JLab E12-14-012 experiment: 2014-2023

C. Mariani
On behalf of the E12-14-012 collaboration
Center for Neutrino Physics, Virginia Tech

Marciana 2023- Lepton Interactions with Nucleons and Nuclei

VIRGINIA TECH

Hongxia Dai
Graduate student VT
(PhD 2019)

Linjie Gu
Graduate student – VT
(PhD 2021)

Matthew Murphy
Graduate student - VT
(PhD 2020)

Daniel Abrams
Graduate student – UVA
(PhD 2021)

Austin Batz
REU student
2019 - VT

Matthew Barroso
REU student
2020 - VT

Adam Dirincan and Zack Jerzyk
REU student 2021 - VT

Dr. Libo Jiang

Post-doc research associate - VT

Dr. Artur Ankowski

Research associate - SLAC

Albrun Johnson
REU student
2022 - VT

Outline

- 2014 – Omar's PAC 42 talk that started our experiment journey

- E12-14-012 Motivations:
    - Neutrino Oscillation Experiments
    - Importance of cross sections in oscillation results
    - Limitation and sample implementation in Neutrino Event generator

- Experimental setup
    - Kinematic configurations
    - Target

- (e,e') results on C, Ar, Ti and Al

- (e,e'p) results on Ar and Ti

2014: Benhar's talk at PAC-42

Measurement of the Spectral Function of ^{40}Ar through the $(e, e'p)$ reaction

PR12-14-012

Omar Benhar

INFN and Department of Physics
"Sapienza" Università di Roma. I-00185 Roma, Italy

PAC 42 Meeting
Jefferson Lab, July 30, 2014

Motivation

- ⋆ The interpretation of the signals detected by most neutrino experiments require a *quantitative* understanding of the nuclear response to electroweak interaction
- ⋆ The results of numerical studies suggest that the impact of nuclear modelling on the determination of oscillation parameters may be of the order of 10%
- ⋆ Over the past decades electron scattering has provided a wealth of information (nucleon form factors, inclusive double differential cross sections, coincidence, semi-inclusive cross sections) that are now beginning to be exploited in the analysis of neutrino data
- ⋆ Currently unavailable electron scattering data will be needed for the analysis of future, high precision, neutrino experiments using liquid Argon detectors
- ⋆ The proposed measurement will provide information required for the simulation of neutrino interactions in argon *in all channels*

Neutrino physics

ν_e, ν_μ, ν_τ

Elementary particles

Weak interaction only

Extremely light

($\Sigma m_\nu < 0.3$ eV)

$\nu \neq \bar{\nu}$?

Dirac or Majorana?

Right-handed ν?

Sterile ν?

Absolute mass?

Why so small?

Neutrinos oscillate!

3 mixing angles & 2 Δm^2 measured

(PMNS matrix)

θ_{23} octant?

$\delta_{CP} \neq 0$?

Majorana phases?

Mass hierarchy?

Matter effects?

Many sources

Solar, atmospheric, supernovae, relic, Earth...

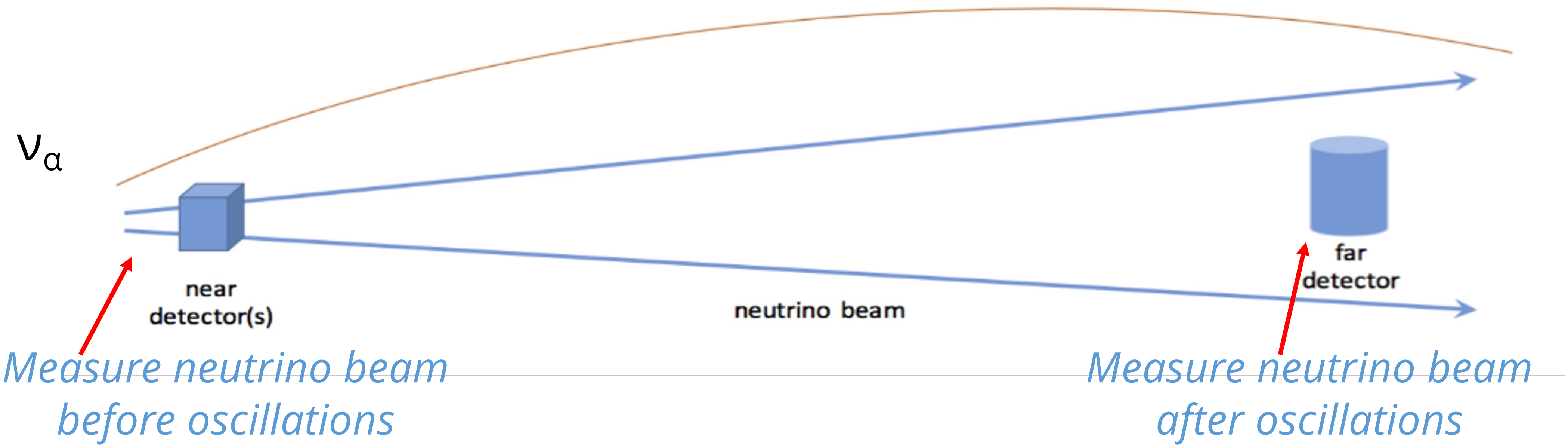
ν astronomy?

High-energy?

Low-energy?

Neutrino physics is a very rich field of research...

Neutrino Oscillation Experiments



Signature of Neutrino Oscillation

- Neutrino Spectrum Distortions

Near to Far extrapolation

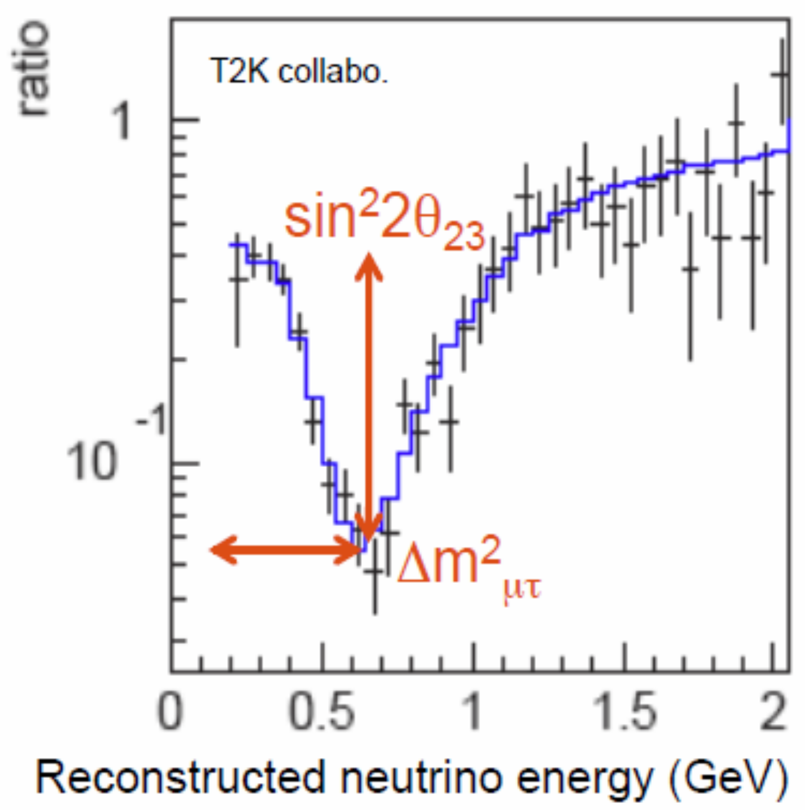
- Provides data-driven estimate of un-oscillated event rate at the Far detector.
- Neutrino spectrum distortions calculated from the ratio of neutrino spectrum at far detector to un-oscillated predicted event rate at far detector
- Influenced by uncertainties in the knowledge of flux and cross sections.

Observable Oscillation Parameters

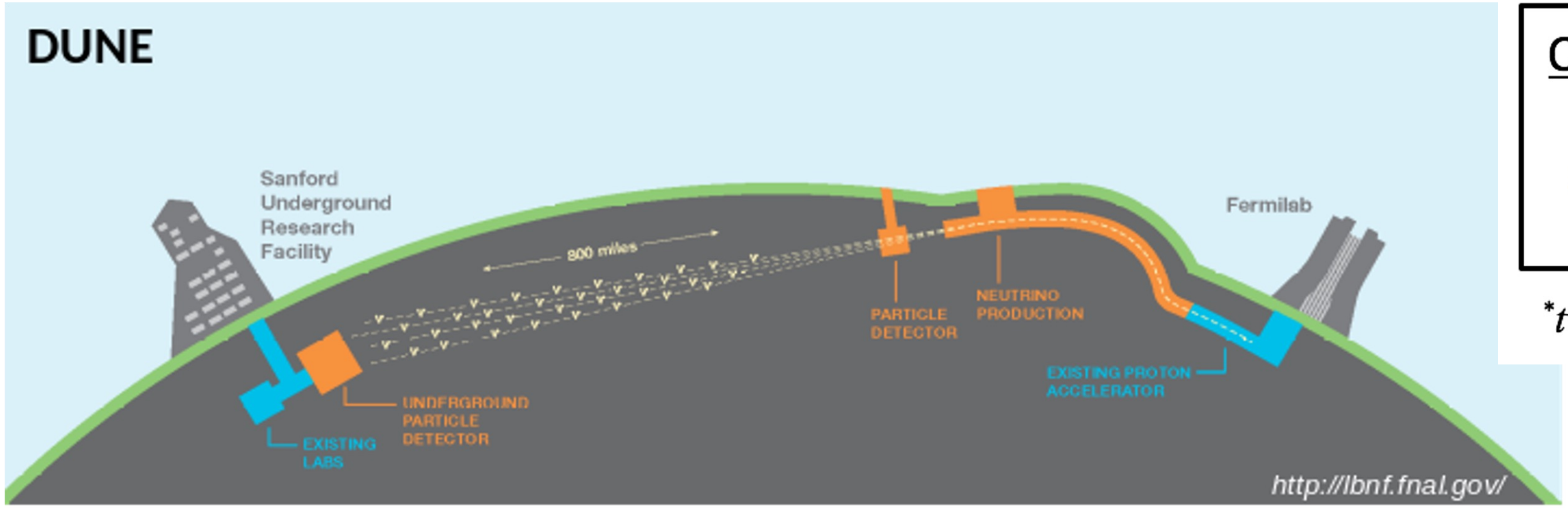
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Neutrino energy >1 GeV

Oscillation parameter determination depends on the reconstructed neutrino energy.



