Physics with Neutrons @ the 2x2 Demonstrator

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Neutrons Interactions in LAr

< 20 MeV

Neutralize on a timescale of 100 μs and then promptly capture

20 MeV < KE < 80 MeV

Neutron capture + low energy elastic/inelastic scatter

> 80 MeV

Neutron inelastic scattering energetic enough to produce visible tracks

Can we work towards an experimental parameterization of missing energy on an event-by-event basis using neutron capture, elastic/inelastic scattering?

Neutrons Interactions in LAr

< 20 MeV

Neutralize on a timescale of 100 μs and then promptly capture

⇒ off-beam calibration & cross section measurement using pulsed neutron source

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Neutron capture + low energy elastic/inelastic scatter

> 80 MeV

Neutron inelastic scattering energetic enough to produce visible tracks

Measure gamma cascade visible energy from from 6.1 MeV neutron binding energy (Standard candle)

- Calibration technique
- Important for precision neutrino physics

Commercial D-D source deployed at ProtoDUNE-SP1 (pulsed, triggerable external source)
potential PNS available on loan from SDSMT

Backgrounds: cosmic-rays, in-situ radioactivity (e.g. Ar39)

Systematics: charge thresholds, absolute charge thresholds, light trigger thresholds

Neutrons Interactions in LAr

< 20 MeV

Neutralize on a timescale of 100 μs and then promptly capture

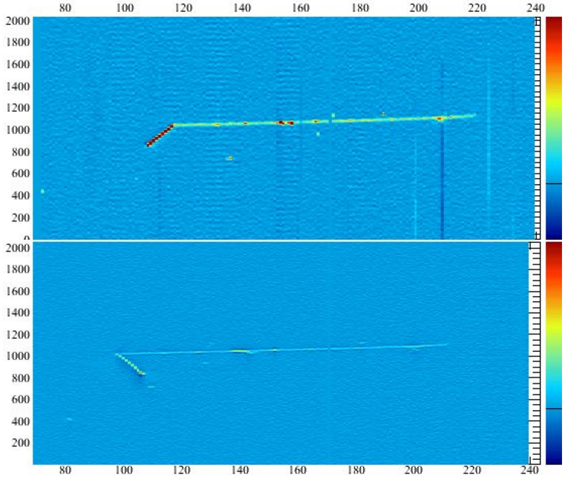
20 MeV < KE < 80 MeV

Neutron capture + low energy elastic/inelastic scatter

⇒ search for blips associated with neutrino vertex

> 80 MeV

Neutron inelastic scattering energetic enough to produce visible tracks



Inelastic scattering of primary neutrons produced from neutrino-Ar interactions, along with photons produced from de-excitation

ArgoNeuT measurement: Phys. Rev. D 99 (2019) 1, 012002

Neutrons Interactions in LAr

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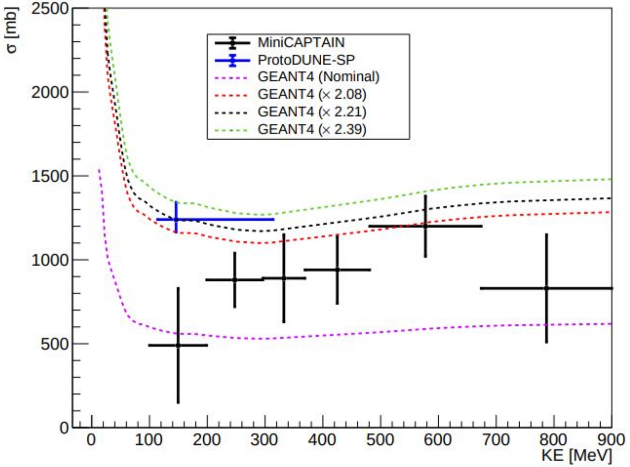
Neutron inelastic scattering energetic enough to produce visible tracks

⇒ search for isolated contained protons correlated with fiducial neutrino vertex

David Rivera, UPenn Dissertation 2021

n-Ar Inelastic Cross Section

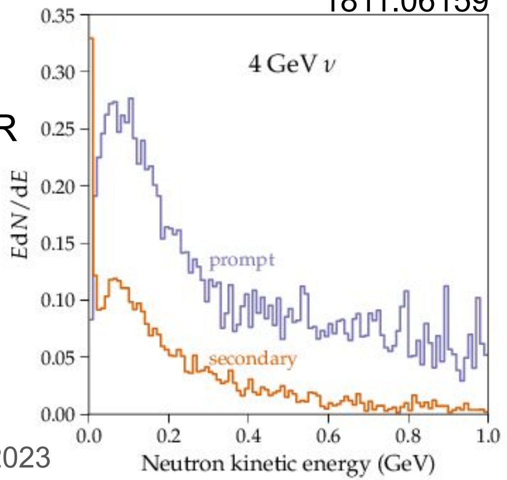


Using charged pion beam at ProtoDUNE-SP
- Vertex radial displacement serves as an effective interaction length
- Neutron KE extracted from simulation

