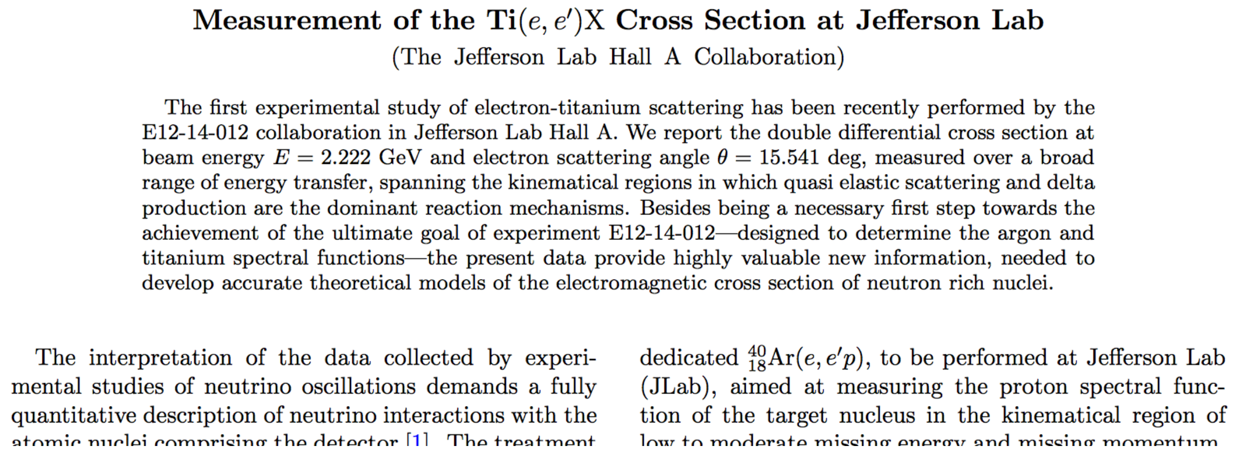
E12-14-012 [Argon Experiment]: Status

First publication draft (prepared to be submitted in PRL) has already been circulated



Measurement of the Ti(e, e')X Cross Section at Jefferson Lab

(The Jefferson Lab Hall A Collaboration)

The first experimental study of electron-titanium scattering has been recently performed by the E12-14-012 collaboration in Jefferson Lab Hall A. We report the double differential cross section at beam energy $E = 2.222$ GeV and electron scattering angle $\theta = 15.541$ deg, measured over a broad range of energy transfer, spanning the kinematical regions in which quasi elastic scattering and delta production are the dominant reaction mechanisms. Besides being a necessary first step towards the achievement of the ultimate goal of experiment E12-14-012—designed to determine the argon and titanium spectral functions—the present data provide highly valuable new information, needed to develop accurate theoretical models of the electromagnetic cross section of neutron rich nuclei.

The interpretation of the data collected by experimental studies of neutrino oscillations demands a fully quantitative description of neutrino interactions with the atomic nuclei comprising the detector [1]. The treatment

dedicated ${}^{40}_{18}$Ar$(e, e'p)$, to be performed at Jefferson Lab (JLab), aimed at measuring the proton spectral function of the target nucleus in the kinematical region of low to moderate missing energy and missing momentum

Vishvas Pandey

(On behalf of the E12-14-012 collaboration)

Center for Neutrino Physics, Virginia Tech,
Blacksburg, Virginia 24061, USA

Hall A Collaboration Meeting, Jan 24-25, JLab, Newport News, VA

E12-14-012: Reminder

- **Primary Goal:** Measurement of the spectral functions of Argon and Titanium through Ar-Ti *(e,e'p)* reactions
  - Data Collected (Feb-March 2017):
    - Ar/Ti/C *(e,e'p)* reactions for five different kinematic set-ups
    - Ar/Ti/C (*e,e'*) reactions for one kinematic set-up

- **Primary Motivation**: To help improve the accuracy of the measurement of the neutrino-oscillation parameters, including the *CP violation in leptonic sector* (one of the top priority of the US particle physics community), in the future neutrino experiments, mainly DUNE, by:
  - Measuring spectral functions of argon nucleus (~ initial momentum and energy distributions of nucleons bound in the argon nucleus) that can directly be used in the reconstruction of neutrino energies (which is currently the major source of uncertainty in neutrino experiments).
  - Using measured argon spectral functions to further develop (extend) a fully consistent parameter-free theoretical (neutrino-nucleus) model that can be used in (every step of) the analysis of neutrino experiments.

More details in following slides…

Accelerator-based neutrino-oscillation experiments

Current Knowledge:

	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}
Normal Ordering	$33.56^{+0.77}_{-0.75}$	$8.46^{+0.15}_{-0.15}$	$41.6^{+1.5}_{-1.2}$	$7.50^{+0.19}_{-0.17}$	$2.524^{+0.039}_{-0.040}$	261^{+51}_{-59}
Inverted Ordering	$33.56^{+0.77}_{-0.75}$	$8.49^{+0.15}_{-0.15}$	$50.0^{+1.1}_{-1.4}$	$7.50^{+0.19}_{-0.17}$	$-2.514^{+0.038}_{-0.041}$	277^{+40}_{-46}

arXiv:1706.03621 [hep-ph]

Current and Future Goals:

- Establish whether there is CP violation in the lepton sector and, if so, measure δ_{CP}
- Improve the accuracy on θ_{23}
- Determine the neutrino mass ordering: $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$

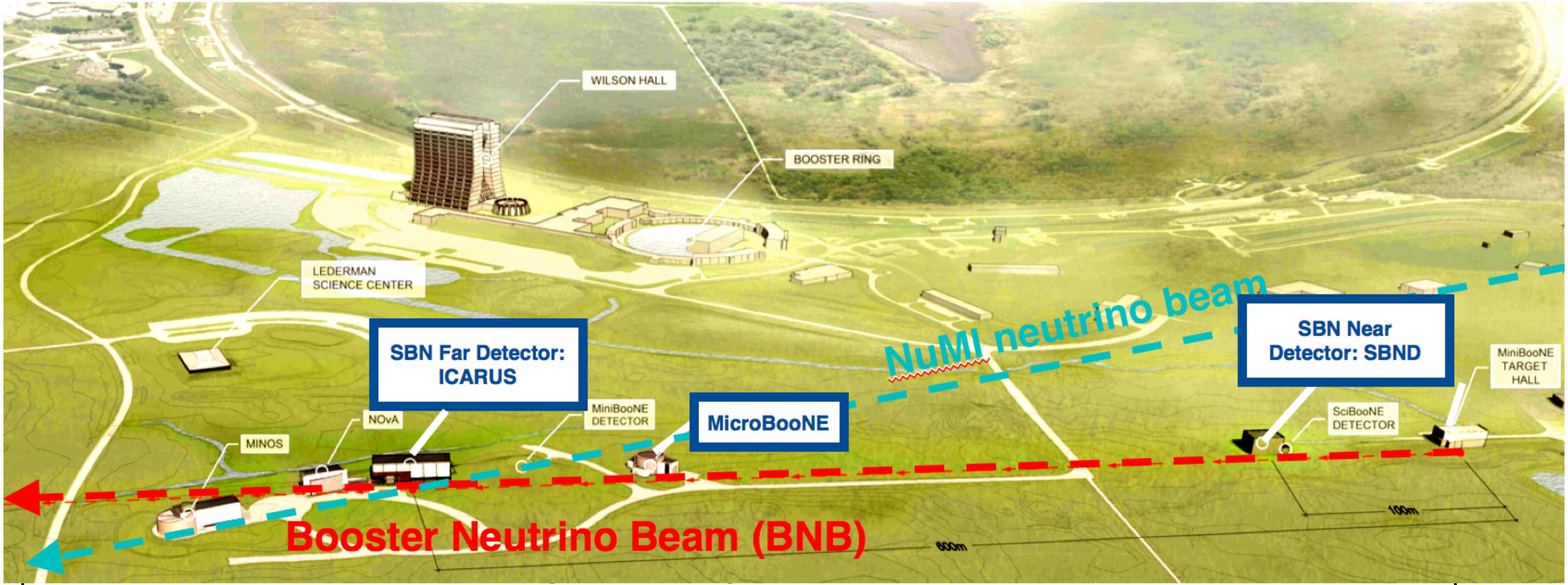
Current and Future Experiments:

- **MiniBooNE** (concluded, re-running), **NOvA** (running), **T2K** (running), **T2HK** (under construction), etc.
- **SBN Program: MicroBooNE** (running), **ICARUS** (under construction), **SBND** (under construction)
- **DUNE** (under construction)

