Uncertainties in h+jets production

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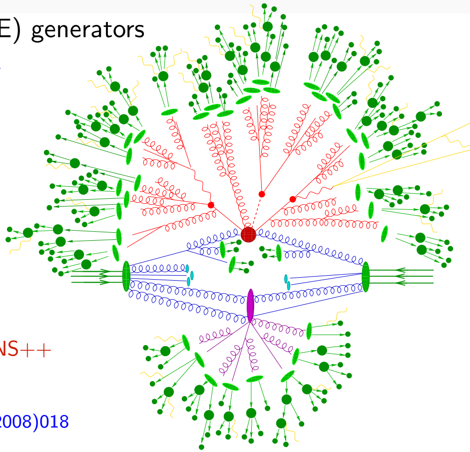
JHEP02(2009)007

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

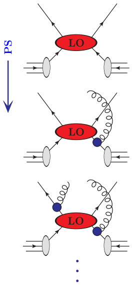


Sherpa's traditional strength is the perturbative part of the event

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

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

MEPS

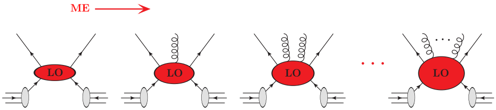


Parton showers

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



Matrix elements

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

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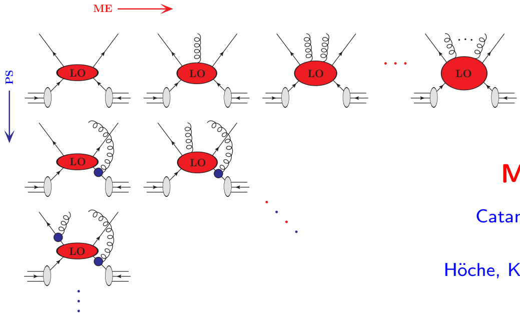

MEPS (CKKW,MLM)

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

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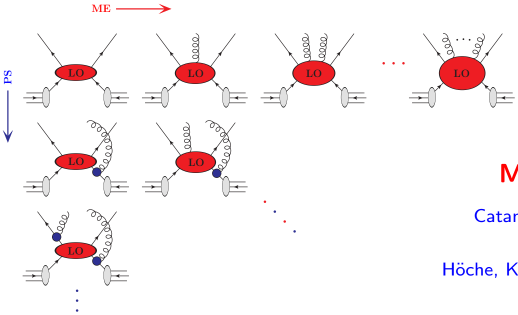

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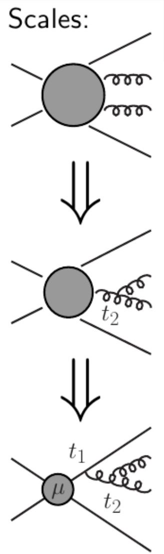

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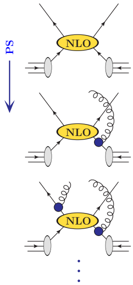
$$\alpha_s^{k+n}(\mu_\mathrm{R}) = \alpha_s^k(\mu_\mathrm{core})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$

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

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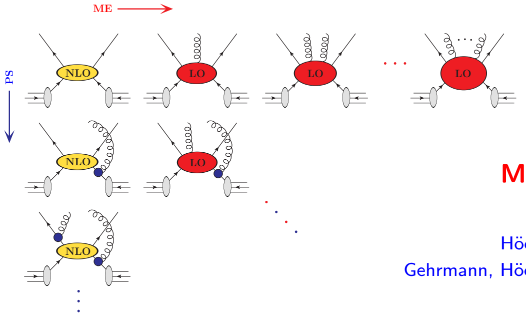

MENLOPS

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

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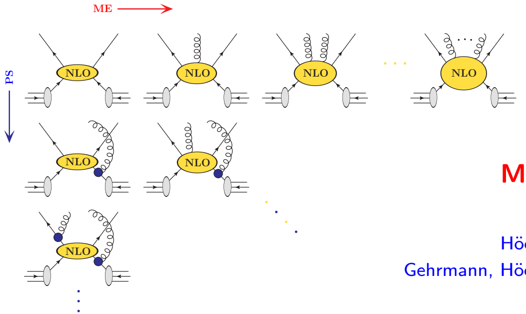

