Neutron Analysis Update ProtoDUNE-SP

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Hadron Analysis Meeting

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Penn
University of Pennsylvania

DUNE

Content

- Introduction
- Simulation updates
- Interaction length studies
- Going forward
- Summary
- Backup

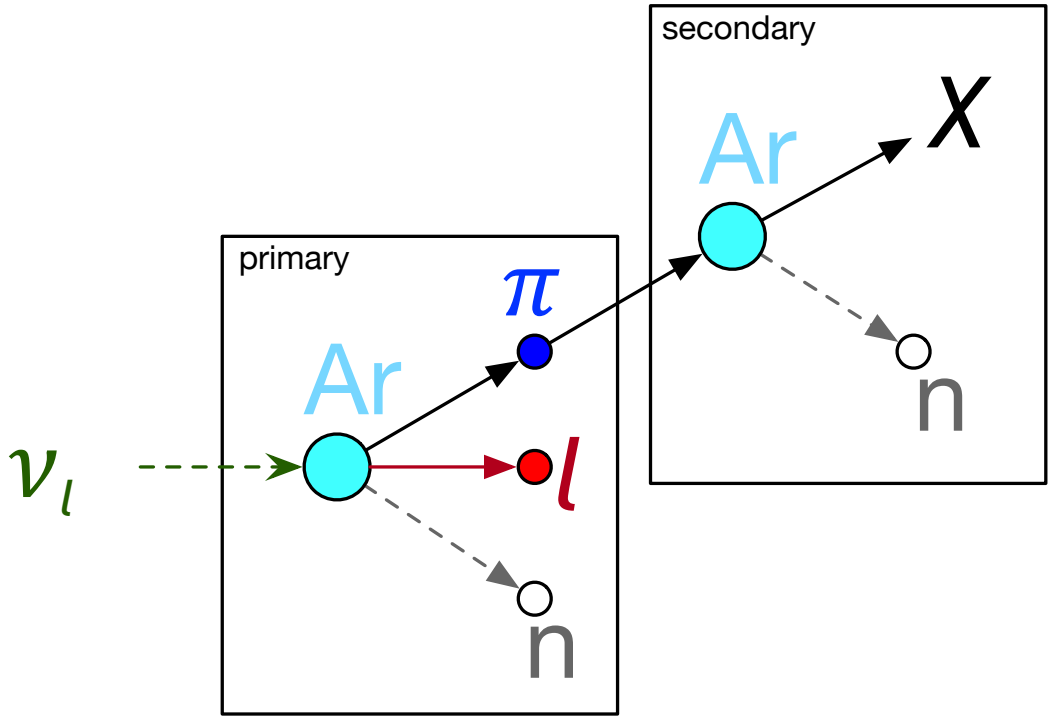
Introduction

Motivation

- Missing/Invisible Energy:
  - Neutrons can carry away a significant portion of the energy for an event
    - Visible energy from neutrons can be delayed and/or manifest as seemingly uncorrelated energy depositions in the detector
  - Energy resolution is limited by our ability to reconstruct and account for all missing energy
    - average missing energy varies with interaction type
    - Event-to-event fluctuations
- In ProtoDUNE-SP, the beam instrumentation offers measurement of the incident beam particle momentum
  - + PID --> Energy measurement
- For DUNE we will have a wide-band neutrino beam ~ few GeV range

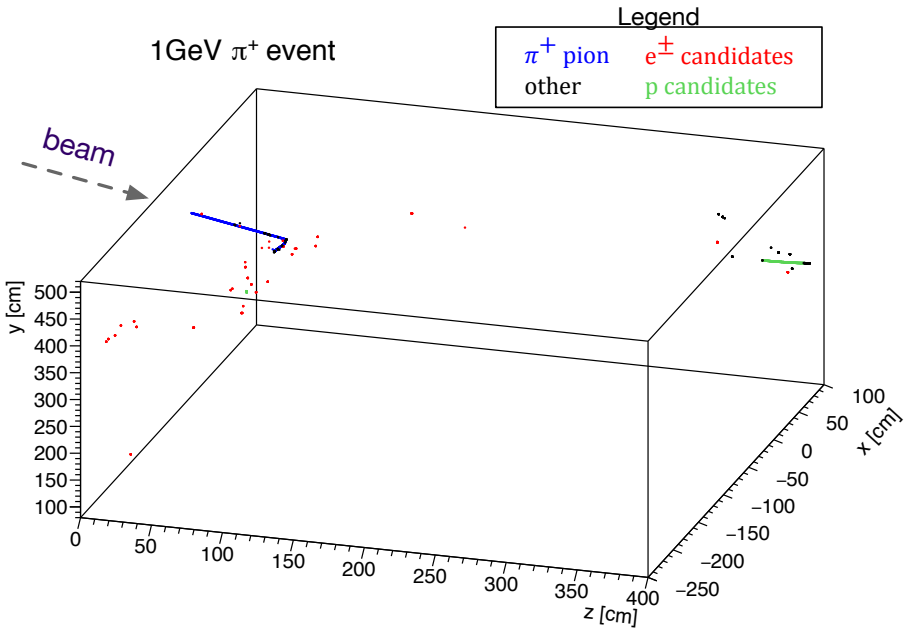
Goals

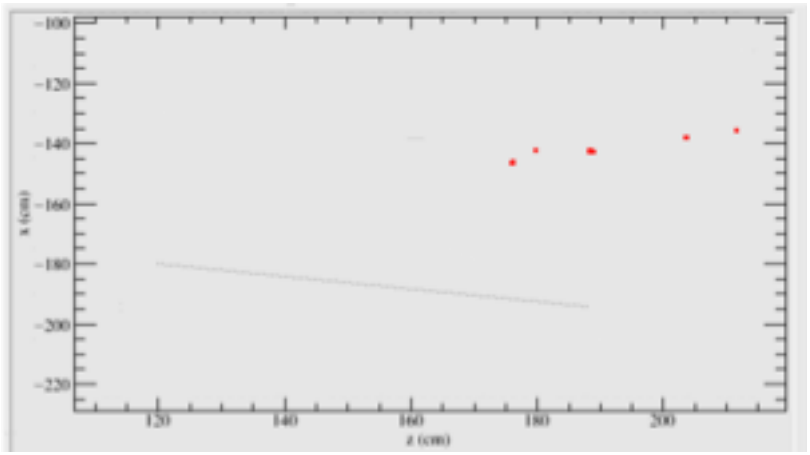
- Would like to:
  - probe the models for neutron production by pions
  - Identify/count neutrons
    - Must identify the best methods for doing so
- Does our model of neutron production from secondaries match data?
- Does this help energy reconstruction of neutrino interactions?



How do we “see” neutrons?

- Quick answer: Indirectly
- Neutron interactions in LAr typically include:
  1. Elastic scattering
  2. Inelastic scattering
  3. Capture
- Neutrons produce visible energy via:
  - Inelastic scattering resulting in charged particle final states
    - E.g. Charge exchange (n+A -> p + X)
  - De-excitation gammas - Inelastic scattering resulting in excited nuclear states which subsequently decay, emitting photons (Ar* -> Ar + N**γ**)
  - Neutron Capture : n + 40Ar -> 41Ar + N**γ**
    - ~O(200μs)
    - ΣE_γ = 6MeV





Simulation updates

- Custom hadronic physics list based on QGSP_BERT_HP
  - HP : High precision model for neutrons (KE < 20 MeV)
  - G4RadioactiveDecayPhysics
  - In larsoft versions v09_xx_xx there was an update in dependencies from **geant4.10.3.p03** to **geant4.10.6.p1**
    - I have remained on **4.10.3.p03**
  - Neutron inelastic cross section multiplier (default = 1.0)

Neutron Interaction length studies

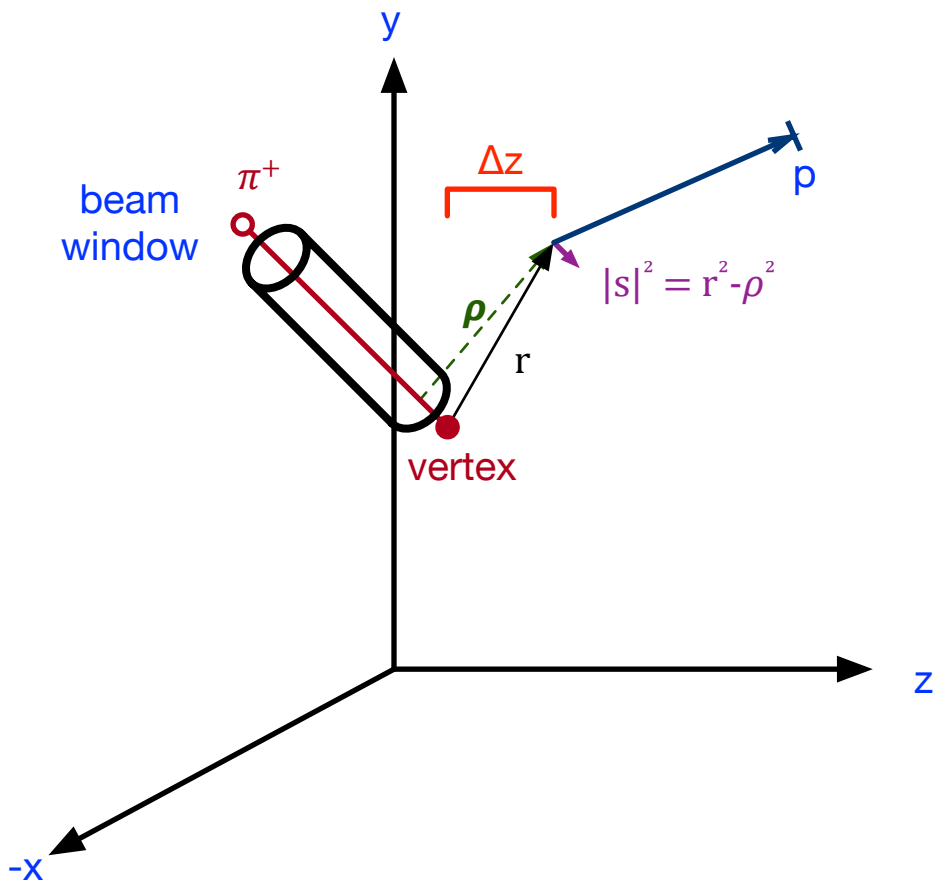
- Production3 MC and Production2 data for run 5387
- Using the output pion analysis tree + neutron analysis on MC Truth

Cuts

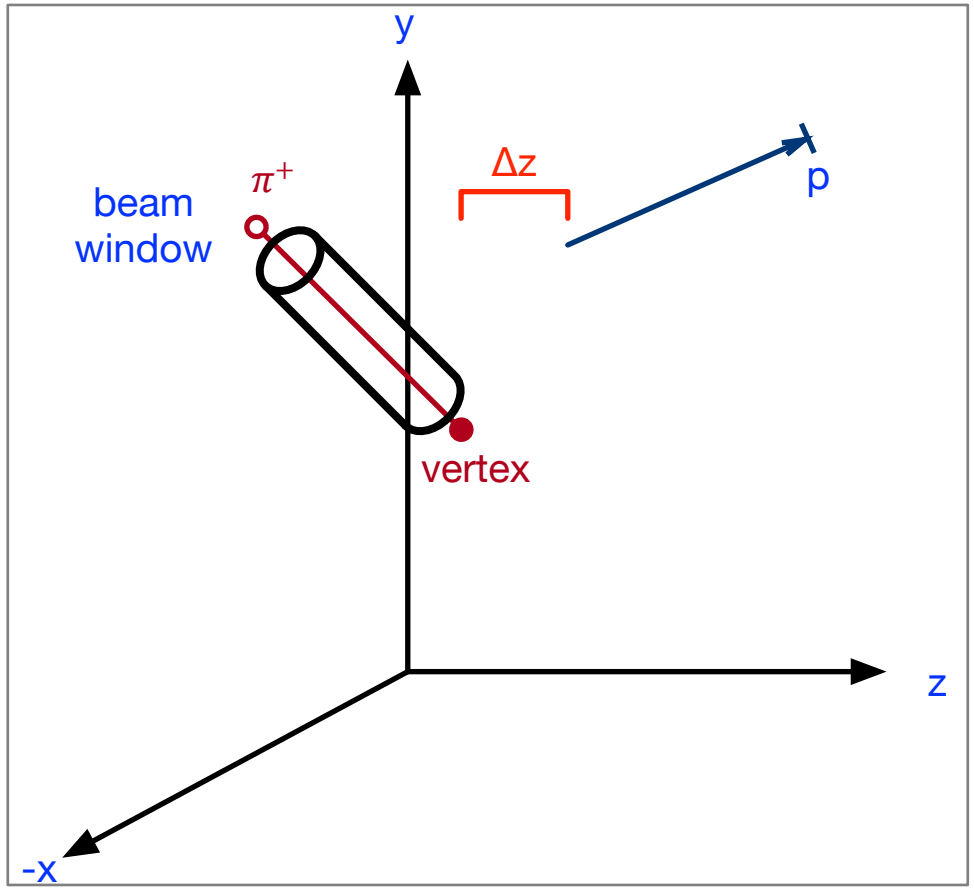
- reco_beam_passes_beam_cuts:
  - IsBeamLike(*thisTrack, evt, ”1”) where “1” is the beam momentum label
  - Beam cuts :
    - TrackStartXCut : [0,10]; TrackStartYCut : [-5,10]; TrackStartZCut : [30, 35]
    - TrackDirCut : 0.93 (cut on the dot product of the expected and reconstructed directions)
- reco_beam_endZ<225. -- primary beam track contained in APA3)
- (reco_daughter_allTrack_Chi2_proton/reco_daughter_allTrack_Chi2_ndof) < 50. – proton-like tracks (get the p-value)
- reco_daughter_PFP_trackScore > 0.3 – reject showers with some confidence
- reco_daughter_allTrack_dR>5 – at least 5cm of separation between the primary vertex and the daughter tracks
- reco_daughter_allTrack_startY < 460 – reject protons entering and some np from cosmic neutrons
- reco_daughter_allTrack_startY > 200 – reject odd tracks near the cryostat floor (might remove)
- reco_daughter_allTrack_startX < 20 – reject most tracks in the non-beam side

