# JLAB CLAS results on pion production from nuclear target

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> NUINT 2015 Osaka, November 2015

Representing the CLAS (EG-2) collaboration

# Why eA? – Goal of this work

 This work aims to produce high statistics, differential, charged pion production measurements on different nuclei that will be useful for learning about and tuning models for FSI.



Steve Dytman, NUINT 2014

"Delta production, pion absorption in GENIE"

# **The CLAS Detector**

• CEBAF(Continuous Electron Beam Accelerator Facility) at JLAB

- Up to 6 GeV  $e^{-}$  and  $\gamma$  beam (upgrading to 12 GeV).

- Hall B, CLAS detector
  - Liquid and/or solid target with  $e^{-}$  and  $\gamma$  beam
- CLAS Components in 6 sectors
  - Super-conducting toroidal magnet
  - Drift chambers for particle tracking
  - Cerenkov counters for e<sup>-</sup> identification
  - TOF Scintillators for particle identification
  - Calorimetry for e<sup>-</sup> identification



# **EG2 Experiment**

- 4 GeV, 5 GeV e<sup>-</sup> beam. 2 targets(liquid & solid) in the beam simultaneously in CLAS.
  - [LD<sub>2</sub>, LH] + [C, Fe, Pb, Sn, Al(2 thicknesses)]
- 5 GeV Beam (EG2c) + (D<sub>2</sub>, C, Fe, Pb) used for this study.
- Events with an electron and at least one detected charged pion were extracted for this study.



# **Evolving Analysis**

If you've been paying attention, we've been working on this for some time ...

- Early work full 5-dimensional distributions in W, Q<sup>2</sup>,  $p_{\pi}$ ,  $\theta_{\pi}$ ,  $\pm$ , inclusive
- Simplified to single pion production (hoping that it is simpler to analyze and interpret)
- Introduced new nuclear model(effective spectral functions)
- At NUINT 2014

- Reported very preliminary distributions in W, Q<sup>2</sup>,  $p_{\pi}$ ,  $\theta_{\pi}$  for D and C targets with rough estimation of background.

- After NUINT 2014
  - Have struggled with background analysis.  $\leftarrow$  MC/data background shapes disagree
  - Have converged on technique to estimate background and will show semi-final results in this talk.

Semi-final? You ask. :-) Semi-final means we hope it is final but we need to go through collaboration approval process.

# **GENIE eA**

Use GENIE version 2.8.0 in eA mode with Q<sup>2</sup>>0.5 GeV<sup>2</sup> Patched with effective spectral function for target momentum. (hep/ph: 1405.0583)





- 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.

# Samples

- EG2 data sample size
  - Deuterium + C/Fe/Pb raw events
  - D/C/Fe/Pb events passing all cuts
  - $\rightarrow \frac{1}{2}$  of D-Fe data excluded due to stability issue.
- Simulated sample size (Genie MC + detector simulation)
  - D/C/Fe/Pb generated events
  - D/C/Fe/Pb events passing all cuts

20.7/5.7/4.7/2.4 (×10<sup>5</sup>)



 $(4) \times 1.0 \times 10^{8}$ 8.8/8.0/6.5/4.5 (×104

### Variables and Fiducial Volume - $\pi$

- π
  - $p_{\pi} : 0.3 \sim 2.5 \text{ GeV} \quad \theta_{\pi} : 24 \sim 54^{\circ}$
  - $\theta_{\pi} > 18.5 + 6.28/(p_{\pi} + 0.029)$ ,
  - θ<sub>π</sub>>28.1-1.30/(p<sub>π</sub>-1.65)
- $\pi^+$ 
  - $p_{\pi}$  : 0.3~4 GeV,  $\theta_{\pi}$  : 10~54°
  - θ<sub>π</sub>>7.06+1.23/(p<sub>π</sub>-0.035)

CLAS has complicated money in an a complicated money of the make mention dependent **Electron Beam** ACCEDIANCE. Well-defined SO, We Make Measurements in the Clons of Dhase space which in Classing of the Measurements in Contained Solution of the AS and the AS and the Solution of the Solution of the Solution of the Solution of the AS and the Solution of Well-Oeinneo Subset of the CLAS or Dnase space which acceptance. Defined on Cerenkov this slide. Counters p,  $\theta$ ,  $\phi \rightarrow$  p,  $\theta$ 

•  $\pi^{-}/\pi^{+}$ 

- They have different fiducial volume ← Magnetic field.





