Pulsed Neutron Source (PNS) Calibration System

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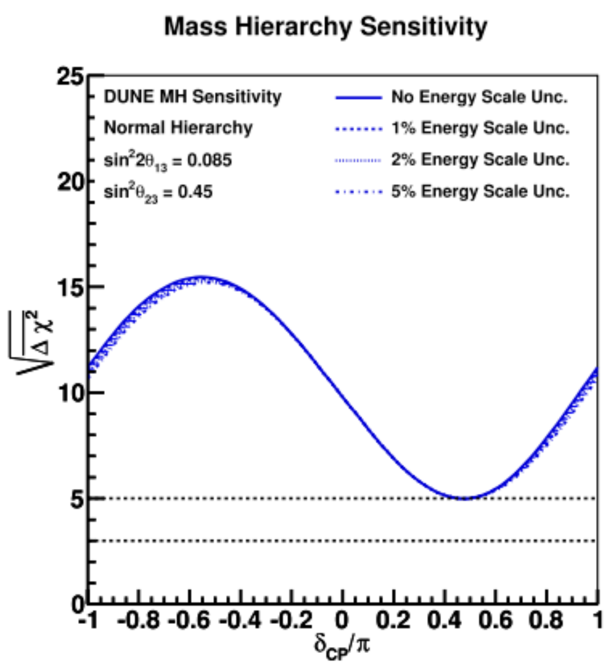
PNS WG Meeting
April 29, 2020

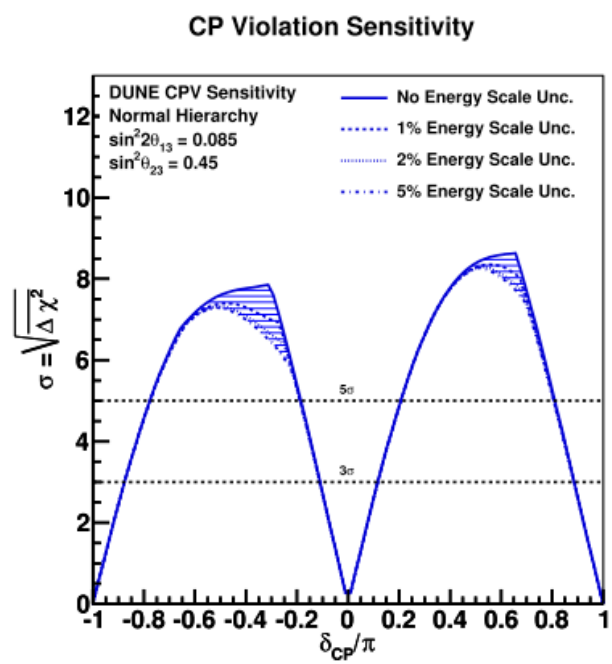
Outline

- Introduction to Pulsed Neutron Source
  - Motivation
  - Working principle
  - Conceptual design in TDR
- Plan of Activities
- Recent Development
- Charge Questions
- Conclusion

Calibration for LBL Physics

- Neutrino Oscillation is a L/E dependent process. Need to measure the energy precisely.
- The DUNE calibration information needs to provide better than 2% understanding of the energy scale and resolution
- CDR study indicates that 2% shift in energy already affect the MH and CPV sensitivities.





CDR

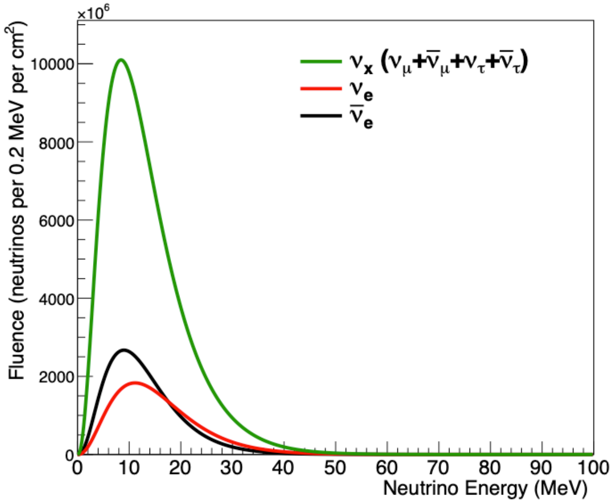
Calibration for Supernova Physics

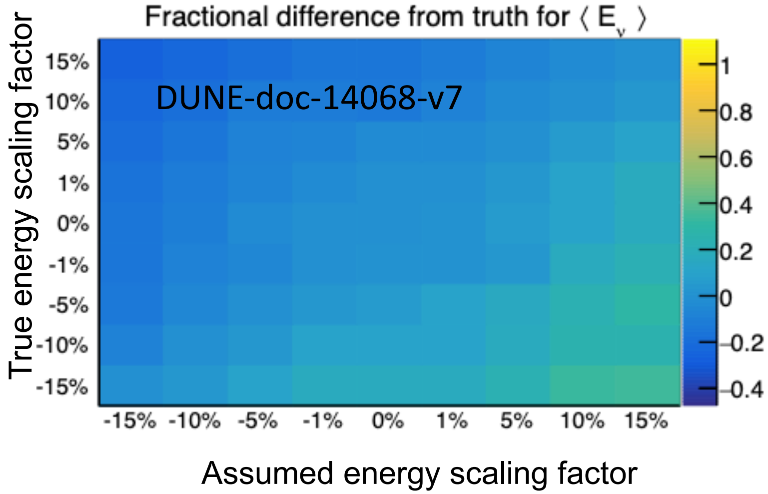
Supernova flux follows the pinched-thermal form

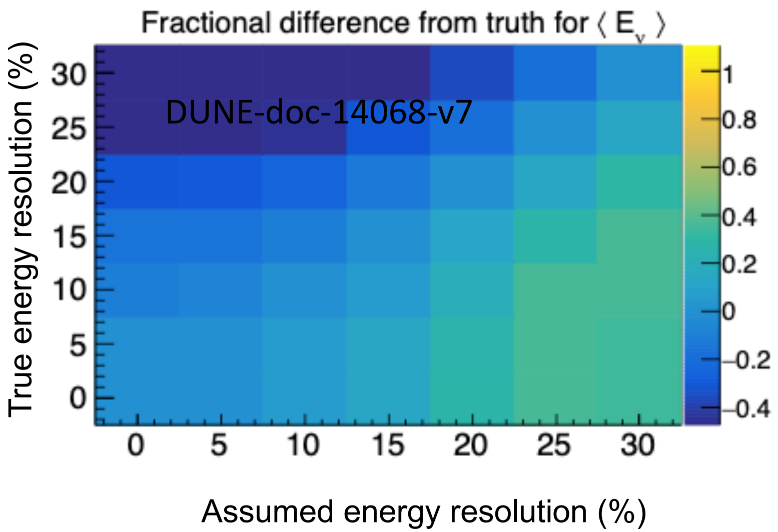
$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

- E_ν is the neutrino energy.
- N is a normalization constant proportional to the neutrino luminosity ε
- $\langle E_\nu \rangle$ is the mean neutrino energy
- α is the "pinching parameter"

Pinched-thermal supernova flux for a 10kpc supernova





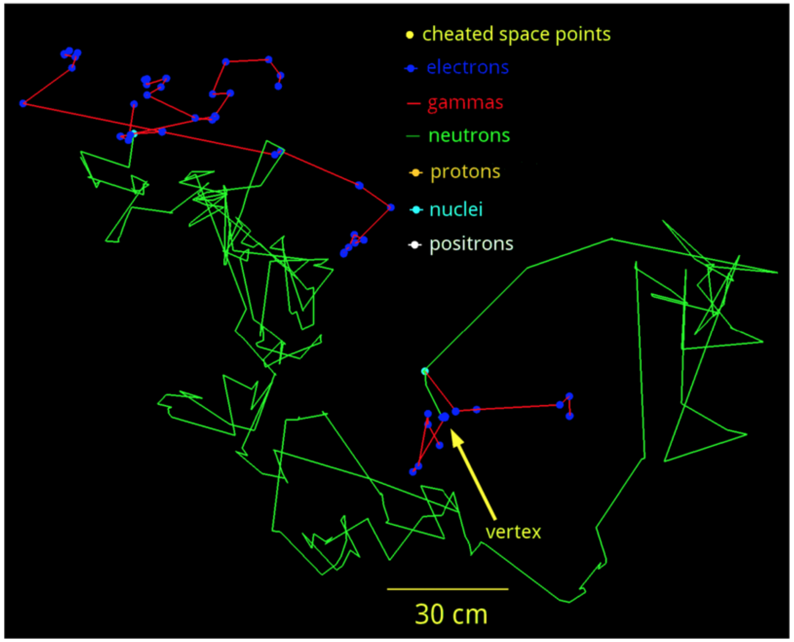


If our prediction is off- diagonal, the extracted physics will be biased

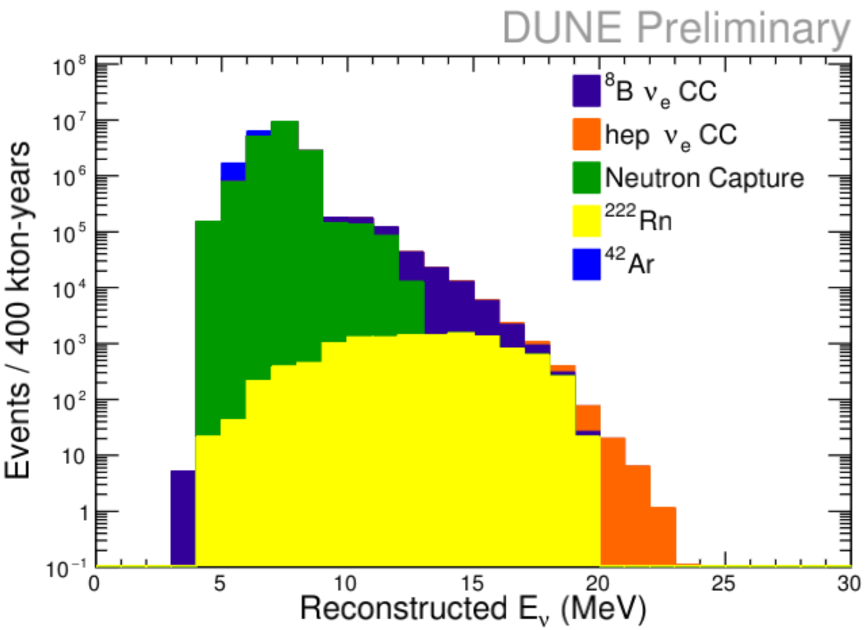
Neutrons in Low-E Physics

- Neutrons are part of the signal components of supernova event: the MARLEY generator suggests that 15-30% of supernova events involve neutron emission. Missing the neutrons could result in large uncertainty in energy reconstruction.
- Neutrons from the surrounding rocks are the dominant background for solar neutrino measurement.
- Need to understand the neutron transport and capture.

Particle trajectories from a simulated SN event in DUNE



Solar neutrino signal and background



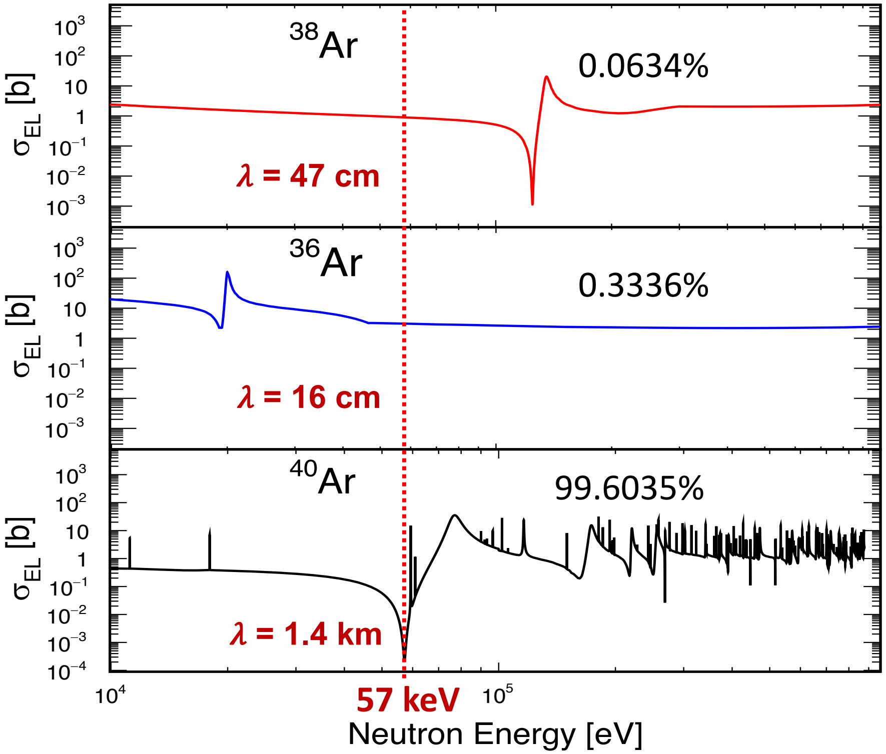
Calibration Using PNS

- **The detector response across the far detector TPC is not uniform** → need calibration at different locations
- **Traditional calibration sources are limited in far detector modules**
  - **1.5 km deep underground** → only 30 stopping muons and 20 Michel electrons /day/10 kt
  - **10 kt large volume** → spatial coverage is limited by the source deployment locations
- **Pulsed Neutron Source (PNS) system is one of the main TDR strategies**
  - Energy calibration technique similar to the method used by SNO and Super-K
  - Provide a fix energy deposition to calibrate the energy scale, energy resolution spatially and temporally across the enormous DUNE volume
  - Provide a well-controlled neutron source to study the neutron transport and capture in liquid argon.

