Inverse Beta Decay Signatures at SoLid

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Introduction

The SoLid experiment
- Sterile neutrino search at baseline 5.5m → 10m
- Resolve the reactor anomaly
- Measure U^{235} anti ν_e energy spectrum

Novel detector technology
- 5cm PVT cubes → EMs (e^+, μ, γ) scintillation
- Sheets of ^{6}Li:ZnS(Ag) → neutron scintillation
- 3D detection via arrays of light fibres (xy)

Decay Channel - IBD
- Inverse beta decay: $\overline{\nu}_e$ + p → e^+ + n
- Positron scintillation and annihilation followed by delayed O(100)μs neutron

Large Scale Prototype - SM1
- 288kg prototype (20% SoLid phase 1)
- Demonstrate novel technology
- Experience running large scale detector

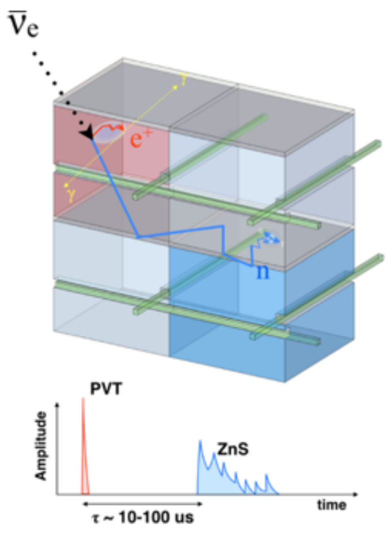


Fig: IBD signal at SoLid.

IBD Analysis Goals at SoLid SM1 Prototype
- Demonstrate **background reduction via segmentation**
  - Study event topology (multiplicity, spatial separation in xyz)
- Perform **initial selection** of IBD events for background studies
  - Inform phase 1 design
- **Develop tools and methods** in preparation for phase 1 data

Particle Identification

Neutrons
- Detected by 225μm 5cm² sheets of ^{6}Li:ZnS(Ag) scintillator
  - Light emitted much slower than EM signals from PVT → pulse shape discrimination for neutron ID
- Ratio of integral to amplitude gives excellent discrimination between Neutrons and EM signals

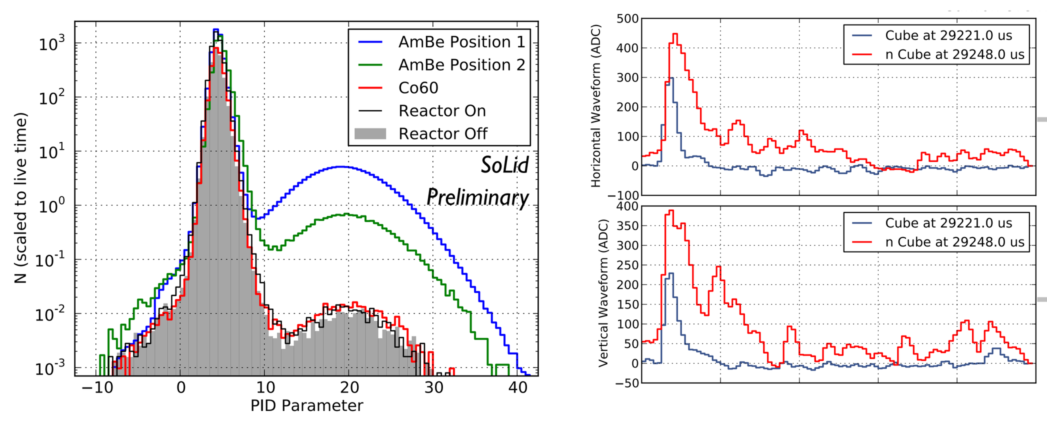


Fig: Neutron PID parameter (left), and example EM and neutron waveforms (4μs, right). **Data**

Muons and Positrons
- EM signals via PVT
  - Important to separate e^+ from μ for background rejection
  - Separated using topology and energy measurements
- Subset of muons can be tracked → standard candle
  - Used for calibration
  - Verify time stability
  - Study overburden

