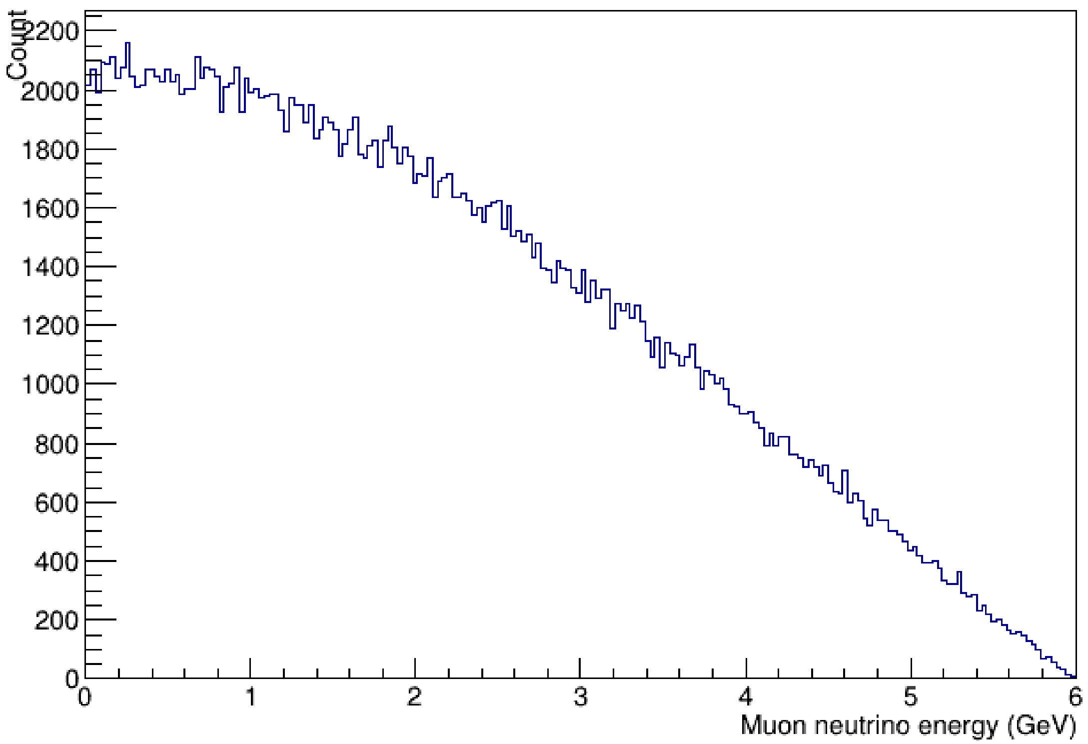
ν_μ interactions

- What might a detector be required to reconstruct?
    - Primary Lepton Momentum and Angle
    - Charged Hadron Multiplicity
    - Proton Multiplicity, Momentum and Angle
    - Charged Pion Multiplicity, Momentum and Angle
    - Neutral Pion Multiplicity, Photon Energy

ν_μ Flux



- Using the highest energy muon neutrino flux
- Generated using NuSim
- Neutrinos cross a plane with a 3m x 3m cross section centered on, and 50 m downstream of, the decay straight

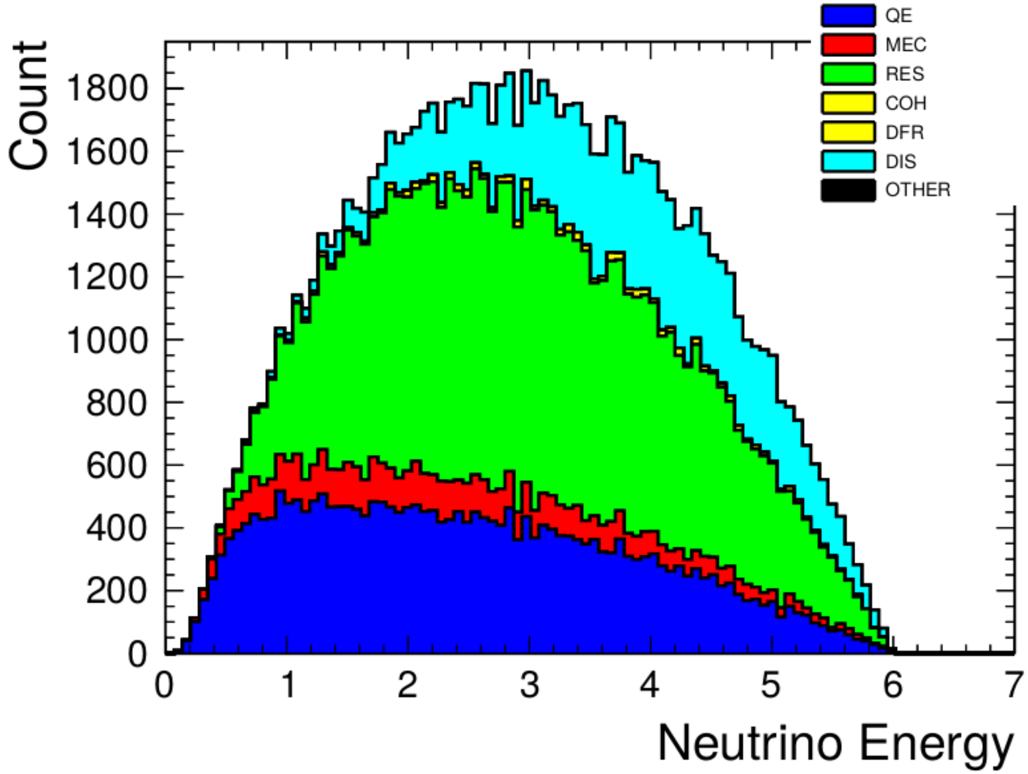
GENIE

- GENIE v3.0.6 with G18_02a_00_000 tune

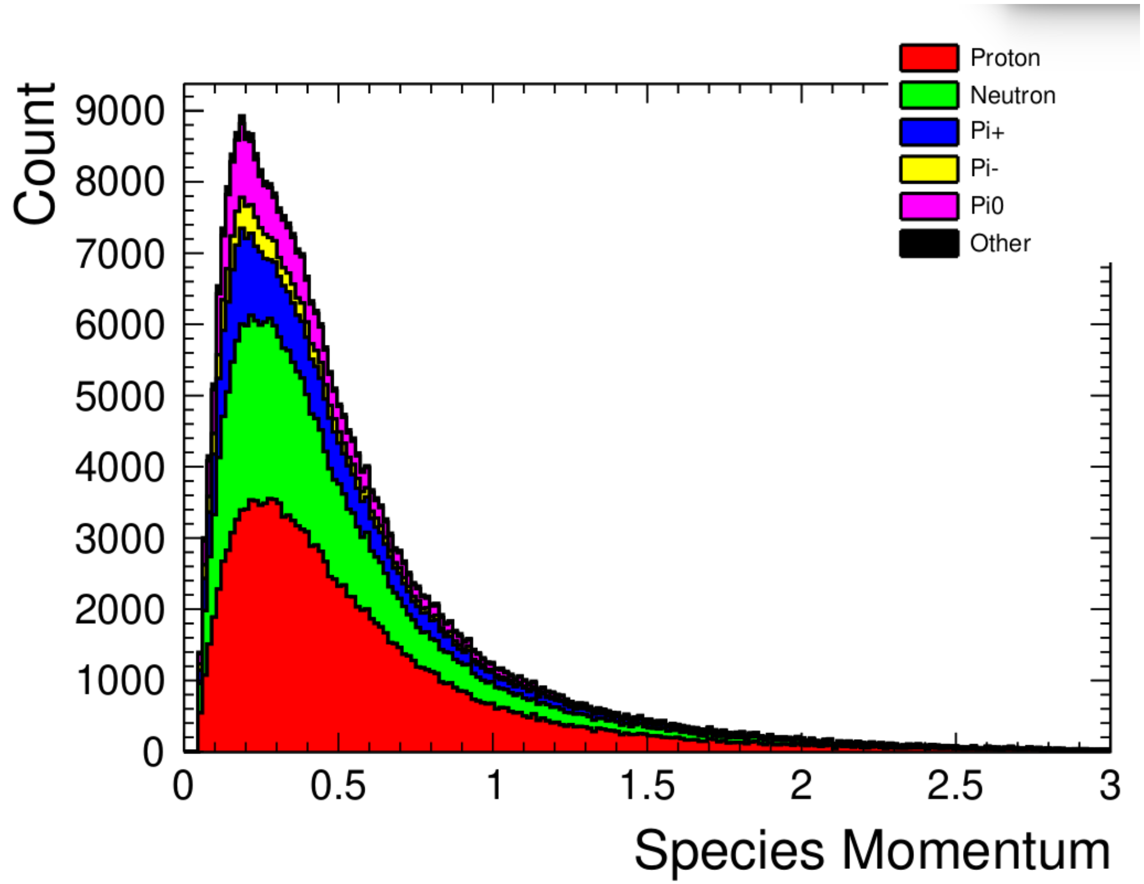
- Initial State Nuclear Model : Rel. Fermi Gas with Bodek-Ritchie tails
- Quasielastic Scattering : Llewellyn-Smith with $m_A = 0.99\ GeV/c^2$
- MEC : Empirical MEC model
- Resonance Production : Berger-Sehgal Resonance Model with miniBoone tune
- Coherent : Berger-Sehgal
- Final State Interactions : HA Intranuke 2018 – data driven using measured proton/pion interaction cross sections.

