NLO & PS

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$(\mathrm{NNLO}_0 + \sum_k \mathrm{NLO}_k + \sum_l \mathrm{LO}_l) \times \mathrm{Resum} \times \mathrm{PS}$

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Nomenclature.

Matching:
Combine a higher-order calculation (NLO, NNLO, ...) for *one* jet multiplicity with showers such as to preserve the repsective fixed order expansion.

Merging:
Combine calculations (LO, NLO, ...) for *several* jet multiplicities with showers such as to reproduce the respective fixed order expansion (and Sudakov surpression) in each jet bin.

Where are we at?

$\text{NLO}_0 \times \text{PS}$

$(\sum_l \text{LO}_l) \times \text{PS}$

$(\sum_k \text{NLO}_k + \sum_l \text{LO}_l) \times \text{PS}$

$(\text{NLO}_0 + \text{NLO}_1) \times \text{Resum} \times \text{PS}$

All under control?

Outline (and summary and input for discussion).

$$\mathrm{PS}\left[\mathrm{d}\sigma^{\text{matched}}_{\text{NLO}}\right] = \mathrm{d}\sigma_{\text{NLO}} + \mathcal{O}(\alpha_s^2) + ?$$

$$\mathrm{PS}\left[\mathrm{d}\sigma^{\text{merged}}\right]\Big|_{>,\geq n\text{-jet}} = \mathrm{d}\sigma^{\text{fixed order}}_{>,\geq n\text{-jet}}\,\Delta_{>,\geq n\text{-jet}} + ?$$

? $\leftrightarrow$ genuine uncertainty or serious problem? What about uncertainties at all?

To what accuracy do we need to push showers for matching/merging?

Slightly off topic (a.k.a. outlook):

- What about combining showers and resummation?
- What about NNLO?

Matching.

$$\mathrm{PS}_\mu \left[\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} \right] = \mathrm{d}\sigma_{\mathsf{NLO}} + \mathcal{O}(\alpha_s^2)$$

Solution is simple:

$$\begin{aligned} \mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} &= [\mathrm{d}\sigma_B(\phi_n) + \mathrm{d}\sigma_{V+I}(\phi_n)]\, u(\phi_n) \\ &+ \left[\mathrm{d}\sigma_{PS}(\phi_{n+1})\theta(q-\mu) - \mathrm{d}\sigma_A(\phi_{n+1}) \right] u(\tilde{\phi}_n) \\ &+ \left[\mathrm{d}\sigma_R(\phi_{n+1}) - \mathrm{d}\sigma_{PS}(\phi_{n+1})\theta(q-\mu) \right] u(\phi_{n+1}) \end{aligned}$$

Whatever $\mathrm{d}\sigma_{PS}$ is: This includes both MC@NLO and POWHEG in various flavours.

Matching.

$$\mathrm{PS}_\mu \left[\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} \right] = \mathrm{d}\sigma_{\mathsf{NLO}} + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\mu^2/Q^2)$$

Solution is simple:

$$\begin{aligned} \mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} &= [\mathrm{d}\sigma_B(\phi_n) + \mathrm{d}\sigma_{V+I}(\phi_n)]\, u(\phi_n) \\ &+ \left[\mathrm{d}\sigma_{PS}(\phi_{n+1}) - \mathrm{d}\sigma_A(\phi_{n+1}) \right] u(\tilde{\phi}_n) \\ &+ \left[\mathrm{d}\sigma_R(\phi_{n+1}) - \mathrm{d}\sigma_{PS}(\phi_{n+1}) \right] u(\phi_{n+1}) \end{aligned}$$

Whatever $\mathrm{d}\sigma_{PS}$ is: This includes both MC@NLO and POWHEG in various flavours.

