Neutron Inelastic Cross Section Measurement on Argon with ProtoDUNE Single-Phase*

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Los Alamos NATIONAL LABORATORY

DUNE

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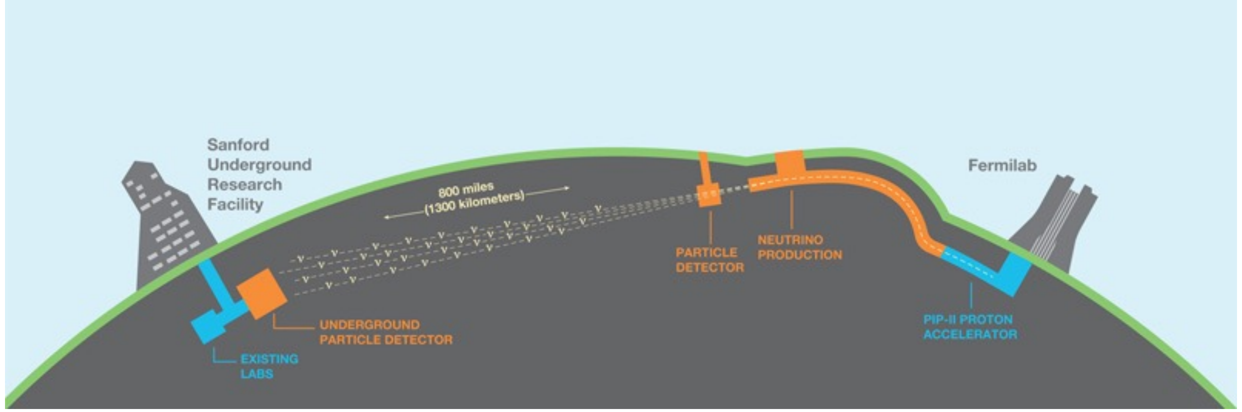
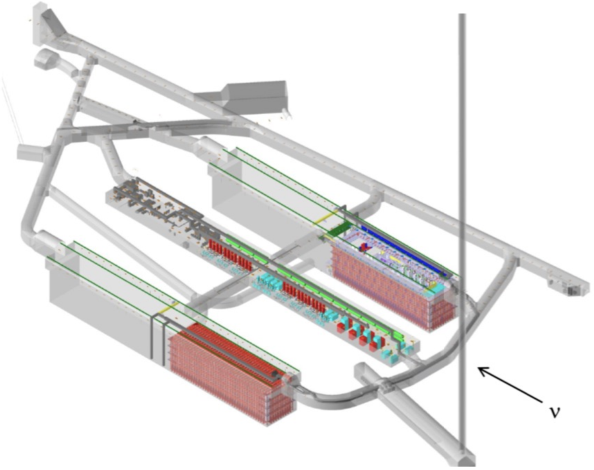
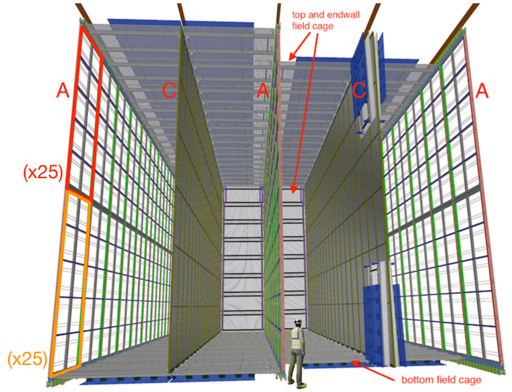
Deep Underground Neutrino Experiment

- U.S. flagship neutrino oscillation experiment
  - 1300 km baseline
  - Near Detector at Fermilab
  - Far detector in South Dakota
- Details on the DUNE physics program can be found in the [DUNE TDR (vol. 2)]
- Far detector:
  - 40 kt of active liquid Argon (LAr) across four modules
  - Liquid Argon Time Projection Chamber



Far Detector



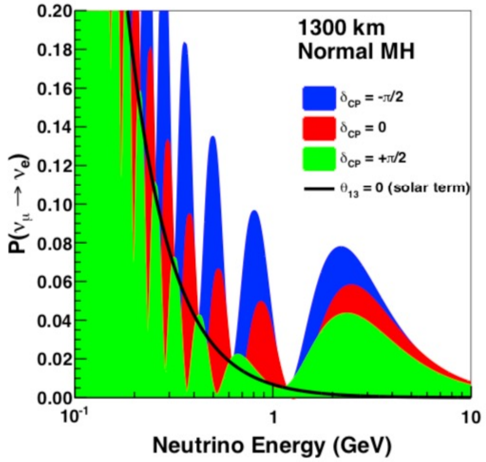


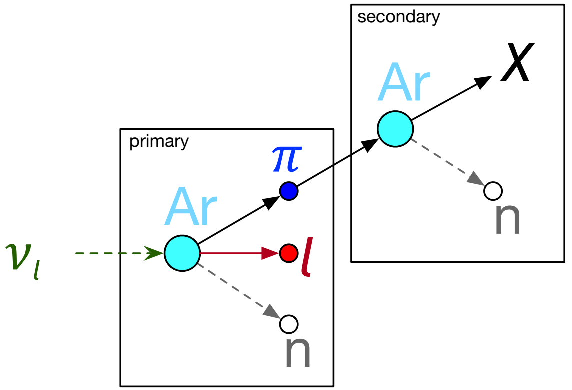
[1] Abi, B. et al. Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV: Far Detector Single-phase Technology. arXiv, 2020b.

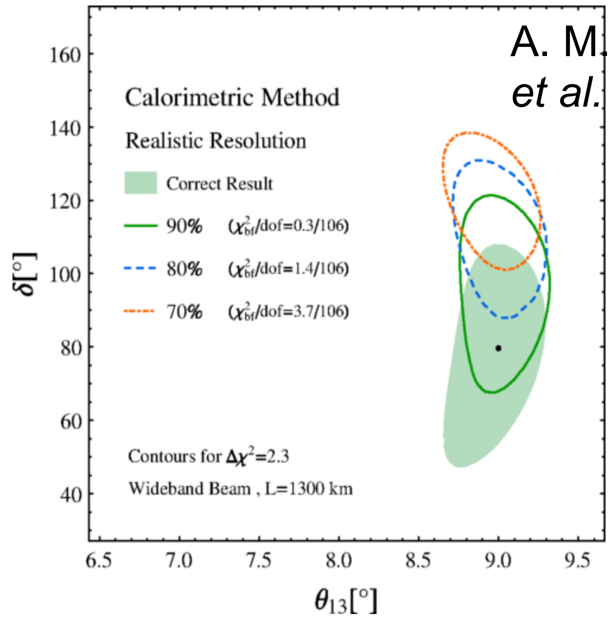
DUNE FD diagram depicting the caverns for the four 10kt modules sitting 1.5 km underground at the Sanford Underground Research Facility (SURF). Original figure from [1].

