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

MCnet meeting

CERN 1/4/14

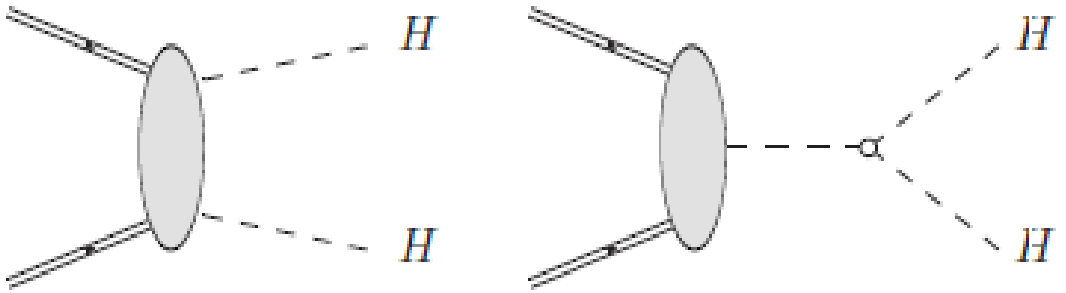
Outline

- 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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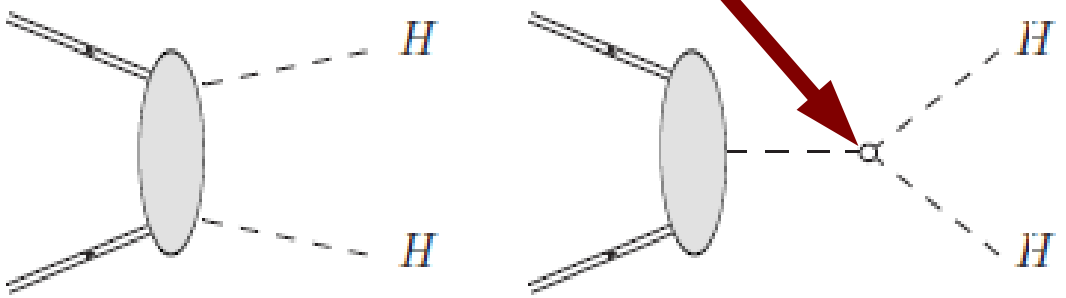

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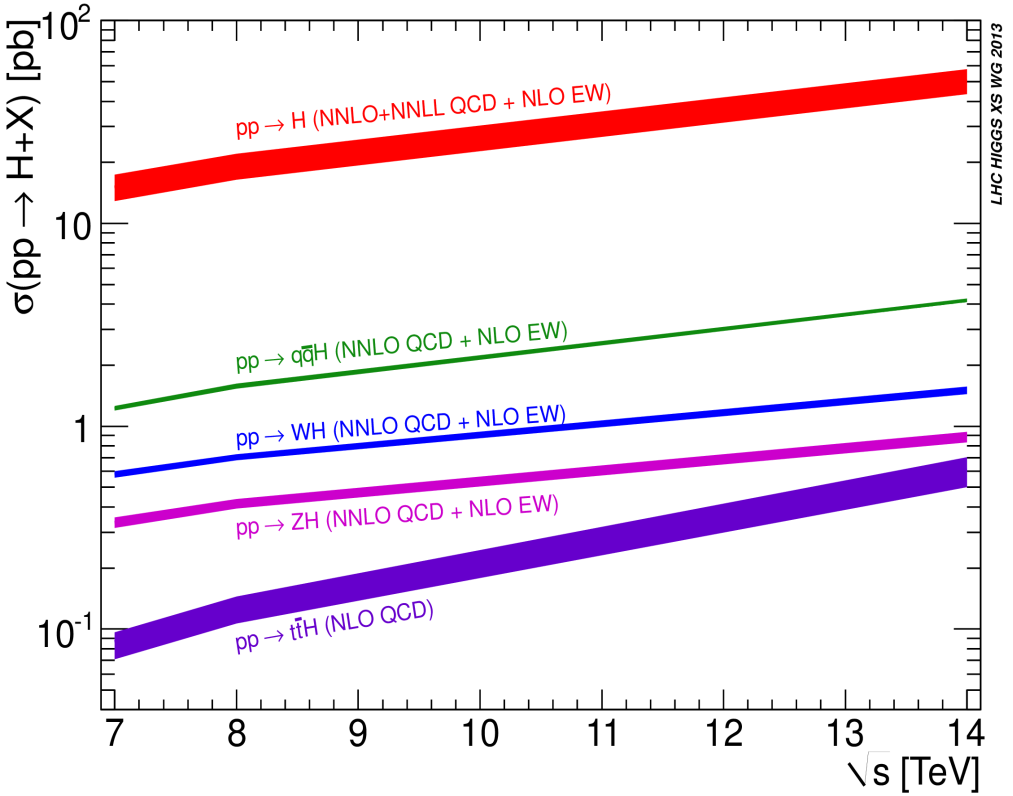
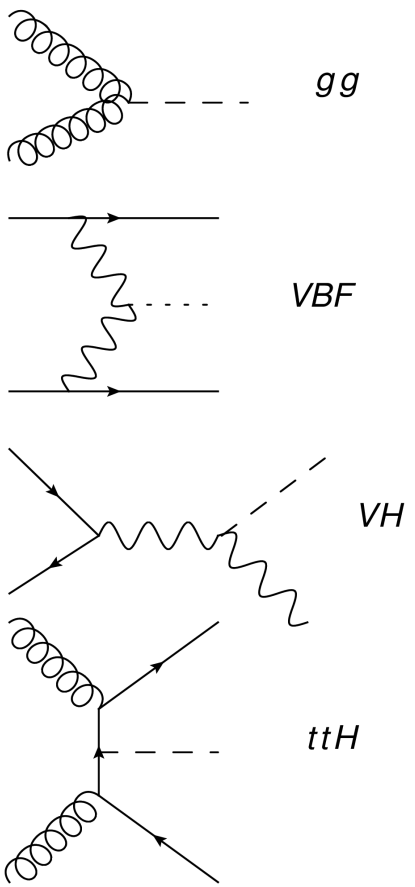
Similar to single Higgs production:

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



LHC Higgs Cross Sections Working Group



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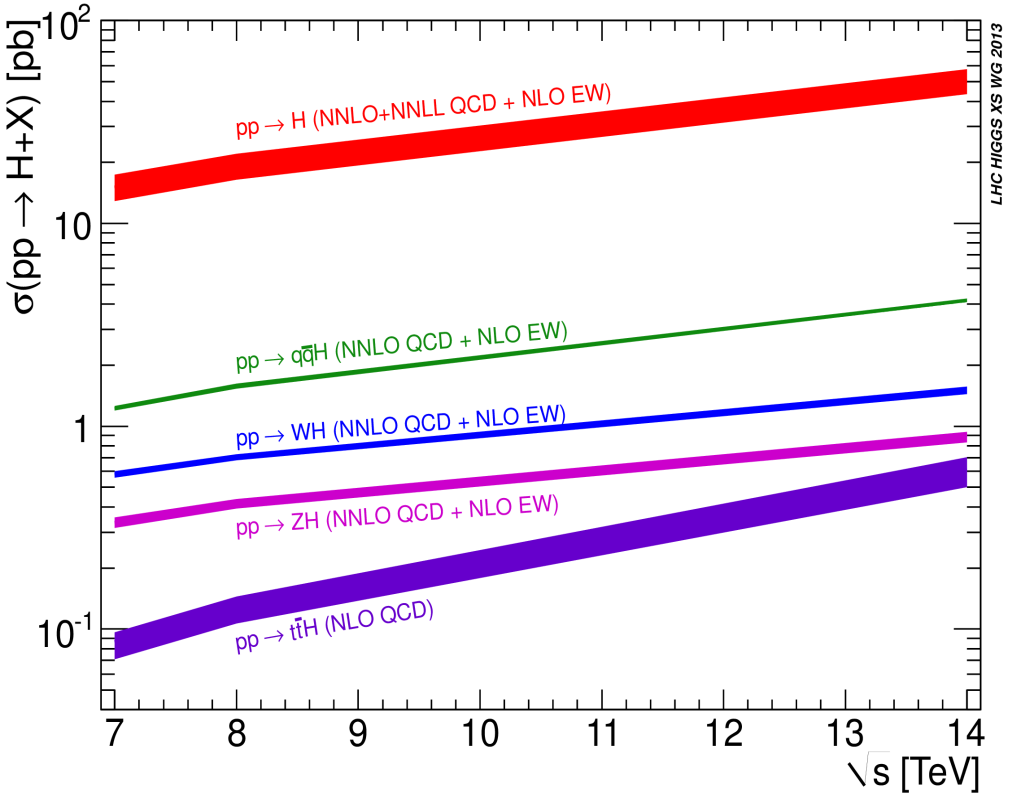

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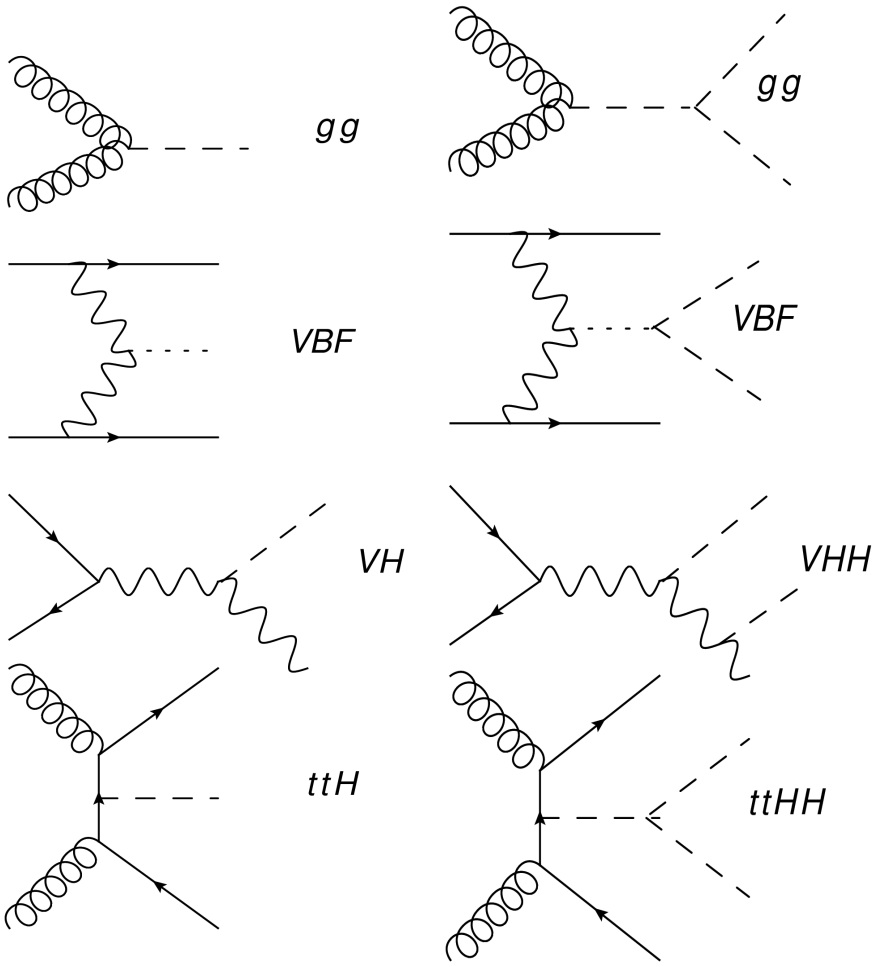

Schematically

Questions about HH?

