Recent developments in SHERPA

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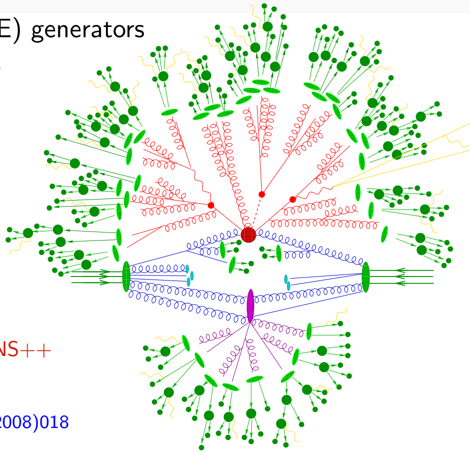
Contents

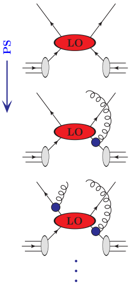
The SHERPA event generator framework



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

Sherpa's traditional strength is the perturbative part of the event
MEPS (CKKW), MC@NLO, MENLOPS, MEPS@NLO
→ full analytic control mandatory for consistency/accuracy

MEPS

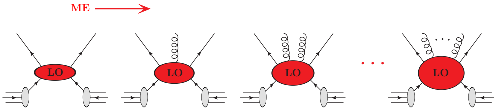


Parton showers

resummation of (soft-)collinear limit
→ intrajet evolution

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

MEPS



Matrix elements

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

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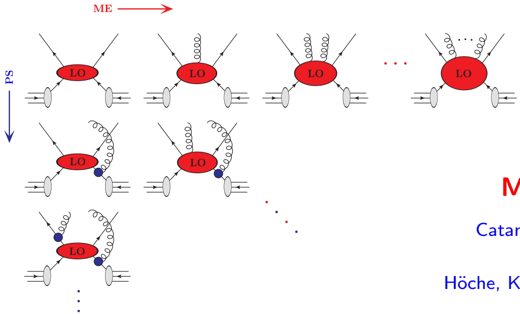

MEPS (CKKW,MLM)

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

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
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Resummation properties of parton showers

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

- splitting kernel $\mathcal{K}_n=\sum\mathcal{K}_i$ and $\mathcal{K}_i(\Phi_1)\propto\frac{\alpha_s}{t}P_i(z)$, $\Phi_1=\{t,z,\phi\}$
- Sudakov form factor

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

- parton shower starting scale μ_Q plays role of resummation scale, at LO commonly identified with μ_F to recover PDF evolution
- resummation in evolution variable t, c_1 correctly described, c_2 at most in $N_c\to\infty$ approximation
- 1-loop running $\alpha_s\to\alpha_s(k_\perp)$ catches dominant terms of higher log. order $\Rightarrow$ **crucial in defining "parton shower accuracy"**

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MEPS

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

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

Multijet merging at leading order:

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

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

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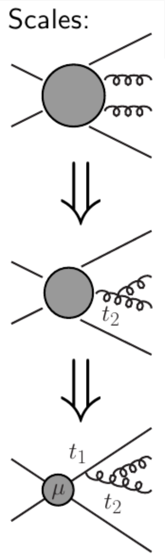

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$$\alpha_s^{k+n}(\mu_{\mathrm{R}}) = \alpha_s^k(\mu_{\mathrm{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$$

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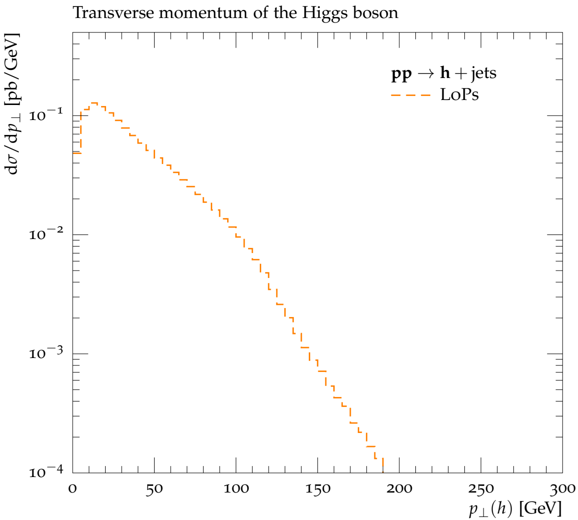

- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \to h +$ jet for $Q_{n+1} > Q_{\text{cut}}$
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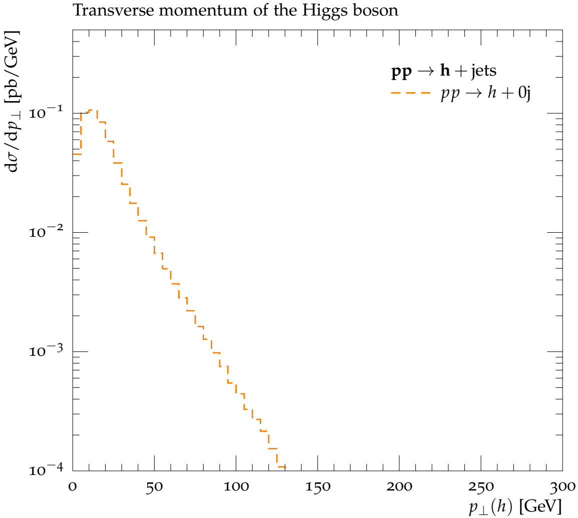

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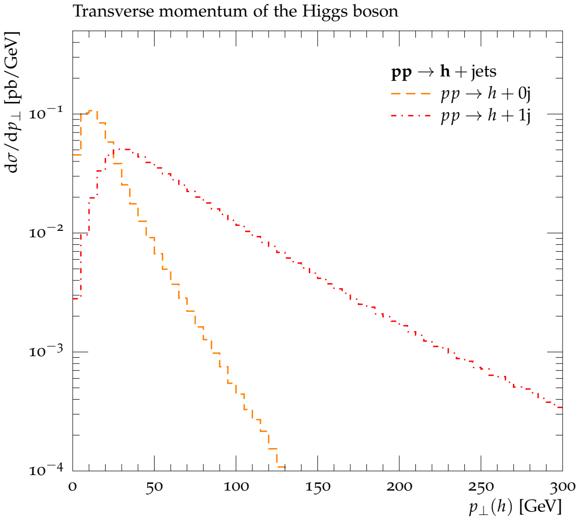

