TMD phenomenology:
from JLab to the LHC

Andrea Signori

Spatial and momentum
tomography
of hadrons and nuclei

INT 17-3
Sept 25 2017
TMD phenomenology
at low and high energy

Andrea Signori

Spatial and momentum tomography of hadrons and nuclei

INT 17-3
Sept 25 2017
I will present some research directions, in collaboration with:

- J. Qiu, LDRD TMD team (JLab)

- M. Grewal, Z. Kang (UCLA)

- A. Bacchetta, G. Bozzi, M. Echevarria, C. Pisano, M. Radici (Pavia)

- T. Kasemets, P. Mulders, M. Ritzmann (Nikhef)

- J. Lansberg (IN2P3)
I will touch different aspects related to phenomenology of TMDs at low and high energy:

1) TMDs and their evolution
2) relevance of the nonperturbative part
3) extractions from low energy data
4) predictions at high energy
5) computational tools
TMDs & their evolution

References (intro and reviews):

- “The 3D structure of the nucleon” EPJ A (2016) 52
- J.C. Collins “Foundations of perturbative QCD”
- material from the TMD collaboration summer school, e.g. :
  * P.J. Mulders’ lecture notes
  * A. Bacchetta’s lecture notes
  * and all the other lecture notes/references on the webpage
quark TMD PDFs

\[ \Phi_{ij}(k, P; S) \sim \text{F.T.} \left\langle PS \mid \bar{\psi}_j(0) U_{[0,\xi]} \psi_i(\xi) \mid PS' \right\rangle |_{LF} \]

<table>
<thead>
<tr>
<th>Quarks</th>
<th>( \gamma^+ )</th>
<th>( \gamma^+ \gamma^5 )</th>
<th>( i\sigma^i + \gamma^5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>( f_1 )</td>
<td></td>
<td>( h_1^\perp )</td>
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<tr>
<td>L</td>
<td></td>
<td>( g_1 )</td>
<td>( h_{1L}^\perp )</td>
</tr>
<tr>
<td>T</td>
<td>( f_{1T}^\perp )</td>
<td>( g_{1T} )</td>
<td>( h_1, h_{1T}^\perp )</td>
</tr>
</tbody>
</table>

- extraction of a quark
  not collinear with the proton
  encode all the possible spin-spin and spin-orbit correlation between the proton and its constituents

**bold** : also collinear
**red** : time-reversal odd (universality properties)
Status of TMD phenomenology

Theory, data, fits: we are in a position to start validating the formalism

<table>
<thead>
<tr>
<th>quark pol.</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
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<tr>
<td>U</td>
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<td>$f_{1T}$</td>
<td>$g_{1T}$</td>
<td>$h_1$, $h_{1T}^\perp$</td>
</tr>
</tbody>
</table>

Twist-2 TMDs

Only first attempts

Limited data, theory, fits

see, e.g., Bacchetta, Radici, arXiv:1107.5755
Anselmino, Boglione, Melis, PRD86 (12)
Echevarria, Idilbi, Kang, Vitev, PRD 89 (14)
Anselmino, Boglione, D’Alesio, Murgia, Prokudin, arXiv: 1612.06413
Anselmino et al., PRD87 (13)
Kang et al. arXiv:1505.05589

Lu, Ma, Schmidt, arXiv:0912.2031
Lefky, Prokudin arXiv:1411.0580
The frontier

**Nuclear Physics**:  
- investigation of nucleon and nuclear structure and associated dynamics  
- observables of non-perturbative QCD  
- non-perturbative quark-gluon dynamics encoded in (TMD) PDFs and FFs

**High-Energy Physics**:  
- precision physics, within and beyond the Standard Model  
- observables of perturbative QCD  
- assuming the knowledge of hadron structure
**W-term & TMDs**

**W-term**: transverse momentum resummation in terms of TMDs

\[
W(q_T, Q) = \int \frac{d^2 b_T}{(2\pi)^2} e^{iq_T \cdot b_T} \tilde{W}(b_T, Q)
\]