LArTPC

Accelerator-based neutrino-oscillation experiments

	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}

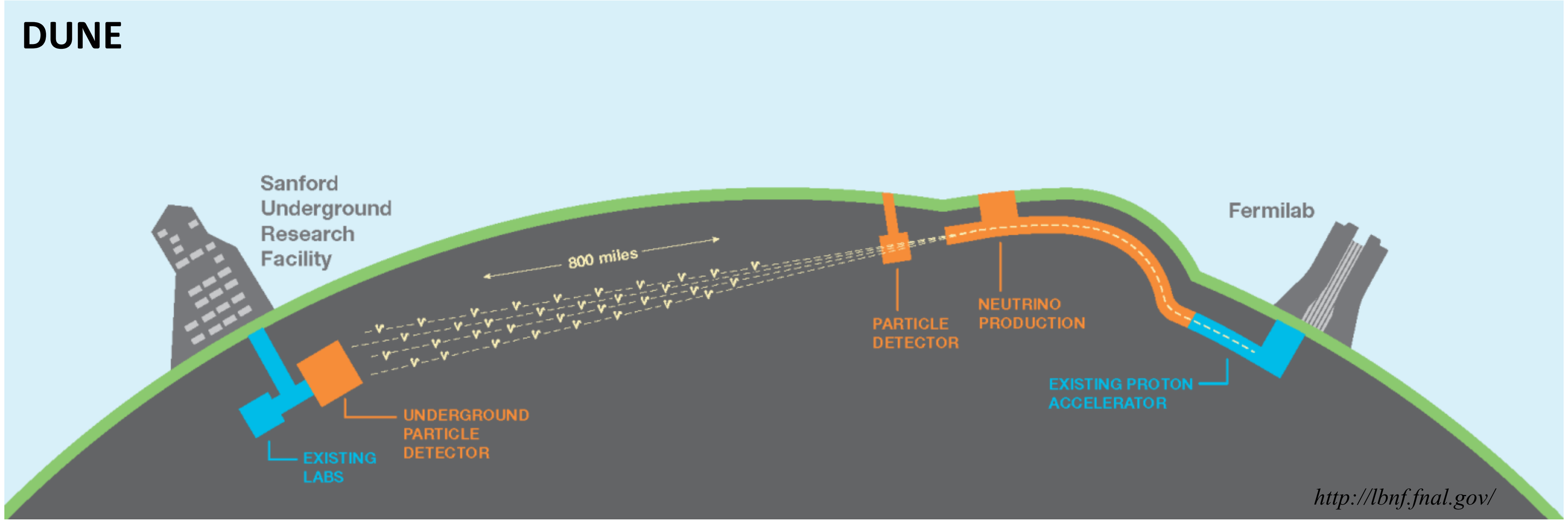


- **SBN Program: MicroBooNE** (running), **ICARUS** (under construction), **SBND** (under construction)
- **DUNE** (under construction)

LArTPC

Accelerator-based neutrino-oscillation experiments

DUNE



http://lbnf.fnal.gov/

Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

*two neutrino flavors, for simplicity

- Experiments measure event rates which, for a given observable topology, can be naively computed as:

Event Rate at near detector:

$$N^{\alpha}_{\rm ND}(\boldsymbol{p}_{\rm reco}) = \sum_i \phi_\alpha(E_{\rm true}) \times \sigma^i_\alpha(\boldsymbol{p}_{\rm true}) \times \epsilon_\alpha(\boldsymbol{p}_{\rm true}) \times R_i(\boldsymbol{p}_{\rm true};\boldsymbol{p}_{\rm reco})$$

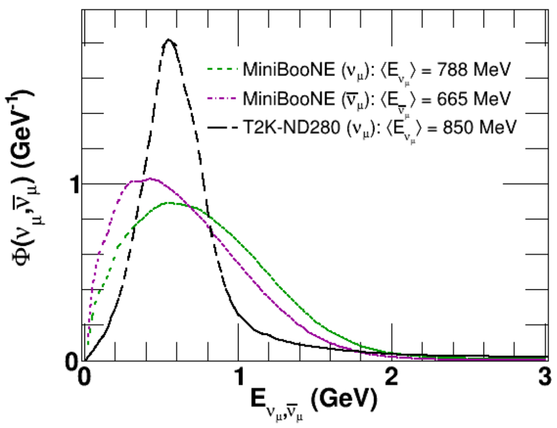
Event Rate at far detector:

$$N^{\alpha\to\beta}_{\rm FD}(\boldsymbol{p}_{\rm reco}) = \sum_i \phi_\alpha(E_{\rm true}) \times P_{\alpha\beta}(E_{\rm true}) \times \sigma^i_\beta(\boldsymbol{p}_{\rm true}) \times \epsilon_\beta(\boldsymbol{p}_{\rm true}) \times R_i(\boldsymbol{p}_{\rm true};\boldsymbol{p}_{\rm reco})$$

Event Rate at far detector:

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}};\boldsymbol{p}_{\mathrm{reco}}):$$

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

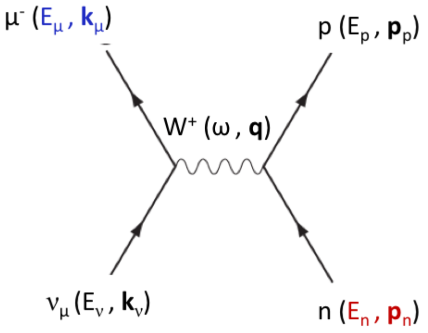

Neutrino energy distribution

Neutrino Energy: Reconstruction

- For CCQE process (assuming single nucleon knock out), The reconstructed neutrino energy is

$$E_\nu = \frac{m_p^2 - m_\mu^2 - E_n{}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n{}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu|\cos\theta_\mu - |\mathbf{p}_n|\cos\theta_n)}$$

where $|k_\mu|$ and θ_μ are measured, while p_n and E_n are the unknown momentum and energy of the interacting neutron.


CCQE process

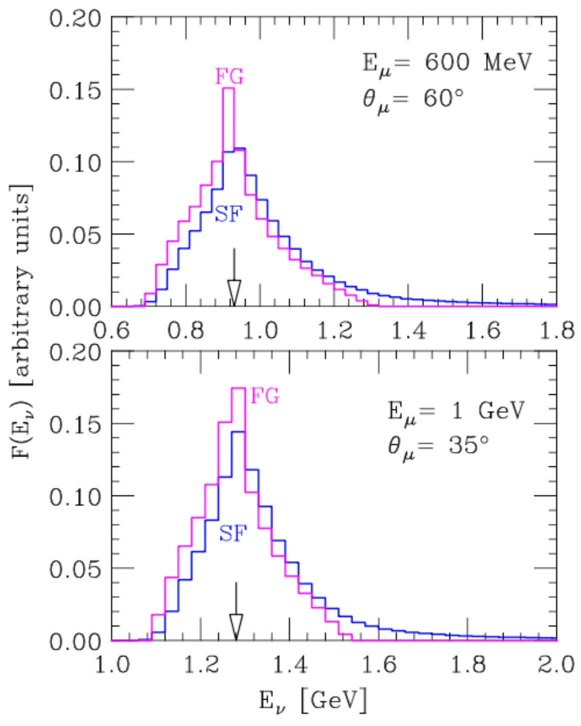
- Existing simulation codes routinely use $|p_n| = 0$, $E_n = m_n - \varepsilon$, with $\varepsilon \sim 20$ MeV for carbon and oxygen, or the Fermi gas (FG) model.

Event Rate at far detector:

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}};\boldsymbol{p}_{\mathrm{reco}});$$

$$P(\nu_i \to \nu_j) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Neutrino Energy: Reconstruction

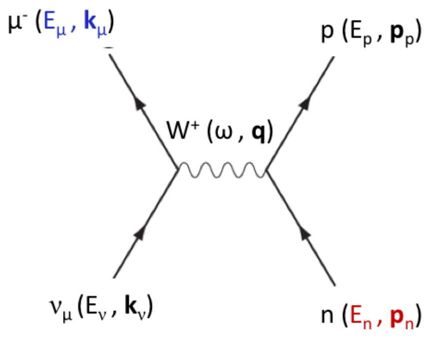


O. Benhar

- For CCQE process (assuming single nucleon knock out), The reconstructed neutrino energy is

$$E_\nu = \frac{m_p^2 - m_\mu^2 - E_n{}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n{}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu|\cos\theta_\mu - |\mathbf{p}_n|\cos\theta_n)}$$

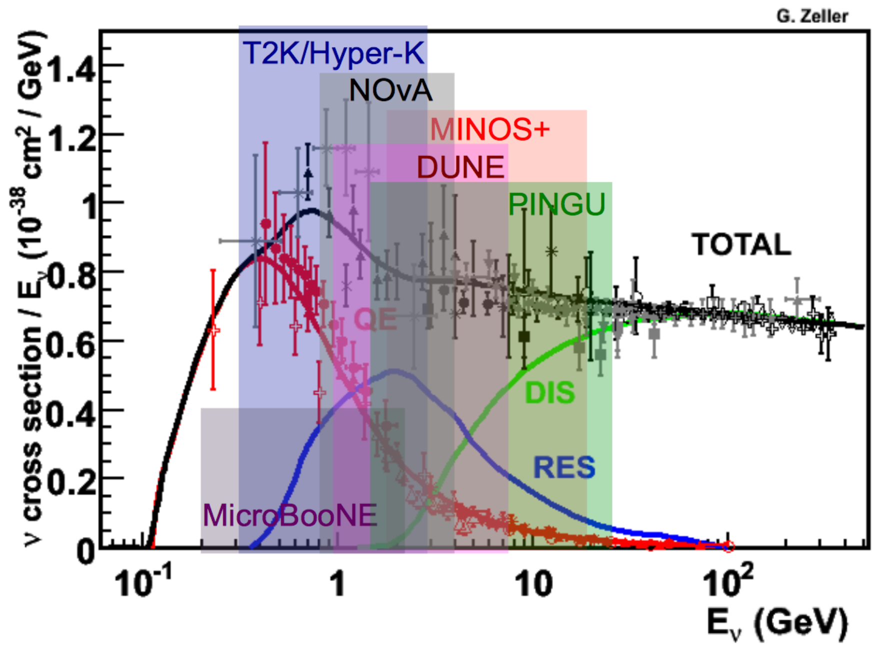
- Neutrino energy reconstructed using 2 ×10^4 pairs of (|p|, E) values sampled from realistic (SF) and FG oxygen spectral functions.
- The average value ⟨E_ν⟩ obtained from the realistic spectral function turns out to be shifted towards larger energy by ~ 70 MeV.

