A JSA Postdoc Award Synopsis: Studying Backward-angle Physics from JLab 12 GeV to EIC

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A postdoc at William and Mary

22/June/2020
Outline

- Introducing the backward angle physics:
  - What is backward angle physics?
  - How do we access it?
  - Why do we want to study it?

- Theory interpretation to the u-channel physics observables

- List of plan tasks during for the post-doc award

- Measure of success

- Progress so far
Backward-angle structure of Atom

- Forward scattered alpha particle: extracting the interaction radius of the nucleus and mapping out the transverse structure of the atom (mostly empty)

- Recoiling alpha particle: stiffness of the “point-like” structure.

- Full structure must incorporate both forward angle and backward angle observables.
Structure of Proton

Transition: Soft structure $\rightarrow$ Hard structure $\rightarrow$ Soft structure

M. Guidal, J.-M. Laget, and M. Vanderhaeghen. 
Hadronic Model: Transition (Evolution) of Proton Structure

- Physical parameters:
  - In $x$, $W$ (or $s$), $Q^2$, $t$, $u$

- $x$ Evolution:
  - Parton momentum fraction: 0.2-0.3 valence quark distribution is pronounced

- $W$ Evolution:
  - Dictate if a process is in the resonance region

- $Q^2$ Evolution
  - Wavelength of the probe, or resolving power

- $t$ Evolution
  - Inversely related to the Impact parameter $b$

- What about $u$? Any role?
**t-Channel $\pi$ vs u-Channel $\omega^0$ Production**

- **Fpi-2 (E01-004) 2003**
  - Spokesperson: Garth Huber, Henk Blok
  - Standard HMS and SOS (e) configuration
  - Electric form factor of charged $\pi$ through exclusive $\pi$ production

- Primary reaction for Fpi-2
  - $p(e, e'\pi^+)n$

- In addition, we have for free
  - $p(e, e'p)\omega$

- Kinematics coverage
  - $W= 2.21$ GeV, $Q^2=1.6$ and $2.45$ GeV$^2$
  - Two $\epsilon$ settings for each $Q^2$

- LT Separation!
Backward Angle $\omega$ Electroproduction from 6 GeV Era

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

2003

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

$\omega (782 \text{ MeV})$}

$\rho (770)$

$\eta (547)$

$\eta' (947)$

Low $\epsilon$

High $\epsilon$

Coincidence time

epX missing mass

epX missing mass

(a) $-u \leq 0.19 \text{ GeV}^2$

(b) $0.19 < -u \leq 0.30 \text{ GeV}^2$

(c) $0.30 < -u \leq 0.50 \text{ GeV}^2$
Backward Angle $\omega$ Electroproduction from 6 GeV Era

• Key observation:
  ○ $\sigma_L$ dropped significantly as question of $Q^2$, as a result: $\sigma_T > \sigma_L$ observed at $Q^2 \approx 2.35$ GeV$^2$
  ○ Sharp u-channel $\omega$ Electroproduction peaks are observed at both 1.75 and 2.35 GeV$^2$
  ○ Forward-backward ratio is 10:1!

The Regge Approach (Soft structure)

- Regge Study by J-M. Laget in 2018
- Key findings:
  - Nucleon pole contribution along could not explain the sharply rising slope at \(-t = -t_{\text{max}}\).
  - Re-scattering within nucleon diagrams is required.
  - Work is in progress. L/T separation study was not attempted.
- Another Regge effort from Be-Geel Yu is also work in progress. Attempting the L/T separation prediction.
Complete description of Nucleon

- **GPD**: is like a hadron tomography of the proton. It is extracted predominately based the forward angle observables.

- **SPD**: Skewed Parton Distribution. Discovered Frankfurt and Strikman in 2003. Hadron tomography of the proton at large skewness. At extreme skewness, known as the **Super SPD**.

