Higgs pair production at the LHC at NLO

Eleni Vryonidou
Université catholique de Louvain

With R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, P. Torrielli and M. Zaro

Based on arxiv:1401.7340

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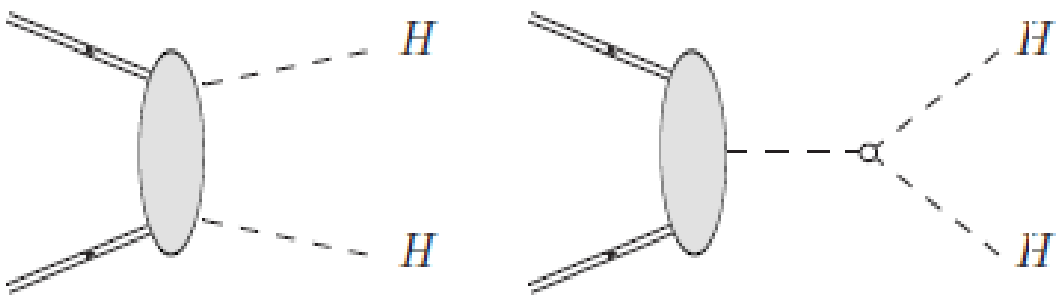
Outline

- Motivation
- HH in gluon gluon fusion
- HH results at NLO
- 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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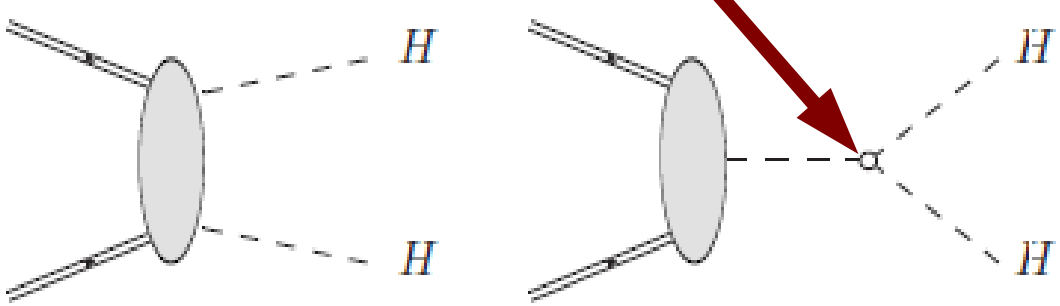

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Higgs Pair Production channels

As in single Higgs production:

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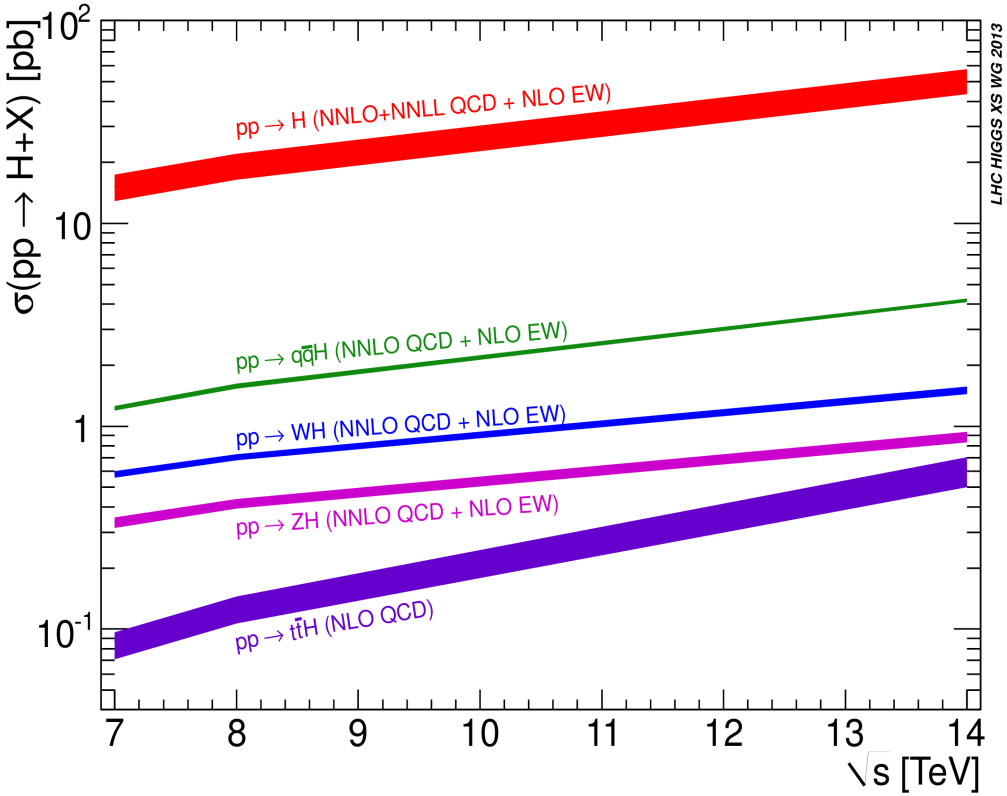
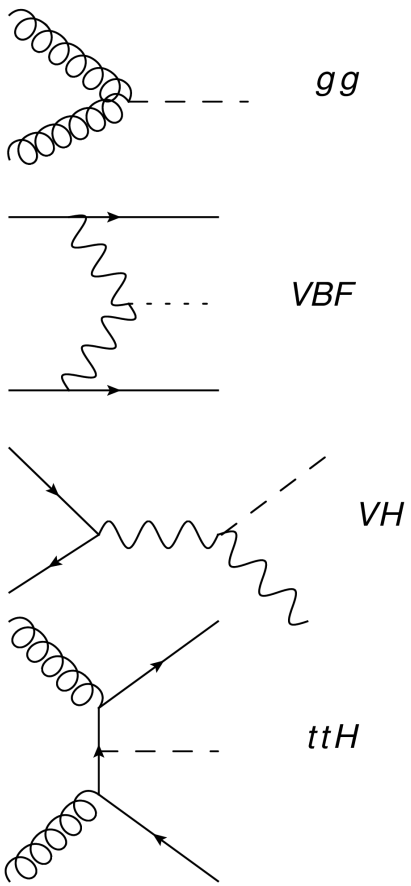


LHC Higgs Cross Sections Working Group



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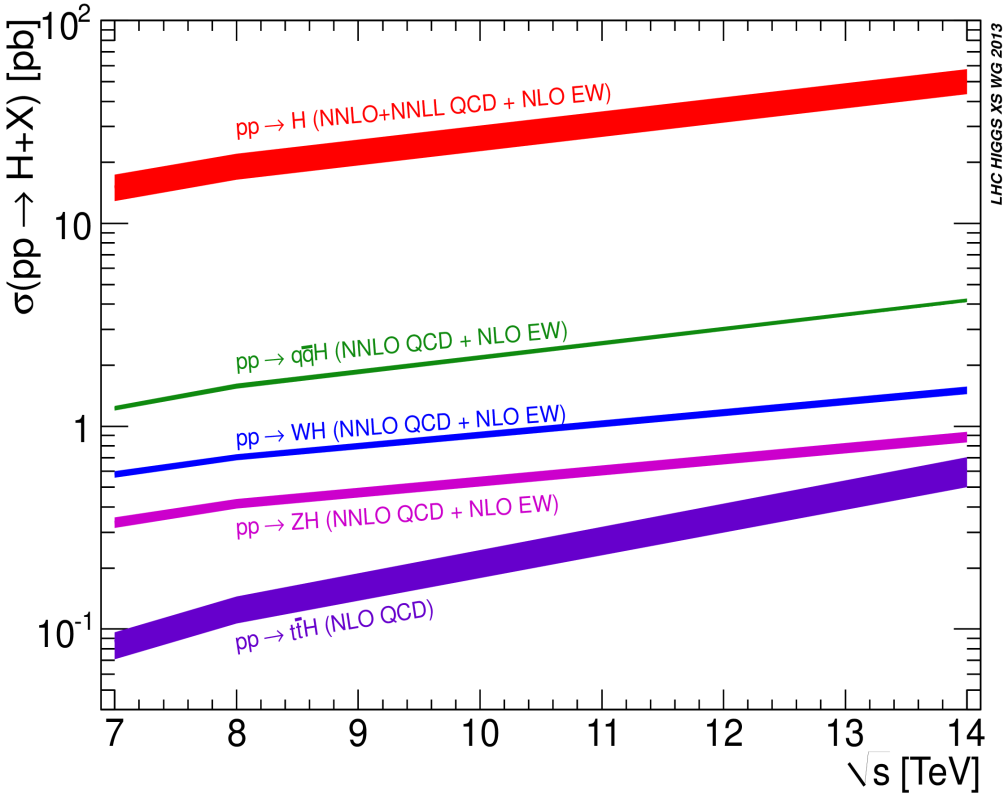

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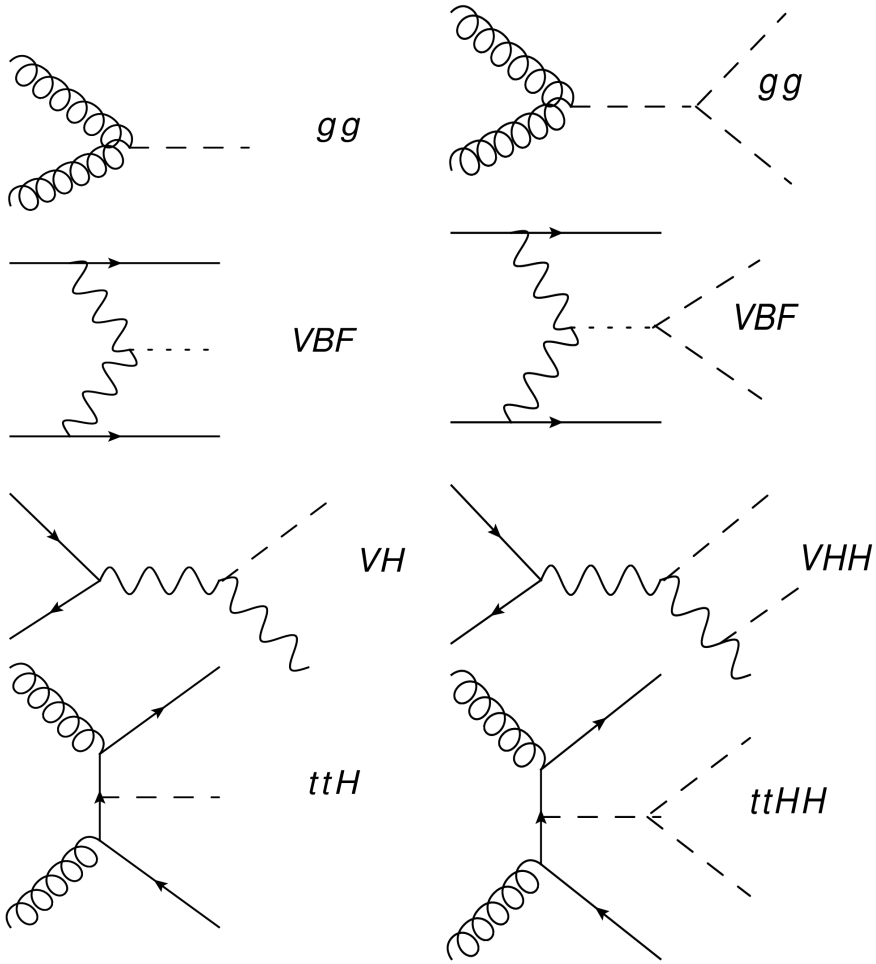

Schematically

Questions about HH

- How does the hierarchy of the channels change for HH at 14TeV? 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?

