Higgs pair production at the LHC

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Based on arxiv:1401.7340 and 1408.6542

HP2
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3/9/14

Outline

- Motivation
- HH production channels
- HH in gluon fusion
- Conclusions

Motivation

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

Good agreement with the SM

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

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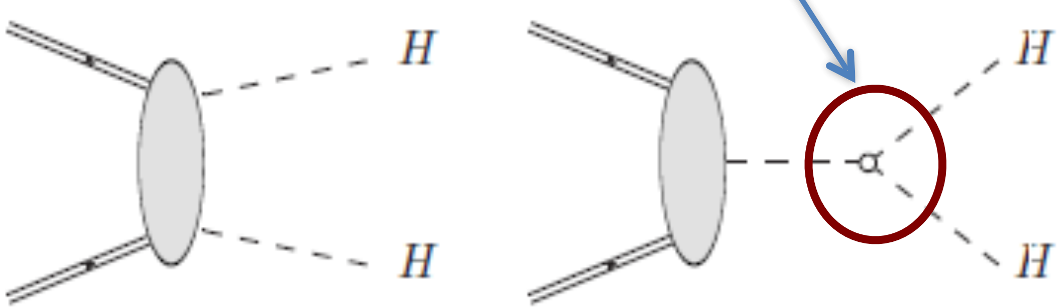


SM and similarly in BSM extensions: e.g. 2HDM

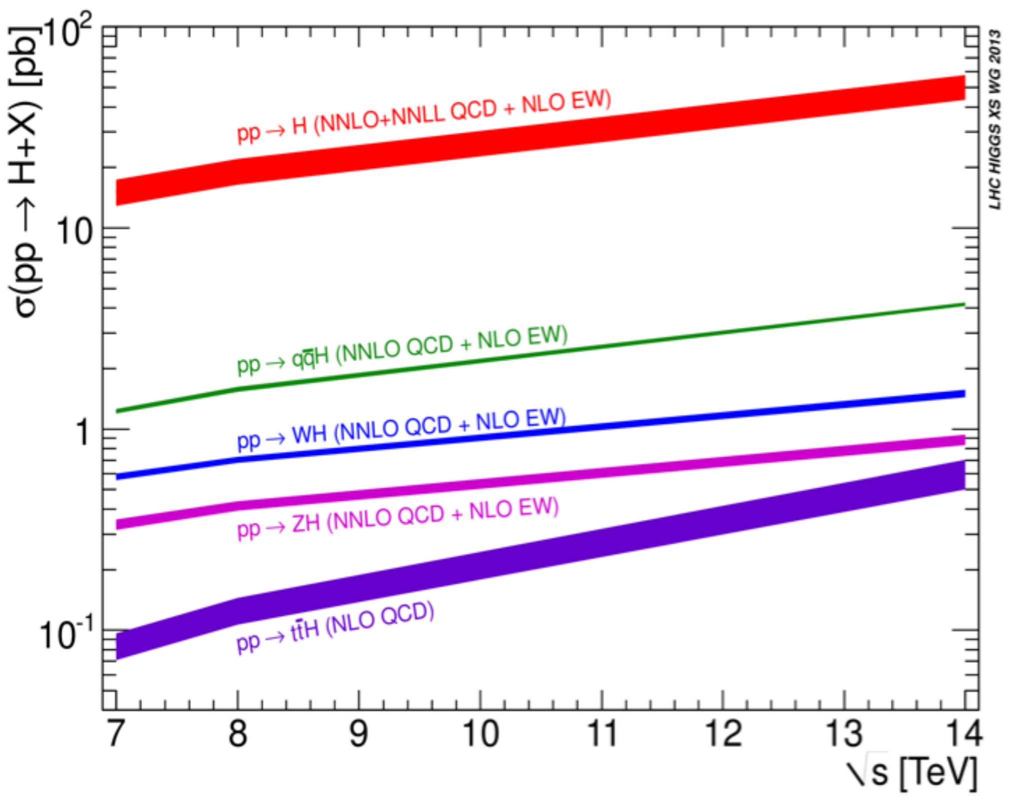
$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

Fixed values in the SM

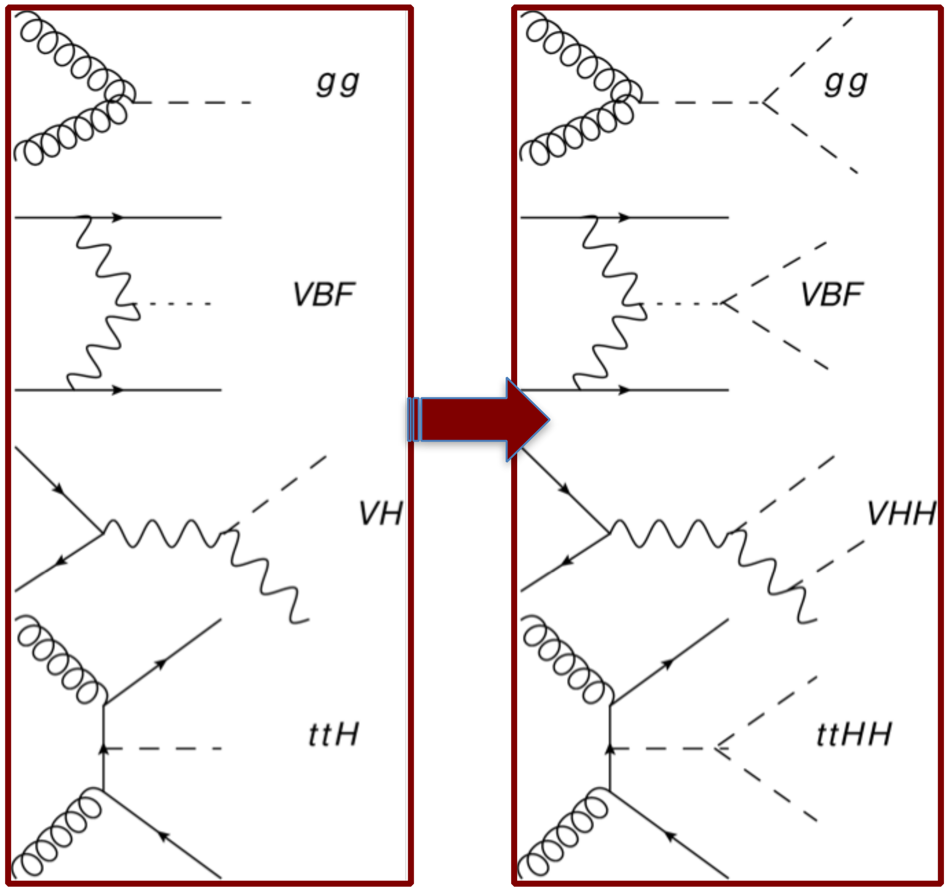
Higgs Pair Production channels

As in single Higgs production:

