

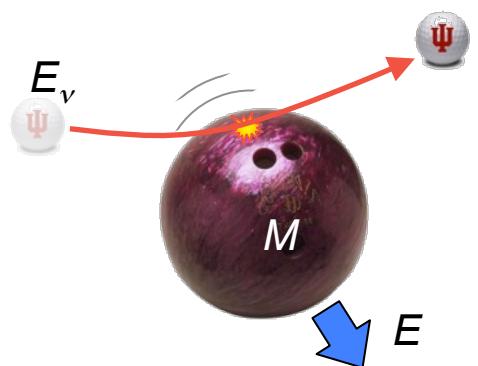
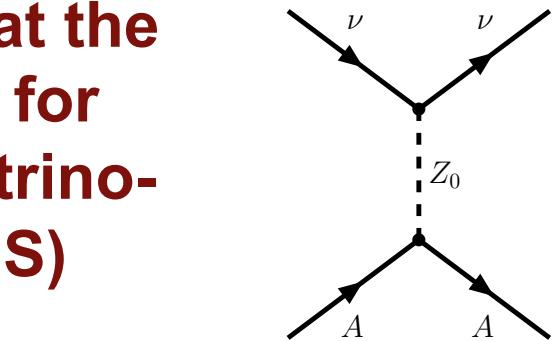
Fast Neutron Measurements at the Booster Neutrino Beamline for Future Coherent Elastic Neutrino- Nucleus Scattering (CENNS) Experiment at Fermilab

- To probe a “large” nucleus ($\text{few} \times 10^{-15} \text{ m}$)

$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

- Recoiling nucleus is detection signature

$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50 \text{ keV}$$



PHYSICAL REVIEW D

VOLUME 9, NUMBER 5

1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman[†]

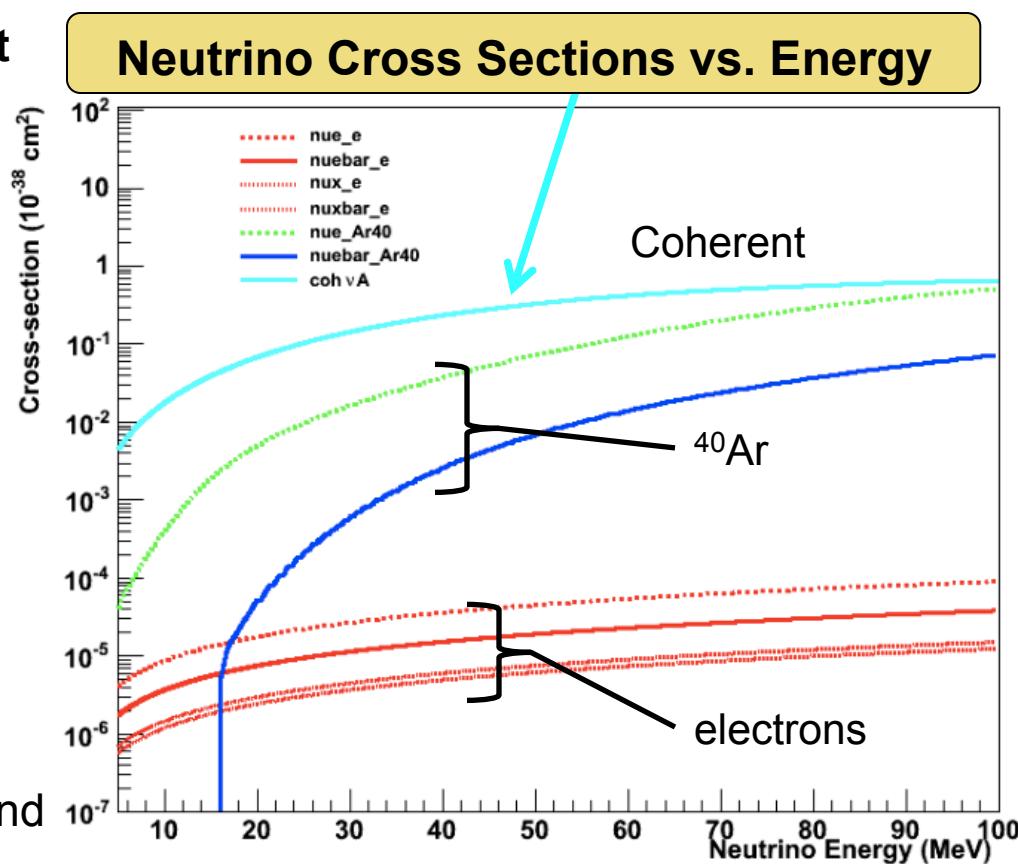
National Accelerator Laboratory, Batavia, Illinois 60510

and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

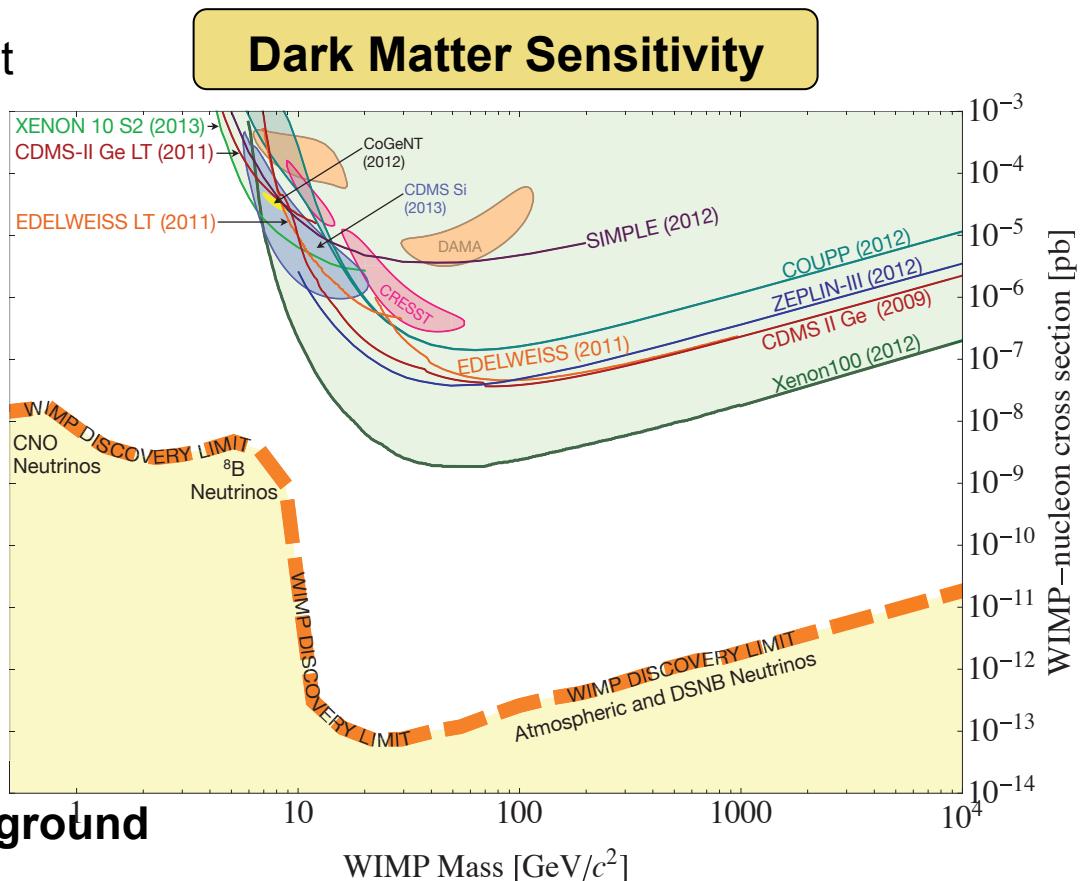
Motivations for CENNS

- Never seen – despite dominant cross section
- Non-standard interactions
- Supernova neutrinos
- Form factors
- SM tests: measure $\sin^2\theta_W$
- Reactor monitoring
- Irreducible dark matter background



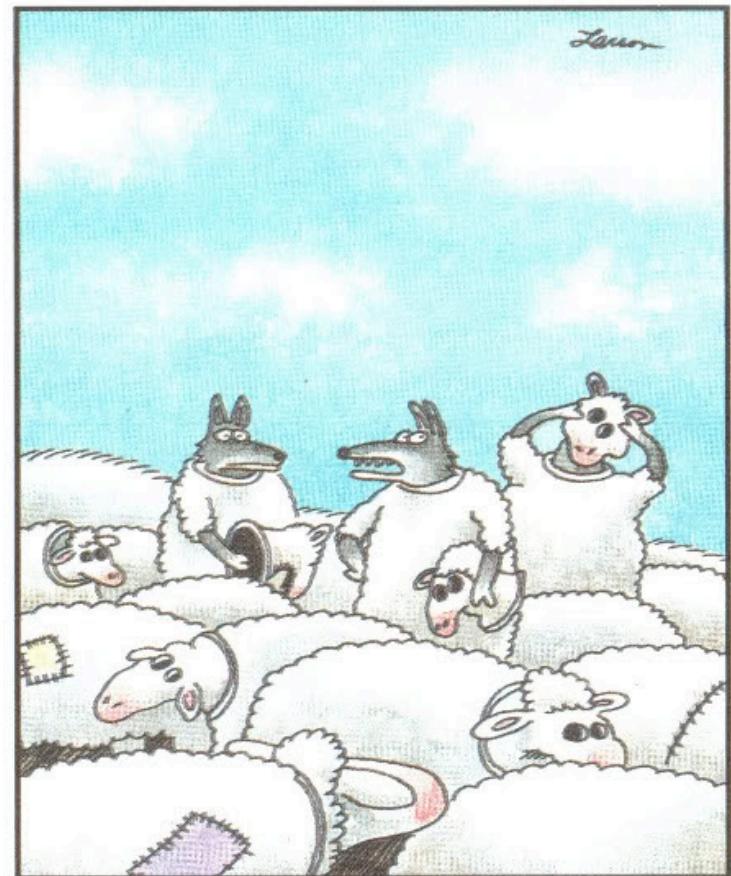
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3 Essential Ingredients for CENNS