Event composition

Interaction Category	Category Tag	%
Quasi-elastic	QE	26
Meson Exchange Current (2p2h)	MEC	7
Resonance Production	RES	47
Coherent/ Diffractive	COH	1
Deep Inelastic Scattering	DIS	19



Particle Composition



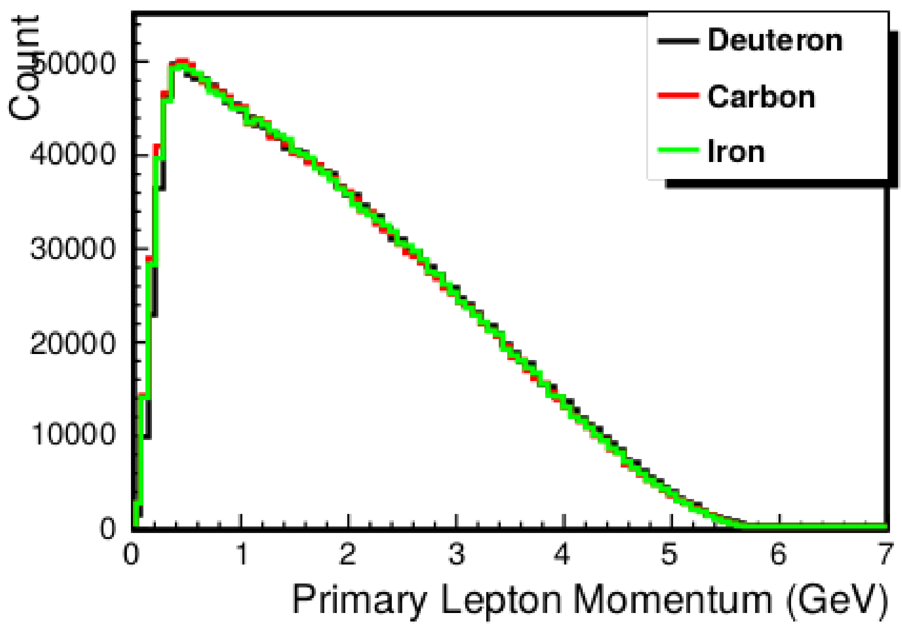
Fraction of events with at least one X in the post-FSI final state

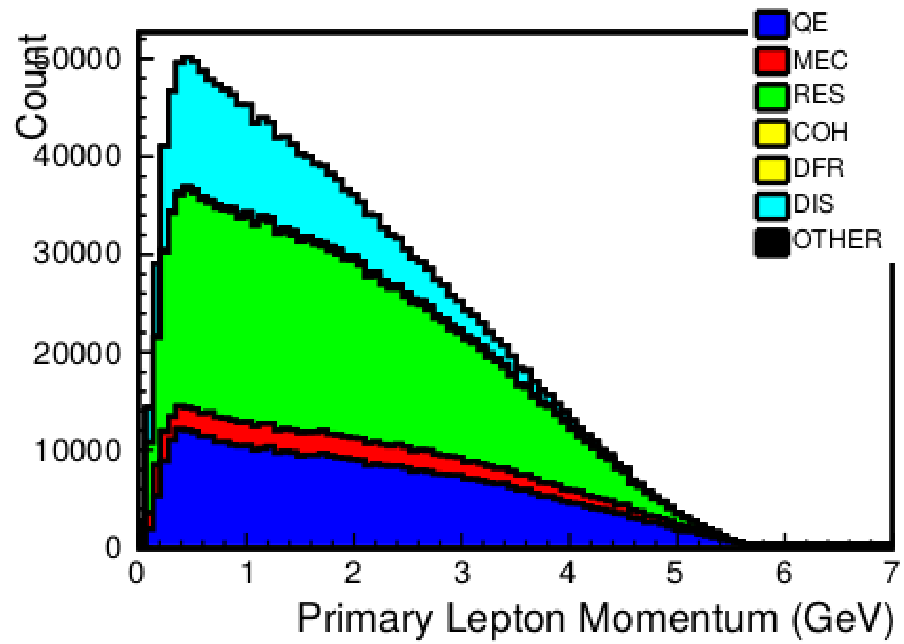
Particle	%
proton	89
neutron	49
π^+	45
π^-	9
π^0	22
$K^\pm$	0.7
K^0	0.3
Other	3.0

Plot Format

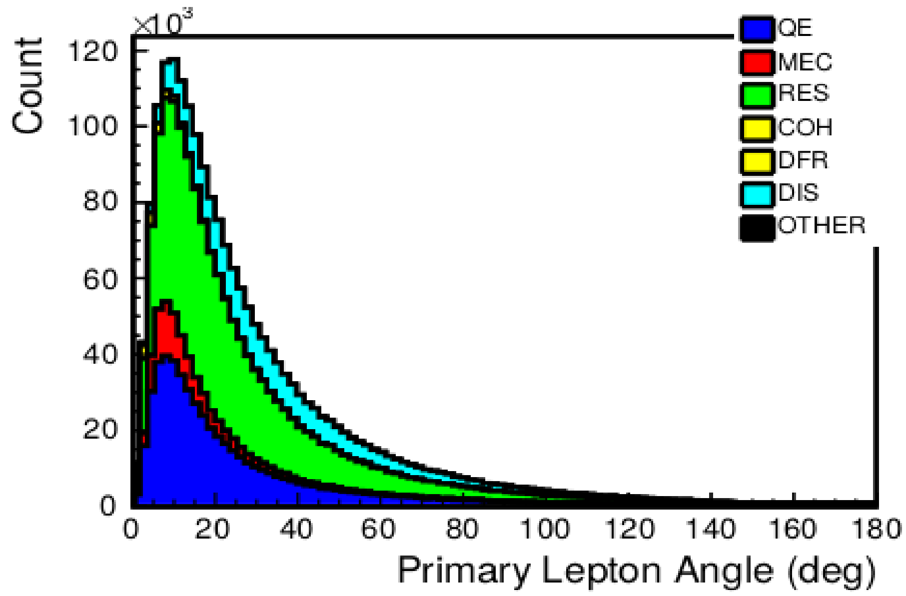
- Distributions in rest of talk are for charged current interactions.
- Distributions are shown for Deuteron, Carbon and Iron targets. These are relatively normalised.
- For **carbon** target, a stacked plot using interaction mode categories is shown
- No cuts applied to final state quantities

Primary Lepton

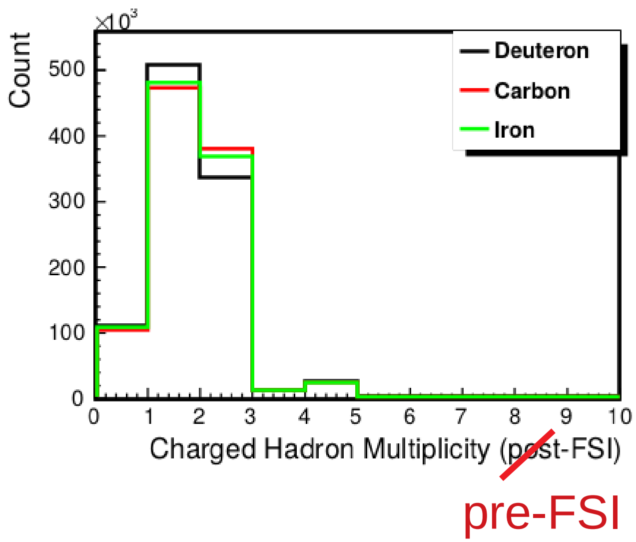


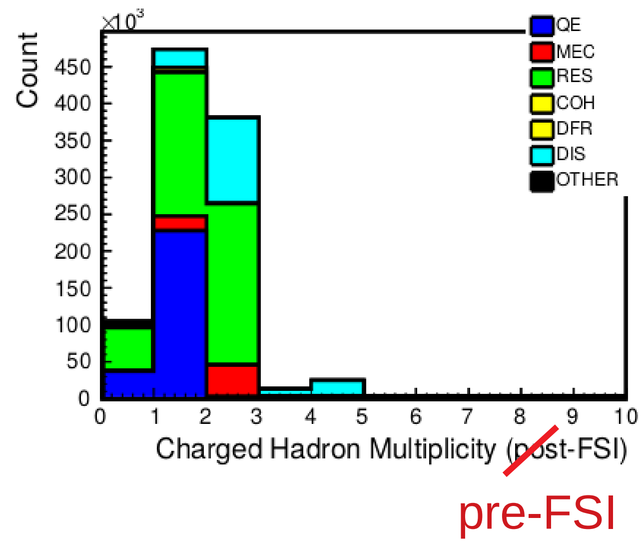


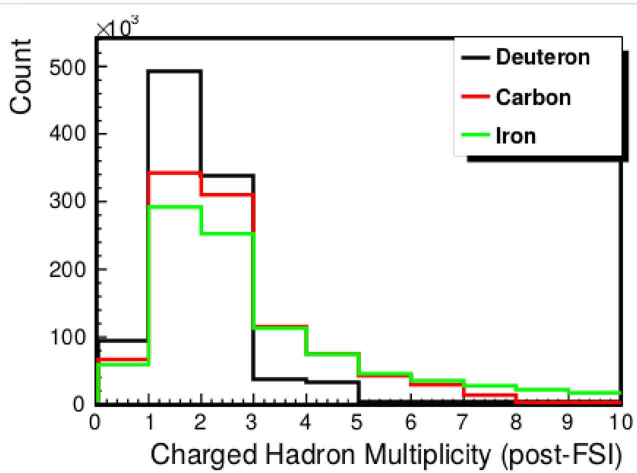
- Average Lepton Momentum ~ 2.0 GeV
- Average Lepton Angle ~ 30^o