Motivation

- Wideband energy neutrino beam (~100Mev – 10GeV) range
- Oscillation studies will rely on reconstructed energy
- Missing/Invisible Energy:
  - Energy resolution is limited by our ability to reconstruct and account for all missing energy
  - Neutrons can carry away a significant portion of the energy for an event
- Primary and secondary sources of neutrons can be confused







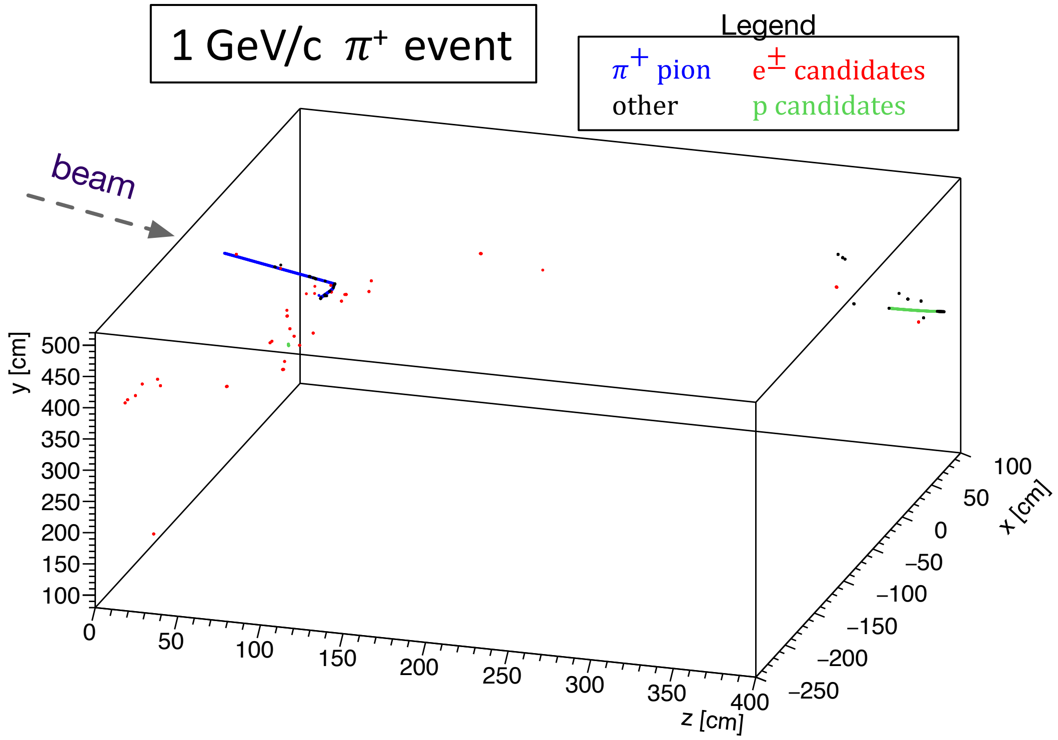
A. M. Ankowski *et al.* [2]

Reprinted figure with permission from [2] Copyright (2021) by the American Physical Society.

[2] A. M. Ankowski, P. Coloma, P. Huber, C. Mariani, and E. Vagnoni. Missing energy and the measurement of the CP-violating phase in neutrino oscillations. Physical Review D, 92(9):091301, 2015. Available from: http://dx.doi.org/10.1103/physrevd.92.091301.

Neutron interactions

- 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
    - (Ar* -> Ar + Nγ)
  - Neutron Capture : n + 40Ar -> 41Ar + Nγ
    - ~O(200μs)
    - ΣE_{γ} = 6MeV
  - Elastic scattering – low energy protons



GEANT4 simulated event in ProtoDUNE geometry

ProtoDUNE-SP

- Surface detector at CERN, Experimental Hall North 1
- Demonstrator for full-scale, single-phase, readout components for the DUNE Far Detector
- Liquid Argon Time Projection Chamber (770t) in a charged-particle test beam
  - Measured incident particle momentum using beamline instrumentation
- 300 MeV/c to 7GeV/c momentum runs in late 2018 before LHC long shutdown
  - Positively charged particles only
- Took data until 2020
- **Physics goal :** Measure particle-liquid Argon cross sections in energy ranges relevant for DUNE

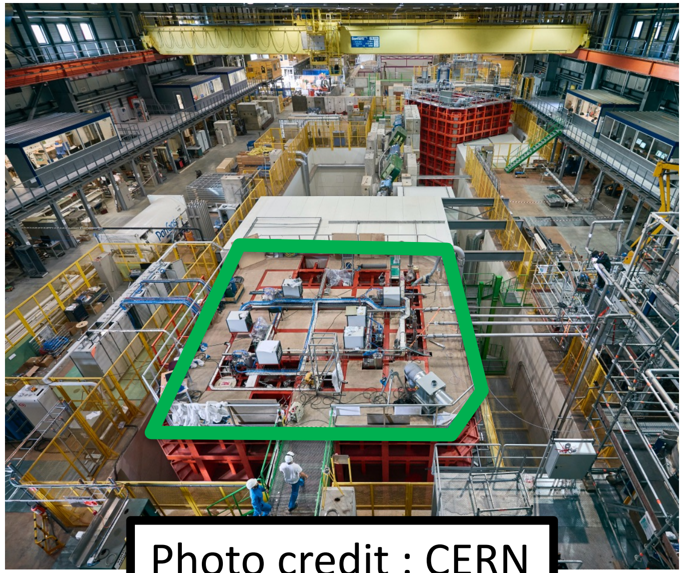
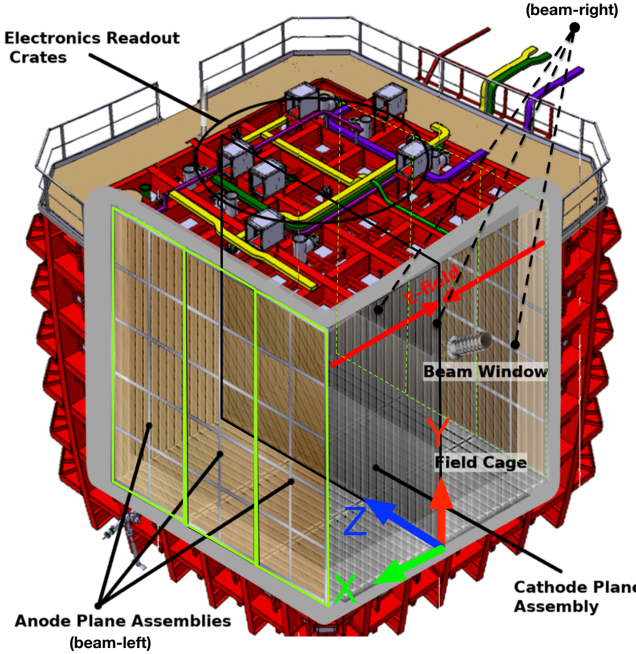
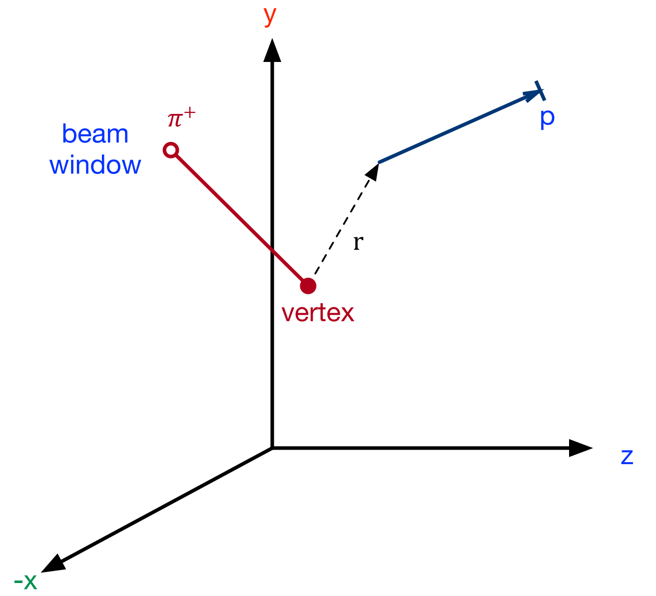


