TECHNISCHE UNIVERSITÄT DRESDEN

Institut für Kern- und Teilchenphysik

FINAL RESULTS FROM SNO

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on behalf of the SNO collaboration

NOW 2012, Otranto, September 2012

DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

Outline

The Sudbury Neutrino Observatory

- Signals
- Phases of Operation

SNO Precision measurements

- Particle identification through Pulse Shape Analysis
- Signal Extraction
- Oscillation analysis results

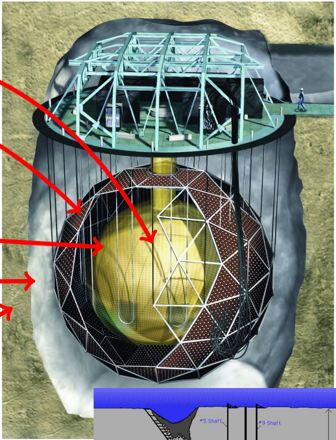
Beyond ^{8}B neutrinos

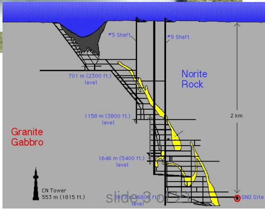
- **hep** neutrinos

The Sudbury Neutrino Observatory

The Detector

- Heavy Water (D_2O) as active medium.
  - 1000t of ultra-pure D_2O.
- PMT Support Structure
  - 9500 PMTs provide $\sim$ **54%** coverage.
  - 80 outward looking PMTs provide cosmics veto.
- Acrylic Vessel (AV).
  - 12m diameter, 5cm thick.
- Light water (H_2O) shielding.
  - 1700 t internal shielding.
  - 5300 t external shielding.
- Urylon liner.
  - Seal backgrounds from rock (Radon).
- 2039m deep (6000 mwe) in Creighton Mine (Sudbury, Ontario).
  - Very low cosmics rate ($\sim$ **80** μ per day).



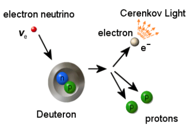


The Sudbury Neutrino Observatory

Detected Signals

CC : $\nu_e + d \rightarrow p + p + e^-$

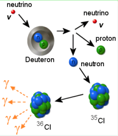
- Good measurement of the ν_e spectrum.
- Some directional information.
- Only sensitive to ν_e.



NC : $\nu_x + d \rightarrow n + p + \nu_x$

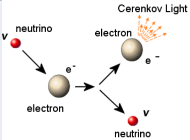
- Measures total ^{8}B flux from the Sun.
- Equal cross-section to all (active) neutrino flavours.

Signature event of SNO



ES : $\nu_e + e^- \rightarrow \nu_e + e^-$

- Strong directional sensitivity.
- Low statistics.

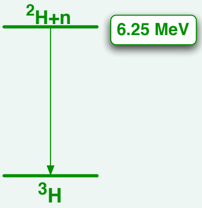


The Sudbury Neutrino Observatory

Phases of Operation

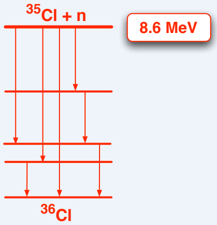
D_2O phase

- May 99 - May 01
- $^2\mathrm{H}\,(n,\gamma)\,^3\mathrm{H}$
- Good CC



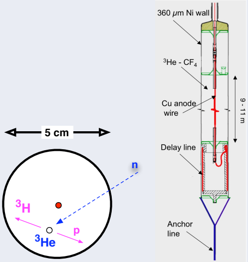
Salt phase

- July 01 - Sep 03
- 2t NaCl added to D_2O
- $^{35}\mathrm{Cl}\,(n,\gamma)\,^{36}\mathrm{Cl}$
- Enhanced NC



NCD phase

- Nov 04 - Nov 06
- 40 proportional counters
- $^3\mathrm{He}\,(n,p)\,^3\mathrm{H}$
- Event by event NC



Statistical separation

Independent detection

Precision measurements in SNO

- Combine different data taking phases into a single analysis.
  - Avoid double counting of common systematics.