DUNE Experiment as an example



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:

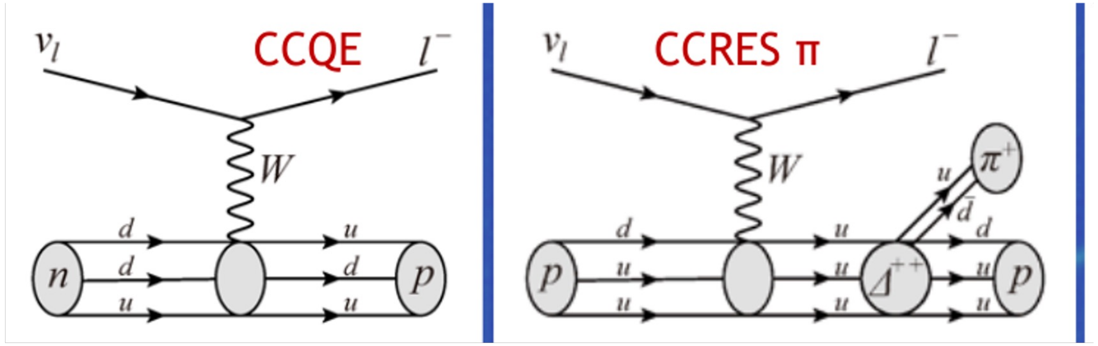
Event Rate at near detector:

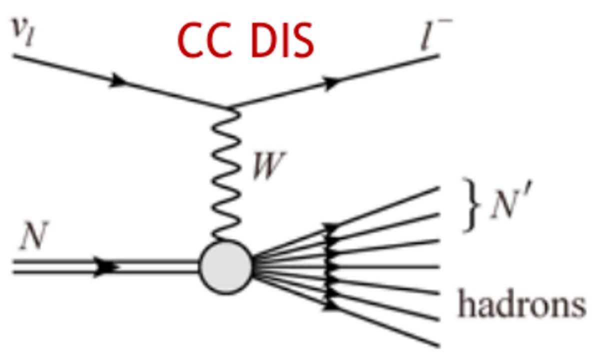
$$N^{\alpha}_{\mathrm{ND}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times \sigma^i_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

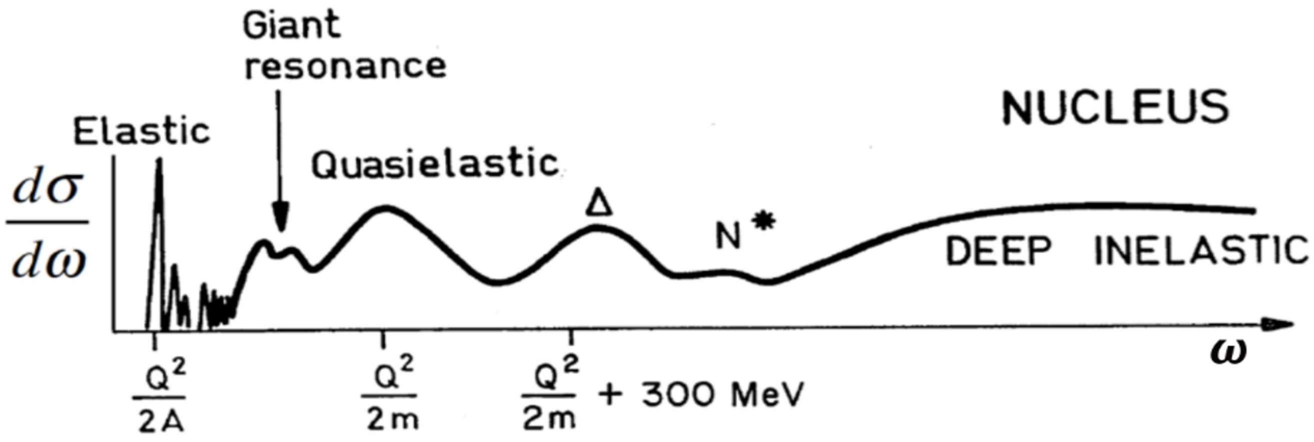
Event Rate at far detector:

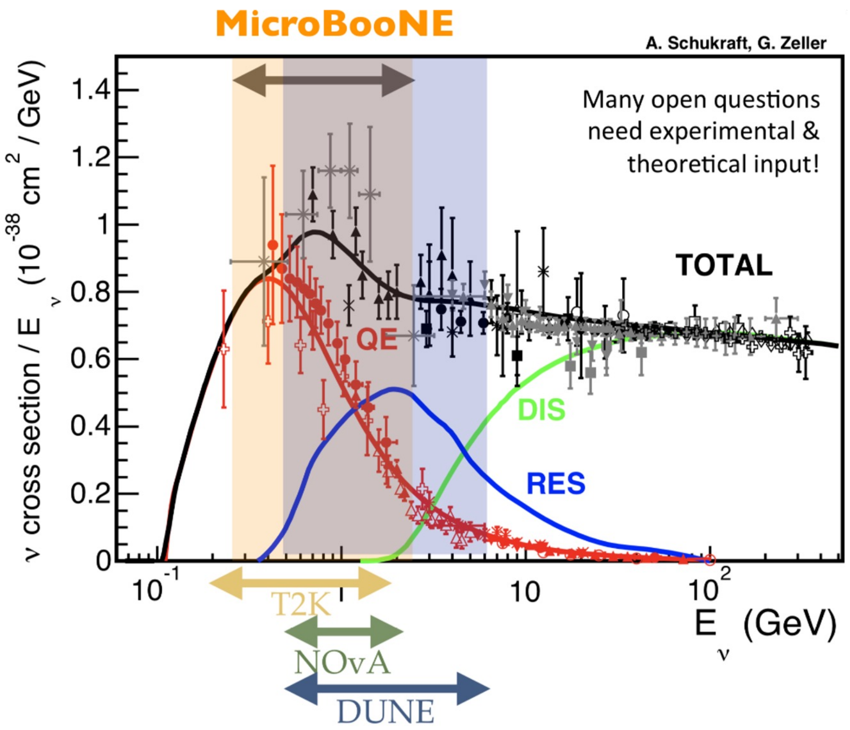
$$N^{\alpha\to\beta}_{\mathrm{FD}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma^i_\beta(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

Neutrino Interactions









Neutrino Oscillations

Neutrino Event Rate:

$N_{FD}(\mathbf{E_\nu}) = \Phi(\mathbf{E_\nu}) \times \sigma(\mathbf{E_\nu}) \times \varepsilon \times \mathbf{P(\nu_\alpha \to \nu_\beta)}$

- $\Phi(\mathbf{E_\nu})$: Flux, $\sigma(\mathbf{E_\nu})$: Cross section
  ε: detector efficiency
- Cross sections always one of the major contributors
- More for T2K (E_ν~0.7GeV) than NOvA (E_ν~2.4GeV)
- DUNE will detect pions, protons, neutrons, etc. with enough accuracy to get neutrino energy accuracy of a few %

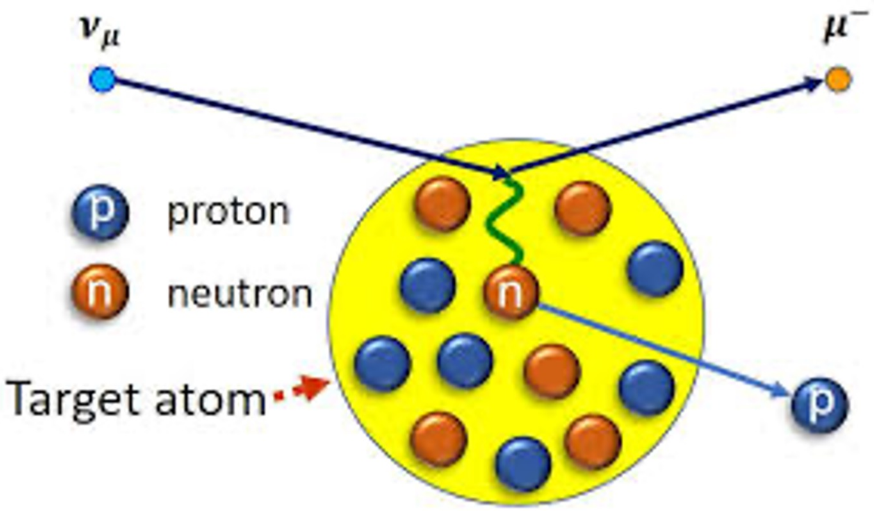
T2K: Systematic uncertainties on far detector event yields

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interactions	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

PRL 121, 171802 (2018)

T2K and NOvA use targets like Carbon and Oxygen for which a lot of existing data and measurements are available. DUNE will use Argon as neutrino target, limited data is available on Argon.

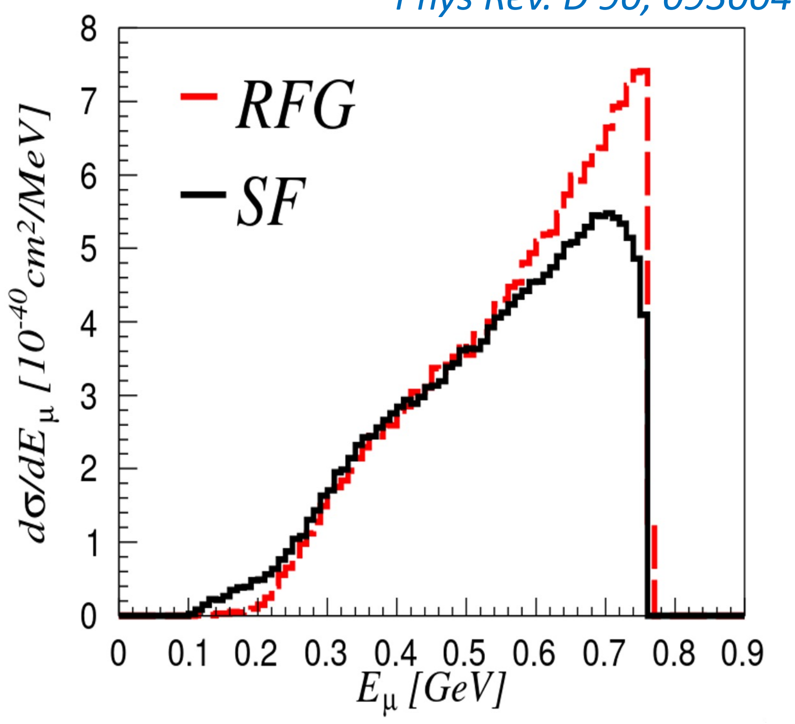
Nuclear Effects - Fermi Motion



All the nucleons embedded in nucleus

- Fermi Motion
  - Determines the momentum/removal energy of the nucleons
  - Models: Fermi Gas, Local Fermi Gas, Spectral functions ……
- Binding energy
  - Models: Constant or dependent on position

Phys Rev. D 90, 093004 (2014)



$$\nu + \mathrm{Ar} \rightarrow \mu + X$$

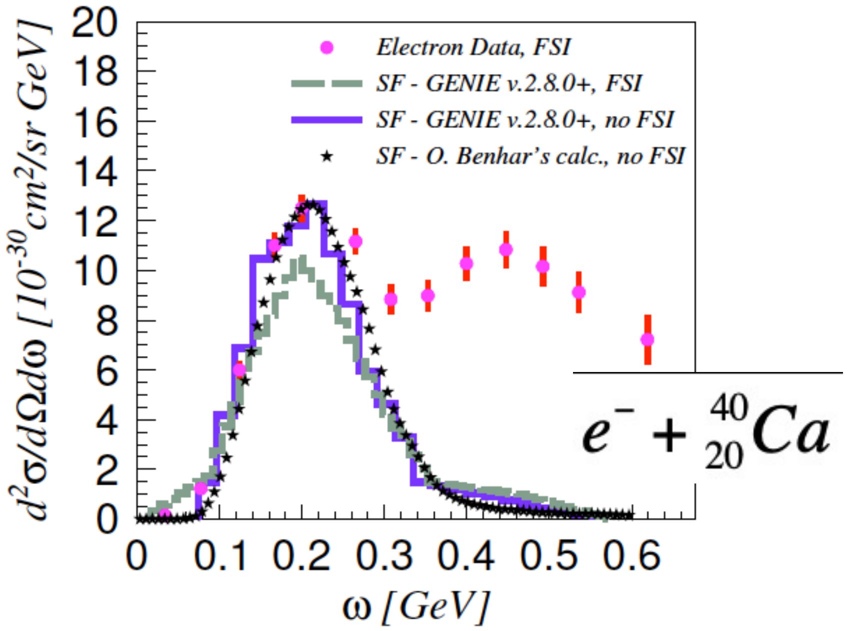
- CCQE interactions in GENIE with both FSI and Pauli blocking included

Phys Rev. D 90, 093004 (2014)
Physics Reports 700 (2017)

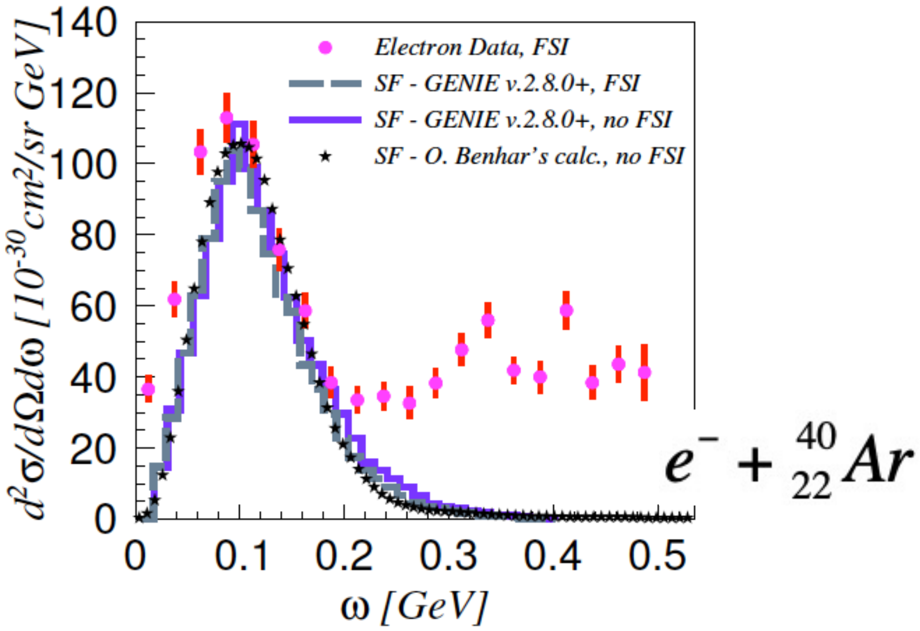
2014: GENIE 2.8.0 + νT *Phys Rev. D 90, 093004 (2014)*

