IBD: Background (Below Ground)

R. Carr

Reactor antineutrino-like events detected:

$$N = \frac{N_s}{4\pi L^2}\varepsilon M_{det}\frac{P_{th}}{\langle E_f \rangle}P_{osc}\sum_i f_i \phi_i \sigma + B$$

Antineutrino Spectrum* Calculations (Wed)

Detector Response Calculations (Thu)

Marc Bergevin
LLNL

June 24th, 2021

LLNL-PRES-823624
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Lawrence Livermore National Laboratory

Challenges in precise underground background measurements

Underground IBD-backgrounds have not been fully characterized yet

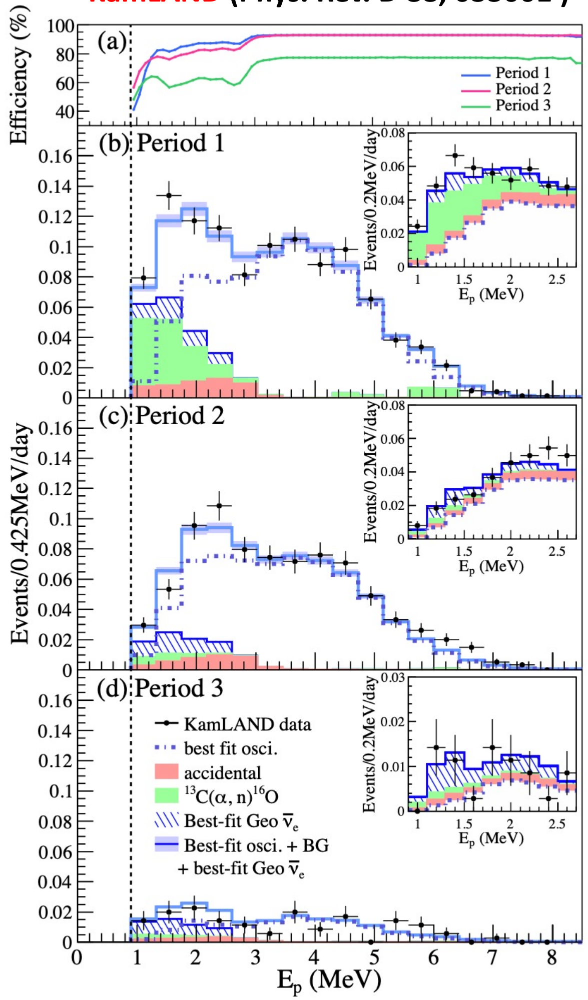
- In most IBD underground measurements to date, reactor-off data is incredibly rare and valuable. For example, Double Chooz was able to significantly constrain their backgrounds **with only 7.53 days of reactor-off data (Phys. Rev. D 87, 011102, 2013)**. It is not economically viable to shut down multiple reactors at a time, and as such precise characterization of certain backgrounds is challenging.

- Some of the underground IBD backgrounds are produced from cosmic muon interactions. The property of these background (production yield, spectral shape) will vary as a function of detector depth. There are remaining uncertainties of the yield functions.

- **Longer-baseline: KamLAND** had an extensive campaign of reactor-off data. However, the detector design was effective at minimizing certain types of external backgrounds and a precise characterization of these backgrounds is not possible.

- **Shorter-baseline:** Precise reactor antineutrino measurement benefit from shorter baseline regime, since one can increase statistics while keeping detector size to a minimum. Geoneutrinos and other backgrounds such a (α,n) may be less dominant in small detectors.

