Karlsruhe Institute of Technology

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Parton-shower Systematics in VBS

Michael Rauch | 16 Nov 2017

INSTITUTE FOR THEORETICAL PHYSICS

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

$\leftrightarrow$ not one answer $\rightarrow$ many choices

- scales: renormalization, factorization, shower-starting
- matching scheme: MC@NLO, Powheg, KrkNLO, ...
- parton shower ordering: p_T, angular-ordered, ...

$\rightarrow$ options equivalent to considered accuracy $\leftrightarrow$ differences of higher order

$\rightarrow$ uncertainties

VBFNLO

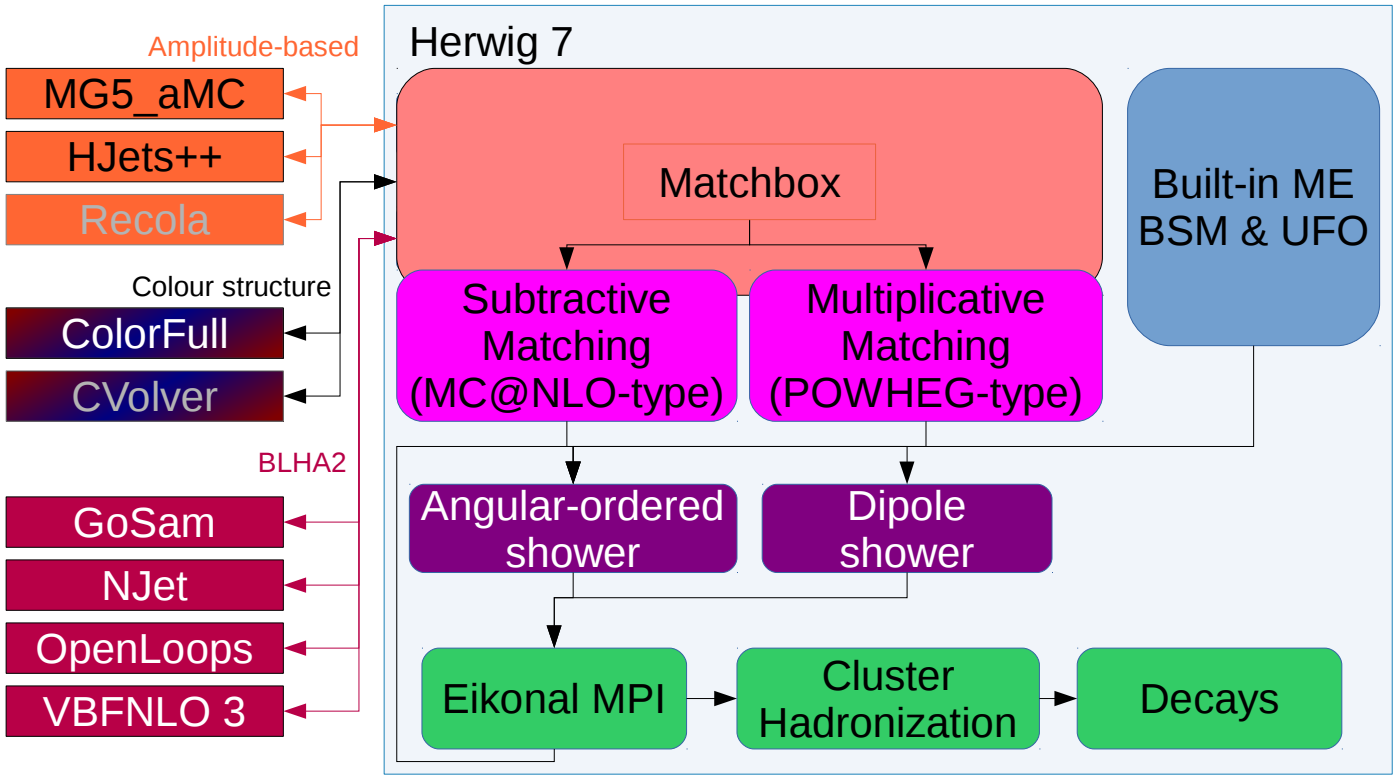
F
~~Ph~~ysics
Vector-Boson-~~Fusion~~ at Next-to-Leading Order

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons
- Process list
  - VBF/VBS production at NLO QCD of
    - Higgs
    - 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 (all combinations)
  - triboson production (all combinations)
    (semi-leptonic decay mode contributes to VBS final state)
  - ...
- new physics models
  - anomalous Higgs, triple and quartic gauge couplings
  - ...
- BLHA interface to Monte-Carlo event generators
  $\rightarrow$ NLO event output

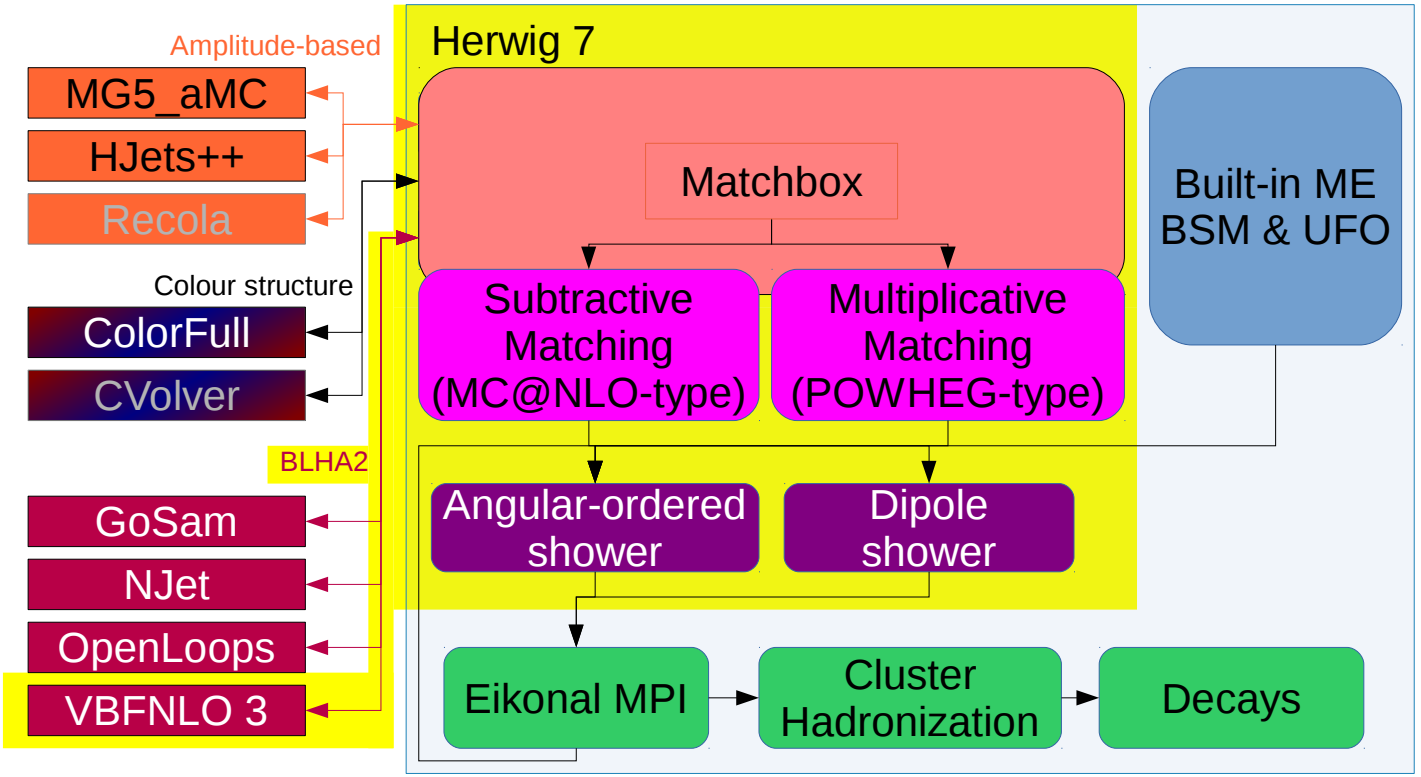
Herwig 7

- 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, $\oplus$) 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

Process: [Plätzer, MR]

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

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)

