Parton shower matching and multijet merging at NLO

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arXiv:1208.2815
The SHERPA event generator framework

- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044
  COMIX JHEP12(2008)039
  CS subtraction EPJC53(2008)501

- A Parton Shower (PS) generator
  CSSHOWER++ JHEP03(2008)038

- A multiple interaction simulation
  à la Pythia AMISIC++ hep-ph/0601012

- A cluster fragmentation module
  AHADIC++ EPJC36(2004)381

- A hadron and $\tau$ decay package HADRONS++

- A higher order QED generator using YFS-resummation
  PHOTONS++ JHEP12(2008)018

Sherpa’s traditional strength is the perturbative part of the event

MePs (CKKW), Mc@NLO, MeNLOPs, MePs@NLO
→ full analytic control mandatory for consistency/accuracy
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Sherpa’s traditional strength is the perturbative part of the event
M@PS (CKKW), MC@NLO, MeNLOPS, MEPS@NLO
→ full analytic control mandatory for consistency/accuracy
\[ \langle O \rangle^{\text{NLO+PS}} = \int d\Phi_B \Bbar^{(A)}(\Phi_B) \left[ \Delta^{(A)}(t_0, \mu^2_Q) O(\Phi_B) ight. \\
+ \int_{t_0}^{\mu^2_Q} d\Phi_1 \frac{D^{(A)}(\Phi_B, \Phi_1)}{B(\Phi_B)} \Delta^{(A)}(t, \mu^2_Q) O(\Phi_R) \\
+ \int d\Phi_R \left[ R(\Phi_R) - \sum_i D_i^{(A)}(\Phi_R) \right] O(\Phi_R) \]

- NLO weighted Born configuration \( \Bbar^{(A)} = B + \Bbar + I + \int d\Phi_1 [D^{(A)} - D^{(S)}] \)
- use \( D_i^{(A)} \) as resummation kernels \( \Delta^{(A)}(t, t') = \exp \left[ \int_{t'}^{t} d\Phi_1 D^{(A)}/B \right] \)
- resummation phase space limited by \( \mu^2_Q = t_{\text{max}} \)
  → starting scale of parton shower evolution
  → should be of the order of the hard resummation scale
  ⇒ first implementation to allow to study \( \mu_Q \) uncertainty
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\left. + \int d\Phi_R \left[ R(\Phi_R) - \sum_i D_i^{(A)}(\Phi_R) \right] O(\Phi_R) \right]. \]

Frixione, Webber JHEP06(2002)029

Höche, Krauss, MS, Siegert arXiv:1111.1220

every term is well defined and NLO and NLL accuracy maintained if:

- \( D^{(A)} = \sum_i D_i^{(A)} \) is full colour correct in soft limit
- \( D^{(A)} = \sum_i D_i^{(A)} \) contains all spin correlations in collinear limit
- \( D_i^{(A)} \) and \( D_i^{(S)} \) have identical parton maps

\( \Rightarrow \) conventional parton showers need to be improved for that

e.g. choose \( D_i^{(A)} = D_i^{(S)} \) up to phase space constraints
Case study: Inclusive jet & dijet production

Describe wealth of experimental data with a single sample (LHC@7TeV)

MC@NLO di-jet production:

- $\mu_{R/F} = \frac{1}{4} H_T$, $\mu_Q = \frac{1}{2} p_\perp$
- CT10 PDF ($\alpha_s(m_Z) = 0.118$)
- hadron level calculation fully hadronised including MPI
- virtual MEs from BLACKHAT
  - Giele, Glover, Kosower
  - Bern et.al. arXiv:1112.3940
- $p_{j1}^\perp > 20$ GeV, $p_{j2}^\perp > 10$ GeV

Uncertainty estimates:

- $\mu_{R/F} \in \left[\frac{1}{2}, 2\right] \mu_{R/F}^{\text{def}}$
- $\mu_Q \in \left[\frac{1}{\sqrt{2}}, \sqrt{2}\right] \mu_Q^{\text{def}}$
- MPI activity in tr. region $\pm 10\%$
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Case study: Inclusive jet & dijet production

Jet transverse momenta (anti-kt R=0.4)

- ATLAS data
- SHERPA MC@NLO
  \( \mu_R = \mu_F = \frac{1}{4} H_T, \mu_Q = \frac{1}{2} p_{\perp} \)
- \( \mu_R, \mu_F \) variation
- \( \mu_Q \) variation
- MPI variation

