JLab E12-14-012 experiment: 2014-2023

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On behalf of the E12-14-012 collaboration
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Outline

- 2014 – PAC 42 talk
- E12-14-012 Motivations:
  - Neutrino Oscillation Experiments
  - Importance of cross sections in oscillation results
- Experimental setup
- (e,e’) results on C, Ar, Ti and Al
- (e,e’p) results on Ar and Ti

2014: Benhar's talk at PAC-42

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*

E12-14-012: Goals and Motivations

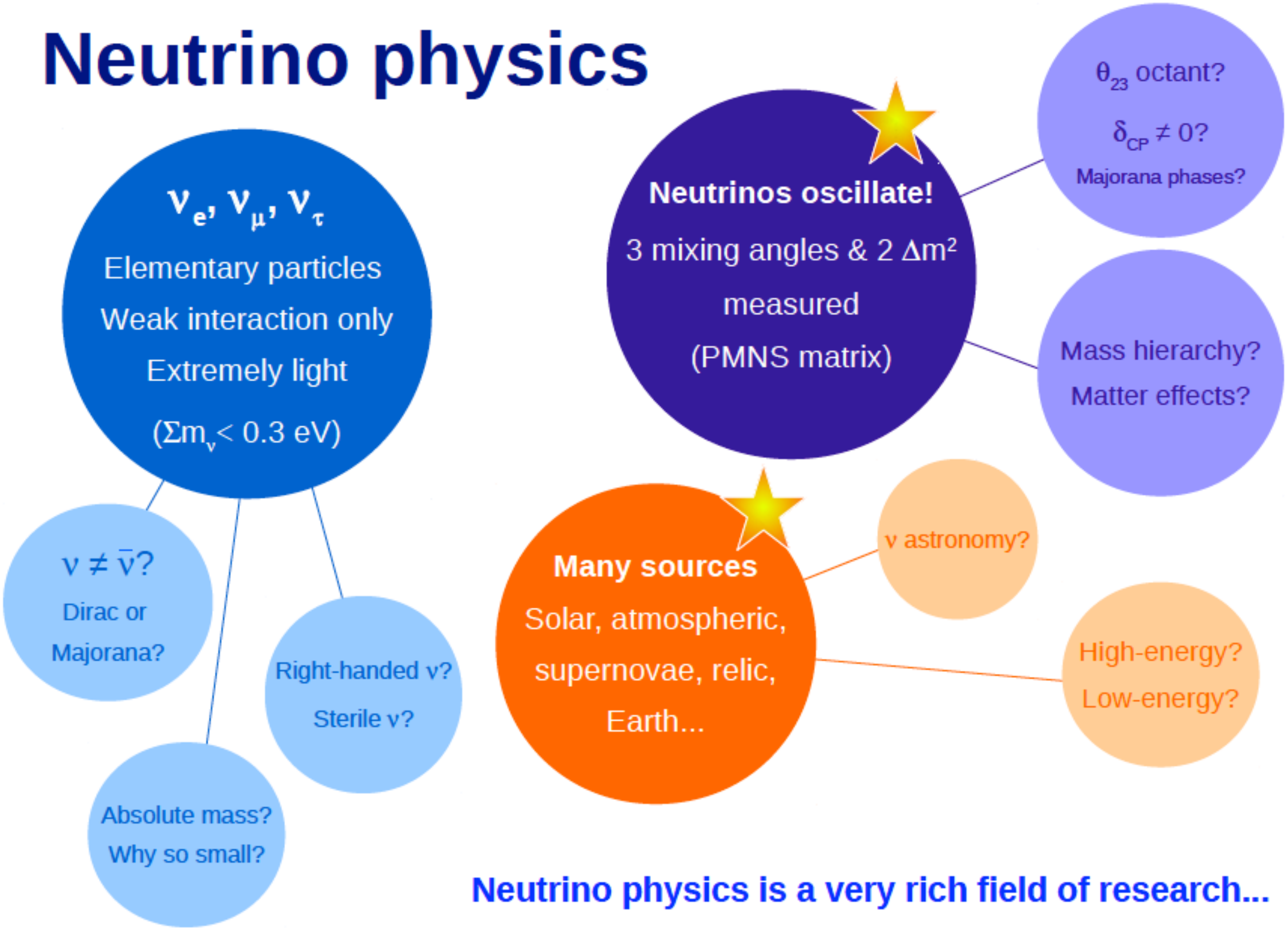
- **Primary Goal:** Measurement of the spectral functions of Argon and Titanium through Ar-Ti *(e,e′p)* reactions
  - Data Collected (Feb-March 2017):
    - Ar/Ti/C/Dummy/Optical *(e,e′p)* reactions for five different kinematic set-ups
    - Ar/Ti/C/Dummy (*e,e′*) reactions for one kinematic set-up

- **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 (~ 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).

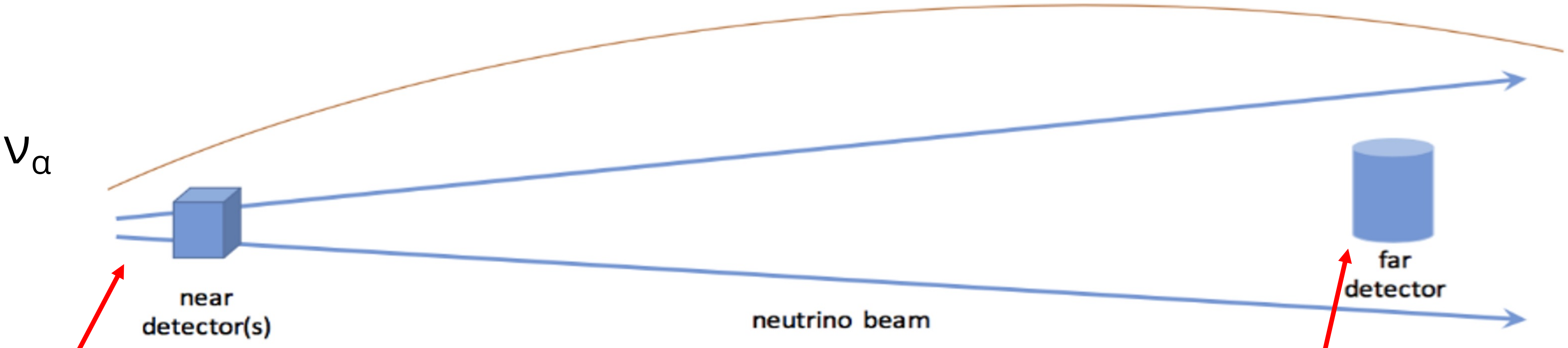
- Using measured argon spectral functions to further develop (extend) a fully consistent parameter-free theoretical (neutrino-nucleus) model that can be used in (every step of) the analysis of long baseline neutrino experiments.

Neutrino physics



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

Neutrino Oscillation Experiments



Measure neutrino beam before oscillations

Measure neutrino beam after oscillations

Signature of Neutrino Oscillation

- Neutrino Spectrum Distortions

Near to Far extrapolation

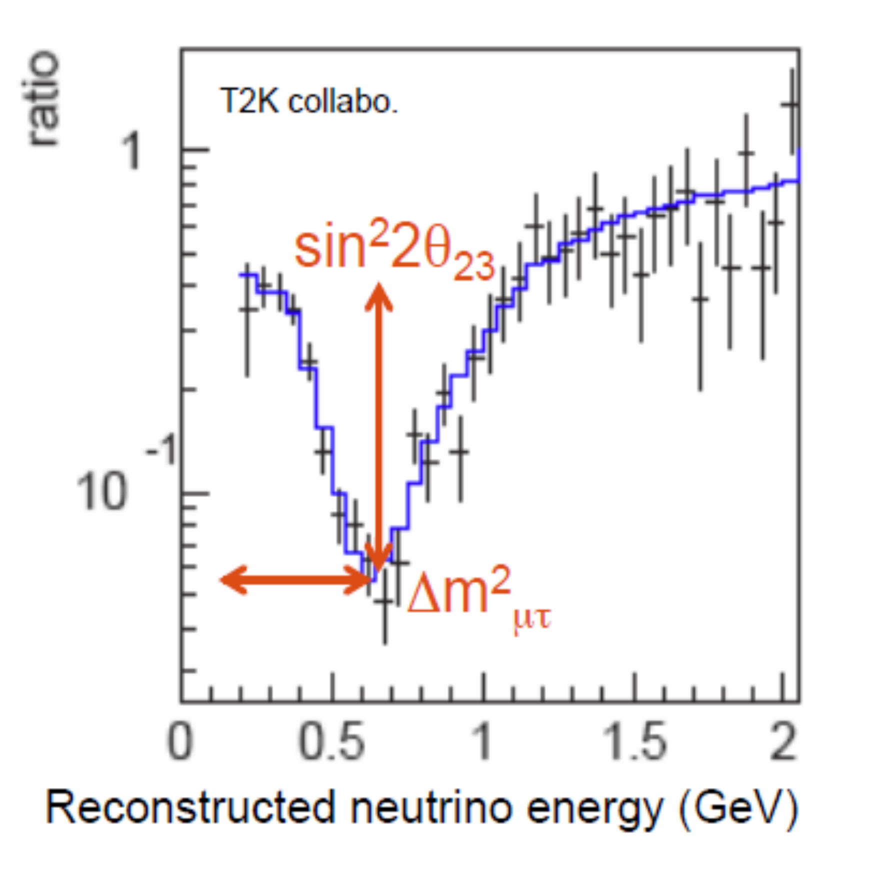
- Provides data-driven estimate of un-oscillated event rate at the Far detector.
- Neutrino spectrum distortions calculated from the ratio of neutrino spectrum at far detector to un-oscillated predicted event rate at far detector
- Influenced by uncertainties in the knowledge of flux and cross sections.

Observable Oscillation Parameters

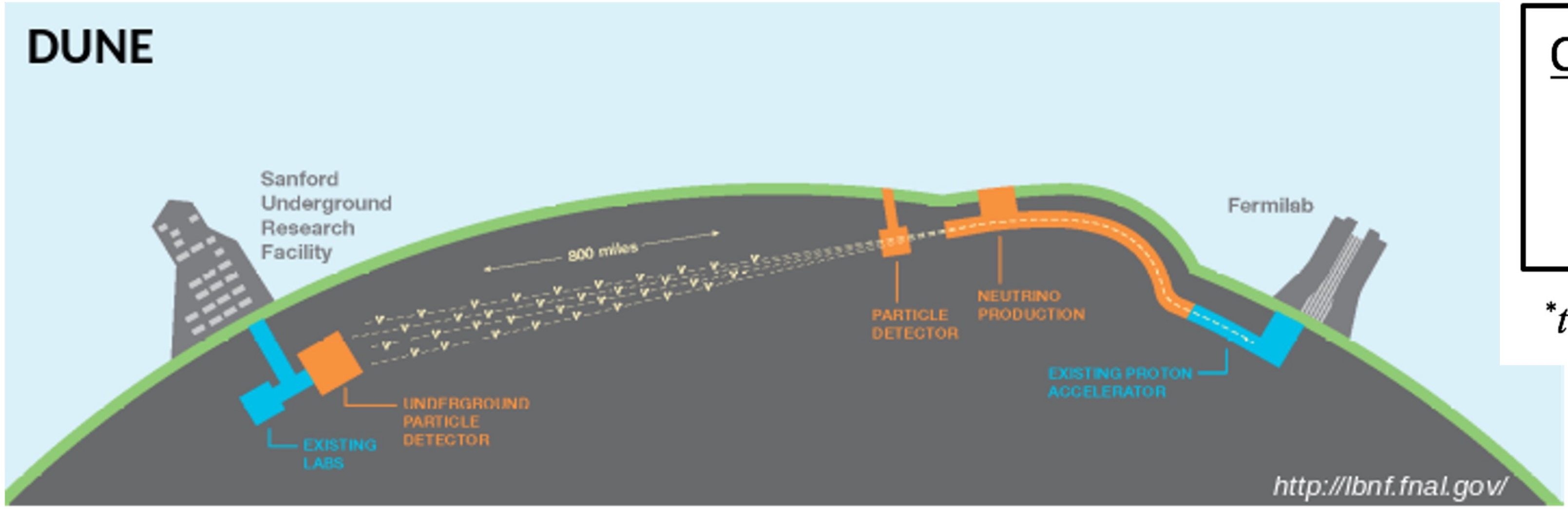
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Neutrino energy >1 GeV

Oscillation parameter determination depends on the reconstructed neutrino energy.



