Measurement of the spectral function of Argon and Titanium through the (e,e'p) reaction

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Outline

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  - Spectral functions
  - Jefferson Lab Hall A
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- Experiment
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  - Target configurations
- Data Analysis
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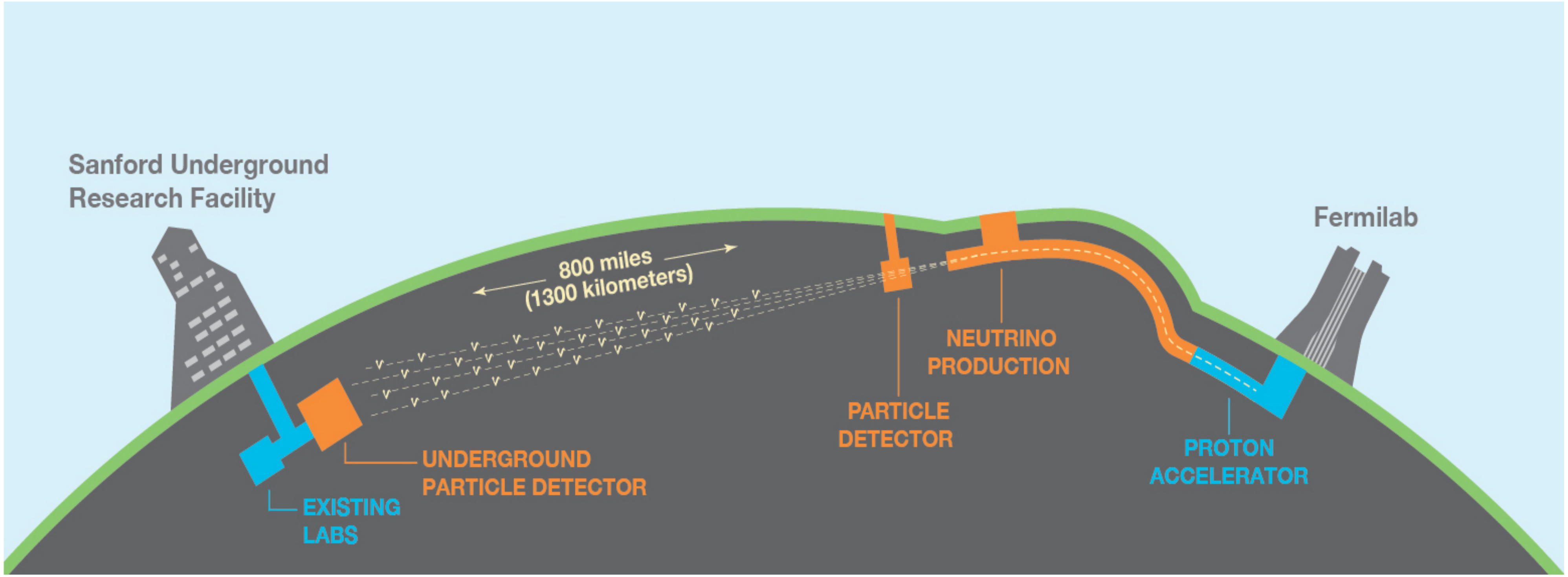
  - Analysis methods
  - Background from target cell
  - Boiling study
  - Results
- Summary

Motivation: Accelerator-based neutrino-oscillation experiments



Deep Underground Neutrino Experiment (**DUNE**)

- DUNE will use Liquid Argon Time-Projection Chamber (LArTPC) detector

<u>Current and Future Experiments:</u>

- MiniBooNE (re-running), NOvA (running), T2K (running), etc. -------- Carbon an Oxygen target
- **SBN Program:MicroBooNE** (running), **ICARUS** (under construction), **SBND** (under construction)
- **DUNE** (under construction)

} **Liquid argon target**

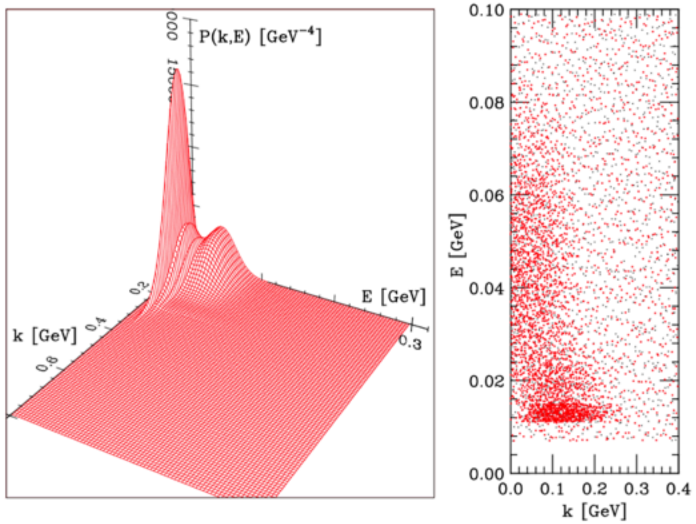
Why do we need spectral function?

- Spectral function S(E,k) describes the probability of finding a nucleon with initial momentum k and energy E in the nucleus

- Being an intrinsic property of the target ground state, the spectral function is relevant to the description of nuclear interactions in ALL channels

- Example: neutrino energy reconstruction in quasi elastic neutrino-nucleus interaction

