Multijet merging at next-to-leading order

Marek Schönherr

Institute for Particle Physics Phenomenology

Aachen, 27/06/2013

JHEP09(2012)049

Phys.Rev.Lett.110(2013)052001

JHEP04(2013)027

JHEP01(2013)144

Phys.Rev.D86(2012)094042

arXiv:1306.2703*

*in collaboration with T. Gehrmann, S. Höche, J. Huang, F. Krauss, G. Luisoni, F. Siegert, J. Winter

Contents

Introduction

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

Introduction

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

Introduction

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

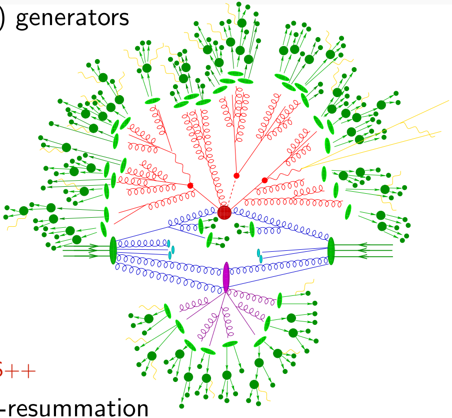
- simultaneous description multijet topologies
  → every jet multiplicity at same fixed order accuracy
- resum hierarchies in emission scales

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

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

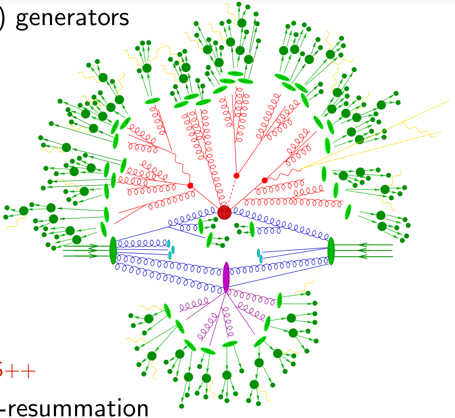


Sherpa's traditional strength is the perturbative part of the event

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

$\rightarrow$ full analytic control mandatory for consistency/accuracy

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 τ 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

Contents

Resummation properties of parton showers

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

- splitting kernel $\mathcal{K}(\Phi_1) \propto \frac{\alpha_s}{t}\,P(z)$, $\Phi_1 = \{t, z, \phi\}$
- Sudakov form factor

$$\Delta^{(\mathcal{K})}(t,t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1\,\mathcal{K}(\Phi_1)\right] = \exp\left[c_1\alpha_s L^2 + c_2\alpha_s L + \ldots\right]$$

- 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

Resummation properties of parton showers

$$\langle O\rangle^{\text{PS}} = \int \mathrm{d}\Phi_B\, \mathrm{B}(\Phi_B) \left[\Delta^{(\mathcal{K})}(t_0,\mu_Q^2)\, O(\Phi_B) + \int\limits_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathcal{K}(\Phi_1)\, \Delta^{(\mathcal{K})}(t,\mu_Q^2)\, O(\Phi_R)\right]$$

- splitting kernel $\mathcal{K}(\Phi_1) \propto \frac{\alpha_s}{t}\, P(z)$, $\Phi_1 = \{t, z, \phi\}$
- Sudakov form factor

$$\Delta^{(\mathcal{K})}(t,t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1\, \mathcal{K}(\Phi_1)\right] = \exp\left[c_1\alpha_s L^2 + c_2\alpha_s L + \ldots\right]$$

- 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

Resummation properties of parton showers

$$\langle O\rangle^{\mathsf{PS}} = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left[\Delta^{(\mathcal{K})}(t_0,\mu_Q^2)\,O(\Phi_B)+\int\limits_{t_0}^{\mu_Q^2}\mathrm{d}\Phi_1\mathcal{K}(\Phi_1)\,\Delta^{(\mathcal{K})}(t,\mu_Q^2)\,O(\Phi_R)\right]$$

- splitting kernel $\mathcal{K}(\Phi_1)\propto\frac{\alpha_s}{t}\,P(z)$, $\Phi_1=\{t,z,\phi\}$
- Sudakov form factor

$$\Delta^{(\mathcal{K})}(t,t')\;=\;\exp\left[-\int_t^{t'}\mathrm{d}\Phi_1\,\mathcal{K}(\Phi_1)\right]\;=\;\exp\left[c_1\alpha_s L^2+c_2\alpha_s L+\ldots\right]$$

- 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

Resummation properties of parton showers

$$\langle O \rangle^{\text{PS}} = \int \mathrm{d}\Phi_B\, \mathrm{B}(\Phi_B) \left[\Delta^{(\mathcal{K})}(t_0, \mu_Q^2)\, O(\Phi_B) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathcal{K}(\Phi_1)\, \Delta^{(\mathcal{K})}(t, \mu_Q^2)\, O(\Phi_R) \right]$$

- splitting kernel $\mathcal{K}(\Phi_1) \propto \frac{\alpha_s}{t} P(z)$, $\Phi_1 = \{t, z, \phi\}$
- Sudakov form factor

$$\Delta^{(\mathcal{K})}(t, t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1\, \mathcal{K}(\Phi_1) \right] = \exp\left[c_1 \alpha_s L^2 + c_2 \alpha_s L + \ldots \right]$$

- 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

Resummation properties of parton showers

$$\langle O\rangle^{\text{PS}} = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left[\Delta^{(\mathcal{K})}(t_0,\mu_Q^2)\,O(\Phi_B) + \int\limits_{t_0}^{\mu_Q^2}\mathrm{d}\Phi_1\mathcal{K}(\Phi_1)\,\Delta^{(\mathcal{K})}(t,\mu_Q^2)\,O(\Phi_R)\right]$$

- splitting kernel $\mathcal{K}(\Phi_1) \propto \frac{\alpha_s}{t}\,P(z)$, $\Phi_1 = \{t, z, \phi\}$
- Sudakov form factor

$$\Delta^{(\mathcal{K})}(t,t') = \exp\left[-\int_t^{t'}\mathrm{d}\Phi_1\,\mathcal{K}(\Phi_1)\right] = \exp\left[c_1\alpha_s L^2 + c_2\alpha_s L + \ldots\right]$$

- 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

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

$$\begin{aligned}\langle O\rangle^{\text{NLO}} = &\int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B) \\ &+ \int \mathrm{d}\Phi_R \quad \Big[\qquad - \sum_i \mathrm{D}_i^{(\mathrm{S})}(\Phi_R) \quad O(\Phi_{B_i})\Big] \\ &+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) \qquad \Big]\, O(\Phi_R)\end{aligned}$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathrm{A})}$
- $\mathrm{D}_i^{(\mathrm{A})}$ and $\mathrm{D}_i^{(\mathrm{S})}$ need to have same momentum maps and IR limit

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

$$\langle O\rangle^{\text{NLO}} = \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B)$$
$$+ \int \mathrm{d}\Phi_R \quad \Big[\sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R) \quad O(\Phi_{B_i}) - \sum_i \mathrm{D}_i^{(\mathsf{S})}(\Phi_R) \quad O(\Phi_{B_i})\Big]$$
$$+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\text{corr}}$$

$$\langle O\rangle^{(\mathsf{A})}_{\text{corr}} = \int \mathrm{d}\Phi_R \sum_i \mathrm{D}_i^{(\mathsf{A})}\big[O(\Phi_R) - O(\Phi_{B_i})\big]$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit

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

$$\langle O\rangle^{\text{NLO}} = \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big] O(\Phi_B)$$
$$+ \sum_i \int \mathrm{d}\Phi_R \Big[\mathrm{D}_i^{(\text{A})}(\Phi_R) - \mathrm{D}_i^{(\text{S})}(\Phi_R)\Big] O(\Phi_{B_i})$$
$$+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\text{A})}(\Phi_R)\Big] O(\Phi_R) + \langle O\rangle^{(\text{A})}_{\text{corr}}$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\text{A})}$
- $\mathrm{D}_i^{(\text{A})}$ and $\mathrm{D}_i^{(\text{S})}$ need to have same momentum maps and IR limit

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

$$\begin{aligned}\langle O\rangle^{\text{NLO}} =& \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B) \\ &+ \sum_i \int \mathrm{d}\Phi_{B_i}\mathrm{d}\Phi_1^i \Big[\mathrm{D}_i^{(\mathsf{A})}(\Phi_{B_i},\Phi_1^i) - \mathrm{D}_i^{(\mathsf{S})}(\Phi_{B_i},\Phi_1^i)\Big]\, O(\Phi_{B_i}) \\ &+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\text{corr}}\end{aligned}$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit

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

$$\begin{aligned}\langle O\rangle^{\text{NLO}} =& \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B) \\ &+ \int \mathrm{d}\Phi_B \sum_i \int \mathrm{d}\Phi_1^i \Big[\mathrm{D}_i^{(\mathsf{A})}(\Phi_B\,,\Phi_1^i) - \mathrm{D}_i^{(\mathsf{S})}(\Phi_B\,,\Phi_1^i)\Big]\, O(\Phi_B) \\ &+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\mathsf{corr}}\end{aligned}$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit

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

$$\langle O\rangle^{\mathsf{NLO}} = \int \mathrm{d}\Phi_B \;\; \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B)\;\, O(\Phi_B)$$

$$+ \int \mathrm{d}\Phi_R \left[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\right] O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\mathsf{corr}}$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit

NLOPs matching

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

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

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

- Sudakov form factor $\Delta^{(\mathcal{K})}(t,t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1\,\mathcal{K}(\Phi_1)\right]$ contains resummation features
- $\langle O\rangle^{(\mathcal{K})}_{\mathsf{corr}}$ generated by one parton shower step

NLOPS matching

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

$$\langle O\rangle^{\text{PS}} = \int \mathrm{d}\Phi_B\, \mathrm{B}(\Phi_B) \left[\Delta^{(\mathcal{K})}(t_0, \mu_Q^2)\, O(\Phi_B) + \int\limits_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathcal{K}(\Phi_1)\, \Delta^{(\mathcal{K})}(t, \mu_Q^2)\, O(\Phi_R) \right]$$

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

- Sudakov form factor $\Delta^{(\mathcal{K})}(t, t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1\, \mathcal{K}(\Phi_1) \right]$ contains resummation features
- $\langle O\rangle^{(\mathcal{K})}_{\text{corr}}$ generated by one parton shower step

NLOPs matching

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

$$\langle O\rangle^{\mathsf{PS}} = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left[\Delta^{(\mathcal{K})}(t_0,\mu_Q^2)\,O(\Phi_B) + \int\limits_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathcal{K}(\Phi_1)\,\Delta^{(\mathcal{K})}(t,\mu_Q^2)\,O(\Phi_R)\right]$$

$$= \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\,O(\Phi_B) + \int\limits_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_R\,\mathrm{B}\cdot\mathcal{K}(\Phi_1)\Big[O(\Phi_R) - O(\Phi_B)\Big] + \mathcal{O}(\alpha_s^2)$$

- Sudakov form factor $\Delta^{(\mathcal{K})}(t,t') = \exp\left[-\int_t^{t'}\mathrm{d}\Phi_1\,\mathcal{K}(\Phi_1)\right]$ contains resummation features
- $\langle O\rangle^{(\mathcal{K})}_{\mathsf{corr}}$ generated by one parton shower step

NLOPs matching

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

$$\langle O\rangle^{\text{PS}} = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left[\Delta^{(\mathcal{K})}(t_0,\mu_Q^2)\,O(\Phi_B) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathcal{K}(\Phi_1)\,\Delta^{(\mathcal{K})}(t,\mu_Q^2)\,O(\Phi_R)\right]$$

$$= \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\,O(\Phi_B) + \langle O\rangle^{(\mathcal{K})}_{\text{corr}} + \mathcal{O}(\alpha_s^2)$$

- Sudakov form factor $\Delta^{(\mathcal{K})}(t,t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1\,\mathcal{K}(\Phi_1)\right]$ contains resummation features
- $\langle O\rangle^{(\mathcal{K})}_{\text{corr}}$ generated by one parton shower step

NLOPS matching

$$\langle O\rangle^{\text{NLOPS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B) \left[\Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\, O(\Phi_B) \right.$$

$$\left. + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathsf{A})}(t,\mu_Q^2)\, O(\Phi_R) \right]$$

$$+ \int \mathrm{d}\Phi_R \left[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R) \right] O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\text{corr}}$$

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

NLOPs matching

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

$$\Delta^{(\mathsf{A})}(t,t') = \exp\left[\int_t^{t'} \mathrm{d}\Phi_1\, \mathrm{D}^{(\mathsf{A})}/\mathrm{B}\right]$$

- use $\mathrm{D}_i^{(\mathsf{A})}$ 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

NLOPs matching

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

$$\Delta^{(\mathsf{A})}(t,t') = \exp\left[\int_t^{t'} \mathrm{d}\Phi_1\, \mathrm{D}^{(\mathsf{A})}/\mathrm{B}\right]$$

- use $\mathrm{D}_i^{(\mathsf{A})}$ 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
- **POWHEG and MC@NLO now differ in choice of $\mathrm{D}_i^{(\mathrm{A})}$ and μ_Q^2**

NLOPs matching

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

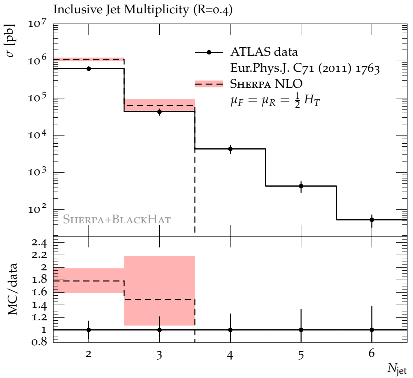
$$\Delta^{(\mathsf{A})}(t,t') = \exp\left[\int_t^{t'} \mathrm{d}\Phi_1\, \mathrm{D}^{(\mathsf{A})}/\mathrm{B}\right]$$

- use $\mathrm{D}_i^{(\mathsf{A})}$ 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
- **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. $H_T^{(y)}$)