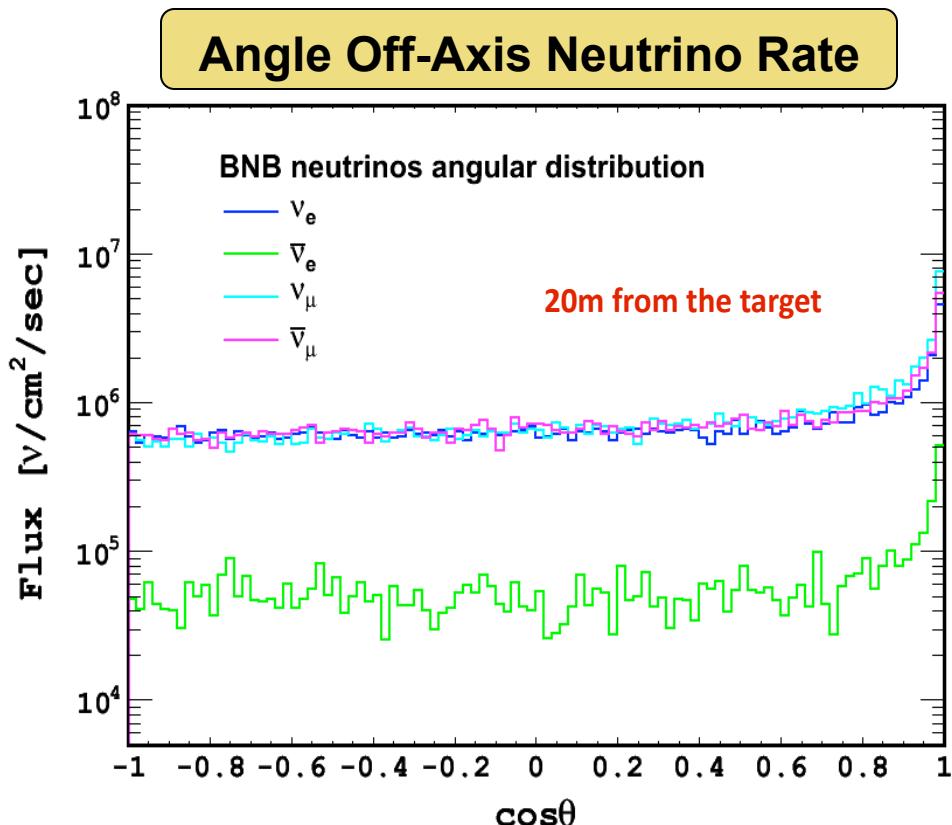
- Produce low-energy neutrinos
- Detect low-energy neutrinos
- Reject backgrounds that resemble neutrinos



"Wait a minute! Isn't anyone here a real sheep?"

A New Alternative Approach at FNAL

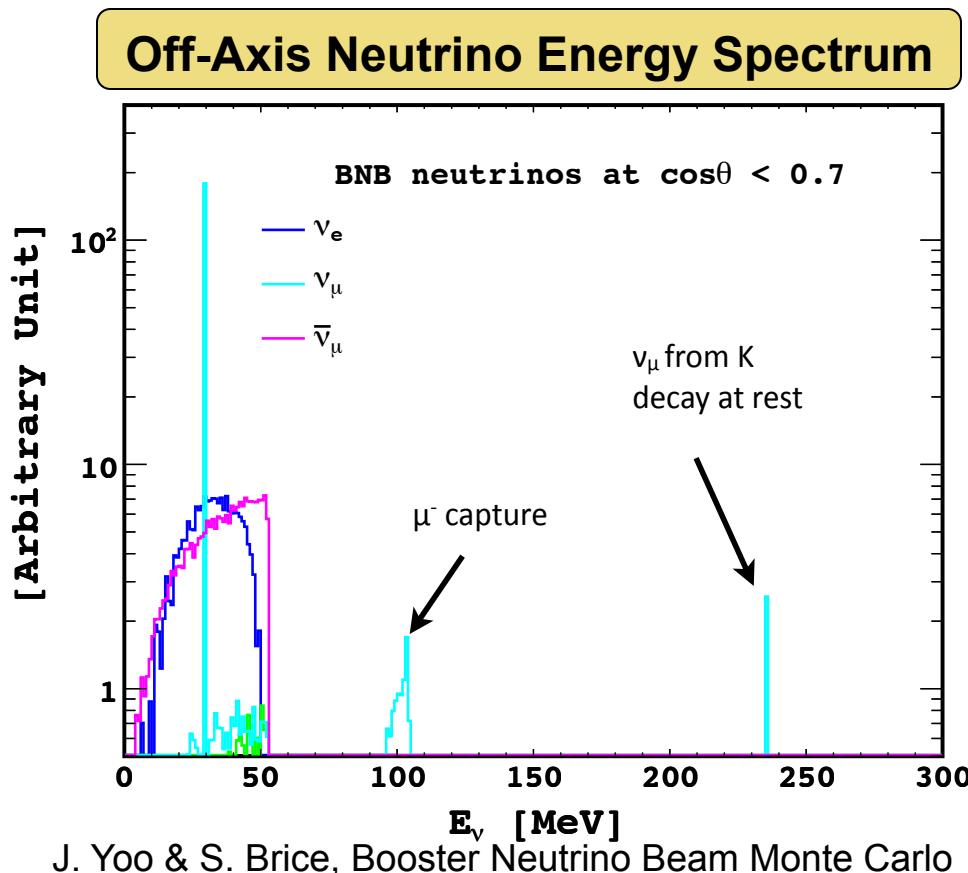
- Booster Neutrino Beam at FNAL is a pion decay in-flight source (8 GeV p^+)
- On-axis multi-GeV neutrinos – not useful for CENNS
- **BUT** far off-axis spectrum is much “softer” – usable!
- BNB flux at 20 m, $\cos \theta < 0.5$
 $\Phi^{\text{BNB}} = 5 \times 10^5 \text{ s}^{-1} \text{ cm}^{-2}$



J. Yoo & S. Brice, Booster Neutrino Beam Monte Carlo

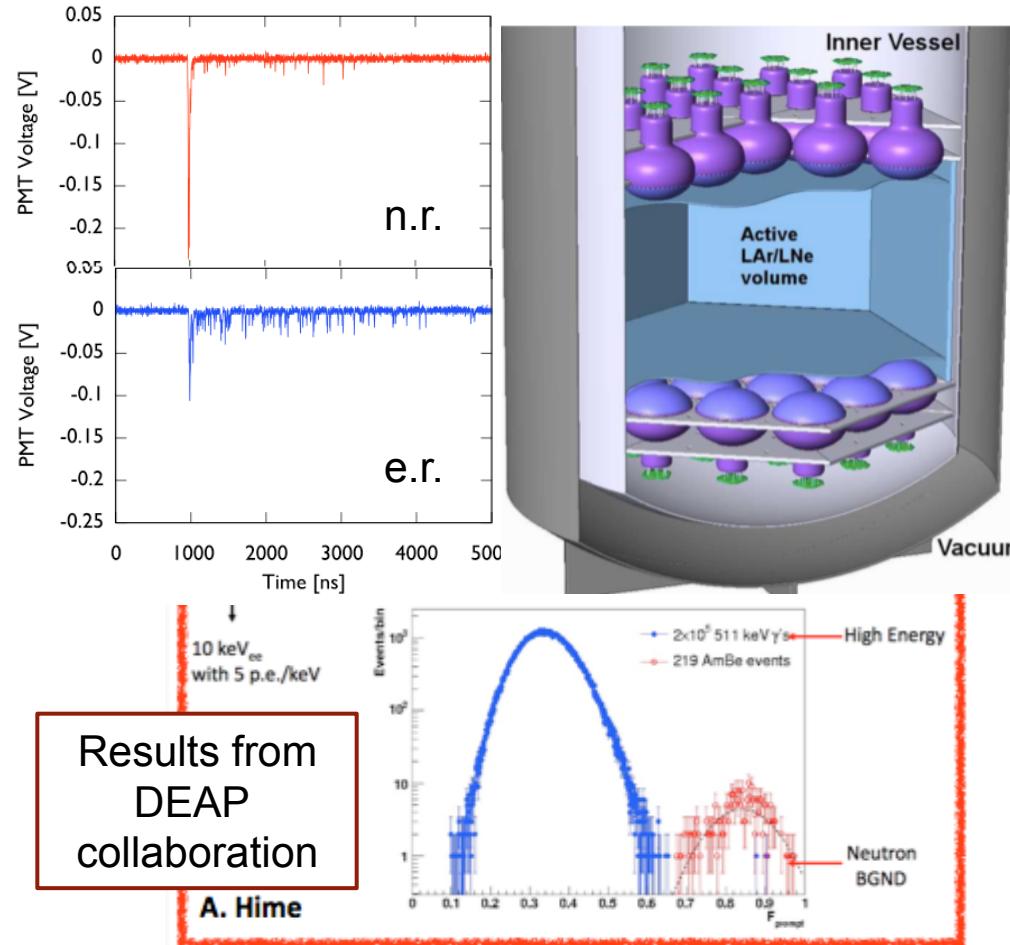
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Detection of Coherent Scattering

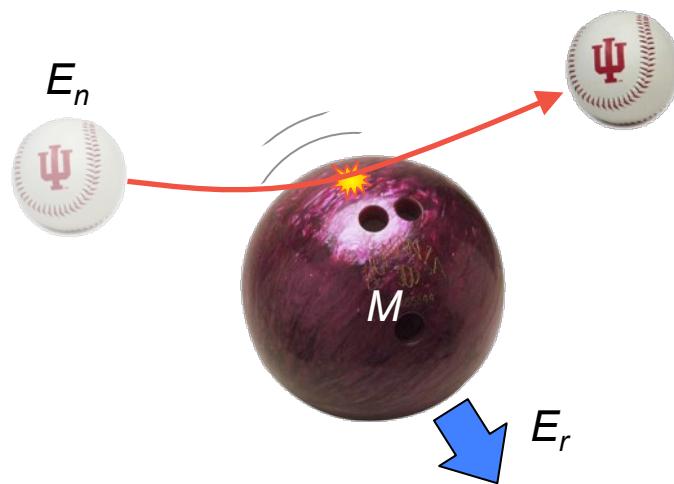
- Detection in general: pick a dark matter technology
- Our proposal: 1-ton, single-phase liquid Argon (LAr)
- Use copious LAr VUV scintillation for readout
- $200 \text{ events ton}^{-1} \text{ year}^{-1}$
(30 keV threshold, 32 kW)



