Matching and Merging at NLO

T. Gehrmann, S. Höche, F. Krauss, M. Schönherr and F. Siegert

arXiv:1207.5030/1 [hep-ph], arXiv:1208.2815 [hep-ph]

TH/LPCC Institute on SM at the LHC

CERN, 02/10/12

MC@NLO basics

[Frixione,Webber] hep-ph/0204244

- Differential event rate to $\mathcal{O}(\alpha_s)$ in PS

$$\frac{\mathrm{d}\sigma_{\mathrm{PS}}}{\mathrm{d}\Phi_n} = \mathrm{B}_n \left[\Delta_n^{(\mathrm{K})}(t_c, \mu_Q^2) + \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1 \, \mathrm{K}_n \, \Delta_n^{(\mathrm{K})}(t(\Phi_1), \mu_Q^2) \right]$$

K_n - sum of PS kernels for n-parton final state

- Modified subtraction for matching ME and PS

$$\bar{\mathrm{B}}_n^{(\mathrm{A})} = \left(\mathrm{B}_n + \tilde{\mathrm{V}}_n + \mathrm{I}_n \right) + \int \mathrm{d}\Phi_1 \left(\mathrm{D}_n^{(\mathrm{A})} - \mathrm{S}_n \right)$$

$$\mathrm{H}_n^{(\mathrm{A})} = \mathrm{R}_n - \mathrm{D}_n^{(\mathrm{A})}$$

$\mathrm{D}_n^{(\mathrm{A})}$ includes phase-space constraint $\Theta(\mu_Q^2 - t)$

- Differential event rate to $\mathcal{O}(\alpha_s)$ in MC@NLO

$$\frac{\mathrm{d}\sigma_{\mathrm{NLOPS}}}{\mathrm{d}\Phi_n} = \bar{\mathrm{B}}_n^{(\mathrm{A})} \left[\Delta_n^{(\mathrm{A})}(t_c) + \int_{t_c} \mathrm{d}\Phi_1 \, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n} \, \Delta_n^{(\mathrm{A})}(t(\Phi_1)) \right] + \int \mathrm{d}\Phi_1 \, \mathrm{H}_n^{(\mathrm{A})}$$

MC@NLO variants

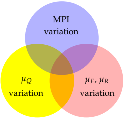
[Frixione,Webber] hep-ph/0204244

- Original algorithm formulated such that $\mathrm{D}_n^{(\mathrm{A})} \to \mathrm{D}_n^{(\mathrm{K})} = \mathrm{B}_n \mathrm{K}_n$,
  i.e. modified subtraction carried out with parton-shower approximation
- Exact only in collinear region
  Missing subleading colour terms in single-logarithmic divergences
- Solved by smoothly fading out real-emission correction in singly-soft region
  Correction for missing terms, but only affects unresolved gluons anyhow

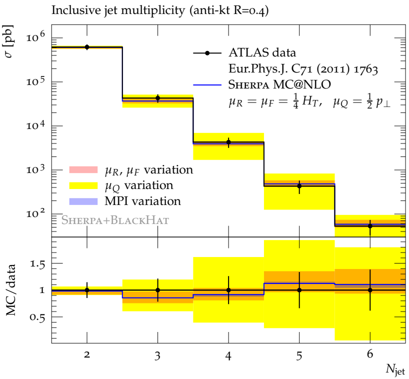
[Krauss,Schönherr,Siegert,SH] arXiv:1111.1220

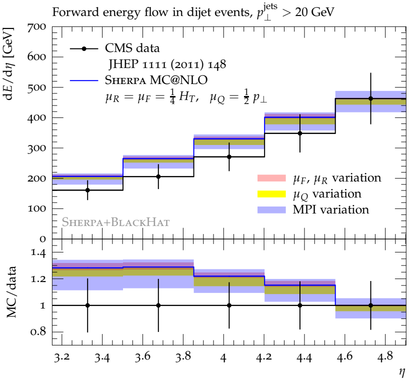
- Alternative solution employs $\mathrm{D}_n^{(\mathrm{A})} \to \mathrm{D}_n^{(\mathrm{S})} = \mathrm{S}_n$
  i.e. parton-shower evolution performed with NLO subtraction terms
- Leads to non-probabilistic Sudakov factor $\Delta_n^{(\mathrm{S})}$
  Requires modification of veto algorithm
- Exact cancellation of all divergences without additional smoothing
  Equivalent to one-step full colour parton shower algorithm