Before answering all of these questions:

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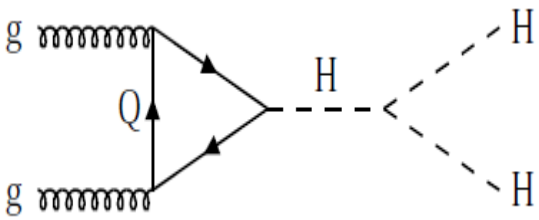
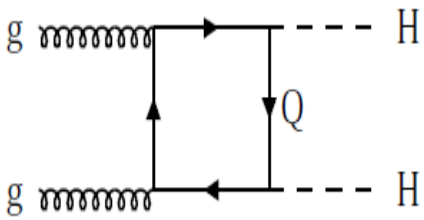
Let's focus on gluon-gluon fusion...

Focussing on gluon-gluon fusion...

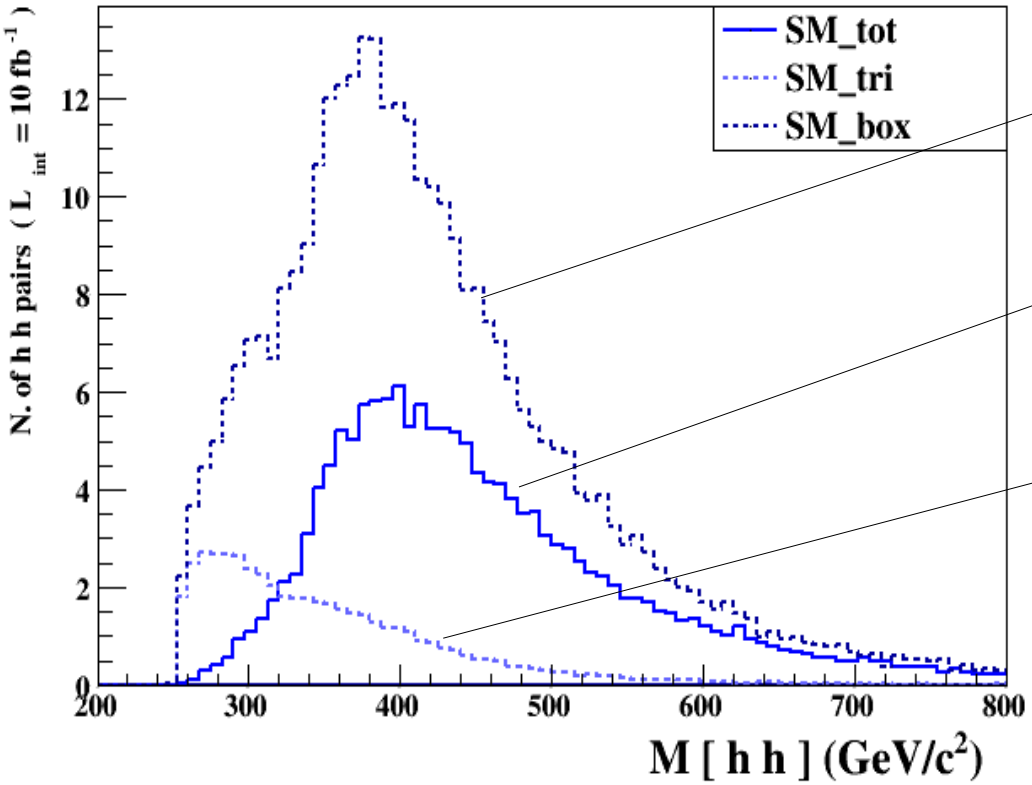
- At LO...





Only loop induced channel

How much does each diagram contribute?



Box

Total

Triangle

Significant cancellation between the two diagrams

HH in gluon-gluon fusion

Loop induced process: not yet automated in MC

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Use a low energy theory, taking the $m_t >> m_H$ limit:

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$$\mathcal{L} \supset + \frac{1}{4}\frac{\alpha_s}{3\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h - \frac{1}{4}\frac{\alpha_s}{6\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2 \,.$$

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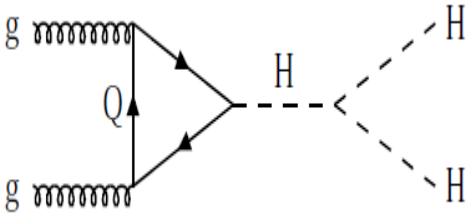

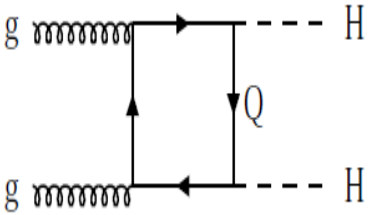

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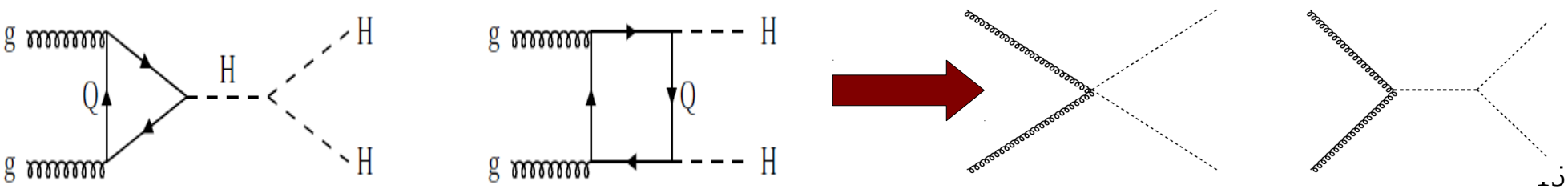

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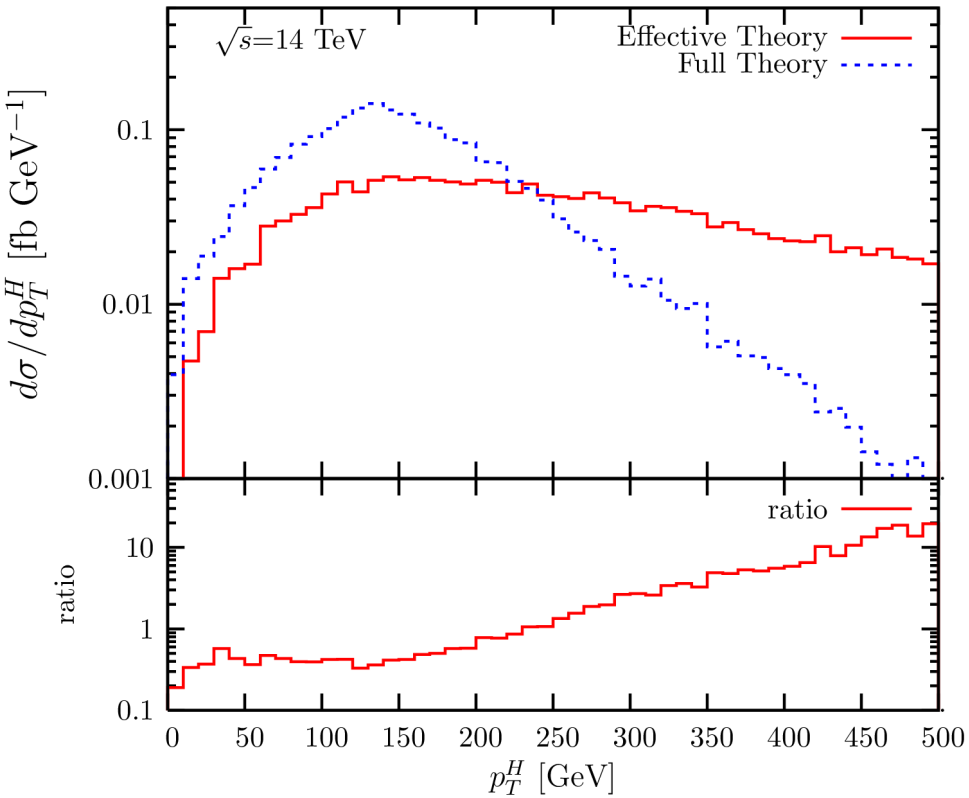