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Lavesson, Lönnblad JHEP12(2008)070
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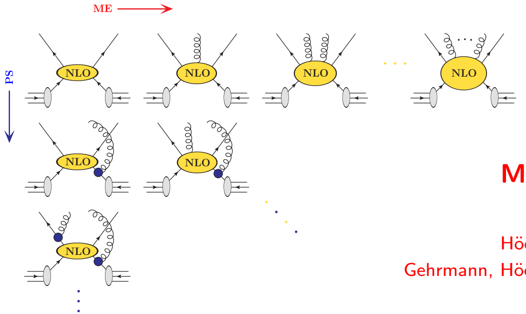

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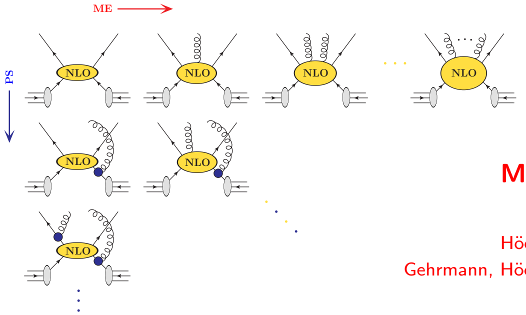

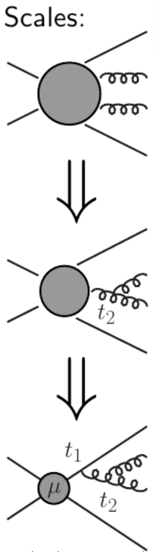

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Resummation properties of parton showers

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

- 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"**

Resummation properties of parton showers

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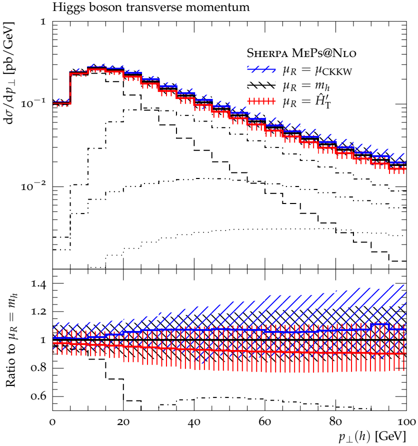
Recent results

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/MCFM
  Höche, Krauss, MS, Siegert, contribution to YR3 arXiv:1307.1347
  Höche, Krauss, MS arXiv:1401.7971
  MS, Zapp, contribution to LH13
- $p\bar{p} \to t\bar{t} +$ jets – SHERPA+GOSAM/OPENLOOPS
  Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040
  Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert arXiv:1402.6293
- $pp \to 4\ell +$ jets – SHERPA+OPENLOOPS
  Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert JHEP01(2014)046
- $pp \to VH +$ jets, $pp \to VV +$ jets, $pp \to VVV +$ jets
  – SHERPA+OPENLOOPS
  Höche, Krauss, Pozzorini, MS, Thompson, Zapp arXiv:1403.7516

Results – pp → h+jets

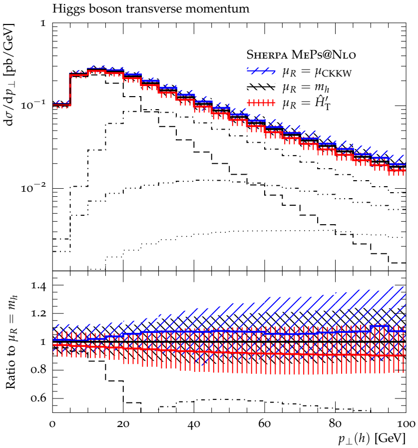


Höche, Krauss, MS, in arXiv:1401.7971

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

- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_Q^{\text{def}}$
- $Q_{\text{cut}} \in \{15, 20, 30\}$ GeV
- NLO dependence for $pp \to h$+0,1,2 jets
  LO dependence for $pp \to h$+3 jets
- virtual MEs from MCFM (hjj)

