Results from Neutrino Physics Experiments

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FPCP 2010

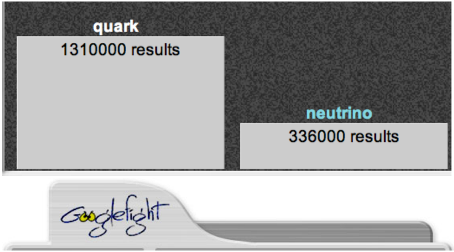
What I'm going to talk about

Preface:

- "...review the most relevant results from neutrino phyisics experiments..." since FPCP2009.
- From A. de Gouvêa's FPCP2009 talk: "...a summary talk ... to a group of people more interested in quarks than neutrinos."

Outline:

Quarks *vs* Neutrinos
Terrestrial Neutrinos
Solar Neutrinos
Extraterrestrial Neutrinos
Artificial Neutrinos
Global fit



Disclosure: I am a collaborator on MINOS, Daya Bay and LBNE.

Parallels of quarks and neutrinos

3 generations

$$|\psi_i >= \sum_j V^*_{ij} |\psi_j >$$

Cabibbo-Kobayashi-Masakawa	V_{ji}	Pontecorvo-Maki-Nakagawa-Sakata
13°	θ_{12}	34°
2.3°	θ_{23}	43°
0.2°	θ_{13}	$< 12^\circ$ (90% CL)
64.5°	δ	$[0, 360]^\circ$
3×10^{-5}	J	$\leq 3500 \times 10^{-5}$
CKMfitter (Oct09)	ref.	arXiv:1001.4524

Magnitude of CPV $\propto$ Jarlskog invariant [1] $J \equiv Im(V_{ij} V_{kl} V^*_{kj} V^*_{il})$

$$V_{ij} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ for $i < j = 1, 2, 3$.

[1] Jarlskog, PRL**55**(1985)1039

What we know about neutrino oscillations

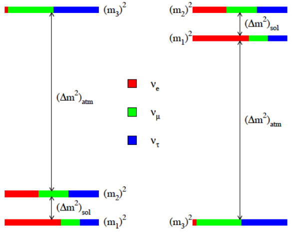
$$V_{ij} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^\circ$
Atmospheric ν
Accelerator ν

$\theta_{13} < 12^\circ$
Short-baseline Reactor ν
Future accelerator ν

$\theta_{12} \approx 35^\circ$
Solar ν
Long-baseline Reactor ν

Neutrinoless double beta decay



normal hierarchy
inverted hierarchy

$\Delta m^2_{21} = 7.6 \times 10^{-5}\ \mathrm{eV}^2$ *(solar)*

$|\Delta m^2_{31}| = 2.4 \times 10^{-3}\ \mathrm{eV}^2$ *(atmospheric)*

ν_μ disappearance in 2-ν approximation:

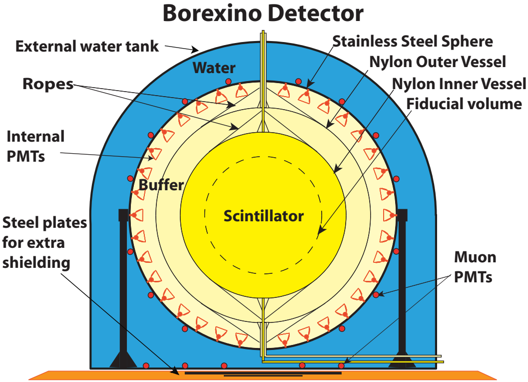
$\mathcal{P}(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$

$L(\mathrm{km})$, $E(\mathrm{GeV})$, $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$ (eV^2)

Topics and recent neutrino results not discussed

- Neutrinoless Double Beta Decay
- Neutrino mass measurement in ^{3}H decay
- Super-Kamiokande: Search for astrophysical ν point sources. Astrophys.J. **704** (2009) 503.
- MiniBooNE: Measurement of ν_μ CC quasielastic double differential cross section. arXiv:1002.2680
- MiniBooNE: Measurement of ν_μ and $\bar{\nu}_\mu$ NC single π^0 production cross section on mineral oil at $E_\nu \sim \mathcal{O}(1\ \mathrm{GeV})$. PRD**81** (2010) 013005.
- MINOS: ν_μ and $\bar{\nu}_\mu$ inclusive CC cross-sections. arXiv:0910.2201
- MINOS: Search for sterile neutrino mixing. arXiv:1001.0336

