Comparing different final-state interaction models in GENIE

Yinrui Liu[1]

Sept. 28, 2023 @ Collaboration Meeting

[1]University of Chicago

Introduction

- This work is based on the study I have been working on this summer with Stephen and Laura at CERN.

See my talk at ProtoDUNE session on Tuesday

- I also work on the hadron-argon cross-section measurement using ProtoDUNE-SP data, which would be useful to constrain the final-state interaction (FSI) models, and thus constrain the relevant systematic uncertainty for neutrino analyses.

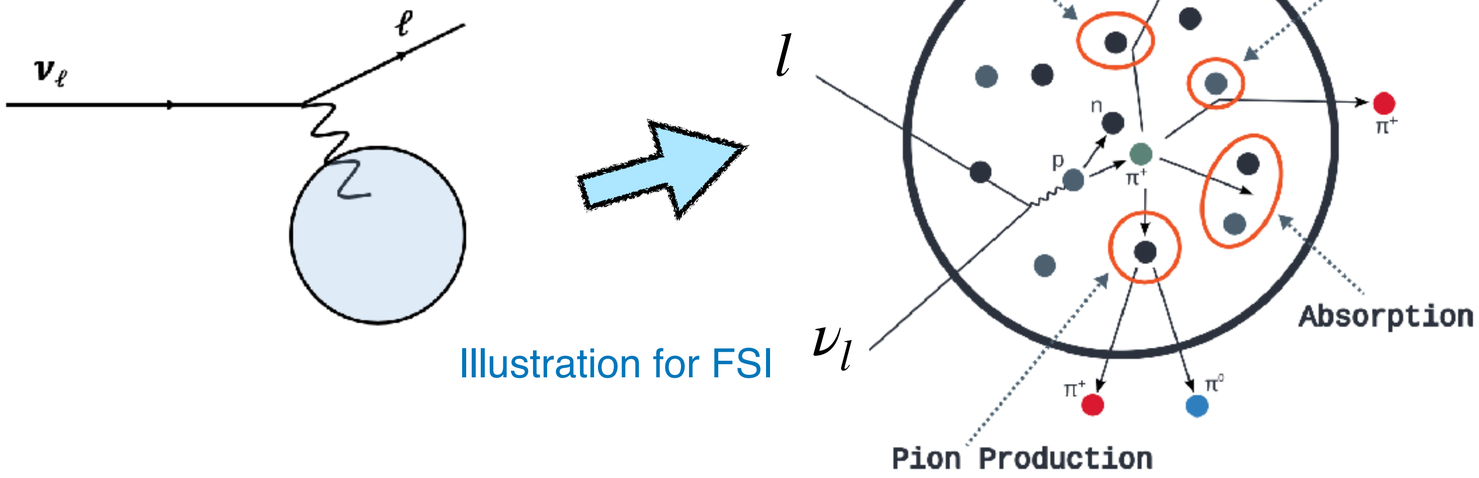
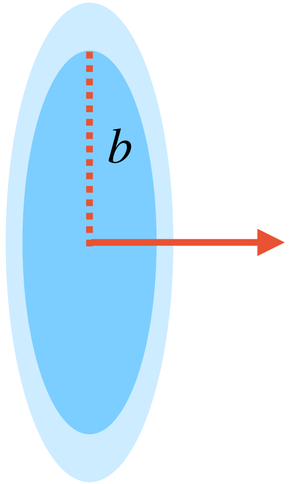


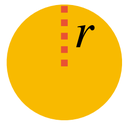
Illustration for FSI

- In this study, we compare different FSI models built in GENIE.

GENIE hadron-nucleus simulation

- We use GENIE to simulate hadron-argon scattering events.





Incident hadron (π^+ or p) beam

b denotes the maximum impact parameter
(for hA2018, hN2018, G4BC, $b = 3r$,
while for INCL, b is energy-dependent)

Argon nucleus

Empirical radius

$$r = r_0 \cdot A^{\frac{1}{3}}$$

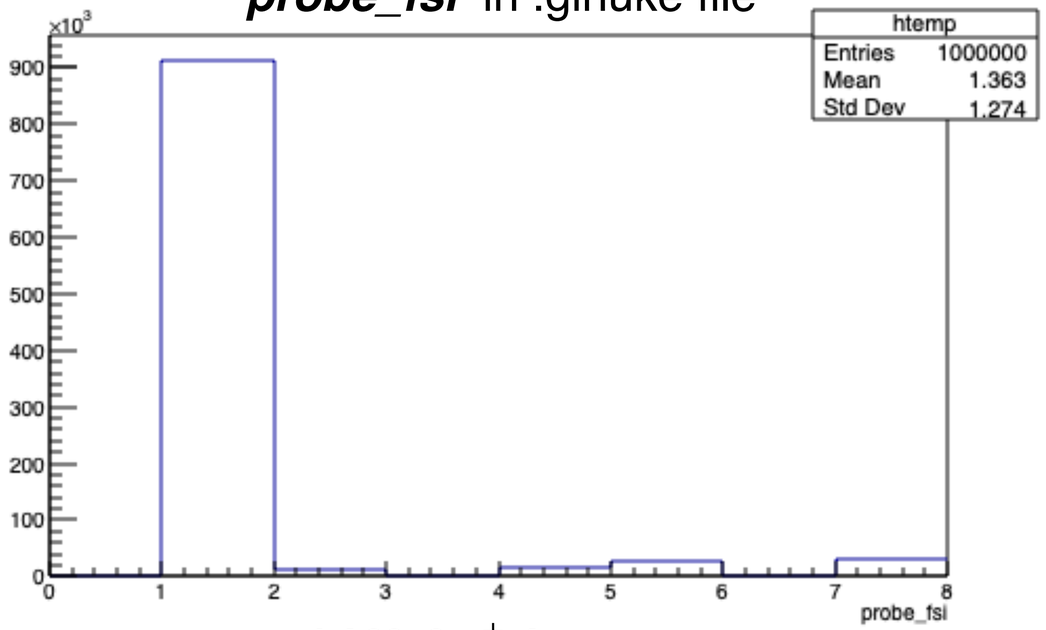
(we use $r_0 = 1.4$ fm)

- Four FSI models: hA2018, hN2018, INCL, and Geant4 Bertini Cascades (G4BC) See next slide

FSI models in GENIE

- Empirical models
  - **hA2018**: the default model used in most current neutrino simulations. It only considers one hadron rescattering.
  - **hN2018**: it considers multiple rescatterings until the hadron escape the nucleus.
- More sophisticated models
  - **INCL**
  - **Geant4 Bertini Cascades (G4BC)**

probe_fsi in .ginuke file



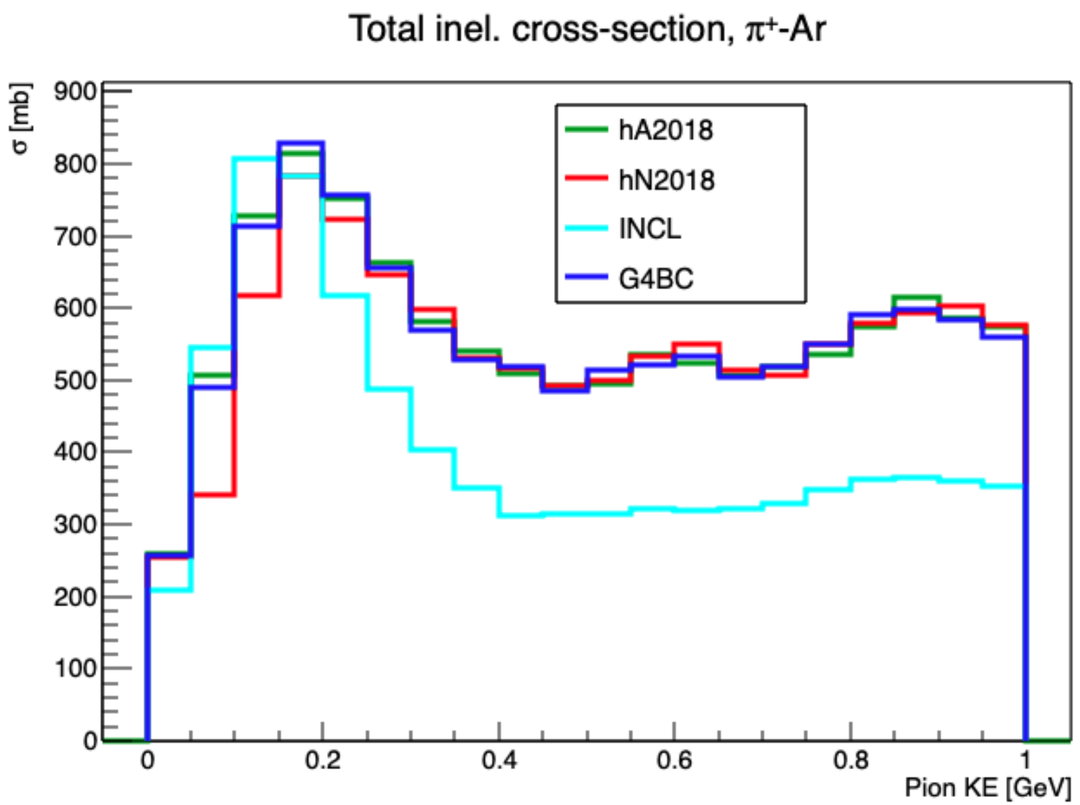
hA2018 π^+-Ar events

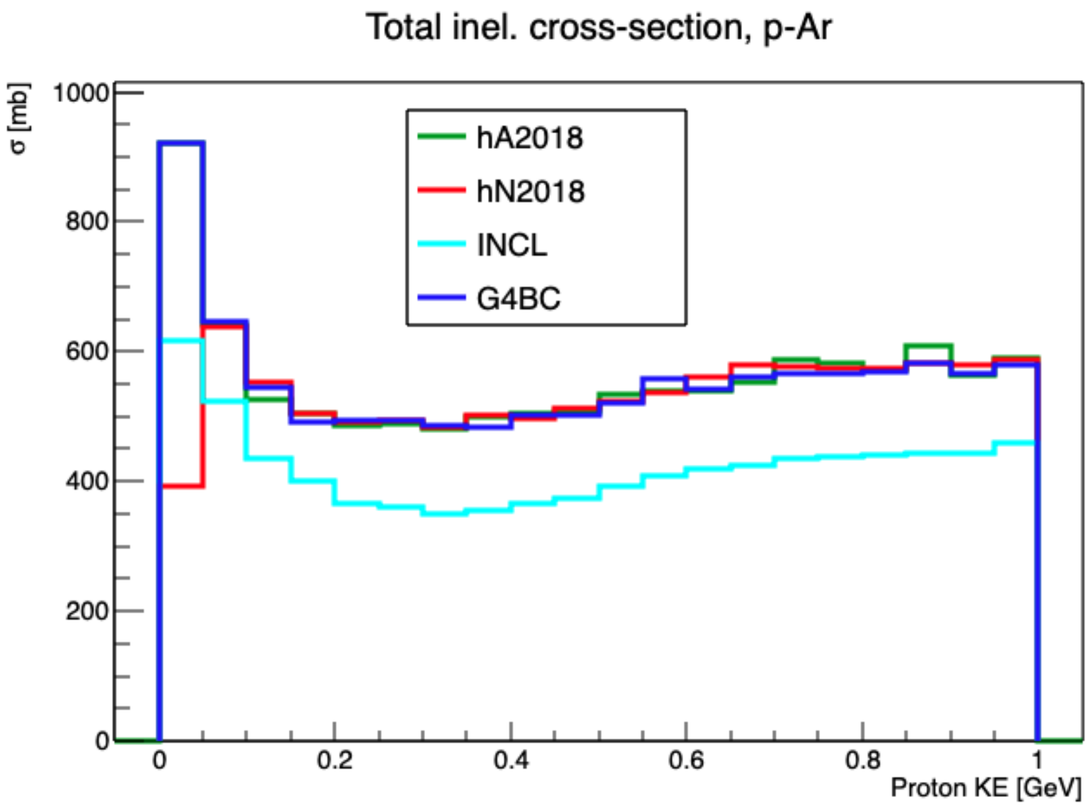
probe_fsi for π^+-Ar

- 1: no interaction
- 2: charge exchange
- 4: quasi-elastic
- 5: absorption
- 7: pion production

FSI models in GENIE

- Judging by ***probe_fsi > 1***, we derive the XS as ***f · hadron_with_fsi / all_incident_hadron***, where ***f*** is a scale factor.

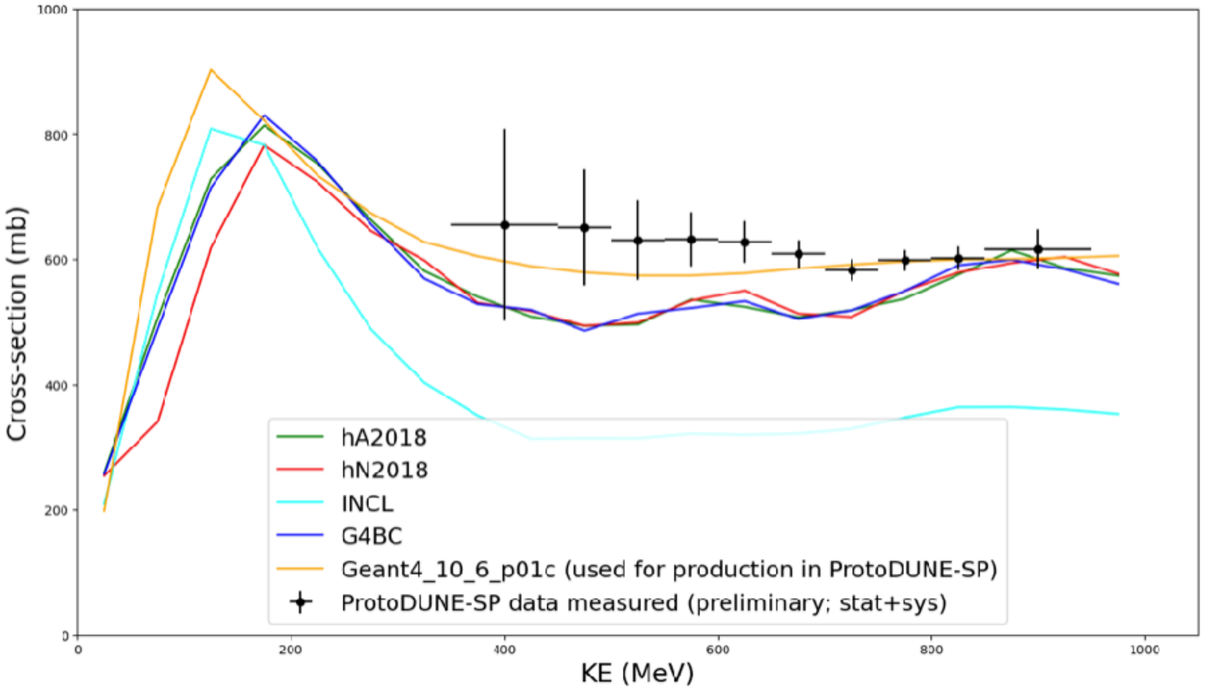


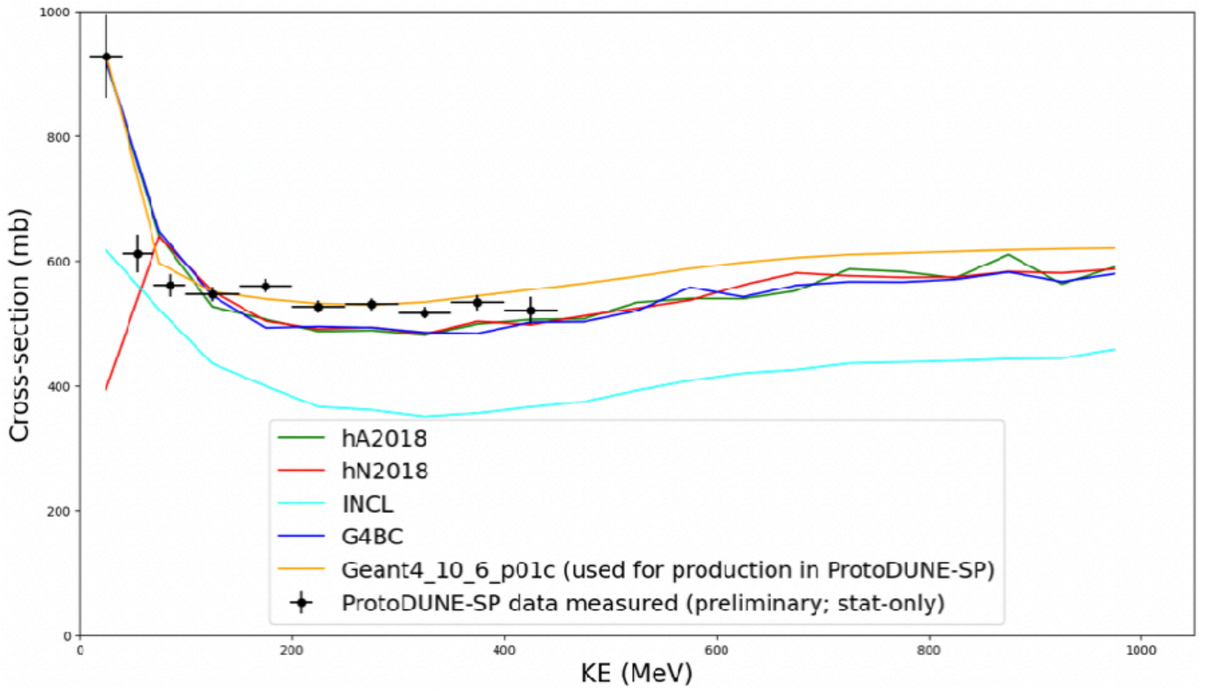


Problem reproducing the impact parameter for INCL model. Checking with Prof. Steven Dytman on this issue.