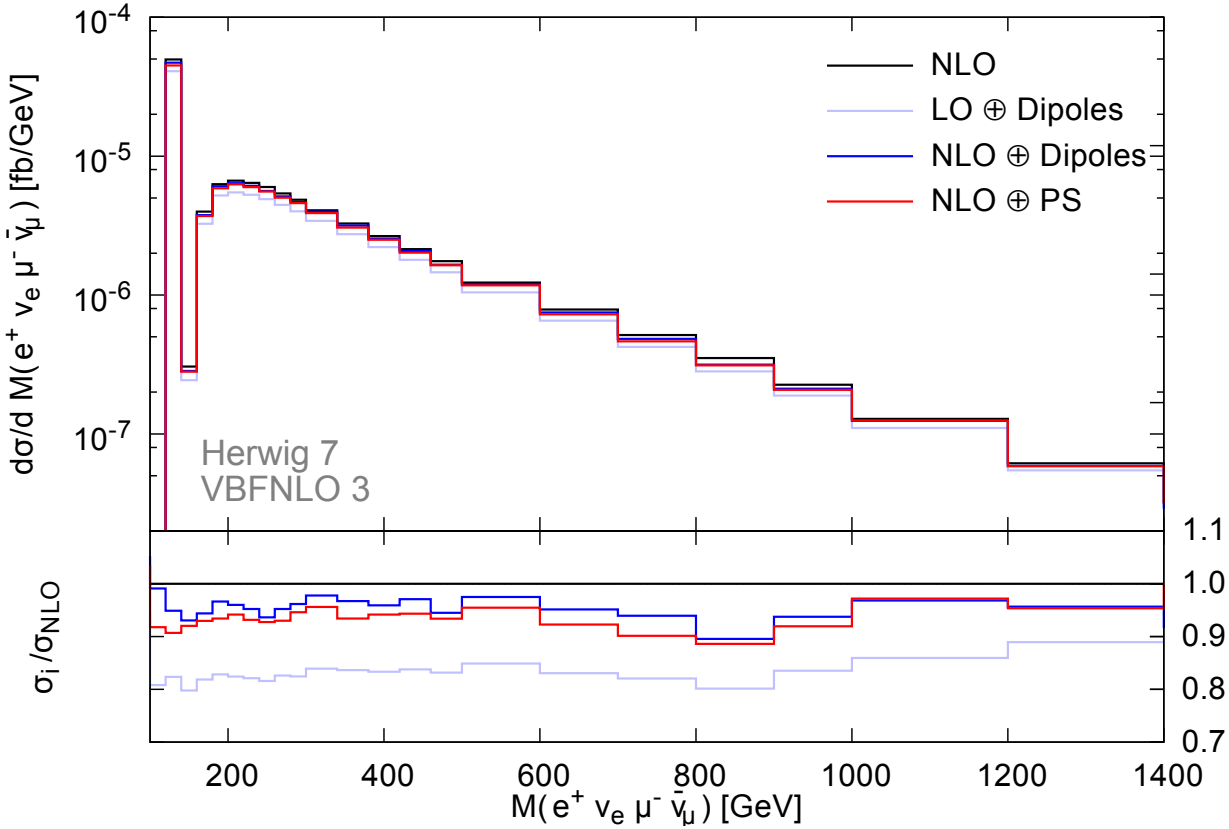
PDF: MMHT2014

central scale choice: transverse momentum of the leading jet

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

Distributions

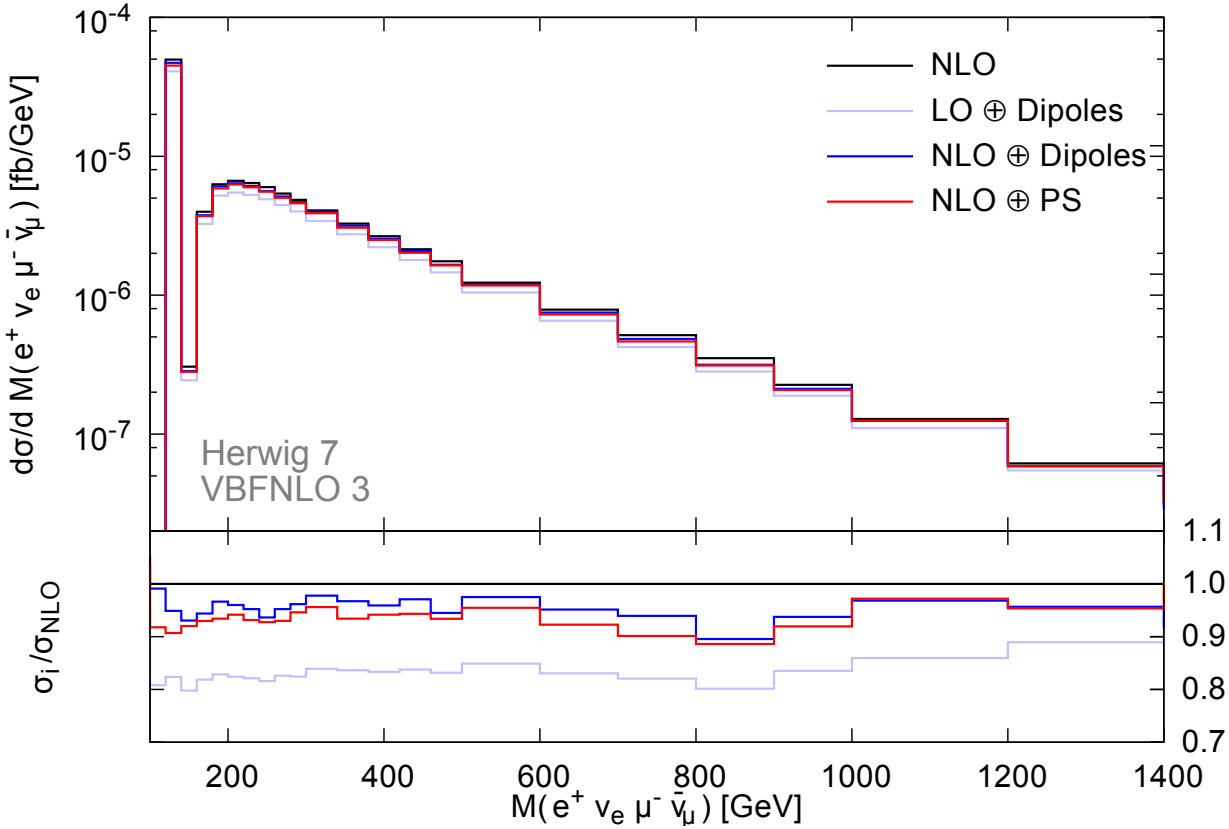
Process as example: $pp \to \big((Hjj \to) W^+W^- jj \to\big) e^+\nu_e\mu^-\bar{\nu}_\mu jj$ via VBS
Four-lepton invariant mass



- 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

Distributions

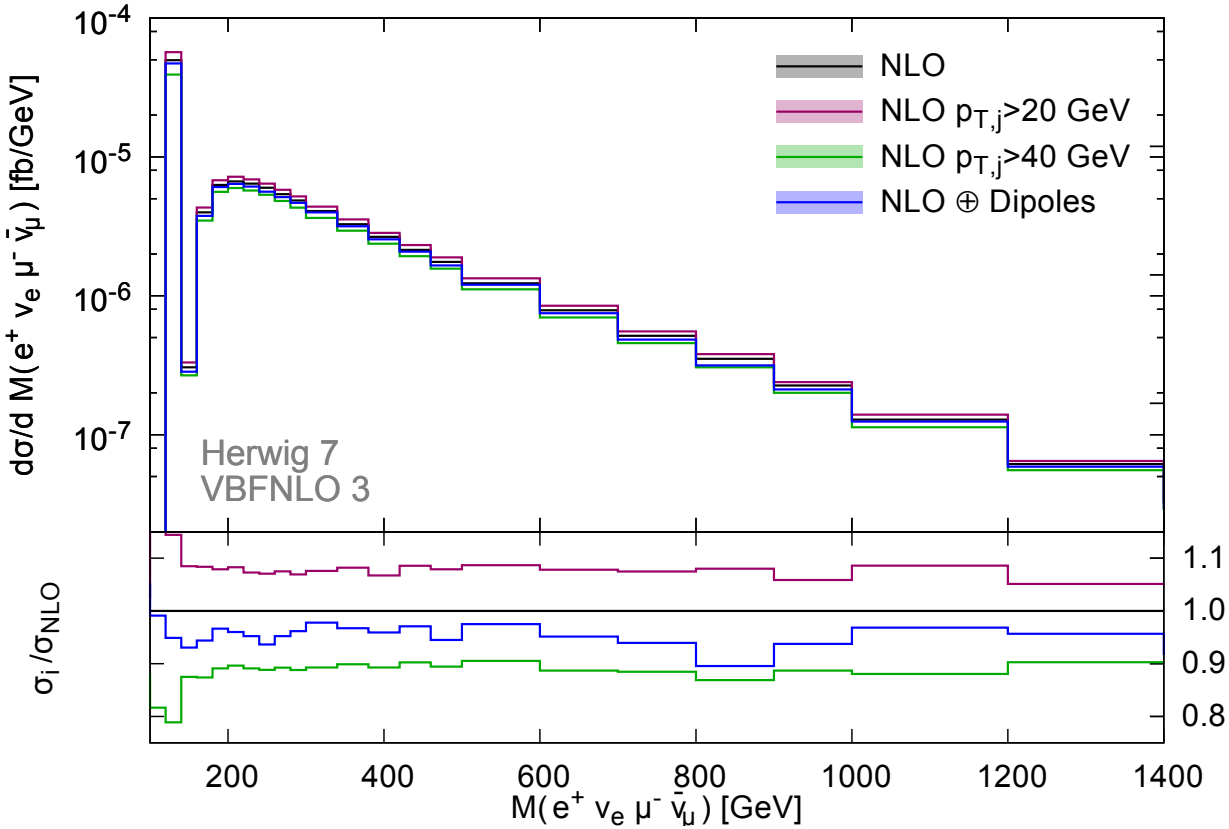
Process as example: $pp \to \big((Hjj \to) W^+W^-jj \to\big) e^+\nu_e\mu^-\bar{\nu}_\mu jj$ via VBS
Four-lepton invariant mass



