NLOPS matching and multijet merging

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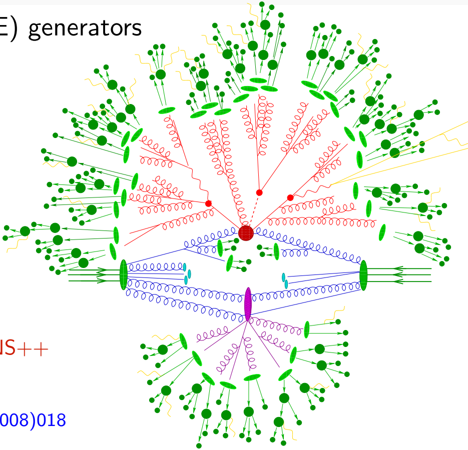
JHEP04(2013)027, JHEP01(2013)144
arXiv:1401.7971, arXiv:1402.6293, arXiv:1403.4788*

*in coll. with S. Höche, F. Krauss, P. Maierhöfer, S. Pozzorini, F. Siegert, J. Thompson, K. Zapp

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

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Importance of matching NLO calculations with parton showers

- exclusive final states
- observable independent combination of fixed order and resummation
- problem double counting: both NLO and PS are approximations to higher order corrections → MC@NLO and POWHEG

Importance of multijet merging

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

Uncertainties of NLOPS matching/MEPS@NLO merging

- usual μ_R and μ_F variation as in NLO calculations
- also μ_Q-variation as in analytic resummations

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Resummation properties of parton showers

$$\mathrm{d}\sigma^{\text{LoPs}} = \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left[\Delta^{(\mathcal{K})}(t_c,\mu_Q^2) + \sum_i \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1\,\mathcal{K}_i\,\Delta^{(\mathcal{K})}(t,\mu_Q^2)\right]$$

- 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

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

- 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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Resummation properties of parton showers

Choices:

- precise definition of evolution variable,
  only needs to behave as $\frac{\mathrm{d}t}{t} = \frac{\mathrm{d}p_\perp^2}{p_\perp^2}$ in the collinear limit
  $\to p_\perp^2$, θ, $\tilde{p}_\perp^2$, ...
- recoil scheme, only needs to be IR-safe
  $\to$ at most power corrections, but can be numerically sizeable
- power corrections and finite terms in splitting functions
  $\to$ (generalised) matrix element corrections
- α_s-running beyond 1-loop
  $\to$ fix 1-loop running to $\alpha_s(k_\perp)$ by counterterm
- $g \to q\bar{q}$ splittings have no LL, free to choose α_s-scale

$\Rightarrow$ **PS formulated probabilisticly, no simple reweighting to other choices**

NLOPs matching

- NLO calculation matched to shower-like resummation

$$\mathrm{d}\sigma^{\mathrm{NLOPs}} = \mathrm{d}\Phi_B \left[\mathrm{B} + \mathrm{V} + \sum_i \int \mathrm{d}\Phi_1^i \, \mathrm{D}_i^{(\mathrm{A})} \, \Theta(\mu_Q^2 - t) \right] + \mathrm{d}\Phi_R \left[\mathrm{R} - \sum_i \mathrm{D}_i^{(\mathrm{A})} \, \Theta(\mu_Q^2 - t) \right]$$

- introduce set of resummation kernels $\mathrm{D}_i^{(\mathrm{A})}$
  $\rightarrow$ needs to reproduce $N_c = 3$ IR limits
- modified shower resummation with

$$\Delta^{(\mathrm{A})}(t, t') = \sum_i \int_t^{t'} \mathrm{d}\Phi_1 \frac{\mathrm{D}_i^{(\mathrm{A})}}{\mathrm{B}}$$

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NLOPs matching

POWHEG (e.g. in POWHEG-BOX, HERWIG++, SHERPA-1.3.x):

- $\mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot R$, $\mu_Q^2 = \frac{1}{2}\, s_{\mathsf{had}}$ Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070
- modify kernels by $f(p_\perp) = h^2/(p_\perp^2 + h^2)$ to emulate an upper limit on resummation phase space Alioli et.al. JHEP04(2009)002

MC@NLO (traditional scheme, e.g. in MC@NLO, aMC@NLO):

- $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{B} \cdot \mathcal{K}_i$, $\mu_Q^2 = t_{\mathsf{max}}$ Frixione, Webber JHEP06(2002)029
- modify soft limit by suitable $f(p_\perp)$ such that $N_c = 3$ limit reproduced Frixione, Nason, Webber JHEP08(2003)007

S-MC@NLO ($N_c = 3$-PS step, e.g. in SHERPA-1.4.x/2.x.y):

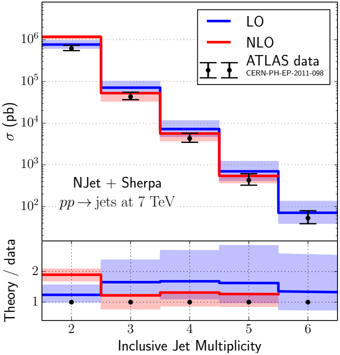
- $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$, $\mu_Q^2 = t_{\mathsf{max}}$ Höche, Krauss, MS, Siegert JHEP09(2012)049
- necessitates weighted shower as $\mathrm{D}_i^{(\mathsf{A})}$ not positive definite

Case study: Inclusive jet & dijet production

Badger, Biedermann, Uwer, Yundin Phys.Rev.D89(2014)034019

NLO:

- poor description in phase space regions with strongly hierarchical scales
- poor perturbative jet-modeling (at most two constituents)
- no hadronisation, MPI effects
- jet-$p_\perp$ turn negative in forward region unless y-dependent scale is used (e.g. $H_T^{(y)}$)



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≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	559(5)	$1193(3)^{+130}_{-135}$	0.95(0.02)	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	39.7(0.9)	$54.5(0.5)^{+2.2}_{-19.9}$	0.92(0.04)	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	3.97(0.08)	$5.54(0.12)^{+0.08}_{-2.44}$	0.92(0.05)	$5.11(0.29)^{+0.08}_{-2.32}$

Bern et.al. Phys.Rev.Lett.109(2012)042001

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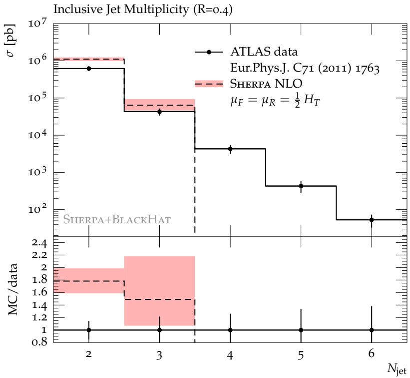

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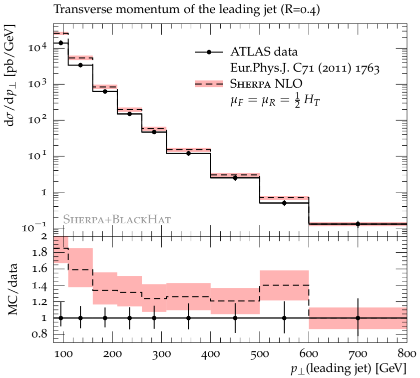

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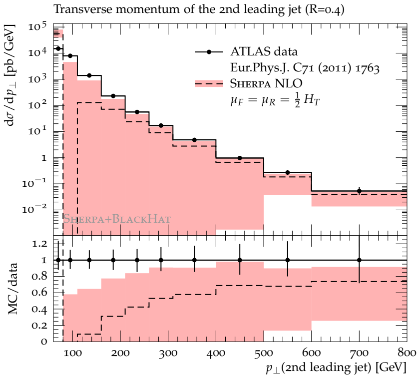

