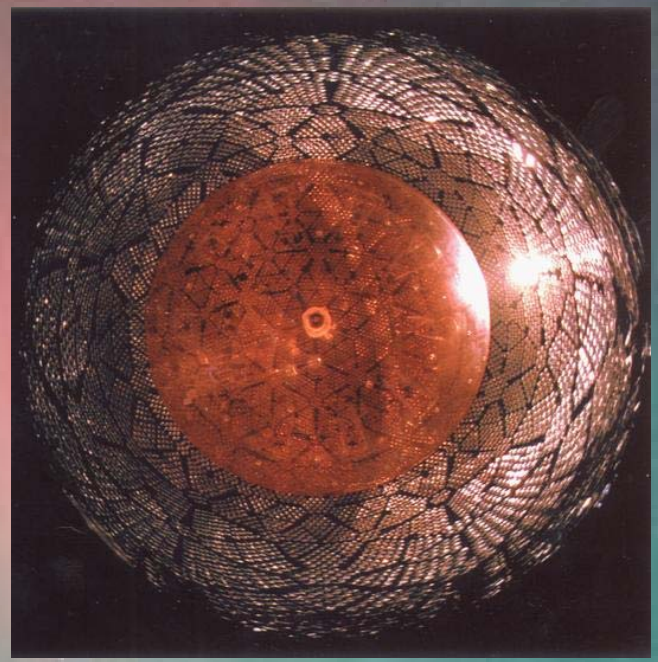
Latest News from SNO

Kevin Graham
Queen's University

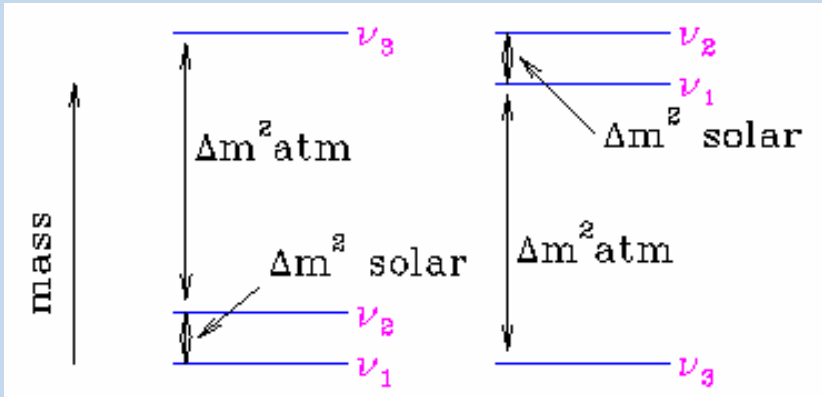


Physics in Collision
June 26-28, 2003
Zeuthen, Germany

Neutrinos – What do we want to know?

- Verify flavour change
- Measure mass splittings/hierarchy
- Mixing angles
- How many types? Sterile? Majorana?
- Measure individual mass eigenstates
- CP violation?
- Magnetic moment?

e	511 keV	ν_e	< 3 eV
μ	106 MeV	ν_μ	<0.19 MeV
τ	1.78 GeV	ν_τ	<18.2 MeV



Solar measuring θ_{12}, Δm_{12}

Using the oscillation framework:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

Solar,Reactor | **Atmospheric** | **CP Violating Phase** | **Reactor...** | **Majorana Phases**

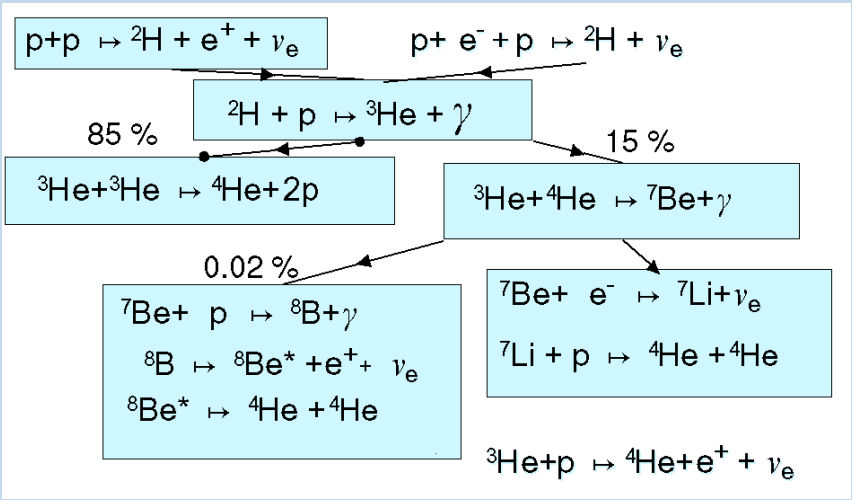
$where\ c_{ij} = \cos\theta_{ij}, and\ s_{ij} = \sin\theta_{ij}$

Range defined for Δm_{12}, Δm_{23}

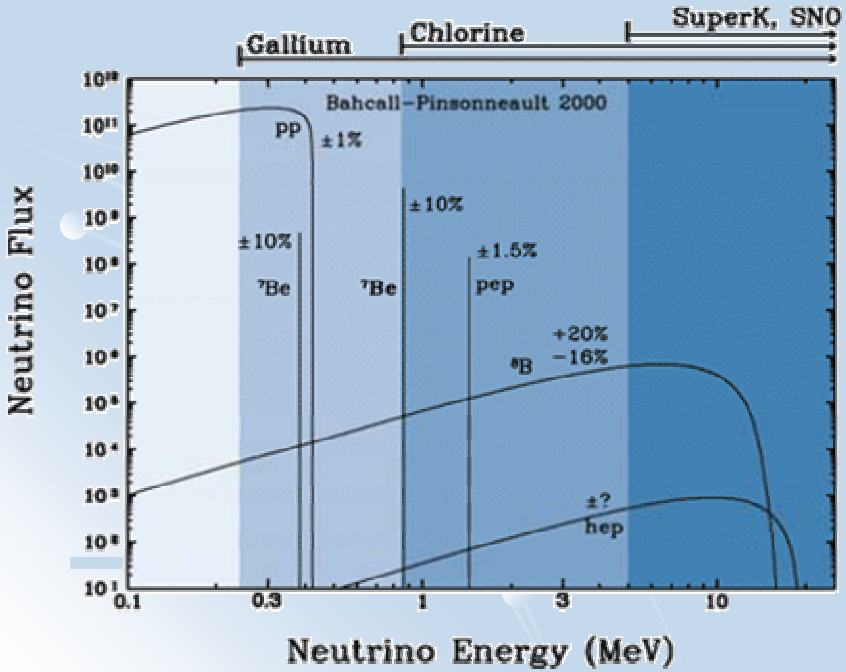
For two neutrino oscillation in a vacuum: (valid approximation in many cases)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

Solar Neutrinos



$\Phi = 6.6 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$



Experimental Results

SAGE+GALLEX/GNO

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

Flux = 0.55 SSM

Homestake

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Flux = 0.34 SSM

Kamiokande+Superkamiokande

$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad \sigma_{\mu\tau} = \frac{1}{6} \times \sigma_e$$

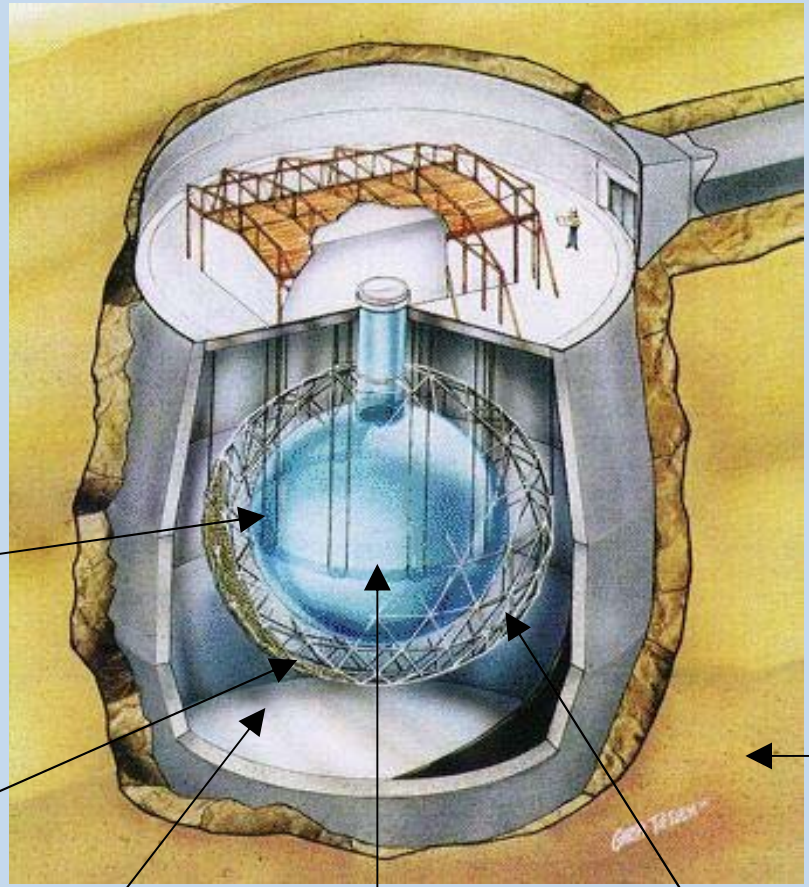
Flux = 0.47 SSM

SNO (CC 0.35)

Flux = 1 SSM

The SNO Detector

2039 m to surface



9438 Inward-Looking PMTs

91 Outward Looking PMTs (Veto)

12 m diameter Acrylic vessel

PMT Support Structure (PSUP)

Norite Rock

5300 tonnes light water

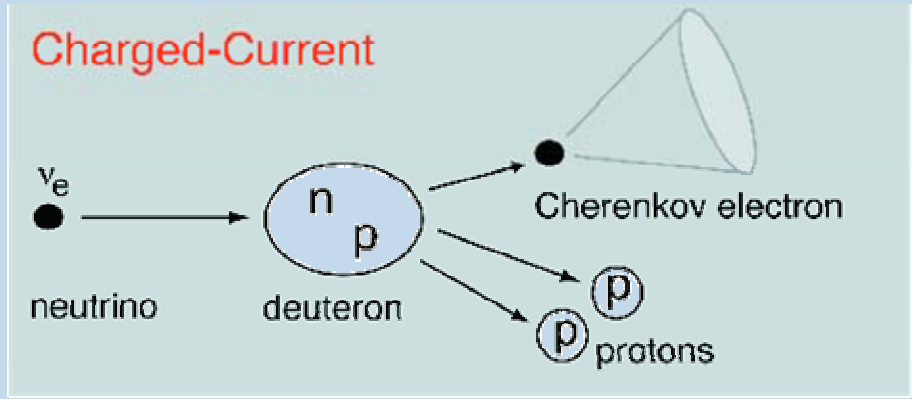
1000 tonnes heavy water

1700 tonnes light water

Neutrino Reactions in SNO

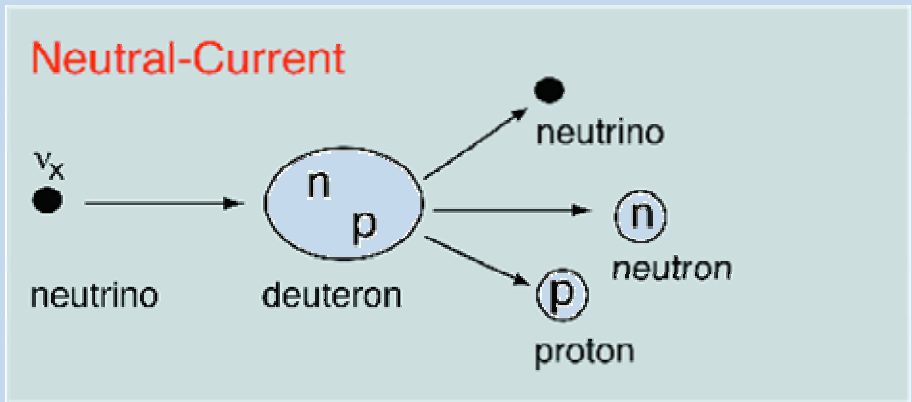
CC $\nu_e + d \rightarrow p + p + e^-$

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only



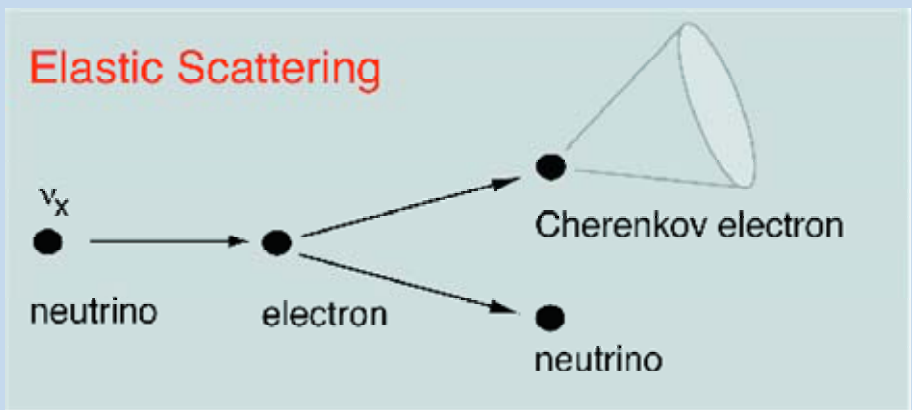
NC $\nu_x + d \rightarrow p + n + \nu_x$

- Q = 2.22 MeV
- measures total ^{8}B ν flux from the Sun
- equal cross section for all ν types



ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity



SNO Data Taking Phases

Phase I (pure D2O):

Neutron capture on D

Single 6.25 MeV γ

Statistical separation (Energy, radius)

High CC-NC correlation

Past

Phase II (dissolved salt):

Neutron capture on Cl

Multiple γ s, 8.6 MeV

Statistical separation (Isotropy)

Better CC-NC separation

Present

Phase III (3He n counters):

$n + {}^3\mathrm{He} \rightarrow p + t$

Independent channel

NC uncorrelated to CC

Future

What have we done so far?