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



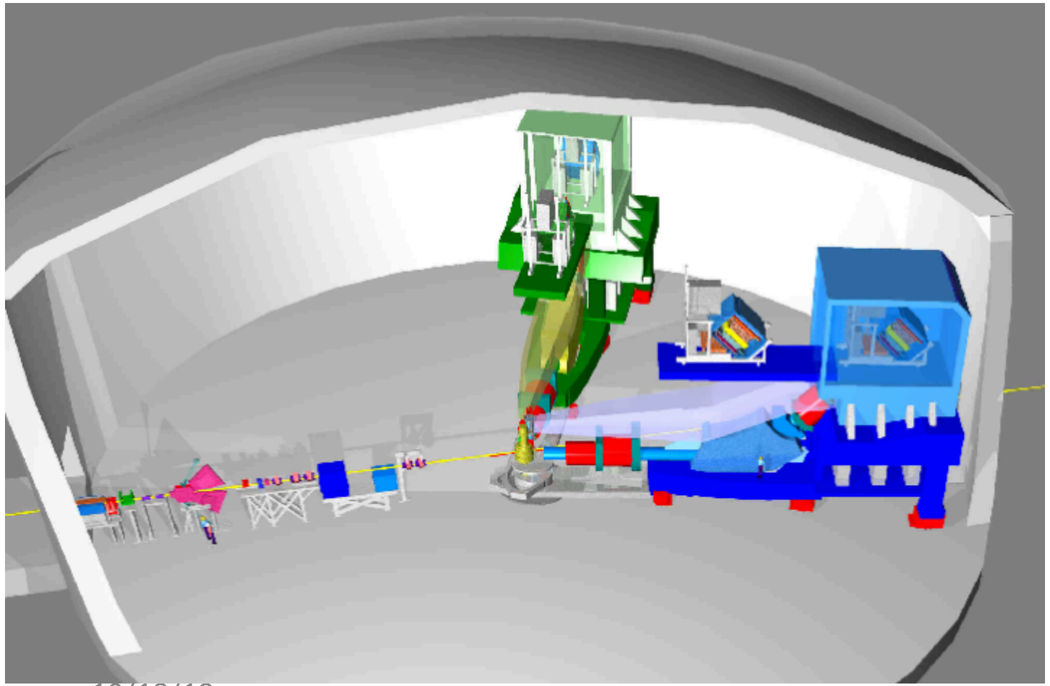
Oxygen spectral function

Jefferson Lab Hall A

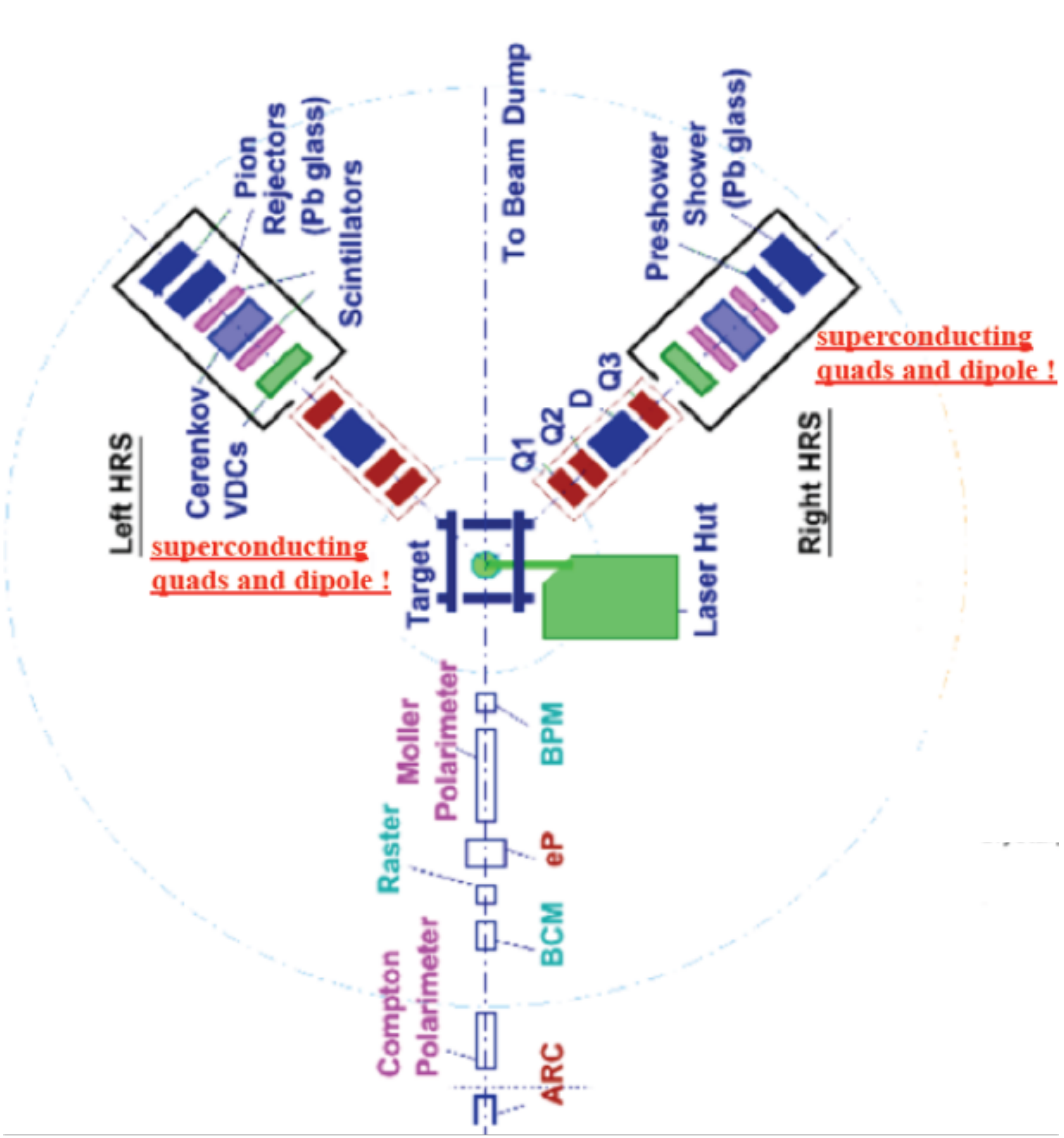
- ❖ Jefferson Lab: Continuous Electron Beam Accelerator Facility(CEBAF), Hall A, B, C, D

- ✓ The Hall A spectrometers have been designed to study the structure of nuclei utilizing the (e,e'p) reaction at very high luminosity and good momentum and angular resolution.

Momentum resolution: 0.02%, Angular resolution: 2 mrad



HALL A Schematics



(e,e'p) and (e,e') Reactions

- (e,e'p) process:

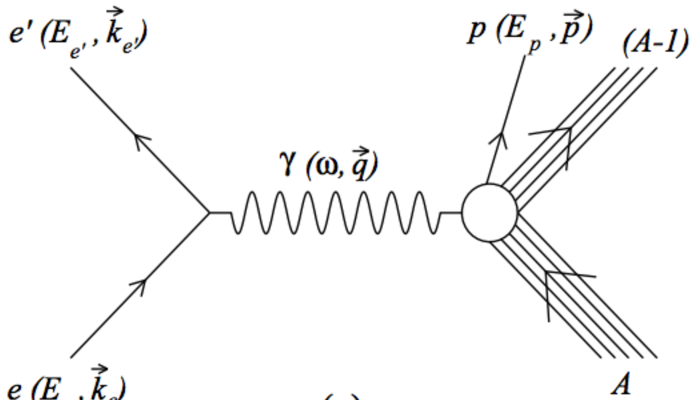
  Both outgoing electron and proton are detected

$$e + A \rightarrow e' + p + (A - 1)$$

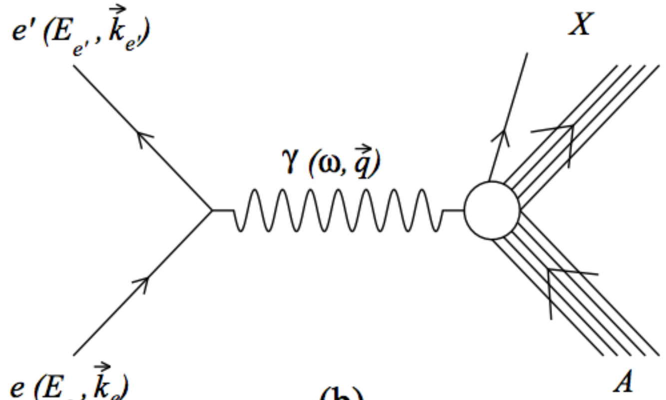
- (e,e') process:

  Only scattered electron is detected

$$e + A \rightarrow e' + X$$



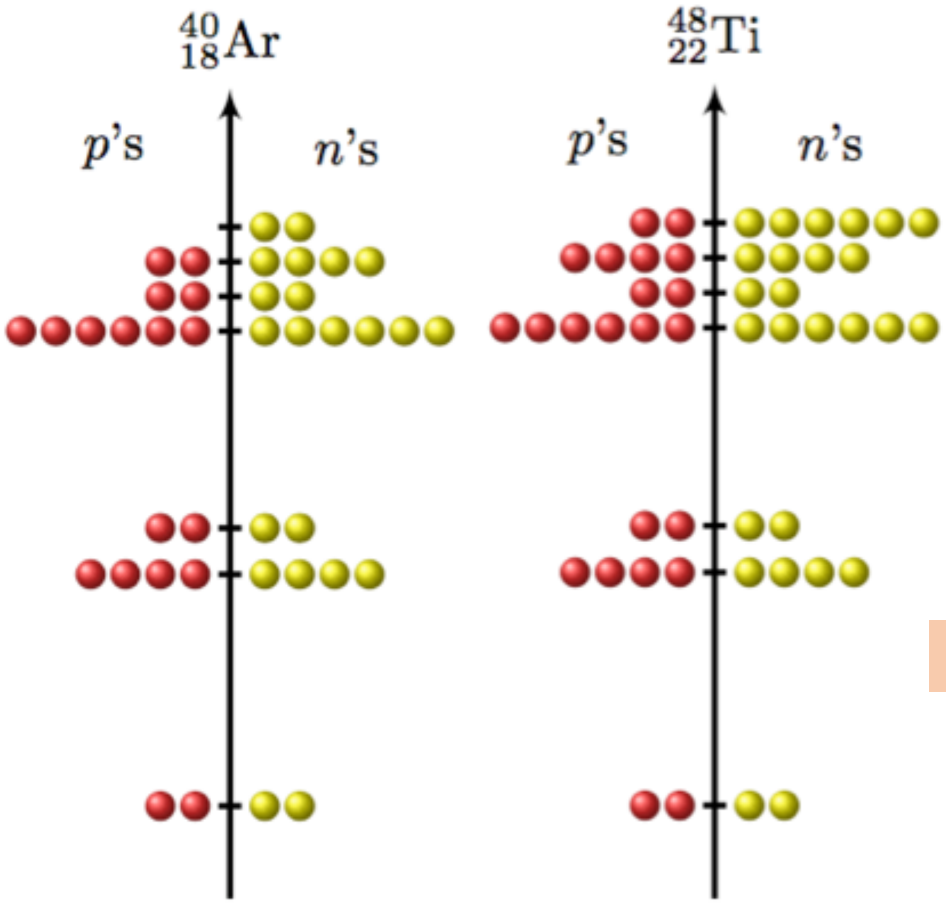
(a)

