Precision calculations in VBF Higgs production

GDR Terascale, Grenoble, 24 November 2015

Frédéric Dreyer

Laboratoire de Physique Théorique et Hautes Énergies & CERN

based on arXiv:1506.02660 and work in progress

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

Outline

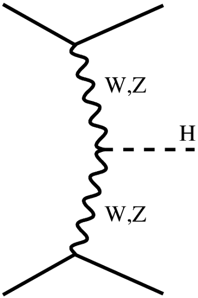
1. Introduction
   - VBF Higgs production
2. QCD corrections in VBFH
   - Structure function approach
   - Going to differential NNLO
3. Results and phenomenology
   - Distributions and cross sections
4. Conclusion

INTRODUCTION

Why study VBF Higgs production?

Higgs production through vector boson fusion is important for several reasons.

- Largest process with tree-level Higgs production.
- Distinctive signature, with two forward jets. This allows to better tag events and identify decays with large background (eg. in $H \to \tau\tau$ and $H \to bb$).
- Higgs transverse momentum non-zero at LO, which facilitates searches of invisible decay modes.
- Sensitivity to CP properties of Higgs from angular correlation of tagging jets.



VBF cuts

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

Example event selection

- At least two jets with $p_t > 25\,\mathrm{GeV}$.
- The hardest jets should have $|y| < 4.5$.
- Rapidity separation $|\Delta y_{j_1,j_2}| > 4.5$ and dijet invariant mass $m_{j_1,j_2} > 600\,\mathrm{GeV}$.
- Require $y_{j_1} y_{j_2} < 0$ (i.e. opposite hemispheres).

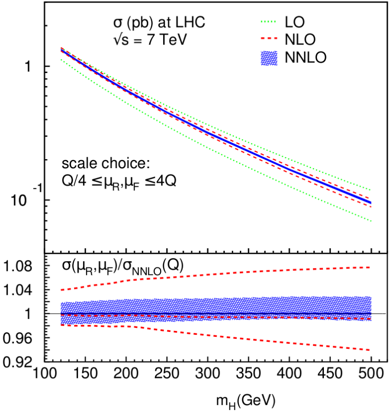
Cuts discriminate against QCD background, such as QCD production of $Z + 2j$ and gluon-fusion $H + 2j$ production.

QCD CORRECTIONS IN VBFH

Inclusive NNLO VBF Higgs production

Fully inclusive VBF Higgs production is known at NNLO.

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



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

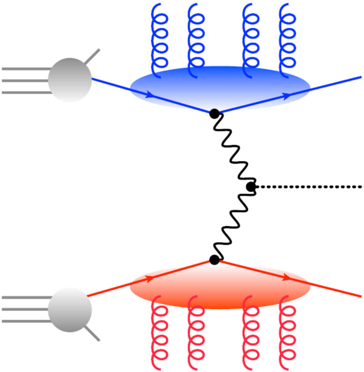
However, VBF cuts cannot be applied to this calculation, since it is inclusive over hadronic final states.

Result is obtained using the structure function approach.

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.

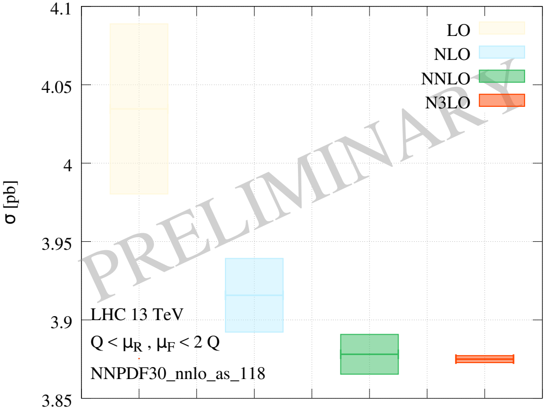
This picture is accurate to better than 1%.

[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.

