Recent Developments in Monte Carlo Simulations

Jennifer Thompson

IPPP
Ogden Centre for Fundamental Physics
University of Durham

jennifer.thompson@durham.ac.uk

09/18/2013

XLIII International Symposium on Multipaticle Dynamics

Outline

1. Motivations for Higher Accuracy in Simulations
2. NLO Matching to Parton Shower:
   - POWHEG method overview
     $\longrightarrow$ Recent POWHEG results
   - MC@NLO method overview
     $\longrightarrow$ Recent MC@NLO results
3. Merging at NLO:
   $\longrightarrow$ Recent SHERPA MEPS@NLO results
   $\longrightarrow$ Recent POWHEG MiNLO results
4. The Next Steps
5. Summary

Motivations for NLO QCD

- **K factors**
  Processes can have large and non-flat K-factors.
  Therefore higher orders in perturbation theory are required for reliable calculations.
- **Scale Dependence**
  Extending simulations to NLO reduces the dependence of the results on unphysical scales.
- **Why in MC**
  Including higher order corrections in a Monte Carlo allows for a meaningful error estimate to be obtained and better accuracy in the modelling of the hardest emission.

Implementation

The POWHEG method is implemented in the POWHEG BOX, HERWIG++ and PYTHIA

JHEP **0411** (2004) 040, *JHEP* **0711** (2007) 070, *JHEP* **1006** (2010) 043, (HERWIG++ and POWHEG) *JHEP* **02** (2007) 051

The POWHEG method:

1. Uses the real/Born matrix elements ratio in Sudakov form factor.
2. Gives positively weighted events.
3. Calculates a local K-factor for each point in phase space.
4. Provides the hardest emission.

POWHEG

$$\sigma_{\text{POWHEG}} = \int d\Phi_B \overline{B}(\Phi_B) \left[\Delta(\mu, \mu_0) + \int_{\mu_0}^{\mu} d\Phi_1 \frac{R(\Phi_B \otimes \Phi_1)}{B(\Phi_B)} \Delta(k_T^2, \mu_0) \right]$$

Here $\overline{B}$ is the modified LO matrix element to NLO accuracy:

$$\overline{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int d\Phi_1 B(\Phi_B) \otimes S(\Phi_1) + \int d\Phi_1 [R(\Phi_B \otimes \Phi_1) - B(\Phi_B) \otimes S(\Phi_1)]$$

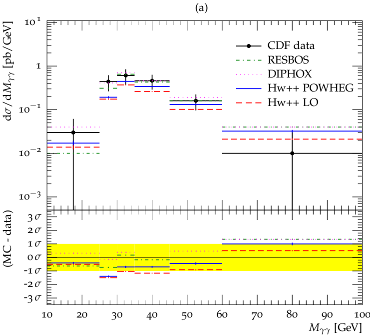
and $\Delta(\mu, \mu_0)$ is the modified Sudakov form factor:

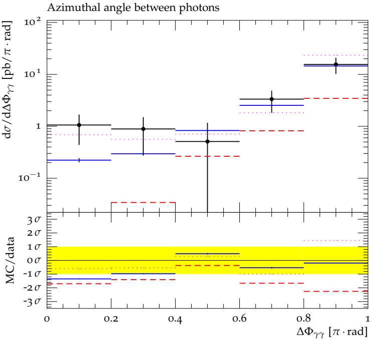
$$\Delta(\mu, \mu_0) = \exp \left[- \int_{\mu_0}^{\mu} d\Phi_1 \frac{R(\Phi_1)}{B} \right]$$

$\longrightarrow$ The real emission matrix element can be divided by introducing an adjustable parameter.

Plots from HERWIG++ POWHEG: Diphoton Production

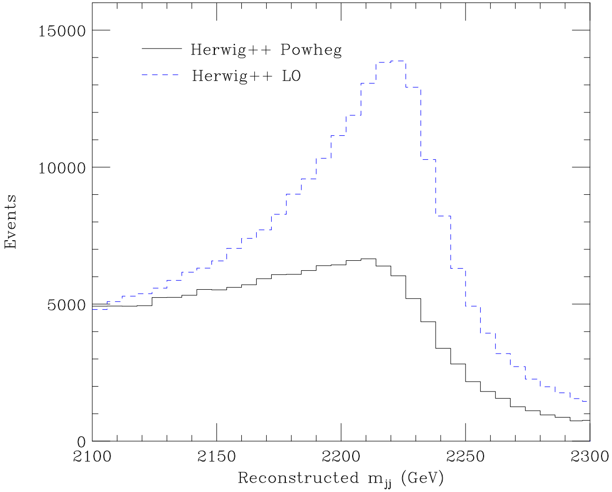
L. D'Errico, P. Richardson *JHEP* **1202** (2012) 130