- 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

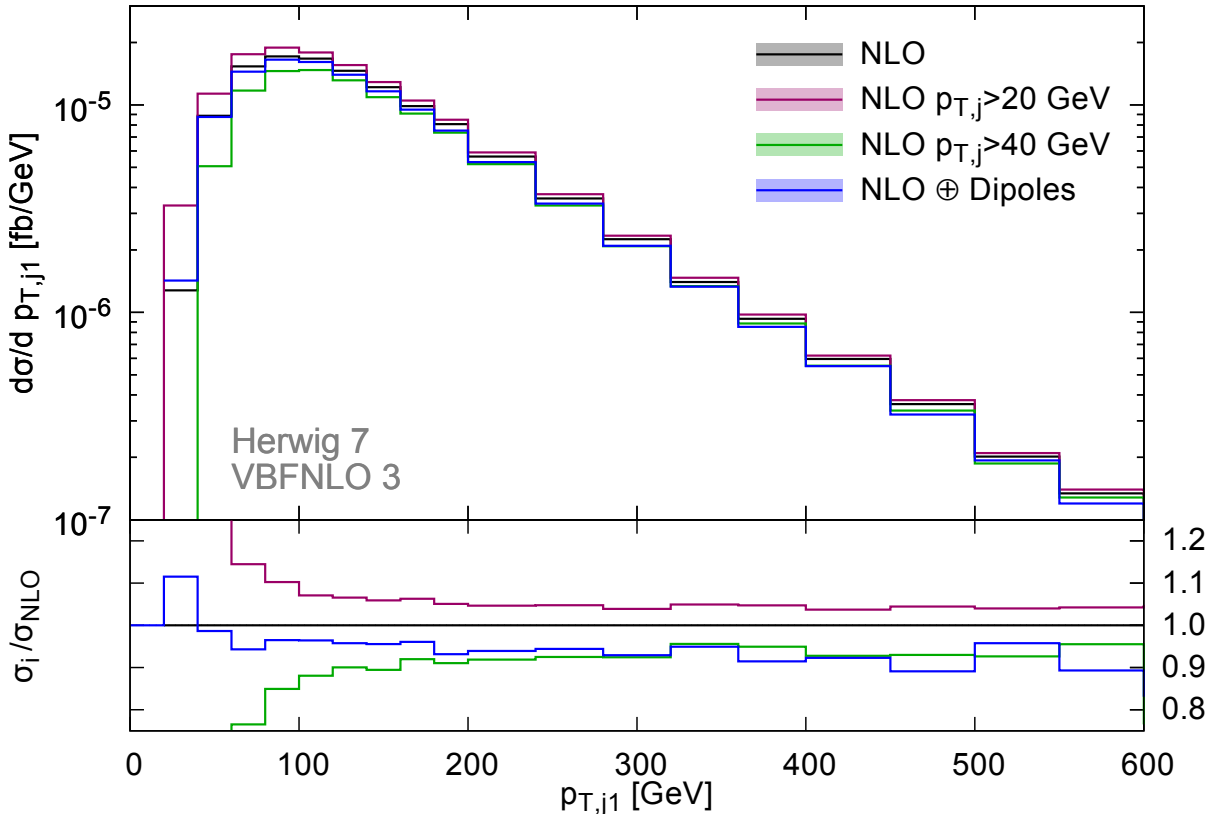
Vary transverse momentum cut of jets (default: $p_{T,j} > 30$ GeV)



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

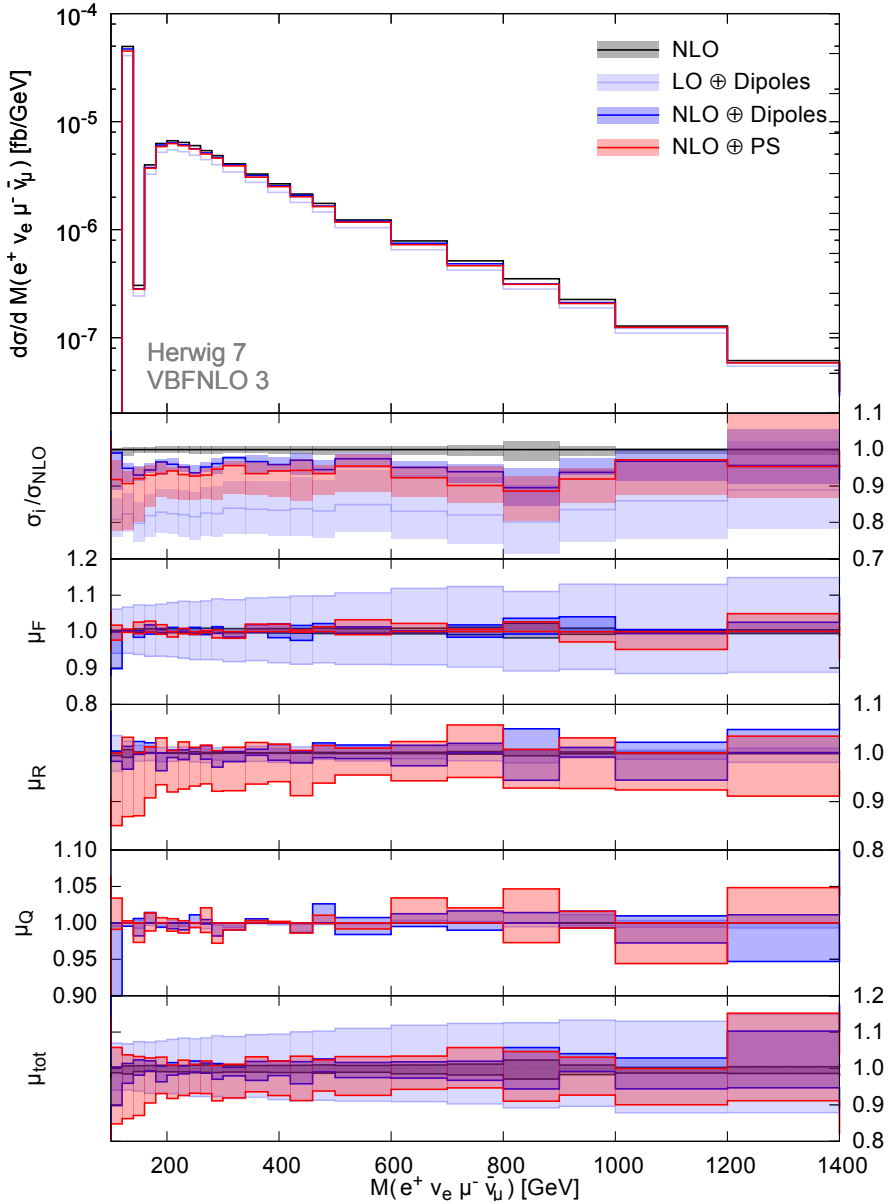
Migration Effects

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



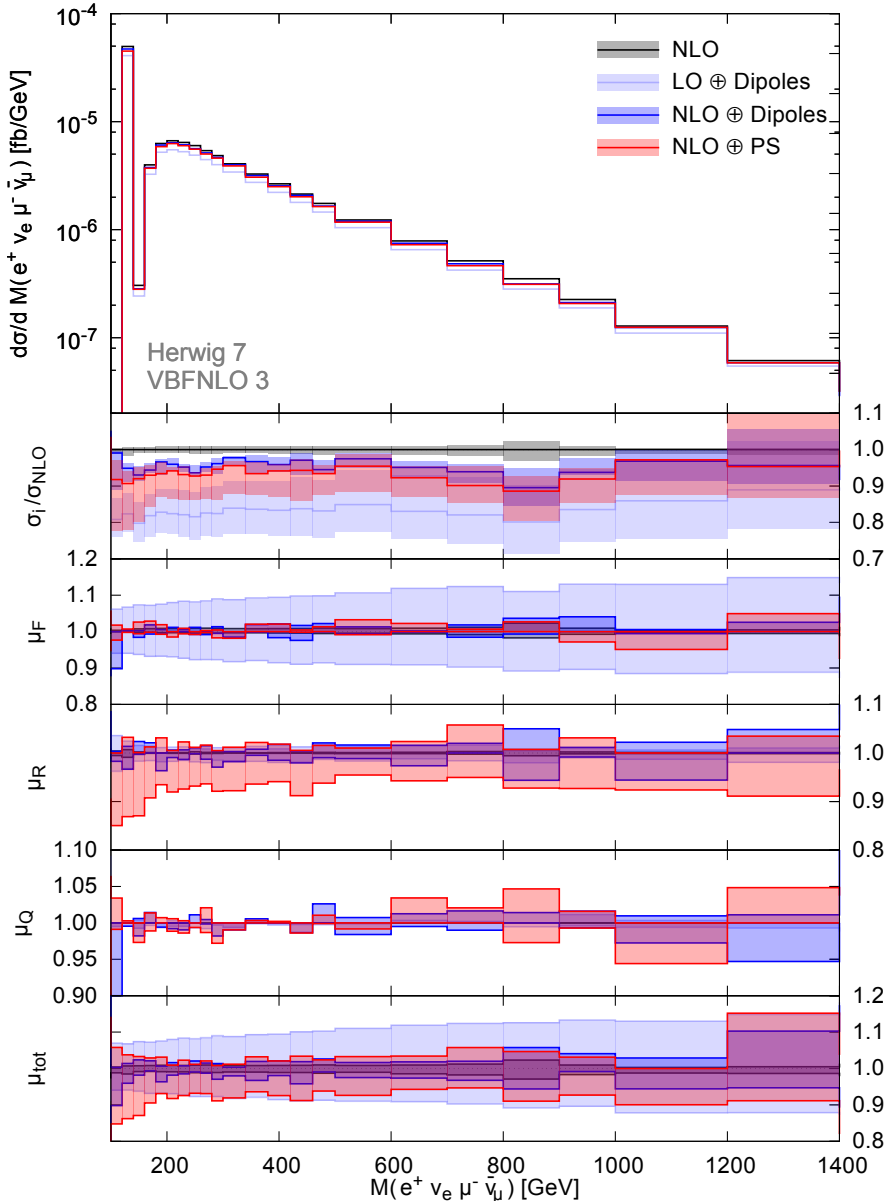
- less pronounced for small $p_{T,j1}$
  $\rightarrow$ VBF cut main source
- $\rightarrow$ migration of events across cut boundary
- $\leftrightarrow$ generation-level vs. analysis-level cuts
- $\Rightarrow$ no tuning of acceptance criteria required
- generation-level cuts nevertheless chosen weaker