How can neutrons help?

- ^{40}Ar is near transparent to **57 keV** neutrons at the "anti-resonance "dip"
- ^{38}Ar and ^{36}Ar have different resonance structures that keep the natural argon from being totally transparent
- **The effective scattering length is ~30 m in natural argon**

Neutron elastic scattering cross-section from ENDF

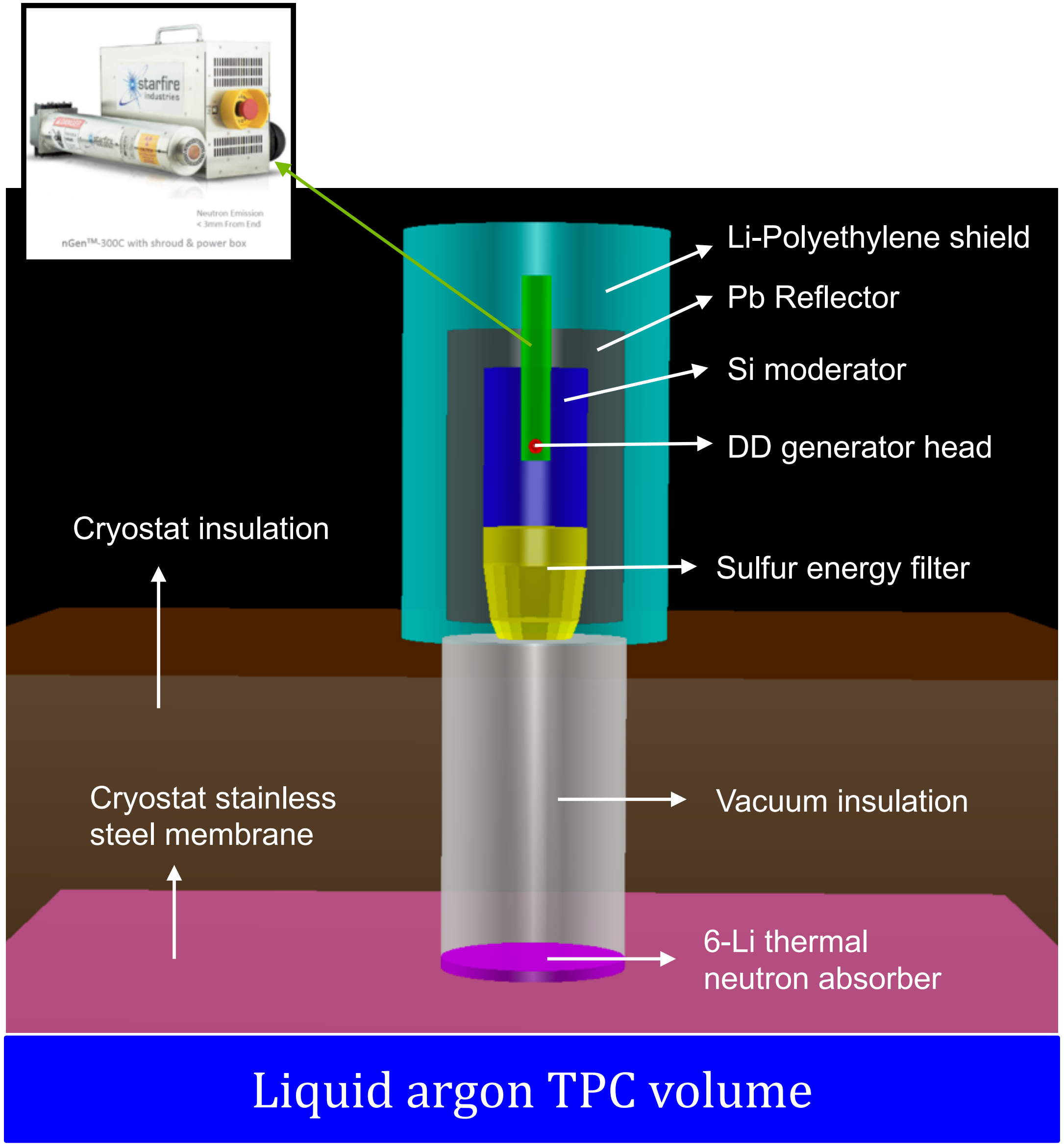


Neutrons above the anti-resonance will lose **4.8%** of energy per scatter until they "fall in the dip" – most neutrons will fall into the dip, and it takes a few scatters for them to get out.

$n + {}^{40}Ar = {}^{41}Ar + 6.1\ MeV$

Low-threshold photon detection can reveal the signature of neutron capture (~150 μs)

Conceptual Moderator Design



Pulsed Neutron Source:

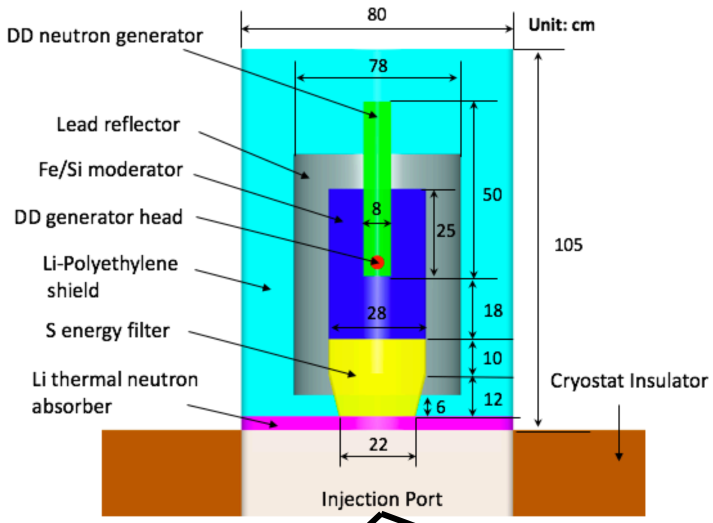
- **DD generator** → 2.5 MeV neutrons
- **Si moderator** → efficiently reduce energy down to below 1 MeV
- **Sulfur filter** → select 73 keV neutrons
- **Pb reflector** → Increase neutron yield
- **6-Li absorber** → suppress thermal neutron fraction
- **Li-Polyethylene shield** → radiation protection

PNS Benefits

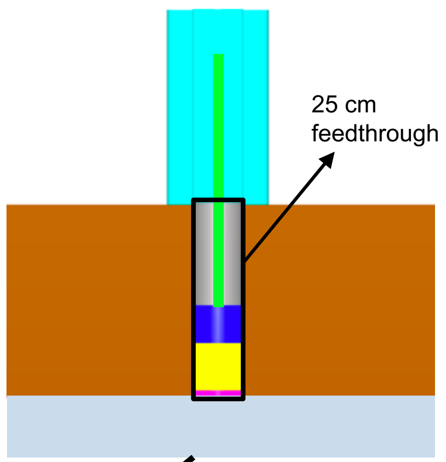
- **External deployment: neutrons mostly ignore the stainless steel membrane of the cryostat**
  - No contamination to argon purity, no field distortion
- **External pulsed trigger: use a pulsed DD generator to produce neutrons:**
  - Well defined t_0 allows reconstruction of neutron capture location
- **Multi-gamma output: neutron capture emits 6.1 MeV gamma cascade**
  - Fixed energy deposition as a “standard candle” to calibrate the energy response as a function of (x, y, z)
- **Wide coverage: anti-resonance neutrons can travel long distance**
  - Scattering length is long: 30 m expected in natural argon

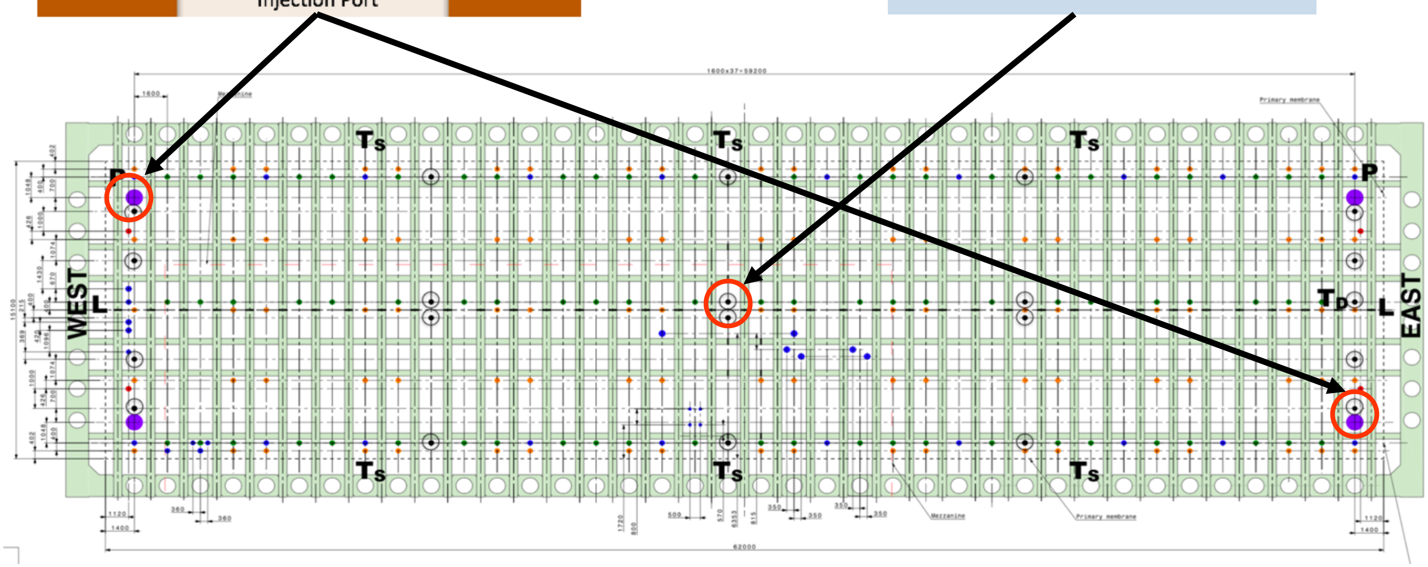
Two PNS Designs in TDR

Baseline Design: Above Manhole



Alternative Design: inside feedthrough





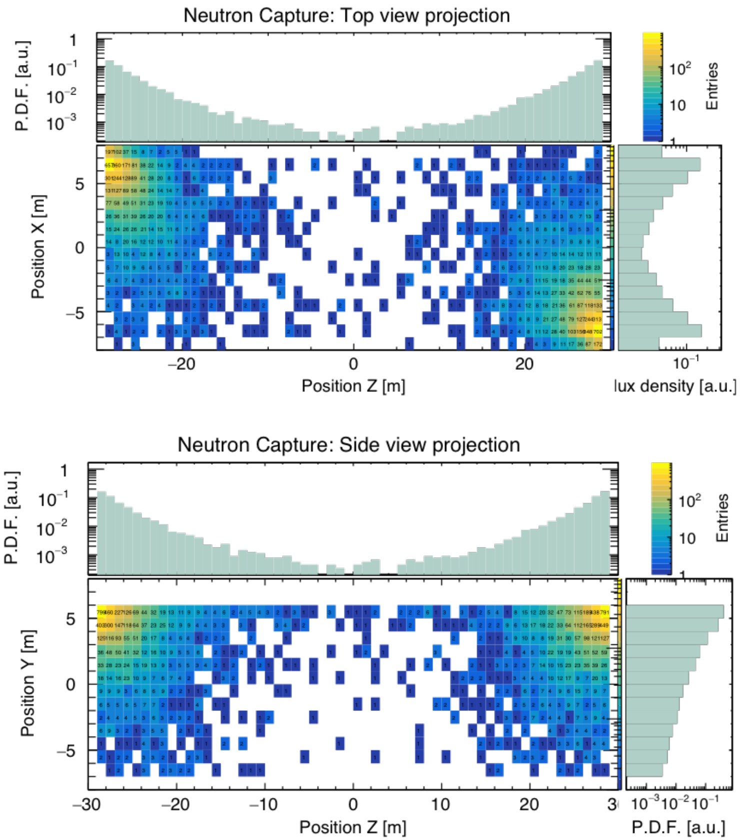
Neutron Transport Simulation in TDR

- Simulation indicates that a middle source is need to cover the volume
- Results will be updated using ARTIE cross-section.