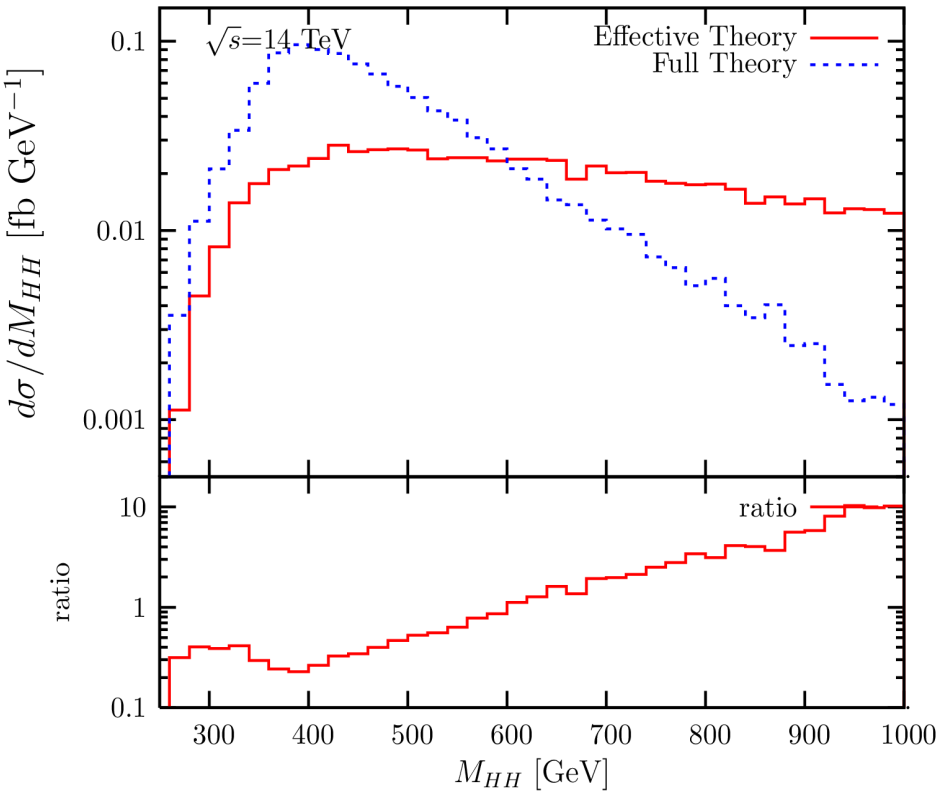

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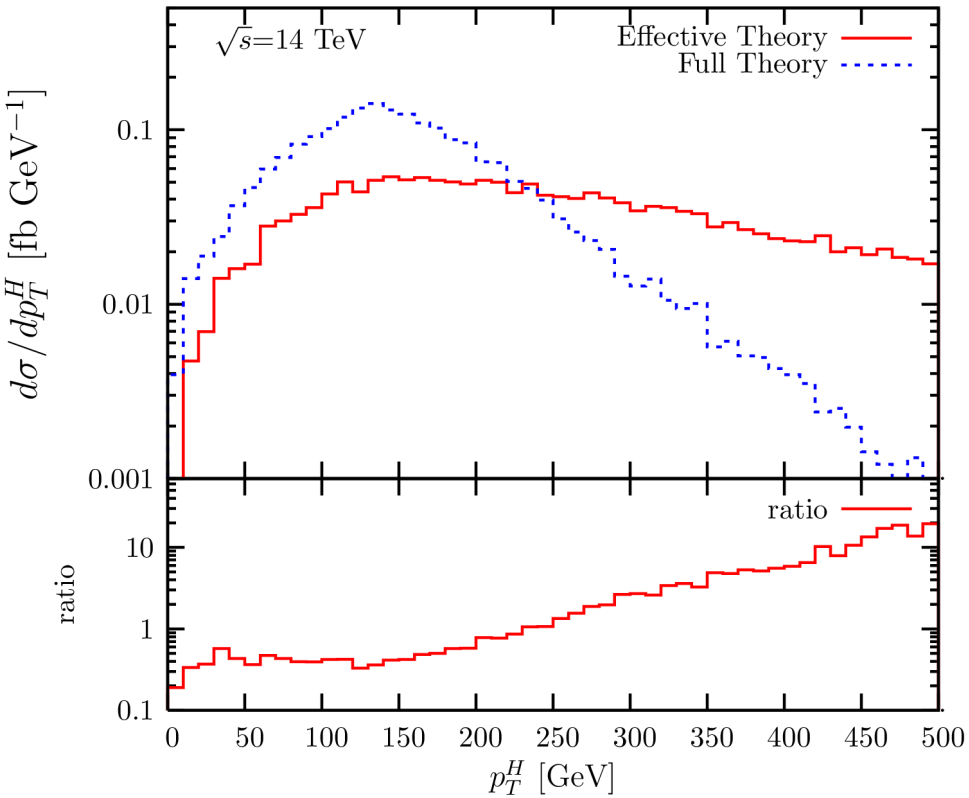

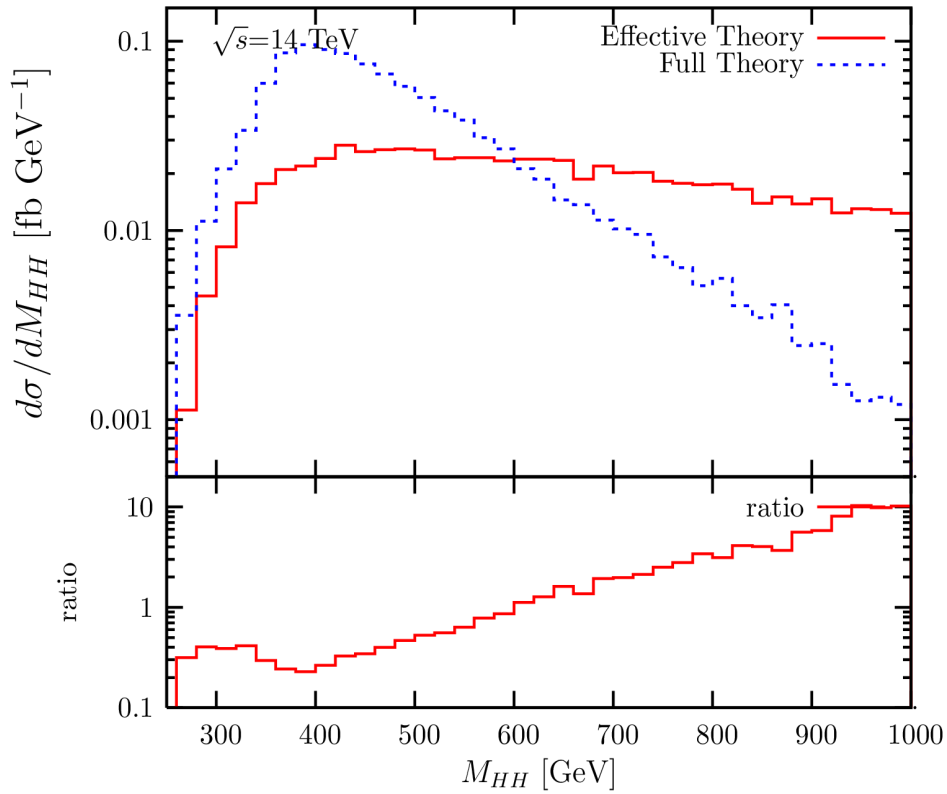

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Low energy theory fails to reproduce kinematic distributions

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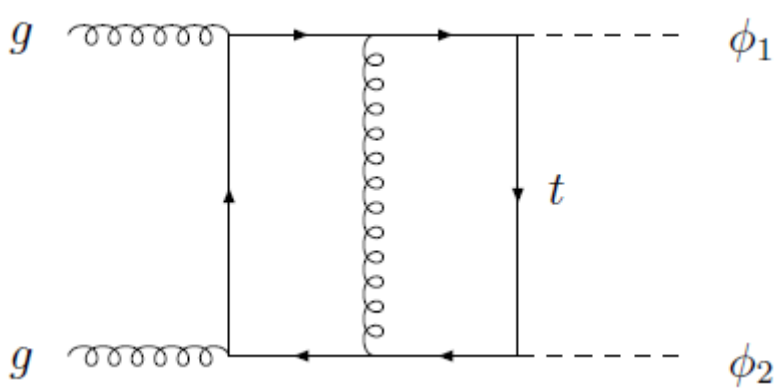

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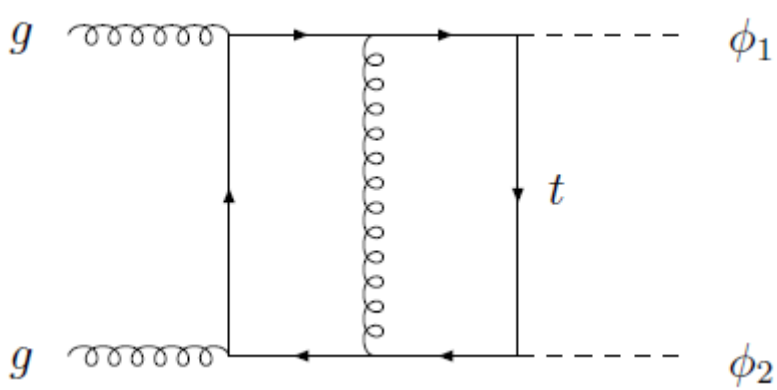
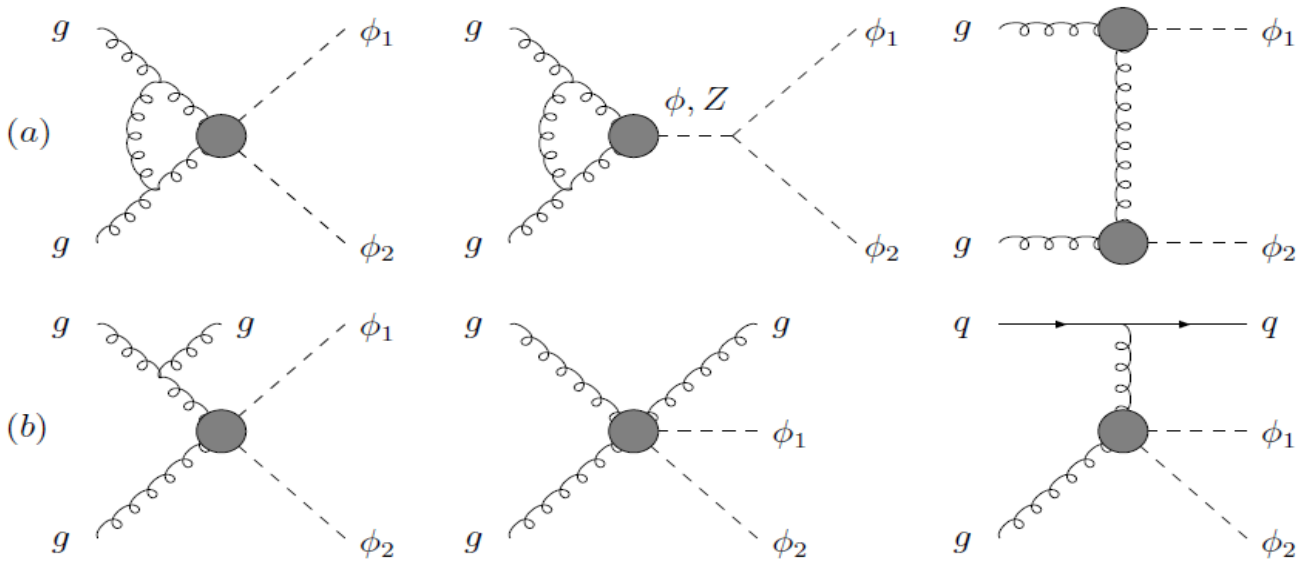


