Sensitivity of a low threshold directional detector to CNO-cycle solar neutrinos

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Results online

https://arxiv.org/abs/1803.07109

Motivation

- Standard Solar Model agrees well with measured neutrino fluxes
- Different models predict different metal abundances
  - Old models agree with Helioseismological measurements of speed of sound to $\sim$0.1%
  - New more accurate models reduce metallicity by $\sim$30%, disagree with above
- CNO cycle depends linearly on metallicity, and so measurement of CNO neutrino flux could solve the Solar Metallicity problem

Current Measurements

- Best current limit on flux from Borexino
- ES recoil electron energy spectrum very similar to ^{210}Bi decays
- Extracting CNO flux requires constraining ^{210}Bi by daughter α decays
- Direction reconstruction gives a separate handle that allows us to reject ^{210}Bi

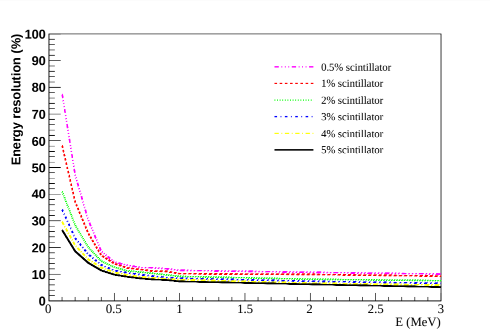
Overview

- Studying sensitivity of a large WbLS detector to CNO neutrino flux
- Sensitivity from 2-D binned maximum likelihood fit in energy and $\cos\theta_{\text{sun}}$
- Consider various detector configurations, background assumptions, directional reconstruction assumptions
    - Angular resolution from 25° to 55°
    - 25 kT vs 50 kT
    - 0.5% to 5% scintillator fraction WbLS
    - 60% vs 90% PMT coverage
    - Various background levels in water
    - BiPo and α rejection from 0% to 95%

PDFs

- All signals simulated with RAT-PAC
  - Decaychain
  - ESGen for solar
  - Survival probability applied on top of simulated ν_e and ν_μ fluxes
- Energy comes from simple reconstruction of MC simulation
- Direction is analytic based on assumed resolution
- No position reconstruction, use 50% fiducial volume, no external backgrounds

Energy spectrum



- Generated spectrum semi-analytically
- Cherenkov component of NHit spectrum fully simulated (includes absorption/reemission of these photons)
- Scintillation contribution taken from table generated at different positions
- Energy reconstruction from NHit lookup table

Angular Resolution

- Assume fixed angular resolution of the form $e^{\frac{1}{\sigma}(\cos\theta - 1)}$
- Assume constant with energy, so conservatively this is resolution at threshold and any improvement at higher energies is a second order effect
- SNO: ^{16}N ($\sim$5 MeV, 36 PMT hits) $\rightarrow$ 26.7°
- Super K: at 6 MeV, $\sim$41 PMT hits $\rightarrow$ 35°
- For 90% coverage 50 kT detector, at 0.5%, from Cherenkov photons expect
  - 0.6 MeV: 12 hits, 3 from direct photons
  - 1.0 MeV: 35 hits, 10 from direct photons
- Consider σ from 25 to 55°
- $\cos\theta_{\text{Sun}}$ distribution includes differential cross section effects for solar signals

Energy Threshold

- Consider energy thresholds from 0.6 to 1 MeV for fit
- Assuming 200 ns trigger window, with 94,000 PMTs $\rightarrow$ 18.8 noise hits per trigger window per kHz PMT dark rate
- PMT hits from scintillation + cherenkov at 0.6 MeV:
    - Pure water: 5.4 hits
    - 0.5% scintillator: 19.3 hits
    - 5% scintillator: 93 hits