KamLAND (Phys. Rev. D 88, 033001)

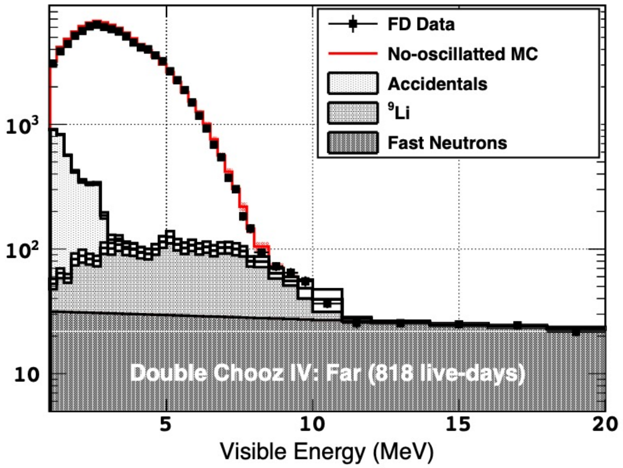


Dominant backgrounds in underground experiments

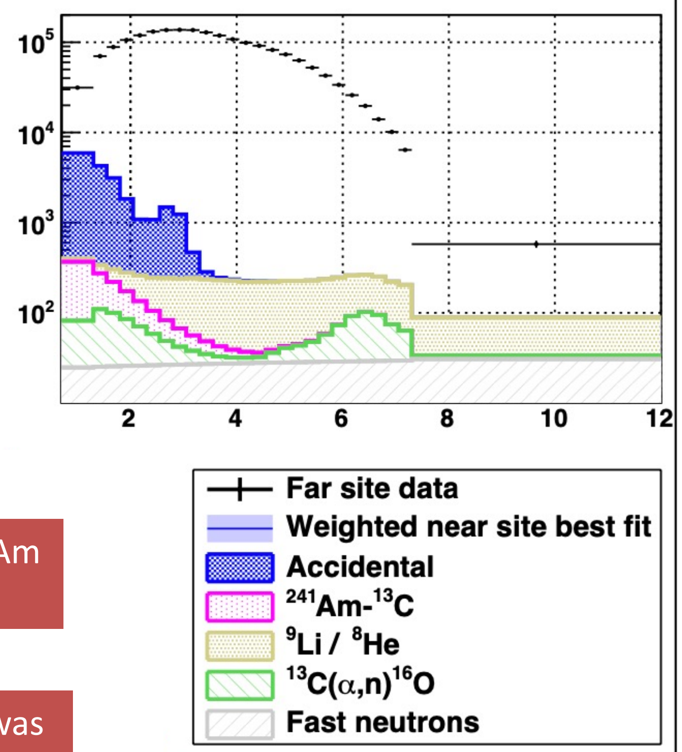
Assuming either a detector fill of Carbon-based or Water-based media

- "Accidental" coincidences or non-correlated events from intrinsic radioactivity $^{232}Th/^{238}U/^{222}Rn$ in PMT glass and in detector media
- Beta-neutron radionuclide production due to cosmic muons traversing the detector:
  - $^{9}Li/^{8}He$ for ^{nat}C, ^{nat}O
  - ^{17}N for ^{nat}O (4.173 s half-life, Q-Value 4.537 MeV)
- "Punch-through" or "fast neutrons" produced from muon activity in the surrounding rock

Double Chooz (PDG*)



Daya Bay (PDG*)



Alpha emitters such as ^{210}Po and ^{241}Am contribute as an IBD background.

A ^{210}Po $^{13}C(\alpha,n)$ calibration source was developed and deployed to characterize this background in the KamLAND detector.

