Karlsruhe Institute of Technology

Jet Clustering Dependence in VBF

Michael Rauch | Workshop “Higgs plus dijets at the LHC”, Jan 2018

INSTITUTE FOR THEORETICAL PHYSICS

Event Topology

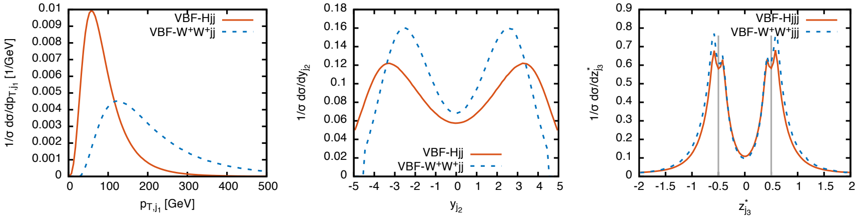
topology of VBF shows distinct signature

- two so-called tagging jets in forward direction
- reduced jet activity in central direction
- leptonic decay products typically between the tagging jets

$\rightarrow$ two-sided deep-inelastic scattering

(LO, $\sqrt{S} = 13$ TeV)

VBF-Hjj: no cuts; (VBF-W^+W^+jj: $p_{T,j} > 30$ GeV, $|y_j| < 4.5$ and $R_{jj} > 0.4$)



$$z^*_{j3} = \left(y_{j3} - \frac{y_{j1} + y_{j2}}{2} \right) / \left| y_{j1} - y_{j2} \right|$$

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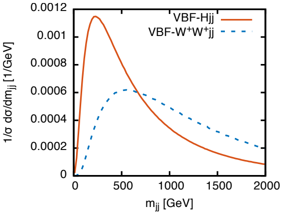
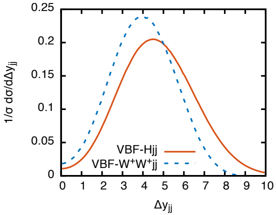
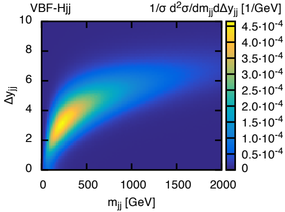
→ two-sided deep-inelastic scattering







- process finite without any cuts[1]
- despite having jets already at leading order
- also true for s-channel Higgsstrahlung contribution[1]

[1] (when neglecting contributions from loop-induced $H\gamma\gamma\,/\,HZ\gamma$ couplings)

Jet Definition

- hard parton (single quark or gluon)
  $\xrightarrow{\text{parton shower, hadronization}}$ (mostly) narrow cone of hadrons
  $\rightarrow$ jets
  $\leftrightarrow$ large-angle emissions, underlying event
- N^xLO calculation
  $\rightarrow$ real emissions describe first step in evolution
- need algorithm to cluster hadrons into jets
  - infrared-safe
  - sequential
- mostly relevant nowadays: k_T family

  two parameters:
  - jet radius R
  - exponent $n = \begin{cases} 1 & k_T, \\ 0 & \text{Cambridge/Aachen (C/A)}, \\ -1 & \text{anti-}k_T. \end{cases}$

k_T-Family Jet Algorithms

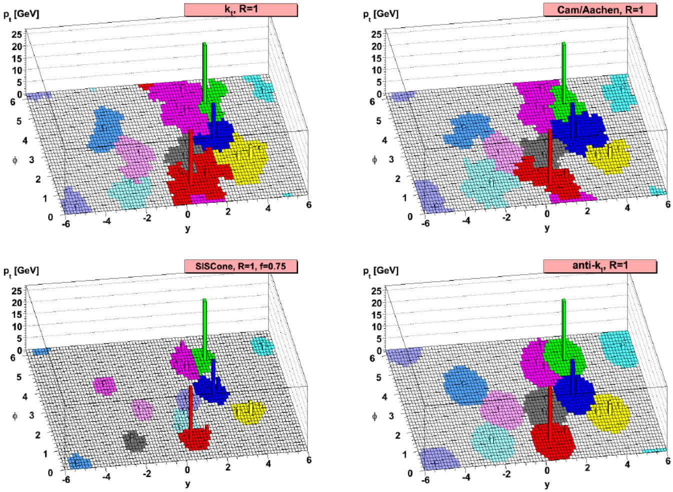
Definition:

- define measure for collinearity

$$y_{ij} = \frac{R_{ij}}{R} \min\left(p_{T,i}^n, p_{T,j}^n\right) \,, \qquad\qquad y_{iB} = p_{T,i}^n$$

- put all final-state partons as jet candidates
- for all combinations $(i, j \neq i)$ of jet candidates:
  - find minimum $y^{\min} = \min_{i,j}\left(y_{ij}, y_{iB}\right)$
  - if $y^{\min} = y_{ij}$, combine i and j to new jet candidate with $k_{ij} = k_i + k_j$
  - if $y^{\min} = y_{iB}$, move candidate i to list of jets
- repeat last item until candidate list empty

Typical shapes for IR and collinear safe algorithms



Effects of Jet Algorithm

processes with single final-state parton:

- LO: no effect (parton$\rightarrow$jet)
- NLO: R determines whether both (real-emission) partons clustered, n irrelevant
- NNLO++: clustering determined by R and n

processes with multiple final-state partons:

- LO: R acts as cut: $R_{jj} > R$, n irrelevant
- NLO++: clustering determined by R and n

VBF processes:

- two final-state partons at LO
  $\rightarrow$ expect multi-parton case
- $\leftrightarrow$ typical VBF cuts require large rapidity separation between tagging jets
- $\rightarrow$ LO partons can never be clustered
- $\rightarrow$ single-parton case for both sides

Higher-order Corrections to Inclusive Process

- NNLO QCD correction to VBF-H production
  first calculated in structure-function approach [Bolzoni, Maltoni, Moch, Zaro]
- $\Rightarrow$ inclusive cross section (no cuts on jets)
- $\leftrightarrow$ no interference effects between upper and lower line
- $\leftrightarrow$ phase-space- and colour-suppressed $\rightarrow$ small

- recently also N^{3}LO QCD calculation available

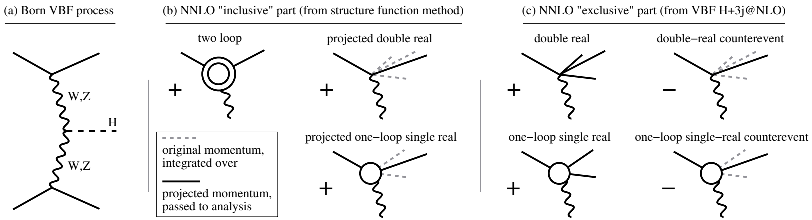
  Results: [Dreyer, Karlberg]

	$\sigma^{\text{(no cuts)}}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$4.099\,^{+0.051}_{-0.067}$	1.032
NLO	$3.970\,^{+0.025}_{-0.023}$	1
NNLO	$3.932\,^{+0.015}_{-0.010}$	0.990
N3LO	$3.928\,^{+0.005}_{-0.001}$	0.989

- small corrections beyond NLO
- mostly reduction of scale uncertainties

From Inclusive to Differential NNLO Corrections

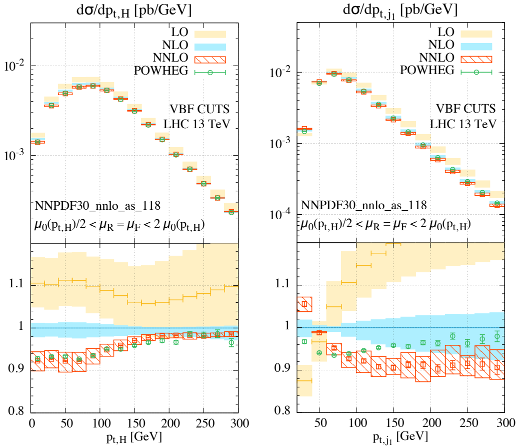
Projection-to-Born method [Cacciari, Dreyer, Karlberg, Salam, Zanderighi]



