SNO+ Recent Results

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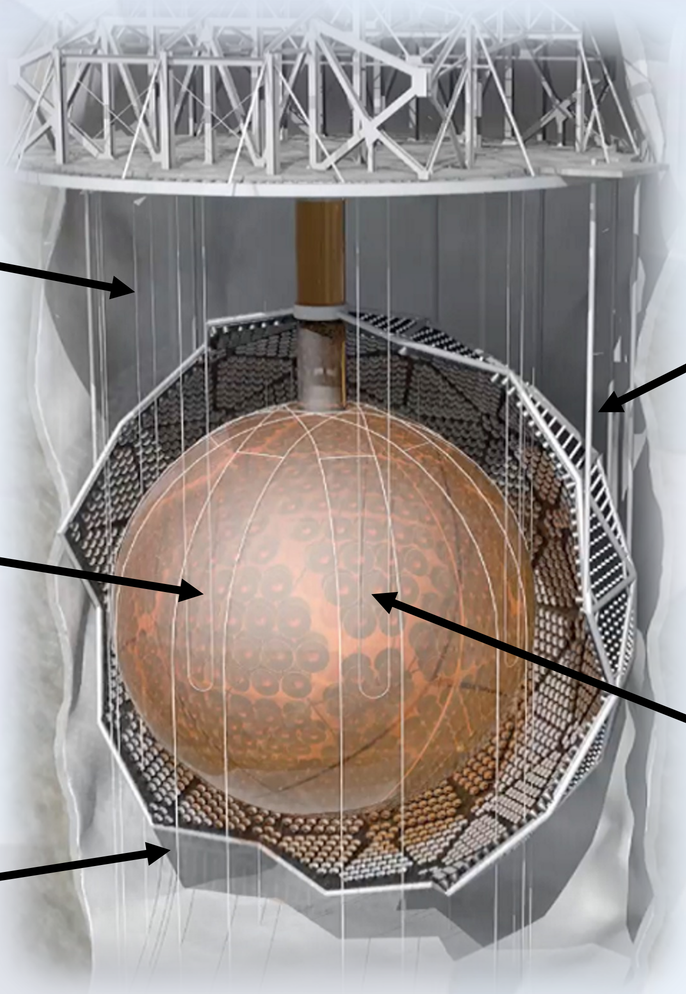
23rd - 30th March 2025

The SNO+ Collaboration

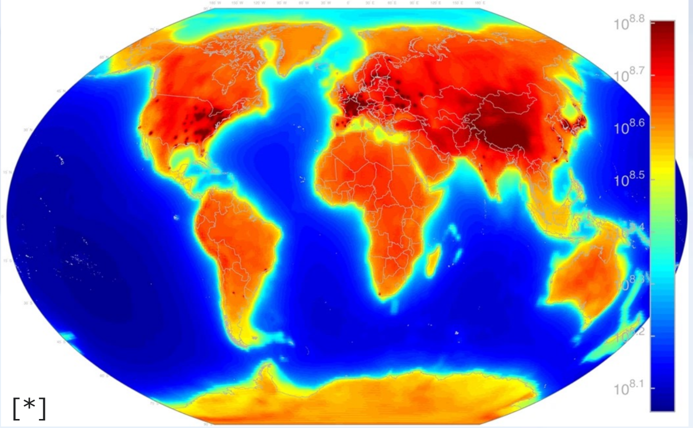
The SNO+ Experiment

Overburden of ~ 6000 m.w.e.

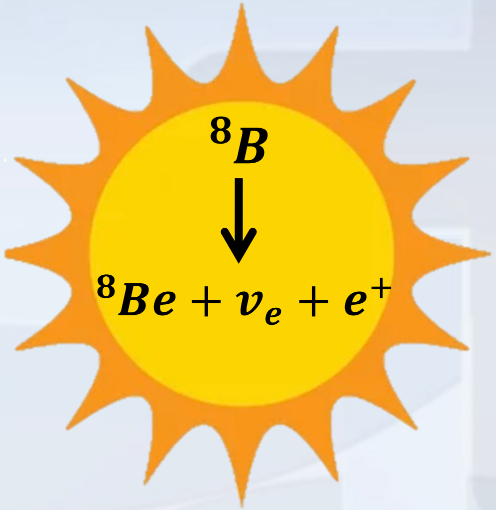


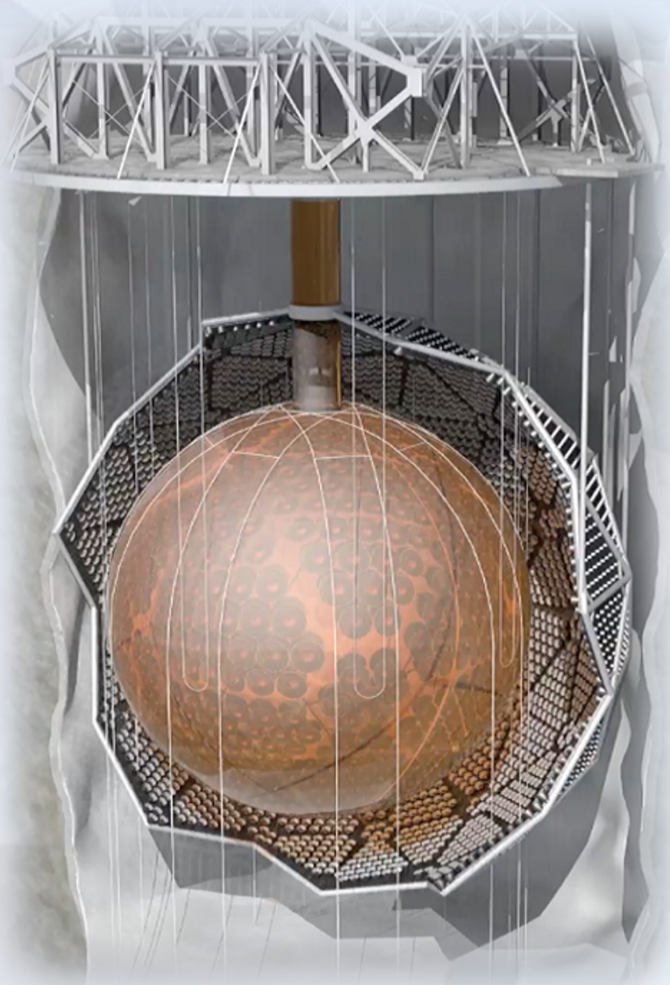
The SNO+ Experiment

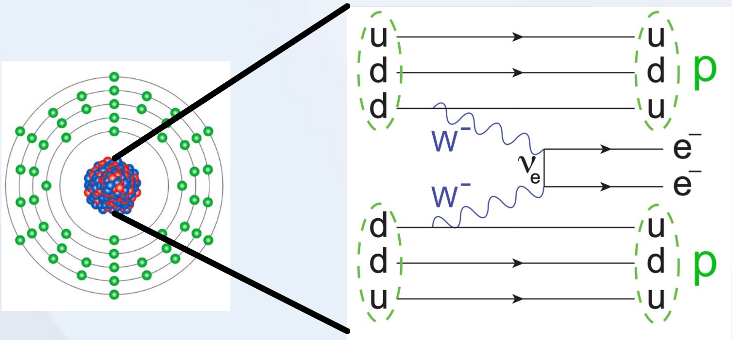
Reactor and Geo Neutrinos



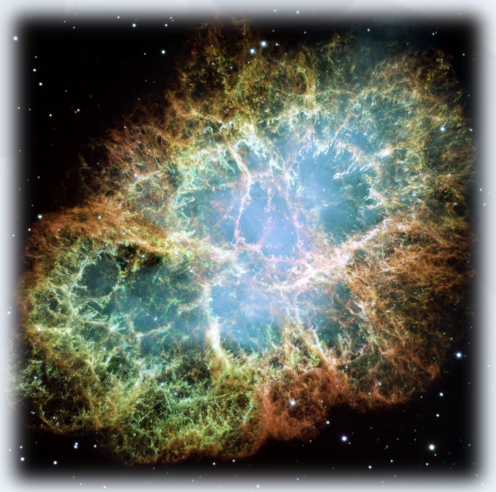
Solar Neutrinos







Neutrinoless Double Deta Decay



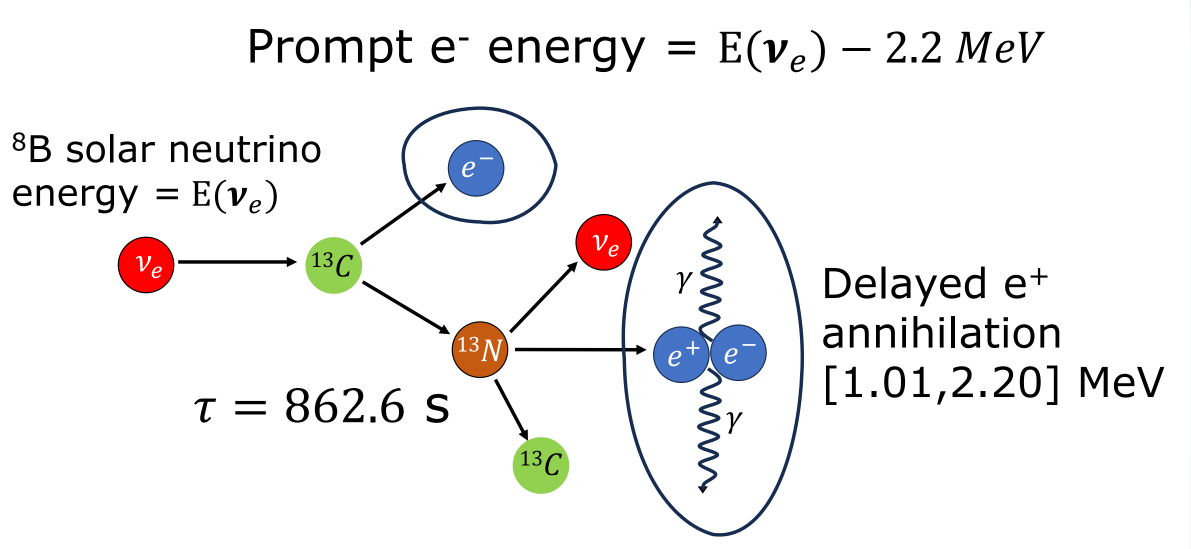
Supernova Neutrinos and Exotic

[*] Usman. S, et al. AGM2015: Antineutrino Global Map 2015. Sci Rep 5, 13945 (2015)

Introduction

The 1.1% natural abundance of Carbon-13 in organic scintillator can undergo a charged current interaction with neutrinos.

- This is a currently unobserved Boron-8 neutrino charged current interaction [1].
- Interaction threshold: 2.2 MeV



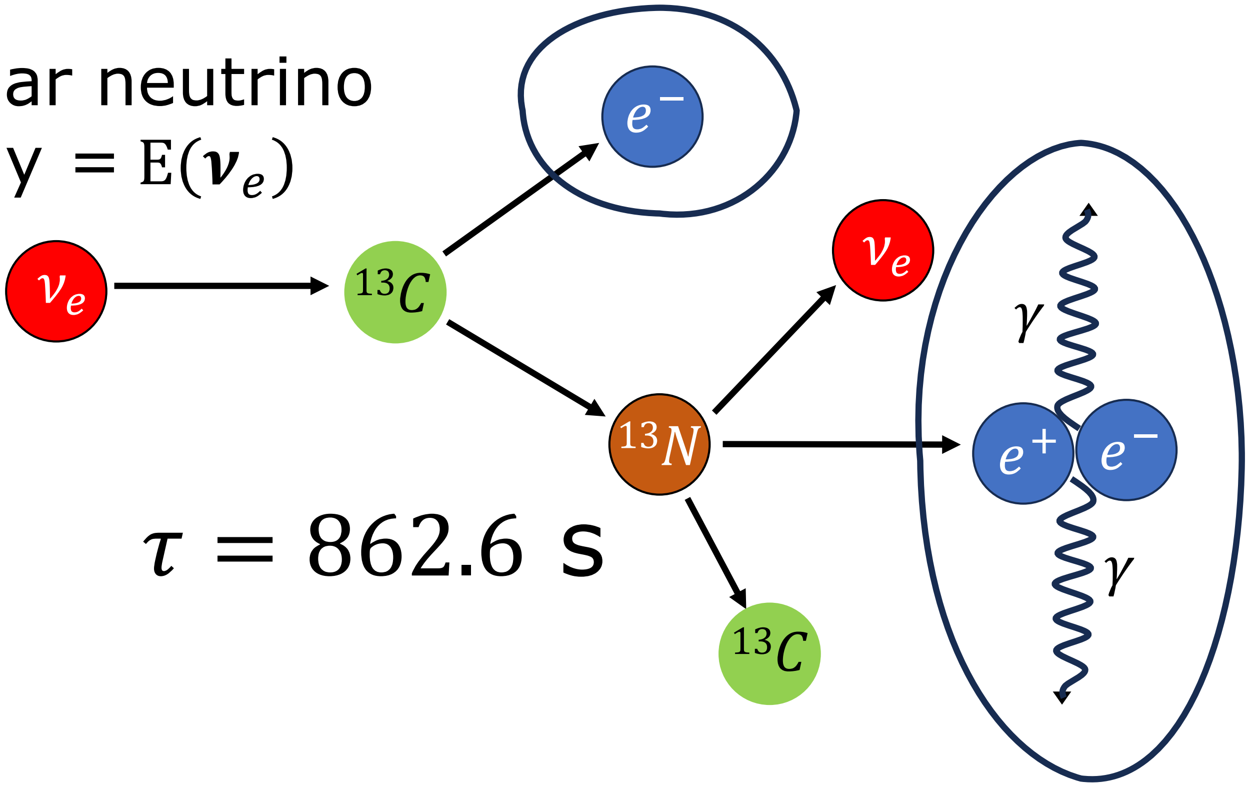
The background rates are data-driven.

SNO+'s depth significantly reduces the cosmogenic backgrounds.