### **Variables and Fiducial Volume - Electron**



# Overall



- Data : eg2c (D, C, Fe, and Pb target)
- MC : GENIE 2.8.0 patched with effective spectral function for target momentum.
- Detector simulation : GSIM, GPP
- Reconstruction : Uana
- Event selection : Filter, PiEG2
  - $\rightarrow$  One and only one charged pion.
- Event-by-event Correction
  - Fiducial volume correction
  - Radiative Correction :

Externals\_all(eg1-dvcs) and Haprad2

- Background subtraction
- Unfolding : RooUnfold (arXiv:1105.1160)
  - Bayesian method with 1 iteration
- Final result
  - 1D differential cross-section (Q<sup>2</sup>, W,  $p_{\pi}$ ,  $\theta_{\pi}$ )

# Missing Mass(Mx) – Background Removal

- Background
  - Major source :  $N\pi$  (including  $\pi^0$ ) due to detector inefficiency.
- Missing mass (Mx)
  - Use cut in  $Mx \rightarrow Assume target nucleon is at rest.$

- For signal (one and only one charged  $\pi$  production), expect the Mx distribution to peak around the target nucleon mass.

- Use signal cut : 0.8<Mx<1.1 GeV for D, 0.7<Mx<1.2 GeV for solid target.



# W vs. missing mass (Mx) [ $\pi^-$ , D]

• Scaling down for DIS(W>1.7 GeV) process is needed.



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D target,  $\pi^{-}$ 

# W vs. missing mass (Mx) [ $\pi^+$ , D]

**MC-RES** 

1.4

1.5

Mx (GeV)

1.3

• At both signal and sideband region, data and MC disagree.

• Scaling up for resonance process is needed.

Data  $\pi^+$  D (nb/GeV<sup>2</sup>)

1.2

d.8

0.9



1.1

1

1.2



# **Background Removal – Tuning in Signal Region**

![](_page_13_Figure_1.jpeg)

# Tuning in Signal Region – W [ $\pi^+$ , D]

Data

Res-n

Res-p Qel

Dis-n-Ws>1.7

Dis-n-Ws<1.7 Dis-p-Ws>1.7

Dis-p-Ws<1.7

An example of W distribution from D target, π<sup>+</sup> before and after MC tuning.

Mx : Stack Histo n<sup>+</sup> D

⊢Data Dis-n-Ws>1.7

Res-n

Res-p

Dis-n-Ws<1.7

Dis-p-Ws>1.7

Dis-p-Ws<1.7

0.5

1

(nb/GeV)

6

0

• Scale factors are chosen from Mx-Q<sup>2</sup> distribution, not from W!!!

1.5

2

2.5

![](_page_14_Figure_3.jpeg)

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3

Mx (GeV)

# Tuning in Signal Region – $\pi$ Momentum [ $\pi$ , D]

- An example of  $\pi$  momentum distribution from D target,  $\pi$ - before and after MC tuning.
- Scale factors are chosen from Mx-Q<sup>2</sup> distribution, ۲ not from  $\pi$  momentum!!!

