Neutron Measurements with the SciBath Detector at FermiLab BNB

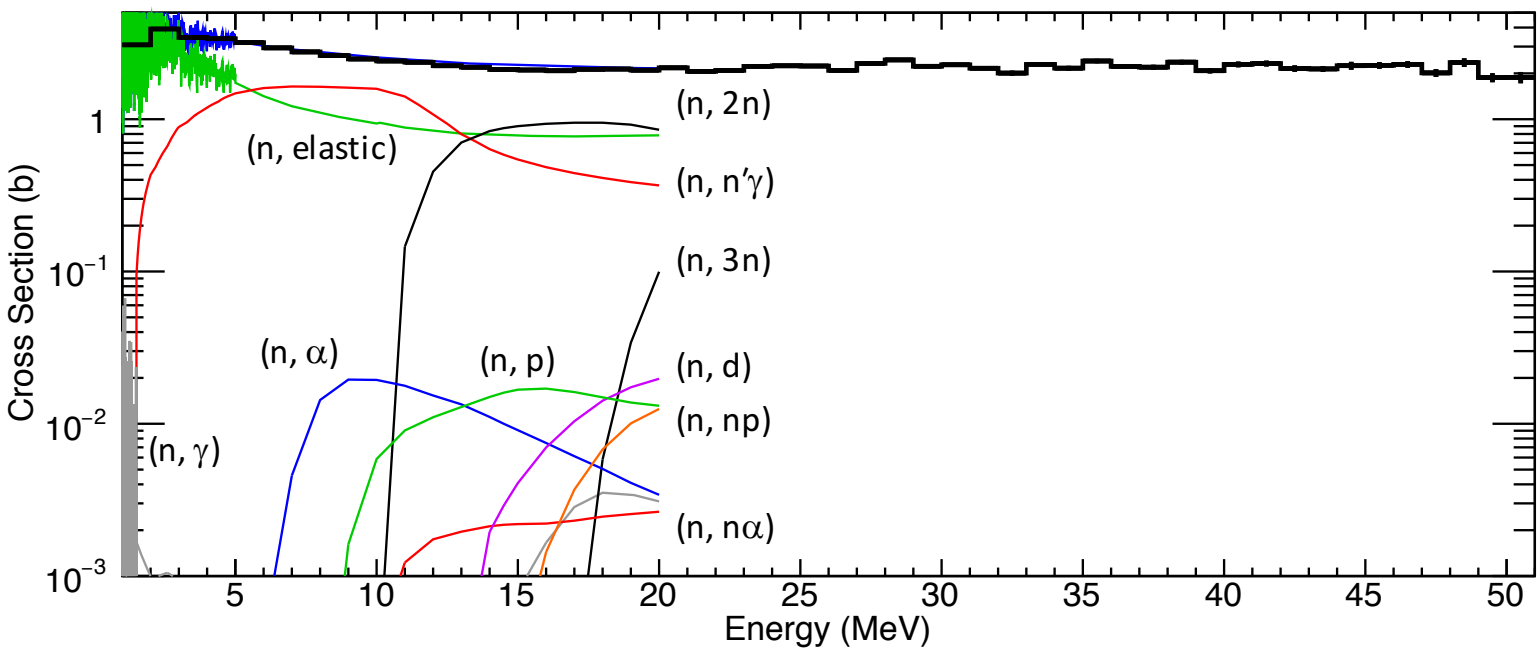
R.L. Cooper, M.R. Heath, R. Tayloe, R.T. Thornton

The Problem with Neutrons

- Neutrino interactions in the dirt are in time with the beam, neutrons are most penetrating
- Difficult to simulate due to complex geometry and how poorly neutron interactions are known
- RF bunch timing can help; if the technology has established fast timing capability
  - Liquid argon?
- Energetic neutrons can look like NC neutrino interactions

Neutrons and Argon

- n-Ar total cross section data to 50 MeV (black hist)
- Others are ENDF "evaluations" only up to 20 MeV
- Above 20 MeV, use models with no data to vet (yet)



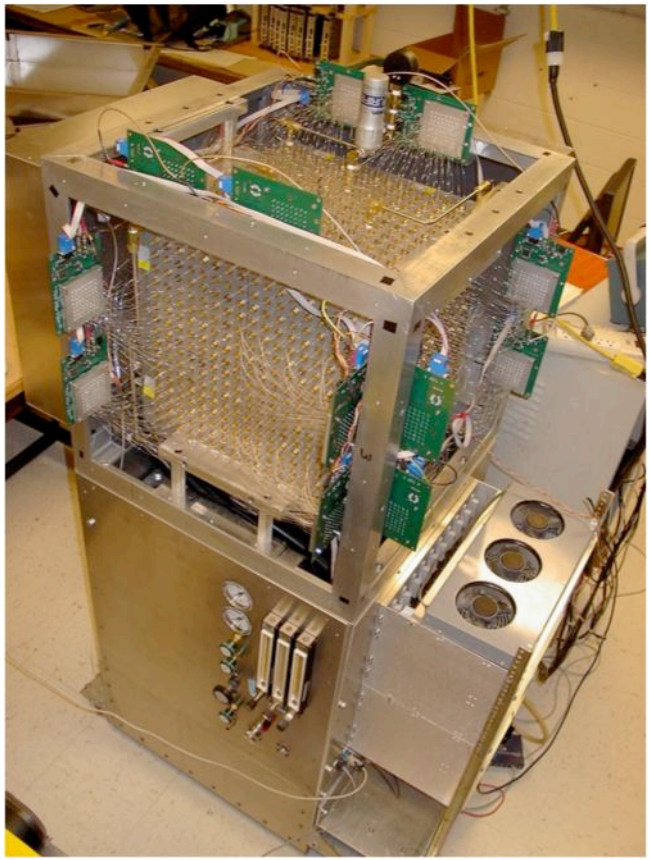
LAr Does Not Stop Neutrons Well

- Using 20 MeV data, mean free path of neutrons in LAr ~20 cm
- Compare this to ~10 cm for water or mineral oil
- Elastic scattering is challenged for heavy targets

$$T^{\max} = \frac{4 m_n M_{\mathrm{Ar}}}{(m_n + M_{\mathrm{Ar}})^2} T_n$$

The SciBath Detector

- SciBath is an 80-L liquid scintillator detector (mineral oil based)
- 768× wavelength shifting fiber readout in 3D grid
- Near-uniform tracking efficiency in all directions
- Neutral particle recoils charged particle which creates scintillation tracks
- Topological separation between proton recoils from neutrons and muon track



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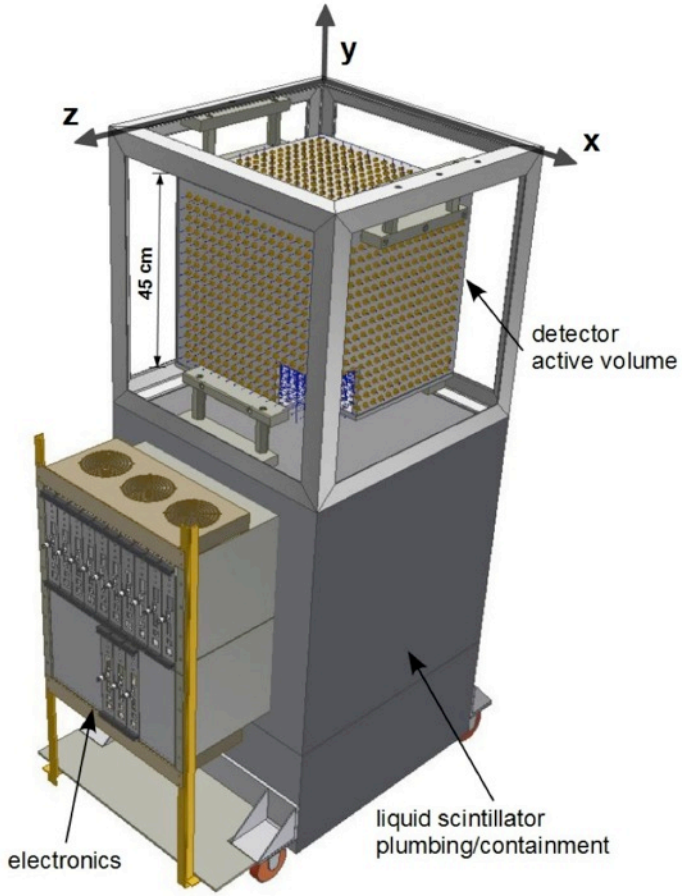

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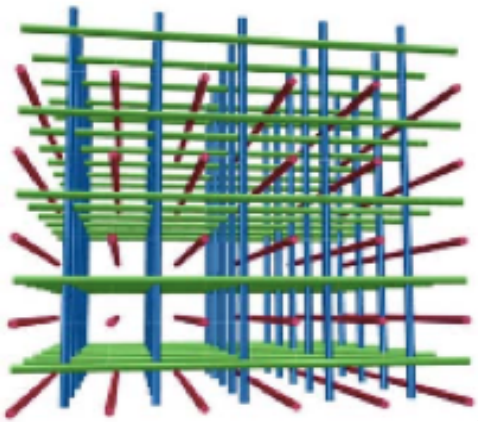
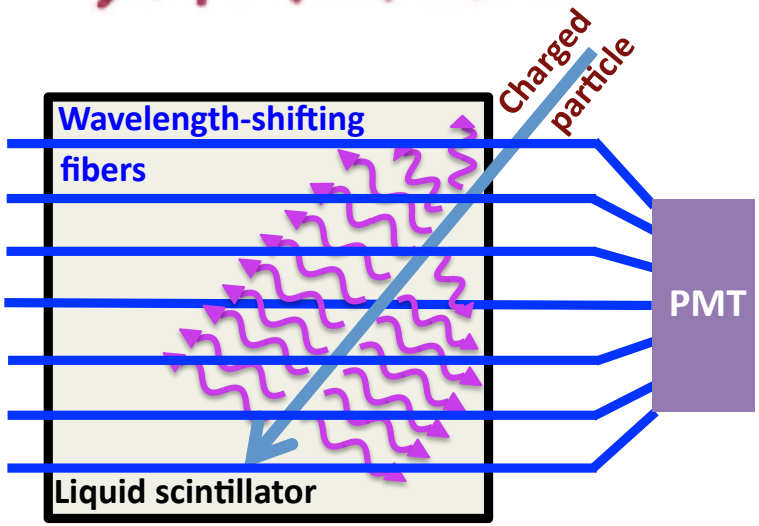
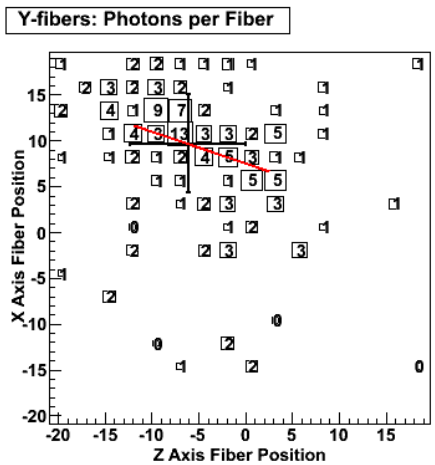
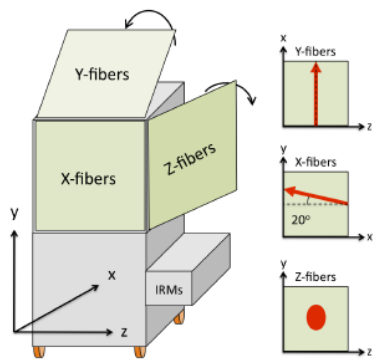


