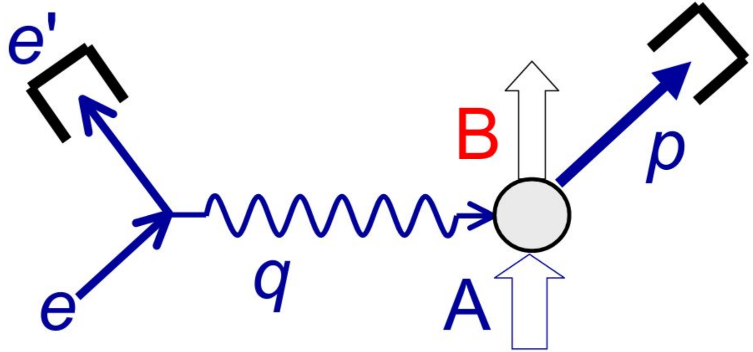
Cross Section Measurement of the Ar(e,e' p) and Ti(e,e' p) in Jefferson Lab Hall A

Libo Jiang (Virginia Tech)

New Directions in Neutrino Nucleus Scattering

(e,e'p) Process

A e →e' p B



Known: *e* and A
Detect: *e'* and *p*

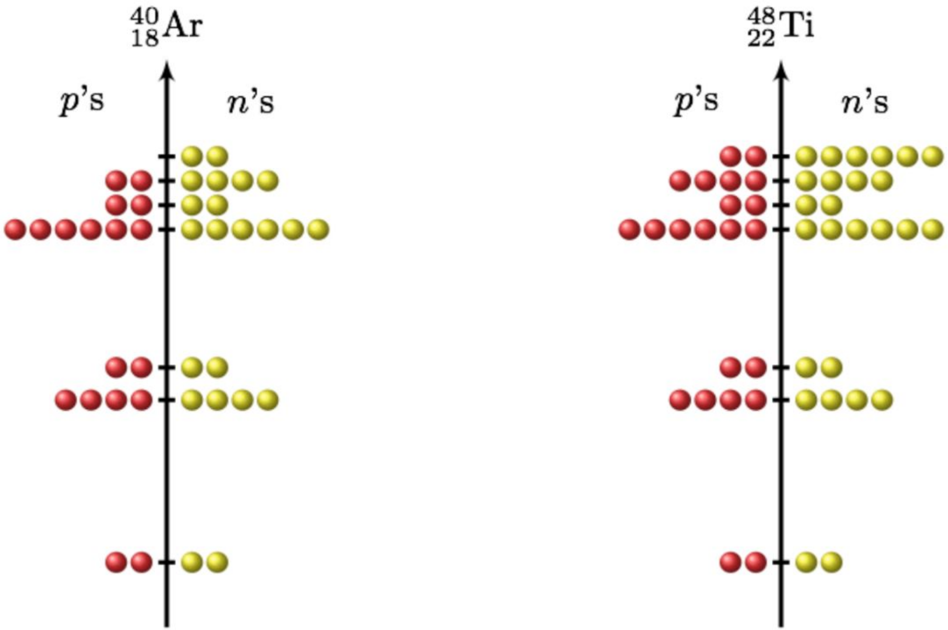
Infer: $\boldsymbol{p}_m = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_B$

- Ideal tool to study and measure:
  - Nuclear Structure/spectroscopic factors
  - Spectral functions
    - Initial momentum and energy distributions of nucleons bound in nucleus
    - Long- and short-range correlations

- To help improve the accuracy of the measurement of the neutrino-oscillation parameters,
  - Neutrino nucleus cross section
  - The CP violation in leptonic sector (one of the top priority of the US particle physics community)

E12-14-012: Review

- 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(Aluminum)/Optical (e,e'p) reactions for five different kinematic set-ups
    - 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.