MC@NLO uncertainties



[Schönherr,SH] arXiv:1208.2815





- Jet multiplicity → uncertainty due to choice of μ_Q^2
- Forward energy flow → major uncertainty from underlying event

MC@NLO for higher parton multiplicity

[Krauss,Schönherr,Siegert,SH] arXiv:1207.5030
[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031

- Compound evolution kernel for $n+k$-parton final state

$$\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k} = \mathrm{D}^{(\mathrm{A})}_{n+k}\,\Theta(t_{n+k}-t_{n+k+1}) + \mathrm{B}_{n+k}\sum_{i=n}^{n+k-1}\mathrm{K}_i\,\Theta(t_i-t_{n+k+1})\Theta(t_{n+k+1}-t_{i+1})$$

t_i - nodal scales of parton emission in corresponding PS history

- Extended modified subtraction

$$\tilde{\mathrm{B}}^{(\mathrm{A})}_{n+k} = \left(\mathrm{B}_{n+k}+\tilde{\mathrm{V}}_{n+k}+\mathrm{I}_{n+k}\right)+\int\mathrm{d}\Phi_1\left(\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k}-\mathrm{S}_{n+k}\right)$$

$$\tilde{\mathrm{H}}^{(\mathrm{A})}_{n+k} = \mathrm{R}_{n+k}-\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k}$$

- Differential event rate for inclusive final state to $\mathcal{O}(\alpha_s)$

$$\frac{\mathrm{d}\sigma^{n+k,\mathrm{incl}}_{\mathrm{NLOPS}}}{\mathrm{d}\Phi_{n+k}} = \Theta(Q_{n+k}-Q_{\mathrm{cut}}) \times\left\{\tilde{\mathrm{B}}^{(\mathrm{A})}_{n+k}\left[\tilde{\Delta}^{(\mathrm{A})}_{n+k}(t_c)+\int_{t_c}\mathrm{d}\Phi_1\,\frac{\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k}}{\mathrm{B}_{n+k}}\,\tilde{\Delta}^{(\mathrm{A})}_{n+k}(t(\Phi_1))\right]+\int\mathrm{d}\Phi_1\,\tilde{\mathrm{H}}^{(\mathrm{A})}_{n+k}\right\}$$

ME+PS merging at NLO

[Krauss,Schönherr,Siegert,SH] arXiv:1207.5030
[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031

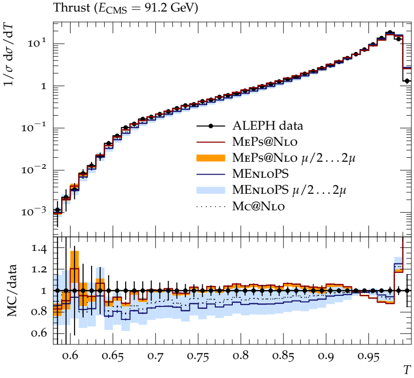
- Differential event rate for exclusive final state to $\mathcal{O}(\alpha_s)$

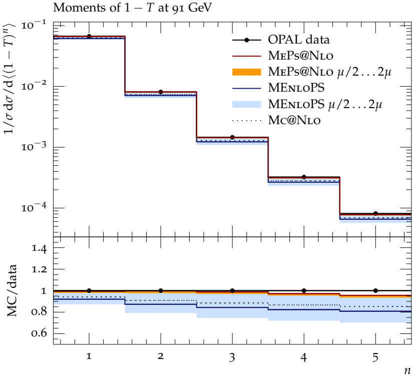
$$\frac{\mathrm{d}\sigma^{n+k,\mathrm{excl}}_{\mathrm{NLOPS}}}{\mathrm{d}\Phi_{n+k}} = \Theta(Q_{n+k} - Q_{\mathrm{cut}})$$
$$\times \left\{ \tilde{\mathrm{B}}^{(\mathsf{A})}_{n+k} \left[\tilde{\Delta}^{(\mathsf{A})}_{n+k}(t_c) + \int_{t_c} \mathrm{d}\Phi_1 \, \frac{\tilde{\mathrm{D}}^{(\mathsf{A})}_{n+k}}{\mathrm{B}_{n+k}} \, \tilde{\Delta}^{(\mathsf{A})}_{n+k}(t(\Phi_1)) \, \Theta(Q_{\mathrm{cut}} - Q_{n+k+1}) \right] \right.$$
$$\left. + \int \mathrm{d}\Phi_1 \, \tilde{\mathrm{H}}^{(\mathrm{A})}_{n+k} \, \tilde{\Delta}^{(\mathrm{K})}_{n+k}(t(\Phi_1); > Q_{\mathrm{cut}}) \, \Theta(Q_{\mathrm{cut}} - Q_{n+k+1}) \right\}$$

