THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
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Matching with KrkNLO

theory and progress

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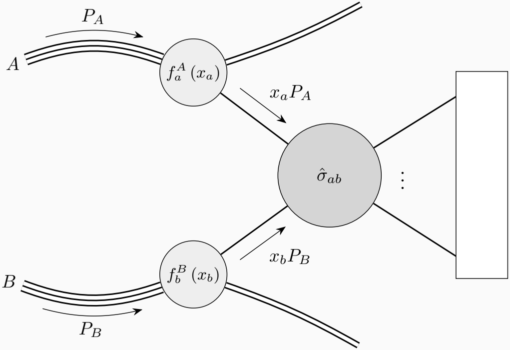
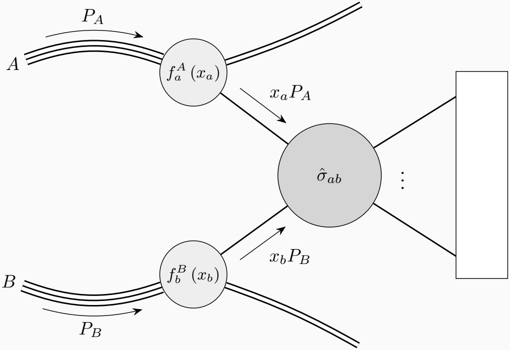
Matching at NLO



$$\mathrm{d}\sigma_{AB\to X}(P_1, P_2) = \sum_{a,b} \int_{[0,1]^2} \mathrm{d}\xi_1 \mathrm{d}\xi_2 \; f_a^A(\xi_1)\, f_b^B(\xi_2)\; \mathrm{d}\hat{\sigma}_{ab\to X}(\xi_1 P_1, \xi_2 P_2)$$

Perturbative QCD + factorisation



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to NLO,

$$\mathrm{d}\hat{\sigma}_{ab} = \left(\frac{\alpha_s}{2\pi}\right)^k \mathrm{d}\hat{\sigma}_{ab}^{\mathrm{B}} + \left(\frac{\alpha_s}{2\pi}\right)^{k+1} \left[\mathrm{d}\hat{\sigma}_{ab}^{\mathrm{V}} + \mathrm{d}\hat{\sigma}_{ab}^{\mathrm{R}}\right] + \ldots$$

Observables

Interested in some[1] function u of phase-space:

$$\sigma[u] = \left(\frac{\alpha_s}{2\pi}\right)^k \int \mathrm{d}\hat{\sigma}_{ab}^{\mathrm{B}}\, u(\phi_m)$$

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divergences $\longrightarrow$ subtraction:

$$= \int \mathrm{d}\phi_m\, u(\phi_m) \left[\mathrm{B}(\phi_m) + \mathrm{V}(\phi_m) + \mathrm{d}\phi_{+1} \sum_\alpha \mathrm{S}^{(\alpha)}(\phi_m \cdot \phi_{+1})\right]$$

[1] infrared and collinear safe

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[1] infrared and collinear safe

New legs from old

What is a parton shower?

$$
\begin{aligned}
\mathrm{PS}\left[u(\phi_m)\right] = {} & \Delta_{\mu_s}^{Q(\phi_m)}\, u(\phi_m) \\
& + \sum_\alpha \int \mathrm{d}q(\phi_m)\, \Theta[\mu_s < \mu(q) < Q(\phi_m)]\, \Delta_{\mu(q)}^{Q(\phi_m)} \\
& \quad \times P_m^{(\alpha)}(q)\, \Theta_{\mathrm{PS}}^{(\alpha)} \left[\Phi_{m+1}^{(\alpha)}(\phi_m; q)\right]\, \mathrm{PS}\left[u(\Phi_{m+1}^{(\alpha)}(\phi_m, q))\right]
\end{aligned}
$$

where

$$
\Delta_{\mu_s}^{Q(\phi_m)} = \exp\left[-\sum_\alpha \int \mathrm{d}q(\phi_m)\, \Theta[\mu_s < \mu(q) < Q(\phi_m)]\, P_m^{(\alpha)}(q)\, \Theta_{\mathrm{PS}}^{(\alpha)}\right]
$$

NLO matching criterion

$$\hat{\sigma}^{\mathrm{NLO+PS}}[u] = \hat{\sigma}^{\mathrm{NLO}}[u] + \mathcal{O}\left(\alpha_s^2\right) + \mathcal{O}\left(\frac{\mu_s}{Q}\right)$$

[2] Based on ongoing work with Simon Plätzer.

