Karlsruhe Institute of Technology

Parton-shower effects in vector-boson-fusion processes

in collaboration with S. Plätzer

Michael Rauch | DIS 2016, Apr 2016

INSTITUTE FOR THEORETICAL PHYSICS

VBF event topology

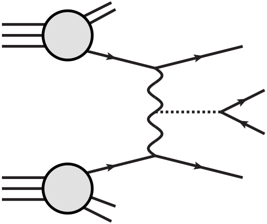
VBF (vector-boson fusion) topology shows distinct signature

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

$\to$ two-sided DIS

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, opposite sign as QCD for $M_H \sim 126$ GeV [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.*]
- advantageous scale choice: momentum transfer q^2 of intermediate vector bosons

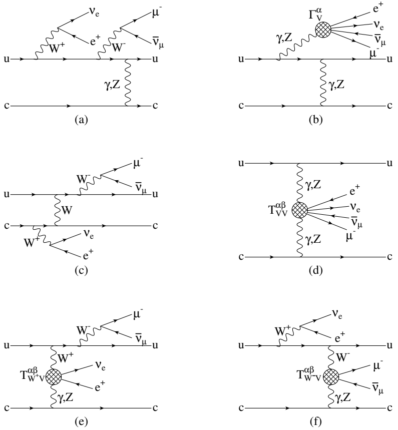


Diboson-VBF production

[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.]



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

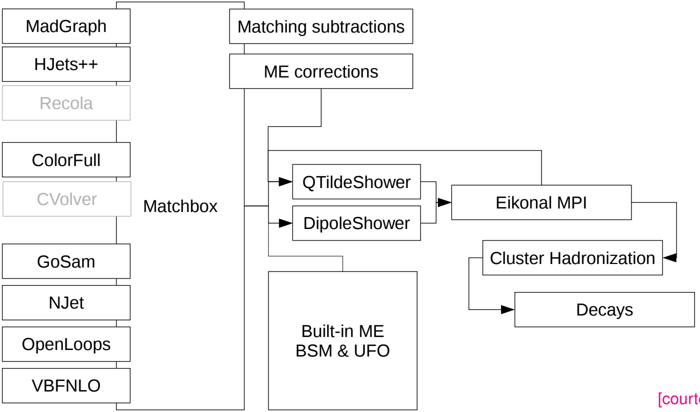
State of the Art

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

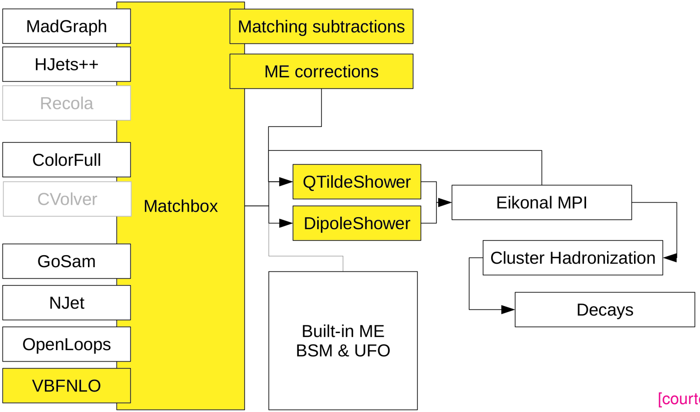
- fully automated matching of NLO to parton showers through Matchbox module
  [work led by S. Plätzer with substantial contributions by J. Bellm, A. Wilcock, MR, C. Reuschle]
- subtractive (MC@NLO-type, ⊕) and multiplicative (POWHEG-type, ⊗) matching
- angular-ordered (QTilde, PS) and dipole (Dipoles)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



[courtesy of S. Plätzer]

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

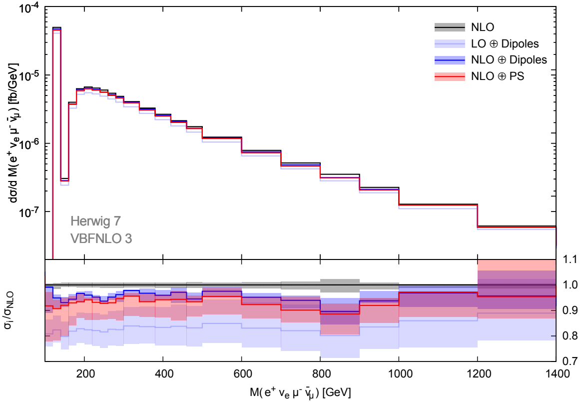


[courtesy of S. Plätzer]

