Spallation Studies in Super Kamiokande

Scott Locke (University of California, Irvine) on behalf of the Super-Kamiokande Collaboration
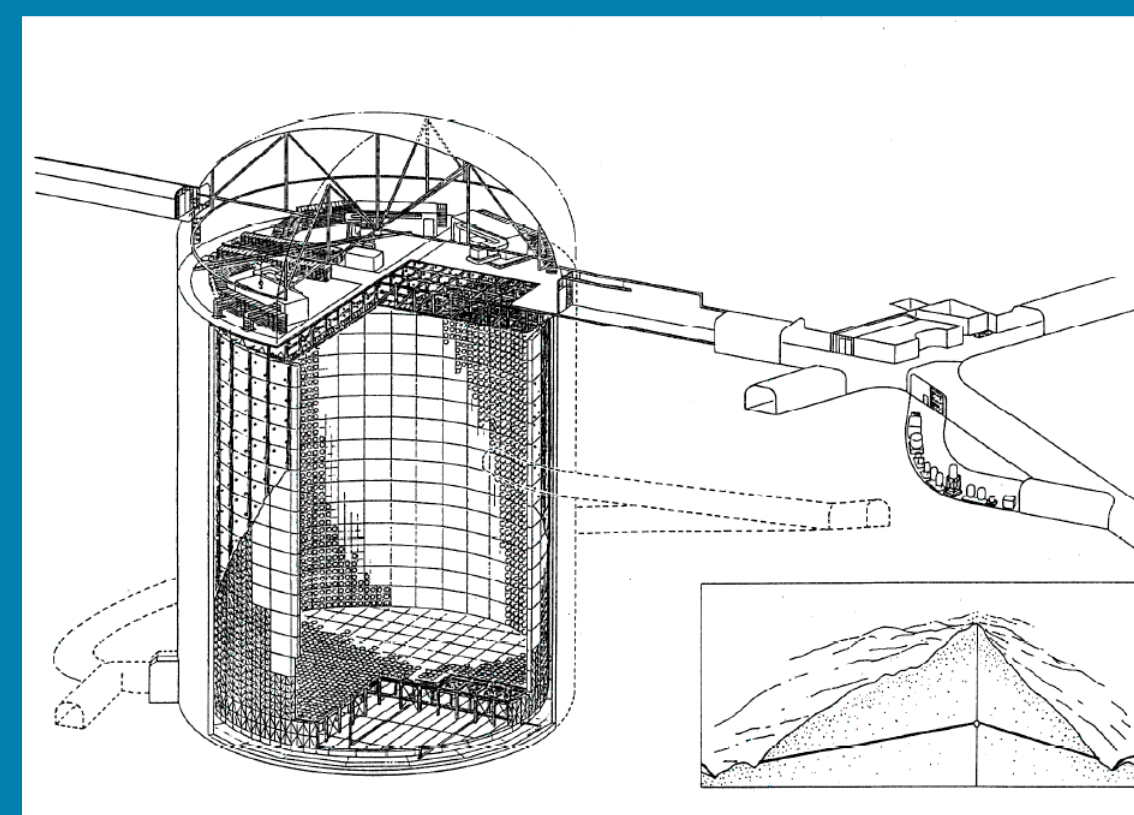
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Super Kamiokande and Spallation

The Super-Kamiokande (SK) water Cherenkov detector started data taking in 1996. Its longest phase finished data taking in 2018, when preparations were made to start doping the water with gadolinium sulfate [$Gd_2(SO_4)_3$].

