Fully differential VBFH at NNLO

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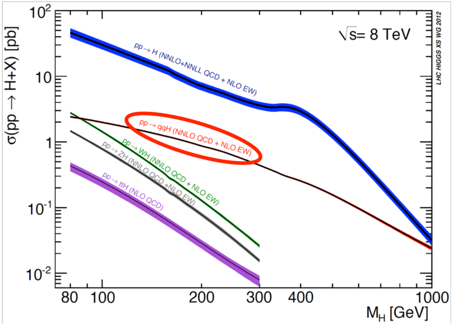
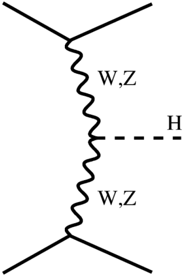
VBF/VH HXSWG 24 June 2015

Based on arXiv:1506.02660 in collaboration with

Matteo Cacciari, Frédéric Dreyer, Gavin Salam & Giulia Zanderighi

Reasons to study VBF





- largest cross section at tree-level and second-largest of all channels
- distinct signature of two forward jets
- tagging reduces backgrounds (eg $H \to b\bar{b}$)
- non-zero Higgs transverse momentum at lowest order
- sensitive to CP properties of the Higgs through correlation of forward jets

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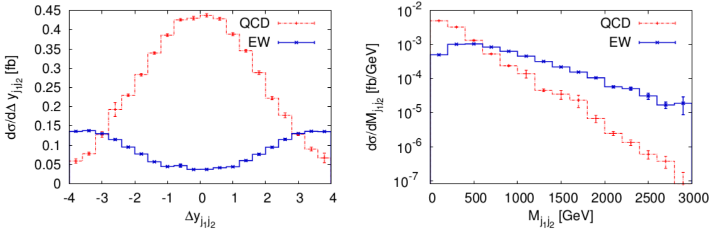
VBF Cuts

Due to huge QCD backgrounds a set of very selective cuts have to be applied. For this study we picked:

- jets defined with anti-k_t, $R = 0.4$ and $p_t > 25$ GeV
- two hardest jets within $|y| < 4.5$
- high dijet invariant mass, $M_{j_1 j_2} > 600$ GeV, and separation, $\Delta y_{j_1 j_2} > 4.5$
- hardest jets in opposite hemispheres, $y_{j_1} y_{j_2} < 0$

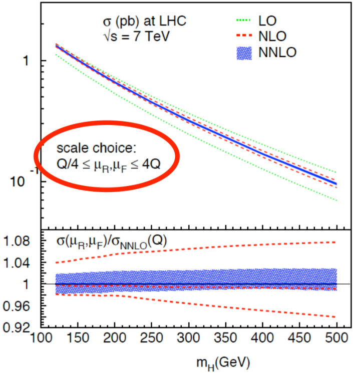


[Jäger, Zanderighi (2011)]

Inclusive NNLO VBF Higgs Production

Currently VBF Higgs production is only known inclusively at NNLO.

[Bolzoni et al. (2010)]



- the calculation suggests tiny renormlisation and factorisation scale variations ($\sim 1 - 2\%$)
- NNLO results well within NLO band
- result obtained in the structure function approach

No cuts can be applied to the calculation, as it is totally inclusive over hadronic final states with the same vector boson momenta.

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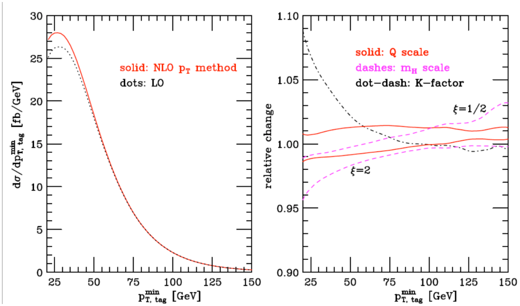
Exclusive NLO VBF Higgs Production

To enable the application of realistic VBF cuts one has to be fully differential. Until recently differential VBF Higgs production was known to NLO(+PS). [Figy, Oleari, Zeppenfeld (2003)]



Calculation suggests small uncertainties from missing higher order corrections ($\sim 2\%$).

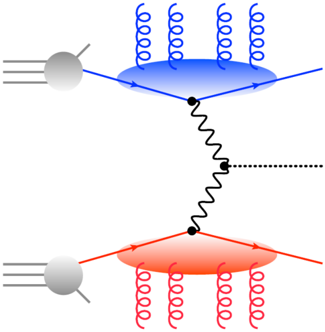
Structure Function Approach

One can think of VBF Higgs production as a double Deep Inelastic Scattering (DIS×DIS) with no cross-talk between the upper and lower sectors.

