Modified TMD Factorization and Sub-leading Power Corrections

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∫dkΠ Doktoratskolleg Particles and Interactions
FWF Der Wissenschaftsfonds.
universität wien

Outline

Power corrections in Drell-Yan

Partonic cross section in Drell-Yan process

$$\frac{d\sigma}{dQ^2 dy d\mathbf{q}_T^2} = \sigma^{\text{Born}} +$$

$$\frac{1}{\mathbf{q}_T^2}\sum_{n=1}\alpha_s^n \frac{d\sigma^{[n,-1]}}{dQ^2 dy d\mathbf{q}_T^2} + \delta^{(2)}(\mathbf{q}_T)\sum_{n=1}\alpha_s^n \frac{d\sigma^{[n,0]}}{dQ^2 dy d\mathbf{q}_T^2} + \frac{1}{Q^2}\sum_{n=1}\left(\frac{\mathbf{q}_T^2}{Q^2}\right)^m \alpha_s^n \frac{d\sigma^{[n,m]}}{dQ^2 dy d\mathbf{q}_T^2}$$

- $\frac{d\sigma^{[n,-1]}}{dQ^2 dy d\mathbf{q}_T^2}$ and $\frac{d\sigma^{[n,0]}}{dQ^2 dy d\mathbf{q}_T^2}$ are leading power contributions. Well studied in TMD factorization Scimemi et al. JHEP **07** (2012), 002; Becher and Neubert, EPJC **71** (2011), 1665
- $\frac{d\sigma^{[n,m]}}{dQ^2 dy d\mathbf{q}_T^2}$ are the power suppressed corrections: kinematic, Operator Product Expansion, SCET factorization

Approach

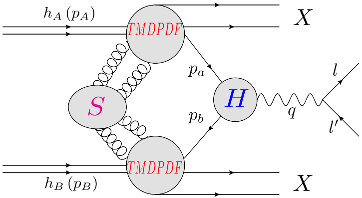
We use ideas from q_T-subtraction method: Catani et al. Nucl. Phys. B **596** (2001), 299-312; Catani et al. Phys. Lett. B **696** (2011), 207-213; Catani et. al. Phys. Rev. Lett. **98** (2007), 222002

$$d\sigma = \lim_{q_T \to 0} d\sigma + \left[d\sigma - \lim_{q_T \to 0} d\sigma \right]$$

- In our case the first term is well described by TMD factorization.
- It contains large logs (due to the expansion) that need to be resummed. TMD formalism is quite convenient for this task.
- The second term includes our power corrections as the difference at partonic level and fixed order.
- Typically the second term is computed using Monte-Carlo event generators. We provide an analytical computation at NLO+NLL.
- We modified the TMD factorization formula for DY to include this second term.

TMD factorization in SCET

- The emerging partons are not parallel to the incoming hadron and are off-shell.
- The partons from the TMDPDFs have a non-negligible transverse momentum $\mathbf{p}_{Ta(b)}$.
- All ingredients can be written as matrix element of QFT operators, which can be further matched onto collinear PDF. Vladimirov et al. EPJC **78** (2018) no.10, 802
- The transverse momentum has to be smaller than the collinear component of the emerging parton, i.e. we are in the limit $q_T^2/Q^2 \ll 1$.



$$\frac{d\sigma^{\text{SCET}}_{h_A h_B \to ll'X}}{dQ^2\,dy\,dq_T^2} = \sum_c \sigma^{\text{Born}} H\left(\alpha_s, Q^2\right) \int \frac{d^2\mathbf{b}_T}{(2\pi)^2} e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_{c\leftarrow h_A}\left(\alpha_s, x_A, b_T^2\right) F_{\bar{c}\leftarrow h_B}\left(\alpha_s\left(Q^2\right), b_T^2, x_B\right) + Y$$

$$\frac{dF_{a\leftarrow h_A}\left(\alpha_S\left(\mu^2\right), b_T^2, x_A, \mu^2, \zeta\right)}{d\ln\mu^2} = \frac{1}{2}\gamma_q\left(\alpha_S\left(\mu^2\right), \mu^2, \zeta\right) F_{a\leftarrow h_A}\left(\alpha_S\left(\mu^2\right), b_T^2, x_A, \mu^2, \zeta\right)$$

$$\frac{dF_{a\leftarrow h_A}\left(\alpha_S\left(\mu^2\right), b_T^2, x_A, \mu^2, \zeta\right)}{d\zeta} = -\mathcal{D}\left(\alpha_S\left(\mu^2\right), \mu^2, b_T^2\right) F_{a\leftarrow h_A}\left(\alpha_S\left(\mu^2\right), b_T^2, x_A, \mu^2, \zeta\right)$$

Y includes the power corrections $\mathbf{q}_T^2/Q^2$ to the SCET factorization formula.
Collins et al. Nucl. Phys. B **250** (1985), 199-224; Collins et al. Phys. Rev. D **94** (2016) no.3, 034014

Sources of power corrections

A lot of work done so far in power corrections: Balitsky et al. JHEP **05** (2018), 150; Balitsky et al. JHEP **05** (2021), 046; Nefedov et al. Phys. Lett. B **790** (2019), 551-556; Ebert et al. 2112.07680 [hep-ph]; Luke et al. Phys. Rev. D **104** (2021) no.7, 076018, Beneke et al. JHEP **03** (2018), 001, Mulders et al. Nucl. Phys. B **667** (2003), 201-241...