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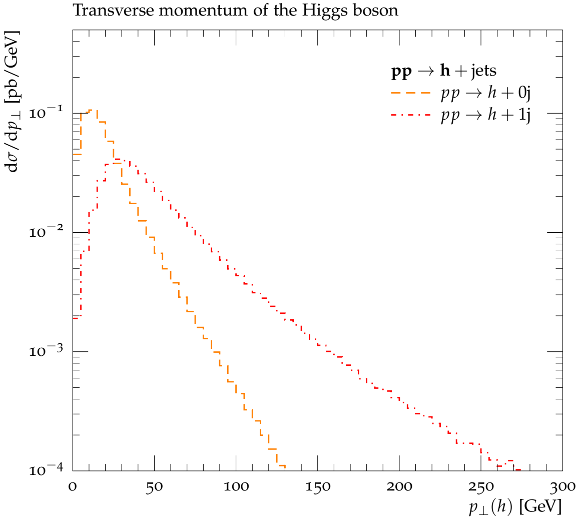

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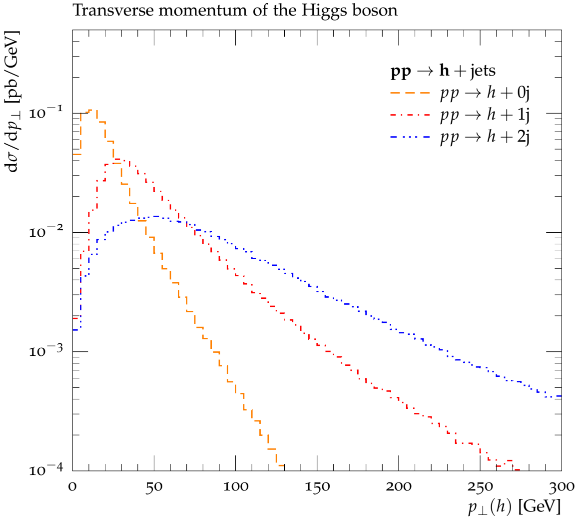

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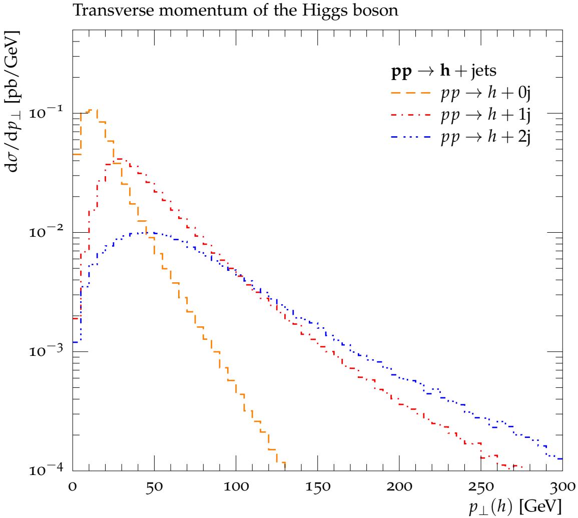

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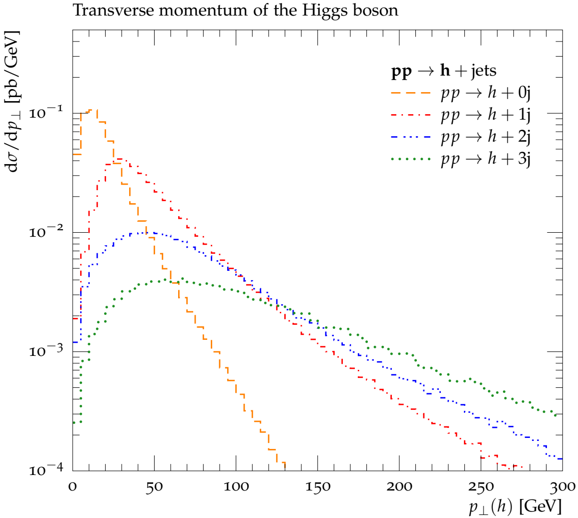

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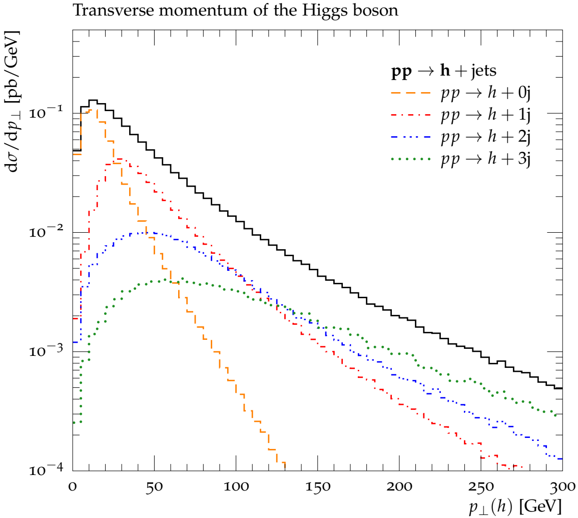
- LOPS $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- LOPS $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions

MEPS



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- iterate
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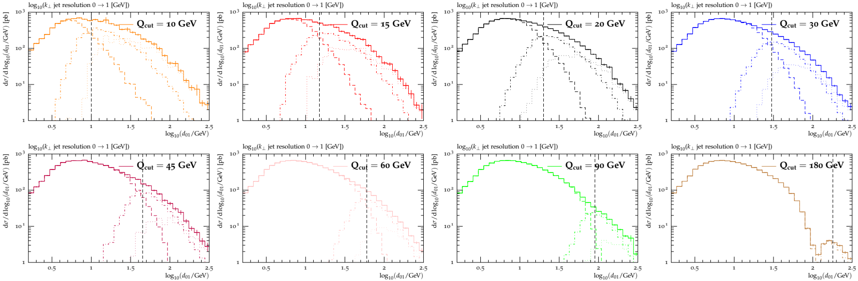
MEPS

Merging cut Q_{cut} dependence ($pp \to Z +$ jets MEPS, up to 2 in ME):