- How does the hierarchy of the channels change for HH at 14TeV? Is gluon fusion the dominant one?
- 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?

Before answering all of these questions:

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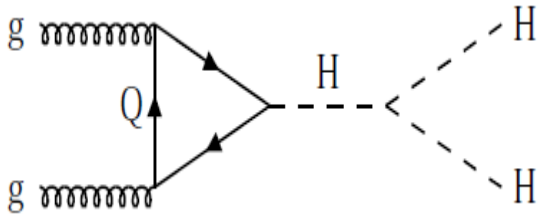
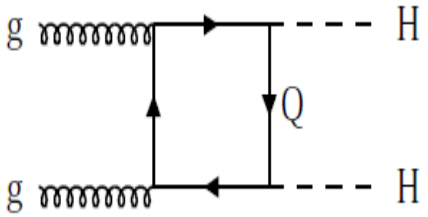
Let's focus on gluon-gluon fusion...

Focussing on gluon-gluon fusion...

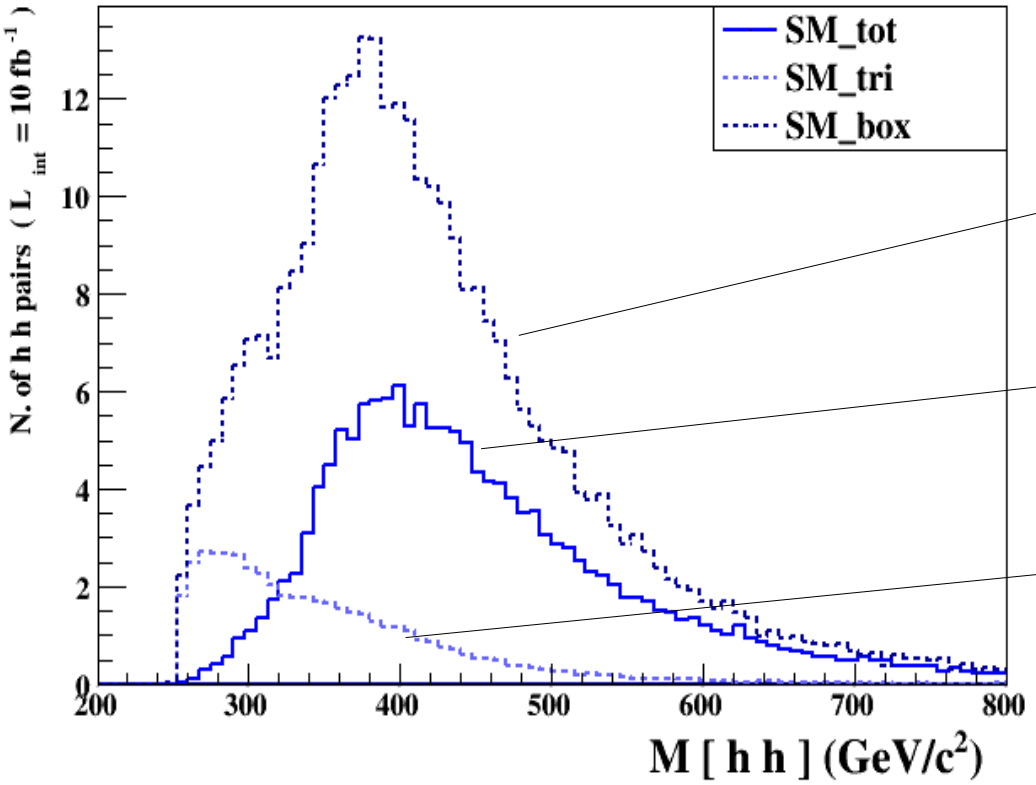
- At LO...





Loop induced

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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Effective Lagrangian

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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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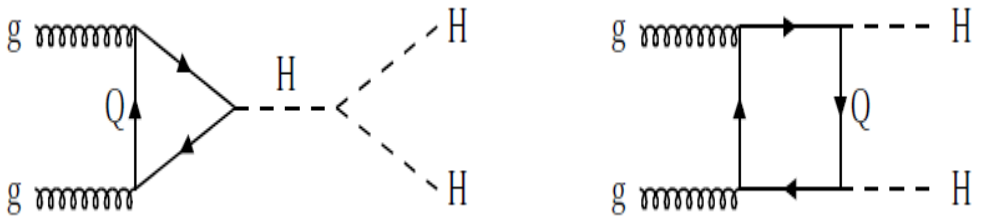

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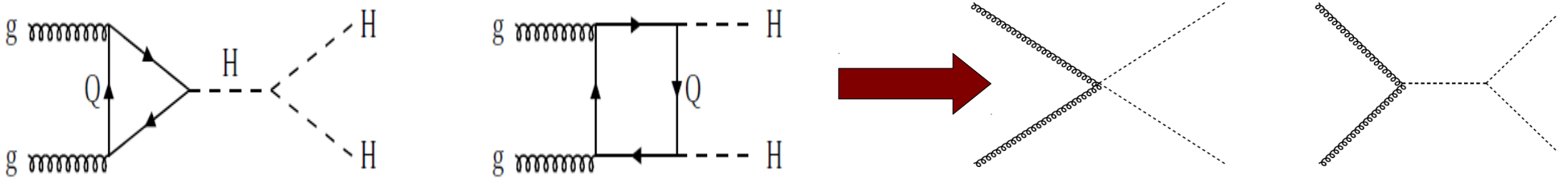

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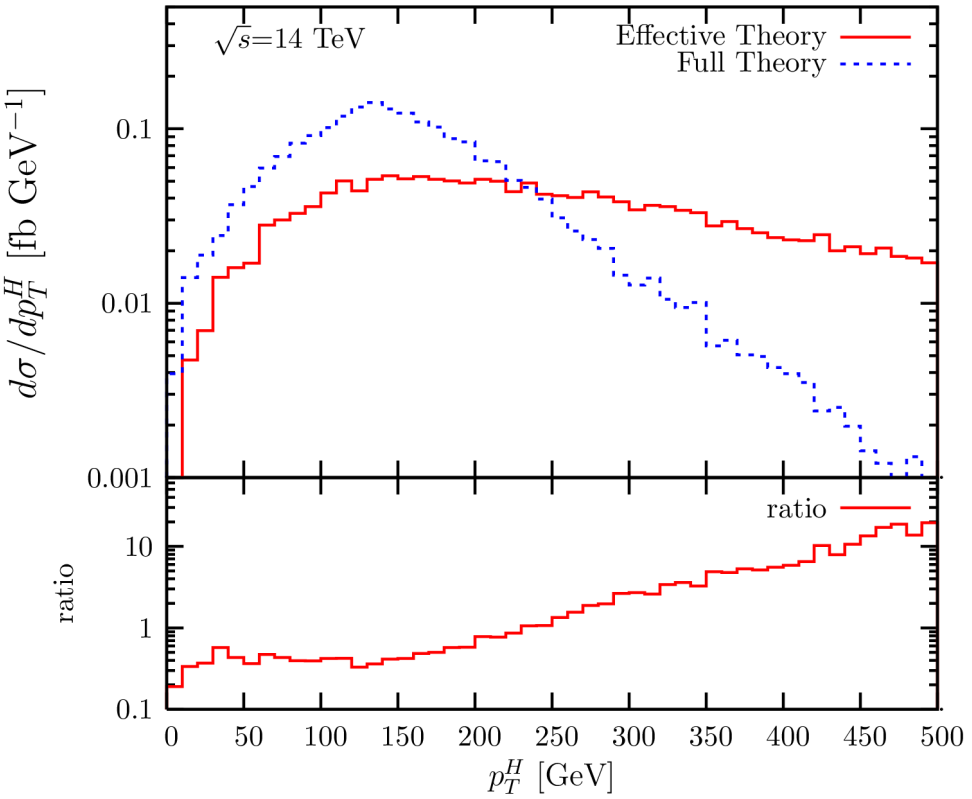
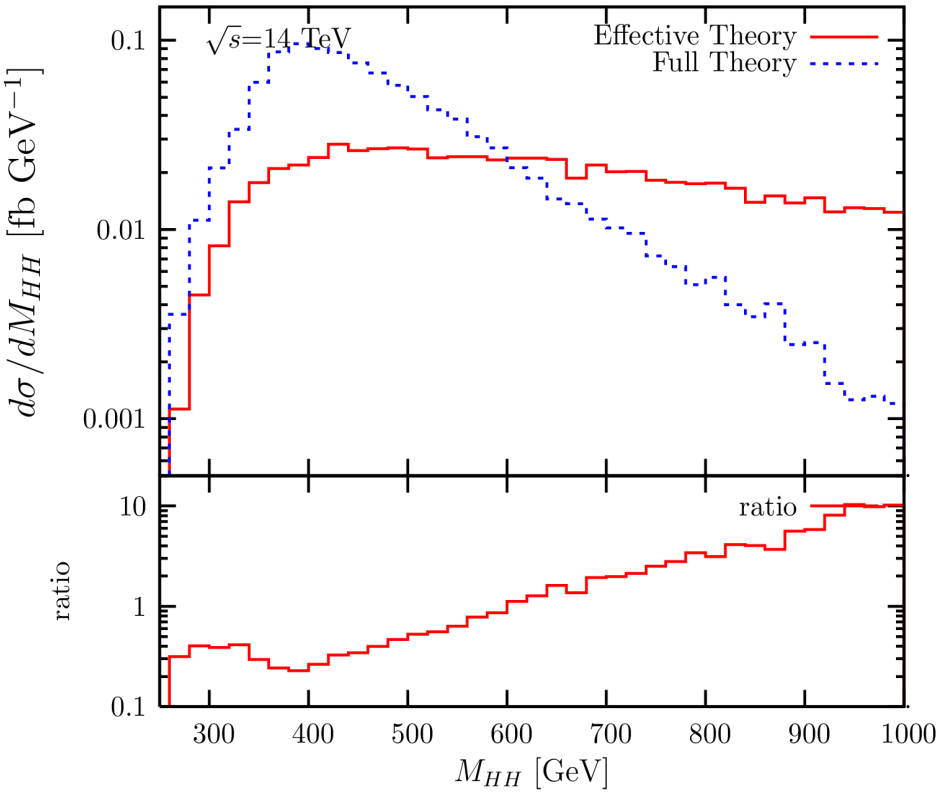
- Is this the case for HH?
- Differential distributions p_T and m_{HH}





