JLab E12-14-012 experiment: First (e,e'p) results

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On behalf of the E12-14-012 collaboration
Virginia Tech

Hall A/C Collaboration Meeting
Jefferson Lab, Newport News, VA
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E12-14-012 analyzer

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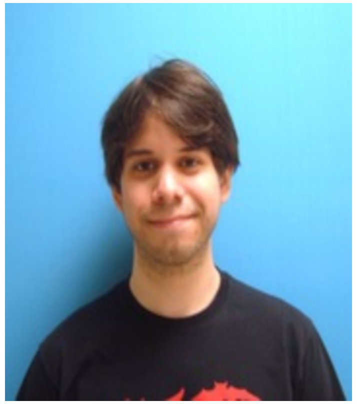

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REU student 2020 - VT

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E12-14-012:Reminder

- **<u>Primary Goal</u>:** 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

- **<u>Primary Motivation</u>**: 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:

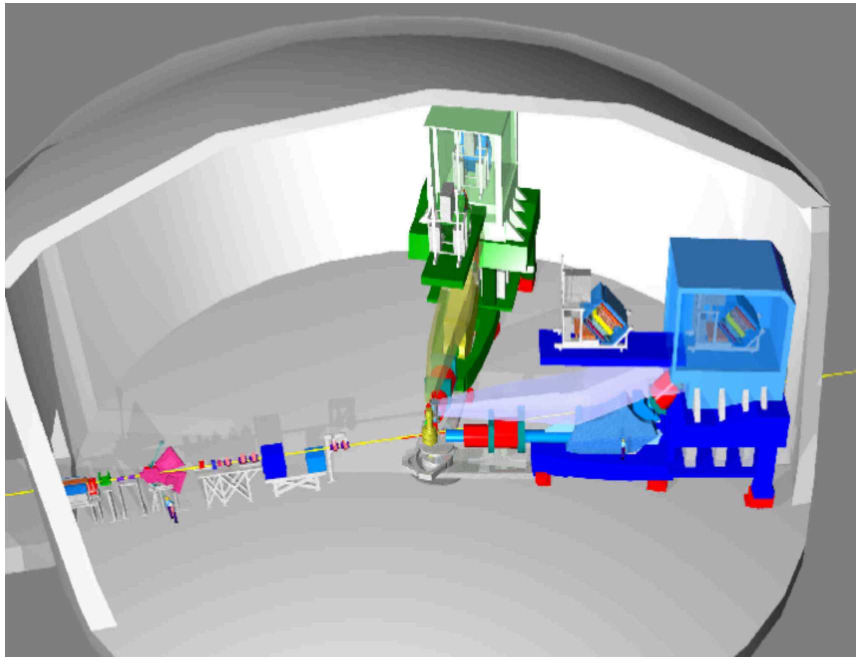
- Measuring spectral functions of argon nucleus (~ initial momentum and energy distributions of nucleons bound in the argon nucleus) that can directly be used in the reconstruction of neutrino energies (which is currently the major source of uncertainty in neutrino experiments).

- 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.

Outline

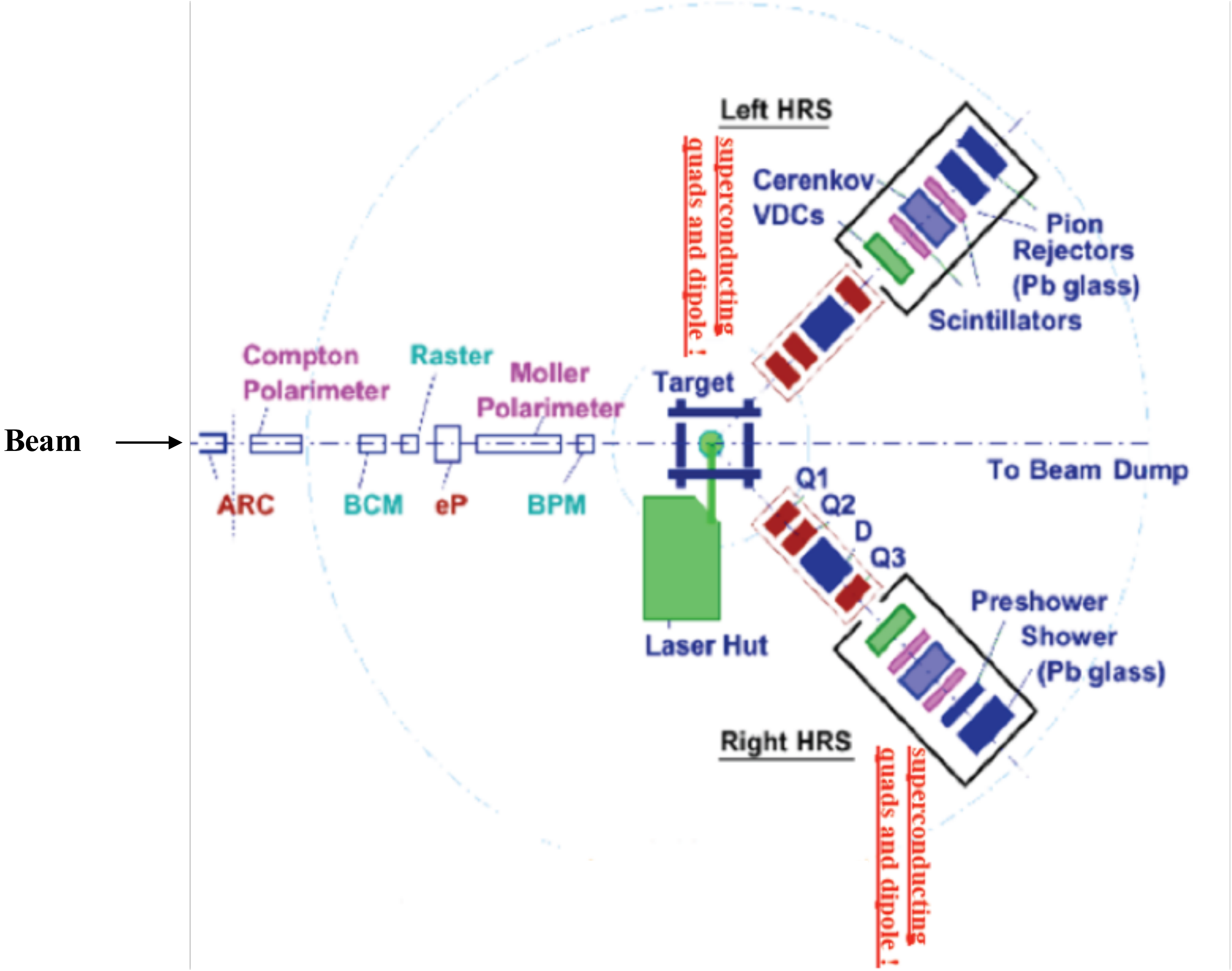
- Experiment
  - Experimental setup – Hall A
  - Target setup
  - Kinematics setup and data taking
- Exclusive analysis
  - Analysis strategy
- FSI analysis
- Spectral function determination/extraction
- Summary

Experimental setup



Hall A overview

HALL A Schematics

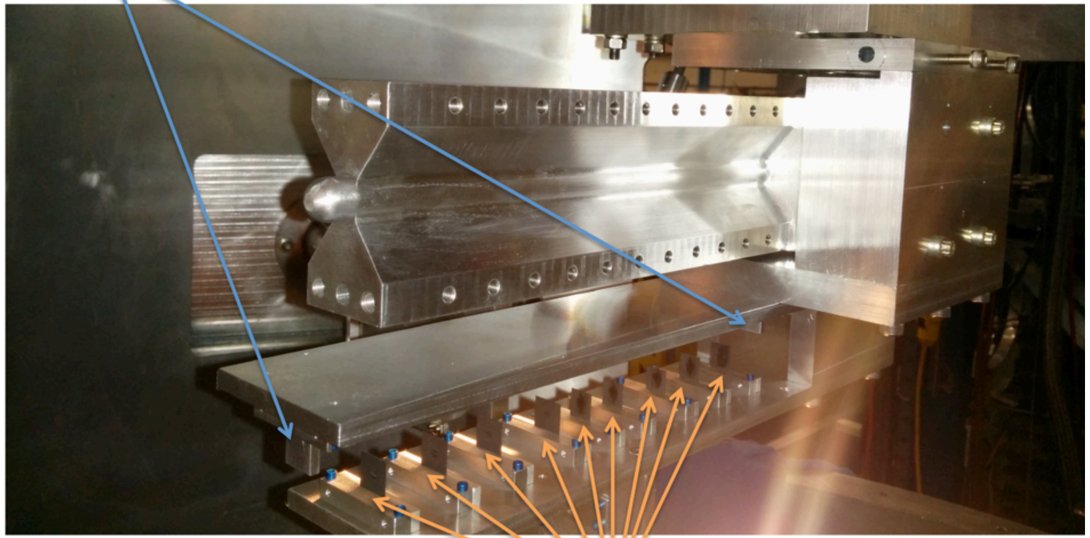


Target setup

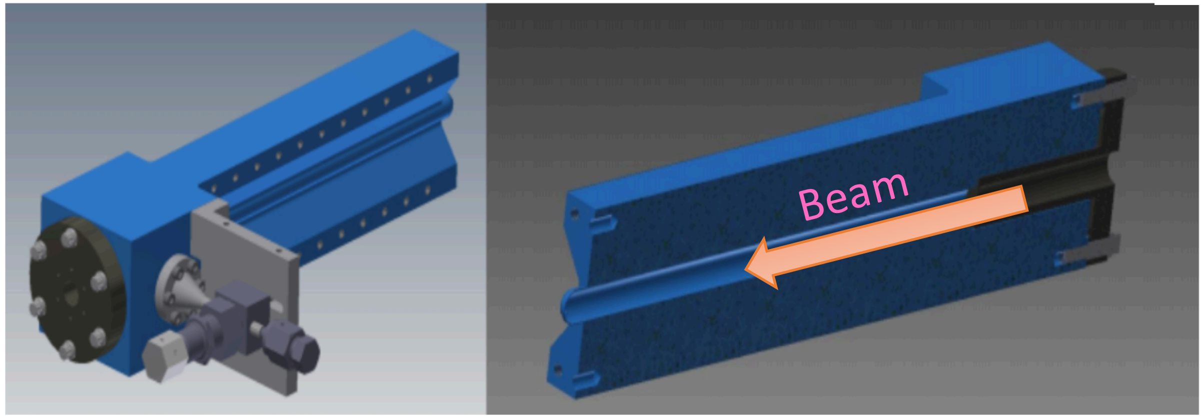
Ar Target

- 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)



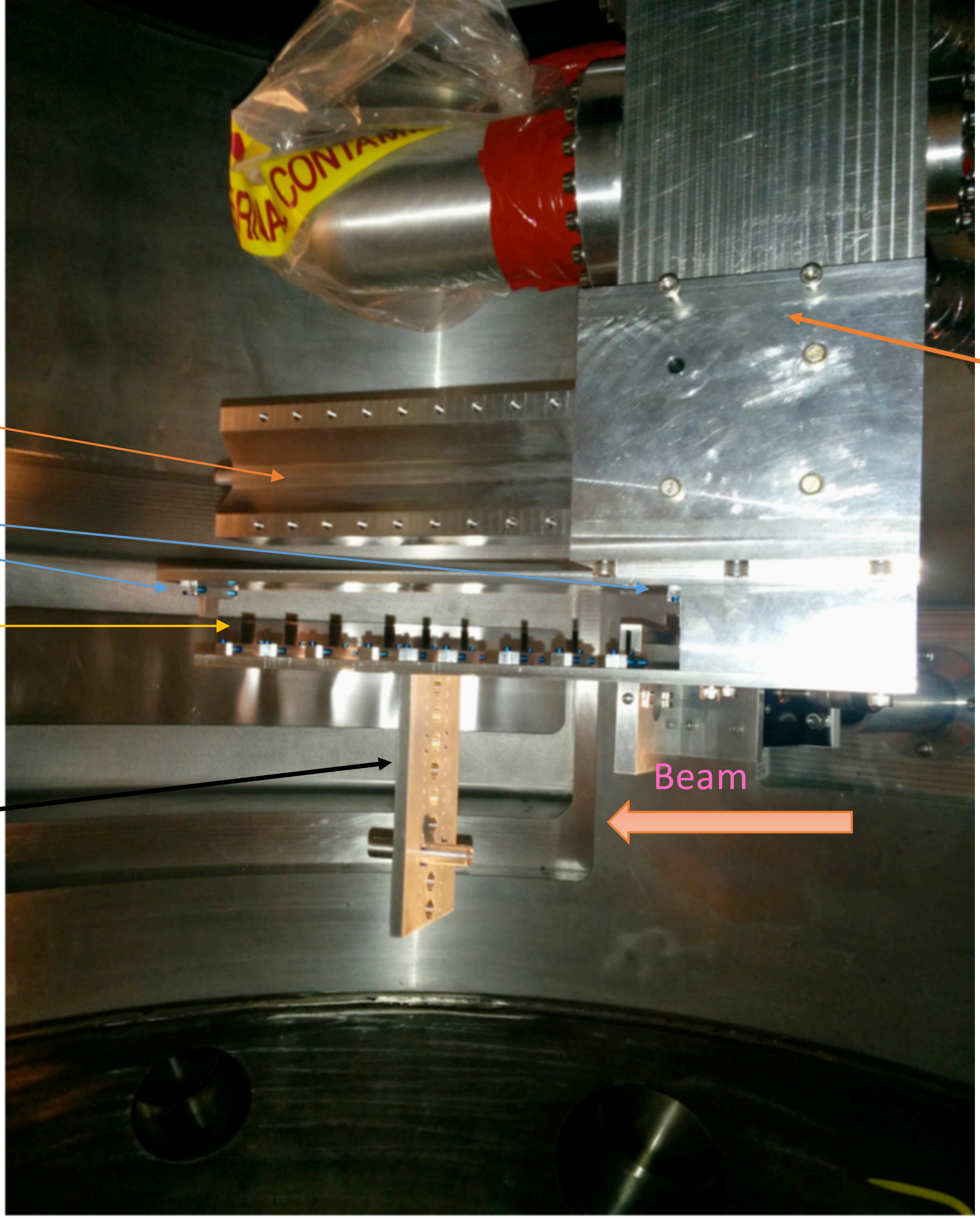
Target setup

Argon target

Dummy target

Optical target

Target ladder (includes titanium and carbon target)

