DEEP UNDERGROUND NEUTRINO EXPERIMENT

ARTIE (near-)final results

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on the behalf of the ARTIE and DUNE Collaborations

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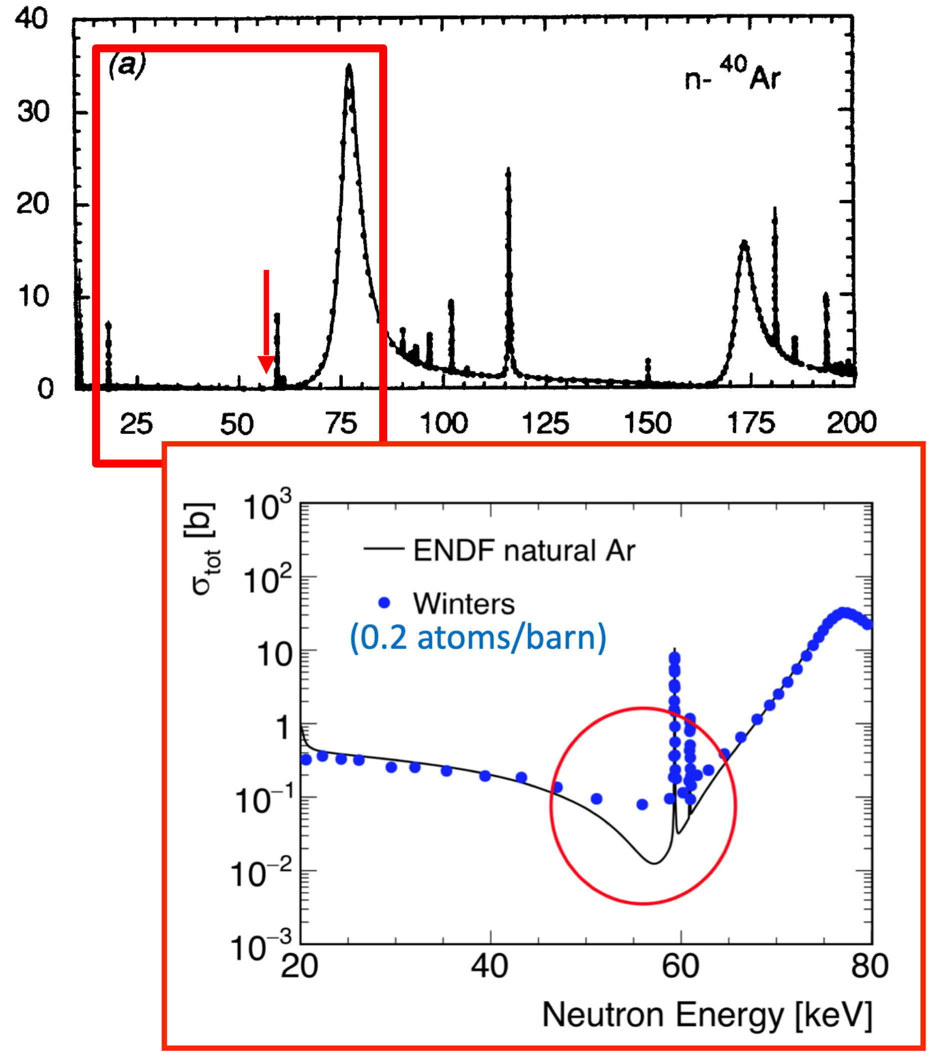
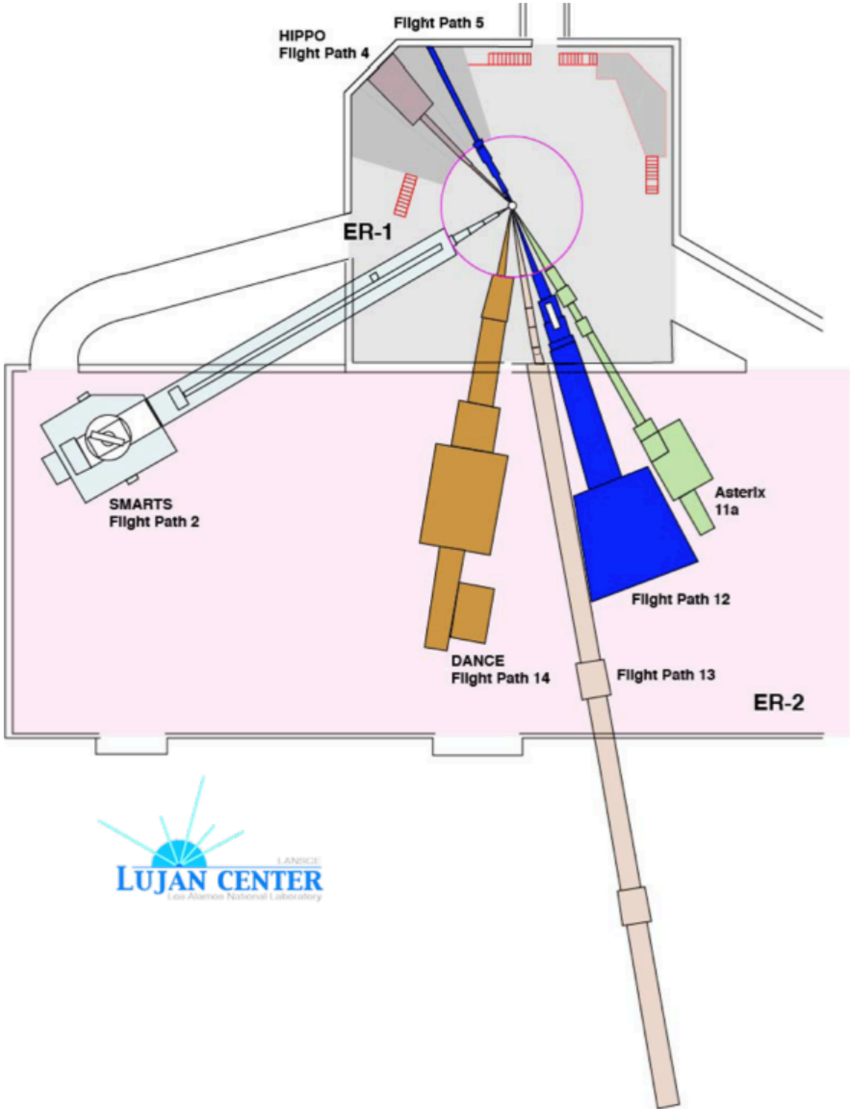
Why ARTIE?