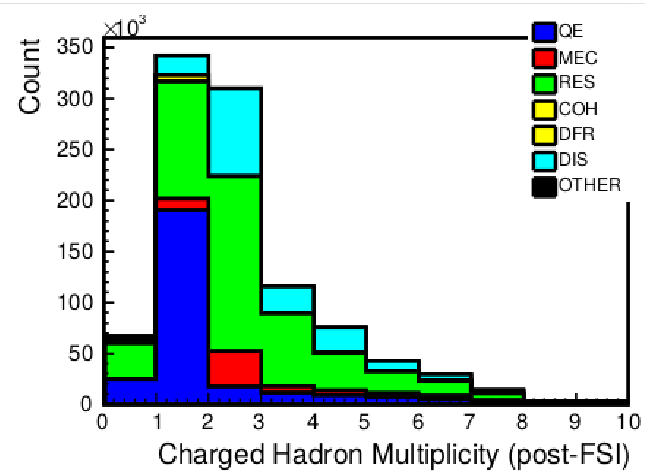


Charged hadron multiplicity



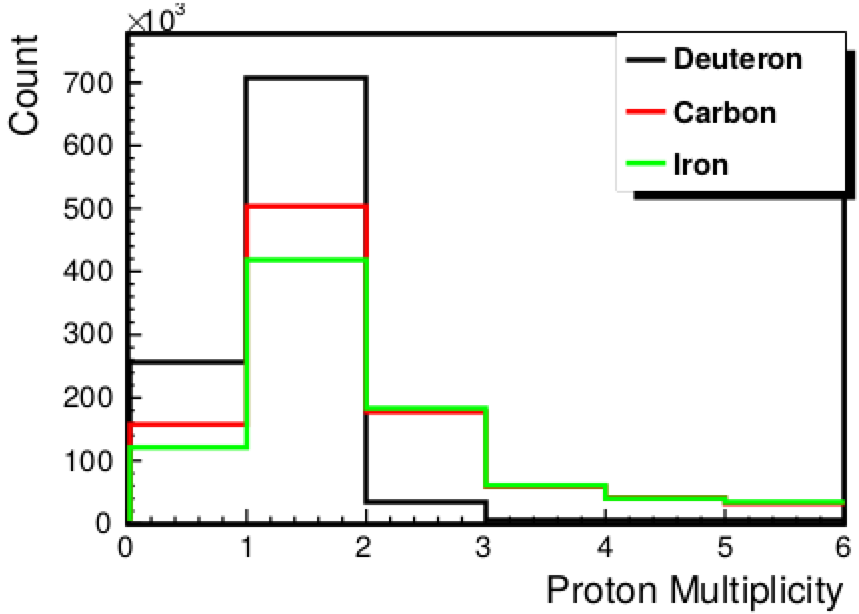


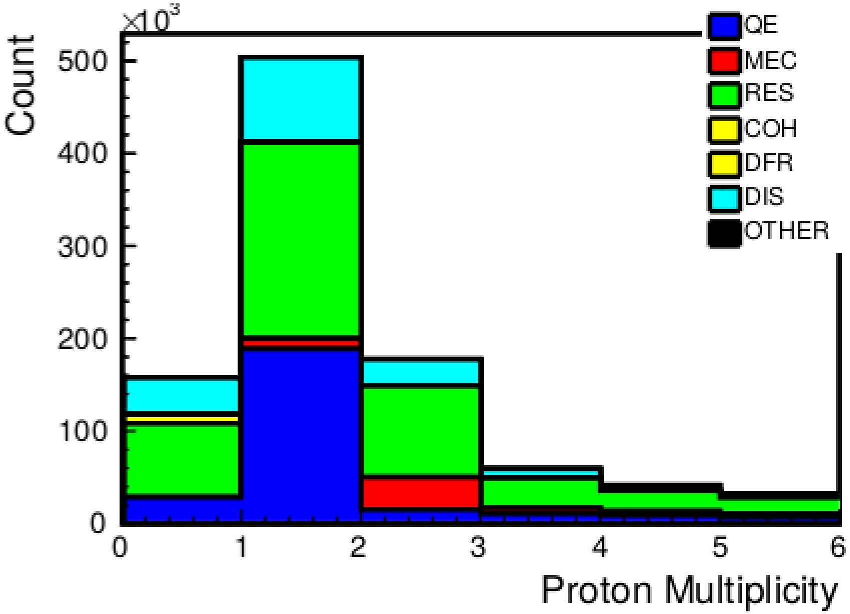




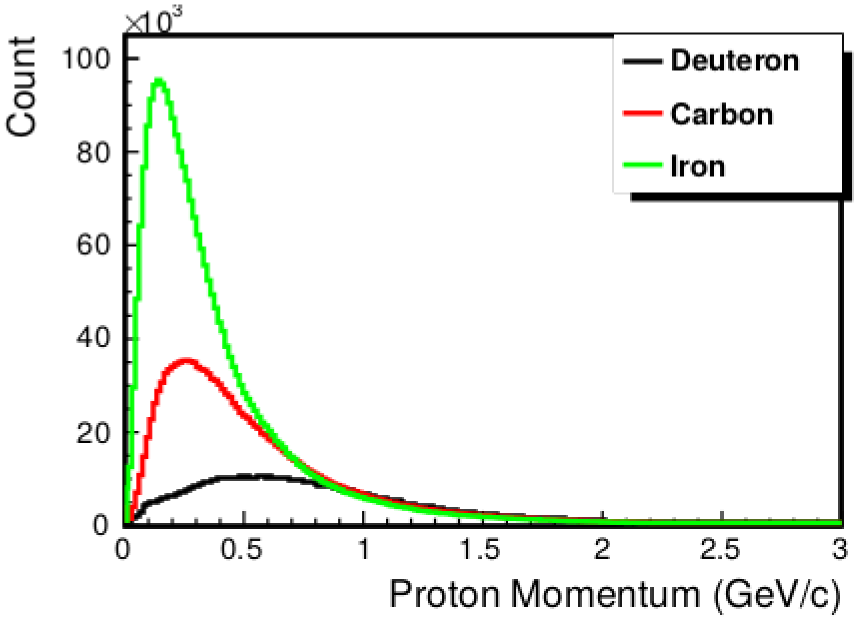
Protons

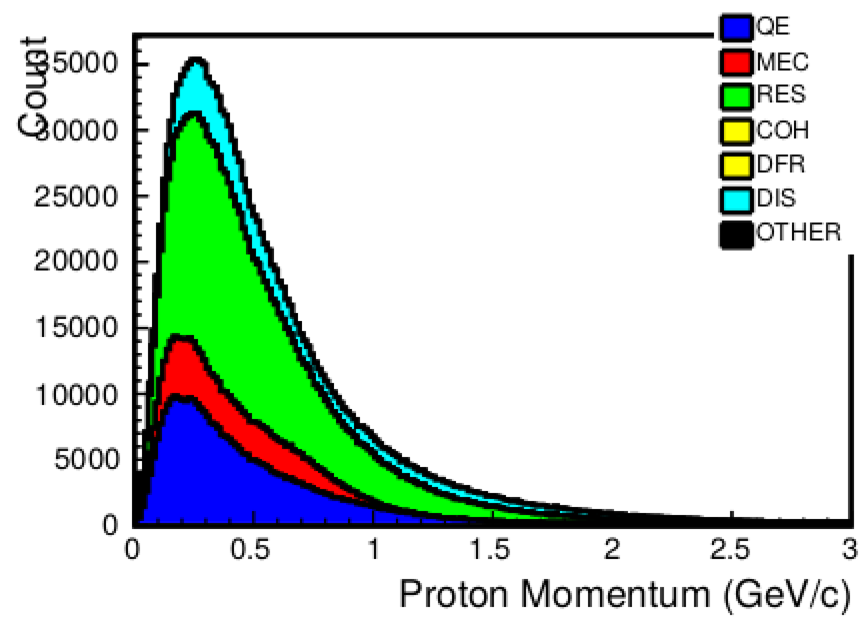
- Post-FSI

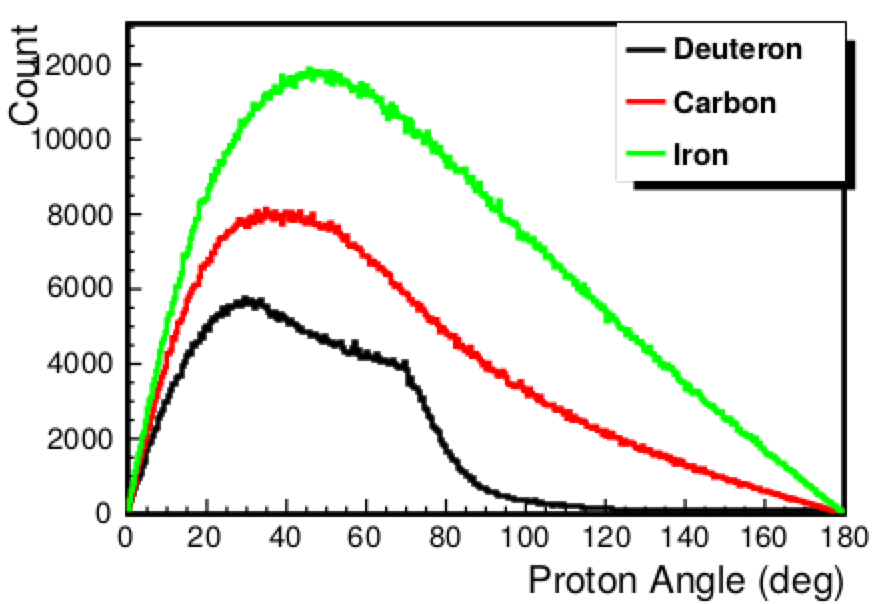


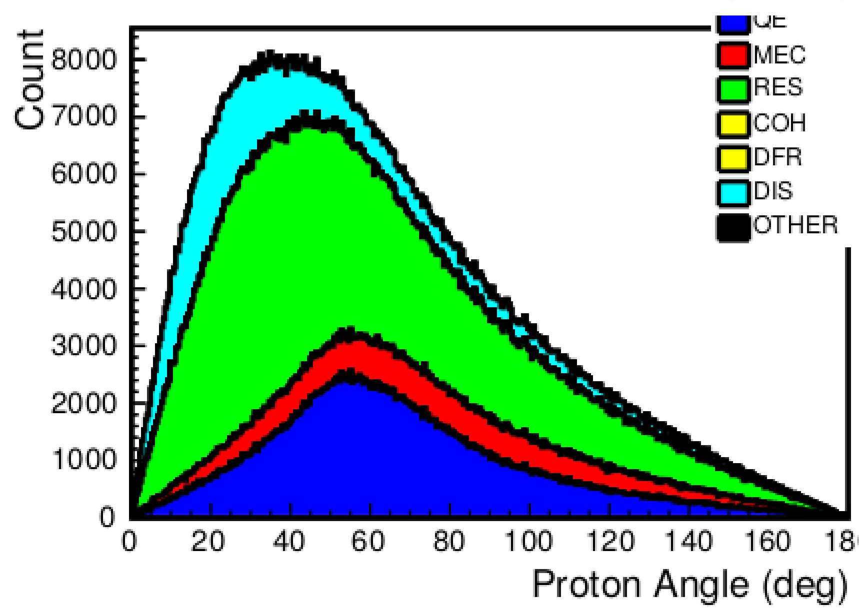


Protons (Post-FSI)