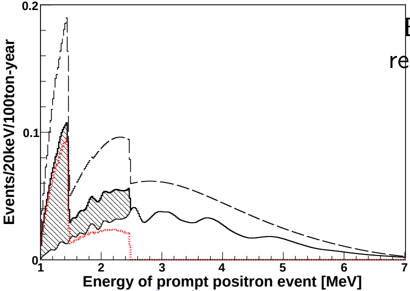
Borexino: Observation of geo-neutrinos arXiv:1003.0284



- Located in LNGS, 3800 m.w.e. overburden
- 278 tons target of high-purity liquid scintillator (8.5m diam. inner vessel)
- 890 tons buffer (11.5m outer vessel, 13.7m SS shell)
- Target viewed by 2212 8" PMTs
- Water-filled external tank, viewed by 208 8" PMTs
- Exposure: 253 ton·year

Borexino: Detection of geo-neutrinos

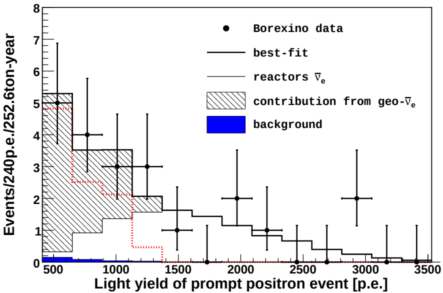
- Geo-neutrinos are $\bar{\nu}_e$ produced by β decays of $^{40}\mathrm{K}$ and nuclides in the $^{238}\mathrm{U}$ and $^{232}\mathrm{Th}$ chains.
- Provide a direct measure of abundance and distribution of radioactive elements in the Earth, and would permit an assessment of the radiogenic contribution of the Earth's heat balance.
- $\bar{\nu}_e$ are detected via inverse beta decay $\bar{\nu}_e p \rightarrow e^+ n$.
  - Prompt e^+ energy $E_{\mathrm{vis}} \approx E_\nu - 0.78\ \mathrm{MeV}$
  - Delayed $np \rightarrow d\gamma$ ($E_\gamma = 2.22$ MeV, $\tau \sim 256\ \mu\mathrm{s}$)



Expected prompt spectrum (without energy resolution)

Dashed	Geo-$\bar{\nu}_e$ & reactor $\bar{\nu}_e$ (no osc.)
Thick	Geo-$\bar{\nu}_e$ & reactor $\bar{\nu}_e$ (with osc.)
Red	Geo-$\bar{\nu}_e$ only

