Jlab E12-14-012 experiment: Update

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

Jefferson Lab

Hall A/C Collaboration Meeting
Jefferson Lab, Newport News, VA
Jan 30, 2020

VIRGINIA TECH

E12-14-012 collaboration members

Hongxia Dai

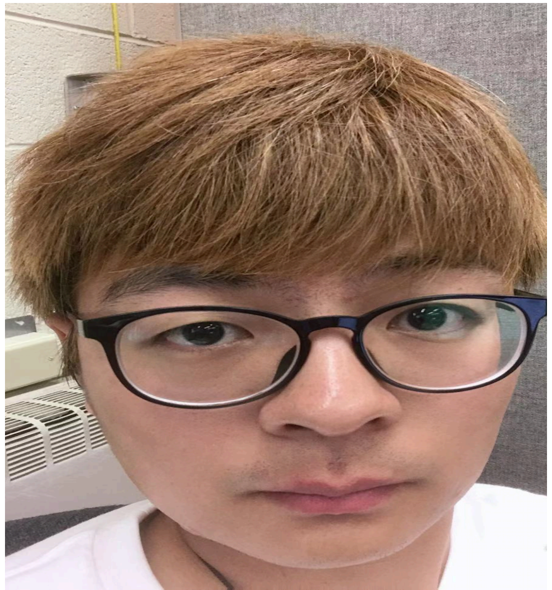
Graduate student (PhD completed in 2019)

Matthew Murphy

Graduate student

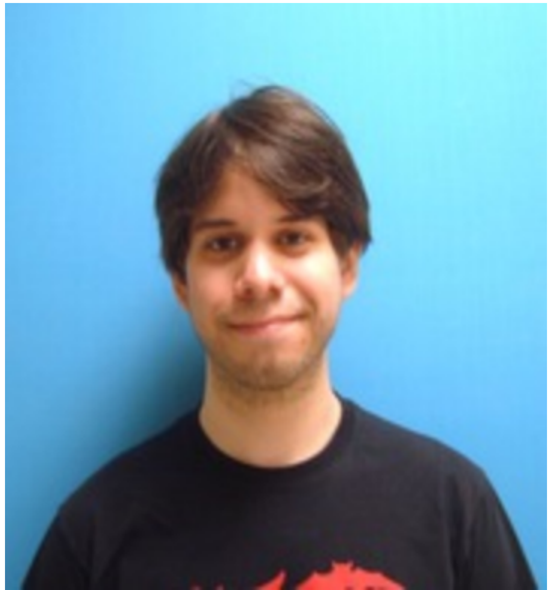
Libo Jiang

Post-doc research associate



Linjie Gu

Graduate student



Daniel Abrams

Graduate student

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 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).

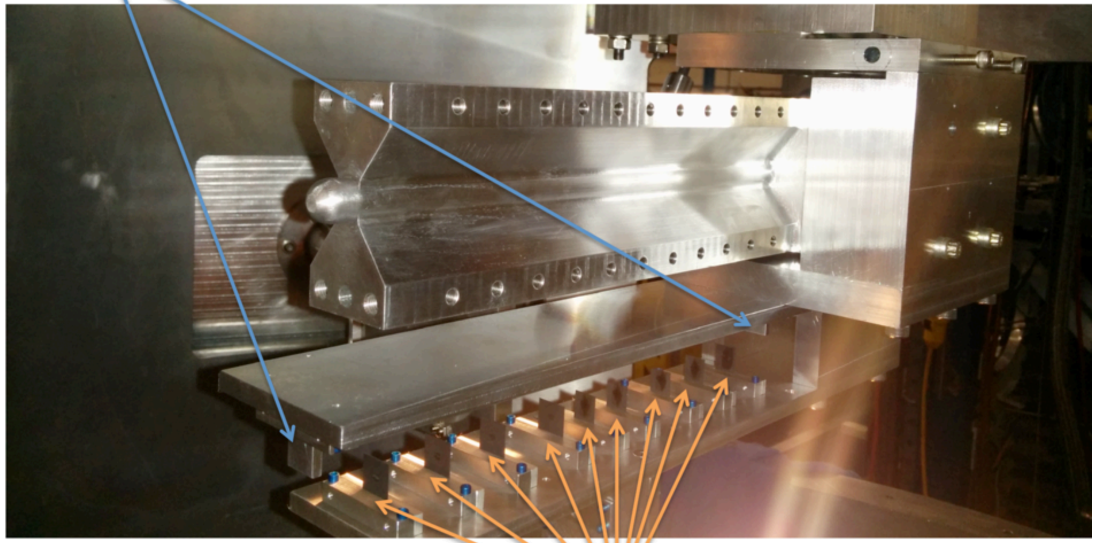
- Using measured argon spectral functions to further develop (extend) a fully consistent parameter-free theoretical (neutrino-nucleus) model that can be used in (every step of) the analysis of long baseline neutrino experiments.

Outline

- Experimental setup
    - target
    - kinematic configurations
- Inclusive analysis - summary
- Exclusive analysis
    - Analysis strategy
    - Cuts
    - Kinematic 1 Argon result
    - Background study in kinematic 1 Argon
        - Background from dummy
        - Background from accidental
    - Kinematic 1 Titanium result
- Summary

Target Setup

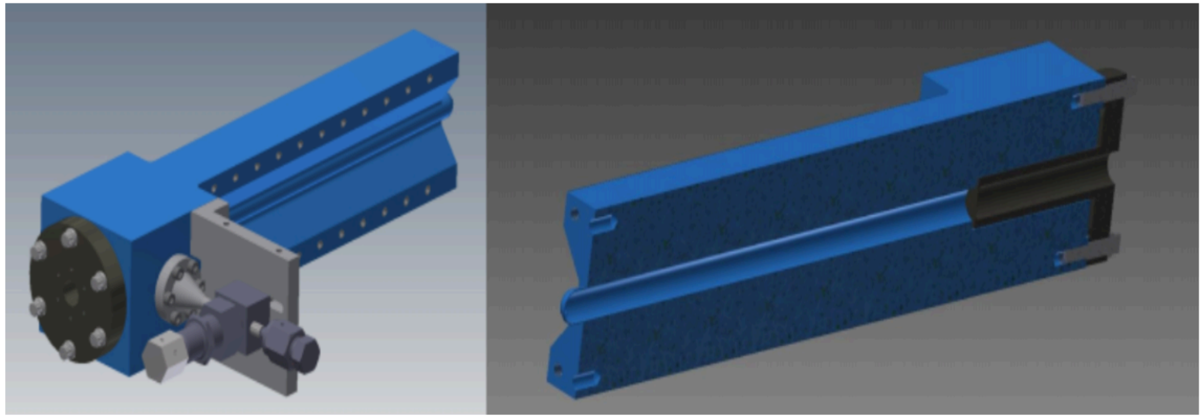
Dummy target: same as the entry and exit window as the gas target



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

Ar Target

- Closed 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}.

