Multijet merging at NLO accuracy

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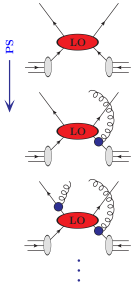
JHEP01(2013)144*

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

MEPS – review

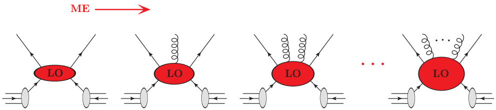


Parton showers

resummation of (soft-)collinear limit
$\rightarrow$ intrajet evolution

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS

MEPS – review



Matrix elements

fixed-order in α_s
$\rightarrow$ hard wide-angle emissions
$\rightarrow$ interference terms

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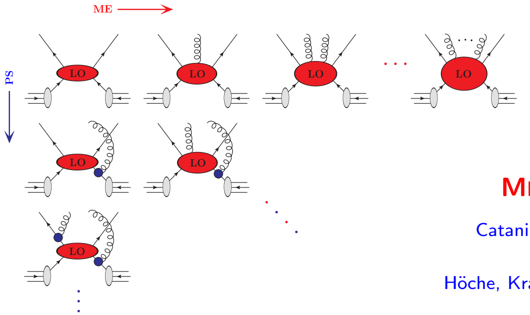

MEPS (CKKW,MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053

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MEPS – review

Parton showers (operate in $N_c \to \infty$ limit):

$$\mathrm{PS}_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} \mathrm{d}t' \mathcal{K}_n(t') \, \Delta_n(t', t_{\max})$$

Multijet merging at leading order:

$$\begin{aligned}\mathrm{d}\sigma^{\mathrm{MEPS}} = \mathrm{d}\sigma_n^{\mathrm{LO}} &\otimes \mathrm{PS}_n \, \Theta(Q_{\mathrm{cut}} - t_{n+1}) \\ &+ \mathrm{d}\sigma_{n+1}^{\mathrm{LO}} \, \Theta(t_{n+1} - Q_{\mathrm{cut}}) \, \Delta_n(t_{n+1}, t_n) \otimes \mathrm{PS}_{n+1} \, \Theta(Q_{\mathrm{cut}} - t_{n+2}) \\ &+ \mathrm{d}\sigma_{n+2}^{\mathrm{LO}} \, \Theta(t_{n+2} - Q_{\mathrm{cut}}) \, \Delta_n(t_{n+1}, t_n) \, \Delta_{n+1}(t_{n+2}, t_{n+1}) \otimes \mathrm{PS}_{n+2}\end{aligned}$$

- restrict the parton shower on $2 \to n$ to emit only below Q_{cut}
- add the $n+1$ ME and its parton shower
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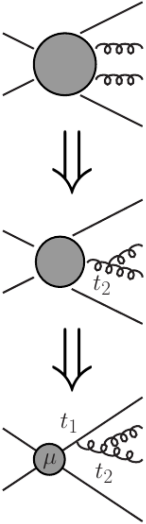
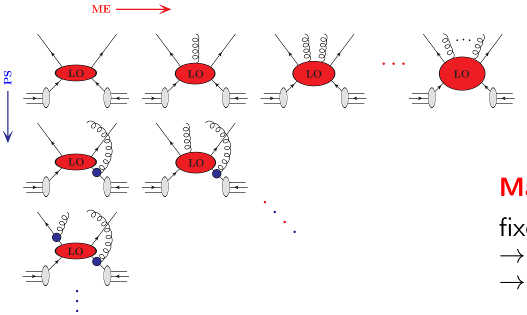
Scales:



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

MEPS@NLO



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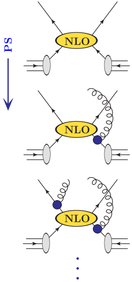

NLOPS (MC@NLO,POWHEG)

Frixione, Webber JHEP06(2002)029
Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070
Höche, Krauss, MS, Siegert JHEP09(2012)049

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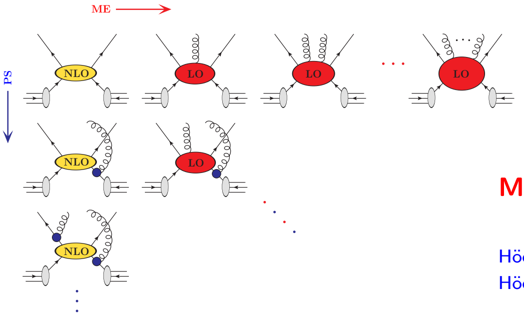

MENLOPS

Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123
Höche, Krauss, MS, Siegert JHEP01(2013)144