Event Diagram

Prompt e$^-$ energy = $\mathrm{E}(\boldsymbol{\nu}_e) - 2.2\,MeV$

^{8}B solar neutrino energy = $\mathrm{E}(\boldsymbol{\nu}_e)$



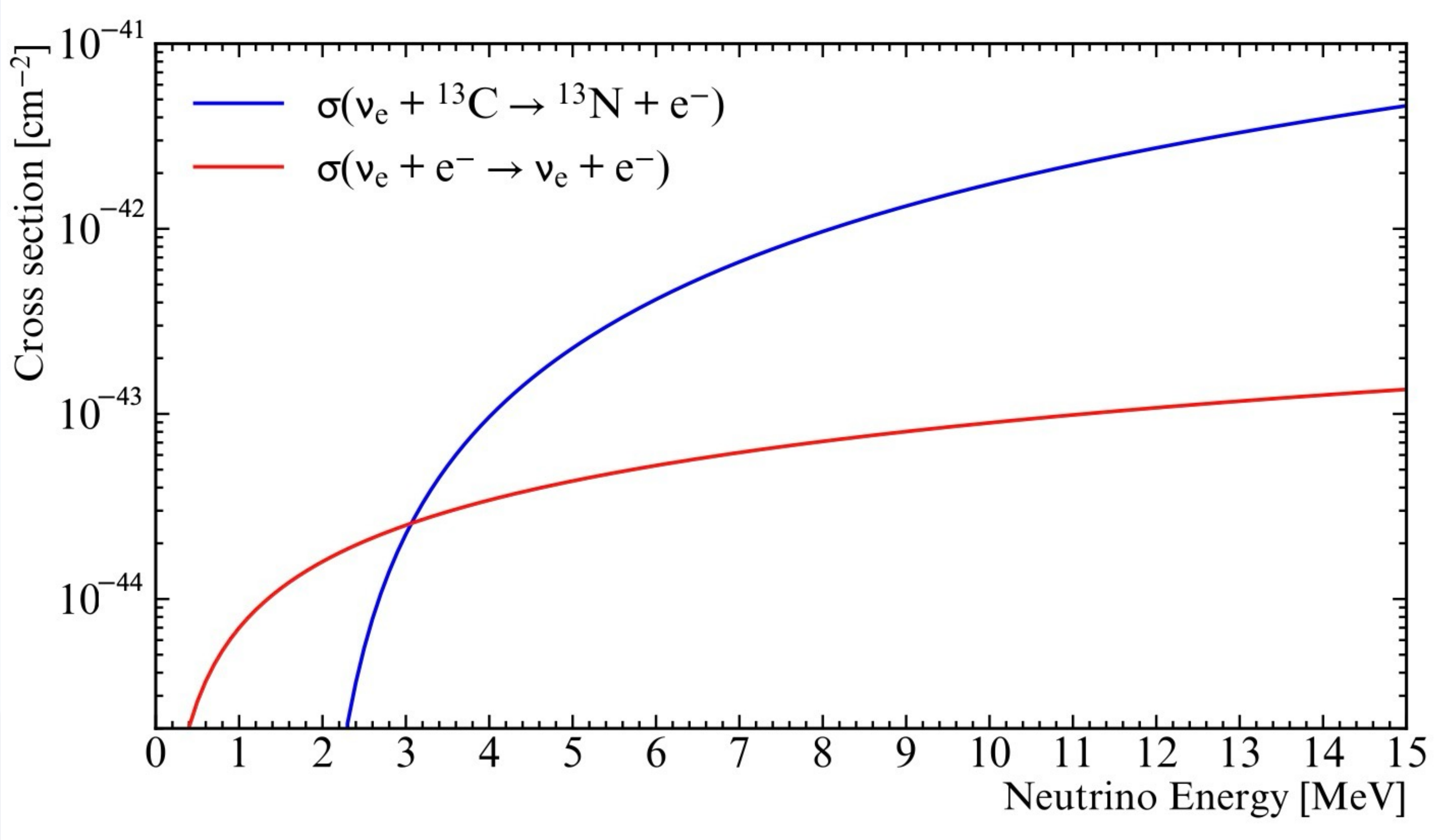
Delayed e$^+$ annihilation [1.01,2.20] MeV

Cross Section

- The cross-section of the interaction is orders of magnitude larger than the electron ES process [2].

- In SNO+, 22 ev/yr/kT ^8B neutrino CC interactions are expected with Carbon-13.

- This is obtained by integrating over the theoretical cross-section [2] and SSM ^8B neutrino flux [3], assuming the globally fit neutrino oscillations parameters [4].

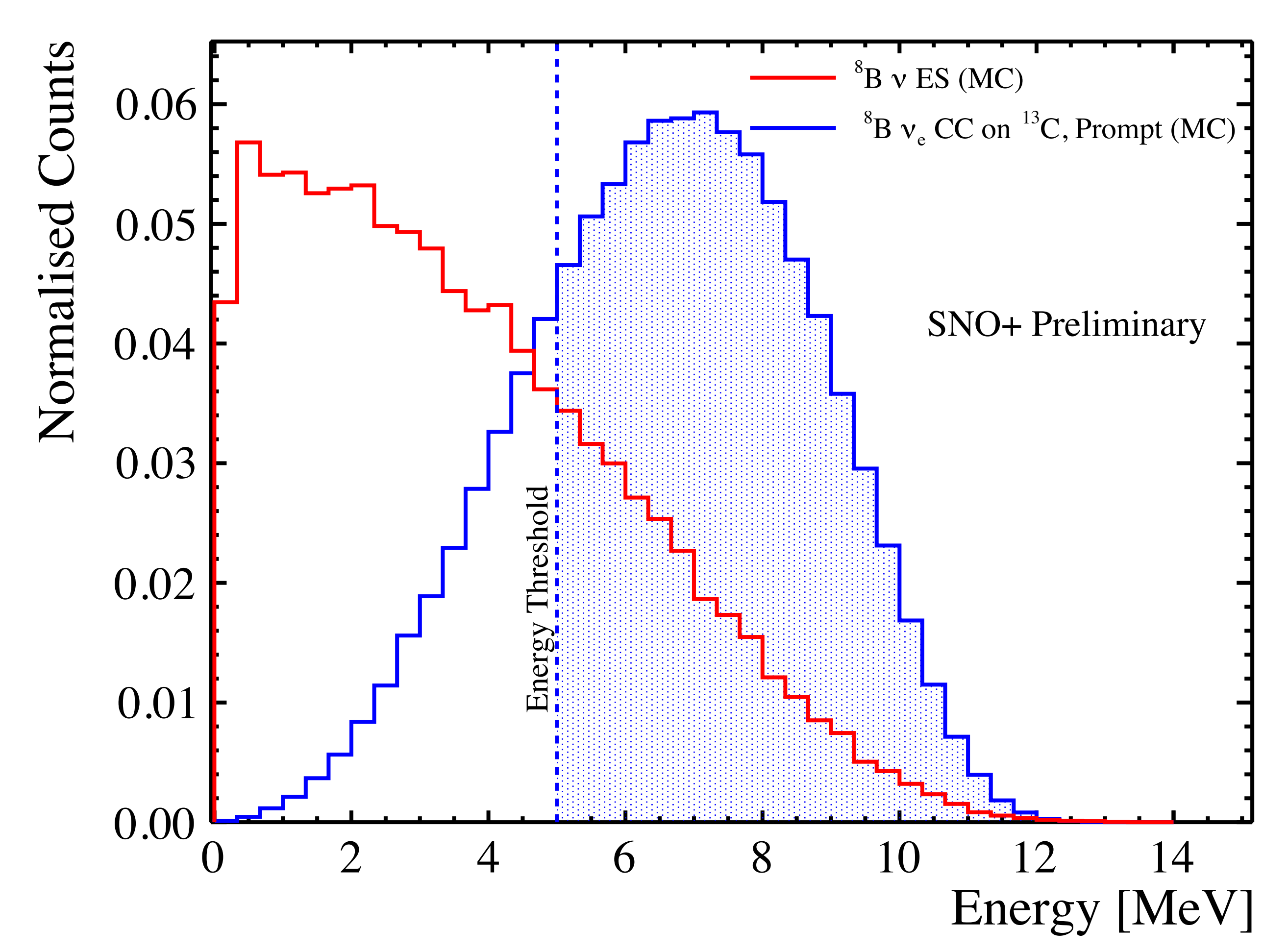


Prompt Event

- An electron with energy $E_{\nu_e} - 2.2$ MeV

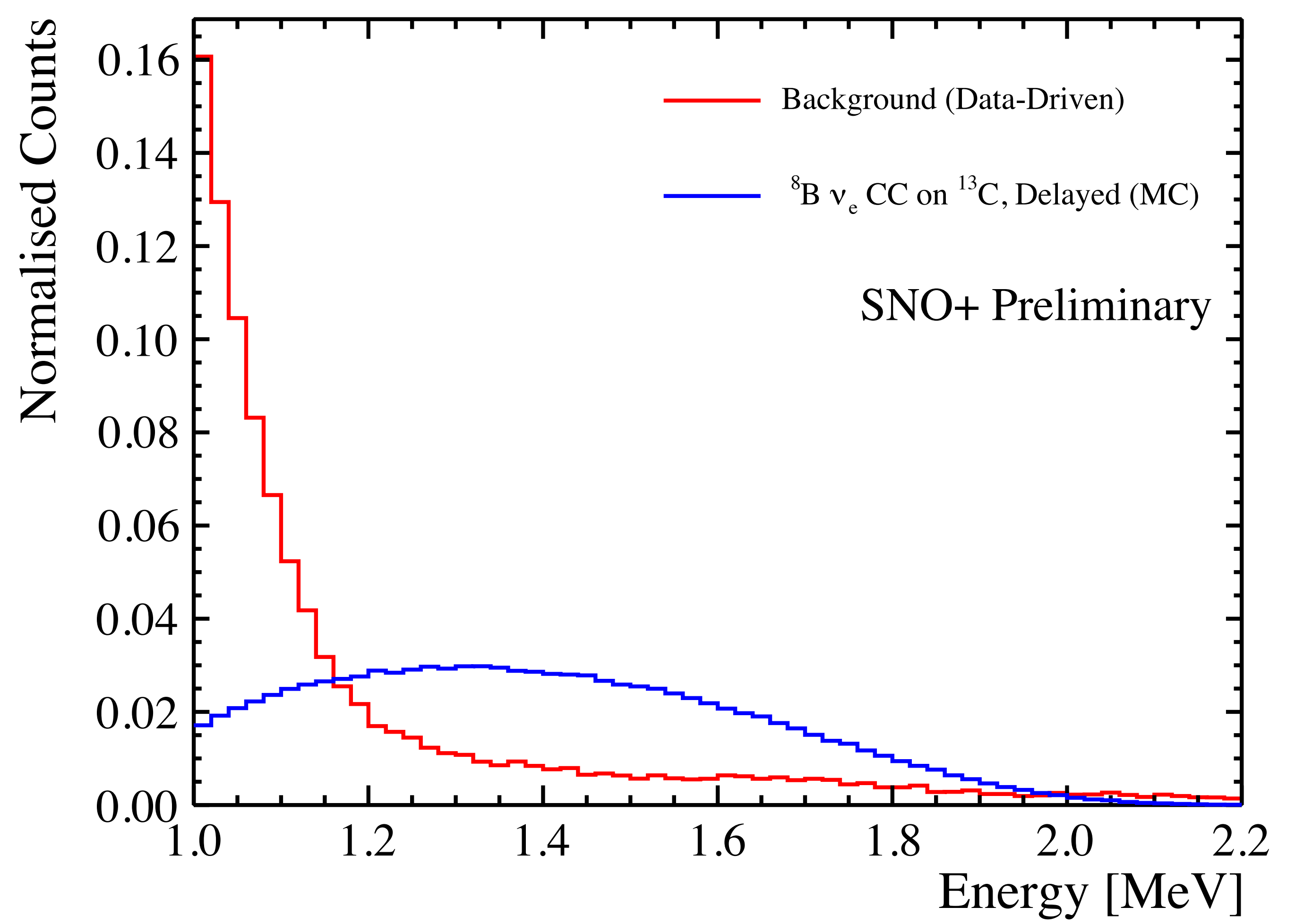
- Imposing a 5 MeV cut removes most background. For example, the Thallium-208 decay (Q = 5 MeV).

- The remaining prompt background is ^{8}B Elastic scattering.



Delayed Event

- A positron with energy: [1.0 to 2.2] MeV.
- The annihilation produces two gammas, which are detected.
- The increase below 1.2 MeV due to ^{210}Bi.



Cosmogenic Background

- The muon spallation products, ^{11}Be and ^{11}C, produce a correlated background signal.

	^{11}Be	^{11}C
Half-life	13.6 s	20.0 min
Decay type	β^-	β^+
Q value (MeV)	11.5	1.98
SNO+ rate (kt/yr)	1.4 ± 0.3	1111 ± 179

- The high overburden (6000 m.w.e), reduces the muon rate to around 3 per hour.

- A 60-second cut can be applied after every muon, reducing the rate to less than 0.0015 ev/yr/kT.

- The correlated NC atmospheric background can also be removed with a neutron tag.

Analysis Method

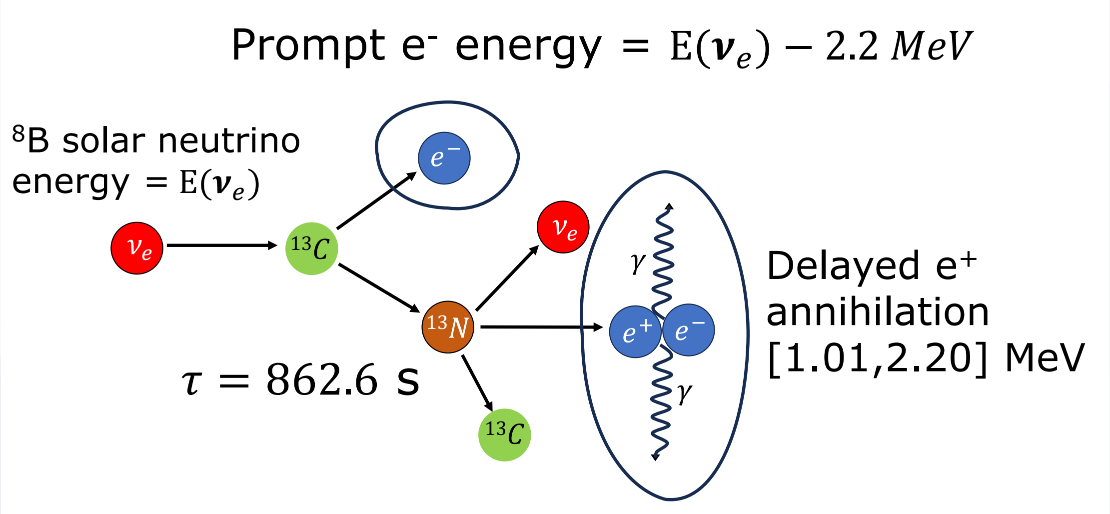
- The relatively long half-life of the Nitrogen-13 (10 minutes) means the dominant background is from accidental coincidences.

