Vector-boson fusion Higgs production at N^{3}LO

Higgs Hunting, Paris, 2 September 2016

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based on Phys.Rev.Lett. 117 (2016) no.7, 072001

and work in collaboration with Matteo Cacciari, Alexander Karlberg, Gavin Salam & Giulia Zanderighi

Outline

1. Introduction

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   - Structure function approach
   - Inclusive and differential NNLO corrections

3. N^3LO QCD corrections
   - Distributions and cross sections
   - Theoretical PDF uncertainties

4. Conclusion

INTRODUCTION

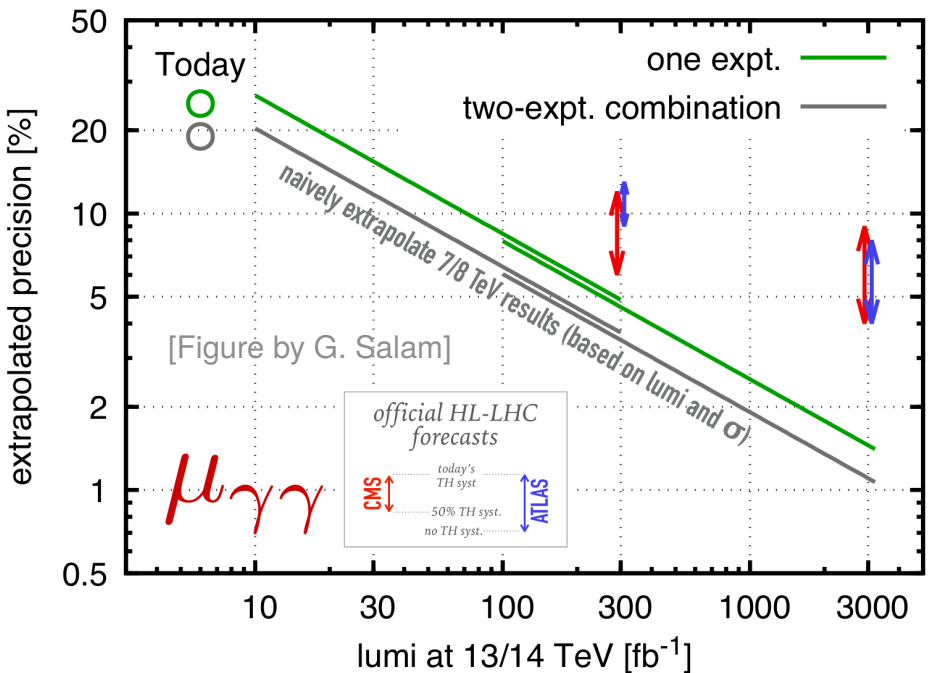
Experimental status and precision outlook

Current measurement of signal strength for VBF Higgs production has uncertainty of about 20%.

Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$	$1.25^{+0.24}_{-0.21}$	$0.84^{+0.19}_{-0.16}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$	$1.21^{+0.33}_{-0.30}$	$1.13^{+0.37}_{-0.34}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$	$1.25^{+0.56}_{-0.52}$	$0.46^{+0.57}_{-0.54}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$	$0.30^{+0.51}_{-0.46}$	$1.35^{+0.58}_{-0.54}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

[ATLAS-CONF-2015-044]

But large improvement can be expected with the HL-LHC.



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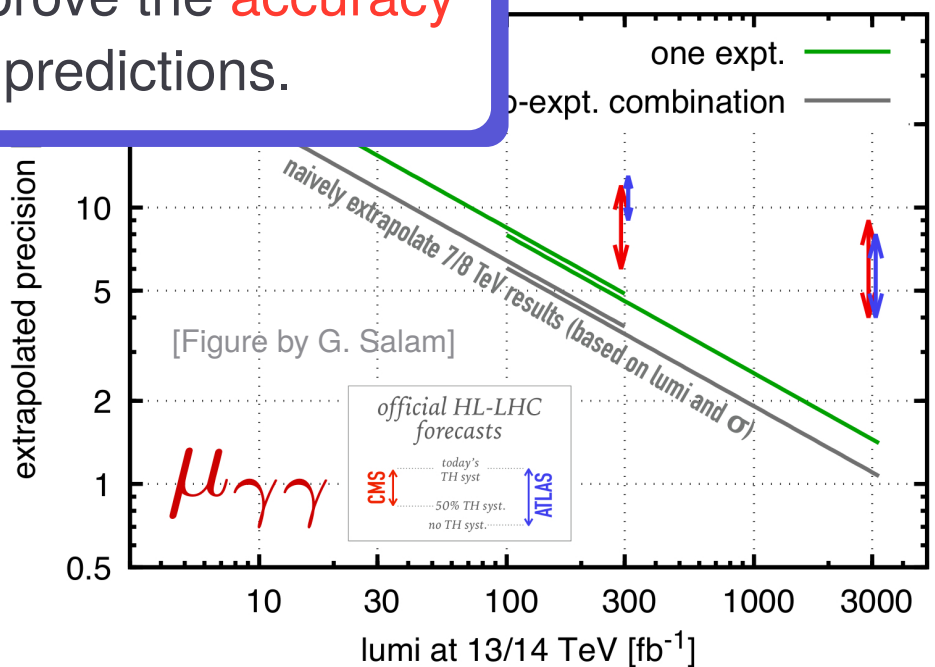
[AT

It is important to improve the accuracy of theoretical predictions.