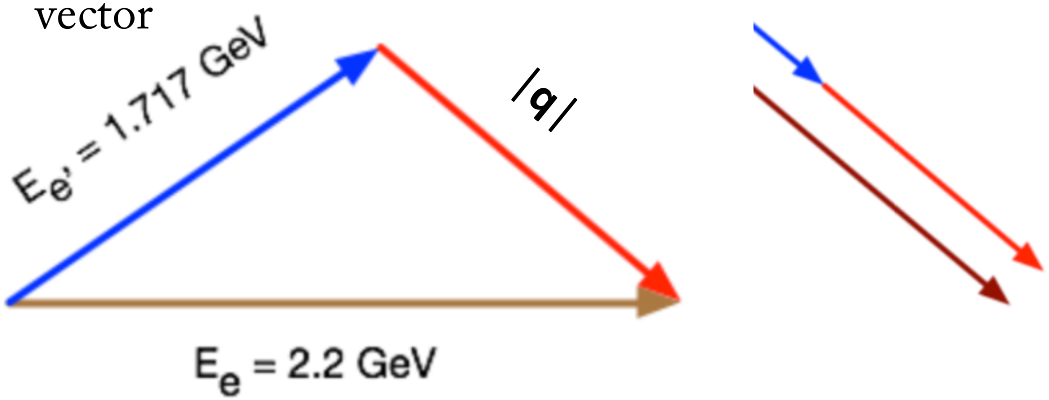


Kinematic Setup

	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

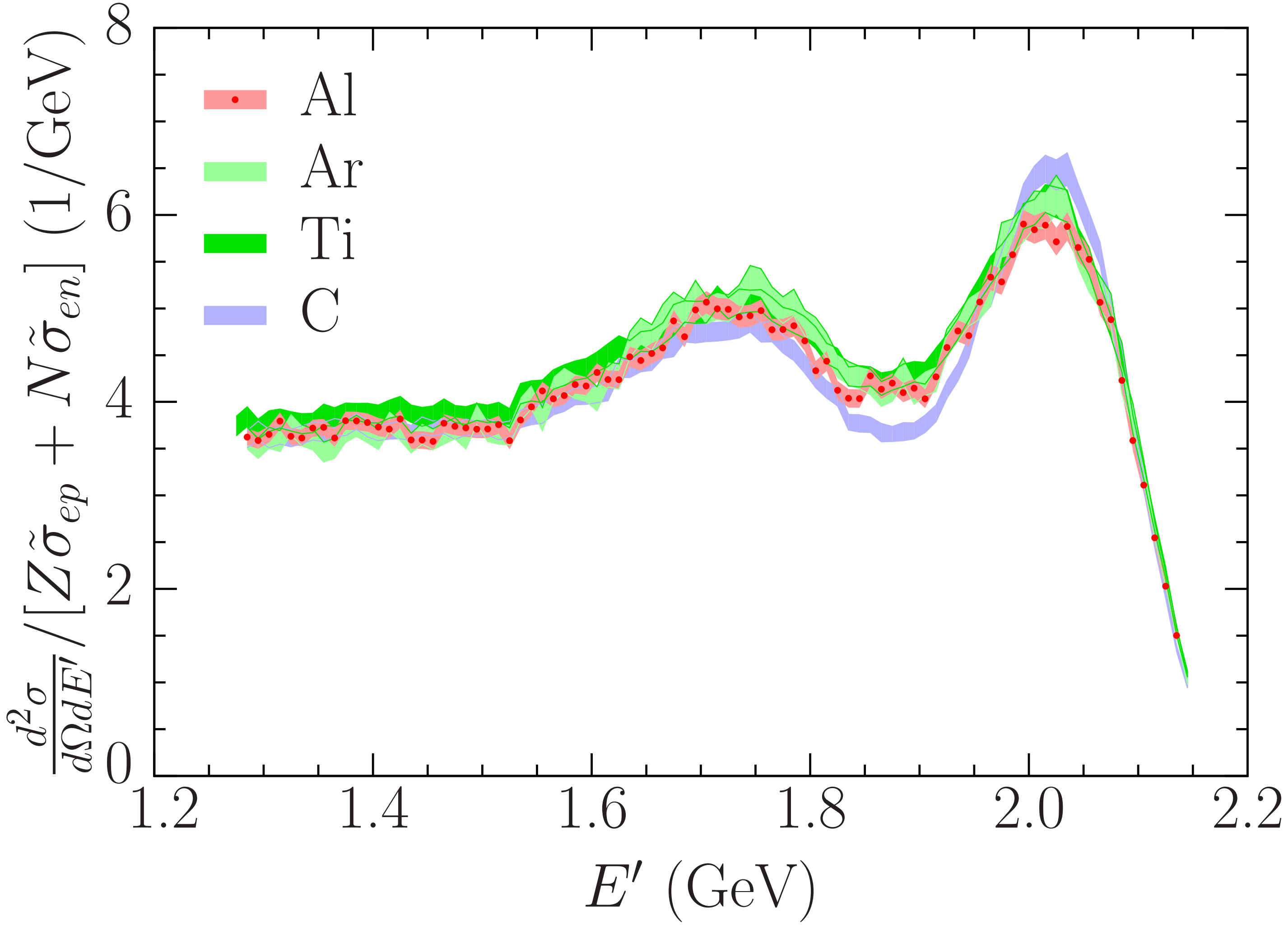
kin5

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

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%

Inclusive analysis – publications

- Ti(e,e') and C(e,e') inclusive cross sections at beam energy E = 2.222 GeV and scattering angle θ = 15.54 deg with uncertainties < 2.75%, have been reported and published in Phys. Rev. C 98, 014617 (2018)

- Ar(e,e') inclusive cross section at beam energy E = 2.222GeV and scattering angle θ = 15.54 deg with uncertainties < 4%, has been reported and published in Phys. Rev. C 99, 054608 (2019)

- Al(e,e') inclusive cross section analysis at E = 2.222 GeV and scattering angle θ = 15.54 deg with uncertainties < 3% has been reported and published in Phys. Rev. C 100, 054606 (2019).

Exclusive analysis

	Ar	Ti
Kin 1	0.5%	0.3%
Kin 2	To be determined	To be determined
Kin 3	13%	To be determined
Kin 4	20%	20%
Kin 5	70%	To be determined

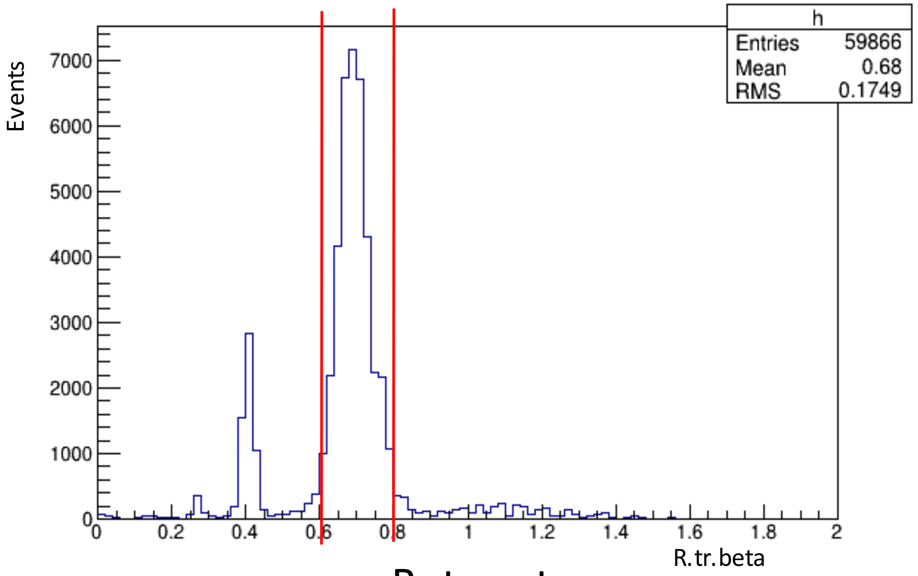
Background/Signal value in different kinematics and targets

- 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 bin by bin
  - Compute cross section as a function of missing momentum using MC ratio method
  - Compute missing momentum with different missing energy range (shell analysis)

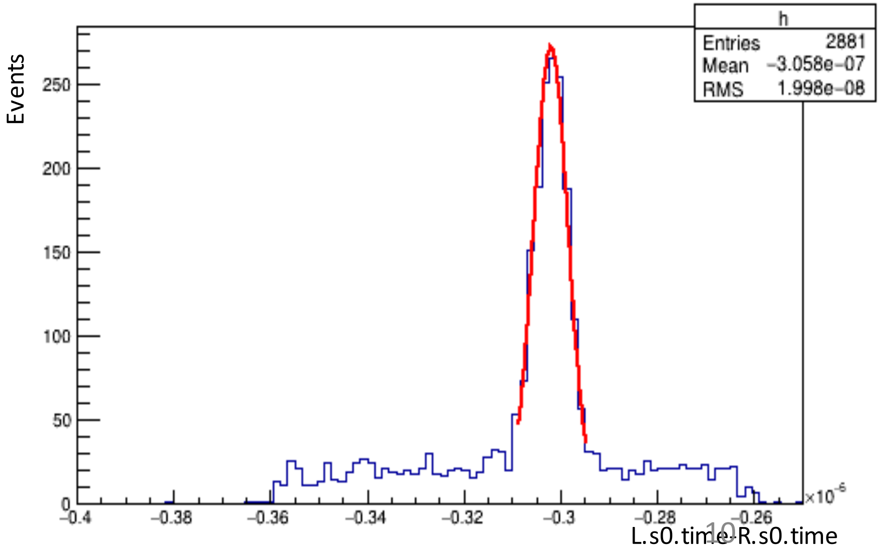
- No FSI effect considered yet in MC. (Check Libo's talk about FSI update)