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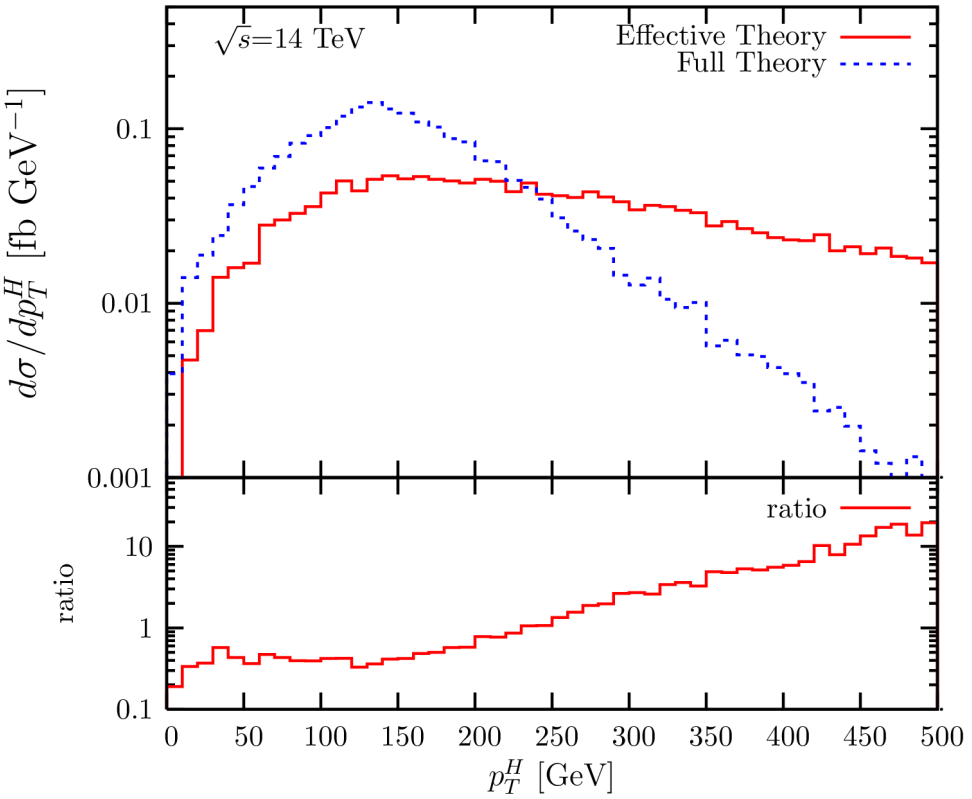

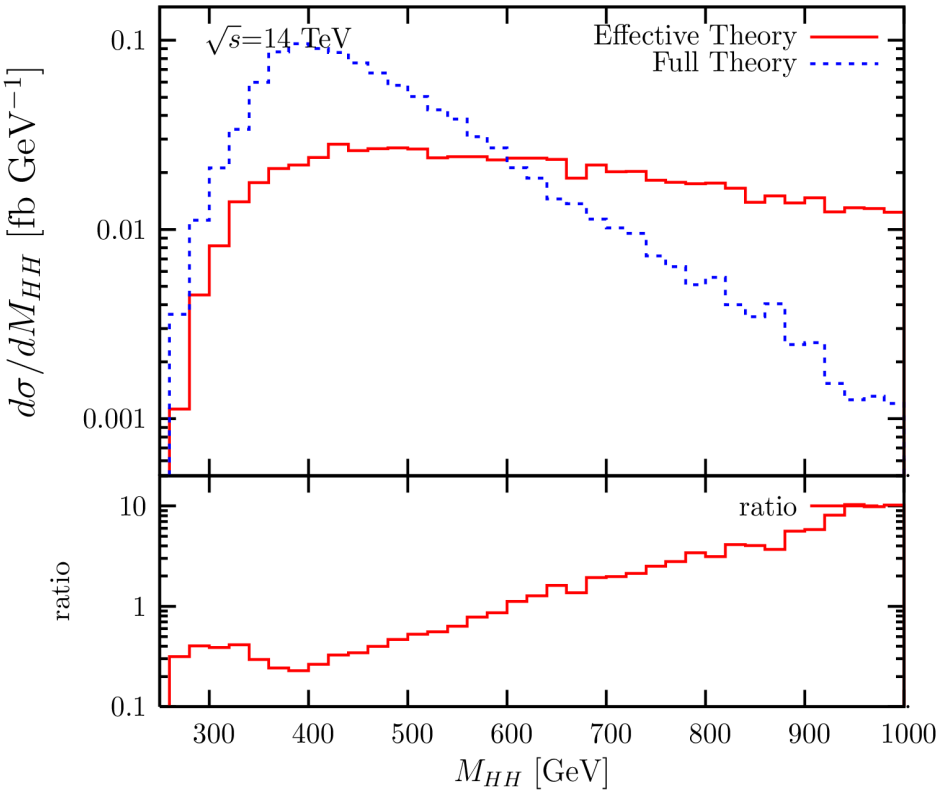

Using MadGraph5 implementation of LET and MadLoop

Low energy theory fails to reproduce kinematic distributions

Gluon fusion at NLO?

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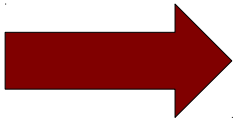

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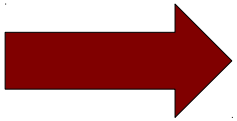

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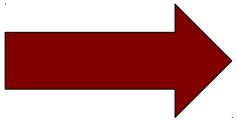

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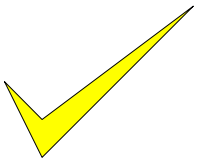

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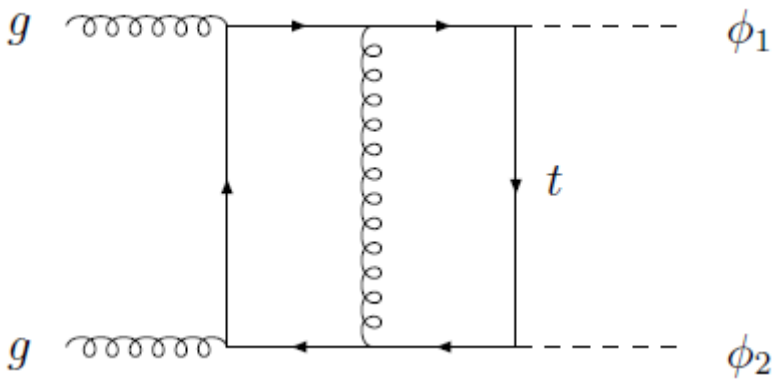

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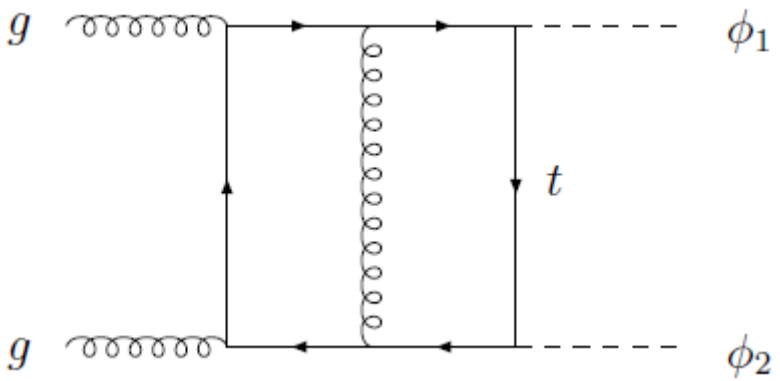
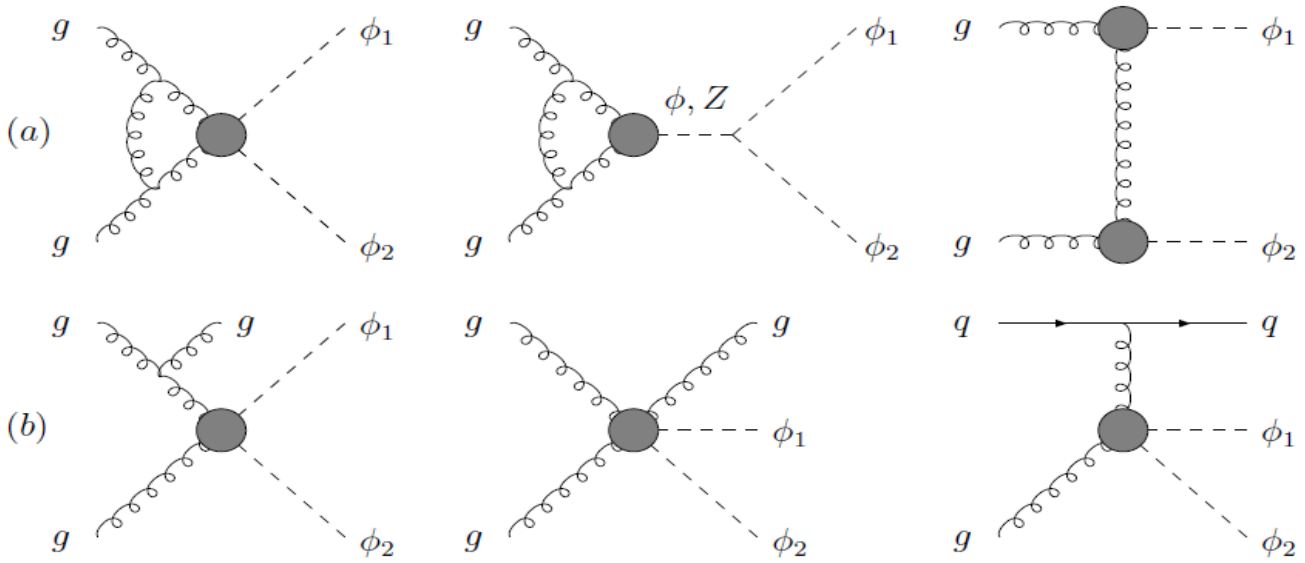