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
- $\mathcal{M}_{\text{4-vertex only}} \propto M_{4\ell}^4$
- $\mathcal{M}_{\text{Higgs}} \propto M_{4\ell}^2$
- $\mathcal{M}_{\text{tot}} \propto$ const.
- $\Rightarrow$ 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
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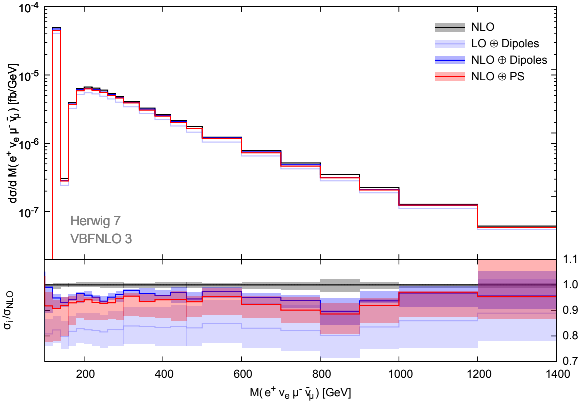
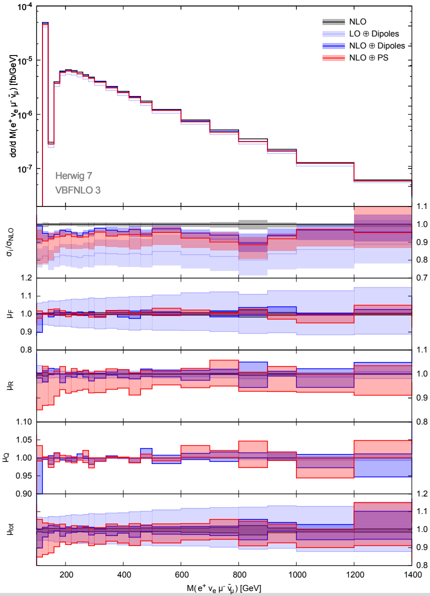


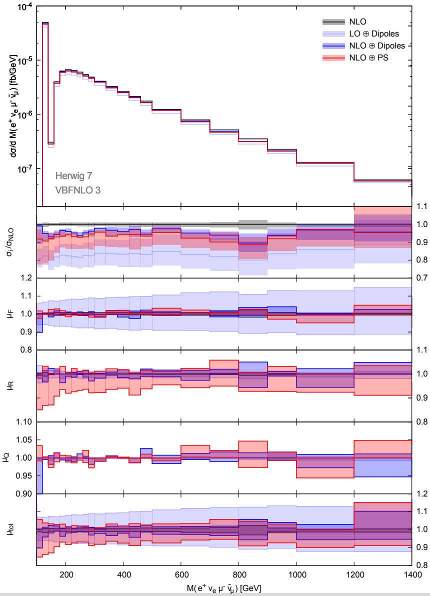
- all parton-shower results smaller than NLO cross section
- additional parton splittings hard, wide-angle → separate jet
- ↔ VBF cut $m_{jj} > 600$ GeV
- no relevant shape changes (as expected: insensitive to QCD effects)

Four-lepton Invariant Mass



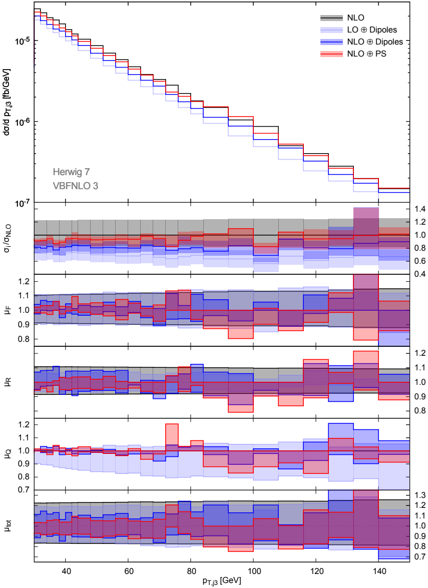
- ← central scale $\mu_0 = p_{T,j1}$ transverse momentum of leading jet
- ← band: scale variation $\{\mu_F, \mu_R, \mu_Q\} / \mu_0 \in [\frac{1}{2}; 2]$ $\mu_i/\mu_j \in [\frac{1}{2}; 2]$
- ← factorization scale $\mu_F \in [\frac{1}{2}; 2]$
- ← renormalization scale $\mu_R \in [\frac{1}{2}; 2]$
- ← shower scale $\mu_Q \in [\frac{1}{2}; 2]$
- ← 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:
  ↔ under investigation
- small variations from shower-scale changes
- modest remaining overall uncertainty