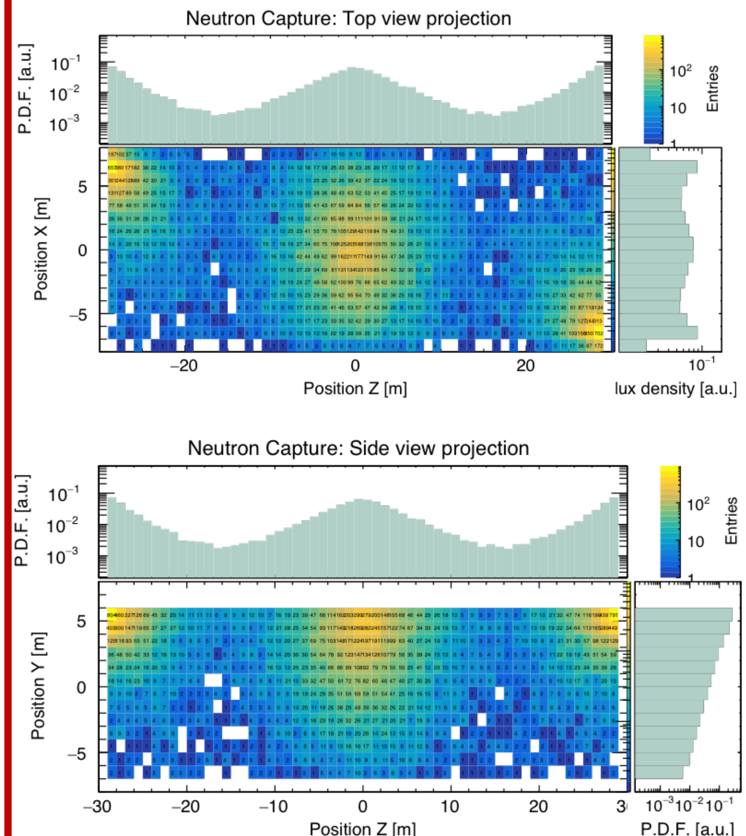
Baseline design

Top view

Side view



Alternative design



Recommendation from 2019 review

1. Continue with the program of measurements and simulations to finalize the source design. (In good progress. CAD design needed)
2. Understand radiation safety issues. (Understood. To be tested at CERN with a real DD generator)
3. Demonstrate the capability of reconstructing the 6.1 MeV shower in simulation. (In progress)
4. Develop a plan for deploying a pulsed neutron source for the 2nd run of ProtoDUNE (Done)s
5. Work with the LBNF facility and TC to understand mechanical constraints. (Will start during the phase of mechanical design)
6. Work with the LBNF facility and TC to understand where to install the third source, under the assumption that two sources will be installed in the manholes at the two ends of the detector (Under discussion).

Activities before May review

ARTIE experiment at LANL	10/08/2019 – 10/20/19
Prepare DD generator test at CERN	12/10/19 – 04/30/20
DD generator arrived at CERN	04/15/20
Preliminary ARTIE data analysis	04/01/20 – 05/30/20
Finalize PNS conceptual design	04/01/20 – 05/30/20
Calibration Review Workshop	05/11/20 – 05/28/20

Activities after May review

▪ DD generator test at CERN	06/01/2020 – 06/30/20
▪ Analyze the DD generator test data	06/01/2020 – 12/31/2020
▪ Ship the DD generator back to US	07/01/2020 – 07/31/2020
▪ PNS CAD first design at UC Davis	07/01/20 – 07/30/20
▪ Set up a PNS test lab	08/01/20 – 11/30/20
▪ Assemble small-format moderator	08/01/20 – 12/31/20
▪ **Test for small-format moderator**	**08/01/2020 – 11/31/2020**
▪ Identify a DD generator	11/01/20 – 02/28/21
▪ Set up full-size PNS system	12/01/20 – 03/31/21
▪ PNS system arrives at CERN	08/31/21
▪ Install PNS system at ProtoDUNE-SP	09/01/2021 – 11/15/2021
▪ ProtoDUNE Run-II	01/01/2022

PNS Risks Defined in TDR

Dedicated experiment @ LANL (done)

Test @ Berkeley
Test @ ProtoDUNE
(to be done at CERN)

High intensity DD generator,
Wider pulse width
(to be investigated with LANL DD generator)

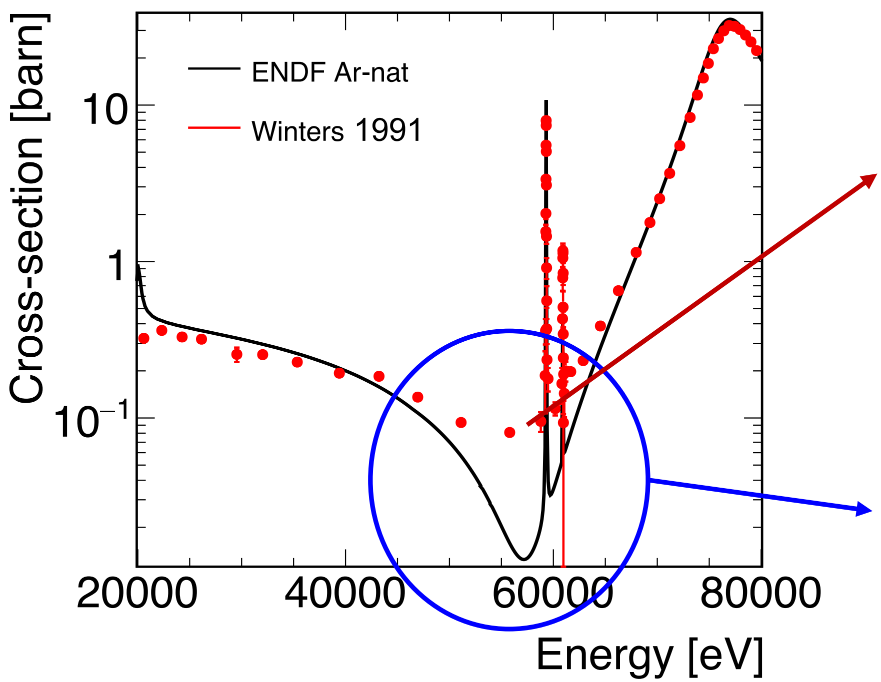
Alternative PNS system at feedthroughs (under discussion)

Table 1.10: Possible risk scenarios for the pulsed neutron source system along with mitigation strategies. The level of risk is indicated by letters "H", "M", and "L" corresponding to high, medium and low level risks.

No.	Risk	Risk Level	Mitigation Strategy
6	The effective attenuation length of 57 keV neutrons in LAr turns out to be significantly smaller than 30 m.	M	A measurement of the transmission at this energy is being proposed at Los Alamos prior to the ProtoDUNE run. The ProtoDUNE run will also provide demonstration.
7	The neutron flux from the DD generator could activate the moderator and cryostat insulation.	L	Neutron activation studies of insulation material, and ProtoDUNE testing at neutron flux intensities and durations well above the run plan, as well as simulation studies done in collaboration with Background Task Force.
8	The neutron yield from DD generator is not high enough to provide sufficient neutron captures inside the TPC.	M	Investigation is being done on both commercially available and lab research DD generators; Placing the neutron source closer to the liquid argon TPC may increase the neutron yield by a factor of 6; Operating the DD generator with wider pulse is under consideration, which would require the photodetector system to provide the neutron capture time t_0. All of this will be tested in the ProtoDUNE-SP-II run.
9	Neutrons produced by the Pulsed Neutron Sources placed at the human access ports at the cryostat corners may not reach the center of the cryostat.	L	An alternative design (Design B in figure 1.13) with neutron source inside the calibration feedthrough ports (centrally located on the cryostat) is being studied. This small format neutron source would be light enough to be moved across different feedthrough ports, providing complementary coverage to the neutron sources at the human access port locations.

Argon Resonant Transport Interaction Experiment (ARTIE)

- There is a large between ENDF prediction and Winters' data (1991).
- ARTIE measured the neutron **total cross-section** in argon around **57 keV,** with much higher precision than Winters' measurement.



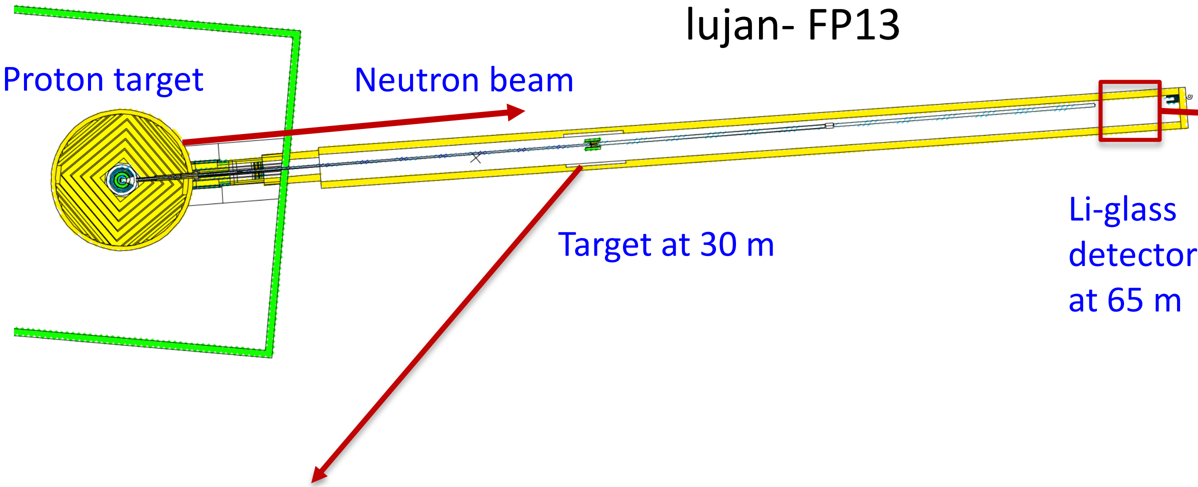
Winters' measurement:

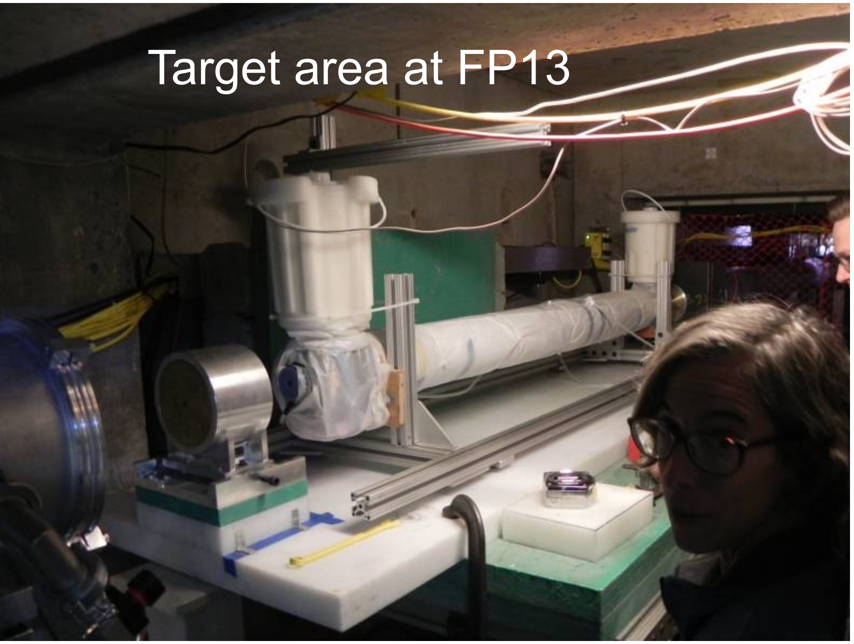
- 2.216 meter long gas target with **0.211 atoms/barn** density: sensitive to high cross-section, but not sensitive to low cross-sections