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



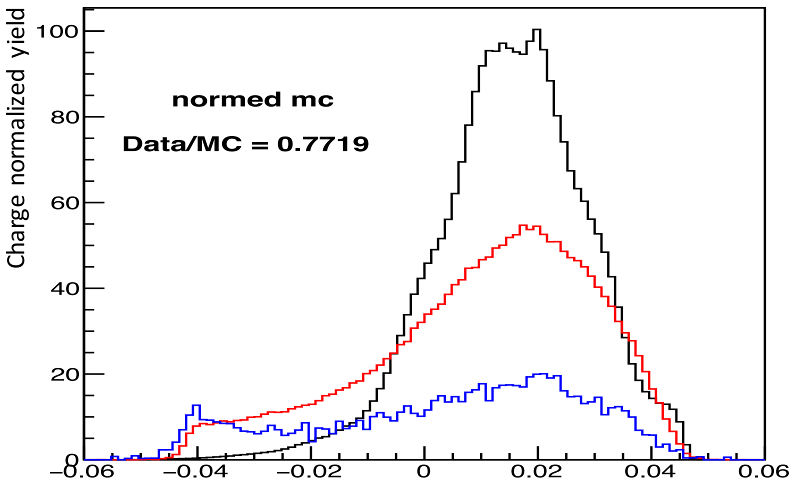
Beta cut



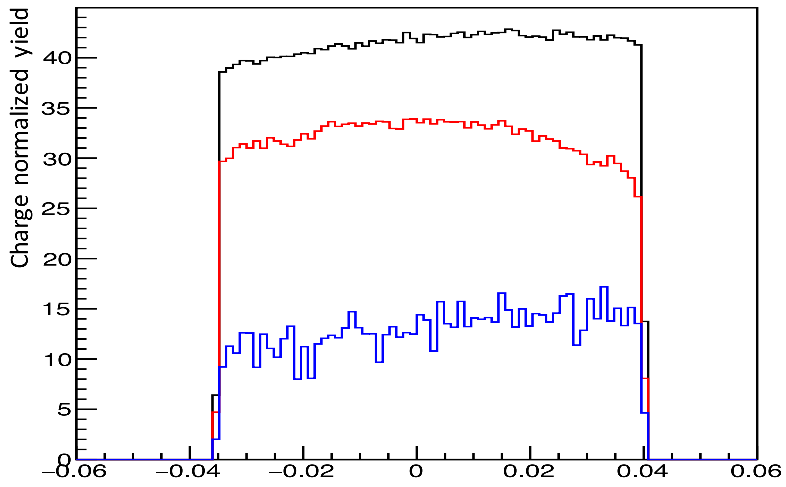
Coincidence time cut

Exclusive analysis - kin1 Ar - Data/MC comparison

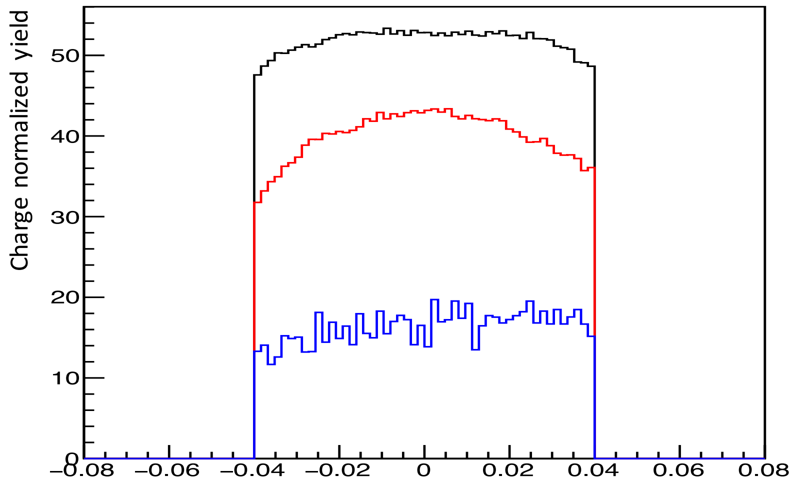
Background ~ 0.5%, is scaled by 100 times



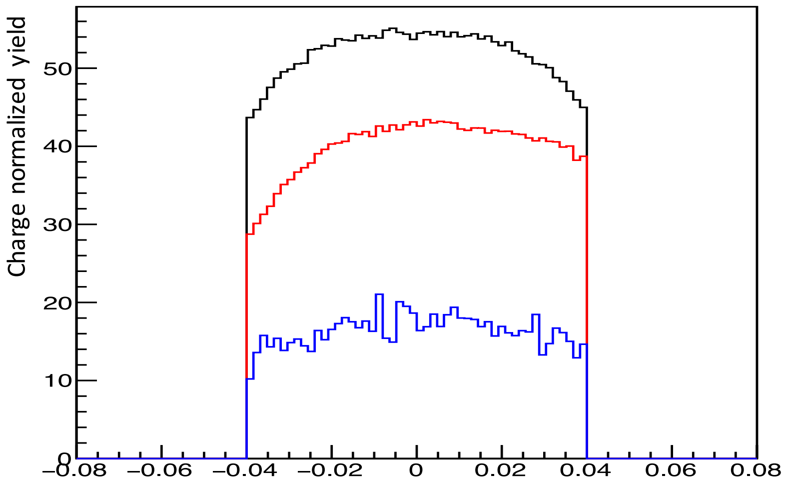
Left arm electron dp/p distribution



Right arm proton dp/p distribution



Left arm electron theta distribution (rad)



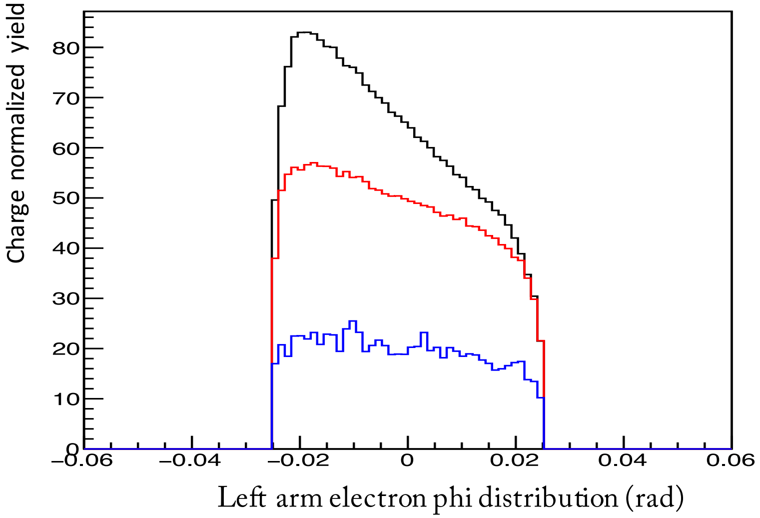
Right arm proton theta distribution (rad)