Inclusive cross section at N^3LO

This method can be extended to VBF Higgs production at N^3LO



Perturbative series converges extremely well.

Very small change in central value . . .

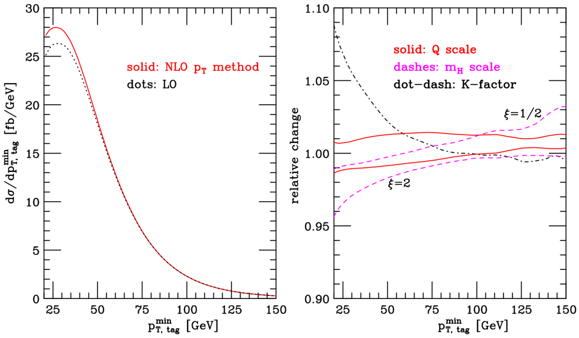
. . . but large reduction in theoretical uncertainty.

Caveat: - How sizeable are the neglected interferences?
- Cross-check of structure functions in progress

Differential VBF Higgs production

To apply VBF cuts, one needs a differential calculation.

Differential VBFH is known only to NLO, and scale dependence suggests small uncertainties from missing higher order corrections.



[Figy, Oleari, Zeppenfeld Phys.Rev. D68 (2003) 073005]

Going to differential NNLO

A differential NNLO calculation can be obtained from two ingredients.

- An inclusive contribution, containing two-loop, one-loop single-real and double-real contributions (but with knowledge only of vector boson momenta).
- An exclusive contribution, containing one-loop single-real and double-real contributions (fully differential)

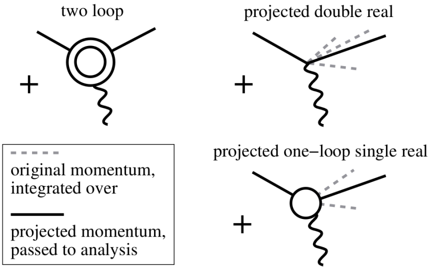
NNLO “inclusive” contribution

Use the structure function approach and vector-boson momenta q_1, q_2 to assign Born-like kinematics (i.e. $2 \to H + 2$) to an event.

$$p_{\text{in},i} = x_i P_i, \qquad p_{\text{out},i} = x_i P_i - q_i, \qquad x_i = \frac{q_i^2}{2 q_i P_i}.$$

The projected momenta are used to compute differential distributions.

Kinematics are correct for the two loop NNLO contribution, but not (yet) for the one-loop single-real and double-real contributions.



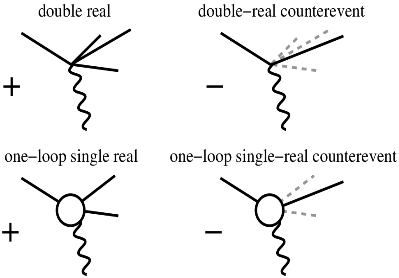
NNLO “exclusive” contribution

Use the EW $H+3$ jets NLO calculation in the factorized approximation

[POWHEG VBF_HJJJ: Jäger, Schissler, Zeppenfeld JHEP 1407 (2014) 125]

[Figy, Hankele, Zeppenfeld JHEP 0802 (2008) 076]

- For each parton, keep track of whether it belongs to the upper or lower sector, and compute vector-boson momenta q_1, q_2.
- For each event, add counter-event with projected Born kinematics and opposite weight.



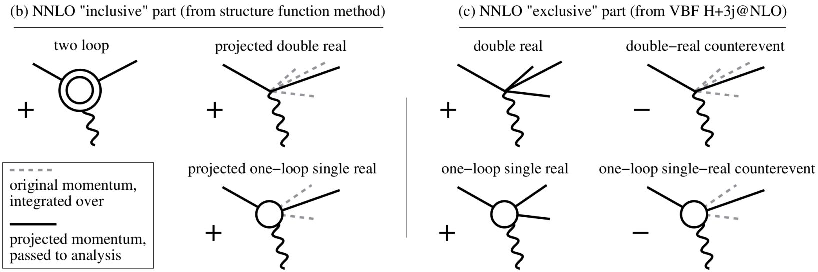
The counter-events cancel with the projected one-loop single-real and double-real terms from the inclusive contribution.