Borexino: Geo-neutrino results

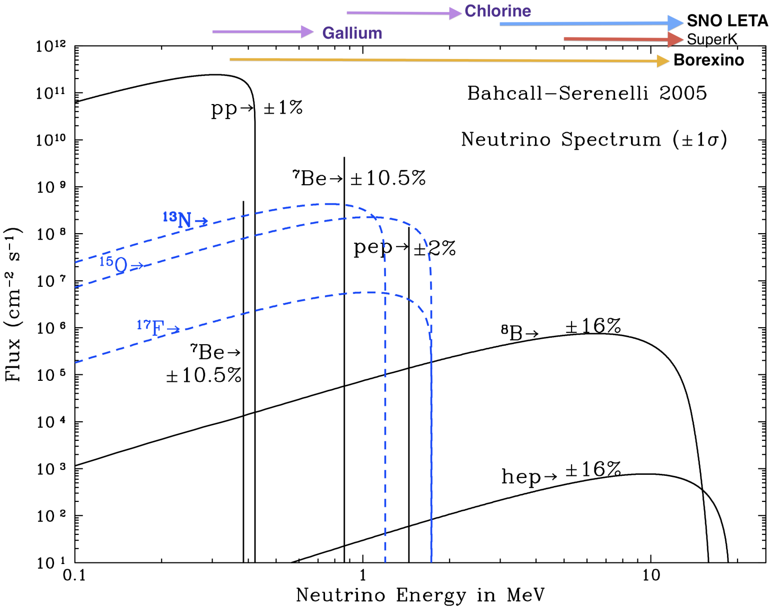


Source	Bkg evts $(100\ \mathrm{ton}\cdot\mathrm{yr})^{-1}$
^{9}Li–^{8}He	0.03±0.02
Fast n's (WT μs)	<0.01
Fast n's (Rock μs)	<0.04
Untagged muons	0.011±0.001
Accid. coinc.	0.080±0.001
Time corr. bkgd	<0.026
(γ,n)	<0.003
Fission in PMTs	0.0030±0.0003
(α,n) in scintillator	0.021±0.002
(α,n) in the buffer	<0.061
Total	0.15±0.02

$N_{\rm geo} = 9.9^{+4.1}_{-3.4}$ ($N_{\rm geo} > 0$ at 99.997% CL) and $N_{\rm reac} = 10.7^{+4.3}_{-3.4}$ events

Consistent with Maximal Radiogenic Earth model: All terrestrial heat produced exclusively by radiogenic elements.

Neutrinos from the Sun



Borexino $^{8}\mathrm{B}$ flux measurement (arXiv:0808.2868v3)

- Solar neutrinos are detected by $\nu e^- \to \nu e^-$ elastic scattering (ES) in Borexino's liquid scintillator. $\sigma_{\mathrm{ES}}(\nu_e e) \approx 6.3\sigma_{\mathrm{ES}}(\nu_{\mu,\tau} e)$.
- A 3 MeV threshold limits background from radioactivity.
- Background is dominated by cosmogenic production of unstable isotopes from $^{12}\mathrm{C}$. ($\sim$4300 muons/day deposit energy in Borexino inner detector)
- Short-lived isotopes are suppressed by a $> 6.5\mathrm{s}$ veto after a muon.
- Longer-lived isotopes ($^{10}\mathrm{C}$, $^{11}\mathrm{Be}$) are suppressed and subtracted.
- From 345.5 live days with a 100t fiducial mass, 75 ± 13 $^{8}\mathrm{B}$ solar ν candidates remain (Solar models: 86 ± 10 or 73 ± 7)

Sudbury Neutrino Observatory arXiv:0910.2984

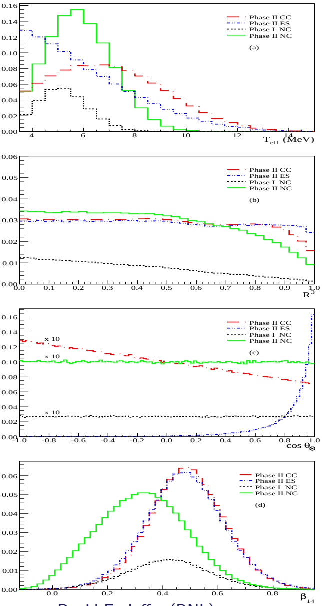
- Located in Creighton Mine,CA, 5890 m.w.e. overburden
- 1000 t $\mathrm{D_2O}$ in 12m diam., 5cm thick acrylic vessel
- 9456 20 cm PMTs mounted on 18m diameter steel frame in 8400 t $\mathrm{H_2O}$
- Extensive calibration system
- Solar neutrino detection [a]

CC $\nu_e + d \rightarrow p + p + e^-$
ES $\nu_x + e^- \rightarrow \nu_x + e^-$
NC $\nu_x + d \rightarrow p + n + \nu'_x$

- Phase I: "$\mathrm{D_2O}$" (resolved solar ν problem)
- Phase II: "Salt phase", +2t NaCl

[a] H.H.Chen, PRL **55** (1985) 1534

SNO: Low-Energy-Threshold Analysis(LETA)



Previous threshold ∼5 MeV, LETA 3.5 MeV

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

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

NC $\nu_x + d \to p + n + \nu'_x$ Phase I (nd)

NC $\nu_x + d \to p + n + \nu'_x$ Phase II (nCl)