Beyond current loop technology

NLO corrections

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

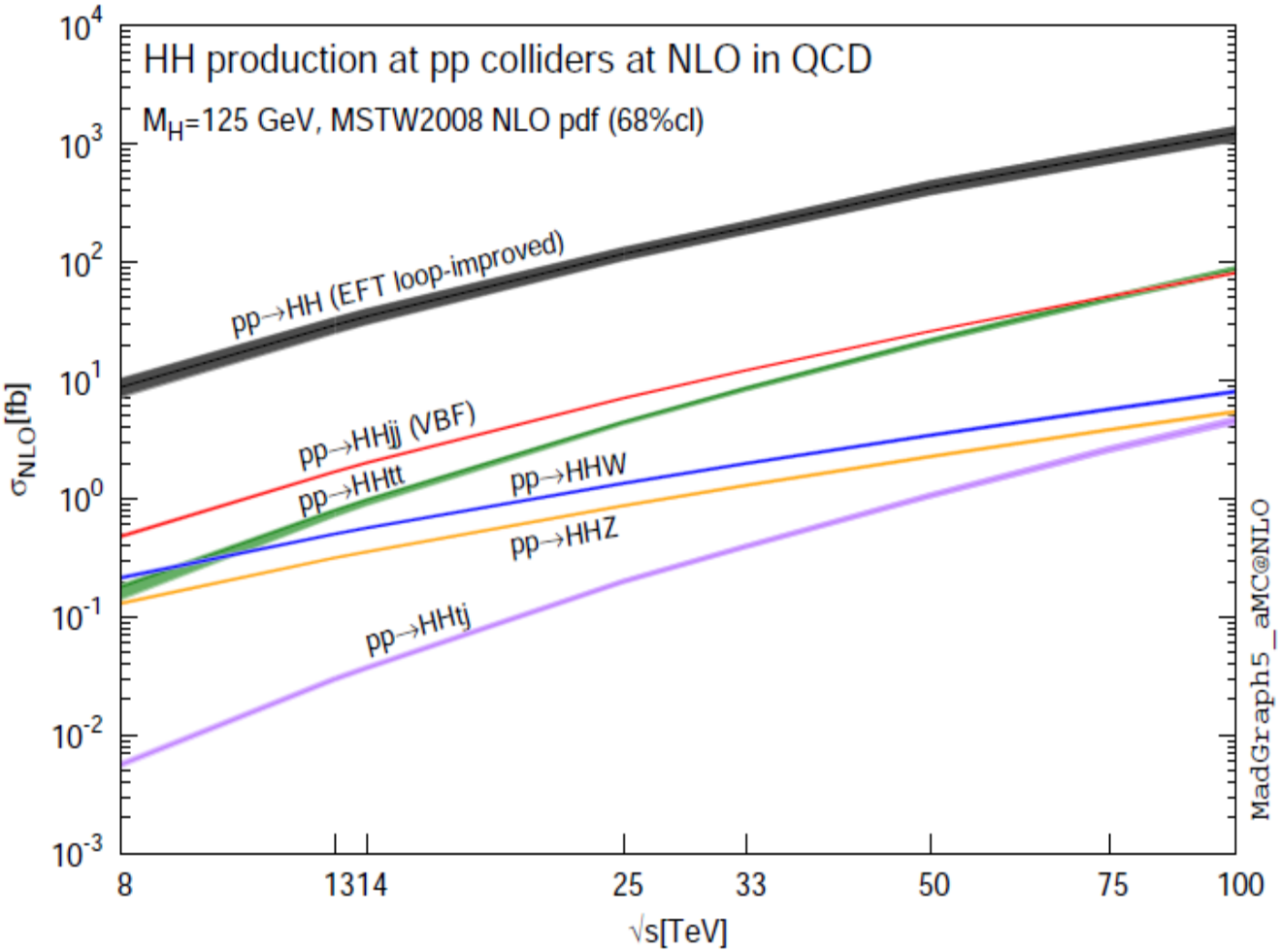


- Improved by using the full loop results for the Born cross section and available in Hpair code (total cross section)

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 previous results, because of better description of real emission processes not included in previous results

aMC@NLO results



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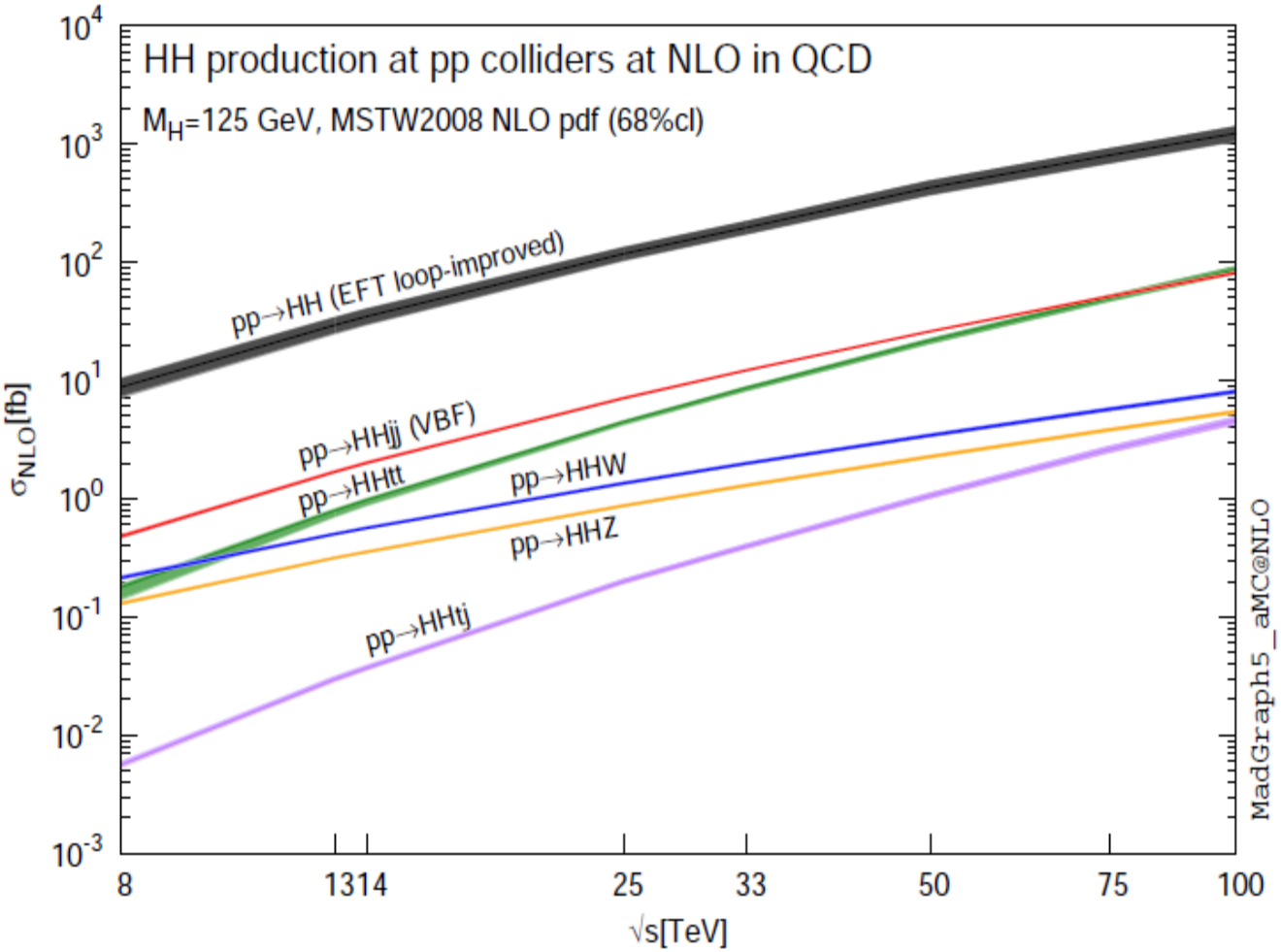

Gluon gluon fusion dominates σ~35fb at 14TeV

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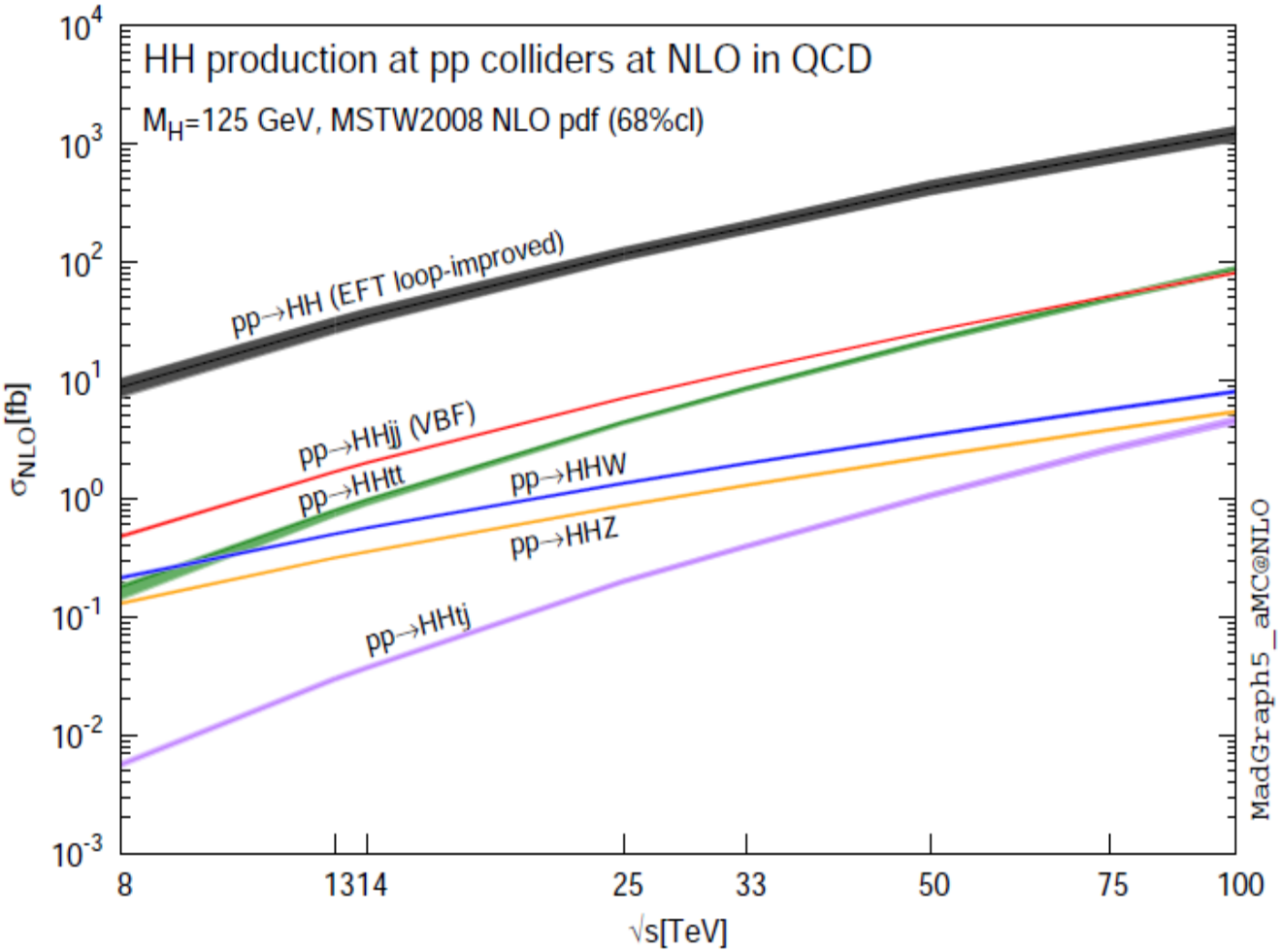