- A data-driven approach was used to determine the accidental rate.
  - Spurious prompt events produced “fake coincidences” with data events satisfying delayed event cuts.

- The random coincidence rate is determined by the fraction of events resulting in fake coincidences.

- Two analysis approaches were used:
  - Cuts-Based Analysis
  - Likelihood approach

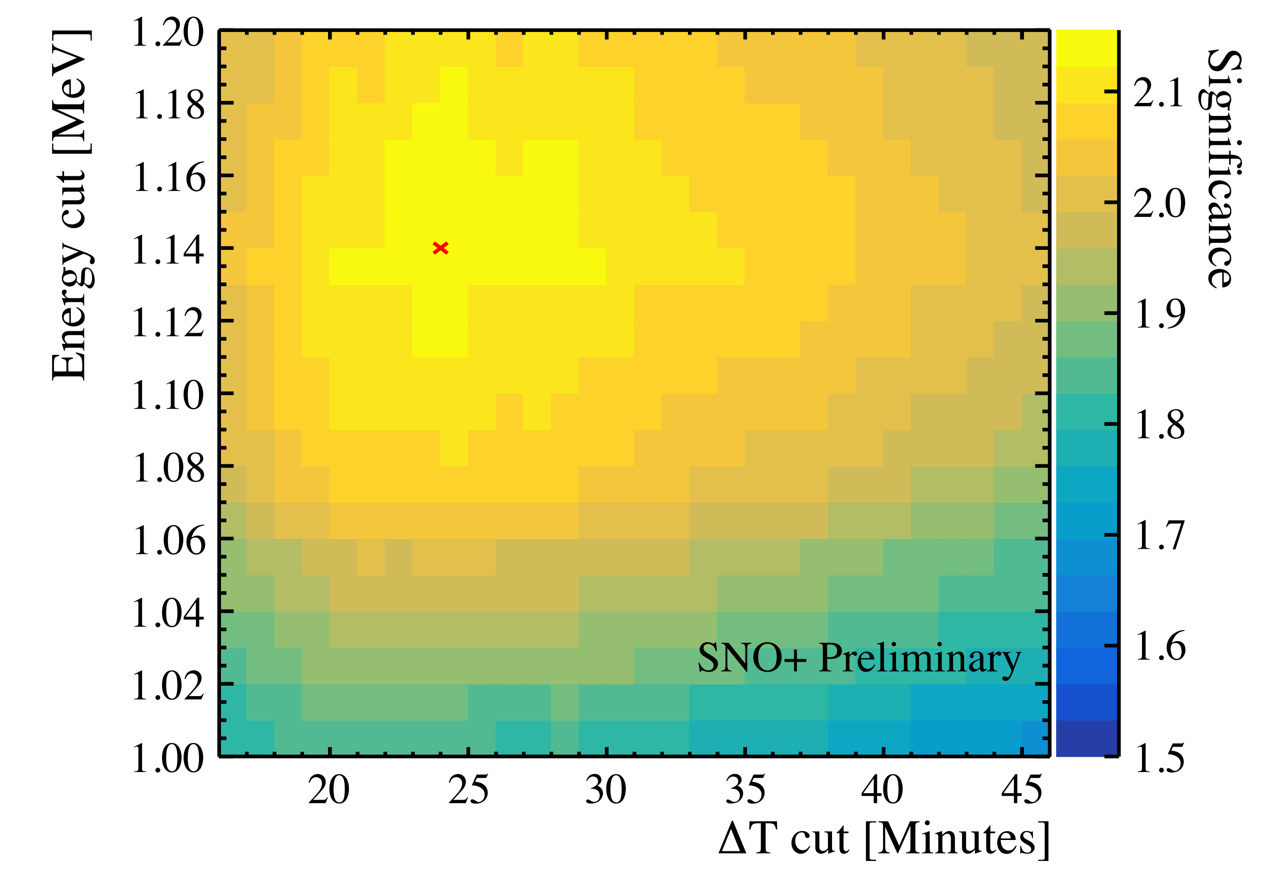
- Around 200 days of livetime.



Cuts-Based Analysis

- The fiducial volume (FV), delayed energy (E_{e^+}), ΔR and ΔT cuts were jointly optimised.

Optimum Cuts
FV < 5.3 m
ΔR < 0.36 m
0.01 < ΔT (min) < 24
1.14 < E_{e^+} MeV < 2.2

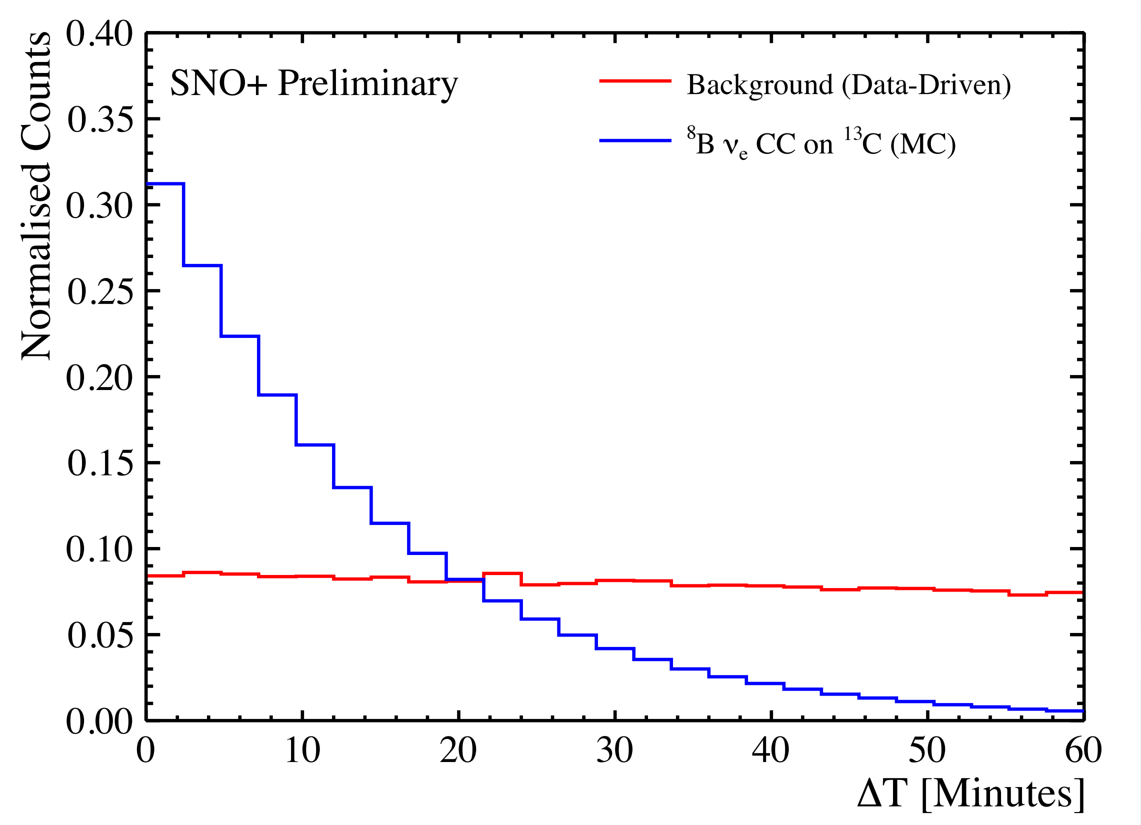


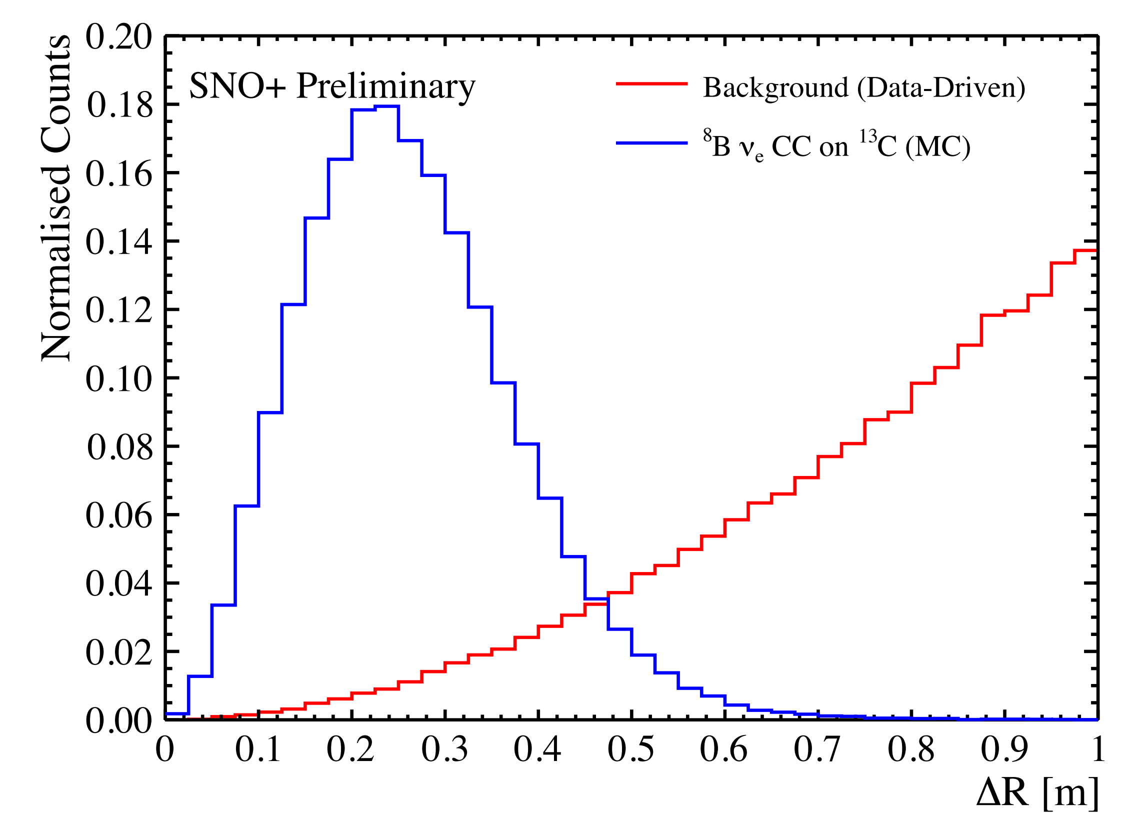
- These cuts give an expected background number of 0.434 and a signal of 2.355

Three events were observed

Likelihood Analysis

- Using PDFs of the delayed energy (1 to 2.2 MeV), ΔT (0.01 to 60 minutes), and ΔR (<1 m), the Likelihood ratio can be constructed.



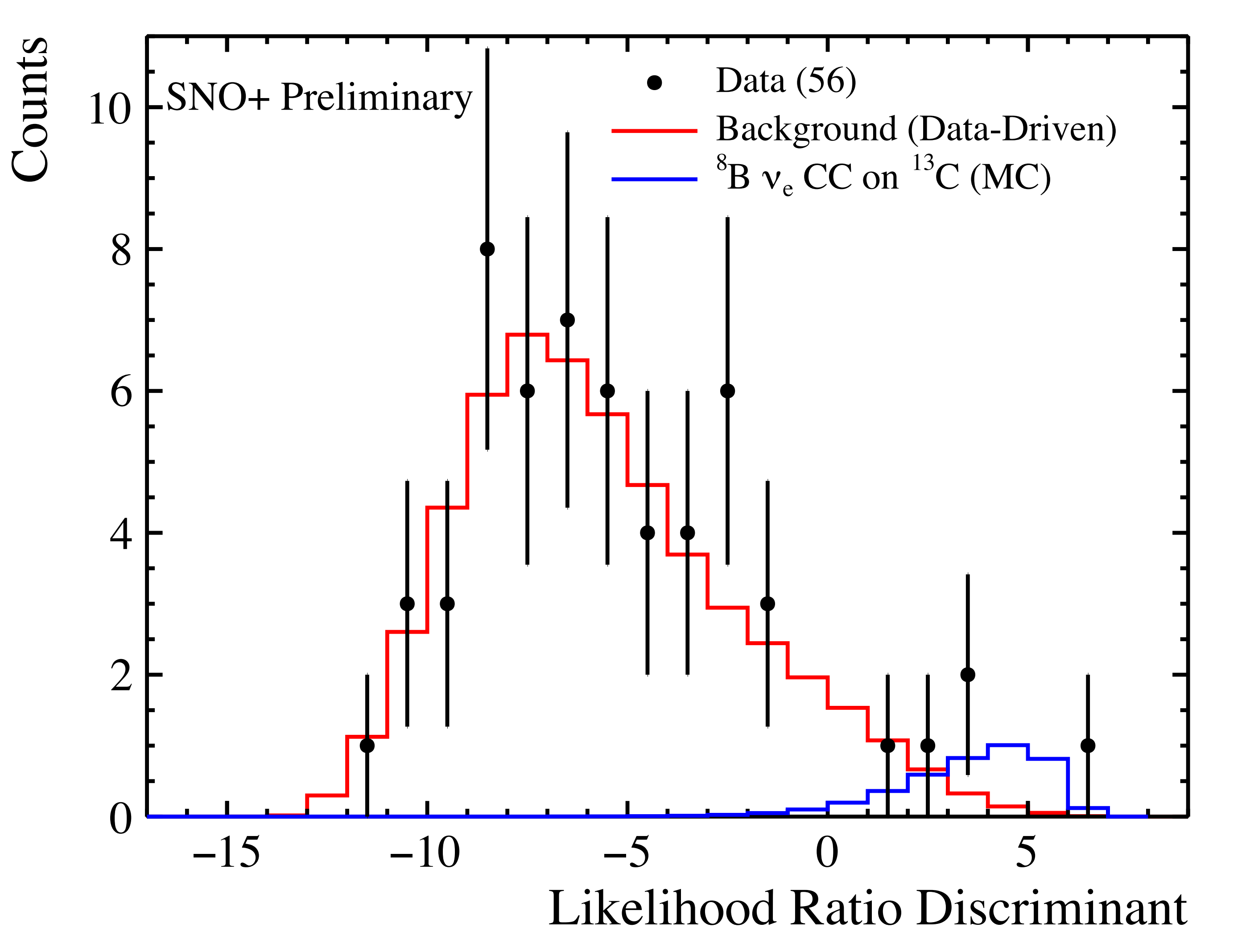


Likelihood Analysis

- Excellent agreement between the data and the background model (56.67 events expected).