Comparing to ProtoDUNE-SP data

https://indico.fnal.gov/event/58097/contributions/276440/attachments/171336/231046/hadronXS_DUNE_230926.pdf





Unsolved issues about the scale factor for INCL model

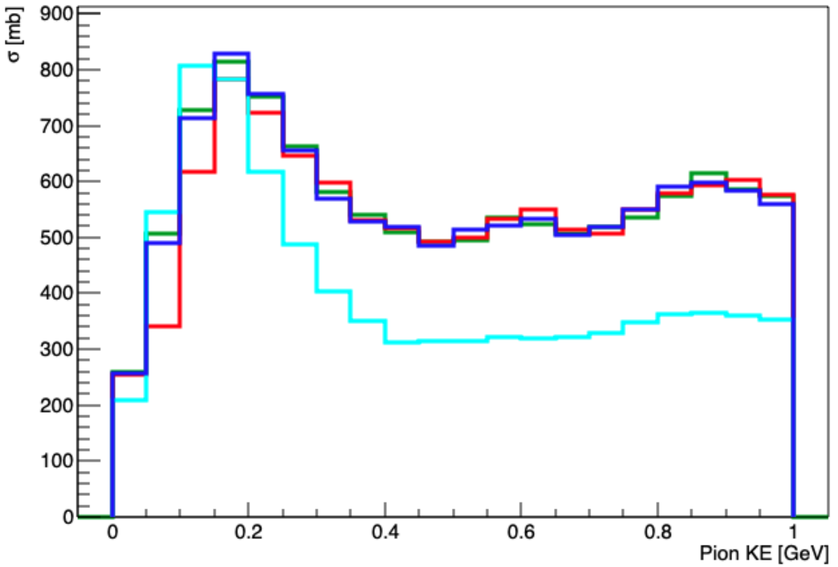
- For quantitative comparisons, we can calculate χ^2 using the data covariance matrix. (See back-ups)

Comparing other variables

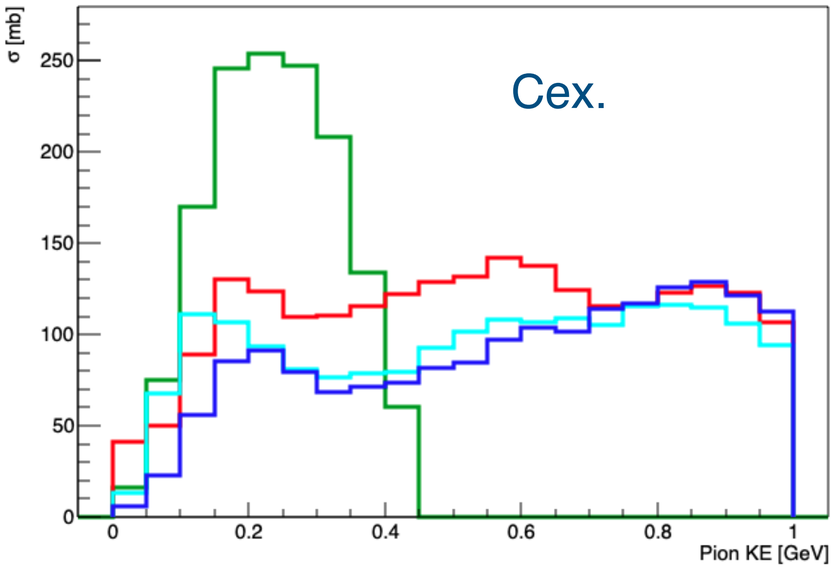
- In terms of the total cross sections, different models look to have similar predictions (except that we need to figure out the scale factors for the INCL model).
- In the next couple of slides, we will show comparisons of some other variables
  - Exclusive cross sections
  - Multiplicity of final-state particles
  - Energy bias

π^+-Ar cross-section in exclusive channels

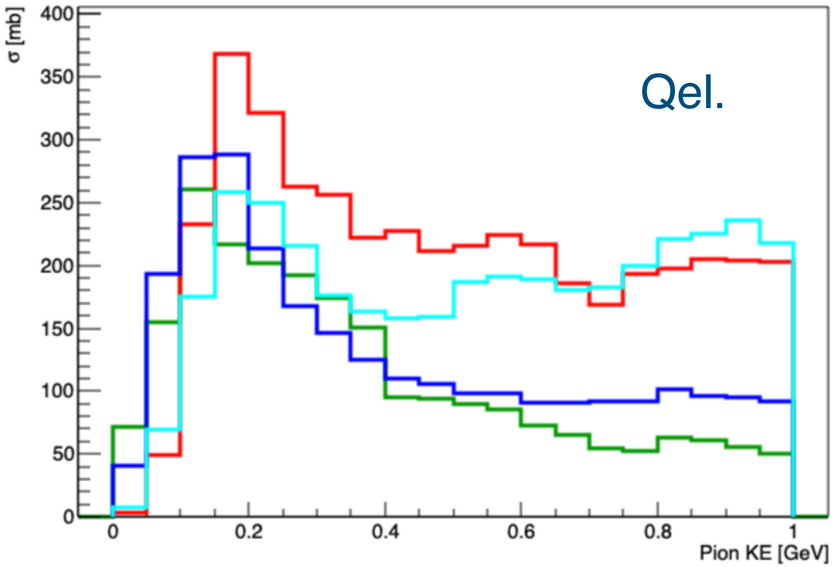
Pion total inelastic, π⁺-Ar



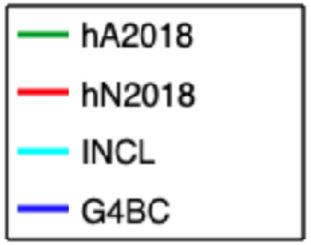
Pion charge exchange, π⁺-Ar



Quasi-elastic, π⁺-Ar

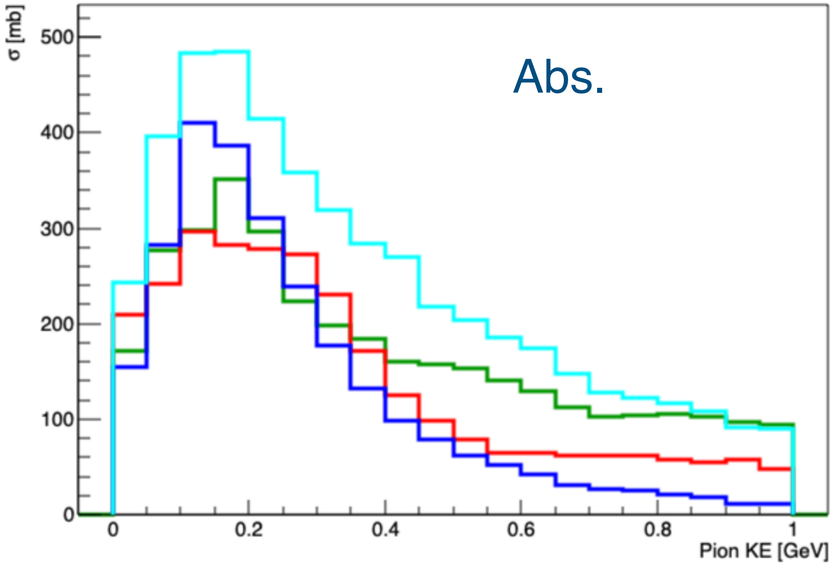


Unsolved issues about the scale factor for INCL model

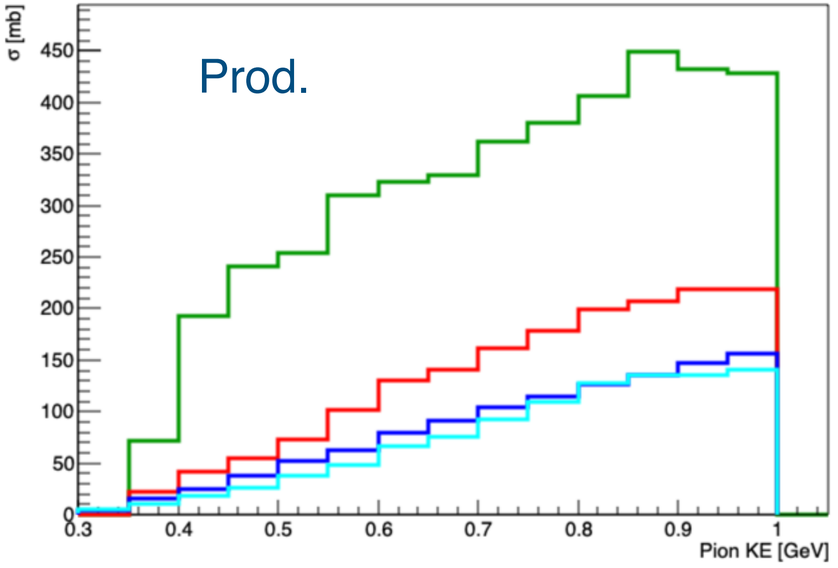


(See back-ups for p-Ar results)

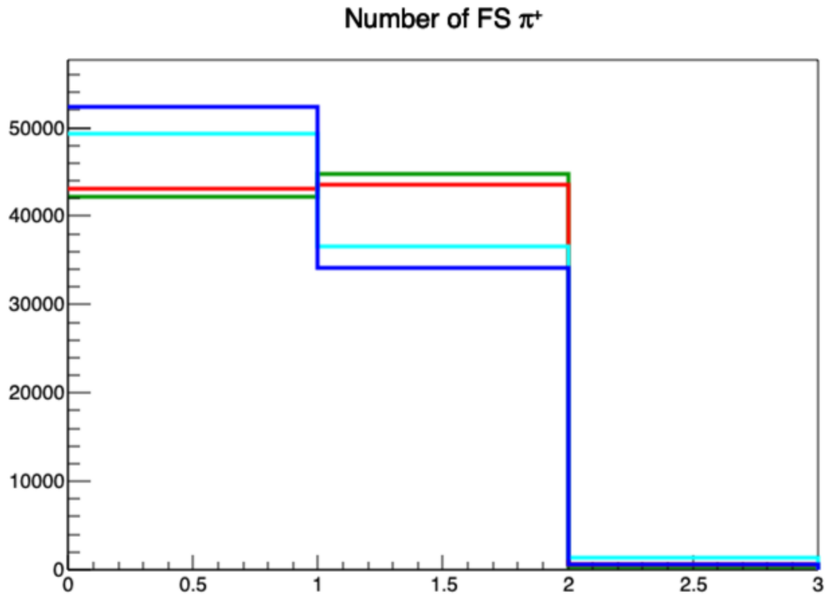
Pion absorption, π⁺-Ar

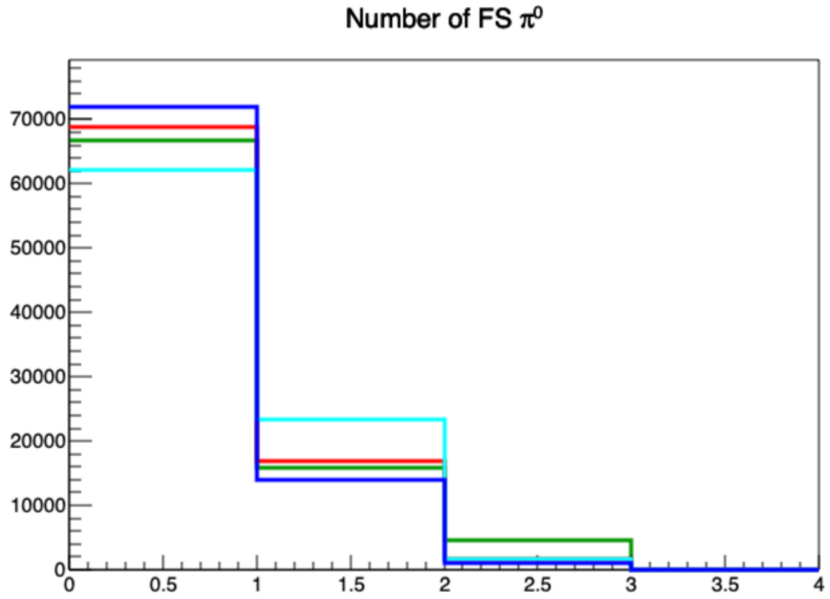


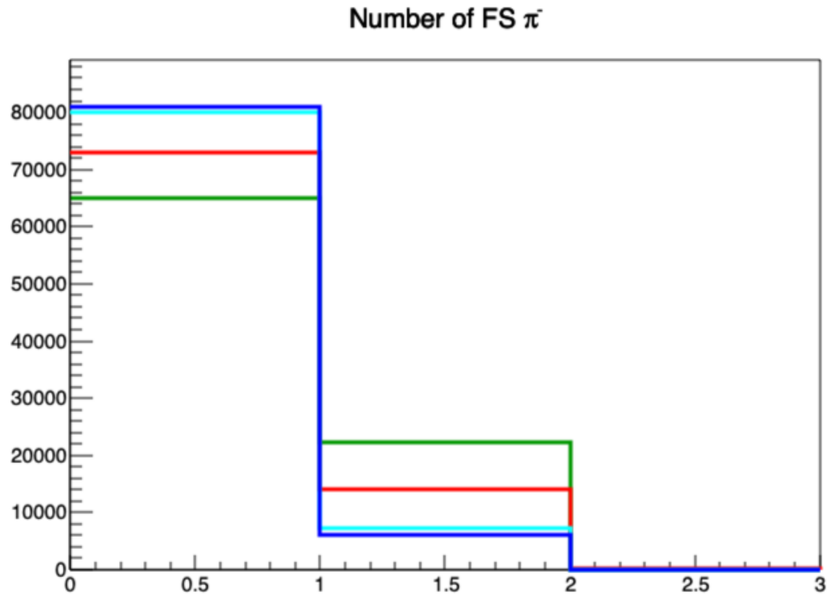
Pion production, π⁺-Ar



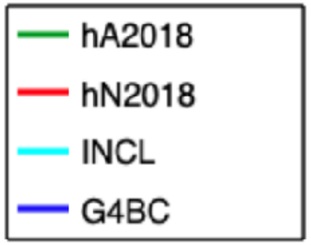
π^+-Ar final-state particle multiplicity



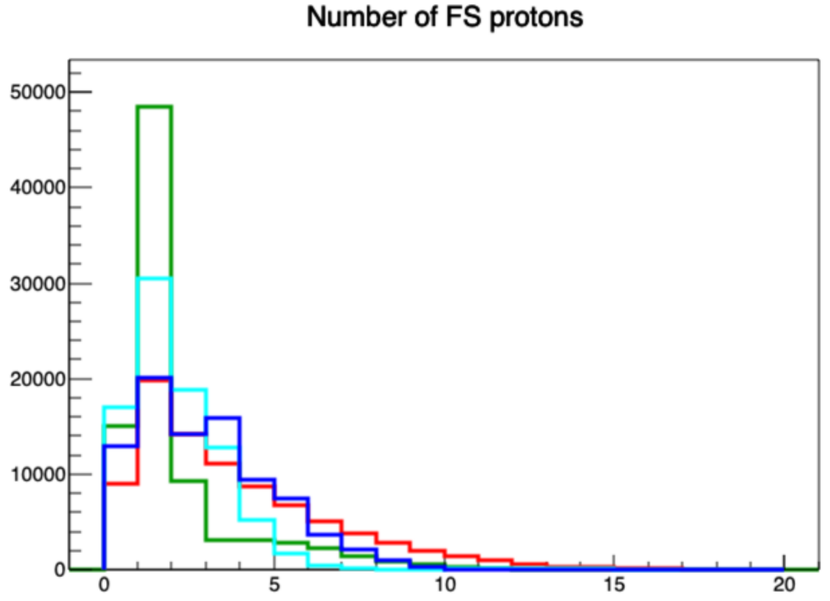


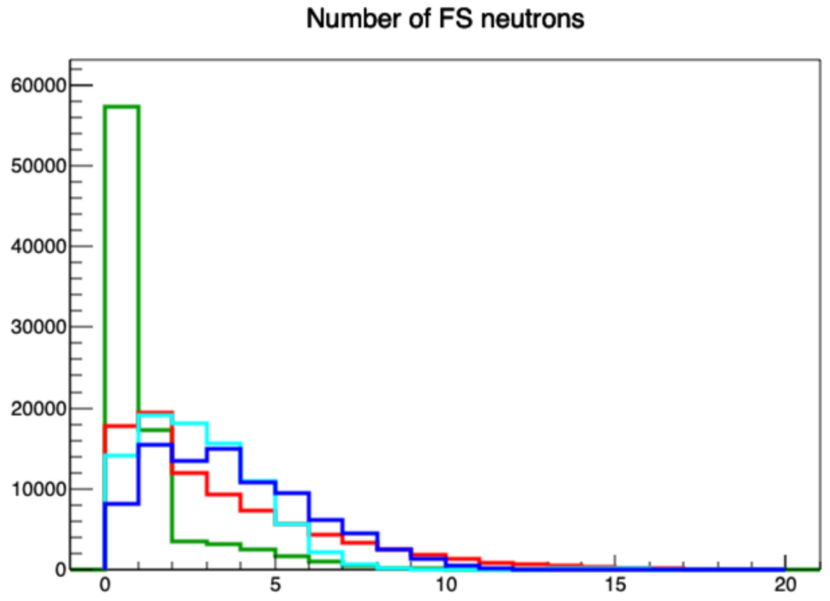


Number of events are normalized to hA2018



(See back-ups for separating into exclusive channels, and for p-Ar results)





Energy bias

- For the incident hadron, T_i denotes its kinetic energy and E_i denotes its total energy.
- In the final state, we define the reconstructable hadronic energy as

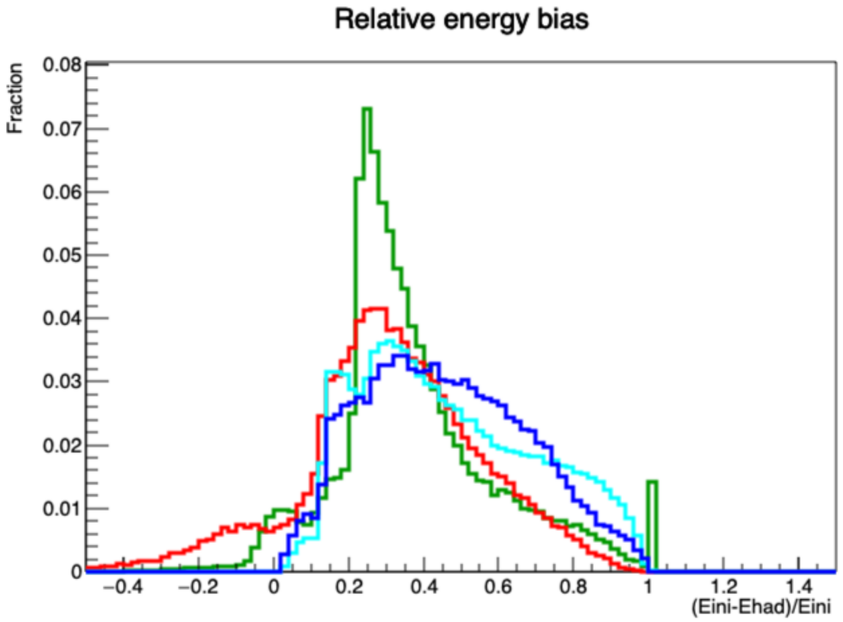
$$E_{\text{had}} = \sum T_p + \sum E_{\pi^{\pm}} + \sum E_{\pi^0} + \sum E_{\text{other}}$$

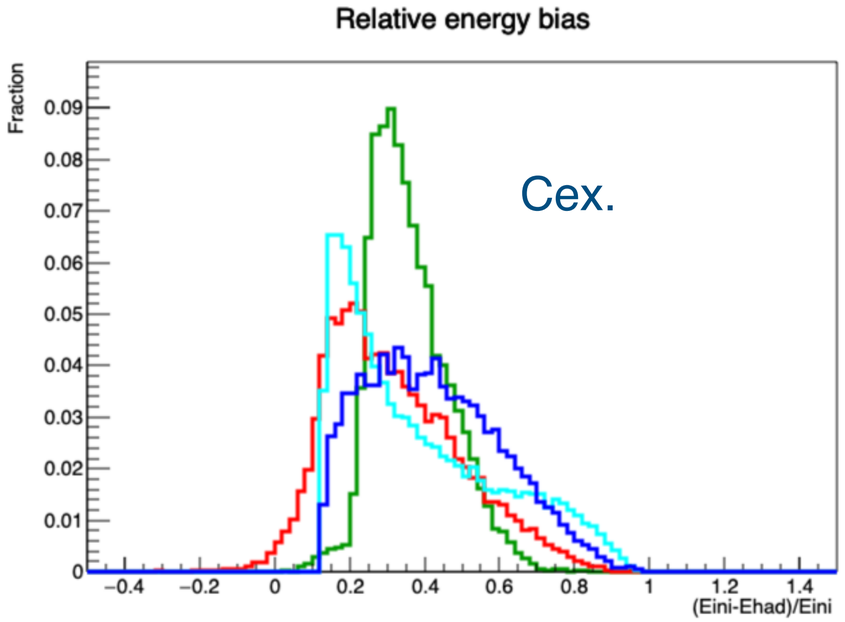
  - T_n is not included under the assumption that it is not measured with LAr detectors.