[Han, Valencia, Willenbrock (1992)]

- this picture is accurate to more than 1%

[Bolzoni et al. (2012)], [Ciccolini, Denner, Dittmaier (2008)], [Andersen et al. (2008)]

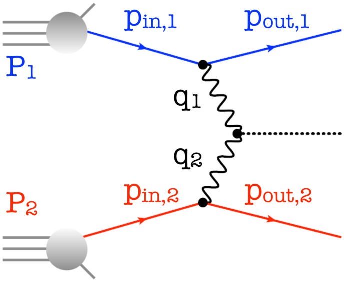


- the factorisation of the two sectors is exact if one imagines two copies of QCD, QCD_1 and QCD_2 , respectively for the upper and lower sectors.
- all DIS coefficients are known to NNLO and some to N^3LO.
- as the DIS coefficients are inclusive over the hadronic final state, the calculation cannot provide differential results.

Beyond the Structure Function Approach

This work: We eliminate the limitations of the Structure Function Approach.

If the scattering is Born like, then the vector boson momenta q_i, and on-shell conditions, fix the incoming and outgoing parton momenta:



$$p_{in,i} = x_i P_i$$

$$p_{out,i} = x_i P_i - q_i$$

$$x_i = \frac{q_i^2}{2 q_i P_i}$$

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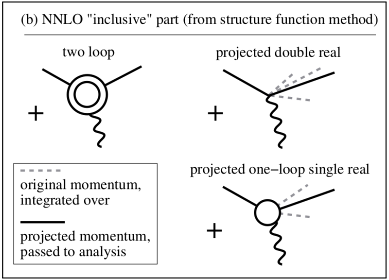
Beyond the Structure Function Approach

The calculation is based on two ingredients:

1. *An "inclusive" contribution*
    - use the Structure Function Approach and use four-vectors q_1, q_2 to assign Born-like kinematics using the equations below
    - use the projected Born-like momenta to compute differential distributions



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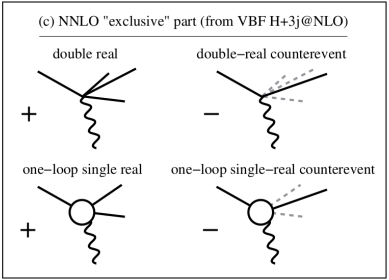
Beyond the Structure Function Approach

The calculation is based on two ingredients:

2. *An "exclusive" contribution*
   - use the electroweak $H + jjj$ NLO calculation in the factorized approximation [Figy et al. (2007)], [Jäger et al. (2014)]



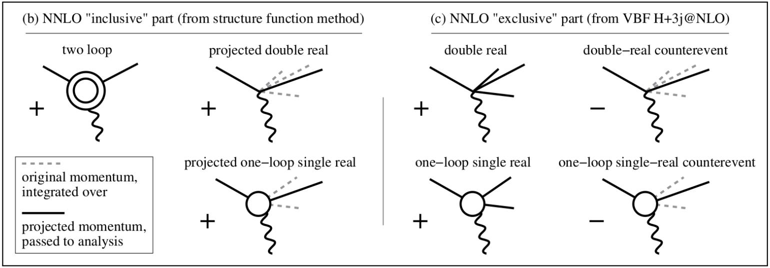
- for each parton, keep track of whether it belongs to the upper or lower sector, and compute vector-boson momenta q_1, q_2
- for each event add counter-event with projected Born kinematics and opposite weight

The counter-events cancel identically with the projected terms from the "inclusive" contribution.

Beyond the Structure Function Approach

Schematically we express the "projection-to-Born" (P2B) method as

$$
\begin{aligned}
d\sigma &= \int d\Phi_B (B+V) + \int d\Phi_R R \\
&= \underbrace{\int d\Phi_B (B+V) + \int d\Phi_R R_{P2B}}_{\text{"inclusive" contribution}} + \underbrace{\int d\Phi_R R - \int d\Phi_R R_{P2B}}_{\text{"exclusive" contribution}}
\end{aligned}
$$



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Beyond the Structure Function Approach

Schematically we express the "projection-to-Born" (P2B) method as

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

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

- from the "exclusive" ingredient we get the full double-real and one-loop single-real contributions.
- when integrated over phase-space, the counter-events cancel the projected double-real and one-loop single-real contributions from the "inclusive" ingredient

Hence the sum of the two contributions gives the complete, fully differential NNLO result.

