Karlsruhe Institute of Technology

New Developments for VBF/VBS in VBFNLO and Herwig

Michael Rauch | MBI 2017, 29 Aug 2017

INSTITUTE FOR THEORETICAL PHYSICS

Introduction

VBFNLO [Baglio, Bellm, Bozzi, Brieg, Campanario, Englert, Feigl, Frank, Figy, Geyer, Hackstein, Hankele, Jäger, Kerner, Kubocz, Löschner, Ninh, Oleari, Palmer, Plätzer, MR, Roth, Rzehak, Schissler, Schlimpert, Spannowsky, Worek, Zeppenfeld]

Vector-Boson-Fusion at Next-to-Leading Order

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Vector-Boson-~~Fusion~~ Physics at Next-to-Leading Order

Introduction

VBFNLO

[Baglio, Bellm, Bozzi, Brieg, Campanario, Englert, Feigl, Frank, Figy, Geyer, Hackstein, Hankele, Jäger, Kerner, Kubocz, Löschner, Ninh, Oleari, Palmer, Plätzer, MR, Roth, Rzehak, Schissler, Schlimpert, Spannowsky, Worek, Zeppenfeld]

F

~~Ph~~ysics

Vector-Boson-~~Fusion~~ at Next-to-Leading Order

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons
  - accurate predictions needed for LHC (both signal and background)
  - MC efficient solution for high number of final-state particles (decays of electroweak bosons included)
- general cuts and distributions of final-state particles
- various choices for renormalization and factorization scales
- any pdf set available from LHAPDF (or hard-wired CTEQ6L1, CT10, MRST2004qed, MSTW2008)
- event files in Les Houches Accord (LHA) or HepMC format (LO only)
- BLHA interface to Monte-Carlo event generators $\rightarrow$ NLO event output

Process overview

List of implemented processes

(New in VBFNLO 2.7.1/3.0.0(β))

- vector-boson fusion production at NLO QCD of
  - Higgs (+NLO EW, NLO SUSY)
  - Higgs plus third hard jet
  - Higgs plus photon
  - Higgs pair

  } (including Higgs decays)

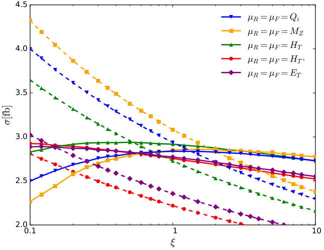
  - vector boson (W, Z, γ)
  - two vector bosons (W^+W^-, $W^\pm W^\pm$, WZ, ZZ, Wγ, Zγ)
- diboson production
  - diboson (WW, WZ, ZZ, Wγ, Zγ, $\gamma\gamma$) (NLO QCD)
  - diboson via gluon fusion (WW, ZZ, Zγ, $\gamma\gamma$) (part of NNLO QCD contribution to diboson)
  - diboson (WW, WZ, ZZ, Wγ) plus hard jet (NLO QCD)
  - diboson ($W^\pm W^\pm$, WZ, Wγ, ZZ, Zγ) plus two hard jets (NLO QCD)
- triboson production (NLO QCD)
- Higgs plus vector boson (NLO QCD) (including Higgs decays)
- Higgs plus two jets via gluon fusion (one-loop LO) (including Higgs decays)
- new physics models
  - anomalous Higgs, triple and quartic gauge couplings
  - K-matrix unitarization for selected couplings
  - Higgsless and spin-2 models
  - Two-Higgs model
- BLHA interface for VBF processes

Study of VBS-$Z\gamma jj$

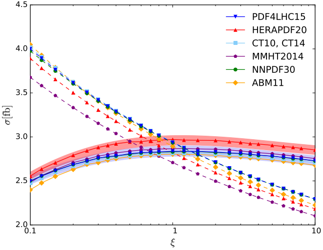
VBS production of $Z\gamma jj$
(including leptonic decay of Z and off-shell effects)

[Campanario, Kerner, Zeppenfeld]

Different scale choices



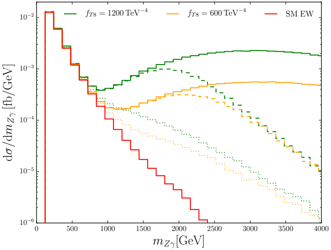
Different PDF choices



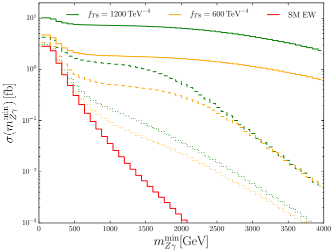
- large scale uncertainty at LO, agreeing well (few percent) at NLO
- PDF uncertainties at same level
- band of different scale/PDF choices typically larger (6%)

Anomalous Couplings Effects

$m_{Z\gamma}$ distribution



C.s. dependence on $m_{Z\gamma}$ cut (cumulative plot)



- huge enhancement at large $m_{Z\gamma}$
- outside of validity of EFT region
- inclusion of form factor (dotted: dipole FF, dotted: complex FF)

$$\mathcal{F}^c(s) = \left(1 - i\,\frac{s^2}{{\Lambda_{FF}^c}^4}\right)^{-1}$$

- suitable choice of $\Lambda_{FF}^{(c)}$ leaves c.s. in physical (non-unitarity-violating) region
- allows for consistent tests of anomalous coupling distributions

Unitarity of Amplitudes

Issue: [$\rightarrow$ talk by Wolfgang Kilian]

- contribution of higher-dimensional EFT operators violates unitarity above certain energy scale
- $\leftrightarrow$ for dim-8 happens well within energy range probed by LHC
- $\rightarrow$ T-matrix unitarization
- only publicly available for longitudinal operators (chiral $\mathcal{L}$: $F_{S,0}$, $F_{S,1}$ $\leftrightarrow$ linear EFT: $\frac{f_{S,0}+f_{S,2}}{2}$, $f_{S,1}$)