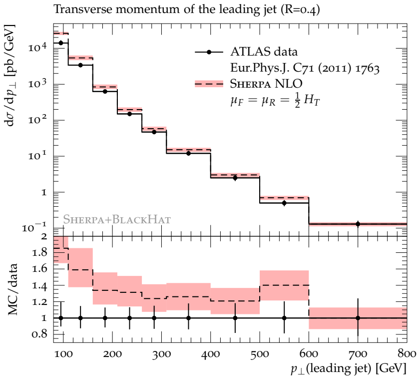
no. jets	ATLAS	LO	ME+PS	NLO	NP factor	NLO+NP
≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	$559(5)$	$1193(3)^{+130}_{-135}$	$0.95(0.02)$	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	$39.7(0.9)$	$54.5(0.5)^{+2.2}_{-19.9}$	$0.92(0.04)$	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 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

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. $H_T^{(y)}$)



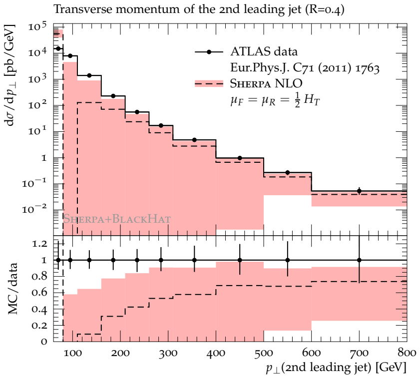
no. jets	ATLAS	LO	ME+PS	NLO	NP factor	NLO+NP
≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	$559(5)$	$1193(3)^{+130}_{-135}$	$0.95(0.02)$	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	$39.7(0.9)$	$54.5(0.5)^{+2.2}_{-19.9}$	$0.92(0.04)$	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 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

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. $H_T^{(y)}$)



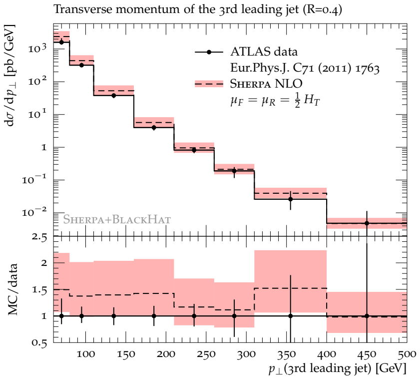
no. jets	ATLAS	LO	ME+PS	NLO	NP factor	NLO+NP
≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	$559(5)$	$1193(3)^{+130}_{-135}$	$0.95(0.02)$	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	$39.7(0.9)$	$54.5(0.5)^{+2.2}_{-19.9}$	$0.92(0.04)$	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 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

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

Case study: Inclusive jet & dijet production

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

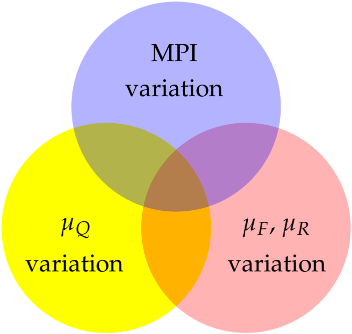
MC@NLO di-jet production:

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%



Case study: Inclusive jet & dijet production

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

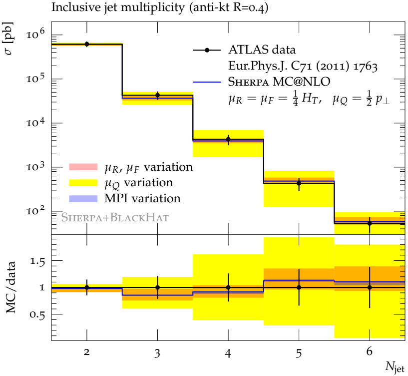
MC@NLO di-jet production:

Höche, MS Phys.Rev.D86(2012)094042

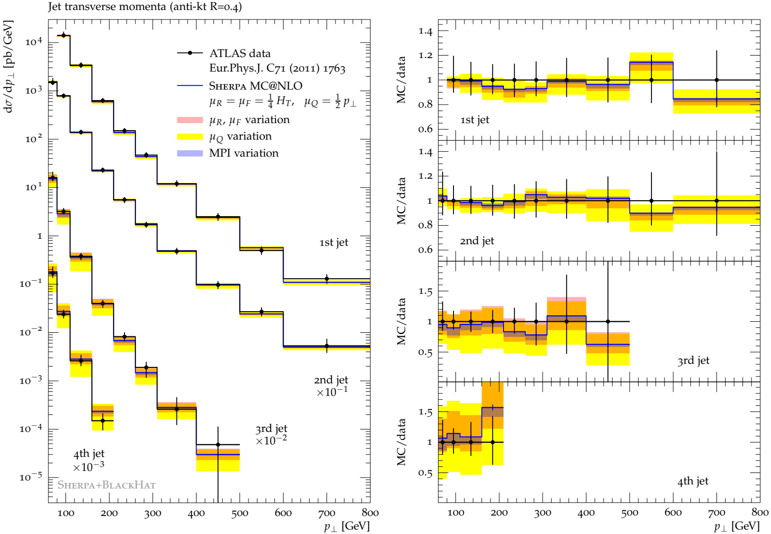
- $\mu_{R/F} = \frac{1}{4}\,H_T$, $\mu_Q = \frac{1}{2}\,p_\perp$
- CT10 PDF ($\alpha_s(m_Z) = 0.118$)
- hadron level calculation, MPI
- virtual MEs from BLACKHAT
  Giele, Glover, Kosower Nucl.Phys.B403(1993)633-670
  Bern et.al. arXiv:1112.3940
- $p_\perp^{j_1} > 20$ GeV, $p_\perp^{j_2} > 10$ GeV

Uncertainty estimates:

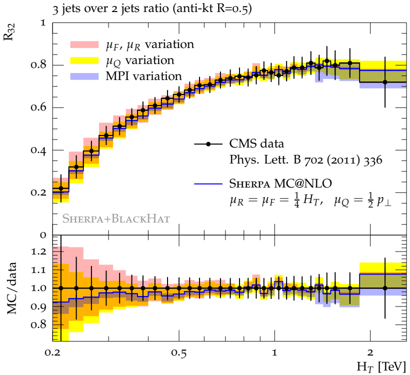
- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_Q^{\text{def}}$
- MPI activity in tr. region $\pm$ 10%



Case study: Inclusive jet & dijet production



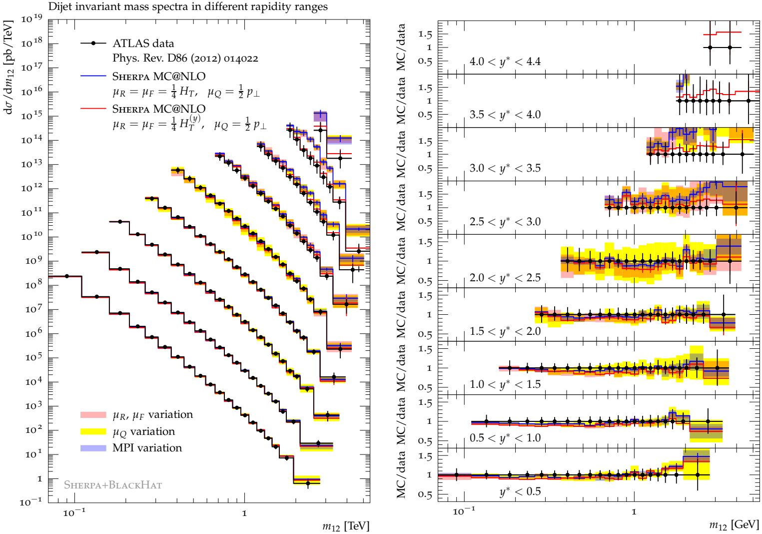
Case study: Inclusive jet & dijet production