- Events are consistent with the Carbon-13 solar neutrino signal.

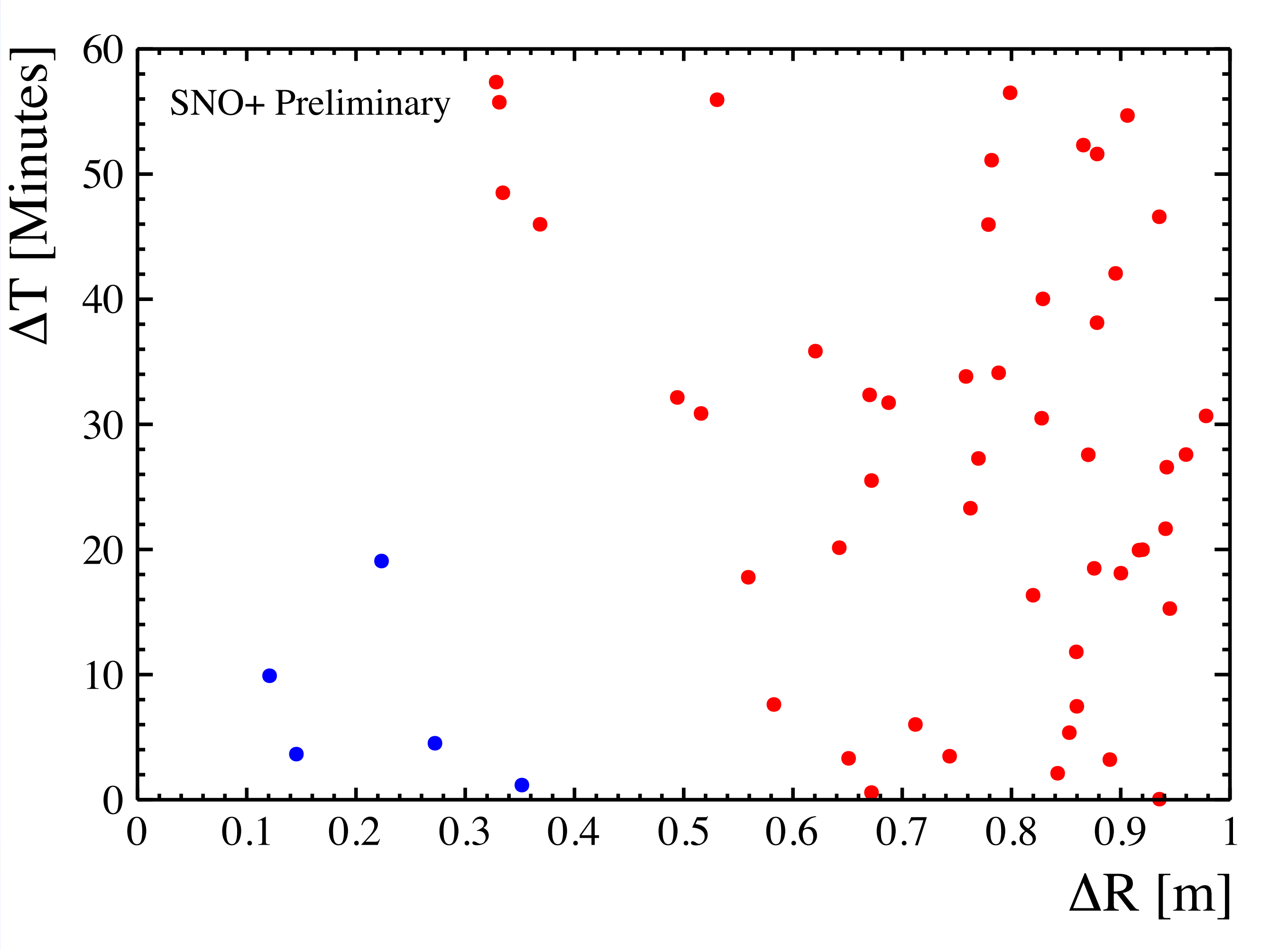
- The observation has a significance of 2.4 sigma.



Note: This is not a fit. It has been scaled to the expected rate.

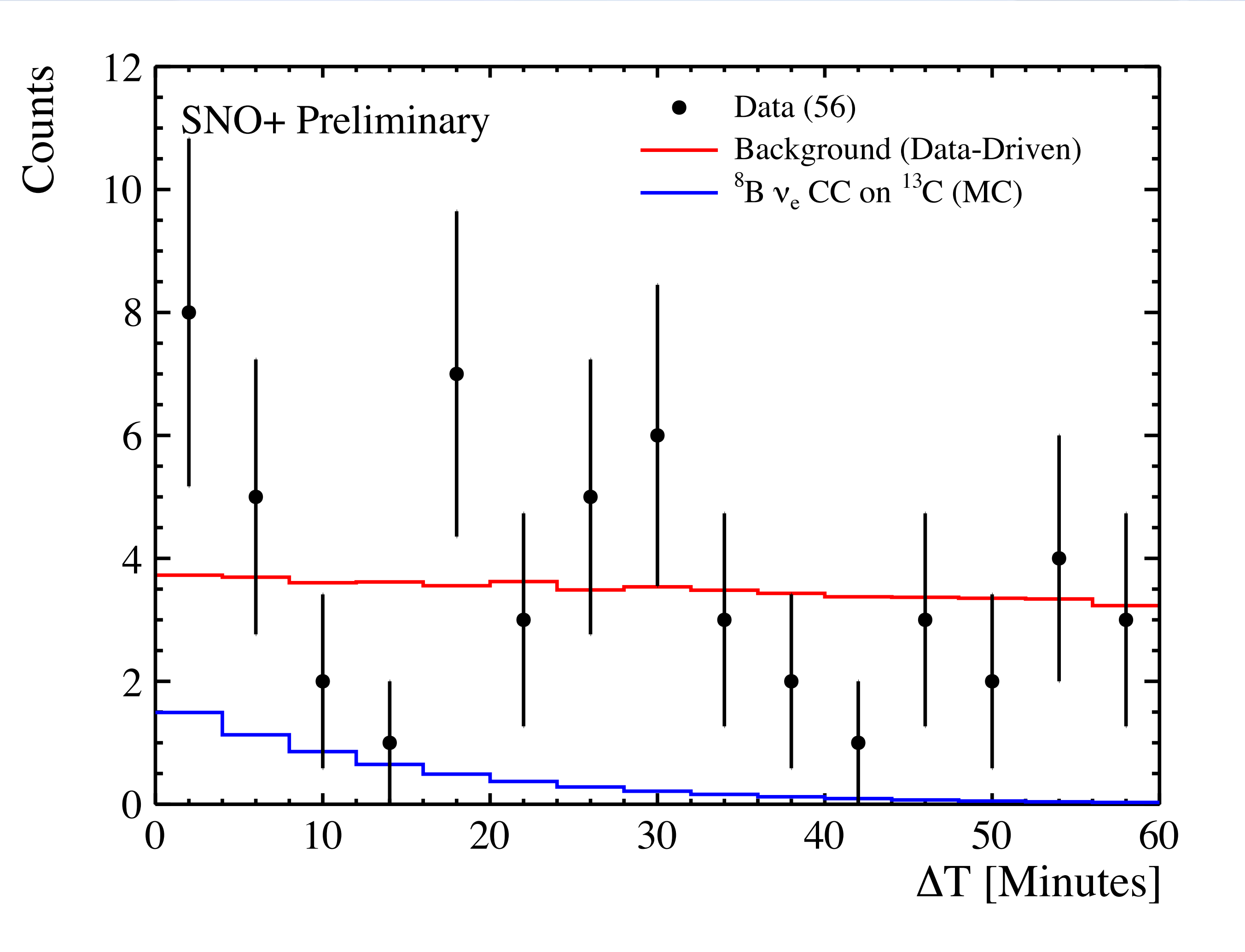
ΔT vs ΔR. PDFs

Separation between the signal and background regions.



ΔT PDF

- Consistent with the expected background distribution.
- No evidence for a correlated background (Carbon-11).

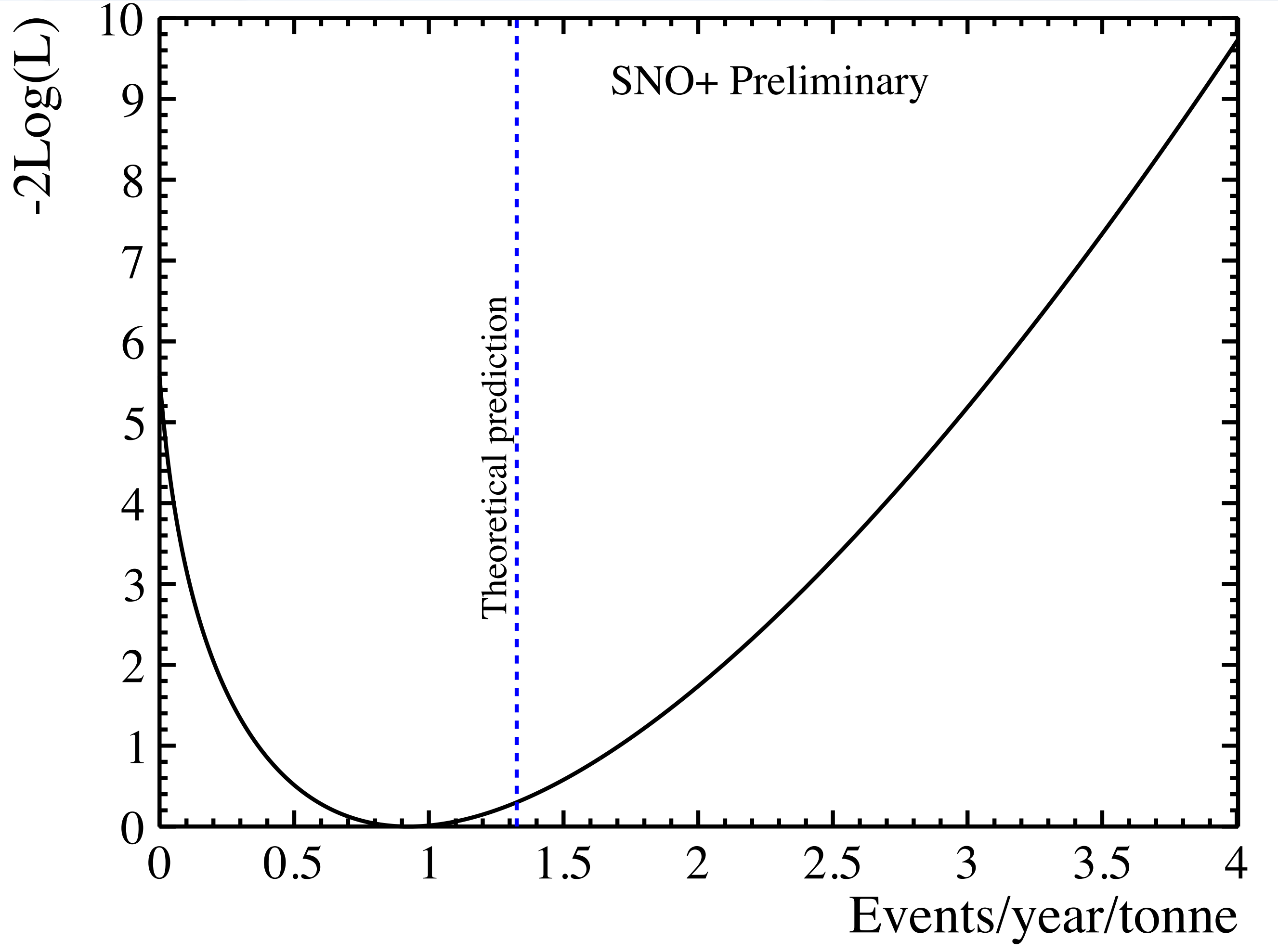


Number of Events

- Calculating the -2*log-likelihood gives the number of signal events.

- Within 5.3 m, there are 5.66 tons of Carbon-13.

