CS kernel determination from MC (PB-TMDs)

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Parton Branching (PB) method

- Evolution of TMDs (and collinear PDFs)
- Resummation of soft gluons at LL and NLL
- Solution valid at LO, NLO and NNLO
- Determination of TMDs from the fully exclusive solution
- **Backward evolution** fully determines the TMD shower

  consistently treats perturbative and non-perturbative transverse momentum effects

Implemented in the CASCADE generator

PB-TMDs in high mass DY production

DY pt spectrum

- Combined with MC@NLO
- Excellent description of DY pT spectrum
- Non-perturbative TMD effects not significant at high pT
- Missing contributions at high pT

ABM et al. [PRD 100, 074027 (2019)]
ABM et al. [EPJC 80, 598 (2020)]

A. Bermúdez Martínez
PB-TMDs to low mass DY production

**DY pt spectrum**

- Combined with MC@NLO
- Excellent description of DY pT spectrum
- First simultaneous description of both low and high-mass DY pT spectrum
- No more low pT crisis (Bacchetta et al. [PRD 100 (2019) 014018]; ABM et al. [EPJC 80, 598 (2020)])

![Graphs showing Drell-Yan production](image-url)
PB-TMDs to DY production

- Description of the pT spectrum over a wide DY mass range
- Valuable non-perturbative information
Glance at TMD factorization

At small \( k_T \):

\[
\frac{d\sigma}{dQ^2 dy dq_T^2} = \frac{2\pi}{9} \frac{\alpha_{em}^2(Q)}{sQ^2} W_{f_1 f_2}(x_1, x_2, Q, q_T),
\]

\[
W_{f_1 f_2} = |C_V(Q)|^2 \int_0^\infty d\beta \beta J_0(bq_T) \sum_q e_q^2 f_{q_1}(x_1, b; Q, Q^2) f_{q_2}(x_2, b; Q, Q^2).
\]

Notice the dependence on two scales of the parton distributions

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Taking the Hankel (Fourier) transform of the xsec:

\[
\Sigma(y, Q; b) = \frac{2\pi}{9} \frac{\alpha_{em}^2(Q)}{sQ^2} |C_V(Q)|^2 \sum_q e_q^2 f_{q_1}(x_1, b; Q, Q^2) f_{q_2}(x_2, b; Q, Q^2).
\]
Glance at TMD factorization

Evolving the parton densities to fixed scales:

\[ \Sigma(y, Q; b) = \frac{2\pi}{9} \frac{\alpha_{em}^2(Q)}{sQ^2} |C_V(Q)|^2 e^{2\Delta(b; Q \rightarrow (\mu_0, \zeta_0))} \sum_q e^2 f_q(x_1, b; \mu_0, \zeta_0) f_{q_2}(x_2, b; \mu_0, \zeta_0), \]

Notice the following points:

- The Q dependence of the parton densities transferred to a \textit{residual exponential factor}
- Ratios of the xsec for different Qs do not depend on the collinear parton densities
- \textbf{Non-perturbative component} of those ratios would then live only in the exponential

\[ \Delta(b; Q \rightarrow (\mu_0, \zeta_0)) = \int_P \left( \gamma_F(\mu, \zeta) \frac{d\mu}{\mu} - D(b, \mu) \frac{d\zeta}{\zeta} \right), \]

Collins-Soper kernel
CS kernel

- Self-contained object
- Perturbative sensitivity at small $b$
- Non-perturbative sensitivity at small $b$
- Existing lattice calculations

Let’s dive into the new method, applied in MC (PB-TMDs) and extendable to real data!!
CS kernel from Parton Branching

Main formula

\[
\frac{\sum_1}{\sum_2} = \frac{s_2}{s_1} \frac{Q_2^2}{Q_1^2} Z(Q_1, Q_2) e^{2\Delta(b; Q_1 \rightarrow Q_2)}
\]

Simulation/Measurement

But in b space!

CS determination process
- DY pT in narrow bins of Q={Q1, Q2}
- Choose \(\{s, y\}\) such that \(x\)'s coincide
- Very fine binning in pT

Get the Fourier transform

Get CS kernel from here

Analytically

Simulation/Measurement

But in b space!
CS kernel from Parton Branching

Hankel/Fourier transform of the xsec

\[ \Sigma(b, Q, y, s) = \int_0^\infty dq_T q_T J_0(bq_T) \frac{d\sigma}{dQ^2 dy d^2q_T^2} \]

CS determination process
- DY pT in narrow bins of Q={Q1, Q2}
- Choose \{s, y\} such that x’s coincide
- Very fine binning in pT
CS kernel from Parton Branching

Determine CS kernel

Ideally
- Different Q’s must coincide
- Different processes must coincide
- Should not depend on y range
- Should not depend on collinear PDF input
CS kernel from Parton Branching

Determine CS kernel

PB-NLO-HERAI+II-2018-set2, $|y| < 4.0$

- $p\bar{p}$, $|y| < 4.0$, [12.0, 16.0] GeV
- $p\bar{p}$, $|y| < 4.0$, [12.0, 20.0] GeV
- $p\bar{p}$, $|y| < 4.0$, [16.0, 20.0] GeV

Ideally

- Different $Q$’s must coincide
- **Different processes must coincide**
- Should not depend on $y$ range
- Should not depend on collinear PDF input
### CS kernel from Parton Branching

#### Determine CS kernel

**pp, [12.0, 16.0] GeV**

- Ideally
  - Different Q’s must coincide
  - Different processes must coincide
  - **Should not depend on y range**
  - Should not depend on collinear PDF input
CS kernel from Parton Branching

Determine CS kernel

$pp, |y| < 4.0, [12.0, 16.0] \text{ GeV}$

Ideally

- Different $Q$'s must coincide
- Different processes must coincide
- Should not depend on $y$ range
- Should not depend on collinear PDF input

PB passed!!
CS kernel from Parton Branching

Uncertainty sources

Statistical propagation

Propagation of statistical uncertainty

Scale variations

Histogram for 78th bin ($b=4.94$), $\mu = 0.49$, $\sigma = 0.01$
CS kernel from Parton Branching

Determine CS kernel

There is a general agreement in shape between MC, Lattice, SV19 at large $b$

MC shape consistent with perturbative calculation at low $b$

- $D(b_T, \mu = 2\text{GeV})$
Conclusions

- CASCADE generator (PB-TMDs) consistent with TMD factorization
- Method to determine CS kernel from MC
- First determination of CS kernel from MC
- MC shape consistent with perturbative calculations at small b
- MC shape consistent with lattice calculations at large b
- Prove of concept → to be used with real measurements