Beyond current loop technology

NLO corrections

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



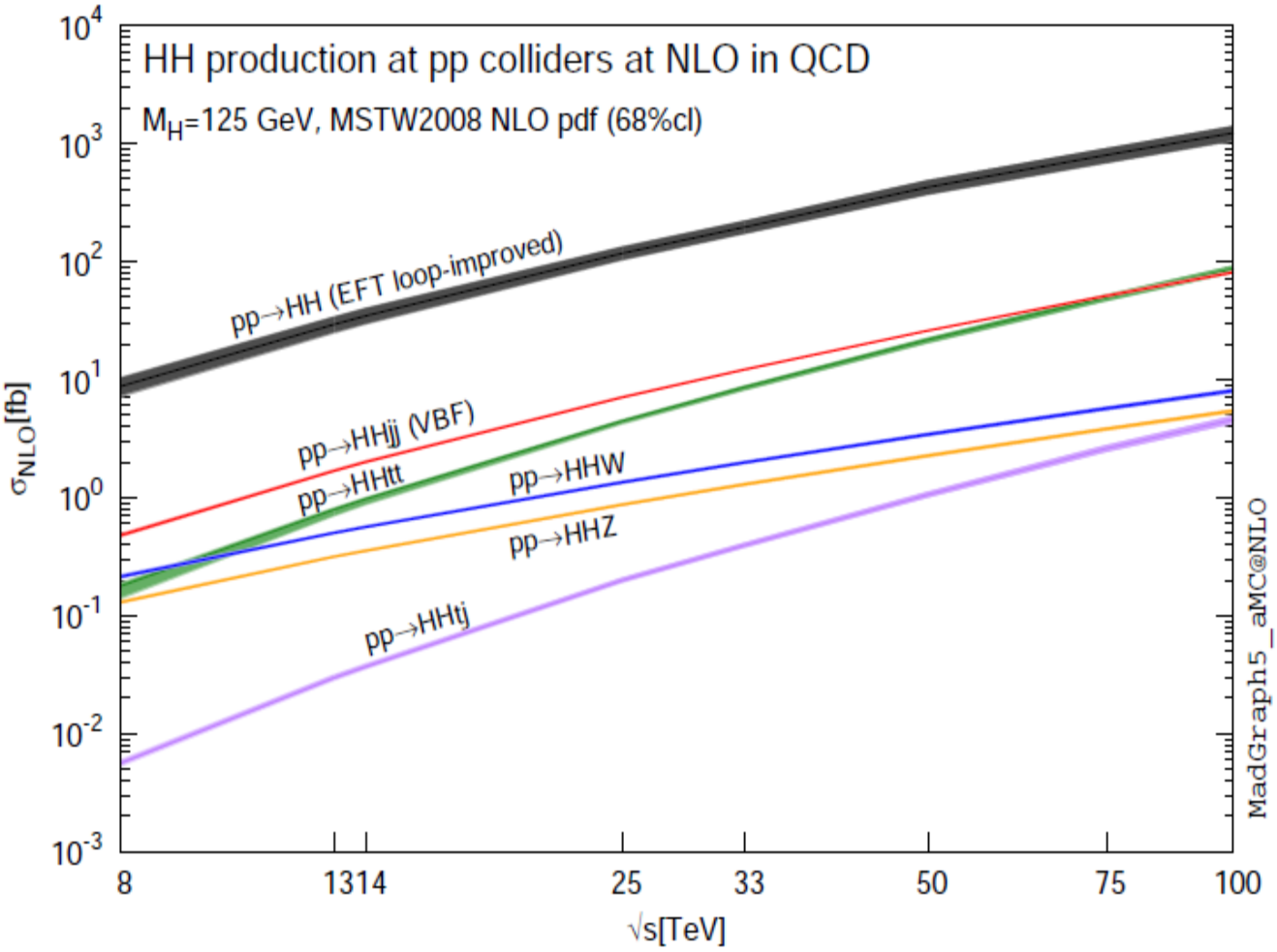
- Improved by using the full loop results for the Born cross section and available in Hpair code (total cross section)

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

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

aMC@NLO results



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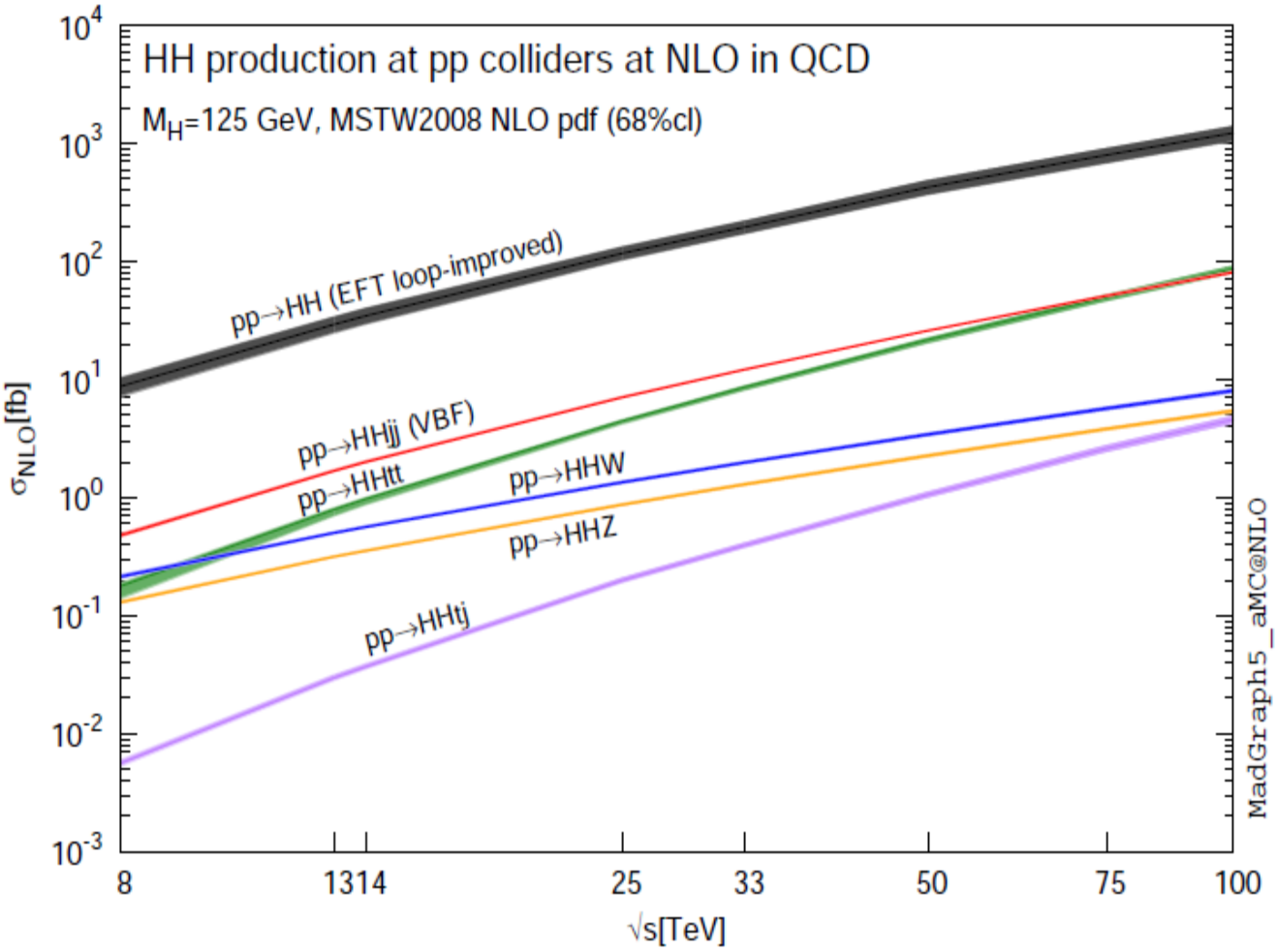

