Overview of Recent Developments In Experiment Neutrino Physics OR What is νew …

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ASPEN Winter Conference, 13th January 2008

Outline

- Introduction : The fascinating ν (hi)story
- Neutrino Experiments

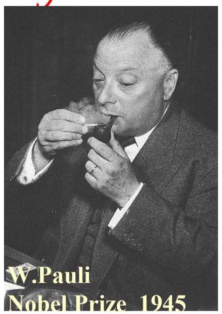
(Past , Present and Future):

  - Cosmic νews
  - Reactor νews
  - Accelerator νews

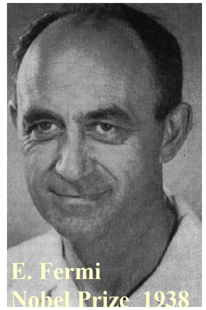
- Summary / Outlook

ν Hi-story : The birth and the detection

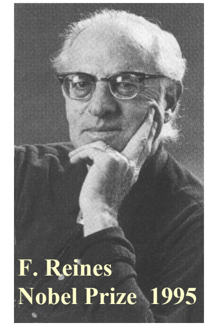
They ***must*** *exist*

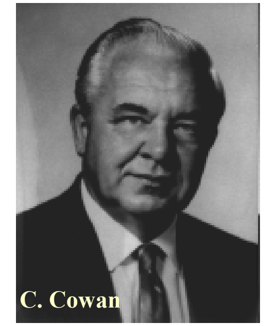


If they exist they ***interact weakly***

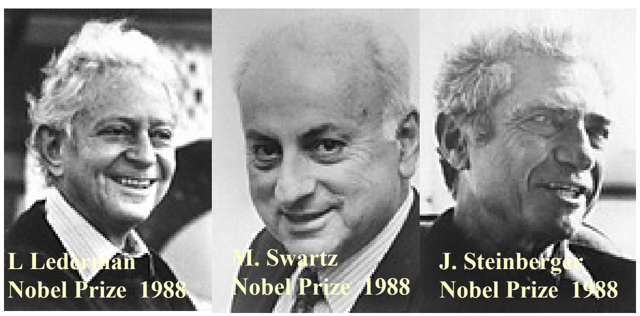


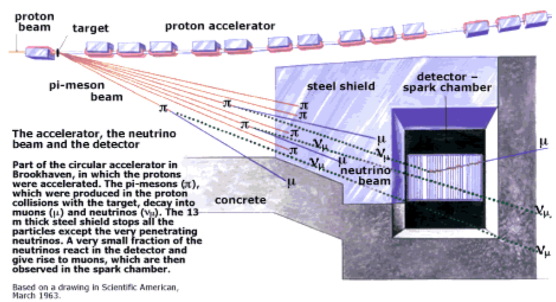
They ***do exist*** *since we can detect them*



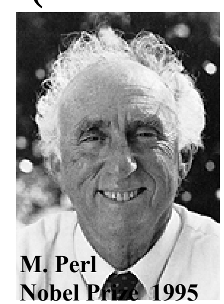


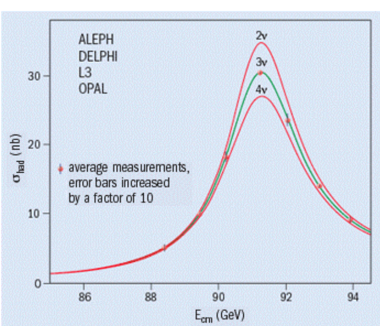
They are at least ***two flavours****, we* ***can make neutrinos and study them in accelerators***



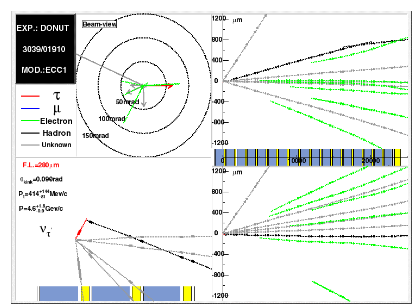


There are more than two flavours *of leptons (and neutrinos)*





There are ***three active light neutrinos***



He have ***directly observed the third one*** *(DONUT Experiment)*

Letter by Wolfgang Pauli

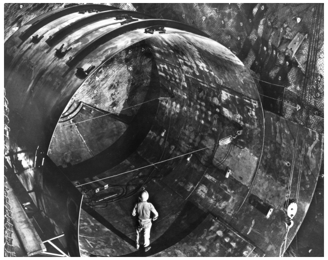
Dear Radioactive Ladies and Gentlemen

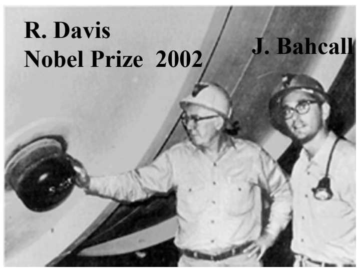
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

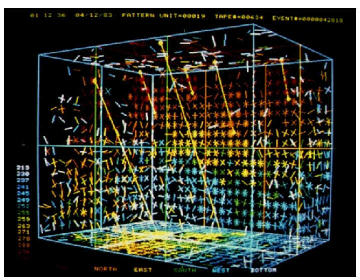
I agree that my remedy could seem incredible because one should have seen those particles very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honored predecessor, Mr. Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

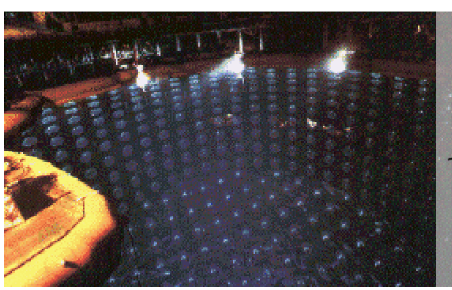
Your humble servant
. W. Pauli

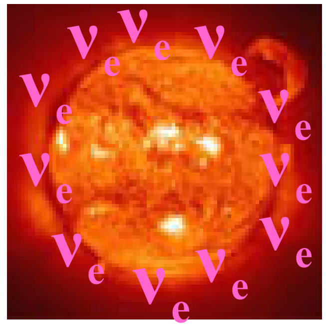
No νews (or missing νews) create "anomalies"

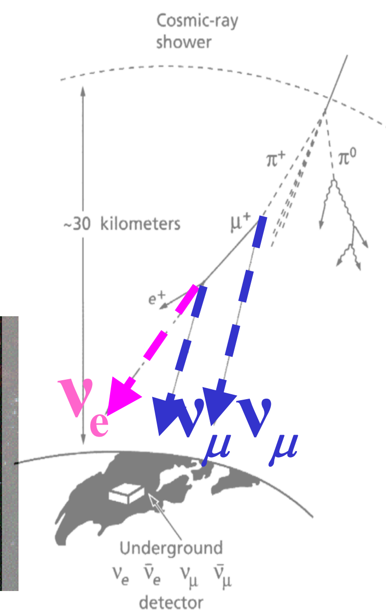












Solar neutrino "anomaly"

R. Davis and J.Bahcall
Homestake experiment

Neutrinos from the Sun less than expected!

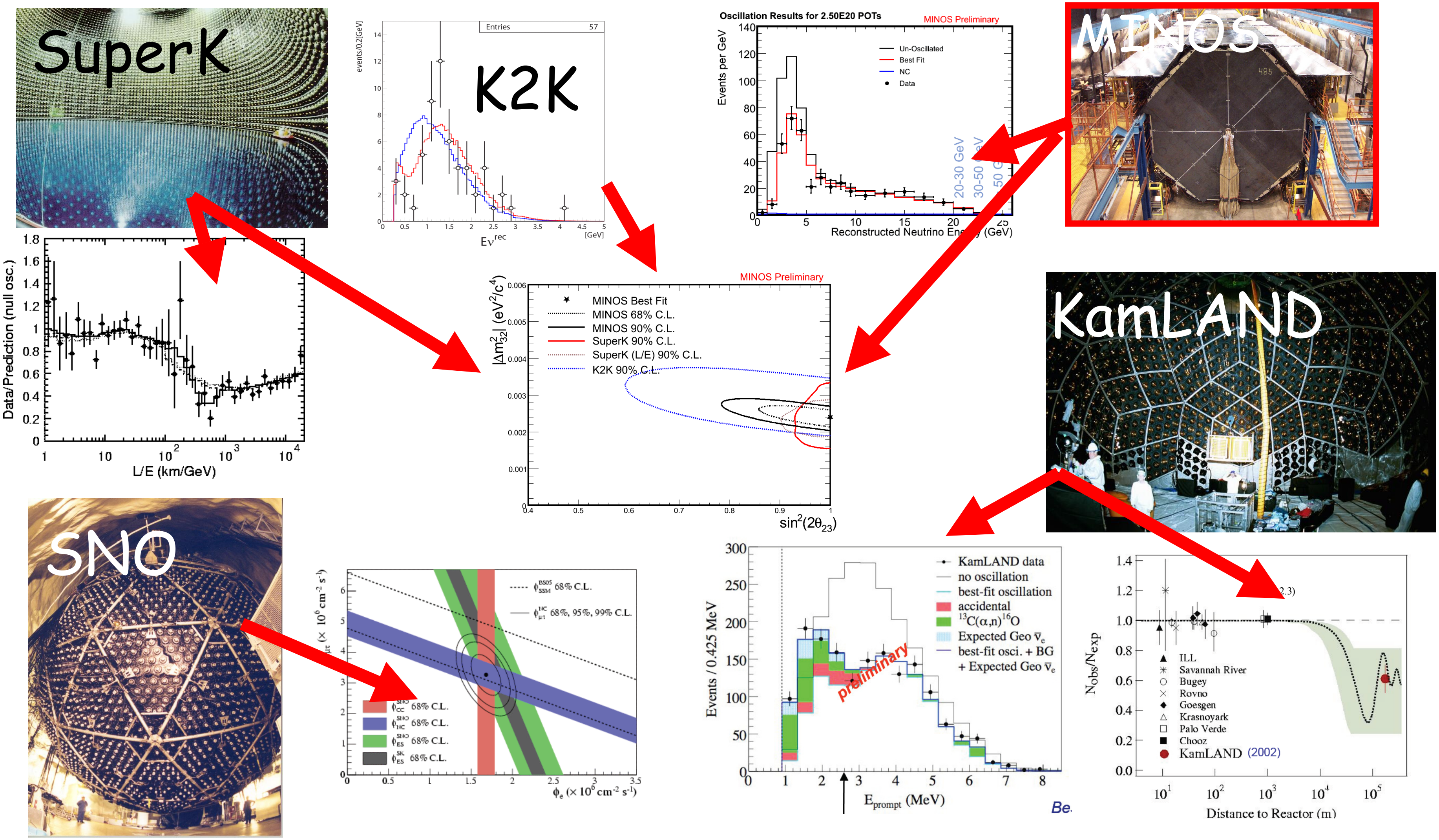
Atmospheric neutrino "anomaly"

Kamiokande and IMB experiments

Neutrinos from the atmosphere less than expected!

What do we know about missing νews

νews are "missing"… because they oscillate



3-Flavor ν Oscillation Formalism

If neutrinos oscillate, then the interaction eigenstates (or weak eigenstates, which is what we observe) can be expressed in terms of the mass eigenstates as follows:

$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\,\nu_i$$

Atmospheric | **Cross Mixing** | **Solar**

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$0\nu\beta\beta$ **decays**

Majorana phases

$$\begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

2-Flavor Neutrino Mixing

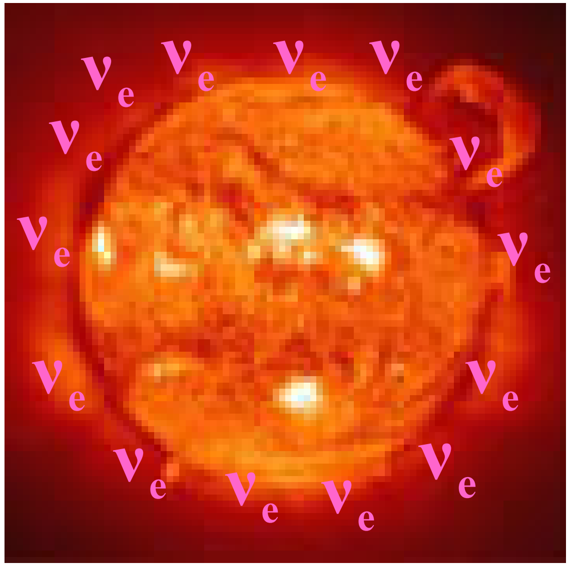
In certain experimental situations only one θ contributes, in which case one can write the oscillation probability as :

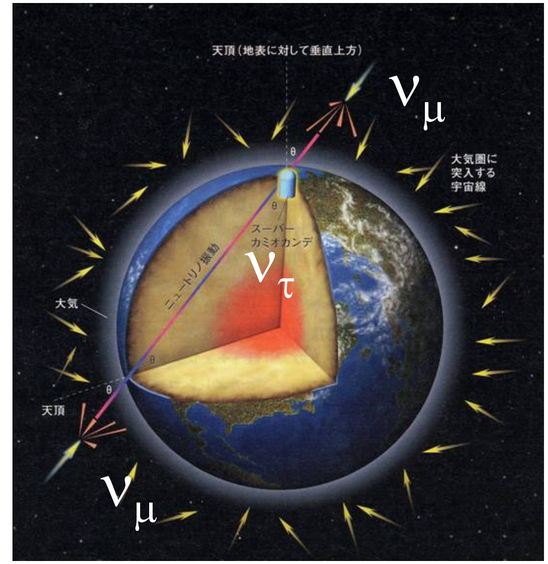
$$P = \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2{}_{23} \cdot L}{E}\right)$$

