Karlsruhe Institute of Technology

Vector-Boson-Fusion:
Parton-shower and Anomalous-coupling Effects

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INSTITUTE FOR THEORETICAL PHYSICS

VBF event topology

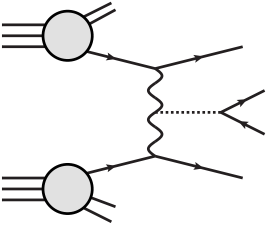
VBF (vector-boson fusion) topology shows distinct signature

- two tagging jets in forward region
- reduced jet activity in central region
- leptonic decay products typically between tagging jets

$\rightarrow$ two-sided deep-inelastic scattering

First studied in context of Higgs searches [Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; . . .]

- $\sim$ 10% compared to main production mode gluon fusion
- NLO QCD corrections moderate ($\mathcal{O}(\lesssim 10\%)$)
- NLO EW same size [Ciccolini *et al.* , Figy *et al.*]
- NNLO QCD known for subsets:
  no significant contributions for integrated c.s.
  [Harlander *et al.* , Bolzoni *et al.*]
  corrections up to 10% in distributions
  [Cacciari *et al.*]
- incl. NNNLO QCD: tiny effects [Dreyer, Karlberg]
- advantageous scale choice:
  momentum transfer q^2 of intermediate vector bosons

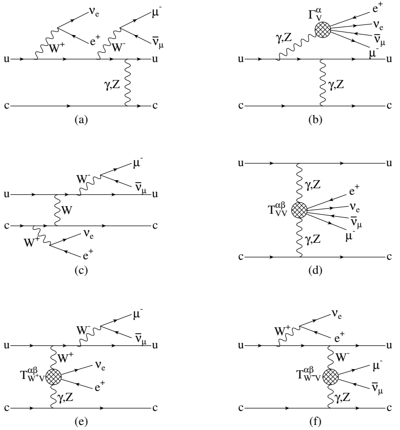


Diboson-VBF production

[Bozzi, Jäger, Oleari, Zeppenfeld (VV); Campanario, Kaiser, Zeppenfeld ($W^{\pm}\gamma$)]
[Denner, Hosekova, Kallweit ($W^{+}W^{+}$)]

- Important process for LHC run-II
- Part of the NLO wish list
  [Les Houches 2005]
- background to Higgs searches
- access to anomalous triple and quartic gauge couplings
- NLO QCD implementation of
  - all boson combinations
  - leptonic and semi-leptonic decays
  - including off-shell and non-resonant contributions
  - VBF approximation

$\rightarrow$ VBFNLO [MR, Zeppenfeld et al.]



Introduction

Karlsruhe Institute of Technology

VBFNLO

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

Introduction

VBFNLO

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

Introduction

VBFNLO

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 2.7.1/3.0.0β1)

- 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)
  - triboson (all combinations of W, Z, γ)
  - triboson (W$\gamma\gamma$) plus hard jet
- Higgs plus vector boson (NLO QCD) (including Higgs decays)
  - Higgs plus vector boson (WH)
  - Higgs plus vector boson plus hard jet (WH)
- 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

NLO plus Parton Shower

Combine advantages of NLO calculations and parton shower

NLO calculation

- normalization correct to NLO
- additional jet at high-p_T accurately described
- theoretical uncertainty reduced

Parton shower

- Sudakov suppression at small p_T
- events at hadron level possible

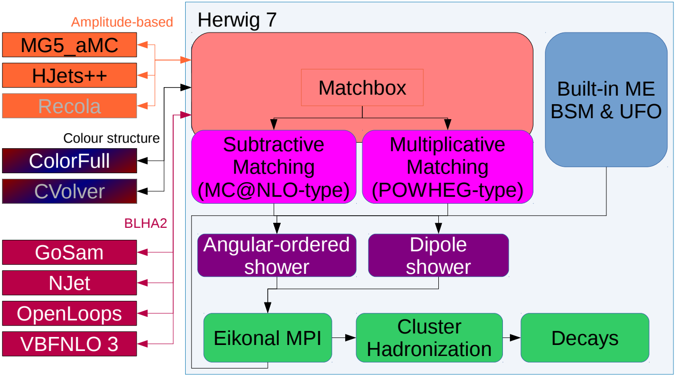
State of the Art

Implementations for specific VBF processses

- POWHEG-BOX [Alioli, Hamilton, Nason, Oleari, Re]
  currently available VBF implementations:
  Z [Jäger, Schneider, Zanderighi]
  $W^\pm$, Z [Schissler, Zeppenfeld]
  $W^\pm W^\pm$, $W^\pm W^\mp$ [Jäger, Zanderighi]
  ZZ [Jäger, Karlberg, Zanderighi]
- VBF-H with POWHEG method [D'Errico, Richardson]
- HJets++ [Campanario, Figy, Plätzer, Sjödahl]