Matching.

$$\mathrm{PS}_\mu\left[\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}}\right] = \mathrm{d}\sigma_{\mathsf{NLO}} + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\mu^2/Q^2) + \mathcal{O}(1/N_c^2)$$

Solution is not so simple:

$$\begin{aligned}
\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} \quad = \quad & \left[\mathrm{d}\sigma_B(\phi_n) + \mathrm{d}\sigma_{V+I}(\phi_n)\right] u(\phi_n) \\
+ \quad & \left[\mathrm{d}\sigma_{PS}(\phi_{n+1}) \qquad - \mathrm{d}\sigma_A(\phi_{n+1}) + \mathrm{d}\sigma_{PS}^{\mathsf{repair}}(\phi_{n+1})\right] u(\tilde{\phi}_n) \\
+ \quad & \left[\mathrm{d}\sigma_R(\phi_{n+1}) - \mathrm{d}\sigma_{PS}(\phi_{n+1}) \qquad - \mathrm{d}\sigma_{PS}^{\mathsf{repair}}(\phi_{n+1})\right] u(\phi_{n+1})
\end{aligned}$$

Whatever $\mathrm{d}\sigma_{PS}$ is: This includes both MC@NLO and POWHEG in various flavours.

Matching.

$$\mathrm{PS}_\mu \left[\mathrm{d}\sigma_{\text{NLO}}^{\text{matched}} \right] = \mathrm{d}\sigma_{\text{NLO}} + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\mu^2/Q^2) + \mathcal{O}(1/N_c^2)$$

$+\mathcal{O}(\mu^2/Q^2)$ not a problem ($\rightarrow$ hadronization). Genuine uncertainty.

$+\mathcal{O}(1/N_c^2)$ is a problem.

Solutions:

- Improve the shower to at least capture subleading-N_c *upon expansion*.

  [Sherpa MC@NLO] [SP & M. Sjödahl '11] [applies to Powheg as well]

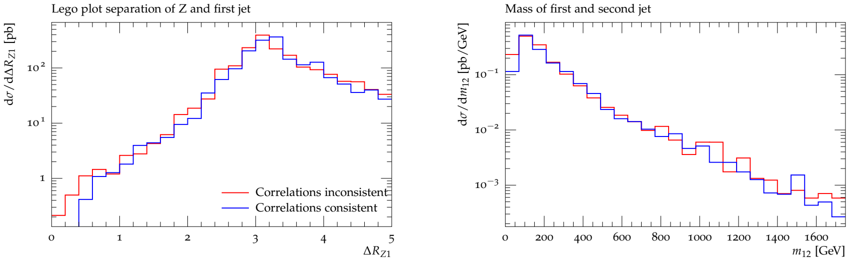
  Note that this does not imply that we get full NLL right.
- Use freedom in power corrections to avoid the problem. [SP – in preparation]

Matching.

$$\mathrm{PS}_\mu \left[\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}} \right] = \mathrm{d}\sigma_{\mathsf{NLO}} + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\mu^2/Q^2) + \mathcal{O}(1/N_c^2)$$

$+\mathcal{O}(1/N_c^2)$ is a problem? $\rightarrow$ need observables to check this.

[SP – work in progress]



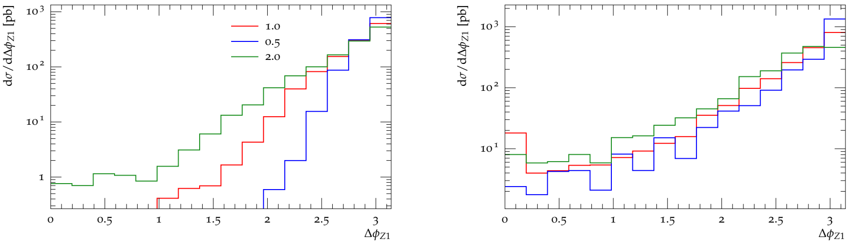
Matching.

Shower hard scale $\leftrightarrow$ resummation scale.

Variations are sensible, impact of *matching* clearly seen.

$Z +$ jet LO$\times$PS vs NLO$\times$PS

[SP – work in progress]



This only works for *sensible* hard scale choices
(or an equivalent cutoff mechanism for exponentiation).