VT group did an implementation in the most used neutrino generator of Spectral Function

E_e=0.841 GeV and θ_e=45.5 deg



E_e=0.7 GeV and θ_e=32 deg



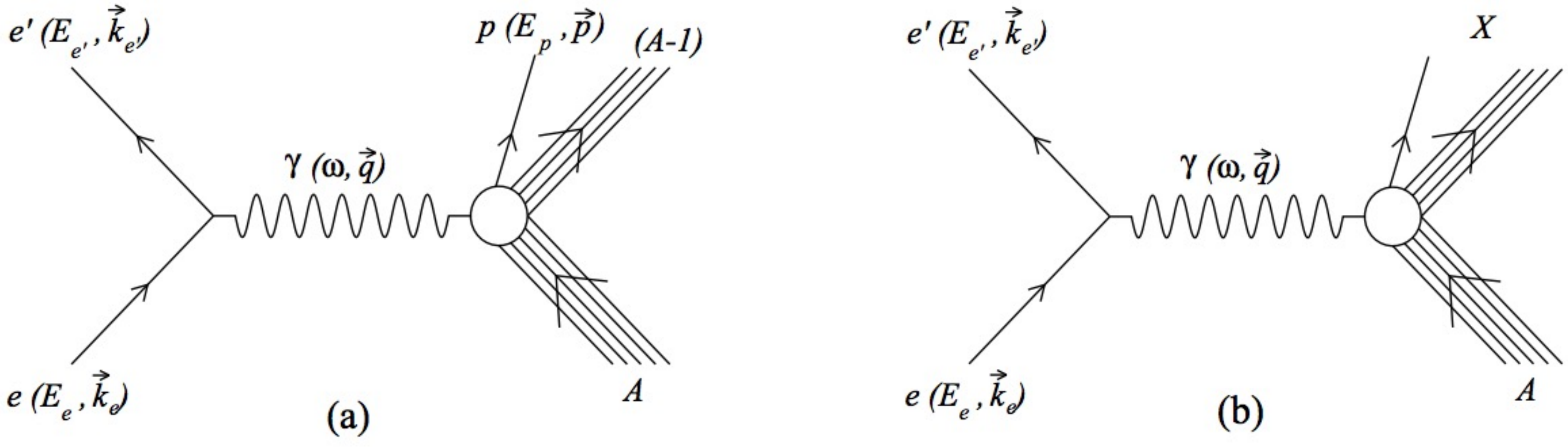
(e,e’) and (e,e’p) processes

- (e, e’p) process (exclusive):
  Both outgoing electron and proton are detected

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

- (e,e’) process (inclusive):
  Only scattered electron is detected

$$e + A \to e' + X$$



(*e,e'p*) cross section

spectral function

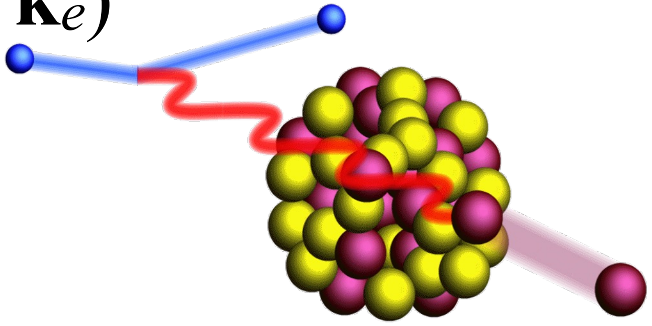
- $(e, e'p)$ cross section

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

- The spectral function describing the probability of removing a nucleon of momentum $\mathbf{p}$ from the nuclear ground state, leaving the residual system with excitation energy E, is trivially related to the two-point Green's function through

$$P(\mathbf{k}, E) = -\frac{1}{\pi} \text{Im}\ G(\mathbf{k}, E)$$

Missing momentum $\mathbf{p}_m$ and missing energy E_m



Without final-state interactions,

$$E_e + M - \underline{E_m} = E_{e'} + E_{p'}$$

known

$$\mathbf{k}_e + \underline{\mathbf{p}_m} = \mathbf{k}_{e'} + \mathbf{p}'$$

$E_m - E_{\text{thr}}$ is the excitation energy

$p_m \equiv |\mathbf{p}_m|$ is the initial proton momentum

Analysis procedure

- ⋆ The measured reduced cross-section defined as

$$P_D(p_m, E_m) = \frac{1}{|\mathbf{p}'|E_{\mathbf{p}'}} \frac{1}{\sigma_{ep}} \frac{d\sigma_A}{dE_{e'} d\Omega_{e'} dE_p d\Omega_p} \ ,$$

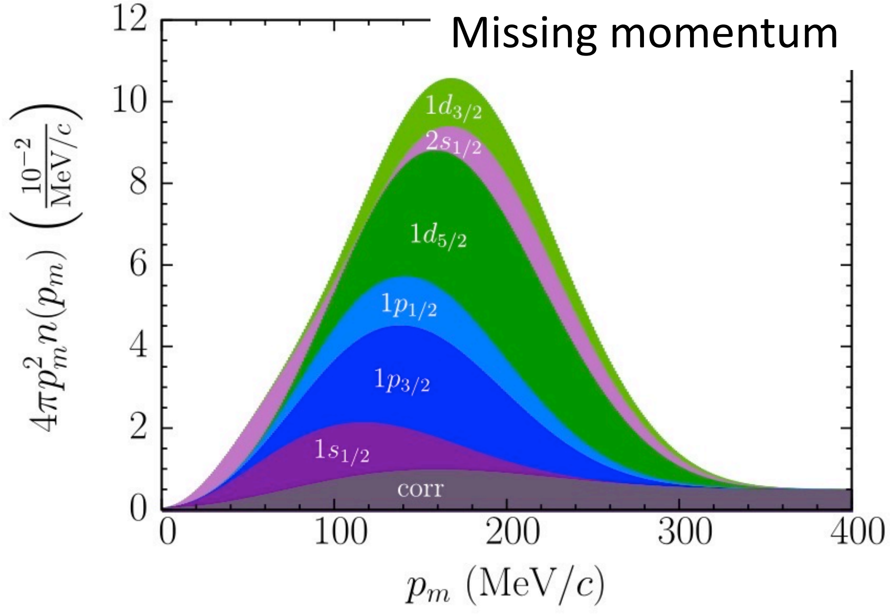
obtained using the off-shell extrapolation of the electron-proton cross section of De Forest (cc1 model), has been fitted using the model distorted spectral function

$$P_D(p_m, E_m) = \sum_h Z_h |\phi_h^D(\mathbf{p}_m)|^2 F_h(E_m - E_h) + P_{\rm corr}^D(p_m, E_m) \ ,$$

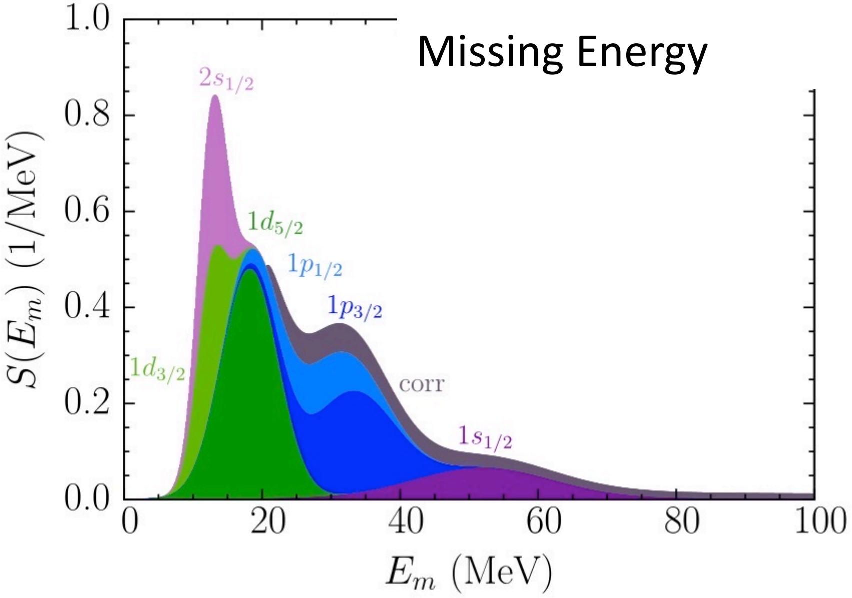
- ⋆ The unit normalised distorted momentum distributions, $|\phi_h^D(\mathbf{p}_m, \mathbf{p})|^2$ are obtained from Relativistic Mean Field calculations (code provided by Carlotta Giusti)
- ⋆ The energy distributions $F_h(E_m - E_h)$, of width Γ_h, have been assumed to have gaussian shape
- ⋆ Correlation contribution, accounting for 20% of the strength, described following a simple model developed by Ciofi degli Atti & SImula

