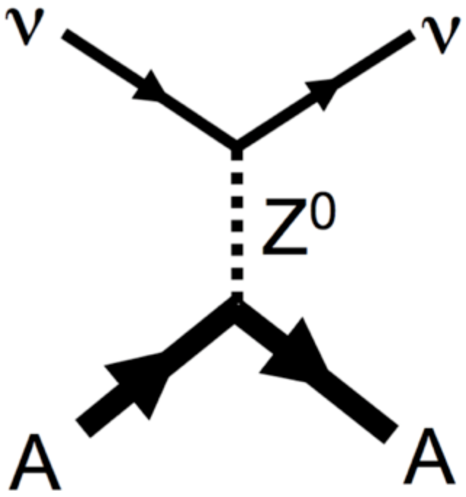
Coherent CAPTAIN-Mills (CCM): Lujan PSR Short Pulse Upgrade

SNOMASS LOI “LANSCE-PSR Short-Pulse Upgrade for Improved Dark Matter and Sterile Neutrino Searches”
Co-Authors: S. Biedron (UNM) and R. Van de Water (LANL) – Representing CCM and LANSCE AOT



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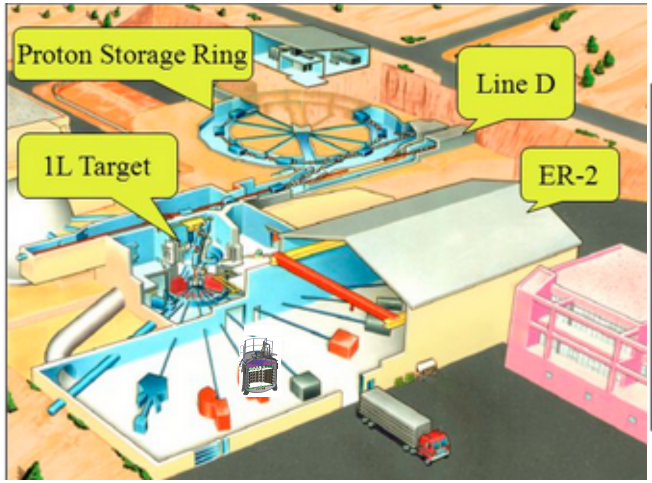
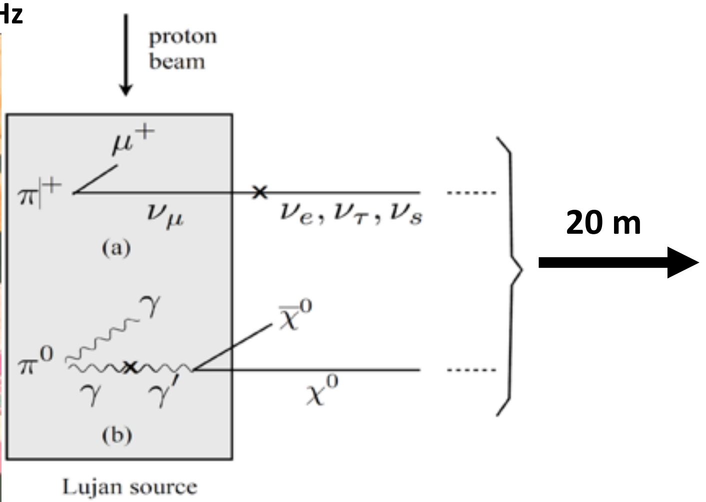
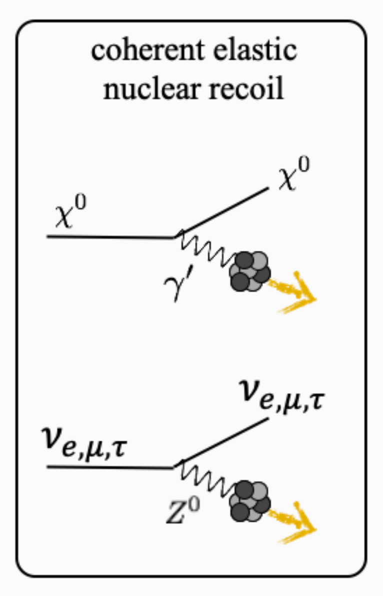
CAPTAIN = “Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos”

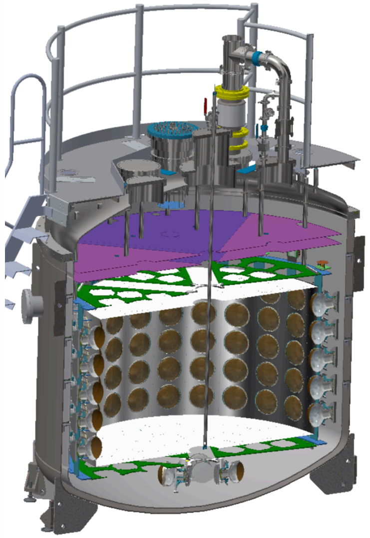
Dark Matter and Sterile Neutrino Searches at LANSCE with the Coherent CAPTAIN-Mills (CCM) Experiment

PSR - 800 MeV protons, 100 kW, 300 nsec@20 Hz









CCM: 10 ton Liquid Argon (LAr) detector instrumented with 200 8" PMT's, veto region, shielding, fast electronics.

LANSCE-PSR-Lujan Target (neutron/stopped pion source): Prolific source of charged and neutral pions that produce neutrinos and potential dark matter candidates.

Current Status:

- Successful full scale prototype beam run in 2019. Lessons learned are being applied for 2021 beam production run.
- Received DOE HEP Dark Matter New Initiative funding to build a second identical detector to improve dark matter and sterile neutrino searches.

Future: Upgrade Proton Storage Ring reducing beam spills to 30 nsec width (from 300 nsec), increasing instantaneous power and search sensitivity by order of magnitude for modest cost and near term time scale.

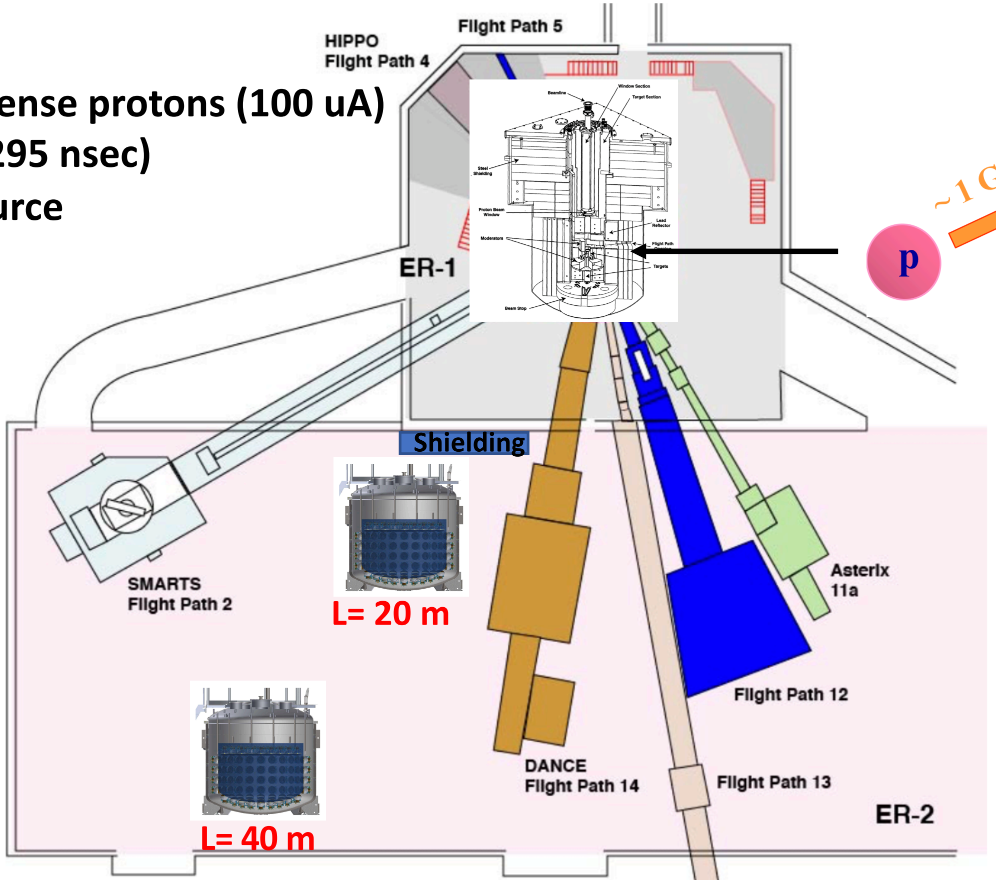
Why LANL: LANSCE/CCM is unique, well-motivated, timely, and flexible enabling future impactful upgrades.