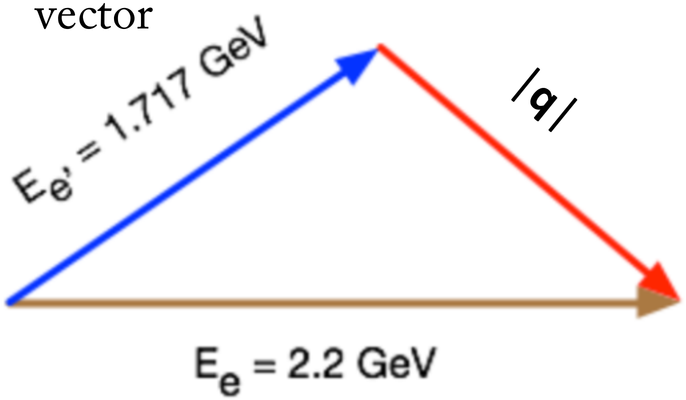


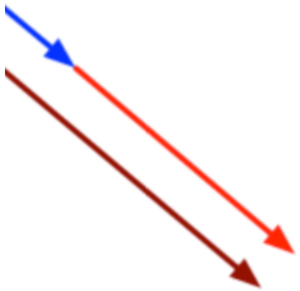
Kinematic Setup

	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
Inc-kin5	2222	-	15.5	-	-	730.3	299.7

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

Exclusive analysis

	Ar	Ti	p_m (MeV/c)
Kin 1	3%	2%	57.7
Kin 2	7%	8%	183.9
Kin 3	13%	11%	174.1
Kin 4	20%	20%	229.7
Kin 5	70%	NA	299.7

Background/Signal value in different kinematics and targets

- Data contains naturally FSI –
  - Identify signal
  - Characterize background:
    - Accidental
    - Target wall and endcaps
  - Subtract background from data
  - Compare data and MC (does not have FSI)
  - Identify set of cuts not theory or FSI dependent
  - Derive missing momentum over all missing energy range (100 bins)
  - Add systematic uncertainties per bin in missing momentum
  - Compute DWIA vs PWIA using external code (Pavia group/Libo/Omar)
    - Evaluate systematic uncertainties
  - Reweight missing momentum distribution in MC by DWIA/PWIA ratio event by event
  - Compute cross section as a function of missing momentum using MC ratio method
  - Compute missing momentum with different missing energy range (shell analysis)

- MC does not include FSI corrections other than for the nuclear transparency.

DWIA – Distorted-Wave Impulse Approximation

FSI 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 elementary cross section

Distorted

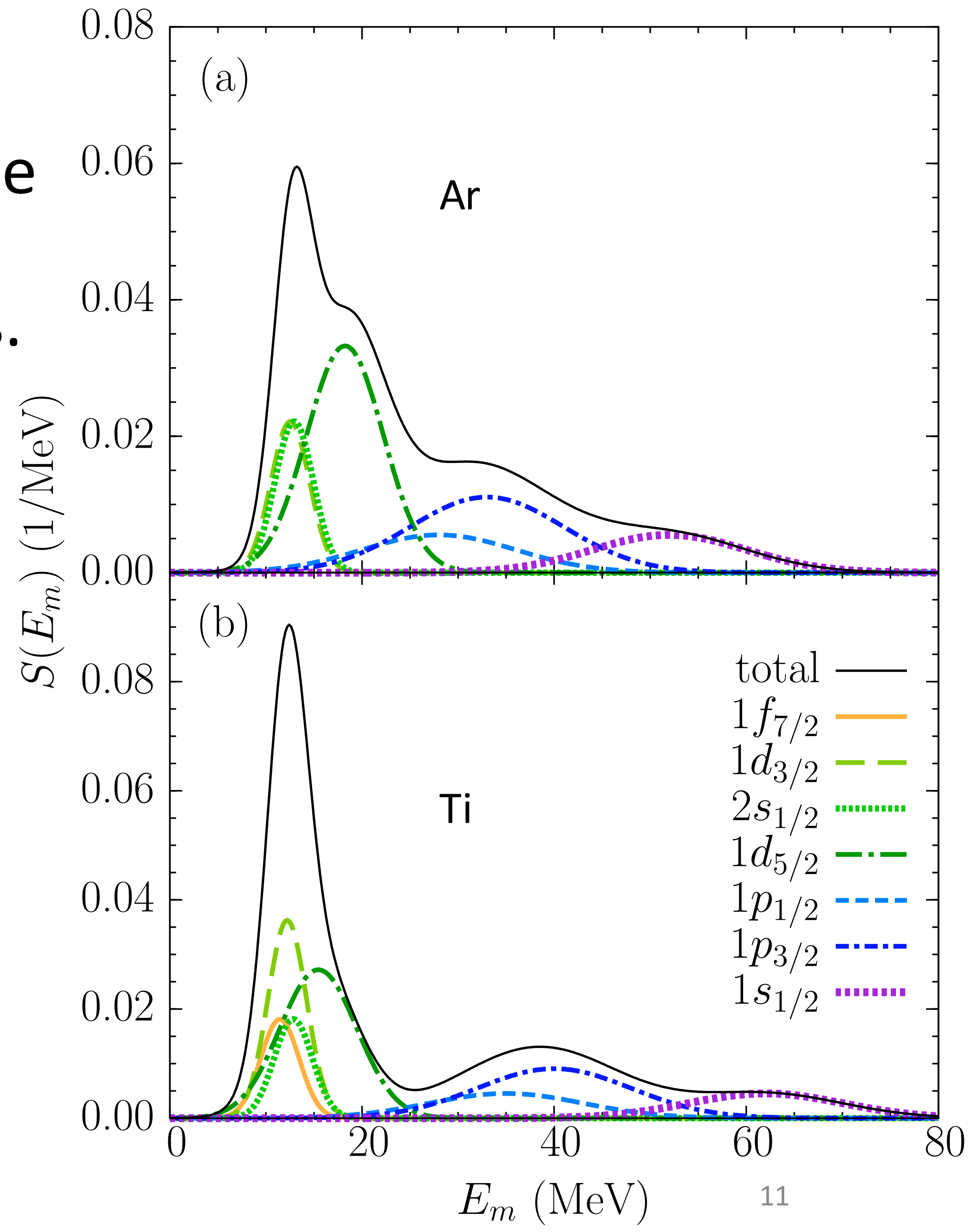
nuclear spectral function

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



Analysis strategy

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$1p_{3/2}$	33.0	8	20	45
$1s_{1/2}$	52.0	8	45	70
		titanium		
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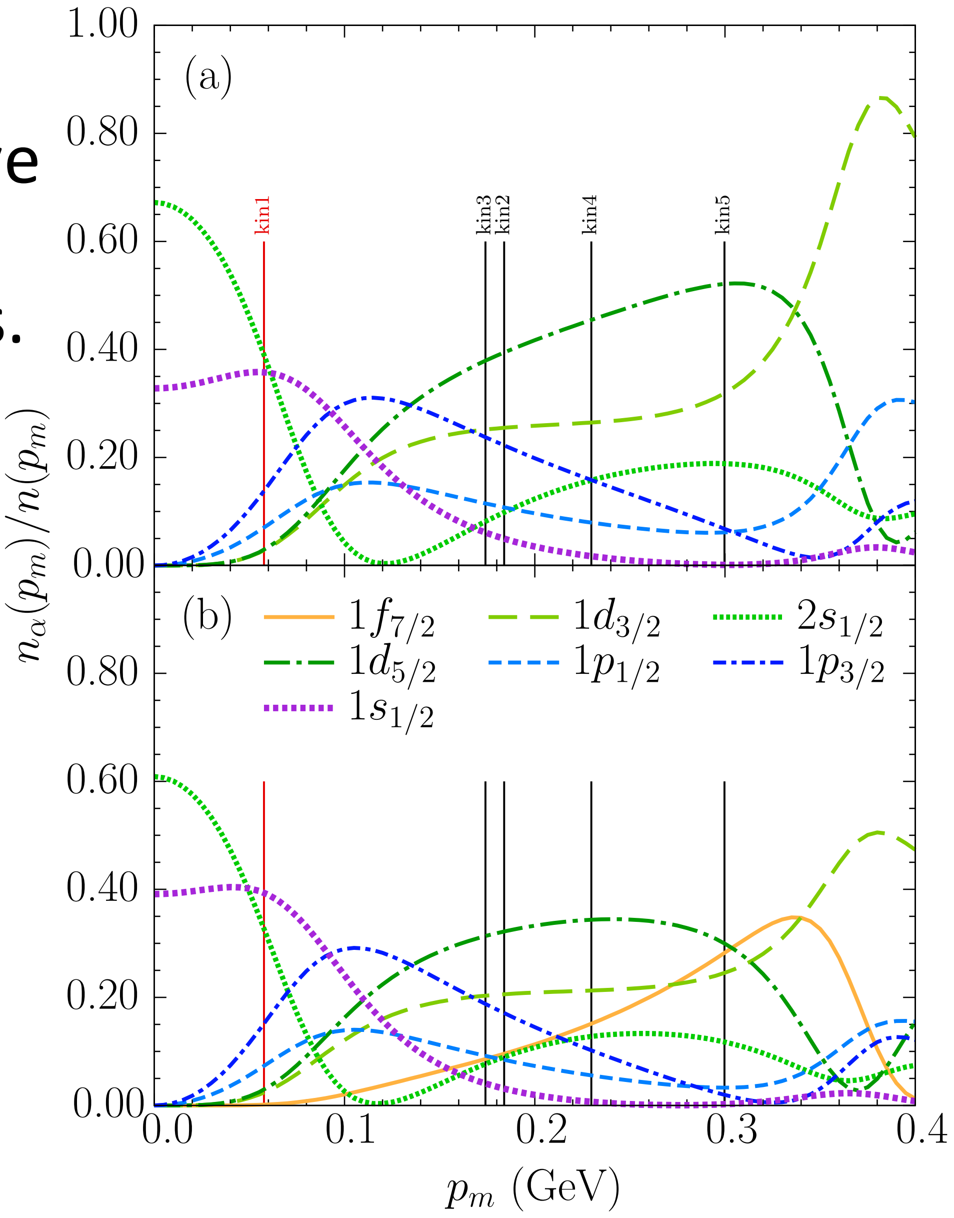
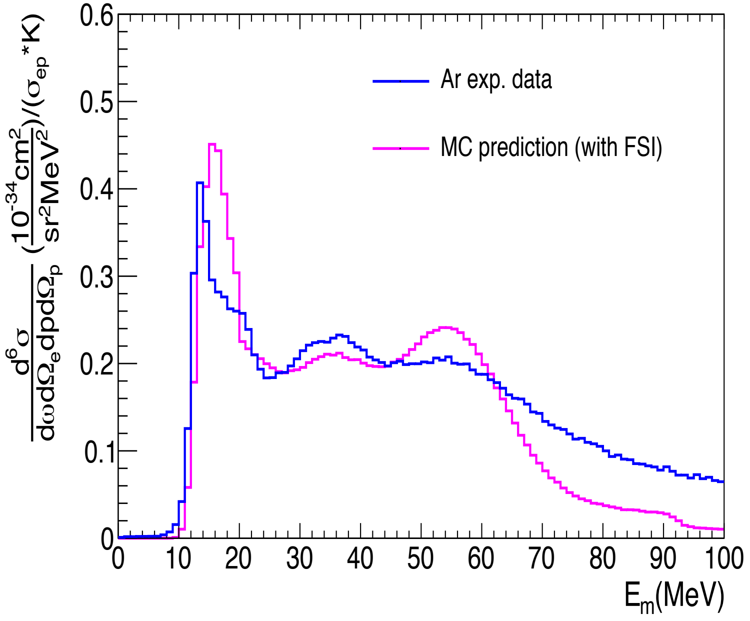
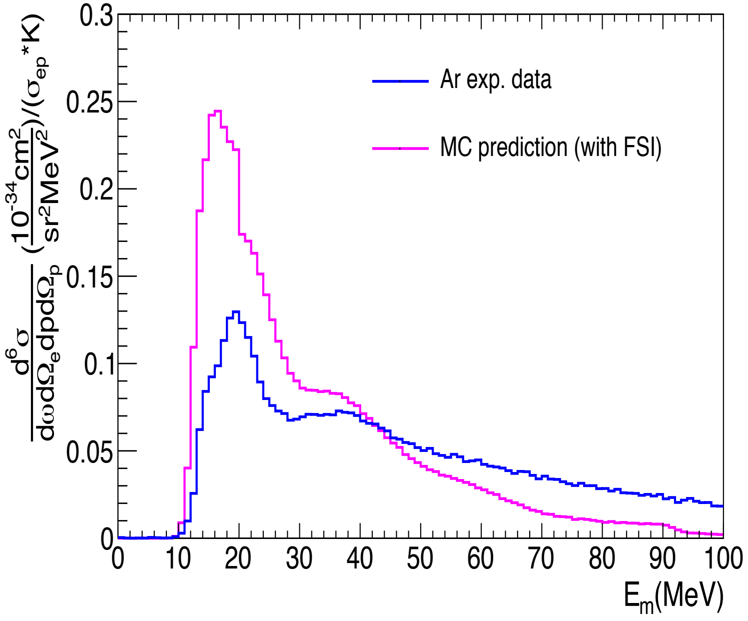


