Some of my Interests

Sebastian Sapeta

CERN Theory Group Retreat
Les Houches, November 5-7, 2014

1. Corrections beyond NLO for processes with large K-factors

2. NLO+Parton Shower matching

3. Forward jets, High Energy Factorization, Transverse Momentum Dependent Factorization

1. Corrections beyond NLO for processes with large K-factors

Higher order QCD corrections

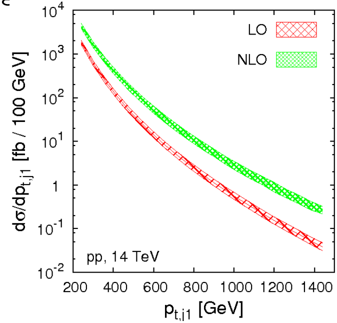
Fixed order perturbative expansion in α_s:

$$\sigma = \underbrace{\sigma_0}_{\text{LO}} + \underbrace{\alpha_s \sigma_1}_{\text{NLO}} + \underbrace{\alpha_s^2 \sigma_2}_{\text{NNLO}} + \cdots$$

Naively, if $\sigma_i \simeq 1$ and $\alpha_s \ll 1$, the series converges and μ_F, μ_R variation should give an estimate of the size of neglected higher orders.

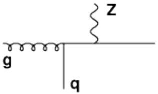
However, quite often we get...

Huge K-factor! $K = \sigma_{\rm NLO}/\sigma_{\rm LO} \simeq 5$

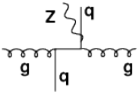


[Rubin, Salam, Sapeta '10]

LO



NLO



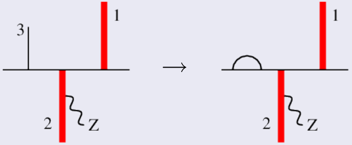
$\Rightarrow$ new incoming channels and new topologies

(though formally NLO diagrams for Z+jet, these are in fact leading contributions)

LoopSim

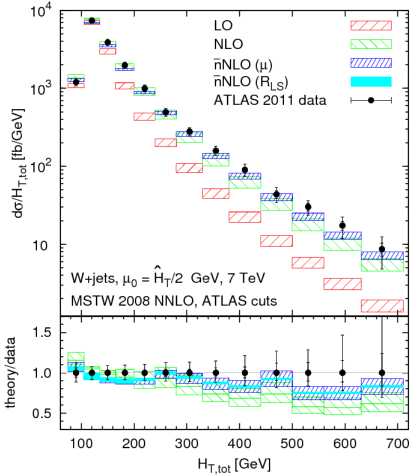
- Determine dominant part of corrections coming from new topologies and new channels that open up at higher orders.
  → Works for broad class of processes and provides bulk of missing higher order corr.

LoopSim [M. Rubin, G. Salam, S.S.]



$$\sigma_{\bar{n}\text{NLO}} - \sigma_{\text{NNLO}} = \mathcal{O}\left(\frac{\alpha_s^2}{K_{\text{NNLO}}}\right)$$

$$K_{\text{NNLO}} \gtrsim K_{\text{NLO}} \gg 1$$



[Maître, Sapeta '13]

Explore and get insight

LoopSim has been tested/used for a number of processes:
Drell-Yan, dijets, Z+jets (Tevatron, LHC), W+jets (LHC), WZ, WW

But there is still more to look at!

- WH at $\bar{n}$NLO: very similar to Drell-Yan process, where LoopSim gets nearly 100% of NNLO, will it be the same here?
- ZZ, Zγ at $\bar{n}$NLO: improved sensitivity to anomalous couplings searches?
- W/Z+jets at $\bar{n}\bar{n}$NLO

Understanding the large K-factors:

- For a set of most common processes ($e^+e^- \to$ jets, DY, DIS, $gg \to H$), at the level of the total cross section, is it possible to understand the pattern of the NLO corrections?
- What are the key elements that are responsible for the large K-factors? Phase space integration, choice of factorization scheme? Could one organize the perturbative expansion in a better way?

2. NLO+Parton Shower matching

NLO+PS matching

- Apart from computing corrections at fixed α_s, another common thing to do is to combine NLO results with the parton shower. The latter resums multiple emissions in collinear approximation.
- Two well established approaches: MC@NLO and POWHEG.

Let's take Drell-Yan in $q\bar{q}$ channel

$$q\bar{q} \to Z \to \ell^+\ell^-$$

The NLO part of the cross section in the collinear factorization in $\overline{\text{MS}}$ scheme

$$\sigma_{\text{DY}}^{\mathcal{O}(\alpha_s)} = \sigma_{\text{DY}}^{B} \otimes f^{\overline{\text{MS}}}(x_1, \mu^2) \otimes \frac{\alpha_s}{2\pi} C_q^{\overline{\text{MS}}}(z) \otimes f^{\overline{\text{MS}}}(x_2, \mu^2)\,,$$

where

$$C_q^{\overline{\text{MS}}}(z) = C_F \left[4\,(1+z^2) \left(\frac{\ln(1-z)}{1-z} \right)_+ - 2\frac{1+z^2}{1-z} \ln z + \; \delta(1-z) \left(\frac{2}{3}\pi^2 - 8 \right) \right].$$

We want to reproduce this with Monte Carlo, in a fully exclusive way.

With $\overline{\text{MS}}$ PDFs, we need to generate these purely collinear terms. But Monte Carlo lives in 4 dimensions and not in the phase space restricted by $\delta(k_T^2)$.