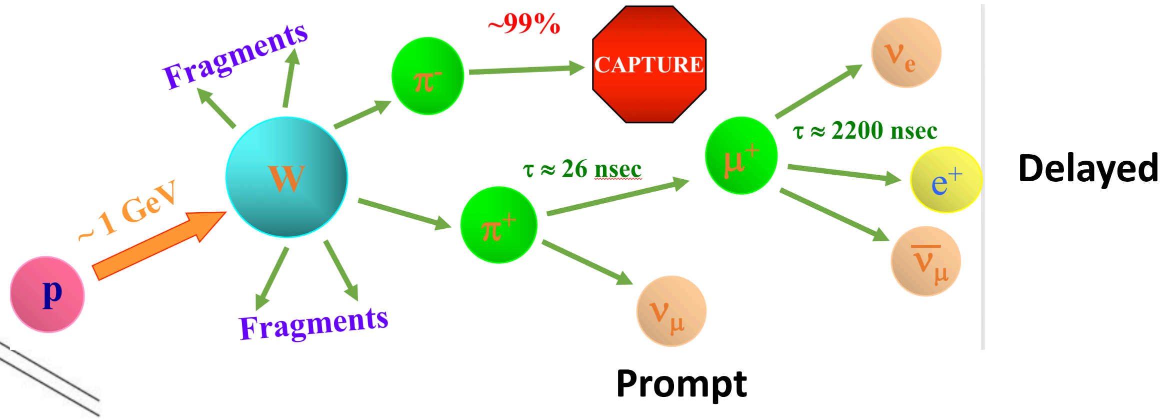
Why Now: Search for new physics with a high instantaneous power stopped pion source and large detectors sensitive to coherent scattering opens a new window on sub-GeV dark matter, axions/ALPs, sterile neutrinos, CEvNS cross sections, and Non Standard Interactions (NSI). Testing many techniques necessary for next generation FNAL/PIP-II stopped pion source.

LANSCE-Lujan Neutron Facility a unique place to perform significant and timely test of Sterile Neutrinos and DM Searches

Muon neutrino flux 4.74x10^5 nu/cm^2/s at 20 m

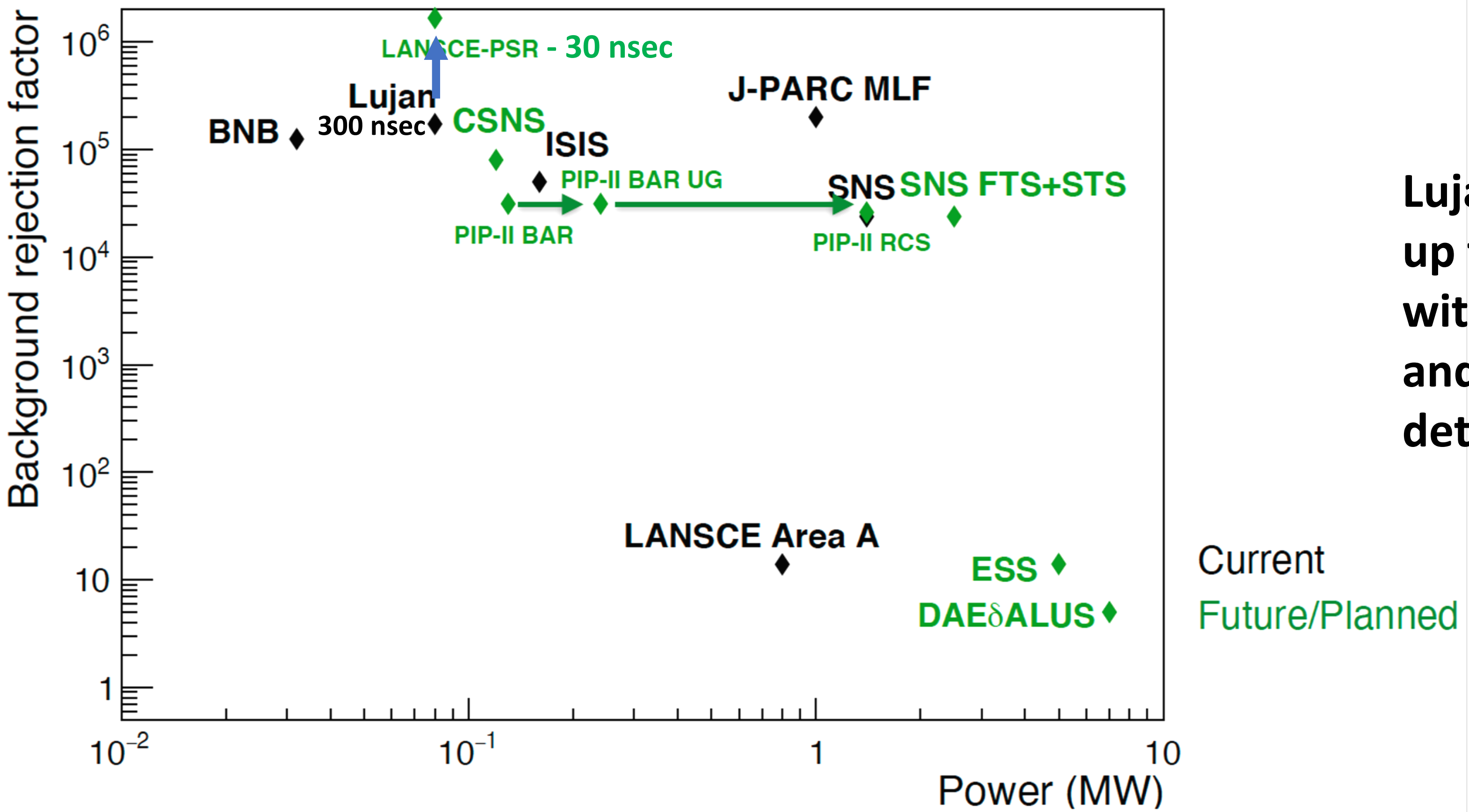
Lujan Target
- 800 MeV intense protons (100 uA)
- Fast Beam (295 nsec)
- Compact source





Lujan Experimental Area
- Space for large 10-ton liquid Argon neutrino detector.
- Run detector in multiple locations.
- Room to deploy shielding, large overhead crane, power, etc

Lujan is a Competitive and Unique Neutrino/Dark Matter Source
Low duty factor critical for background rejection



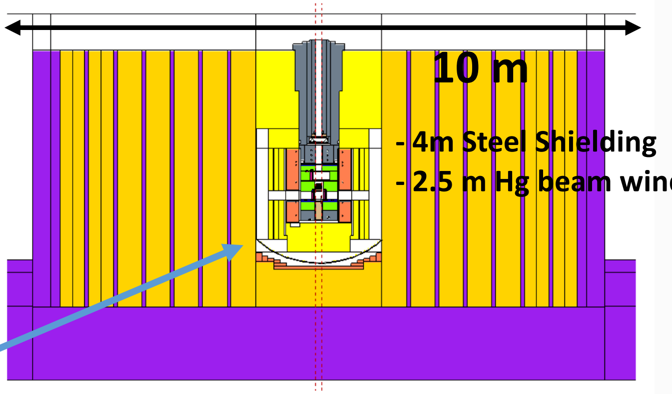
Plot via K. Scholberg and Jacob Zettlemoyer (FNAL)

Lujan/CCM makes up for less power with large, sensitive, and fast 10 ton LAr detector!

- **Neutrino experiments require high instantaneous power – measure of Signal/Background (S/B):** SNS (FWHM 350 nsec @ 60 Hz)= 0.060 kJ/nsec; Lujan(FWHM 150 nsec @ 20 Hz)= 0.028 kJ/nsec
- Upgrade to 30 nsec would increase instantaneous power and S/B by order magnitude or more
  - Improved rejection of backgrounds (Ar39, neutron activation, etc) and improve particle identification.