Four-lepton Invariant Mass



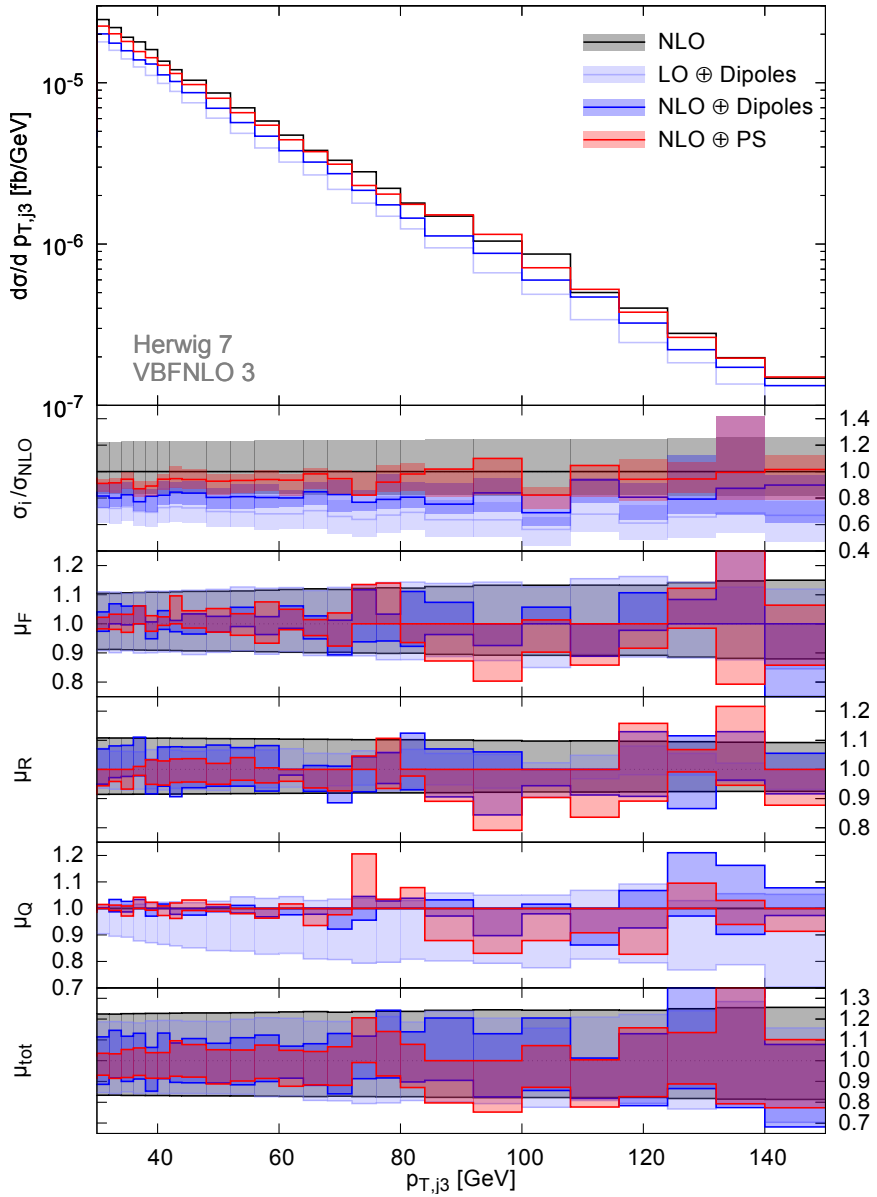
- ← central scale $\mu_0 = p_{T,j1}$ transverse momentum of leading jet
- ← band: scale variation $\{\mu_F, \mu_R, \mu_Q\}/\mu_0 \in [\frac{1}{2}; 2]$ $\mu_i/\mu_j \in [\frac{1}{2}; 2]$
- ← factorization scale $\mu_F/\mu_0 \in [\frac{1}{2}; 2]$
- ← renormalization scale $\mu_R/\mu_0 \in [\frac{1}{2};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

Four-lepton Invariant Mass



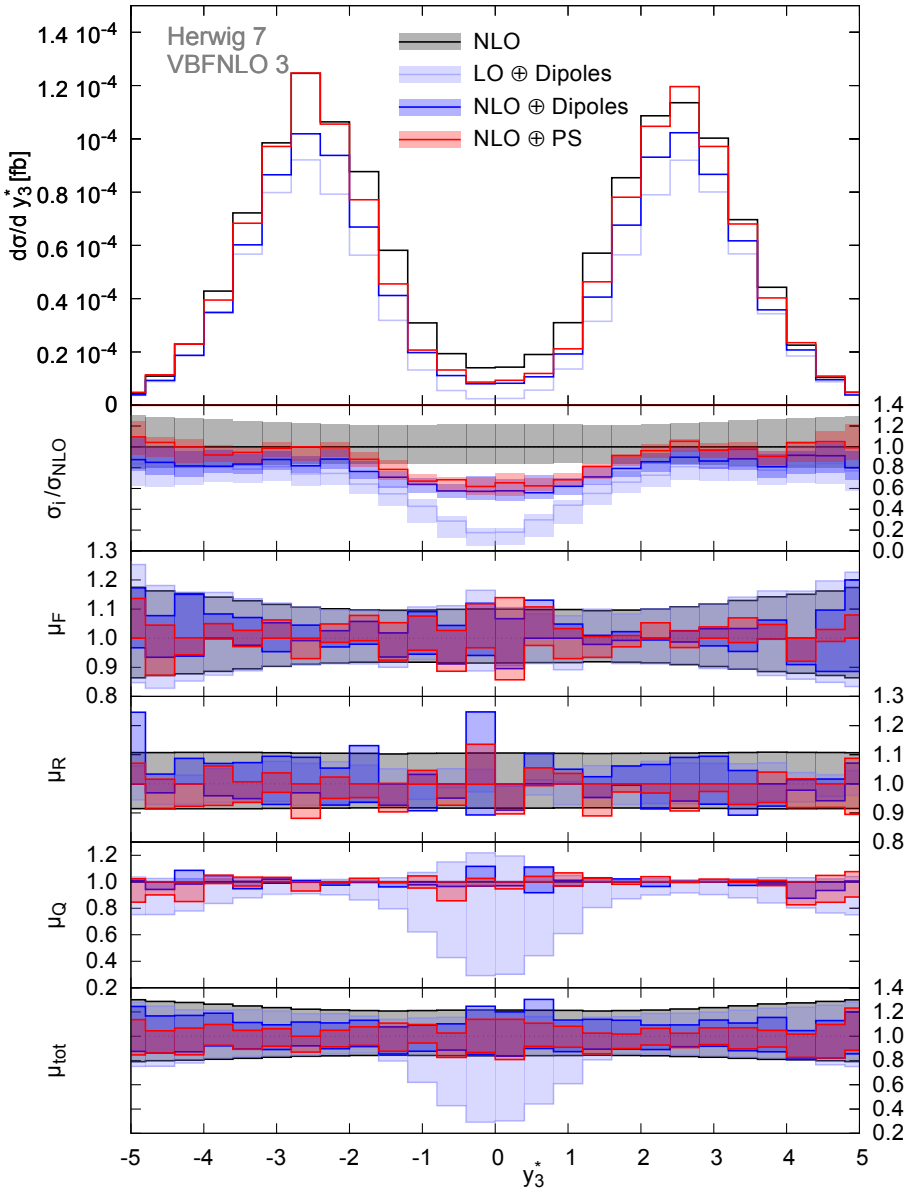
- consistent variation of scales between hard process and parton shower
- large factorization scale dependence for LO result
- larger dependence for down variation of renormalization scale in angular-ordered shower:
  larger $\alpha_s \rightarrow$ more splittings
  $\rightarrow$ bigger migration effects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