Typical Sources of Uncertainty

- Duty factor ($\sim 10^{-5}$) give total exposure ~ 300 s / year
 \rightarrow cosmic background small
- Neutrino flux uncertainty
 $\sim 5\text{-}10\%$ \rightarrow improvements?
- Quenching & scintillation efficiency L_{eff} uncertainties
- Beam-correlated neutrons mimic neutrino signal

Neutron Scatter on ${}^{40}\text{Ar}$

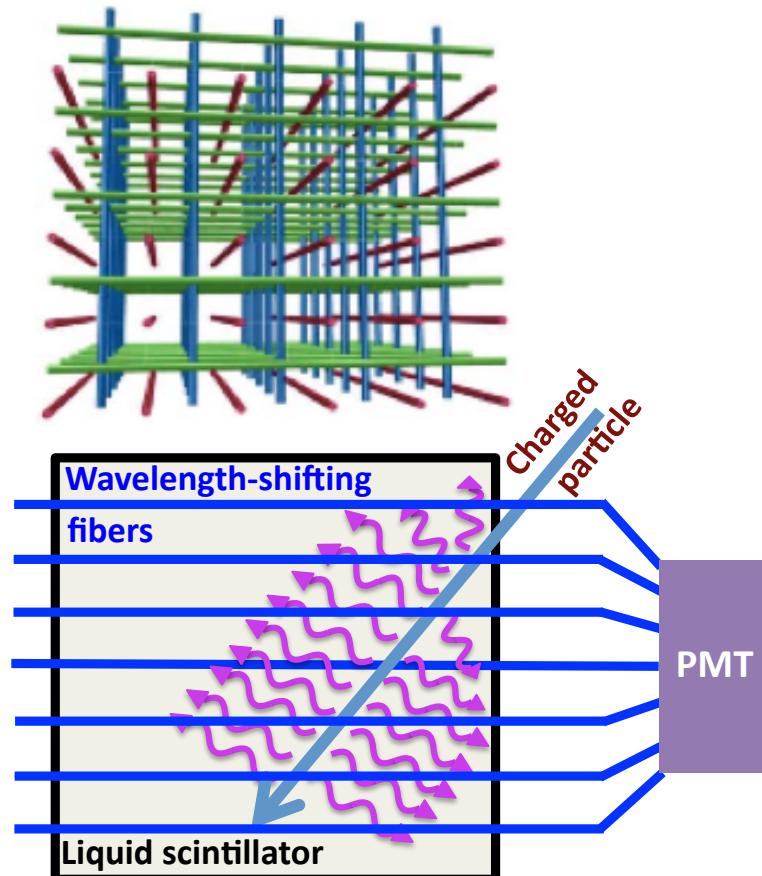


$$E_r^{\max} = \frac{4\mathcal{M}}{(\mathcal{M} + 1)^2} E_n \simeq 0.1 E_n$$

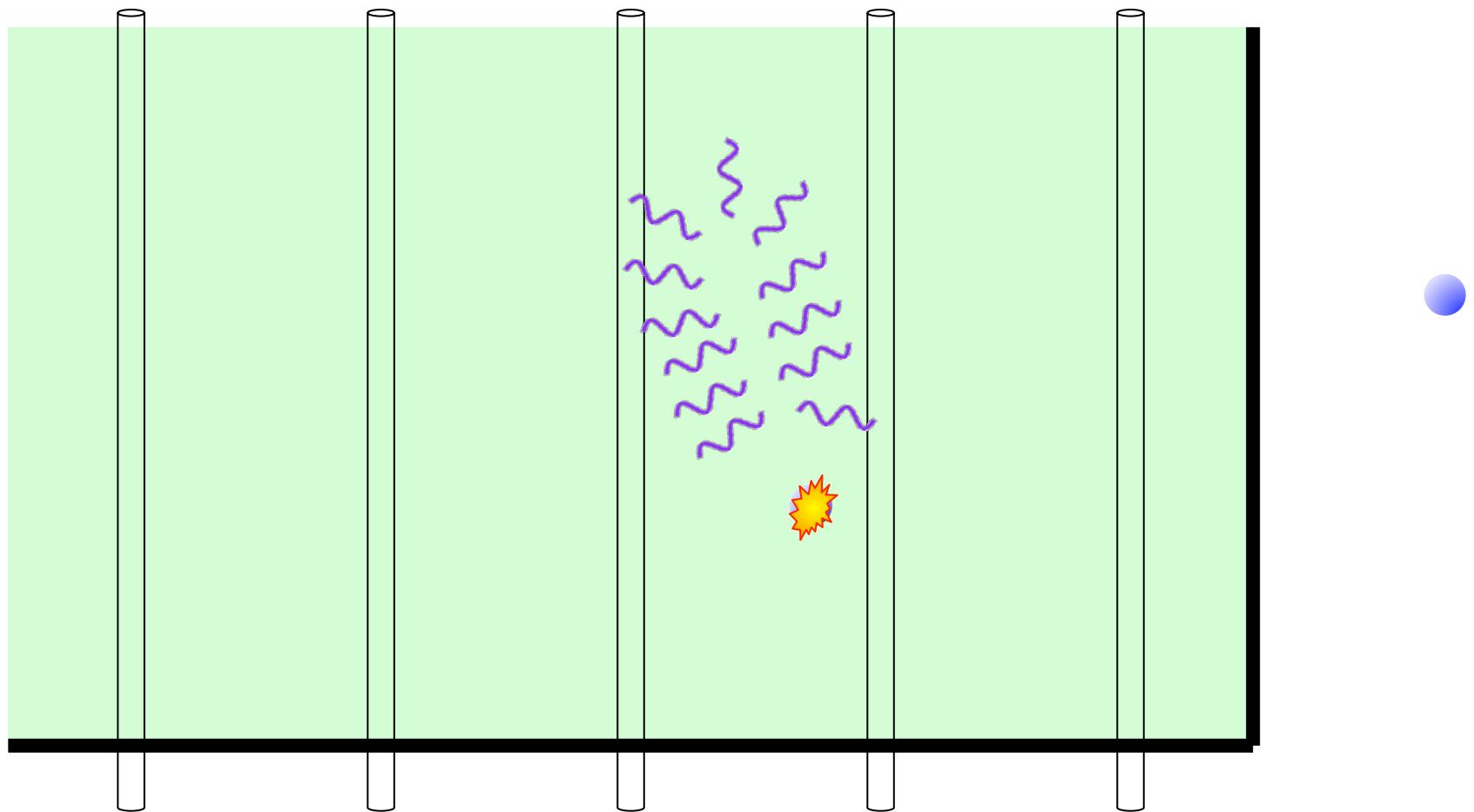
where $\mathcal{M} = M/m_n$

SciBath Detector

- 80 L open volume of mineral oil based liquid scintillator
- Neutrons recoil off protons, create scintillation
- 768 wavelength shifting fibers readout
- IU built custom digitizer: 12 bit, 20 MS / s

