# Parton shower matching and multijet merging at NLO

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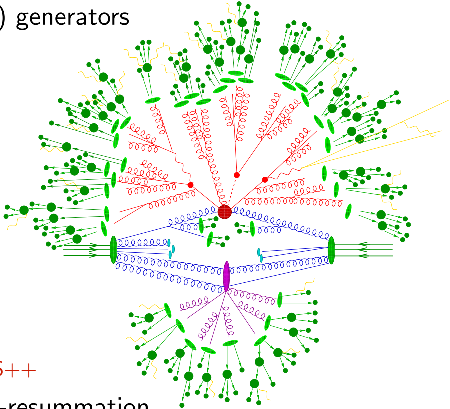
arXiv:1111.1220, arXiv:1201.5882
arXiv:1207.5030, arXiv:1207.5031
arXiv:1208.2815

JHEP02(2009)007

# The SHERPA event generator framework

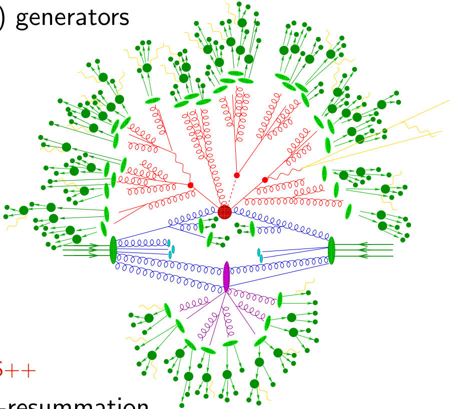


- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044
  COMIX JHEP12(2008)039
  CS subtraction EPJC53(2008)501
- A Parton Shower (PS) generator
  CSSHOWER++ JHEP03(2008)038
- A multiple interaction simulation
  à la Pythia AMISIC++ hep-ph/0601012
- A cluster fragmentation module
  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
$\rightarrow$ full analytic control mandatory for consistency/accuracy

JHEP02(2009)007

# The Sherpa event generator framework



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MePs (CKKW), **Mc@Nlo**, MeNloPs, **MePs@Nlo**
$\rightarrow$ full analytic control mandatory for consistency/accuracy

# Mc@Nlo

Frixione, Webber JHEP06(2002)029

$$\langle O\rangle^{\mathsf{NLO+PS}} = \int d\Phi_B\, \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B)\Bigg[\Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\, O(\Phi_B) + \int_{t_0}^{\mu_Q^2} d\Phi_1\, \frac{\mathrm{D}^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathsf{A})}(t,\mu_Q^2)\, O(\Phi_R)\Bigg] + \int d\Phi_R\Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R)$$

Höche, Krauss, MS, Siegert arXiv:1111.1220

- NLO weighted Born configuration $\bar{\mathrm{B}}^{(\mathsf{A})} = \mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I} + \int d\Phi_1 [\mathrm{D}^{(\mathsf{A})} - \mathrm{D}^{(\mathsf{S})}]$
- use $\mathrm{D}_i^{(\mathsf{A})}$ as resummation kernels $\Delta^{(\mathsf{A})}(t,t') = \exp\left[\int_t^{t'} d\Phi_1\, \mathrm{D}^{(\mathsf{A})}/\mathrm{B}\right]$
- resummation phase space limited by $\mu_Q^2 = t_{\mathsf{max}}$
  → 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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every term is well defined and NLO and NLL accuracy maintained if:

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

$\Rightarrow$ **conventional parton showers need to be improved for that**

e.g. choose $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$ up to phase space constraints

# Case study: Inclusive jet & dijet production

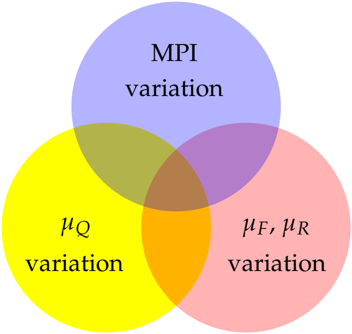
Describe wealth of experimental data with a single sample (LHC@7TeV)

