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# Vector Boson Fusion and Scattering: Parton-Shower Effects

Michael Rauch | Workshop “Future of VBF Measurements”, 22 Sep 2016

INSTITUTE FOR THEORETICAL PHYSICS

# VBF event topology

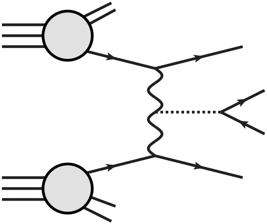
VBF (vector-boson fusion) topology shows distinct signature

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

$\rightarrow$ 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

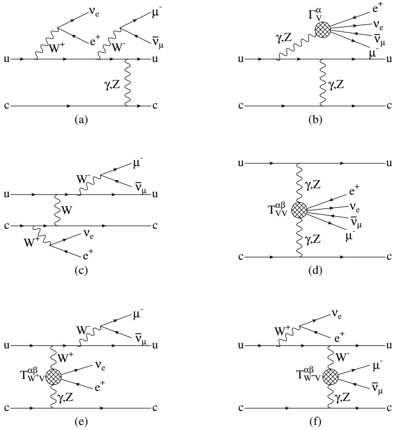
[Bozzi, Jäger, Oleari, Zeppenfeld (VV); Campanario, Kaiser, Zeppenfeld ($W^{\pm}\gamma$)]
[Denner, Hosekova, Kallweit ($W^{+}W^{+}$)]

- 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.]



# NLO plus Parton Shower

Combine advantages of NLO calculations and parton shower

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## 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

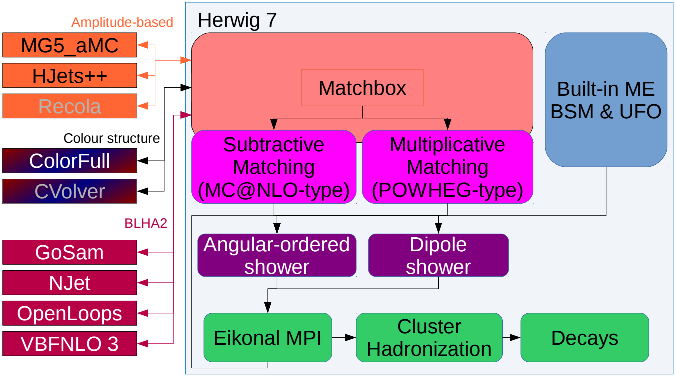
## State of the Art

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]
  - $H$+3jets [Jäger, Schissler, Zeppenfeld]
- VBF-$H$ with POWHEG method [D'Errico, Richardson]
- HJets++ [Campanario, Figy, Plätzer, Sjödahl]

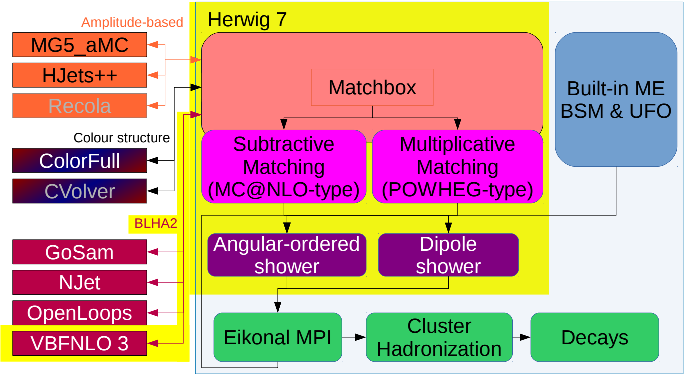
# Herwig 7 H7

- 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, $\oplus$) 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 – 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



# Setup

[Plätzer, MR]

Process:

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

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

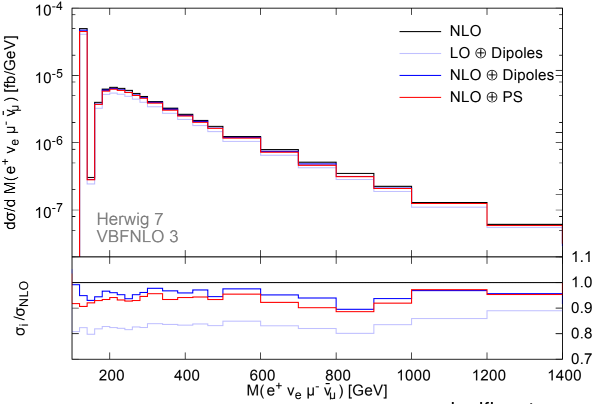
central scale choice: transverse momentum of the leading jet

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

(close to momentum transfer $|q^2|$ in VBF region)