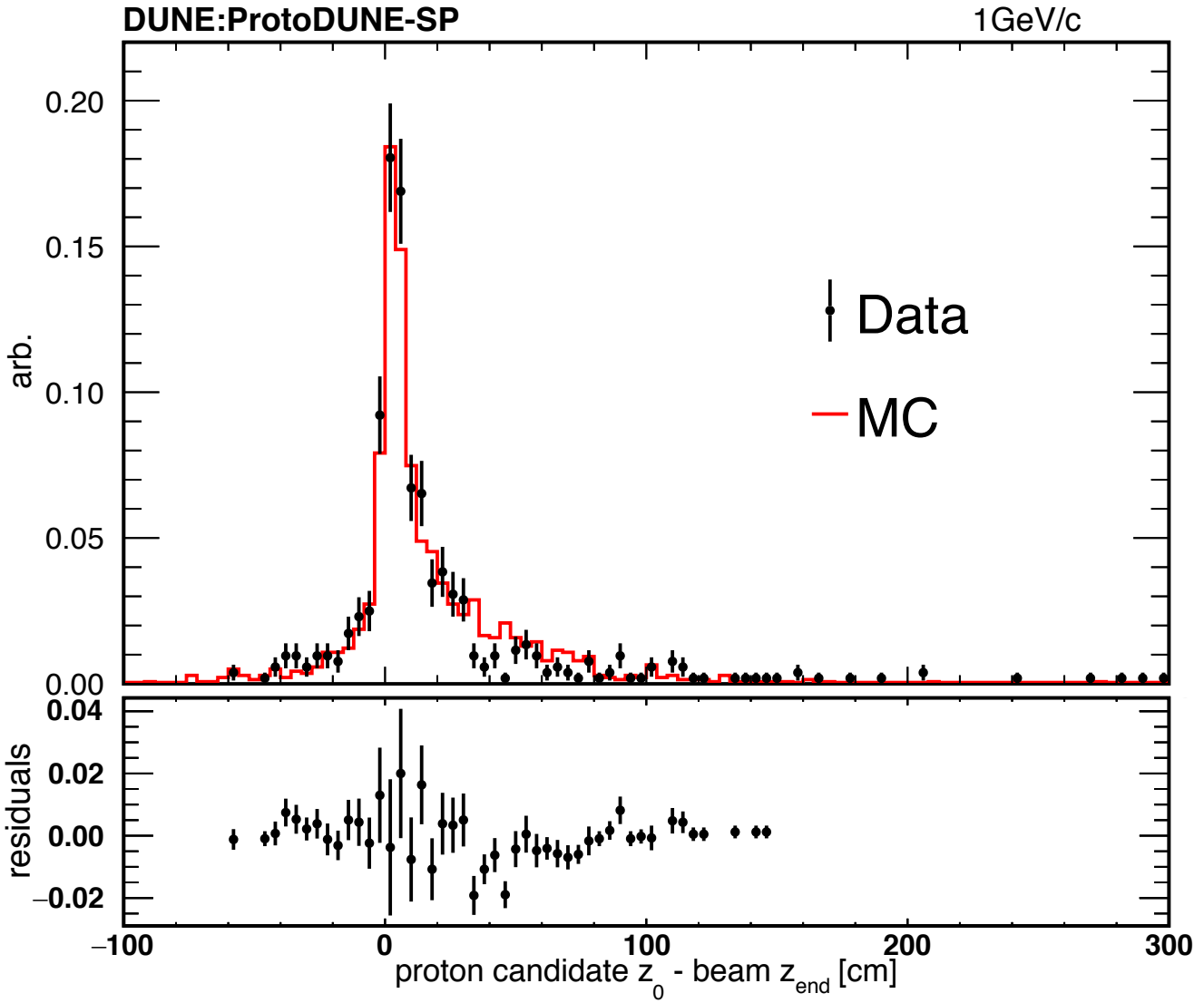
Handles on the neutron interaction length

- A basic geometric cut is created based on the reconstructed beam track direction and vertex
- Three length parameters are considered:
  - Radial distance from the vertex to the start of the proton candidate track (r)
  - Perpendicular distance from the plane of the track (rho)
  - Distance in the reconstructed beam direction of the proton candidate (s)

