Extraction of partonic TMDs from SIDIS and Drell-Yan data

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MANUALE D'USO DEL MARCHIO
Motivation

- Are unpolarized quark TMDs universal?
- Does TMD evolution allow for a description of the data at different $Q^2$?
- How wide is the transverse momentum distribution? Is it wider at low $x$?

Bacchetta, Delcarro, CP, Radici, Signori (Pavia 2016)
Semi-inclusive DIS vs DY

\[ l(\ell) + N(P) \rightarrow l(\ell') + h(P_h) + X \]

\[ A + B \rightarrow \gamma^* \rightarrow l^+l^- \]
\[ A + B \rightarrow Z \rightarrow l^+l^- \]
Experiments

\[ Q^2 \text{ [GeV}^2] \]

- **Z production@**
  - Fermilab
  - Abbot et al. hep-ex/9909020
  - Affolder et al. hep-ex/0001021
  - Abazov et al. arXiv:0712.0803

- **Drell-Yan@**
  - Fermilab
  - Ito et al., PRD93 (81)
  - Moreno et al. PRD 43 (91)
  - Antreyan et al. PRL47 (81)

- **SIDIS@**
  - hermes
  - Airapetian et al., PRD87 (2013)

- **SIDIS@**
  - COMPASS
  - Adolph et al., EPJ C73 (13)
Extraction of unpolarized quark TMDs
State of the art

<table>
<thead>
<tr>
<th>Study</th>
<th>Accuracy</th>
<th>HERMES</th>
<th>COMPASS</th>
<th>DY production</th>
<th>N of points</th>
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<tbody>
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<td>KN 2006</td>
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<tr>
<td>Pavia 2013 (+Amsterdam,Bilbao)</td>
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<td>✗</td>
<td>✗</td>
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<tr>
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<td>NLL</td>
<td>1 (x,Q²) bin</td>
<td>1 (x,Q²) bin</td>
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<td>✓</td>
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<tr>
<td>Pavia 2016</td>
<td>NLL</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
</tbody>
</table>
SIDIS structure function

\[ F_{UU,T}(x, z, P_{hT}^2, Q^2) = \sum_a H_{UU,T}^a(Q^2; \mu^2) \int d^2k_T d^2P_T \frac{f_1^a(x, k_T^2; \mu^2)}{D_{1}^{h/a}(z, P_{T}^2; \mu^2)} \delta^2(zk_T - P_{hT} + P_T) \]

\[ + Y_{UU,T}(Q^2, P_{hT}^2) + \mathcal{O}(M^2/Q^2) \]

\[ Y_{UU,T}(Q^2, P_{hT}^2) \text{ not implemented in Pavia 2016} \]

Multiplicities:

\[ m_N^h(x, z, P_{hT}^2, Q^2) = \frac{d\sigma_N^h/dx \, dz \, dP_{hT}^2 \, dQ^2}{d\sigma_{DIS}/dx \, dQ^2} \approx \frac{2\pi |P_{hT}| F_{UU,T}(x, z, P_{hT}^2, Q^2)}{F_T(x, Q^2)} \]
Different schemes have been suggested

Assumption for nonperturbative evolution: $g_K = -g_2 \frac{b_T^2}{2}$

Rogers, Aybat, PRD 83 (11)
Collins, *Foundations of Perturbative QCD* (11)

Collins, Soper, Sterman, NPB 250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)
These choices are arbitrary: they should be checked/challenged in the future

\[
\bar{b}_* \equiv b_{\text{max}} \left( \frac{1 - e^{-b_T^4 / b_{\text{max}}^4}}{1 - e^{-b_T^4 / b_{\text{min}}^4}} \right)^{\frac{1}{4}}
\]

\[
b_{\text{max}} = 2e^{-\gamma_E} \\
\mu_b = \frac{2e^{-\gamma_E}}{\bar{b}_*} \\
b_{\text{min}} = \frac{2e^{-\gamma_E}}{Q}
\]

