Multi-jet merging with NLO matrix elements

Frank Siegert [1]

Institute for Particle Physics Phenomenology, Durham University;
Department of Physics & Astronomy, University College London

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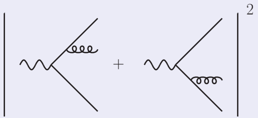
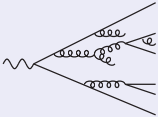
MCnet UCL Durham University IP3 www.ippp.dur.ac.uk

[1] In collaboration with Thomas Gehrmann, Stefan Höche, Frank Krauss & Marek Schönherr

Review: Multi-jet merging at tree level

JHEP 0111 (2001) 063, JHEP 0205 (2002) 046,
JHEP 0208 (2002) 015, JHEP 0905 (2009) 053

Two approaches to real higher-order corrections

Matrix Element	**Parton Shower**
	
+ **Exact** to fixed order – Perturbative series breaks down due to **large logarithms**	+ Resums logarithmically enhanced contributions to **all orders** – Only **approximation** for real ME

$\Downarrow$

Goal: Combine advantages ⇒ ME⊗PS

- Describe **particular final state** by **ME** (hard radiation)
- Don't spoil the **inclusive picture** provided by the **PS** (intrajet evolution)

Problem: PS and higher-order ME describe the same final state!

Solution: Phase space slicing by parton separation criterion Q_{cut}

Features and shortcomings

Example

Diphoton production at Tevatron

- Recently published by DØ Phys.Lett.B690:108-117,2010
- Isolated hard photons with:
  - $E_\perp^{\gamma^1} > 21$ GeV
  - $E_\perp^{\gamma^2} > 20$ GeV
  - $|\eta_\gamma| < 0.9$
  - Isolation: $E_\perp(R = 0.4) - E_\perp^\gamma < 2.5$ GeV
- Here: Azimuthal angle between the diphoton pair

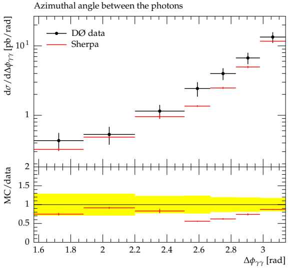
ME⊗PS simulation using SHERPA 1.2.2 with QCD+QED interleaved shower and merging as in Phys.Rev.D81:034026,2010

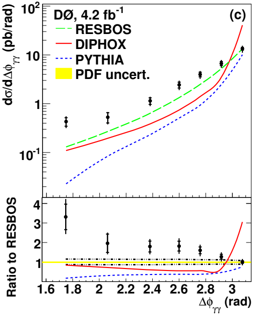
Conclusions

Shapes described very well even for this non-trivial process/observable for both:

- Hard region, e.g. $\Delta\Phi_{\gamma\gamma} \to 0$
- Soft region, e.g. $\Delta\Phi_{\gamma\gamma} \to \pi$

Total cross section too low ⇒ Virtual matrix elements needed





The POWHEG master formula

Why POWHEG?

- Matches full NLO matrix element and parton shower for the hardest emission
- Generates positive weights (almost always)
- Independent of shower algorithm
- Will use it as basic ingredient in ME⊗PS@NLO

Master formula JHEP 0411:040,2004, JHEP 0711:070,2007

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \bar{B}(\Phi_B)\mathrm{d}\Phi_B \left[\bar{\Delta}(k_{\perp,0}) + \sum \int_{k_{\perp,0}} \mathrm{d}\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \bar{\Delta}(k_\perp)\right]$$

Two problems to be solved:

1. Differential NLO cross section $\bar{B} = B + V + I + \mathrm{d}\Phi_{R|B}[R - S]$
   - **B**orn and **R**eal MEs from automated tree-level generators
   - **V**irtual ME e.g. via Binoth Les Houches Accord Comput.Phys.Commun.181:1612-1622,2010
   - Catani-Seymour **I**ntegrated/**S**ubtraction terms automated, e.g. Eur.Phys.J.C53:501-523,2008
   - Special integrator for extra emission on top of Born phase space
2. POWHEG Sudakov $\bar{\Delta}(k_\perp) = \exp\left(-\sum \int_{k_\perp} \mathrm{d}\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)}\right)$

