Multijet merging at next-to-leading order

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*in collaboration with T. Gehrmann, S. Höche, F. Krauss, F. Siegert

Contents

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Importance of matching NLO calculations with parton showers

- exclusive final states
- observable independent combination of fixed order and resummation
- problem double counting: both NLO and PS are approximations to higher order corrections → MC@NLO and POWHEG

Importance of multijet merging

- simultaneous description multijet topologies
  → every jet multiplicity at same fixed order accuracy
- resum hierarchies in emission scales

Uncertainties of NLOPS matching/MEPS@NLO merging

- usual μ_R and μ_F variation as in NLO calculations
- also μ_Q-variation as in analytic resummations

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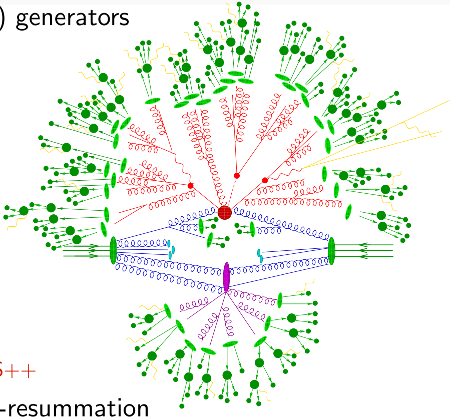
The SHERPA event generator framework



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MEPS (CKKW), MC@NLO, MENLOPS, MEPS@NLO

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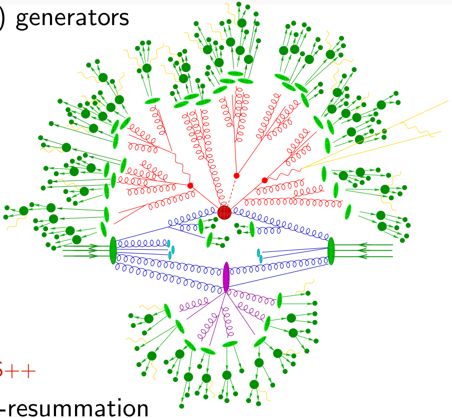

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Resummation properties of parton showers

$$\langle O\rangle^{\text{PS}} = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\,O(\Phi_B)$$

- splitting kernel $\mathcal{K}(\Phi_1) \propto \frac{\alpha_s}{t}\,P(z)$, $\Phi_1 = \{t, z, \phi\}$
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- parton shower starting scale μ_Q plays role of resummation scale, at LO commonly identified with μ_F to recover PDF evolution
- resummation in evolution variable t, c_1 correctly described, c_2 at most in $N_c \to \infty$ approximation
- $\alpha_s \to \alpha_s(k_\perp)$ catches dominant terms of higher log. order

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General NLO calculations

- NLO calculation with subtraction methods

Frixione, Kunszt, Signer Nucl.Phys.B467(1996)399-442
Catani, Seymour Nucl.Phys.B485(1997)291-419

$$
\begin{aligned}
\langle O\rangle^{\text{NLO}} =& \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B)+\mathrm{V}(\Phi_B)+\mathrm{I}(\Phi_B)\Big]\, O(\Phi_B)\\
&+\int \mathrm{d}\Phi_R \Big[\qquad - \sum_i \mathrm{D}_i^{(\mathrm{S})}(\Phi_R) \quad O(\Phi_{B_i})\Big]\\
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- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathrm{A})}$
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NLOPS matching

- parton shower/resummation kernel $\mathcal{K}_i(\Phi_1)$, $\Phi_1 = \{t, z, \phi\}$

$$\langle O\rangle^{\mathsf{PS}} = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\,O(\Phi_B)$$

$$= \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\,O(\Phi_B) +$$

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- use $\mathrm{D}_i^{(\mathrm{A})}$ as resummation kernels
- resummation phase space limited by $\mu_Q^2 = t_{\text{max}}$
  $\rightarrow$ starting scale of parton shower evolution
  $\rightarrow$ should be of the order of the hard resummation scale

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- **Powheg and Mc@Nlo now differ in choice of $\mathrm{D}_i^{(\mathrm{A})}$ and μ_Q^2**

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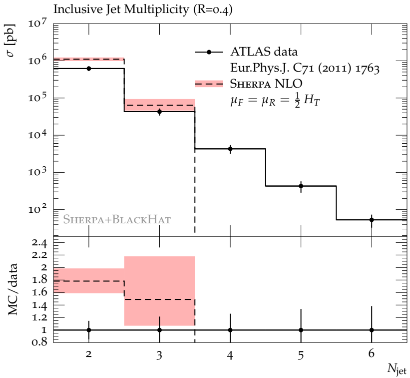
- **SHERPA:** $\mathrm{D}_i^{(\mathrm{A})} = \mathrm{D}_i^{(\mathrm{S})}\,\Theta(\mu_Q^2 - t)$ **($N_c = 3$ CS kernels), μ_Q free**

Case study: Inclusive jet & dijet production

NLO:

- poor description in phase space regions with strongly hierarchical scales
- poor perturbative jet-modeling (at most two constituents)
- no hadronisation, MPI effects
- jet-$p_\perp$ turn negative in forward region unless y-dependent scale is used (e.g. $H_T^{(y)}$)



no. jets	ATLAS	LO	ME+PS	NLO	NP factor	NLO+NP
≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	$559(5)$	$1193(3)^{+130}_{-135}$	$0.95(0.02)$	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	$39.7(0.9)$	$54.5(0.5)^{+2.2}_{-19.9}$	$0.92(0.04)$	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	$3.97(0.08)$	$5.54(0.12)^{+0.08}_{-2.44}$	$0.92(0.05)$	$5.11(0.29)^{+0.08}_{-2.32}$

Bern et.al. Phys.Rev.Lett.109(2012)042001

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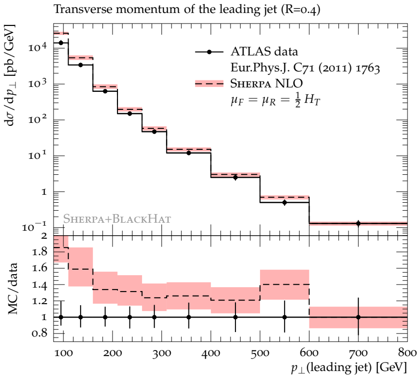