10.1016/j.nima.2007.12.002

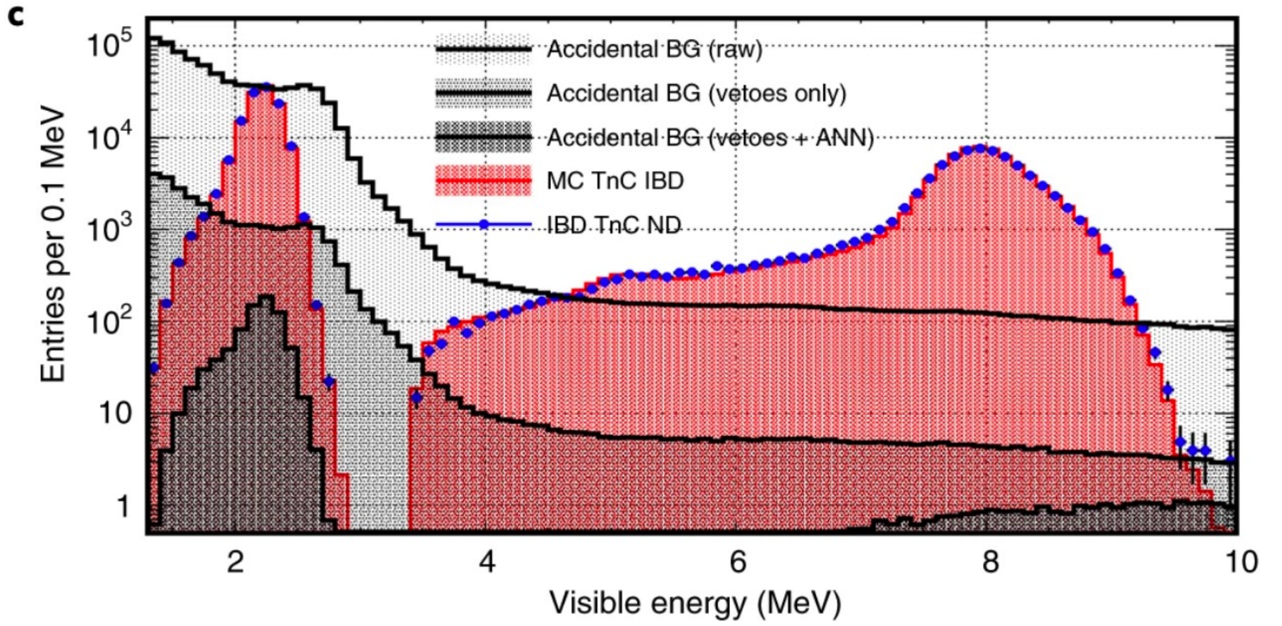
PDG* P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Challenges in precise background measurements

Accidentals

- "Accidental" coincidences or non-correlated events from intrinsic radioactivity ^{232}Th/^{238}U/^{222}Rn in PMT glass and in detector media
    - Can measure spectral shape in-situ. Well determined from non-coincidence or "singles" events
- Beta-neutron radionuclide production due to cosmic muons traversing the detector:
    - ^{9}Li/^{8}He for ^{nat}C, ^{nat}O
    - ^{17}N for ^{nat}O (4.173 s half-life, Q-Value 4.537 MeV)
- "Punch-through" or "fast neutrons" produced from muon activity in the surrounding rock

Double Chooz *Nat. Phys.* **16,** 558–564 (2020)



Data cleaning: Spacetime coincidence definition relies on a multivariable ANN (artificial neural network). Significant rejecting random (uncorrelated) BG coincidences

Challenges in precise background measurements

Beta-neutron isotopes

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  - $^{9}Li/^{8}He$ for ^{nat}C, ^{nat}O
  - ^{17}N for ^{nat}O (4.173 s half-life, Q-Value 4.537 MeV)
  - Well understood spectral shape
  - Can be tagged with production muon/ usually produced from hadronic showering muons
- "Punch-through" or "fast neutrons" produced from muon activity in the surrounding rock