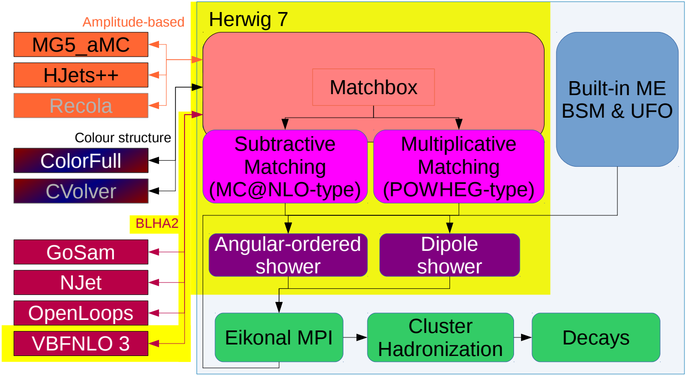
Herwig 7 H7

- 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, ⊕) and multiplicative (POWHEG-type, ⊗) matching
- angular-ordered (QTilde, PS) and dipole (Dipoles) shower
- matrix elements through binary interface, no event files



VBFNLO 3 & Herwig 7 – this talk

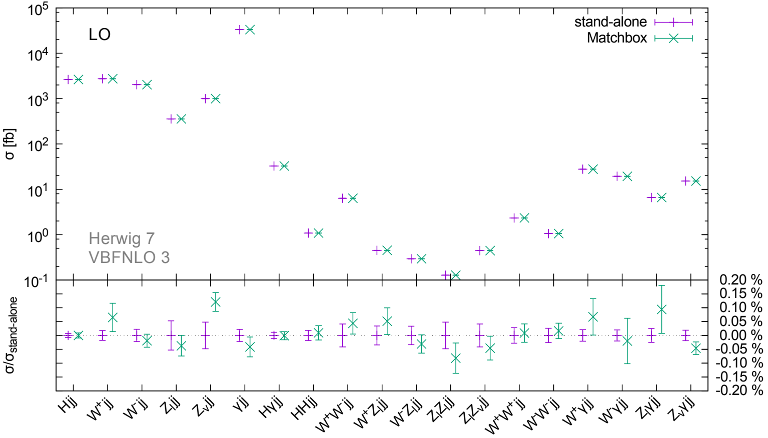
- matrix elements from VBFNLO via BLHA2 interface [Binoth et al., Alioli et al.]
- extensions to make accessible
  - phase-space sampling
  - (electroweak) random helicity summation
  - anomalous couplings



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

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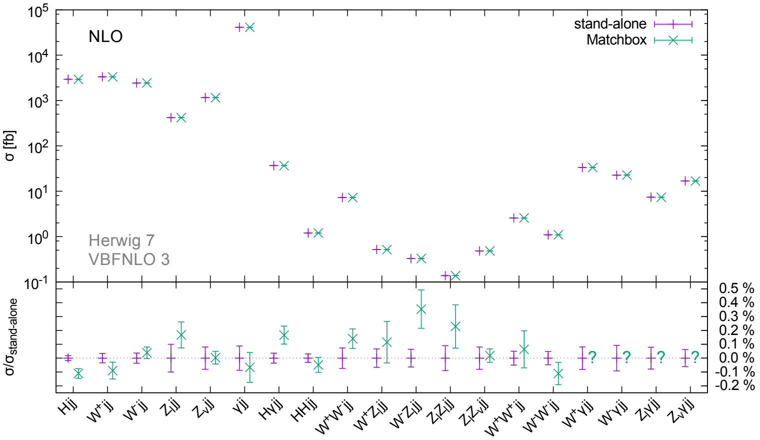


→ good agreement

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

Setup

Process: [Plätzer, MR]

$$pp \to ((Hjj \to) W^+ W^- jj \to) e^+ \nu_e \mu^- \bar{\nu}_\mu jj \text{ via VBF}$$