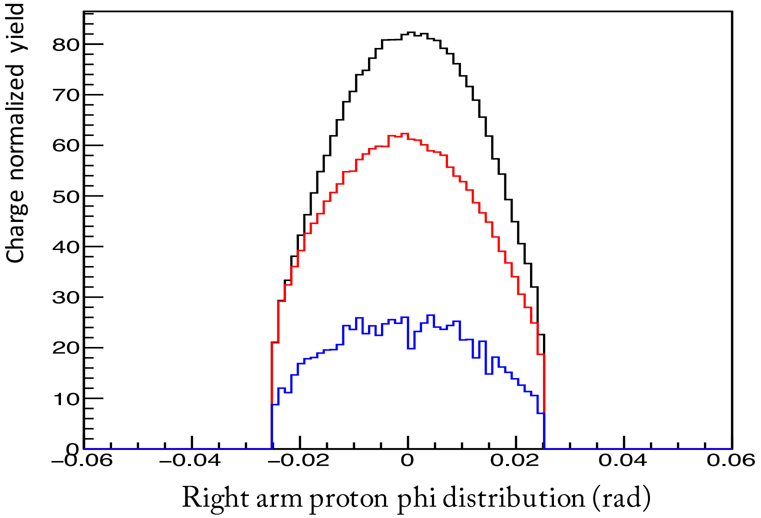
Red: data
Black: SIMC
Blue: background

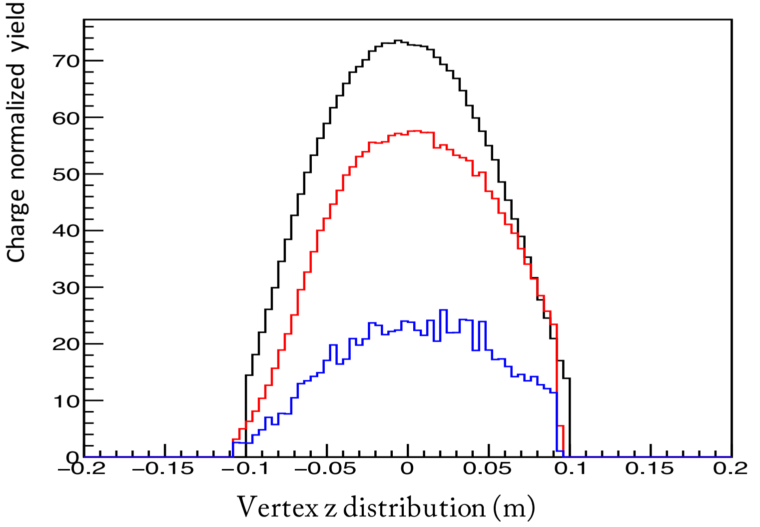
Data/mc ratio = 0.77

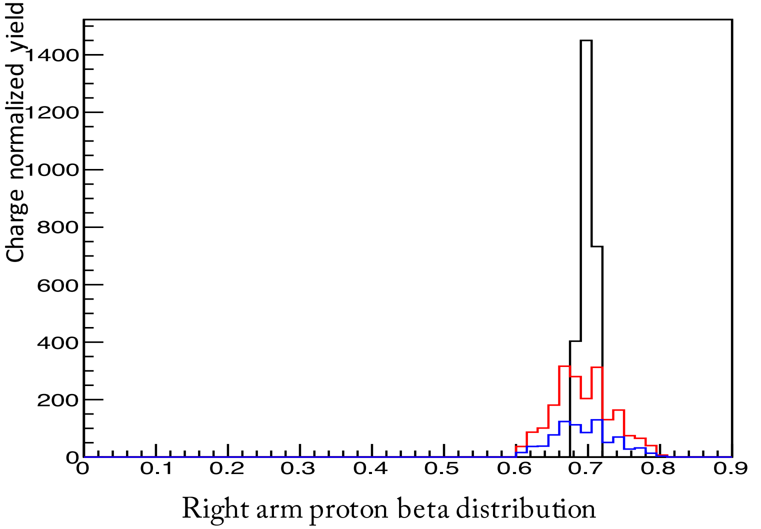
- Corrections of efficiencies, livetime and boiling effect have been applied in the plots
- The events are normalized by the total charge
- FSI is not included yet in the MC

Exclusive analysis - kin1 Ar - Data/MC comparison

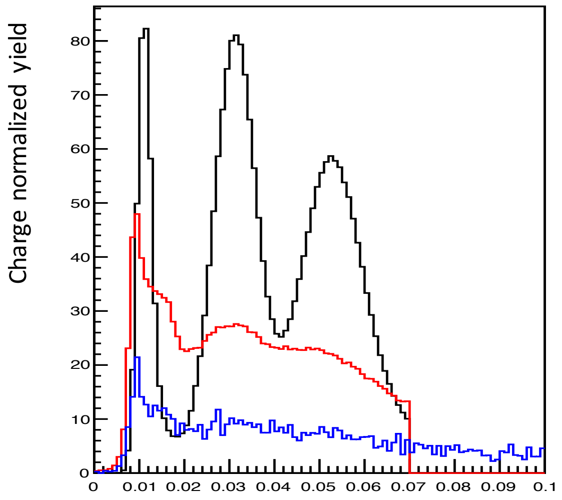




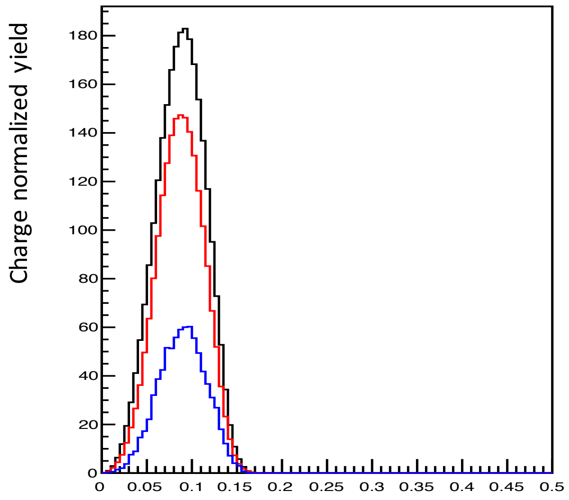




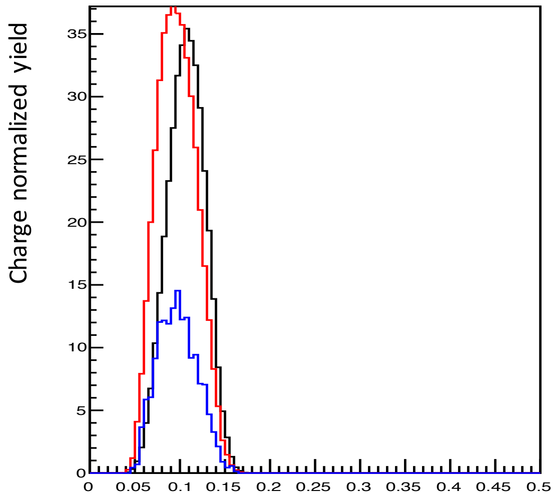
Exclusive analysis - kin1 Ar - Data/MC comparison



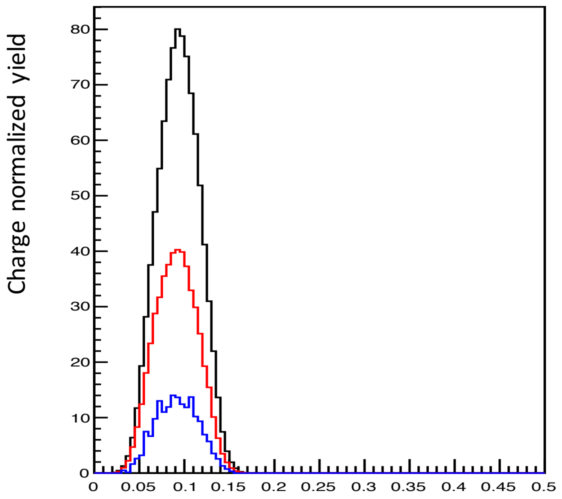
Missing energy distribution (GeV)



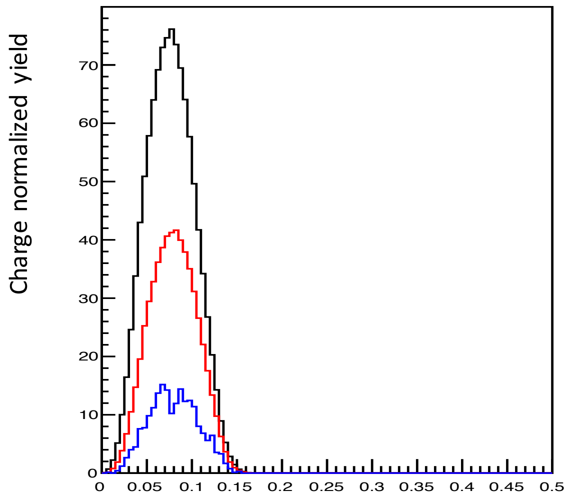
Missing momentum distribution (GeV/c)



Pm1 distribution (GeV/c)



Pm2 distribution (GeV/c)



Pm3 distribution (GeV/c)

Pm1: $0.005 < Em < 0.02$
Pm2: $0.02 < Em < 0.04$
Pm3: $0.04 < Em < 0.07$

Effect of FSI

- Energy spectrum will shift towards smaller momentum
- A reduction of the cross section which is more or less constant in the momentum range considered
- Broaden the extracted energy distribution

List of systematic uncertainties – kin1 Ar

- 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 ?