McNLO di-jet production: Höche, MS arXiv:1208.2815

- $\mu_{R/F} = \frac{1}{4}\,H_T$, $\mu_Q = \frac{1}{2}\,p_\perp$
- CT10 PDF $(\alpha_s(m_Z) = 0.118)$
- hadron level calculation
  fully hadronised including MPI
- virtual MEs from BlackHat
  Giele, Glover, Kosower Nucl.Phys.B403(1993)633-670
  Bern et.al. arXiv:1112.3940
- $p_\perp^{j_1} > 20$ GeV, $p_\perp^{j_2} > 10$ GeV

Uncertainty estimates:

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_Q^{\text{def}}$
- MPI activity in tr. region $\pm$ 10%



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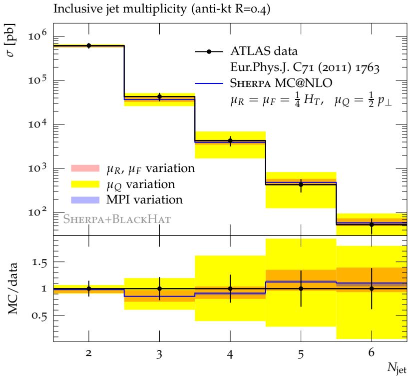

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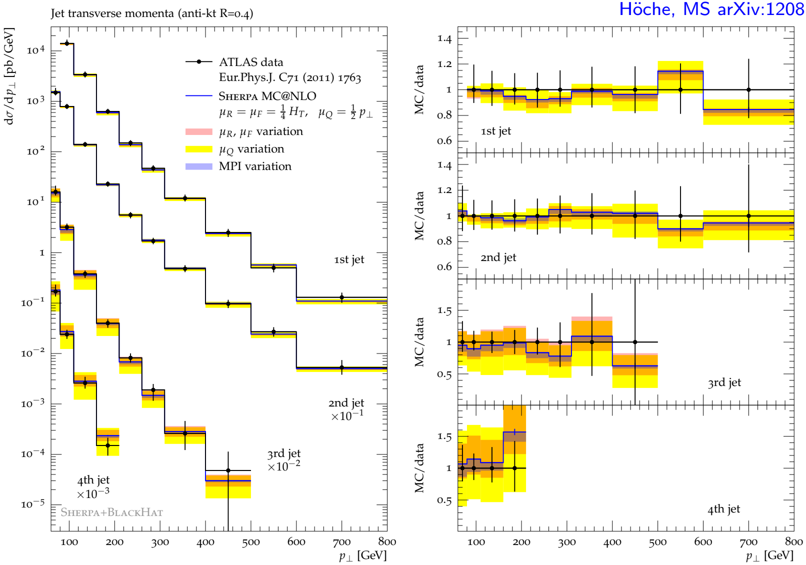

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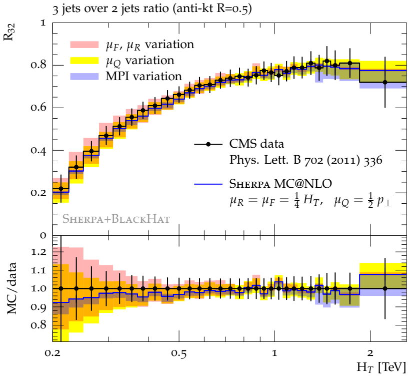