ARTIE measurement:

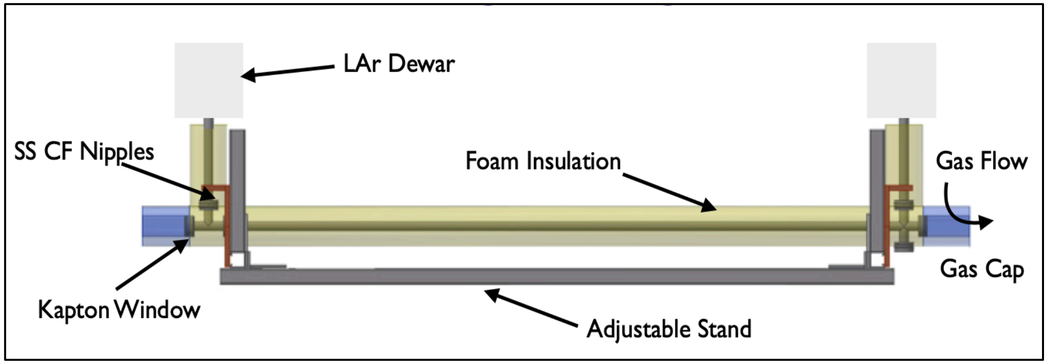
- 168 cm long liquid argon target with **3.5 atoms/barn** density: blind to high cross-section but very sensitive to low-cross sections

ARTIE Experimental Setup



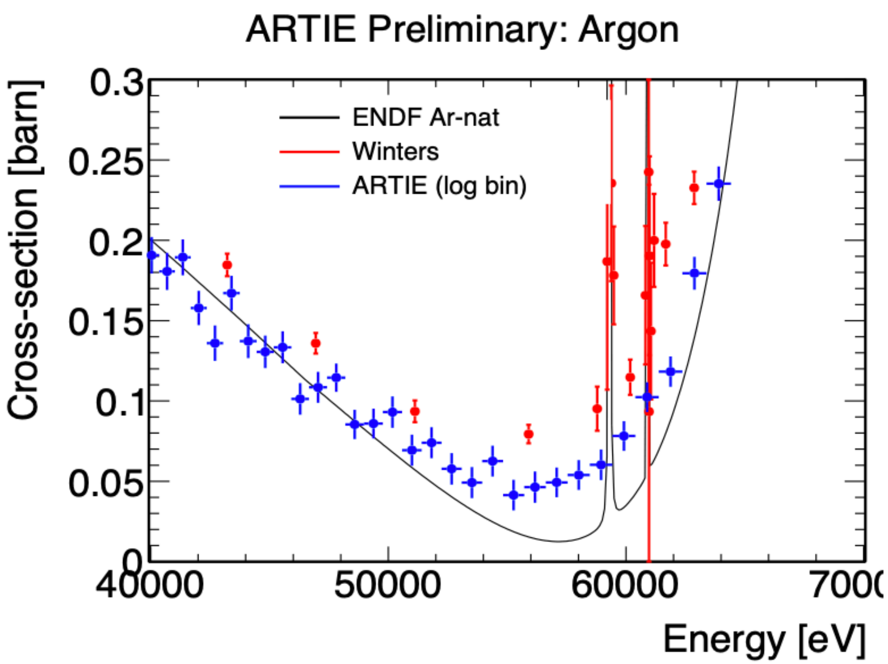


- 1” OD target is wrapped by foam and sealed by Kapton windows on both ends
- Kapton windows are protected from air moisture by flushing dry nitrogen through the gas cap
- Thermometers are used to monitor the liquid level



ARTIE Preliminary Analysis

- We took neutron beam data at **LANL** in 10/2019.
- **Currently working on background and systematic uncertainties. Result to be presented in the scope review.**
- Result is important for the PNS calibration idea, and is also of particular interest to supernova and solar neutrino physics



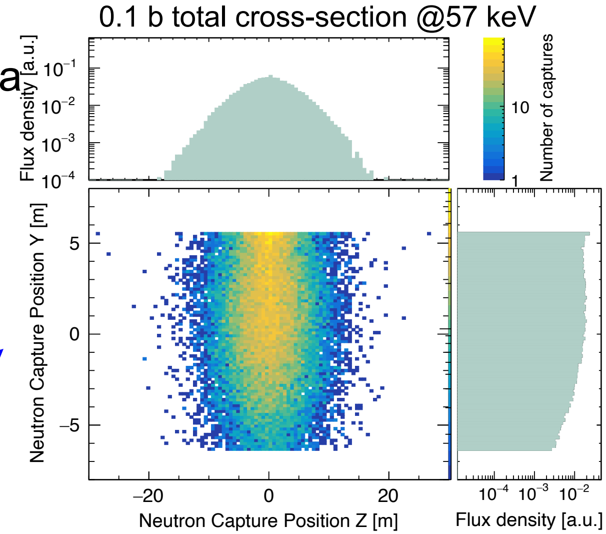
No background subtraction applied.
Error is statistical.

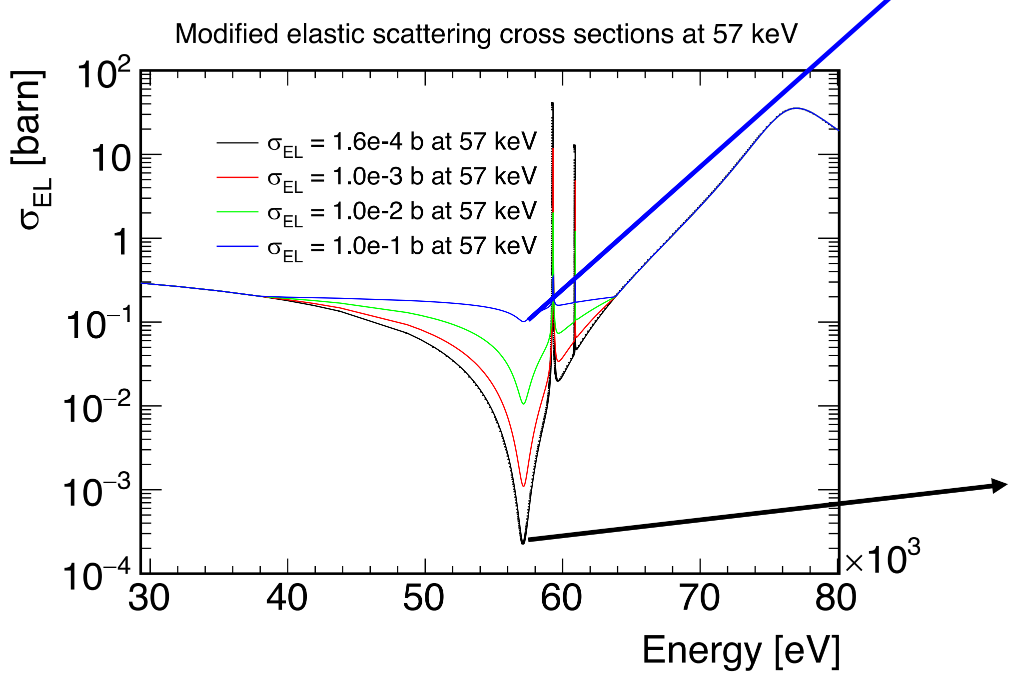
Result shown here is the upper bound.

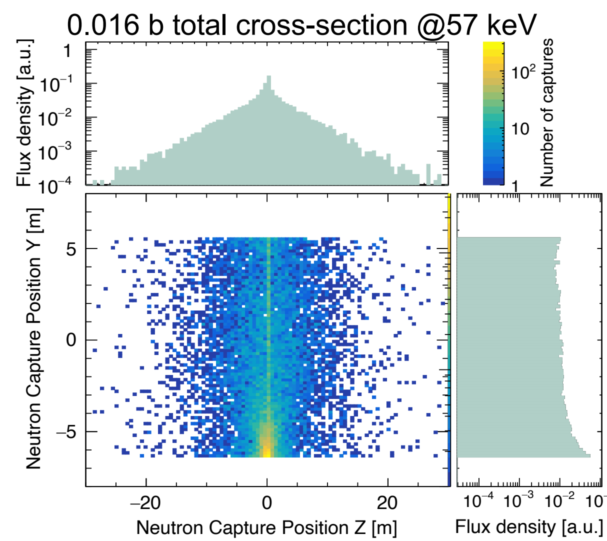
First results reported to DUNE Collaboration Meeting in 01/2020.
(More details in backup slides)

Simulation with Dummy Cross-section

- Prepared several sets of elastic scattering cross-section dummy data to replace the ENDF default data file.
- Performed neutron transport simulation using exact 57 keV energy.
- To be updated with realistic neutron spectrum and ARTIE result



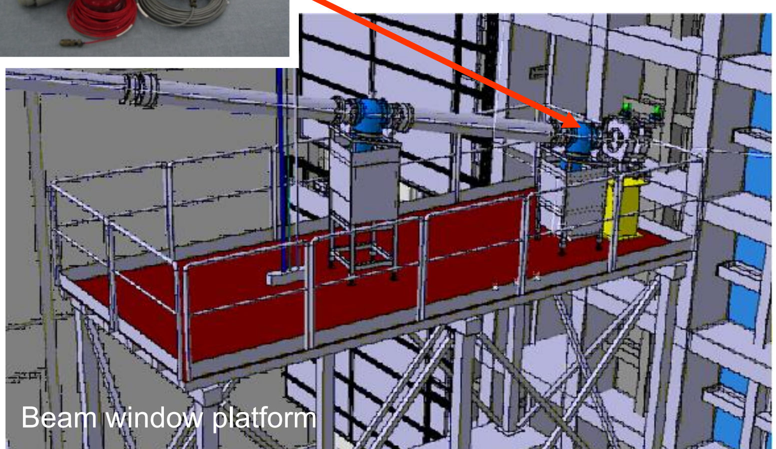




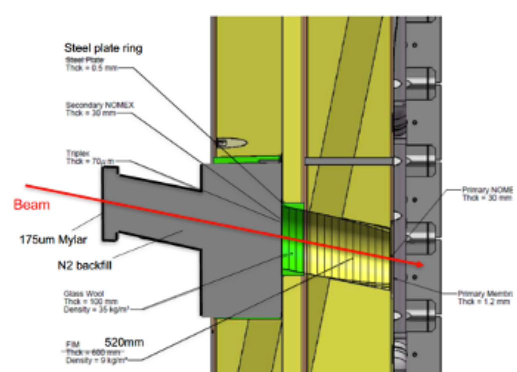
DD Generator Test at ProtoDUNE

- We are planning a DD generator test at ProtoDUNE-SP in June 2020. The main purpose is to take some neutron capture data in real LArTPC
- We will use the data to test our neutron transport model and develop neutron capture reconstruction algorithms. Also, we will gain experience of the neutron generator operation from this test.
- The idea is to inject 2.5 MeV DD neutrons into active of ProtoDUNE-SP detector volume through the existing beam plug.

