eA pion production at CLAS aimed at neutrinos

S. Manly & Hyupwoo Lee
University of Rochester
Department of Physics and Astronomy
INT Workshop
Seattle, December 2013

Representing the CLAS (EG-2) collaboration
Motivation – why eA?

- High statistics.
- Control over initial energy and interaction point – gives kinematic constraints and ability to optimize detector.

Summary slide from talk by Costas Andreopolos at NUINT 2009
“Electron scattering data and its use in constraining neutrino models”

- Electron (and muon) scattering data provide a wealth of information about the nucleon and nuclear structure and in-medium modifications
  - Nucleon Elastic Form Factors
  - PDFs, $R$, $d/u$, ...
  - Resonances & QE $\to$ DIS transition, Non-Resonance Backgrounds
  - Nucleon momentum distributions and binding energies
  - Nuclear charge distributions, energy levels, ...
  - N-N correlations
  - Medium modifications
    - EMC effect, ...
    - Effects on hadronization: Landau-Pomeranchuck-Migdal and Cronin effects
  - ...

This information has been central in building comprehensive picture of neutrino interactions in the ~few GeV energy range
Why eA? – Well … this group at INT has shown quite a few slides I could put here …

Interactions are on nuclei rather than nucleons

Input from eA has been important in helping us understand the potential effects of SRC and MEC, for example
Why eA? – This work

- Measure flux and backgrounds in near detector and propagate to far detector and the uncertainties “cancel out”

- Cross-sections, nuclear effects and backgrounds don’t cancel simply/completely, even in the limit of identical detectors.

Model

- Even more important if near and far detectors are not the same material

GIBUU, Lalakulich and Mosel, NUINT 2012

S. Manly, University of Rochester

INT 2013, Seattle
December, 2013
Old deuterium data on single pion production: large errors

Comparisons with MiniBooNE differential distributions suggest our understanding of FSI is problematic or measurement is problematic …

Lacking a perfect model, experiment must turn knobs to adjust model to agree with data as well as possible and estimate error induced by this process/model AND seek other data to help constrain model.
Why eA? – This work

This work aims to produce high statistics, multidimensional, differential, charged pion production measurements on different nuclei. The hope is that this will be useful for learning about and tuning models for FSI.
Jefferson Lab (Newport News, Virginia)

$E_{\text{max}} \approx 6 \text{ GeV}$

$I_{\text{max}} \approx 200 \mu\text{A}$

Duty Factor $\approx 100\%$

$\sigma_E/E \approx 2.5 \times 10^{-5}$

Beam $P \approx 80\%$

12 GeV upgrade underway

S. Manly, University of Rochester

INT 2013, Seattle
December, 2013
**CLAS: CEBAF Large Acceptance Spectrometer (Hall B)**

- **Drift Chambers**
  - 35,000 wires
  - $\sigma_R = 350 \text{ \mu m}$

- **Superconducting Toroidal Magnet**
  - $B d l \approx 1.7 \text{ T-m}$

- **Cerenkov Counters**
  - 216 channels
  - 99.5% efficient over 50 m$^2$ area

- **Time of Flight Counters**
  - 500+ channels, 145 ps resolution

- **Electromagnetic Shower Calorimeters**
  - 1700+ channels
  - $\sigma/E = 10\% / E^{0.5}$

---

S. Manly, University of Rochester  
INT 2013, Seattle  
December, 2013
CLAS Single Event Display

- Charged particle angles 8°-144°
- Neutral particle angles 8°-70°
- Momentum resolution ~0.5% (charged)
- Angular resolution ~0.5 mr (charged)
- Identification of p, \(\pi^+/\pi^-\), K^+/K^-, e^+/e^-, etc.
- CLAS - International collaboration of ~230 scientists
  - Physics data-taking started in May of 1997
  - Wide variety of run conditions: e-/γ beams, 0.5<E<6 GeV (polarized), $^1$H, $^3$He, $^{12}$C, $^{56}$Fe, etc.
- EG2 running period for JLab experiments E02-104 (Quark propagation through cold QCD matter) and E02-110 (Q$^2$ dependence of nuclear transparency for incoherent rho electroproduction)
  - deuterium, carbon, lead, tin, iron, aluminum
CLAS EG2 Targets

- Two targets in the beam simultaneously
- 2 cm LD2, upstream
- Solid target downstream
- Six solid targets:
  - Carbon
  - Aluminum (2 thicknesses)
  - Iron
  - Tin
  - Lead
GENIE eA

Using GENIE version 2.6.8 in eA mode with $Q^2 > 0.5$ for acceptance calculations and comparison