- The **A**rgon **R**esonant **T**ransmission **I**nteraction **E**xperiment (**ARTIE**) is a measurement of the depth of the anti-resonance at 57keV in the total cross section of neutrons on argon
- Theoretical calculation (ENDF) predicts anti-resonance but the only experiment before ARTIE did not observe it
- Knowledge of this parameter is of utmost importance when argon is used as a target or a shield (*e.g.* rate at which neutrons from environment enters the fiducial volume, or how far neutrons can travel from an interaction vertex and thus contribute to lost energy in calorimetry)

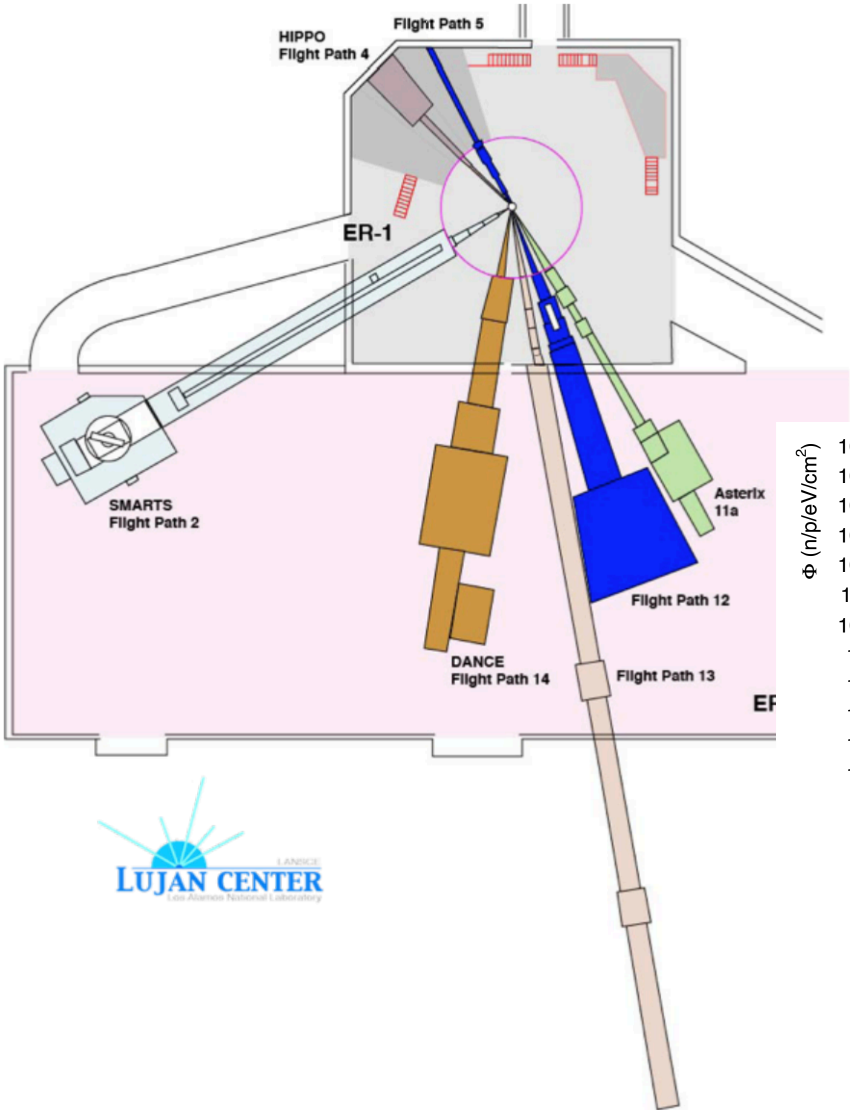


What is ARTIE?

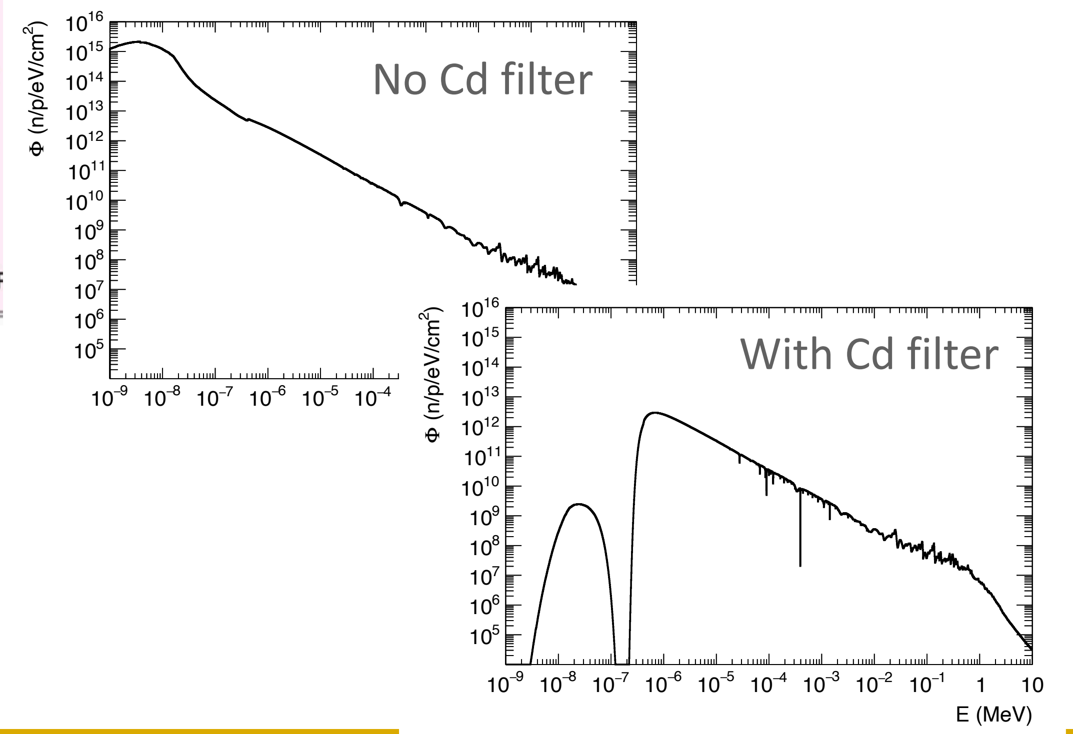


- ARTIE is located on Flight Path 13 (FP13) at the Lujan Neutron Scattering Center (LANSCE) at LANL and data was collected during 10-20th October 2019
- ARTIE uses Time Of Flight (TOF) technique to measure neutron energy
- ARTIE designed to contain liquid argon (LAr) at atmospheric pressure
- ARTIE uses a **1.68 m** long (longest to fit at FP13) x **1”** diameter (» beam size) liquid argon (99.99% pure) target with a column density of **3.5 atoms/b**
  - Because of its thickness, the target is nearly opaque to neutrons away from anti-resonance: **ROI is 30-70keV**

