

# Proton spectral function from the Ar&Ti( $e, e'p$ ) cross sections

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for the Jlab E12-14-012 experiment**

**CIPANP, Aug. 29–Sep.4, 2022**

# 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/Dummy/Optical ( $e,e'p$ ) reactions for five different kinematic set-ups
    - Ar/Ti/C/Dummy ( $e,e'$ ) 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 function of argon ( $\sim$  initial momentum and energy distributions of nucleons bound in argon) that can directly be used in the reconstruction of neutrino energies (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 long baseline neutrino experiments.



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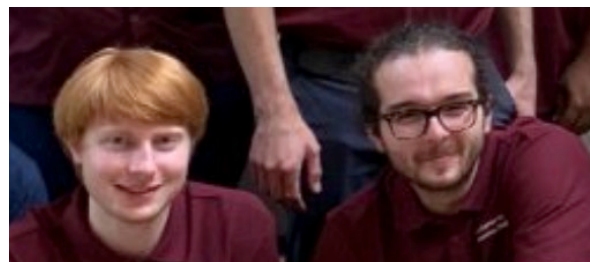
Matthew  
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# Outline

## Neutrino Oscillation Experiments - DUNE

- Importance of cross sections in oscillation results
- Connection between electron and neutrino cross section

## Experimental setup

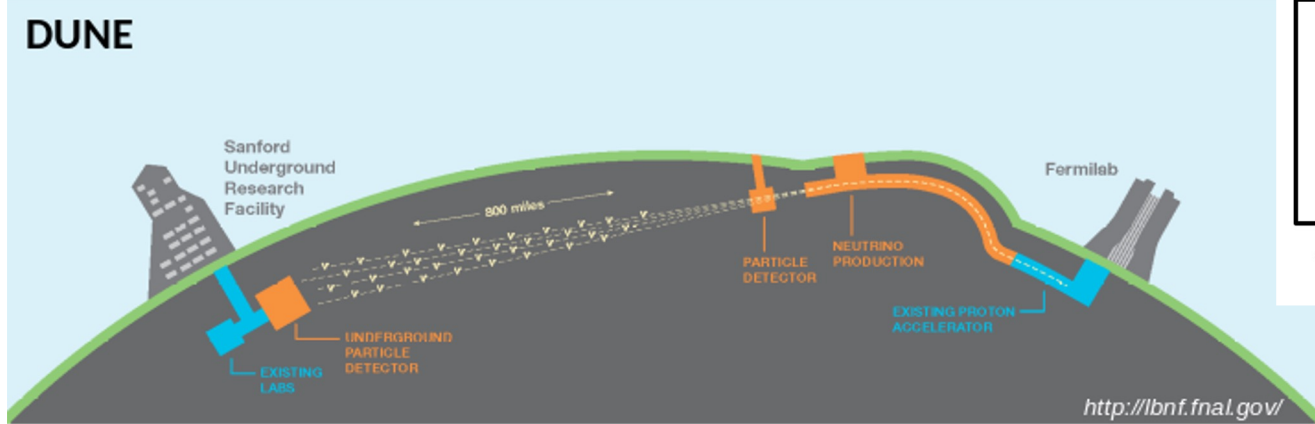
- Jefferson Lab – Hall A
- E12-14-012
  - Motivations and goals
  - Target
  - Kinematic configurations
  - Publications

## E12-14-012 - Exclusive analysis

- Analysis strategy
- Missing Energy and Missing momentum fits
  - Ar
  - Ti

## Summary

# DUNE Experiment



Oscillation Probability\*:

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

\*two neutrino flavors, for simplicity

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

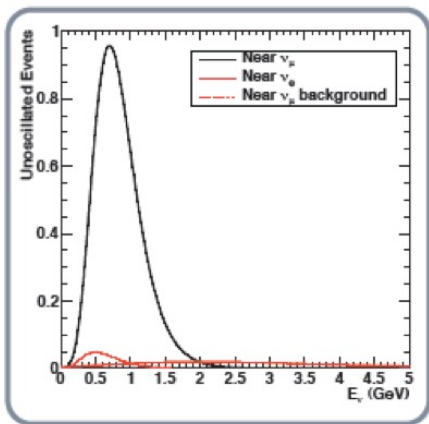
Event Rate at near detector:

$$N_{\text{ND}}^\alpha(\mathbf{p}_{\text{reco}}) = \sum_i \phi_\alpha(E_{\text{true}}) \times \sigma_\alpha^i(\mathbf{p}_{\text{true}}) \times \epsilon_\alpha(\mathbf{p}_{\text{true}}) \times R_i(\mathbf{p}_{\text{true}}; \mathbf{p}_{\text{reco}})$$

Event Rate at far detector:

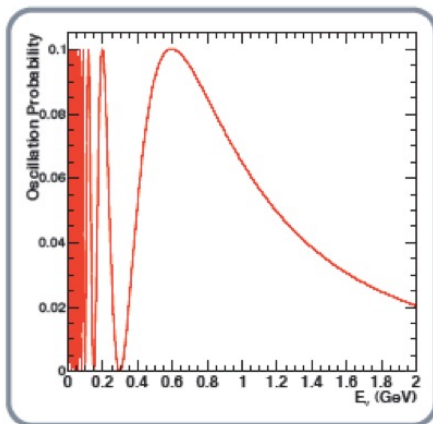
$$N_{\text{FD}}^{\alpha \rightarrow \beta}(\mathbf{p}_{\text{reco}}) = \sum_i \phi_\alpha(E_{\text{true}}) \times P_{\alpha\beta}(E_{\text{true}}) \times \sigma_\beta^i(\mathbf{p}_{\text{true}}) \times \epsilon_\beta(\mathbf{p}_{\text{true}}) \times R_i(\mathbf{p}_{\text{true}}; \mathbf{p}_{\text{reco}})$$

### Near detector



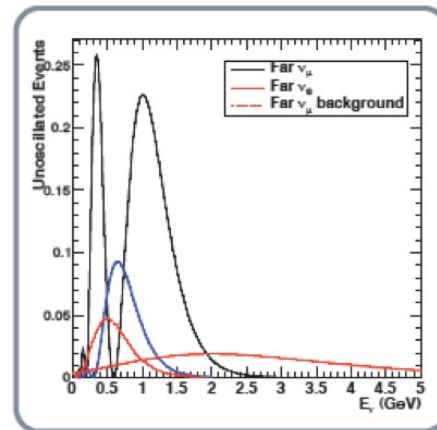
measure # events =  
flux x cross section