# Distributions

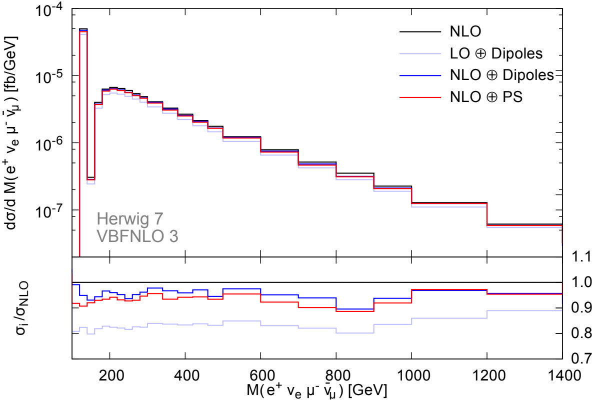
Process as example: $pp \to ((Hjj \to) W^+ W^- jj \to) e^+ \nu_e \mu^- \bar{\nu}_\mu jj$ via VBF
Four-lepton invariant mass




- 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

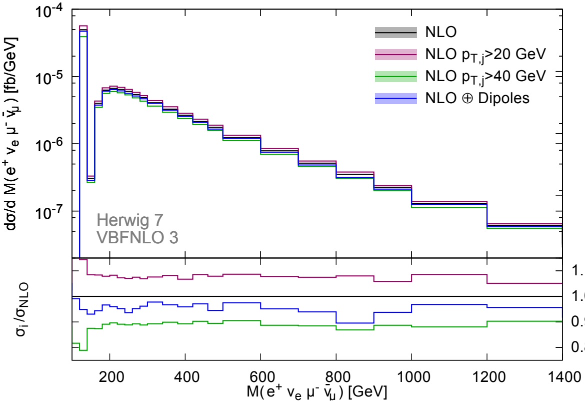
Process as example: $pp \to ((Hjj \to) W^+ W^- jj \to) e^+ \nu_e \mu^- \bar{\nu}_\mu jj$ via VBF
Four-lepton invariant mass




- 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)

# Migration Effects

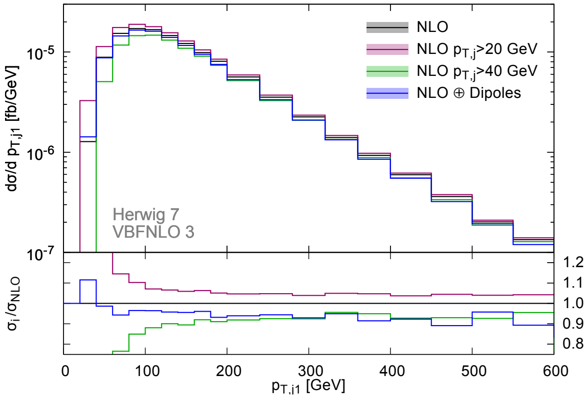
Vary transverse momentum cut of jets (default: $p_{T,j} > 30$ GeV)