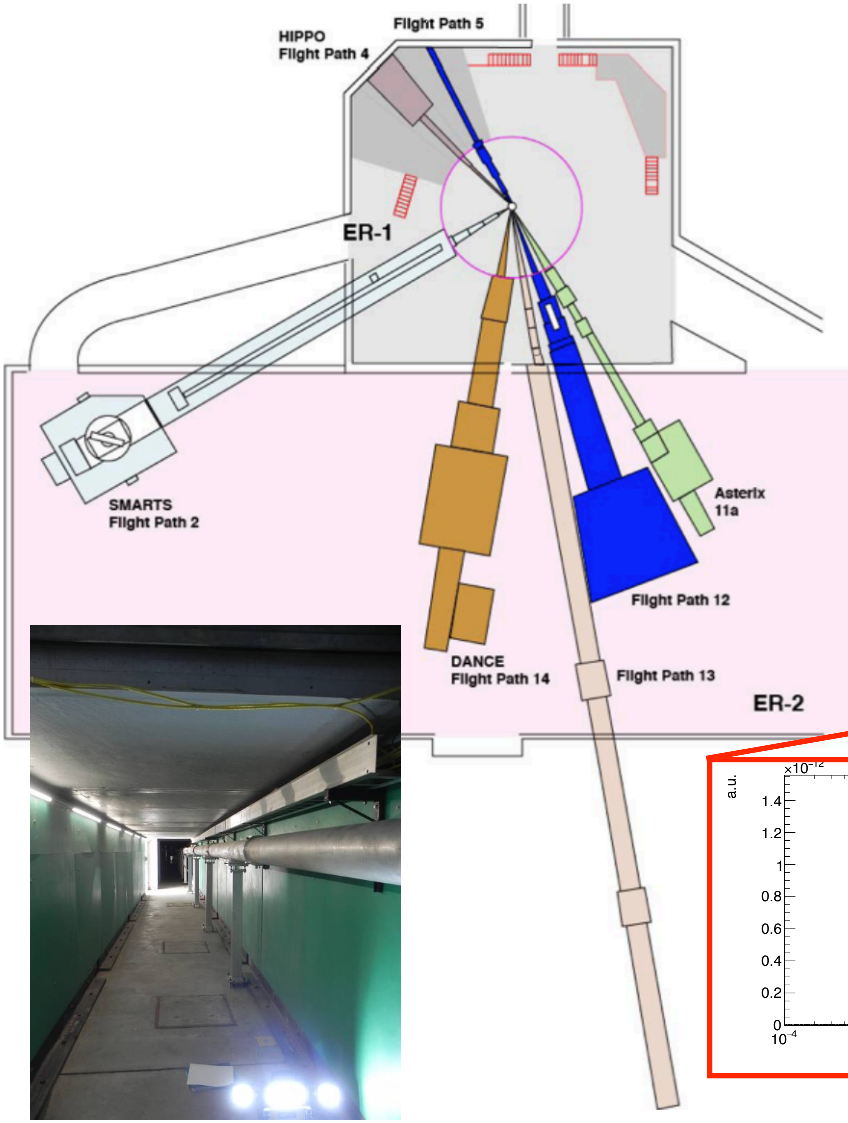
Neutron energy flux



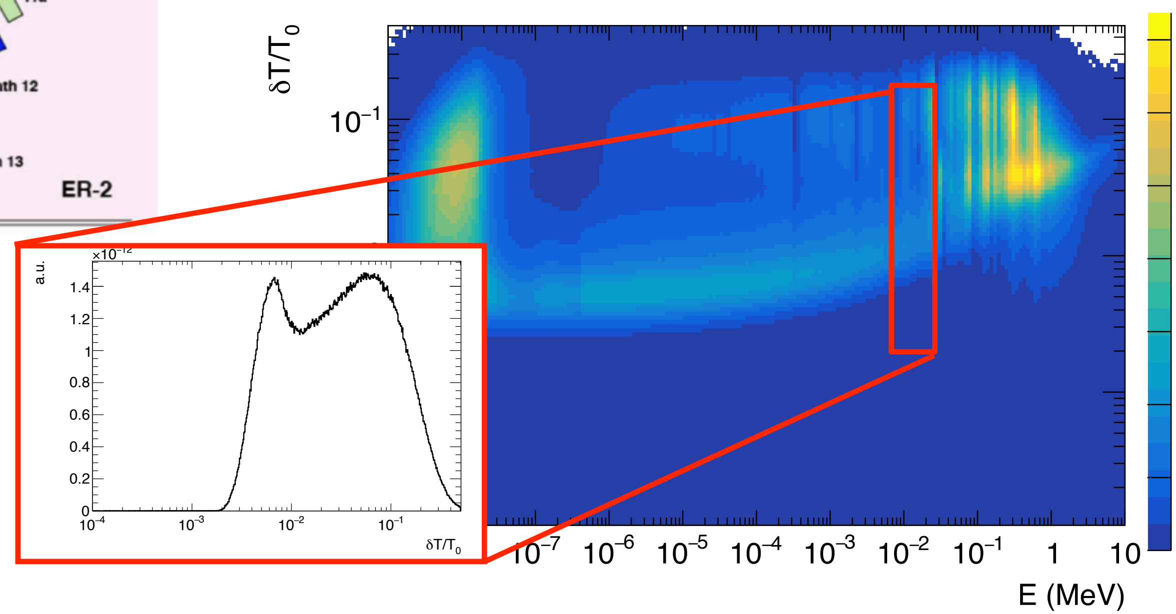
- Neutrons are produced via spallation reactions caused by an 800 MeV proton beam impinging on a tungsten target (typical beam current of 80µA) at a repetition of 20Hz
- A 1/16'' Cadmium filter is used to suppress slow neutron flux below 0.5eV (important to remove most "overlap" between pulses and and thermal neutron background which can lead to dead time)