- **TDA**: meson-nucleon Transition Distribution Amplitude (TDA), similar to super SPD. Rediscovered by B. Pire, and L Szymanowski and K Semenov-Tian-Shansky. Tomography of partonic distributions in the nucleon --> meson and vice versa transitions probed in the backward angle kinematics.
Two qualitative predictions from TDA:

- $\sigma_T \sim 1/Q^8$ scaling behavior
- $\sigma_T > \sigma_L$, $\sigma_L \sim 0$

Three phases of validating TDA with JLab 12 GeV meson electroproduction:

- Stage 0: find $u$-channel peaks for all mesons (12 GeV)
- Stage 1: test TDA predictions (12 GeV)
- Stage 2: extractions of TDAs

Upcoming PAC 48 proposal

In the very planning stage

Confirmed! By Hall C 6 GeV $\omega$
JSA Award List of Tasks

- Invite Dr. K. Semenov-Tian-Shansky (as a TDA expert) for a research visit to deepen discussion in u-channel physics

- Developing coherent and comprehensive 12 GeV strategy
  - Priorities list of prime observables: takes into account realistic constrains and avaialbe resources
  - $u$-channel DVCS: kinematics survey
  - Supporting more single pion beam spin assymmetries development from CLAS

- TDA cross section predictions 12 GeV and EIC kinematics

- Hosting first $u$-channel physics workshop

Measure of Success:

- Completing and publishing the workshop white paper on the backward angle physics strategy for JLab 12 GeV.

- Completing and publishing the EIC backward-angle $\pi^0$ feasibility study (work in progress).

- Completing the relevent section in Yellow report (work in progress).

- Presenting PAC48 proposal (submitted to PAC).
JLab 12 GeV to EIC Transition: $u$-channel $\pi^0$ production


$s = 10$ GeV$^2$, $\pi^0$ u-Channel Production

$q^2$ scaling

PAC 48 proposal

$Q^2$ scaling

Same TDAs for PANDA and EIC, the ultimate universality check
Progress Report on PAC 48 Proposal: Backward-angle $\pi^0$

First dedicated $u$-channel electroproduction study above the resonance region: $^1\text{H}(e,e'p)\pi^0$
- $Q^2$ coverage: $2.0 < Q^2 < 6.25$ GeV$^2$.
- $x=0.36$
- $u$ coverage: $0 < -u' < 0.5$ GeV$^2$

Objective:
- Study soft-hard transition
- Validating TDA

Submitted to PAC 48!
Progress Report on $u$-channel $\pi^0$ @ EIC

$100$ GeV Proton

$5$ GeV electron

$\pi^0 \rightarrow \gamma + \gamma$

Dipoles and Quadrupoles

$32$ m from IR

$ZDC$

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<tr>
<th>Detector</th>
<th>Angular Acceptance</th>
<th>Notes</th>
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<td>$\theta &lt; 5.5$ mrad</td>
<td>About $4.0$ mrad at $\varphi \sim \pi$</td>
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<td>Roman Pots</td>
<td>$0.0 &lt; \theta &lt; 5.0$ mrad</td>
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<td>Off-Momentum Detectors</td>
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<td>B0 Sensors</td>
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$u' = 0$ GeV
Progress Report on $u$-channel $\pi^0$ @ EIC

Preliminary conclusion:
- $u$-channel $\pi^0$ at EIC with current design is a feasible measurement
- Ideal expected trigger: $e^+p'+2\gamma$, is very clean with very little background, with reduced efficiency
- Next step: process to full geant4 simulation

The EIC fellowship award will help completing the YR and feasibility studies

ZDC $2\gamma$ hit pattern @ 40 GeV/c $\pi^0$ 4.5 mrad acceptance
Progress Report: First $u$-channel Physics Workshop