Cuts:

$$p_{T,j} > 30 \text{ GeV}, \qquad |y_j| < 4.5,$$
$$\text{anti-}k_T \text{ jets with } R = 0.4, \qquad b\text{-quark veto}$$

$$p_{T,\ell} > 20 \text{ GeV}, \qquad |y_\ell| < 2.5,$$
$$m_{e^+,\mu^-} > 15 \text{ GeV},$$

$$m_{j1,j2} > 600 \text{ GeV}, \qquad |y_{j1} - y_{j2}| > 3.6$$

(inspired from ATLAS VBF category in $H \to WW$, CMS similar)

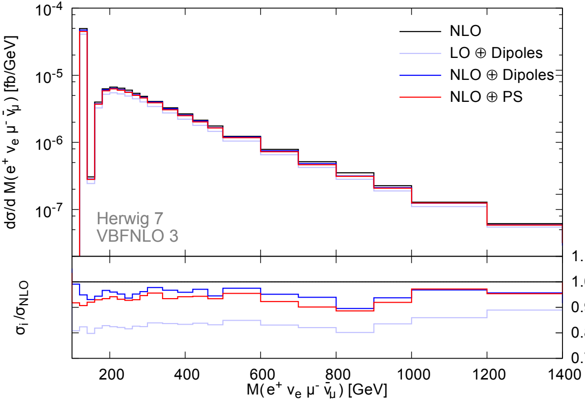
PDF: MMHT2014

central scale choice: transverse momentum of the leading jet

$$\mu_0 = p_{T,j1}$$

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
- $\Rightarrow$ ideal test for anomalous couplings

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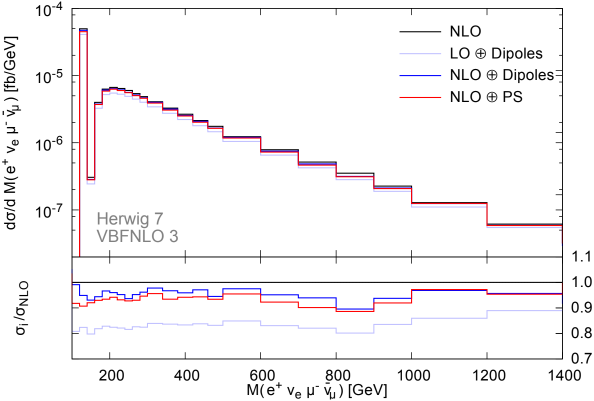
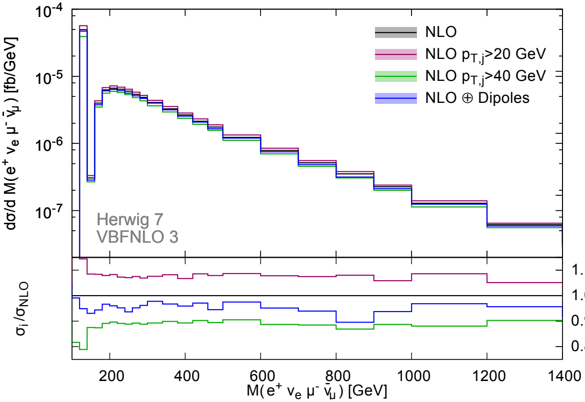


- all parton-shower results smaller than NLO cross section
- additional K-factor effect for LO $\oplus$ Dipoles result ($K = 1.077$)
- no relevant shape changes
  (as expected: insensitive to QCD effects)

Migration Effects

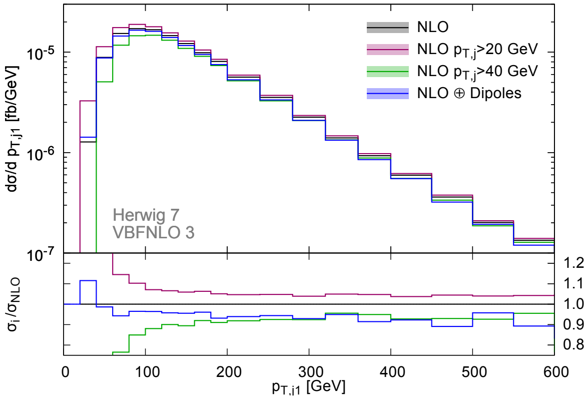
Vary transverse momentum cut of jets (default: $p_{T,j} > 30$ GeV)