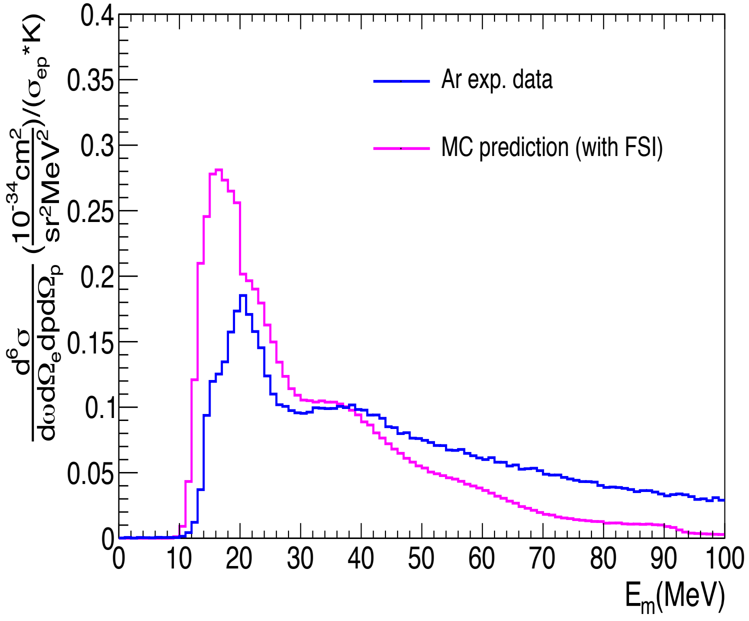
Exclusive analysis – Ar Missing energy Distributions



Kin 1

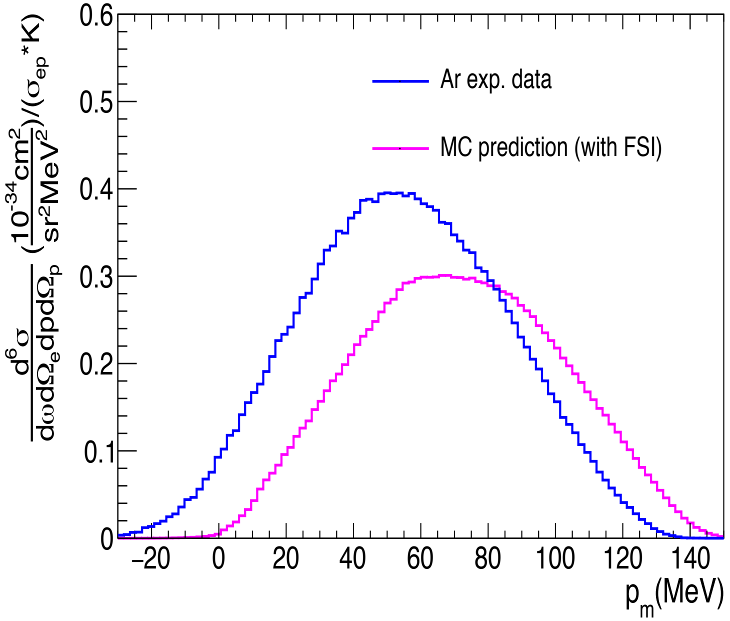


Kin 2

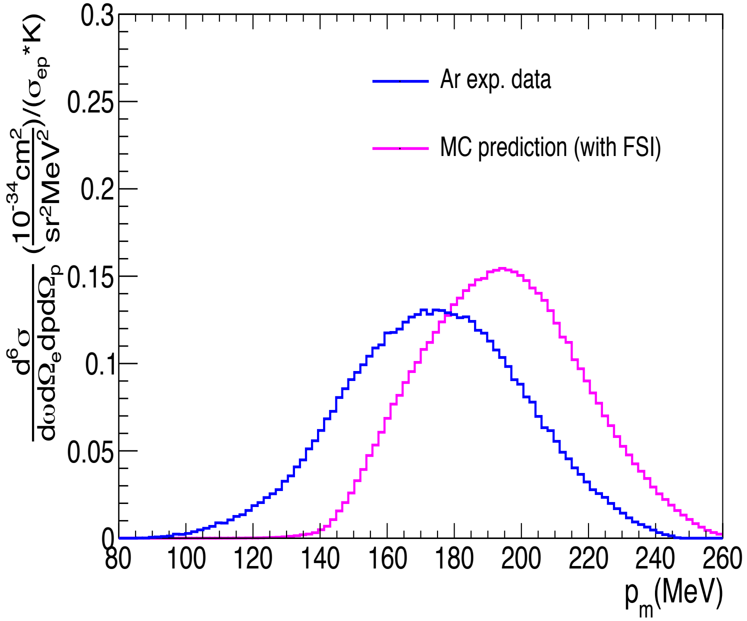


Kin 3

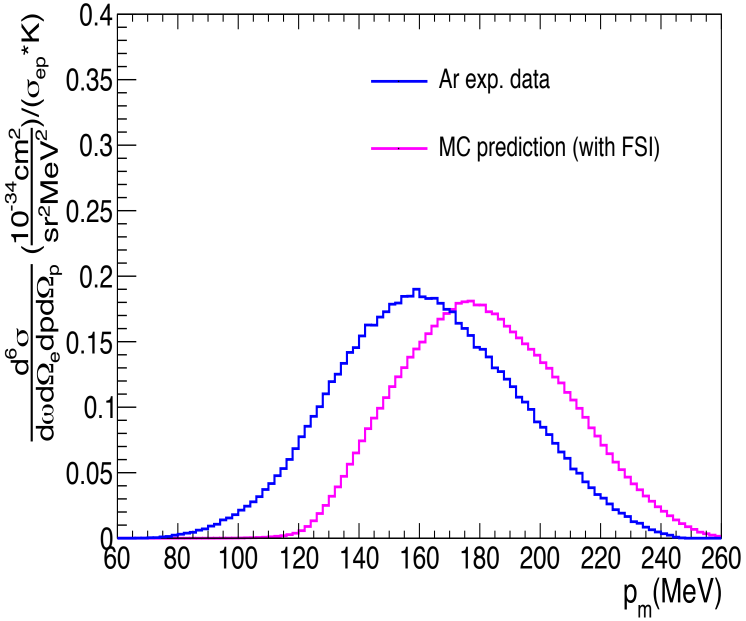
Exclusive analysis – Ar Missing momentum Distributions



Kin 1

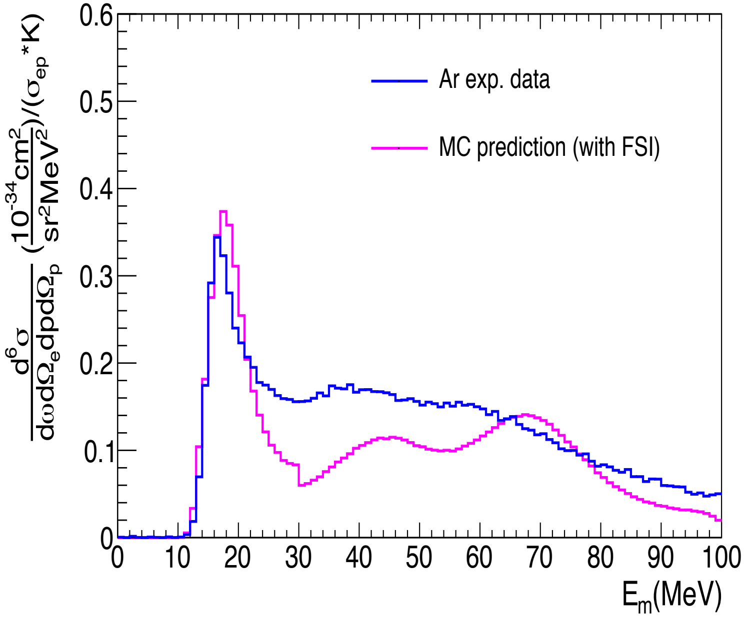


Kin 2

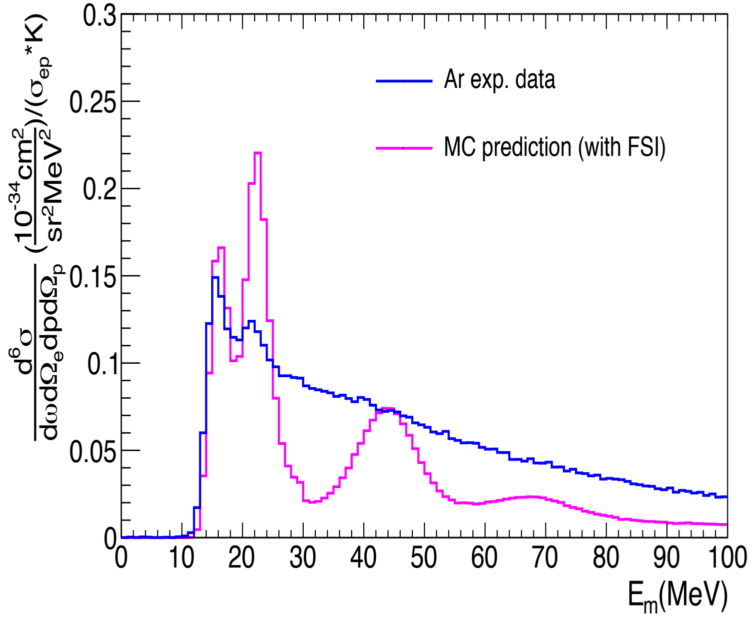


Kin 3

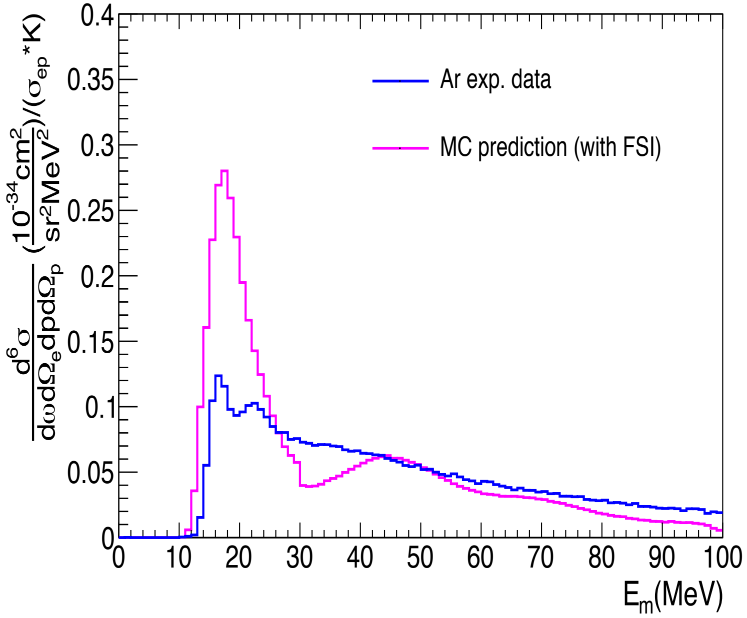
Exclusive analysis – Ti Missing energy Distributions



Kin 1

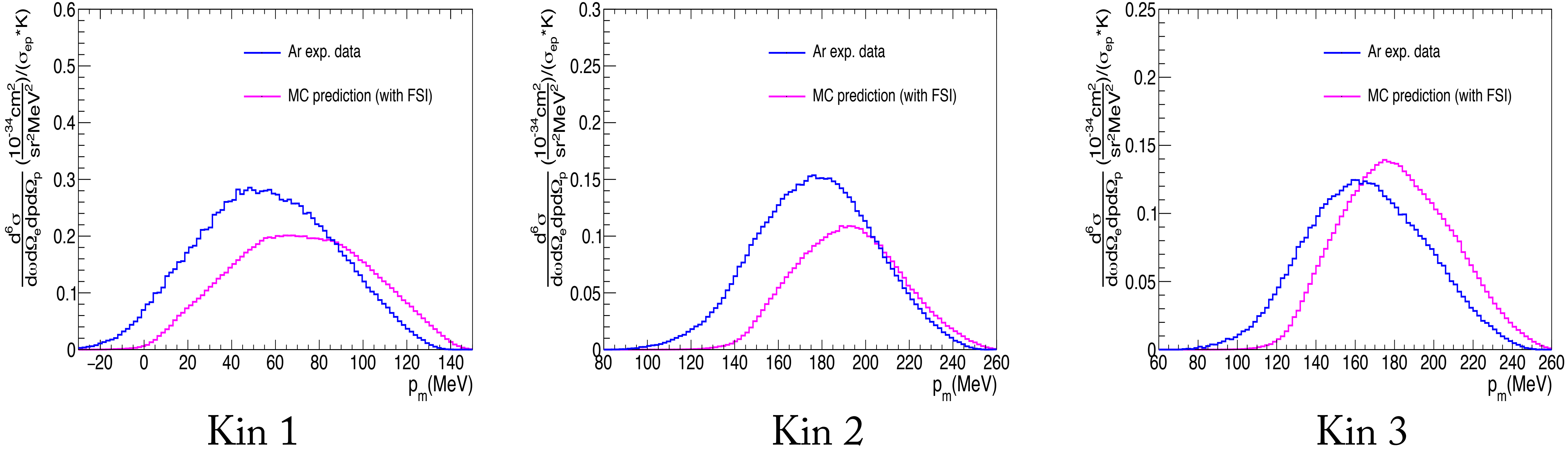


Kin 2



Kin 3

Exclusive analysis – Ti Missing momentum Distributions



Summary

- We've completed the first part of the analysis for the (e,e'p) analysis of Kinematic 1 for both Argon and Titanium.
- First exclusive paper has already been submitted to Physics Review C.
- Background is at very low level ~ 2% and we can characterize it well
- Systematic uncertainties are at the level of 2-3% as for our proposal
- FSI framework is now ready and we will use use it to extract physics quantities
- Will focus on the data analysis and data quality and systematic uncertainties
- Extract spectroscopic factor and other physical quantities in the next papers.

Thank you!