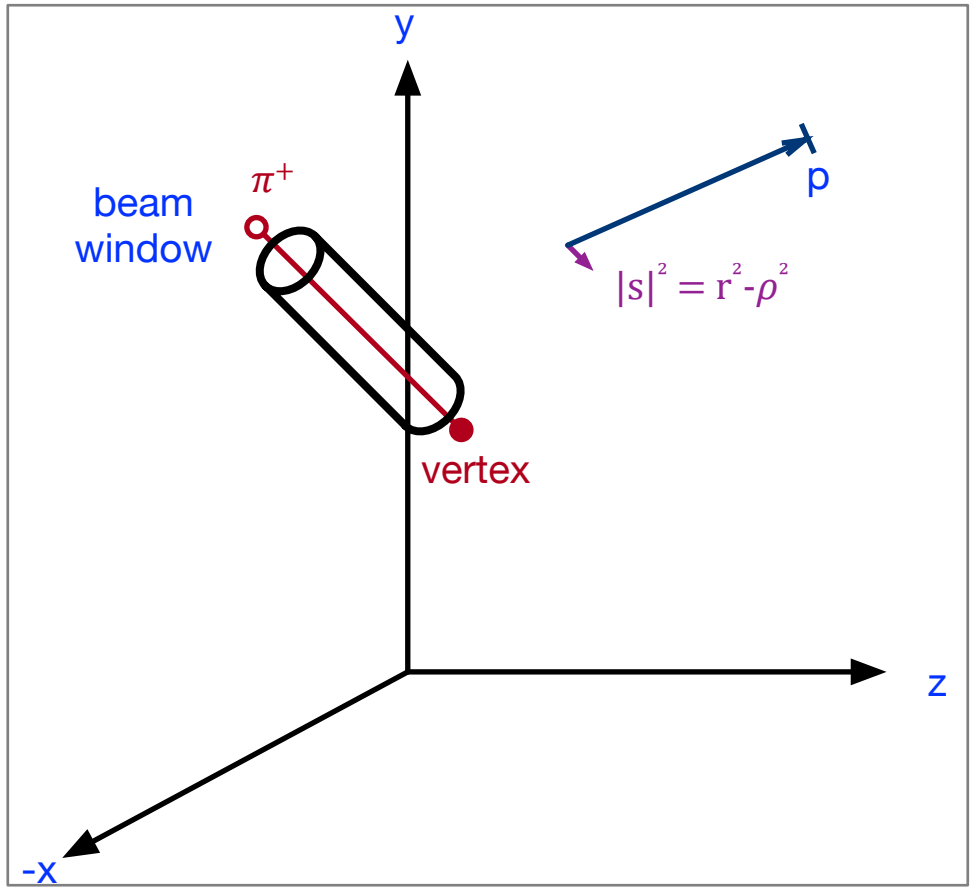


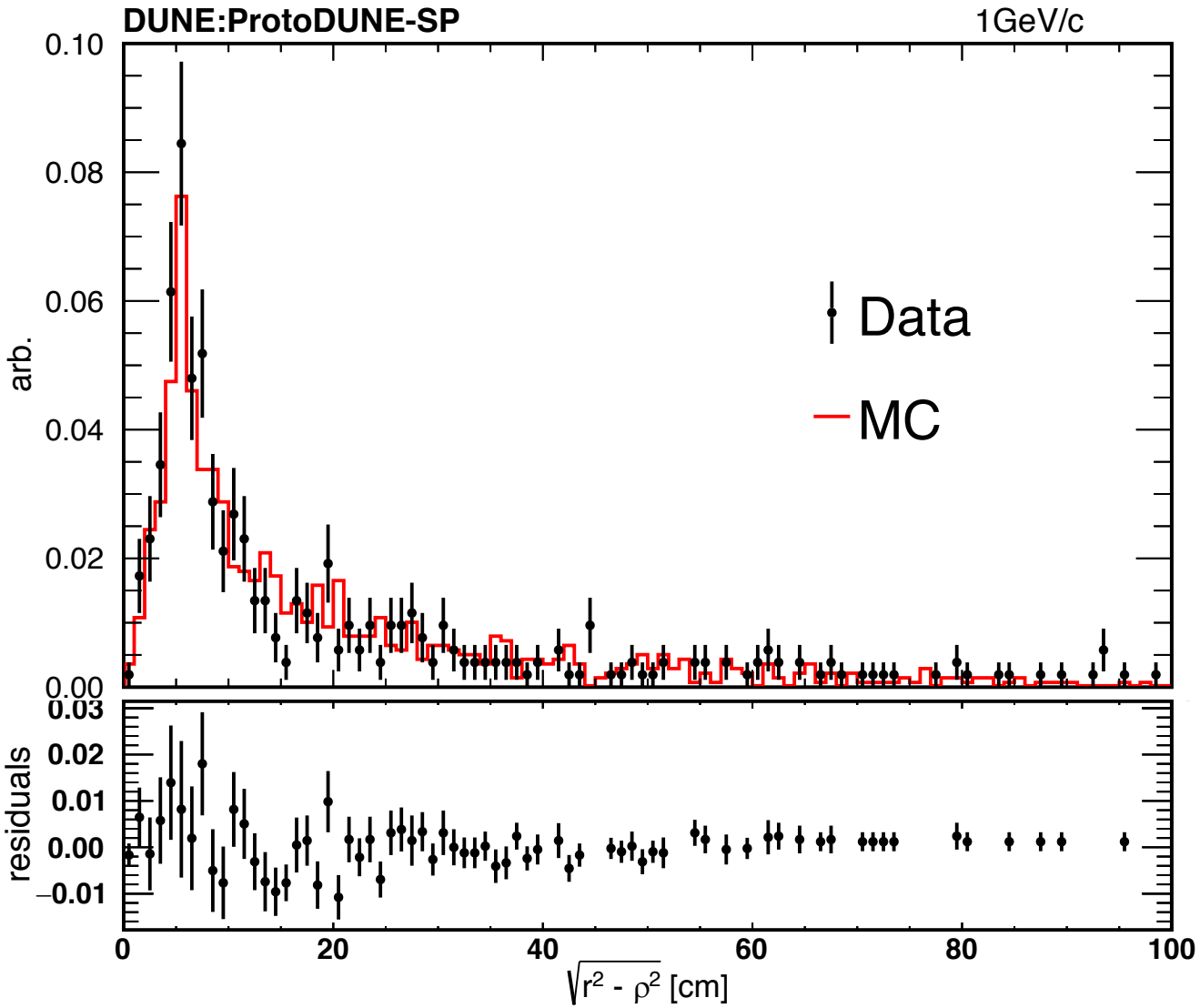
z displacement Data-MC comparison



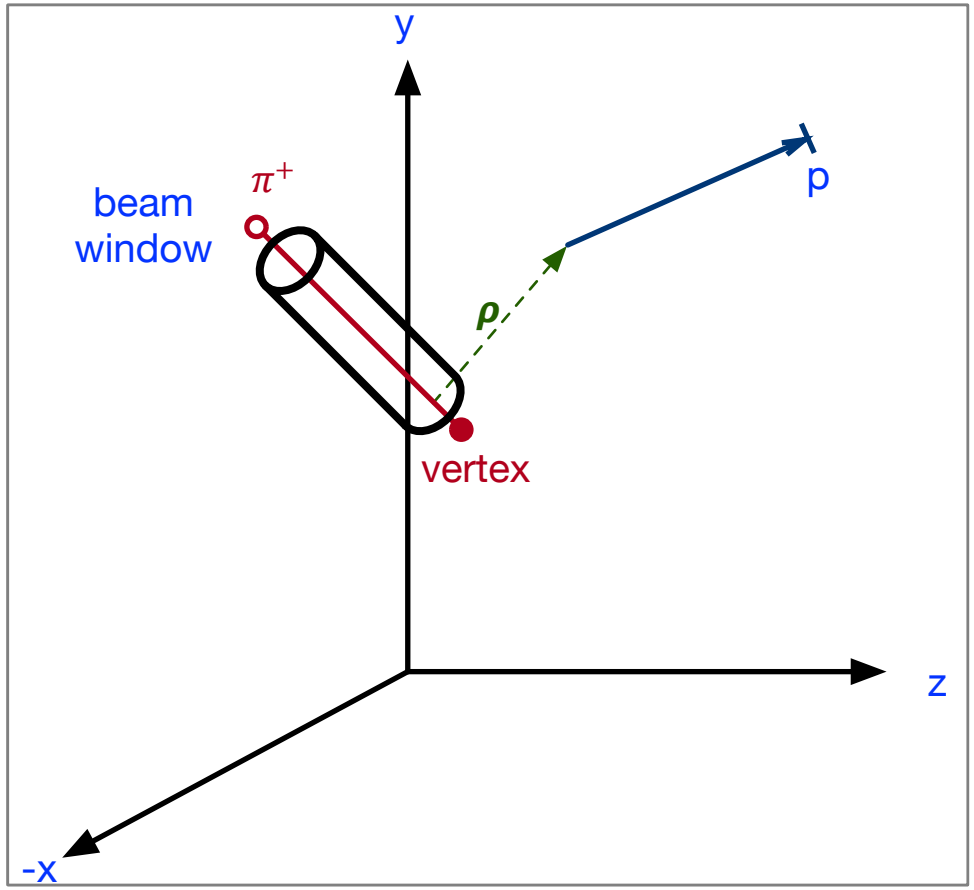


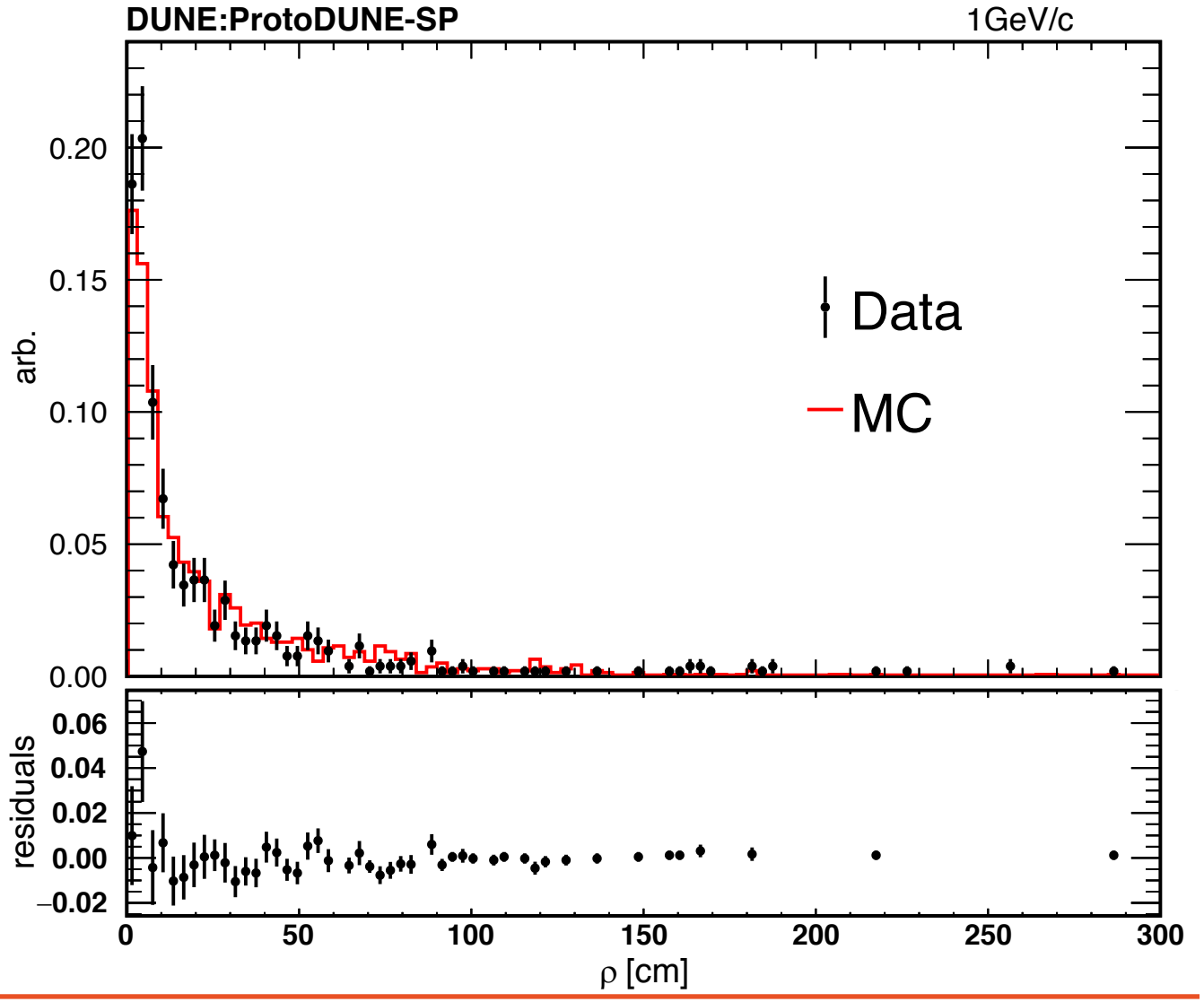
s distance Data-MC comparison





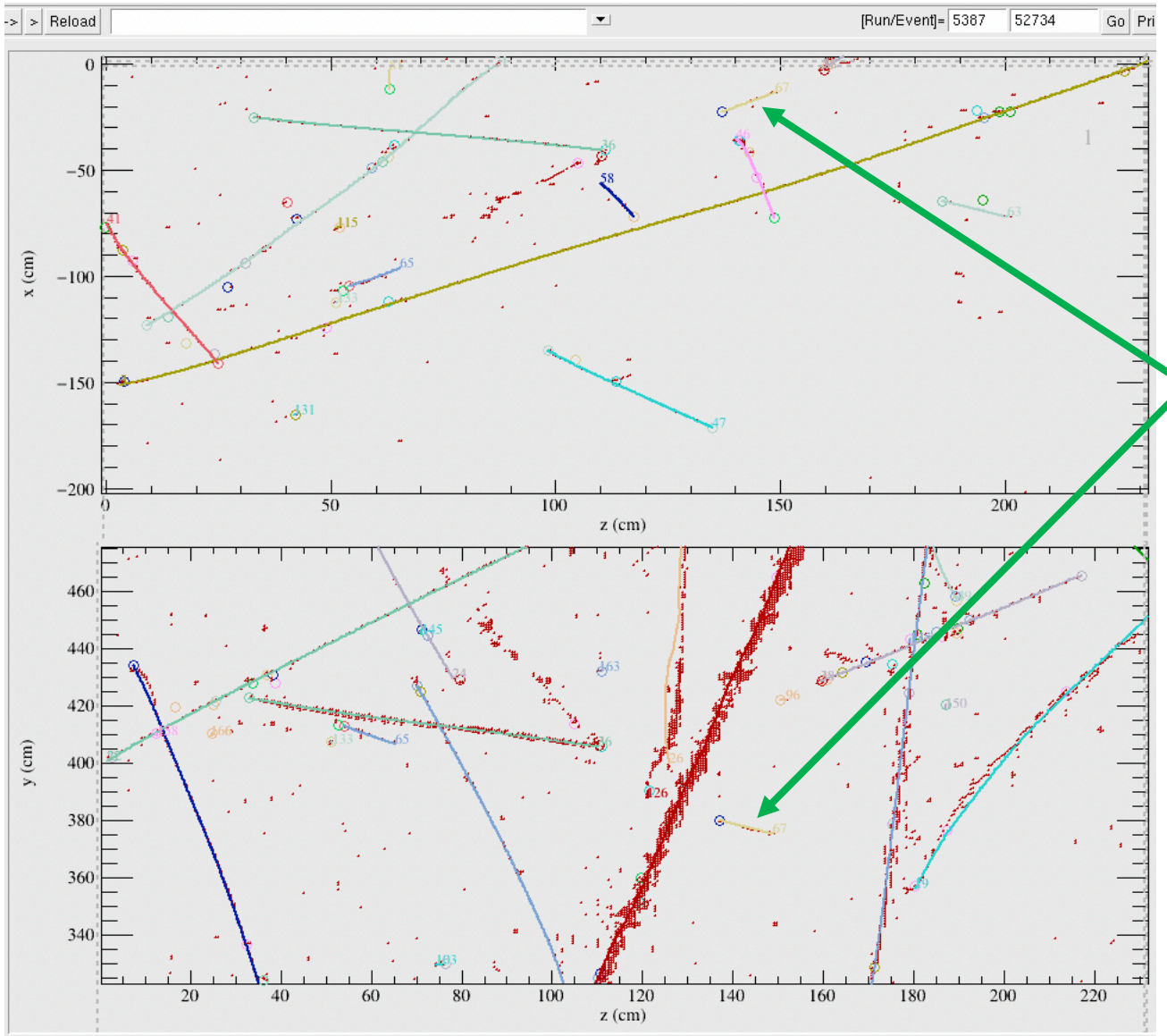
ρ distance Data-MC comparison





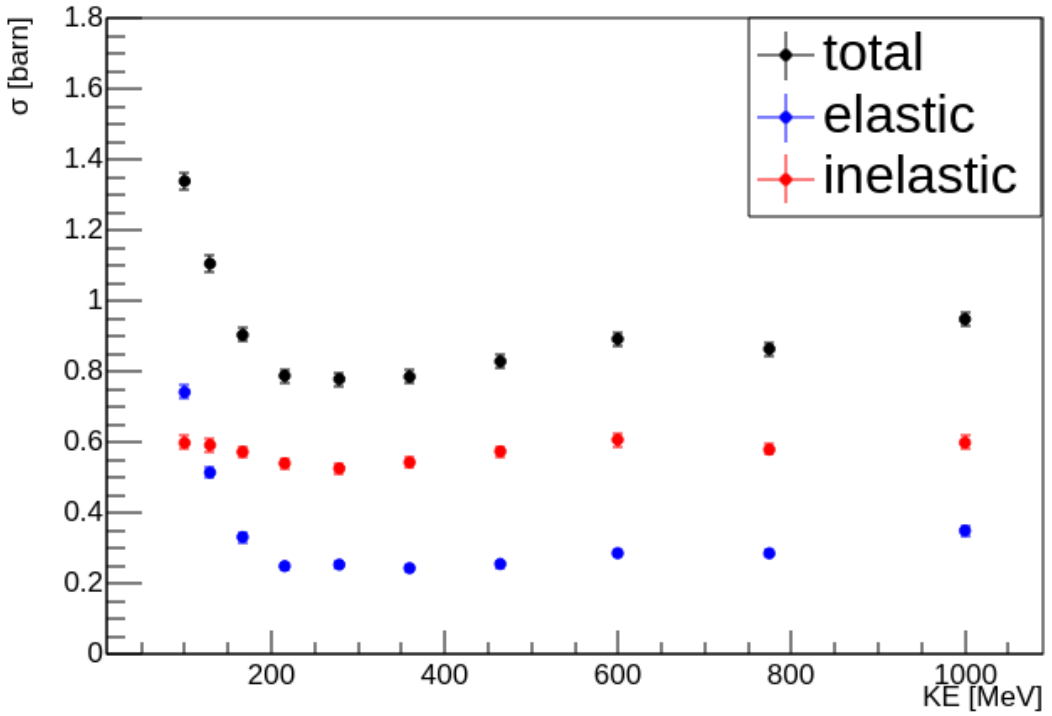
Candidate proton

- Looked at data events that passed the selection
- A disjoint proton candidate can be observed
- Run 5387, event 52734

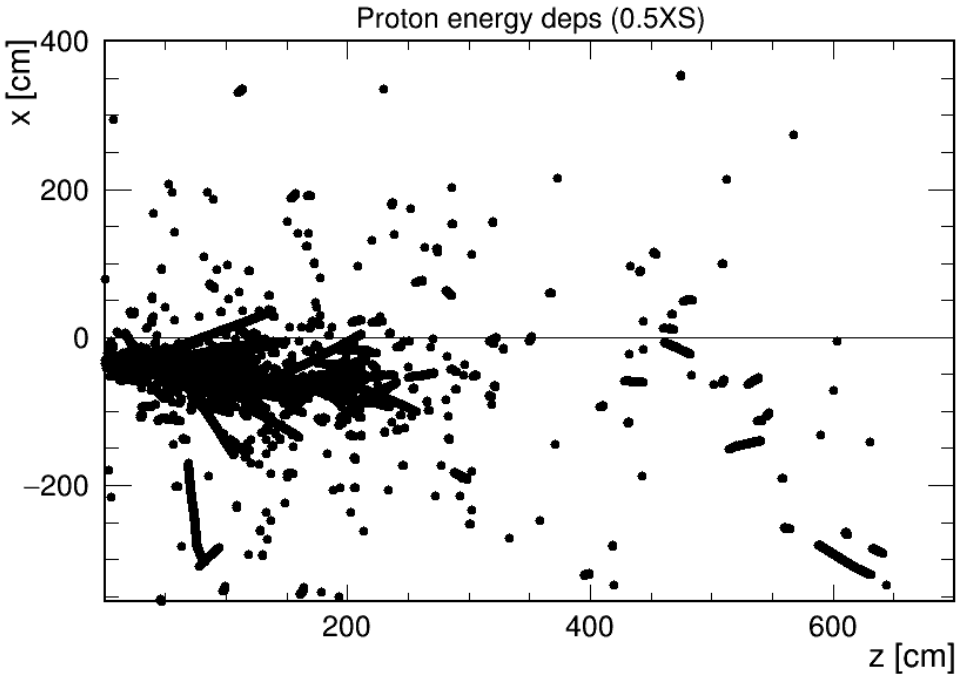


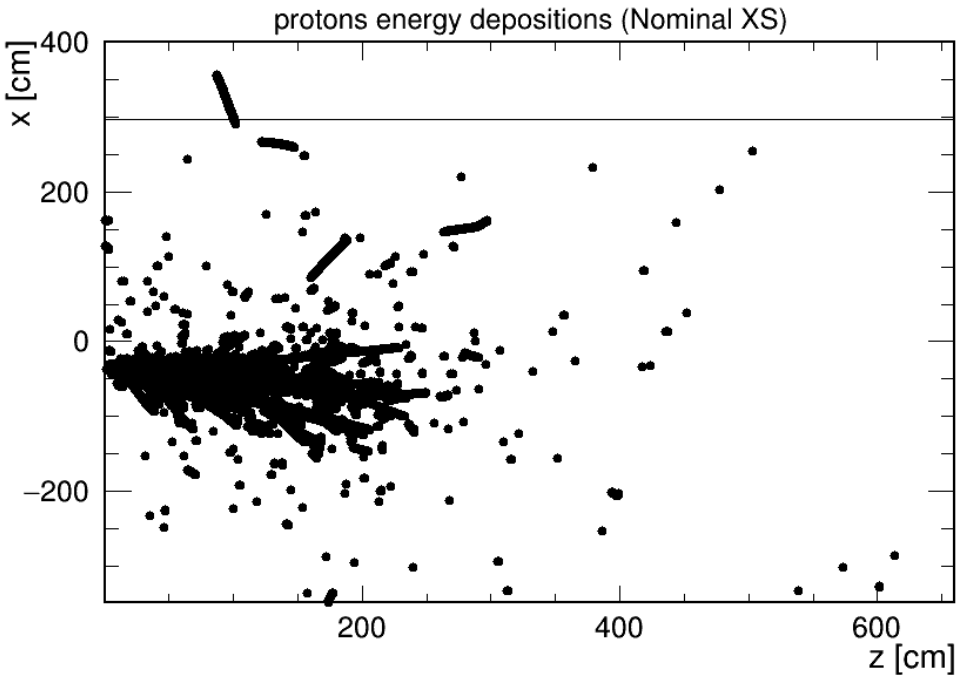
Modifying the cross section

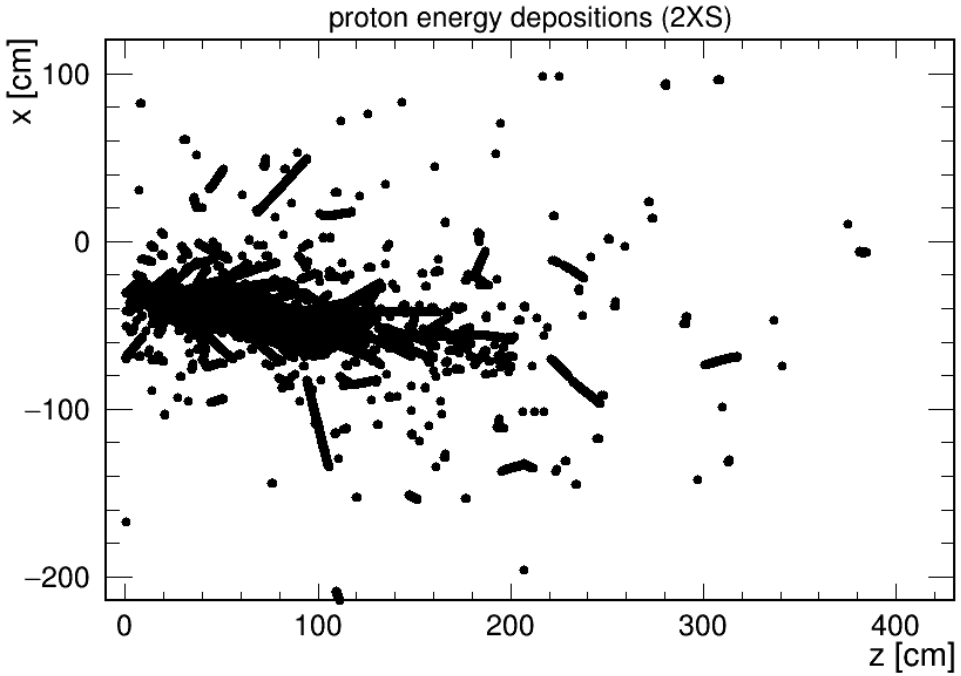
- Created a custom physics list with a knob on the neutron inelastic XS
- Can tune this to study the sensitivity of the neutron length parameters on the XS