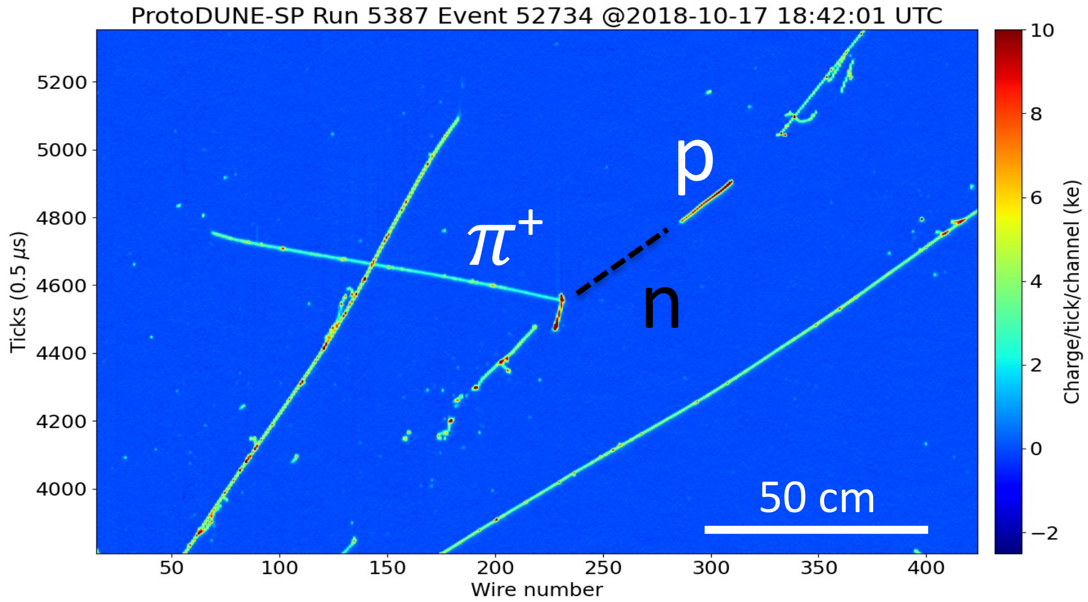
Photo credit : CERN



Neutron interaction length



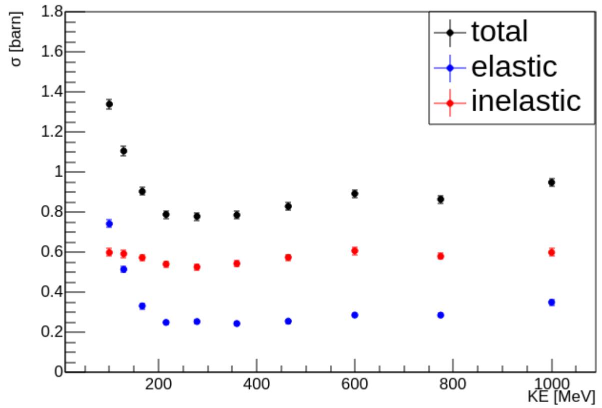
- Majority of neutron inelastic collisions (KE > 30 MeV) result in proton tracks
  - Search for disjoint proton tracks in beam interactions
- Selection cuts include :
  - Beam quality
  - Fiducial volume
  - Require disjoint track
  - Proton candidate quality
- Selection applied to all 1 GeV/c data captured
- **Measurement**: radial displacement (r)
  - r ⟶ interaction length ↔ cross section



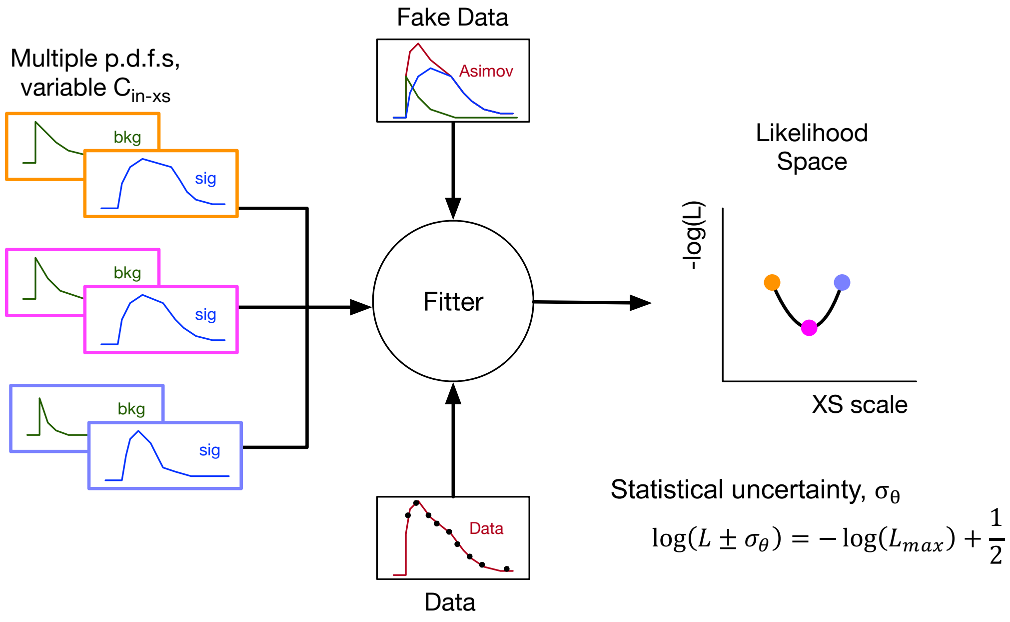
Neutron candidate event in run 5387.

Analysis approach

- Vary the GEANT4 neutron inelastic cross section (σ) by a constant scale factor ($C_{in\text{-}xs}$)
  - $\sigma(KE)' = \boldsymbol{C_{in-xs}} \cdot \sigma_{nominal}(KE)$
- Perform neutron candidate selection
- Extract simulated signal (sig) and background (bkg) radial displacement (r) probability distribution functions (p.d.f.s)
- Perform likelihood fits to Monte Carlo and data using p.d.f.s
  - $N_{candidates}(r) = n_{bkg} * bkg(r) + n_{sig} * sig(r)$
- Map the likelihood space and determine the best fit value for $C_{in\text{-}xs}$



GEANT4 neutron cross section curves



Fitting procedure for neutron analysis

Leading systematic uncertainty

- The neutron inelastic cross section measurement relies on the radial displacement as a handle on the interaction length / cross section
- Gamma interactions in LAr are more well understood than those of neutrons
  - Radiation length (X_0) in LAr = 14 cm
  - Conversion length (L_{pair}) can be approximated [5] (Eq. 1.50a):

$$X_0 = L_{pair}\left(\frac{7}{9}\right) \Rightarrow L_{pair} = \frac{9}{7}(14\ cm) \approx 18\ cm$$

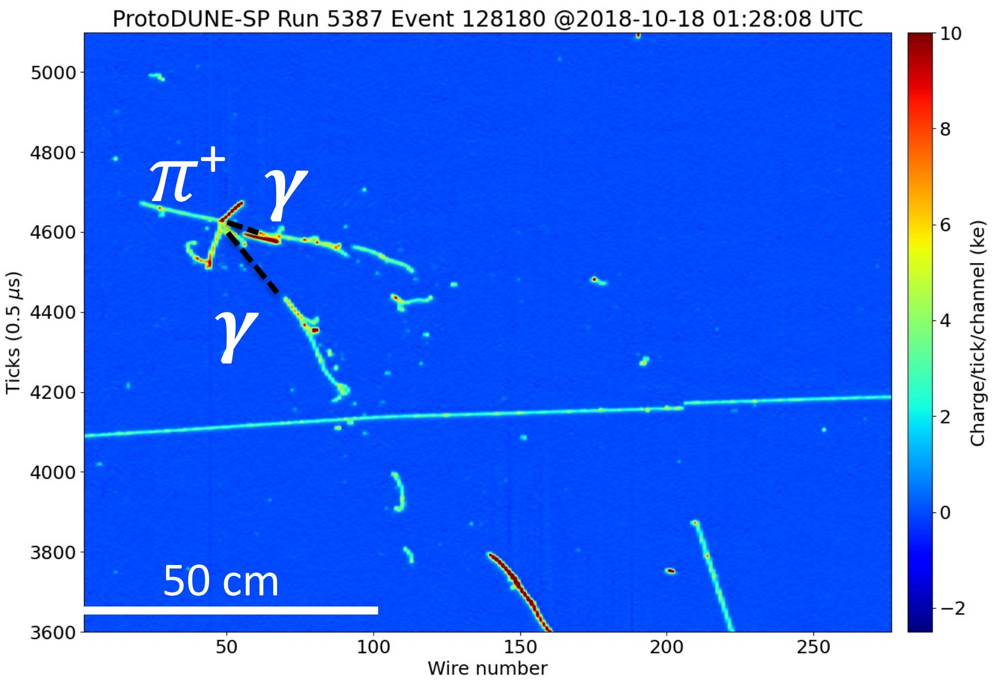
- The gamma conversion length can be used to quantify a scale factor (α) uncertainty on the distance metric (r)
  - $f(r) = f\big((1+\alpha)r_{reco}\big)$