Generating the POWHEG Sudakov

Exponentiating $\Gamma(k_\perp) = \sum \int_{k_\perp} \mathrm{d}\Phi_{R|B} \frac{R}{B}$

Standard MC technique to dice $k_\perp$ from Sudakov: Comput.Phys.Commun.82:74-90,1994

- Find invertible overestimate $\tilde{\Gamma}$
- Dice random number $\#_1$ and calculate $k_\perp = \tilde{\Gamma}^{-1}(-\log \#_1)$
- Accept $k_\perp$ with weight $w = \Gamma(k_\perp)/\tilde{\Gamma}(k_\perp)$

Tricky bit: Find suitable $\tilde{\Gamma}$

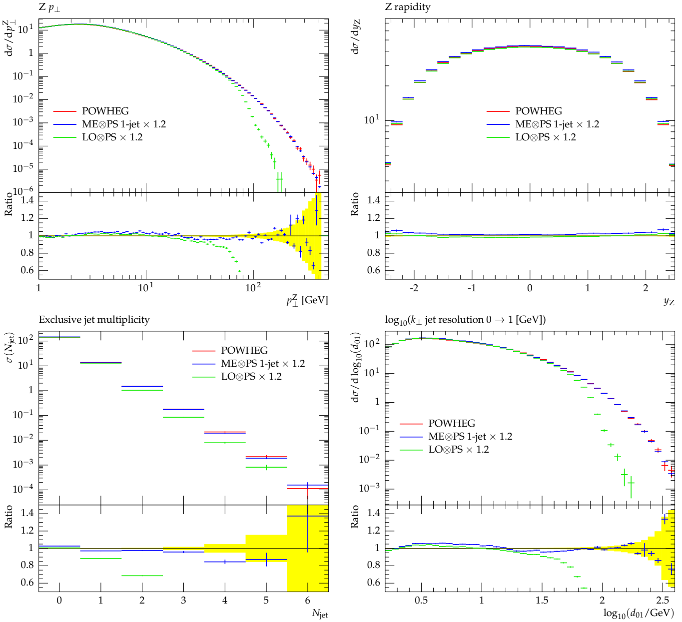
$\tilde{\Gamma}$ should be sufficiently similar to Γ

- Otherwise the efficiency in the last step will be very low
- But still has to overestimate in full phase space

Good candidate: Splitting functions in parton showers

- In SHERPA: Dipole-like parton shower based on CS subtraction JHEP 0803:038,2008
- Multiplied with automatically determined enhancement factors such that always overestimating

POWHEG results from SHERPA for $p\bar{p} \to$ Z+jets at 1960 GeV



- LO predictions scaled with K-factor 1.2
- POWHEG and ME⊗PS with up to 1-jet agree within a few percent
- Both show improvements over ordinary parton shower predictions in the region of hard emissions

Multi-jet merging with full NLO matrix elements in SHERPA

ME⊗PS "master formula" for first emission

$$\mathrm{d}\sigma_{\mathrm{NLO}} = B(\Phi_B)\mathrm{d}\Phi_B \left[\overbrace{\Delta(k_{\perp,0})}^{\text{unresolved}} + \sum \int_{k_{\perp,0}} \mathrm{d}\Phi_{R|B} \left(\overbrace{\Theta(Q_{\mathrm{cut}} - Q) \quad \mathcal{K}_{\mathrm{ab}} \quad \Delta(k_\perp)}^{\text{PS domain}} + \underbrace{\Theta(Q - Q_{\mathrm{cut}}) \; \frac{R(\Phi_R)}{B(\Phi_B)} \; \Delta(k_\perp)}_{\text{ME domain}} \right) \right]$$

Already very similar to POWHEG, but:

- $\Delta(k_\perp)$ doesn't contain R/B $\Rightarrow \Big[\ldots\Big]$ is only approximately unitary
- B instead of $\bar{B} \Rightarrow$ LO accuracy only