But large improvement can be expected with the HL-LHC.

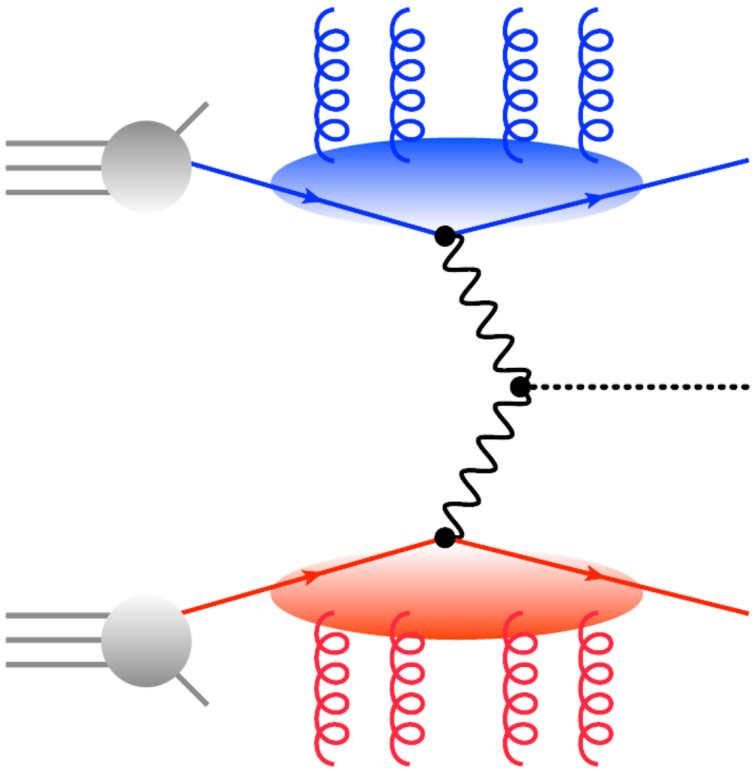


QCD CORRECTIONS IN VBFH

Structure function approach

Assume that lower and upper sector factorize from each other (i.e. no cross-talk).

[Han, Valencia, Willenbrock Phys.Rev.Lett. 69 (1992) 3274-3277]



One can then think of VBFH as DIS×DIS.

This picture is accurate to better than 1%.

[Bolzoni et al. PRD85 (2012) 035002,
Ciccolini et al. PRD77 (2008) 013002,
Andersen et al. JHEP 0802 (2008) 057]

Since DIS coefficients are inclusive over hadronic final states, this calculation cannot provide differential results for the jets.

Structure function approach

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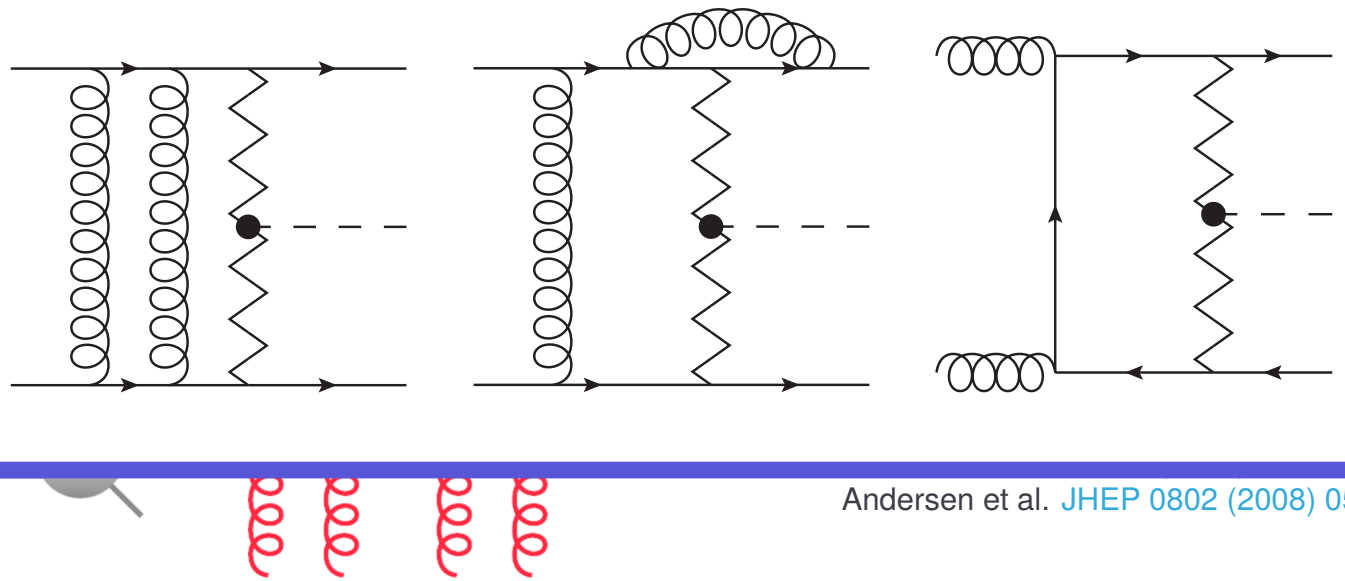
[Han, Valencia, Willenbrock Phys.Rev.Lett. 69 (1992) 3274-3277]