### Oscillation probability



×

### Far detector

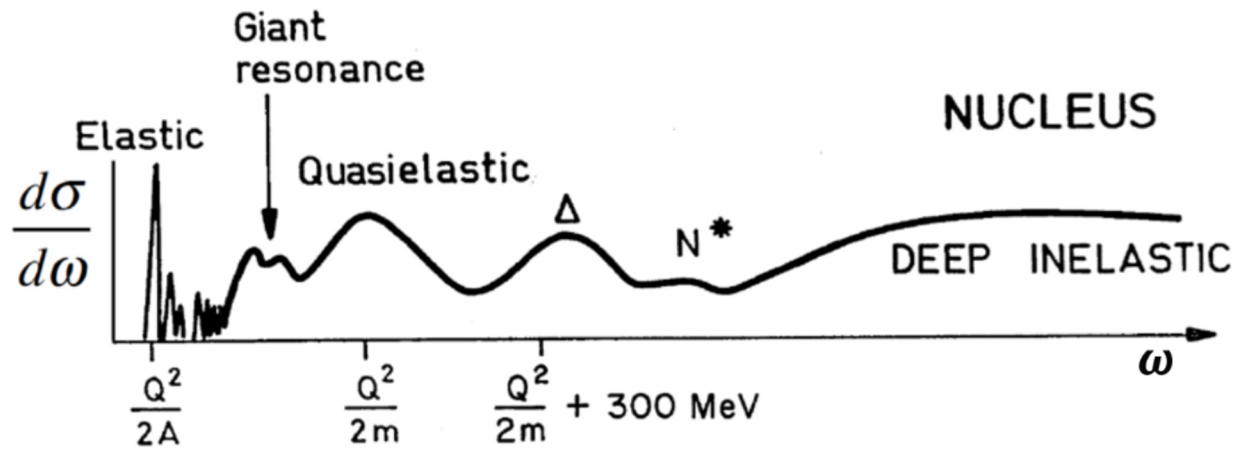
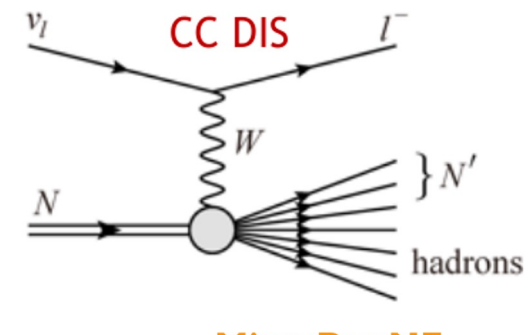
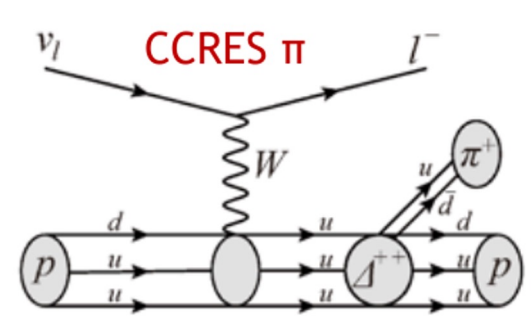
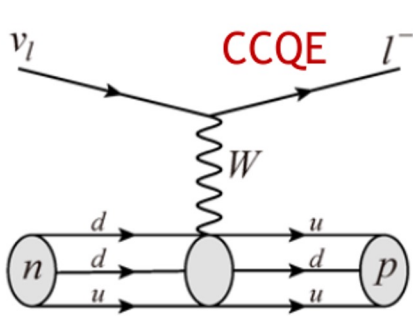


=

Black curve:  $\nu_\mu$  disappearance  
Blue curve:  $\nu_e$  appearance  
Red curve: intrinsic  $\nu_e/\nu_\mu$  bkg

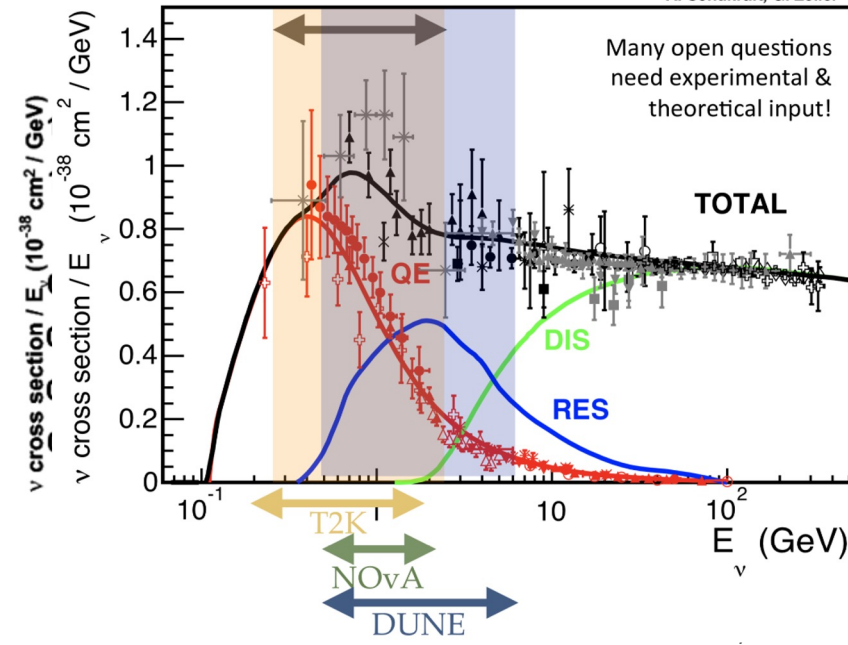
Beam between  
Near and Far  
detector is not  
the same:  
divergence

