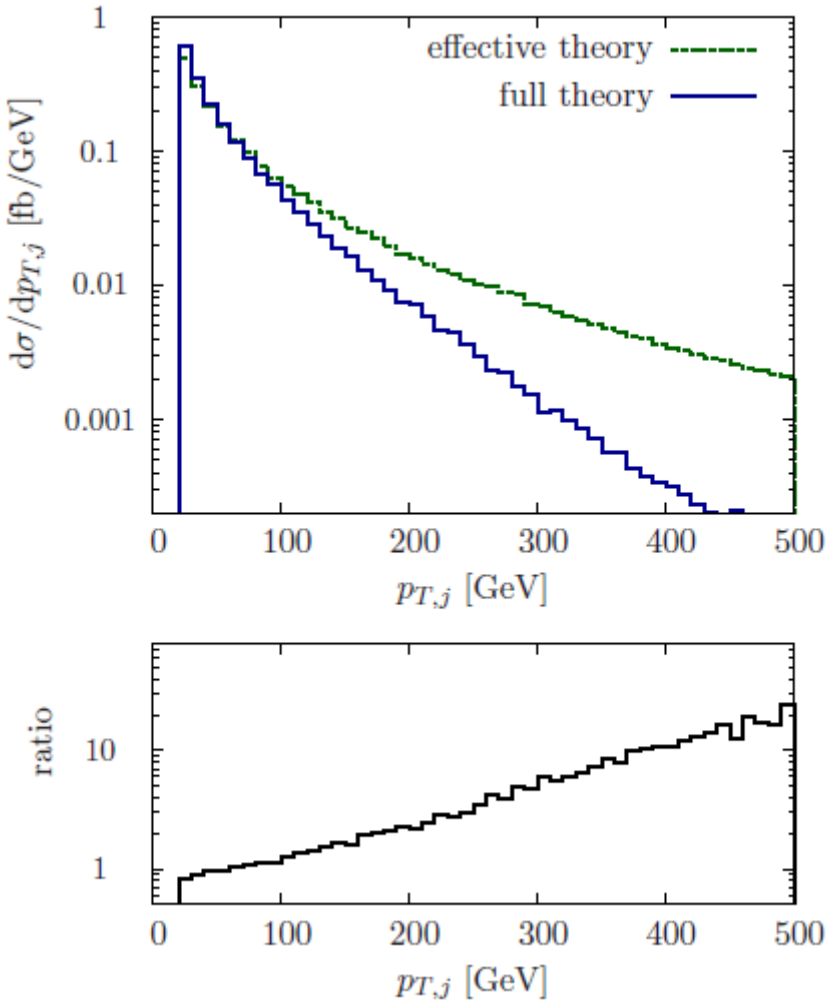
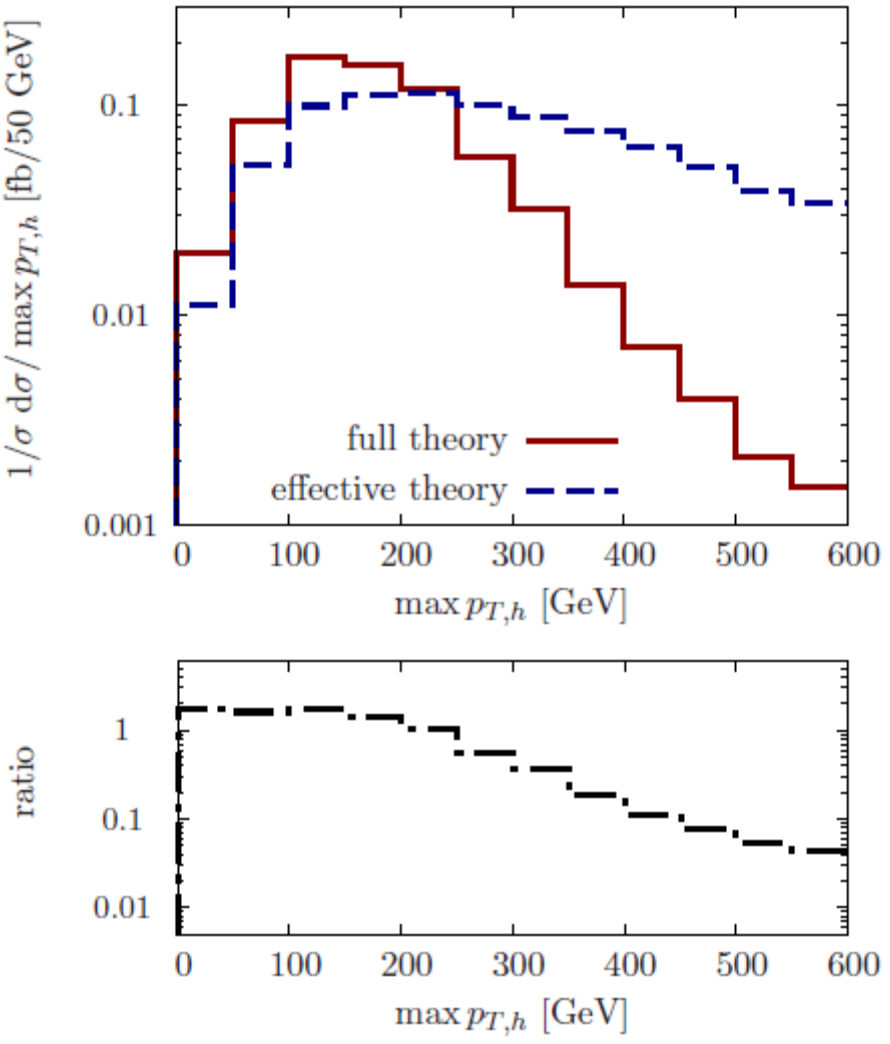
10-20% difference in the total cross section at 14 TeV(depending on the scale choice)

