Update on JLab Experiment **E12-14-012**:

Inclusive (*e*,*e*′) and Exclusive (*e*,*e*′*p*) Electron Scattering from ^{12}C, ^{48}Ti and ^{40}Ar.

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Hall A Collaboration Meeting
January 30, 2019

Presentation Outline

Experiment E12-14-012

- Motivation - Neutrino oscillations
- Physics - electron scattering from nuclei
- HRS kinematics
- Argon target cell

Part I: Inclusive Analysis

- Cross Section Extraction Methods
- Systematic Uncertainties
- Results

Part II: Exclusive Analysis

- Particle Identification
- Preliminary Analysis Results

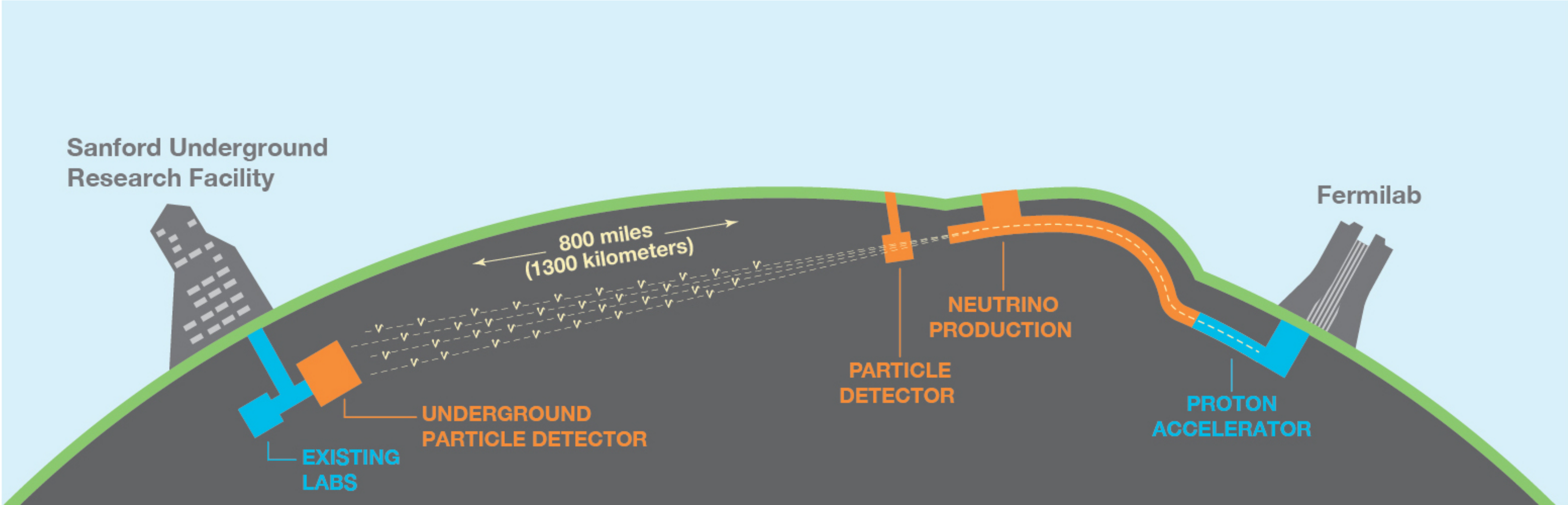
JLab Experiment E12-14-012:

Primary Goal: Measurement of the spectral functions of argon through coincidence (*e*,*e*′*p*) scattering off of ^{40}Ar and ^{48}Ti.

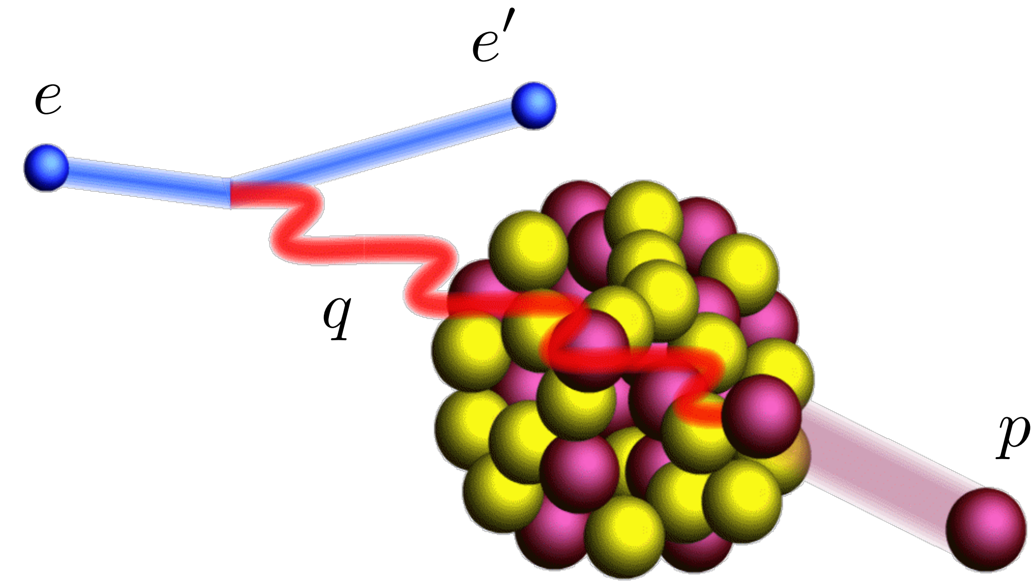
Primary Motivation: To help improve the accuracy of the measurement of the neutrino oscillation parameters (including the CP violation in the leptonic sector) in future neutrino experiments, such as LBNE/DUNE.

The argon spectral function is key to the reconstruction of neutrino energies, currently the largest source of uncertainty in neutrino experiments.

Virtually no argon-electron scattering data available - collection of coincidence (*e*,*e*′*p*) data will serve as a benchmark to test nuclear models against.



Electron Scattering from Nuclei



Exclusive (*e*,*e′p*): Scattered electron and knocked-out proton detected in coincidence

$$\frac{d^6\sigma_A}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} = K\frac{\alpha^2}{Q^4}\frac{E_{e'}}{E_e}L^{\mu\nu}W_{\mu\nu}$$

$L^{\mu\nu}$ is the leptonic tensor

$W_{\mu\nu}$ is the target response tensor

K a kinematical factor

Single particle wave functions $\Phi_i(p)$ with energies ϵ_i are the basic quantities accessed in knockout reactions

Can construct a probability function to describe the shell structure of the nucleus:

$$S(|\mathbf{P}|, E) = \sum_i |\Phi_i(p)|^2 \delta(E + \epsilon_i)$$

$$d^6\sigma \propto S(|\mathbf{P}|, E)$$

Inclusive (*e*,*e′*): Only scattered electron detected

Integrate over exclusive spectrum to get inclusive cross section:

$$\frac{d^2\sigma}{d\Omega dE'} \propto \int d^3\mathbf{P}_p \int dE'_p \left(\frac{d\sigma_p}{d\Omega_e}\right) S(|\mathbf{P}_p|, E'_p)\delta(\ldots)$$

Energy integral of spectral function gives nucleon momentum distribution:

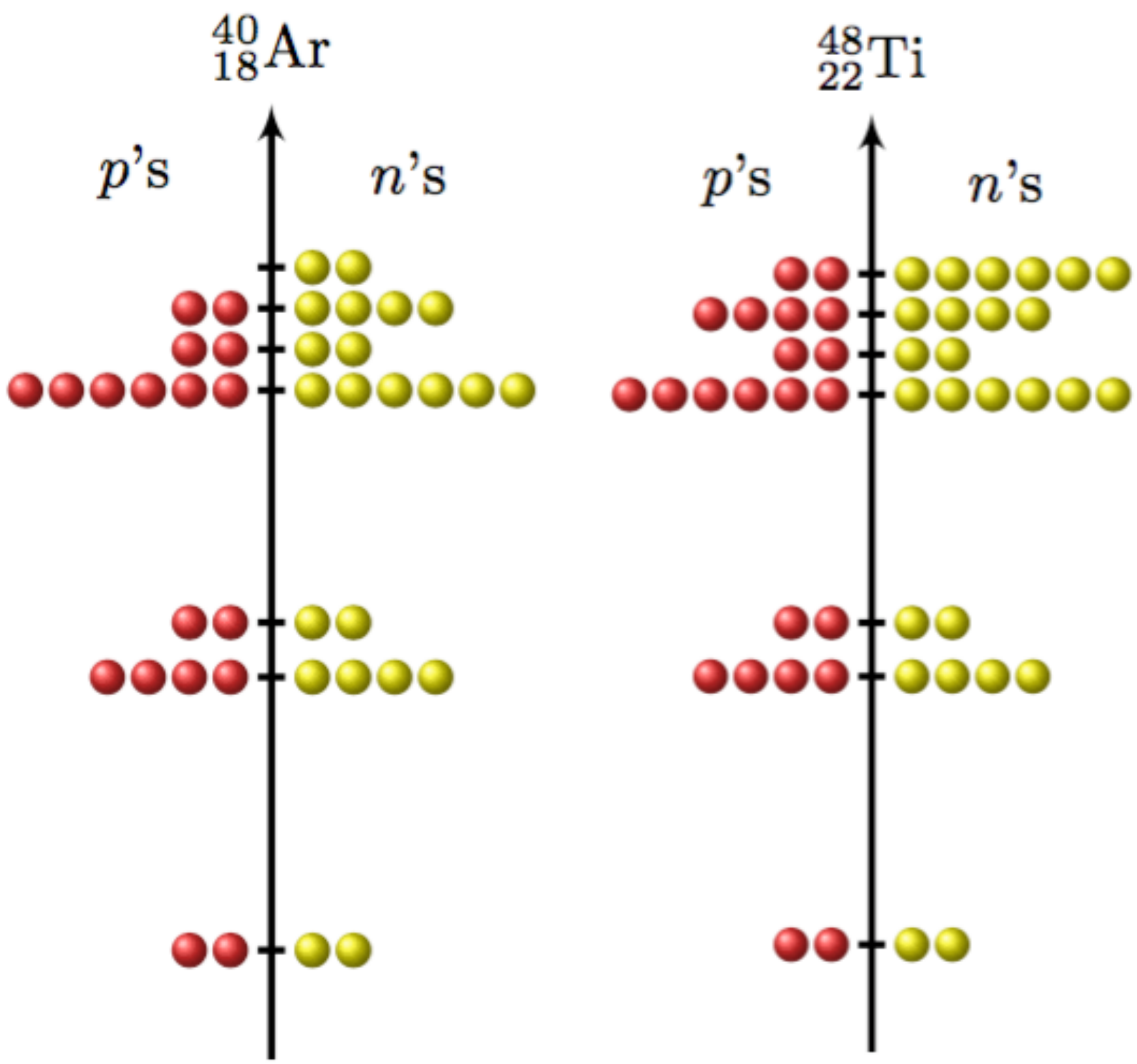
$$n(p) \propto \int dE'_p\, S(p, E'_p)$$

Electron Scattering from Nuclei

Why Titanium?