NLO matching criterion

$$\hat{\sigma}^{\mathrm{NLO+PS}}[u] = \hat{\sigma}^{\mathrm{NLO}}[u] + \mathcal{O}\left(\alpha_s^2\right) + \mathcal{O}\left(\frac{\mu_s}{Q}\right)$$

leads to:[2]

$$\begin{aligned}
\mathrm{d}\phi_m\; u(\phi_m)\,\Theta_{\mathrm{cut}}[\phi_m] \quad & \Bigg[\Bigg\{\mathrm{B}(\phi_m) + \mathrm{V}(\phi_m) + \sum_\alpha \Big[\mathrm{I}^{(\alpha)}(\phi_m) + \mathrm{d}x\,(\mathrm{P}+\mathrm{K})^{(\alpha)}(x;\phi_m)\Big]\Bigg\} \\
& - \sum_\alpha \mathrm{d}q^{(\alpha)} \left\{\mathrm{D}^{(\alpha)}\left(\Phi^{(\alpha)}_{m+1}\right)\right\} + \sum_\alpha \mathrm{d}q^{(\alpha)} \left\{f^{(\alpha)}(\Phi^{(\alpha)}_{m+1})\right\} \\
& + \sum_\alpha \mathrm{d}q^{(\alpha)} \left\{\Theta^{(\alpha)}_{\mathrm{PS}}\left[\Phi^{(\alpha)}_{m+1}\right]\ \mathrm{PS}^{(\alpha)}\left[\Phi^{(\alpha)}_{m+1}\right]\ \Theta^{(\alpha)}_{\mu_s}\right\}\Bigg] \\
+\mathrm{d}\phi_{m+1}\; u(\phi_{m+1}) \quad & \Bigg[\mathrm{R}(\phi_{m+1})\,\Theta_{\mathrm{cut}}[\phi_{m+1}] - \sum_\alpha \left\{f^{(\alpha)}(\phi_{m+1})\right\} \Theta_{\mathrm{cut}}\left[\Phi^{(\alpha)}_m(\phi_{m+1})\right] \\
& - \sum_\alpha \left\{\Theta^{(\alpha)}_{\mathrm{PS}}[\phi_{m+1}]\ \mathrm{PS}^{(\alpha)}[\phi_{m+1}]\ \Theta^{(\alpha)}_{\mu_s}\right\} \Theta_{\mathrm{cut}}\left[\Phi^{(\alpha)}_m(\phi_{m+1})\right]\Bigg]
\end{aligned}$$

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Add or multiply?

Multiplication of NLO contributions by factors $1 + \mathcal{O}(\alpha_s)$ retains accuracy:

$$\begin{aligned}
&\mathrm{d}\phi_m\ u(\phi_m)\ \Theta_{\mathrm{cut}}\left[\phi_m\right] && \Bigg[\Big\{\mathrm{B}(\phi_m) + \mathrm{V}(\phi_m)\Big\}\Delta_{\mu_s}^{Q(\phi_m)} \\
& && + \sum_\alpha \mathrm{d}q^{(\alpha)} \left\{\Theta_{\mathrm{PS}}^{(\alpha)}\left[\Phi_{m+1}^{(\alpha)}\right]\ \frac{\mathrm{R}}{\mathrm{PS}}\ \mathrm{PS}^{(\alpha)}\left[\Phi_{m+1}^{(\alpha)}\right]\ \Theta_{\mu_s}^{(\alpha)}\right\}\Bigg] \\
&+\mathrm{d}\phi_{m+1}\ u(\phi_{m+1}) && \Bigg[\mathrm{R}(\phi_{m+1})\ \Theta_{\mathrm{cut}}\left[\phi_{m+1}\right] \\
& && - \sum_\alpha \left\{\frac{\mathrm{R}}{\mathrm{PS}}\ \Theta_{\mathrm{PS}}^{(\alpha)}\left[\phi_{m+1}\right]\ \mathrm{PS}^{(\alpha)}\left[\phi_{m+1}\right]\ \Theta_{\mu_s}^{(\alpha)}\right\}\ \Theta_{\mathrm{cut}}\left[\Phi_m^{(\alpha)}(\phi_{m+1})\right]\Bigg]
\end{aligned}$$

so (given full phase-space coverage):

$$\begin{aligned}
&\mathrm{d}\phi_m\ u(\phi_m)\ \Theta_{\mathrm{cut}}\left[\phi_m\right] && \Bigg[\Big\{\mathrm{B}(\phi_m) + \mathrm{V}(\phi_m)\Big\}\Delta_{\mu_s}^{Q(\phi_m)} \\
& && + \sum_\alpha \mathrm{d}q^{(\alpha)} \left\{\frac{\mathrm{R}}{\mathrm{PS}}\ \Theta_{\mathrm{PS}}^{(\alpha)}\left[\Phi_{m+1}^{(\alpha)}\right]\ \mathrm{PS}^{(\alpha)}\left[\Phi_{m+1}^{(\alpha)}\right]\ \Theta_{\mu_s}^{(\alpha)}\right\}\Bigg]
\end{aligned}$$

KrkNLO[4] multiplicative matching

This can be realised with the algorithm used in KrkNLO[3]:

1. generate a LO/Born phase-space point, ME and shower:
   - if an emission is generated, reweight to R
   - if not, reweight to $B + V$
2. matching complete; allow the shower to proceed!