- Thanks to the support from JLab, JSA and William & Mary, workshop is on track for September 21st-23rd, 2020.
  - Indico page of the workshop: [https://www.jlab.org/indico/event/375](https://www.jlab.org/indico/event/375)
- The workshop have representatives from all four halls, from JLab 6, 12 GeV, PANDA and EIC
  - $u$-channel electroproduction examples at 12 GeV
    - Backward DVCS (Hall B, C)
    - CLAS 12 single pion spin asymmetry (Hall B)
    - U-channel meson production (omega, rho, phi) production from Kaon LT experiment (Hall C)
  - $u$-channel photoproduction examples at 12 GeV
    - Timelike Compton scattering (Hall B, C and D)
    - Wide angle compton scattering (Hall C)
    - $\omega$ Photoproduction off Proton Target at Backward Angles (Hall D)
    - $\Sigma$-$K^+$ Photoproduction at Backward Angle at GlueX Experiment (Hall D)
    - $\omega$ Photoproduction off Proton Target at Backward Angles (Hall D)
  - Theory prospective:
    - Meson-Nucleon Transition Distribution Amplitude
    - Photon-nucleon together with meson-nucleon TDAs
    - Skewed Parton Distribution
    - $u$-channel Regge Approach
  - Future prospective of $u$-channel physics
    - $u$-channel $\pi^0$ production at EIC
    - Studying TDA with $pp \rightarrow e^+e^- + \pi^0$ at the PANDA Experiment
- A summary whitepaper is planned: outlining the JLab 12 GeV to EIC $u$-channel physics strategy
Now is the time to resurrect $u$-channel meson productions at 12 GeV kinematics and future EIC.

Goal of our activity: to inspire a wave of backward-angle physics measurements.
Thank you for your attention!

Elephant Wave function

Forward angle

-\( t \) evolution

Backward angle

Illustration: Hans Møller, mollers.dk

I think this guy is “right”!
Thank you for the supports

- Gratitude to the JSA, JLUO award selection committee,
- Gratitude to Garth and Justin guidance, advance and support
- Gratitude to the TDA theorist: Bernard, Lech and Kirill, and assistance from JLab theory center: Christian
- Thanks to my Hall A/C, CLAS TDA working group and Hall D colleagues
- My people from the postdocs and graduate students community
- Great support from William and Mary Physics department
Backup
Backward-angle structure of Proton

- Complete description of Nucleon
  - GPD = Hadron tomography of the proton
  - TDA = tomography of partonic distributions in the nucleon
    → meson and vice versa transitions probed in the backward angle kinematics

- Backward-angle cross section is not 0!
  - backward angle cross section is 1/10 of the forward angle cross section at observed $Q^2$
Backward angle physics in this talk: backward angle physics above the resonance region (W>2 GeV²)

- $u' \rightarrow u_{\text{min}}$, $t > Q^2$

A systematic backward angle physics program:
- JLab 6 → JLab 12 → EIC

Charged Pion Production from CLAS 6

$^1H(e, e'\pi^+)X$
- $Q^2$ Scaling

W > 2 GeV resonance region studies

Hall C experiment E001-004

$^1H(e, e'p)X$
- Parasitic data
- Full L/T separation
Comparison to TDA calculation

\[ W = 2.21 \, \text{GeV}, \quad Q^2 = 1.6 \, \text{GeV} \]

\[ \sigma_T \text{ vs } -u \]

Over predicted by a factor of 7!

\[ W = 2.21 \, \text{GeV}, \quad Q^2 = 2.45 \, \text{GeV} \]

\[ \sigma_T \text{ vs } -u \]

Almost bang-on!


0 < -u < 0.5 GeV^2
2.0 < W < 2.4 GeV

TDA calculation:
- dark blue band: COZ N DA
- light blue band: KS N DA

Hall C Omega Production

Indication of early TDA scaling!?
Impact to the efficiency

• Double photon efficiency for the nominal $\pi^0$ event is larger than 20%.

• Detector (magnetic aperture) constrains:
  - Fixing center of the neutral particle at ZDC
  - Ensuring largest possible symmetrical acceptance

$\pi^0$ Momentum vs Theta ($\int L=10 fb^{-1}$)

30 - 50 GeV pion

$Q^2 = 10 \text{ GeV}^2$

$Q^2 = 6 \text{ GeV}^2$

Momentum (GeV)
Physics background (to our current best knowledge)

- **Double photon case:**
  - Primary reaction: $e+p \rightarrow e'+p' + \pi^0$
  - Ideal expected trigger: $e'+p'+2\gamma$
  - Physics background: none
  - Less than ideal trigger: $e'+2\gamma$
  - Background: $\Lambda \rightarrow n+\pi^0$