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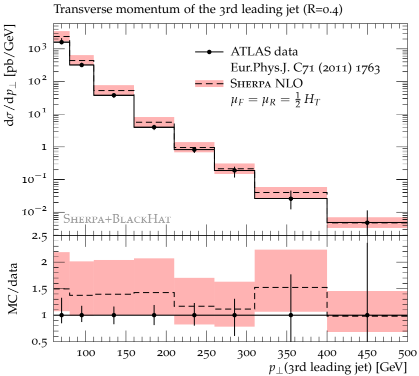

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Bern et.al. Phys.Rev.Lett.109(2012)042001

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

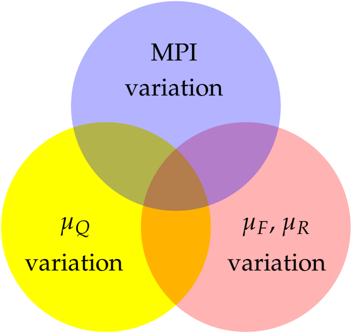
MC@NLO di-jet production:

Höche, MS Phys.Rev.D86(2012)094042

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

Uncertainty estimates:

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



Case study: Inclusive jet & dijet production

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

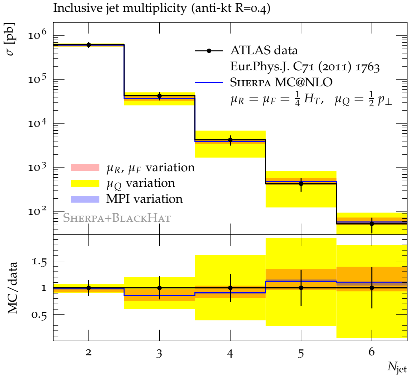
MC@NLO di-jet production:

Höche, MS Phys.Rev.D86(2012)094042

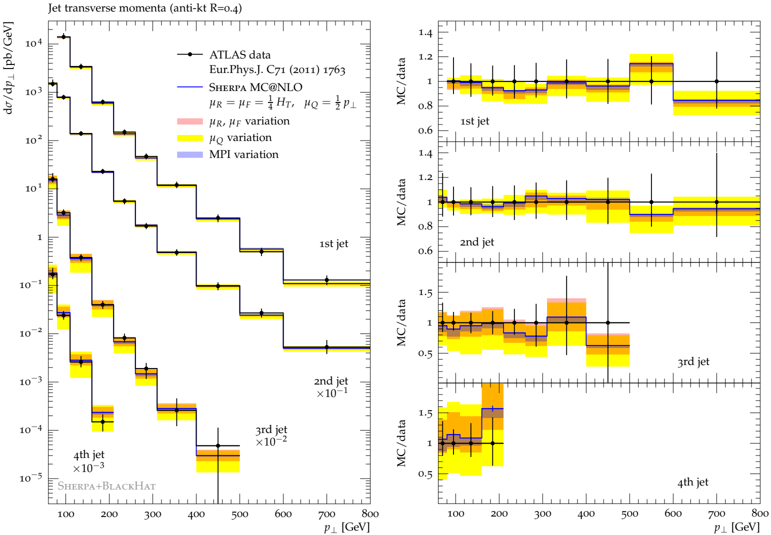
- $\mu_{R/F} = \frac{1}{4}\,H_T$, $\mu_Q = \frac{1}{2}\,p_\perp$
- CT10 PDF ($\alpha_s(m_Z) = 0.118$)
- hadron level calculation, MPI
- virtual MEs from BlackHat
  Giele, Glover, Kosower Nucl.Phys.B403(1993)633-670
  Bern et.al. arXiv:1112.3940
- $p_\perp^{j_1} > 20$ GeV, $p_\perp^{j_2} > 10$ GeV

Uncertainty estimates:

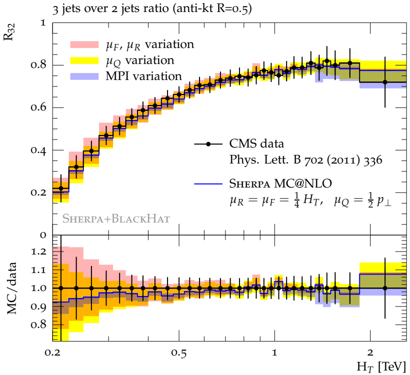
- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_Q^{\text{def}}$
- MPI activity in tr. region $\pm$ 10%



Case study: Inclusive jet & dijet production



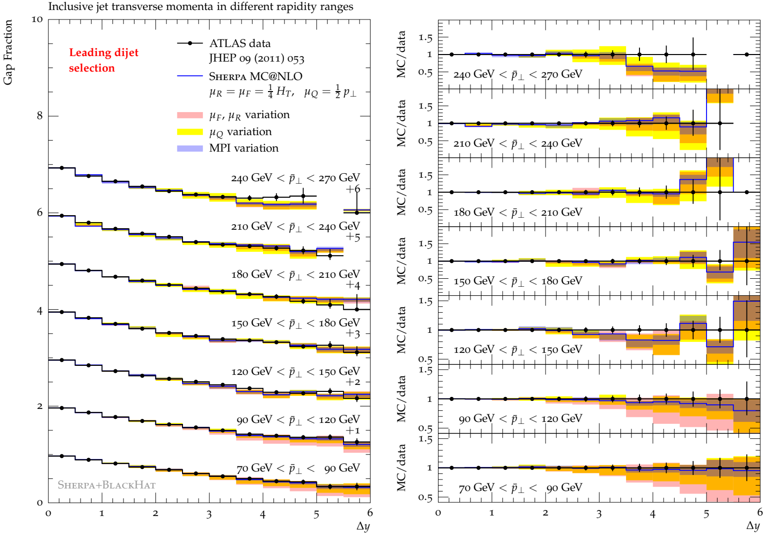
Case study: Inclusive jet & dijet production



3-jet-over-2-jet ratio

- determined from incl. sample
  2-jet rate at NLO+NLL
  3-jet rate at LO+LL
- common scale choices
  $\rightarrow$ varied simultaneously
- at large H_T large MPI uncertainties
  $\rightarrow$ better MPI physics needed (soft QCD)
- similar description of related ATLAS observables

Case study: Inclusive jet & dijet production



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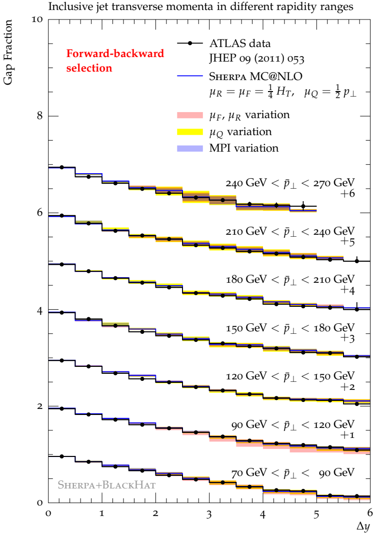
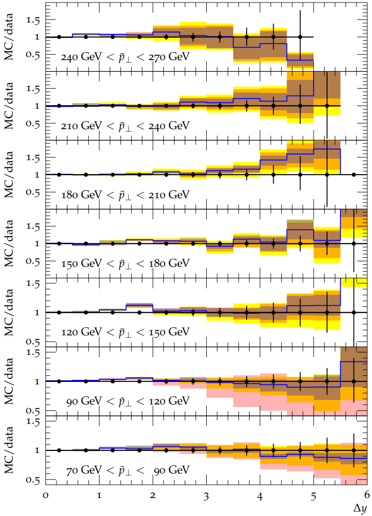