Main Elements of the Exclusive Analysis

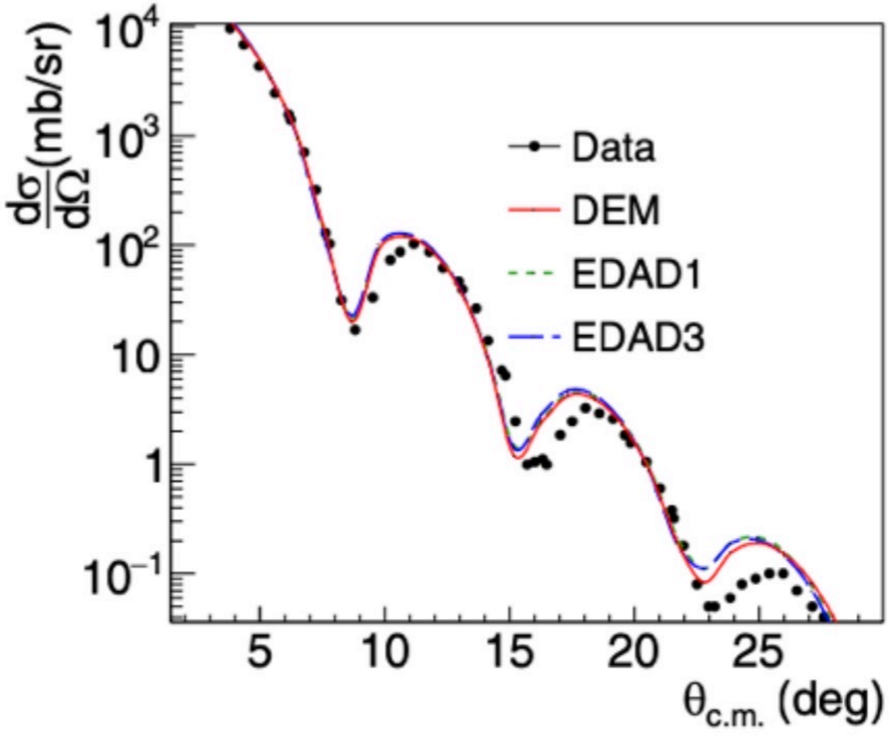
Missing momentum



Missing Energy

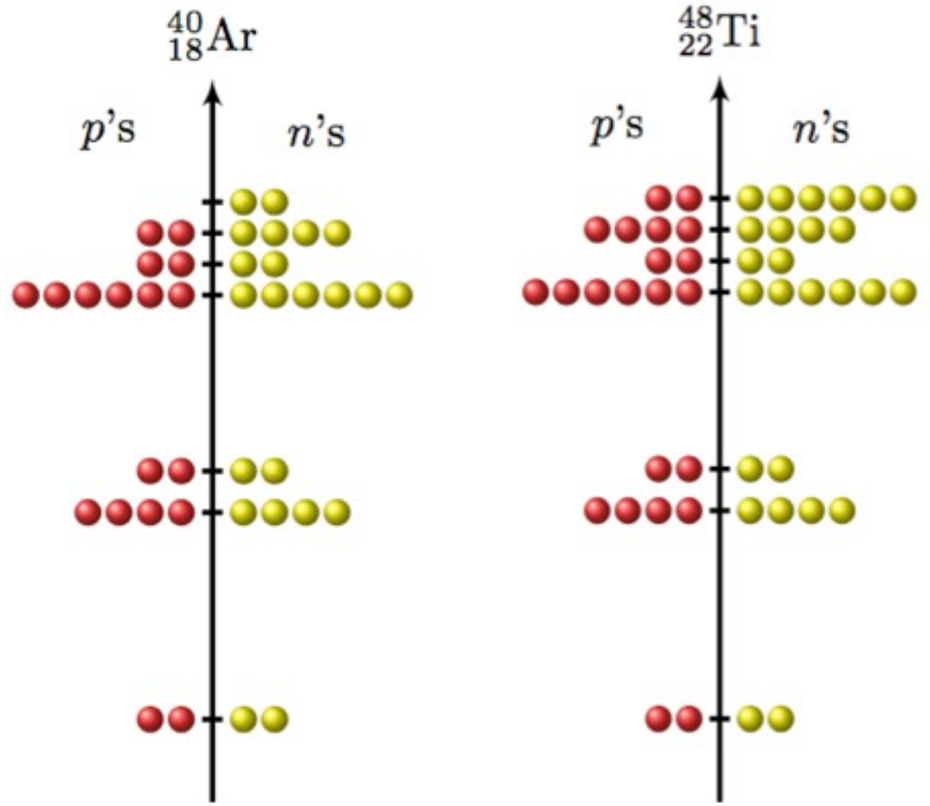


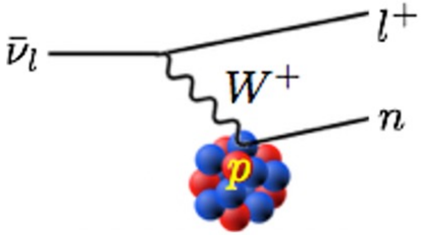
Differential cross section for elastic scattering of 800 MeV protons on Argon. Theoretical results obtained from the optical potential employed in the analysis



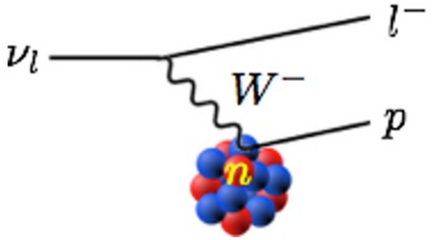
Titanium Idea – extension physics reach

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

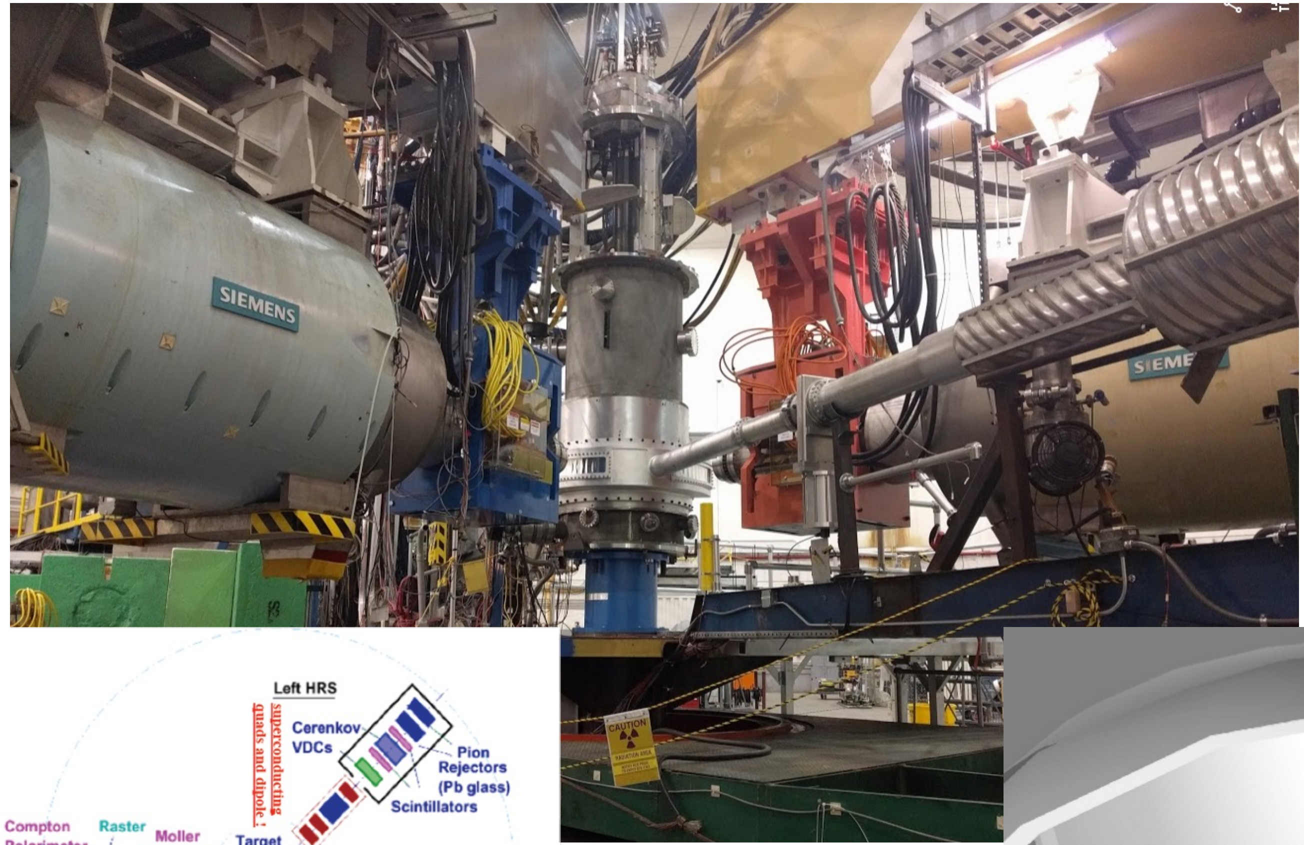
Relevance to Neutrino Experiments

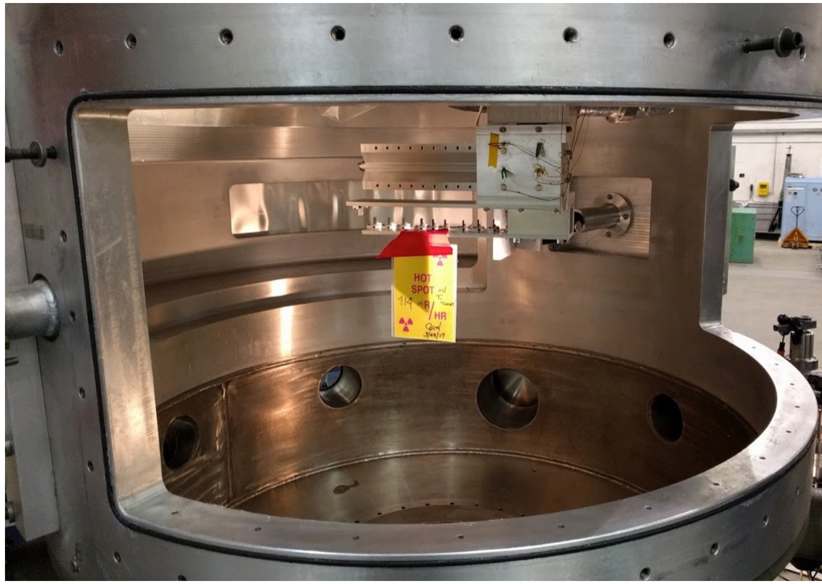
- ⋆ The approach based on factorisation and the spectral function formalism provides a fully consistent theoretical framework, uniquely suited to meet the challenges posed by the interpretation of neutrino interactions

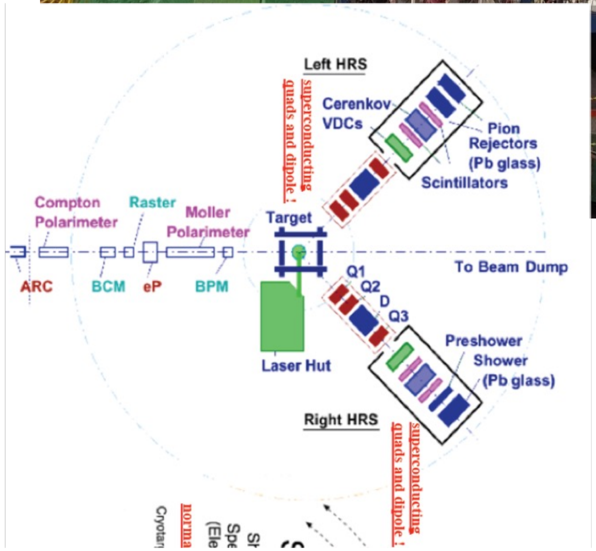
  - ► It allows to combine an accurate description of nuclear structure and dynamics—which can be obtained from non relativistic nuclear many-body theory—with a fully relativistic treatment of the variety of the hadronic final states produced in scattering processes involving broad-band neutrino beams

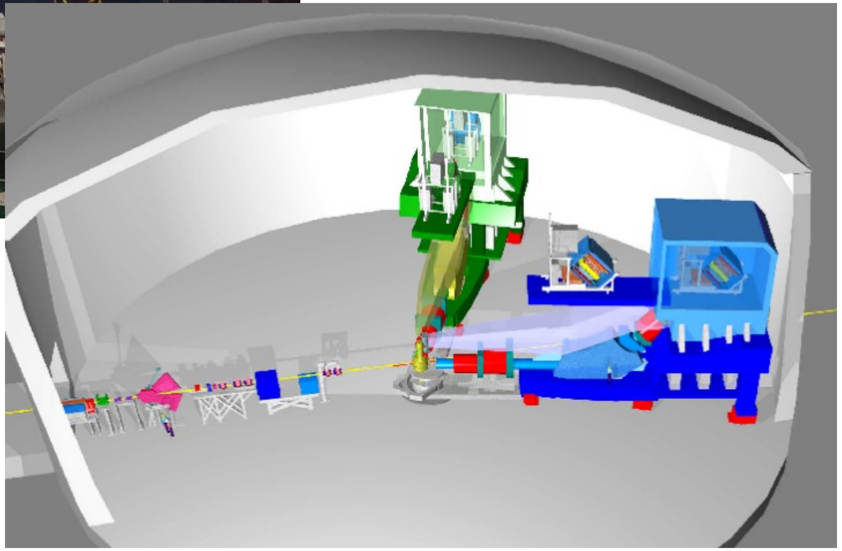
- ⋆ The spectral functions extracted from $\mathrm{Ar}(e, e'p)$ and $\mathrm{Ti}(e, e'p)$ will be essential for the description of events observed by accelerator-based neutrino experiments using liquid argon detectors