These types of contributions are neglected in this limit:



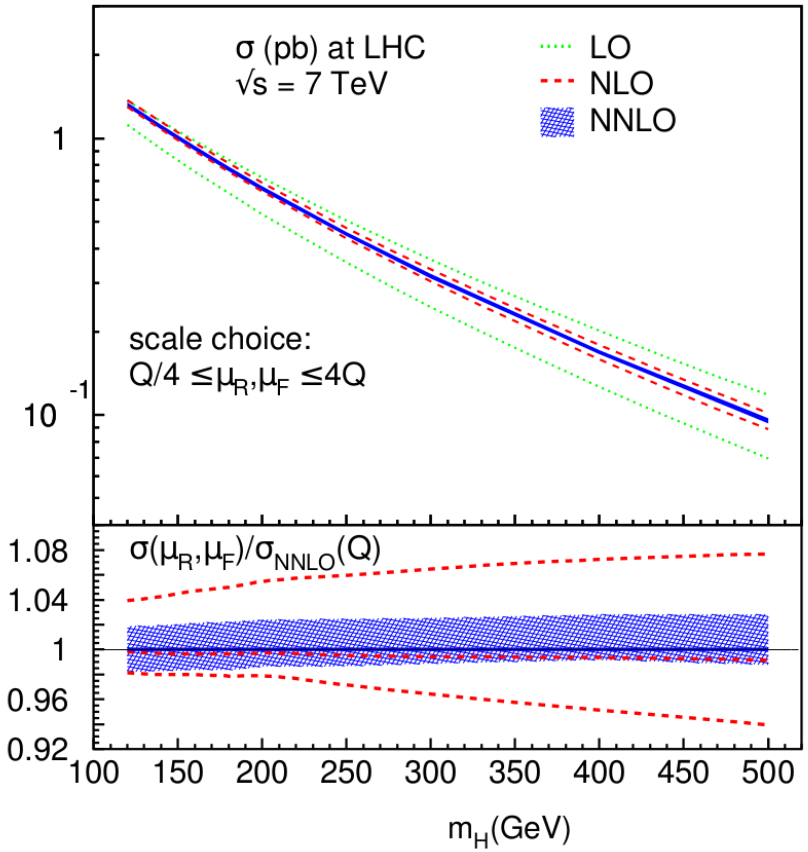
Andersen et al. JHEP 0802 (2008) 057]

Since DIS coefficients are inclusive over hadronic final states, this calculation cannot provide differential results for the jets.

Inclusive NNLO VBF Higgs production

Fully inclusive VBF Higgs production has been known at NNLO for some time.

[Bolzoni, Maltoni, Moch, Zaro Phys.Rev.Lett. 105 (2010) 011801]



Calculation suggests small renormalization and factorization scale variations ($\sim 1 - 2\%$), with NNLO values within NLO bands.