Different spectral function for protons, neutrons.

Exploiting the correspondence of the level structures of ^{40}Ar and ^{48}Ti, the neutron spectral function can be obtained from the proton spectral function of titanium.



Ar(e,$e'p$) gives the proton spectral function for Ar

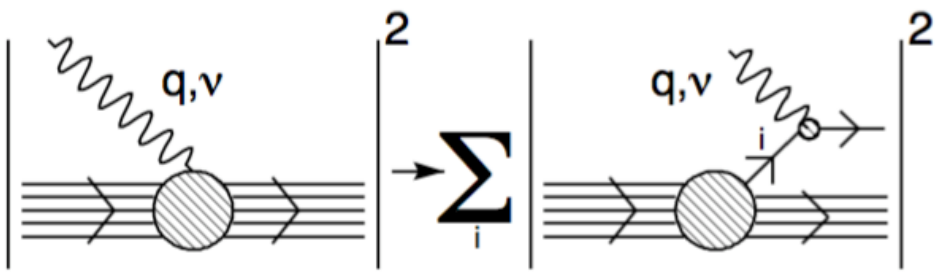
$$e + {}^{40}_{18}\mathrm{Ar} \rightarrow e' + p + \mathrm{X} \quad \Longrightarrow \quad S_p(|\vec{\mathbf{p}}|, E)$$

Ti(e,$e'p$) gives the **neutron** spectral function for **Ar**

$$e + {}^{48}_{22}\mathrm{Ti} \rightarrow e' + p + \mathrm{X} \quad \Longrightarrow \quad S_n(|\vec{\mathbf{p}}|, E)$$

Electron Scattering from Nuclei

Plane Wave Impulse Approximation (PWIA)



- Scattering off of nuclear target reduces to incoherent sum of elementary scattering processes involving individual bound nucleons
- FSI between proton and recoiling nucleus are negligible

$$\sigma = K \left(\frac{d\sigma_p}{d\Omega_e} \right) S(|\vec{\mathbf{p}}_m|, E_m)$$

K a kinematic factor

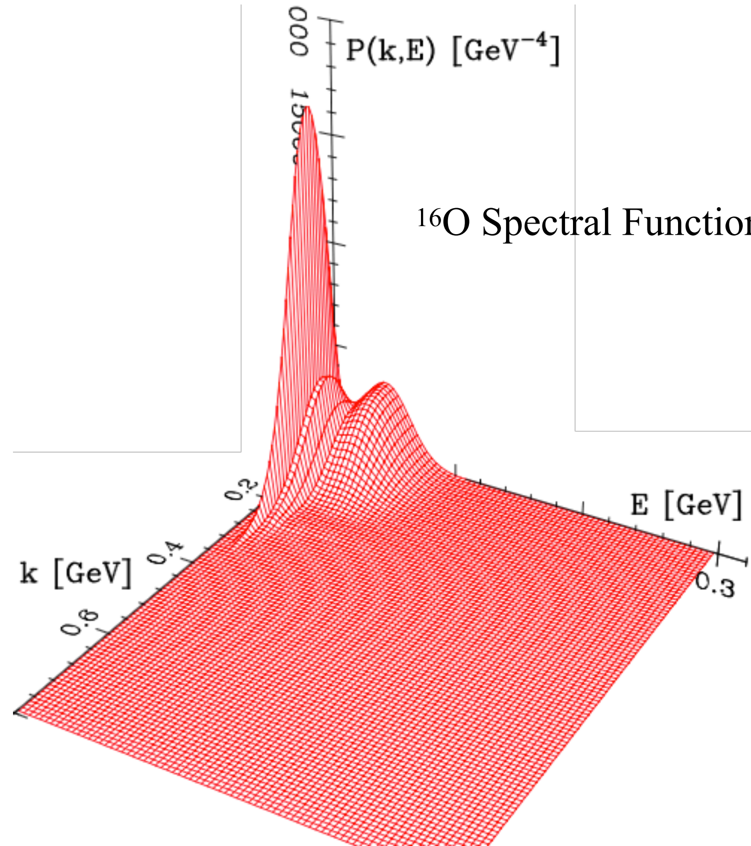
$\frac{d\sigma_p}{d\Omega_e}$ the elastic electron-proton cross section

$S(|\vec{\mathbf{p}}_m|, E_m)$ the spectral function

Distorted Wave Impulse Approximation (DWIA)

- Accounts for FSI with spin-independent optical potential
- Appropriate choice of kinematics reduces FSI
- Potential has minimal effect on outgoing proton momentum
- Factorization of differential cross-section holds!
- DWIA implemented in MC using Carlotta's code

$$\frac{d^6\sigma_A}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} = K \left(\frac{d\sigma_p}{d\Omega_e} \right) S^D(E_m, |\vec{\mathbf{p}}_m|, |\vec{\mathbf{p}}|)$$



Connection to Neutrino Physics

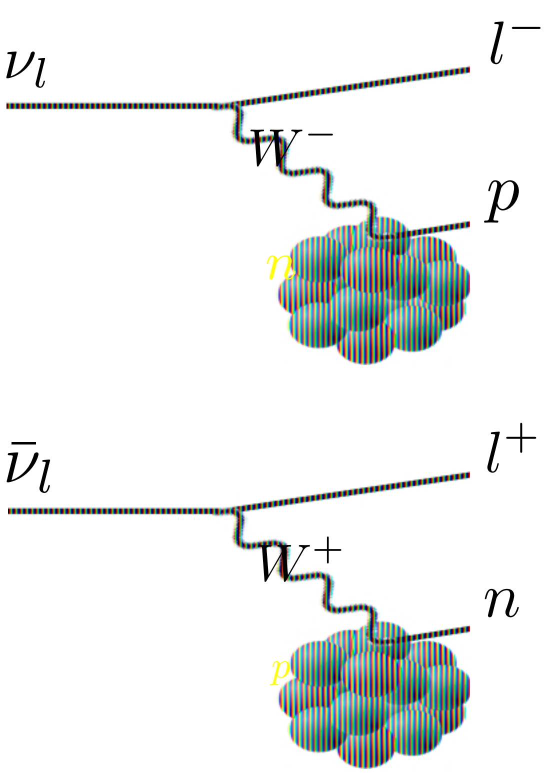
How does the Argon spectral function help with neutrino physics?

The reconstruction of (anti-)neutrino energy in the LArTPC detectors requires understanding of the spectral functions describing both neutrons and protons.

$$E_\nu = \frac{m_n^2 - m_\mu^2 - E_p^2 + 2E_\mu E_p - 2|\mathbf{k}_\mu||\mathbf{P}_p| + P_p^2}{2(E_p - E_\mu + |\mathbf{k}_\mu|\cos\theta_\mu - |\mathbf{P}_p|\cos\theta_p)}$$

E_p and P_p are distributed according to the proton spectral function.

In the detectors, the neutrinos will interact with the argon nucleus through the charged-current weak interactions: $\nu_l + n \to l^- + p$ and $\bar{\nu}_l + p \to l^+ + n$



Physics of these neutrino interactions is analogous to $(e,e'p)$

In the PWIA/DWIA approximation scheme, the neutrino cross sections can be written in terms of a spectral function

The spectral function is an intrinsic property of the nuclear ground state, and hence can describe interactions involving different particle probes

E12-14-012: Kinematics and Data Summary

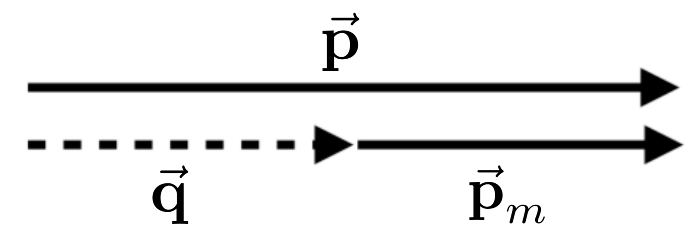
	E_e MeV	$E_{e'}$ MeV	θ_e deg	P_p MeV/c	θ_p deg	$\|\mathbf{q}\|$ MeV/c	p_m MeV/c	x
kin1	2222	1799	21.5	915	−50.0	857.5	57.7	0.70
kin2	2222	1716	20.0	1030	−44.0	846.1	183.9	0.48
kin3	2222	1799	17.5	915	−47.0	740.9	174.1	0.47
kin4	2222	1799	15.5	915	−44.5	658.5	229.7	0.37
kin5	2222	1716	15.5	1030	−39.0	730.3	299.7	0.29

Data collection from Feb-March 2017

Ar/Ti/C(e,$e'p$) for five kinematic settings

Ar/Ti/C(e,e') for kin5 only

Data collection used "parallel kinematics" to reduce the effects of FSI on the cross-section



Kin 1		
Target Type	Hours	Events
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

Kin 3
Target Type
Ar
Ti
Dummy

Kin 2		
Target Type	Hours	Events
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

Kin 4
Target Type
Ar
Ti
Dummy
Optics
C

Kin 5		
Target Type	Hours	Events
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

Kin 5 - Inclusive
Target Type
Ar
Ti
Dummy
C

momentum delta scan

Run	Target	E_0 [GeV]	θ_L [deg]
730	C	2.222	15.5
731	C	2.222	15.5
739	C	2.222	15.5
740	C	2.222	15.5
747	C	2.222	15.5
748	C	2.222	15.5
755	C	2.222	15.5
756	C	2.222	15.5
763	C	2.222	15.5

E12-14-012 Targets

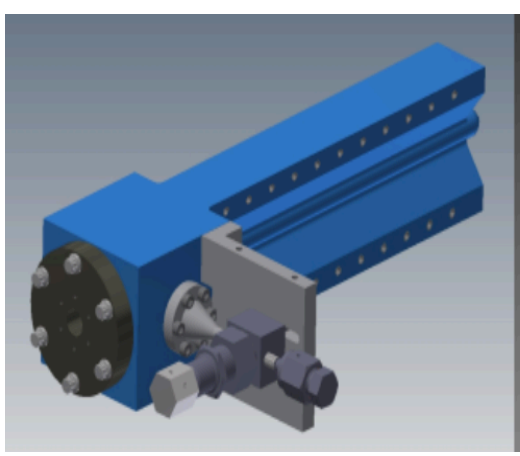
- Carbon
- Titanium
- Argon
- 25cm Al dummy
- Optics