Two combined analyses:

- Low Energy Threshold Analysis (LETA) (`Phys.Rev.C81:055504,2010`).
  - Combination of Phase I (D_2O) and Phase II (Salt) datasets.
  - Lower reconstructed energy threshold of 3.5 MeV.
  - Reduction of backgrounds and systematic uncertainties
- **Combined 3-Phase analysis (`arXiV:1109.0763`).**
  - **Particle identification through Pulse Shape Analysis of NCD data.**
  - **Fitted data to MC derived PDFs for neutrino signals and backgrounds.**
  - **Extract ^{8}B flux and ν_e survival probability (P_{ee}).**

Improvements

- Enhanced NC (^{8}B) measurement.
  - Joint fit with NCD phase data.
  - Pulse Shape Analysis (PSA).
- Improved neutrino oscillation analysis.
  - Finer, Linear scan on oscillation parameters.
  - Updated Solar and Earth Models.
  - Improved analysis of other experiments.
- New *hep* analysis.
  - Three times more statistics.

Difficulties

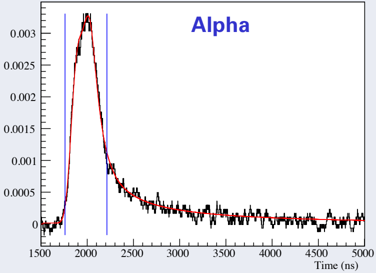
- NCD phase has very different energy response.
  - Accounted for by working in neutrino energy (survival probability fit).

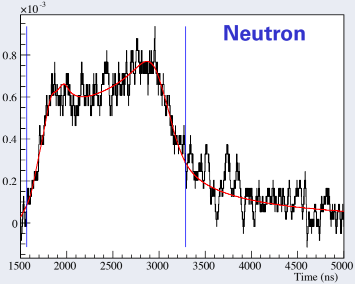
Pulse Shape Analysis

Particle identification

- Independent analysis of NCD data.
- Tag digitized shape of ionization signal.
  - Separate neutron signals from background (mostly α).
- Three analysis methods applied.

Example Waveforms

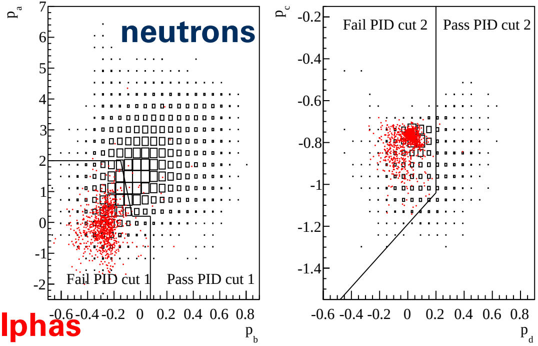




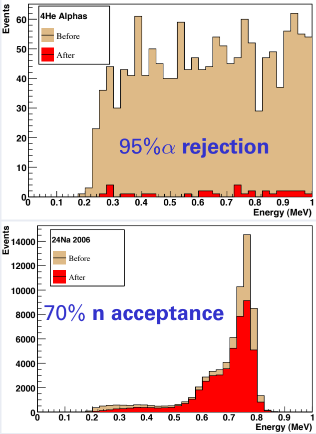
Pulse Shape Analysis
Performance

- Fit NCD data with PSA scales.
- Polynomial fit for remaining backgrounds.

Use NCD result as NC constraint in PMT data.