Phys. Rev. 132, 328 – Published 1 October 1963

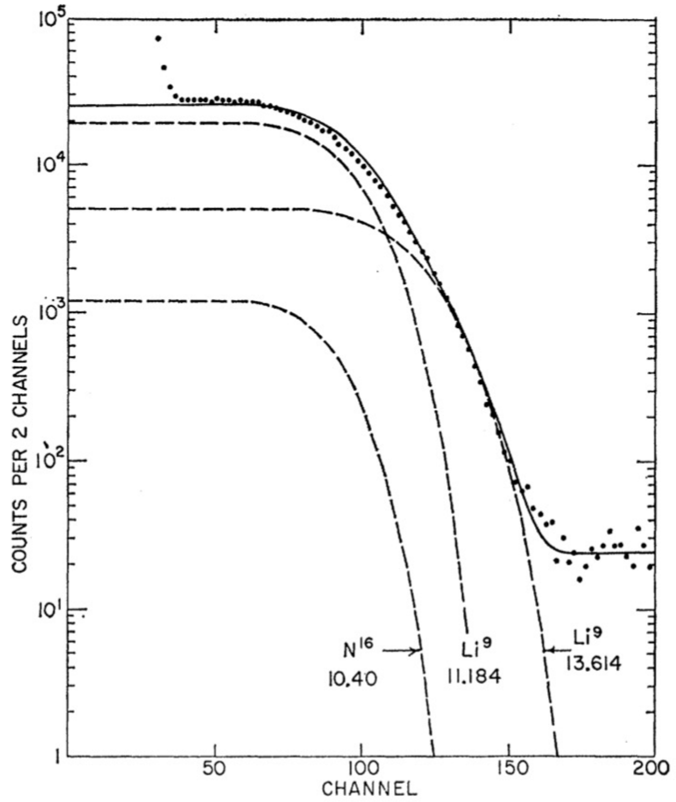

FIG. 4. Shape analysis of the Li⁹ beta-ray spectrum in order to obtain the branching ratios. The dashed curves were constructed from the shape of the Be¹¹ ground-state beta-ray spectrum and their sum (solid curve) gives the best fit to the experimental points.

Challenges in precise background measurements

Fast-neutron

- "Accidental" coincidences or non-correlated events from intrinsic radioactivity ^{232}Th/^{238}U/^{222}Rn in PMT glass and in detector media
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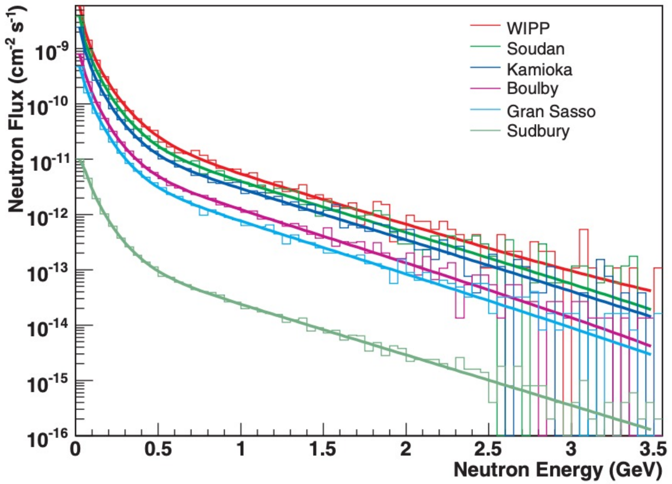
  - Can be tagged with production muon/ usually produced from hadronic showering muons
- "Punch-through" or "fast neutrons" produced from muon activity in the surrounding rock
  - Uncertainty on production yield as a function of depth
  - Disagreement between Geant4 and Fluka response

Predicted neutron energy in rock.

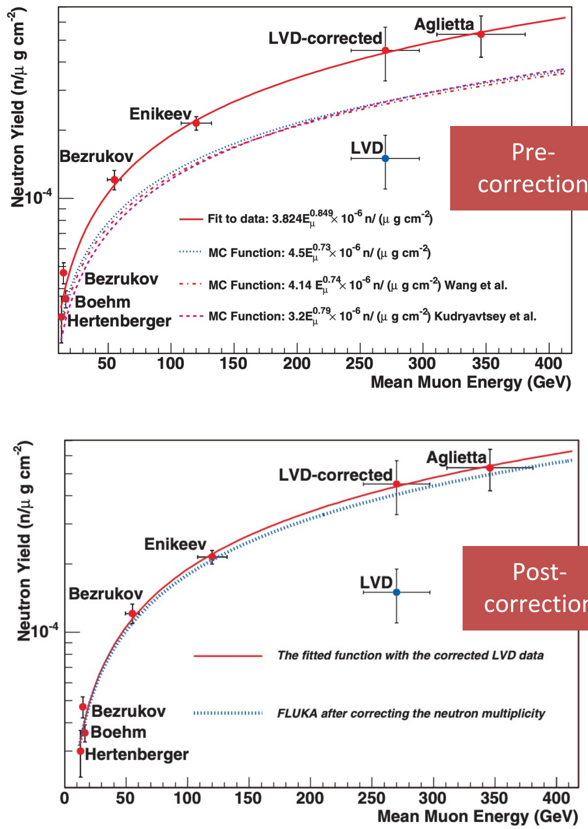


Model predicts external neutron energy in the GeV scaled

We rely on Geant4/FLUKA to model the detector response of these interactions

Neutron production in liquid scintillators. Good agreement with data after correction.