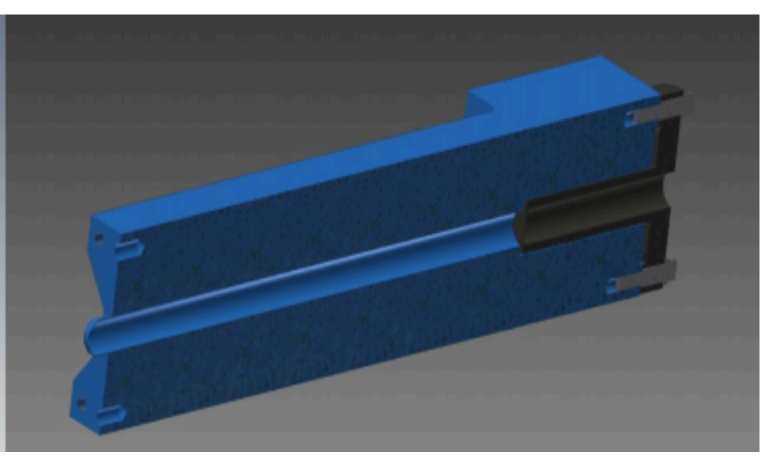
Length = 25 cm
Pressure = 500 PSI
Temperature = 300 K

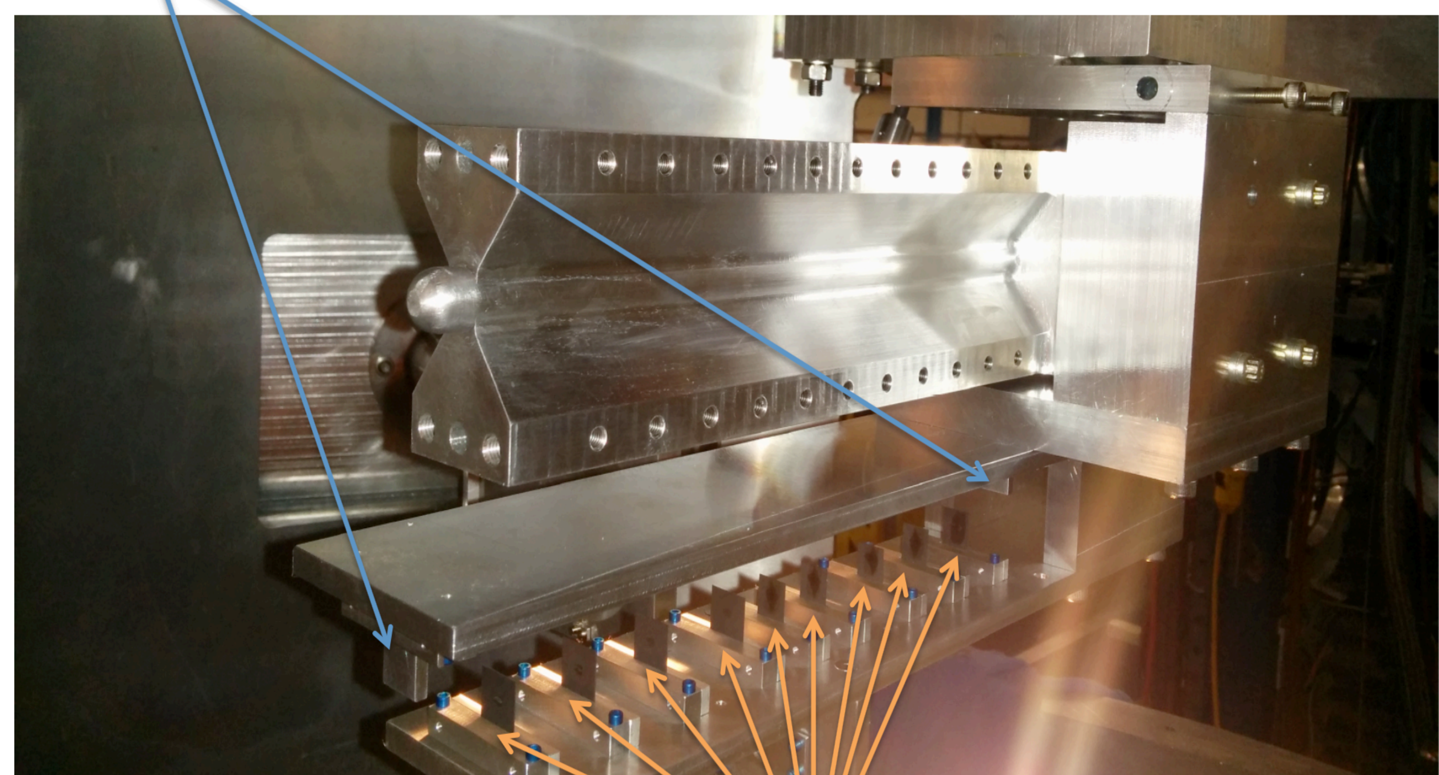
C and Ti targets are foils

Ar target is a sealed gas cell

Dummy target: same as the entry and exit window as the gas target







Optical target: a series of foils of carbon (9) to check the alignment of target and spectrometers (optics)

E12-14-012 Argon Target Boiling Study

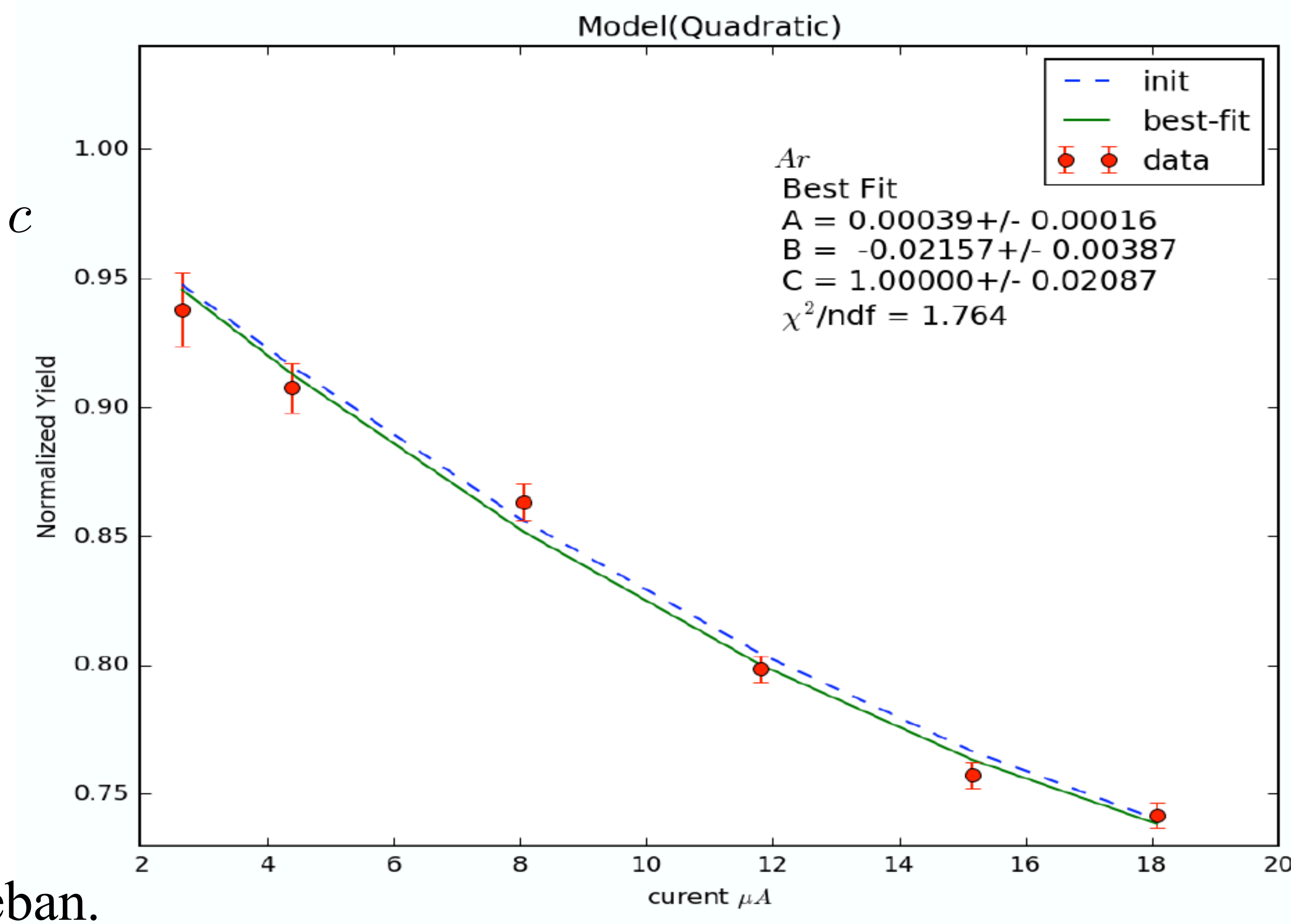
Calculate normalized yield for different currents

A change in the yield represents a change in the target density: $\Delta Y \Rightarrow \Delta\rho_{\text{targ}}$

Fit the yield data with a function $f(I_{\text{CEBAF}})$ such that $f(0) = 1$

Density correction factor:

$$f(I_{\text{CEBAF}}) = a \cdot I^2_{\text{CEBAF}} + b \cdot I_{\text{CEBAF}} + c$$



Boiling study courtesy of Nathaly Santiesteban.
Available at: arXiv:1811.12167

PART I

Inclusive (e,e') Scattering from ^{12}C, ^{48}Ti, ^{40}Ar, and ^{27}Al

Cross Section Extraction Methods

Acceptance Method:

Number of detected events:

$$N^{-} - BG = L \cdot \sigma \cdot (\Delta E' \Delta\Omega) \cdot \varepsilon \cdot A(E', \theta)$$

Let Y = $N^{-} - BG$, and solve for the cross-section:

$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)_{exp} = \frac{\text{Yield}}{L \cdot \varepsilon \cdot (\Delta E' \Delta\Omega) \cdot A(E', \theta)}$$

L is the (integrated) luminosity
σ is the differential cross section
ε is the total detector efficiency
$A(E',\theta)$ is the HRS acceptance function

Yield Ratio Method:

Calculate the "yield" for both the data and MC simulation:

$$\text{Yield} = \frac{N_s \cdot \text{DAQ}_{\text{pre-scale}}}{N_e \cdot LT \cdot \varepsilon}$$

Multiply model cross section by data/MC yield ratio:

$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)_{exp} = \left(\frac{d^2\sigma}{d\Omega dE'}\right)_{\text{MC}} \cdot \frac{\text{Yield}_{\text{data}}}{\text{Yield}_{\text{MC}}}$$

Carbon Comparison Method:

Scale the Carbon cross section by the titanium-to-carbon yield ratio:

$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)^i_{\text{Ti}} = \left(\frac{d^2\sigma}{d\Omega dE'}\right)^i_{\text{C}} \cdot \frac{\text{Yield}^i_{\text{Ti}}}{\text{Yield}^i_{\text{C}}}$$

Inclusive Analysis: Systematic Uncertainty

Total systematic uncertainty ≈ 3%

Beam charge ~ 0.3 %

Beam energy ~ 0.1 %

Beam x and y offset ~ 0.8 %

HRS x and y offset ~ 0.8 %

Target boiling ~ 0.7 %

Acceptance ~ 0.6 %

Cherenkov cut ~ 0.02 %

COSY ~ 0.64 %

Radiative corrections ~ 1 %

- RC on model ~ 0.49 %

Radiative corrections calculated using the peaking approximation of Mo and Tsai.