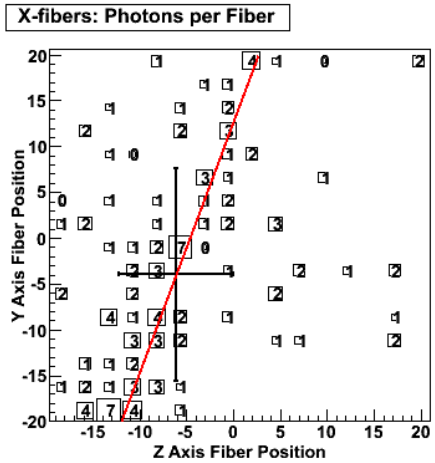


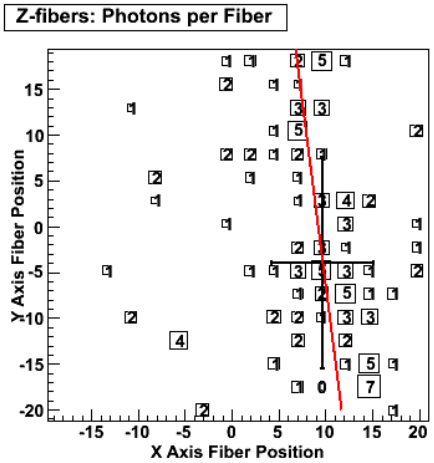
Sample Muon Candidate Event

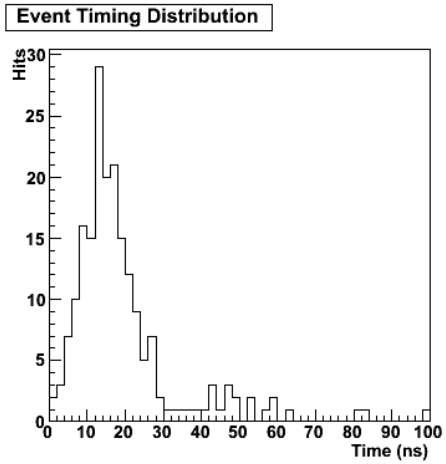




Event Num: 109 (1206)
Multiplicity: 204
Total PEs: 412.6
PEs -- X: 126.0 Y: 158.1 Z: 128.5
PEs^2 -- X: 337.9 Y: 668.8 Z: 360.9
T0: 3.272227153 s
Time to last BIB: 0.0009486 s
$\bar{x}$ = 9.7 ± 5.4 cm -- skew = -1.64 -- kurt = 6.62
$\bar{y}$ = -4.0 ± 11.6 cm -- skew = 0.47 -- kurt = 2.14
$\bar{z}$ = -6.1 ± 6.1 cm -- skew = 0.90 -- kurt = 4.70
$\bar{t}$ = 24.7 ± 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 ± 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







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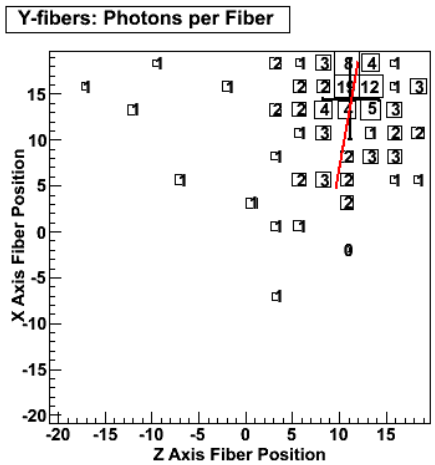
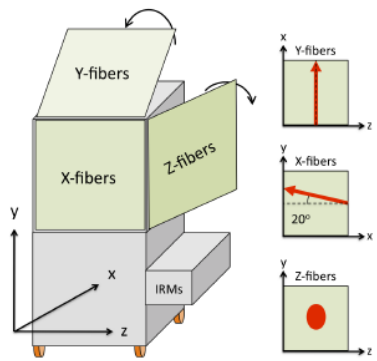
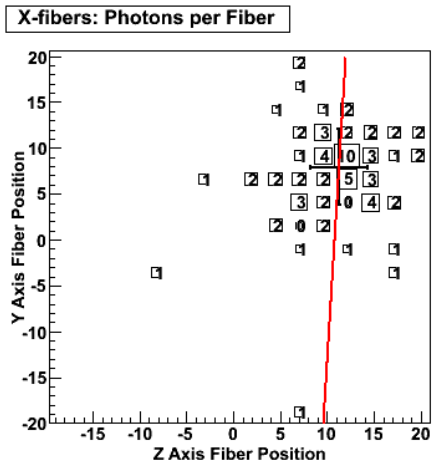
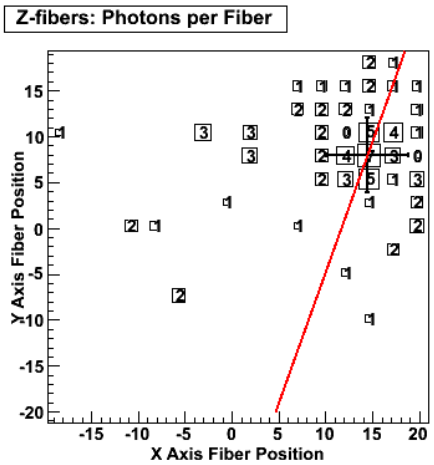
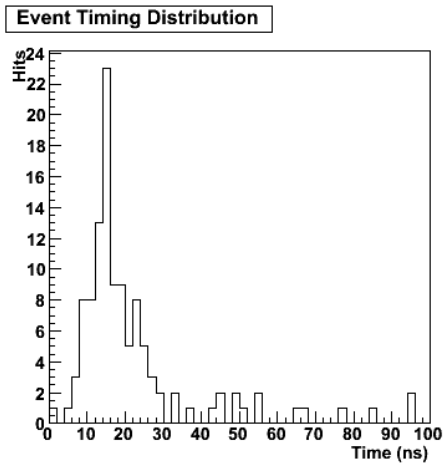




Event Num: 10642 (95796)
Multiplicity: 124
Total PEs: 283.0
PEs -- X: 80.8 Y: 115.8 Z: 86.4
PEs^2 -- X: 282.5 Y: 784.6 Z: 252.9
T0: 92.284587701 s
Time to last BIB: 0.0001213 s
$\bar{x}$ = 14.4 ± 4.4 cm -- skew = -2.92 -- kurt = 13.34
$\bar{y}$ = 7.9 ± 4.1 cm -- skew = -1.55 -- kurt = 10.71
$\bar{z}$ = 11.3 ± 3.0 cm -- skew = -2.21 -- kurt = 17.16
$\bar{t}$ = 30.6 ± 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 ± 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

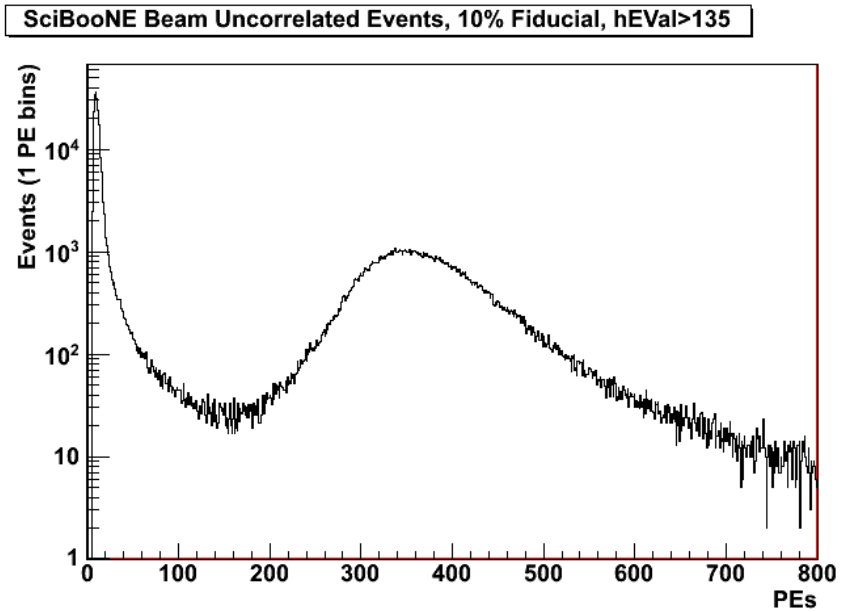


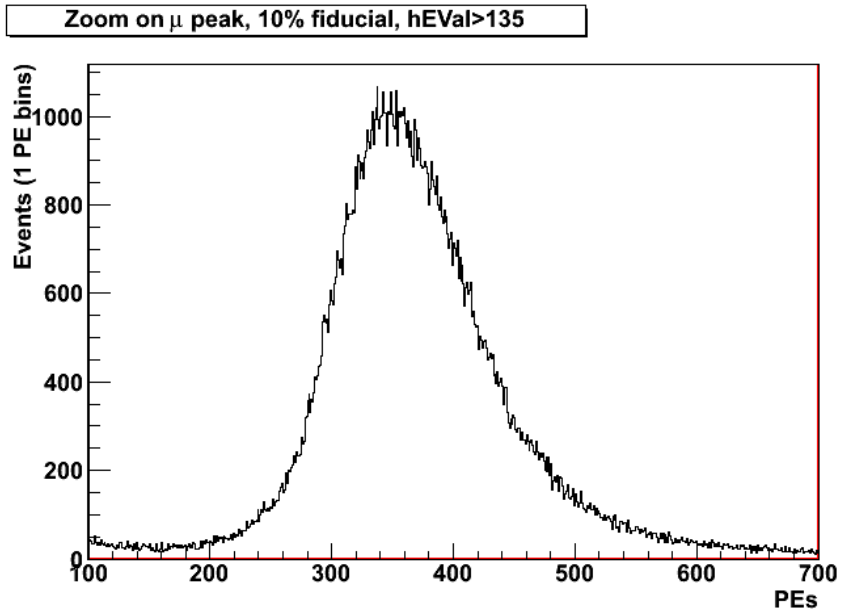




n-μ Topological Separation

- Minimum ionizing particles ~350 photoelectrons
- Pulse shape parameter (115 in this case) allows for n-μ selection above "high-energy" PE cut





