Experimental TDA program at FAIR, JLAB, EIC and JPARC

Stefan Diehl
Justus Liebig University Giessen
University of Connecticut

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Hard exclusive meson production

GPD based description
large $Q^2$ and $s$, $x_B$ fixed
small $t$ channel contribution
➔ meson in forward region

TDA based description
large $Q^2$ and $s$, $x_B$ fixed
small $u$ channel contribution
➔ meson in backward region

J. Collins, L. Frankfurt, M. Strikman '97

colinear factorization theorem

L. Frankfurt, M. V. Polyakov, M. Strikman et al.'02

Stefan Diehl, JLU + UCONN
Light Cone 2021, Jeju Island, Korea
11/30/2021
Light-cone matrix elements of non-local bilinear quark and gluon operators

Describe hadronic structural information in terms of quark and gluon degrees of freedom

Spin-dependent 2D transverse coordinate space + 1D longitudinal momentum space images of the nucleon

Tool to study the nature and origin of the nucleon spin

Access to basic properties of the nucleon, like pressure distributions, tensor charge ...

Impact parameter space: spatial femto-photographs of the hadron structure in the transverse plane

Physics content

GPDs (-t/Q² << 1)

GPDs (Generalized Parton Distributions)

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Light Cone 2021, Jeju Island, Korea

11/30/2021
Baryon to meson TDAs \((-u/Q^2 << 1)\)

- Light-cone matrix elements of non-local three quark operators
- Encoded physical picture close to GPDs
- Probe partonic correlations between states of different baryonic charge
  - Access to non-minimal Fock components of baryon light-cone wave functions
- Improved access to the valence and sea quark components of the nucleon wave function
- Impact parameter space: Femto-photography of hadrons from a new perspective

"knocking a proton out of a proton"
Physics motivation

- Exclusive u-channel interactions in the deep regime are mostly unexplored territory
- Small cross sections (1/10 – 1/100 of the t-channel peak)
- No unified framework available due to the lack of experimental data
- Recent and upcoming high statistics experiments (like at JLAB) offer new opportunities to study the u-channel regime

Goals for theory ↔ experiment:

- Obtain new insights in the nucleon structure, complementary to the forward regime
  - Develop a **unified Regge model**
    - Validate our understanding of the relevant exchange mechanisms
    - Probe the soft-hard transition in QCD for different kinematic regions
    - Available Regge models including backward angles:
  - Develop a **TDA framework** similar to GPDs in the forward region
The TDA model: Experimentaly accessible features

Transition distribution amplitudes and hard exclusive reactions with baryon number transfer  

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B. Pire \textsuperscript{a}, K. Semenov-Tian-Shansky \textsuperscript{b,c,*}, L. Szymanowski \textsuperscript{d}

Characteristic features of the TDA-based mechanism:

$\rightarrow$ Dominance of the transverse polarisation of the virtual photon leads to a suppression of the longitudinal cross section $\sigma_L$ at large $Q^2$ by at least a factor $1/Q^2 \rightarrow \sigma_T \gg \sigma_L$

$\rightarrow$ The transverse cross section $\sigma_T$ shows a characteristic $1/Q^8$ scaling behaviour for fixed $x_B$

More distinguishing features become accessible with a polarized target:

$\rightarrow$ Transverse target single spin asymmetry $\sim Im$ part of the amplitude

$\rightarrow$ TDA approach predicts a non vanishing and $Q^2$-independent TSA

$\rightarrow$ Two component TDA model predicts 10-15% TSA for $\gamma^* N \rightarrow \pi N$
Experimental facilities at JLAB

- **CLAS** (operation till 2012)
  - up to 6 GeV longitudinally polarized electron beams
  - unpolarized hydrogen target
  - large acceptance spectrometer

- **CLAS12** (operation since 2018)
  - 10.6, 6.6, 7.5 GeV longitudinally polarized electron beams
  - unpolarized and polarized hydrogen targets and deuterium (neutron) target
**Experimental facilities at JLAB**

- **HALL C**
  - Longitudinally polarized electron beams with different beam energies ($< 6, 11$ GeV)
  - Different targets (i.e., unpolarized hydrogen)
  - Two arm high precision spectrometer

- **HALL D (GlueX)**
  - Tagged photon beam
  - Different targets (i.e., hydrogen)
  - u-channel photoproduction
Hard exclusive $\pi^+$ electroproduction in the backward regime