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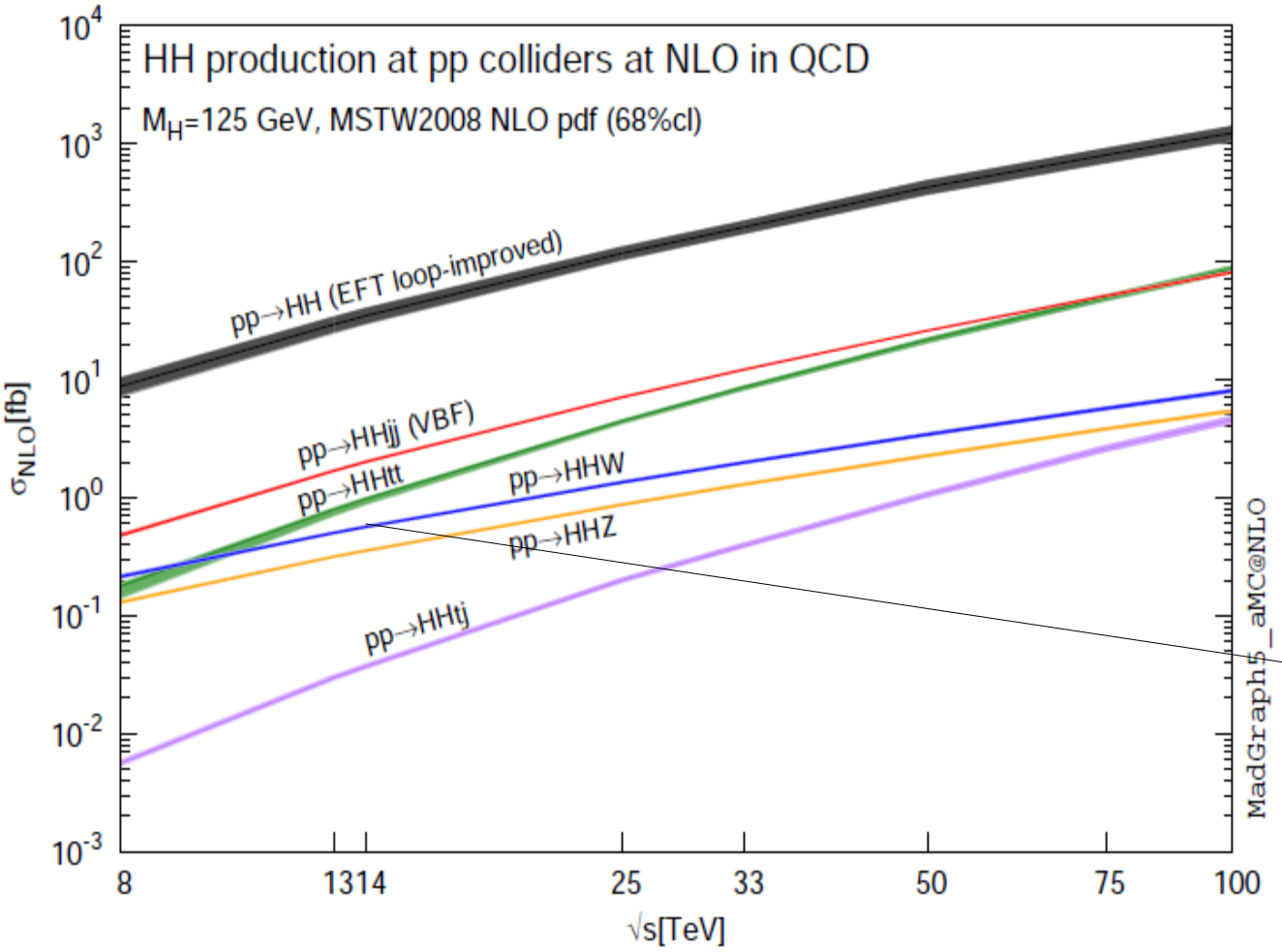
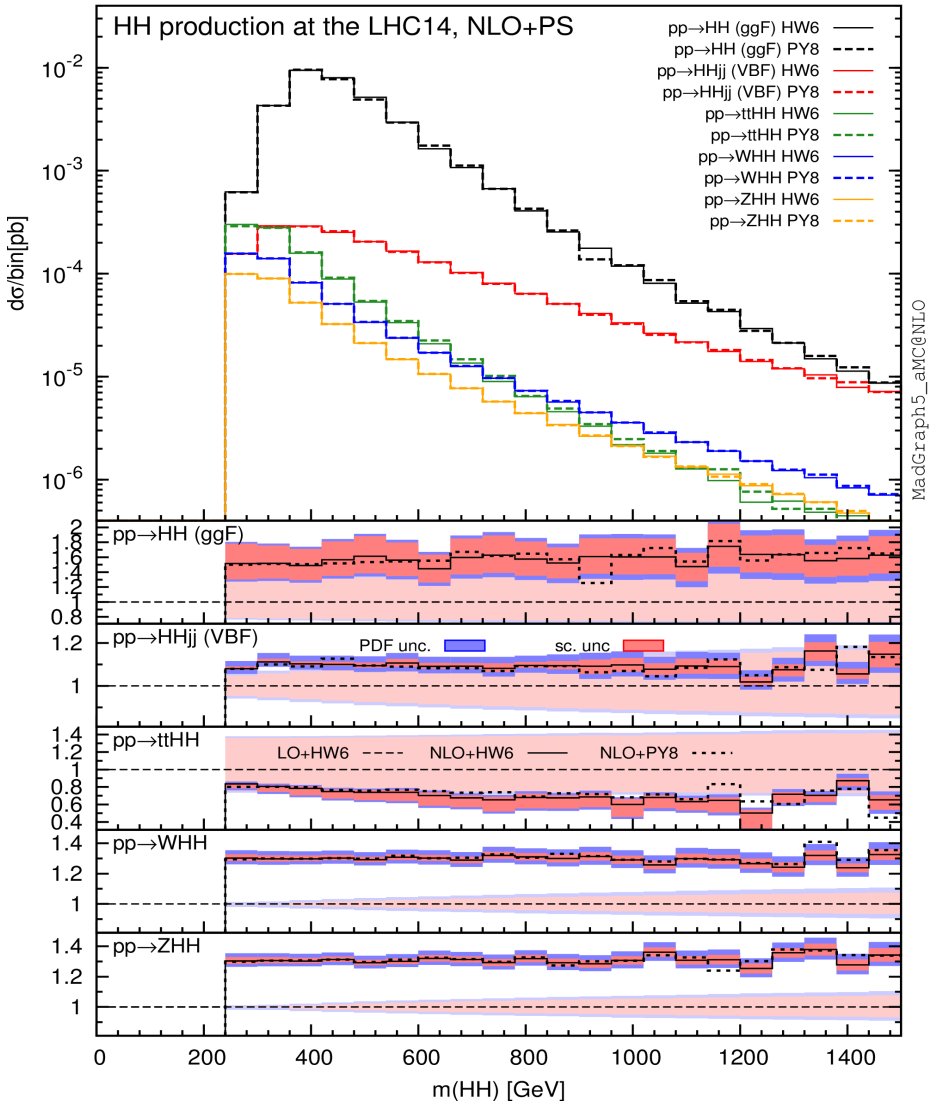
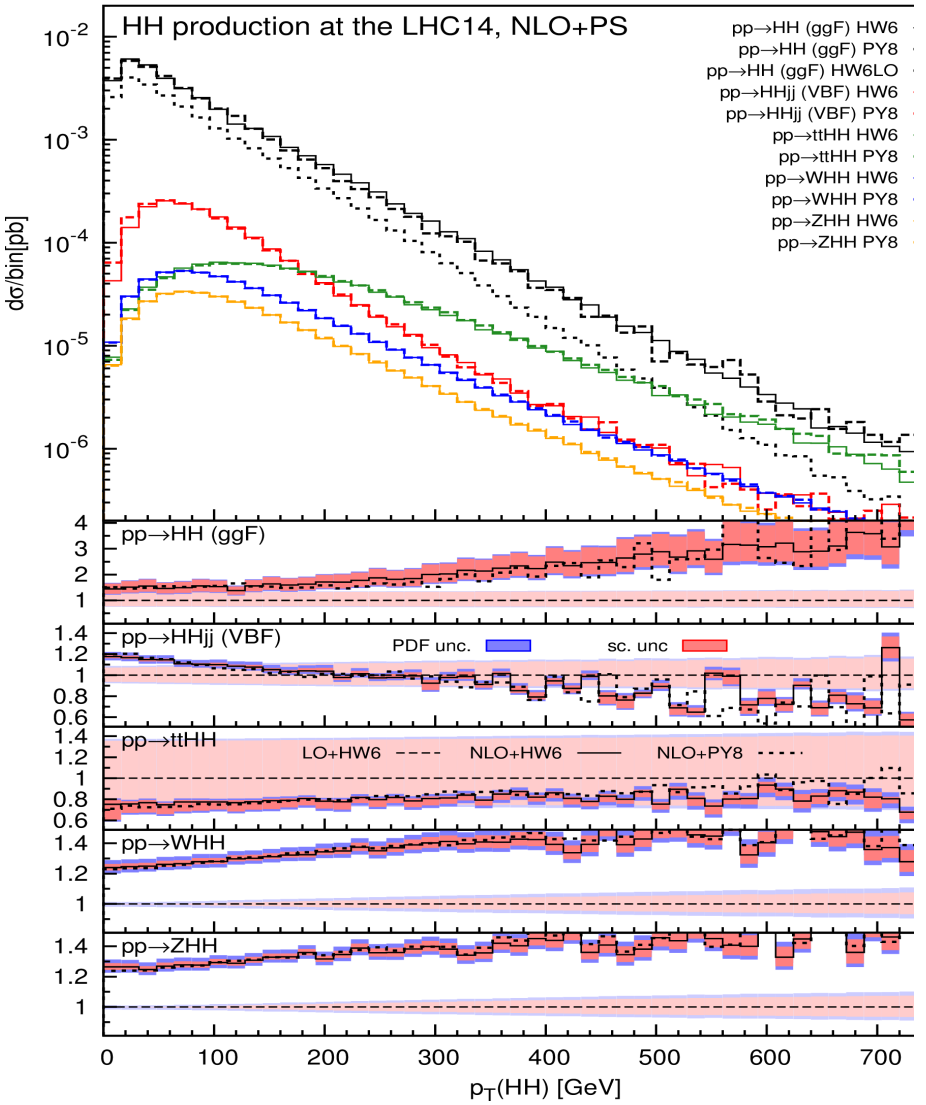