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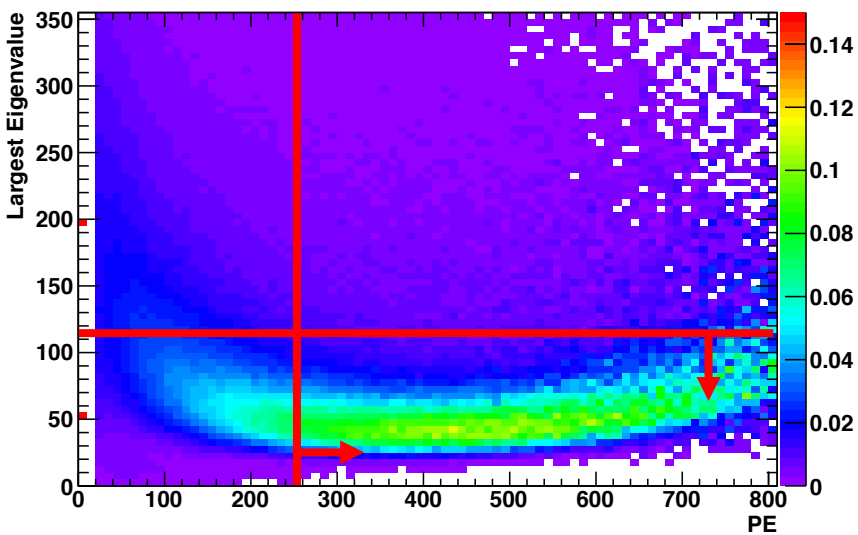
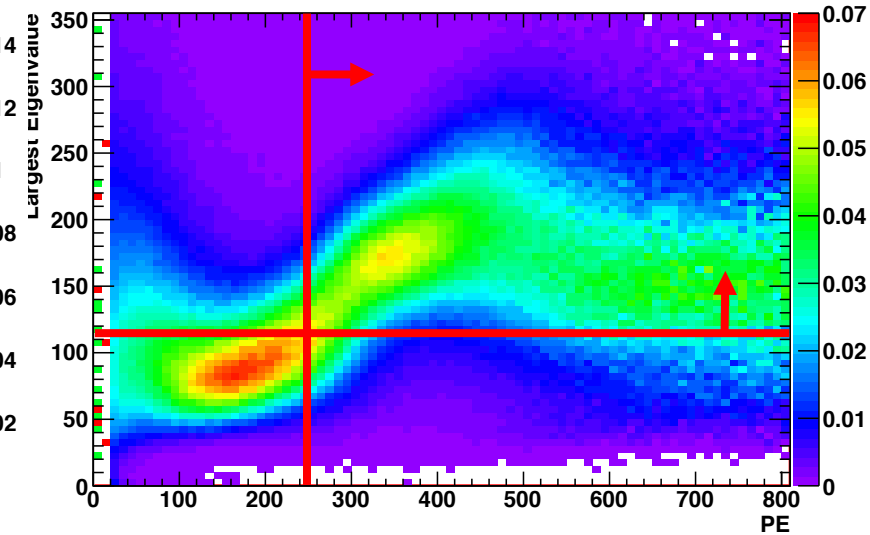
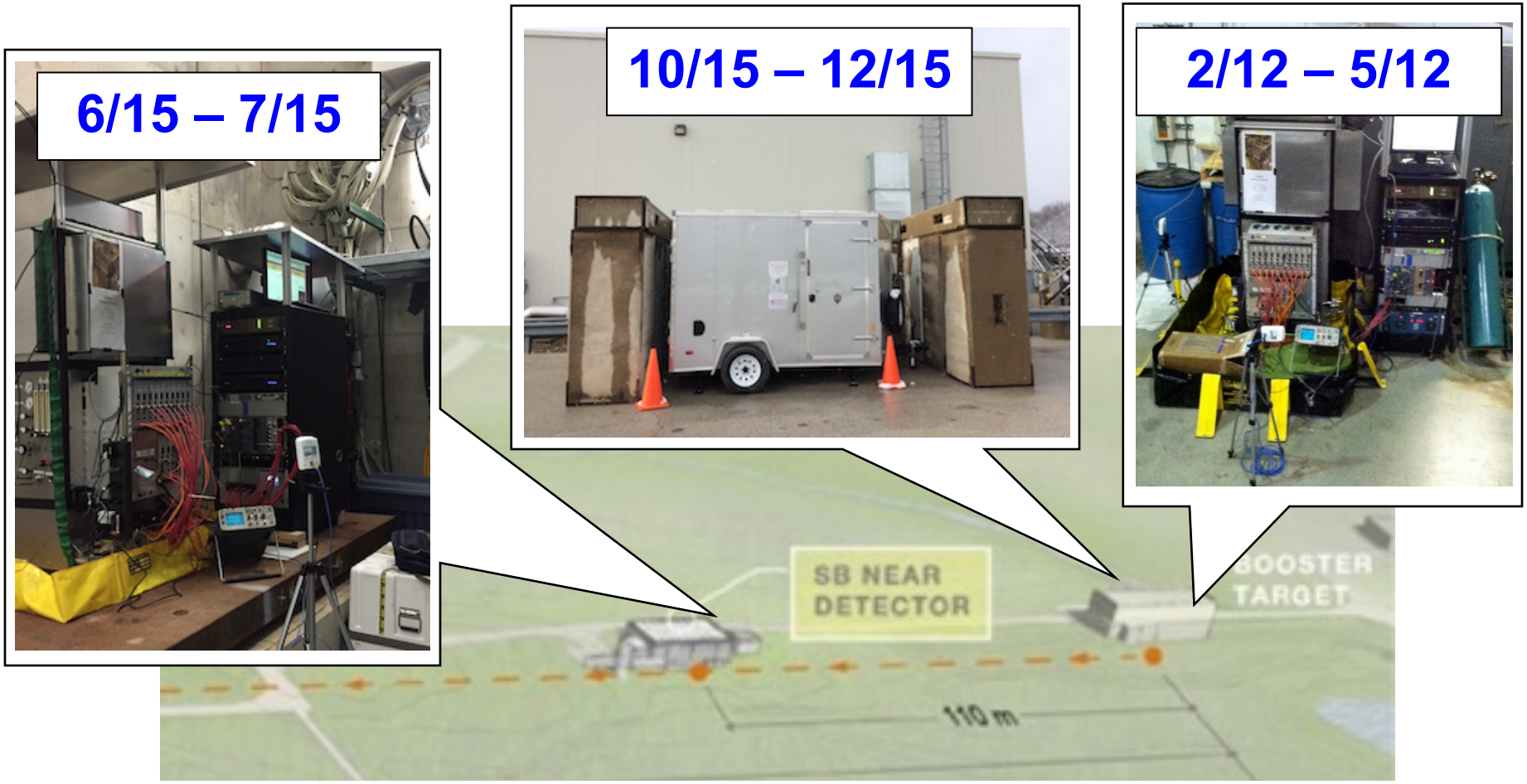
Neutron-Rich Data Sample