D.-M. MEI AND A. HIME **(2006)**



Pre-correction

Post-correction

PHYSICAL REVIEW D **73,** 053004 (2006)

Challenges in precise background measurements

Fast-neutrons

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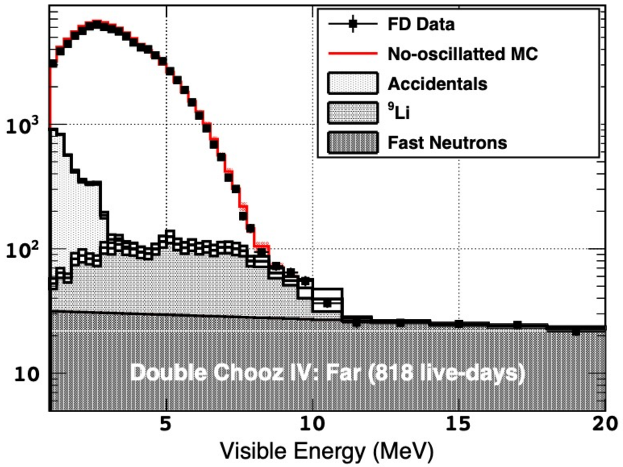
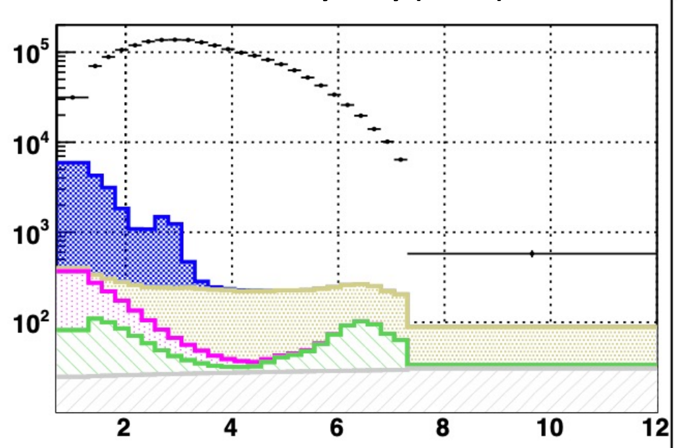
  - Well understood spectral shape
  - Can be tagged with production muon/ usually produced from hadronic showering muons
- "Punch-through" or "fast neutrons" produced from muon activity in the surrounding rock
  - Uncertainty on production yield as a function of depth
  - Disagreement between Geant4 and Fluka response
  - Can be mitigated with adequate veto.
  - Uncertainty on spectral shape. Shape of fast-neutron prompt and 4.44 MeV gamma line.

Double Chooz (PDG*)



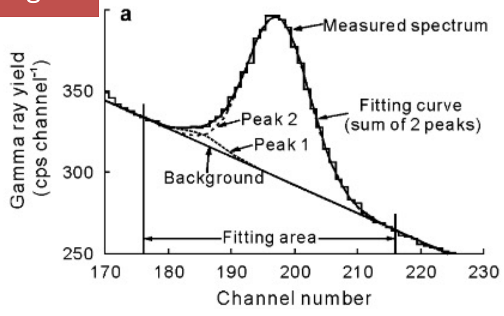
Daya Bay (PDG*)



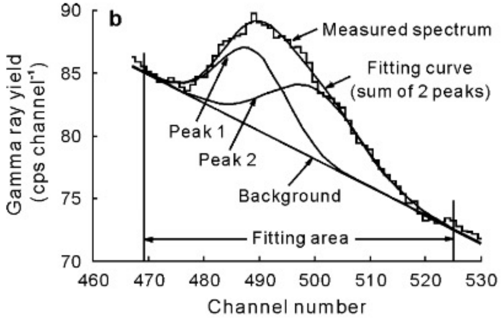
The ^{13}C resonance associated with a fast neutron has not yet been observed in an underground setting

Scanning Mode Application of Neutron-Gamma Analysis for Soil Carbon Mapping
https://doi.org/10.1016/S1002-0160(19)60806-4

1.78 MeV peak



4.44 MeV peak



External methods for evaluating relevant background

Mean muon energy changes as function of depth, impacting the radioisotope yield

Mean muon energy changes as function of depth, impacting the radioisotope yield.

