JLAB Experiment E12-14-012

Measurement of the Argon and Titanium spectral functions through the Ar - Ti (e, e'p) reactions

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Jefferson Lab Experiment E12-14-012

- Collaboration of 31 physicists, from 8 institutions, based in USA, Europe and Japan
- C. Mariani - Contact Person and Spokesman
- Approved in July 2014
  Scientific Grade A-
  Request coming from the HEP
- Experimental Readiness Review in July 2016
- Data taking started in Feb. 2017
- Data taking completed Mar. 2017

PR12-14-012

Scientific Rating: A-

Recommendation: Approve

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

Spokespersons: O. Benhar, C. Mariani, C.-M. Jen, D.B. Day, D. Higinbotham

Motivation: This experiment is motivated by the need to model the response of liquid Argon detectors to neutrino beams. This information is important for the LBNF program (and other oscillation experiments) that use liquid Ar. The critical issue is that reconstruction of the neutrino energy depends on the spectral functions of neutrons and protons in ^{40}Ar. The neutrino beam has an energy spread and hence the neutrino flux as a function of energy has to be extracted by simulations that include the correct nuclear physics. A challenge is that the next generation of neutrino oscillation experiments aim at a precision of 1% and hence ensuring that the nuclear corrections are properly addressed is critical. This data will provide experimental input to construct the argon spectral function, thus allowing the most reliable estimate of the neutrino cross sections. In addition, the analysis of the (e,e'p) data will help a number of theoretical developments, such as the description of final-state interactions needed to isolate the initial-state contributions to the observed single-particle peaks, that is also needed for the interpretation of the signal detected in neutrino experiments.

This experiment has significant support from the neutrino community. Letters of support for this proposal were received from the Fermilab management, and spokespeople from LBNE, ArgoNeuT, Captain, LArIAT, and MicroBooNE. The analysis and simulation groups of these experiments will use these data.

Measurement and Feasibility: The experimenters propose a measurement of the (e, e'p) cross section on argon. Kinematics will be chosen to scan the missing energy domain extending from $E_m \sim 8$ MeV to $E_m \sim 60$ MeV, using the Hall A HRS spectrometers. Similar (e,e'p) experiments have been performed at JLAB and hence this measurement should be straightforward. Kinematical conditions corresponding to interactions with protons moving parallel to the incoming electron beam will be selected to minimize the final state interactions. To test the final-state interaction corrections, and inform such corrections needed for neutrino interactions, the experimenters also propose to measure two days in anti-parallel kinematics where final state interactions should be largest.

Issues: The proposal did not describe how the precision of the proposed experiment would translate into a precision in neutrino oscillation experiments. Given the uncertainty in correction for final-state interactions, it is likely that the systematic errors will be larger than the quoted 3%. However we anticipate that larger errors are likely to be acceptable. The energy resolution will also be larger than the quoted value, but again this appears to be acceptable. The PAC also noted that for anti-neutrino experiments the spectral functions of the neutrons are also important, but this experiment will only determine the proton spectral functions. An appropriate model will be needed to infer neutron spectral functions from the proton data taken in this experiment.

Recommendation: Approve for the requested 9 days of beam time.

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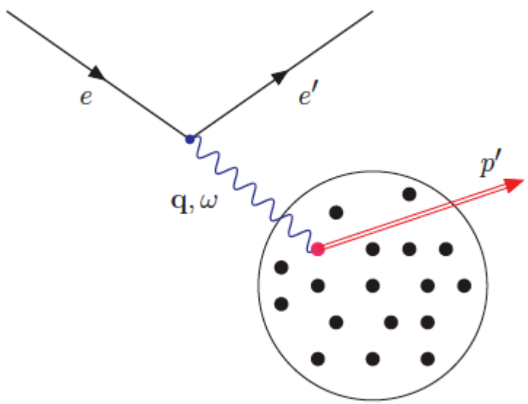
The (e, e'p) Reaction

- Consider the process $e + A \to e' + p + (A-1)$ in which both the outgoing electron and the proton, carrying momentum p', are detected in coincidence, and the recoiling nucleus can be left in any bound state



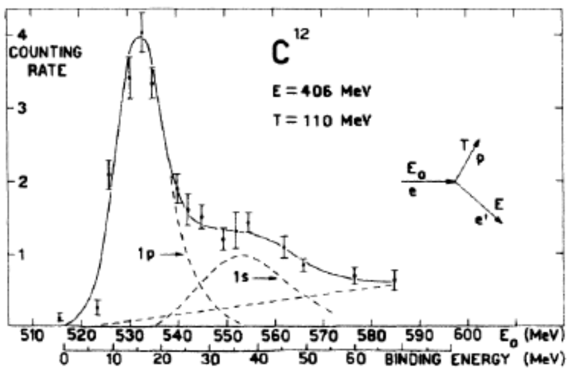
- In the absence of final state interactions (FSI), the initial energy and momentum of the knocked out nucleon can be identified with the *measured* missing momentum and energy, respectively

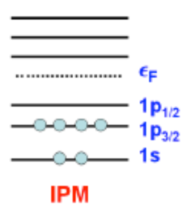
$$\mathbf{p}_m = \mathbf{p}' - \mathbf{q} \quad , \quad E_m = \omega - T_{\mathbf{p}'} - T_{A-1} \approx \omega - T_{\mathbf{p}'}$$