Physics **Experiment**

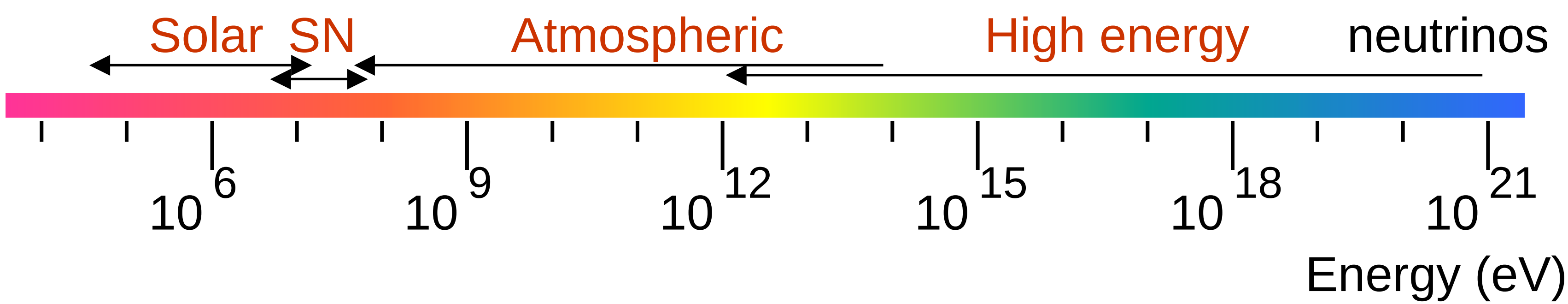
Different neutrino experiments , depending on what components of the mixing matrix they want to measure involve:

- **Different baselines**
- **Different neutrino energies**
- **Different neutrino flavors**

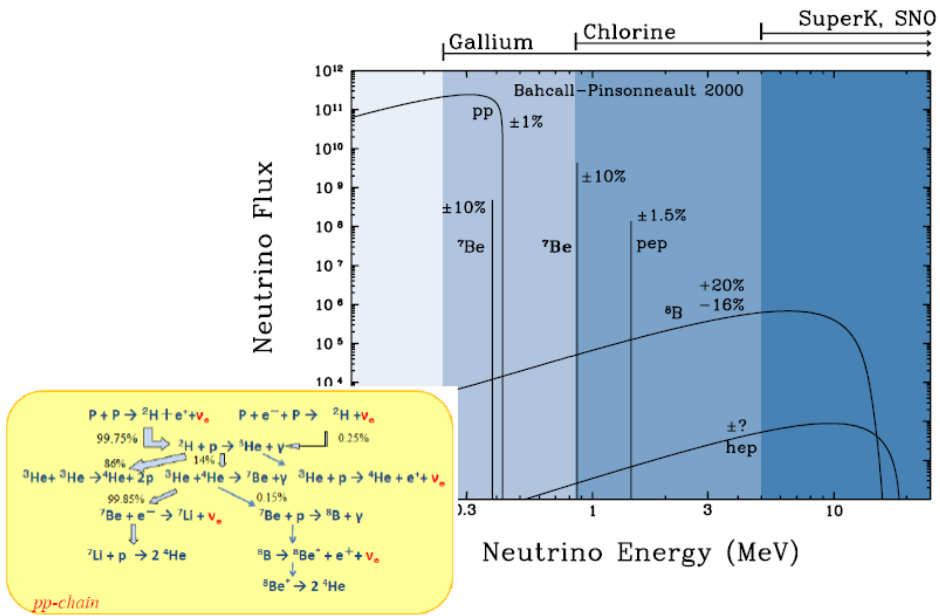




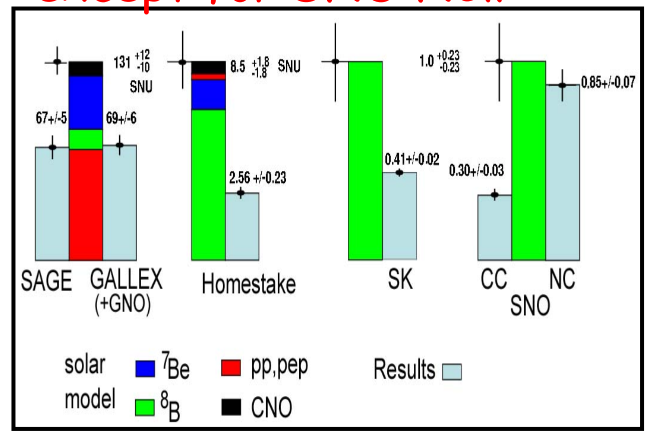
Solar - Atmospheric Neutrinos : What are they telling us?

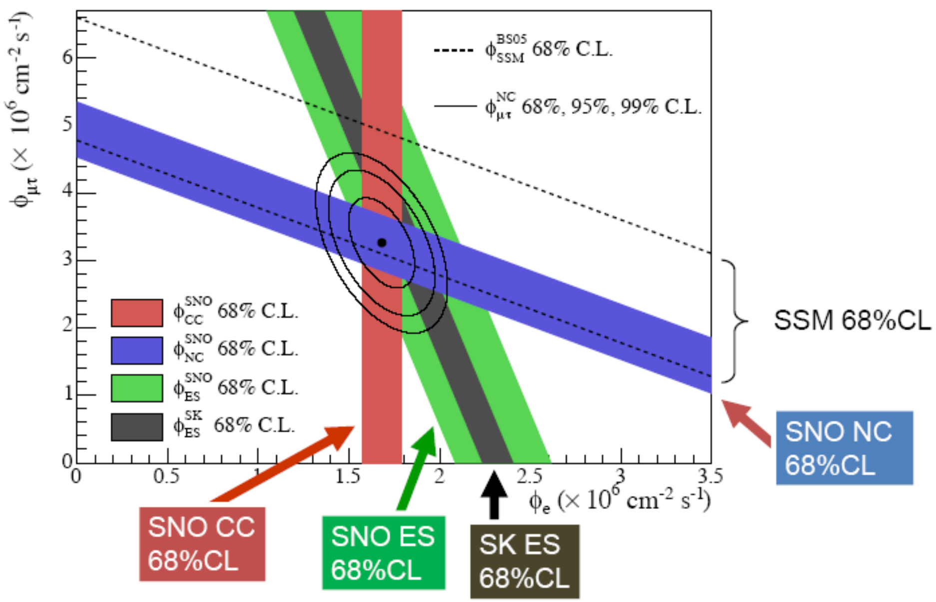


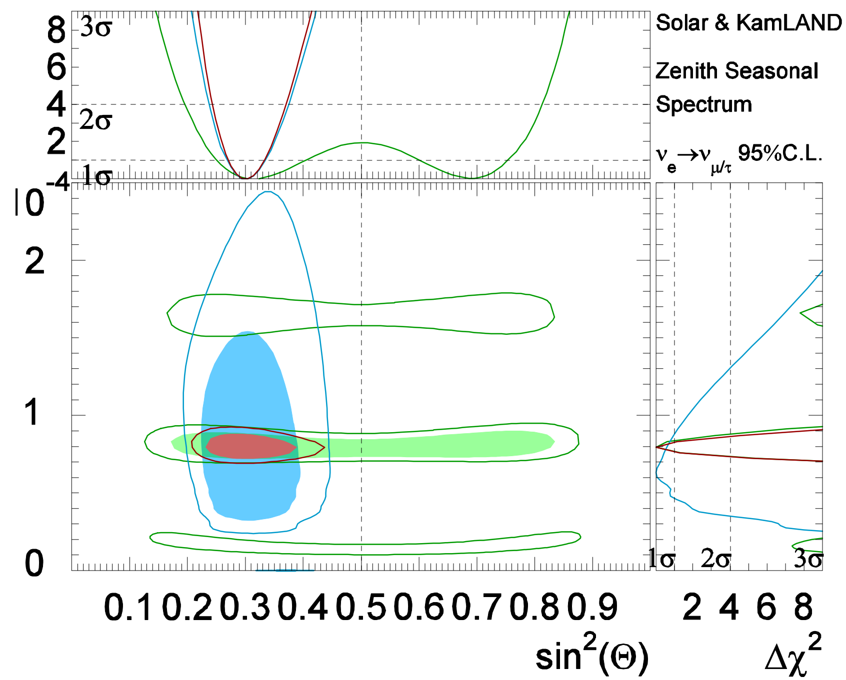
Solar Neutrino Oscillations :What do we know



Deficit of measured fluxes except for SNO NC!!







2001 SNO (Canada) : The solar neutrino "anomaly" is … indeed an "anomaly"

Confirm the Solar Neutrino "anomaly" 30 years after is was first observed (Davis and Bachall) and made measurements that give confidence that the Solar Model (**J. Bahcall**) is PRECISE!!

"I feel very much like the way I expect that these prisoners that are sentenced for life do when a D.N.A. test proves they're not guilty, for 33 years, people have called into question my calculations on the Sun."

Better Late Than Never

Open Questions with Solar νews

- How large is ^{7}Be neutrino flux?
  - BOREXINO
  - KamLAND

- Is ^{8}B spectrum distorted as expected from LMA solution?

  -SK-III plan to measure with lower energy threshold
  -SNO data analysis with lower threshold

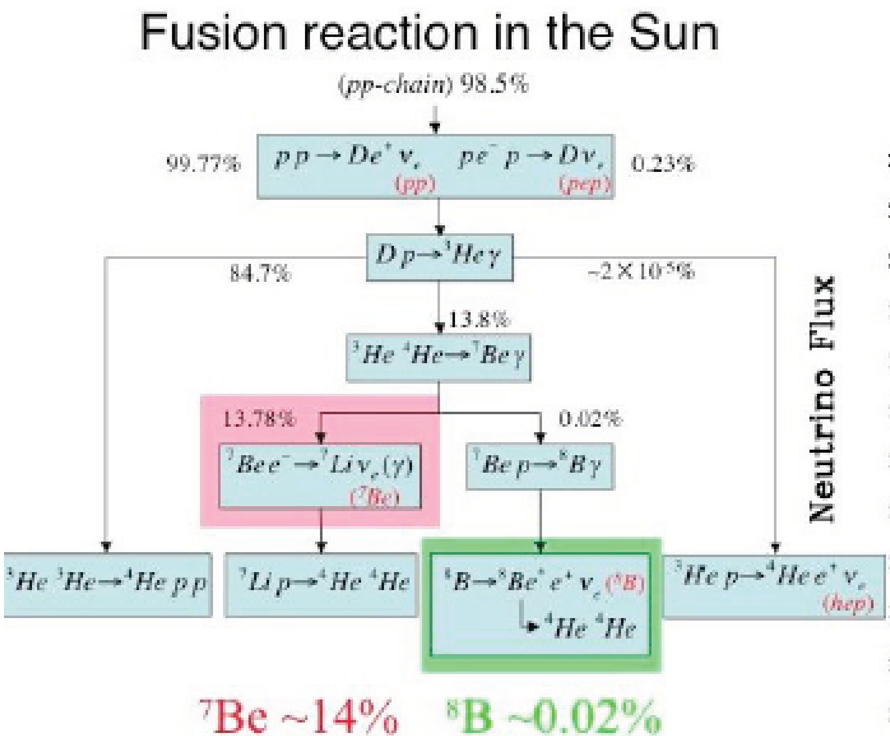
- pp neutrinos by real time experiments?

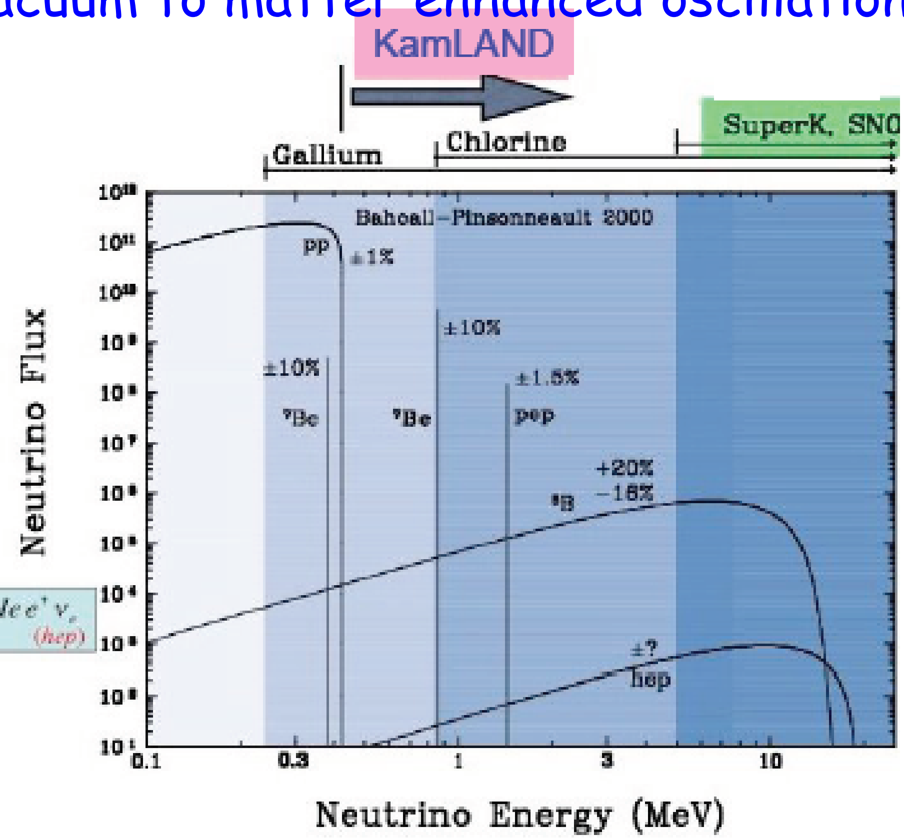
  -Future experiments (LENS, XMASS, CLEAN ...).