Hall A at Jefferson Lab



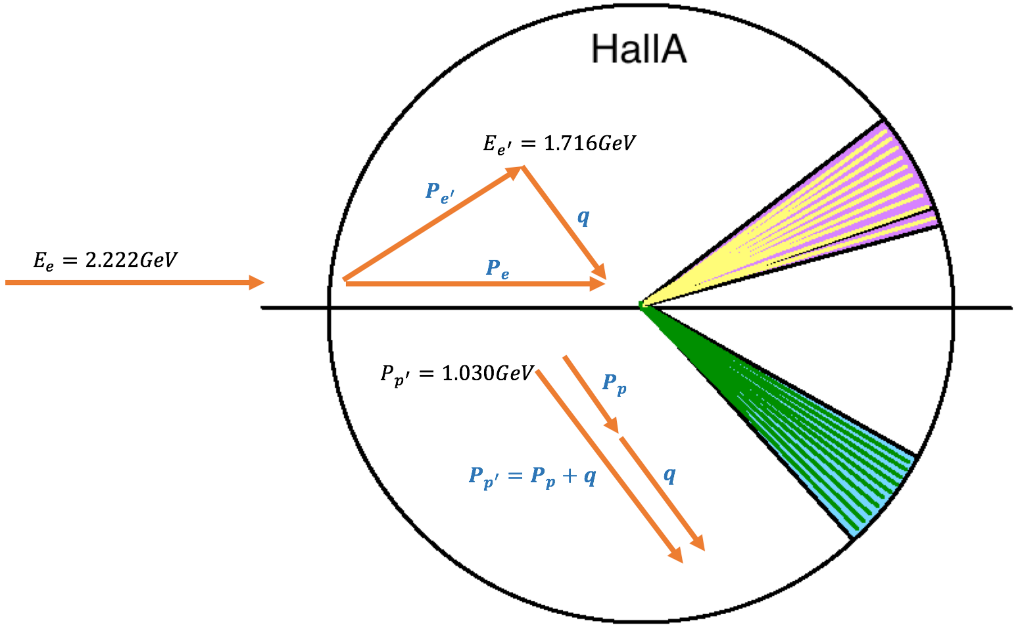






Kinematic Setup

	E'_e (GeV)	θ_e (deg)	$\lvert\mathbf{p}'\rvert$ (MeV)	$\theta_{p'}$ (deg)	$\lvert\mathbf{q}\rvert$ (MeV)	p_m (MeV)	E_m (MeV)
kin1	1.777	21.5	915	−50.0	865	50	73
kin2	1.716	20.0	1030	−44.0	846	184	50
kin3	1.799	17.5	915	−47.0	741	174	50
kin4	1.799	15.5	915	−44.5	685	230	50
kin5	1.716	15.5	1030	−39.0	730	300	50



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

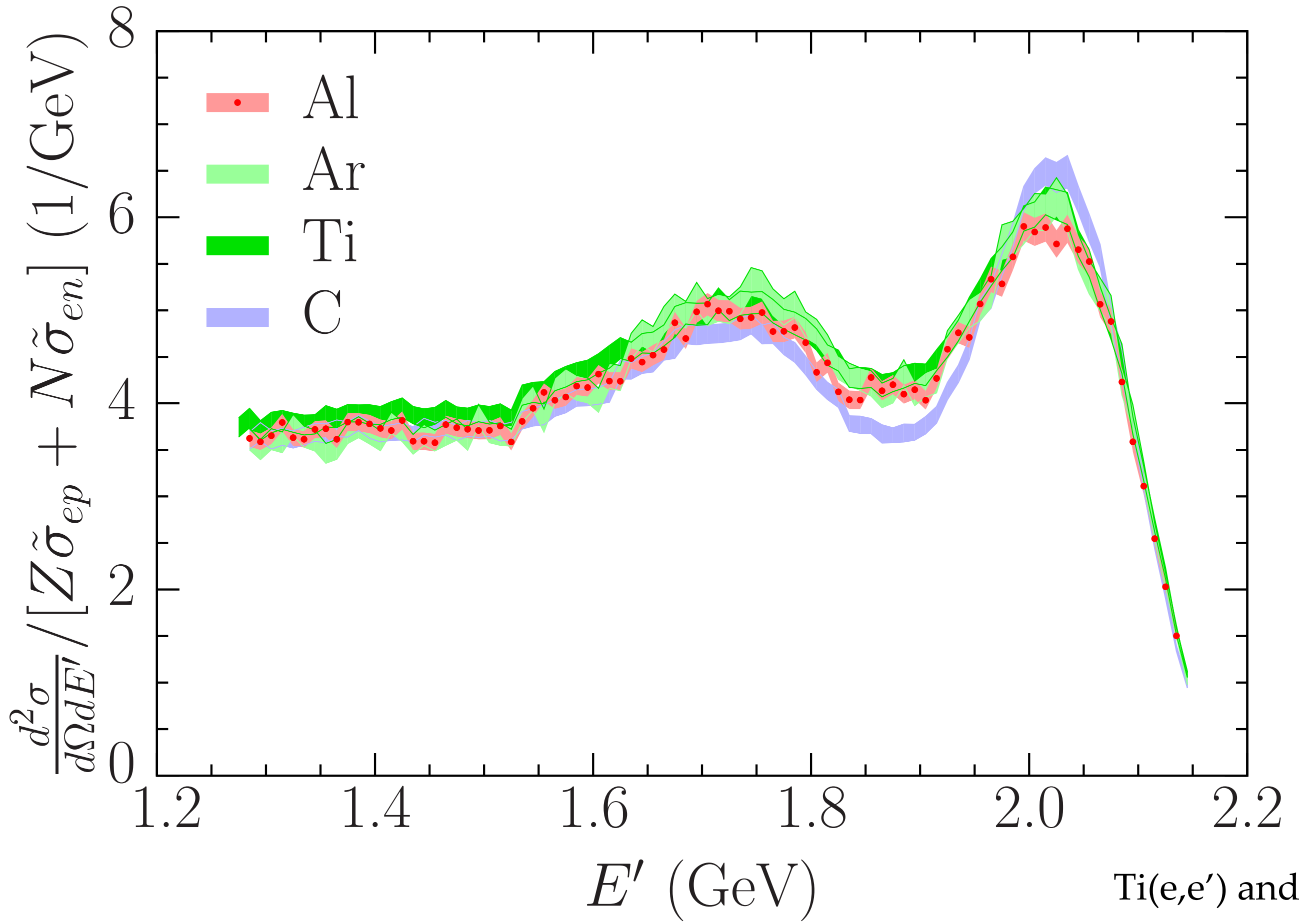
kin5

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

Inclusive analysis



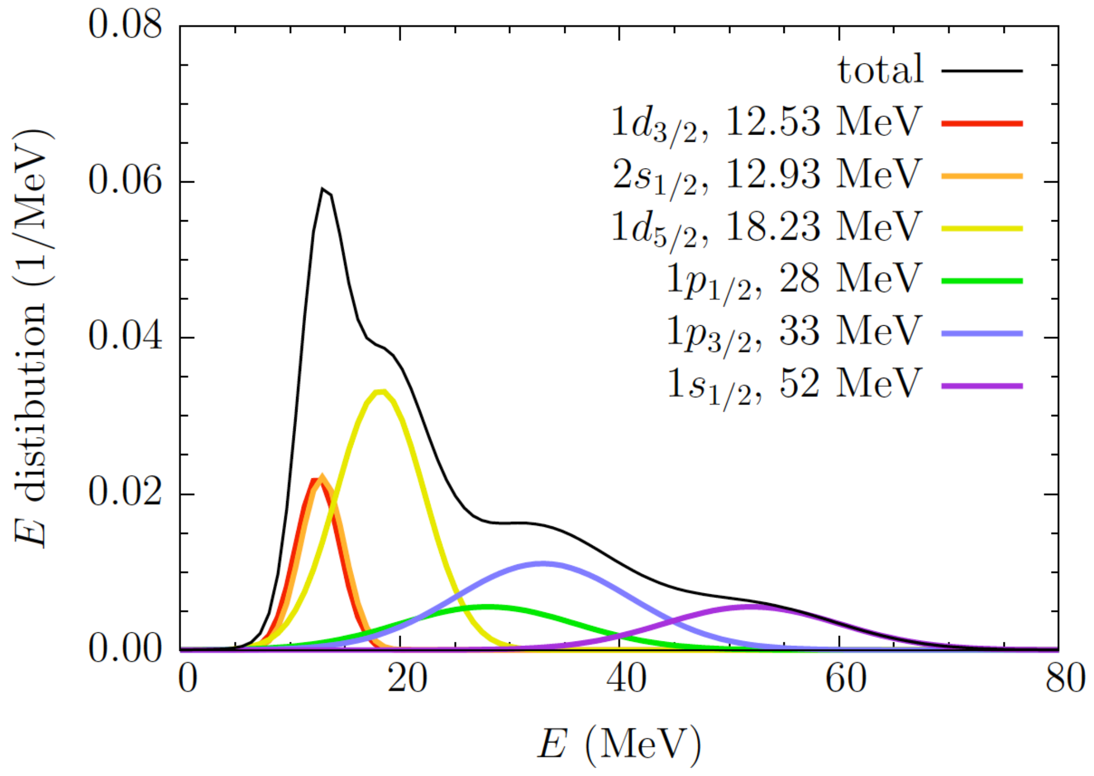
1.	Total statistical uncertainty	1.7–2.9%
2.	Total systematic uncertainty	1.8–3.0%
	a. Beam charge and beam energy	0.3%
	b. Beam offset x and y	0.4–1.0%
	c. Target thickness and boiling effect	0.7%
	d. HRS offset x and y + optics	0.6–1.2%
	e. Acceptance cut (θ,ϕ,dp/p)	0.6–2.4%
	f. Calorimeter and Čerenkov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

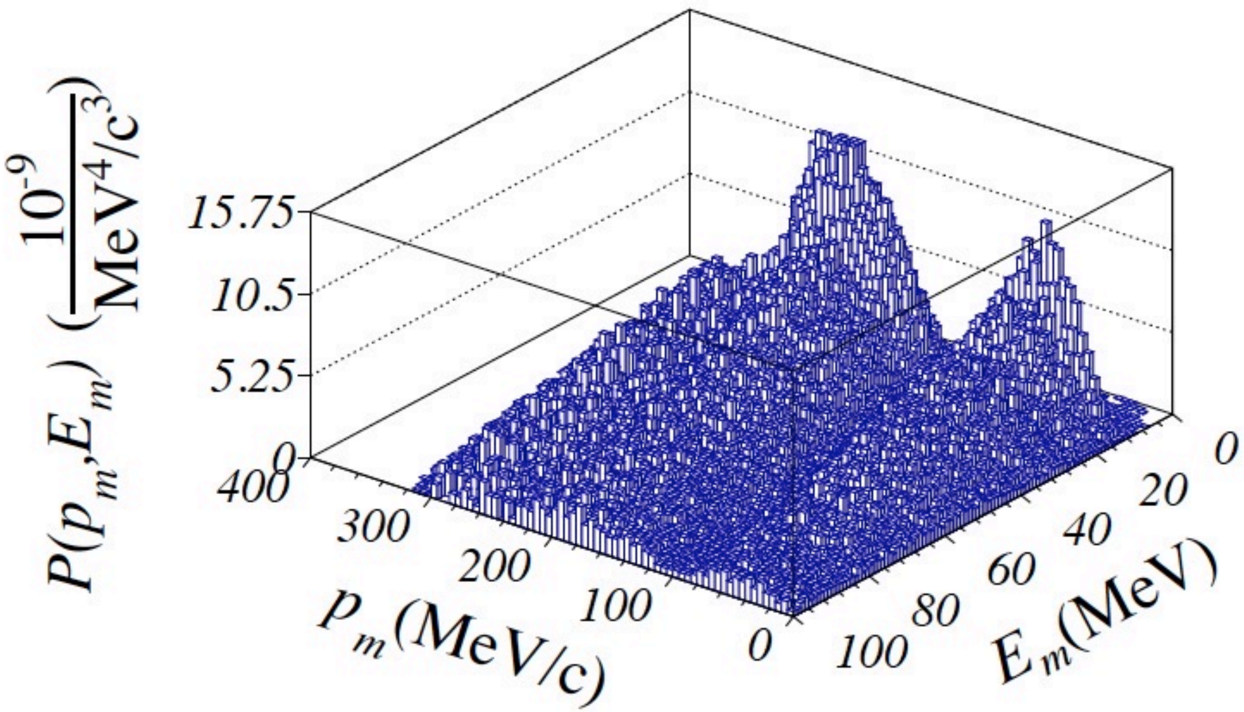
Ti(e,e′) and C(e,e′) inclusive cross sections published Phys. Rev. C 98, 014617 (2018)
Ar(e,e′) inclusive cross published in Phys. Rev. C 99, 054608 (2019)
Al(e,e′) inclusive cross section analysis published in Phys. Rev. C 100, 054606 (2019)