We can express the "projection-to-Born" method as

$$d\sigma = \int d\Phi_B (B+V) + \int d\Phi_R R$$

$$= \underbrace{\int d\Phi_B (B+V) + \int d\Phi_R R_{P2B}}_{\text{inclusive contribution}} + \underbrace{\int d\Phi_R R - \int d\Phi_R R_{P2B}}_{\text{exclusive contribution}} ,$$

$P2B$ = projection-to-Born



Combining the NNLO ingredients

We can express the "projection-to-Born" method as

$$d\sigma = \int d\Phi_B (B+V) + \int d\Phi_R R$$

$$= \underbrace{\int d\Phi_B (B+V) + \int d\Phi_R R_{P2B}}_{\text{inclusive contribution}} + \underbrace{\int d\Phi_R R - \int d\Phi_R R_{P2B}}_{\text{exclusive contribution}},$$

$P2B$ = projection-to-Born

The inclusive and exclusive contributions are separately finite.

After integration over phase-space, counter-events cancel projected real contributions from inclusive ingredient.

Sum gives complete, fully differential, NNLO result.

Details and cross-checks

For the inclusive part

- Use phase space from `POWHEG`'s `VBF_H`
- evaluate structure functions with `HOPPET`, using parametrized DIS coefficient functions.

For the exclusive part

- Use `POWHEG`'s `VBF_HJJJ`, extended to uniquely associate radiation with each sector.
- Determine vector-boson momenta q_1, q_2 for each event, and compute corresponding counter-event.

Check of tagging: as rapidity between the two jets increases, the rate of partons assigned to the wrong sector decreases.

RESULTS AND PHENOMENOLOGY

Total cross-sections

We consider 13 TeV LHC, anti-k_t with R=0.4, and NNPDF30_nnlo_as_0118.

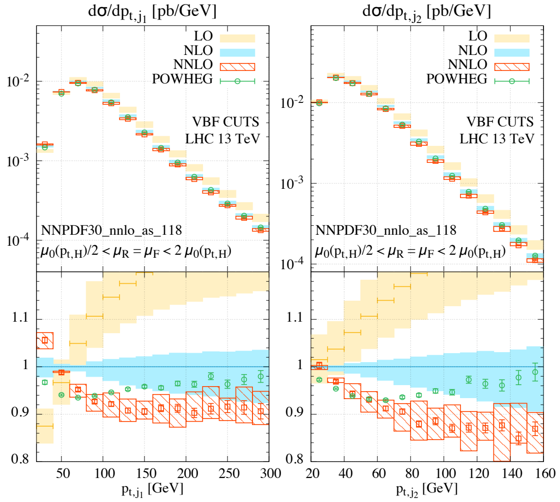
Central scale is choosen to approximate $\sqrt{Q_1 Q_2}$,

$$\mu_0^2(p_{t,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{t,H}^2}\,.$$

Inclusive cross section and cross-section after VBF cuts (from p.2)

	$\sigma^{\text{(no cuts)}}$ [pb]	$\sigma^{\text{(VBF cuts)}}$ [pb]
LO	$4.032\,^{+0.057}_{-0.069}$	$0.957\,^{+0.066}_{-0.059}$
NLO	$3.929\,^{+0.024}_{-0.023}$	$0.876\,^{+0.008}_{-0.018}$
NNLO	$3.888\,^{+0.016}_{-0.012}$	$0.826\,^{+0.013}_{-0.014}$

After VBF cuts, NNLO brings $\sim 5\%$ correction, outside NLO bands.