$\rightarrow$ extend to transverse and mixed operators

Things to consider:

- unitarization considers $VV \rightarrow VV$ ($2 \rightarrow 2$) process: incoming V on-shell
- $\leftrightarrow$ physical process VBF/VBS ($2 \rightarrow 5/6$): incoming V space-like
- $\Rightarrow$ need proper mapping between both

[$\leftrightarrow$ talk by Rafael Delgado]

Generalized T-Matrix

Procedure:

[Perez, Sekulla, Zeppenfeld]

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- split off $2 \to 2$ subprocess with off-shell polarization vectors

$$\mathcal{M}_{qq\to 4fjj} = \sum_{\lambda_i} J^{\mu}_{q\to jV} J^{\nu}_{q\to jV}\, \epsilon_\mu \epsilon_\nu \quad \mathcal{M}_{VBS}(q_i, \lambda_i) \quad \epsilon^*_\rho \epsilon^*_\sigma\, J^{\rho}_{V\to \bar{f}f} J^{\sigma}_{V\to \bar{f}f}$$

- resulting interaction matrix $\mathbf{T}(\mathcal{M}_{VBS})$ not normal
  $\to$ define additional entries with time-like mom. k, where $k_1^2 = q_3^2$, $\vec{k}_1 = \vec{q}_1$, etc.:

$$\mathbf{T}_0 = \begin{pmatrix} \mathbf{A}_{t\leftarrow t} & \mathbf{A}_{t\leftarrow s} \\ \mathbf{A}_{s\leftarrow t} & \mathbf{A}_{s\leftarrow s} \end{pmatrix} \to \begin{pmatrix} 0 & \mathbf{A}_{t\leftarrow s} \\ \mathbf{A}_{s\leftarrow t} & 0 \end{pmatrix}$$

- apply standard T-matrix formula

$$\mathbf{T}_T = \left(\mathrm{Re}\left(\mathbf{T}_0^{-1}\right) - \frac{i}{2}\mathbb{1}\right)^{-1}, \qquad \mathbf{T}_L = \left(\mathbb{1} - \frac{i}{2}\mathbf{T}_0^{\dagger}\right)^{-1} \mathrm{Re}\left(\mathbf{T}_0\right)$$

- spoils Breit-Wigner shape of incoming bosons
  $\to$ use approximate T-matrix scheme with

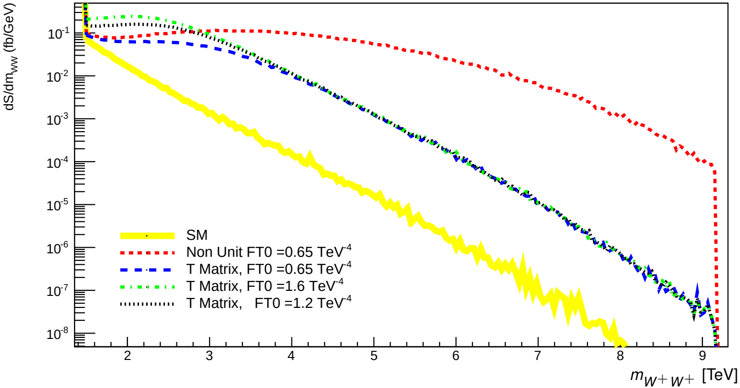
$$\mathbf{A}^{\text{unit}}_{t\leftarrow s} = \mathbf{A}_{t\leftarrow s}\left(1 + \frac{1}{4}\lambda_{\max}\right)^{-1}$$

with $\lambda_{\max}$ largest eigenvalue of $\mathbf{A}_{t\leftarrow s}\mathbf{A}_{s\leftarrow t}$

Results

(preliminary, work in progress) [Perez, Sekulla, Zeppenfeld]

$pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$



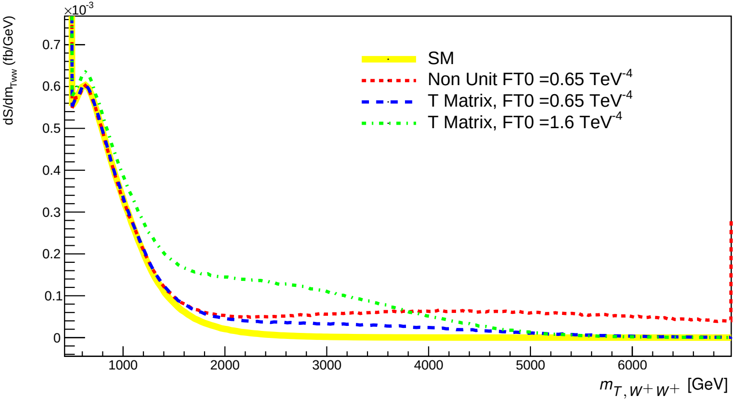
to appear in future version of VBFNLO

Results

(preliminary, work in progress)

[Perez, Sekulla, Zeppenfeld]

$pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$



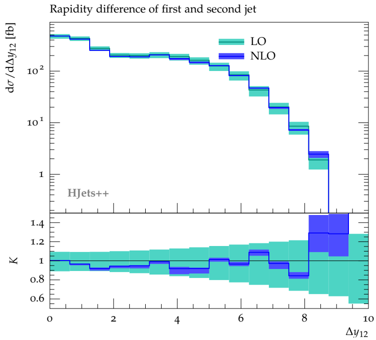
to appear in future version of VBFNLO

HJets

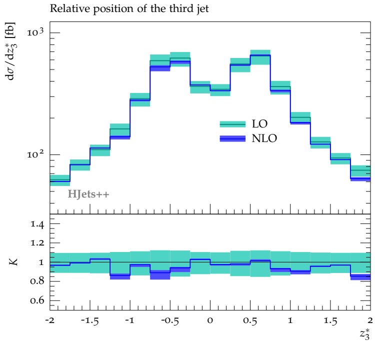
Electroweak Higgs + 3 jets production at NLO QCD [Campanario, Figy, Plätzer, Sjödahl]

including all contributions, i.e. VBF, Higgsstrahlung and interferences

rapidity difference of first and second jet



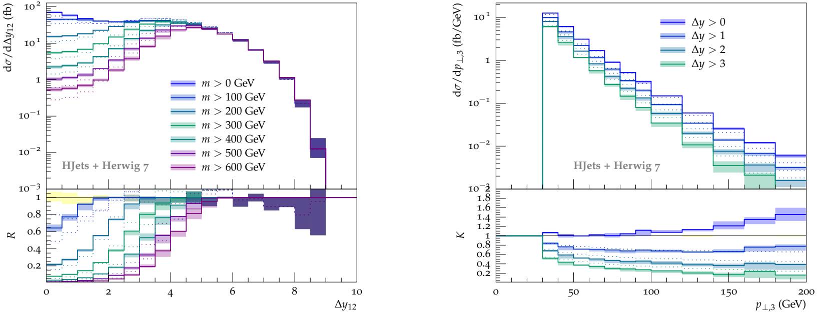
relative position of third jet



- relative position of third jet still shows some central gap

HJets Results

Extensive study of QCD corrections vs VBF cuts in progress

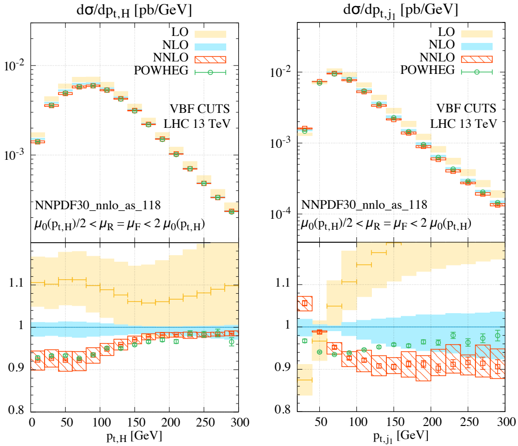


- at LO Higgsstrahlung contribution gives $m_{jj} \simeq M_{W,Z}$
- at NLO/NLO+jet separation becoming less clear
  $\leftrightarrow$ partons may be non-observed
- $\leftrightarrow$ experimental cuts might be relatively loose

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,
$\Delta y_{jj} > 4.5$, $y_{j1} \cdot y_{j2} < 0$

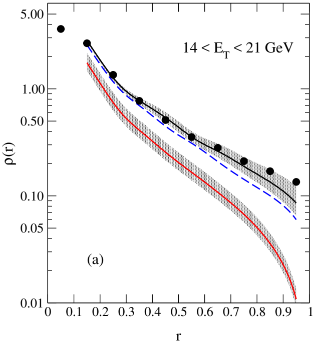
- tiny corrections to inclusive cross section
- significant ($\mathcal{O}(-10\%)$) corrections in VBF region

Jet-Clustering Dependence

- in NNLO calculation fixed choice of jet-clustering parameters (R, n)
- $\leftrightarrow$ no dependence at LO
  $\Rightarrow$ can use VBF-H+3jets NLO QCD calculation, [MR, Zeppenfeld]
  to convert between different values

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

- energy flow in DIS jets at HERA [Kauer, Reina, Repond, Zeppenfeld]

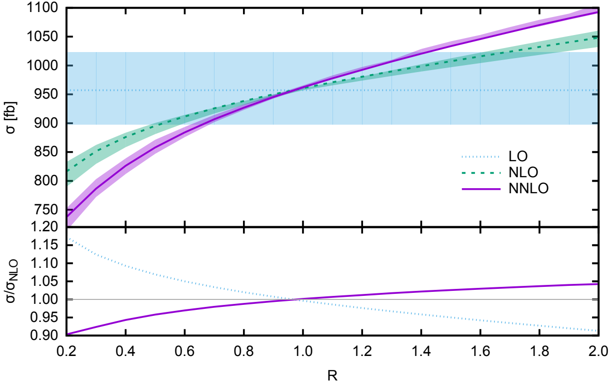


- differential E_T-distribution inside jet cone
  (ZEUS: black dots)
- Energy flow significantly smaller for NLO (max. 2 partons, red) than for NNLO (up to 3 partons, blue)

Integrated Cross Section

VBF-Hjj, $\sqrt{S} = 13$ TeV, $m_{jj} > 600$ GeV, $\Delta y_{jj} > 4.5$

[MR, Zeppenfeld]

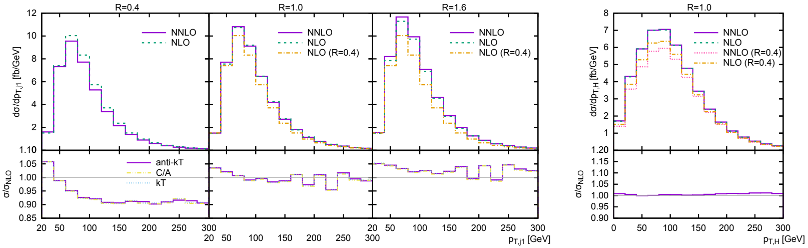


- band: uncertainty from scale variation
- small cone misses part of the jet energy
  $\Rightarrow$ smaller m_{jj}
  $\Rightarrow$ less events with $m_{jj} > 600$ GeV

Differential Cross Sections

VBF-Hjj, $\sqrt{S} = 13$ TeV, $m_{jj} > 600$ GeV, $\Delta y_{jj} > 4.5$

[MR, Zeppenfeld]



- good agreement between NLO and NNLO result also in distributions
- remaining effects in some phase-space regions
  possible explanations: 2-loop effects,
  suppressed radiation between tagging jets
- disclaimer:
  nothing special about $R = 1$ for VBF-Higgs production
  $\leftrightarrow$ possible large corrections by other effects
  (underlying event, pile-up, ...)