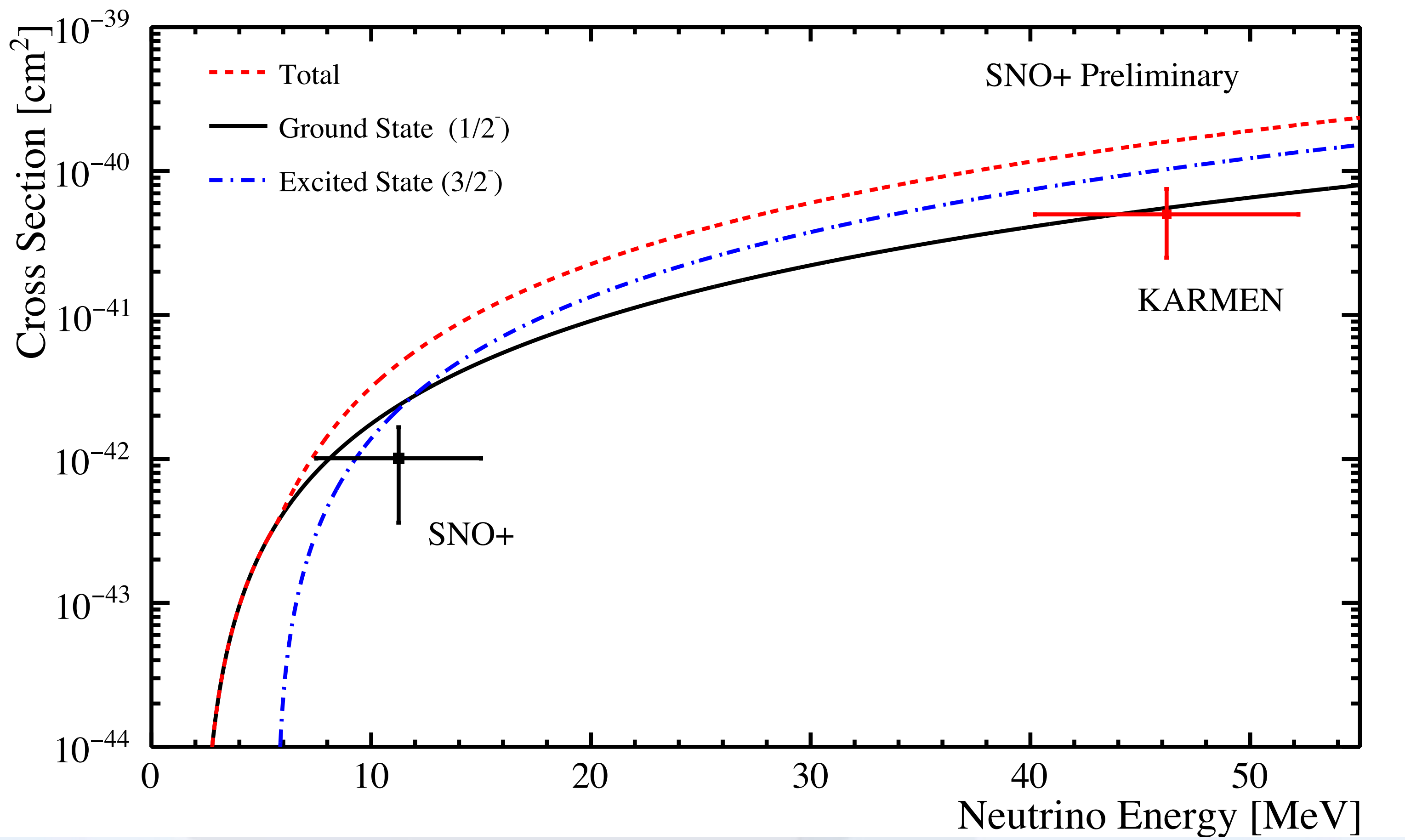
- Good agreement with the theoretical prediction [2]



Cross Section

Converting the observed number into an average cross section:

$$\langle\sigma(E_\nu)\rangle = (10.1 \pm 6.6)\times 10^{-43}\ \text{cm}^2$$

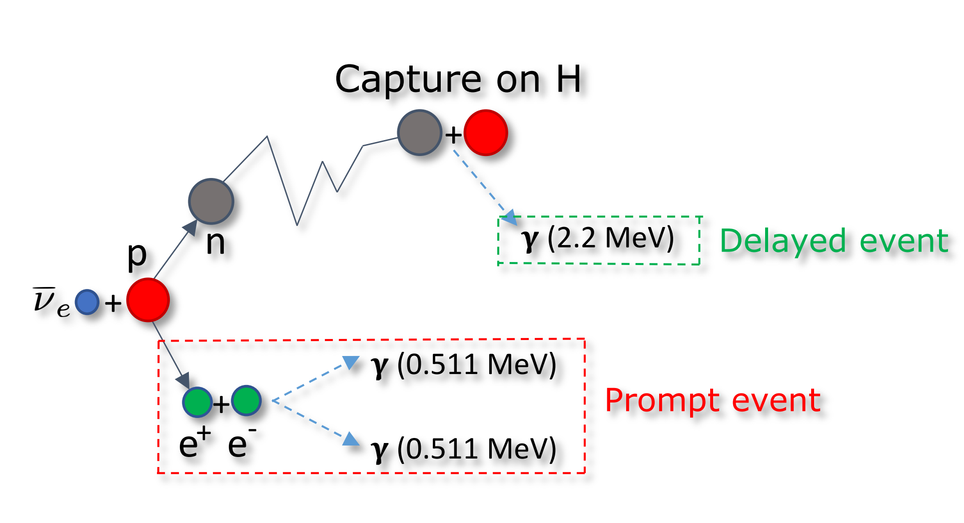


Ref: Theoretical cross section [2], KARMEN result [5]

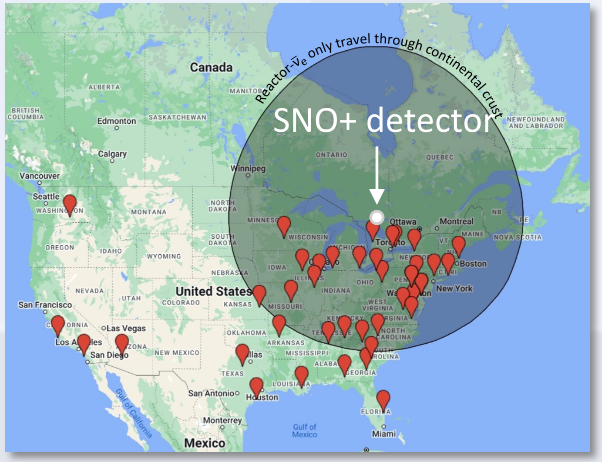
Statistical error only

Antineutrino Results

- 60% of reactor antineutrino flux comes from three PHWRs in Ontario, with baselines 260-350 km.
- Antineutrinos inverse beta decay on hydrogen nuclei.
- Produce coincidence events:
  - Prompt positron ($E_{e^+} = E_\nu - 0.8\ MeV$)
  - Delayed neutron capture ($E_\gamma = 2.2\ MeV$)



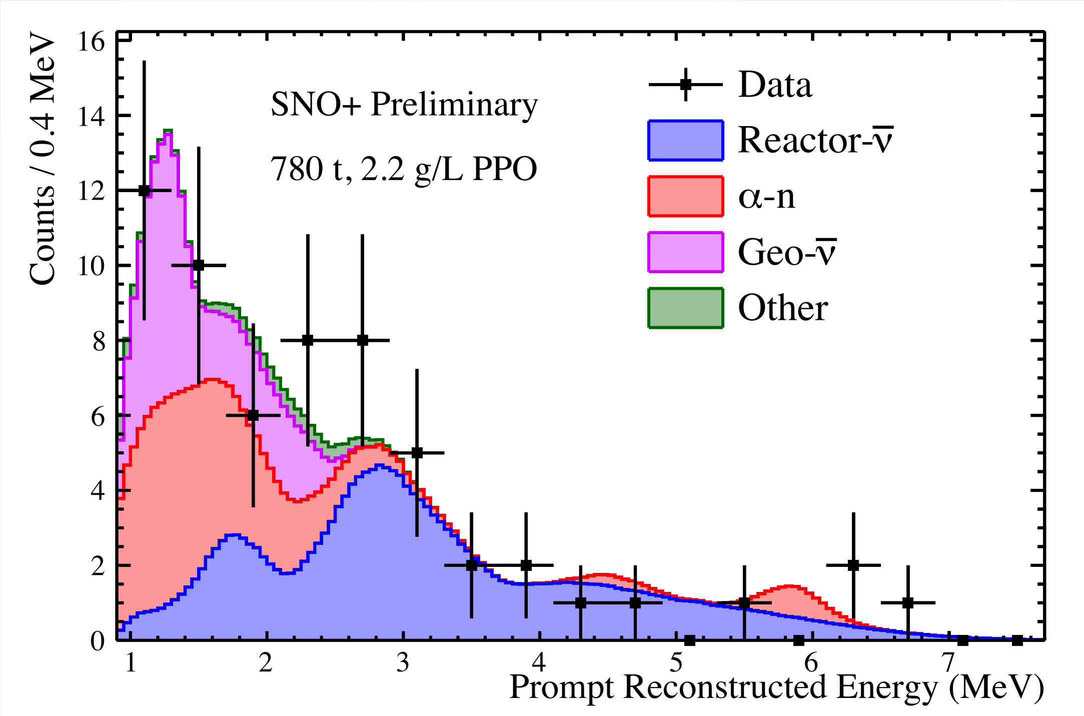
- Main background is α particles from internal ^{210}Po decays which capture on Carbon-13 mimicking the IBD coincidence signal.

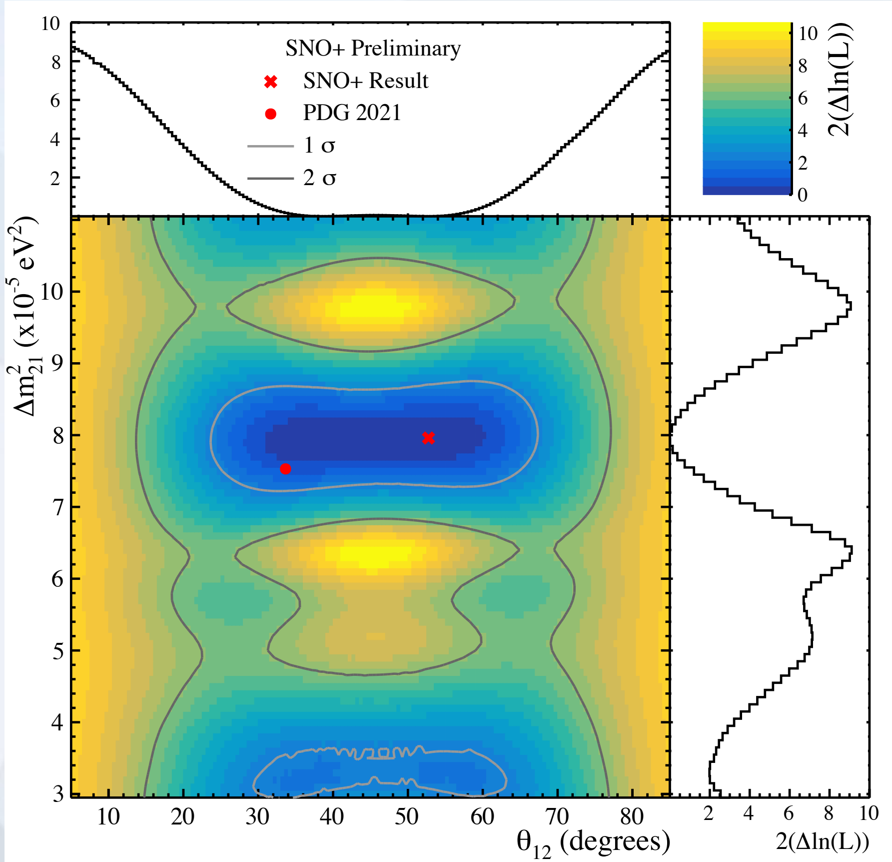


Antineutrino Results

- 59 events in 134.5 days of livetime.
- Unconstrained oscillation fit.
- Geoneutrino Flux 64 ± 44 TNU*

$$\Delta m^2_{21} = 7.96^{+0.48}_{-0.41} \times 10^{-5} eV^2$$





(α, n) classifier will significantly improve both the Geoneutrino flux and Δm^2_{21} measurements

*using PDG prior constraints

Conclusion

- SNO+ is filled with liquid scintillator and taking physics data.
- Presented the first indications of boron-8 solar neutrinos interacting on Carbon-13.
  - The low background and cosmogenic rates in SNO+ make correlating the minutes long coincidence possible.
- Paper in progress with more data being added soon.

- Antineutrino measurement of $\Delta m^2_{21} = 7.96^{+0.48}_{-0.41} \times 10^{-5} eV^2$.
- Geoneutrino Flux 64 ± 44 TNU, using PDG prior constraints.
- Precision will improve with more data and (α, n) classifier.

Backup

Joint Optimization

Optimise the log likelihood ratio for the expected observation of $S + B$ under the hypothesis of $\mu = S + B$ vs the null hypothesis of $\mu = B$

Where for given cuts (FV, ΔR, ΔT, E_{e^+}):

- S – Number of signal events
- B – Number of background events

Once optimized, use these cuts to find the total background rate and then compare to the observed rate.