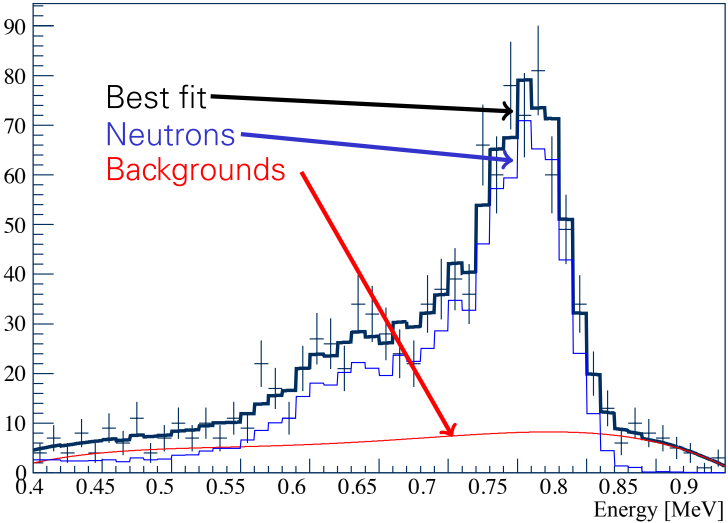


Performance



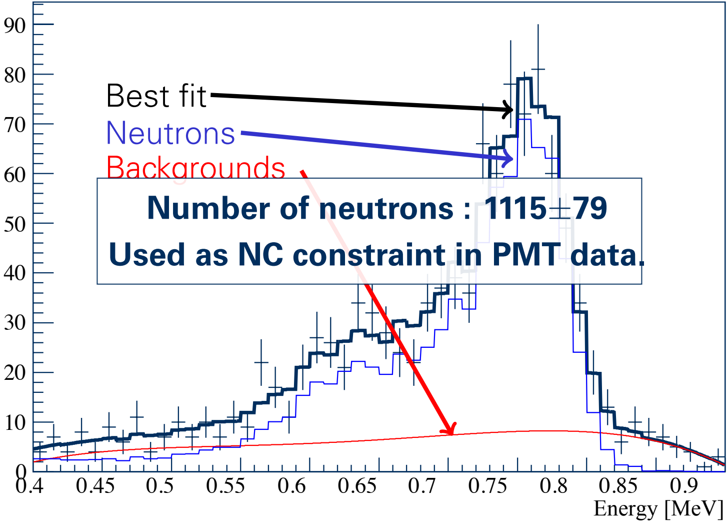
Pulse Shape Analysis

Fit to NCD array data



Pulse Shape Analysis

Fit to NCD array data



Signal Extraction

Survival Probability Fit

- Parameterize distortion for expected ^{8}B spectrum, i.e, the survival probability.
- Fit on $P_{ee}(E_\nu)$ instead of T_{eff} distribution.
- Model independent.
  - Survival Probability independent of any flux model.
  - Use NC as normalization and constrain on CC and ES.
- distortion parameterized by a quadratic function:

$$P_{ee}^{day}(E_\nu) = c_0 + c_1\,(E_\nu - 10MeV) + c_2\,(E_\nu - 10MeV)^2$$

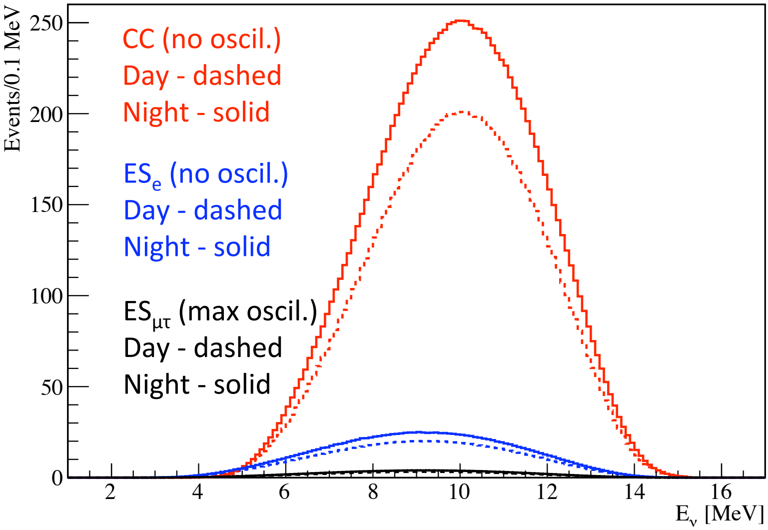
$$P_{ee}^{d/nasym.}(E_\nu) = a_0 + a_1\,(E_\nu - 10MeV)$$

$$P_{ee}^{night}(E_\nu) = P_{ee}^{day}(E_\nu)\frac{2 + P_{ee}^{d/nasym.}(E_\nu)}{2 - P_{ee}^{d/nasym.}(E_\nu)}$$

- Energy response different for each phase.
  - Critical for 3-Phase analysis.