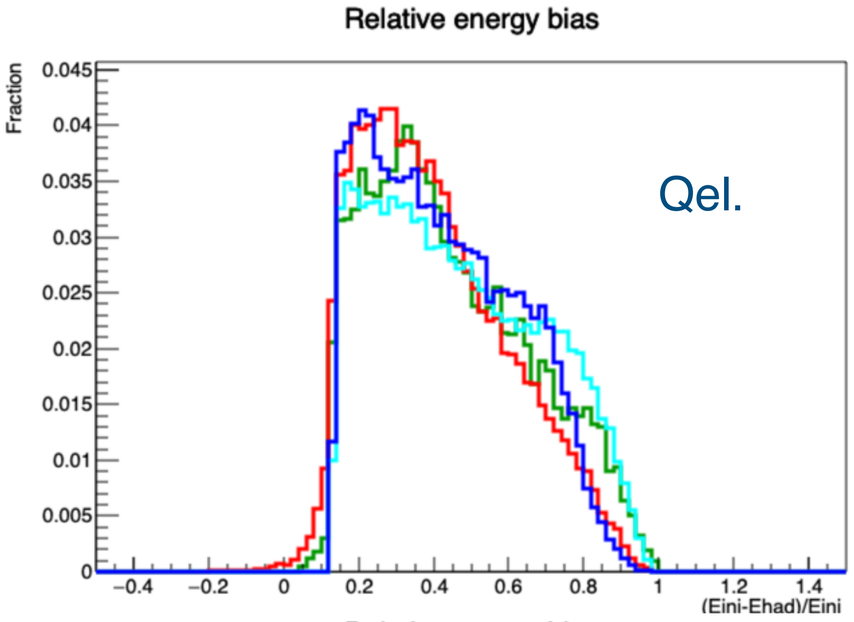
- We calculate the **relative energy bias** as
  - $\frac{E_i - E_{\text{had}}}{E_i}$ for pion events
  - $\frac{T_i - E_{\text{had}}}{T_i}$ for proton events

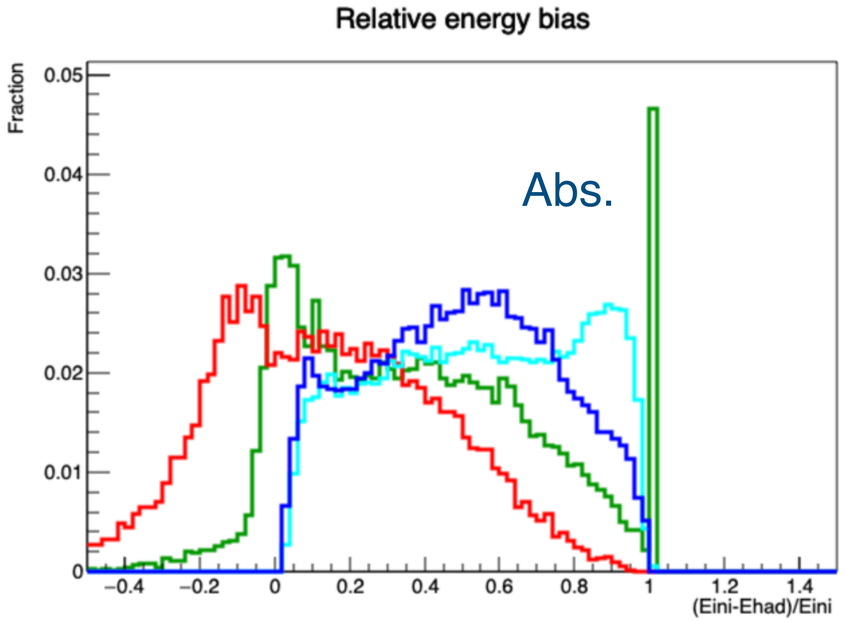
The bias is 0 if the incident hadron does nothing but escapes the nucleus and is detected; it is 1 if the energy of the incident hadron becomes completely undetectable.

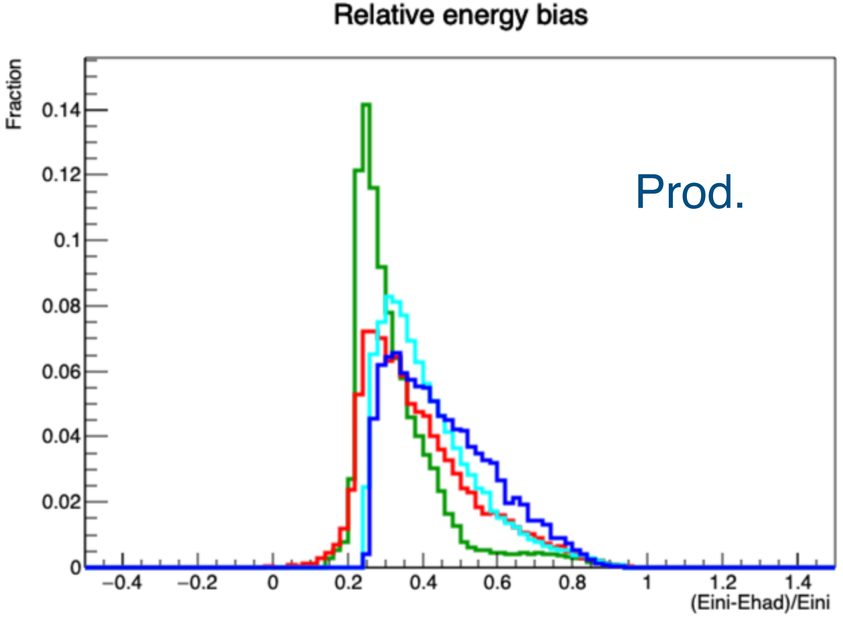
π^+-Ar relative energy bias

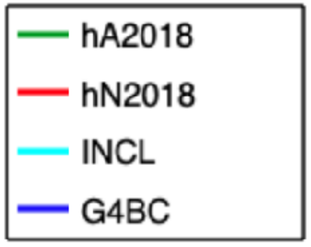








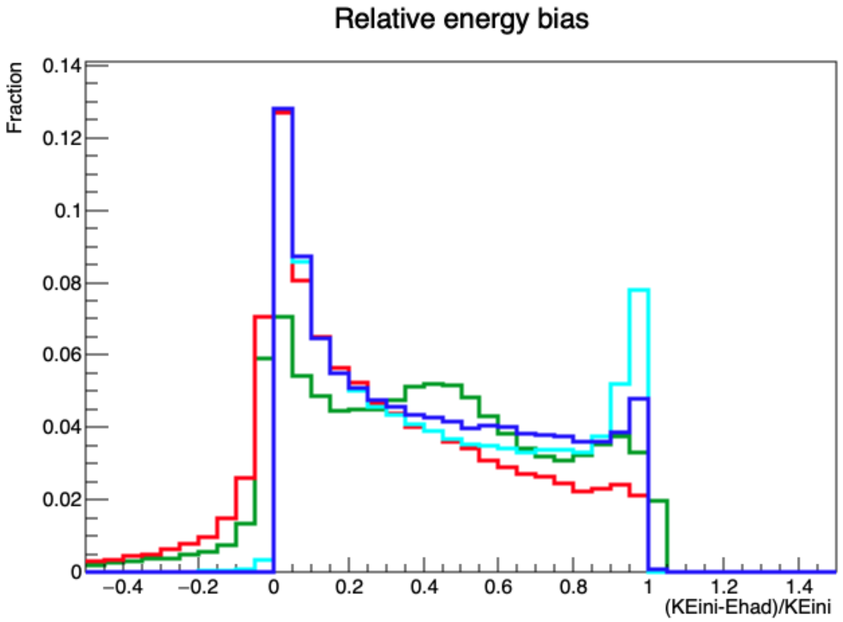


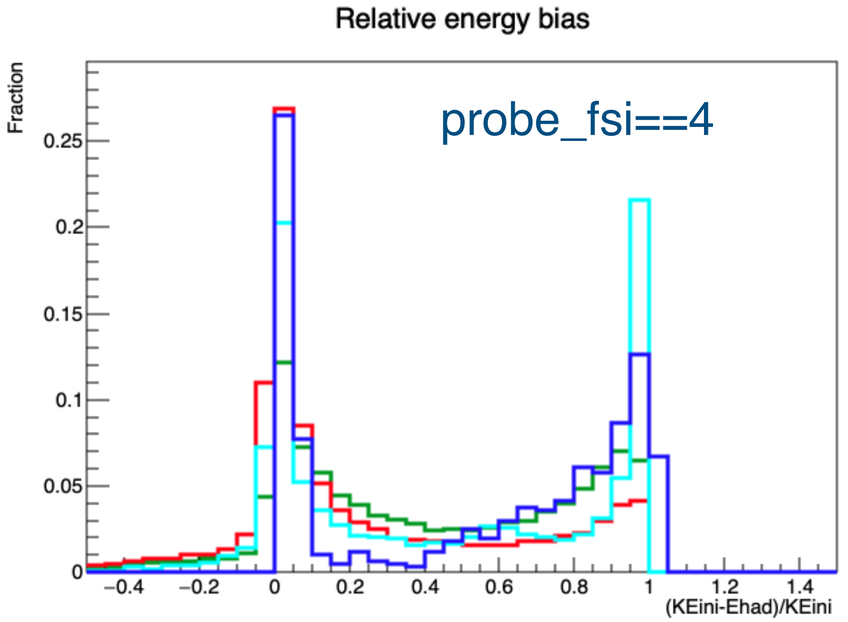


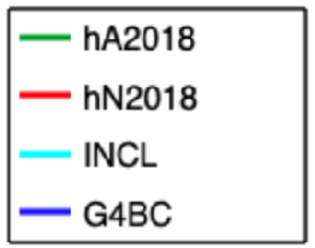
— hA2018 and hN2018 have negative energy bias?

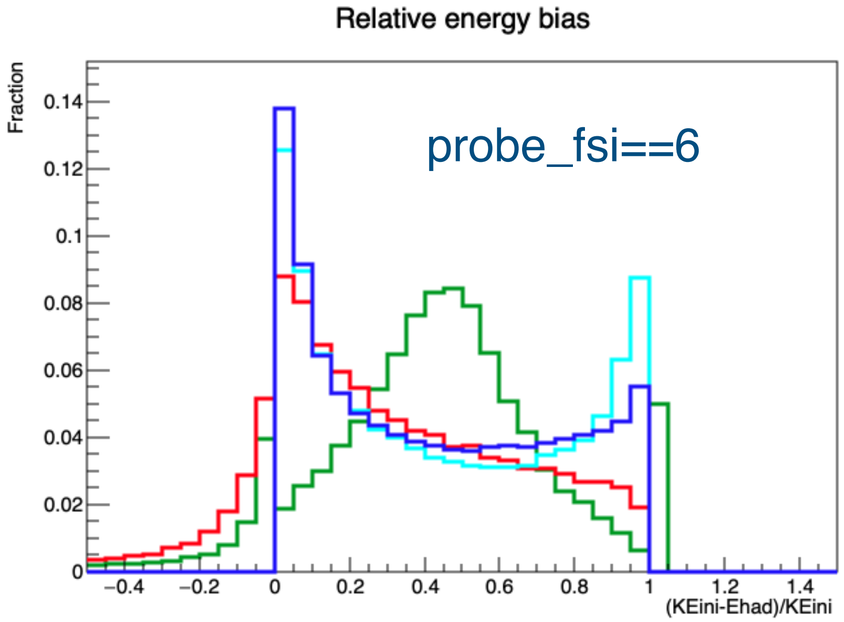
— Possibly due to nucleon vs nucleus rest frame.

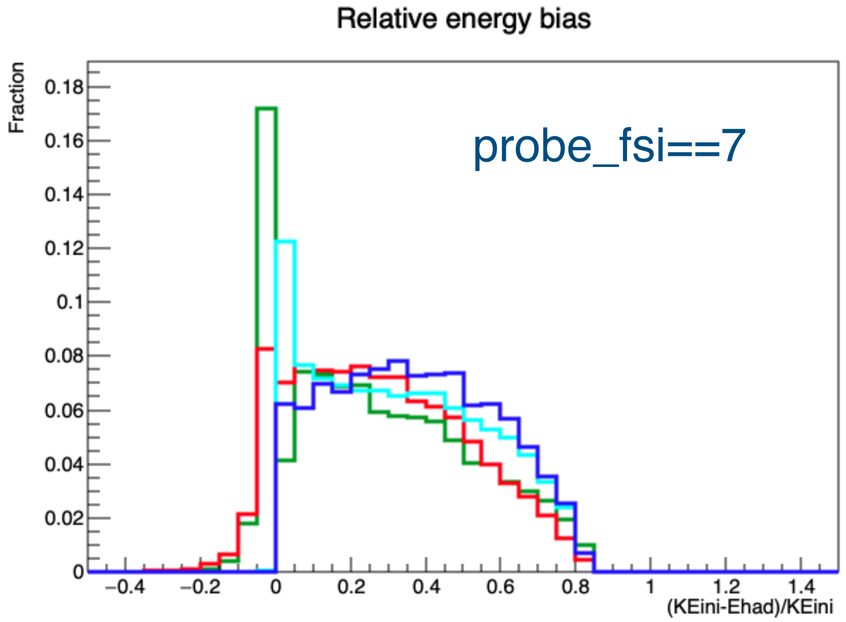
p-Ar relative energy bias







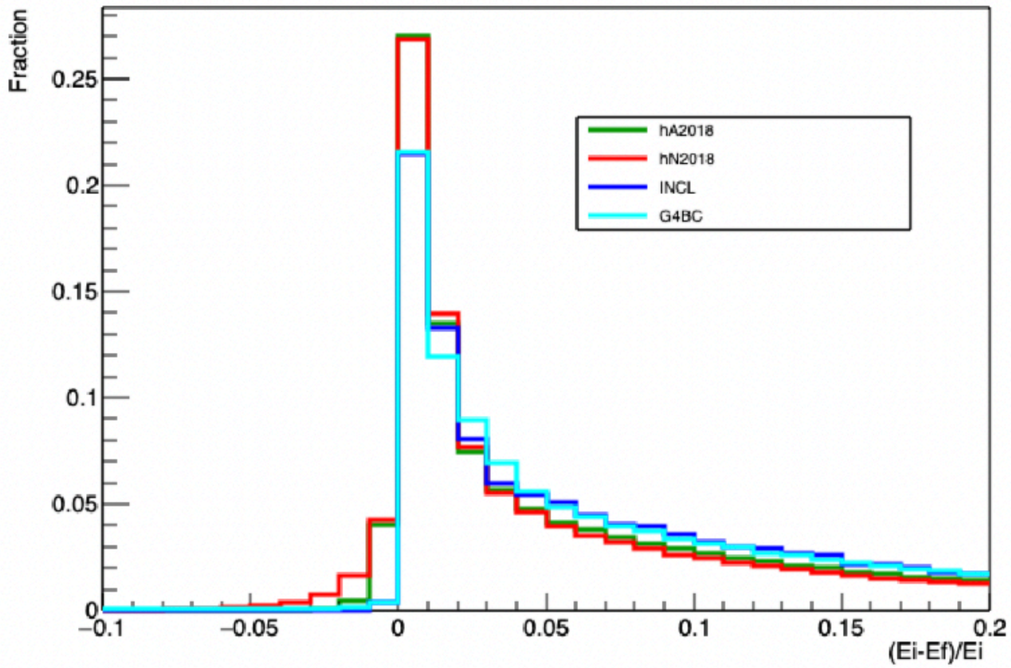


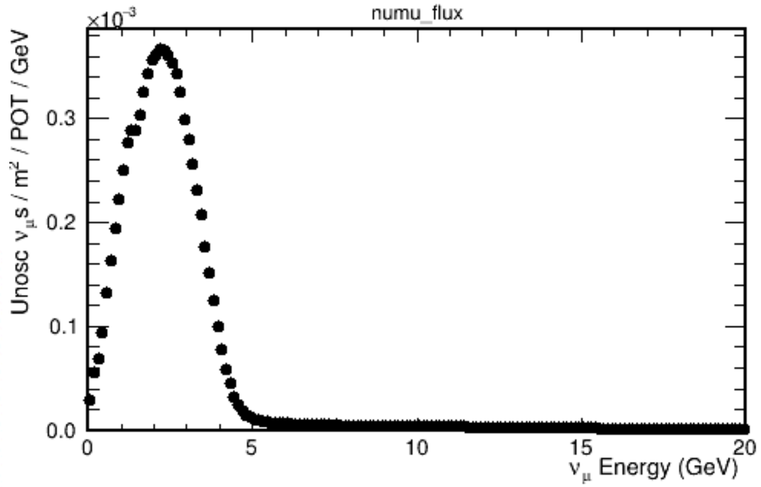


Generating neutrino events

- From the comparisons of variables, we see that different FSI models have obviously different predictions. We want to study if it also has large impact on neutrino events.
- We use DUNE estimated neutrino spectrum at ND as input flux.
- The relative energy bias for neutrino events is given as

$$\frac{E_\nu - E_l - E_{\mathrm{had}}}{E_\nu}$$



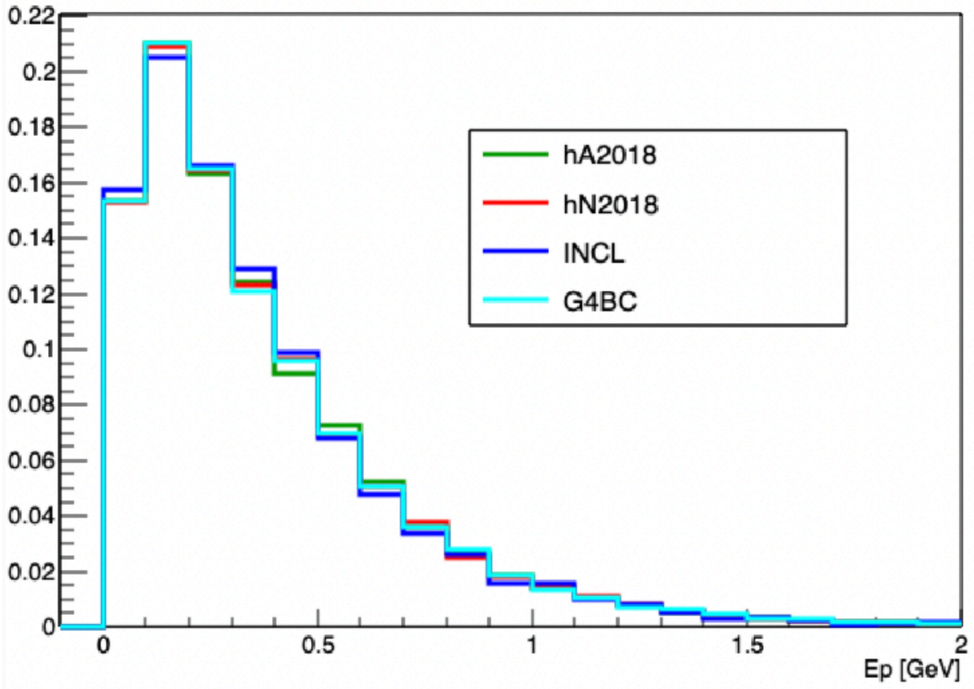


Using GENIE tunes
- G18_10a_00_000
- G18_10b_00_000
- G18_10c_00_000
- G18_10d_00_000

for the four FSI models

Comparing neutrino results and hadron results

- There are non-negligible difference in neutrino results for different FSI models.
- We want to study if the effects are similar as in hadron results.
  - In order to do so, take proton for example, we select true neutrino events with only one intermediate proton and no neutrons, which is $\nu_\mu + n \rightarrow \mu + p$.
  - Then we get the energy spectrum of such protons.



