Multijet merging in SHERPA

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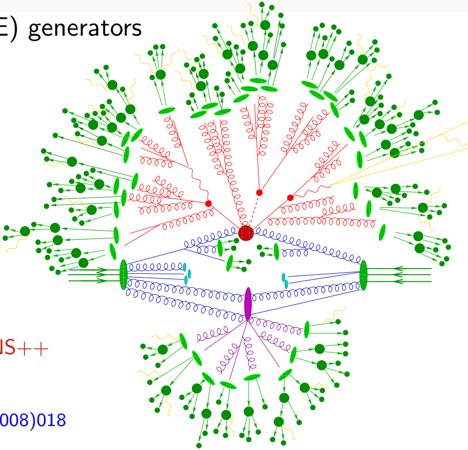
Contents

JHEP02(2009)007

The SHERPA event generator framework



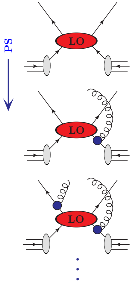
- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044, EPJC53(2008)501
  COMIX JHEP12(2008)039, PRL109(2012)042001
- A Parton Shower (PS) generator
  CSSHOWER++ JHEP03(2008)038
- A multiple interaction simulation
  à la Pythia AMISIC++ hep-ph/0601012
- A cluster fragmentation module
  AHADIC++ EPJC36(2004)381
- A hadron and τ decay package HADRONS++
- A higher order QED generator using
  YFS-resummation PHOTONS++ JHEP12(2008)018
- A minimum bias simulation SHRiMPS to appear

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

MEPS

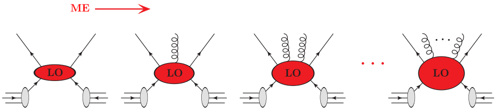


Parton showers

resummation of (soft-)collinear limit
→ 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



Matrix elements

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

- 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
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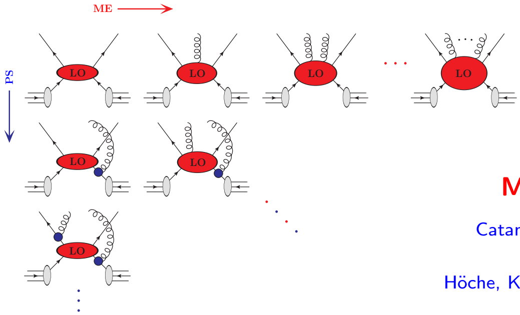
MePs



MePs (CKKW,MLM)

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

- 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
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Resummation properties of parton showers

$$\langle O\rangle^{\mathsf{PS}} = \int \mathrm{d}\Phi_n\, \mathrm{B}_n(\Phi_n) \left[\Delta_n^{(\mathcal{K})}(t_c,\mu_Q^2)\, O(\Phi_n) + \int\limits_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathcal{K}_n(\Phi_1)\, \Delta_n^{(\mathcal{K})}(t,\mu_Q^2)\, O(\Phi_{n+1}) \right]$$

- splitting kernel $\mathcal{K}_n = \sum \mathcal{K}_i$ and $\mathcal{K}_i(\Phi_1) \propto \frac{\alpha_s}{t} P_i(z)$, $\Phi_1 = \{t, z, \phi\}$
- 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
- 1-loop running $\alpha_s \to \alpha_s(k_\perp)$ catches dominant terms of higher log. order
  $\Rightarrow$ **crucial in defining "parton shower accuracy"**

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MEPS

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

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

Multijet merging at leading order:

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

- restrict the parton shower on $2 \to n$ to emit only below Q_{cut}
- arbitrary jet measure $Q_n = Q_n(\Phi_n)$
- add the $n+1$ ME and its parton shower
- multiply by Sudakov wrt. $2 \to n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

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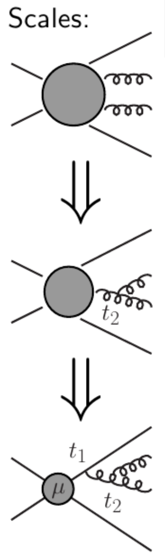

$$\alpha_s^{k+n}(\mu_{\mathsf{R}}) = \alpha_s^k(\mu_{\mathsf{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$$

MEPS

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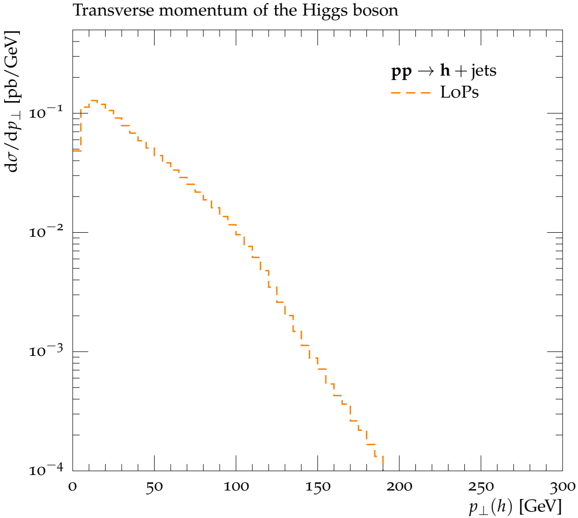
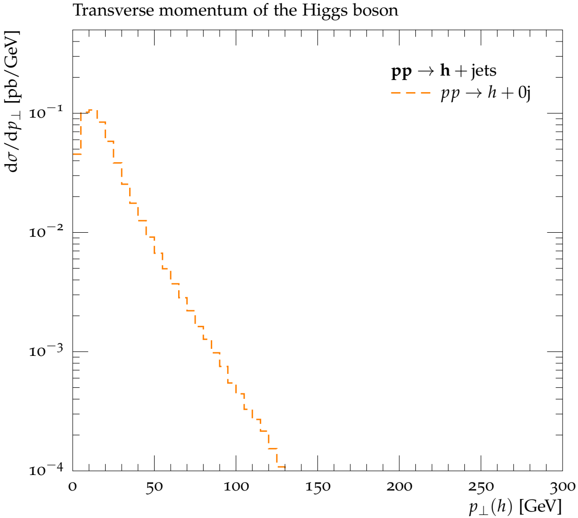
MePs



- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LoPs $pp \to h +$ jet for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h +$ jet to $Q_{n+2} < Q_{\text{cut}}$
- LoPs $pp \to h +$ 2jets for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions

MePs



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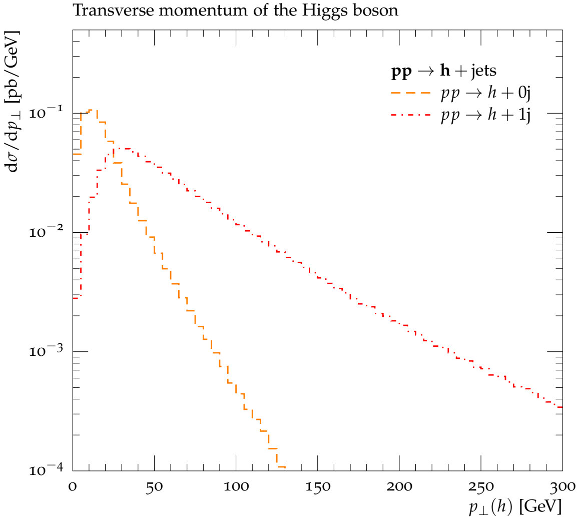

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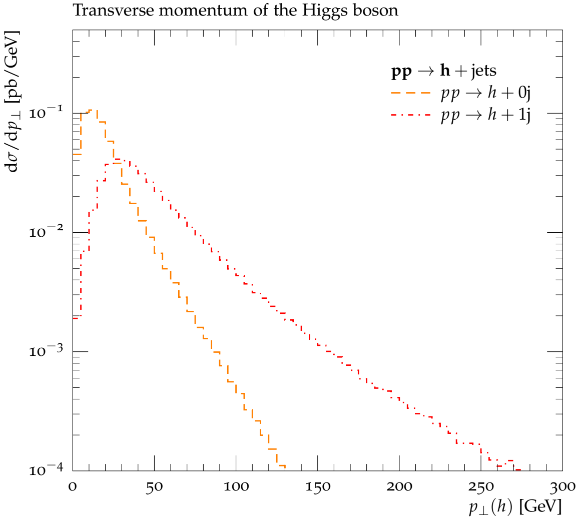

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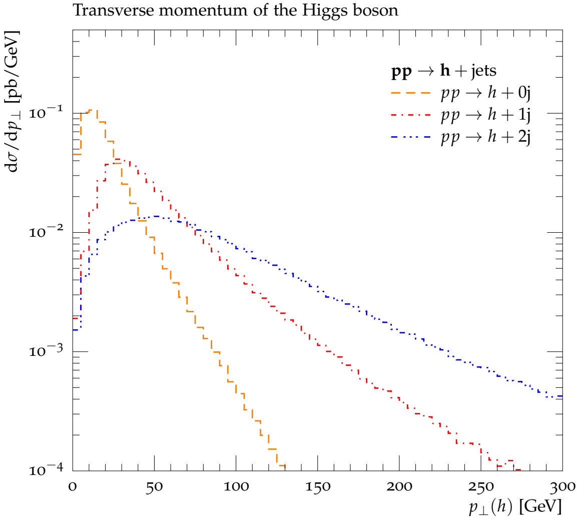

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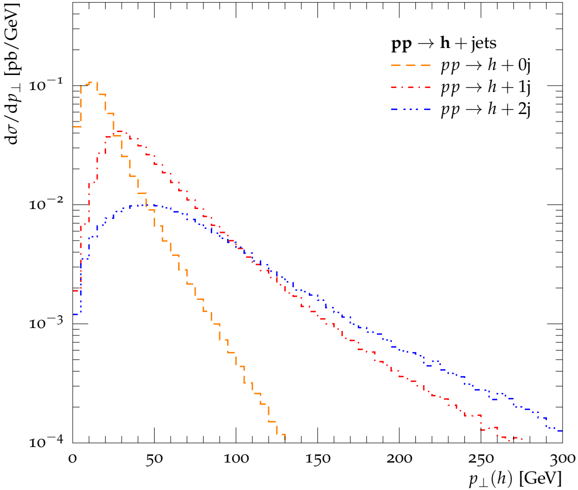
MePs