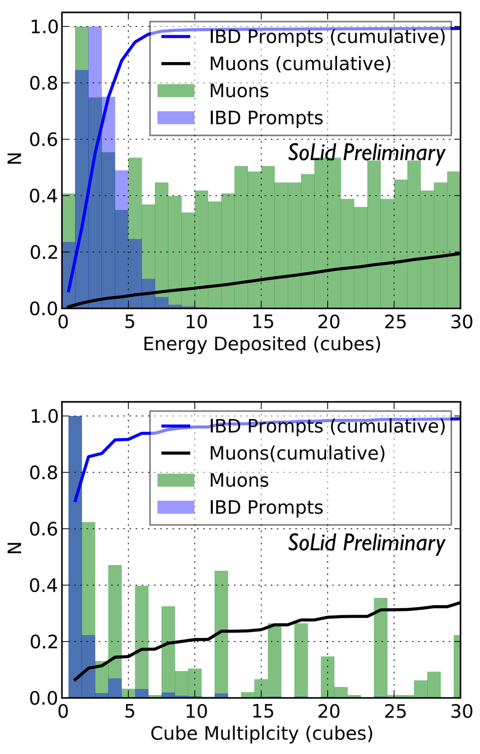
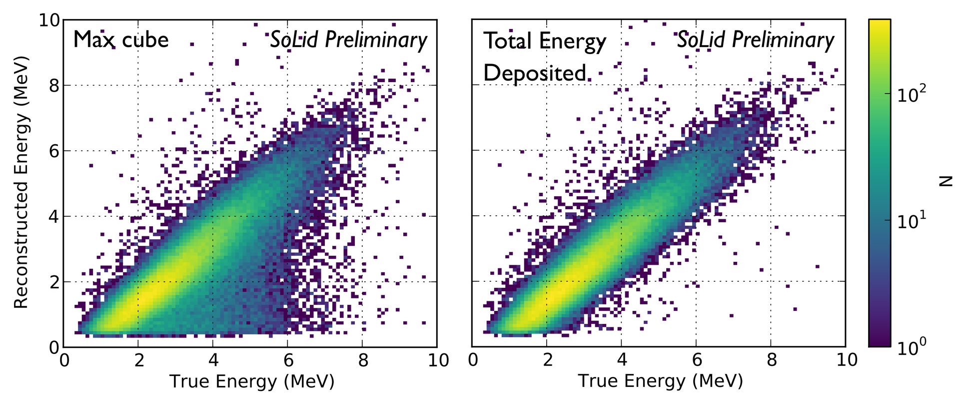


Fig: Energy (top) and cube multiplicity (bottom) distributions for e^+ and μ events. **Sim**

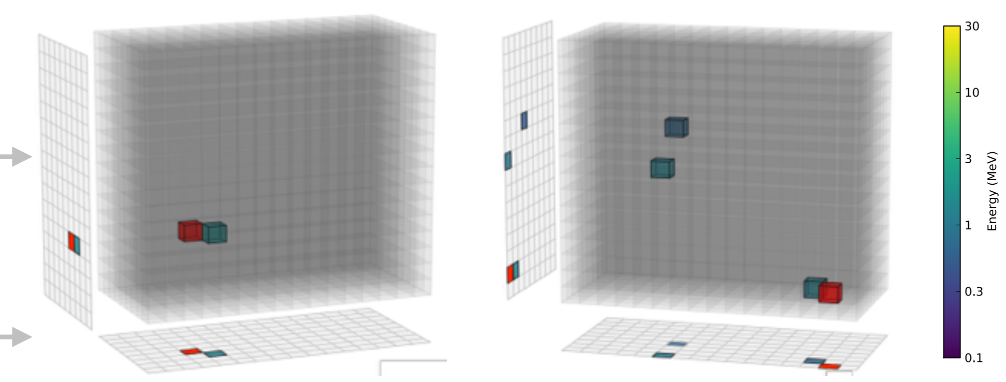
Prompt Reconstruction - Positron Energy
- Positron with two annihilation photons (negligible γ detection efficiency in SM1 prototype)
- Two estimators compared for energy reconstruction
  - Maximum Cube (results in ambiguous cases)
  - Total energy deposited in detector