\(b_T\) is the Fourier-conjugated variable of the [partonic and observed] transverse momenta

\[
\tilde{W}(b_T, Q) \sim \tilde{F}_i^{h_1}(x_1, b_T; \mu, \zeta_1) \tilde{F}_j^{h_2}(x_2, b_T; \mu, \zeta_2)
\]

Product of Fourier-transformed TMDs

**TMD evolution** is multiplicative in \(b_T\) space
W-term & TMDs

FT of TMDs:

\[ \tilde{F}_i(x, b_T; Q, Q^2) = \tilde{F}_i(x, b_T, \mu_{b_T}, \mu_{b_T}^2) \times \]

\[ \exp \left\{ \int_{\mu_{b_T}}^{Q} \frac{d\mu}{\mu} \gamma_F[\alpha_s(\mu), Q^2/\mu^2] \right\} \left( \frac{Q^2}{\mu_{b_T}^2} \right)^{-K(\hat{b}_T; \mu_{b_T})} - g_K(\bar{b}_T; \{\lambda\}) \]

Sudakov form factor: perturbative and nonperturbative contributions
W-term & TMDs

FT of TMDs:

\[ \tilde{F}_i(x, b_T; Q, Q^2) = \tilde{F}_i(x, b_T, \mu^2_b) \times \exp \left\{ \int_{\mu^2_b}^{Q} \frac{d\mu}{\mu} \gamma_F[\alpha_s(\mu), Q^2/\mu^2] \right\} \left( \frac{Q^2}{\mu^2_b} \right)^{-K(b_T; \mu^2_b)} g_K(b_T; \{\lambda\}) \]

Sudakov form factor: perturbative and nonperturbative contributions

[input] TMD distribution: Wilson coefficients and intrinsic part

\[ \tilde{F}_i(x, b_T; \mu^2_b) = \sum_{j=q, \bar{q}, g} C_{i/j}(x, \hat{b}_T; \mu^2_b) \otimes f_j(x; \mu^2_b) \tilde{F}_{i,NP}(x, \bar{b}_T; \{\lambda\}) \]

Nonperturbative parts defined in a “negative” way: observed-calculable
Phenomenology

consolidate the formalism +
extractions of TMDs

predictions for
“unexplored/known” effects
in
“unexplored/known” regions

new data
Phenomenology

- extraction of unpolarized quark TMDs: see talks by A. Bacchetta, A. Vladimirov

- formalism for unpolarized gluon TMDs: see talks by S. Cotogno, C. Pisano, and next section

consolidate the formalism + extractions of TMDs

predictions for “unexplored/known” effects in “unexplored/known” regions
consolidate the formalism + extractions of TMDs

predictions for “unexplored/known” effects in “unexplored/known” regions

examples of predictions for “known” effects in “known” regions:
- W qT-spectrum at LHC [quark TMDs]
- Higgs qT-spectrum at LHC [gluon TMDs]
Phenomenology

All kinematic regions (namely data) are important: some are more suited to **constrain NP part** of TMDs and their evolution, others to **test the accuracy needed for TMD evolution**

What is the **best kinematic region** to **constrain the NP part of TMDs** and what is the best **region to be predictive**?

**predictive power & nonperturbative input**

predictions for “unexplored/known” effects in “unexplored/known” regions

consolidate the formalism + extractions of TMDs
Saddle point approximation

\[ W(x_{1,2}, q_T, Q) = \int \frac{d^2 b_T}{(2\pi)^2} e^{i q_T \cdot b_T} \tilde{W}(x_{1,2}, b_T, Q) \]

\[ = \int \frac{db_T}{2\pi} b_T J_0(q_T b_T) \tilde{W}(x_{1,2}, b_T, Q) \]