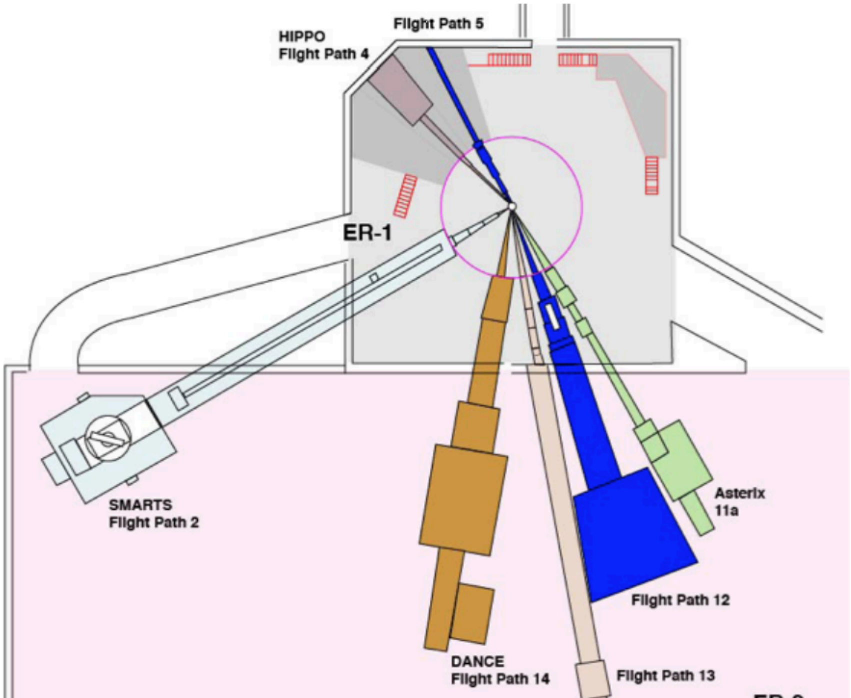
Liquid hydrogen moderator & vacuum lines

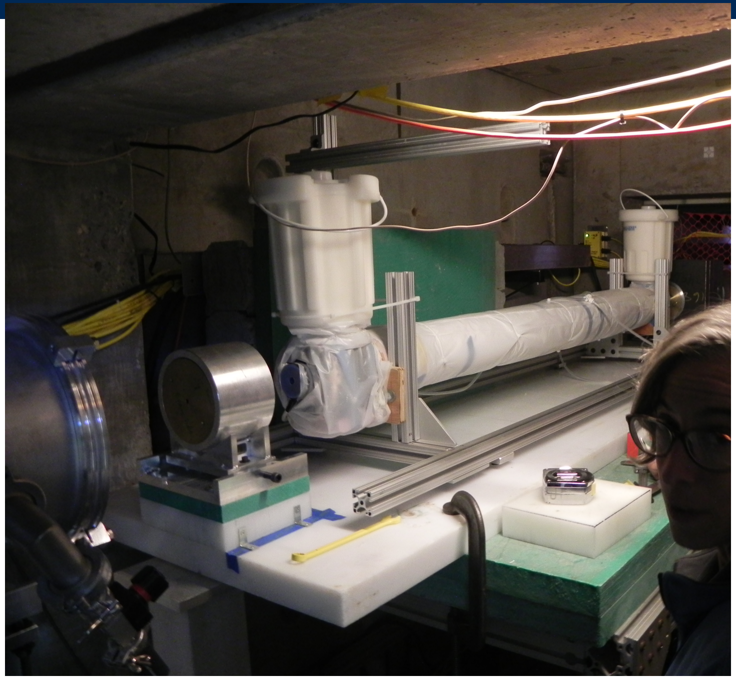


- A liquid hydrogen moderator is present ~31m upstream from the target
- Moderator induces a time delay to neutrons modeled via Monte Carlo simulation (Moderator Response Function - MRF)



ARTIE target and neutron detector





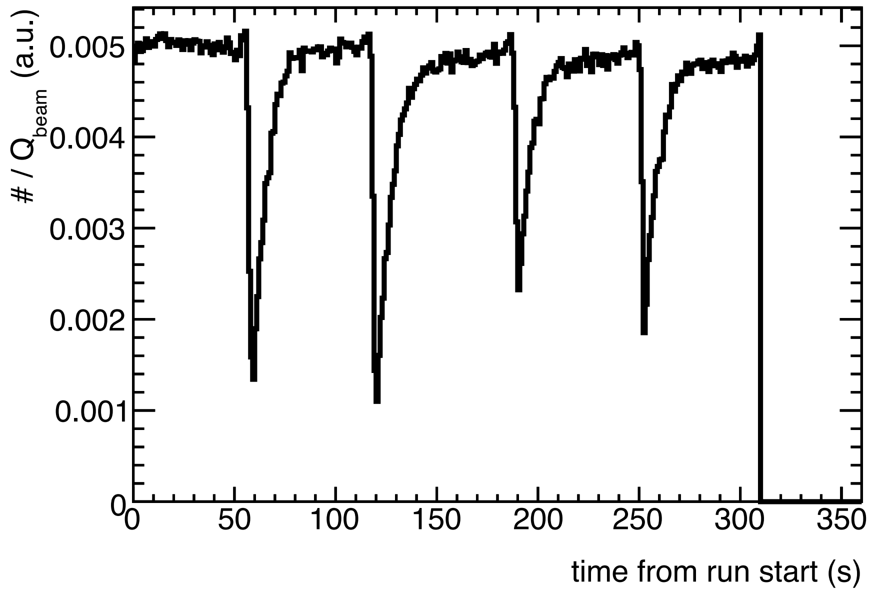
- The ARTIE target design features a dewar vented to the atmosphere at each end cap
- It is located at ~64m from the moderator neutrons are detected by a ^{6}Li-glass scintillator detector coupled to 2 5'' PMTs
  - Neutrons detected by $n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H$, Q=4.78MeV

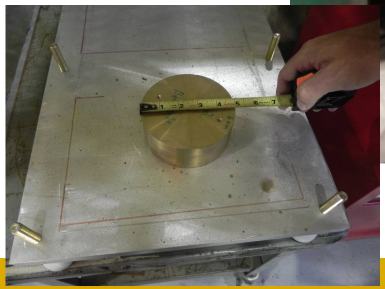
How to measure the cross section

- For any given filling the # of neutron reaching the TOF detector is:
- $N(E) = f(E)\, Q\, T(E)$
  - where $T(E) = \exp(-n\, \sigma(E))$ is the transmission coefficient, Q is the # of produced neutrons, f is a scaling factor, and n, and σ are respectively the column density (atoms/b) — which depends on the dimensions d and density ρ —, and cross section (b) of the target material
  - $n = d[cm] * N_A[atoms/mol] * \rho[g/cm^3] / m_A[g/mol] * 10^{-24}\ cm^2/b$
- Consider data taken with target in — with liquid argon (LAr) — and target out — with gaseous argon (GAr) — then
  - $\boldsymbol{\sigma(E) = -1/(n_{in} - n_{out})\ \ln(N_{in}\, Q_{out} / N_{out}\, Q_{in})}$