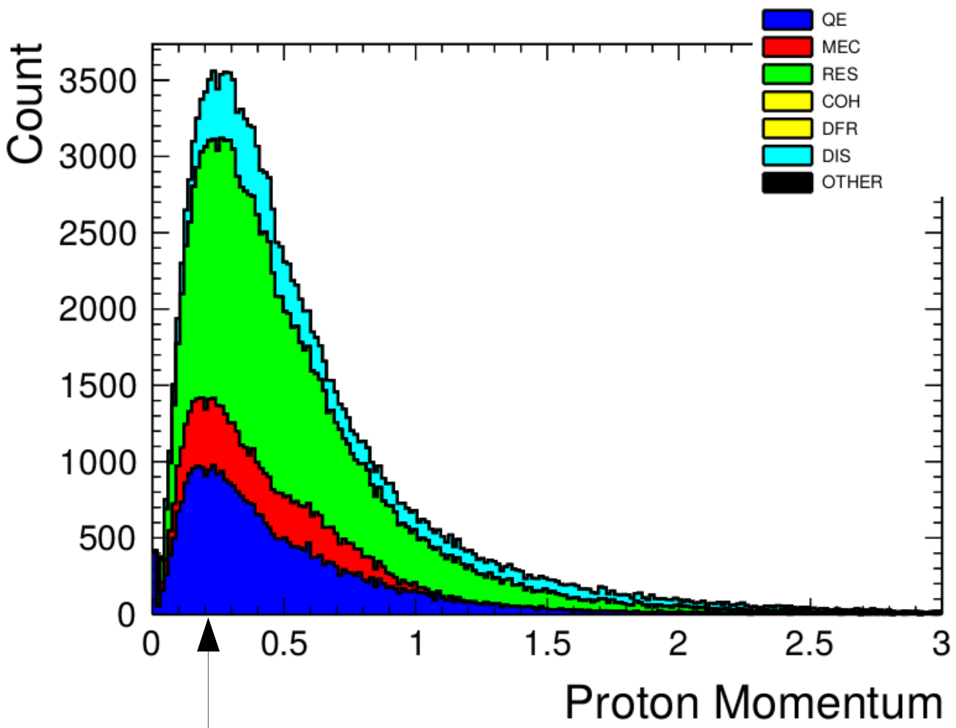


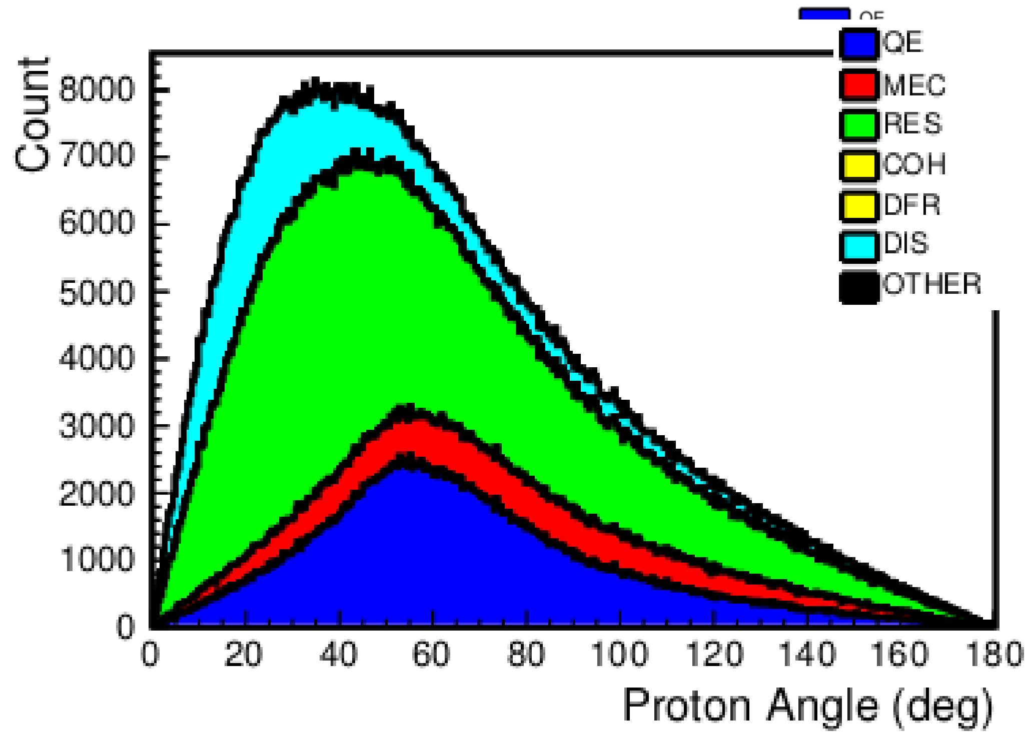






Proton Kinematics



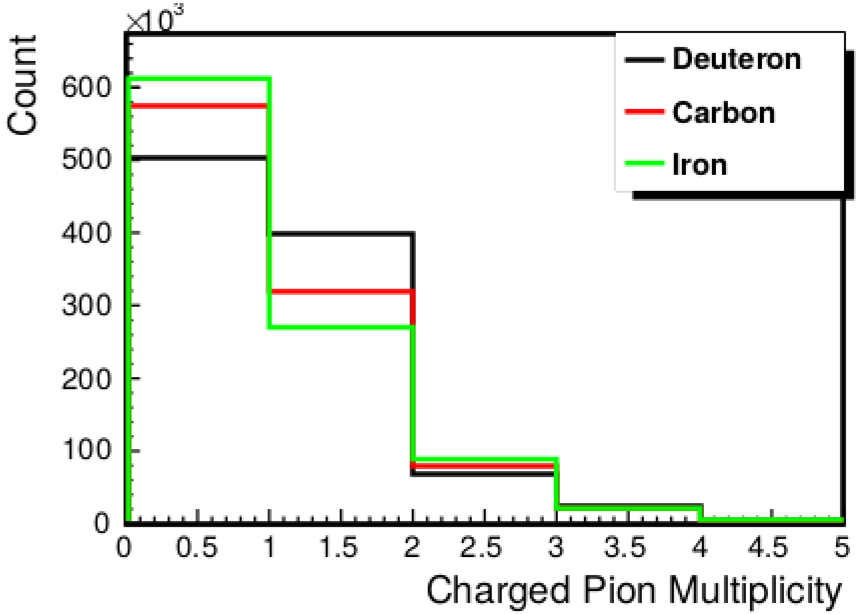


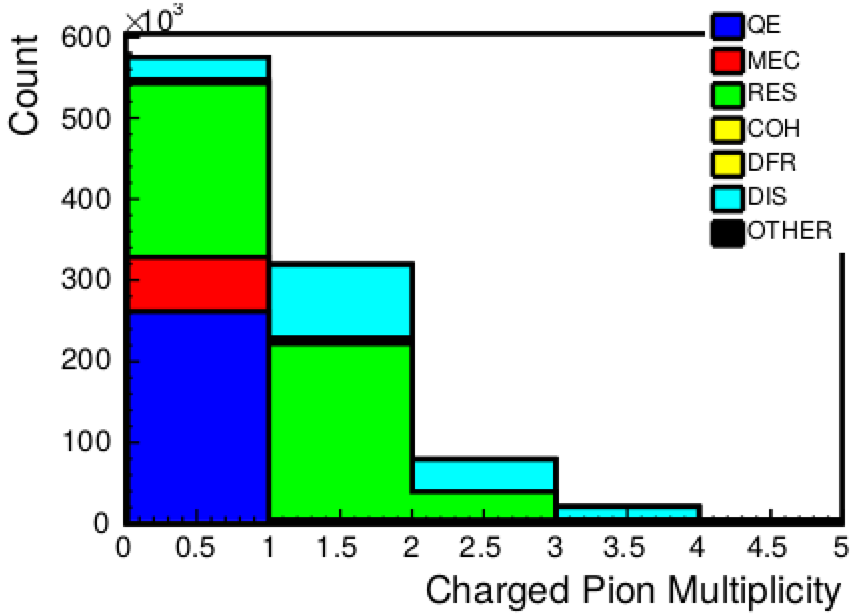
For a 200 MeV/c proton (NIST database)

Material	Range (cm)
Gaseous Argon (1 / 10 atm)	400 / 40
Liquid Argon	0.4
Plastic scintillator	0.35