**CLAS:** $ep \rightarrow en\pi^+$

$$\frac{d^4\sigma}{dsdQ^2d\phi dt} = C \times \left[ \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \varepsilon \cos 2\phi \frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi \frac{d\sigma_{LT}}{dt} + h\sqrt{2\varepsilon(1-\varepsilon)} \frac{d\sigma_{LT'}}{dt} \sin \phi \right]$$

**DATA**

- $W = 2.0 - 2.4$ GeV
- $Q^2 = 1.6 - 4.5$ GeV$^2$
- $-u = 0.5$ GeV$^2$
- $\phi = 0^\circ - 360^\circ$

**Yield/20 MeV**

- $W = 2-2.4$ (GeV), $Q^2 = 1.87-2.23$ (GeV$^2$)
- $\Delta t^2 = 0-0.5$ (GeV$^2$), $\varphi^*_s = 60$ (deg)
- $P_{2\text{Re}} = -11.896$
- $P_{3\text{Re}} = 18.053$

Hard exclusive $\pi^+$ electroproduction in the backward regime

$$ep \rightarrow en\pi^+$$

TDA model calculations for $\sigma_U$:

$\rightarrow$ Results depend on the input for the nucleon distribution amplitude


Hard exclusive $\pi^+$ electroproduction beam spin asymmetry

\[ ep \rightarrow en\pi^+ \]

**CLAS:**


\[ \text{https://doi.org/10.1103/PhysRevLett.125.182001} \]

**DIS cuts:**
- \( W > 2 \) GeV
- \( Q^2 > 1 \) GeV

\[ BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)} \]

\[ A_{LU}^{\sin\phi} = \frac{\sqrt{2\varepsilon(1-\varepsilon)} \sigma_{LT'}}{\sigma_T + \varepsilon\sigma_L} \]
Hard exclusive $\pi^+$ electroproduction beam spin asymmetry

Hard exclusive $\pi^+$ electroproduction beam spin asymmetry

\begin{align*}
\text{small -t} & \\
\text{small -u} & \\
\end{align*}

$Q^2$

$\chi_B$

\begin{align*}
\text{forward region} & \\
\text{backward region} & \\
\end{align*}

Backward $\omega$ production in hall C at JLAB

**Hall C:** Analysis by: W. B. Li, G. Huber *et al.* (Jefferson Lab $F_{\pi}$ collaboration)


**JLAB Hall C:** 2.6 - 5.2 GeV electron beam on a liquid hydrogen target
- Recoil protons and scattered electrons detected with the hall C high precision particle spectrometers

- $Q^2 = 1.60$ and 2.45 GeV$^2$
- $<W> = 2.21$ GeV

**Missing mass of $ep \rightarrow e'pX$:**

$\rightarrow$ Clear signal from backward regime for $ep \rightarrow e'p\omega$

![Graph showing missing mass distribution with data and simulations](image)
Backward $\omega$ production in hall C at JLAB

$$\frac{d^2 \sigma}{dt} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}$$

⇒ Full Rosenbluth separation to extract $\sigma_T$ and $\sigma_L$

Theory: Cross-channel nucleon exchange model for $p \rightarrow \omega$ TDAs


⇒ A generalization of the TDA formalism for the case of light vector mesons ($\rho$, $\omega$, $\phi$)

For $Q^2 = 2.45 \text{ GeV}^2$:

$$\frac{\sigma_L}{\sigma_T} < \frac{\mu^2}{Q^2}$$

and $\sigma_T \gg \sigma_L$

W. B. Li et al. (Jefferson Lab F$_\pi$ Collaboration)
Backward $\omega$ production in hall C at JLAB

Combined (CLAS and $F_{\pi-2}$ data for $\gamma p \rightarrow \omega p$)

TDA-based predictions vs the Regge-based J.M. Laget's (JML18) model

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W. B. Li et al. (Jefferson Lab $F_{\pi}$ Collaboration)
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• Additional data was recorded in hall C with the KaonLT experiment
  → Parallel recording of \( p(e, e'p)X \)

**u-channel ϕ:** Access to \( s\bar{s} \) content of the nucleon

• More data from the PionLT experiment (\( Q^2 = 8.5 \text{ GeV}^2 \))