Higgs pair plus 1,2 jets

How good or bad is the LET?



Dolan et al. 1206.5001



Dolan et al. 1310.1084

BSM physics in HH

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- Other BSM contributions?
  - Non SM Yukawa couplings (1205.5444, 1206.6663)
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  - Vector-like quarks (1009.4670, 1206.6663)
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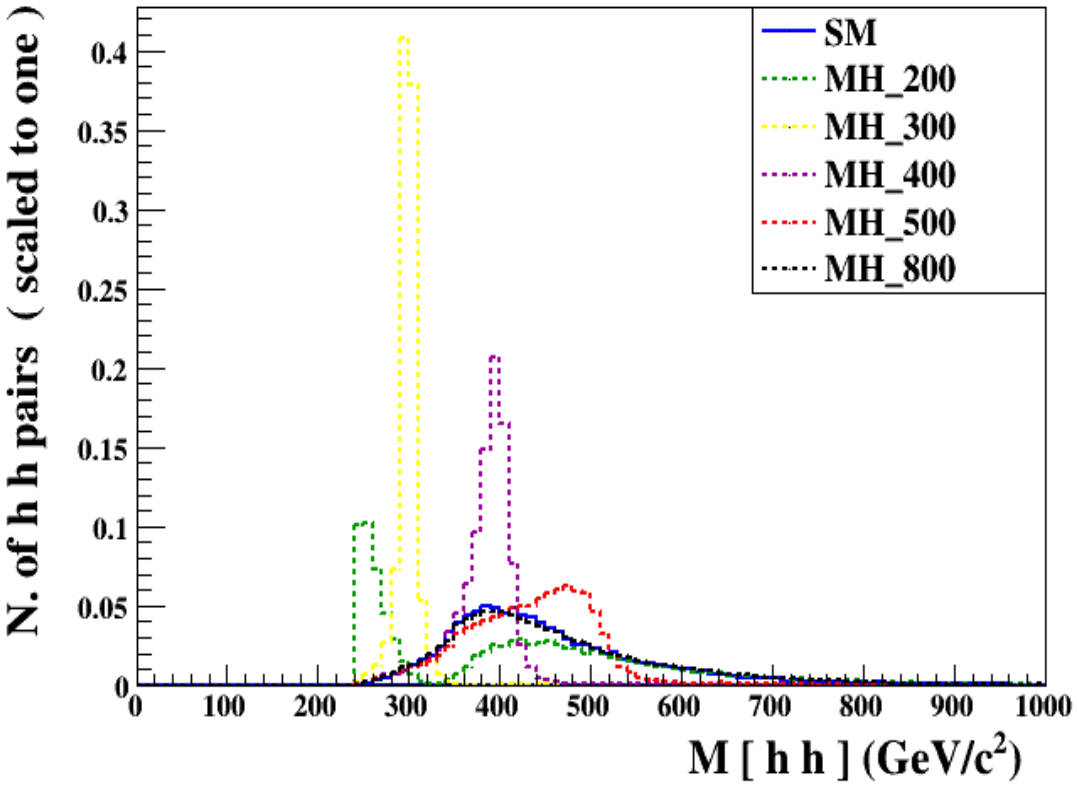
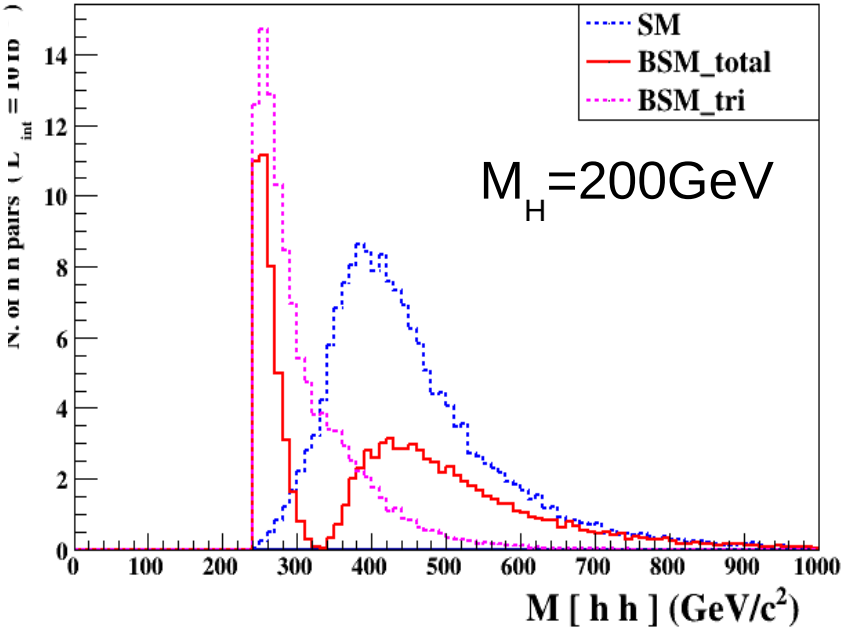
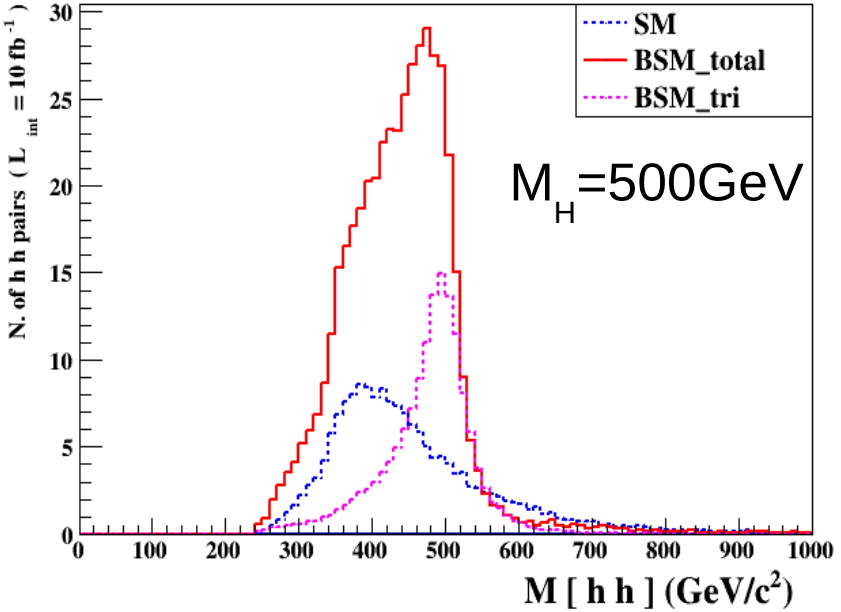
RICH PHENOMENOLOGY