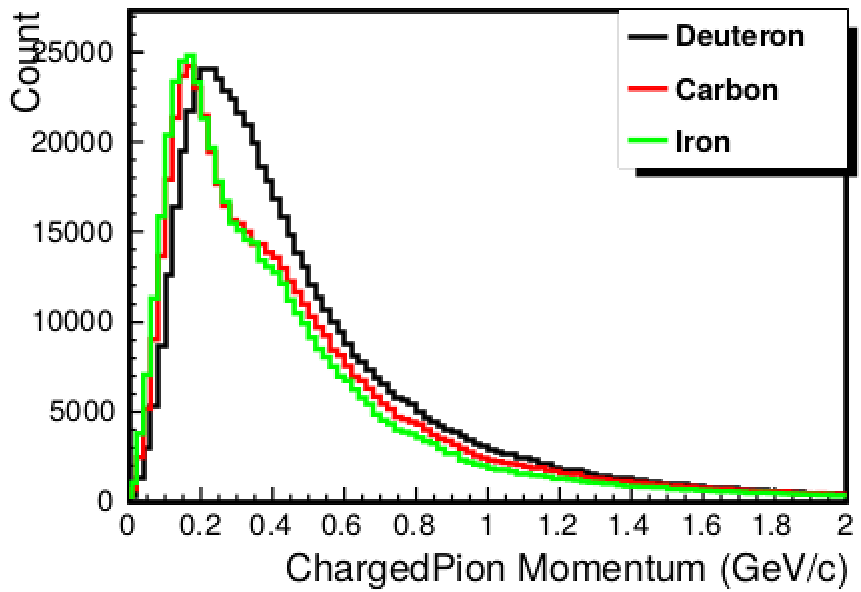
Charged Pions

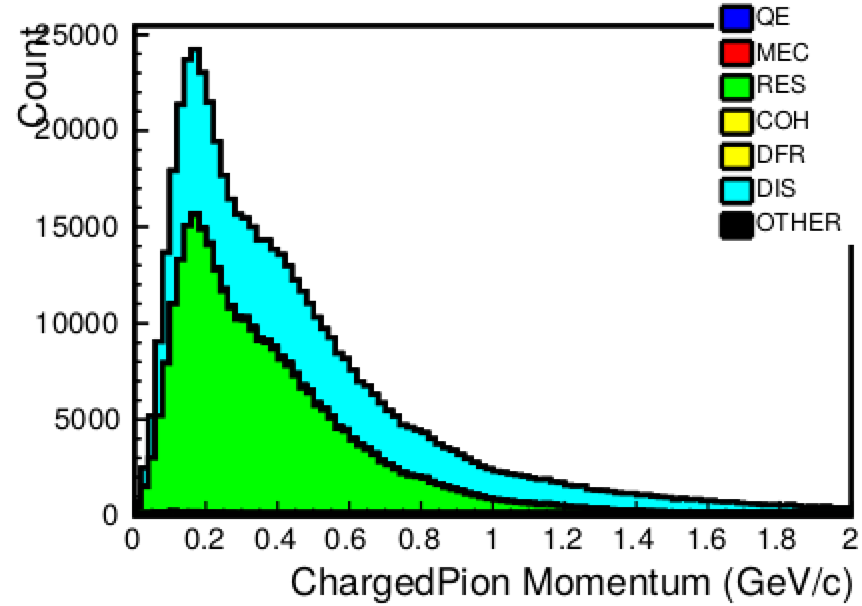
- post-FSI

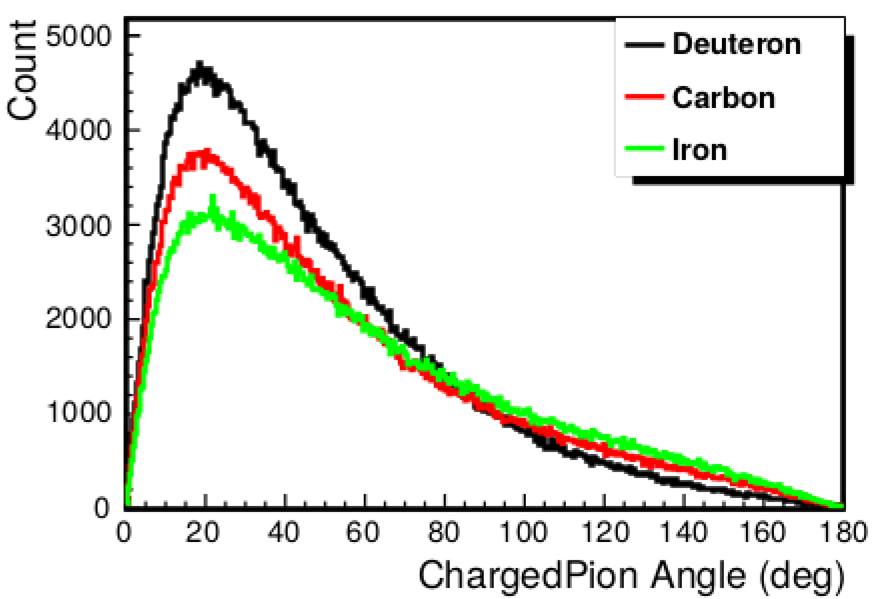


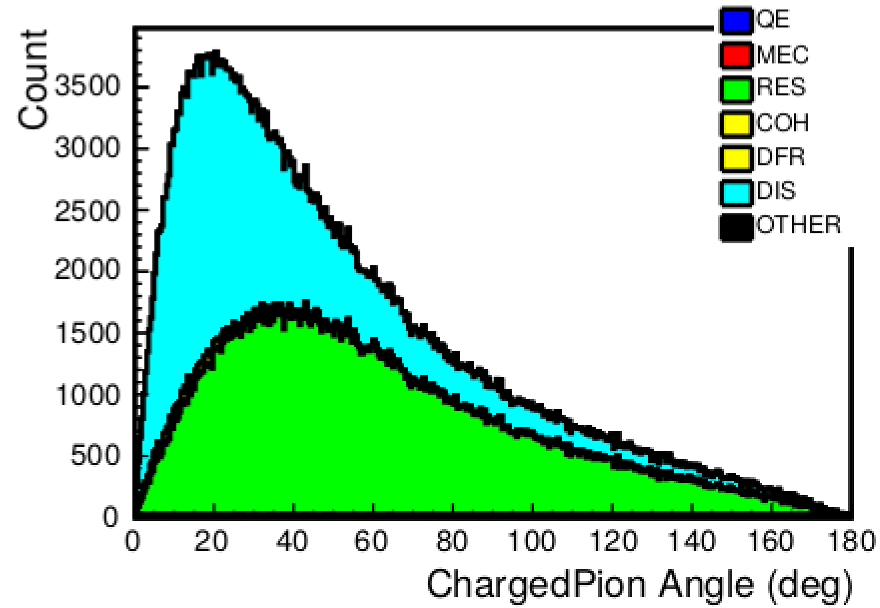


Charged Pions

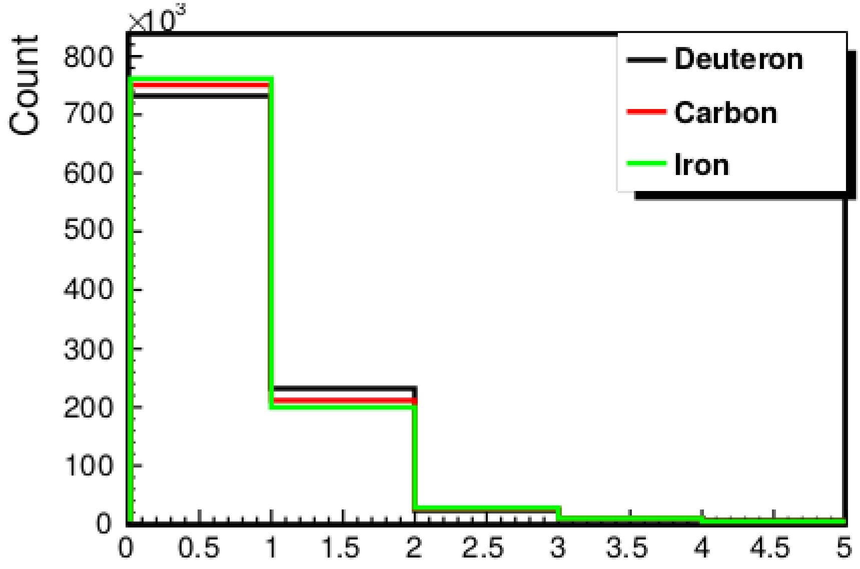


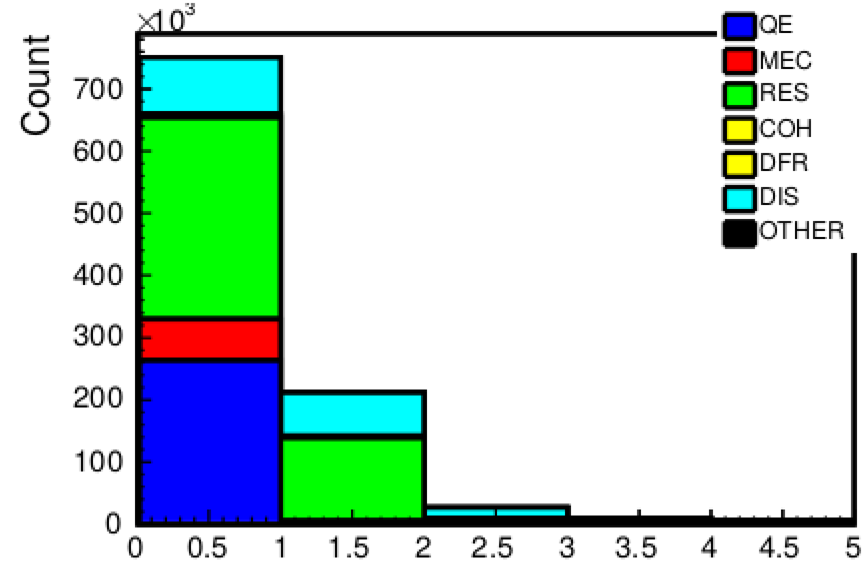


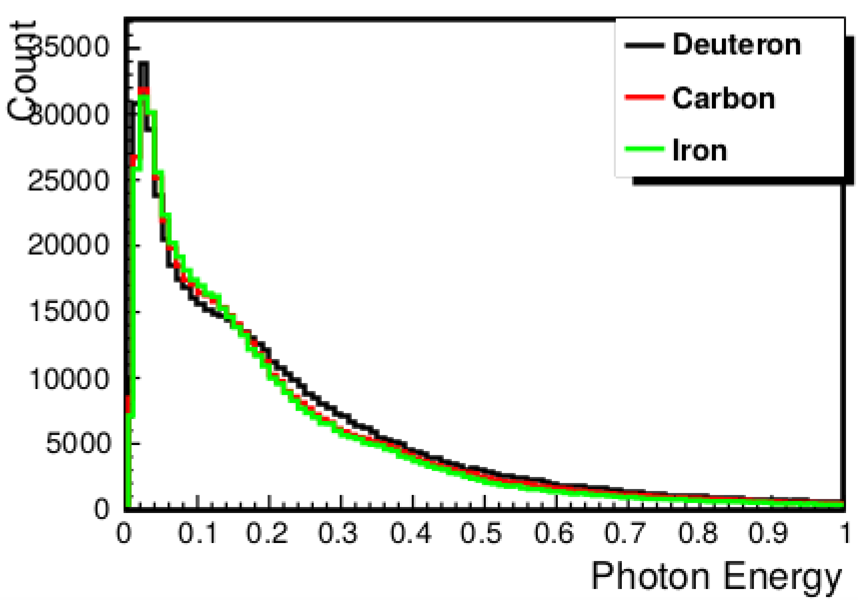


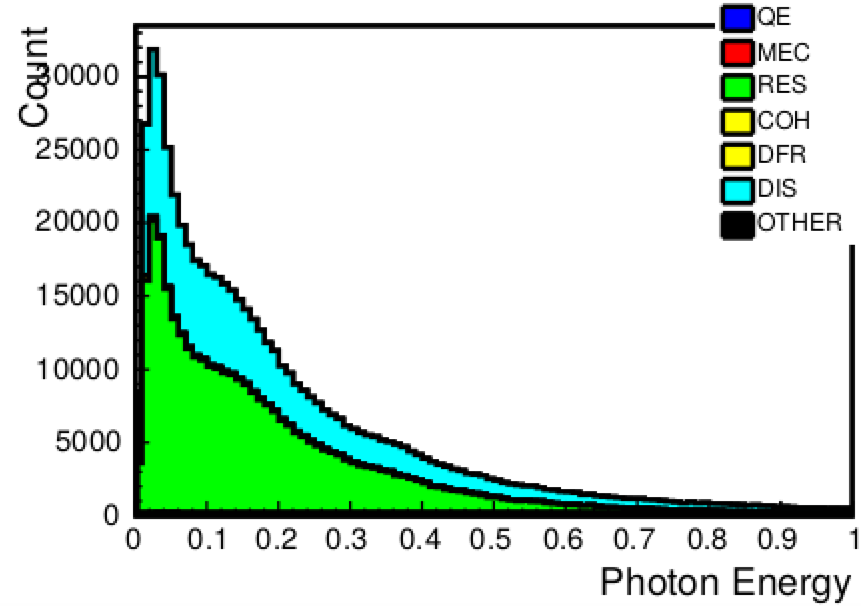


Neutral Pions









Musings

- Timeline:
  - T2K/HK will have precise measurements over large fraction of available phase space on Carbon in 0-3 GeV neutrino energy range. Physics expected by mid-2020's.
  - DUNE will have precise measurements over large fraction of available phase space on Argon in 0 – 6 GeV neutrino energy range. Physics expected around the early 2030's.
- Measurements required in other areas of the phase space – different energy and different target types.