To determine the effect of the cross section model used to calculate the radiative correction factor, we scaled the original MC model by $\sqrt{Q^2}/2$ and recalculated the correction factor.

$$RC = \frac{\sigma_{born}}{\sigma_{rad}}$$

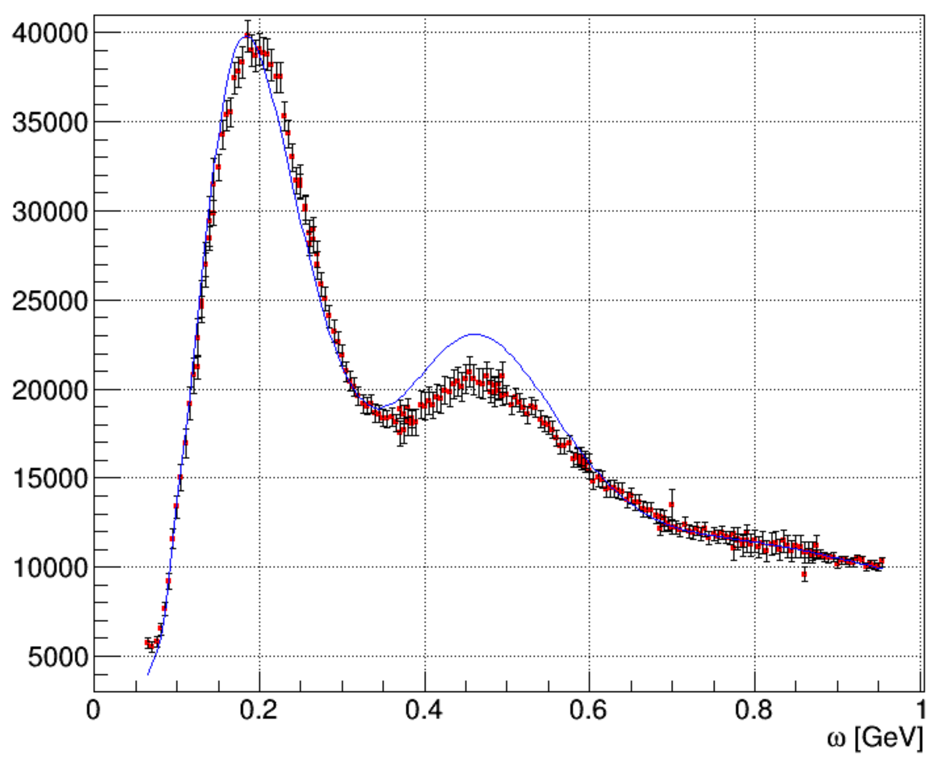
We use the code COSY to generate the optical matrix for simulation.
To estimate the optical matrix uncertainty due to the magnetic field settings of Q1, Q2, and Q3, we varied the individual settings by 1%

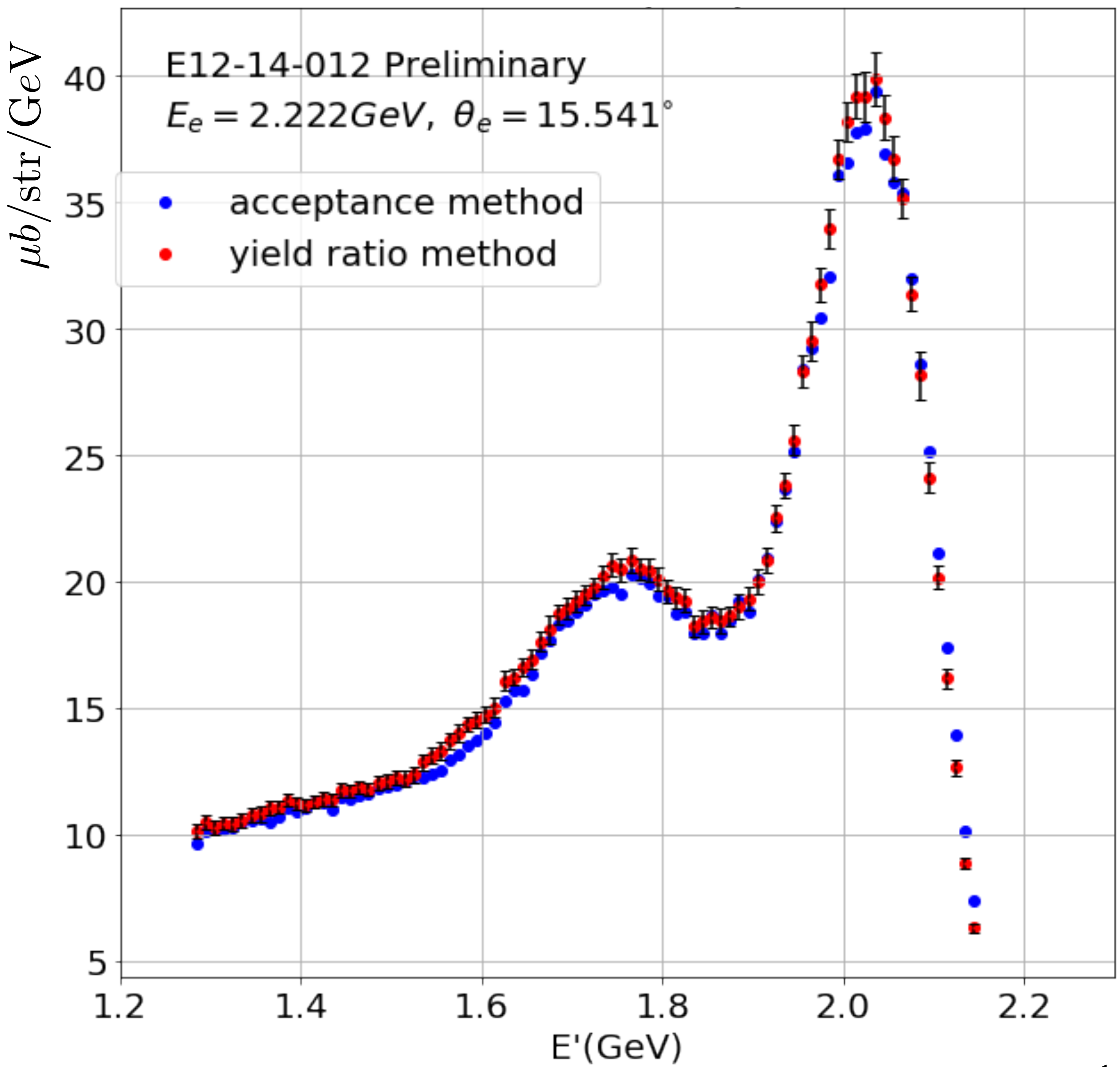
$^{12}C(e,e')$ Cross Section

$\sigma_{stat} < 1.20\%$

$\sigma_{syst} < 2.95\%$

Compare result with MC model:





Results published in Phys. Rev. C **98**, 014617

^{48}Ti(e,e') Cross Section

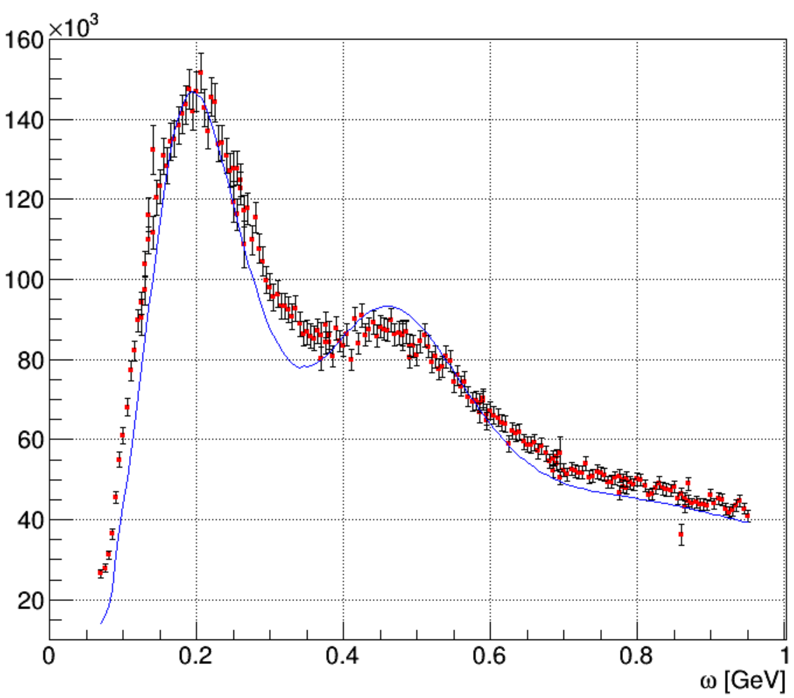
$E_0 = 2.222$ GeV

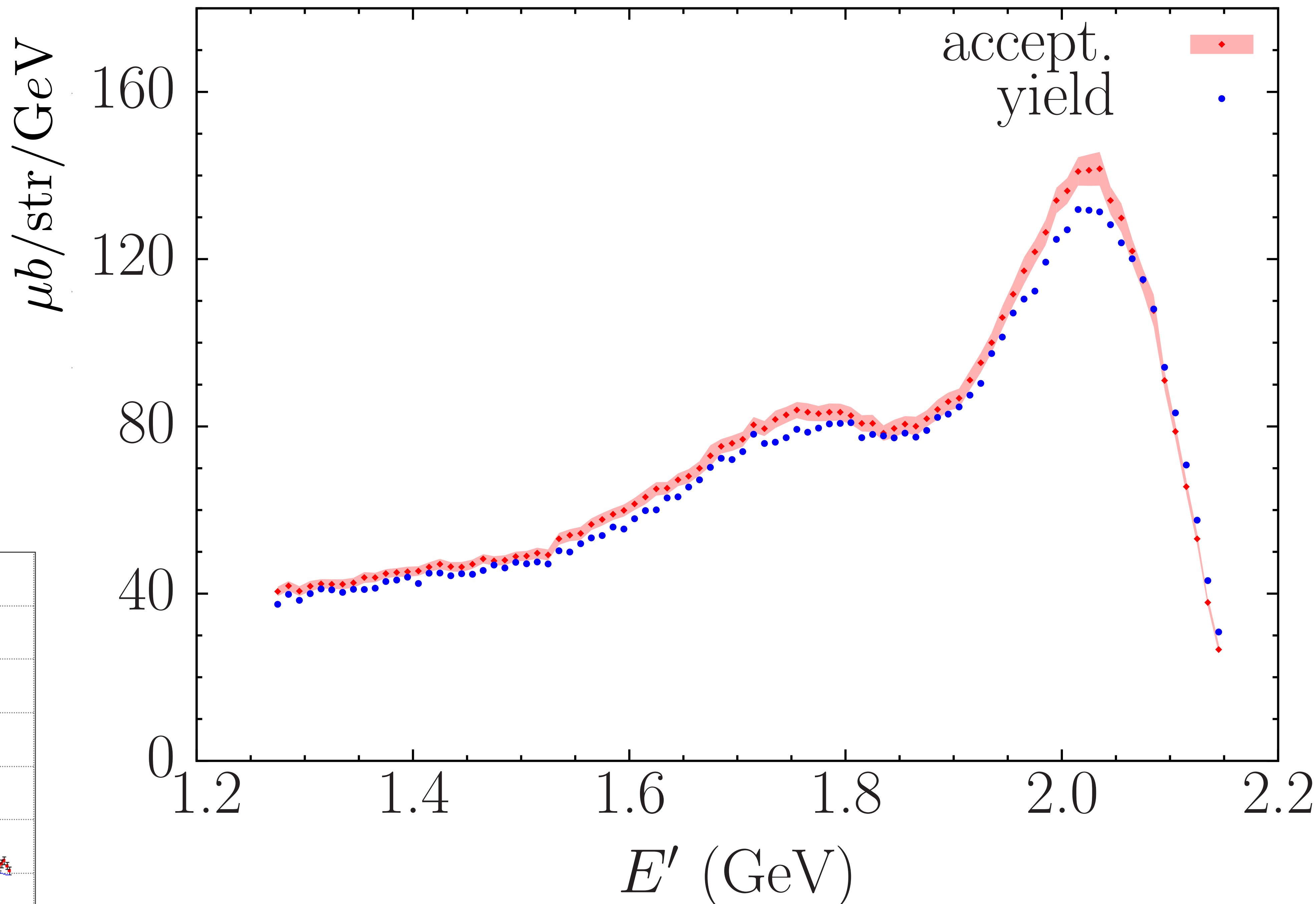
$\theta = 15.541°$

$\sigma_{stat} < 1.24\%$

$\sigma_{syst} < 2.63\%$

Compare result with MC model:





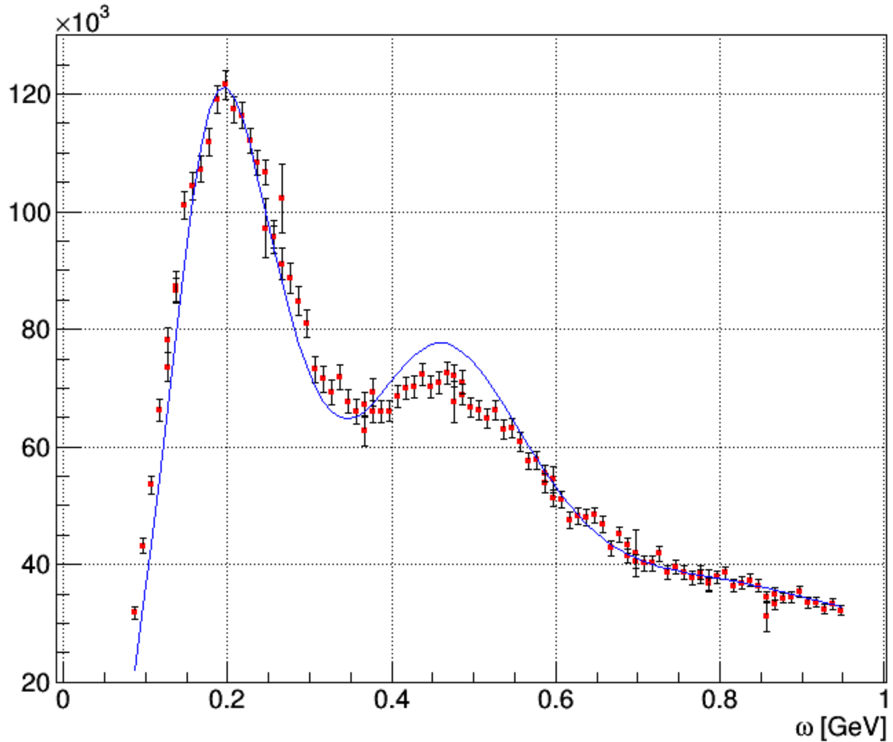
Results published in Phys. Rev. C **98**, 014617

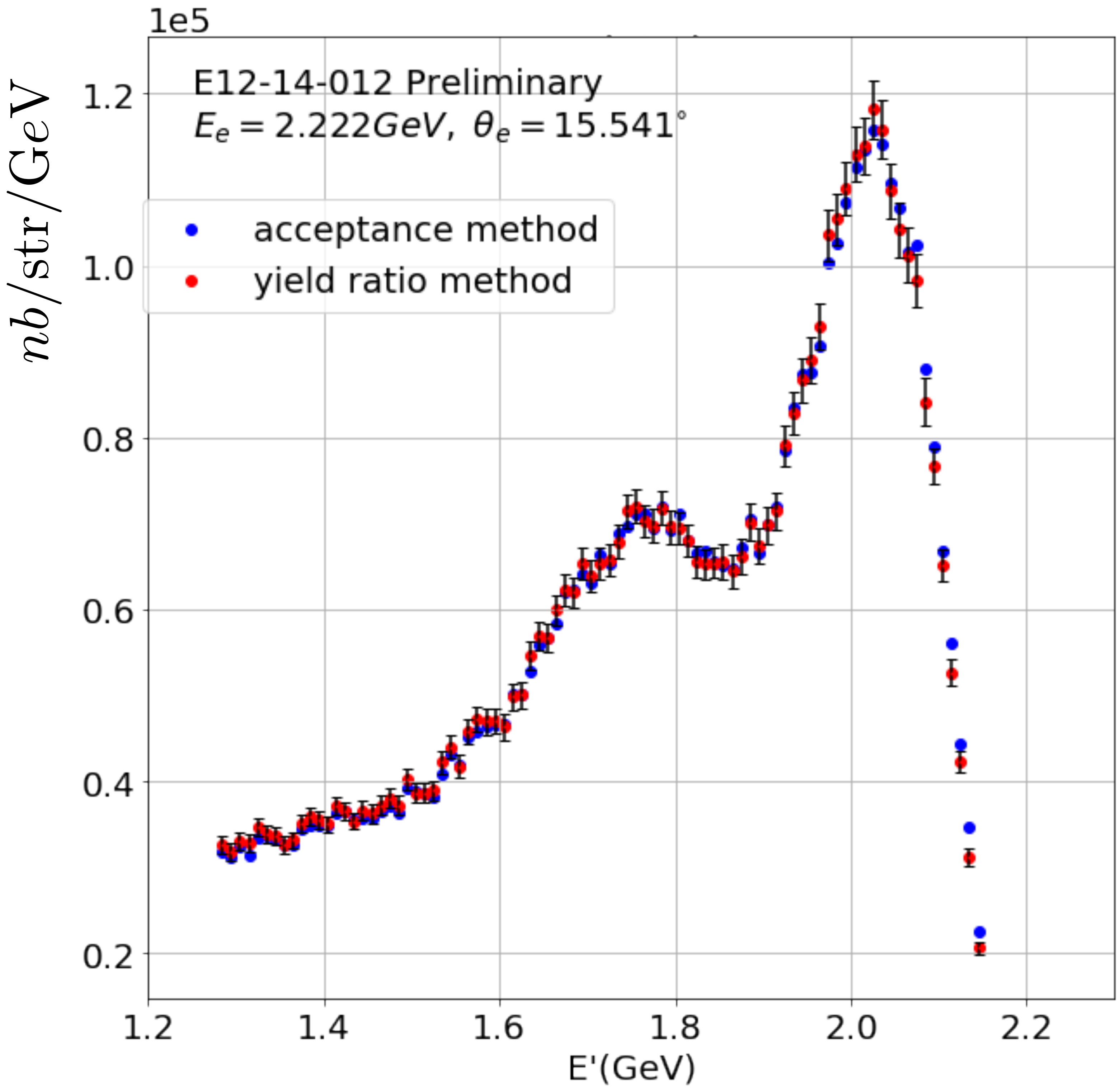
^{40}Ar(e,e') Cross Section

$$\sigma_{stat} \leq 2.9\%$$

$$\sigma_{syst} \leq 3.0\%$$

Compare result with MC model:





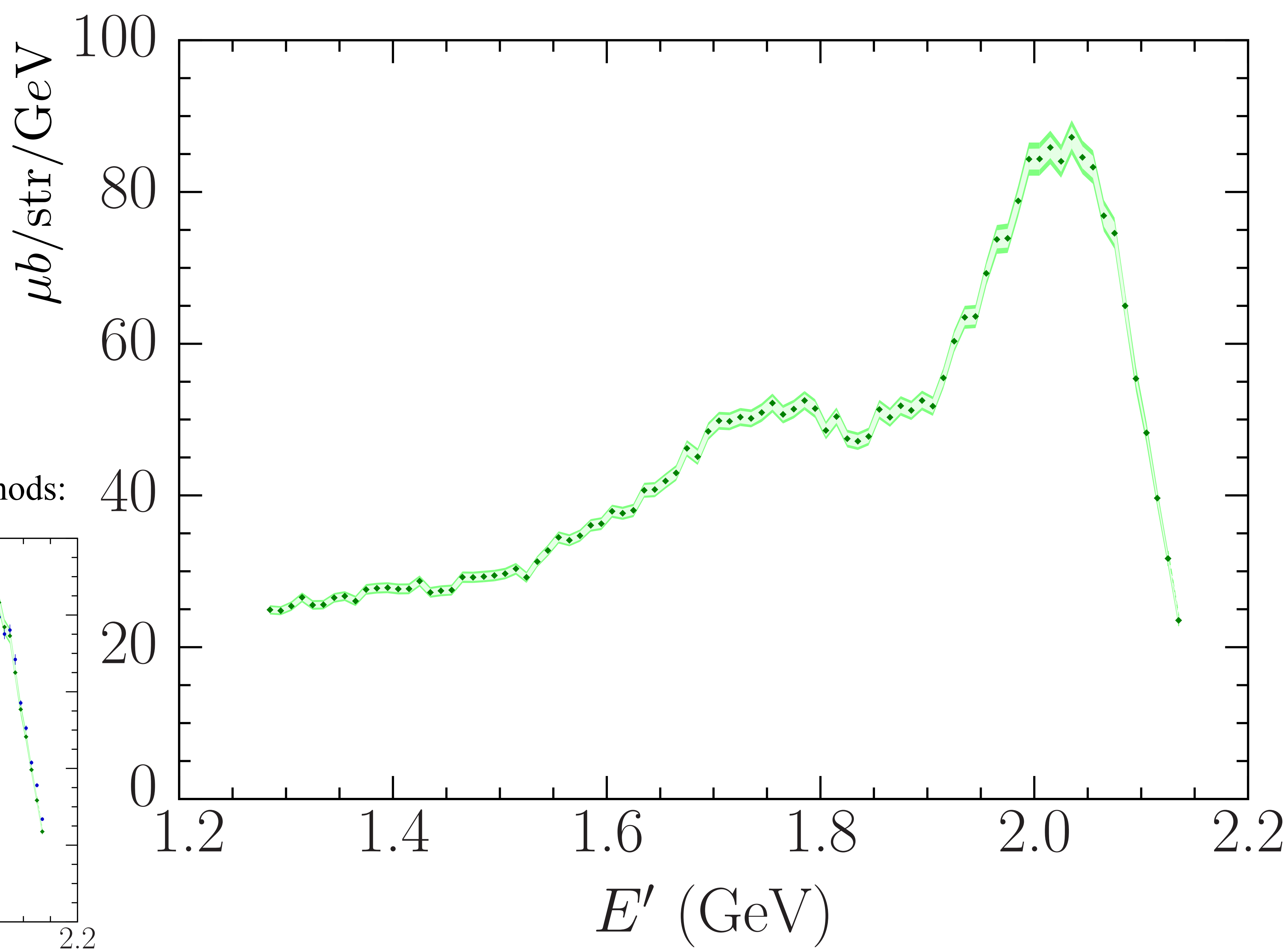
Available at: arXiv:1810.10575, under review at PRL