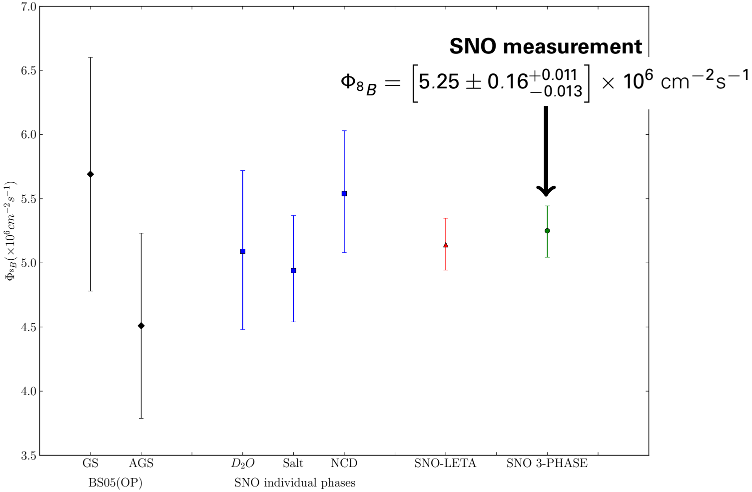
Signal Extraction

Detectable neutrino spectrum



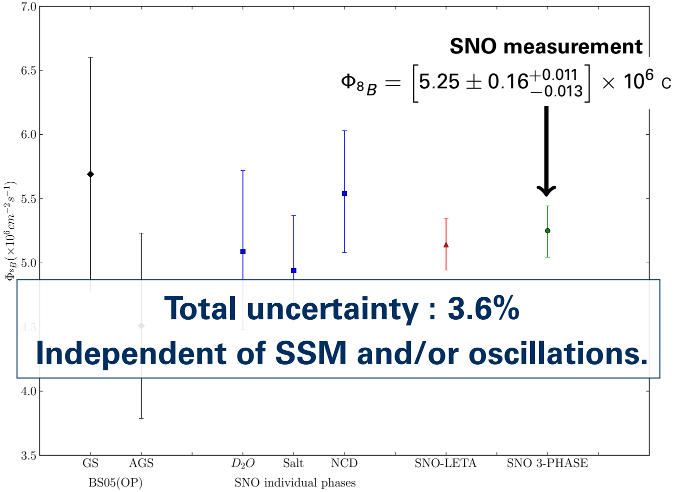
Signal Extraction Results

^{8}B neutrino flux



Signal Extraction Results

^{8}B neutrino flux



SNO measurement

$$\Phi_{^8B} = \left[5.25 \pm 0.16^{+0.011}_{-0.013}\right] \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Total uncertainty : 3.6%

Independent of SSM and/or oscillations.

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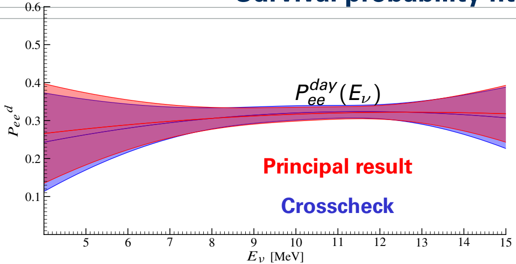
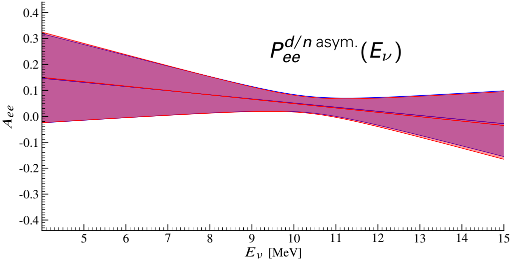
Signal extraction results

