First cross section results from e-Ar experiment at Jefferson Lab

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E12-14-012 Experiment: In a nutshell

- **Primary Goal:** Measurement of the **spectral functions** of **argon nucleus** through (e,e'p) reaction

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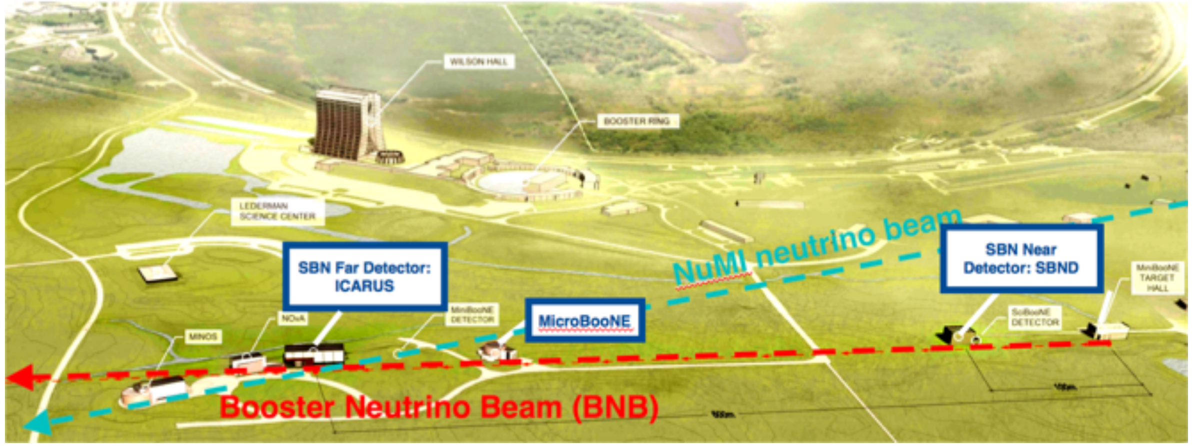
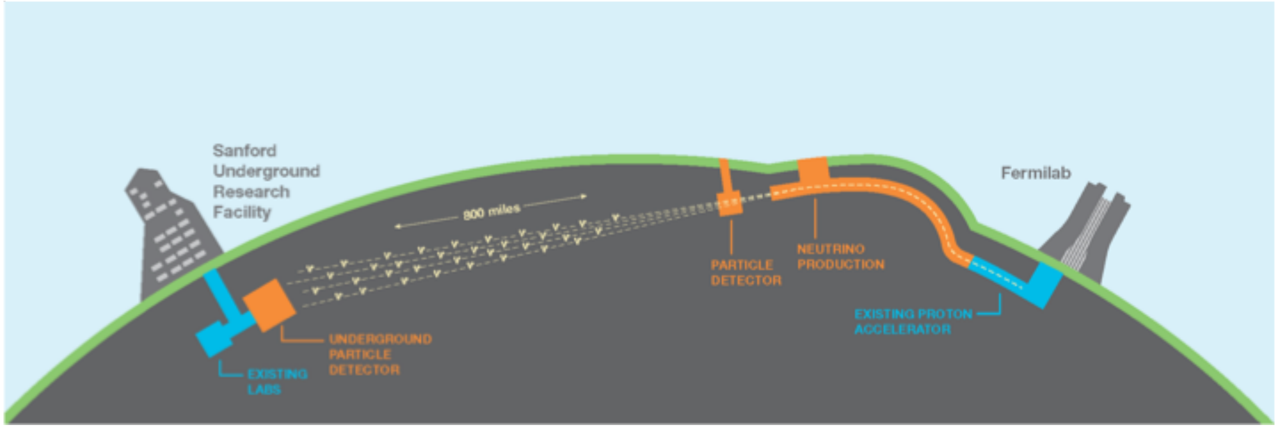
- The short- (SBN program) and the long-baseline (DUNE) neutrino experiments (will) employ detectors based on the liquid-**argon** time-projection chambers (L**Ar**TPCs) technology. Apart from precision goal of oscillation parameter measurement (θ_{23}), we are moving towards searching ***CP violation in leptonic sector.***

- **SBN Program at FNAL**



- **DUNE**



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

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- The lack of adequate modeling of neutrino-nucleus interactions and nuclear effects in Monte-Carlo simulations, has been recognized as the major source of systematic uncertainty even with the relatively well-know isospin symmetric nuclei such as ^{12}C and ^{16}O - pertinent for water Cherenkov and mineral-oil detectors.

- The magnitude of uncertainty is expected to rise significantly considering almost non-existence electron scattering studies on argon and hence no empirical testbed available to develop accurate models.

- Furthermore, a careful modeling of an isospin asymmetric nucleus, argon, is more vital in the test of CP violation considering neutrino and antineutrino may behold different nuclear effects on argon (because of different number of neutrons and protons).

E12-14-012 Experiment: In a nutshell

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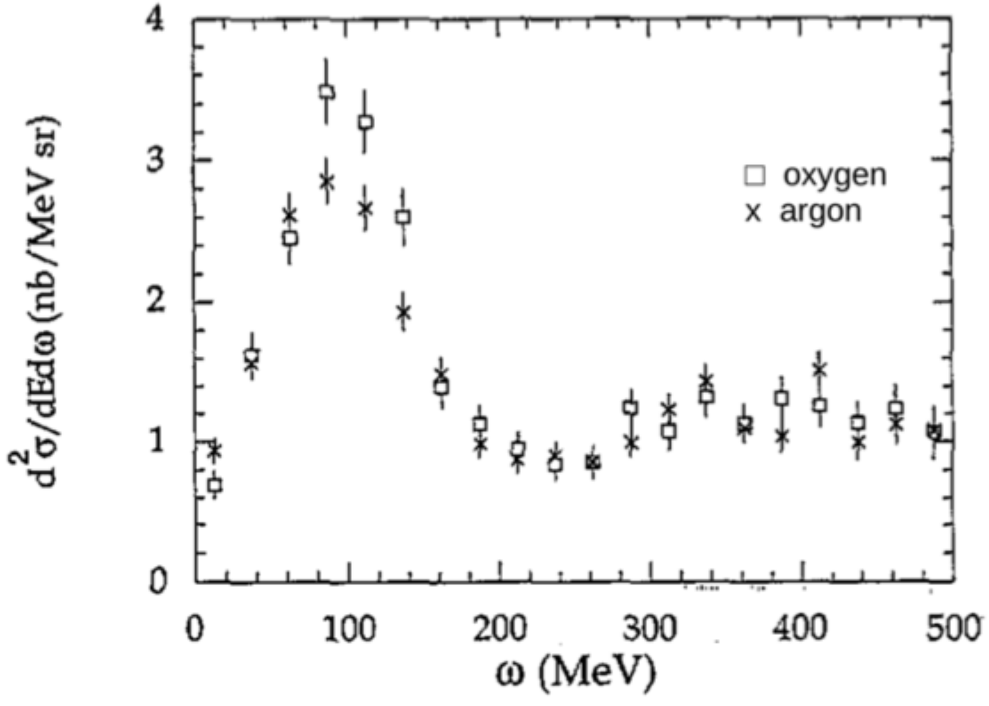
Why Argon?

- The only available e-Ar data is (e,e') cross section measured at Frascati National Laboratory using the electron-positron collider ADONE and a jet target.
- To achieve the precision level required for the discovery of CP violation in lepton sector, clearly, more high precision e-Ar data is needed.

E = 700 MeV, θ = 32 deg



M. Anghinolfi et al., J. Phys. G21, L9 (1995)

E12-14-012 Experiment: In a nutshell

- **Primary Goal:** Measurement of the **spectral functions** of **argon nucleus** through (e,e'p) reaction

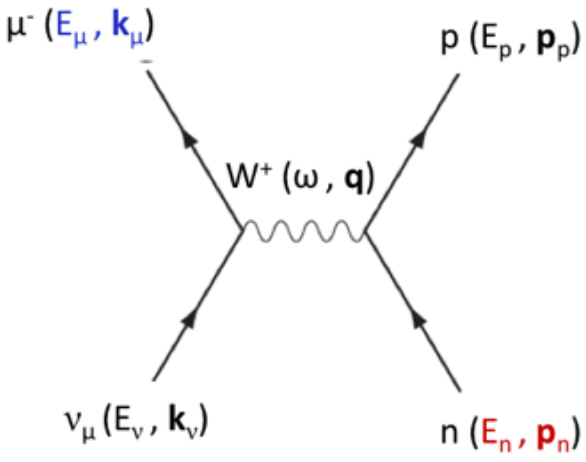
Why Spectral Functions?

I. **Energy Reconstruction:** Measuring spectral functions of argon nucleus will provide the energy and momentum distribution of protons and neutrons bound in argon nucleus that will allows more accurate reconstruction of the incoming neutrino and antineutrino energies (which is currently the major source of uncertainty in these experiments).

Kinematic Energy Reconstruction for CCQE process:

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

where $|k_\mu|$ and θ_μ are measured, while p_n and E_n are the unknown momentum and energy of the interacting neutron that can be measured at E12-14-012 experiment.