**JLAB experiment E12-0-007:** Approved by PAC 48 for hall C
  → First dedicated u-channel experiment
  → Study of the TDA framework by probing \( {}^1H(e, e'p)\pi^0 \) exclusive electroproduction

\[
W = 3.1 \text{ GeV} \quad (s = 10 \text{ GeV}^2) \quad 2 < Q^2 < 6.25 \text{ GeV}^2
\]
Perspectives for CLAS12

• CLAS 12 can access the TDA regime for the following reactions:

  \textbf{RG-A + RG-K: } ep \rightarrow e' n \pi^+ \quad ep \rightarrow e' p \rho \quad (ep \rightarrow e' p \omega) \quad (ep \rightarrow e' p \phi)

  \textbf{RG-B: } en \rightarrow e' p \pi^-

  \textbf{upcoming RGs: } polarized targets

⇒ A significant amount of data has already been recorded and is currently in the analysis phase (BSA and all cross section terms)

\textbf{Example: } CLAS12 kinematic coverage of \( ep \rightarrow e' \pi^+ (n) \)
### Summary of the TDA program status at JLAB

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\sigma_T &gt; \sigma_L$</th>
<th>$1/Q^8$ Scaling</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>$\square$</td>
<td>$\square$</td>
<td>hall C</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>CLAS / CLAS12</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$\checkmark$</td>
<td></td>
<td>CLAS12</td>
</tr>
<tr>
<td>$K^0$</td>
<td></td>
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</tr>
<tr>
<td>$K^\pm$</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$\eta$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>hall C</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$\checkmark$</td>
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<td>CLAS12</td>
</tr>
<tr>
<td>$\omega$</td>
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<td>$\checkmark$</td>
<td>hall C / CLAS12?</td>
</tr>
<tr>
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<td>$\checkmark$</td>
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<td>hall C</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>hall C</td>
</tr>
<tr>
<td>VCS</td>
<td>$\triangle$</td>
<td>$\triangle$</td>
<td>hall C</td>
</tr>
</tbody>
</table>

- $\square$: experiment approved
- $\checkmark$: parasitic data may be available
- $\checkmark\checkmark$: confirmed by existing data
- $\triangle$: in the early planning stage
TDA measurements with the future PANDA detector at FAIR

- 1.5 GeV/c – 15 GeV/c antiproton beam
- cluster jet / pellet target
- L = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}

- Barrel with endcaps and forward spectrometer
- \sim 4\pi coverage

start of operation ~ 2026
TDA measurements with the future PANDA detector at FAIR

TDAs also occur in the factorized description of:

\[ \bar{N} + N \rightarrow \gamma^* (q) + \pi \rightarrow \ell^+ + \ell^- + \pi \]
\[ \bar{N} + N \rightarrow J/\psi + \pi \rightarrow \ell^+ + \ell^- + \pi \]

TDA measurements with the future PANDA detector at FAIR

\[ \overline{p}p \rightarrow \gamma^* \pi^0 \rightarrow e^+ e^- \pi^0 \]

\[ \frac{d\sigma}{dt \ dq^2 \ d\cos \theta^*_\ell} \bigg|_{\text{Leading twist}} = \frac{K}{s - 4M^2} \left( \frac{1}{(q^2)^5} \right) (1 + \cos^2 \theta^*_\ell) \]

\[ \frac{d\sigma}{dq^2} \sim \frac{1}{(q^2)^5} \]

\( q^2 \) scaling of the cross section is a test for the QCD factorisation

\[ s = 5 \ \text{GeV}^2 \]

\[ L = 2 \ \text{fb}^{-1} \]

\[ \frac{\Delta \sigma}{\sigma} \sim 12\% \]

\[ s = 10 \ \text{GeV}^2 \]

\[ L = 2 \ \text{fb}^{-1} \]

\[ \frac{\Delta \sigma}{\sigma} \sim 24\% \]

Test of the dominance of the transverse polarisation of the virtual photons

\[ \frac{d\sigma}{dq^2} \sim (1 + \cos^2 \theta^*) \]

\( s = 5 \text{ GeV}^2 \)

\( s = 10 \text{ GeV}^2 \)

Very clean signal (S/B > 10)