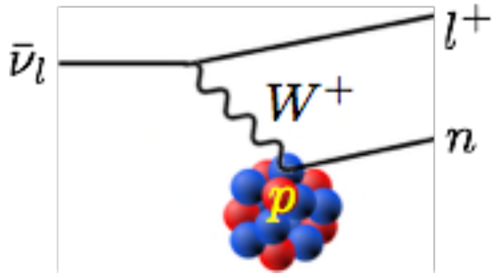


(b)

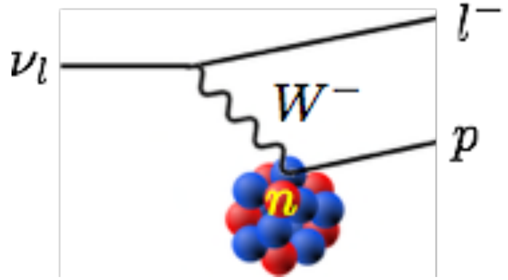
Why Titanium?

The shell model structure of the **protons in Ti** is nearly identical to that of the **neutrons in Ar**





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



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

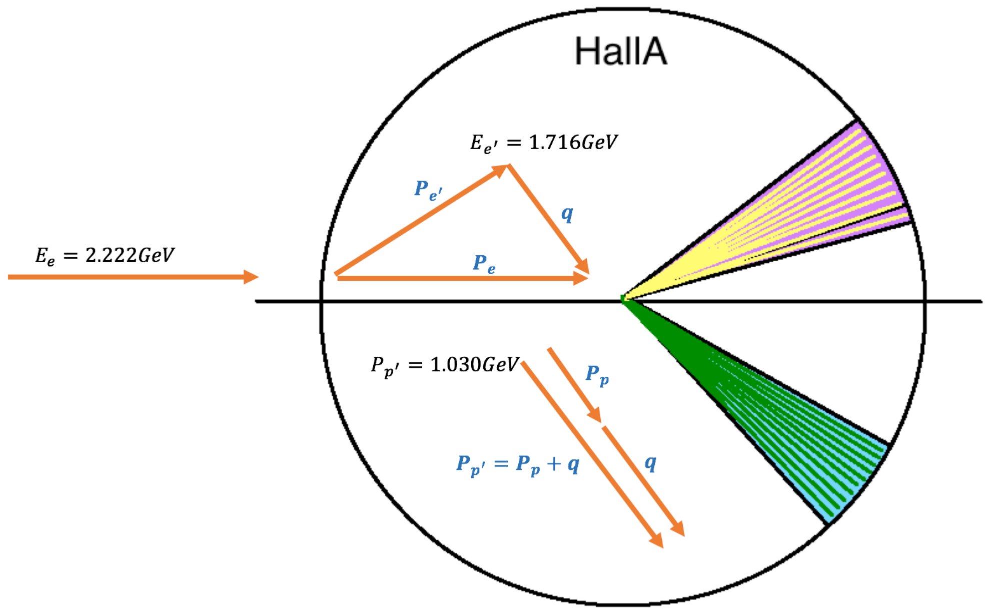
Ar(e,e'p)->SF of protons in Ar nucleus

Ti(e,e'p)->SF of neutrons in Ar nucleus

Kinematics Setup

	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\|\mathbf{q}\|$	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	1716	15.5	-	-	-	-

Parallel Kinematics: $P_p//q$



Data Summary

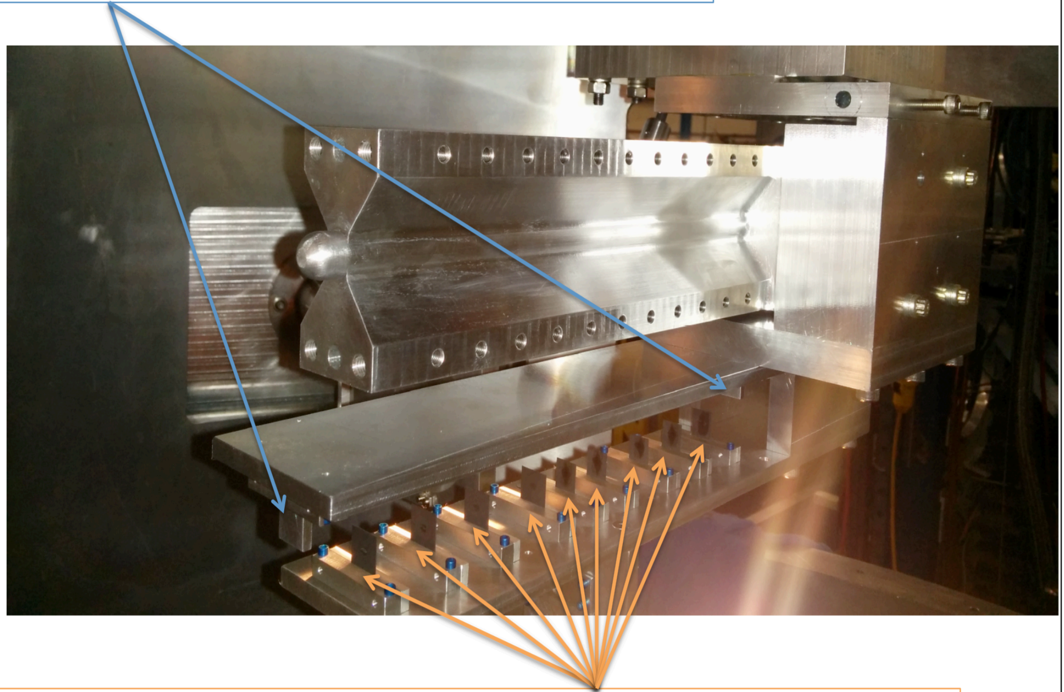
Kin 1			Kin 3		
Target Type	Hours	Events	Target Type	Hours	Events
Ar	29.6	43955	Ar	13.5	73176
Ti	12.5	12755	Ti	8.6	28423
Dummy	0.75	955	Dummy	0.6	2948
Kin 2			**Kin 4**		
Target Type	Hours	Events	Target Type	Hours	Events
Ar	32.1	62981	Ar	30.9	158682
Ti	18.7	21486	Ti	23.8	113130
Dummy	4.3	5075	Dummy	7.1	38591
Optics	1.15	1245	Optics	0.9	4883
C	2.0	2318	C	3.6	21922
Kin 5			**Kin 5 - Inclusive**		
Target Type	Hours	Events	Target Type	Minutes	Events
Ar	12.6	45338	Ar	57	2928
Ti	1.5	61	Ti	50	2993
Dummy	5.9	16286	Dummy	56	3235
Optics	2.9	160	C	115	3957

- Experiment approved in Jul 2014
- Data taking started in Feb 2017
- Data taking completed in Mar 2017

Target Setup

- 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 cm^{-2} sec^{-1}

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)

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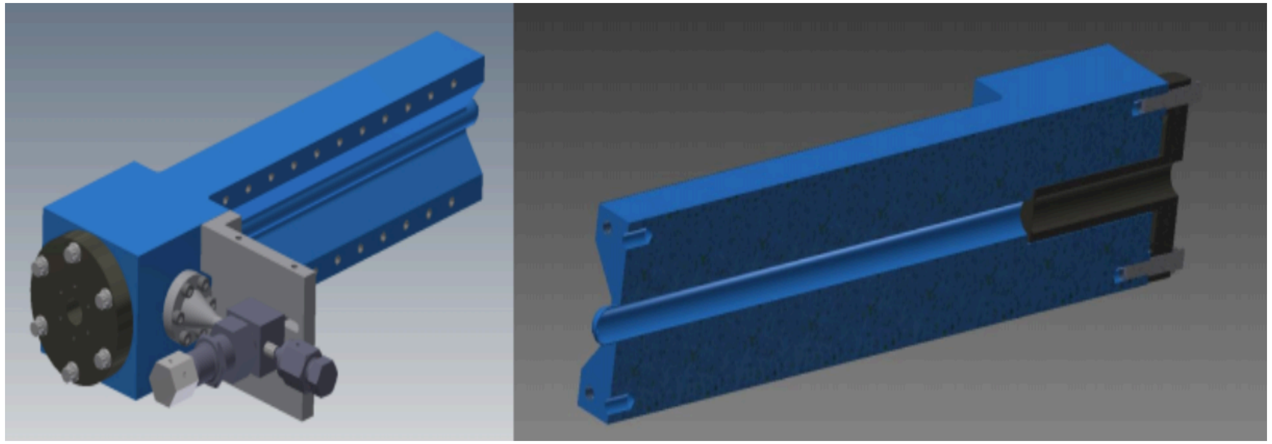