^{27}Al(e,e') Cross Section

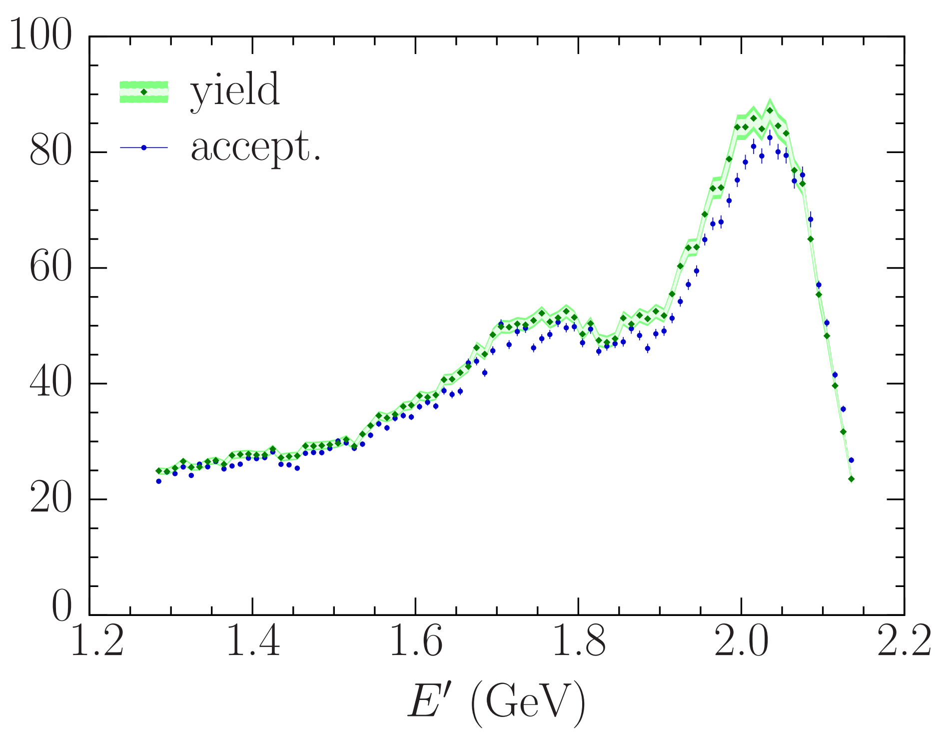
$E_0 = 2.222$ GeV

$\theta = 15.541°$

$\sigma_{syst} \leq 2.7\%$



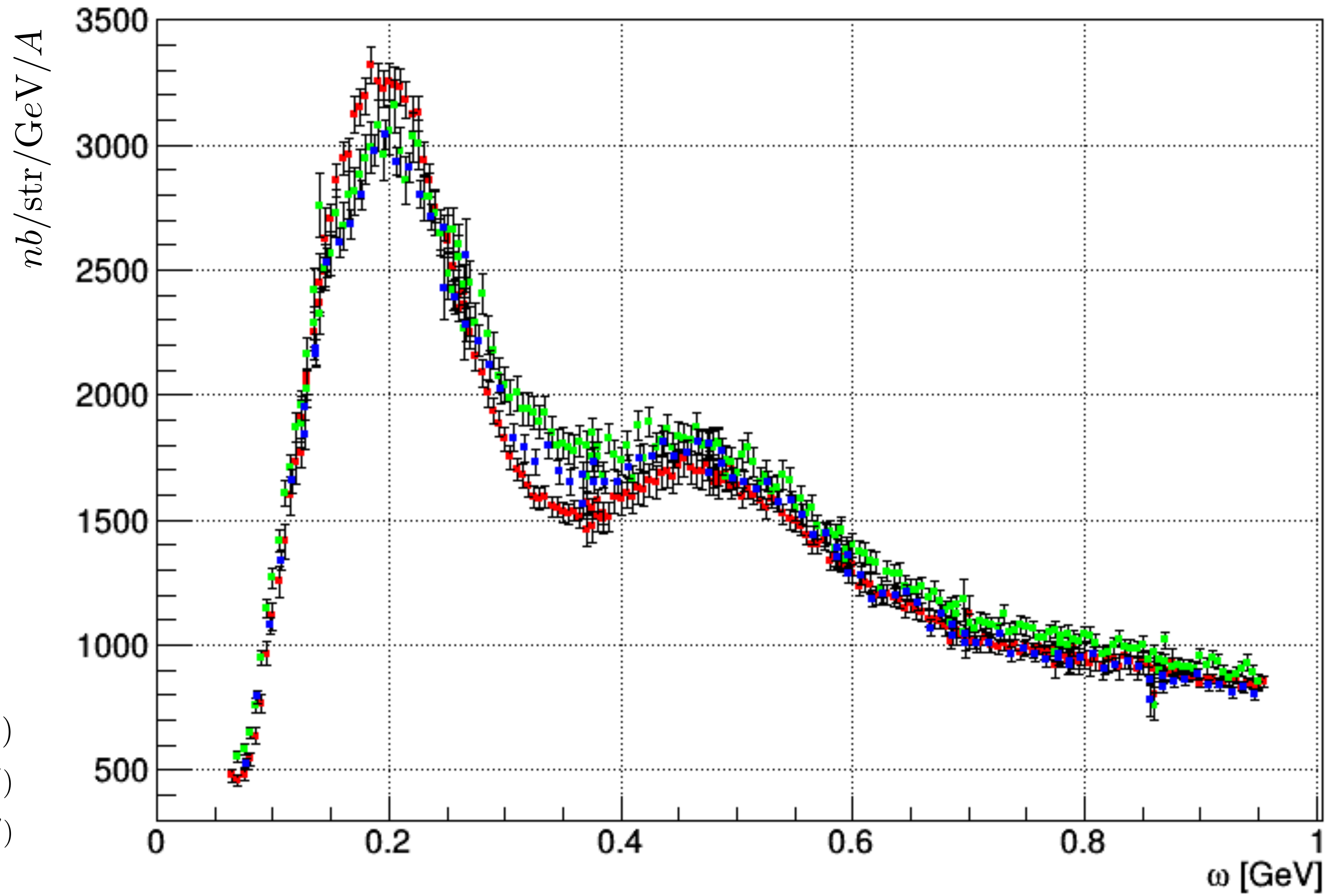
Compare yield and acceptance methods:



University of Virginia

Jefferson Lab

Inclusive Cross Sections Per Nucleon



$^{12}\mathrm{C}(e,e')$

$^{48}\mathrm{Ti}(e,e')$

$^{40}\mathrm{Ar}(e,e')$

PART II

Exclusive $(e,e'p)$ Scattering from ^{40}Ar: Preliminary Analysis

E12-14-012 Exclusive Analysis

LHRS Data Cuts

dp: (0.01,0.04)

θ: (−0.04,0.04)

ϕ: (−0.02,0.015)

Vertex Z: $\pm$ 9 cm

RHRS Data Cuts

dp: (0,0.03)

θ: (−0.04,0.04)

ϕ: (−0.02,0.015)

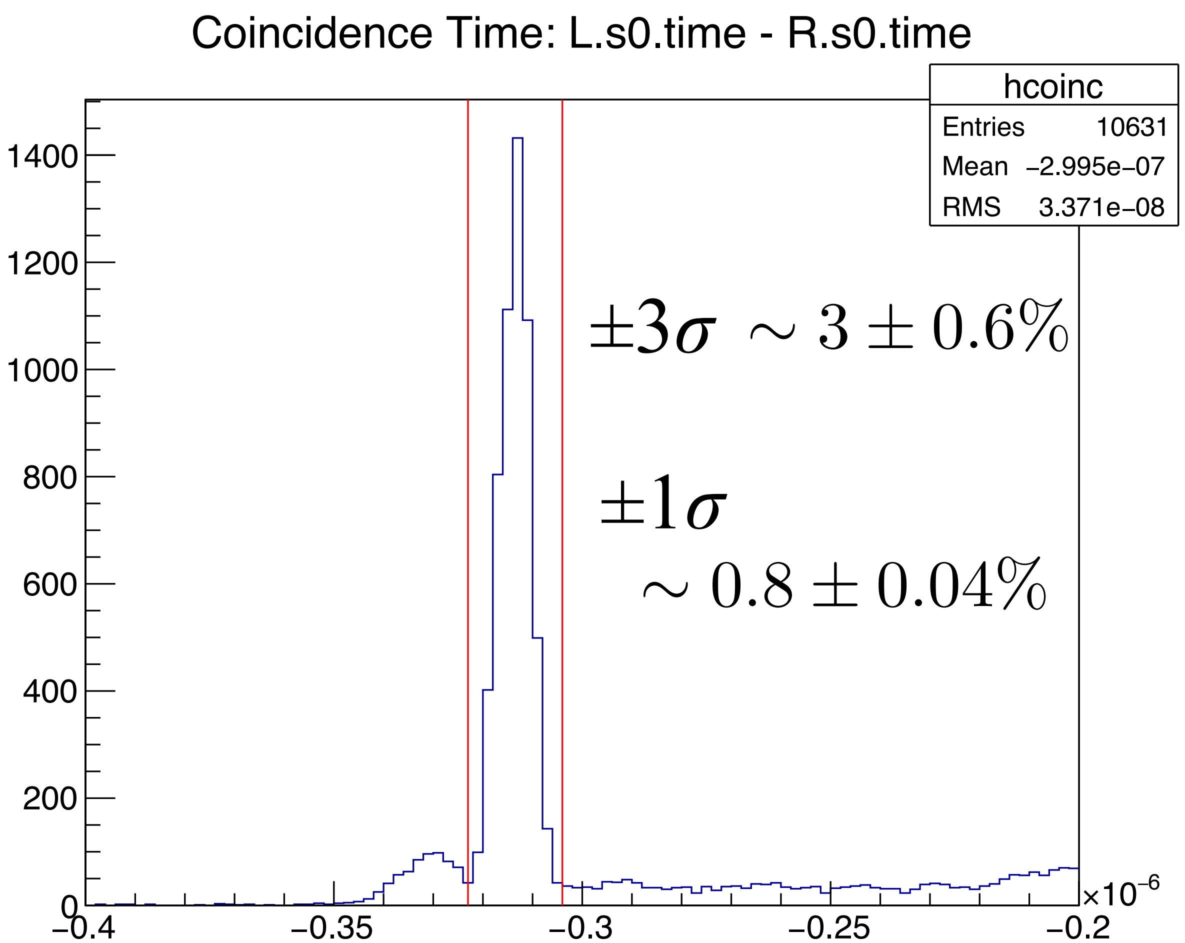
$\beta > 0.6$

Coincidence Time: $\pm 1\sigma$

(e,$e'p$) Particle Identification and Proton Selection

Coincidence trigger cut: `T1`

Coincidence time: `L.s0.time - R.s0.time`



$e + p \rightarrow e' + p + \pi^0$ ⟵ True coincidence!

