Hadron Physics at EIC Facility

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- Hadron Spectroscopy.
- Opportunities with pion beams.
- Spectroscopy of hyperons.
- Meson spectroscopy.
- Physics opportunities.
- Summary.

135 endorsers from 77 institutes worldwide

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Hadron Spectroscopy

• To reap full benefit of high-precision studies and to advance our knowledge in Baryon and Meson Spectroscopy, new high-statistics data from measurements with meson beams, with good angle and energy coverage for a wide range of reactions are critically needed.

• To address this situation, we propose a state-of-the-art Meson Facility.
There are Many Ways to Study $N^*$

- **Prolific source** of $N^*$ and $\Delta^*$ baryons is to measure many channels with different combinations of quantum numbers.

Most of **PDG Listings** info comes from these sources.
- $\pi N$ elastic scattering is simplified due to constraints.
- **Resonance** spectra are correlated.
- Two-body final states need few amplitudes.
Baryon Sector in PDG14

- PDG14 has 112 Baryon Resonances (58 of them are 4^* & 3^*).
- For example for SU(6) x O(3), it would be 434 resonances, if all revealed 70 three and 56 four star multiplets were completed.

- A check of PDG Listings reveals that resonance parameters of many established states are not well determined.

- There are many more states in QCD inspired models than currently observed.
Why We Need Meson Beams

• Much has been achieved over last two decades in increasing our knowledge of Baryon and Meson Spectroscopy with the help of meson photo- and electro-production data of unprecedented quality and quantity coming out of major EM facilities such as JLab, MAMI, ELSA, SPring-8, ELPH, BEPC, etc.

• Meson-beam data for different final states are mostly outdated, largely of poor quality, or even non-existent, thus limit us in fully exploiting full potential of new EM data.

• We emphasize that what we advocate here is not a competing project, but experimental program that provides hadronic complement of ongoing EM program, to furnish common ground for better & more reliable phenomenological & theoretical analyses based on high-quality data.
Status of Data for Specific Reactions

• Measurements of final states involving single pseudoscalar meson & spin-1/2 baryon are particularly interesting due to simple interpretation.

• The reactions involving $\pi N$ channels include:

\[ \gamma p \rightarrow \pi^0 p \]
\[ \gamma p \rightarrow \pi^+ n \]
\[ \gamma n \rightarrow \pi^- p \]
\[ \gamma n \rightarrow \pi^0 n \]

\[ \pi^+ n \rightarrow \pi^0 p \]
\[ \pi^+ n \rightarrow \pi^+ n \]
\[ \pi^- p \rightarrow \pi^- p \]
\[ \pi^- p \rightarrow \pi^0 n \]
\[ \pi^+ p \rightarrow \pi^+ p \]

• Only $\pi^+ p \rightarrow \pi^+ p$ corresponds to isospin 3/2 while rest of reactions is mixture of isospins 1/2 & 3/2.

Data for $\pi N$ elastic scattering are incomplete.

• Additional measurements of $P$, $A$, & $R$ observables (limited data available) are needed to construct unbiased PW amplitudes.
World Neutral and Charged $\gamma N \rightarrow \pi N$ Data

$W < 2.5$ GeV

$\gamma p \rightarrow \pi^0 p$

$\gamma p \rightarrow \pi^+ n$

$\gamma n \rightarrow \pi^- p$

$\gamma n \rightarrow \pi^0 n$

$\gamma p \rightarrow \pi^0 p$ data are mainly $d\sigma/d\Omega$, only 15% from polarized measurements.
World Pion-Nucleon Elastic (CEX) Data

\[ \pi^+ p \rightarrow \pi^+ p \]
\[ \pi^- p \rightarrow \pi^- p \]
\[ \pi^- p \rightarrow \pi^0 n \]

\( W < 2.5 \) GeV

Full
UnPol
Pol

CEX database is small fraction of measurements.
New Observables

• ΠN scattering data:
  \[ \frac{d\sigma}{d\Omega} \] (unpolarized)
  \[ P \] (polarized target or recoil nucleon)
  \[ R \text{ and } A \] (polarized target and recoil measured)

Not Independent: \[ P^2 + R^2 + A^2 = 1 \]

• Older PWA solutions may be not able to reproduce New measurements.