Multi-jet merging with full NLO matrix elements in SHERPA

ME⊗PS "master formula" for first emission

$$\mathrm{d}\sigma_{\mathrm{NLO}} = B(\Phi_B)\mathrm{d}\Phi_B \Bigg[\overbrace{\Delta(k_{\perp,0})}^{\text{unresolved}} + \sum \int_{k_{\perp,0}} \mathrm{d}\Phi_{R|B} \Bigg(\overbrace{\Theta(Q_{\mathrm{cut}} - Q) \quad \mathcal{K}_{\mathrm{ab}} \quad \Delta(k_\perp)}^{\text{PS domain}} + \underbrace{\Theta(Q - Q_{\mathrm{cut}}) \, \frac{R(\Phi_R)}{B(\Phi_B)} \, \Delta(k_\perp)}_{\text{ME domain}} \Bigg) \Bigg]$$

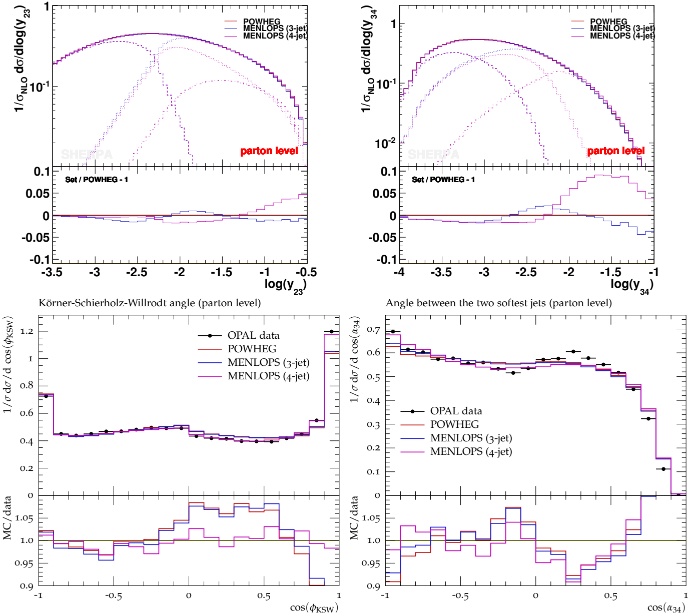
How can this be improved to (almost) full NLO accuracy? JHEP 1006:039,2010

- Replace unresolved and PS part by POWHEG
- Apply K-factor for R such that $\bar{B}/B$ is reproduced

$$\mathrm{d}\sigma_{\mathrm{NLO}} = \bar{B}(\Phi_B)\mathrm{d}\Phi_B \Bigg[\bar{\Delta}(k_{\perp,0}) + \sum \int_{k_{\perp,0}} \mathrm{d}\Phi_{R|B} \Bigg(\Theta(Q_{\mathrm{cut}} - Q) \, \frac{R(\Phi_R)}{B(\Phi_B)} \, \bar{\Delta}(k_\perp) + \Theta(Q - Q_{\mathrm{cut}}) \, \frac{R(\Phi_R)}{B(\Phi_B)} \, \Delta(k_\perp) \Bigg) \Bigg]$$

- recently implemented by Hamilton & Nason JHEP 1006:039,2010 in a simplified version: **global** K-factor to generate $\frac{\bar{B}}{B}R$
- we use a **local** K-factor $\bar{B}(\Phi_B)/B(\Phi_B)$ as above

Results for $e^+e^- \to$ jets

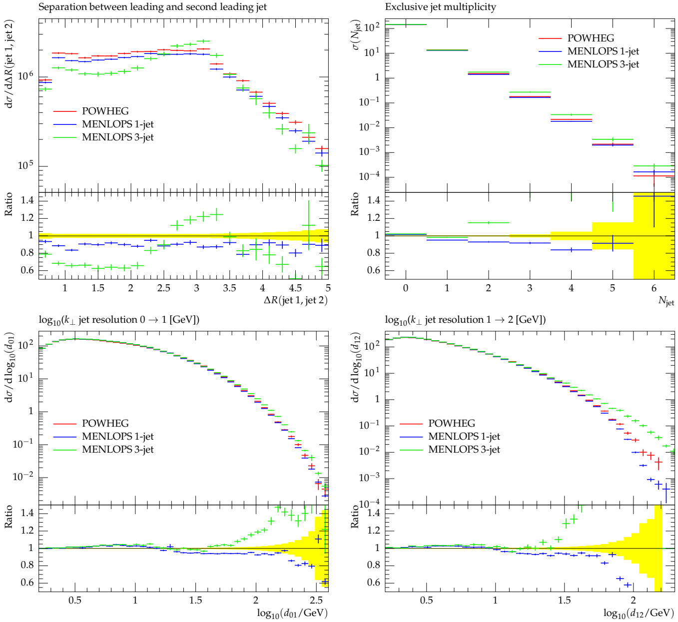


- POWHEG and MENLOPS with up to one additional jet agree well
- No “kink” around merging cut