SK experiences muons at a rate of ~2 Hz, with most depositing a few GeV of energy in the detector but some depositing much more. Hadronic showers from these muons have a chance to spall nuclei in the water, creating radioactive isotopes. The decay of these isotopes are the largest background in the 5.49-19.49 MeV kinetic energy region. Work has been done to add and improve tagging techniques. The published[1] method for tagging spallation for the solar neutrino analysis accrues 20% dead time with 90% tagging efficiency.
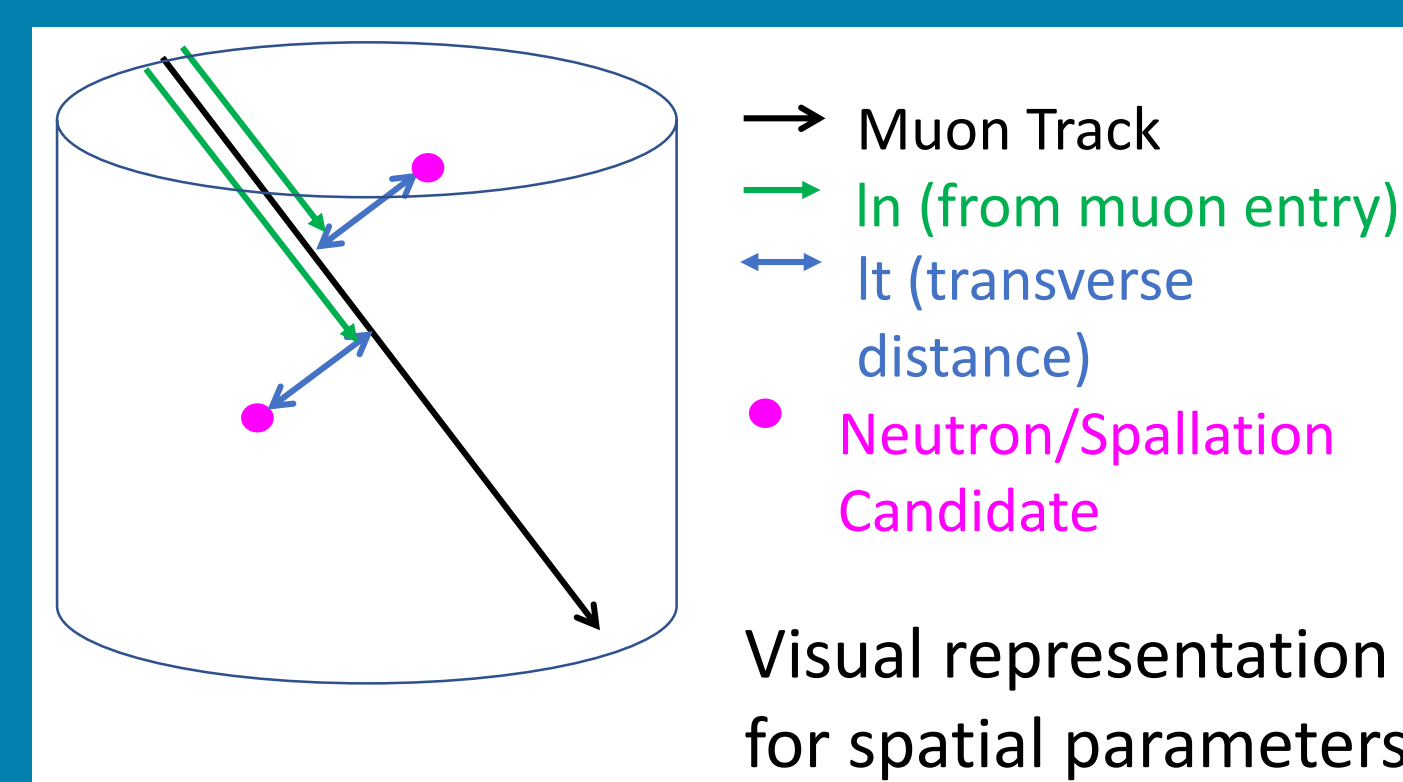
Parameter Definition

Transverse distance (lt):
    Distance of closest approach of event to track
Longitudinal distance (ln):
    Distance along track in reference to shower
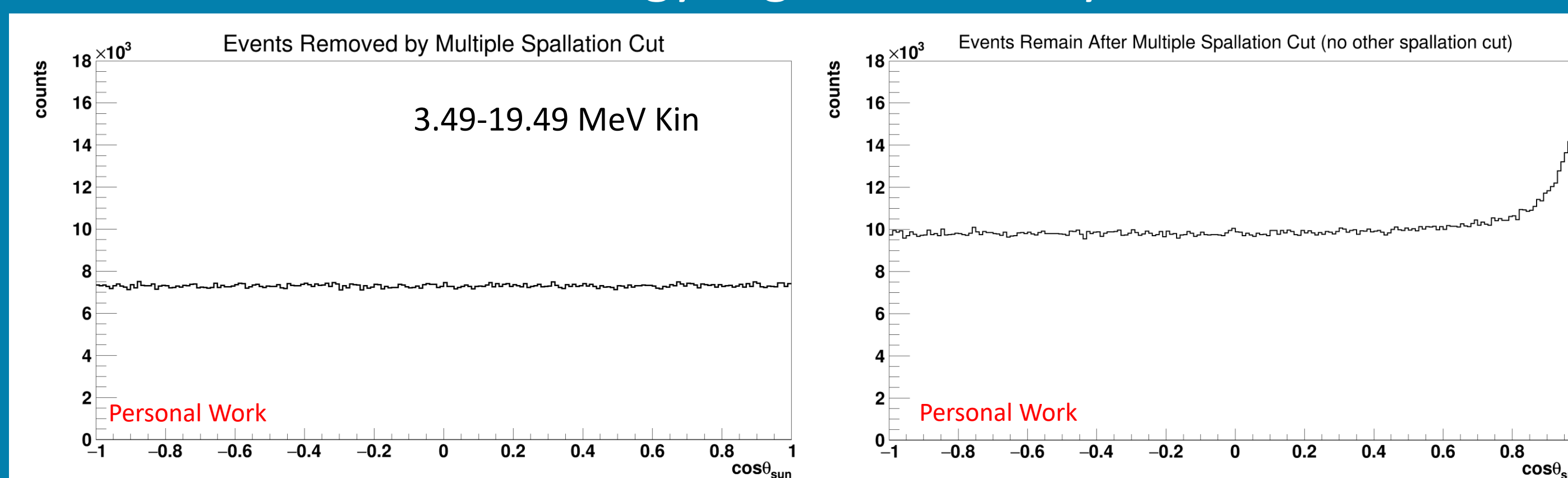Time difference (dt)
    Time from muon to candidate
Multiplicity:
    Number of candidate events for a muon