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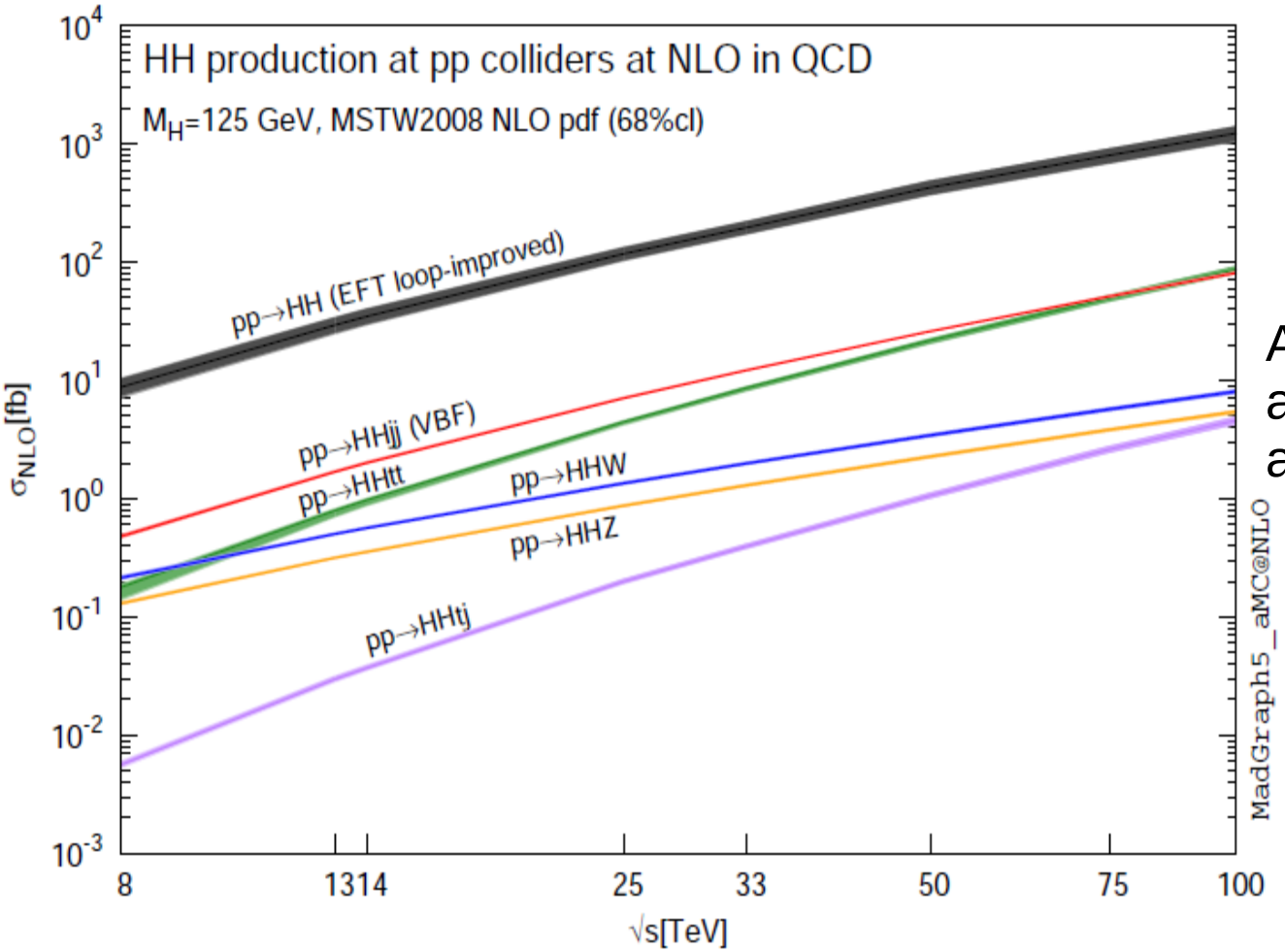

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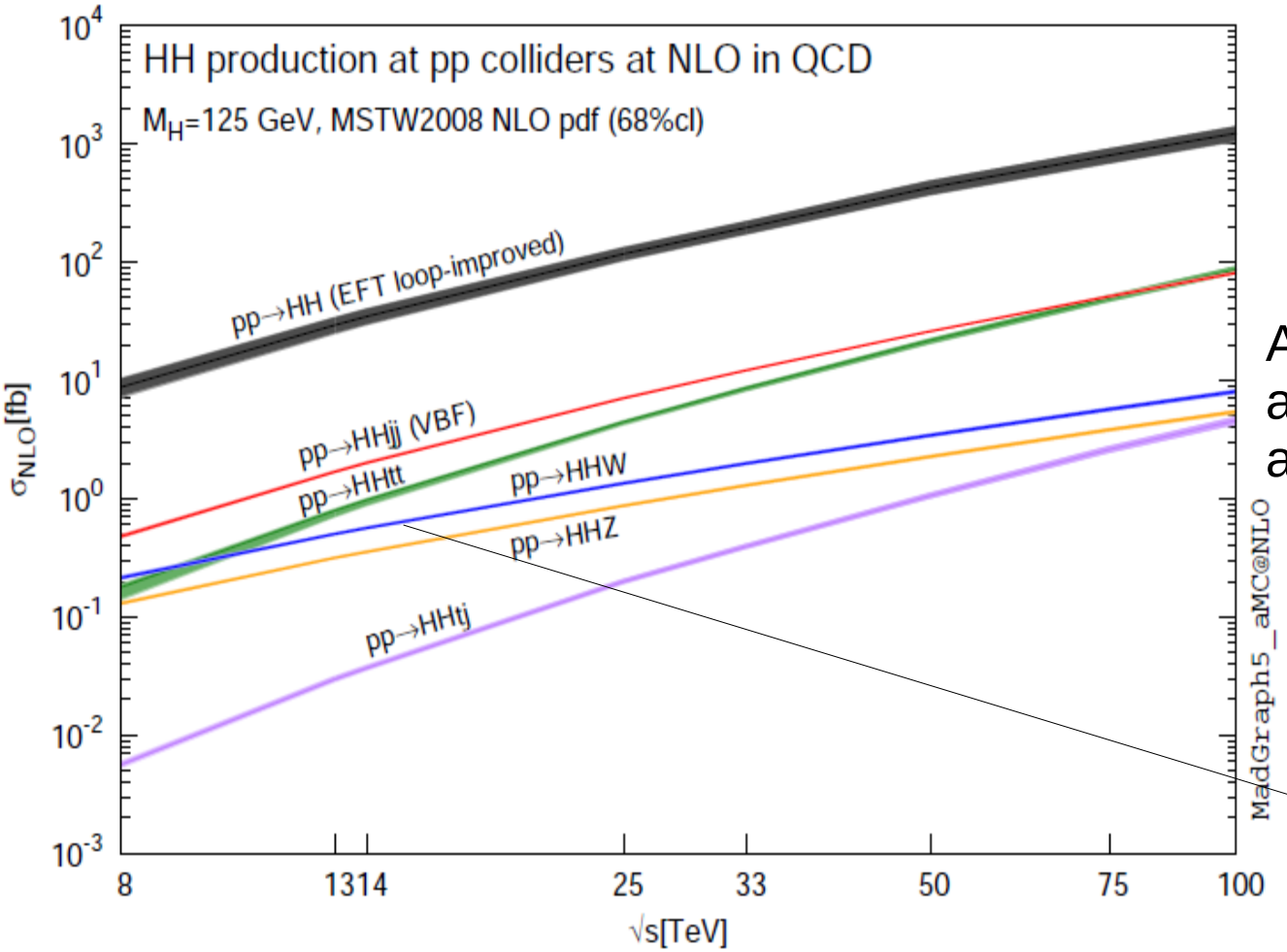

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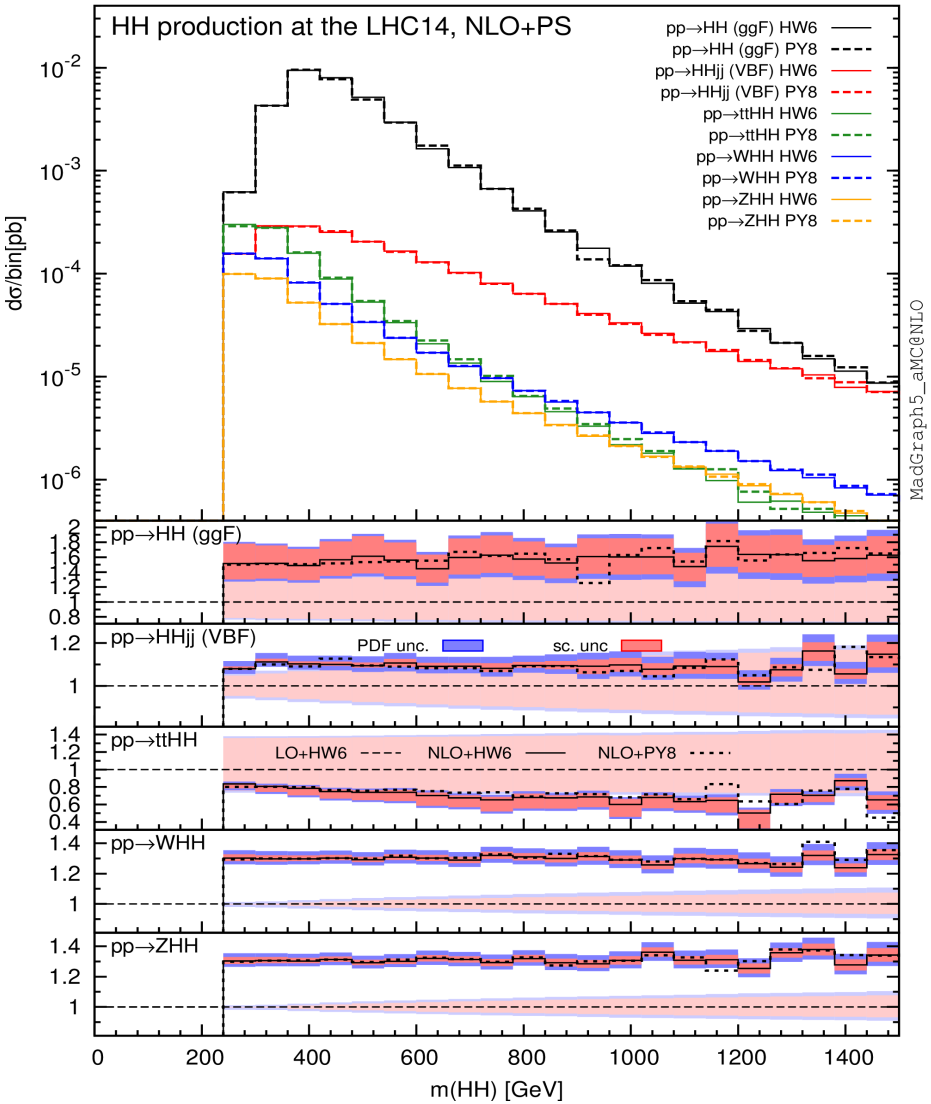
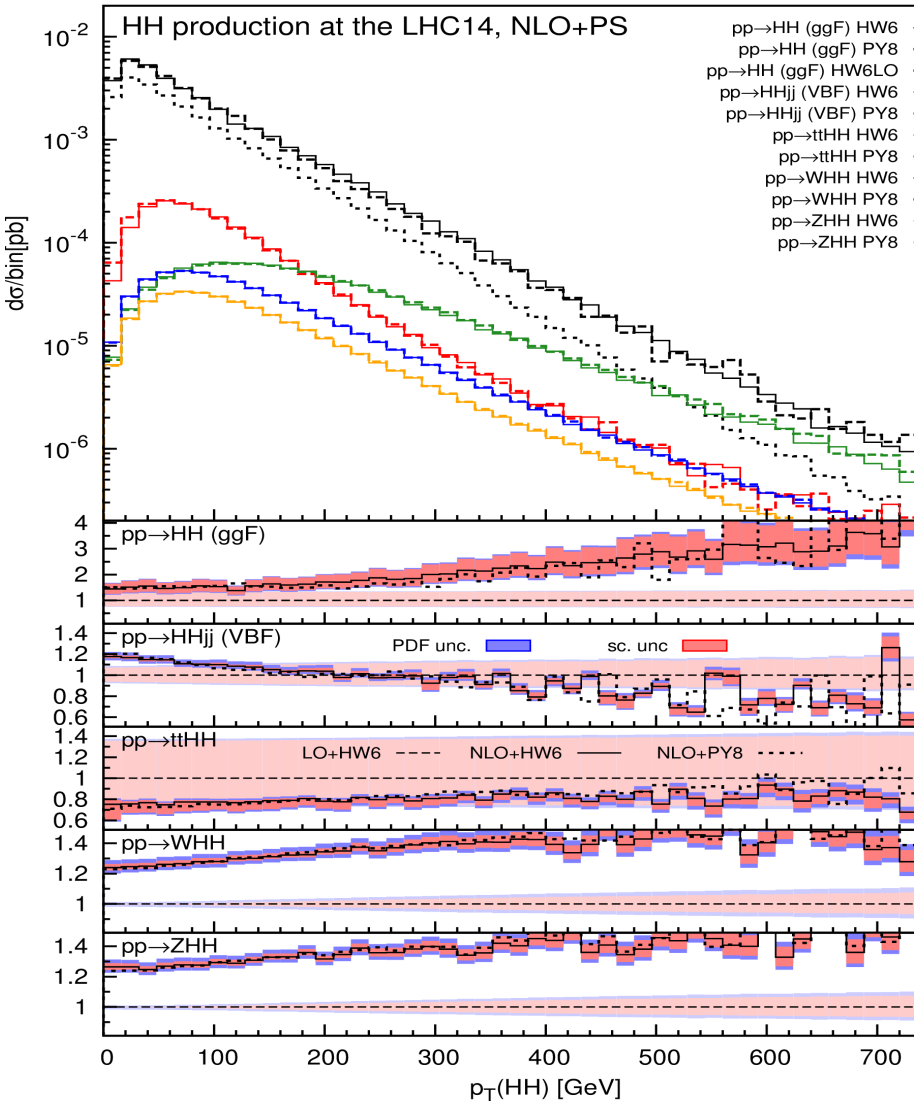
Small difference from single Higgs at 14 TeV:
Vector boson associated production and ttHH hierarchy reversed