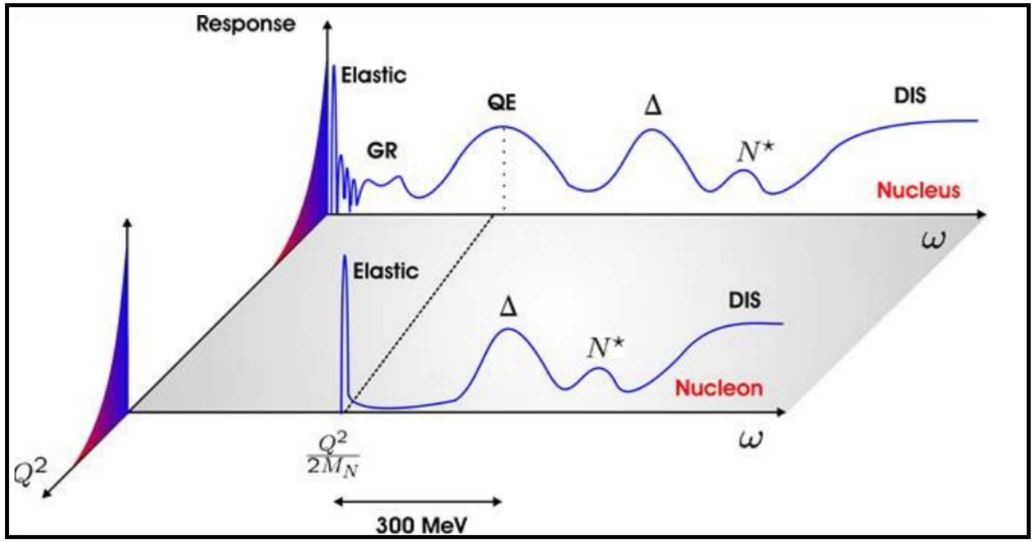


Event Rate at far detector:

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma^i_\beta(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}};\boldsymbol{p}_{\mathrm{reco}});$$

Neutrino-nucleus cross section

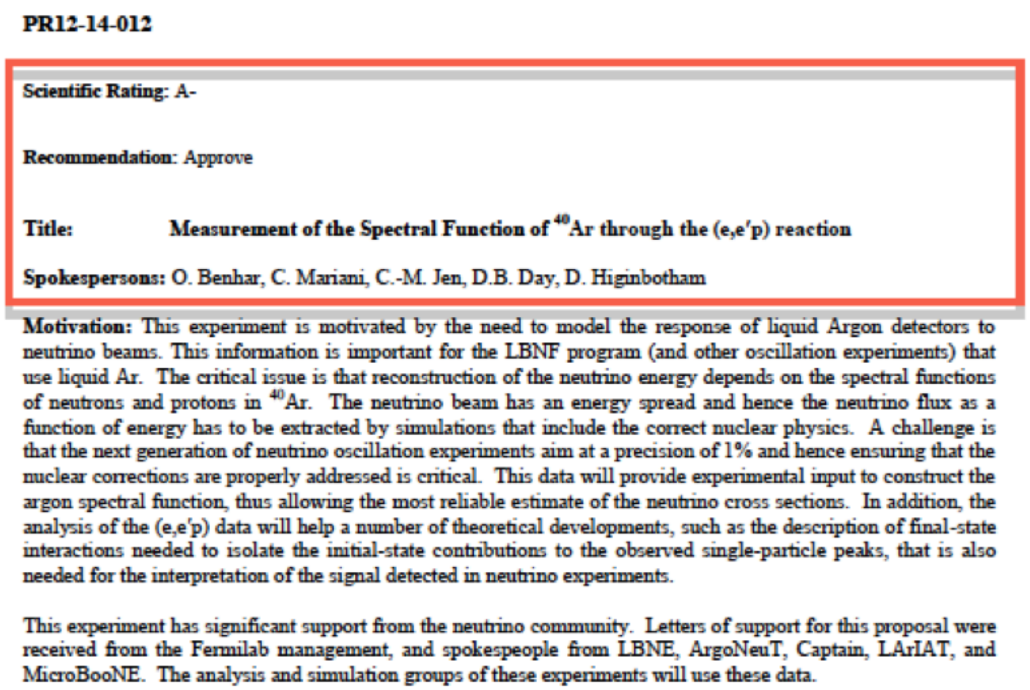




- Need realistic nuclear model (in Monte-Carlo simulations) that can describe neutrino-nucleus cross sections over a wide range of energies.

- To achieve an accuracy comparable to that required for precise neutrino experiments a high statistics electron - ^{40}Ar scattering data is needed!

Jefferson Lab Experiment E12-14-012 in Hall A



PR12-14-012

Scientific Rating: A-

Recommendation: Approve

Title: **Measurement of the Spectral Function of ^{40}Ar through the (e,e′p) reaction**

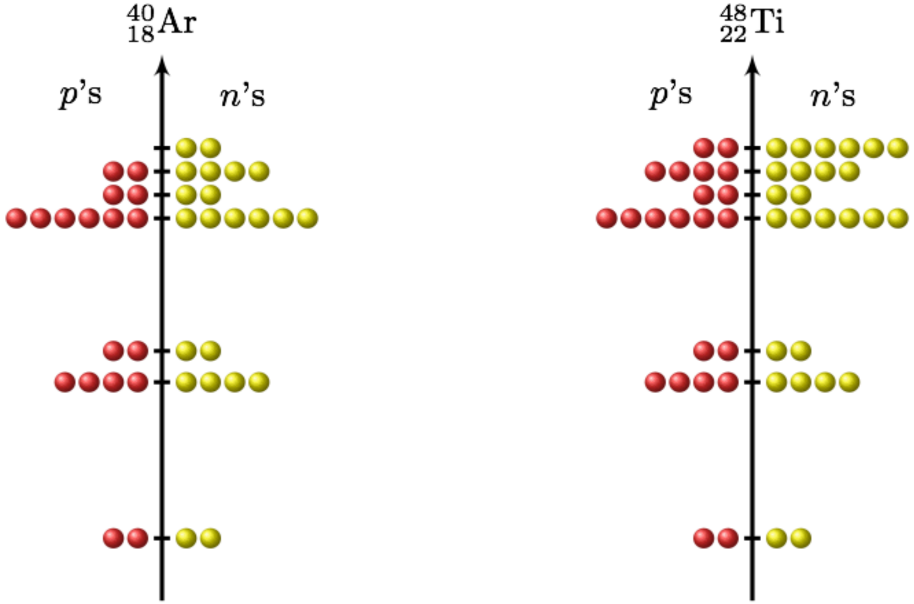
Spokespersons: O. Benhar, C. Mariani, C.-M. Jen, D.B. Day, D. Higinbotham

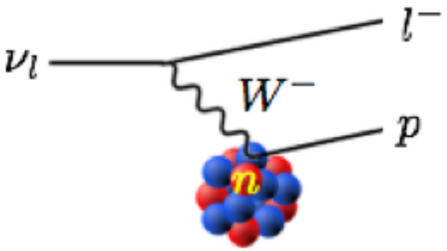
Motivation: This experiment is motivated by the need to model the response of liquid Argon detectors to neutrino beams. This information is important for the LBNF program (and other oscillation experiments) that use liquid Ar. The critical issue is that reconstruction of the neutrino energy depends on the spectral functions of neutrons and protons in ^{40}Ar. The neutrino beam has an energy spread and hence the neutrino flux as a function of energy has to be extracted by simulations that include the correct nuclear physics. A challenge is that the next generation of neutrino oscillation experiments aim at a precision of 1% and hence ensuring that the nuclear corrections are properly addressed is critical. This data will provide experimental input to construct the argon spectral function, thus allowing the most reliable estimate of the neutrino cross sections. In addition, the analysis of the (e,e'p) data will help a number of theoretical developments, such as the description of final-state interactions needed to isolate the initial-state contributions to the observed single-particle peaks, that is also needed for the interpretation of the signal detected in neutrino experiments.

This experiment has significant support from the neutrino community. Letters of support for this proposal were received from the Fermilab management, and spokespeople from LBNE, ArgoNeuT, Captain, LArIAT, and MicroBooNE. The analysis and simulation groups of these experiments will use these data.

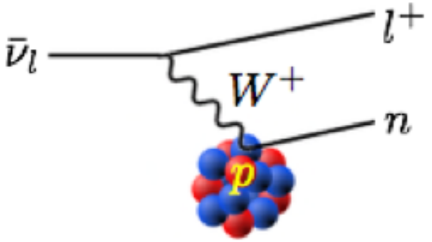
Why Titanium?

