Modified TMD Factorization and Sub-leading Power Corrections

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$\int dk \Pi$ Doktoratskolleg Particles and Interactions

FWF Der Wissenschaftsfonds.

universität wien

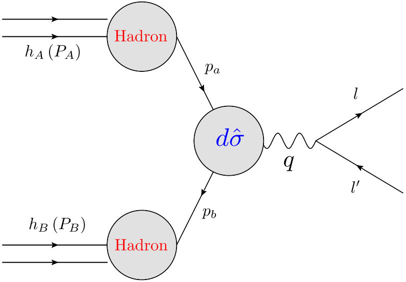
Outline

Factorization theorem

Partonic cross section in Drell-Yan process

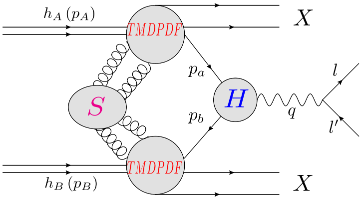
$$\frac{d\hat{\sigma}}{dQ^2 dy d\mathbf{q}_T^2} = \sigma^{\text{Born}} + \frac{1}{\mathbf{q}_T^2}\sum_{n=1}\alpha_s^n \frac{d\hat{\sigma}^{[n,-1]}}{dQ^2 dy d\mathbf{q}_T^2} + \delta^{(2)}(\mathbf{q}_T)\sum_{n=1}\alpha_s^n \frac{d\hat{\sigma}^{[n,0]}}{dQ^2 dy d\mathbf{q}_T^2} + \frac{1}{Q^2}\sum_{m,n=1}\left(\frac{\mathbf{q}_T^2}{Q^2}\right)^m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

- $\frac{d\sigma^{[n,-1]}}{dQ^2 dy d\mathbf{q}_T^2}$ and $\frac{d\sigma^{[n,0]}}{dQ^2 dy d\mathbf{q}_T^2}$ are leading power contributions. Well studied in TMD and Collinear factorization Scimemi et al. JHEP **07** (2012), 002; Becher and Neubert, EPJC **71** (2011), 1665; Catani, Grazzini et al. Nucl. Phys. B. (2001); Grazzini et al. Phys. Rev. Lett. (2000)
- $\frac{d\hat{\sigma}^{[n,m]}}{dQ^2 dy d\mathbf{q}_T^2}$ are the power suppressed corrections: kinematics, Operator Product Expansion, SCET lagrangian.



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 elements 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: $p^2_{a(b)T}/Q^2 \sim q_T^2/Q^2 \ll 1$ up to power corrections.



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

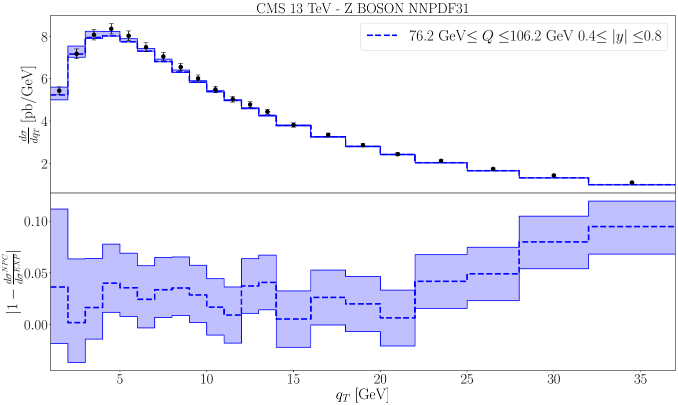
$$\mu^2 \frac{dF_{a\leftarrow h_A}\left(\alpha_S\left(\mu^2\right), b_T^2, x_A, \mu^2, \zeta\right)}{d\mu^2} = \frac{1}{2}\gamma_q\left(\alpha_S\left(\mu^2\right), \mu^2, \zeta\right) F_{a\leftarrow h_A}\left(\alpha_S\left(\mu^2\right), b_T^2, x_A, \mu^2, \zeta\right)$$

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

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

TMD factorization vs data

CMS collaboration JHEP **12** (2019), 061



The differential cross section is integrated in the intervals 66 GeV$\leq Q \leq$ 116 GeV and $0.4 \leq |y| \leq 0.8$.

Sources of power corrections

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...