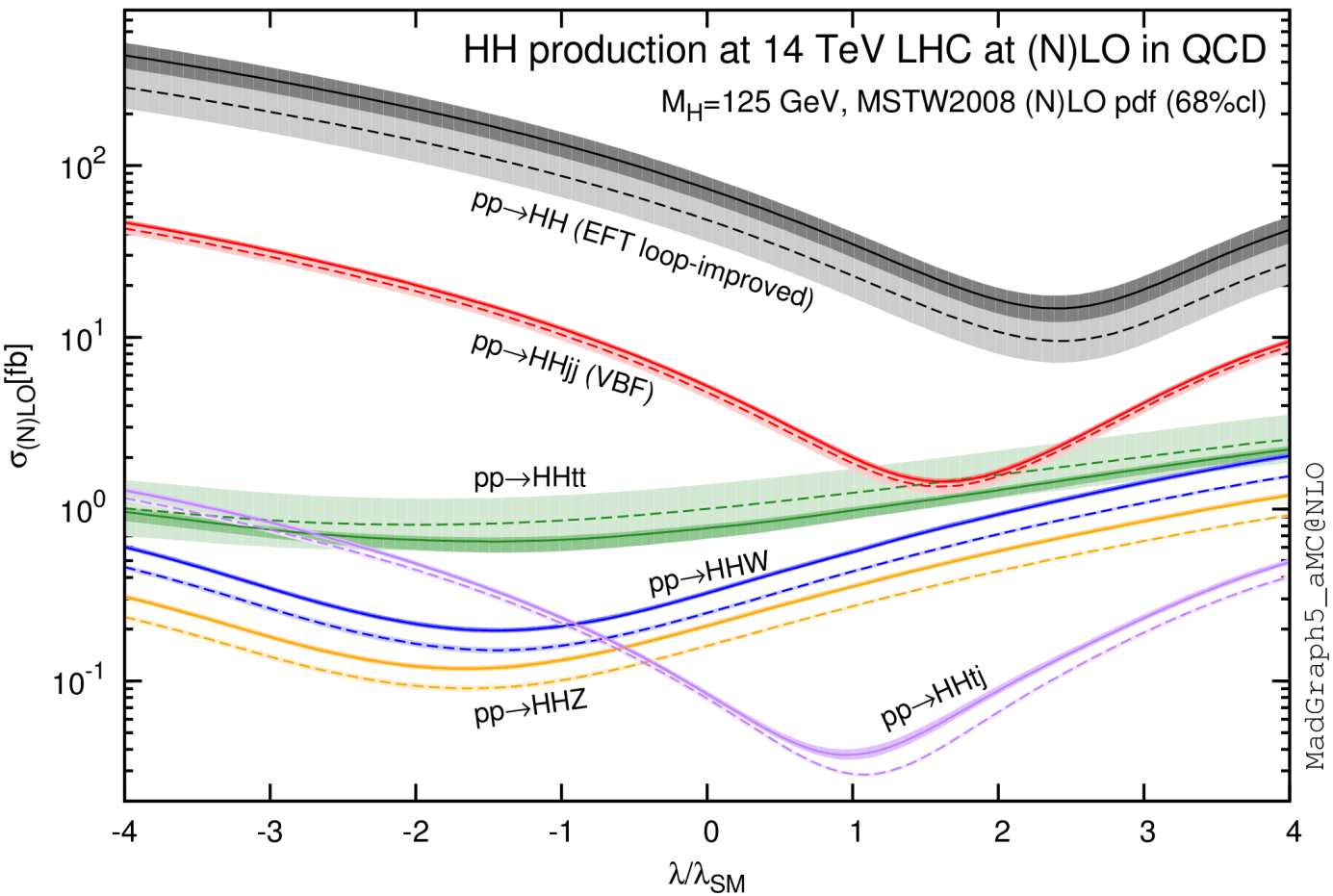
Differential distributions





Including NLO and PS effects: best available predictions

Dependence on the trilinear Higgs coupling



Sensitivity of different channels to λ

Conclusions and future plans

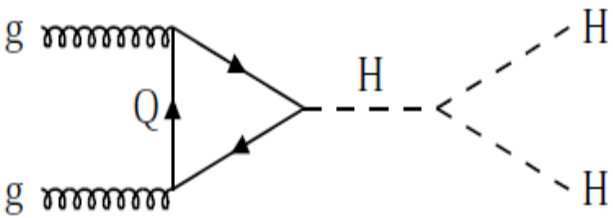
- Higgs pair production key to the measurement of triple Higgs coupling
- Presented results of an efficient MC implementation of the process at NLO provided in an automated way by aMC@NLO
- Results can now be used for phenomenological studies
- Extend to HH production in BSM scenarios like the 2HDM

Thanks for your attention...

ADDITIONAL SLIDES

Gluon-gluon fusion

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



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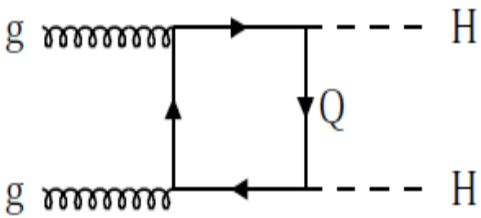

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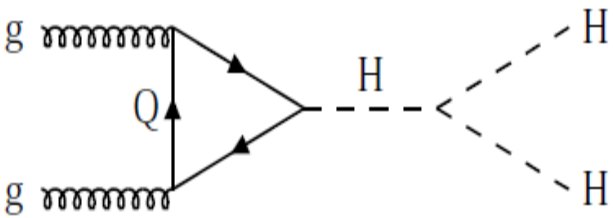

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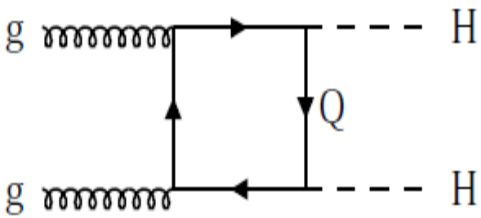

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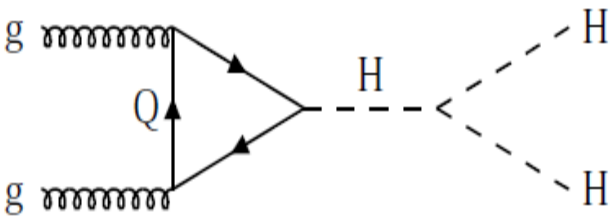

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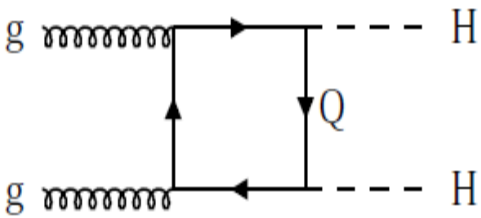

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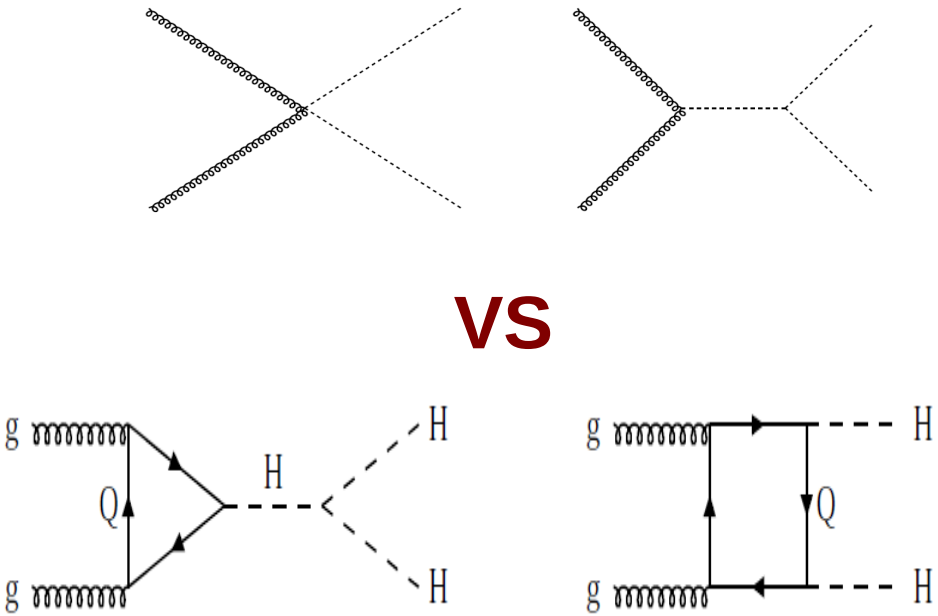