Muon-Rich Data Sample



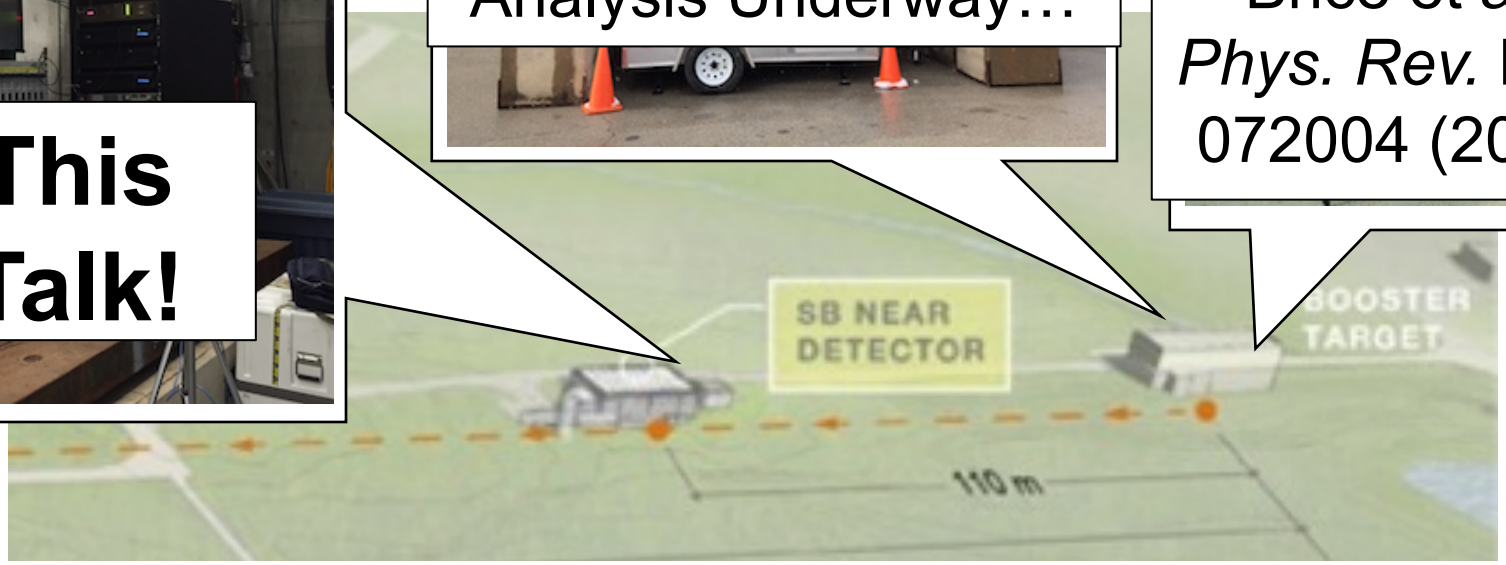
BNB Measurement Sites



BNB Measurement Sites

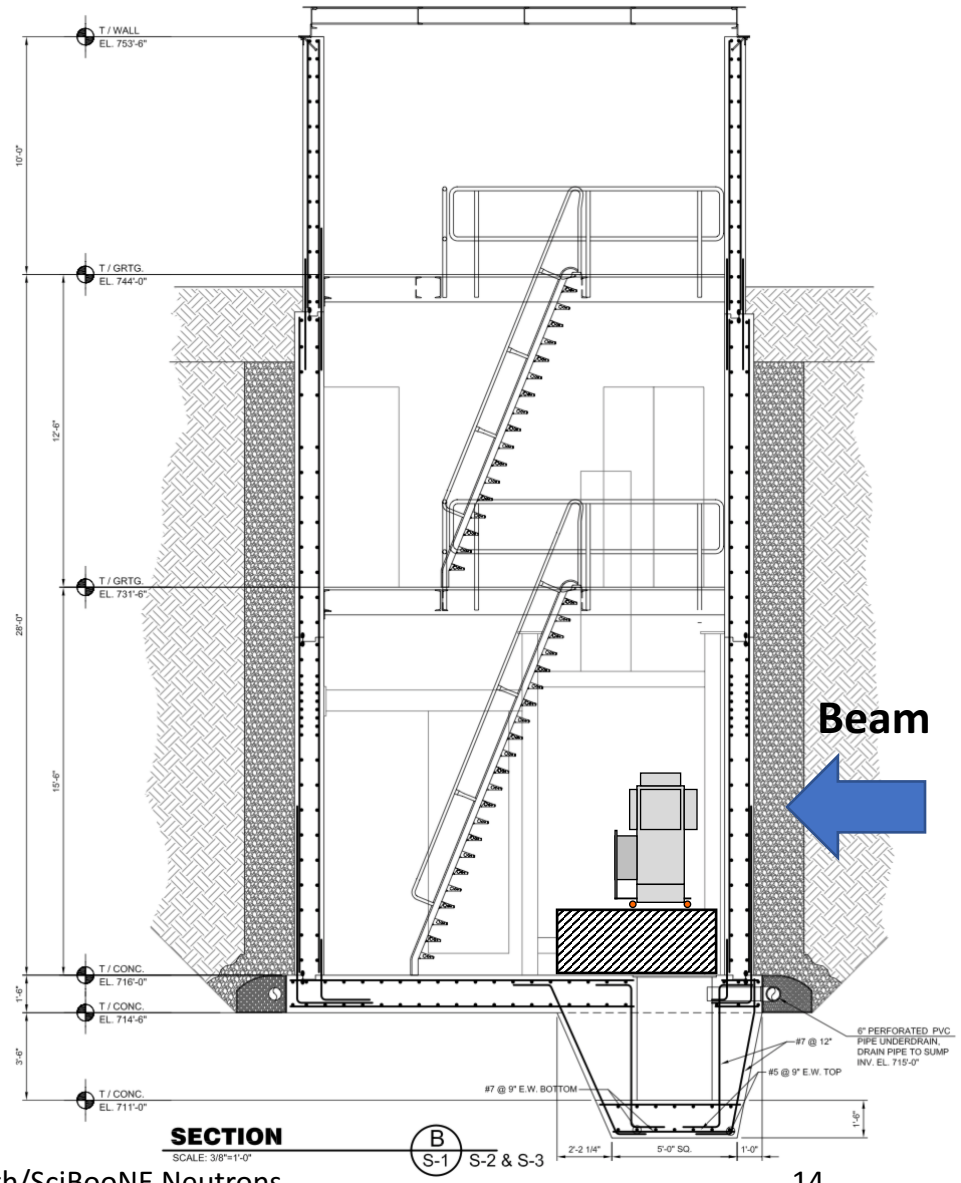
Analysis Underway…

Brice et al., *Phys. Rev.* **D89**, 072004 (2014)

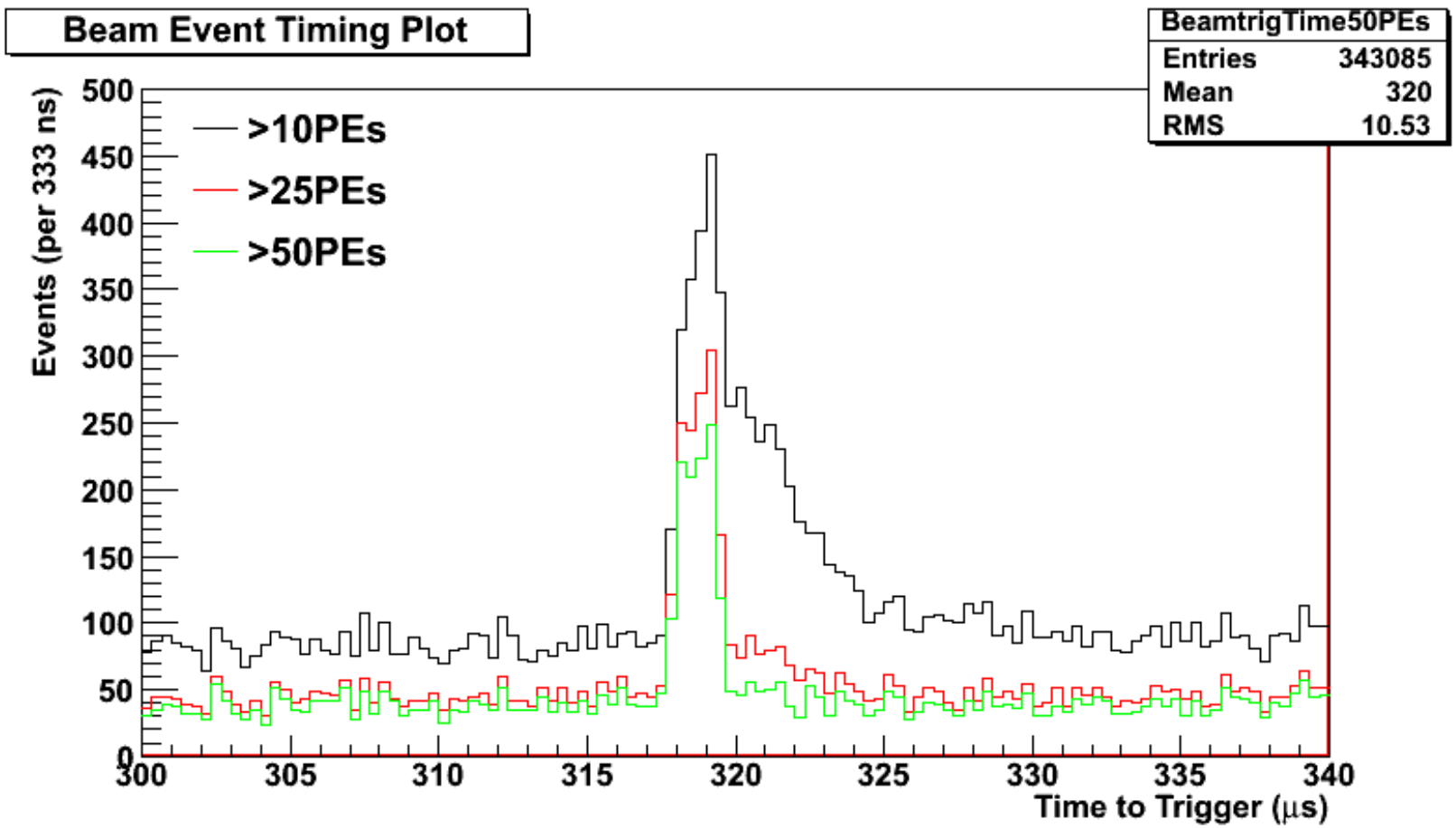


SciBooNE Run

- SciBath beam-centered
- Fluxes reported:
  1. High-energy beam-related dirt neutrons
  2. Beam-related dirt muons
  3. Beam-related thermal neutrons
- ~1 week run
  - 3.524×10^6 spills
  - ~3.6×10^{12} POT per spill



Event Timing Spectrum vs. PE



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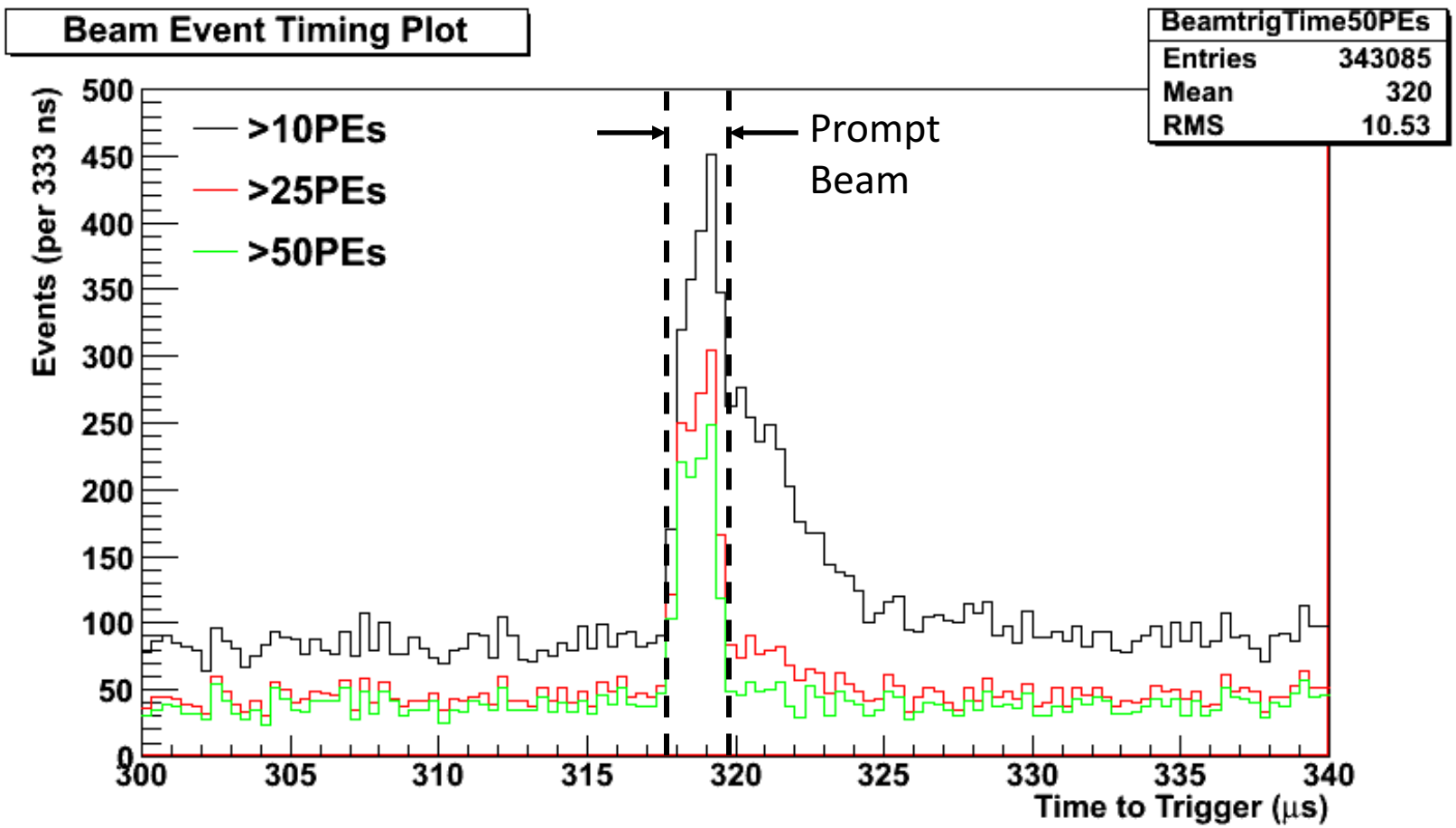