DUNE Experiment



<u>Oscillation Probability*:</u>

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

two neutrino flavors, for simplicity

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

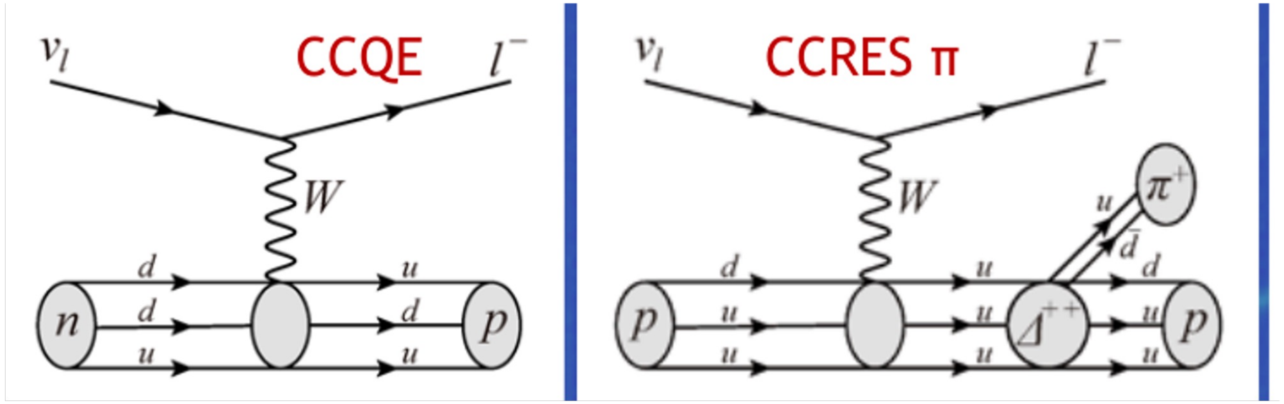
<u>Event Rate at near detector:</u>

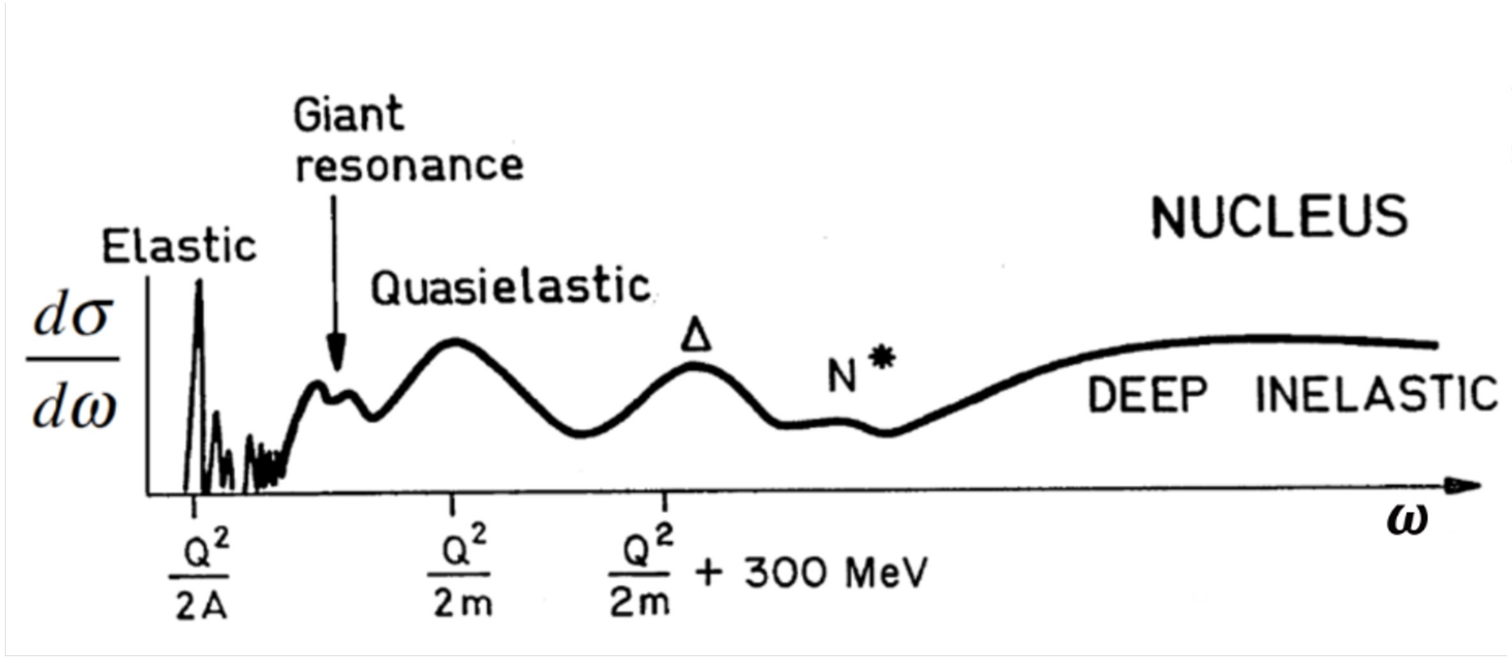
$$N^{\alpha}_{\rm ND}(\boldsymbol{p}_{\rm reco}) = \sum_i \phi_\alpha(E_{\rm true}) \times \sigma^i_\alpha(\boldsymbol{p}_{\rm true}) \times \epsilon_\alpha(\boldsymbol{p}_{\rm true}) \times R_i(\boldsymbol{p}_{\rm true}; \boldsymbol{p}_{\rm reco})$$