Data and Cuts

target	E'(GeV)	theta
C / Ti / Ar	2.160	15.541
C / Ti / Ar	2.030	15.541
C / Ti / Ar	1.909	15.541
C / Ti / Ar	1.794	15.541
C / Ti / Ar	1.686	15.541
C / Ti / Ar	1.585	15.541
C / Ti / Ar	1.490	15.541
C / Ti / Ar	1.401	15.541
C / Ti / Ar	1.317	15.541

- Set of cuts :
  - Trigger cut: Trigger3 for single arm left
  - Single track cut
  - PID cut:
    - cerenkov>400
    - (preshower+shower)/p_rec>0.3
  - Acceptance cut:
    - dp [-0.035,0.033]
    - theta [-0.03,0.03]
    - phi[-0.015,0.015]
  - Z cut: [-7.5cm,5cm] → Only for Ar

Two methods for extracting cross section from yields

For each bin in ΔE, ΔΩ, the number of detected electrons is:

$$N^- = L * \left(\frac{d\sigma}{d\Omega dE'}\right) * (\Delta E'\Delta\Omega) * \epsilon * A(E',\theta) + BG$$

With L : Integrated Luminosity*(#of beam electrons*targets/area)*

ϵ : Total efficiency for detection

$A(E',\theta)$: Acceptance for bin

BG: Background events

The efficiency corrected electron yield is

$$Y = \frac{N^- - BG}{\epsilon} = L * \sigma^{data} * (\Delta E\Delta\Omega) * A(E',\theta)$$

For known $A(E',\theta)$, $\frac{d\sigma}{d\Omega dE'} = Y(E',\theta)/[(\Delta E\Delta\Omega) * A(E',\theta) * L]$ (Acceptance correction method)

$A(E',\theta)$ is the probability that a particle will make it through the spectrometer and must be measured or determined from simulation!

Conversely, we can simulate Monte Carlo data using a cross section model to obtain

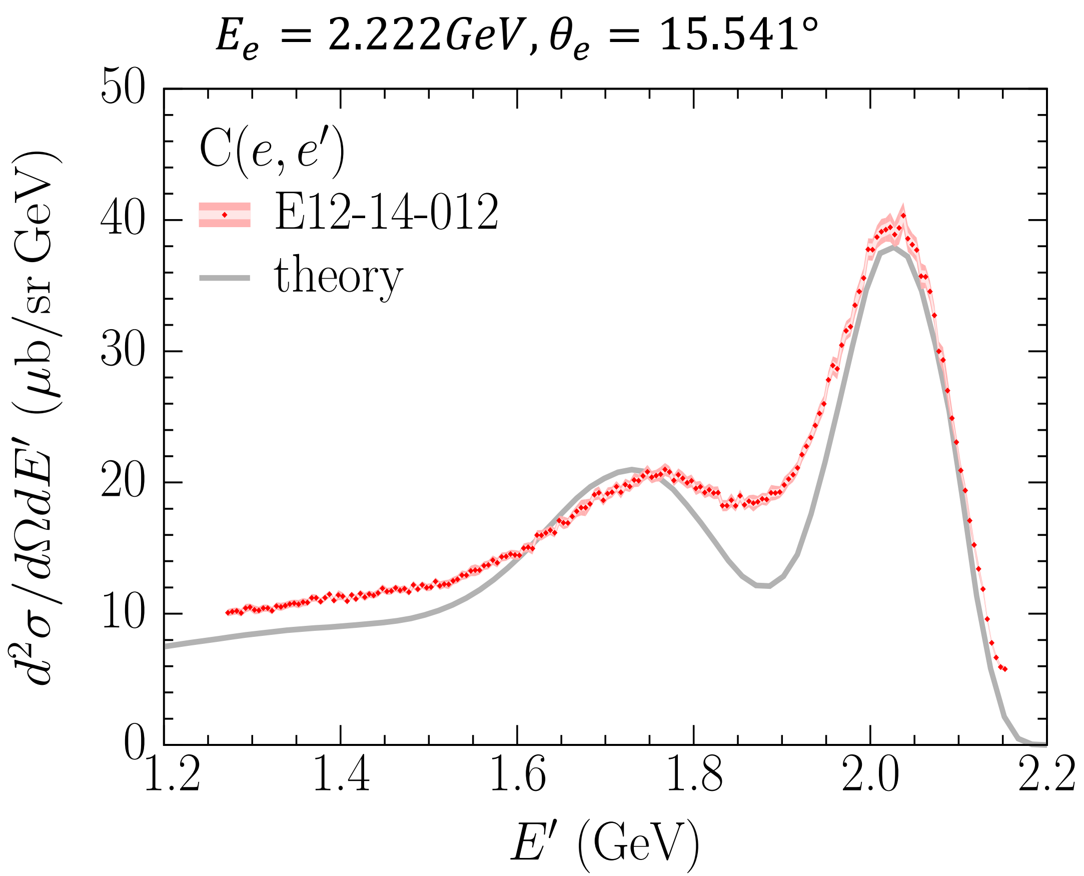
$$Y_{MC}(E',\theta) = L * \sigma^{mod} * (\Delta E\Delta\Omega) * A_{MC}(E',\theta)$$

Taking ratio to data and assuming that $A_{MC} = A$, yields

$$\frac{d\sigma}{d\Omega dE'} = \sigma^{mod}[Y(E',\theta)/Y_{MC}(E',\theta)]$$ (MC ratio method)

Results: Inclusive cross section of Carbon

Phys. Rev. C 98, 014617 (2018)



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.

1. Total statistical uncertainty	1.2%
2. Total systematic uncertainty	2.0–2.9%
a. Beam charge & Beam Energy	0.3%
b. Beam offset x&y	0.1%–0.4%
c. Target thickness	0.1%–0.4%
d. HRS offset x&y+ Optics	1.3%–2.0%
e. Acceptance cut(θ,ϕ,dp/p)	1.0%–1.4%
f. Calorimeter & Čerenkov cuts	0.01%–0.02%
g. Cross Section Model	0.1%–0.2%
h. Radiative +Coulomb Corr.	1.0–1.3%