Transverse momentum of the Higgs boson



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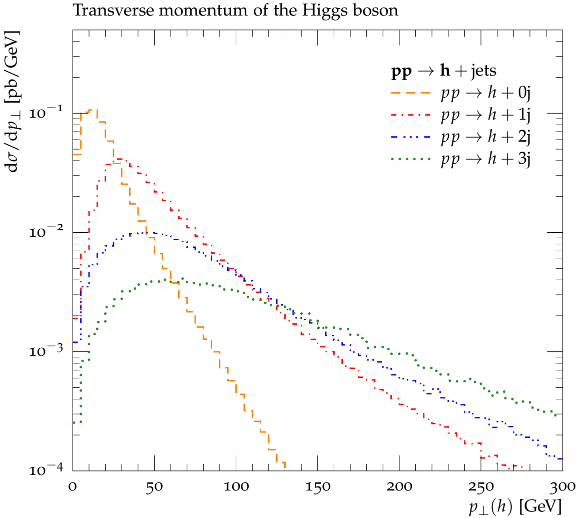
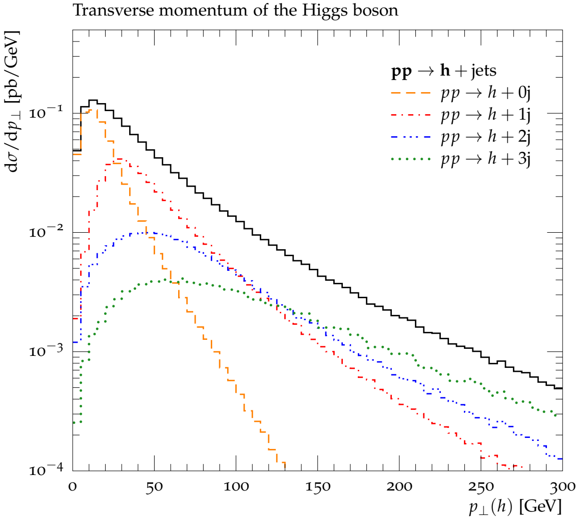
- sum all contributions

MePs



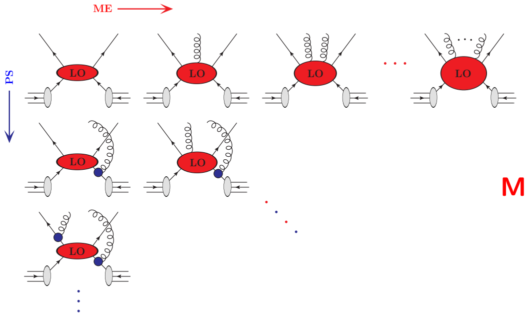
- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LoPs $pp \to h +$ jet for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h +$ jet to $Q_{n+2} < Q_{\text{cut}}$
- LoPs $pp \to h +$ 2jets for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions

MePs



- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LoPs $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- LoPs $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions

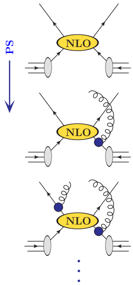
MEPS@NLO



MEPS (CKKW,MLM)

- 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@NLO combines multiple NLOPS – keeping either accuracy

MEPS@NLO



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

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
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- MEPS@NLO combines multiple NLOPS – keeping either accuracy

NLOPS – S-MC@NLO

Höche, Krauss, MS, Siegert JHEP09(2012)049

$$\langle O\rangle^{\text{NLOPS}} = \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})}(\Phi_n)\Bigg[\Delta_n^{(\mathsf{A})}(t_c,\mu_Q^2)\,O(\Phi_n) + \int_{t_c}^{\mu_Q^2}\mathrm{d}\Phi_1\,\frac{\mathrm{D}_n^{(\mathsf{A})}(\Phi_n,\Phi_1)}{\mathrm{B}_n(\Phi_n)}\,\Delta_n^{(\mathsf{A})}(t,\mu_Q^2)\,O(\Phi_{n+1})\Bigg] + \int \mathrm{d}\Phi_{n+1}\Big[\mathrm{R}_n(\Phi_{n+1}) - \sum_i \mathrm{D}_{n,i}^{(\mathsf{A})}(\Phi_{n+1})\Big]\,O(\Phi_{n+1})$$

- use $\mathrm{D}_{n,i}^{(\mathsf{A})}$ as resummation kernels
  $\rightarrow$ must reproduce $N_c = 3$ infrared limits
- resummation phase space limited by $\mu_Q^2 = t_{\mathsf{max}}$
  $\rightarrow$ starting scale of parton shower evolution
  $\rightarrow$ should be of the order of the hard interaction scale
- POWHEG and MC@NLO now differ in choice of $\mathrm{D}_{n,i}^{(\mathrm{A})}$ and μ_Q^2
- SHERPA: $\mathrm{D}_{n,i}^{(\mathrm{A})} = \mathrm{D}_{n,i}^{(\mathrm{S})}\,\Theta(\mu_Q^2 - t_n)$ ($N_c = 3$ CS kernels), μ_Q free

S-MC@NLO – pp → jets

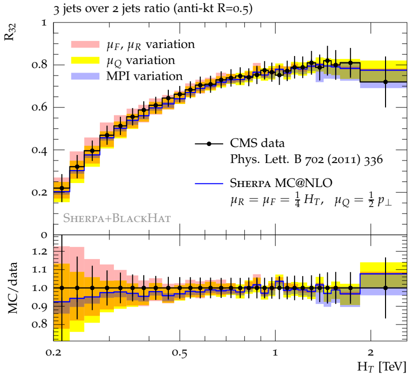
Höche, MS Phys.Rev.D86(2012)094042

MC@NLO di-jet production:

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



S-Mc@Nlo – $pp \to t\bar{t}\,b\bar{b}$

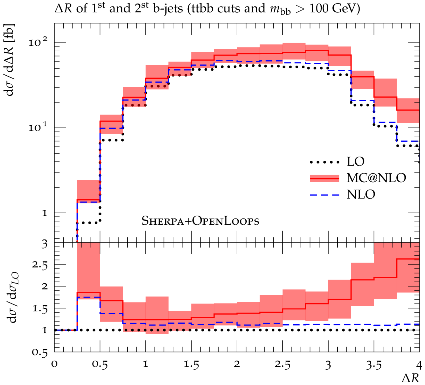
Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.0500