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



LHC Higgs Cross Sections Working Group

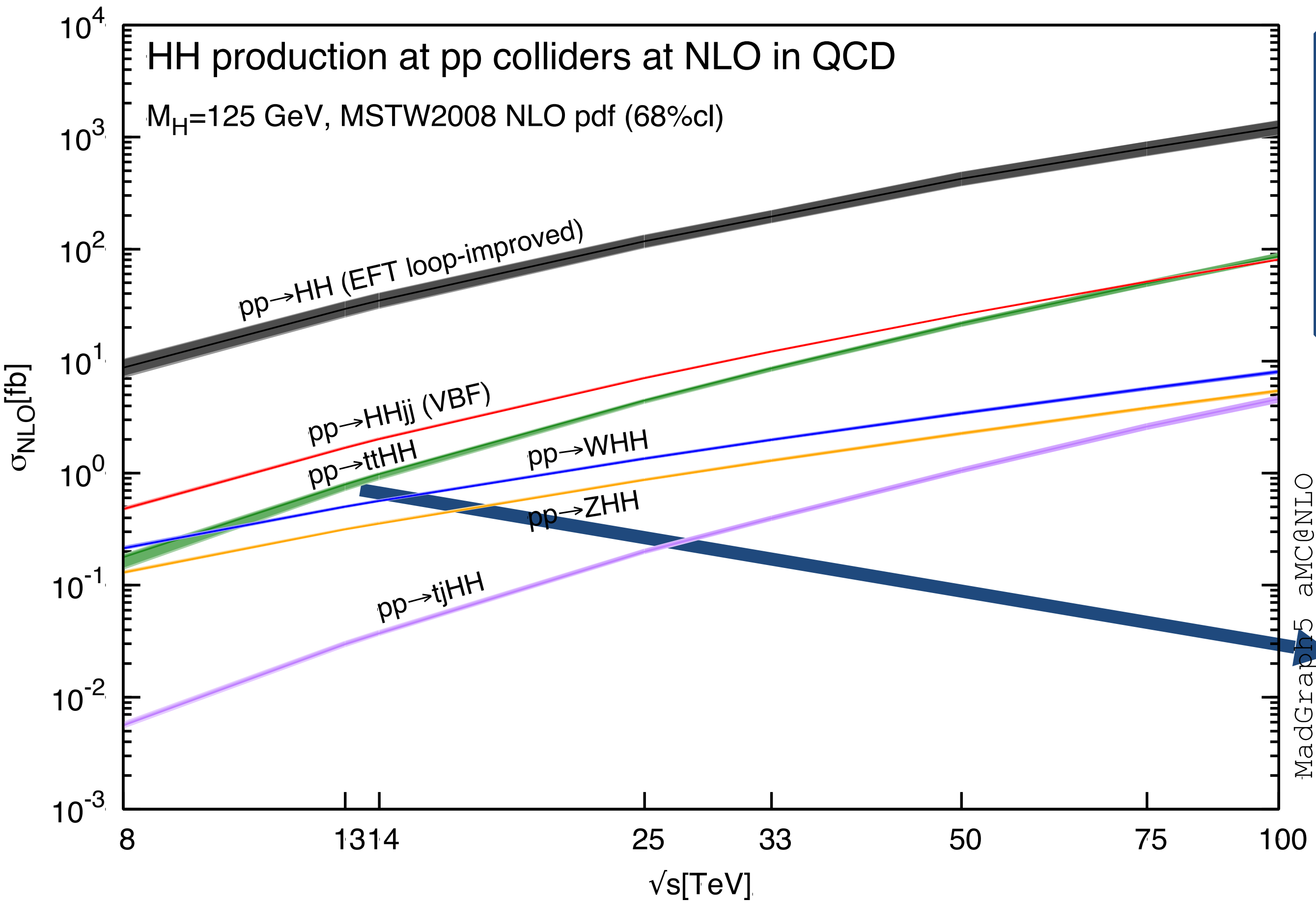


Schematically

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?
- Do we have NLO predictions for all the channels?
- Do we have an efficient fully differential Monte Carlo implementation of the process?
- How does the cross section depend on the value of the trilinear Higgs coupling?
- What are the promising decay channels?…

MadGraph5_aMC@NLO results



Gluon gluon fusion dominates
σ~35fb at 14TeV

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

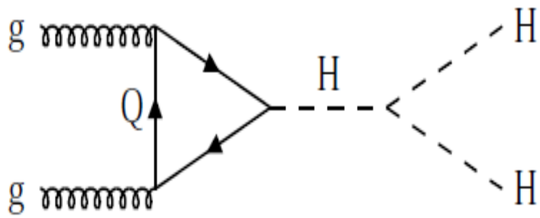
- **Automatic calculation of the scale and PDF uncertainties**

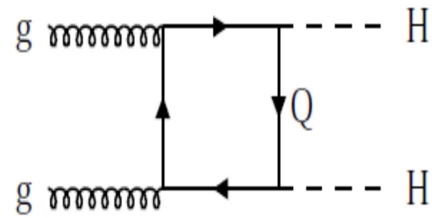
Frederix et al. arxiv:1401.7340

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

Focussing on gluon-gluon fusion...

At LO...

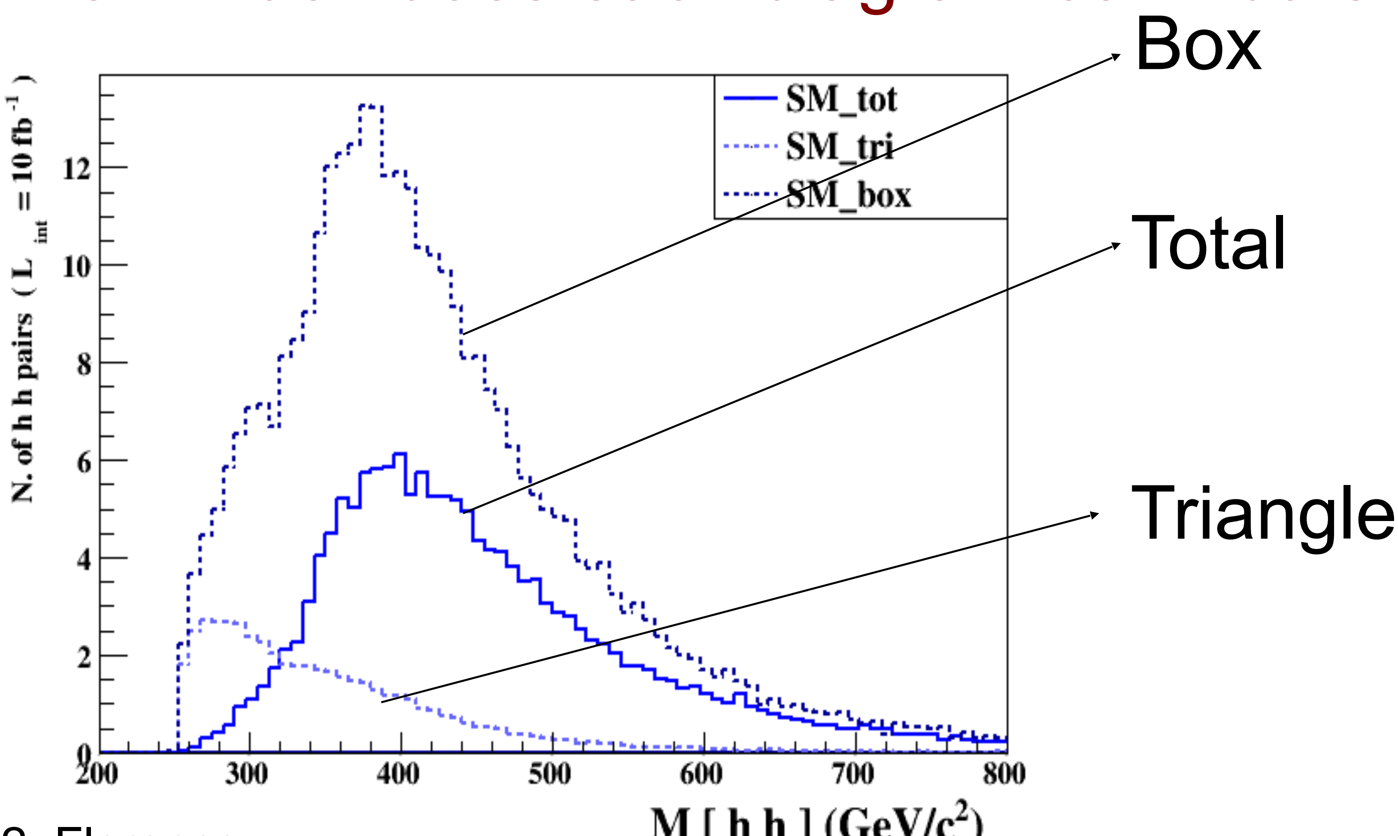




Biggest cross section
Only loop induced channel

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

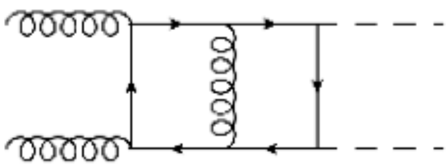
How much does each diagram contribute?



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 (doable) ✔
  - Virtual corrections: Include 2-loop amplitudes ✗



Beyond current loop technology

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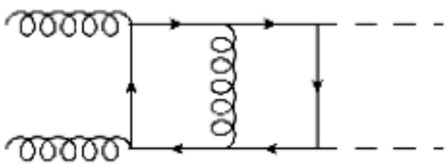

Beyond current loop technology

- But the difficulty of higher-order computations is similar in single Higgs production…

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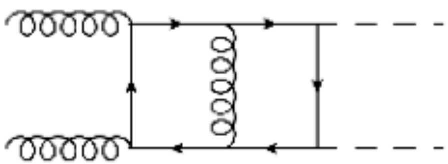

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→ **Use a low energy theory**

Effective Lagrangian

(top quark integrated out)

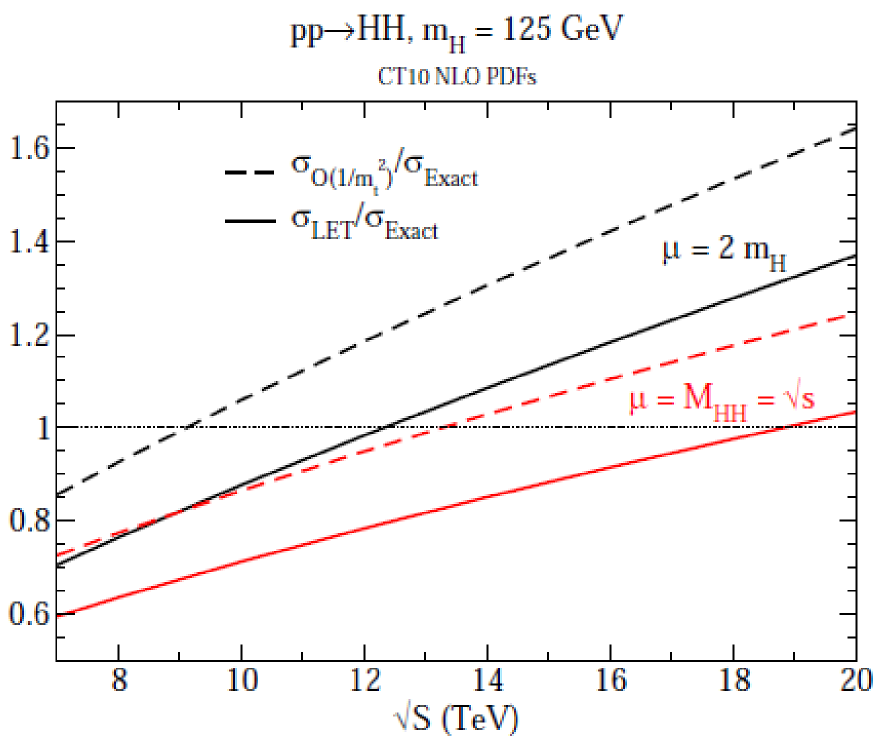
$$\mathcal{L}_{\rm eff} = \frac{1}{4}\frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1+h/v)$$