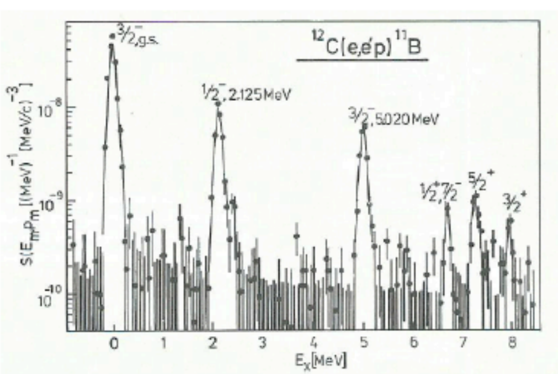
(e, e'p) at moderate missing energy

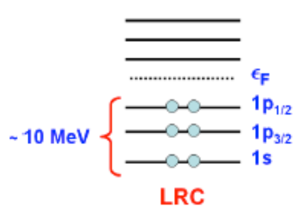
- Observing the shell structure of nuclei: Carbon as an example

- Missing energy spectrum. Three decades of progress: 1966-1996

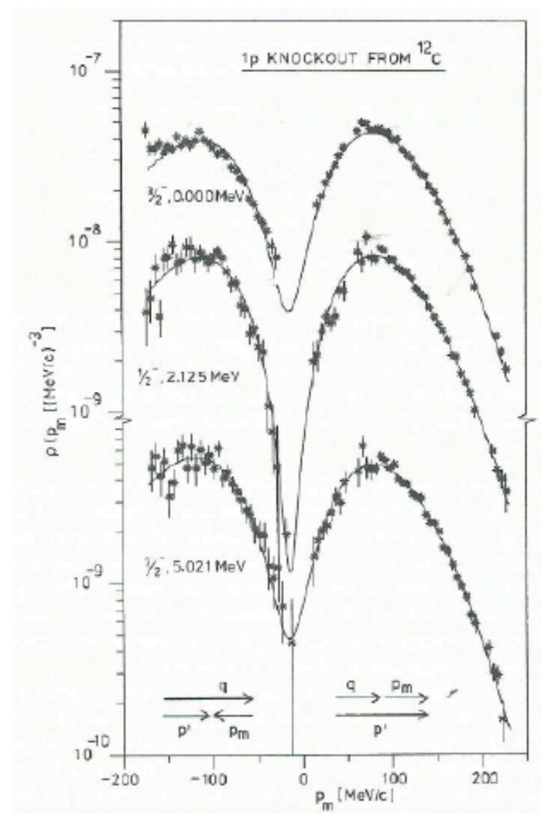








- Distorted momentum distributions. Final state interactions under control



Determining the Spectral Function from DATA

- In the absence of FSI

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

- Kállën-Lehman representation

$$P_(\mathbf{p}_m, E_m) = P_{\rm MF}(\mathbf{p}_m, E_m) + P_{\rm corr}(\mathbf{p}_m, E_m)$$

- In the kinematical region corresponding to knock-out from the shell-model states ($6 \lesssim E_m \lesssim 60$ MeV and $|\mathbf{p}_m| \lesssim 350$ MeV for Argon)

$$P_{\rm MF}(\mathbf{p}_m, E_m) = \sum_{\alpha \in \{F\}} Z_\alpha \, |\phi_\alpha(\mathbf{p}_m)|^2 \, F_\alpha(E_m - \epsilon_\alpha)$$

  Z_α and width of F_α obtained from the measured cross section.
  Neglecting correlations: $Z_\alpha \to 1$, $F_\alpha(E_m - \epsilon_\alpha) \to \delta(E_m - \epsilon_\alpha)$

- $P_{\rm corr}(\mathbf{p}_m, E_m)$ from theoretical calculations of uniform nuclear matter and Local Density Approximation (LDA)

Why do we need Spectral Function ?

- Being an intrinsic properties of the target ground state, the spectral function is relevant to the description of nuclear interactions in **ALL** channels

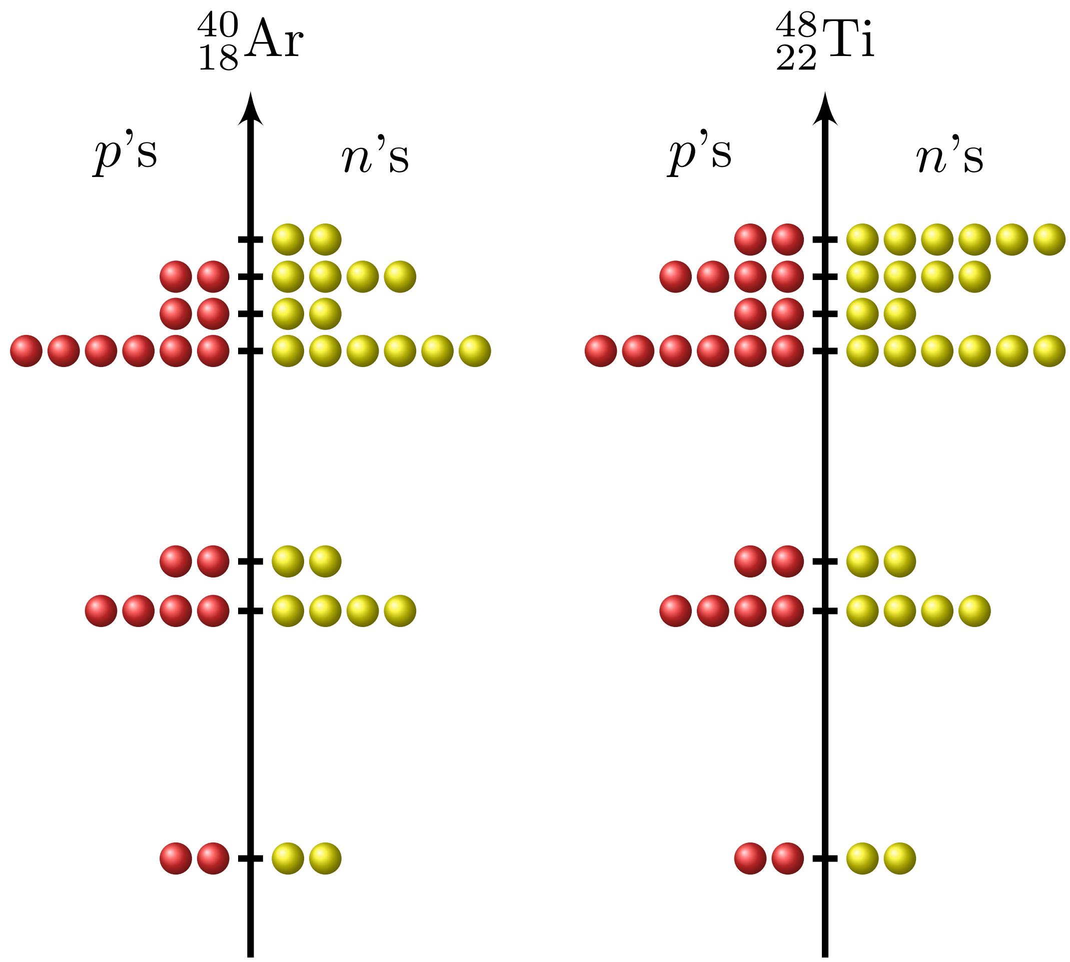
- Example: $\bar{\nu}$ energy reconstruction in quasi elastic $\bar{\nu}$-nucleus interactions