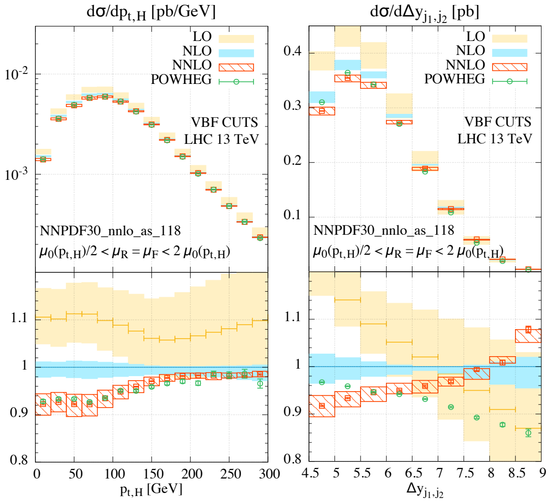


NNLO corrections appear to make the jets softer.

NNLO corrections are generally outside of NLO bands.

NNLO corrections are up to $\sim 10 - 12\%$.

Differential distributions: Higgs p_t and rapidity separation



NLO + Parton shower agrees well with NNLO in some cases (e.g. $p_{t,H}$).

But in others it does not (e.g. $\Delta y_{j_1,j_2}$)

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

CONCLUSION

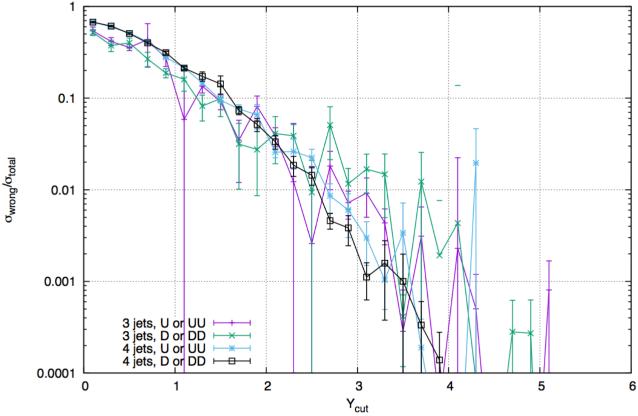
Conclusion

- We showed the first fully differential NNLO calculation for VBF Higgs production.
- This result is achieved with a new "projection-to-Born" method. We combine an exclusive VBF $H+3$ NLO calculation with an inclusive VBF $H+2$ NNLO result in the structure function approach.
- Differential NNLO is necessary for precision phenomenology, with corrections up to $10-12\%$.
- For comparison: hadronisation effects are small ($\sim 1\%$), while UE is comparable ($\sim 5\%$).
- Method could in principle be extended to compute differential N^3LO.

BACKUP SLIDES

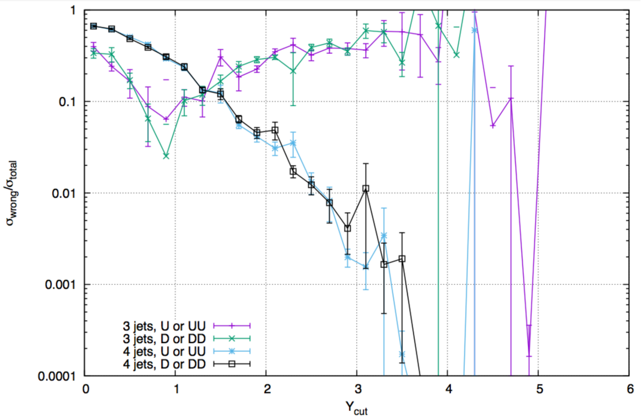
Check of tagging

If tagging is correct: rate of up (down) tagged partons with negative (positive) rapidity should decrease as rapidity separation between the jets increases.



Check of tagging

If tagging is correct: rate of up (down) tagged partons with negative (positive) rapidity should decrease as rapidity separation between the jets increases.

