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Higgs pair production at the LHC without gluon fusion

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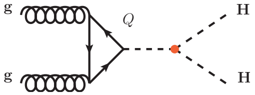
INSTITUT FÜR THEORETISCHE PHYSIK

Outline

1. Overview
2. Vector boson fusion
3. Double Higgs-strahlung
4. Associated production with a top quark pair
5. Conclusion

The main *HH* production channels

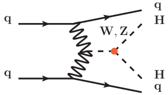
- gluon fusion



NNLO in QCD

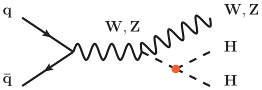
[De Florian, Mazzitelli, PRL 111 (2013) 201801]

- vector boson fusion



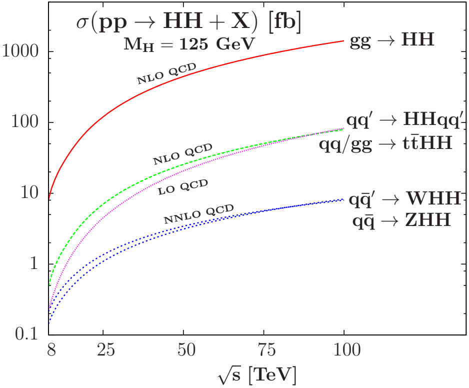
NNLO in QCD
(see next slides)

- double Higgs–strahlung

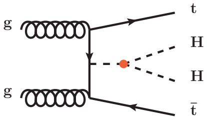


NNLO in QCD

[J.B. *et al*, JHEP 1304 (2013) 151]



- associated production with a top pair



NLO in QCD

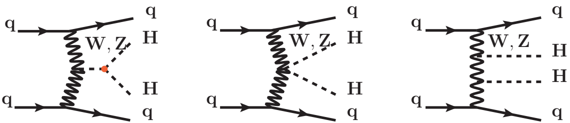
[Frederix *et al*, Phys.Lett. B732 (2014) 142]

$\sim$ 1000 times smaller than $\sigma(pp \to H + X)$

[J.B. *et al*, JHEP 1304 (2013) 151]

Vector boson fusion at NLO

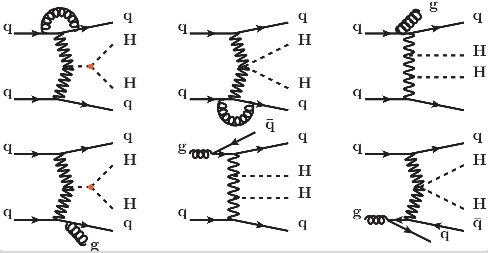
$pp \to qq \to qq\, WW/ZZ \to qqHH$: the second production channel at the LHC



LO inclusive cross section known for a while [Keung, Mod.Phys.Lett. A2 (1987) 765; Eboli *et al*, Phys.Lett. B197 (1987) 269; Dicus, Kao, Willenbrock, Phys.Lett. B203 (1988) 457; Dobrovolskaya, Novikov, Z.Phys. C52 (1991) 427; see also Djouadi, Kilian, Mühlleitner, Zerwas, Eur.Phys.J. C10 (1999) 45]

QCD corrections: **NLO corrections to inclusive rates and differential distributions** [J.B. *et al*, JHEP 1304 (2013) 151] **implemented in** `VBFNLO` **(publicly available)** [Arnold *et al* Comput.Phys.Comm. 180 (2009) 1661; J.B. *et al*, arXiv:1404.3940]

Calculation also done by `MadGraph5_aMC@NLO` collaboration [Frederix *et al*, Phys.Lett. B732 (2014) 142]



$\simeq +7\%$ correction
(similar to single Higgs case)

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}$ [fb]
8	0.49
14	2.01
33	12.05
100	79.55

Infrared singularities in VBFNLO

- What about Infrared singularities? Soft and collinear singularies arise in the calculation, notabely cumbersome for a Monte-Carlo program as they arise in different phase–spaces $\Rightarrow$ substraction method to handle them!

