

Multijet merging at NLO

Marek Schönherr

Institute for Particle Physics Phenomenology

LHCphenonet annual meeting
CERN, 05/12/2013



LHCphenonet



Contents

- ① **MEPs– review**
- ② **MEPs@NLO**
- ③ **Recent results**
- ④ **Conclusions**

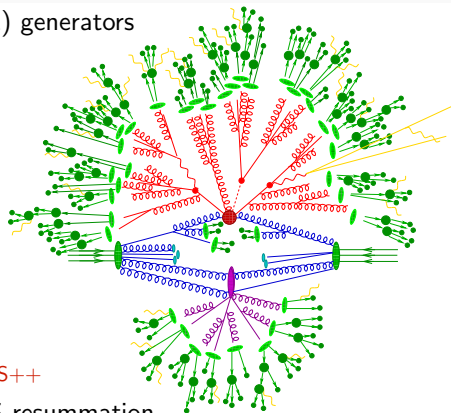
The SHERPA event generator framework

- Two multi-purpose Matrix Element (ME) generators
AMEGIC++ JHEP02(2002)044
COMIX JHEP12(2008)039
CS subtraction EPJC53(2008)501
- 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

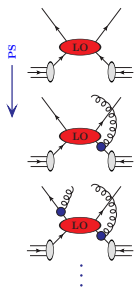
Sherpa's traditional strength is the perturbative part of the event

MEPs (CKKW), Mc@NLO, MENLOPs, MEPs@NLO

→ full analytic control mandatory for consistency/accuracy



MEPs – review

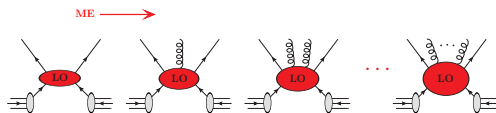


Parton showers

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 – review



Matrix elements

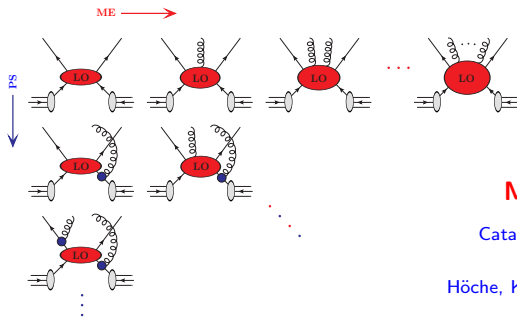
fixed-order in α_s

→ hard wide-angle emissions

→ interference terms

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

MEPs – review



MEPs (CKKW, MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063

Lönnblad JHEP05(2002)046

Höhe, Krauss, Schumann, Siegert JHEP05(2009)053

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

MEPs – review

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

$$\text{PS}_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \mathcal{K}_n(t') \Delta_n(t', t_{\max})$$

Multijet merging at leading order:

$$d\sigma^{\text{MEPs}} = d\sigma_n^{\text{LO}} \otimes \text{PS}_n(t_0, t_{\max})$$

- restrict the parton shower on $2 \rightarrow n$ 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. $2 \rightarrow n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

MEPs – review

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

$$PS_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \mathcal{K}_n(t') \Delta_n(t', t_{\max})$$

Multijet merging at leading order:

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

- restrict the parton shower on $2 \rightarrow n$ 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. $2 \rightarrow n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

MEPs – review

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

$$\text{PS}_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \mathcal{K}_n(t') \Delta_n(t', t_{\max})$$

Multijet merging at leading order:

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

- restrict the parton shower on $2 \rightarrow n$ 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. $2 \rightarrow n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

MEPs – review

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

$$\text{PS}_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \mathcal{K}_n(t') \Delta_n(t', t_{\max})$$

Multijet merging at leading order:

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

- restrict the parton shower on $2 \rightarrow n$ 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. $2 \rightarrow n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

MEPs – review

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

$$\text{PS}_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \mathcal{K}_n(t') \Delta_n(t', t_{\max})$$

Multijet merging at leading order:

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

- restrict the parton shower on $2 \rightarrow n$ 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. $2 \rightarrow n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

MEPs – review

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

$$\text{PS}_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \mathcal{K}_n(t') \Delta_n(t', t_{\max})$$

Multijet merging at leading order:

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

- restrict the parton shower on $2 \rightarrow n$ 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. $2 \rightarrow n$ process to restore resummation
- iterate
 - if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps

MEPS – review

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

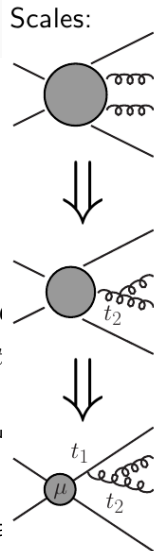
$$\text{PS}_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \mathcal{K}_n(t') \Delta_n(t'),$$

Multijet merging at leading order:

$$\begin{aligned} d\sigma^{\text{MEPS}} = & d\sigma_n^{\text{LO}} \otimes \text{PS}_n \Theta(Q_{\text{cut}} - Q_{n+1}) \\ & + d\sigma_{n+1}^{\text{LO}} \Theta(Q_{n+1} - Q_{\text{cut}}) \Delta_n(t_{n+1}, t_n) \otimes \text{PS}_{n+1} \Theta(Q_{\text{cut}} - Q_{n+2}) \\ & + d\sigma_{n+2}^{\text{LO}} \Theta(Q_{n+2} - Q_{\text{cut}}) \Delta_n(t_{n+1}, t_n) \Delta_{n+1}(t_{n+2}, t_{n+1}) \otimes \text{PS}_{n+2} \Theta(Q_{\text{cut}} - Q_{n+3}) \end{aligned}$$

- restrict the parton shower on $2 \rightarrow n$ 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. $2 \rightarrow n$ process to restore resummation
- iterate