Comparison with previous data

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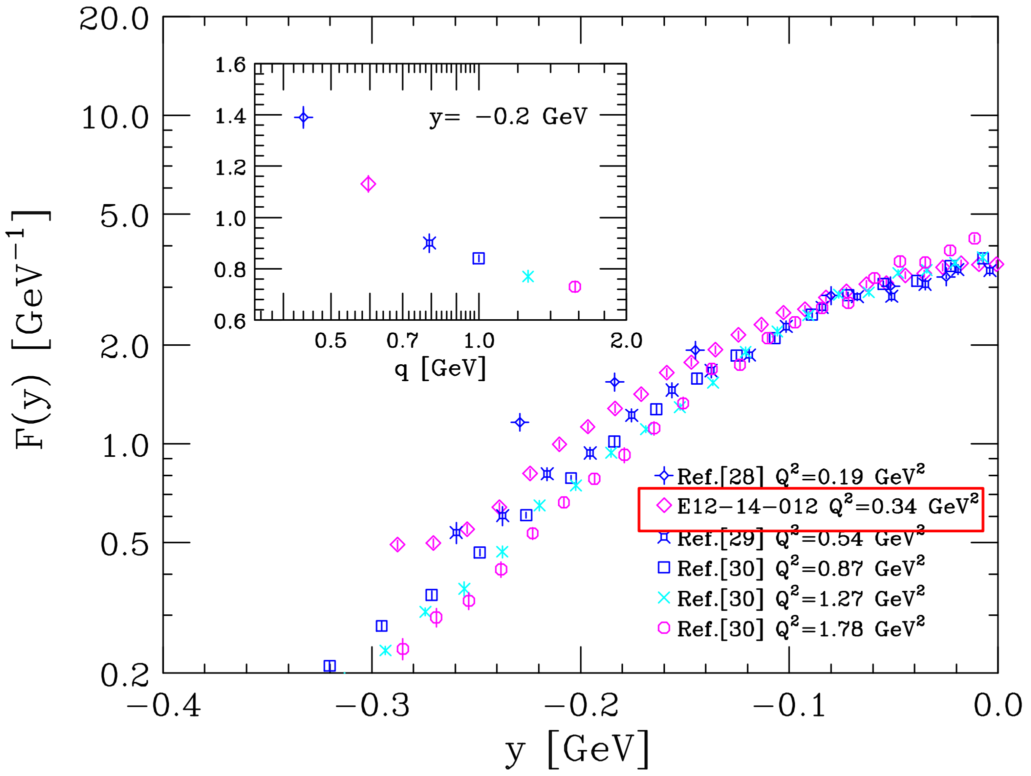
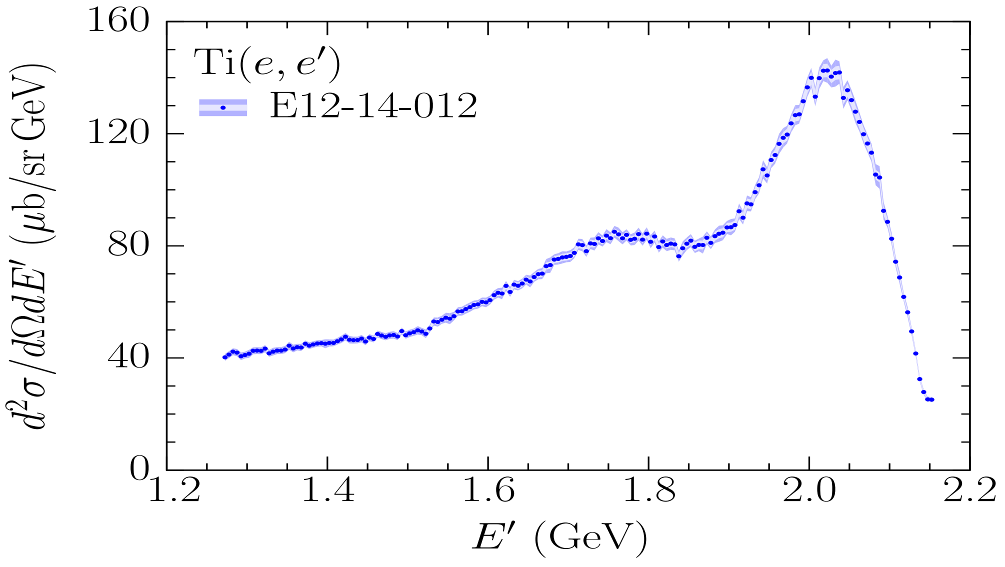


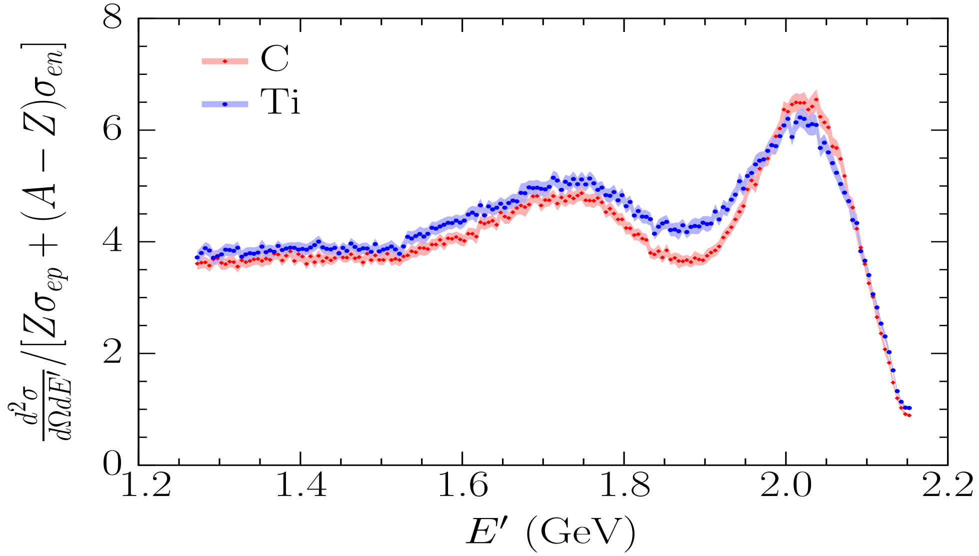
- Comparison between the scaling function F(y) obtained from the E12-14-012 data and those obtained from previous data
- The data sets are labeled by the value of Q^2 corresponding to the top of the quasi elastic peak

✓ Our results are consistent with those of previous experiments

Results: First inclusive cross section of Titanium

Phys. Rev. C 98, 014617 (2018)





- Total error : ~2.75%
- Statistical error: ~ 1.65%
- Systematic error : ~2.2%

$$\frac{d^2\sigma}{d\Omega dE'}/[Z\sigma_{ep} + (A - Z)\sigma_{en}]$$

- The quantities σ_{ep} and σ_{en} are the elastic electron-proton and electron-neutron cross sections stripped of the energy-conserving delta function

- The difference between the results obtained using the measured carbon and titanium cross sections reflect different nuclear effects

Argon analysis: Background from target cell

- We measure the dummy yield and scale it according to the thickness of the entry and exit of the argon target cell

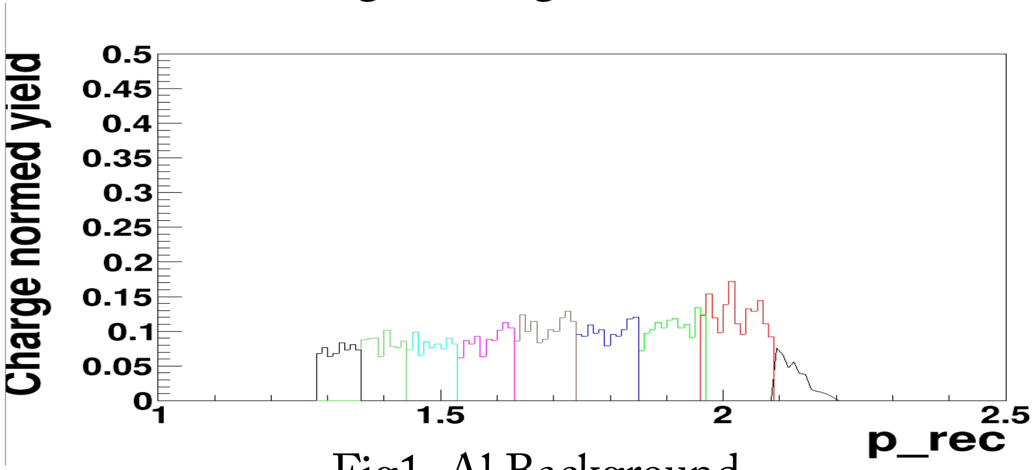
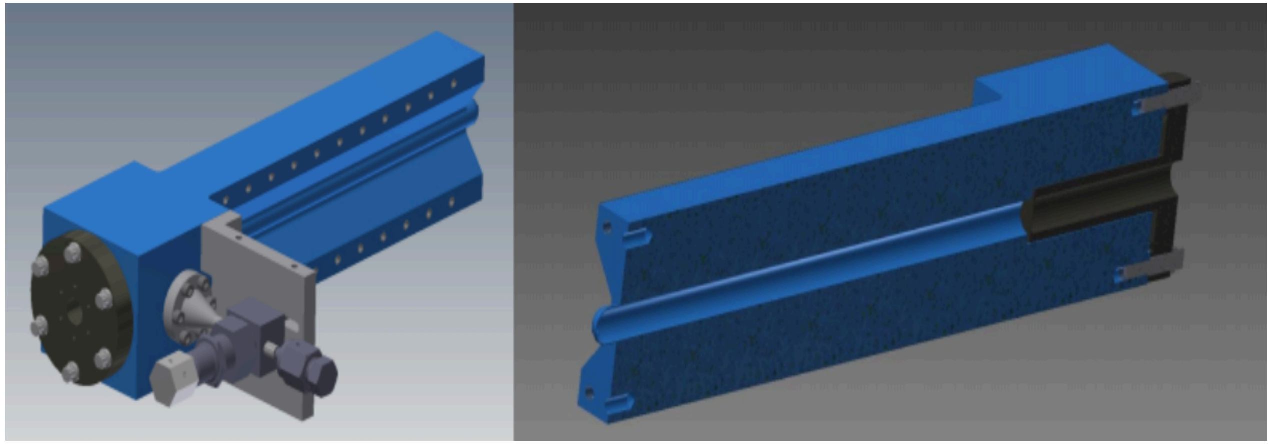