- The reconstruction of neutrino and antineutrino energy in liquid argon detectors will require the understanding of the spectral functions describing both neutrons and protons.
- Exploiting the correspondence of the level structures, the neutron spectral function of argon can be obtained from the proton spectral function of titanium.



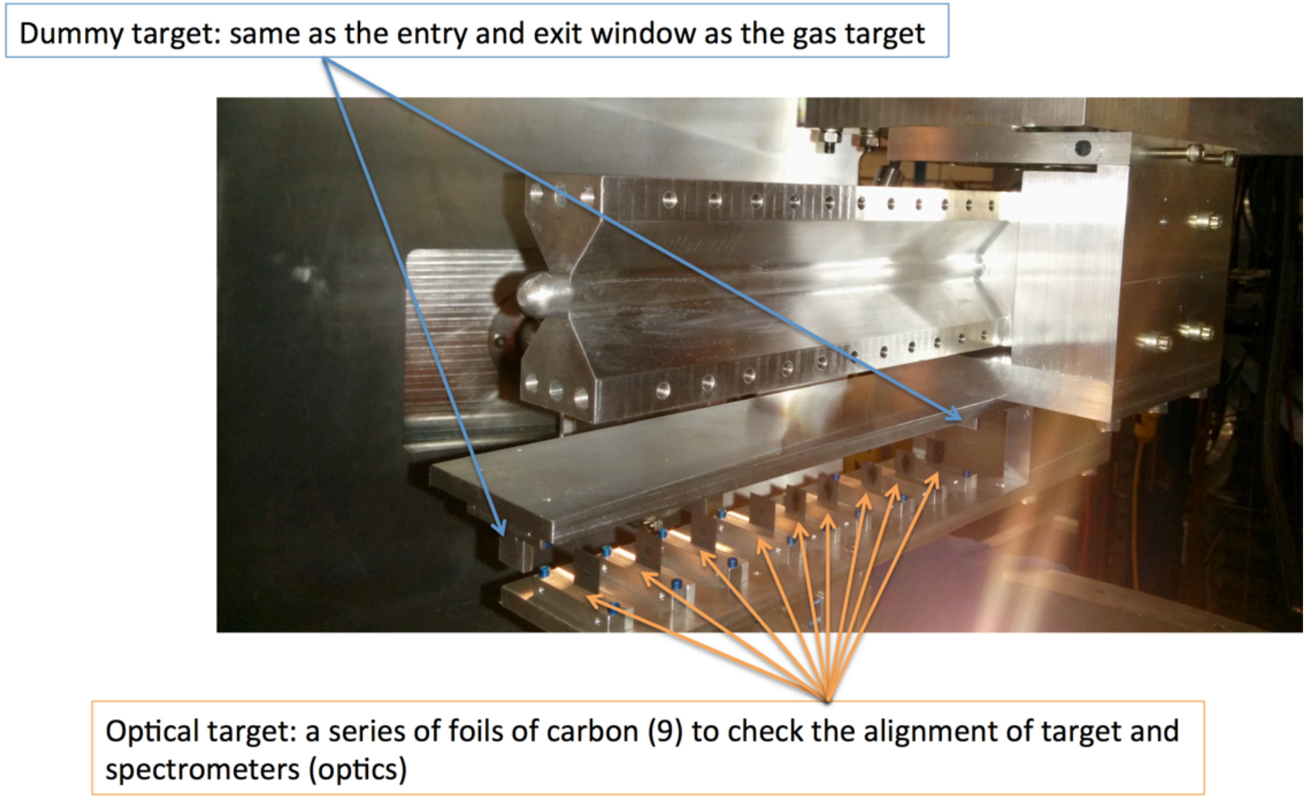


$$\nu_l + n \rightarrow l^- + p$$



$$\bar{\nu}_l + p \rightarrow l^+ + n$$

Target setups

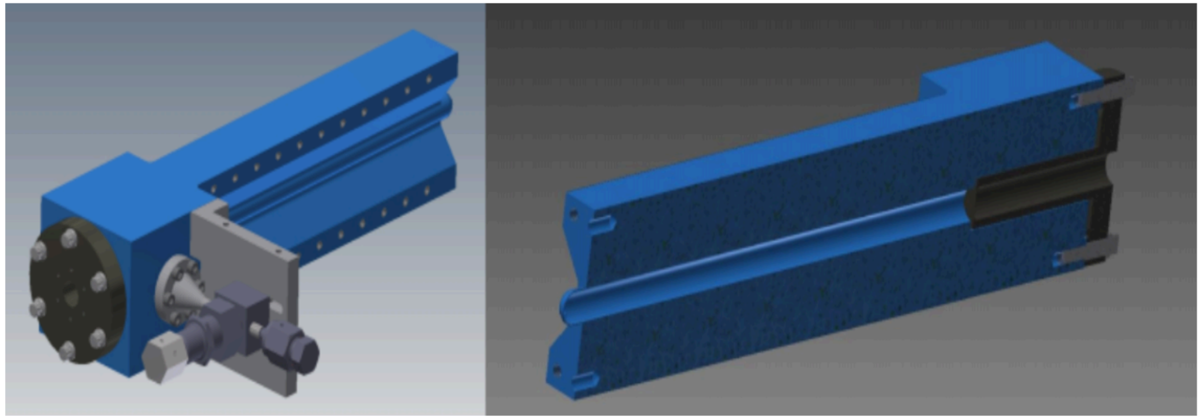


Dummy target: same as the entry and exit window as the gas target

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

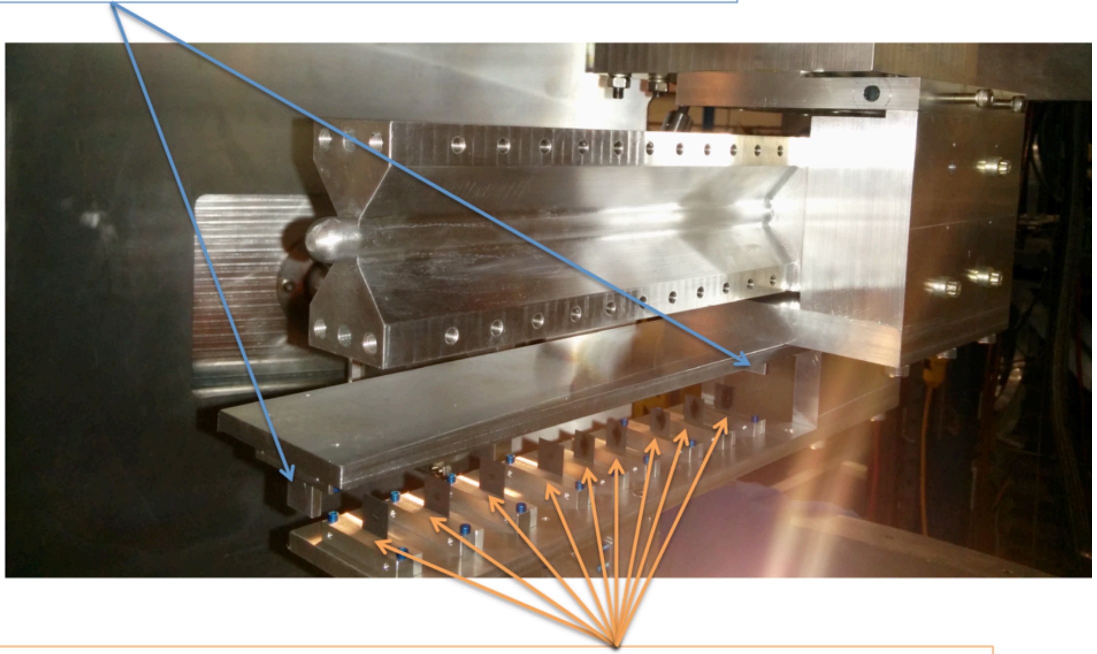
Ar Target

- Gas Cell
- Length = 25 cm
- Pressure = 500 PSI
- Temperature = 300 K.
- Target thickness = 1.381 g cm^{-2}
- Luminosity = 4.33×10^{37} atoms $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$.