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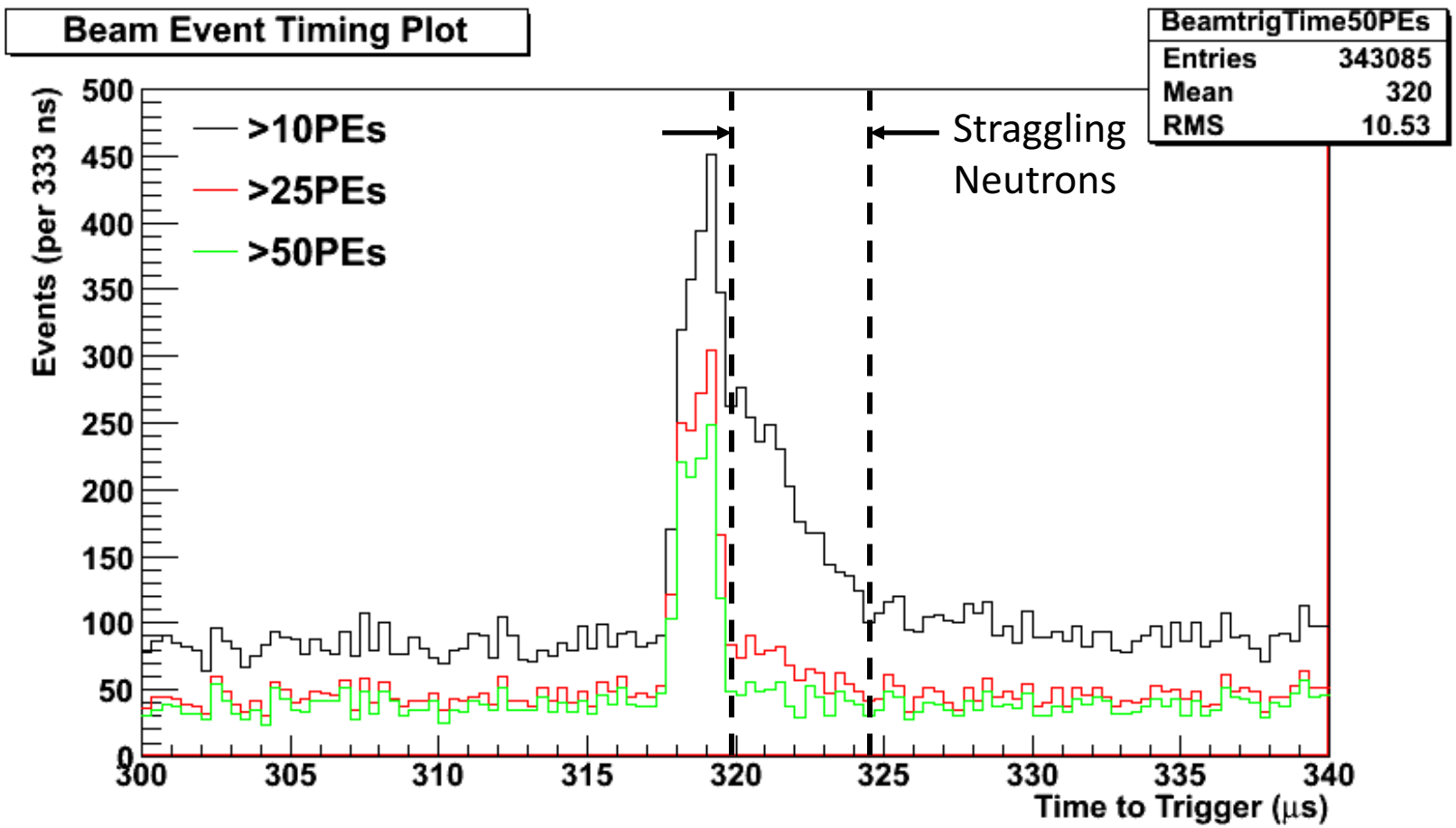

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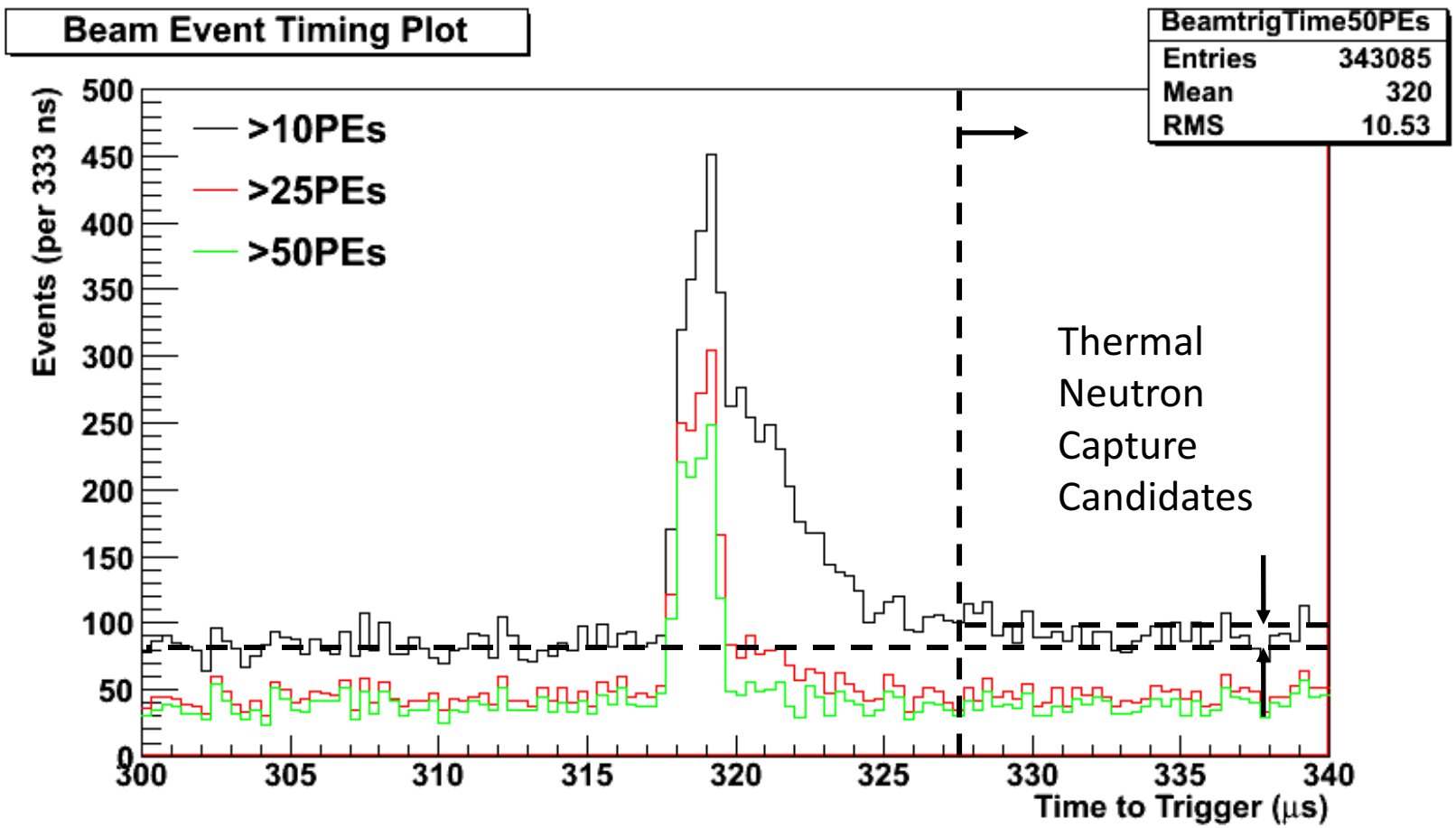
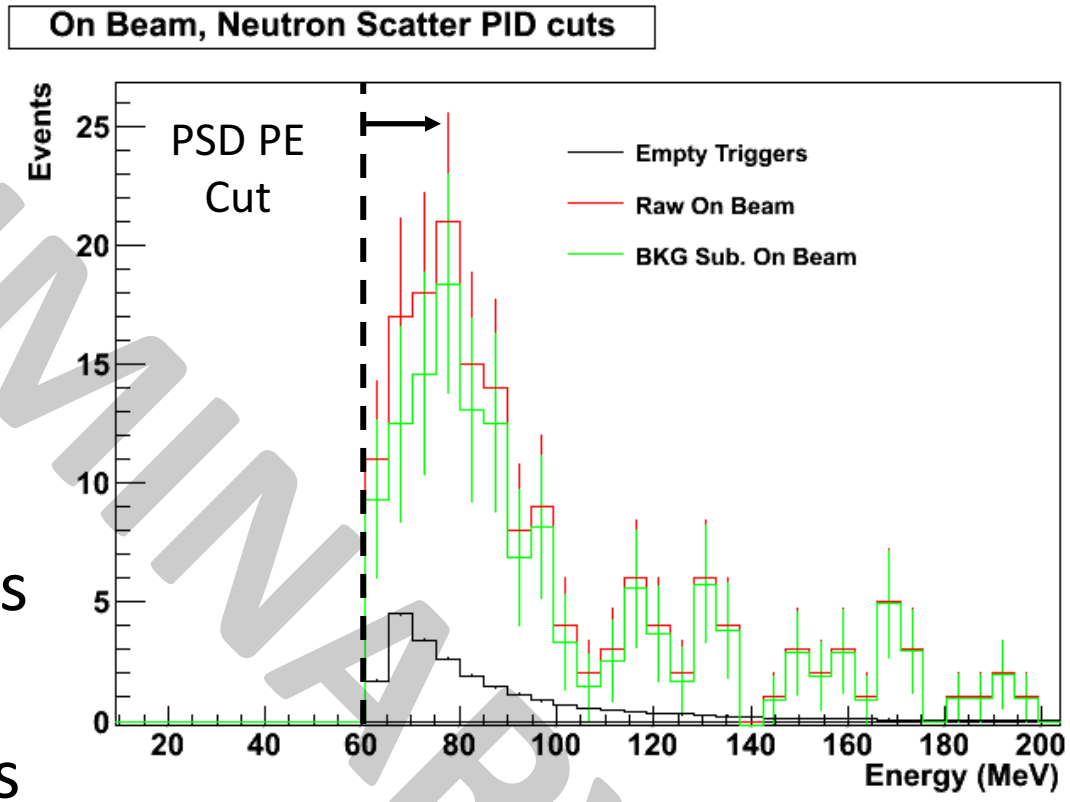


High-Energy Neutron Analysis

- Apply cuts:
  - Basic event quality cuts (e.g., clustered fiber hit times)
  - No fiducial for maximum acceptance
  - High-energy, neutron-like PSD cuts
  - Events around prompt beam (some straggling neutrons)
  - Background subtracted
- Recorded 152 ± 13 events
- Effective area for neutrons (from MC) 0.291 m^2
- Neutron flux: $(1.48 \pm 0.13) \times 10^{-4}\ m^{-2}\ spill^{-1}$

Energy Deposit Spectrum

- Energy deposit assumes single proton recoil
- Light output quenching removed
- Incident energy spectrum unfolding is in progress
- Conservatively, flux is above 60 MeV