- parton shower is trusted to corectly describe emissions $\lesssim Q_{\text{cut}}$
- changes the region where higher accuracy is used for calculation
  $\to$ part of the uncertainty is due to degraded accuracy for large Q_{cut}
- all samples are identical for $Q < Q_{\text{cut}}^{\text{smallest}}$ and $Q > Q_{\text{cut}}^{\text{largest}}$ by construction
- Q_{cut} dependence usually small

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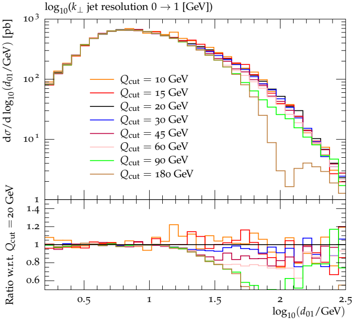

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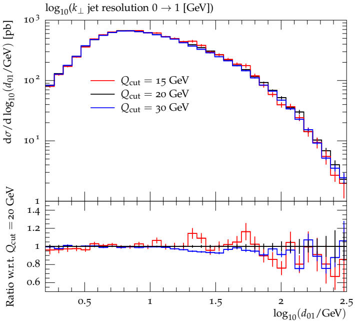

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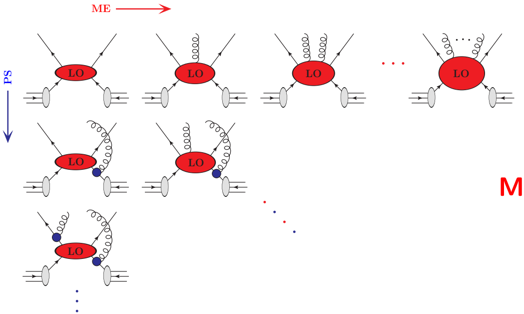
MEPS@NLO



MEPS (CKKW,MLM)

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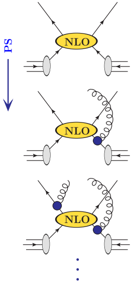
MEPS@NLO



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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NLOPS – S-MC@NLO

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

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

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

S-MC@NLO – $pp \to$ jets

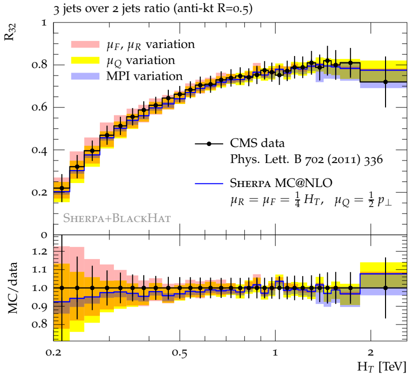
MC@NLO di-jet production:

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

Uncertainty estimates:

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

Höche, MS Phys.Rev.D86(2012)094042



S-MC@NLO – $pp \to t\bar{t}\,b\bar{b}$

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

MC@NLO $pp \to t\bar{t}\,b\bar{b}$ production:

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

Uncertainty estimates:

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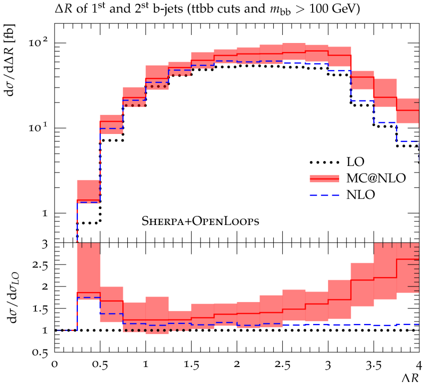
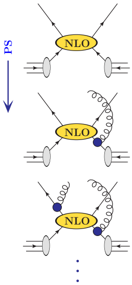


MEPS@NLO



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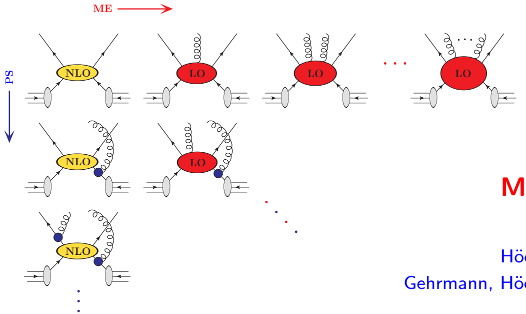

MENLOPS

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

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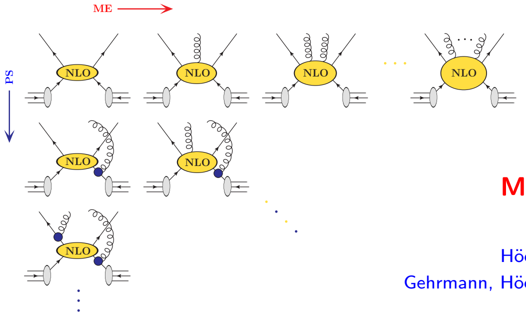

MEPS@NLO

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

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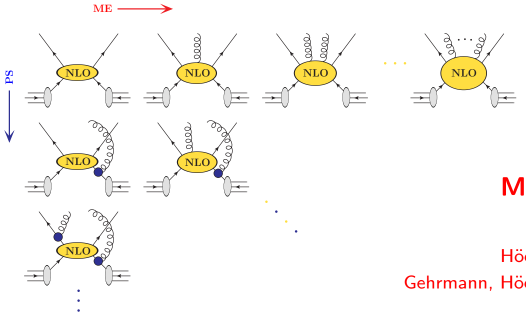
MEPS@NLO



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

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

Multijet merging at next-to-leading order:

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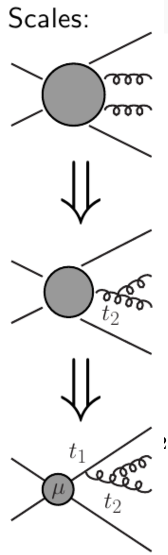

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Multijet merging at next-to-leading order:

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

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

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

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

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

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

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

MEPS@NLO

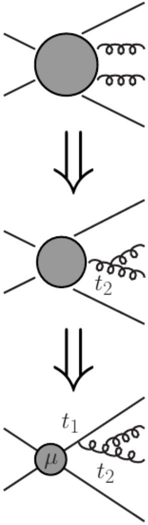
Parton showers for NLOPS (need to reproduce $N_c = 3$ singular li... .):