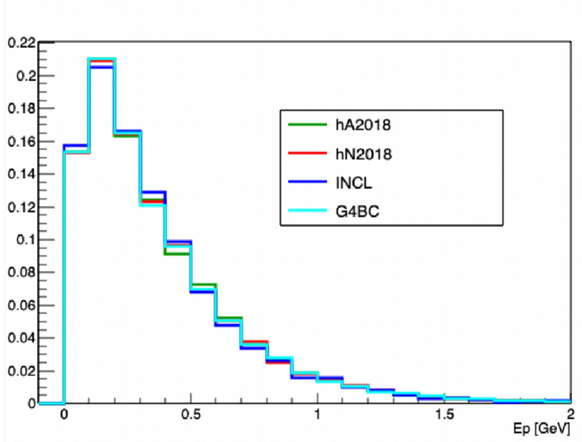
Note: the difference among FSI models here should be only due to statistical fluctuation.

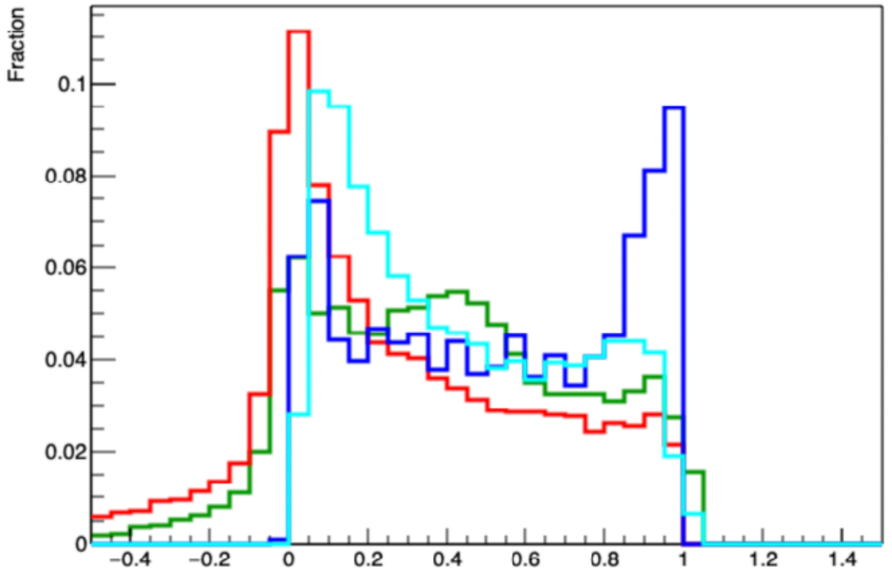
Comparing neutrino results and hadron results

- Continue with these $\nu_\mu + n \rightarrow \mu + p$ events, and consider p as incident particle, calculating the energy bias for events with FSI.

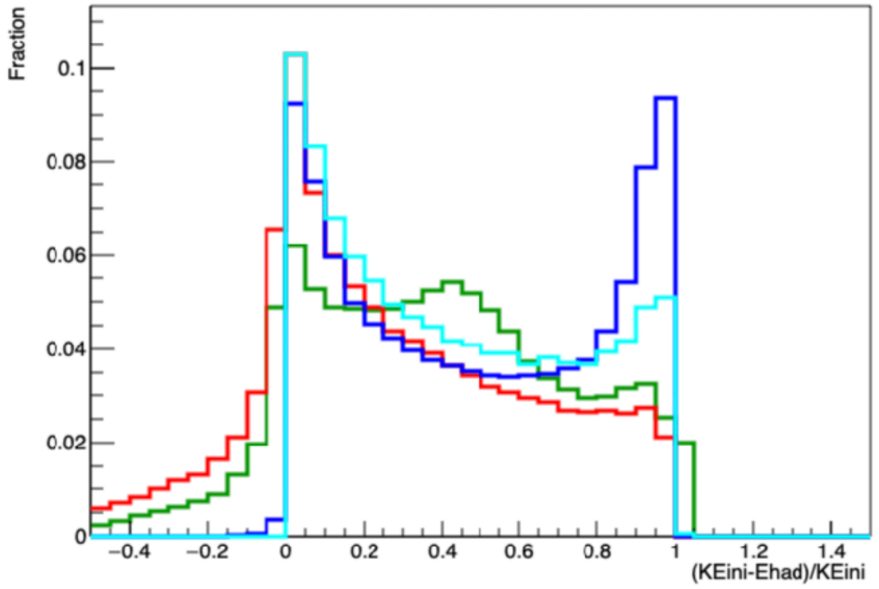
Relative energy bias $\dfrac{T_p - E_{\text{had}}}{T_p}$

- Use the same input flux, generate proton events.

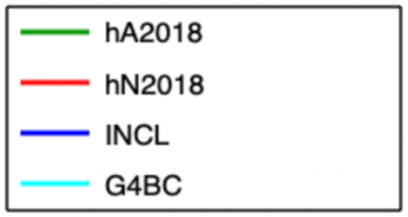


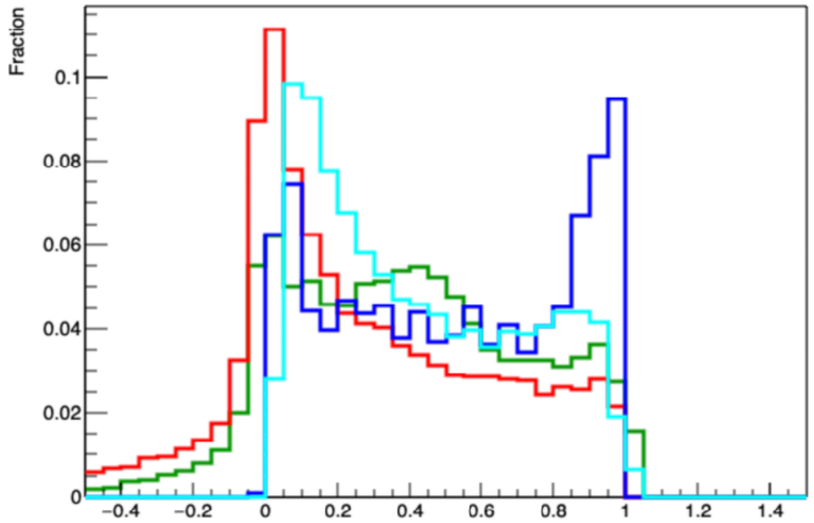


Relative energy bias from neutrino events (1M generated)

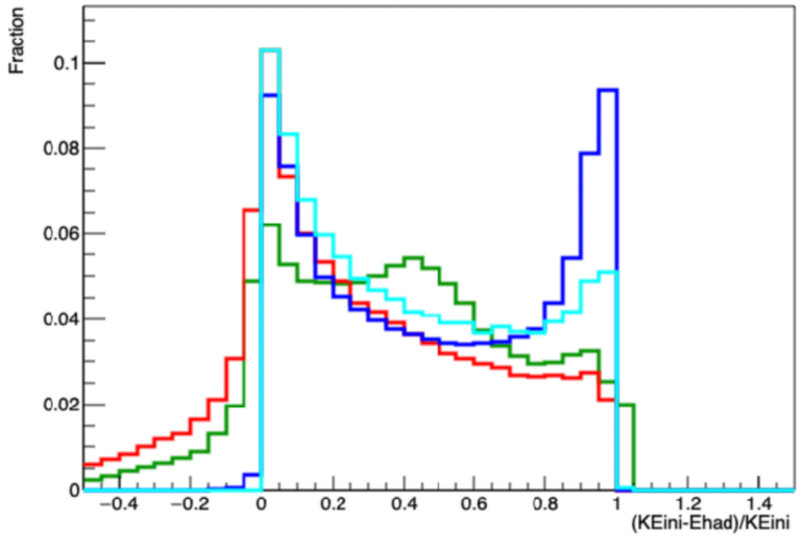


Relative energy bias from proton events (1M generated)



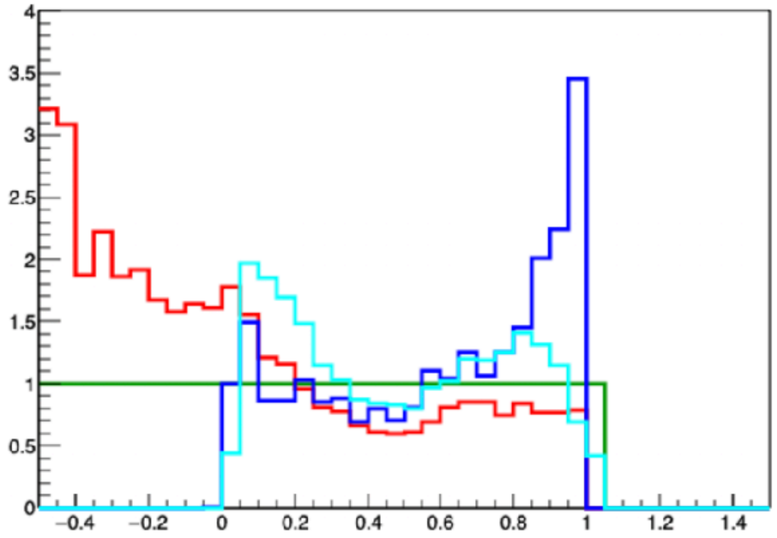


Relative energy bias (1M neutrino events)

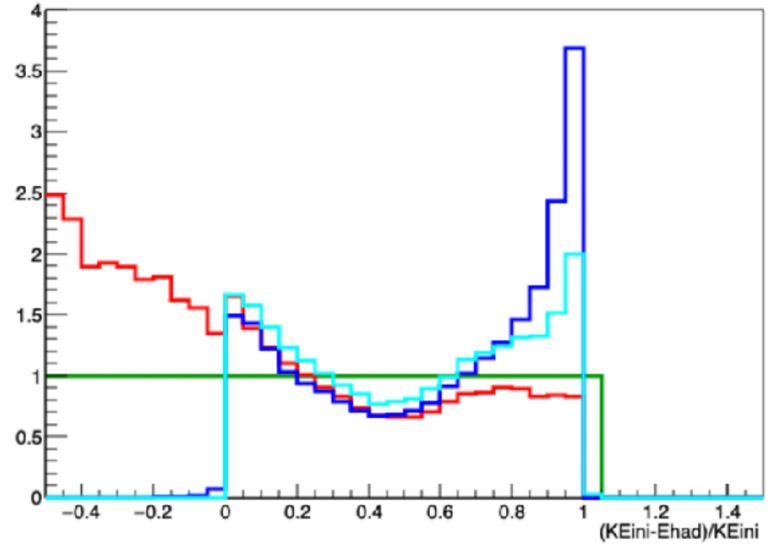


Relative energy bias (1M proton events)

Similar features in neutrino mode and proton mode



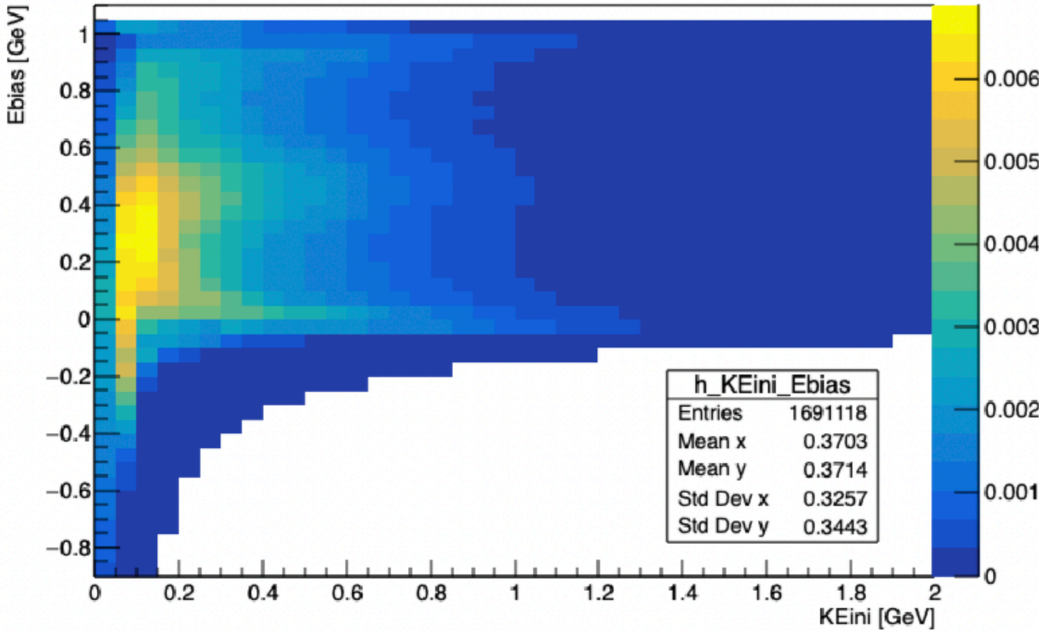
Ratio to hA2018 (1M neutrino events)

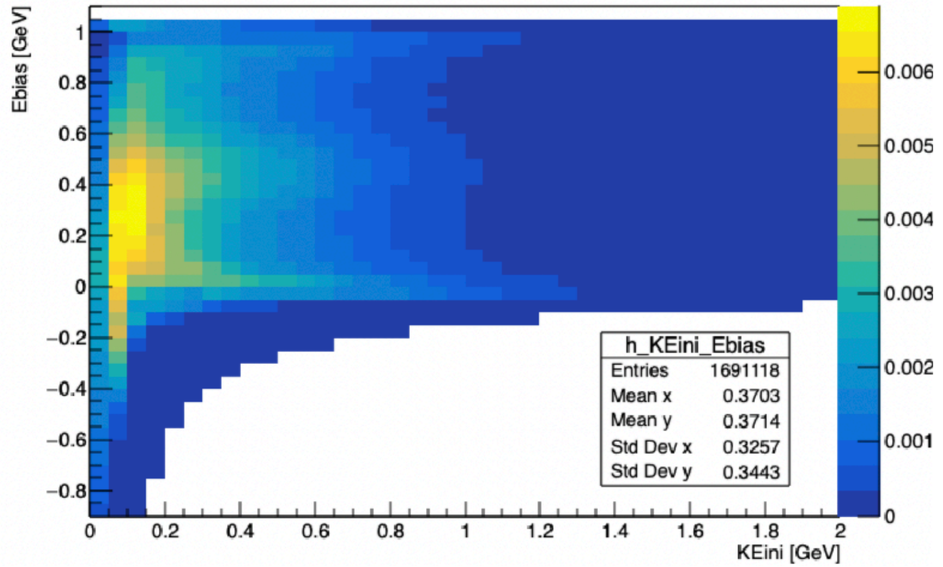


Ratio to hA2018 (1M proton events)

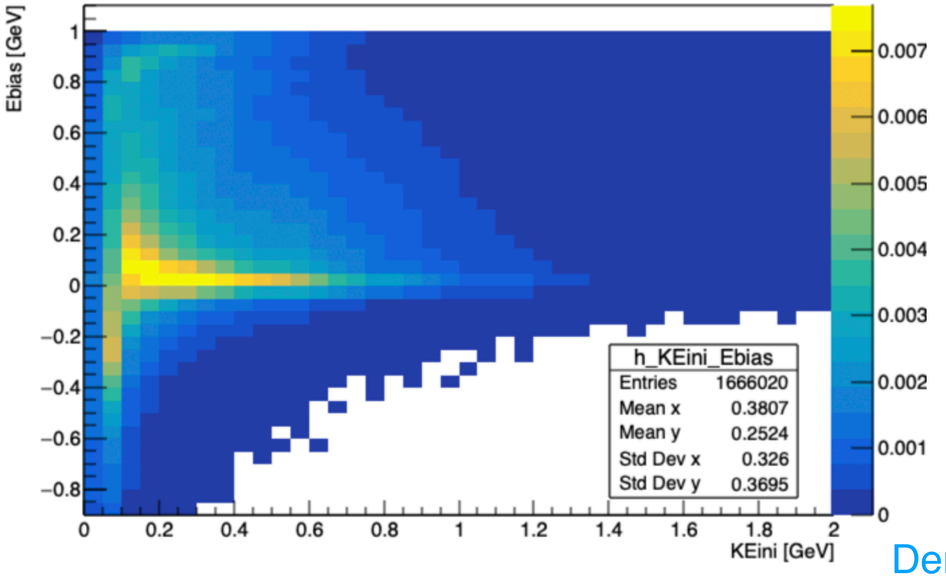
Create FSI dials/template in GENIE

- The neutrino results and proton results have similar features, which suggests the feasibility to use proton samples to study the effects of different FSI models in neutrino events.
  - We assume it is also the case for pion, whose feasibility is hard to be proved in the same way.
- Therefore, we plan to generate large sample of proton events, creating 2D plots of incident proton KE vs energy bias for the four FSI models.
- These 2D plots can serve as reweighting template for neutrino events.