Mc@Nlo $pp \to t\bar{t}\,b\bar{b}$ production:

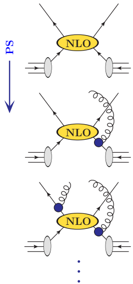
- 4F scheme, finite m_b, m_t
- $\mu_R = \sqrt[4]{\prod_{i=t,\bar{t},b,\bar{b}} E_{\perp,i}}$
- $\mu_F = \frac{1}{2}\,\left(E_{\perp,t} + E_{\perp,\bar{t}}\right)$
- $\mu_Q = \mu_F$
- MSTW2008NLO PDF
- parton level calculation
- virtual MEs from OpenLoops

Uncertainty estimates:

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



MePs@Nlo

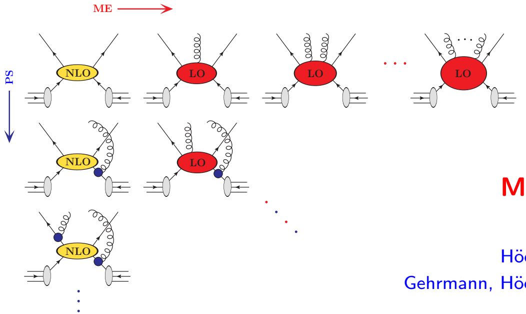


NloPs (Mc@Nlo,Powheg)

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

- 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@NLO



MENLOPS

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

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
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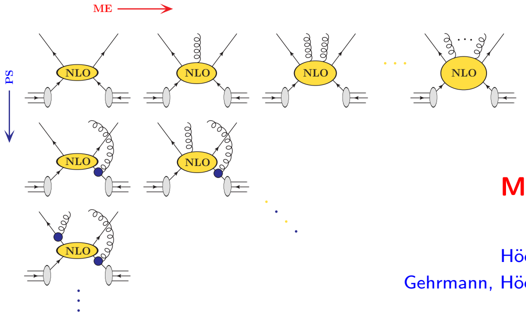
MePs@Nlo

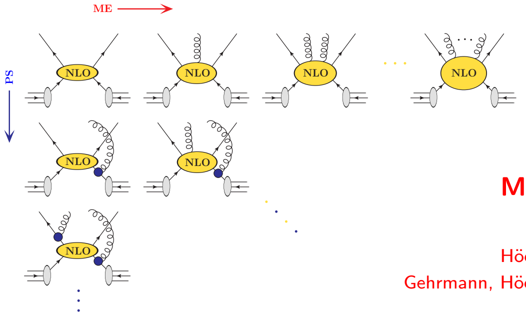


MePs@Nlo

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
Lönnblad, Prestel JHEP03(2013)166

- 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@Nlo combines multiple NloPs – keeping either accuracy

MePs@Nlo



MePs@Nlo

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
Lönnblad, Prestel JHEP03(2013)166

- 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@Nlo combines multiple NloPs – keeping either accuracy**

MEPS@NLO

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

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

MEPS@NLO

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

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

Multijet merging at next-to-leading order:

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

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

MEPS@NLO

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

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

Multijet merging at next-to-leading order:

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

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

MePs@Nlo

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

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

Multijet merging at next-to-leading order:

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

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

MePs@Nlo

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

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

Multijet merging at next-to-leading order:

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

- NloPs for $2 \to n$, restricted to emit only below Q_{cut}
- add the NloPs for $2 \to n+1$
- 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.):

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

Multijet merging at next-to-leading order:

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

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

MEPS@NLO

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

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

Multijet merging at next-to-leading order:

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

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

MEPS@NLO

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

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

Multijet merging at next-to-leading order:

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

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

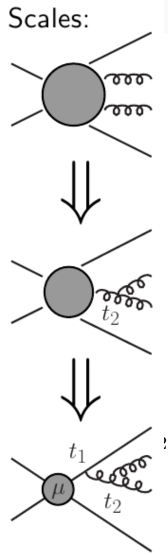
MEPS@NLO

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

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

Multijet merging at next-to-leading order:

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



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

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

MEPS@NLO

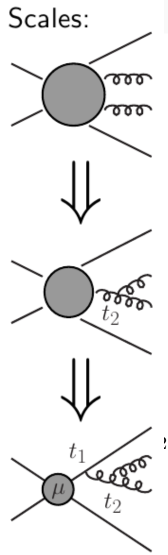
Parton showers for NLOPS (need to reproduce $N_c = 3$ singular li .):

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

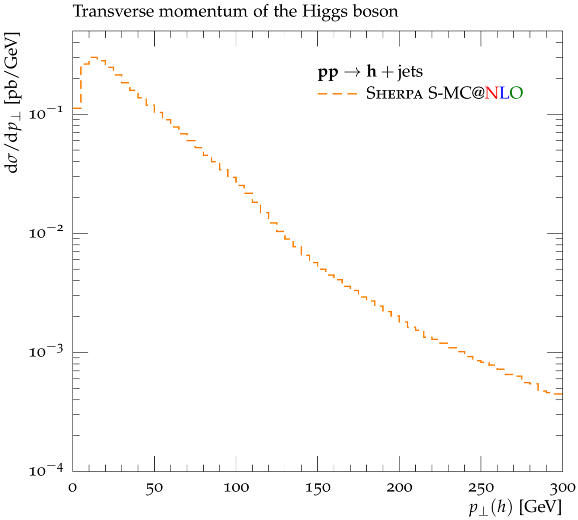
Multijet merging at next-to-leading order:

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

- NLOPS for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPS for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resumma
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

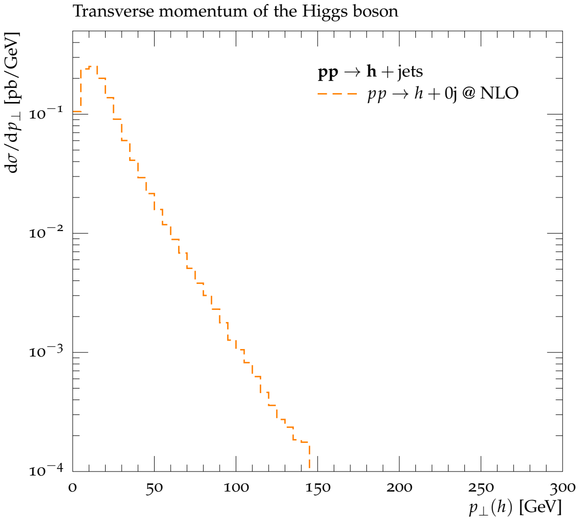


MePs@Nlo



- first emission by NLOPs, restrict to $Q_{n+1} < Q_{\text{cut}}$
- NLOPs $pp \to h+$jet for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h+$jet to $Q_{n+2} < Q_{\text{cut}}$
- NLOPs $pp \to h+$2jets for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions

MePs@Nlo



- first emission by NLOPS , restrict to $Q_{n+1} < Q_{\text{cut}}$
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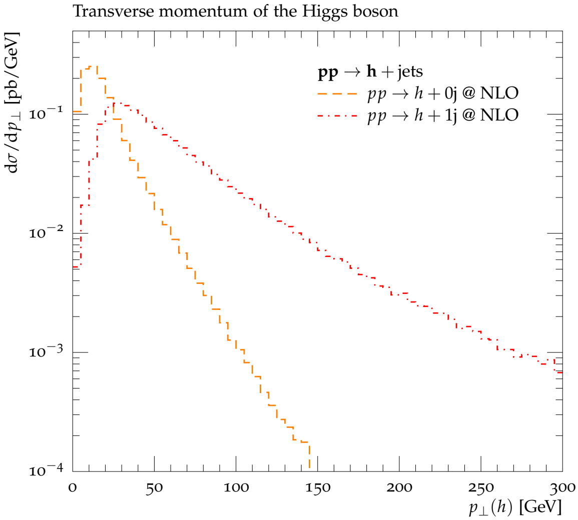
- sum all contributions

MePs@Nlo



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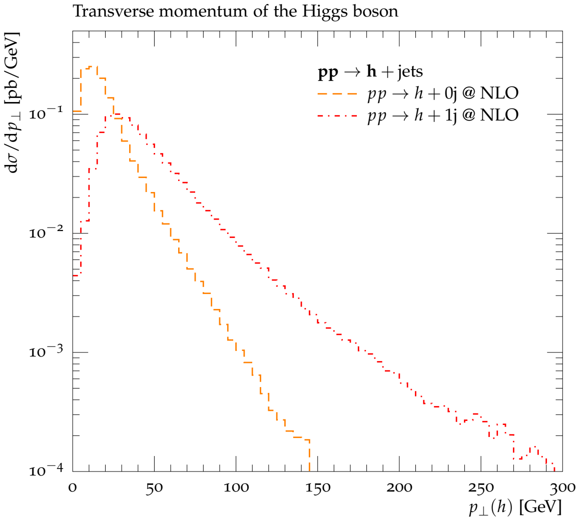
- sum all contributions

MePs@Nlo



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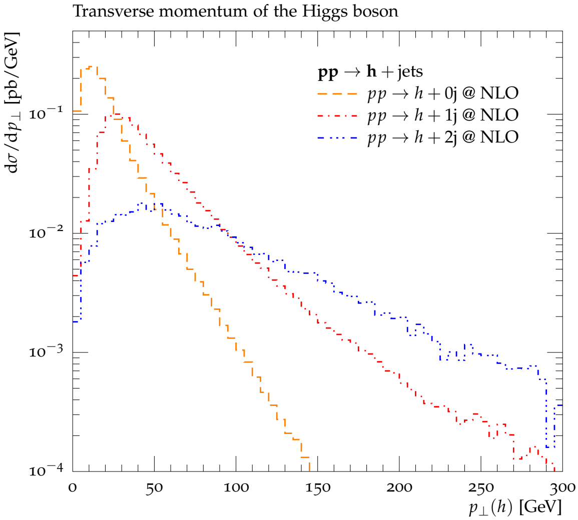
MePs@Nlo



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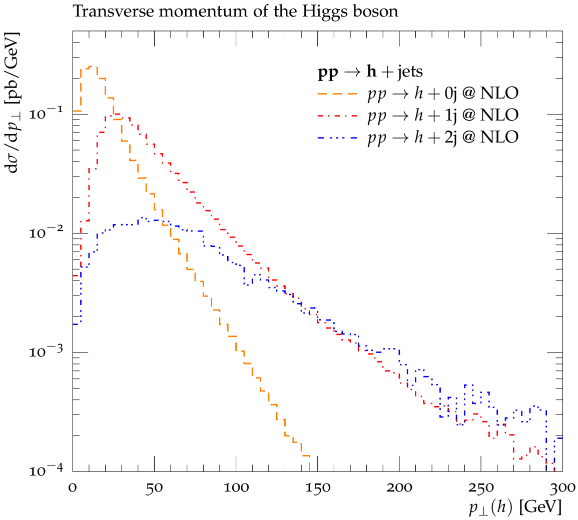
- sum all contributions