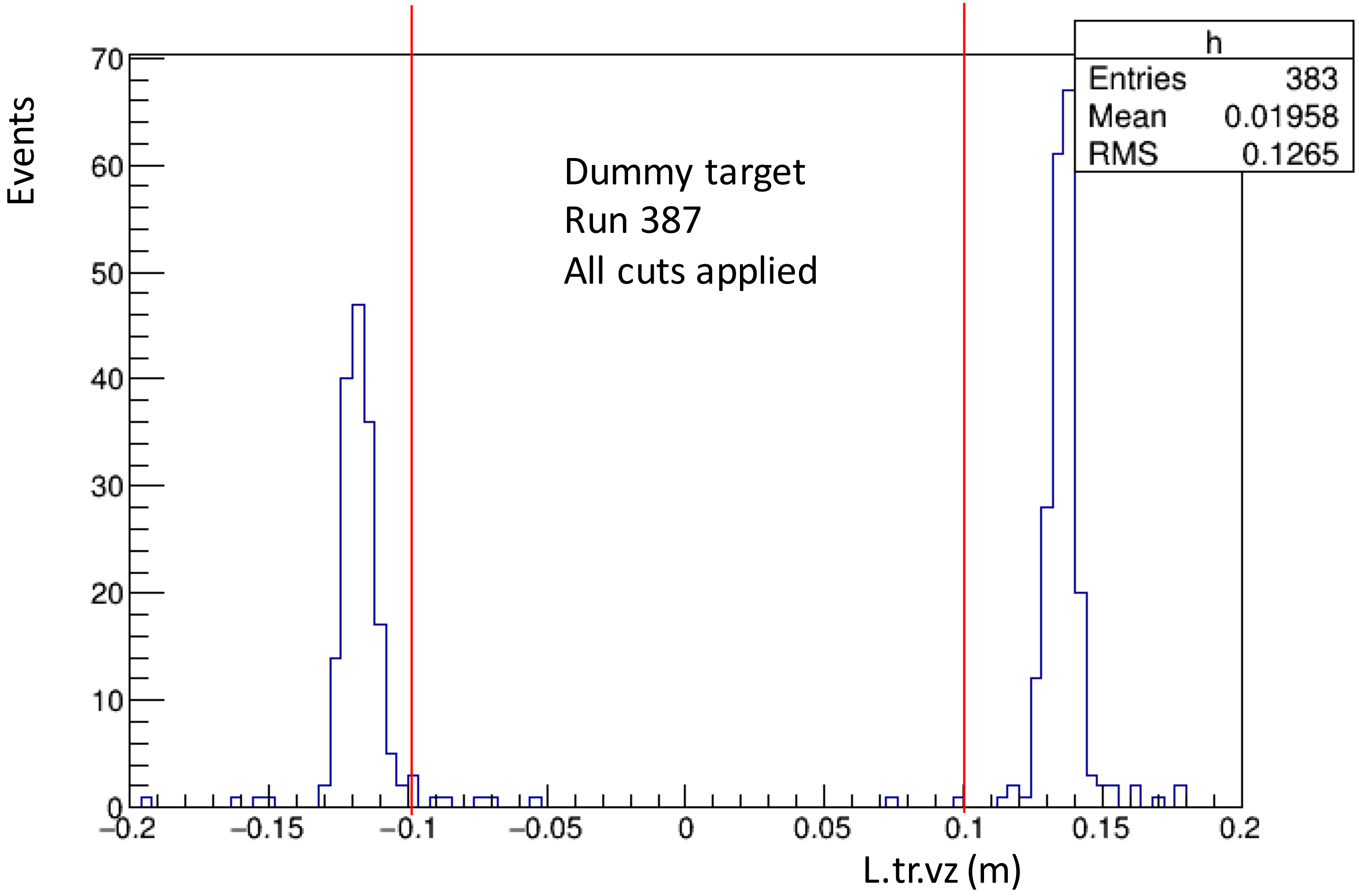
- COSY:

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:

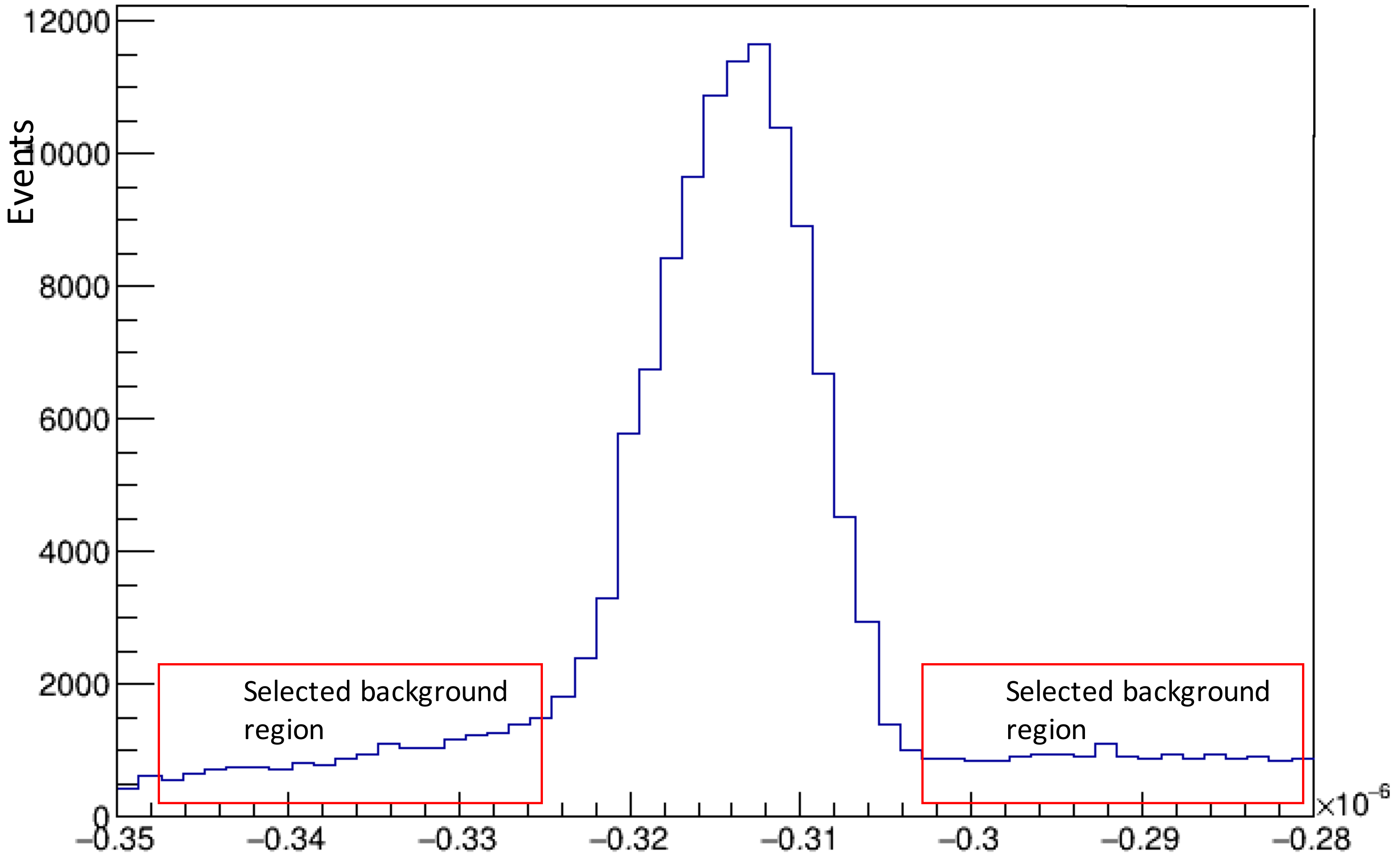
We scale the cross section model by $\sqrt{Q^2}/2$, and recalculate the radiative correction factor.