Herwig 7

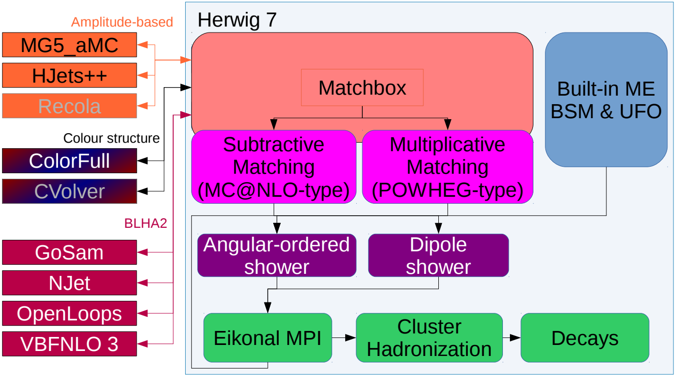
multi-purpose particle physics event generator

current version: 7.1.1 [Bellm, Gieseke, Grellscheid, Kirchgaeßer, Loshaj, Nail, Papaefstathiou, Plätzer, Podskubka, MR, Reuschle, Richardson, Schichtel, Seymour, Siódmok, Webster]

- two showers (angular-ordered, dipole)
- automated NLO
- multiple matrix-element interfaces
- three NLO matching schemes (MC@NLO-, POWHEG-like, KrkNLO)
- NLO merging in dipole shower
- spin correlations in angular-ordered shower
- QED radiation in angular-ordered shower
- massive dipole shower
- improved sampling/integration
- improved documentation
- on-the-fly reweighting
- new soft model

Herwig 7 H7

- fully automated matching of NLO to parton showers through Matchbox module
  [work led by S. Plätzer with substantial contributions by J. Bellm, A. Wilcock, MR, C. Reuschle]
- subtractive (MC@NLO-type, $\oplus$) and multiplicative (POWHEG-type, $\otimes$) matching
- angular-ordered (QTilde, PS) and dipole (Dipoles) shower
- matrix elements through binary interface, no event files



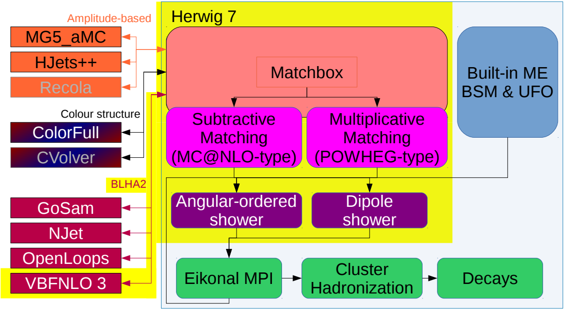
VBFNLO 3 & Herwig 7

[Binoth et al., Alioli et al.]

- matrix elements from VBFNLO via BLHA2 interface
- extensions to make accessible
  - phase-space sampling
  - (electroweak) random helicity summation
  - anomalous couplings

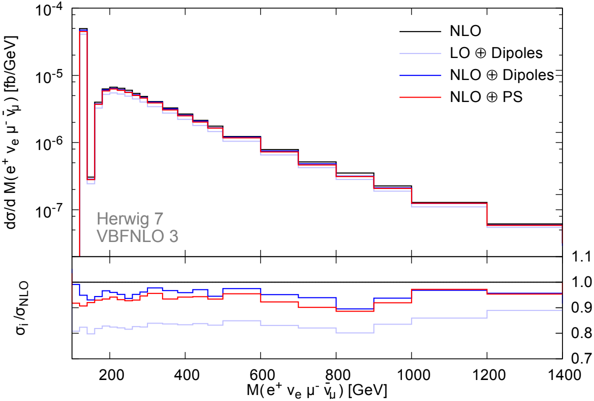
already working for:

- VBF/VBS (all boson combinations)
- VBF-H+3jets
- QCD-$W^{\pm}jj$, $W^{\pm}Zjj$, $W^{\pm}\gamma jj$, other combinations coming soon



Distributions

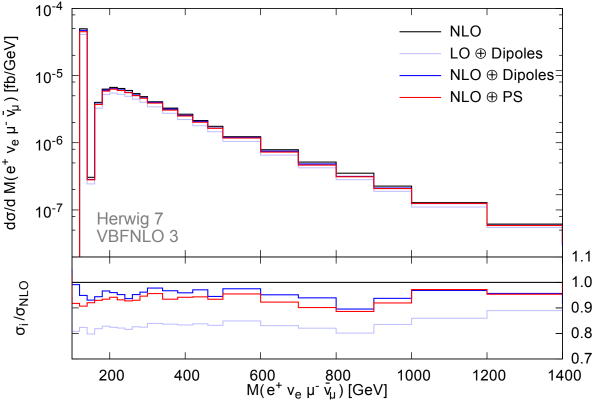
Process as example: $pp \to ((Hjj \to)W^+W^-jj \to)e^+\nu_e\mu^-\bar{\nu}_\mu jj$ via VBF
Four-lepton invariant mass



- Higgs peak at 125 GeV
- *WW* continuum production above 180 GeV
- significant cancellation between diagrams at high invariant masses
- ⇒ ideal test for anomalous couplings