KamLAND Future : Search for Be^7 νews

Be^7 Observation and study of interaction of Be^7 ν from the Sun of great importance:

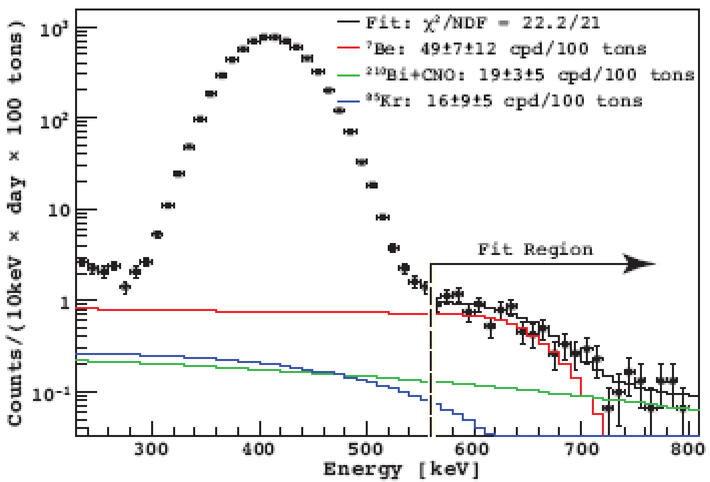
- Verification of low energy ν flux from Sun
- Observe transitions from vacuum to matter enhanced oscillations

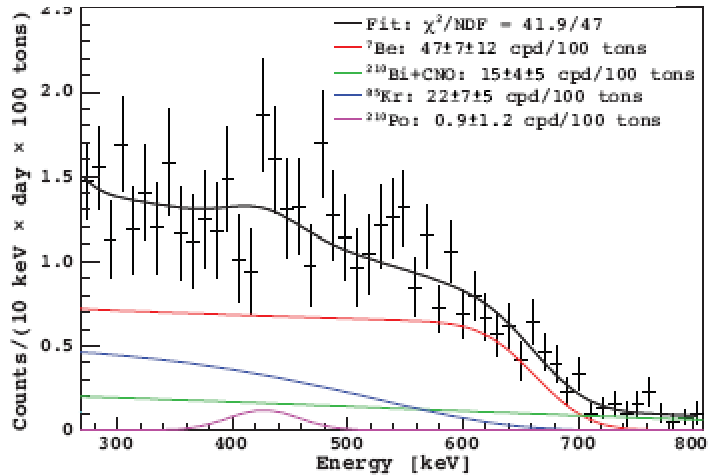




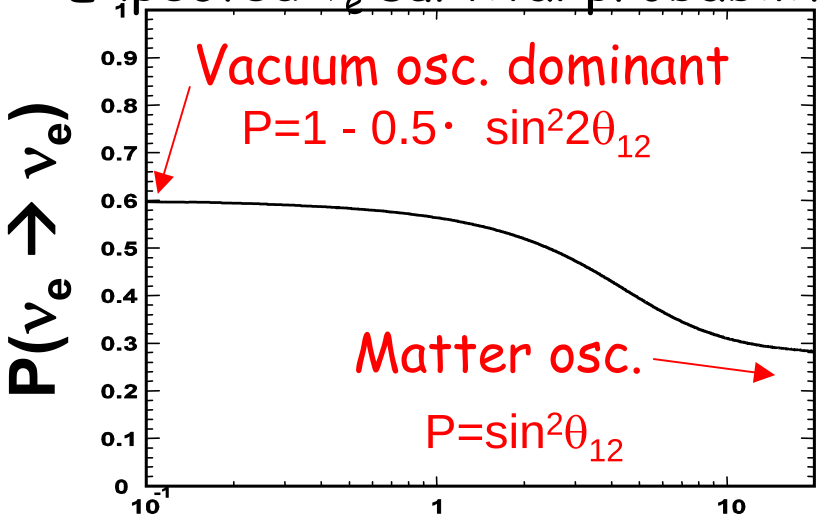
First Results from BOREXINO

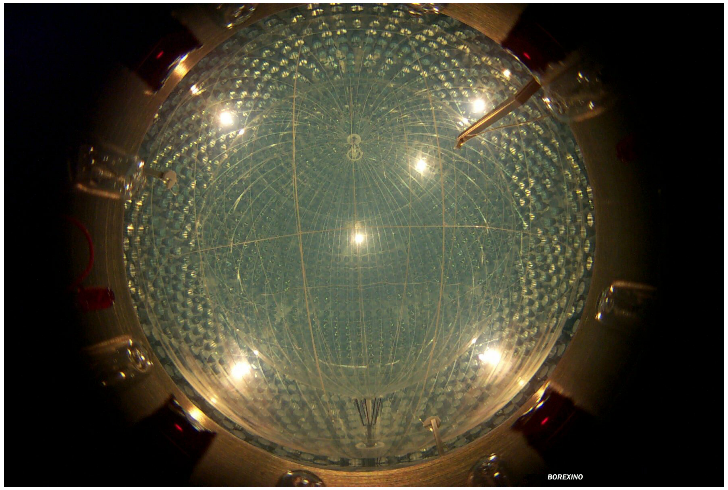
First real time detection of ^{7}Be solar neutrinos by Borexino





Expected ν_e survival probability

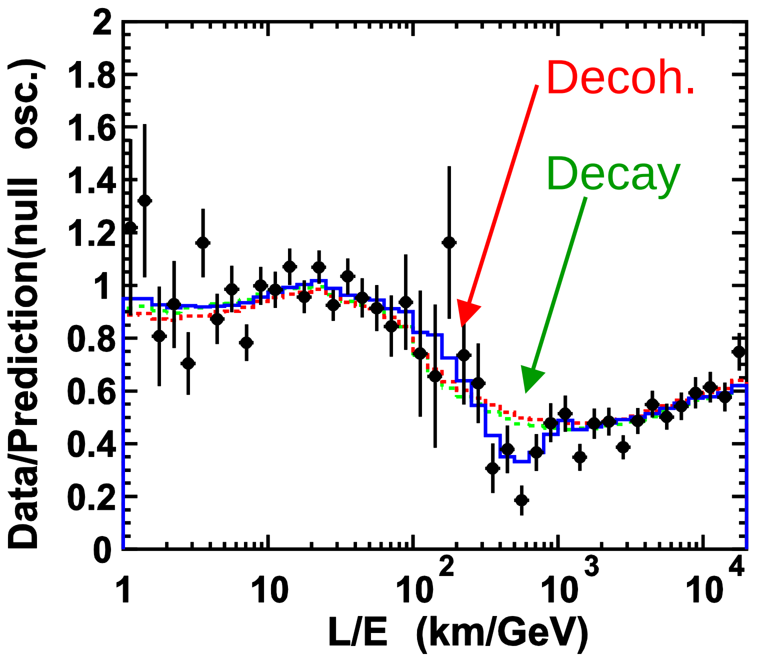




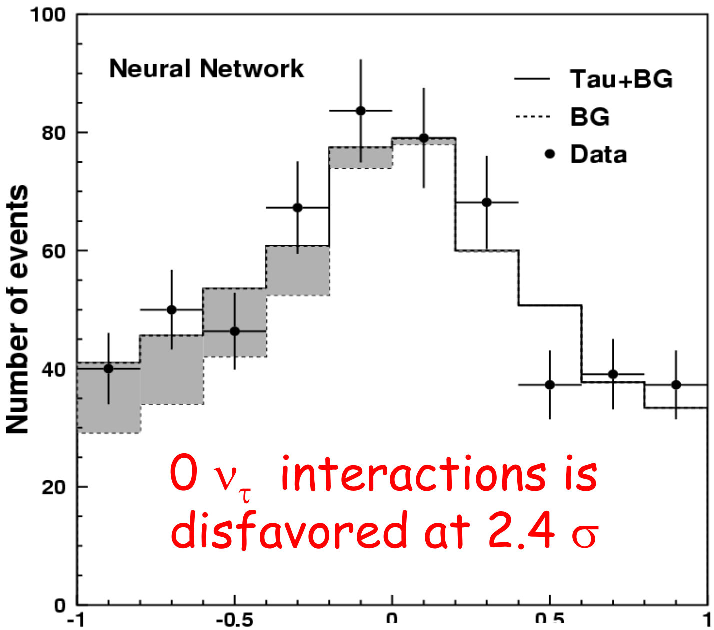
This paper reports a direct measurement of the ^{7}Be solar neutrino signal rate performed with the Borexino low background liquid scintillator detector. This is the first real-time spectral measurement of sub-MeV solar neutrinos. The result for 0.862 MeV ^{7}Be neutrinos is $47 \pm 7_{stat} \pm 12_{sys}$ counts/(day · 100 ton), consistent with predictions of Standard Solar Models and neutrino oscillations with LMA-MSW parameters.

Super-Kamiokande
First Strong Evidence of ν Oscillations

SK-collab. Phys.Rev.Lett.97:171801,2006



NN analysis



3 bins in L/E distribution seem to disfavor ν decay/decoherence at 4.8 and 5.3 σ respectively

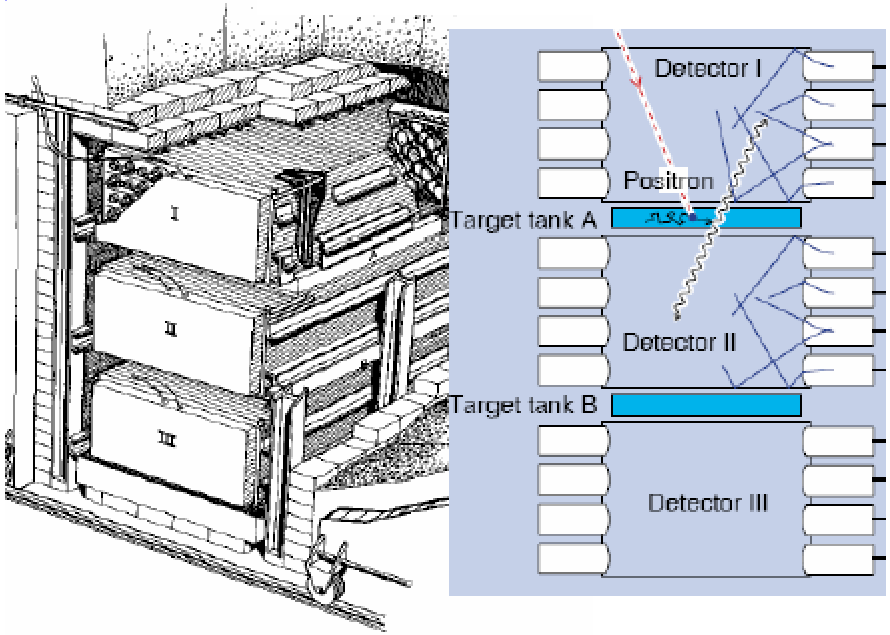
Fitted number of τ events	134±48(stat) + / -16(syst)
Exp'd number of τ events	78±27 (syst)

Reactor νews

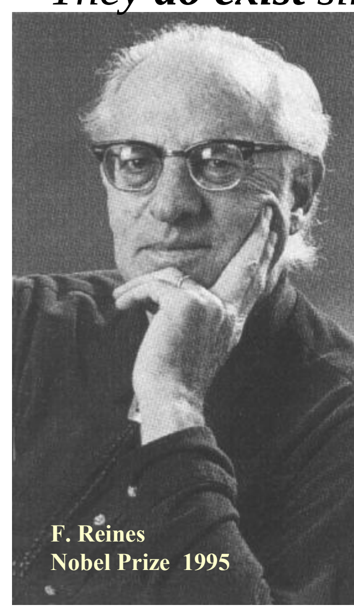
What are reactor νews telling us?

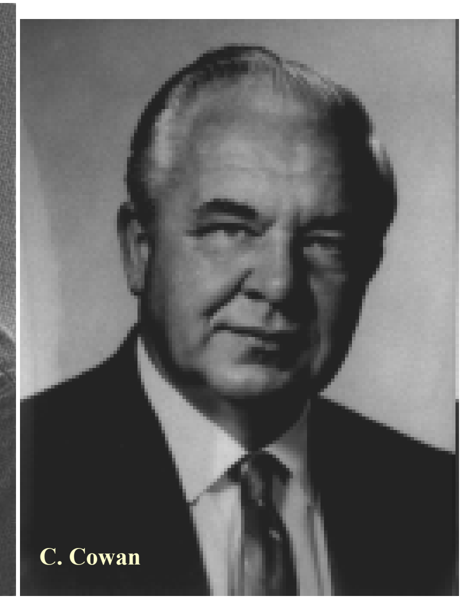
Well…First of all they told us neutrinos DO EXIST

The first successful neutrino detector

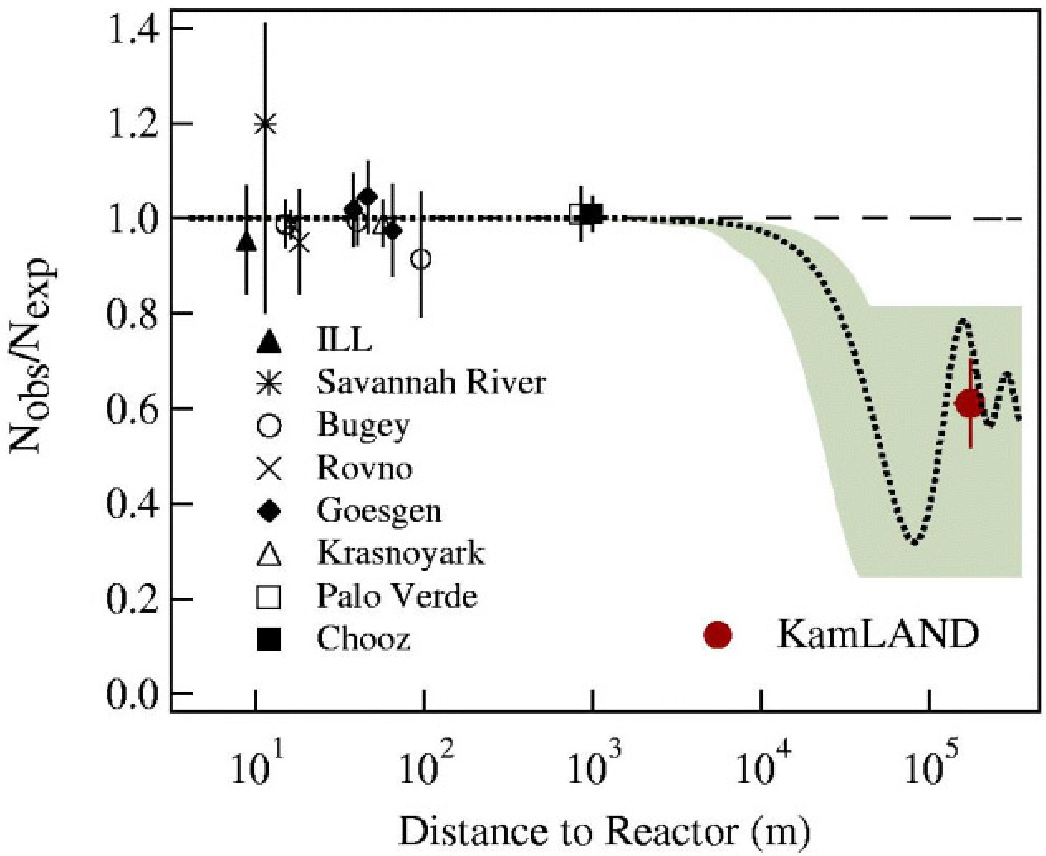


*They **do exist** since we can detect them*





Reactor νews : For long time they were telling us neutrinos do not oscillate (wrong L)…until KamLAND