  $\log(y_{\text{cut}}) = -2.25$

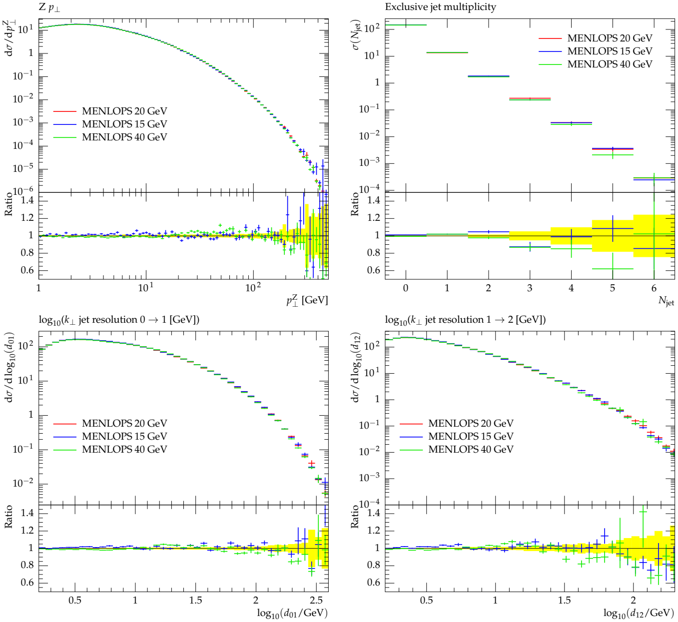
- Higher order tree-level MEs improve description in some regions of phase space

MENLOPS results for $p\bar{p} \to$ Z+jets at 1960 GeV



- Generated with $Q_{\text{cut}} = 20$ GeV
- k_T jets with $p_\perp^{\text{min}} = 20$ GeV
- POWHEG and MENLOPS with up to 1-jet agree fairly well
- For observables sensitive to additional hard emissions the merging of higher order MEs is necessary

Stability of the merging



- Generated with $Q_{\text{cut}} = 15, 20$ and 40 GeV for up to 3 jets
- Only very small variations in results

$\Rightarrow$ Stable and consistent MENLOPS merging

Conclusions and outlook

Conclusions

- Tree-level ME+PS merging works well for shapes, but needs K-factor for cross section
- POWHEG reproduces full NLO cross section and shape of first emission but fails for additional hard radiation
- Combination of full NLO and higher order tree-level MEs with shower achieves both of the above
- Recently much progress and already first implementations
- Automation within SHERPA framework in reach
- Full NLO only in core process, not in higher order corrections . . .

Outlook

- . . . yet
- Application to more processes
- Public availability in a SHERPA release,
  as simple to use as tree-level merging

JHEP **0905** (2009) 053 [arXiv:0903.1219 [hep-ph]]

Main idea

Phase space slicing for extra QCD radiation:

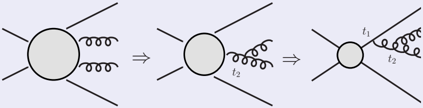
- Hard emissions from matrix element
- Soft/collinear emissions from parton shower

Two main ingredients

Shower on top of higher order MEs

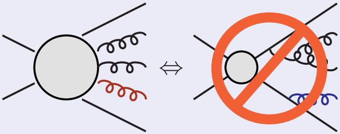
Problem: ME only gives final state, no history as shower input

Solution: Backward-clustering (running the shower reversed)



$\Rightarrow$ Branching history corresponding to the ME final state

Avoid double-counting of emissions



- Populate full real-emission phase space with *either* ME *or* PS
- Make MEs exclusive by rejection of events with hard shower emissions