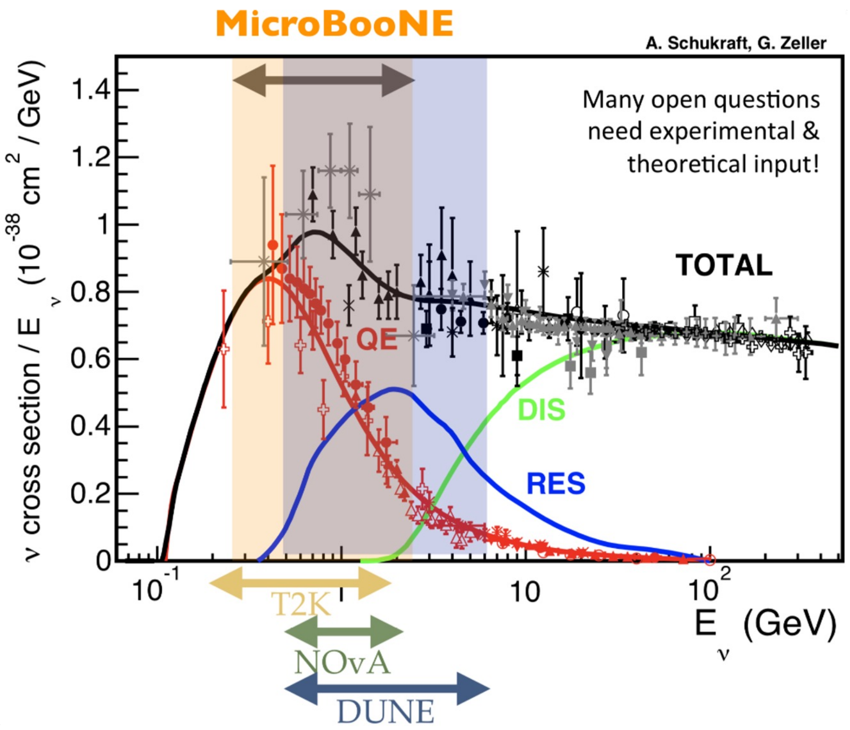
<u>Event Rate at far detector:</u>

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

Neutrino Interactions



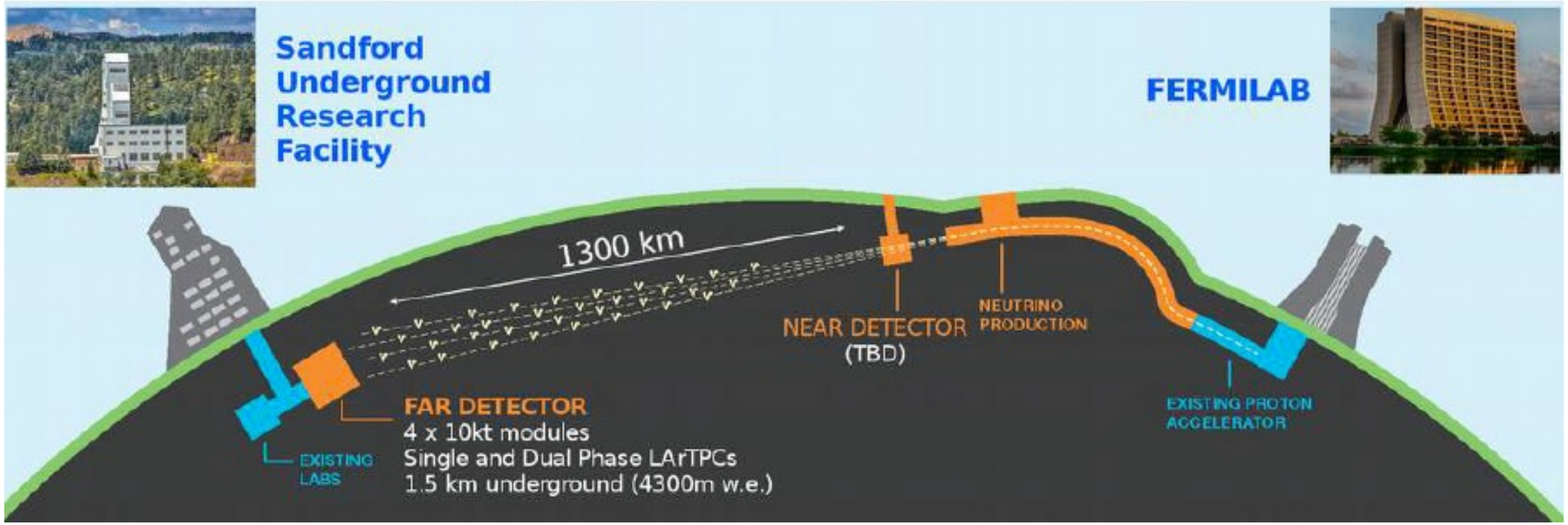




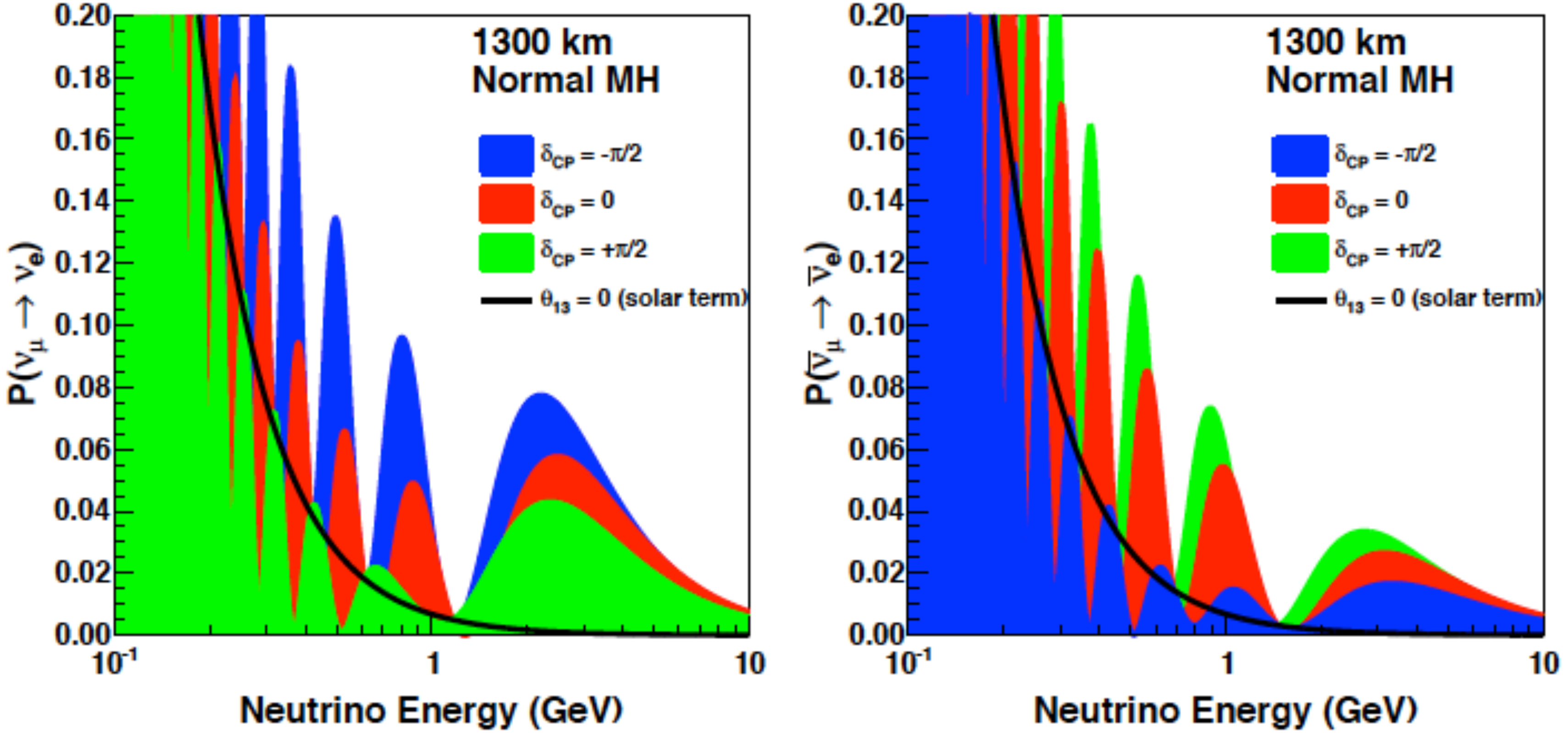
Deep Underground Neutrino Experiment

- DUNE is a future long-baseline neutrino oscillation and proton decay experiment
- 1300 km baseline, new broad-band (0.5–7 GeV) mega-watt scale $\nu_\mu / \overline{\nu}_\mu$ beam from Fermilab to SURF

  → 1.2 MW (2026) up to 2.4 MW (2032)
- Large international collaboration: 1100+ physicists, 178+ institutions, 32+ countries

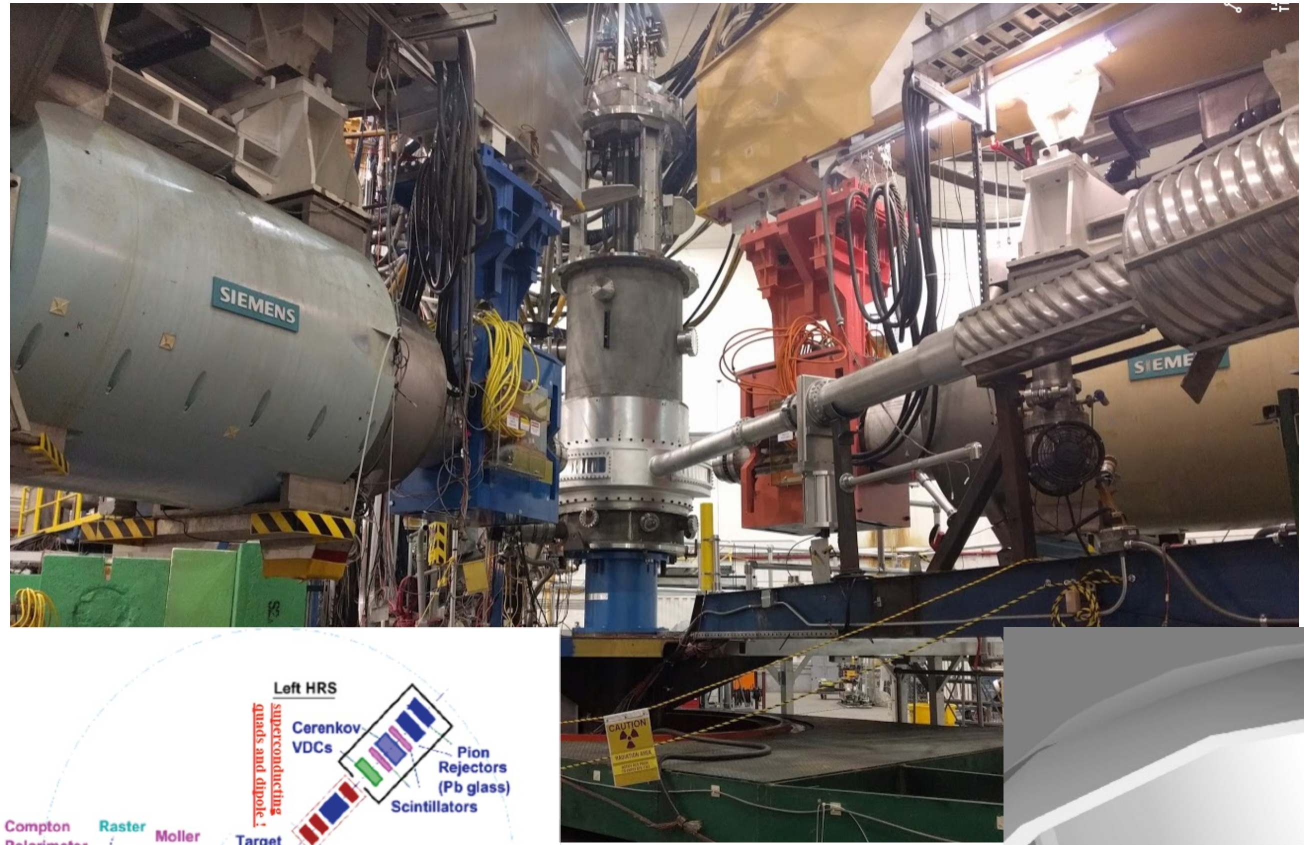


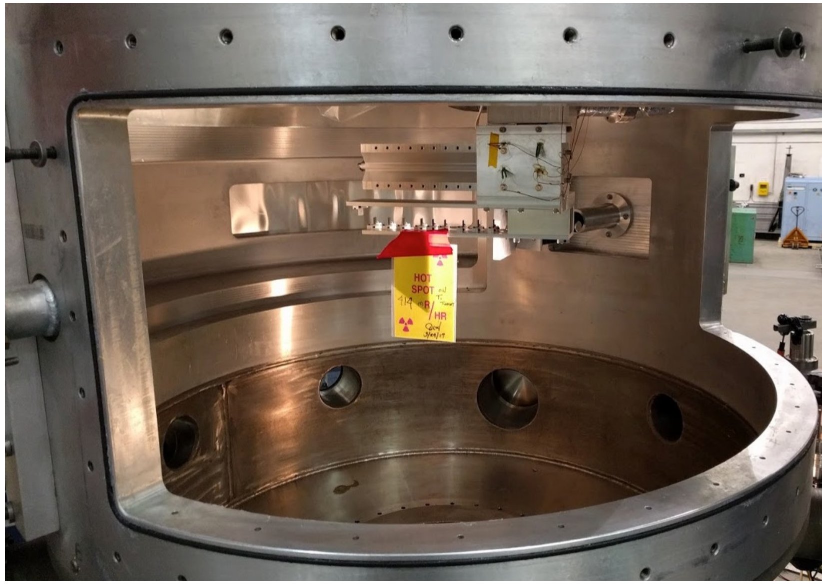
Appearance Probability as function of neutrino energy

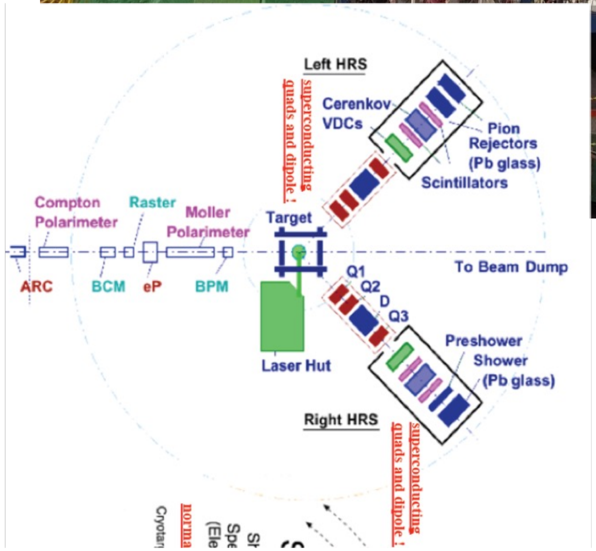


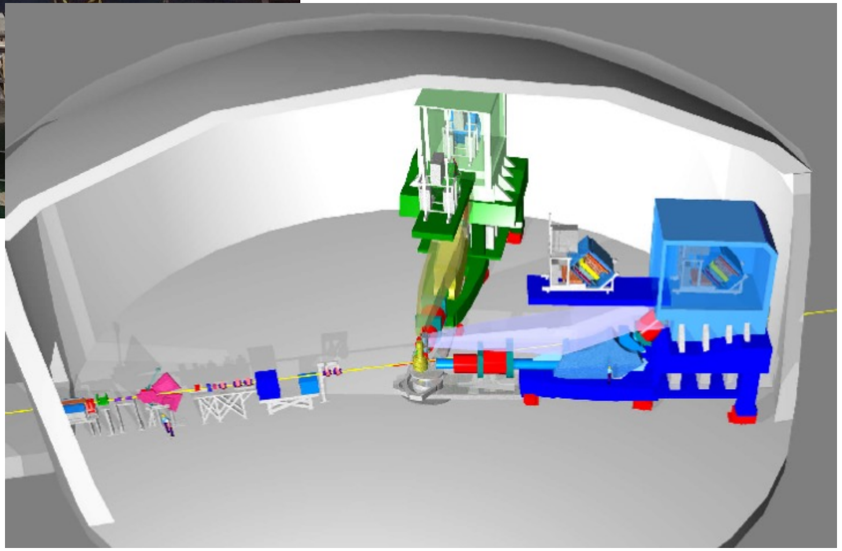
Need energy to distinguish between different δ_{CP}