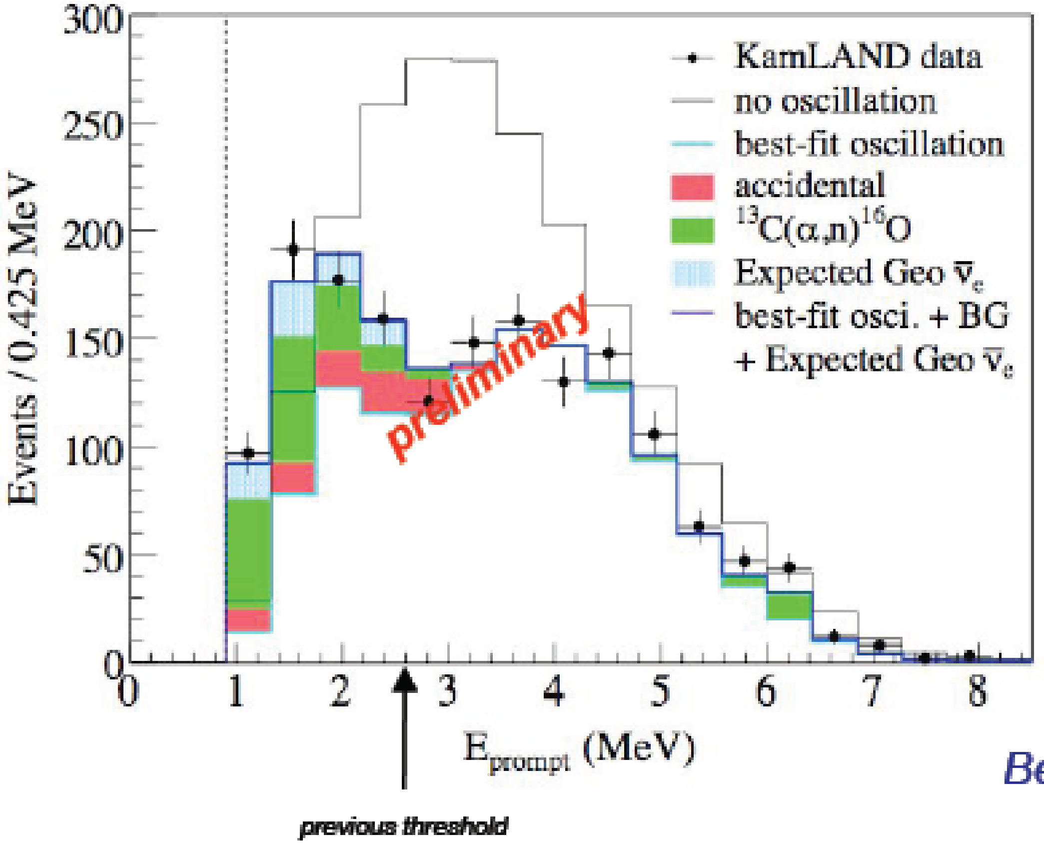


Well, they also determined the upper limit of mixing angle θ_{13} ($\sin^2 2\theta_{13} < 0.17$ - Chooz)

We will revisit that later…

Recent Results from KamLAND (2007)

Unbinned likelihood fit (rate + shape + time)
2-flavor oscillation analysis w/ Earth-matter effects
geoneutrino U+Th amplitude is a free parameter



2178 events (+ 276.1±23.5 bg) expected for no osc.

1609 events observed
8.5σ disappearance sig.

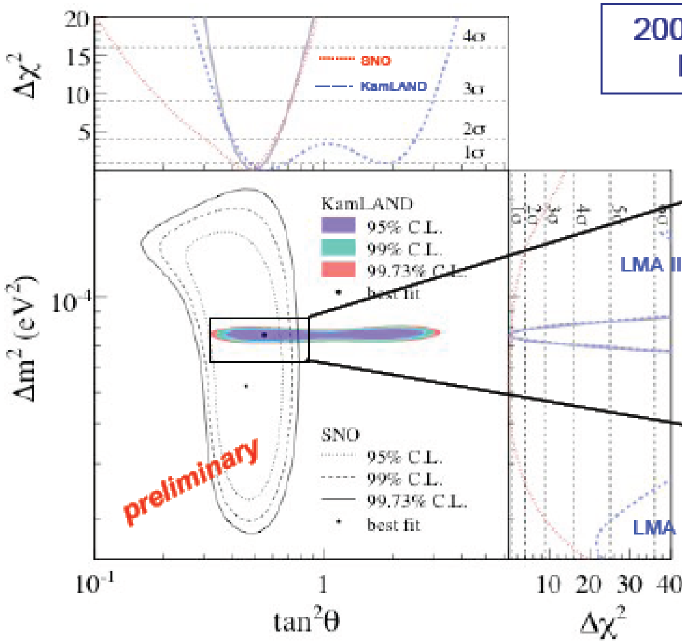
$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\ eV^2$

$\tan^2\theta = 0.56^{+0.14}_{-0.09}$

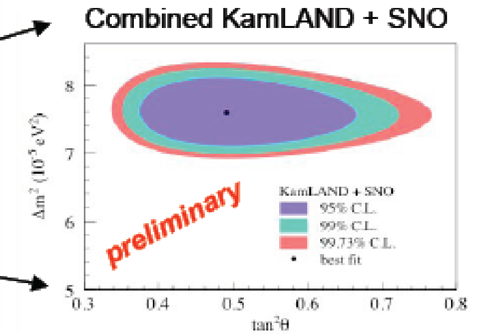
Significance of spectral distortion > 5σ

Goodness of Fit:
Best-Fit $\chi^2/dof = 21.0/16$ *(16% CL)*

Recent Results from KamLAND (2007) con'd



2007 KamLAND result excludes LMA 0 and LMA II at > 4σ



Combined Best-Fit Parameters:

$$\Delta m^2 = 7.59^{+0.21}_{-0.20} \times 10^{-5}\ eV^2$$

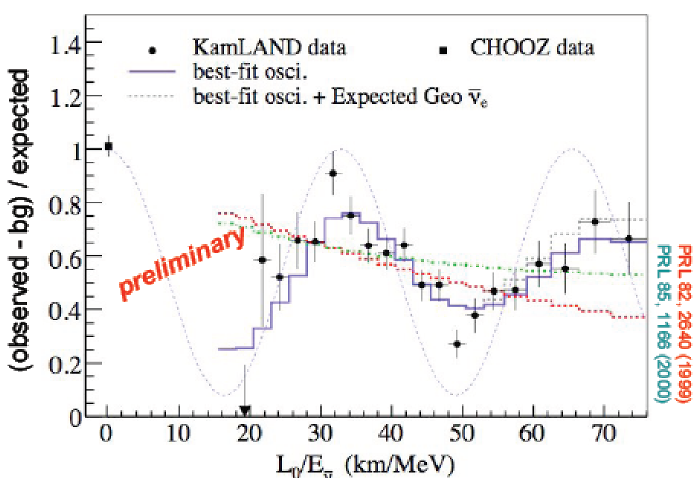
$$\tan^2\theta = 0.49^{+0.07}_{-0.05}$$

SNO ref: Phys Rev C 72, 055502(2005)

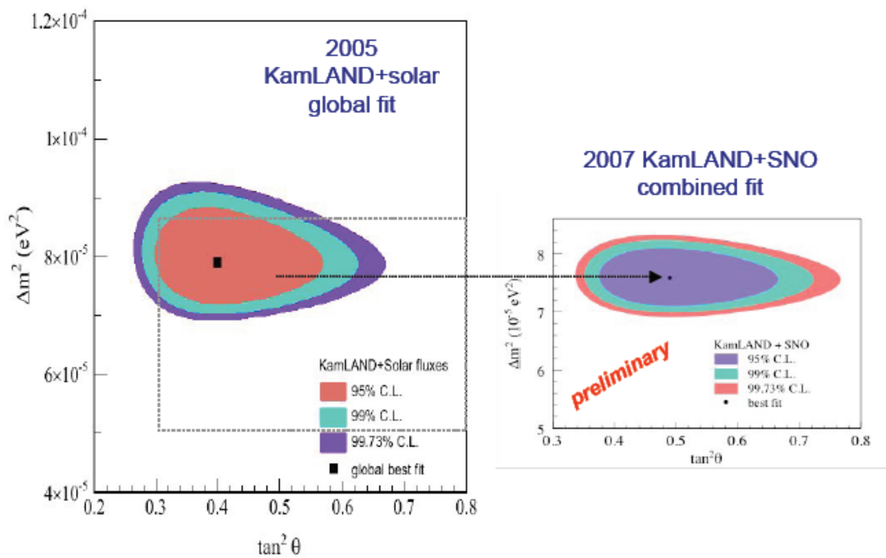
Alternate Hypotheses Disfavored at > 3σ

Best-Fit Decay: χ^2/dof = 46.53/16 (3.9σ)

Best-Fit Decoherence χ^2/dof = 55.18/16 (4.6σ)



L_0 = 180km flux-weighted average reactor distance



vews to come : What will they tell us in the Near Future?

What is the value of the "third" mixing angle (the other two indicate nearly maximal mixing, the limit for the third indicates a pretty low value…) (Reactor experiments, NOVA, T2K)

- Is there CP violation in the neutrino sector ?? (which might explain why we are here !!!) (NoVA + T2K)

Are there sterile neutrinos??? (MiniBoone) ✓

What is after all, the neutrino MASS?? (absolute value not mass squared difference) (kinematics of beta decay)

?? **Cross Mixing**

Atmospheric | Cross Mixing | Solar | 0νββ decays | Majorana phases

$$U=\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & -s_{23}\\ 0 & s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & -s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ s_{13}e^{-i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{ia_1/2} & 0 & 0\\ 0 & e^{ia_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}$$

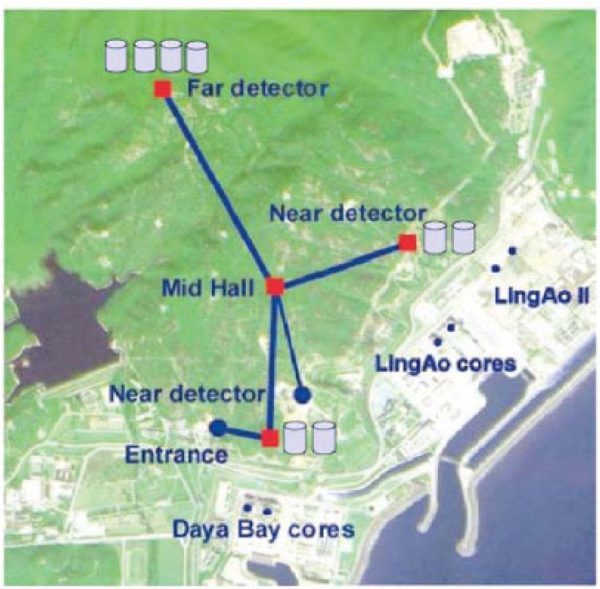
- Do "man made" ν_μ's oscillate? ✓
- What is "precisely" the mass squared difference and the mixing angle? (K2K -MINOS)

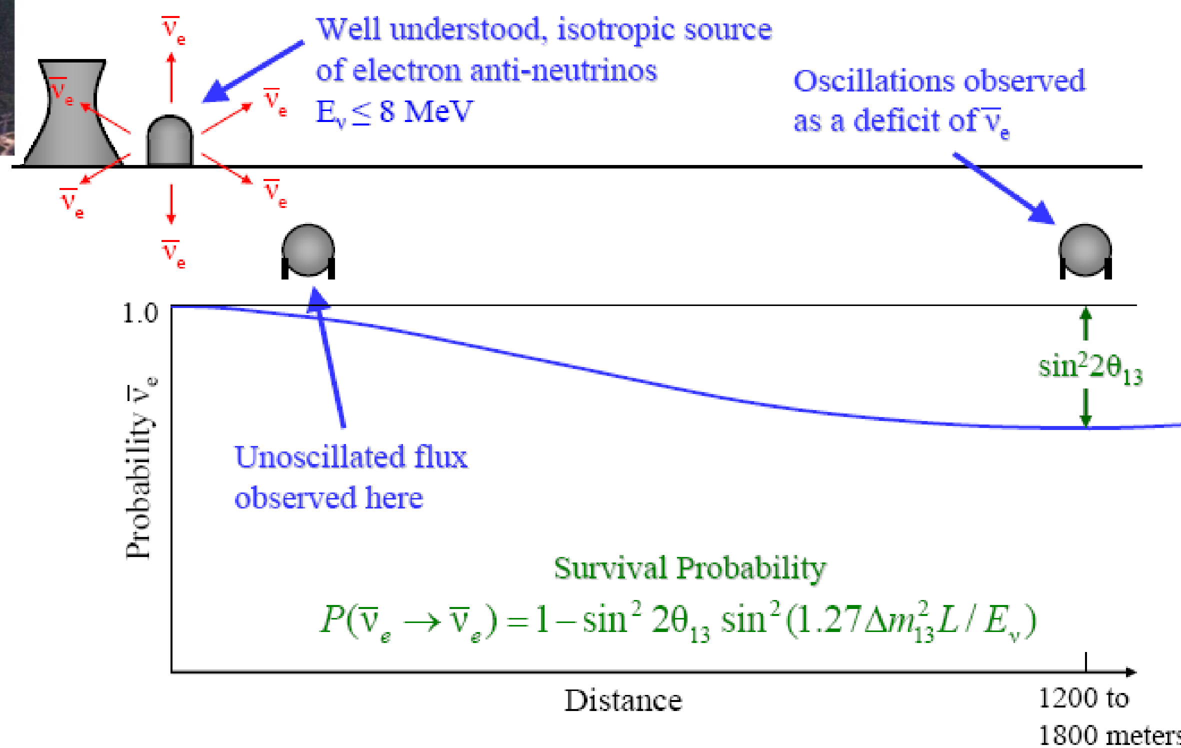
DO NOT FORGET
Which is the heaviest one? (NOVA, T2K)

- Are neutrinos and anti neutrinos the same ?? (Majorana particles) (neutrino-less double beta decays)

Future Reactor Experiments :
Double CHOOZ & Daya Bay
Hunt for a non-zero θ_{13} "cleanly"

If $\sin^2(2\theta_{13})$ > ~ 0.02 we will know by ~ 2012





Why use accelerator νews to study ν_μ oscillations??