Z-boson production

\[ b_T J_0(q_T b_T) \tilde{W}(x_{1,2}, b_T, Q) \]

the idea is to calculate which b-region dominates the integral as a function of the kinematics

small-b region: computed in pQCD
high-b region: need nonperturbative model
let's look at the integrand at $q_T=0$ to quantify the importance of the high $b_T$ region

$$W(x_{1,2}, q_T = 0, Q) = \int \frac{db_T}{2\pi} b_T \tilde{W}(x_{1,2}, b_T, Q)$$

$$\frac{d}{db_T} \left[ b_T \tilde{W}(x_{1,2}, b_T, Q) \right]_{b_T=b_{sp}} = 0$$

from the **Sudakov** term

higher $Q$ smaller $x$

from **DGLAP**

lower $Q$ higher $x$
We’d like to check if the same statement holds for a single quark TMD PDF:

\[ f(x, k_T = 0, Q) = \int \frac{db_T}{2\pi} b_T \tilde{f}(x, b_T, Q) \]

map the role of the NP contribution as a function of x and Q

accuracy: NLO and NLL

high-Q, small-x
\[ Q = M_w \]
\[ x = 0.001 \]
\[ g_2 = 0.2 \]
\[ g_2 = 0.4 \]
\[ g_2 = 0.8 \]

high-Q, high-x
\[ Q = M_w \]
\[ x = 0.1 \]
\[ g_2 = 0.2 \]
\[ g_2 = 0.4 \]
\[ g_2 = 0.8 \]

\[ \text{integral} \]
+5% \quad g_2 = 0.2

-7% \quad g_2 = 0.8

+8% \quad g_2 = 0.2

-13% \quad g_2 = 0.8
We’d like to check if the same statement holds for a single quark TMD PDF.

\[ b_T(\tilde{f}(x, b_T, Q)) = \int \frac{d b_T}{2\pi} b_T \tilde{f}(x, b_T, Q) \]

**low-Q, small-x**
- \( Q = 3 \text{ GeV} \)
- \( x = 0.001 \)
- \( g_2 = 0.2 \)
- \( g_2 = 0.4 \)
- \( g_2 = 0.8 \)

**low-Q, high-x**
- \( Q = 3 \text{ GeV} \)
- \( x = 0.1 \)
- \( g_2 = 0.2 \)
- \( g_2 = 0.4 \)
- \( g_2 = 0.8 \)

Integral:
- \( g_2 = 0.4 \)
- \(+24\% \quad g_2 = 0.2 \)
- \(-32\% \quad g_2 = 0.8 \)

Accuracy: NLO and NLL
The message

- **small-Q and high-x**: the region where the (quark) TMD PDF is most sensitive to the NP part (but also higher-twists, thresholds, ...); data in this region are precious to constrain the NP part.

  example: extractions of unpolarized quark TMDs [see Bacchetta, Vladimirov]

  **example: formalism for $\eta_{b,c}$ production at the LHC or AFTER@LHC**

- **high-Q and small-x**: the region where the formalism is most predictive and has less sensitivity to the NP corrections; **example $W$ production at LHC**

  in this case, what is the actual impact of the NP part on physical observables?
$\eta_{b,c}$ production at LHC

(Some) References:

- AS, PhD thesis
- D. Boer, C. Pisano, arXiv:1208.3642
gluon TMD PDFs

gluon TMDs

\( \frac{d\sigma}{dq_T} \sim \Phi_U A \Phi_U B |M|^2 \)

\sim C[ f_{1g/A} \ f_{1g/B} ] \pm C[ h_{1g/A} \ h_{1g/B} ]

unpolarized gluons

lin. polarized gluons

pseudoscalar quarkonium production:

\( p \ p \rightarrow \eta_b \ X \quad M = 9.39 \text{ GeV} \)

\( p \ p \rightarrow \eta_c \ X \quad M = 2.98 \text{ GeV} \)

[see also talk by C. Pisano week 4]
\( \eta_c \) production at LHC

full transverse momentum spectrum:
low qT matched with high qT region

\[ \frac{d\sigma}{dq_T} = \omega_1 W + \omega_2 Z \]

\( \omega_1 \sim \left( \frac{q_T + m}{Q} \right)^{-2} \), \( \omega_2 \sim \left( \frac{m}{q_T} \right)^{-2} \)