Hall A at Jefferson Lab









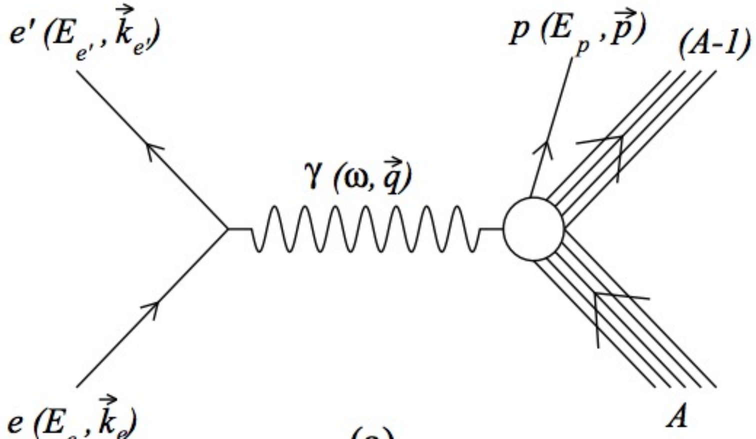
(e,e’) and (e,e’p) processes

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

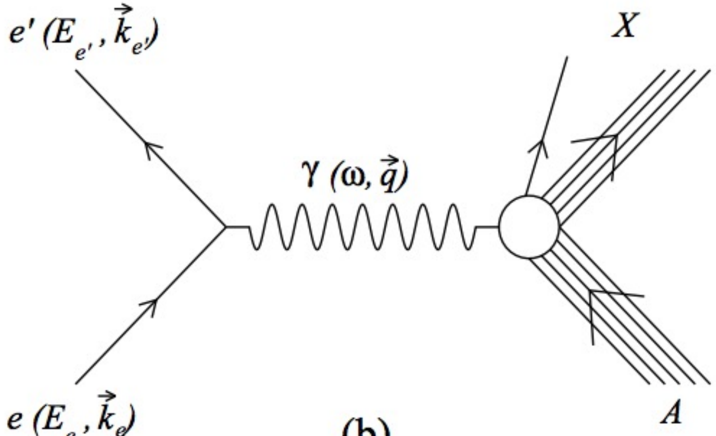
$$e + A \rightarrow e' + p + (A-1)$$

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

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



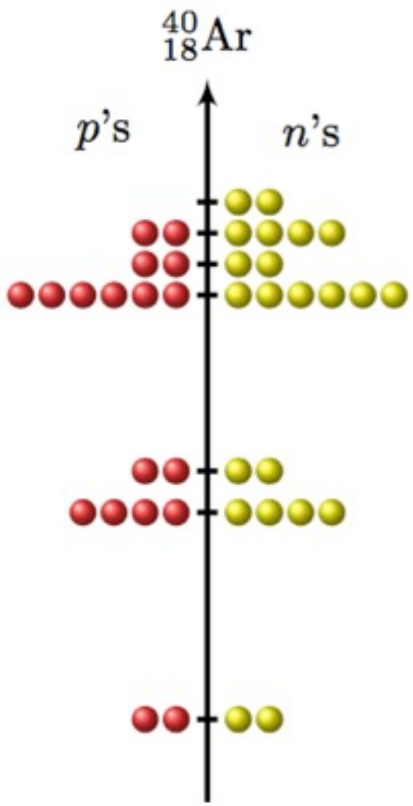
(a)

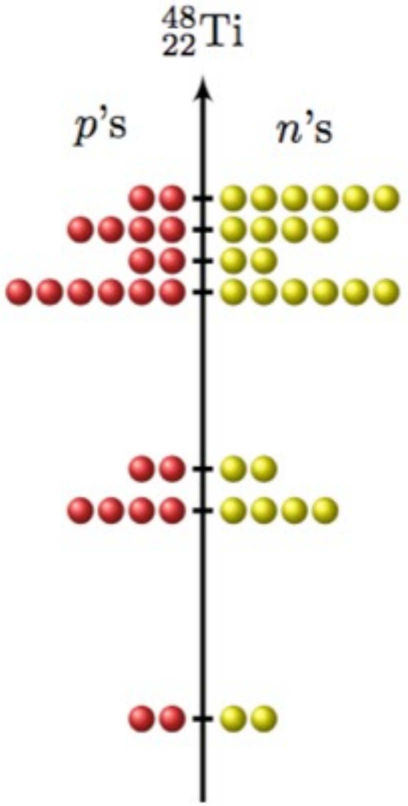


(b)

Why Titanium?

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



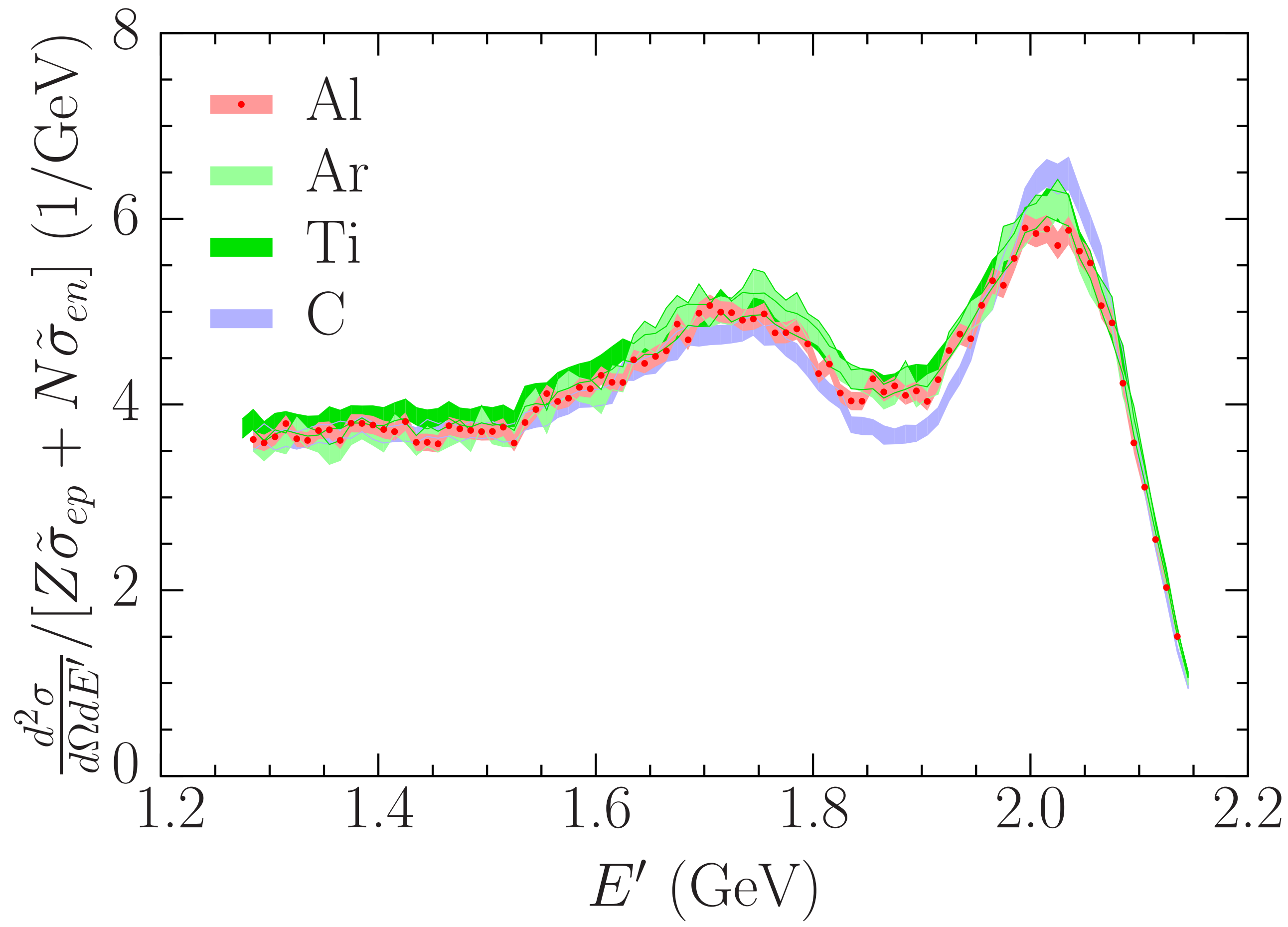


$$\bar{\nu}_l + p \rightarrow l^+ + n$$

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

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

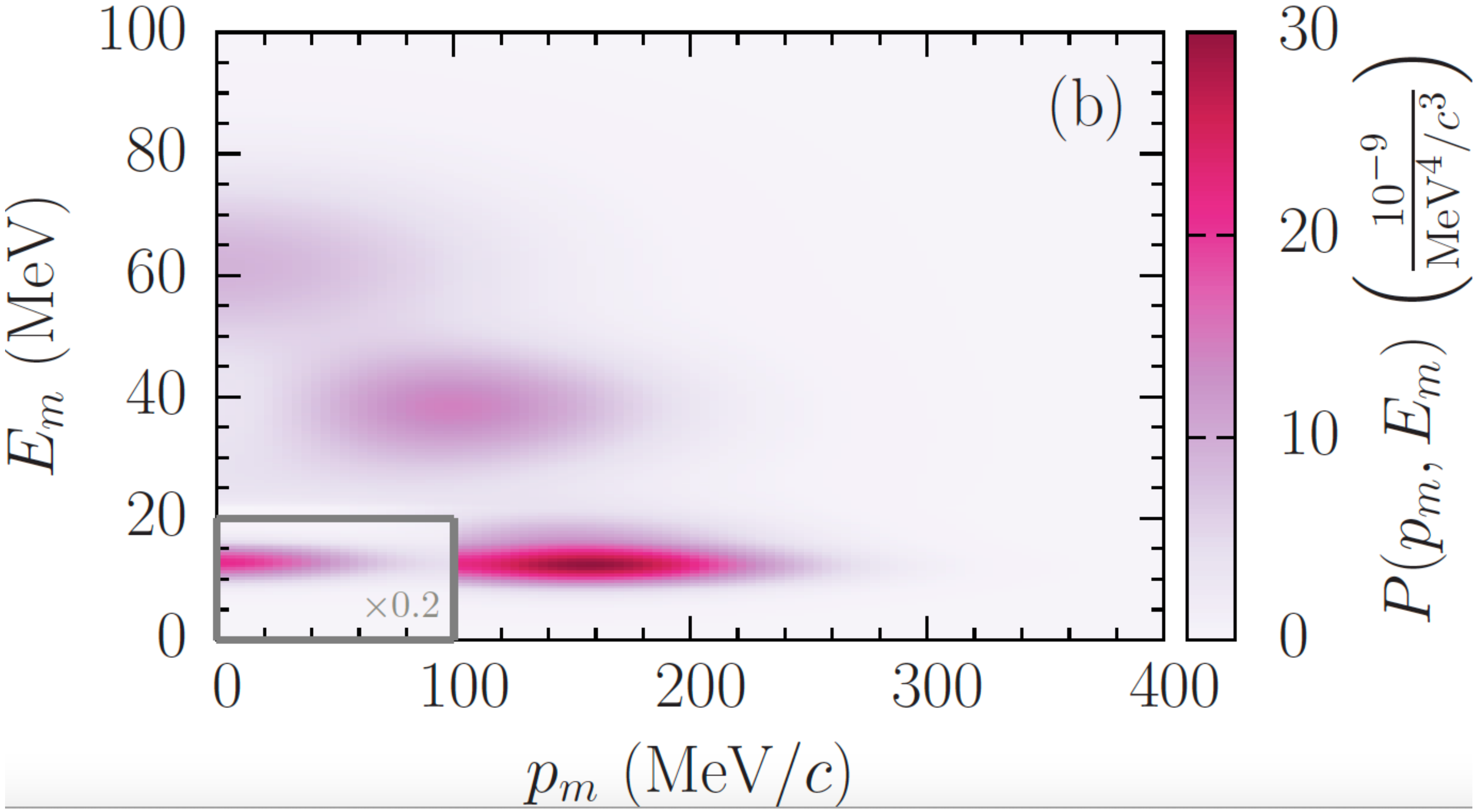
Inclusive analysis



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).

(e,e’p) analysis: extraction of the spectral function



- Universal property of the nucleus, independent of the interaction.