Figs: Reconstructed energy vs true energy for prompt IBD events using two estimators for the SM1 prototype. Effects from detector response included. **Sim**

IBD Candidate Selection

Signal
- EM prompt (P) event with delayed (D) neutron event
  - Correlated in time and space
- Prompt contained in two touching cubes in >95% cases



Figs: IBD Candidate from prototype data (left), and another with tagged accidentals (right). EM signals use the (shared) colour scale. Neutrons marked in red. **Data** (288kg prototype SM1)

Accidental Background - B_{Acc}
- Random EM event (e.g. muon) associated to a random neutron (e.g. reactor neutron)
- Combated by topology and lower energy selections

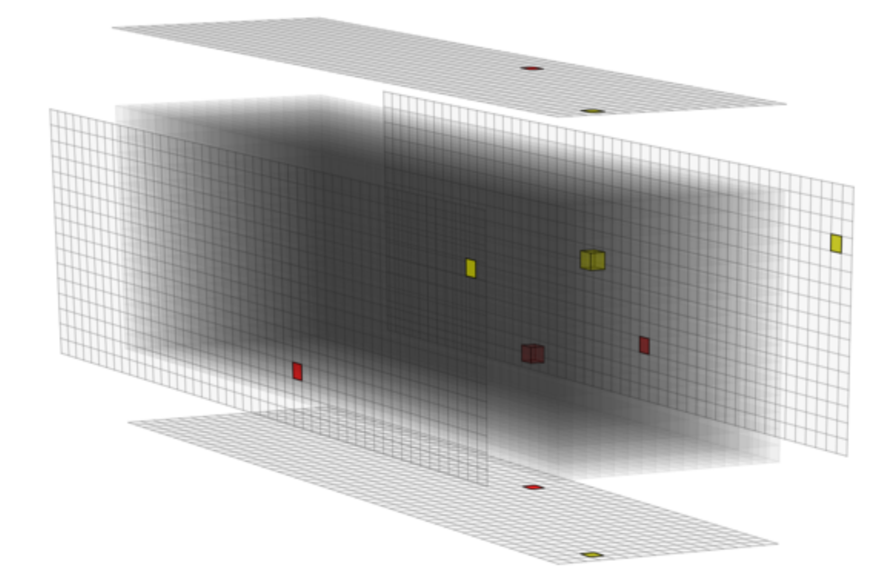


Fig: Example accidental event. **Sim** of phase 1 (1T mass).

Correlated Background - B_{Cor}
- EM event and neutron produced in same process
  - Muon spallation in the detector - combat with muon ID
  - High energy neutron - combat with multiplicity selections