Survival probability fit





$$c_0 = 0.317 \quad \pm 0.016 \pm 0.009$$

$$c_1 = 0.0039 \quad {}^{+0.0065}_{-0.0067} \pm 0.0045$$

$$c_2 = -0.0010 \quad \pm 0.0029\, {}^{+0.0014}_{-0.0016}$$

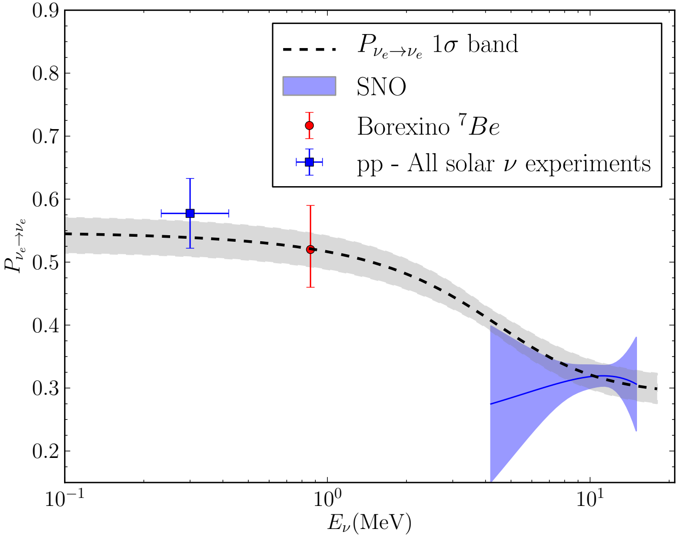
$$a_0 = 0.046 \quad \pm 0.031\, {}^{+0.014}_{-0.013}$$

$$a_1 = -0.016 \quad \pm 0.025\, {}^{+0.010}_{-0.011}$$

Approx. 20% improvement over previous analysis.

- **No significant evidence for a distortion of the energy spectrum observed.**
- **No difference between day and night flux.**

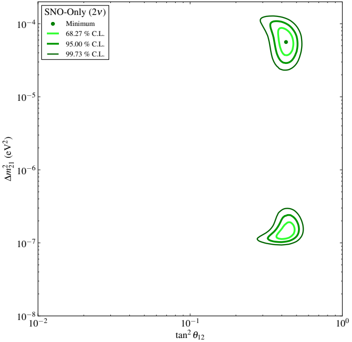
Neutrino Oscillation Analysis
MSW solution

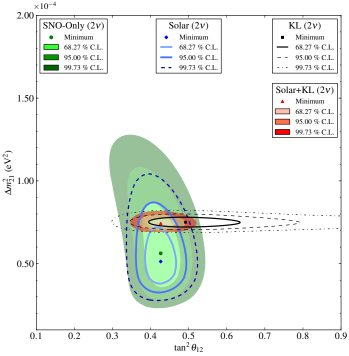


Neutrino Oscillation Analysis

Two flavors results

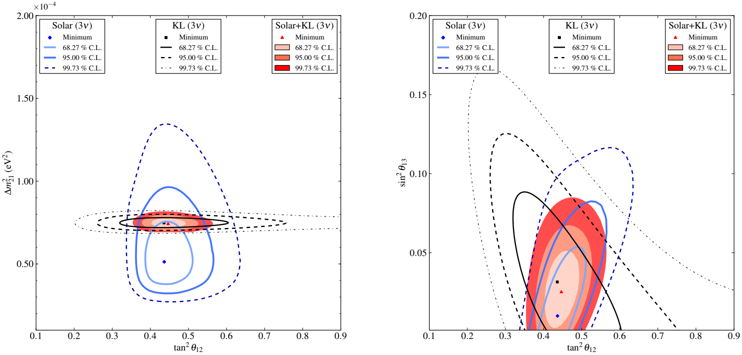
- SNO dominates the precision θ_{12}.
  - $\sin^2\theta_{12} \sim \dfrac{N^{CC}}{N^{NC}}$.
- SNO alone can't eliminate LOW.
  - Eliminated independently by Borexino (and KamLAND).





Neutrino Oscillation Analysis

Three flavors results

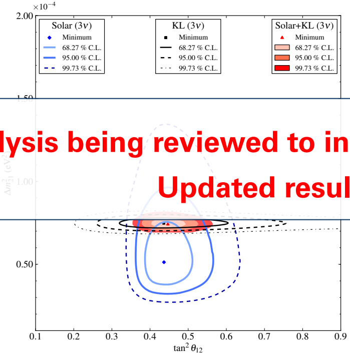


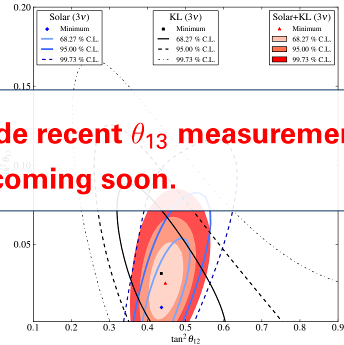
$$\tan^2\theta_{12} = 0.446^{+0.048}_{-0.036} \qquad \Delta m^2_{21} = \left(7.41^{0.21}_{-0.19}\right) \times 10^{-5}\ \text{eV}^2$$