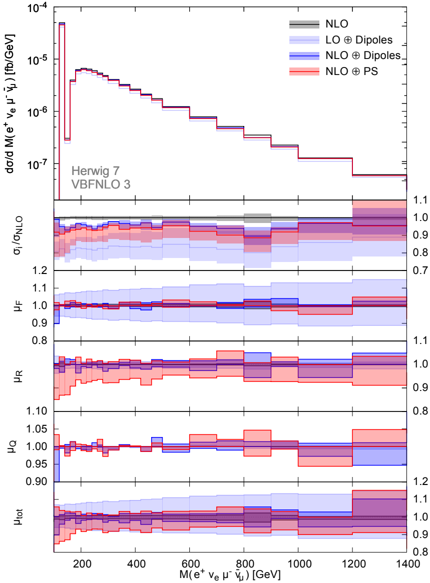
Distributions

Process as example: $pp \to ((Hjj \to)W^+W^-jj \to)e^+\nu_e\mu^-\bar{\nu}_\mu jj$ via VBF
Four-lepton invariant mass



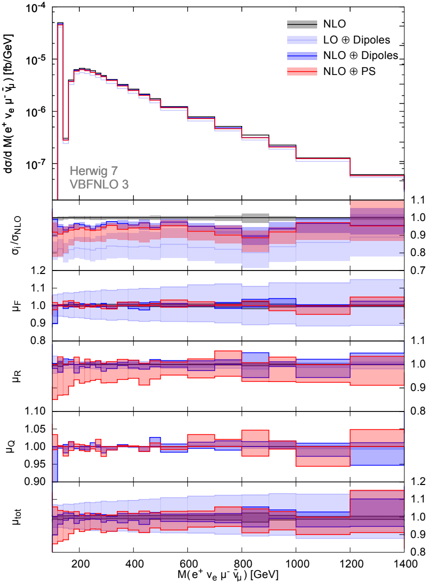
- all parton-shower results smaller than NLO cross section
- additional K-factor effect for LO $\oplus$ Dipoles result ($K = 1.077$)
- no relevant shape changes
  (as expected: insensitive to QCD effects)

Four-lepton Invariant Mass



- ← central scale $\mu_0 = p_{T,j1}$ transverse momentum of leading jet
- ← band: scale variation $\{\mu_F, \mu_R, \mu_Q\}/\mu_0 \in [\frac{1}{2}; 2]$ $\mu_i/\mu_j \in [\frac{1}{2}; 2]$
- ← factorization scale $\mu_F/\mu_0 \in [\frac{1}{2}; 2]$
- ← renormalization scale $\mu_R/\mu_0 \in [\frac{1}{2}; 2]$
- ← shower scale $\mu_Q/\mu_0 \in [\frac{1}{2}; 2]$
- ← all three scales

Four-lepton Invariant Mass



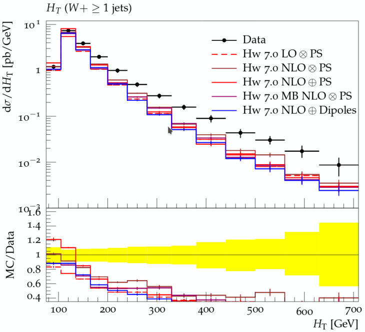
- consistent variation of scales between hard process and parton shower
- large factorization scale dependence for LO result
- larger dependence for down variation of renormalization scale in angular-ordered shower:
  larger $\alpha_s \rightarrow$ more splittings
  $\rightarrow$ bigger migration effects
- small variations from shower-scale changes
- modest remaining overall uncertainty

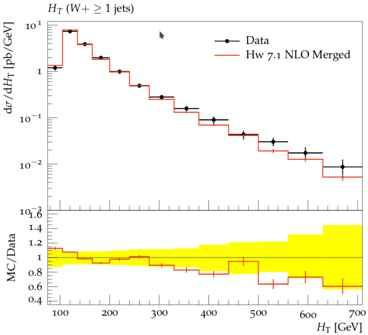
NLO Merging

New in Herwig 7.1:

NLO merging with improved unitarization [Bellm, Gieseke, Plätzer]

Motivation: W+jets production

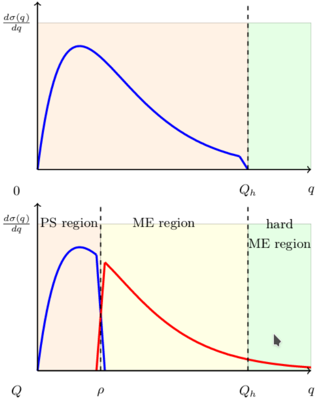




Merging Implementation

Combine NLO matrix elements with different jet multiplicity
e.g. W^+ + 0,1,... jets
remove any double-counting appearing

- basic idea:
  divide phase-space into matrix-element and parton-shower regions
- overlapping phase-spaces naively produce dead regions if not treated properly
- unitary approach
  $\rightarrow$ cross section (mostly) conserved

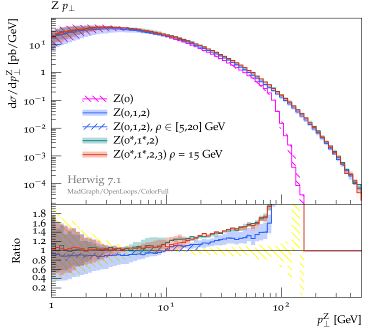


Results

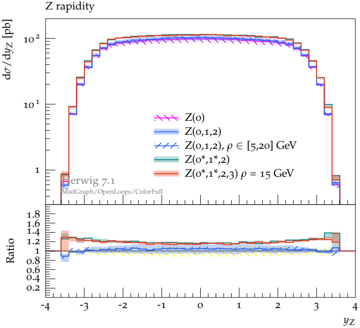
[Bellm, Gieseke, Plätzer]

Z production
comparing samples with different levels of merging
(*: NLO accuracy)

Transverse momentum of *Z*



Rapidity of *Z*



- Merged samples needed to fill full phase space
- NLO corrections for first emission reduce uncertainty above merging scale
- rapidity: example for unitarized cross section

Conclusions

- VBFNLO https://www.itp.kit.edu/vbfnlo
  - BLHA interface working – stay tuned for more processes
  - release of final version 3.0 soon
  - generalized T-matrix unitarization for dim-8 operators
  - study: jet clustering dependence for VBF-H
- HJets https://hjets.hepforge.org/
  - electroweak H + 3 jets production
  - study of QCD corrections vs VBF cuts
- Herwig https://herwig.hepforge.org/
  - fully automated NLO with 2 showers and 3 matching schemes
  - NLO merging with improved unitarization
  - latest version 7.1
  - more in the pipeline . . .