Additional scalar with SM couplings Toy model







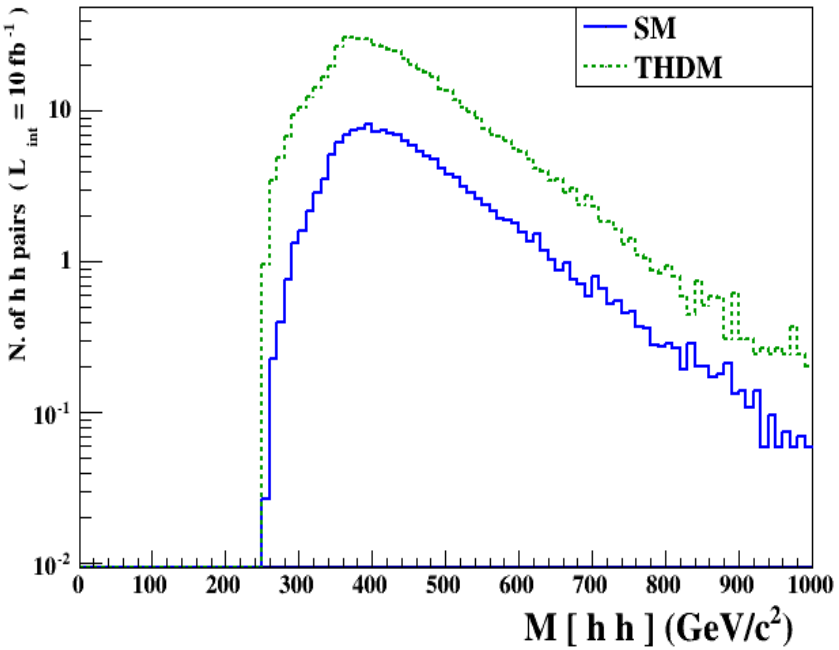
Interference changing sign for different masses

THDM

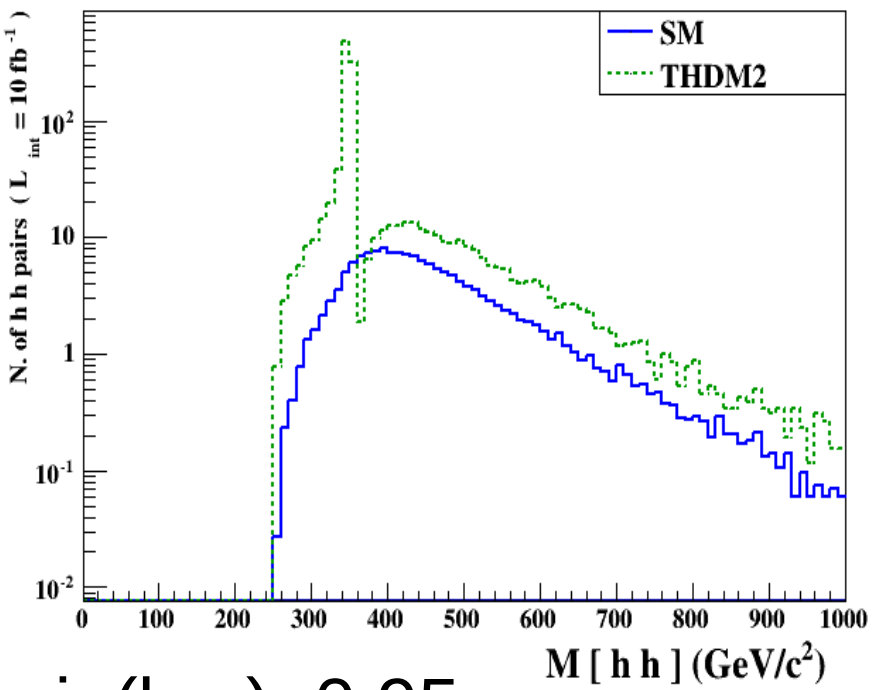
Results for 2 THDM benchmark points (provided kindly by David Lopez Val)

Results strongly depend on the modification of the light Higgs couplings and the suppression of heavy Higgs couplings

M_H=350GeV



sin(b-a)=0.8



sin(b-a)=0.95

Results from aMC@NLO?