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

HEFT approach in HH production

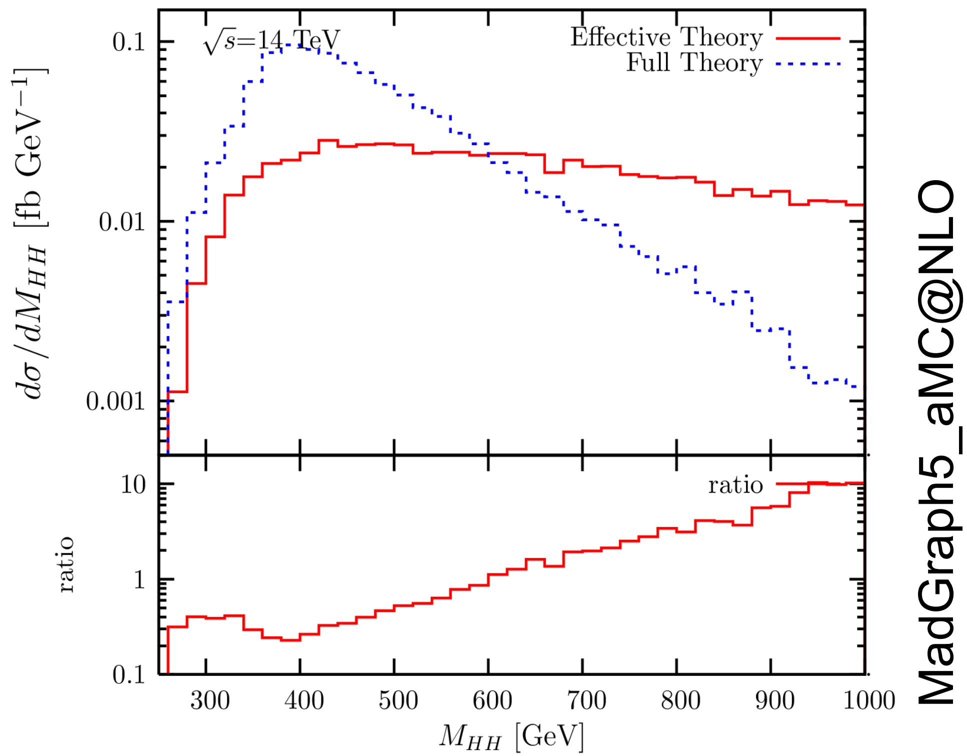
HEFT known to work well for single Higgs production

How well does the HEFT work for HH at LO?



Dawson, Furlan, Lewis 1206.6663

10-20% difference for the total cross section

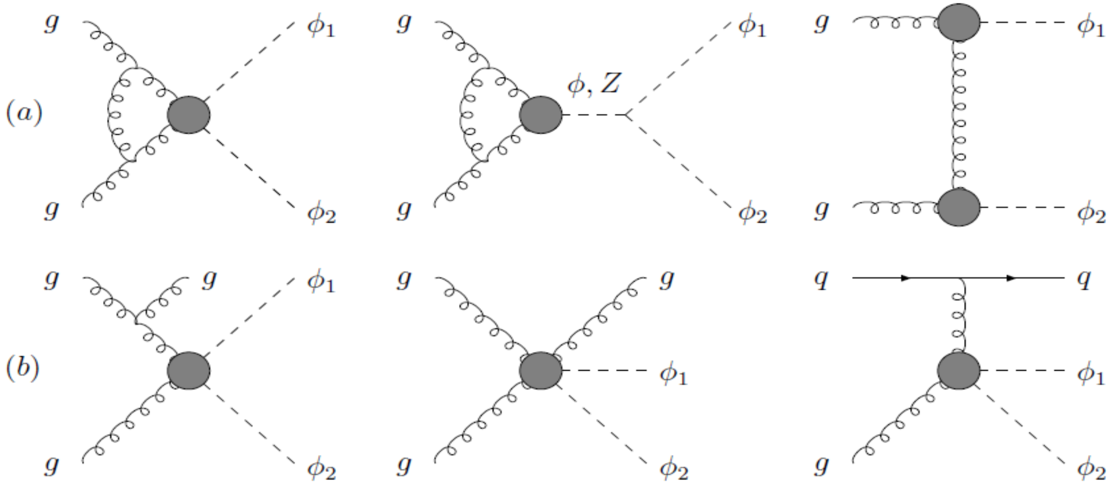


HEFT fails to reproduce the differential distributions

Mass effects are important and need to be included

NLO approximations for HH: Hpair

- Given the lack of the exact NLO results:
  - NLO results in the HEFT
  - Dawson, Dittmaier, Spira hep-ph/9805244
  - Implemented in code Hpair: total cross-section calculation
  - Improved by exact LO contribution



$$\sigma_{\rm LO} = \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\rm LO}(Q^2 = \tau s)$$

$$\Delta\sigma_{\rm virt} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\rm LO}(Q^2 = \tau s) \, C,$$

$$\Delta\sigma_{gg} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\rm LO}(Q^2 = z\tau s) \left\{ -zP_{gg}(z) \log \frac{M^2}{\tau s} - \frac{11}{2}(1-z)^3 + 6[1+z^4+(1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\}$$

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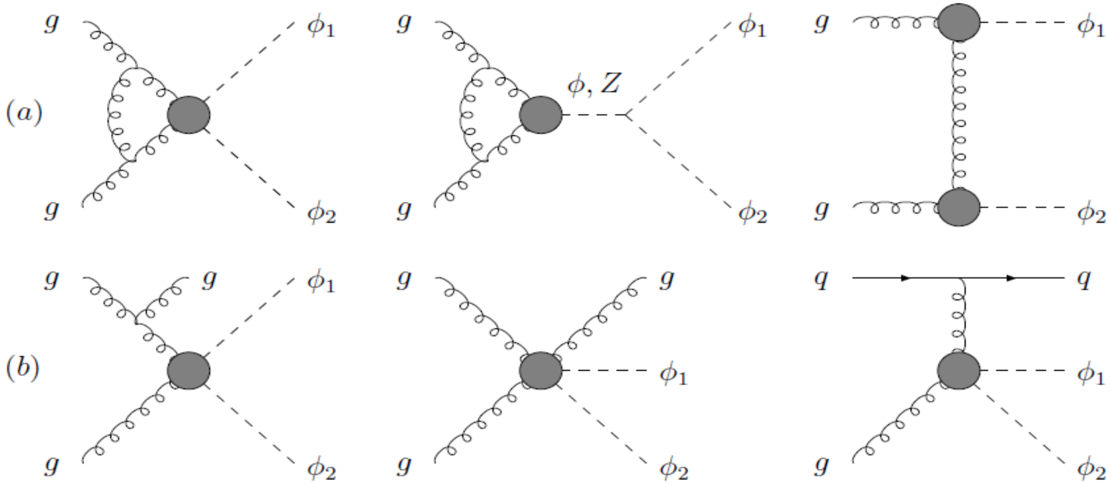

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Real and virtual contributions factorised into Born x α_s correction factor

Born cross-section replaced by the exact one

NLO approximations for HH: A step further

Hpair approximation a first step and given that the computation of the two-loop amplitudes will take time…

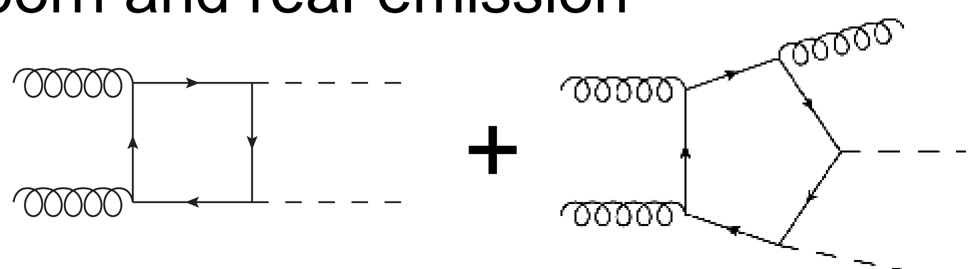
What else can we do?