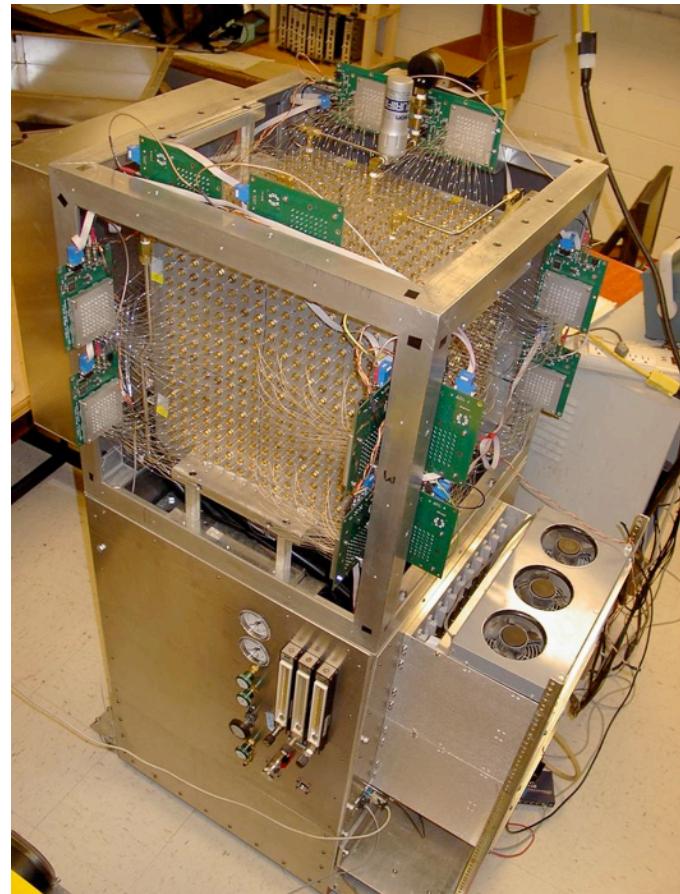


SciBath Principle of Operation



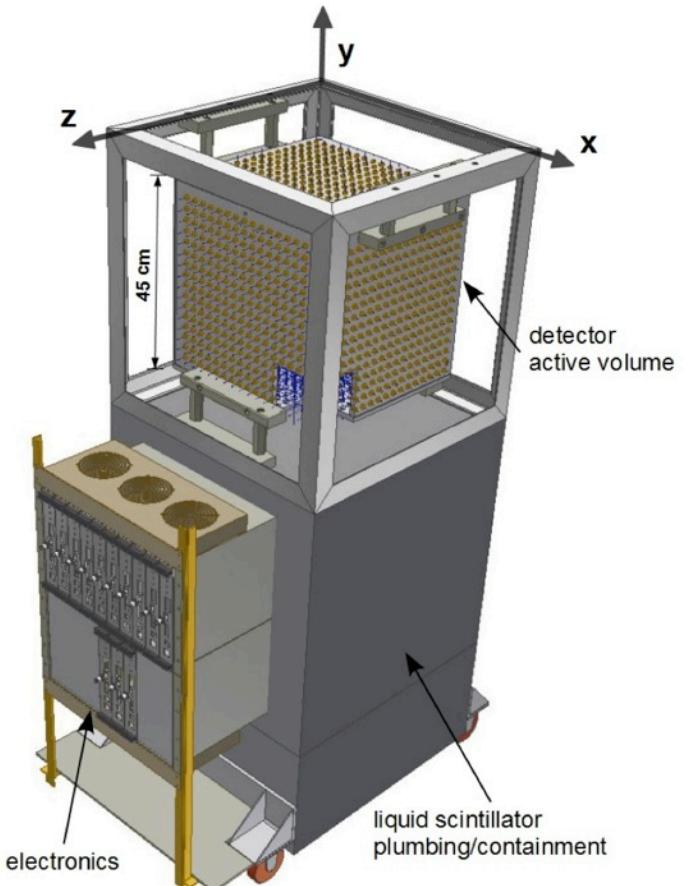
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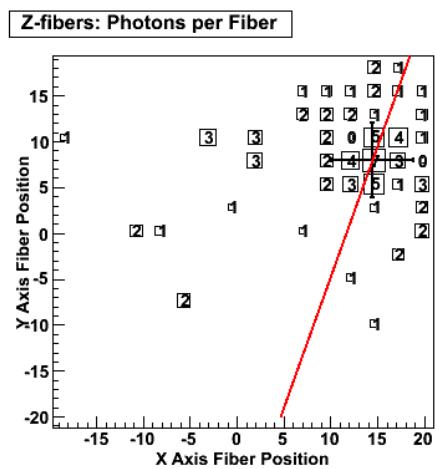
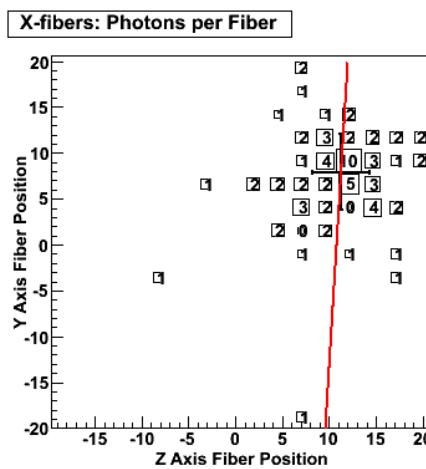
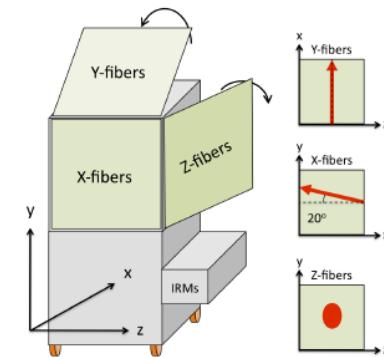
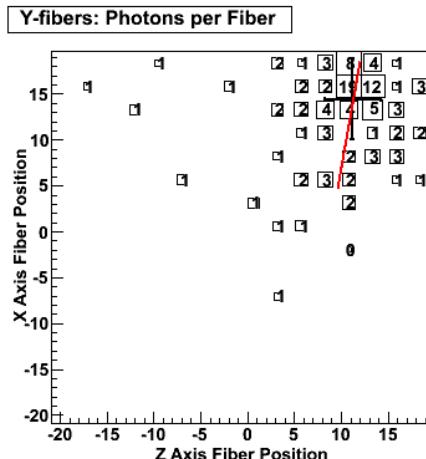


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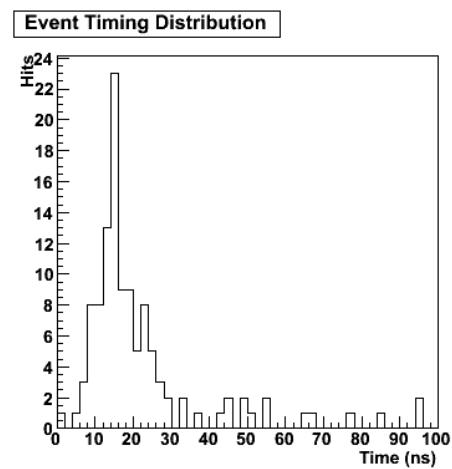
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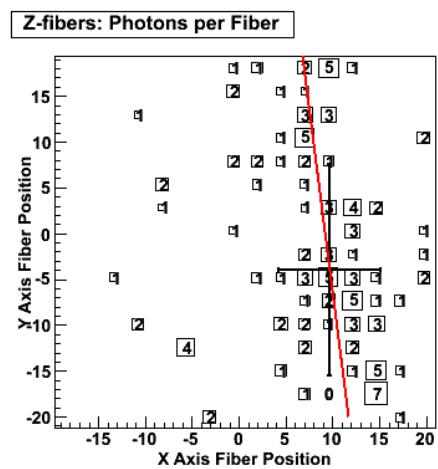
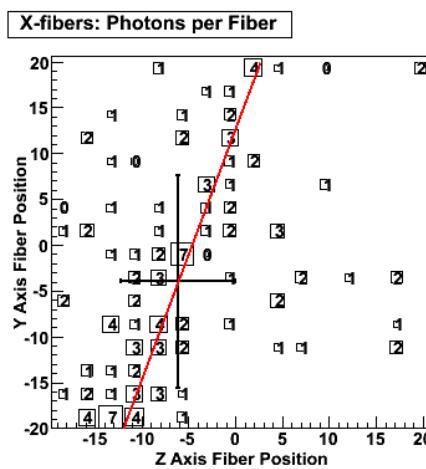
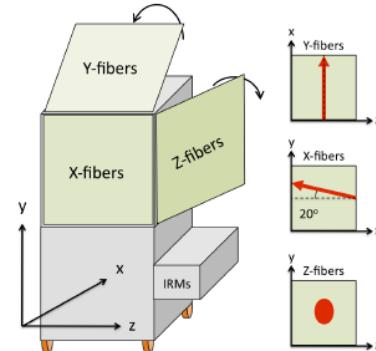
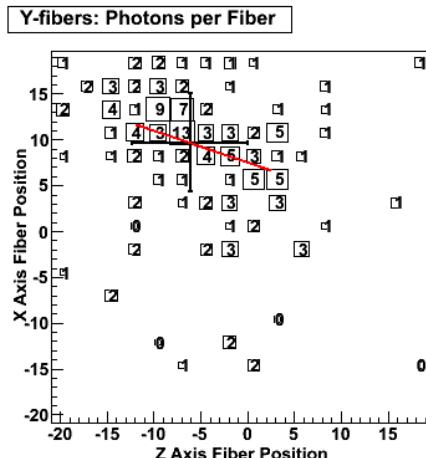
Sample Neutron Candidate Event



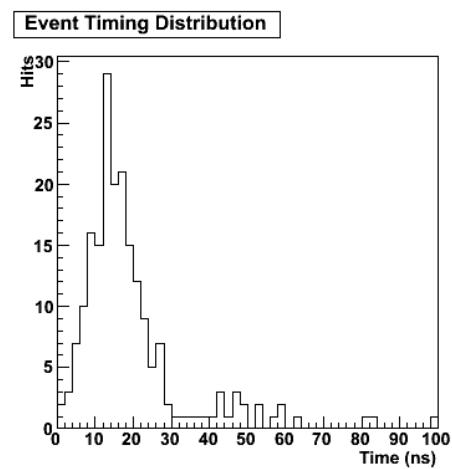
Event Num: 10642 (95796)
 Multiplicity: 124
 Total PEs: 283.0
 PEs -- X: 80.8 Y: 115.8 Z: 86.4
 PEs^2 -- X: 282.5 Y: 784.6 Z: 252.9
 T0: 92.284587701 s
 Time to last BIB: 0.0001213 s
 $\bar{x} = 14.4 \pm 4.4$ cm -- skew = -2.92 -- kurt = 13.34
 $\bar{y} = 7.9 \pm 4.1$ cm -- skew = -1.55 -- kurt = 10.71
 $\bar{z} = 11.3 \pm 3.0$ cm -- skew = -2.21 -- kurt = 17.16
 $\bar{t} = 30.6 \pm 43.4$ s -- skew = 5.84 -- kurt = 45.41
 EigenVals: 71.20, 30.03, 14.64
 EigenVect 1: $-0.03\hat{x} + -0.05\hat{y} + 1.00\hat{z}$
 EigenVect 2: $-0.94\hat{x} + 0.33\hat{y} + -0.01\hat{z}$
 EigenVect 3: $0.33\hat{x} + 0.94\hat{y} + 0.06\hat{z}$
 Point χ^2 : 683.47 Track χ^2 : 1541.23
 $\bar{d} = 12.9 \pm 3.2$ cm -- skew = -5.15 -- kurt = 63.69
 Track length, ellipsoid: 29.43, rod: 24.65
 Spherical radius: 9.83 Eigenvector length: 42.42