Cuts-Based Analysis

- The fiducial volume (FV), delayed energy (E_{e^+}), ΔR and ΔT cuts were jointly optimised

Optimum Cuts
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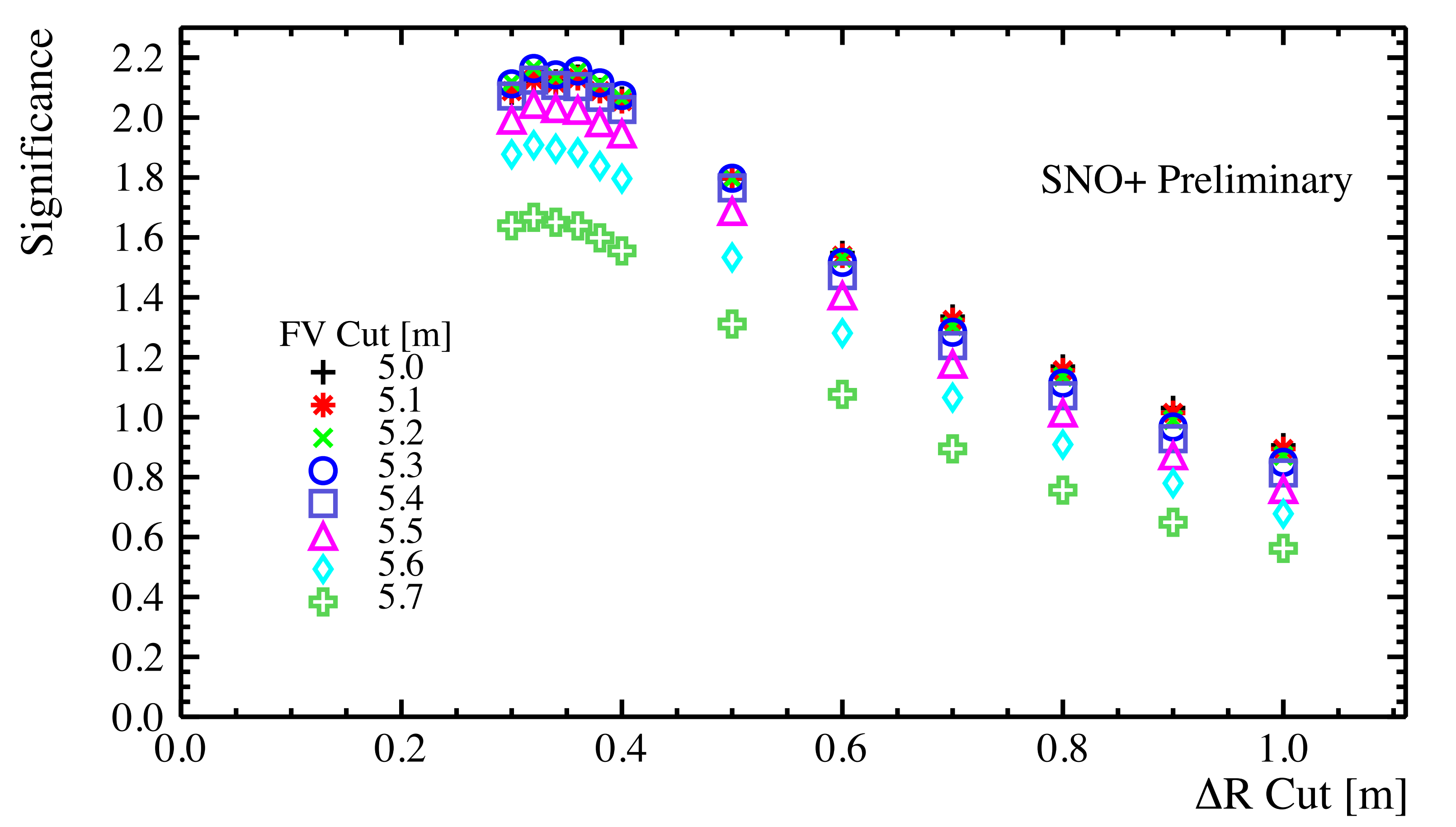
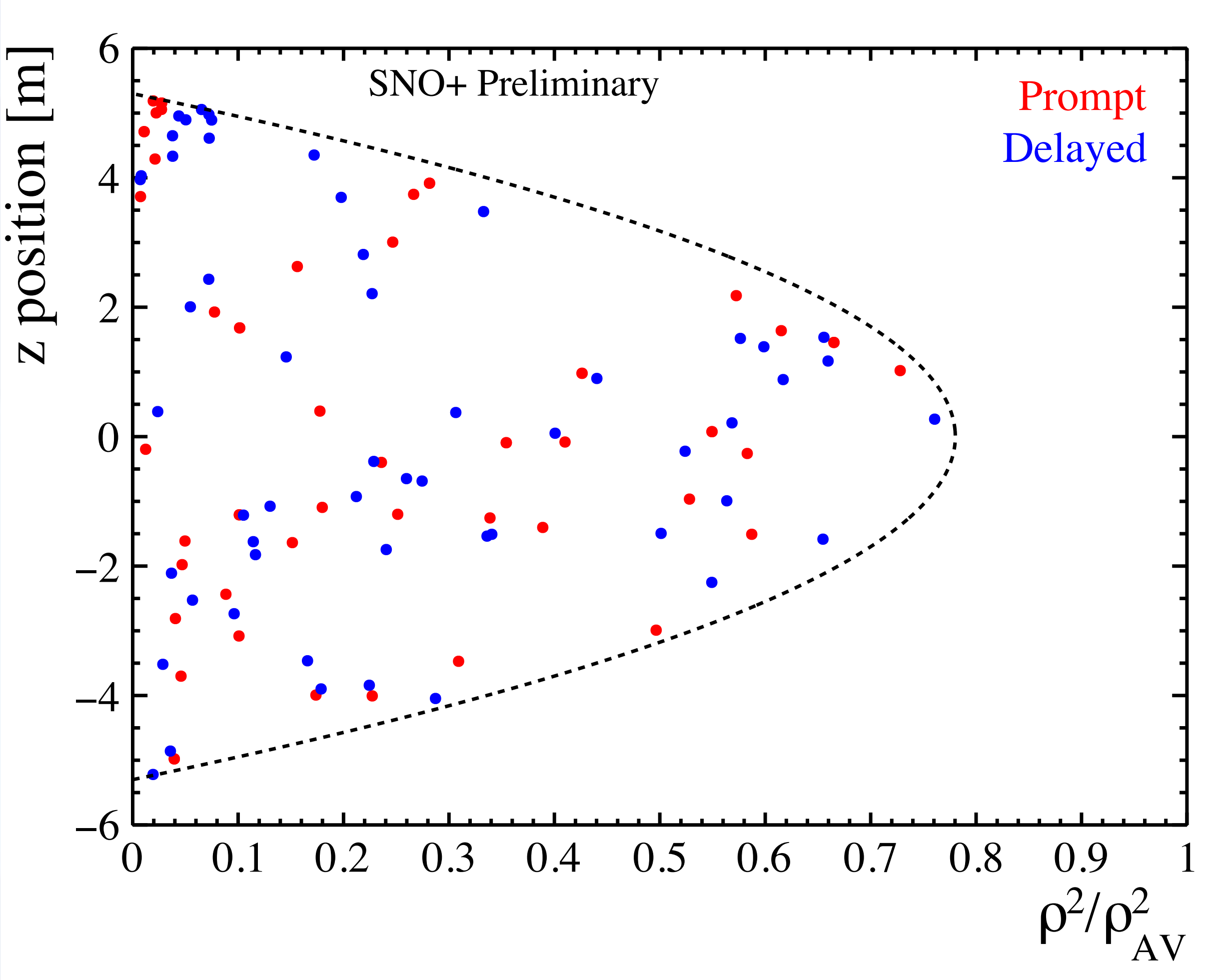
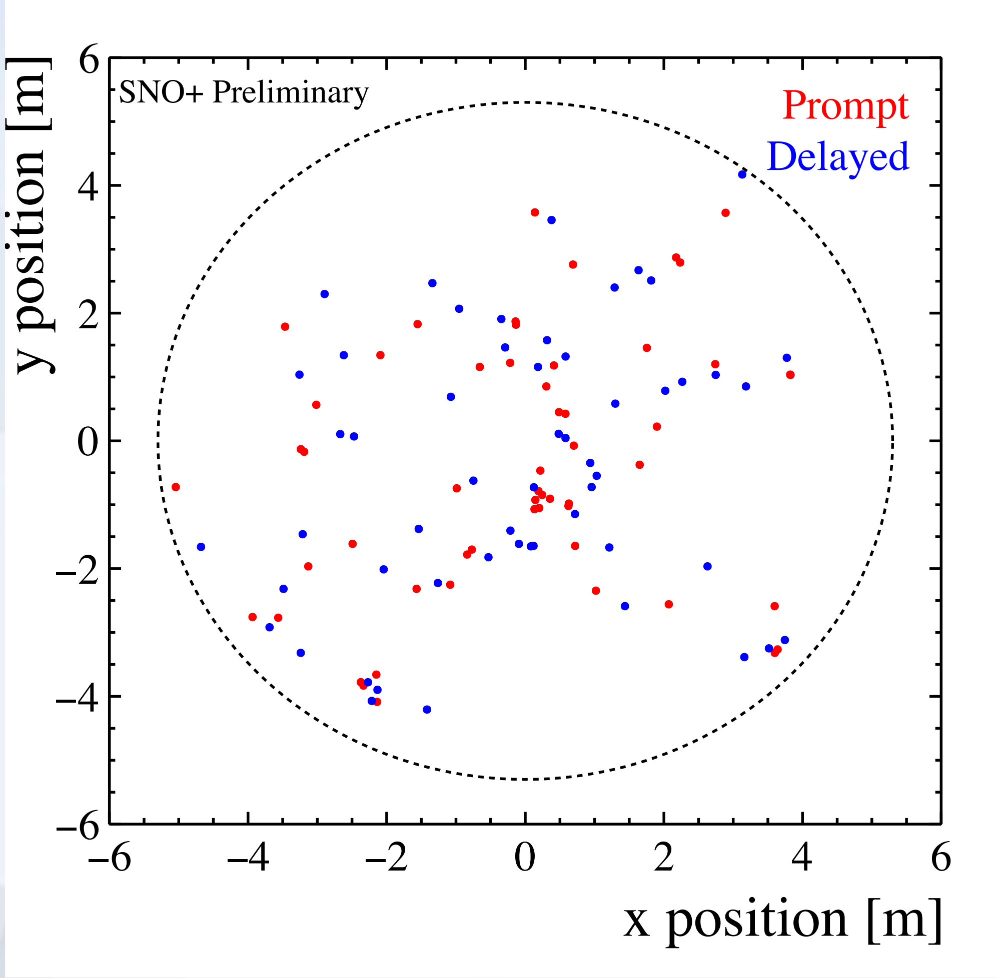
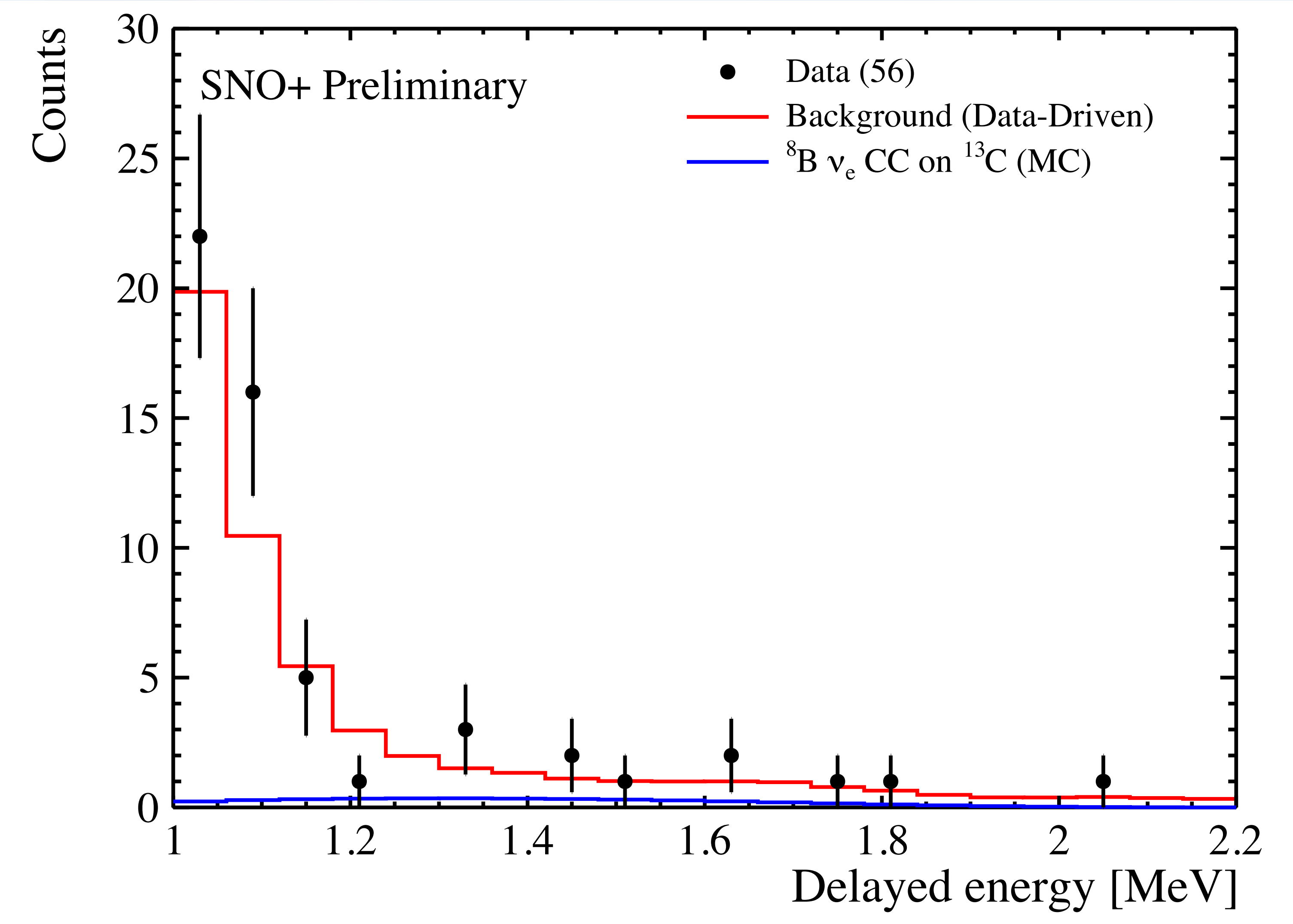