Data:
ITEP: \( \pi^+ p \to \pi^+ p \) @ 1300 MeV
PWA:
KA84: Karlsruhe-Helsinki fit, 1984
KB84: KH Barrelet corrected solution, 1997
SP06: GW fit, 2006

• Polarized measurements would also be important part of hadron program.
Recent ITEP for $\pi^- p \rightarrow \pi^- p$

- New precise cross section measurements:
  \[ \Delta\sigma = 0.5\% \text{ stat}, \ \Delta p = 1 \text{ MeV}, \ \Delta\theta = \pm 1^\circ \]

- Predictions: WI08, KH80, KA84, CMB

CMB analysis is here more successful compared to versions of KH analyses.
Status of Data for Specific Reactions

- Reactions that involve $\eta N$ and $K\Lambda$ channels are notable because they have pure isospin-1/2 contributions:

- Analyses of photoproduction combined with pion-induced reactions permit separating EM & hadronic vertices.

- It is only by combining information from analyses of both $\pi N$ elastic scattering & $\gamma N \rightarrow \pi N$ that make it possible to determine $A_{1/2}$ & $A_{3/2}$ helicity couplings for $N^*$ & $\Delta^*$ resonances.
Revival of $\pi^- p \rightarrow \eta n$

- $\gamma p \rightarrow \eta p$ is one of key reactions in which experimentalists hope to do ``complete measurement'' and determine PW amplitudes directly.
- Coupled-channel analysis of those measurements need precise data for $\pi^- p \rightarrow \eta n$.

- Most of available data for $\pi^- p \rightarrow \eta n$ come from measurements published in 1970s, which have been evaluated by several groups as being unreliable above $W = 1620$ MeV.
- Precise data were measured by Crystal Ball Collab, but these extend only up to peak of first $S_{11}$-resonance.

Very few polarized data for this reaction exist. $d\sigma/d\Omega$ and $P$ are taken at different energies.

- Available data for $\pi^- p$ reactions with $KY$, $\eta'N$, $\omega N$, & $\phi N$ final states are generally equally bad or even worse.
Improvement of $\pi^- p \rightarrow \eta \pi$ and $\pi^- p \rightarrow K^0 \Lambda$ Data

- Projection data with 5% uncertainties and with an energy scan at 10 MeV intervals, which is comparable to modern photoproduction measurements.

- More precise data for reaction $\pi^- p \rightarrow K^0 \Lambda$ (together with $K^- p \rightarrow \pi^0 \Lambda$ & $\pi^0 \Sigma^0$) would enable study of SU(3) symmetry & its breaking.

Large discrepancy in exp data around 1.7 GeV.
Status of Data with Strangeness Production

- Group of related reactions involve $K\Sigma$ channel:

\begin{align*}
\gamma p &\rightarrow K^+\Sigma^0 \\
\gamma p &\rightarrow K^0\Sigma^+ \\
\gamma n &\rightarrow K^+\Sigma^- \\
\gamma n &\rightarrow K^0\Sigma^0
\end{align*}

- Except for $\pi^+p\rightarrow K^+\Sigma^+$, these reactions involve mixture of isospins $1/2$ & $3/2$.

- Although there have been number of recent high-quality measurements involving $K\Sigma$ photoproduction, status of complementary reactions measured with pion beams is rather bleak.

- Measurements like these, over more comprehensive energy range, will greatly improve PWA's of $K\Sigma$ final state and, in return, help to extract $S$-wave contribution needed, e.g., in approaches based on unitarized chiral perturbation theory.

There are generally fewer data for $\pi^-p\rightarrow\eta n$ reactions with $K\Sigma$, $\eta'N$, $\omega N$, & $\phi N$ final states than for $\pi^-p\rightarrow\eta n$.