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Implementation

1. "inclusive" code
   - matrix elements coded with structure functions using parametrised versions of the DIS coefficient functions evaluated by `HOPPET`
   - phase-space taken from `POWHEG`'s `VBF_H` generator
2. "exclusive" code
   - start with the `VBF_HJJJ` calculation in `POWHEG` (based on vbfnlo)
   - extend `POWHEG`'s tags to uniquely associate radiation with each sector (upper or lower line)
   - for each event map the kinematics onto Born-like kinematics and determine the vector-boson momenta q_1, q_2 using the equations on p.7.

- we have tested the "inclusive" code against a private version of the structure function calculation (thanks to Marco Zaro) and the structure functions themselves against `APFEL` 2.4.1.
- we have tested that the "exclusive" code reproduces the original `VBF_HJJJ` result. The sum of "inclusive" and "exclusive" at NLO agrees with `VBF_H`
- tagging tested by checking that the probablity of assigning a parton to the wrong sector decreases as the rapidity between the two hardest jets increases

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Phenomenology

We study 13 TeV LHC collisions with $M_H = 125$ GeV and NNPDF3.0_nnlo_as118. We use VBF cuts as decribed above:

- Jets defined with anti-k_t, $R = 0.4$ and $p_t > 25$ GeV
- Two hardest jets within $|y| < 4.5$
- High dijet invariant mass, $M_{j_1 j_2} > 600$ GeV, and separation, $\Delta y_{j_1 j_2} > 4.5$
- Hardest jets in opposite hemispheres, $y_{j_1} y_{j_2} < 0$

We choose a central scale which approximates well $\sqrt{Q_1 Q_2}$ and symmetrically vary by a factor 2 up and down

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

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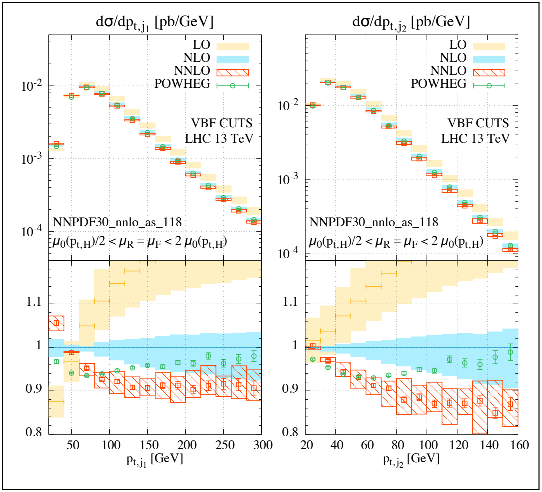
Phenomenology

	$\sigma^{(\text{no cuts})}$ [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	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

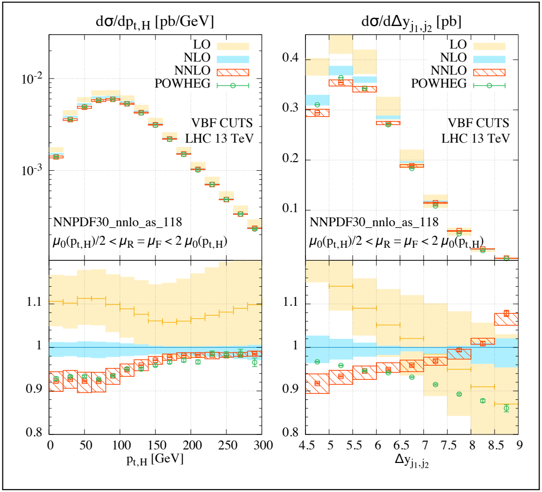
- NNLO corrections tiny ($\sim 1\%$) without cuts and sizeable with VBF cuts ($\sim 5\%$)
- NNLO results outside NLO band (also true when using NLO PDFs)
- corrections tend to be dominated by the extra real radiation. The effect is softer jets and hence fewer events pass the cuts