We want to use all 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 one-loop matrix elements: born and real-emission



arxiv:1401.7340 and 1408.6542

A reweighting approach for HH

- NLO HEFT event generation: MC@NLO method

$$d\sigma^{(\mathbb{H})} = d\phi_{n+1}\left(\mathcal{R} - \mathcal{C}_{MC}\right),$$

$$d\sigma^{(\mathbb{S})} = d\phi_{n+1}\left[\left(\mathcal{B} + \mathcal{V} + \mathcal{C}^{int}\right)\frac{d\phi_n}{d\phi_{n+1}} + \left(\mathcal{C}_{MC} - \mathcal{C}\right)\right]$$

Structure of the NLO computation matched to parton showers

- Different weights stored internally: virtual, real and counter terms
- Reweight on an event-by-event basis using the results of the exact loop matrix elements. Schematically:

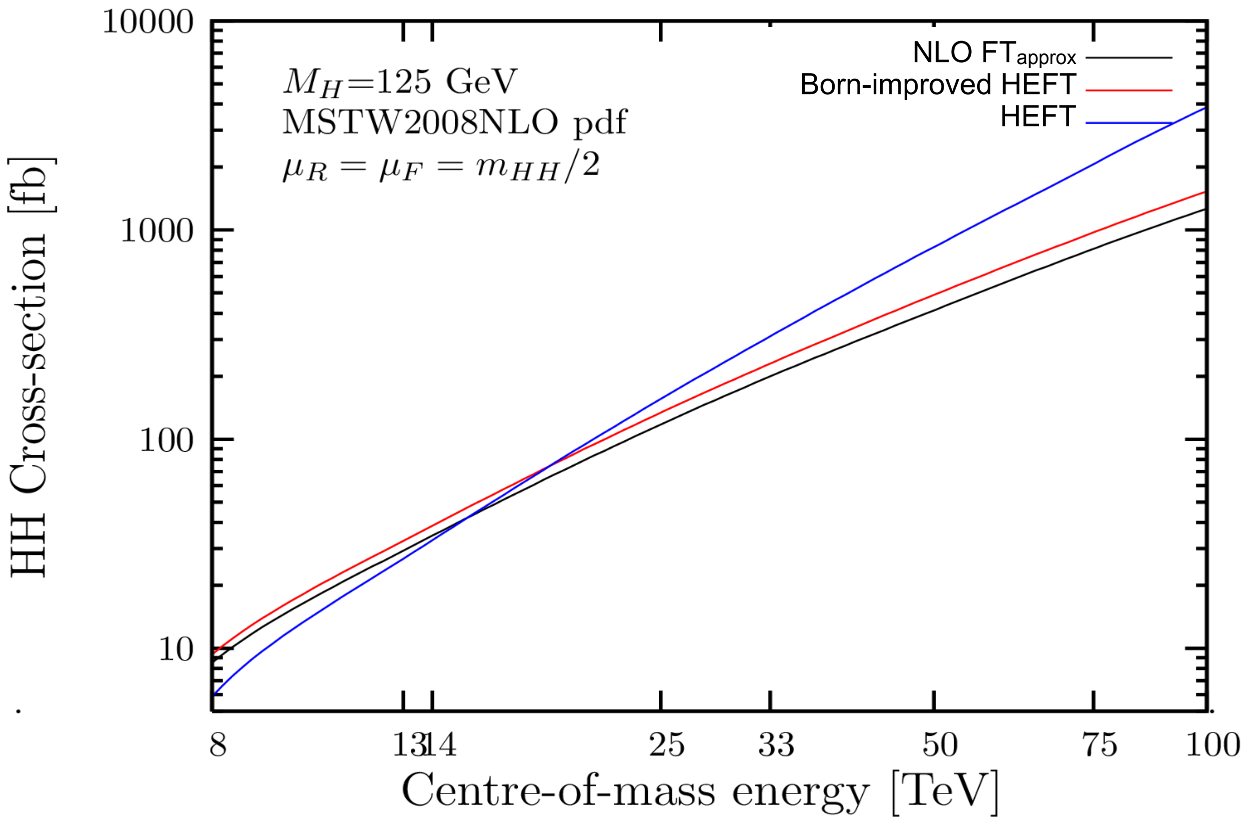
$$\mathcal{B}, \mathcal{V}, \mathcal{C}^{(int)}, \mathcal{C}_{MC} \quad \times \quad \mathcal{B}_{FT}/\mathcal{B}_{HEFT}$$

$$\mathcal{R} \quad \times \quad \mathcal{R}_{FT}/\mathcal{R}_{HEFT}$$

- Fully differential reweighting
- Setup allows implementation of a Born (Hpair-type) reweighting if all weights are reweighted by $\mathcal{B}_{FT}/\mathcal{B}_{HEFT}$
- Matching to parton showers with the MC@NLO method
- Reweighting method is general and efficient and can be applied in other loop-induced processes

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

- Effect of including the exact real emission amplitudes:
  - Reduction of the cross section by about 10% compared to the Born-improved results at 14 TeV
- EFT quickly rises at high energies

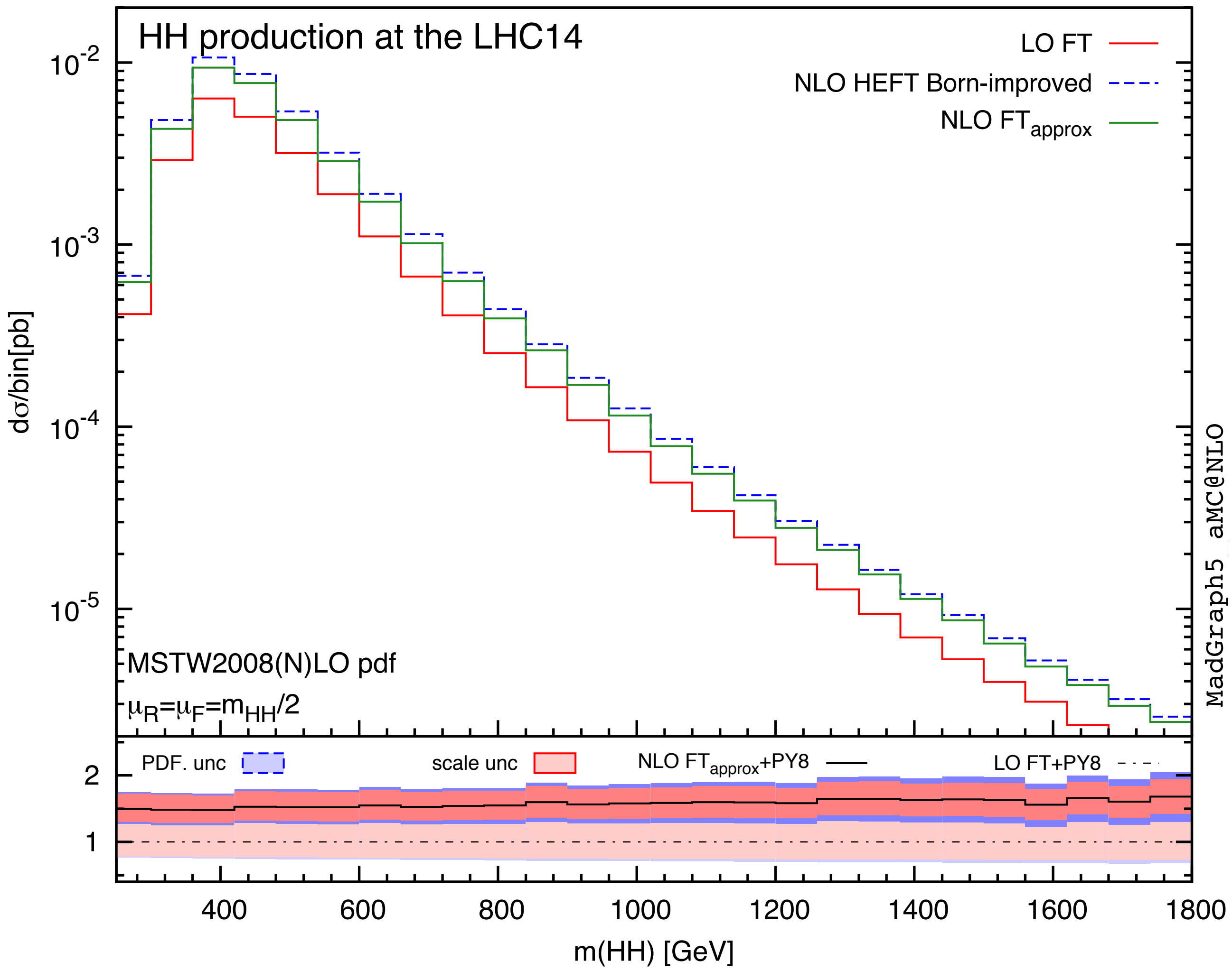
Results at 14 TeV [fb]

