Multijet merging and jet substructure

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Institute for Particle Physics Phenomenology

BOOST, London, 20/08/2014

Introduction

Two aspects of event generation are important for boosted observables

1. production of boosted systems
   - production of hard jets or boosted heavy resonances usually requires (multiple) jets to recoil against
   - jet/resonance production at large $p_\perp$ is usually accompagnied by (many) additional jets

   $\Rightarrow$ **multijet merging to describe such topologies**

2. description of intrajet dynamics
   - parton evolution well described by parton shower
   - contributions from multiple interactions
   - important aspects from hadronisation and hadron decays

   $\Rightarrow$ **multijet merging must not upset parton shower resummation**

   $\Rightarrow$ **good soft-physics models important at high scales as well**

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$\Rightarrow$ **good soft-physics models important at high scales as well**

Terminology

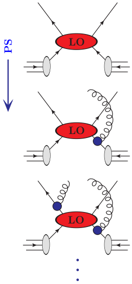
LoPs/NLoPs matching ⇒ **see Keith's talk**

- combine LO/NLO description of a single process with parton shower
  → only this one process described to LO/NLO accuracy
  → subsequent multiplicities added at PS-accuracy
- multiple schemes, different ways to resolve overlap of competing descriptions
- examples: $pp \to h$, $pp \to W + j$, ...

Multijet merging

- combine multiple LoPs (→MePs)/NLoPs (→MePs@NLo) of subsequent multiplicity
  → resums emission scale hierarchies identical to parton shower wrt. the most inclusive process considered
  → corrects hard emission of jets to LO/NLO accuracy
- multiple schemes, different ways to resolve overlap of competing descriptions
- examples: $pp \to h$+jets, $pp \to t\bar{t}$+jets, ...

MePs

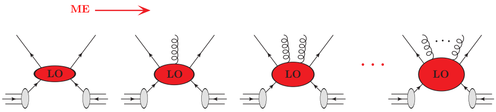


Parton showers

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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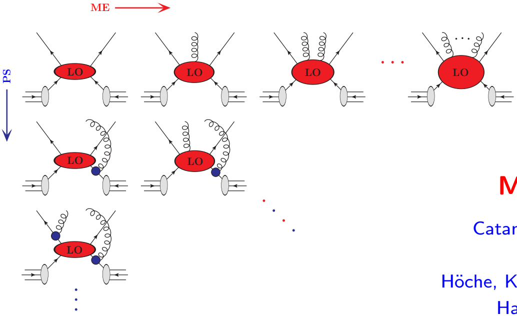

MePs (CKKW-like)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053
Hamilton, Richardson, Tully JHEP11(2009)038

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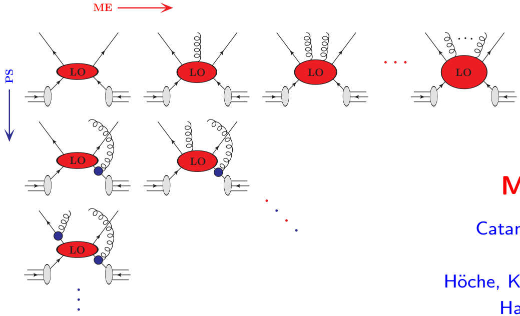

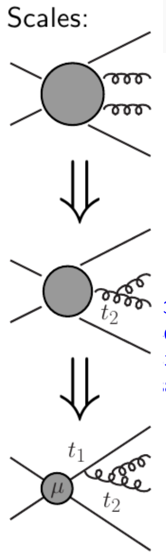

MEPS (CKKW-like

Catani, Krauss, Kuhn, Webb ... 3
Lönnbl... 6
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- MEPS combines multiple LOPS – keeping either accuracy
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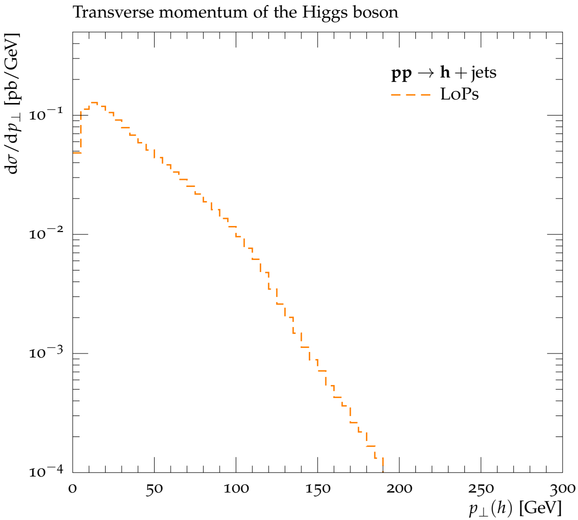
$$\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$

MePs



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- iterate
- sum all contributions
- eg. $p_\perp(h)$>200 GeV has contributions fr. multiple topologies

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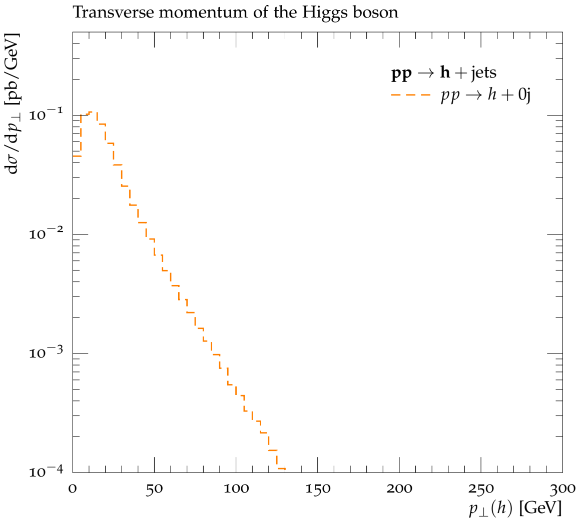