- same effect when slightly raising $p_{T,j}$ cut
- additional parton splittings: if hard & wide-angle emission $\rightarrow$ separate jet
- $\rightarrow$ reduces energy and transverse momentum of emitting parton
- $\leftrightarrow$ $p_{T,j}$ cut, VBF cut $m_{jj} > 600$ GeV

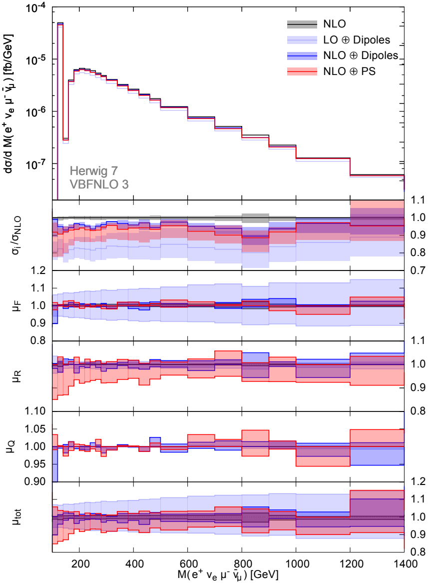
Migration Effects

Vary transverse momentum cut of jets (default: $p_{T,j} > 30$ GeV)



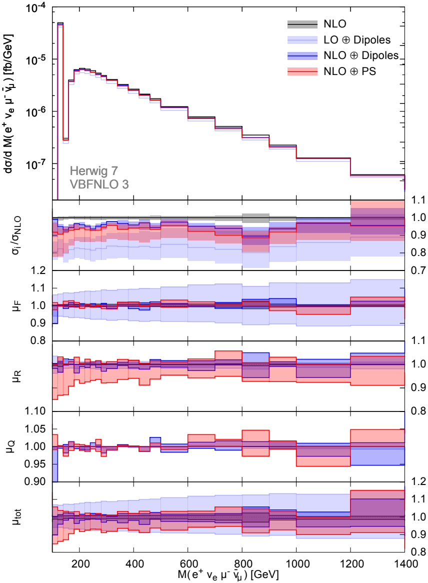
- less pronounced for small $p_{T,j1}$
  $\rightarrow$ VBF cut main source
- $\rightarrow$ migration of events across cut boundary
- $\leftrightarrow$ generation-level vs. analysis-level cuts
- $\Rightarrow$ no tuning of acceptance criteria required
- generation-level cuts nevertheless chosen weaker

Four-lepton Invariant Mass



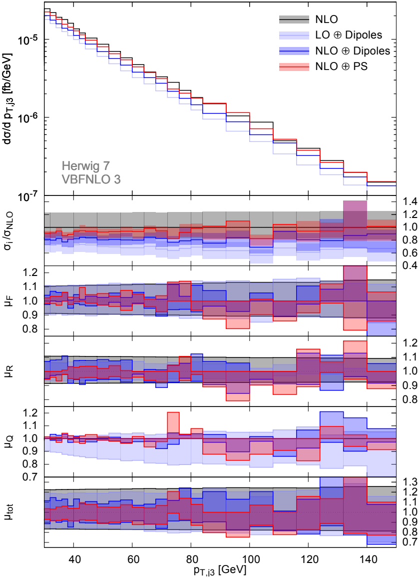
- ← central scale $\mu_0 = p_{T,j1}$ transverse momentum of leading jet
- ← band: scale variation $\{\mu_F, \mu_R, \mu_Q\} / \mu_0 \in [\frac{1}{2}; 2]$ $\mu_i/\mu_j \in [\frac{1}{2}; 2]$
- ← factorization scale $\mu_F/\mu_0 \in [\frac{1}{2}; 2]$
- ← renormalization scale $\mu_R/\mu_0 \in [\frac{1}{2};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

Four-lepton Invariant Mass



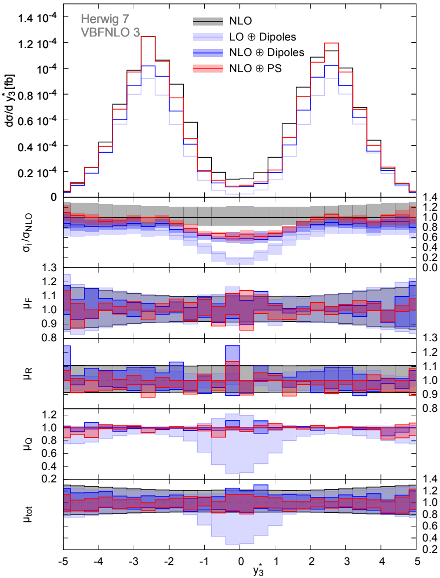
- consistent variation of scales between hard process and parton shower
- large factorization scale dependence for LO result
- larger dependence for down variation of renormalization scale in angular-ordered shower:
  larger $\alpha_s \to$ more splittings
  $\to$ bigger migration effects
- small variations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