E12-14-012 Experiment: In a nutshell

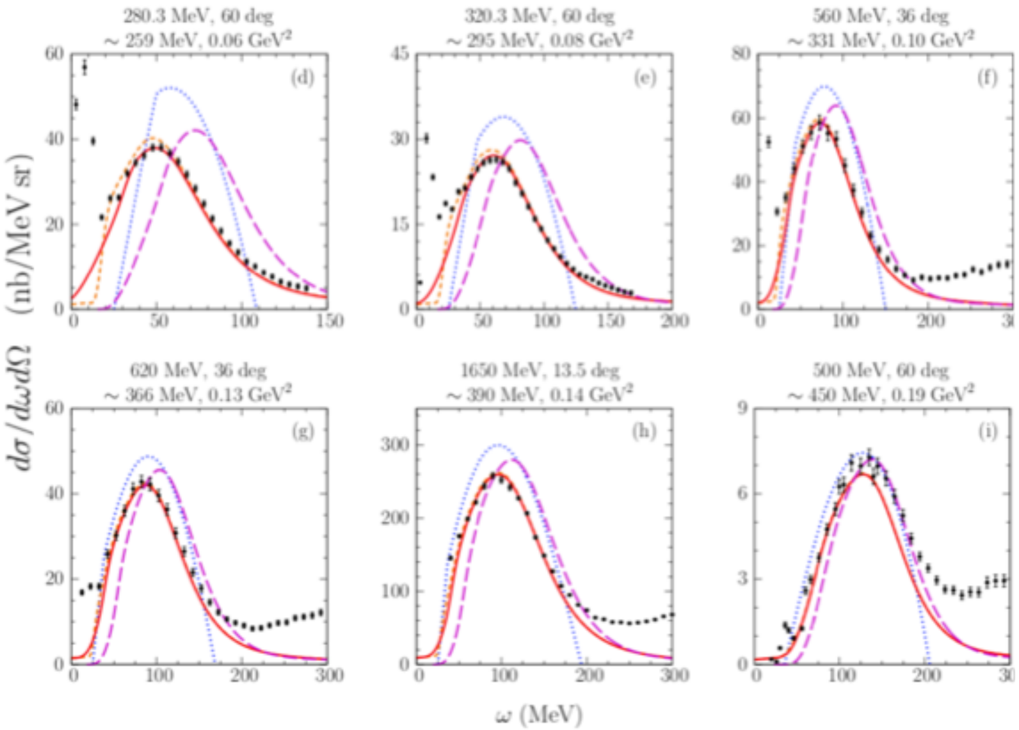
- **Primary Goal:** Measurement of the **spectral functions** of **argon nucleus** through (e,e′p) reaction

Why Spectral Functions?

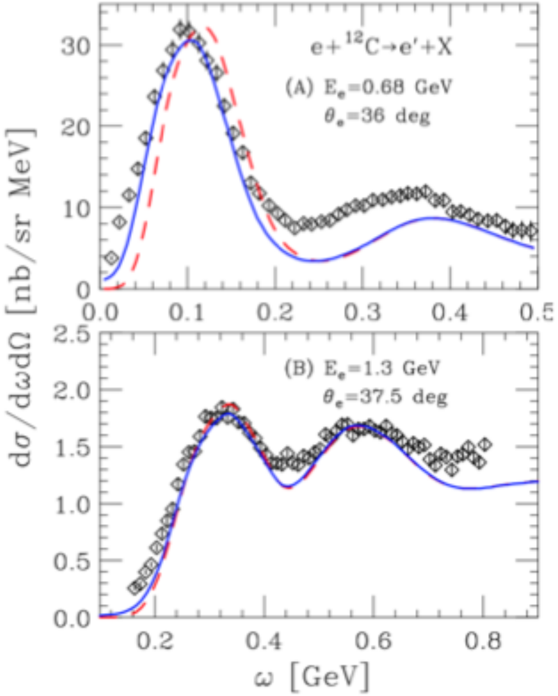
II. **Nuclear Model:** The measured argon spectral functions will provide vital input to the theoretical model based on the factorization *ansatz* dictated by the impulse approximation and spectral function formalism [*Benhar et al.*].

The approach which has been successful in describing inclusive electron-scattering data in a variety of kinematical regimes.

And has been extended to the analysis of neutrino scattering.



A. M. Ankowski, O. Benhar, M. Sakuda, Phys. Rev. D 91, 054616 (2015).



N. Rocco, A. Lovato, O. Benhar, Phys. Rev. Lett. 116, 192501 (2016).

E12-14-012 Experiment: In a nutshell

- **Primary Goal:** Measurement of the **spectral functions** of **argon nucleus** through (e,e′p) reaction

↓

- Nevertheless, a new high precision e-Ar data will provide vital information about argon nucleus and it's electroweak interaction to the community that can be used as a testbed for the development of theoretical models/frameworks. And will be a significant step ahead in improving the accuracy of the measurement of the neutrino-oscillation parameters, more importantly the CP violation phase in leptonic sector.

Extracting Spectral Functions from Data

- We plan to study the **coincidence (e,e'p) processes** in the **kinematical region** in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

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Coincidence *(e,e'p)* process:

- Both the outgoing electron and the proton are detected in coincidence, and the recoiling nucleus can be left in any bound state.

- Within the Plane Wave Impulse Approximation (PWIA) scheme:

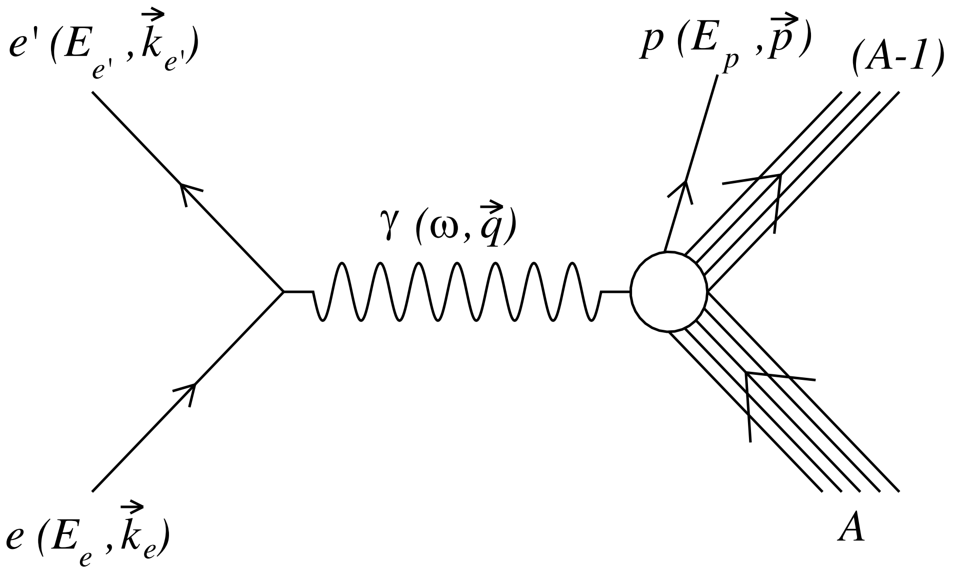
$$\frac{d\sigma_A}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- The initial energy and momentum of the knocked out nucleon can be identified with the measured missing momentum and energy, respectively as

$$\mathbf{p}_m = \mathbf{p} - \mathbf{q}$$

$$E_m = \omega - T_p - T_{A-1} \sim \omega - T_p$$

Where $T_p = E_p - m$, is the kinetic energy of the outgoing proton.



Extracting Spectral Functions from Data

- We plan to study the **coincidence (e,e'p) processes** in the **kinematical region** in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

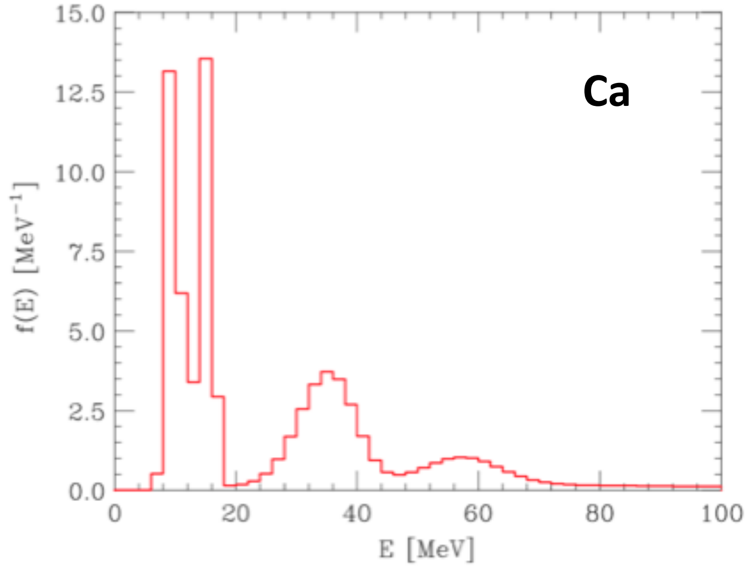
Kinematic region:

- Separation energies of the proton and neutron shell model states for Ca and Ar ground states