Atmospheric neutrinos

- ➔ Very wide neutrino flight length
- ➔ Wide neutrino energy
- ➔ Mixture of ν_μ, anti-ν_μ, ν_e and anti-ν_e

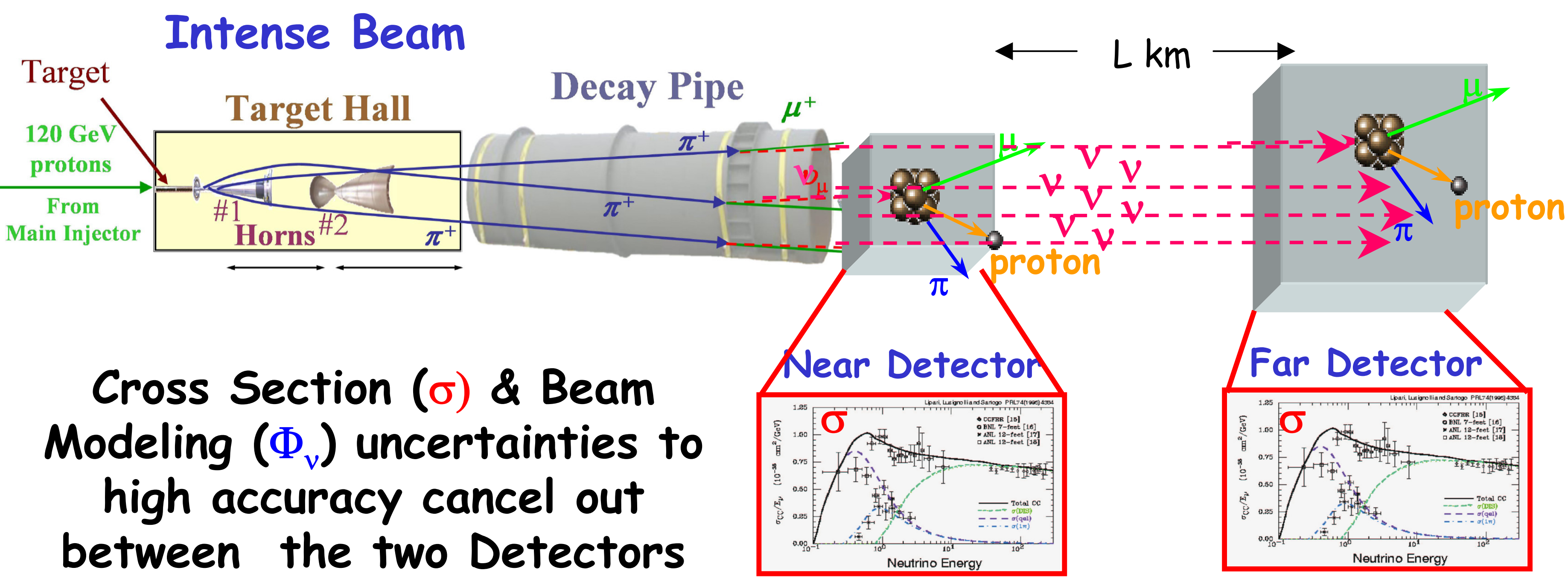
Long baseline Experiments

- ➔ Single flight length
- ➔ Controlled neutrino energy
- ➔ almost pure ν_μ (or anti-ν_μ)

Initial discovery ➔ *Precise studies*

Basic Idea of accelerator ν oscillation two-detector experiments

Basic Idea : 2 detectors "identical" in all their important features.



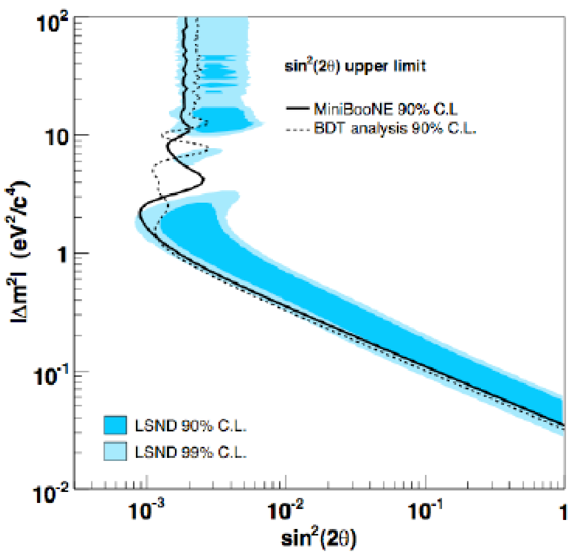
Cross Section (σ) & Beam Modeling (Φ_ν) uncertainties to high accuracy cancel out between the two Detectors

$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$

Impressive Results (2007) from an Accelerator ν oscillation Experiment with "just one" detector : MiniBooNE

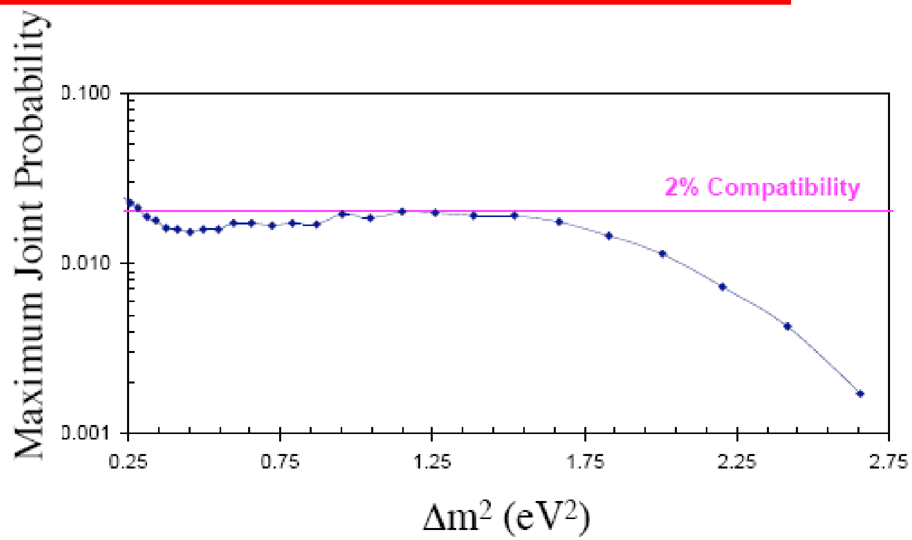
Long Standing LNSD "anomaly" solved (at least as an interpretation of muon neutrino to electron neutrino oscillations)

Boosted Decision Tree analysis shows no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.



Energy-fit analysis:
solid: TB
dashed: BDT

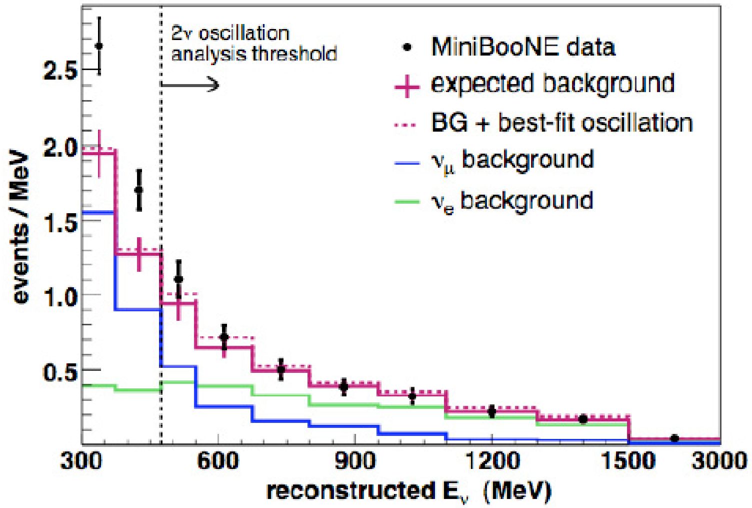
Independent analyses are in good agreement.



MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance only interpretation of LSND at 98% CL

MiniBooNE : Outlook

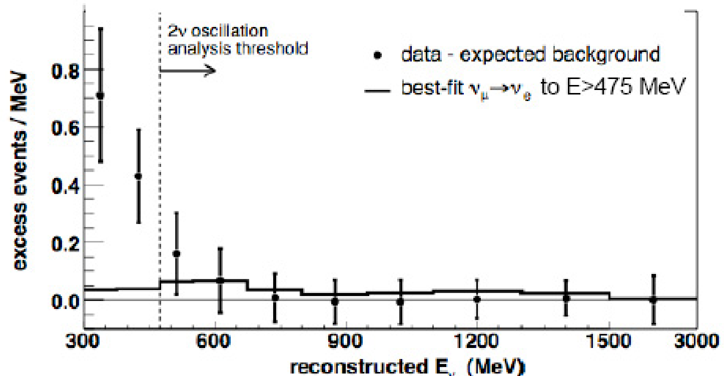
As planned before opening the box....
Report the full range:
$300 < E_\nu^{QE} < 3000$ MeV



$96 \pm 17 \pm 20$ events above background, for $300 < E_\nu^{QE} < 475$MeV

Deviation: 3.7σ

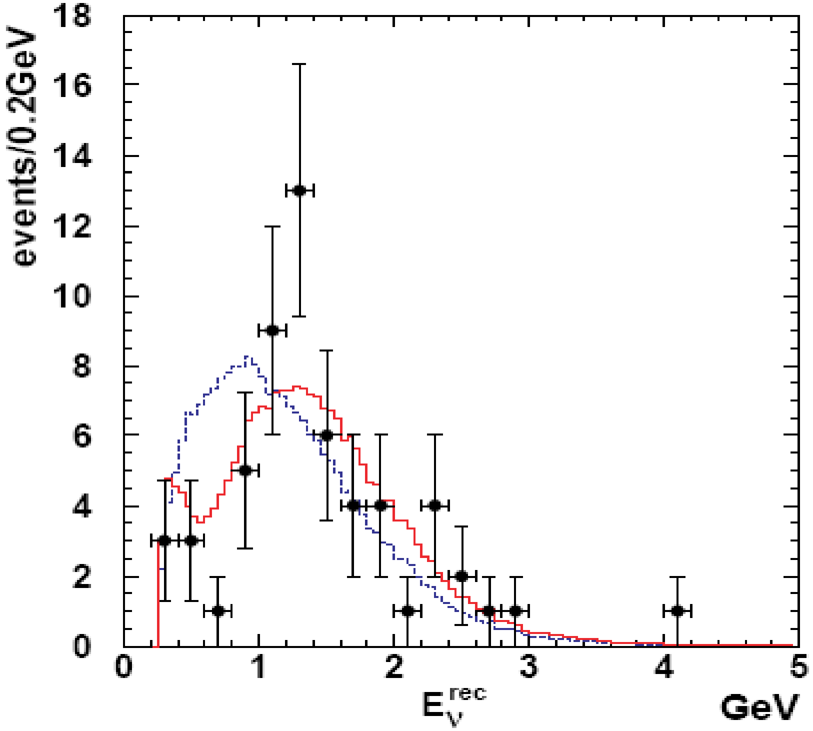
Background-subtracted:



- Further investigation of the "low energy excess"
- Further analysis of neutrino data including exotic models for the LSND effect
- Anti-neutrino data taking mode has started

K2K: 1st Long-baseline Accelerator-based Experiment

Goal was to confirm SuperK result with accelerator muon neutrinos

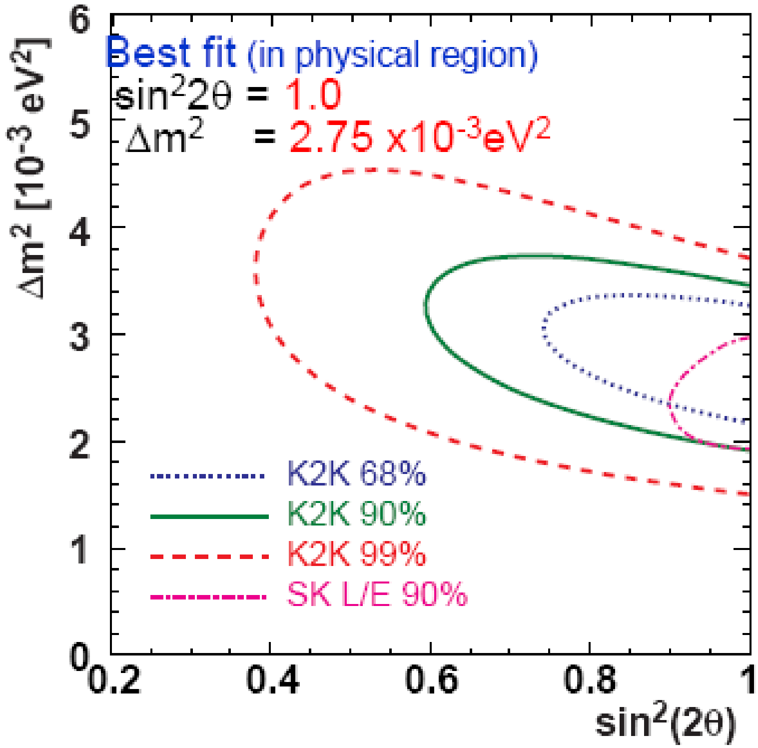


Phys.Rev.D 74, 072003,2006

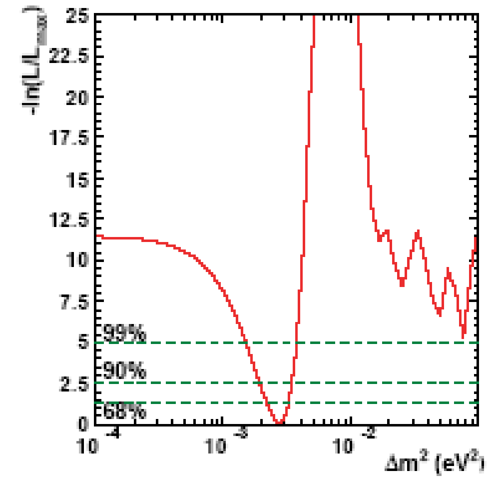
K2K I+II	DATA	MC
FC : 22.5 kt	112	$158.1^{+9.2}_{-8.6}$
1-ring	67	
e-like	9	
μ-like	58	
Multi-ring	45	