Fig1. Al Background



Argon gas target cell

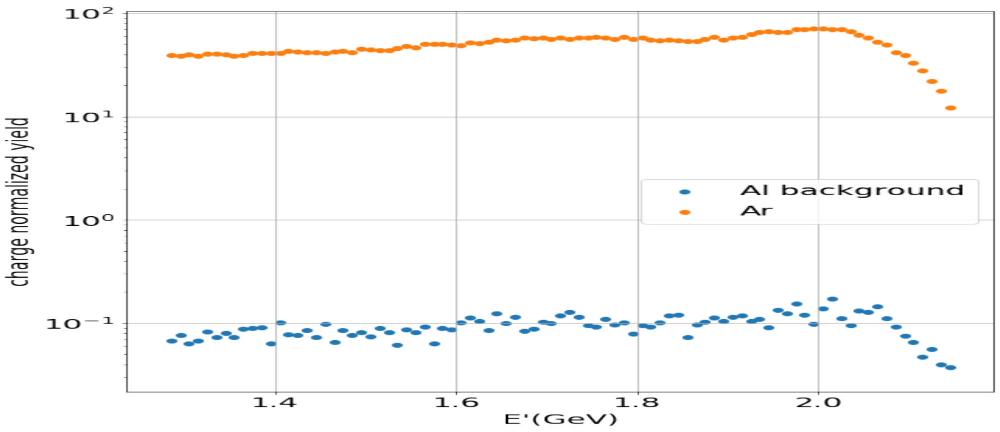


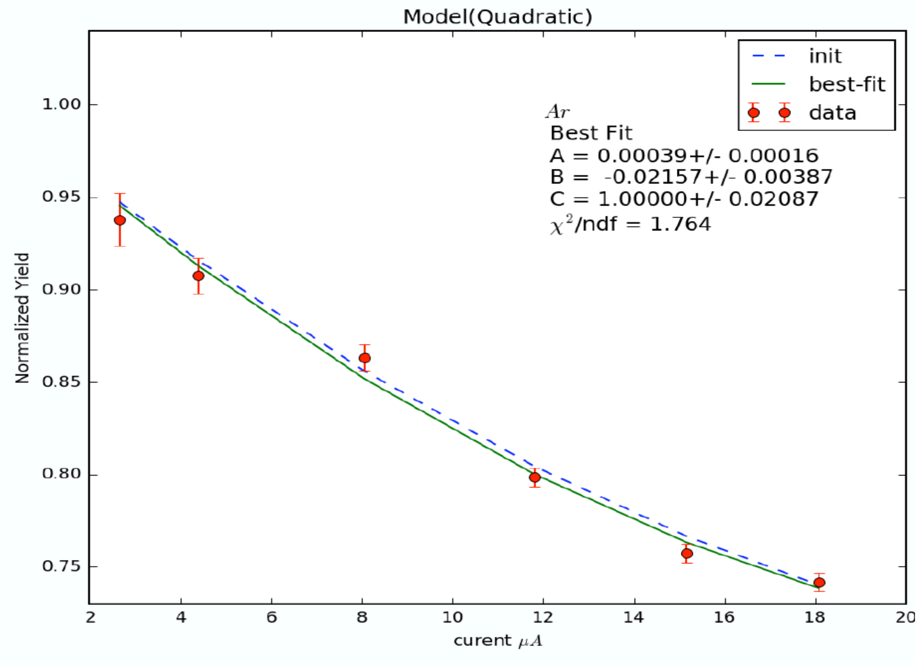
Fig2. Background yield and argon yield

The background from target cell is ~0.2%

Argon analysis: Boiling study

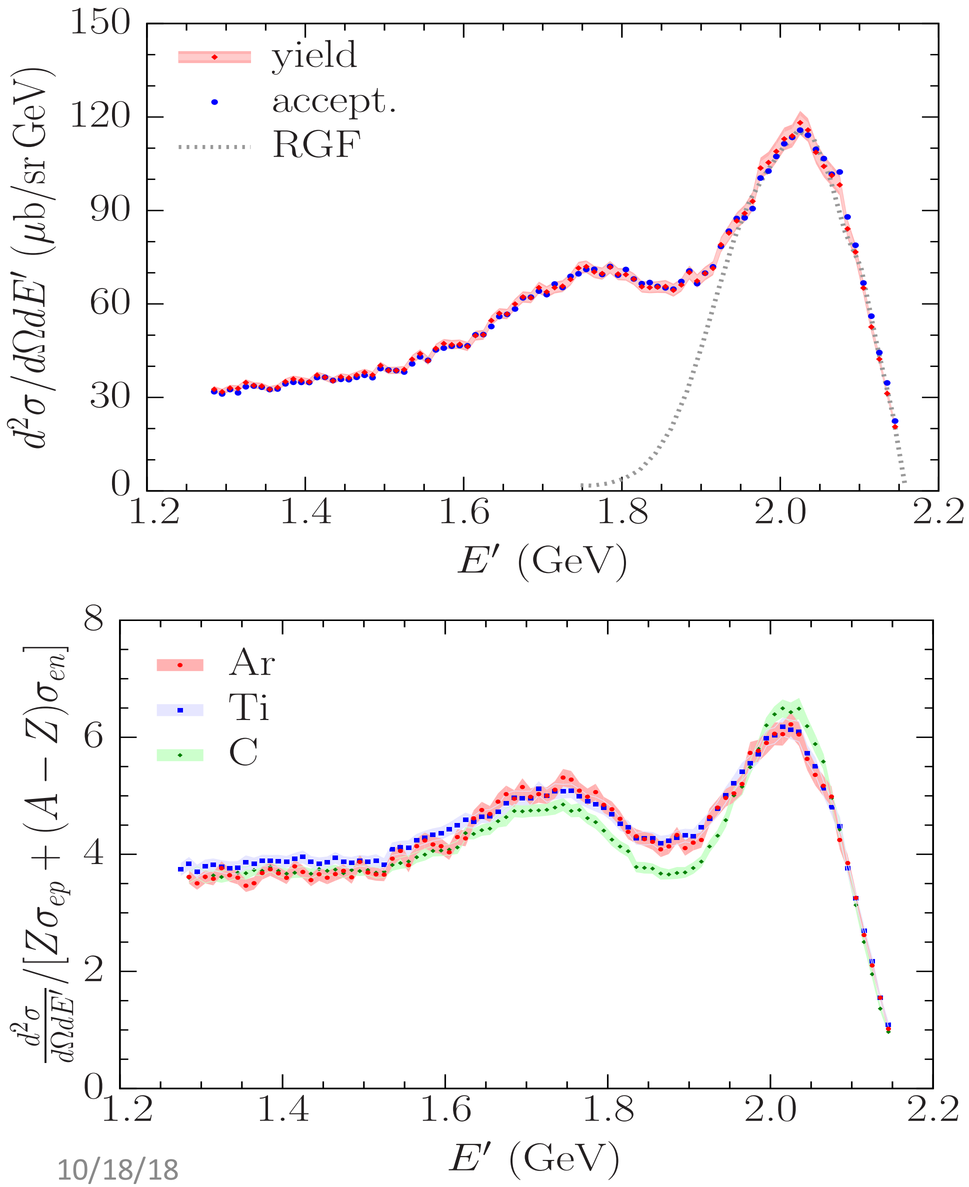
- We calculated the normalized yield for different currents, and the change in yield represents change in target density
- The normalization is done with respect to the lowest current
- We fit the numbers with quadratic function and fix the I=0 point to 1
- When $I = 9.67\mu A$,within 2% for all the runs, the boiling effect is 17.2%, with 0.7% uncertainty.