LANL DD generator

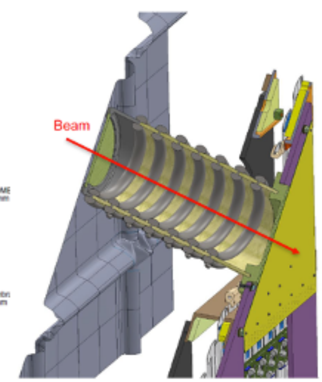


cryostat penetration



52 cm foam

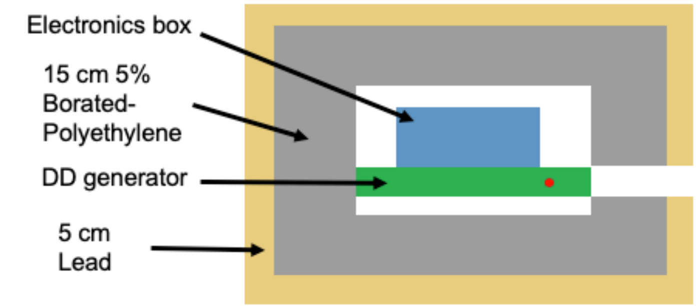
Beam plug



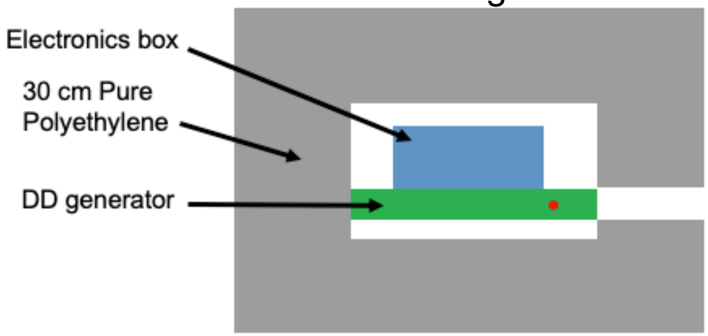
DD Generator Shield Design

- CERN requirement for shield: The DDG will be located in an area, which will be classified as Supervised Radiation Area during personal access (neutron generator off). The **radiation level must then stay below 15 μSv/h**. Furthermore, **Non-designated Areas where the DDG will be operated, must have radiation levels below 2.5 μSv/h** for low occupancy and otherwise 0.5 μSv/h.

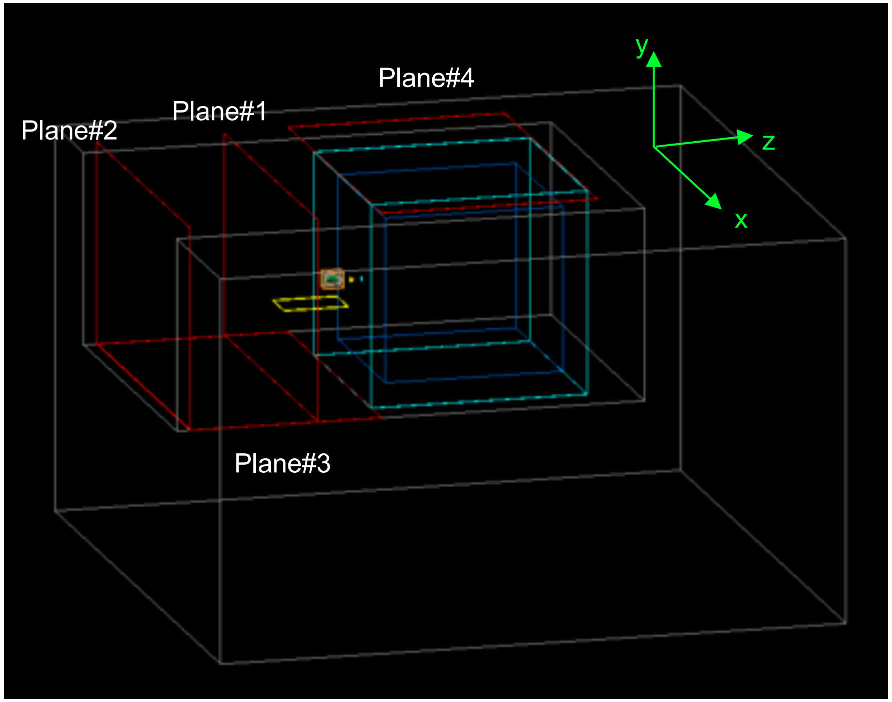
Shield design #1



Shield design #2

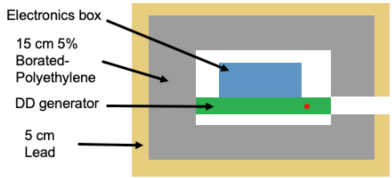


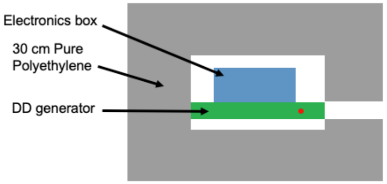
Simplified geometry



DD Generator Shield Simulation

- Both design satisfy the radiation limit for the selected locations. We are considering Shield#2 with additional iron plate for gamma mitigation.
- Submitted to CERN for safety review.





	Description	Shield Design#1		Shield Design#2	
		Neutron Dose rate (μsV/h)	Gamma Dose rate (μsV/h)	Neutron Dose rate (μsV/h)	Gamma Dose rate (μsV/h)
Plane#1	Vertical, 3m from cryostat	<0.022	<0.043	<0.006	<1.2
Plane#2	Vertical, 6m from cryostat	<0.011	<0.018	<0.005	<0.17
Plane#3	Horizontal, on the floor below platform	<0.015	<0.02	<0.006	<0.28
Plane#4	Horizontal, on top of cryostat	<0.005	<0.012	<0.003	<0.12

PNS Simulation Update

- **Neutron source design**
  - Neutron moderator design in Geant4 (done)
  - Radiation shield design (done)
- **Neutron transport simulation with real TPC materials (done)**
  - Single Phase TPC: APA, CPA, Photodetector, Field cage, Foam insulation…
  - Dual Phase TPC: CRP, Field cage, Photodetector, Foam insulation…
  - Back of the envelope estimate is that these effects are on the order of 10%-20%
- **Neutron capture tagging in TPC**
  - Neutron capture tagging (in progress). Need to Incorporate new measurements of the gamma cascade (done)
  - Photodetector sim & reco for t_0 determination (no effort yet, low priority)
- **Analysis**
  - Simulation and analysis without cosmic and radiological background (done)
  - Validation with full simulation: energy scale, electron lifetime, field non-uniformity… (in progress)

Charge Questions

1. Does the system have a well-justified role in safeguarding the far detectors and facilitating their operation, and if so, what is the minimum amount of system scope needed to carry out this role? (Cryogenic Instrumentation only)
2. Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?
3. Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?
4. Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?
5. Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?
6. Does the functionality of the system justify its overall cost?

Charge Question#2

Does the system have a well-justified role in facilitating the analysis of far detector data, and if so, what is the minimum amount of system scope required to fulfill this role?

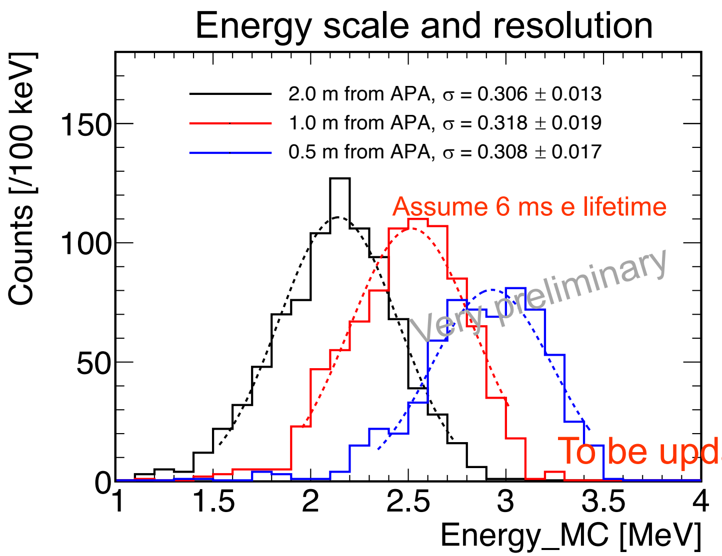
- The PNS is important to measure energy scale, energy resolution and detection threshold spatially and temporally across the enormous DUNE volume. Expect to complete a calibration run within one day.
- DUNE Supernova trigger efficiency can be tested using neutron captures.
- The PNS system provides real TPC data to study the neutron transport and capture in DUNE far detector, which is essential for low energy physics programs such as supernova and solar neutrinos.

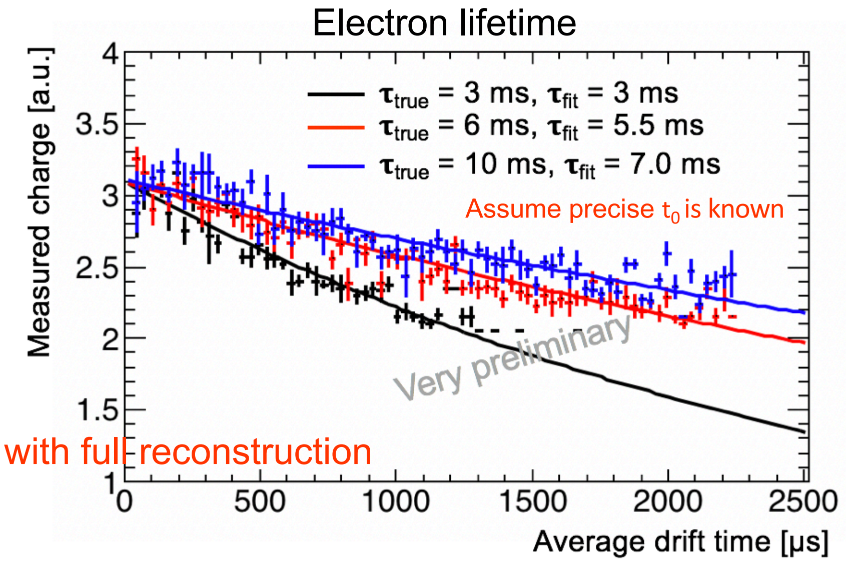
Simulation Studies

Place holders to be updated

- Left plot: reconstructed energy for different point source locations
- Right plot: Lifetime fit from uniform neutron capture distribution

Idealized simulation with no corrections for recombination or argon purity

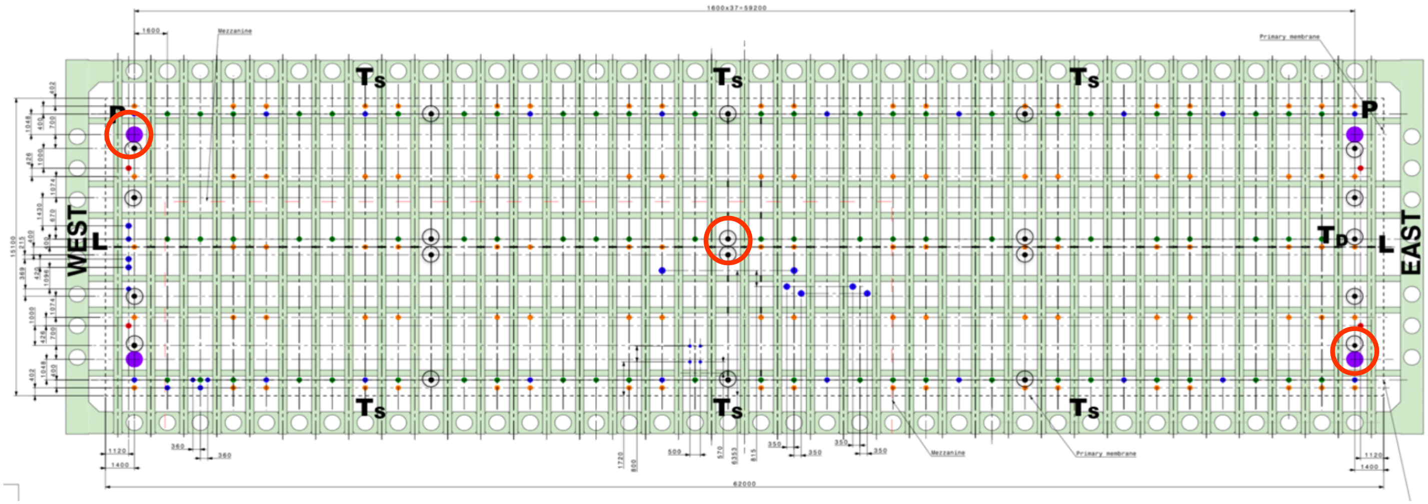




To be updated with full reconstruction

Minimum amount of system scope

- Need three PNS deployments to cover the detector volume.
- Baseline: two large-format PNS systems at the corner manholes.
- Alternative: one additional small-format PNS system in the middle at the existing 25 cm calibration port or any other instrumentation ports (availability to be checked)



Charge Question#3

Have all technical issues related to the feasibility of the system (including those raised in the previous workshops) been resolved?