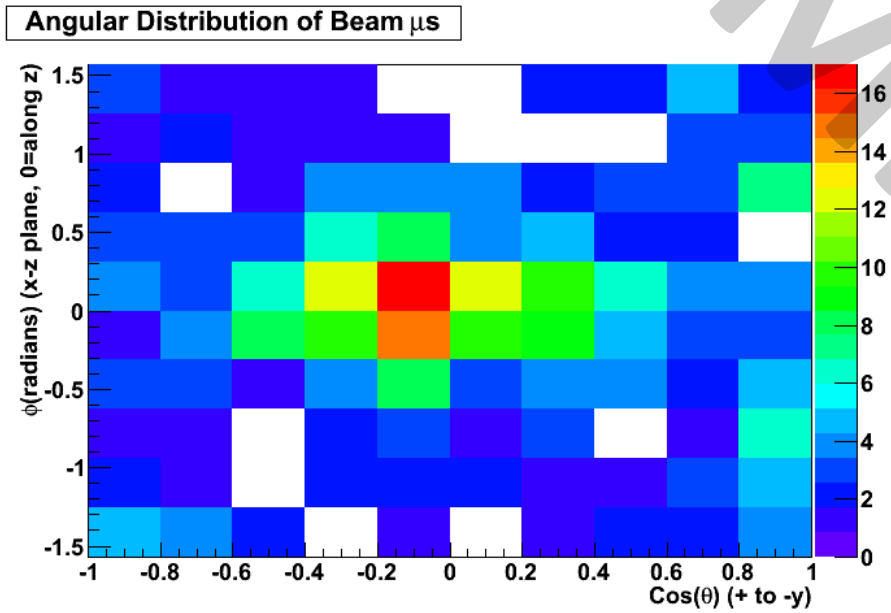


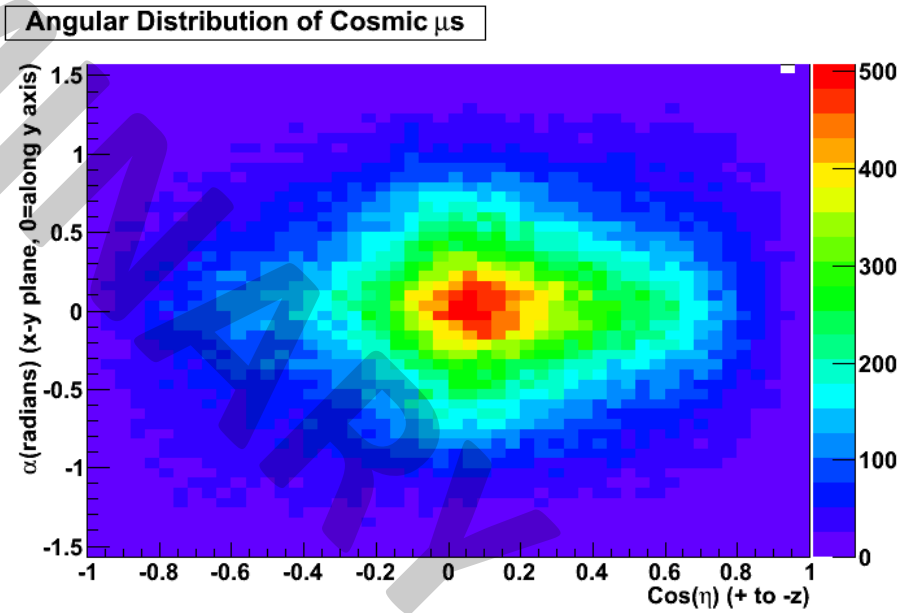
Beam-Related Muon Analysis

- Apply cuts:
  - Basic event quality cuts (e.g., clustered fiber hit times)
  - 26% fiducial avoids "corner clippers"
  - High-energy, muon-like PSD cuts
  - Events around prompt beam
  - Background subtracted
- Recorded 235 ± 18 events
- Effective area for muons (from MC) 0.095 m^2
- Muon flux: $(7.00 \pm 0.67) \times 10^{-4}\ m^{-2}\ spill^{-1}$

Muon Angular Distribution

- Angular reconstruction shows background muons are vertical while beam muons are horizontal



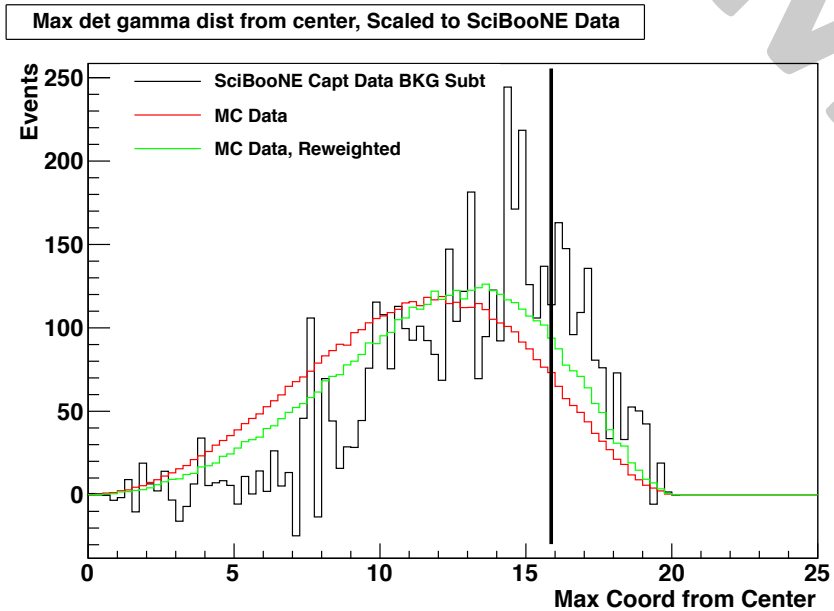


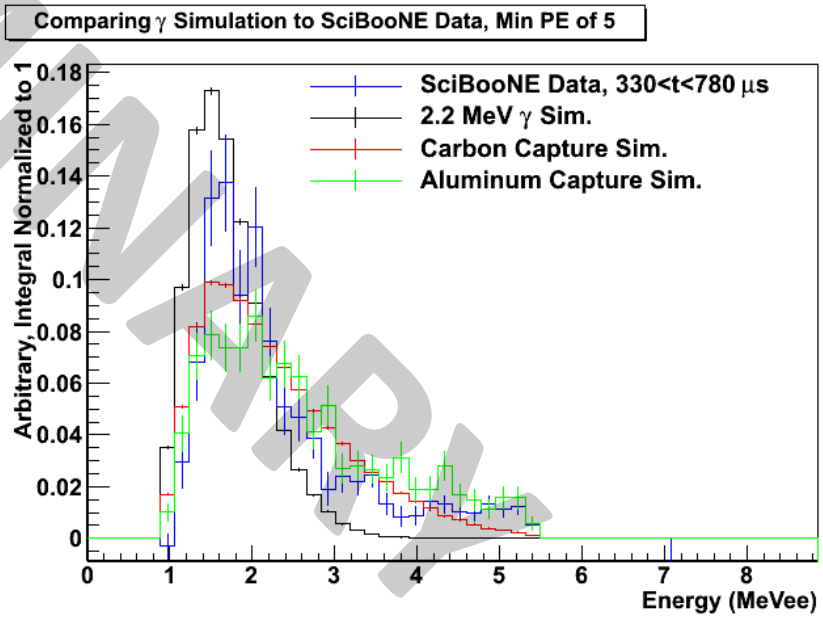
Thermal Neutron Analysis

- Apply cuts:
  - Basic event quality cuts (e.g., clustered fiber hit times)
  - No fiducial for maximum acceptance
  - High-energy, neutron-like PSD cuts
  - Events 10-460 μs after beam
  - Background subtracted
- Recorded 3866 ± 274 events
- Effective area for neutrons (from MC) 0.025 m^2
- Thermal neutron flux: $(4.39 \pm 1.39) \times 10^{-2}\ m^{-2}\ spill^{-1}$

Neutron Capture Channels

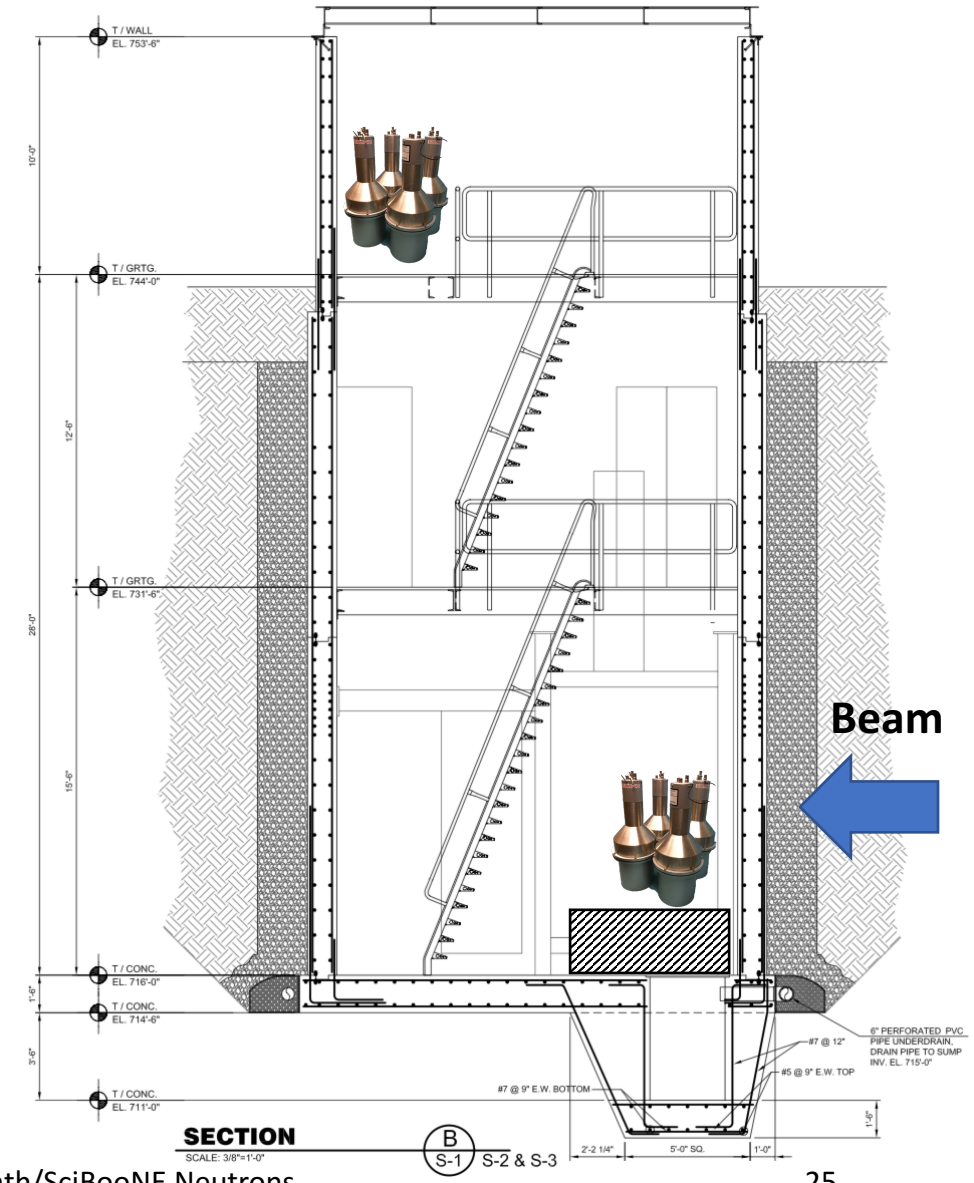
- Capture gamma reconstruction matched MC
- PE shape favors significant Al capture (7 MeV cascade from $^{28}Al^*$) along with dominant H capture