Energy dependence error remain large.

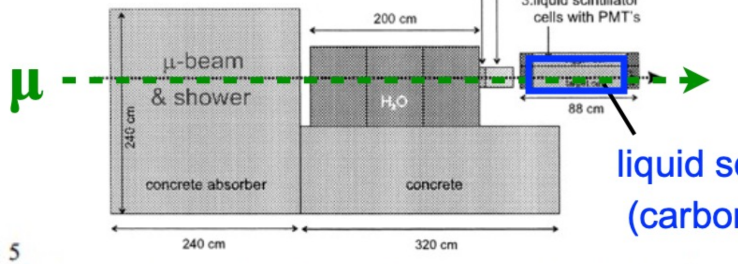
As underground detector are costly, campaigns to characterize detector media by external methods can prove cost effective.

Inclusion of more complex media samples (i.e. LS+Gd, WbLS+Gd, …) in these type of measurements may be very valuable to underground measurements.

Muon Beam Experiment

spallation data (100, 190 GeV)

T. Hagner et al., Astropart. Phys. 14, 33 (2000)



^{11}C rate variation

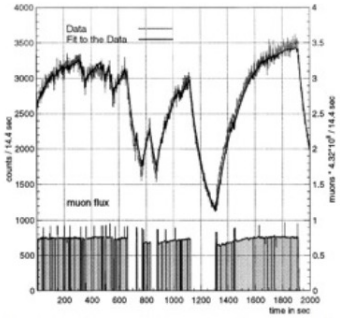


Table 5

Cross-sections σ and energy dependences α for all muon-induced radioactive isotopes which can be produced in a scintillator (^{12}C) target[a]

Isotopes	σ in μbarn for E_μ (GeV) 100	190	Energy dependence exponent α
^{11}C	576 ± 45	905 ± 58	0.70 ± 0.16
^{7}Be	127 ± 13	230 ± 23	0.93 ± 0.23
^{11}Be	<1.22 (68% CL)	<2.34 (68% CL)	
^{10}C	77.4 ± 4.9	115.4 ± 14.6	0.62 ± 0.22
^{8}Li	2.93 ± 0.80	4.02 ± 1.46	0.50 ± 0.71
^{6}He	10.15 ± 1.0	16.02 ± 1.60	0.71 ± 0.22
^{8}B	4.16 ± 0.81	7.13 ± 1.46	0.84 ± 0.45
^{9}C		4.83 ± 1.51	
$^{9}Li + {}^{8}He$		2.12 ± 0.35	

[a] The cross-sections (given in μbarn) have been measured at two different muon beam energies, $E_\mu = 100$ GeV and $E_\mu = 190$ GeV, respectively. The weighted mean value of the exponent α is $\langle\alpha\rangle = 0.73 \pm 0.10$.

$\sigma(E) \propto E^\alpha$

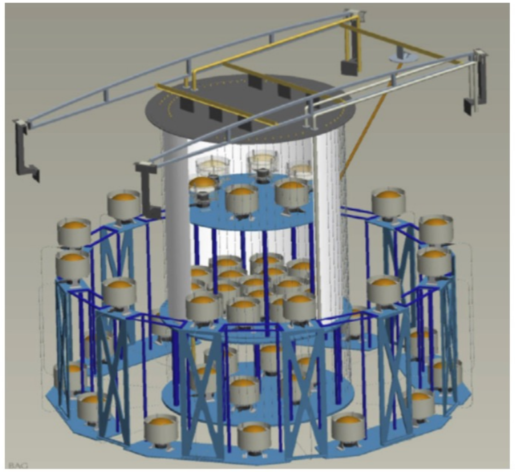
Spallation Background, 3rd Open Meeting for the Hyper-Kamiokande Project! June 21, 2013, I. Shimizu