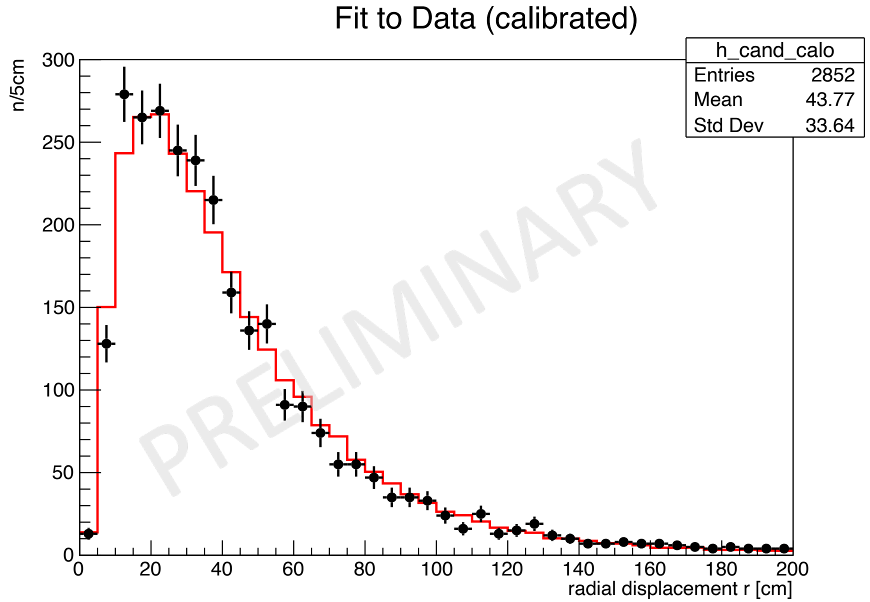
[5] Rossi, B. & Greisen, K. Cosmic-Ray Theory. (1941). Cosmic-Ray Theory, *13*(4), 240–309.
http://doi.org/10.1103/RevModPhys.13.240

Calibration sample

- **Source of gammas**: Decays of π^0 from π^+ charge exchange interactions
- Selection criteria are equivalent to those on neutrons
  - Event quality cuts
  - Disjoint shower requirement
  - Shower quality cut
- **Top:** Candidate π^0 event in ProtoDUNE-SP
- **Bottom:** MC with $\alpha = 1.9\%$ overlaid with data
  - For neutrons, α conservatively taken to be $\pm\, 2.1\%$

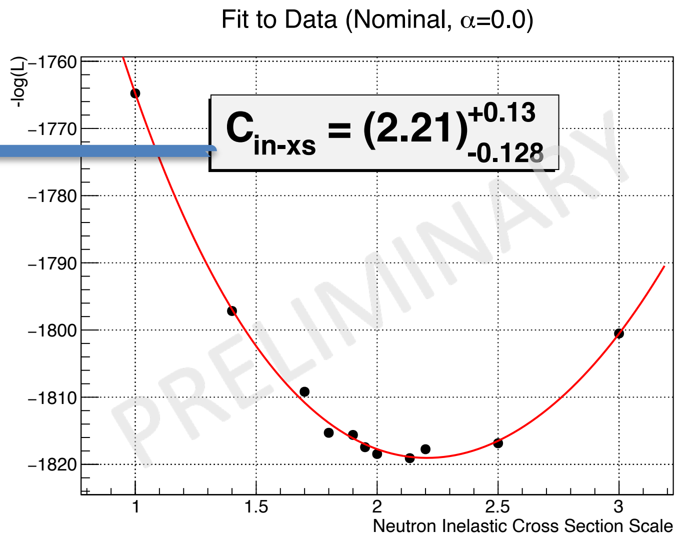
$$\alpha = 0.019^{+0.002}_{-0.007}\ (\text{stat.})$$

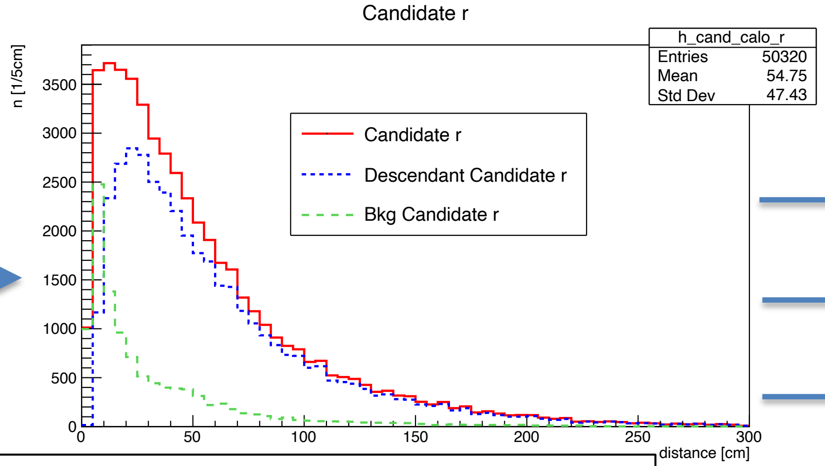




Fit to data

- **Top Left:** Likelihood for 11 different cross section scales ($C_{in\text{-}xs}$)
- **Bottom-right:** best fit using p.d.f.s from $C_{in\text{-}xs}$=2.21
  - Systematic uncertainties from applying a scale factor on the radial displacement, **α** = ± 2.1%