Analysis: Run quality cut and beam-target alignment

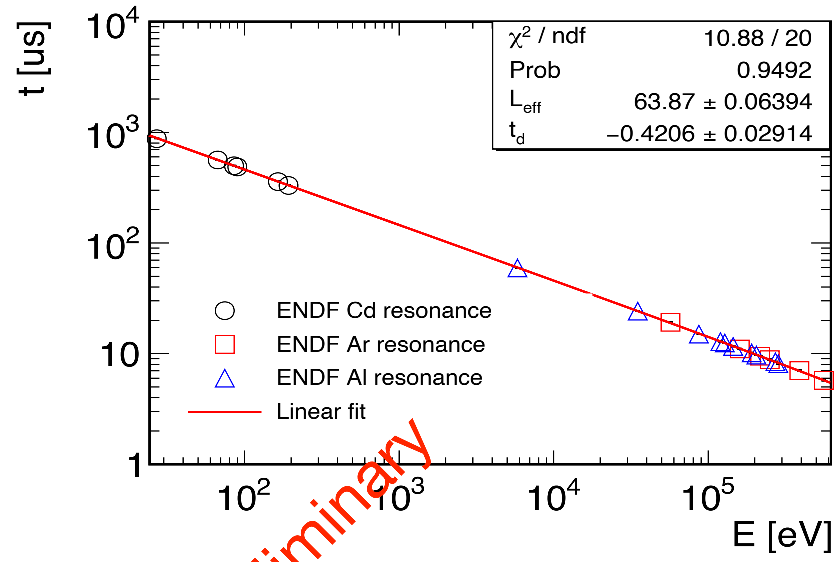
- Good data were selected excluding periods where DAQ had problems or the neutron beam was unstable
- For liquid argon runs, observed a big change in event rate (factor ~2) in correspondence with each filling (independent of the neutron energy): during re-fill some liquid or vapor gas spilled onto brass collimator causing misalignment (Δt~200K causes ~0.5mm shrinkage). These periods are excluded
  - This cut accounts for a 12% data loss for liquid argon runs and introduces a ~5% uncertainties (conservative) in the neutron flux

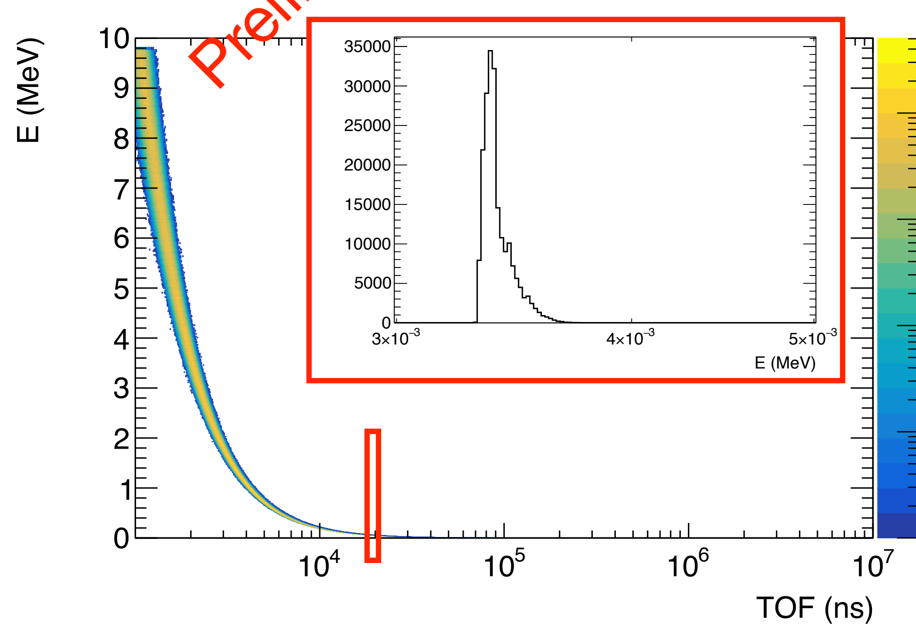




Analysis: Energy calibration & energy resolution

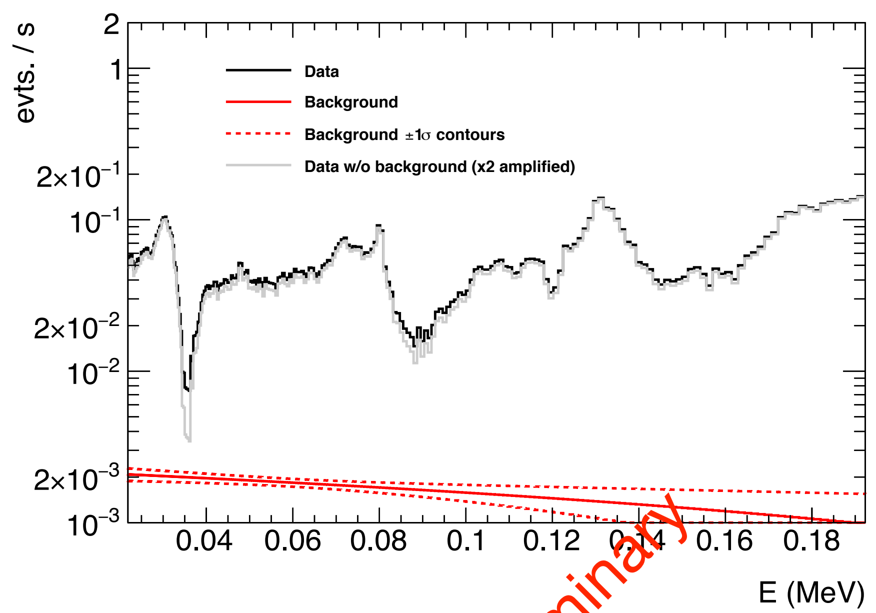
- TOF technique: energy is determined by measuring the time (t) a neutron travels through the flight path distance (L)
  - $E = mc^2 (1/\sqrt{1-L^2/c^2t^2} - 1)$
- Observed TOF ($t_{meas}=t-\delta t_{MRF}$) relates to t by subtracting the delay due to the MRF and other causes so that:
  - $E = mc^2 (1/\sqrt{1-L^2_{eff}/c^2t^2_{eff}} - 1)$
- Using several known resonances (from Al and Cd), obtain effective length and delay: L_{eff}=63.87±0.06m and t_{eff}=0.42±0.03μs
- Various factors affect energy resolution ΔE/E (initial proton pulse width, MRF, Leff, ^{6}Li-glass detector and PMTs response). In ROI, ΔE/E=+3.1,-1.3%