Recent results

Fixed-mulitplicity NLOPS (S-MC@NLO)

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

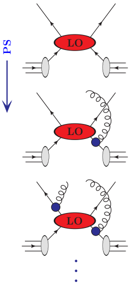
  Höche, Krauss, MS, Siegert Phys.Rev.Lett.110(2013)052001
- $pp \to$ jets – SHERPA+BLACKHAT Höche, MS Phys.Rev.D86(2012)094042
- $pp \to t\bar{t}b\bar{b}$ – SHERPA+OPENLOOPS

  Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.0500
- $pp \to t\bar{t}H$ – SHERPA+TTH

  S. Höche, L. Reina contribution to YR3 arXiv:1307.1347

Contents

MEPs

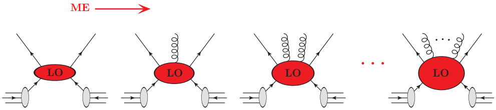


Parton showers

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
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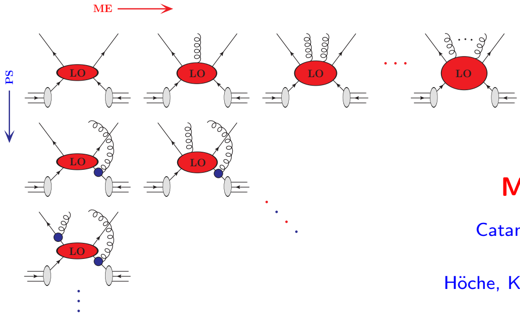
MEPs



MEPs (CKKW,MLM)

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

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MEPs

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

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

Multijet merging at leading order:

$$\mathrm{d}\sigma^{\text{MEPs}} = \mathrm{d}\sigma_n^{\text{LO}} \ldots$$

[illegible]

- 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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Multijet merging at leading order:

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

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$$+ \mathrm{d}\sigma_{n+2}^{\mathsf{LO}}\, \Theta(Q_{n+2} - Q_{\mathsf{cut}})\, \Delta_n(t_{n+1}, t_n)\, \Delta_{n+1}(t_{n+2}, t_{n+1}) \otimes \mathsf{PS}_{n+2}$$

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MEPS

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

Multijet merging at leading order:

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MEPs

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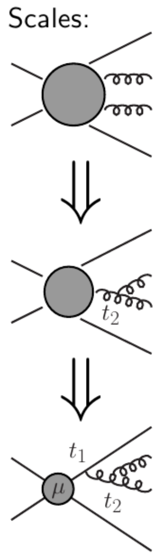

$$\alpha_s^{k+n}(\mu_{\mathsf{R}}) = \alpha_s^k(\mu_{\mathsf{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$$

MEPs

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

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

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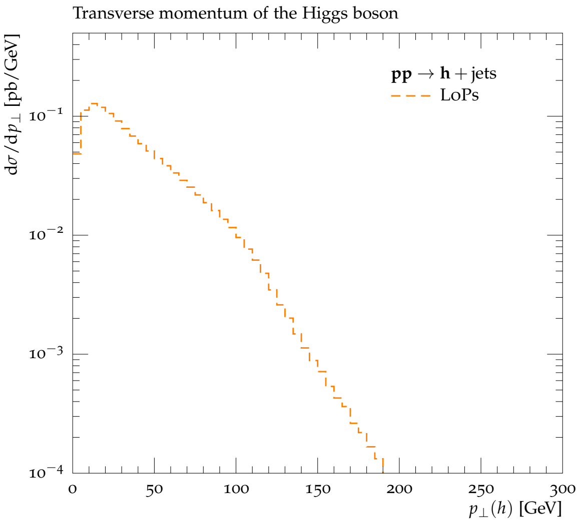
MEPs



- 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 $Q_{n+2} < Q_{\text{cut}}$
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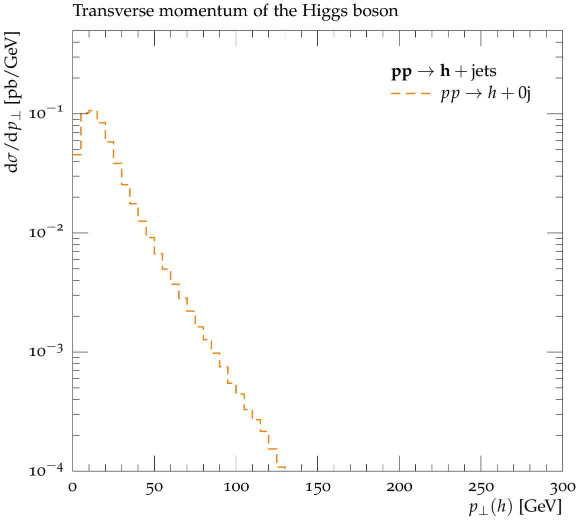
- iterate
- sum all contributions

MePs



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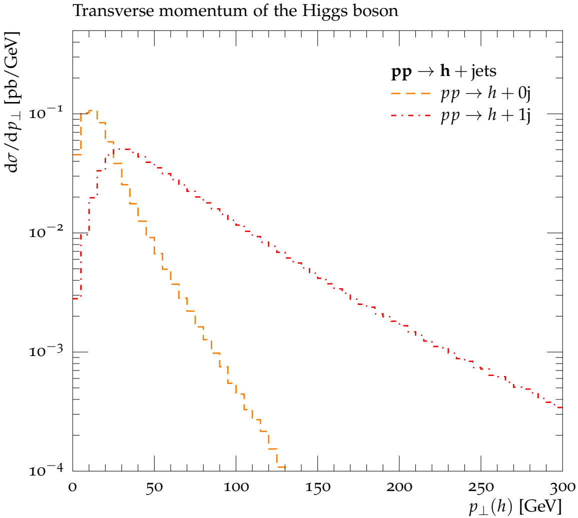

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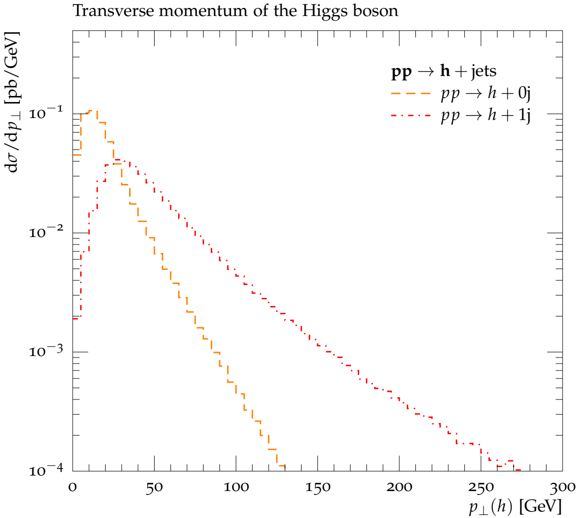

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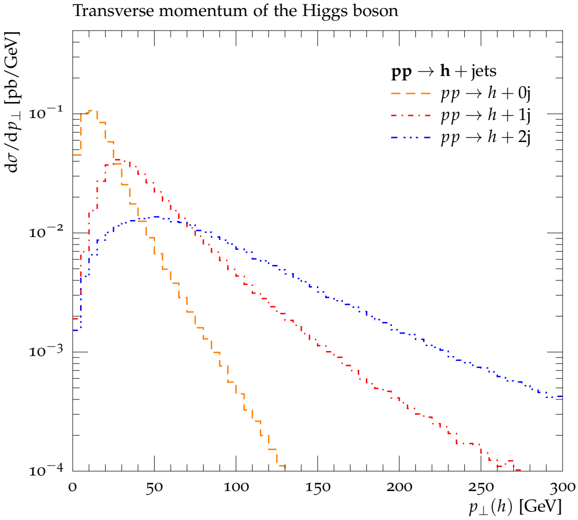
MEPS