- 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

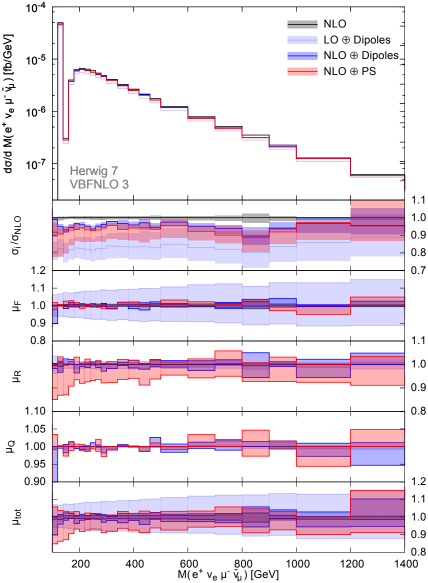
# Migration Effects

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

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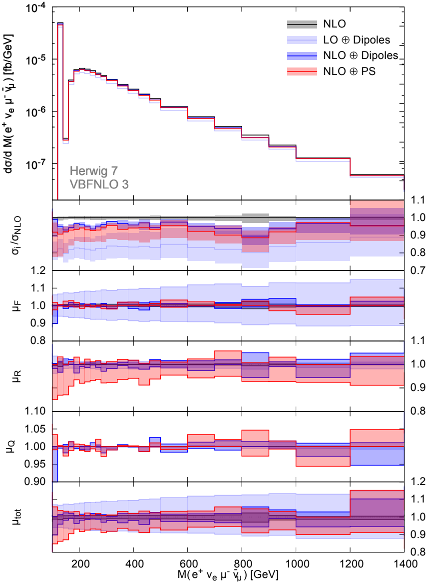
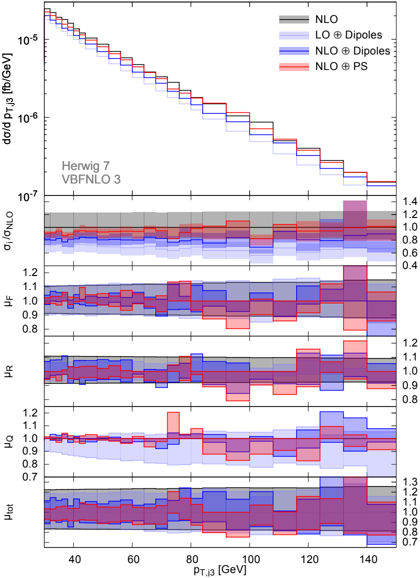
- ← central scale $\mu_0 = p_{T,j1}$ transverse momentum of leading jet
- ← band: scale variation $\{\mu_F, \mu_R, \mu_Q\} / \mu_0 \in [\frac{1}{2}; 2]$ $\mu_i/\mu_j \in [\frac{1}{2}; 2]$
- ← factorization scale $\mu_F/\mu_0 \in [\frac{1}{2}; 2]$
- ← renormalization scale $\mu_R/\mu_0 \in [\frac{1}{2};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

# Four-lepton Invariant Mass



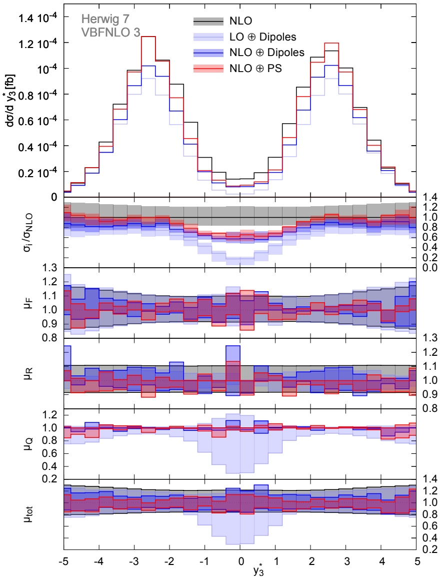

- consistent variation of scales between hard process and parton shower
- large factorization scale dependence for LO result
- larger dependence for down variation of renormalization scale in angular-ordered shower: larger $\alpha_s \to$ more splittings $\to$ bigger migration effects
- small variations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

# Transverse Momentum Third Jet



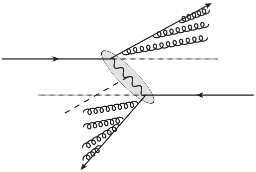

- large scale variation bands for
  - shower scale in LO⊕Dipoles
    
    → pure parton-shower effect
  - fact./ren. scale in “NLO”
    
    → LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10-20\%)$
- → call for multi-jet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

# Rapidity of third jet



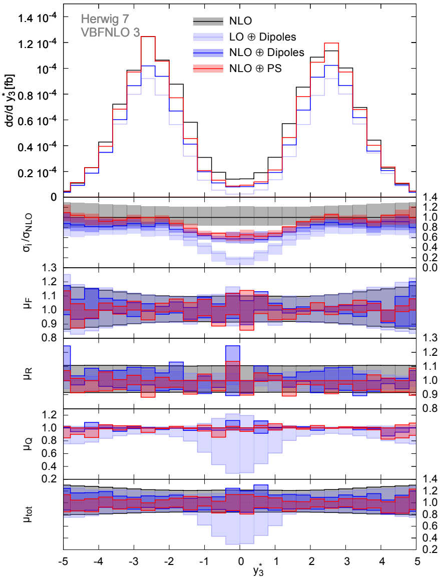

Rapidity of third jet relative to two tagging jets

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



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

# Rapidity of third jet

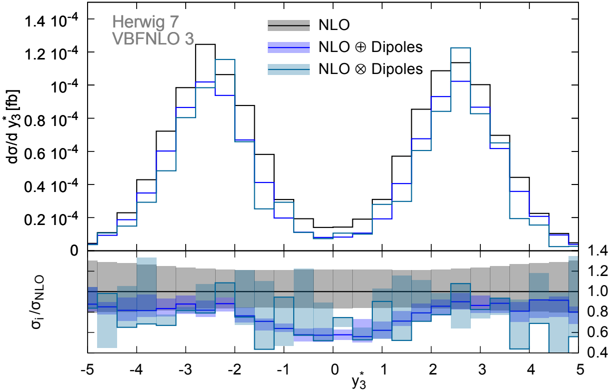



Rapidity of third jet relative to two tagging jets

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

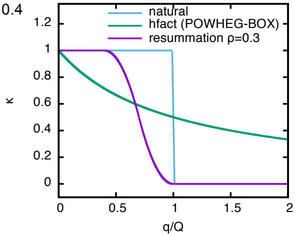
- impact of parton showers (+LO) long unclear
- Herwig predicts very low radiation in central region
- large shower-scale unc.
- stabilised when combining with NLO
- still reduction present
- scale variation bands not overlapping
- only small effects in forward region (mostly global normalization)