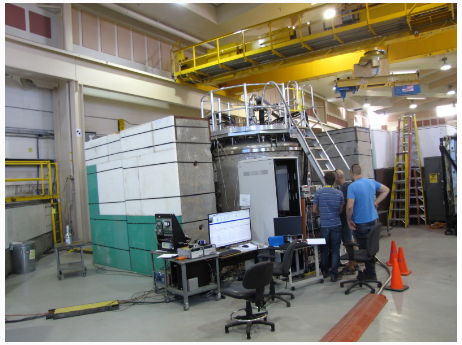
Lujan Neutron Target

(800 MeV protons, 100 kW, 20 Hz, 295 nsec triangle pulse)



Nuclear Instruments and Methods in Physics Research A 594 (2008) 373–381
Nuclear Instruments and Methods in Physics Research A 632 (2011) 101–108

Extensive Shielding around target and detector…



However, require timing to reduce beam neutrons to manageable levels.

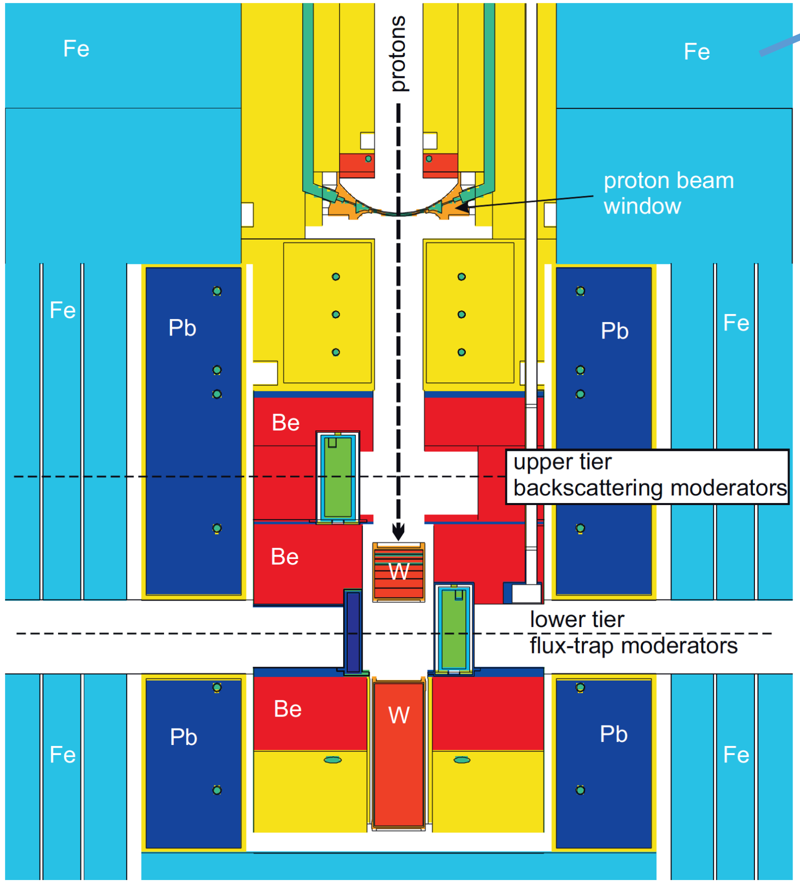
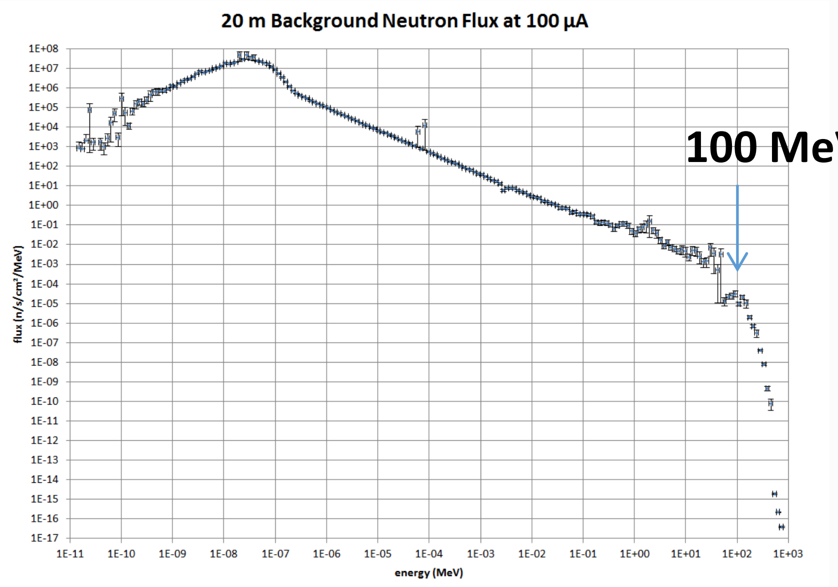


Fig. 1. Elevation view of the Lujan Center's TMRS geometry used in our calculations. The main components are labeled: split tungsten target (W), beryllium reflector (Be), lead reflector–shield (Pb), and the steel reflector–shield (Fe).

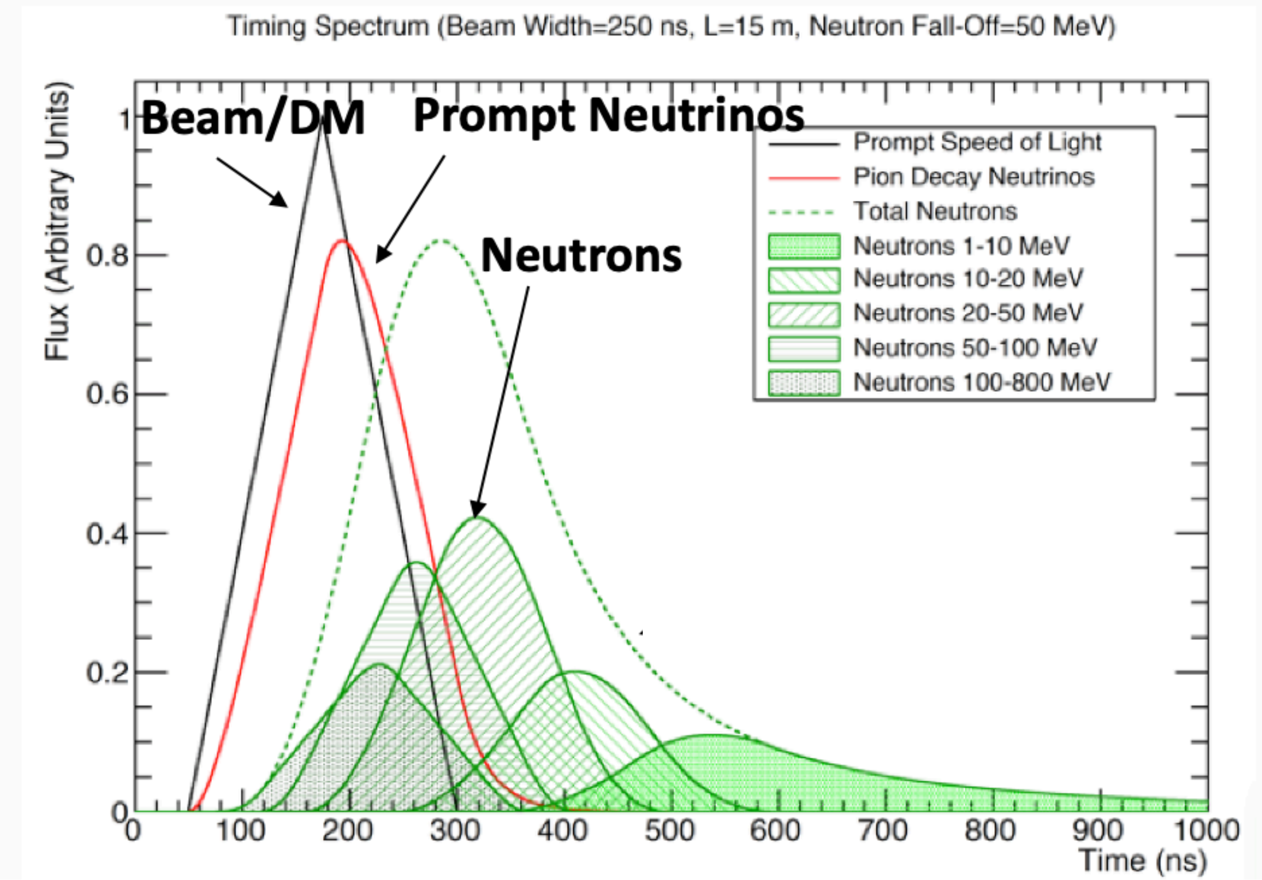
- Simulations has confirmed hand calculated flux of ~4.74×10^5 nu/cm^2/s at 20 m
- Horizontal extend of neutrino production at the source of 8 cm (1 sigma position error)
- Simulated neutron backgrounds



Absolute Beam Timing versus Detector Time: Extracting a region free of slow moving neutrons

Lujan/CCM Measured Beam Timing and Signal Region

Reduce beam neutron backgrounds by using fast timing to separate slow neutrons from speed of light particles traversing 20m. Requires absolute beam T0.