- structure-function approach contains real emission in integrated-out form
- use VBF-$H + 3$ jets calculation to generate real-emission structure
- events + corresponding counter-events, which subtract from inclusive result
- $\rightarrow$ differential calculation

NNLO QCD corrections to VBF-Higgs

VBF-Higgs production in NNLO QCD [Cacciari, Dreyer, Karlberg, Salam, Zanderighi]



	$\sigma^{\text{(no cuts)}}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$4.032\,^{+0.057}_{-0.069}$	1.026
NLO	$3.929\,^{+0.024}_{-0.023}$	1
NNLO	$3.888\,^{+0.016}_{-0.012}$	0.990

	$\sigma^{\text{(VBF cuts)}}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$0.957\,^{+0.066}_{-0.059}$	1.092
NLO	$0.876\,^{+0.008}_{-0.018}$	1
NNLO	$0.826\,^{+0.013}_{-0.014}$	0.943

central scale:

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

jets: anti-k_T, $R = 0.4$,
$p_{T,j} > 25$ GeV, $|y_j| < 4.5$

VBF cuts: $m_{jj} > 600$ GeV,
$\Delta y_{jj} > 4.5$, $y_{j1} \cdot y_{j2} < 0$

- tiny corrections to inclusive cross section
- significant ($\mathcal{O}(-10\%)$) corrections in VBF region

Conversion between Different Jet Clusterings

- in NNLO calculation fixed choice of jet-clustering parameters (R, n)
- $\leftrightarrow$ no dependence at LO
  $\rightarrow$ two-loop contributions unaffected
- $\Rightarrow$ $H + 3$ partons process sufficient to convert between different values

[MR, Zeppenfeld]

$$\mathrm{d}\sigma_{Hjj}^{\mathrm{NNLO}}(R,n) = \mathrm{d}\sigma_{Hjj}^{\mathrm{NNLO}}(R{=}0.4, n{=}-1) \underbrace{-\mathrm{d}\sigma_{H3+}^{\mathrm{NLO}}(R{=}0.4, n{=}-1) + \mathrm{d}\sigma_{H3+}^{\mathrm{NLO}}(R,n)}_{=\Delta(R,n)}$$

- $\rightarrow$ subtract one-loop single-real and double real contributions at given clustering parameters
- $\rightarrow$ add same contributions at new clustering parameters
- requires using same values of cuts, scales, PDFs, etc.

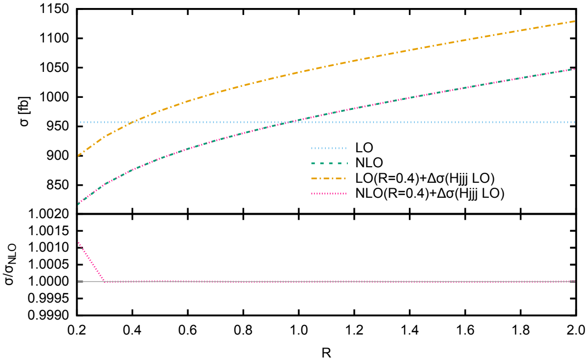
Verification at NLO QCD

Verification:

apply to NLO QCD calculation

$$\rightarrow \quad \sigma^{NLO}_{Hjj}(R) = \sigma^{NLO}_{Hjj}(R{=}0.4) - \sigma^{LO}_{H3+}(R{=}0.4) + \sigma^{LO}_{H3+}(R)$$