Current (µA)	Number of events	Yield (ev/µC)	Normalized Yield
2.65 +/- 0.14	4898	1571.63 +/- 23.86	1 +/- 0.015
4.39+/-0.14	10283	1523.80 +/- 15.97	0.97 +/- 0.01
8.06 +/- 0.15	17460	1454.32 +/- 11.69	0.925 +/- 0.007
11.81 +/- 0.17	26848	1352.62 +/- 8.77	0.860 +/- 0.005
15.15 +/- 0.19	25764	1287.83 +/- 8.52	0.8194 +/- 0.0054
18.08 +/- 0.21	26065	1263.59 +/- 8.31	0.804 +/- 0.0053



Results: Inclusive cross section of Argon

In preparation for PRL



1. Total statistical uncertainty	1.7%–2.9%
2. Total systematic uncertainty	1.8%–3.0%
a. Beam charge & Beam energy	0.3%
b. Beam offset $x\&y$	0.4%–1.0%
c. Target thickness and boiling effect	0.7%
d. HRS offset $x\&y$ + Optics	0.6%–1.2%
e. Acceptance cut (θ,ϕ,dp/p)	0.6%–2.4%
f. Calorimeter & Čerenkov cuts	0.01%–0.03%
g. Cross Section Model	0.0%–1.3%
h. Radiative + Coulomb Correction	1.0%

RGF: Relativistic Green's Function Approach (C. Giusti, etal.)

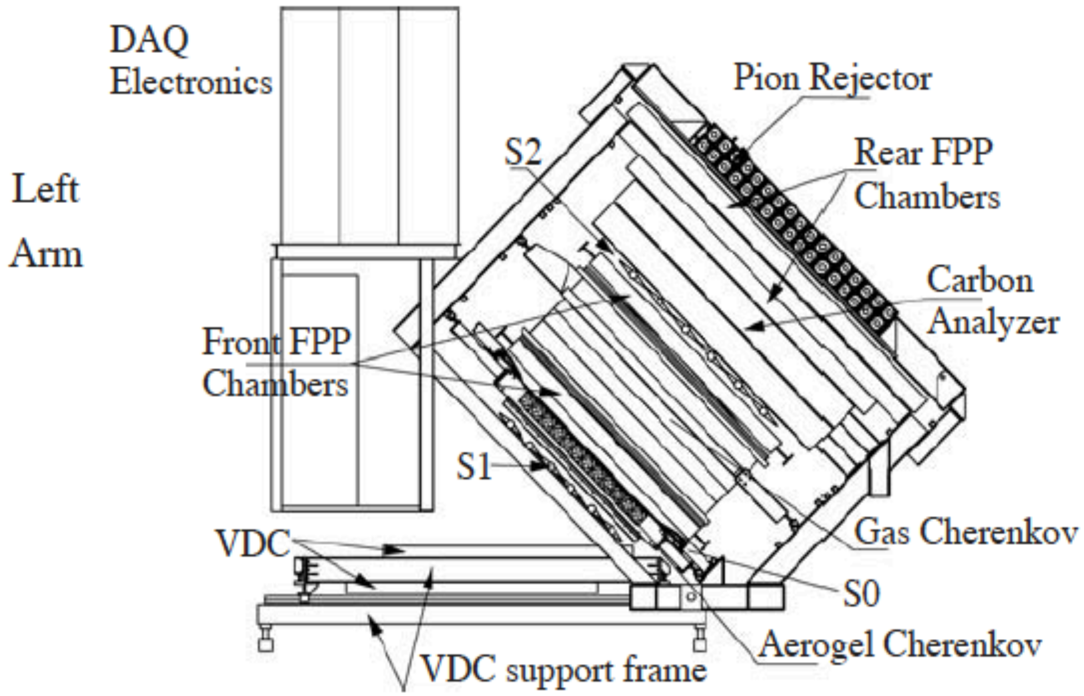
Summary & Outlook

- We performed the electron scattering experiment at Jefferson Lab, the data was collected on Argon, Titanium and Carbon
  - Important to the upcoming neutrino oscillation experiments
- We've extracted the (e,e') cross section of Carbon, Titanium and Argon
  - Total error is within 5%
- Future: (e,e'p) analysis of Argon and Titanium