- The conceptual design is near-finalized. The neutron transport study will be updated with GEANT4 using the ARTIE cross-section result.
- The CAD design of PNS will start after the workshop. During this phase, we will work with the LBNF facility and TC to understand mechanical constraint about the details of the source deployment.
- The assembly and installation procedures will be tested before the entire system is shipped to CERN.
- Other technical issues, including the PNS installation, cabling and wiring, triggering, and many others, will be tested during the DD generator test at CERN.

Charge Question#4

Are there any risks to overall detector performance associated with the implementation of the system, and if so, is there a plan in place for mitigating these risks?

- To our knowledge, there are minor risks to other systems.
- Radiation protection could be an issue for people present in the experimental area. The radiation dose rate due to the PNS system is well understood. Radiation shield will be tested at CERN using the LANL DD generator.
- Issues about electrical noise and thermal conduction will be investigated during ProtoDUNE Run-II.

Charge Question#5

- ***Is there a credible plan in place for demonstrating system performance in ProtoDUNE-II?***

- We made a development plan aiming at the operation in ProtoDUNE-II
- Before ProtoDUNE-II, we will test the DD generator performance at ProtoDUNE-SP at CERN
- In ProtoDUNE-II, a full size PNS system will be deployed on top of the manhole
  - Installation and operational procedures will be tested.
  - Neutron transport will be compared between data and MC simulation
  - Neutron capture data will be used to test the calibration performance for essential detector parameters.

Charge Question#6

- Does the functionality of the system justify its overall cost?

Description	Items	Price ($)	Quantity	Total Price ($)
DD generator			1	170,000
Neutron moderator	Silicon	350 /kg	31.4 kg	10,990
	Sulphur	22 /kg	30.56 kg	672
	Pb reflector	5.9 /kg	1232.88 kg	7,274
	B-10 neutron absorber	100000 /kg	0.286 kg	28,600
Radiation Shield	7.5% Li-poly shield	100 /kg	330 kg	33,000
Neutron Monitor				10,000
Shipping Costs				5000
Total Tax (7.25%)				18,889
Total Cost				279,425

PNS Working Group

- **UC Davis**: Robert Svoboda, Mike Mulhearn, Jingbo Wang, Junying Huang, Yashwanth Sai Bezawada
- **SDSM&T:** Juergen Reichenbacher
- **LANL**: Sowjanya Gollapinni
- **University of Pittsburgh**: Donna Naples, Logan Rice
- **LIP (Portugal)**: Jose Maneira, Sofia Andringa
- **Michigan State University** : Kendall Mahn
- **Boston University**: Chris Grant
- **University of Iowa:** Paul Debbins, Jane Nachtman, Yasar Onel

Conclusion

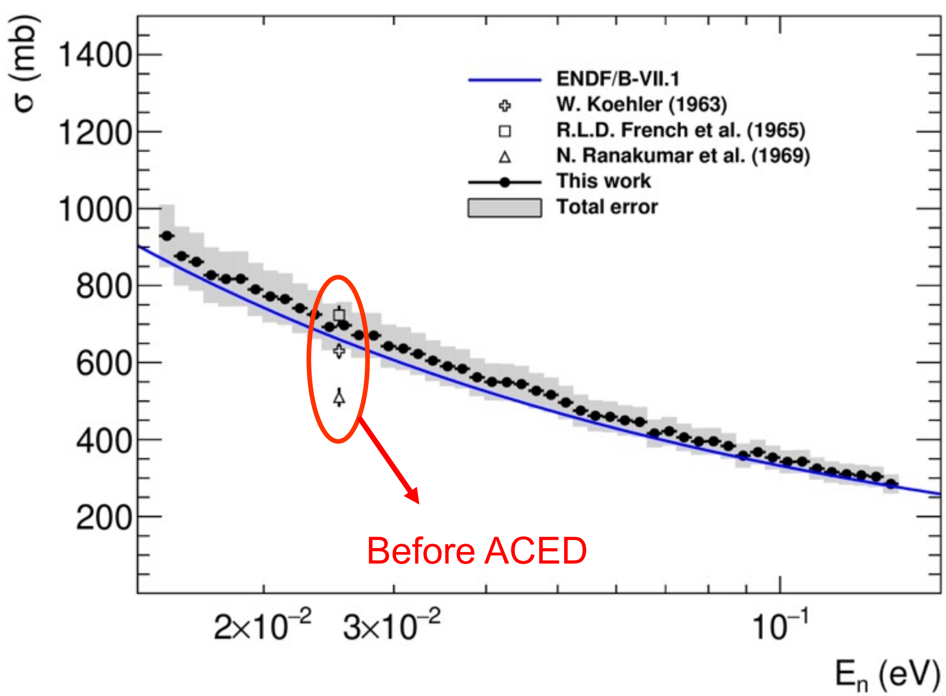
- Pulsed Neutron Source system provides a method to calibrate the energy scale, resolution, electron lifetime as a function of (x,y,z)
- Made a clear plan for PNS development, aiming at ProtoDUNE Run-II.
- Performed ARTIE experiment to verify the anti-resonance cross-section. Need to redo the simulation with ARTIE data.
- Currently planning for the DD generator test at CERN. Neutron shield designs are being reviewed by CERN safety officers.
- Need to expand the future efforts to institutions within the working group: DD generator test, Moderator test, PNS assembly, Simulation&analysis…

Backup

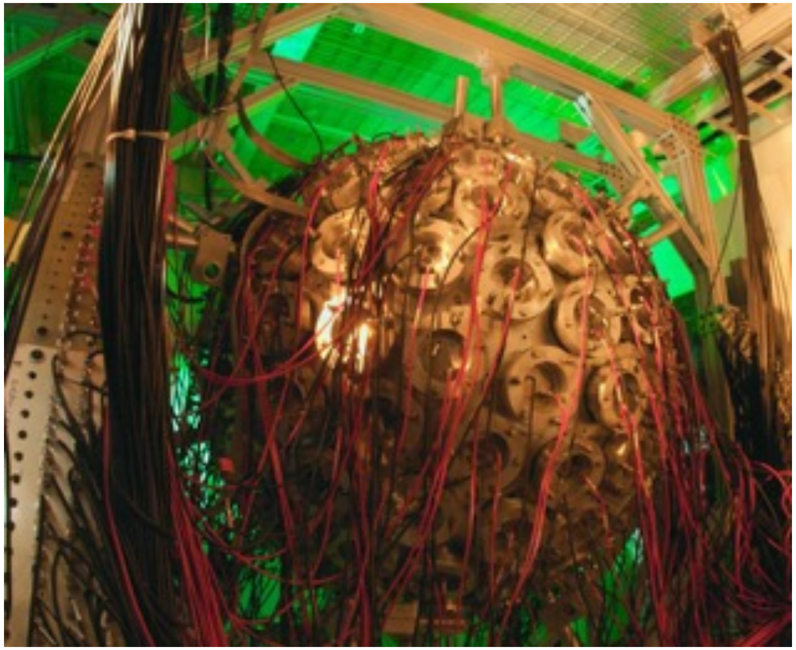
Argon Capture Experiment at DANCE (ACED)

- ACED collaboration measured the **thermal neutron capture cross-section** and the **correlated-gamma cascade** (never measured before)
- **Two papers published:**
  - **Neutron capture cross section:** *arXiv:1902.00596* (**PRD**)
  - **Thermal neutron beam calibration** using sodium: *arXiv:1902.01347* (**NIM A**)

Neutron capture cross-section



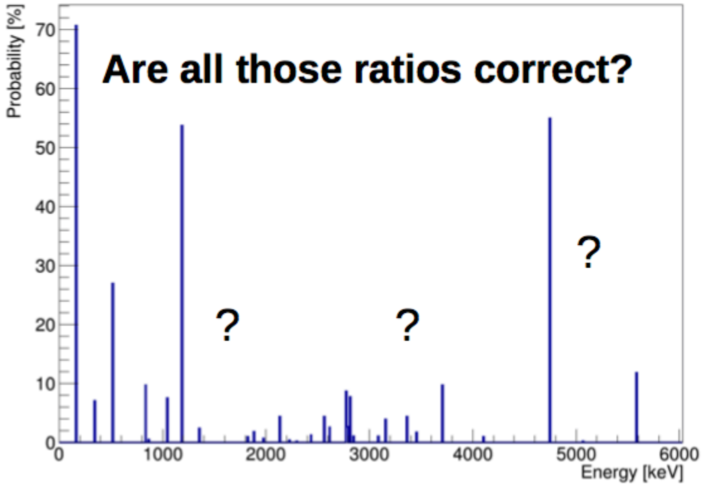
DANCE detector @lujan- FP14

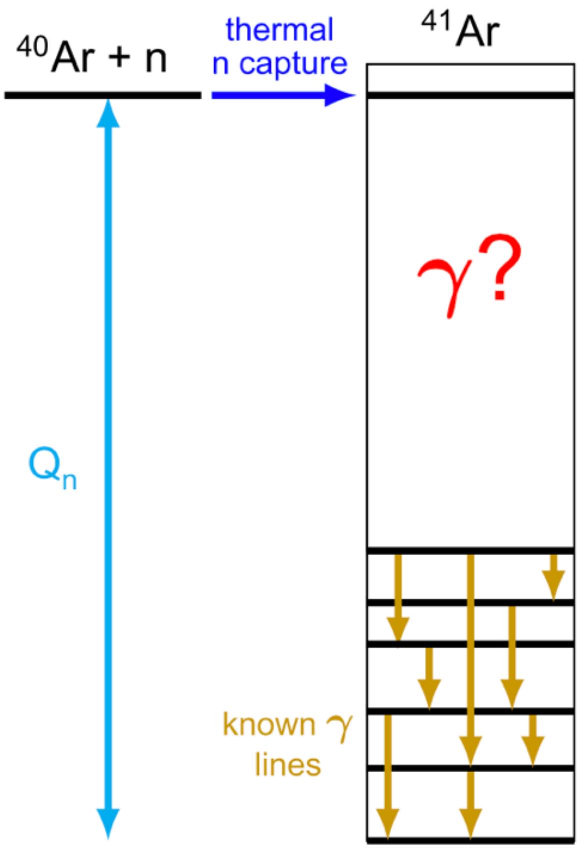


ACED Analysis: Gamma Cascade

- The 3rd paper will be about the **correlated gamma cascade**
- **Problem: Branching ratios of known gamma lines could be incorrect**
- **Problem: Many high-lying levels where gammas are unknown, and are difficult to model theoretically**
- ACED will use a statistical method to study the correlation of gammas in cascades

Gammas emitted after a capture (from ENDF)

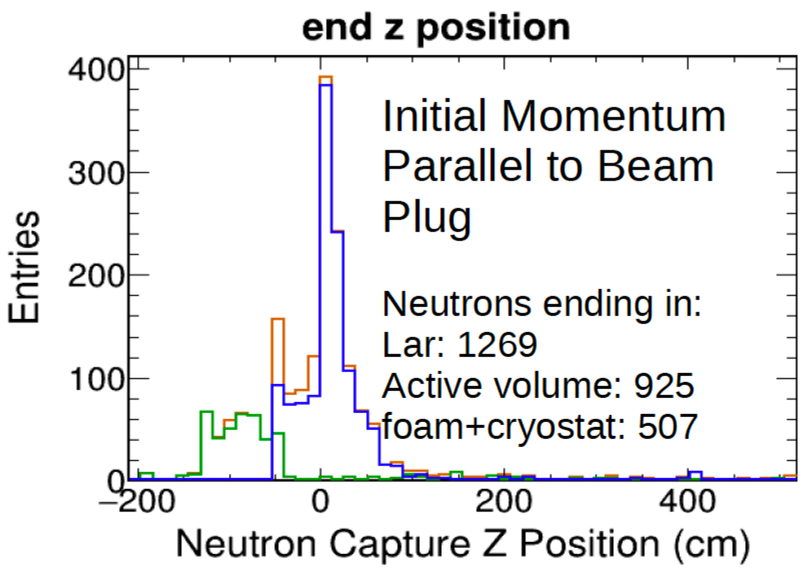


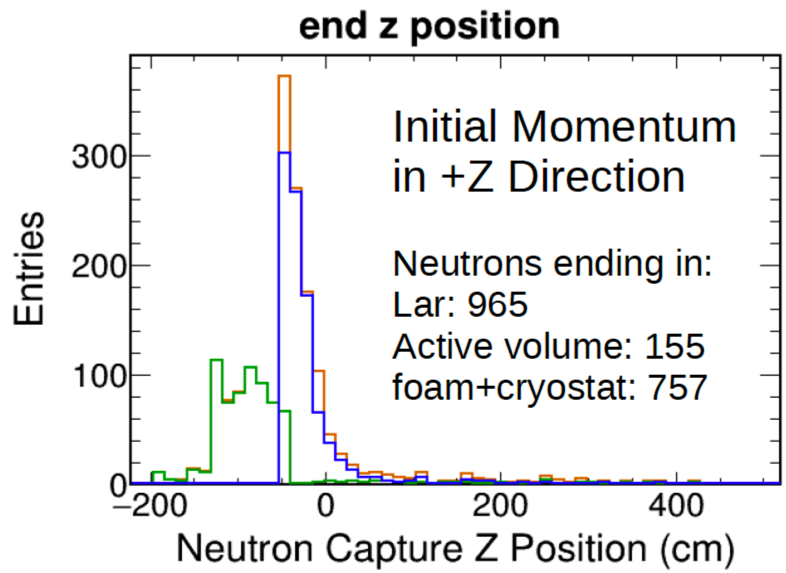


DD Generator Test at ProtoDUNE

- **Neutron transport simulation in LArsoft**

L. C. J. Rice, University of pittsburgh





How far do the neutrons go in the beam direction?