- Low \(b_T\) modification: integrated result is recovered (unitarity constraint)
- \(\mu_b\) never bigger than \(Q\) now
- Large effect at low \(Q\) (inhibits gluon radiation)
Functional form of TMDs
Input distributions at $Q^2 = 1 \text{ GeV}^2$

$$f_{NP}^a = \mathcal{F.T.} \left( e^{-\frac{k_{\perp}^2}{\langle k_{\perp}^2, a \rangle}} + \lambda k_{\perp}^2 e^{-\frac{k_{\perp}^2}{\langle k_{\perp}^2, a \rangle'}} \right)$$

$x$-dependent width:

$$\langle k_{Ta}^2 \rangle(x) = \langle \hat{k}_{Ta}^2 \rangle \frac{(1 - x)^\alpha x^\sigma}{(1 - \hat{x})^\alpha \hat{x}^\sigma}$$

where

$$\langle \hat{k}_{Ta}^2 \rangle \equiv \langle k_{Ta}^2 \rangle(\hat{x}) \quad \text{with} \quad \hat{x} = 0.1$$

$\alpha, \sigma, \langle \hat{k}_{Ta}^2 \rangle, \lambda$: free parameters (4 for TMD PDFs, 6 for TMD FFs)
Data selection and analysis

\[ Q^2 > 1.4 \text{ GeV}^2 \]

\[ 0.2 < z < 0.7 \]

\[ P_{hT}, q_T < \text{Min}[0.2Q, 0.7Qz] + 0.5 \text{ GeV} \]

Problems in separating the fragmentation regions in SIDIS at low \( Q^2 \)

Boglione et al., PLB 766 (2017)

Fit of 200 replicas of the data
Summary of the results

Total number of data points: 8059

Total number of free parameters: 11
- 4 for TMD PDFs
- 6 for TMD FFs
- 1 for TMD evolution

Total $\chi^2$/dof = 1.55 ± 0.05
**HERMES data**

**Kaon production**

\[ \chi^2 / \text{dof} \]

0.91

0.82

1.31

2.54
$\chi^2/\text{dof} = 1.01$
SIDIS $h^-$ COMPASS data

$\chi^2$/dof = 1.61
Drell-Yan data

χ²/dof

- 0.32
- 0.84
- 0.99
- 1.12

E288, √s = 27.4 GeV

y = 0.03

E288, √s = 23.8 GeV

y = 0.21

E288, √s = 19.4 GeV

y = 0.4

E605, √s = 38.8 GeV

x_F = 0.1

The peak is now at about 1 GeV, it was at 0.4 GeV
Z-boson production

$\chi^2$/dof

- CDF: $\sqrt{s} = 1.8$ TeV
- D0: $\sqrt{s} = 1.8$ TeV
- CDF: $\sqrt{s} = 1.96$ TeV
- D0: $\sqrt{s} = 1.96$ TeV

The peak is now at 4 GeV

Most of the $\chi^2$ is due to normalization
TMD evolution is not uniquely determined by pQCD calculations
Different schemes may behave differently
Nonperturbative input is needed to determine evolution precisely

<table>
<thead>
<tr>
<th></th>
<th>$g_2$ (GeV$^2$)</th>
<th>$b_{\text{max}}$(GeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLNY 2003</td>
<td>0.68 ± 0.02</td>
<td>0.5</td>
</tr>
<tr>
<td>KN 2006</td>
<td>0.184 ± 0.018</td>
<td>1.5</td>
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<tr>
<td>EIKV 2014</td>
<td>0.18</td>
<td>1.5</td>
</tr>
<tr>
<td>Pavia 2016</td>
<td>0.13 ± 0.01</td>
<td>1.123</td>
</tr>
</tbody>
</table>

**Faster evolution:** transverse momentum increases faster due to gluon radiation

**Slower evolution:** the effect of gluon radiation is weaker
Correlation between transverse momenta

Pavia 2016 results

Anticorrelation between transverse momentum in TMD PDFs and in TMD FFs
Mean transverse momentum
\[ Q^2 = 1 \text{ GeV}^2 \]

In TMD distribution functions

In TMD fragmentation functions
Conclusions

- We demonstrated for the first time that it is possible to fit simultaneously SIDIS, DY, and Z boson production data.
- We extracted unpolarized quark TMDs using more than eight thousand data points.
- The TMD framework seems to work quite well.
- Most of the discrepancies come from the normalizations.
- The $Y$ term still needs to be implemented.