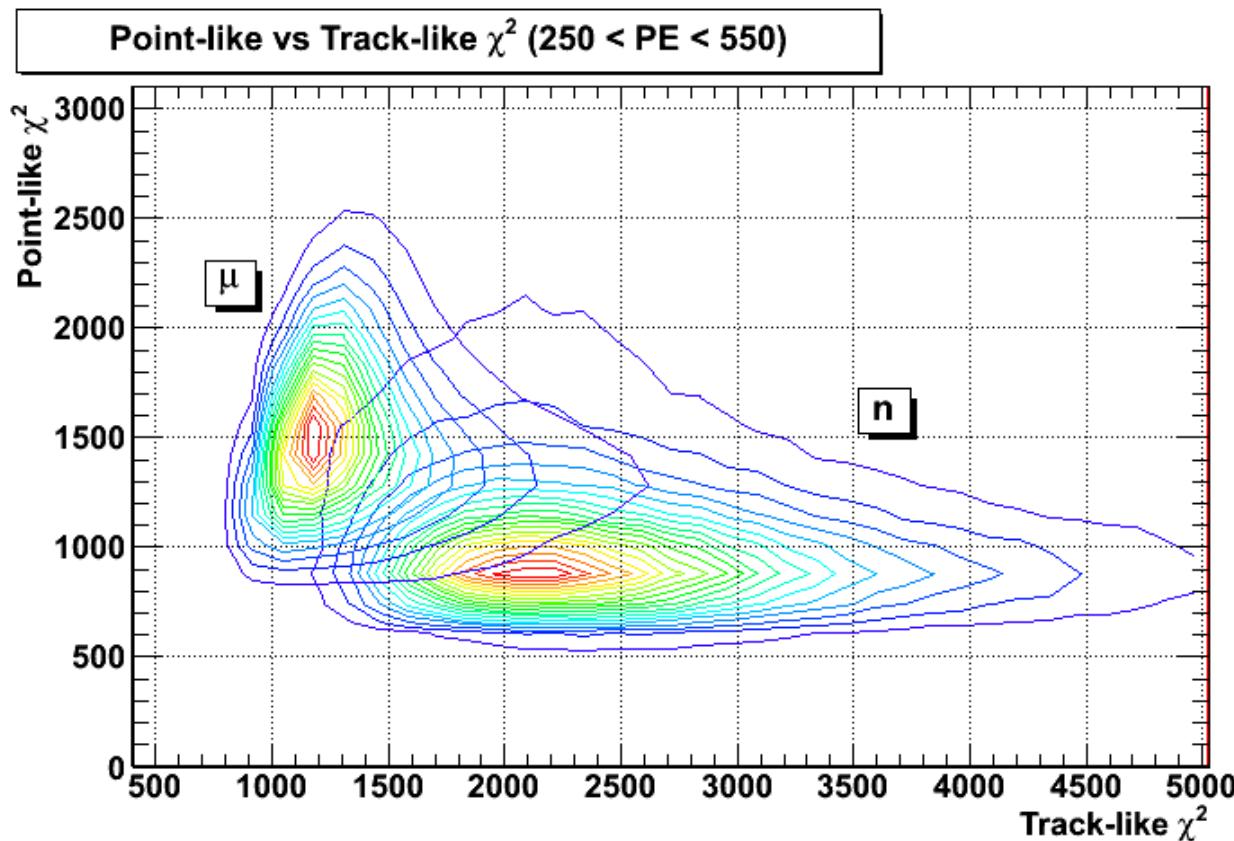
Sample Muon Candidate Event



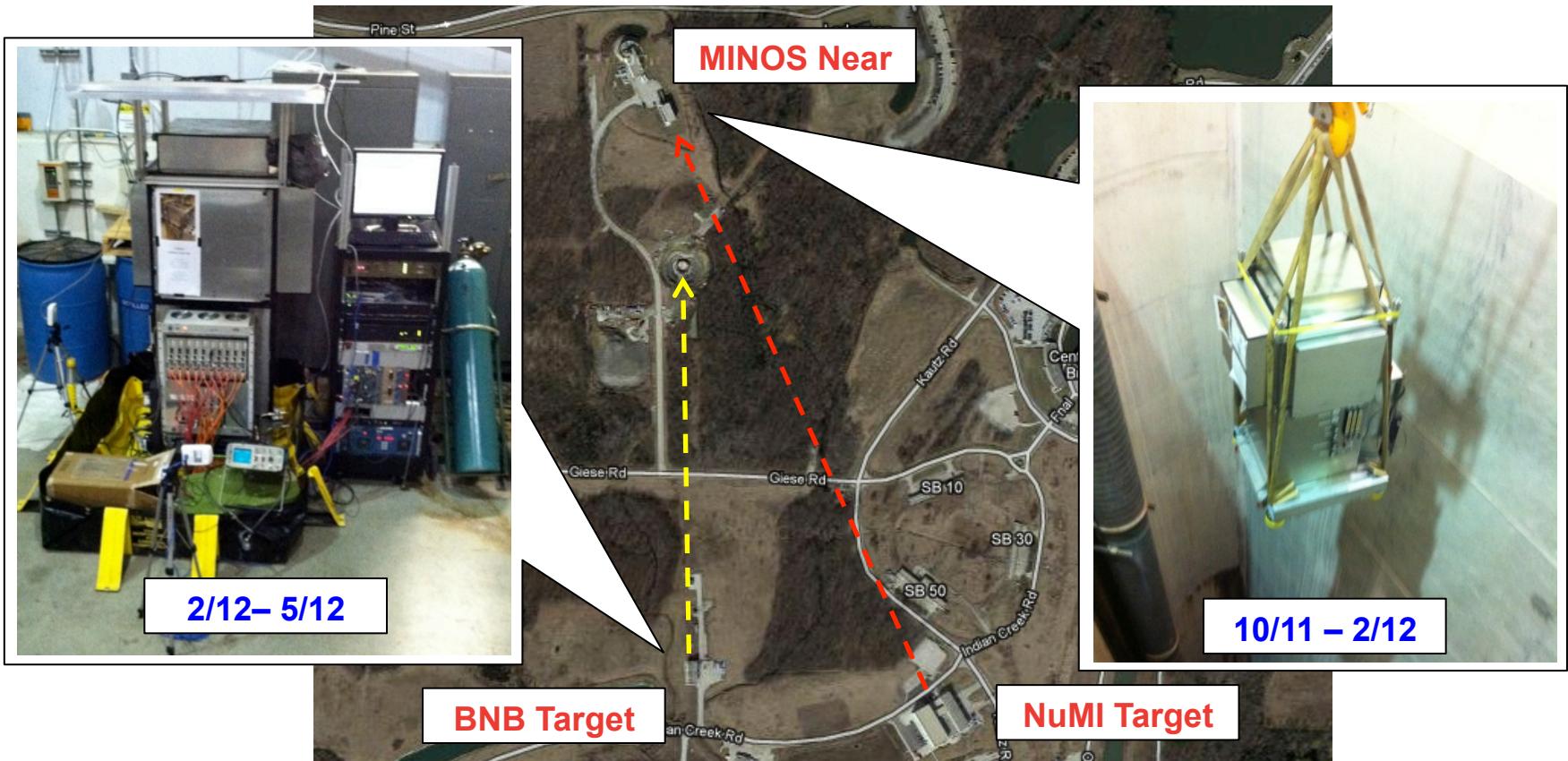
Event Num: 109 (1206)
Multiplicity: 204
Total PEs: 412.6
PEs -- X: 126.0 Y: 158.1 Z: 128.5
PEs² -- X: 337.9 Y: 668.8 Z: 360.9
T0: 3.272227153 s
Time to last BIB: 0.0009486 s
 $\bar{x} = 9.7 \pm 5.4$ cm -- skew = -1.64 -- kurt = 6.62
 $\bar{y} = -4.0 \pm 11.6$ cm -- skew = 0.47 -- kurt = 2.14
 $\bar{z} = -6.1 \pm 6.1$ cm -- skew = 0.90 -- kurt = 4.70
 $\bar{t} = 24.7 \pm 36.9$ s -- skew = 6.92 -- kurt = 60.43
EigenVals: 196.01, 183.20, 34.72
EigenVect 1: $0.65\hat{x} + -0.19\hat{y} + 0.74\hat{z}$
EigenVect 2: $-0.75\hat{x} + -0.31\hat{y} + 0.58\hat{z}$
EigenVect 3: $0.12\hat{x} + -0.93\hat{y} + -0.34\hat{z}$
Point χ^2 : 1502.27 Track χ^2 : 1496.78
 $\bar{d} = 6.9 \pm 12.7$ cm -- skew = -0.41 -- kurt = 2.00
Track length, ellipsoid: 58.69 , rod: 47.70
Spherical radius: 18.57 Eigenvector length: 42.86



n / μ Particle Discrimination

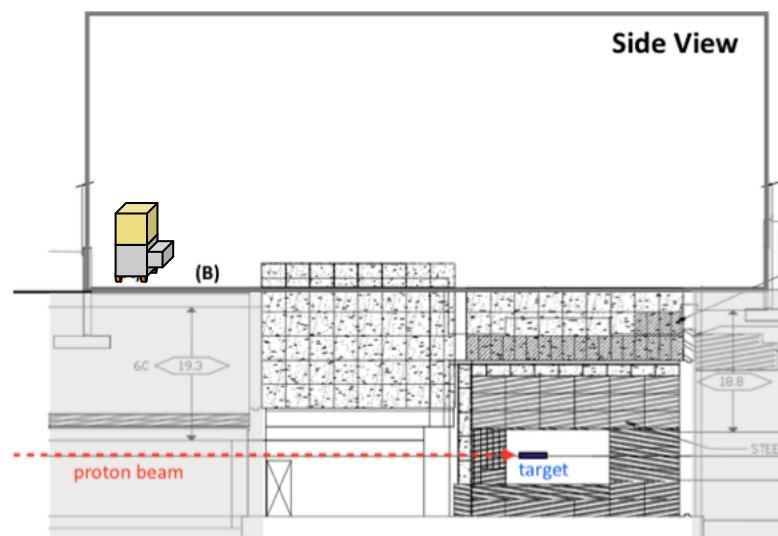
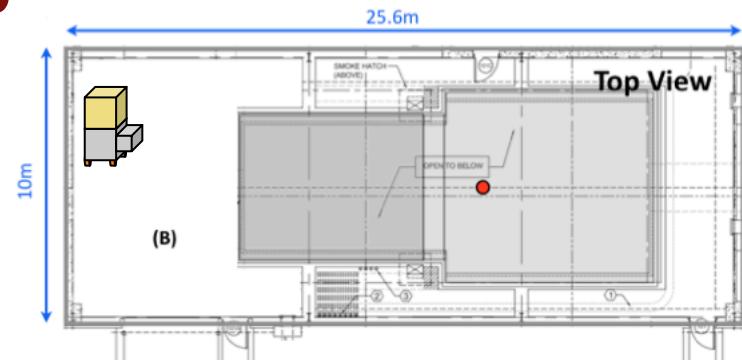