$$E_{\bar{\nu}} = \frac{m_n^2 - m_\mu^2 - E_p^2 + 2E_\mu E_p - 2\mathbf{k}_\mu \cdot \mathbf{p}_p + |\mathbf{p}_p{}^2|}{2(E_p - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_p| \cos\theta_p)} ,$$

- E_p and p_p are distributed according to the **proton** spectral function measured in (e, e'p):
  - **Ar(e,e'p)** provides the energy and momentum distribution of **neutrons** in the Ar target nucleus -- $\boldsymbol{\nu}$-nucleus interactions in Ar
  - **Ti(e,e'p)** provides the energy and momentum distribution of **protons** in the Ar target nucleus -- $\bar{\boldsymbol{\nu}}$-nucleus interactions in Ar

Neutron and proton spectral function - Ar&Ti

- Using the correspondence of the level structure between Ar and Ti, the neutron spectral function of Ar can be obtained from the proton spectral function of Ti



Kinematic setups

	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\|\mathbf{q}\|$	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

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

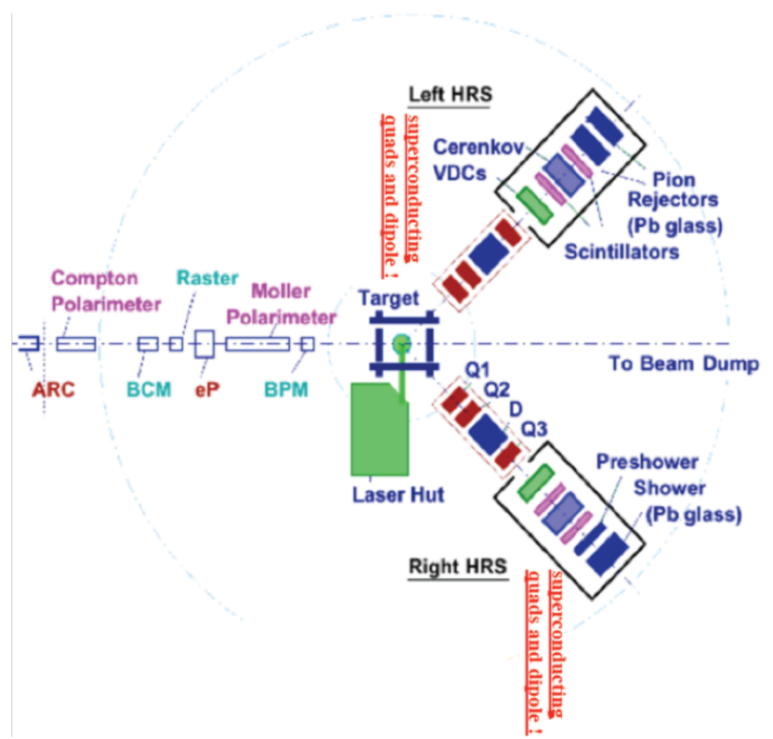
Collected Data	Hours	Events (k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

kin5

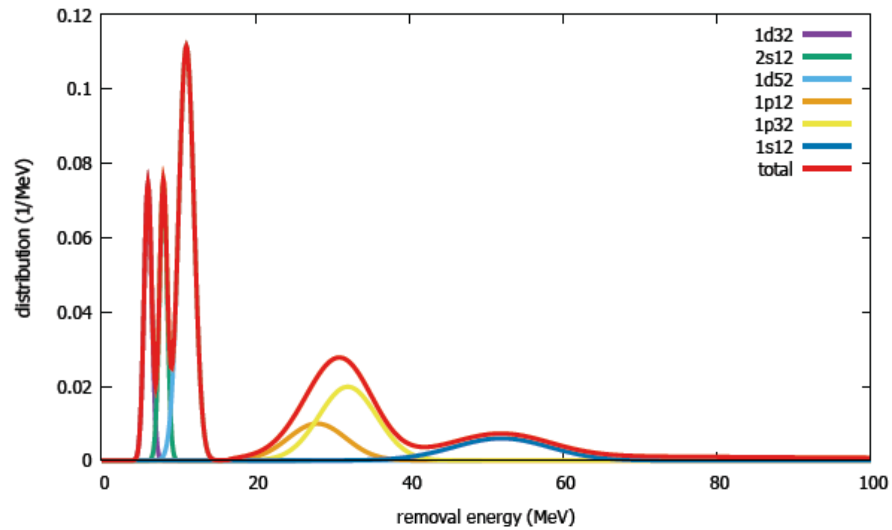
Collected Data	Hours	Events (k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