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

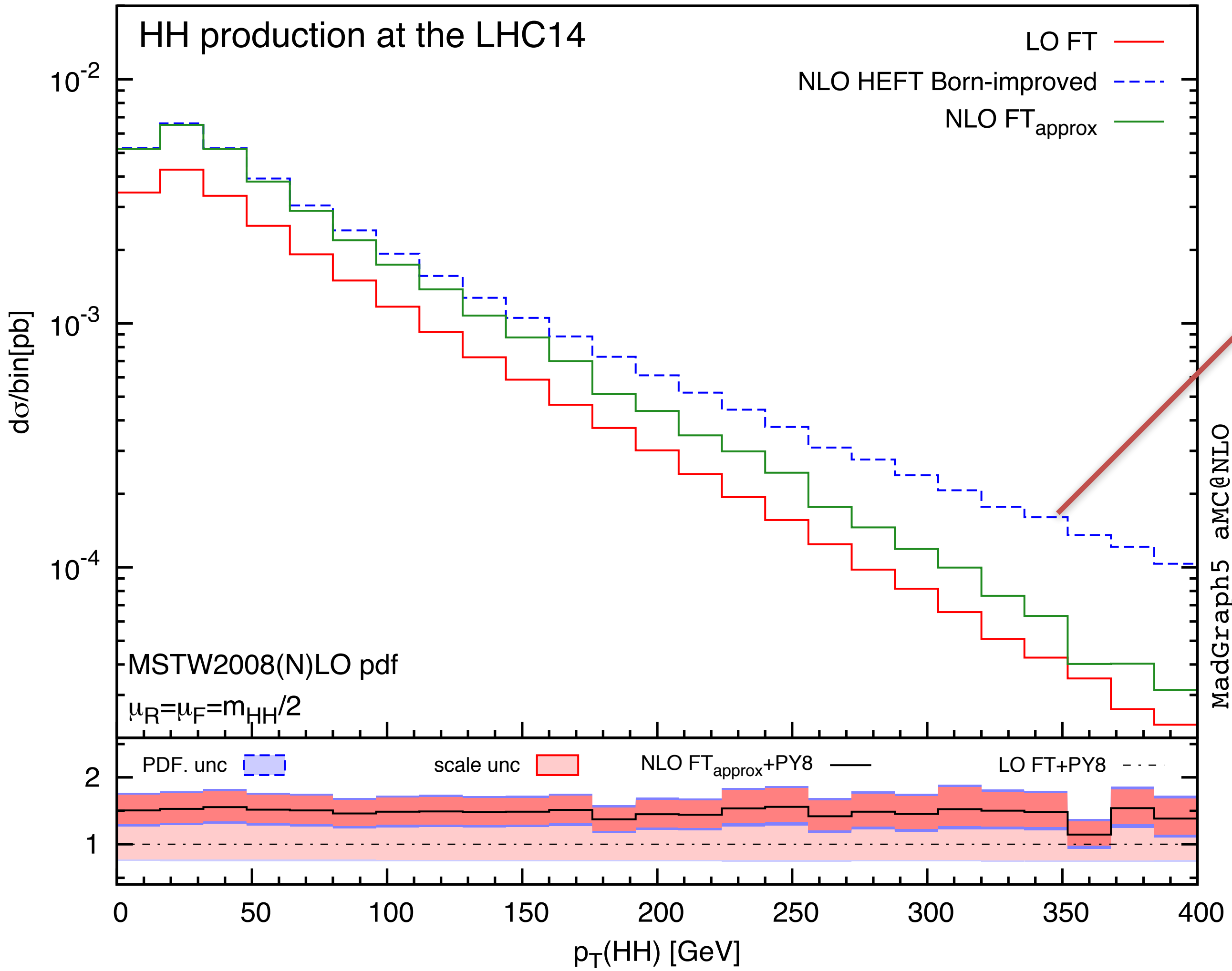
10% : Exact real emission amplitudes

Differential distributions for the LHC



Best available differential predictions: NLO plus PS

Differential distributions for the LHC



Including the exact matrix elements has a bigger effect in the region of hard parton emission: tail of pT(HH) distribution

Exact matrix elements give a better description

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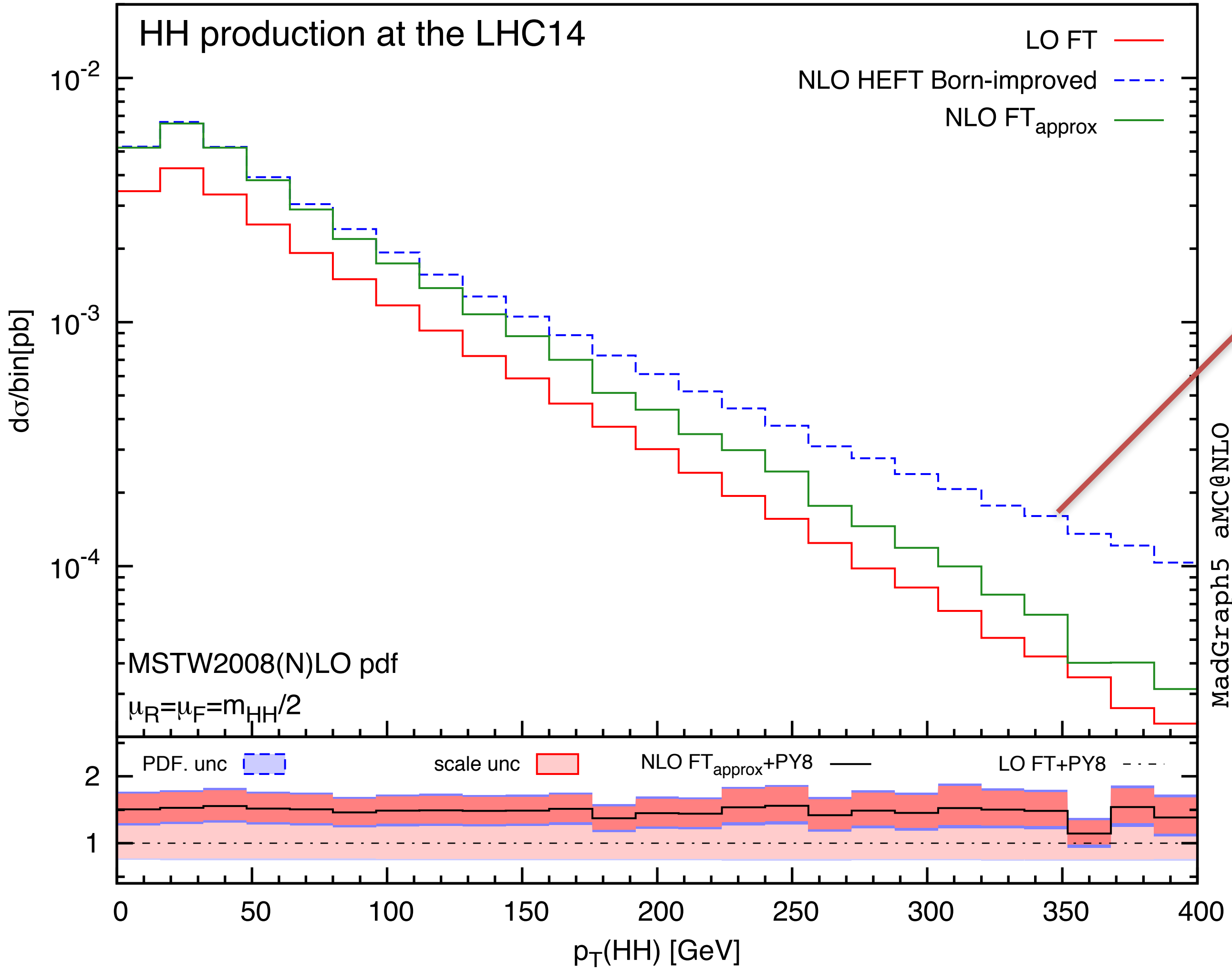

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Exact matrix elements give a better description

✔ Automatic computation of the scale and PDF uncertainties at a fully differential level

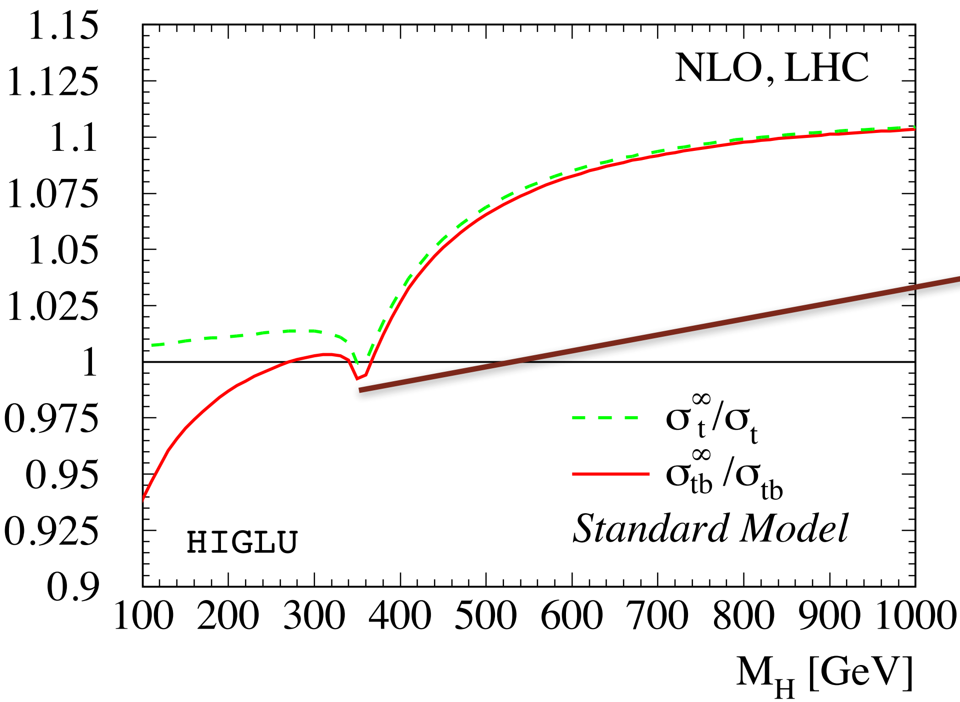
Best available differential predictions: NLO plus PS

Are our results robust?