- Corrections from the relevant kinematic variable:

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

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

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

- 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

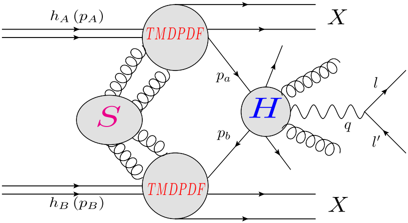
Modified Factorization Formula

$$\frac{d\sigma_{h_A h_B \to ll' X}}{dQ^2 dy d\mathbf{q}_T^2} = \sum_{a,b,c} \sigma_c^{\text{Born}} \int d^2\mathbf{p}_{Ta} d^2\mathbf{p}_{Tb} d^2\mathbf{q}'_T \delta^{(2)}\left(\mathbf{q}_T - \mathbf{p}_{Ta} - \mathbf{p}_{Tb} - \mathbf{q}'_T\right)$$

$$\int_{x_A}^1 \frac{dz_a}{z_a} \int_{x_B}^1 \frac{dz_b}{z_b} \theta\left(\frac{(z_a - x_A)(z_b - x_B)}{x_A x_B} - \frac{\mathbf{q}_T^{2\prime}}{Q^2 + \mathbf{q}_T^2}\right) \tilde{H}_{c \leftarrow a, \bar{c} \leftarrow b}\left(\alpha_s, Q^2, \frac{x_A}{z_a}, \frac{x_B}{z_b}, \mathbf{q}_T^{2\prime}, \mathbf{q}_T^2\right)$$

$$F_{a \leftarrow h_A}\left(\alpha_s, z_a, \mathbf{p}_{Ta}^2\right) F_{b \leftarrow h_B}\left(\alpha_s, z_b, \mathbf{p}_{Tb}^2\right)$$

- 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 and their evolution remains the same.
  $\zeta = \mu_F^2 = \mu_R^2 = \frac{(Q^2+\mathbf{q}_T^2) z_a z_b}{x_A x_B}$
- $x_{A(B)} = \sqrt{\frac{Q^2+\mathbf{q}_T^2}{s}} e^{\pm y}$



Subtraction Methods

Grazzini QCD@WORK 2019

NNLO methods

Broadly speaking there are two approaches that we can follow:

- Organise the calculation from scratch so as to cancel all the singularities
  - Sector Decomposition (SD) — Binoth, Heinrich (2000,2004); Anastasiou, Melnikov, Petriello (2004)
  - antenna subtraction — Gehrmann, Glover (2005)
  - colourful subtraction — Somogyi, Trocsanyi, Del Duca (2005, 2007)
  - subtraction+sector decomposition (stripper, nested subtractions…) — Czakon (2010,2011); Boughezal, Melnikov, Petriello (2011); Caola, Melnikov, Rontsch (2017)
- Start from an inclusive NNLO calculation (sometimes obtained through resummation) and combine it with an NLO calculation for n+1 parton process
  - q_T subtraction — Catani, MG (2007) → PDF → TMDPDF
  - N-jettiness method — Boughezal, Focke,Liu, Petriello (2015); Tackmann et al. (2015)
  - born projection (P2B) method — Cacciari, Dreyer, Karlberg, Salam,Zanderighi (2015)

Search for an "ideal" subtraction method that can be applied as easily as CS or FKS at NLO is still subject of intense work

Approach

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

Computation at NLO+NLL

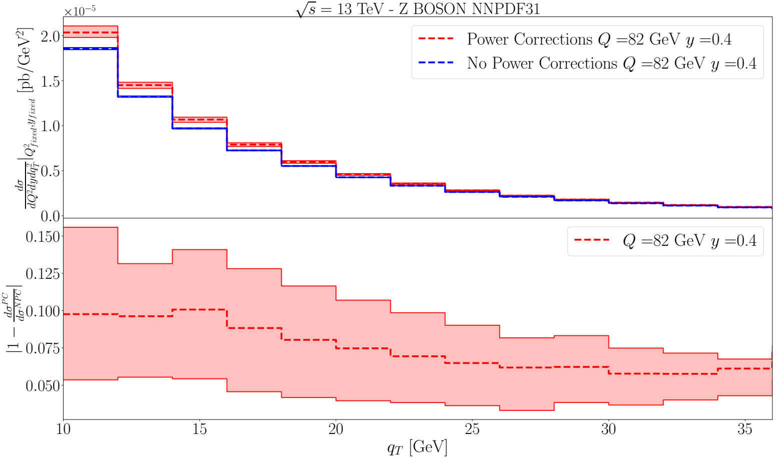
We compute

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

- 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 regularize 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.

