Far Forward Reconstruction Studies for Deep Exclusive Meson Production Reactions at the EIC

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One of the lessons learned from HERA is to integrate hermetic detector coverage with the accelerator from the outset, as it is being designed.

**ePIC Far-Forward/Far-Backward Detectors**

- **Main Function:** detection of forward scattered neutrons and γ
- **Technology:**
  - EMCal: 2x2x20 cm³ PbWO₄ calorimeter
  - Synergy with backward ECal
  - HCAL: Steel-SiPM-on-Tile
  - Synergy with forward HCal

- **Luminosity System**
- **Low-Q2 Taggers**
- **Zero Degree Calorimeter**
- **Roman Pots and Off-Momentum Detectors**
  - **Main Function:** detection of forward scattered protons and nuclei
  - **Technology:**
    - 2 stations with 2 tracking layers each
    - AC-LGAD / EICROC (500x500 µm² pixel)
    - Synergy with forward ToF
  - EMCal: 2x2x20 cm³ PbWO₄ calorimeter
  - Synergy with backward ECal

Figure courtesy of Elke Aschenauer (BNL)
Far Forward and Far Backward detector arrays allow a Rich Physics Program, needed for EIC’s primary physics objectives.
Physics Motivation:

- $\pi^+$ and $K^+$ structure studies are important for understanding QCD’s transition from “weak” and “strong” domains, and understanding DCSB’s role in generating hadron properties.
- Definite answers to these questions require high $Q^2$ data well beyond JLab’s reach, the EIC may provide these data.

Experimental Issues:

- The DEMP cross section is small, can the exclusive $p(e,e'\pi^+)n$ and $p(e,e'K^+)$ channels be cleanly identified?
  - Count rates, Detector Acceptances?
- Is the detector resolution sufficient to reliably reconstruct $(Q^2,W,t)$?
- How to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction?

- Created a MC event generator by parameterizing CKY $\sigma_L, \sigma_T$ for $5<Q^2 (GeV^2)<35$, $2.0<W (GeV)<10$, $0<-t (GeV^2)<1.2$

- Extended to $p(e,e'K^+){\Lambda}[\Sigma^0]$ by parameterizing Regge-based model of M. Guidal, J.M. Laget, M. Vanderhaeghen (VGL) [PRC 61 (2000) 025204]

- New paper describing our generator arXiv:2403.06000
Assure exclusivity of $p(e,e'\pi^+n)$ reaction by detecting all 3 particles

IR6: $5(e^-) \times 100(p)$ GeV Collisions $\rightarrow E_{cm}=44.7$ GeV

Scattered electrons:
5–6 GeV/c,
25–50° from outgoing e beam

Pions:
3–40 GeV/c,
3–40° from p beam

Neutrons:
65–98 GeV/c
<0.7° of outgoing proton beam

e−π−n triple coincidences, weighted by cross section, truth info
Vital to isolate exclusive $p(e,e'\pi^+n)$ process from competing inclusive reactions

EIC measurement impossible unless recoil high momentum neutron is efficiently detected
Proposed SiPM–on–Tile design of ZDC divides HCAL into hexagonal cells

HEXSPIT algorithm defines cells with overlap, assigns weights according to overlap, uses this to reconstruct energy based on subcell energy

S. Paul, M. Arratia arXiv:2308.06939
\( p(e,e'\pi^+n) \) Neutron reconstruction in ZDC

- 5x41 e+p collisions
- High proportion of neutron hits have multi–clusters
  - No cluster recombining algorithm is implemented yet
- Single cluster events look good
- \((x,y)\) acceptance of ZDC fully filled
Significantly more challenging than $p(e,e'\pi^+)n$ reconstruction
Need to efficiently identify $\Lambda \rightarrow n\pi^0 \rightarrow n\gamma\gamma$ decay (~33%)
- Neutral products take straight line paths
- Cleanly distinguishing n from $\gamma$ clusters is main challenge

Dominant $\Lambda \rightarrow p\pi^-$ channel (~67%) has its own challenges
- Avoids issue of distinguishing n from $\gamma$ clusters
- Main issue is that p, $\pi^-$ are deflected in opposite directions by proton ring magnetic elements, and it will not be possible to efficiently detect both of them

Additional reconstruction issue:
- Do not know $\Lambda$ decay vertex when reconstructing $\pi^0 \rightarrow \gamma\gamma$ decay
- SiPM will provide enough information about spatial extent of showers to extract incident angle of $\gamma$ on EMCAL to enable full 4–vector reconstruction of $\pi^0$. Is it sufficiently good?
Some ZDC Design Choices