Backgrounds

	H2O Level (g/gH2O)	LS Level (g/gLAB)
^{238}U Chain	6.63e-15 [36]	1.6e-17 [34]
^{232}Th Chain	8.8e-16 [36]	6.8e-18 [34]
^{40}K	6.1e-16[a]	1.3e-18 [35]
^{85}Kr	2.4e-25[b]	2.4e-25 [35]
^{39}Ar	2.75e-24[b]	2.75e-24 [35]
^{210}Bi	3.78e-28[b]	3.78e-28 [35]
^{11}C	0	1.0e5 (ev/kT/year) [4]

- Use weighted sums of LS and water components
- Levels set by SNO and Borexino measurements

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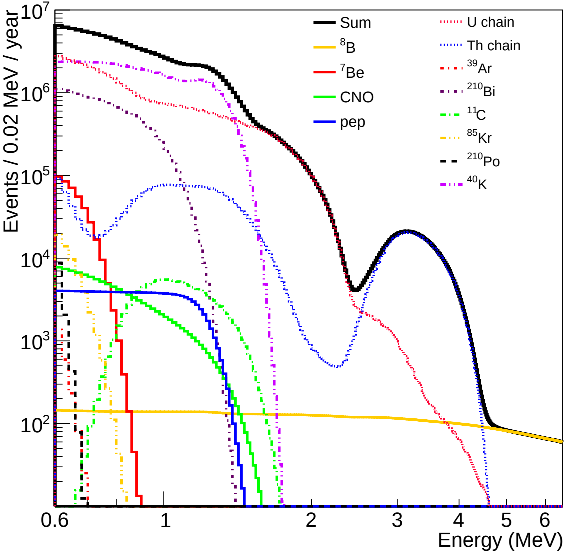
- Vary ^{40}K,^{85}Kr,^{39}Ar,^{210}Bi level in water
- ^{85}Kr,^{39}Ar,^{210}Bi level in water taken to be Borexino measured level in scintillator x1 up to x10000
- ^{11}C taken to be Borexino level
- Assume 95% BiPo rejection in 400 ns window, 100% BiPo rejection outside

Baseline configuration

- 50 kT detector, 90% coverage, 5% scintillator, 25° angular resolution
- Background levels match SNO and Borexino with
  - ^{40}K at 0.1x Borexino water level
  - ^{85}Kr,^{39}Ar,^{210}Bi level in water at Borexino measured level in scintillator
- 0.6 MeV energy threshold
- 50% fiducial volume, no external backgrounds
- 5 year livetime

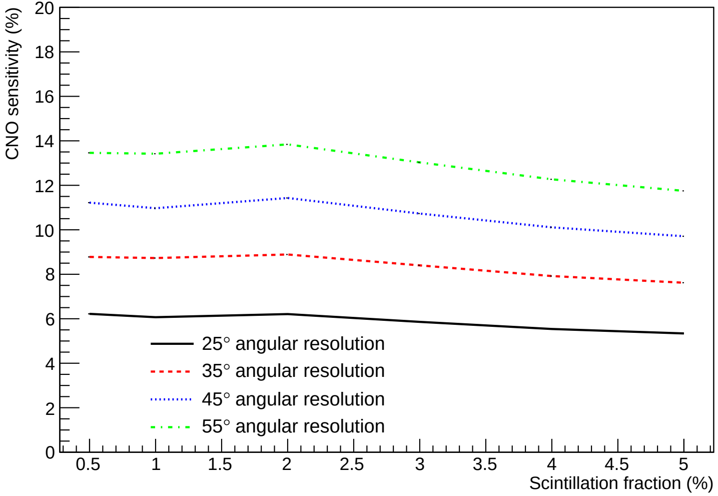
Energy Spectrum for baseline configuration