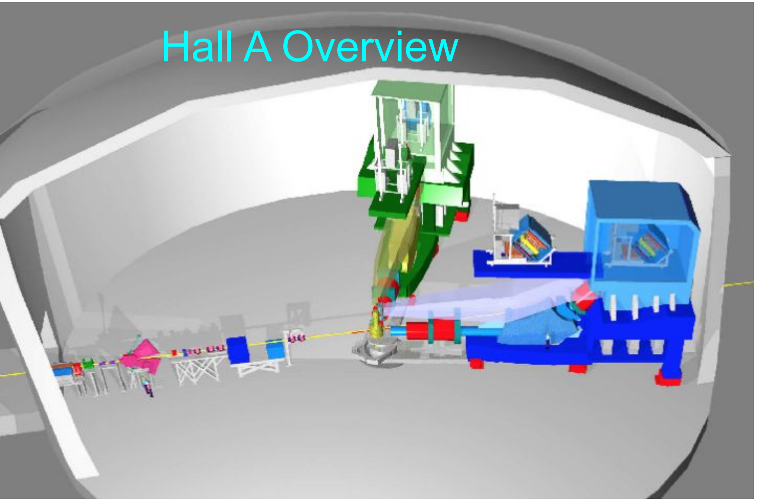


Shell Model Structure of Argon and Titanium

Outline

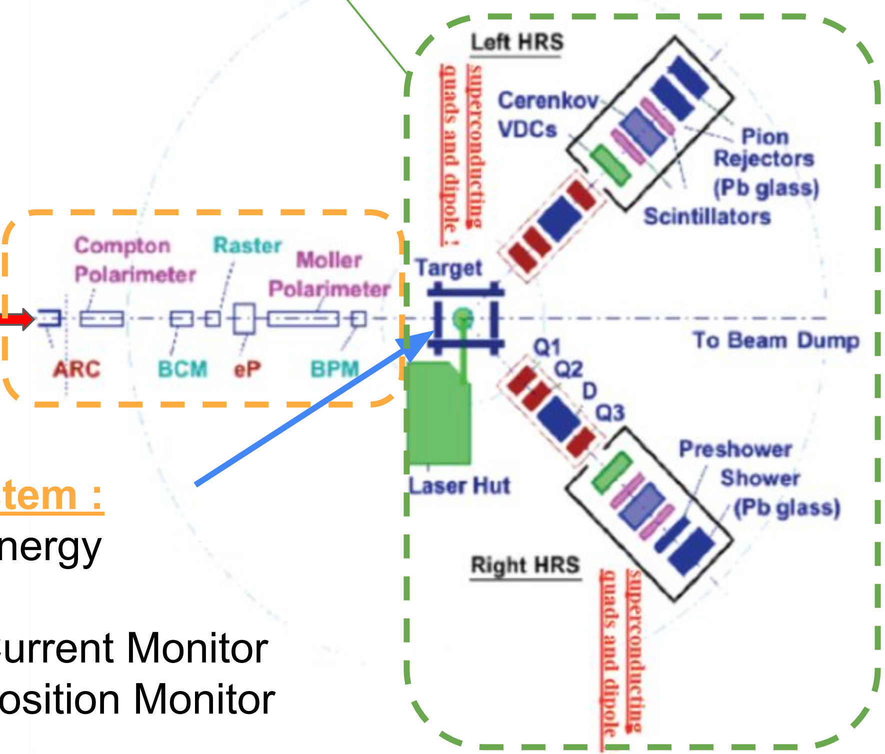
- Experimental Setup
  - Target
  - Kinematic configurations
- Inclusive Analysis - Summary
- Exclusive Analysis
  - Analysis Strategy
  - Kinematic 1 Argon result
  - Kinematic 1 Titanium result
- Summary

Experimental Setup



Target and Detector Package

Top View of Hall A



Electron Beam

<u>Electron Beam (2.222GeV):</u>
the Continuous Electron Beam Accelerator Facility (CEBAF)

<u>Beam Monitor System :</u>

- ARC: Beam Energy Measurement
- BCM: Beam Current Monitor
- BPM: Beam Position Monitor