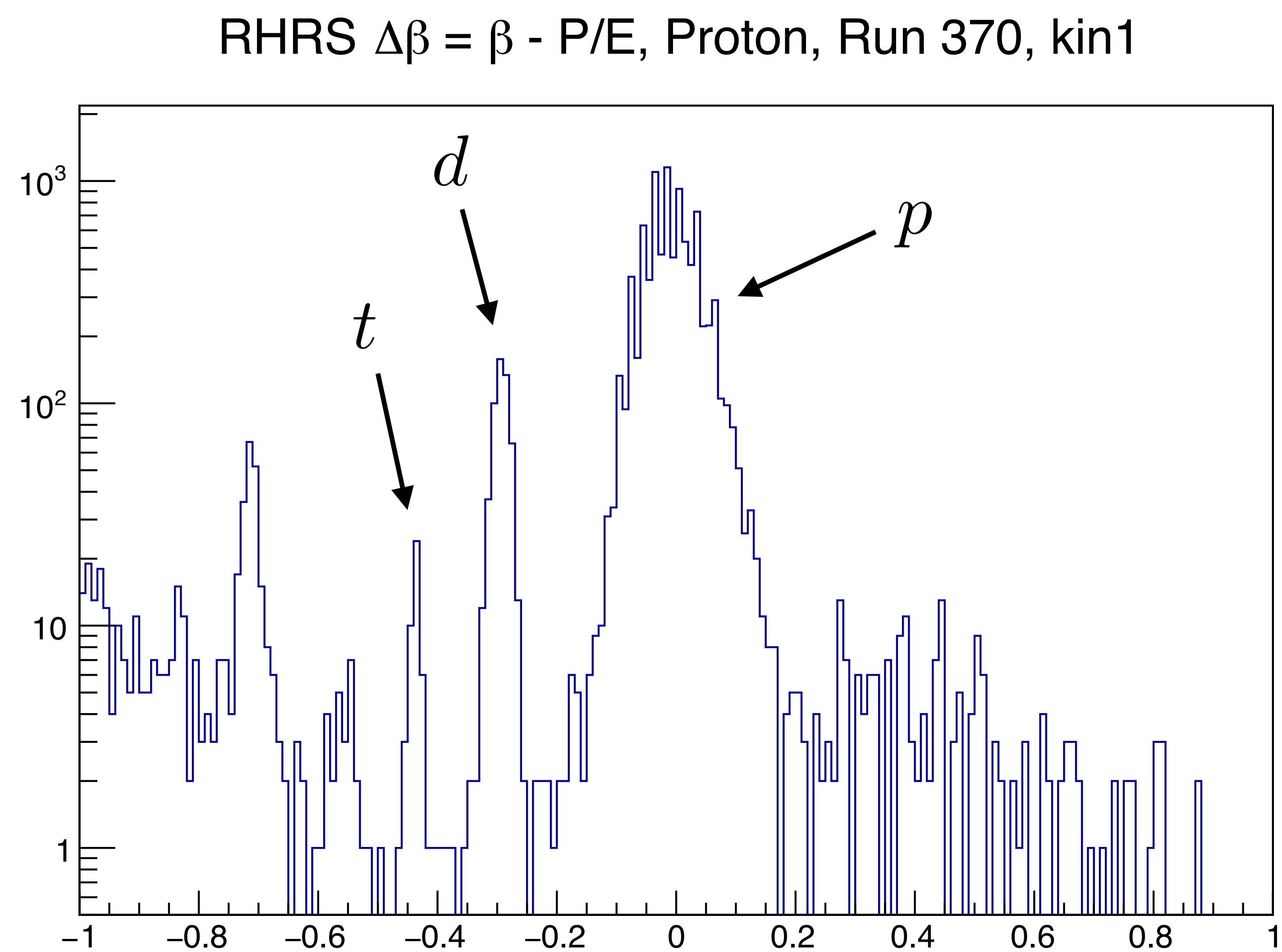
$e + p \rightarrow e' + n + \pi^+$

$e + n \rightarrow e' + p + \pi^-$

Accidental coincidences!

RHRS β: `R.tr.beta`

$$\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}}$$



E12-14-012 Exclusive Analysis

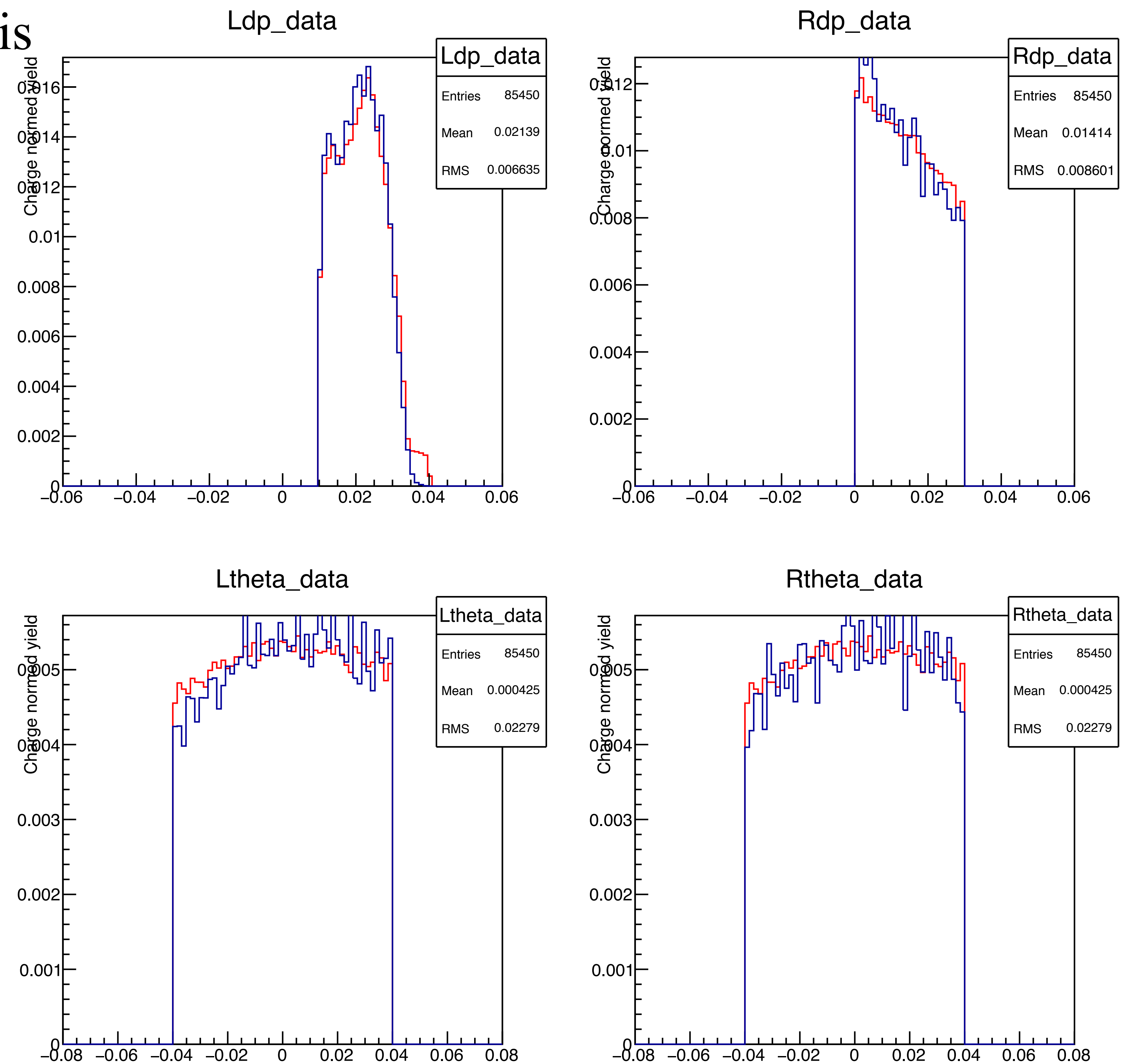
Analysis of full exclusive data underway for Ar target, Ti analysis upcoming