Phenomenology



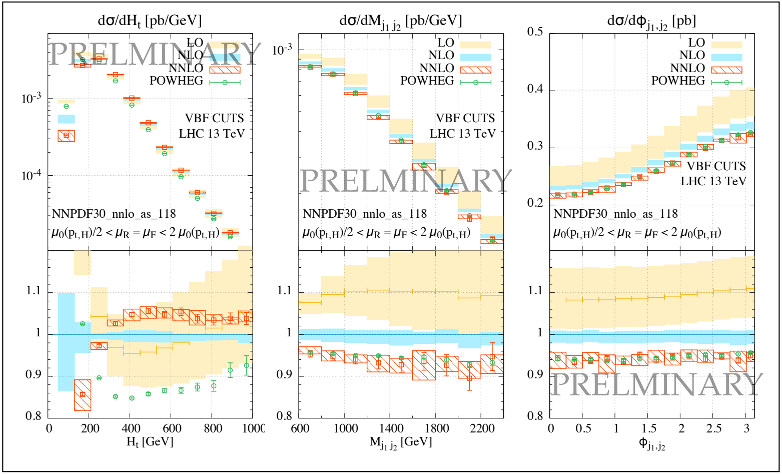
- NNLO corrections can be large $\mathcal{O}(10\%)$ and are often outside the NLO band
- the NNLO corrections tend to be dominated by extra real radiation. These appear to make the jets softer
- NOTE: NNLO PDF used everywhere. Similar results hold when using LO/NLO PDFs
- expanding the scale variation from 3-point to 7-point doesn't change the size of the NLO bands noticeably

More Phenomenology



- in some cases NLO+PS agrees very well with the NNLO result (in particular $p_{t,H}$, M_{jj} and ϕ_{jj})
- in some cases not ($\Delta y_{j_1,j_2}$ and H_t)
- in general only modest shrinkage of bands from NLO to NNLO
- non-trivial kinematic dependence on k-factors (both LO/NLO and NNLO/NLO)

Even More Phenomenology



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Conclusions

- we have shown the first fully differential NNLO calculation of VBF Higgs production using a novel "projection-to-Born" method
- NNLO corrections are sizeable, $\mathcal{O}(10\%)$, and necessary for precision phenomenology
- only moderate shrinkage of NNLO bands compared to NLO bands
- (not discussed here) EW corrections are comparable to NNLO corrections and should be included. Hadronisation effects are small $\mathcal{O}(1\%)$ and UE larger $\mathcal{O}(5\%)$
- method can be extended to compute fully differential VBF Higgs at N^{3}LO

Code will be made public in the future. Until then total cross sections with specific cuts can be provided.

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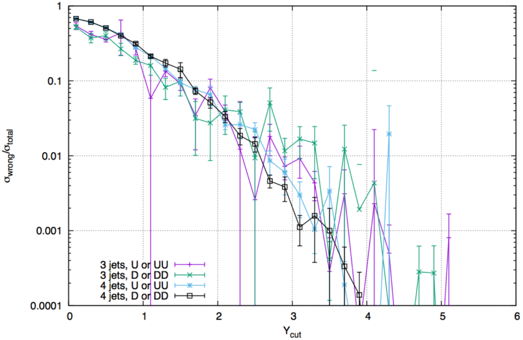
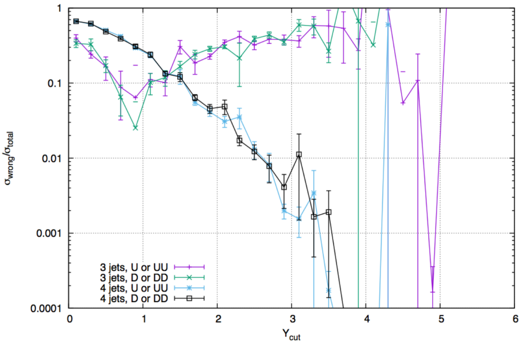
Tagging



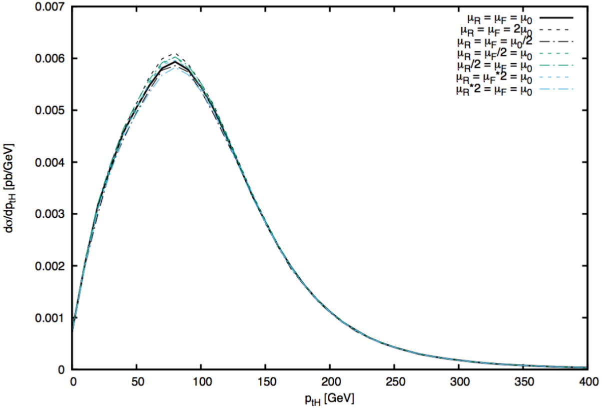
With no bug in the code, the probability of a tagged parton having wrong rapidity decreases with increasing rapidity separation between the two hardest jets.