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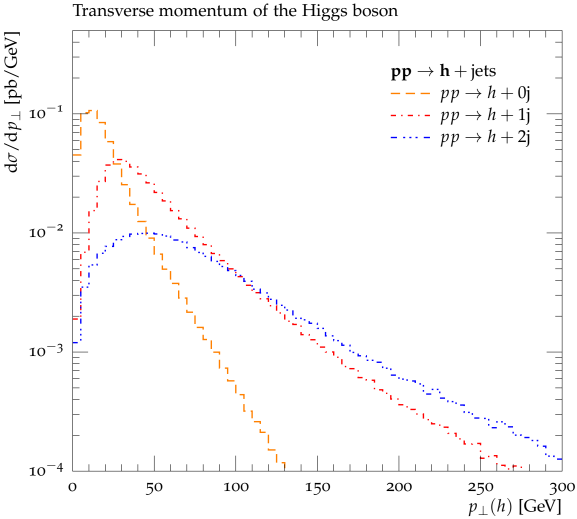

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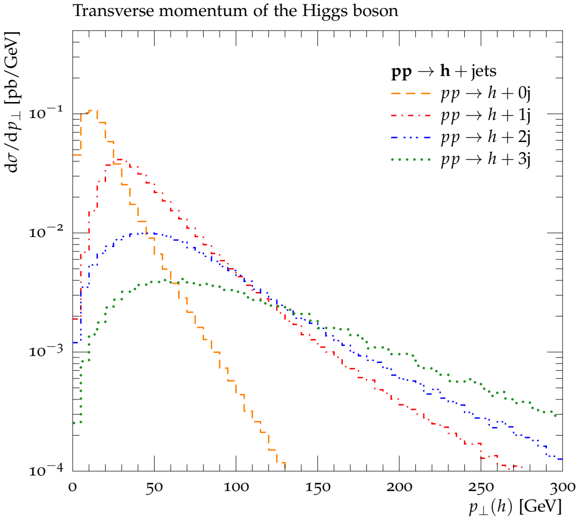

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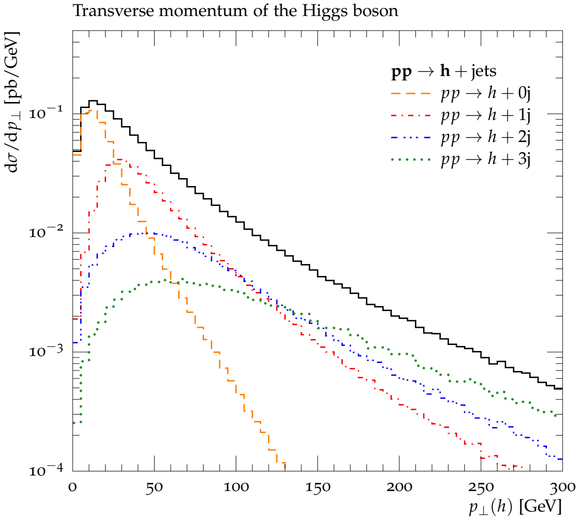

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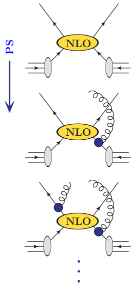
MEPS@NLO



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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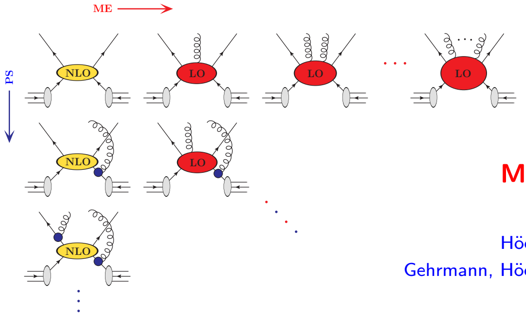
MEPS@NLO



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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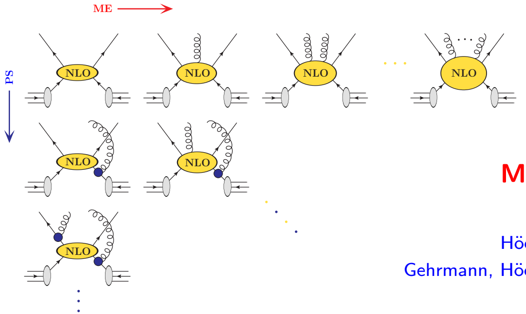
MePs@Nlo



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
Plätzer JHEP08(2013)114

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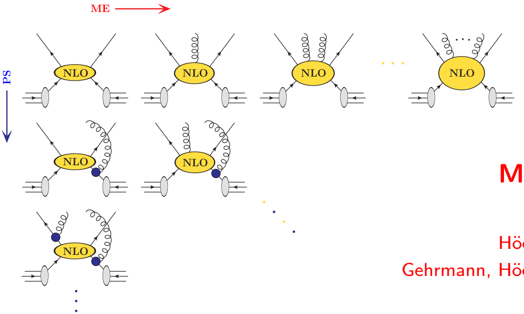
- MePs combines multiple LoPs – keeping either accuracy
- NLoPs elevate LoPs to NLO accuracy
- MeNLoPs supplements core NLoPs with higher multiplicities LoPs
- MePs@Nlo combines multiple NLoPs – keeping either accuracy

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
Plätzer JHEP08(2013)114

- 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.):

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

Multijet merging at next-to-leading order:

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

- 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.):

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

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

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$$\times \left(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_{n+1})\right) \otimes \widetilde{\mathrm{PS}}_{n+2}$$

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- 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 limits for 1st em.):

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

Multijet merging at next-to-leading order:

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

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

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

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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}}) \left(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}(t_{n+1}, t_n) \right) \\
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- 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 limits for 1st em.):

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

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MEPS@NLO

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

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

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}) \\
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&\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) \\
&\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}
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- add the NLOPS for $2 \to n+1$
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- 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 limits for 1st em.):

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

Multijet merging at next-to-leading order:

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

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

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

Multijet merging at next-to-leading order:

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

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

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

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

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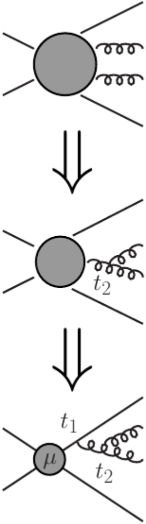
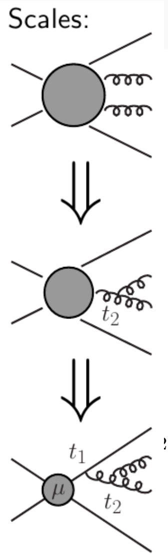
- multiply by Sudakov wrt. $2 \to n$ process to restore resumma
- remove overlap of Δ_n and $\mathrm{d}\sigma_{n+1}^{\text{NLO}}$, iterate

Scales:



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

MEPS@NLO



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

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

Multijet merging at next-to-leading order:

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

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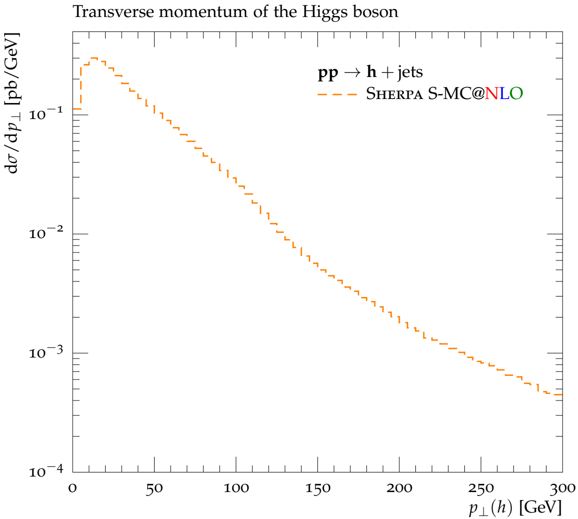
$$\times \Big(\Delta_{n+1}(t_{n+2}, t_{n+1}) - \Delta_{n+1}^{(1)}(t_{n+2}, t_n$$