$T_{\rm eff}$ = effective electron kinetic energy

R^3 = $(R_{\rm fit}/R_{\rm AV})^3$

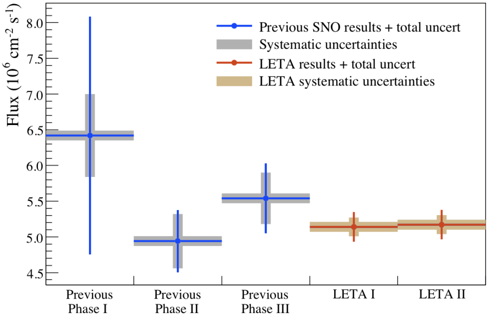
$\cos\theta_\odot$ = direction wrt ν from Sun

β_{14} = ‘isotropy’ (small β_{14} = high isotropy)

LETA improvements:

1. A more sophisticated energy reconstruction narrowed the resolution by ∼6%, reducing the low-energy backgrounds by ∼60%.
2. Better background rejection cuts
3. Better data quality cuts

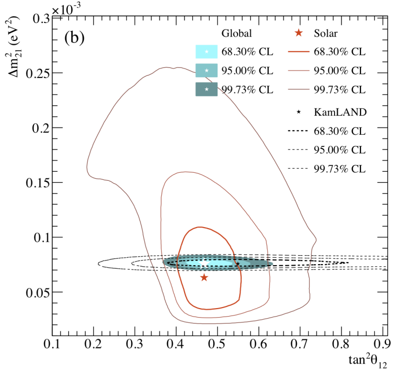
Results of SNO LETA (1)

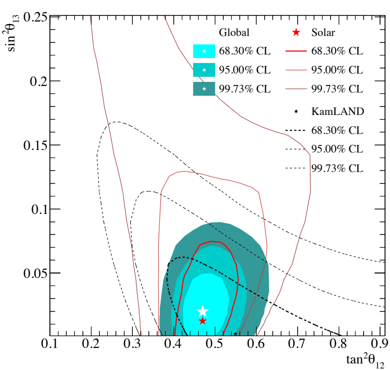


Total $^8\mathrm{B}$ neutrino flux LETA results using the NC ($\nu_x d \rightarrow pn\nu_x$)reaction compared to previous results.
Assuming unitarity, the NC, CC and ES measurements can be combined to yield the most precise measurement of the solar $^8\mathrm{B}$ neutrino flux:

$$\Phi(^8\mathrm{B}) = (5.046^{+0.159}_{-0.152}(\mathrm{stat})^{+0.107}_{-0.123}(\mathrm{syst})) \times 10^6/\mathrm{cm}^2/\mathrm{s}$$

Results of SNO LETA (2)



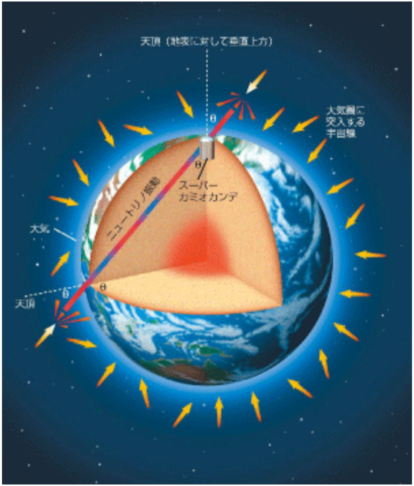


Results of 3ν fit to solar + KamLAND data. (Solar: SNO, Cl, SAGE, Gallex/GNO, Borexino, SK)

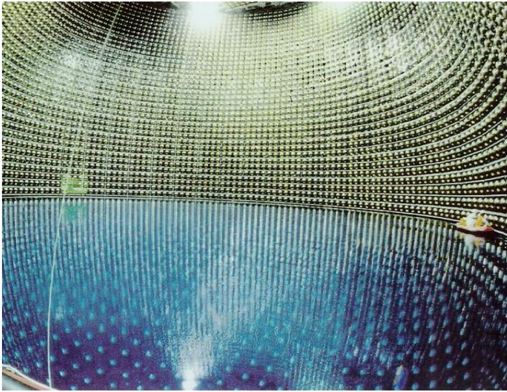
$$\theta_{12} = 34.06^{+1.16\circ}_{-0.84} \qquad \Delta m^2_{21} = (7.59^{+0.20}_{-0.21}) \times 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2\theta_{13} = (2.00^{+2.09}_{-1.63}) \times 10^{-2} \ \text{ or } \ < 0.057 \text{ at } 95\% \text{ CL}$$