Tagging



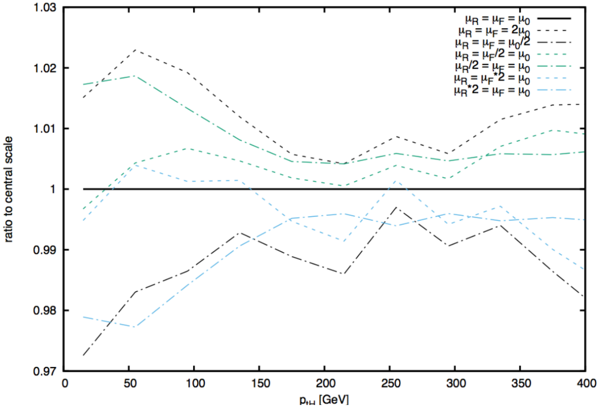
With an $\mathcal{O}(1)$ bug in the code, this is clearly not the case any more.

3-point vs 7-point scale variations



3- and 7-point scale variations are very close to eachother.

3-point vs 7-point scale variations



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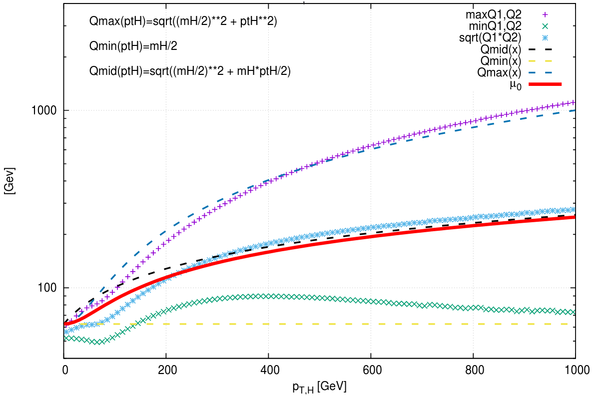
Choice of scale



Our choice of $\mu_0^2(p_{t,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{t,H}^2}$ is very close to a choice of $\mu = \sqrt{Q_1 Q_2}$.

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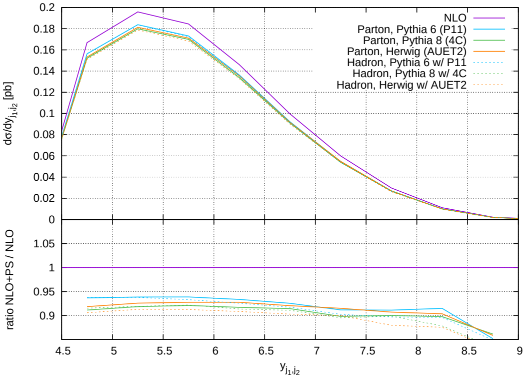
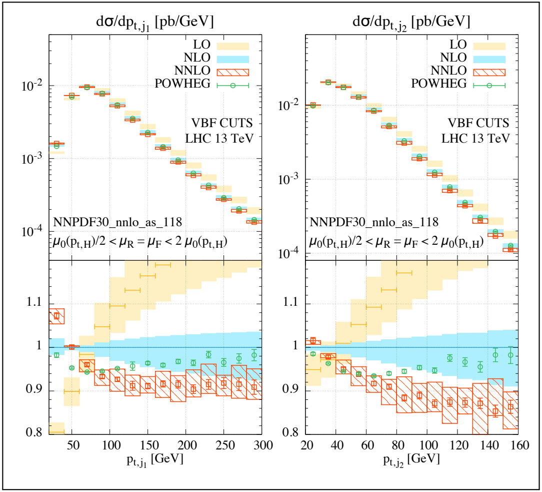
VBF and Parton Shower



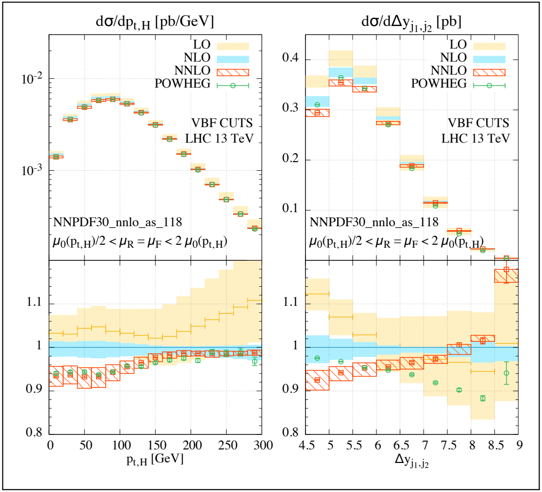
- different parton showers give relatively similar results
- hadronisation effects are consistently small

NNLO/NLO/LO PDFs



- LO results with LO PDFs
- NLO results with NLO PDFs
- NNLO results with NNLO PDFs

NNLO/NLO/LO PDFs



- LO results with LO PDFs
- NLO results with NLO PDFs
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