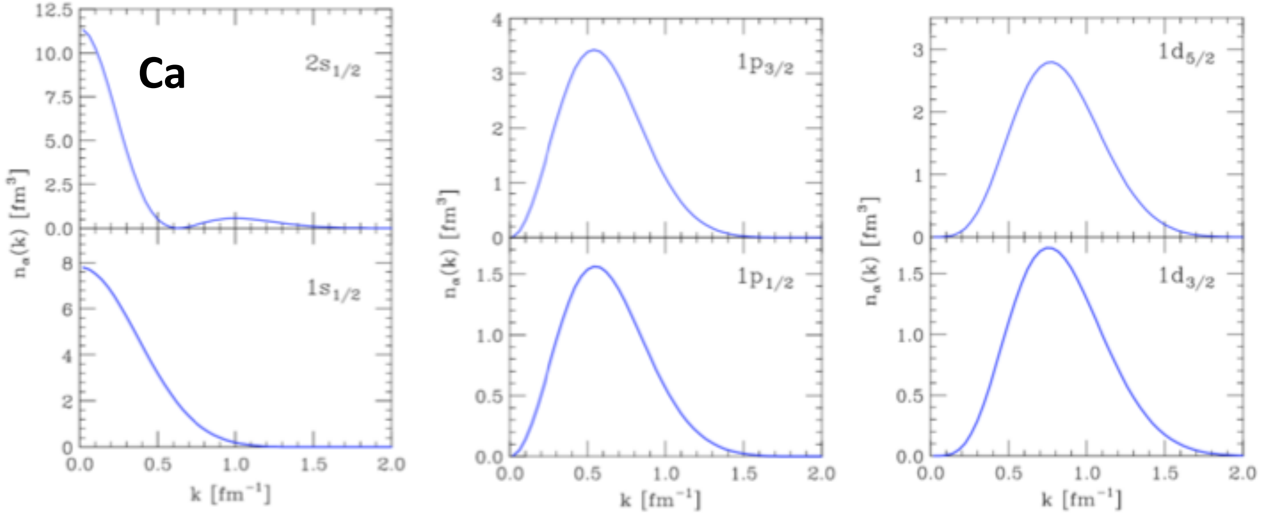
	protons		neutrons	
	$^{40}_{20}$Ca	$^{40}_{18}$Ar	$^{40}_{20}$Ca	$^{40}_{18}$Ar
$1s_{1/2}$	57.38	52	66.12	62
$1p_{3/2}$	36.52	32	43.80	40
$1p_{1/2}$	31.62	28	39.12	35
$1d_{5/2}$	14.95	11	22.48	18
$2s_{1/2}$	10.67	8	17.53	13.15
$1d_{3/2}$	8.88	6	15.79	11.45
$1f_{7/2}$				5.56

- The energy distribution

$$f(E) = 4\pi \int dk\ k^2 P(k, E)$$



- The momentum distribution



> ➢ Kinematic region for argon
> 6 MeV ≲ E_m ≲ 60 MeV
> $\mathbf{p}_m$ ≲ 350 MeV

A. M. Ankowski and J. T. Sobczyk, Phys. Rev. C77, 044311 (2008)

Extracting Spectral Functions from Data

- We plan to study the **coincidence (e,e'p) processes** in the **kinematical region** in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

- Cross section within the Plane Wave Impulse Approximation (PWIA) scheme:

$$\frac{d\sigma_A}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- The spectral function extracted from the data will be

$$P_{MF}(p_m, E_m) = \sum_\alpha Z_\alpha \, |\xi_\alpha(p_m)|^2 F_\alpha(E_m - E_\alpha)$$

In the absence of correlations, $Z_\alpha \to 1$, and $F_\alpha(E_m - E_\alpha) \to \delta(E_m - E_\alpha)$.

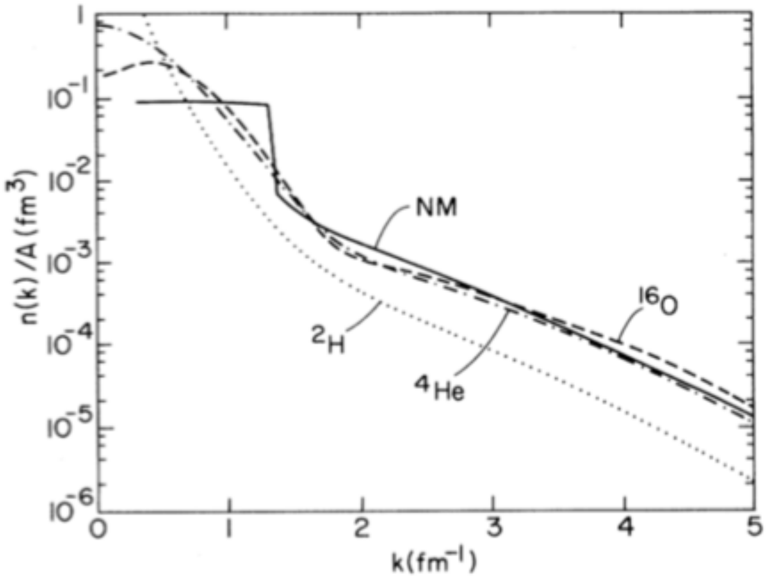
- The correlation contribution to the spectral function of a finite nucleus of mass number A can be calculated within the Local Density Approximation (LDA):

$$P_{\rm corr}(p_m, E_m) = \int d^3r \; \rho_A(\mathbf{r}) P^{NM}_{\rm corr}(p_m, E_m; \rho = \rho_A(\mathbf{r}))$$

- In Kahlen-Lehman representation: the full LDA spectral function is given by the sum

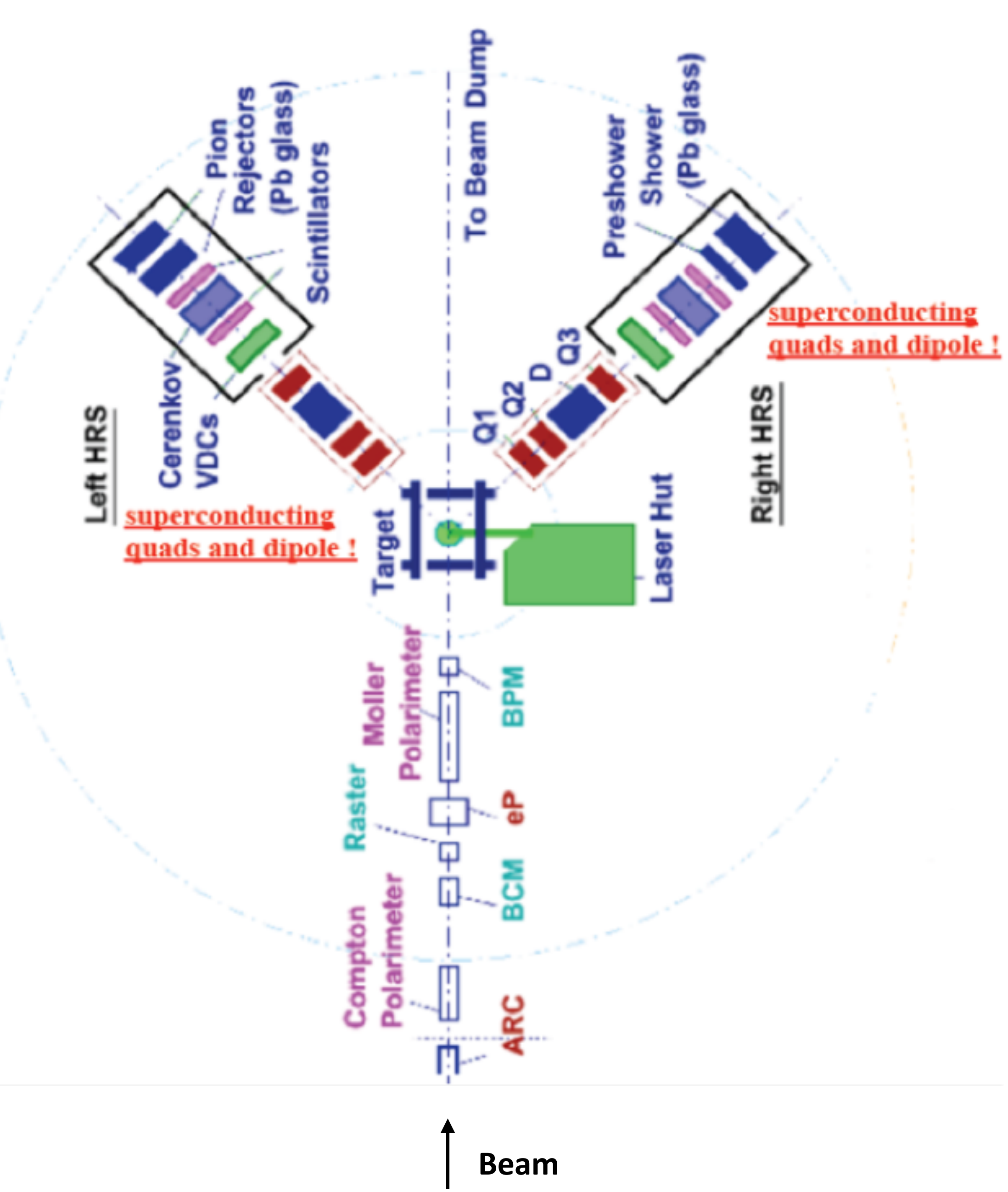
$$P(p_m, E_m) = P_{MF}(p_m, E_m) + P_{\rm corr}(p_m, E_m)$$

$$n(p_m) = \int dE \; P(p_m, E_m)$$



O. Benhar, S. C. Pieper, V. R. Pandharipande, Rev. Mod. Phys. 65, 817 (1993).

HALL A Schematics



HRS: High Resolution Spectrometer

High Resolution Spectrometer

Superconducting magnets:

- large acceptance in both angle and momentum
- good resolution in position and angle

Detector Package:

Vertical Drift Chambers:

- collecting tracking information (position and direction)