Both MiniCaptain and ProtoDUNE-SP n-Ar cross section measurements suggest Geant4 cross section mis-modeling

⇒ *Neither using n from* ν

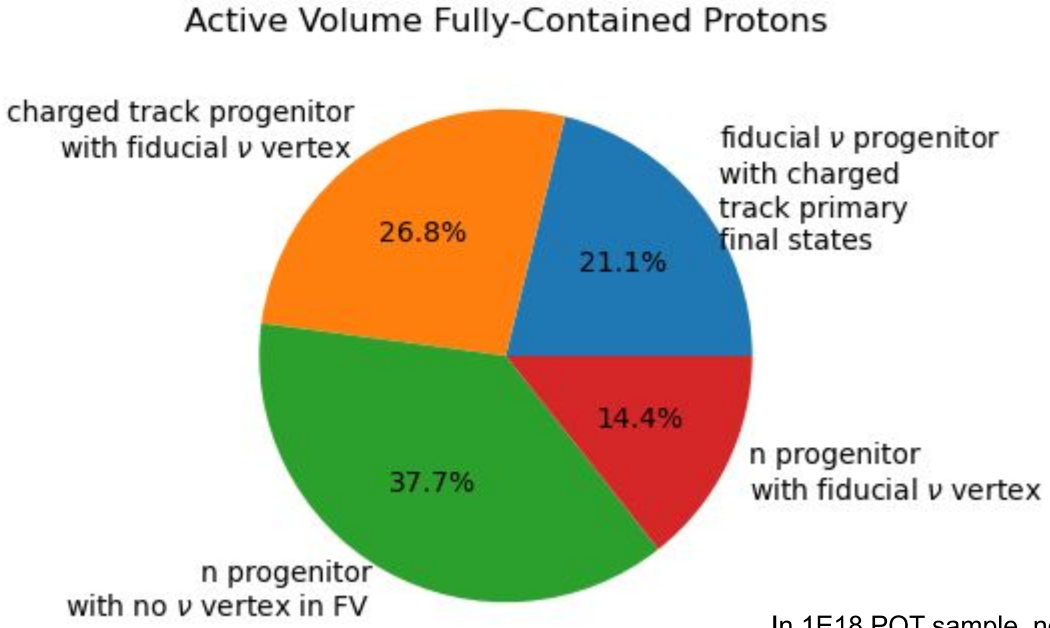
1811.06159



Inform DUNE OA hadronic energy uncertainty

⇒ 20% energy response uncertainty ascribed to neutrons in FD TDR

Measure neutron inelastic cross section by searching for disjoint proton tracks associated to neutrino interaction in ME NuMI



In 1E18 POT sample, no contribution from:

- fiducial ν progenitor <u>without</u> charged track primary final states in 1E18 POT
- progenitor ν vertex outside fiducial volume and another ν vertex inside fiducial volume

Distinguish progenitor neutron primaries from secondaries, tertiaries, etc. based on ν interaction final states