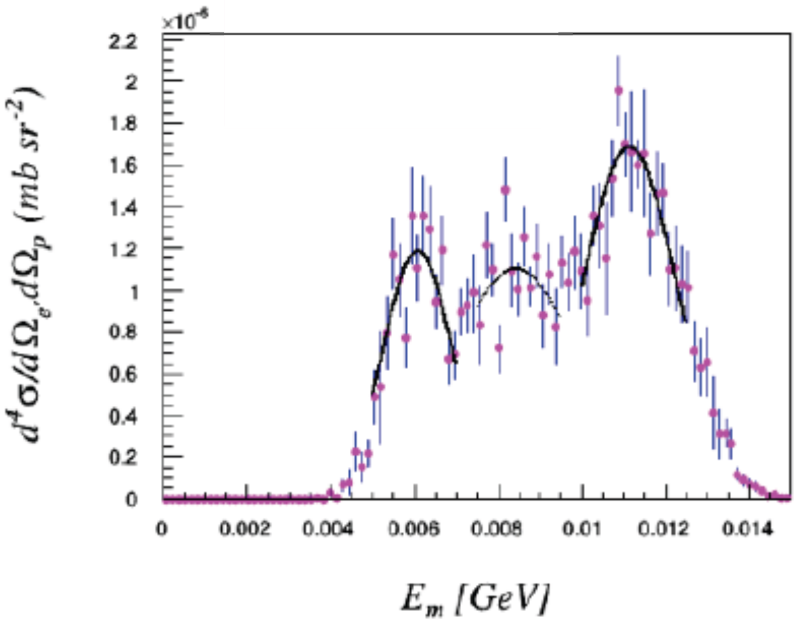
kin5 - Inclusive

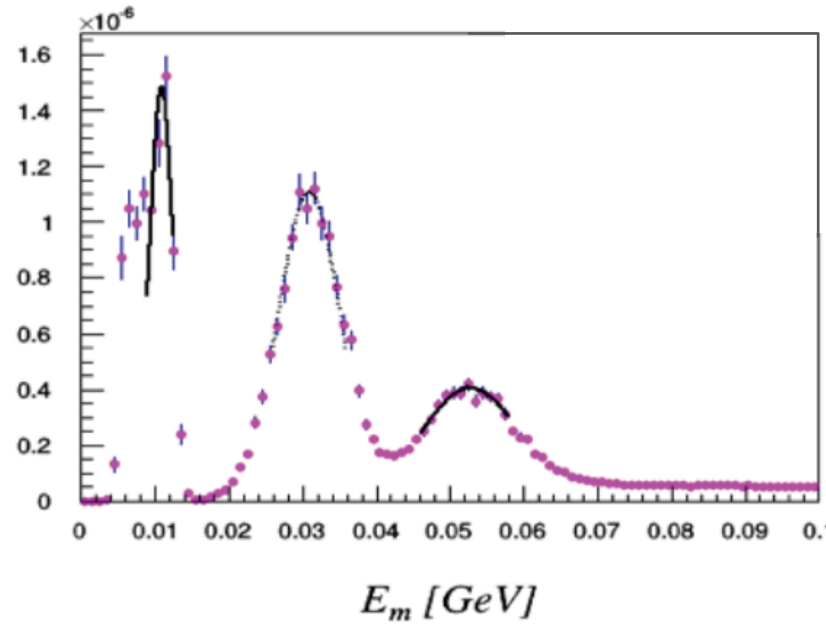
Collected Data	Minutes	Events (k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957