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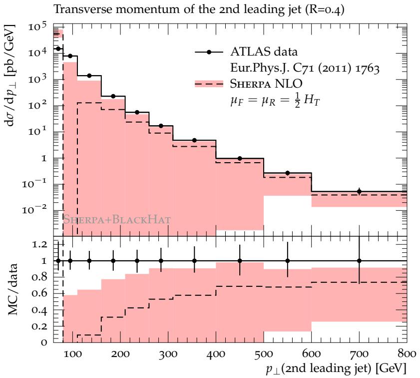
≥ 4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	$3.97(0.08)$	$5.54(0.12)^{+0.08}_{-2.44}$	$0.92(0.05)$	$5.11(0.29)^{+0.08}_{-2.32}$

Bern et.al. Phys.Rev.Lett.109(2012)042001

Case study: Inclusive jet & dijet production

NLO:

- poor description in phase space regions with strongly hierarchical scales
- poor perturbative jet-modeling (at most two constituents)
- no hadronisation, MPI effects
- jet-$p_\perp$ turn negative in forward region unless y-dependent scale is used (e.g. $H_T^{(y)}$)



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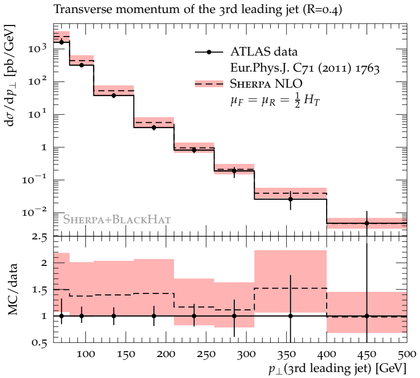

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Bern et.al. Phys.Rev.Lett.109(2012)042001

Case study: Inclusive jet & dijet production

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

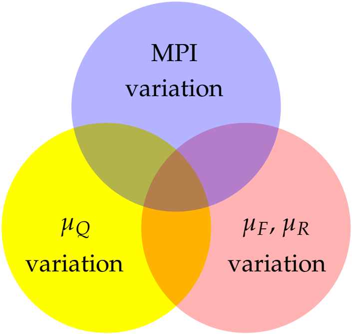
MC@NLO di-jet production:

Höche, MS Phys.Rev.D86(2012)094042

- $\mu_{R/F} = \frac{1}{4}\,H_T$, $\mu_Q = \frac{1}{2}\,p_\perp$
- CT10 PDF $(\alpha_s(m_Z) = 0.118)$
- hadron level calculation, 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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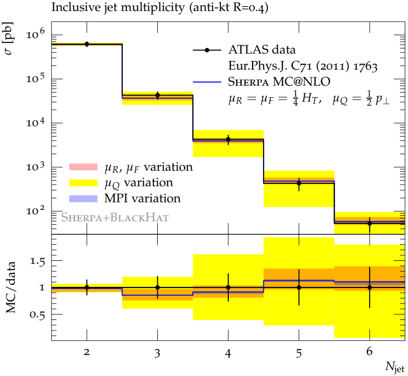

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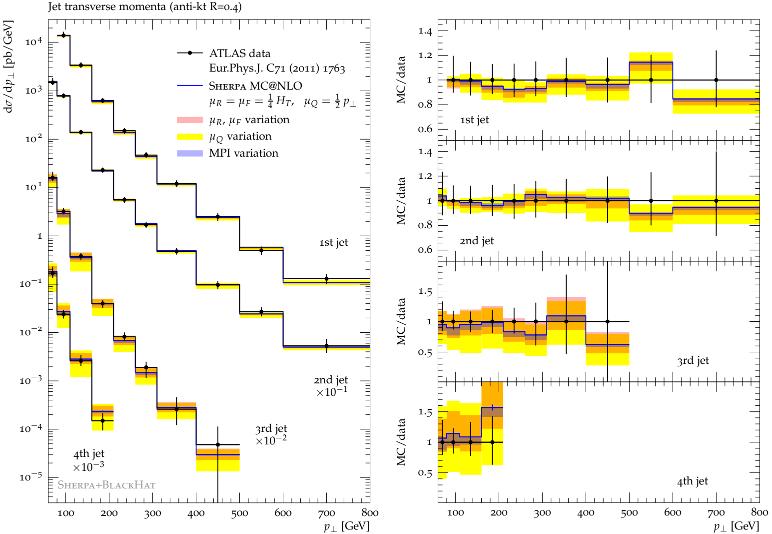

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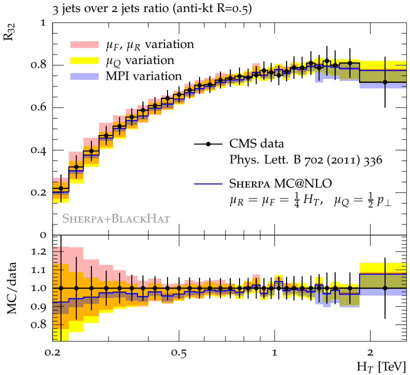
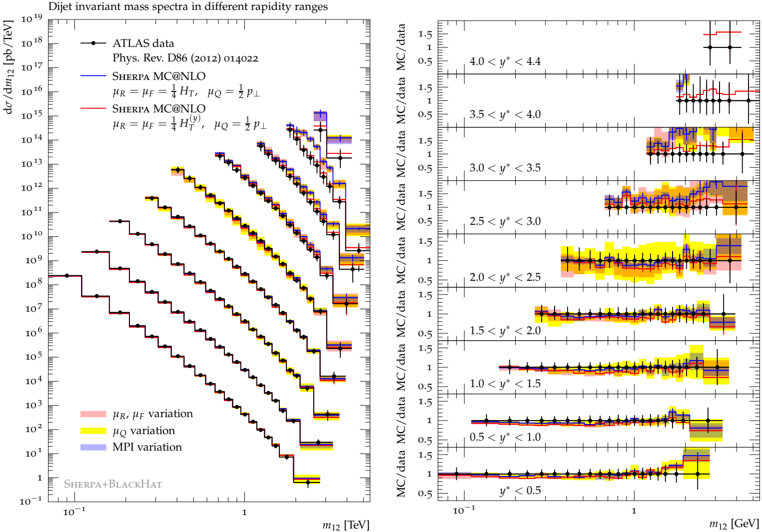