Fermilab Measurement Sites



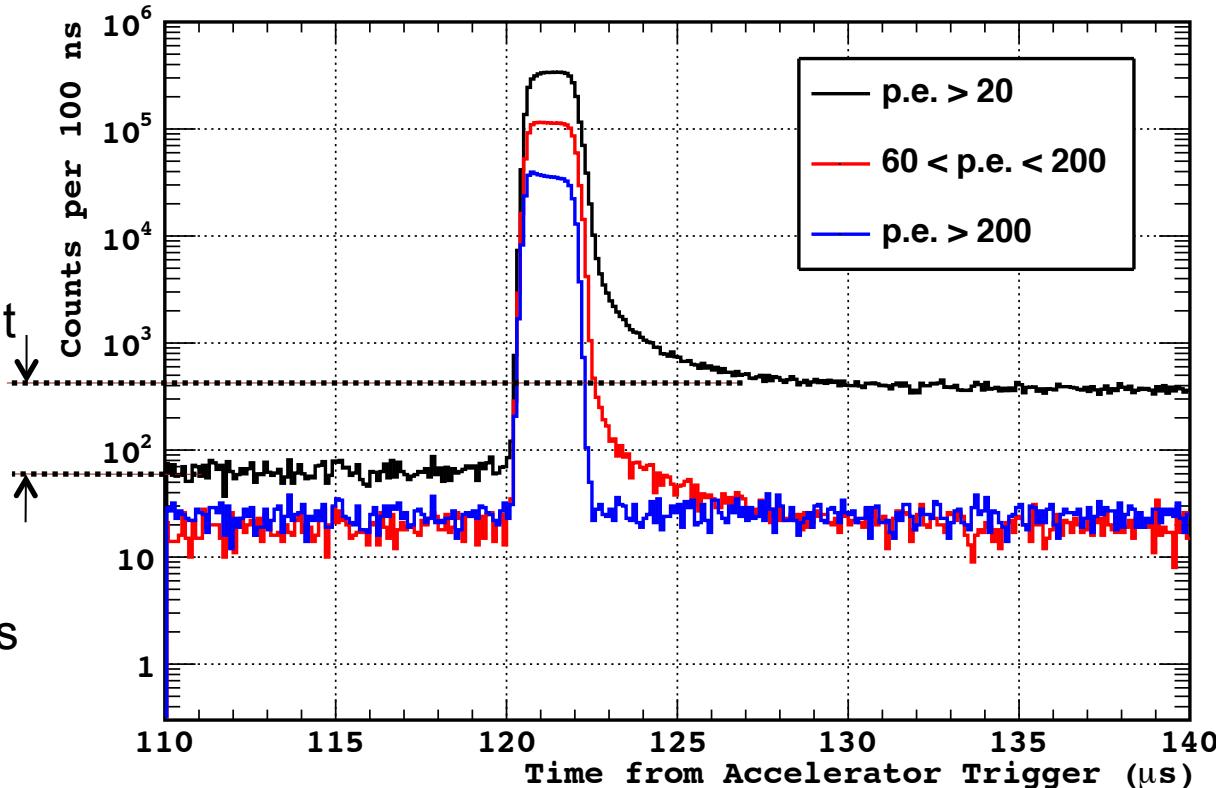
MI-12 Neutron Background Run

- Neutron flux ~20 m from target
- In-line behind beam target (ground)
- 29 Feb. – 23 Apr.
- 4.9×10^{19} total protons on target (POT)
(4.5×10^{12} per pulse)



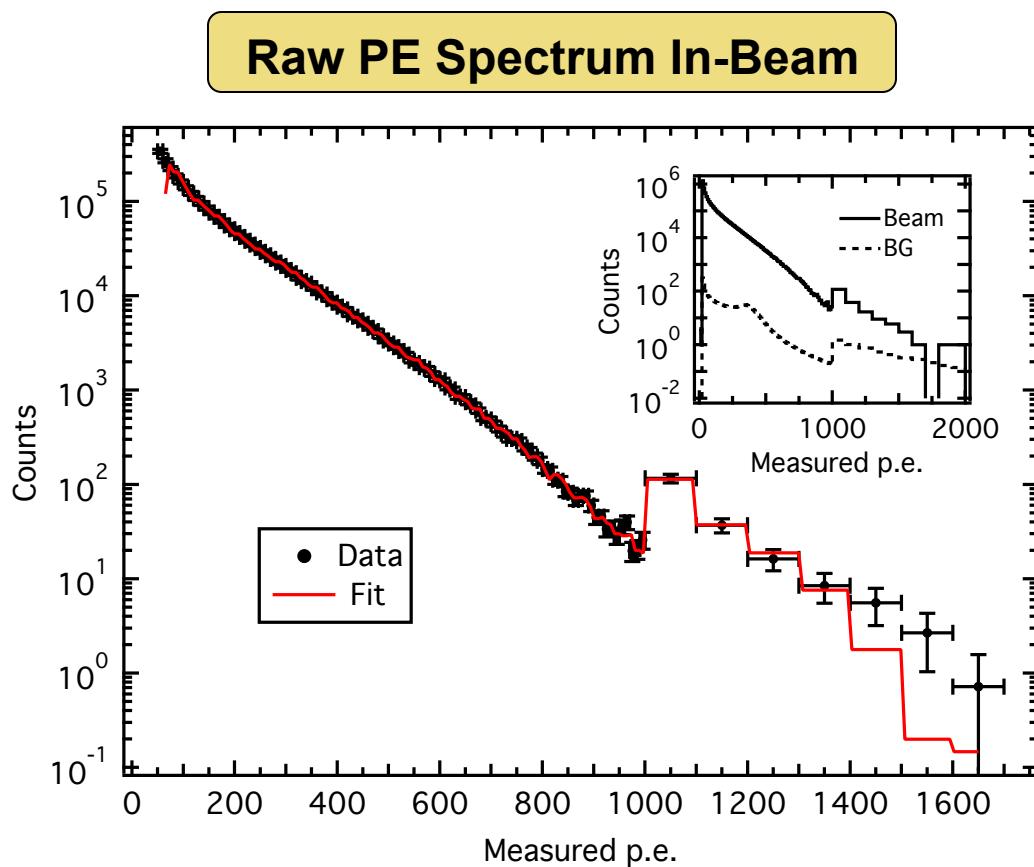
MI-12 Beam Time Per PE “Group”

- **HIGH PE** group (proxy for high energy) is consistent with beam time structure
- **MEDIUM PE** group has a few μs excess – consistent with slower neutrons and moderation in shield
- **LOWEST PE** group has significant excess – 200 μs lifetime from $n(p, d)\gamma$ neutron capture reaction



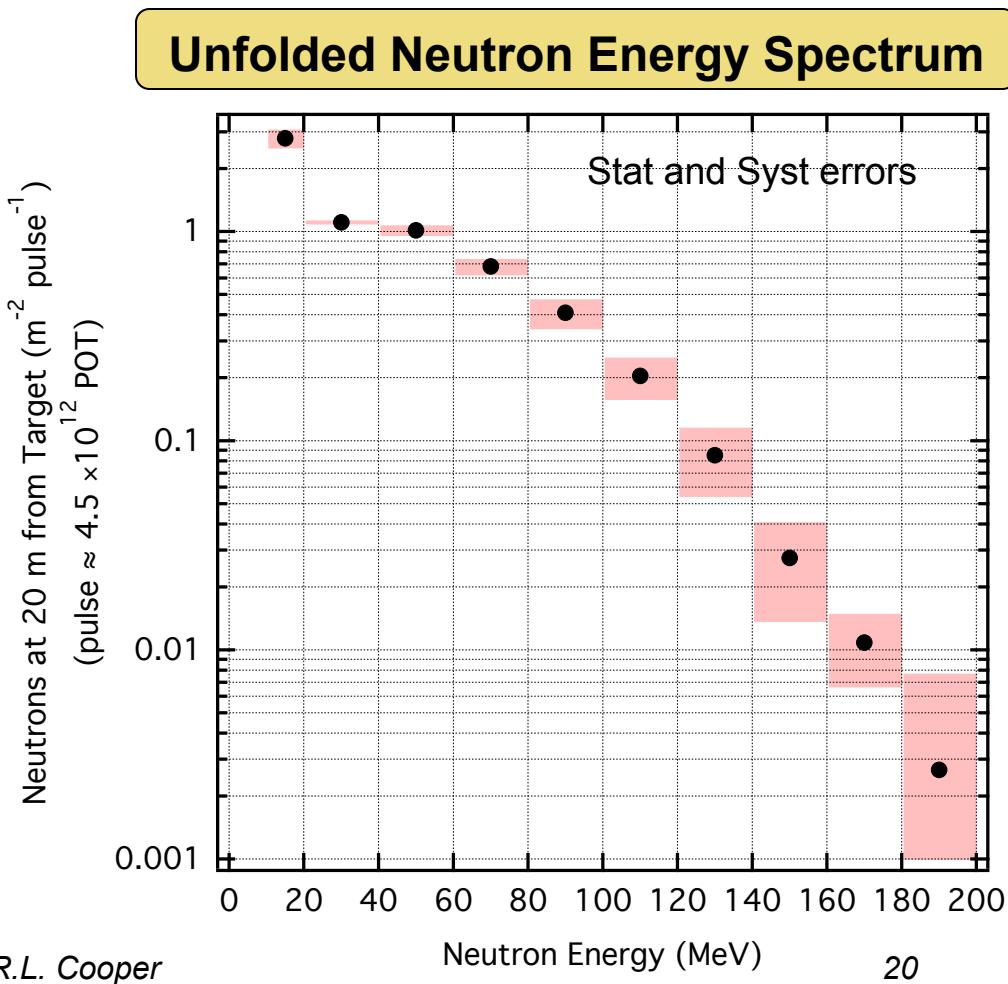
BNB Neutron Energy Spectrum

- E_n unfolded from PEs using fit and MC response function
- Soft threshold at 10 MeV
- $2.44 \pm 0.34 \text{ pulse}^{-1} \text{ m}^{-2}$
($E_n > 40 \text{ MeV}$)
- Fit loses sensitivity above 200 MeV; fit truncated
- Neutron spectrum 20 m from BNB