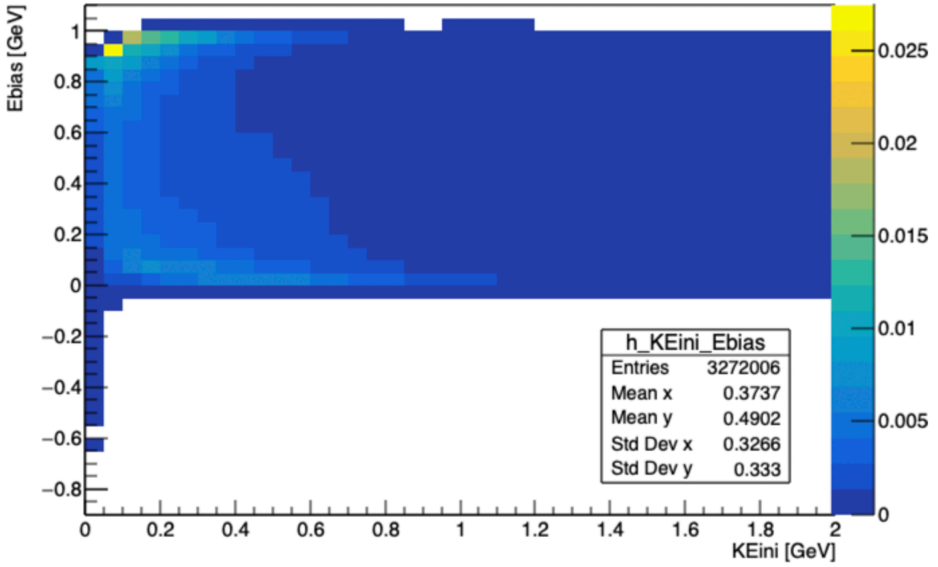


hA2018

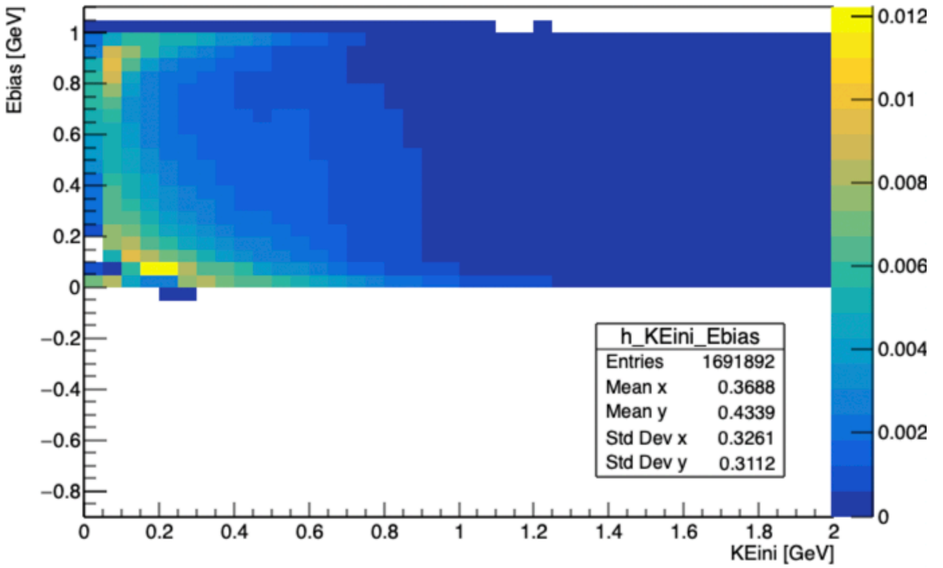


hN2018

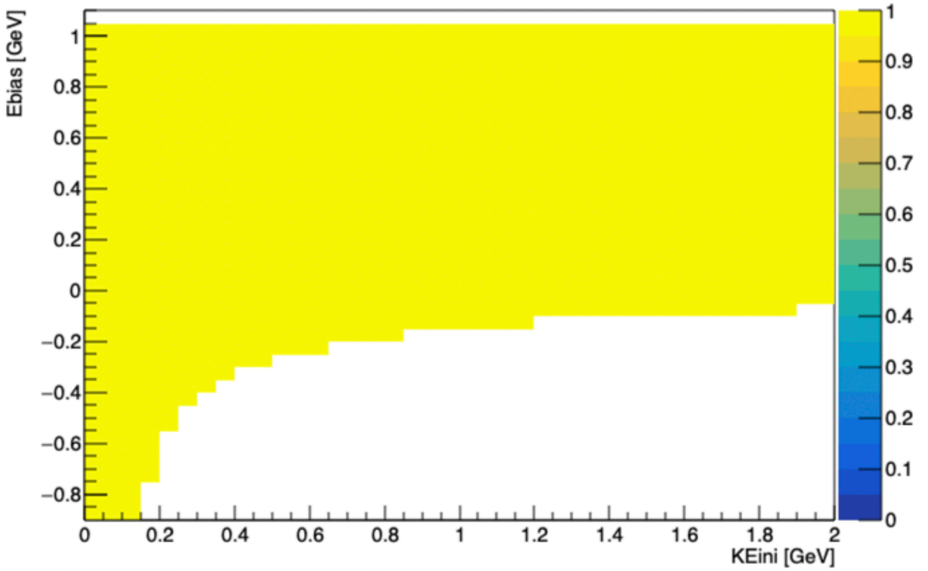
Derived from 20M generated events in each model



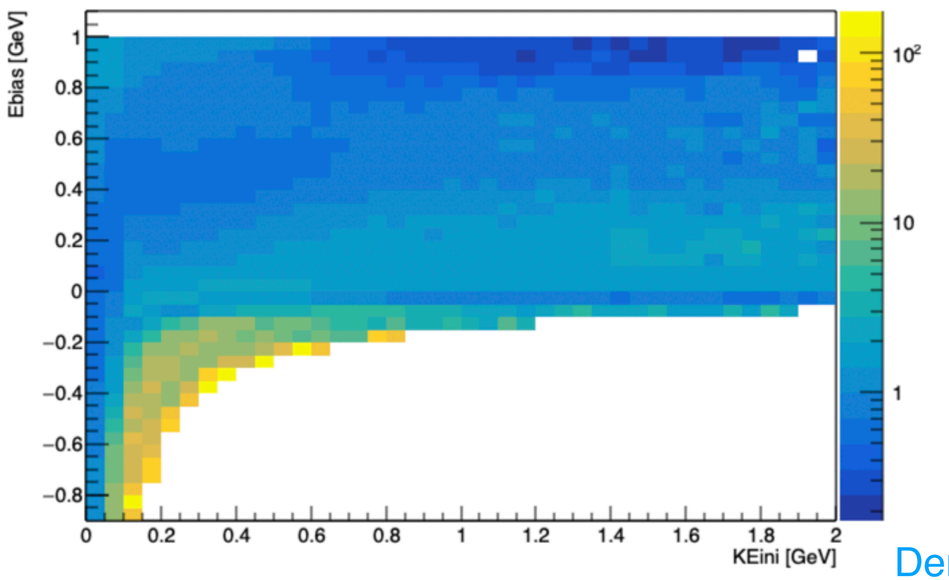
INCL



G4BC

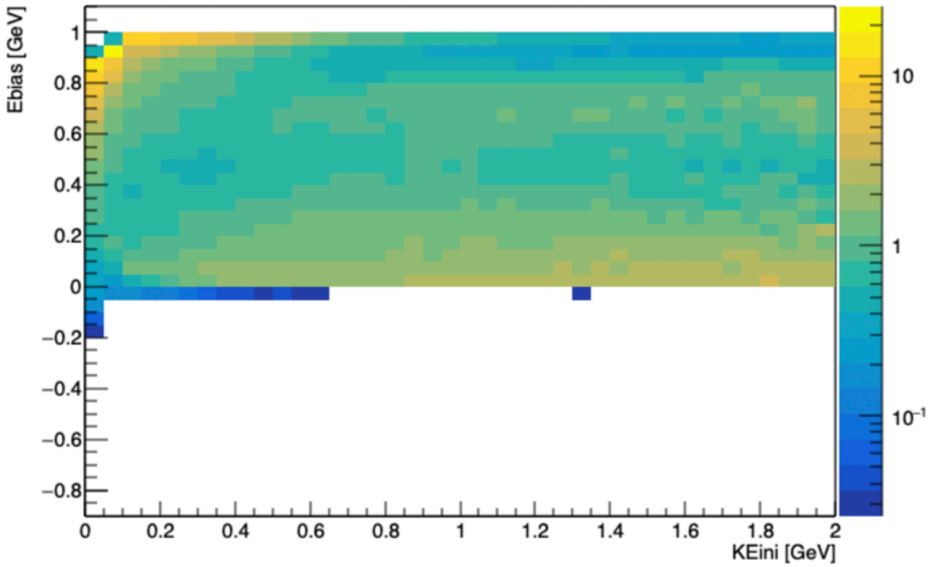


hA2018 / hA2018

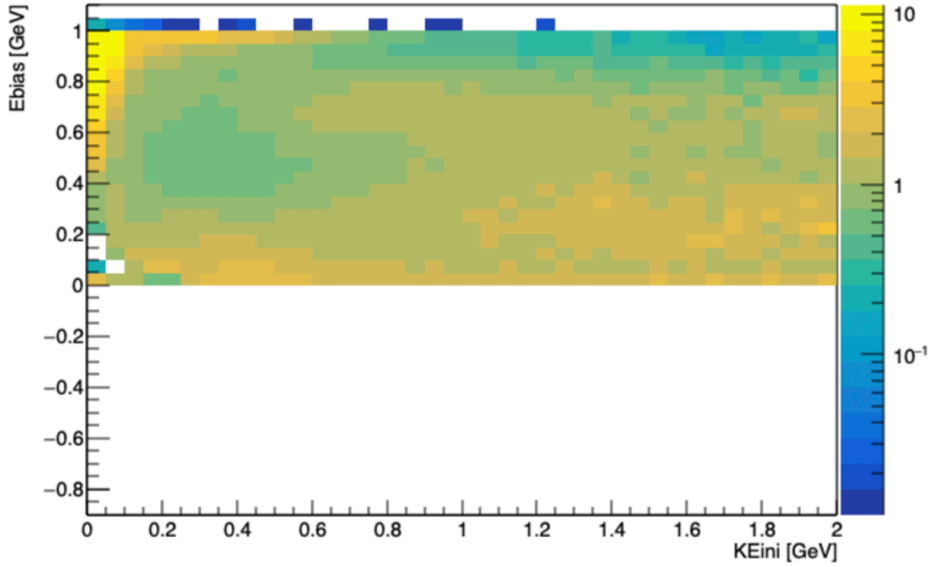


hN2018 / hA2018

Derived from 20M generated events in each model



INCL / hA2018



G4BC / hA2018

Summary

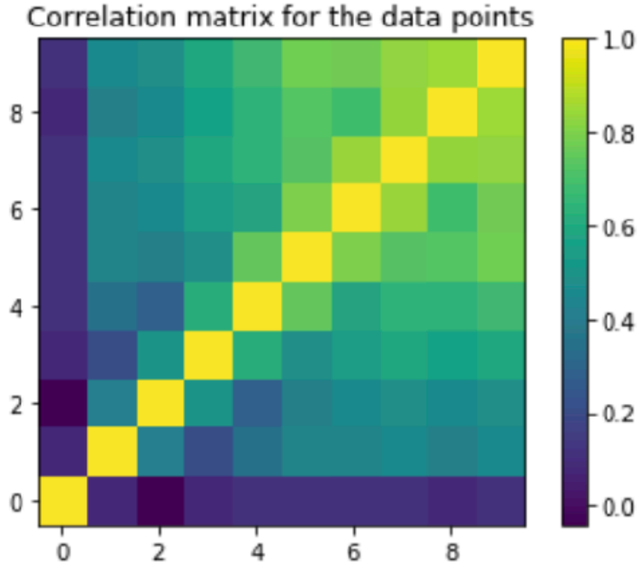
- Final-state interaction (FSI) is an important effect involved in neutrino detections. We need to model the FSI effect properly.
- Previously, we mainly consider the fluctuations of hA model for FSI-related uncertainty in neutrino analyses. For different FSI models in GENIE, large differences are seen, which could account for new source of systematic uncertainty for neutrino analyses.
- We showed different FSI models have similar features in both hadron events and neutrino events.
- This inspires us to directly use hadron beam sample to create reweighting templates to study this potential systematic effect for neutrino events.

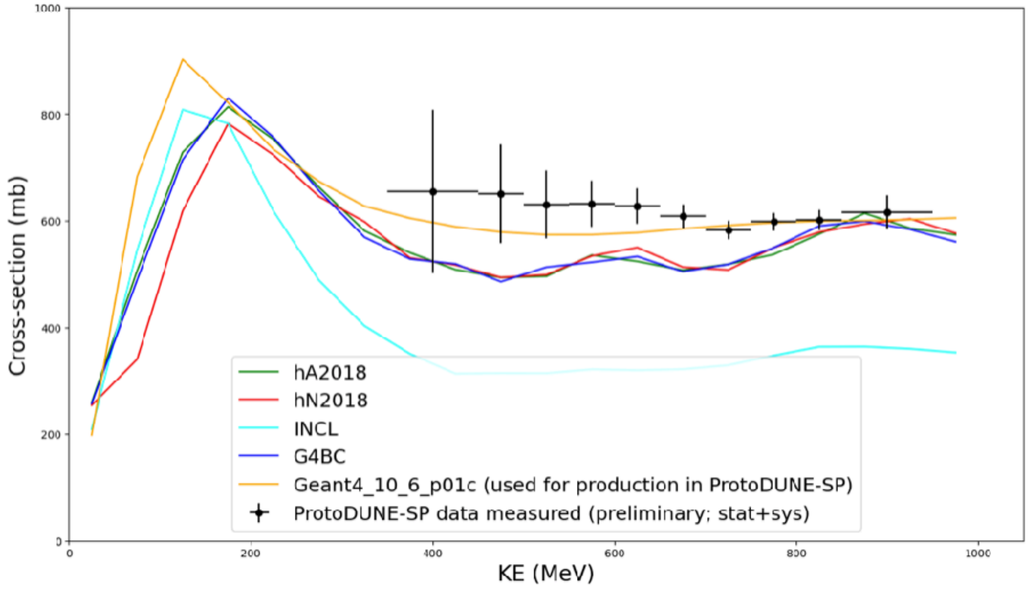
Back-ups

Comparing GENIE XS to ProtoDUNE-SP data

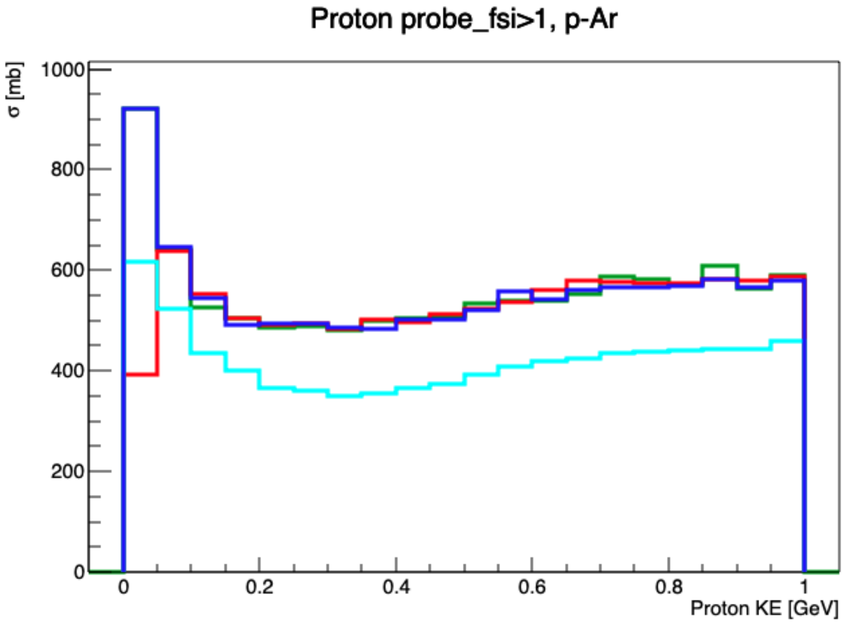
- Calculate the chi2 of the measured data points against a model curve
  - $\chi^2 = (x_{\text{data}} - x_{\text{curve}}) \cdot V_{\text{data}}^{-1} \cdot (x_{\text{data}} - x_{\text{curve}})^T$
  - V_{data} is the covariance matrix for the measured data points
- $\chi^2/N_{\text{bins}} \approx 1$ suggests consistency.
  - hA2018: Chi2/Ndf = 93.15/10 = 9.31
  - hN2018: Chi2/Ndf = 79.94/10 = 7.99
  - INCL: Chi2/Ndf = 1603.02/10 = 160.30

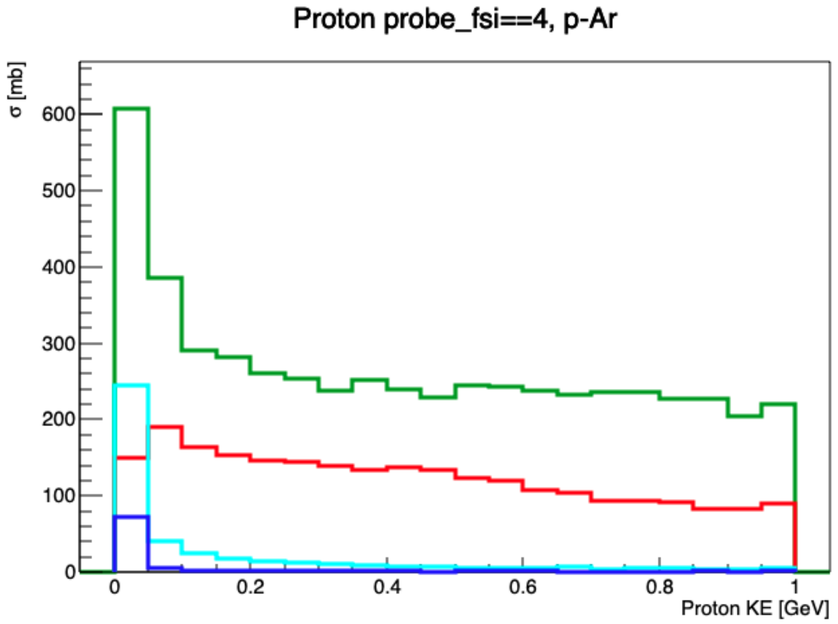
    (Unsolved issues about the scale factor for INCL model)
  - G4BC: Chi2/Ndf = 95.85/10 = 9.58
  - Gean4_10_6_p01c: Chi2/Ndf = 16.36/10 = 1.64