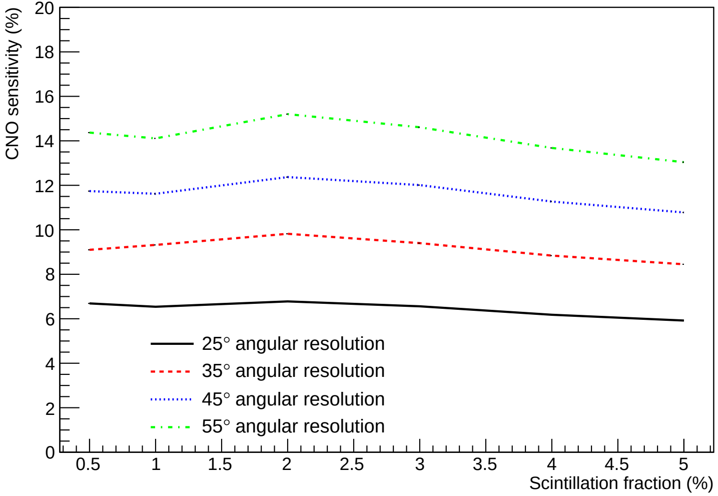
Results for baseline configuration

Signal	Normalization sensitivity (%)
^{8}B ν	0.4
^{7}Be ν	0.4
pep ν	3.8
CNO ν	5.3
^{210}Bi	0.1
^{11}C	11.5
^{85}Kr	10.5
^{40}K	0.04
^{39}Ar/^{210}Po	21.9
^{238}U chain	0.02
^{232}Th chain	0.05

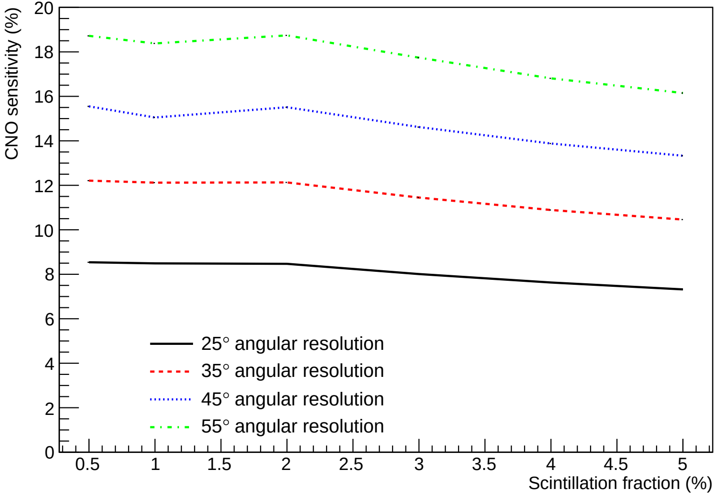
Results for baseline configuration



Results for baseline configuration - 60% PMT coverage



Results for baseline configuration - 25 kT



Results at Borexino ^{40}K level

Signal	Normalization sensitivity (%)
^{8}B ν	0.4
^{7}Be ν	0.9
pep ν	8.6
CNO ν	11
^{210}Bi	0.2
^{11}C	25
^{85}Kr	22
^{40}K	0.01
^{39}Ar/^{210}Po	45
^{238}U chain	0.02
^{232}Th chain	0.05

- CNO sensitivity degrades to 32% by 0.5%, 55° resolution

Results for other backgrounds

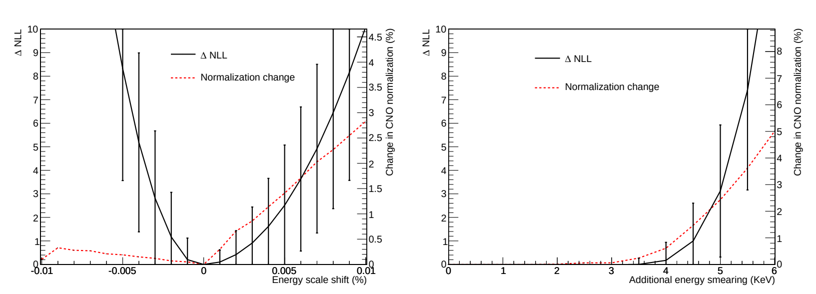
Fraction of nominal contamination	Isotope ^{11}C	^{210}Bi	^{85}Kr	^{39}Ar
0.1x	5.3	–	–	–
1x	5.3	5.3	5.3	5.3
10x	5.4	5.4	5.3	5.3
100x	5.5	6.0	5.4	5.4
1000x	–	9.4	5.6	5.4
10000x	–	–	5.9	5.5