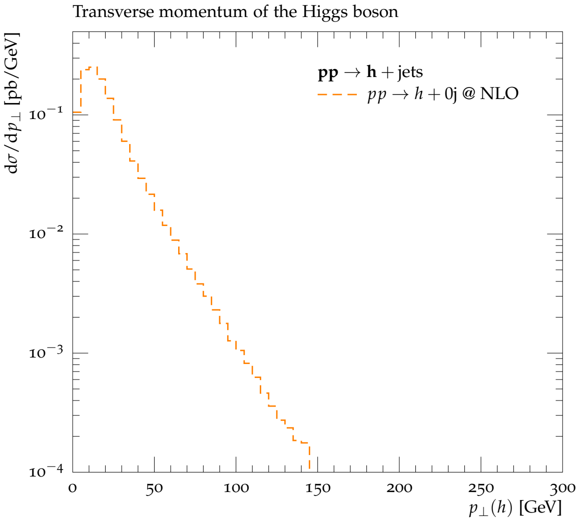
- NLOPS for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPS for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resumma…
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

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



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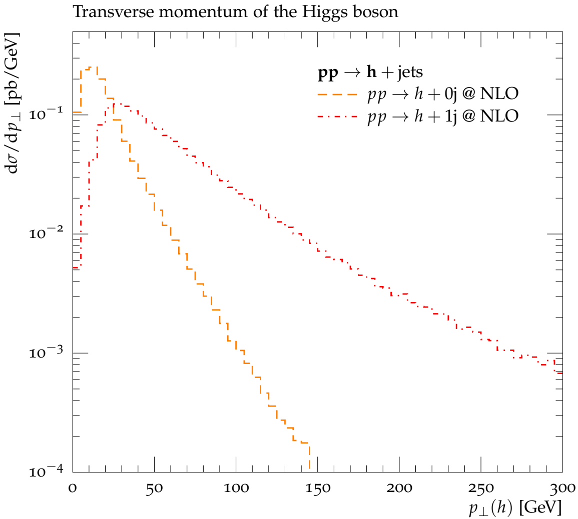
MEPS@NLO



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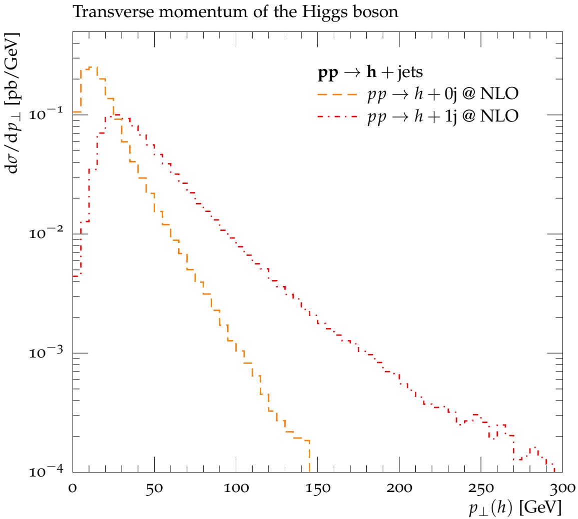
MEPS@NLO



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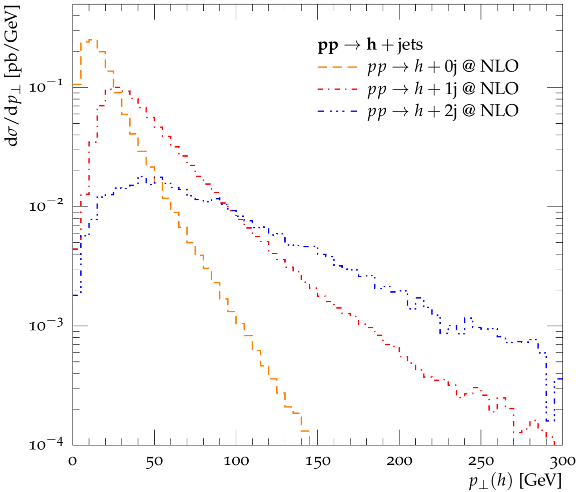
MEPS@NLO

Transverse momentum of the Higgs boson



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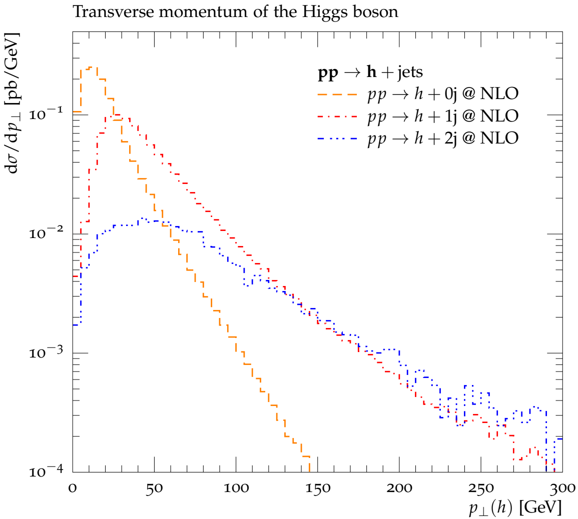
- sum all contributions

MEPS@NLO



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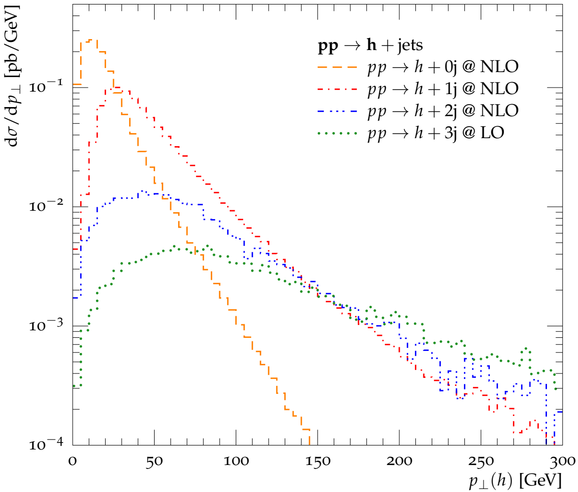
MEPs@NLO

Transverse momentum of the Higgs boson



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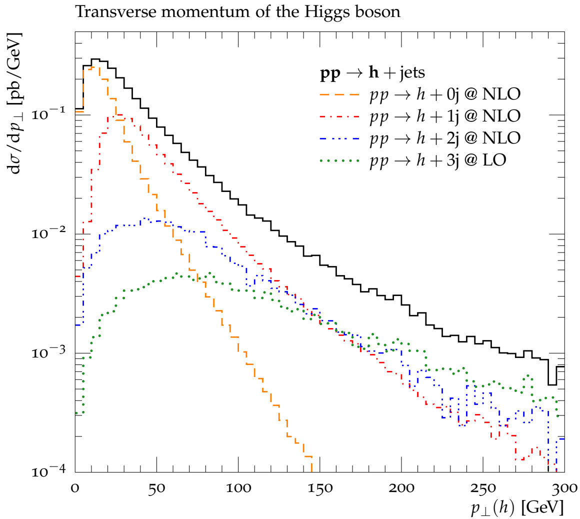
MEPS@NLO