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

Multijet merging at next-to-leading order:

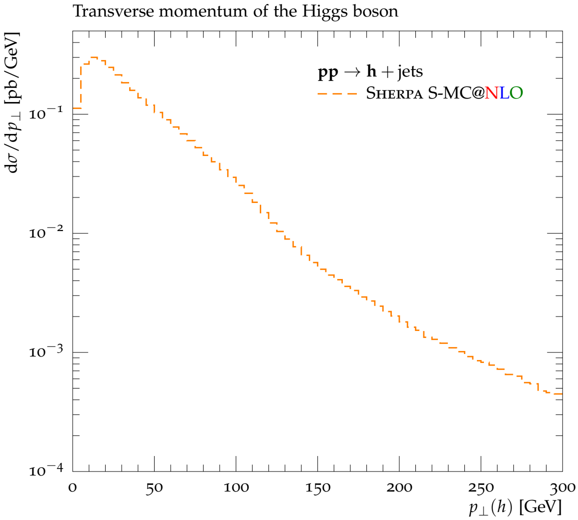
$$\mathrm{d}\sigma^{\mathrm{MEPS@NLO}} = \mathrm{d}\sigma_n^{\mathrm{NLO}} \otimes \widetilde{\mathrm{PS}}_n\, \Theta(Q_{\mathrm{cut}} - Q_{n+1})$$
$$+ \mathrm{d}\sigma_{n+1}^{\mathrm{NLO}}\, \Theta(Q_{n+1} - Q_{\mathrm{cut}}) \Big(\Delta_n(t_{n+1}, t_n) - \Delta_n^{(1)}$$
$$\otimes \widetilde{\mathrm{PS}}_{n+1}\,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

Scales:



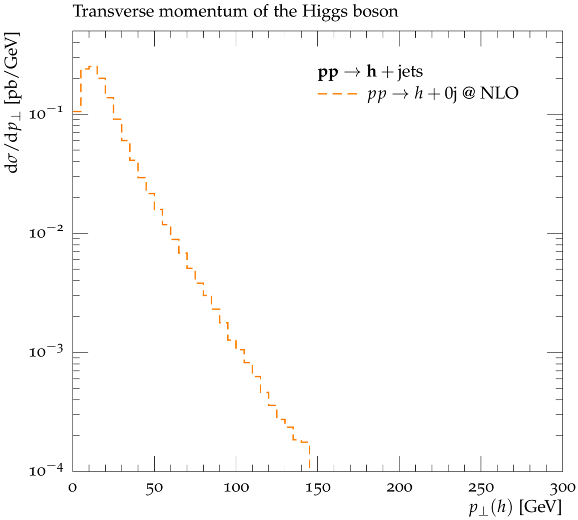
- NLOPS for $2 \to n$, restricted to emit only below Q_{cut}
- add the NLOPS for $2 \to n+1$
- multiply by Sudakov wrt. $2 \to n$ process to restore resumma
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

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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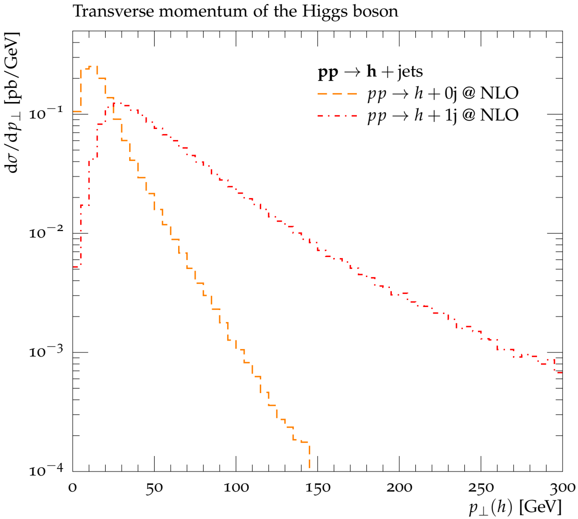
MEPS@NLO



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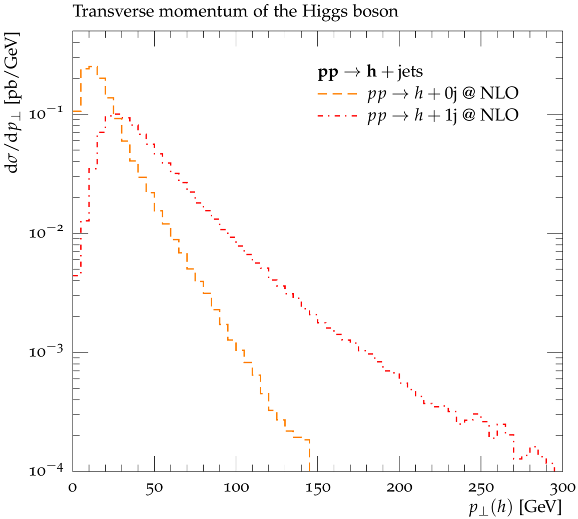
- sum all contributions

MEPS@NLO



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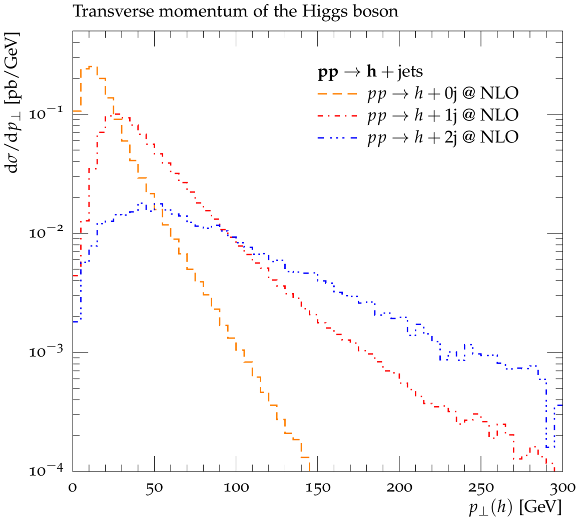
- sum all contributions