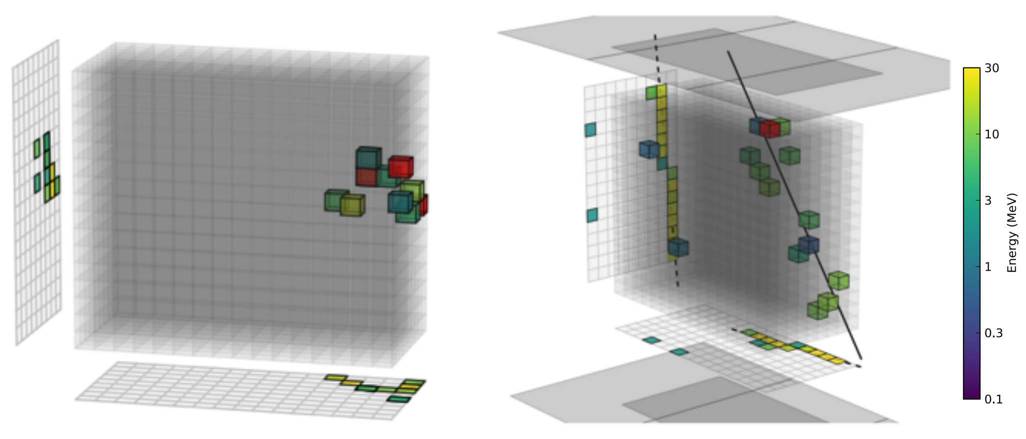


Fig: Cosmic fast neutron candidate. **Sim**

Fig: Muon spallation candidate. Muon umbrella included. **Data**

Particle Identification

Time Difference - Δt
- P and D correlated at n thermalisation time scale (for S and B_{Cor})
- B_{Acc} gives flat contribution - studied with off-time windows
  - Different for reactor on and reactor off

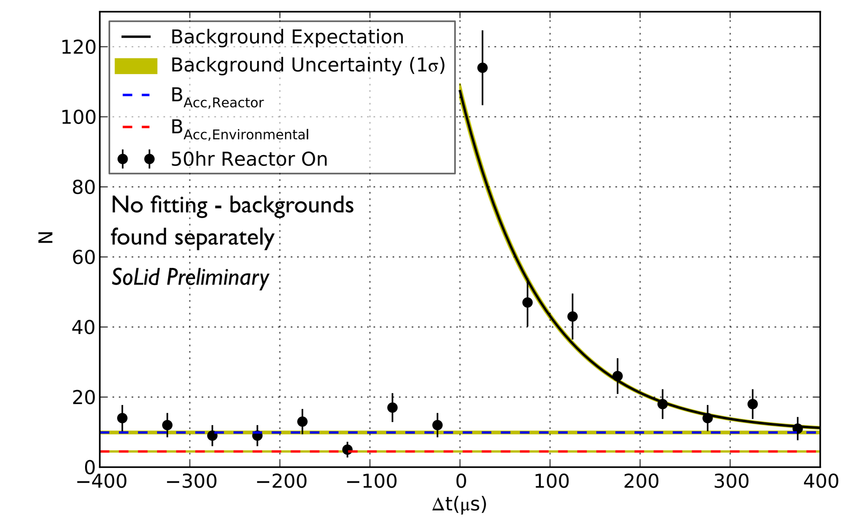
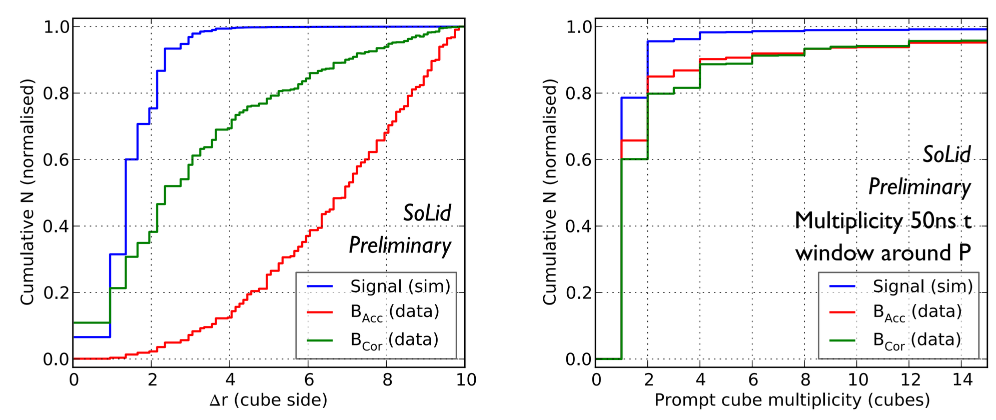


Fig: Δt distribution for reactor on data (all other selections applied). Background expectation in solid black line (**no fitting**). Sample statistically limited obscuring neutrino signal. **Data**

Topology - Δr and Multiplicity
- Radial separation for signal extremely effective for B rejection
  - Signal: 90% cases P and D separated by <3 cubes
  - Effective for tackling B_{Acc}
- Multiplicity around the prompt effective to reduce B_{Cor}
  - Proton recoils produced through fast n thermalisation



Figs: Δr (left) and multiplicity (right) distributions for signal (**Sim**) and backgrounds (**Data**).