MEPS@NLO



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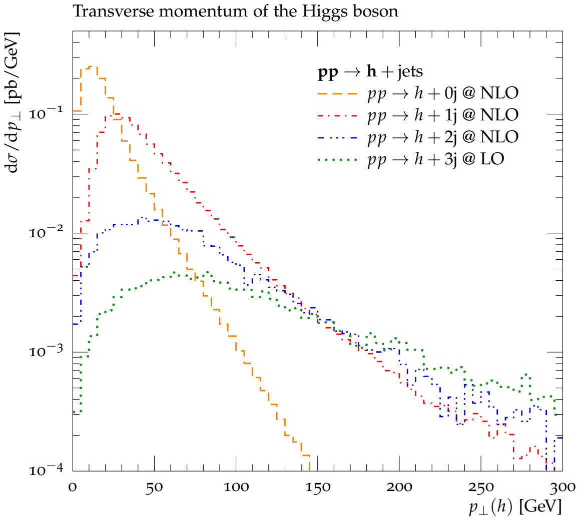
MEPS@NLO



- first emission by NLOPS , restrict to $Q_{n+1} < Q_{\text{cut}}$
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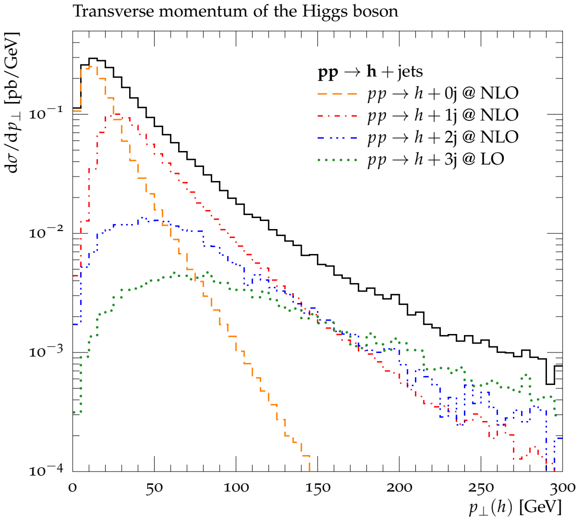
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- NLOPS $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions

MePs@Nlo



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- iterate
- sum all contributions

Recent results

Fixed-mulitplicity NLOPS (S-MC@NLO)

- $pp \to W + 0, 1, 2, 3$jets – SHERPA+BLACKHAT

  Höche, Krauss, MS, Siegert Phys.Rev.Lett.110(2013)052001
- $pp \to$ jets – SHERPA+BLACKHAT Höche, MS Phys.Rev.D86(2012)094042
- $pp \to t\bar{t}b\bar{b}$ – SHERPA+OPENLOOPS

  Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.0500

Multijet merging at NLO accuracy (MEPS@NLO)

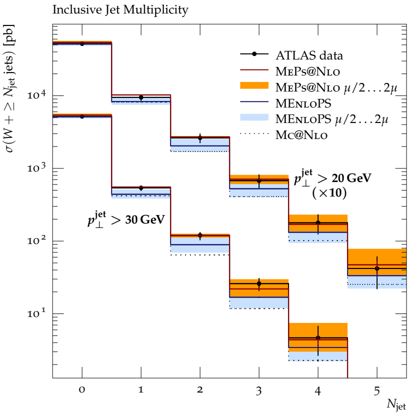
- $pp \to W +$ jets – SHERPA+BLACKHAT Höche, Krauss, MS, Siegert JHEP04(2013)027
- $e^+e^- \to$ jets – SHERPA+BLACKHAT

  Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
- $pp \to h +$ jets – SHERPA+GOSAM Höche, Krauss, MS, Siegert, in YR3 arXiv:1307.1347
- $p\bar{p} \to t\bar{t} +$ jets – SHERPA+GOSAM

  Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040
- $pp \to 4\ell +$ jets – SHERPA+OPENLOOPS

  Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert arXiv:1309.5912

Results – pp $\to$ W+jets

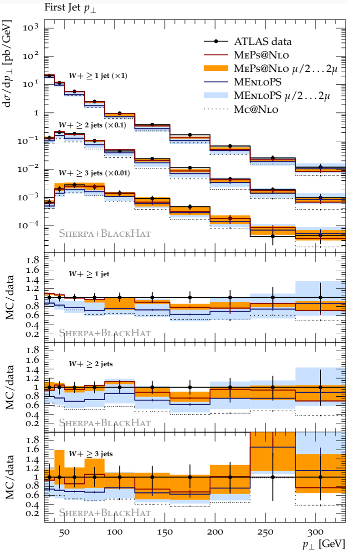


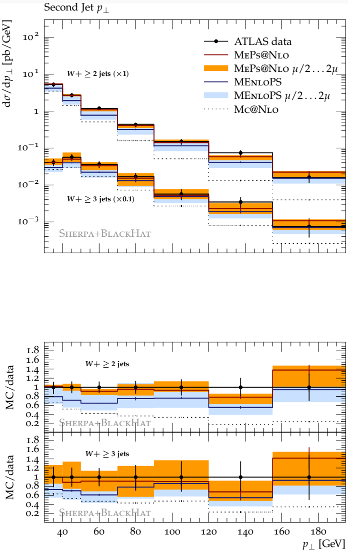
$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