Neutron's whose end process is inelastic scattering (or capture) in foam insulation or cryostat steel
Neutron's whose end process is capture (or inelastic scattering in liquid argon)
All neutron's ending position for all processes in all materials.

10 / 12

Other Relevant Questions

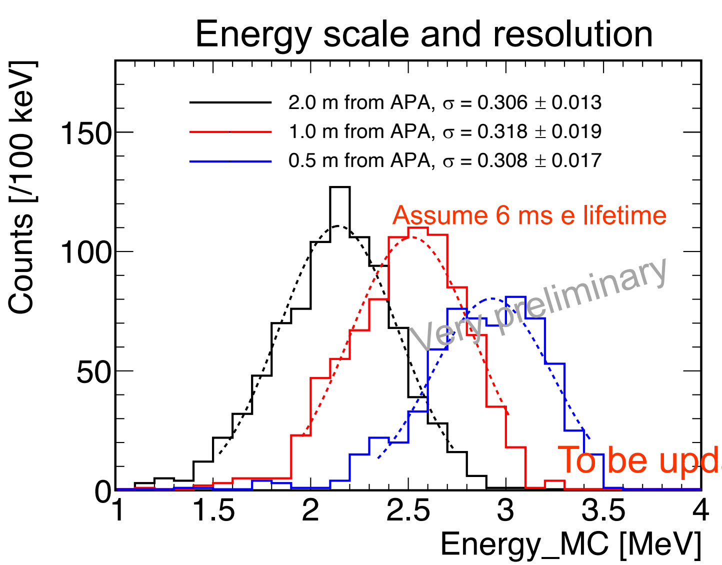
1. What exactly are the parameters being determined by the PNS?
2. How many wires will a neutron capture cloud hit? How much above noise (~1000 ENC) will the smaller hits be? Does the analysis need clustering algorithms to reduce noise?
3. Given the cross section from ARTIE, what is the fraction of detector volume that can be "illuminated" (more than 100 n/m^3) with a 1hr run of a single source in a corner human access port
4. Is there a realistic design for a moderator? Does it obey radiation safety rules? Does it need weight support from cryostat I-beams?
5. What is the ratio between close/far capture rates? What is the DD generator rate and total calibration time needed to calibrate the farthest volumes?

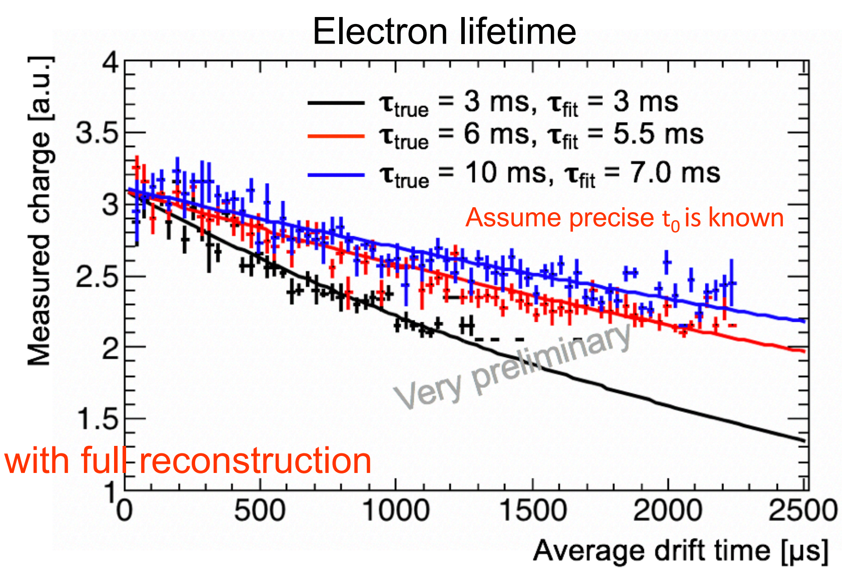
Question#1

Question#1: What exactly are the parameters being determined by the PNS?

- Primary calibrations: Energy scale and resolution, rough electron lifetime
- Neutron capture position is determined by TPC reconstruction
  - Rough t_0 provided by the DD generator pulse
  - Precise t_0 provided by the photodetector system
- Supernova trigger efficiency can be tested. Further study needed.

Idealized simulation with no corrections for recombination or argon purity





To be updated with full reconstruction

Question#2

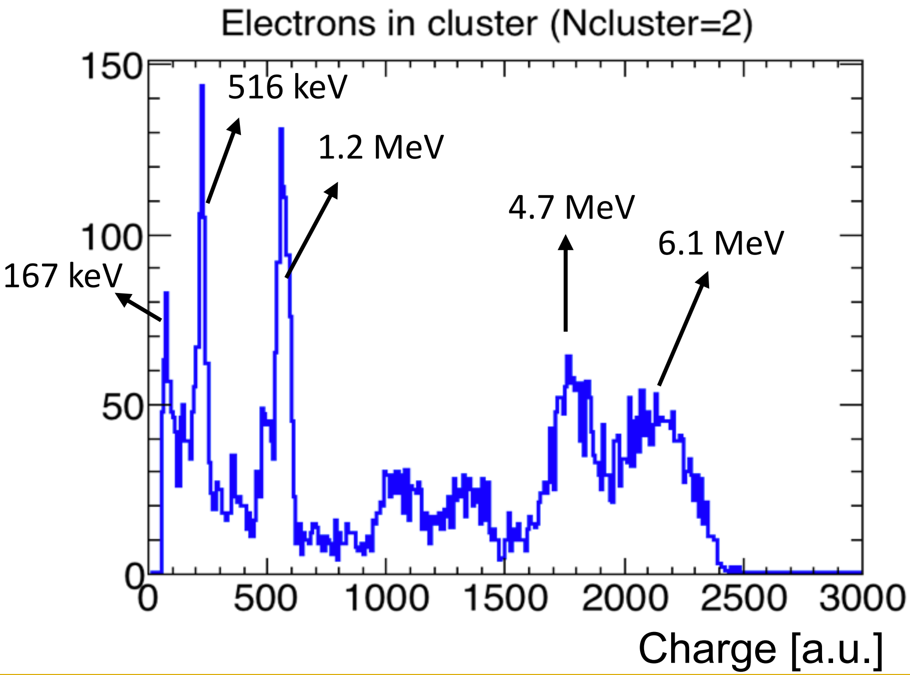
Questions#2: How many wires will a neutron capture cloud hit? How much above noise (~1000 ENC) will the smaller hits be? Does the analysis need clustering algorithms to reduce noise?

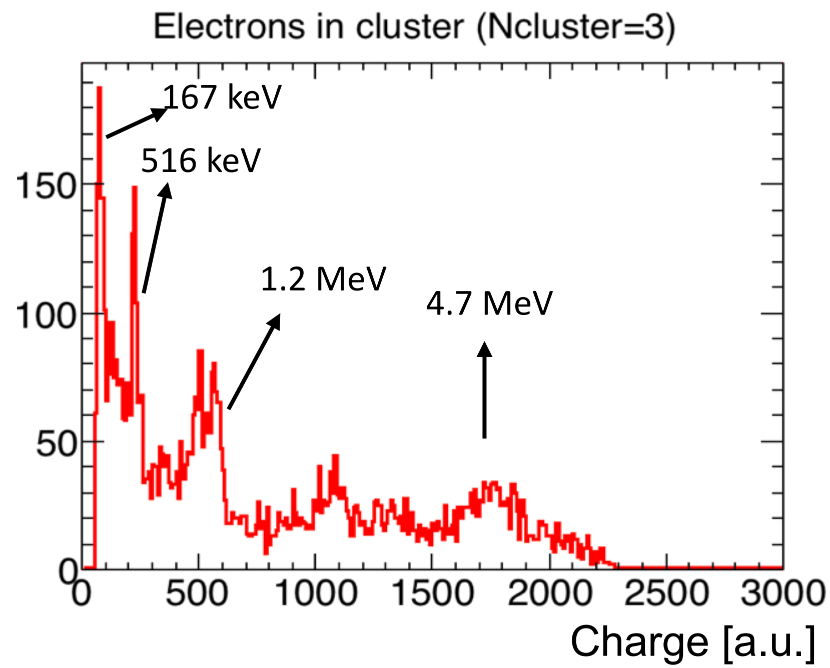
- The neutron capture is identified as a cascade of gammas. Each gamma fires only a few wires. Rough estimate of wires fired would be fewer than 15 (can be verified by simulation)
- The energy-electron conversion factor is 4.237e7 electrons/GeV. 1 MeV gamma can release 4.237e4 electrons, which is well above the ENC~500. In ProtoDUNE-SP, the signal-to-noise ratio is very high after noise mitigation (~40 for collection plane, 15-20 for induction plane). ProtoDUNE-SP has demonstrated few hundred keV level threshold level.

Question#2 (continue)

Questions#2: How many wires will a neutron capture cloud hit? How much above noise (~1000 ENC) will the smaller hits be? Does the analysis need clustering algorithms to reduce noise?

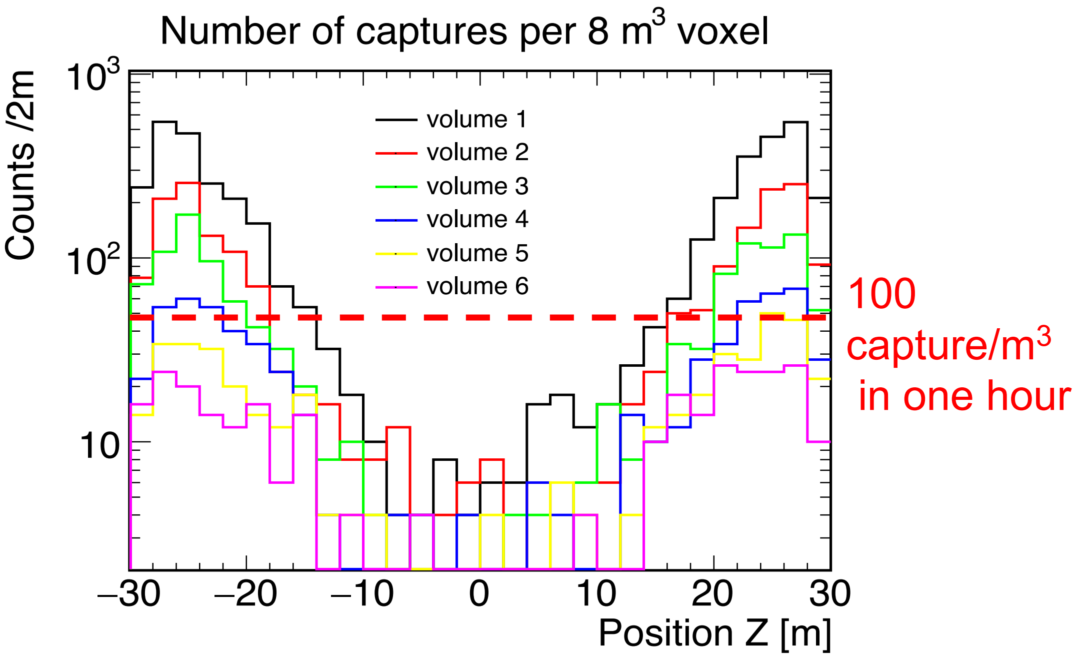
- Clustering algorithms are needed to identify a gamma from neutron capture. Geant4 simulation was done using the low energy Livermore model, and clustering with truth information worked well. LArSoft clustering is being investigated. Noise and background should be added.