3-jet-over-2-jet ratio

- 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

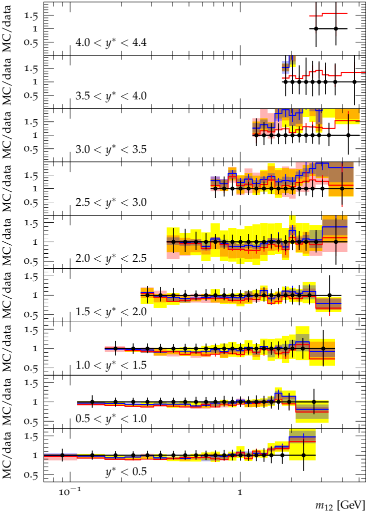


Case study: Inclusive jet & dijet production

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 $y_\text{boost} = 1/n_\text{jets} \sum_{i\in\text{jets}} y_i$
- 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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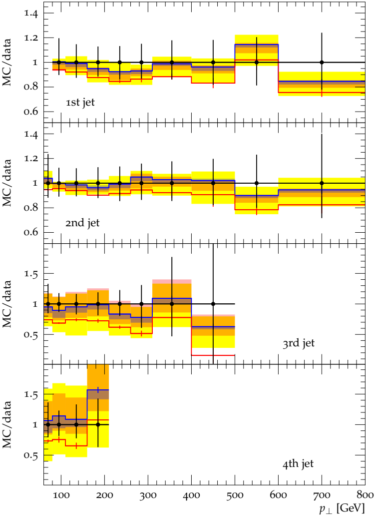

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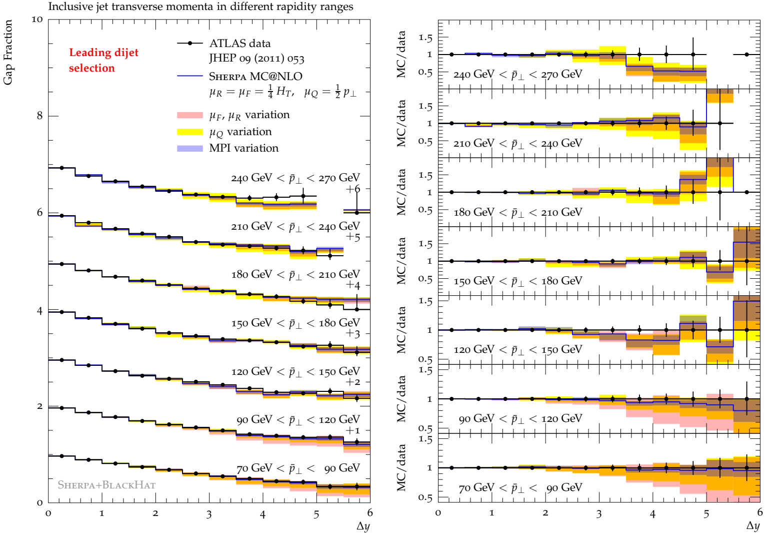

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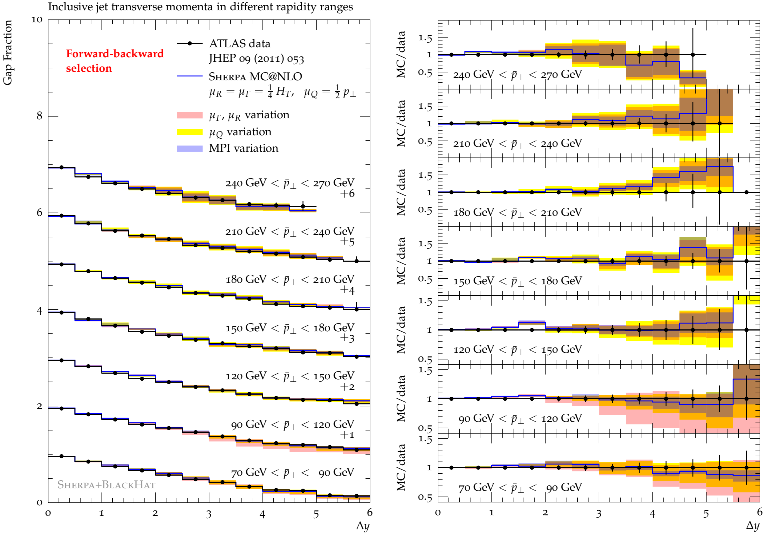

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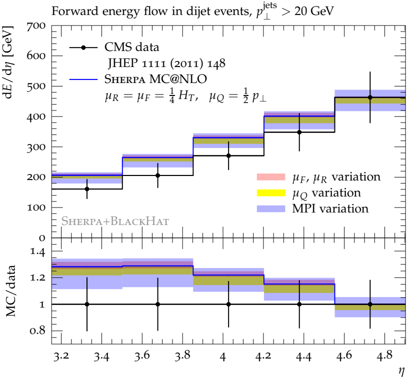
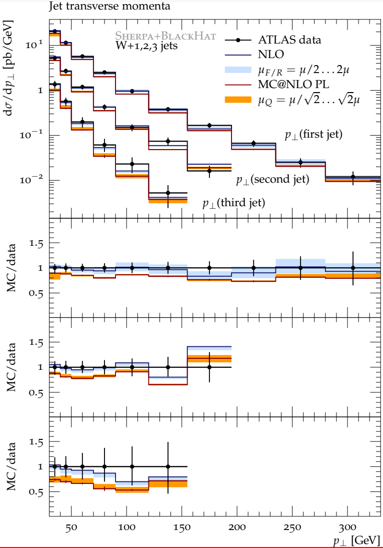


Forward energy flow

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

$W + n$ jet production



Höche, Krauss, MS, Siegert
Phys.Rev.Lett.110(2013)052001

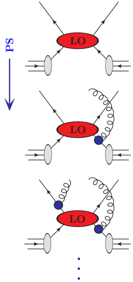
$pp \to W + 1, 2, 3$ jets

- 3 separate samples/calculations
- NLO accuracy for inclusive observables of respective jet multiplicity
- resummation of softest/LO jet, i.e. 4th jet in $pp \to W + 3$ jets
- no resummation of sample-defining jet multiplicity, i.e. first 3 jets in $pp \to W + 3$ jets
- scales: $\mu_{R/F} = \frac{1}{2}\,\hat{H}'_T,\ \mu_Q = p_\perp(j_n)$