C. Andreopoulos: GENIE eA mode is a “straightforward adaptation of the neutrino generator”

- Use charged lepton predictions of cross-section models: Rein-Sehgal, Bodek-Yang, etc.
- Transition region handled as in neutrino mode.
- Nuclear model (Bodek-Ritchie, Fermi-Gas) same as in neutrino mode.
- Intranuclear cascade (INTRANUKE/hA) same as in neutrino mode.
- Small modifications to take into account probe charge for hadronization model and resonance event generation.
- In-medium effects to hadronization same as in neutrino mode.
GENIE eA with different Fermi gas models (red is default)

Comparison with electron quasi-elastic scattering data

S. Manly, University of Rochester

INT 2013, Seattle
December, 2013
GENIE eA validation

Using GENIE version 2.5.1

Data from Hampton University and JLab Hall C resonance data archive
http://hallcweb.jlab.org/resdata/

Comparison with electron scattering resonance data

-From C. Andreopoulos

S. Manly, University of Rochester

INT 2013, Seattle
December, 2013
Samples

EG-2 data sample size ($E_{\text{beam}}=5.015$ GeV):

Deuterium + C/Fe/Pb raw events 1.1/2.2/1.5 ($\times 10^9$)
D2/C/Fe/Pb events passing all cuts 28.1/5.0/7.6/2.5 ($\times 10^6$)

Simulated sample size (Genie MC + detector simulation):

D2/C/Fe/Pb generated events (4)$\times 1.0\times 10^8$
D2/C/Fe/Pb events passing all cuts 7.9/6.4/5.5/4.8 ($\times 10^6$)
Analysis cuts

- Demand electron enter calorimeter safely away from edges
- Demand energy deposit as function of depth in ECAL be uneven
- Adjust vertex Z position for sector-by-sector beam offset
- Demand momentum of outgoing e-: $p > 0.64$ GeV (or $y < 0.872$) (removes bias due to electromagnetic energy threshold in trigger)
- Implement “relatively” easy to model cuts in $W$, $Q^2$, $\theta$ for the electron and $p_\pi$, $\theta_\pi$ for the pion
Fiducial volume complications

- The optimal fiducial regions for the detector are not conveniently modeled for comparison to calculations

Six azimuthal regions of angular acceptance that are a function of $\theta$, $p$, charge
Fiducial volume complications

- Report results with geometric correction to be azimuthally symmetric
- Implement “relatively” easy to model cuts in $W$, $Q^2$, $\theta$ for the electron and $p_\pi$, $\theta_\pi$ for the pion
For $e^-$
- $y>0.872$
- $1 \text{GeV}^2 < Q^2 < 4 \text{ GeV}^2$
- $1 \text{ GeV} < W < 2.8 \text{ GeV}$
- red line shown

For $\pi^-$ ($\pi^+$ has distinct but similar cuts)
- $0.3 < p_\pi < 2$
- $24^\circ < \theta_\pi < 54^\circ$
- red line shown

$W = -2.25(\text{GeV}^4) \times Q^2 + 4.9(\text{GeV})$

$\Theta = -18(\text{GeV}-1) \times p_\pi + 40(\text{degrees})$
Radiative corrections

- Use “externals_all” routine designed for EG1-DVCS experiment (P. Bosted, EG1-DVCS technical note 5, 2010)
- Calculate differential cross sections ($W, Q^2$) with and without QED radiative effects in the process.
- Remove (quasi-)elastic contribution (since we demand a pion be present)
- Only consider leptonic side (in neutrinos we don’t typically worry about the radiative corrections on the hadronic side)
Acceptance and bin migration

- Work in 4-dimensional space \((W, Q^2, p_\pi, \theta_\pi)\)
- Multi-dimensional acceptance correction and bin migration correction from MC (<10%, typically smaller)
- Non-acceptance corrected GENIE distributions look very similar to the data distributions – reasonable to use the GENIE samples for the acceptance corrections.
- Require at least one \(\pi^\pm\) reconstructed, take leading pion as the analysis pion
- MC indicates single \(\pi^\pm\) sample to originate from ~40% percent single \(\pi^\pm\) with most of the rest from multiple \(\pi\) events.
- Missing mass analysis improves single-\(\pi\) purity with a big loss in statistics. Not using for current results.
Caveats

- All results shown here are preliminary
- The errors shown are statistical only
- Systematic errors are under investigation
- Expectation/goal is to hold the systematic errors to <10%
- Vast amount of differential data. Only sampling shown here.
- Ask if you want to see preliminary result on something I do not have time to show here.
Systematics (under study)

- observed pion/beam current stability
- target thickness
- acceptance stability with different generator
- also have haprad implemented for radiative corrections
- Integrated total x-secs agree roughly with GENIE
- Looking to compare with published delta xsec measurements
- May release ratios
Data-MC comparison
(no acceptance corrections, detector optimized fiducial definition)

- GENIE events run through CLAS detector simulation (GSIM) with EG2 target geometry and same analysis chain as data
- Require single $\pi^\pm$ reconstructed

Deuterium

- W distribution (other variables integrated over)