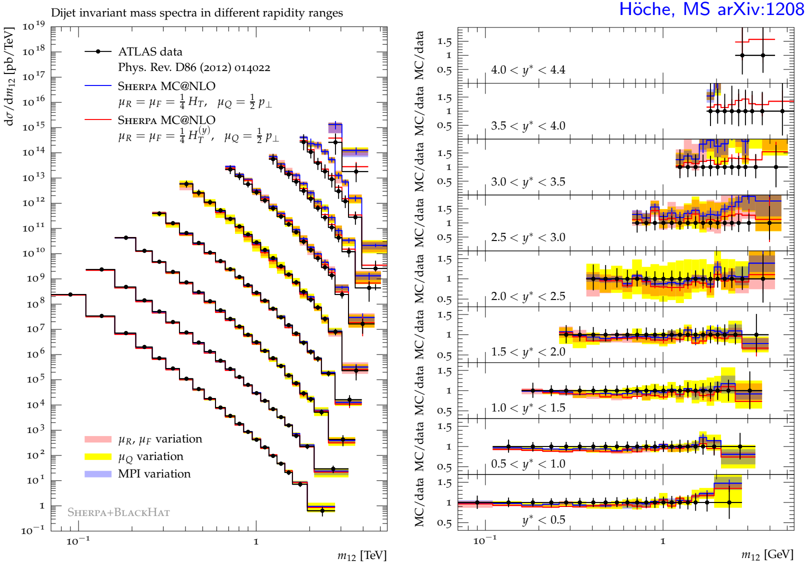

Höche, MS arXiv:1208.2815

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

Höche, MS arXiv:1208.2815

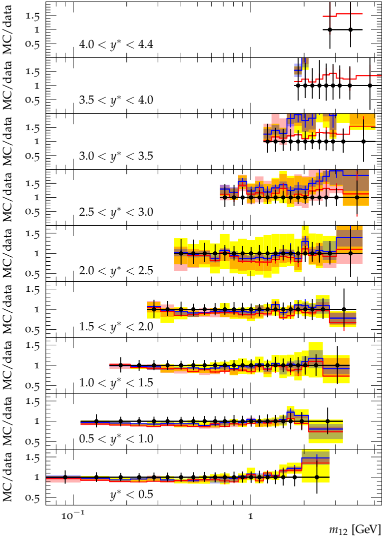
Try different scale

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



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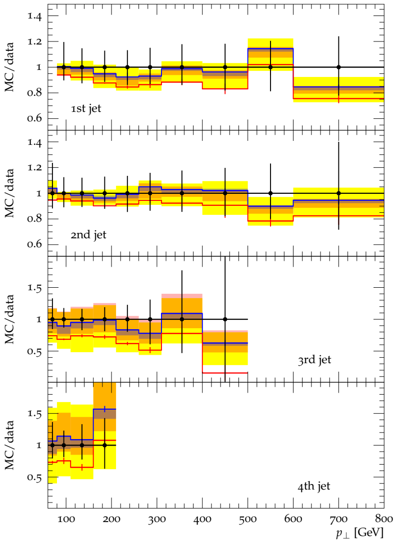

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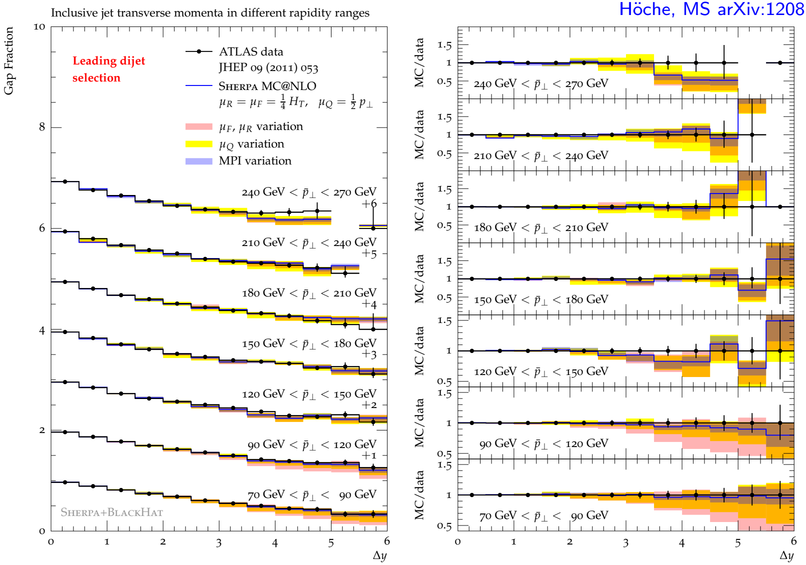