BLHA Interface

Defined standardized interface between Monte Carlo tools and one-loop programs

→Binoth Les Houches Accord (BLHA) [arXiv:1001.1307, arXiv:1308.3462]

- tree-level evaluation of matrix elements well under control
- modular structure of NLO calculations
- algorithms for treatment of infrared singularities (Catani-Seymour, FKS, ...)
- → incorporate one-loop matrix element information into MC tools

Distribution of tasks:

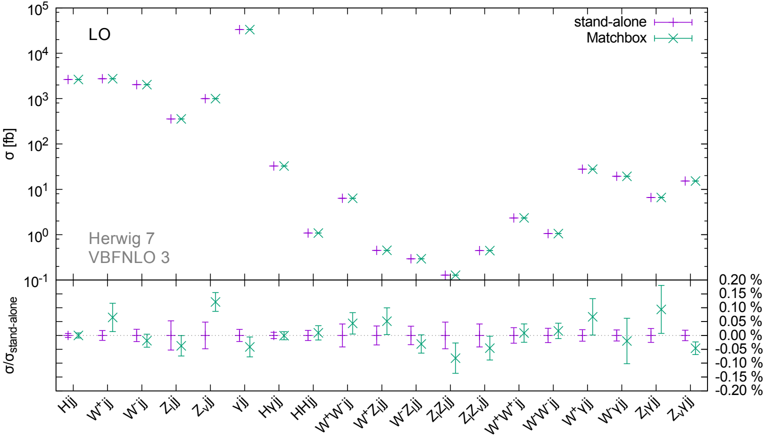
- MC tool:
  - cuts, histograms, parameters
  - Monte Carlo integration
  - phasespace (→ VBFNLO)
  - IR subtraction
  - Born, colour- and spin-correlated Born (only BLHA1)
- One-loop provider (OLP):
  - one-loop matrix elements $2\Re(\mathcal{M}_{\text{LO}}^{\dagger}\mathcal{M}_{\text{virt}})$ (coefficients of ϵ^{-2}, ϵ^{-1}, ϵ^{0}; $|\mathcal{M}_{\text{LO}}|^2$)
  - Born, colour- and spin-correlated Born (only BLHA2)

Setup stage via “contract” file
(needed for tools which generate code on the fly)
Run-time stage via binary interface (function calls) → fast

Validation

Compare LO results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox

(inclusive cuts, with leptonic gauge boson decays into single different-flavour combination, Higgs non-decaying)



→ good agreement at or below permill level

Validation

Compare NLO results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox

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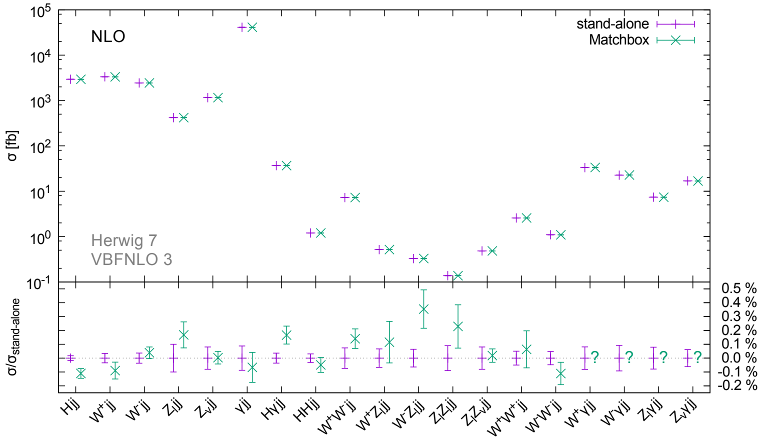


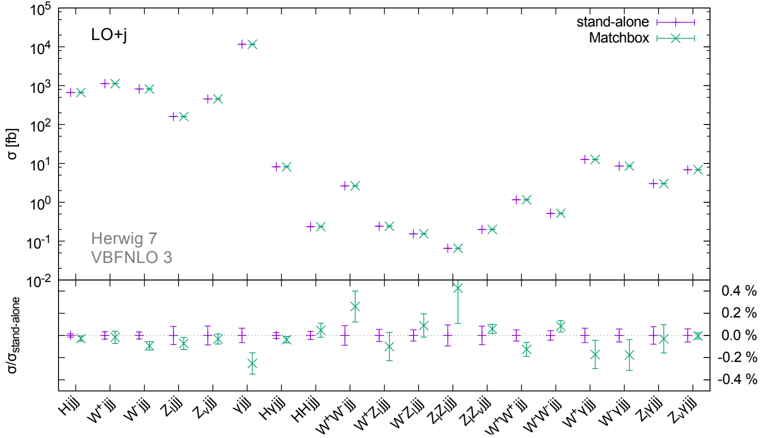
→ good agreement

$V\gamma$ processes: $\pm 0.7\%$ deviation ↔ beyond errors → under investigation

Validation

Compare LO+j results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox

(inclusive cuts, with leptonic gauge boson decays into single different-flavour combination, Higgs non-decaying)