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
  $\rightarrow$ varied simultaneously
- at large H_T large MPI uncertainties
  $\rightarrow$ better MPI physics needed (soft QCD)
- similar description of related ATLAS observables

Case study: Inclusive jet & dijet production



Case study: Inclusive jet & dijet production

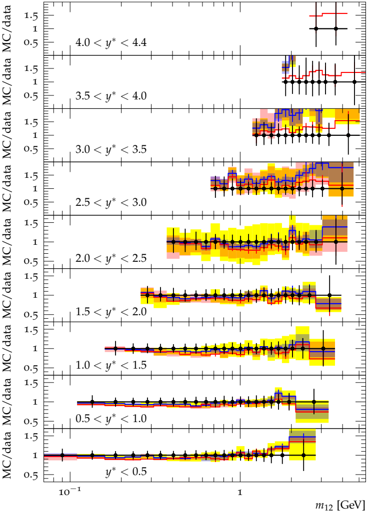
Try different scale

- $\mu_{R/F} = \frac{1}{4}\,H_T^{(y)}$ 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)



Case study: Inclusive jet & dijet production

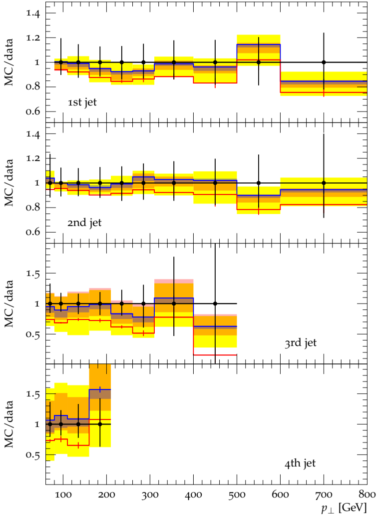
Try different scale

- $\mu_{R/F} = \frac{1}{4}\, H_T^{(y)}$ 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

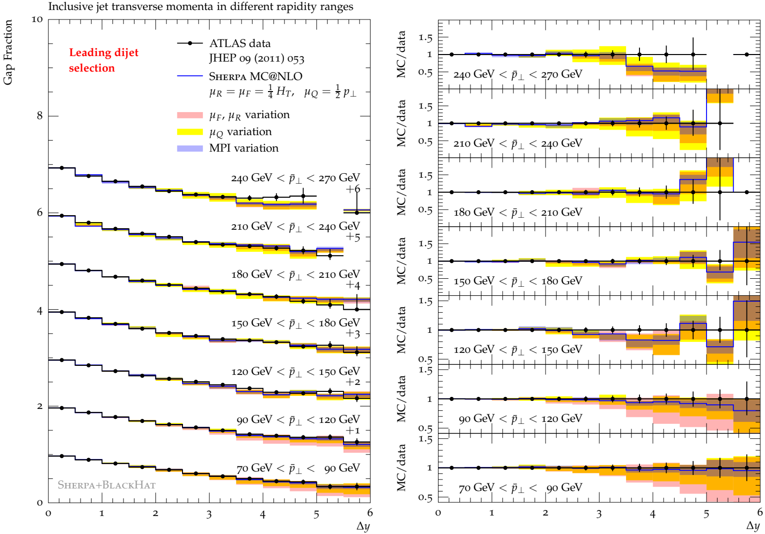
  Ellis, Kunszt, Soper PRD40(1989)2188
- better description of data at large rapidities, as expected

description of most other observables worsened

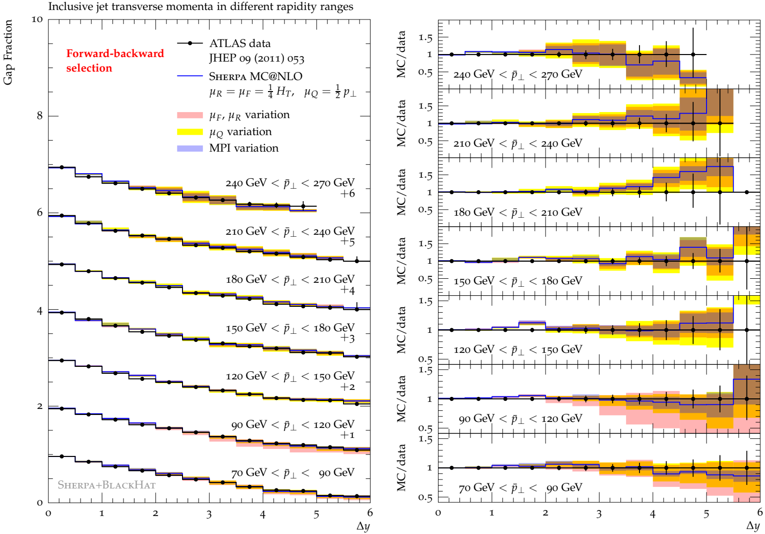
need proper description of forward physics (e.g. (B)FKL)



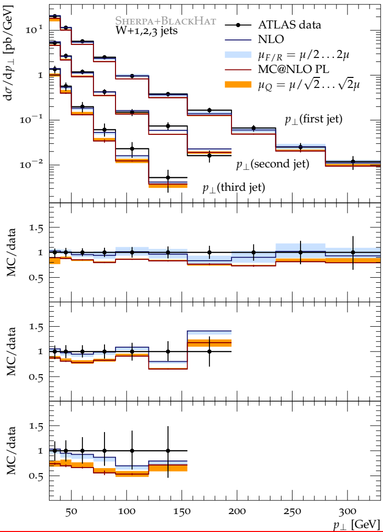
Case study: Inclusive jet & dijet production



Case study: Inclusive jet & dijet production



$W + n$ jet production



Höche, Krauss, MS, Siegert

Phys.Rev.Lett.110(2013)052001

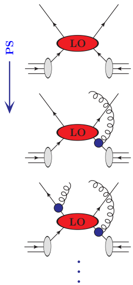
$pp \to W + 1, 2, 3$ jets

- 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



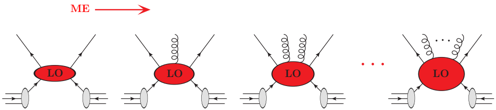
LO $pp \to 2$ with parton showers vs. **LO $pp \to n$ matrix elements**

+ 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

MEPs – Multijet merging at LO



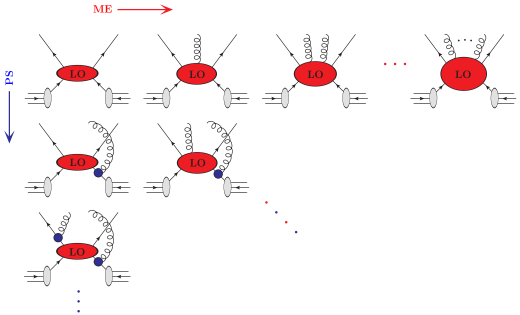
LO $pp \to 2$ with parton showers vs. **LO $pp \to n$ matrix elements**