Kinematic setups

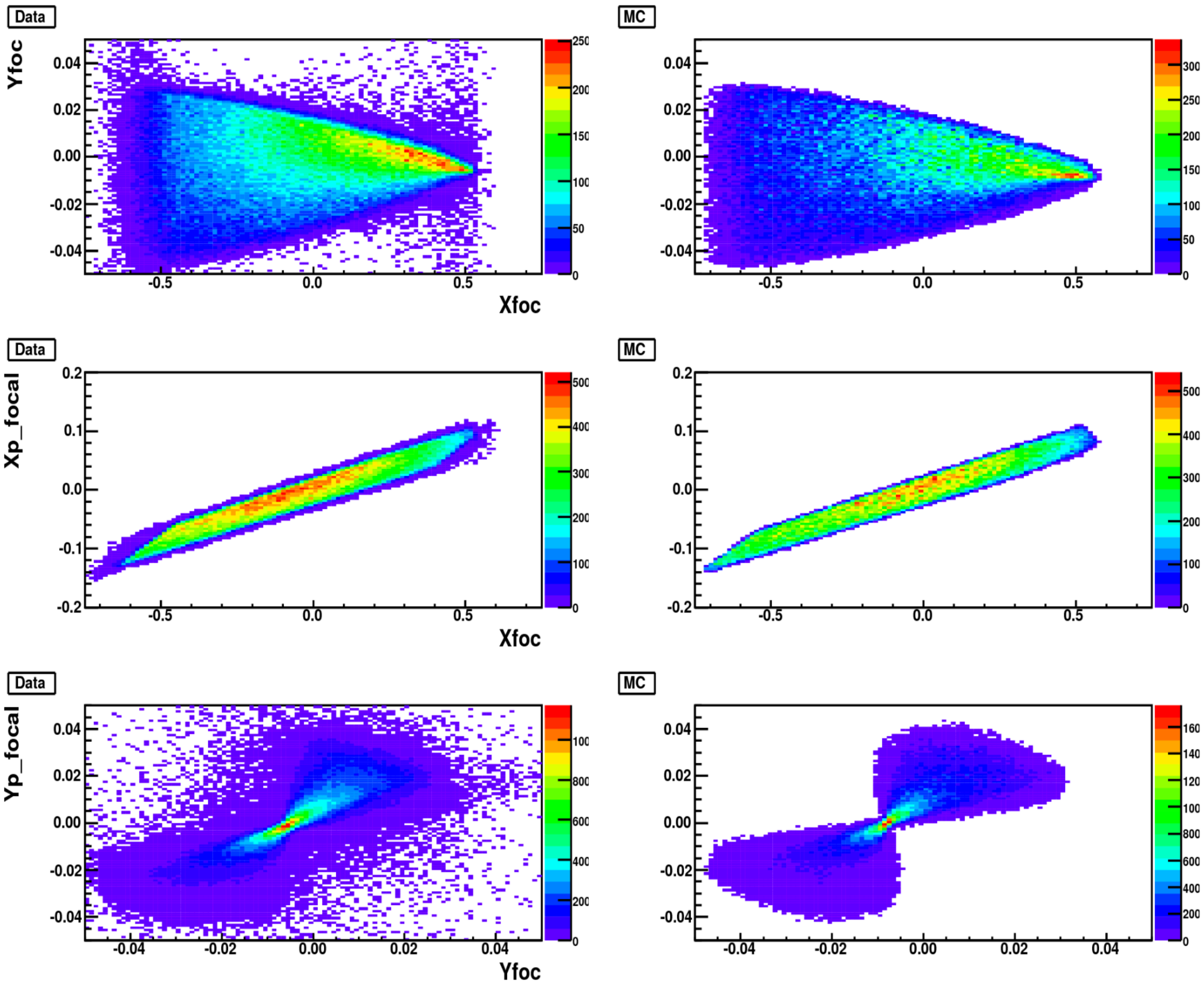


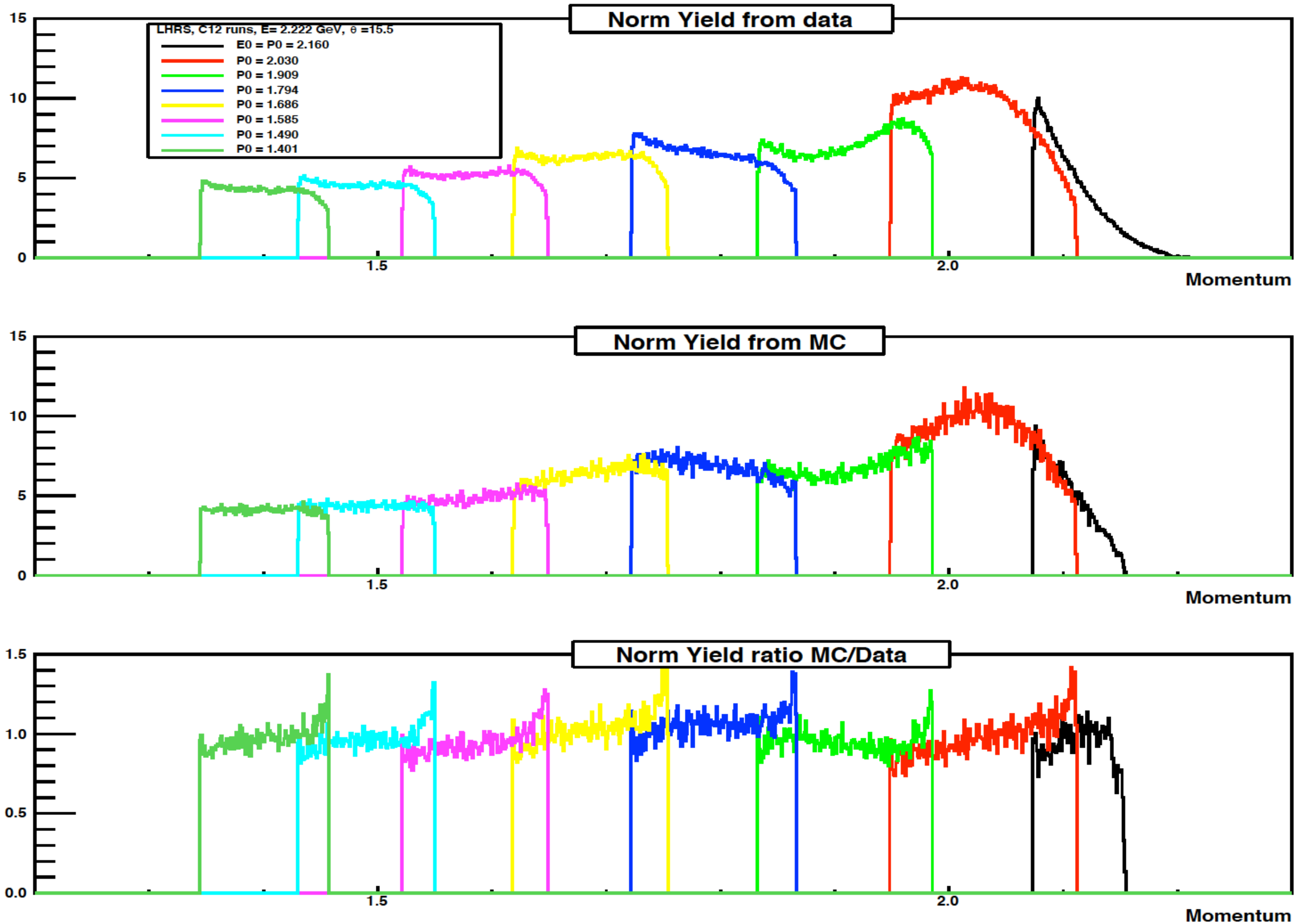




First comparison data vs MC

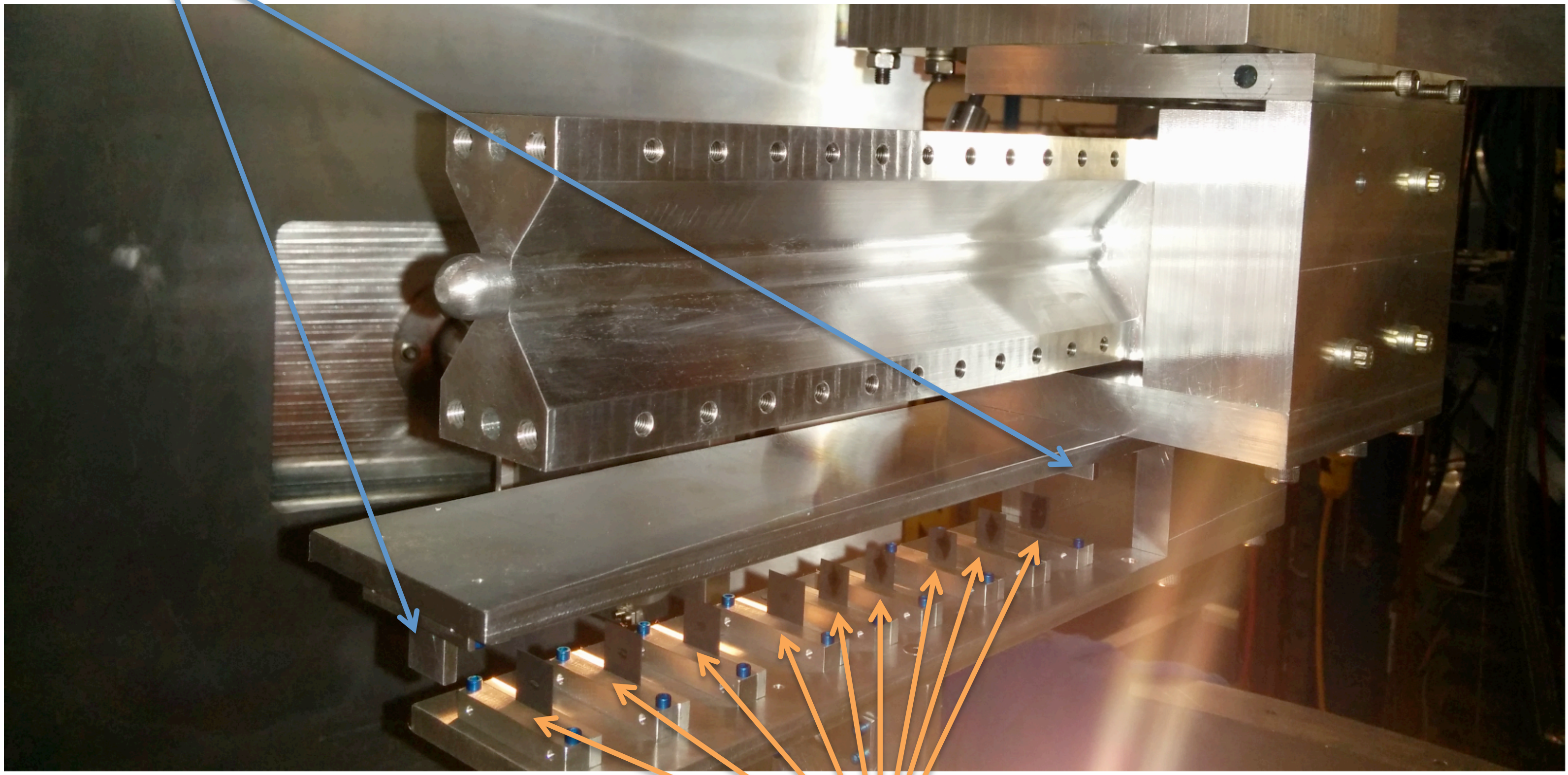
Focal plane comparison for highest P0 run 731




Norm Yield from data
LHRS, C12 runs, E= 2.222 GeV, θ =15.5
E0 = P0 = 2.160
P0 = 2.030