(*e,e'p*) cross section

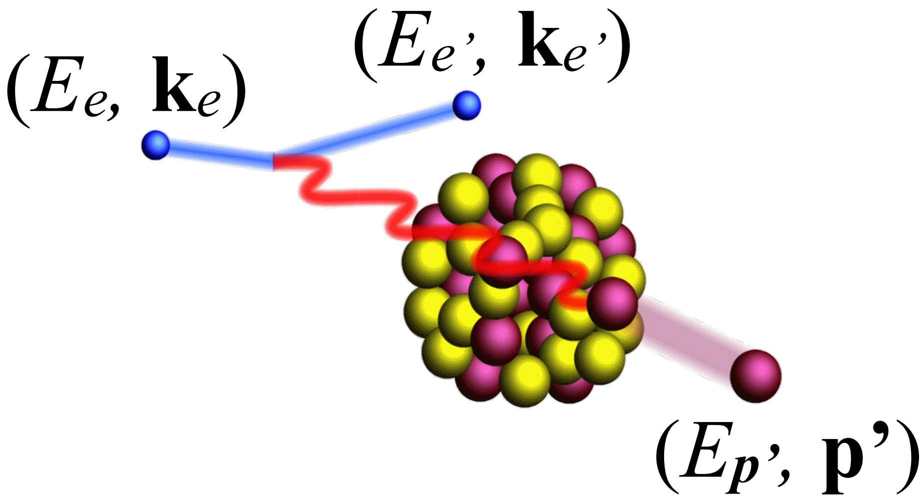
elementary cross section

nuclear transparency

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

spectral function

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

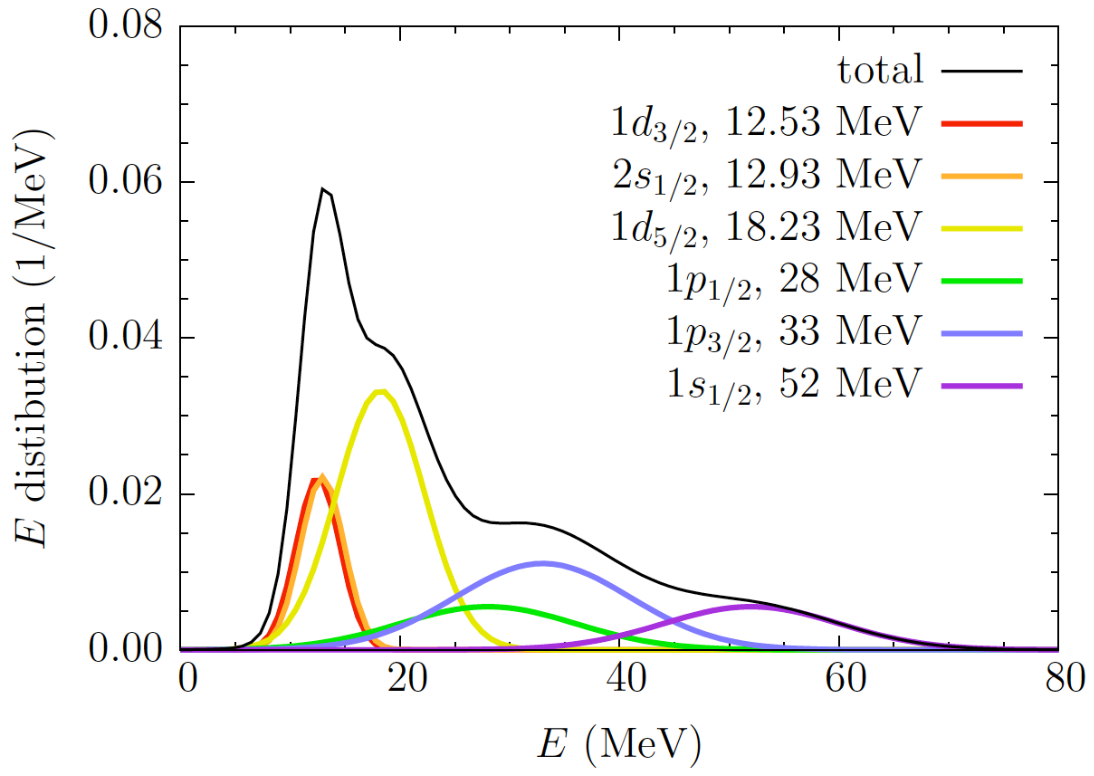
1) Extract of the (*e,e'p*) cross section

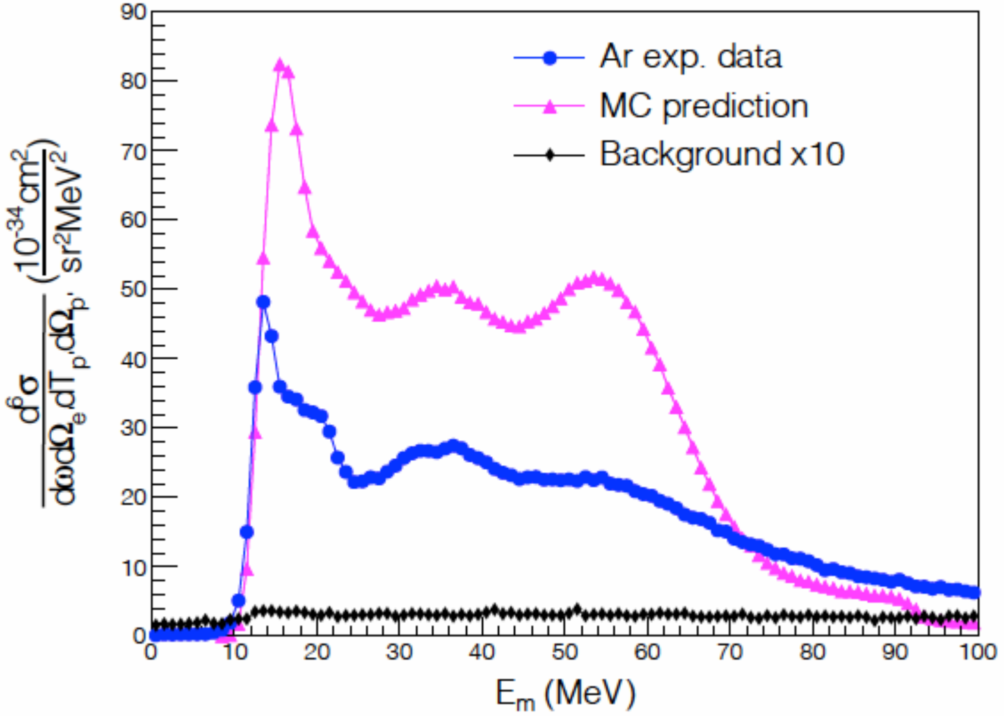
2) Using σ_{cc1} of de Forest and nuclear transparency, obtain the reduced cross sections as a function of (a) p_m and (b) E_m.

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.

Exclusive analysis – kin1 - Ar - Missing energy and missing momentum





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

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

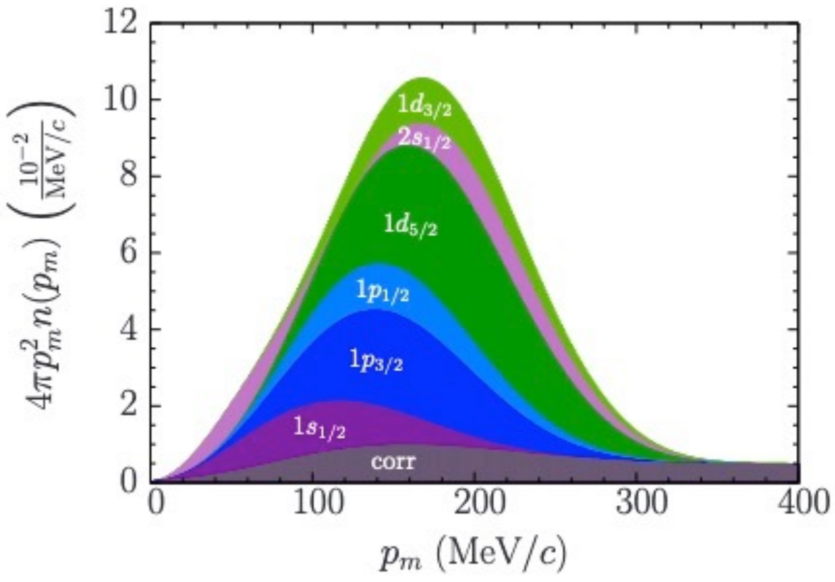
$$\frac{d^2\sigma^{\text{red}}_{cc1}}{d\Omega dE'} = \left(\frac{d^2\sigma^{\text{red}}_{cc1}}{d\Omega dE'}\right)_{\text{MC}} \times \frac{Y(E',\theta)}{Y_{\text{MC}}(E',\theta)}$$

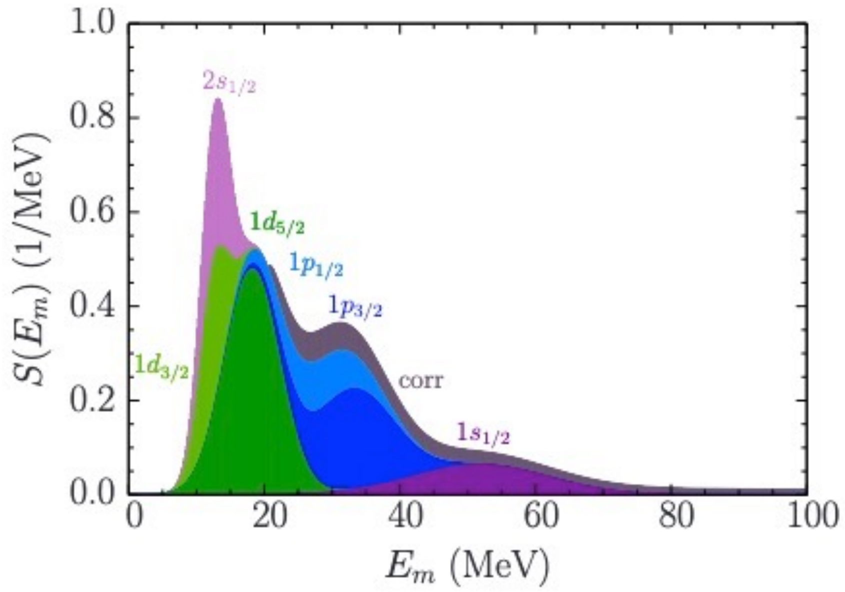
The fit performs a χ^2 minimization using the TMinuit package available in root.

The index i labels the missing momentum(energy) bin, α is the orbital index, $f^{pred}_{\alpha}(i)$ is the parametrized prediction evaluated at bin i in the missing momentum spectra for orbital α, S_α 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)