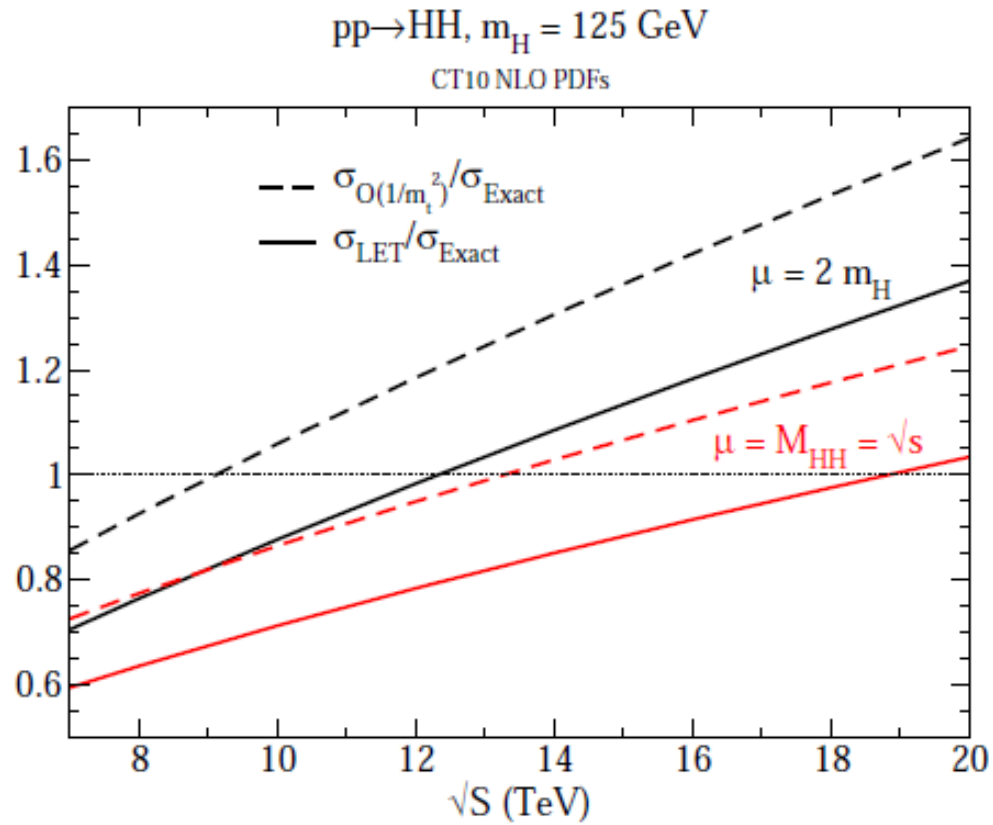

Dawson et al 1206.6663

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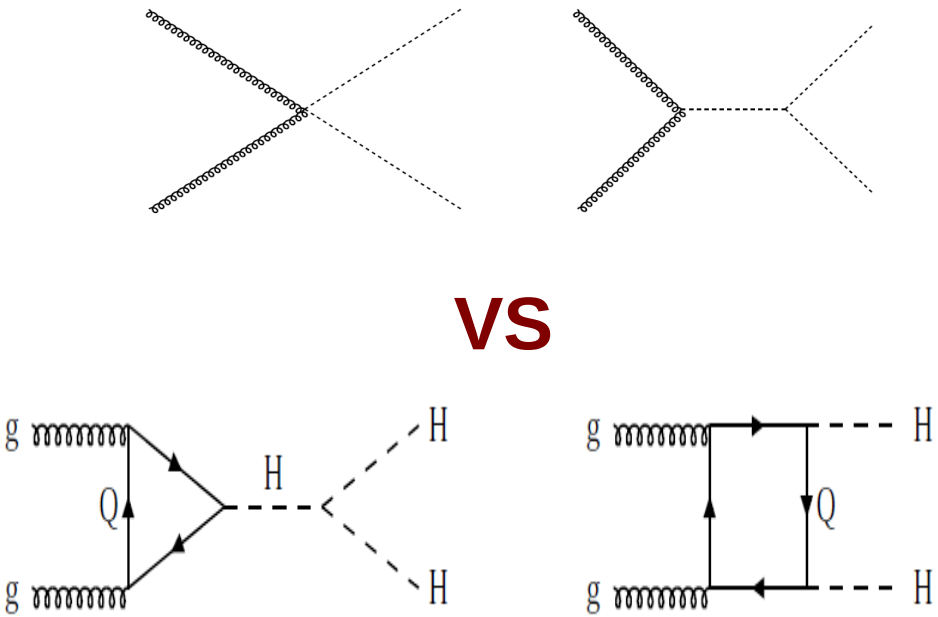
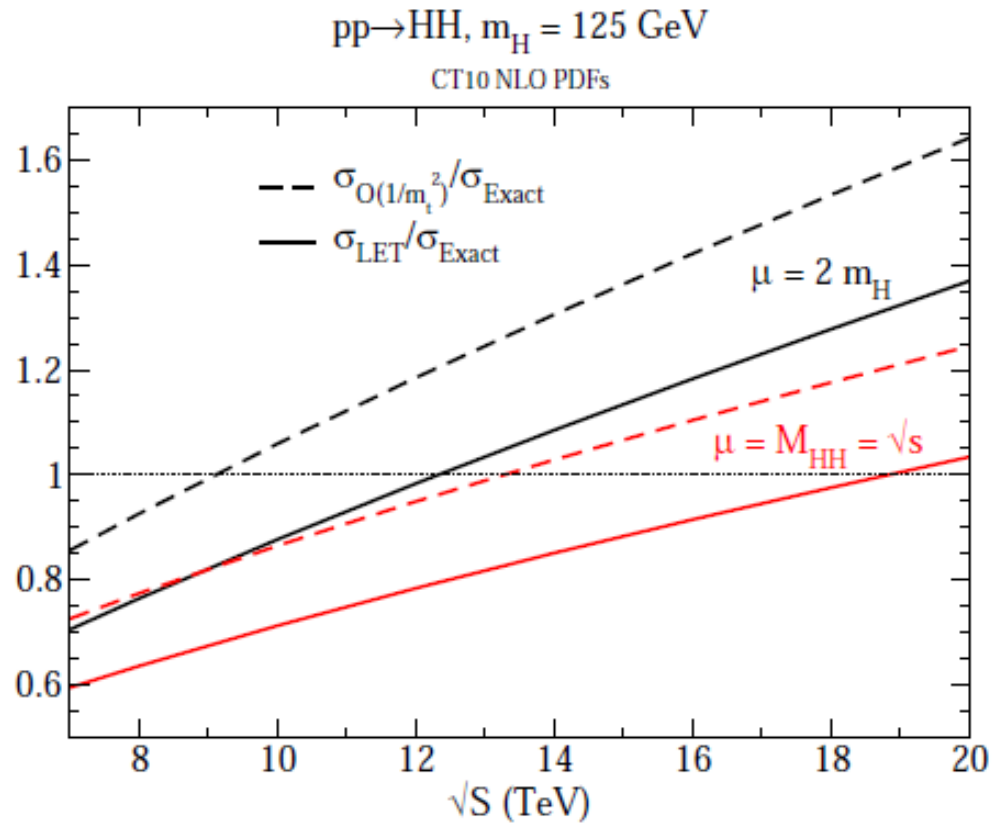


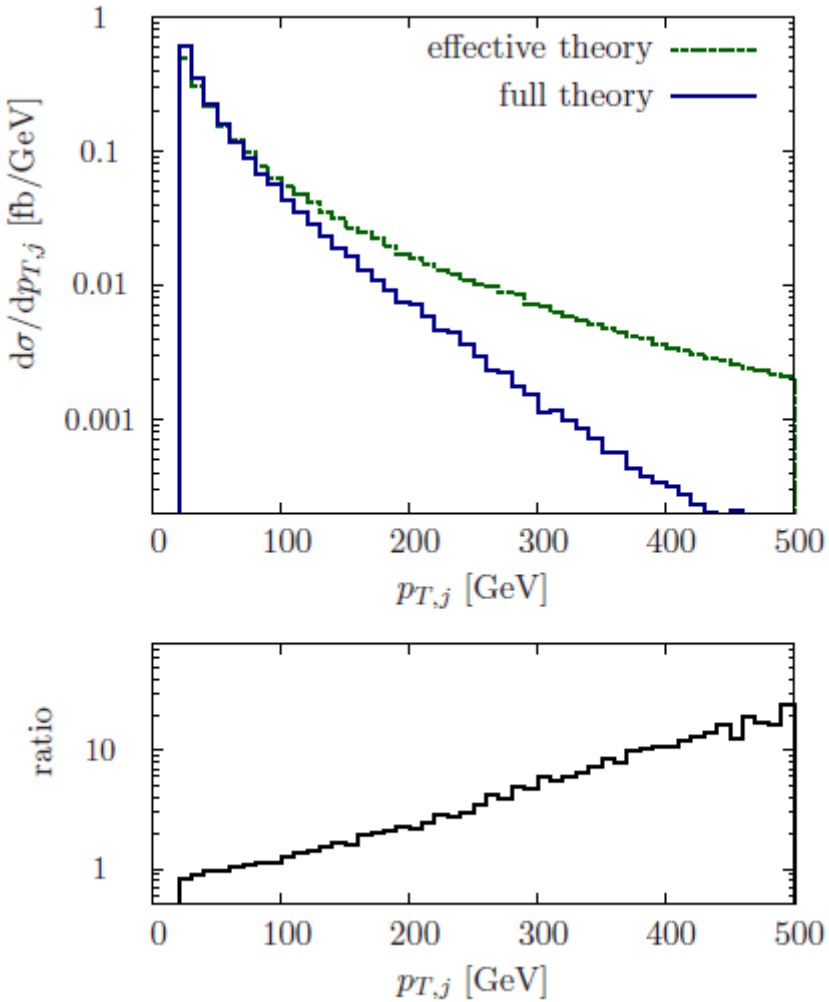


Dawson et al 1206.6663

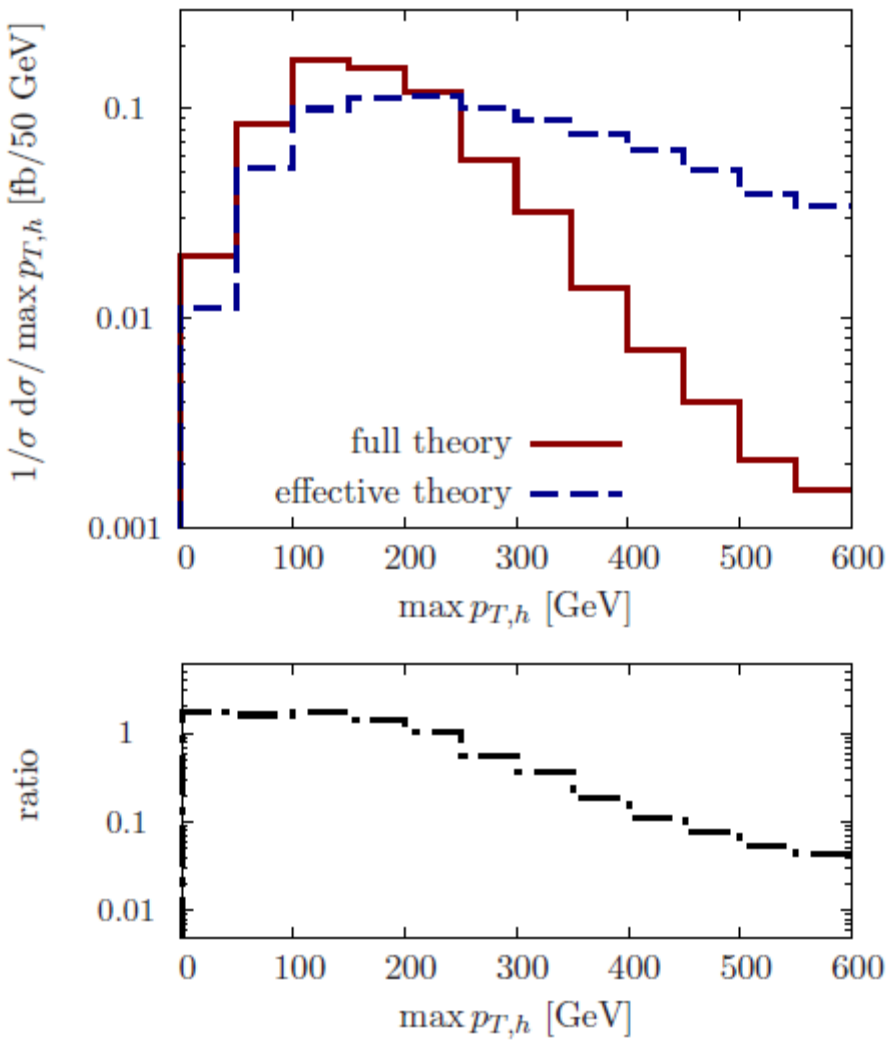
10-20% difference in the total cross section at 14 TeV(depending on the scale choice)