Target setups

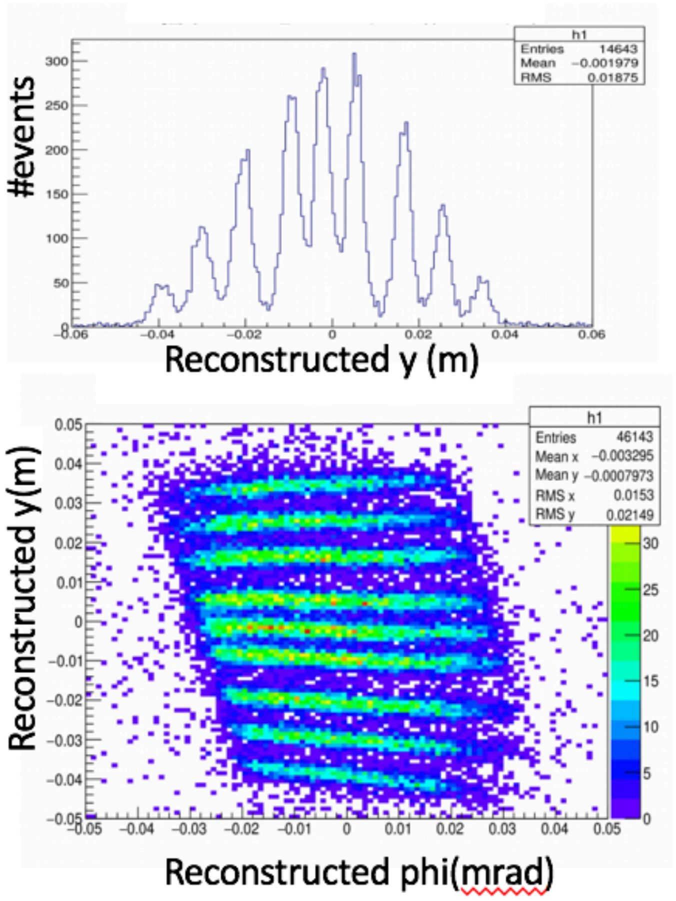
Dummy target: same as the entry and exit window as the gas target



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

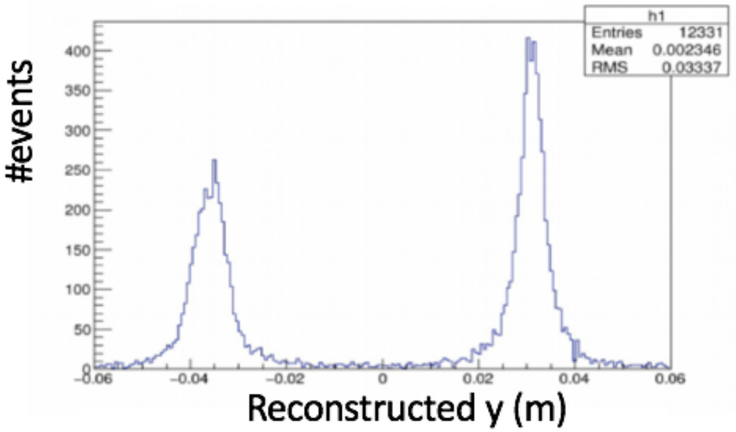
Multiple foil:

LEFT



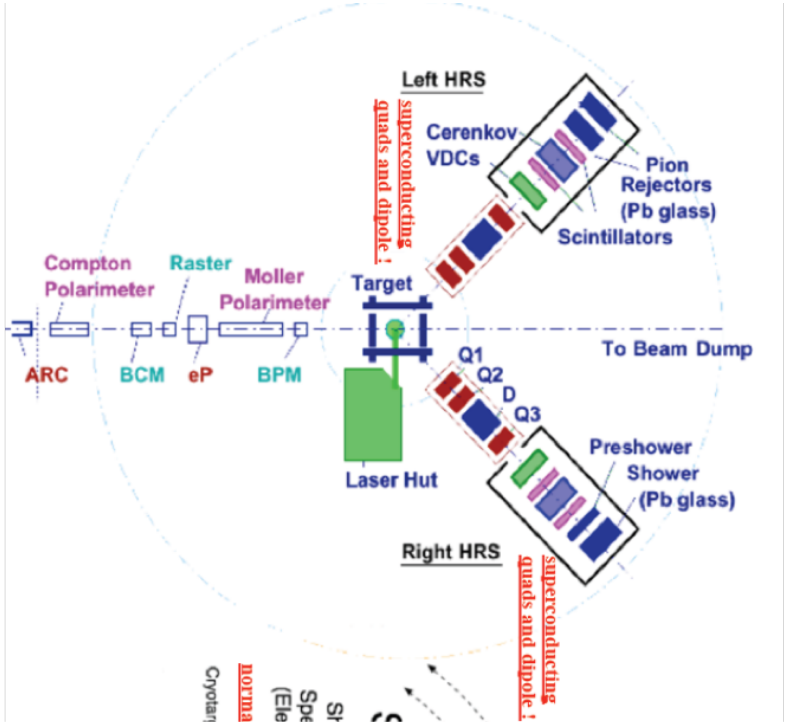
Dummy:

Left



Kinematic setups

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



kin1

Collected Data	Hours	Events (k)
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

kin3

Collected Data	Hours	Events (k)
Ar	13.5	73176
Ti	8.6	28423
Dummy	0.6	2948

kin2

Collected Data	Hours	Events(k)
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

kin4

Collected Data	Hours	Events(k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

kin5

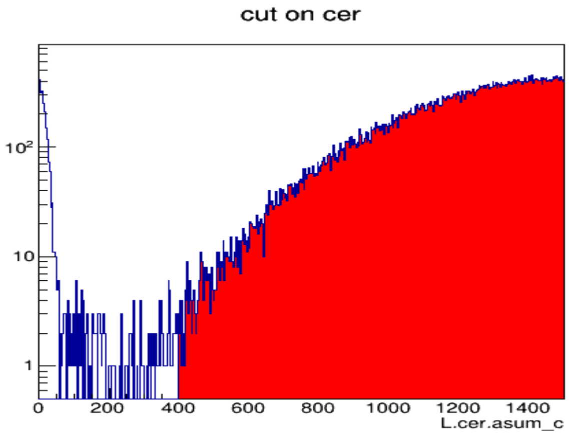
Collected Data	Hours	Events (k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

kin5 - Inclusive

Collected Data	Minutes	Events (k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

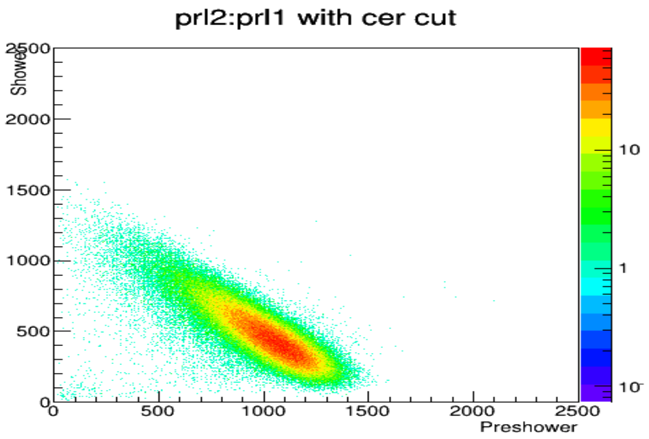
C(e,e’) Analysis:

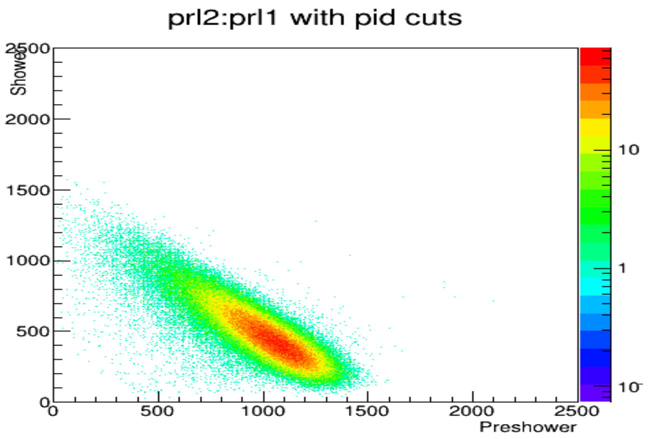
- **Particle Identification and Electron Selection**



Cerenkov cut: cer > 400

Calorimeter cut: E/p > 0.3





- Charge symmetric background

- e$^-$ from pair production caused by different processes.
- We did not take any positive polarity (positron data) because there should be negligible contamination at our kinematics.
- We associate a preliminary ~ 0.5% uncertainty (we are checking the size of this BG) due to charge symmetric background?

- Pion contamination

- Negligible

C(e,e’) Analysis:

VDC efficiency

- Non-zero track ratio: R1
  - Cut1: Trigger, PID cut
  - $R1 = \frac{N_{track>0}}{N_{sample1}}$
- One track ratio: R2
  - Cut2: Trigger, PID cut, acceptance cut
  - $R2 = \frac{N_{track==1 \&\& \text{y within } 5\sigma}}{N_{sample2}}$
- Efficiency=R1*R2 ~ 95 %

Calorimeter cut efficiency

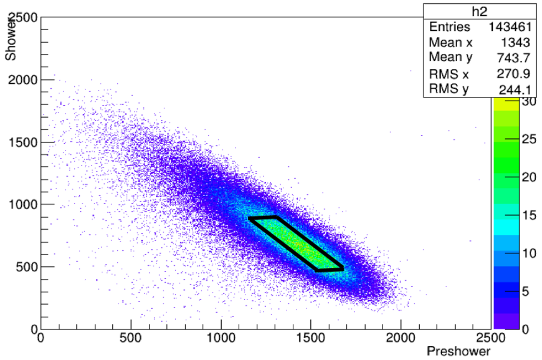
- Set cut as E/p0 > 0.3
- Select Sample events
  - T3 (S0&&S2)&&(GC||PR)
  - Single track
  - Acceptance cuts
  - Cerenkov cut
- $\epsilon = \frac{\#events\ with\ E/p0>0.3}{\#sample\ events}$
- Efficiency ~ 99.9 %

Trigger Efficiency

- Production trigger: T3: (S0&&S2) && (GC||PR) [LEFT]
- Efficiency trigger: T5: (S0||S2) && (GC||PR) [LEFT]
- Selected Sample
  - T5
  - Single track cut
  - Acceptance Cuts
  - PID Cuts
- $Eff = \frac{\#events\ with\ signal\ on\ both\ S0\ and\ S2}{\#sample\ events}$ ~ 99.9 %