K2K: 1st Long-baseline Accelerator-based Experiment con'd

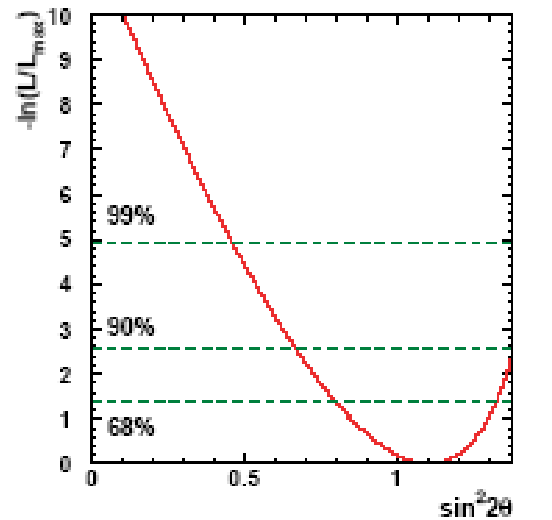
Based on Number of events + Spectrum shape



Δlikelihood @ $\sin^2 2\theta=1.0$

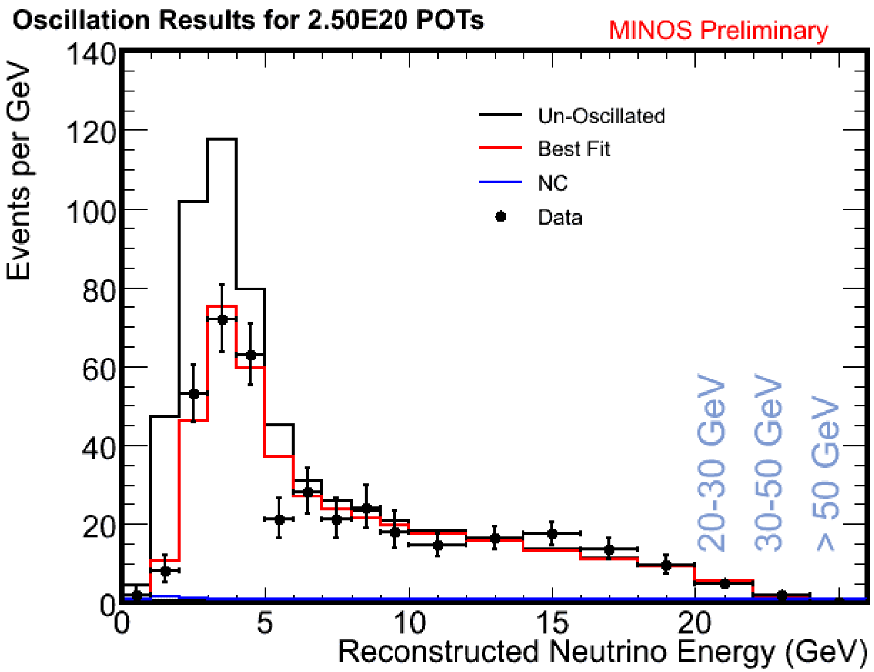


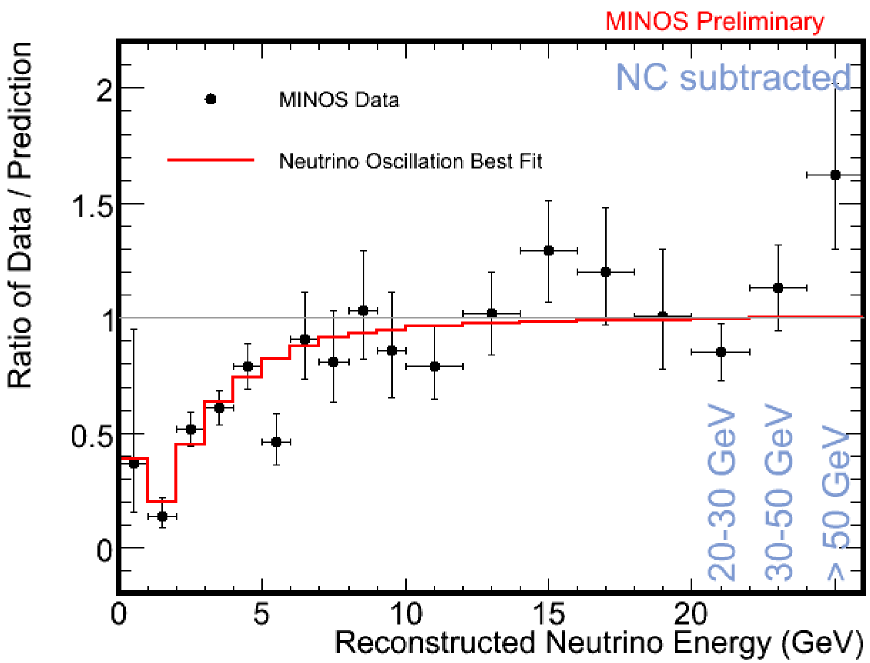
Δlikelihood @ $\Delta m^2=2.8\times10^{-3}$



Phys.Rev.D 74, 072003,2006

MINOS 2007 Results: Best Fit Spectrum





Oscillation Hypothesis best fit

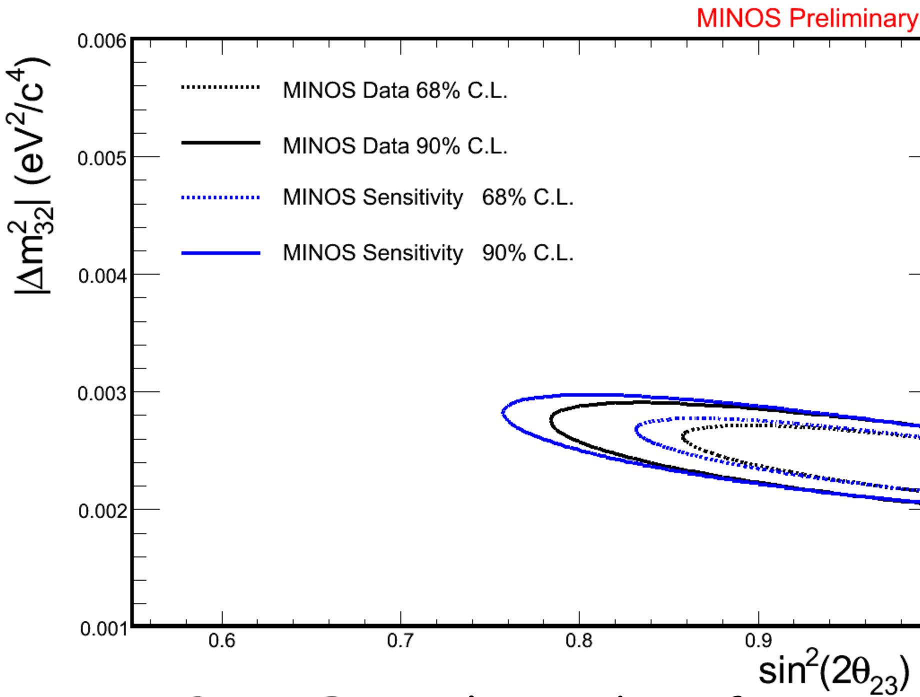
χ^2 /n.d.f = 41.2/34 = 1.2 P(χ^2,n.d.f) = 0.18

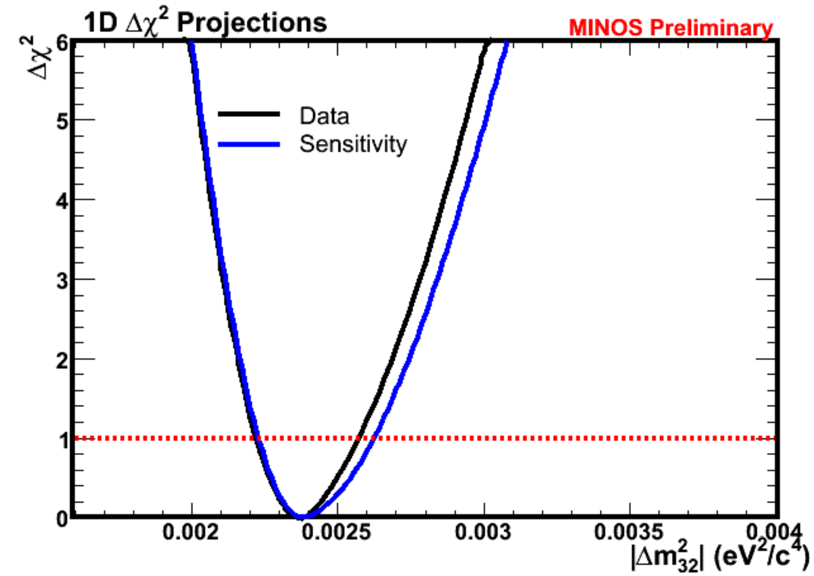
No Disappearance Hypothesis

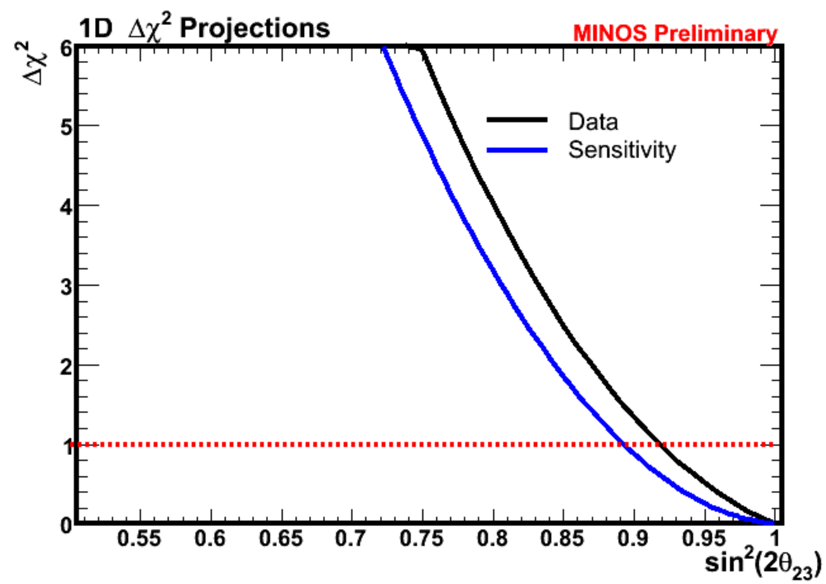
χ^2 /n.d.f = 139.2/36 =3.9 P(χ^2,n.d.f) is negligible

- Strong energy-dependent suppression of ν_μ events observed.
- Consistent with the neutrino oscillation hypothesis.

MINOS 2007 Result : Allowed Region







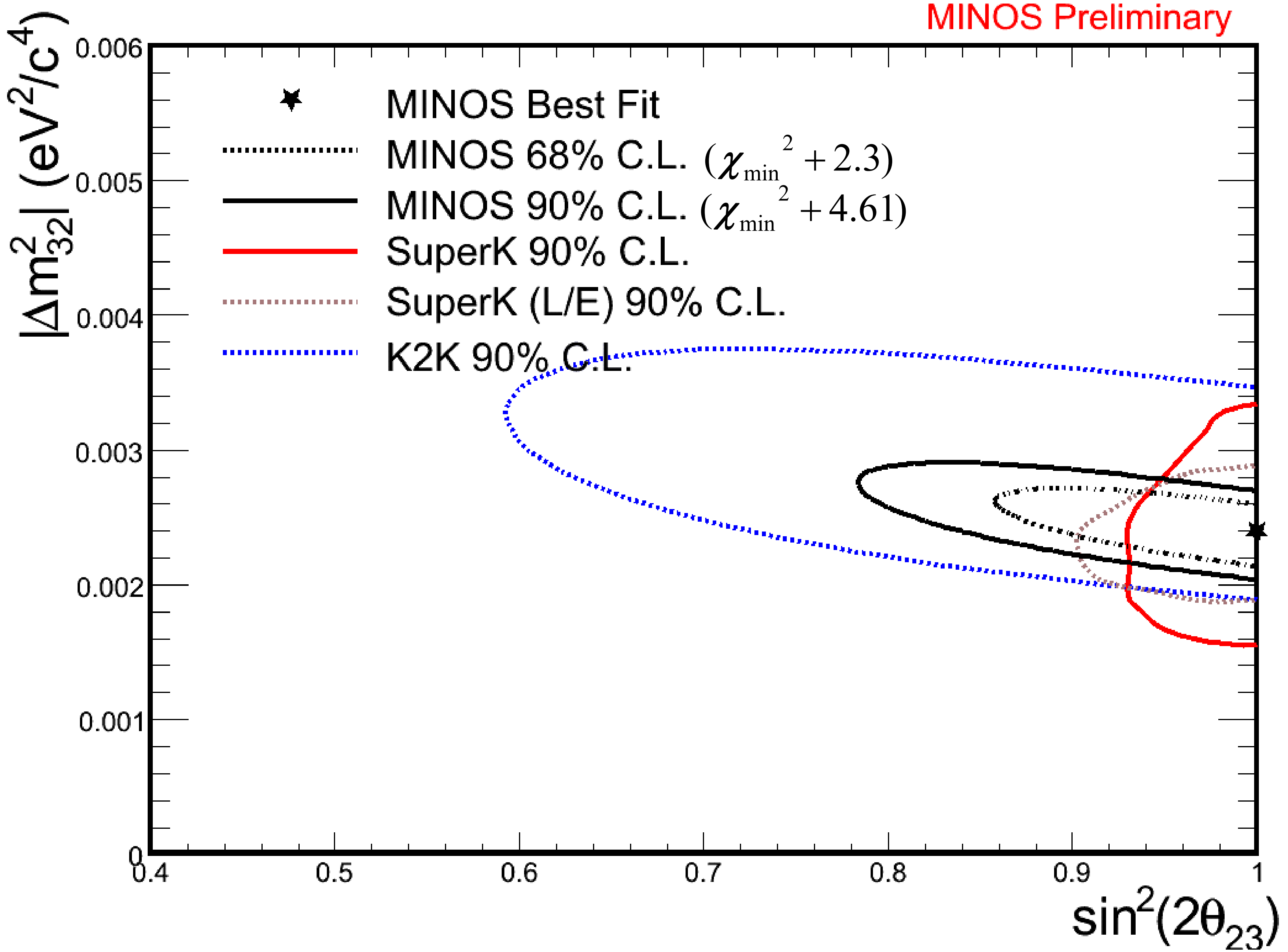
Best Fit Values when fit Constrained to the Physical Region