Power corrections vs Leading power

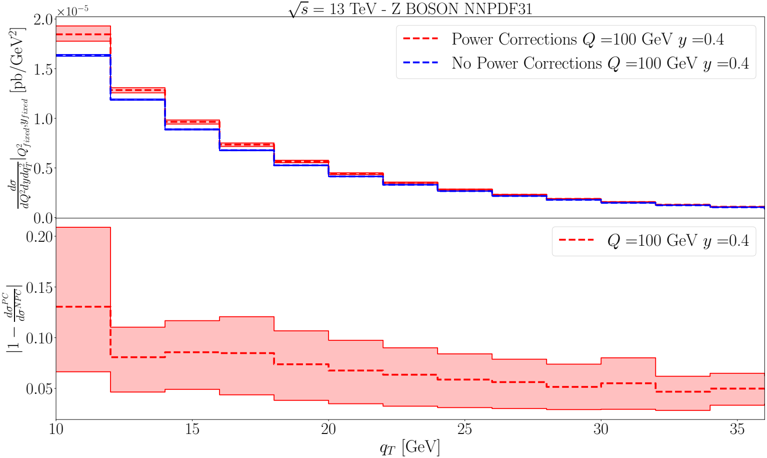
Preliminary



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

Preliminary



Bigger than electroweak corrections Grazzini et al. Phys. Rev. Lett. **128** (2022) no.1, 012002; Sborlini et al. JHEP **08** (2018), 165

SUMMARY & OUTLOOK

SUMMARY

- At small $\mathbf{q}_T^2/Q^2$ our factorization formula reproduces TMD factorization.
- At $|\mathbf{q}_T| = Q \cdot 0.10$ we start to appreciate the effects of power corrections.
- The power corrections increase the cross section at large q_T, making it closer 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 $\mathbf{b}_T$

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

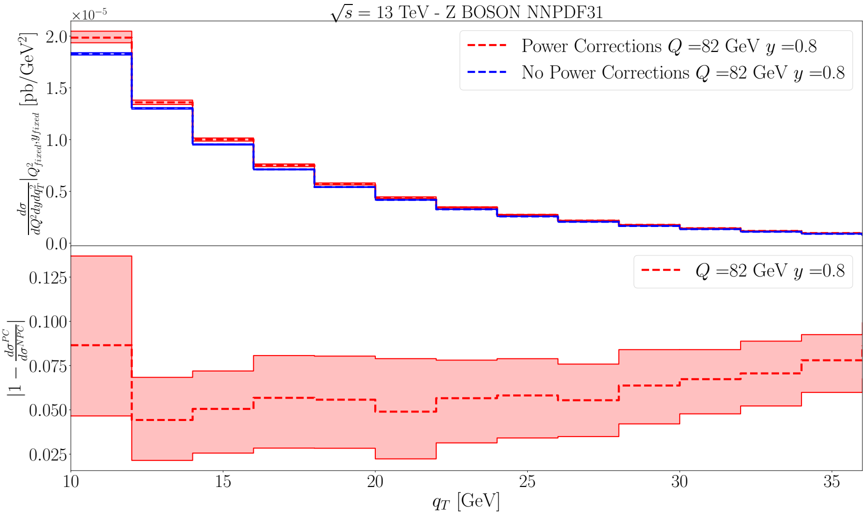
$$\alpha_s^2 \left(c_0^{[2]} \log \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} + c_1^{[2]} \log^2 \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} + c_2^{[2]} \log^3 \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} + c_3^{[2]} \log^4 \frac{Q^2 \mathbf{b}_T^2}{4e^{-2\gamma_E}} \right) + \cdots$$