- Technically same as LO algorithm, including truncated vetoed PS
- Sudakov factor on top of $\mathrm{H}^{(\mathrm{A})}_{n+k}$ is $1 + \mathcal{O}(\alpha_s)$
  $\rightarrow$ trivially NLO correct in exclusive $n + k$-jet region
- Extended modified subtraction cumbersome
  $\rightarrow$ avoid by using CKKW-L or setting $t = Q^2$

$e^+e^- \to$ hadrons at LEP

[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031

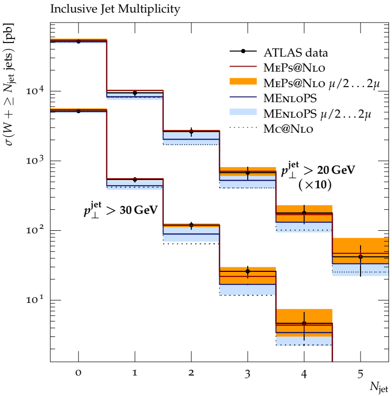


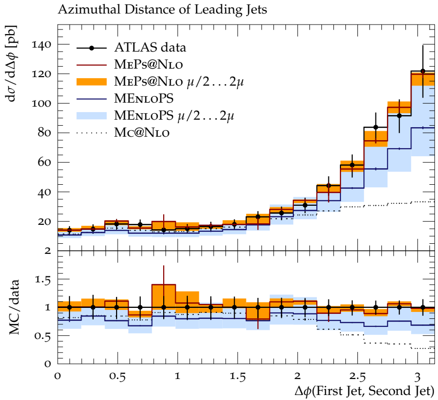


- MEPS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO
- MENLOPS with 3-6 jet PL at LO

W+jets at LHC

[Krauss,Schönherr,Siegert,SH] arXiv:1207.5030

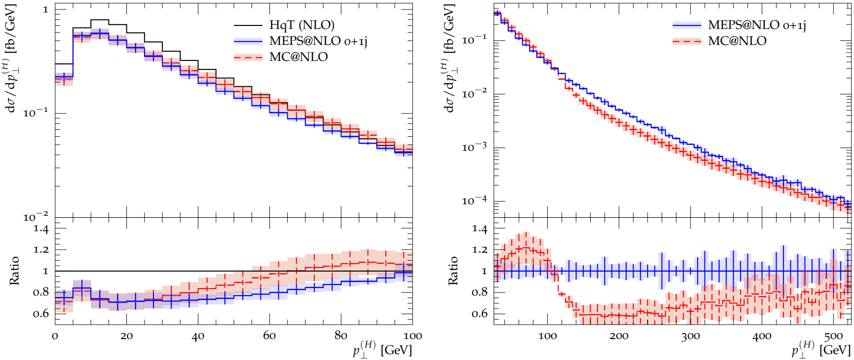




- MEPS@NLO with 0,1&2 jet PL at NLO plus 3&4 jet PL at LO
- MENLOPS with 1-4 jet PL at LO

h+jets at LHC

[Krauss,Schönherr,Siegert,SH] arXiv:12mm.nnnn



- MEPS@NLO with 0&1 jet PL at NLO

Closed issues:

- Automated MC@NLO
  Only ingredient needed is virtual ME $\rightarrow$ BLHA
- ME+PS Merging at NLO
  Current bottleneck is speed of virtual at high multiplicity

Some open questions:

- How to quantify PS uncertainties in matching?
  Need to get closer to analytical approaches
  Up to now only μ_Q-variation
- Full-color parton showers needed?
  Reduce uncertainties in MEPS@NLO
- Weighted parton showers
  Do speed and convenience justify weights?