- Kinematic corrections due to the definition of relevant variables four the process

$$\text{DY:} \quad x_{A(B)} = \sqrt{\frac{Q^2 + \mathbf{q}_T^2}{s}}\, e^{\pm y}, \quad \text{SIDIS:} \quad \mathbf{q}_T^2 = \frac{p_\perp^2}{z^2} \frac{1+\gamma^2}{1 - \gamma^2 \frac{p_\perp^2}{z^2 Q^2}}$$

- Matching TMDPDF(FF) onto PDF(FF)
  Vladimirov et al. Eur. Phys. J. C **78** (2018) no.10, 802

$$F_{a\leftarrow h_A}(\mathbf{b}_T, x) = \sum_{r,n} \left(\frac{\mathbf{b}_T}{M^2}\right)^n C^n_{a\leftarrow r}\left(\ln \mathbf{b}_T^2 \mu^2, x\right) \otimes f_{r\leftarrow h_A}(x)$$

- Corrections to the TMD factorization included in the $Y-$term
  Collins et al. Nucl. Phys. B **250** (1985), 199-224; Collins et al. Phys. Rev. D **94** (2016) no.3, 034014

Computation at NLO+NLL

We compute

$$\frac{d\sigma_{h_A h_B \to l l' X}}{dQ^2 dy d\mathbf{q}_T^2} = \frac{d\sigma^{\text{SCET}}_{h_A h_B \to l l' X}}{dQ^2 dy d\mathbf{q}_T^2} + \left[\frac{d\sigma_{h_A h_B \to l l' X}}{dQ^2 dy d\mathbf{q}_T^2} - \frac{d\sigma^{\text{SCET}}_{h_A h_B \to l l' X}}{dQ^2 dy d\mathbf{q}_T^2} \right]$$

- The first term contains large logs due to the expansion in $\mathbf{q}_T^2 / \left(Q^2 + \mathbf{q}_T^2\right)$.
- We perform a NLO+NLL analytic computation of the second term.
- No need to regularized divergences using +-distributions
- The logarithmically enhanced contributions cancel out order by order in α_s.
- We seek for a modified factorization formula that at fixed order reproduces powers behaviour.

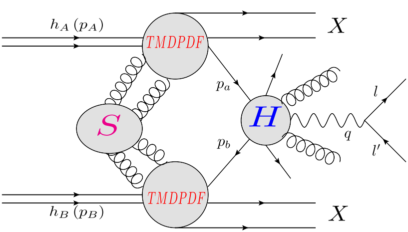
Modified Factorization Formula

$$\frac{d\sigma_{h_A h_B \to l l' X}}{dQ^2 dy d\mathbf{q}_T^2} =$$

$$\sum_{a,b,c} \sigma_c^{\text{Born}} \int d^2\mathbf{p}_{Ta} d^2\mathbf{p}_{Tb} d^2\mathbf{q}'_T \delta^{(2)}\left(\mathbf{q}_T - \mathbf{p}_{Ta} - \mathbf{p}_{Tb} - \mathbf{q}'_T\right) \int_{x_A}^{1} \frac{dz_a}{z_a} \int_{x_B}^{1} \frac{dz_b}{z_b} \theta\left(\frac{(z_a - x_A)(z_b - x_B)}{x_A x_B} - \frac{\mathbf{q}_T^{2\prime}}{Q^2 + \mathbf{q}_T^2}\right)$$

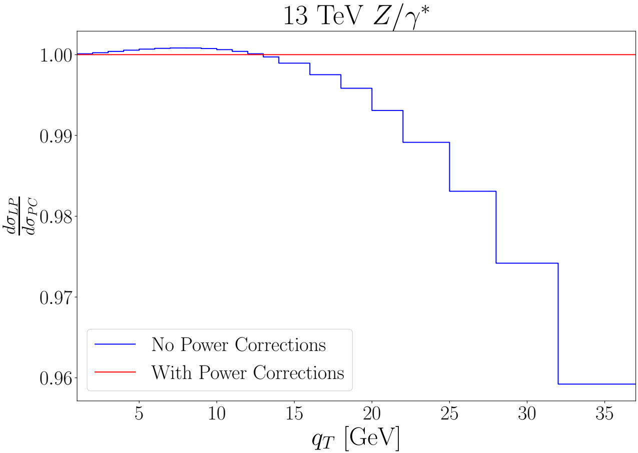
$$\tilde{H}_{c\leftarrow a,\bar{c}\leftarrow b}\left(\alpha_s, Q^2, \frac{x_A}{z_a}, \frac{x_B}{z_b}, \mathbf{q}_T^{2\prime}, \mathbf{q}_T^2\right) F_{a\leftarrow h_A}\left(\alpha_s, z_a, \mathbf{p}_{Ta}^2\right) F_{b\leftarrow h_B}\left(\alpha_s, z_a, \mathbf{p}_{Tb}^2\right)$$