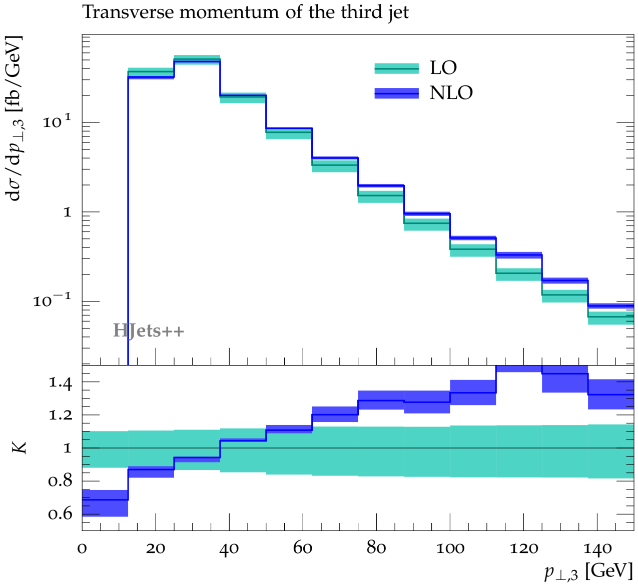


HERWIG++ POWHEG: NLO Graviton Production

P. Richardson and A. Wilcock



Campanario, Figy, Plätzer, Sjödahl



Notes on the MC@NLO method

Implementation

The MC@NLO method has been implemented by the aMC@NLO group and in SHERPA.

arxiv:1103.0621, *Phys.Rev.Lett.* **110** (2013) 052001, *JHEP* **09** (2012) 049

1. The MC@NLO formula can be obtained from POWHEG by splitting the matrix element contributions.
2. This allows the appearance of some negatively weighted events.
3. This method still calculates a local K-factor and provides one emission to NLO accuracy.

MC@NLO

Splitting the real matrix element to soft (R^S) and hard (R^H) such that $R = R^S + R^H$:

$$\sigma_{\text{MC@NLO}} = \int d\Phi_B \overline{B}(\Phi_B) \left[\Delta(\mu, \mu_0) + \int_{\mu_0}^{\mu} d\Phi_1 \frac{R^S(\Phi_B \otimes \Phi_1)}{B(\Phi_B)} \Delta(k_T^2, \mu_0)\right] + \int d\Phi_R R^H(\Phi_R)$$

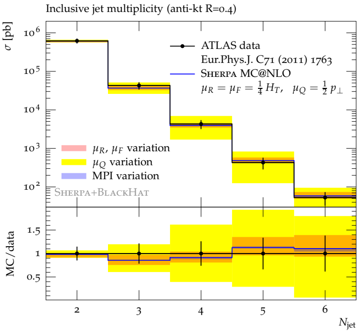
The modified marix element is now

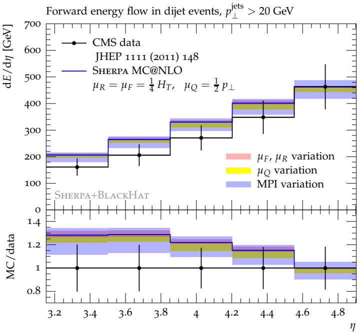
$$\overline{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int d\Phi_1 B(\Phi_B) \otimes S(\Phi_1) + \int d\Phi_1 \left[R^S(\Phi_B \otimes \Phi_1) - B(\Phi_B) \otimes S(\Phi_1)\right]$$

and the Sudakov form factor is given by

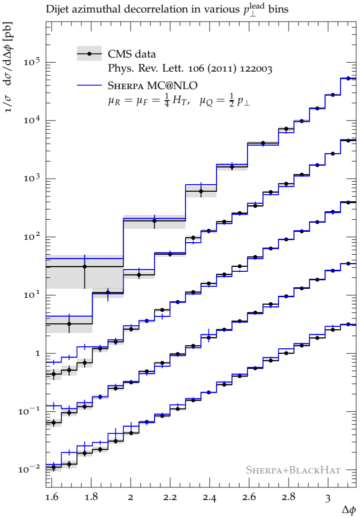
$$\Delta(\mu, \mu_0) = \exp\left[-\int_{\mu_0}^{\mu} d\Phi_1 \frac{R^S(\Phi_B \otimes \Phi_1)}{B(\Phi_B)}\right]$$