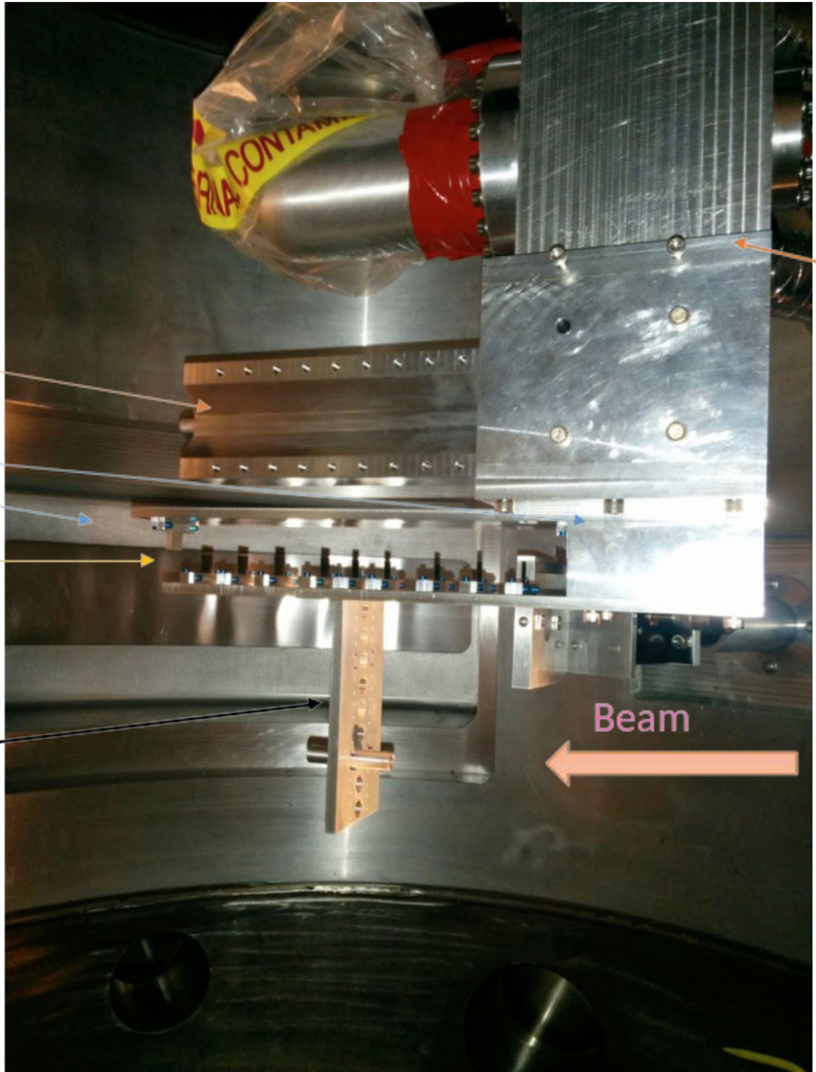
Experimental Setup

Argon target

Dummy target

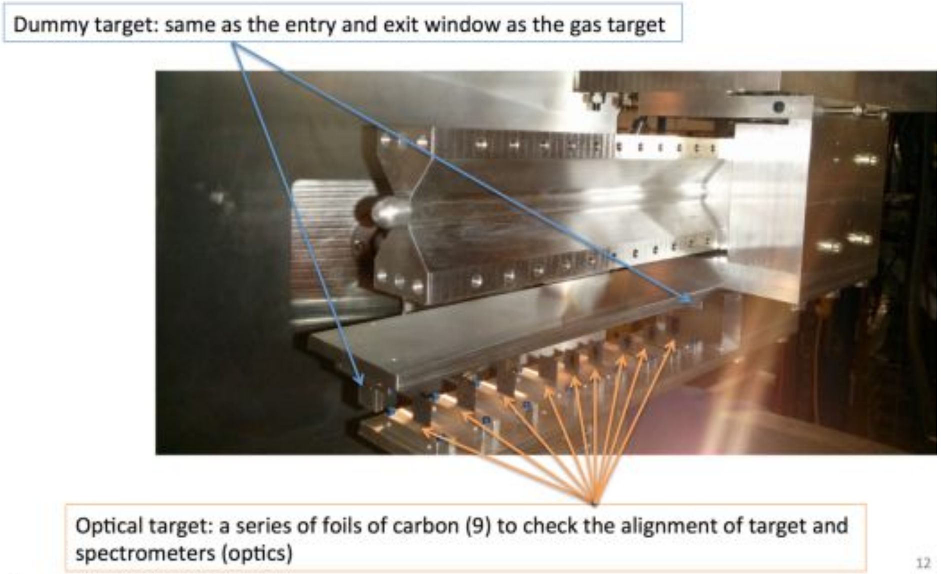
Optical target

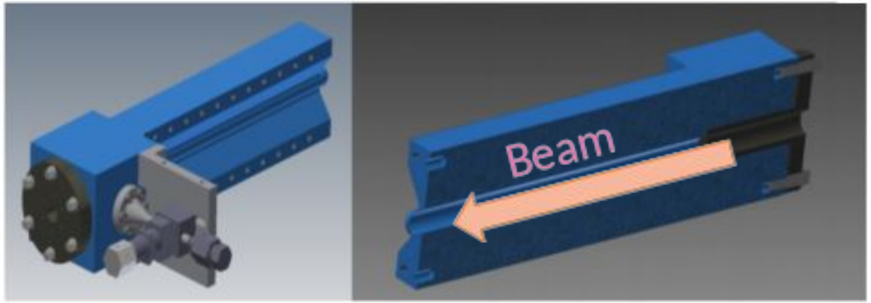
Target ladder (includes titanium and carbon target)



Experimental Setup

Ar Target
Gas Cell
Length = 25 cm
Pressure = 500 PSI
Temperature = 300 K.
Target thickness = 1.381 g cm-2
Luminosity = 4.33×1037 atoms cm-2 sec-1.





PWIA: Plane-Wave Impulse Approximation

Non-relativistic PWIA (no FSI):

$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K \sigma_{ep} S(p_m, \varepsilon_m)$$

"σ_{ep}" is the cross section of ep scattering, related or can be expressed as a function of σ_M

nuclear spectral function

Suitable Kinematic Factor $K = E_p|\mathbf{p}_p|$

DWIA: Distorted Plane-Wave Impulse Approximation

FSI is not negligible

$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K \sigma_{ep} S^D(p_m, \varepsilon_m)$$

"σ_{ep}" is the cross section of ep scattering, related or can be expressed as a function of σ_M