+ 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

MEPs – Multijet merging at LO



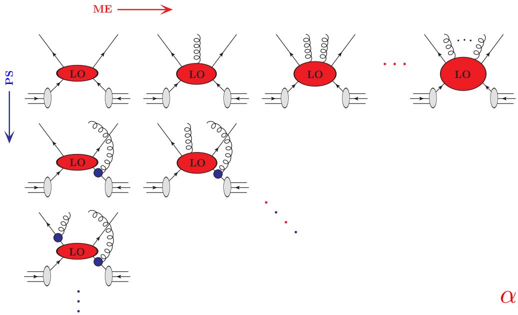
LO $pp \to 2$ with parton showers vs. **LO $pp \to n$ matrix elements**

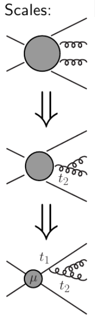
+ exponentiation of large IR logarithms
– poor hard/wide angle emission pattern

+ 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

MEPS – Multijet merging at LO





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

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

LO $pp \to 2$ with parton showers
+ exponentiation of large IR logarithms
– poor hard/wide angle emission pattern

LO $pp \to n$ matrix elements
+ 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

Multijet merging

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

MEPs – Multijet merging at LO

$$
\begin{aligned}
\langle O\rangle^{\text{MEPs}}
&= \int \mathrm{d}\Phi_n\, \mathrm{B}_n \bigg[\Delta_n^{(\mathcal{K})}(t_0,\mu_Q^2)\, O_n \\
&\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathcal{K}_n\, \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\bigg] \\
&+ \int \mathrm{d}\Phi_{n+1}\, \mathrm{B}_{n+1}\, \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \\
&\qquad \times \bigg[\Delta_{n+1}^{(\mathcal{K})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \mathcal{K}_{n+1}\, \Delta_{n+1}^{(\mathcal{K})}(t_{n+2},t_{n+1})\, O_{n+2}\bigg]
\end{aligned}
$$

- 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
- truncated showering to account for mismatch of t and Q Nason JHEP11(2004)040

MEPS – Multijet merging at LO

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

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

$$+ \int \mathrm{d}\Phi_{n+1}\, \mathrm{B}_{n+1}\, \Delta_n^{(\mathcal{K})}(t_{n+1}, \mu_Q^2)\, \Theta(Q - Q_{\text{cut}}) \times \bigg[\Delta_{n+1}^{(\mathcal{K})}(t_0, t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \mathcal{K}_{n+1}\, \Delta_{n+1}^{(\mathcal{K})}(t_{n+2}, t_{n+1})\, O_{n+2} \bigg]$$

- 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

MEPS – Multijet merging at LO

$$
\begin{aligned}
\langle O\rangle^{\text{MEPS}}
&= \int \mathrm{d}\Phi_n\, \mathrm{B}_n \Bigg[\Delta_n^{(\mathcal{K})}(t_0,\mu_Q^2)\, O_n \\
&\qquad\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathcal{K}_n\, \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\Bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \mathrm{B}_{n+1}\, \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \\
&\qquad\quad \times \Bigg[\Delta_{n+1}^{(\mathcal{K})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \mathcal{K}_{n+1}\, \Delta_{n+1}^{(\mathcal{K})}(t_{n+2},t_{n+1})\, O_{n+2}\Bigg]
\end{aligned}
$$

- 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
- truncated showering to account for mismatch of t and Q Nason JHEP11(2004)040

MEPs – Multijet merging at LO

$\langle O\rangle^{\text{MEPs}}$

$$= \int \mathrm{d}\Phi_n\, \mathrm{B}_n \bigg[\Delta_n^{(\mathcal{K})}(t_0,\mu_Q^2)\, O_n + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathcal{K}_n\, \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\bigg]$$
$$+ \int \mathrm{d}\Phi_{n+1}\, \mathrm{B}_{n+1}\, \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \times \bigg[\Delta_{n+1}^{(\mathcal{K})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \mathcal{K}_{n+1}\, \Delta_{n+1}^{(\mathcal{K})}(t_{n+2},t_{n+1})\, O_{n+2}\bigg]$$

- 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
- truncated showering to account for mismatch of t and Q Nason JHEP11(2004)040

MEPS – Multijet merging at LO

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

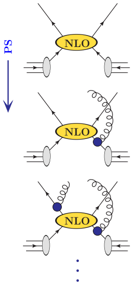
$$= \int \mathrm{d}\Phi_n\, \mathrm{B}_n \Bigg[\Delta_n^{(\mathcal{K})}(t_0,\mu_Q^2)\, O_n + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathcal{K}_n\, \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1} \Bigg]$$

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

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

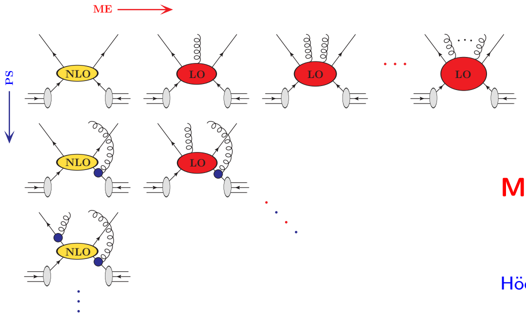
- LOPS for n-jet process restricted to region $Q < Q_{\text{cut}}$
- LOPS for $n+1$-jet process with additional Sudakov wrt. n-jet process
  $\rightarrow$ implements correct resummation behaviour wrt. incl. sample
- truncated showering to account for mismatch of t and Q Nason JHEP11(2004)040

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

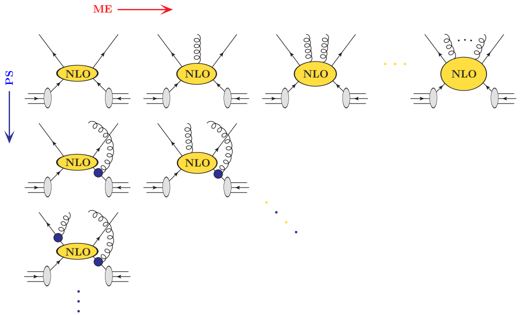


MENLOPS

Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123

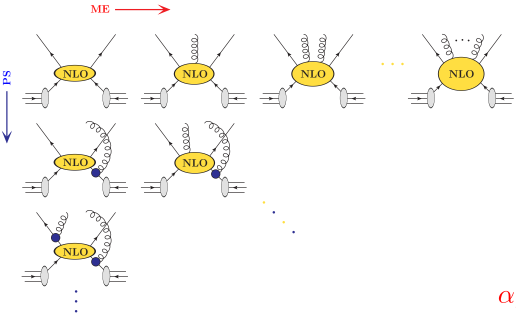
- promote LOPS to NLOPS (POWHEG, MC@NLO)
  $\rightarrow$ can assess uncertainties (part I)
- combine NLOPS for successive multiplicities into incl. sample (MEPS@NLO), preserve NLO+(N)LL accuracy in every jet multiplicity
  restore resummation wrt. to inclusive sample (part II)
- scale setting scheme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