The Pure D_2O Phase Dataset

- Livetime: 306.4 days (November 2, 1999 ➡ May 27, 2001)
  Day: 128.5 days Night: 177.9 days
- Energy Threshold: 5 MeV Kinetic
- Fiducial Volume Cut: 550 cm
- Total Number of Events after cuts: 2928
  Neutron Bkg 78^{+12}_{-12} Cherenkov Bkg 45^{+18}_{-12}

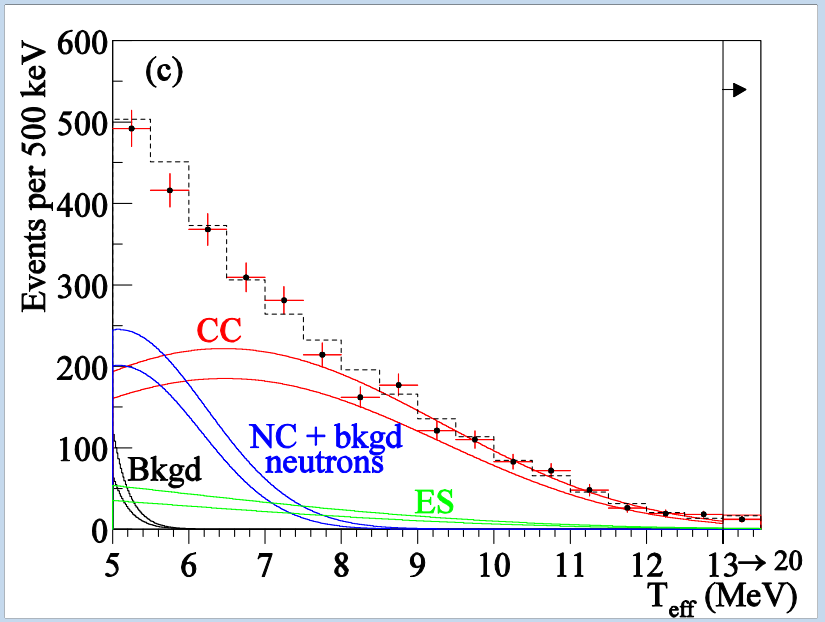
The data set is used for a hypothesis test of no neutrino oscillations by assuming no MSW distortion and comparing NC and CC. rates

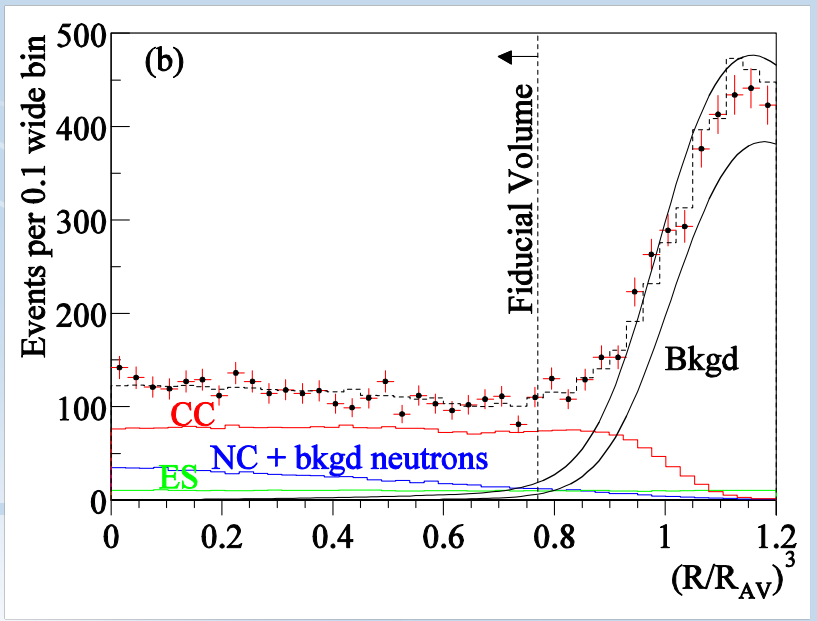
Signal Extraction Results – Pure D_2O Phase

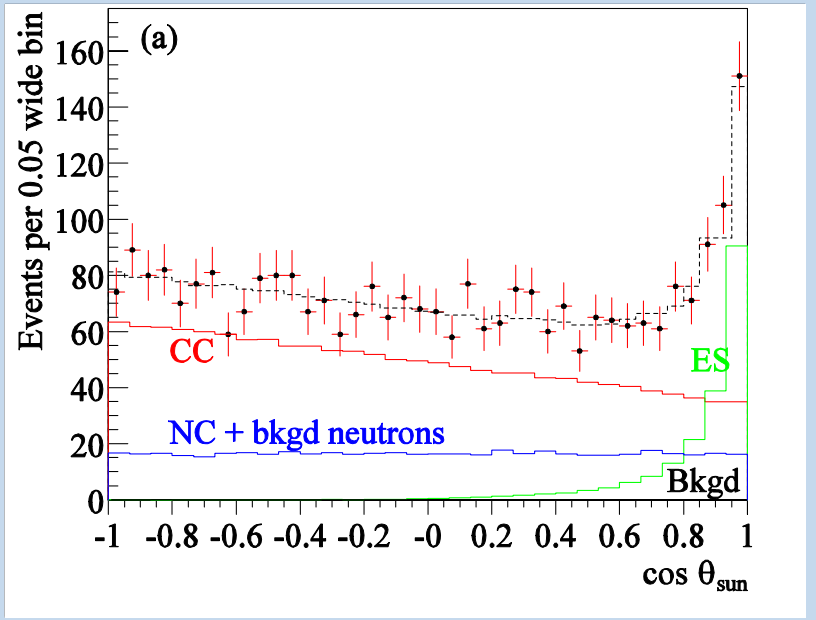
306.4 Live Days

#EVENTS

CC	$1967.7^{+61.9}_{+60.9}$	
ES	$263.6^{+26.4}_{+25.6}$	
NC	$576.5^{+49.5}_{+48.9}$	







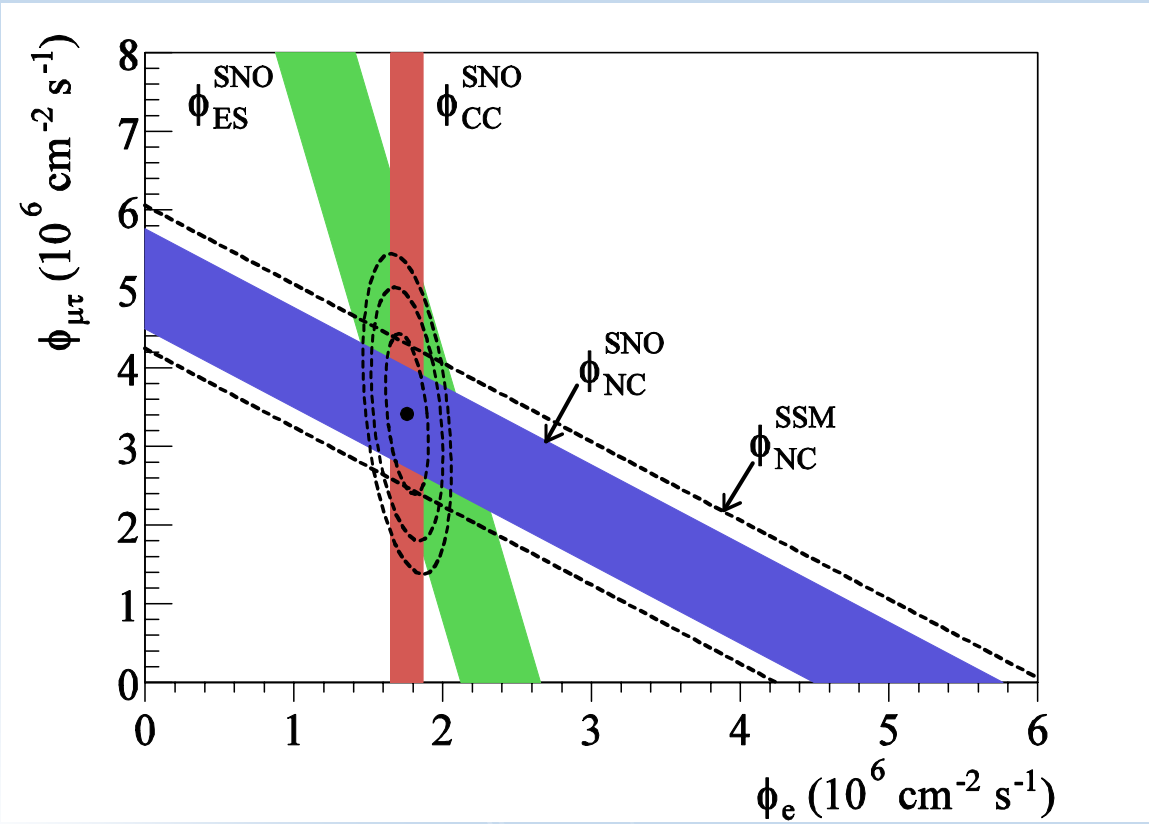
Flux Results – Pure D_2O Phase

$$\Phi_e = 1.76^{+0.05}_{-0.05}(stat.)^{+0.09}_{-0.09}(syst.) \times 10^6\,\mathrm{cm}^{-2}s^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(stat.)^{+0.48}_{-0.45}(syst.) \times 10^6\,\mathrm{cm}^{-2}s^{-1}$$

5.3σ effect

Neutrinos Massive



Constrained Fit for flavour change test

$$\Phi_{SSM} = 5.05^{+1.01}_{-0.81}$$

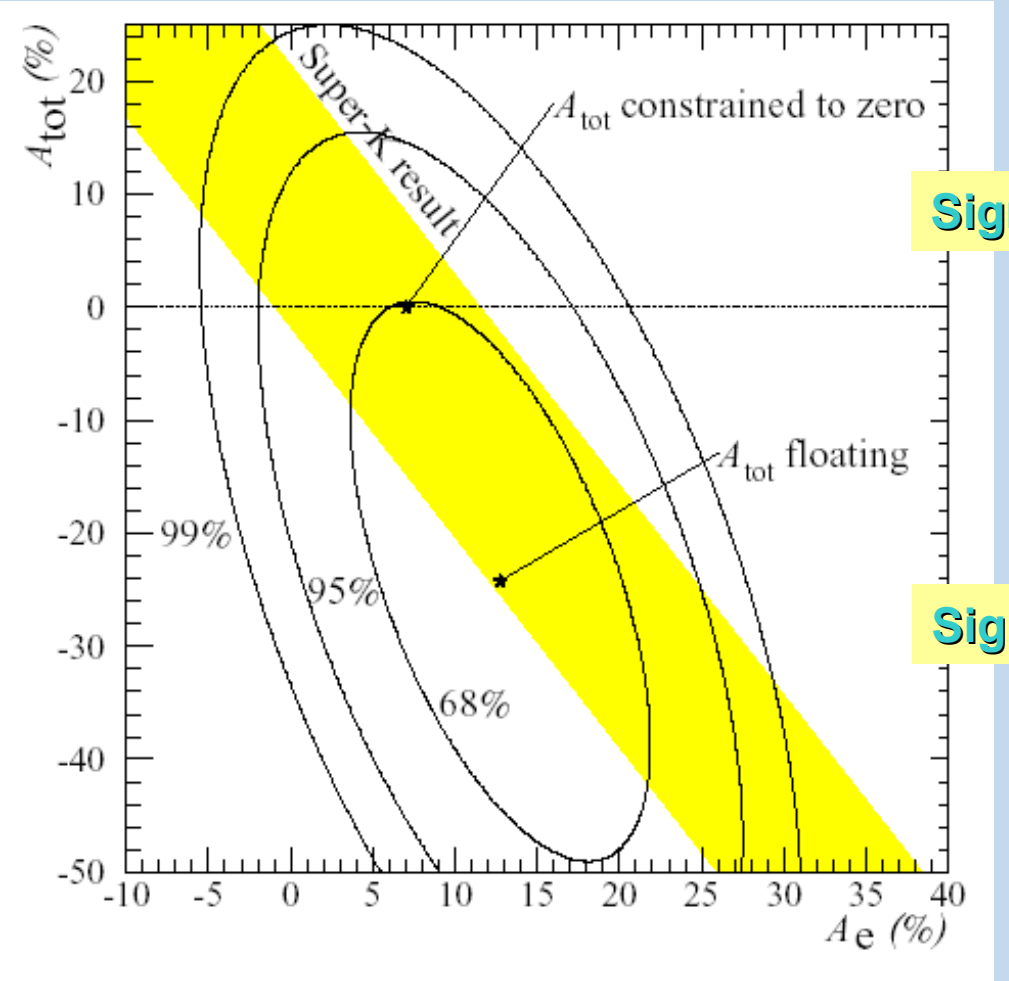
$$\Phi_{SNO} = 5.09^{+(0.44\oplus0.46)}_{-(0.43\oplus0.43)}$$

Without Constraint

$$\Phi_{SNO} = 6.42^{+(1.57\oplus0.55)}_{-(1.57\oplus0.58)}$$

Day/Night Asymmetry

$$A_x = \frac{2(\Phi_x^{night} - \Phi_x^{day})}{(\Phi_x^{night} + \Phi_x^{day})}$$



Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES}.

$$A_{cc} = 14.0 \pm 6.3^{+1.5}_{-1.4}$$

$$A_{nc} = 20.4 \pm 16.9^{+2.4}_{-2.5}$$

Signal Extraction in Φ_e, Φ_{total},

$$A_e = 12.8 \pm 6.2^{+1.5}_{-1.4}$$

$$A_{tot} = -24.2 \pm 16.1^{+2.4}_{-2.5}$$

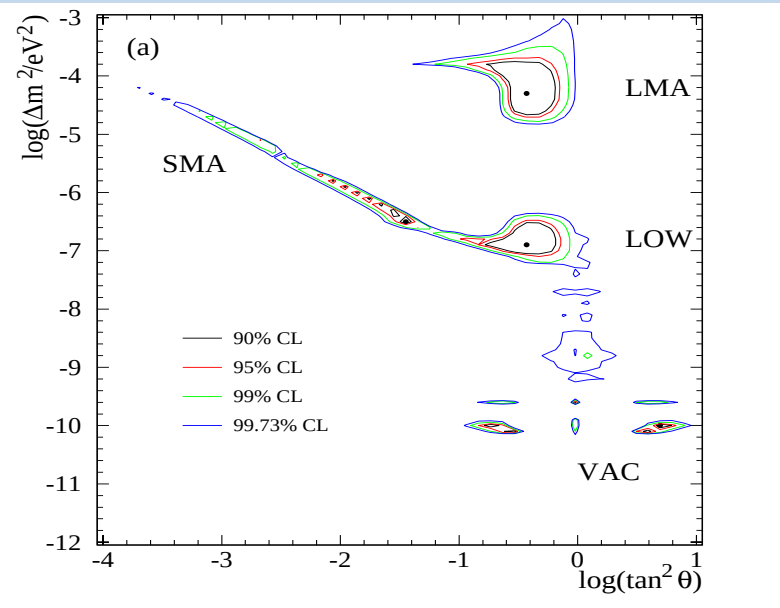
Signal Extraction in Φ_e, Φ_{total}, + A_{total} = 0

$$A_e = 7.0 \pm 4.9^{+1.3}_{-1.2}$$

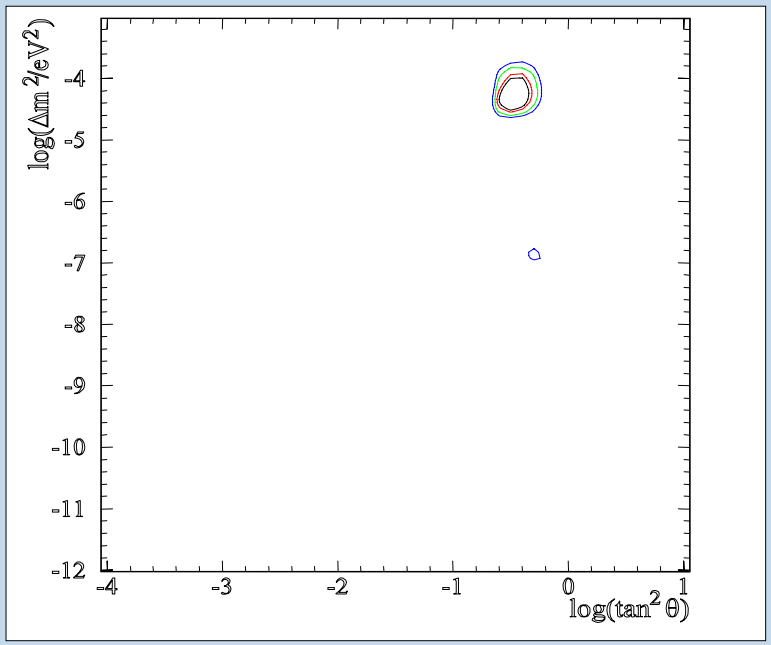
$$A_e^{sk} = 5.3 \pm 3.7^{+2.0}_{-1.7}$$

Physics Interpretation: MSW Parameters

SNO Day and Night Energy Spectra Alone



Combining All Experimental and Solar Model information



region	χ^2/dof	ϕ_B/SSM	A_e	Δm^2 (eV^2)	$\tan^2\theta$	CL
LMA	57/72	1.16	6.4%	5.0×10^{-5}	0.34	---
LOW	68/72	0.98	5.9%	1.3×10^{-7}	0.55	99.5%

What are we doing now?