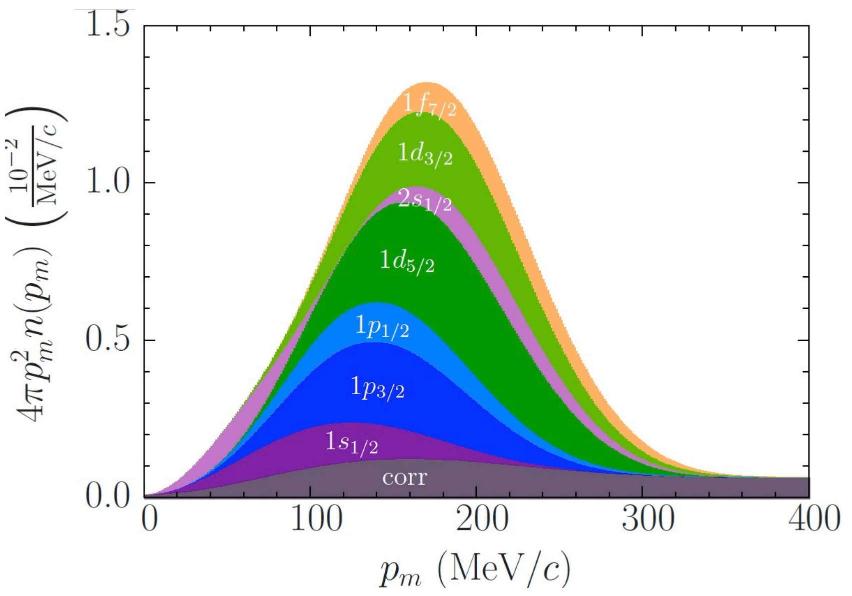


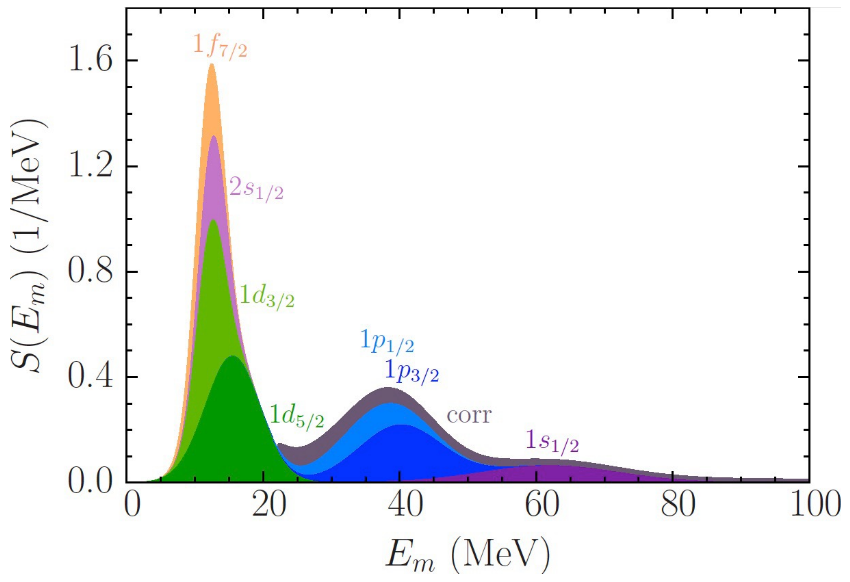


		all priors	w/o p_m	w/o corr.
α	N_α		S_α	
$1d_{3/2}$	2	0.89 ± 0.11	1.42 ± 0.20	0.95 ± 0.11
$2s_{1/2}$	2	1.72 ± 0.15	1.22 ± 0.12	1.80 ± 0.16
$1d_{5/2}$	6	3.52 ± 0.26	3.83 ± 0.30	3.89 ± 0.30
$1p_{1/2}$	2	1.53 ± 0.21	2.01 ± 0.22	1.83 ± 0.21
$1p_{3/2}$	4	3.07 ± 0.05	2.23 ± 0.12	3.12 ± 0.05
$1s_{1/2}$	2	2.51 ± 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 (e,e'p) – Phys. Rev. D 107, 012005, (2023)





		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

- 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.
  - 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 cross section for Ar, [Jiang *et al.*, PRD 105, 112002 (2022)]
  - Exclusive cross section for Ti, [Jiang *et al.*, PRD 107, 012005 (2023)]
  - H. Dai (VT), PhD thesis, 2019
  - M. Murphy (VT), PhD thesis, 2020
  - L. Gu (VT), PhD thesis, 2021
  - D. Abrams (UVA), PhD thesis, 2022
  - C. Lanham (VT), MS thesis, 2023

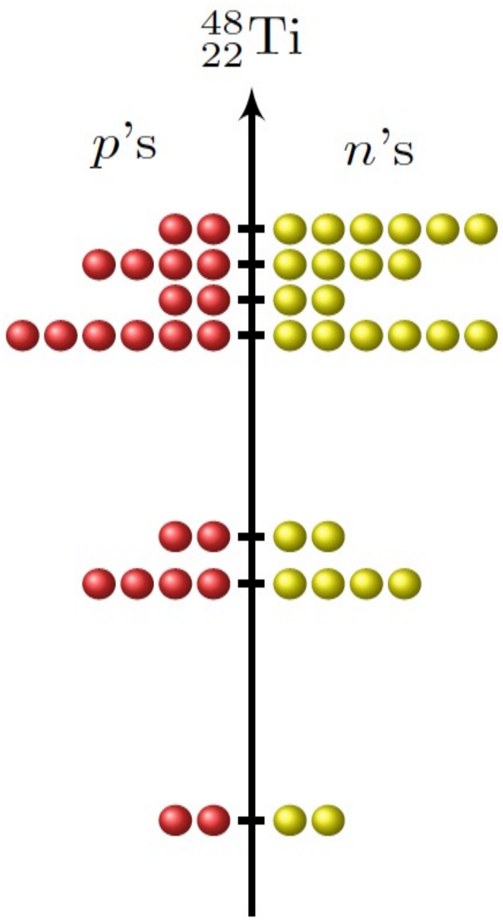
Summary

- Separation of individual contributions requires improved analysis. Numerous theoretical developments are necessary. But we have data now.
- Interpretation of the Ti proton spectral function in terms of neutron spectral function on Ar is in progress, new theory development will be needed.

Thank you

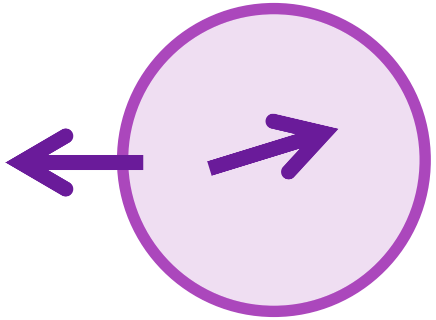
Back up

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

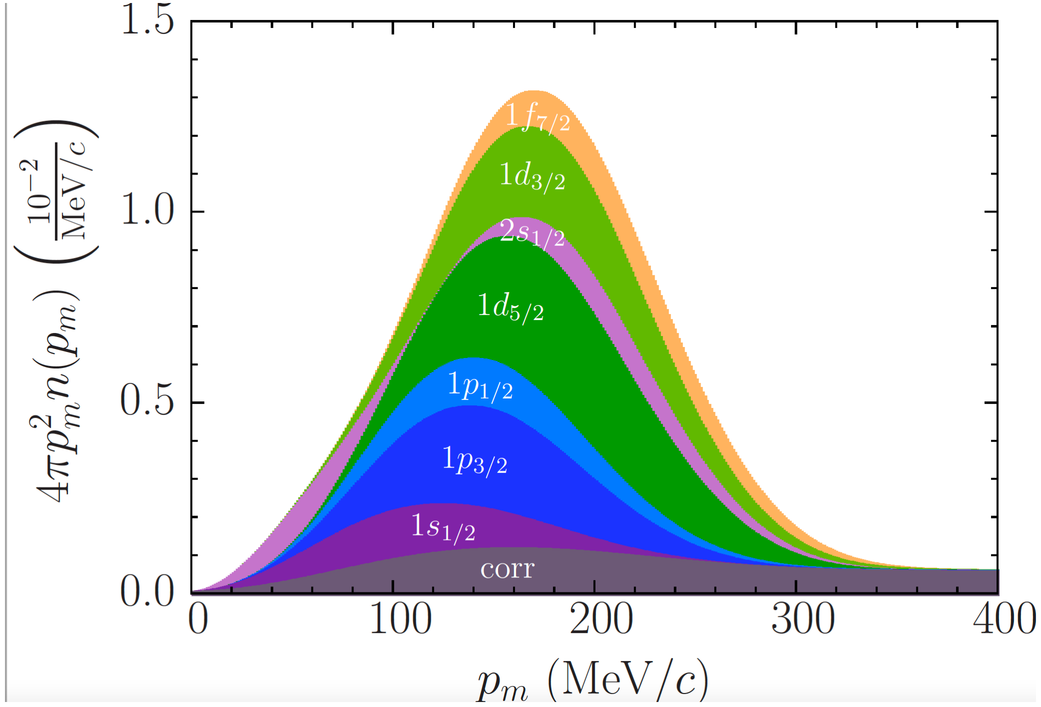
spectroscopic factor

energy distribution

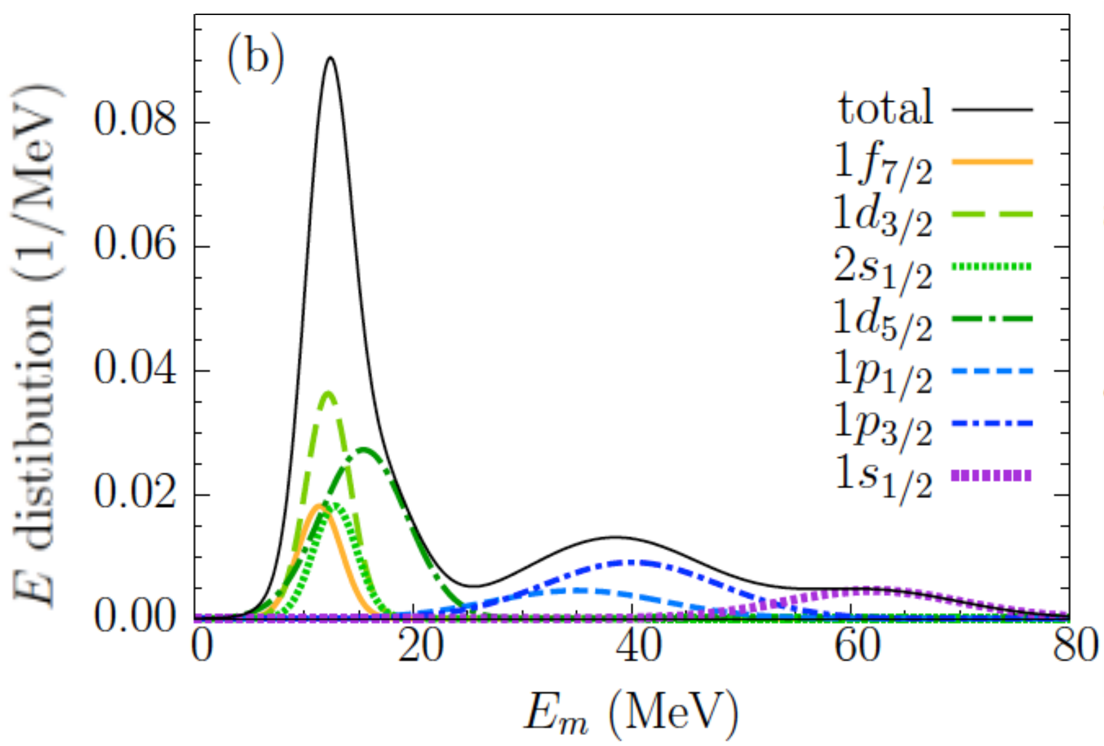
$$P_{\rm MF}(p_m, E_m) = \sum_{\alpha} S_\alpha |\phi_\alpha(p_m)|^2 f_\alpha(E_m)$$