1st jet

2nd jet

3rd jet

4th jet

Höche, MS arXiv:1208.2815
Case study: Inclusive jet & dijet production

3-jet-over-2-jet ratio

- determined from incl. sample
- 2-jet rate at NLO+NLL
- 3-jet rate at LO+LL

- common scale choices
  → varied simultaneously

- at large $H_T$ large MPI uncertainties
  → better MPI physics needed
  (soft QCD)

- similar description of related ATLAS observables
Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815
Case study: Inclusive jet & dijet production

Try different scale

- \( \mu_{R/F} = \frac{1}{4} H_T(y) \) with
  \[ H_T(y) = \sum_{i \in \text{jets}} p_{\perp,i} e^{0.3|y_{\text{boost}} - y_i|} \]
  with \( y_{\text{boost}} = \frac{1}{n_{\text{jets}}} \sum_{i \in \text{jets}} y_i \)
- reduces to \( \mu_{R/F} = \frac{1}{2} p_\perp e^{0.3y^*} \) with \( y^* = \frac{1}{2}|y_1 - y_2| \)
  for \( 2 \rightarrow 2 \) and captures real emission dynamics

Ellis, Kunszt, Soper PRD40(1989)2188

- better description of data at large rapidities, as expected

Höche, MS arXiv:1208.2815
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  and captures real emission dynamics

Ellis, Kunszt, Soper PRD40(1989)2188

- better description of data at large rapidities, as expected

description of most other observables worsened

need proper description of forward physics (e.g. (B)FKL)
Case study: Inclusive jet & dijet production

Inclusive jet transverse momenta in different rapidity ranges

Leading dijet selection

Höche, MS arXiv:1208.2815
Case study: Inclusive jet & dijet production

Inclusive jet transverse momenta in different rapidity ranges

Δy

Gap Fraction

Forward-backward selection

MC/data

Höche, MS arXiv:1208.2815

240 GeV < \( \bar{p}_\perp < 270 \) GeV

210 GeV < \( \bar{p}_\perp < 240 \) GeV

180 GeV < \( \bar{p}_\perp < 210 \) GeV

150 GeV < \( \bar{p}_\perp < 180 \) GeV

120 GeV < \( \bar{p}_\perp < 150 \) GeV

90 GeV < \( \bar{p}_\perp < 120 \) GeV

70 GeV < \( \bar{p}_\perp < 90 \) GeV

\( \mu_R = \mu_F = \frac{1}{4} H_T, \mu_Q = \frac{1}{2} p_\perp \)

\( R = F_\mu, \mu \)

\( p_\perp < 90 \) GeV

\( p_\perp < 120 \) GeV

\( p_\perp < 150 \) GeV

\( p_\perp < 180 \) GeV

\( p_\perp < 210 \) GeV

\( p_\perp < 240 \) GeV

\( p_\perp < 270 \) GeV

\( R = \frac{1}{\sqrt{\mu_R}} \)

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\( R = \frac{1}{\sqrt{\mu_R}} \)
Case study: Inclusive jet & dijet production

- small-$\Delta y$ region
  $\Rightarrow$ small uncertainty on additional jet production
- large-$\Delta y$ region
  $\Rightarrow$ all uncertainties sizable
- small-$\vec{p}_T$ region
  $\Rightarrow$ dominated by perturbative uncertainties
- small-$\vec{p}_T$ region
  $\Rightarrow$ non-perturbative uncertainties as large as perturbative uncertainties

Reduction of theoretical uncertainty necessitates better understanding of soft QCD and non-factorisable contributions
**Case study: Inclusive jet & dijet production**

Forward energy flow

- energy flow in rapidity interval per event with a central back-to-back di-jet pair
- normalisation reduces $\mu_R/F$ and $\mu_Q$ dependence
- dominated by MPI modeling uncertainty

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Höche, MS arXiv:1208.2815
NLO merging

LO merging:
- LO accuracy for $n \leq n_{\text{max}}$-jet processes
- preserve LL accuracy of the parton shower

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053
Hamilton, Richardson, Tully JHEP11(2009)038
Lönnblad, Prestel JHEP03(2012)019

NLO merging:
- NLO accuracy for $n \leq n_{\text{max}}$-jet processes
- preserve LL accuracy of the parton shower