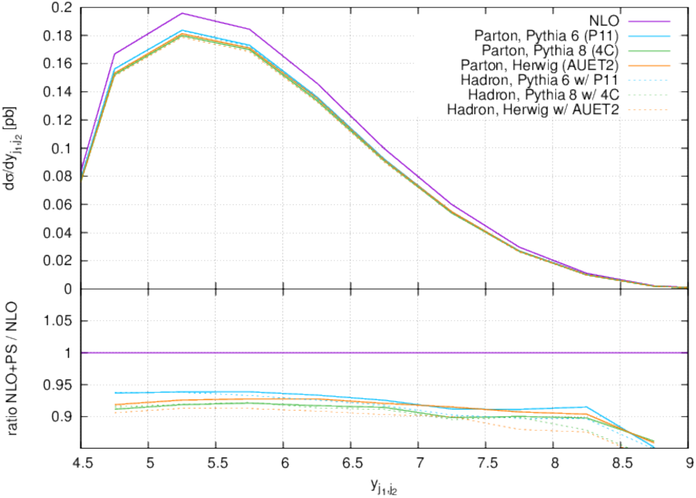


Introducing a bug in virtual contribution.

NLO + Parton shower

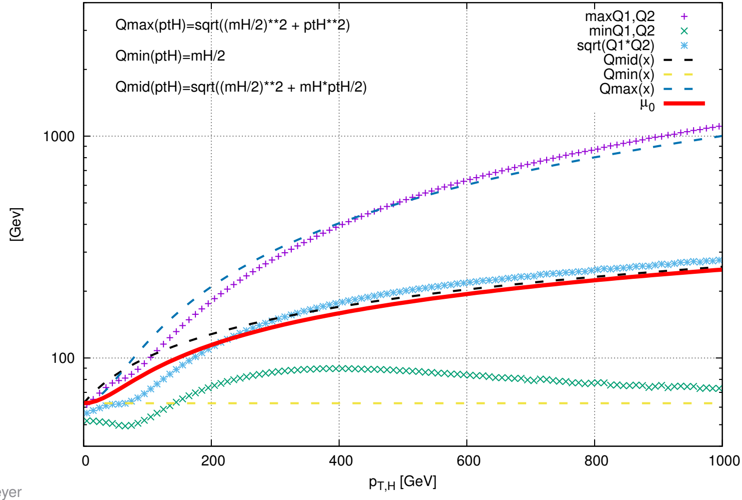
Different parton showers yield similar results.

Hadronisation in dotted lines, is a consistently small effect.

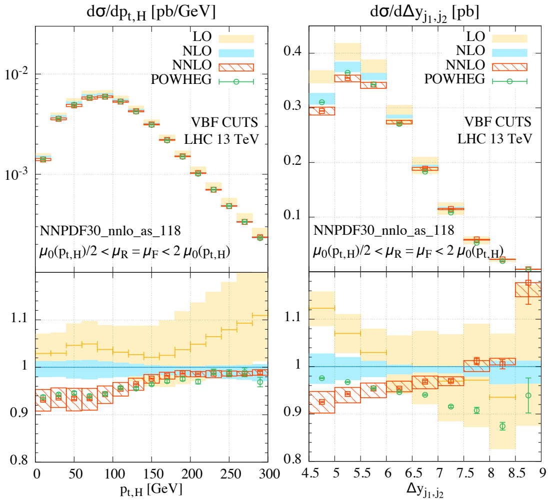


Comparison to $\max / \min(Q_1, Q_2)$, $\sqrt{Q_1, Q_2}$

$$\mu_0^2(p_{t,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{t,H}^2}\,.$$



Impact of PDF order



There is some freedom in choice of PDF order.

Previously in this talk: only NNLO PDFs

Here we consider

- LO with LO PDFs.
- NLO with NLO PDFs.
- NNLO with NNLO PDFs.

NNLO/NLO ratio is similar to that obtained with NNLO PDFs.