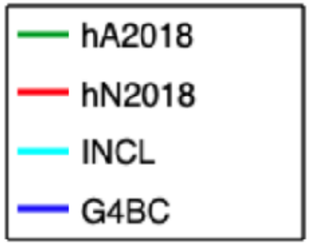


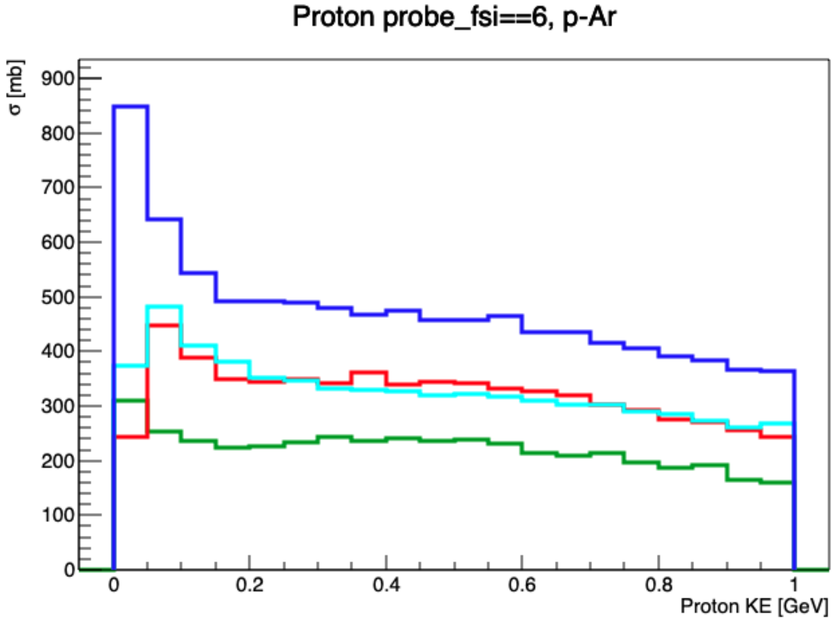
p-Ar cross-section in different channels

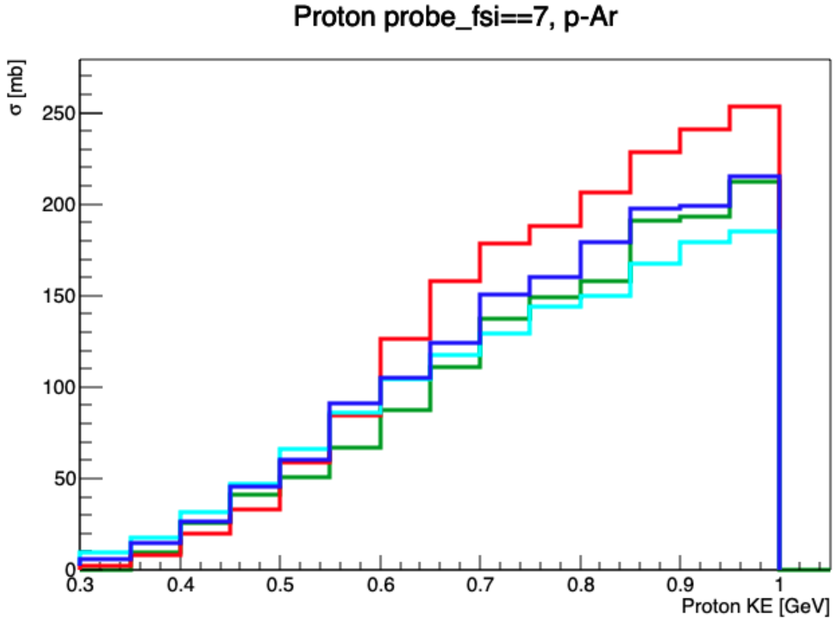




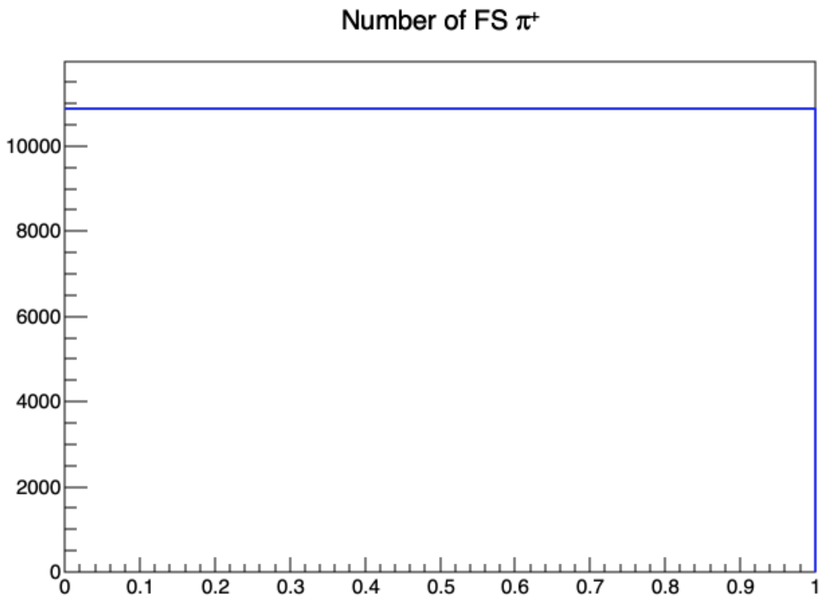
Unsolved issues about the scale factor for INCL model

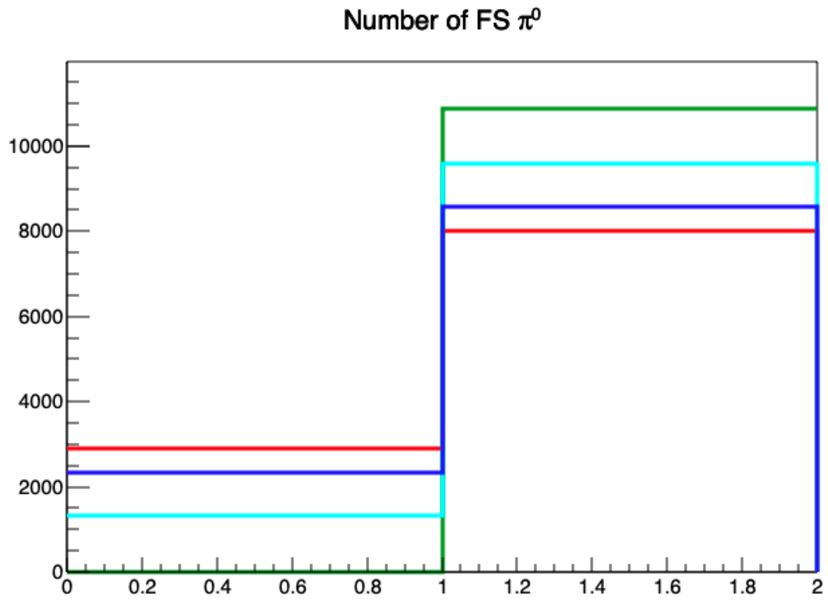


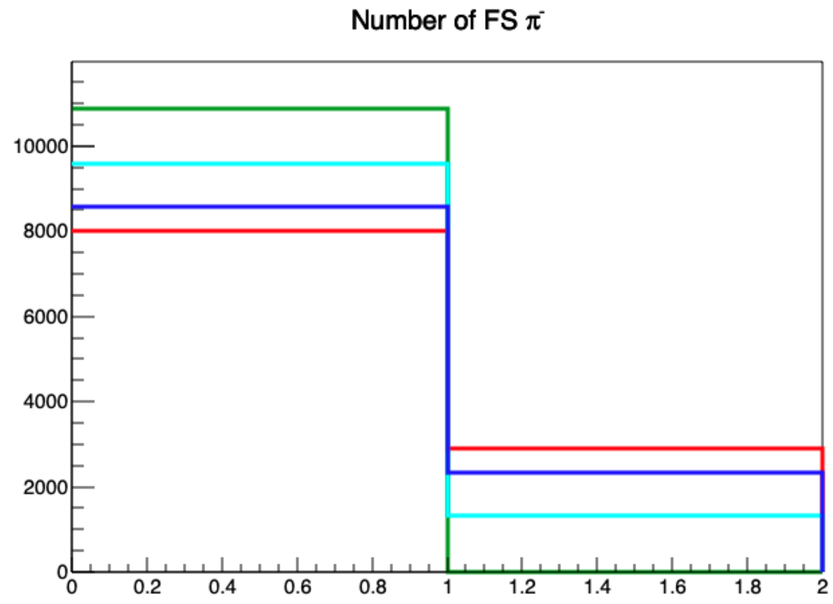


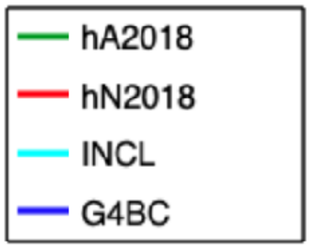


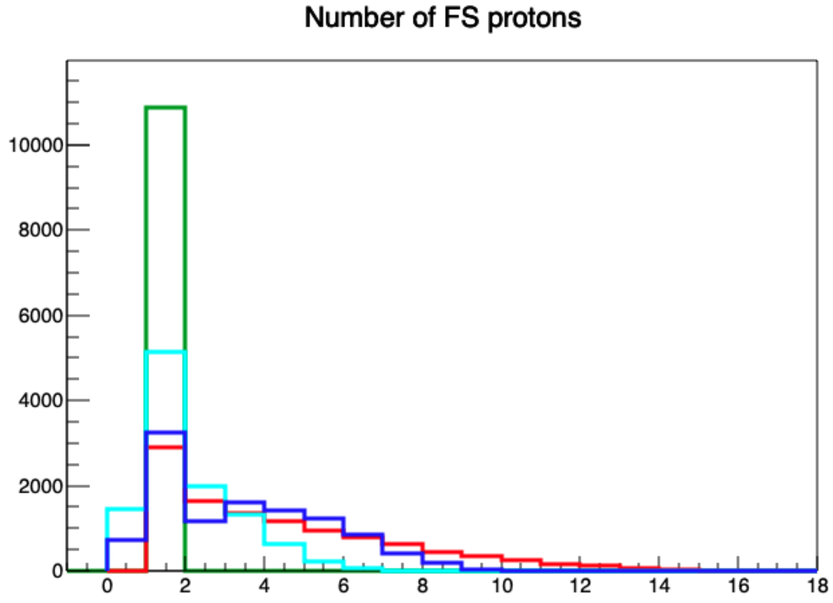
π^+-Ar FS particle multiplicity in Cex. channel

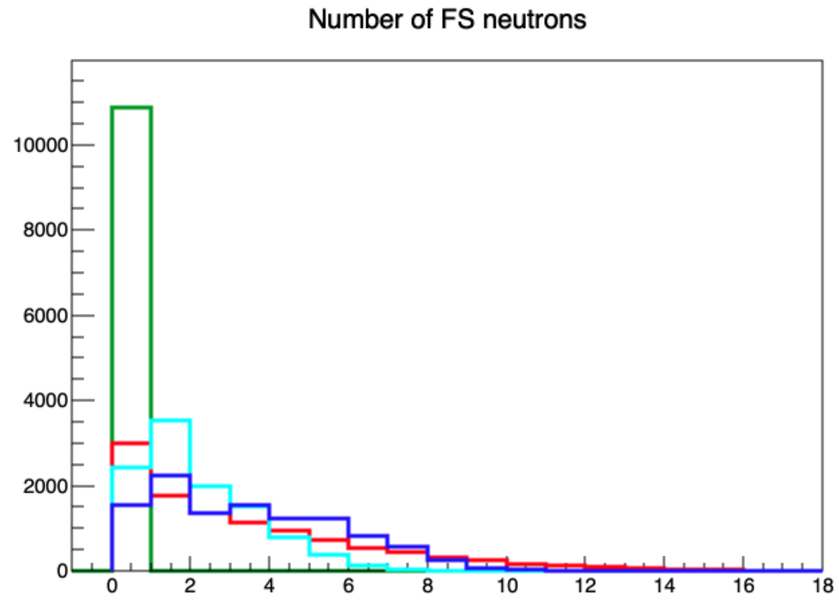




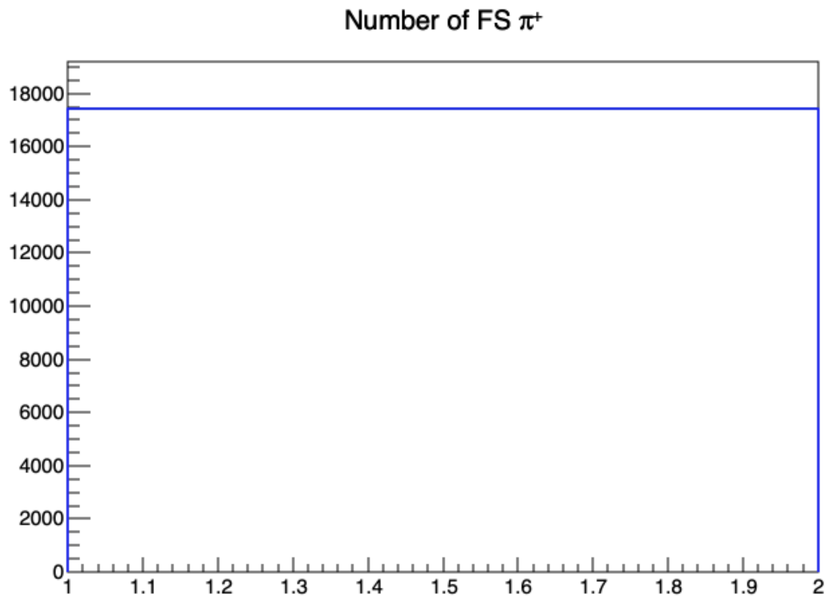


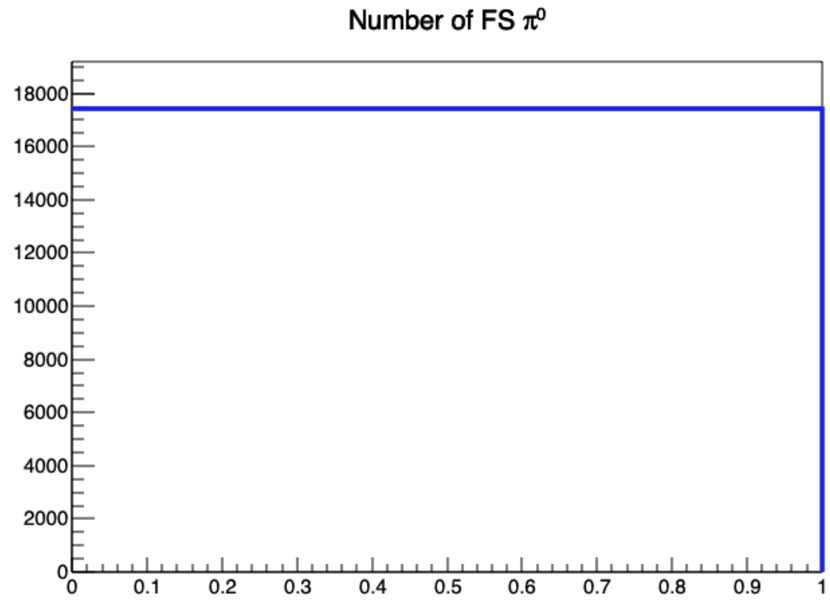


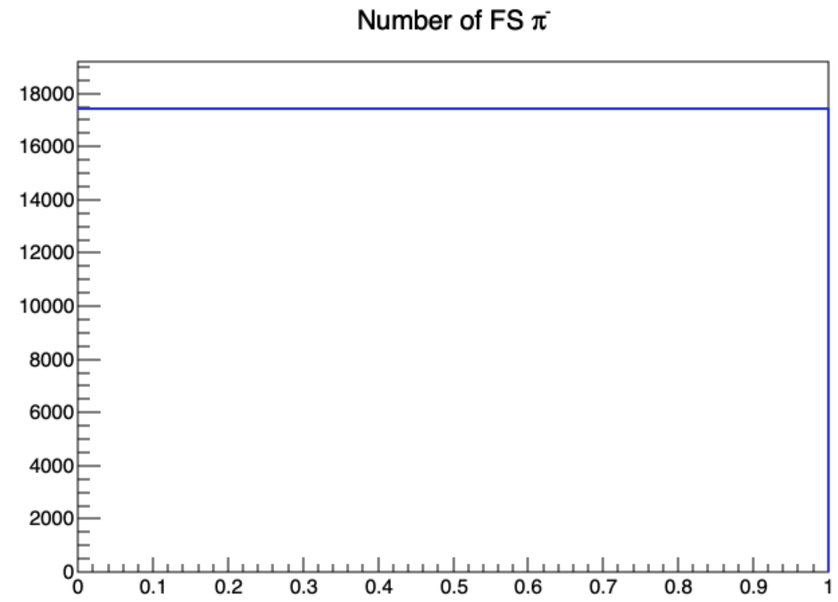


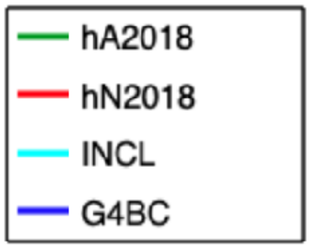


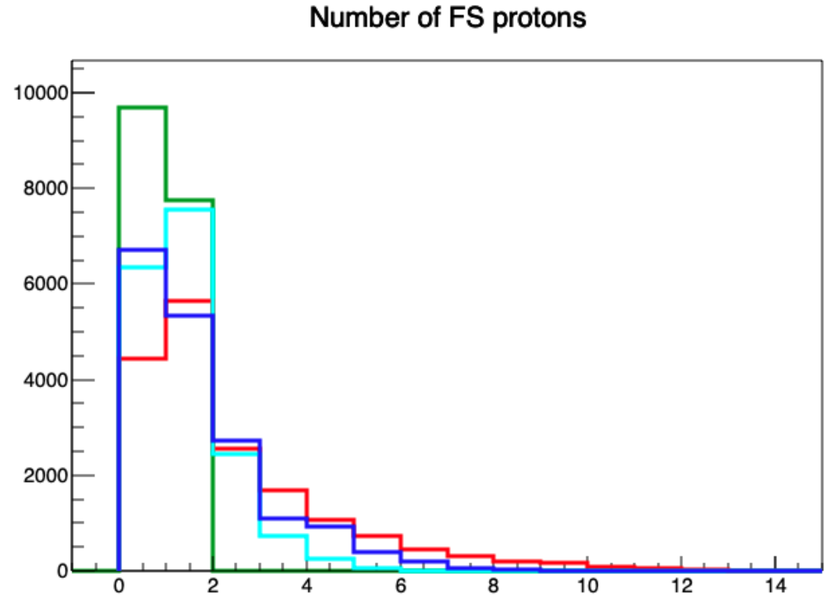
π^+-Ar FS particle multiplicity in Qel. channel