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- NLOPS $pp \to h +$ 2jets for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions

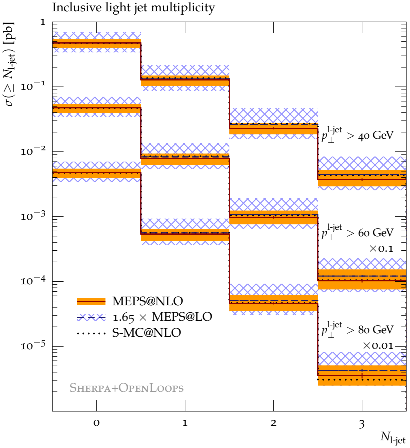
Recent results

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 → $t\bar{t}$+jets

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



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

- scales:

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

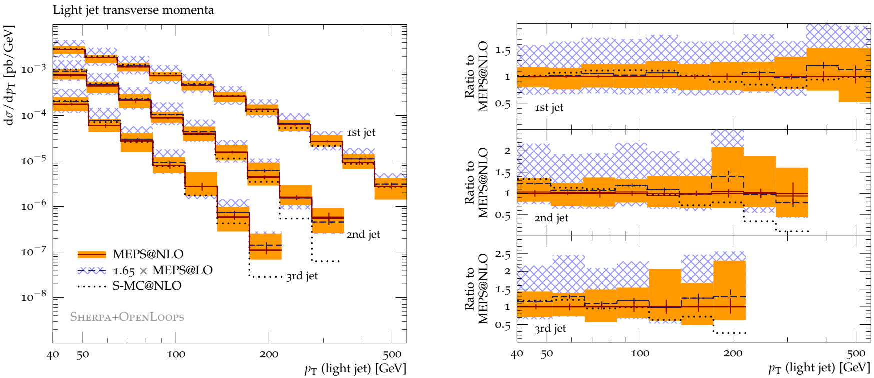
  $\mu_F = \mu_Q = \mu_{\text{core}}$ on $2 \to 2$

  $Q_{\text{cut}} = 30$ GeV

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

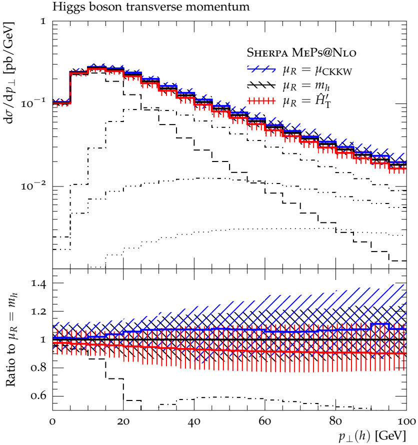
- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{R/F}^{\text{def}}$
- $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_Q^{\text{def}}$
- $Q_{\text{cut}} \in \{20, 30, 40\}$ GeV

Results – pp → $t\bar{t}$+jets



- Shapes are stable
- Uncertainties are much smaller where higher accuracy is employed

Results – pp → h+jets

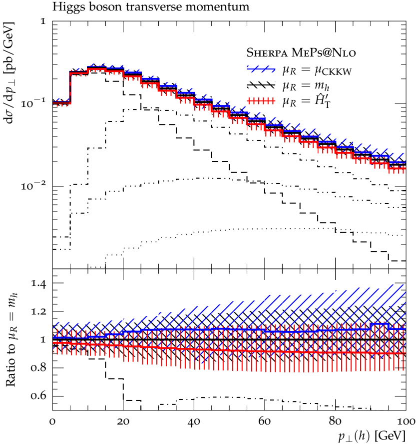


Höche, Krauss, MS, in arXiv:1401.7971

$pp \to h$+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
- 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. $\mu_R = \hat{H}'_T$

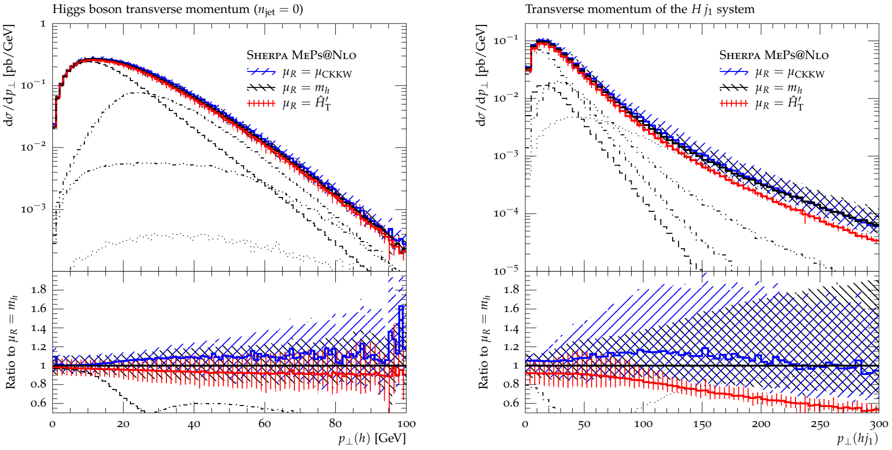
need to include ren. term

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

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

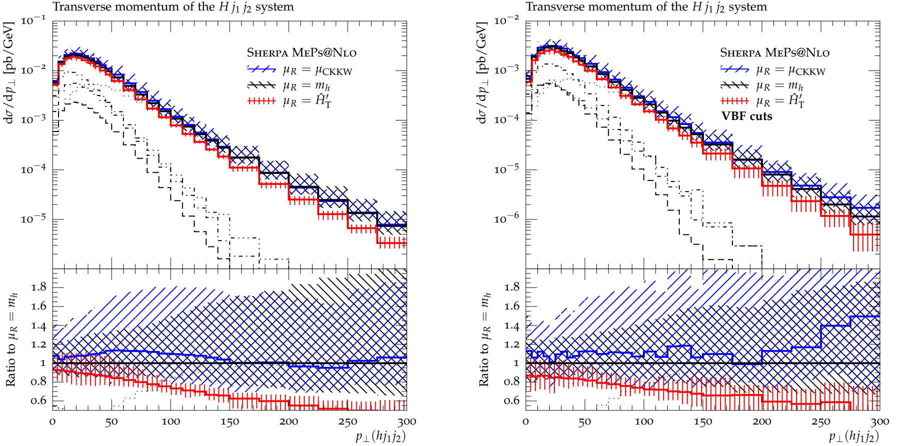
→ same as in UNLOPS approach
Lönnblad, Prestel JHEP03(2013)166
Plätzer JHEP08(2013)114

Results – pp → h+jets



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

Results – pp → h+jets



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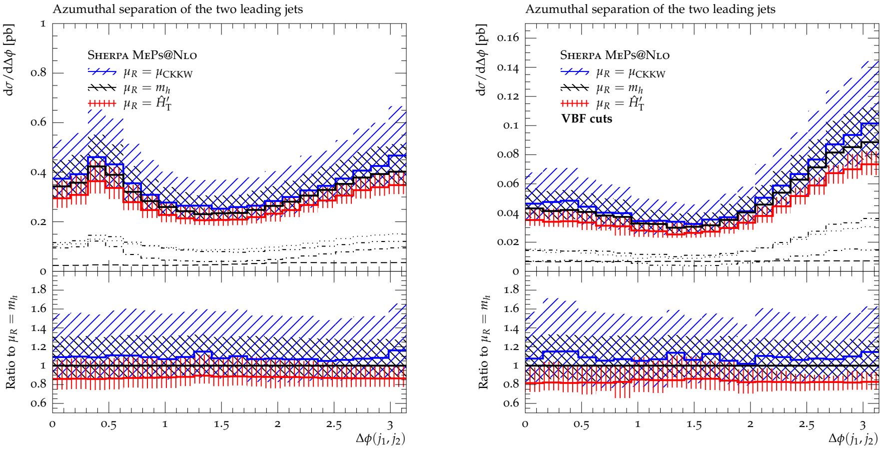