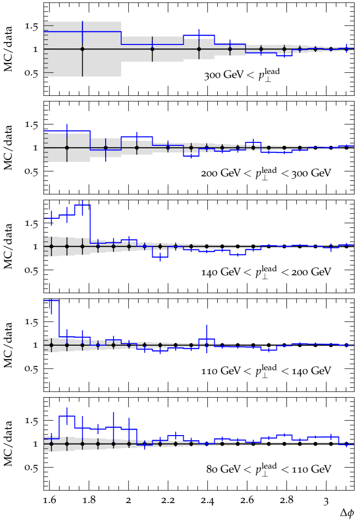
SHERPA MC@NLO: dijets



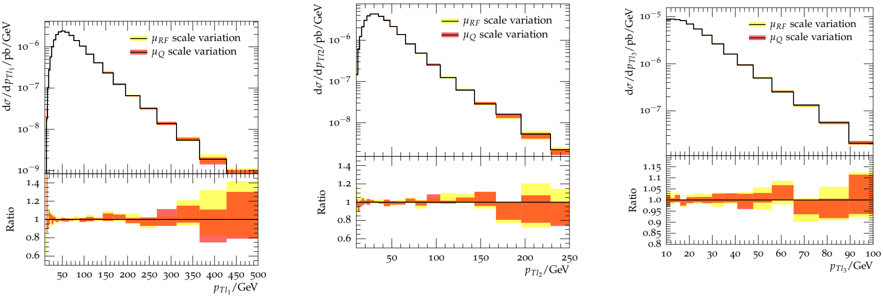


SHERPA MC@NLO: dijets



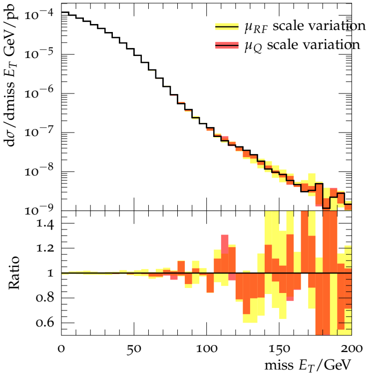


SHERPA MC@NLO: $W^{\pm}H(\rightarrow W^{+}W^{-})$

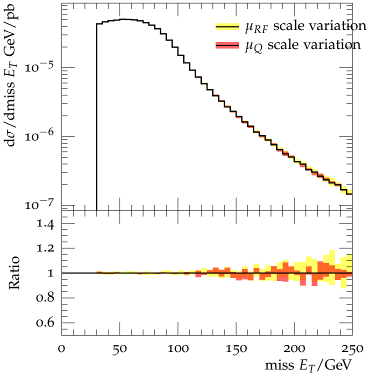


SHERPA MC@NLO: $W^{\pm}H(\rightarrow W^{+}W^{-})$ ATLAS and CMS Analysis

ATLAS



CMS

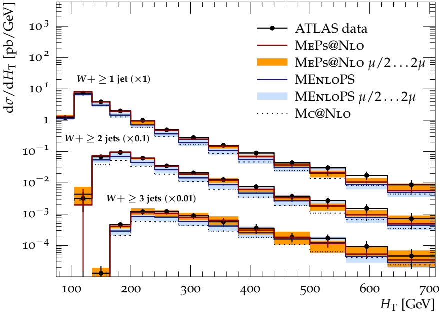


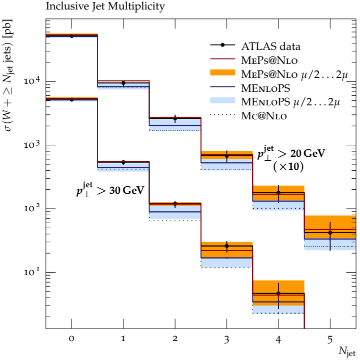
Multijet Merging

- Use the parton shower for soft collinear approximation.
- Use the matrix element for hard phase space.
- This means using a mixture of the matrix element and the parton shower to fill all phase space.
- Contributions are combined with a merging procedure.
- The extension of merging to NLO is a matter of reweighting the contributions by K-factors.
- Methods: MEPS@NLO and MiNLO