Atmospheric neutrinos and Super-Kamiokande

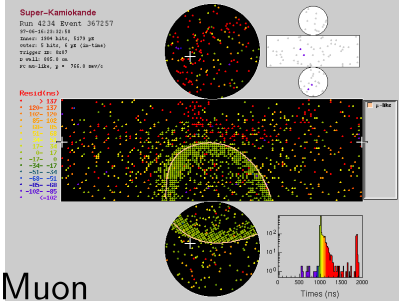


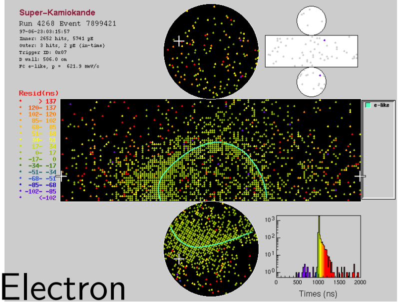
$$\pi \rightarrow \mu\nu_\mu \;\; \mu \rightarrow e\nu_e\bar{\nu}_\mu$$
$$N(\nu_\mu) \approx 2N(\nu_e)$$

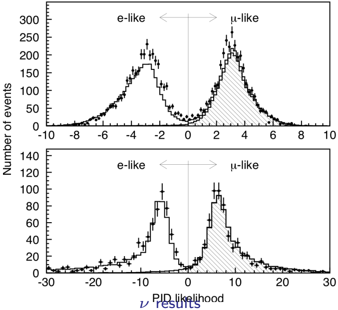


Super-Kamiokande:
cylinder with 39m diam., 41m h.
50kt ultra pure water
2700 mwe overburden
∼11000 20" PMTs (∼40% coverage)

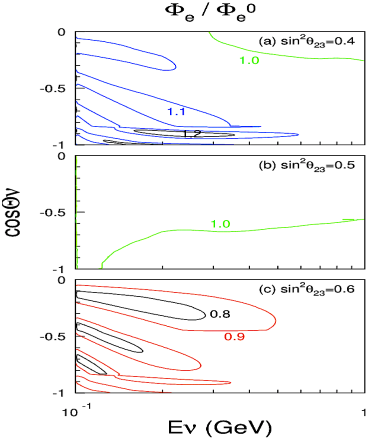
Particle identification in SuperK



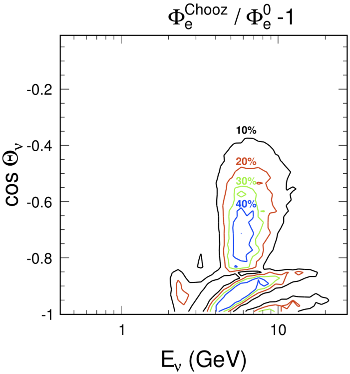




Atmos. ν osc. analysis with sub-leading effects (arXiv:1002.3471)

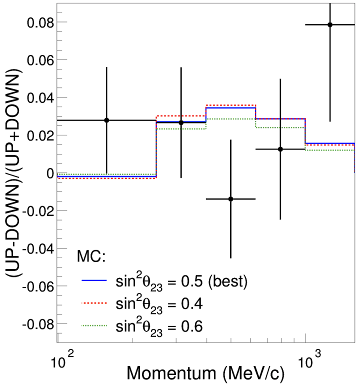


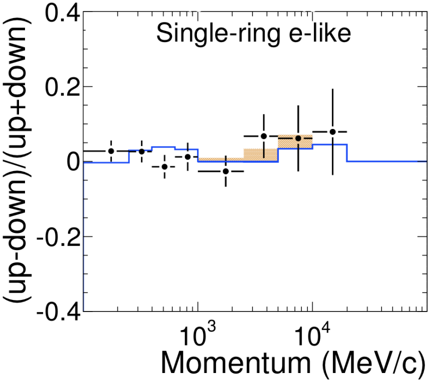
Change in ν_e flux as a function of neutrino zenith angle and energy assuming $\theta_{13} = 0$.



Change in ν_e flux as a function of neutrino zenith angle and energy for θ_{13} at 90%CL upper limit with $\Delta m^2_{23} = 0.0021\ \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.5$, normal hierarchy.