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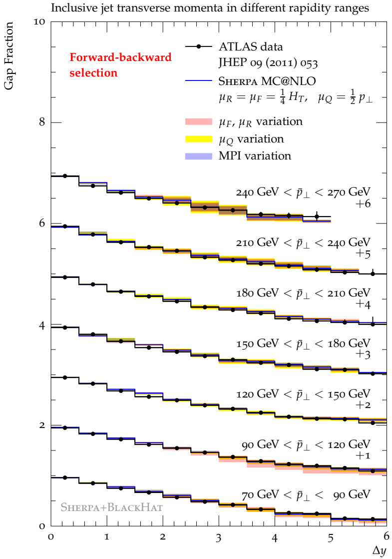
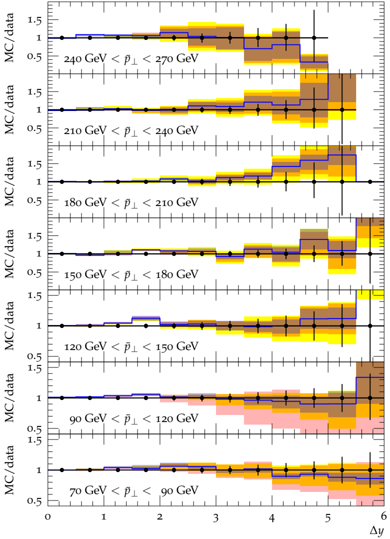


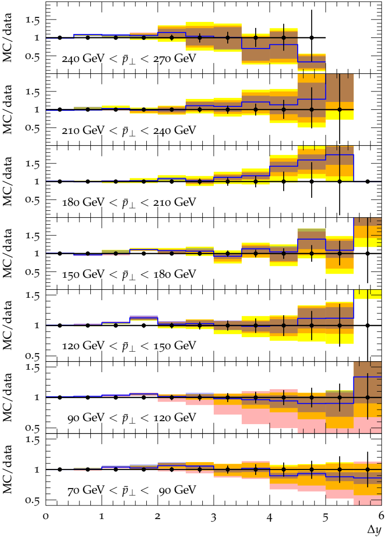
# Case study: Inclusive jet & dijet production

- small-$\Delta y$ region
  $\Rightarrow$ small uncertainty on additional jet production
- large-$\Delta y$ region
  $\Rightarrow$ all uncertainties sizable

- small-$\bar{p}_\perp$ region
  $\Rightarrow$ dominated by perturbative uncertainties
- small-$\bar{p}_\perp$ region
  $\Rightarrow$ non-perturbative uncertainties as large as perturbative uncertainties

**Reduction of theoretical uncertainty necessitates better understanding of soft QCD and non-factorisable contributions**

Höche, MS arXiv:1208.2815



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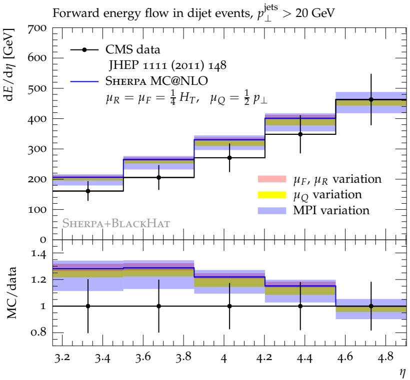


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Forward energy flow

- 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

# 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

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Lavesson, Lönnblad JHEP12(2008)070

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031

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Höche, Krauss, MS, Siegert arXiv:1207.5030

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\langle O\rangle^{\textsc{MePs@Nlo}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \left[ \Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n \right.\\
&\qquad \left. + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\mathrm{cut}}-Q)\, O_{n+1} \right]\\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\right] \Theta(Q_{\mathrm{cut}}-Q)\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1}\\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}\, \Theta(Q-Q_{\mathrm{cut}})\\
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$$\langle O\rangle^{\text{MePs@Nlo}}$$

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\langle O \rangle^{\text{MePs@Nlo}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathrm{A})} \Bigg[ \Delta_n^{(\mathrm{A})}(t_0,\mu_Q^2)\, O_n \\
&\qquad\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathrm{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1} \Bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[ \mathrm{R}_n - \mathrm{D}_n^{(\mathrm{A})} \right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathrm{A})} \left[ 1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n \right] \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \\
&\qquad\qquad \times \left[ \Delta_{n+1}^{(\mathrm{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathrm{A})}(t_{n+2},t_{n+1})\, O_{n+2} \right] \\
&\quad + \int \mathrm{d}\Phi_{n+2} \left[ \mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathrm{A})} \right] \Delta_{n+1}^{(\mathrm{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\, O_{n+2}
\end{aligned}
$$

# NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031

$$\langle O\rangle^{\text{MEPS@NLO}}$$

$$= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathrm{A})} \left[ \Delta_n^{(\mathrm{A})}(t_0,\mu_Q^2)\, O_n + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathrm{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1} \right]$$

$$+ \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathrm{A})}\right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1}$$

$$+ \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathrm{A})} \left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n \right] \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})$$

$$\times \left[ \Delta_{n+1}^{(\mathrm{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathrm{A})}(t_{n+2},t_{n+1})\, O_{n+2} \right]$$

$$+ \int \mathrm{d}\Phi_{n+2} \left[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathrm{A})}\right] \Delta_{n+1}^{(\mathrm{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\, O_{n+2}$$

# NLO merging – Generation of MC counterterm

$$\left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1 \, \mathrm{K}_n\right]$$

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

$$\left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1 \, \mathrm{K}_n\right] \Delta_n^{(\mathsf{PS})}(t_{n+1}, \mu_Q^2)$$

$\Rightarrow$ **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 $t_i$

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

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

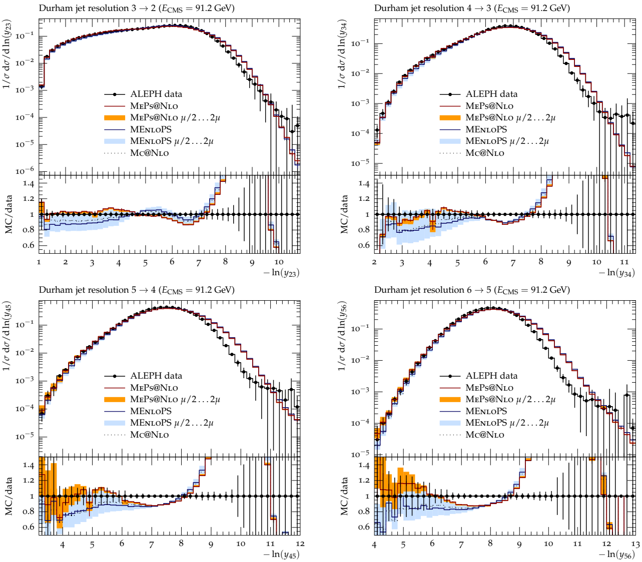
$$\alpha_s(\tilde{\mu}_R^2)^k \left(1 - \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\,\beta_0 \sum_{i=1}^{k} \ln \frac{t_i}{\tilde{\mu}_R^2}\right)$$

Factorisation scale:

- $\mu_F$ determined from core $n$-jet process
- change of scales $\mu_F \to \tilde{\mu}_F$ in MEs necessitates one-loop counter term

$$\mathrm{B}_n(\Phi_n)\,\frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\,\log\frac{\mu_F^2}{\tilde{\mu}_F^2}\left(\sum_{c=q,g}^{n}\int_{x_a}^{1}\frac{\mathrm{d}z}{z}\,P_{ac}(z)\,f_c(x_a/z,\tilde{\mu}_F^2)+\ldots\right)$$

# Results: $e^+e^- \to$ hadrons




$ee \to$ hadrons (2,3,4 @ NLO; 5,6 @ LO)

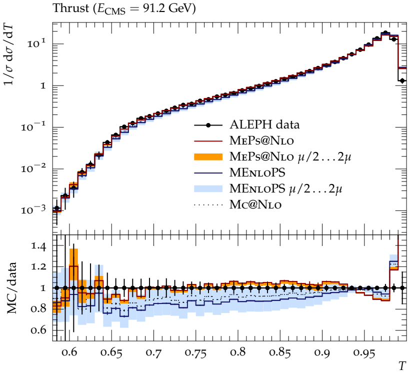
Jet resolutions (Durham measure)