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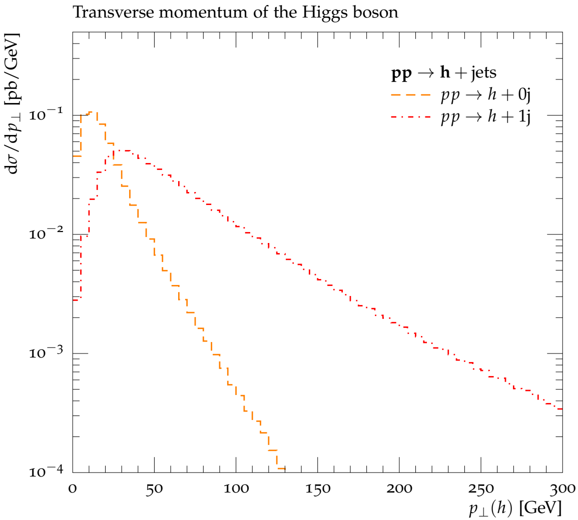

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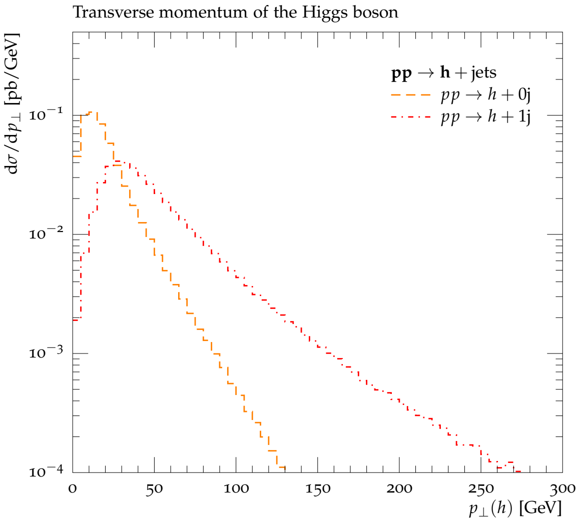

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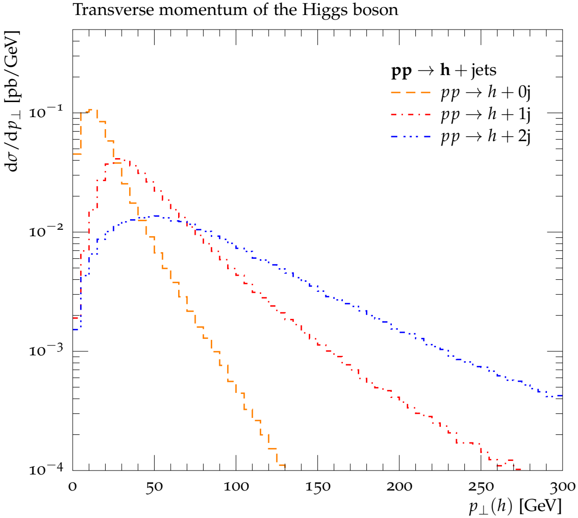

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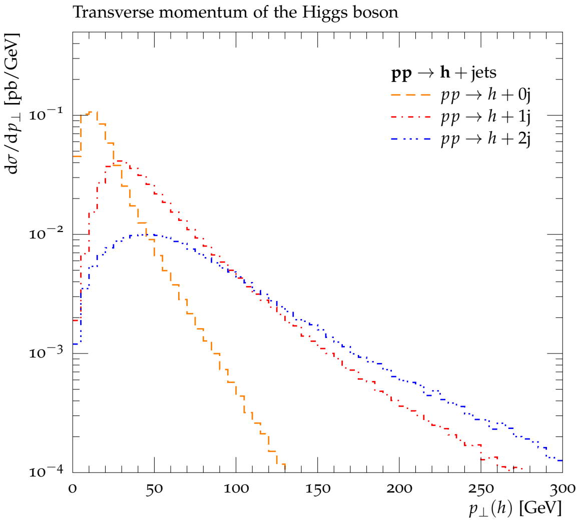

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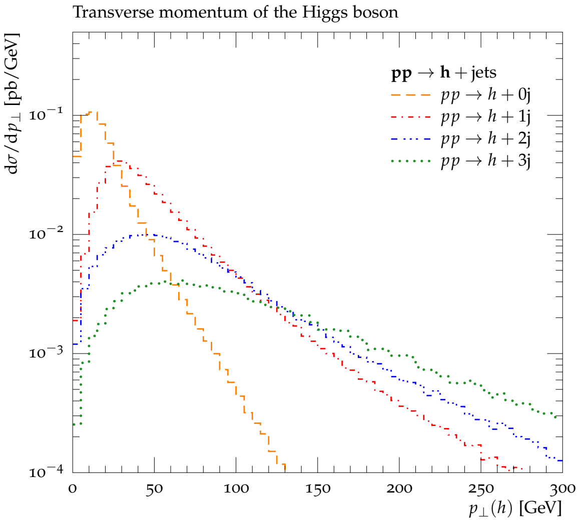