One might argue that we are spoiling possible cancellations by including the exact top mass dependence in the real corrections but not in the virtual corrections…

Let's look at single Higgs production: Comparison of

- Born-rescaled HEFT results $\sigma^{NLO}_{HEFT} \times \sigma^{LO}_{FT}/\sigma^{LO}_{HEFT}$
- Available exact results



At the $2m_t$ threshold a cancellation must be happening between the top mass effects in the real and virtual corrections as the Born-rescaled HEFT result is very close to the exact one

Harlander, arxiv:0311.005

But such a cancellation would be spoiled by our approach…

Is there a way to check how big the effect of such a cancellation would be for HH production?

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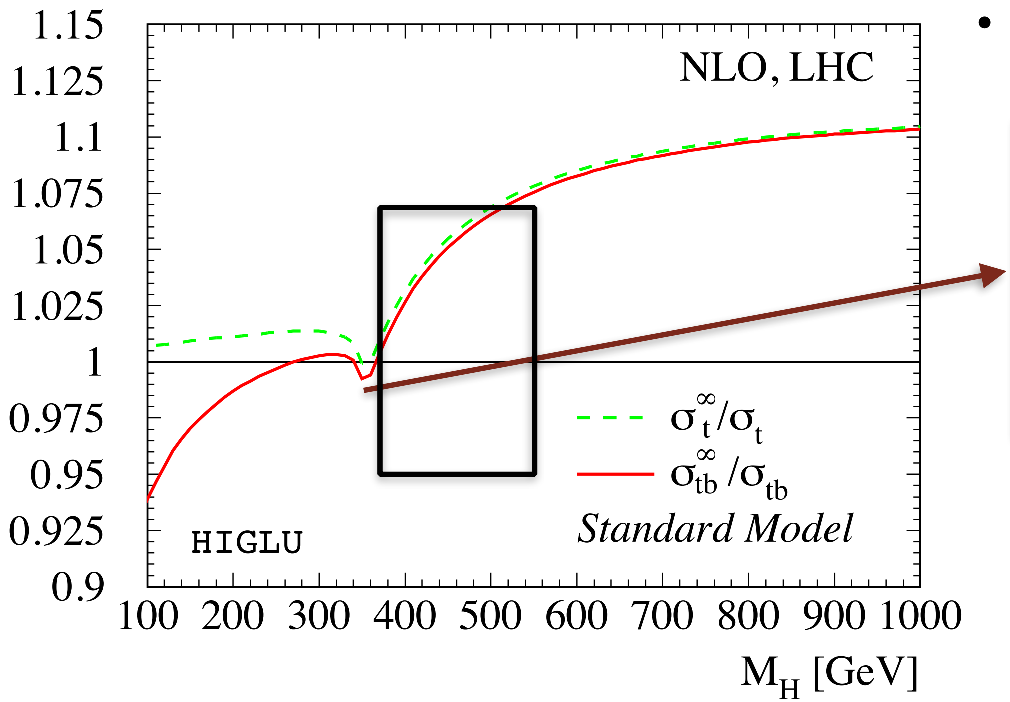

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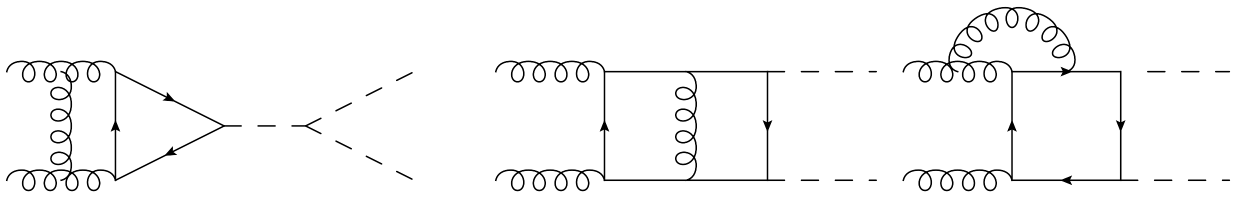
Approximate the virtual corrections

Let's recall the typical virtual correction diagrams for HH:



- Part of the virtual corrections is known as they are part of the single Higgs NLO corrections
- Corrections known as a function of the Higgs and top masses (e.g. SUSHI)

Adhoc assumption: Assume these corrections factorise in the same way for the box and triangle i.e.

$$\sigma^{HH}_{virt} = \frac{\sigma^{H}_{virt}}{\sigma^{H}_{Born}} \times \sigma^{HH}_{Born}$$

NLO results at 14 TeV [fb]

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$\mathrm{FT}_{\mathrm{approx}}$ (virtuals: Born-rescaled HEFT)	$34.3^{+15.0+1.5\%}_{-13.4-2.4\%}$
$\mathrm{FT}'_{\mathrm{approx}}$ (virtuals: estimated from single Higgs in FT)	$35.0^{+15.7+2.0\%}_{-13.7-2.4\%}$

2% effect
As the invariant mass peaks at values higher that $2m_t$
Results stable in that respect

Comparison to other gluon-gluon results

Comparison to $1/m_t$ expansion for the NLO results:

Grigo et al. arxiv:1305.7340

$$\sigma^{(1)}_{ij,N} = \sigma^{(0)}_{gg,\mathrm{exact}} \Delta^{(N)}_{ij}, \qquad \Delta^{(N)}_{ij} = \frac{\sigma^{(1)}_{ij,\mathrm{exp}}}{\sigma^{(0)}_{gg,\mathrm{exp}}} = \frac{\sum_{n=0}^{N} c^{\mathrm{NLO}}_{ij,n} \rho^n}{\sum_{n=0}^{N} c^{\mathrm{LO}}_{gg,n} \rho^n},$$

Computation of an $1/m_t$ expanded k-factor combined with the exact Born cross section

Result: Total cross section increased by 10% compared to $\sigma^{NLO}_{HEFT} \times \sigma^{LO}_{FT}/\sigma^{LO}_{HEFT}$

An effect opposite in sign to what we find
but note that even for single heavy Higgs of 400-500 GeV the $1/m_t$ expansion overshoots the exact result without any high-energy matching

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Other recent gluon fusion results:

- Merged samples (LO accuracy): Li, Yan, Zhao arXiv:1312.3830
  Maierhofer, Papaefstathiou arXiv:1401.0007
  Exact one-loop born and real emission matrix elements
- Threshold resummation: Shao et al. arXiv:1301.1245
- NNLO EFT corrected by exact LO, De Florian and Mazzitelli, arxiv:1309.6594
  Total cross section K-factor ~2.3 at 14TeV
- Completed by the computation of the 3-loop matching coefficient: arxiv:1408.2422

Outlook

- Top mass effects are important: ~10% uncertainty due to missing effects

  Need for the exact NLO calculation
- Next step:

  Phenomenology with a ~35fb cross-section: Not easy
- Which are the promising decay channels to observe the process?

  Recent progress with boosted techniques
  - $bb\gamma\gamma$ (1212.5581)
  - $bb\tau\tau$ (1206.5001, 1212.5581)
  - bbWW (1209.1489, 1212.5581)
  - bbbb (1404.7139)
- Prospects for the measurement of the trilinear Higgs coupling?

Optimistic estimate of 30% accuracy with 3000 fb^{-1} at 14 TeV (arxiv: 1404.7139)