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



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

MEPS – review

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

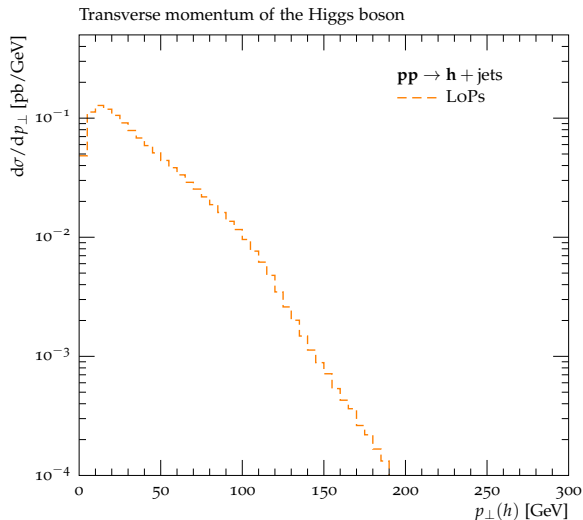
$$\text{PS}_n(t_0, t_{\max}) = \Delta_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \mathcal{K}_n(t') \Delta_n(t', t_{\max})$$

Multijet merging at leading order:

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

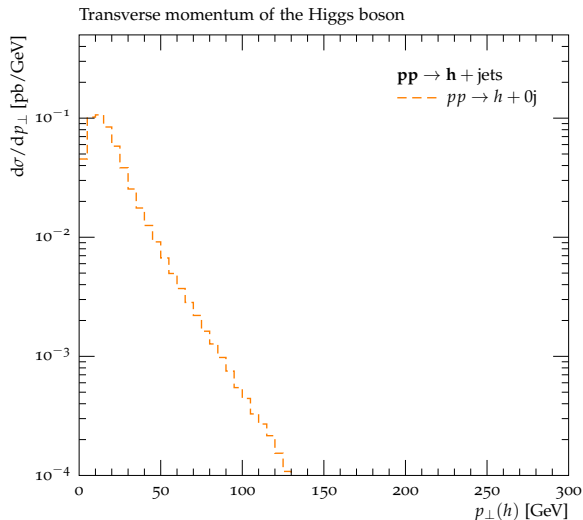
- restrict the parton shower on $2 \rightarrow n$ to emit only below Q_{cut}
- arbitrary jet measure $Q_n = Q_n(\Phi_n)$
- add the $n + 1$ ME and its parton shower
- multiply by Sudakov wrt. $2 \rightarrow n$ process to restore resummation
- iterate
- if $t_n(\Phi_n) \neq Q_n(\Phi_n)$ truncated shower needed to fill gaps [Nason JHEP11\(2004\)040](#)

MEPs – review



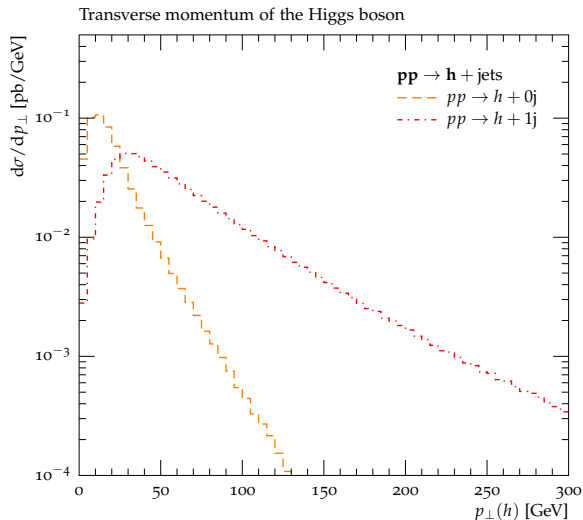
- first emission by PS
restrict to
 $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + \text{jet}$
for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off
 $pp \rightarrow h + \text{jet}$ to
 $Q_{n+2} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + 2\text{jets}$
for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs – review



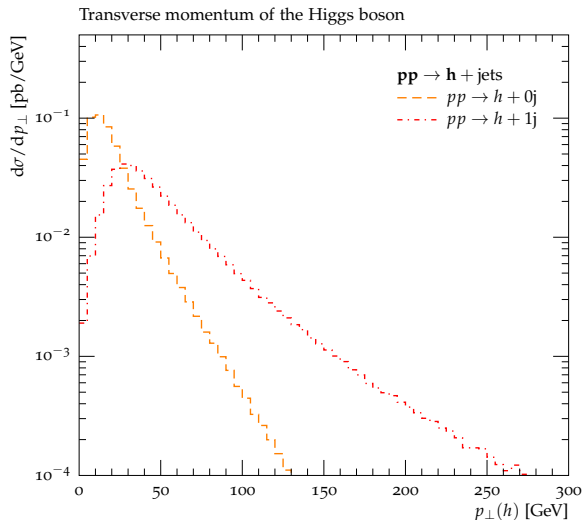
- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs – review



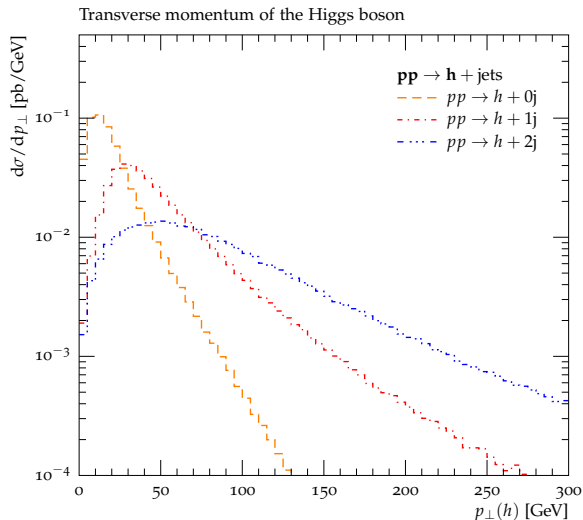
- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
 - restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
 - LOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
 - iterate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

MEPs – review



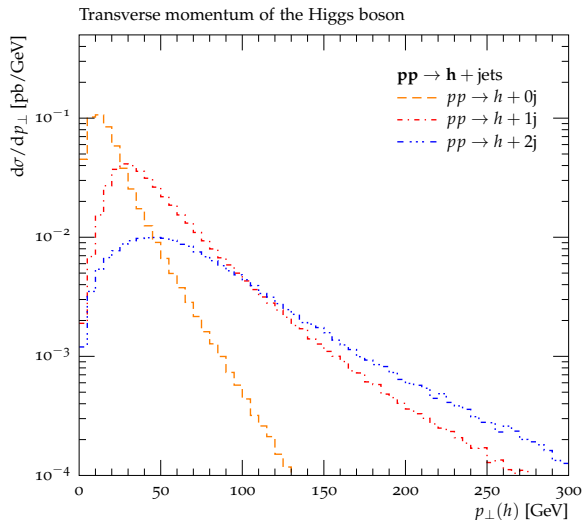
- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs – review