Distorted

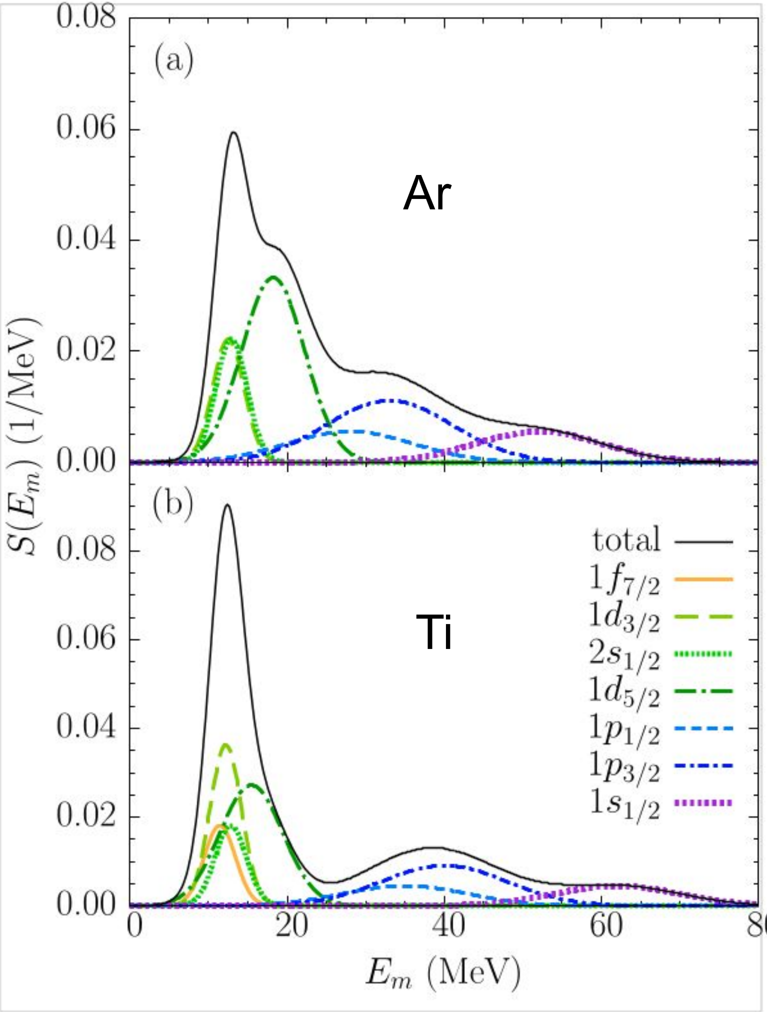
nuclear spectral function

Suitable Kinematic Factor K= $E_p|\mathbf{p}_p|$

Analysis Strategy

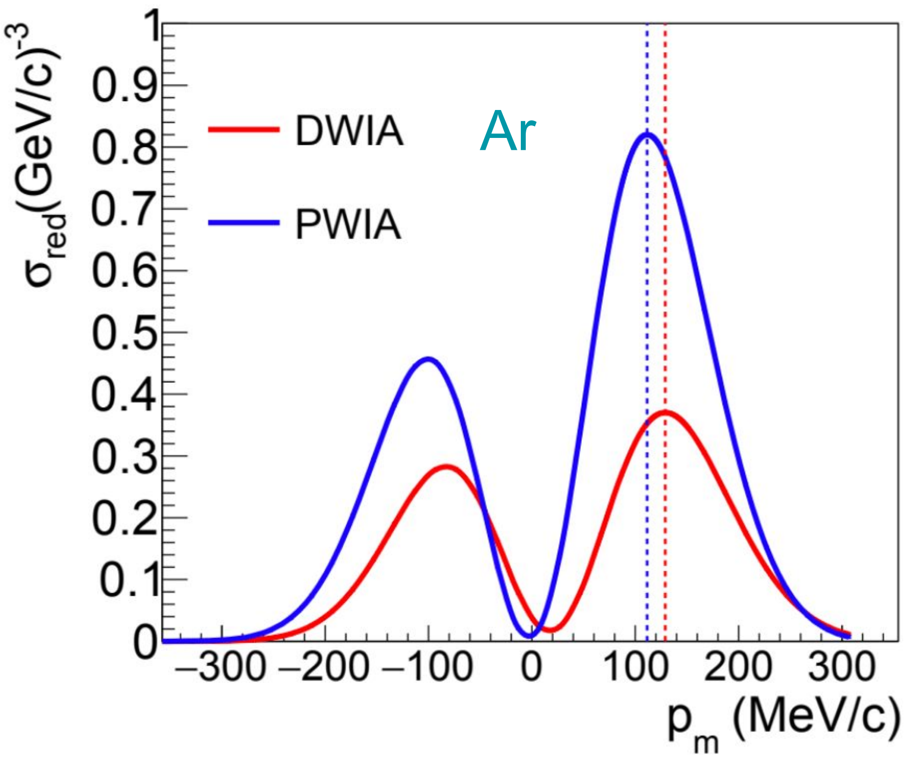
- Compute reduced cross section for various wave functions, identify the energy and momentum distribution for each orbital for each kinematics.

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

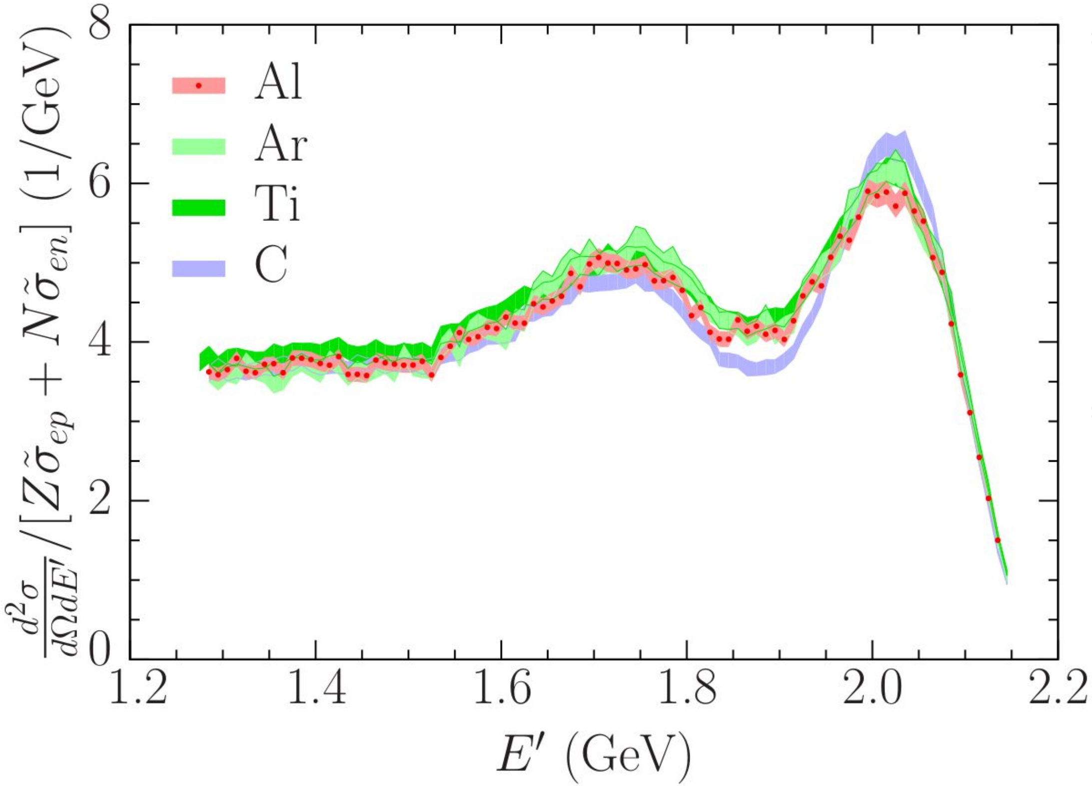


Effect of FSI

- Within DWIA, FSI between the outgoing proton and the spectator nucleons are described by a complex, energy dependent, phenomenological optical potential (OP)
  - OPs were obtained by a theoretical recipe and a fit to an existing data
    - Further tested using proton nucleon scattering on argon
  - Shift and reduction compared to PWIA in missing momentum
    - Used to reweight and shift MC event by event for the FSI correction



Inclusive Summary



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 $(\theta,\phi,dp/p)$	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%

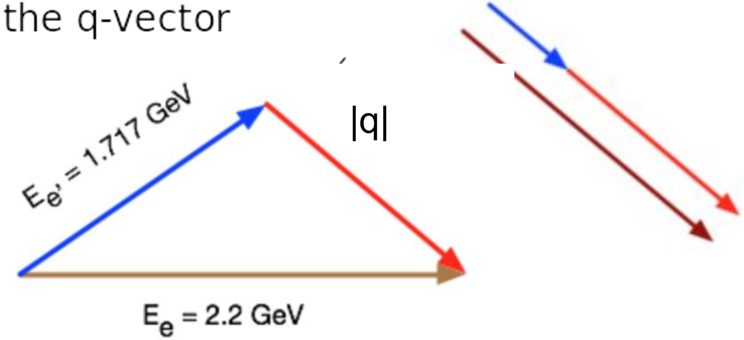
- Radiative and Coulomb correction have a theoretical uncertainty about 1%