~~solar *neutrino* problem~~

neutrino parameters puzzle?

Salt Dataset

- Salt added to detector
- May 27, 2001 to October 10, 2002
- 503 days
- 288.8 neutrino live-days (57.4%)

- improved NC statistics
- improved CC-NC separation from isotropy

→ improved measurement of CC/NC ratio

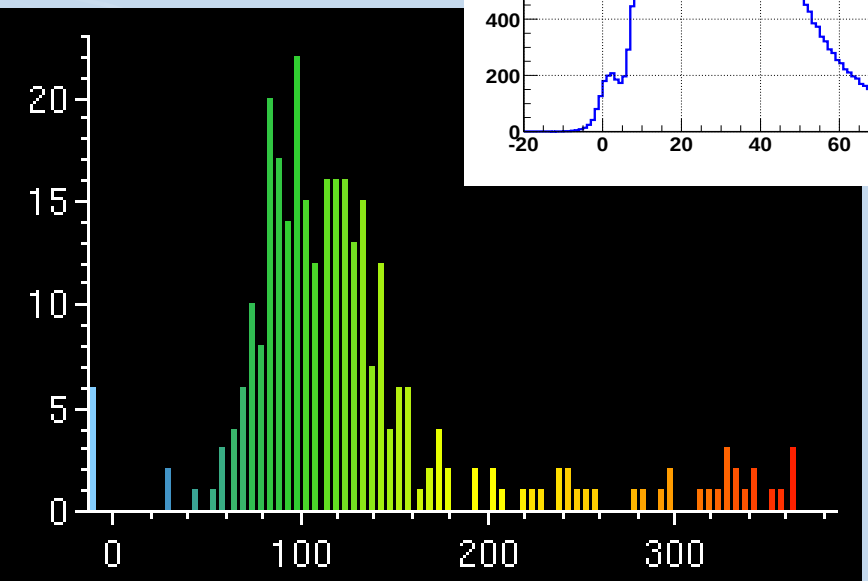
→ precision unconstrained result

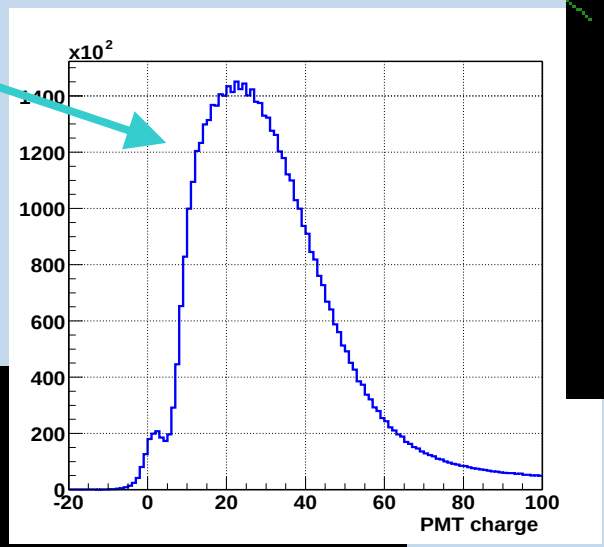
→ improved day/night result

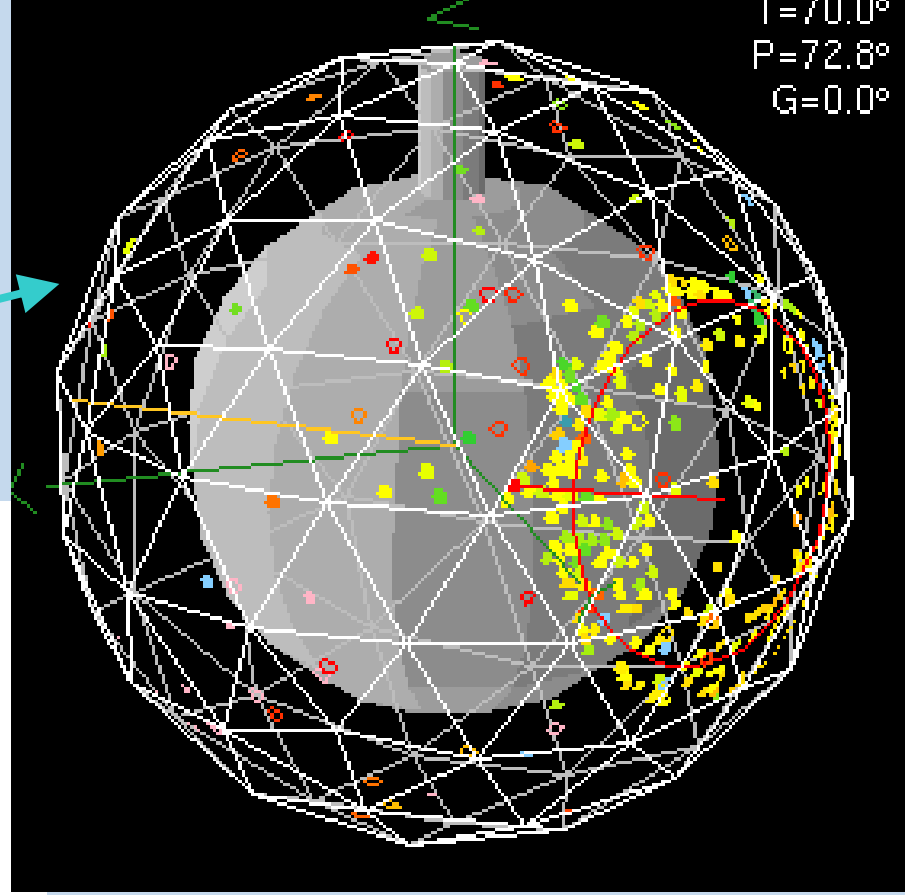
What We Measure

PMT Measurements

-position
-charge
-time



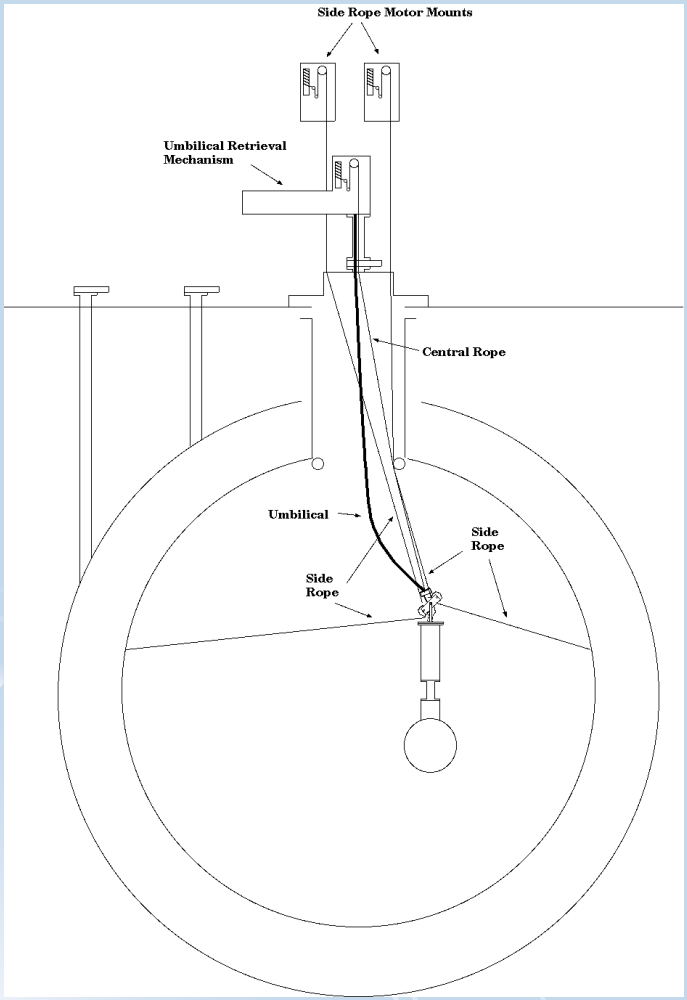




Reconstructed Event

-event vertex
-event direction
-energy
-isotropy

Detector Calibration



Optics
Energy
Event Reconstruction
Neutron Capture
Backgrounds

Tools

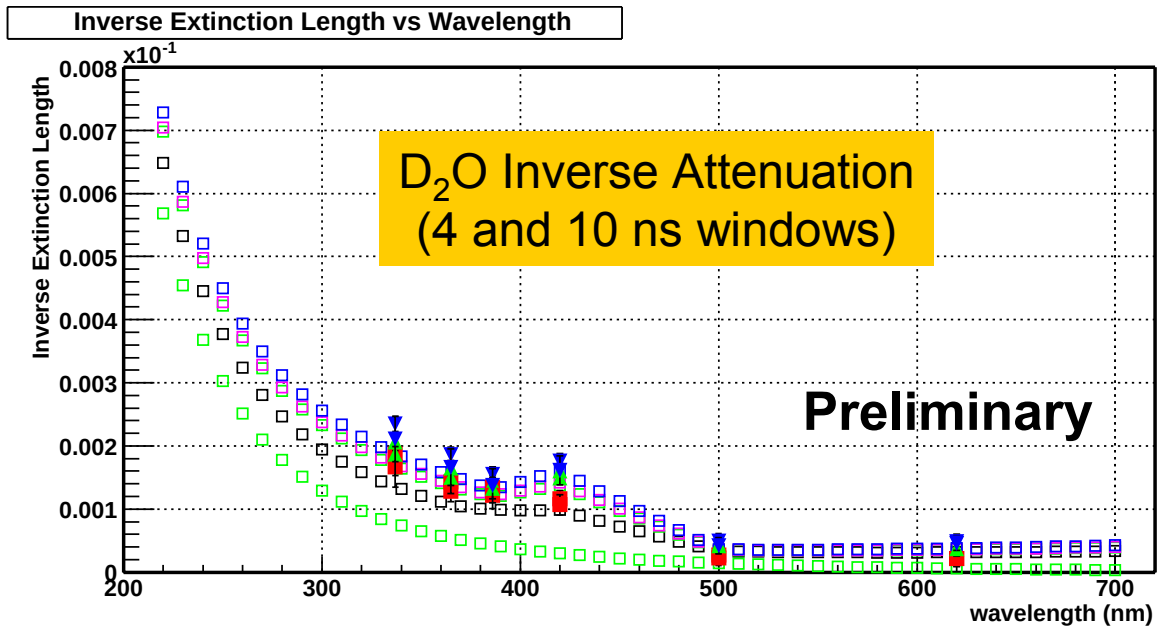
Pulsed Laser	337nm to 620 nm
16N	6.13 MeV γ's
3H(p,γ)4He	19.8 MeV γ's
8Li	<13.0 MeV β's
252Cf	neutrons
U/Th	214Bi & 208Tl β–γ's
Monte Carlo	

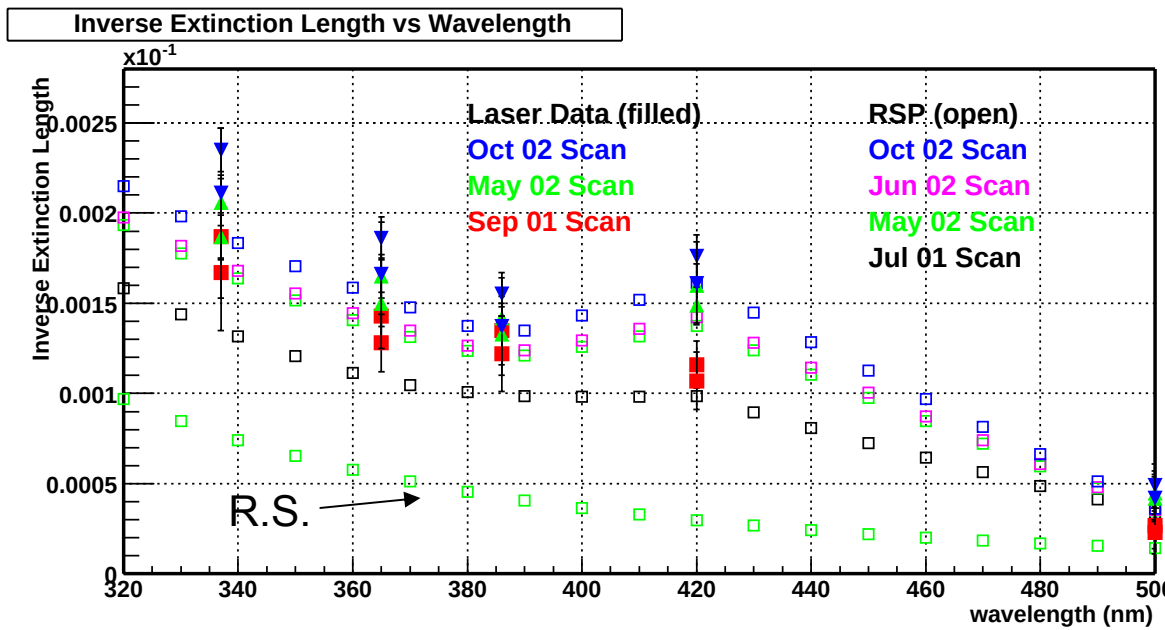
Optical Measurements from Laserball

Optical Constants

- ⇨laser at 6 wavelengths
- ⇨scan through detector
- •D2O Attenuation
- •H2O+AV attenuation
- •PMT Angular Response
- •Rayleigh Scattering