Sub-leading effects in atm. ν in SuperK: Results

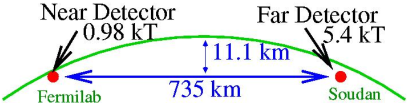




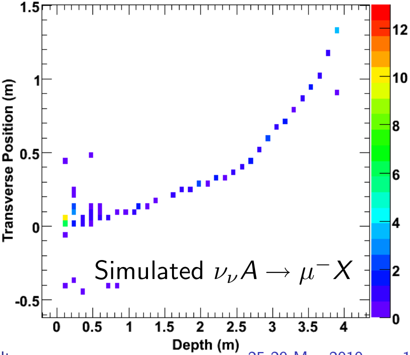
Fit assuming $\theta_{13} = 0$:
$0.407 < \sin^2\theta_{23} < 0.583$
(90%CL).

	$\sin^2\theta_{13}$ (90%CL)	Δm^2 eV^2	$\sin^2\theta_{23}$	$\frac{\chi^2}{\mathrm{DOF}}$
NH	< 0.04	0.0021	0.50	468.7/417
IH	< 0.09	0.0021	0.53	468.4/417

MINOS beam and detectors



A ~3 GeV ν beam (93% ν_μ, 6% $\bar{\nu}_\mu$, 1% $\nu_e + \bar{\nu}_e$) sent from FNAL to Soudan. MINOS Near (100m depth) and Far (700m depth) Detectors are alternating layers of magnetized steel (2.54cm, 1.4 X_0) and scintillator strips (4.1cm wide).



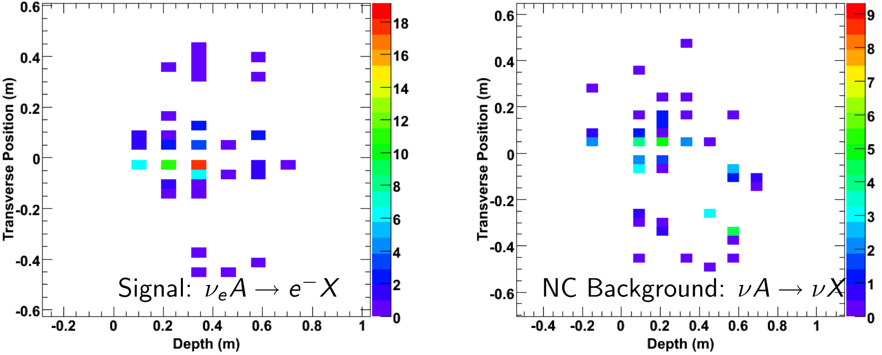
$\nu_\mu \longrightarrow \nu_e$ with matter effect (Freund, hep-ph/0103300)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad \approx \quad & \sin^2 2\theta_{13} \sin 2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2} \\
& -8\alpha(J \sin\Delta - I \cos\Delta) \frac{\sin A\Delta \sin(1-A)\Delta}{A(1-A)} \\
& +\alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 A\Delta}{A^2}
\end{aligned}
$$

$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \approx 0.03 \qquad \Delta \equiv \Delta m^2_{31} L/4E$
$A = 2VE/\Delta m^2_{31} \approx (E_\nu/11GeV)$ for earth's crust
$J \equiv Im(V_{ij}V_{kl}V^*_{kj}V^*_{il}) = \frac{1}{8} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$
$I \equiv Re(V_{ij}V_{kl}V^*_{kj}V^*_{il}) = \frac{1}{8} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$

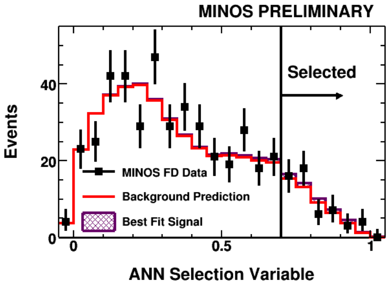
ν_e appearance probability depends not only on θ_{13} but also on δ and the sign of Δm^2_{31} (the mass hierarchy)