Geant4 neutron-Argon cross section





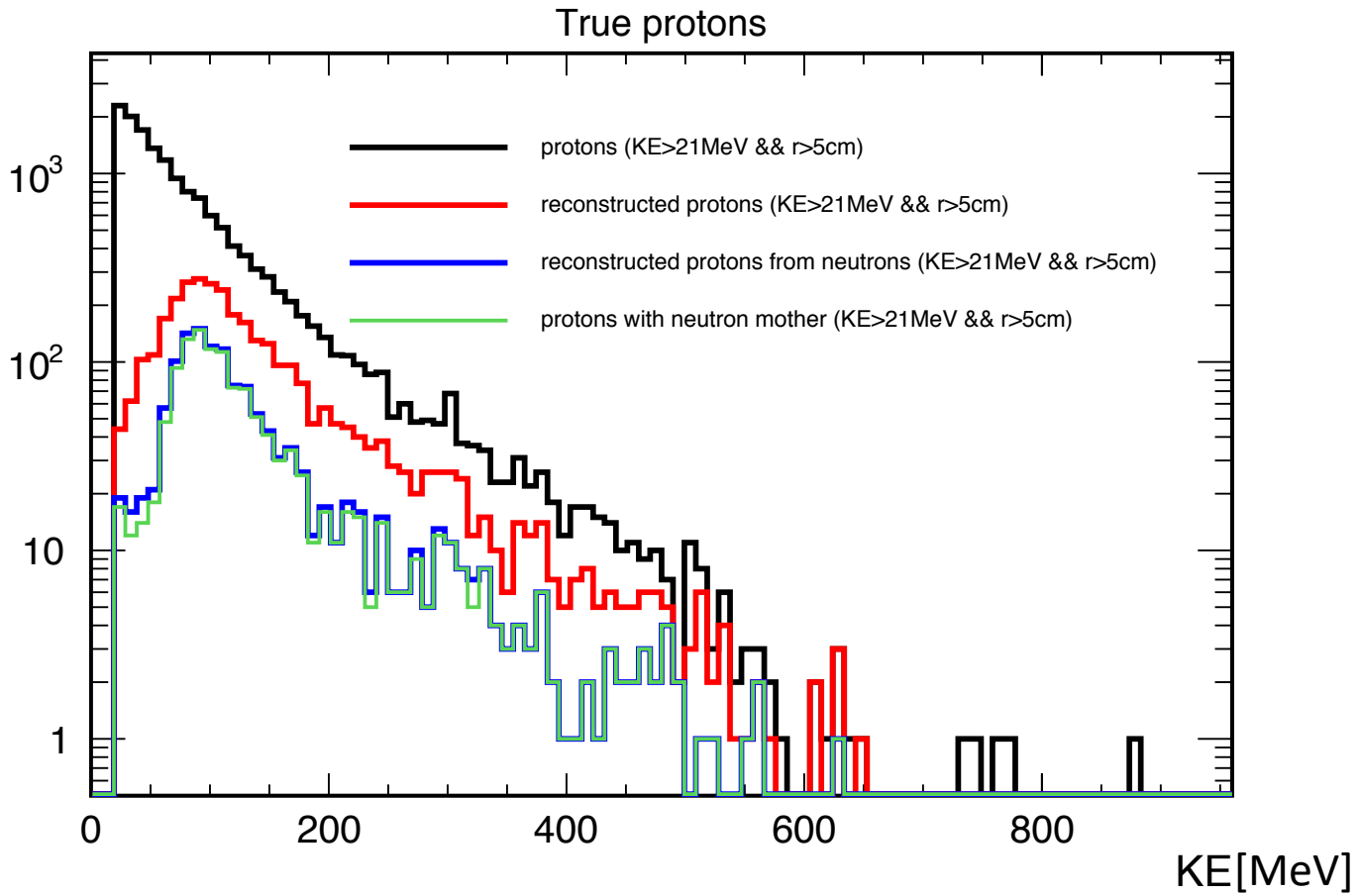


- Notice the reduction in the axis ranges for sample with a scale factor of 2.0 on the neutron inelastic xs

Simulations

- Doing full MC simulation (cosmics, radiologicals, beam halo..) would be costly
- Generated single, p=1GeV π^+ samples
  - Reconstruction plays a big role in the acceptance of proton candidates
- Reconstructed single particle samples proved comparable to reconstructed data

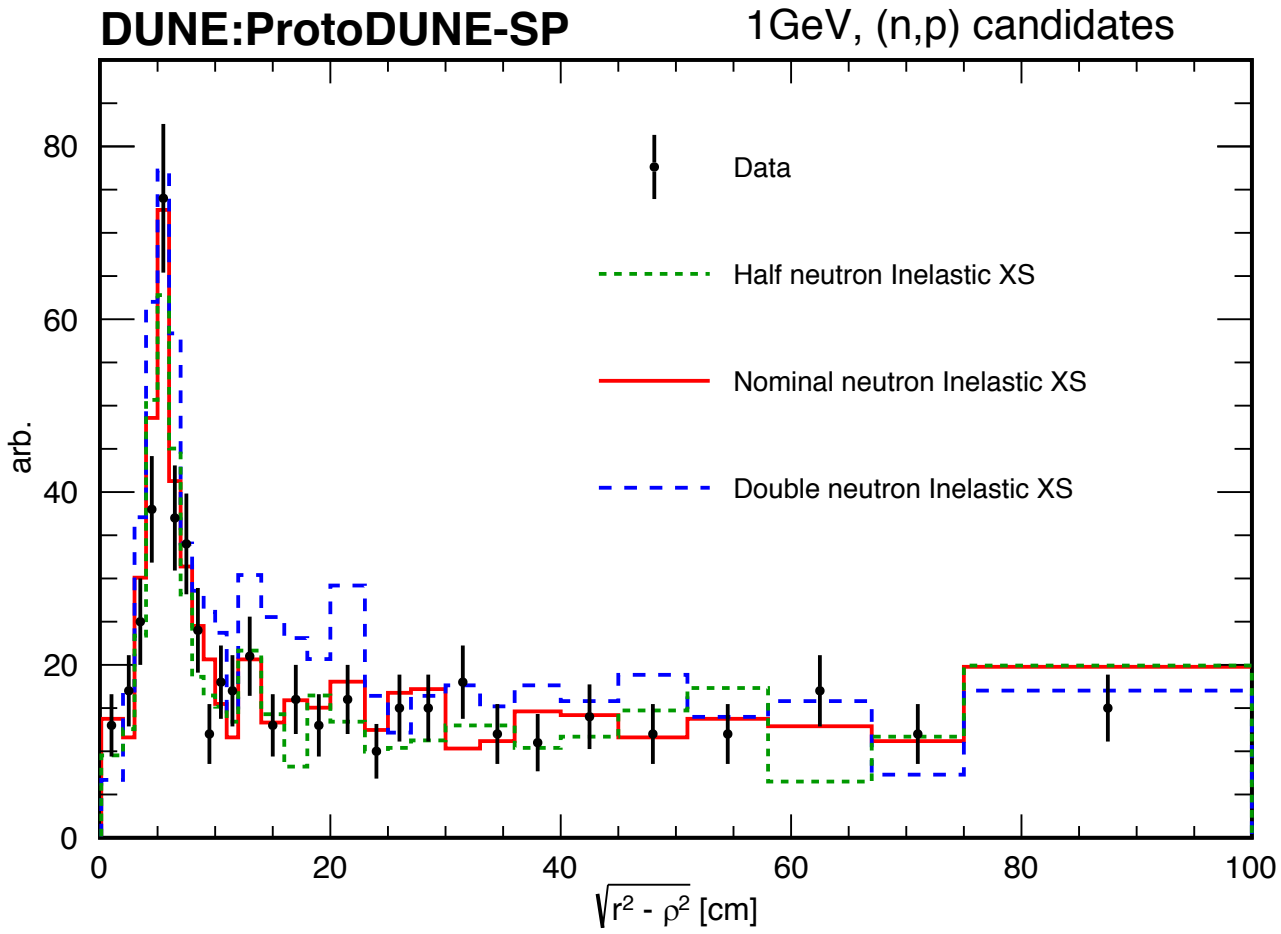
Nominal XS sample



Half, nominal, and double xs

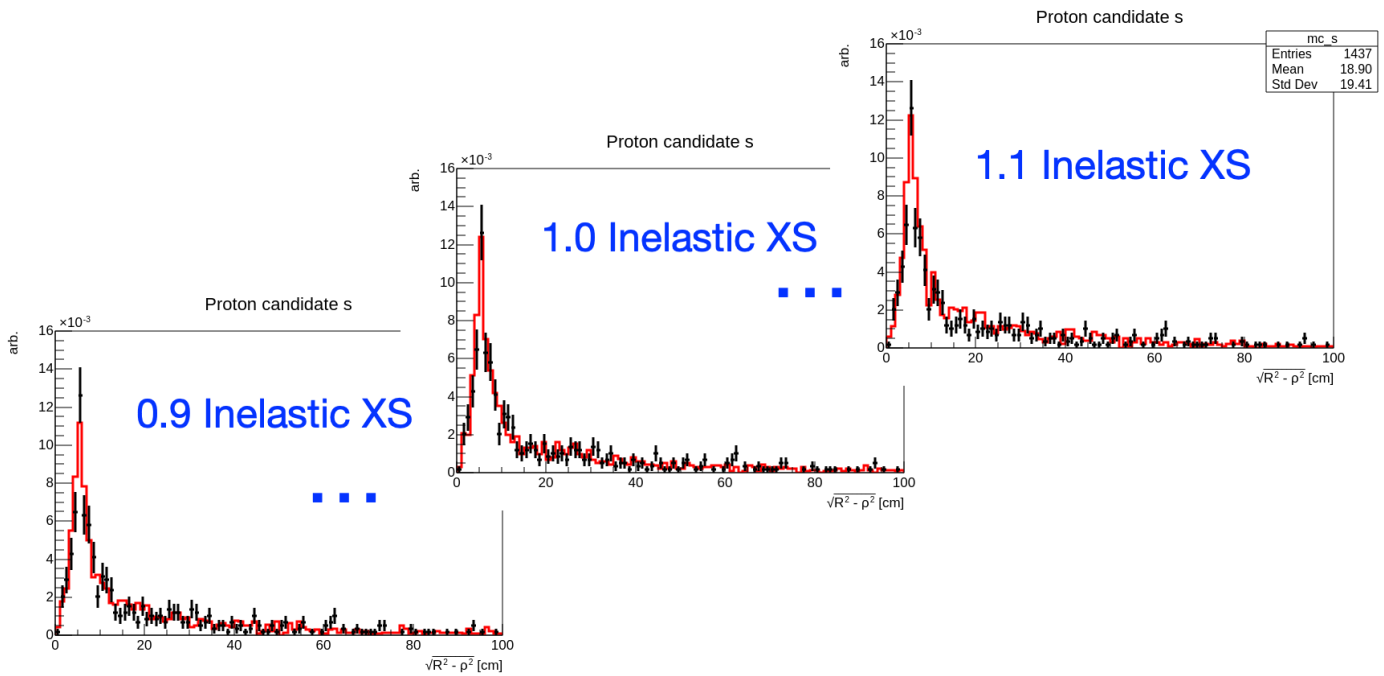
- Rebinned to ensure at least 10 entries per bin
- Data Unweighted
- MC weighted to match the number of valid beam events

XS bias factor	χ^2	n.d.o.f.	p
0.5	28.8	27	0.37
1.0	16.26	27	0.95
2.0	31.2	27	0.26



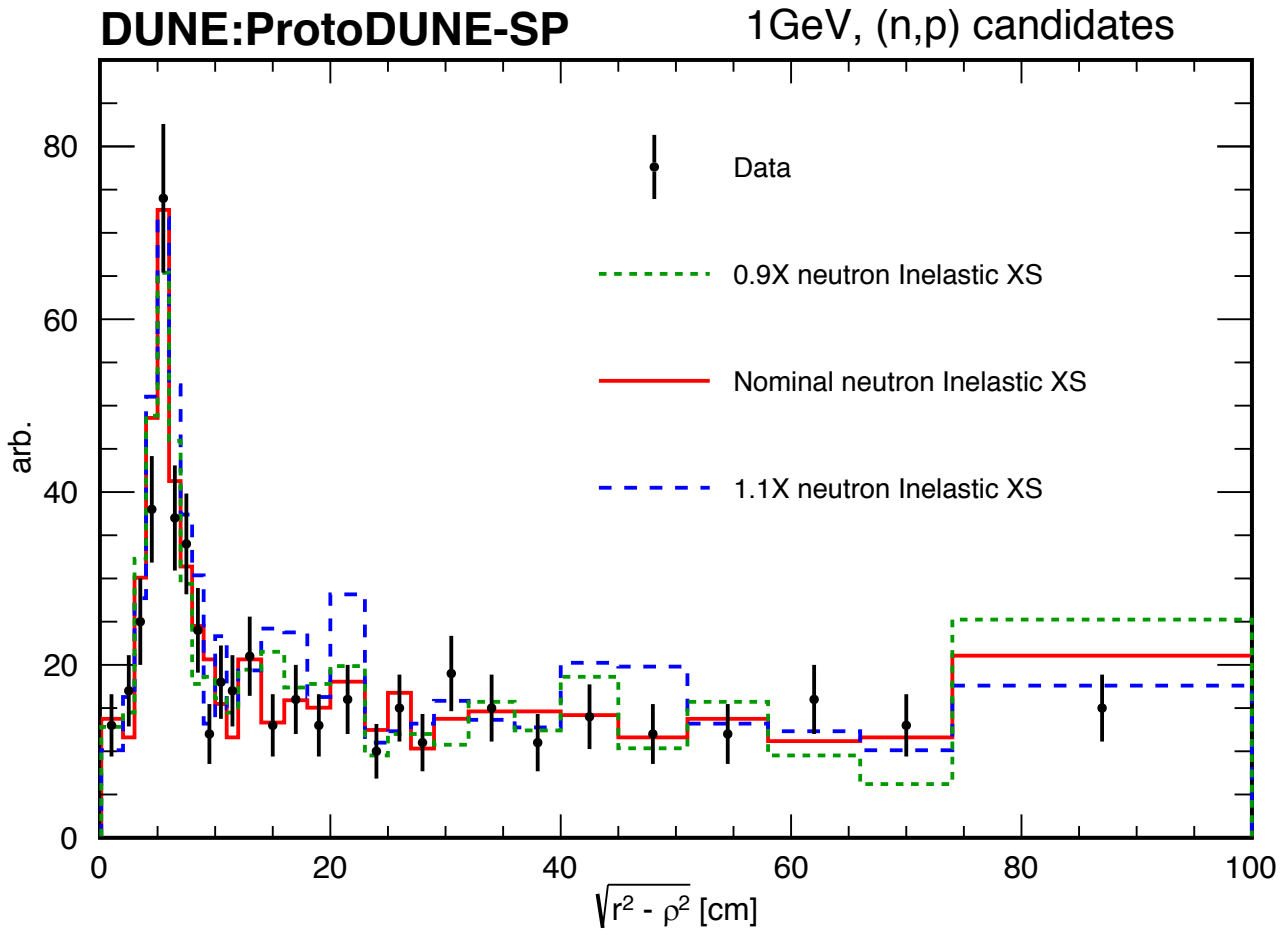
Neutron XS determination

- The matching to the data is closest with the nominal inelastic xs
- (In progress) Generate single particle samples with (Nominal ± 10%) neutron inelastic XS in 1% increments
- Apply a log-likelihood method to determine the best match