$\leftrightarrow$ compare with NLO calculation directly evaluated at different R



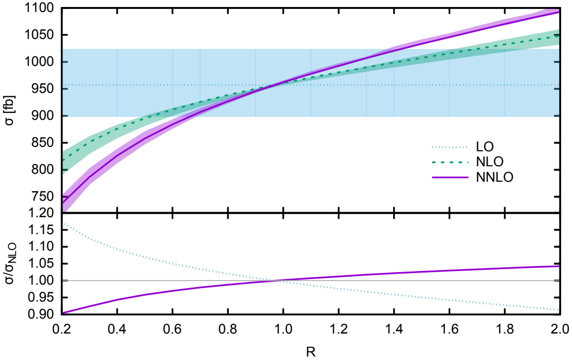
$\rightarrow$ excellent agreement

Integrated NNLO Cross Section

Repeat same procedure based on NNLO result

$$\sigma_{\text{NNLO}}(R,n) = \sigma_{\text{NNLO}}(R_{\text{ref}}, n_{\text{ref}}) + \sigma_{Hjjj\ \text{NLO}}(R,n) - \sigma_{Hjjj\ \text{NLO}}(R_{\text{ref}}, n_{\text{ref}})$$

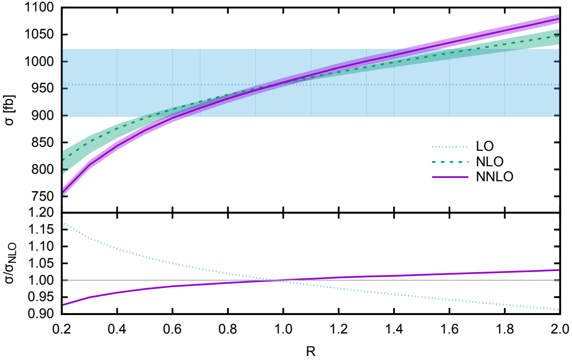
[MR, Zeppenfeld; using NNLO QCD result from Cacciari *et al.*]



- band: uncertainty from scale variation
- small cone misses part of the jet energy
  $\Rightarrow$ smaller m_{jj}
  $\Rightarrow$ less events with $m_{jj} > 600$ GeV

Fixed Integrated NNLO Cross Section

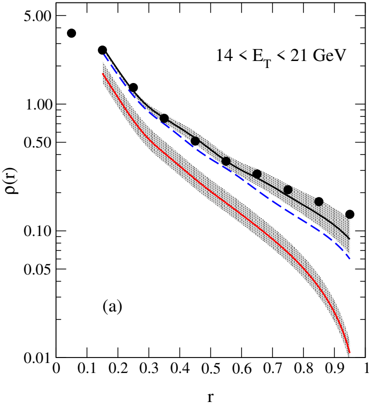
Results with the H+3 jets bug fix – Preliminary [thanks to Alexander for updated NNLO result]



- matching point stays at $R = 1.0$
- slope of NNLO R-dependence reduced
- scale-variation overlap over larger R range

Jets at HERA

energy flow in DIS jets at HERA



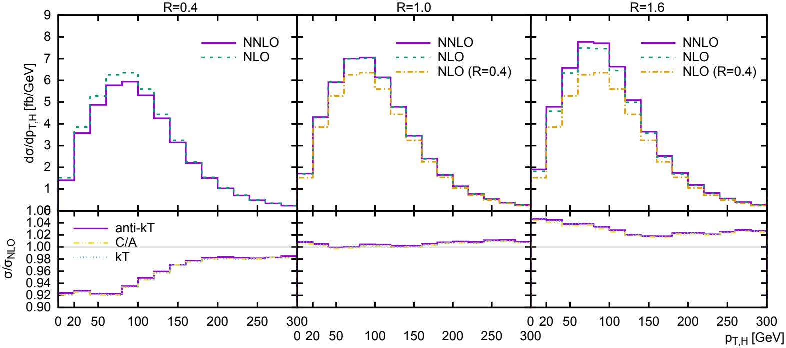
[Kauer, Reina, Repond, Zeppenfeld]