Calibration used for
-MC simulation
-Energy calibration
-Check systematics

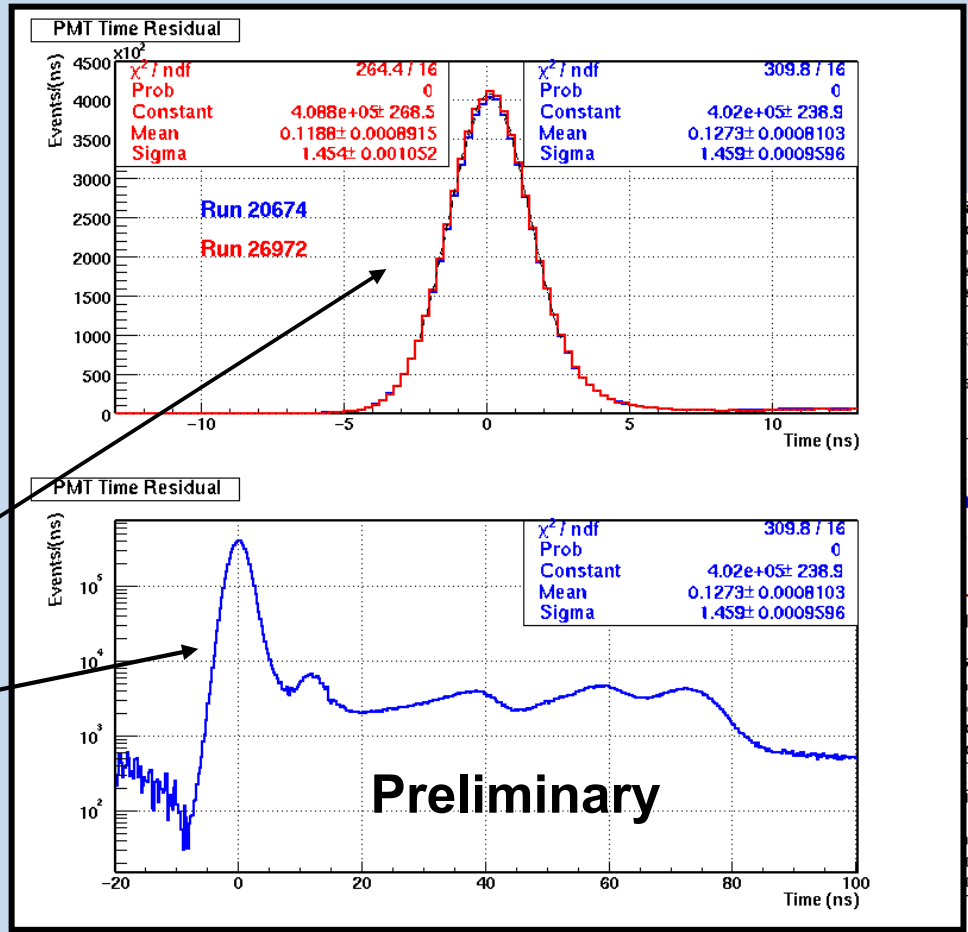


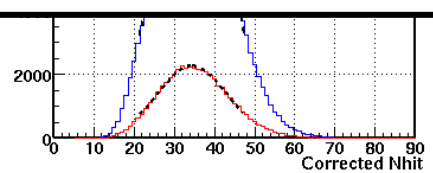


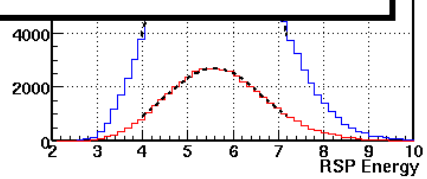
Energy Calibration

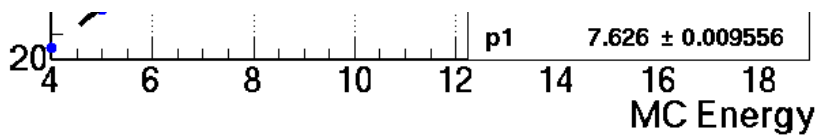
With Optical Constants:
Process data
Calibrate MC energy scale
Quality checks

Energy Calibration
- Prompt Time
- Detector State Corrections
- Optical Correction to Centre
- ^{16}N to set scale
- MC table MeV/Hits
- Energy Resolution Function









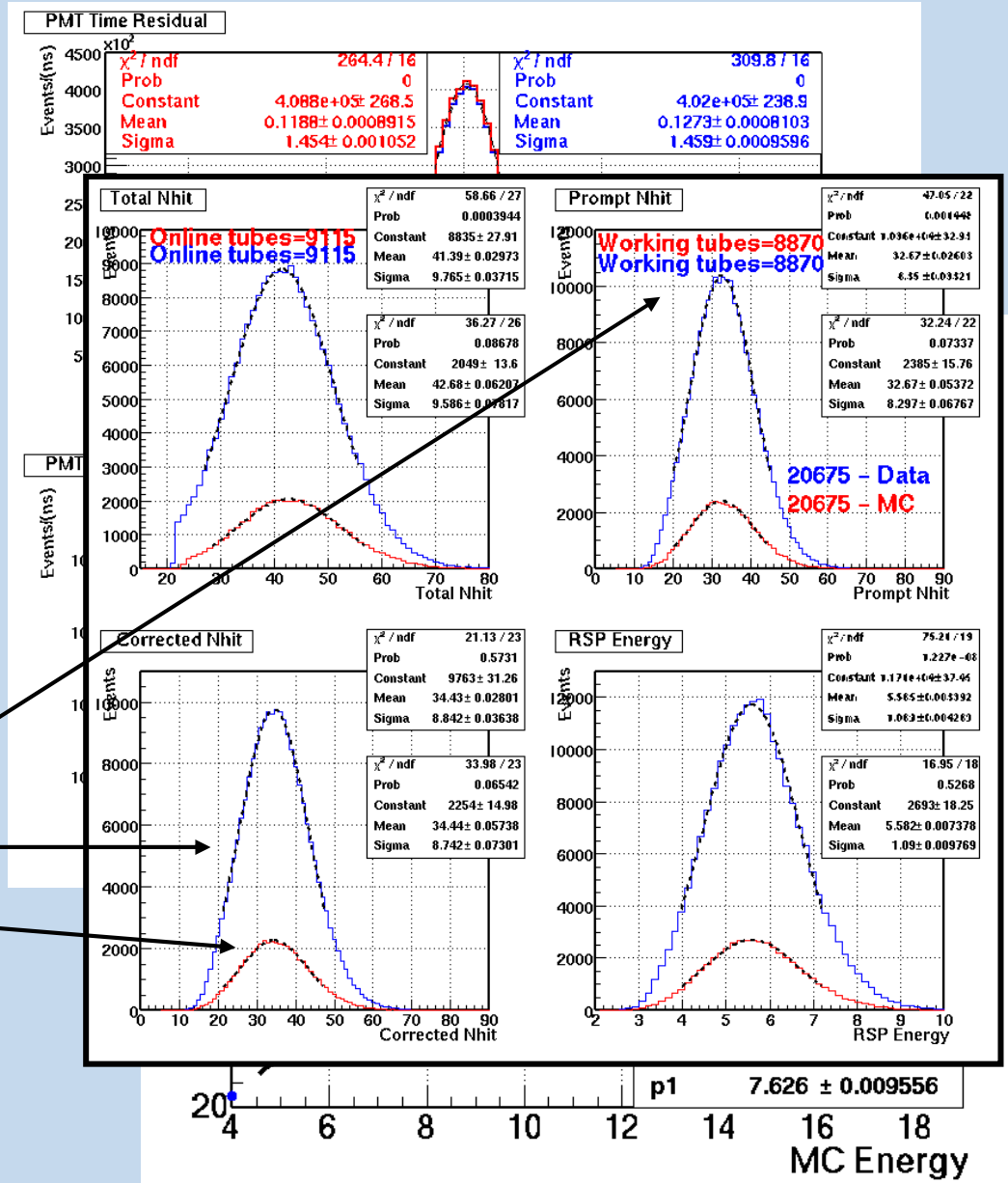
Energy Calibration

With Optical Constants:

Process data

Calibrate MC energy scale

Quality checks

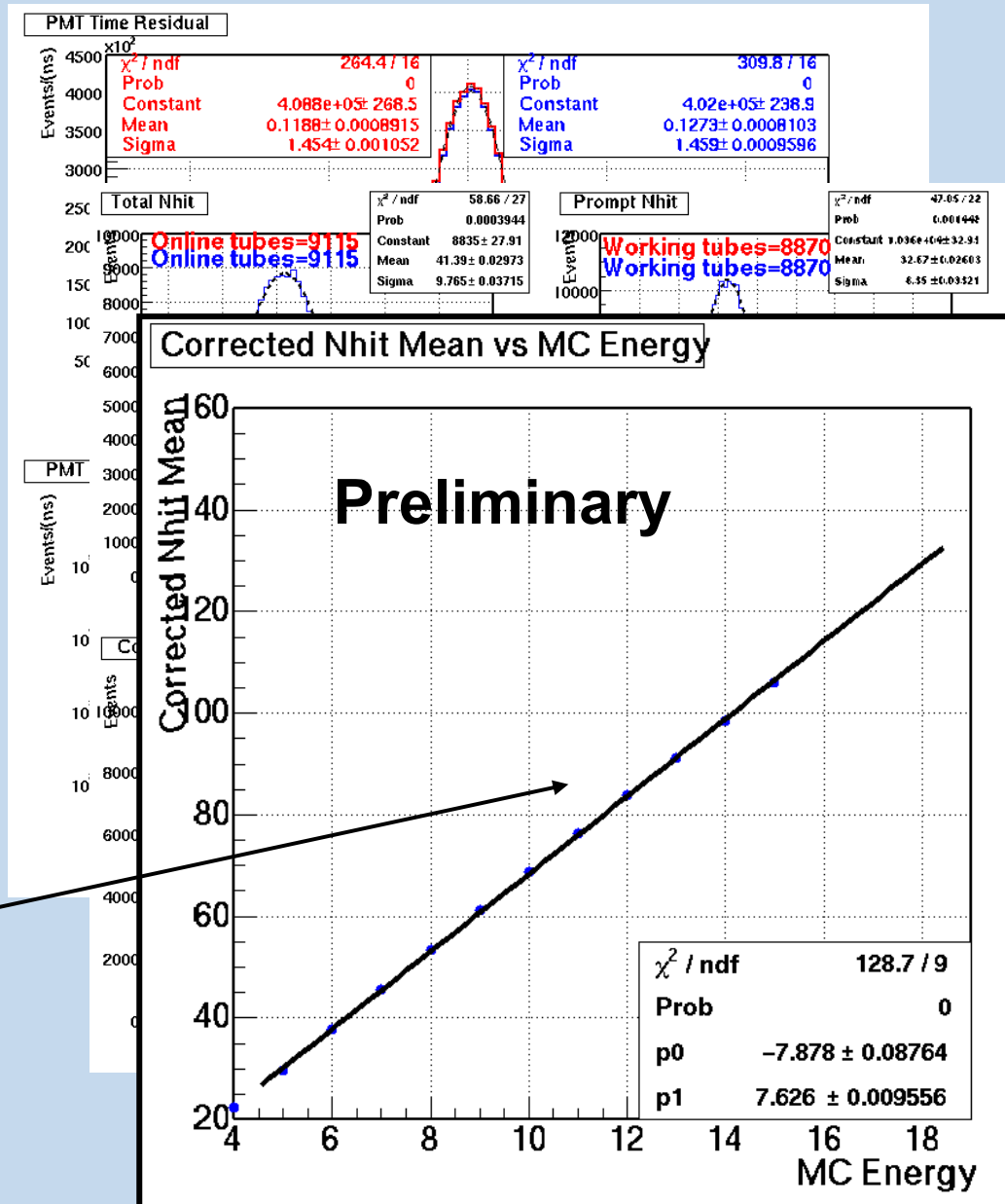


Energy Calibration

- Prompt Time
- Detector State Corrections
- Optical Correction to Centre
- ^{16}N to set scale
- MC table MeV/Hits
- Energy Resolution Function

Energy Calibration

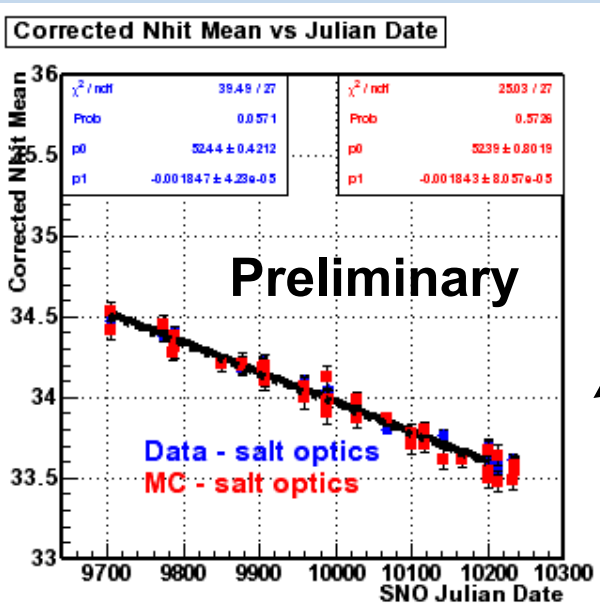
With Optical Constants:
Process data
Calibrate MC energy scale
Quality checks

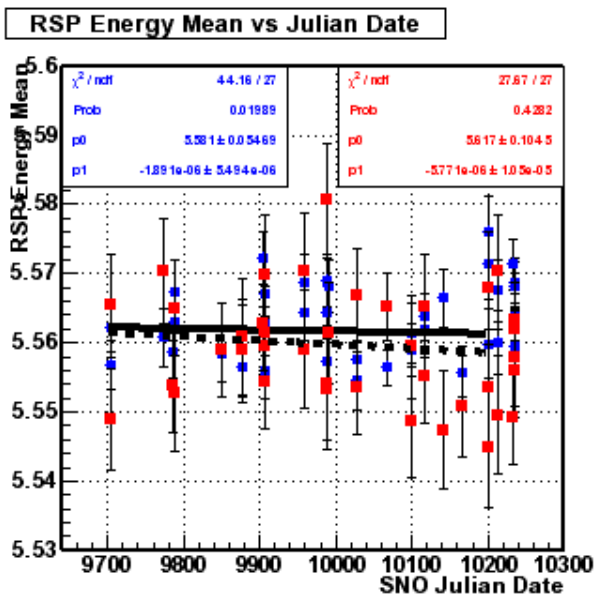


Energy Calibration
- Prompt Time
- Detector State Corrections
- Optical Correction to Centre
- ^{16}N to set scale
- MC table MeV/Hits
- Energy Resolution Function

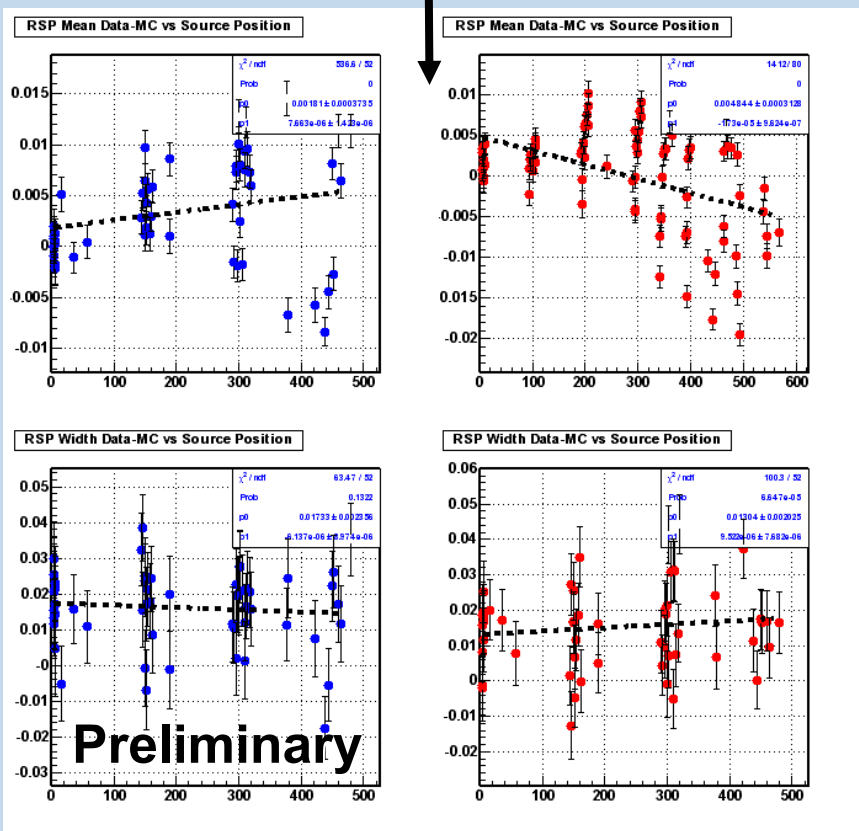
Energy Systematics

Sources Include:
Detector State
Stability ⇨16N Runs
Optical Model
Radial/Asymmetry
Studies
Timing