Transverse Momentum Third Jet



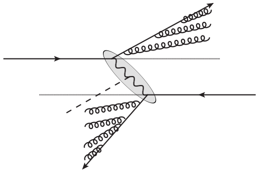
- large scale variation bands for
  - shower scale in LO⊕Dipoles
    - → pure parton-shower effect
  - fact./ren. scale in “NLO”
    - → LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10-20\%)$
- → call for multi-jet merging

Rapidity of third jet



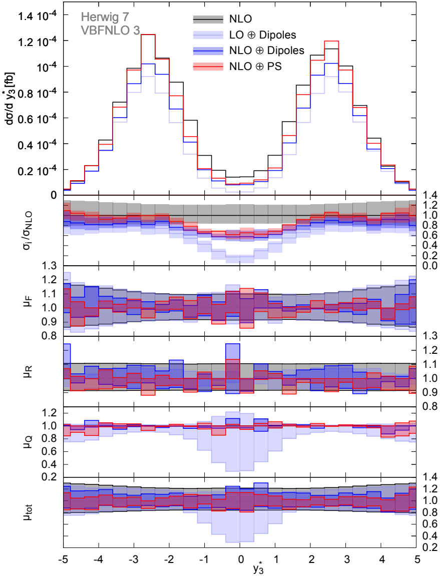
Rapidity of third jet
relative to two tagging jets

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



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

Rapidity of third jet



Rapidity of third jet relative to two tagging jets

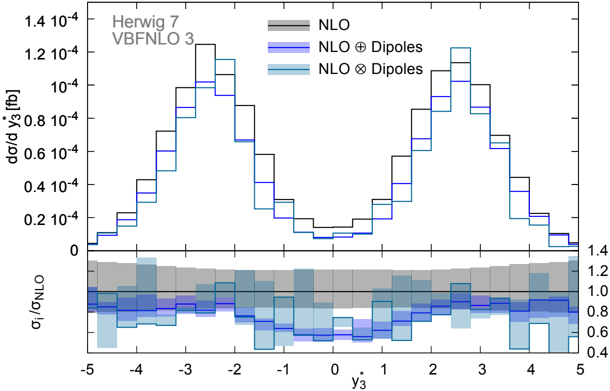
$$y_3^* = y_3 - \frac{y_1+y_2}{2}$$

- 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

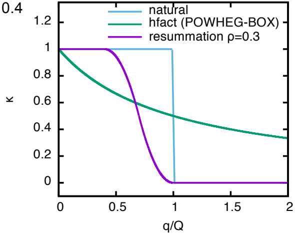
- only small effects in forward region (mostly global normalization)

Rapidity of third jet – POWHEG

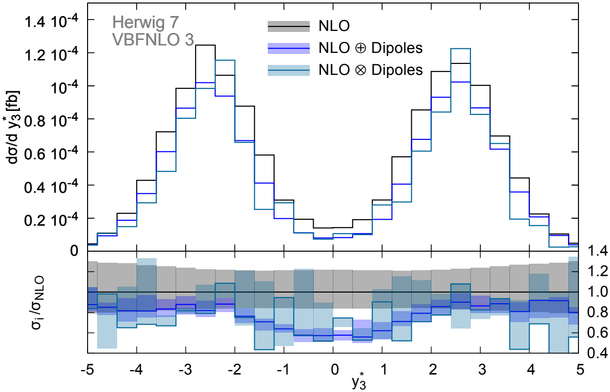


- POWHEG-like (⊗) using resummation scheme [Plätzer]:

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



Rapidity of third jet – POWHEG

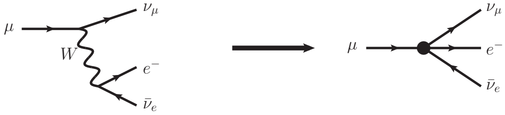


- band: joint variation $\mu_F = \mu_R = \mu_Q \in [\frac{1}{2}, 2]\ \mu_0$
- similar predictions from MC@NLO-like ($\oplus$) and POWHEG-like ($\otimes$) matching
- also holds for other distributions