Transverse Momentum Third Jet

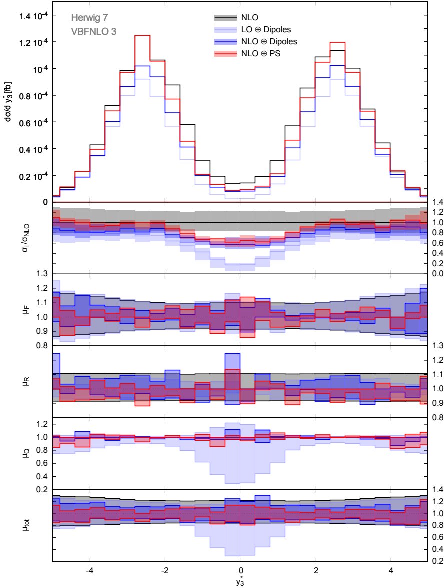


- large scale variation bands for
  - shower scale in LO⊕Dipoles

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

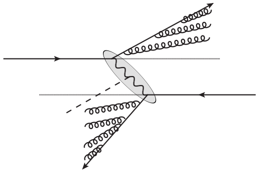
    → LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10-20\%)$
- → call for multi-jet merging

Rapidity of third jet



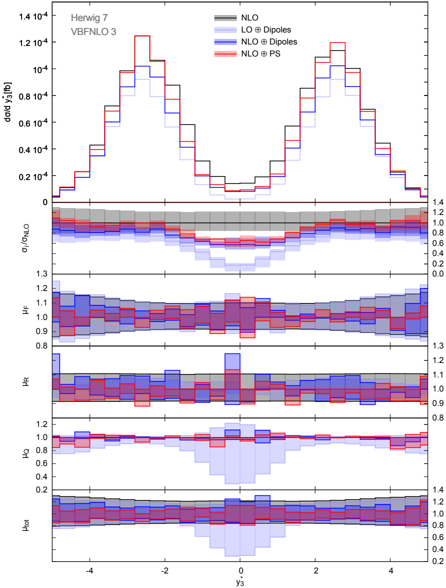
Rapidity of third jet relative to two tagging jets

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



- 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

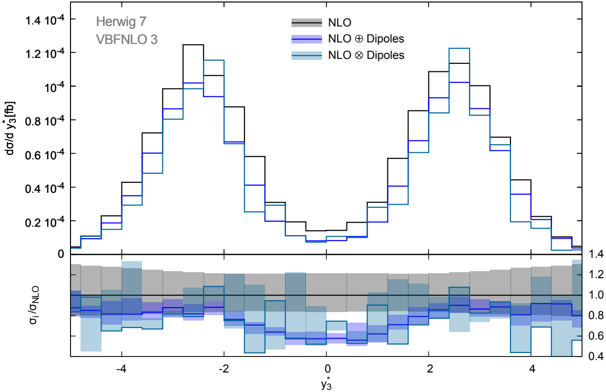


Rapidity of third jet
relative to two tagging jets

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

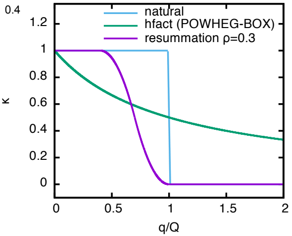
- impact of parton showers (+LO) long unclear
- Herwig predicts very low radiation in central region
- large shower-scale unc.
- stabilised when combining with NLO
- still reduction present
- scale variation bands not overlapping
- only small effects in forward region (mostly global normalization)