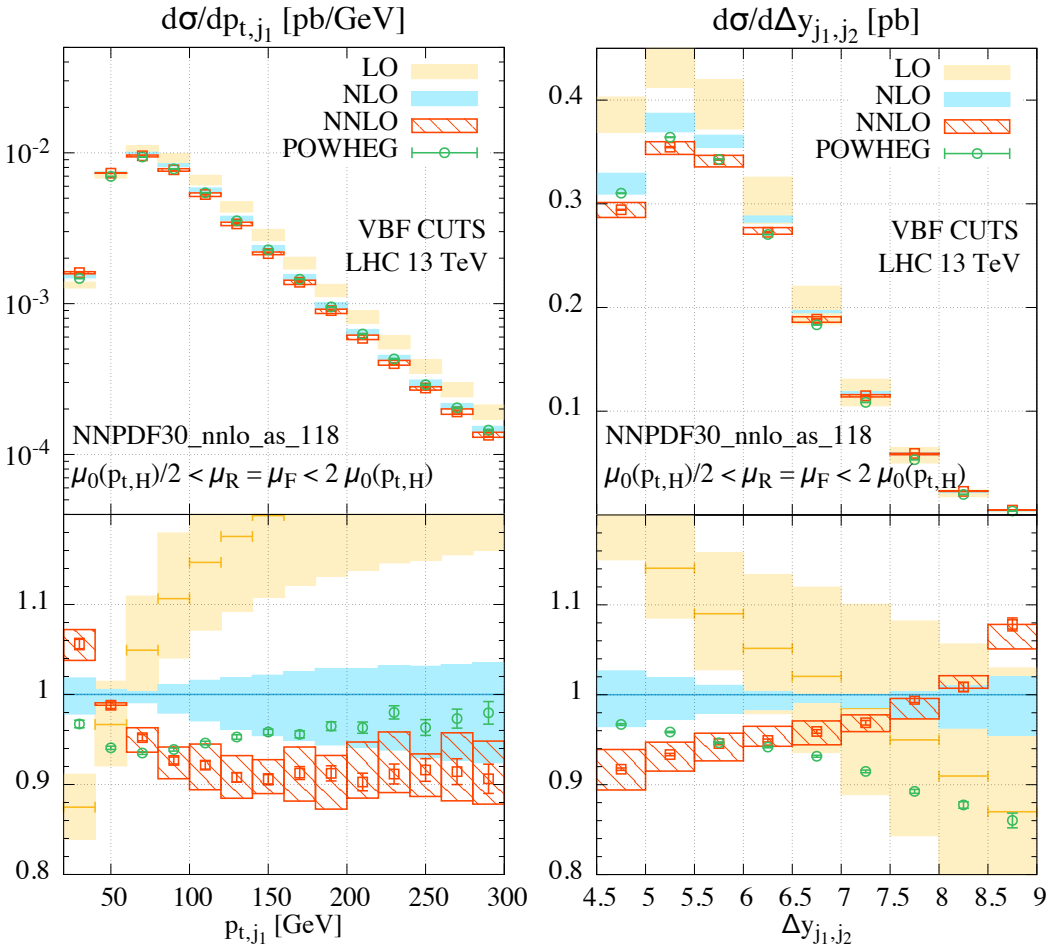
This calculation is **inclusive** over all hadronic final states.

Result is obtained using the structure function approach.

Differential NNLO VBF Higgs production

Using novel "projection-to-Born" method, differential results were derived recently in the DIS×DIS limit.

[Cacciari, FD, Karlberg, Salam, Zanderighi Phys.Rev.Lett. 115 (2015) no.8, 082002]



NNLO corrections are up to ~ 10 – 12% after VBF cuts.

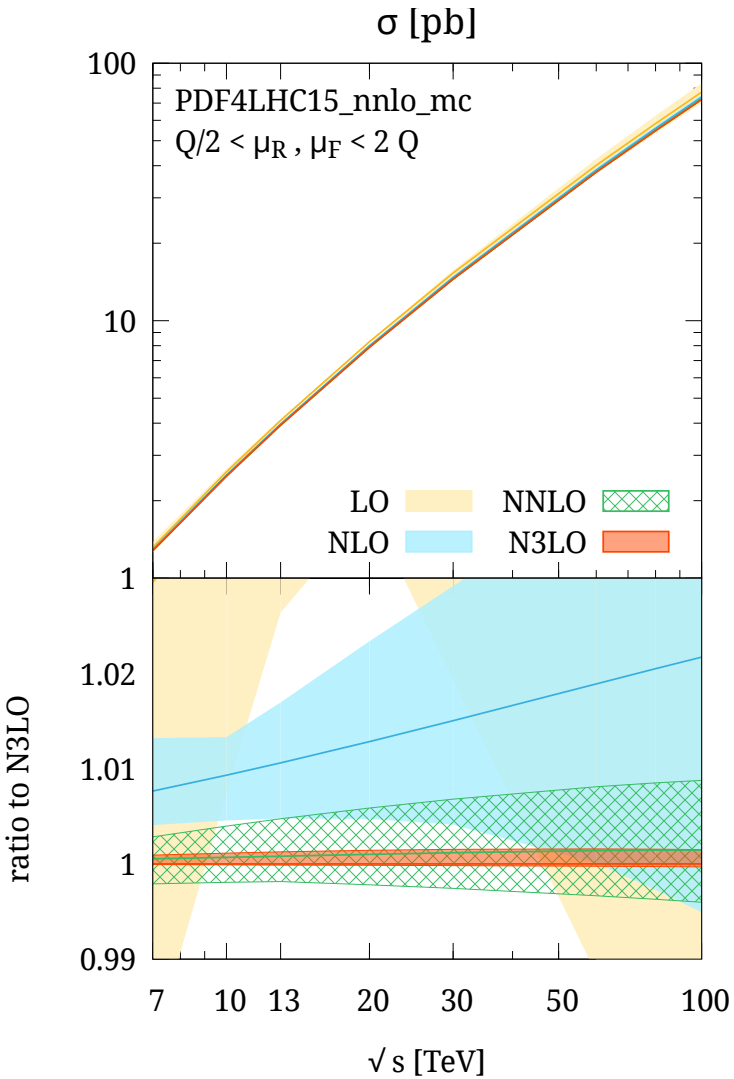
There is a non-trivial kinematic dependence of K-factors.