Results – pp → h+jets



⇒ **difference beyond accuracy**

scale choices: $\mu_F = \mu_Q = m_h$

1. $\mu_R = \mu_{\text{CKKW}}$
   $$\alpha_s^{2+n}(\mu_{\text{CKKW}}) = \alpha_s^2(m_h)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$
2. $\mu_R = m_h$
3. $\mu_R = \hat{H}'_T$

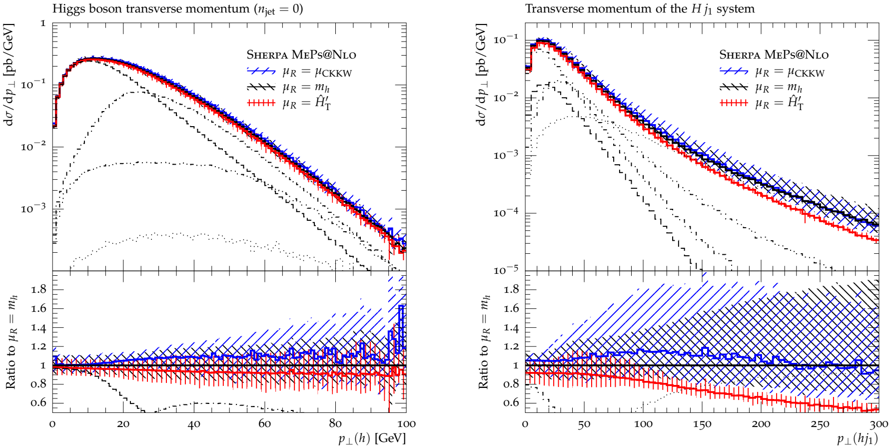
need to include ren. term

$$\mathrm{B}_n\,\frac{\alpha_s(\mu_R)}{\pi}\,\beta_0\,\left(\log\frac{\mu_R}{\mu_{\text{CKKW}}}\right)^{2+n}$$

to restore 1-loop running to μ_{CKKW}
→ otherwise PS-accuracy violated

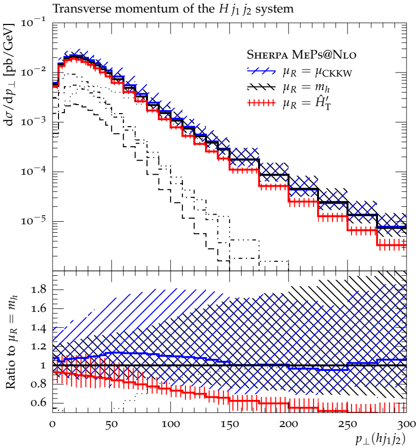
→ same as in UNLOPS approach
Lönnblad, Prestel JHEP03(2013)166
Plätzer JHEP08(2013)114

Results – pp → h+jets



- all predictions identical to MEPS@NLO accuracy
- vastly differing size of uncertainties

Results – pp → h+jets



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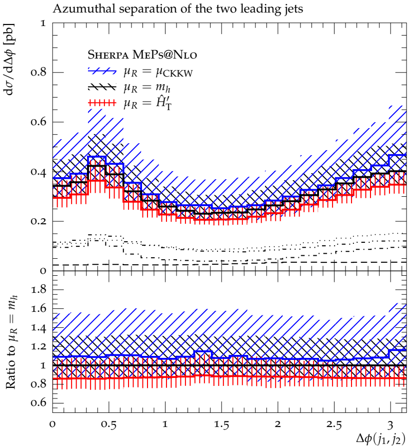