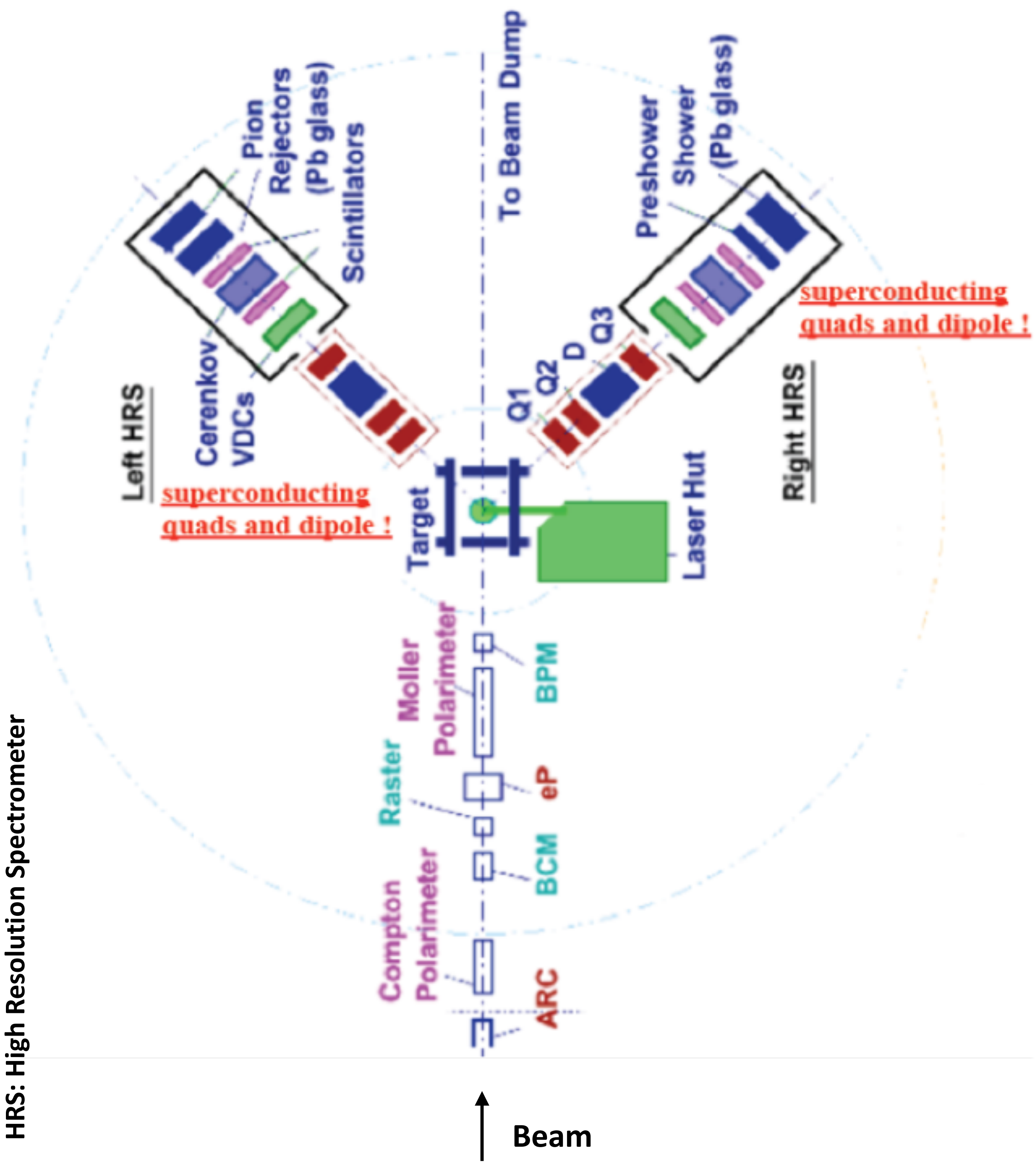
Scintillators:

- trigger to activate the data-acquisition electronics
- precise timing information for time-of-flight measurements and coincidence determination

Cherenkov:

- The particle identification, obtained from a variety of Cherenkov type detectors (aerogel and gas) and lead-glass shower counters

HALL A Schematics



HRS: High Resolution Spectrometer

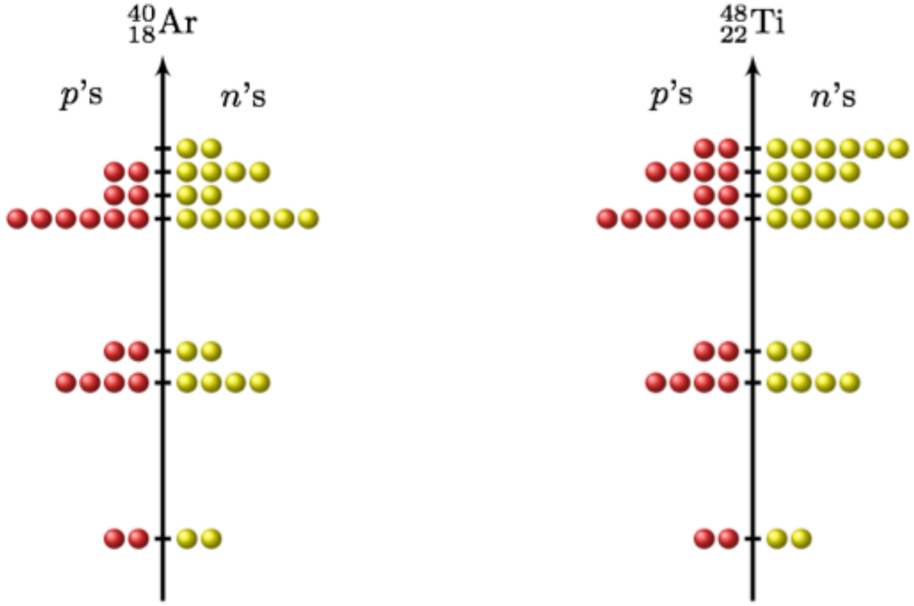
HALL A Characteristics

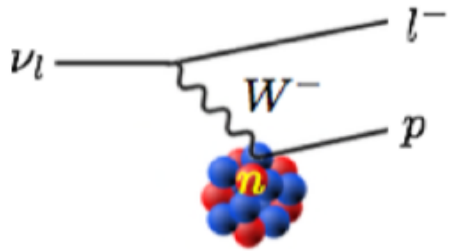
Beam energy resolution	5×10^{-4}
Momentum range	0.3 – 4.0 GeV/c
Momentum acceptance	$-4.5\% < \delta p/p < +4.5\%$
Momentum resolution	2×10^{-4}
Angular range	
HRS-L	$12.5^0 - 150^0$
HRS-R	$12.5^0 - 130^0$
Angular acceptance	
Horizontal	$\pm$ 30 mrad
Vertical	$\pm$ 60 mrad
Angular resolution	
Horizontal	0.5 mrad
Vertical	1.0 mrad

Why Titanium?

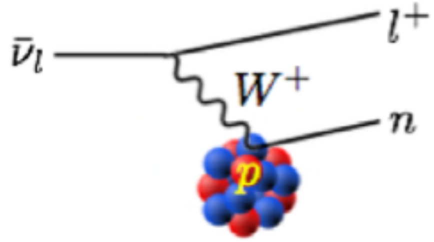
- The reconstruction of neutrino and antineutrino energy in liquid argon detectors will require the understanding of the spectral functions describing both neutrons and protons.

- Exploiting the correspondence of the level structures, the neutron spectral function of argon can be obtained from the proton spectral function of titanium.





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



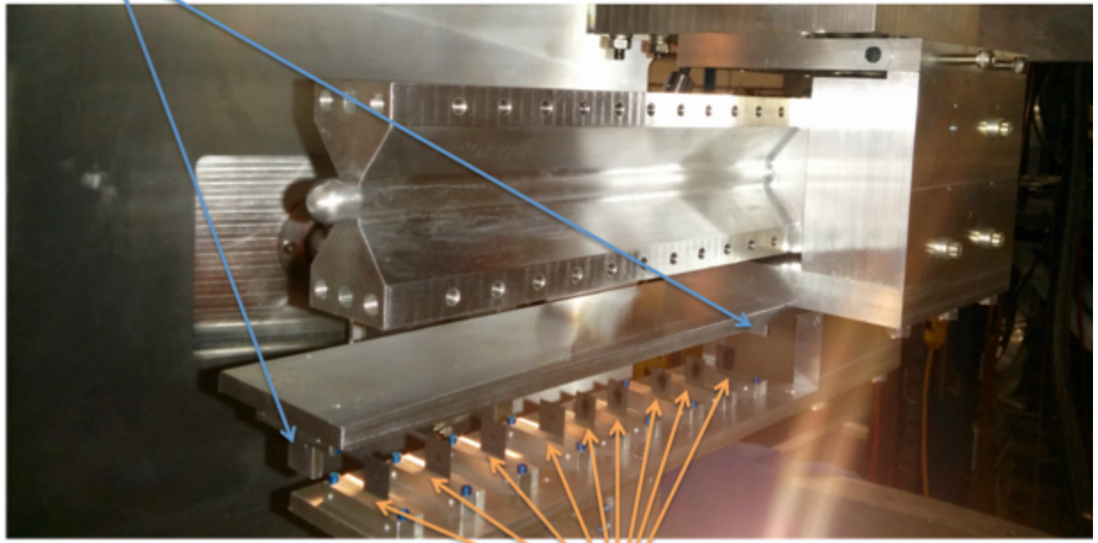
$$\bar{\nu}_l + p \rightarrow l^+ + n$$

Target setups

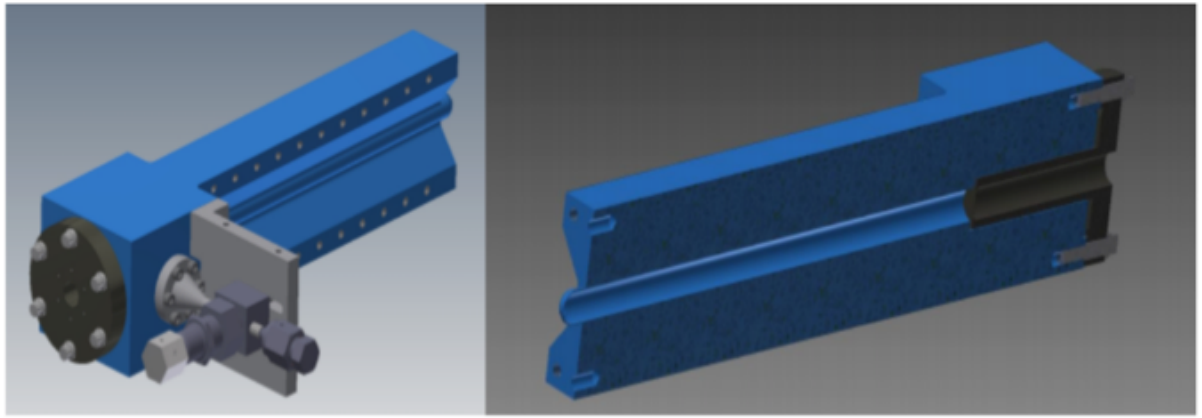
<u>Ar Target</u>

- 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)