→ Muon Track
→ ln (from muon entry)
↔ lt (transverse distance)
● Neutron/Spallation Candidate

Visual representation for spatial parameters

Residual Charge (resq):
    Excess light from muon, above minimum ionizing particle
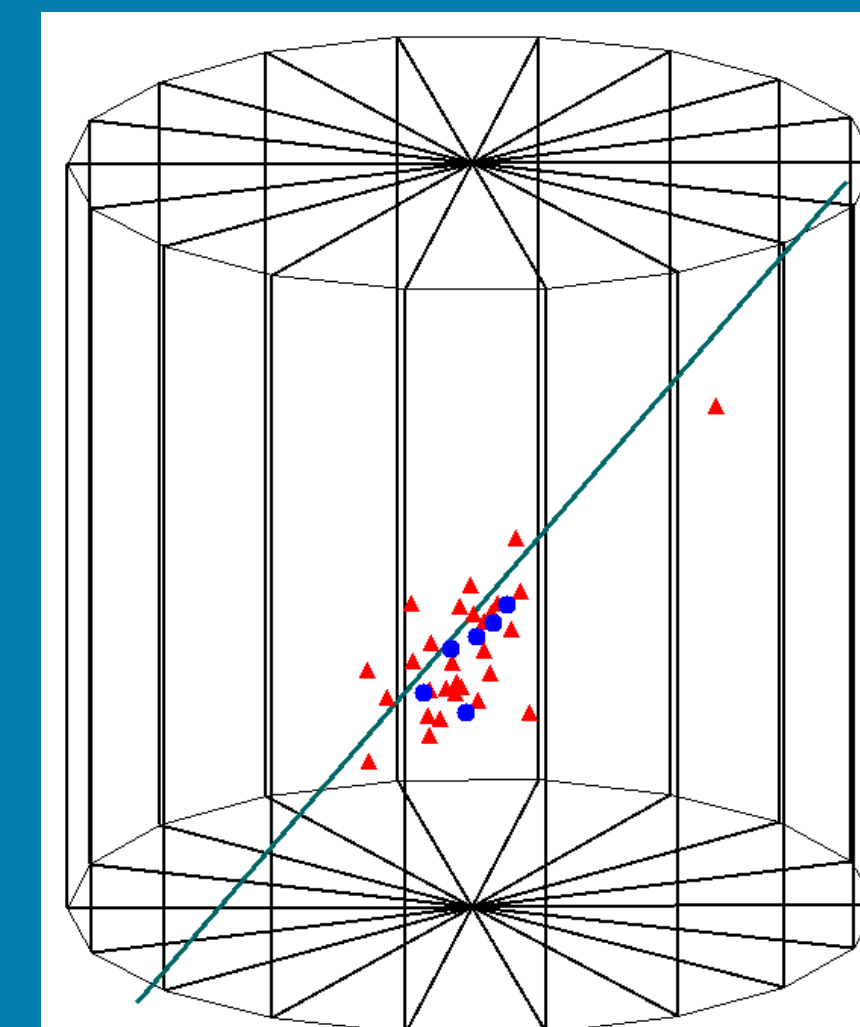 $E_{tot} - (E_{MIP}$ per cm)*(track length)

Multiple Spallation

This novel approach to use spallation to tag itself does not use muon information. Since multiple solar neutrino events are not expected to be nearby in space and time, we can use multiple events as a veto. By cutting events within 4m and 60s of each other, ~45% of spallation events are removed in the 5.49-19.49 MeV kin. energy region with only 1.4% deadtime