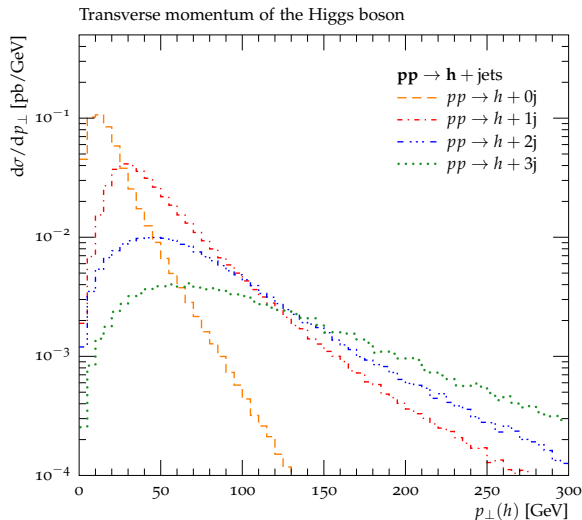
- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs – review



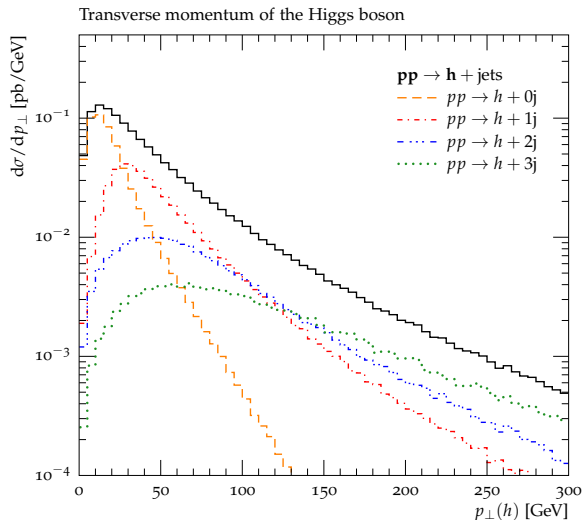
- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs – review



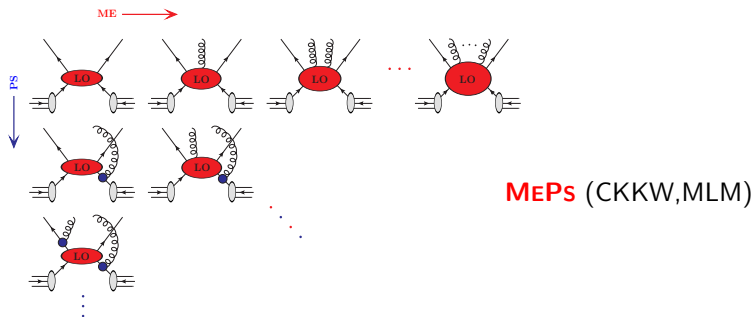
- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs – review



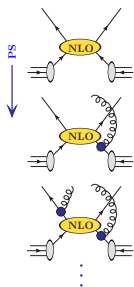
- first emission by PS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- LOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs@NLO



- 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



NLOPS (MC@NLO, POWHEG)

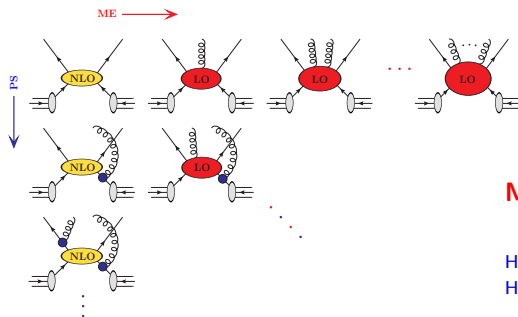
Frixione, Webber JHEP06(2002)029

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

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

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

MEPs@NLO



MENLOPs

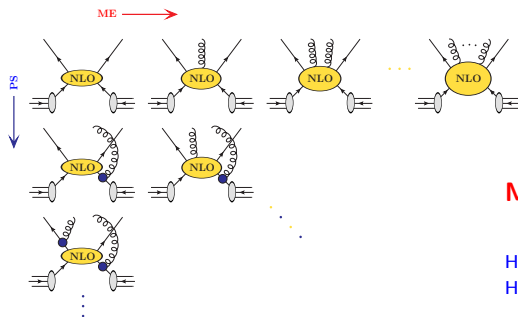
Hamilton, Nason JHEP06(2010)039

Höhe, Krauss, MS, Siebert JHEP08(2011)123

Höhe, Krauss, MS, Siebert JHEP01(2013)144

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

MEPs@NLO



MEPs@NLO

Lavesson, Lönnblad JHEP12(2008)070

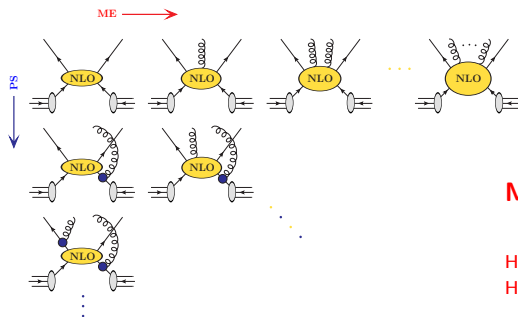
Höhe, Krauss, MS, Siebert JHEP04(2013)027

Höhe, Krauss, MS, Siebert JHEP01(2013)144

Lönnblad, Prestel JHEP03(2013)166

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

MEPS@NLO



MEPS@NLO

Lavesson, Lönnblad JHEP12(2008)070

Höche, Krauss, MS, Siebert JHEP04(2013)027

Höche, Krauss, MS, Siebert JHEP01(2013)144

Lönnblad, Prestel JHEP03(2013)166

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

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

$$d\sigma^{\text{MEPs@NLO}} = d\sigma_n^{\text{NLO}} \otimes \widetilde{\text{PS}}_n + d\sigma_{n+1}^{\text{NLO}} \otimes \widetilde{\text{PS}}_{n+1}$$