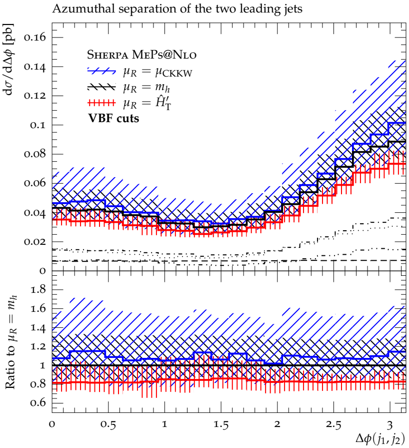

- all predictions identical to MEPS@NLO accuracy
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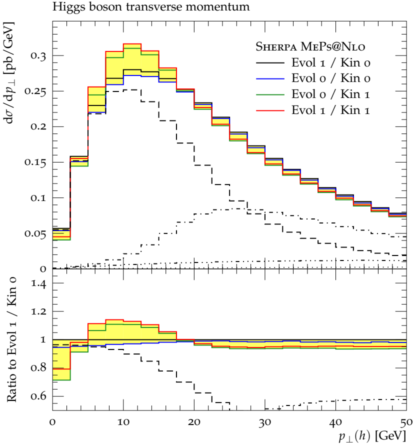
Results – $\mathrm{pp} \to \mathrm{h}+$jets

	$\mu_R = \mu_{\text{CKKW}}$	$\mu_R = m_h$	$\mu_R = \hat{H}'_{\mathrm{T}}$
$\sigma^{\text{incl}}_{\text{0 jet}}$	$12.2^{+1.6}_{-1.5}$ pb	$11.6^{+1.7}_{-1.4}$ pb	$10.9^{+1.4}_{-1.2}$ pb
$\sigma^{\text{excl}}_{\text{0 jet}}$	$8.05^{+0.82}_{-0.82}$ pb	$7.71^{+0.96}_{-0.85}$ pb	$7.37^{+0.86}_{-0.76}$ pb
$\sigma^{\text{incl}}_{\text{1 jet}}$	$4.16^{+0.91}_{-0.73}$ pb	$3.91^{+0.78}_{-0.54}$ pb	$3.54^{+0.63}_{-0.48}$ pb
$\sigma^{\text{excl}}_{\text{1 jet}}$	$3.08^{+0.48}_{-0.51}$ pb	$2.92^{+0.50}_{-0.42}$ pb	$2.68^{+0.46}_{-0.39}$ pb
$\sigma^{\text{incl}}_{\text{2 jet}}$	$1.07^{+0.46}_{-0.22}$ pb	$0.99^{+0.30}_{-0.13}$ pb	$0.86^{+0.18}_{-0.10}$ pb
$\sigma_{\text{VBF cuts}}$	$0.165^{+0.070}_{-0.039}$ pb	$0.152^{+0.043}_{-0.021}$ pb	$0.126^{+0.021}_{-0.014}$ pb
$\sigma^{\text{central jet veto}}_{\text{VBF cuts}}$	$0.124^{+0.048}_{-0.028}$ pb	$0.113^{+0.031}_{-0.017}$ pb	$0.096^{+0.018}_{-0.013}$ pb

Results – pp → h+jets



Parton shower uncertainties

- evolution scale

	Final State
0	$2\, p_i p_j\, \tilde{z}_{i,jk}(1-\tilde{z}_{i,jk})$
1	$2\, p_i p_j \begin{cases} \tilde{z}_{i,jk}(1-\tilde{z}_{i,jk}) & \text{if } i,j=g \\ 1-\tilde{z}_{i,jk} & \text{if } j=g \\ \tilde{z}_{i,jk} & \text{if } i=g \\ 1 & \text{else} \end{cases}$
	Initial State
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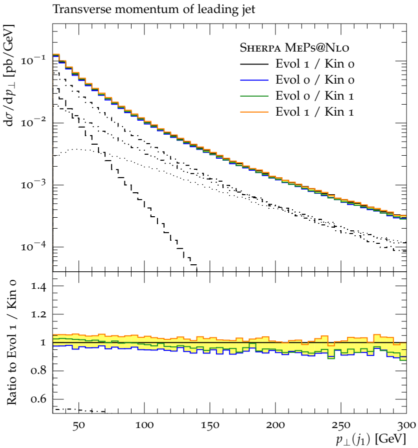
- recoil scheme