Effective Field Theory

Assumption: new physics is heavy

Classic example: μ decay $\rightarrow$ Fermi theory (t-channel W integrated out)



$$G_F = \frac{\sqrt{2}}{8} \frac{g^2}{m_W^2}$$

$\Rightarrow$ Effective Lagrangian

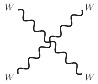
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- operators $\mathcal{O}$ contain SM fields only
- respect SM gauge symmetries
- suppressed by $1/\Lambda^{d-4}$ (Λ: scale of new physics)
  $\rightarrow$ keep only leading order(s) (lowest dimension $d = 6$)
- building blocks:
  - Higgs field Φ
  - (covariant) derivative ∂^μ, D^μ
  - field strength tensors $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$
  - fermion fields ψ

Unitarity Violation

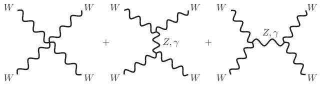
Important gauge cancellations between different diagram types

- longitudinal W scattering through quartic gauge boson vertex



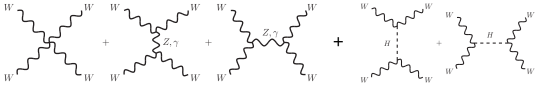
  high energy limit: centre-of-mass energy $\sqrt{s} \to \infty$
  $\mathcal{M}_{\text{quartic vertex}} \propto s^2 \quad \to$ cross section diverges $\quad \sigma \propto s^4/s = s^3 \to \infty$

- add triple gauge boson vertices



  $\mathcal{M}_{\text{quartic+triple vertices}} \propto s \to$ still divergent

- additional Higgs diagrams



  remove divergence exactly $\quad \sigma \propto 1/s \to 0$

Anomalous gauge couplings spoil cancellation $\to$ stringent tests

Unitarization

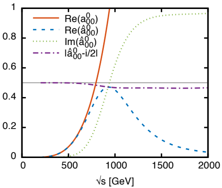
Anomalous gauge couplings spoil cancellation
$\leftrightarrow$ effects can become large $\rightarrow$ unitarity violation

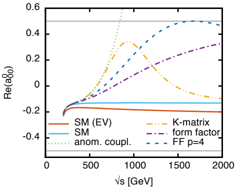
Several solutions:

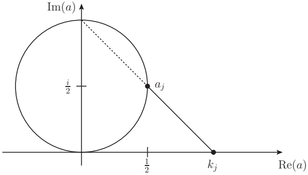
- consider only unitarity-conserving phase-space regions
  throws away information $\rightarrow$ reduced sensitivity
- (dipole) form factor multiplying amplitudes

$$\mathcal{F}(s) = \frac{1}{\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^n} \qquad \Lambda_{FF}^2,\ n\text{: free parameters}$$

- *K*-matrix unitarization [Alboteanu, Kilian, Reuter, Sekulla]
  based on partial-wave analysis [Jacob, Wick]
  project amplitude back onto Argand circle

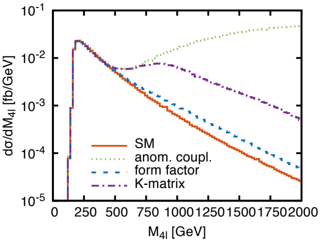


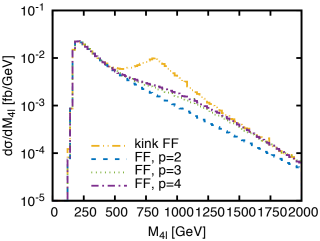




Cross Section Results

Example Process: $pp\ (\to W^+W^+jj) \to e^+\nu_e\mu^+\nu_\mu jj$ at NLO QCD accuracy





- kink form factor (simplified projection for comparison):

$$F_{\text{kink}}(E) = \begin{cases} 1 & \text{for } E \leq \Lambda_{\text{FF,kink}}\,, \\ \left(\frac{\Lambda_{\text{FF,kink}}}{E}\right)^4 & \text{for } E > \Lambda_{\text{FF,kink}}\,, \end{cases}$$