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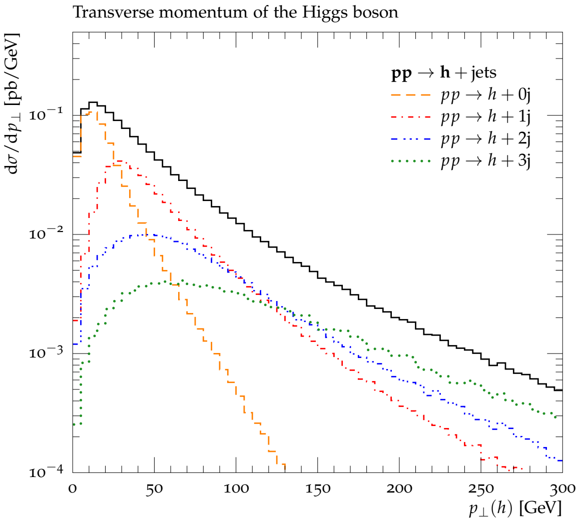

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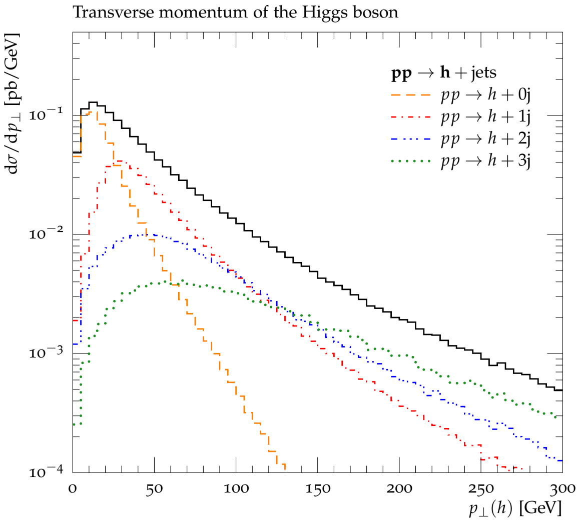

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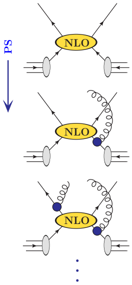
MePs@Nlo



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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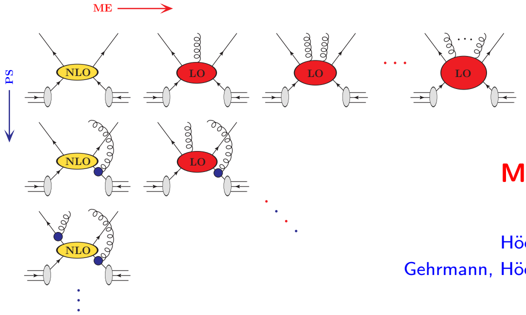

MeNloPs (CKKW-like)

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

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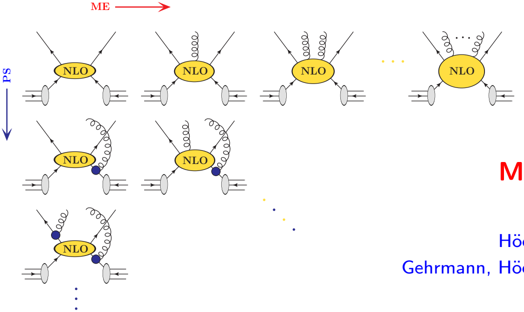

MEPS@NLO (CKKW-like)

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
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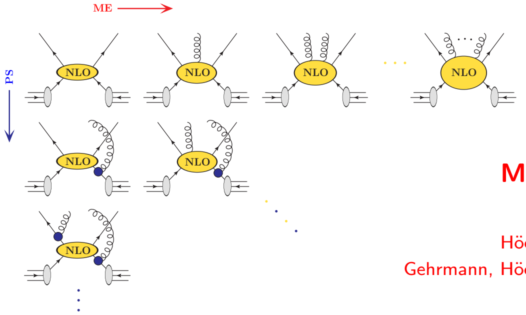

MePs@Nlo (CKKW-like)

Lavesson, Lönnblad JHEP12(2008)070
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- **MePs@Nlo combines multiple NloPs – keeping either accuracy**

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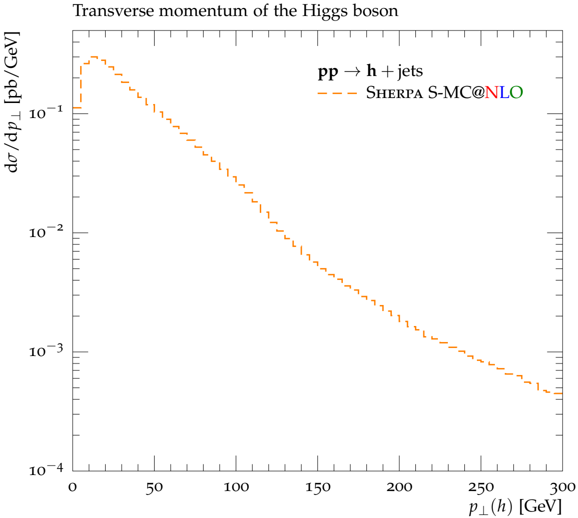