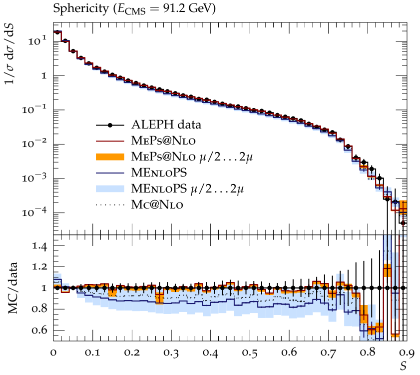
- MEPS@NLO vs MENLOPS
- at $y \ll 1$ dominated by hadr. effects $\to$ needs retuning
- much improved ren. scale dependence

ALEPH data
EPJC35(2004)457-486

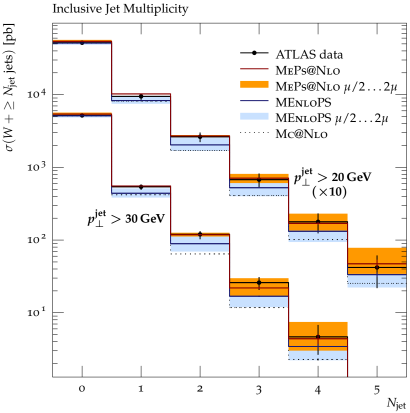
# Results: $e^+e^- \to$ hadrons

ALEPH data EPJC35(2004)457-486



# Results: $pp \to W$+jets

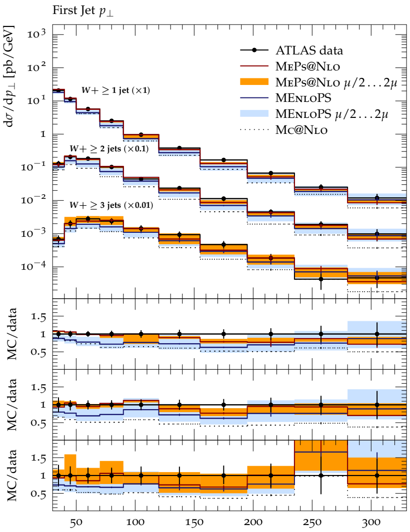



$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

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

ATLAS data Phys.Rev.D85(2012)092002

# Results: $pp \to W$+jets




$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

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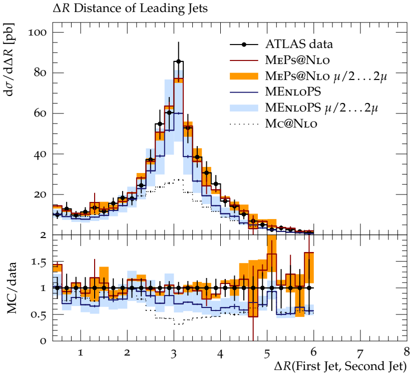
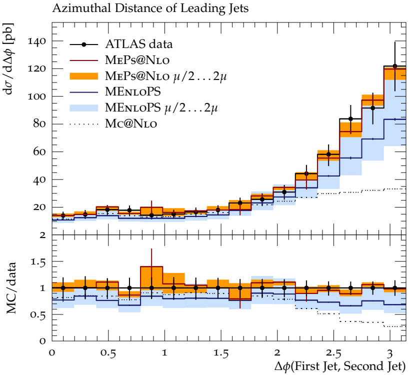
# Results: pp → W+jets