Data: ATLAS Phys.Rev.D85(2012)092002

Contents

MEPs – Multijet merging at LO



LO $pp \to 2$ with parton showers vs. **LO $pp \to n$ matrix elements**

+ exponentiation of large IR logarithms
− poor hard/wide angle emission pattern

+ dominant terms for hard/wide angle rad.
− breakdown of α_s-expansion in log. region

- MEPs schemes: CKKW-type, MLM-type
  LO+(N)LL accuracy in every jet multiplicity
- scale setting scheme essential to preserve PS-resummation properties

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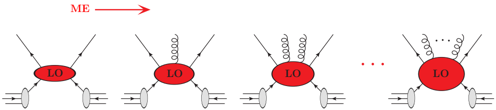

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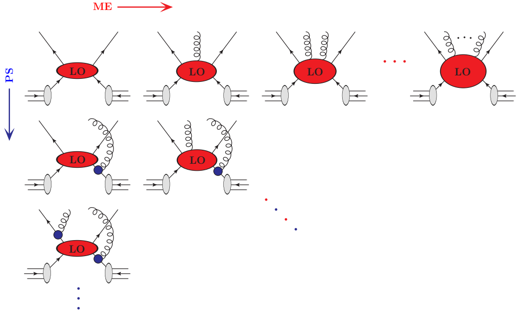

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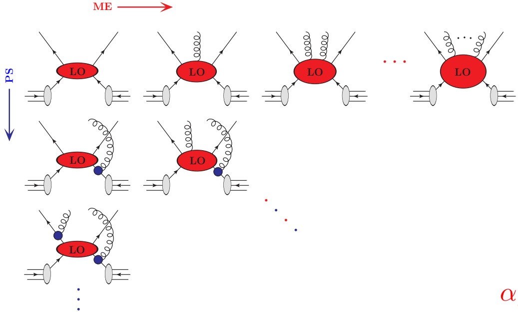

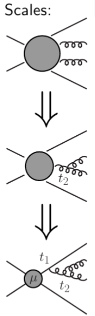

$$\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$

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Multijet merging

LO merging:

- LO accuracy for $n \leq n_{\mathsf{max}}$-jet processes
- preserve (N)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

MePs – Multijet merging at LO

$$\langle O\rangle^{\text{MePs}} = \int \mathrm{d}\Phi_n\, \mathrm{B}_n \Bigg[\Delta_n^{(\mathcal{K})}(t_0,\mu_Q^2)\, O_n + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathcal{K}_n\, \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\Bigg]$$

- LoPs for n-jet process restricted to region $Q < Q_{\text{cut}}$
- LoPs for $n+1$-jet process
- truncated showering to account for mismatch of t and Q Nason JHEP11(2004)040

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$$+ \int \mathrm{d}\Phi_{n+1} \, \mathrm{B}_{n+1} \, \Delta_n^{(\mathcal{K})}(t_{n+1}, \mu_Q^2) \, \Theta(Q - Q_{\text{cut}})$$

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

- LOPs for n-jet process restricted to region $Q < Q_{\text{cut}}$
- LOPs for $n+1$-jet process with additional Sudakov wrt. n-jet process
  $\Rightarrow$ implements correct resummation behaviour wrt. incl. sample
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$$
\begin{aligned}
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+ \int \mathrm{d}\Phi_{n+1}\, \mathrm{B}_{n+1}\, &\Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \\
&\times \Bigg[\Delta_{n+1}^{(\mathcal{K})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \mathcal{K}_{n+1}\, \Delta_{n+1}^{(\mathcal{K})}(t_{n+2},t_{n+1})\, O_{n+2}\Bigg]
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- α_s scales in $\mathrm{B}\cdot\mathcal{K}$ and B_{n+1} must be the same to retain resummation properties of the parton shower
- interprete B_{n+1} as PS splitting on top of B
  $\rightarrow$ need to use inverse parton shower

MEPs – Multijet merging at LO

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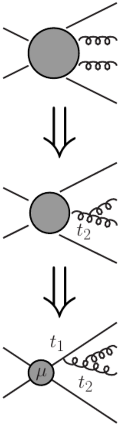
Scales:



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mismatch of $\mathcal{O}(\frac{1}{N_c}\,\alpha_s\,L)$

$$+ \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \left(\mathcal{K}_n\,\Theta(Q_{\text{cut}}-Q) + \frac{\mathrm{B}_{n+1}}{\mathrm{B}_n}\,\Theta(Q-Q_{\text{cut}})\right)$$

$$\times\;\Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, O_{n+2}\Bigg]$$

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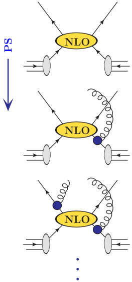
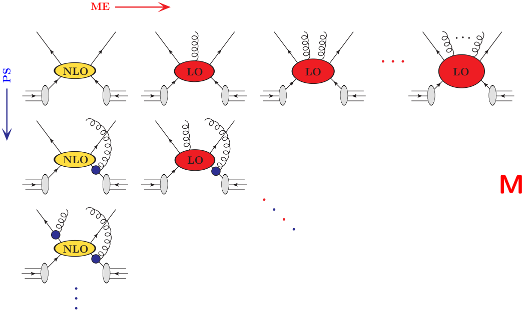
MEPS@NLO – Multijet merging at NLO



- promote LOPS to NLOPS (POWHEG, MC@NLO)
  → can assess uncertainties (part I)
- combine NLOPS for successive multiplicities into incl. sample (MEPS@NLO),
  preserve NLO+(N)LL accuracy in every jet multiplicity
  restore resummation wrt. to inclusive sample (part II)
- scale setting scheme essential to preserve PS-resummation properties

MEPS@NLO – Multijet merging at NLO



MENLOPS

- promote LOPS to NLOPS (POWHEG, MC@NLO)
  → can assess uncertainties (part I)
- combine NLOPS for successive multiplicities into incl. sample (MEPS@NLO),
  preserve NLO+(N)LL accuracy in every jet multiplicity
  restore resummation wrt. to inclusive sample (part II)
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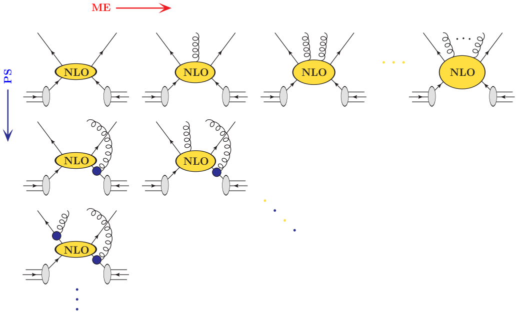