\( L = 2 \text{ fb}^{-1} \)

\[ D \cdot (1 + C \cos^2 \theta_{\pi^0}) \]

\[ D \cdot (1 + C \cos^2 \theta_{\pi^0}) \]

\[ C = 1.0 \pm 0.2 \]
\[ D = (660 \pm 30) \text{ fb} \]

\[ C = 1.0 \pm 0.5 \]
\[ D = (86 \pm 11) \text{ fb} \]
TDA measurements with the future PANDA detector at FAIR

\[ \bar{p}p \rightarrow J/\Psi \, \pi^0 \rightarrow e^+ e^- \pi^0 \]

\[ \frac{d\sigma}{dq^2} \sim (1 + \cos^2 \theta^*_\ell) \]

\[ L = 2 \text{ fb}^{-1} \]

\[ \Delta \sigma(t,u) / \sigma(t,u) \sim 5\% - 10\% \]

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Stefan Diehl, JLU + UCONN

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Opportunities for TDA measurements at JPARC

**J-PARC**: Intense pion and kaon beams with $p = 10 – 20$ GeV/c

- **Different opportunities for TDA studies**
    - J.P. Lansberg et al. (2012)
Opportunities for TDA measurements at JPARC

- Charmonium production in association with a nucelon
- Hyperon production in association with a virtual photon
- Antiproton annihilation

$\pi^- p \to n + J/\psi$

$K^- N \to \Lambda \gamma^*$

$\bar{p}N \to \gamma^* \pi$

=> Check for the universality of TDAs

see PANDA
Opportunities for TDA measurements at the EIC

electron – proton and
electron – ion collisions
with up to 18 GeV/c x 275 GeV/c

 remotely

\[ \sqrt{s} = 70 \text{ GeV} \]
\[ \sqrt{s} = 20 \text{ GeV} \]

\[ \text{JLab 12 GeV} \]

\[ \text{EIC} \]

\[ x \]

\[ y \]

\[ 10^2 \]

\[ 10^1 \]

\[ 10^{-3} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 1 \]

\[ 100 \text{ ft} \]

Extension of the TDA program into the high energy, high $Q^2$ regime
Access to heavy (charmed) mesons

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Opportunities for TDA measurements at the EIC

First feasibility studies for
\[ e + p \rightarrow e' + p' + \pi^0 \]

→ Can be well measured in u-channel kinematics
  - 4\pi coverage of the EIC detector
  - capability for forward proton tagging

→ Also the backward production of
\[ e + p \rightarrow e' + p' + \omega \]
has been found to be feasible

→ More channels like the exclusive J/Ψ and Y meson production are under investigation for the different detector proposals

C. Ayerbe Gayoso et. al, Progress and Opportunities in Backward angle (u-channel) Physics, accepted by Eur. Phys. J. A
Expected global dataset for u-channel $\pi^0$ production

$$e + p \rightarrow e' + p' + \pi^0 \quad \text{for} \quad u \sim u_{\text{min}}$$

![Graph showing differential cross section $d\sigma/dq^2$ vs. $Q^2$ with data points from PANDA, JLab E12-20-007, EIC, and GlueX.]

$$s = 10 \text{ GeV}^2$$
Summary and Outlook

• Nucleon-to-meson TDAs provide new information about correlations of partons inside the nucleon

• In the impact parameter space, TDAs provide a spatial imaging of the structure of the pion cloud inside the nucleon

• JLAB 6 GeV data provided first hints for the validity of the TDA based description

• JLAB 12 GeV data will provide more detailed measurements in the TDA regime

• PANDA and J-PARC will allow a check of the universality of TDA

• The EIC will enable an extension of the JLAB program to higher energies and higher $Q^2$

Progress and Opportunities in Backward angle ($u$-channel) Physics

C. Ayerbe Gayoso$^1$, L. Bibrzycki$^2$, S. Diehl$^{1,4}$, S. Heppelmann$^5$, D.W. Higinbotham$^6$, G.M. Huber$^7$, S.J.D. Kay$^7$, S.R. Klein$^8$, J.M. Laget$^6$, W.B. Li$^{9,6}$, V. Mathieu$^{10,11}$, K. Park$^{12}$, R.J. Perry$^{13}$, B. Pire$^{14}$, K. Semenov-Tian-Shansky$^{15,16}$, A. Stanek$^8$, J.R. Stevens$^9$, L. Szymanowski$^{17}$, C. Weiss$^6$, B.-G. Yu$^{18}$

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