$$\sin^2\theta_{13} = 0.025^{+0.018}_{-0.015} \qquad [< 0.0534 (95\%\ \text{C.L.})]$$

Neutrino Oscillation Analysis

Three flavors results





Analysis being reviewed to include recent θ_{13} measurements.

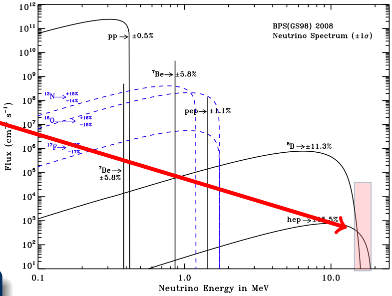
Updated results coming soon.

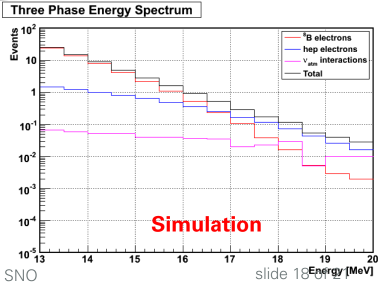
$\tan^2\theta_{12} = 0.446^{+0.048}_{-0.036}$ $\quad \Delta m^2_{21} = \left(7.41^{0.21}_{-0.19}\right) \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2\theta_{13} = 0.025^{+0.018}_{-0.015}$ $\quad [< 0.0534 (95\%\ \mathrm{C.L.})]$

Beyond ^{8}B
hep neutrino analysis

- Highest energy solar neutrinos but lowest flux.
  - $\sim$ 1000 smaller than ^8B.
  - Look for shoulder at endpoint of ^8B spectrum.
- Now includes all SNO data (**1054.0 days**).
- Use SNO survival probability fits and ^8B constraint to fit shape of energy spectrum.





Present limits:

SK:	$< 1.5 \times 10^5 cm^{-2}s^{-1}(90\% C.L.)$
	(PRD 73, 112001, 2006)
SNO Phase I:	$< 23 \times 10^3 cm^{-2}s^{-1}(90\% C.L.)$
	(ApJ 653:1545-1551, 2006)
SSM prediction:	$(8.0 \pm 1.2) \times 10^3 cm^{-2}s^{-1}$

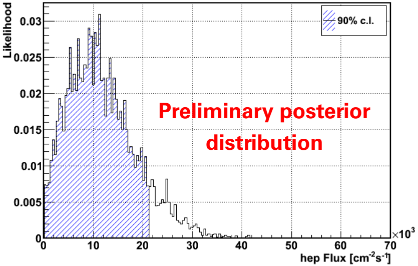
hep analysis

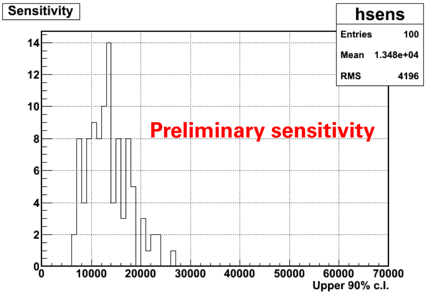
New 3-phase limit from SNO

- Preliminary fit to all SNO data.
  - Using Bayesian analysis with flat prior.
  - $\Phi_{hep} < 21 \times 10^3 cm^{-2} s^{-1}$.
- Expected sensitivity: $\Phi_{hep} < 13 \times 10^3 cm^{-2} s^{-1}$.
- Effective limit worse due to excess of events.

Results consistent with SSM prediction.

Separate publication being prepared.