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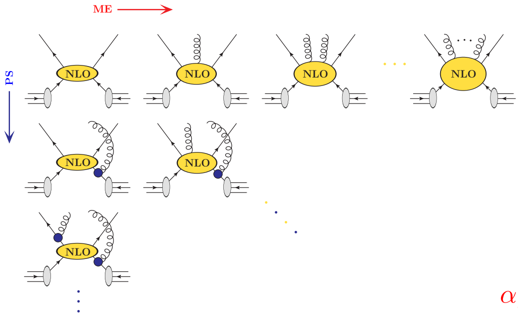

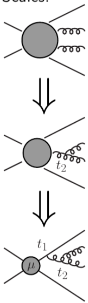

$$\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$

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MePs@Nlo – Multijet merging at NLO

LO merging:

- LO accuracy for $n \leq n_{\text{max}}$-jet processes
- preserve (N)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 accuracy for $n \leq n_{\text{max}}$-jet processes
- preserve (N)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

MEPS@NLO – Multijet merging at NLO

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

$$
\begin{aligned}
\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 \right.\\
&\qquad\left. + \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]\\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathrm{A})}\right] \Theta(Q_{\text{cut}}-Q)\, 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}})\\
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Höche, Krauss, MS, Siegert arXiv:1207.5030

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MEPs@NLO – Multijet merging at NLO

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

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$$

MePs@Nlo – Multijet merging at NLO

$\langle O \rangle^{\text{MePs@Nlo}}$

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

$$
\begin{aligned}
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\end{aligned}
$$

NLO merging – Generation of MC counterterm

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

- 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 $Q>Q_{\mathsf{cut}}$, multiply event weight with $\mathrm{B}_{n+1}/\bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}$, restart evolution at t', do not apply emission kinematics
  3. treat every subsequent emission as in standard truncated vetoed shower
- generates

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

$\Rightarrow$ **identify $\mathcal{O}(\alpha_s)$ counterterm with the omitted 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

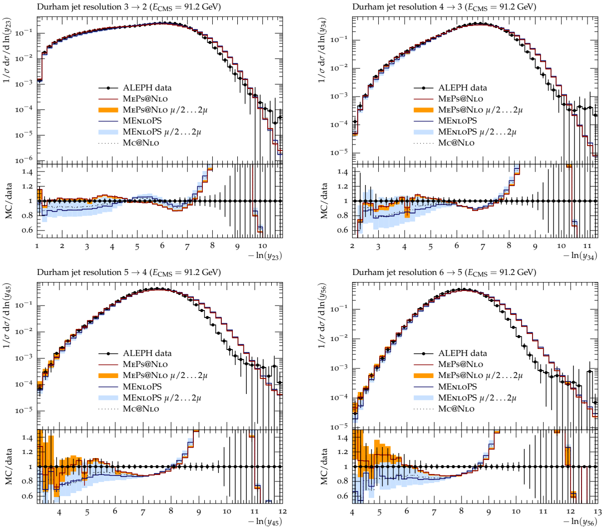
$$\alpha_s(\tilde{\mu}_R^2)^k \left(1 - \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\,\beta_0 \sum_{i=1}^{k} \ln \frac{t_i}{\tilde{\mu}_R^2}\right)$$

Factorisation scale:

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

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

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



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

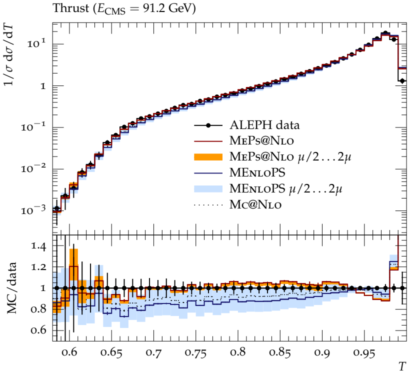
Jet resolutions (Durham measure)

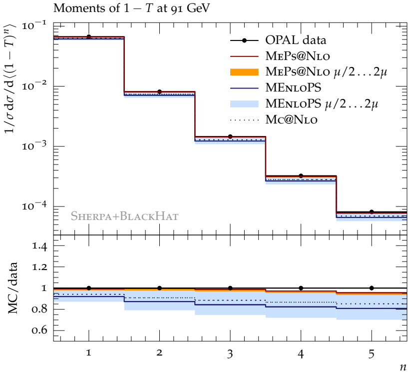
- MEPS@NLO vs MENLOPS
- at $y \ll 1$ dominated by hadr. effects $\to$ needs retuning
- much improved ren. scale dependence

ALEPH data EPJC35(2004)457-486

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

ALEPH data EPJC35(2004)457-486, OPAL data EPJC40(2005)287-316





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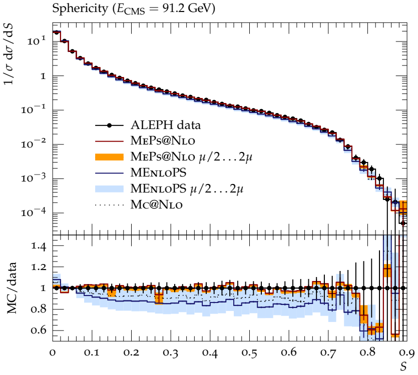
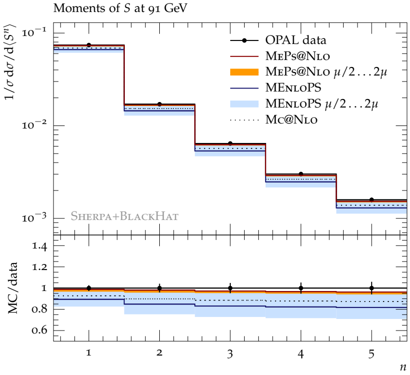
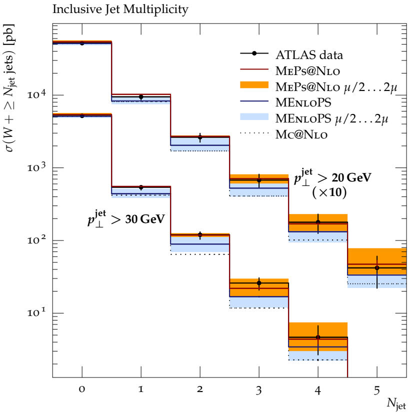
ALEPH data EPJC35(2004)457-486, OPAL data EPJC40(2005)287-316