No reduction of theoretical uncertainty at NNLO after VBF cuts.

N^3LO QCD CORRECTIONS

Inclusive cross section at N^{3}LO

Inclusive calculation can be extended to VBF Higgs production at N^{3}LO



using third order coefficient functions:

[Moch, Vermaseren, Vogt PLB606 (2005) 123-129]
[Vermaseren, Vogt, Moch NPB724 (2005) 3-182]
[Vermaseren, Moch, Vogt NPPS 160 (2006) 44-50]
[Moch, Rogal, Vogt NPB790 (2008) 317-335]

which have been implemented in HOPPET v1.2.0-devel.

[Salam, Rojo CPC 180 (2009) 120-156]

Perturbative series converges extremely well.

Very small change in central value . . .

. . . but large reduction in theoretical uncertainty.

Total cross-sections

We consider pp collisions, and use `PDF4LHC15_nnlo_mc`.

Central scale is set to the vector boson energies, Q_1, Q_2, and varied up and down by a factor two keeping $0.5 < \mu_R/\mu_F < 2$.

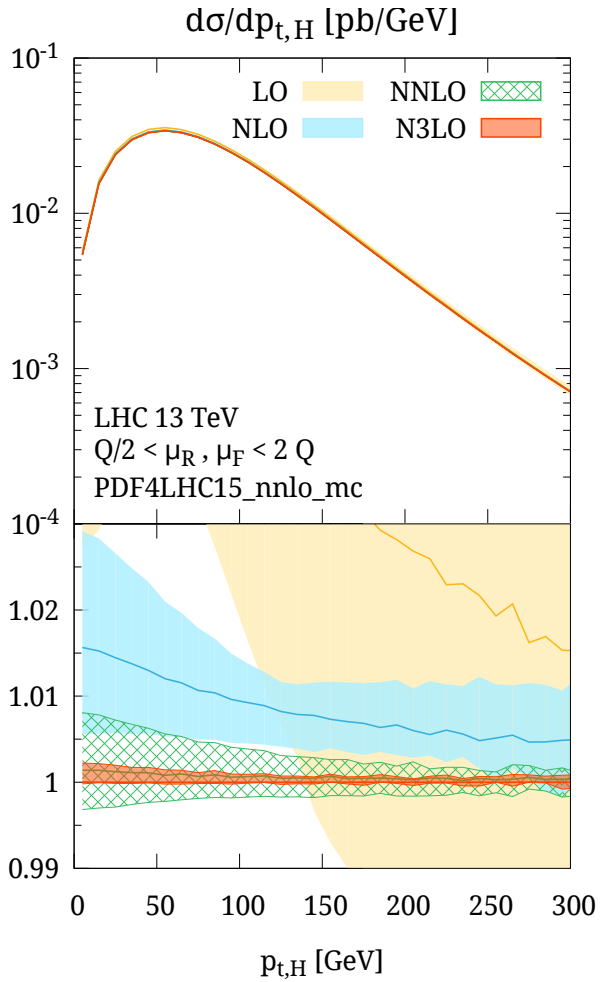
Inclusive cross section (no cuts)