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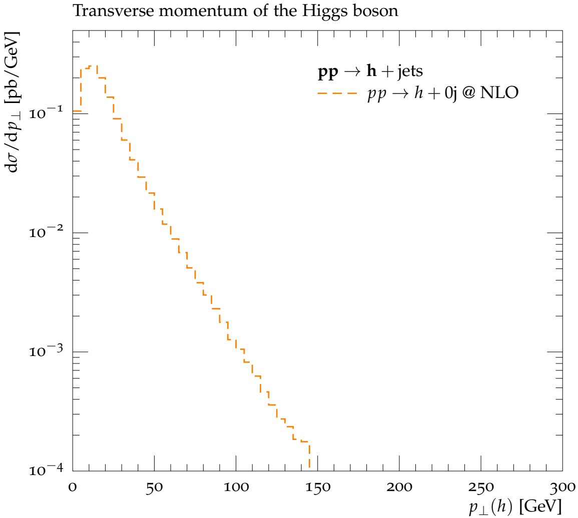

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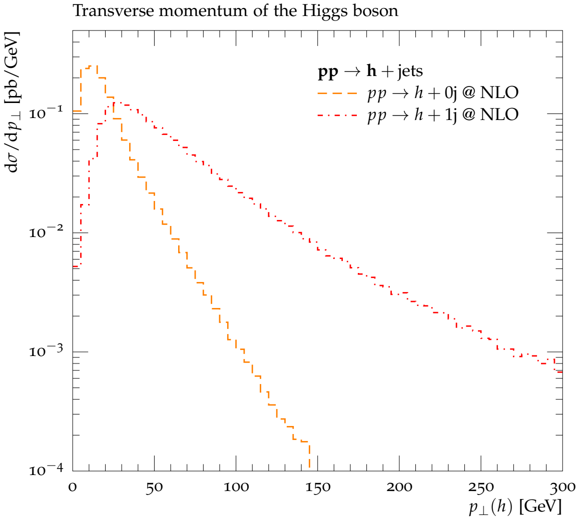

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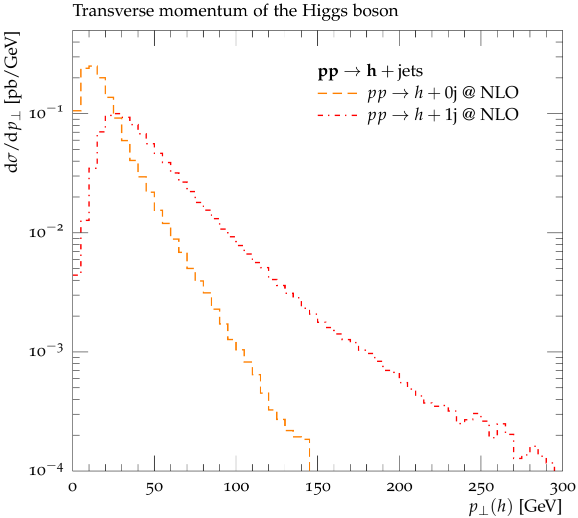

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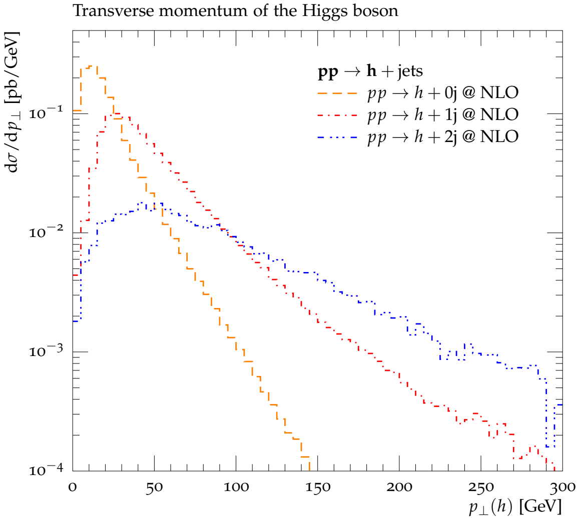

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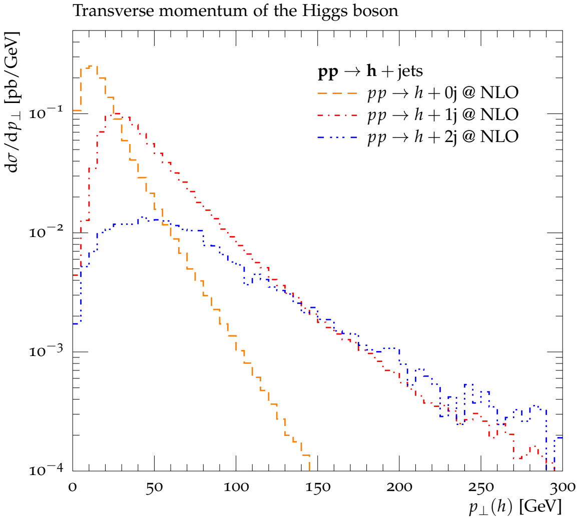

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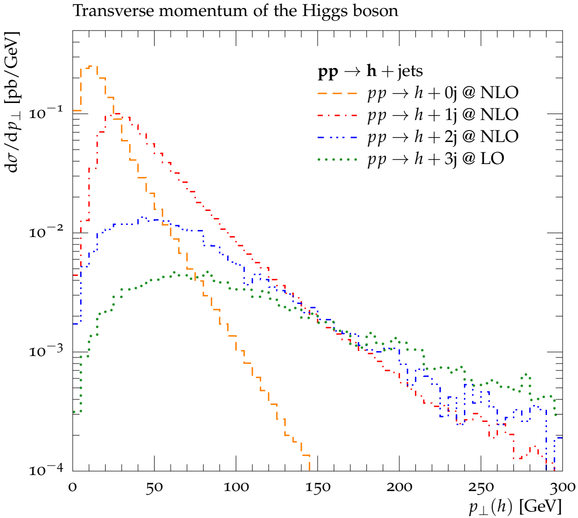