Prompt intime with beam events:

1. DM from pi0 decay
2. Muon neutrinos from pi+ decay.

- Can separate prompt muon neutrinos and dark matter from slow moving neutrons using time of flight. Need fast ~nsec detector and measure beam T0

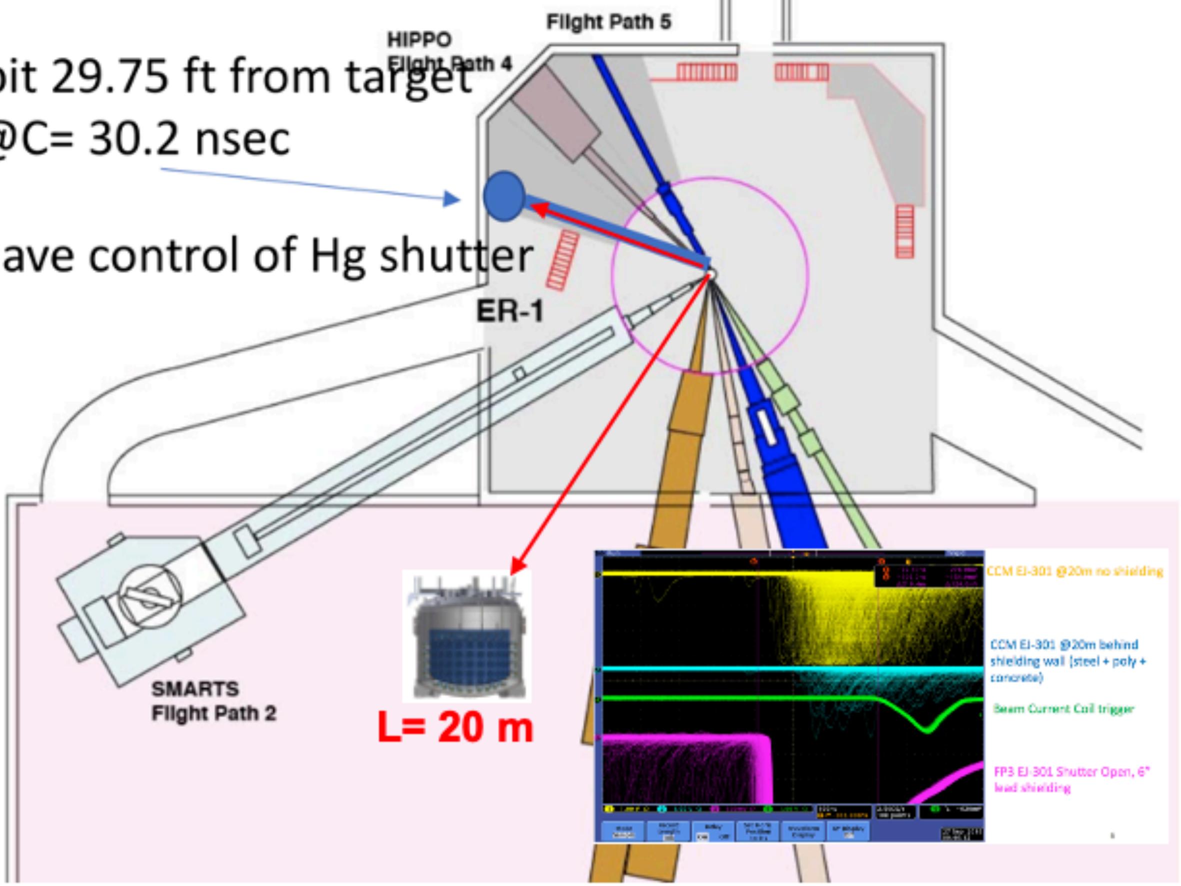
Measuring Beam T0 using proton gamma-flash

EJ301 Detector Placed in Flight Path 3

- Liquid scintillator detector sitting on beam line with no shielding between it and the target to observe γ-flash
- Used to measure the time offset between the t_0 and the CCM events time
- Not all time delays in the trigger signal could be measured