MEPS@NLO



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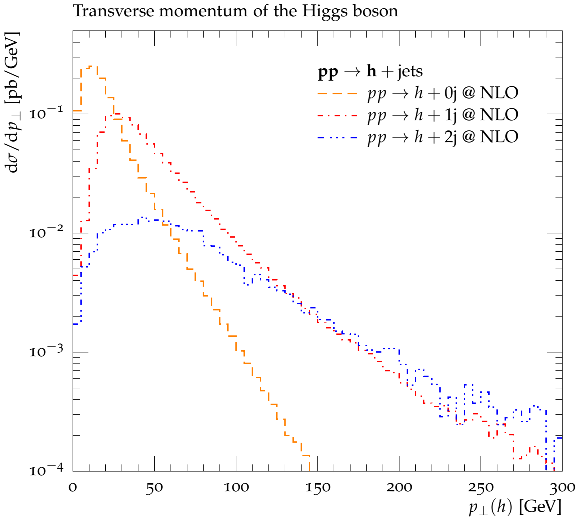
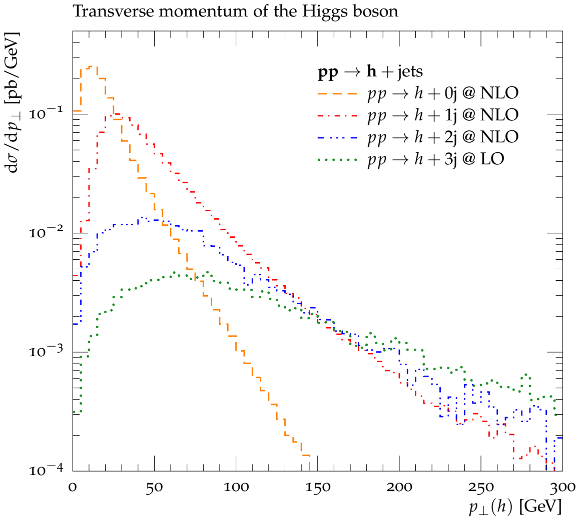
MEPS@NLO



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

MEPS@NLO



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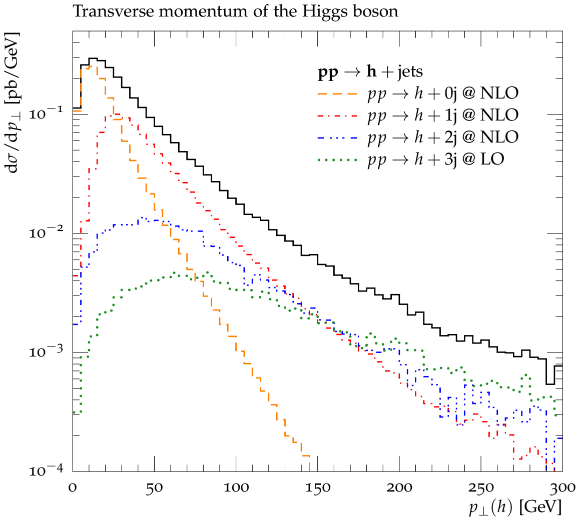
MEPS@NLO



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- iterate
- sum all contributions

Recent results

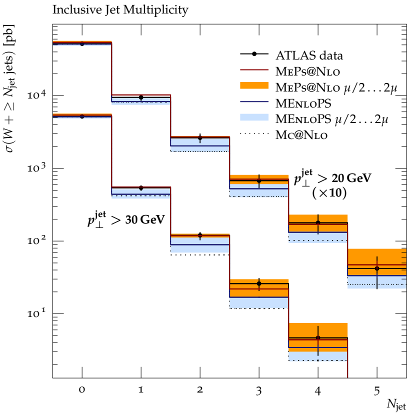
Fixed-mulitplicity NLOPS (S-MC@NLO)

- $pp \to W + 0, 1, 2, 3$jets – SHERPA+BLACKHAT
  Höche, Krauss, MS, Siegert Phys.Rev.Lett.110(2013)052001
- $pp \to$ jets – SHERPA+BLACKHAT Höche, MS Phys.Rev.D86(2012)094042
- $pp \to t\bar{t}b\bar{b}$ – SHERPA+OPENLOOPS
  Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.0500

Multijet merging at NLO accuracy (MEPS@NLO)

- $pp \to W +$ jets – SHERPA+BLACKHAT Höche, Krauss, MS, Siegert JHEP04(2013)027
- $e^+e^- \to$ jets – SHERPA+BLACKHAT
  Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
- $pp \to h +$ jets – SHERPA+GOSAM Höche, Krauss, MS, Siegert, in YR3 arXiv:1307.1347
- $p\bar{p} \to t\bar{t} +$ jets – SHERPA+GOSAM
  Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040
- $pp \to 4\ell +$ jets – SHERPA+OPENLOOPS
  Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert arXiv:1309.5912

Results – pp → W+jets

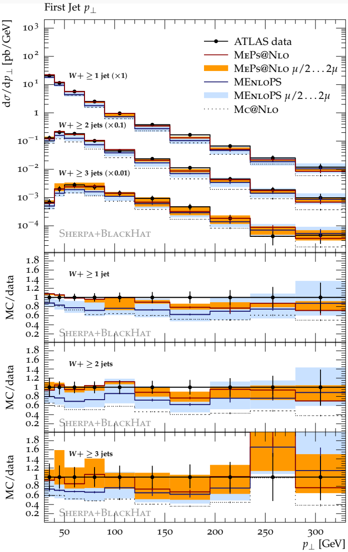


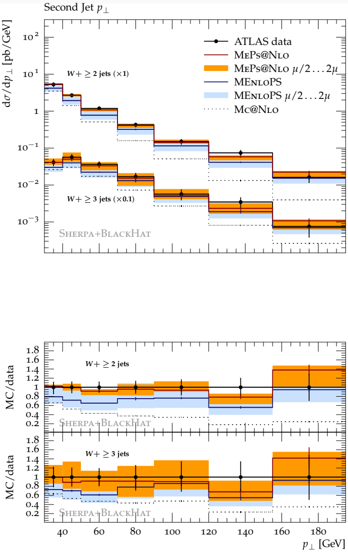
$pp \to W+$jets (0,1,2 @ NLO; 3,4 @ LO)