Exclusive Analysis Kinematic Setup

	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
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

Parallel kinematics

Proton's initial-momentum is parallel to the q-vector



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

List of systematic uncertainties - Ar Kinematic 1

- Statistical uncertainty ~ 0.53%
- Total systematic uncertainty ~2.42%
  - Beam x and y offset ~0.63%
  - HRS x and y offset ~0.83%
  - Boiling ~0.70%
  - Acceptance and z cuts ~1.16%
  - Cerenkov and Calorimeter cuts ~0.02%
  - COSY ~0.94%
  - Radiative and Coulomb corrections ~1%
  - Beta cut ~0.47%
  - Coincidence time cut ~0.92%
  - FSI ?

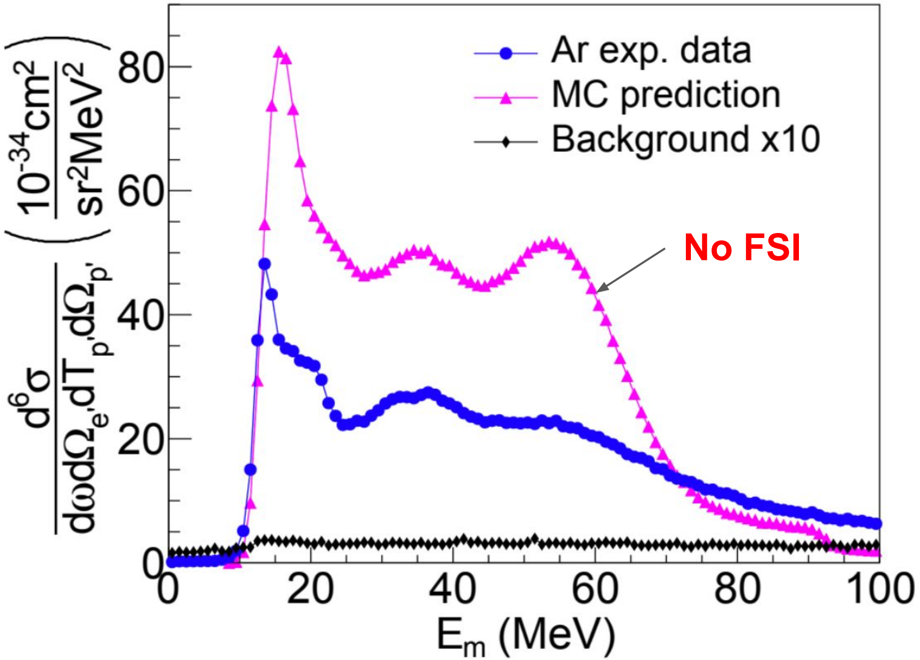
- **COSY:**

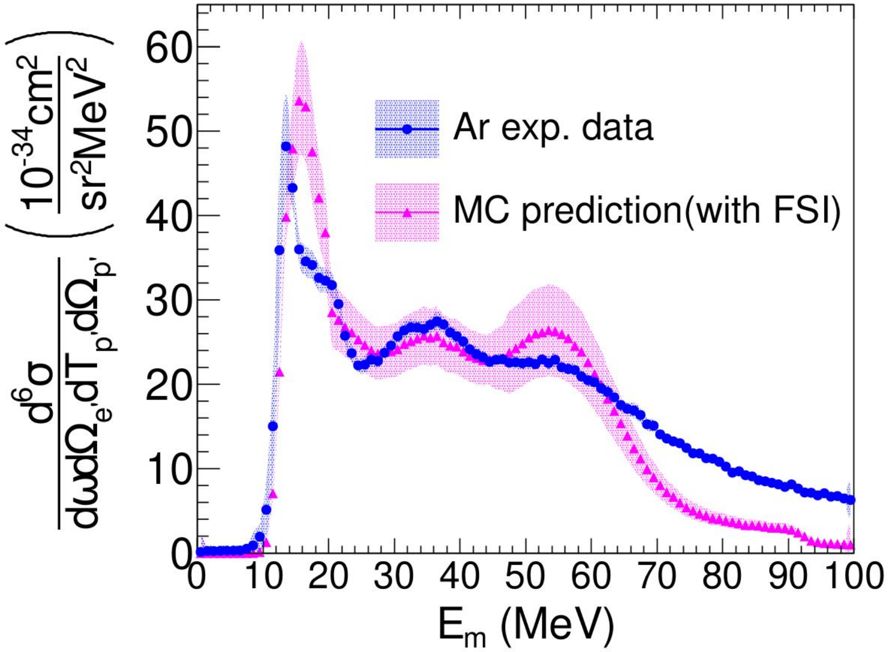
We use the code COSY to generate the optical matrix for simulation, to estimate the optical matrix uncertainty due to the magnetic field settings of Q1, Q2 and Q3 , we vary the individual setting by 1%

- **Rad_corr dependence on cross section model**

We scale the cross section model by sqrt(Q^2)/2 , and recalculate the radiative correction factor.