$$|\Delta m_{32}{}^2| = 0.00238^{+0.00020}_{-0.00016}\ \text{eV}^2/\text{c}^4$$

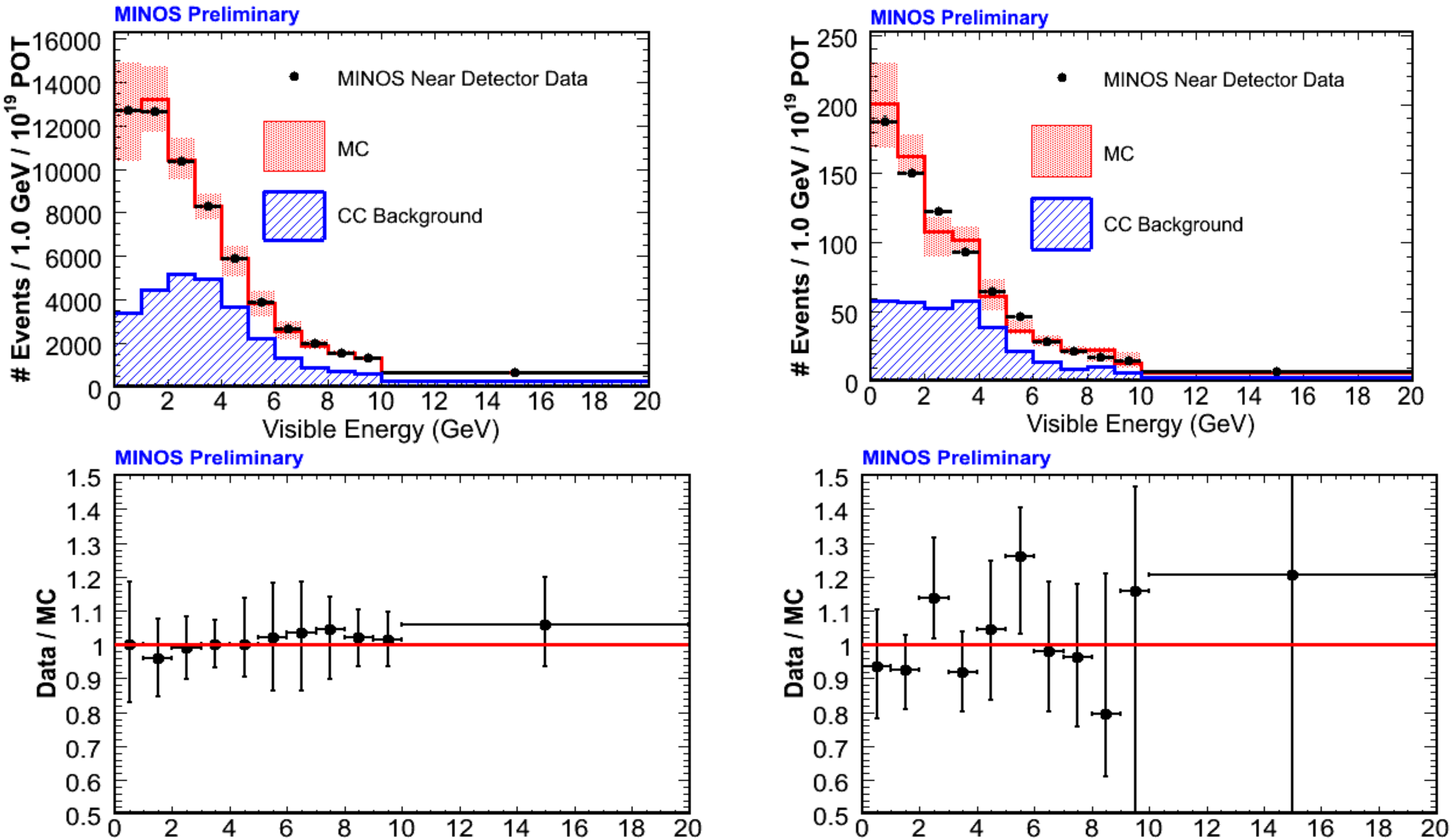
$$\sin^2(2\theta_{23}) = 1.00_{-0.08}$$

$$\chi^2/\text{n.d.f} = 41.2/34 = 1.2$$

MINOS-SuperK-K2K Allowed Region

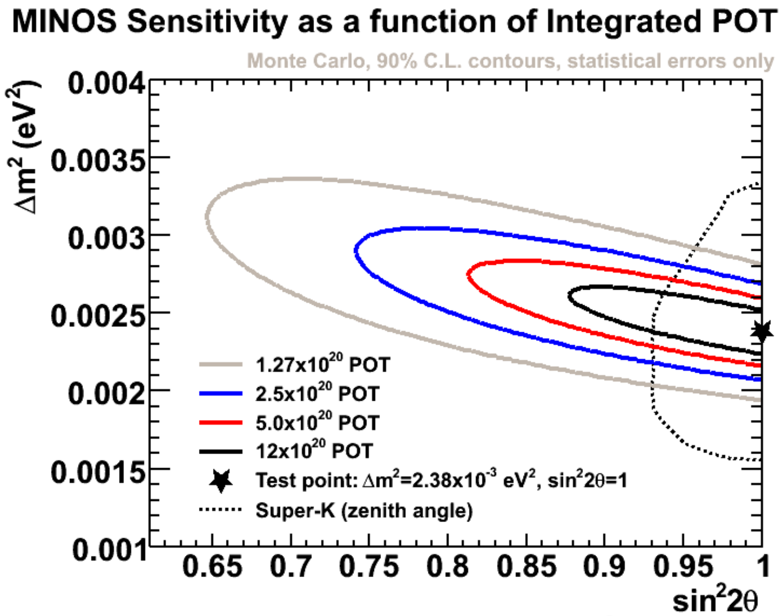


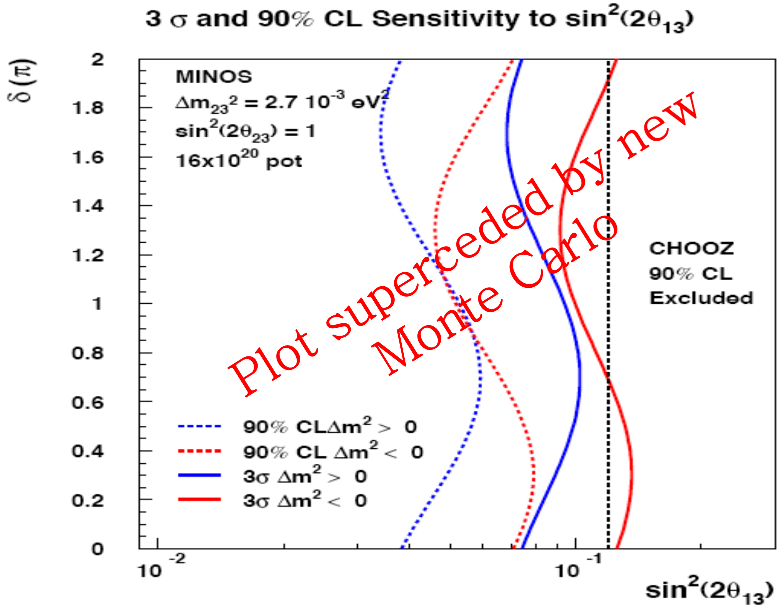
MINOS Neutral Current Analysis : Near Detector NC-like Spectrum cont'd



- MC error band includes contributions from beam, cross-section and energy scale uncertainties
- Both methods (high and low multiplicity data cleaning) give results consistent with each other and with expectations.

MINOS Outlook

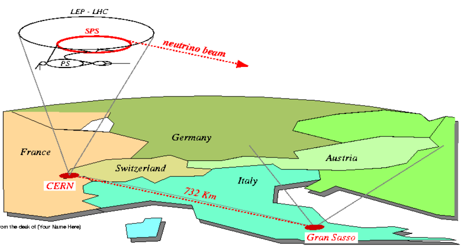


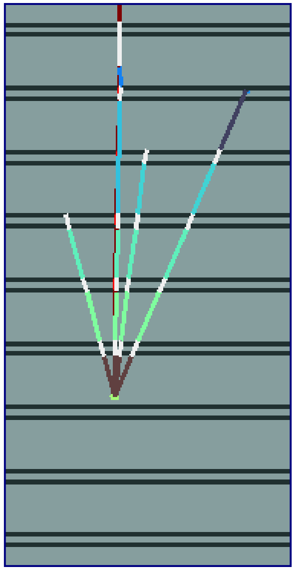


- Muon neutrino disappearance
  - 6e20 pots by the end 2008
- Electron neutrino appearance by 2008
- Anti-neutrino oscillations
  - in neutrino beam
  - anti-ν running > 09
- Search for exotics
  - Sterile neutrinos (NC analysis box opening SOON!)
  - Neutrino decay/decoherence

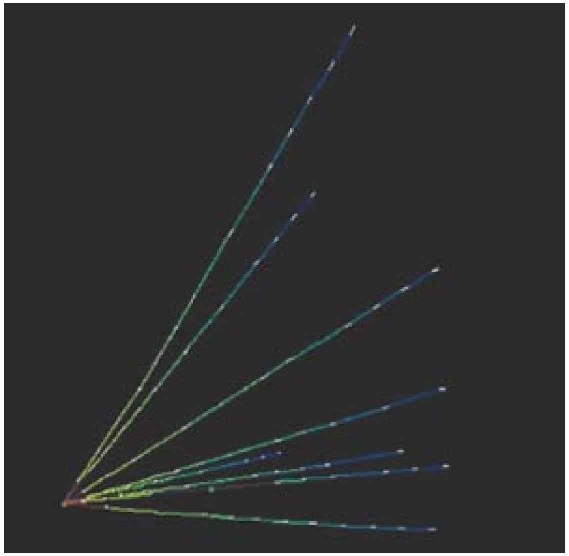
Is it really $\nu_\mu \rightarrow \nu_\tau$?
Ideal/direct confirmation would come from observing the ν_τ …: OPERA

CERN to Gran Sasso Neutrino Beam



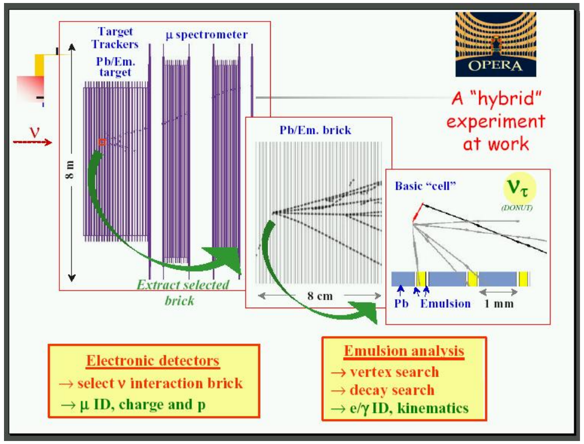


ν_μ interaction vertex from test exposure at NuMI beam (FERMILAB):



October 2 2007 : First neutrino interaction in the emulsion bricks of the OPERA Experiment! (Many more recorded since then)

Emulsion Cloud Chamber



Physics goals:

- Verify oscillation of ν_μ **is to** ν_τ
- Search for ν_e appearance

CNGS L/E = 0.04km/MeV (17GeV E_ν)

12 events expected, 1 bkg, after 5 yrs

Turned on Sep. of 2007 50-60kbricks

Full compliment March 08

Are there more questions to answer??

What is the value of the "third" mixing angle (the other two indicate nearly maximal mixing, the limit for the third indicates a pretty low value...) (Reactor experiments, NOVA, T2K)

- Is there CP violation in the neutrino sector ?? (which might explain why we are here !!!) (NoVA + T2k)

Are there sterile neutrinos??? (MiniBoone) ✔

What is after all, the neutrino MASS?? (absolute value not mass squared difference) (kinematics of beta decay)

Atmospheric | ?? Cross Mixing | Solar | $0\nu\beta\beta$ decays

$$U=\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & -s_{23}\\ 0 & s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & -s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ s_{13}e^{-i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{ia_1/2} & 0 & 0\\ 0 & e^{ia_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}$$

Majorana phases

✔ Do "man made" ν_μ's oscillate?