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert arXiv:1207.5030
Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031
\[ \langle O \rangle^{\text{MEPS@NLO}} = \int d\Phi_n \bar{B}^{(A)}_n \left[ \Delta^{(A)}_n(t_0, \mu_Q^2) O_n \right. \\
+ \int_{t_0}^{\mu_Q^2} d\Phi_1 \frac{D^{(A)}_n}{B_n} \Delta^{(A)}_n(t_{n+1}, \mu_Q^2) \Theta(Q_{\text{cut}} - Q) O_{n+1} \left. \right] \\
+ \int d\Phi_{n+1} \left[ R_n - D^{(A)}_n \right] \Theta(Q_{\text{cut}} - Q) \Delta^{(PS)}_n(t_{n+1}, \mu_Q^2) O_{n+1} \\
+ \int d\Phi_{n+1} \bar{B}^{(A)}_{n+1} \left. \right] \times \left[ \Delta^{(A)}_{n+1}(t_0, t_{n+1}) O_{n+1} + \int_{t_0}^{t_{n+1}} d\Phi_1 \frac{D^{(A)}_{n+1}}{B_{n+1}} \Delta^{(A)}_{n+1}(t_{n+2}, t_{n+1}) O_{n+2} \right] \\
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NLO merging

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NLO merging

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\times \left[ \Delta_{n+1}^{(A)}(t_0, t_{n+1}) \, O_{n+1} + \int_{t_0}^{t_{n+1}} d\Phi_1 \, \frac{D_{n+1}^{(A)}}{B_{n+1}} \, \Delta_{n+1}^{(A)}(t_{n+2}, t_{n+1}) \, O_{n+2} \right] \\
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\]
\[ \langle O \rangle^{\text{MEPS@NLO}} \]

\[
= \int d\Phi_n \bar{B}^{(A)}_n \left[ \Delta^{(A)}_n(t_0, \mu_Q^2) O_n \\
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NLO merging – Generation of MC counterterm

\[ 1 + \frac{B_{n+1}}{\bar{B}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} d\Phi_1 K_n \]

- same form as exponent of Sudakov form factor \( \Delta_n^{(PS)}(t_{n+1}, \mu_Q^2) \)
- truncated parton shower on \( n \)-parton configuration underlying \( n + 1 \)-parton event
  1. no emission → retain \( n + 1 \)-parton event as is
  2. first emission at \( t' \) with \( Q > Q_{\text{cut}} \), multiply event weight with \( B_{n+1}/\bar{B}_{n+1}^{(A)} \), restart evolution at \( t' \), do not apply emission kinematics
  3. treat every subsequent emission as in standard truncated vetoed shower
- generates

\[ \left[ 1 + \frac{B_{n+1}}{\bar{B}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} d\Phi_1 K_n \right] \Delta_n^{(PS)}(t_{n+1}, \mu_Q^2) \]

⇒ identify \( \mathcal{O}(\alpha_s) \) counterterm with the emitted emission
NLO merging

Renormalisation scales:

- determined by clustering using PS probabilities and taking the respective nodal values $t_i$

$$\alpha_s(\mu^2_R)^{k} = \prod_{i=1}^{k} \alpha_s(t_i)$$

- change of scales $\mu_R \rightarrow \tilde{\mu}_R$ in MEs necessitates one-loop counter term

$$\alpha_s(\tilde{\mu}^2_R)^{k} \left( 1 - \frac{\alpha_s(\tilde{\mu}^2_R)}{2\pi} \beta_0 \sum_{i=1}^{k} \ln \frac{t_i}{\tilde{\mu}^2_R} \right)$$

Factorisation scale:

- $\mu_F$ determined from core $n$-jet process

- change of scales $\mu_F \rightarrow \tilde{\mu}_F$ in MEs necessitates one-loop counter term

$$B_n(\Phi_n) \frac{\alpha_s(\tilde{\mu}^2_R)}{2\pi} \log \frac{\mu^2_F}{\tilde{\mu}^2_F} \left( \sum_{c=q,g}^{n} \int_{x_a/\tilde{\mu}_F}^{1} \frac{dz}{z} P_{ac}(z) f_c(x_a/z, \tilde{\mu}^2_F) + \ldots \right)$$
Results: $e^+e^- \rightarrow$ hadrons

$ee \rightarrow$ hadrons
(2,3,4 $\oplus$ NLO; 5,6 $\oplus$ LO)