P0 = 1.909
P0 = 1.794
P0 = 1.686
P0 = 1.585
P0 = 1.490
P0 = 1.401
15
10
5
0
1.5
2.0
Momentum
Norm Yield from MC
15
10
5
0
1.5
2.0
Momentum
Norm Yield ratio MC/Data
1.5
1.0
0.5
0.0
1.5
2.0
Momentum

Target setups

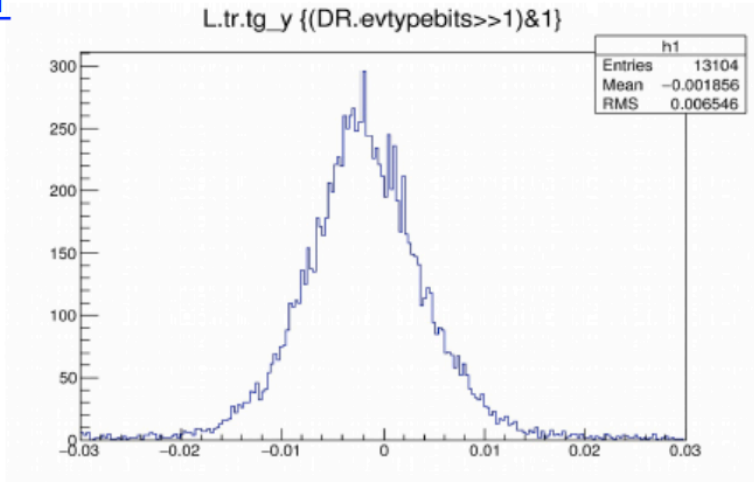
Dummy target: same as the entry and exit window as the gas target