# Neutrino Interactions

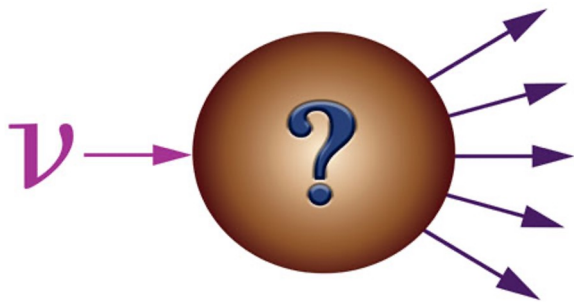


**MicroBooNE**

A. Schukraft, G. Zeller



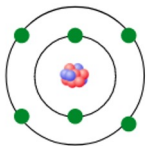
# Nuclear Effects



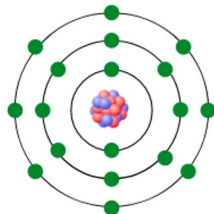
Hydrogen



Deuterium



Carbon



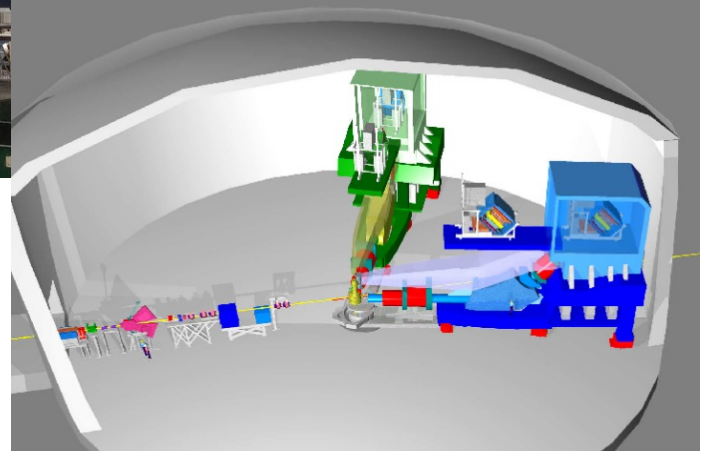
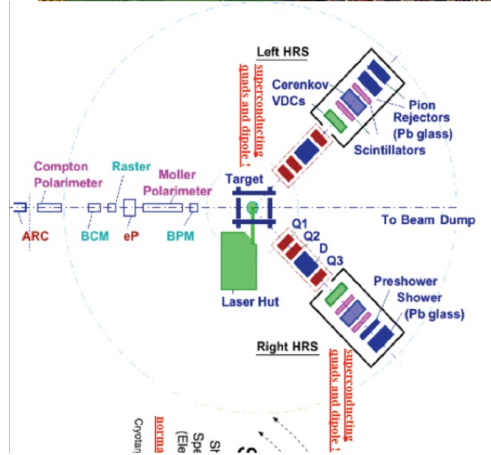
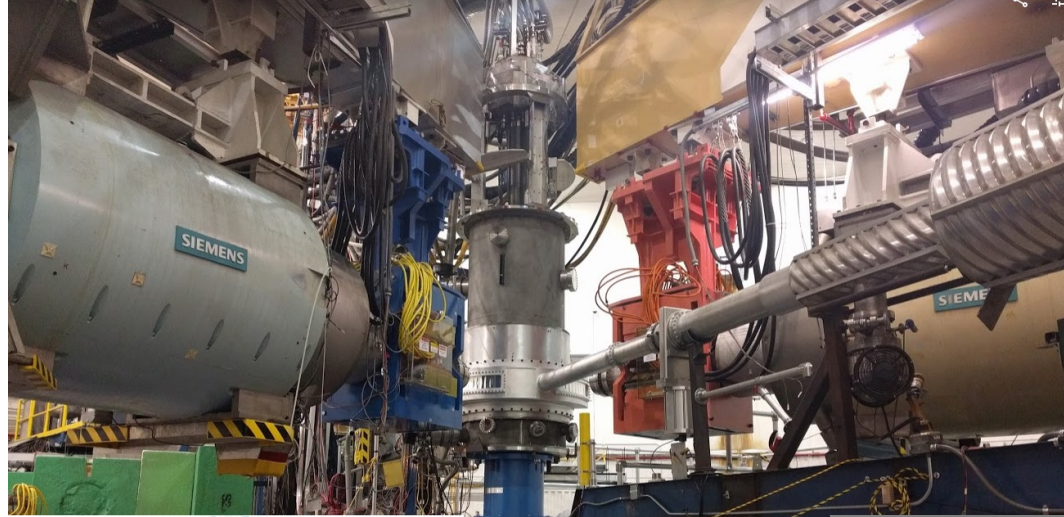
Argon

DUNE

- 1970-1990's
  - Hydrogen/deuterium filled bubble chambers:
    - Experiments: ANL (hydrogen), BNL (hydrogen and deuterium)
    - Test the V-A nature of weak interactions
    - Measure nucleon axial vector form factor
- 1990-present
  - Complex nuclei as targets: C, Fe, **Ar**
  - $Z \neq N$  in Argon, neutrino and anti-neutrino QE could be different (arXiv: 1603.01072)
  - **Heavier targets have more complex nuclear effects**



# Hall A at Jefferson Lab

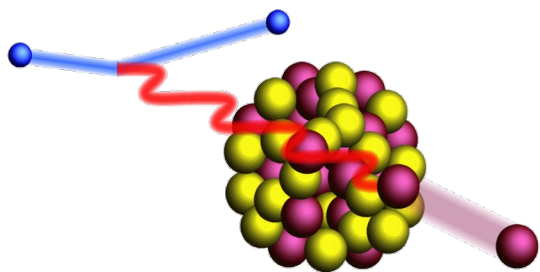


# E12-14-012: $(e, e')$ and $(e, e'p)$ on Ar and Ti

**Aim:** Obtaining the experimental input indispensable to construct the argon spectral function, thus paving the way for a reliable estimate of the neutrino cross sections in DUNE. In addition, stimulating a number of theoretical developments, such as the description of final-state interactions.

[Benhar *et al.*, arXiv:1406.4080]

$$E_e = 2.222 \text{ GeV}$$



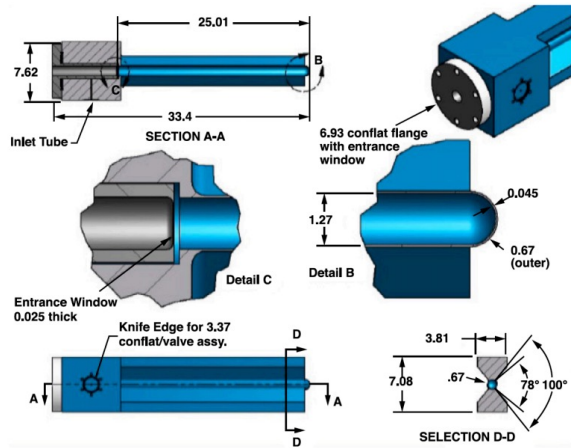
	$E'_e$ (GeV)	$\theta_e$ (deg)	$ \mathbf{p}' $ (MeV)	$\theta_{p'}$ (deg)	$ \mathbf{q} $ (MeV)	$p_m$ (MeV)	$E_m$ (MeV)
kin1	1.777	21.5	915	-50.0	865	50	73
kin2	1.716	20.0	1030	-44.0	846	184	50
kin3	1.799	17.5	915	-47.0	741	174	50
kin4	1.799	15.5	915	-44.5	685	230	50
kin5	1.716	15.5	1030	-39.0	730	300	50

Exploratory analysis of the full dataset

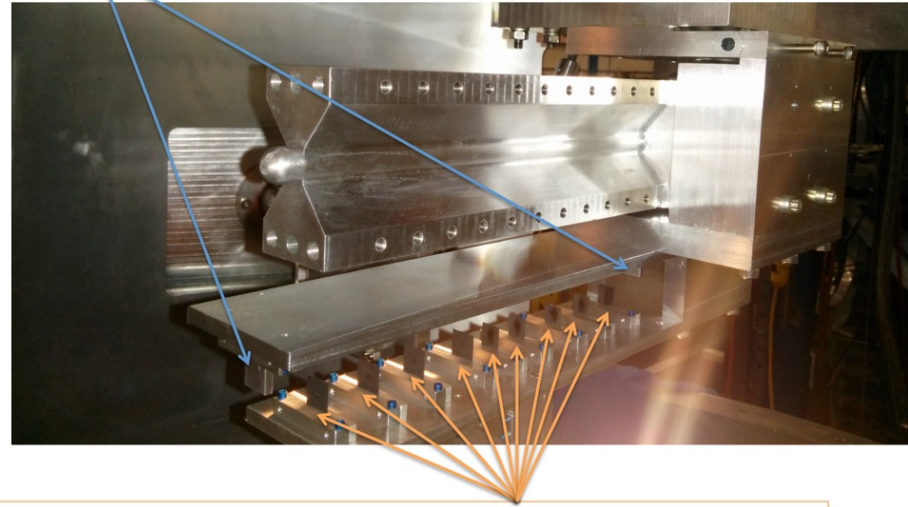
# Target Setup

## Ar Target

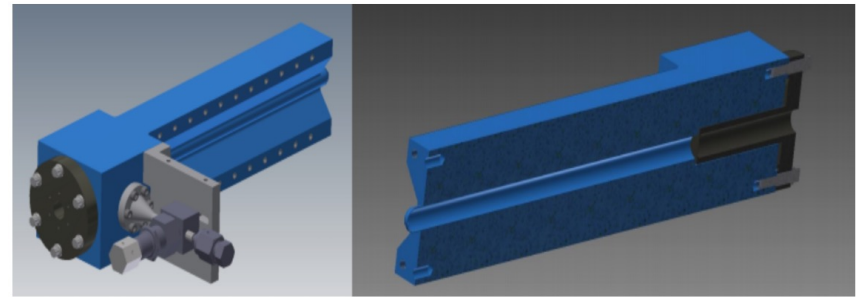
- Closed Gas Cell
- Length = 25 cm
- Pressure = 500 PSI
- Temperature = 300 K.
- Target thickness =  $1.381 \text{ g cm}^{-2}$
- Luminosity =  $4.33 \times 10^{37} \text{ atoms cm}^{-2} \text{ sec}^{-1}$ .