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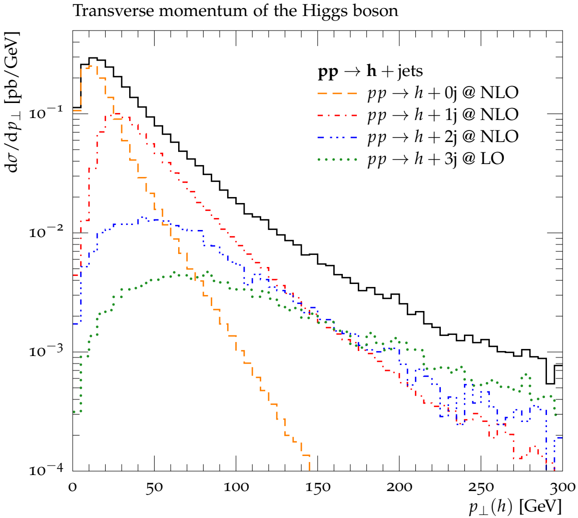

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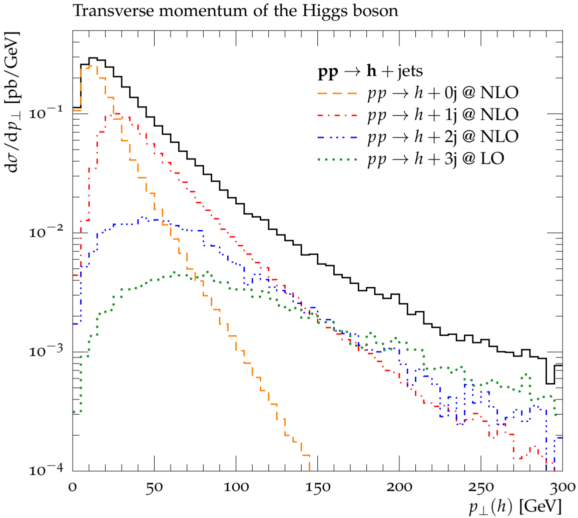

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Recent results in SHERPA

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 arXiv:1405.1067
- $p\bar{p} \to t\bar{t}+$ jets – SHERPA+GOSAM/OPENLOOPS

  Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040

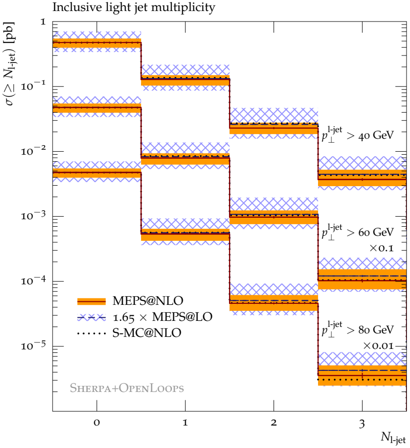
  Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert arXiv:1402.6293
- $pp \to 4\ell+$ jets – SHERPA+OPENLOOPS

  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 Phys.Rev.D89(2014)114006

$pp \to t\bar{t}$+jets

Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert in arXiv:1401.7971



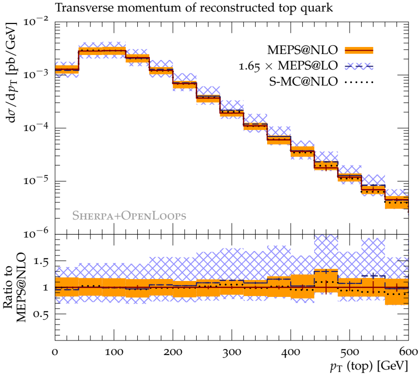
$pp \to t\bar{t}$+jets (0,1,2 @ NLO; 3 @ LO)

- scales:
  $$\alpha_s^{2+n}(\mu_R) = \alpha_s^2(\mu_{\text{core}}) \prod_{i=1}^{n} \alpha_s(t_i),$$
  $\mu_F = \mu_Q = \mu_{\text{core}}$ on $2 \to 2$
  $Q_{\text{cut}} = 30$ GeV

$$\mu_{\text{core}} = -\frac{2}{\frac{1}{p_0 p_1} + \frac{1}{p_0 p_2} + \frac{1}{p_0 p_3}}$$

- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_Q^{\text{def}}$
- $Q_{\text{cut}} \in \{20, 30, 40\}$ GeV
- spin-correlated dileptonic decays at LO accuracy

$pp \to t\bar{t}$+jets



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

Reconstructed top $p_\perp$

- again, shapes are stable
- noticable reduction in uncertainty
- inclusive observable, but large number of events with ≥1 jet necessitates mutlijet merging for best accuracy

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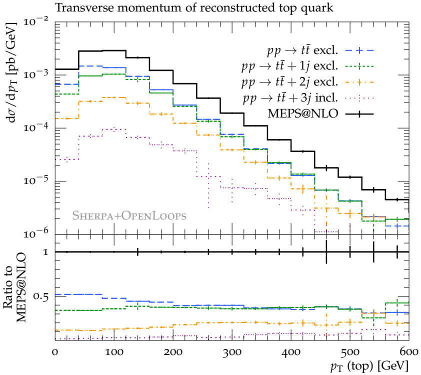