FP3 pit 29.75 ft from target
TOF@C= 30.2 nsec

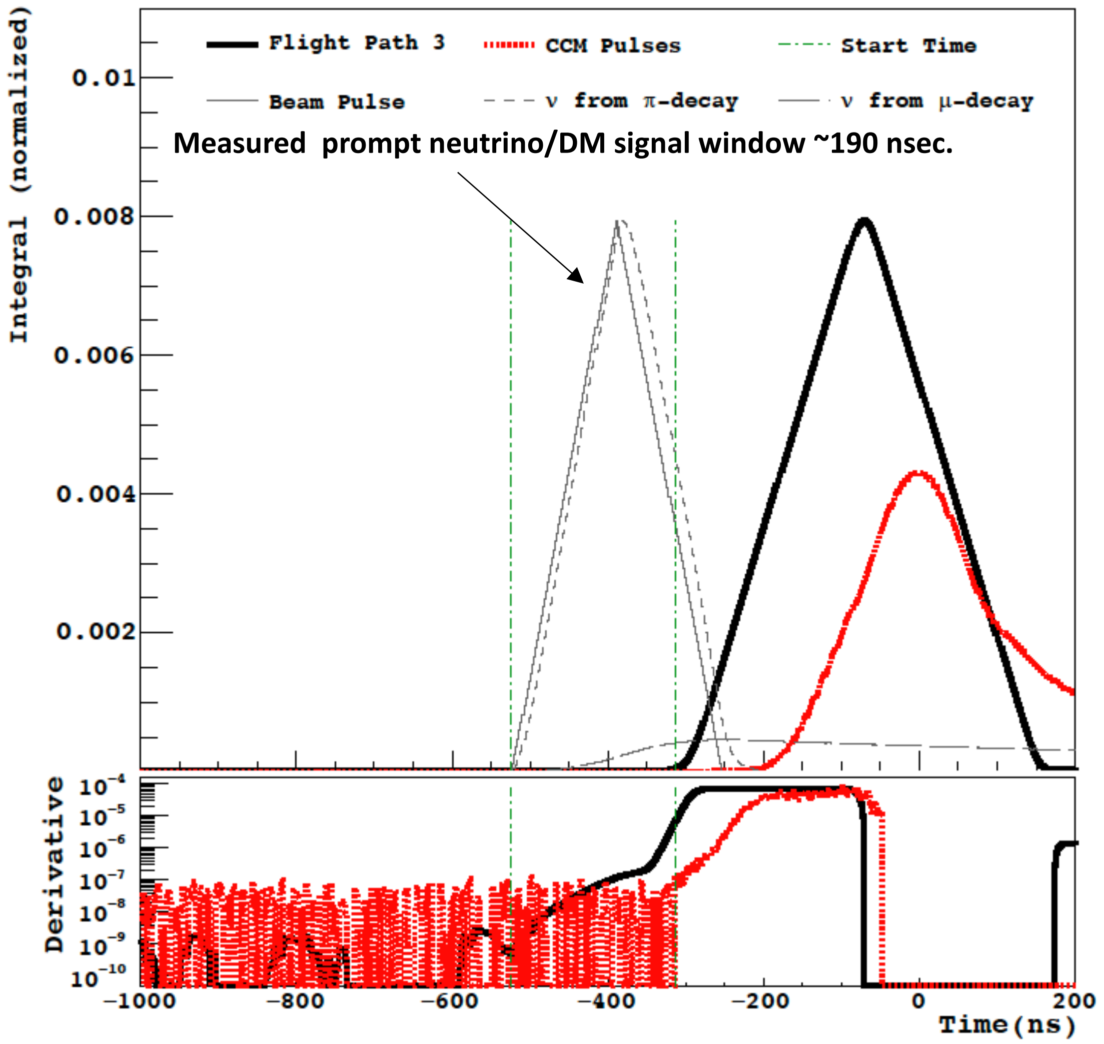
We have control of Hg shutter



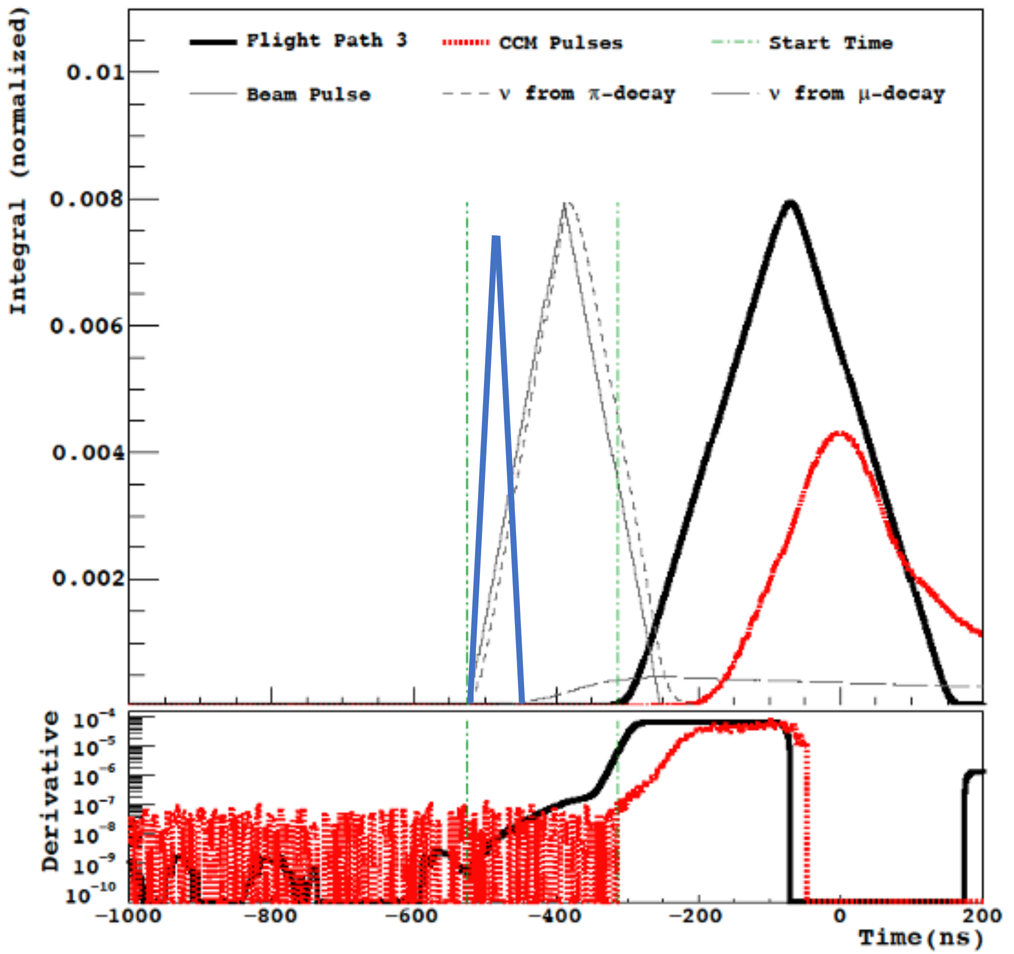
Absolute Beam Timing versus Detector Time: Determining the region free of slow moving neutrons

Beam Related Background Free Region

- Based on the turn on of the FP3 detector, we expect speed of light particles from π^0 decay to arrive 210 ns before events we seen in CCM
- Because of change in efficiencies of cuts near the CCM turn on the signal region will be 190 ns
- This consists of:
  - 80% of π^0-decay events
  - 74% of $\pi^{\pm}$-decay events
  - 4% of $\mu^{\pm}$-decay events that would fall within our DAQ window



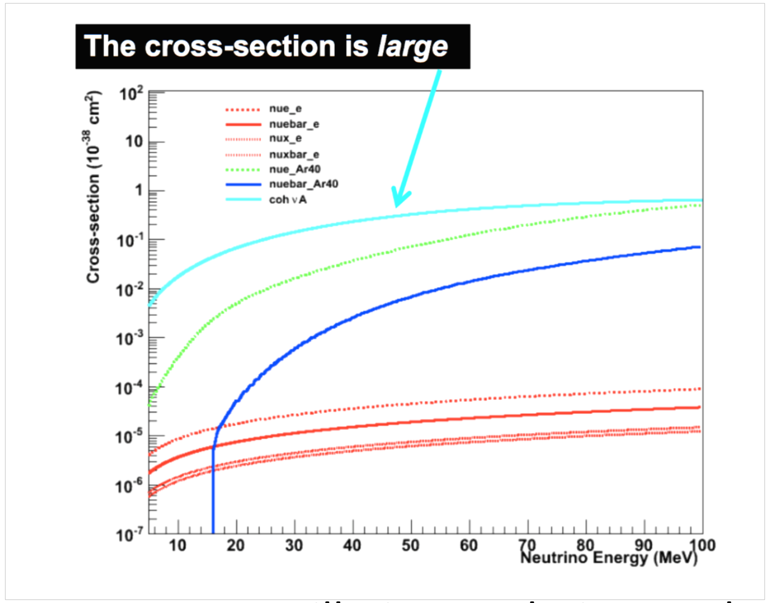
Lujan Improved S/B with Upgrade 30 nsec Beam



Shorter beam pulse reduces random backgrounds from Ar39 decay and neutron activation

- If we shorten PSR pulse from 300 nsec to **30 nsec (Blue),** would increase signal efficiency and reduce random backgrounds, estimate increase **S/B (30 nsec) > 100**.
  - Factor 10 reduction in random backgrounds from Ar39 and neutron activation
  - Factor 10 reduction of EM events relative to nuclear scattering using Singlet/Triplet light PID.

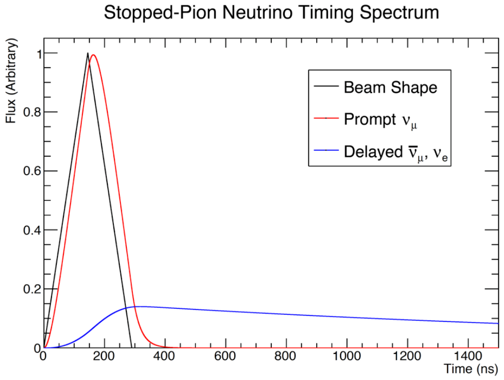
Expected CAPTAIN-Mills LAr Event Rates – No Threshold Cuts (100 kW @ 12 months (two year run), 5 tons LAr)

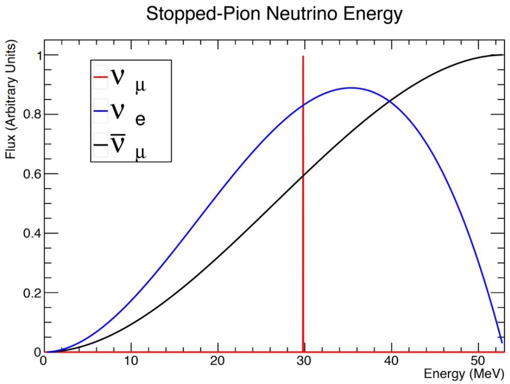


Large LAr **coherent eleastic neutrino-nucleus scattering (CEvNS)** cross sections -> 1000's events!