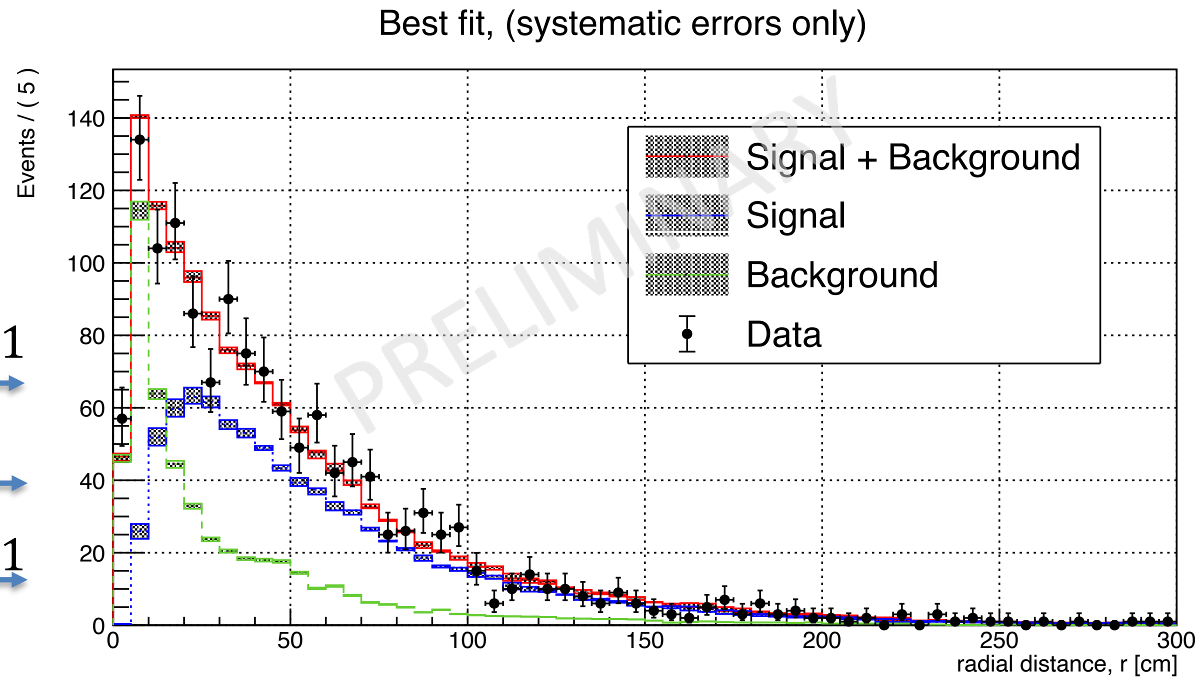


Signal and background p.d.f.s prior to fitting

$\alpha = +0.021$

$\alpha = 0.0$

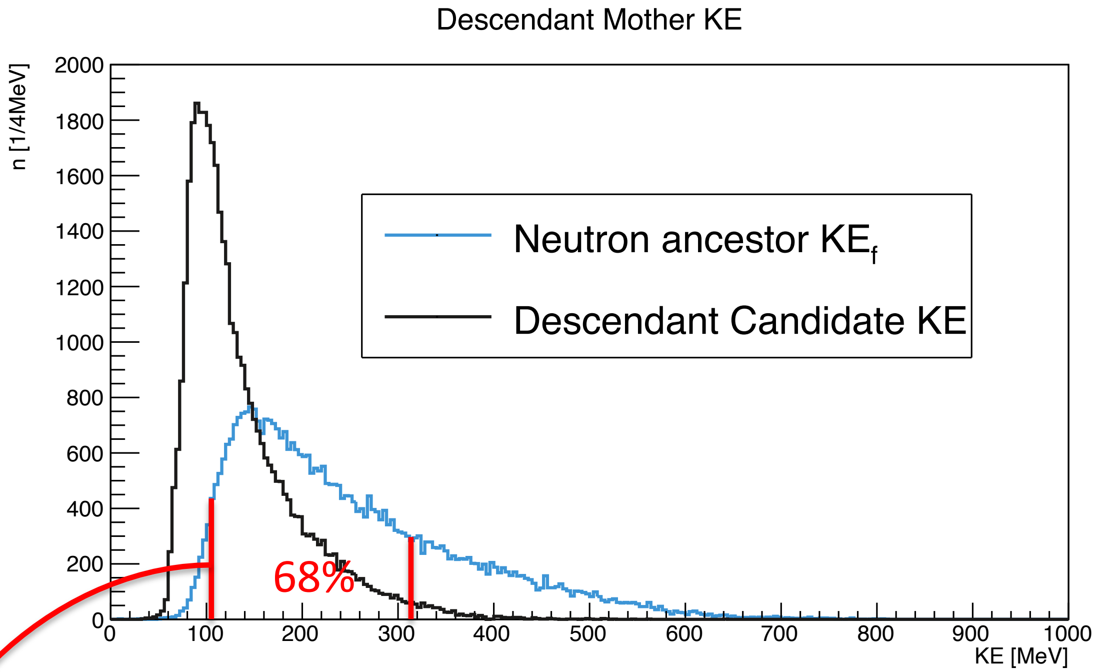
$\alpha = -0.021$

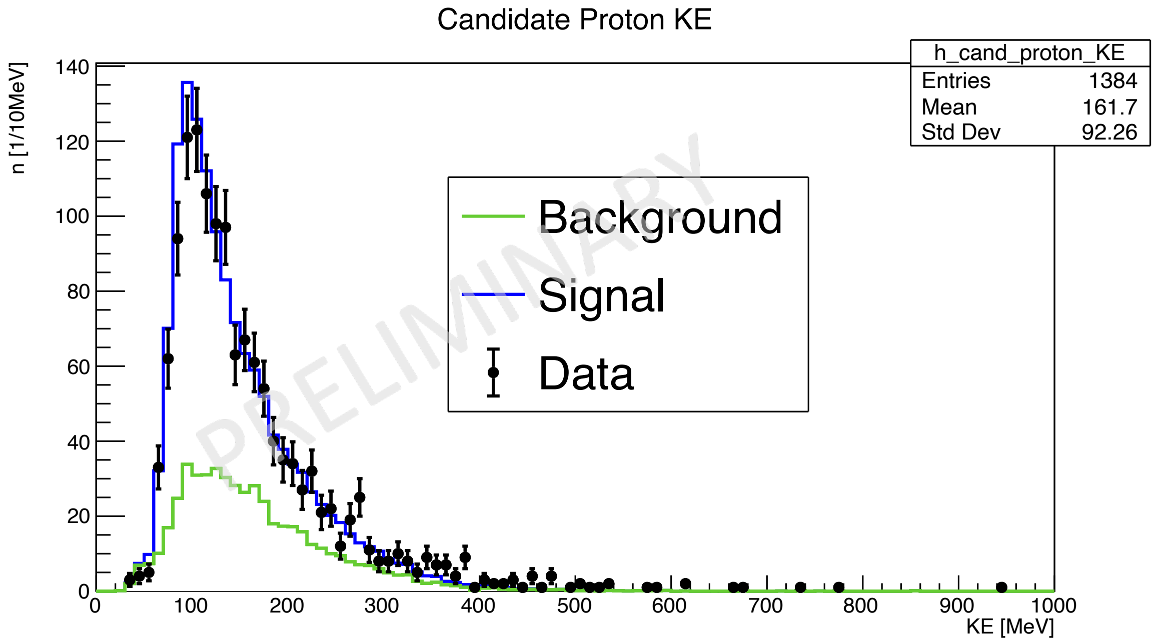


Candidate KE

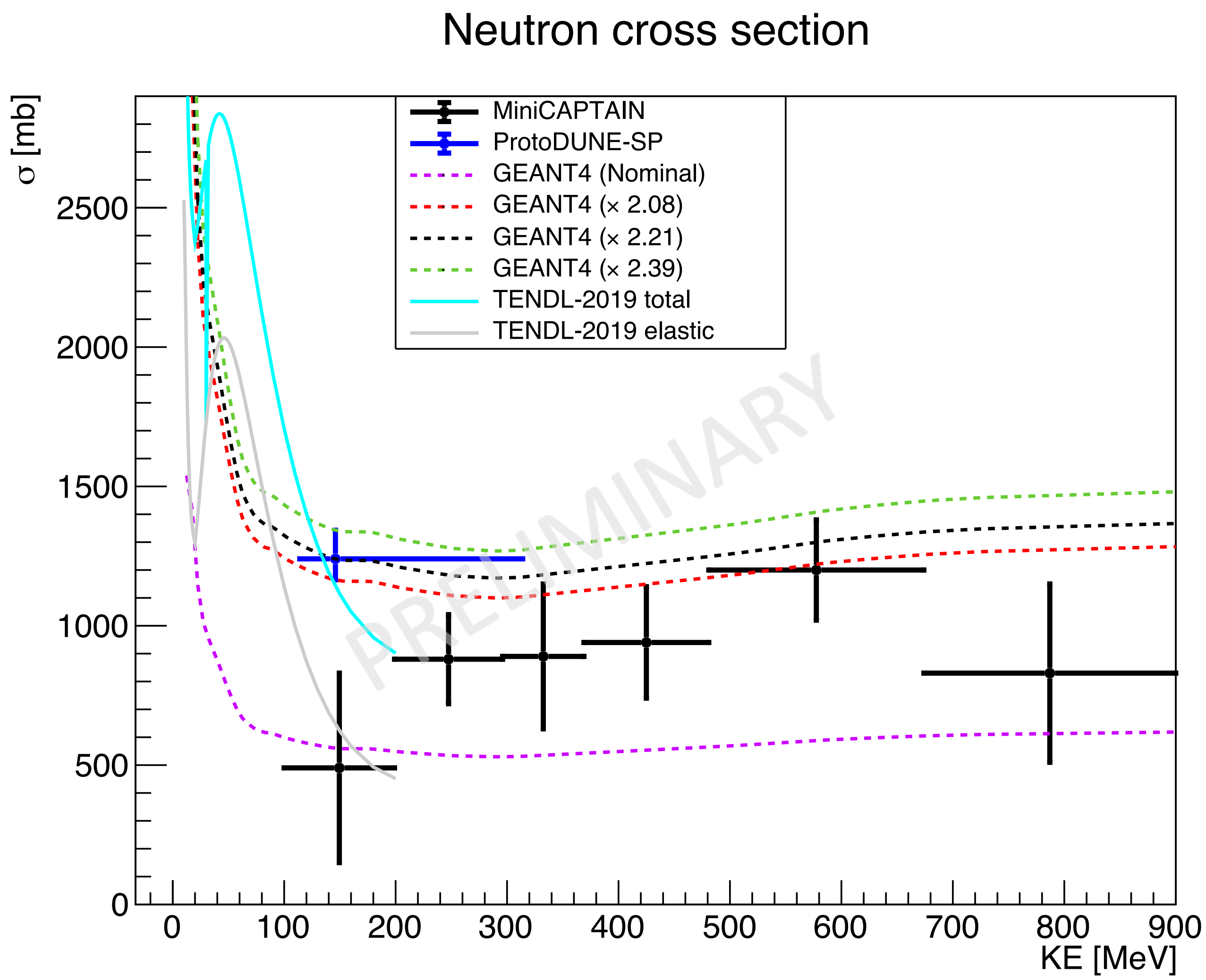
- Reconstructed momentum based on track range and proton hypothesis
  - $KE_{proton} = \sqrt{m_p^2 c^4 + p^2 c^2} - m_p c^2$
- **Top:** MC-Truth KE distributions for neutrons and their proton candidate descendants
- **Bottom:** MC-Data comparison of candidate reco KE