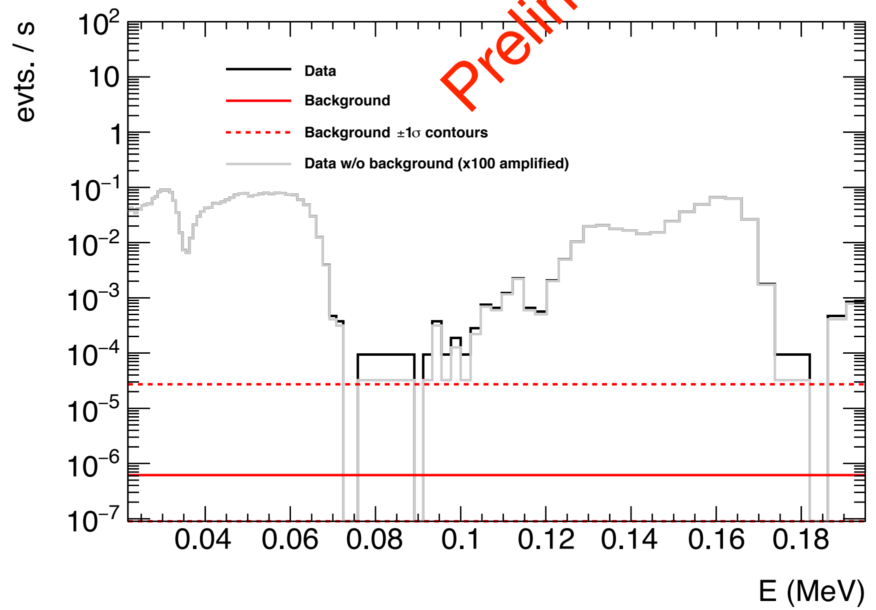




Analysis: Background subtraction

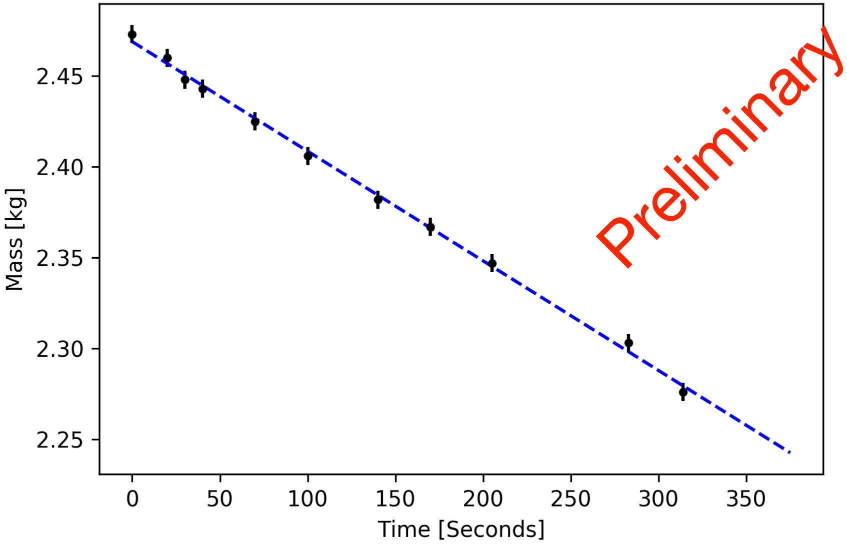
- $T(E) = (N_{in}-B_{in})\, Q_{out} / (N_{out}-B_{out})\, Q_{in}$ where N represents counts with target in/out and Bs are backgrounds
- Bs are determined using the "black notch" method: compare measured vs. expected transmission coefficient where materials in the beam line should produce a negligible number of events due to large absorption resonances. Events in the notch must be background
- **Aluminum** (1" thick): two deep resonance s at 35 and 88keV. Background modeled as linear
- **Argon**: well-measured absorption resonance at ~100keV. Flat background assumed
- **Backgrounds are small** (~1% correction)





Uncertainty: Effective density

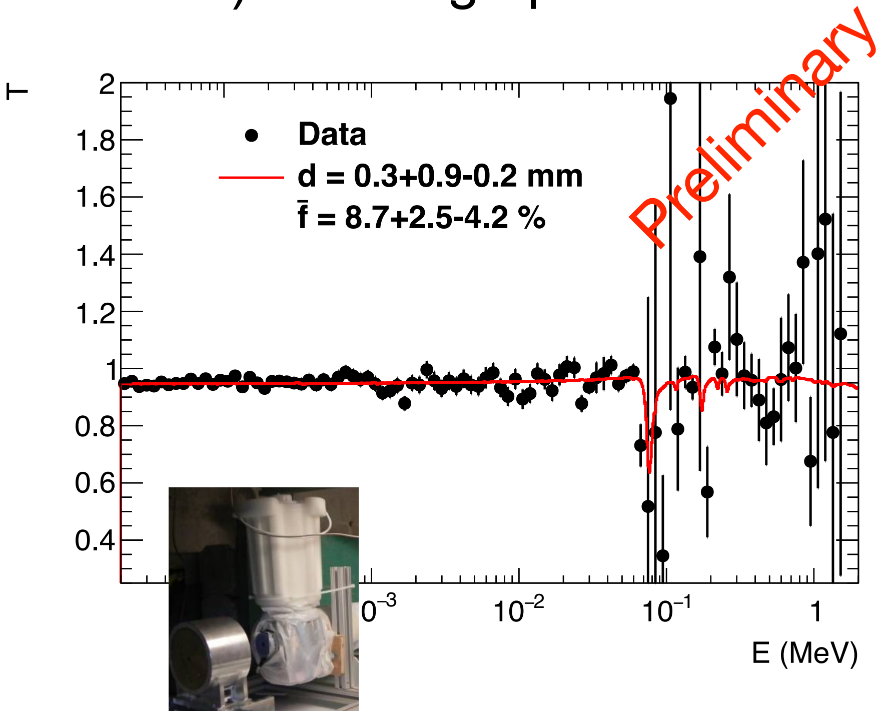
- Unpressurized vessel makes target a mixture of gaseous and liquid argon (argon constantly slow boiling inside) characterized by effective density ρ_{eff}
- A separate experiment done at UC Davis mimicking the fill/boil cycle as done at LANSCE. The target filled with argon was allowed to boil off naturally while measuring its mass and liquid level as a function of time
- Measuring boil of rate of 1.56L/h allows to determine ρ_{eff}=1.32±0.02kg/L (~6% fraction of gas mixed in the target)