Events Removed by Multiple Spallation Cut
3.49-19.49 MeV Kin
Personal Work

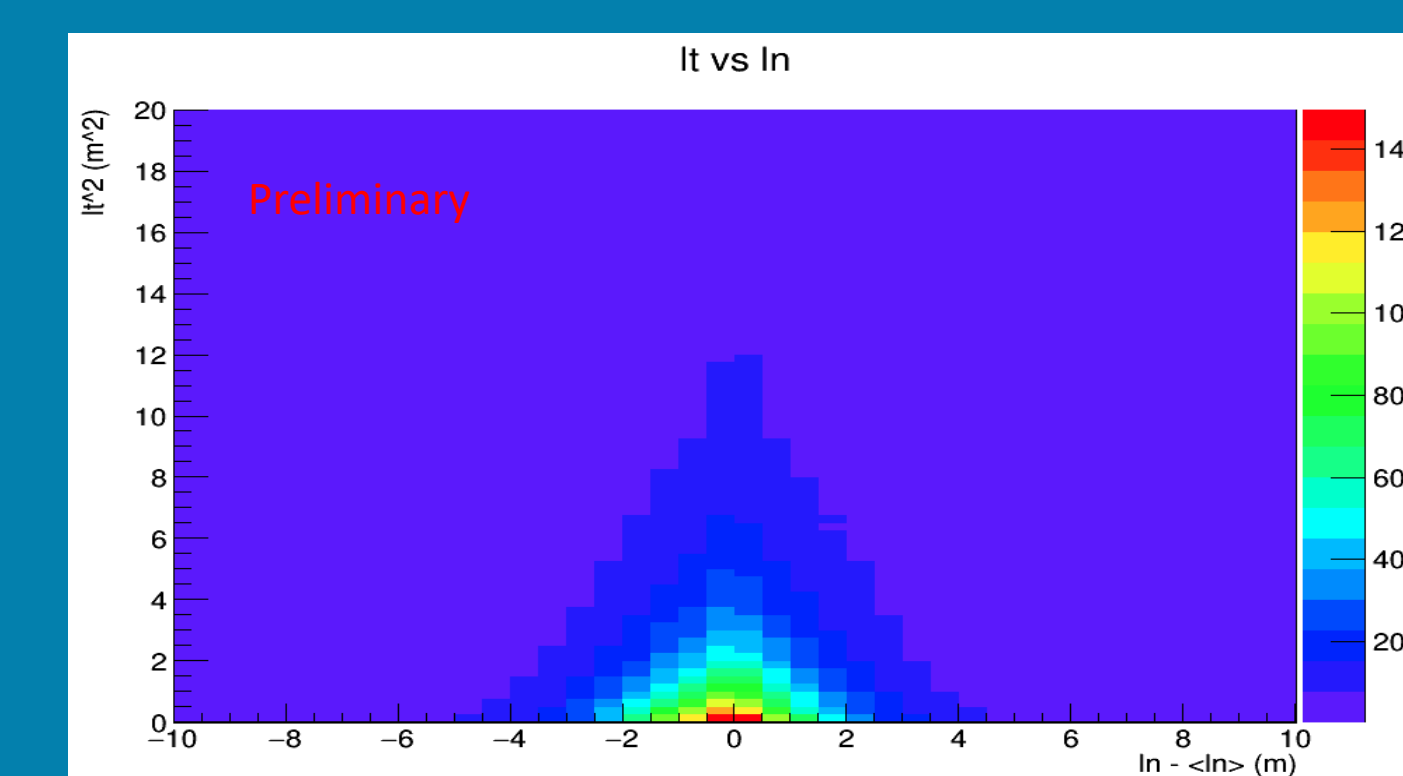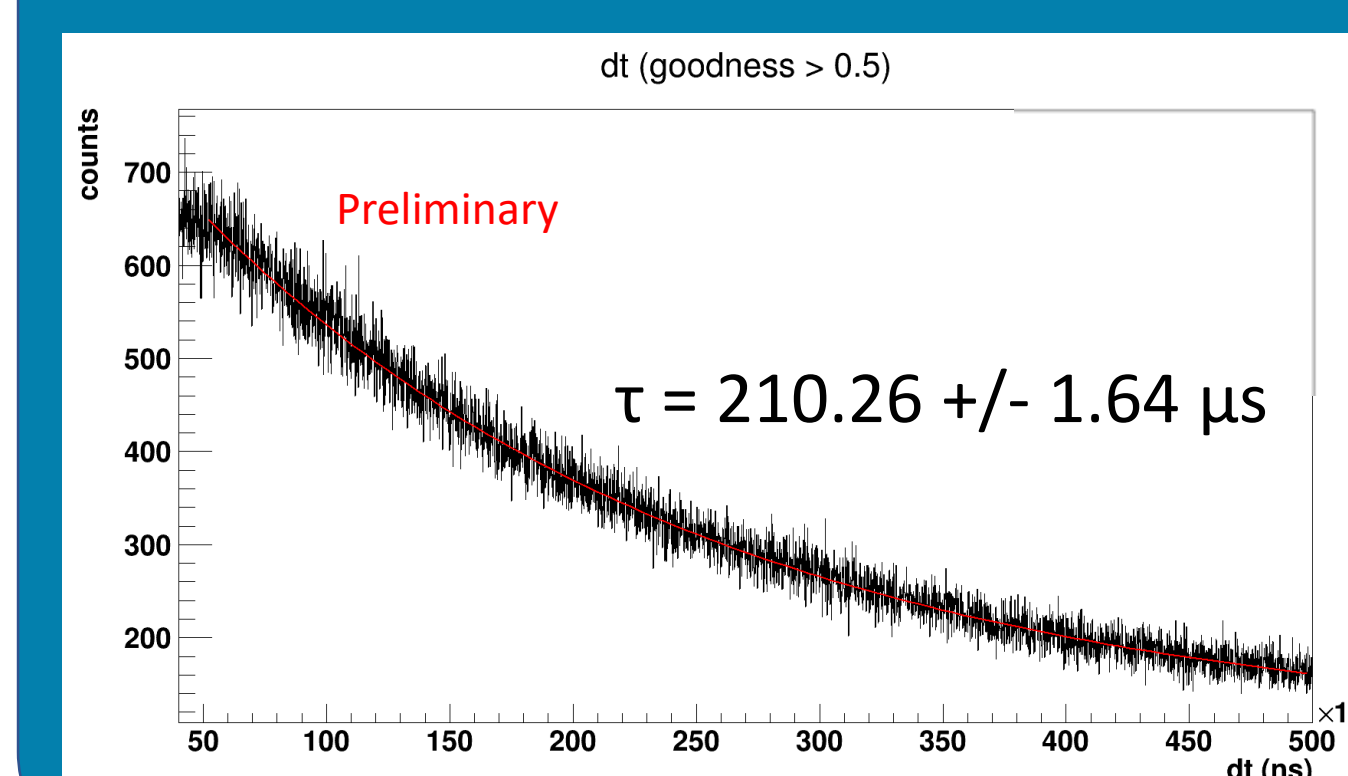Events Remain After Multiple Spallation Cut (no other spallation cut)
Personal Work