- **Single photon case:**
  - Primary reaction: $e+p \rightarrow e'+p' + \pi^0$
  - Ideal expected trigger: $e'+p'+\gamma$
  - Physics background: DVCS, eta, $\Lambda \rightarrow n+\pi^0$
  - Less than ideal trigger: $e'+\gamma$
  - Background: many many possibility

- We can use the double photon event to normalize the single photon events
U-channel Meson Production Setup

100 GeV Proton

$e'$

5 GeV electron

$\pi^0$

$Q^2$ vs S intentionally constraint

No issue will detection

Detected with poor resolution

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ZDC acceptance is an issue
New Proposal to PAC 48 on Backward-angle $\pi^0$ Production

First dedicated $u$-channel electroproduction study above the resonance region
- $^1\text{H}(e,e'p)\pi^0$
- $Q^2$ coverage: $2.0 < Q^2 < 6.25 \text{ GeV}^2$
- L/T separation at $Q^2 = 2.0, 3.0, 4.0$ and $5.0 \text{ GeV}^2$
- Fixed $x=0.36$ for all settings
- $u$ coverage: $0 < -u' < 0.5 \text{ GeV}^2$
New Proposal to PAC 48 on Backward-angle $\pi^0$ Production

Experiment objective
1. Demonstrate existence of u-channel peaks
2. $u$-dependence of L/T separated cross section
3. If peaks exist, test TDA prediction: $\sigma_T > \sigma_L$
4. If $\sigma_T > \sigma_L$, test $\sigma_T \propto 1/Q^8$

We are pleased to report the proposal was submitted to PAC 48
Preliminary conclusion:

- $u$-channel $\pi^0$ at EIC with current design is a feasible measurement
- Ideal expected trigger: $e^+p' + 2\gamma$, is very clean with very little background, with reduced efficiency
- Next step: process to full geant4 simulation

2 $\gamma$ hit pattern

$40$ GeV/c $\pi^0$

$4.5$ mrad acceptance
Budget & Measure of Success

Planned Budget (in the proposal):

- Dr. Kirill Semonov-Tian-Shansky’s research trip to WM
  - Accommodation: $ 3000
  - Airfare: $1600
  - Visa application: $ 800
  - Transportation: $ 600
- Participating conferences (Bill and Kirill): 3000
- Computational equipment (storage hard drives): $ 900
- Office space is provided by WM in kind

Measure of Success:

- PAC48 proposal on backward-angle pi0 production above the resonance region (submitted to PAC).
- Hosting u-channel physics workshop and completing a white paper on the backward angle physics strategy for JLab 12 GeV.
- Completing and publishing the EIC backward-angle pi0 feasibility study (work in progress).
- Completing the pi0 u-channel pi0 production section in Yellow report (work in progress).
Mandelstam variables \((s,t,u\text{-Channels})\)

- **\(t\):** Four-momentum-transfer squared between target before and after interaction.
  
  \[ \xi = 0, \; t \approx t_{min}, \; u \approx u_{max}, \; t < Q^2 \]

- **\(u\):** Four-momentum-transfer squared between virtual photon before interaction and target after interaction.
  
  \[ \xi = 1, \; t \approx t_{max}, \; u \approx u_{min}, \; t > Q^2 \]

- **\(t\)-channel:** \(-t \sim 0\), after interaction
  - Target: stationary,
  - Meson: forward

- **\(u\)-channel:** \(-u \sim 0\), after interaction
  - Target: forward
  - Meson: stationary
  - Disclaimer: “Backward physics” is a marketing term, and it is equivalent to u-channel physics
  - Equivalent to “extremely large momentum transfer”
List of Tasks for the JSA Award

- Knowledge exchange within in theory community (K)
  - Inspire more collaboration between local and European experts on u-channel physics

- Developing coherent and comprehensive 12 GeV strategy (K+B)
  - Priorities list of prime observables: takes into account realistic constraints and available resources (K+B)
  - u-channel DVCS: kinematics survey (B)
  - Supporting more single pion beam spin asymmetries development from CLAS (K)

- TDA cross section predictions 12 GeV and EIC kinematics (K)

- Hosting first u-channel physics workshop (B)

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Strategy Based on TDA, SPD and Regge approach