- BSM? A wide range of possibilities: e.g. 2HDM (arxiv:1407.0281) …

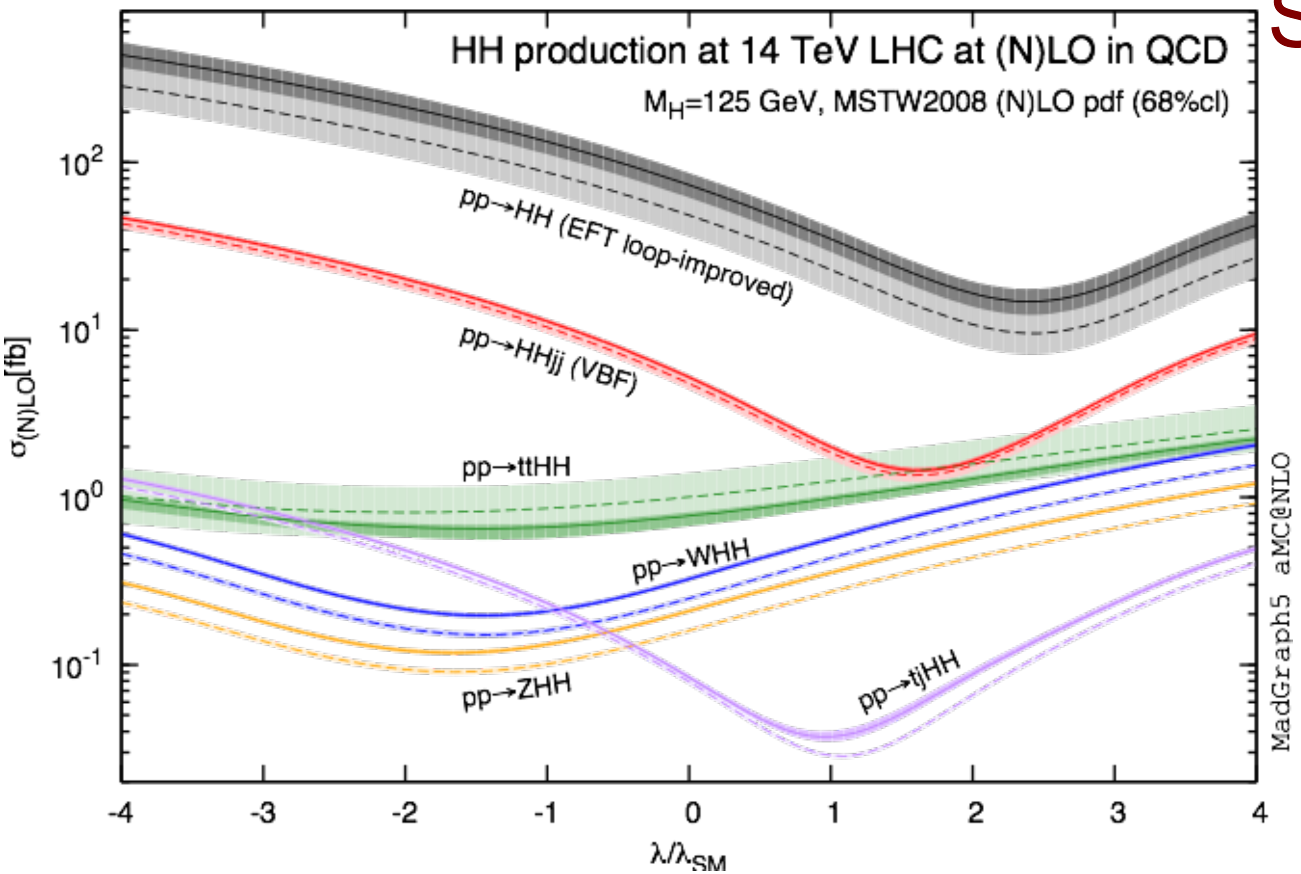
Conclusions

- Higgs pair production key to the measurement of the triple Higgs coupling, key to explore the Higgs potential
- Exact NLO computation not available, approximations of higher order corrections in the infinite top mass limit
- New MC implementation of the process at approximate NLO, provided within MG5_aMC@NLO for the SM
- Results are obtained by employing the exact matrix elements for the real emission amplitudes, gives a better description of the kinematics and a total cross section different by -10% from the Born-rescaled result
- By comparing to other approximations in the literature the predictions lead to an estimate of 10% for the uncertainty due to the missing mass effects

Thanks for your attention...

ADDITIONAL SLIDES

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 in the 2HDM

2HDM: Additional Higgs doublet

BSM physics
enhancements

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New particles
Resonances

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Higher dimensional operators

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Higher dimensional 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)
- Dimension-6 gluon Higgs operators (0609.049)
- many more BSM scenarios….

Higgs pair production in the 2HDM

2HDM: Additional Higgs doublet

BSM physics enhancements

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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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Pair production in gluon fusion

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

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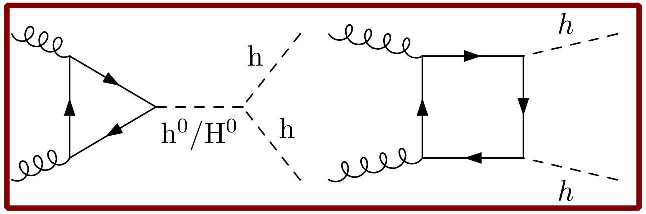
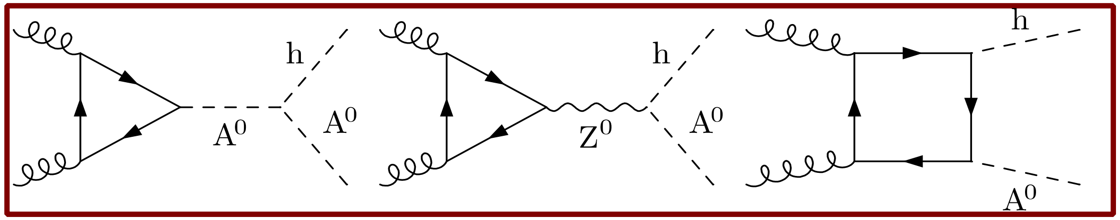
Topologies:





Higgs pair production in the 2HDM

2HDM: Additional Higgs doublet

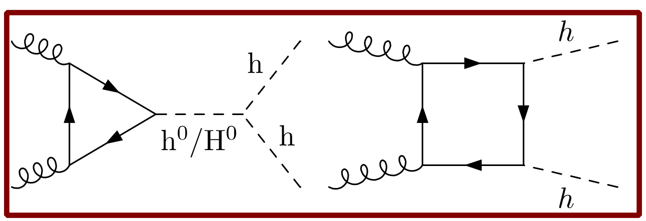
h light CP even
H heavy CP even
A CP odd
H^+ H^- Charged

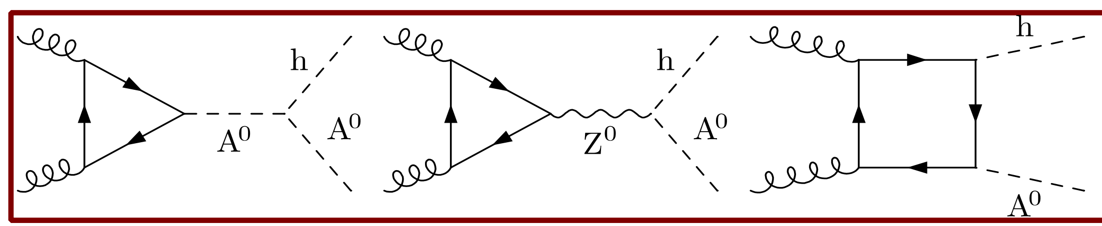
Type-I and Type-II setups
2HDM input:
$\tan\beta$, $\sin\alpha$, m_h, m_H, m_A, m_{H+}, m_{12}^2

Pair production in gluon fusion

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

Topologies:





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

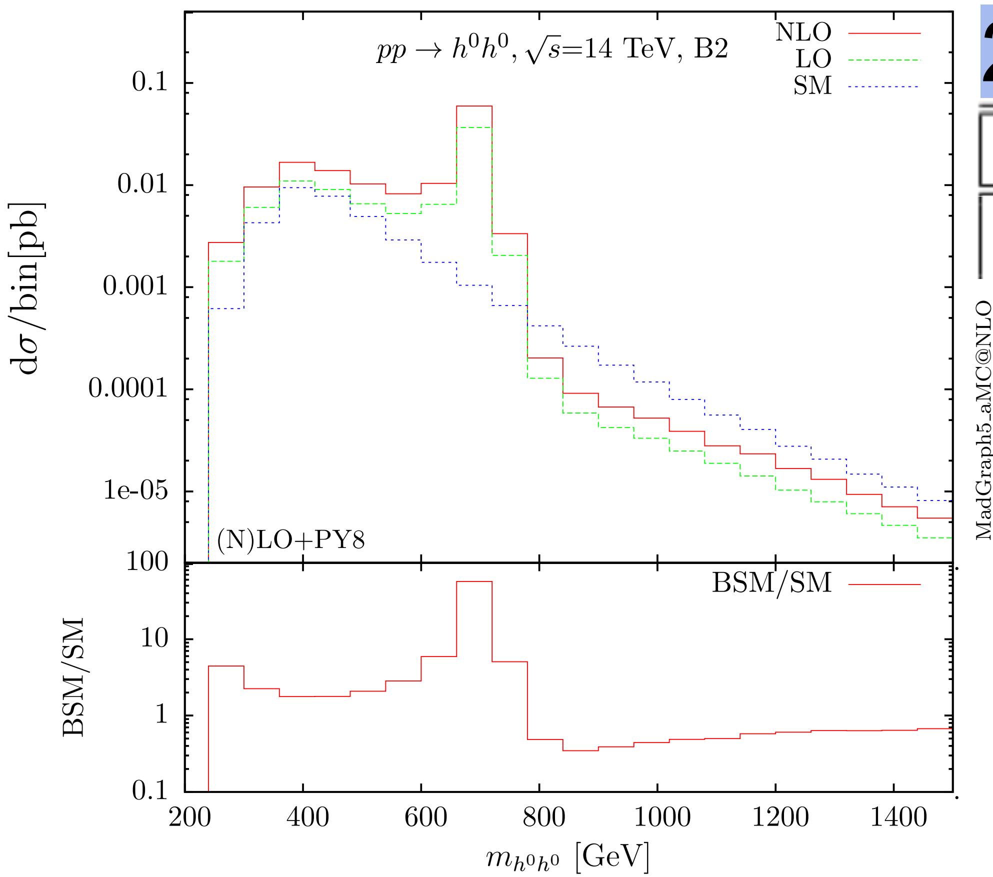
Higgs pair production in gluon fusion in the 2HDM