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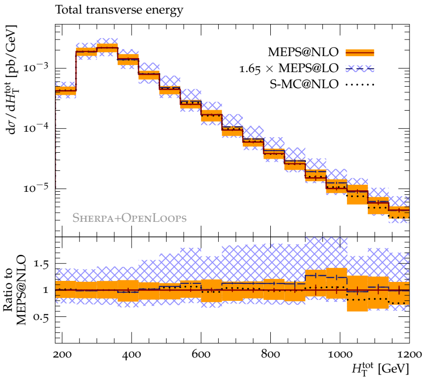


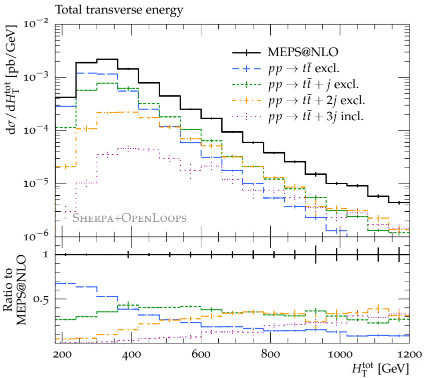
$pp \to t\bar{t}$+jets (0,1,2 @ NLO; 3 @ LO)

Total transverse energy

$$H_T^{tot} = \sum_{\text{b-jets}} p_\perp + \sum_{\text{l-jets}} p_\perp + \sum_{\text{lep}} p_\perp + E_T^{miss}$$

- relevant observable for new physics searches
- slight correction to MEPS shapes at high H_T^{tot}
- noticable reduction in uncert., especially at high H_T^{tot}
- inclusive observable, but dominated by configurations with different number of jets at successively higher H_T^{tot}

$\mathrm{pp} \to \mathrm{t\bar{t}}$+jets



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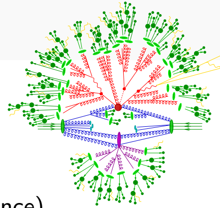
Jet properties



Jet production comprises contributions from all energy regimes:

- perturbative contributions
  - hard seed parton(s) $\rightarrow$ fixed order matrix elements
  - soft & collinear emissions (parton shower w/ colour coherence)
- non-perturbative contributions
  - (uncorrelated) contributions from additional partonic interactions
  - hadronisation and hadron decays

$\Rightarrow$ **small scale contributions especially important for intrajet observables**

- necessity to describe intrajet observables well to be useful in jet substructure analysis
- need to describe hard emissions well
  - recoil to produce boosted heavy particles (production xsecs/dists)
  - good chance they will end up in same fat jet (Q_{cut} usally $k_\perp$-type)

$\Rightarrow$ **multijet merging must preserve soft physics**

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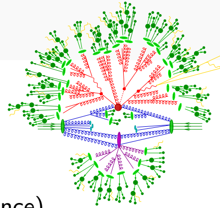

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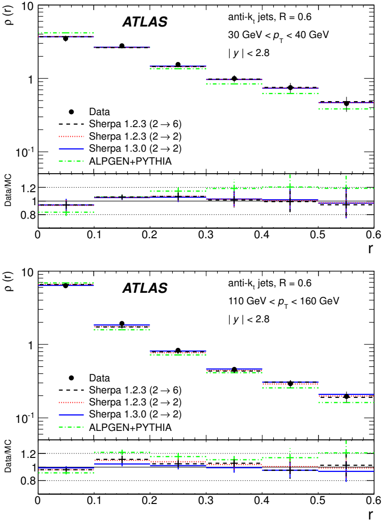
Jet shapes – differential jet shape $\rho(r)$

ATLAS collaboration Phys.Rev.D83(2011)052003, ATL-PHYS-PUB-2011-010



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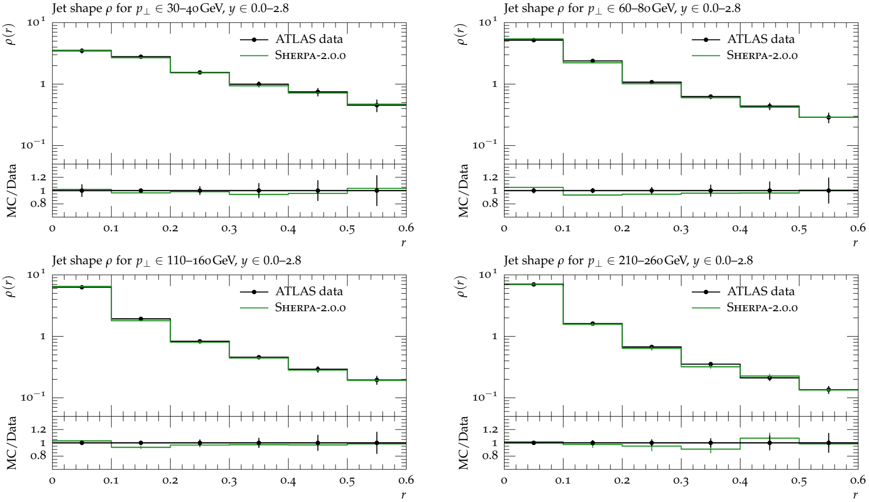
ATLAS data Phys.Rev.D83(2011)052003