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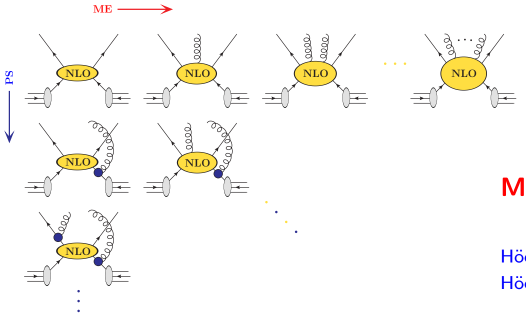

MEPS@NLO

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Höche, Krauss, MS, Siegert JHEP01(2013)144

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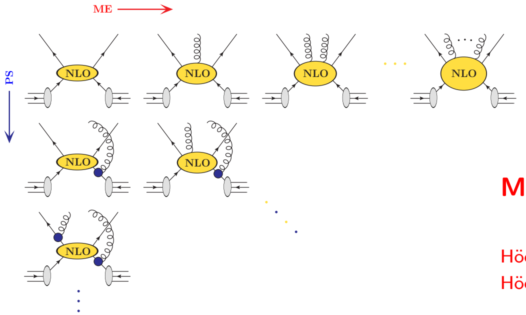

MEPS@NLO

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MePs@Nlo

Parton showers for NloPs (need to reproduce $N_c = 3$ singular limits for 1st em.):

$$\widetilde{\mathrm{PS}}_n(t_0, t_{\mathrm{max}}) = \tilde{\Delta}_n(t_0, t_{\mathrm{max}}) + \int_{t_0}^{t_{\mathrm{max}}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', t_{\mathrm{max}})$$

Multijet merging at next-to-leading order:

$$\begin{aligned}\mathrm{d}\sigma^{\mathrm{MePs@Nlo}} = \mathrm{d}\sigma_n^{\mathrm{NLO}} &\times \widetilde{\mathrm{PS}}_n\, \Theta(Q_{\mathrm{cut}} - t_{n+1}) \\ &+ \mathrm{d}\sigma_{n+1}^{\mathrm{NLO}}\, \Theta(t_{n+1} - Q_{\mathrm{cut}}) \left(\Delta_n(t_{n+1}, \mu_Q) - \Delta_n^{(1)}(t_{n+1}, \mu_Q)\right) \\ &\quad \times \widetilde{\mathrm{PS}}_{n+1}\, \Theta(Q_{\mathrm{cut}} - t_{n+2}) \\ &+ \mathrm{d}\sigma_{n+2}^{\mathrm{NLO}}\, \Theta(t_{n+2} - Q_{\mathrm{cut}}) \left(\Delta_n(t_{n+1}, \mu_Q) - \Delta_n^{(1)}(t_{n+1}, \mu_Q)\right) \\ &\quad \times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1})\right) \times \widetilde{\mathrm{PS}}_{n+2}\end{aligned}$$

- restrict the NloPs on $2 \to n$ to emit only below Q_{cut}
- add the $n+1$ NloPs
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\mathrm{NLO}}$

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&+ \mathrm{d}\sigma_{n+2}^{\mathrm{NLO}}\, \Theta(t_{n+2} - Q_{\mathrm{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\
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Multijet merging at next-to-leading order:

$$\begin{aligned}\mathrm{d}\sigma^{\mathsf{MEPS@NLO}} = {}& \mathrm{d}\sigma_n^{\mathsf{NLO}} \otimes \widetilde{\mathsf{PS}}_n\, \Theta(Q_{\mathsf{cut}} - t_{n+1}) \\ & + \mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}\, \Theta(t_{n+1} - Q_{\mathsf{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\ & \otimes \widetilde{\mathsf{PS}}_{n+1}\, \Theta(Q_{\mathsf{cut}} - t_{n+2}) \\ & + \mathrm{d}\sigma_{n+2}^{\mathsf{NLO}}\, \Theta(t_{n+2} - Q_{\mathsf{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\ & \times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1})\right) \otimes \widetilde{\mathsf{PS}}_{n+2}\end{aligned}$$

- restrict the NLOPS on $2 \to n$ to emit only below Q_{cut}
- add the $n+1$ NLOPS
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}$

MEPS@NLO

Parton showers for NLOPS (need to reproduce $N_c = 3$ singular limits for 1st em.):

$$\widetilde{\mathsf{PS}}_n(t_0, t_{\mathsf{max}}) = \tilde{\Delta}_n(t_0, t_{\mathsf{max}}) + \int_{t_0}^{t_{\mathsf{max}}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', t_{\mathsf{max}})$$