Cerenkov cut efficiency

- Negligible pion contamination, cer cut at 400
- Select Sample events
  - T3 (S0&&S2)&&(GC||PR)
  - Single track
  - Acceptance cuts
  - Calorimeter cut
- $\epsilon = \frac{\#events\ with\ cer>400}{\#sample\ events}$ ~ 99.9%



Inclusive cross section extraction:

- **Yield ratio method:**

For ith bin:

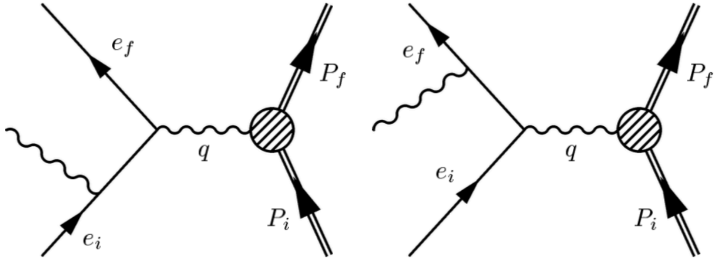
$$\boxed{{\sigma^{i}}_{data} = {\sigma^{i}}_{model} \frac{{Y^{i}}_{data}(E', \theta)}{{Y^{i}}_{MC}(E', \theta)}}$$

Where,

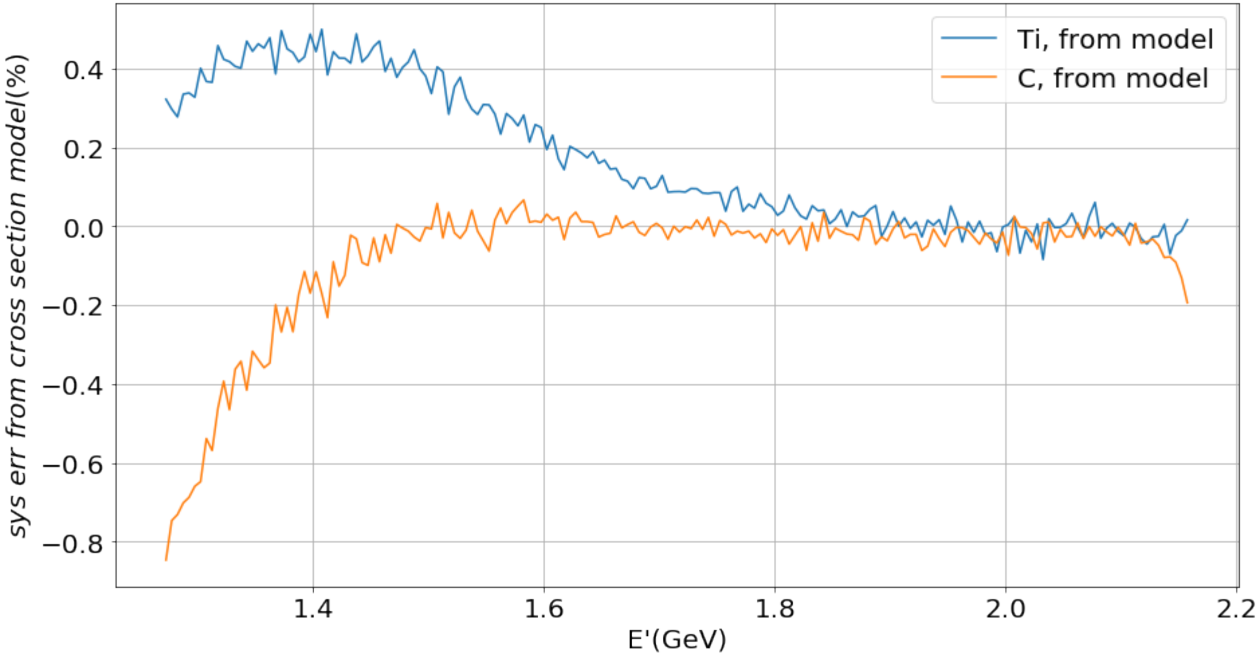
$${Y^{i}}_{data} = \frac{N_s^i * prescale}{N_e * (live\ time) * \epsilon_{eff}}$$

N_s^i : Number of scattered electrons
N_e : Total number of electrons in the beam
ϵ_{eff} : Total efficiency

Radiative Corrections



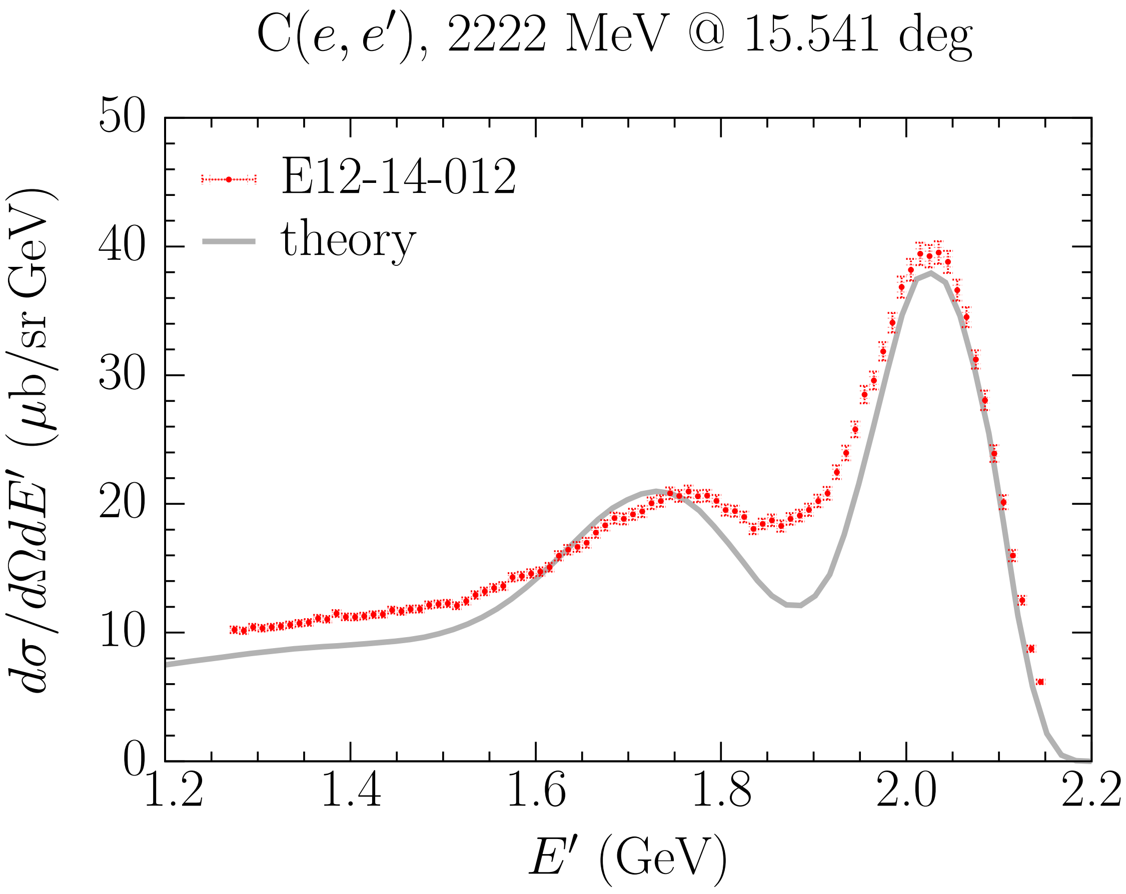
- Using the peaking approximation method of Mo and Tsai
- To determine the systematic uncertainty - scale the model by √(Q^2/2) and recalculate the correction factor.
- We associated systematic uncertainty ~ 1% due to radiative correction.



- **C(e,e’) cross section:**

  - The carbon data allowed us to study systematics and to compare our measurements with the previous experiments.