[K. Shirotori et al, Phys Rev Lett 109, 132002 (2012)]
Status of Data for Multi-Pion Reactions

• Important reactions that can be studied are those with $\pi\pi N$ final states:

\[
\begin{align*}
\gamma p &\rightarrow \pi^0\pi^0 p \\
\gamma p &\rightarrow \pi^0\pi^+ n \\
\gamma p &\rightarrow \pi^+\pi^- p \\
\gamma n &\rightarrow \pi^0\pi^- p \\
\gamma n &\rightarrow \pi^0\pi^0 n \\
\gamma n &\rightarrow \pi^+\pi^- n
\end{align*}
\]

\[
\begin{align*}
\pi^+ n &\rightarrow \pi^0\pi^0 p \\
\pi^+ n &\rightarrow \pi^0\pi^+ n \\
\pi^+ n &\rightarrow \pi^+\pi^- p \\
\pi^- p &\rightarrow \pi^0\pi^- p \\
\pi^- p &\rightarrow \pi^0\pi^0 n \\
\pi^- p &\rightarrow \pi^+\pi^- n
\end{align*}
\]

• $\pi N \rightarrow \pi\pi N$ reactions have the lowest energy threshold of all inelastic hadronic reactions & some of largest cross sections.

• Analysis & interpretation of data from these reactions are more complex because of 3-body final states.

• Dominant inelastic decays for most established $N^*$ & $\Delta^*$ resonances are to $\pi\pi N$ final states.

• Our knowledge of $\pi\Delta$, $\rho N$, & other quasi-two-body $\pi\pi N$ channels comes mainly from isobar-model analyses of $\pi N \rightarrow \pi\pi N$ data.

• Larger experimental database (including pol measurements) is needed to determine precisely the PW amplitudes because so many amplitudes are required to describe 3-body final states.
Form-Factor Measurements

- **Inverse Pion Electroproduction** is the only process which allows determination of EM nucleon and pion form-factors in intervals:

\[ 0 < k^2 < 4 M^2 \quad 0 < k^2 < 4 m_\pi^2 \]

which are kinematically **unattainable** from \( e^+e^- \) initial states.

- \( \pi^-p \rightarrow e^+e^-n \) measurements will significantly complement current studies of the evolution of **baryon** properties with increasing momentum transfer in **electroproduction** by investigating the case of **time-like virtual photon**.
Spectroscopy of Hyperons

- Our current experimental knowledge of $\Lambda^*$ and $\Sigma^*$ resonances is far worse than our knowledge of $N^*$ and $\Delta^*$ resonances, but they are equally fundamental.

- **Pole** position for hyperons began to be studies only recently, for instance for $\Lambda(1520)$.

- Clearly, complete understanding of three-quark bound states requires to learn baryon resonances in `strange sector`.

- One of secondary beam problems is that Kaon yield is less than pion one by factor of about 500.
- This is main reason why there are limited exp data for Kaon induced measurements & there are negligible polarized measurements.

- Line shape of $\Lambda(1405)1/2^-$ can be studied in $K^-p$ & $K^-d$ ($K^-n$) reactions.
  Comparison between pion- & Kaon-induced reactions together with photoprod is important.
- Measured $\pi\Sigma/\pi\pi\Sigma$ BR for $\Sigma(1670)$ produced in reaction $K^-p\rightarrow\pi^-\Sigma(1670)^+$ depends strongly on momentum transfer, and it has been suggested that there exist two $\Sigma(1670)$'s with the same mass and quantum numbers, one with large $\pi\pi\Sigma$ BR and other with large $\pi\Sigma$ BR.
Status of Data for Kaon Induced Reactions

- Hyperons $\Lambda^*$ and $\Sigma^*$ have been systematically studied in following formation processes:

  \[
  \begin{align*}
  K^- p &\rightarrow K^- p \\
  K^- p &\rightarrow K^0 n \\
  K^- p &\rightarrow \pi^0 \Lambda \\
  K^- n &\rightarrow \pi^- \Lambda \\
  K^- n &\rightarrow \pi^0 \Sigma^- \\
  K^- n &\rightarrow \pi^- \Sigma^0
  \end{align*}
  \]

- Most of our knowledge about multi-strange baryons was obtained from old data measured with Bubble Chambers.