Musings

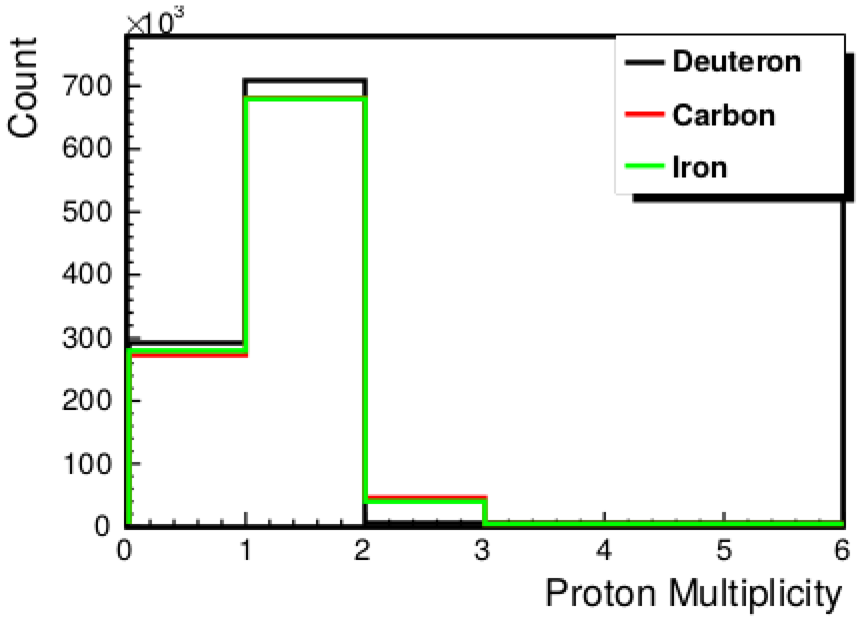
- What sort of detector do we build?
- Final state protons would seem to be one the most challenging charged object we would need to reconstruct. Requirements for these probably include:
    - a light tracking medium
    - as isotropic as we can get (needed for pions too)
    - thin, or active, neutrino targets
- Reconstructing π^0 probably drives the electromagnetic design. A detector should detect electromagnetic components from 50 MeV (photons) up to 6 GeV (electrons)
- require a magnetic field for charge and momentum measurement (a 5% muon momentum resolution for a 6 GeV muon with a 5 meter track length and 1mm hit resolution needs something like 0.2 T)
- should have different nuclear targets (including low-Z!).

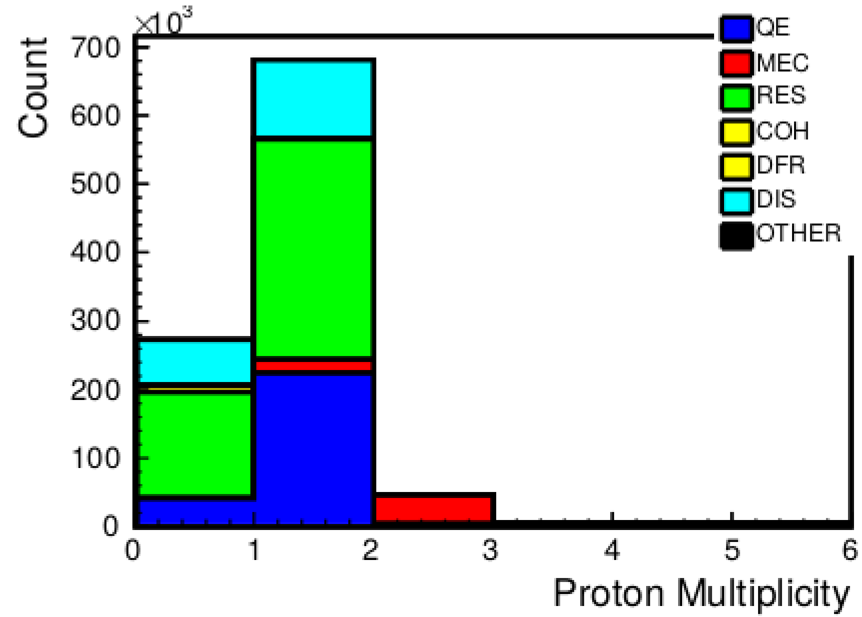
Event Listing

WARWICK
THE UNIVERSITY OF WARWICK

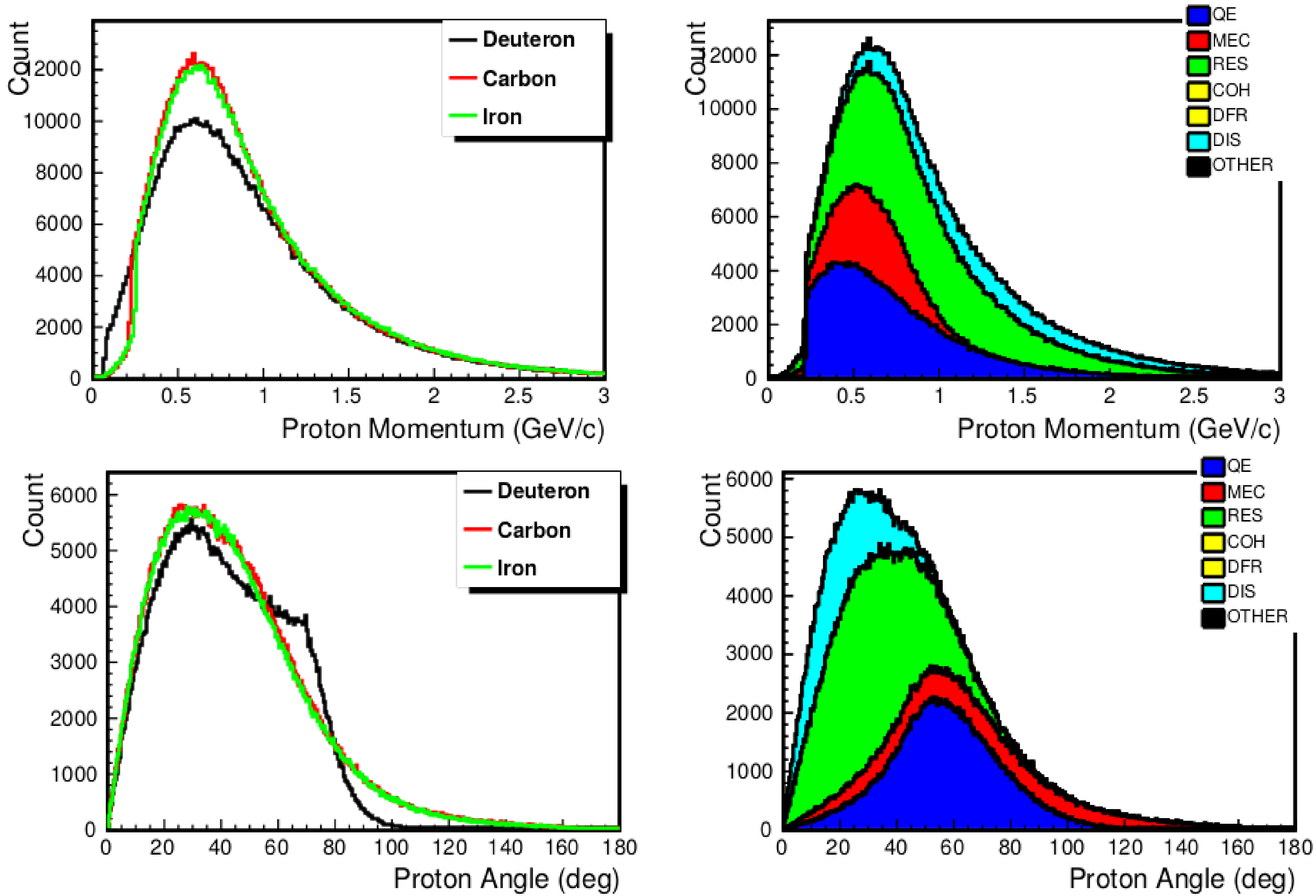
```
|----------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                      |
|----------------------------------------------------------------------------------------------------------------|
| Idx |             Name | Ist |          PDG |    Mother   | Daughter   |        Px |        Py |        Pz |         E |         m  |
|----------------------------------------------------------------------------------------------------------------|
|   0 |            nu_mu |   0 |           14 |  -1 |    -1 |   4 |    4 |     0.000 |     0.000 |     2.602 |     2.602 |     0.000 |
|   1 |              C12 |   0 |   1000060120 |  -1 |    -1 |   2 |    3 |     0.000 |     0.000 |     0.000 |    11.175 |    11.175 |
|   2 |          neutron |  11 |         2112 |   1 |    -1 |   5 |    5 |     0.046 |     0.138 |    -0.071 |     0.920 |  **0.940 | M = 0.905
|   3 |              C11 |   2 |   1000060110 |   1 |    -1 |  20 |   20 |    -0.046 |    -0.138 |     0.071 |    10.255 |    10.254 |
|   4 |            nu_mu |   1 |           14 |   0 |    -1 |  -1 |   -1 |     0.286 |    -0.445 |     1.943 |     2.014 |     0.000 | P = (-0.142,0.221,-0.965)
|   5 |           Delta0 |   3 |         2114 |   2 |    -1 |   6 |    7 |    -0.240 |     0.584 |     0.588 |     1.508 |  **1.233 | M = 1.237
|   6 |          neutron |  14 |         2112 |   5 |    -1 |   8 |    8 |    -0.358 |     0.402 |     0.625 |     1.250 |     0.940 | FSI = 4
|   7 |              pi0 |  14 |          111 |   5 |    -1 |  19 |   19 |     0.118 |     0.181 |    -0.037 |     0.257 |     0.135 | FSI = 1
|   8 |         HadrClus |  16 |   2000000300 |   6 |    -1 |   9 |   18 |    -0.358 |     0.402 |     0.625 |     0.361 |  **0.000 | M = -0.742
|   9 |           proton |   1 |         2212 |   8 |    -1 |  -1 |   -1 |    -0.102 |     0.274 |     0.305 |     1.029 |     0.938 |
|  10 |           proton |   1 |         2212 |   8 |    -1 |  -1 |   -1 |    -0.275 |     0.022 |     0.108 |     0.984 |     0.938 |
|  11 |           proton |   1 |         2212 |   8 |    -1 |  -1 |   -1 |    -0.064 |    -0.035 |    -0.199 |     0.962 |     0.938 |
|  12 |           proton |   1 |         2212 |   8 |    -1 |  -1 |   -1 |     0.125 |    -0.058 |     0.083 |     0.952 |     0.938 |
|  13 |          neutron |   1 |         2112 |   8 |    -1 |  -1 |   -1 |     0.097 |     0.024 |     0.093 |     0.949 |     0.940 |
|  14 |          neutron |   1 |         2112 |   8 |    -1 |  -1 |   -1 |    -0.121 |     0.113 |     0.049 |     0.955 |     0.940 |
|  15 |          neutron |   1 |         2112 |   8 |    -1 |  -1 |   -1 |    -0.215 |     0.071 |    -0.170 |     0.981 |     0.940 |
|  16 |          neutron |   1 |         2112 |   8 |    -1 |  -1 |   -1 |     0.269 |    -0.050 |    -0.010 |     0.979 |     0.940 |
|  17 |          neutron |   1 |         2112 |   8 |    -1 |  -1 |   -1 |     0.022 |    -0.177 |     0.198 |     0.977 |     0.940 |
|  18 |          neutron |   1 |         2112 |   8 |    -1 |  -1 |   -1 |    -0.093 |     0.216 |     0.168 |     0.983 |     0.940 |
|  19 |              pi0 |   1 |          111 |   7 |    -1 |  -1 |   -1 |     0.118 |     0.181 |    -0.037 |     0.257 |     0.135 |
|  20 |         HadrBlob |  15 |   2000000002 |   3 |    -1 |  -1 |   -1 |    -0.046 |    -0.138 |     0.071 |     1.754 |  **0.000 | M = 1.747
|----------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                                      |    -0.000 |    -0.000 |     0.000 |     0.000 |            |
|----------------------------------------------------------------------------------------------------------------|
|       Vertex:         nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s) |
|----------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                                 none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:   YES                      |
|----------------------------------------------------------------------------------------------------------------|
| sig(Ev) =       1.15909e-38 cm^2  | d2sig(W,Q2;E)/dWdQ2 =     6.56397e-38 cm^2/GeV^3 | Weight =          1.00000 |
|----------------------------------------------------------------------------------------------------------------|
```