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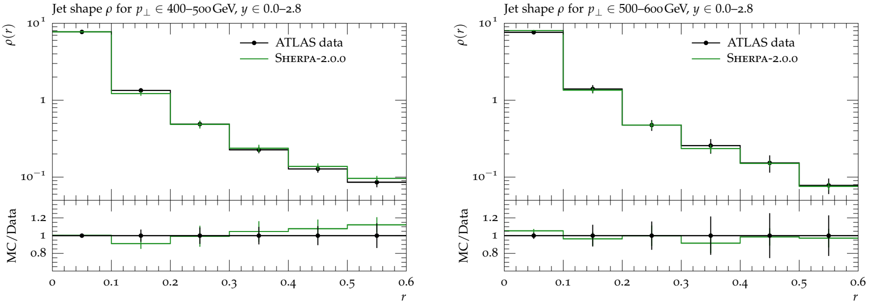
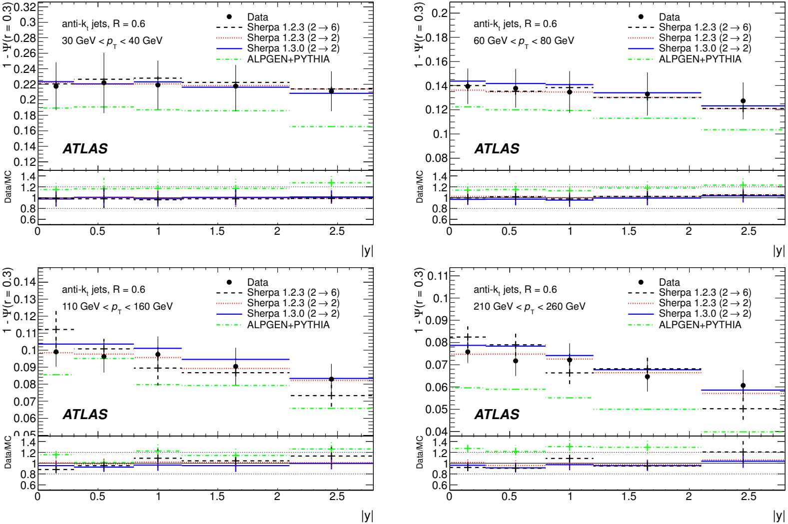


Jet shapes – integrated jet shape $1 - \Psi(r = 0.3)$

ATLAS collaboration Phys.Rev.D83(2011)052003, ATL-PHYS-PUB-2011-010



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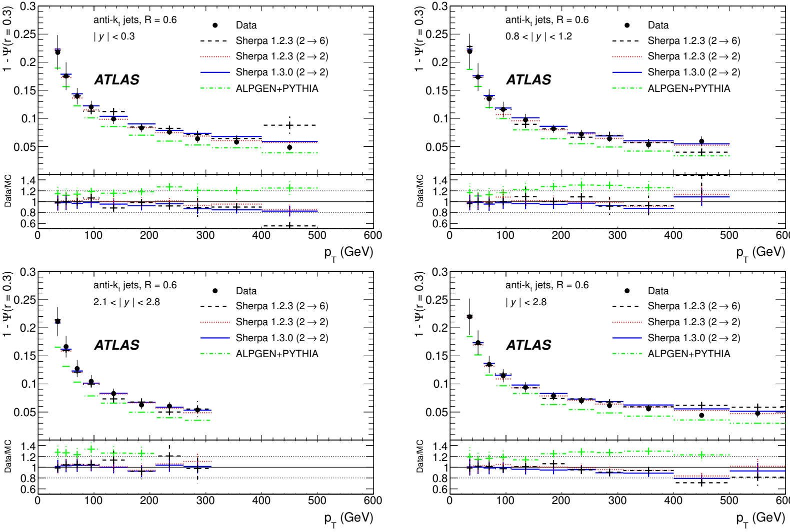

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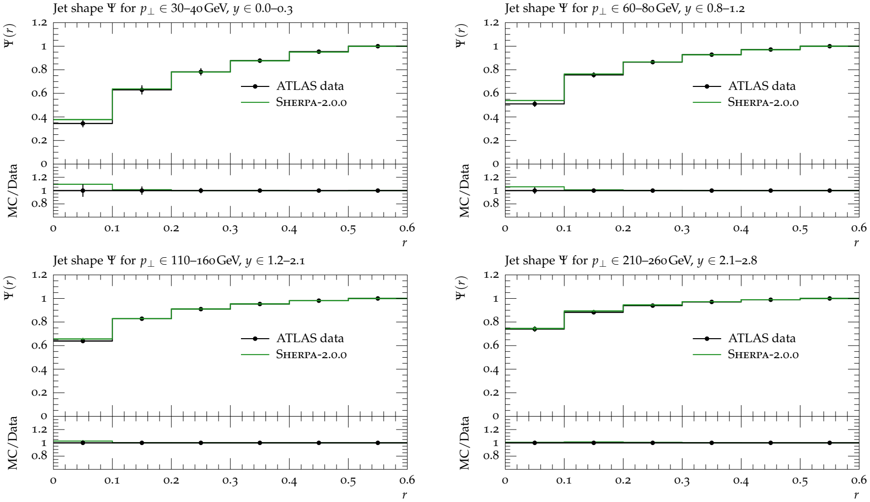