Results – pp → W+jets

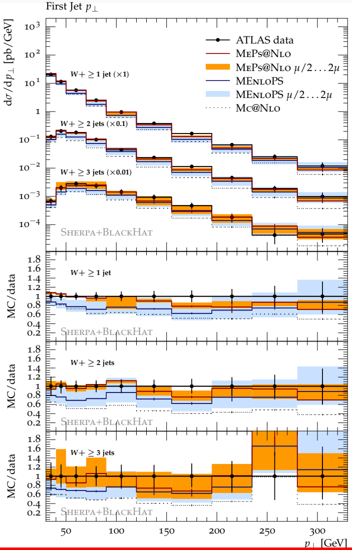


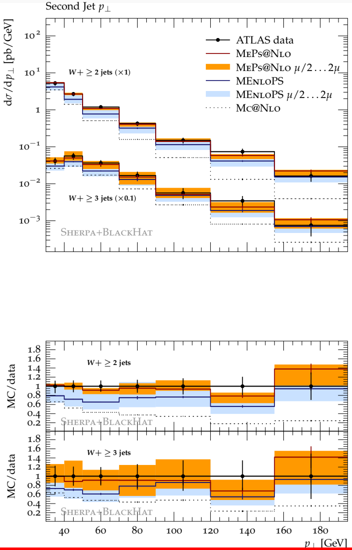
$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  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

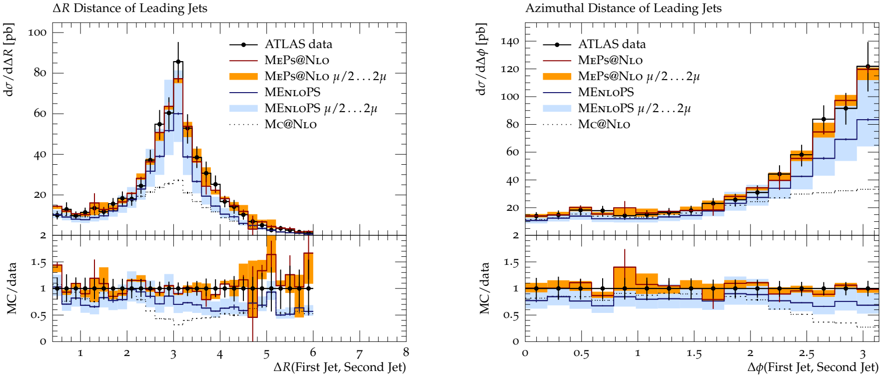
Results – pp → W+jets





Results – pp → W+jets

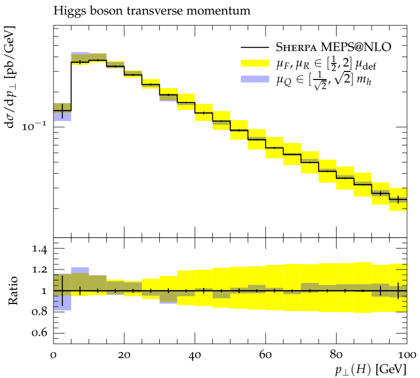
ATLAS data Phys.Rev.D85(2012)092002



Results – pp → h+ jets

Setup: $pp \to H+$jets (ggF)

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  2,3 jets @ LO
  $Q_{\text{cut}} = 20$ GeV, $N_{\text{max}} = 3$
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, m_h$
- variation of merging parameter $Q_{\text{cut}} \in \{15, 20, 30\}$ GeV and max. ME multi $N_{\text{max}} \in \{1, 2, 3\}$
- inclusive calculation
  → scales of each jet-multiplicity subsample not independent

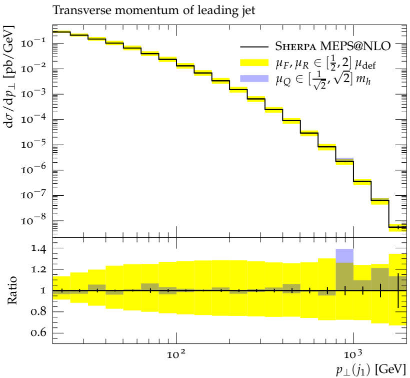


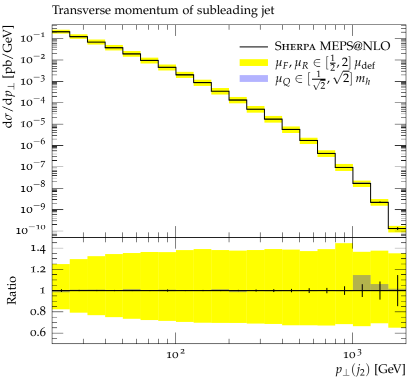
- inclusive cross section

$$\sigma = 15.2\, {}^{+2.5}_{-1.5}\, {}^{+1.0}_{-0.4}\, {}^{+0.3}_{-0.0}\, {}^{+0.2}_{-1.0}\ \text{pb}$$

$\mu_{R/F}$-, μ_Q-, Q_{cut}-, N_{max} var.

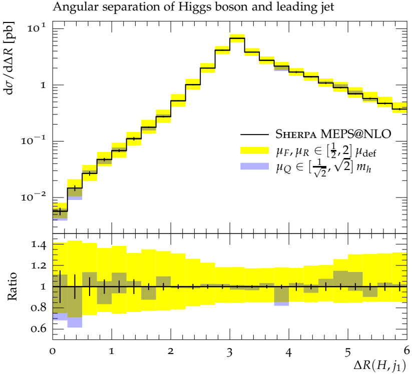
Results – pp → h+ jets

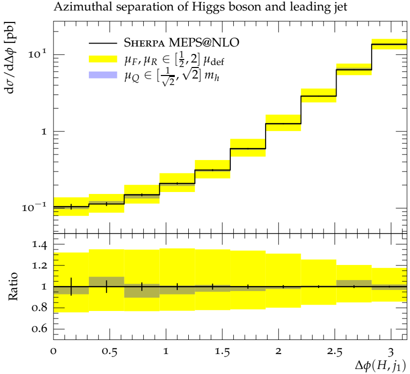




- transverse momenta of leading jets
- only small resummation scale dependence
- bulk of scale dependence comes from μ_R-dependence of effective vertex