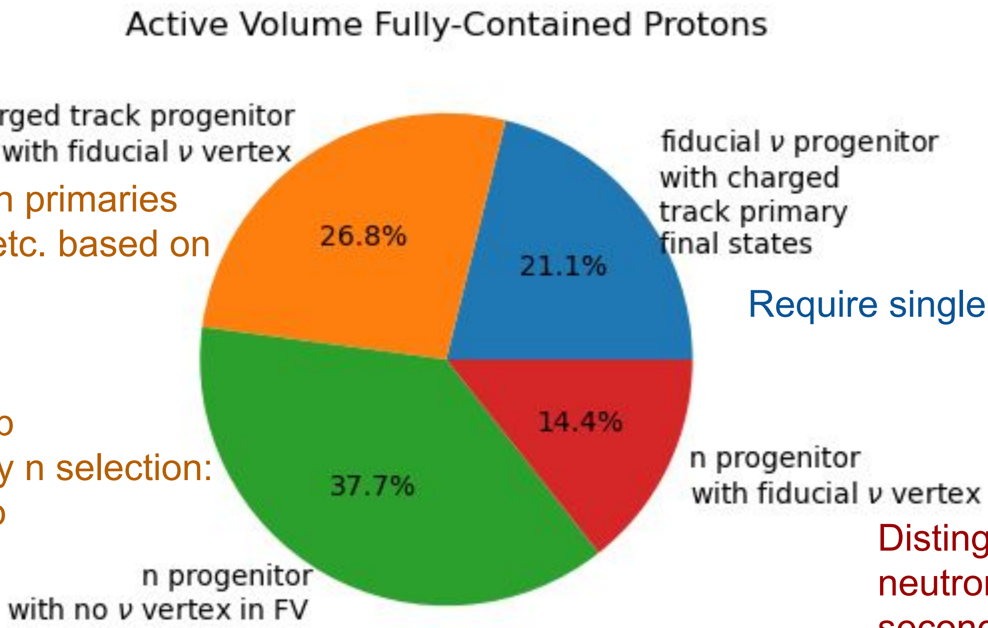
Non-primary n selection:

$$\nu_x \rightarrow \pi^{+/-} \rightarrow n \rightarrow p$$

Indistinguishable from primary n selection:

$$\nu_x \rightarrow \pi^{+/-} + n \rightarrow p$$

Require muon matched to And throughgoing to MINERνA



Require single MIP track

Require proton track disjoint from fiducial volume contained ν vertex

Distinguish progenitor neutron primaries from secondaries, tertiaries, etc. based on ν interaction final states

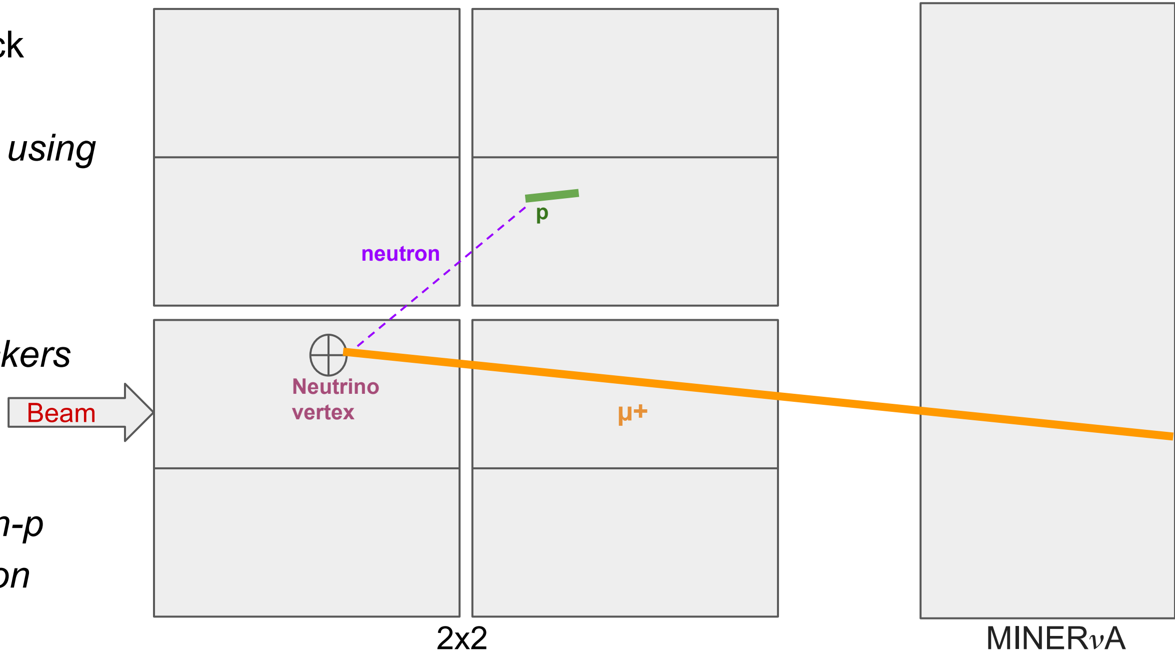
Primary n selection:

$$\nu_\mu \rightarrow \mu^{+/-} + n \rightarrow p$$

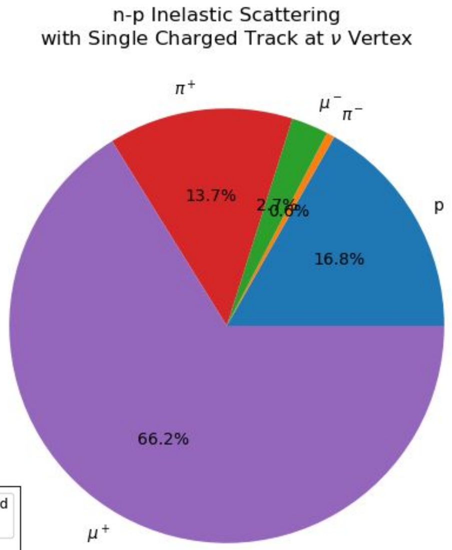
n-p Inelastic Scattering Search Strategy at 2x2

- ν vertex identified in fiducial volume
  - *3D reconstruction of ν signal*
- Fully fiducialized & isolated proton track causally constrained to same ν
  - *signal matching across modules using Q+L*
- Single track topology matched to and throughgoing to MINERνA
  - *track matching with external trackers*

Signal topology mitigates secondary n-p scattering from hadrons contamination



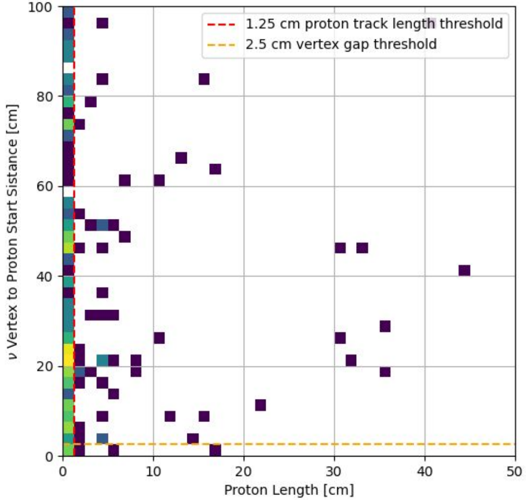
N-p inelastic scattering at 2x2



13% of events with single charged track

~⅔ of single charged tracks are muons

Signal statistics dependent on neutrino-to-proton “gap” and proton length requirements (i.e. reconstruction fidelity) → expect O(100) events per week



Expected leading systematics:

- Proton versus MIP separation
- Track versus shower separation
- Tracking threshold
- Recombination
- “Dirt” modeling
- Beam pileup

~156 events per 2.5×10^{19} POT

Summary

- Variety of neutron analyses viable at the 2x2 Demonstrator+MINERνA requiring varying levels of reconstruction sophistication

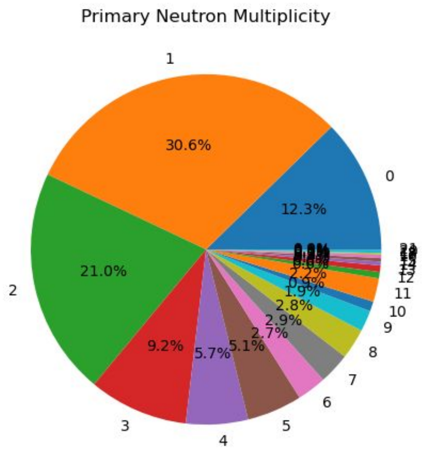
- n-p inelastic scattering at 2x2 poses a unique opportunity to make a competitive measurement which is also relevant to DUNE OA analyses

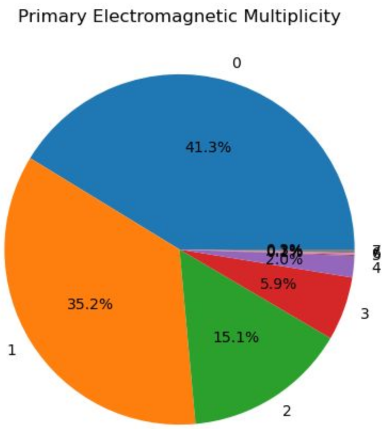
  - simple signal topology with limited PID requirements expect O(100) events per week

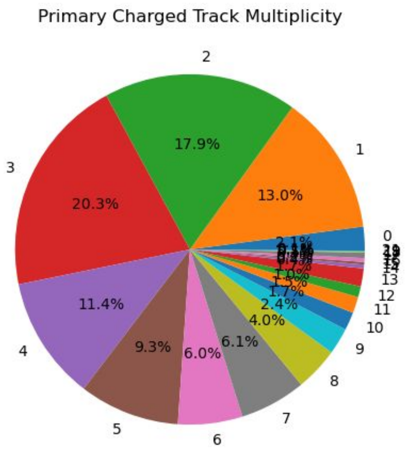
  - exercises key technical ND-LAr design capabilities, most notably Q+L matching across modules