- differential E_T-distribution inside jet cone (ZEUS: black dots)
- Energy flow significantly smaller for NLO (max. 2 partons, red) than for NNLO (up to 3 partons, blue)

Differential Distributions

→ look at differential distributions

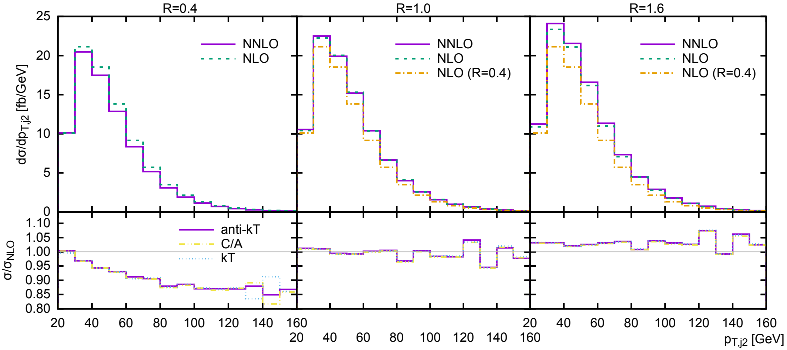
Transverse momentum of the Higgs boson



- good agreement between NLO and NNLO calculation when using $R = 1.0$ (matching point between NLO and NNLO calculation)
- influence of exponent n (k_T, C/A, anti-k_T) small

Differential Distributions

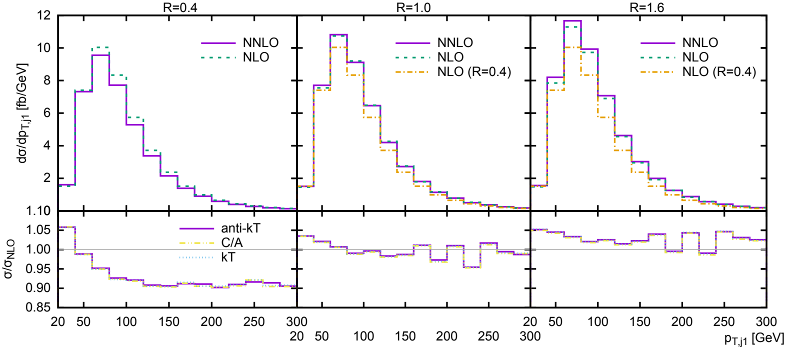
Transverse momentum of second jet



- again good agreement between NLO and NNLO calculation for $R = 1.0$

Differential Distributions

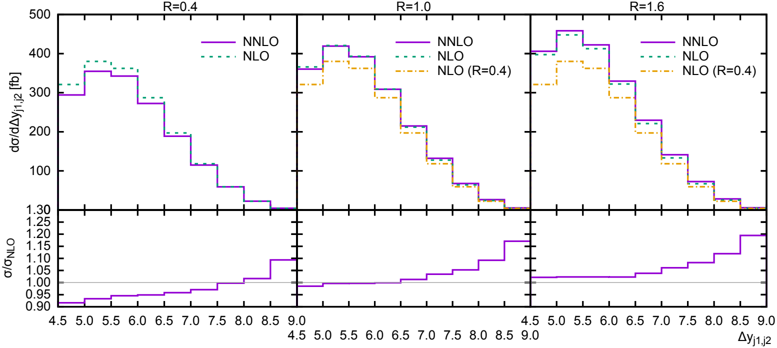
Transverse momentum of leading jet



- overall good agreement between NLO and NNLO calculation for $R = 1.0$
- some remaining effects $\mathcal{O}(5\%)$ for small transverse momenta

Differential Distributions

Rapidity difference between two tagging jets



- again good agreement with $R = 1.0$ for smaller values $\Delta y_{jj} \lesssim 7$
- cannot explain deviations at large Δy_{jj} values