- The origin of θ is pure kinematic.
- The coefficient $\tilde{H}$ is free of large logarithm contributions. All of them are absorbed by the TMDPDF.
- The TMD operators are unchanged, its evolution remains the same. $\zeta = \mu_F^2 = \mu_R^2 = \frac{\left(Q^2+\mathbf{q}_T^2\right) z_{a(b)}}{x_{A(B)}}$
- $x_{A(B)} = \sqrt{\frac{Q^2+\mathbf{q}_T^2}{s}}\, e^{\pm y}$



Power corrections vs Leading power

Preliminary



$0.4 \leq |y| \leq 0.8$, $76.18\text{GeV} \leq Q \leq 106.19\text{GeV}$.
Bigger than electroweak corrections Grazzini et al. Phys. Rev. Lett. **128** (2022) no.1, 012002; Sborlini et al. JHEP **08** (2018), 165

Power corrections vs Leading power

Next steps in the numerical analysis

- The convolution in $\mathbf{p}_{Ta}$ and $\mathbf{p}_{Tb}$ is done from $-\infty$ to ∞. We need to introduce a cut off to perform the numerical integral.
- The code is to be optimized for this cut-off such that the numerical contribution above is truly negligible.
- So far we have used $p_{Ta}^{\text{cut-off}} = p_{Tb}^{\text{cut-off}} = \sqrt{Q^2 + \mathbf{q}_T^2} \cdot 0.25$. A better choice would be $p_{Ta}^{\text{cut-off}} = p_{Tb}^{\text{cut-off}} = \sqrt{Q^2 + \mathbf{q}_T^2}\sqrt{\frac{z_{a(b)}}{x_{A(B)}}} \cdot 0.25$

Summary & Outlook

SUMMARY

- At small $\mathbf{q}_T^2/Q^2$ our factorization formula reproduces TMD factorization.
- At $|\mathbf{q}_T| = Q \cdot 0.30$ we start to appreciate the effects of power corrections.
- The power corrections increase the cross section at large q_T, making it more close the experimental data.
- Electroweak corrections are subleading compared to power corrections Grazzini et al. Phys. Rev. Lett. **128** (2022) no.1, 012002; Sborlini et al. JHEP **08** (2018), 165

OUTLOOK

- Improvement of the code for integration in $\mathbf{p}_T$ of the TMDPDF.
- Extension to e^+e^- to jets/hadrons.
- Study of polarized processes.
- New extraction of TMDPDFs.
- Inclusion of power suppressed terms in the matching of TMDs onto PDFs.

THANK YOU FOR YOUR ATTENTION

Backup

Large logs

- Momentum Space $\mathbf{q}_T$

$$\frac{d\sigma}{dQ^2 dy d\mathbf{q}_T^2} \sim c_1^{[1]} \frac{\alpha_s}{\mathbf{q}_T^2} \log \frac{Q^2}{\mathbf{q}_T^2} + \frac{\alpha_s^2}{\mathbf{q}_T^2} \left(c_1^{[2]} \log \frac{Q^2}{\mathbf{q}_T^2} + c_2^{[2]} \log^2 \frac{Q^2}{\mathbf{q}_T^2} + c_3^{[2]} \log^3 \frac{Q^2}{\mathbf{q}_T^2} \right) + \cdots$$

- Impact parameter space $\mathbf{b}_T$

$$\frac{d\sigma}{dQ^2 dy d\mathbf{b}_T^2} \sim \alpha_s \left(c_0^{[1]} \log \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} + c_1^{[1]} \log^2 \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} \right) +$$

$$\alpha_s^2 \left(c_0^{[2]} \log \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} + c_1^{[2]} \log^2 \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} + c_2^{[2]} \log^3 \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} + c_3^{[2]} \log^4 \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} \right) + \cdots$$

Small $\mathbf{q}_T$ expansion at NLO.

Using the methods presented in Bacchetta et al. JHEP **08** (2008), 023; Soper et al. Phys. Rev. D **54** (1996), 1919-1935

$$\delta\left((p_a - p_b - q)^2\right) =$$

$$\frac{1}{Q^2+\mathbf{q}_T^2}\left[\frac{1}{(1-x_a)_+}\delta(1-x_b) + \frac{1}{(1-x_a)_+}\delta(1-x_a) - \delta(1-x_a)\,\delta(1-x_b)\ln\frac{\mathbf{q}_T^2}{Q^2+\mathbf{q}_T^2}\right] + \mathcal{O}\left(\frac{\mathbf{q}_T^2}{Q^2}\right)$$