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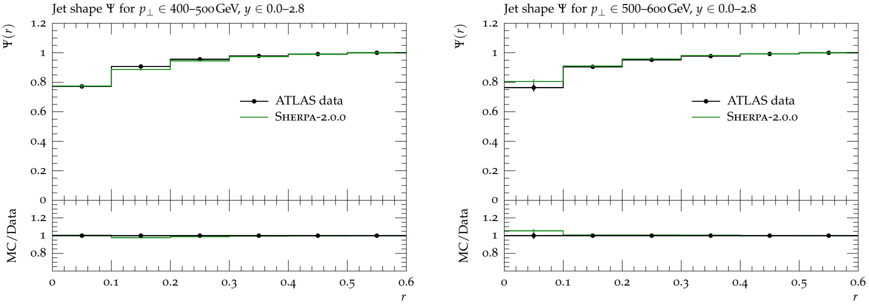
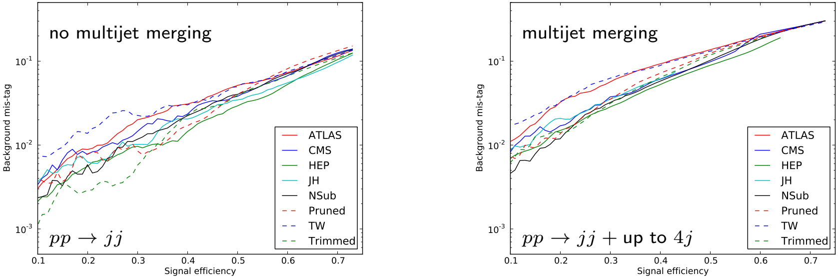


Jet substructure – background mis-tag rate

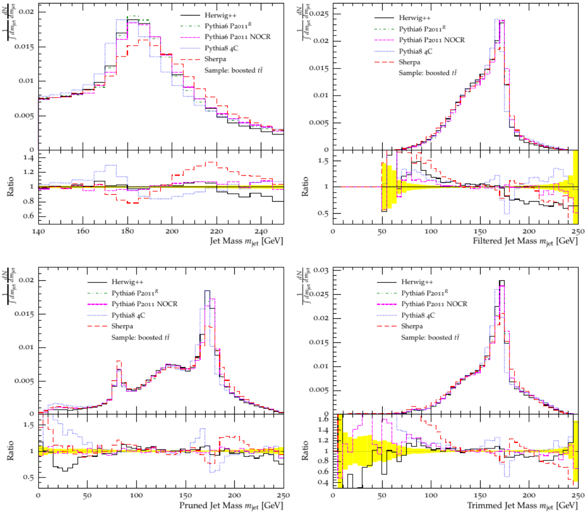
BOOST2011 arXiv:1201.0008

Multijet background mis-tag rate in $pp \to t\bar{t} +$ jets production



- need to properly describe additional hard radiation that can end up in the fat jet leading to large (sub-)jet masses
- otherwise mis-tag rates etc. underestimated

Jet substructure – signal observables



BOOST2012 arXiv:1311.2708

$pp \to t\bar{t} +$ jets production

- some observables very sensitive to additional hard radiation
- can be reduced by various techniques, but effects remain in tails

Conclusions

Multijet merging

- describes both hard radiation and intrajet evolution
  $\rightarrow$ reliable estimate of event yields
  $\rightarrow$ good description of jet substructure
- for large cone radii and/or high boosts partons of large relative $k_\perp$, Q_{ij}, etc. land in the fat jet
  $\rightarrow$ multijet merging must preserve resum. accuracy to describe these configs

$\Rightarrow$ tool of choice for boosted observables

- various formulations and implementations exist
- accuracy for hard emissions has recently been elevated to NLO
  accuracy for soft-collinear resummation remains at (N)LL

SHERPA: current release SHERPA-2.1.1

http://sherpa.hepforge.org

Thank you for your attention!

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:

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

- 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

MePs

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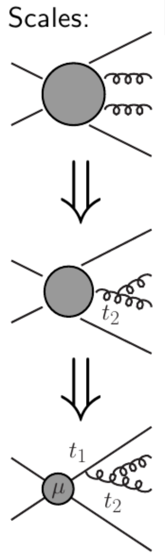

$$\alpha_s^{k+n}(\mu_{\text{R}}) = \alpha_s^k(\mu_{\text{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$$

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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:

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

- 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
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

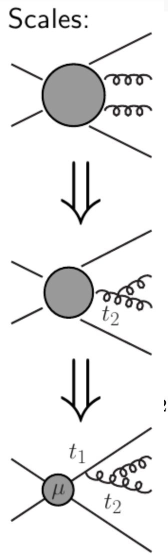
MePs@Nlo

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

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

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

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

MENLOPS

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

- 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}

$$
k_n(\Phi_{n+1}) = \frac{\bar{\mathrm{B}}_n\,(\Phi_n(\Phi_{n+1}))}{\mathrm{B}_n\,(\Phi_n(\Phi_{n+1}))}\left(1 - \frac{\mathrm{H}_n(\Phi_{n+1})}{\mathrm{R}_n(\Phi_{n+1})}\right) + \frac{\mathrm{H}_n(\Phi_{n+1})}{\mathrm{R}_n(\Phi_{n+1})}
$$

- iterate

Scale choices

CKKW scales

$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2)\,\alpha_s(t_1)\cdots\alpha_s(t_n) \qquad \mu_{F,a/b}^2 = t_{\text{ext},a/b} \qquad \mu_Q^2 = \mu_{\text{core}}^2$$

Free choices

1. μ_{core} – scale of core process identified through clustering with inverse parton shower
2. $\mu_{R/F}$ beyond 1-loop running
   - calculate with chosen $\mu_{R/F}$
   - include renormalisation and factorisation terms to shift the 1-loop running to above

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

   and

$$\mathrm{B}_n\,\frac{\alpha_s}{2\pi}\,\log\frac{\mu_F}{t_{\text{ext}}}\sum_{c=q,g}\int_{x_a}^{1}\frac{\mathrm{d}z}{z}\,P_{ac}(z)f_c(x_a/z,\mu_F^2)$$

$\rightarrow$ same as in UnLoPs Lönnblad, Prestel JHEP03(2013)166, Plätzer JHEP08(2013)114