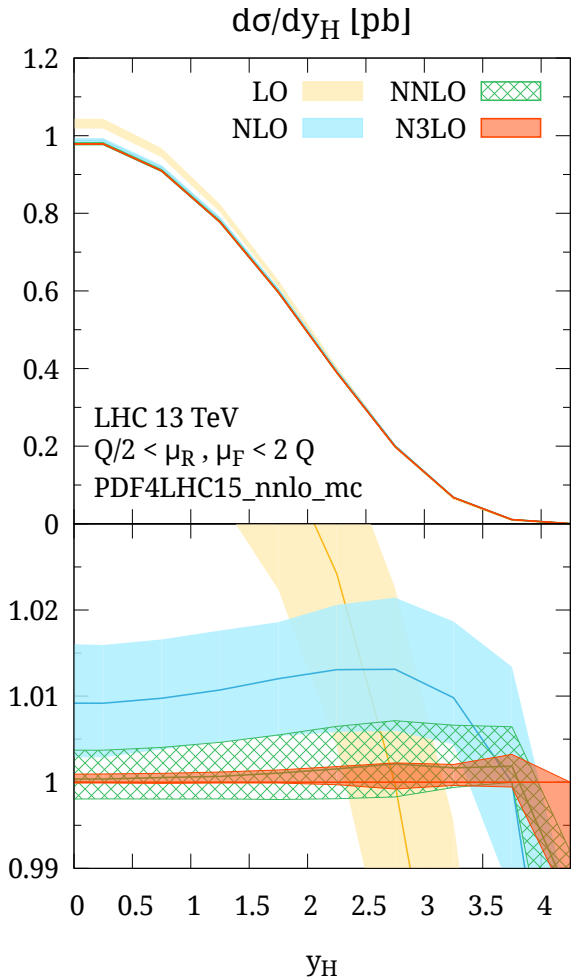
	$\sigma^{(13\,\text{TeV})}$ [pb]	$\sigma^{(14\,\text{TeV})}$ [pb]	$\sigma^{(100\,\text{TeV})}$ [pb]
LO	$4.099\,^{+0.051}_{-0.067}$	$4.647\,^{+0.037}_{-0.058}$	$77.17\,^{+6.45}_{-7.29}$
NLO	$3.970\,^{+0.025}_{-0.023}$	$4.497\,^{+0.032}_{-0.027}$	$73.90\,^{+1.73}_{-1.94}$
NNLO	$3.932\,^{+0.015}_{-0.010}$	$4.452\,^{+0.018}_{-0.012}$	$72.44\,^{+0.53}_{-0.40}$
N^{3}LO	$3.928\,^{+0.005}_{-0.001}$	$4.448\,^{+0.006}_{-0.001}$	$72.34\,^{+0.11}_{-0.02}$

N^{3}LO corrections tiny, at 2‰ level, but reduce theoretical uncertainties by a factor of 5.

Differential distributions: Higgs p_t and rapidity

Using vector-boson momenta, we can reconstruct the Higgs momentum and obtain differential distributions w.r.t. Higgs kinematics.





N^{3}LO corrections are tiny and within NNLO scale variation bands.

But no information on kinematics of tagging jets.

Theoretical PDF uncertainties

One source of unknown N^{3}LO corrections: missing higher orders in PDF determination.

Only NNLO PDF sets are available, which are missing two main contributions:

- Higher order splitting functions in PDF evolution
- Higher order corrections to coefficient functions relating observables to PDFs

Theoretical PDF uncertainties

One source of unknown N^{3}LO corrections: missing higher orders in PDF determination.

Only NNLO PDF sets are available, which are missing two main contributions:

- Higher order splitting functions in PDF evolution $\Rightarrow$ less than $\mathcal{O}(1‰)$
- Higher order corrections to coefficient functions relating observables to PDFs

Theoretical PDF uncertainties

We provide two estimates of impact of missing higher orders in PDFs

A. Estimate from difference between NLO and NNLO PDF

$$\delta_A^{\text{PDF}} = \frac{1}{2}\left|\frac{\sigma^{\text{NNLO}}_{\text{NNLO-PDF}} - \sigma^{\text{NNLO}}_{\text{NLO-PDF}}}{\sigma^{\text{NNLO}}_{\text{NNLO-PDF}}}\right| = 1.1\%$$

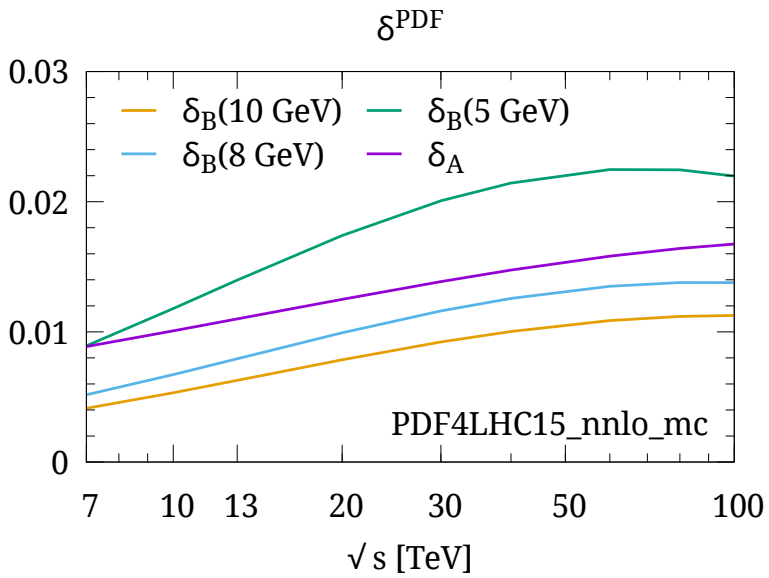
[Anastasiou et al. JHEP 1605 (2016) 058]