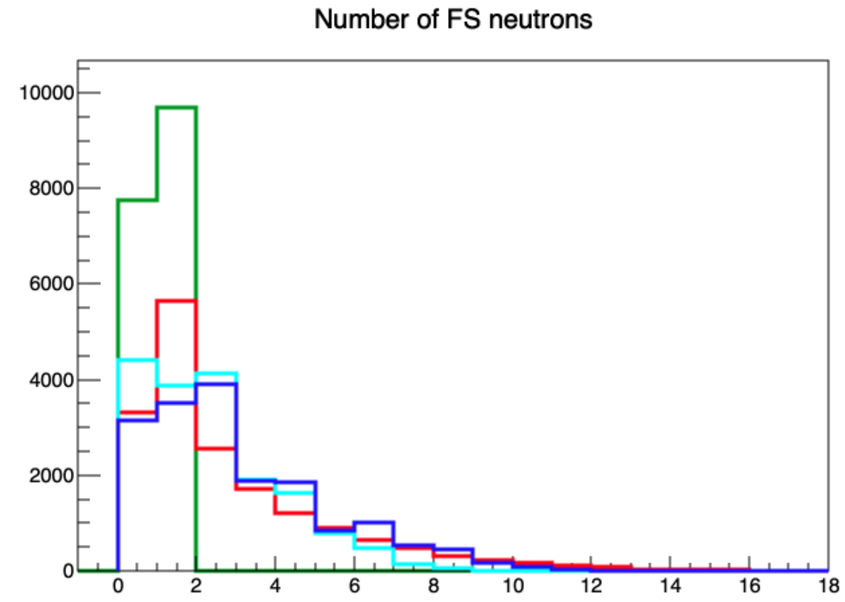




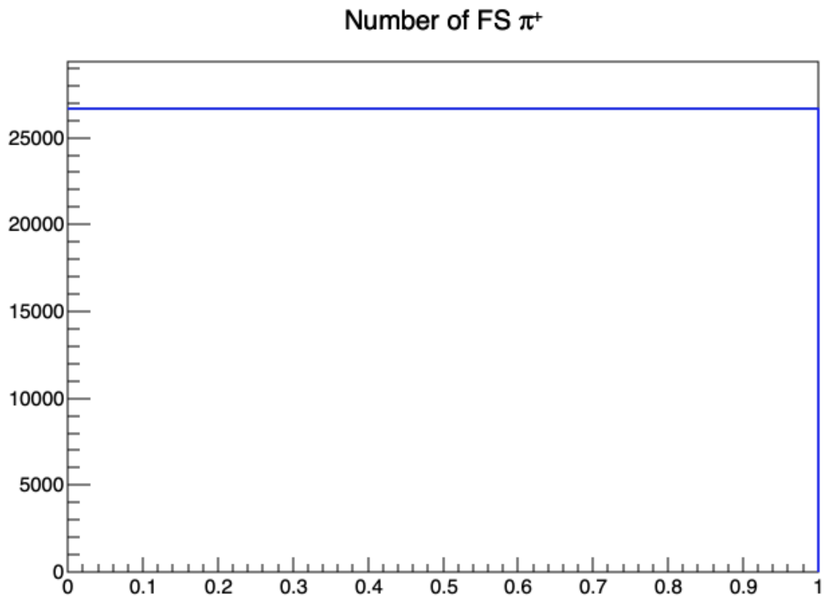


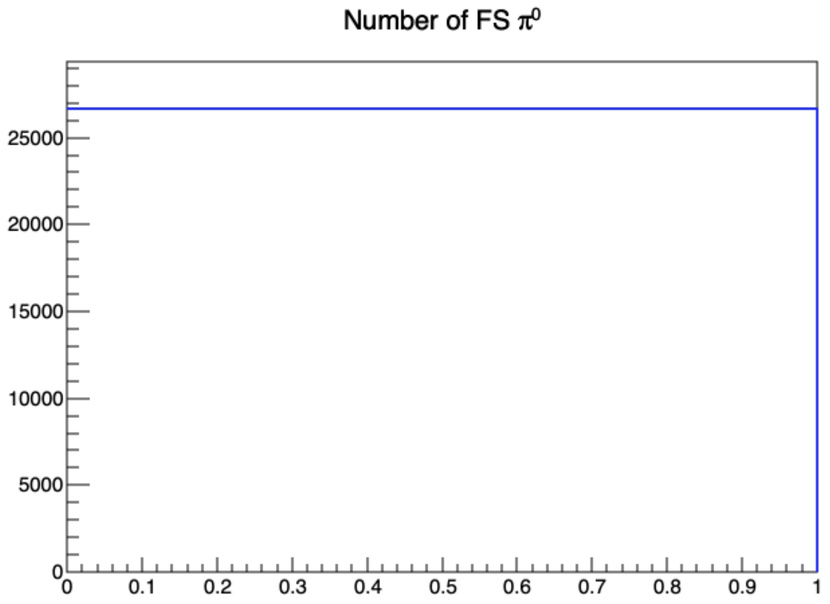


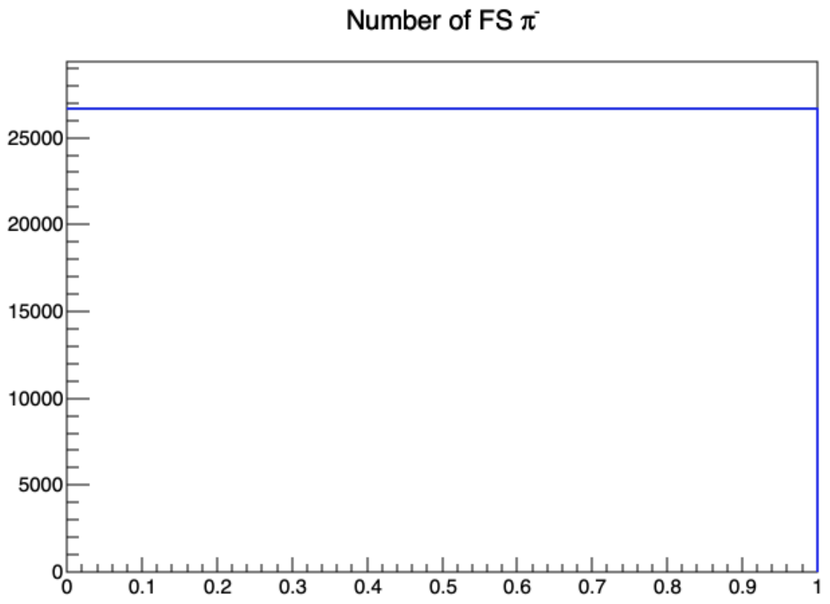


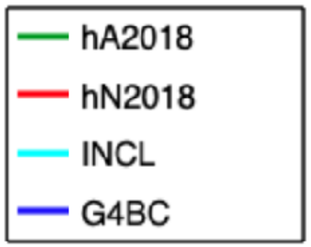


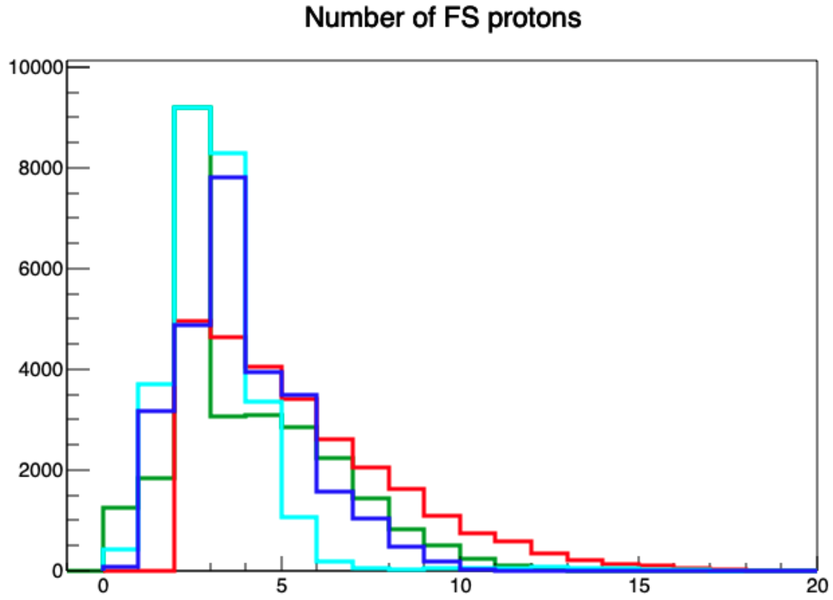
π^+-Ar FS particle multiplicity in Abs. channel

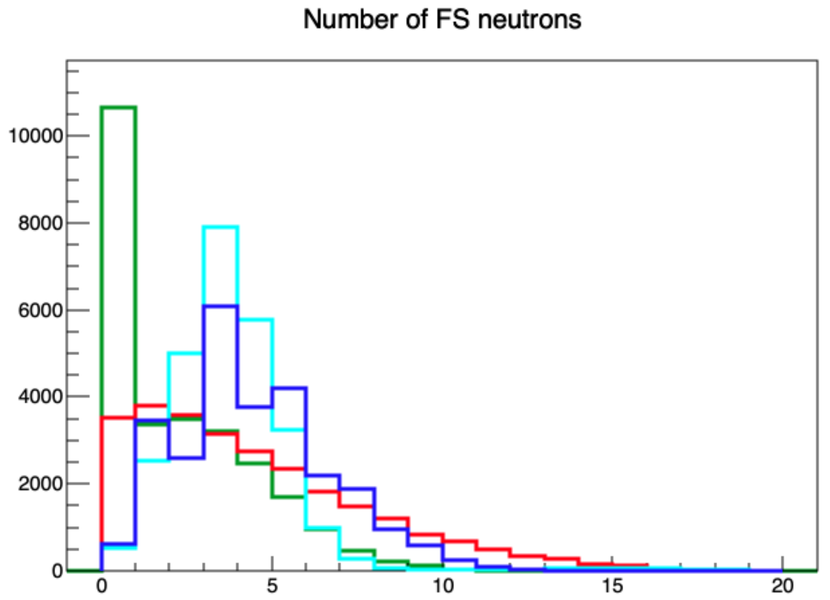




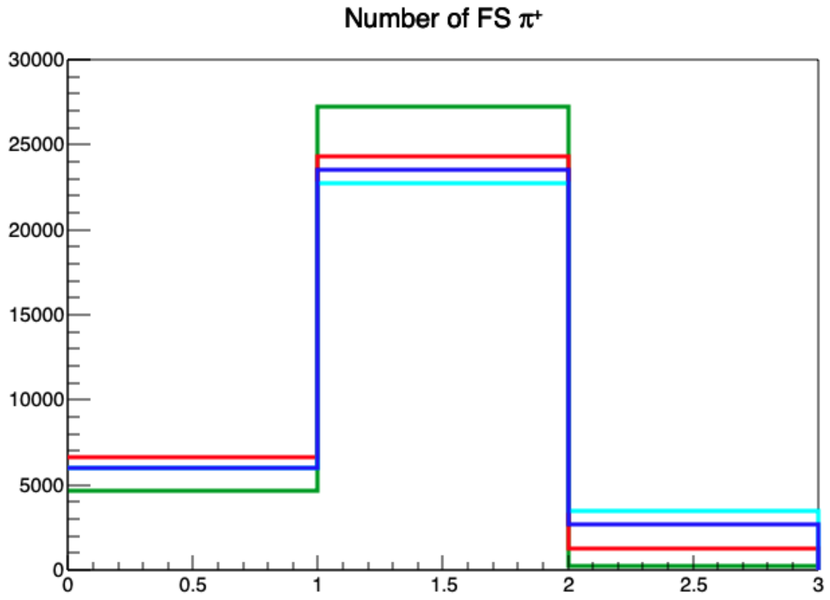


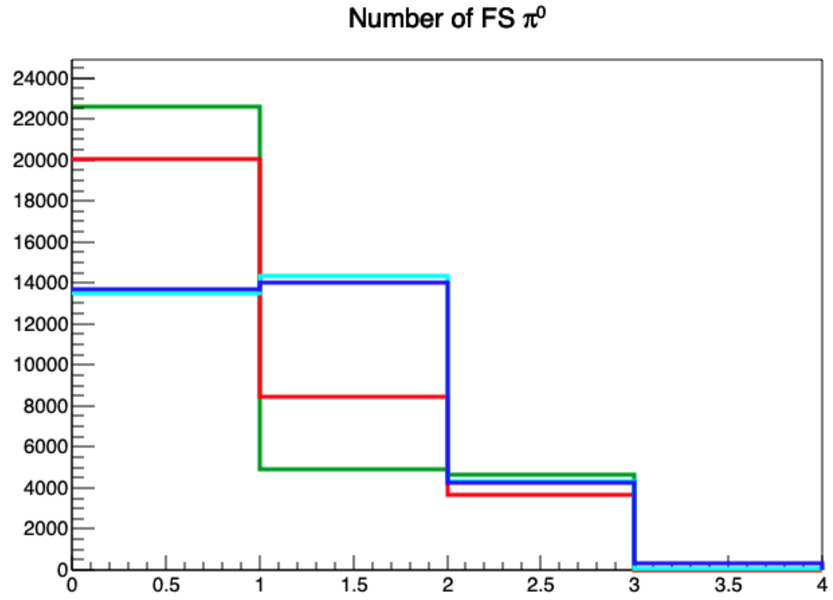


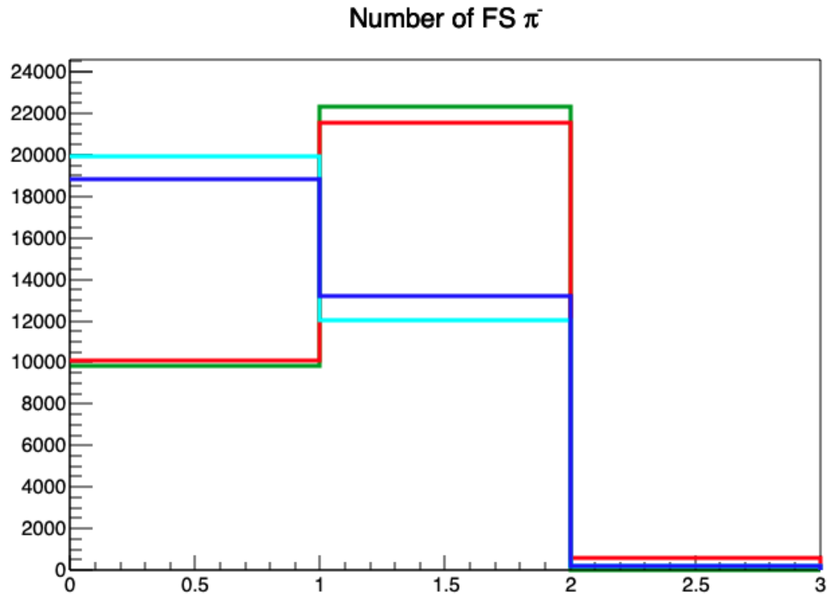


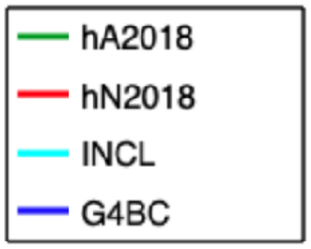


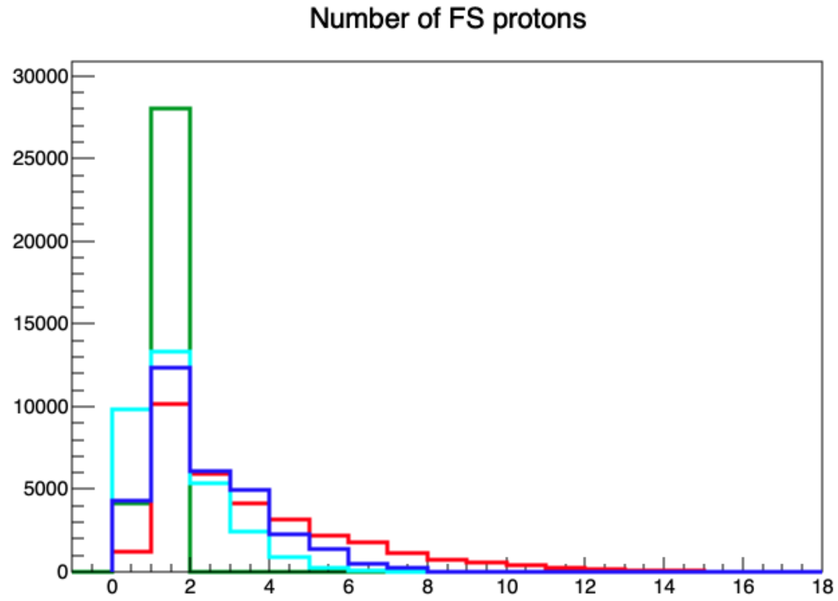
π^+-Ar FS particle multiplicity in Prod. channel