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

ATLAS data Phys.Rev.D85(2012)092002

Results – pp → W+jets



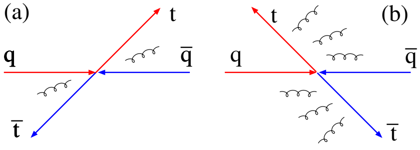


Recent results – $pp \to t\bar{t} + \text{jets}$

Skands, Webber, Winter JHEP07(2012)151

Parton showers and the $t\bar{t}$-asymmetry at the Tevatron

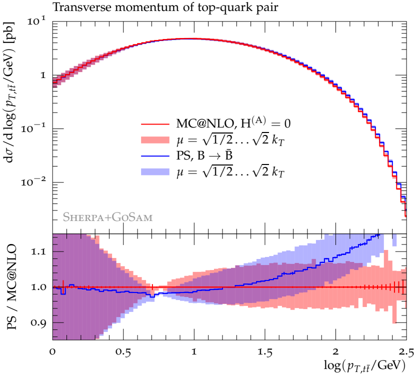
- if colour coherence is respected, PS creates an asymmetry because of asymmetric colour flow
- HERWIG respects colour correlations through angular ordering



- CSSHOWER++ (CS dipoles, 1→2 splittings, recoil to large-N_c partner) → respects colour correlations by choice of radiating dipoles/recoil partners

⇒ **it is important to respect colour-correlations**

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

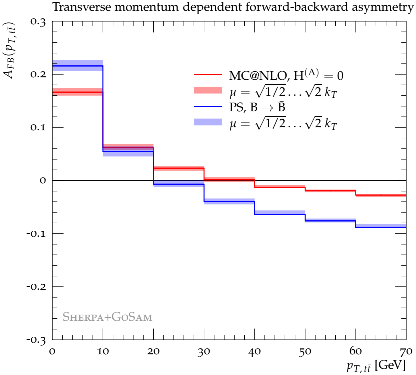


Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

Importance of
$N_c = 3$ colour coherence
(SHERPA's MC@NLO)
vs.
$N_c \to \infty$ colour coherence
(SHERPA's CSSHOWER++)

- small effect on standard (rapidity blind) observables, e.g. $p_{\perp,t\bar{t}}$
  $\to$ some destructive interference at large $p_{\perp,t\bar{t}}$
- large effect on $A_{FB}(p_{\perp,t\bar{t}})$
  $\to$ subleading colour terms increase asym. radiation pattern

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



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- large effect on $A_{FB}(p_{\perp,t\bar{t}})$
  $\to$ subleading colour terms increase asym. radiation pattern

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

- Definition of forward-backward asymmetry of an observable $\mathcal{O}$

$$A_{\mathsf{FB}}(O) \;=\; \frac{\left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y>0} - \left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0}}{\left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y>0} + \left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0}}$$

- A_{FB} is ratio of expectation values
  $\to$ conventional scale variations by factor 2 will largely cancel for uncertainty on A_{FB}

$\Rightarrow$ use different functional forms of the scale defintion that behave differently in $\Delta y > 0$ and $\Delta y < 0$ for a realistic estimate of uncertainty

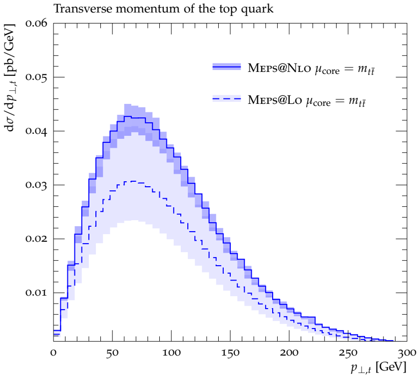
- applies to other ratio observables, e.g. normalised observables, as well

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

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

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

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- virtual MEs from GOSAM
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV



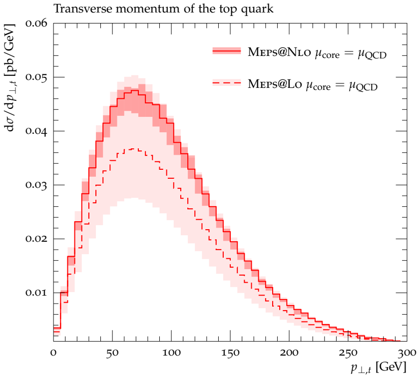
- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}})\,\alpha_s(t_1)\cdots\alpha_s(t_n)$
  1) $\mu_{\text{core}} = m_{t\bar{t}}$
  2) $\mu_{\text{core}} = \mu_{\text{QCD}} = \sqrt{2\,|p_i p_j|}$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between s, t, u

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

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

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

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



- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- virtual MEs from GOSAM
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV
- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$

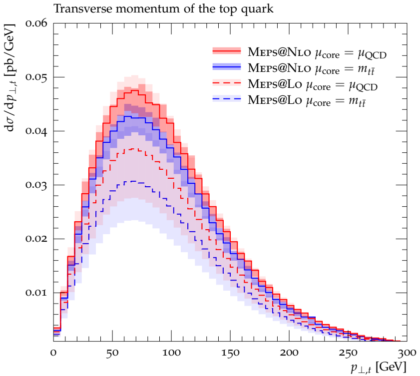
  1) $\mu_{\text{core}} = m_{t\bar{t}}$

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

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

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

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



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

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

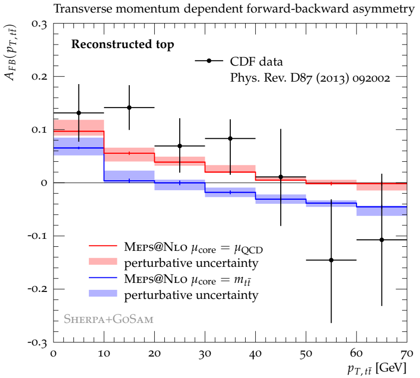
$\Rightarrow$ different behaviour for forward/backward configurations

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

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

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- virtual MEs from GoSam
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV

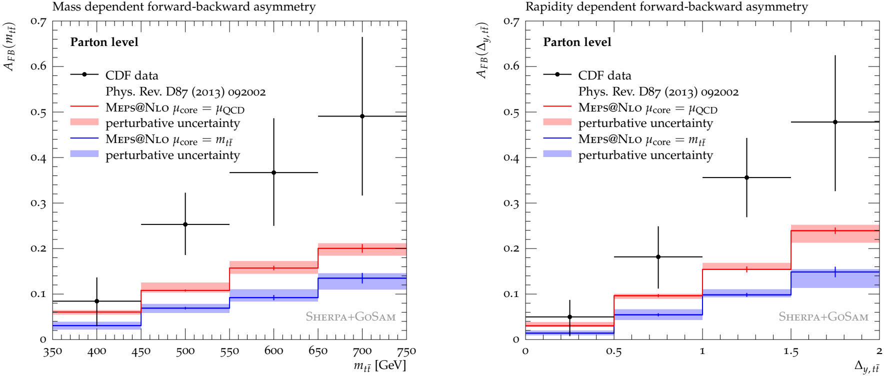
Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703



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

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

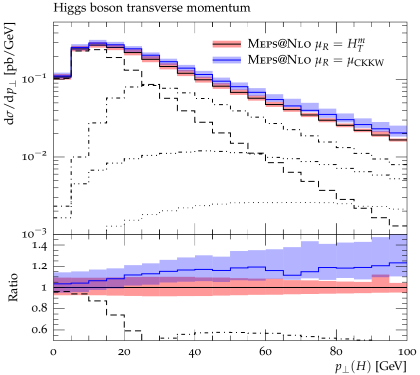
Recent results – $pp \to t\bar{t} + \text{jets}$



- no EW corrections ($\approx 20\%$) effected
- right qualitative bahviour, but consistently below data

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

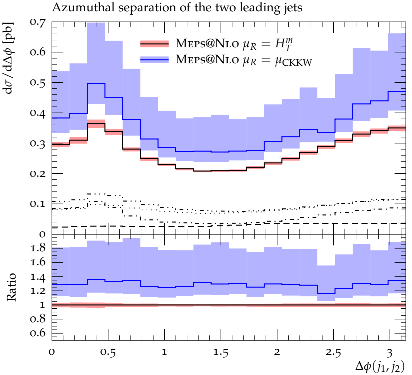
Höche, Krauss, MS contrib to LH2013

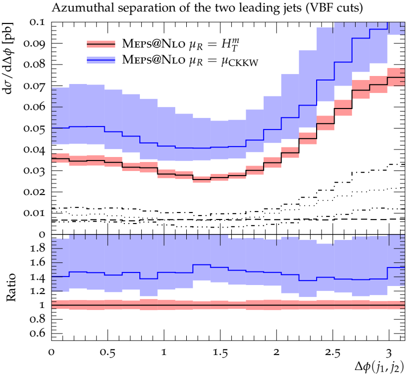


$pp \to h +$ jets in gluon fusion

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

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





- general features present with both scale choices
- overall shift in normalisation
- very similar findings as in YR3

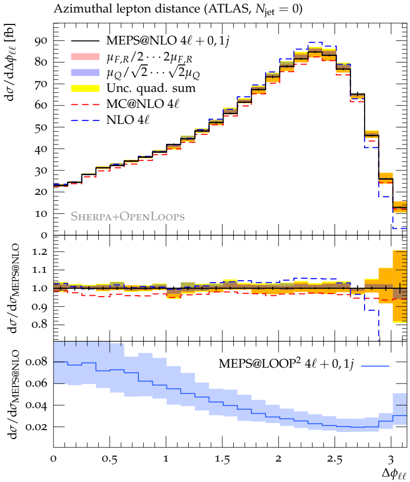
Recent results – $pp \to 4\ell +$ jets

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

$pp \to 4\ell +$ jets

- 0,1 jets @ NLO
- virtuals from OPENLOOPS
- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{core}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
  $\mu_{\text{core}} = \frac{1}{2}\left(E_\perp^{W^+} + E_\perp^{W^-}\right)$
- NLO dependence
  for $pp \to 4\ell$+0,1 jets
  LO dependence
  for $pp \to 4\ell$+2 jets
- $Q_{\text{cut}} = 20$ GeV

includes loop-induced processes
$gg \to 4\ell$ and
$gg \to 4\ell + g$, $gq \to 4\ell + q$, $q\bar{q} \to 4\ell + g$



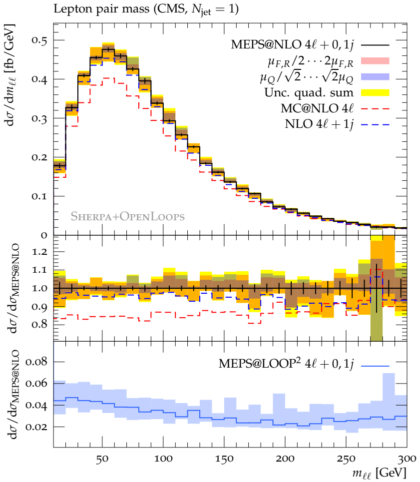
Recent results – $pp \to 4\ell + \text{jets}$

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

$pp \to 4\ell +$ jets

- 0,1 jets @ NLO
- virtuals from OPENLOOPS
- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{core}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\,\mu_{\text{core}}$
  $\mu_{\text{core}} = \frac{1}{2}\left(E_\perp^{W^+} + E_\perp^{W^-}\right)$
- NLO dependence for $pp \to 4\ell$+0,1 jets
  LO dependence for $pp \to 4\ell$+2 jets
- $Q_{\text{cut}} = 20$ GeV

includes loop-induced processes
$gg \to 4\ell$ and
$gg \to 4\ell+g$, $gq \to 4\ell+q$, $q\bar{q} \to 4\ell+g$



Matrix element weights and reweighting

SHERPA-2.0.0 will contain an Python interface
(available since SHERPA-2.0.β_2)

- gives access to SHERPA's matrix elements (AMEGIC++ & COMIX)
- takes external four momenta and flavours
- returns colour and helicity summed/averaged matrix elements including symmetry and flux factors

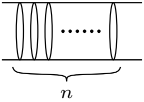
$\Rightarrow$ **suitable for matrix element method at LO**