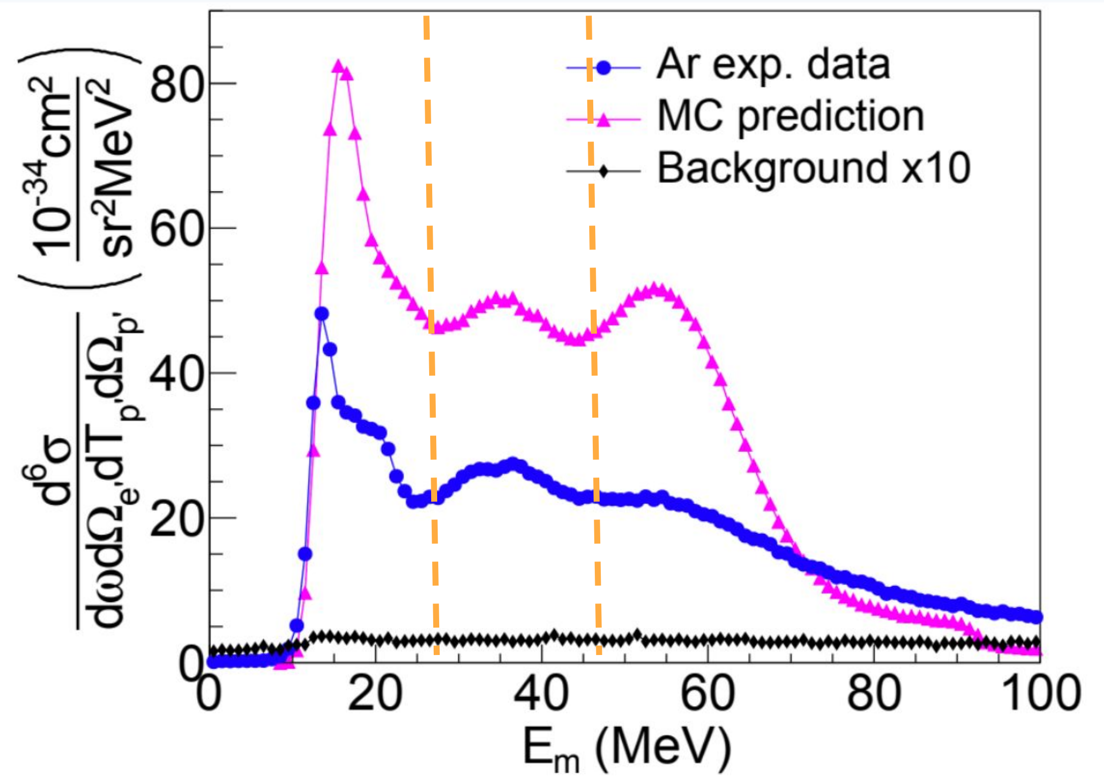
Analysis Result - Argon Kinematic 1





- Missing energy spectrum
- FSI Correction
  - Shift and reweight MC event by event
  - Shift and reweight factors calculated from difference between DWIA and PWIA

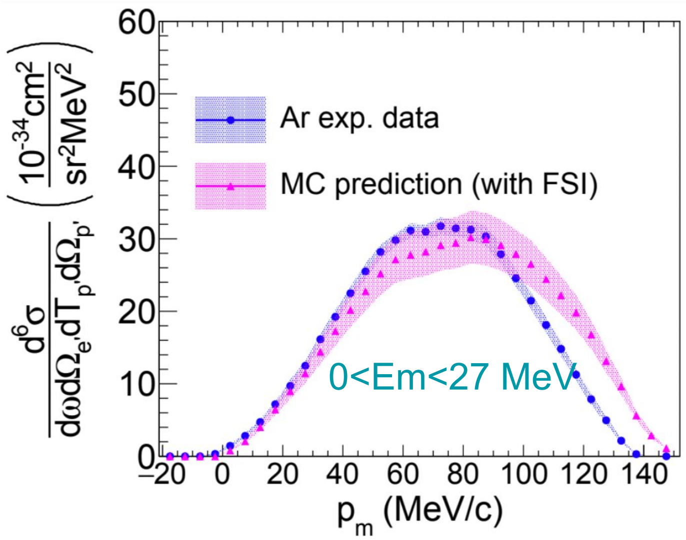
Analysis Results - Argon Kinematic 1

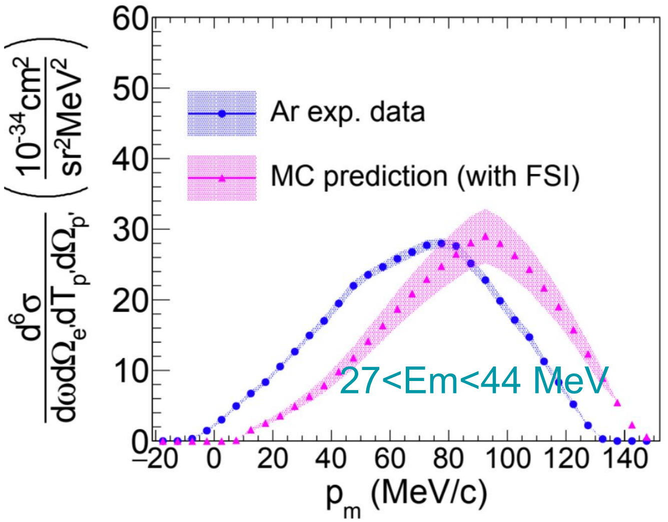


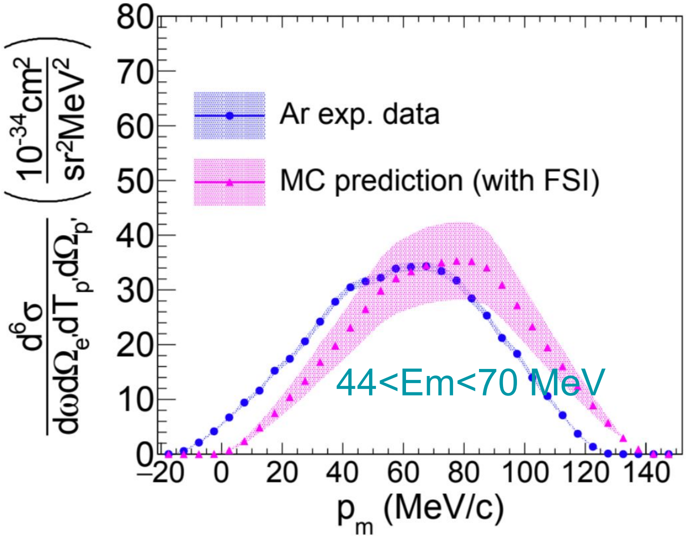
- Figure: Missing energy distributions of Argon
  - MC without FSI
  - Reweight and shifted event by event to include the FSI correction