  0 initial state as if final state + ⊥-boost
  Höche, Schumann, Siegert Phys.Rev.D81(2010)034026

  1 original CS
  Catani, Seymour Nucl.Phys.B485(1997)291-419
  Schumann, Krauss JHEP03(2008)038

  → similar ideas in Gieseke, Plätzer JHEP01(2011)024

Results – pp → h+jets



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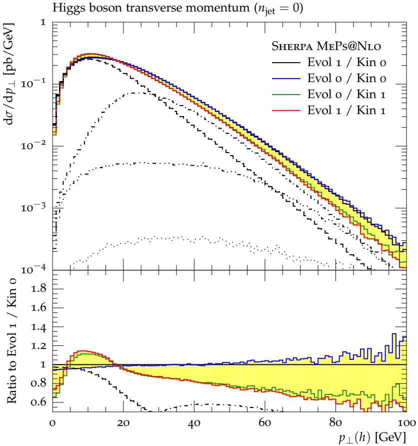
→ similar ideas in Gieseke, Plätzer JHEP01(2011)024

Results – pp → h+jets



Parton shower uncertainties

- evolution scale

	Final State
0	$2\,p_i p_j\,\tilde{z}_{i,jk}(1-\tilde{z}_{i,jk})$
1	$2\,p_i p_j \begin{cases} \tilde{z}_{i,jk}(1-\tilde{z}_{i,jk}) & \text{if } i,j=g \\ 1-\tilde{z}_{i,jk} & \text{if } j=g \\ \tilde{z}_{i,jk} & \text{if } i=g \\ 1 & \text{else} \end{cases}$

	Initial State
0	$2\,p_a p_j\,(1-x_{aj,k})$
1	$2\,p_a p_j \begin{cases} 1-x_{aj,k} & \text{if } j=g \\ 1 & \text{else} \end{cases}$

- recoil scheme

  0 initial state as if final state + ⊥-boost
  Höche, Schumann, Siegert Phys.Rev.D81(2010)034026

  1 original CS
  Catani, Seymour Nucl.Phys.B485(1997)291-419
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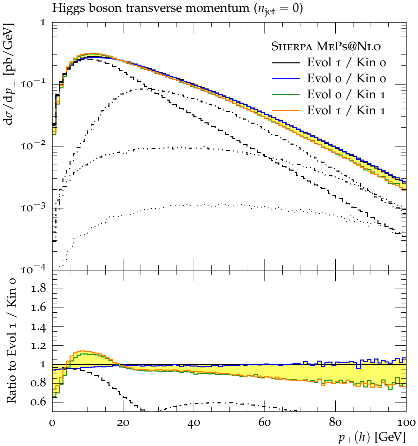

Parton shower uncertainties

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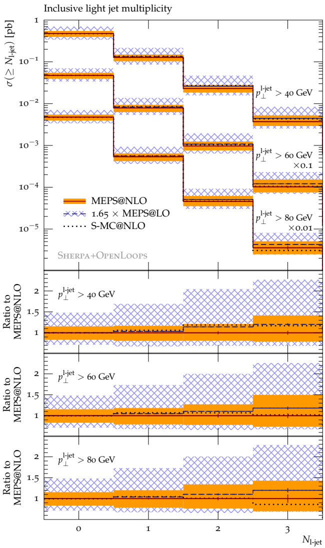
Results – $pp \to t\bar{t} + \text{jets}$



Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert

arXiv:1402.6293

$pp \to t\bar{t}$+jets (0,1,2 @ NLO; 3 @ LO)