- NLOPS for $2 \rightarrow n$
- add the NLOPS for $2 \rightarrow n + 1$
- multiply by Sudakov wrt. $2 \rightarrow n$ process to restore resummation
- remove overlap of Δ_n and $d\sigma_{n+1}^{\text{NLO}}$

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

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

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

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

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

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

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

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

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

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

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

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

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

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

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

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

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

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

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t', t_{\max})$$

Multijet merging at next-to-leading order:

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

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

MEPs@NLO

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

$$\widetilde{\text{PS}}_n(t_0, t_{\max}) = \widetilde{\Delta}_n(t_0, t_{\max}) + \int_{t_0}^{t_{\max}} dt' \widetilde{\mathcal{K}}_n(t') \widetilde{\Delta}_n(t')$$

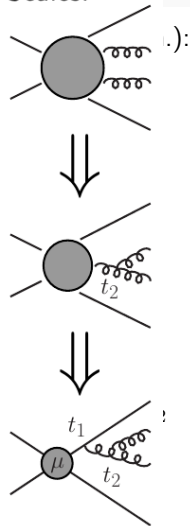
Multijet merging at next-to-leading order:

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

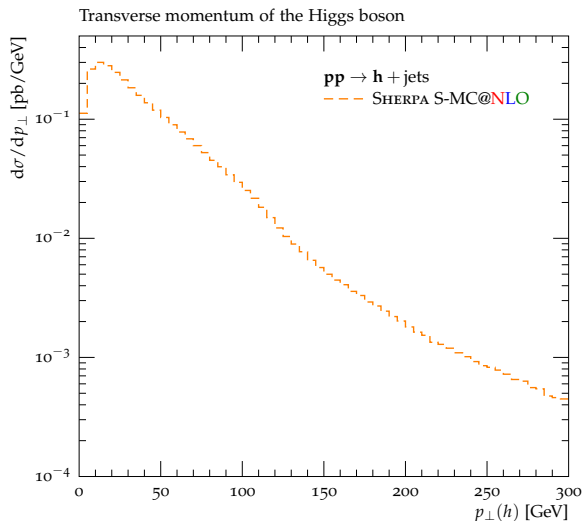
- NLOPS for $2 \rightarrow n$, restricted to emit only below Q_{cut}
- add the NLOPS for $2 \rightarrow n+1$
- multiply by Sudakov wrt. $2 \rightarrow n$ process to restore resummation

• remove overlap of Δ_n and $d\sigma_{n+1}^{\text{NLO}}$, iteratively $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}}) \alpha_s(t_1) \cdots \alpha_s(t_n)$

Scales:

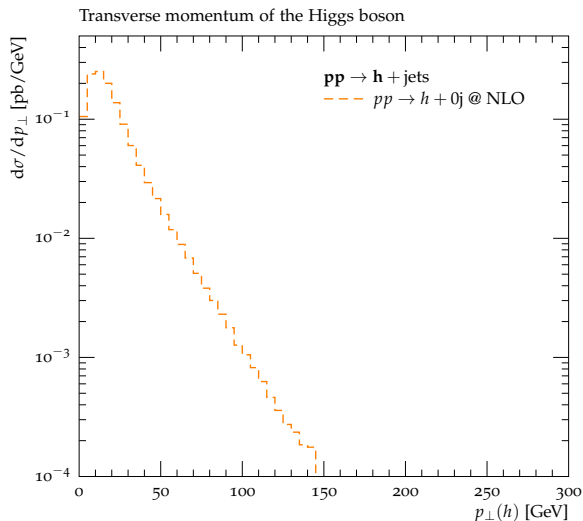


MEPs@NLO



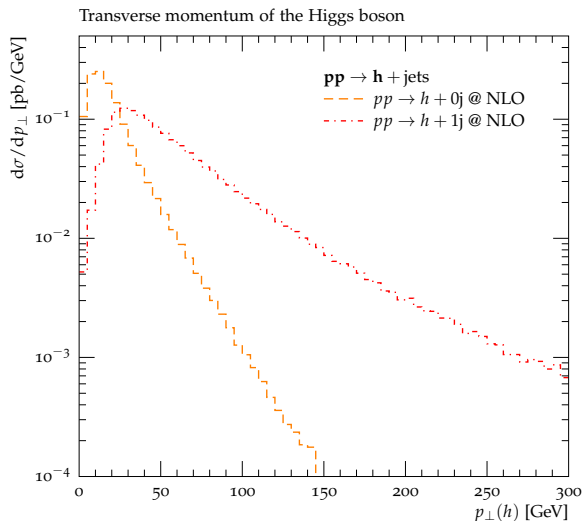
- first emission by NLOPS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs@NLO



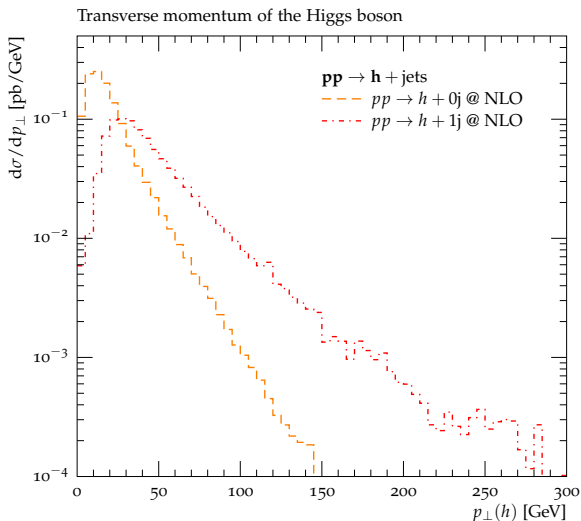
- first emission by NLOPS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs@NLO



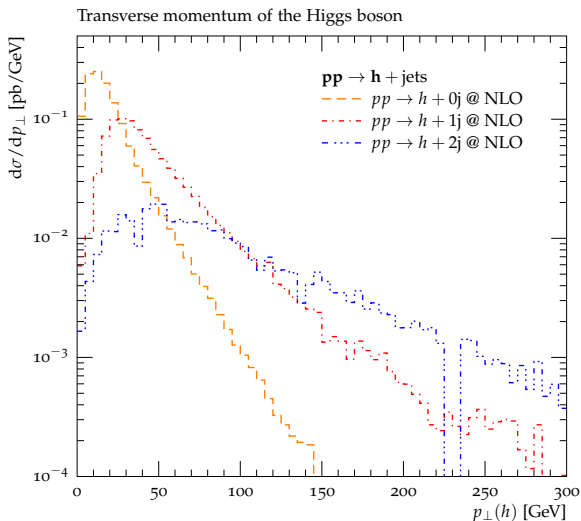
- first emission by NLOPS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
 - restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
 - NLOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
 -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