Reaction	L = 20 m (events/yr)	L = 40 m (events/yr)
Coherent ν_μ (E = 30 MeV)	2709	677
Coherent $\nu_e + \bar{\nu}_\mu$	9482	2370
Charged Current ν_e	257	64
Neutral Current ν_μ	36	18
Neutral Current $\bar{\nu}_\mu$	79	20

- Two oscillation analysis samples with different strategy/backgrounds:
  - **PROMPT** with beam (mono-energetic $\boldsymbol{\nu_\mu}$) – scattering end point energy 50 keV
  - **DELAYED** 4 usec after the beam ($\boldsymbol{\nu_e + \overline{\nu_\mu}}$) - scattering end point energy 148 keV

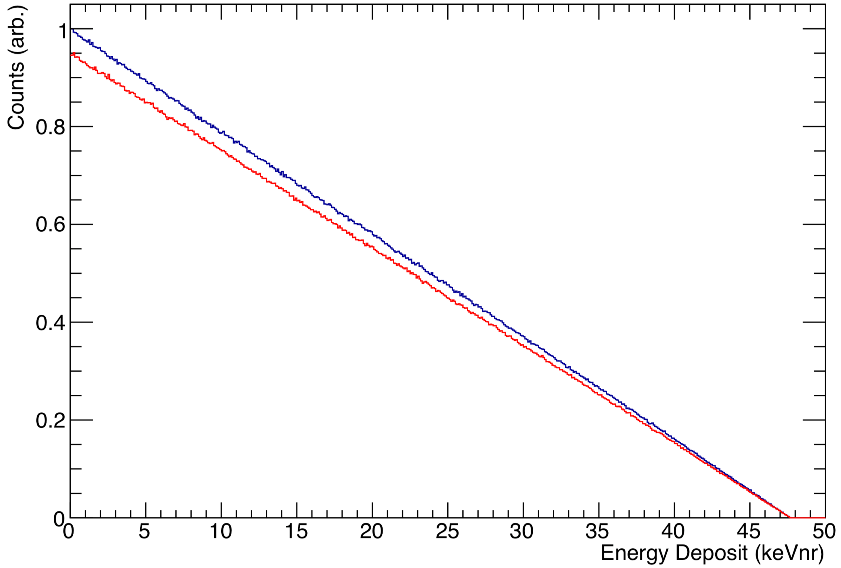




Coherent Neutrino-Nucleus Scattering Energy Spectrum

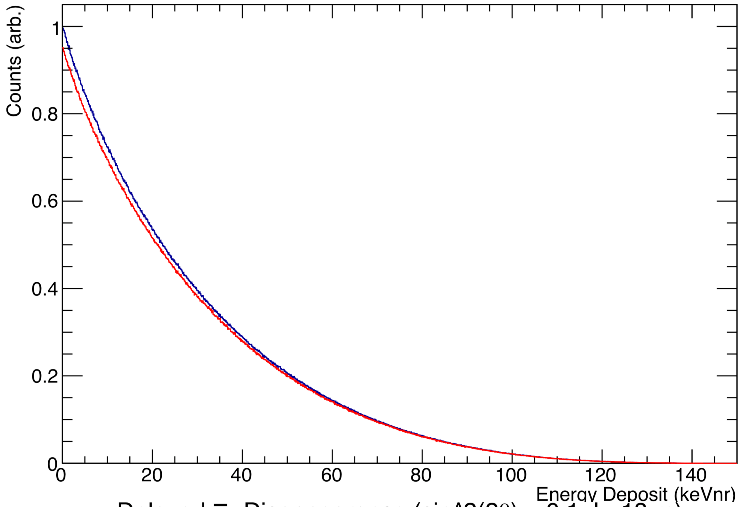
Prompt Neutrinos E_{muon}= 30 MeV

Prompt ν_μ Disappearance (sin^2(2θ) = 0.1, L=18 m)

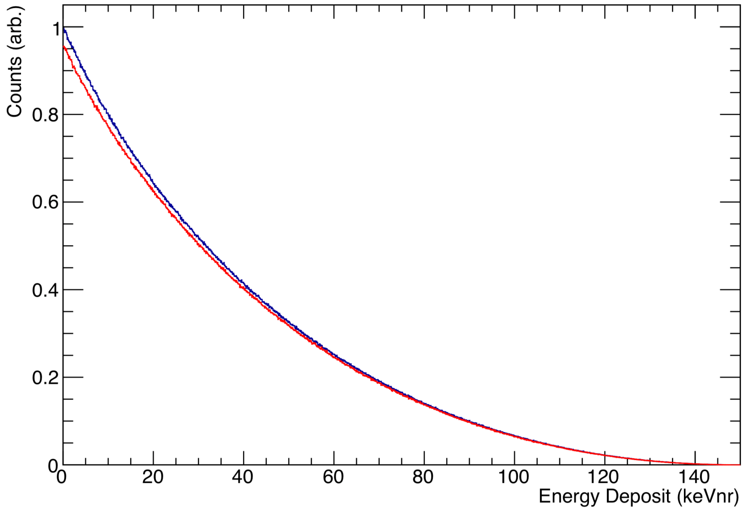


Delayed Neutrinos

Delayed ν_e Disappearance (sin^2(2θ) = 0.1, L=18 m)

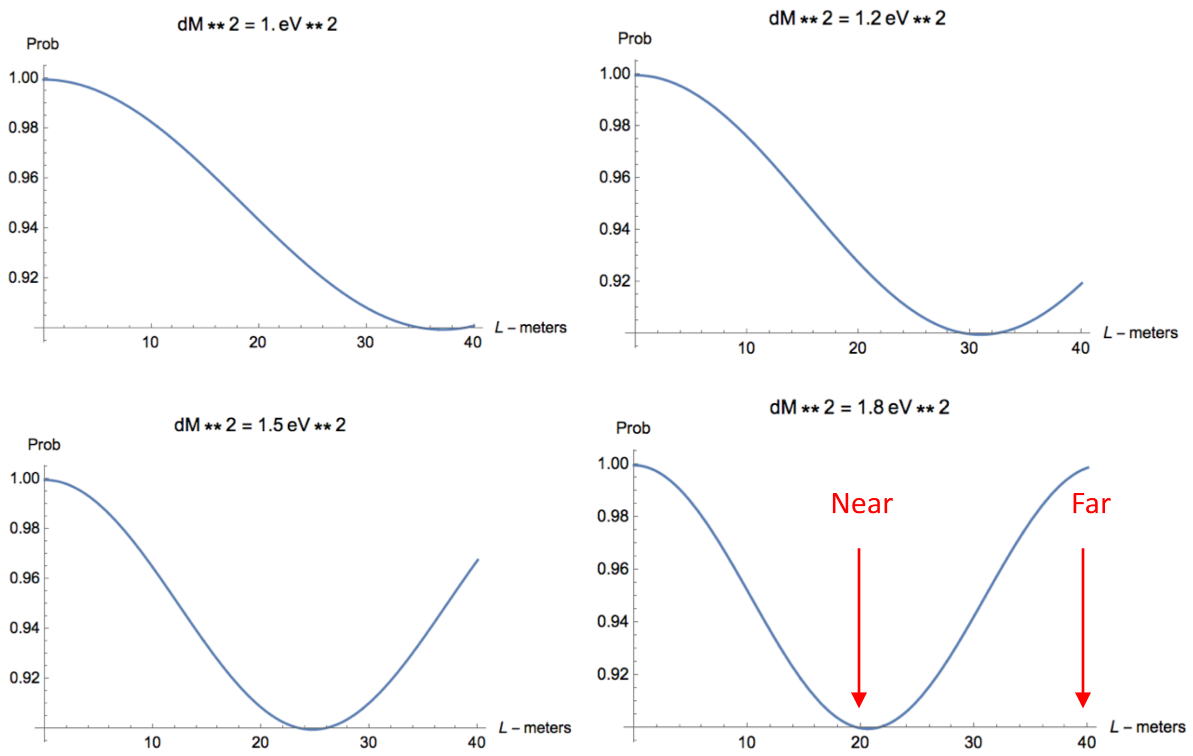


Delayed $\bar{\nu}_\mu$ Disappearance (sin^2(2θ) = 0.1, L=18 m)

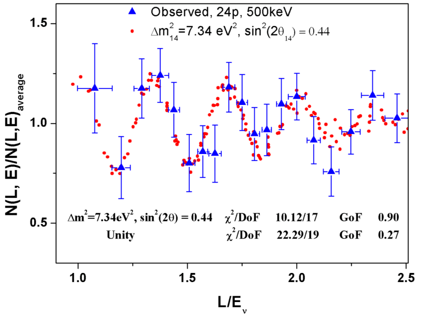


Signal Strategy

- **Looking for up to ~10% disappearance over 15-40 m**
  - ~1,000 CEvNS events 3 years – far detector.
  - Near/far cancellation to reduce systematic errors.
  - Can move detector to multiple positions (sample L/E).