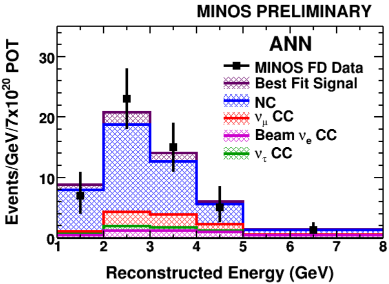
MINOS ν_e appearance: Signal and background



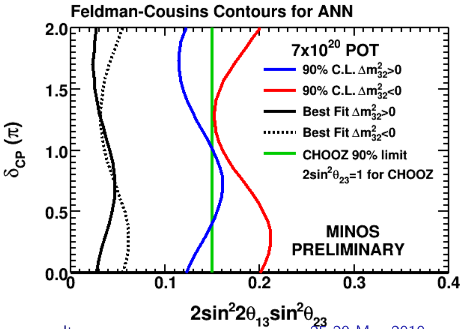
- Other background: ν_μ CC with short μ track, intrinsic beam ν_e, $\nu_\mu \to \nu_\tau$.
- Use artificial neural network (ANN) with 11 shower shape variables to discriminate signal and background.
- Utilize near detector to obtain a background sample and extrapolate to predict the far detector background.

MINOS ν_e appearance: Result (7×10^{20} POT, to be submitted to PRL)





Component	Events
NC	36
ν_μ CC	6
Beam ν_e	5
ν_τ CC	2
Total Bkgd	49.1 ± 7.5
Observation	54



Global fit

- Global analysis of Gonzalez-Garcia, Maltoni and Salvado (arXiv:1001.4524). Similar results from other analyses: arXiv:0905.3546, arXiv:1003.5800
- Uses Borexino, SNO LETA, SuperK and MINOS data shown in this talk.
- Also includes Chlorine, Gallex/GNO, SAGE radiochemical experiments, SuperK solar neutrino results and KamLAND.
- Includes uncertainties due to ν_e capture cross-section in gallium and in the solar model (low- and high-metallicity).

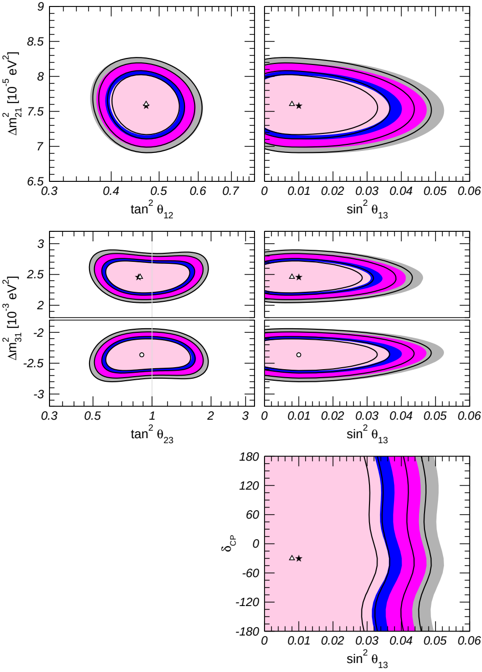
Global fit: Results

$$\Delta m^2_{21} = (7.59^{+0.61}_{-0.69}) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = \begin{cases} (-2.36 \pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \\ (+2.46 \pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \end{cases}$$

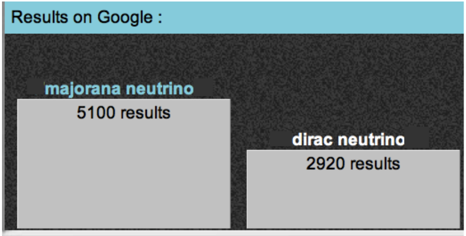
$$\theta_{12} = (34.4^{+3.2}_{-2.9})^\circ$$
$$\theta_{23} = (42.8^{+10.7}_{-7.3})^\circ$$
$$\theta_{13} \le 12.5^\circ$$
$$\delta_{CP} \in [0,\ 360]^\circ$$

(Uncertainties, limits are at 3σ)
Different contours correspond to 90%, 95%, 99% and 3σ CL.
Full regions: High-metallicity solar model.
Void regions: Low-metallicity solar model.