Neutron Clouds

The WIT (Wideband Intelligent Trigger) system independently triggers and reconstructs 2.2 MeV γs from n-capture on H. Spallation producing showers typically have many neutrons, and neutrons from WIT define a bubble cut around the showers.

However, WIT's neutron detection efficiency is low, so this method alone is insufficient to tag all spallation in pure water: ~55% of spallation is tagged with only 1.3% deadtime.

● Neutron Candidate
● Spallation Candidate

Example shower with neutron (red) and spallation (blue) candidates

dt (goodness > 0.5)
Preliminary
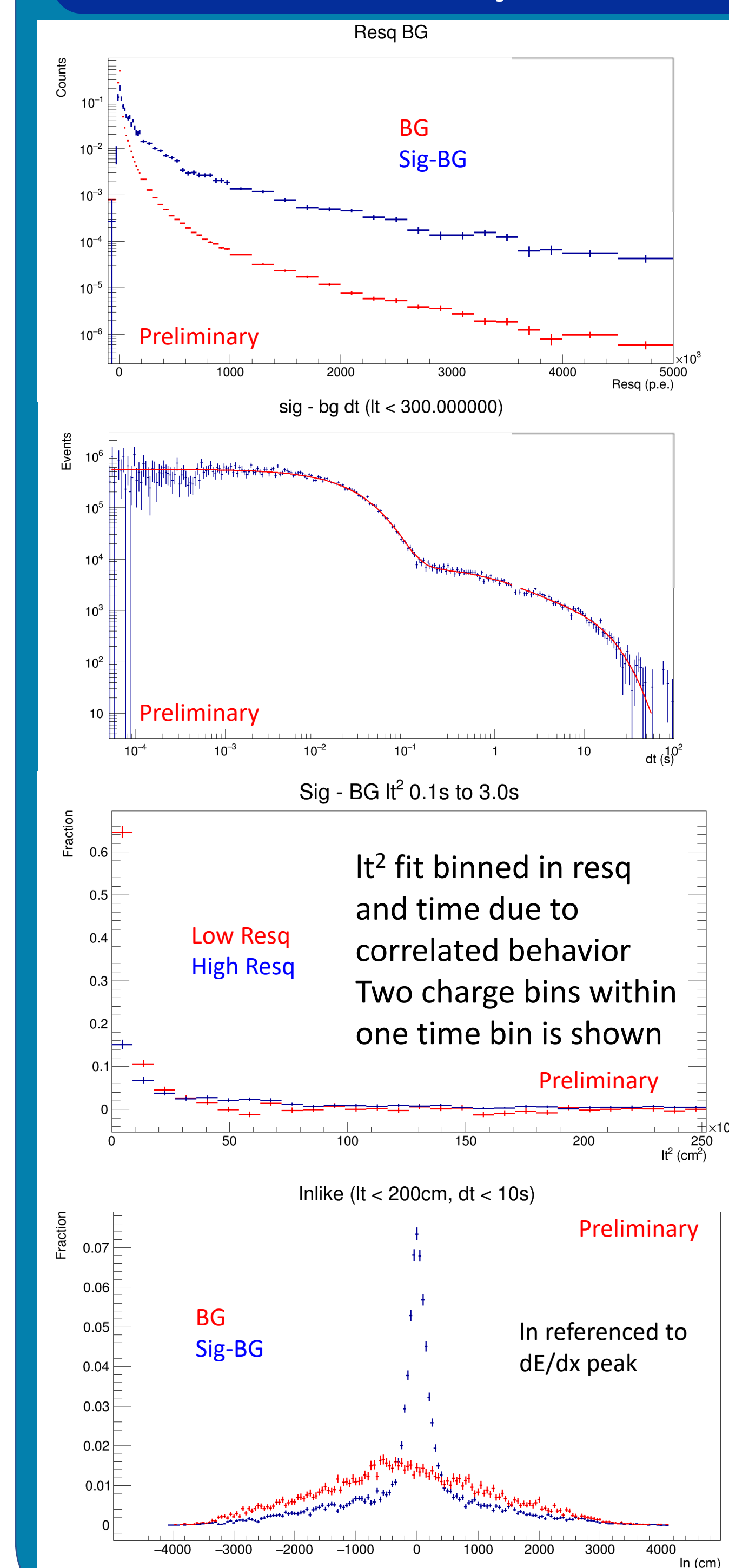τ = 210.26 +/- 1.64 μs