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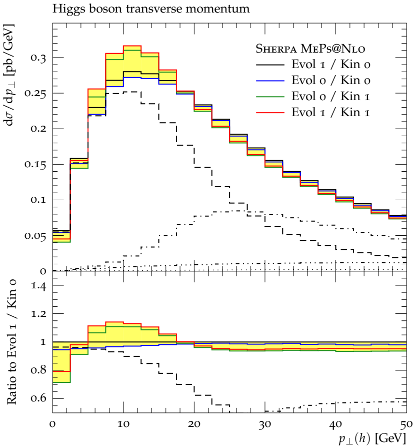


Parton shower uncertainties

- evolution scale

	Final State
0	$2\,p_ip_j\,\tilde{z}_{i,jk}(1-\tilde{z}_{i,jk})$
1	$2\,p_ip_j \begin{cases} \tilde{z}_{i,jk}(1-\tilde{z}_{i,jk}) & \text{if } i,j=g \\ 1-\tilde{z}_{i,jk} & \text{if } j=g \\ \tilde{z}_{i,jk} & \text{if } i=g \\ 1 & \text{else} \end{cases}$
	Initial State
0	$2\,p_ap_j\,(1-x_{aj,k})$
1	$2\,p_ap_j \begin{cases} 1-x_{aj,k} & \text{if } j=g \\ 1 & \text{else} \end{cases}$

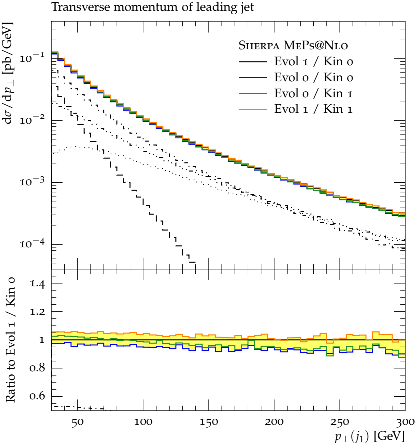
- recoil scheme

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
Schumann, Krauss JHEP03(2008)038

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

Results – pp → h+jets



Parton shower uncertainties

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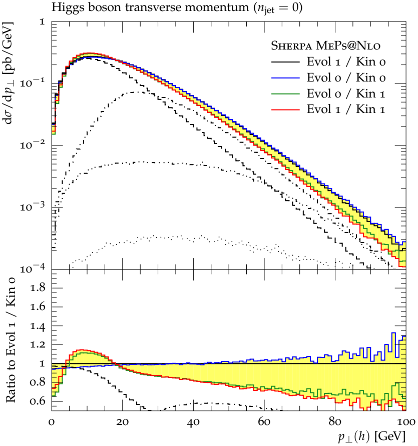

Parton shower uncertainties

- evolution scale

	Final State
0	$2\,p_ip_j\,\tilde{z}_{i,jk}(1-\tilde{z}_{i,jk})$
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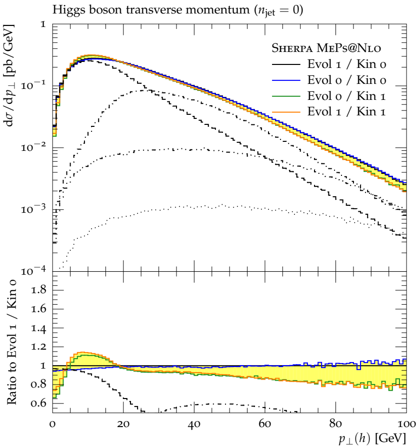

Parton shower uncertainties

- evolution scale

	Final State
0	$2\,p_ip_j\,\tilde{z}_{i,jk}(1-\tilde{z}_{i,jk})$
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→ similar ideas in Gieseke, Plätzer JHEP01(2011)024

Results – Trilepton production

Höche, Krauss, Pozzorini, MS, Thompson, Zapp arXiv:1403.4788

- trilepton (e, μ) production analysis in VH search regions
  $\rightarrow$ focus on theoretical uncertainties
- model all signal and background processes with consistent setup at largest available accuracy at particle level
  $\rightarrow$ need to describe lepton isolation and jet veto efficiency simultaneously
- produce bosons on shell, model off-shell effects through Breit-Wigner smearing
  $\rightarrow$ QCD/QED corrections to intermediate states and decay products
- most important event selection criteria

	CMS-inspired analysis	ATLAS-inspired analysis
Z veto	$\lvert m_Z - m_{\text{SFOS}}\rvert > 25$ GeV	no SFOS
jet veto	$p_\perp^{\text{jet}} < 40$ GeV	$p_\perp^{\text{jet}} < 20$ GeV

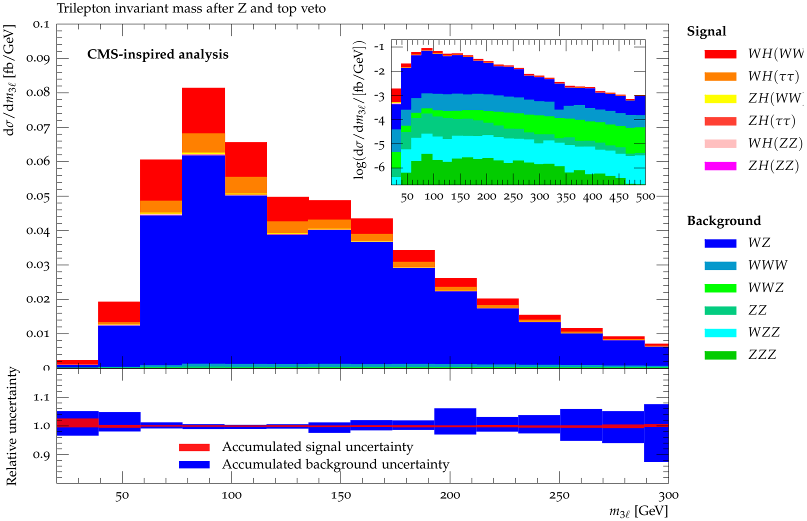
- include $V \rightarrow \tau \rightarrow e, \mu$ decay chains and possibilities to "loose" leptons
- separate $VVVj(j)$ from tVV and $t\bar{t}W$ by disallowing final state b-quarks

Results – Trilepton production

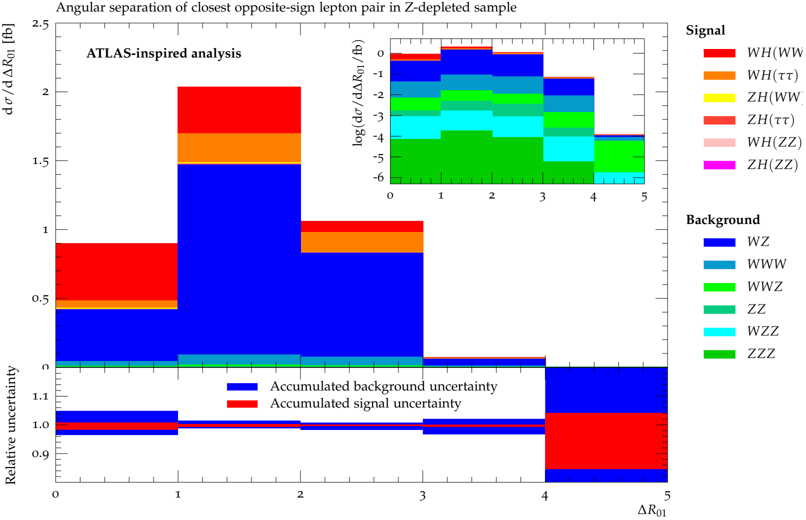
Höche, Krauss, Pozzorini, MS, Thompson, Zapp arXiv:1403.4788