Gluon gluon fusion dominates as in single Higgs

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

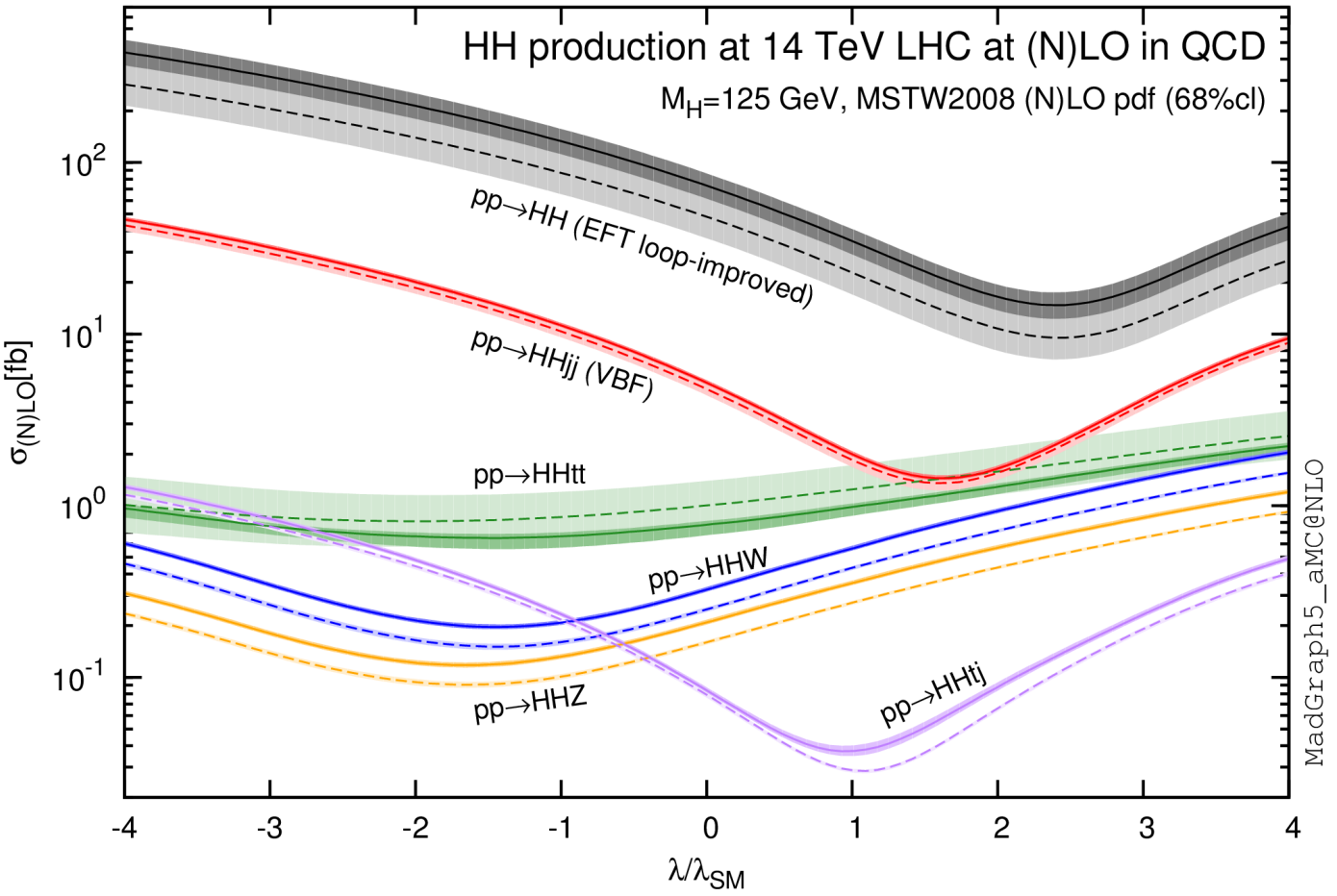
Differential distributions





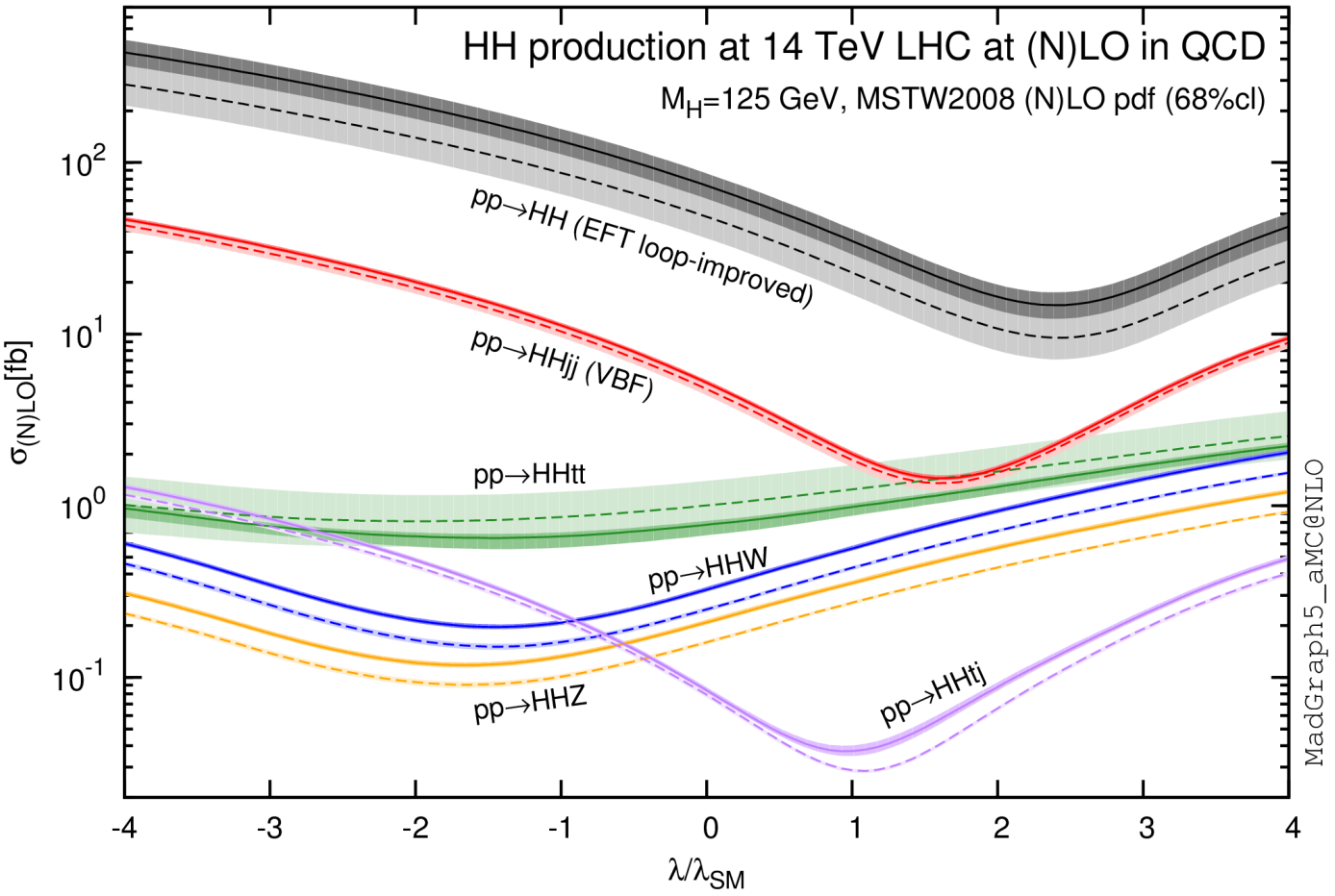
Including NLO and PS effects: best available predictions

Dependence on the trilinear Higgs coupling



Sensitivity of different channels to λ

Dependence on the trilinear Higgs coupling



Sensitivity of different channels to λ

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

Conclusions and future plans

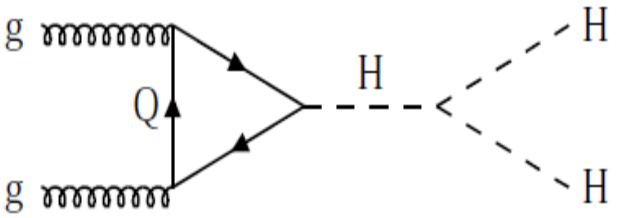
- Higgs pair production key to the measurement of triple Higgs coupling
- Presented results of an efficient MC implementation of the process at NLO provided in an automated way by aMC@NLO
- Results can be used for phenomenological studies
- Currently:
  - Extending this approach to 2HDM for all combinations of Higgses: h, H, A, h+, h-
  - Used to study specific 2HDM benchmarks

Thanks for your attention...

ADDITIONAL SLIDES

Gluon-gluon fusion

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



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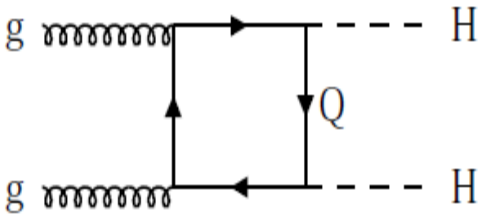

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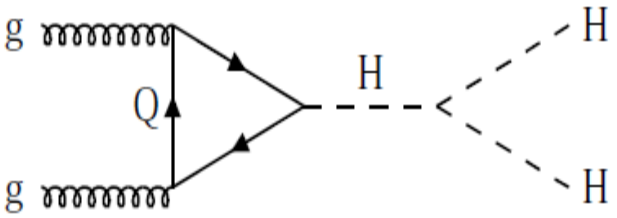

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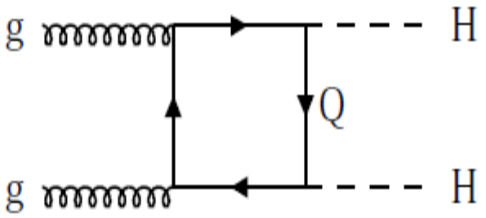

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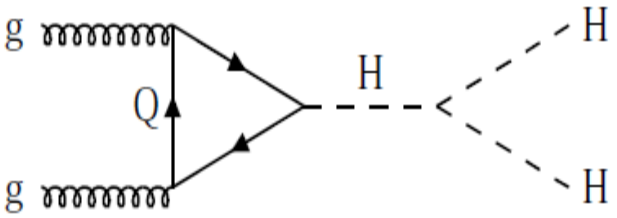

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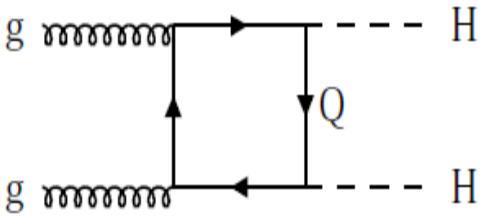

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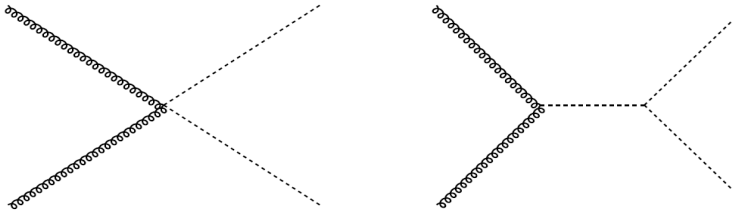

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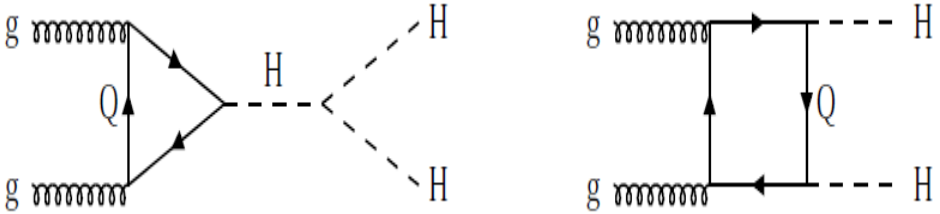