Multijet merging at next-to-leading order:

$$\begin{aligned}
\mathrm{d}\sigma^{\mathsf{MEPS@NLO}} = \mathrm{d}\sigma_n^{\mathsf{NLO}} \otimes \widetilde{\mathsf{PS}}_n\, \Theta(Q_{\mathsf{cut}} - t_{n+1}) \\
+ \mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}\, \Theta(t_{n+1} - Q_{\mathsf{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\
\otimes \widetilde{\mathsf{PS}}_{n+1}\, \Theta(Q_{\mathsf{cut}} - t_{n+2}) \\
+ \mathrm{d}\sigma_{n+2}^{\mathsf{NLO}}\, \Theta(t_{n+2} - Q_{\mathsf{cut}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\right) \\
\times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1})\right) \otimes \widetilde{\mathsf{PS}}_{n+2}
\end{aligned}$$

- restrict the NLOPS on $2 \to n$ to emit only below Q_{cut}
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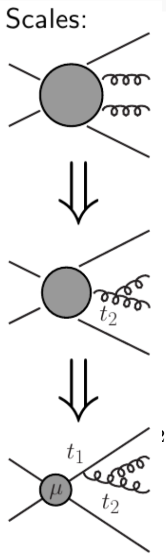
MEPS@NLO

Parton showers for NLOPS (need to reproduce $N_c = 3$ singular li… .):

$$\widetilde{\mathsf{PS}}_n(t_0, t_{\text{max}}) = \tilde{\Delta}_n(t_0, t_{\text{max}}) + \int_{t_0}^{t_{\text{max}}} \mathrm{d}t' \tilde{\mathcal{K}}_n(t')\, \tilde{\Delta}_n(t', \ldots$$

Multijet merging at next-to-leading order:

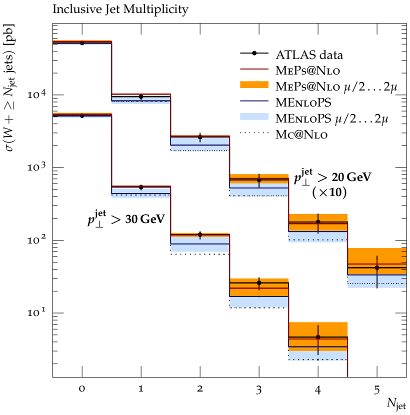
$$\mathrm{d}\sigma^{\text{MEPS@NLO}} = \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\mathsf{PS}}_n\, \Theta(Q_{\text{cut}} - t_{n+1})$$
$$+ \mathrm{d}\sigma_{n+1}^{\text{NLO}}\, \Theta(t_{n+1} - Q_{\text{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(\ldots$$
$$\otimes \widetilde{\mathsf{PS}}_{n+1}\, \Theta(Q_{\text{cut}} - t_{n+2})$$
$$+ \mathrm{d}\sigma_{n+2}^{\text{NLO}}\, \Theta(t_{n+2} - Q_{\text{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t \ldots$$
$$\times \Big(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_n \ldots$$



- restrict the NLOPS on $2 \to n$ to emit only below Q_{cut}
- add the $n+1$ NLOPS
- multiply by Sudakov wrt. $2 \to n$ process to restore resumma…
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\text{NLO}}$