# Rapidity of third jet – POWHEG

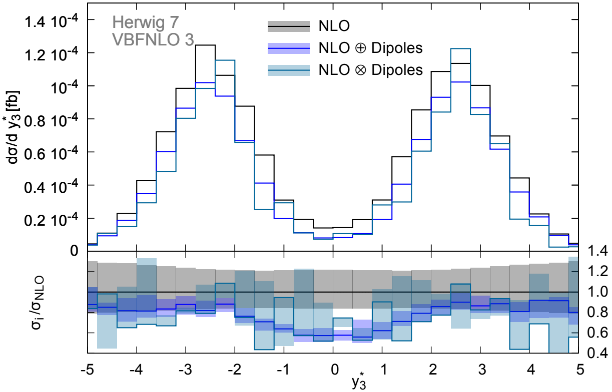



- POWHEG-like (⊗) using resummation scheme [Plätzer]:

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



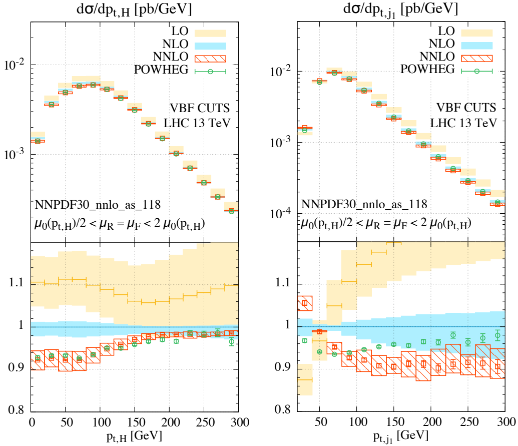
# Rapidity of third jet – POWHEG




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

# NNLO QCD vs. Parton Shower for VBF-$H$

[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,

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

- NNLO effects well approximated by NLO plus parton-shower results for some distributions, remaining differences for others

# 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

# 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:

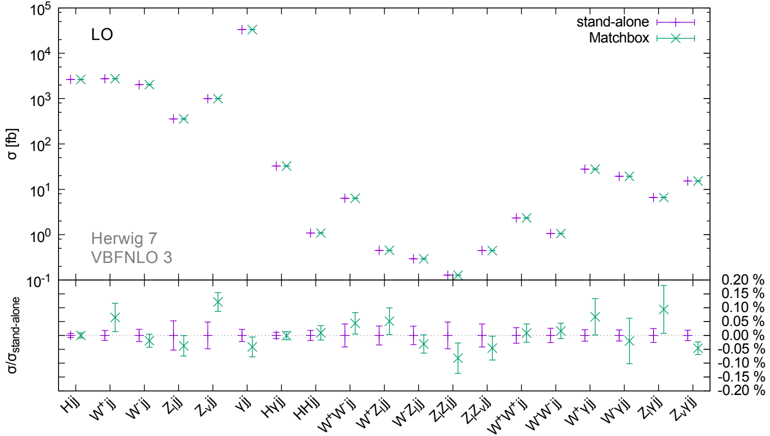
- MC tool:
  - cuts, histograms, parameters
  - Monte Carlo integration
  - phasespace (→ VBFNLO)
  - IR subtraction
  - Born, colour- and spin-correlated Born (only BLHA1)
- One-loop provider (OLP):
  - one-loop matrix elements $2\Re(\mathcal{M}_{\text{LO}}^{\dagger}\mathcal{M}_{\text{virt}})$ (coefficients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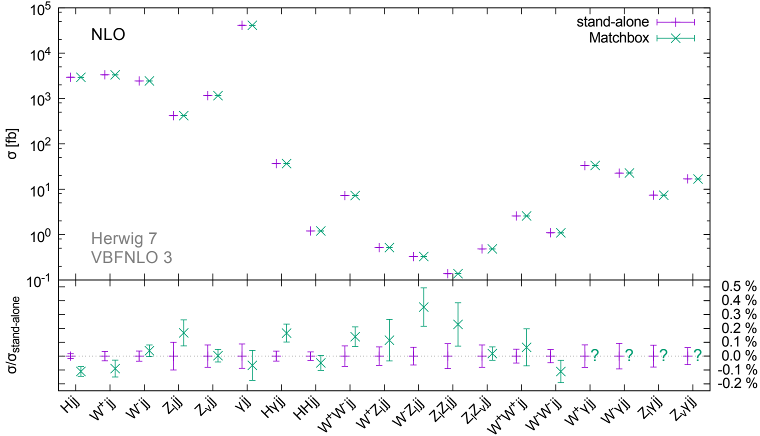