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

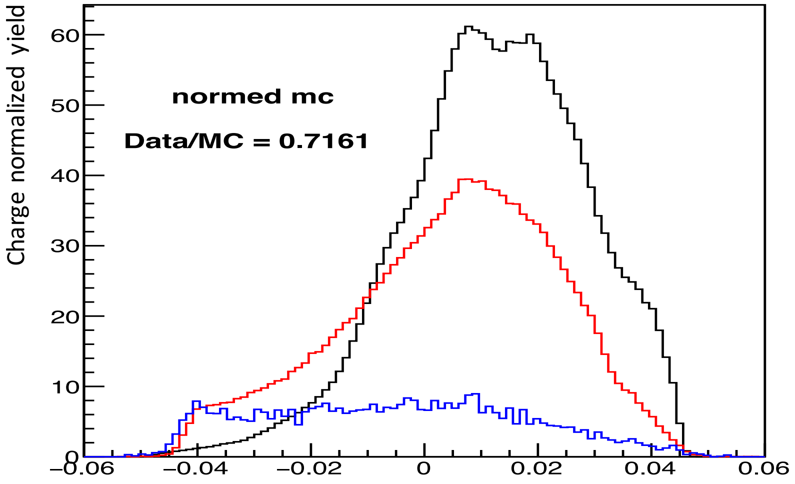
Steps for calculating the background from accidental:

- 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

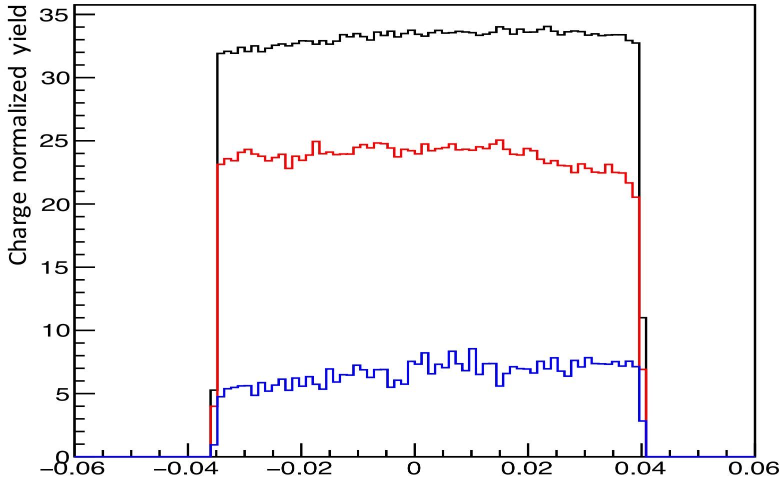
Exclusive analysis - kin1 Ti - Data/MC comparison

Background ~ 0.3%, is scaled by 100 times

Red: data
Black: SIMC
Blue: background

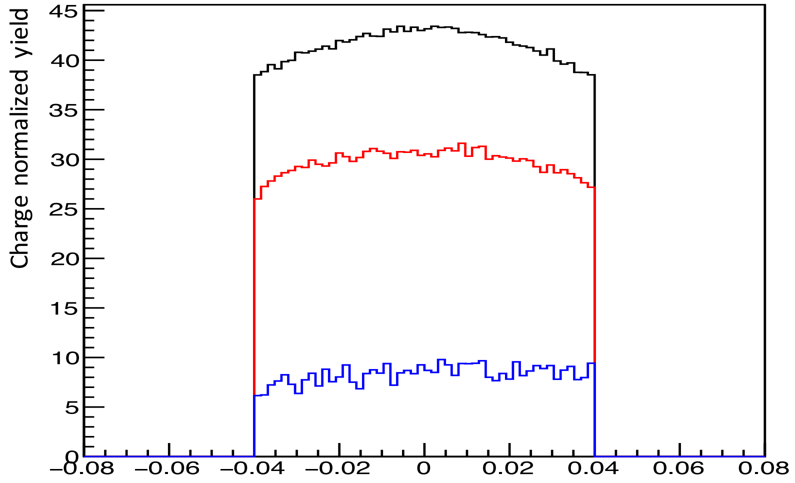


Left arm electron dp/p distribution

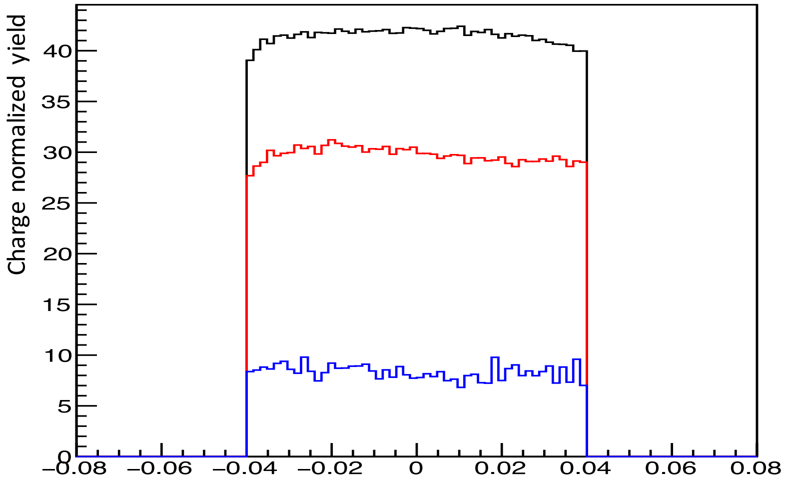


Right arm proton dp/p distribution

Data/mc ratio = 0.72



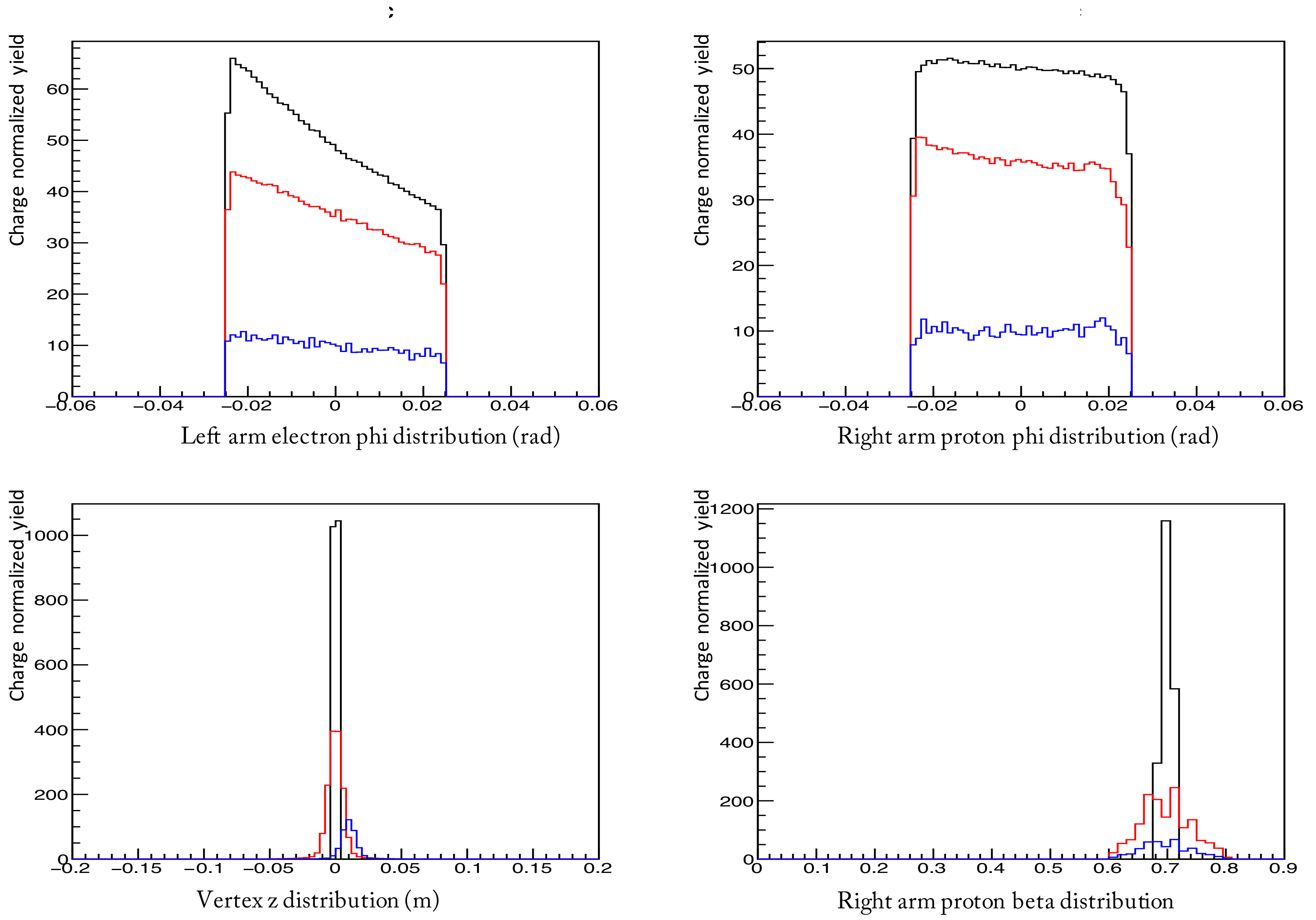
Left arm electron theta distribution (rad)