[3] NB: there is more to KrkNLO not being discussed here...

[4] S. Jadach et al. "Matching NLO QCD with parton shower in Monte Carlo scheme — the KrkNLO method". arXiv: 1503.06849 [hep-ph], Stanislaw Jadach et al. "New simpler methods of matching NLO corrections with parton shower Monte Carlo". arXiv: 1607.00919 [hep-ph].

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2. matching complete; allow the shower to proceed!

This is NLO accurate, but differs from other methods at higher orders.

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Validation

Seeing Sudakovs

To verify the real weight, we must *unweight* the Sudakov:

- numerical integration of dipole kernels considered in shower algorithm;
- over the same splitting phase-space/kinematic region used in the shower algorithm;
- with the same scales, PDF arguments, α_s etc

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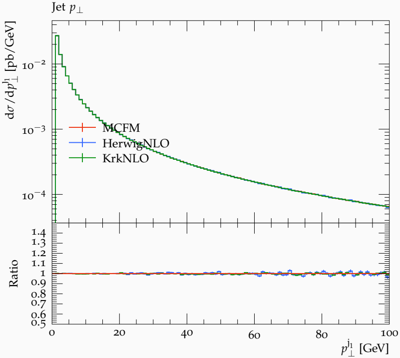
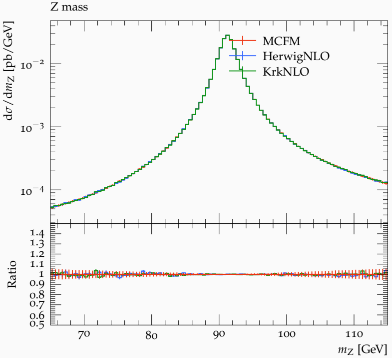
$$\Delta_{\mu_s}^{Q(\phi_m)} = \exp\left[-\sum_{\alpha}\int \mathrm{d}q(\phi_m)\,\Theta[\mu_s < \mu(q) < Q(\phi_m)]\,P_m^{(\alpha)}(q)\,\Theta_{\mathrm{PS}}^{(\alpha)}\right]$$

This is non-trivial!

Does it work?

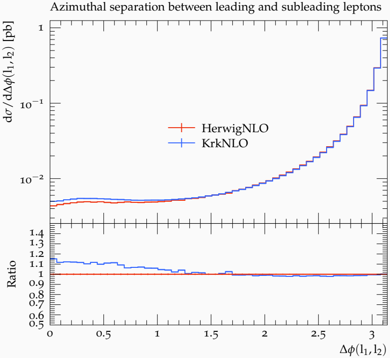


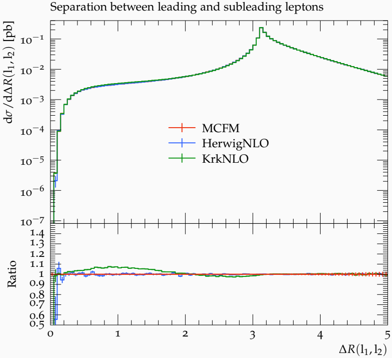
Jet $p_\perp$
$d\sigma/dp_\perp^{j_1}$ [pb/GeV]
MCFM
HerwigNLO
KrkNLO
Ratio
$p_\perp^{j_1}$ [GeV]



Z mass
$d\sigma/dm_Z$ [pb/GeV]
MCFM
HerwigNLO
KrkNLO
Ratio
m_Z [GeV]

Still to fix...





...spin correlations[5]

5 Michael H. Seymour. "A Simple prescription for first order corrections to quark scattering and annihilation processes". arXiv: hep-ph/9410244.

Roadmap

- new processes
- virtual validation
- PDF factorisation scheme[6]
- automation!

[6] S. Jadach et al. "Parton distribution functions in Monte Carlo factorisation scheme". arXiv: 1606.00355 [hep-ph], S. Jadach. "On the universality of the KRK factorization scheme". arXiv: 2004.04239 [hep-ph].

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...and physics

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Thank you!