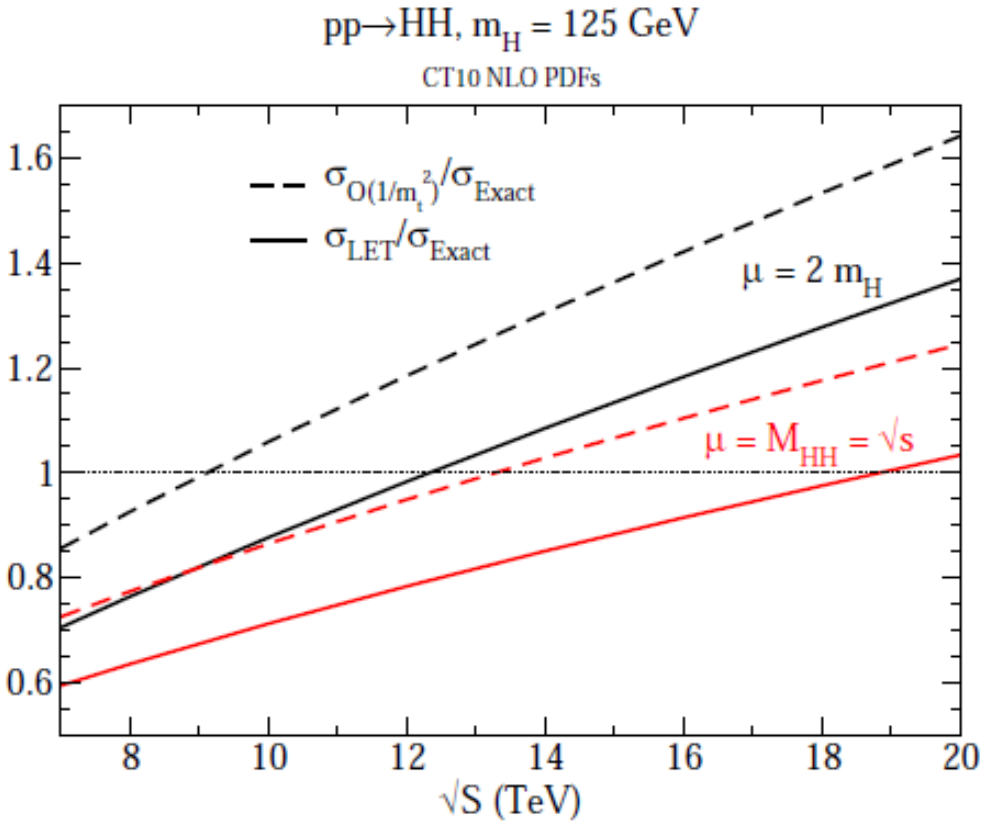

Dawson et al 1206.6663

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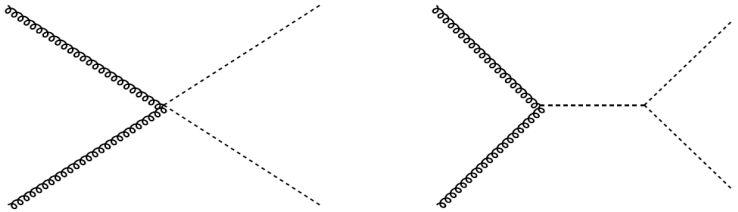

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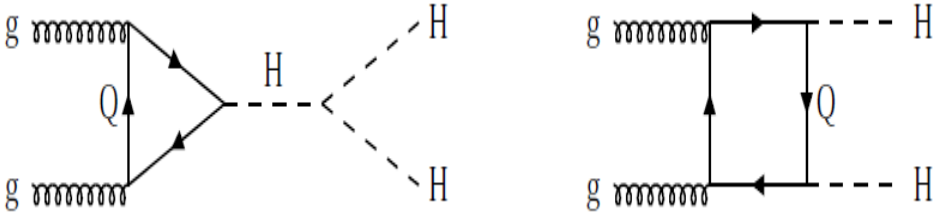
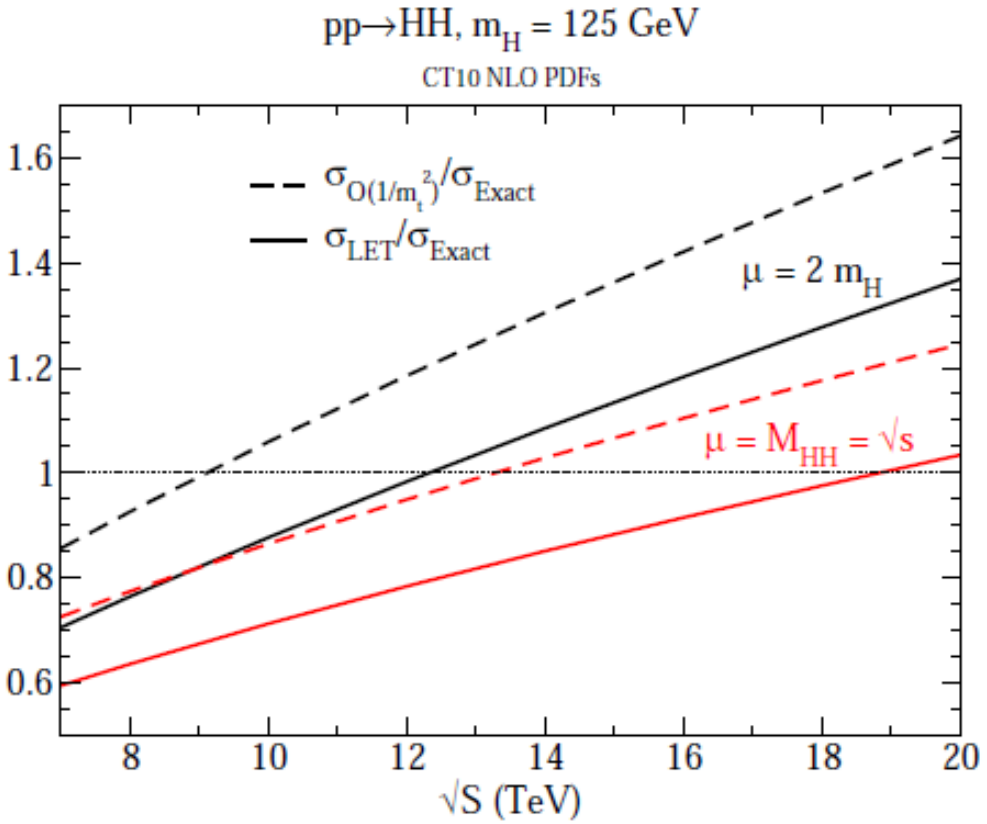


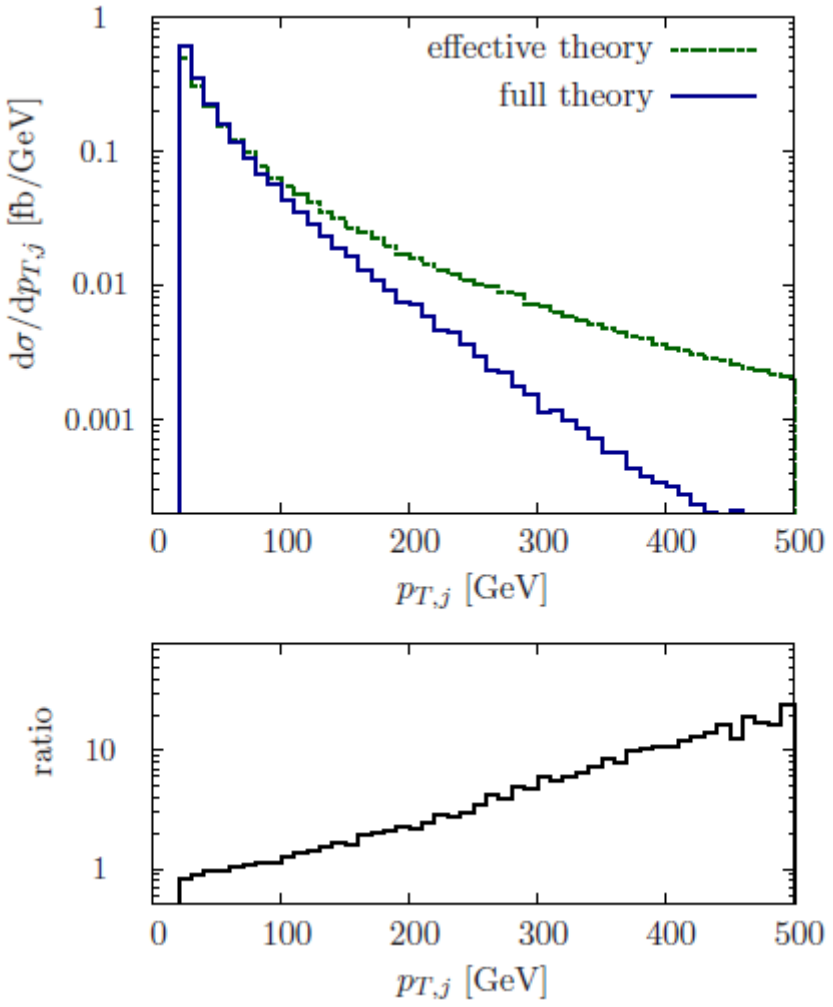


Dawson et al 1206.6663

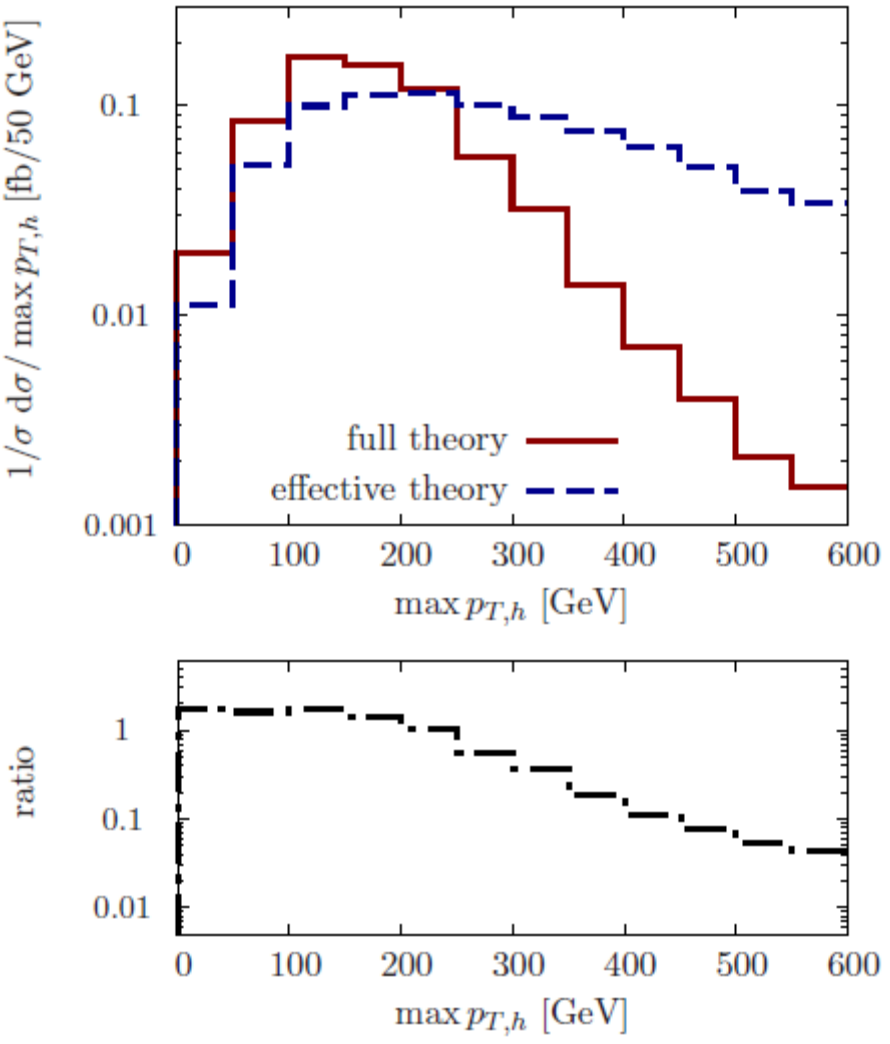
10-20% difference in the total cross section at 14 TeV(depending on the scale choice)