(nb/GeV)

2.5

1.5

0.5

![](_page_15_Figure_3.jpeg)

 $\pi$  momentum in signal region

PiMom : Stack Histo  $\pi^{-}$  D : with Mx cut

### Errors

- Statistical error
  - Data :~5%
  - Acceptance :  $\sim 1\%$
- Systematic error Global(normalization)
  - Total beam Q : Faraday cup  $\ <\!\!1\%$
  - Target properties : Area density D/C/Fe/Pb  $\rightarrow$  1.0/0.2/0.3/0.7%
- Systematic error Bin-by-bin
  - MC : Use GENIE reweighting ~8%
  - Background subtraction  $\sim 3.5\%$
  - Radiative correction  $\sim 1\%$
  - Unfolding  $\sim 3.5\%$
  - Detector geometry  $\leftarrow$  Only for  $\theta \pi \sim 4\%$
- Average total fractional error -Q<sup>2</sup>/W/p<sub> $\pi$ </sub>/ $\theta_{\pi} \rightarrow 10/11/13/12$  %

![](_page_16_Figure_14.jpeg)

# Caveats

- All results shown here are preliminary
  - Currently writing documentation to get results reviewed/approved by CLAS
  - We believe the significant parts of the analysis are all in place and hope things will not change much before results are finalized.

![](_page_17_Picture_4.jpeg)

### Final Result : Differential X-section π<sup>-</sup>

![](_page_18_Figure_1.jpeg)

### Final Result : Differential X-section π<sup>+</sup>

![](_page_19_Figure_1.jpeg)

# Finally...

- We (CLAS/EG2) are producing 1-π<sup>±</sup> production cross-sections on different nuclei (D, C, Fe, Pb) in a region of phase space relevant for the current precision neutrino physics program.
- Hope to publish final results in early 2016.

![](_page_20_Picture_3.jpeg)

# Backup

• Difficulties for theorists to use our results because of CLASoptimized fiducial cuts(Function of momentum and 2 angles.)

 $\rightarrow$  Changing analysis to use cuts that are more easily modeled for comparison to theory.

 Main idea → Assuming azimuthal symmetry, reduce a variable [azimuthal angle] in the function for fiducial cut.

- Cut only on polar angle for fixed momentum(No cut for azimuthal angle).

- The cut should be reasonably greater than the lower limit of polar angle in fiducial volume.

# **Pseudo-Fiducial Volume : Define**

![](_page_23_Figure_1.jpeg)

- Fiducial volume[FV]  $\rightarrow$  A+C
- Pseudo-fiducial volume[PFV] → A+B
  !!! FV is not a sub-volume of PFV
- Cut on angle where FV to PFV ratio greater than 25%.  $\frac{dA(\theta_C)}{dA(\theta_C)} = 0.25$

$$\frac{dA(\theta_C)}{dA(\theta_C) + dB(\theta_C)} = 0.2$$

### **Pseudo-Fiducial Volume : Electron**

![](_page_24_Figure_1.jpeg)

- Use  $Q^2$  and W, instead of electron  $p_e$  and  $\theta_e$ .
- Ratio  $\rightarrow A/[A+B]$  at given Q<sup>2</sup> and W
- $\theta_e < 54$ , W > 5.08-2.46\*Q<sup>2</sup>

### **Pseudo-Fiducial Volume :** $\pi^{-}$

Fiducial Volume Ratio : π<sup>-</sup>

![](_page_25_Figure_2.jpeg)

- Ratio  $\rightarrow$  A/[A+B] at given  $p_{\pi}$  and  $\theta_{\pi}$ .
- $24 < \theta_{\pi} < 54$ ,  $\theta_{\pi} > 18.5 + 6.28/(p_{\pi} + 0.029)$ ,  $\theta_{\pi} > 28.1 1.30/(p_{\pi} 1.65)$

### **Pseudo-Fiducial Volume :** $\pi^+$

![](_page_26_Figure_1.jpeg)

- Ratio  $\rightarrow$  A/[A+B] at given  $p_{\pi}$  and  $\theta_{\pi}$ .
- $10 < \theta_{\pi} < 54$ ,  $\theta_{\pi} > 7.06 + 1.23/(p_{\pi} 0.035)$

#### • Externals\_all

- For RC calculation in the process of inclusive electron scattering.
- It is designed for eg1-dvcs and being used for eg1 and eg4.
- Need 2 leptonic variables with fixed beam energy :  $W, Q^2$ .
- Calculate differential X-sections with/without QED radiative effects.
- Contribution from (Quasi-)elastic parts are excluded for our study.
  - $\leftarrow We select events with pion(s).$
- Being used as our RC calculation for this talk.