Likelihood Discriminator
- IBD feature distributions combined to form likelihood discriminator - global likelihood (GL)
  - Backgrounds trained from data, signal trained from sim
- 15% more signal retained compared to using orthogonal cuts

GL = L/(L_{uncorr}+L_{corr}+L_{sim})

with

$L_i = P^i_{\Delta x}(\Delta x) \cdot P^i_{\Delta y}(\Delta y) \cdot P^i_{\Delta z}(\Delta z) \cdot P^i_{\Delta t}(\Delta t)$

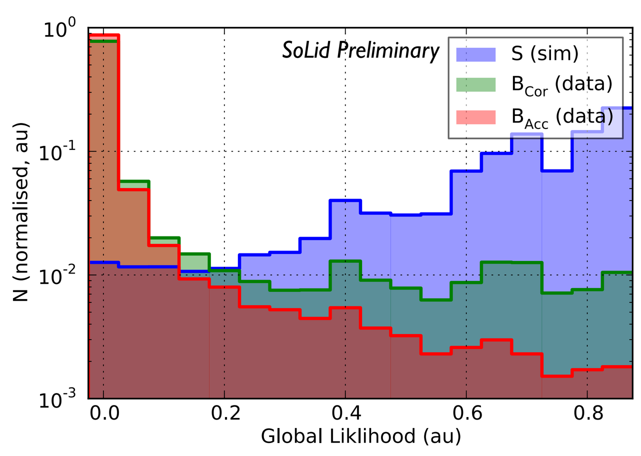


Fig: Global likelihood distributions.

Particle Identification

- Cut based selections on IBD features (prompt energy, timing, topology) to tackle backgrounds
- Factor of **O(10) reduction** in B_{Cor}, **O(100) reduction** in B_{Acc} → largely from topology
- **Good agreement between data and sim** for prototype module backgrounds!

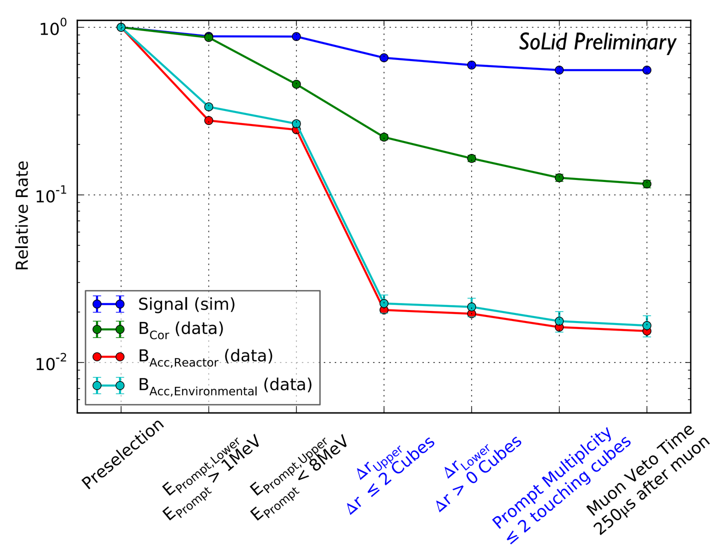


Fig: Selection efficiencies for signal and backgrounds.