Total Uncertainty ~1-2%



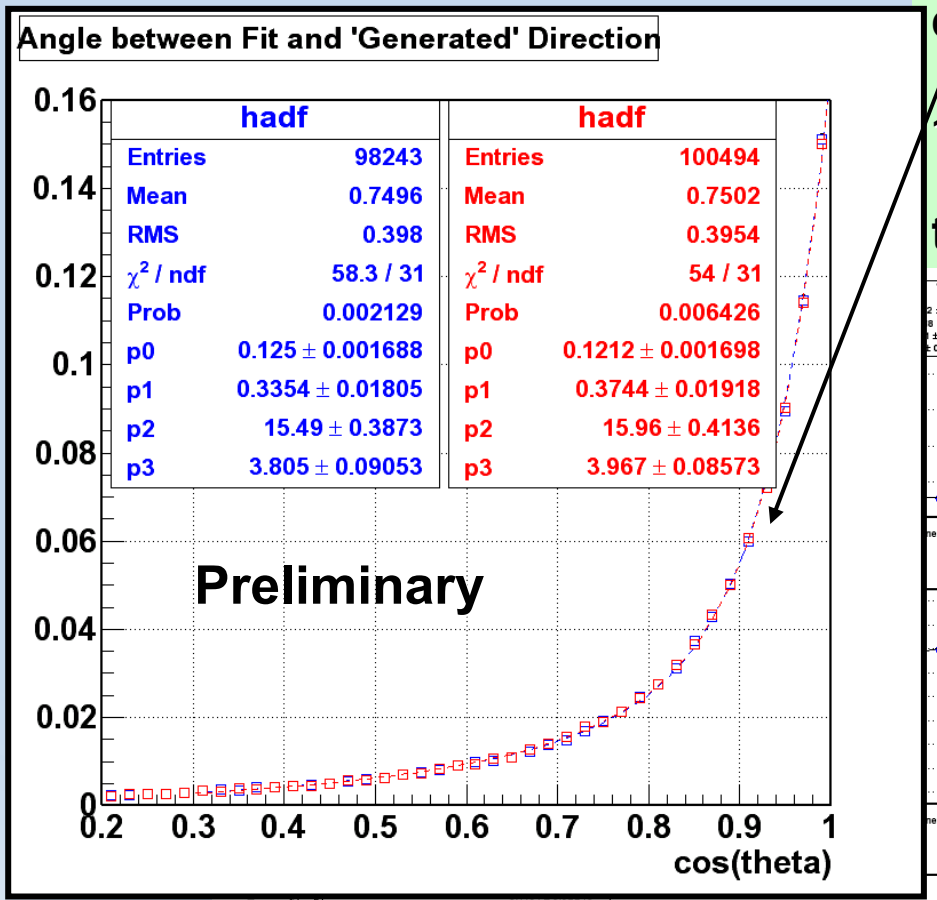
Angular Resolution

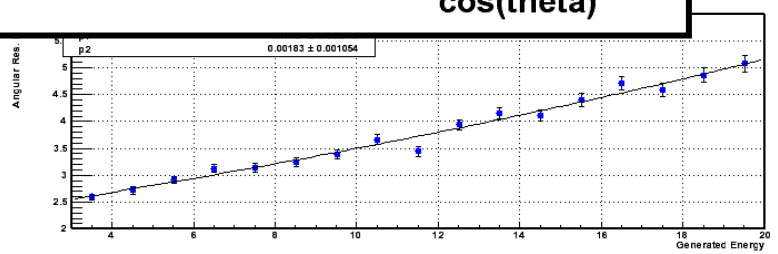
Fit to $\cos(\theta)=u_{fit} \bullet u_{gen}$

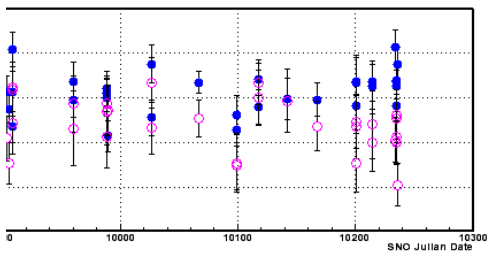
electron MC gives nominal values

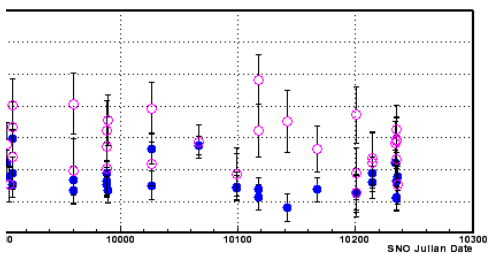
^{16}N use $u_{gen}=x_{fit}-x_{source}$ for $R_{source}>R_{cut}$

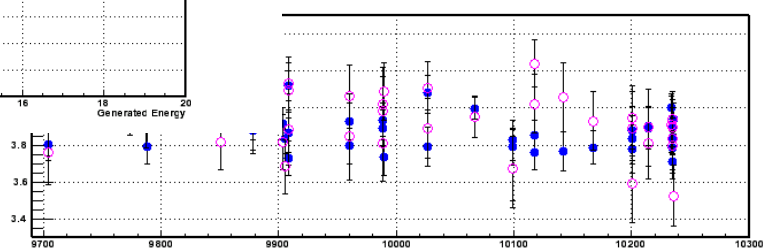
to verify MC and determine uncertainties











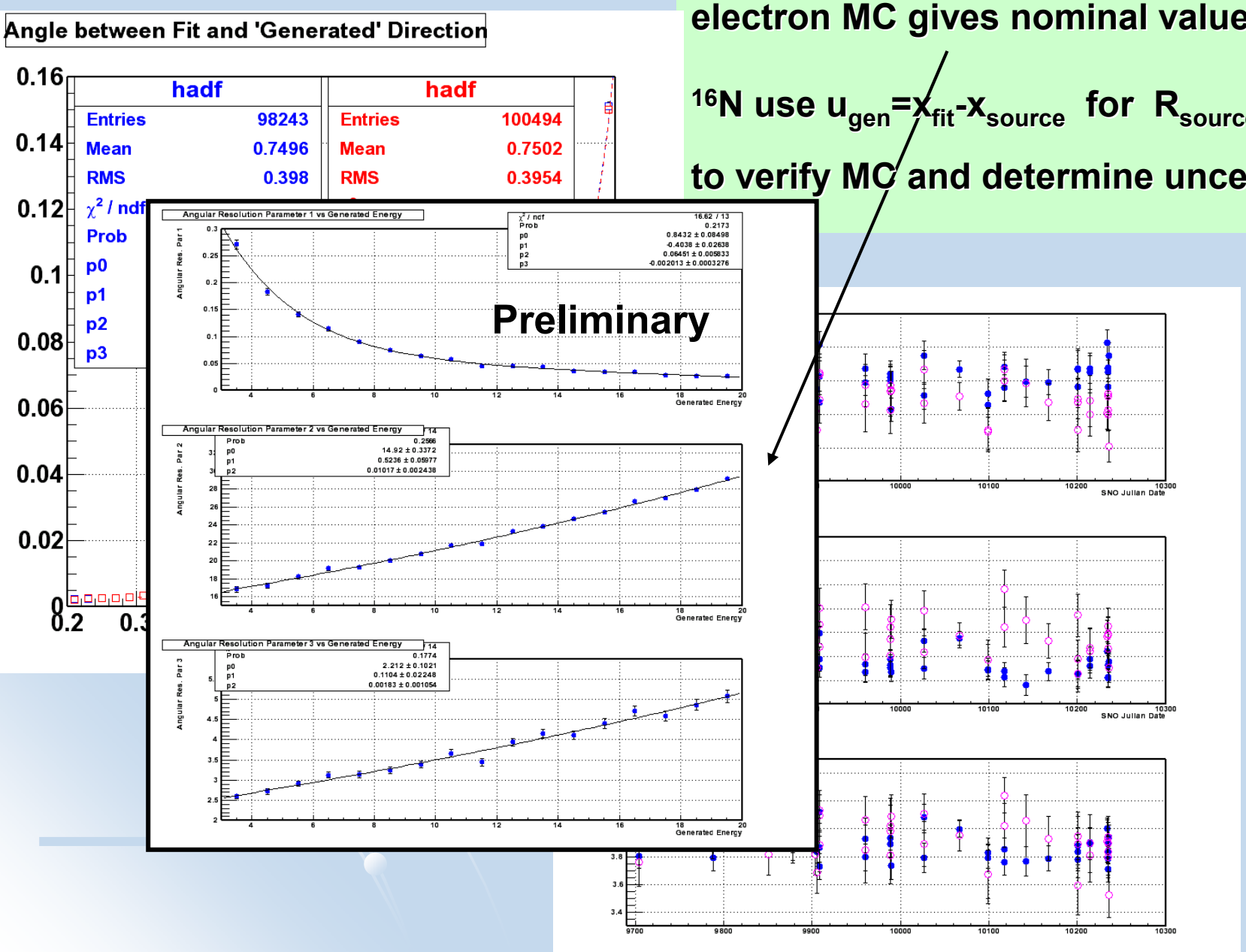
Angular Resolution

Fit to $\cos(\theta)=u_{fit} \bullet u_{gen}$

electron MC gives nominal values

^{16}N use $u_{gen}=x_{fit}-x_{source}$ for $R_{source}>R_{cut}$

to verify MC and determine uncertainties



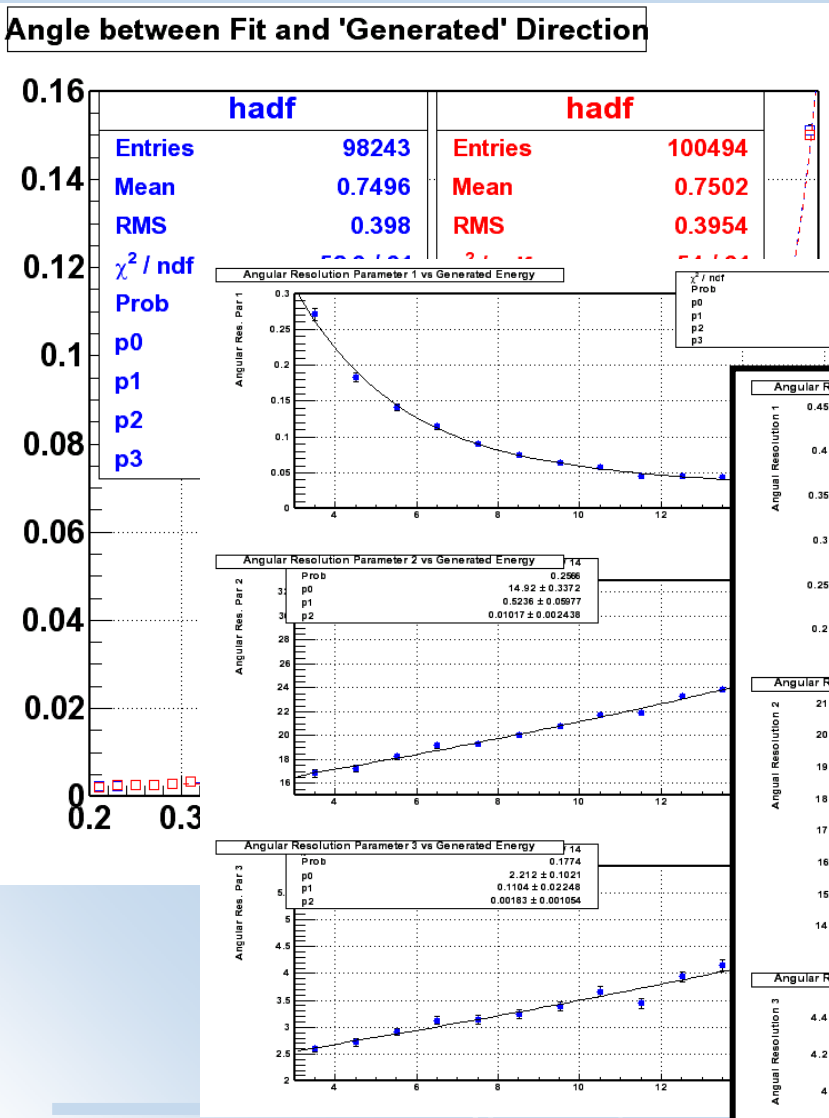
Angular Resolution

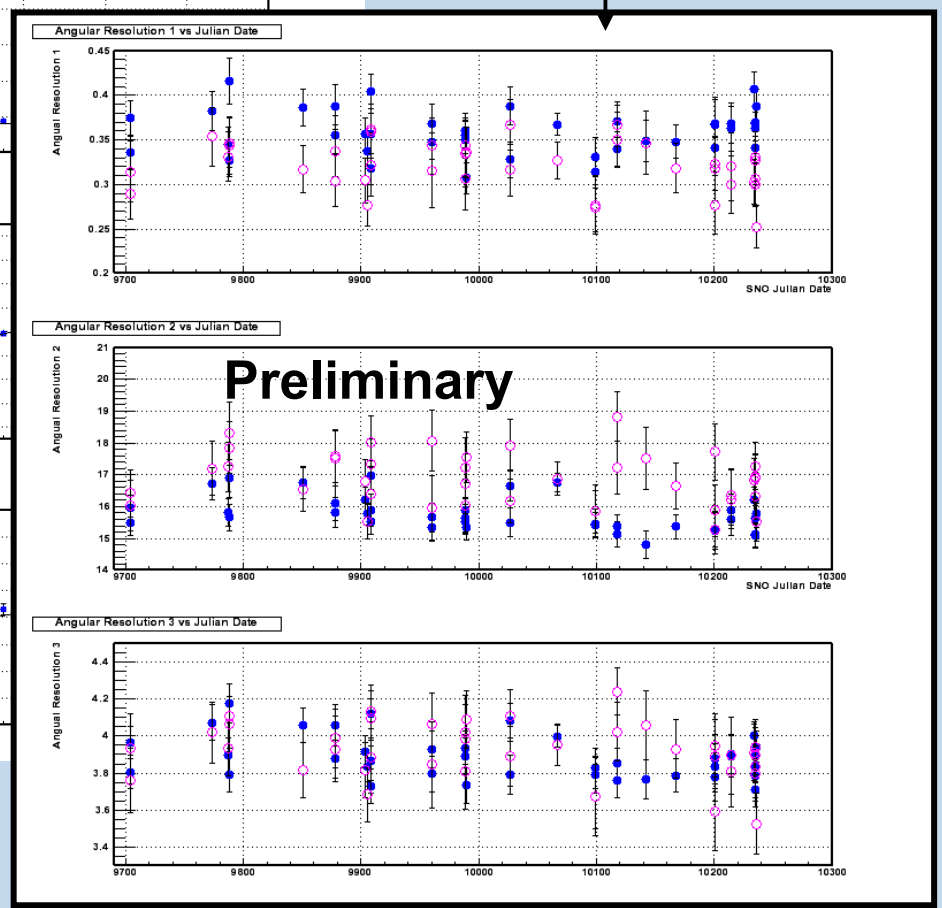
Fit to $\cos(\theta)=u_{fit} \bullet u_{gen}$