$KE_f \ \epsilon \ [114, 314] \ \mathrm{MeV}$





Results



ProtoDUNE-SP results overlaid over MiniCAPTAIN total neutron cross section results

- ProtoDUNE result:

$$\sigma_{\text{inelastic}} = \left(C_{in-xs} \cdot \sigma_0\right)^{\Delta C_+ \cdot \sigma_0}_{\Delta C_- \cdot \sigma_0} \quad (3.12)$$

$$= 1240^{+100}_{-80} \text{ millibarns}$$

$$= 1.24^{+0.10}_{-0.08} \text{ barns}$$

- Comparison to TENDL-2019 is shown in cyan (total cross section in Argon)
- Neutron cross section consistently higher than in nominal simulations with GEANT4 (v4.10.6.p1) across two experiments

Summary

- Understanding neutron energy transport will be critical for DUNE
- ProtoDUNE-SP is well-suited to study the secondary neutron component for DUNE
- Both ProtoDUNE-SP and MiniCAPTAIN results suggest neutron cross section in liquid argon is higher than in nominal Geant4 (QGSP_BERT)

Next Steps :

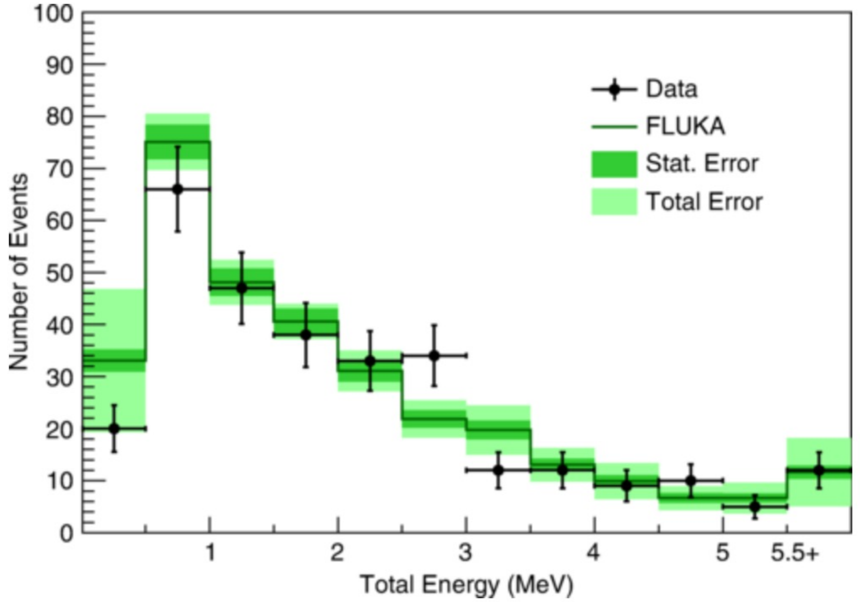
- Evaluate additional systematics
  - Elastic scattering cross section
- Comparison to other simulation engines
  - FLUKA, MCNP
- Propagate cross section results to neutrino simulations for DUNE

Questions?

Backup

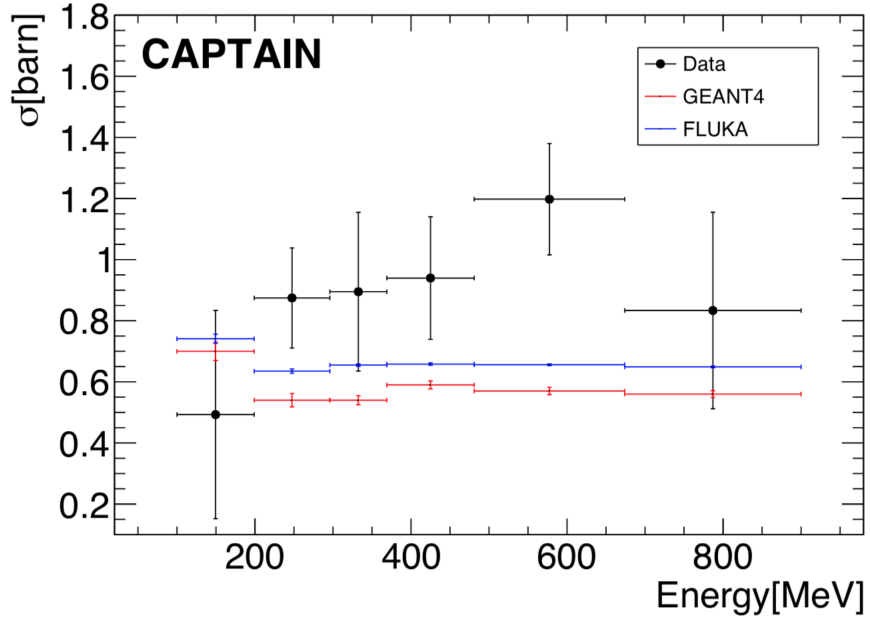
LAr Experiments

The ArgoNeut collaboration demonstrated reconstruction of MeV-scale activity [3]



CAPTAIN collaboration published neutron cross section paper [4]