- α, BiPo rejection also found to have small effect, with no rejection sensitivity of 6.4%

Results vs threshold

Energy threshold (MeV)	CNO sensitivity (%)
0.6	5.3
0.7	5.9
0.8	9.2
0.9	13.7
1.0	24.0

Systematic uncertainties



- Consider energy scale and energy resolution
  - Fixed percentage shift in energy PDF
  - Smearing PDF with gaussian of fixed width
- Refit data and look at change in mean reconstructed flux value and NLL

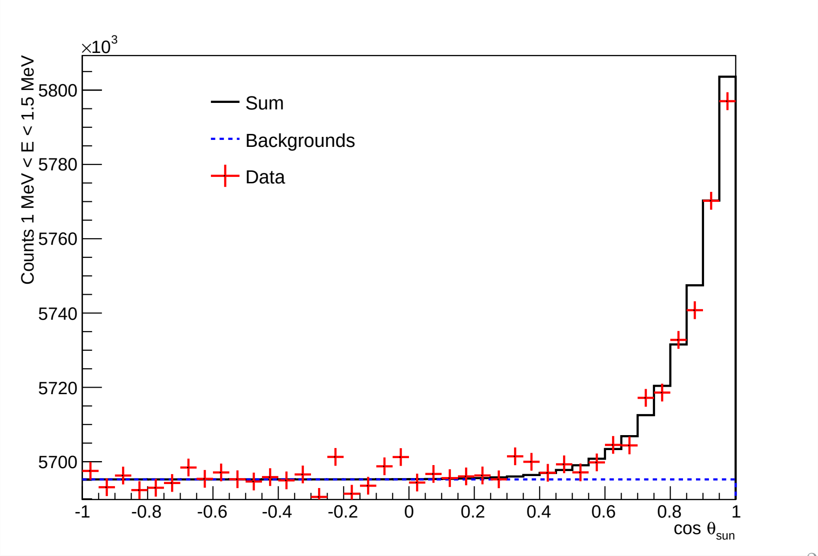
Conclusion

- Direction reconstruction allows us to separate solar signals from large and similar background
- Possibility of measuring CNO flux down to ∼5%
- Requires maintaining direction reconstruction down to <1 MeV
- ^{40}K in water must be limited, other backgrounds not as critical

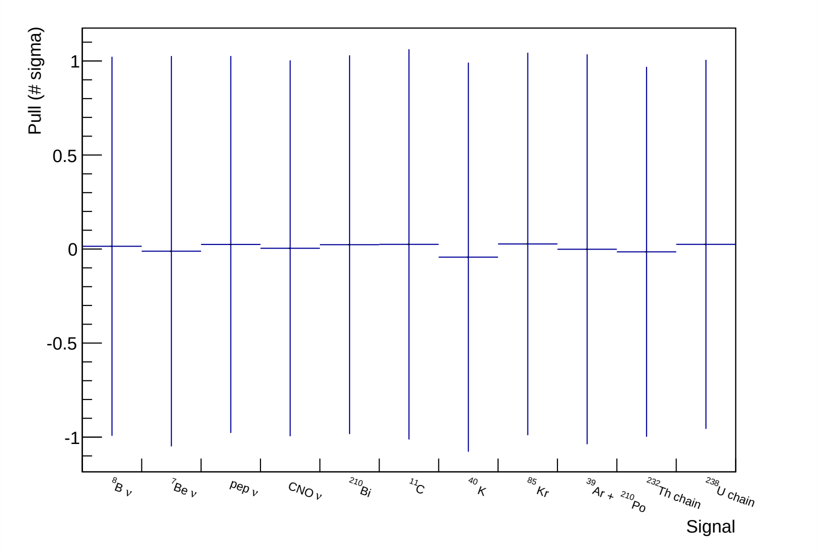
Results online at https://arxiv.org/abs/1803.07109