Optical target: a series of foils of carbon (9) to check the alignment of target and spectrometers (optics)

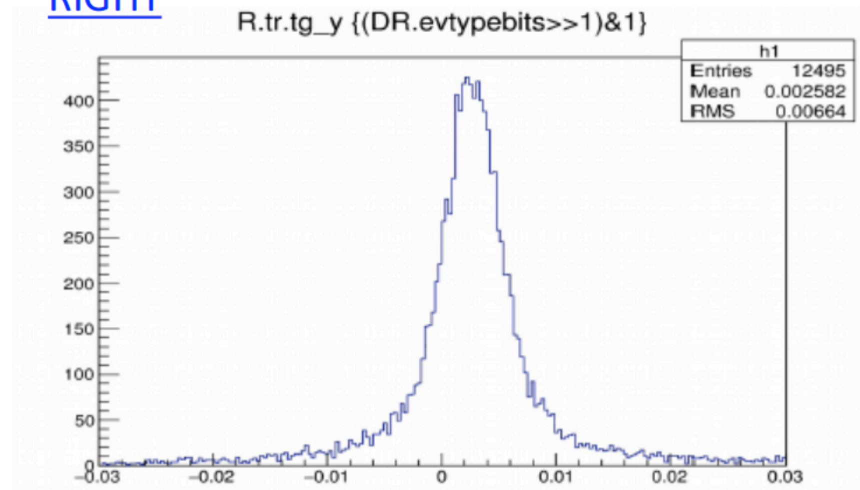
Single foil: run_373: E0 =2.222, P0_L = 1.777, Theta_L = 21, P0_R = 0.915, Theta_R = -50
Dummy: Run_597: E0 = 2.222, P0_L = 1.799, Theta_L=15.53, P0_R=0.915, Theta_R=-44.5

LEFT



Target Reconstructed position (m)

RIGHT



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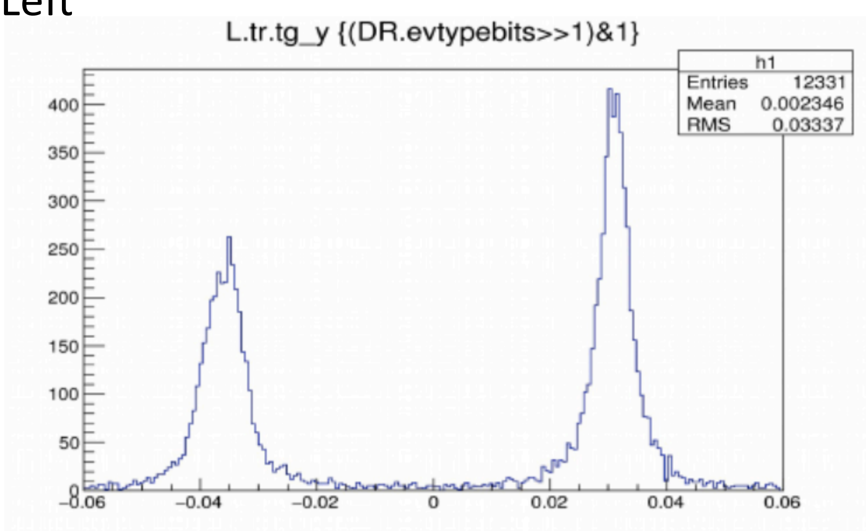
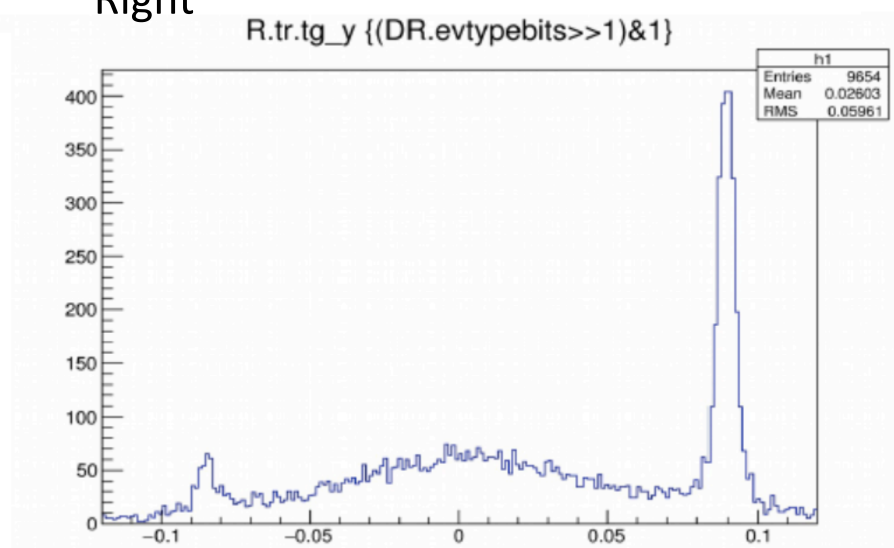


Target Reconstructed position (m)