Protons (Pre-FSI)

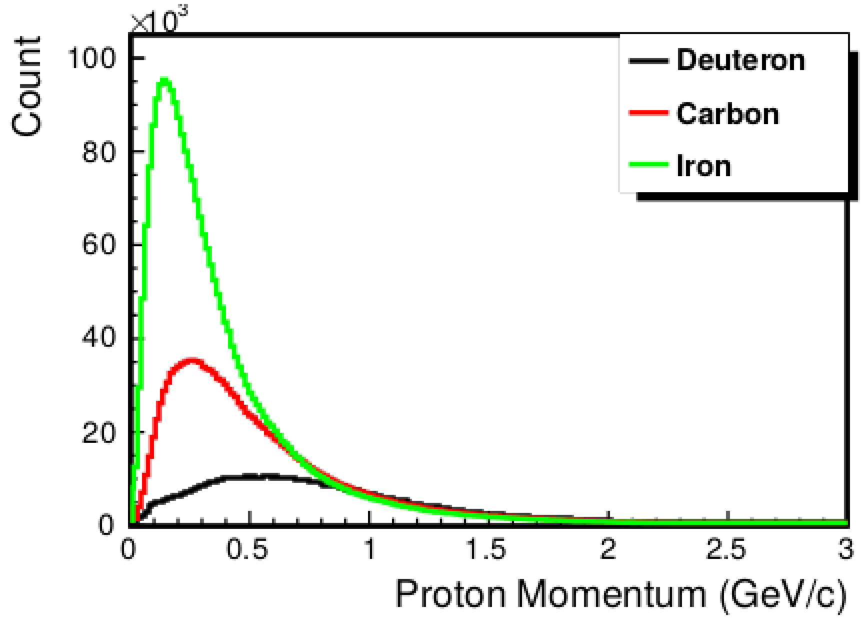




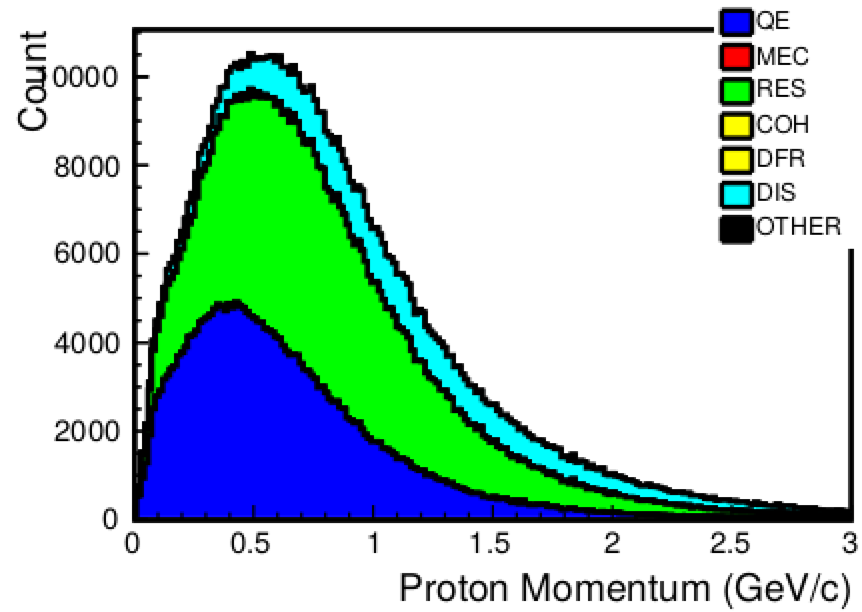
Protons (pre-FSI)



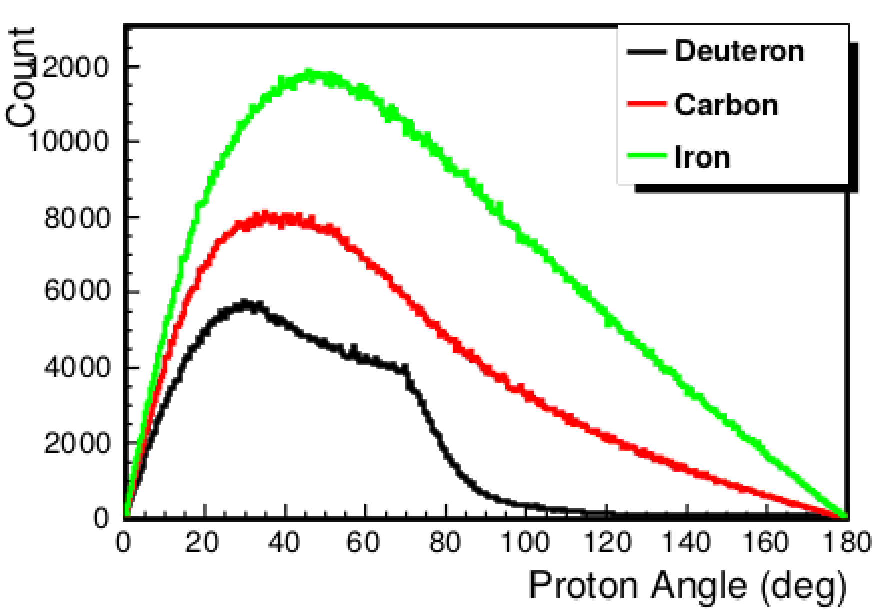
Protons - H2



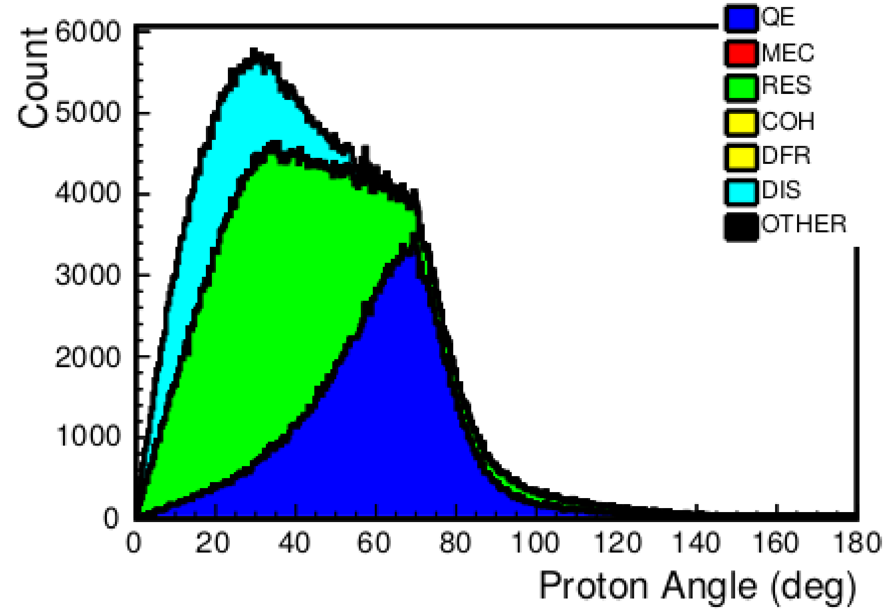
Count
×10³
Deuteron
Carbon
Iron
Proton Momentum (GeV/c)



Count
QE
MEC
RES
COH
DFR
DIS
OTHER
Proton Momentum (GeV/c)

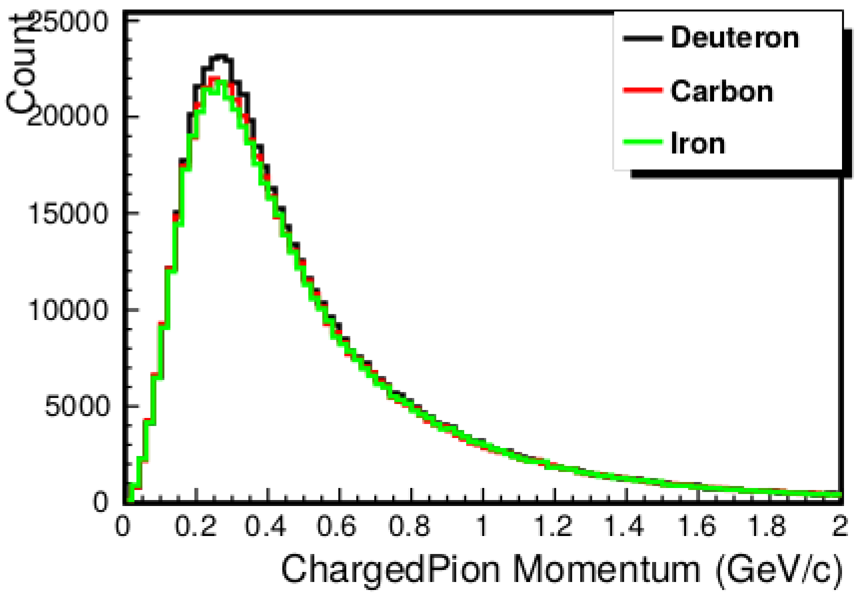


Count
Deuteron
Carbon
Iron
Proton Angle (deg)