Backup Slides

Fiducialized vertex primary n-p inelastic scattering neutrino events

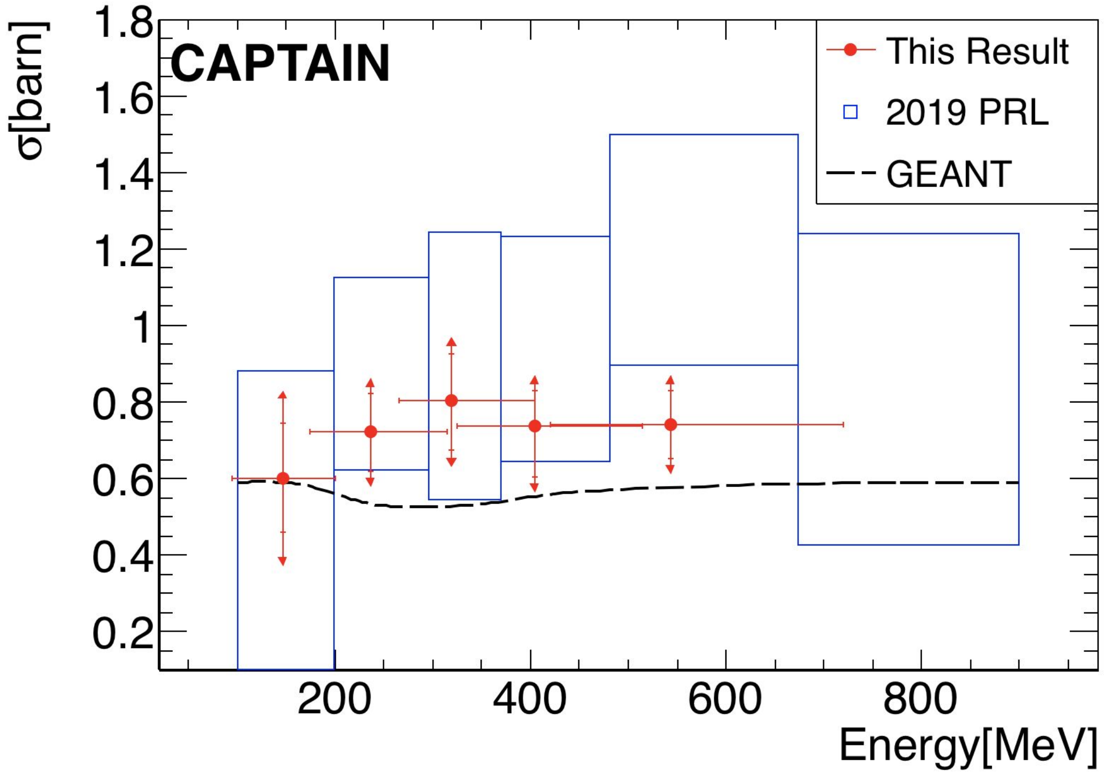






MiniCaptain 2022 measurement

PRD **107**, 072009



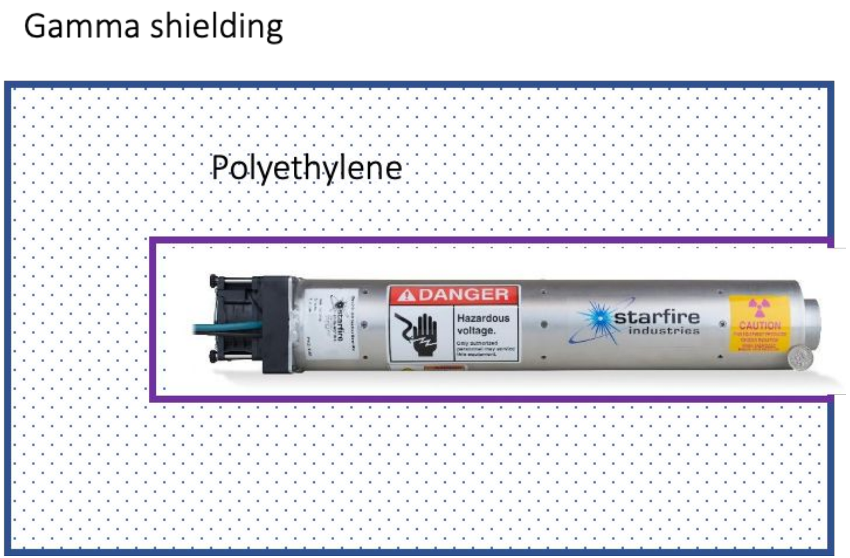
A new source from the Pulsed Neutron Source WG