### Accumulated Charge

Take all eg2c runs and accumulate all the charge which counted by faraday cup during DAQ-live time.

D<sub>2</sub>: 14.7 *mC* C: 3.4 *mC* Fe: 6.0 *mC* Pb: 5.3 *mC* 

Mass Number of Target

 $D_2: 2.014$  C: 12.011 Fe: 55.845 Pb: 207.2

• Thickness of Target

D<sub>2</sub>: 2 cm C: 0.1723 cm Fe: 0.040 cm Pb: 0.014 cm

• Mass Density of Target

Liquid D<sub>2</sub> : 0.162  $g/cm^3$ 

C: 1.747 g/cm<sup>3</sup> Fe: 7.874 g/cm<sup>3</sup> Pb: 11.34 g/cm<sup>3</sup>

- "GENIE Physics and User Manual" from http://www.genie-mc.org/
- GENIE eA mode uses 3 event generators based on their cross section models.
- Quasi-Elastic Scattering (QEL)
  - Does not play a significant role in pion production.
- Baryon Resonance Production (RES)
  - Based on Rein-Sehgal model.
  - Covers only on "resonance-dominance" region where Ws(hadronic W) smaller than 1.7 GeV.
- Non-Resonance Inelastic Scattering (DIS)
  - Deep (and not-so-deep) inelastic scattering  $\rightarrow$  Not same as nuclear physics definition.
  - Based on Bodek and Yang model.
  - Covers resonance-dominance region(Ws < 1.7 GeV) also.

# **Background Removal – Sideband Tuning?**

- Use Q<sup>2</sup> in sideband (1.2 <Mx<1.4 GeV) to get the scale factors for multi-pion background.
- MC significantly disagrees with data → Complications for background subtraction in signal region
  - Data/MC shape difference in W and  $\pi$  momentum distribution.
  - Total integrals of Data/MC distribution are very different.
- Sideband tuning method is problematic

![](_page_30_Figure_6.jpeg)

### New Basis : Mx

![](_page_31_Figure_1.jpeg)

# Tuning : D

• In signal regoin.

![](_page_32_Figure_2.jpeg)

#### Q2 : Stack Histo $\pi$ D Tuned by Q2 : with Mx cut

![](_page_32_Figure_4.jpeg)

# Before Tuning : [ C, pi- ]

• In signal region.

![](_page_33_Figure_2.jpeg)

# After Tuning : [ C, pi-]

• Fit from Mx-Q2 In signal region.

![](_page_34_Figure_2.jpeg)

# **Systematic Error - Global**

Total Q – Gated Faraday cup liq\_Mul:run 1.12 trig\_file\_bit1:run - < 1%1.115 2200 trig\_file bit1 2000 1800 1.11 1600 1400 1.105 Target 1200 1000 800 1.1 - Liquid(D2) : ~1.0% 600 400 1.095 Fe1<sup>•</sup> Pb - Solid · 0 2~0 7% Fe<sub>2</sub> 41400 41600 41800 42000 42200 1.09 41200 41600 42000 41400 41800 42200 - X. Zheng, Cryogenic Target Thickness Study for EG2  $\pi$  multiplicity  $Up \rightarrow Liquid target$  $\rightarrow$  EG2 internal note, May 2003  $Down \rightarrow Solid target$ - H. Hakobyan et al., NIM A 592 (2008) 218 sol Mul:run 1.11 1.105 Stability 1.1 1.095 - Problem at first half part of iron target. 1.09 1.085 - We are finding absolute x-section. 1.08 Fe1 Fe<sub>2</sub>  $\rightarrow$  Excluded 1.075 41200 41400 41600 41800 42000 42200