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

ATLAS data Phys.Rev.D85(2012)092002

Results – pp → W+jets



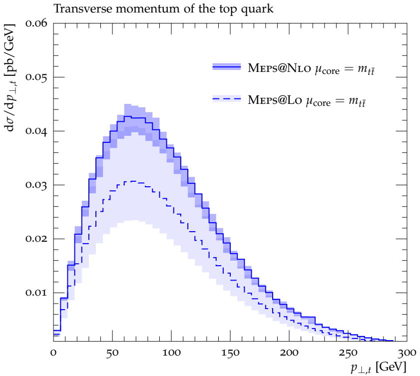


Recent results – $pp \to t\bar{t} + \text{jets}$

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

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- virtual MEs from GoSam
- 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



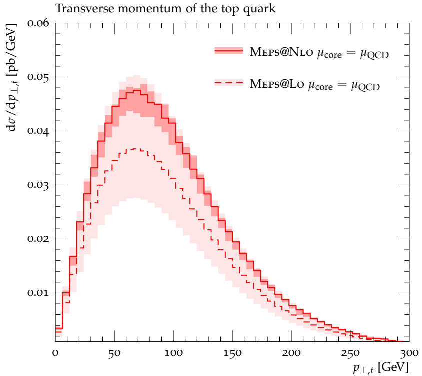
- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$
  1) $\mu_{\text{core}} = m_{t\bar{t}}$
  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = \sqrt{2\,|p_i p_j|}$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u

$\Rightarrow$ different behaviour for forward/backward configurations

Recent results – $pp \to t\bar{t} + $ jets

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

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703



- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- virtual MEs from GoSam
- 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: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$

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

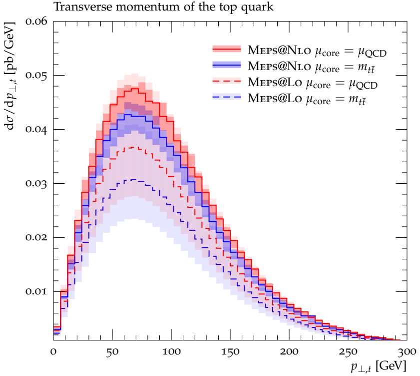
  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = \sqrt{2\,|p_i p_j|}$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u

$\Rightarrow$ different behaviour for forward/backward configurations

Recent results – $pp \to t\bar{t} + \text{jets}$

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

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703



- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{cut} = 7$ GeV
- virtual MEs from GoSam
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{def}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{core}$
- variation of merging parameter
  $Q_{cut} \in \{5, 7, 10\}$ GeV
- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{core})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$
  1) $\mu_{core} = m_{t\bar{t}}$
  2) $\mu_{core} = \mu_{QCD} = \sqrt{2\,|p_i p_j|}$
  $i, j\ \ldots\ N_c \to \infty$ colour partners, chooses between s, t, u

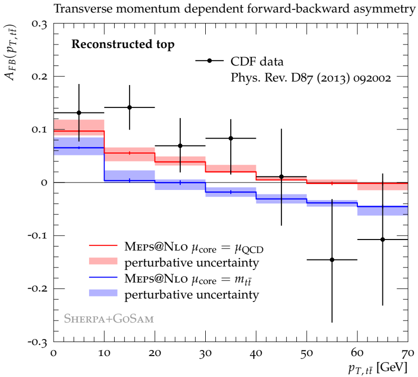
$\Rightarrow$ **different behaviour for forward/backward configurations**

Recent results – $pp \to t\bar{t} + \text{jets}$

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
- virtual MEs from GoSam
- 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

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

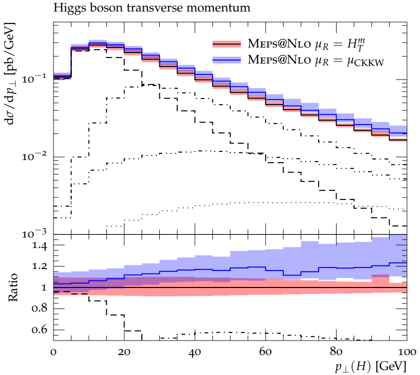


- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_\text{core})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$
  1) $\mu_\text{core} = m_{t\bar{t}}$
  2) $\mu_\text{core} = \mu_\text{QCD} = \sqrt{2\,|p_i p_j|}$
  $i, j \;\ldots\; N_c \to \infty$ colour partners, chooses between s, t, u

$\Rightarrow$ different behaviour for forward/backward configurations

Recent results – $pp \to h + $ jets MEPS@NLO (ggh)