$$\sigma^{\text{NLO}} = \int_{\phi_n} d\sigma^{\text{Born}} + \int_{\phi_n} d\sigma^{\text{virt}} + \int_{\phi_{n+1}} d\sigma^{\text{real}}$$

  with each contribution divergent $\Rightarrow$ cancel soft & collinear singularities before Monte-Carlo integration:

$$\sigma^{\text{NLO}} = \int_{\phi_{n+1}} \left(d\sigma^{\text{real}}|_{\varepsilon=0} - d\sigma^{A}|_{\varepsilon=0} \right) + \int_{\phi_n} \left(d\sigma^{\text{Born}} + d\sigma^{\text{virt}} + \int_{\phi_1} d\sigma^{\text{A}} \right) |_{\varepsilon=0}$$

  where $d\sigma^{\text{A}}$ a substraction term with the following properties:
  - $d\sigma^{\text{A}}$ cancels soft & collinear divergences of $d\sigma^{\text{real}}$
  - $\int_{\phi_1} d\sigma^{\text{A}}$ done (partially) analytically in d dimensions $\Rightarrow$ I, P, K operators, left–over collinear singularities absorbed into PDFs

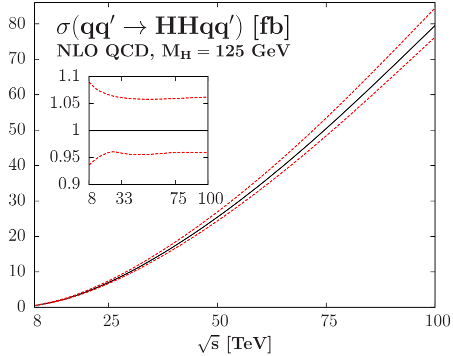
The calculation has been done in VBFNLO with Catani-Seymour dipoles

[Catani, Seymour, Nucl.Phys. B485 (1997) 291]

Vector boson fusion: theoretical uncertainties

***qq* → *HHqq* is a clean process:**

- Scale uncertainty: $\Delta^{\rm scale} \simeq +2\%/-1\%$ at 14 TeV
  Good precision compared to LO $\Delta^{\rm scale} \simeq \pm 10\%$
- PDF uncertainty: $\Delta^{\rm PDF+\alpha_s}_{\rm 90\%CL} \simeq +6\%/-4\%$ at 14 TeV



Total uncertainty: $\simeq +8\%/-5\%$ ($\simeq +6\%/-4\%$ at 100 TeV) [J.B. *et al*, JHEP 1304 (2013) 151]

NNLO QCD corrections in the structure function approach: $+0.5\%$ on top of the NLO result, scale uncertainty at the percent level [L. Liu-Sheng *et al*, Phys.Rev. D89 (2014) 073001]

Vector boson fusion: differential distributions

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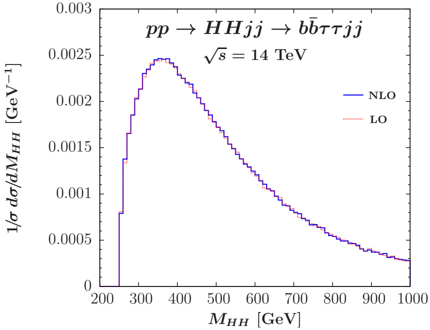
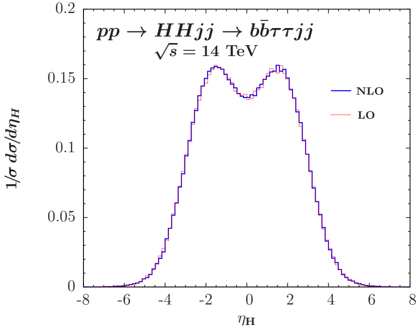
`VBFNLO` can also produce NLO differential distributions for VBF $\to H(\to b\bar{b})H(\to XX)jj$:

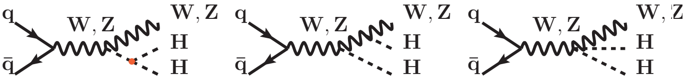




Cuts can also be implemented

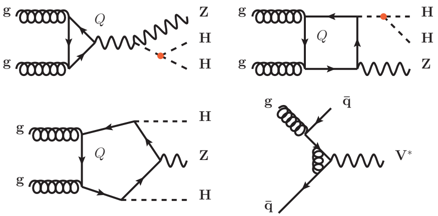
Double Higgs-strahlung: associated W/Z + 2 Higgs

$\mathbf{pp \to Z^*/W^* \to Z/W + HH}$: clean but very small rates



[Barger, Han, Phillips, Phys.Rev. D38 (1988) 2766]

- NLO QCD corrections: Drell-Yan $\sigma(pp \to V^*)$ corrections $\simeq +20\%$ [J.B. *et al*, JHEP 1304 (2013) 151]
- NNLO QCD corrections: Drell-Yan $\simeq +4\%$ [J.B. *et al*, JHEP 1304 (2013) 151]
- NNLO QCD corrections (II): specific $gg \to ZHH$ channel $\Rightarrow \simeq +20$ - 30%, sharp contrast with $\simeq +5\%$ in ZH production [J.B. *et al*, JHEP 1304 (2013) 151]



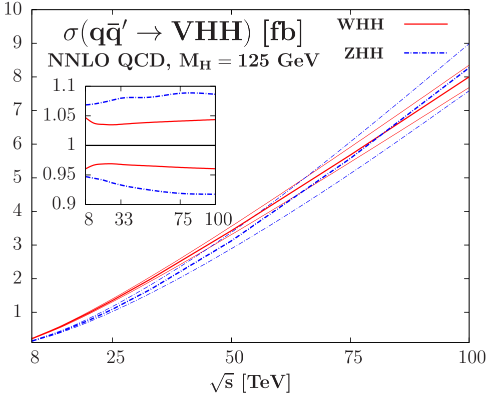
$\sqrt{s}$ [TeV]	$\sigma^{\rm NNLO}_{WHH}$ [fb]	$\sigma^{\rm NNLO}_{ZHH}$ [fb]
8	0.21	0.14
14	0.57	0.42
33	1.99	1.68
100	8.00	8.27

Theoretical uncertainties in double Higgs–strahlung

pp $\rightarrow$ VHH is also a very clean process:

- Scale uncertainty: calculated at NNLO with $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$, $\mu_0 = M_{VHH}$;
  $\Delta^{\text{scale}} < 1\%$ in *WHH* channel
  In *ZHH* channel, worse due to $gg \rightarrow ZHH$: $\Delta^{\text{scale}}_{ZHH} \simeq \pm 3\%$

- PDF uncertainty: total $\Delta^{\text{PDF}+\alpha_s}_{90\%\text{CL}} \simeq \pm 4\%$ ($\simeq \pm 3\%$ at 100 TeV)



Total uncertainty:

$\Delta^{\text{tot}}_{\text{WHH}} \simeq \pm 4\%$, $\Delta^{\text{tot}}_{\text{ZHH}} \simeq \pm 7\%$

[J.B. *et al*, JHEP 1304 (2013) 151]

Double Higgs–strahlung differential distributions

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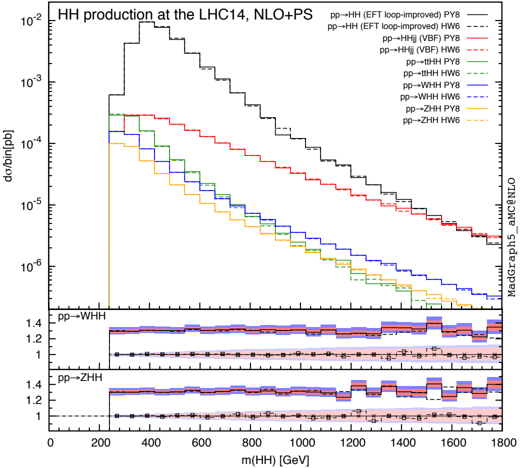
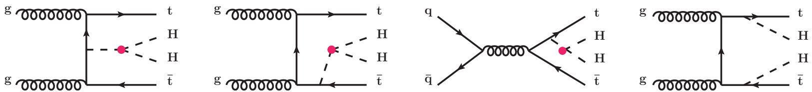
VHH is known fully differentially at NLO:



[Frederix *et al*, Phys.Lett. B732 (2014) 142]

$t\bar{t}HH$ production

$t\bar{t}HH$: the third process at the LHC, the second at greater energies



Process known only at LO for a while due to a very complicated topologies with pentagons and hexagons diagrams at NLO

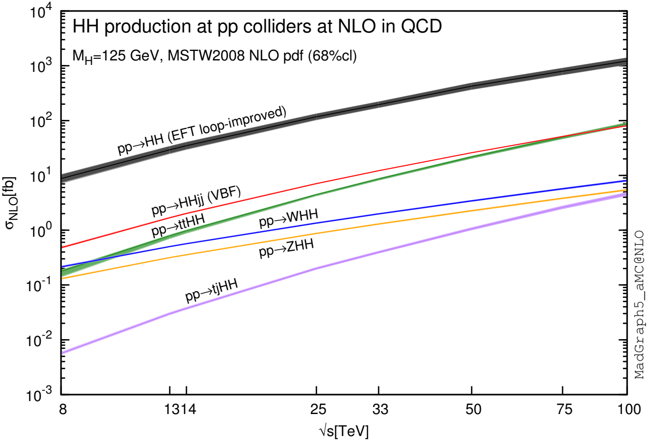
NLO corrections: tackled in 2014 with `MadGraph5_aMC@NLO` ! [Frederix *et al*, Phys.Lett. B732 (2014) 142]
$\Rightarrow -20\% \; - 30\%$ effect on inclusive rates

$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{NLO}}_{t\bar{t}HH}$ [fb]
8	0.177
13	0.792
14	0.981

Strong reduction of scale uncertainty: from $+40\%/-25\%$ down to $+3\%/-10\%$ at 13 TeV; central scale $\mu_0^4 = m_T(H_1) m_T(H_2) m_T(t) m_T(\bar{t})$

$t\bar{t}HH$ production

$t\bar{t}HH$: the third process at the LHC, the second at greater energies

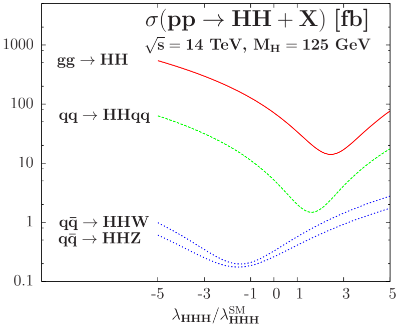


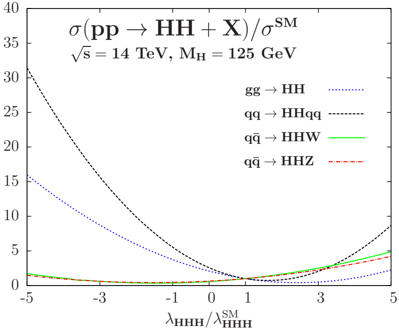
[Frederix *et al*, Phys.Lett. B732 (2014) 142]

Sensitivity to the triple Higgs coupling

The VBF mode is the most sensitive channel to the triple Higgs coupling

Update of a study done in [Djouadi, Kilian, Mühlleitner, Zerwas, Eur.Phys.J C10 (1999) 45]





[J.B. *et al*, JHEP 1304 (2013) 151]

Conclusion

HH production in other channels than gluon fusion:

- Inclusive VBF and Double Higgs–strahlung productions known at NNLO QCD and have very limited theoretical uncertainties $< 10\%$
- VBF process perfectly ready for NLO differential analyses
- $t\bar{t}HH$ process the second process for very high energies $\Rightarrow$ to be considered for VLHC?
- VBF the most sensitive to the triple Higgs coupling $\Rightarrow$ worth investigating it in details!