H. Dai (VT), PhD thesis, 2019
M. Murphy (VT), PhD thesis, 2020

Ar - Missing energy and missing momentum

Phys. Rev. D 105, 112002, (2022)



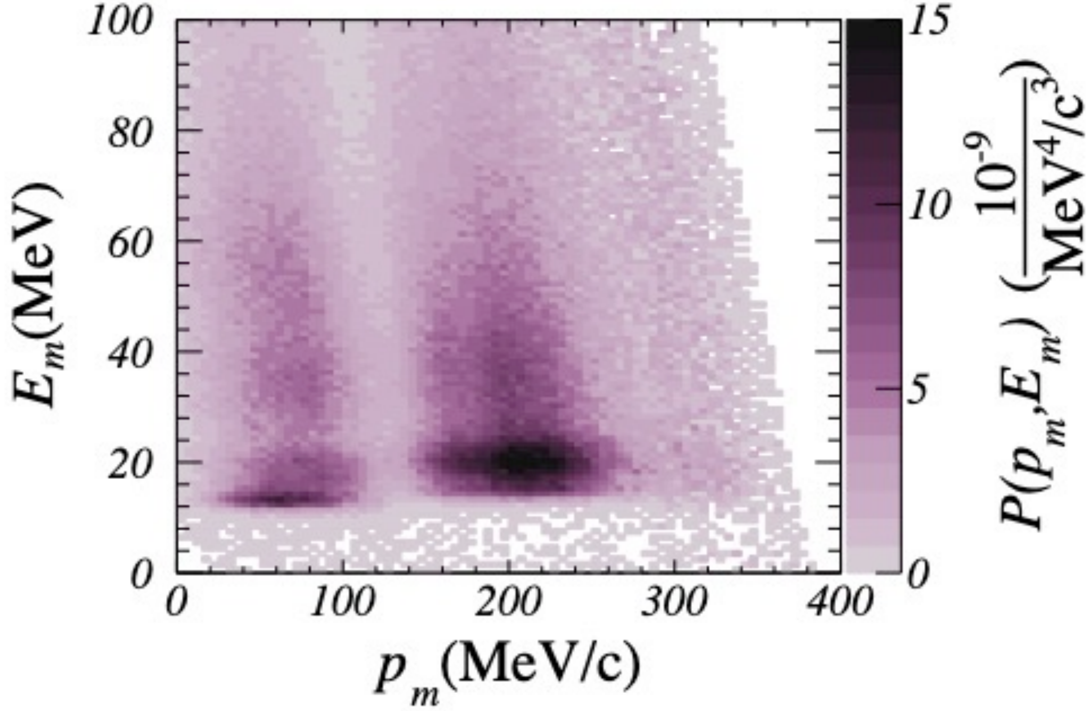


Effect of FSI

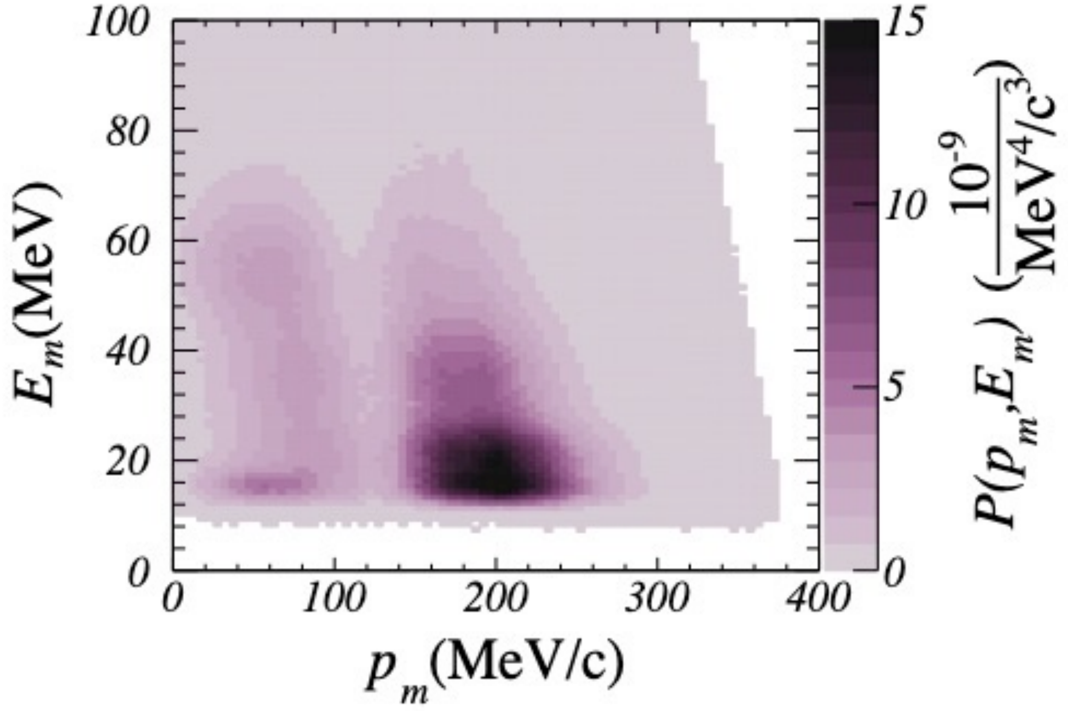
- A reduction of the cross section which is more or less constant in the momentum range considered
- Shift of the cross section in missing momentum

Ar (e,e'p) Missing momentum

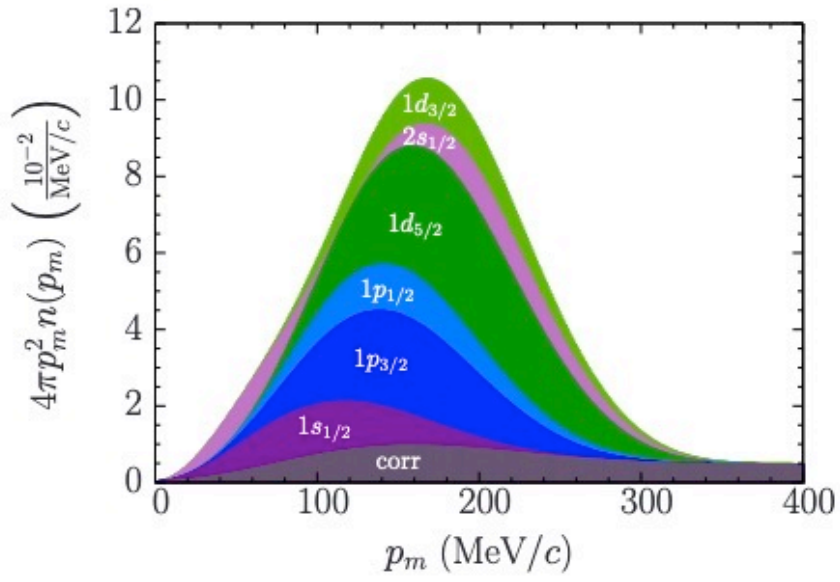
Phys. Rev. D 105, 112002, (2022)

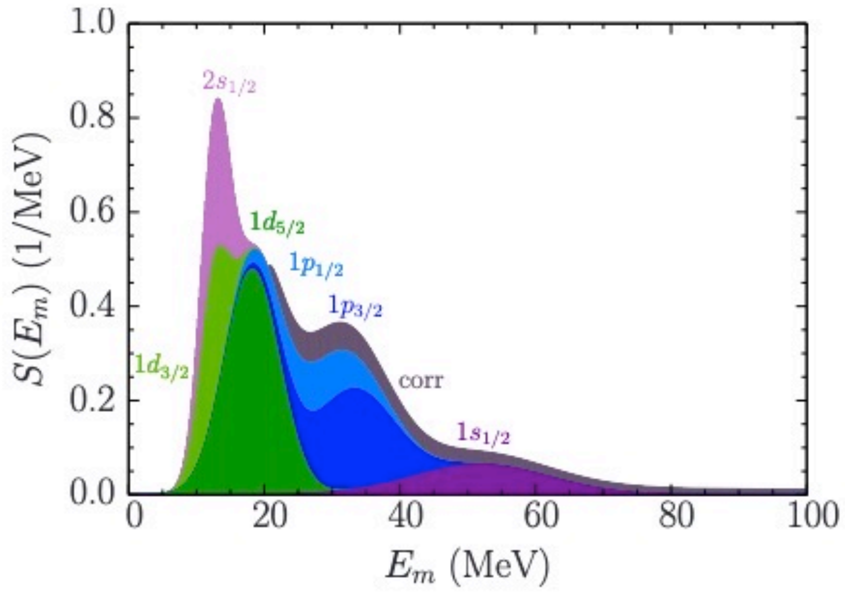


(a) Data



(b) MC



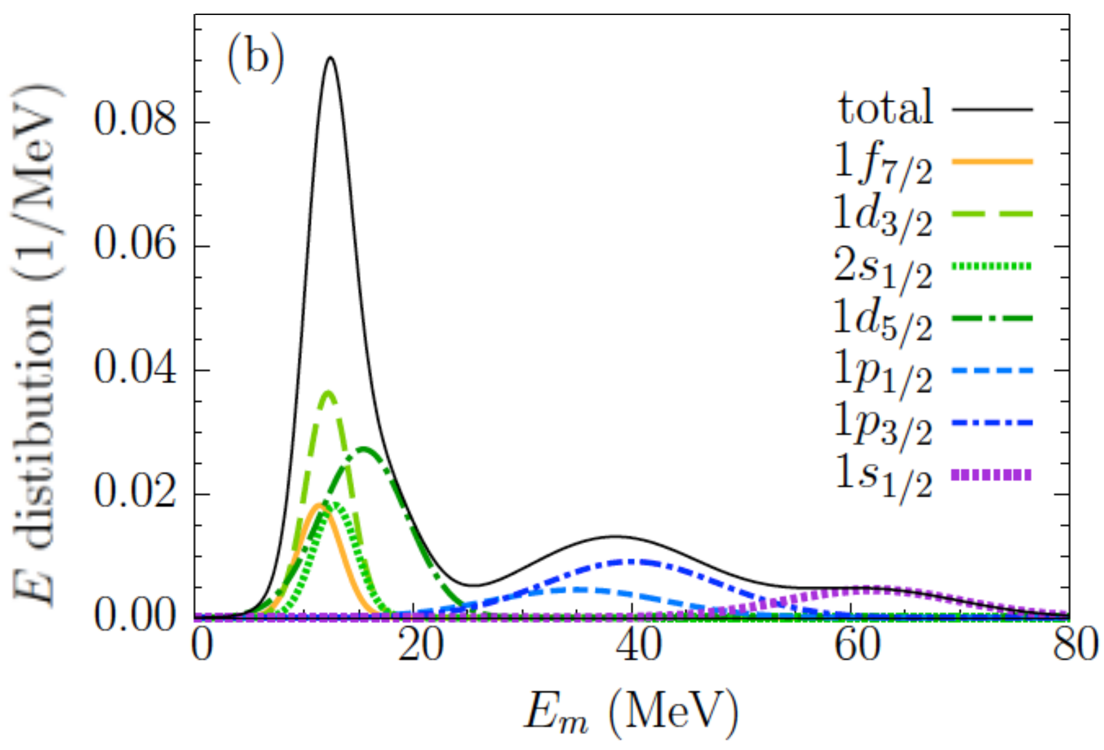


		all priors	w/o p_m	w/o corr.
α	N_α		S_α	
$1d_{3/2}$	2	0.89 ± 0.11	1.42 ± 0.20	0.95 ± 0.11
$2s_{1/2}$	2	1.72 ± 0.15	1.22 ± 0.12	1.80 ± 0.16
$1d_{5/2}$	6	3.52 ± 0.26	3.83 ± 0.30	3.89 ± 0.30
$1p_{1/2}$	2	1.53 ± 0.21	2.01 ± 0.22	1.83 ± 0.21
$1p_{3/2}$	4	3.07 ± 0.05	2.23 ± 0.12	3.12 ± 0.05
$1s_{1/2}$	2	2.51 ± 0.05	2.05 ± 0.23	2.52 ± 0.05
corr.	0	3.77 ± 0.28	3.85 ± 0.25	excluded
$\sum_\alpha S_\alpha$		17.02 ± 0.48	16.61 ± 0.57	14.12 ± 0.42
d.o.f		206	231	232
χ^2/d.o.f.		1.9	1.4	2.0