- The lack of appropriate beams and detectors in past greatly limits our knowledge.

- Cascade hyperon resonances could be studied with high-momentum Kaon beams and modern multi particle spectrometers.

  Currently only cascade ground states of spin-1/2 & spin-3/2 are well identified.

- For excited states, possible production reactions with Kaon beams are:
Meson Spectroscopy

• Although it was light Hadron Spectroscopy that led the way to discovery of color degrees of freedom & QCD, much of field remains poorly understood, both theoretically & experimentally.

• Availability of pion & Kaon beams provide important opportunity to improve situation.

• Experimentally, Meson Spectroscopy can be investigated by using PWA’s to determine quantum numbers from angular distributions of final-state particle distributions.

• The chief areas of interest in Meson Spectroscopy are scalar mesons, multiquark states, glueballs, & hybrids.

• Experimental effort with meson beams will complement GlueX experiment at JLab, which seeks to explore properties of hybrids with photon beam.
Physics Opportunities

• The current plans of runs at modern Hadron Facilities [J-PARC, HADES, COMPASS, & PANDA] will greatly improve database; however, there are no plans for polarized measurements.

• New Meson Facility would need large-acceptance detector and availability of polarized target.

• In particular, such dedicated facility should be able to provide features listed in our recent White Paper:
1. “Continue existing projects: CEBAF, FRIB, RHIC.”

2. “…a U.S.-led ton-scale neutrinoless double beta decay experiment.”

3. “…a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.”

4. “…small-scale and mid-scale projects and initiatives that enable forefront research at universities and labs.”

“A major experimental initiative continues to be the search for the so-called ‘missing baryons’...
The experimental data are, therefore, suggestive of a more intricate manifestation of QCD in baryons…”

“For many years, there were both theoretical and experimental reasons to believe that the strange sea quarks might play a significant role in the nucleon's structure; a better understanding of the role of strange quarks became an important priority.”
Why EIC and Why at Jefferson Lab?

- **EIC Facility** design meets experimental needs:
  - Broad CM energy range.
  - High luminosity.
  - Wide range of ion species.

- **Green Field** new **Ion Complex** provide opportunity for modern design for highest performance.

- Large established **user community** at **JLab**.

- **Meson Facility** would keep **JLab Ion Booster** busy longer (to use much more than "several minutes" a day), which would be much more effective use of **EIC Facility**, without significant increase of the cost of **JLab Ion Booster**.
Meson Facility [good to have]:

- **Pions:**
  - $< 3$ GeV.
  - $10^7$ s$^{-1}$.
  - $\Delta p/p < 2\%$.

- **Kaons:**
  - $< 2$ GeV.
  - $10^5$ s$^{-1}$.

EIC Facility:

- $W = 15 - 65$ GeV.
- **Protons:** $20 - 100$ GeV.
- **Luminosity:**
  - $10^{33}$ to $10^{34}$ cm$^{-2}$s$^{-1}$ per IP.
- **Circumference:** 2.2 km.

Ion Booster:

- **Protons:** 8 GeV.
- Booster design based on super-ferric magnet technology.
- **Circumference:** 273 m.
JLab for Hyperon Spectroscopy
We have outlined some of physics programs that could be advanced with EIC especially appended by Meson Facility.

Those include studies of baryon spectroscopy, particularly search for “missing resonances” with hadronic beam data that would be analyzed together with photo- & electro-production data using modern coupled-channel analysis methods.

Meson Facility would also advance hyperon spectroscopy and study of strangeness in nuclear & hadronic physics.

Searches for exotic states (highly anticipated, but never observed unambiguously), such as multiquarks, glueballs, & hybrids would be greatly enhanced by availability of Meson Facility.

Simply discovering of missing low-lying meson states would also assist in constructing new models for apparent properties of QCD, thereby improving our understanding of this strongly coupled non-linear quantum field theory.
Thank You

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