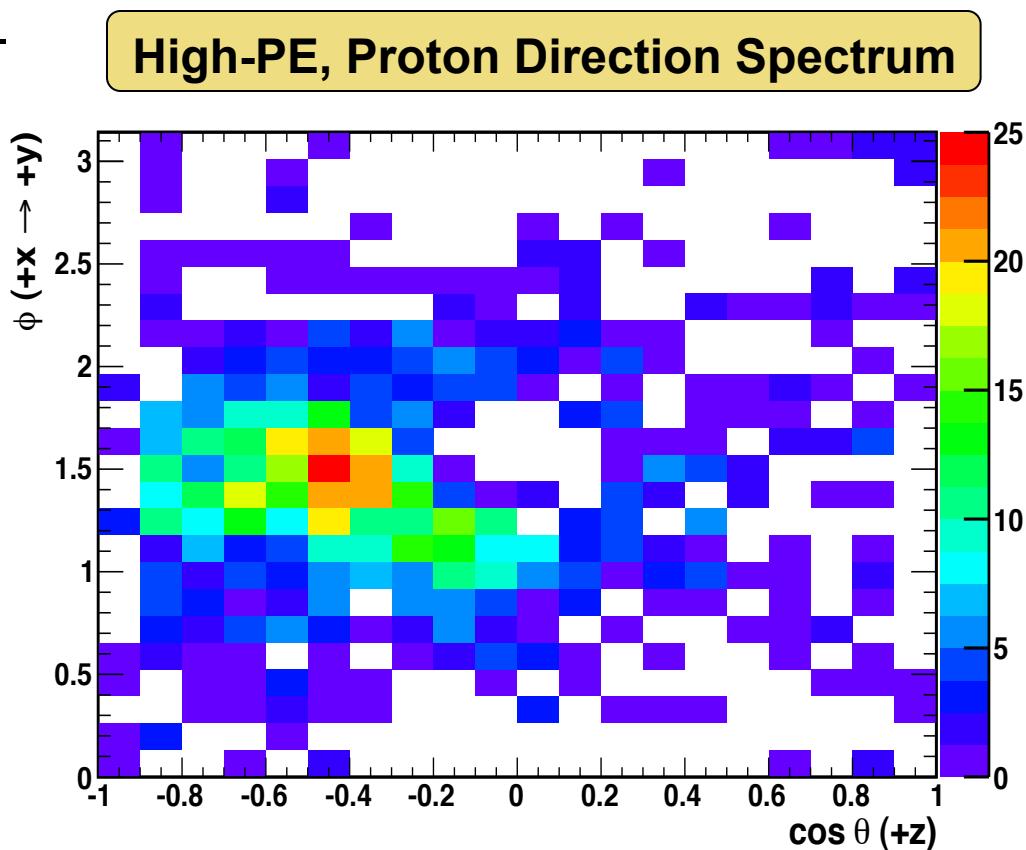
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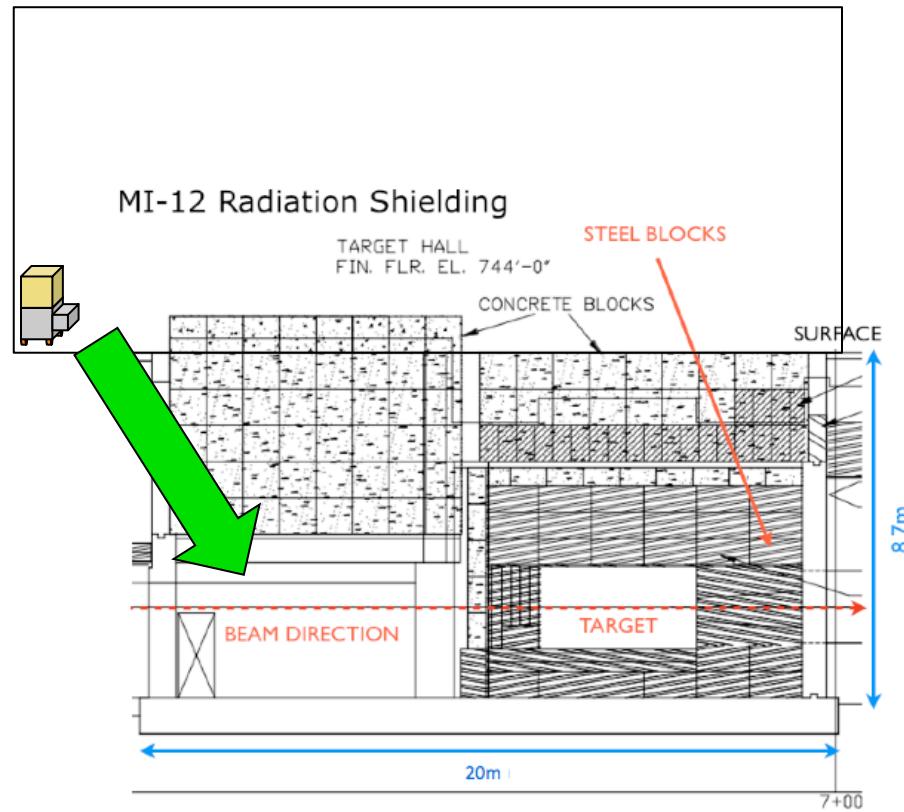
Direction Spectrum

- High PE protons will be track-like; can be imaged
- Principle component analysis yields eigenvector
- Back-projecting direction spectrum tends to point upstream of target ?!
- Tracking validated with cosmic rays and NuMI beam



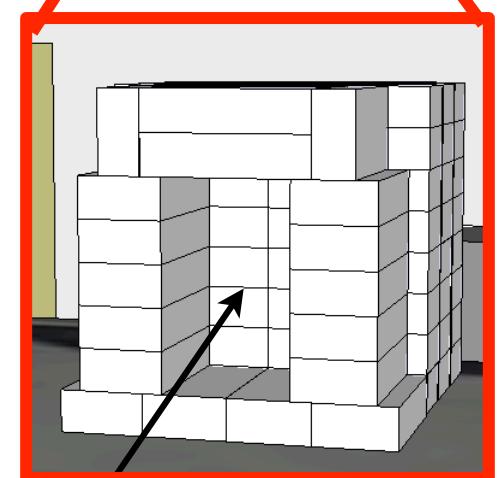
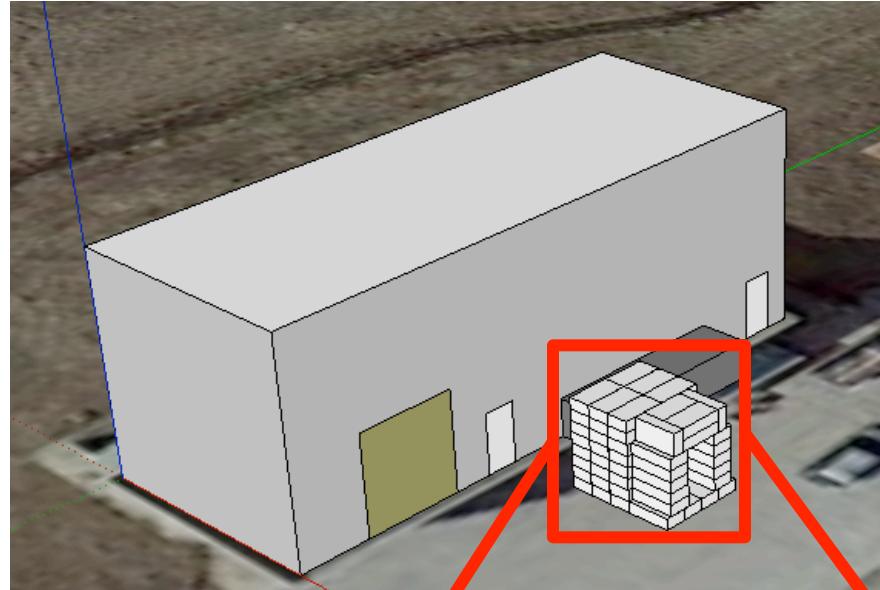
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Further Studies

- House the SciBath detector to test shield configuration
- Many standard concrete shielding blocks at FNAL
- Typical size (1.5' x 3' x 5')
- Return this Fall to measure more neutrons



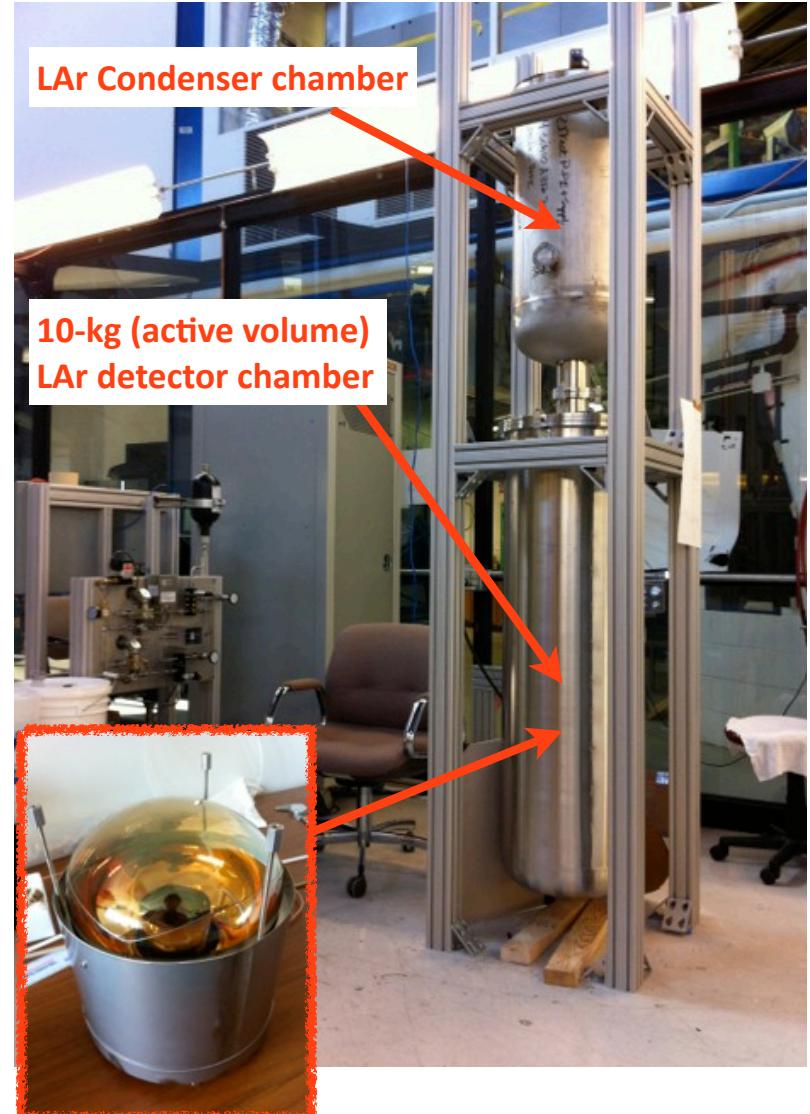
CENNS-10

Goals

- Neutron background study
- Demonstrate detector performance
- Light collection R&D (energy threshold study)