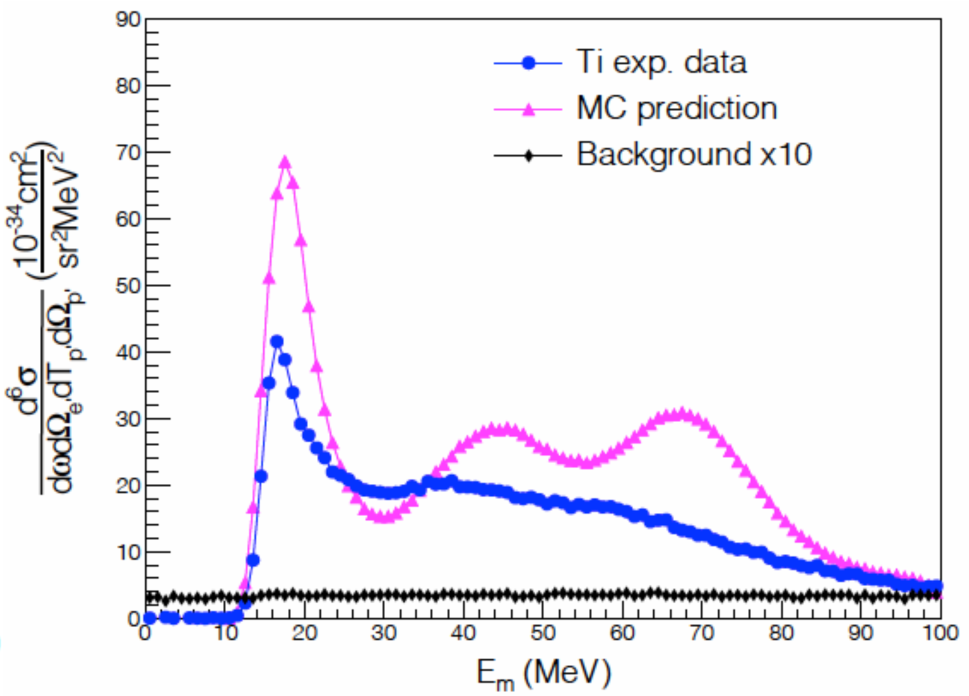
wave function in momentum space

Relativistic MF calculations by C. Giusti



Exclusive analysis - kin1 - Ti - Missing energy and missing momentum



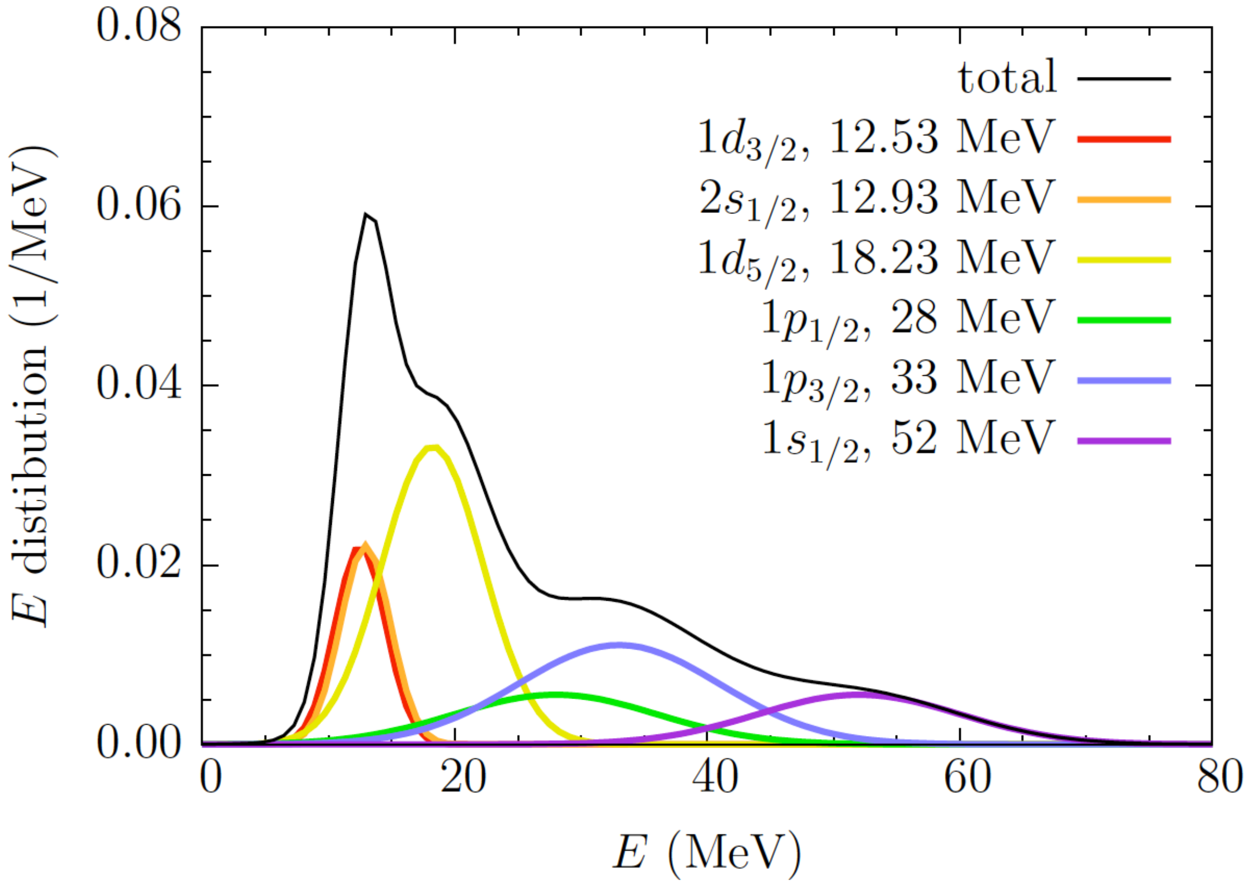


Effect of FSI

- 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 missing energy distribution

Work by A. Ankowski



Shapes – drawn in different colors represent the contribution of different orbitals

First three orbital shapes are estimates

Last three level are derived from data

FSI analysis

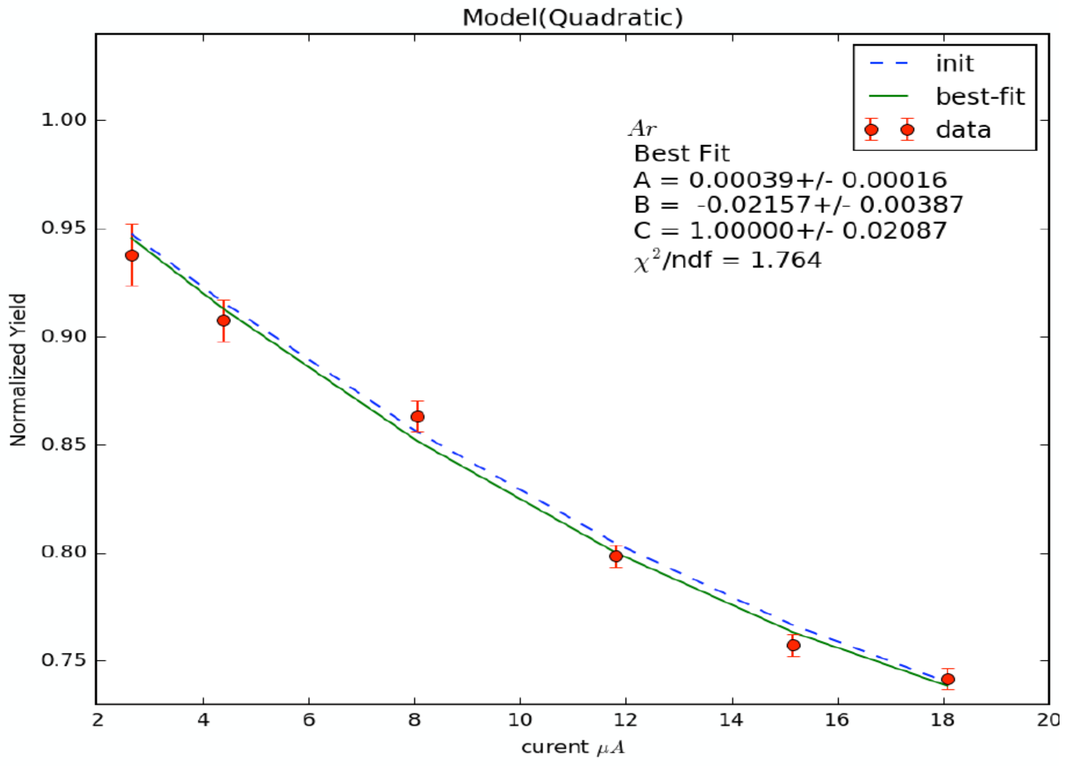
- C. Giusti provided a relativistic code, tested against old data on ^{16}O and ^{12}C up to ^{40}Ca
- Compute reduced cross section both PWIA and DWIA for various wave functions, identify the energy for each orbital

α	E_α	σ_α	E^α_{low}	E^α_{high}
			argon	
$1d_{3/2}$	12.53	2	8	14
$2s_{1/2}$	12.93	2	8	14
$1d_{5/2}$	18.23	4	14	20
$1p_{1/2}$	28.0	8	20	45
$1p_{3/2}$	33.0	8	20	45
$1s_{1/2}$	52.0	8	45	70
			titanium	
$1f_{7/2}$	11.45	2	8	14
$2s_{1/2}$	12.21	2	14	30
$1d_{3/2}$	12.84	2	14	30
$1d_{5/2}$	15.46	4	14	30
$1p_{1/2}$	35.0	8	30	54
$1p_{3/2}$	40.0	8	30	54
$1s_{1/2}$	62.0	8	53	80

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

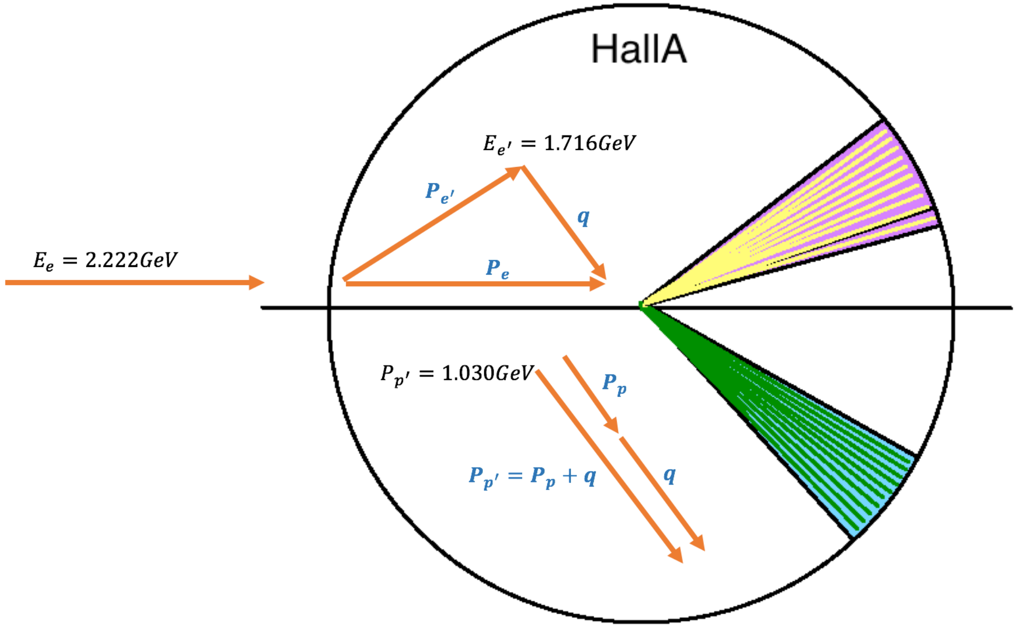
- We calculated the normalized yield for different currents, and the change in yield represents change in target density
- The normalization is done with respect to the lowest current
- We fit the numbers with quadratic function and fix the I=0 point to 1
- When $I = 9.67\mu A$, within 2% for all the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



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

The $(e, e'p)$ cross section within PWIA

- ⋆ Factorization of the final state of the semi-exclusive process

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

leads to the simple expression

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

with the missing momentum and missing energy defined by

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

$$\omega + M_A = \sqrt{(M_A - m + E_m)^2 + |\mathbf{p}_m|^2} + \sqrt{\mathbf{p}^2 + m^2} \rightarrow E_m \approx \omega - T_{\mathbf{p}}\ ,$$