B. Estimate using N^{3}LO structure functions

$$\delta_B^{\text{PDF}}(Q_0) = \left|\frac{\sigma^{\text{N}^3\text{LO}} - \sigma^{\text{N}^3\text{LO}}_{\text{rescaled}}(Q_0)}{\sigma^{\text{N}^3\text{LO}}}\right| = 7.9‰$$

where rescaled cross section is obtained with

$$f^{\text{N}^3\text{LO,approx.}}(x,Q) = f^{\text{NNLO}}(x,Q)\frac{F_2^{\text{NNLO}}(x,Q_0)}{F_2^{\text{N}^3\text{LO}}(x,Q_0)}$$



CONCLUSION

Conclusion

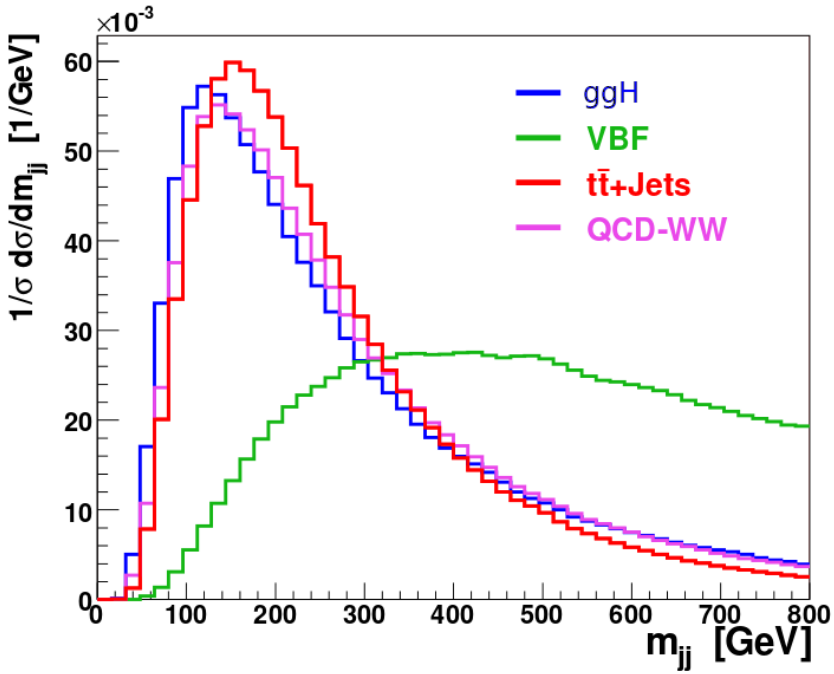
- VBF channel brought to the same formal accuracy as gluon-gluon fusion.
- Inclusive N^{3}LO corrections are tiny, few permille, but reduce theoretical uncertainties substantially.
- How do **VBF cuts** affect the size of the N^{3}LO QCD corrections ?
  $\Longrightarrow$ will require calculation differential in the parton kinematics.
- How "small" are neglected non-factorisable corrections at NNLO ?

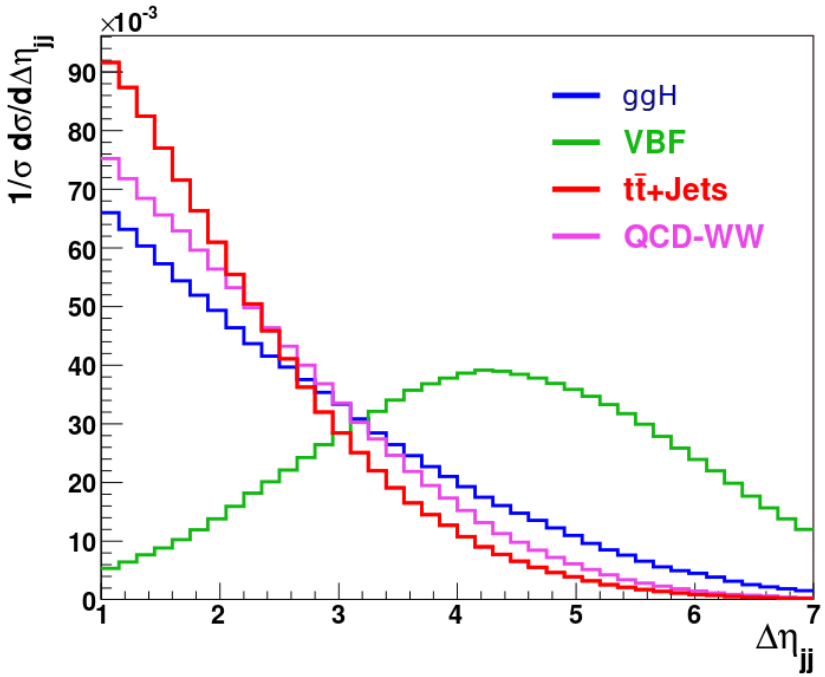
The code will be made public.