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

- Sensibility to BSM trilinear coupling (1206.5001,1210.8166,1311.2931)
- Other BSM contributions?
  - 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)
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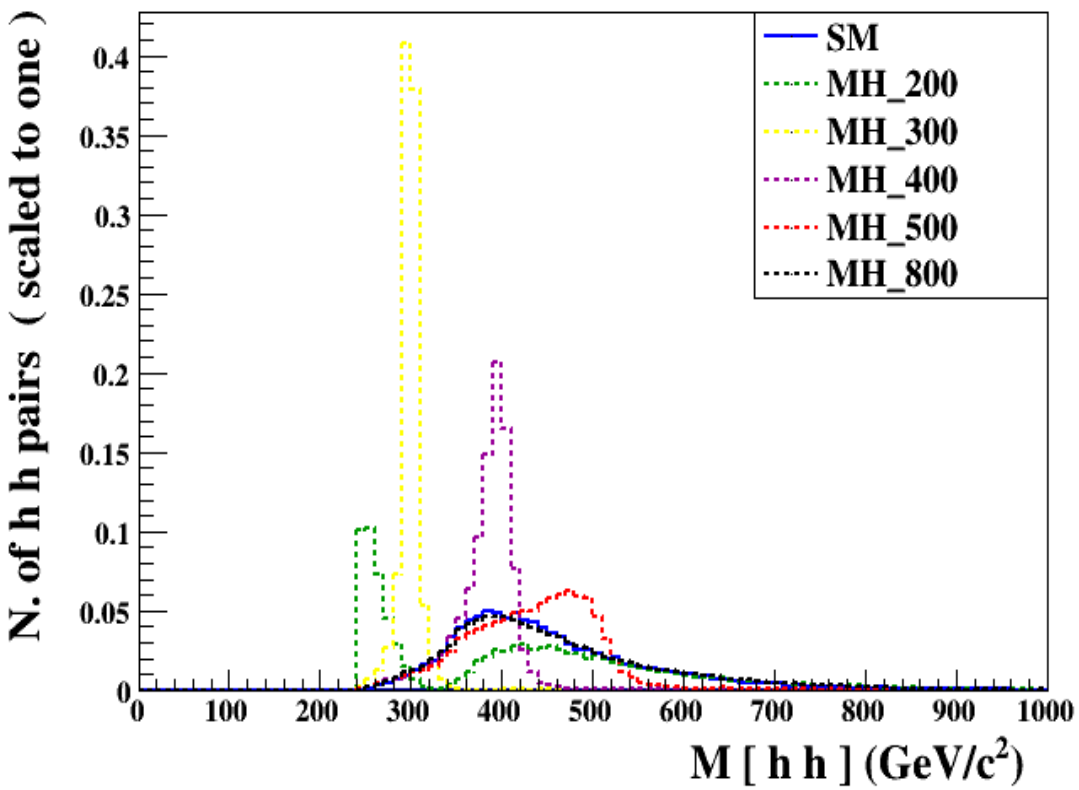
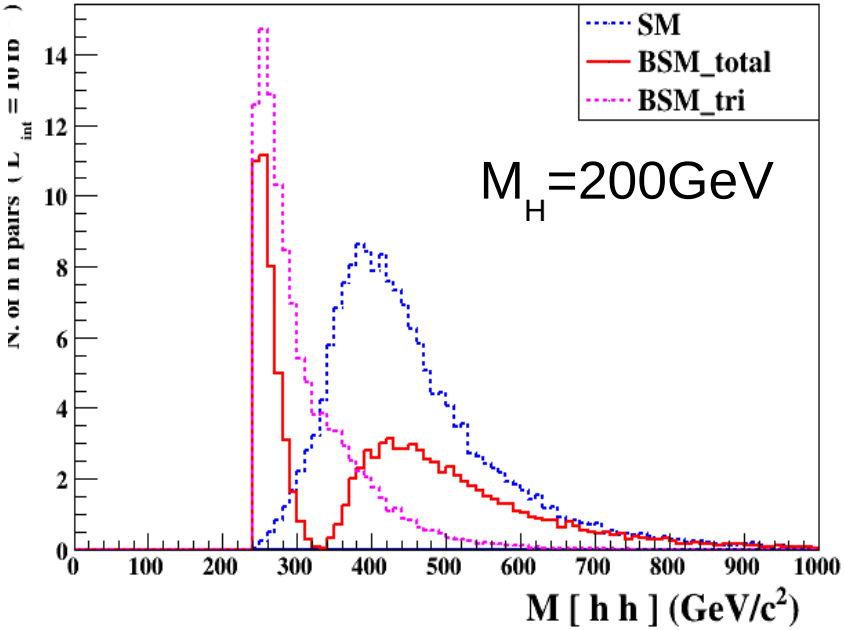
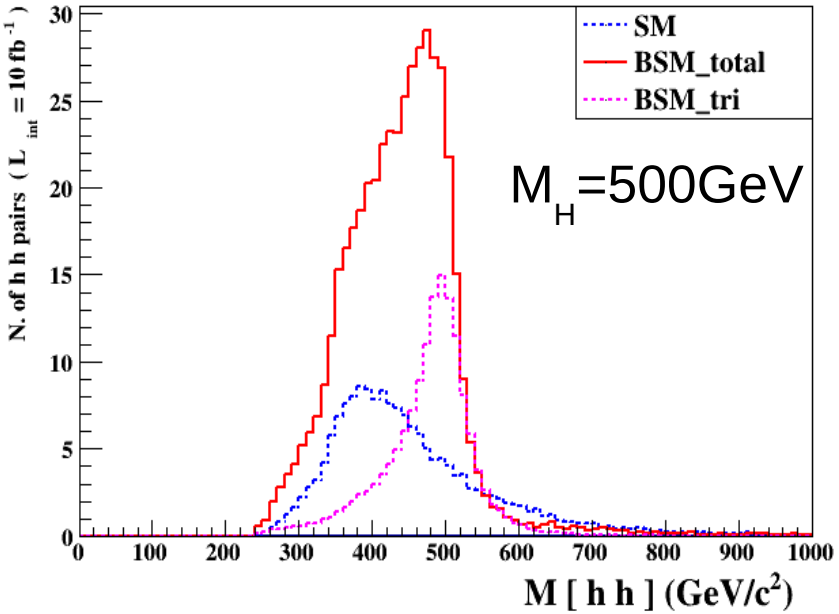
RICH PHENOMENOLOGY

Additional scalar with SM couplings
Toy model







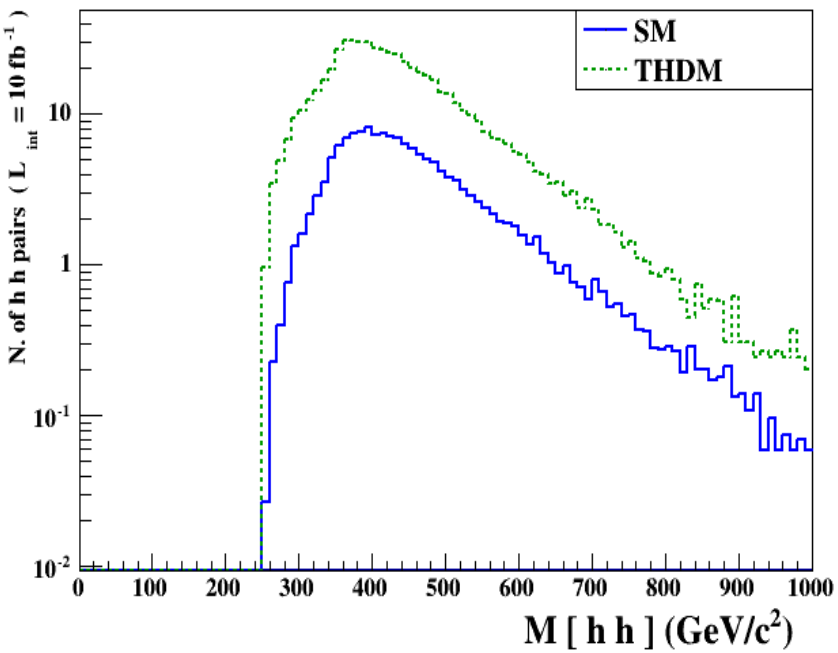
Interference changing sign for different masses

THDM

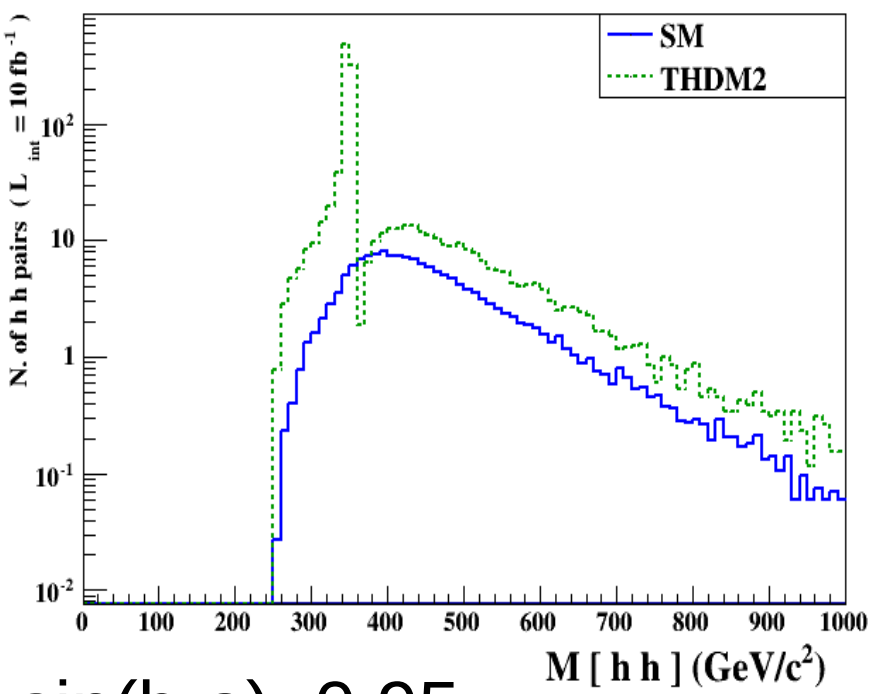
Results for 2 THDM benchmark points (provided by David Lopez Val)

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 was 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