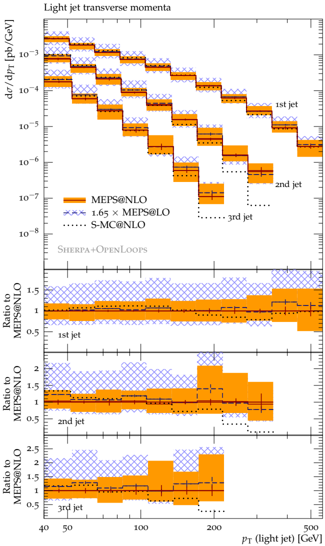
- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_Q^{\text{def}}$
- $Q_{\text{cut}} \in \{20, 30, 40\}$ GeV
- virtual MEs from OPENLOOPS

scale choices

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

$$\mu_{\text{core}}^2 = \frac{2}{\frac{1}{p_0 p_1} + \frac{1}{p_0 p_2} + \frac{1}{p_0 p_3}} = \frac{1}{\frac{1}{s} + \frac{1}{m_t^2 - t} + \frac{1}{m_t^2 - u}}$$

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



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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
  $\rightarrow$ beyond 1-loop running the scales can of course be freely chosen

current release SHERPA-2.1.0

http://sherpa.hepforge.org

Thank you for your attention!

MePs

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

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

Multijet merging at leading order:

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

- restrict the parton shower on $2 \to n$ to emit only below Q_{cut}
- 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
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MEPS

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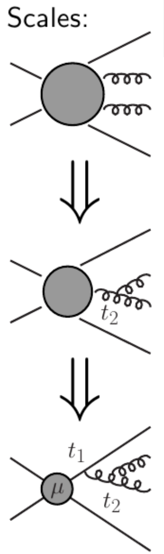

$$\alpha_s^{k+n}(\mu_{\mathsf{R}}) = \alpha_s^k(\mu_{\mathsf{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$$

MEPS

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MEPS@NLO

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

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Multijet merging at next-to-leading order:

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& \otimes \widetilde{\mathsf{PS}}_{n+1}\,\Theta(Q_{\mathsf{cut}} - Q_{n+2}) \\
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& + \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:

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

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MEPS@NLO

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& \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}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n)\Big) \\
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\end{aligned}$$

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MEPS@NLO

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Multijet merging at next-to-leading order:

$$\mathrm{d}\sigma^{\mathsf{MEPS@NLO}} = \mathrm{d}\sigma_n^{\mathsf{NLO}} \otimes \widetilde{\mathsf{PS}}_n\, \Theta(Q_{\mathsf{cut}} - Q_{n+1})$$

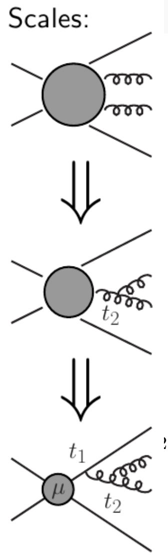
$$+\, \mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}\, \Theta(Q_{n+1} - Q_{\mathsf{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}$$

$$\otimes\, \widetilde{\mathsf{PS}}_{n+1}\, \Theta(Q_{\mathsf{cut}} - Q_{n+2})$$

$$+\, \mathrm{d}\sigma_{n+2}^{\mathsf{NLO}}\, \Theta(Q_{n+2} - Q_{\mathsf{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}($$

$$\times \Big(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_n$$

- 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
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\mathsf{NLO}}$, itera



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

MEPS@NLO

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

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

Multijet merging at next-to-leading order:

$$\mathrm{d}\sigma^{\text{MEPS@NLO}} = \mathrm{d}\sigma_n^{\text{NLO}} \otimes \widetilde{\mathrm{PS}}_n\,\Theta(Q_{\text{cut}} - Q_{n+1})$$

$$+\,\mathrm{d}\sigma_{n+1}^{\text{NLO}}\,\Theta(Q_{n+1} - Q_{\text{cut}})\Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)} \ldots$$

$$\otimes\,\widetilde{\mathrm{PS}}_{n+1}\,\Theta(Q_{\text{cut}} - Q_{n+2})$$

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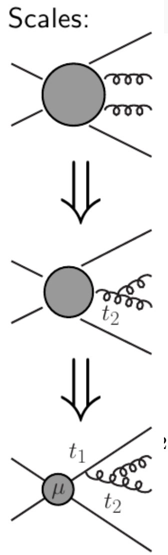
$$\times\Big(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n} \ldots$$



- 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