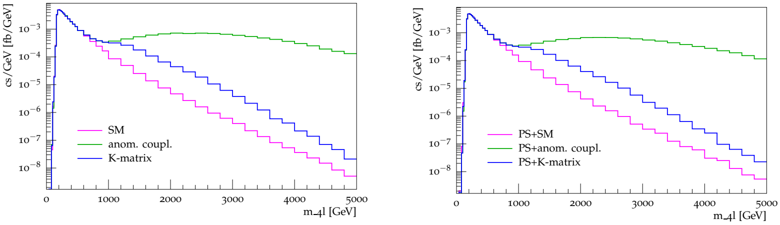
- huge effects for un-unitarized result $\leftrightarrow$ unphysical
- K-matrix method maximising contribution while staying in physical region
- $\to$ study parton-shower and hadronization impact

Combination with Parton Shower

Can also combine K-matrix in setup with parton shower [VBFNLO 3 & Herwig 7]

Example: VBF-W^+W^+ ($pp \to e^+ \nu_e \, \mu^+ \nu_\mu \, jj$)
anom. coupl.: $f_{S,1} = 100$ TeV^{-4}

fixed-order NLO | NLO+PS (MC@NLO + dipole shower)



No significant shape changes in $m_{4\ell}$ when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

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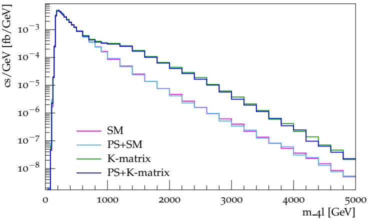
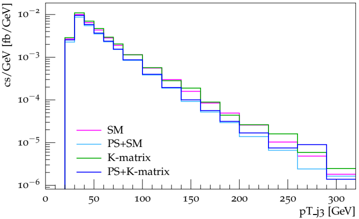
$m_{4\ell}$ – Comparison



$p^T_{j,3}$ – Comparison



No significant shape changes in $m_{4\ell}$ when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

$\leftrightarrow$ $p^T_{j,3}$ mostly sensitive to parton-shower effects

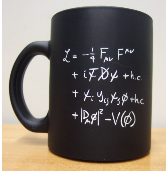
Conclusions

Parton-shower and scale variation effects in

W^+W^-jj production via vector-boson-fusion

- important process for the LHC
  - Higgs properties – unitarity in WW scattering
  - testing anomalous (triple and) quartic gauge couplings
- study performed with Herwig 7 & VBFNLO 3
- compatible behavior of both parton showers and matching schemes
- small parton-shower effects for distributions of variables already present at LO

  mostly reduction of inclusive cross section due to additional jet radiation
- presence of central rapidity gap stabilised
- $\rightarrow$ multi-jet merging to further reduce uncertainties
- $\rightarrow$ study hadronization impact



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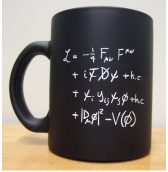
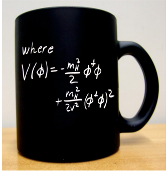




Conclusions

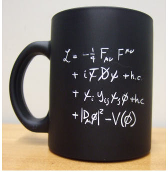
Karlsruhe Institute of Technology

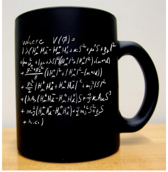
Parton-shower and scale variation effects in

W^+W^-jj production via vector-boson-fusion

- important process for the LHC
  - Higgs properties – unitarity in WW scattering
  - testing anomalous (triple and) quartic gauge couplings
- study performed with Herwig 7 & VBFNLO 3
- compatible behavior of both
  parton showers and matching schemes
- small parton-shower effects for
  distributions of variables already present at LO

  mostly reduction of inclusive cross section due to
  additional jet radiation
- presence of central rapidity gap stabilised
- $\rightarrow$ multi-jet merging to further reduce uncertainties
- $\rightarrow$ study hadronization impact





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:

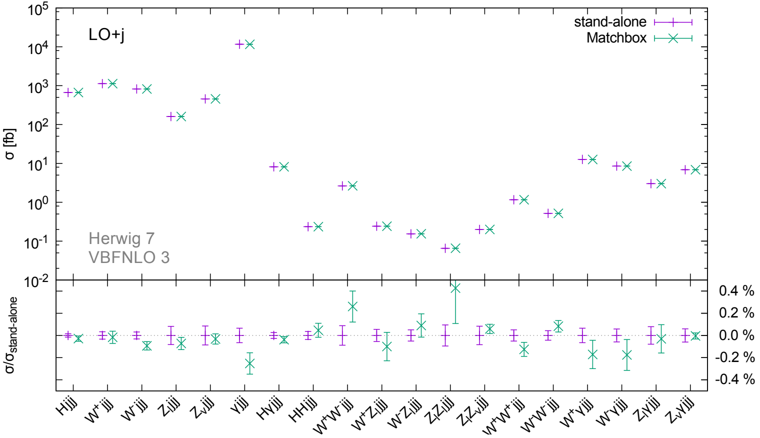
- MC tool:
  - cuts, histograms, parameters
  - Monte Carlo integration
  - phasespace (→ VBFNLO)
  - IR subtraction
  - Born, colour- and spin-correlated Born (only BLHA1)
- One-loop provider (OLP):
  - one-loop matrix elements $2\Re(\mathcal{M}_{\text{LO}}^{\dagger}\mathcal{M}_{\text{virt}})$ (coefficients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

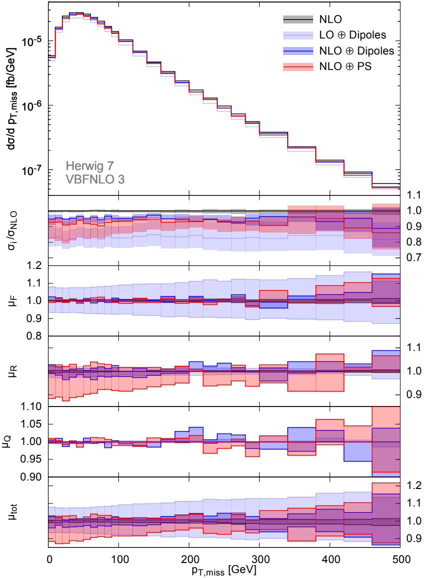
Generation-level cuts:

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

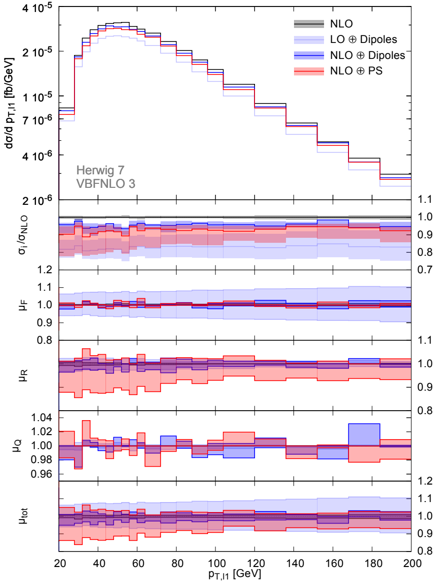
Analysis-level cuts:

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

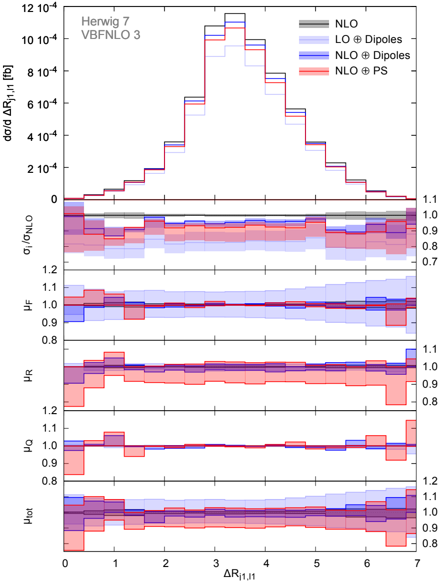
Missing Transverse Momentum



Transverse Momentum of Leading Lepton



R Separation of Leading Jet and Leading Lepton

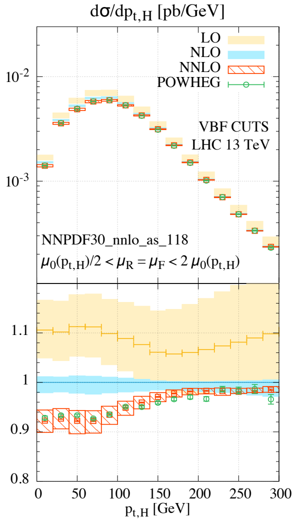


$$\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$$

Jacobian peak at $\Delta R_{j1\ell1} = \pi$

NNLO QCD Correction to VBF-H

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi]



- NNLO effects well approximated by NLO plus parton-shower results