→ good agreement

Setup

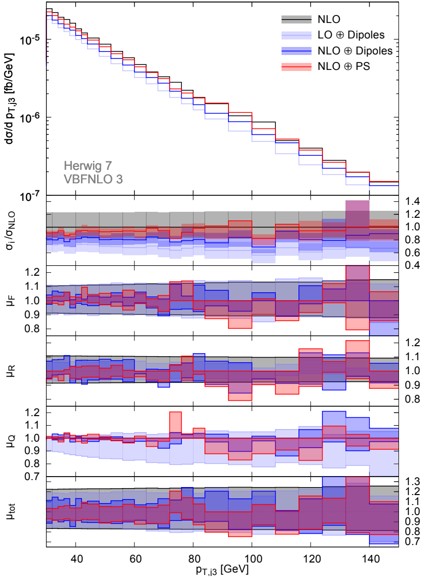
Generation-level cuts:

$$p_{T,j} > 20\text{ GeV}\,, \qquad |y_j| < 5.0\,,$$
$$\text{anti-}k_T\text{ jets with } R = 0.4\,, \qquad b\text{-quark veto}$$
$$p_{T,\ell} > 15\text{ GeV}\,, \qquad |y_\ell| < 3.0\,,$$
$$m_{e^+,\mu^-} > 15\text{ GeV}\,,$$
$$m_{j1,j2} > 400\text{ GeV}\,, \qquad |y_{j1} - y_{j2}| > 3.0$$

Analysis-level cuts:

$$p_{T,j} > 30\text{ GeV}\,, \qquad |y_j| < 4.5\,,$$
$$\text{anti-}k_T\text{ jets with } R = 0.4\,, \qquad b\text{-quark veto}$$
$$p_{T,\ell} > 20\text{ GeV}\,, \qquad |y_\ell| < 2.5\,,$$
$$m_{e^+,\mu^-} > 15\text{ GeV}\,,$$
$$m_{j1,j2} > 600\text{ GeV}\,, \qquad |y_{j1} - y_{j2}| > 3.6$$

Transverse Momentum Third Jet

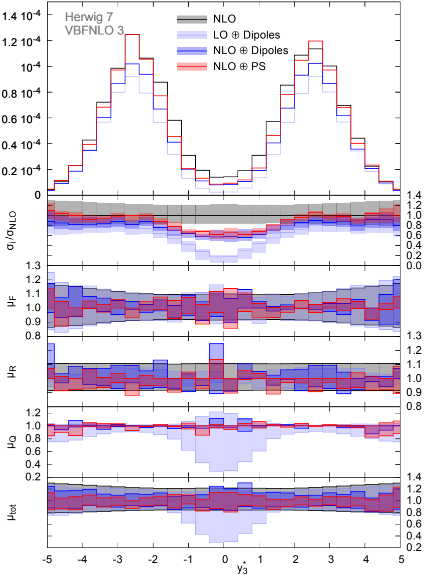


- large scale variation bands for
  - shower scale in LO⊕Dipoles

    → pure parton-shower effect
  - fact./ren. scale in "NLO"

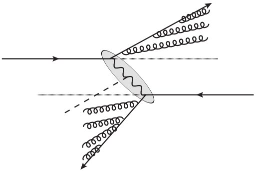
    → LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10 - 20\%)$
- → call for multi-jet merging

Rapidity of third jet



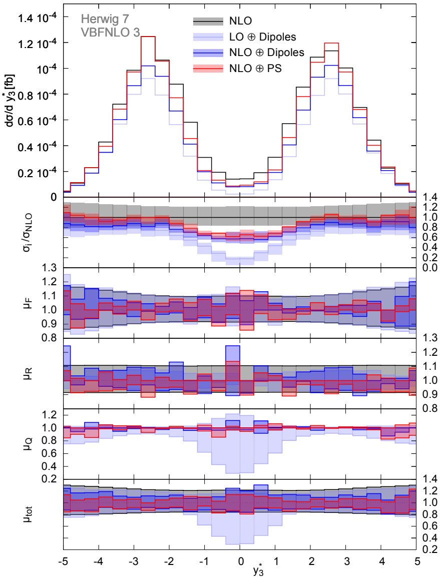
Rapidity of third jet relative to two tagging jets

$$y_3^* = y_3 - \frac{y_1 + y_2}{2}$$



- VBF colour structure suppresses additional central jet radiation
- colour connection between tagging jet and remnant
- ↔ distinction from QCD-induced production

Rapidity of third jet

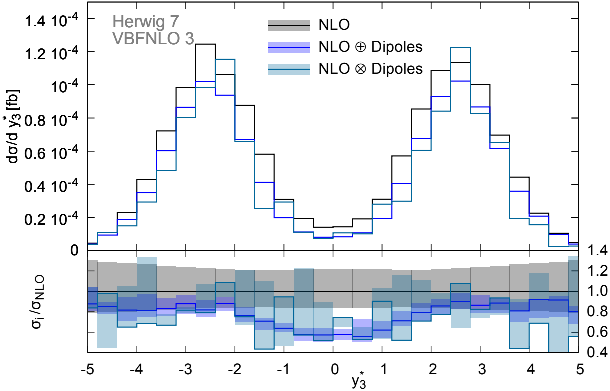


Rapidity of third jet relative to two tagging jets

$$y_3^* = y_3 - \frac{y_1 + y_2}{2}$$

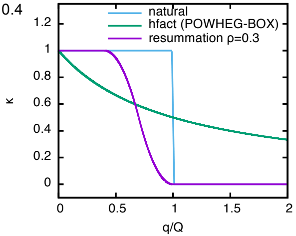
- impact of parton showers (+LO) long unclear
- Herwig predicts very low radiation in central region
- large shower-scale unc.
- stabilised when combining with NLO
- still reduction present
- scale variation bands not overlapping
- only small effects in forward region (mostly global normalization)