Results – pp → h+ jets

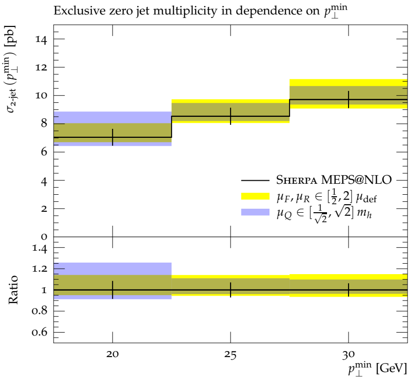




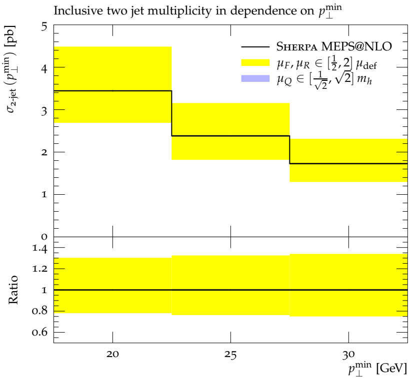
- angular correlations of leading jet and Higgs
- shape rather stable against variation

Results – $pp \to h+$ jets

exclusive 0-jet multiplicity

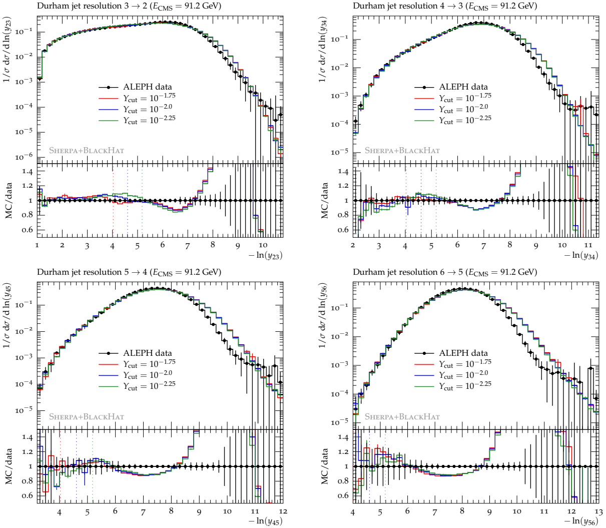


inclusive 2-jet multiplicity



- Determined from inclusive sample
  $\to$ common scale choice
  $\to$ correlated variations
  $\to$ needs improved resummation

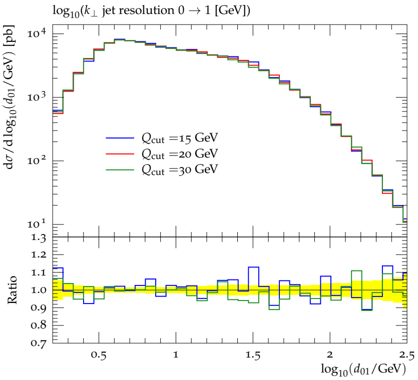
Q_{cut} dependence



$$y_{\text{cut}} = \left(\frac{Q_{\text{cut}}}{E_{\text{cms}}}\right)^2 = \begin{cases} 10^{-1.75} \\ 10^{-2.0} \\ 10^{-2.25} \end{cases}$$

- variation up to 10% in merging region
- very stable above and below
- incl. cross section $<1\%$

Q_{cut} dependence



$pp \to W+$ jets

- 0,1 @ NLO, 2 @ LO
- $Q_{cut} = 15, 20, 30$ GeV
- variation ≈5%

Conclusions

- NLOPS matching methods allow for observable independent matching of NLO calculations and parton shower resummation
  $\rightarrow$ allow for continuation into non-perturbative regime (hadronisation, multiple parton interactions)
- NLOPS is LO+(N)LL matching

- multijet merging at NLO proceeds schematically as at LO
  $\rightarrow$ introduce MC-counterterm to retain NLO accuracy
- scale setting essential for recovering PS resummation
- can be improved by adding higher order calculations
  - (N)NLL resummation
  - NNLO corrections

to be released SHERPA-2.0.β_2, when fully tuned SHERPA-2.0.0

http://sherpa.hepforge.org

Thank you for your attention!

MENLOPS for MC@NLO

$$
\begin{aligned}
\langle O\rangle^{\text{MENLOPS}} =& \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B) \Bigg[\Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\, O(\Phi_B) \\
&\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathsf{A})}(t,\mu_Q^2)\, O(\Phi_R)\, \Theta(Q_{\text{cut}}-Q)\Bigg] \\
&+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big] O(\Phi_R)\, \Theta(Q_{\text{cut}}-Q) \\
&+ \int \mathrm{d}\Phi_R \left[\frac{\bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_R)}{\mathrm{B}(\Phi_R)}\left(1-\frac{\mathrm{H}(\Phi_R)}{\mathrm{R}(\Phi_R)}\right)+\frac{\mathrm{H}(\Phi_R)}{\mathrm{R}(\Phi_R)}\right] \mathrm{R}(\Phi_R)\, \Delta^{(\mathsf{A})}(t_R,\mu_Q^2)\, O(\Phi_R)\, \Theta(Q-Q_{\text{cut}})
\end{aligned}
$$

- restrict MC@NLO expression to region $Q < Q_{\text{cut}}$
- add in real radiation explicitly, as in MEPS
- restore logarithmic behaviour by explicit Sudakov
- local K-factor for continuity at Q_{cut}

MENLOPS for MC@NLO

$$\langle O \rangle^{\text{MENLOPS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B) \Bigg[\Delta^{(\mathrm{A})}(t_0,\mu_Q^2)\, O(\Phi_B) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}^{(\mathrm{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathrm{A})}(t,\mu_Q^2)\, O(\Phi_R)\, \Theta(Q_{\text{cut}}-Q) \Bigg]$$

$$+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathrm{A})}(\Phi_R) \Big] O(\Phi_R)\, \Theta(Q_{\text{cut}}-Q)$$

$$+ \int \mathrm{d}\Phi_R \quad \mathrm{R}(\Phi_R) \quad O(\Phi_R)\, \Theta(Q-Q_{\text{cut}})$$