Minimum bias: the SHRiMPS model

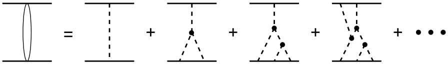
exploits optical theorem,
eikonal ansatz:

$$A_{\text{el}}(s,b) = i\left(1 - e^{-\Omega(s,b)/2}\right)$$

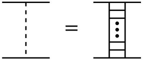
$$= i\sum_{n=1}^{\infty}$$



KMR model: Khoze, Martin, Ryskin



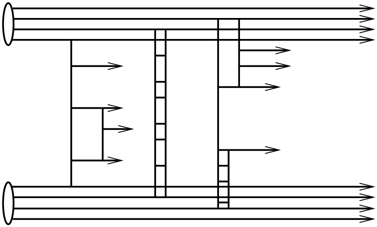
where



'gluon' ladder with effective vertices and propagators

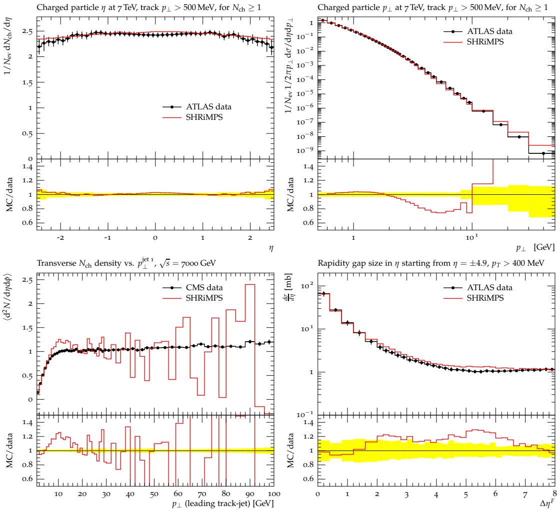
SHRiMPS

- cut KMR diagrams to obtain differential total cross section



- allow for parton showering
- hadronise

SHRiMPS: preliminary results



compared to LHC data

data reproduced well in applicable regions

room for tuning of free parameters

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-2.0.0

http://sherpa.hepforge.org

Thank you for your attention!

MEPS – Multijet merging at LO

$$\langle O\rangle^{\text{MEPS}}$$

$$= \int d\Phi_n \, \mathrm{B}_n \bigg[\Delta_n^{(\mathcal{K})}(t_c, \mu_Q^2)\, O_n + \int_{t_c}^{\mu_Q^2} d\Phi_1 \, \mathcal{K}_n \, \Delta_n^{(\mathcal{K})}(t_{n+1}, \mu_Q^2)\, \Theta(Q_{\text{cut}} - Q)\, O_{n+1} \bigg]$$

$$+ \int d\Phi_{n+1} \, \mathrm{B}_{n+1} \, \Delta_n^{(\mathcal{K})}(t_{n+1}, \mu_Q^2)\, \Theta(Q - Q_{\text{cut}})$$

$$\times \bigg[\Delta_{n+1}^{(\mathcal{K})}(t_c, t_{n+1})\, O_{n+1} + \int_{t_c}^{t_{n+1}} d\Phi_1 \, \mathcal{K}_{n+1} \, \Delta_{n+1}^{(\mathcal{K})}(t_{n+2}, t_{n+1})\, O_{n+2} \bigg]$$

- LOPS for n-jet process restricted to region $Q < Q_{\text{cut}}$
- LOPS for $n+1$-jet process with additional Sudakov wrt. n-jet process
  $\rightarrow$ implements correct resummation behaviour wrt. incl. sample
- truncated showering to account for mismatch of t and Q

Nason JHEP11(2004)040

MEPS – Multijet merging at LO

$$\langle O\rangle^{\text{MEPS}}$$

$$= \int \mathrm{d}\Phi_n\, \mathrm{B}_n \Bigg[\Delta_n^{(\mathcal{K})}(t_c,\mu_Q^2)\, O_n$$

mismatch of $\mathcal{O}(\frac{1}{N_c}\,\alpha_s\,L)$

$$+ \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1 \left(\mathcal{K}_n\, \Theta(Q_{\text{cut}}-Q) + \frac{\mathrm{B}_{n+1}}{\mathrm{B}_n}\, \Theta(Q-Q_{\text{cut}})\right)$$

$$\times\; \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, O_{n+2}\Bigg]$$

- α_s scales in $\mathrm{B}\cdot\mathcal{K}$ and B_{n+1} must be the same to retain resummation properties of the parton shower
- interprete B_{n+1} as PS splitting on top of B_n
  $\to$ need to use inverse parton shower

MEPS@NLO – Multijet merging at NLO

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

$$\langle O\rangle^{\text{MEPS@NLO}}$$

$$= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathrm{A})} \left[\Delta_n^{(\mathrm{A})}(t_c,\mu_Q^2)\, O_n + \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathrm{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\right]$$

$$+ \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathrm{A})}\right] \Theta(Q_{\text{cut}}-Q)\, O_{n+1}$$

$$+ \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathrm{A})} \left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathcal{K}_n\right] \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})$$

$$\times \left[\Delta_{n+1}^{(\mathrm{A})}(t_c,t_{n+1})\, O_{n+1} + \int_{t_c}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(\mathrm{A})}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathrm{A})}(t_{n+2},t_{n+1})\, O_{n+2}\right]$$

$$+ \int \mathrm{d}\Phi_{n+2} \left[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathrm{A})}\right] \Delta_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\, O_{n+2}$$

MEPS@NLO – Multijet merging at NLO

$$\langle O\rangle^{\text{MEPS@NLO}}$$

$$= \int \mathrm{d}\Phi_n\, \mathrm{B}_n \Bigg[\Delta_n^{(\mathcal{K})}(t_c,\mu_Q^2)\, O_n$$

mismatch of $\mathcal{O}(\frac{1}{\mathbf{N_c}}\,\alpha_s^2\,\mathbf{L^3})$

$$+ \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1 \left(\frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q) \right.$$

$$\left. + \frac{\bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}}{\mathrm{B}_n}\, \tilde{\Delta}_n^{(\mathcal{K})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \right)$$

$$\times\; O_{n+2} \Bigg]$$

- α_s scales in $\mathrm{D}_n^{(\mathsf{A})}$ and $\bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}$ must be the same to retain resummation properties of the parton shower
- interprete B_{n+1} as PS splitting on top of B_n
  $\rightarrow$ need to use inverse parton shower