Back up

PWIA – Plane-Wave Impulse Approximation

Non-relativistic PWIA:

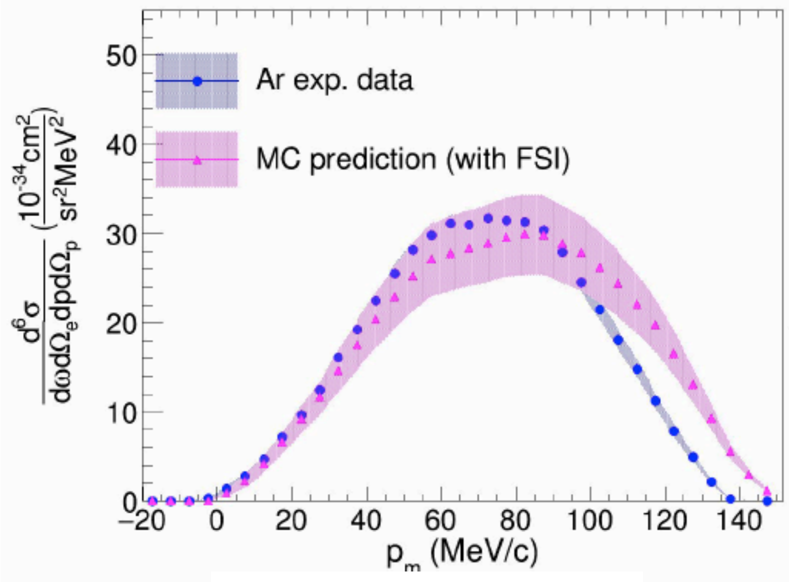
$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K \sigma_{ep} S(p_m, \varepsilon_m)$$

σ_{eN} is the half off-shell electron nucleon cross section which is related or can be expressed as a function of σ_M

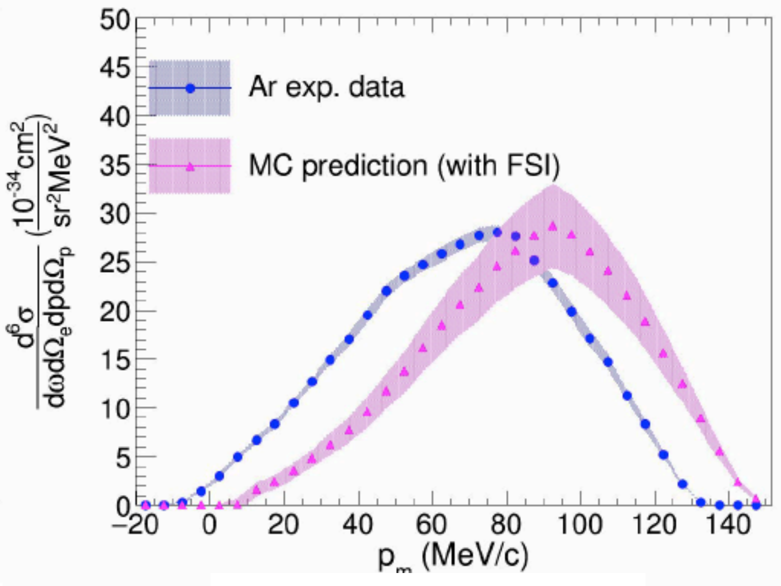
nuclear spectral function

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

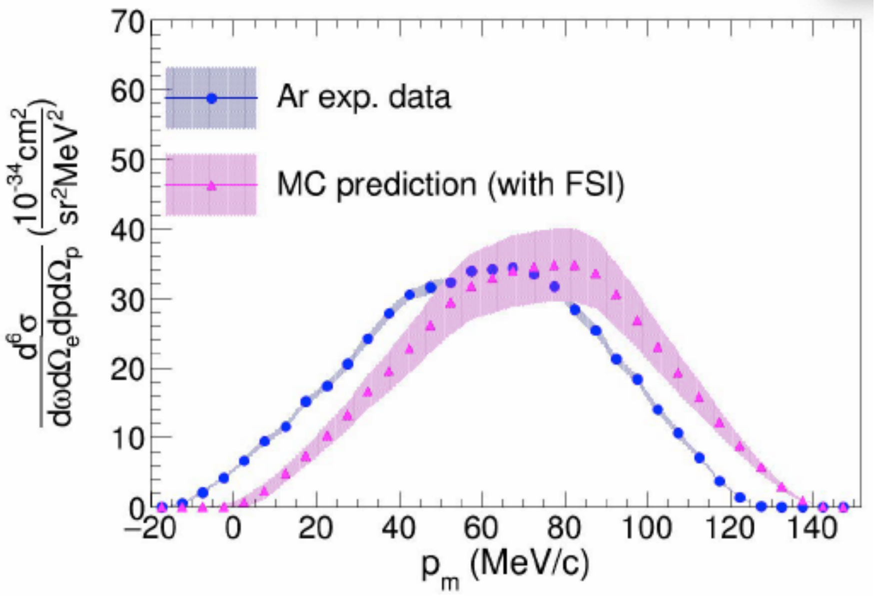
Exclusive analysis – Ar Missing momentum Distributions



P_m distribution (MeV/c) for
E_m< 27 MeV



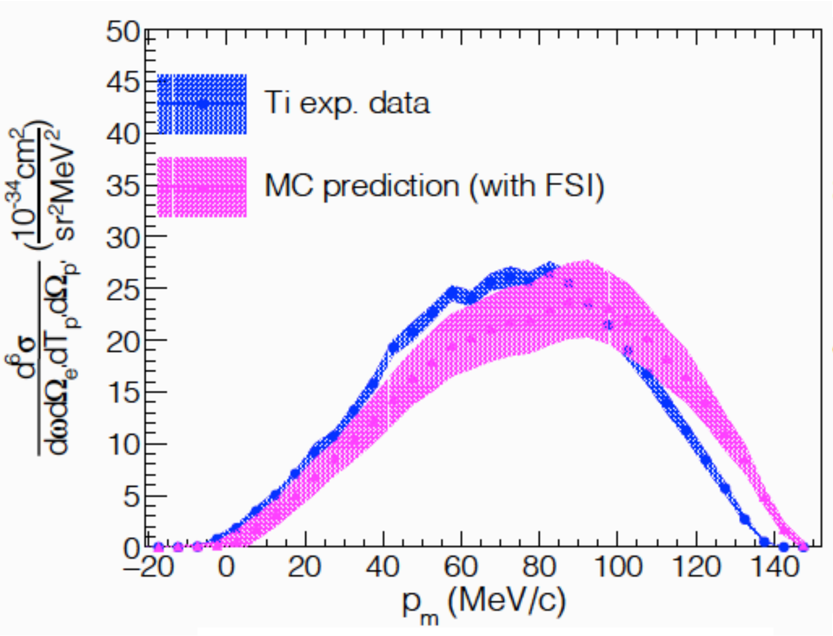
P_m distribution (GeV/c) for
27 MeV < E_m< 44 MeV



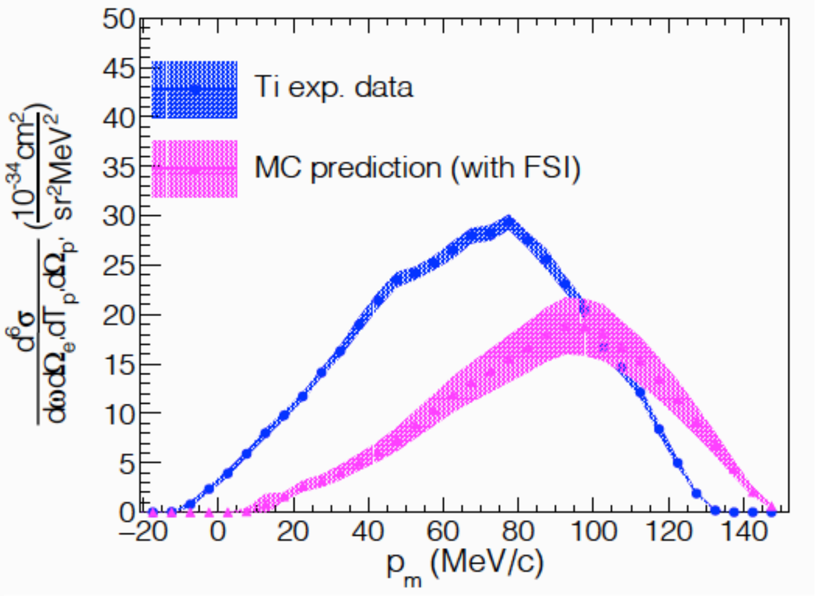
P_m distribution (GeV/c) for
44 MeV < E_m< 70 MeV

(MC + FSI) includes preliminary systematic uncertainties (σ_{ep}, form factors, optical potential, wave function pairing)

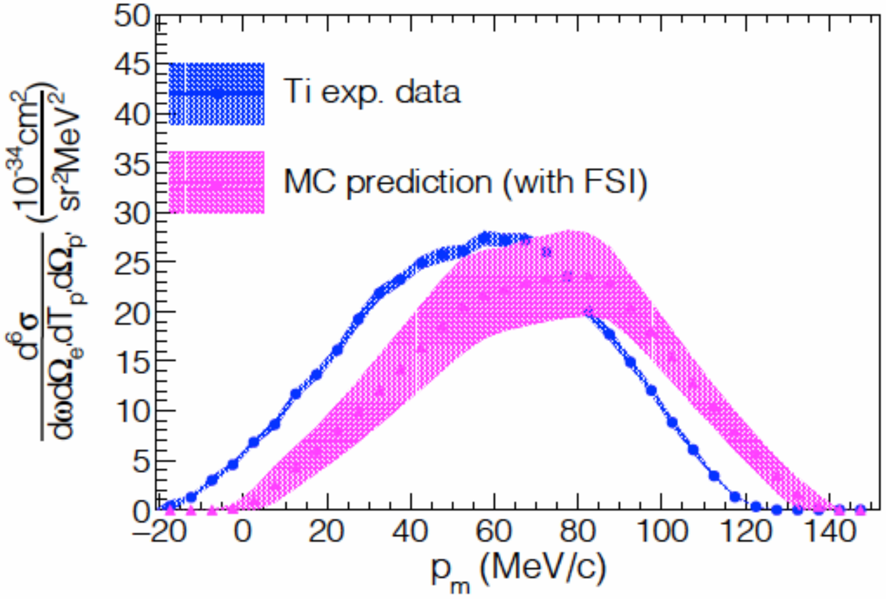
Exclusive analysis – Ti - Missing momentum Distributions



P_m distribution (MeV/c) for
5 MeV < E_m< 30 MeV



P_m distribution (GeV/c) for
30 MeV < E_m< 54 MeV

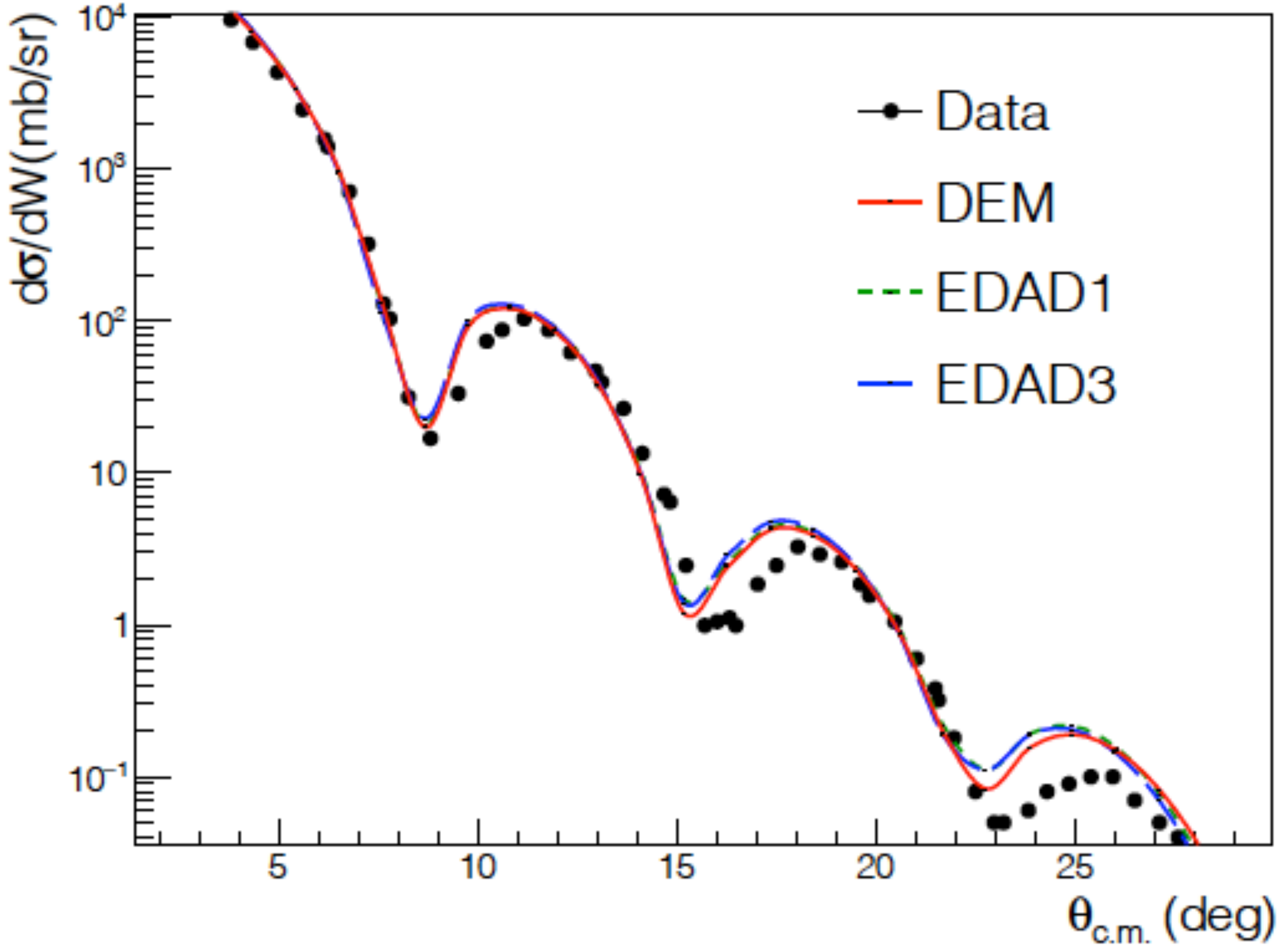


P_m distribution (GeV/c) for
54 MeV < E_m< 90 MeV

(MC + FSI) includes preliminary systematic uncertainties (σ_{ep}, form factors, optical potential, wave function pairing)