**blue band**: uncertainty from matching

the matching is performed as a weighted average of the calculations at low and high transverse momentum

the weights are related to the power corrections to TMD and collinear factorization:
**η_c production at LHC**

full transverse momentum spectrum:
low qT matched with high qT region

**blue band**: uncertainty from matching

**grey band**: scale uncertainty

\( \mu_i^2 = \zeta_i = \mu_b^2 \), \( \mu_{F.O.} = m_T \)

fact. 2 variation and envelope

<table>
<thead>
<tr>
<th>LHCb</th>
<th>Resummed</th>
<th>Fixed-order</th>
<th>Average</th>
<th>Scale uncertainty</th>
</tr>
</thead>
</table>

\( \eta_c \) production
NP model 1502.05354
\( b_{\text{min}} \) and \( b_{\text{max}} \)
\( \sqrt{s} = 7 \) TeV
\( R_0^2 = 0.921533 \)
\( 2 < y < 4.5 \)

preliminary
\( \eta_c \) production at LHC

full transverse momentum spectrum:
low qT matched with high qT region

- **blue band**: uncertainty from matching
- **grey band**: scale uncertainty
- **red band**: nonpert. uncertainty

\[
S_{NP}(\bar{b}_T) = - \left[ \frac{a_1}{2} + \frac{a_2}{2} \ln Q^2 \right] \bar{b}_T^2
\]

- \( a_i = 0.5 \text{ GeV}^2 \), var. 50\%, envelope
  - both for unpolarized and linearly polarized distributions

the formalism is in good shape!
we need the data at low qT
W production at LHC

References:

- AS, PhD thesis
- Bacchetta, Bozzi, Radici, Mulders, Ritzmann, AS - in preparation
Uncertainties - mass

Uncertainties on $m_W$ [MeV] from $p_T$ fit

<table>
<thead>
<tr>
<th>Source</th>
<th>$W \rightarrow \mu\nu$</th>
<th>$W \rightarrow e\nu$</th>
<th>Common</th>
</tr>
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<tbody>
<tr>
<td>Lepton energy scale</td>
<td>7</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Lepton energy resolution</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Lepton efficiency</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Lepton tower removal</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Recoil scale</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Recoil resolution</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Backgrounds</td>
<td>5</td>
<td>3</td>
<td>0</td>
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<tr>
<td>PDFs</td>
<td>9</td>
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<td>9</td>
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<tr>
<td>$W$ boson $q_T$</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Photon radiation</td>
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<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Statistical</td>
<td>18</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>25</td>
<td>28</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 7.1. Uncertainties on $m_W$ (in MeV) as resulting from charged-lepton transverse-momentum fits in the $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$ samples. “$W$ boson $q_T$” refers to sources discussed before (7.2.1). The last column reports the portion of the uncertainty that is common in the $\mu\nu$ and $e\nu$ results. Original version and definitions in [260].
Nonperturbative effects

$$\frac{d\sigma^{Z/W^\pm}}{dq_T} \sim \text{FT} \sum_{i,j} \exp \left\{ -g_{ij}b_T^2 \right\}$$

$$g_{ij} \sim \langle k_T^2 \rangle_i + \langle k_T^2 \rangle_j + \text{soft gluons}$$

$g$ comes from 2 TMD PDFs and **controls the position of the peak**

$p\bar{p}\rightarrow Z X$ (ECM = 1.8 TeV)

P. Nadolsky - 10.1063/1.1896698
Z vs W: flavor content

Intrinsic kT effects have been measured on Z data and used to predict the W distribution, assuming they are the same for Z and W

This reflects a flavor independent approach and might not be optimal because of the different flavor content:

the intrinsic contributions are different in Z and W± production
### Uncertainties - peak

<table>
<thead>
<tr>
<th>Source</th>
<th>$W^+$</th>
<th>$W^-$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_R = \mu_c/2, 2\mu_c$</td>
<td>+0.30</td>
<td>-0.09</td>
<td>+0.29</td>
</tr>
<tr>
<td>pdf (90% cl)</td>
<td>+0.03</td>
<td>-0.05</td>
<td>+0.06</td>
</tr>
<tr>
<td>$\alpha_S = 0.121, 0.115$</td>
<td>+0.14</td>
<td>-0.12</td>
<td>+0.14</td>
</tr>
<tr>
<td>f.i. $\langle k_T^2 \rangle = 1.0, 1.96$</td>
<td>+0.16</td>
<td>-0.16</td>
<td>+0.16</td>
</tr>
<tr>
<td>f.d. $\langle k_T^2 \rangle$ (max $W^+$ effect)</td>
<td>+0.09</td>
<td>-0.06</td>
<td>±0</td>
</tr>
<tr>
<td>f.d. $\langle k_T^2 \rangle$ (max $W^-$ effect)</td>
<td>-0.03</td>
<td>+0.05</td>
<td>±0</td>
</tr>
</tbody>
</table>