Transverse Momentum Third Jet



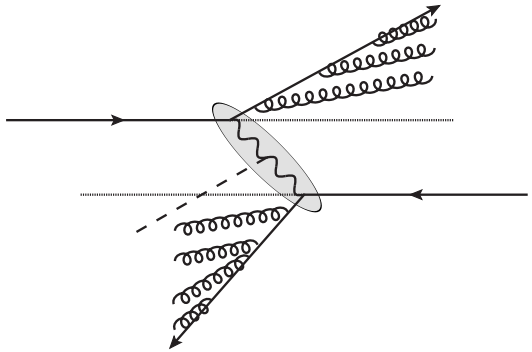
- large scale variation bands for
  - shower scale in LO⊕Dipoles
    → pure parton-shower effect
  - fact./ren. scale in “NLO”
    → LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10-20\%)$
- → call for multi-jet merging

Rapidity of third jet



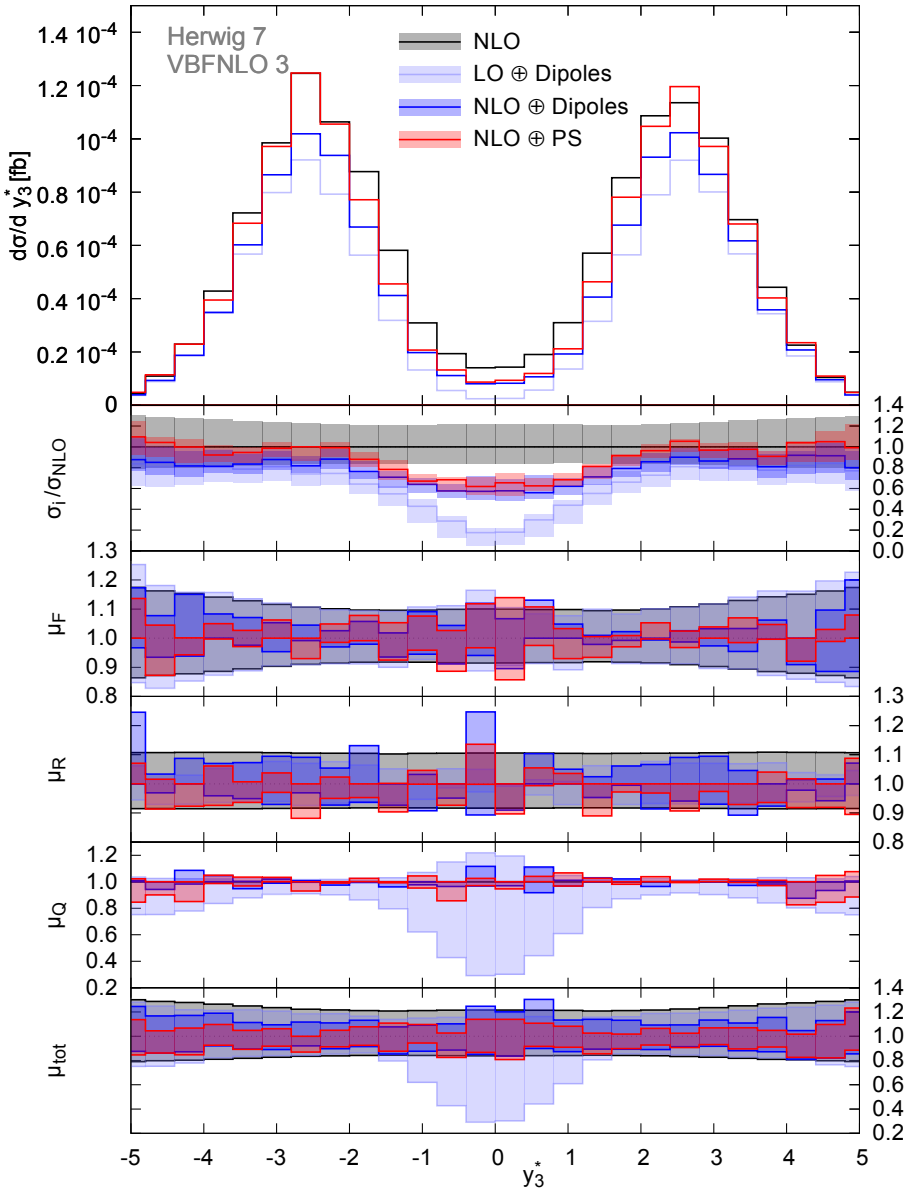
Rapidity of third jet
relative to two tagging jets

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



- 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

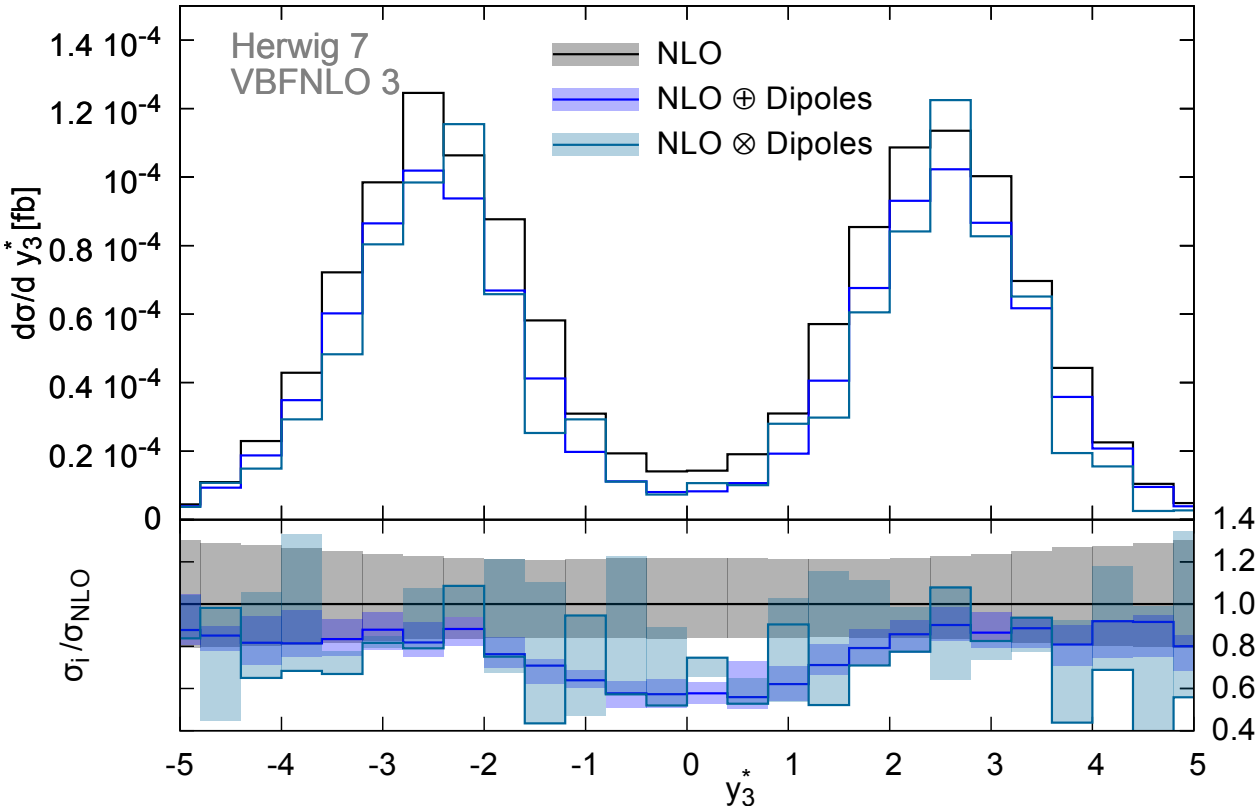


Rapidity of third jet
relative to two tagging jets

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

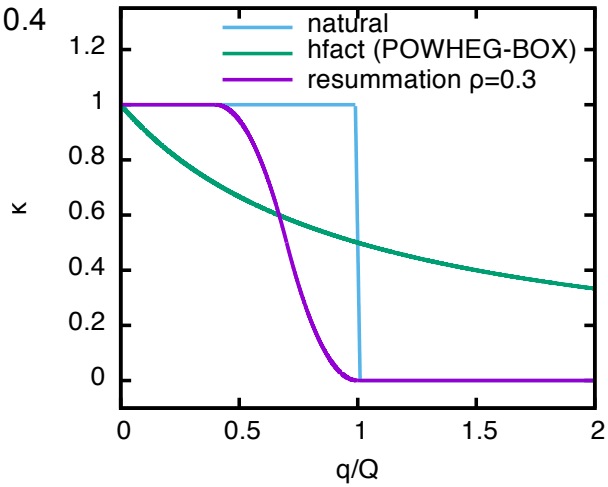
- impact of parton showers (+LO) long unclear
- Herwig predicts very low radiation in central region
- large shower-scale unc.
- stabilised when combining with NLO
- still reduction present
- scale variation bands not overlapping
- only small effects in forward region (mostly global normalization)