- restrict MC@NLO expression to region $Q < Q_{\text{cut}}$
- add in real radiation explicitly, as in MEPS
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MENLOPS for MC@NLO

$$\langle O\rangle^{\text{MENLOPS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B)\Bigg[\Delta^{(\mathrm{A})}(t_0,\mu_Q^2)\,O(\Phi_B) + \int_{t_0}^{\mu_Q^2}\mathrm{d}\Phi_1\,\frac{\mathrm{D}^{(\mathrm{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\,\Delta^{(\mathrm{A})}(t,\mu_Q^2)\,O(\Phi_R)\,\Theta(Q_{\text{cut}}-Q)\Bigg]$$
$$+\int \mathrm{d}\Phi_R\left[\mathrm{R}(\Phi_R)-\sum_i \mathrm{D}_i^{(\mathrm{A})}(\Phi_R)\right]O(\Phi_R)\,\Theta(Q_{\text{cut}}-Q)$$
$$+\int \mathrm{d}\Phi_R\left[\frac{\bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B)}{\mathrm{B}(\Phi_B)}\left(1-\frac{\mathbb{H}(\Phi_R)}{\mathrm{R}(\Phi_R)}\right)+\frac{\mathbb{H}(\Phi_R)}{\mathrm{R}(\Phi_R)}\right]\mathrm{R}(\Phi_R)\,\Delta^{(\mathcal{K})}(t,\mu_Q^2)\,O(\Phi_R)\,\Theta(Q-Q_{\text{cut}})$$

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MENLOPS for MC@NLO

$$
\begin{aligned}
\langle O\rangle^{\text{MENLOPS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B) \Bigg[& \Delta^{(\mathrm{A})}(t_0,\mu_Q^2)\, O(\Phi_B) \\
& + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}^{(\mathrm{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathrm{A})}(t,\mu_Q^2)\, O(\Phi_R)\, \Theta(Q_{\text{cut}}-Q) \Bigg] \\
+ \int \mathrm{d}\Phi_R & \left[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathrm{A})}(\Phi_R) \right] O(\Phi_R)\, \Theta(Q_{\text{cut}}-Q) \\
+ \int \mathrm{d}\Phi_R & \left[\frac{\bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B)}{\mathrm{B}(\Phi_B)} \left(1 - \frac{\mathbb{H}(\Phi_R)}{\mathrm{R}(\Phi_R)}\right) + \frac{\mathbb{H}(\Phi_R)}{\mathrm{R}(\Phi_R)} \right] \mathrm{R}(\Phi_R)\, \Delta^{(\mathcal{K})}(t,\mu_Q^2)\, O(\Phi_R)\, \Theta(Q - Q_{\text{cut}})
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MC@NLO – $\mathrm{D}_i^{(\mathrm{A})} = \mathrm{D}_i^{(\mathrm{S})}$ scheme

Implemented in SHERPA – full-colour first parton shower emission

Tricky point: $\mathrm{D}_i^{(\mathrm{A})} < 0$ e.g. for subleading colour dipoles

Use modified Sudakov veto algorithm Höche, Krauss, MS, Siegert JHEP09(2012)049

- Assume $f(t)$ as function to be generated, and overestimate $g(t)$
  Standard probability for *one* acceptance with n rejections

$$\frac{f(t)}{g(t)}\,g(t)\exp\left\{-\int_t^{t_1}\mathrm{d}\bar{t}\,g(\bar{t})\right\}\prod_{i=1}^{n}\left[\int_{t_{i-1}}^{t_{n+1}}\mathrm{d}t_i\left(1-\frac{f(t_i)}{g(t_i)}\right)g(t_i)\exp\left\{-\int_{t_i}^{t_{i+1}}\mathrm{d}\bar{t}\,g(\bar{t})\right\}\right]$$

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MC@NLO – $D_i^{(A)} = D_i^{(S)}$ scheme

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Mc@Nlo – $D_i^{(A)} = D_i^{(S)}$ scheme

Implemented in Sherpa – full-colour first parton shower emission

Tricky point: $D_i^{(A)} < 0$ e.g. for subleading colour dipoles

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POWHEG

Special choices: Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot \mathrm{R}$ with $\rho_i = \mathrm{D}_i^{(\mathsf{S})} / \sum_i \mathrm{D}_i^{(\mathsf{S})}$
  $\rightarrow$ each $\rho_i \cdot \mathrm{R}$ contains only one divergence structure as defined by $\mathrm{D}_i^{(\mathsf{S})}$

Consequences:

- no $\mathbb{H}$-events, resummation scale μ_Q^2 at kinematic limit $\frac{1}{2}\, s_{\text{had}}$
- in CS-subtraction instabilities in ρ_i due to different cuts on R and $\mathrm{D}_i^{(\mathsf{S})}$
- exponentiation of R through matrix element corrected parton shower
  NLO accuracy depends crucially on presence of exact same terms in subtraction and parton shower

Modifications:

- introduce suppression function $f(p_\perp) = h^2/(p_\perp^2 + h^2)$ Alioli et.al. JHEP04(2009)002
  $\rightarrow \mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot \mathrm{R} \cdot f(p_\perp)$
  $\rightarrow$ continuous dampening of resummation kernel at large $p_\perp$

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MC@NLO – traditional scheme

Special choices: Frixione, Webber JHEP06(2002)029

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{B} \cdot \mathcal{K}_i$ with $\mathcal{K}_i$ parton shower kernels

Consequences:

- resummation scale $\mu_Q^2 = t_{\mathsf{max}}$ parton shower starting scale
- in general, $\mathrm{D}_i^{(\mathsf{A})}$ only leading colour approximation
  NLO accuracy depends crucially on correctness of IR-limit

Modifications: Frixione, Nason, Webber JHEP08(2003)007

- introduce soft modification function $f(p_\perp)$ such that

$$\sum \mathrm{B} \cdot \mathcal{K}_i \cdot f(p_\perp) \xrightarrow{p_\perp \to 0} \sum \mathrm{D}_i^{(\mathsf{S})}$$

- $f(p_\perp)$ process dependent in general

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Special choices: Höche, Krauss, MS, Siegert JHEP09(2012)049

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$

Consequences:

- simplification of $\bar{\mathrm{B}}^{(\mathsf{A})}$-integral
- resummation scale $\mu_Q^2 = t_{\mathsf{max}}$ set by phase space limitation of subtraction terms
  $\rightarrow$ subtraction constrained in parton shower t needed for physical resummation
  $\rightarrow$ instructive example: use α_{cut} to explore effects Nagy PRD68(2003)094002
- trivially NLO correct independent of the process without arbitrary parameter choices

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