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)

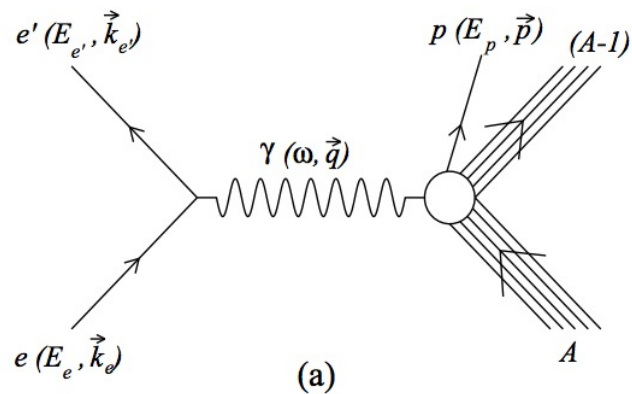


# $(e, e')$ and $(e, e'p)$ processes

$(e, e'p)$  process (exclusive):

Both outgoing electron and proton are detected

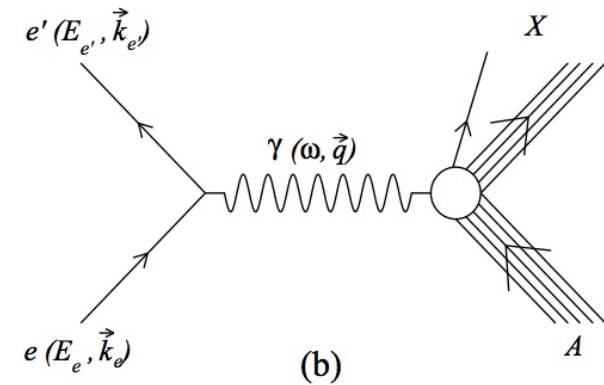
$$e + A \rightarrow e' + p + (A - 1)$$



$(e, e')$  process (inclusive):

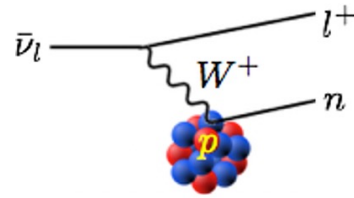
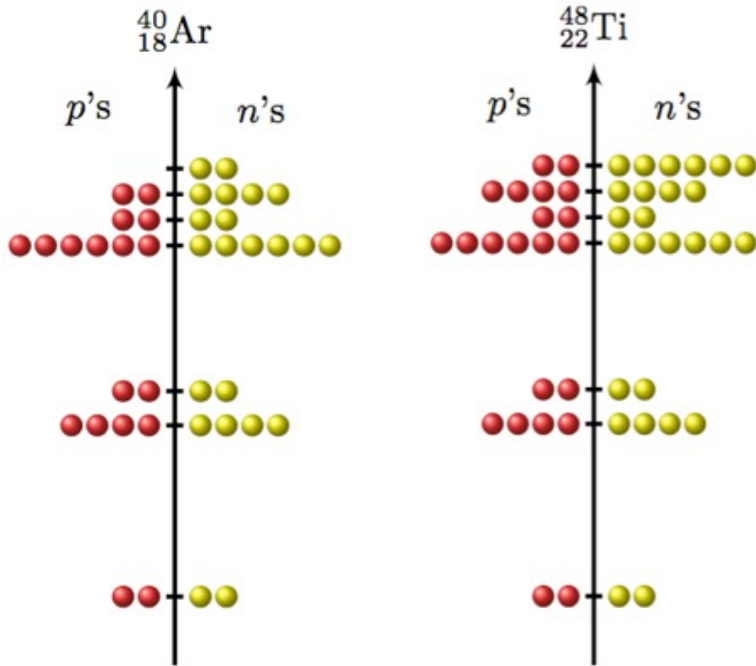
Only scattered electron is detected

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



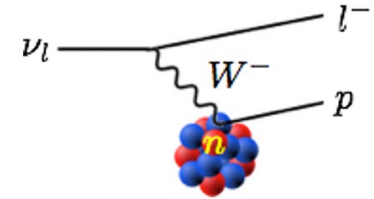
# Why Titanium?