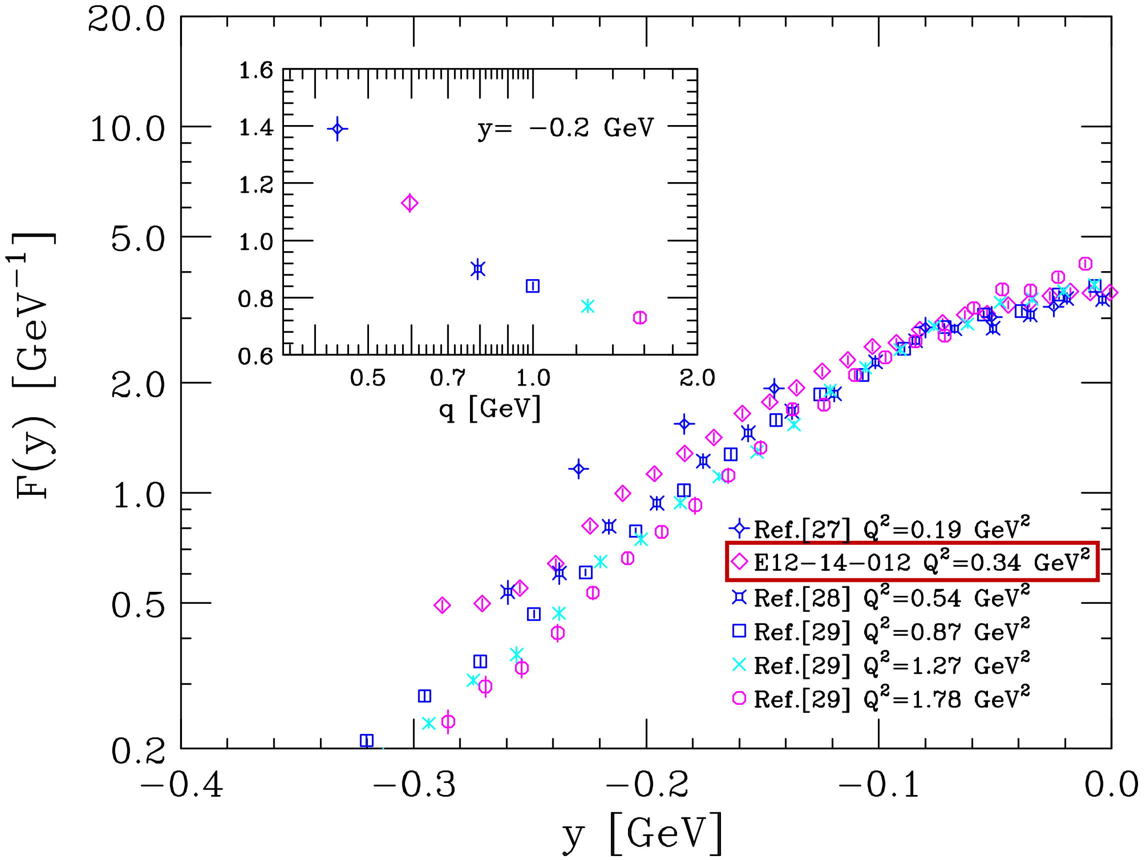
    - Uncertainty < 3.18 % - including both the statistical and systematic added in quadrature (and treated as fully uncorrelated).
    - **Theoretical** calculations *[Benhar et al.] are* based on the factorization ansatz dictated by the impulse approximation (IA) and the spectral function formalism. The approach does not involve any adjustable parameters, and allows for a consistent inclusion of single-nucleon interactions—both elastic and inelastic—and meson-exchange current (MEC) contributions.



C(e,e') measurements in comparison to previous data

- The y-scaling function, F(y), obtained from the cross section measured by the E12-14-012 experiment to those obtained from the previous data spanning a kinematical range corresponding to $0.20 \lesssim Q^2 \lesssim 1.8$ GeV^2.

  - At $y \approx 0$, the data exhibit a remarkable scaling behavior corresponding to $\omega \approx Q^2/2M$.
  - At large negative values of *y*, a sizable scaling violations, to be mainly ascribed to FSI, are observed.
  - The F(y) as a function of q, at y = −0.2 GeV, demonstrates that in the kinematical setup of our experiment, corresponding to $|q| \approx 600$ MeV, the effects of FSI are still significant.
  - Our results are fully consistent with those of previous experiments.



[27] J. S. O'Connell et al., Phys. Rev. C 35, 1063 (1987).
[28] R. M. Sealock et al, Phys. Rev. Lett. 62, 1350 (1989).
[29] D. B. Day et al, Phys. Rev. C 48, 1849 (1993).

Ti(e,e') Analysis:

- We used the same definitions and cuts as in carbon *[note: both measurements are performed at the same kinematics]*

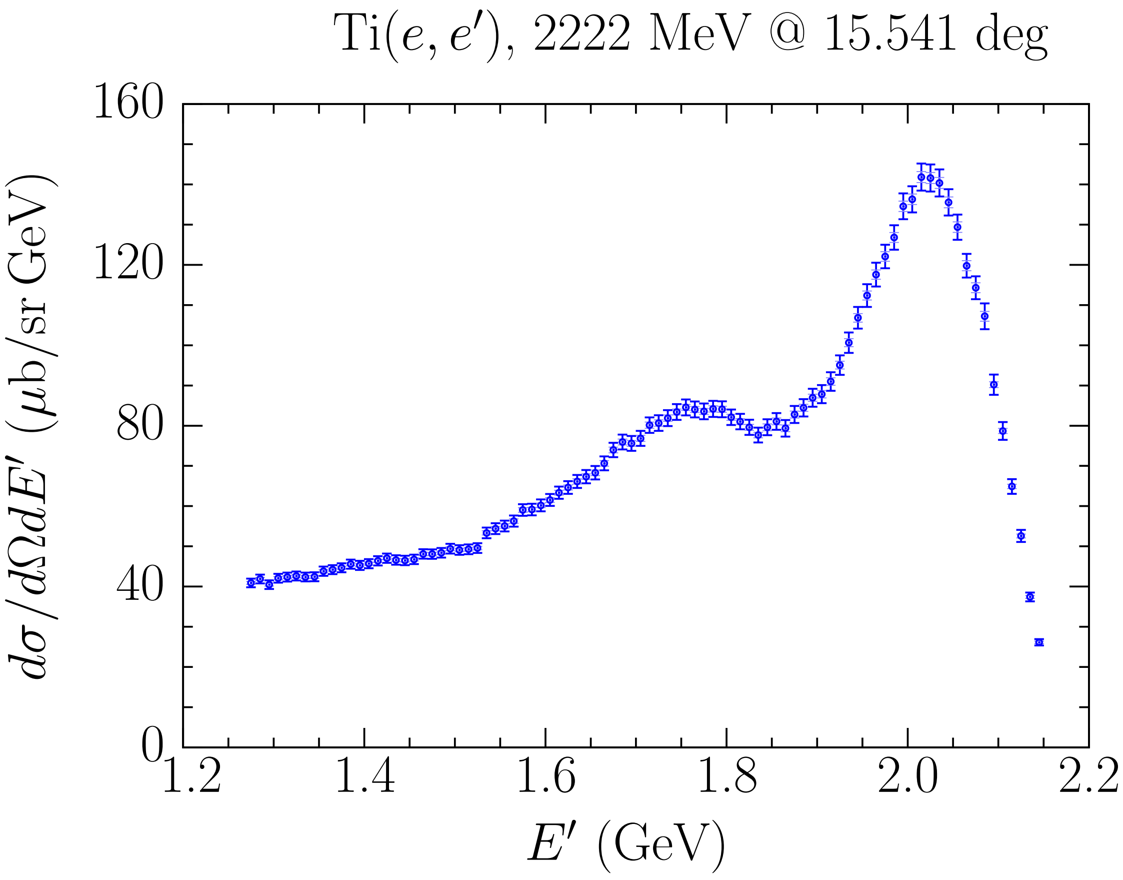
- In the absence of any previous e-Ti cross section studies (no MC model), we determine the Ti(e,e') cross section using the ratio of luminosity (per density) normalized yields with respect to carbon

$$\sigma_{Ti}=\frac{Y(Ti)}{Y(C)}*\frac{Density(C)}{Density(Ti)}*\sigma_{C}(measured)$$

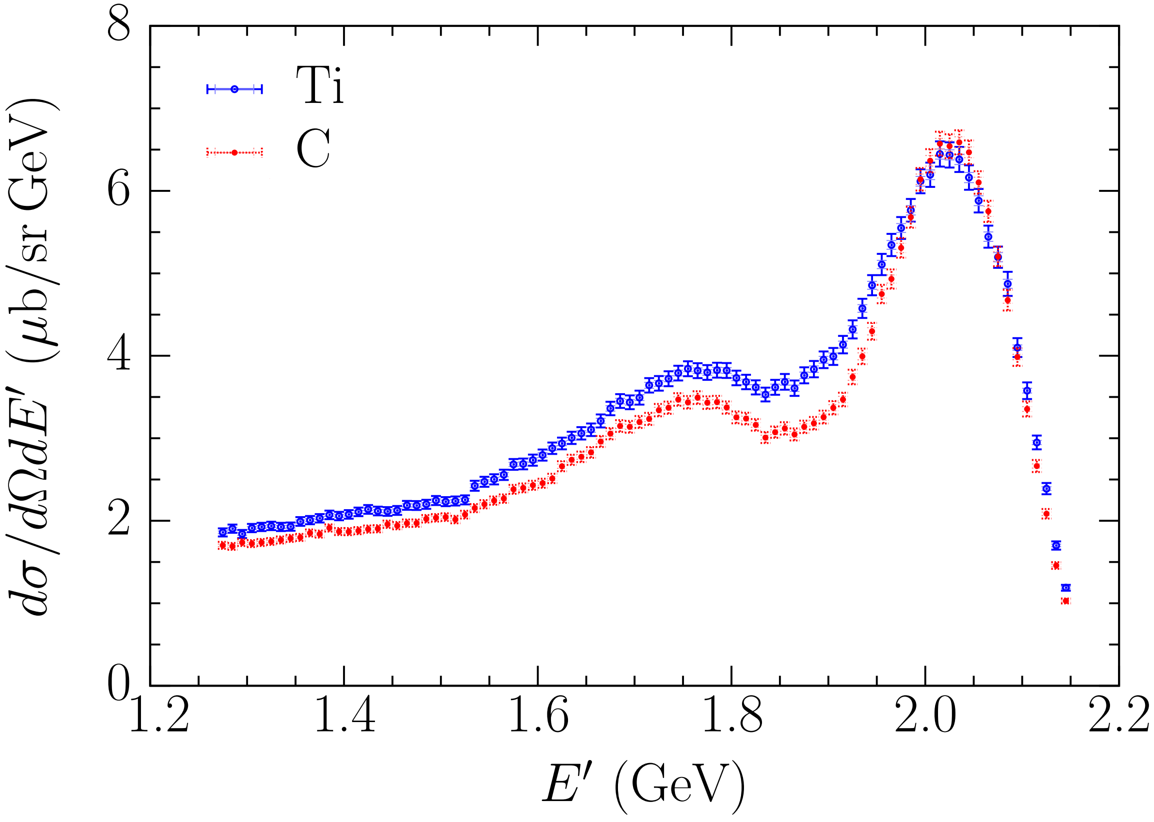
- We used a data driven approach for the systematic evaluations on Ti, exploiting the high precision carbon data collected in the same kinematics and using the same phase-space regions.