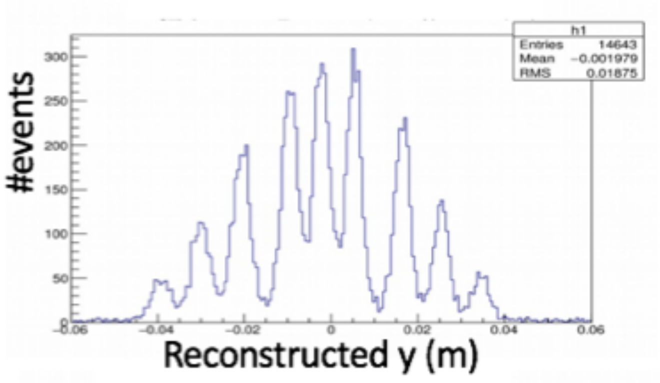


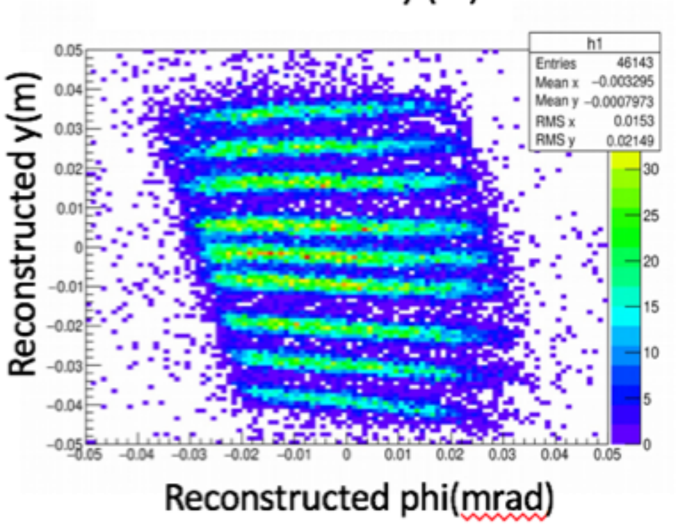
Target setups

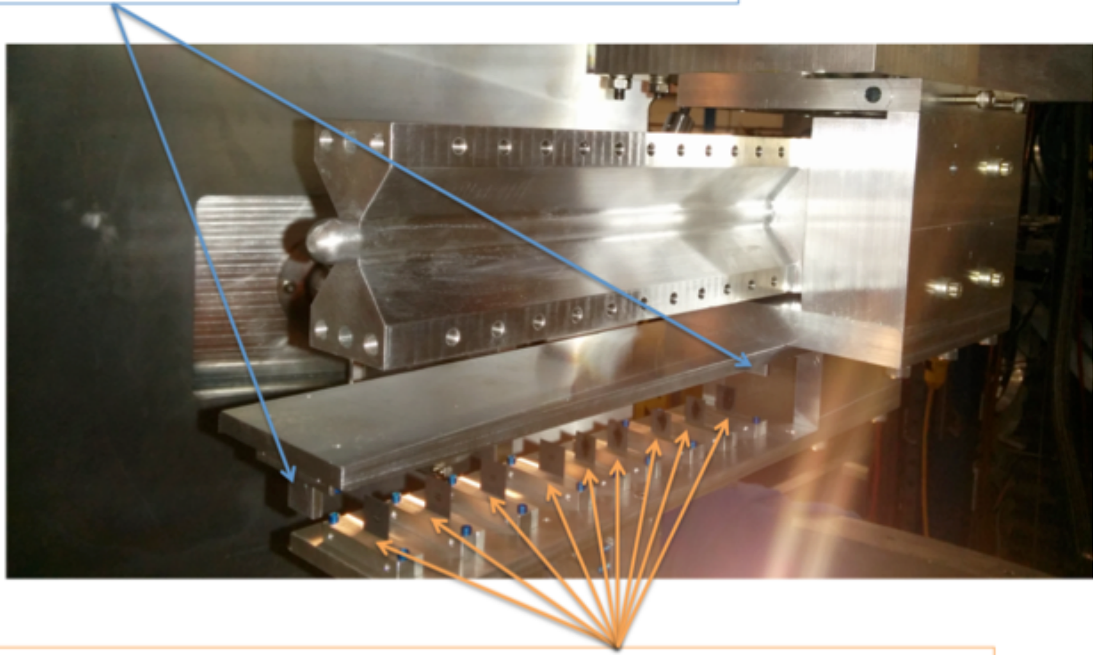
Dummy target: same as the entry and exit window as the gas target

Multiple foil:

LEFT







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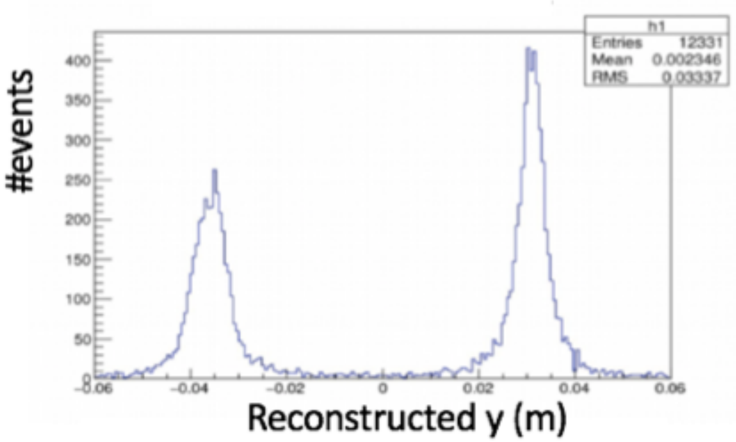
12

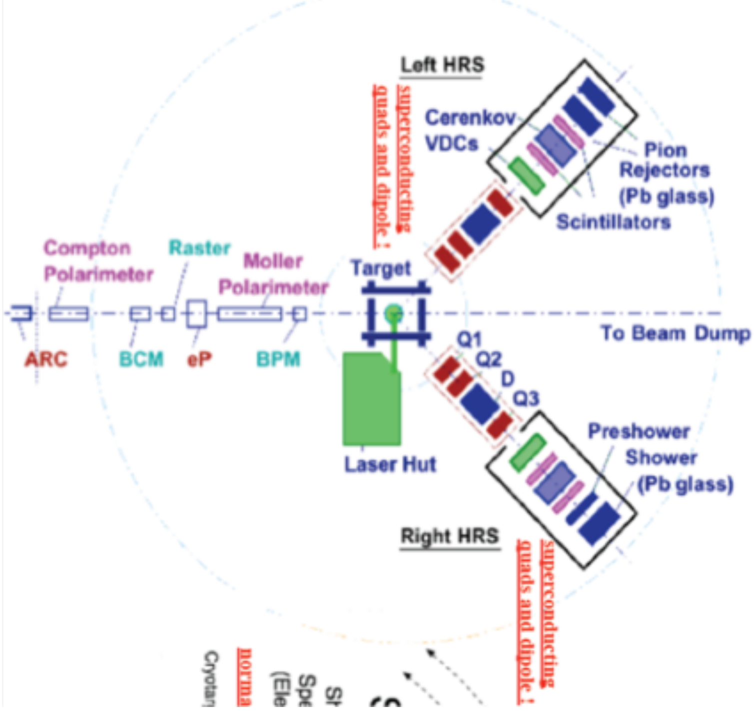
Dummy:

Left



Kinematic setups

	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	-	15.5	-	-	730.3	299.7



Run Period: Feb-March 2017

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

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
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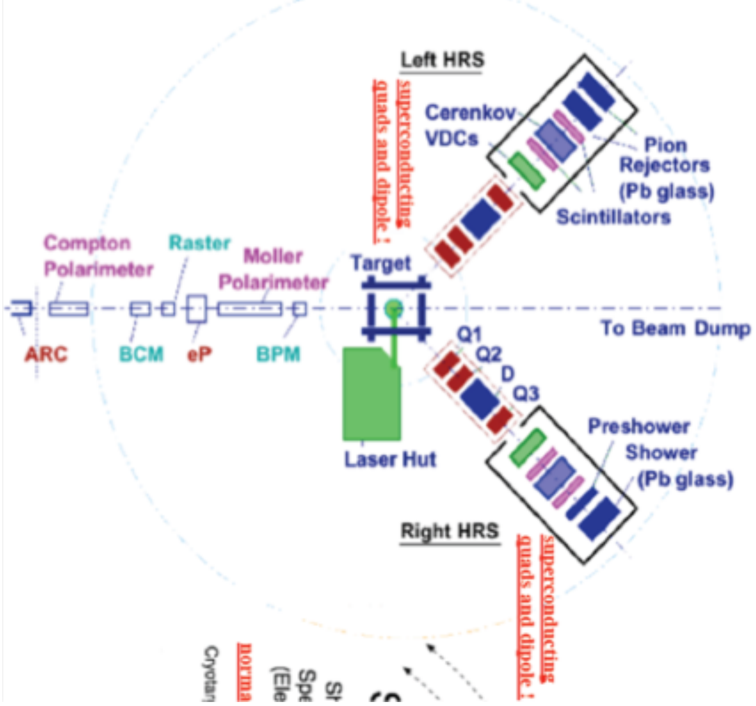