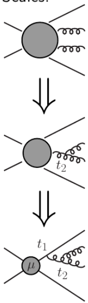
MEPs@NLO – Multijet merging at NLO



- 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





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

- 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

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 JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

MEPS@NLO – Multijet merging at NLO

Höche, Krauss, MS, Siegert JHEP04(2013)027

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

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

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

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

MePs@Nlo – Multijet merging at NLO

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

Höche, Krauss, MS, Siegert JHEP04(2013)027

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

$$
\begin{aligned}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \left[\Delta_n^{(\mathsf{A})}(t_0, \mu_Q^2)\, O_n \right.\\
&\qquad\qquad \left. + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1}, \mu_Q^2)\, \Theta(Q_{\mathsf{cut}} - Q)\, O_{n+1} \right]\\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})} \right] \Theta(Q_{\mathsf{cut}} - Q)\, O_{n+1}
\end{aligned}
$$

MEPs@NLO – Multijet merging at NLO

Höche, Krauss, MS, Siegert JHEP04(2013)027

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

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

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

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

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

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

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

MEPS@NLO – Multijet merging at NLO

Höche, Krauss, MS, Siegert JHEP04(2013)027

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

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

MEPS@NLO – Multijet merging at NLO

Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

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

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

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

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

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

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

NLO merging – Generation of MC counterterm

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

- 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

$$\alpha_s(\mu_R^2)^{n+k} = \alpha_s(\mu_{\text{core}})^n \cdot \prod_{i=1}^{k} \alpha_s(t_i)$$

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

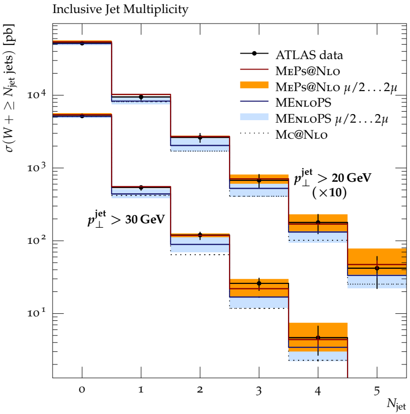
$$\alpha_s(\tilde{\mu}_R^2)^k \left(1 - \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\,\beta_0 \sum_{i=1}^{k} \ln\frac{t_i}{\tilde{\mu}_R^2}\right)$$

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

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

Results – pp → W+jets

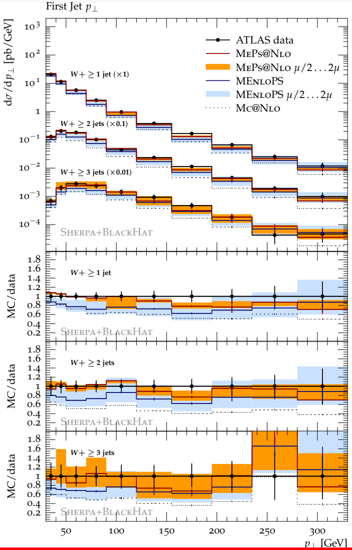


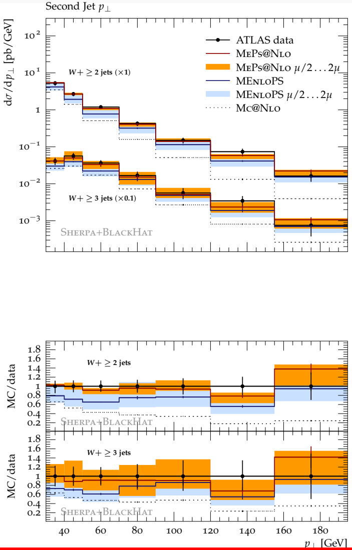
$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

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

ATLAS data Phys.Rev.D85(2012)092002

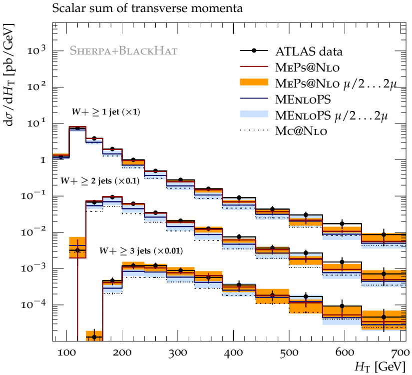
Results – pp → W+jets

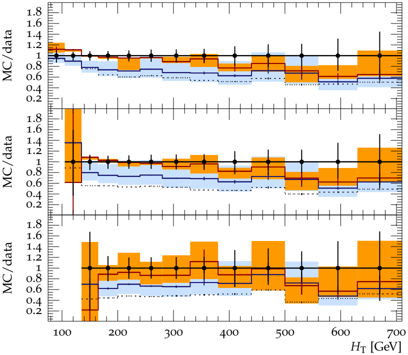




Results – pp → W+jets

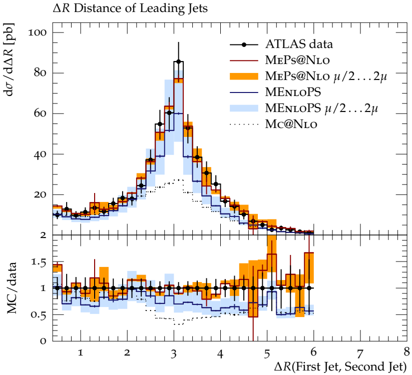
ATLAS data Phys.Rev.D85(2012)092002

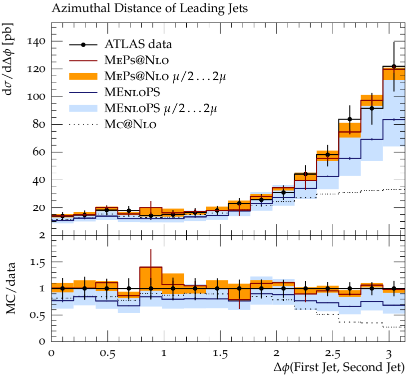




Results – pp → W+jets

ATLAS data Phys.Rev.D85(2012)092002

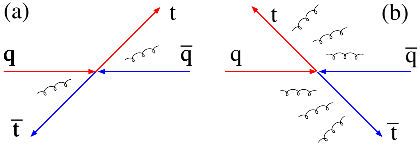




Results – $p\bar{p} \to t\bar{t} + \text{jets}$

Skands, Webber, Winter JHEP07(2012)151

Parton showers and the $t\bar{t}$-asymmetry at the Tevatron



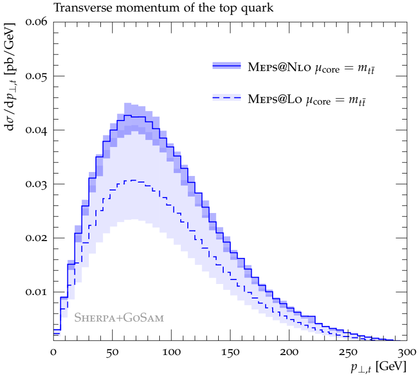
- if colour coherence is respected, PS creates an asymmetry because of asymmetric colour flow
- HERWIG respects colour correlations through angular ordering
- CSSHOWER++ (CS dipoles, 1→2 splittings, recoil to large-N_c partner) → respects colour correlations by choice of radiating dipoles/recoil partners