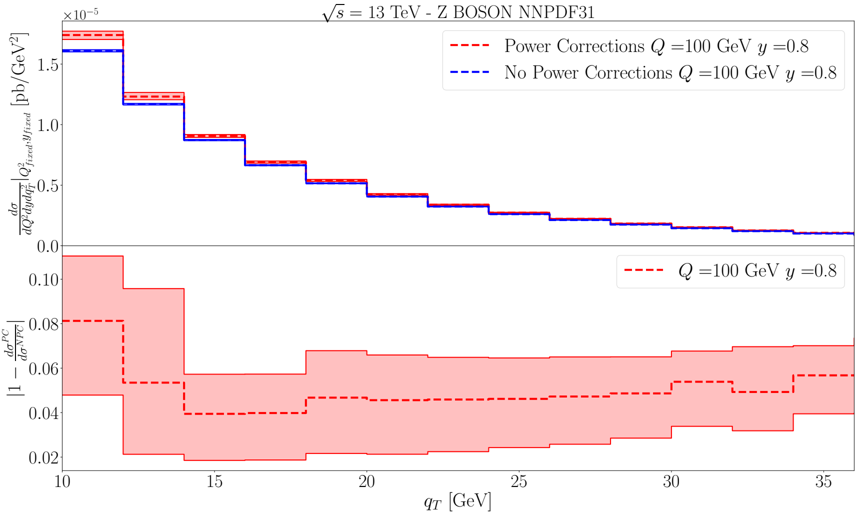
Small $\mathbf{q}_T$ expansion at NLO.

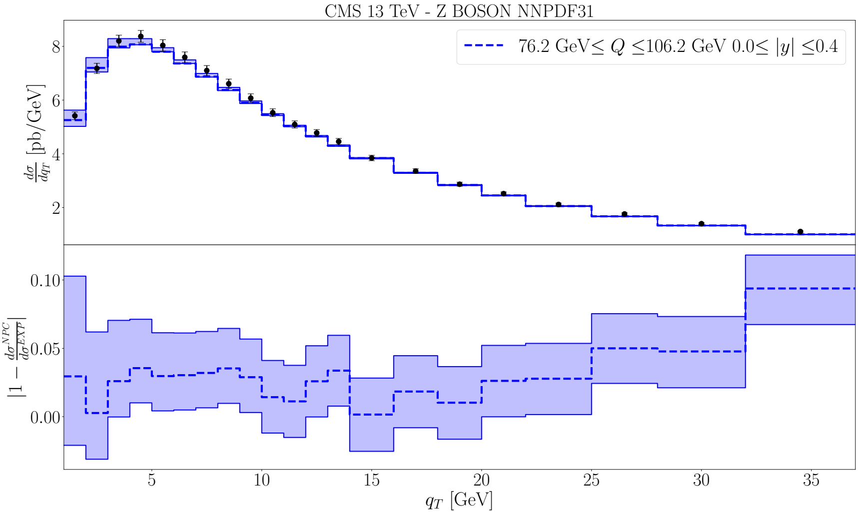
Using the methods presented in Bacchetta et al. JHEP **08** (2008), 023; Soper et al. Phys. Rev. D **54** (1996), 1919-1935

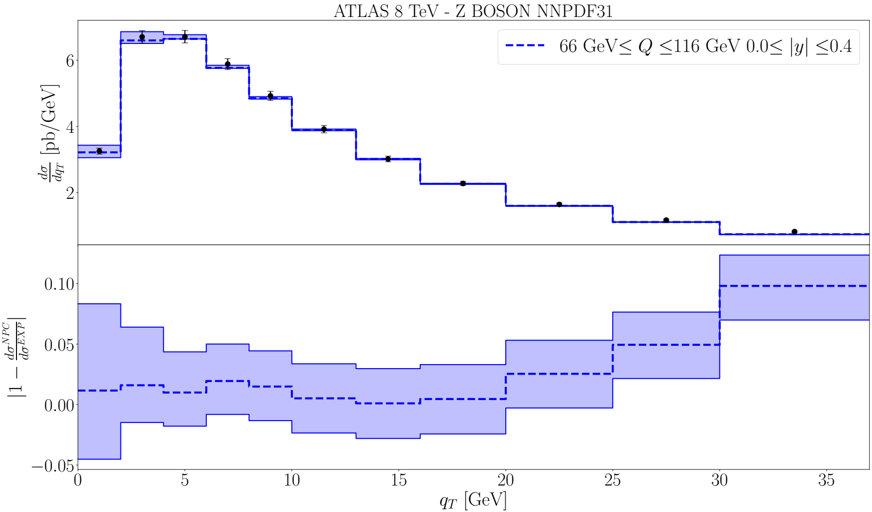
$$\delta\left((p_a - p_b - q)^2\right) =$$