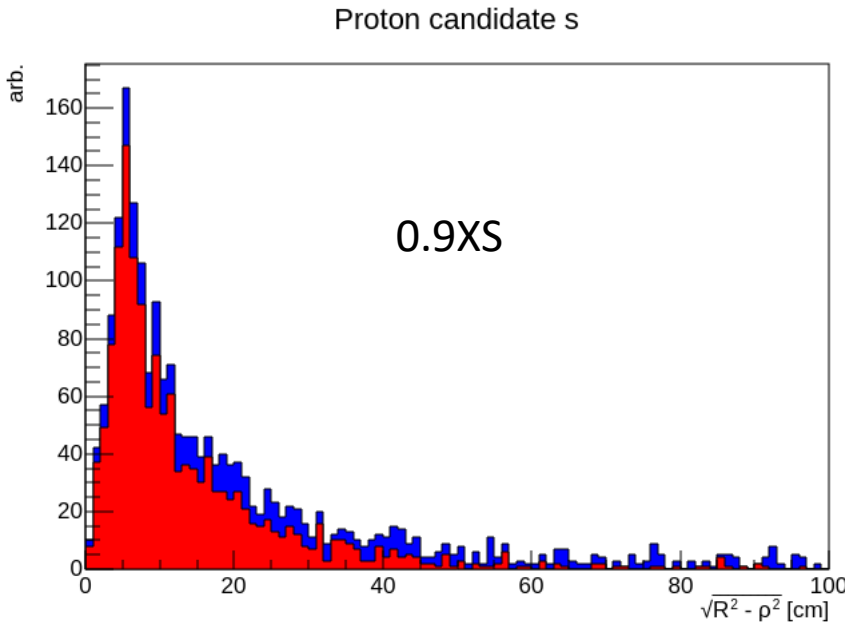


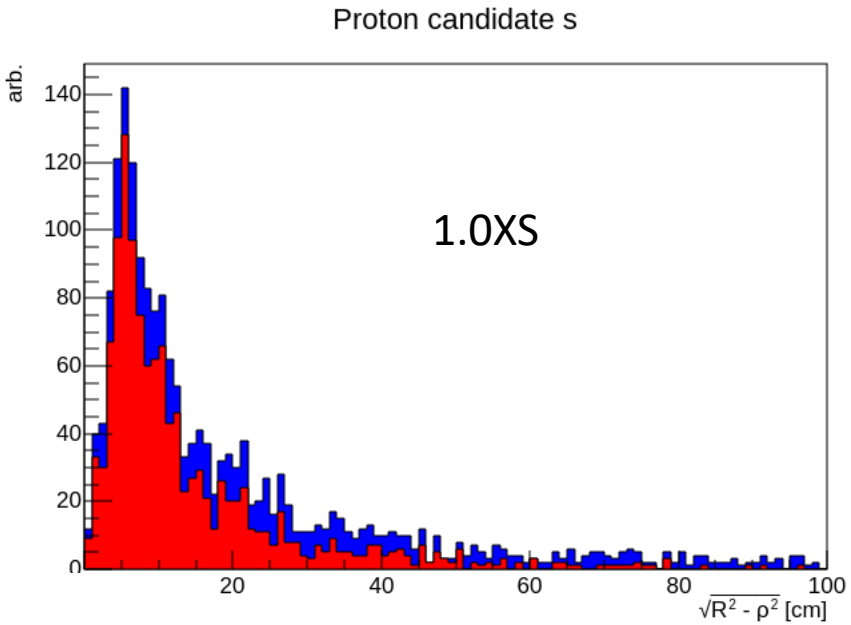
0.9, nominal, and 1.1 xs

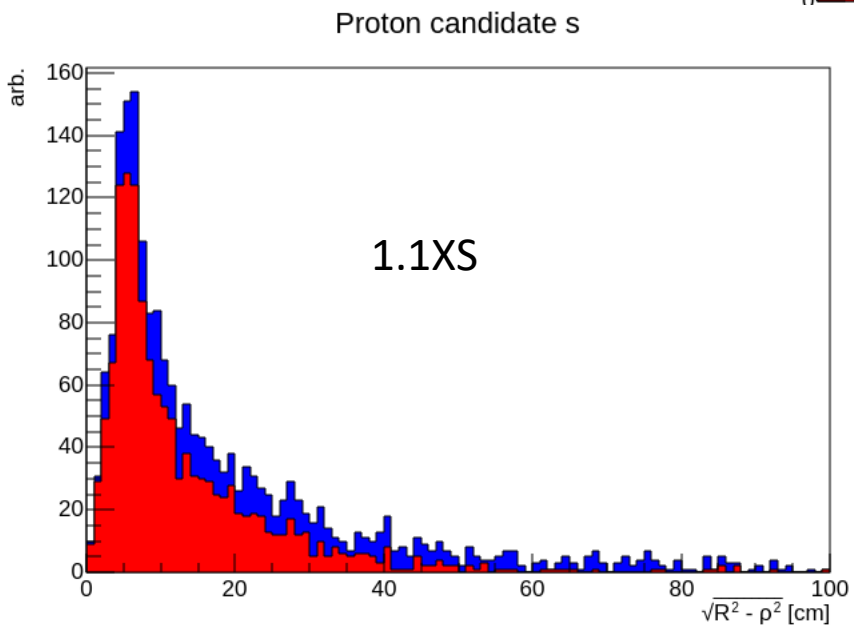
XS bias factor	χ^2	n.d.o.f.	p
0.9	30.9	27	0.28
1.0	14.8	27	0.97
1.1	20.6	27	0.80



Candidate ancestry (MCTruth)







Blue : protons with neutron ancestors
Red : protons with no neutron ancestors

Event cuts

- Single pi+ events
- Overall beam event quality cuts

Cut	Pass	All	Eff	Cumulative Eff
beamType cut	608852	609456	99.90%	99.90%
Beam cut	486011	608852	79.82%	79.75%
APA3 cut	452358	486011	93.08%	74.22%
Beam chi2 PID cut (not proton-like)	439538	452358	91.17%	72.12%

Additional event cuts

- Filter events that don't have at least one proton candidate
- Filter events that don't have at least one candidate that meets the fiducial cut

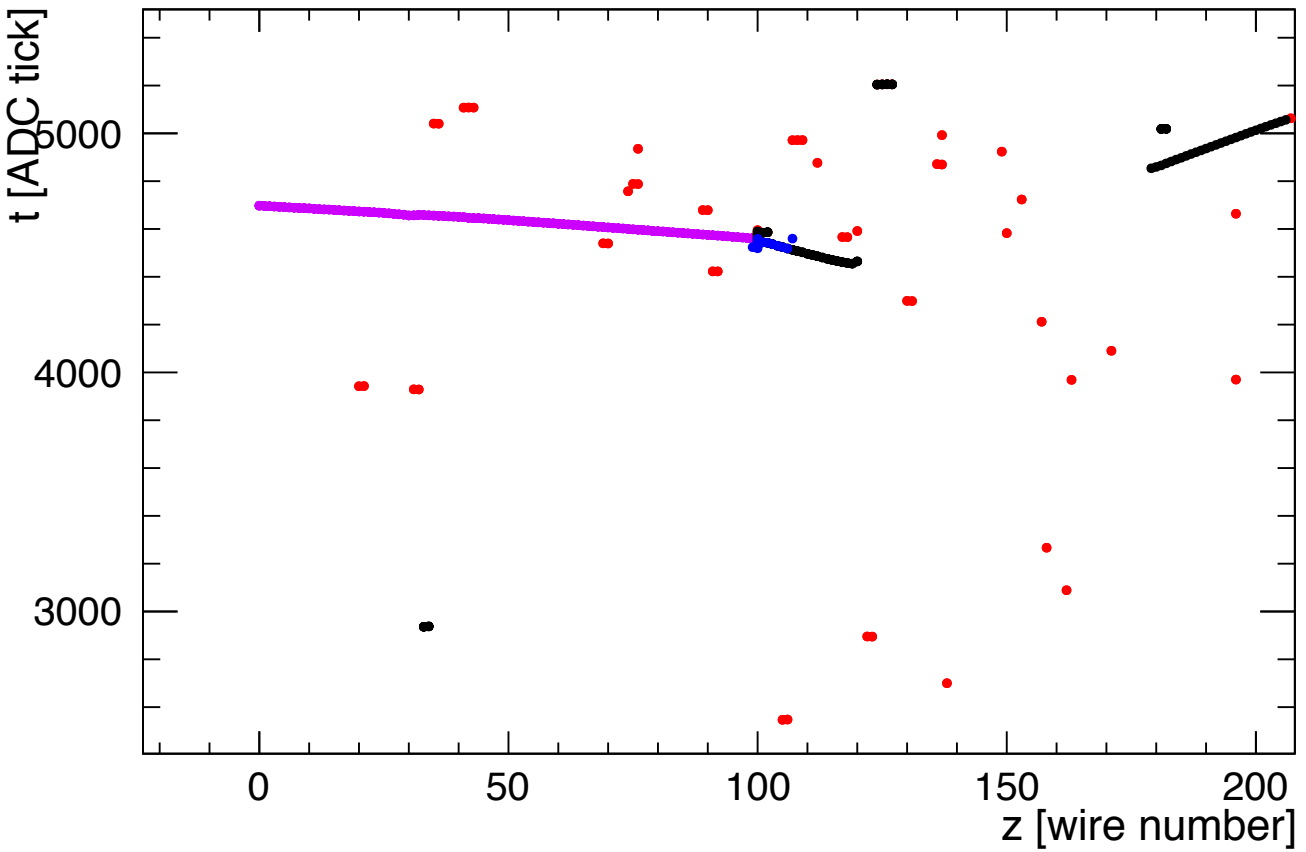
Cut	Pass	All	Eff	Cumulative Eff
Proton candidate cut	196369	439538	44.68%	32.22%
Fiducial cut	194959	19369	99.28%	31.99%

Candidate cuts

- Previous cuts accepted a lot of non-signal protons
- The daughter distance cut (r>5cm) was not sufficient to reject these backgrounds
  - Tingjun suggested taking a similar approach to Ajib's Michel removal
- I check collection plane hits and trackhit metadata positions to better identify when a track is "disjoint"
- For collection plane hits, the join radius is :
  - $r_{join} = \sqrt{(n_{wire} * wire_{pitch})^2 + \left(time\ over\ threshold * v_{drift}\right)^2}$
  - Disjointness: $r_{join} > 5cm$

Event example

- Magenta : beam pion
- Black : other reconstructed track hits
- Blue : nearby track hits



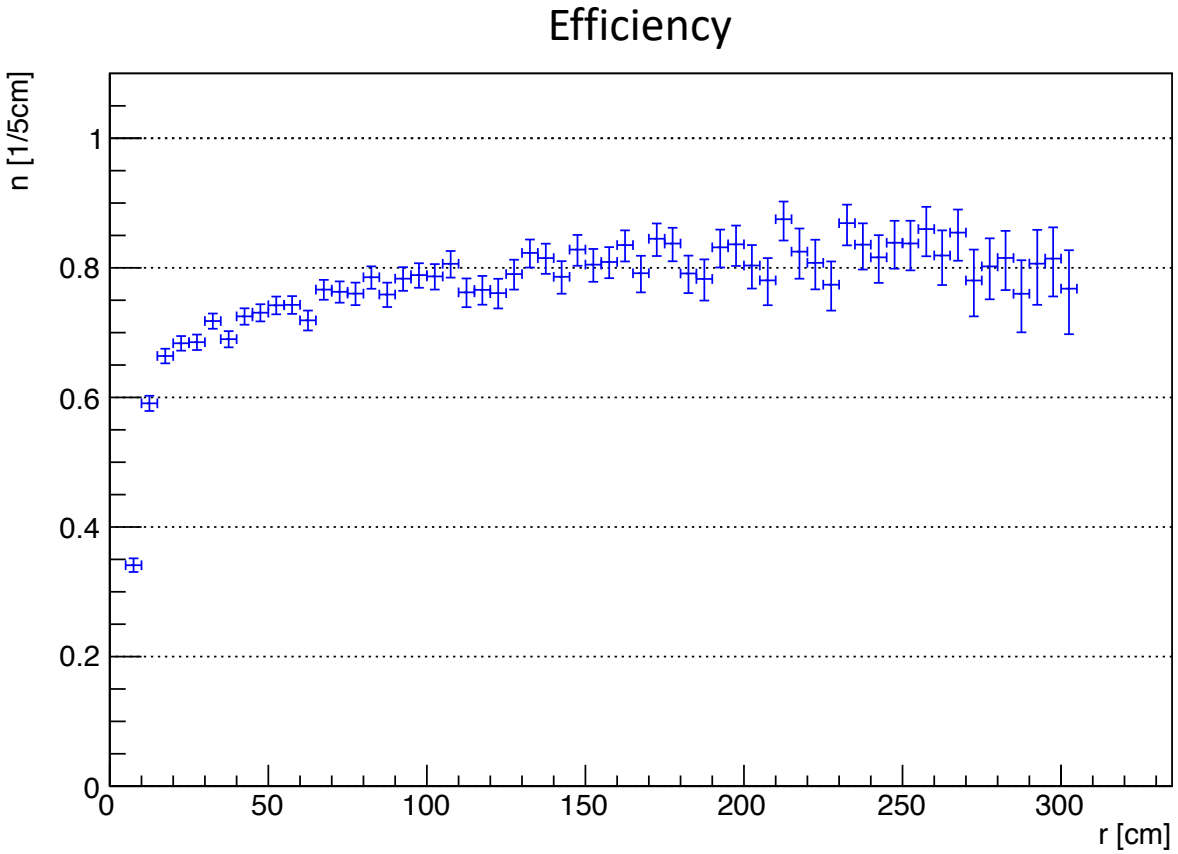
Candidate cuts

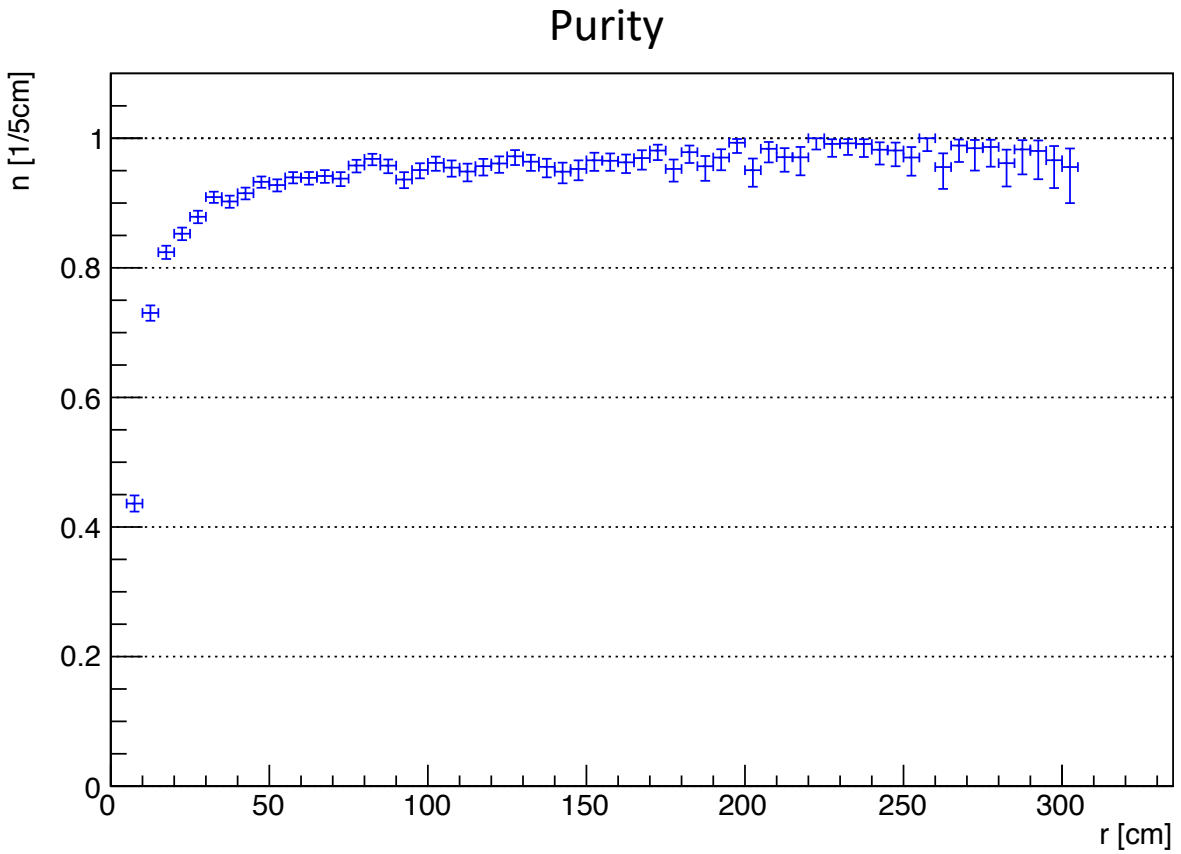
- trackScore > 0.3
- Chi2/ndof under proton hypothesis > 50.
- Disjoint track start