Conclusions

- significant reduction of cross section seen
  for NNLO calculation of VBF-Hjj with VBF cuts w.r.t. NLO
- $\leftrightarrow$ not present in inclusive cross sections

- can study jet clustering dependence using NLO calculation of VBF-$H + 3$ partons

- differences reduced when using larger R value
  - $R = 1.0$ as matching value determined from integrated cross section
  - some distributions reproduced well ($p_{T,H}$, $p_{T,j2}$)
  - remaining differences for others ($p_{T,j1}$, Δy_{jj})
    ($\leftrightarrow$ impact of $H + 3$ jets bug?)

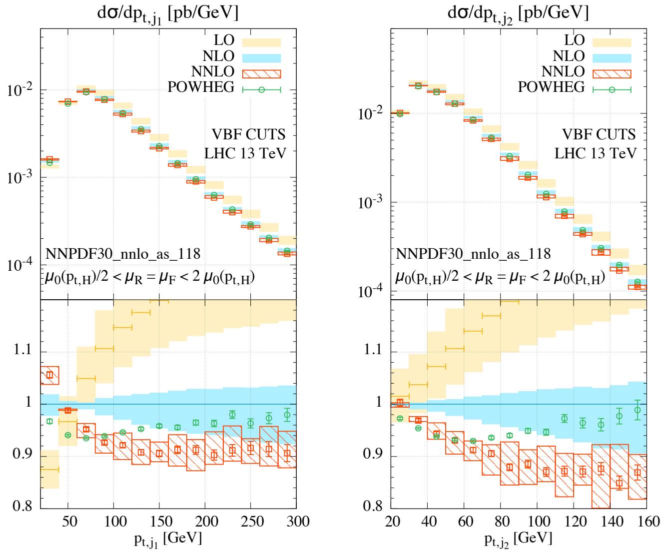
$\rightarrow$ Jet shape dependence intrinsic effect for all processes with jets at LO

$\rightarrow$ should be taken into account as uncertainty

NNLO QCD corrections to VBF-Higgs

VBF-Higgs production in NNLO QCD

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi]



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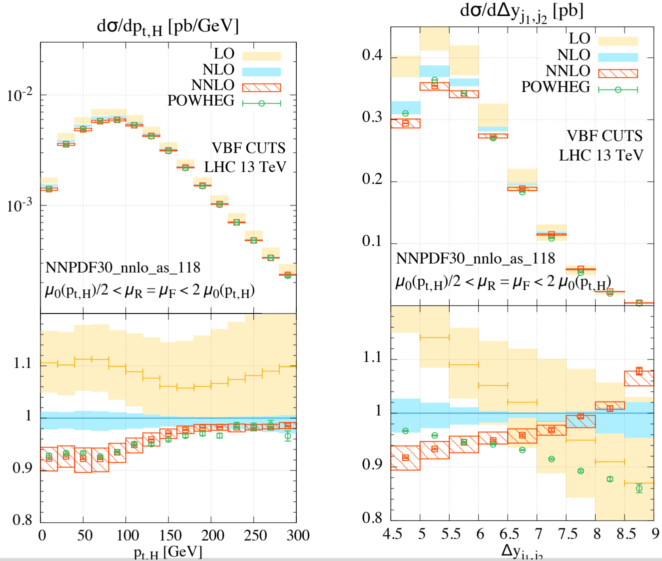
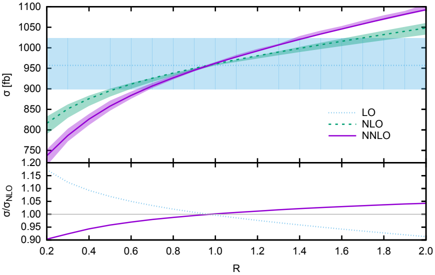


Fixed Integrated NNLO Cross Section

original result



result with bugfix