Rapidity of third jet – POWHEG

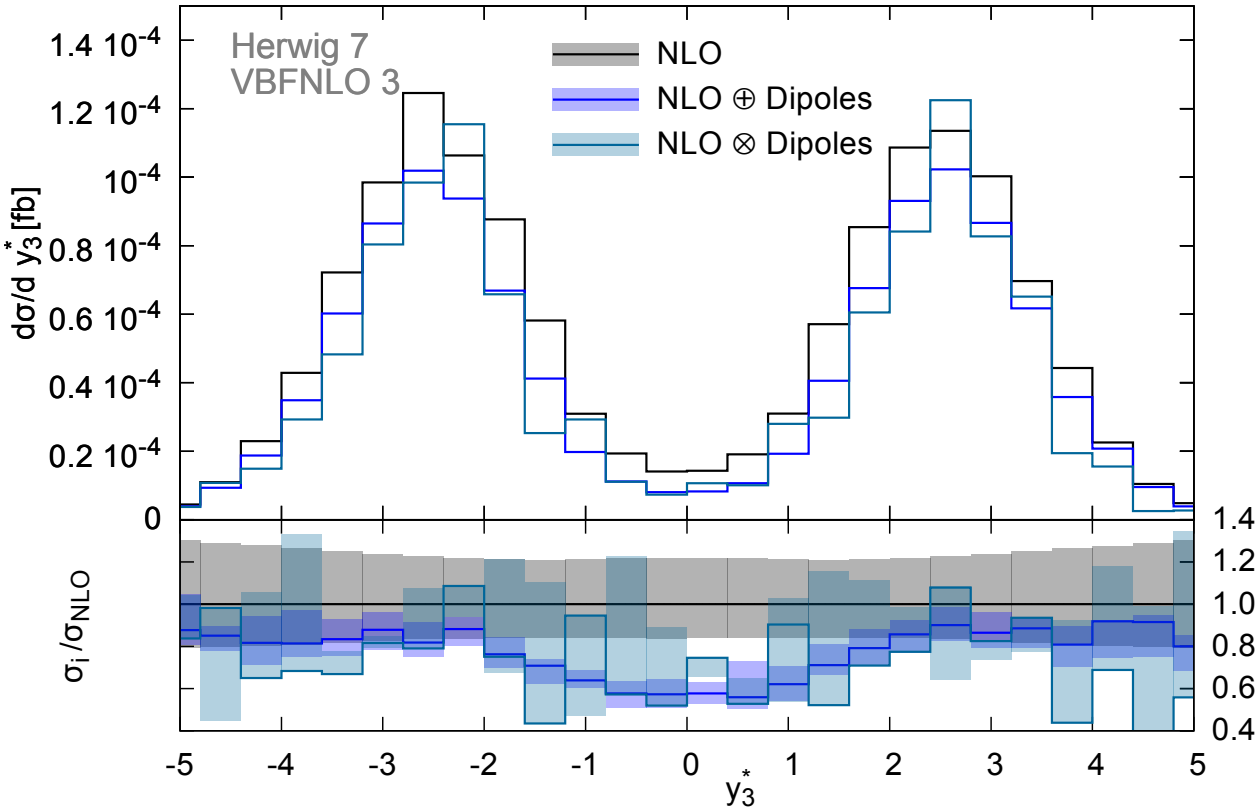


- POWHEG-like ($\otimes$) using resummation scheme [Plätzer]:

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



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

VBSCAN Comparison

VBSCAN project:

Comparison between different codes at NLO+PS accuracy

currently:

- POWHEG-Box & Pythia 8 (NLO $\otimes$ p_T-ordered shower)
- VBFNLO 3 & Herwig 7 (NLO $\oplus$ Dipole shower)

level of simulation:

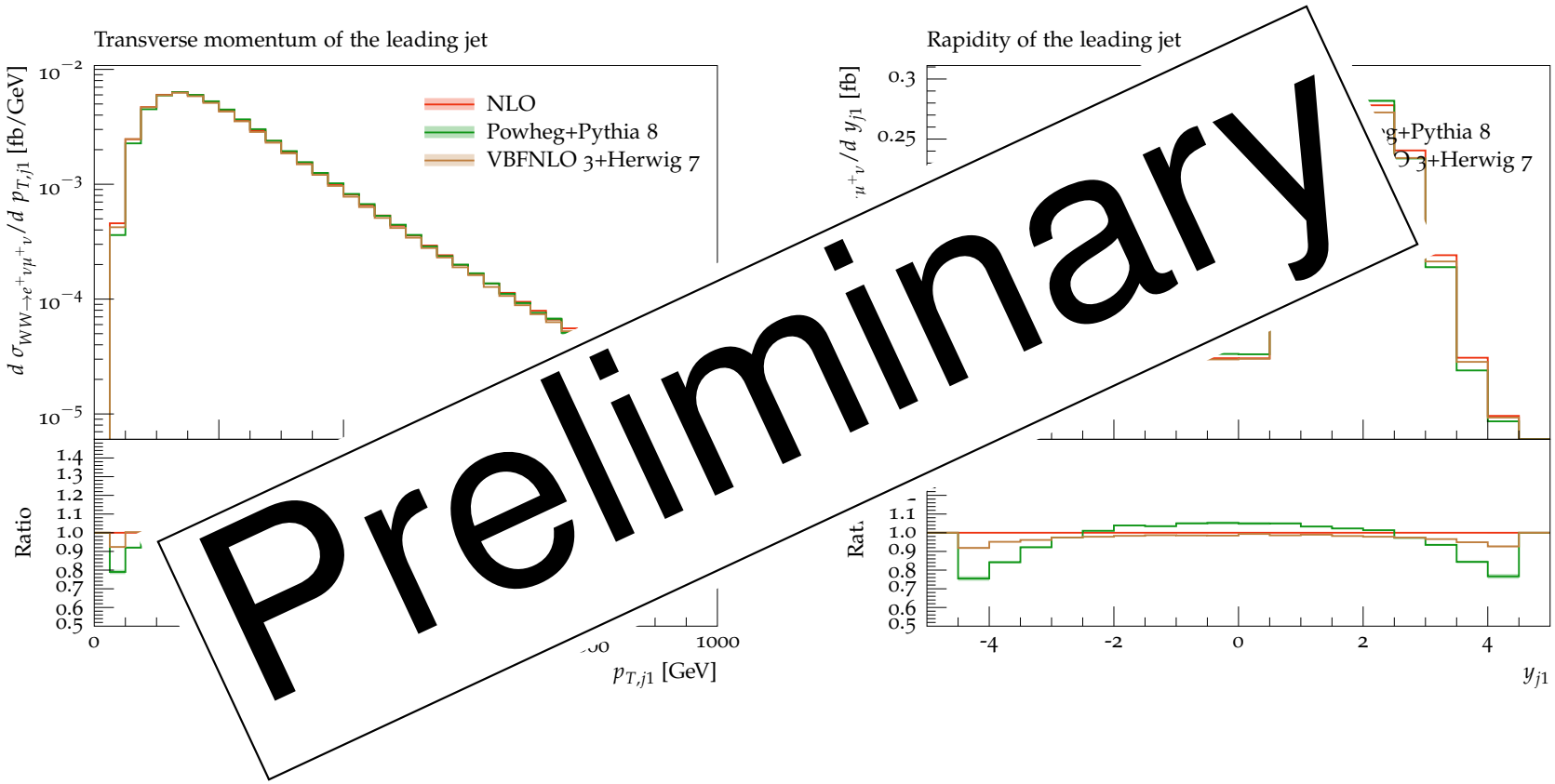
- NLO QCD calculation of hard process
- parton shower
- hadronization without hadron decays
- no underlying event
- joint Rivet analysis for distributions