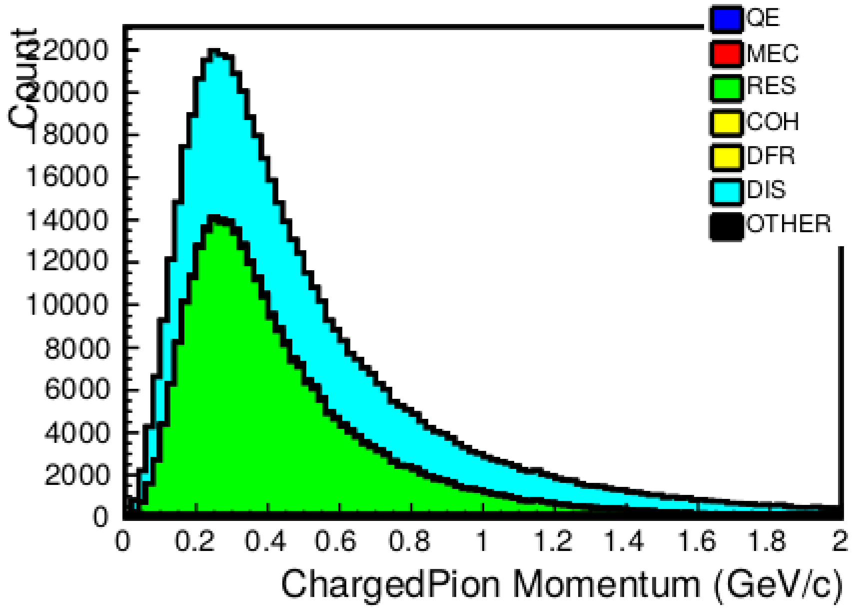


Count
QE
MEC
RES
COH
DFR
DIS
OTHER
Proton Angle (deg)

Pion - pre-FSI

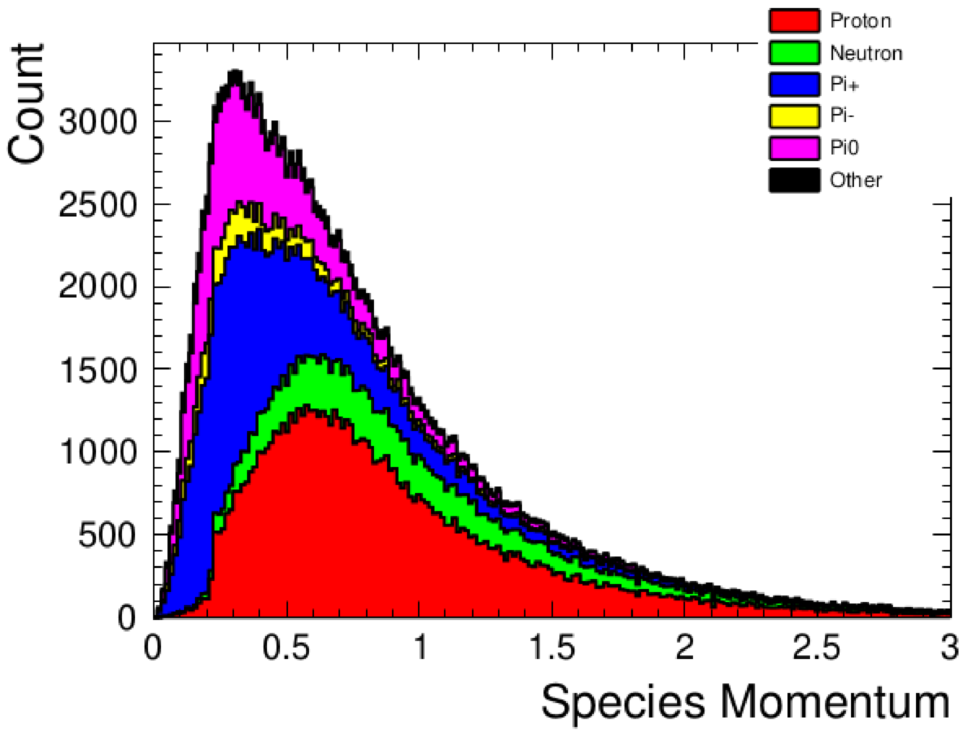


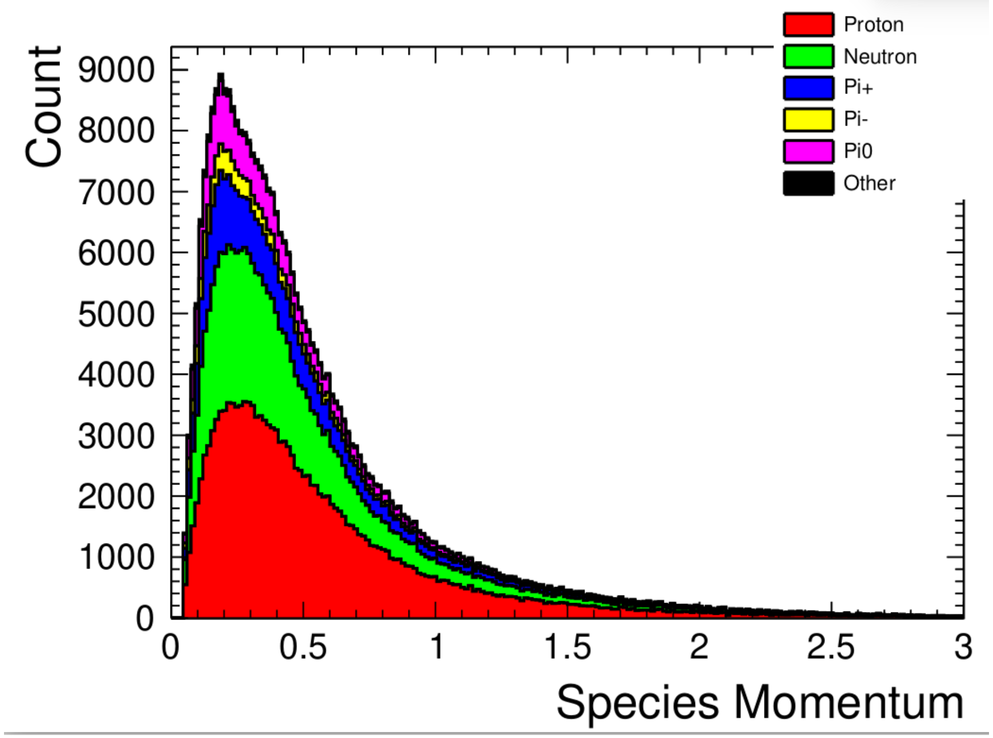
Count
25000
20000
15000
10000
5000
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
ChargedPion Momentum (GeV/c)
Deuteron
Carbon
Iron



Count
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
ChargedPion Momentum (GeV/c)
QE
MEC
RES
COH
DFR
DIS
OTHER

Before and After FSI

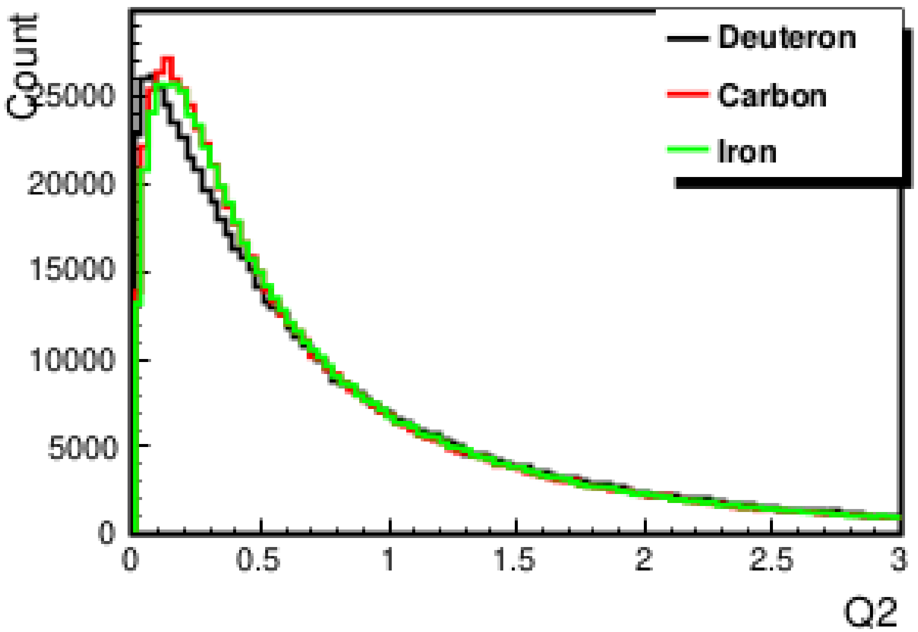




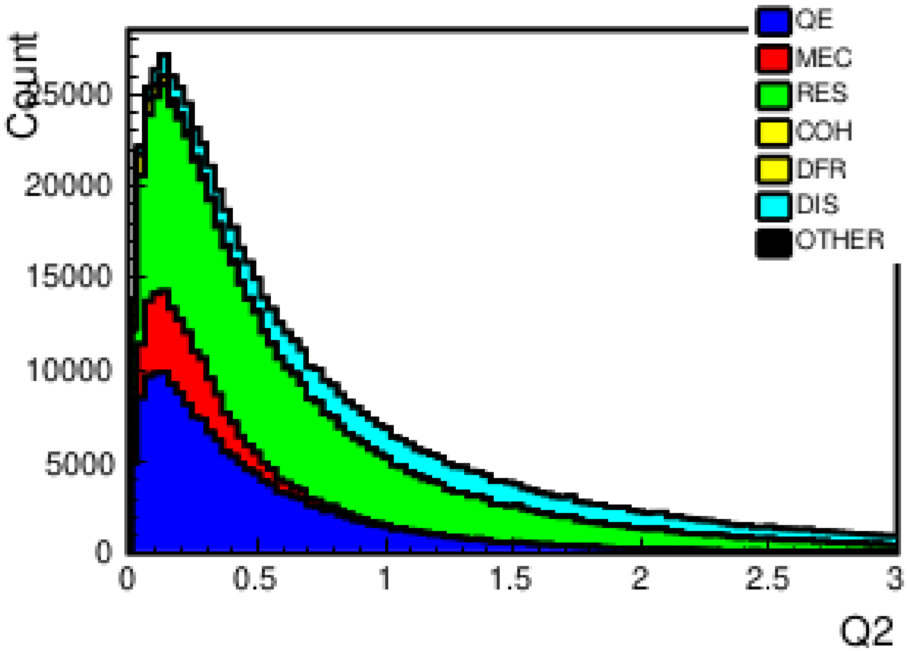
Before FSI

After FSI

Q2



Count
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
3
Q2
Deuteron
Carbon
Iron



Count
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
3
Q2
QE
MEC
RES
COH
DFR
DIS
OTHER