FSI analysis

- Check optical potential



C. Giusti/R. Lindgren

Data is from:

Elastic and Inelastic Scattering of 0.8 GeV protons from ^{40}A
G.S. Blanpied et al - Phys Rev C 37 (1304) 1988

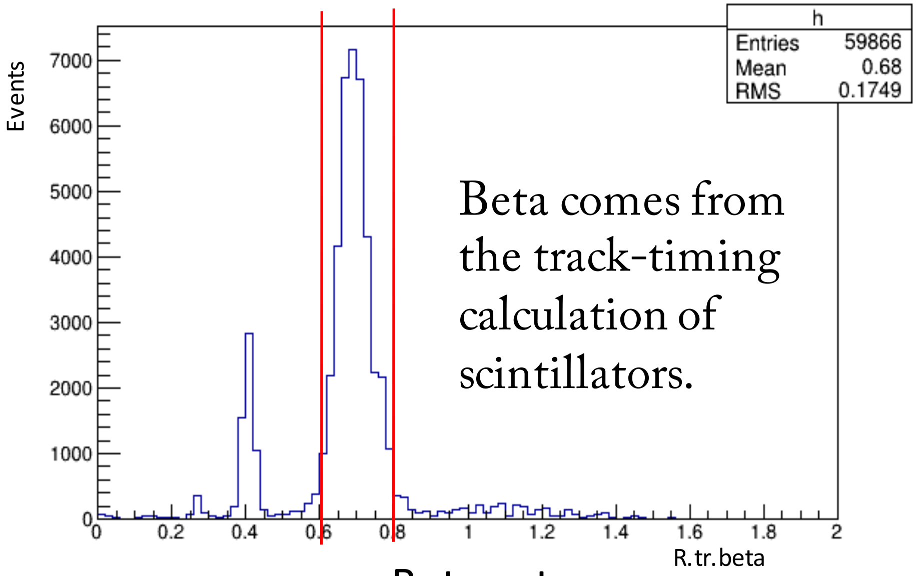
FSI analysis

- Reweight MC event by event
  - Use missing energy per event to identify the most probable electron shell, then apply the reweight and shift in missing momentum for that event
- Systematic uncertainties summary

Optical model	Ar: 1.5% - 5.4%	Ti: 3.3%-7.5%
Wave function pairing	Ar: 0.4%	Ti: 5.3%

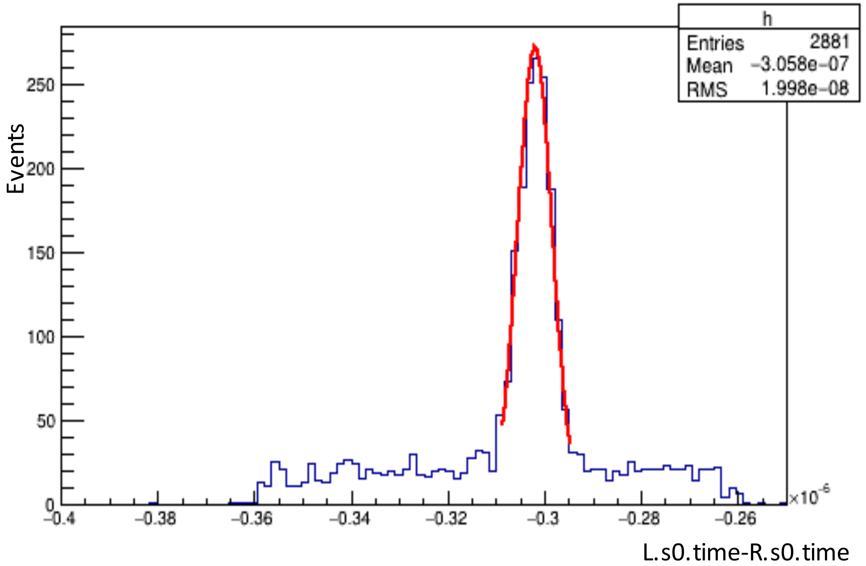
Exclusive analysis - Cuts

- Trigger cut: Trigger1
  - (S0&&S2) && (GC||PR) [LEFT] and (S0&&S2) [RIGHT]
- Single track cut for both arms
- Particle Identification (PID) cut:
  - cherenkov>400
  - (preshower+shower)/p_rec>0.3
- Acceptance cut for both arms:
  - dp [-0.04,0.04]
  - theta [-0.060.06](rad)
  - phi[-0.03,0.03](rad)
- Z cut: [-10,10](cm)
- Beta cut for right arm:
  - beta [0.6,0.8]
- Coincidence time cut



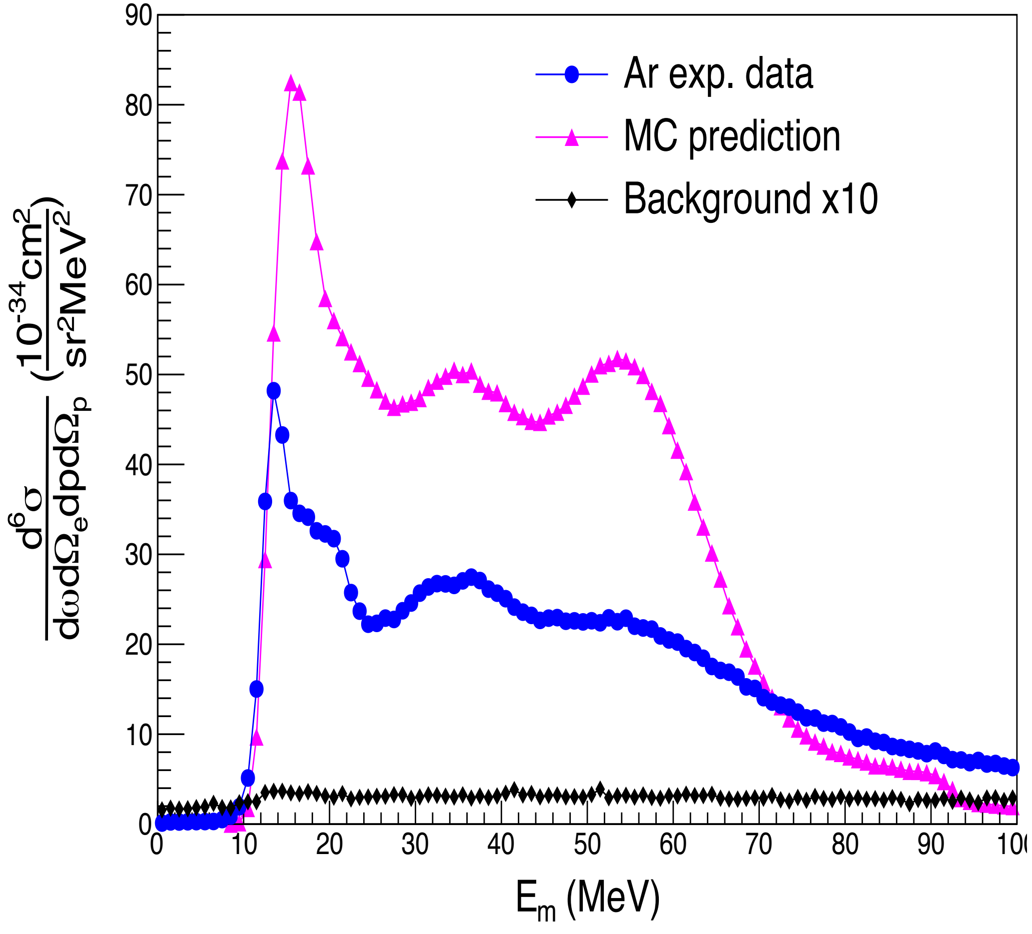
Beta comes from the track-timing calculation of scintillators.

