Automated QED NLO parton shower matching

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Outline

Introduction

- Next-to-leading order (NLO) electroweak corrections now needed for many observables at the LHC
- EW Sudakov high-energy resummation already used Denner, Pozzorini '00, Bothmann, Napoletano '20
- QED resummation effects also need to be included for any leptonic final state
- Either YFS matched to higher orders Yennie, Frautschi, Suura '61, Krauss, Schönherr '08, Krauss, Price, Schönherr '22, LF, Schönherr '22 or NLO-matched QED parton showers
- Use well-tested methods developed for QCD: MC@NLO Frixione, Webber '02, POWHEG Nason '04, Frixione, Nason, Oleari '07

NLO matching

Anatomy of an NLO calculation

A general NLO calculation of an infrared-safe observable O in a $2 \to n$ process can be written schematically in the form

$$\begin{aligned}\langle O\rangle^{\mathrm{NLO}} &= \int \mathrm{d}\Phi_n \left[B + \tilde{V}\right] O\left(\{p_n\}\right) + \int \mathrm{d}\Phi_{n+1}\, R_{n+1} O\left(\{p_{n+1}\}\right) \\ &= \int \mathrm{d}\Phi_n \left[B + \tilde{V} + \sum_{\widetilde{ij},\tilde{k}} I^S_{\widetilde{ij},\tilde{k}}\right] O\left(\{p_n\}\right) \\ &\quad + \int \mathrm{d}\Phi_{n+1} \left[R_{n+1} O\left(\{p_{n+1}\}\right) - \sum_{ij,k} D^S_{ij,k}\, O\left(\{p_n\}\right)\right]\end{aligned}$$

where $D^S_{ij,k}$ are a set of process-independent subtraction terms and $I^S_{\widetilde{ij},\tilde{k}}$ are their analytic d-dimensional integrals.

Introducing the parton shower

A leading-order plus parton shower calculation has the form

$$\langle O \rangle^{\mathrm{PS}} = \int \mathrm{d}\Phi_n \, B \, \mathcal{F}_n(\Phi_n, O)$$

where $\mathcal{F}_n(\Phi_n, O)$ is the unitary parton shower factor, defined recursively as

$$\mathcal{F}_n(\Phi_n, O) = \Delta_n(\mu_Q^2, t_c) \, O(\{p_n\}) + \int \mathrm{d}\Phi_1 \, \Delta_n(\mu_Q^2, t) \, \mathcal{F}_{n+1}(\Phi_{n+1}, O) \, \mathcal{K}$$

where

$$\Delta_n(\mu_Q^2, t) = \exp\left(-\int_t^{\mu_Q^2} \mathrm{d}\Phi_1 \, \mathcal{K} \right)$$

is the Sudakov form factor which describes the no-emission probability, and $\mathcal{K}$ is the parton shower splitting kernel.

What is NLO matching?

NLO matching: producing a prediction for $\langle O \rangle$ which contains the parton shower factor $\mathcal{F}_n(\Phi_n, O)$ but which gives the correct NLO value for the observable:

$$\langle O \rangle^{\text{Matched}} = \langle O \rangle^{\text{NLO}} + \mathcal{O}(\alpha^{m+2})$$

Crucially, we must avoid double counting of the first emission.

Starting point: interleaved dipole QCD+QED shower (to be published) and SHERPA's implementation of the QCD MC@NLO Höche et al. '12

The MC@NLO matching method can be written as

$$\langle O\rangle^{\text{MC@NLO}} = \int \mathrm{d}\Phi_n \bar{B}\left[\bar{\Delta}\, O\left(\{p_n\}\right) + \sum_{ij,k}\int \mathrm{d}\Phi_1 O\left(\{p_{n+1}\}\right)\frac{D^A_{ij,k}}{B}\bar{\Delta}\right]$$

$$+\int \mathrm{d}\Phi_{n+1}\left[R - \sum_{ij,k} D^A_{ij,k}\right] O\left(\{p_{n+1}\}\right)$$

where the modified Sudakov factor is

$$\bar{\Delta}(\mu_Q^2, t) = \exp\left(-\int_t^{\mu_Q^2}\mathrm{d}\Phi_1 \sum_{ij,k}\frac{D^A_{ij,k}}{B}\right)$$

and we have introduced the shorthand (suppressing sums and indices)

$$\bar{B} = B + \tilde{V} + I^S + \int d\Phi_1\left[D^A - D^S\right]$$

What is NLO matching?