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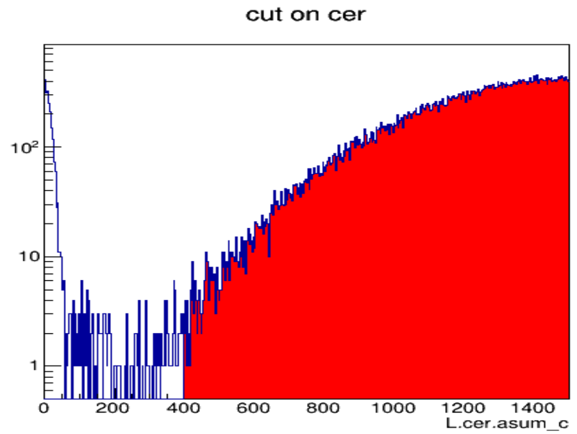
C	115	3957

C(e,e') Analysis:

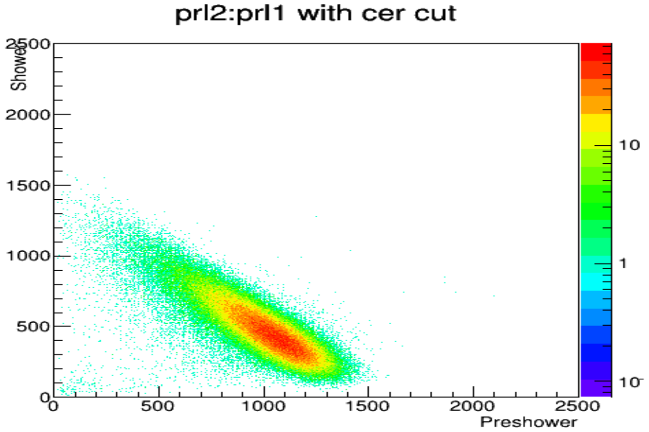
- *Analysis is mainly performed by graduate students - Hongxia Dai (VTech), Matt Murphy (VTech), and Daniel Abrams (UVA).*

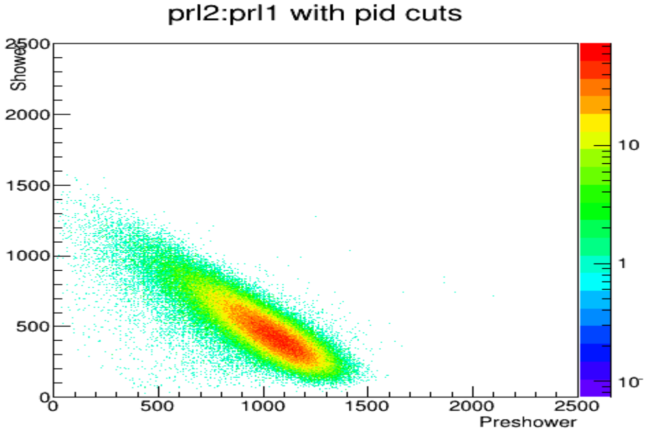
Particle Identification and Electron Selection



Cerenkov cut: cer > 400

Calorimeter cut: E/p > 0.3





- Charge symmetric background
  - e^- from pair production caused by different processes – negligible contamination.
- 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 %

Trigger Efficiency

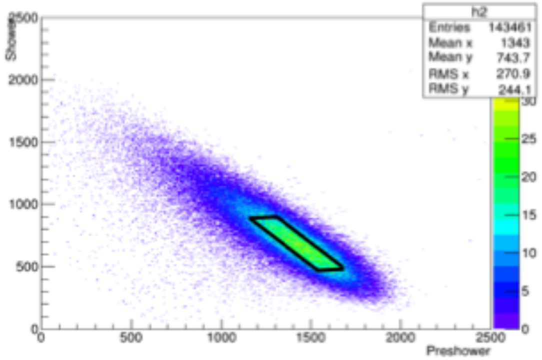
- Production trigger: T3: (S0&&S2) && (GC||PR) [LEFT]
- Efficiency trigger: T5: (S0||S2) && (GC||PR) [LEFT]
- Selected Sample
  - T5
  - Single track cut
  - Acceptance Cuts
  - PID Cuts
- $Eff = \frac{\#events\ with\ signal\ on\ both\ S0\ and\ S2}{\#sample\ events}$ ~ 99.9 %

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 %

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 i[th] bin:

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

Where,

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

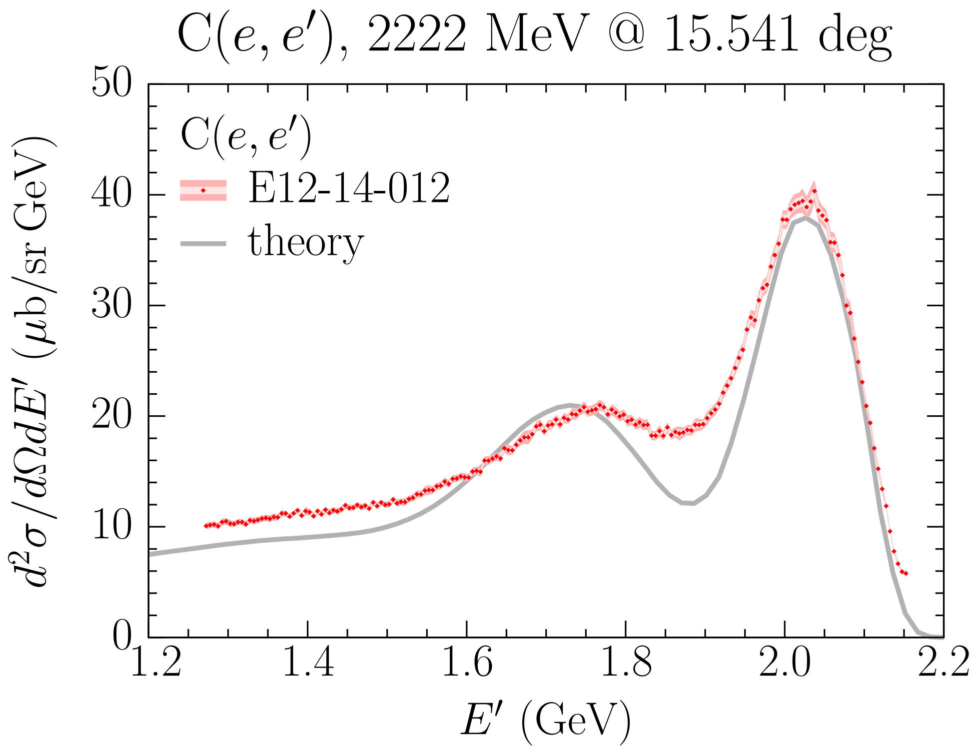
N_S^i : Number of scattered electrons
N_e : Total number of electrons in the beam
ϵ_{eff} : Total efficiency

▪ C(e,e') cross section:

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

- Error bars up to ~ 2.5%, corresponding to the statistical (1.2%) and systematic (2.2%) uncertainties summed in quadrature.

- **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.

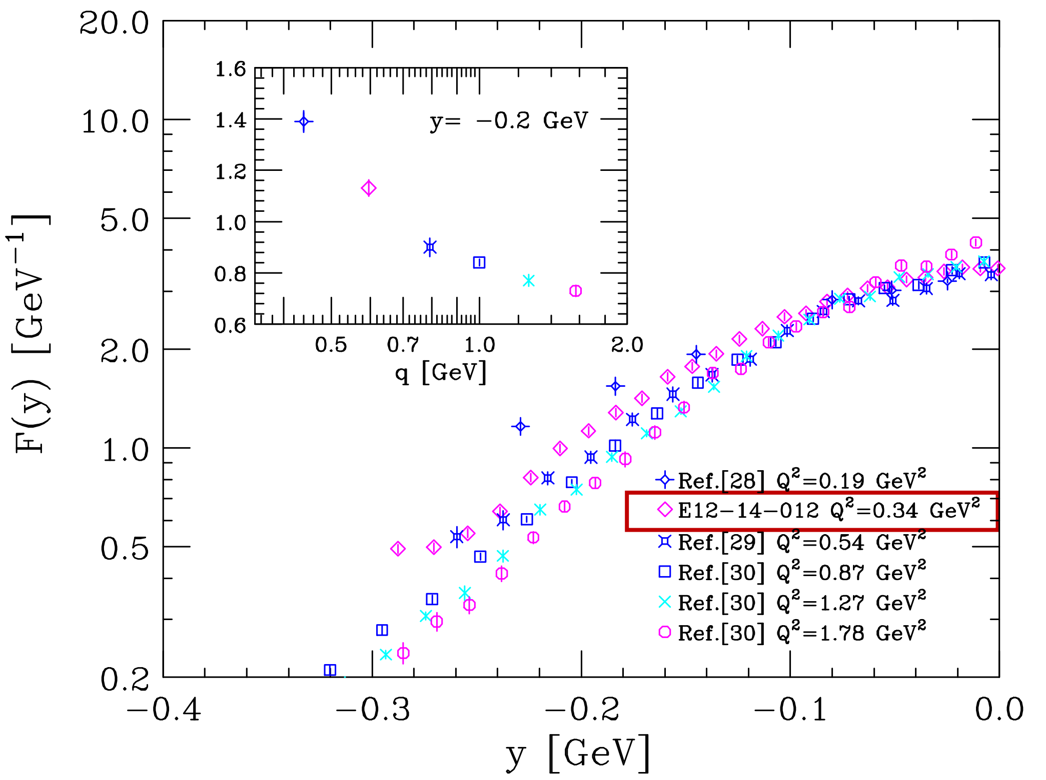


- **C(e,e’) measurements in comparison to previous data**

NEW RESULTS

- 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| ≈ 600 MeV, the effects of FSI are still significant.
  - Our results are fully consistent with those of previous experiments.