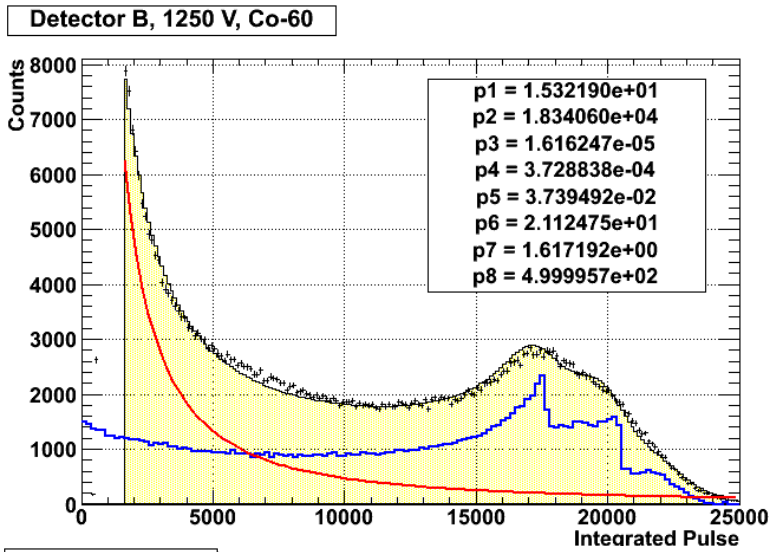


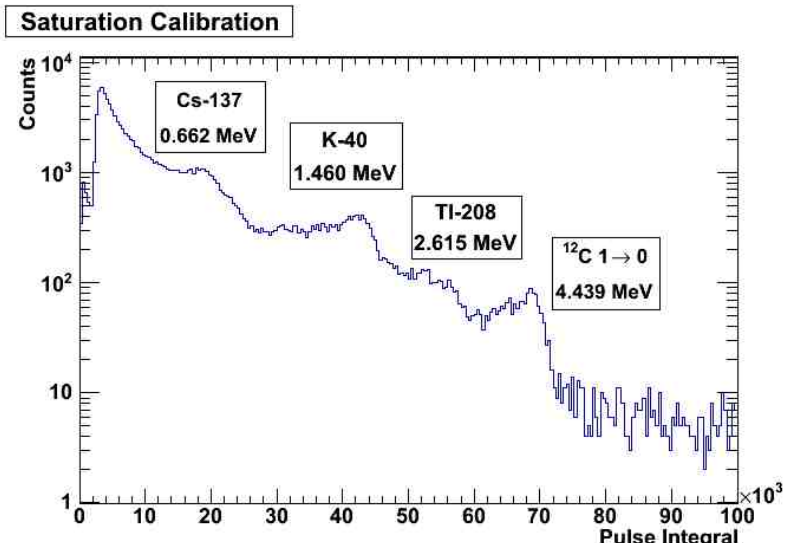
5-kg Neutron Detector

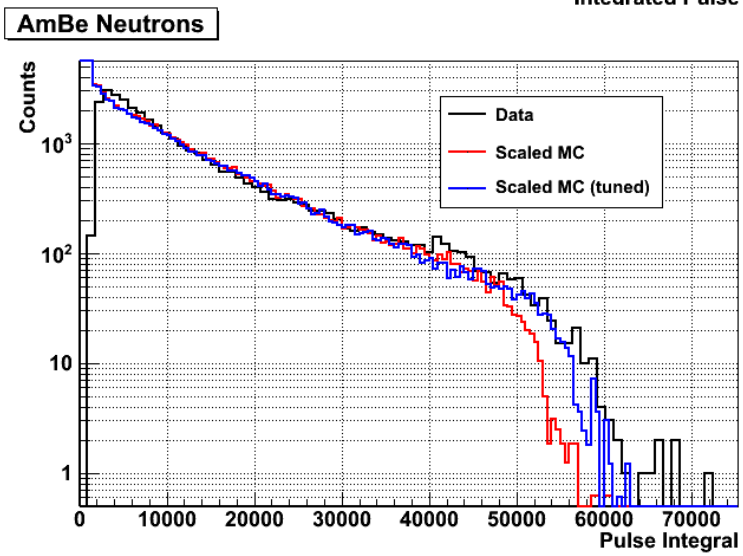
- Eljen EJ-30X cells:
  - High light yield
  - n/γ PSD
- 5-6 days running at:
  1. Near surface
  2. Below ground near beam center
- Boron-loaded detector used to look at thermal neutron events