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



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

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

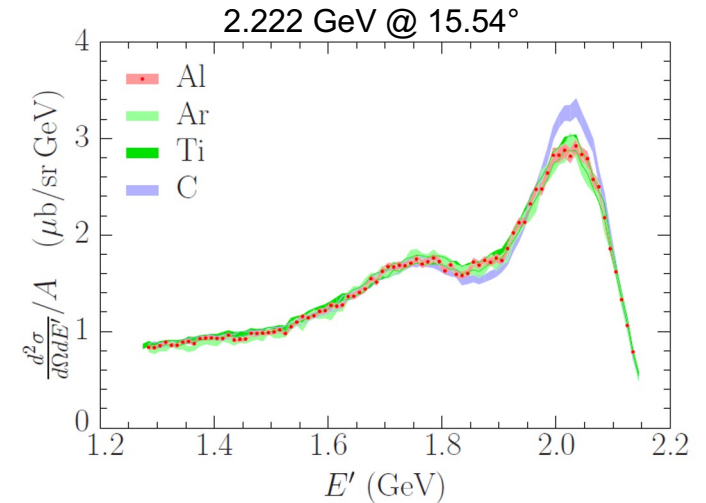


$$\nu_l + n \rightarrow l^- + p$$

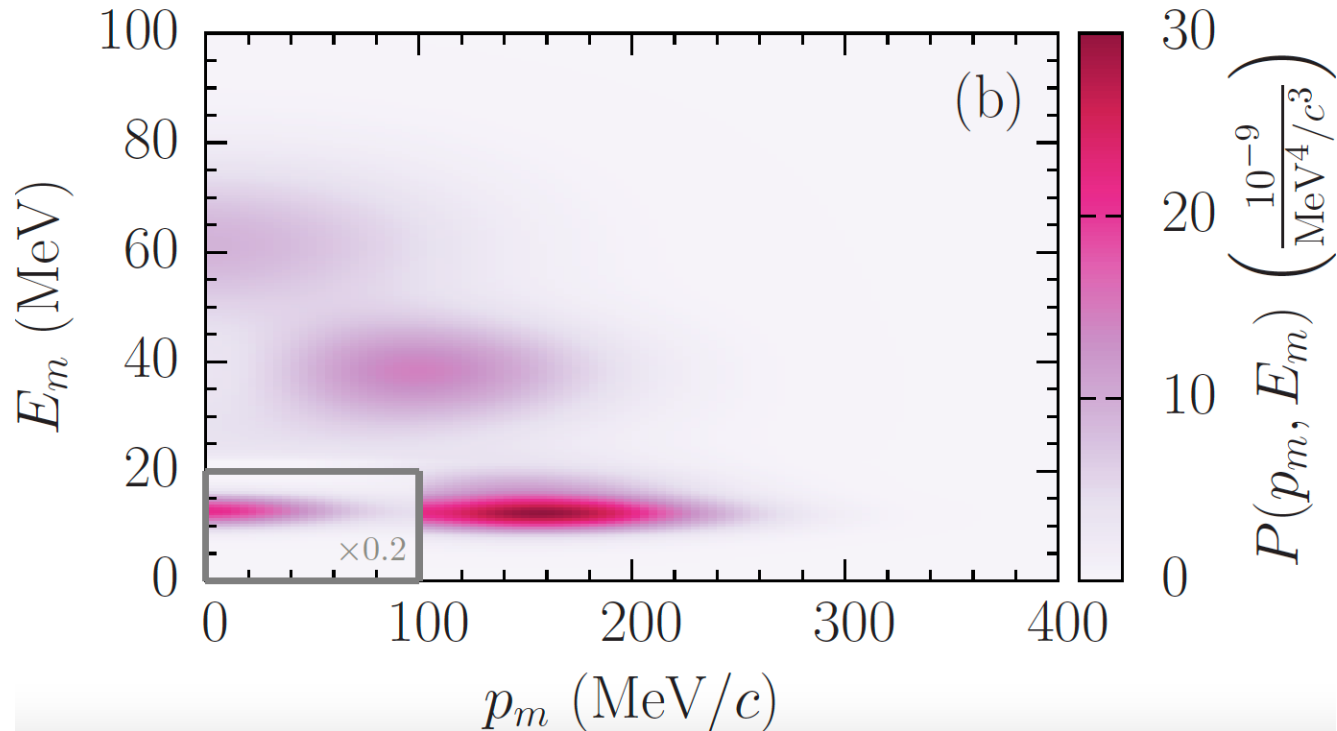
Ti(e,e'p)->SF of neutrons in Ar nucleus

# Publications

- ❖ Inclusive cross sections for C and Ti, [Dai *et al.*, PRC 98, 014617 (2018)]
- ❖ Inclusive cross section for Ar, [Dai *et al.*, PRC 99, 054608 (2019)]
- ❖ Inclusive cross section for Al-7075, Ar, C and Ti of all  $(e, e')$  data [Murphy *et al.*, PRC 100, 054606 (2019)]
- ❖ Exclusive Ar & Ti cross sections for a single kinematics,  $p_m \sim 50\text{--}60$  MeV,  $E_m \sim 50\text{--}70$  MeV [Gu *et al.*, PRC 103, 034604 (2021)]
- ❖ Exclusive Ar cross sections for all kinematics,  $p_m \sim 50\text{--}350$  MeV/c,  $E_m \sim 10\text{--}70$  MeV [Jiang *et al.*, PRD 105, 112002 (2022)]

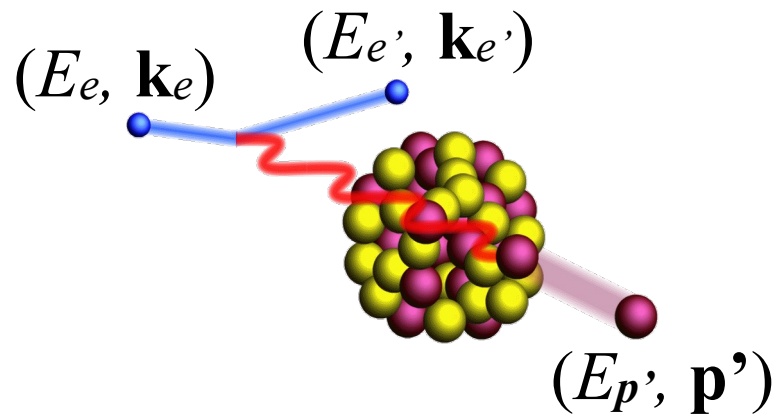


# Extraction of the spectral function



Universal property of the nucleus, independent of the interaction.

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



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

known

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



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

elementary cross section

nuclear transparency

$$\frac{d^6 \sigma_{IA}}{d\Omega_{e'} dE_{e'} d\Omega_{p'} dE_{p'}} \propto \sigma_{ep} S(p_m, E_m) T(E_{p'})$$

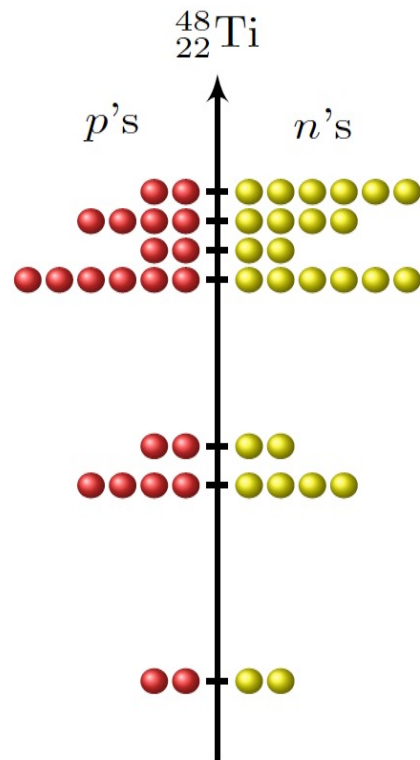
spectral function

The diagram illustrates the components of the  $(e, e'p)$  cross section. The central equation is  $\frac{d^6 \sigma_{IA}}{d\Omega_{e'} dE_{e'} d\Omega_{p'} dE_{p'}} \propto \sigma_{ep} S(p_m, E_m) T(E_{p'})$ . Three blue arrows point from the labels 'elementary cross section', 'nuclear transparency', and 'spectral function' to the terms  $\sigma_{ep}$ ,  $T(E_{p'})$ , and  $S(p_m, E_m)$  respectively.

# Analysis procedure

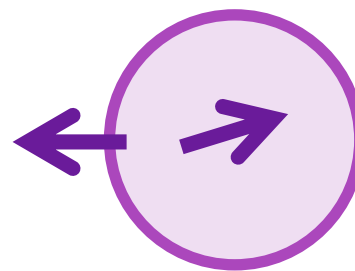
- 1) Extract of the  $(e, e'p)$  cross section
- 2) Using  $\sigma_{cc1}$  of de Forest and nuclear transparency, obtain the reduced cross sections as a function of (a)  $p_m$  and (b)  $E_m$ .
- 3) Find the parameters of the spectral function (*i.e.*, spectroscopic factors) from the fits to the reduced cross sections as a function of  $p_m$ .
- 4) Using the priors from Step 3), find the parameters of the spectral function (*i.e.*, spectroscopic factors, peak positions, distribution widths) from the fits to the reduced cross sections as a function of  $E_m$ . Correct for transparency.