Definitions

- To reduce backgrounds, I still place a cut on r of 5cm
- Eff(r) $= \frac{No.\,true\ proton\ candidates\ in\ final\ selection\ (r)}{No.\,true\ protons\ (r)}\ I_{r > 5cm}$
  - Efficiency of the candidate cuts
- Purity(r) $= \frac{No.\,true\ protons\ candidates\ in\ final\ selection(r)}{No.\,candidate\ protons\ in\ selection\ (r)}\ I_{r > 5cm}$
  - Candidate purity

Efficiency and purity in 5cm < r < 305cm



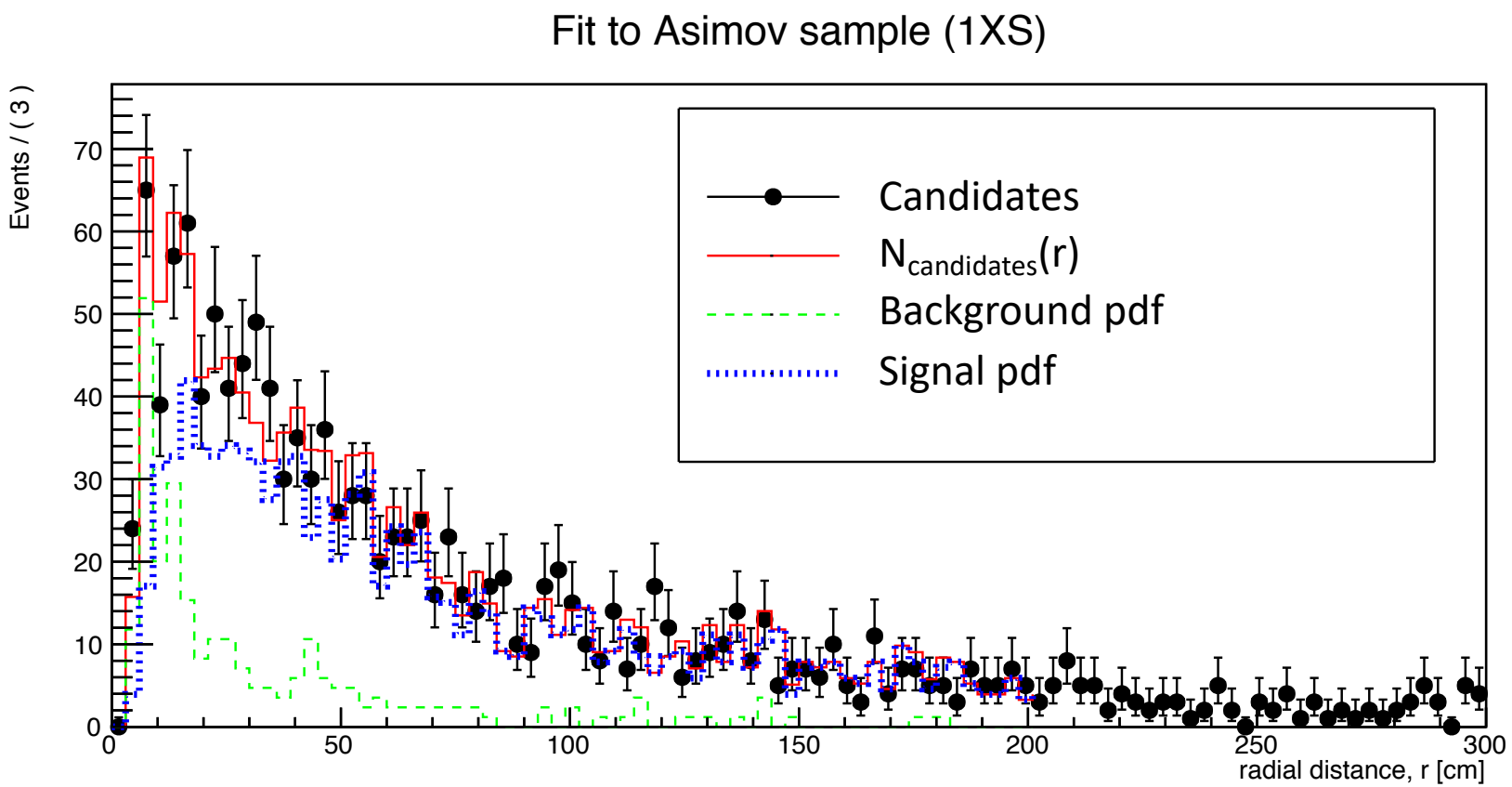


Samples

- Single pion samples
- Varying neutron inelastic XS scaling
  - 0.5, 0.9, 0.95, 1.0, 1.1, 2.0
- 1.0xs Asimov sample
- Geant4.10.3.p03

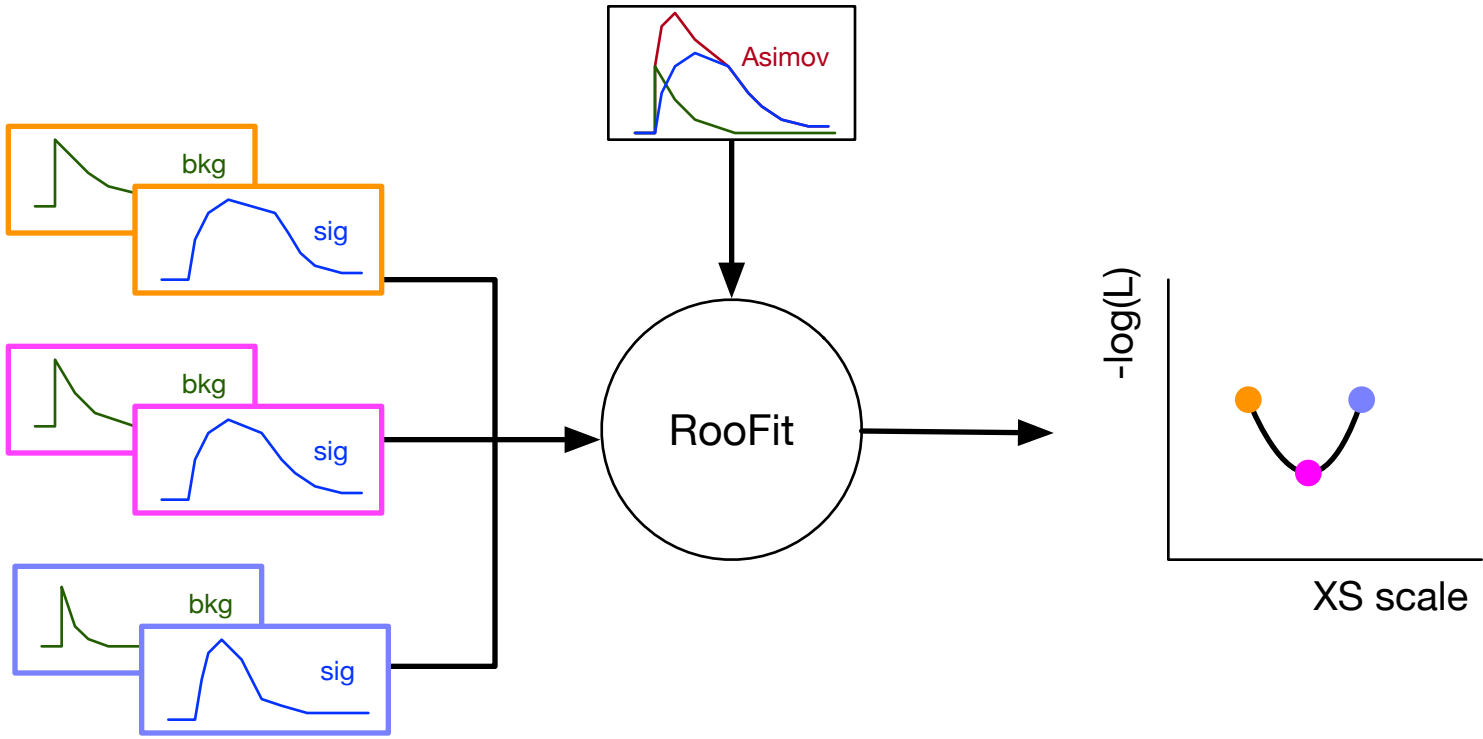
Fitting

- $N_{candidates}(r) = n_{bkg} * bkg(r) + n_{sig} * sig(r)$



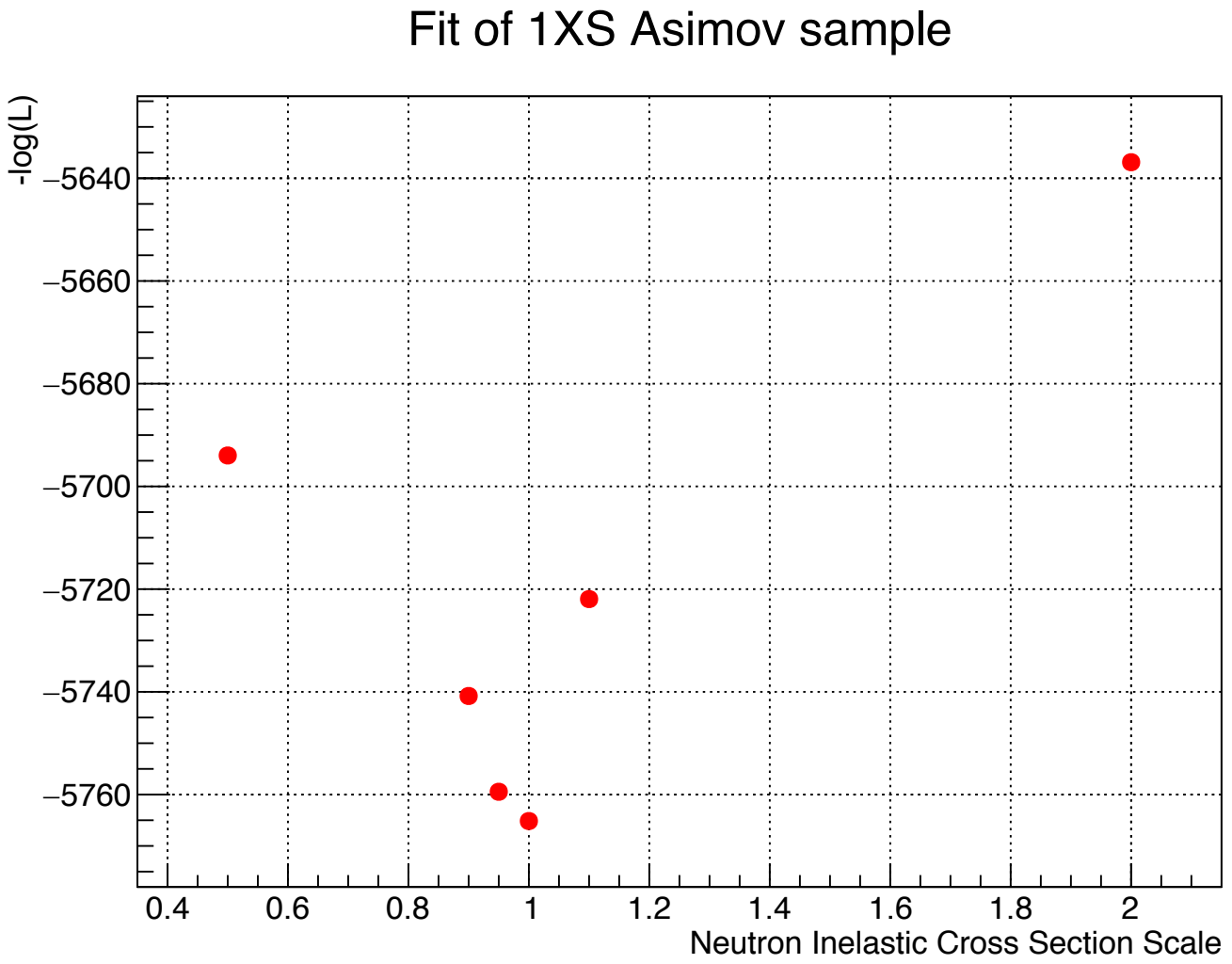
Methods

- Using RooFit
- Provide files with distance parameter probability distribution functions (PDFs/templates)
  - r, s, ρ, Δz
- Provide fake data, Asimov sample
- Calculate the likelihood that the Asimov comes from the various pdfs