Jingbo Wang (SDSMT) has two D-D generators

$$^{2}H + {}^{2}H \rightarrow {}^{3}H + n + Q(2.5\,MeV)$$

Source on loan from LANL

- Deployed at ProtoDUNE-SP
- To be sent to CERN for ProtoDUNE-II operation on September timescale - window exists to loan this source beforehand
- 250 Hz pulse rate



Newly purchased source

- Thermo Fisher MP320 DD neutron generator
- Delivery expected May 2023
- Capable of 1 Hz pulse rate
- 10^6 n/s maximum yield
- First tests at SDSMT June-July
- Available as early as late summer

Generator shielding on-hand

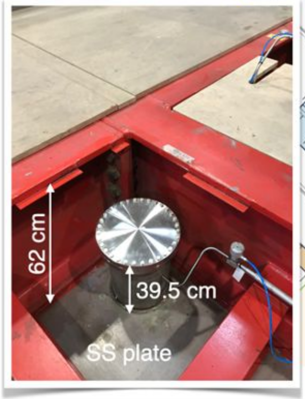
*NEXUS DD generator cleared for operation in MINOS experimental hall

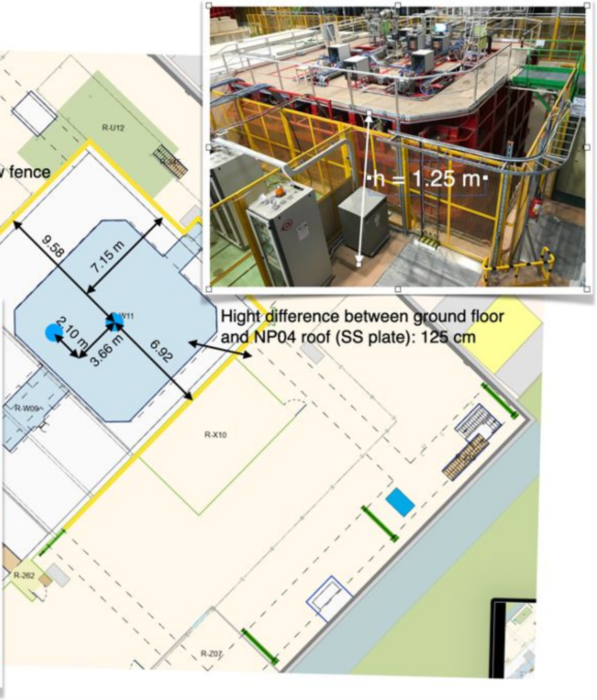
Pulsed neutron source @ ProtoDUNE-SP

Challenges:

- @Surface high flux of cosmics
- Limited readout capacity of <1 Hz vs neutron pulse of 250 Hz
- Long readout window and Pile-up
- Noise (~1000 ENC), threshold few hundred keV
- Installation on top of a port, 2.6 m away from the active TPC.
  < 0.14% of primary neutrons were captured inside the TPC
- Shielding: 15 cm Polyethylene (No extra gamma shielding)
  Gamma glow was visible in data on top of the detector
- Two weeks reserved for DDG test
- Weight: 11 kg

DDG is 2.6 m away from active TPC. <0.14 % of primary neutrons are captured inside the TPC.





CERN requirement for shielding:
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.

Pulsed Neutron Source @ 2x2

Standard candle $^{40}Ar(n,\gamma)^{41}Ar$ signal – 6.1 MeV multi-gamma cascade

Technical demonstrations:

- Novel calibration data (in advance of NuMI beam operation)
- Q+L calorimetry
- Fine-grained electron lifetime measurement

10^6 n/s source intensity ⇒ detailed simulation needed:

- Optimized source placement
- Number of captures in active volume
- Containment in one TPC, in 2x2

Leverage unique features of 2x2 @ NuMI underground facility:

- Much fewer cosmics at 100 m underground relative to surface
- LRS system capable of identifying 4.7 MeV gamma flash
- CRS system has ~100% up time 3D readout with ~200 keV thresholds