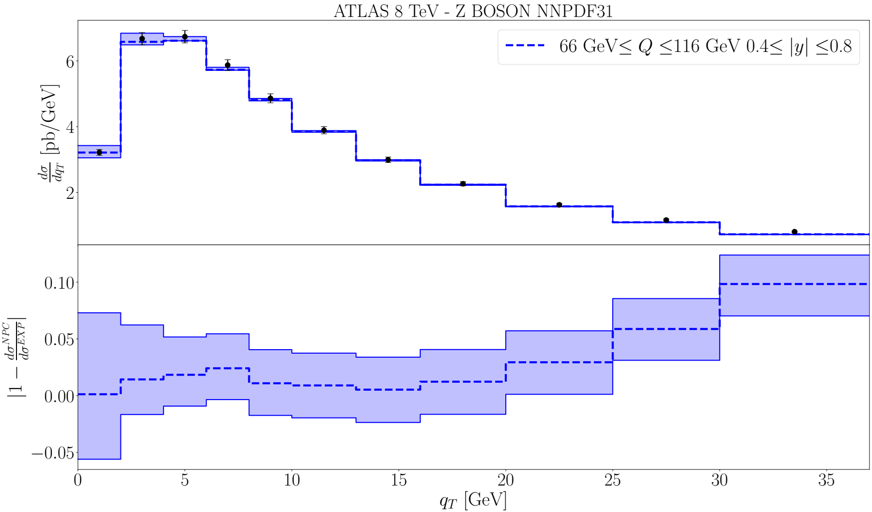
$$\frac{1}{Q^2+\mathbf{q}_T^2}\left[\frac{1}{(1-x_a)_+}\delta(1-x_b) + \frac{1}{(1-x_b)_+}\delta(1-x_a) - \delta(1-x_a)\delta(1-x_b)\ln\frac{\mathbf{q}_T^2}{Q^2+\mathbf{q}_T^2}\right] + \mathcal{O}\left(\frac{\mathbf{q}_T^2}{Q^2}\right)$$


$\sqrt{s}$ = 13 TeV - Z BOSON NNPDF31
$\times 10^{-5}$
Power Corrections Q =82 GeV y =0.8
No Power Corrections Q =82 GeV y =0.8
$\frac{d\sigma}{dQ^2 dy dq_T^2}|Q^2_{fixed}, y_{fixed}$ [pb/GeV^2]
$|1 - \frac{d\sigma^{PC}}{d\sigma^{NPC}}|$
Q =82 GeV y =0.8
q_T [GeV]


$\sqrt{s}$ = 13 TeV - Z BOSON NNPDF31
$\times 10^{-5}$
Power Corrections Q =100 GeV y =0.8
No Power Corrections Q =100 GeV y =0.8
$\frac{d\sigma}{dQ^2 dy dq_T^2}|_{Q^2_{fixed}, y_{fixed}}$ [pb/GeV^2]
1.5
1.0
0.5
0.0
Q =100 GeV y =0.8
$|1 - \frac{d\sigma^{PC}}{d\sigma^{NPC}}|$
0.10
0.08
0.06
0.04
0.02
10
15
20
25
30
35
q_T [GeV]


CMS 13 TeV - Z BOSON NNPDF31
76.2 GeV≤ Q ≤106.2 GeV 0.0≤ |y| ≤0.4
dσ/dqT [pb/GeV]
|1 − dσNPC/dσEXP|
qT [GeV]


ATLAS 8 TeV - Z BOSON NNPDF31
66 GeV≤ Q ≤116 GeV 0.0≤ |y| ≤0.4
dσ/dq_T [pb/GeV]
|1 − dσ^NPC/dσ^EXP|
q_T [GeV]
0
5
10
15
20
25
30
35
2
4
6
0.10
0.05
0.00
−0.05


ATLAS 8 TeV - Z BOSON NNPDF31
66 GeV≤ Q ≤116 GeV 0.4≤ $|y|$ ≤0.8
$\frac{d\sigma}{dq_T}$ [pb/GeV]
$|1 - \frac{d\sigma^{NPC}}{d\sigma^{EXP}}|$
q_T [GeV]
0
5
10
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0.10
0.05
0.00
−0.05