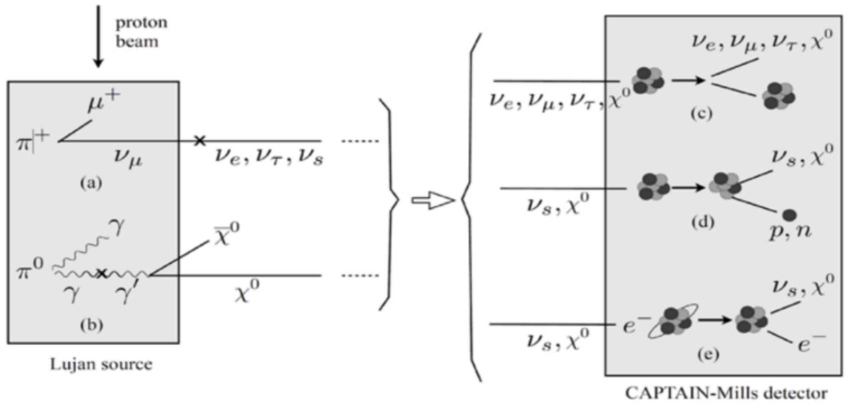


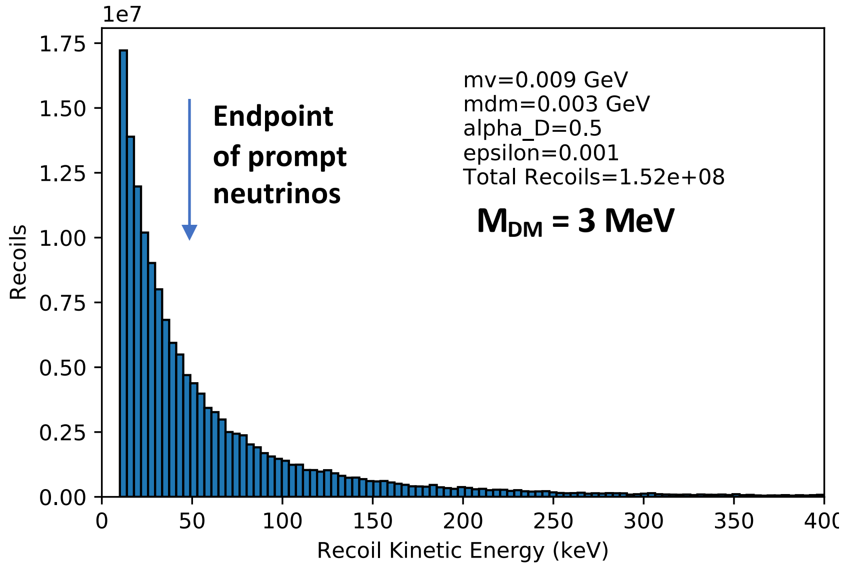
Can Adapt: new Neutrino-4 result $7eV^2$ -> ~5m oscillations

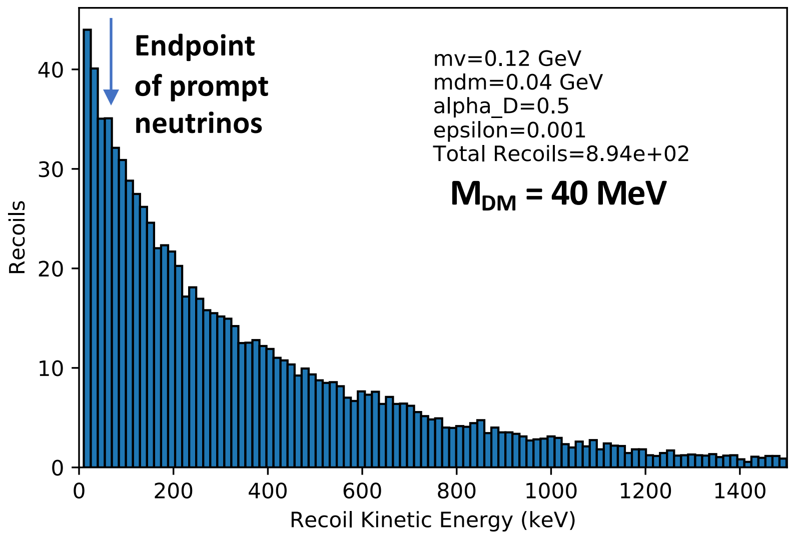


With two detectors, run in fixed near/far positions for the entire beam cycle, i.e. simplifies operations!

Vector portal model: DM produced via prompt π^0 decay from 800 MeV stopped pion source, detector at 90º, coherent scatter off Argon







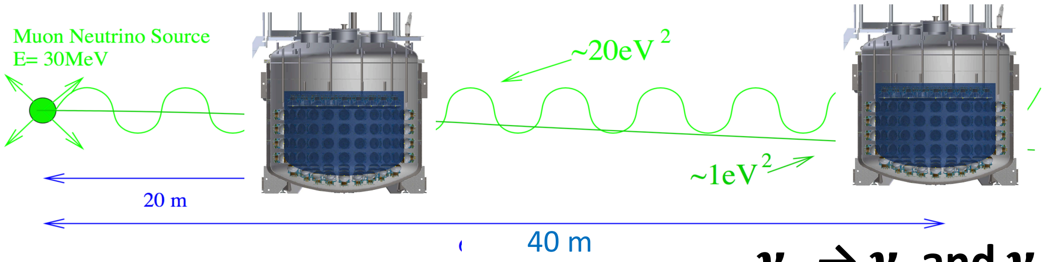
Plots from Patrick DeNiverville (LANL)

Energy cut removes prompt neutrinos.
DM produced in time with beam (prompt), and more energetic than CEvNS.

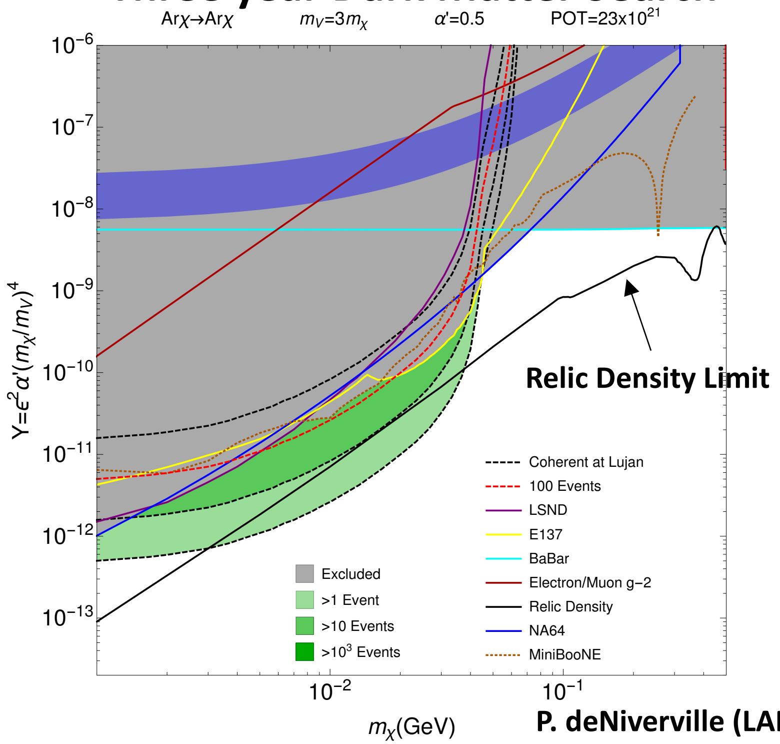
With Two CCM Detectors, Twice as Much Physics!

Near for sensitive Dark Matter search.

Near/Far rate comparison and error cancellation for improved/sensitive sterile neutrino search.