Backup slides

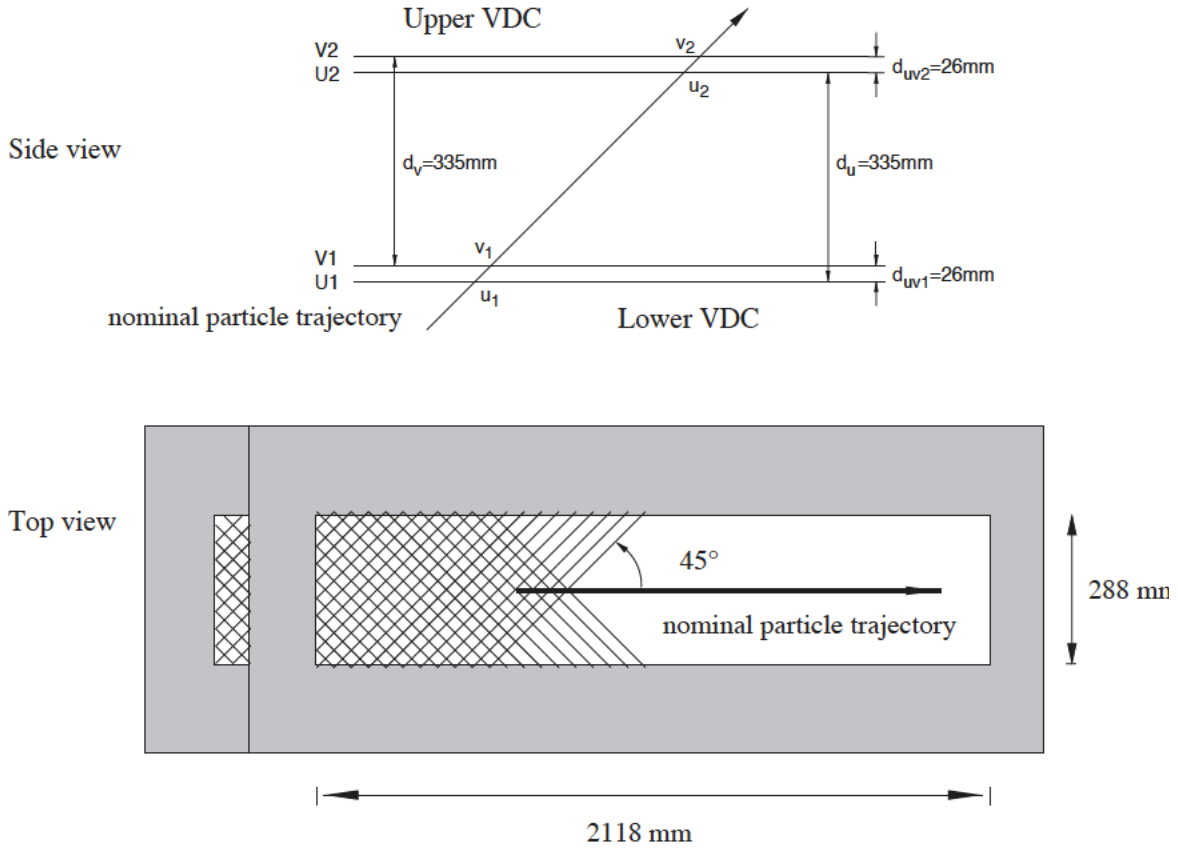
Detector Package

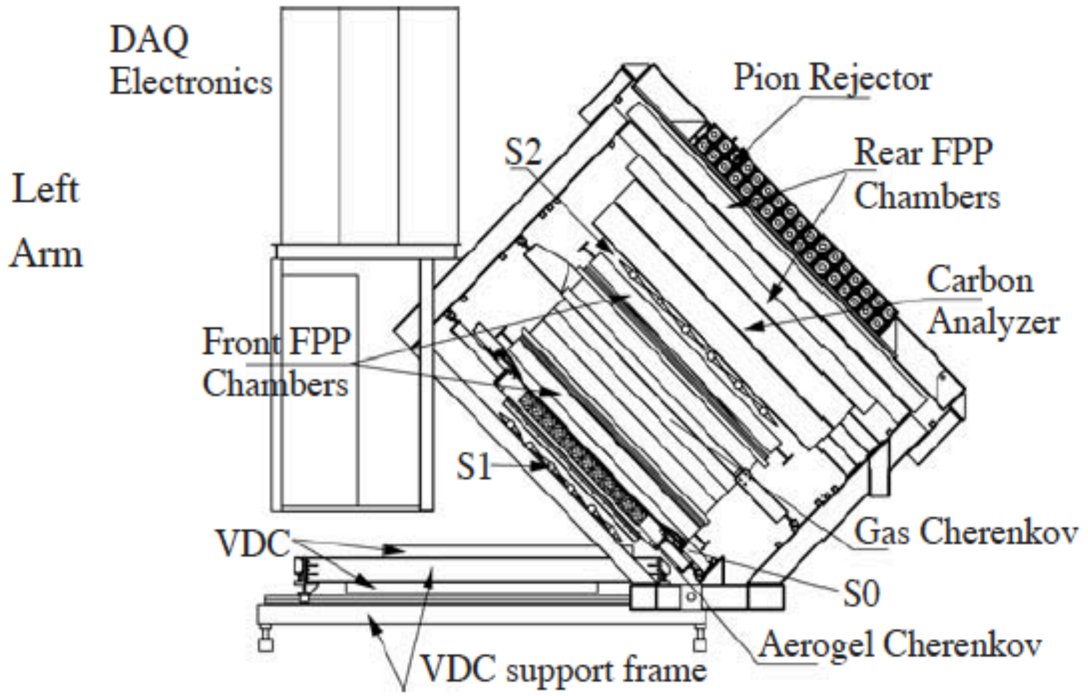
- Vertical Drift Chamber(VDC)
- Scintillator Counter
- Gas Cerenkov Detector
- Lead Glass Calorimeter



Vertical Drift Chamber(VDC)

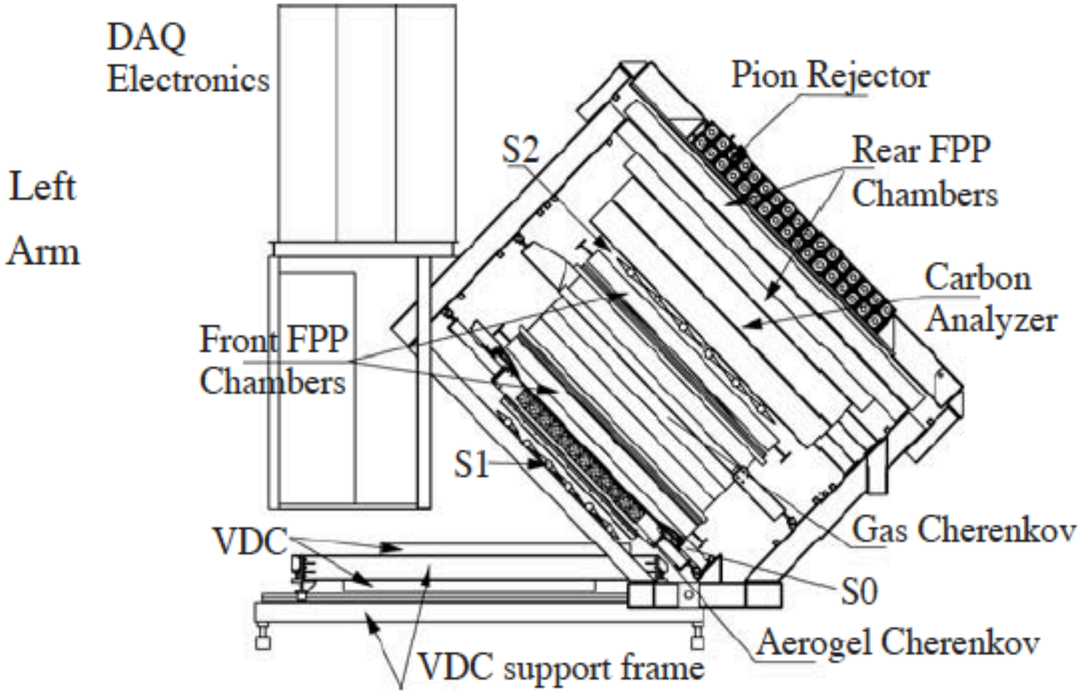
- Tracking information is provided by a pair of VDCs in each HRS





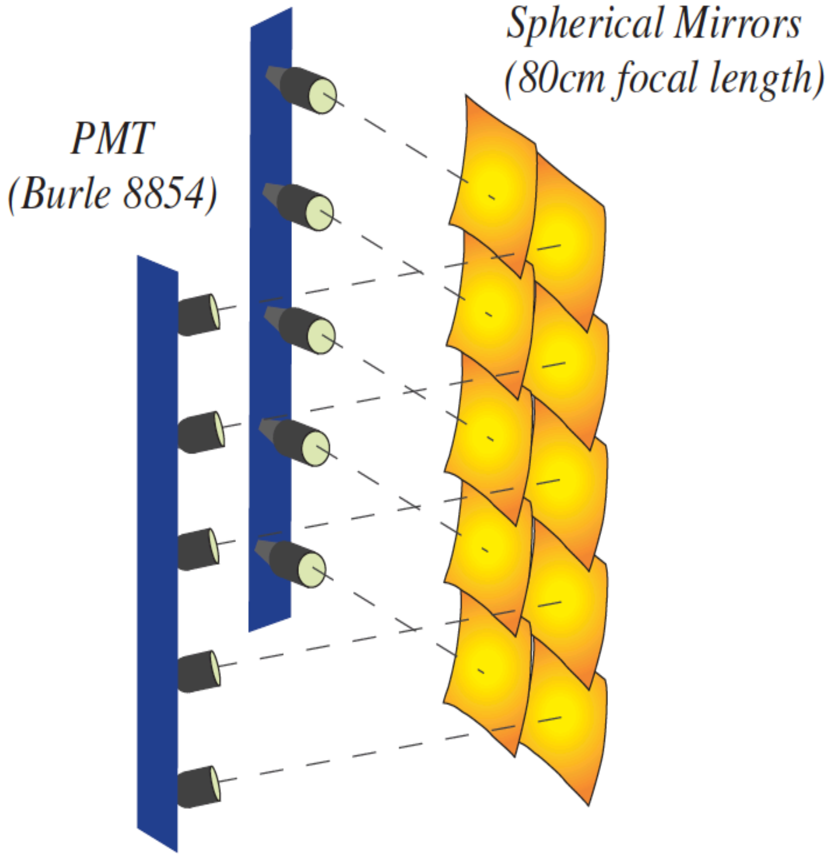
Scintillator Counter

- Form the trigger to activate the data-acquisition electronics
  - Example: trigger3
    - T3 = (S0&&S2) && (GC||PR) [LEFT]
- Provide Precise timing information for time-of-flight measurements and coincidence determination



Gas Cerenkov Detector

- The Gas Cerenkov box is filled with atomspheric pressure CO_2, with index of refraction 1.00041
- A high energy charged particle radiates Cerenkov light when it travels in a medium with its speed faster than that of light
- Cerenkov can discriminate particles with different masses
  - Momentum threshold for electron to radiate Cerenkov light: 18MeV/c
  - Momentum threshold for pion to radiate Cerenkov light: 4.9GeV/c
  - Momentum coverage of HRS is from 0.5GeV/c to 4.3GeV/c
  - Only electron can emit Cerenkov light in this detector
  - Pions may produce signals in the GC when they interact with the gas and create low-energy electrons



Lead Glass Calorimeter

- Calorimeter measures the energy of charged particles
- Calorimeter is composed of two layers of lead glass blocks (Pion-Rejector-1 and Pion-Rejector-2) and associated PMTs
- The charged particles lose energy through Bremsstrahlung radiation