- **Ti(e,e’) cross section:**
  - The first electron-scattering data ever collected on titanium target.

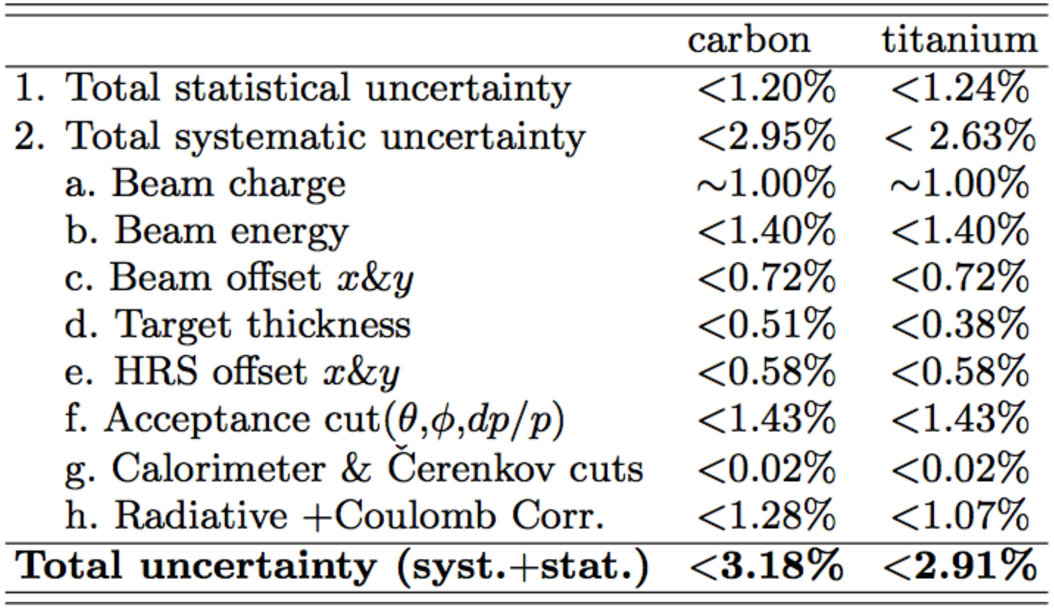
    - The total uncertainty (syst.+stat.) on the cross section is up to < 2.9%.



- **Ti(e,e’) vs C(e,e’) cross sections (per proton):**



- **Uncertainties in the cross sections**

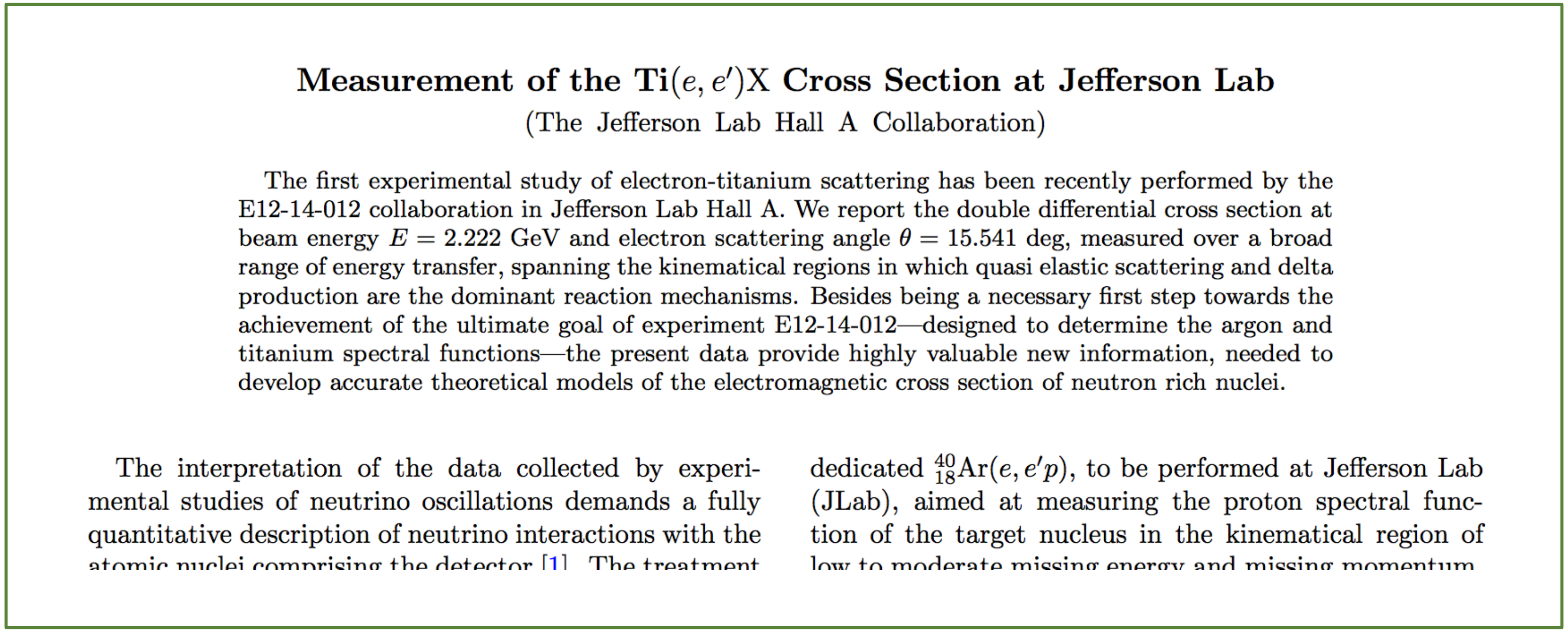


	carbon	titanium
1. Total statistical uncertainty	<1.20%	<1.24%
2. Total systematic uncertainty	<2.95%	< 2.63%
a. Beam charge	~1.00%	~1.00%
b. Beam energy	<1.40%	<1.40%
c. Beam offset $x\&y$	<0.72%	<0.72%
d. Target thickness	<0.51%	<0.38%
e. HRS offset $x\&y$	<0.58%	<0.58%
f. Acceptance cut(θ,ϕ,dp/p)	<1.43%	<1.43%
g. Calorimeter & Čerenkov cuts	<0.02%	<0.02%
h. Radiative +Coulomb Corr.	<1.28%	<1.07%
Total uncertainty (syst.+stat.)	**<3.18%**	**<2.91%**

- Statistical uncertainty include target density, detector and trigger efficiencies, DAQ live- time, VDC one-track efficiency and charge-symmetry background.

First Results: Measurement of the Ti(e,e')X and C(e,e')X Cross Section at E = 2.222 GeV, θ = 15.541 deg

- Publication draft, prepared to be submitted to PRL, is currently under collaboration review



Measurement of the Ti(e, e')X Cross Section at Jefferson Lab

(The Jefferson Lab Hall A Collaboration)

The first experimental study of electron-titanium scattering has been recently performed by the E12-14-012 collaboration in Jefferson Lab Hall A. We report the double differential cross section at beam energy $E = 2.222$ GeV and electron scattering angle $\theta = 15.541$ deg, measured over a broad range of energy transfer, spanning the kinematical regions in which quasi elastic scattering and delta production are the dominant reaction mechanisms. Besides being a necessary first step towards the achievement of the ultimate goal of experiment E12-14-012—designed to determine the argon and titanium spectral functions—the present data provide highly valuable new information, needed to develop accurate theoretical models of the electromagnetic cross section of neutron rich nuclei.

The interpretation of the data collected by experimental studies of neutrino oscillations demands a fully quantitative description of neutrino interactions with the atomic nuclei comprising the detector [1]. The treatment

dedicated $^{40}_{18}$Ar$(e, e'p)$, to be performed at Jefferson Lab (JLab), aimed at measuring the proton spectral function of the target nucleus in the kinematical region of low to moderate missing energy and missing momentum

- *Special credit to graduate students - Hongxia Dai (VTech), Matt Murphy (VTech), and Daniel Abrams (UVA) - for performing this analysis.*

Summary

- During Feb-March 2017, we completed collecting (e,e’p) and (e,e’) data on Ar, Ti and C targets.
- The first results, inclusive Ti and C cross sections at E = 2.222 GeV and θ = 15.541 deg, with uncertainties ~ 3%, are nearly ready for submission to PRL.
- Next step: We are already working on the analysis of inclusive cross section on Ar and Al, will be ready for publication in March/April 2018.