# Test spectral function: 80% mean-field + 20% *NN* correlations



Independent-particle shell model

+



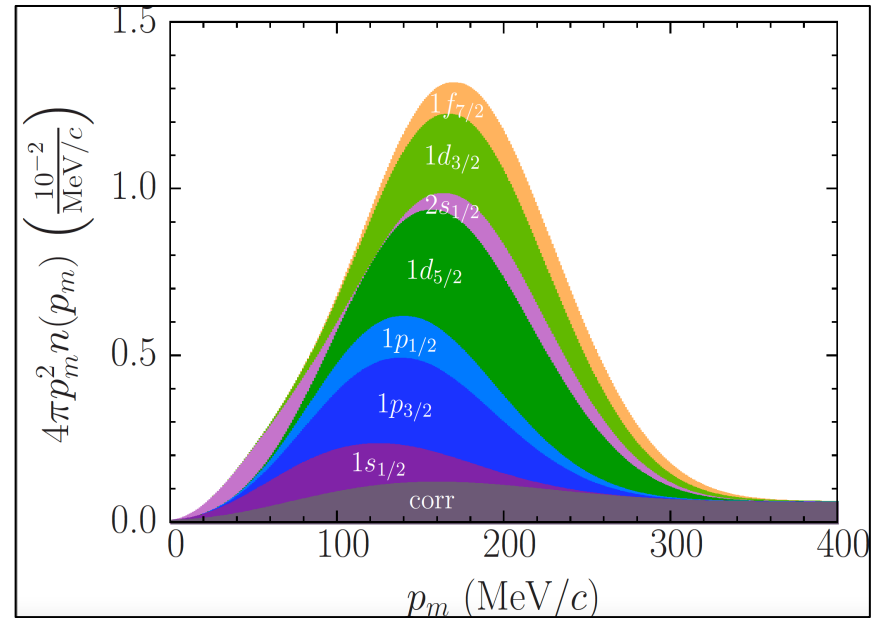
Convolution model of the correlated spectral function

# Mean-field part of the spectral function

spectroscopic factor      energy distribution

$$P_{\text{MF}}(p_m, E_m) = \sum_{\alpha} S_{\alpha} |\phi_{\alpha}(p_m)|^2 f_{\alpha}(E_m)$$

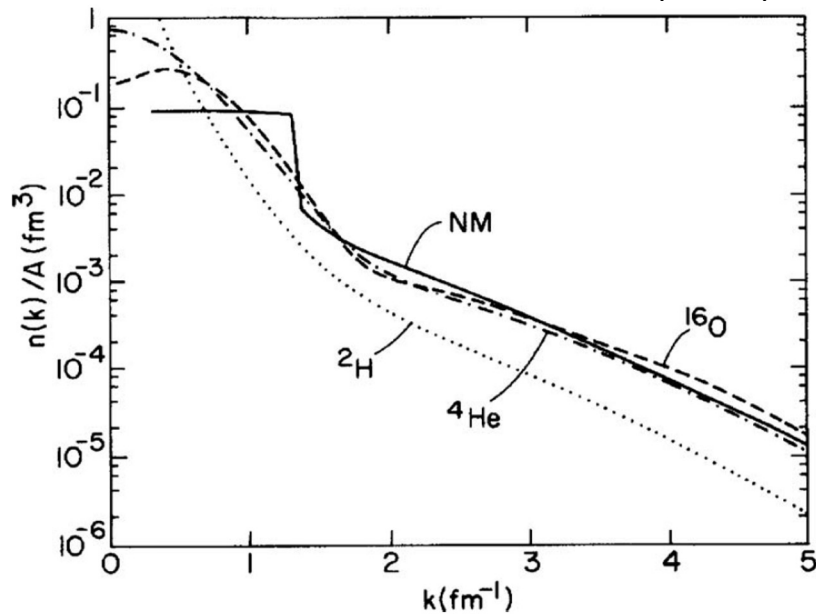
wave function in momentum space



Relativistic MF calculations by C. Giusti

# 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

# Fit procedure and minimization

For each bin in the spectra of missing energy (100 bins between 1 and 100 MeV) and missing momentum (40 bins with momentum range changing between kinematics), we determined the product of the reduced MC cross section and the ratio of the data to simulation yield

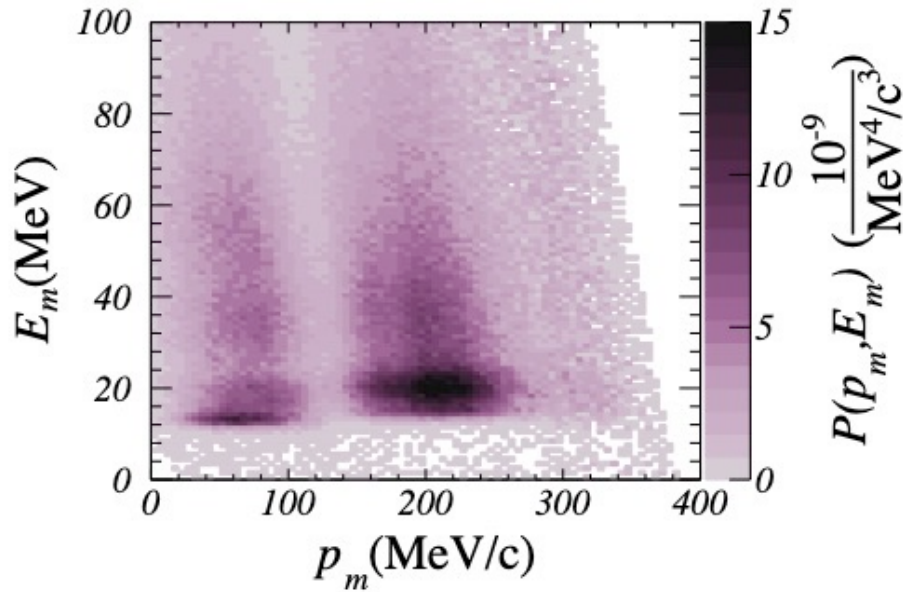
$$\frac{d^2 \sigma_{cc1}^{\text{red}}}{d\Omega dE'} = \left( \frac{d^2 \sigma_{cc1}^{\text{red}}}{d\Omega dE'} \right)_{\text{MC}} \times \frac{Y(E', \theta)}{Y_{\text{MC}}(E', \theta)}$$

The fit performs a  $\chi^2$  minimization using the TMinuit package available in root.