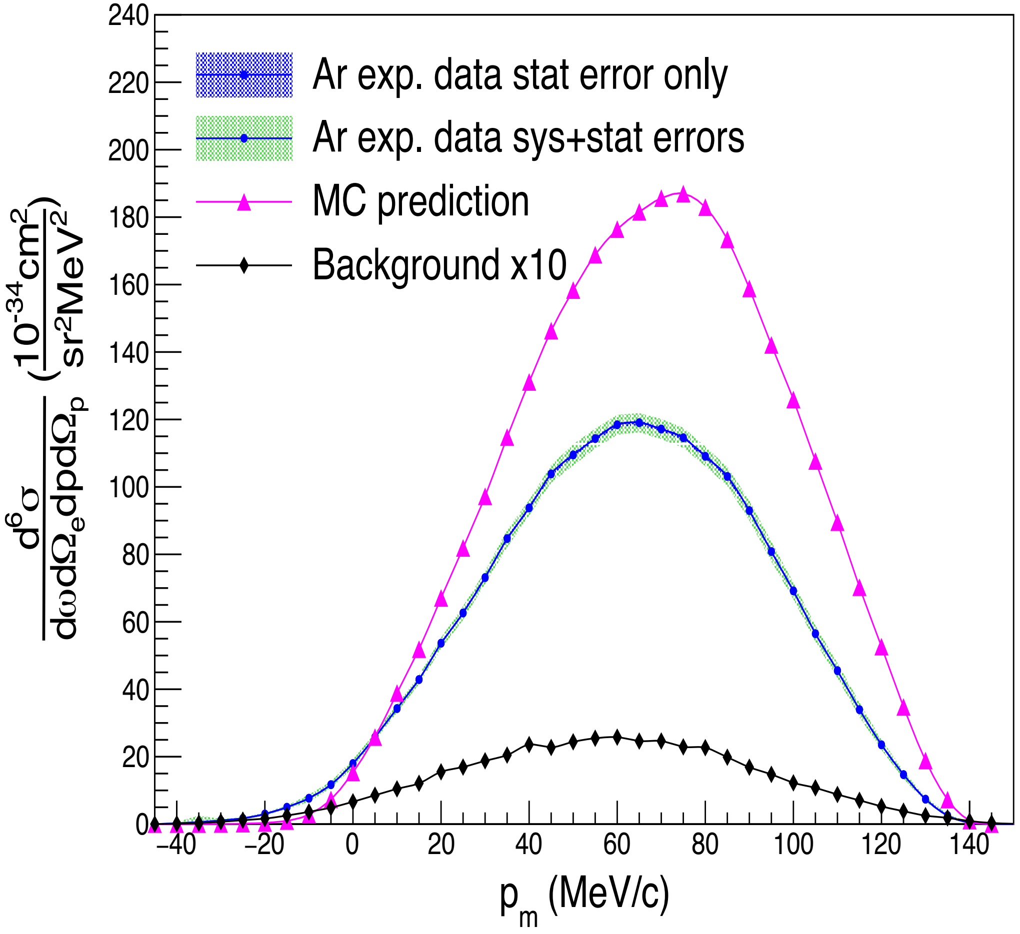
Beta cut



Coincidence time cut

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

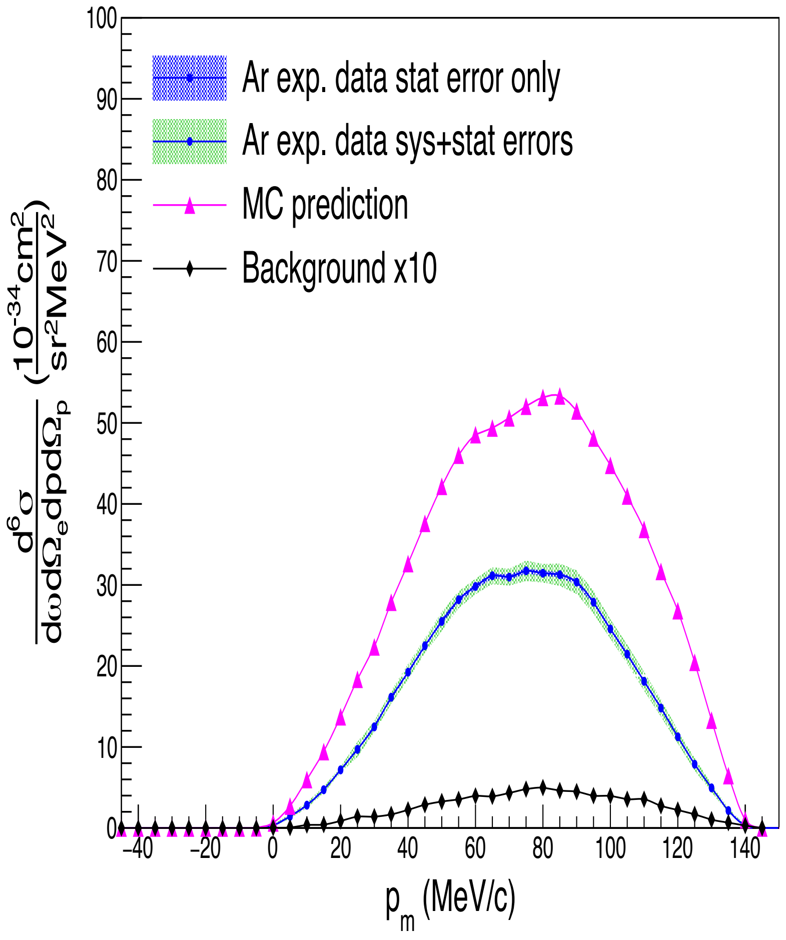




Effect of FSI

- 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

Exclusive analysis – Ar Missing Momentum Distributions



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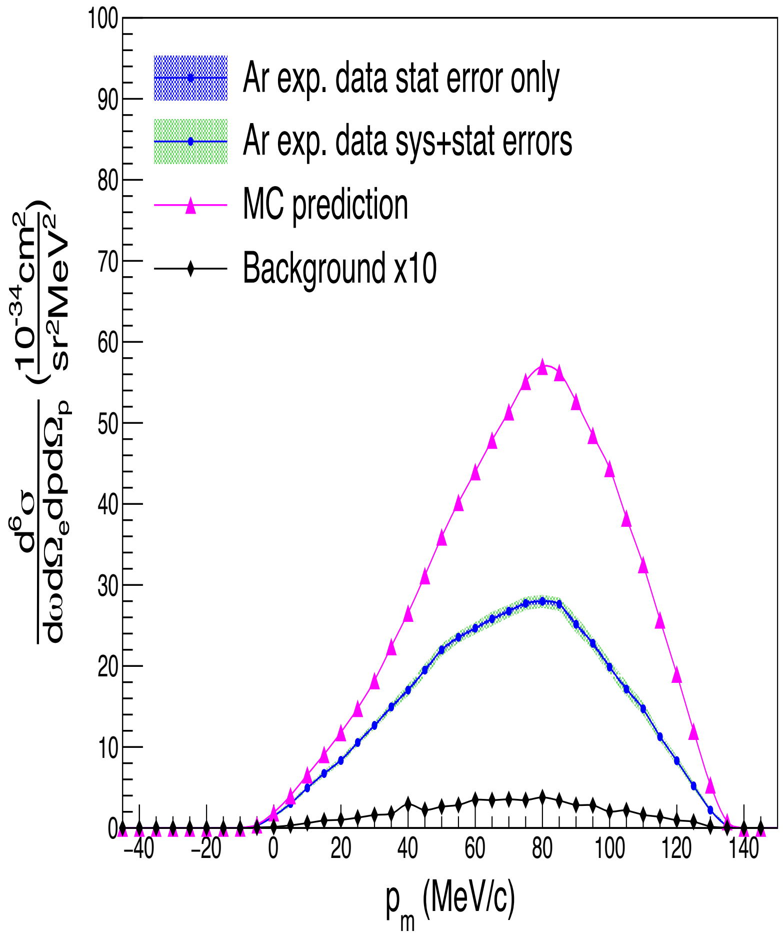
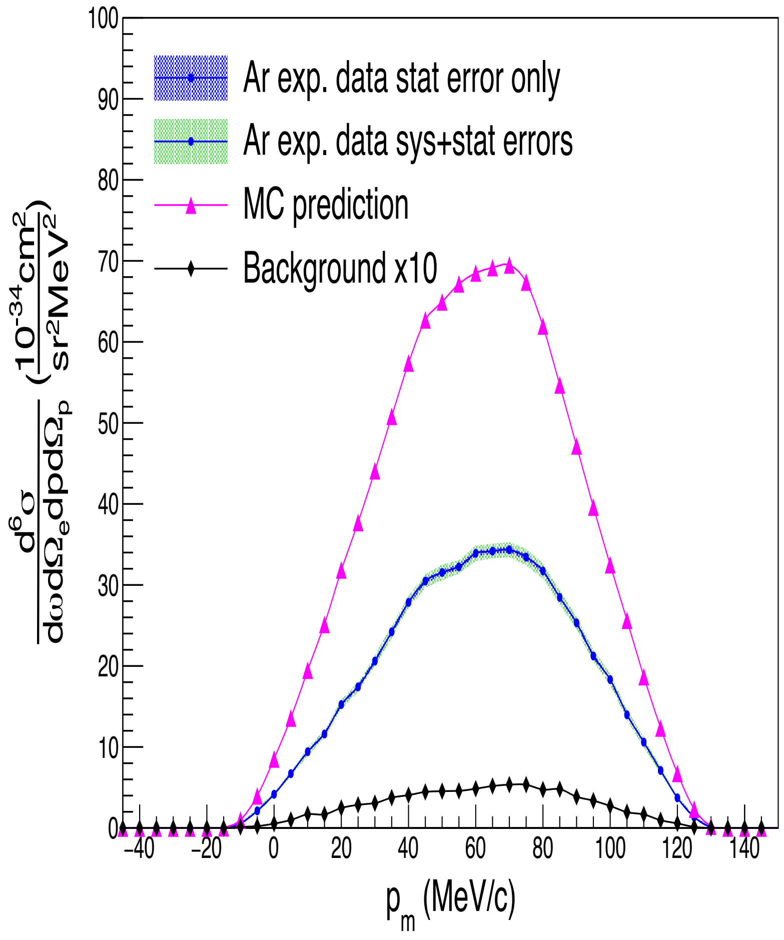


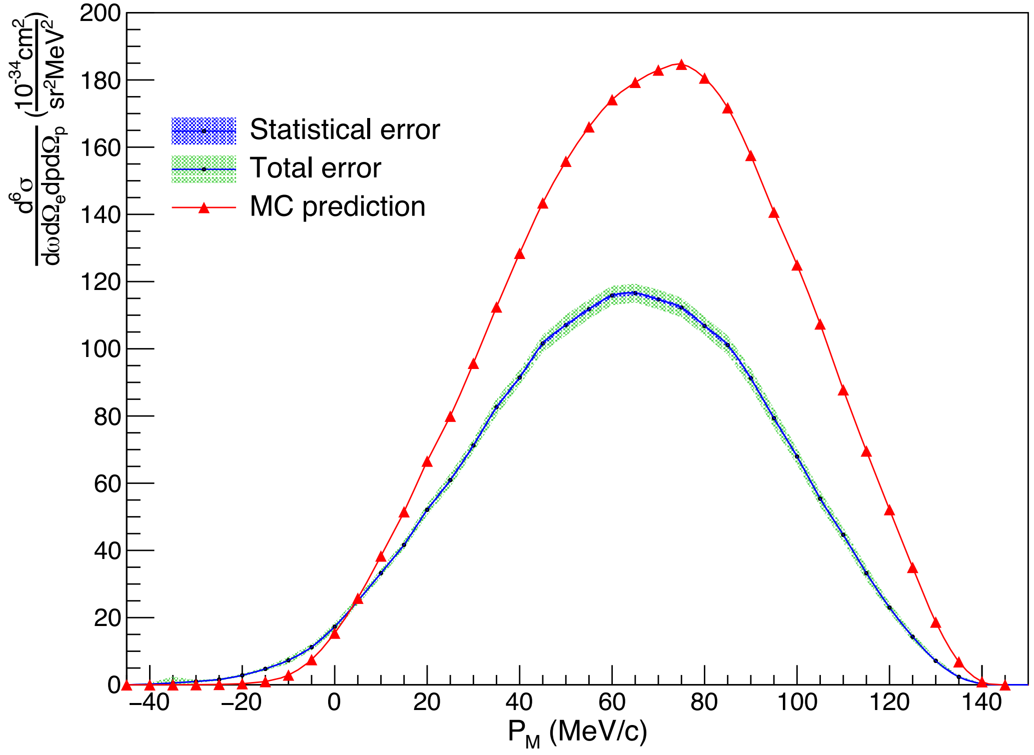
P_m distribution (GeV/c) for
27 MeV < E_m< 44 MeV



P_m distribution (GeV/c) for
44 MeV < E_m< 70 MeV

Systematic uncertainty calculation

- Systematics from acceptance, z cuts, calorimeter, Cerenkov cuts and so on
  - Calculate the number of events within the cut for data and MC.
  - Compute the ratio : $r = \frac{Events\ in\ data}{Events\ in\ MC}$
  - Vary the cut, re-compute the ratio r
  - The difference of the ratio is considered as the systematic uncertainty of this cut



Divide Pm distribution into 40 bins from -50 to 150 MeV

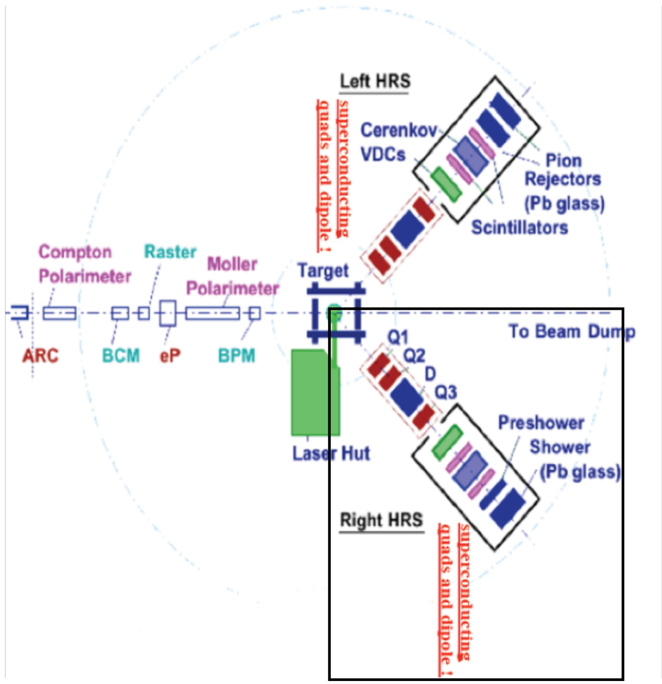
Systematic uncertainty calculation

- Systematics from beam and Spectrometer offsets
  - Calculate the number of events within all the cut for MC.
  - Re-generate the MC after varying the offset with the resolution, get the number of events within all the cut for new MC.
  - The difference of the events is considered as the Systematic uncertainty.

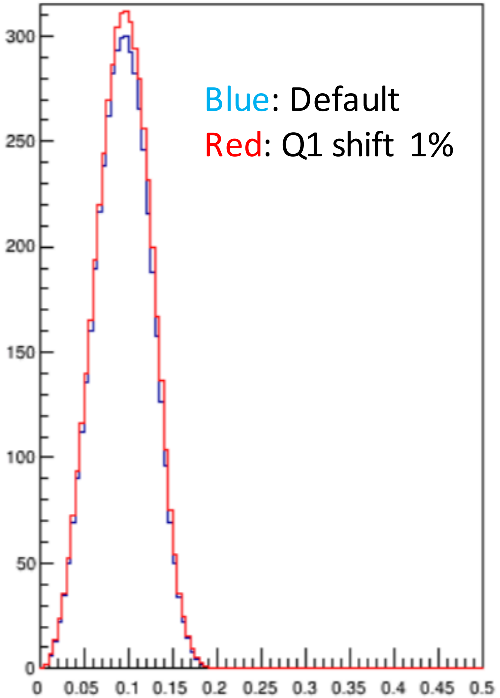
- Beam x offset 0.0075 +/- 0.004
- Beam y offset 0.118 +/- 0.005
- Spectrometer x offset 0.122 +/- 0.0005
- Spectrometer y offset 0.098 +/- 0.0005

Systematic uncertainty calculation

- Systematics from optical matrix (magnetic field)
  - Calculate the number of events within all the cut for MC.
  - Regenerate the MC after varying the magnet filed Q1, Q2, Q3 by 1% separately, get the number of events within all the cut for new MC.
  - The difference of the events is considered as the Systematic uncertainty.



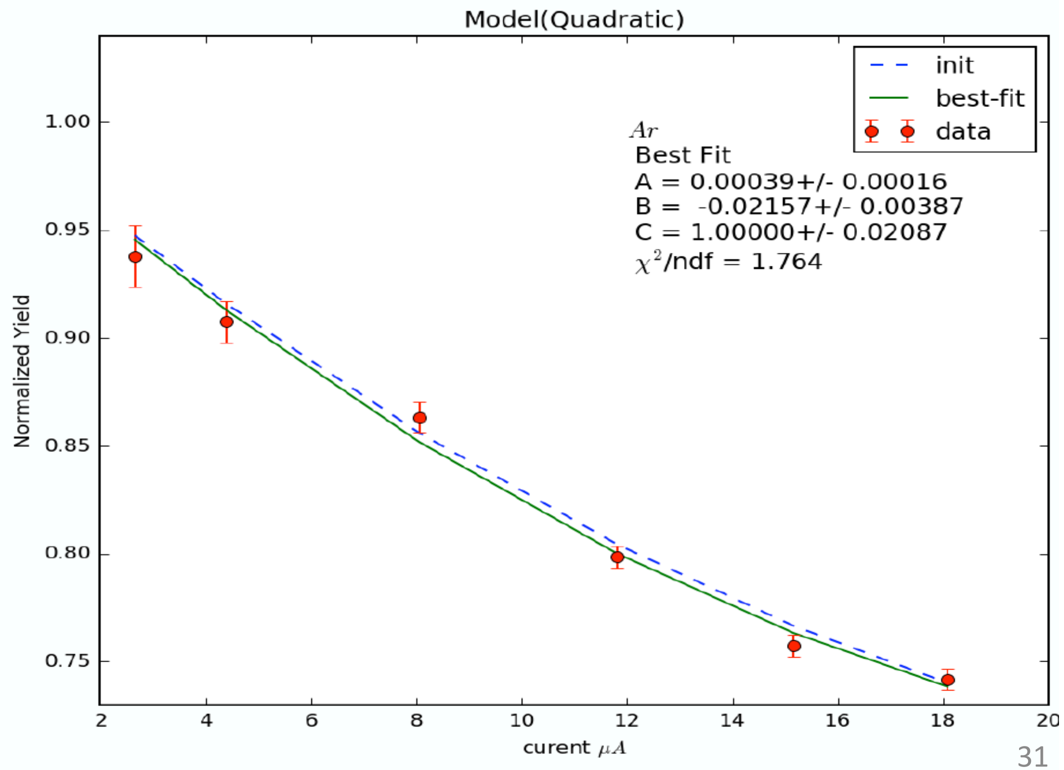
Zoom In



Systematic uncertainty calculation

- 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



List of systematic uncertainties – kin1 Ar

- 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 ?