- All events are divided into 3 regions for further study
  - 0<Em<27 MeV
  - 27<Em<44 MeV
  - 44<Em<70 MeV

Analysis Results - Argon Kinematic 1

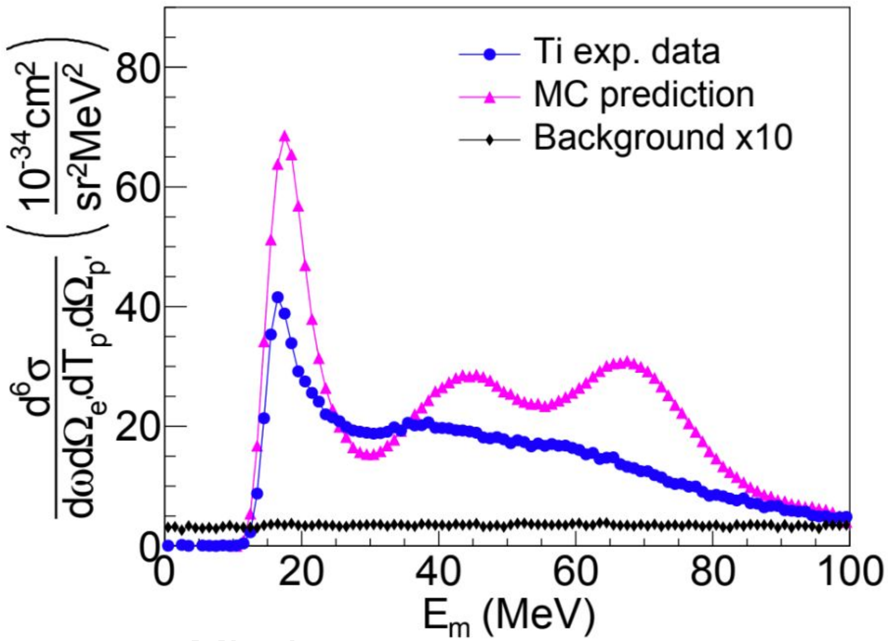


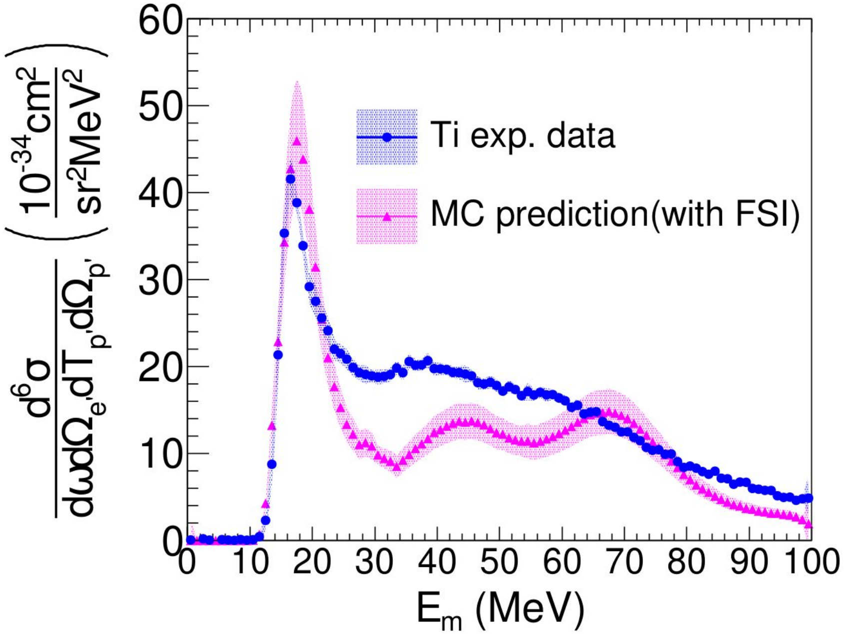




- Error in MC is the FSI theory uncertainty

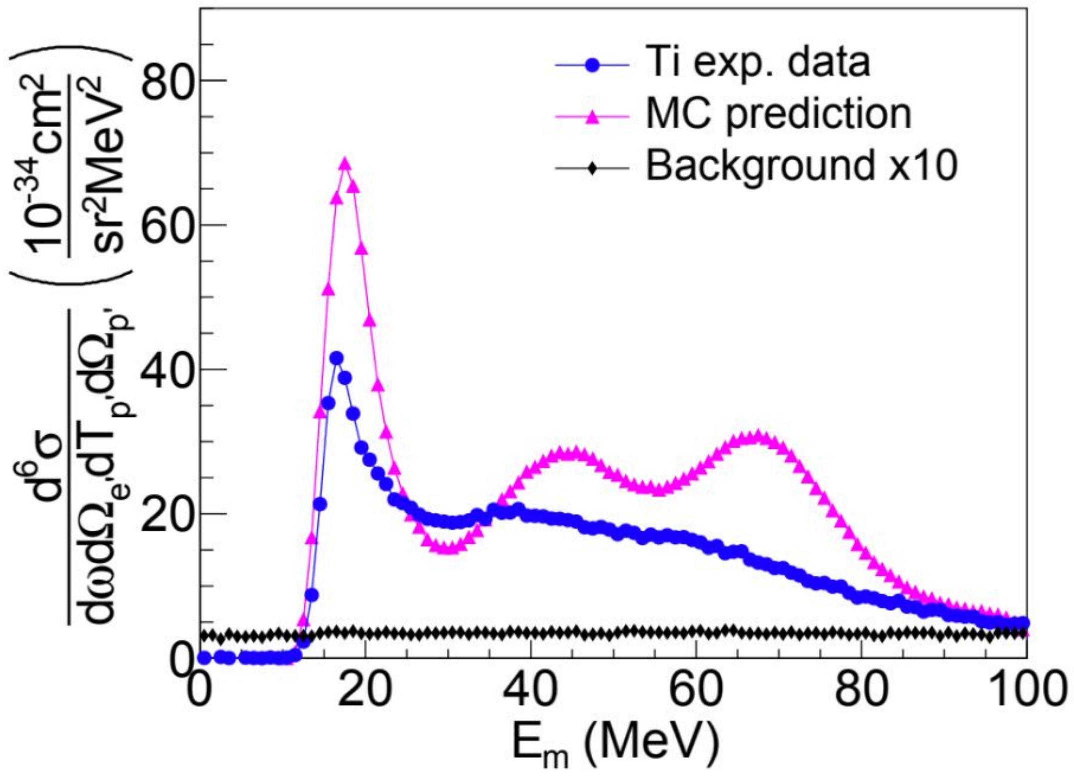
Analysis Result - Titanium Kinematic 1





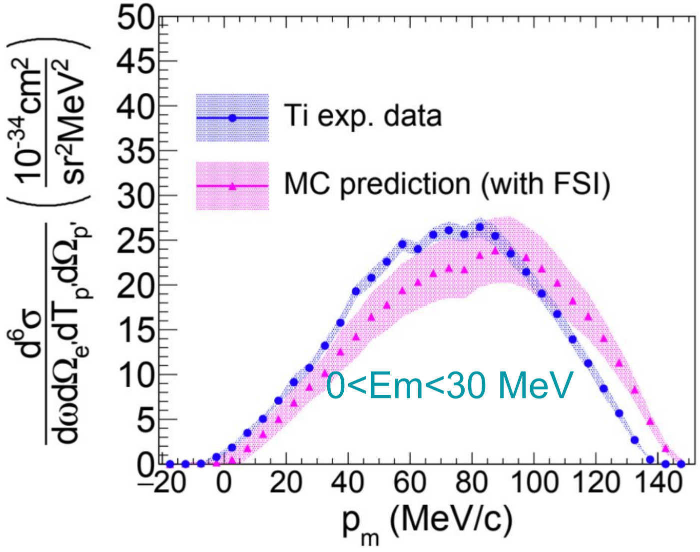
- Missing energy spectrum
- FSI Correction
  - Shift and reweight MC event by event
  - Shift and reweight factors calculated from difference between DWIA and PWIA

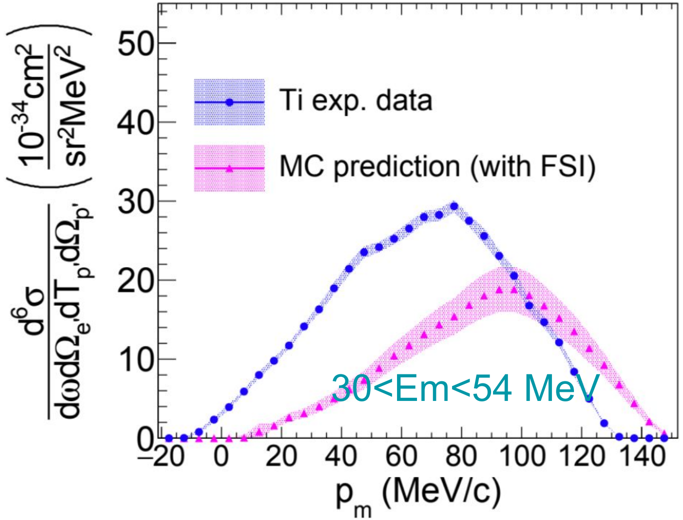
Analysis Results - Titanium Kinematic 1

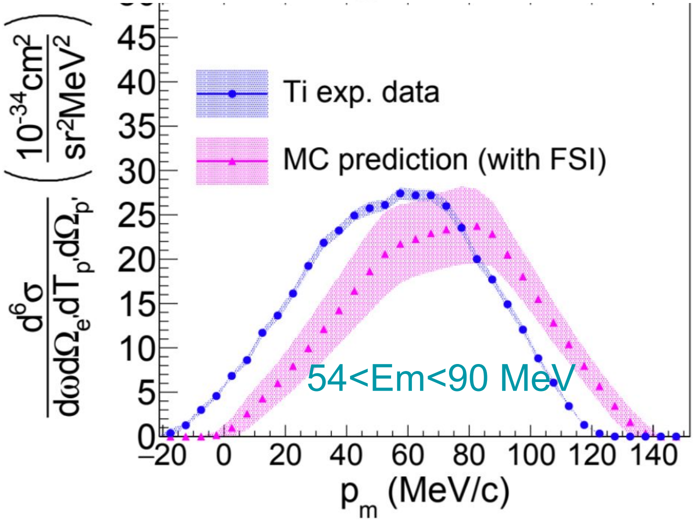


- Figure: Missing energy distributions of Titanium
  - MC without FSI
  - Reweight and shifted event by event to include the FSI correction
- All events are divided into 3 regions for further study
  - 0<Em<30 MeV
  - 30<Em<54 MeV
  - 54<Em<90 MeV

Analysis Results - Titanium Kinematic 1







Summary

- Theoretical cross sections are calculated with parameters fitting from previous experimental result
    - Works well for some orbitals and Em range, not all
    - Need to be tuned against E12-14-012 measurement
- We’ve finished (e,e’p) analysis of Kinematic 1 Argon and Titanium.
    - The 1 March 2021 issue of Physical Review C (Vol. 103,No. 3)
- FSI and other Kinematics analysis are ongoing.
- Expect a paper with details about the physical interpretation of our data within 2021

Backup

- Theoretical cross sections are calculated with parameters fitting from previous experimental result
  - Works well for some orbitals and Em range, not all
  - Need to be tuned against E12-14-012 measurement