Summary

- The first publication of SNO resolved the Solar Neutrino Problem.
- Major improvements for the combined three phase analysis:
  - Chosen signal parameterisation allows direct extraction of ^{8}B flux and survival probability functions.
  - Various changes to the previous analyses made to improve the accuracy of the results and uncertainties.
  - Particle identification in the NCD data allowed the ^{8}B measurement to become less sensitive to our understanding of the backgrounds.
- Definitive ^{8}B SNO results from combined three-phase analysis:
  - Most precise, model independent, measurement of the total ^{8}B flux.
  - Most accurate uncertainties for the solar survival probability function.
  - Further constrain hypothesis for neutrino oscillations.
- A separate hep neutrino analysis aims to reach the best ever limit.

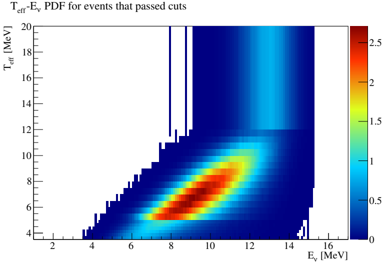
Thank you for your attention

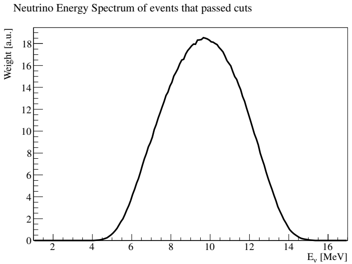
Last SNO collaboration meeting @ SNOLAB

Backup Slides

Interpreting the polynomial fit

- Intrinsic limitation:
  - Fitting a complex distribution with a simple polynomial function.
  - The interpretation (oscillation analysis) has to account for this.
- Fit the model with the same parameterization.
  - Extract the model "polynomial" parameterization.
  - Use detector sensitivity function to weight the fit.
- New "observables" are polynomial coefficients.





Signal Extraction
Fit parameterisation

- Signal extraction process uses an extended log-likelihood function

$$ELL = -\sum_{j=1}^{n_{classes}} \alpha_j \nu_{j_{exp}}(\eta_j) + \sum_{i=1}^{n_{events}} \log\left[\sum_{j=1}^{n_{classes}} \alpha_j \nu_{j_{exp}}(\eta_j) f(x_i|j,\eta_j)\right] + LL_{measurements}(\alpha,\nu,\eta)$$

$\nu_{j_{exp}}(\eta_j)$: expected number of detected events

α_j: Scales containing the dependencies on the fitted signal and background production rates.

  - Parameterised to measure α_B and $P_{\nu_e \to \nu_e}$

In SNO

$$\alpha_{CC} = \alpha_B \int_{-\inf}^{+\inf} P_{ee}(E_\nu) f(E_\nu|CC) dE_\nu$$

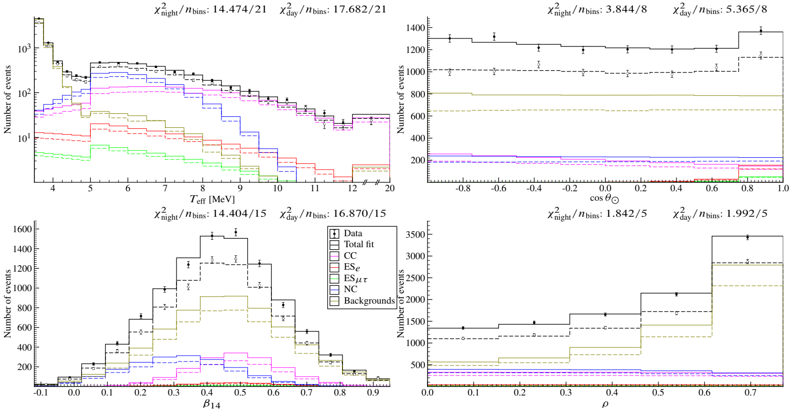
$$\alpha_{ES_e} = \alpha_B \int_{-\inf}^{+\inf} P_{ee}(E_\nu) f(E_\nu|ES_e) dE_\nu$$

$$\alpha_{ES_{\mu\tau}} = \alpha_B \int_{-\inf}^{+\inf} \left[1 - P_{ee}(E_\nu)\right] f(E_\nu|ES_{\mu\tau}) dE_\nu$$

$$\alpha_{NC} = \alpha_B$$

Signal Extraction

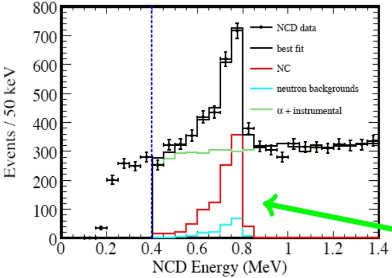
Observables (Salt phase)