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

Results – pp → W+jets

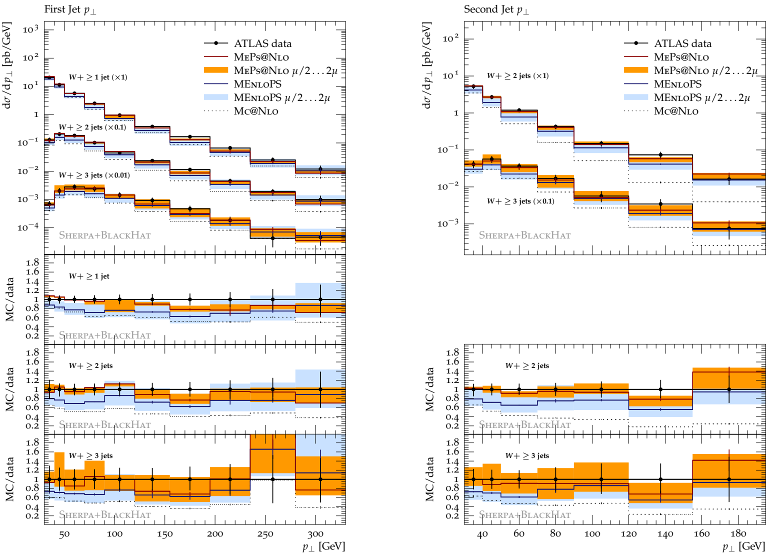


$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

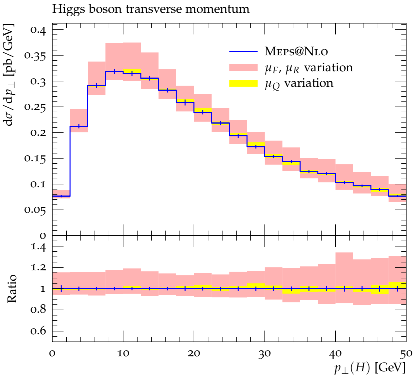
- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  scale uncertainty much reduced
- NLO dependence
  for $pp \to W$+0,1,2 jets
  LO dependence
  for $pp \to W$+3,4 jets
- $Q_{\text{cut}} = 30$ GeV
- good data description

ATLAS data Phys.Rev.D85(2012)092002

Results – pp → W+jets



Results – pp → h+jets (ggF)

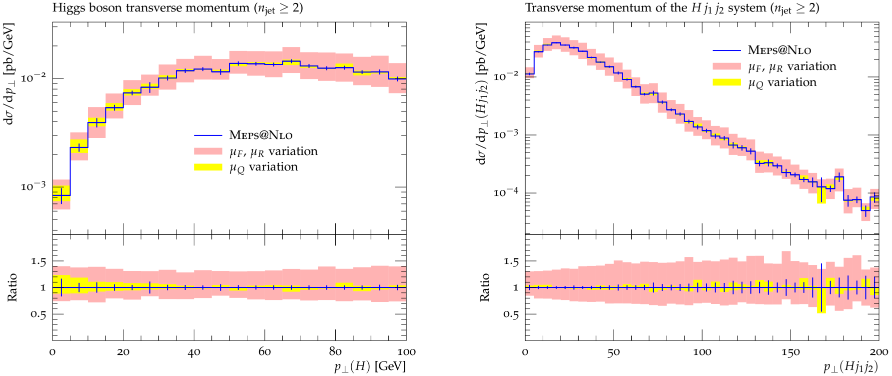


$pp \to h$+jets (0,1,2 @ NLO; 3 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, m_h$
- NLO dependence for $pp \to h$+0,1,2 jets
  LO dependence for $pp \to h$+3 jets
- $Q_{\text{cut}} = 20$ GeV

Results – pp → h+jets (ggF)

Observables for $pp \to h+ \geq 2$ jets



- $p_\perp(h)$ predicted at NLO accuracy, $p_\perp(hjj)$ at LO accuracy
- hierarchies of jet emission scales are resummed
- resummation scale dependence minimal

Conclusions

- multijet merging at NLO proceeds schematically as at LO
  $\rightarrow$ introduce MC-counterterm to retain NLO accuracy
- preserves NLO accuracy of the ME and accuracy of the PS in resumming hierarchies of emission scales
  $\rightarrow$ scale setting essential for recovering PS resummation
- can be improved by adding higher order calculations
  - (N)NLL resummation
  - NNLO corrections

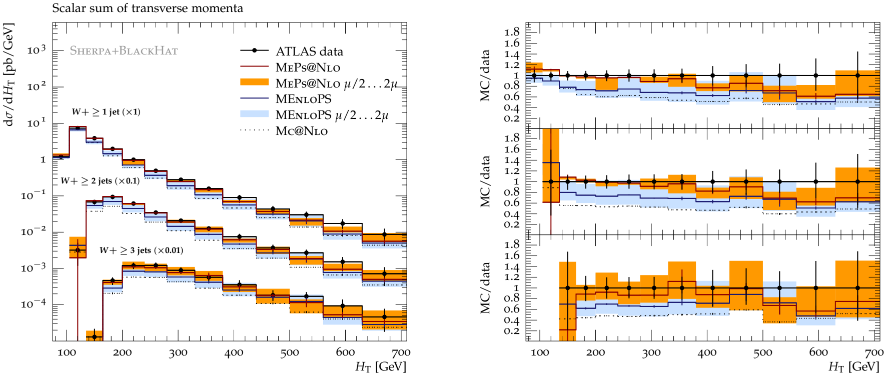
current release SHERPA-2.0.β_2, when fully tuned SHERPA-2.0.0

http://sherpa.hepforge.org

Thank you for your attention!

Results – pp → W+jets

ATLAS data Phys.Rev.D85(2012)092002



Results – pp → W+jets

ATLAS data Phys.Rev.D85(2012)092002