# **GENIE Reweighting**

- Use reweighting tool on 18 physics parameters in GENIE which related to eA production.
  - Cross section model, hadronization, and intranuclear rescattering.
  - GENIE knob name

"MFP\_pi", "MFP\_N", "FrCEx\_pi", "FrElas\_pi", "FrInel\_pi", "FrAbs\_pi", "FrPiProd\_pi", "FrCEx\_N", "FrElas\_N", "FrInel\_N", "FrAbs\_N", "FrPiProd\_N", "RDecBR1gamma", "RDecBR1eta", "AGKYxF1pi", "AGKYpT1pi", "AhtBYshape", "BhtBYshape"

- Tweak  $\pm \sigma$  shifts for each parameter.
  - Go through the entire analysis chain and get the final x-section result bin-by-bin.
    - $\rightarrow$  Differences with central value as its error.
  - Assume as they are independent.
    - $\rightarrow$  Take square sum of them and use as total MC systematic error for each bin.
- AGKY hadronization model  $\rightarrow$  Major source of error.
- Gives ~8% average fractional error.

# [Background Subtraction], [Radiative Correction]

#### Background Subtraction

- Use error matrix of 5 fit parameters for MC tuning

Make (100 universes)\*(3 variables which is used for tuning)

 $\pi$  angle is not used for tuning.

Fit results from Q2 used as CV.

- Average ~3.5% fractional error
- Radiative Correction
  - Use 2 different programs

External\_all(eg1-dvcs) : Only use electron information to get the corrections.(2 variables)

Haprad2 : Include pion information (5 variables)

 $\rightarrow$  Phys.Lett.B672:35-44,2009

- Take the difference between 2 as error.
- Gives  $\sim 1\%$  average fractional error.

# **Unfolding – Bin migration**

- RooUnfold
  - Bayesian method with 1 iteration.
- Basic Idea
  - Bin migrations are related to detector performance and mostly independent on targets
  - Apply response matrices from other targets on MC reconstructed sample  $\rightarrow$  Get unfolded sample and compare with MC truth sample.
  - For example... ( $\rightarrow$  Response matrix from Pb, MC recon and truth from D  $\rightarrow$  A set of error on D target.)
  - Take mean of errors which are taken 3 possible combinations.
- Gives ~2.5% average fractional error.

# Structure in $\pi$ Angle Distribution

• Fiducial volume correction?

Assuming azimuthal symmetry, reduce a variable[azimuthal angle] in the function for fiducial cut for simplicity.  $\rightarrow$  Take the ratio inside fiducial region for fixed momentum and polar angle.

- This looks like the source of strange structure in pion angle distribution.
  - If there exist certain region where the fit function does not work well...  $\rightarrow$  It's more likely with polar angle due to the detector geometry  $\rightarrow$  Could give wrong corrections in that region.
- Error estimation?
  - Making a smooth fit function on final distribution and take the difference as error.

NUINT :

 $\rightarrow$  Our current plan. Any other suggestion?

![](_page_39_Figure_8.jpeg)

![](_page_39_Figure_9.jpeg)

# **Error pim D**

![](_page_40_Figure_1.jpeg)

# **Error pim C**

![](_page_41_Figure_1.jpeg)

### **Error pim Fe**

![](_page_42_Figure_1.jpeg)

### **Error pim Pb**

![](_page_43_Figure_1.jpeg)

# **Error pip D**

![](_page_44_Figure_1.jpeg)

# **Error pip C**

![](_page_45_Figure_1.jpeg)

### **Error pip Fe**

![](_page_46_Figure_1.jpeg)

# **Error pip Pb**

![](_page_47_Figure_1.jpeg)