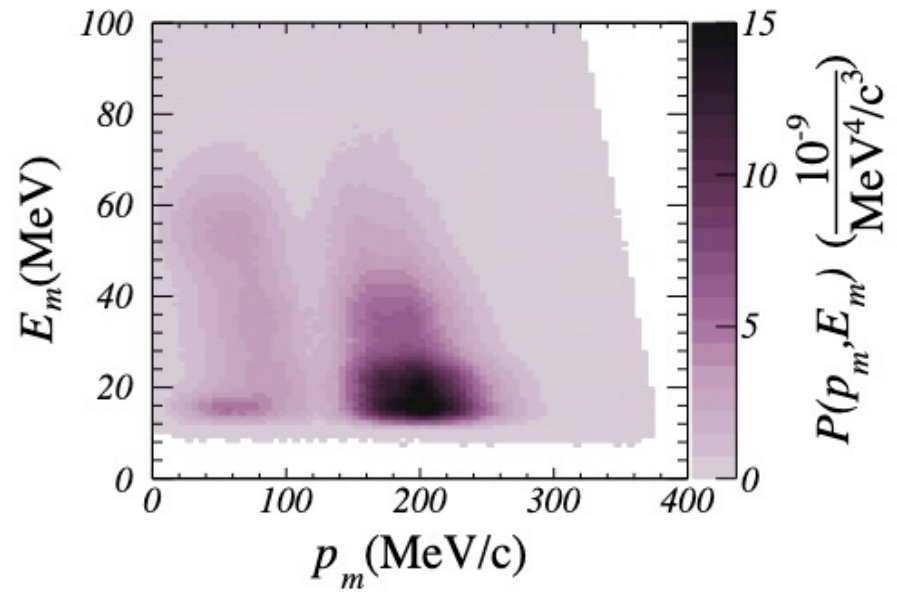
The index  $i$  labels the missing momentum(energy) bin,  $\alpha$  is the orbital index,  $f_{\alpha}^{\text{pred}}(i)$  is the parametrized prediction evaluated at bin  $i$  in the missing momentum spectra for orbital  $\alpha$ ,  $S_{\alpha}$  is the spectroscopic factor.

$$\chi^2 = \sum_i \chi_i^2 = \sum_i \left( \frac{\sigma_i^{\text{red, obs}} - \sum_{\alpha} S_{\alpha} f_{\alpha}^{\text{pred}}(i)}{\sigma_{\sigma_i}^{\text{red, obs}}} \right)^2$$

# $Ar (e, e'p)$ – Phys. Rev. D 105, 112002, (2022)

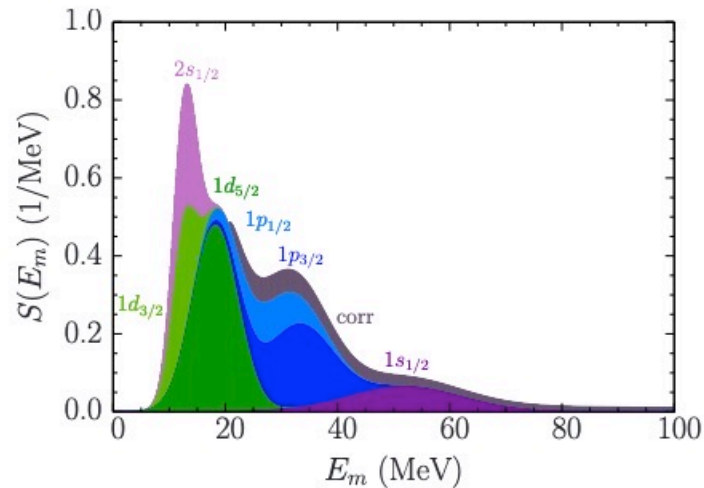
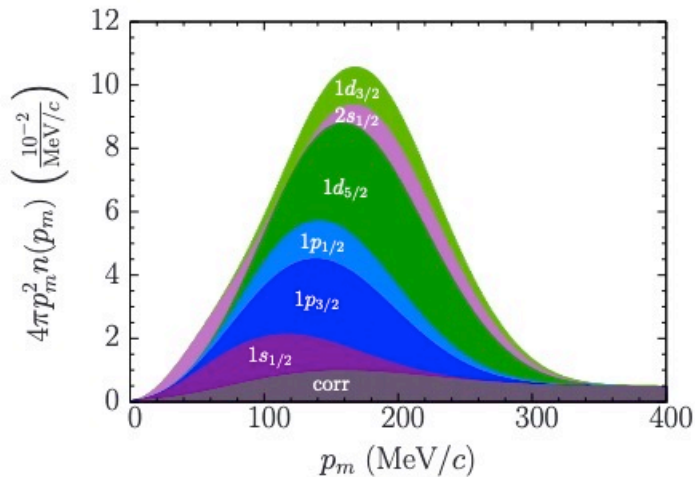


(a) Data



(b) MC

# Ar (e, e'p) – Phys. Rev. D 105, 112002, (2022)

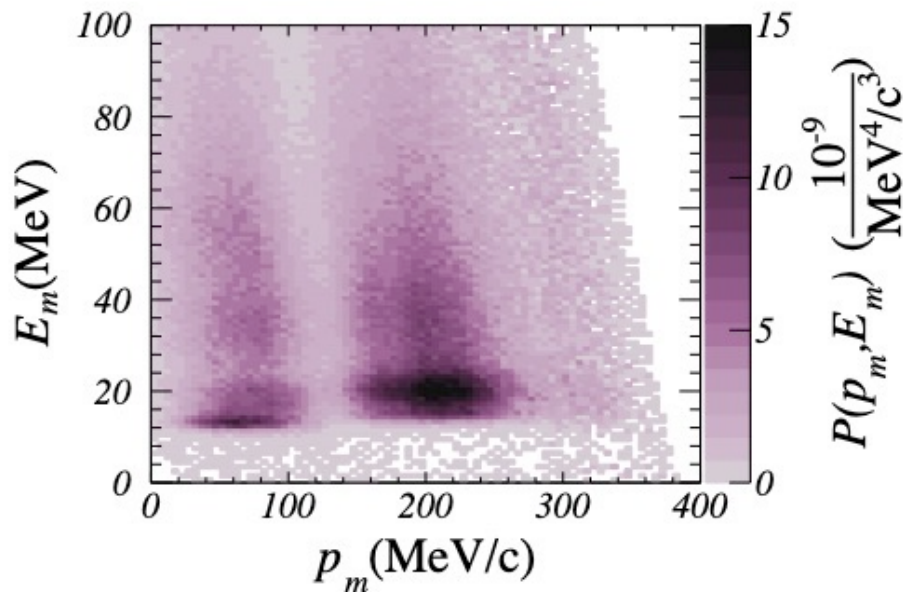


		all priors	w/o $p_m$	w/o corr.
$\alpha$	$N_\alpha$		$S_\alpha$	
$1d_{3/2}$	2	$0.89 \pm 0.11$	$1.42 \pm 0.20$	$0.95 \pm 0.11$
$2s_{1/2}$	2	$1.72 \pm 0.15$	$1.22 \pm 0.12$	$1.80 \pm 0.16$
$1d_{5/2}$	6	$3.52 \pm 0.26$	$3.83 \pm 0.30$	$3.89 \pm 0.30$
$1p_{1/2}$	2	$1.53 \pm 0.21$	$2.01 \pm 0.22$	$1.83 \pm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