Smaller dedicated experiments can have major impact

The WATCHBOY detector is an example of a small-scale effort with good returns

- An example of a small-scale (2-ton target, 16 target PMTs)
- Fluka results are consistent with measured data at depth (300~400 m.w.e)
- Error on models remain large

Watchboy detector



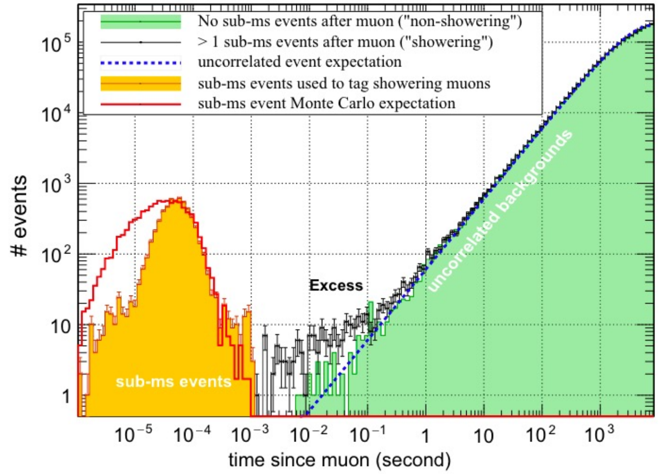
Raduionuclide

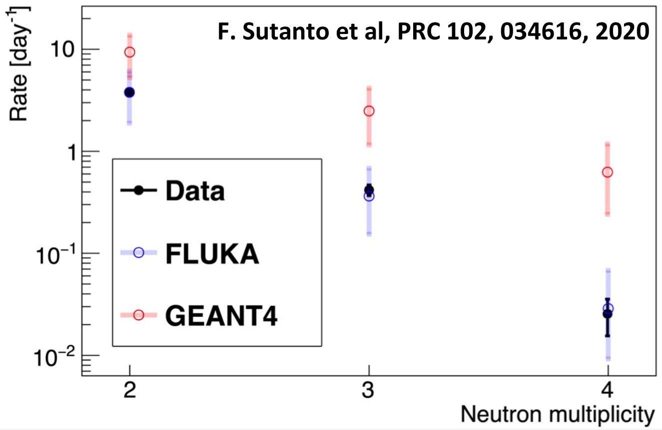
Hadronic shower tag

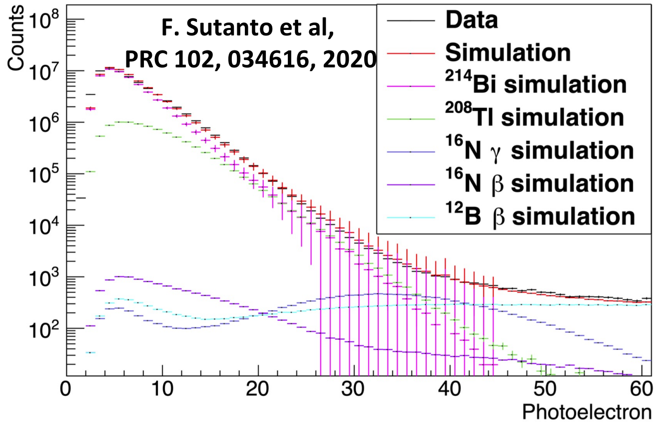
Observation without tag

Fast-neutron response

S. Dazeley et al. NIMA 821 (2016) 151–159







For larger scale experiments, atmospheric neutrino backgrounds

Neutral current background if ^{nat}O is present

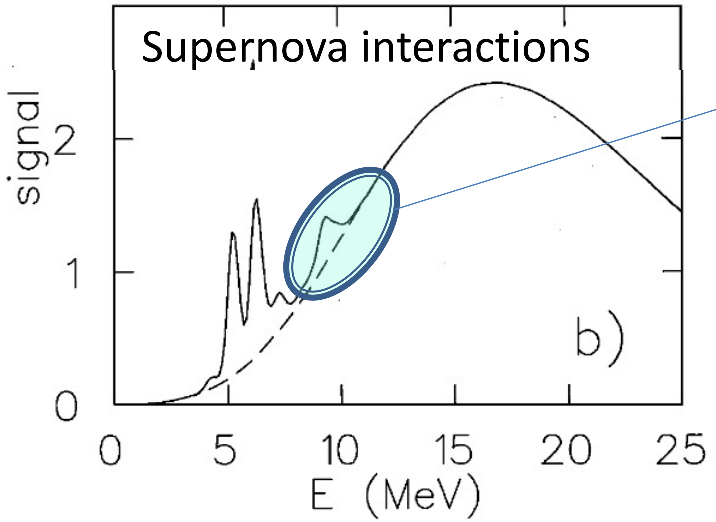
$$\nu + {}^{16}\mathrm{O} \rightarrow \nu + {}^{15}\mathrm{O} + n + \gamma,$$

$$\nu + {}^{16}\mathrm{O} \rightarrow \nu + {}^{15}\mathrm{N} + p + \gamma,$$

Super-Kamiokande (Phys. Rev. D 99, 032005) measured atmospheric neutrino neutral current.

$$\overset{(-)}{\nu}_x + {}^{16}\mathrm{O} \rightarrow {}^{16}\mathrm{O}^* + \overset{(-)}{\nu}_x,$$
$$ {}^{16}\mathrm{O}^* \rightarrow {}^{15}\mathrm{O} + n + \gamma \; (\sim 10\%)$$

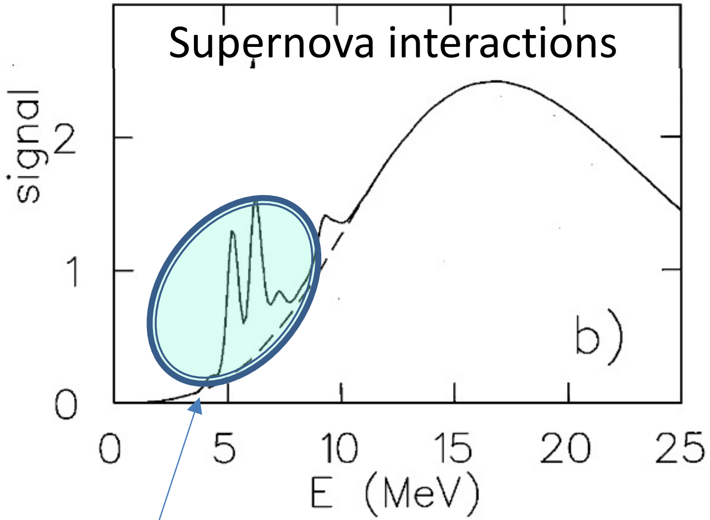
Langanke, Vogel and Kolbe PhysRevLett.76.2629



Super-Kamiokande measured ~0.4 NCQE events per kiloton per year

Note: Measurement made with higher energy threshold on prompt (>7.5 MeV), a neutron detection efficiency (~30%)

Langanke, Vogel and Kolbe PhysRevLett.76.2629



Beam experiments such as ANNIE may be able to measure the rate of these background events.

Summary

- In precision underground experiments it will remain vital to optimize detector designs to minimize backgrounds.
- There remain large uncertainties on key backgrounds. A dedicated program to fully characterize IBD underground backgrounds may prove cost effective.
  - Further experiment dedicated to more precise fast-neutron measurements in different detector media would greatly impact future detector design.
  - External methods, such as the muon beam experiments, should be revisited for new detector cocktails such as LS-Gd, WbLS, WbLS-Gd, H_2O-Gd, etc.
- One must be careful in performing multiple detector comparisons, as yield change with detector depth leading to subtle variations.

$$N = \frac{N_s}{4\pi L^2}\varepsilon M_{det}\frac{P_{th}}{\langle E_f\rangle}P_{osc}\sum_i f_i\phi_i\sigma + B - B_{estimated}$$

In relative measurement one must still subtract expected background, which may be site specific.

Lawrence Livermore National Laboratory