- $\Lambda \rightarrow n\pi^0 \rightarrow n\gamma\gamma$ reconstruction studies will inform ZDC design choices

1. **20cm EMCAL + SiPM–on–Tile:** E resolution is very good, but lose $\gamma$ angular information needed for $\Lambda$ reconstruction

2. **~10cm EMCAL + SiPM–on–Tile:** EMCAL can act as a sort of “pre–shower” while still enabling $\gamma$ angular information

3. **SiPM–on–Tile ONLY:** Allows best $\gamma$ angular reconstruction, but might lose low–E photon capability, potentially more difficult hadronic/EM shower separation

Figure courtesy of Alex Jentsch (BNL)
Later Stage $p(e,e'K^+)\Lambda[\Sigma^0]$ Reconstruction

- Far Forward large acceptance is even more important for $K^+$ form factor than for $\pi^+$ form factor
- Detection of $e'K^+\Lambda[\Sigma^0]$ triple coincidence over wide range of $-t$ essential for identification of $K$–pole process, needed for $K^+$ form factor extraction from data
  - $\Lambda\rightarrow n\pi^0\rightarrow n2\gamma$ and $\Sigma\rightarrow \Lambda\gamma\rightarrow n3\gamma$ identification over wide $-t$ only possible if ZDC calorimeter acceptance is extended with addition of a B0 calorimeter
  - Not only essential for $F_K$, but also would improve forward acceptance for $u$–channel DVCS, and nuclear coherent diffraction studies

Possible B0 Calorimeter
- Greatly extends acceptance!
Summary

- Higher $Q^2$ data on $\pi^+$ and $K^+$ form factors are vital to our better understanding of hadronic physics
  - Pion and kaon properties are intimately connected with dynamical chiral symmetry breaking (DCSB), which explains the origin of more than 98% of the mass of visible matter in the universe

- Measurement of $F_\pi$ at EIC has various challenges
  - Need efficient identification of $p(e,e'\pi^+n)$ triple coincidences
  - Neutron reconstruction in ZDC is underway, studies promising, but algorithm still needs some improvements (cluster merging)

- Measurement of $F_K$ at EIC even more challenging
  - $\Lambda$ reconstruction studies are likely to inform ZDC design choices
  - Expectation is that a reduction of ZDC–EMCAL thickness to $\sim10\text{cm}$ will be beneficial
Isolating Exclusive $p(e,e'\pi^+)n$ Events

- Can we isolate a clean sample of exclusive $p(e,e'\pi^+)n$ events by detecting the neutron, or are other requirements needed in addition?

- For a source of background $p(e,e'\pi^+)X$ events we used the EIC SIDIS generator written by Tianbo
  - located on JLab farm at /work/eic/evgen/SIDIS_Duke/e5p100

- Since the generator does not output the neutron momentum, we use the missing momentum as a proxy

- The SIDIS and DEMP event generators are used to create LUND format files
- Generated events are fed into ECCE Geant4 simulation for both IP6 and IP8 to study acceptance and resolution requirements for different beam energy combinations
$p_{\text{miss}}$ cut vs $Q^2$–bin (IR6)  

\[ p_{\text{miss}} = |\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}| \]

Plots by Stephen Kay

Exclusive $p(e,e'\pi^+)n$

Foreground

SIDIS $p(e,e'\pi^+)X$

Background

(arbitrarily normalized, actually much larger than DEMP)
Another Cut to Remove Background

- Make use of high angular resolution of ZDC to further reduce background events
  - Compare hit \((\theta, \phi)\) positions of energetic neutron on ZDC to calculated position from \(p_{\text{miss}}\)
  - If no other particles are produced (i.e. exclusive reaction) these quantities should be highly correlated
  - Energetic neutrons from inclusive background processes will be less correlated, since additional lower energy particles are produced

Differences between hit and calculated neutron positions on ZDC for DEMP events (IR6)

**Cuts applied:** \(|\Delta \theta|<0.6^\circ\) \(|\Delta \phi|<3.0^\circ\) in addition to triple coincidence cuts
Detection efficiency per \((Q^2, t)\) bin (IR6)

Require EXACTLY two tracks:
- One positively charged track in \(+z\) direction \((\pi^+)\)
- One negatively charged track in \(-z\) direction \((e')\)

AND at least one hit in Zero Degree Calorimeter (ZDC)
- For 5x100 events, require the hit has Energy Deposit > 40 GeV
Improving *neutron* reconstruction resolution

- Exclusive $p(e,e'\pi^+n)$ event selection requires exactly one high energy ZDC hit as a veto.