S. Manly, University of Rochester

INT 2013, Seattle
December, 2013
Data-MC comparison
(no acceptance corrections, detector optimized fiducial definition)

Deuterium

Q^2 distribution (other variables integrated over)

Preliminary

Carbon

Using GENIE
version 2.5.1

S. Manly, University of Rochester

INT 2013, Seattle
December, 2013
Data-MC comparison
(no acceptance corrections, detector optimized fiducial definition)

Momentum of $\pi$ in the lab frame
(other variables integrated over)
Data-MC comparison
(no acceptance corrections, detector optimized fiducial definition)

Deuterium

Carbon

Angle of $\pi$ with respect to the beam direction
(other variables integrated over)
Data-MC comparison

(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown, three variables integrated over $W$).

$W : D_2$ target, $\pi^+$

$W : C$ target, $\pi^+$

$W : \pi^+$

Data/MC ratio, all targets
Data-MC comparison

(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown, three variables integrated over)

$Q^2$, $\pi^+$

Data/MC ratio, all targets
Data-MC comparison
(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown, three variables integrated over)

\[ p_\pi, \pi^+ \]

Data/MC ratio, all targets
Data-MC comparison

(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown, three variables integrated over)

\[ p_{\pi}, \pi^- \]

Data/MC ratio, all targets
Data-MC comparison
(Comparison friendly fiducial region, corrected for acceptance and radiative effects, only statistical errors shown, three variables integrated over)

\[ \theta_\pi, \pi^+ \]

Data/MC ratio, all targets
High precision neutrino results are a product of many pieces carefully fit together.

CLAS/EG2 is making significant progress toward releasing multi-dimensional precision $\pi^\pm$ production cross-sections on different nuclei in a region of phase space relevant for the current precision neutrino physics program. We hope for final results to be released in the spring/early summer.

Let’s finish this up. I need to graduate!
Wish list?

- Limited capacity to do much beyond this, but …
- If your favorite generator (or new and improved release) has eA mode that produces output we can digest, we can include, *in principle*, comparisons with data in paper (data will be generally available for comparison after paper published). Probably need the MC in ~February (takes a month to generate the events for comparison).
- Conversation with Jan Sobczyk over breakfast: look at W over single pion threshold and use missing mass to measure events with zero pions. Will have low stats, but only two dimensions.
The CLAS Collaboration

Arizona State University, Tempe, AZ
University of California, Los Angeles, CA
California State University, Dominguez Hills, CA
Carnegie Mellon University, Pittsburgh, PA
Catholic University of America
CEA-Saclay, Gif-sur-Yvette, France
Christopher Newport University, Newport News, VA
University of Connecticut, Storrs, CT
Edinburgh University, Edinburgh, UK
Florida International University, Miami, FL
Florida State University, Tallahassee, FL
George Washington University, Washington, DC
University of Glasgow, Glasgow, UK

Idaho State University, Pocatello, Idaho
INFN, Laboratori Nazionali di Frascati, Frascati, Italy
INFN, Sezione di Genova, Genova, Italy
Institut de Physique Nucléaire, Orsay, France
ITEP, Moscow, Russia
James Madison University, Harrisonburg, VA
Kyungpook University, Daegu, South Korea
University of Massachusetts, Amherst, MA
Moscow State University, Moscow, Russia
University of New Hampshire, Durham, NH
Norfolk State University, Norfolk, VA
Ohio University, Athens, OH
Old Dominion University, Norfolk, VA

Rensselaer Polytechnic Institute, Troy, NY
Rice University, Houston, TX
University of Richmond, Richmond, VA
University of South Carolina, Columbia, SC
Thomas Jefferson National Accelerator Facility, Newport News, VA
Union College, Schenectady, NY
Virginia Polytechnic Institute, Blacksburg, VA
University of Virginia, Charlottesville, VA
College of William and Mary, Williamsburg, VA
Yerevan Institute of Physics, Yerevan, Armenia
Brazil, Germany, Morocco, and Ukraine, as well as other institutions in France and in the USA, have individuals or groups involved with CLAS, but with no formal collaboration at this stage.
Super-conducting toroidal magnet with six kidney-shaped coils
5 m diameter, 5 m long, 5 M-Amp-turns, max. field 2 Tesla
From Will Brooks at NUINT02

$H$ target with $E_{beam} = 4$ GeV illustrates the power of CLAS
Analysis cuts

Stay away from edges

Remove events with even energy deposition in the two layers of the ECAL

Calorimetric fiducial and ID cuts on outgoing $e^-$

Mostly pions and muons

S. Manly, University of Rochester

INT 2013, Seattle

December, 2013
Analysis cuts

- Momentum of outgoing e-: $p > 0.64 \text{ GeV}$ (or $y < 0.872$)
- Removes bias due to electromagnetic energy threshold in trigger.
- Also reduces sensitivity to radiative effects.