BACKUP SLIDES

VBF cuts

To reduce background noise, cuts on rapidity separation and jet p_t are essential.





Cuts discriminate against background, such as gluon-fusion $H + 2j$ production and $t\bar{t}$ production.

VBF cuts

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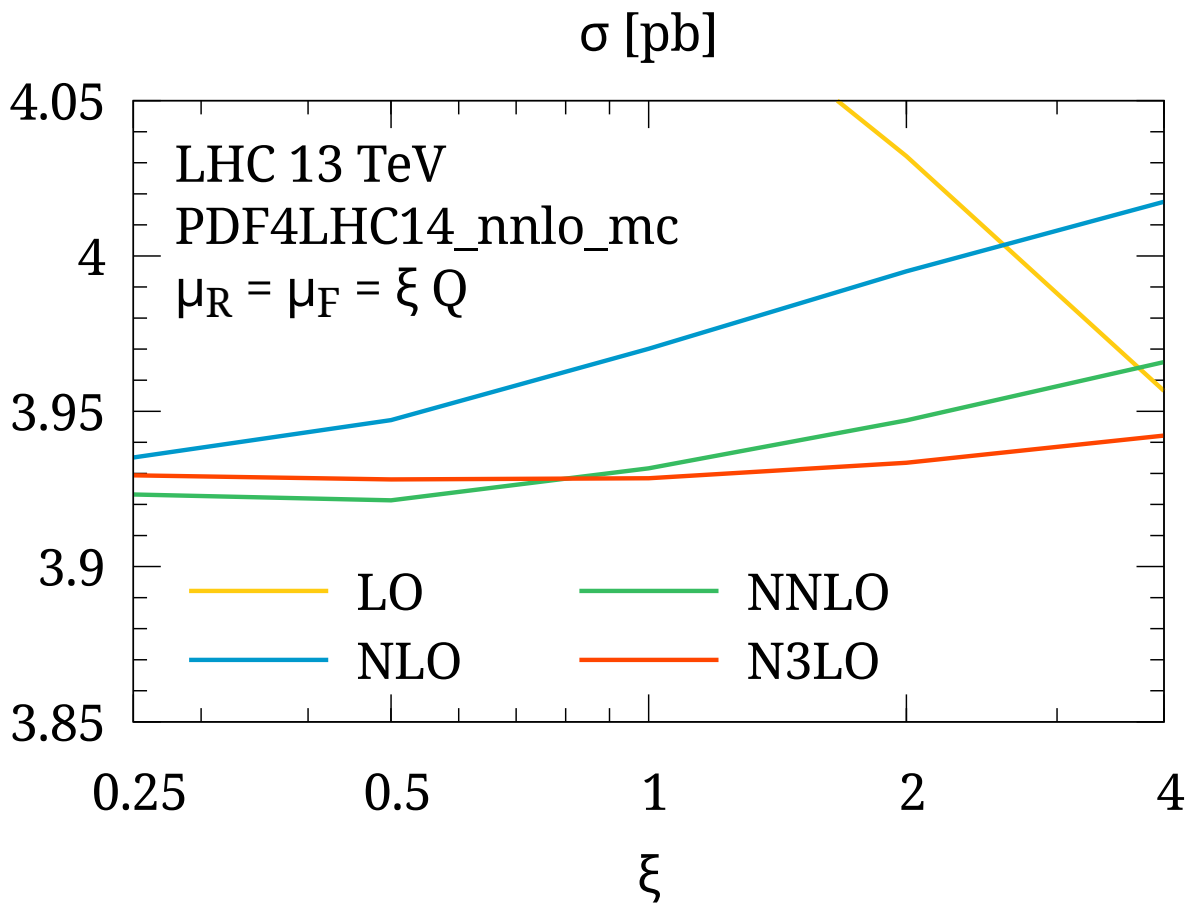
Example event selection

- At least two jets with $p_t > 25\,\mathrm{GeV}$ and $|y| < 4.5$.
- Rapidity separation $|\Delta y_{j_1,j_2}| > 4.5$.
- Dijet invariant mass $m_{j_1,j_2} > 600\,\mathrm{GeV}$.

Cuts discriminate against background, such as gluon-fusion $H + 2j$ production and $t\bar{t}$ production.

Scale variation up to N^{3}LO

Dependence of cross section on renormalisation and factorisation scale



Very stable convergence of perturbative series.