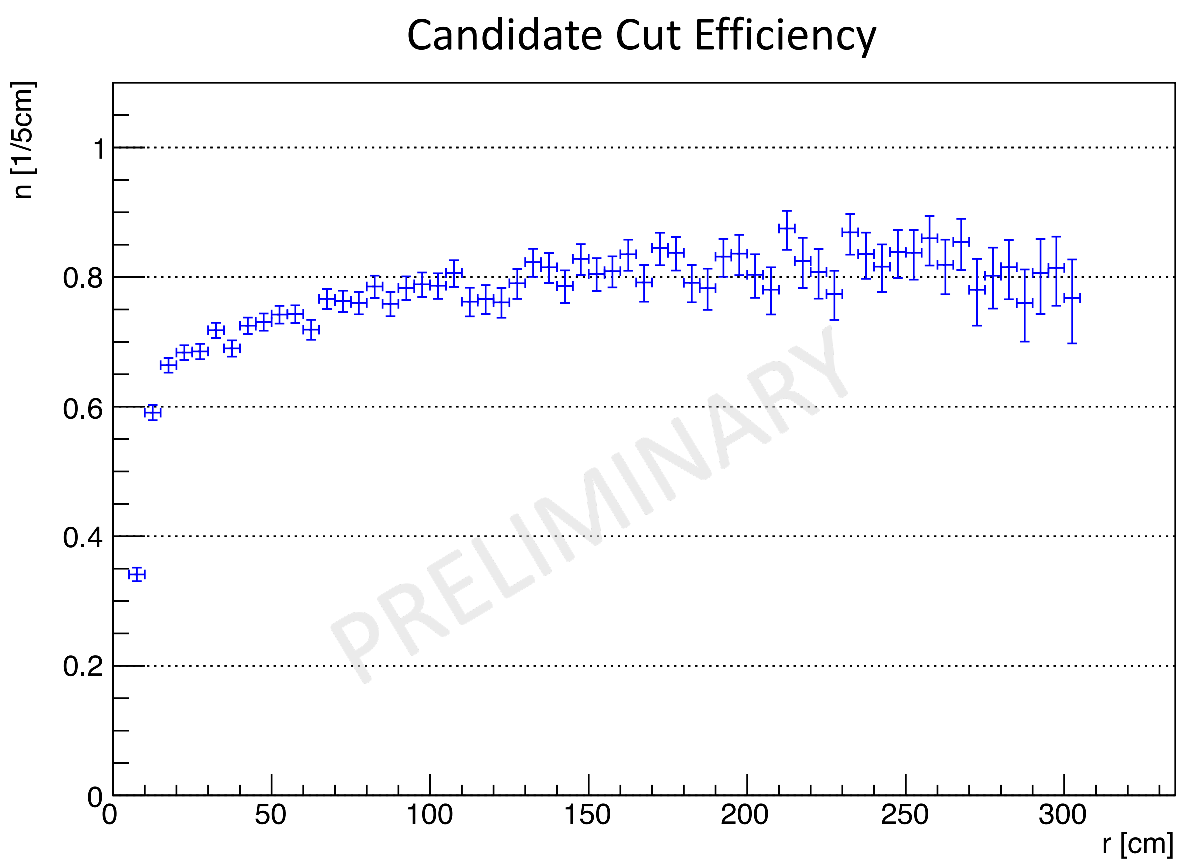
- 100-800 MeV neutron beam at Los Alamos Neutron Science Center

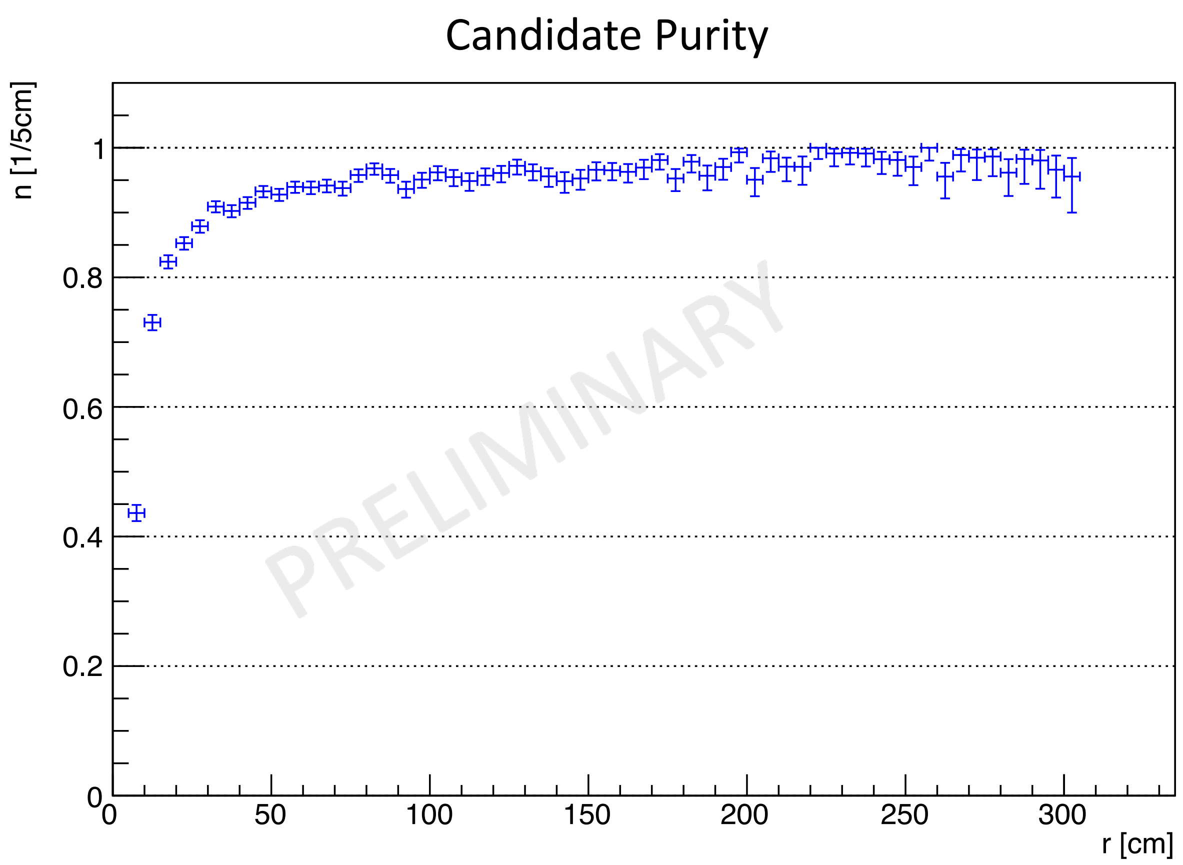


[3] ArgoNeuT Collaboration , (2018, October 15). Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT. *arXiv.org*. American Physical Society. http://doi.org/10.1103/PhysRevD.99.012002

[4] Bhandari, B., Bian, J., Bilton, K., Callahan, C., Chaves, J., Chen, H., et al. (2019, March 12). First Measurement of the Total Neutron Cross Section on Argon Between 100 and 800 MeV. *arXiv.org*. American Physical Society. http://doi.org/10.1103/PhysRevLett.123.042502

Efficiency and purity in 5cm < r < 305cm



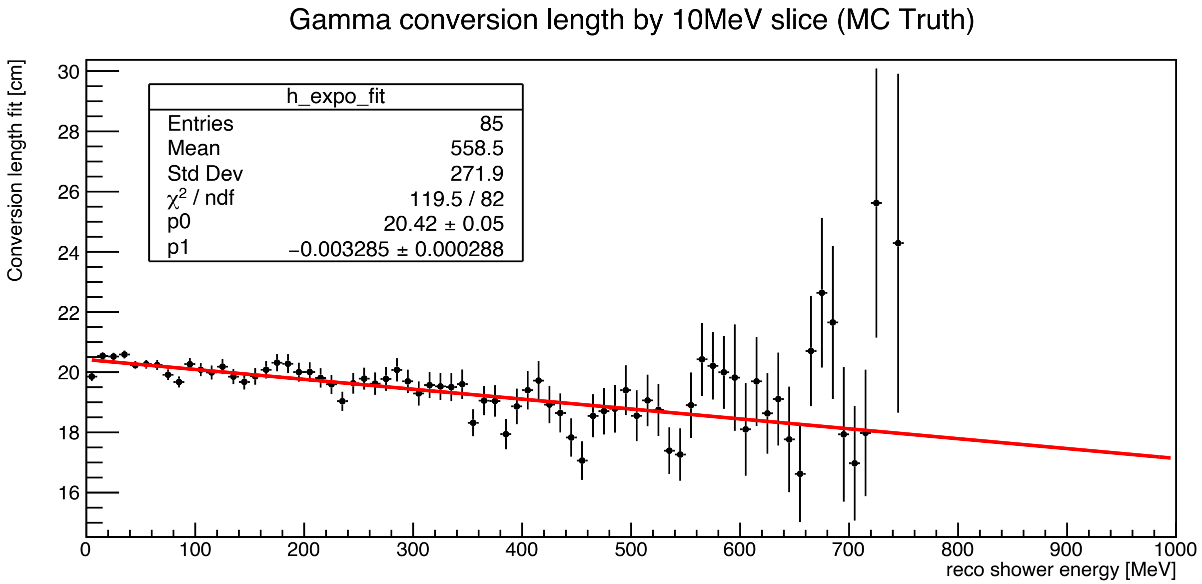


$$\text{Eff}(r) = \frac{No.\,true\ proton\ candidates\ in\ final\ selection\ (r)}{No.\,true\ protons\ (r)}\Big|_{r>5cm}$$