Using MCEEP for MC model

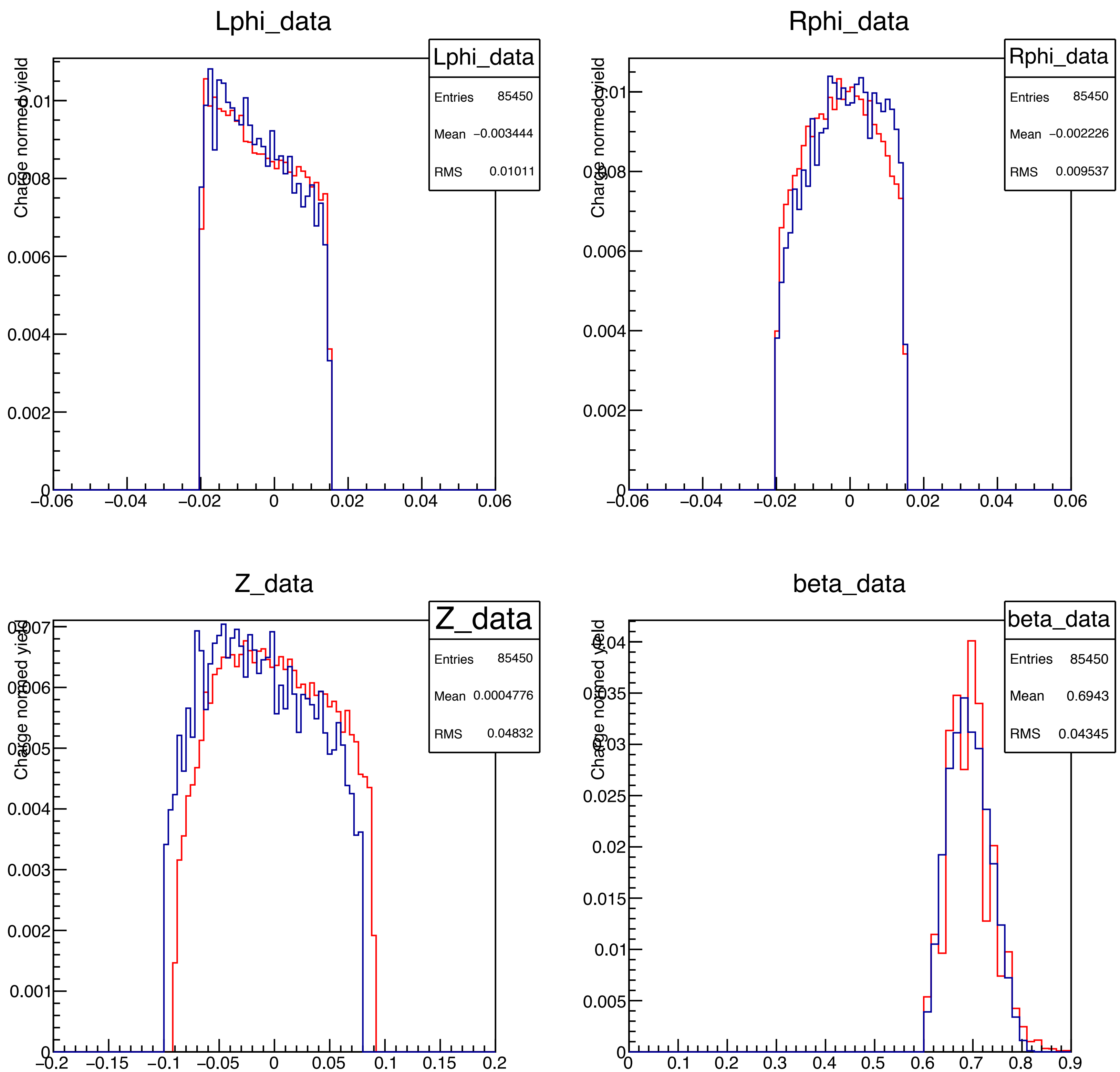
MCEEP Input file:
e^- Arm P_0: 1762 GeV
e^- Arm Spec. θ offset: -7 mrad
p Arm Spec. θ offset: -7 mrad

Data: Run 370
e^- Arm P_0: 1777 GeV

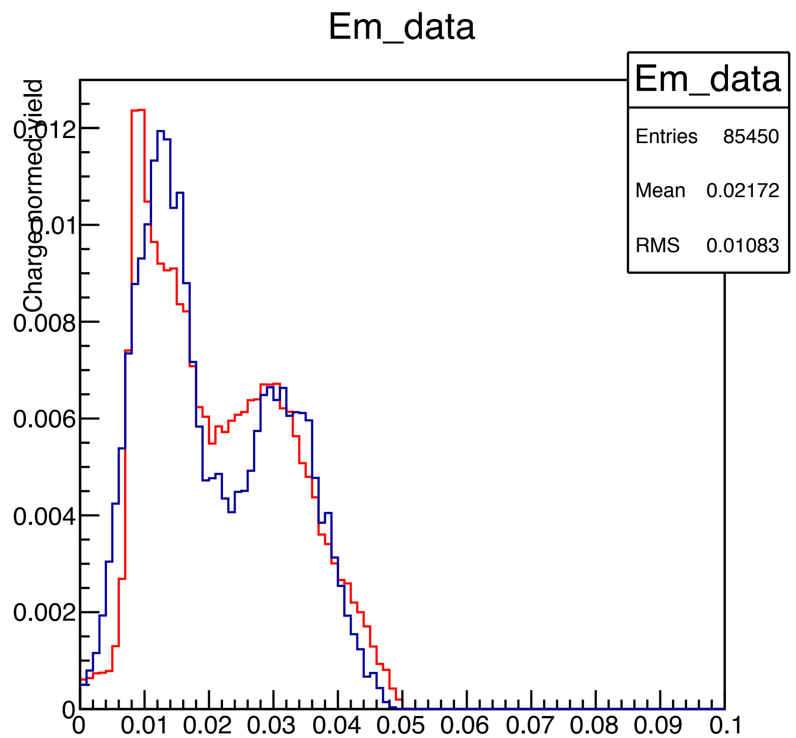
Red: normalized data
Blue: MCEEP

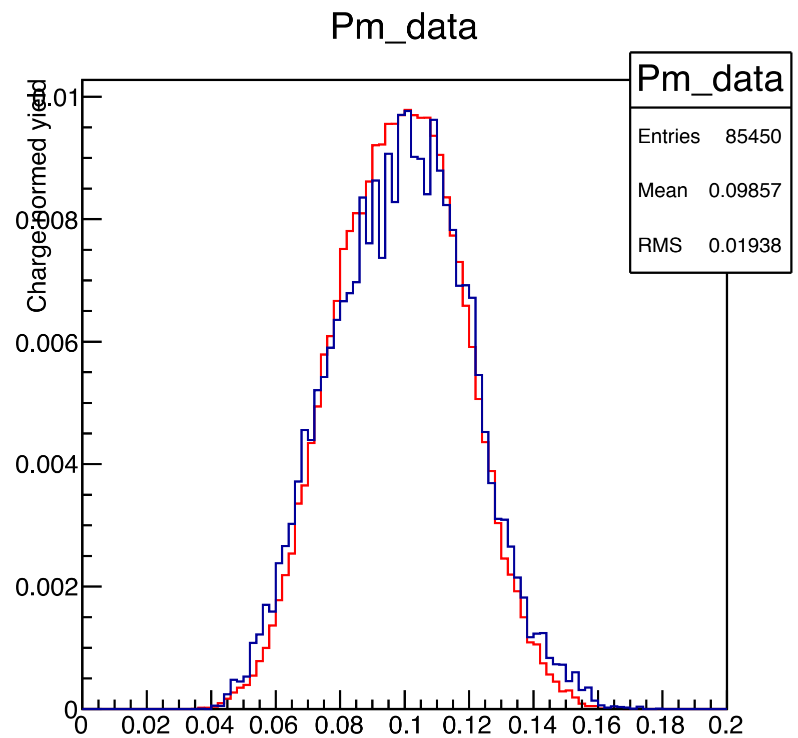


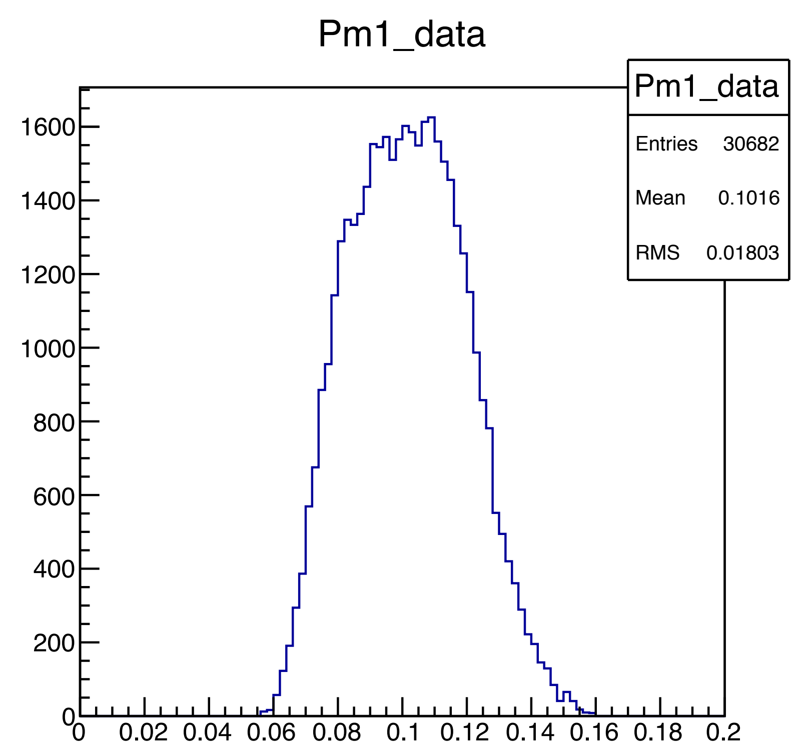
E12-14-012 Exclusive Analysis

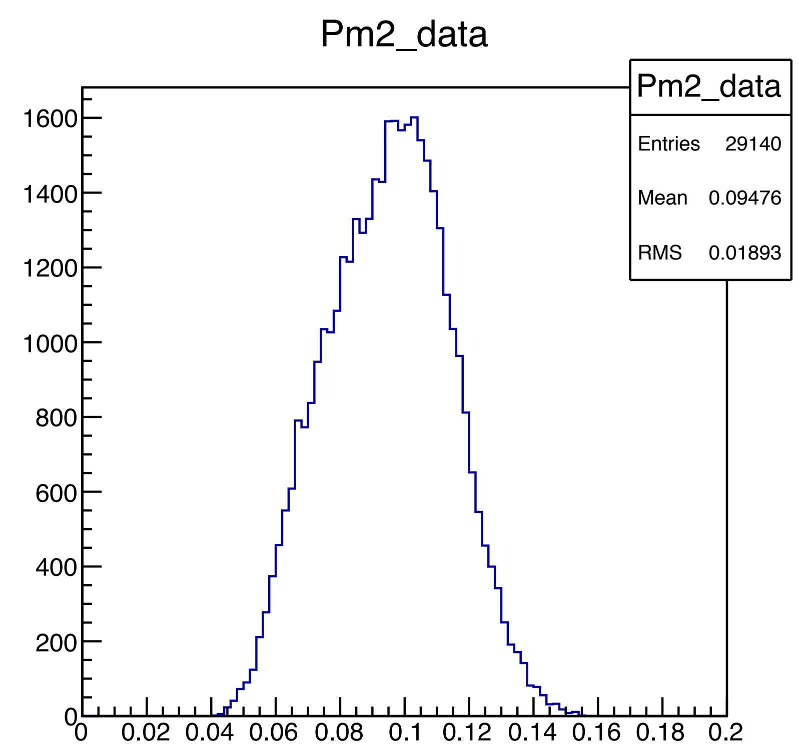


E12-14-012 Exclusive Analysis









E12-14-012 Exclusive Analysis

Whats next for exclusive analysis?

Include FSI in calculations

Isolate shells with cut on E_{miss}

Calculate momentum distribution $n(p)$ for each shell

Repeat everything for titanium!

Special Thanks To:

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MCEEP by P. Ulmer

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