Status

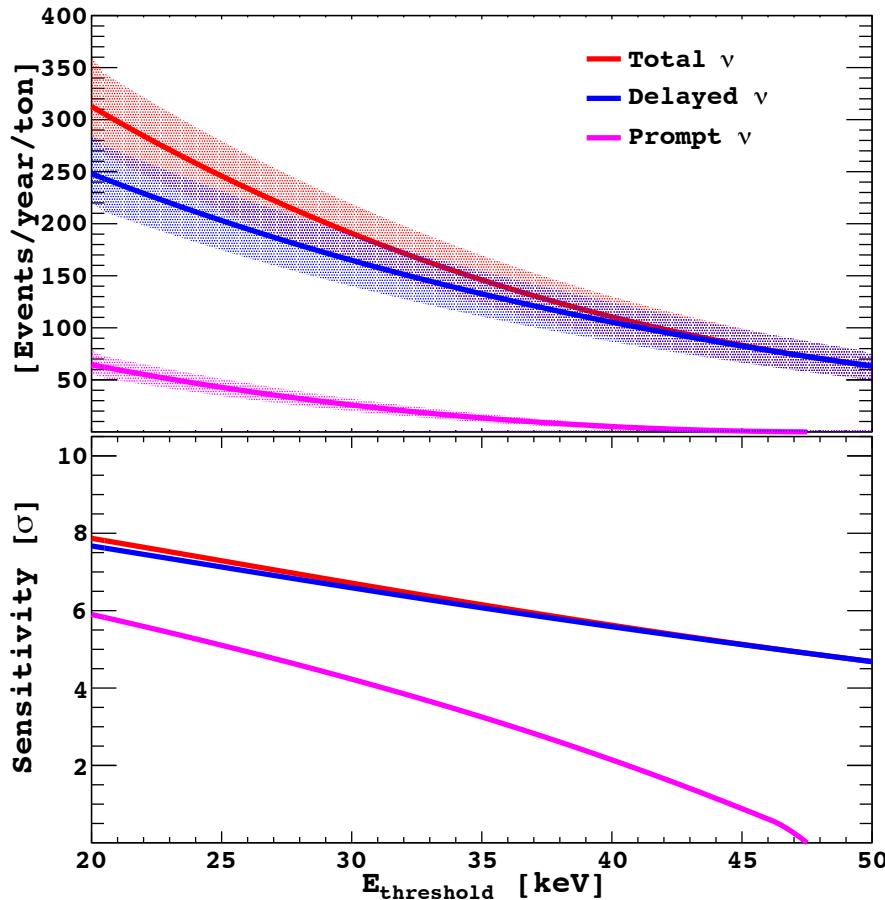
- Parts ordered (initial phase is 2× R5912-02MOD (8" PMT))
- Assembly nearly complete



Conclusions

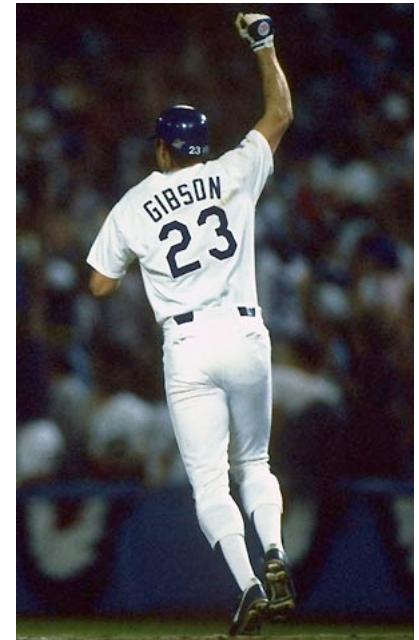
- Fermilab BNB with 1-ton LAr is proposed
- SciBath shows neutrons are manageable – will return this fall for more neutron measurements
- See our recent paper
Phys.Rev.D 89, 0072004
(2014)

Discovery Potential vs. detector threshold (nominal BNB)





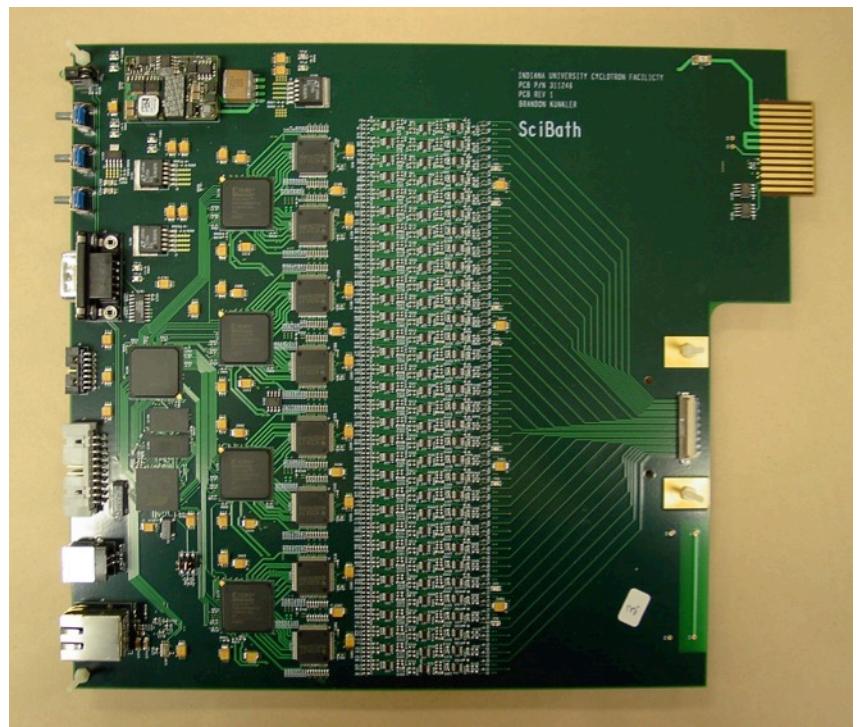
INDIANA UNIVERSITY



PINCH HITTERS (BACKUPS)

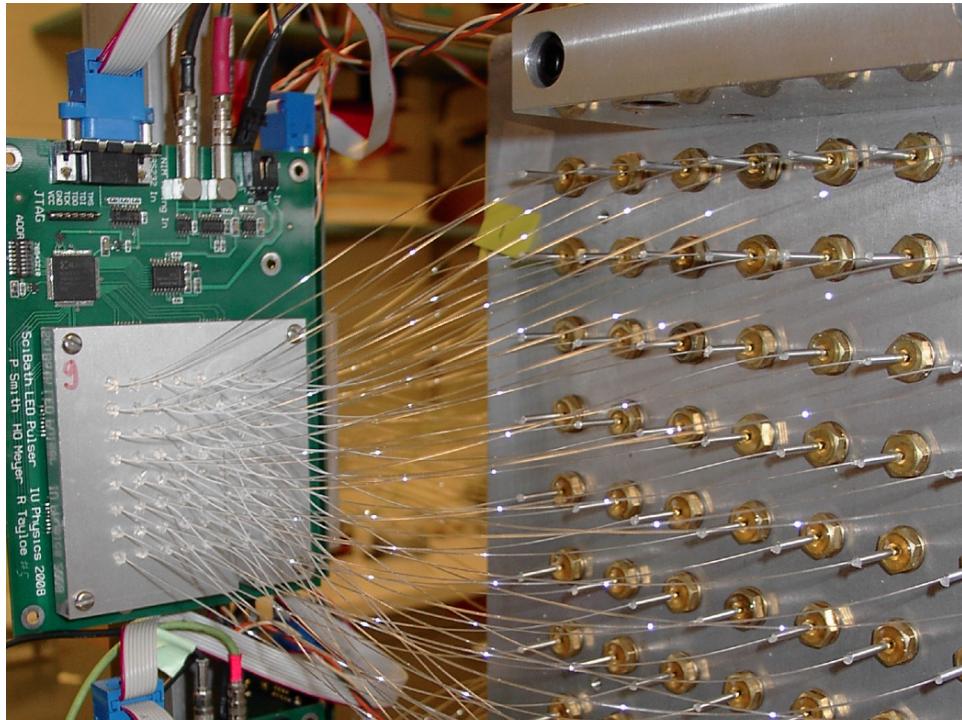
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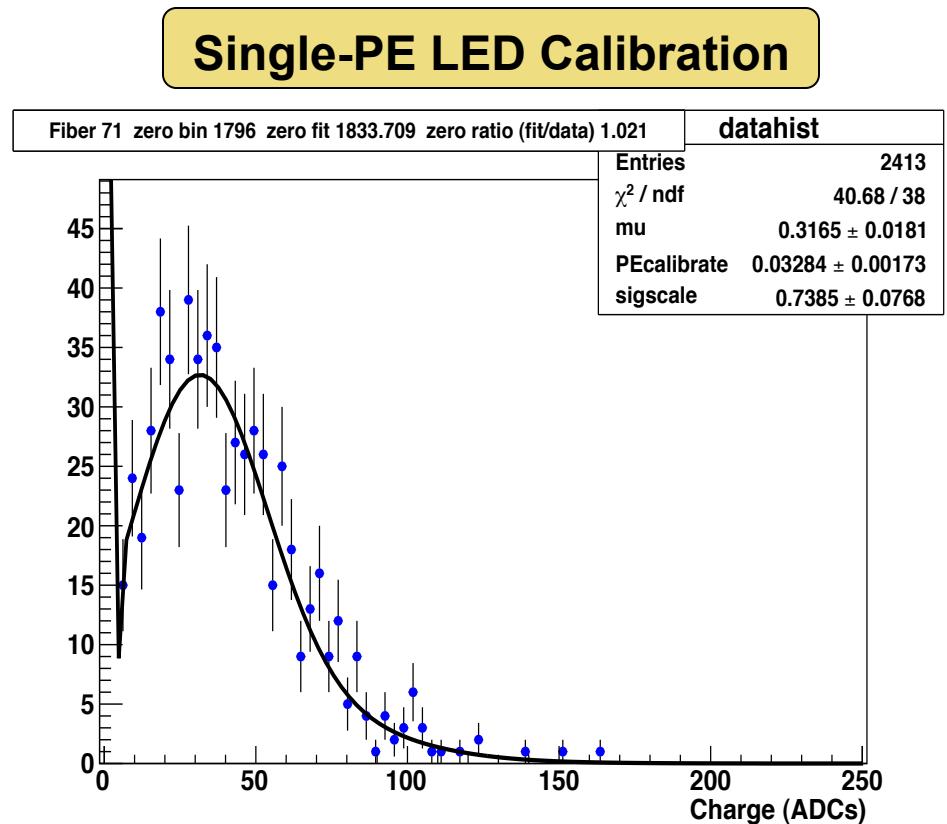
Photoelectron to ADC Calibration

- **Photoelectron (PE)**: an optical photon ejects an electron from PMT surface via the photoelectric effect
 - Low-light LED calibrates ADC to single photons
 - Approximately 30 ADC channels per PE
 - PMTs balanced with HV



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Cosmic Ray Calibrations

- Cosmic ray muons are minimum ionizing
- Deposits approximately 65 MeV at 390 PE peak
- 6 detected PE / MeV
- $n(p, d)\gamma$ 2.2 MeV gamma rays validate calibration
- Expanded calibration program underway