Process	Accuracy	Decays ($\ell = e, \mu, \tau$)
WH+jets	0,1j@NLO, 2j@LO	$H \to WW$, $W \to \ell\nu$, $Z \to \ell\ell$, $\tau \to \ell\nu\nu$
		$H \to \tau\tau$, $W \to \ell\nu$, $Z \to \ell\ell$, $\tau \to \ell\nu\nu$
		$H \to ZZ$, $W \to$ all, $Z \to$ all, $\tau \to$ all
ZH+jets	0,1j@NLO, 2j@LO	$H \to WW$, $W \to$ all, $Z \to \ell\ell$, $\tau \to$ all
		$H \to \tau\tau$, $Z \to \ell\ell$, $\tau \to$ all
		$H \to ZZ$, $Z \to$ all, $\tau \to$ all
WZ+jets	0,1j@NLO, 2j@LO	$W \to \ell\nu$, $Z \to \ell\ell$, $\tau \to \ell\nu\nu$
WWW+jets	0,1j@NLO, 2j@LO	$W \to \ell\nu$, $\tau \to \ell\nu\nu$
WWZ+jets	0j@NLO, 1,2j@LO	$W \to$ all, $Z \to \ell\ell$, $\tau \to$ all
ZZ+jets	0j@NLO, 1,2j@LO	$Z \to \ell\ell$, $\tau \to$ all
WZZ+jets	0j@NLO, 1,2j@LO	$W \to$ all, $Z \to$ all, $\tau \to$ all
ZZZ+jets	0j@NLO, 1,2j@LO	$W \to$ all, $Z \to$ all, $\tau \to$ all

Results – Trilepton production



Results – Trilepton production



Conclusions

- NLOPS matching is dependent on specifics of resummation
  $\rightarrow$ choose resummation kernels and μ_Q^2
- 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
- full uncertainty evalution (perturbative and non-perturbative) in controlled environment feasible
- includes spin correlated $1 \rightarrow 2$ and $1 \rightarrow 3$ decays, with intermediate parton showering and QED corrections

current release SHERPA-2.1.0

http://sherpa.hepforge.org

Thank you for your attention!

MENLOPS

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

- 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}

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

- iterate

MENLOPS

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

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$$

- iterate

General NLO calculations

- NLO calculation with subtraction methods

Frixione, Kunszt, Signer Nucl.Phys.B467(1996)399-442
Catani, Seymour Nucl.Phys.B485(1997)291-419

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

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

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

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

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$$+ \sum_i \int \mathrm{d}\Phi_{B_i} \mathrm{d}\Phi_1^i \Big[\mathrm{D}_i^{(\mathsf{A})}(\Phi_{B_i},\Phi_1^i) - \mathrm{D}_i^{(\mathsf{S})}(\Phi_{B_i},\Phi_1^i)\Big]\, O(\Phi_{B_i})$$
$$+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\text{corr}}$$

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- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit

General NLO calculations

- NLO calculation with subtraction methods

Frixione, Kunszt, Signer Nucl.Phys.B467(1996)399-442
Catani, Seymour Nucl.Phys.B485(1997)291-419

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

- introduce second set of resummation kernels $\mathrm{D}_i^{(\mathrm{A})}$
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$$\langle O\rangle^{\mathsf{NLO}} = \int \mathrm{d}\Phi_B \;\; \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B) \;\; O(\Phi_B)$$

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

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NLOPS matching

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

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

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

- Sudakov form factor $\Delta^{(\mathcal{K})}(t,t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1\, \mathcal{K}(\Phi_1)\right]$ contains resummation features
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$$= \int \mathrm{d}\Phi_B\, \mathrm{B}(\Phi_B)\, O(\Phi_B) +$$

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NLOPS matching

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

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

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

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

NLOPs matching

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

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

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- **SHERPA:** $\mathrm{D}_i^{(\mathrm{A})} = \mathrm{D}_i^{(\mathrm{S})}\,\Theta(\mu_Q^2 - t)$ **(**$N_c = 3$ **CS kernels),** μ_Q **free**

POWHEG

Special choices: Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot \mathrm{R}$ with $\rho_i = \mathrm{D}_i^{(\mathsf{S})} / \sum_i \mathrm{D}_i^{(\mathsf{S})}$
  $\rightarrow$ each $\rho_i \cdot \mathrm{R}$ contains only one divergence structure as defined by $\mathrm{D}_i^{(\mathsf{S})}$

Consequences:

- no $\mathbb{H}$-events, resummation scale μ_Q^2 at kinematic limit $\frac{1}{2}\,s_{\mathsf{had}}$
- in CS-subtraction instabilities in ρ_i due to different cuts on R and $\mathrm{D}_i^{(\mathsf{S})}$
- exponentiation of R through matrix element corrected parton shower
  NLO accuracy depends crucially on presence of exact same terms in subtraction and parton shower

Modifications:

- introduce suppression function $f(p_\perp) = h^2/(p_\perp^2 + h^2)$ Alioli et.al. JHEP04(2009)002
  $\rightarrow \mathrm{D}_i^{(\mathsf{A})} = \rho_i \cdot \mathrm{R} \cdot f(p_\perp)$
  $\rightarrow$ continuous dampening of resummation kernel at large $p_\perp$

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MC@NLO – traditional scheme

Special choices: Frixione, Webber JHEP06(2002)029

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{B}\cdot\mathcal{K}_i$ with $\mathcal{K}_i$ parton shower kernels

Consequences:

- resummation scale $\mu_Q^2 = t_{\mathsf{max}}$ parton shower starting scale
- in general, $\mathrm{D}_i^{(\mathsf{A})}$ only leading colour approximation
  NLO accuracy depends crucially on correctness of IR-limit

Modifications: Frixione, Nason, Webber JHEP08(2003)007

- introduce soft modification function $f(p_\perp)$ such that

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

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S-Mc@Nlo

Special choices: Höche, Krauss, MS, Siegert JHEP09(2012)049

- exponentiation kernel $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$

Consequences:

- simplification of $\bar{\mathrm{B}}^{(\mathsf{A})}$-integral
- resummation scale $\mu_Q^2 = t_{\mathsf{max}}$ set by phase space limitation of subtraction terms
  $\rightarrow$ subtraction constrained in parton shower t needed for physical resummation
  $\rightarrow$ instructive example: use α_{cut} to explore effects Nagy PRD68(2003)094002
- trivially NLO correct independent of the process without arbitrary parameter choices

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S-MC@NLO

Implemented in SHERPA – full-colour first parton shower emission

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

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

- Assume $f(t)$ as function to be generated, and overestimate $g(t)$
  Standard probability for *one* acceptance with n rejections

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

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

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

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

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

NLO merging – Generation of MC counterterm

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

- same form as exponent of Sudakov form factor $\Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)$
- truncated parton shower on n-parton configuration underlying $n+1$-parton event
  1. no emission $\to$ retain $n+1$-parton event as is
  2. first emission at t' with $Q > Q_{\text{cut}}$, multiply event weight with $\mathrm{B}_{n+1}/\bar{\mathrm{B}}^{(\mathrm{A})}_{n+1}$, restart evolution at t', do not apply emission kinematics
  3. treat every subsequent emission as in standard truncated vetoed shower
- generates

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

$\Rightarrow$ **identify $\mathcal{O}(\alpha_s)$ counterterm with the omitted emission**