- 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

Light Higgs pair production
Resonant 2HDM scenario



2HDM input: Type-ii

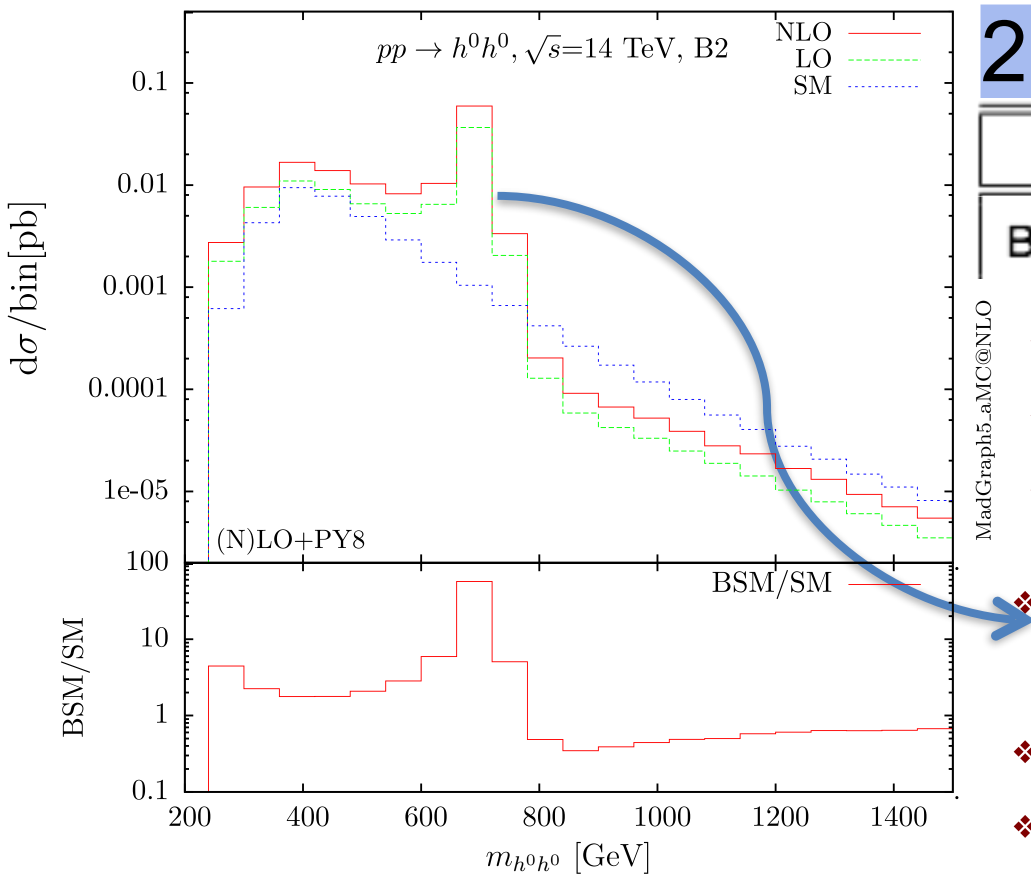
	tan β	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m^2_{12}
B2	1.50	-0.2162	700	701	670	180000

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

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

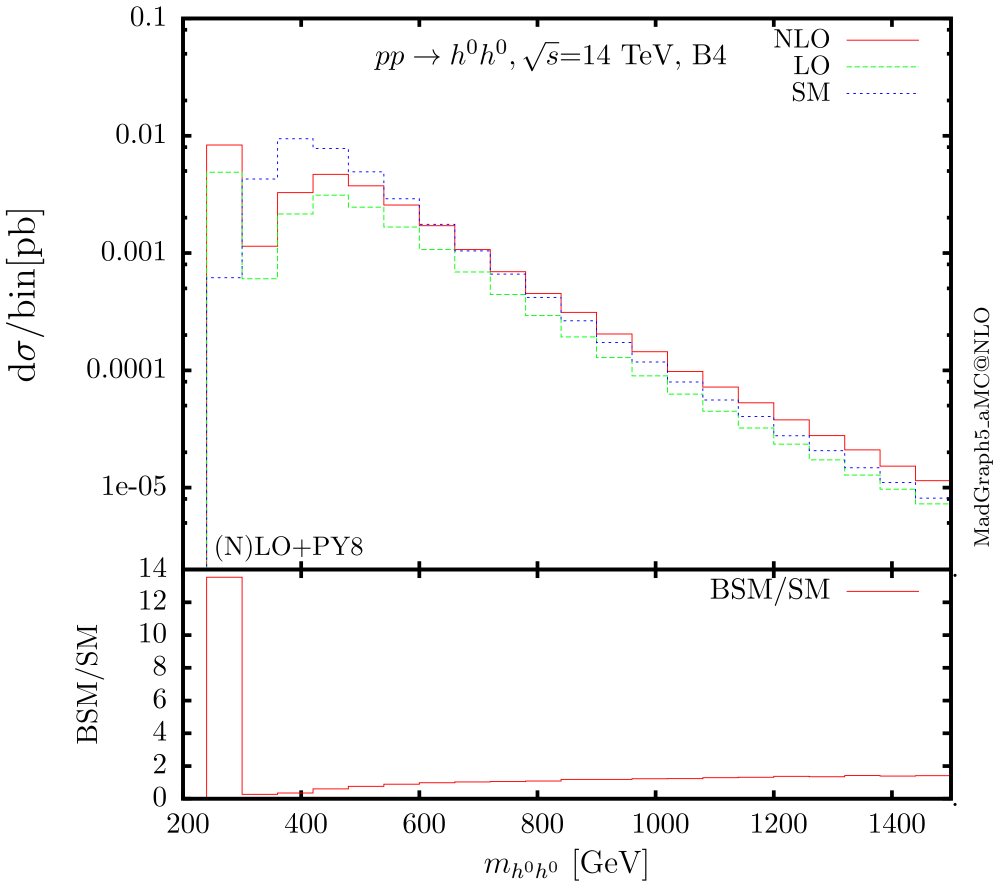
- **Slightly reduced top Yukawa**
- **Reduced hhh coupling**
- **Enhanced Hhh coupling**

- 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

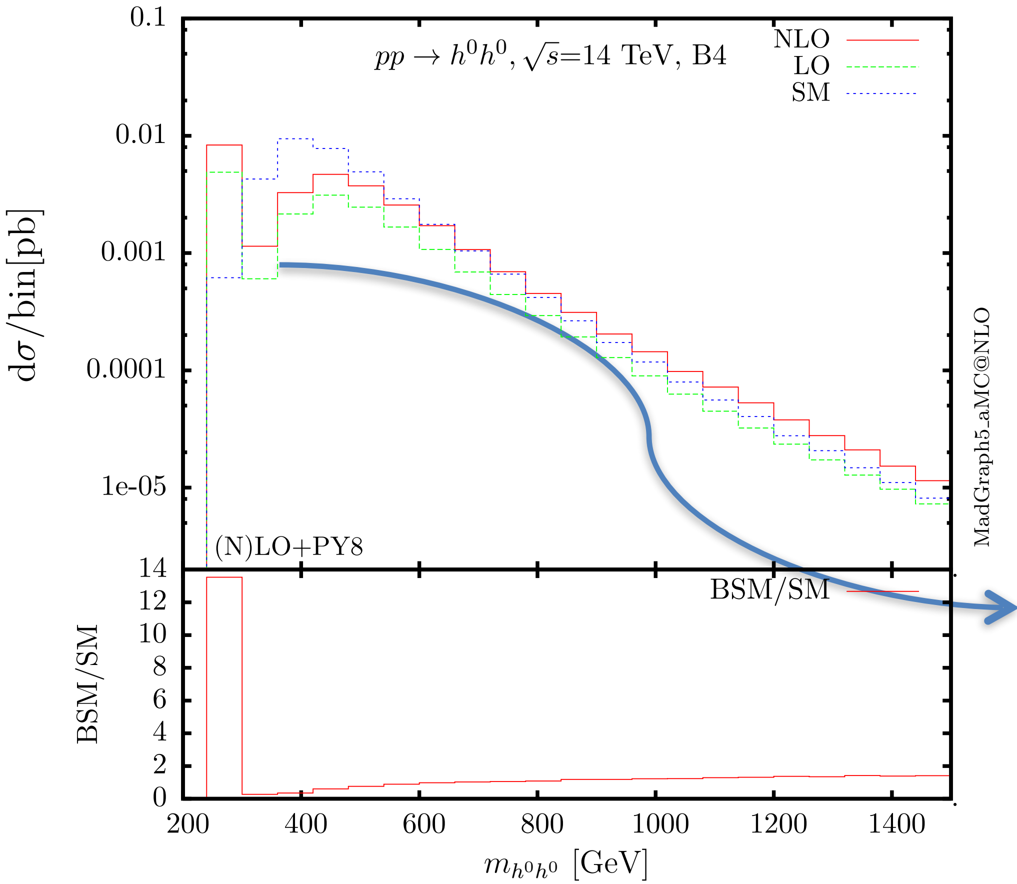
	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B4	1.20	-0.1760	200	500	500	-60000

- **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



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

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

arxiv:1407.0281