Jet resolutions (Durham measure)
- MEPS@NLO vs MENLOPs
- at $y \ll 1$ dominated by hadr. effects → needs retuning
- much improved ren. scale dependence

ALEPH data
**Results:** $e^+e^- \rightarrow \text{hadrons}$


Thrust ($E_{\text{CMS}} = 91.2$ GeV)

Sphericity ($E_{\text{CMS}} = 91.2$ GeV)
Results: \( pp \rightarrow W + \text{jets} \)

\[ pp \rightarrow W + \text{jets} \ (0,1,2 \ @ \ NLO; \ 3,4 \ @ \ LO) \]

- \( \mu_{R/F} \in [\frac{1}{2}, 2] \mu_{\text{def}} \)
  - scale uncertainty much reduced
- NLO dependece for \( pp \rightarrow W + 0,1,2 \text{ jets} \)
- LO dependence for \( pp \rightarrow W + 3,4 \text{ jets} \)
- \( Q_{\text{cut}} = 30 \text{ GeV} \)
- good data description

Results: $pp \rightarrow W + \text{jets}$

$pp \rightarrow W + \text{jets}$ (0,1,2 @ NLO; 3,4 @ LO)

- $\mu_{R/F} \in \left[\frac{1}{2}, 2\right] \mu_{\text{def}}$
- Scale uncertainty much reduced
- NLO dependence for $pp \rightarrow W + 0,1,2$ jets
- LO dependence for $pp \rightarrow W + 3,4$ jets
- $Q_{\text{cut}} = 30$ GeV
- Good data description

Results: \(pp \rightarrow W + \text{jets}\)

Conclusions

- SHERPA’s MC@NLO formulation allows full evaluation of perturbative uncertainties ($\mu_F, \mu_R, \mu_Q$)
- MC@NLO can be easily combined with MEPS $\rightarrow$ MENLOPS
- MC@NLO is a necessary input for NLO merging $\rightarrow$ MEPS@NLO
- MEPS@NLO gives full benefits of NLO calculations (scale dependences, normalisations) while also retaining full (N)LL accuracy of parton shower
  $\Rightarrow$ will be included in next major release

Current release: SHERPA-1.4.1
http://sherpa.hepforge.org

- better description of perturbative QCD is only part of the story to achieve higher precision for (hard) collider observables
Thank you for your attention!
Case study: Inclusive jet & dijet production

Dijet azimuthal decorrelation in various $p_{\perp}$ bins

- CMS data
- Sherpa MC@NLO
  - $\mu_R = \mu_F = \frac{1}{2} \mu_T$
  - $\mu_Q = \frac{1}{2} p_{\perp}$
- $\mu_R, \mu_F$ variation
- $\mu_Q$ variation
- MPI variation

Höche, MS arXiv:1208.2815
Case study: Inclusive jet & dijet production

Inclusive jet transverse momenta in different rapidity ranges

\( p_\perp [\text{GeV}] \)

\( \frac{d\sigma}{dp_\perp} [\text{pb/GeV}] \)

- ATLAS data
- MC@NLO
- SHERPA MC@NLO

\( \mu_R = \mu_F = \frac{1}{2} H_T, \quad \mu_Q = \frac{1}{2} p_\perp \)

\( \mu_R, \mu_F \) variation

\( \mu_Q \) variation

MPI variation

Höche, MS arXiv:1208.2815
Case study: Inclusive jet & dijet production

Central transverse thrust in different leading jet $p_{\perp}$ ranges

CMS data

SHERPA MC@NLO
$\mu_R = \mu_F = \frac{1}{2} H_T$, $\mu_Q = \frac{1}{2} p_{\perp}$

- $\mu_R$, $\mu_F$ variation
- $\mu_Q$ variation
- MPI variation

Höche, MS arXiv:1208.2815
Central transverse thrust minor in different leading jet $p_\perp$ ranges

\begin{align*}
\frac{1}{N} \frac{dN}{d\ln(T_{m,C})} \text{ [pb]} & \\
& \text{CMS data} \\
& \text{Phys. Rev. Lett. 106 (2011) 122003} \\
& \text{Sherpa MC@NLO} \\
& \mu_R = \mu_F = \frac{1}{4} H_T, \ \mu_Q = \frac{1}{2} p_\perp \\
& \mu_R, \mu_F \text{ variation} \\
& \mu_Q \text{ variation} \\
& \text{MPI variation} \\
\end{align*}

Höche, MS arXiv:1208.2815