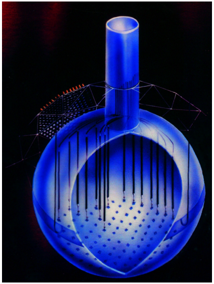


The Sudbury Neutrino Observatory

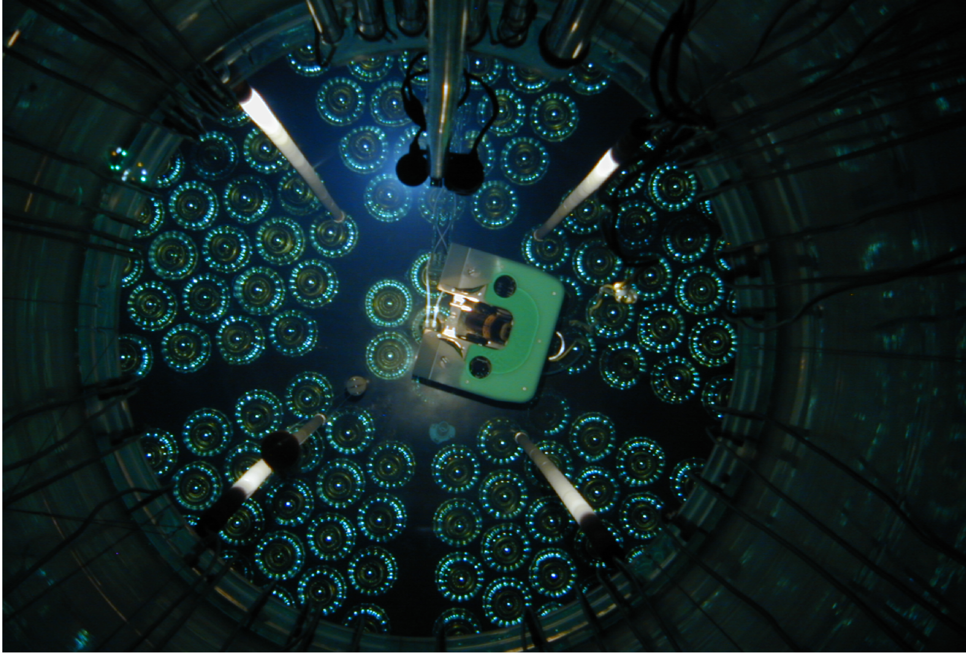
NCD Phase

- Proportional counters with $^3\mathrm{He}$, 10m long, in a 1×1m grid.
- Independent measurement of NC flux.
- Harder PMT event reconstruction (NCD shadows, reflections and increased backgrounds in Čerenkov light).
- Break correlations between CC and NC.



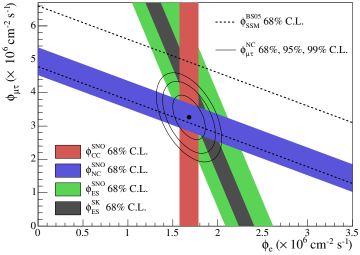


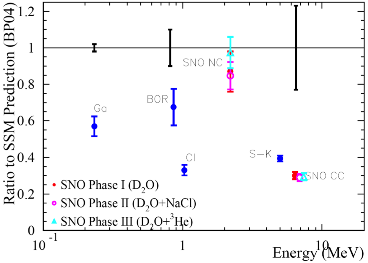
9% NC uncertainty (total)
Phys.Rev.Lett.101:111301,2008



What SNO told us
Individual phases

- Measurement of ^{8}B flux without Solar model constraints.
  - Confirm SSM.
- Neutrino flavour change.
  - Non-electron Solar neutrinos observed.
  - Solve the Solar Neutrino Problem
- Measurement of θ_{12} independent of SSM possible.





Solar neutrinos

Solar neutrino spectrum