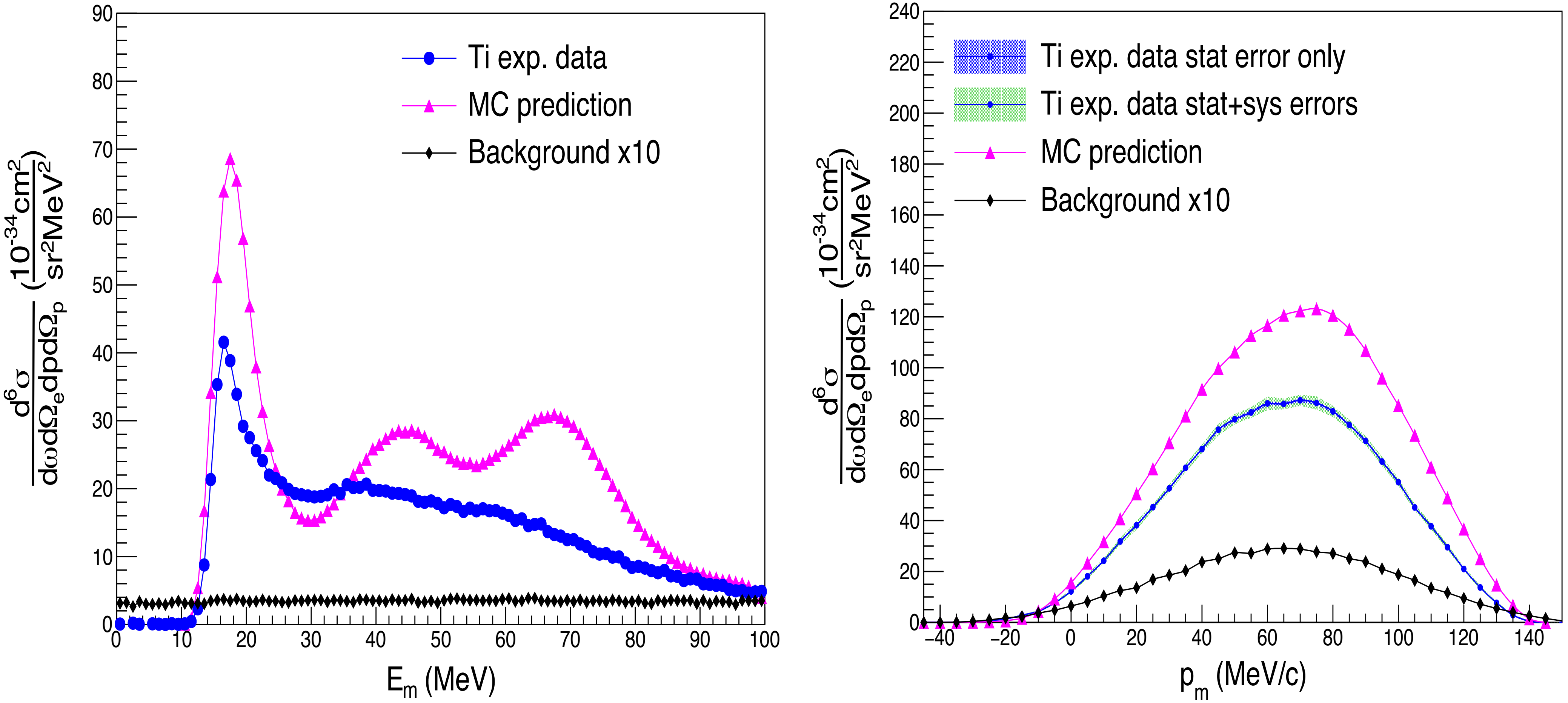
- Optical Matrix:

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.

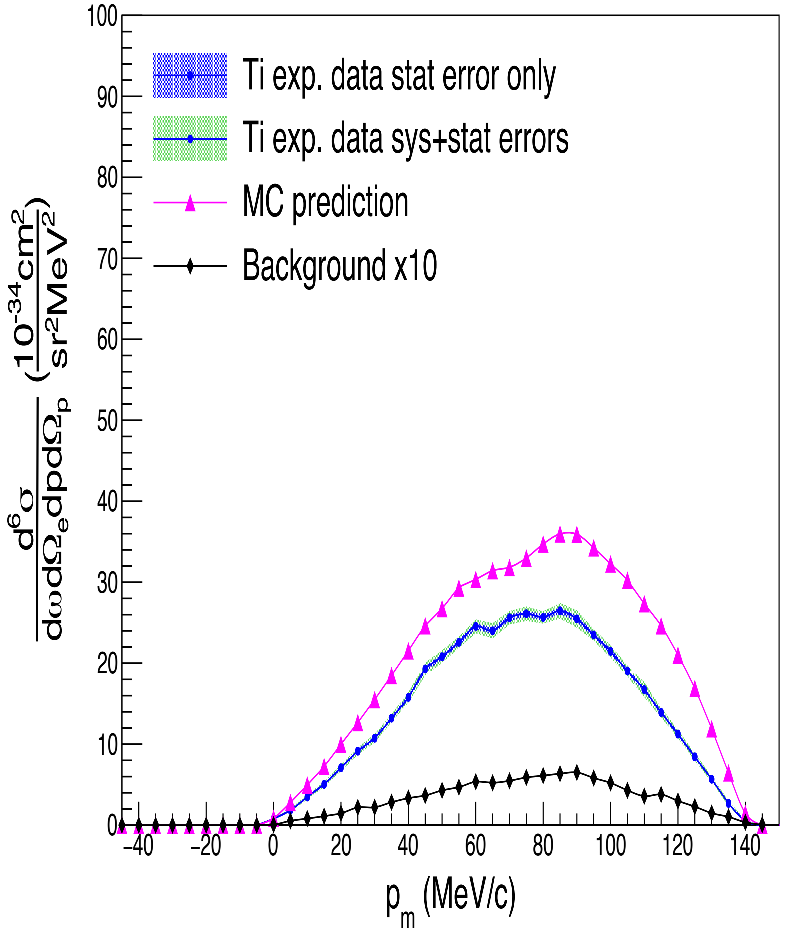
Exclusive analysis - kin1 - Ti - Missing energy and missing momentum



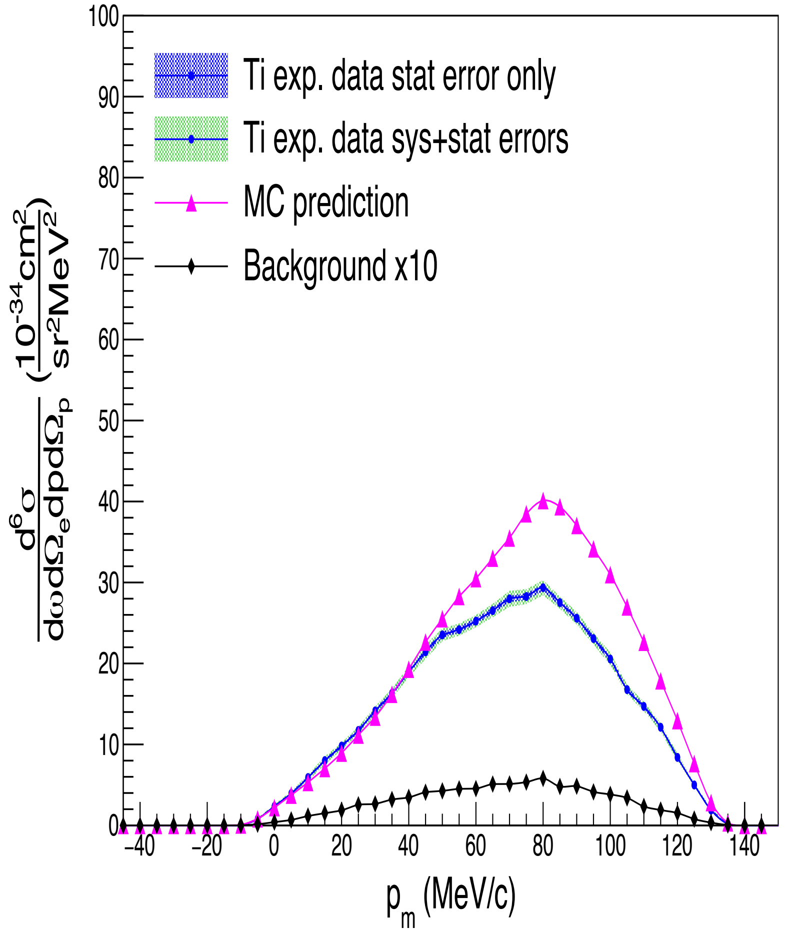
Effect of FSI

- 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

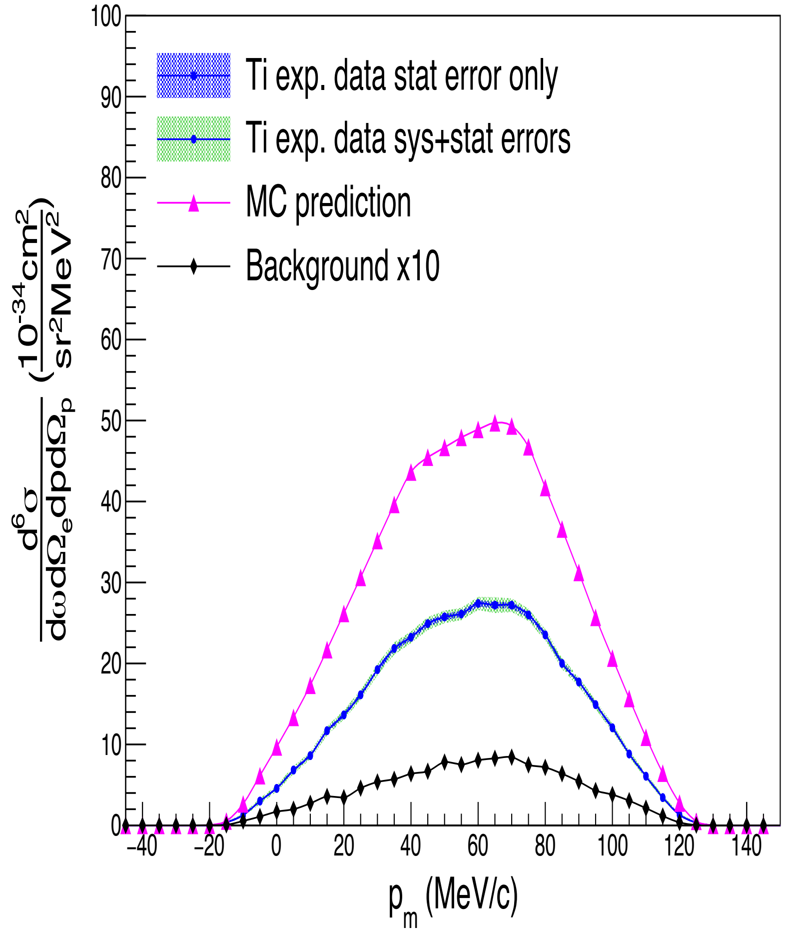
Exclusive analysis – Ti - Missing Momentum Distributions



P_m distribution (MeV/c) for
5 MeV < E_m< 30 MeV



P_m distribution (GeV/c) for
30 MeV < E_m< 54 MeV



P_m distribution (GeV/c) for
54 MeV < E_m< 90 MeV

List of systematic uncertainties – kin1 Ti

- Statistical uncertainty ~ 0.78%
- Total systematic uncertainty ~2.11%
  - Beam x and y offset ~0.49%
  - HRS x and y offset ~0.58%
  - Target thickness ~0.2%
  - Acceptance cuts ~1.36%
  - Cerenkov and Calorimeter cuts ~0.02%
  - COSY ~0.48%
  - Radiative and Coulomb corrections ~1%
  - Beta cut ~0.39%
  - Coincidence time cut ~0.78%
  - FSI ?

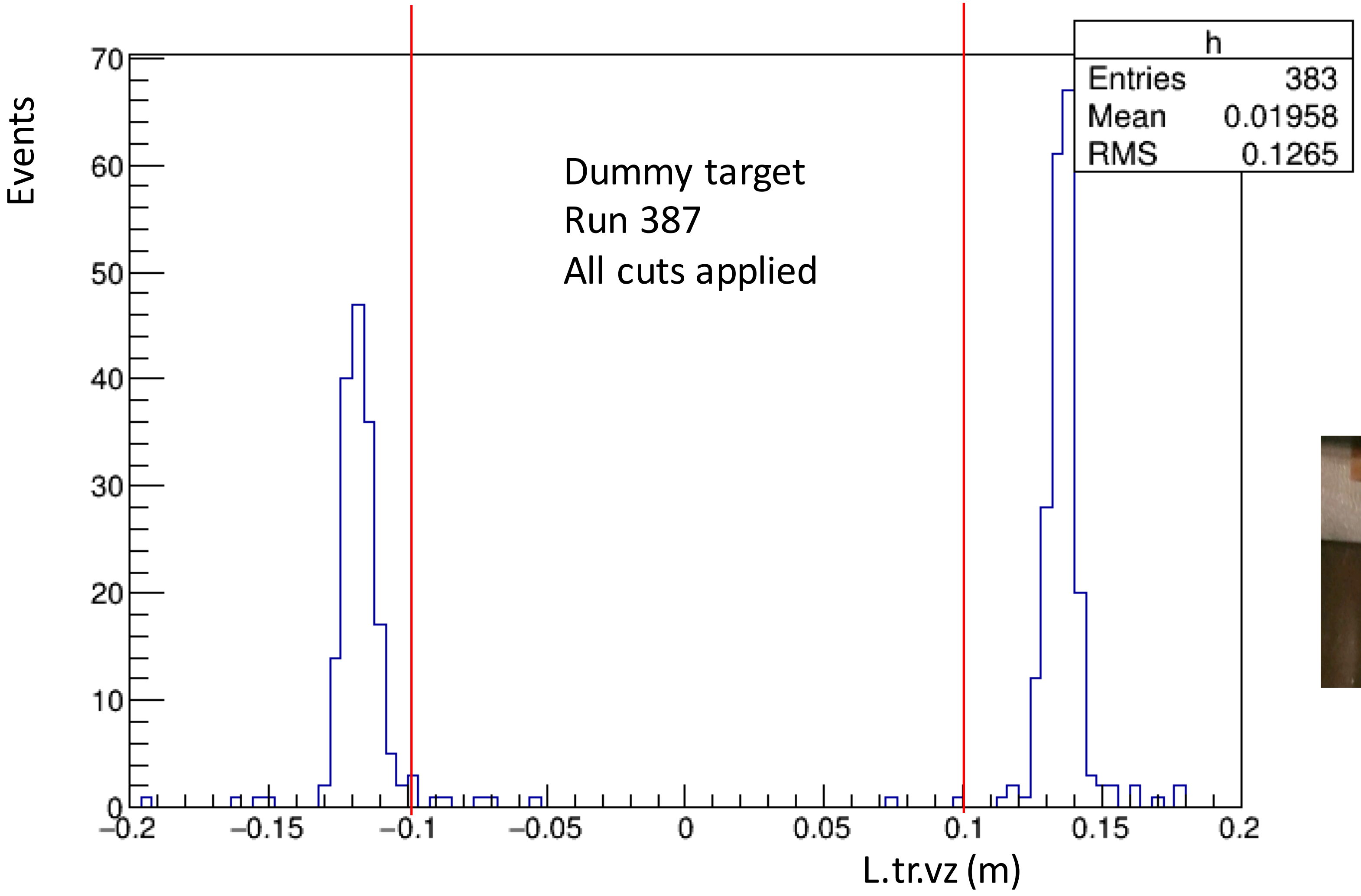
- Optical Matrix:

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:

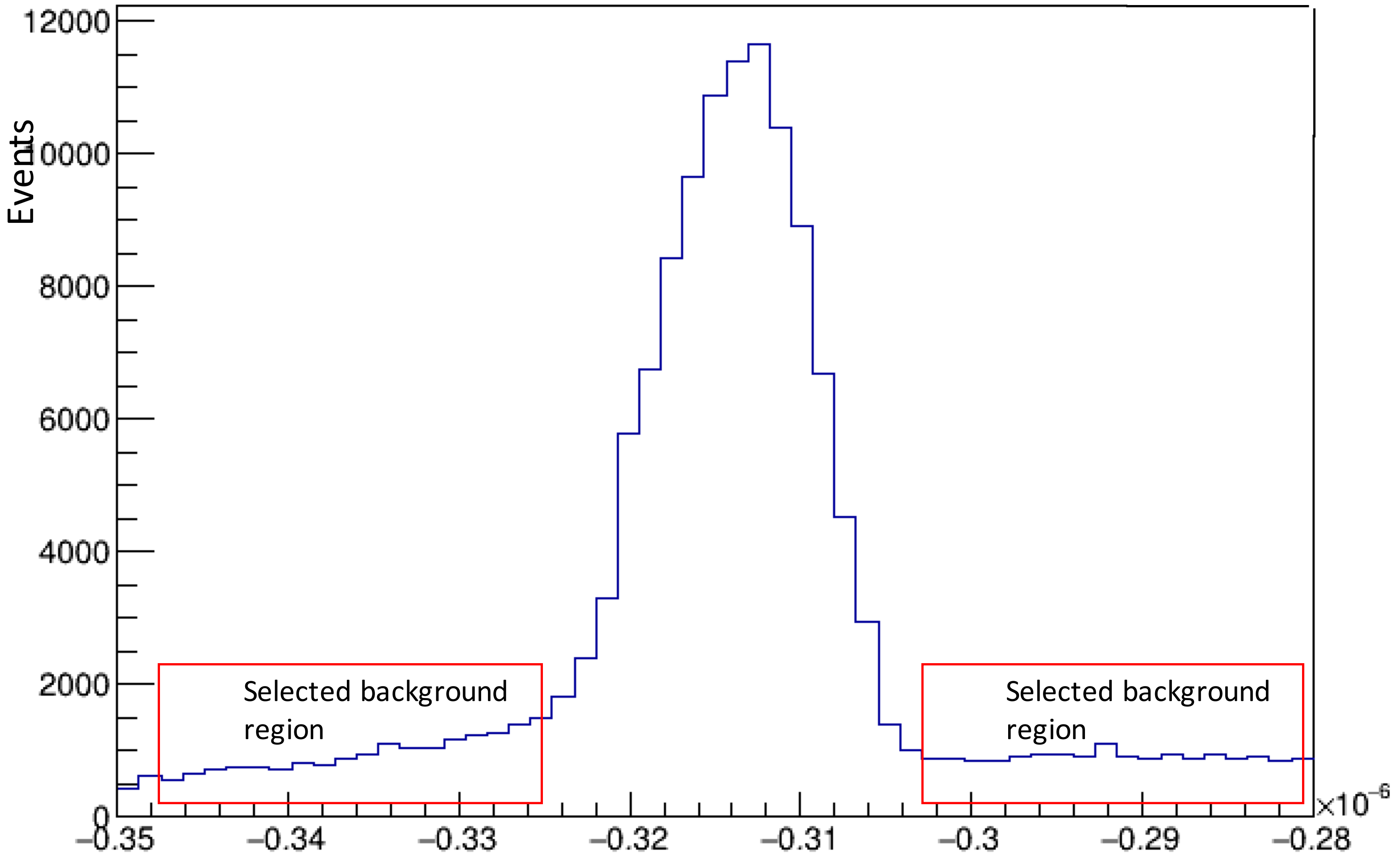
We scale the cross section model by $\sqrt{Q^2}/2$, and recalculate the radiative correction factor.

Background study in Kin1 Ar - from dummy



- Background from dummy is ignorable in selected z cut range [-0.1,0.1](m)

Background study in Kin1 Ar – from accidental



Coincidence time distribution

Steps for calculating the background from accidental:

- Pick one or two (both sides) background region
- Find the background range width and events number in the region
- Scaled background events = 2*sigma*(background events/background range)
- Background rate = scaled background events/ total events

Efficiency definition

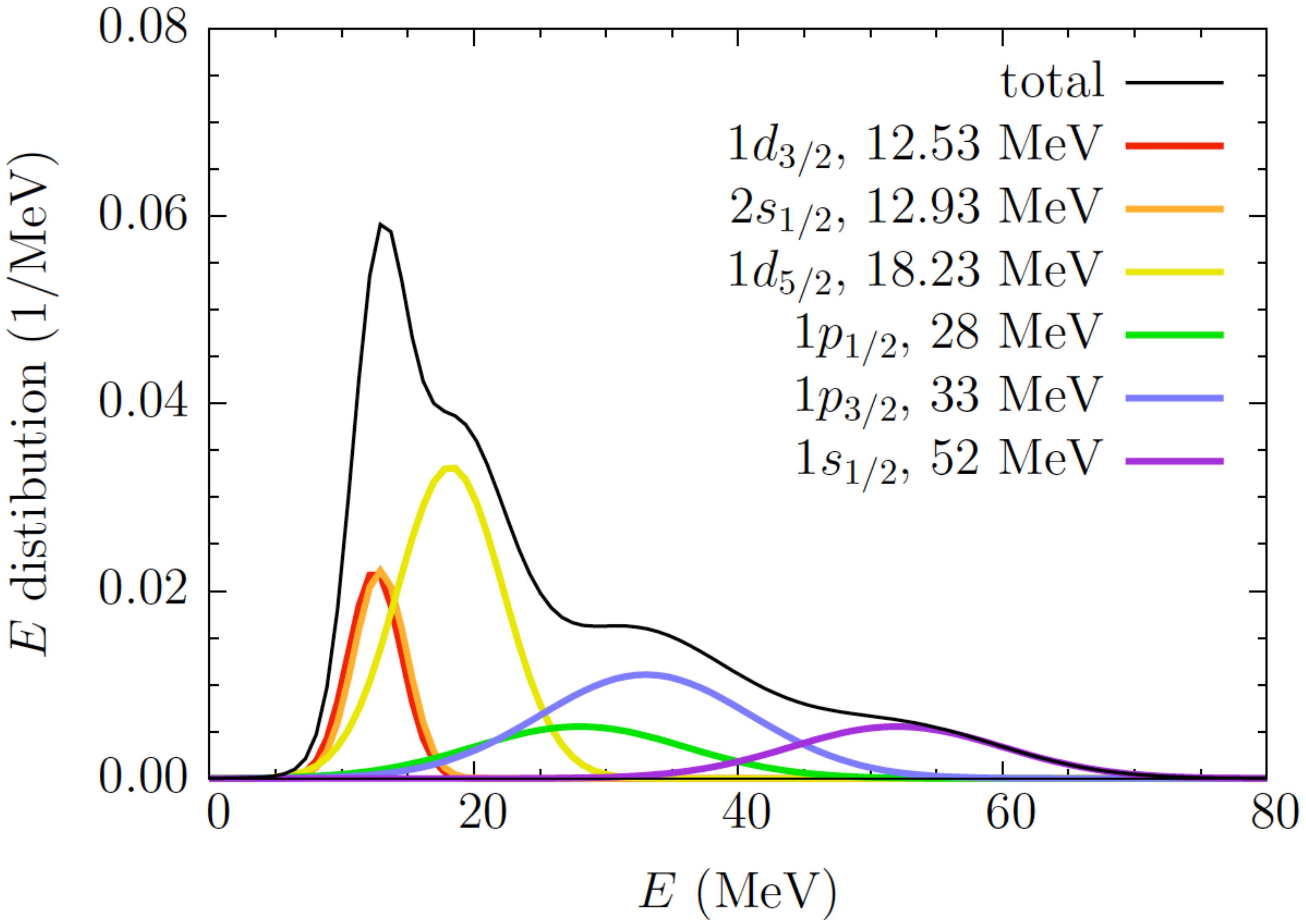
Efficiency	definition
livetime	Without any cuts
Trigger eff	(two arms acceptance + left arm z+ Current + Trigger1)/(two arms acceptance + let arm z + Current + Trigger2)
PID eff	Cer_eff: (Calo + Curent + Cer + Trigger1)/(Calo + Current + Trigger1)
	Calo_eff: (Calo+ Current + Cer Trigger1)/(Cer + Current + Trigger1)
Tracking eff	Left none_zero track: (Trigger1 + PID + Current +L.tr.n>0)/(Trigger1 + PID + Current)
	Left one track: (Trigger1 + PID + left arm acceptance + left arm z + Current +L.tr.n==1)/(Trigger1 + PID + left arm acceptance + left arm z + Current) (based on dp cut, bin by bin)
	Right none_zero track: (Trigger1 + PID + Current +R.tr.n>0)/(Trigger1 + PID + Current)
	Right one track: (Trigger1 + PID + right arm acceptance + Current +R.tr.n==1)/(Trigger1 + PID + right arm acceptance+ Current)
Beta cut eff	(Trigger1 + PID + L.tr.n==1 + R.tr.n==1 + two arms acceptance + left arm z + Current+ tight time_diff cut + beta)/(Trigger1 + PID + beta + L.tr.n==1 + R.tr.n==1 + two arms acceptance + left arm z + Current + tight time_diff cut)
Coincidence time eff	(Trigger1 + PID + tight beta cut+ L.tr.n==1 + R.tr.n==1 + two arms acceptance + left arm z + Current+ time_diff)/(Trigger1 + PID + tight beta cut+ L.tr.n==1 + R.tr.n==1 + two arms acceptance + left arm z + Current)

List of Systematic uncertainties

- Beta cut: [0.6,0.8]
- Beta cut efficiency is recalculated each time after each variation of the beta cut

Case No.	Rootfile Name	Change compared to original
0	original	No change
1	L_theta_cut_1	L_theta + [-0.0002,0] (rad)
2	L_theta_cut_2	L_theta + [+0.0002,0] (rad)
3	L_theta_cut_3	L_theta + [0,-0.0002] (rad)
4	L_theta_cut_4	L_theta + [0,+0.0002] (rad)
5	L_phi_cut_1	L_phi + [-0.0002,0] (rad)
6	L_phi_cut_2	L_phi + [+0.0002,0] (rad)
7	L_phi_cut_3	L_phi + [0,-0.0002] (rad)
8	L_phi_cut_4	L_phi + [0,+0.0002] (rad)
9	R_dp_cut_1	R_dp + [-0.0002,0]
10	R_dp_cut_2	R_dp + [+0.0002,0]
11	R_dp_cut_3	R_dp + [0,-0.0002]
12	R_dp_cut_4	R_dp + [0,+0.0002]
13	R_theta_cut_1	R_theta + [-0.0002,0] (rad)
14	R_theta_cut_2	R_theta + [+0.0002,0] (rad)
15	R_theta_cut_3	R_theta + [0,-0.0002] (rad)
16	R_theta_cut_4	R_theta + [0,+0.0002] (rad)
17	R_phi_cut_1	R_phi + [-0.0002,0] (rad)
18	R_phi_cut_2	R_phi + [+0.0002,0] (rad)
19	R_phi_cut_3	R_phi + [0,-0.0002] (rad)
20	R_phi_cut_4	R_phi + [0,+0.0002] (rad)
21	z_cut_1	z + [-0.6,0] (cm)
22	z_cut_2	z + [+0.6,0] (cm)
23	time_diff_1	coincidence time cut sigma vary +0.3ns
24	time_diff_2	coincidence time cut sigma vary -0.3ns
25	beta_1	beta + [-0.05,0]
26	beta_2	beta + [+0.05,0]
27	beta_3	beta + [0,-0.05]
28	beta_4	beta + [0,+0.05]
29	beam_x_1	targ_x_offset - 0.04 (cm)
30	beam_x_2	targ_x_offset + 0.04 (cm)
31	beam_y_1	targ_y_offset - 0.05 (cm)
32	beam_y_2	targ_y_offset + 0.05 (cm)
33	HRS_ex_1	spec_E_arm_x_offset - 0.0005 (cm)
34	HRS_ex_2	spec_E_arm_x_offset + 0.0005 (cm)
35	HRS_ey_1	spec_E_arm_y_offset - 0.0005 (cm)
36	HRS_ey_2	spec_E_arm_y_offset + 0.0005 (cm)
37	HRS_px_1	spec_P_arm_x_offset - 0.0005 (cm)
38	HRS_px_2	spec_P_arm_x_offset + 0.0005 (cm)
39	HRS_py_1	spec_P_arm_y_offset - 0.0005 (cm)
40	HRS_py_2	spec_P_arm_y_offset + 0.0005 (cm)
41	COSY_q1	COSY Q1 shift up 1% (Both arms)
42	COSY_q2	COSY Q2 shift up 1% (Both arms)
43	COSY_q3	COSY Q3 shift up 1% (Both arms)

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