Rapidity of third jet – POWHEG

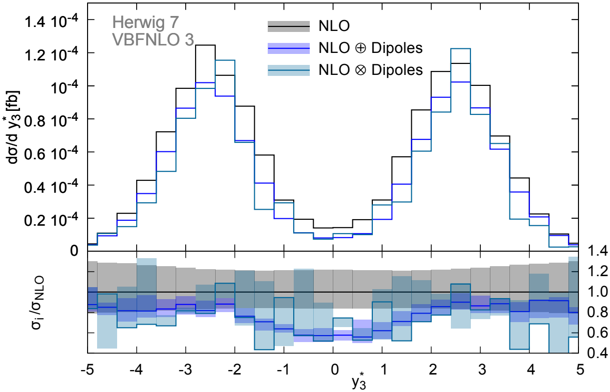


- POWHEG-like (⊗) using resummation scheme [Plätzer]:

$$\kappa(Q,q;\rho) = \begin{cases} 1 & \text{for } q < (1-2\rho)Q \\ 1 - \frac{(1-2\rho-\frac{q}{Q})^2}{2\rho^2} & \text{for } (1-2\rho)Q < q < (1-\rho)Q \\ \frac{(1-\frac{q}{Q})^2}{2\rho^2} & \text{for } (1-\rho)Q < q < Q \\ 0 & \text{for } q > Q \end{cases}$$

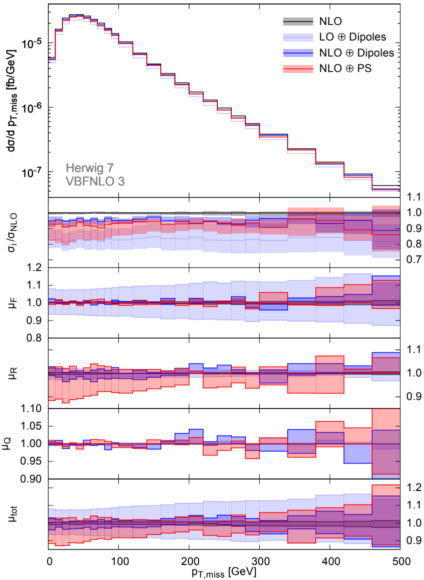


Rapidity of third jet – POWHEG

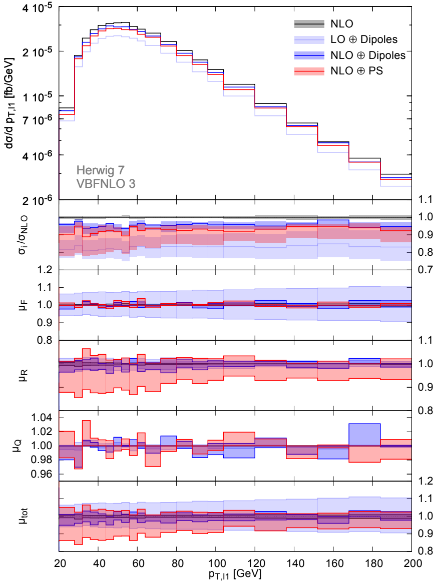


- band: joint variation $\mu_F = \mu_R = \mu_Q \in [\frac{1}{2}, 2]\ \mu_0$
- similar predictions from MC@NLO-like ($\oplus$) and POWHEG-like ($\otimes$) matching
- also holds for other distributions

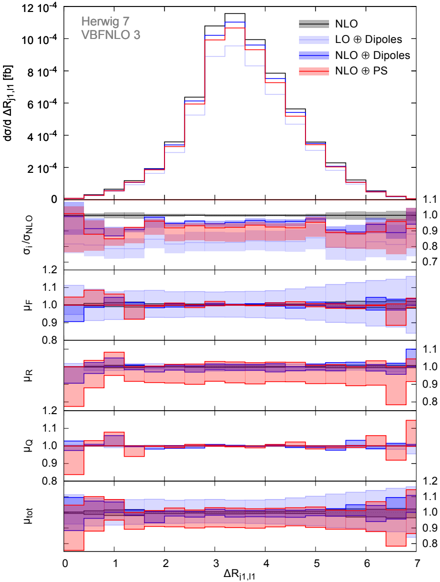
Missing Transverse Momentum



Transverse Momentum of Leading Lepton



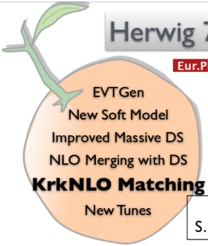
R Separation of Leading Jet and Leading Lepton



$$\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$$

Jacobian peak at $\Delta R_{j1\ell 1} = \pi$

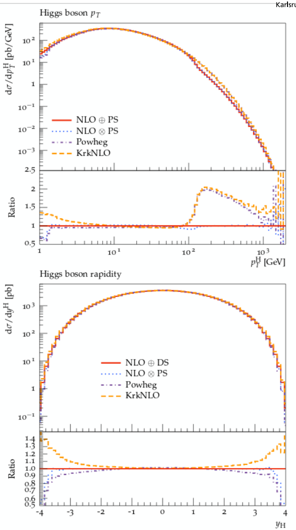
KrkNLO



S. Jadach , G. Nail, W. Płaczek,
S. Sapeta, A. Siodmok, M. Skrzypek

- Introducing MC scheme for PDFs
- Redefine PDFs
- Idea close to what CMW is for α_S, here for PDFs
- Currently limited to Drell-Yan like processes
- No kink at the hard shower scale

https://krknlo.hepforge.org



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