Tree level merging.

Merging condition: LO $\times$ products of splitting kernels $\to$ exact tree level ME.

$$\mathrm{PS}_\mu \left[\mathrm{d}\sigma^{\text{merged}}_{N,\mu} \right] = \sum_{k=0}^{N-1} \mathrm{d}\sigma^{(0)}_\mu(\phi_k, q_k)\Delta_k(\mu|q_k|\cdots|q_0) \; + \mathrm{PS}_\mu \left[\mathrm{d}\sigma^{(0)}_\mu(\phi_N, q_N)\Delta_{N-1}(q_N|\cdots|q_0) \right]$$

- Parton shower infrared cutoff applied to reclustered tree level matrix elements,
- proper Sudakov form factors to account for exclusiveness,
- no merging scale required in the first place.

Tree level merging.

Cut off matrix elements at $\rho > \mu$:

$$\mathrm{PS}_\mu \left[\mathrm{d}\sigma^{\mathsf{merged}}_{N,\rho} \right] =$$

$$\sum_{k=0}^{N-1} \mathrm{PS}_{\mu|\rho} \left[\mathrm{d}\sigma^{(0)}_\rho(\phi_k, q_k) \Delta_k(\rho|q_k|\cdots|q_0) \right] + \mathrm{PS}_\mu \left[\mathrm{d}\sigma^{(0)}_\rho(\phi_N, q_N) \Delta_{N-1}(q_N|\cdots|q_0) \right]$$

- ‘Traditional’ ME+PS merging, [CKKW, /Lönnblad, ...]
- no restriction on showering off the highest multiplicity.

Inclusive cross sections?

[Lönnblad & Prestel '12] [SP, '12]

Exclusive cross sections are fine by the very definition of the merging condition.

Inclusive cross sections are generally spoiled, say $\geq N-1$ (parton shower) jets:

$$\mathrm{d}\sigma_\rho^{(0)}(\phi_{N-1}, q_{N-1})\Delta_{N-2}(q_{N-1}|\cdots|q_0) +$$
$$\int_\rho^{q_{N-1}} \mathrm{d}q_N \left(\frac{\mathrm{d}\sigma_\rho^{(0)}(\phi_N, q_N)}{\mathrm{d}q_N} - \frac{\mathrm{d}\phi_N}{\mathrm{d}\phi_{N-1}\mathrm{d}q_N} P_\rho(\phi_{N-1}, q_N)\mathrm{d}\sigma_\rho^{(0)}(\phi_{N-1}, q_{N-1}) \right) \times$$
$$\Delta_{N-1}(q_N|\cdots|q_0)$$

Natural consequence of replacing splitting kernels by matrix elements *except for the Sudakov exponents.* [cf. matrix element correction approaches like Vincia, Skands et al.]

Not a problem as long as the shower kernels approximate the singly-unresolved limits of the *tree level matrix elements* sufficiently good.

For NLO merging $\mathrm{d}\sigma_\rho^{(0)} = \mathrm{d}\sigma_\rho^{\mathrm{LO}} \to \mathrm{d}\sigma_\rho^{\mathrm{NLO}}$: troublesome.

Discussion.

$$\mathrm{PS}_\mu\left[\mathrm{d}\sigma_{\mathsf{NLO}}^{\mathsf{matched}}\right] = \mathrm{d}\sigma_{\mathsf{NLO}} + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\mu^2/Q^2) + \mathcal{O}(1/N_c^2)$$

Need to accept $\mathcal{O}(\mu^2/Q^2)$. $\mathcal{O}(1/N_c^2)$ could be relevant.
Various uncertainties hidden in $\mathcal{O}(\alpha_s^2)$ – which one of those should we consider and how?

What about inclusive cross sections in merging and accuracy in low multi jet bins?

Shower phase space $\leftrightarrow$ resummation scale variation, what logs?

Exponentiation of finite terms: bug or feature or part of the uncertainty?

Combination with resummation: Is this settled at all? Do we screw up shower features?