MEPs@NLO



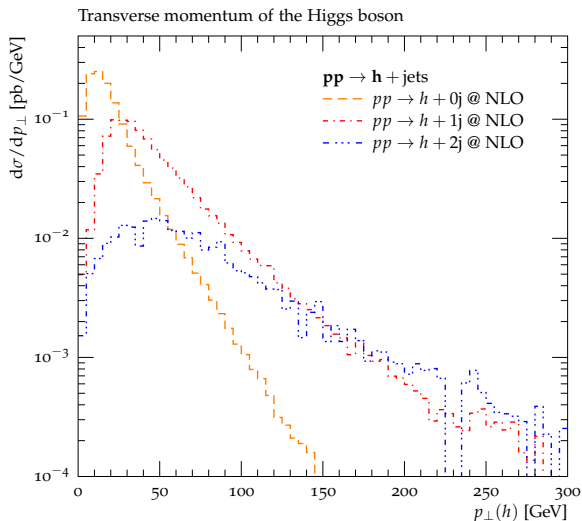
- first emission by NLOPS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs@NLO



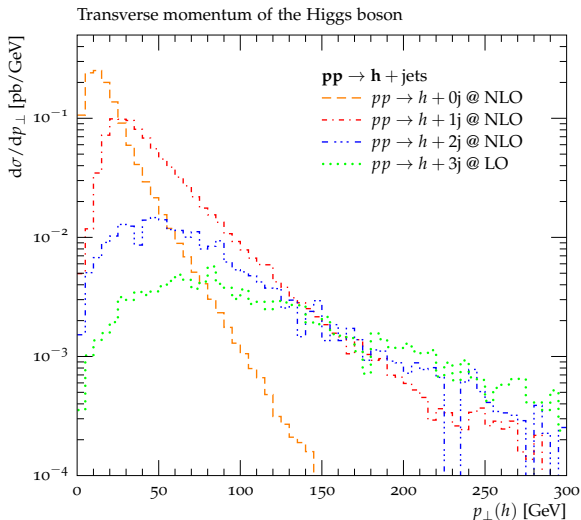
- first emission by NLOPS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs@NLO



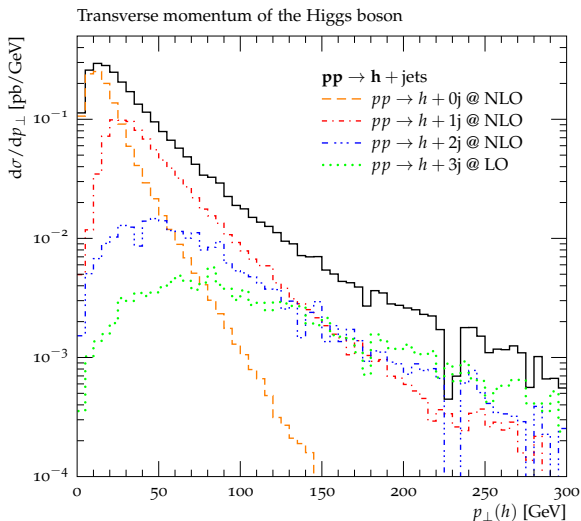
- first emission by NLOPS, restrict to $Q_{n+1} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- NLOPS $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate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

MEPs@NLO



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

MEPs@NLO



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

Recent results

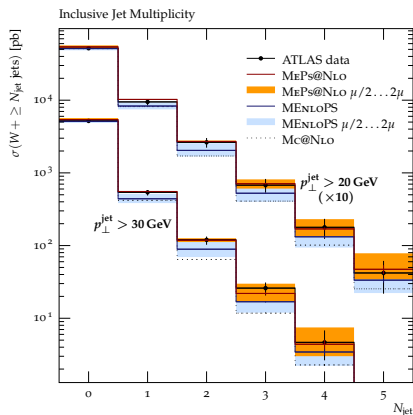
Fixed-multiplicity NLOs (MC@NLO)

- $pp \rightarrow W + 0, 1, 2, 3\text{jets}$ – SHERPA+BLACKHAT
Höche, Krauss, MS, Siebert *Phys.Rev.Lett.*110(2013)052001
- $pp \rightarrow \text{jets}$ – SHERPA+BLACKHAT
Höche, MS *Phys.Rev.D*86(2012)094042
- $pp \rightarrow t\bar{t}b\bar{b}$ – SHERPA+OPENLOOPS
Casoli, Maierhöfer, Moretti, Pozzorini, Siebert *arXiv:1309.0500*

Multijet merging at NLO accuracy (MEPs@NLO)

- $pp \rightarrow W + \text{jets}$ – SHERPA+BLACKHAT
Höche, Krauss, MS, Siebert *JHEP*04(2013)027
- $e^+e^- \rightarrow \text{jets}$ – SHERPA+BLACKHAT
Gehrmann, Höche, Krauss, MS, Siebert *JHEP*01(2013)144
- $pp \rightarrow h + \text{jets}$ – SHERPA+GOSAM
Höche, Krauss, MS, Siebert, in YR3 *arXiv:1307.1347*
- $p\bar{p} \rightarrow t\bar{t} + \text{jets}$ – SHERPA+GOSAM
Höche, Huang, Luisoni, MS, Winter *Phys.Rev.D*88(2013)014040
- $pp \rightarrow 4\ell + \text{jets}$ – SHERPA+OPENLOOPS
Casoli, Höche, Krauss, Maierhöfer, Pozzorini, Siebert *arXiv:1309.5912*