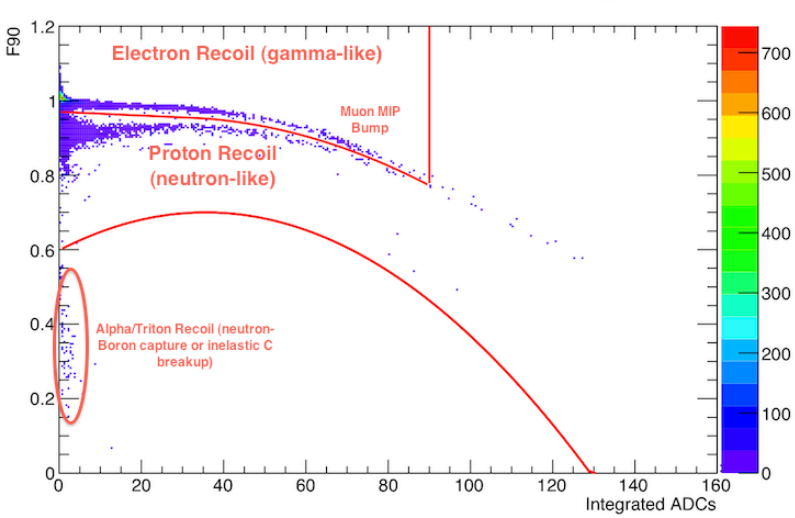


Well Calibrated

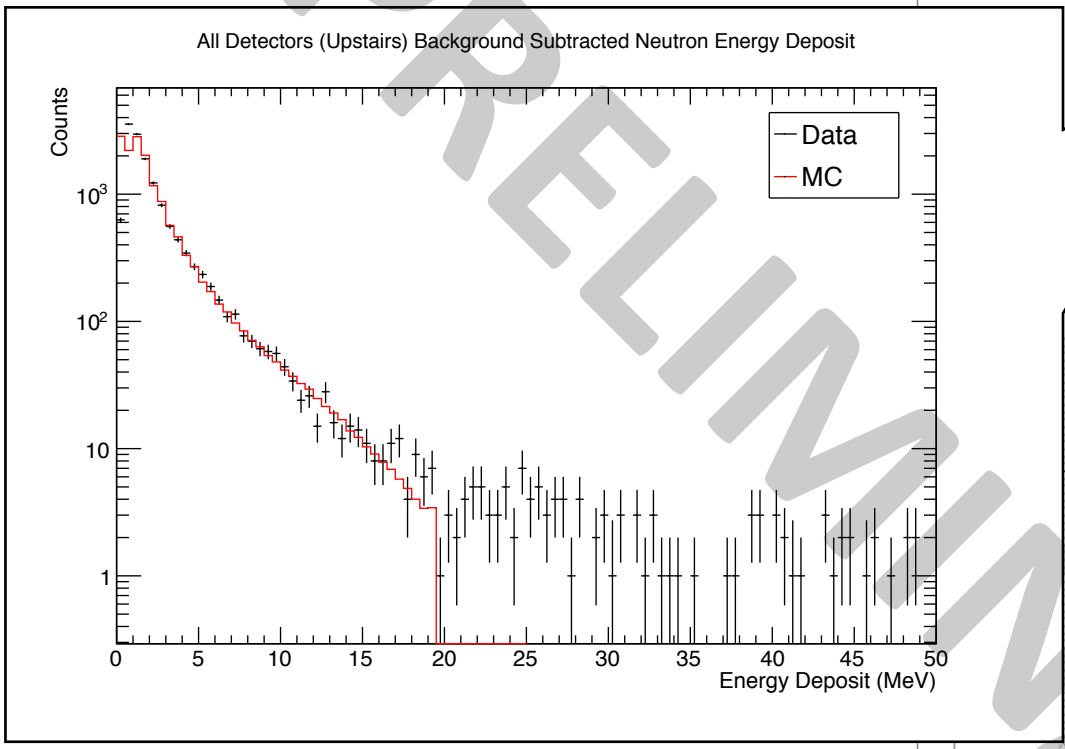


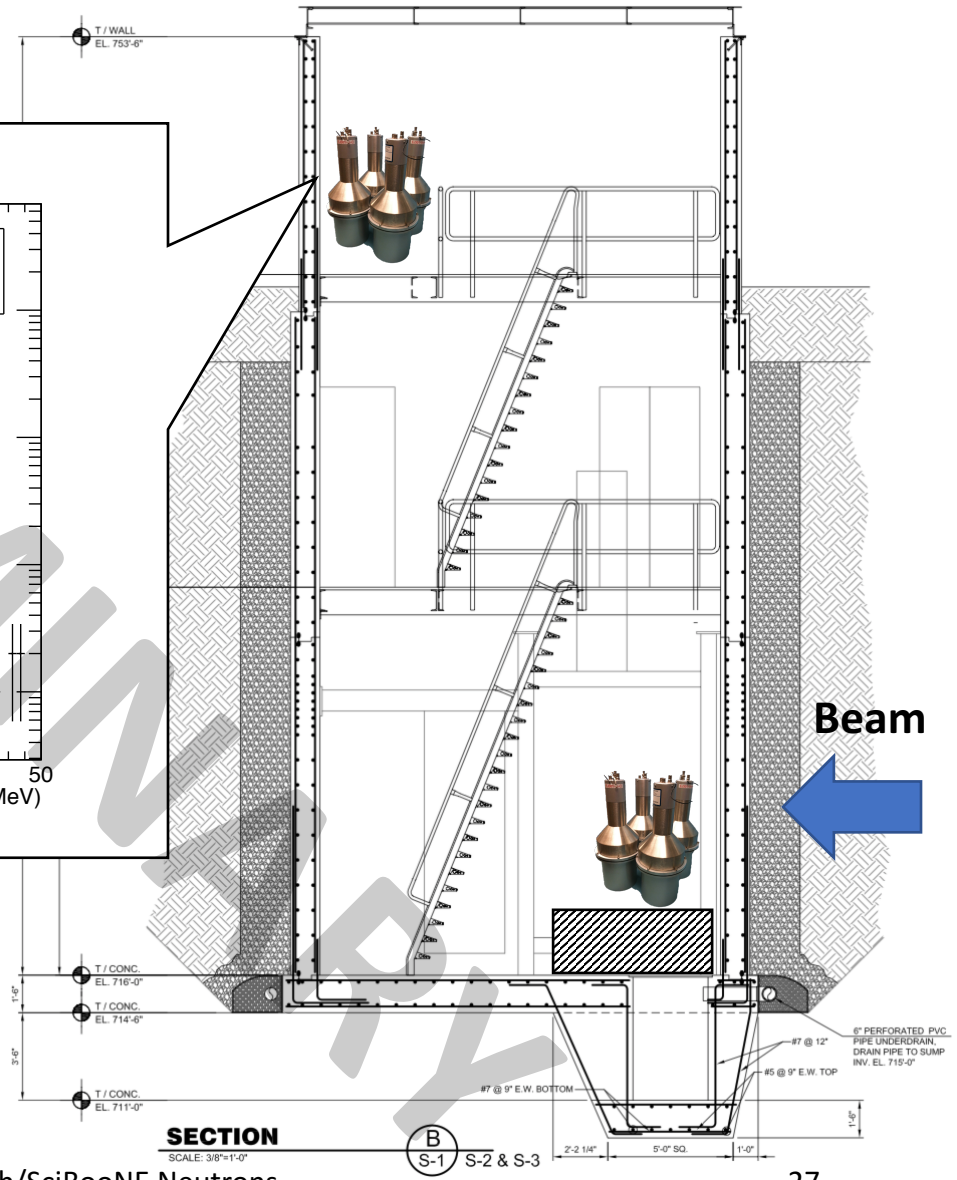






At the Surface

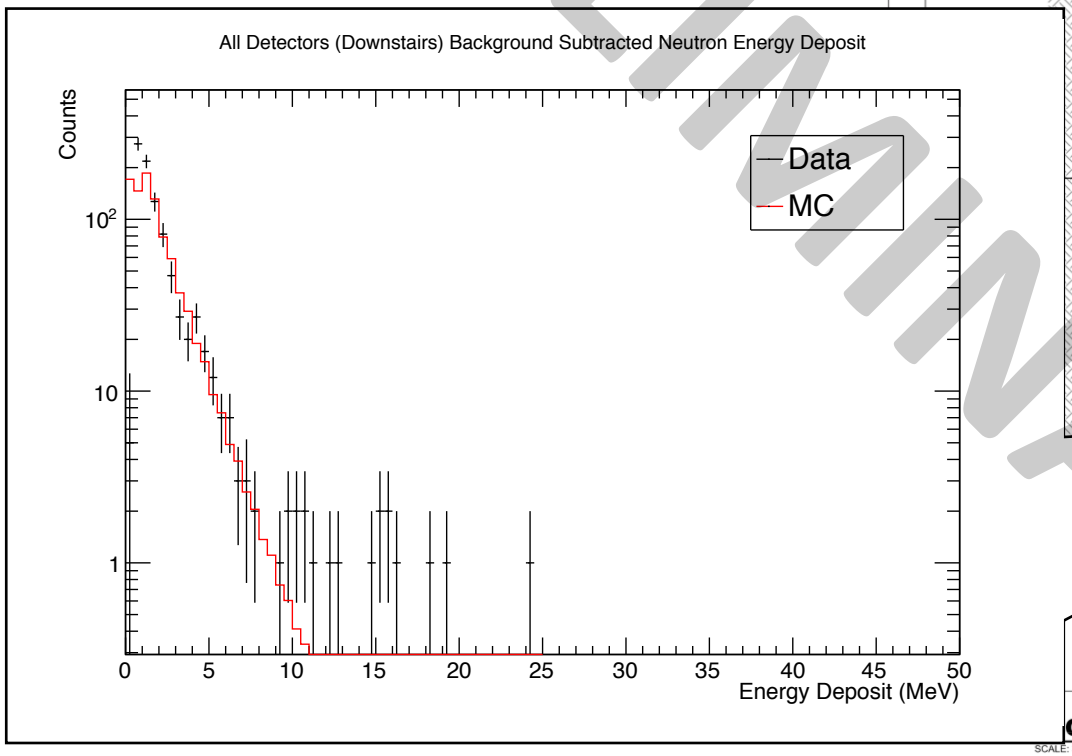


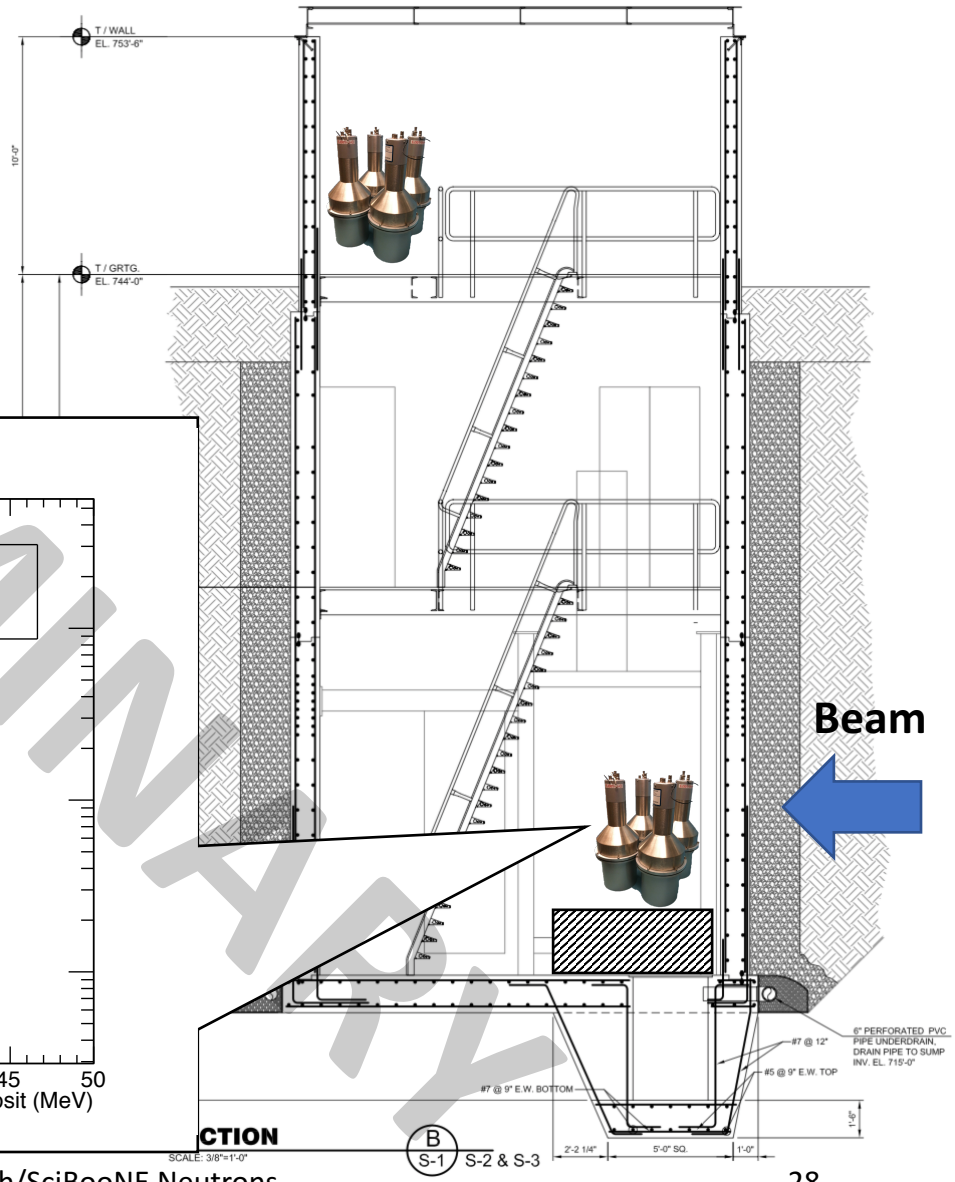


- Higher rate and more energetic spectrum

Below Ground

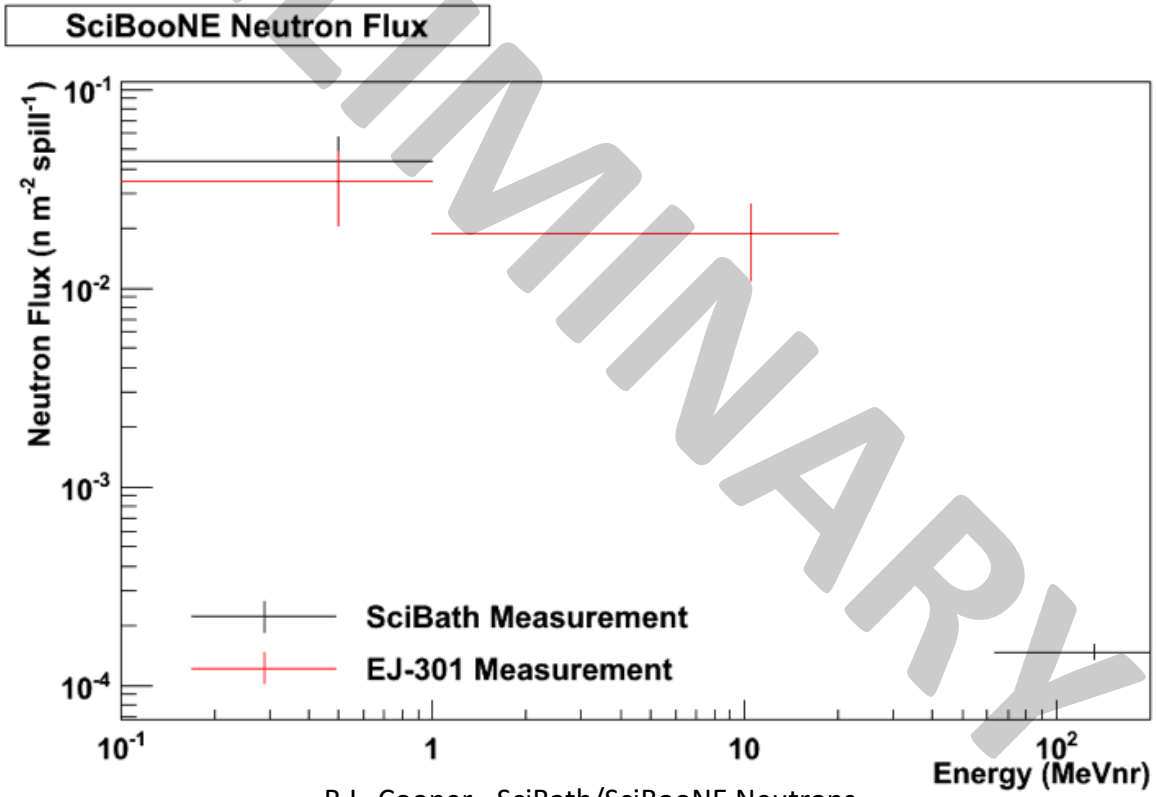
- Could skyshine account for the rate and energy spectrum differences?





Putting It All Together

- Can combine EJ-30X measurements with SciBath to broaden energy range



A Shameless Plug for CAPTAIN

- MiniCAPTAIN is a 400-kg LAr TPC prototype
- Measuring LAr response to TOF-tagged 20-800 MeV neutrons
- Ran in February 2016
- Run again in July 2017
- Improvements to purification and DAQ are underway

MiniCAPTAIN Results

- Feb. 2016 results showing the light output vs. TOF-tagged neutron energy up to 800 MeV
- First results of its kind