Matching in MC scheme: KrkNLO method

[Jadach, Kusina, Płaczek, Skrzypek, Sławińska '13]

1. Change the factorization scheme from $\overline{\text{MS}}$ to MC scheme

$$q_{\rm MC}(x, Q^2) \quad = \quad q_{\overline{\rm MS}}(x, Q^2) + \int_x^1 \frac{dz}{z}\, q_{\overline{\rm MS}}\left(\frac{x}{z}, Q^2\right) \Delta C_{2q}(z)$$

$$\Delta C_{2q}(z) \quad = \quad \frac{\alpha_s}{2\pi}\, C_F \left[\frac{1+z^2}{1-z} \ln \frac{(1-z)^2}{z} + 1 - z\right]_+$$

2. Reweight the shower with virtual+soft

$$W^{q\bar{q}}_{V+S} = \frac{\alpha_s}{2\pi} C_F \left[\frac{4}{3}\pi^2 - \frac{5}{2}\right] ,$$

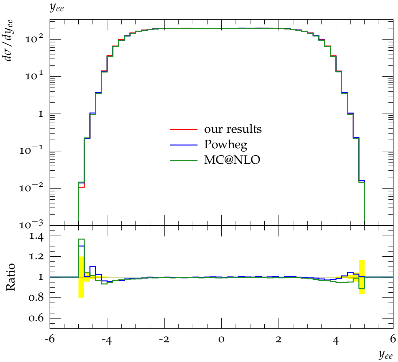
and real weight

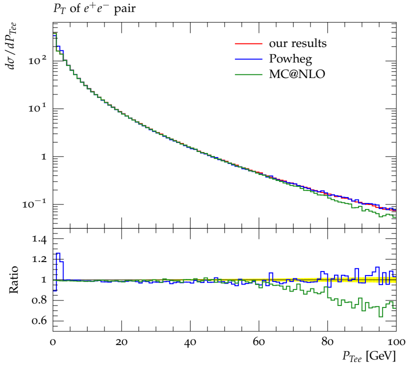
$$W^{q\bar{q}}_R(\alpha, \beta) = 1 - \frac{2\alpha\beta}{1 + (1-\alpha-\beta)^2} ,$$

where $\alpha = 2k \cdot p_B/\sqrt{s}$ and $\beta = 2k \cdot p_F/\sqrt{s}$.

Matched results

[Jadach, Płaczek, Sapeta, Siódmok, Skrzypek; in preparation]





Next:

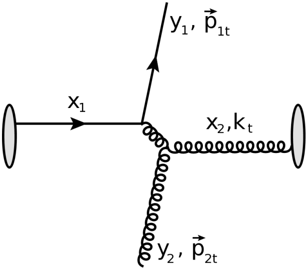
- Implementation with Herwig
- Phenomenology
- PDFs fitted directly in MC scheme?

3. Forward jets, High Energy Factorization, Transverse Momentum Dependent Factorization

Forward jets

$$x_1 = \frac{1}{\sqrt{s}}\left(p_{1t}e^{y_1} + p_{2t}e^{y_2}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{1t}e^{-y_1} + p_{2t}e^{-y_2}\right)$$



In the forward limit

$$y_1,\ y_2 \gg 1 \qquad \Rightarrow \qquad x_1 \sim 1,\ x_2 \ll 1$$

$\hookrightarrow$ Sensitivity to low-x region of gluon density.

$$k_t^2 = |\vec{p}_{1t} + \vec{p}_{2t}|^2 = p_{1t}^2 + p_{2t}^2 + 2p_{1t}p_{2t}\cos\Delta\phi$$

In the back-to-back limit

$$\Delta\phi \sim \pi \qquad \Rightarrow \qquad k_t \sim 0$$

$\hookrightarrow$ Sensitivity to small k_t region of gluon density.

High Energy Factorization

In the small-x limit and for nearly back-to-back configurations,

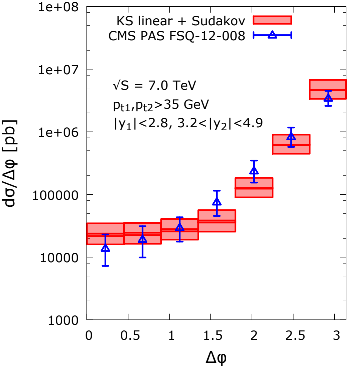
$$Q_s \ll k_t \ll |\vec{p}_{1t}|, |\vec{p}_{2t}|$$

one can use the High Energy Factorization

$$\frac{d\sigma^{pA\to\mathrm{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_{a,c,d} \frac{1}{16\pi^3(x_1 x_2 s)^2} |\overline{\mathcal{M}_{ag\to cd}}|^2 x_1 f_{a/p}(x_1,\mu^2)\, \mathcal{F}_A(x_2,k_t) \frac{1}{1+\delta_{cd}}$$

And it gives you good description of data!

[van Hameren, Kotko, Kutak, Sapeta '14]



Effective Transverse Momentum Factorization

But for $Q_s \sim k_t \ll |\vec{p}_{1t}|, |\vec{p}_{2t}|$, only effective factorization can be established

[Dominguez, Marquet, Xiao, Yuan '11]

$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \frac{\alpha_s^2}{(x_1 x_2 s)^2}\Big[\sum_q x_1 f_{q/p}(x_1,\mu^2) \sum_i H_{qg}^{(i)} \mathcal{F}_{qg}^{(i)}(x_2,k_t) + \frac{1}{2} x_1 f_{g/p}(x_1,\mu^2) \sum_i H_{gg}^{(i)} \mathcal{F}_{gg}^{(i)}(x_2,k_t)\Big]$$

Questions:

- Where exactly is the HEF formalism justified and where does it break?
- Could we introduce k_t dependence to the "matrix elements", $H^{(i)}$, of the effective TMD formula?
- What happens to the effective TMD factorization beyond large-N_c limit?