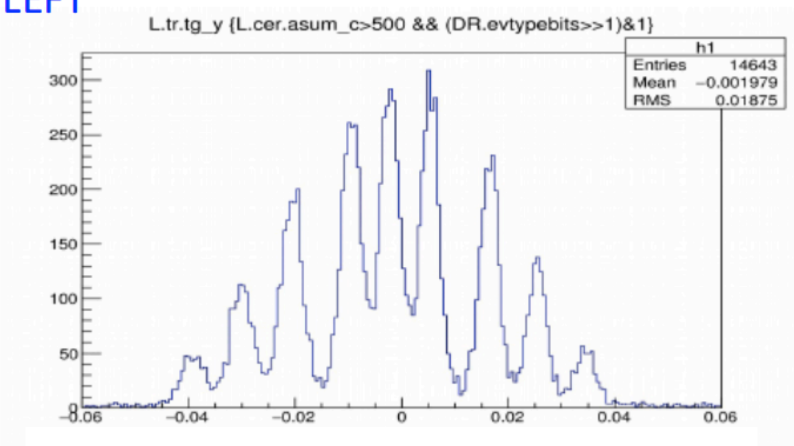
Right



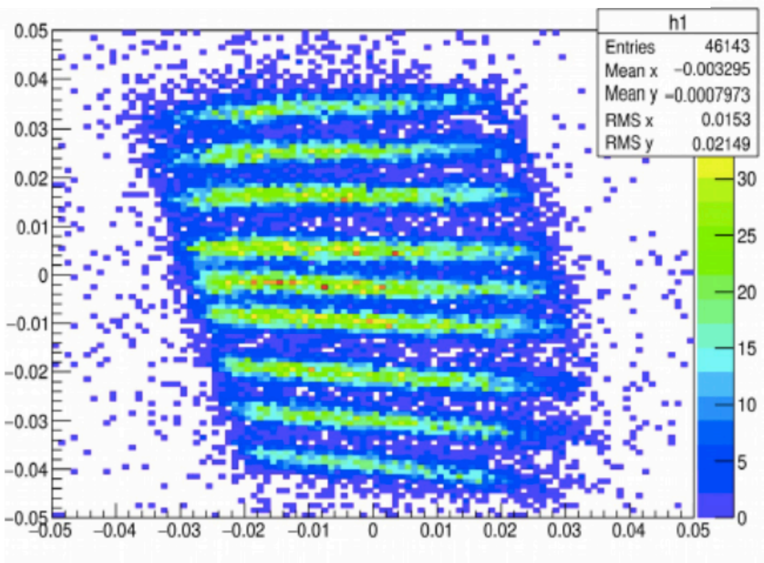
Target Reconstructed position (m)

Multiple foil: run_375: E0 =2.222, P0_L = 1.777, Theta_L = 21, P0_R = 0.915, Theta_R = -50

LEFT



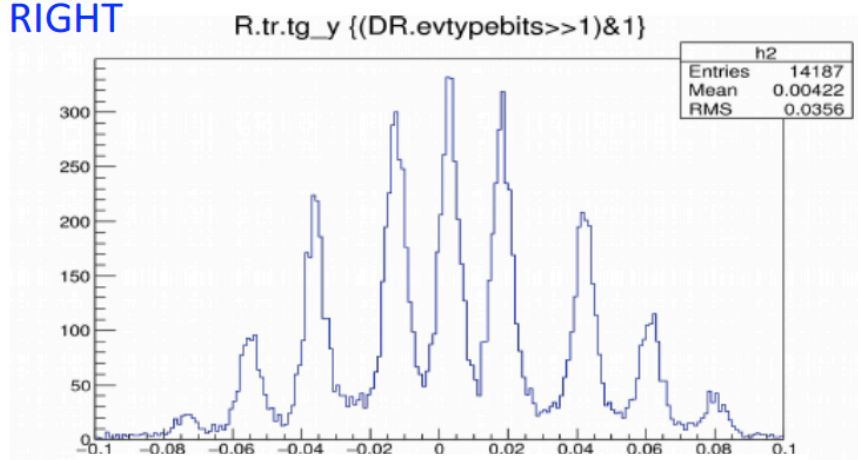
Target Reconstructed position (m)



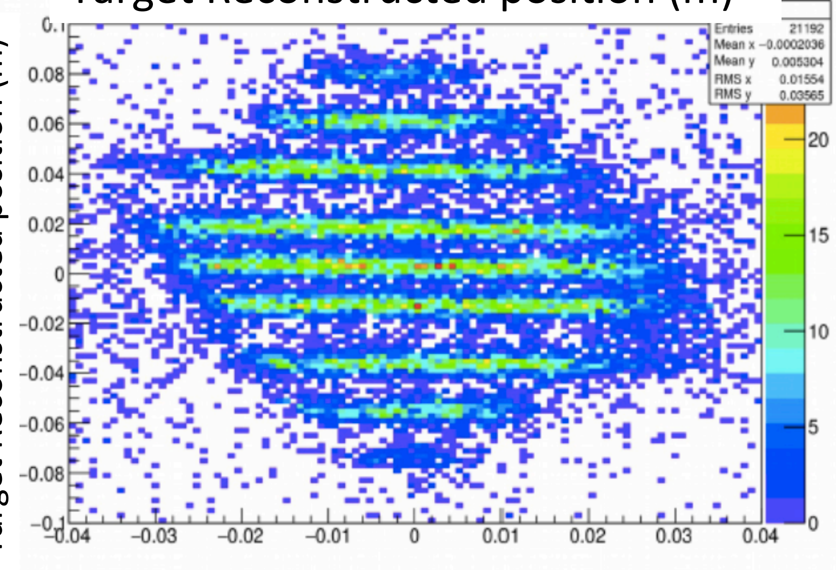
Target Reconstructed position (m)

Target angle (rad)

RIGHT



Target Reconstructed position (m)



Target Reconstructed position (m)

Target angle (rad)

Conclusions

- E12-14-012 took data successfully in 2017, just 3 years after the experiment was proposed

- Physics reach was extended:
  - include the data taking on Ti
  - inclusive scanning in momentum to measure inclusive cross sections on Ar, Ti and C (for comparison with old data)

- Experiment will produce 2-3 PhD thesis and a very good opportunity for students and PD to see an experiment on its all, from proposal, to data taking, analysis and publications

- First publication and data release expected for Fall 2017
  - inclusive cross section measurements on Ar and Ti

- Spectral Functions for Ar proton and neutron will be released in late 2018

- Special thanks to Jefferson Lab for the opportunity