$$\text{Purity}(r) = \frac{No.\,true\ protons\ candidates\ in\ final\ selection(r)}{No.\,candidate\ protons\ in\ selection\ (r)}\Big|_{r>5cm}$$

Conversion length

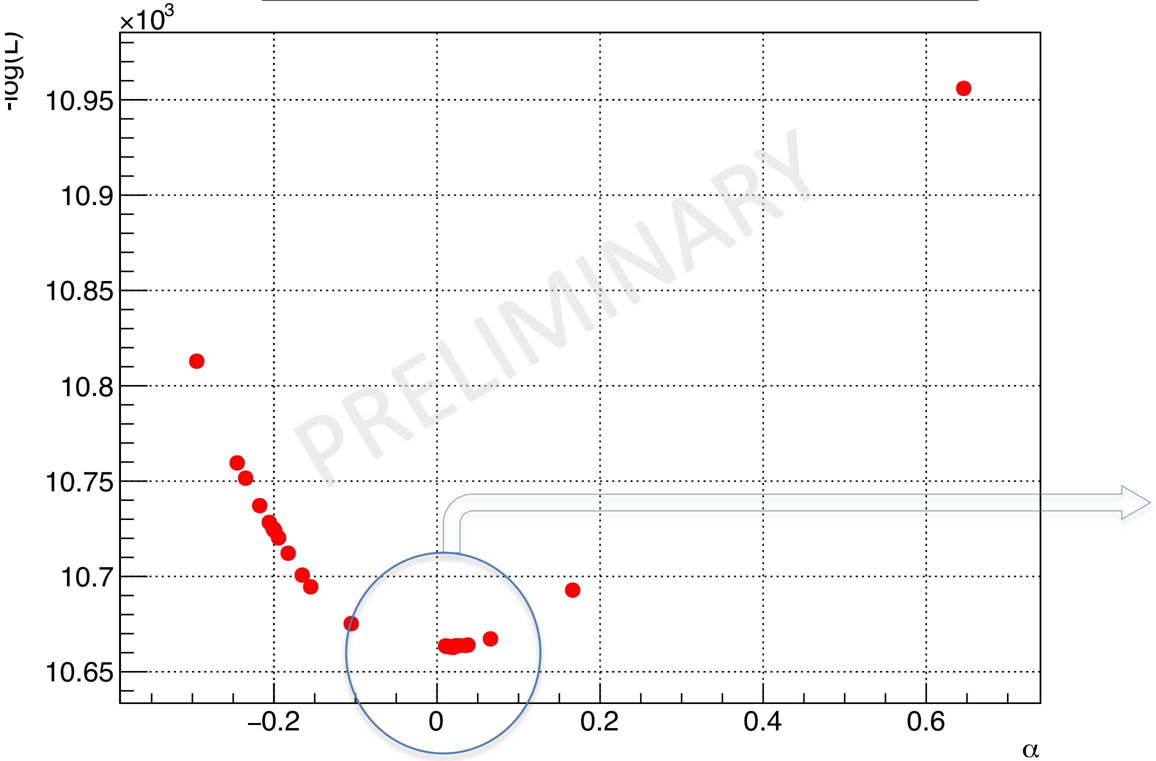
- Systematic uncertainty of position reconstruction can be studied by using decay gammas from π^0
  - $\pi^+ + N(Z,A) \rightarrow \pi^0 + N(Z+1,A)$
- The conversion length is a function of the energy
  - Agrees with theory



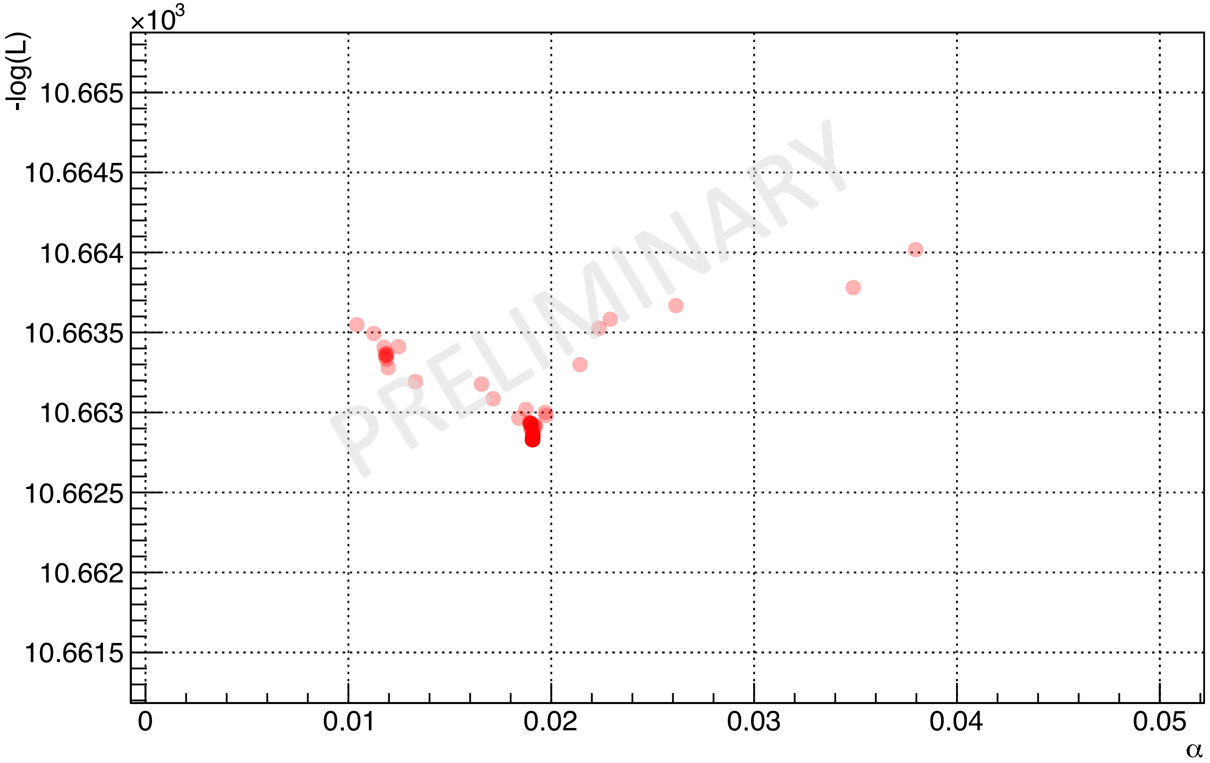
Gamma conversion length from exponential fit in 10 MeV slices, approaching 18 cm with increasing energy

Scale factor systematic from gammas

Likelihood space for scale factor, α



Likelihood space for scale factor, α, zoomed around the minimum



$$\alpha = 0.019^{+0.002}_{-0.007}\ \text{(stat.)}$$

$$\log(L \pm \sigma_\theta) = -\log(L_{max}) + \frac{1}{2}$$