Results – $pp \rightarrow W + \text{jets}$

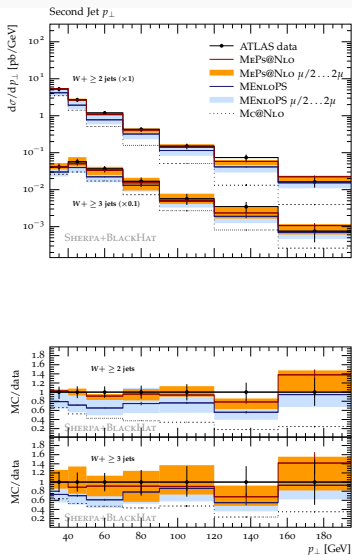
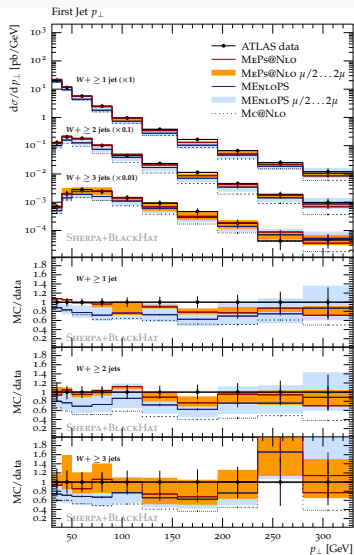


$pp \rightarrow W + \text{jets}$ (0,1,2 @ NLO; 3,4 @ LO)

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

ATLAS data Phys.Rev.D85(2012)092002

Results – $pp \rightarrow W + \text{jets}$



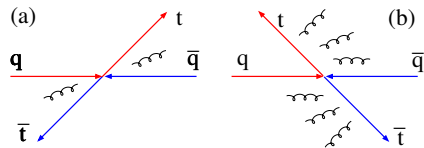
Recent results – $pp \rightarrow t\bar{t} + \text{jets}$ MEPs@NLO

Skands, Webber, Winter JHEP07(2012)151

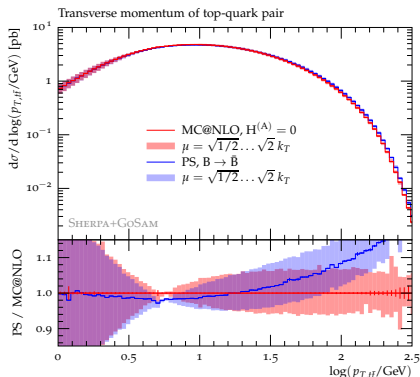
Parton showers and the $t\bar{t}$ -asymmetry at the Tevatron

- if colour coherence is respected, PS creates an asymmetry because of asymmetric colour flow
- HERWIG respects colour correlations through angular ordering
- CSSHOWER++ (CS dipoles, $1 \rightarrow 2$ splittings, recoil to large- N_c partner) \rightarrow respects colour correlations by choice of radiating dipoles/recoil partners

\Rightarrow **it is important to respect colour-correlations**



Recent results – $pp \rightarrow t\bar{t} + \text{jets}$ MEPs@NLO



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

Importance of

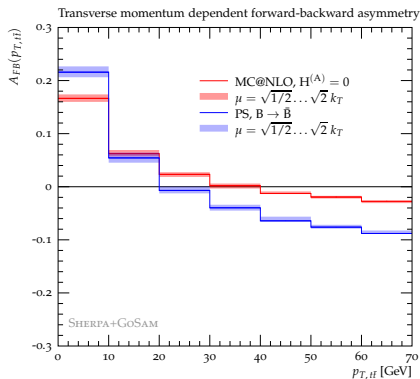
$N_c = 3$ colour coherence
 (SHERPA's MC@NLO)

vs.

$N_c \rightarrow \infty$ colour coherence
 (SHERPA's CSSHOWER++)

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

Recent results – $pp \rightarrow t\bar{t} + \text{jets}$ MEPs@NLO



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

Importance of

$N_c = 3$ colour coherence
(SHERPA's MC@NLO)

vs.

$N_c \rightarrow \infty$ colour coherence
(SHERPA's CSSHOWER++)

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

Recent results – $pp \rightarrow t\bar{t} + \text{jets}$ MEPs@NLO

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

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

- A_{FB} is ratio of expectation values
 → conventional scale variations by factor 2 will largely cancel for uncertainty on A_{FB}
- ⇒ use different functional forms of the scale definition 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 – $pp \rightarrow t\bar{t} + \text{jets}$ MEPS@NLO

Setup: $p\bar{p} \rightarrow t\bar{t} + \text{jets}$

- purely perturbative calculation (no hadronisation, MPI, etc.)

- 0,1 jets @ NLO

$$Q_{\text{cut}} = 7 \text{ GeV}$$

- perturbative scale variations

$$\mu_{R/F} \in \left[\frac{1}{2}, 2\right] \mu_{\text{def}}$$

$$\mu_Q \in \left[\frac{1}{\sqrt{2}}, \sqrt{2}\right] \mu_{\text{core}}$$

- variation of merging parameter

$$Q_{\text{cut}} \in \{5, 7, 10\} \text{ GeV}$$

- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}}) \alpha_s(t_1) \cdots \alpha_s(t_n)$

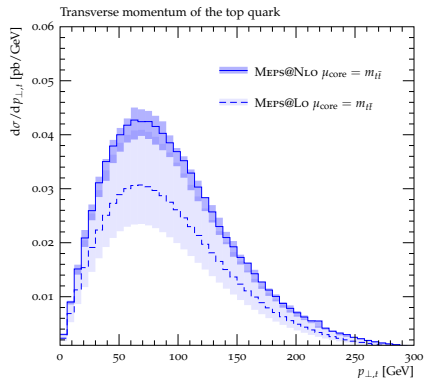
- 1) $\mu_{\text{core}} = m_{t\bar{t}}$

- 2) $\mu_{\text{core}} = \mu_{\text{QCD}} = \sqrt{2} |p_i p_j|$

$i, j \dots N_c \rightarrow \infty$ colour partners, chooses between s, t, u

\Rightarrow different behaviour for forward/backward configurations

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



Recent results – $pp \rightarrow t\bar{t} + \text{jets}$ MEPS@NLO

Setup: $p\bar{p} \rightarrow t\bar{t} + \text{jets}$

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
 $Q_{\text{cut}} = 7 \text{ GeV}$
- 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
 $Q_{\text{cut}} \in \{5, 7, 10\} \text{ GeV}$
- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}}) \alpha_s(t_1) \cdots \alpha_s(t_n)$