Distribution of Events

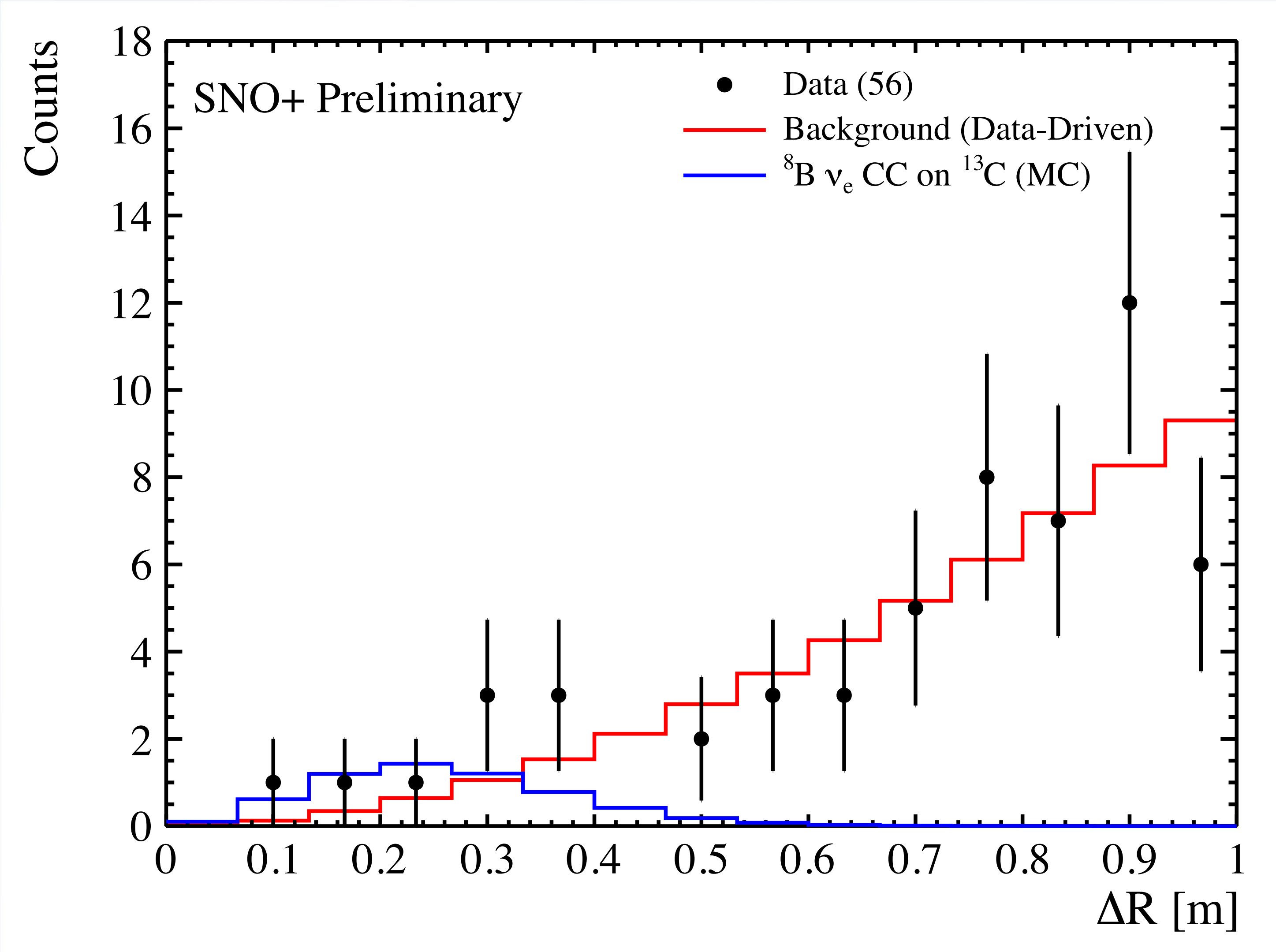




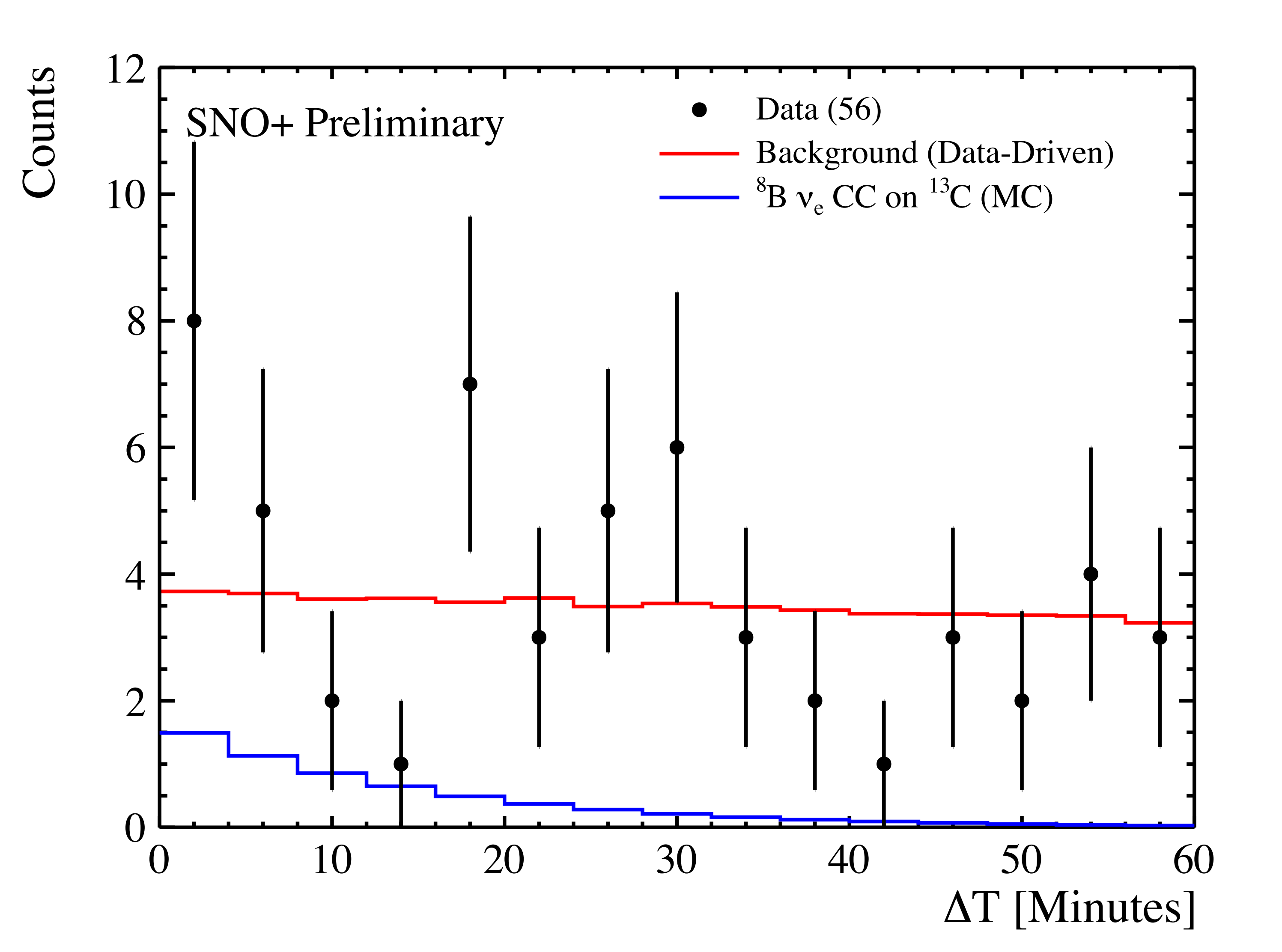
PDF – Delayed Energy



PDF - ΔR


SNO+ Preliminary
Counts
ΔR [m]
Data (56)
Background (Data-Driven)
^{8}B ν_e CC on ^{13}C (MC)
0
2
4
6
8
10
12
14
16
18
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

PDF - ΔT



SNO+ Preliminary
Data (56)
Background (Data-Driven)
$^{8}B\ \nu_e$ CC on ^{13}C (MC)
Counts
ΔT [Minutes]
0
2
4
6
8
10
12
0
10
20
30
40
50
60

Number of Events

The analysis allows for a prompt to have multiple delayed events

- The data-driven approach gives the expected fraction:

Multiplicity	Expected Fraction (%)	Observed Fraction (%)
0	69.8	70.8
1	23.6	22.1
2	5.4	7.1
3	1.0	0.0

Consistent with the expectation

Note: None of the “signal-like” events have the same prompt

NC Atmospheric Background

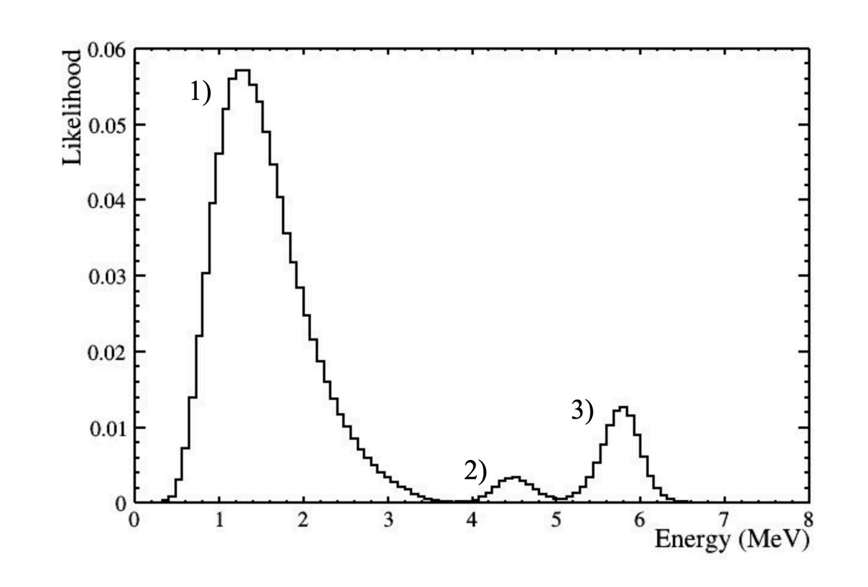
- Most Atmospheric neutrino interactions are too high energy and have a short timescale so don’t interfere with the Carbon-13 signal.
- However, the NC on Carbon-12 can produce isotopes which mimic the delayed signal for example Carbon-11:

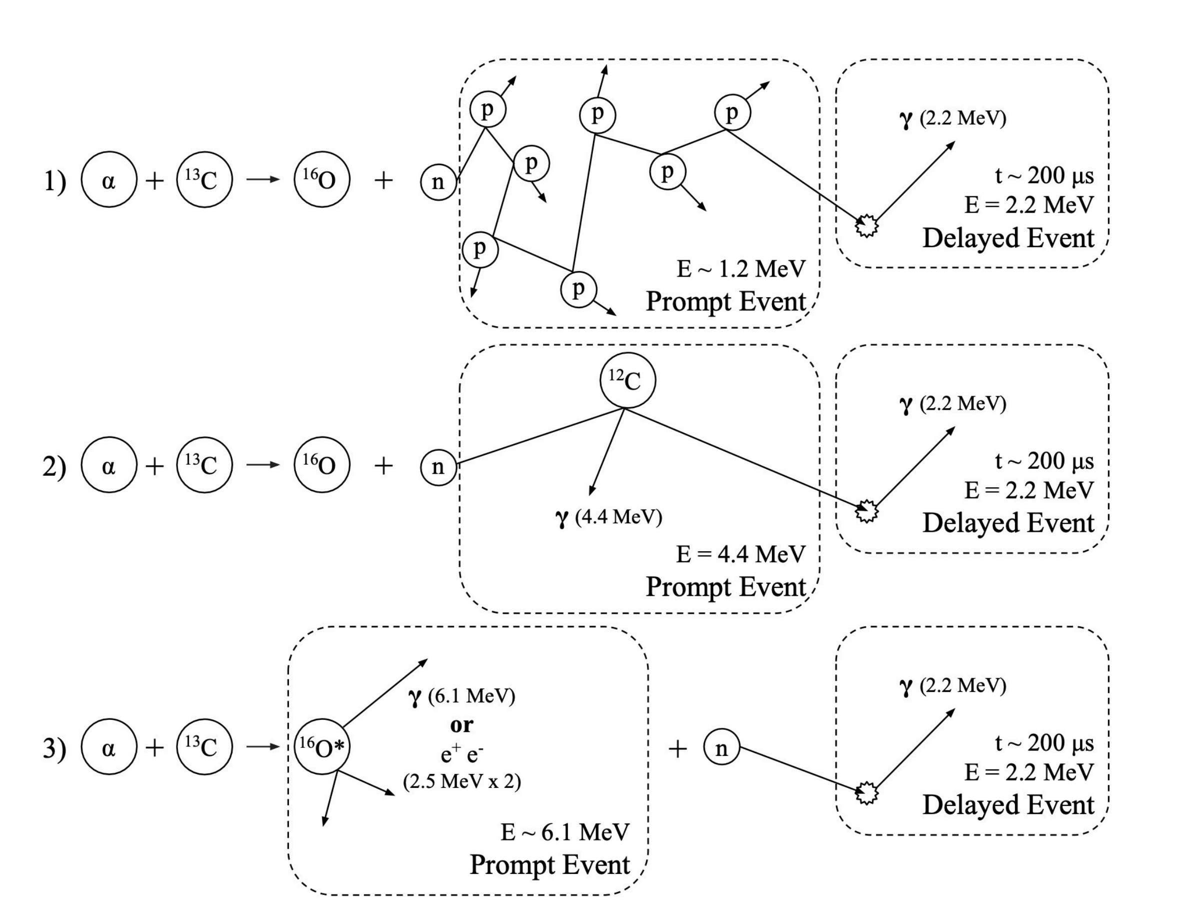
$$\nu_x + {}^{12}C \rightarrow \nu_x + n + {}^{11}C$$

- The half-life of Carbon-11 ~ 20 minutes
- This is significantly reduced (< 0.01 ev/yr/kT) by tagging the the neutron when its captured and releases the characteristic 2.2 MeV gamma.