**Table 7.2.** Summary of the shifts in GeV for the peak position for $q_T$ spectra of $W^\pm/Z$ arising from different sources. The colors for the flavor dependent (f.d.) and independent (f.i.) variations match the ones in Sec. 7.4.6.

The uncertainty including intrinsic transverse momentum is comparable in magnitude with the one associated to collinear PDFs!
Event generators

References:

- M. Diefenthaler’s talk - week 4
Study of Hadronization in **NP** and **HEP**

**LDRD:**
- started in FY17
- at **JLab**

**Urgent requirement**
- MCEG for TMDs
- Understanding of hadronization process

**Unique approach**
- Connection between hadronization phenomena in **NP** and **HEP**.

**By doing so:**
- **NP** Improve theoretical framework for TMDs.
- **HEP** Improve hadronization models.

**Connection between NP and HEP**
- Correlation functions of TMD factorization
- Pythia MCEG LUND string model
Work plan

**FY17**
- Publication: DIS in Pythia8
- Publication: LUND validation
- Hadronization plugin
  - user model for one phenomenon
  - rest from Pythia8
- Spin-dependent hadronization
  - Incorporate model of transverse spin effects into Pythia8
  - Anna Martin and Albi Kerbizi will join project in FY18

**FY18**
- + TMD observables
- Hadronization in NP and HEP
  - comparison Pythia8-TMD factorization
  - language dictionary
  - Pythia8 with spin-independent TMDs

**FY19**
- top-bottom approach: incorporate TMD effects in a fully exclusive event generator (Pythia 8)
LDRD personnel (FY17)

- **JLab**
  - PI: Diefenthaler
  - Co-PI: Melnitchouk
  - Co-PI: Rogers
  - Co-PI: Rogers

- **Pythia**
  - Co-PI: Collins
  - Co-PI: Sato
  - Co-PI: Lönnblad

- **Other**
  - Co-PI: Joosten
  - Co-PI: Signori
  - Co-PI: Ethier
  - Co-PI: Prestel
Conclusions and future developments

- the **relevance** of the **nonperturbative part of TMDs** changes according to the **kinematic** region explored

- we have extractions of unpolarized quark TMDs; for gluons we are setting up the formalism (first calculation of full transverse momentum spectrum for $\eta$ production at the LHC)

- **high-Q & small-x** is the region where the formalism is most **predictive**; even here, though, NP corrections leave **sizable footprints** in observables; see $W$ production at the LHC

- the **EIC** will be very helpful, since it will be able to provide new data ranging from low to high Q and from low to high x
Nature is “smooth”: understand the link between TMDs & PDFs

From: Modelling the nucleon structure by M. Burkardt and B. Pasquini (left)
Introduction to GPDs and TMDs by Markus Diehl (right)
quark TMD PDFs

\[ \Phi_{ij}(k, P; S) \sim \text{F.T.} \langle PS | \bar{\psi}_j(0) U_{[0,\xi]} \psi_i(\xi) | PS' \rangle_{LF} \]

extraction of a quark not collinear with the proton

courtesy A. Bacchetta
quark TMD PDFs

\[
\Phi_{ij}(k, P; S, T) \sim \text{F.T. } \langle PS' | \bar{\psi}_j(0) U_{[0,\xi]} \psi_i(\xi) | PS' \rangle |_{LF}
\]

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extraction of a quark
not collinear with the proton

bold: also collinear
red: time-reversal odd (generalized universality properties)
The frontier

**Nucleon tomography in momentum space:**
To understand how hadrons are built in terms of the elementary degrees of freedom of QCD

**High-energy phenomenology:**
To improve our understanding of high-energy scattering experiments and their potential to explore BSM physics

A selection of open questions (formalism):

1) How well do we understand collinear and TMD factorization?