different choices for matching scheme and parton shower

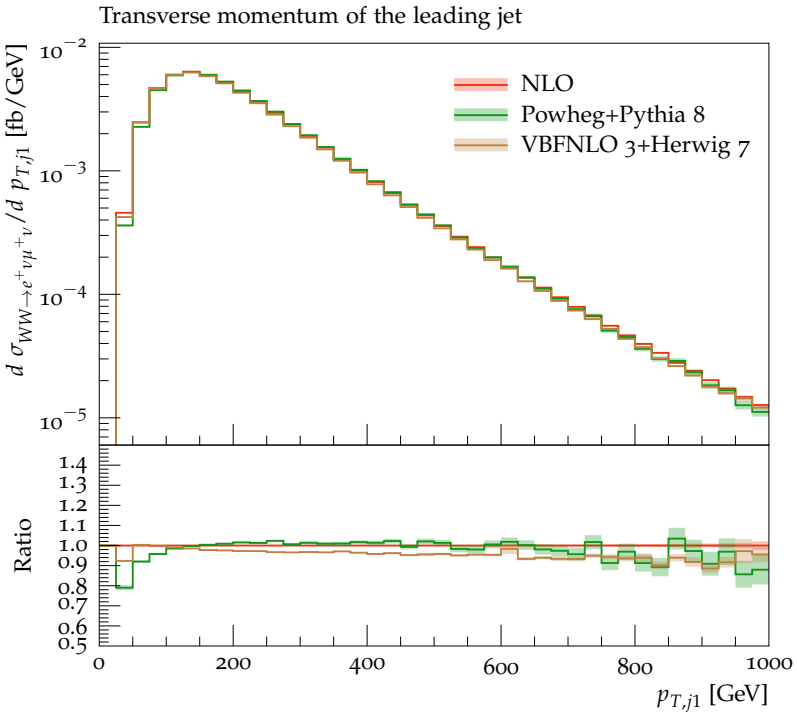
$\rightarrow$ deviations expected

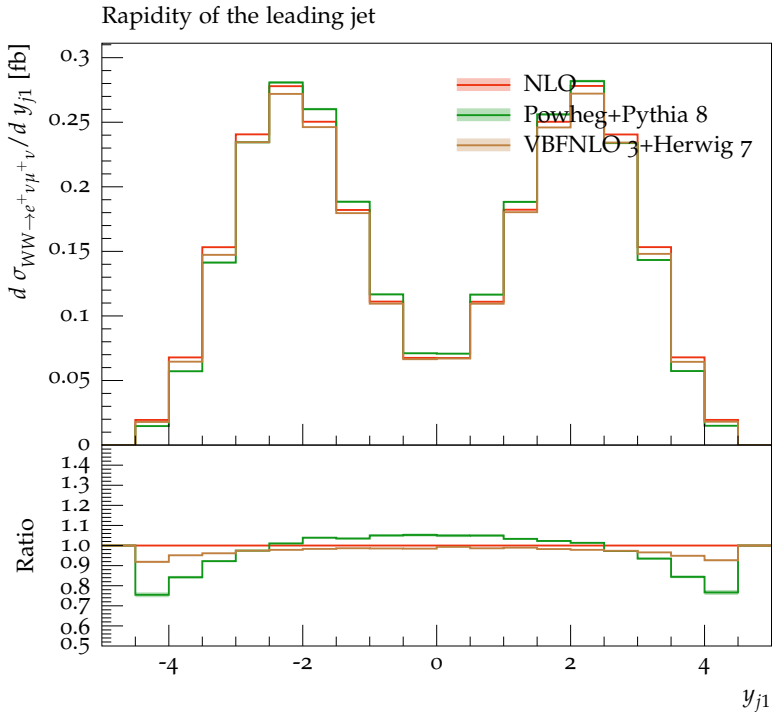
$\rightarrow$ uncertainty of theory prediction

Distributions



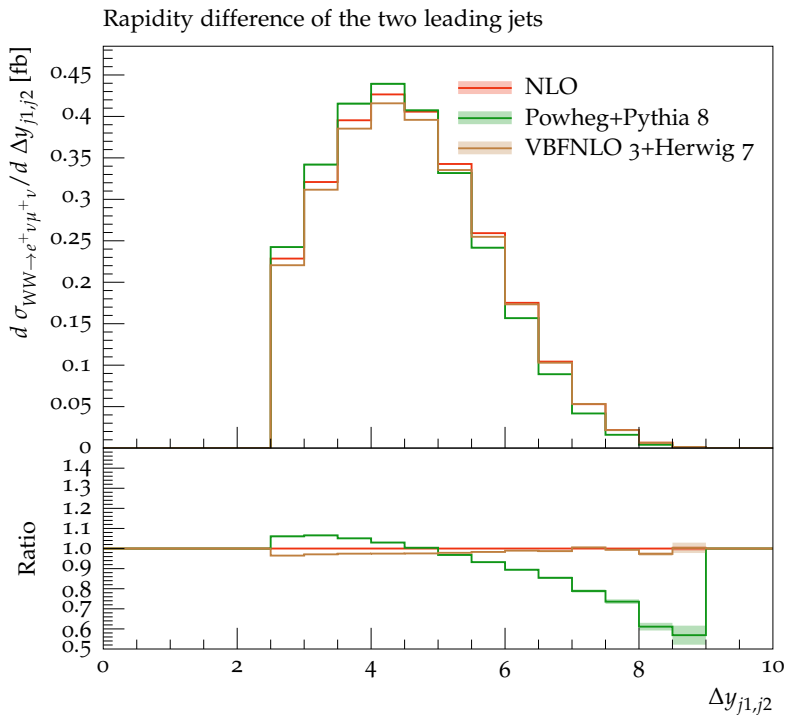
Distributions

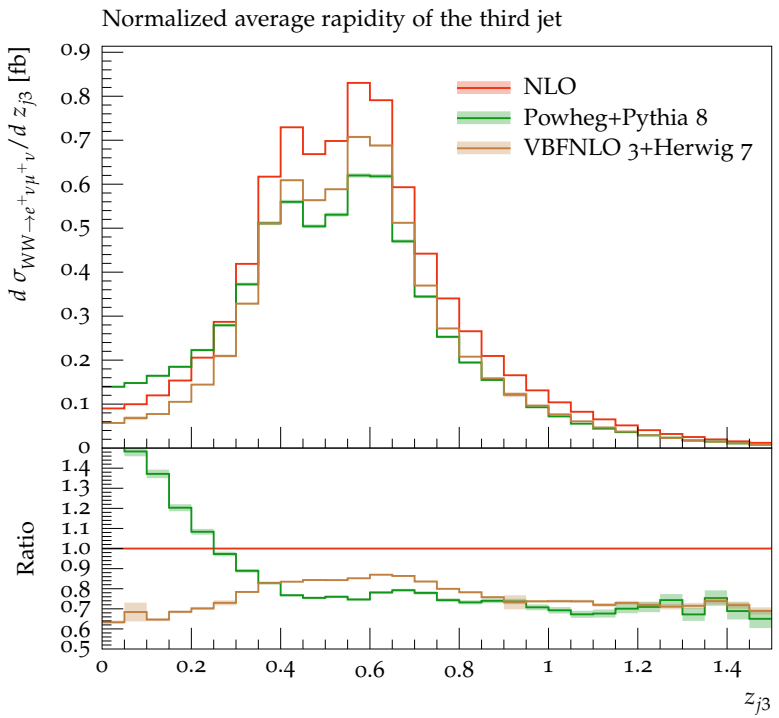




- reasonable agreement on distributions
- size of differences compatible with higher-order effects

Distributions





- significant differences
- third jet in hard process described at LO only
- $\rightarrow$ needs to be understood

Conclusions

Parton-shower and scale variation effects in VBS

- 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

VBSCAN project (as part of MC study):

- Comparison between Powheg&Pythia 8, VBFNLO 3&Herwig 7, ... started
- $\rightarrow$ first results, need to be understood

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

Setup

Generation-level cuts:

$$p_{T,j} > 20\ \text{GeV}\,, \qquad |y_j| < 5.0\,,$$
$$\text{anti-}k_T \text{ jets with } R = 0.4\,, \qquad b\text{-quark veto}$$

$$p_{T,\ell} > 15\ \text{GeV}\,, \qquad |y_\ell| < 3.0\,,$$
$$m_{e^+,\mu^-} > 15\ \text{GeV}\,,$$

$$m_{j1,j2} > 400\ \text{GeV}\,, \qquad |y_{j1} - y_{j2}| > 3.0$$

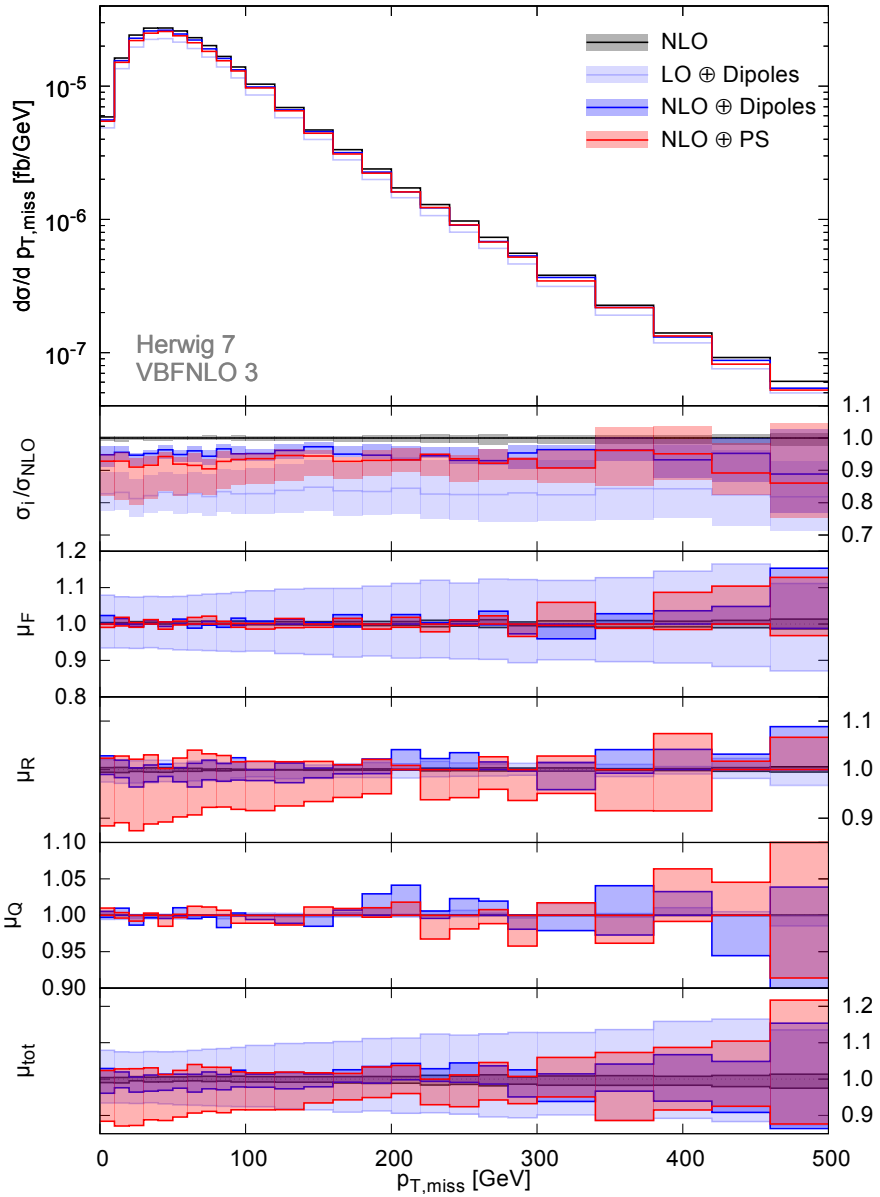
Analysis-level cuts:

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

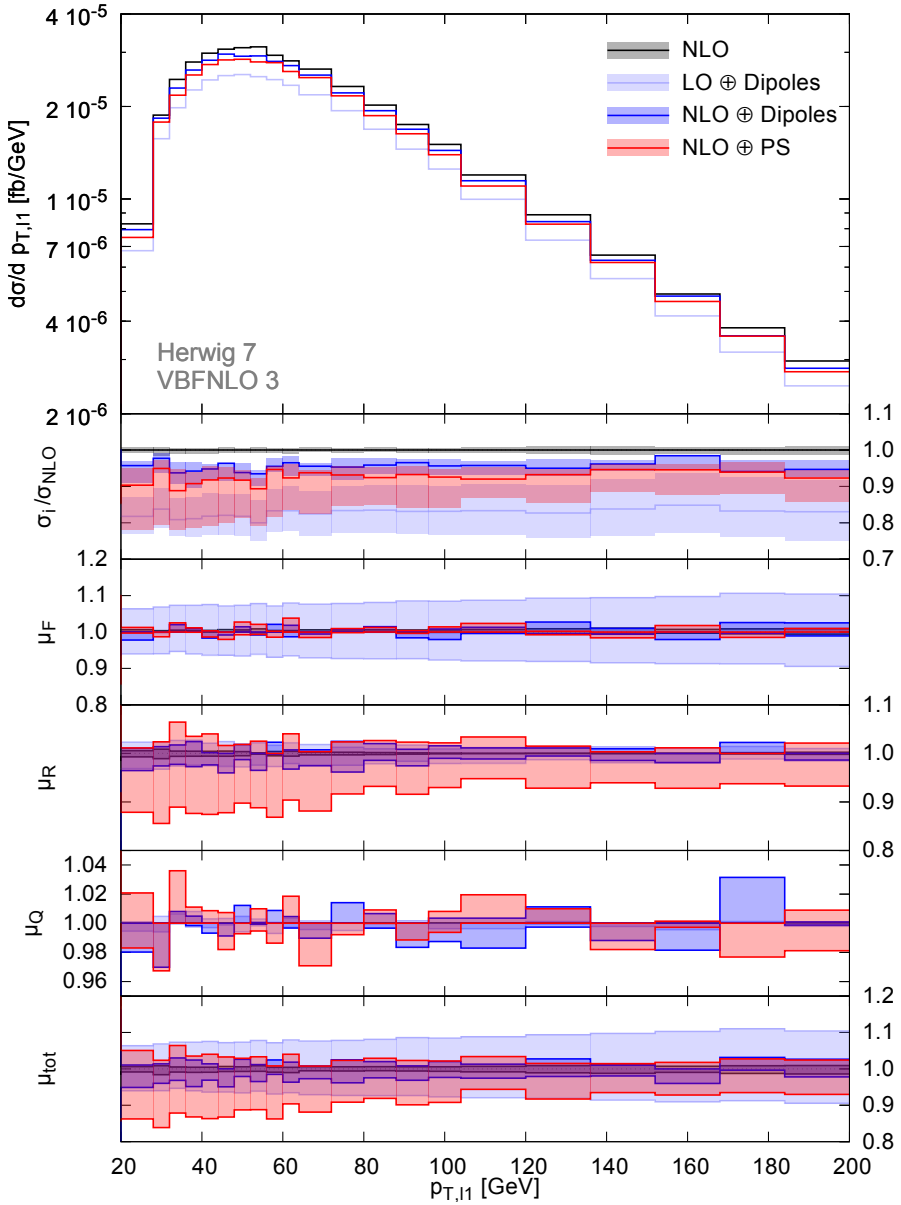
$$p_{T,\ell} > 20\ \text{GeV}\,, \qquad |y_\ell| < 2.5\,,$$
$$m_{e^+,\mu^-} > 15\ \text{GeV}\,,$$

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

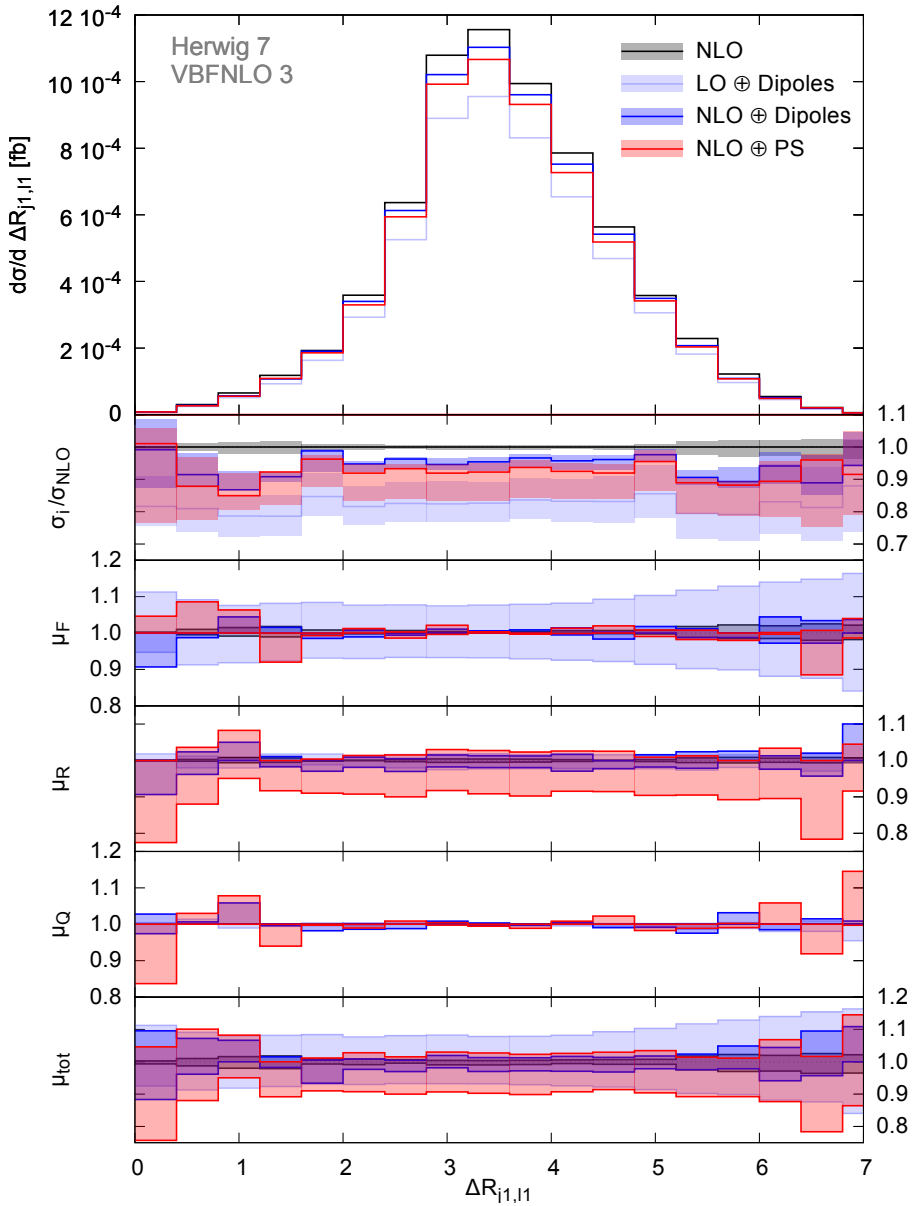
Missing Transverse Momentum



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