[28] J. S. O’Connell et al., Phys. Rev. C 35, 1063 (1987).
[29] R. M. Sealock et al, Phys. Rev. Lett. 62, 1350 (1989).
[30] 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 electron-scattering studies carried out using a titanium target (no MC model), we determine the **Ti(e,e')** cross section using:

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

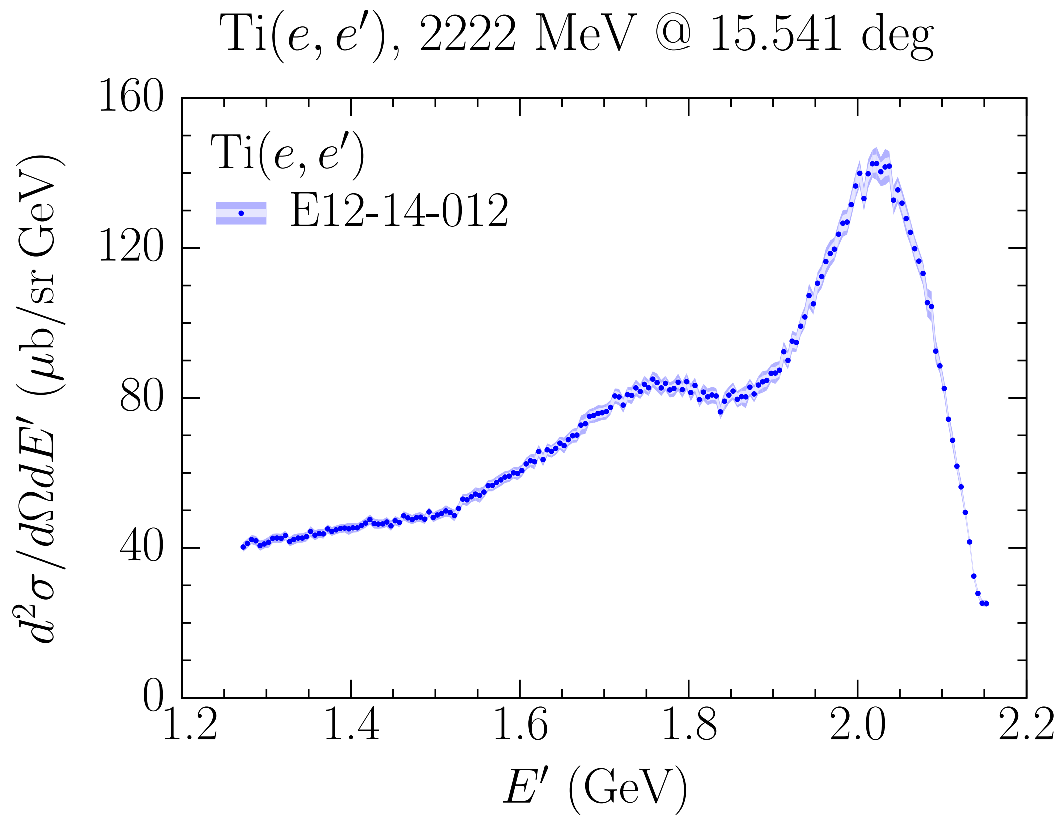
- In this approach, most of the systematic uncertainties are fully correlated between C and Ti, due to the fact that the data was collected in the same kinematical setup and analyzed using the same cuts of the carbon data.

NEW RESULTS

- **Ti(e,e') cross section:**

  - The first electron-scattering data ever collected on titanium target.

- Error bars up to ~ 2.75%, corresponding to the statistical (1.65%) and systematic (2.2%) uncertainties summed in quadrature.

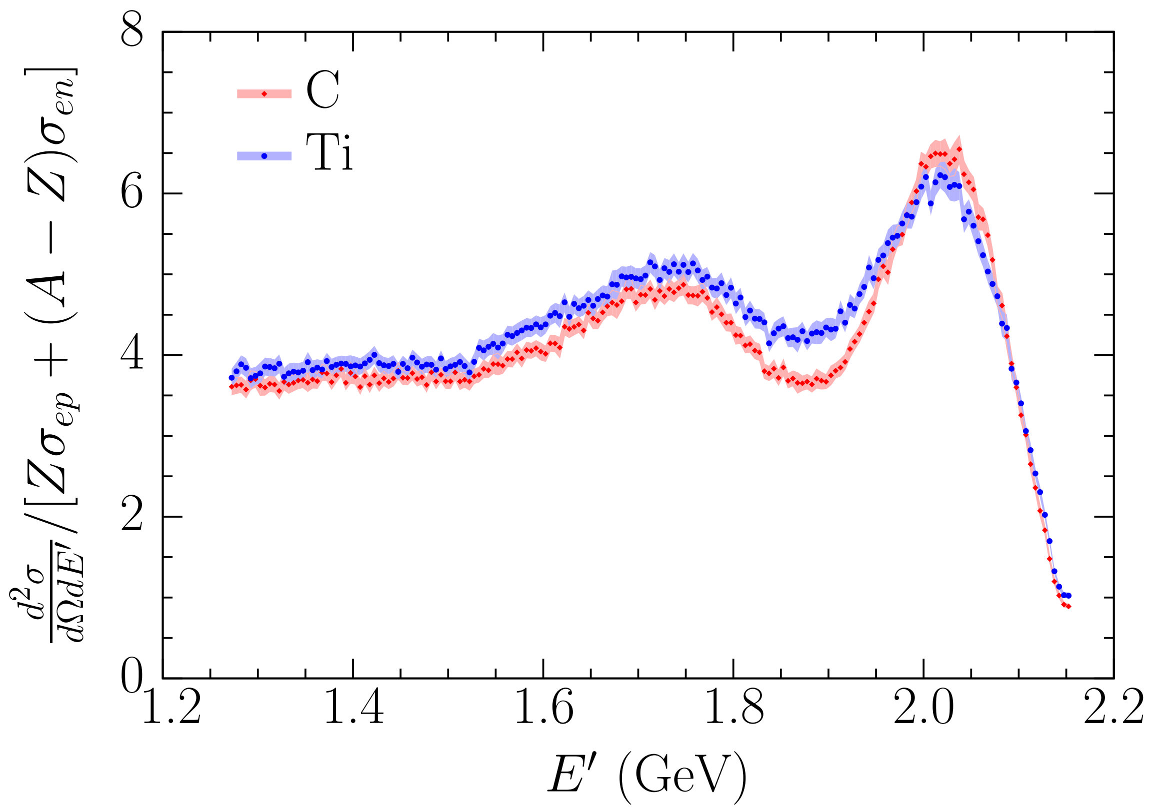


- **Comparing Ti(e,e') and C(e,e') cross sections:**

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

- The quantities σ_{ep} and σ_{en} are the elementary electron-proton and electron-neutron cross sections in the QE channel stripped of the energy-conserving delta function.

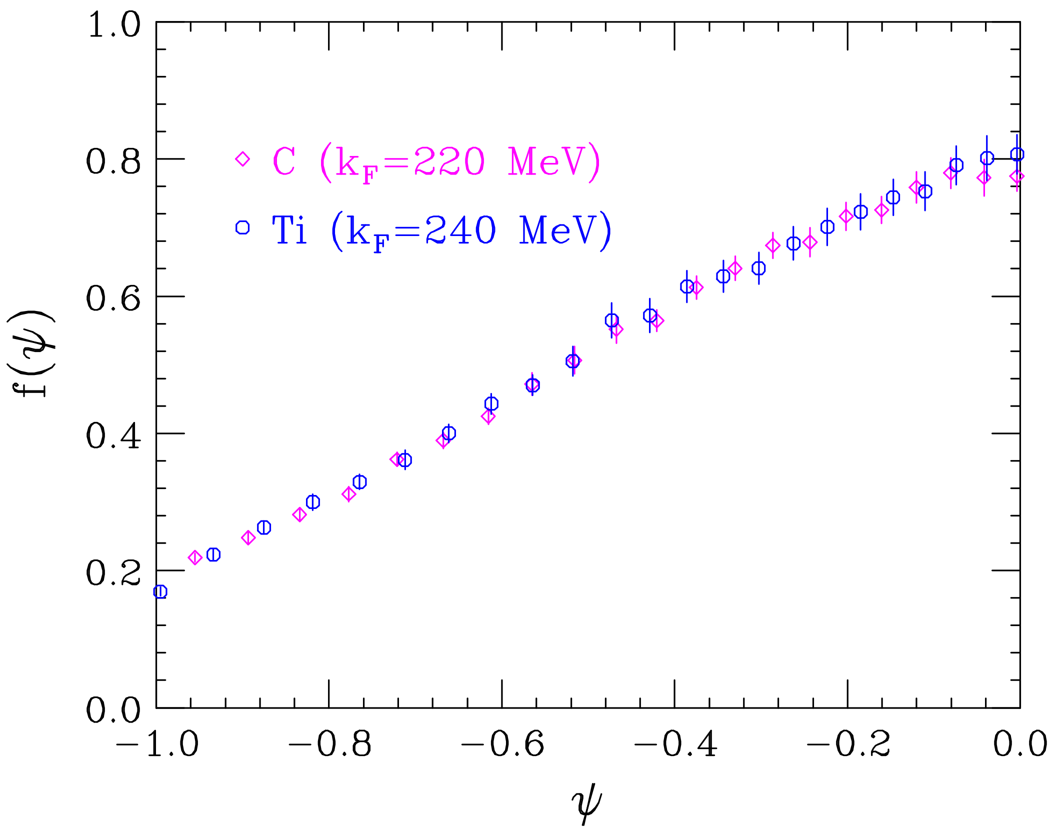
- The difference between the results obtained using the measured carbon and titanium cross sections reflect different nuclear effects.