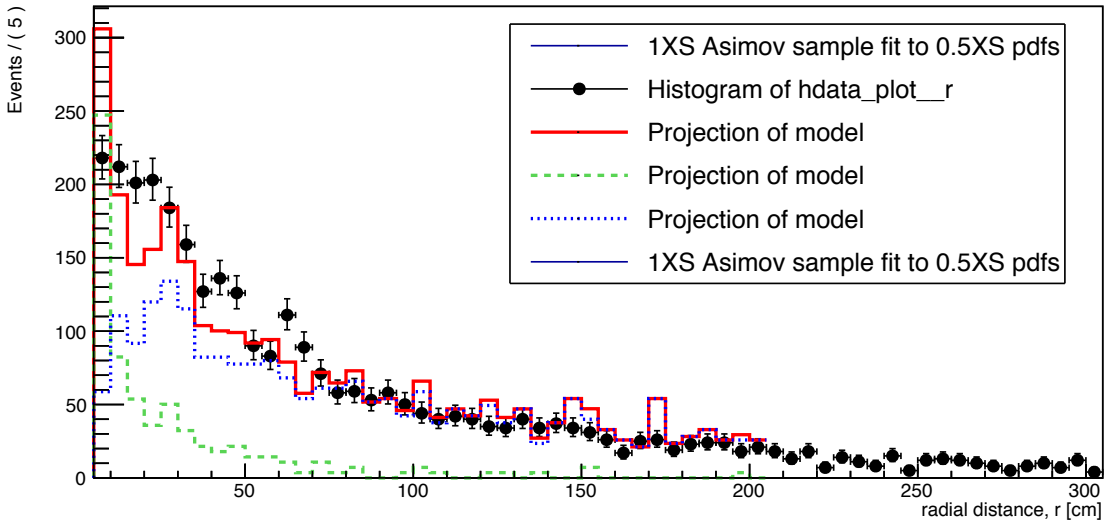


Log Likelihood

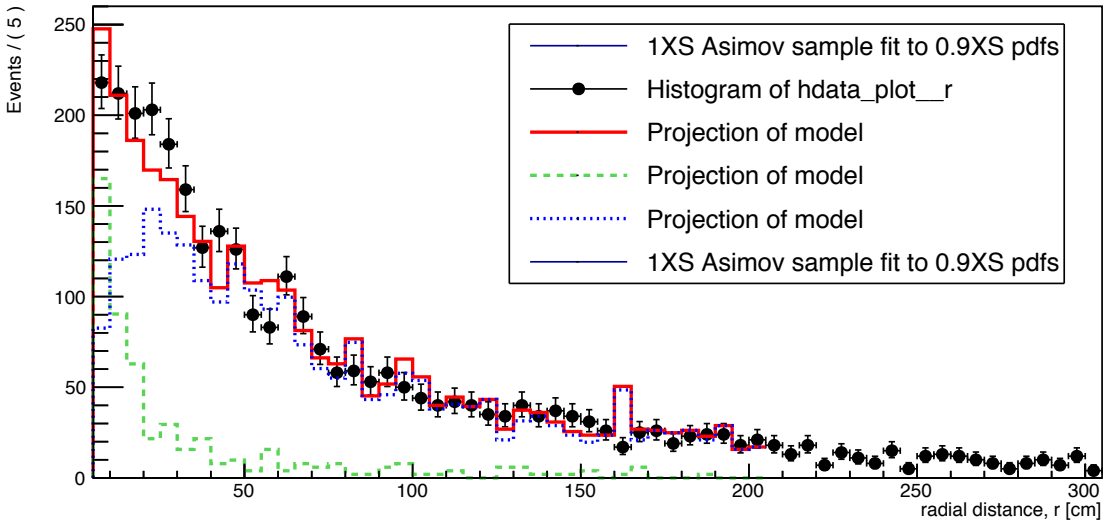
- I fit the fake data using templates with different (hard-coded) neutron inelastic XS templates
- Would need a few more points to ensure that the minimum has been reached
- Computationally expensive to generate large enough samples



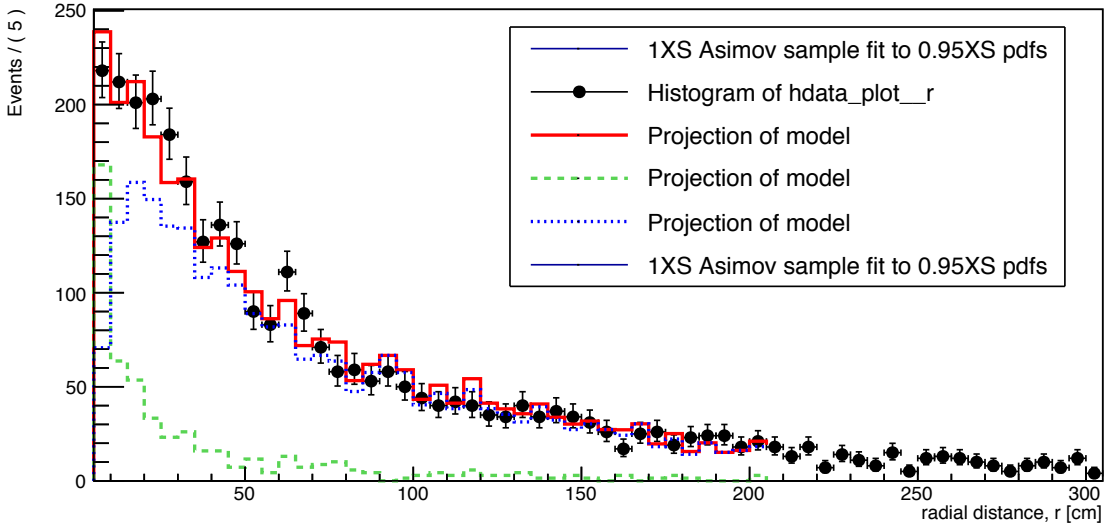
1XS Asimov sample fit to 0.5XS pdfs



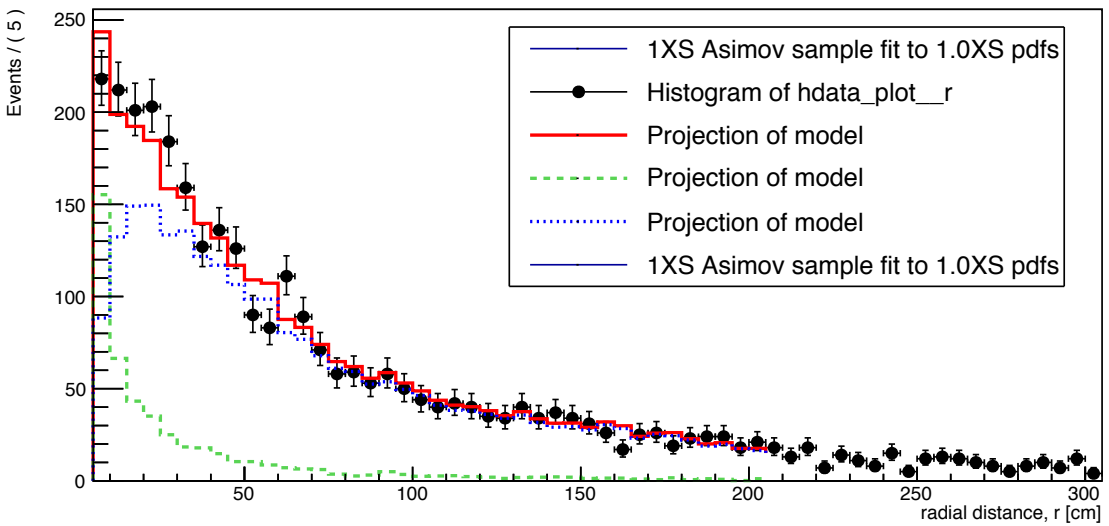
1XS Asimov sample fit to 0.9XS pdfs

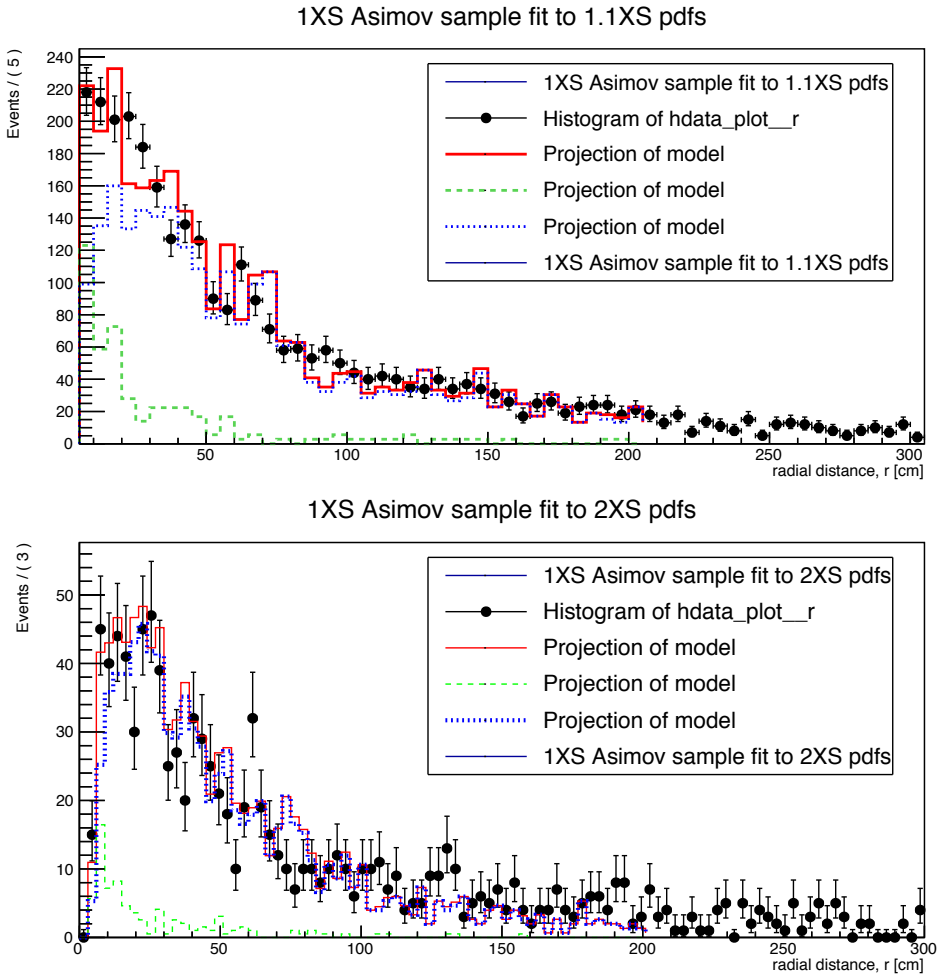


1XS Asimov sample fit to 0.95XS pdfs



1XS Asimov sample fit to 1.0XS pdfs

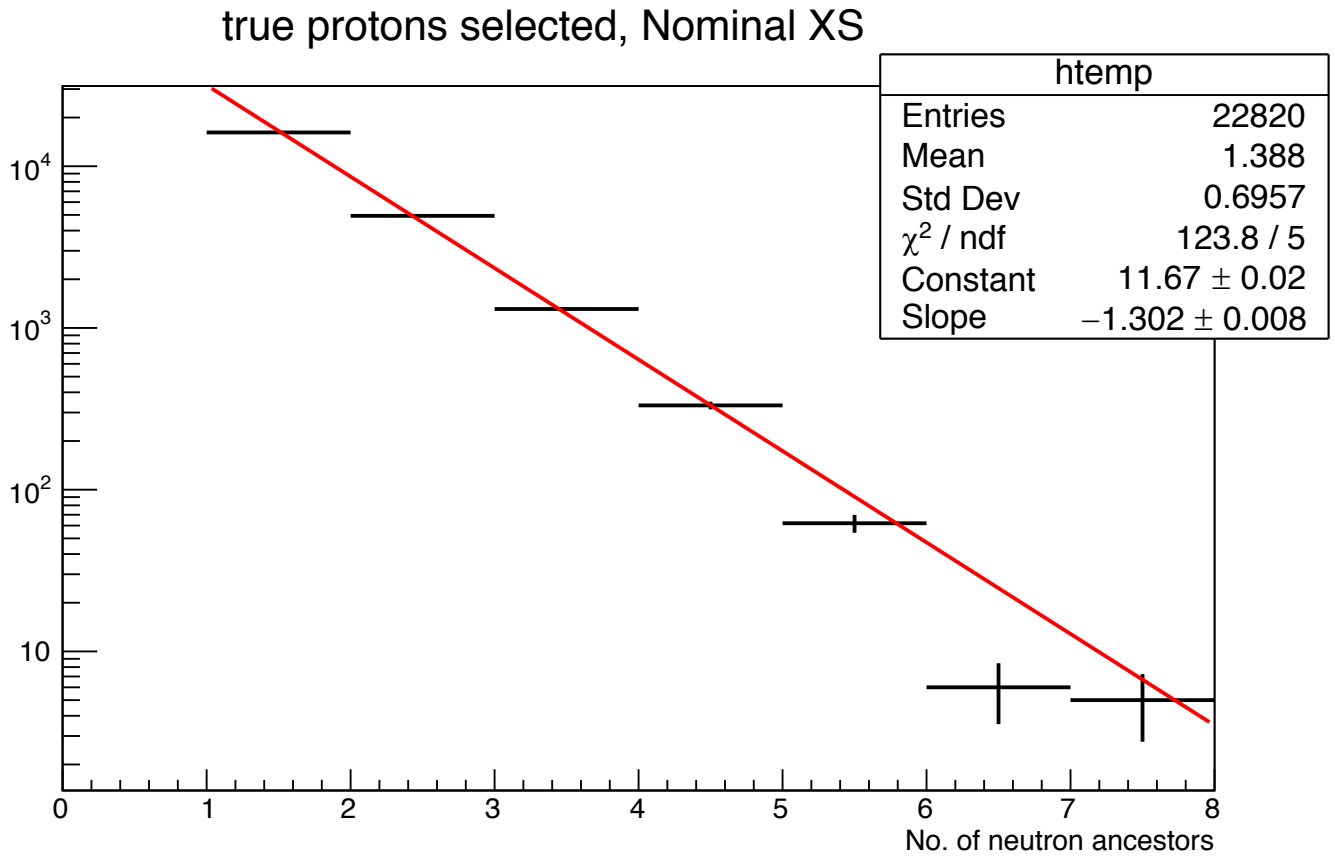




- Would need significantly more stats
- Will utilize some of these samples to cross-check the reweighting