⇒ **it is important to respect colour-correlations**

Results – $\mathrm{p\bar{p}} \to \mathrm{t\bar{t}} + \mathbf{jets}$

Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV
- scale choices:
  1) $\mu_{\text{core}} = m_{t\bar{t}}$
  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u



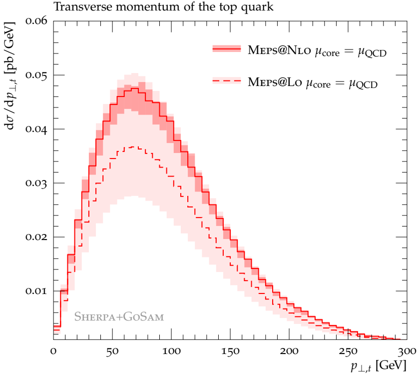
Results – $p\bar{p} \to t\bar{t} + \text{jets}$

Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV
- scale choices:

  1) $\mu_{\text{core}} = m_{t\bar{t}}$

  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u

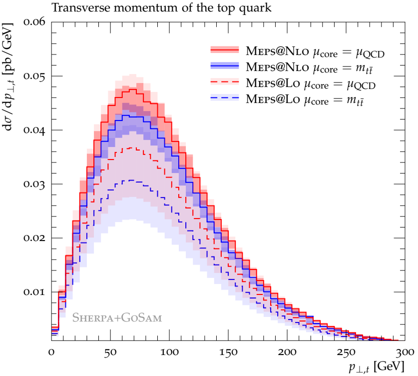


Results – $p\bar{p} \to t\bar{t} + $jets

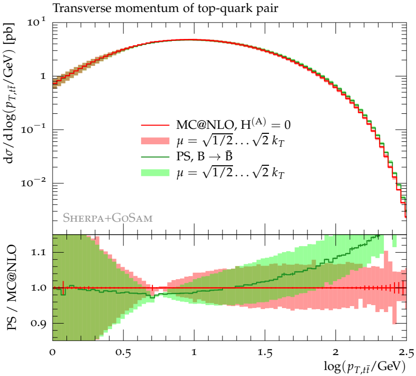
Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV
- scale choices:

  1) $\mu_{\text{core}} = m_{t\bar{t}}$
  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j \ \ldots\ N_c \to \infty$ colour partners, chooses between s, t, u



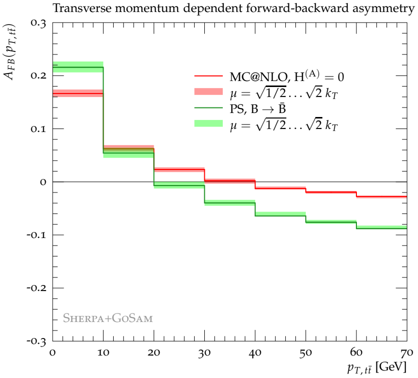
Results – $p\bar{p} \to t\bar{t} + \text{jets}$



Importance of
$N_c = 3$ colour coherence vs.
$N_c \to \infty$ colour coherence

- small effect on standard (rapidity blind) observables, e.g. $p_{\perp,t\bar{t}}$
  → some destructive interference at large $p_{\perp,t\bar{t}}$
- large effect on $A_{FB}(p_{\perp,t\bar{t}})$
  → subleading colour terms lead to asymmetric radiation pattern

Results – $p\bar{p} \to t\bar{t} + \text{jets}$

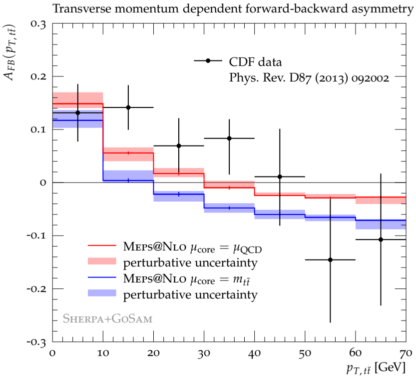


Importance of
$N_c = 3$ colour coherence vs.
$N_c \to \infty$ colour coherence

- small effect on standard (rapidity blind) observables, e.g. $p_{\perp,t\bar{t}}$
  $\to$ some destructive interference at large $p_{\perp,t\bar{t}}$
- large effect on $A_{FB}(p_{\perp,t\bar{t}})$
  $\to$ subleading colour terms lead to asymmetric radiation pattern

Results – $p\bar{p} \to t\bar{t} + \text{jets}$

CDF data Phys.Rev.D87(2013)092002

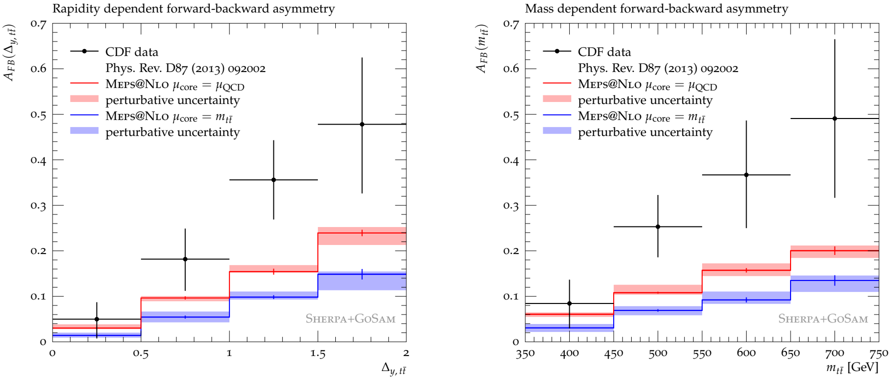


$p\bar{p} \to t\bar{t}$+jets (0,1 @ NLO)

- $A_{FB}(p_{\perp,t\bar{t}})$ NLO accurate in all but the first bin
- no EW corrections

Results – $p\bar{p} \to t\bar{t} + \text{jets}$

CDF data Phys.Rev.D87(2013)092002



- no EW corrections ($\approx 20\%$) effected
- right qualitative bahviour, but consistently below data

Results – $\mathrm{p\bar{p}} \to \mathrm{t\bar{t}} + \mathbf{jets}$

Inclusive asymmetries

CDF data Phys.Rev.D87(2013)092002

Source	A_{FB} [%]	$A_{\mathrm{FB}}(m_{t\bar{t}})$ [%]		$A_{\mathrm{FB}}(p_{T,t\bar{t}})$ [%]	
	inclusive	$m < 450$ GeV	$m > 450$ GeV	$p_T < 50$ GeV	$p_T > 50$ GeV
CDF data	16.4 ± 4.7	8.4 ± 5.5	29.5 ± 6.7	–	–
MEPs@NLO, $\mu = \mu_{\mathrm{QCD}}$	$8.5\,^{+0.5}_{-0.5}$	$6.1\,^{+0.2}_{-0.1}$	$12.7\,^{+1.1}_{-0.6}$	$9.5\,^{+0.7}_{-0.0}$	$-3.4\,^{-0.8}_{-0.1}$
MEPs@NLO, $\mu = m_{t\bar{t}}$	$4.8\,^{+0.7}_{-0.3}$	$3.1\,^{+0.8}_{+0.1}$	$7.9\,^{+0.5}_{-1.1}$	$5.8\,^{+0.8}_{-0.4}$	$-7.2\,^{+0.5}_{-0.4}$
MEPs, $\mu = \mu_{\mathrm{QCD}}$	$15.0\,^{+1.9}_{-1.4}$	$11.0\,^{+1.4}_{-1.1}$	$22.2\,^{+2.3}_{-2.0}$	$16.6\,^{+2.2}_{-1.6}$	$-1.1\,^{+1.7}_{-1.2}$
MEPs, $\mu = m_{t\bar{t}}$	$8.2\,^{+0.9}_{-0.8}$	$5.9\,^{+0.6}_{-0.6}$	$12.5\,^{+1.3}_{-1.2}$	$9.9\,^{+1.1}_{-1.1}$	$-7.9\,^{+0.6}_{-0.6}$
NLO $p\bar{p} \to t\bar{t}$	6.0	4.1	9.3	7.0	−11.1