Höche, Krauss, MS contrib to LH2013

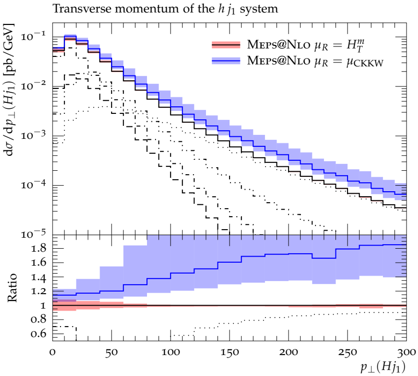


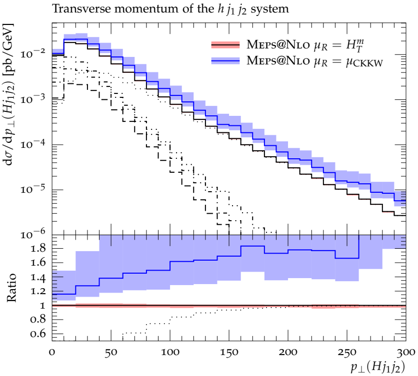
$pp \to h +$ jets in gluon fusion

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1,2 jets @ NLO, 3 jets @ LO
  $Q_{\text{cut}} = 20$ GeV
- perturbative scale variations
  $\mu_F \in [\frac{1}{2}, 2]\,\mu_{\text{CKKW}}$
  $\mu_R \in [\frac{1}{2}, 2]\,\mu_R^{\text{def}}$
  ~~$\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,m_h$~~
  $Q_{\text{cut}} \in \{15, 20, 30\}$ GeV
- renormalisation scale choice:
  1-loop running has to be $\alpha_s^{k+n}(\mu_{\text{CKKW}}) = \alpha_s^k(\mu_{\text{core}})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$
  1. use $\mu_R^{\text{def}} = \mu_{\text{CKKW}}$ (very low scale)
  2. use $\mu_R^{\text{def}} = H_T^m = \sum m_\perp = m_\perp^h + H_T^{\text{partons}}$ (very high scale)

  correct 1-loop running to μ_{CKKW} by adding $\text{B}_n \frac{\alpha_s}{\pi}\beta_0 \log\left(\frac{\mu_R^{\text{def}}}{\mu_{\text{CKKW}}}\right)^{k+n}$

Recent results – $pp \to h + \text{jets}$ MEPS@NLO (ggh)





- different shapes, but resummation region uneffected
- $\mu_R = H_T^m$ increases to very high values
  $\to$ symmetric μ_R and μ_F uncertainties cancel each other
- $\mu_R = \mu_{\text{CKKW}}$ has very one-sided scale uncertainty

Interface to loop generators

- standardised BLHA interface (currently enhanced version 1)
  $\rightarrow$ quick interface to any code
- dedicated interfaces to
  - BlackHat
  - OpenLoops
  - selected dedicated calculations
  - Mcfm (selected processes)

  offers more flexibility
  better accommodates specifics of individual generators
  better accommodates specific/non-standard standards
- dedicated interfaces can be added by user without touching/modifying/recompiling Sherpa
  $\rightarrow$ provide library linked at runtime (same as 1-loop code in BLHA)

Typical run card - fixed order

```
(run){
  EVENTS 1M;

  % scales, tags for scale variations
  FSF:=1.; RSF:=1.;
  SCALES VAR{FSF*sqr(80.4)}{RSF*sqr(80.4)};

  % me generator settings
  ME_SIGNAL_GENERATOR Amegic;
  EVENT_GENERATION_MODE Weighted;

  % collider setup
  BEAM_1 2212; BEAM_ENERGY_1 = 4000.;
  BEAM_2 2212; BEAM_ENERGY_2 = 4000.;
  PDF_LIBRARY LHAPDF;
  PDF_SET CT10;
}(run)

(processes){
  Process 93 93 -> 90 91;
  Order_EW 2;
  NLO_QCD_Mode Fixed_Order;
  ME_Generator Amegic;
  Loop_Generator BlackHat;
  End process;
}(processes)
```

Typical run card – MC@NLO

```
(run){
  EVENTS 1M;

  % scales, tags for scale variations
  FSF:=1.; RSF:=1.; QSF:=1.;
  SCALES VAR{FSF*sqr(80.4)}{RSF*sqr(80.4)}{QSF*sqr(80.4)};

  % me generator settings
  ME_SIGNAL_GENERATOR Amegic;
  EVENT_GENERATION_MODE Weighted;

  % collider setup
  BEAM_1 2212; BEAM_ENERGY_1 = 4000.;
  BEAM_2 2212; BEAM_ENERGY_2 = 4000.;
  PDF_LIBRARY LHAPDF;
  PDF_SET CT10;
}(run)

(processes){
  Process 93 93 -> 90 91;
  Order_EW 2;
  NLO_QCD_Mode MC@NLO;
  ME_Generator Amegic;
  Loop_Generator BlackHat;
  End process;
}(processes)
```

Typical run card – MEPS@NLO

```
(run){
  EVENTS 1M;

  % scales, tags for scale variations
  FSF:=1.; RSF:=1.; QSF:=1.;
  SCALES METS{FSF*MU_F2}{RSF*MU_R2}{QSF*MU_Q2};

  % me generator settings
  ME_SIGNAL_GENERATOR Comix Amegic;
  EVENT_GENERATION_MODE Weighted;

  % collider setup
  BEAM_1 2212; BEAM_ENERGY_1 = 4000.;
  BEAM_2 2212; BEAM_ENERGY_2 = 4000.;
  PDF_LIBRARY LHAPDF;
  PDF_SET CT10;
}(run)

(processes){
  Process 93 93 -> 90 91 93{4};
  Order_EW 2; CKKW sqr(20./E_CMS);
  NLO_QCD_Mode MC@NLO {2,3,4};
  ME_Generator Amegic {2,3,4};
  Loop_Generator BlackHat {2,3,4};
  End process;
}(processes)
```

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
- residual freedom in scale choice
  $\rightarrow$ μ_{core}
  $\rightarrow$ beyond 1-loop running the scales can chosen freely

current release SHERPA-2.0.0

http://sherpa.hepforge.org

Thank you for your attention!