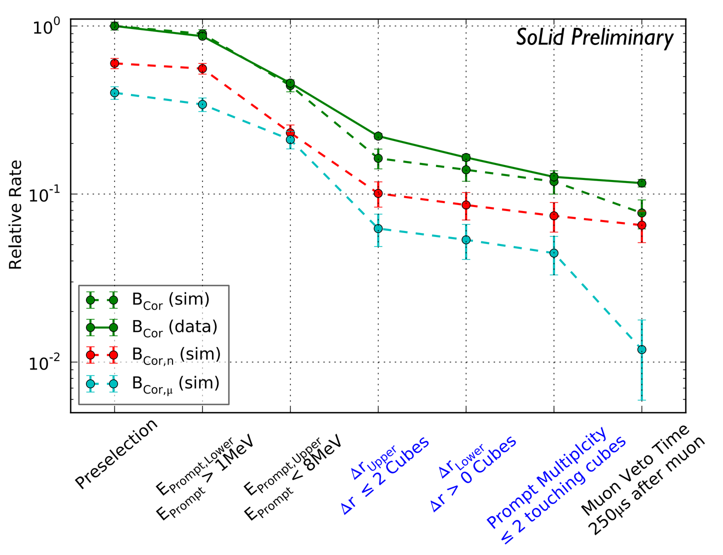
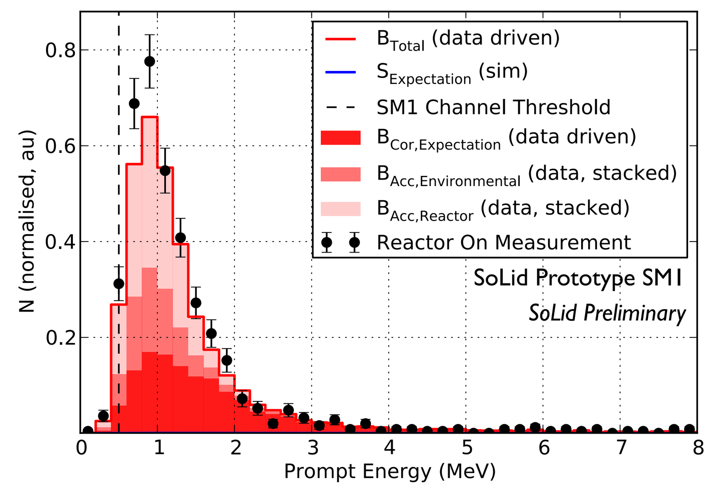
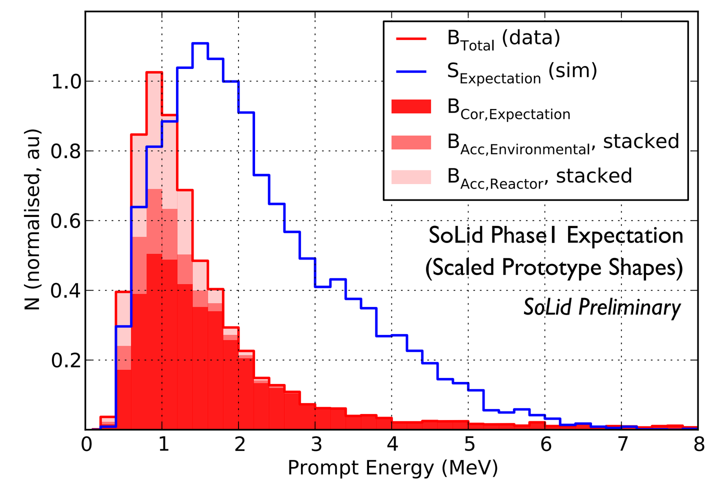


Fig: Simulation-data comparison for correlated background.

Outlook - Phase 1 Sensitivity

- Orthogonal cuts and likelihood discriminators used to select Inverse Beta Decay events at SoLid
  - Signal selection efficiency ~50% with large B rejection
- Expect **S:N ~ 3:1 in SoLid Phase 1** (E_{Prompt} > 1MeV)
- Phase 1 improvements
  - Passive shielding (50cm water + steel sheets)
  - Novel neutron trigger with O(ms) buffer
  - Increased light yield and more uniform readout





Figs: Prompt energy distributions expectations (all other selections applied) for prototype (left, with data), and phase 1 (right).