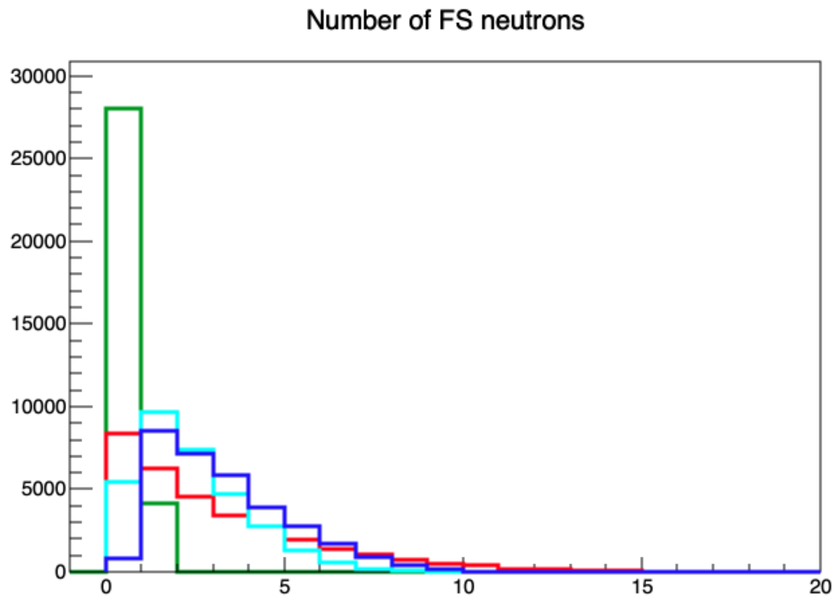




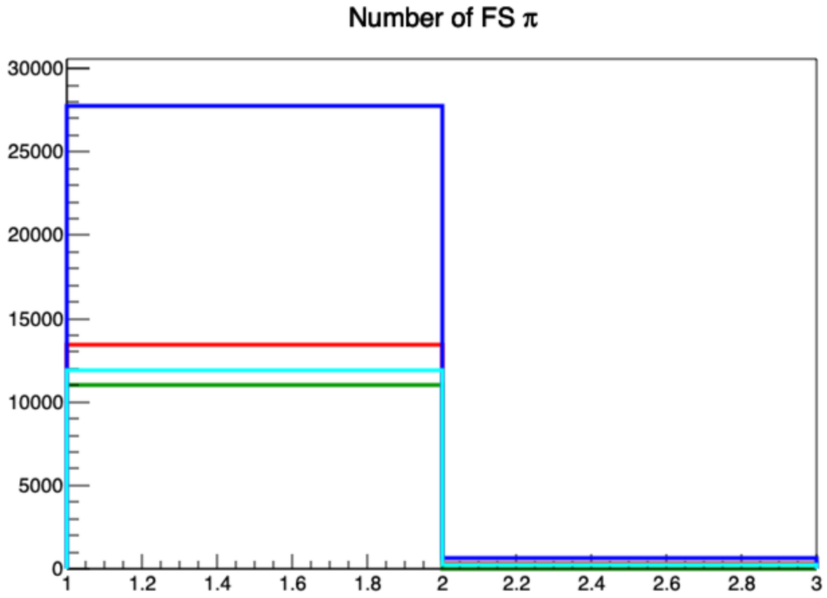


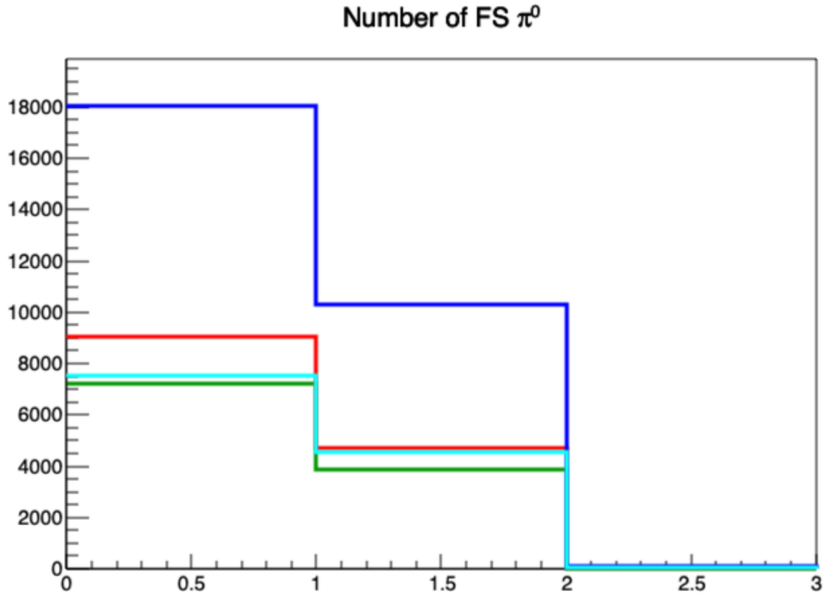


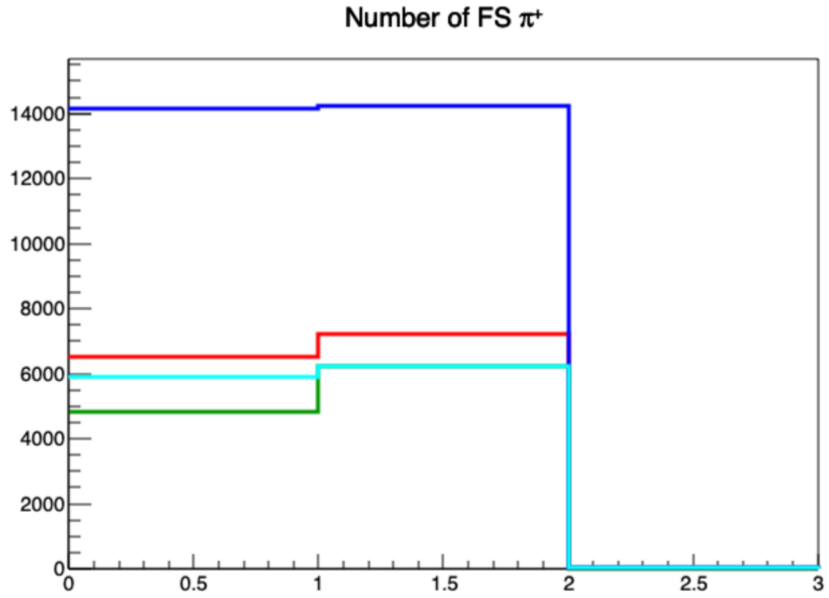


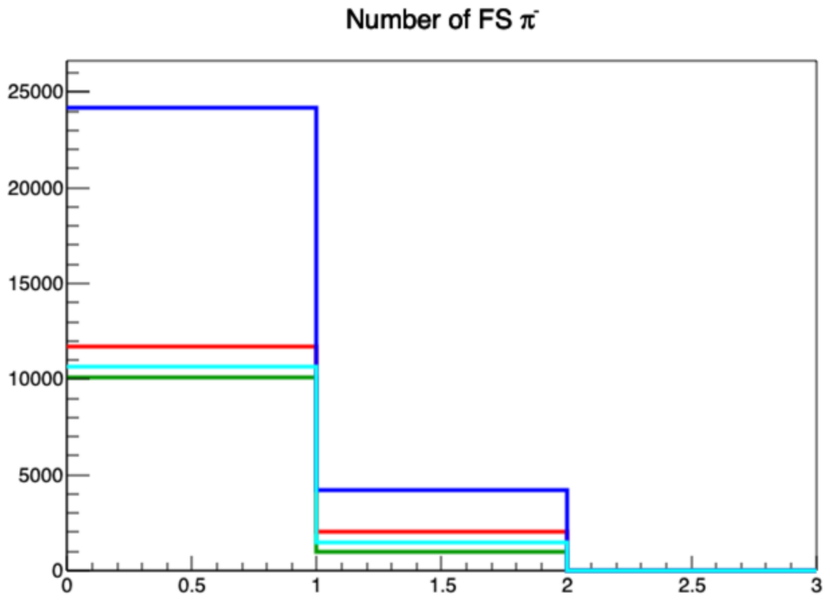


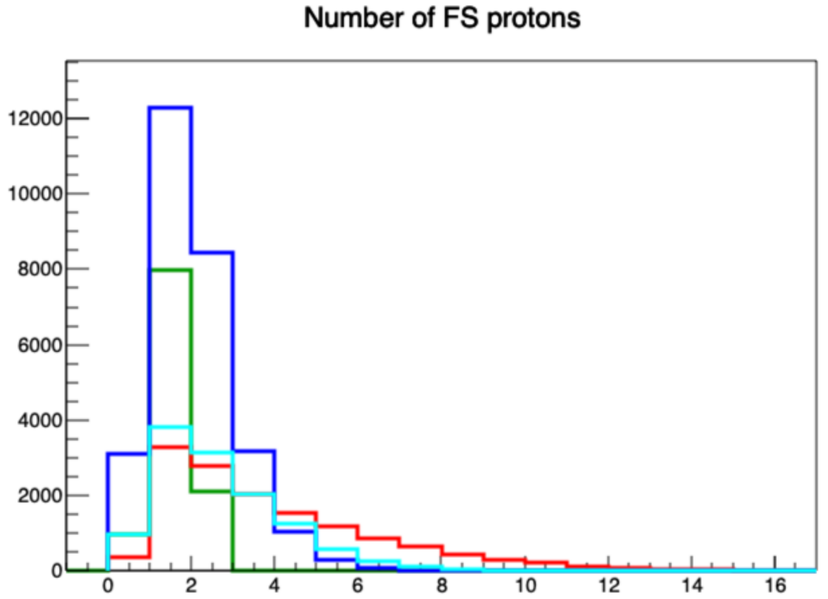
p-Ar FS particle multiplicity for probe_fsi==7

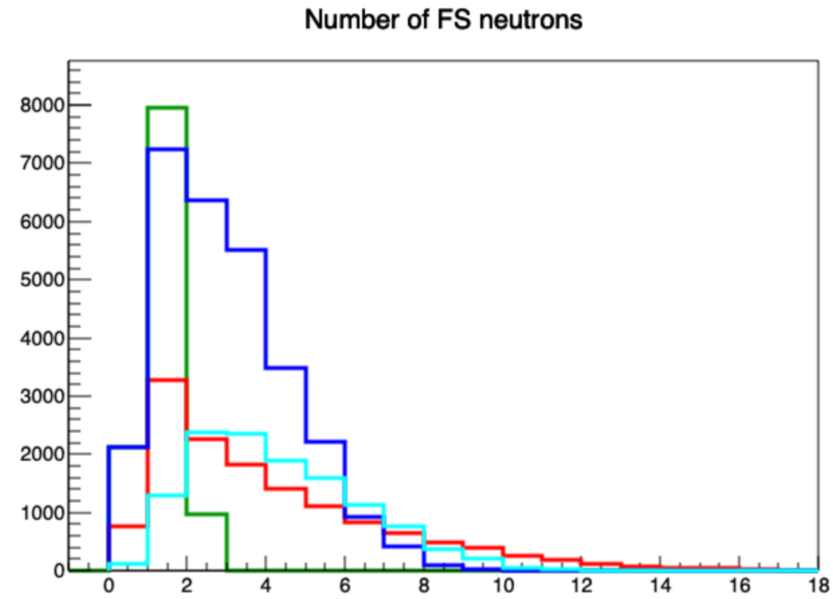




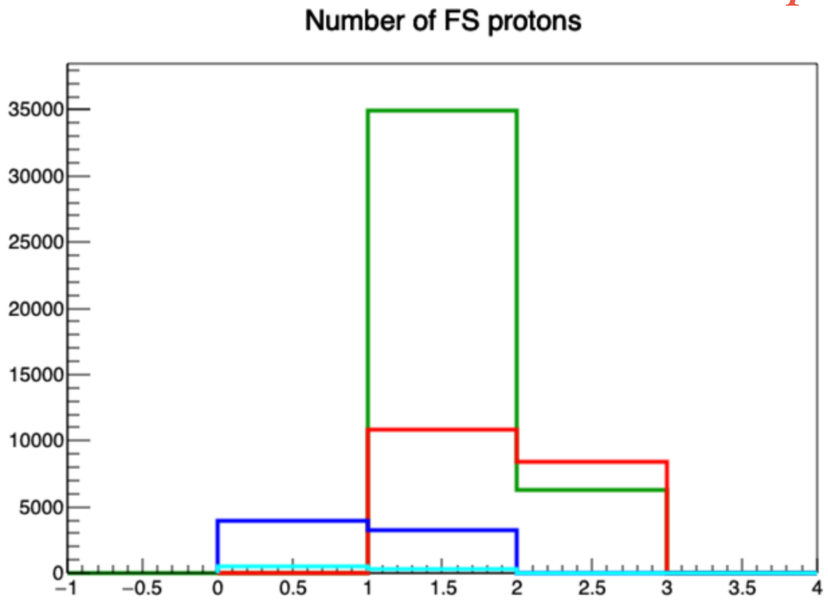


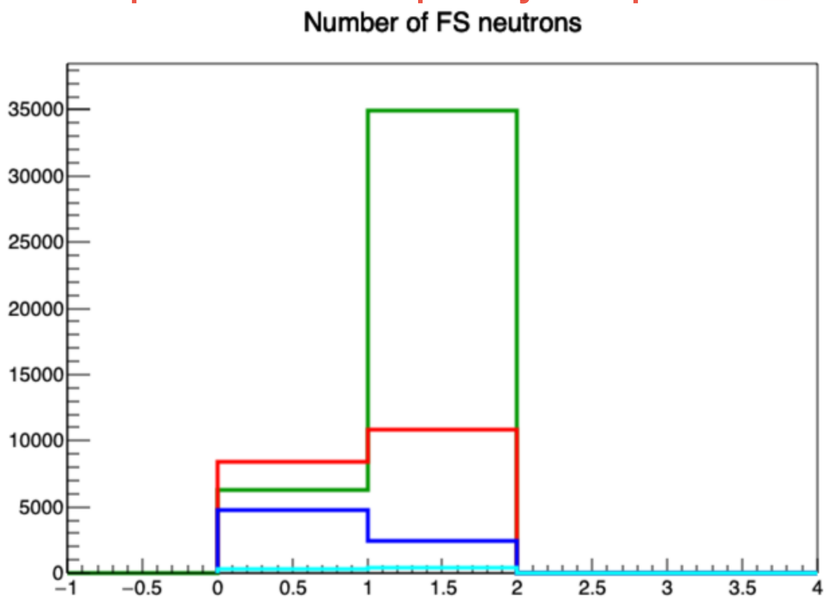


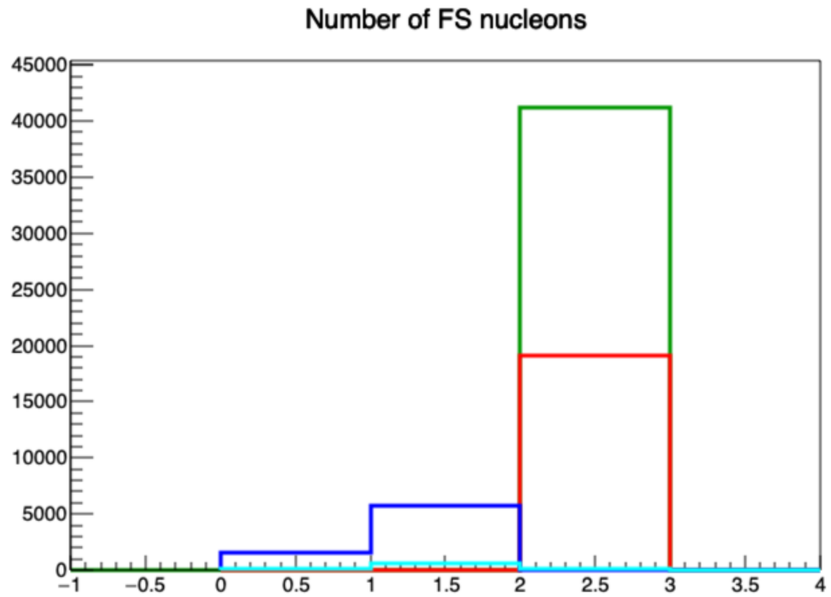
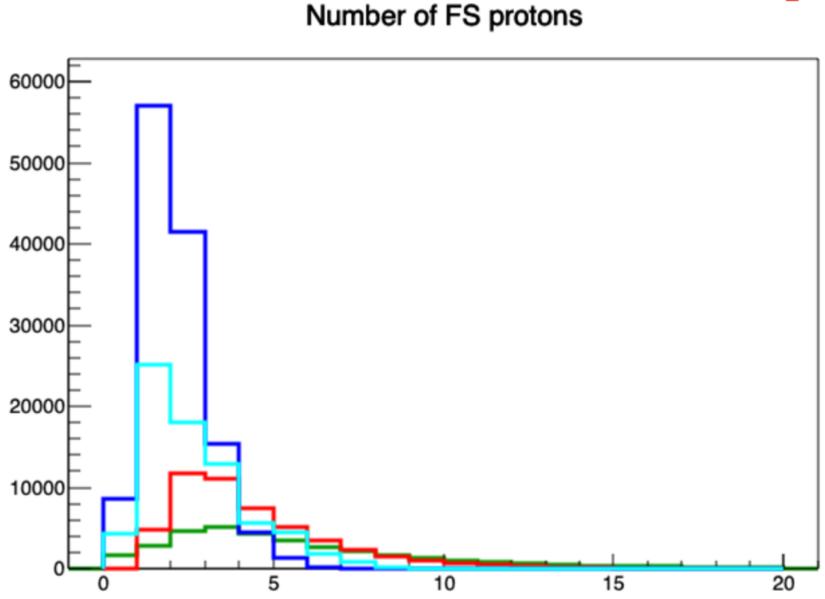
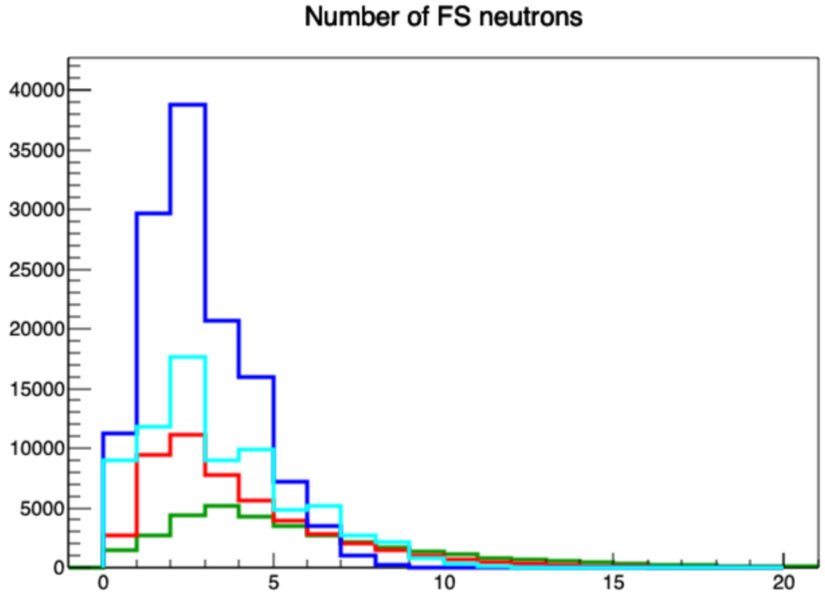
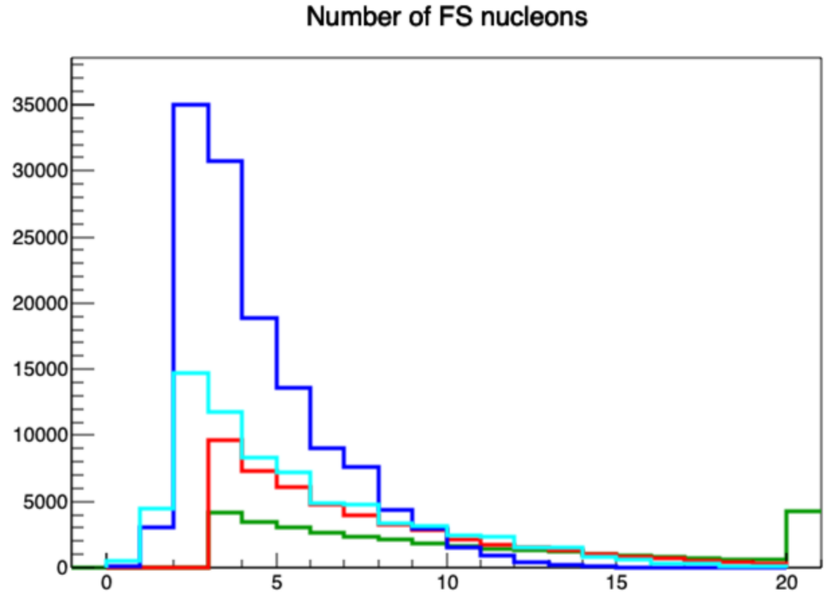




p-Ar FS particle multiplicity for probe_fsi==4







p-Ar FS particle multiplicity for probe_fsi==6