→ good agreement

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

# Validation

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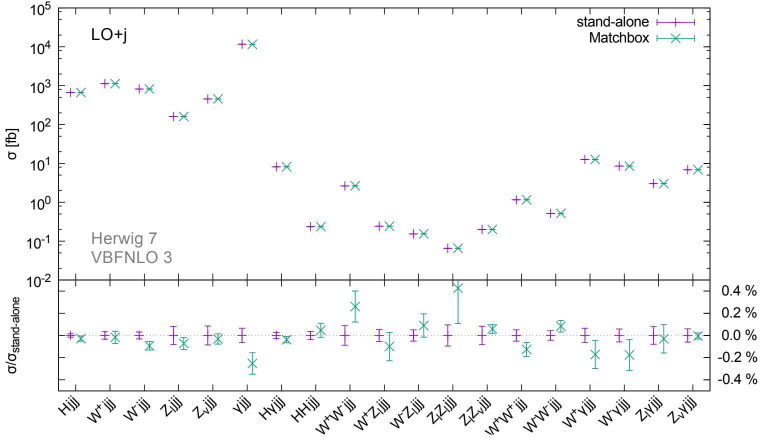
Compare LO+j results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox

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




→ good agreement

# Setup

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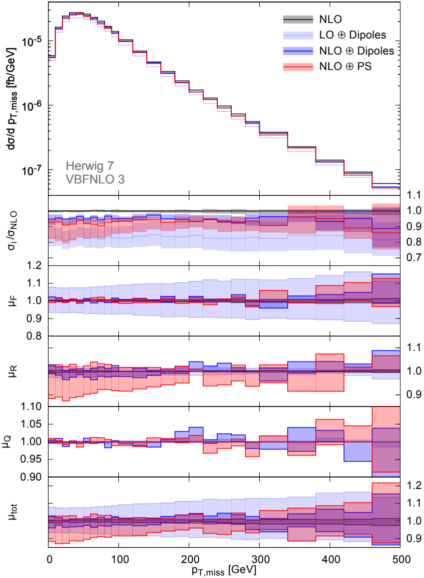
Generation-level cuts:

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

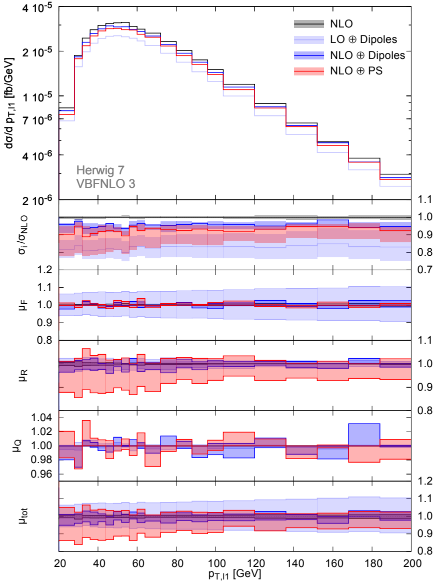
Analysis-level cuts:

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

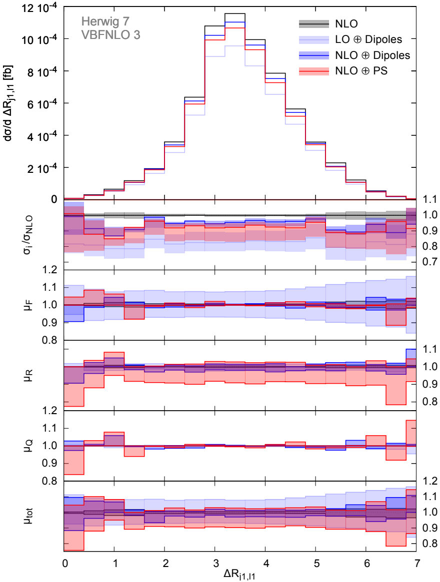
# Missing Transverse Momentum



# 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 $\Delta R_{j1\ell 1} = \pi$