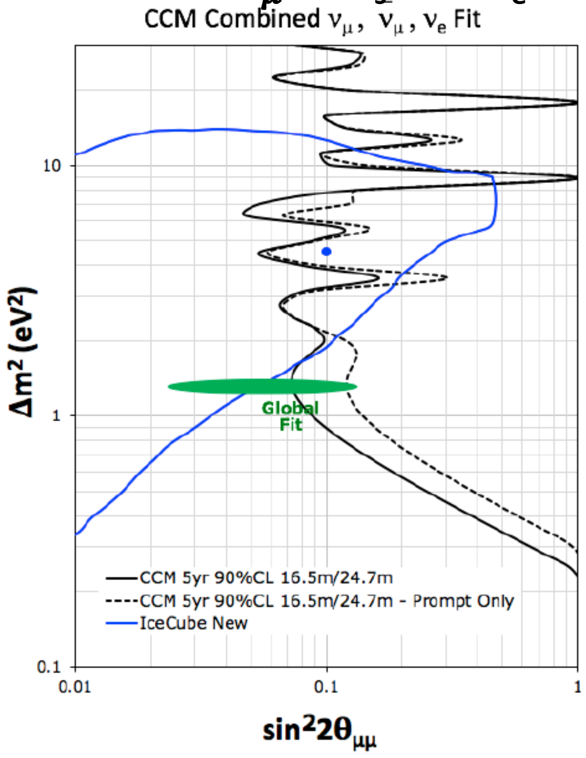


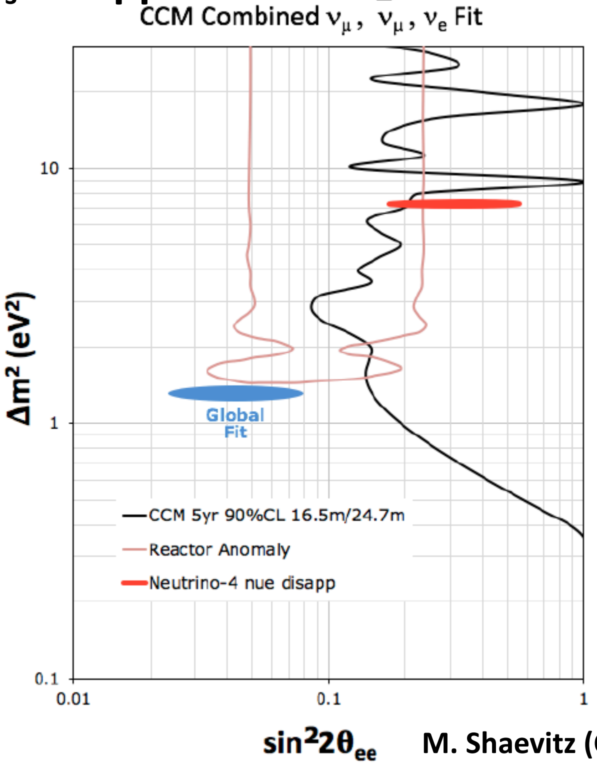
Three year Dark Matter Search



P. deNiverville (LANL)

$\nu_\mu \rightarrow \nu_s$ and $\nu_e \rightarrow \nu_s$ Disappearance





M. Shaevitz (Columbia)

- **Reduce PSR timing will significantly increase S/B ensuring we reach physics goals!**
- **Testing techniques for future higher power PIP-II stopped pion source - Snowmass LOI "O(1 GeV) Fixed-Target New Physics Searches at Fermilab"**

LANSCE-PSR Technical Requirements/Plan – Staged approach

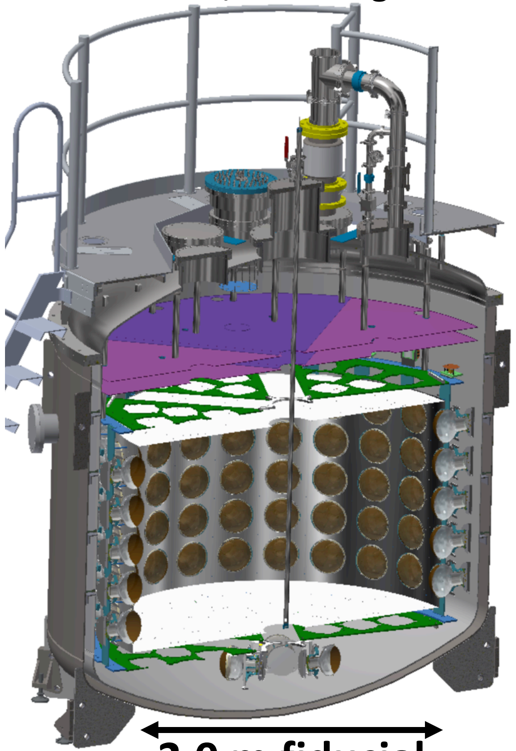
- Present beam spill time width -> 300 ns with intensity of 2.9×10^{13} protons per pulse at 20 Hz.
- **Goal**: Upgrades to the PSR, the beam spill width could possibly be compressed to 100 ns and possibly 30 ns with minimal intensity loss enabling an S/B increase of more than 100 and resulting sensitivity increase of an order of magnitude for dark matter and sterile neutrino searches.

Test or Upgrade	Timeline	Cost (ROM)	Results
Simulations	M 1-3	100k	
Experiments to feed into a machine model (parameter scans)	M 1-4	200k	
NN-based machine model for rapid simulation and on-line control	M 1-5	250k	
Repeat and improve upon active damping experiments through the implementation of digital vertical feedback system and through the implementation of heated ferrites.	M 3-8	500k	- Attempt 100-ns goal (test, not continuous) - Attempt less than 100 ns (test, not continuous)
Replace ferrites with novel magnetic materials and repeat studies, update machine model.	M 8-13	1M	- Reach 100-ns goal (sustained) - Attempt less than 100 ns (test, not continuous) - Updated machine model
Based on experimental results and modeling, design and implement a new active transverse feedback system in both the vertical and horizontal plane to control the (e-p) instability which incorporates the machine model	M 11-20	2.6M	- Reach 100-ns goal (sustained) - Attempt less than 100 ns (test, not continuous)
Studies to attempt 30 ns	M 20-22	300k	- Attempt 30 ns (test, not continuous) at lower charge
Make necessary additional upgrades	M 20-28	~2M	- Attempt 30 ns
Total	28 Months	6.95 M	

Backups: The Neutrino Scatters Here!

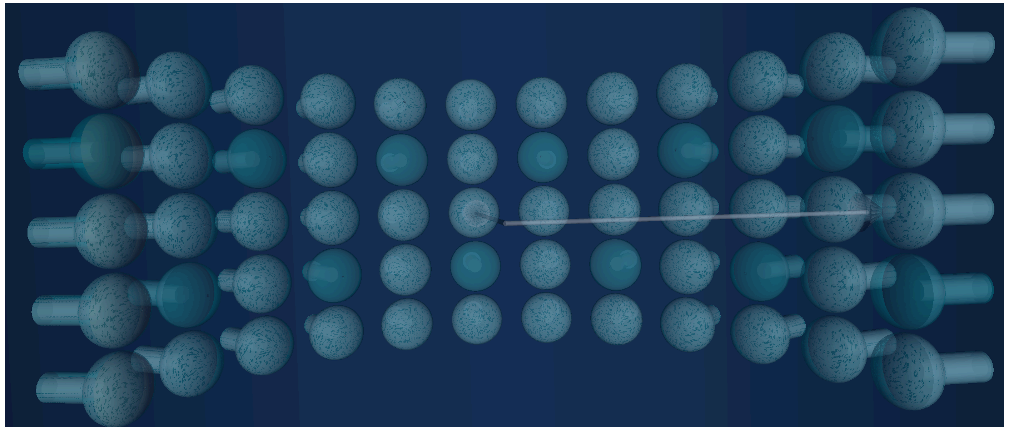
Detecting Coherent Neutrinos:
Maximizing Scintillation Light Detection!

- **120 R5912 PMT's, wavelength shifting TPB foils**



2.0 m fiducial

RAT/GEANT Detector Simulation



Simulations predict ~0.5 PE/keVnr

- **Liquid Argon scintillates at 128 nm with 40,000 photon/MeV, or 40 photons/keV.**
  - fast 6 nsec and slower ~1.6 usec time constants.
  - TPB wavelength shifting coating on PMT's and foils to convert photons to visible light.
- Detailed RAT/GEANT4 simulation predicts 10-20 keV detection threshold, ran extensive calibrations to determine energy scale.
- 7 tons LAr Fiducial volume, 3 tons LAr instrumented Veto (2-3 radiation lengths)