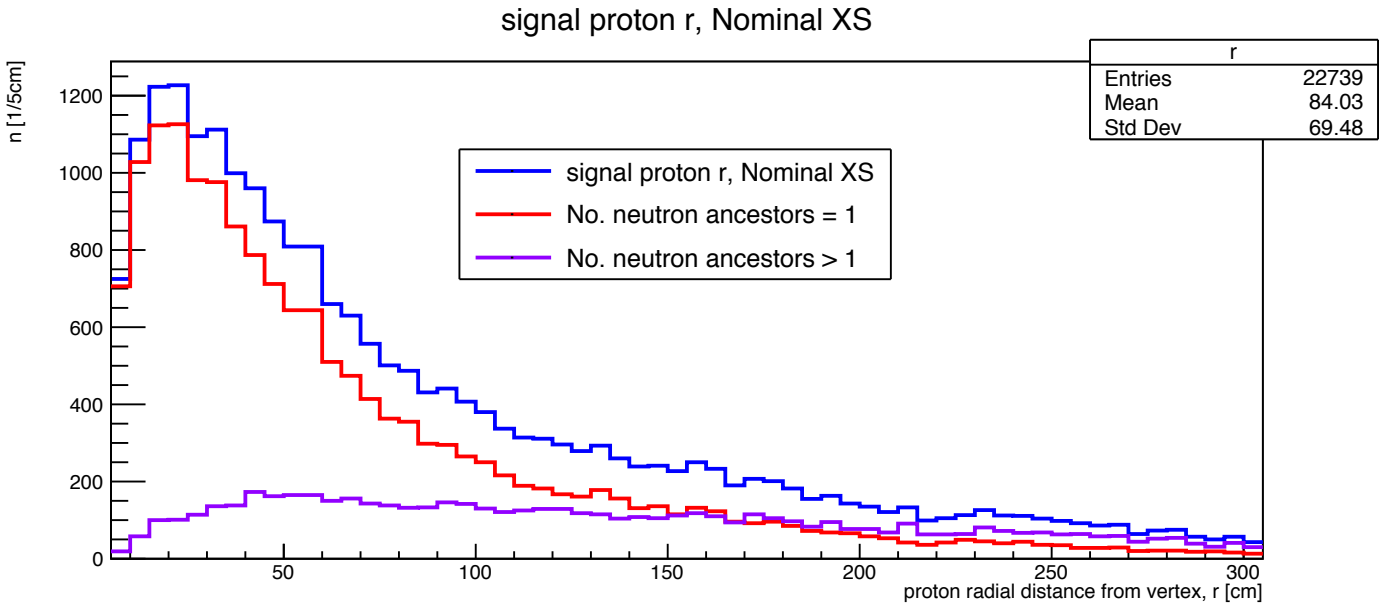
Neutron ancestry

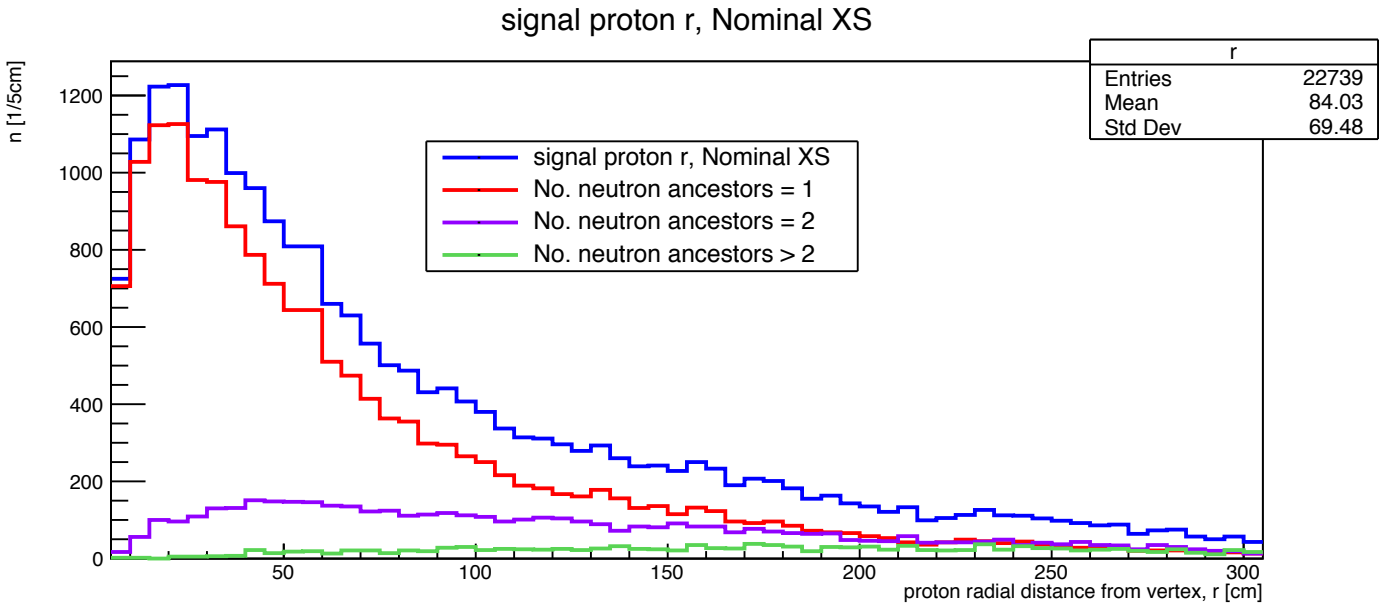
- Nominal XS template
- Protons can have multiple neutron ancestors e.g. :
  - $n \rightarrow n \rightarrow p$
  - Exponentially suppressed



Radial distribution

- Will try fitting templates for No. ancestors = 1 and >1 independently





Reweighting

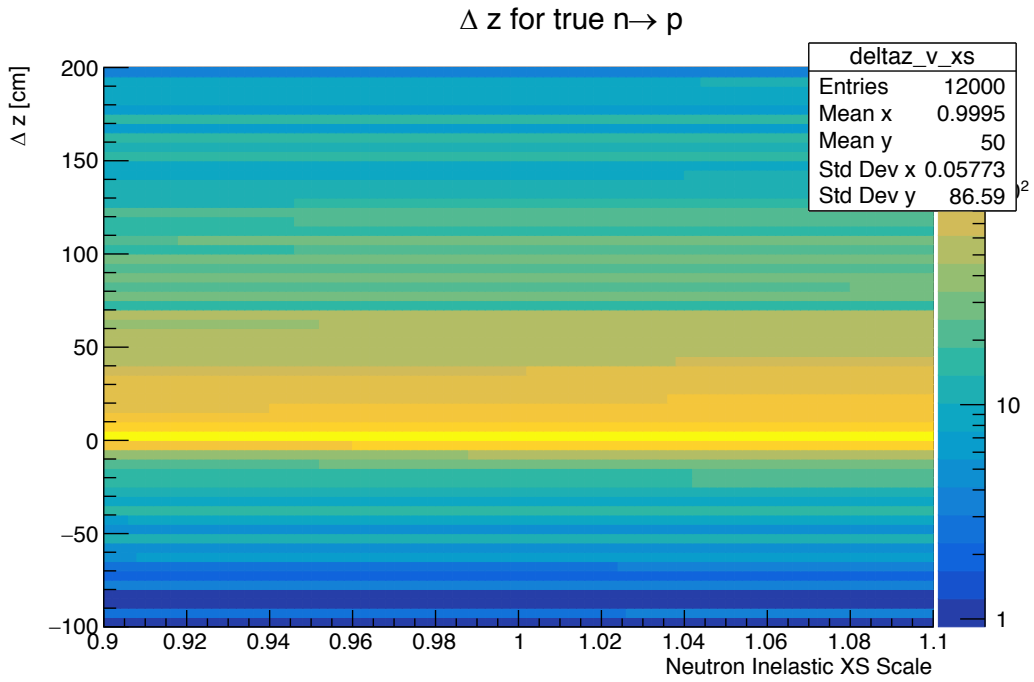
- Jake has added support for neutrons in [Geant4Reweight]
- Neutrons are not directly visible so the reweighting can be applied to the interaction neutron end point / proton start point

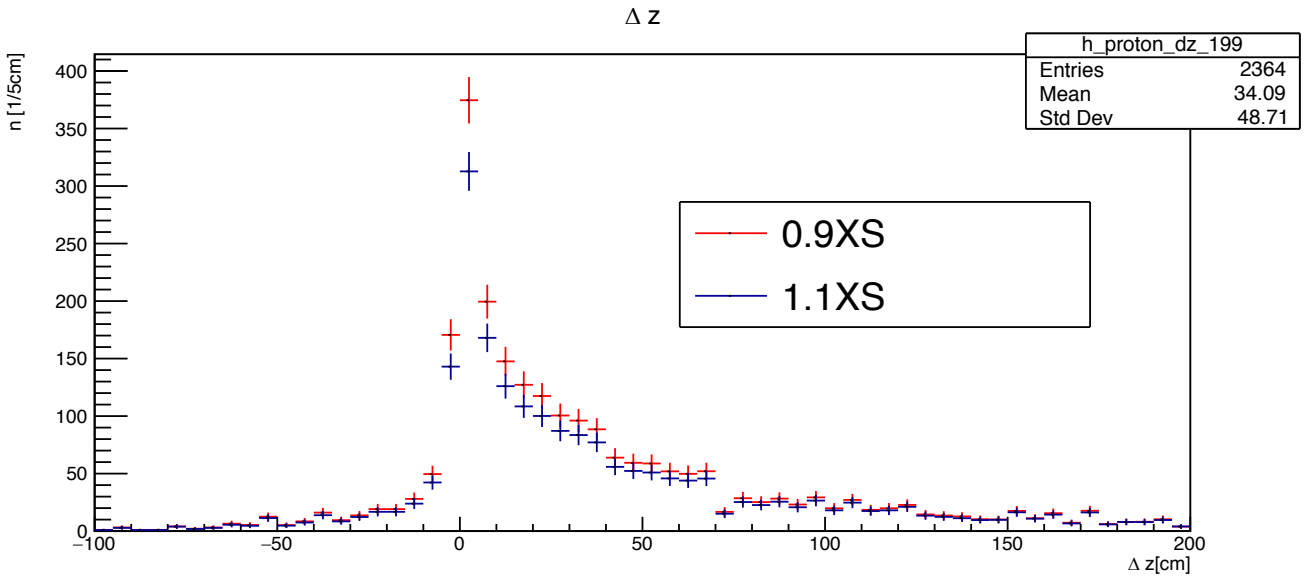
```
G4ReweightParameterMaker::G4ReweightParameterMaker( const std::vector< fhi

  std::vector< std::string > all_cuts;
  switch (pdg) {
    case 211: {
      all_cuts = {"abs", "cex", "dcex", "prod", "inel", "reac"};
      break;
    }
    case -211: {
      all_cuts = {"abs", "cex", "dcex", "prod", "inel", "reac"};
      break;
    }
    case 2212: {
      all_cuts = {"total", "reac"};
      //all_cuts = {"0n0p", "1n0p", "0n1p", "1n1p", "Other", "reac"};
      break;
    }
    case 2112: {
      all_cuts = {"total", "reac"};
      break;
    }
    case 321: {
      all_cuts = {"total", "reac"};
      break;
    }
    case -321: {
      all_cuts = {"total", "reac"};
      break;
    }
```

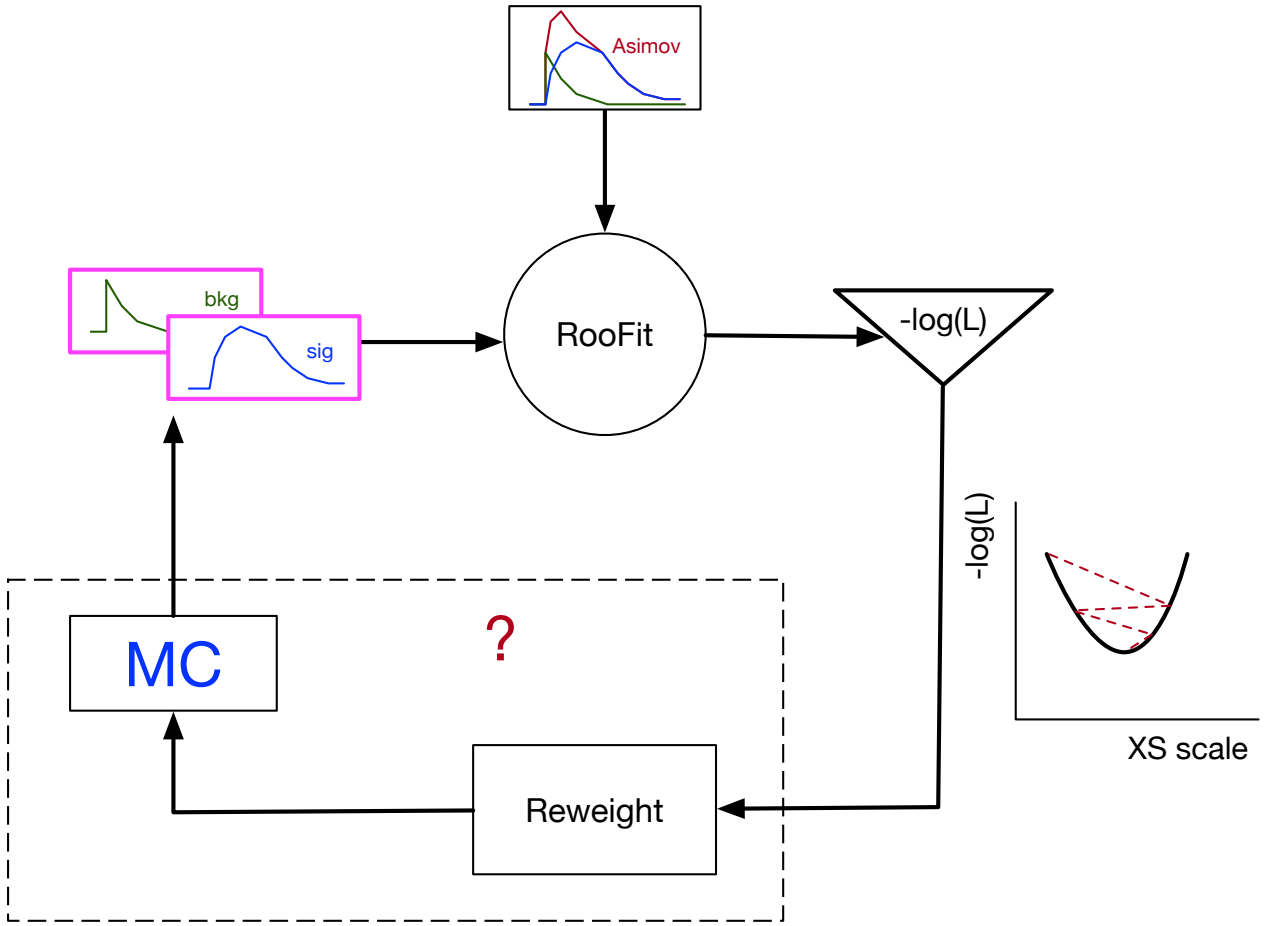
Neutron Reweighting

- Vary the inelastic cross section
  - Obtain weights for neutrons with proton daughters
- Can easily select a range of XS scales
- Weights are calculated per trajectory in the event loop
- These weights can then be applied to the distance parameters for the outgoing protons





- Ideally would like to be able to call the reweighter as part of the fitting procedure
- Could then vary the XS iteratively until the minimum log(L) is reached
- HighLAND?



Next steps

- Investigate whether there is a bias
  - Look at the pull distribution for an ensemble of Asimov samples
- Separate the contributions from No. ancestors = 1 and >1 as a test
- Compare reweighted results to samples with modified XS
- Incorporate reweighting into the analysis
- Compare to Data
  - currently reprocessing

Questions?

Thanks

- Tereza and Josh for guidance and discussions
- Richie and Jake for help with the reweighter

Summary

- Understanding neutron energy transport will be critical for DUNE
- Identifying the associated n-p and/or low energy interactions will improve the energy resolution
- The neutron interaction length can serve as an independent measurement to be used for calibrating our detectors
- We have a way to study in more detail the neutron production models

Backup

Purity

- 1073/1390 proton candidates are true protons = 77%

Radial distance