	E_α (MeV)		σ_α (MeV)	
α	w/ priors	w/o priors	w/ priors	w/o priors
$1d_{3/2}$	12.53 ± 0.02	10.90 ± 0.12	1.9 ± 0.4	1.6 ± 0.4
$2s_{1/2}$	12.92 ± 0.02	12.57 ± 0.38	3.8 ± 0.8	3.0 ± 1.8
$1d_{5/2}$	18.23 ± 0.02	17.77 ± 0.80	9.2 ± 0.9	9.6 ± 1.3
$1p_{1/2}$	28.8 ± 0.7	28.7 ± 0.7	12.1 ± 1.0	12.0 ± 3.6
$1p_{3/2}$	33.0 ± 0.3	33.0 ± 0.3	9.3 ± 0.5	9.3 ± 0.5
$1s_{1/2}$	53.4 ± 1.1	53.4 ± 1.0	28.3 ± 2.2	28.1 ± 2.3
corr.	24.1 ± 2.7	24.1 ± 1.7	—	—

Ti - Missing energy and missing momentum

Phys. Rev. D 107, 012005, (2023)



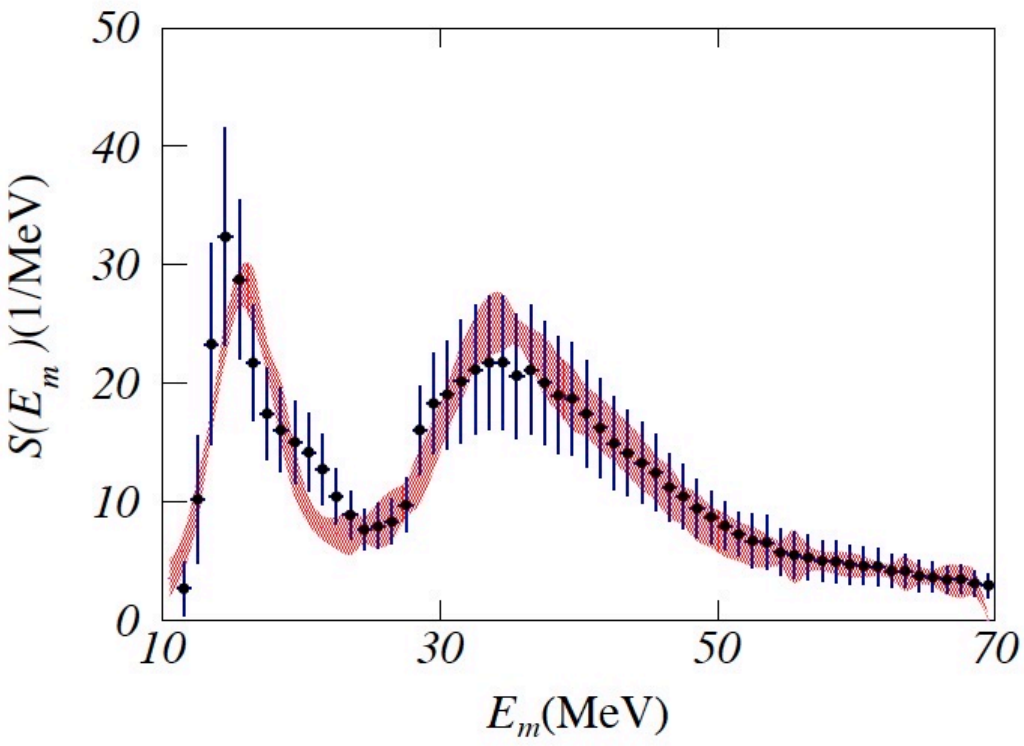
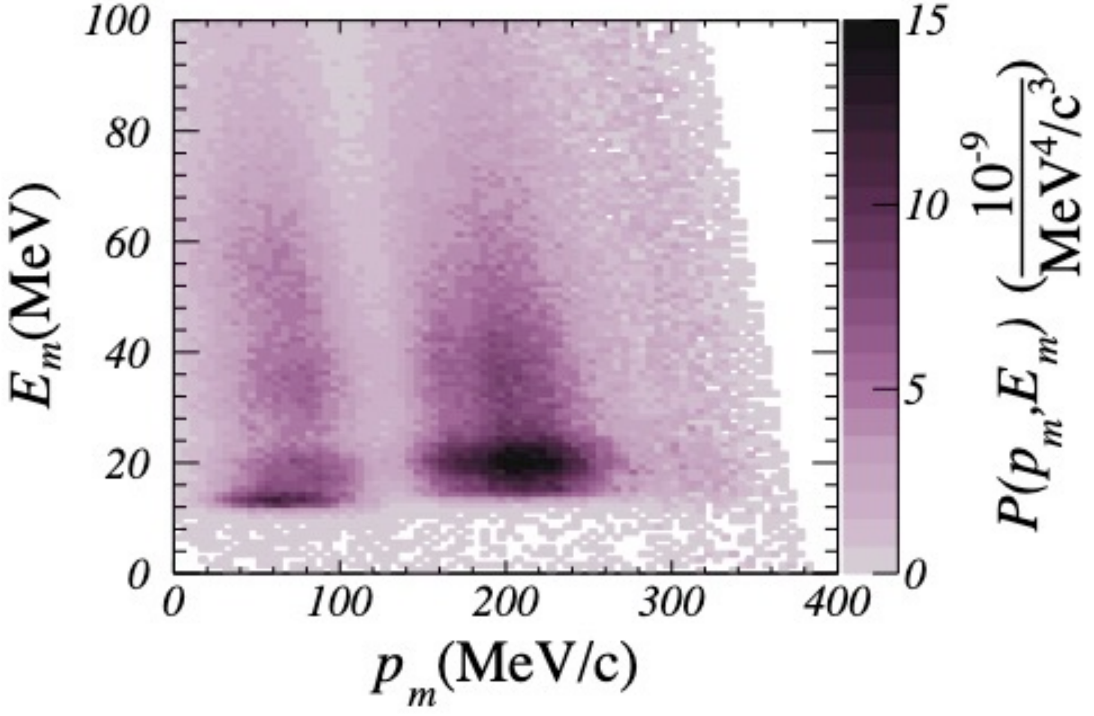
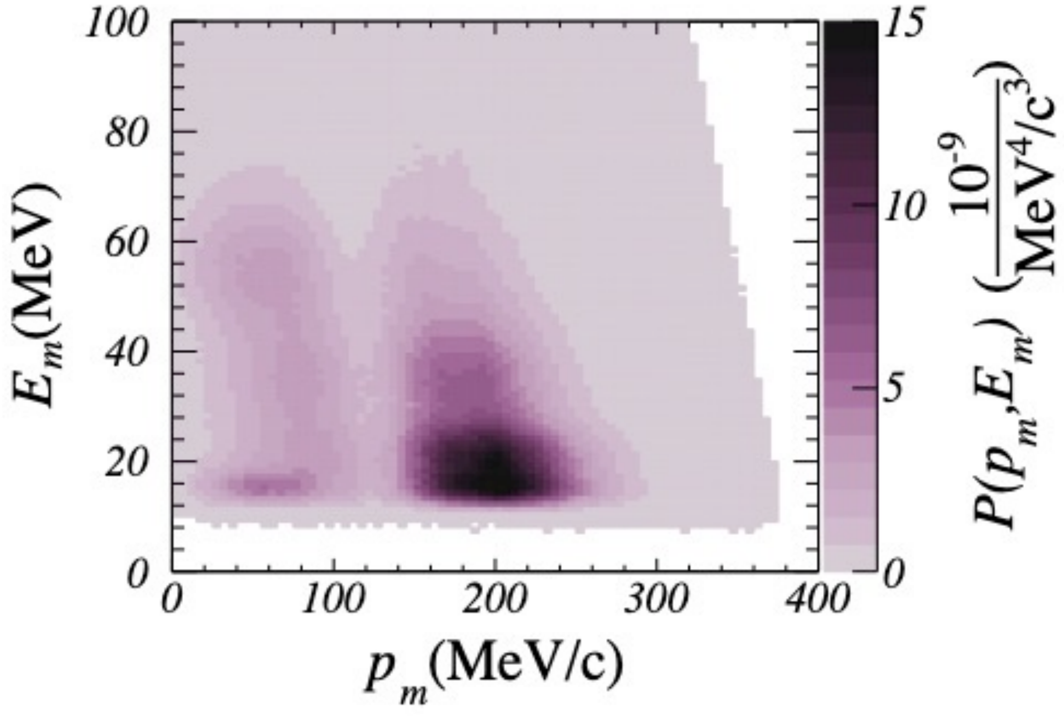


FIG. 3. Missing energy distributions obtained for natural titanium for $130 < p_m < 260$ MeV/c. The red band indicates the final fit results including the full error uncertainties.

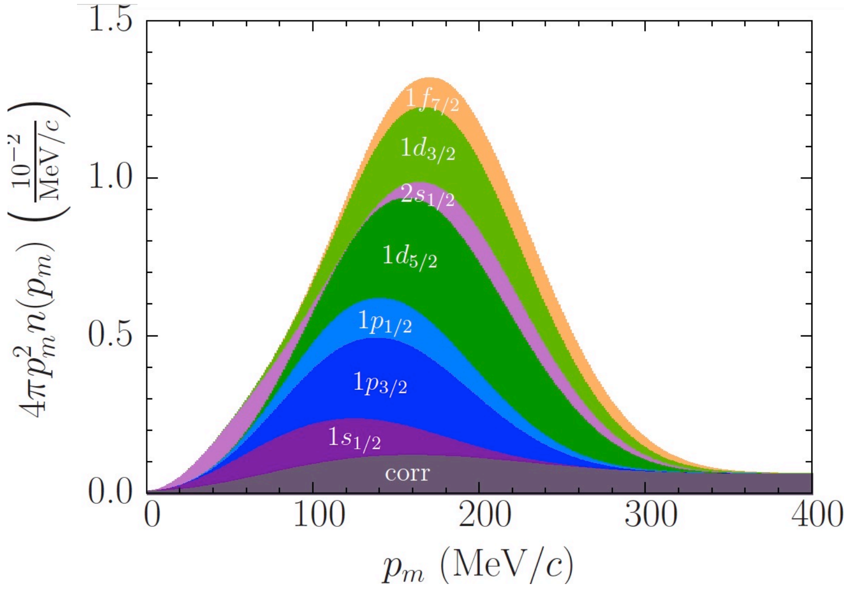
Ti (e,e'p) – Phys. Rev. D 107, 012005, (2023)

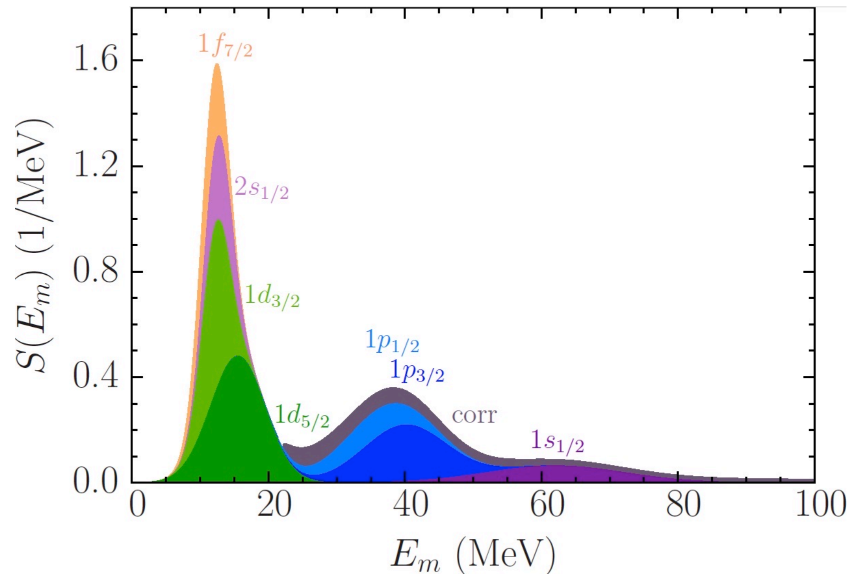


(a) Data



(b) MC





		all priors	w/o p_m	w/o corr.
α	N_α		S_α	
$1f_{7/2}$	2	1.53 ± 0.25	1.55 ± 0.28	1.24 ± 0.22
$1d_{3/2}$	4	2.79 ± 0.37	3.15 ± 0.54	3.21 ± 0.37
$2s_{1/2}$	2	2.00 ± 0.11	1.78 ± 0.46	2.03 ± 0.11
$1d_{5/2}$	6	2.25 ± 0.16	2.34 ± 0.19	3.57 ± 0.29
$1p_{1/2}$	2	2.00 ± 0.20	1.80 ± 0.27	2.09 ± 0.19
$1p_{3/2}$	4	2.90 ± 0.20	2.92 ± 0.20	4.07 ± 0.15
$1s_{1/2}$	2	2.14 ± 0.10	2.56 ± 0.30	2.14 ± 0.11
corr.	0	4.71 ± 0.31	4.21 ± 0.46	excluded
$\sum_\alpha S_\alpha$		20.32 ± 0.65	20.30 ± 1.03	18.33 ± 0.59
d.o.f		121	153	125
χ^2/d.o.f.		0.95	0.71	1.23