lt vs ln
Preliminary

Spallation Likelihood

The published method to tag spallation is a likelihood cut based on three variables of the muon and spallation candidate pair: lt, dt, and resq. Changes to these three PDFs and the addition of a fourth variable, ln, based on the reconstructed muon dE/dx further improves the tagging. Updating the muon fitter used to calculate the likelihood has also yielded significant gain to tagging this background.

The cut point was chosen to maintain previously published spallation tagging efficiency, 90%, minimizing deadtime.
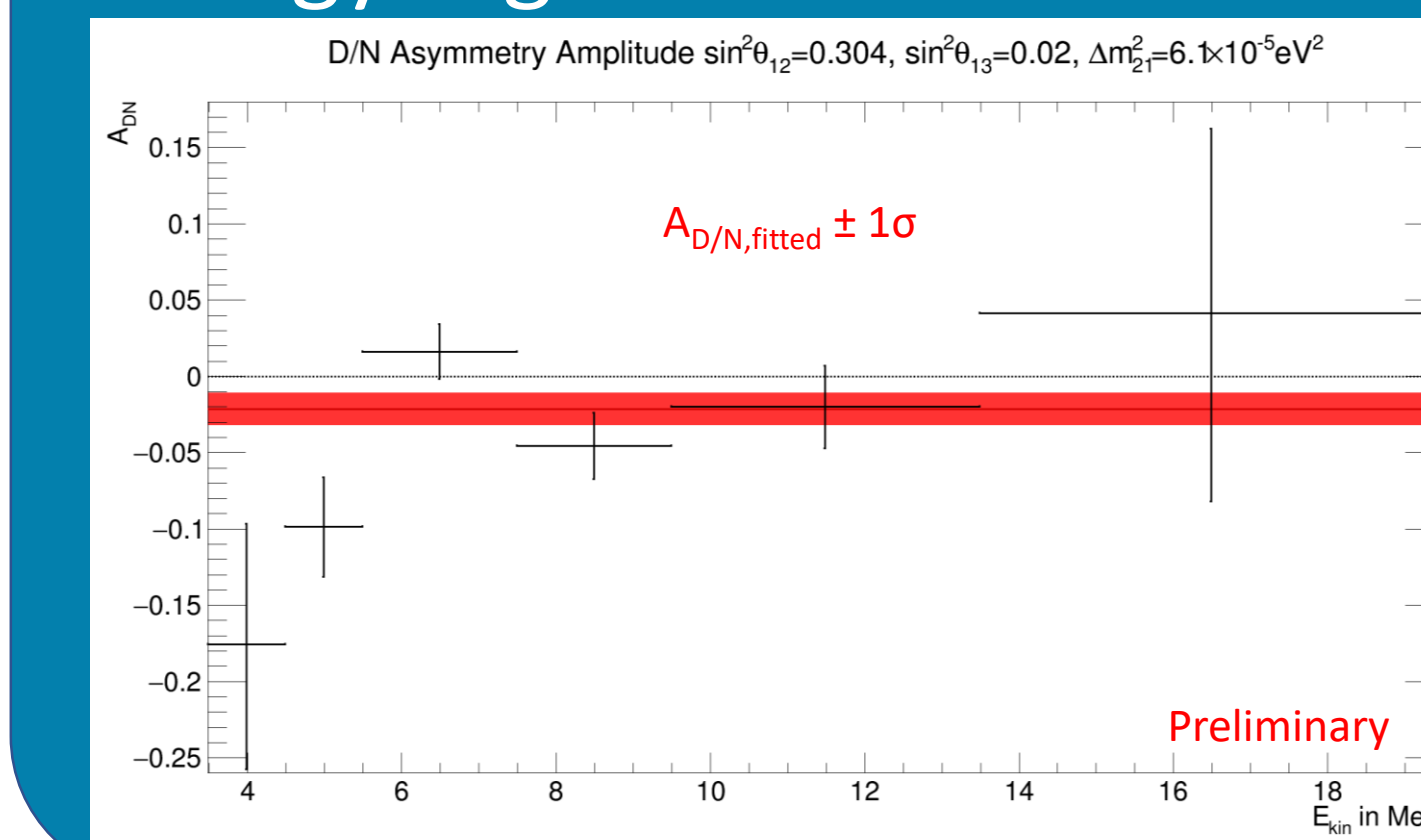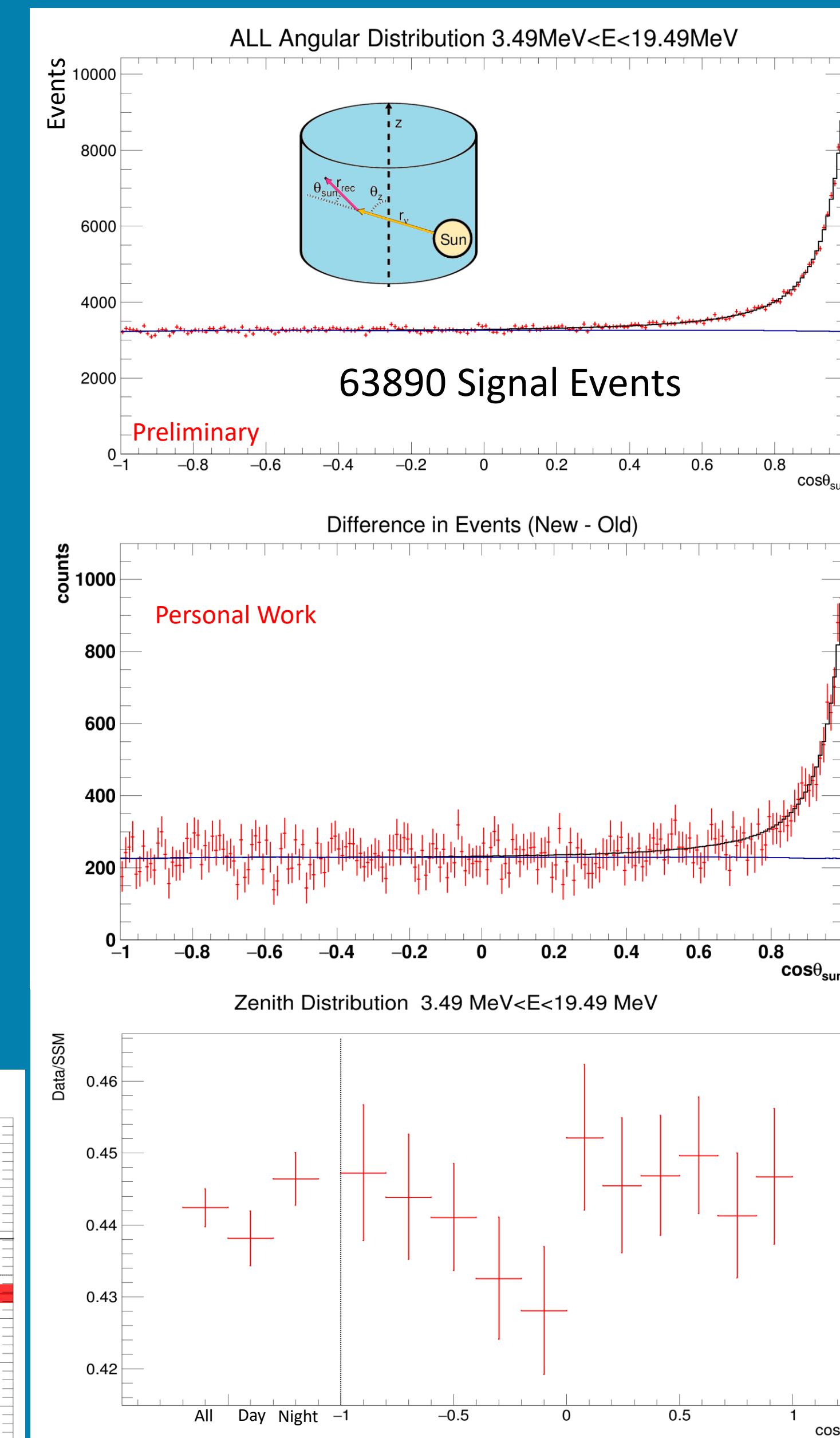
Resq BG
BG
Sig-BG
Preliminary

sig - bg dt (lt < 300.000000)
Preliminary

Sig - BG lt² 0.1s to 3.0s
Low Resq
High Resq
Preliminary
lt² fit binned in resq and time due to correlated behavior
Two charge bins within one time bin is shown