NEW RESULTS

- **Scaling of second kind:**

- The difference between C and Ti cross sections, which reflect different nuclear effects, can be conveniently parametrized in terms of a nuclear Fermi momentum exploiting the concept of superscaling.



Summary

- The progress in accelerator-based neutrino-oscillation experimental program, and the search for CP violation in leptonic sector is substantially challenged by the lack of precise understanding of the neutrino-nucleus signal in the detector resulting into high systematic uncertainties.

- The challenges are magnified with the use of liquid Argon TPC [LArTPC] (in the SBN program leading to DUNE) with almost non-existent knowledge of the electroweak response of the ^{40}Ar.

- JLab Ar-Ti (e,e'p) experiment (E12-14-012) took data successfully in 2017.

- The first results, consisting of the Ti(e,e') and C(e,e') cross sections at beam energy E = 2.222 GeV and scattering angle θ =15.541 deg with uncertainties < 2.75%, are presented and will be available online this week.

- Our measurement, providing the first experimental information ever on electron-titanium scattering, will be of great value for the development of realistic models of the electroweak response of neutron-rich nuclei.

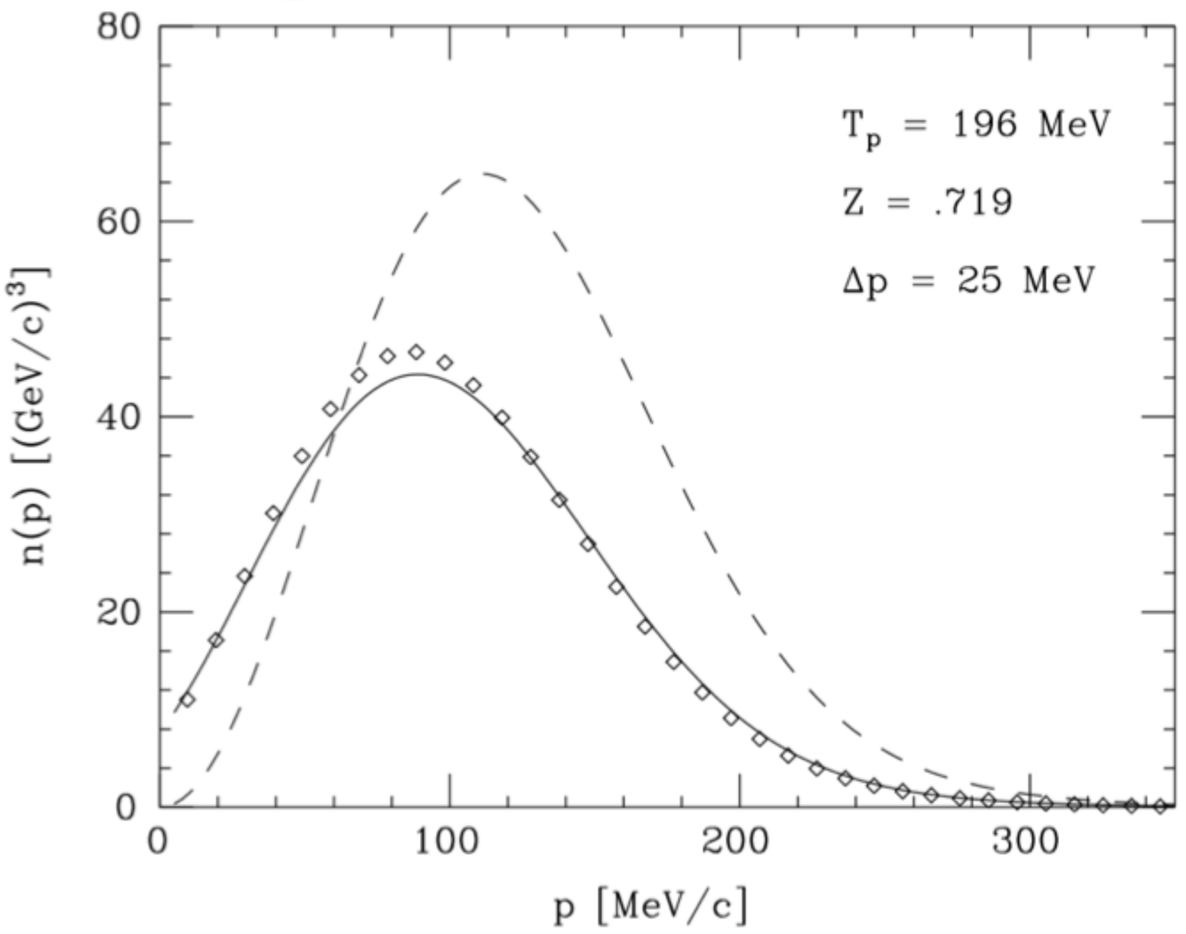
- Stay tuned for our first argon results - Ar(e,e') cross section – this summer!

Back-up

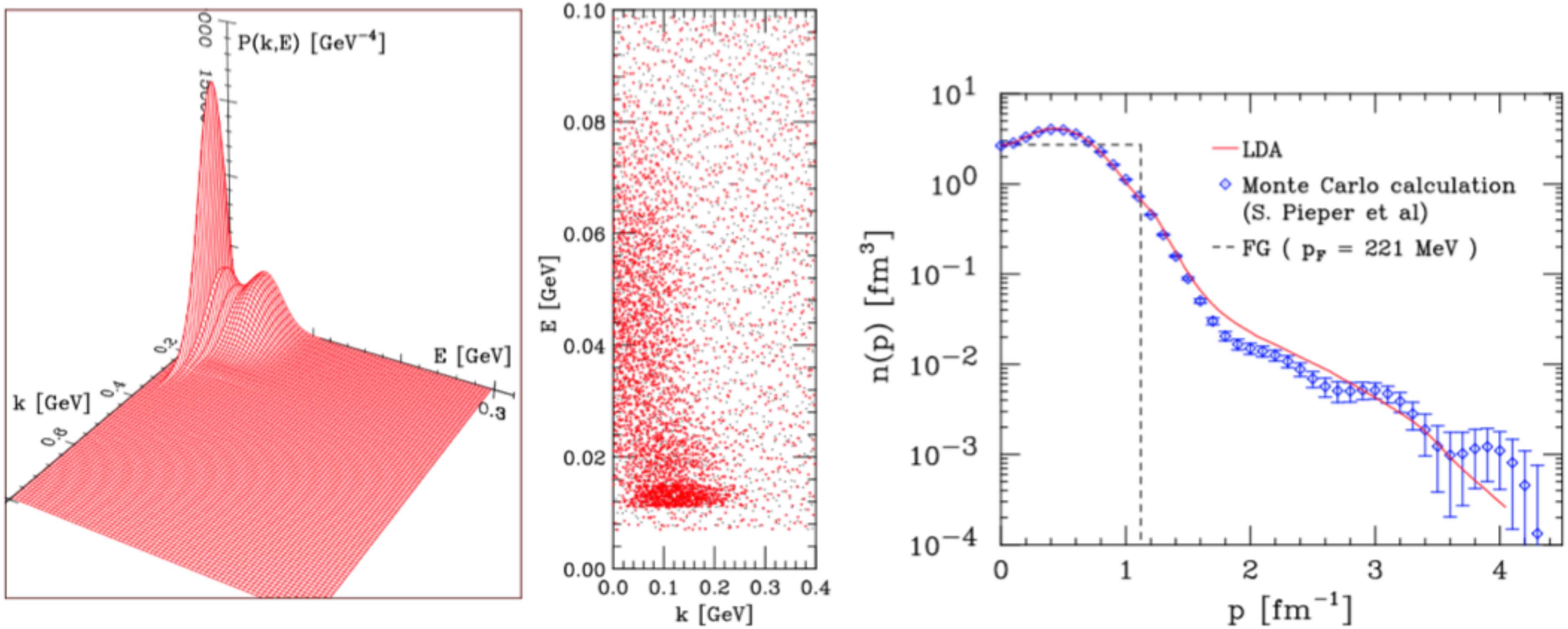
Inclusion of Final State Interations

- The Distorted Wave Impulse Approximation (DWIA), obtained from a complex potential fitted to proton-nucleus scattering data.

- The real part of the optical potential shifts the momentum distribution of the shell model states by an amount Δp, while inclusion of the the imaginary part leads to a significant reduction of the PWIA result, typically by a factor $Z \sim 0.7$.



Oxygen Spectral Function



- FG model: $P(\mathbf{p}, E) \propto \theta(p_F - |\mathbf{p}|)\, \delta(E - \sqrt{|\mathbf{p}|^2 + m^2} + \epsilon)$
- shell model states account for $\sim 80\%$ of the strenght
- the remaining $\sim 20\%$, arising from NN correlations, is located at high momentum *and* large removal energy ($|\mathbf{p}| \gg p_F \sim 220$ MeV, $E \gg \epsilon$)

Kinematic setups