	E_α (MeV)		σ_α (MeV)	
α	w/ priors	w/o priors	w/ priors	w/o priors
$1f_{7/2}$	11.32 ± 0.10	11.31 ± 0.10	8.00 ± 5.57	8.00 ± 6.50
$1d_{3/2}$	12.30 ± 0.24	12.33 ± 0.24	7.00 ± 0.61	7.00 ± 3.84
$2s_{1/2}$	12.77 ± 0.25	12.76 ± 0.25	7.00 ± 3.76	7.00 ± 3.84
$1d_{5/2}$	15.86 ± 0.20	15.91 ± 0.22	2.17 ± 0.27	2.23 ± 0.29
$1p_{1/2}$	33.33 ± 0.60	33.15 ± 0.65	3.17 ± 0.45	3.03 ± 0.48
$1p_{3/2}$	39.69 ± 0.62	39.43 ± 0.68	5.52 ± 0.70	5.59 ± 0.70
$1s_{1/2}$	53.84 ± 1.86	52.00 ± 3.13	11.63 ± 1.90	13.63 ± 2.59
corr.	25.20 ± 0.02	25.00 ± 0.29	—	—

Summary

- ⋆ The formalism based on factorisation and target spectral functions is emerging as a framework uniquely suited to deal with the complexity of neutrino interactions in the broad kinematical range relevant to accelerator-based neutrino experiments
- ⋆ The Ar and Ti$(e, e'p)$ cross-sections measured at Jefferson Lab by the E12-14-012 collaboration, have allowed the determination of the Argon and Titanium spectral function, needed to describe neutrino and antineutrino interactions in liquid Argon detectors
- ⋆ The E12-14-012 data set—also comprising the inclusive cross sections of Argon, Titanium, Carbon and Aluminum—will be useful for the development of more advanced theoretical models of the spectral function
- ⋆ A refined analysis involving a two-dimensional fit of the data is being considered
- ⋆ The extent to which a proton in Titanium is a good proxy for a neutron in Argon, as well as the feasibility of a neutron knockout experiment, needs to be carefully investigated.

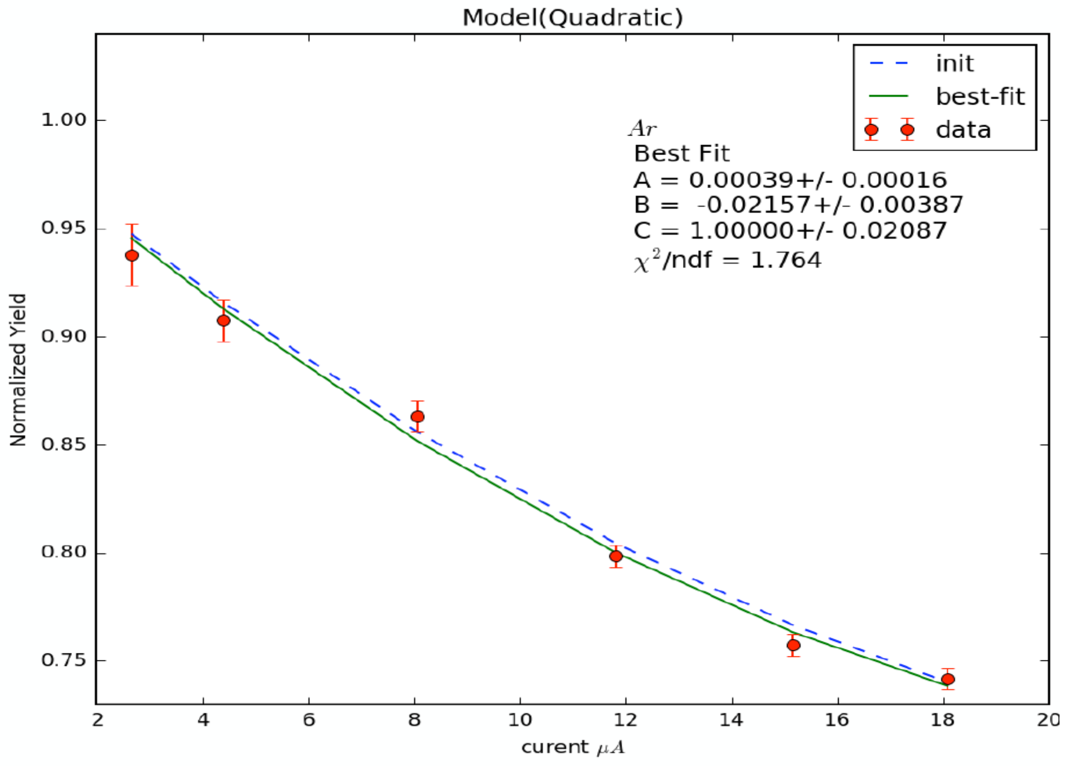
Thank you

Back up

Boiling Study-----Nathaly Santiesteban and H. Dai

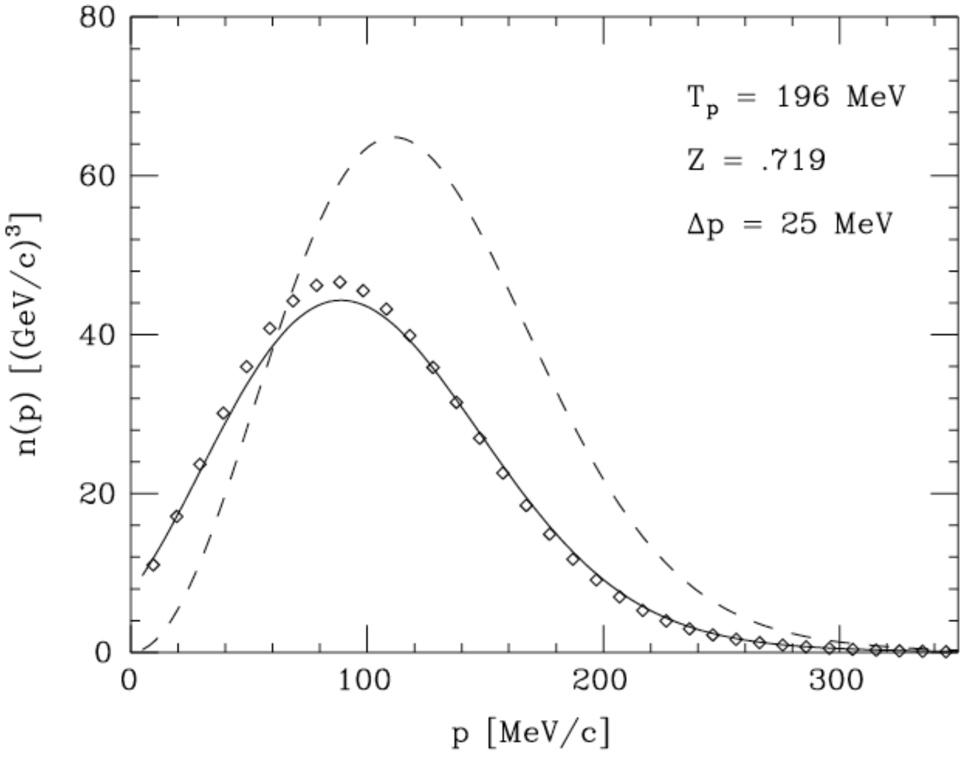
- We calculated the normalized yield for different currents, and the change in yield represents change in target density
- The normalization is done with respect to the lowest current
- We fit the numbers with quadratic function and fix the I=0 point to 1
- When $I = 9.67\mu A$, within 2% for all the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



Inclusion of Final State Interactions (FSI)

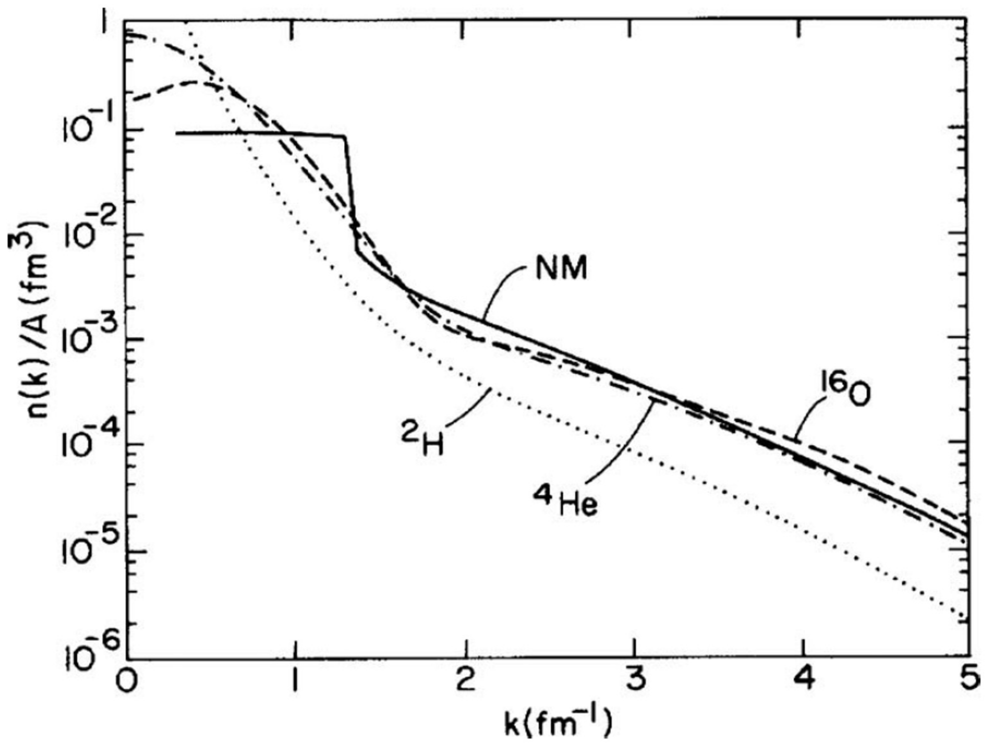
- ★ Distorted Wave Impuse Approximation (DWIA). The plane-wave describing the outgoing nucleon is replaced by a *distorted wave*, obtained from a complex optical potential fitted to proton-nucleus scattering data
- ★ The momentum distributions of the shell model states are shifted by an amount Δ_p and quenched by a factor $\tilde{Z}$



- ★ For $A \leq 16$, the accuracy of the optical potential approach has been tested comparing to the results of many-body calculations of the relevant overlaps
- ★ FSI effects beyond DWIA are minimized in *parallel kinematics*

Correlated part of the spectral function

Benhar *et al.*, RMP **80**, 189 (2008)



- Ciofi degli Atti and Simula, PRC **53**, 1689 (1996)

- Correlated nucleons form quasi-deuteron pairs, with the relative momentum distributed as in deuteron.
- *NN* pairs undergo CM motion (Gaussian distrib.)
- Excitation energy of the $(A-1)$-nucleons is their kinetic energy plus the *pn* knockout threshold