- Since the neutron hit position from ZDC is known to high accuracy, this information can be used to “correct” the missing momentum track:

$$p_{\text{miss}} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$$
Reconstructing Mandelstam \( t \) (IR6)

Extraction of pion form factor from \( p(e,e'\pi^+n) \) data requires \( t \) to be reconstructed accurately, as we need to verify dominance of the \( t \)–channel process from the dependence of \( d\sigma/dt \) upon \( t \).

\[
t = (p_\gamma^* - p_\pi)^2
\]

\[
t = (p_p - p_n)^2
\]

Correct \( p_{\text{miss}} \) w/ ZDC(\( \theta,\varphi \))

Unusable \( t \) reconstruction

\[
\sigma_{t\text{ reconstr}} = 3.4 \text{ GeV}^2
\]

Best \( t \) reconstruction

\[
\sigma_{t\text{ reconstr}} = 0.073 \text{ GeV}^2
\]
Separating $\sigma_L$ from $\sigma_T$ in e–p Collider

$\varepsilon = \frac{2(1 - y)}{1 + (1 - y)^2}$, where the fractional energy loss $y = \frac{Q^2}{x(s_{tot} - M_N^2)}$

- Systematic uncertainties in $\sigma_L$ are magnified by $1/\Delta\varepsilon$.
- Desire $\Delta\varepsilon > 0.2$.
- To access $\varepsilon < 0.8$, one needs $y > 0.5$.
  - This can only be accessed with small $s_{tot}$, i.e. low proton collider energies (5–15 GeV), where luminosities are too small for a practical measurement.
- A conventional L–T separation is impractical, need some other way to identify $\sigma_L$. 
Isolate $d\sigma_L/dt$ using a Model

- In the hard scattering regime, QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$.

- At high $Q^2$, $W$ accessible at EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$.

- The most practical choice might be to use a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$.

- In this case, it is very important to confirm the validity of the model used.

- Predictions are for $\varepsilon > 0.995$ $Q^2, W$ kinematics shown earlier.
Assumptions:
- $5(e^-) \times 100(p)$
- Integrated $L=20 \text{ fb}^{-1}/\text{yr}$
- Clean identification of exclusive $p(e,e'\pi^+n)$ events
- $t$ reconstruction resolution based on ECCE detector design
- Syst. Unc: 2.5% pt–pt and 12% scale
- $R=\sigma_L/\sigma_T=0.013$–0.14 at lowest $-t$ from VR model, and $\delta R=R$ syst. unc. in model subtraction to isolate $\sigma_L$.
- $\pi$ pole dominance at small $-t$ confirmed in $^2\text{H}$ $\pi^-/\pi^+$ ratios.
Can we measure $F_K$ at the EIC?

- Can the “kaon cloud” of proton be used in same way as the pion to extract kaon form factor via $p(e,e'K^+\Lambda)$?
- Kaon pole further from kinematically allowed region
- Many of these issues are being explored in JLab E12–09–011
- Propose to use $p(e,e'K^+\Lambda/\Sigma)$ reactions for pole dominance test

$$R = \frac{\sigma_L[p(e,e'K\Sigma^0)]}{\sigma_L[p(e,e'K\Lambda)]} \rightarrow R \approx \frac{g^2_{pK\Sigma}}{g^2_{pK\Lambda}}$$

- Decay modes: $\Lambda \rightarrow n\pi^0$ 36%, $\Lambda \rightarrow p\pi^-$ 64%
  - Neutral channel most likely best option
  - Avoids deflection of $p\pi^-$ away from detectors by ion ring elements
- $\Sigma^0$ identified from $\Sigma^0 \rightarrow \Lambda\gamma \rightarrow \Lambda\pi^0 \rightarrow n3\gamma$ decay
UofR student Love Preet is working on adding $K^+$ physics module to our DEMP event generator

- Parameterize Regge–based model in similar way to $\pi^+$
- $K^+\Lambda$ (soon also $K^+\Sigma$) modules are based on Vanderhaeghen Guidal Laget model [PRC 61 (2000) 025204]
- $\sigma_L,\sigma_T$ parameterizations for: $1<Q^2<35\ 2<W<10\ \ -t<2.0\ \text{GeV}^2$
  - Polynomial
  - Exponential

Study will need $\Lambda\rightarrow n\pi^0$ tracking to be fixed in Geant4 simulation. For ECCE studies, only $\Lambda\rightarrow p\pi^-$ was working
Two photon detection efficiency

- $Q^2 = 6 \text{ GeV}^2$
- $Q^2 = 10 \text{ GeV}^2$

ZDC + B0 calorimeter

- $\pm 28 \text{ mrad}$

ZDC Acceptance only

- $\pm 5 \text{ mrad}$

B0 Calorimeter

B0 Trackers