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

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- Other BSM contributions?
  - Non SM Yukawa couplings (1205.5444, 1206.6663)
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  - Resonances from extra dimensions (1303.6636)
  - Vector-like quarks (1009.4670, 1206.6663)
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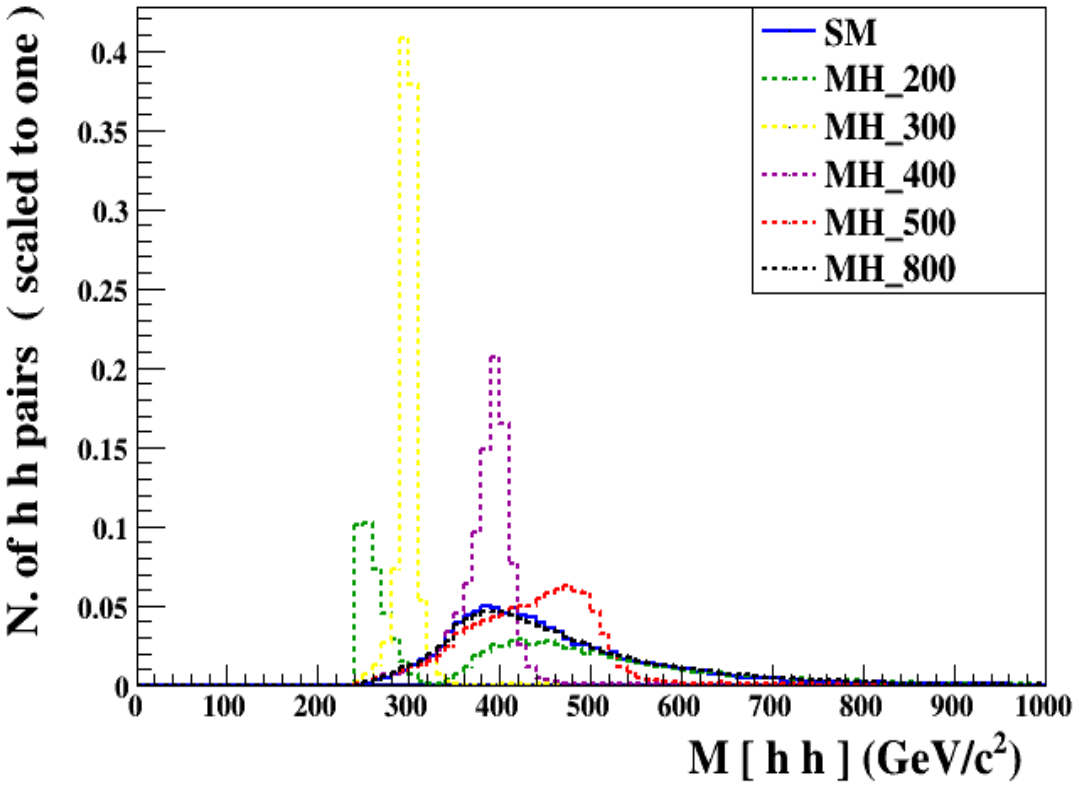
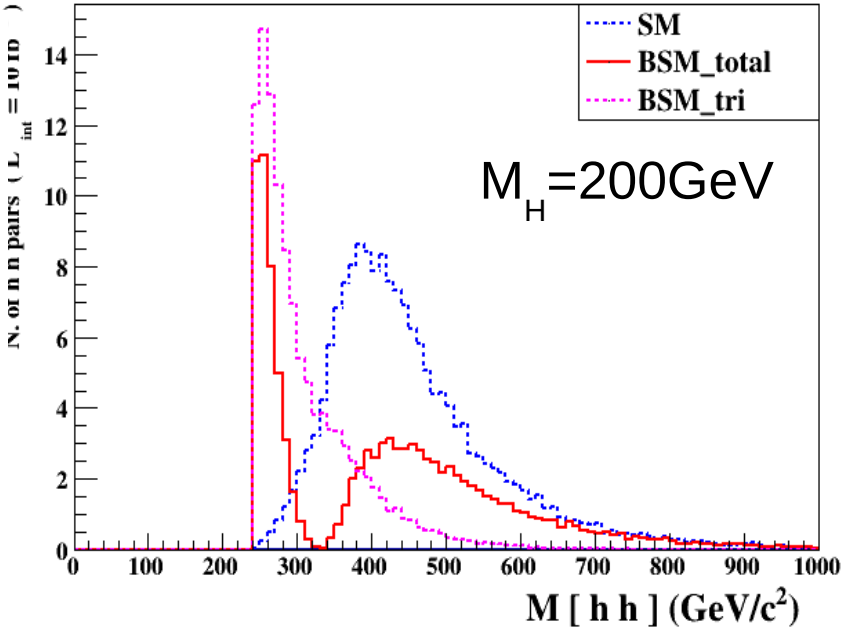
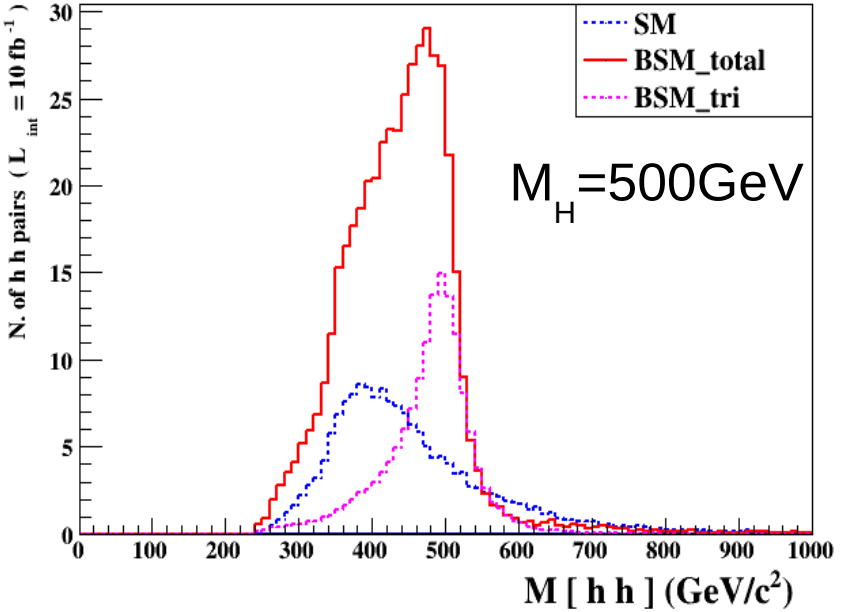
RICH PHENOMENOLOGY

Additional scalar with SM couplings Toy model







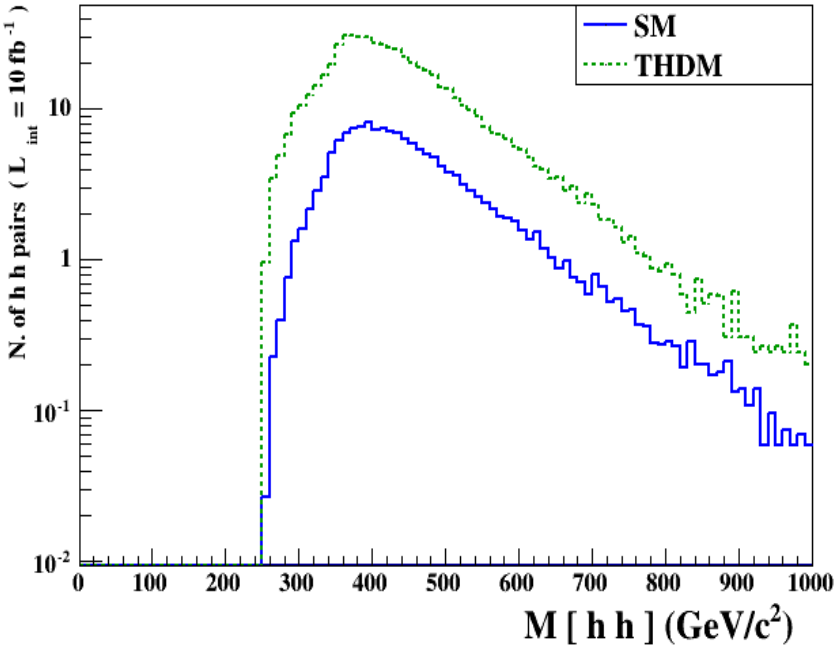
Interference changing sign for different masses

THDM

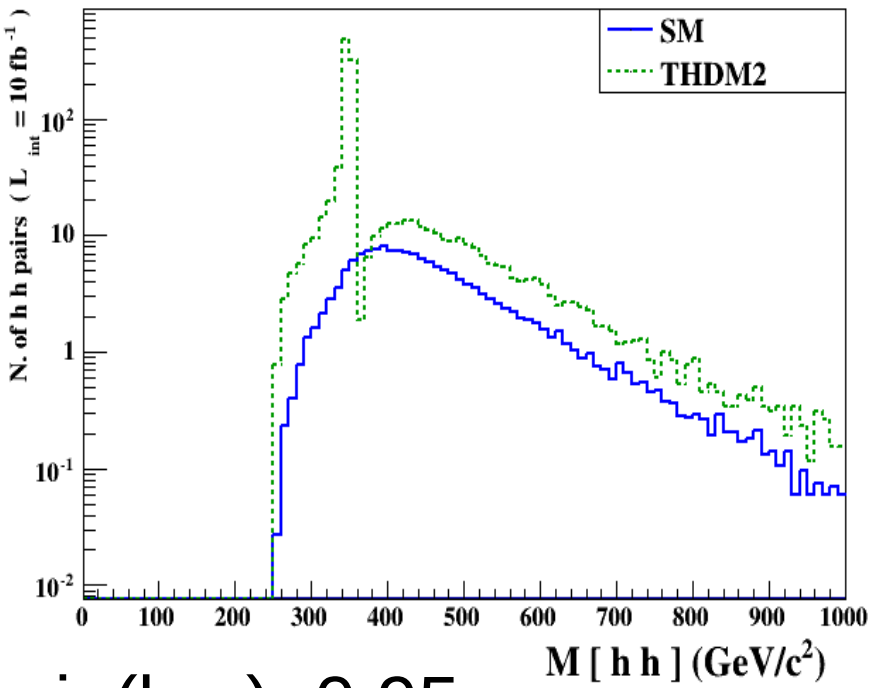
Results for 2 THDM benchmark points (provided by David Lopez Val)

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