2) How (well) can we match collinear and TMD factorization?

3) Can we quantify factorization breaking effects?

4) How can we investigate gluon TMDs?

...
The frontier

**Nucleon tomography in momentum space:**
to understand how hadrons are built in terms of the elementary degrees of freedom of QCD

**High-energy phenomenology:**
to improve our understanding of high-energy scattering experiments and their potential to explore BSM physics

**More open questions (phenomenology):**

1) what is the *functional form* of TMDs at low transverse momentum ?

2) what is its *kinematic* and *flavor* dependence ?

3) can we attempt a global fit of TMDs ?

4) can we test the generalized *universality* of TMDs ?

5) what’s the impact of hadron structure on the *high-energy physics* processes ?
W-term and TMDs

Distribution for intrinsic transverse momentum (and its FT):

\[
\tilde{F}_{i, NP}(x, \bar{b}_T; \{\lambda\})
\]

Is this a Gaussian?

Soft gluon emission

\[
g_K(\bar{b}_T; \{\lambda\})
\]
W-term and TMDs

Distribution for intrinsic transverse momentum (and its FT):

\[ \tilde{F}_{i, NP}(x, \bar{b}_T; \{\lambda\}) \]

\( a \) Gaussian?

Soft gluon emission

\[ g_K(\bar{b}_T; \{\lambda\}) \]

Separation of \( b_T \) regions

\[ \hat{b}_T(b_T; b_{\text{min}}, b_{\text{max}}) \]

\( b_{\text{max}} \), \( b_T \to +\infty \)

\( \sim b_T \), \( b_{\text{min}} \ll b_T \ll b_{\text{max}} \)

\( b_{\text{min}} \), \( b_T \to 0 \)

High \( b_T \) limit: avoid Landau pole

Low \( b_T \) limit: recover fixed order expression
Collinear and TMD factorization

Let's consider a process with three separate scales:

- **hadronic mass scale**
- **hard scale**
- (related to the) transverse momentum of the observed particle

The ratios

\[
\frac{\Lambda_{QCD}}{Q}, \quad \frac{\Lambda_{QCD}}{q_T}, \quad \frac{q_T}{Q}
\]

select the factorization theorem that we rely on.

According to their values we can access different “projections” of hadron structure.

(SIDIS, Drell-Yan, e+e- to hadrons, pp to quarkonium, ... )
Collinear and TMD factorization

The key of phenomenology: emergence of TMD and collinear distributions from factorization theorems.

fixed $Q$, variable $q_T$

$d\sigma/dq_T$

$q_T \geq Q$

collinear factorization

relative error $= O(\lambda_{QCD}/q_T)$

degraded description!

fixed-order term

$\sim \Phi_A(x_a) \Phi_B(x_b)$

collinear PDFs

Jefferson Lab
Collinear and TMD factorization

The key of phenomenology: emergence of TMD and collinear distributions from factorization theorems

-fixed Q, variable $q_T$

$$d\sigma/dq_T$$

$q_T \ll Q$

resummed term [(W)]

TMD factorization

collinear factorization

fixed-order term

$\Phi_A(x_a, k_{Ta}) \Phi_B(x_b, k_{Tb}) \sim \text{TMD PDFs}$

relative error $= O(q_T/Q)$

degraded description!

$\Phi_A(x_a) \Phi_B(x_b)$

collinear PDFs
Collinear and TMD factorization

The key of phenomenology: emergence of TMD and collinear distributions from factorization theorems

fixed $Q$, variable $q_T$

$\frac{d\sigma}{dq_T}$

$q_T \ll Q$

Matching region

resummed term (W)

TMD factorization

collinear factorization

degraded descriptions

W, relative error = $O(q_T/Q)$

F.O., relative error = $O(\Lambda_{QCD}/q_T)$

We need a prescription to deal with the region where both descriptions are not good
Collinear and TMD factorization