electron MC gives nominal values

^{16}N use $u_{gen}=x_{fit}-x_{source}$ for $R_{source}>R_{cut}$

to verify MC and determine uncertainties

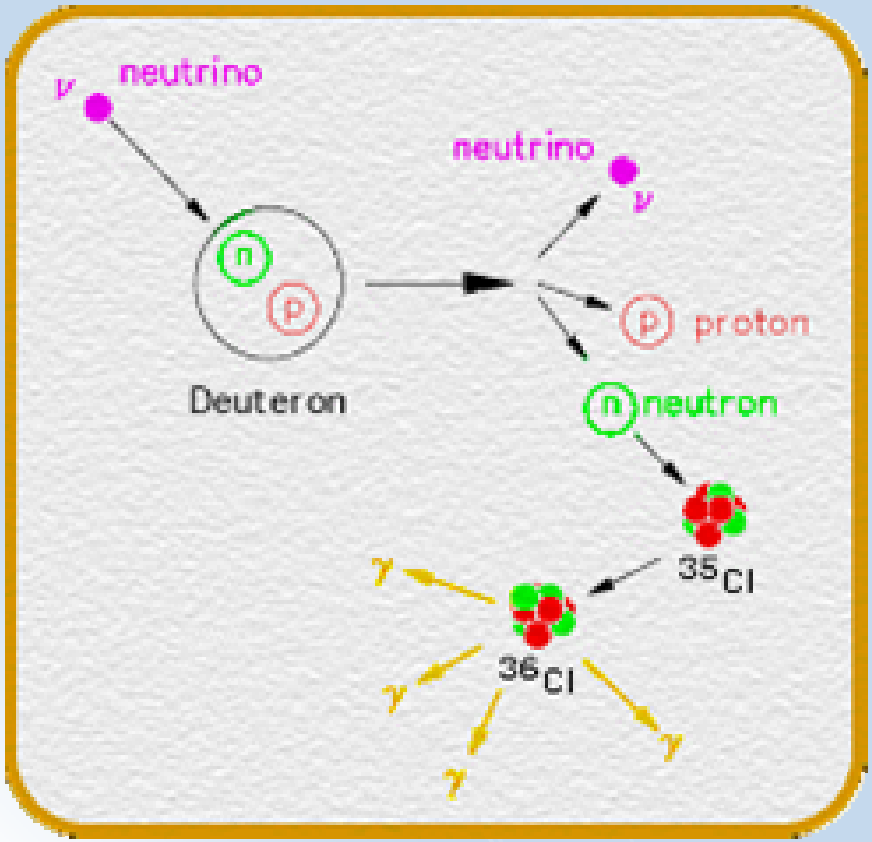


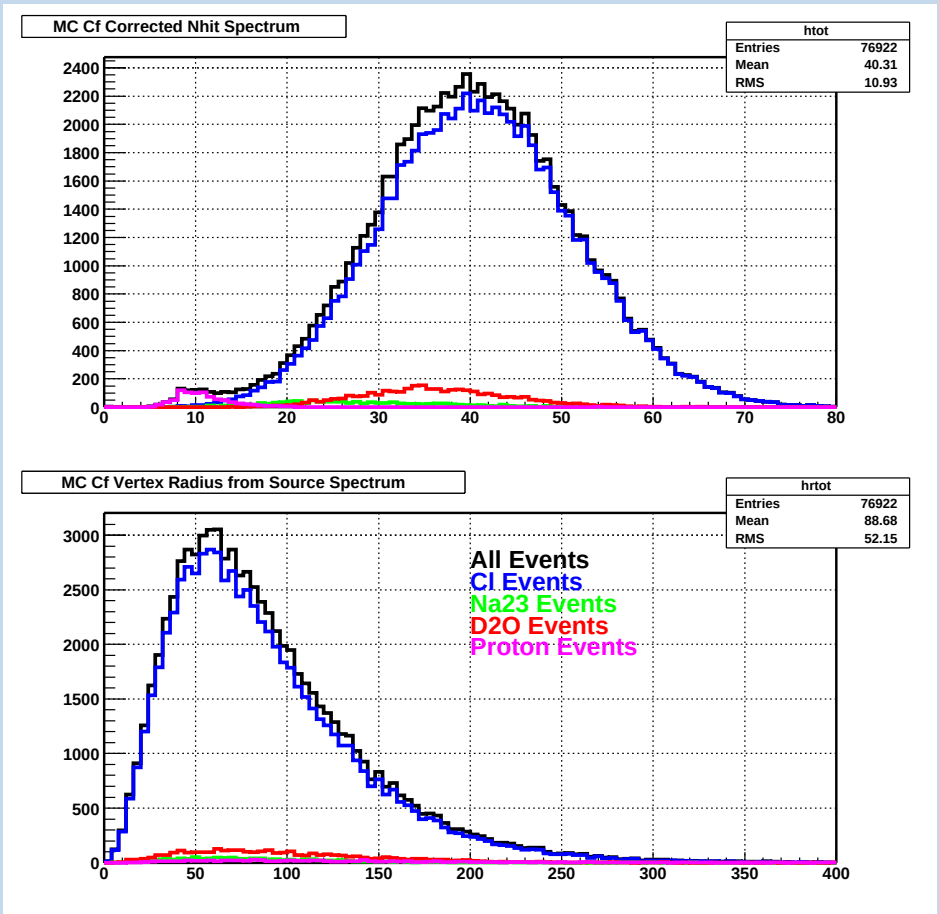


Neutrons in Salt

Capture on $^{35}Cl \Rightarrow {}^{36}Cl$ cascade
- Multi-photon events ⇨isotropy
- Energy peaks higher

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$ ($E\Sigma\gamma$ = 8.6 MeV)

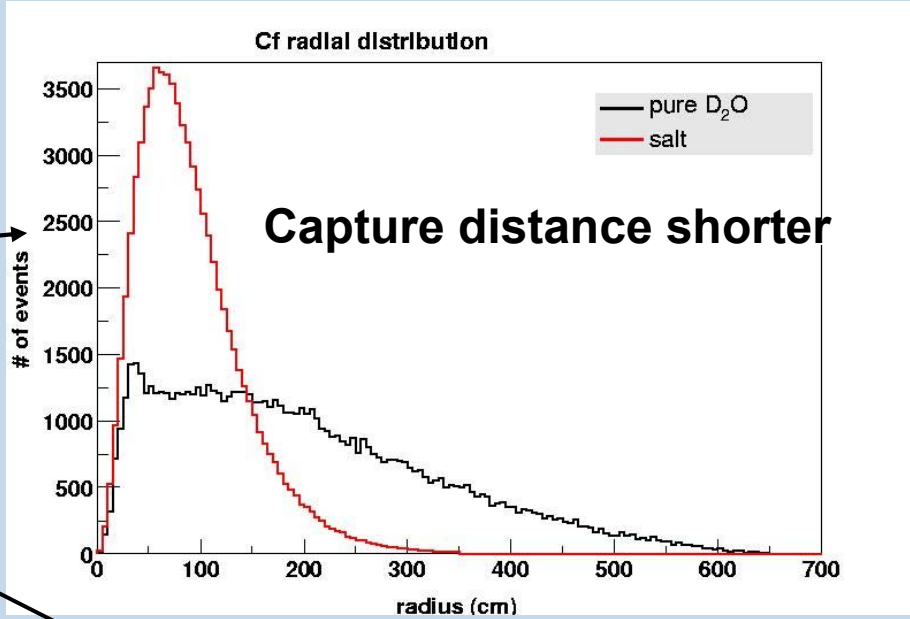


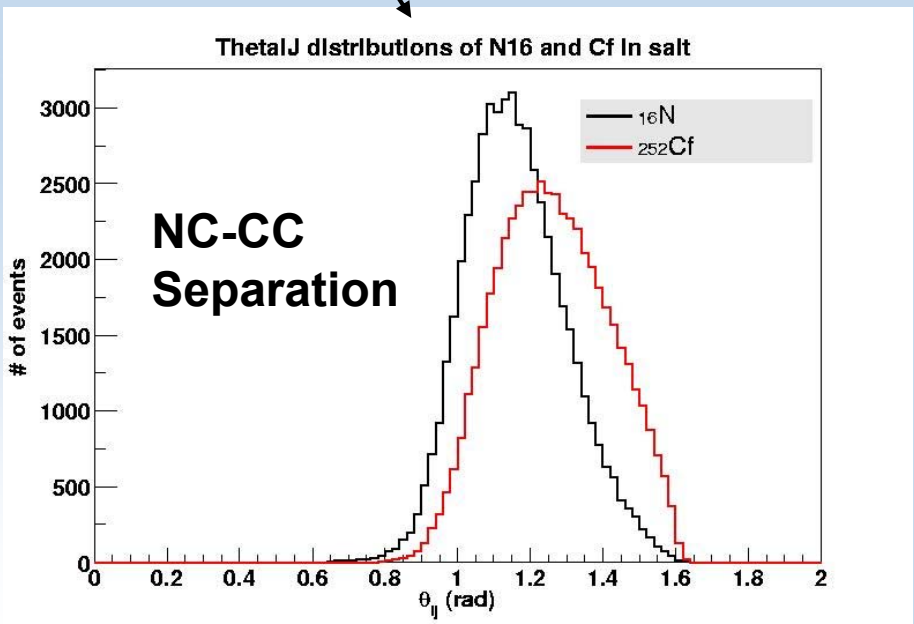


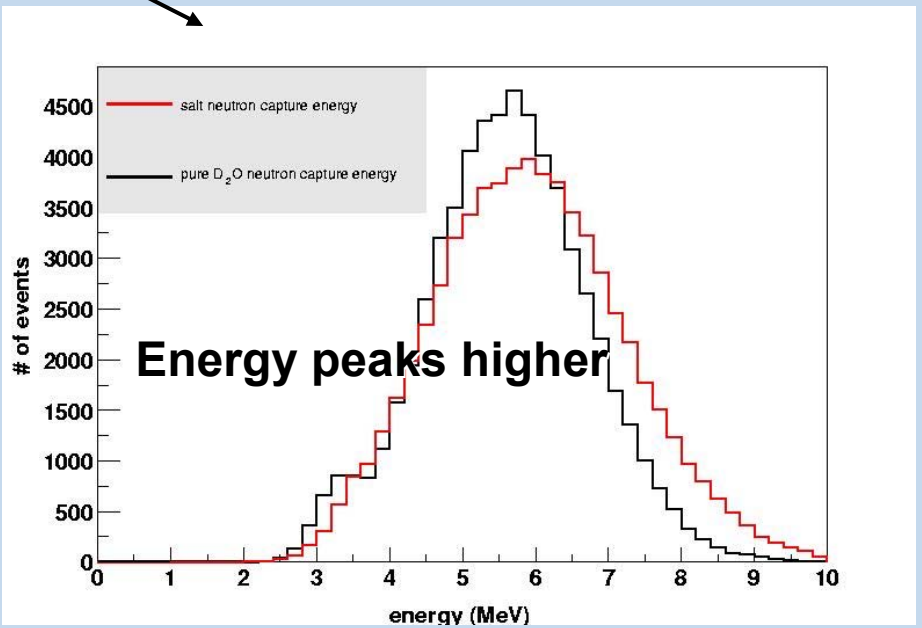
Neutron Distributions in Salt

Cl capture changes response distributions:

- **Radial Profile**
- **Energy Spectrum**
- **Isotropy Distribution**





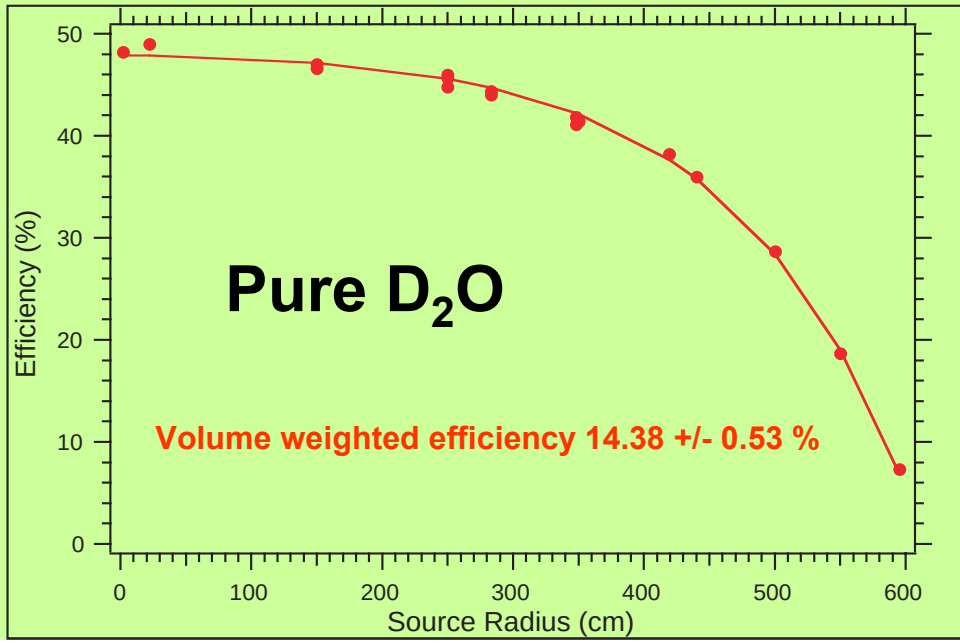


Neutron Response

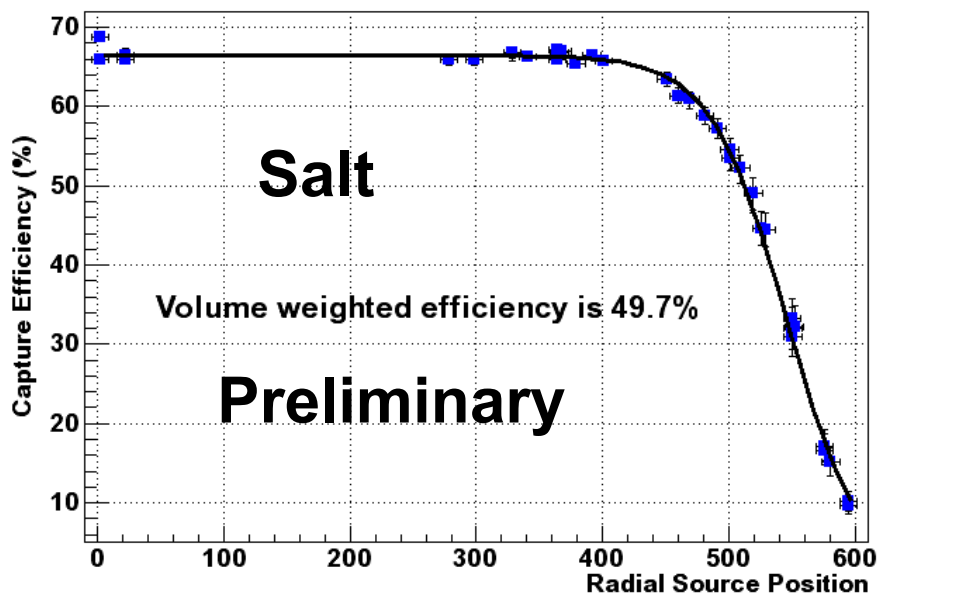
Factor of ~3-4 increase in stats
- larger capture cross-section
- energy reponse peaks higher

Systematics Include:
- energy scale and resolution
- vertex reconstruction
- source position
- ^{252}Cf source strength
- burst selection
- background

Total ⇨Percent Level



Point Source Efficiencies Above 5.5MeV for Fiducial Volume < 550cm



Signal Extraction

Variables: E, R^3, $\cos\theta_{sun}$, θ_{ij}

Unconstrained

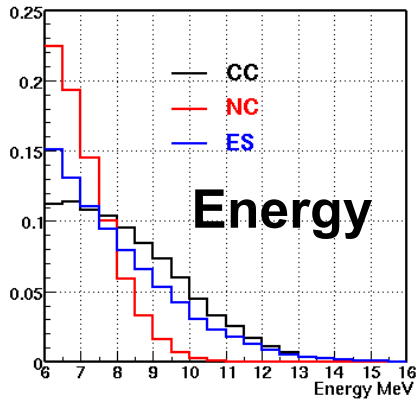
^{8}B Shape Constrained

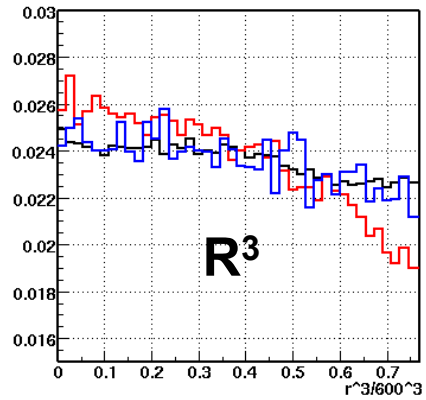
Extended ML Fit

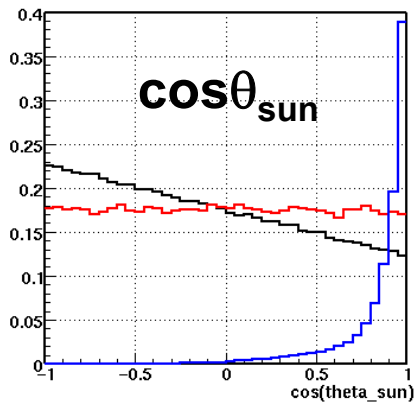
Signal	Bkg	
CC, NC, ES } Φ_e, $\Phi_{\mu\tau}$	Cerenkov Photodis.	
Fit	Fix	⇨Fluxes
Perturb Variables	Shift PDF's	⇨Systematic Uncertainties

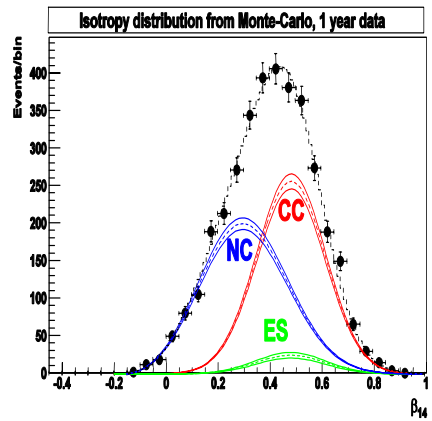
NC E higher

Less Rad. Sep.