Rapidity of third jet – POWHEG

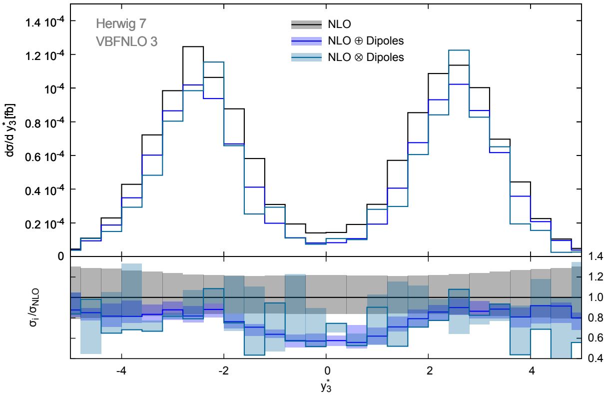


- POWHEG-like (⊗) using resummation scheme [Plätzer]:

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



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

Conclusions

Parton-shower and scale variation effects in

W^+W^- 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

Setup

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Cuts:

$$p_{T,j} > 30\text{ GeV}\,, \qquad |y_j| < 4.5\,,$$
$$p_{T,\ell} > 20\text{ GeV}\,, \qquad |y_\ell| < 2.5\,,$$
$$m_{j1,j2} > 600\text{ GeV}\,, \qquad |y_{j1} - y_{j2}| > 3.6\,,$$

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

BLHA Interface

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

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

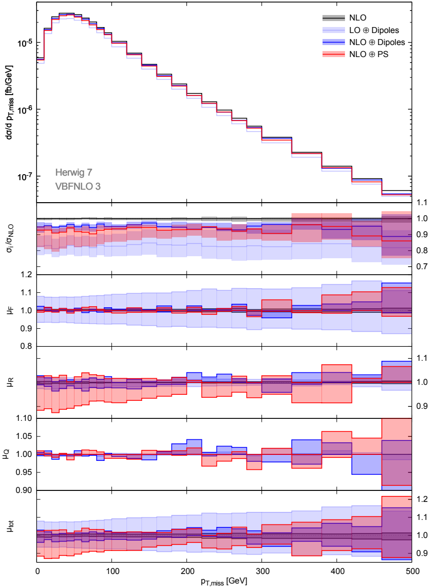
- tree-level evaluation of matrix elements well under control
- modular structure of NLO calculations
- algorithms for treatment of infrared singularities (Catani-Seymour, FKS, . . .)
- → incorporate one-loop matrix element information into MC tools

Distribution of tasks:

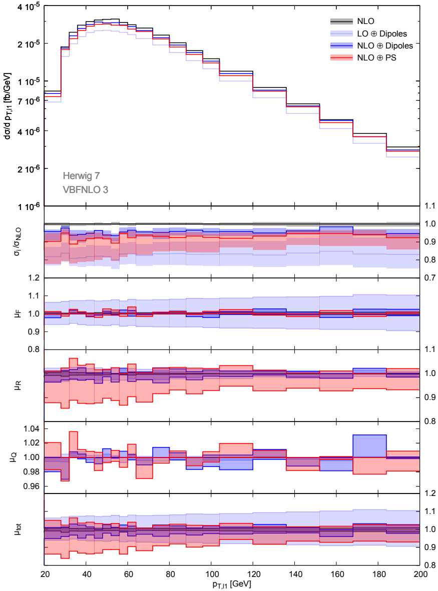
- MC tool:
  - cuts, histograms, parameters
  - Monte Carlo integration
  - phasespace (→ VBFNLO)
  - IR subtraction
  - Born, colour- and spin-correlated Born (only BLHA1)
- One-loop provider (OLP):
  - one-loop matrix elements $2\Re(\mathcal{M}_{\text{LO}}^{\dagger}\mathcal{M}_{\text{virt}})$ (coefficients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

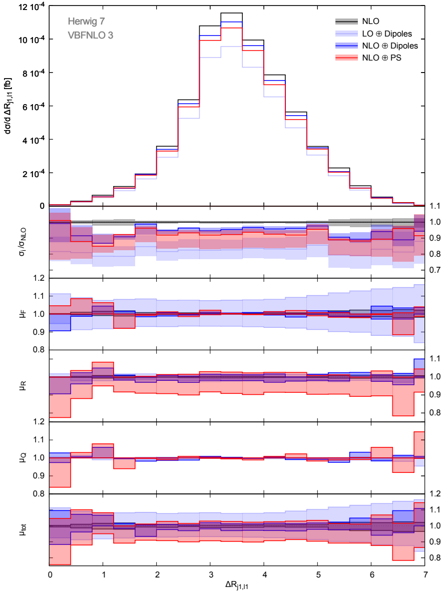
Missing Transverse Momentum



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 $\Delta R_{j1\ell1} = \pi$