Question#3

Question#3: Given the cross section from ARTIE, what is the fraction of detector volume that can be "illuminated" (more than 100 n/m³) with a 1hr run of a single source in a corner human access port



Slide 2x2x2 meter box along detector axis for 30 minute dual run of corner PNS

Exact number to be updated with ARTIE result

For 100 captures/m³ at the center we would need to run both PNS for 50-100 hours.

Typical lifetime of these sources is around 1000 hours (SK experienced more like 300-400 hours)

Question#4

Question#4: Is there a realistic design for a moderator? Does it obey radiation safety rules? Does it need weight support from cryostat I-beams?

- We have two types conceptual designs: 1) baseline design with large-format PNS systems and 2) alternative design with small-format PNS systems
- Radiation dose for both neutrons and gammas were calculated. The radiation level is well below the safety rules. Now we are working with CERN safety officers to implement a design for the DD generator test at ProtoDUNE-SP. Having this experience, we will go back to review the design proposed for the full size PNS systems.
- The baseline PNS design has a weight of about 1-1.5 ton, including all components. The support from the I-beams is definitely needed.

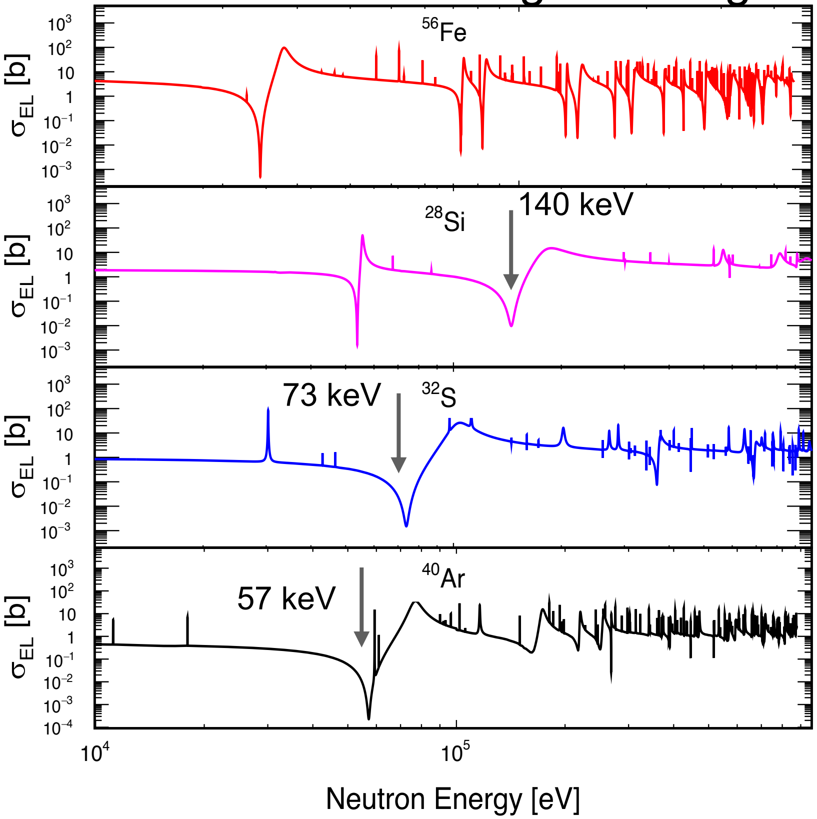
Question#5

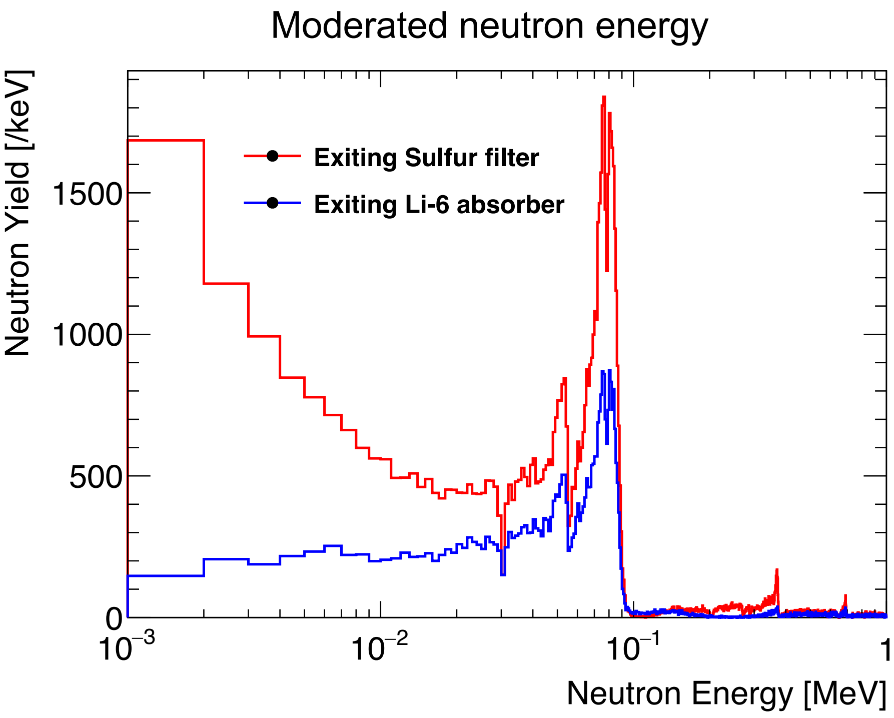
Question#5: What is the ratio between close/far capture rates? What is the DD generator rate and total calibration time needed to calibrate the farthest volumes?

- This is relevant to Question#3. The close capture rate is expected to be satisfactory, but the far capturer rate would be very low. The two baseline PNS systems at manhole locations cannot reach the middle of the far detector. Running the source for longer time (for example >50 hours) won't help much to reach the required statistics.
- The lifetime of a DD generator is 1000 hours. Recharge the depletion target may cost a lot. Instead of running for longer time, it is significantly beneficial to deploy a small-format PNS system in the middle of the detector using one of the multi-purpose calibration port. This is an alternative plan for DUNE, which is being considered and discussed.

Simulated Moderator Performance

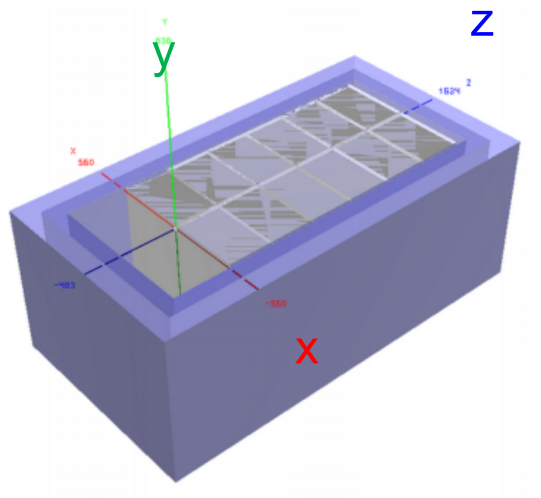
- Moderator makes use of the anti-resonance features of the moderating materials: silicon, sulfur
- The moderator is expected to make 50-80 keV neutrons (4.5% of the primary DD generator neutrons)
- Other moderator design is being investigated (work in progress)





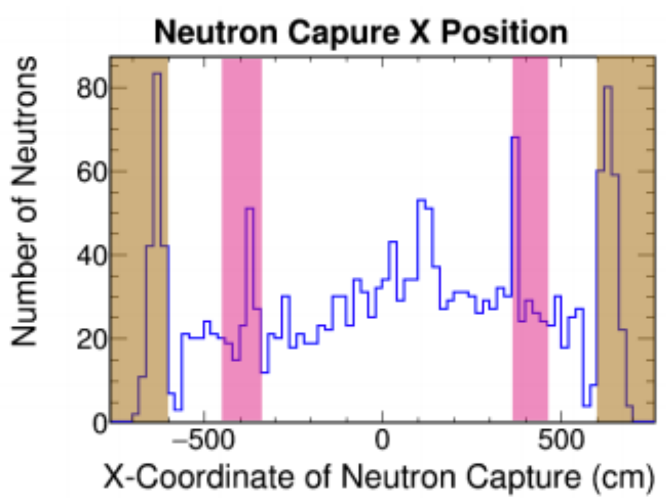
Realistic Neutron Transport in LArSoft

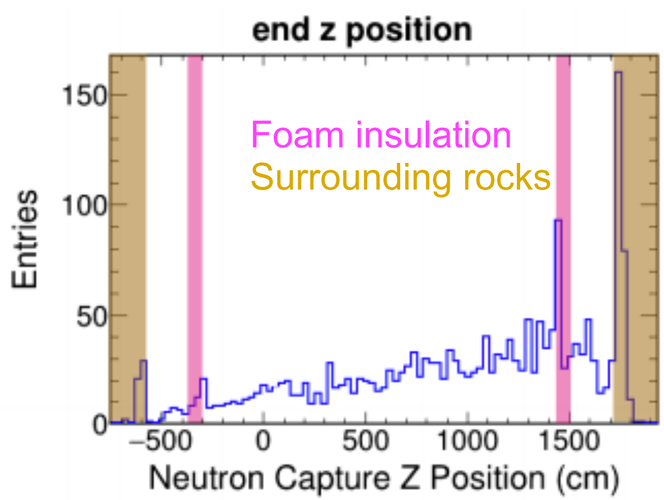
- Validation of neutron transport in LArSoft
  - Use real TPC materials
  - Shoot ideal 57 keV neutrons along z direction
- Neutrons travel through argon; captures may be concentrated in TPC components
- To do: Update the simulation with ARTIE result and realistic neutron spectrum.



L. C. J. Rice, University of pittsburgh

Shoot ideal 57 keV neutrons along z direction

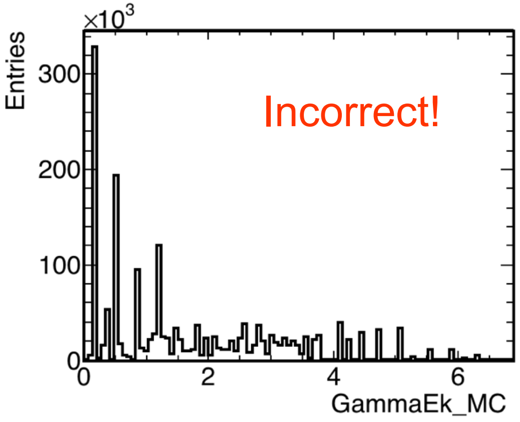




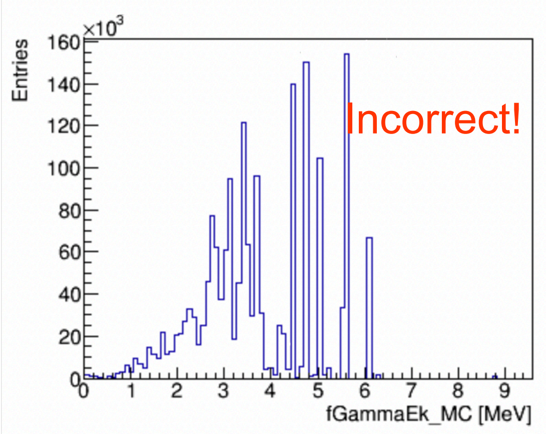
Neutron Capture Gamma Generator

- The default gamma cascade generator is incorrect in LArSoft (photon evaporation model)
- The gamma cascade generator with ENDF library is also incorrect (Final state model).
- We wrote a new physics process in Geant4 to generate the NNDC gamma cascade (https://www.nndc.bnl.gov/capgam/index.html). This is a critical step toward the full simulation.

LArsoft Cap-Gamma with photon evaporation model



LArsoft Cap-Gamma with ENDF-VIII Final State model



New Cap-Gamma generator being implemented in LArSoft