Vague prognostications

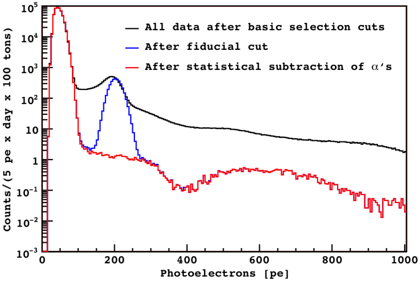
1. 2-3 mixing is nearly maximal. θ_{23} might be 45°.
2. θ_{13} is small. It might be zero.
3. I predict the next two speakers will try to tell us when we will know
   3.1 θ_{13},
   3.2 the mass hierarchy,
   3.3 the mass of the neutrino,
   3.4 if CP is violated for leptons, and
   3.5 if neutrinos are their own anti-particles.

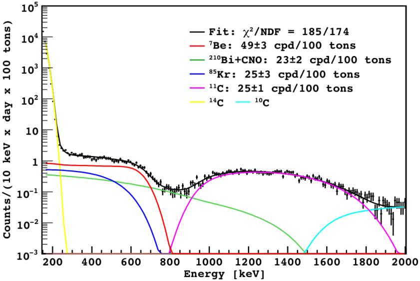



Thanks to Michael Sivertz and Brett Viren for comments on these slides.

Additional slides

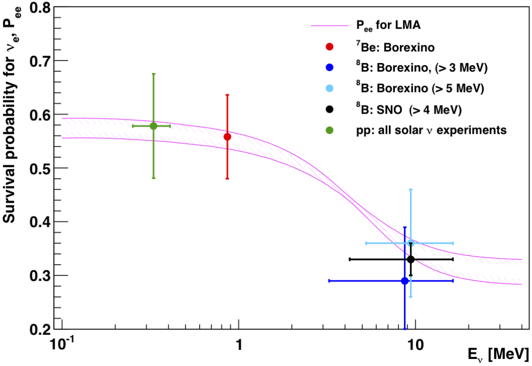
Borexino $^7\mathrm{Be}$ flux measurement (PRL **101**, 091302 (2008))





- Signature of monoenergetic 0.862 MeV $^7\mathrm{Be}$ neutrino is Compton-like edge of the recoil electrons at 665 keV
- Suppression of radioactive backgrounds requires outer 2/3 of scintillator to serve as an active shield yielding a 78.5t fiducial mass.
- α background from $^{210}\mathrm{Po}$ at $\sim$400 keV statistically subtracted using pulse-shape discrimination

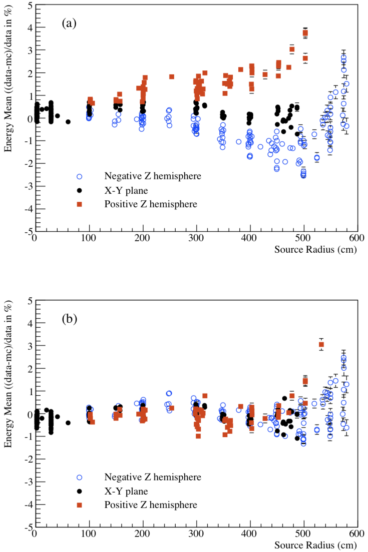
Resolving the sign of Δm^2_{21} with solar neutrinos



$$\mathcal{H} = \mathcal{H}_{\rm vac} + \mathcal{H}_{\rm matter}(r) = \frac{\Delta m^2_{21}}{4E}\begin{bmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{bmatrix} + \begin{bmatrix} V(r) & 0 \\ 0 & 0 \end{bmatrix}$$

$$V(0) \approx 0.75 \times 10^{-5}\ {\rm eV}^2/{\rm MeV} \qquad \Delta m^2_{21} = 7.6 \times 10^{-5}\ {\rm eV}^2$$

SNO LETA



Energy reconstruction algorithm improved by inclusion of scattered and reflected Čerenkov light. Validated by extensive comparison of calibration data and simulated data. Calibration sources: Laser, ^{16}N, ^{8}Li, ^{252}Cf, Am-Be, cosmogenic neutrons, etc.

Figure: Difference in ^{16}N data and MC energy scale *vs.* radius. (a) before and (b) after spatial energy correction.

χ^2 *vs* $\sin^2\theta_{13}$