Backup

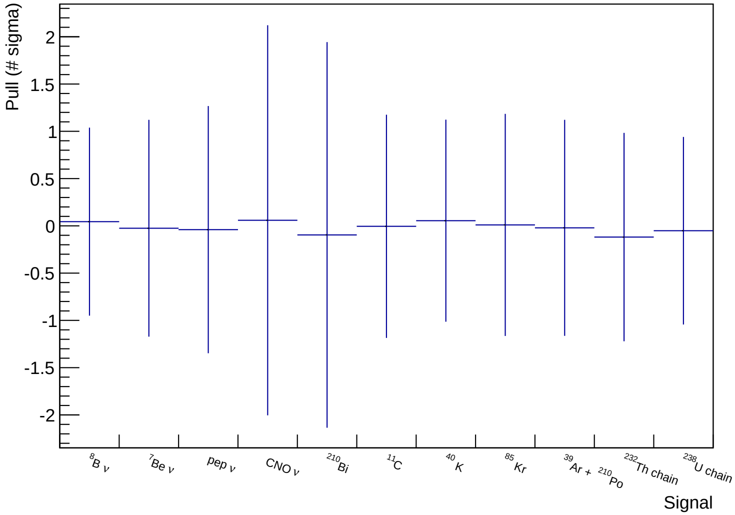
Projection of example fit in $\cos\theta_{sun}$ between 1 and 1.5 MeV for 25° resolution



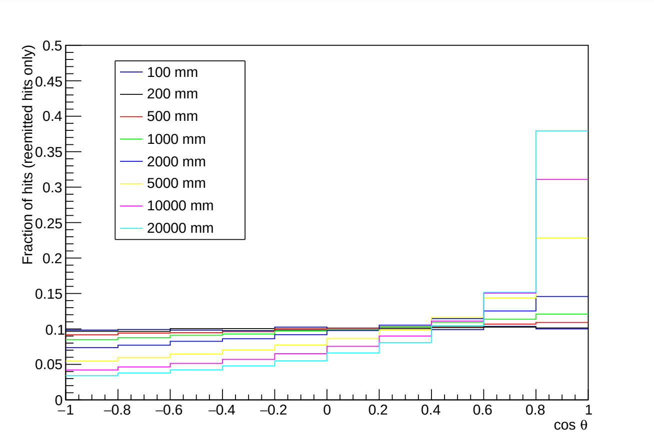
Pull distribution for baseline configuration



Pull distribution for pure LS energy only fit

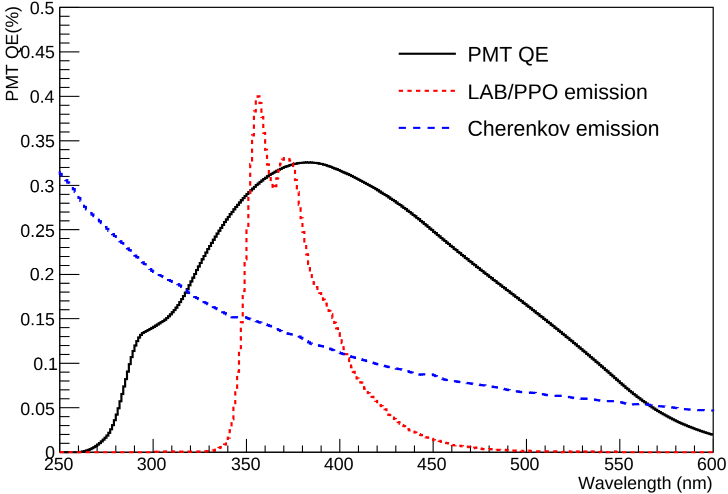


WLS reemission and direction



- Toy MC, generate isotropic in FV in all directions, absorb and reemit isotropic, look at angle between initial direction and final path

PMT QE



PMT QE(%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
250
300
350
400
450
500
550
600
Wavelength (nm)
PMT QE
LAB/PPO emission
Cherenkov emission

NHit comparison