Total cross-section results

	$\sqrt{s} = 8\,\text{TeV}$		$\sqrt{s} = 13\,\text{TeV}$		$\sqrt{s} = 14\,\text{TeV}$	
	(LO)	NLO	(LO)	NLO	(LO)	NLO
HH (reweighted)	(5.44^{+38}_{-26})	$8.73^{+17+2.9}_{-16-3.7}$	(19.1^{+33}_{-23})	$29.3^{+15+2.1}_{-14-2.5}$	(22.8^{+32}_{-23})	$34.8^{+15+2.0}_{-14-2.5}$
HH (EFT loop-improved)	(5.04^{+37}_{-25})	$9.68^{+21+4.1}_{-17-5.0}$	(16.6^{+32}_{-23})	$32.6^{+19+3.0}_{-16-3.8}$	(20.3^{+32}_{-23})	$38.5^{+18+2.9}_{-16-3.7}$
$HHjj$ (VBF)	(0.436^{+12}_{-10})	$0.479^{+1.8+2.8}_{-1.8-2.0}$	$(1.543^{+9.4}_{-8.0})$	$1.684^{+1.4+2.6}_{-0.9-1.9}$	$(1.839^{+8.9}_{-7.7})$	$2.017^{+1.3+2.5}_{-1.0-1.9}$
$t\bar{t}HH$	(0.265^{+41}_{-27})	$0.177^{+4.7+3.2}_{-19-3.3}$	(1.027^{+37}_{-25})	$0.792^{+2.8+2.4}_{-10-2.9}$	(1.245^{+36}_{-25})	$0.981^{+2.3+2.3}_{-9.0-2.8}$
W^+HH	$(0.111^{+4.0}_{-3.9})$	$0.145^{+2.1+2.5}_{-1.9-1.9}$	$(0.252^{+1.4}_{-1.7})$	$0.326^{+1.7+2.1}_{-1.2-1.6}$	$(0.283^{+1.1}_{-1.3})$	$0.364^{+1.7+2.1}_{-1.1-1.6}$
W^-HH	$(0.051^{+4.2}_{-4.0})$	$0.069^{+2.1+2.6}_{-1.9-2.2}$	$(0.133^{+1.5}_{-1.7})$	$0.176^{+1.6+2.2}_{-1.2-2.0}$	$(0.152^{+1.1}_{-1.4})$	$0.201^{+1.7+2.2}_{-1.1-1.8}$
ZHH	$(0.098^{+4.2}_{-4.0})$	$0.130^{+2.1+2.2}_{-1.9-1.9}$	$(0.240^{+1.4}_{-1.7})$	$0.315^{+1.7+2.0}_{-1.1-1.6}$	$(0.273^{+1.1}_{-1.3})$	$0.356^{+1.7+1.9}_{-1.2-1.5}$
$tjHH(\cdot 10^{-3})$	$(5.057^{+2.0}_{-3.2})$	$5.606^{+4.4+3.9}_{-2.3-4.2}$	$(23.20^{+0.0}_{-0.8})$	$29.77^{+4.8+2.8}_{-2.8-3.2}$	$(28.79^{+0.0}_{-1.2})$	$37.27^{+4.7+2.6}_{-2.7-3.0}$

Significant decrease of scale and PDF uncertainties for the NLO results

All results apart from gluon fusion are completely automated

What is currently available?

- Hpair: Fortran code by Spira
  - Parton level full theory LO and approximate (LET) NLO results
  - Total cross section
- MadGraph 5
  - Exact LO matrix elements for pair production
  - Some information in:
    - https://cp3.irmp.ucl.ac.be/projects/cp3admin/wiki/UsersPage/Physics/Exp/HHproduction