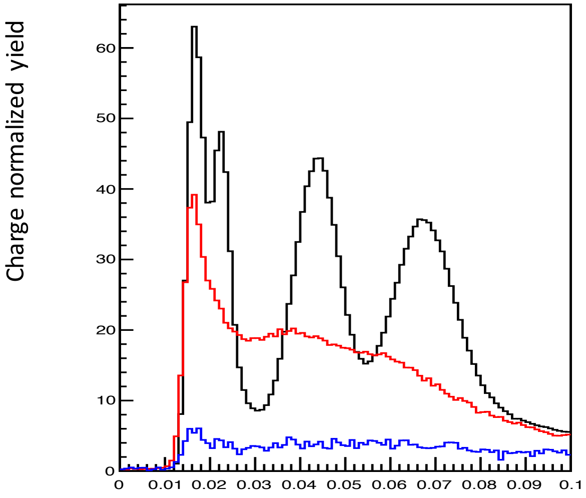
Right arm proton theta distribution (rad)

- Corrections of efficiencies and livetime have been applied in the plots
- The events are normalized by the total charge
- FSI is not included yet in the MC

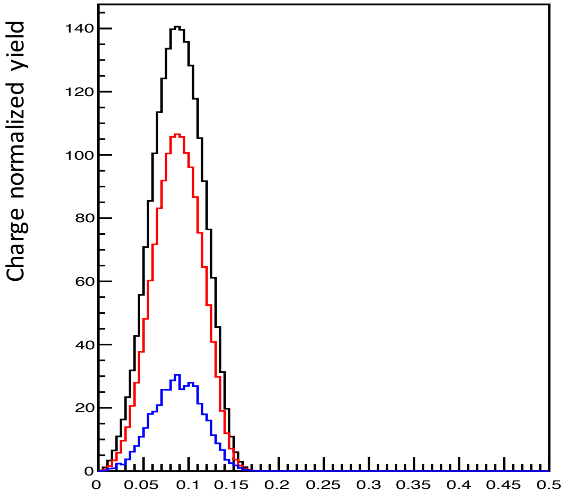
Exclusive analysis - kin1 Ti - Data/MC comparison



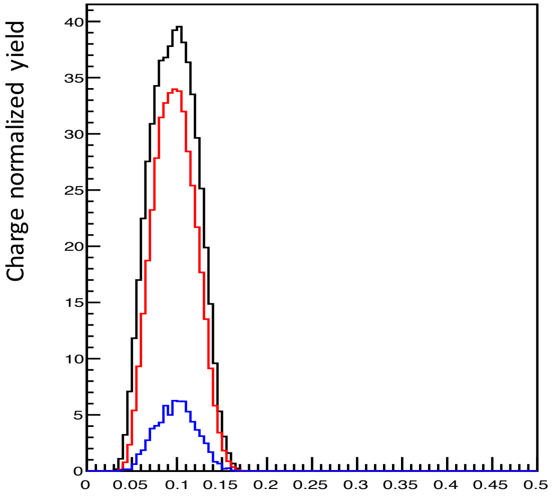
Exclusive analysis - kin1 Ti - Data/MC comparison



Missing energy distribution (GeV)

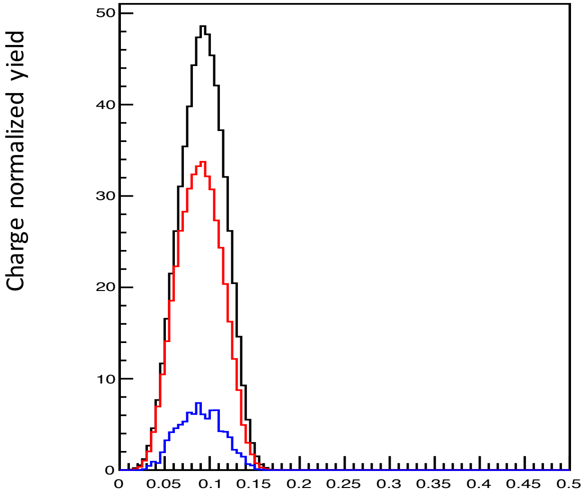


Missing momentum distribution (GeV/c)

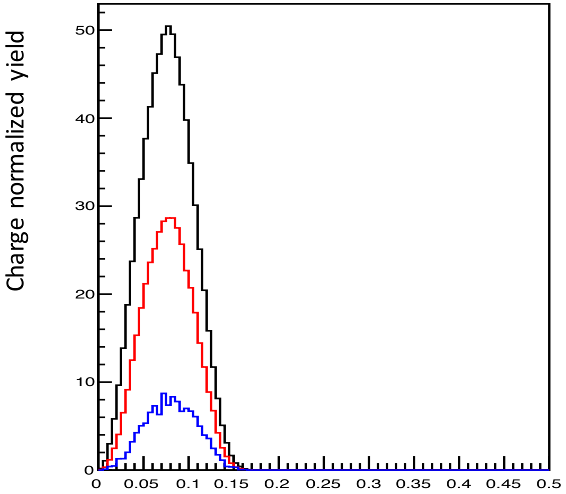


Pm1 distribution (GeV/c)

Pm1: 0.005<Em<0.03
Pm2: 0.03<Em<0.054
Pm3: 0.054<Em<0.09



Pm2 distribution (GeV/c)



Pm3 distribution (GeV/c)

List of systematic uncertainties – kin1 Ti

- 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 ?

- 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.

Summary

- We've finished (e,e'p) analysis of Kinematic 1 Argon and Titanium.
- FSI studies ongoing should be completed in the next month or so
- First paper for the exclusive analysis is expected to be circulated by end of May.
- Currently working on Kinematic 2 and 3.
- More results soon.