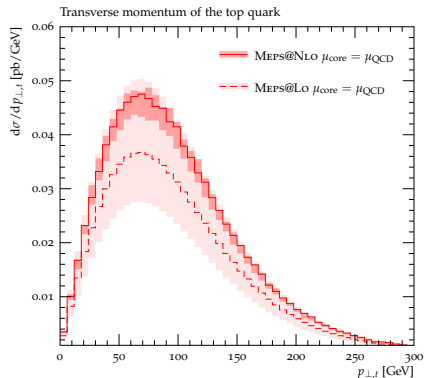
1) $\mu_{\text{core}} = m_{i\bar{i}}$

2) $\mu_{\text{core}} = \mu_{\text{QCD}} = \sqrt{2} |p_i p_j|$

$i, j \dots N_c \rightarrow \infty$ colour partners, chooses between s, t, u

\Rightarrow different behaviour for forward/backward configurations

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



Recent results – $pp \rightarrow t\bar{t} + \text{jets}$ MEPS@NLO

Setup: $p\bar{p} \rightarrow t\bar{t} + \text{jets}$

- purely perturbative calculation (no hadronisation, MPI, etc.)

- 0,1 jets @ NLO

$$Q_{\text{cut}} = 7 \text{ GeV}$$

- perturbative scale variations

$$\mu_{R/F} \in \left[\frac{1}{2}, 2\right] \mu_{\text{def}}$$

$$\mu_Q \in \left[\frac{1}{\sqrt{2}}, \sqrt{2}\right] \mu_{\text{core}}$$

- variation of merging parameter

$$Q_{\text{cut}} \in \{5, 7, 10\} \text{ GeV}$$

- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}}) \alpha_s(t_1) \cdots \alpha_s(t_n)$

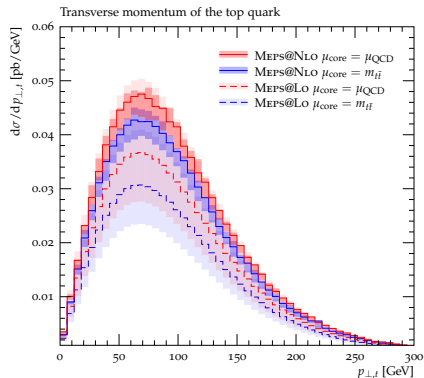
- 1) $\mu_{\text{core}} = m_{t\bar{t}}$

- 2) $\mu_{\text{core}} = \mu_{\text{QCD}} = \sqrt{2} |p_i p_j|$

$i, j \dots N_c \rightarrow \infty$ colour partners, chooses between s, t, u

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

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



Recent results – $pp \rightarrow t\bar{t} + \text{jets}$ MEPs@NLO

Setup: $p\bar{p} \rightarrow t\bar{t} + \text{jets}$

- purely perturbative calculation (no hadronisation, MPI, etc.)

- 0,1 jets @ NLO
 $Q_{\text{cut}} = 7 \text{ GeV}$

- perturbative scale variations

$$\mu_{R/F} \in \left[\frac{1}{2}, 2\right] \mu_{\text{def}}$$

$$\mu_Q \in \left[\frac{1}{\sqrt{2}}, \sqrt{2}\right] \mu_{\text{core}}$$

- variation of merging parameter

$$Q_{\text{cut}} \in \{5, 7, 10\} \text{ GeV}$$

- scale choices: $\alpha_s^{k+n}(\mu_R) = \alpha_s^k(\mu_{\text{core}}) \alpha_s(t_1) \cdots \alpha_s(t_n)$

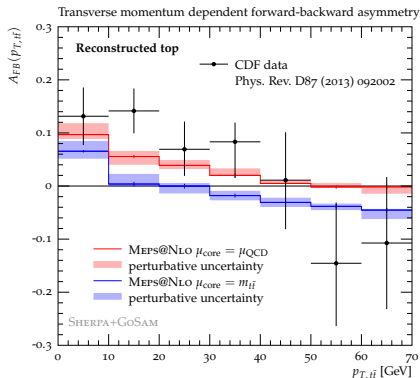
- 1) $\mu_{\text{core}} = m_{t\bar{t}}$

- 2) $\mu_{\text{core}} = \mu_{\text{QCD}} = \sqrt{2} |p_i p_j|$

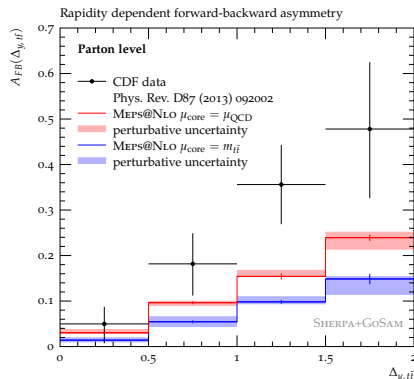
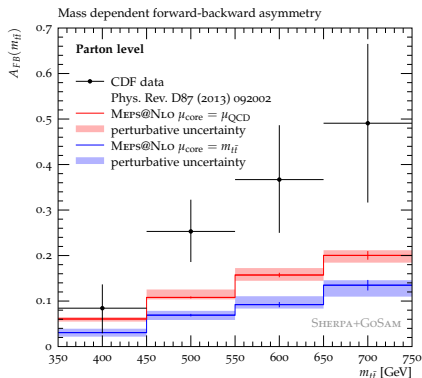
$i, j \dots N_c \rightarrow \infty$ colour partners, chooses between s, t, u

⇒ **different behaviour for forward/backward configurations**

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



Recent results – $pp \rightarrow t\bar{t} + \text{jets}$ MEPs@NLO



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

Conclusions

- multijet merging at NLO proceeds schematically as at LO
→ introduce MC-counterterm to retain NLO accuracy
- preserves NLO accuracy of the ME and accuracy of the PS in resumming hierarchies of emission scales
→ scale setting essential for recovering PS resummation

current release SHERPA-2.0.0

<http://sherpa.hepforge.org>

Thank you for your attention!