lnlike (lt < 200cm, dt < 10s)
Preliminary
BG
Sig-BG
ln referenced to dE/dx peak

Method	Deadtime
Previous	20%
WIT	9.0%
Non-WIT	10.8%

Results

Since WIT neutron data starts in 2016, two cuts were chosen for the WIT/non-WIT periods. The reduction in deadtime has resulted in 12% more events, and a decrease of 6.5% in relative error. The 6,862 more events is around an extra year of solar data.
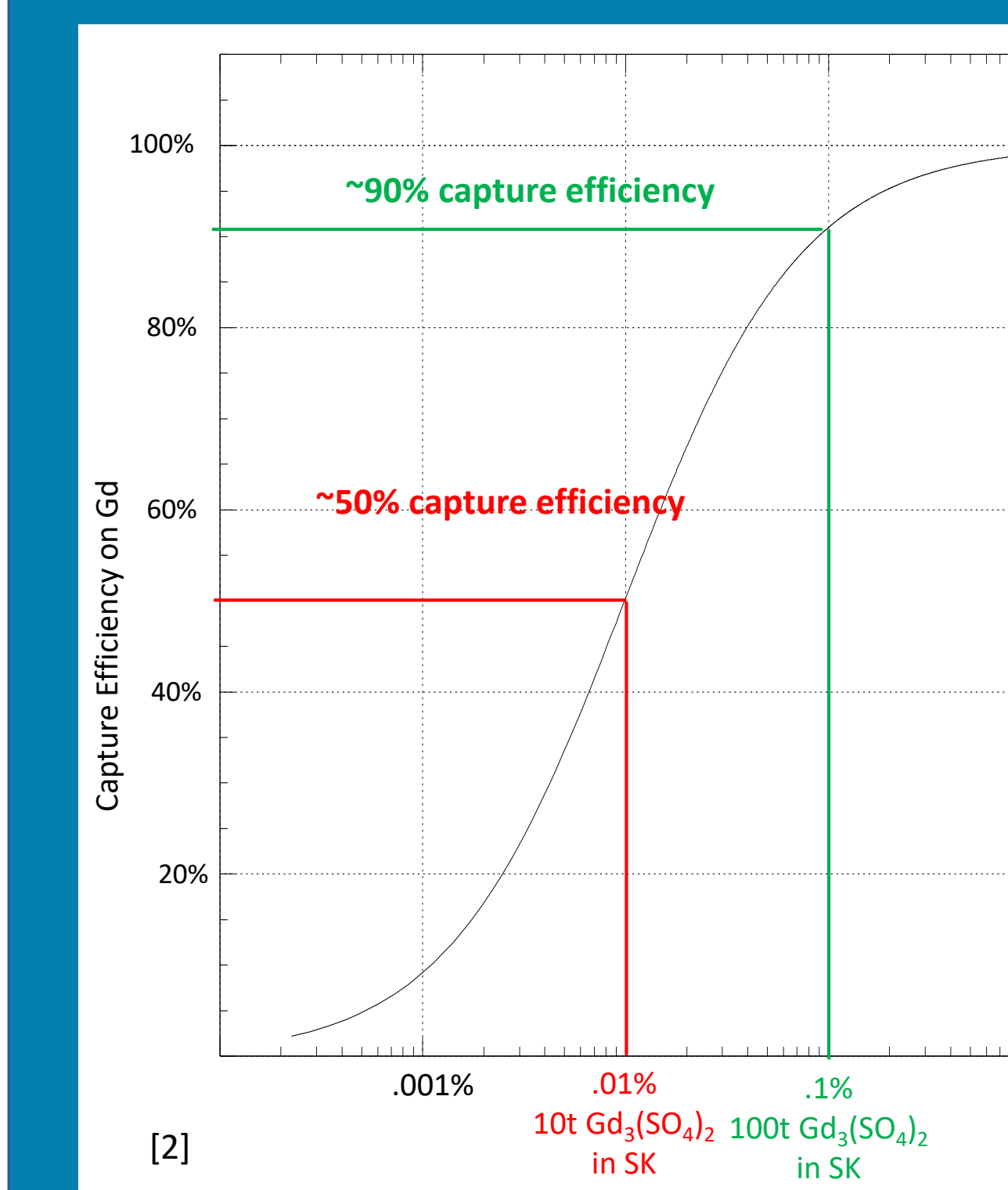
Calculated $A_{D/N}$ (Day/Night asymmetry) is -1.9% ± 1.2% for 3.49 to 19.49 MeV kinetic energy. The fitted $A_{D/N}$ is -2.1% ± 1.1% for the same energy region.

ALL Angular Distribution 3.49MeV<E<19.49MeV
63890 Signal Events
Preliminary

Difference in Events (New - Old)
Personal Work

Zenith Distribution 3.49 MeV<E<19.49 MeV

D/N Asymmetry Amplitude sin²θ₁₂=0.304, sin²θ₁₃=0.02, Δm²₂₁=6.1×10⁻⁵eV²
$A_{D/N,fitted}$ ± 1σ
Preliminary

Future

Currently 9% of neutron captures are seen and pass cuts. With the coming addition of Gd to the detector, neutron capture tagging efficiency will greatly improve. In the first phase of Gd loading, we expect ~5x more neutrons meeting the same criteria, as well as better vertex resolution resulting in higher confidence on shower location.

Other analyses, such as the DSNB search, have started to use these new methods and improvements.

~90% capture efficiency
~50% capture efficiency
Capture Efficiency on Gd
.001%   .01%   .1%
10t Gd₂(SO₄)₂ in SK   100t Gd₂(SO₄)₂ in SK
[2]