Back up

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

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)

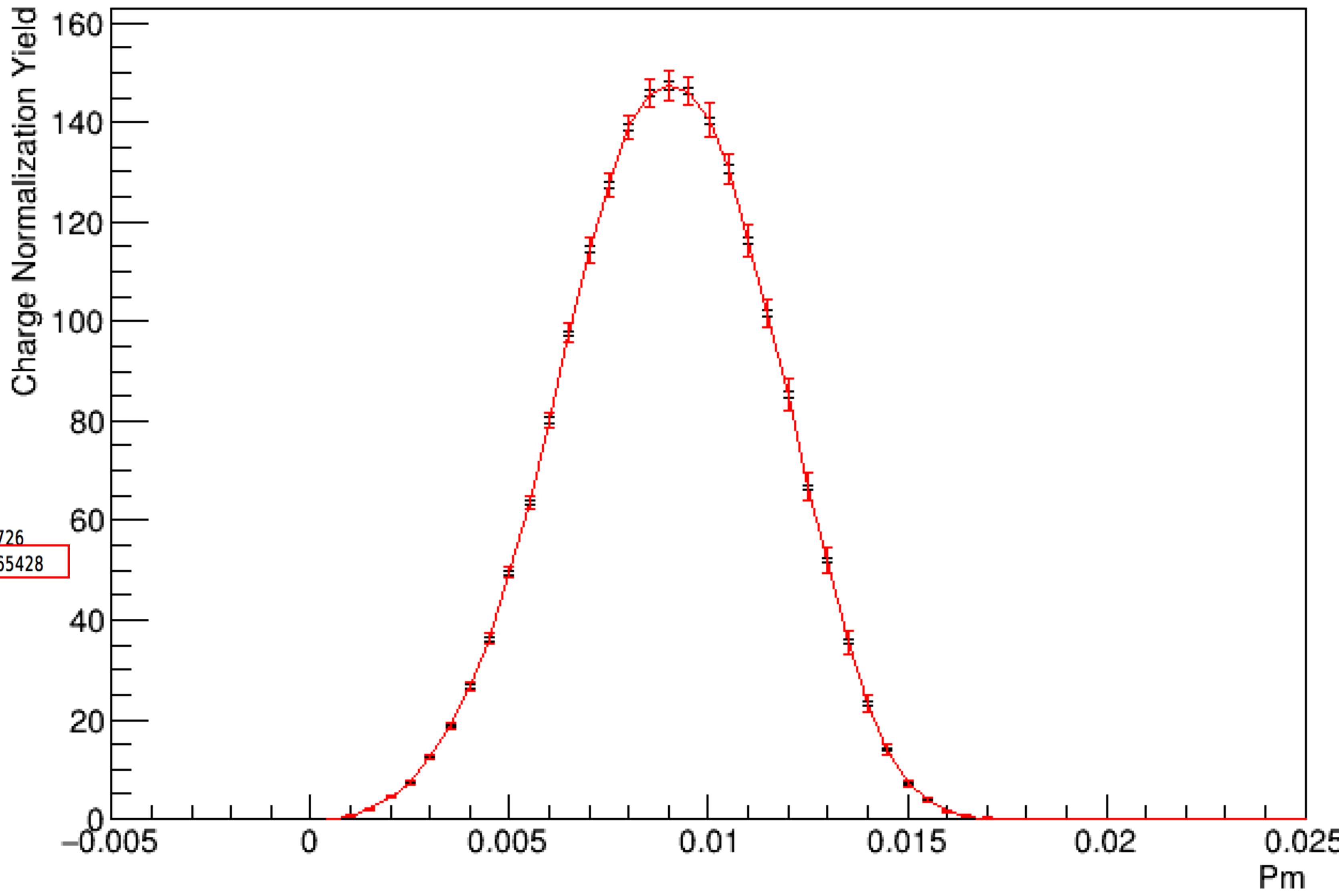
- Beta cut: [0.6,0.8]
- Beta cut efficiency is recalculated each time after each variation of the beta cut

Statistical uncertainty and total uncertainty in Kin1 Ar

Black err bar: statistical

Red err bar: Total uncertainty

Total uncertainty = sqrt(statistical**2 + systematic**2)




```
20.4124   7.39221   4.14513   2.86652   2.20809   1.71398   1.39509   1.1721
1.00357   0.857903  0.757402  0.67509   0.611784  0.56536   0.535157  0.512726
0.500526  0.497981  0.499563  0.510197  0.528901  0.560658  0.599017  0.65428
0.738435  0.837179  1.01015   1.2498    1.61754   2.22994   3.09641   4.61757
7.33236   13.7361   31.6228   100   0   0   0   0
0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0
```

Statistical uncertainty around the Pm peak (in percentage)

Statistical uncertainty and total uncertainty in Kin1 Ti

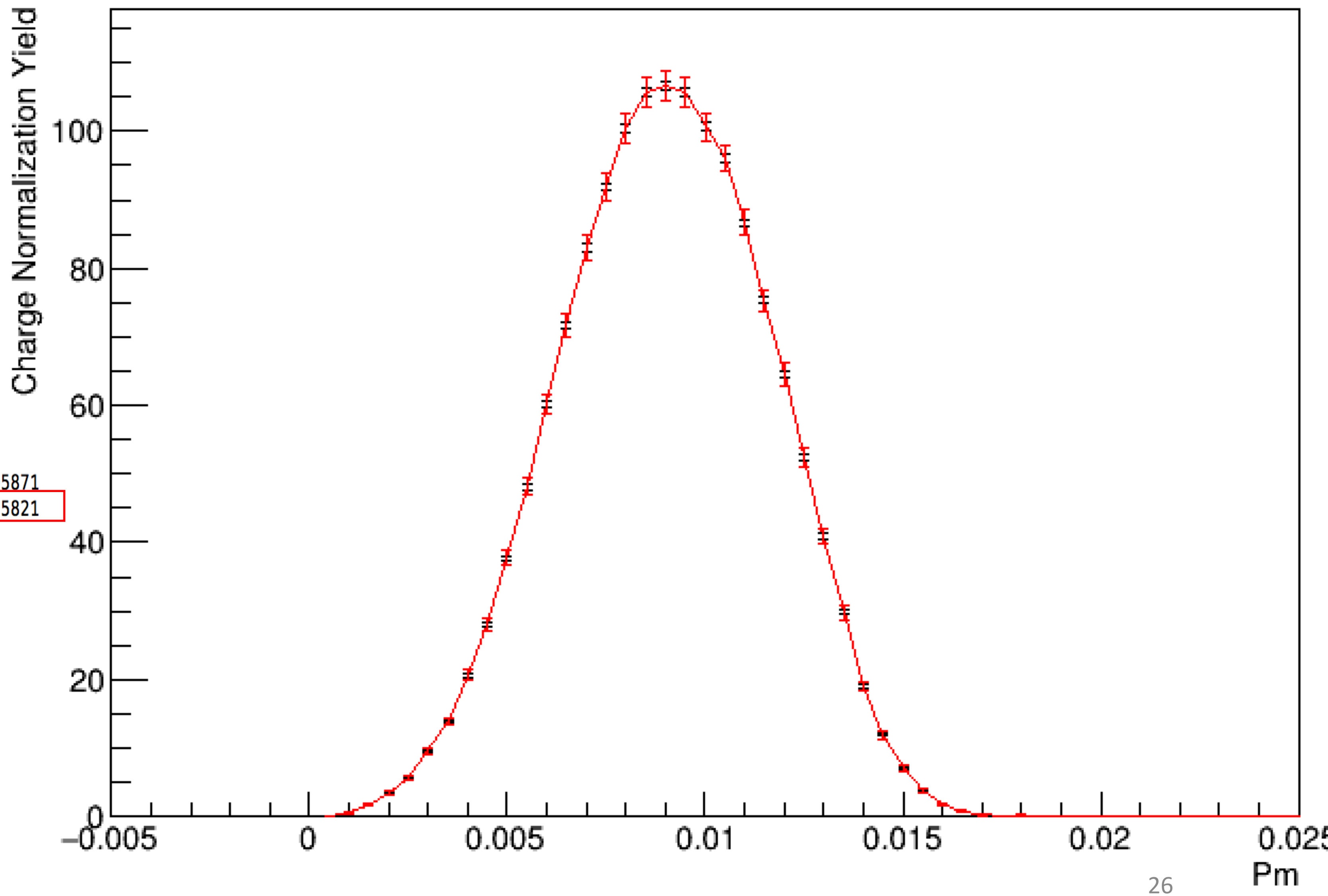
Black err bar: statistical

Red err bar: Total uncertainty

Total uncertainty = sqrt(statistical**2 + systematic**2)

22.3607	8.33333	4.79463	3.2987	2.52217	1.95928	1.62844	1.33571
1.14776	0.988212	0.874305	0.781799	0.716814	0.665927	0.633368	0.605871
0.590621	0.588419	0.59091	0.605605	0.619757	0.652564	0.699574	0.755821
0.839122	0.950014	1.11331	1.39333	1.75736	2.28814	3.19928	4.64739
7.08881	11.7041	17.1499	26.7261	70.7107	100	57.735	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Statistical uncertainty around the Pm peak (in percentage)



Boiling Study-----Nathaly Santiesteban

- 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