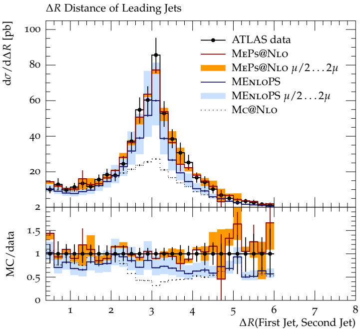
SHERPA NLO: $W^{\pm}$+jets

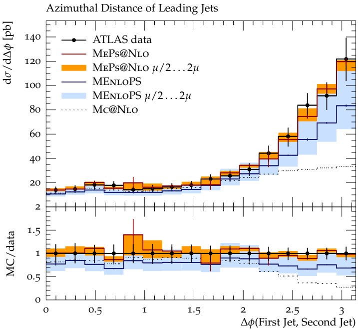
W + 2 jets at NLO with BlackHat, arXiv:1207.5031[hep-ex]



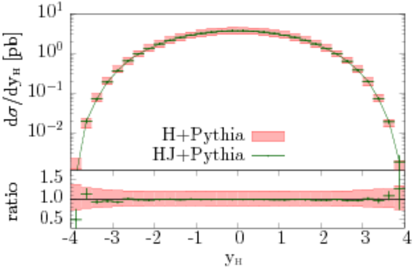


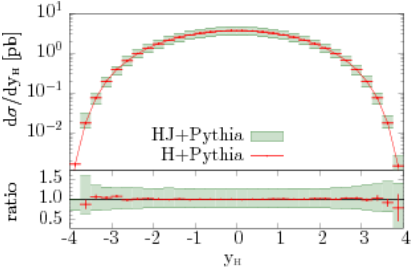
SHERPA NLO: $W^{\pm}$+jets



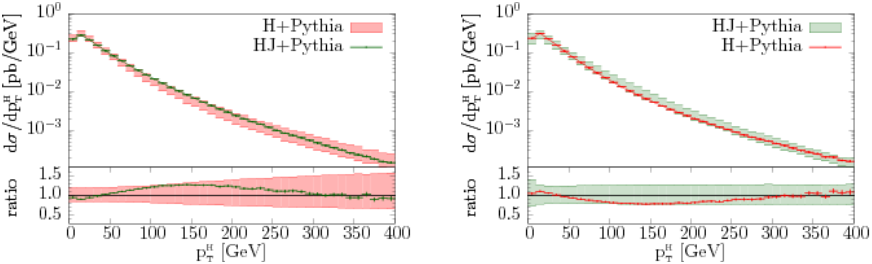


MiNLO POWHEG: Higgs Production

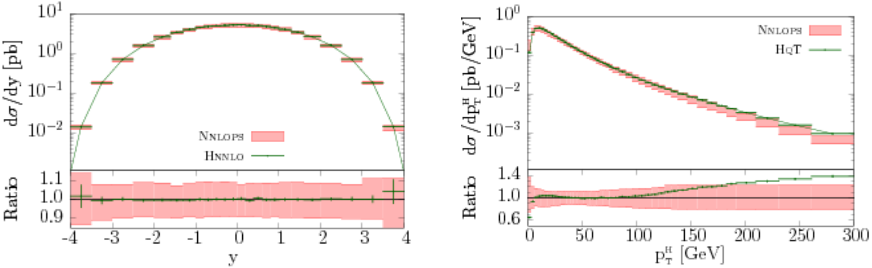




MiNLO POWHEG: Higgs Production



NNLO POWHEG



NNLOPS
HNNLO
dσ/dy [pb]
Ratio
y
NNLOPS
HQT
dσ/dp$_T^H$ [pb/GeV]
Ratio
p$_T^H$ [GeV]

Outlook for the Future

The current work in the Monte Carlo community now is to:

1. Compare NLO matched and merged Monte Carlo samples to data for through validation of our efforts so far.
2. Move to even greater accuracy with NNLO QCD and NLO EW corrections.
3. Look for sensitive variables in experiment to help us further understand the underlying Physics.

Summary

- The Monte Carlo community has moved into including higher order QCD corrections in simulations.
- Currently have automated inclusion of NLO QCD corrections to several LHC processes.
- The logical next step is to increase the accuracy in QCD and to begin looking at EW corrections.