Uncertainty: Ice buildup on the target

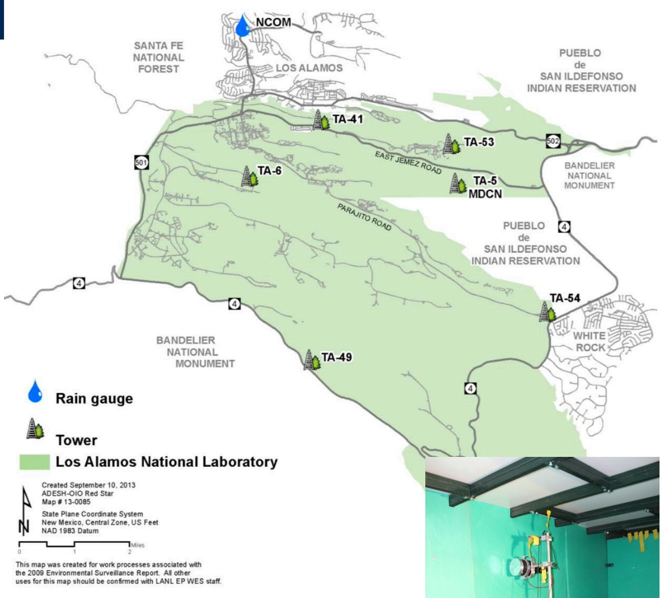
- Despite flushing target's end-cap windows with dry gases, a thin layer of ice formed on the Kapton windows over the course of many hours
- To reduce ice effect, target was warmed up to allow the ice to melt
- To assess the ice layer thickness, data immediately before (thickest ice layer) and after (windows are free of ice) warming up are compared

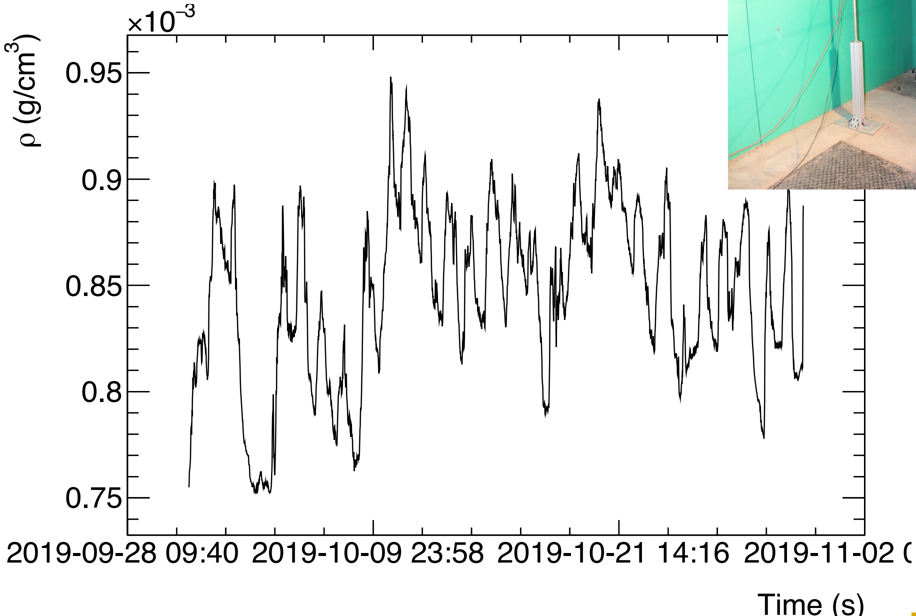
- Fitting function accounts for different conditions of the target setup and is informed via a toy Monte Carlo
- Ice thickness d=0.3 mm induces a maximum reduction in number of neutrons when the target is filled with liquid of ~3.8% (independent of energy in the ROI)
- Maximum ice effect is taken as a systematic uncertainty for LAr runs



Uncertainty: Environment air density

- Part of the flight path (~2 m) is not under vacuum but is exposed to ambient conditions
- Day-to-day and day-night temperature/pressure variation can affect the neutron flux at the detector
- Air density variation is determined thanks to data provided by LANL meteorological stations
- During data tacking period: $<\rho>=0.00085\ g/cm^3$ with +12% and -11% maximum variation
  - Via simulation of the air column, a neutron counts reduces by 3.4±0.4%