Many different methods, but here we use the S-MC@NLO method Höche et al. '12

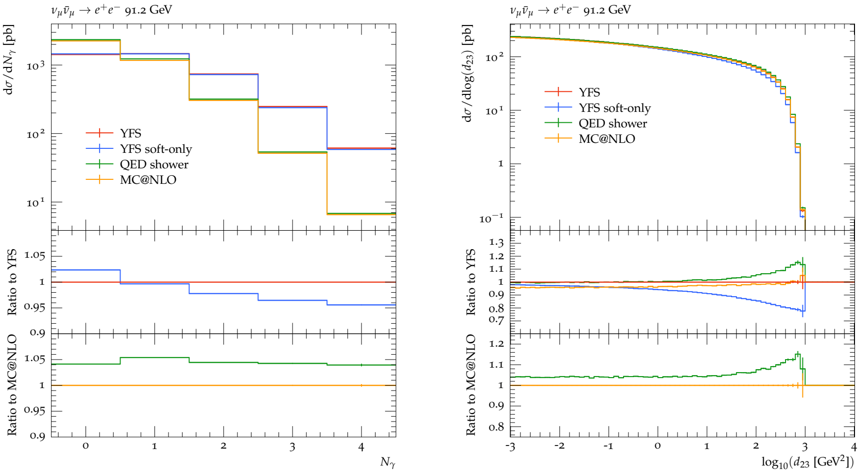
$$B\,\mathcal{K}_{ij,k} = D^{A}_{ij,k} = D^{S}_{ij,k}\Theta(\mu_Q^2 - t)$$

where μ_Q^2 is the shower starting scale.
This means that the $\bar{B}$ function does not (usually) depend on the radiative phase space, so the evaluation is simpler.

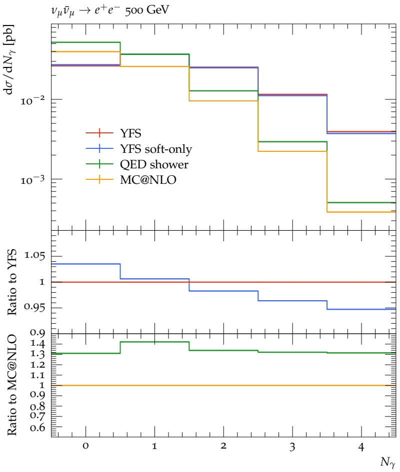
Results

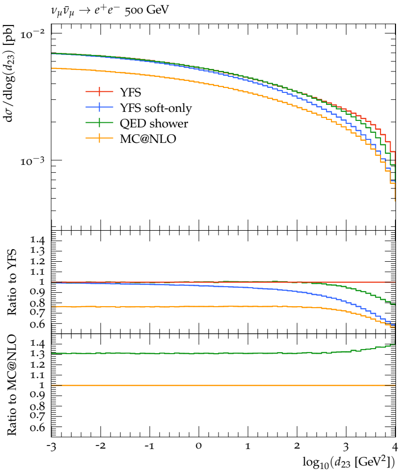
[all plots are preliminary]

QED shower and MC@NLO for $\nu_\mu \bar{\nu}_\mu \to e^+ e^-$

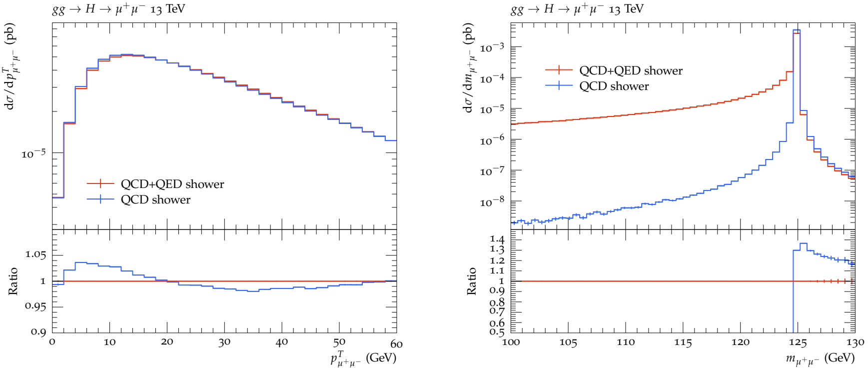


QED shower and MC@NLO for $\nu_\mu\bar{\nu}_\mu \to e^+e^-$ at 500 GeV

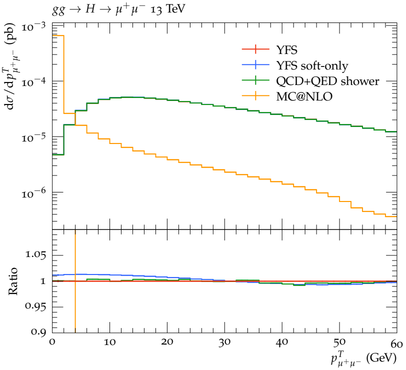


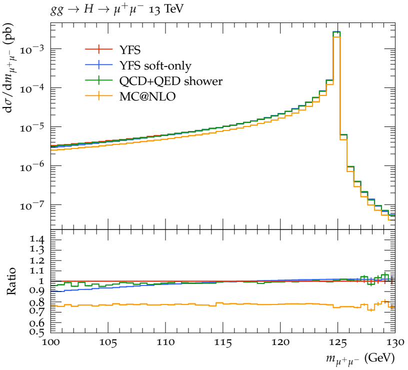


QCD+QED shower for $gg \to H \to \mu^+\mu^-$



QED MC@NLO for $gg \to H \to \mu^+\mu^-$





Conclusions

- We developed an interleaved QCD+QED parton shower
- We introduced an automated method to match QED NLO with a final-state QED parton shower
- Next step: QCD+QED MC@NLO
- These developments will be released in a future version of SHERPA (3.x)

YFS vs QED shower for $gg \to H \to \mu^+\mu^-e^+e^-$

Preliminary