The key of phenomenology: emergence of TMD and collinear distributions from factorization theorems

\[ \frac{d\sigma}{dq_T} \]

fixed $Q$, variable $q_T$

$Q_T \ll Q$

Matching region

TMD factorization
collinear factorization
degraded descriptions

fixed-order term
collinear PDFs

resummed term (W)
TMD PDFs

Crucial, especially at low $Q$ (e.g. JLab kinematics), where the regions shrink

Pheno: we are making progress

The extraction of the nonperturbative (NP) part of TMDs is affected by the description of the whole $q_T$ range

polarization?
**W-term & TMDs**

**W-term**: transverse momentum resummation in terms of TMDs

\[
W(q_T, Q) = \int \frac{d^2 b_T}{(2\pi)^2} e^{i q_T \cdot b_T} \tilde{W}(b_T, Q)
\]

\(b_T\) is the Fourier-conjugated variable of the (partonic and observed) transverse momenta

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**Need a regularization to recover collinear factorization upon integration over \(q_T\):**

\[b_T \rightarrow \bar{b}_T \geq b_{\text{min}} \sim 1/Q \quad \Rightarrow \quad \int d^2 q_T \, W(q_T, Q) \sim f_{i}^{h_1}(x_1; \mu) \, f_{j}^{h_2}(x_2; \mu)\]

Collins et al. PRD94 2016

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\[\tilde{W}(b_T, Q) \sim \tilde{F}_{i}^{h_1}(x_1, b_T; \mu, \zeta_1) \, \tilde{F}_{j}^{h_2}(x_2, b_T; \mu, \zeta_2)\]

Product of Fourier-transformed TMDs

**TMD evolution** is multiplicative in \(b_T\) space
Quark TMD PDF

\[ \bar{W}_{QZ}(b, Q, x_A, x_B) = \begin{cases} \bar{W}(b, Q, x_A, x_B), & b \leq b_{max}; \\ \bar{W}(b_{max}, Q, x_A, x_B) \bar{F}_{QZ}^{NP}(b, Q, x_A, x_B; b_{max}), & b > b_{max}; \end{cases} \]

\[ \bar{F}_{QZ}^{NP}(b, Q, x_A, x_B; b_{max}) = \exp \left\{ -\ln \left( \frac{Q^2 b^2_{max}}{c^2} \right) \left\{ g_1 [(b^2)^\alpha - (b_{max}^2)^\alpha] + g_2 (b^2 - b_{max}^2) \right\} - g_2 (b^2 - b_{max}^2) \right\} \]

parameters:
- \( b_{max}, g_1, g_2, \alpha \)

\( g_1 \) and \( \alpha \) are fixed as a function of \( g_2, b_{max} \) requiring continuity in \( b_{max} \) of the first and second derivative

Qiu-Zhang, Phys. Rev. D 63 114011
ηc production at LHC

Low-energy process
\[ Q = M(\eta_c) = 2.98 \text{ GeV} \]

\[ b_{\text{min}} \text{ and } b_{\text{max}} \text{ prescriptions} \]

Smooth matching from \( W \) to FO
- \( W \) dominates for \( q_T < 1 \text{ GeV} \)
- FO dominates for \( q_T > 3 \text{ GeV} \)

Blue band: uncertainty from log-average matching

Red band: uncertainty from improved \( W+Y \) matching (larger)
TMD approach

**Philosophy**: check if the structure of the IR divergencies is the same as in ‘full’ QCD. If yes, the factorized form works as QCD, namely factorization is “established”

\[ \sigma_{\text{virt},(1)} \leftrightarrow \{ \mathcal{H} \tilde{f}_1/A \tilde{g}/B \}^{(1)}_{\text{virt}} \]

? same IR?

**no:**
It does not reproduce the physical (\(=QCD\)) result

**yes:**
It reproduces the physical result and the hard part can be calculated by subtraction
PDF uncertainties

Intrinsic transverse momentum effects

Impact on Higgs physics

Impact on Higgs physics

PDF uncertainties

Intrinsic transverse momentum effects

$p p \rightarrow H + X \quad m_H = 125$ GeV
$\sqrt{s} = 14$ TeV