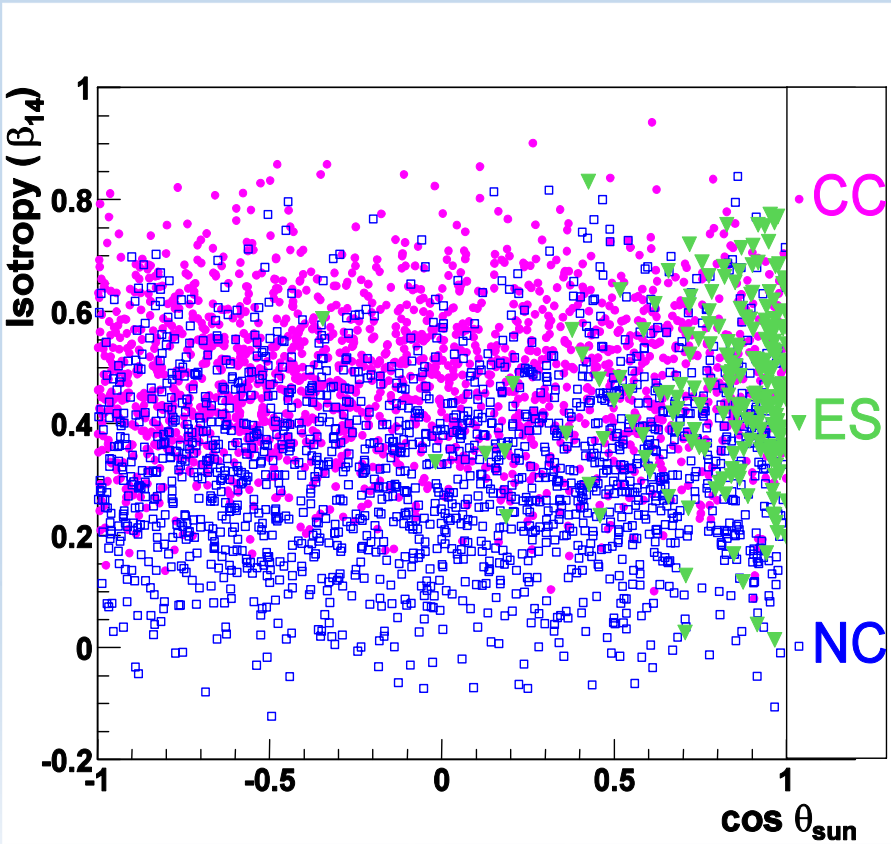


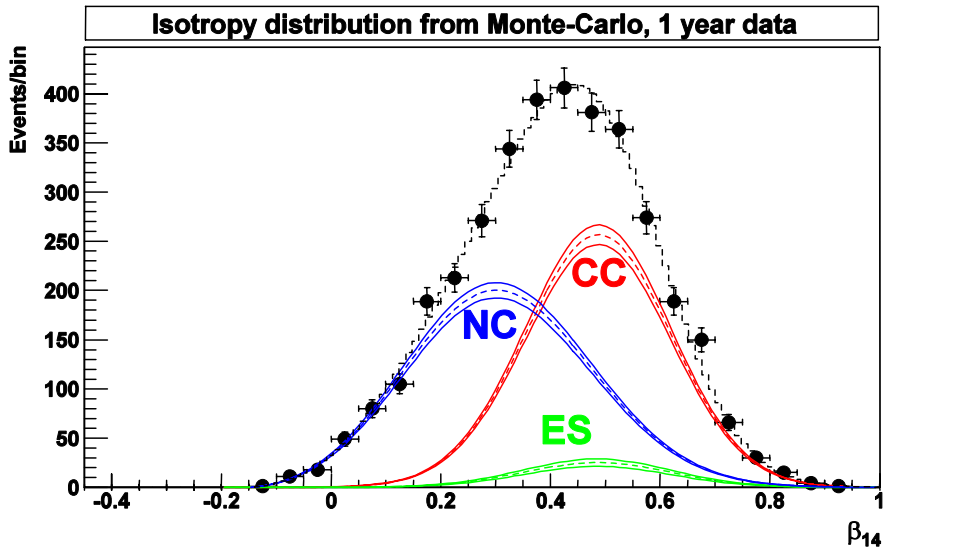


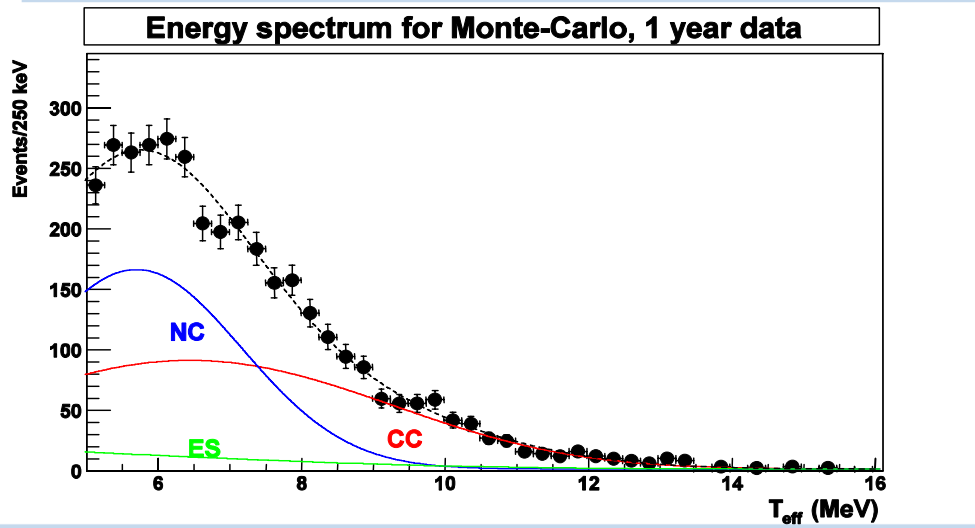
Directionality Unchanged

Isotropy Separation!

Statistical Signal Separation Using Angular Information







Fit Result Uncertainties (Monte-Carlo)

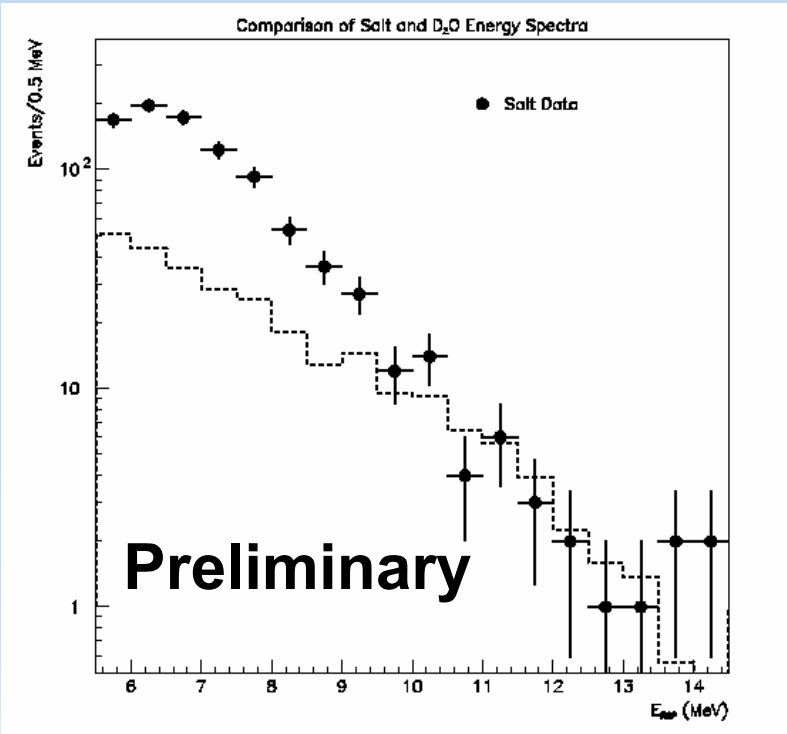
	Variables	CC Stat. Error	NC Stat. Error	ES Stat. Error
D2O results	E,R,θ_{sun}	3.4%	8.6%	10%
Simulated Salt Phase Results	E,R,θ_{sun}	4.2%	6.3%	10%
	E,R,θ_{sun},Iso	3.3%	4.6%	10%
	R,θ_{sun},Iso	3.8%	5.3%	10%

Published D2O energy-unconstrained stat. Error was 24%

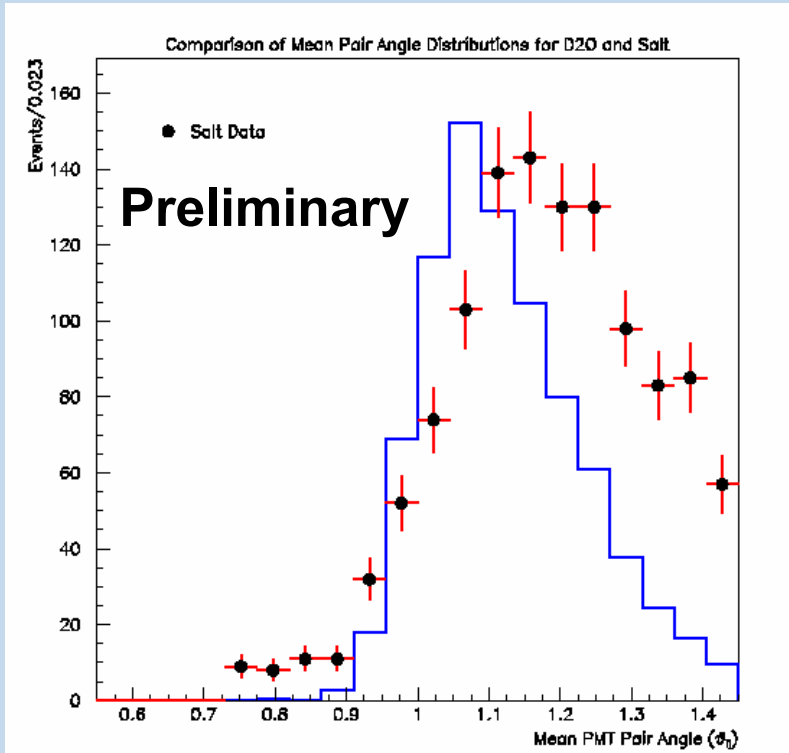
Simulations assume 1 yr of data with central values and cuts from D2O phase results

Salt Phase data

Higher E and capture σ reduces background problem

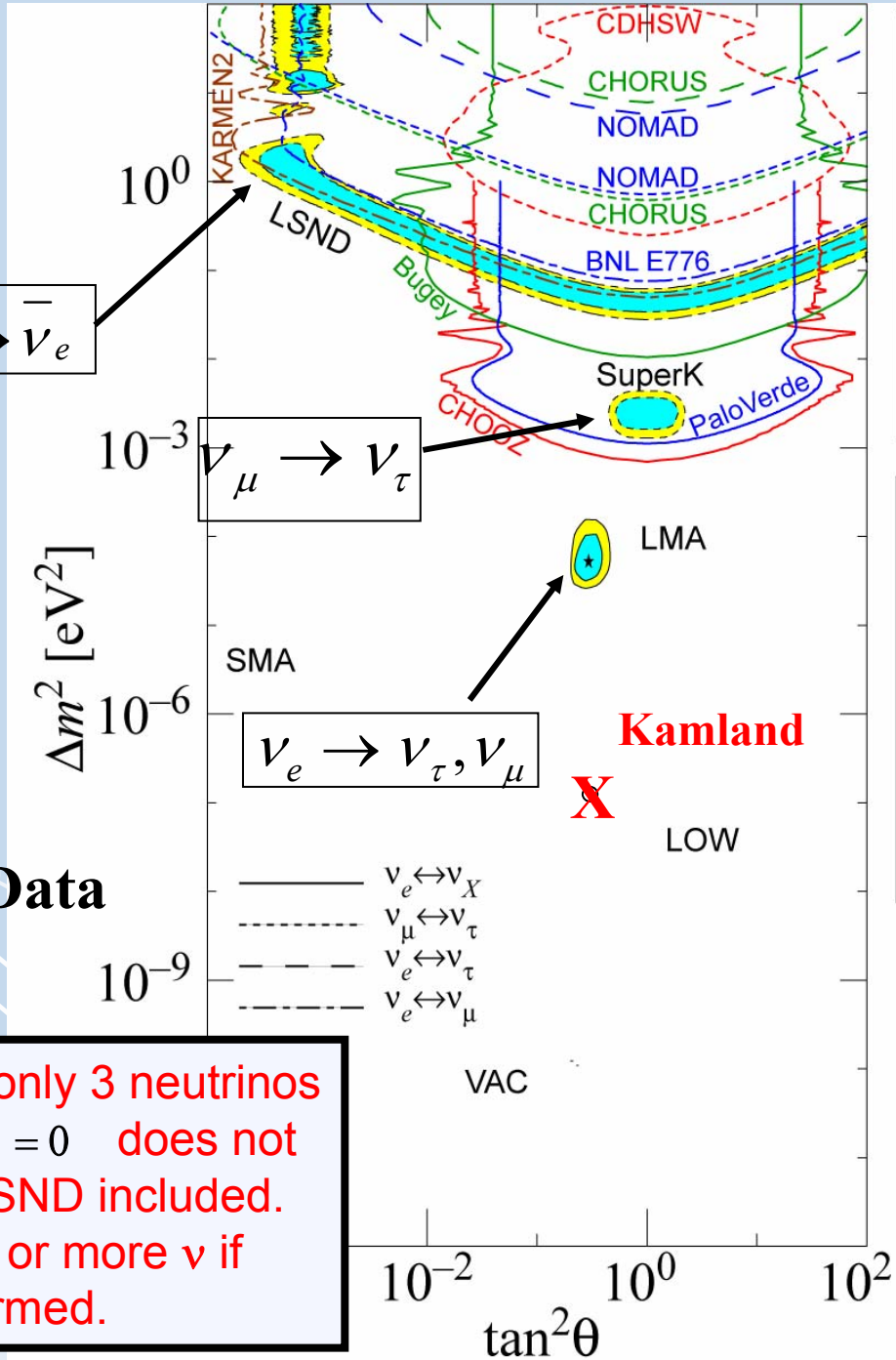


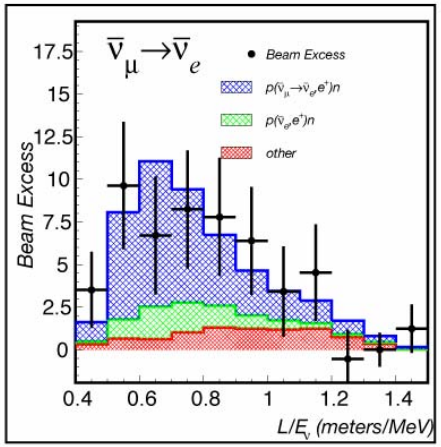
Event isotropy helps break signal covariances



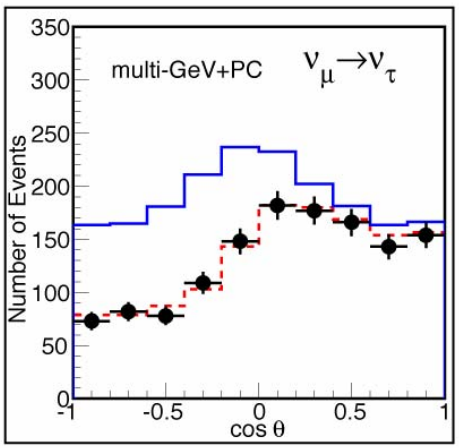
Data is being analyzed with a blindness parameter added. We are Completing the final calibrations and will be removing the salt soon.