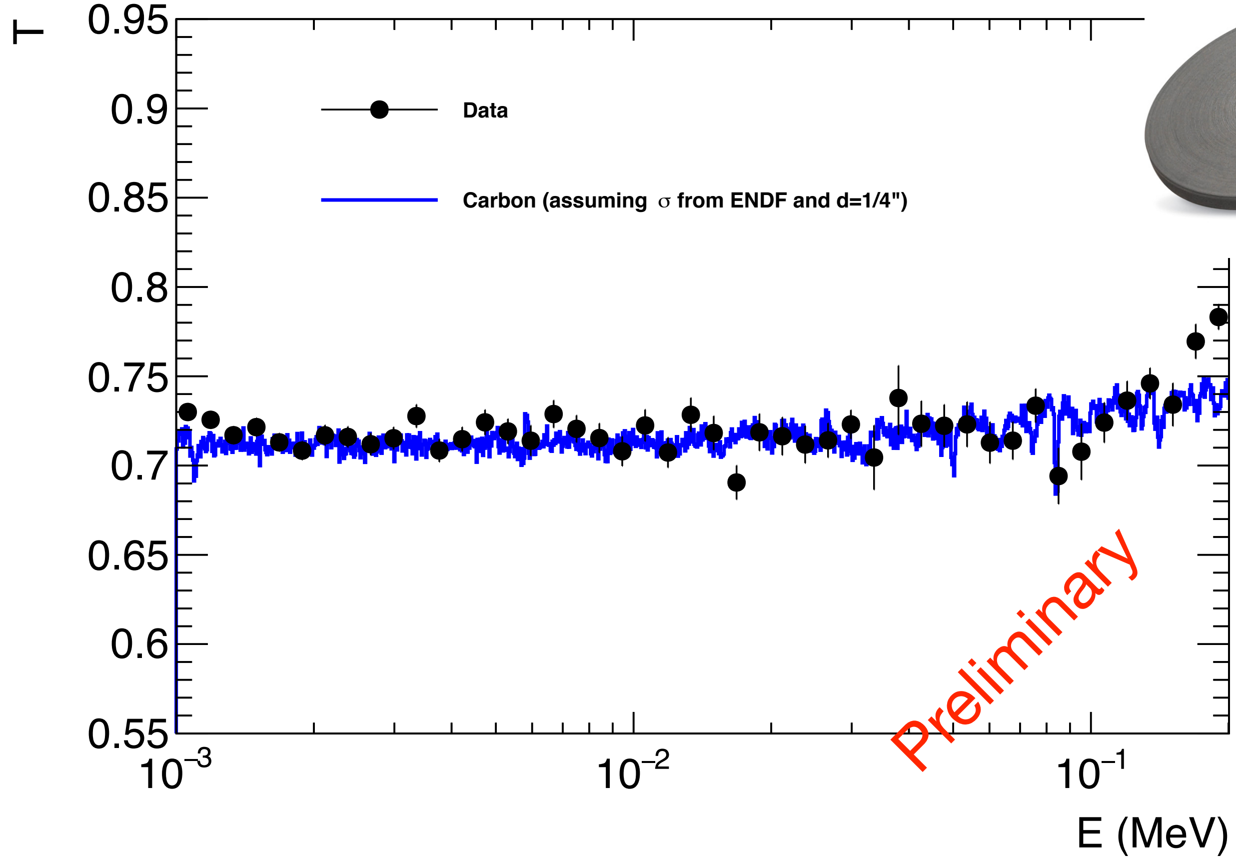


Uncertainties

- Summary of the various uncertainties and how they affect cross section
- Others:
  - Nitrogen contamination of the LAr measured by RGA (0.4 ppm): negligible
  - Dead time: each neutron recorded triggers a latency of 200 ns in the electronic. A second neutron arriving in this time window is lost. Analytical correction and toy Monte Carlo simulation suggests a ~1% and 0.2% correction for gaseous and liquid target respectively
  - Background due to other experiment: found that activities nearby ARTIE produces variation on background but it is negligible

ERROR	PAR UNCERTANTY (%)	σ UNCERTANTY (%)
Overall beam stability	±1.1	±1
Filling period stability	-5	-3.1
Effective density	±1.5	±1.5
Ice build up	-3.8	-2.4

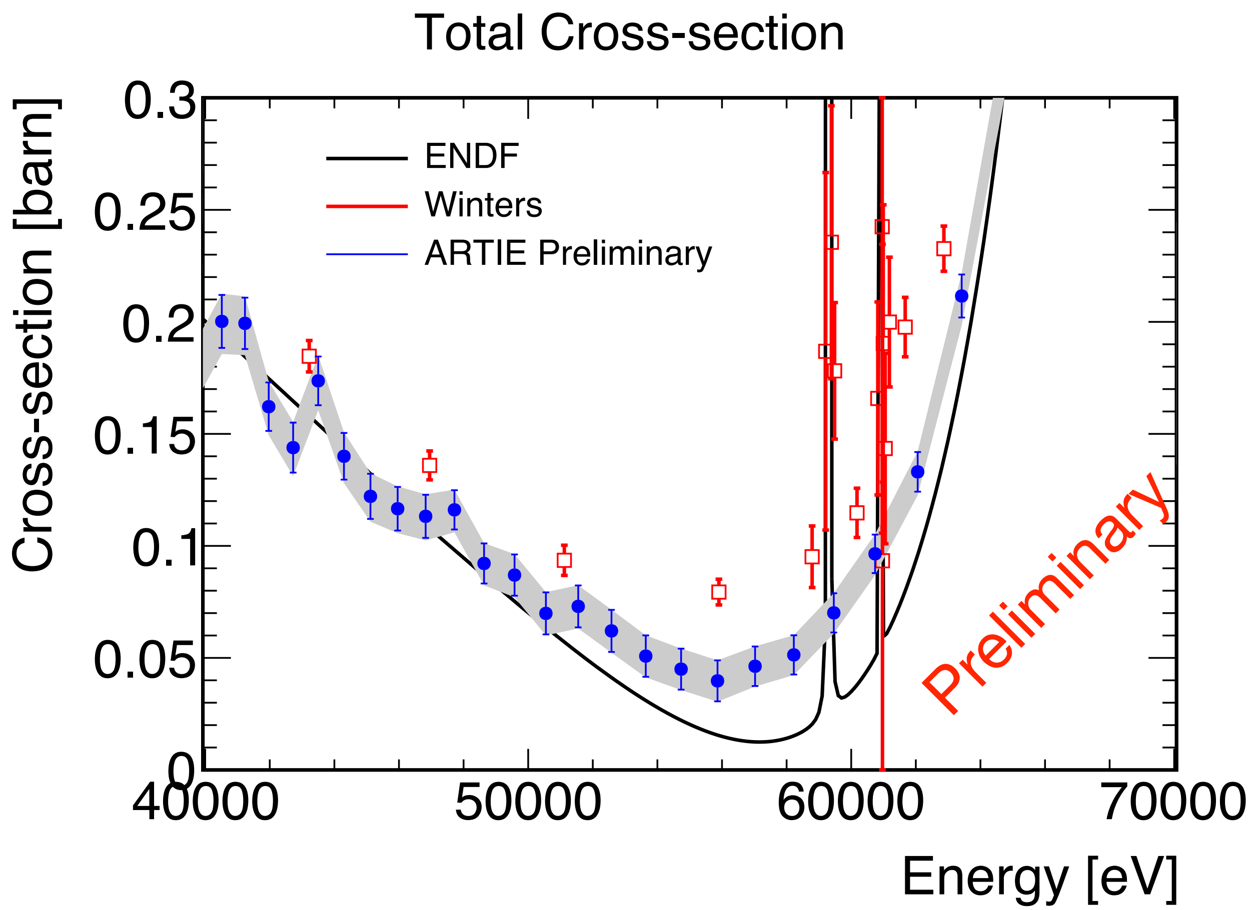
Analysis cross check: carbon data



Carbon (Graphite) (C) Sputtering Target by Kurt J. Lesker

- Analysis strategy repeated on a carbon sample of known composition (99.999% purity) and dimension (x2 0.125±0.010''): good agreement (χ^2/NDF=2.7/6) found between obtained T and theoretical prediction of ENDF smeared by the ARTIE energy resolution

(Near-)final results & conclusions



- Conclusions: *"In medio stat virtus"* (latin proverb: virtue stands in the middle)
- Paper in preparation: stay tuned!