Resummation properties of parton showers

$$\langle O \rangle^{\text{PS}} = \int d\Phi_B B(\Phi_B) \left[\Delta^{(\mathcal{K})}(t_0, \mu_Q^2) O(\Phi_B) + \int_{t_0}^{\mu_Q^2} d\Phi_1 \mathcal{K}(\Phi_1) \Delta^{(\mathcal{K})}(t, \mu_Q^2) O(\Phi_R) \right]$$

- splitting kernel $\mathcal{K}(\Phi_1) \propto \frac{\alpha_s}{t} P(z)$, $\Phi_1 = \{t, z, \phi\}$
- Sudakov form factor

$$L = \log \frac{t}{t'}$$

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

- 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 $N_c \rightarrow \infty$ approximation
- $\alpha_s \rightarrow \alpha_s(k_\perp)$ catches dominant terms of higher log. order

NLOs matching

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

$$\begin{aligned} \langle O \rangle^{\text{NLOPs}} = & \int d\Phi_B \bar{B}^{(A)}(\Phi_B) \left[\Delta^{(A)}(t_0, \mu_Q^2) O(\Phi_B) \right. \\ & \left. + \int_{t_0}^{\mu_Q^2} d\Phi_1 \frac{D^{(A)}(\Phi_B, \Phi_1)}{B(\Phi_B)} \Delta^{(A)}(t, \mu_Q^2) O(\Phi_R) \right] \\ & + \int d\Phi_R \left[R(\Phi_R) - \sum_i D_i^{(A)}(\Phi_R) \right] O(\Phi_R) \end{aligned}$$

$$\Delta^{(A)}(t, t') = \exp \left[- \int_t^{t'} d\Phi_1 D^{(A)}/B \right]$$

- use $D_i^{(A)}$ as resummation kernels
- resummation phase space limited by $\mu_Q^2 = t_{\max}$
 - starting scale of parton shower evolution
 - should be of the order of the hard resummation scale
- POWHEG and MC@NLO now differ in choice of $D_i^{(A)}$ and μ_Q^2
- SHERPA: $D_i^{(A)} = D_i^{(S)} \Theta(\mu_Q^2 - t)$ ($N_c = 3$ CS kernels), μ_Q free

MEPs – Multijet merging at LO

$$\begin{aligned}
 \langle O \rangle^{\text{MEPs}} &= \int d\Phi_n B_n \left[\Delta_n^{(\mathcal{K})}(t_0, \mu_Q^2) O_n \right. \\
 &\quad \left. + \int_{t_0}^{\mu_Q^2} d\Phi_1 \mathcal{K}_n \Delta_n^{(\mathcal{K})}(t_{n+1}, \mu_Q^2) \Theta(Q_{\text{cut}} - Q) O_{n+1} \right] \\
 &+ \int d\Phi_{n+1} B_{n+1} \Delta_n^{(\mathcal{K})}(t_{n+1}, \mu_Q^2) \Theta(Q - Q_{\text{cut}}) \\
 &\quad \times \left[\Delta_{n+1}^{(\mathcal{K})}(t_0, t_{n+1}) O_{n+1} + \int_{t_0}^{t_{n+1}} d\Phi_1 \mathcal{K}_{n+1} \Delta_{n+1}^{(\mathcal{K})}(t_{n+2}, t_{n+1}) O_{n+2} \right]
 \end{aligned}$$

- 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
→ 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

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

$$= \int d\Phi_n B_n \left[\Delta_n^{(\mathcal{K})}(t_0, \mu_Q^2) O_n \right. \\ \left. + \int_{t_0}^{\mu_Q^2} d\Phi_1 \left(\mathcal{K}_n \Theta(Q_{\text{cut}} - Q) + \frac{B_{n+1}}{B_n} \Theta(Q - Q_{\text{cut}}) \right) \right. \\ \left. \times \Delta_n^{(\mathcal{K})}(t_{n+1}, \mu_Q^2) O_{n+2} \right]$$

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

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

MEPs@NLO – Multijet merging at NLO

$\langle O \rangle_{\text{MEPs@NLO}}$

Höche, Krauss, MS, Siegert arXiv:1207.5030

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

$$\begin{aligned}
 &= \int d\Phi_n \bar{B}_n^{(A)} \left[\Delta_n^{(A)}(t_0, \mu_Q^2) O_n \right. \\
 &\quad \left. + \int_{t_0}^{\mu_Q^2} d\Phi_1 \frac{D_n^{(A)}}{B_n} \Delta_n^{(A)}(t_{n+1}, \mu_Q^2) \Theta(Q_{\text{cut}} - Q) O_{n+1} \right] \\
 &+ \int d\Phi_{n+1} \left[R_n - D_n^{(A)} \right] \Theta(Q_{\text{cut}} - Q) O_{n+1} \\
 &+ \int d\Phi_{n+1} \bar{B}_{n+1}^{(A)} \left[1 + \frac{B_{n+1}}{\bar{B}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} d\Phi_1 \mathcal{K}_n \right] \Delta_n^{(K)}(t_{n+1}, \mu_Q^2) \Theta(Q - Q_{\text{cut}}) \\
 &\quad \times \left[\Delta_{n+1}^{(A)}(t_0, t_{n+1}) O_{n+1} + \int_{t_0}^{t_{n+1}} d\Phi_1 \frac{D_{n+1}^{(A)}}{B_{n+1}} \Delta_{n+1}^{(A)}(t_{n+2}, t_{n+1}) O_{n+2} \right] \\
 &+ \int d\Phi_{n+2} \left[R_{n+1} - D_{n+1}^{(A)} \right] \Delta_n^{(K)}(t_{n+1}, \mu_Q^2) \Theta(Q - Q_{\text{cut}}) O_{n+2}
 \end{aligned}$$

MEPs@NLO – Multijet merging at NLO

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

$$\begin{aligned}
 = \int d\Phi_n B_n & \left[\Delta_n^{(\mathcal{K})}(t_0, \mu_Q^2) O_n \right. \\
 & + \int_{t_0}^{\mu_Q^2} d\Phi_1 \left(\frac{D_n^{(A)}}{B_n} \Delta_n^{(A)}(t_{n+1}, \mu_Q^2) \Theta(Q_{\text{cut}} - Q) \right. \\
 & \quad \left. \left. + \frac{\bar{B}_{n+1}^{(A)}}{B_n} \tilde{\Delta}_n^{(\mathcal{K})}(t_{n+1}, \mu_Q^2) \Theta(Q - Q_{\text{cut}}) \right) \right. \\
 & \quad \left. \times O_{n+2} \right]
 \end{aligned}$$

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

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