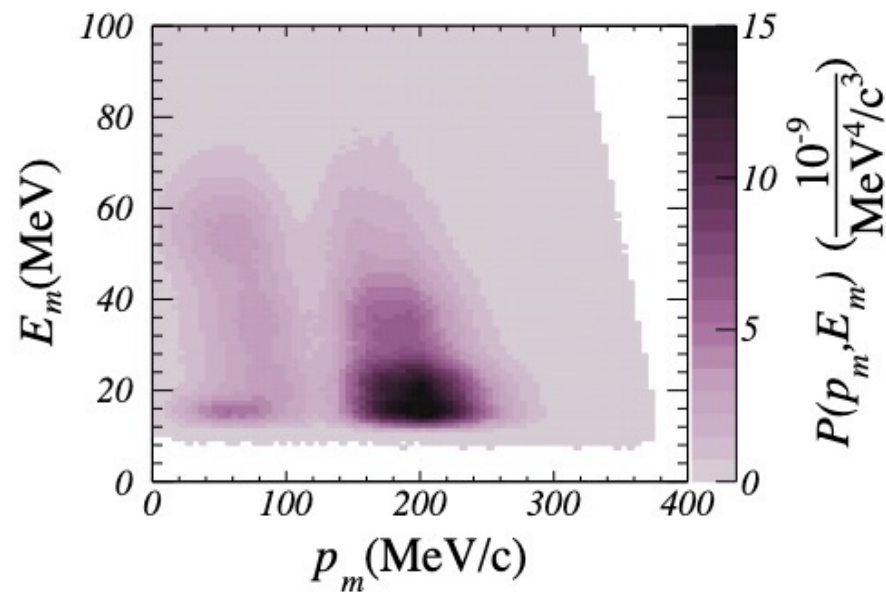
	$E_\alpha$ (MeV)		$\sigma_\alpha$ (MeV)	
$\alpha$	w/ priors	w/o priors	w/ priors	w/o priors
$1d_{3/2}$	$12.53 \pm 0.02$	$10.90 \pm 0.12$	$1.9 \pm 0.4$	$1.6 \pm 0.4$
$2s_{1/2}$	$12.92 \pm 0.02$	$12.57 \pm 0.38$	$3.8 \pm 0.8$	$3.0 \pm 1.8$
$1d_{5/2}$	$18.23 \pm 0.02$	$17.77 \pm 0.80$	$9.2 \pm 0.9$	$9.6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



# $Ti (e, e'p)$ – to be submitted to PRD letter

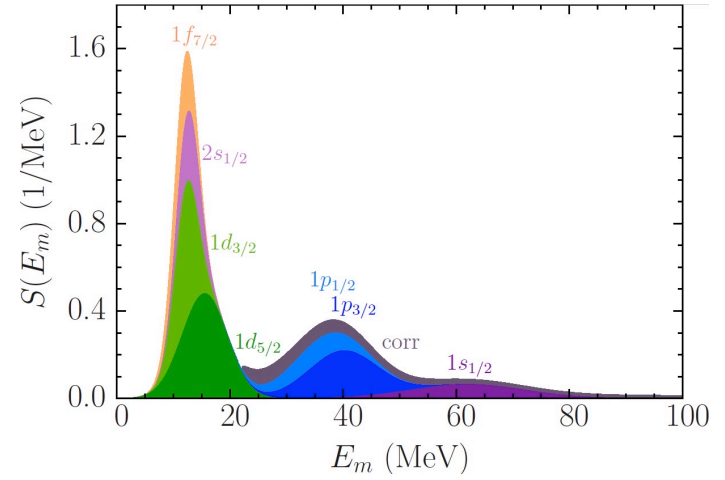
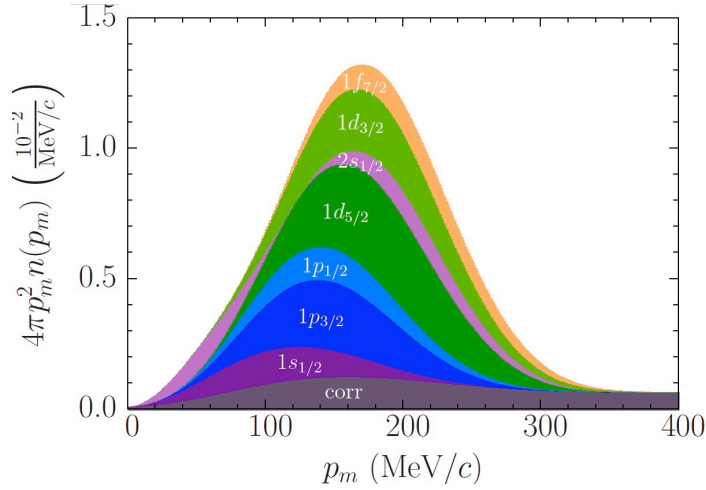


(a) Data



(b) MC

# Ti ( $e, e'p$ ) – Phys. Rev. D 105, 112002, (2022)



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

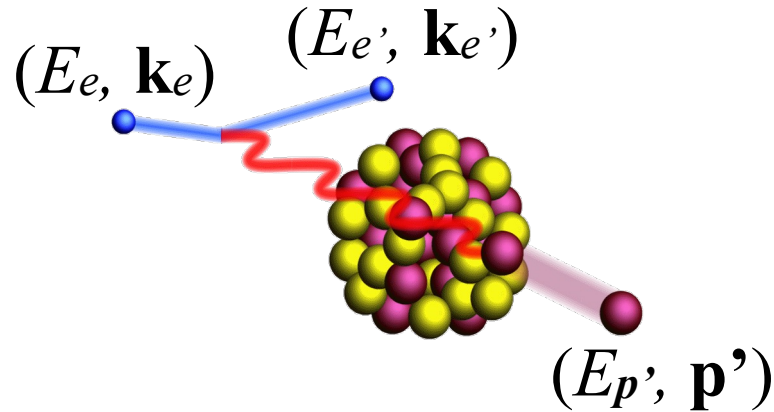
$\alpha$	$E_\alpha$ (MeV)		$\sigma_\alpha$ (MeV)	
	w/ priors	w/o priors	w/ priors	w/o priors
$1f_{7/2}$	$11.32 \pm 0.10$	$11.31 \pm 0.10$	$8.00 \pm 5.57$	$8.00 \pm 6.50$
$1d_{3/2}$	$12.30 \pm 0.24$	$12.33 \pm 0.24$	$7.00 \pm 0.61$	$7.00 \pm 3.84$
$2s_{1/2}$	$12.77 \pm 0.25$	$12.76 \pm 0.25$	$7.00 \pm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

# Summary

- ❖ We completed the data analysis for the full data set collected by the E12-14-012 experiment at Jefferson Lab in 2017.
- ❖ Data has been published for both inclusive and exclusive analysis – 5 publications from 2017, 4 PhD thesis.
- ❖ We found reasonable parametrization for both the Ar and Ti spectral functions and reach the goal of the experiment.
- ❖ Separation of individual contributions requires improved analysis. Numerous theoretical developments are necessary. But we have now data.
- ❖ Interpretation of the Ti proton spectral function in term of neutron spectral function on Ar is in progress, new theory development will be needed.



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



$$E_e + M_A = E_e' + E_{p'} + \underline{E_{A-1}^*}$$

known

determined

$$\mathbf{k}_e + 0 = \mathbf{k}_e' + \mathbf{p}' + \underline{\mathbf{p}_{A-1}}$$

In the absence of final state interactions

–  $\mathbf{p}_{A-1} = \mathbf{p}_m$  initial proton momentum;  $p_m \equiv |\mathbf{p}_m|$

$$E_{A-1}^* = \sqrt{(M_A - M + E_m)^2 + \mathbf{p}_m^2}, \text{ with excitation energy } E_m - E_{\text{thr}}$$