$\mathbf{q}$ and ω being the momentum and energy transfer, respectively

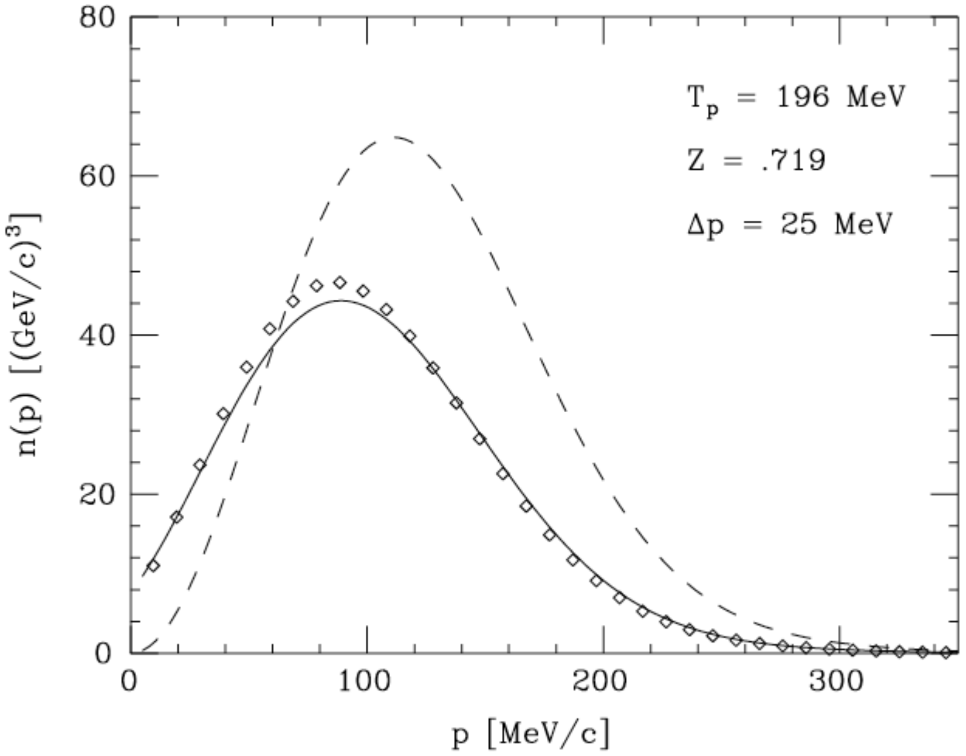
- ⋆ Warning: while providing a clear interpretation of the reaction mechanism, PWIA fails to account for final state interactions of the outgoing nucleon

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 $\tilde{Z}$

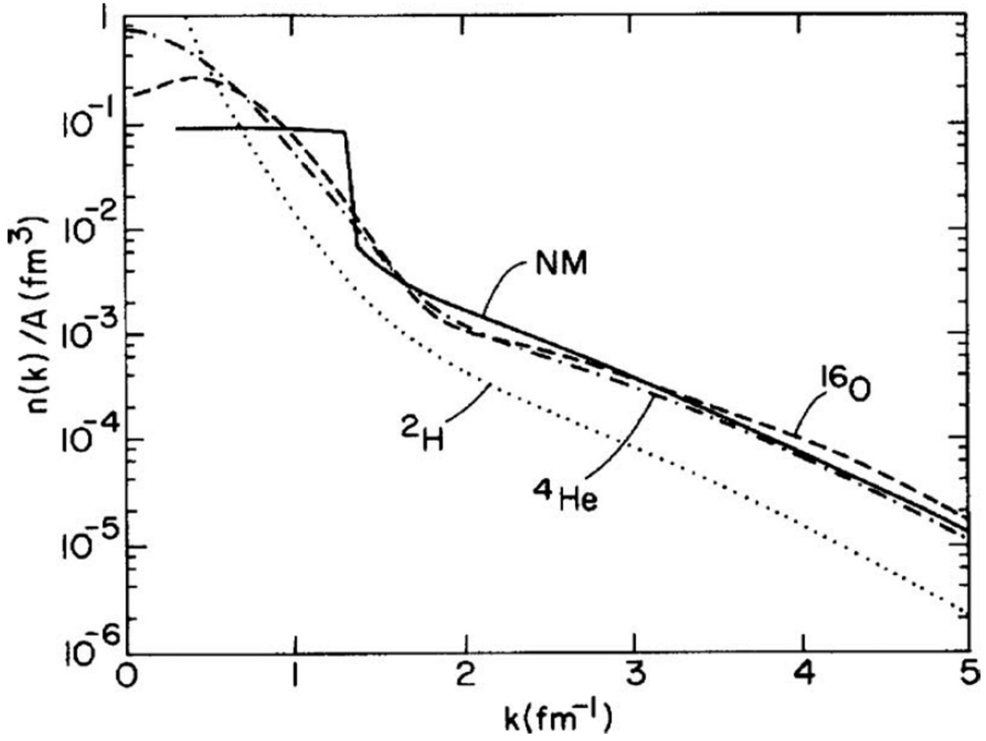
- For $A \leq 16$, the accuracy of the optical potential approach has been tested comparing to the results of many-body calculations of the relevant overlaps



- FSI effects beyond DWIA are minimized in *parallel kinematics*

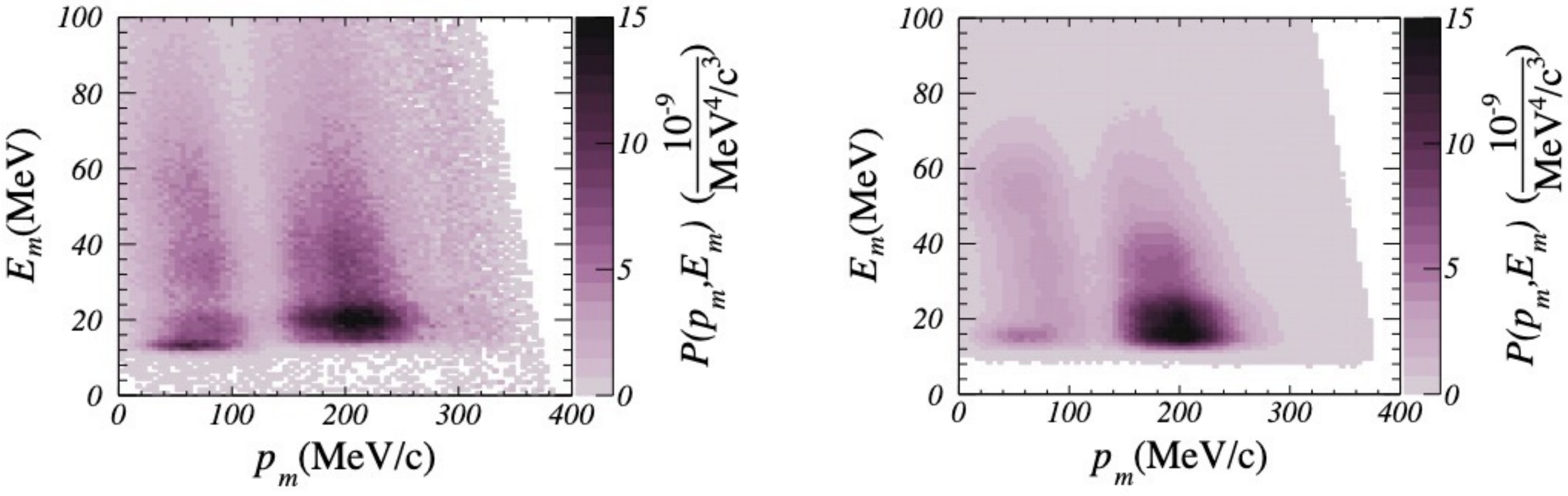
Correlated part of the spectral function

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

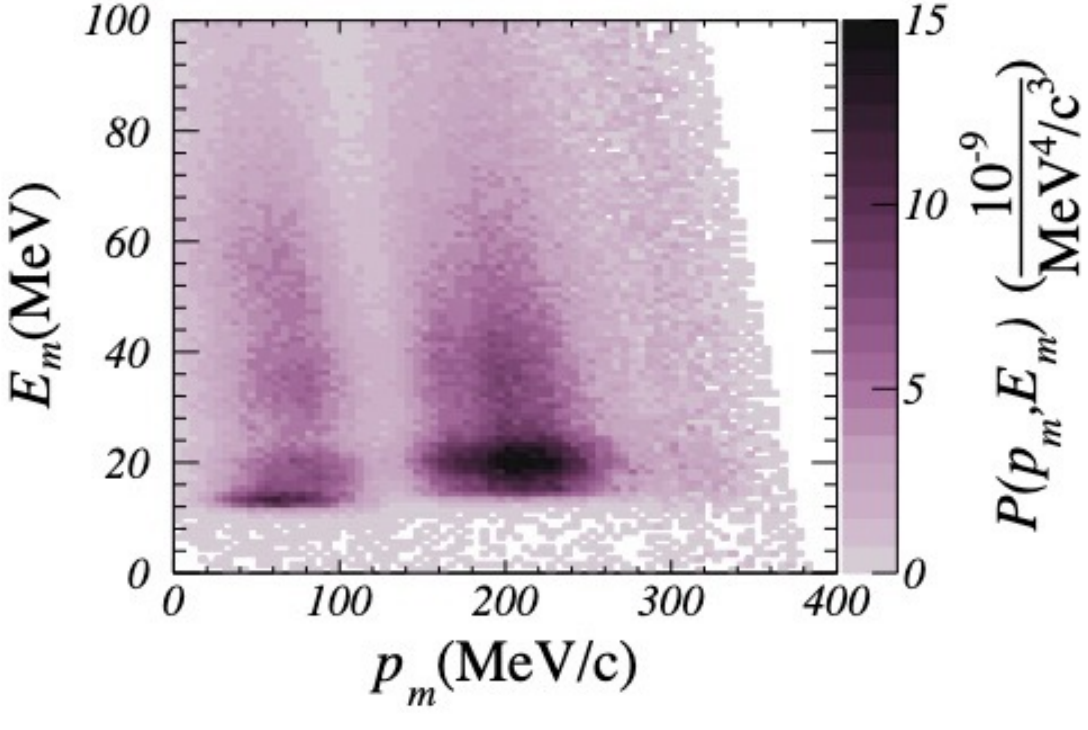
Ar (e,e'p) – Phys. Rev. D 105, 112002, (2022)



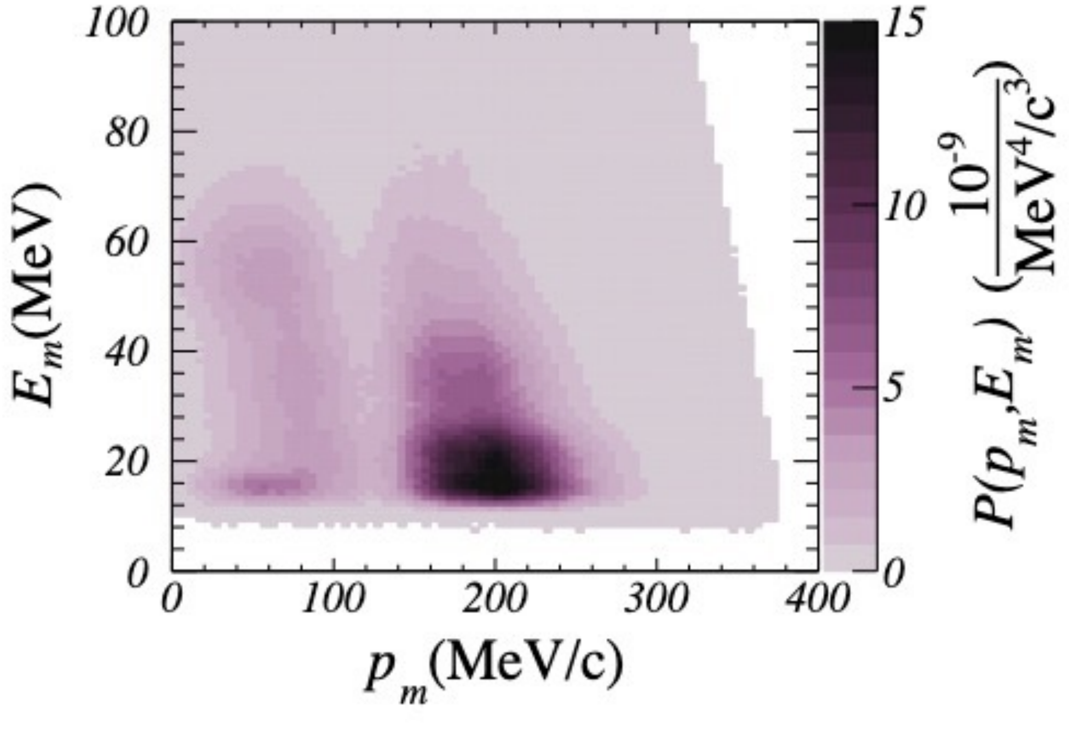
(a) Data

(b) MC

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



(a) Data



(b) MC