(α, n) Background

- Main background to antineutrino IBD is (α, n).
- α particles from internal ^{210}Po decays capture on Carbon-13 mimicking the IBD coincidence signal.
- Three possible prompt events:
  1. Neutron recoils on proton
  2. Neutron scatters off Carbon-12
  3. Exited ^{16}O produced which deexcites



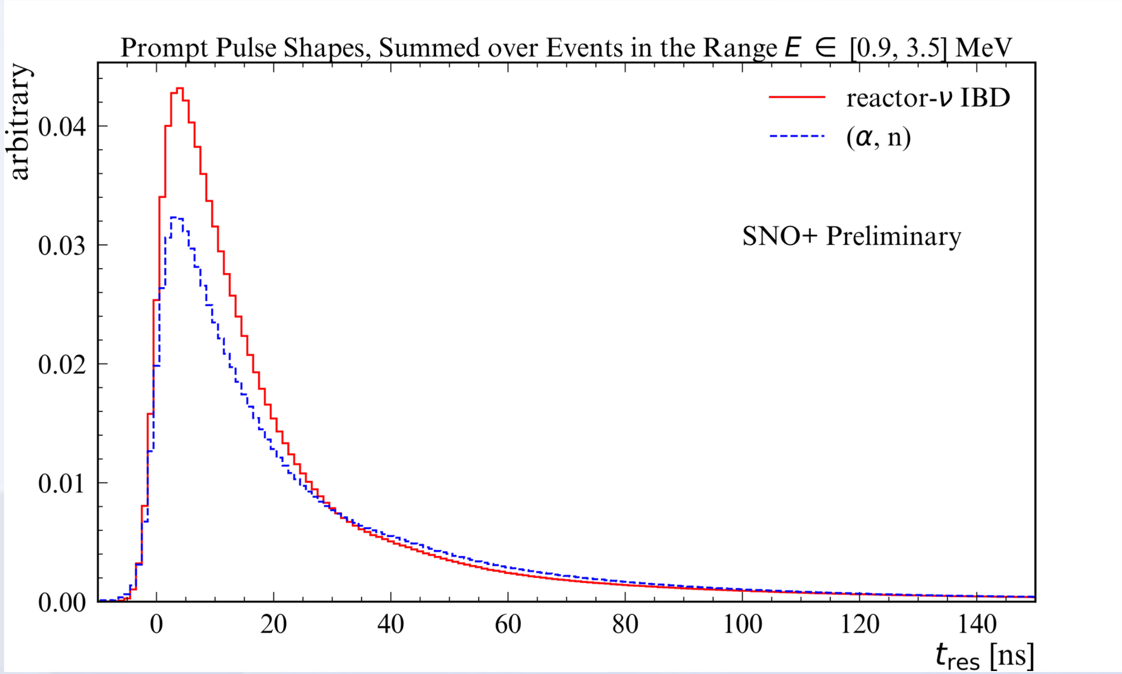


(α, n) Classifier

- (α, n) prompt events deposit energy over a slightly longer time than IBD prompt events

- Scintillation timing is also different for βs and protons
    - β timing calibrated using in-situ ^{214}Bi and ^{214}Po decay pairs
    - Proton timing to be calibrated with ^{241}Am-^{9}Be source

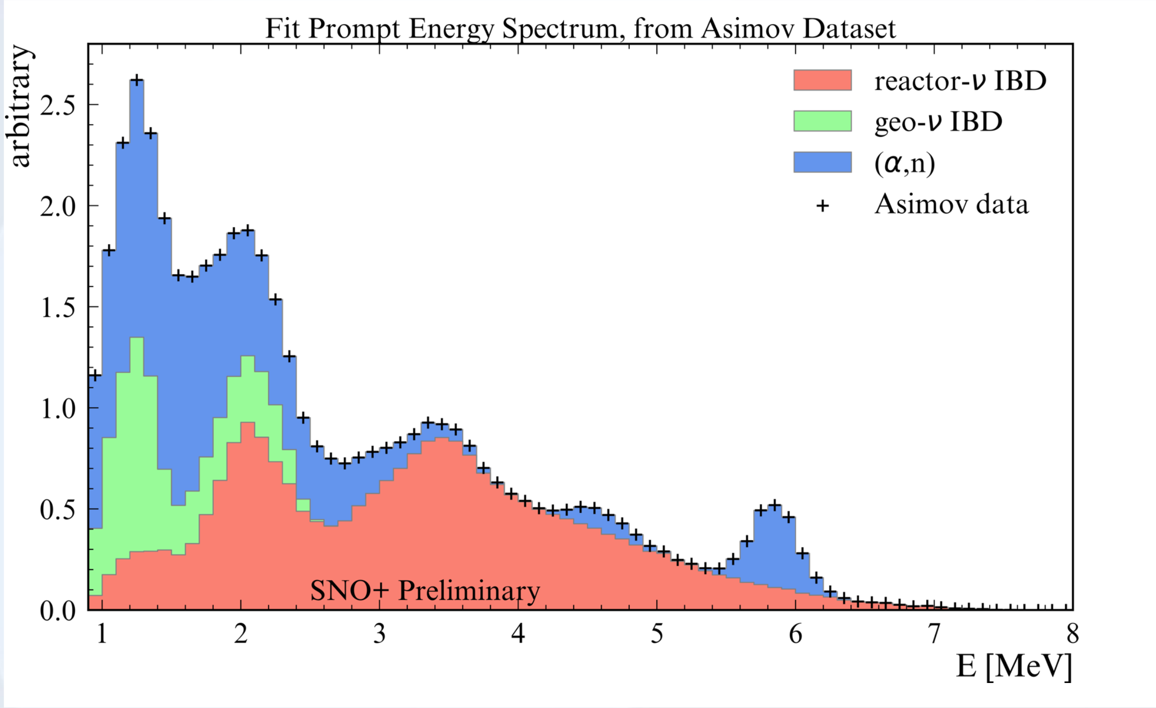
- Results in a different pulse shape that can be used to distinguish from IBD events



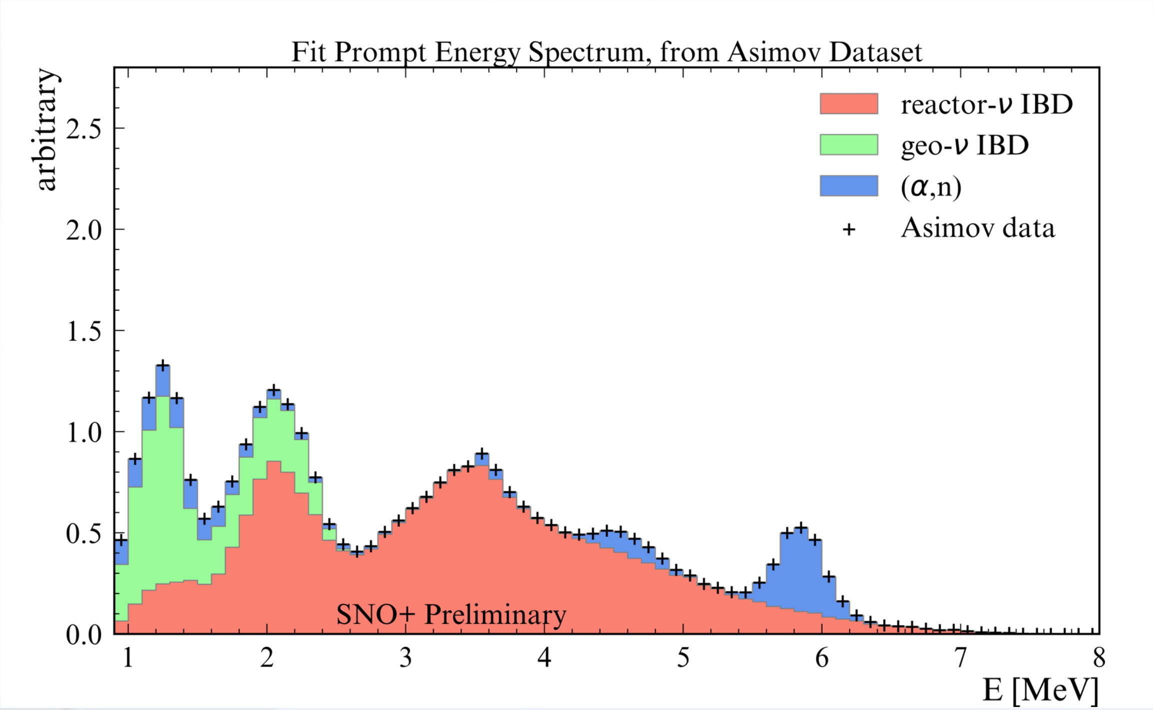
(α, n) Classifier

Simulated impact on prompt energy spectrum:

Pre-Classifier

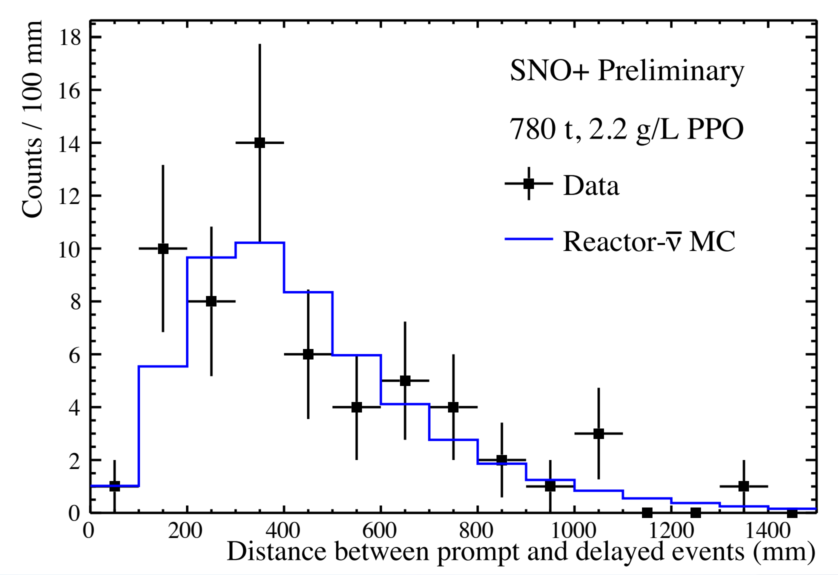


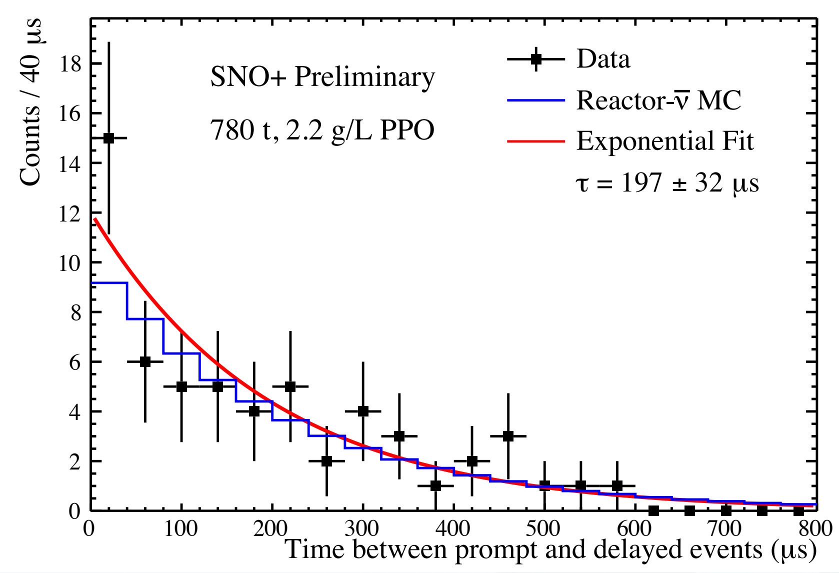
Post-Classifier

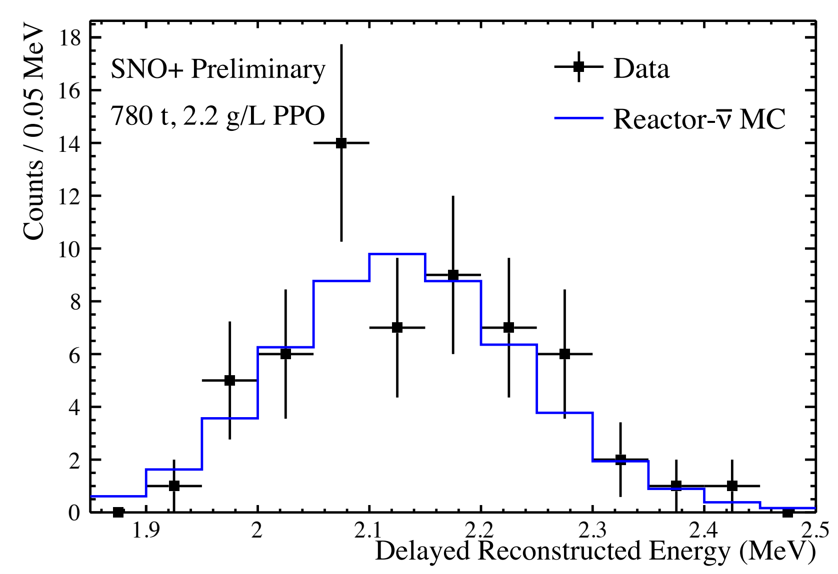


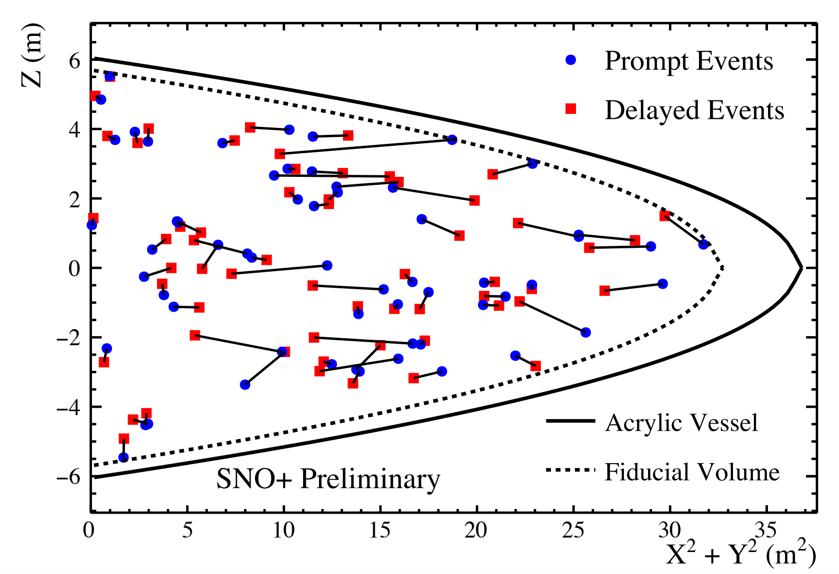
Significantly improves both the Geoneutrino flux and Δm^2_{21} measurements

Antineutrino Events









References

[1]: A. Ianni, D. Montanino, F.L. Villante, How to observe 8B solar neutrinos in liquid scintillator detectors, Phys Lett.B 627, 38-48, 2005.

[2]: T. Suzuki, A.B. Balantekin, T. Kajino, Neutrino capture on 13C Phys. Rev. C 86, 015502, 2012.

[3]: Borexino Collaboration, M. Agostini et al., Comprehensive measurement of pp-chain solar neutrinos, Nature 562, 2018.

[4]: P. A. Zyla et al. (Particle Data Group). Review of Particle Physics. Prog. Theor. Exp. Phys. 083C01, 2020.

[5]: Klaus Eitel, Measurement of neutrino–nucleus interactions in the energy regime of supernovae,J. Phys. G: Nucl. Part. Phys. 35 014055, 2008.