ATLAS data Phys.Rev.D85(2012)092002



# 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

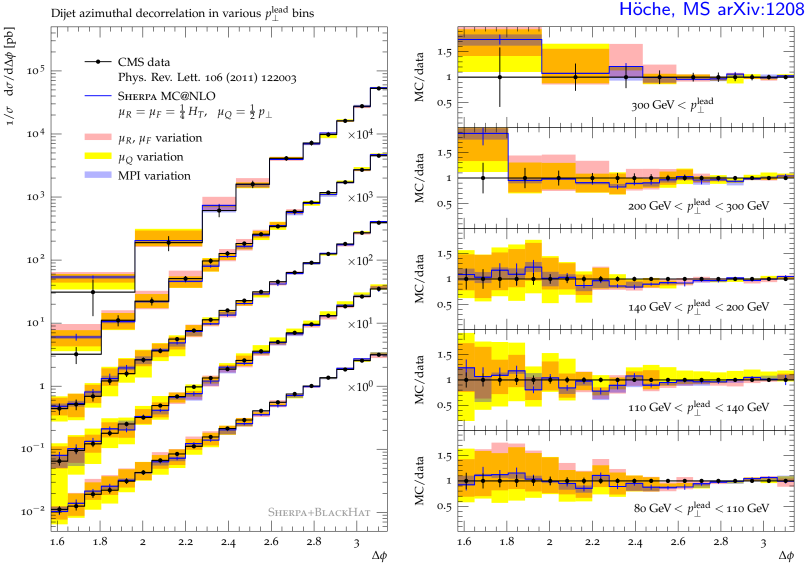
http://sherpa.hepforge.org

- better description of perturbative QCD is only part of the story to achieve higher precission for (hard) collider observables

Thank you for your attention!

# Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815



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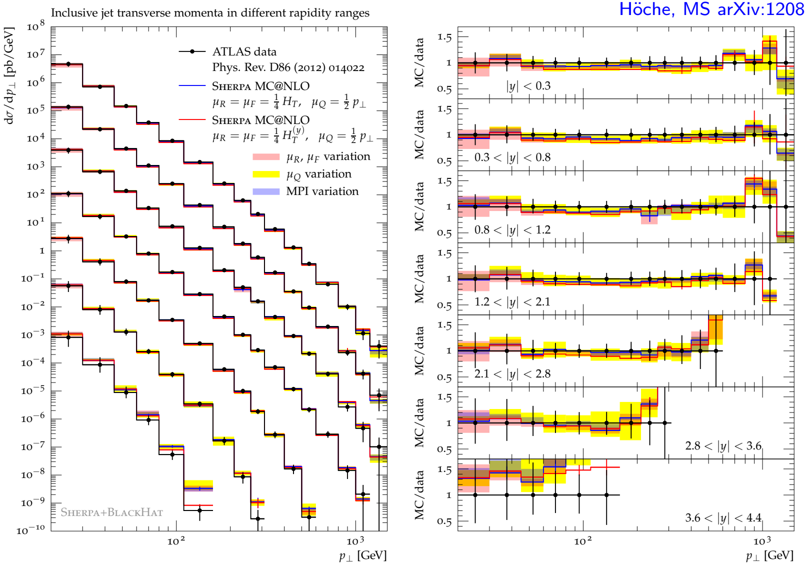

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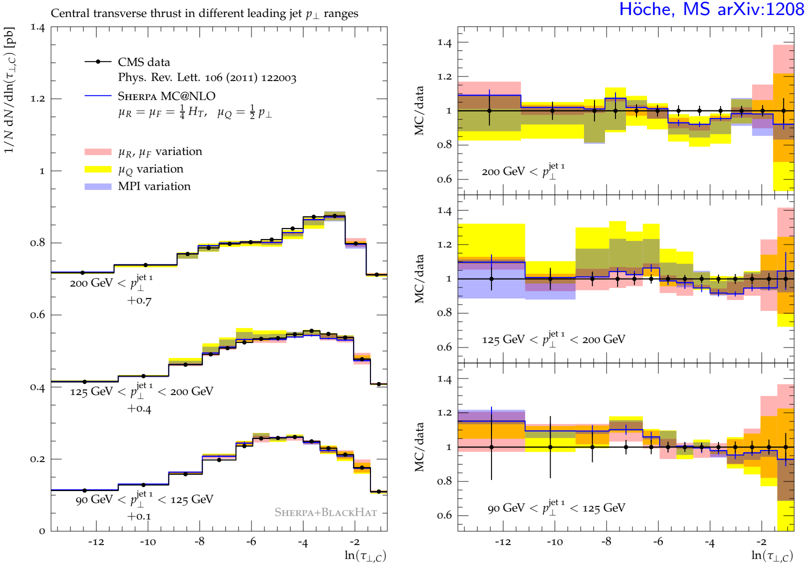

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