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

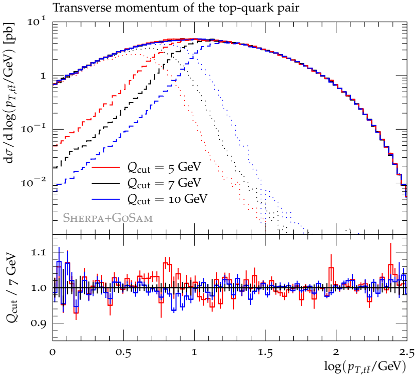
- multijet merging at NLO proceeds schematically as at LO
  $\rightarrow$ introduce MC-counterterm to retain NLO accuracy
- scale setting essential for recovering PS resummation
- can be improved by adding higher order calculations
  - (N)NLL resummation
  - NNLO corrections

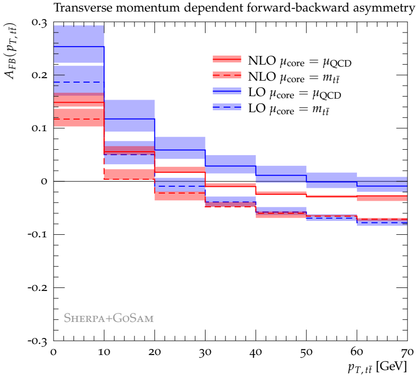
current release SHERPA-2.0.β_2, when fully tuned SHERPA-2.0.0

http://sherpa.hepforge.org

Thank you for your attention!

Results – $p\bar{p} \to t\bar{t} + \text{jets}$





- very small Q_{cut} dependence
- scale variation shrinks going LO to NLO (both factor and functional form)

MENLOPS for MC@NLO

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

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

$$+ \int \mathrm{d}\Phi_R\left[\frac{\mathrm{B}^{(\mathsf{A})}(\Phi_R)}{\mathrm{B}(\Phi_R)}\left(1-\frac{\mathrm{H}(\Phi_R)}{\mathrm{R}(\Phi_R)}\right)+\frac{\mathrm{H}(\Phi_R)}{\mathrm{R}(\Phi_R)}\right]\mathrm{R}(\Phi_R)\,\Delta^{(\mathsf{PS})}(t_R,\mu_Q^2)\,O(\Phi_R)\,\Theta(Q-Q_{\text{cut}})$$

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

MENLOPS for MC@NLO

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

- restrict MC@NLO expression to region $Q < Q_{\mathsf{cut}}$
- 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

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

- 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

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

- 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

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

- 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}

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 $p_\perp$

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 $\frac{1}{2}\,s_{\mathsf{had}}$
- 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 $p_\perp$

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 $p_\perp$

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

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

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

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

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

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

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

MC@NLO – $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$ scheme

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
  $\rightarrow \mathrm{D}^{(\mathsf{A})} = \mathrm{D}^{(\mathsf{S})}\,\Theta(\mu_Q - t)$
- trivially NLO correct independent of the process without arbitrary parameter choices

MC@NLO – $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$ scheme

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
  $\to$ subtraction constrained in parton shower t needed for physical resummation
  $\to \mathrm{D}^{(\mathsf{A})} = \mathrm{D}^{(\mathsf{S})}\,\Theta(\mu_Q - t)$
- trivially NLO correct independent of the process without arbitrary parameter choices

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

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

- Can split weight into MC and **analytic** part using auxiliary function $h(t)$

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

$$w(t,t_1,\ldots,t_n) = \frac{g(t)}{h(t)}\prod_{i=1}^{n}\frac{g(t_i)}{h(t_i)}\,\frac{h(t_i)-f(t_i)}{g(t_i)-f(t_i)}$$

MC@NLO – $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$ scheme

Implemented in SHERPA – full-colour first parton shower emission

Tricky point: $\mathrm{D}_i^{(\mathsf{A})} < 0$ 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

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

- Can split weight into MC and **analytic** part using auxiliary function $h(t)$

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

$$w(t,t_1,\ldots,t_n) = \frac{g(t)}{h(t)}\prod_{i=1}^{n}\frac{g(t_i)}{h(t_i)}\,\frac{h(t_i)-f(t_i)}{g(t_i)-f(t_i)}$$

MC@NLO – $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$ scheme

Implemented in SHERPA – full-colour first parton shower emission

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

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

- Can split weight into MC and **analytic** part using auxiliary function $h(t)$

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

$$w(t,t_1,\ldots,t_n) = \frac{g(t)}{h(t)}\prod_{i=1}^{n}\frac{g(t_i)}{h(t_i)}\,\frac{h(t_i)-f(t_i)}{g(t_i)-f(t_i)}$$

Identify $f(t)$, $g(t)$, $h(t)$:

- $f(t)$ determined by MC@NLO $\Rightarrow \mathrm{D}_i^{(\mathsf{A})}$
- $h(t)$ determined by parton shower $\Rightarrow \mathrm{D}_i^{(\mathsf{PS})}$
- $g(t)$ **can be chosen freely** $\Rightarrow$ const. $\cdot\, f$
  constraints: $\mathrm{sign}(f) = \mathrm{sign}(g)$, $|f| \leq |g|$

MEPs – Multijet merging at LO

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

- 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

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

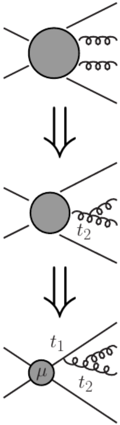
$$= \int \mathrm{d}\Phi_n\, \mathrm{B}_n \Bigg[\Delta_n^{(\mathcal{K})}(t_0,\mu_Q^2)\, O_n$$

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

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

- α_s scales in $\mathrm{B}\cdot\mathcal{K}$ and B_{n+1} must be the same to retain resun properties of the parton shower
- interprete B_{n+1} as PS splitting on top of B
  $\rightarrow$ need to use inverse parton shower

Scales:



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

MEPs – Multijet merging at LO

$$\langle O\rangle^{\text{MEPs}}$$

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

mismatch of $\mathcal{O}(\frac{\mathbf{1}}{\mathbf{N_c}}\,\alpha_\mathbf{s}\,\mathbf{L})$

- 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