Neutrino Data 2002



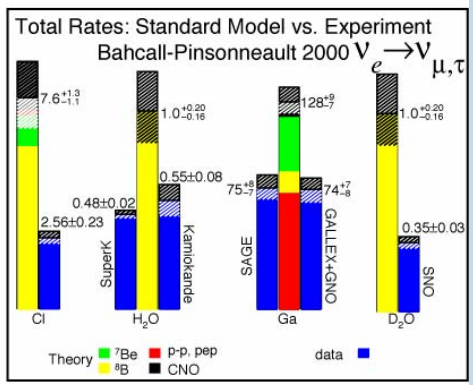


LSND



Super-K

Δm_{23}



Solar

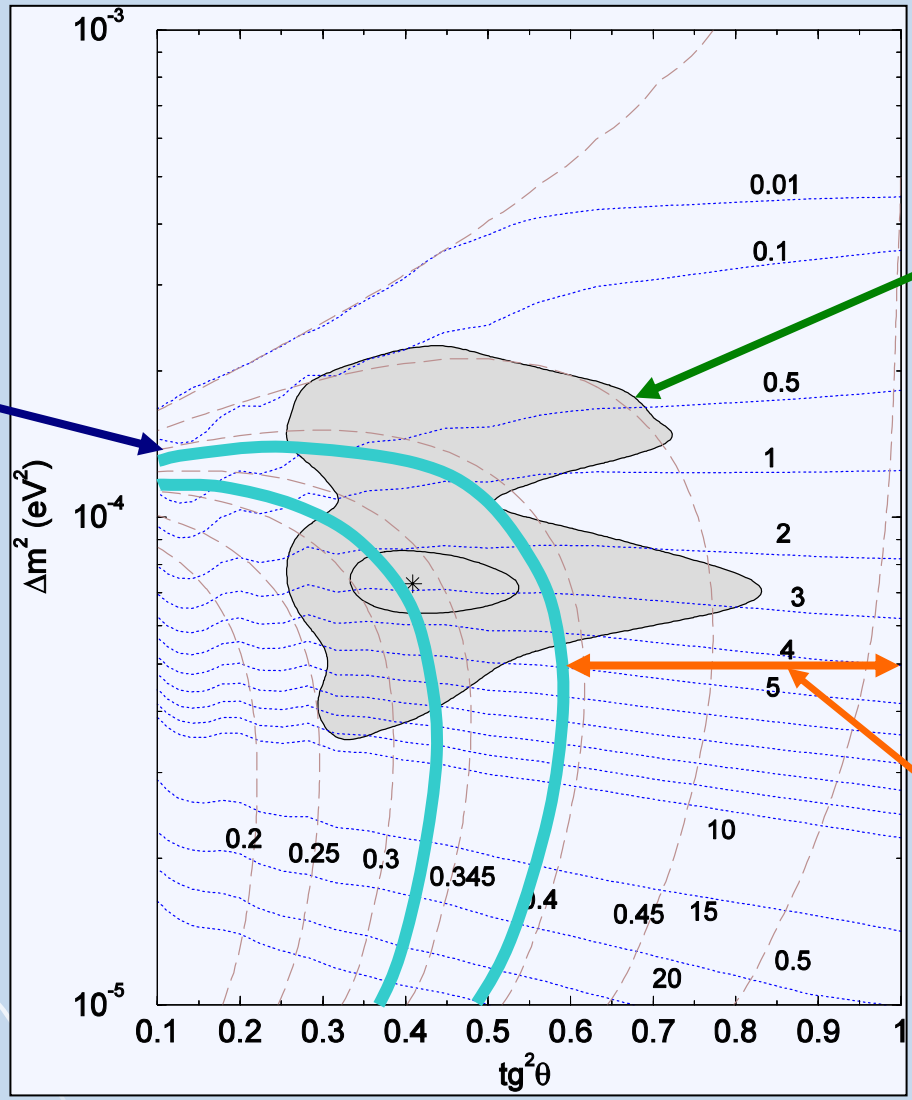
Δm_{12}

If there are only 3 neutrinos then $\sum \Delta m^2 = 0$ does not work with LSND included. Therefore 4 or more ν if LSND confirmed.

Sensitivity to Mixing Parameters

Projected sensitivity from SNO salt phase

Assuming D_2O phase NC result



Combined Solar + KAMLAND data

Bahcall/Pena-Garay
$\tan^2\theta < 5.5\sigma$

Improve limit on maximal 1-2 mixing

Bound on Sterile Neutrinos: Solar/Kamland data

$\nu_e \rightarrow (\cos\eta)\,\nu_x + (\sin\eta)\,\nu_s$

f_B = ^{8}B Total Flux/SSM (BP00)

Fit to f_B and η

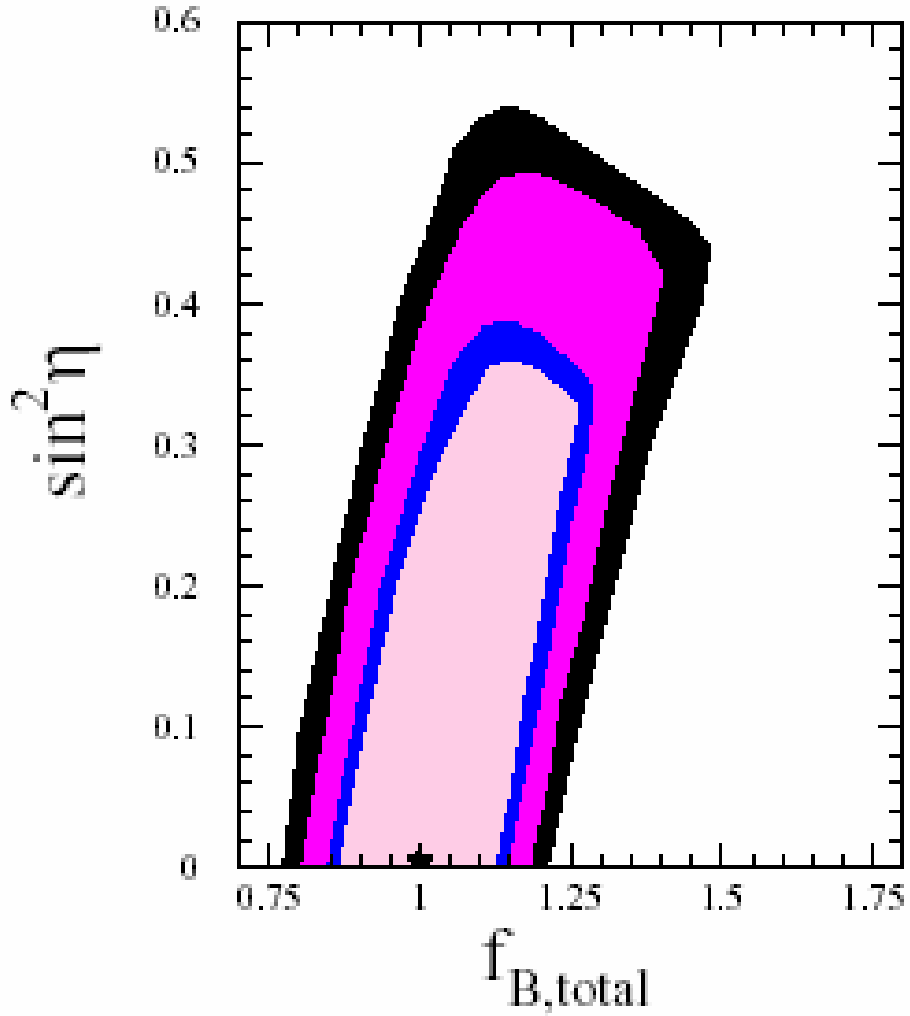
χ^2 min:

$\sin^2\eta = 0,\ f_B = 1.00$

$\sin^2\eta$:

< 0.13 (1 σ)

< 0.52 (3 σ)



Bahcall, Gonzales-Garcia, Pena-Garay, hep-ph/0212147

Summary

Pure D_2O Phase:

- Flavour Transformation
- Neutrinos Massive
- SSM working well

Combined ν Results:

→ MSW Model → LMA Favoured Region

Salt:

- Increased NC statistics – Additional Isotropy Separation
- Precision Fluxes with ***No Shape Constraint***
- Improved CC/NC Measurement
- Day/Night and Spectral Shape
- →improved precision in MSW space

Next Phase: NCDs in shortly
^{3}He counters
event-by-event separation

Current and Future Prospects

- **Homestake/GALLEX : completed**

- Sage/GNO: running – GNO 1 solar cycle
- SK: running (impressive turnaround)
- SNO: salt results pending – next phase NCD's soon
- KamLAND: not just reactors…

- Borexino: scintillator target (^{7}Be)

- Lens: coincidence events ^{176}Yb (pp-^{7}Be)
- Clean: liquid neon (pp)
- Genius: elastic scattering HPGe (pp)
- MOON: inverse beta-decay ^{100}Mo (pp-^{7}Be)
- HELLAZ: helium (pp-^{7}Be)
- HERON: superfluid helium (pp-^{7}Be)
- ICARUS: bubble chambers (^{8}B)
- XMASS liquid xenon (pp-^{7}Be)

Verify Flavour Change
Evidence for Oscillation
MSW Parameters
Solar Physics

The SNO Collaboration

G. Milton, B. Sur
Atomic Energy of Canada Ltd., Chalk River Laboratories

S. Gil, J. Heise, R.J. Komar, T. Kutter, C.W. Nally, H.S. Ng, Y.I. Tserkovnyak, C.E. Waltham
University of British Columbia

J. Boger, R.L Hahn, J.K. Rowley, M. Yeh
Brookhaven National Laboratory

R.C. Allen, G. Bühler, H.H. Chen*
University of California, Irvine

I. Blevis, F. Dalnoki-Veress, D.R. Grant, C.K. Hargrove, I. Levine, K. McFarlane, C. Mifflin, V.M. Novikov, M. O'Neill, M. Shatkay, D. Sinclair, N. Starinsky
Carleton University

T.C. Andersen, P. Jagam, J. Law, I.T. Lawson, R.W. Ollerhead, J.J. Simpson, N. Tagg, J.-X. Wang
University of Guelph

J. Bigu, J.H.M. Cowan, J. Farine, E.D. Hallman, R.U. Haq, J. Hewett, J.G. Hykawy, G. Jonkmans, S. Luoma, A. Roberge, E. Saettler, M.H. Schwendener, H. Seifert, R. Tafirout, C.J. Virtue
Laurentian University

Y.D. Chan, X. Chen, M.C.P. Isaac, K.T. Lesko, A.D. Marino, E.B. Norman, C.E. Okada, A.W.P. Poon, S.S.E Rosendahl, A. Schülke, A.R. Smith, R.G. Stokstad
Lawrence Berkeley National Laboratory

M.G. Boulay, T.J. Bowles, S.J. Brice, M.R. Dragowsky, M.M. Fowler, A.S. Hamer, A. Hime, G.G. Miller, R.G. Van de Water, J.B. Wilhelmy, J.M. Wouters
Los Alamos National Laboratory

J.D. Anglin, M. Bercovitch, W.F. Davidson, R.S. Storey*
National Research Council of Canada

J.C. Barton, S. Biller, R.A. Black, R.J. Boardman, M.G. Bowler, J. Cameron, B.T. Cleveland, X. Dai, G. Doucas, J.A. Dunmore, H. Fergani, A.P. Ferrarris, K. Frame, N. Gagnon, H. Heron, N.A. Jelley, A.B. Knox, M. Lay, W. Locke, J. Lyon, S. Majerus, G. McGregor, M. Moorhead, M. Omori, C.J. Sims, N.W. Tanner, R.K. Taplin, M.Thorman, P.M. Thornewell, P.T. Trent, N. West, J.R. Wilson
University of Oxford

E.W. Beier, D.F. Cowen, M. Dunford, E.D. Frank, W. Frati, W.J. Heintzelman, P.T. Keener, J.R. Klein, C.C.M. Kyba, N. McCauley, D.S. McDonald, M.S. Neubauer, F.M. Newcomer, S.M. Oser, V.L Rusu, S. Spreitzer, R. Van Berg, P. Wittich
University of Pennsylvania

R. Kouzes
Princeton University

E. Bonvin, M. Chen, E.T.H. Clifford, F.A. Duncan, E.D. Earle, H.C. Evans, G.T. Ewan, R.J. Ford, K. Graham, A.L. Hallin, W.B. Handler, P.J. Harvey, J.D. Hepburn, C. Jillings, H.W. Lee, J.R. Leslie, H.B. Mak, J. Maneira, A.B. McDonald, B.A. Moffat, T.J. Radcliffe, B.C. Robertson, P. Skensved
Queen's University

D.L. Wark
Rutherford Appleton Laboratory, University of Sussex

R.L. Helmer, A.J. Noble
TRIUMF

Q.R. Ahmad, M.C. Browne, T.V. Bullard, G.A. Cox, P.J. Doe, C.A. Duba, S.R. Elliott, J.A. Formaggio, J.V. Germani, A.A. Hamian, R. Hazama, K.M. Heeger, K. Kazkaz, J. Manor, R. Meijer Drees, J.L. Orrell, R.G.H. Robertson, K.K. Schaffer, M.W.E. Smith, T.D. Steiger, L.C. Stonehill, J.F. Wilkerson
University of Washington