- What is "precisely" the mass squared difference and the mixing angle? (K2K - MINOS)

DO NOT FORGET

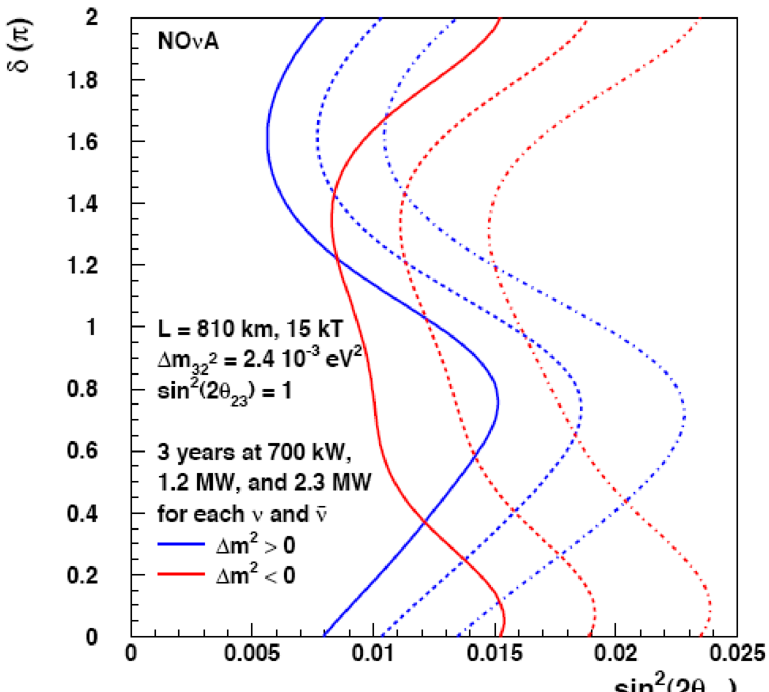
Which is the heaviest one? (NOvA, T2K)

- Are neutrinos and anti neutrinos the same ?? (Majorana particles) (neutrino-less double beta decays)

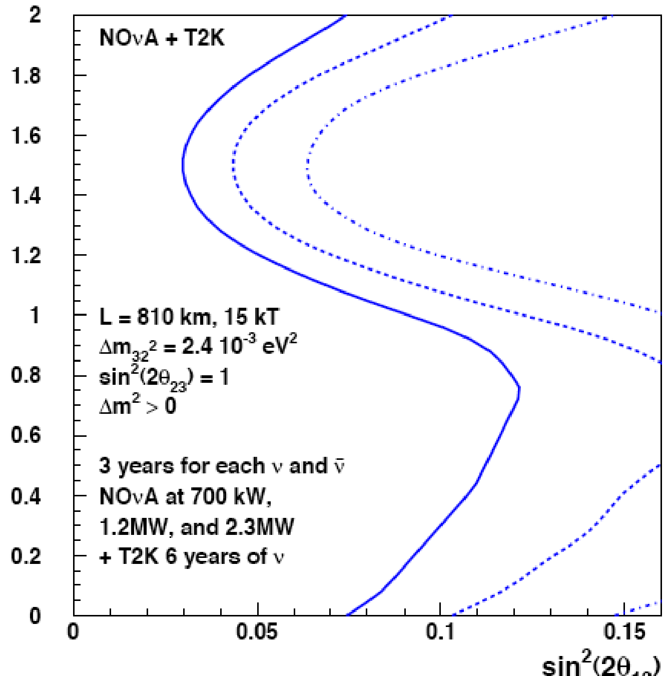
Hunt for a non-zero θ_{13} (+more): PHASE I

Accelerator Experiments : NOνA & T2K

3 σ Sensitivity to $\sin^2(2\theta_{13}) \neq 0$



95% CL Resolution of the Mass Ordering

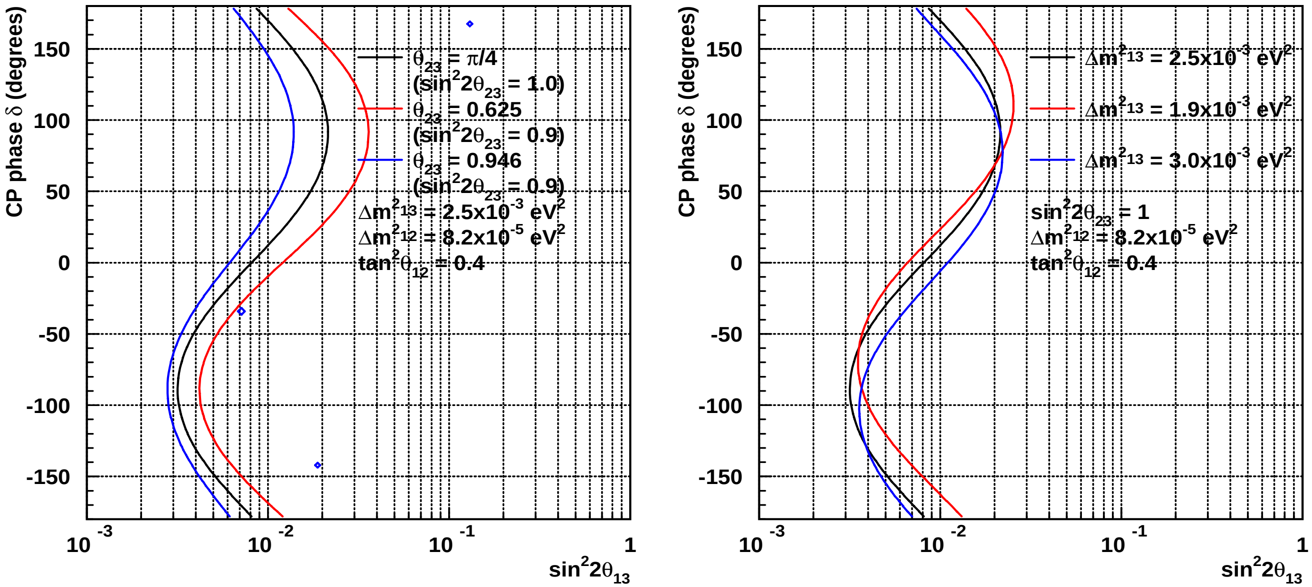


The NOνA far detector will be a 15 kT "totally active" liquid scintillator detector, located 15 mrad (12 km) **off the NuMI beamline axis** near Ash River, MN, 810 km from Fermilab

Depending on the value of the third mixing angle NOνA could determine the neutrino mass hierarchy (normal or inverted)

Hunt for a non-zero θ_{13} (+more): PHASE I

Accelerator Experiments : NOνA & T2K (Japan)



Plot from I. Kato/T2K

The T2K far detector will be a 50 kt Water Cerenkov detector, located ~2.5^0 **off axis (JHF beam), 300km away in the same mine as SuperK.**

T2K , due to the sorter baseline has no sensitivity to the mass hierarchy, and has sensitivity to CP violation if run with antineutrinos

NOνA and T2K : Best Measurements and discovery potential will come from combination of T2K and NOνA.

Future ν Oscillation Experiments

- Phase II : Develop a Plan based on Phase I Results (Double CHOOZ, Daya Bay, T2K, NOvA will inform us of $\sin^2 2\theta_{13}$ down to ~0.02 by ~ 2012-2014).
- In the Future Long Baseline Neutrino Study (Joint Fermilab - BNL study) we explored indicative configurations of detectors (and detector masses), off axis and on-axis locations and protons on target (beam power). **We also explored capabilities using the 2.3 MW beam power of Project X**.
- Main options for Neutrino Beams are :

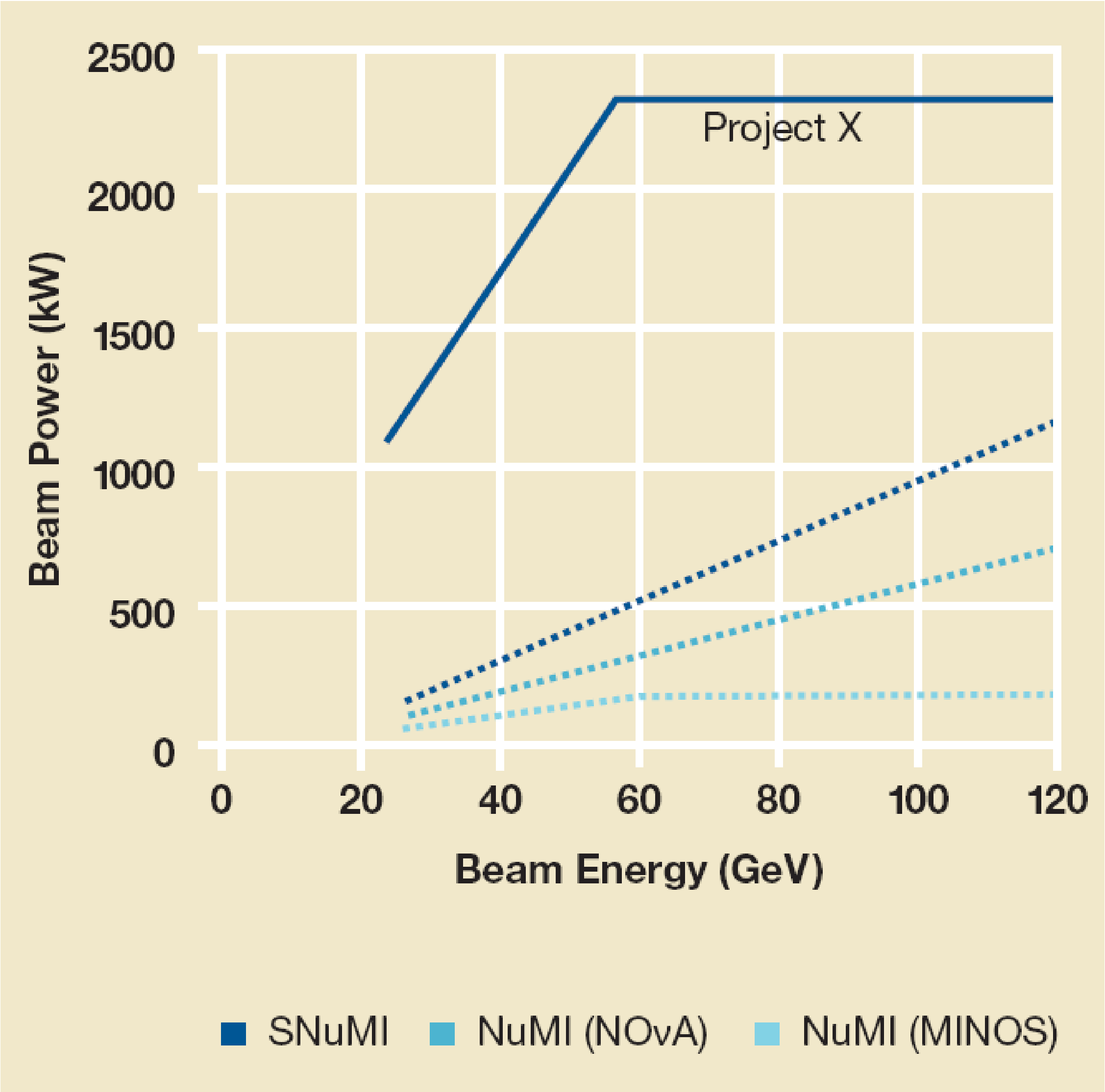
  Off Axis Beam . This is a Narrow Band Beam but if we choose to place **2 detectors @ different off axis angles we get an off -axis "Pseudo - Wide Band Beam"**

  Wide Band Neutrino Beam which gives the ability to study energy dependence on oscillation phenomena.

- Main options for Detectors are:

  Liquid Argon TPC **(~ 100 kton mass)**
  Water Cerenkov Detectors (~ 300 kton mass)

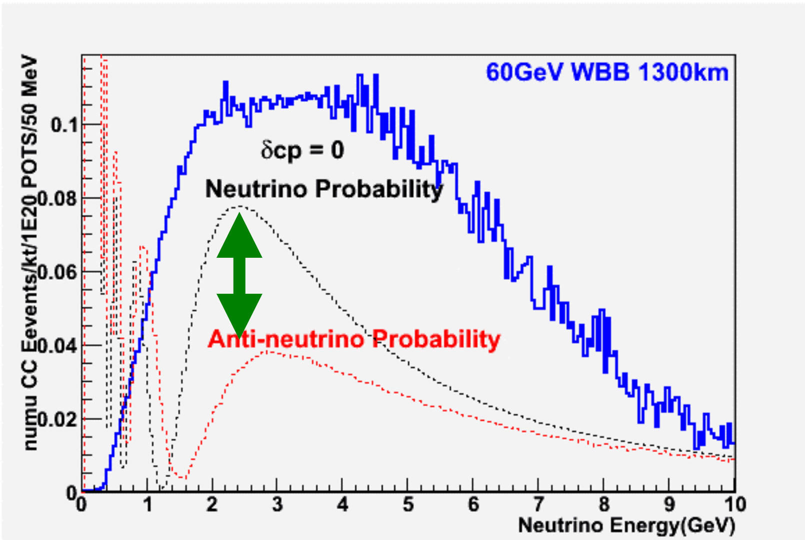
NuMI Neutrino Beam: Capabilities & Advantages

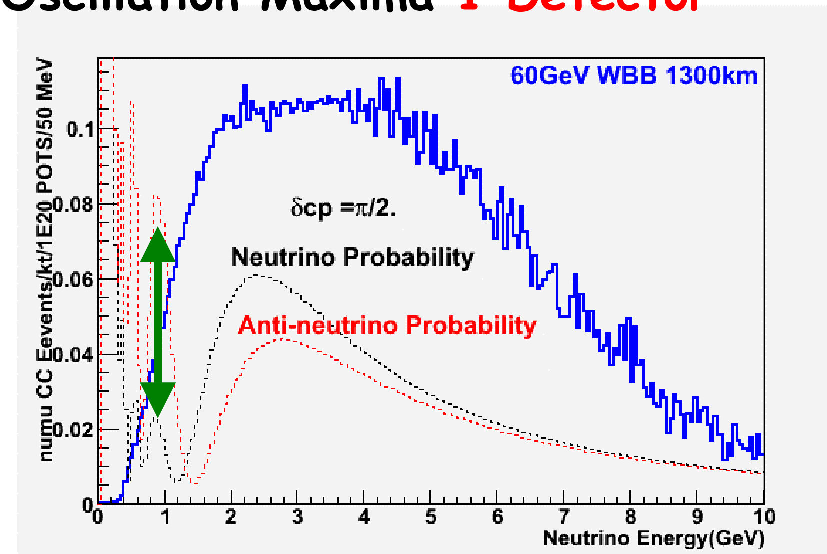


There exists a well defined upgrade plan for the NUMI Beam

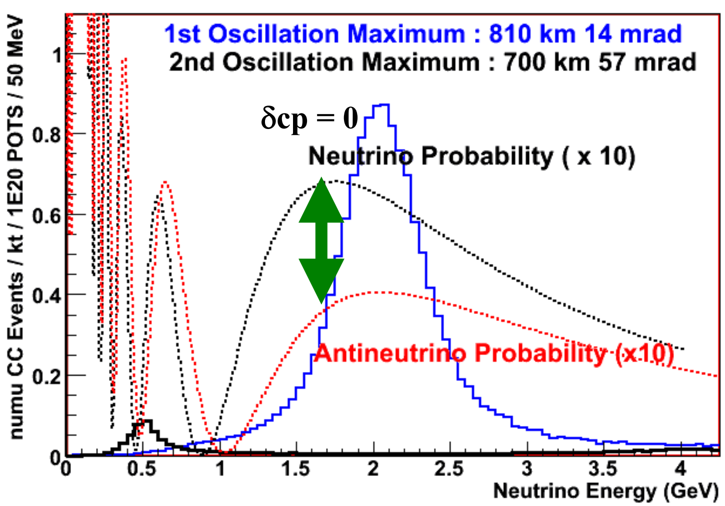
NUMI (off-axis) Beam, Fermilab WBB

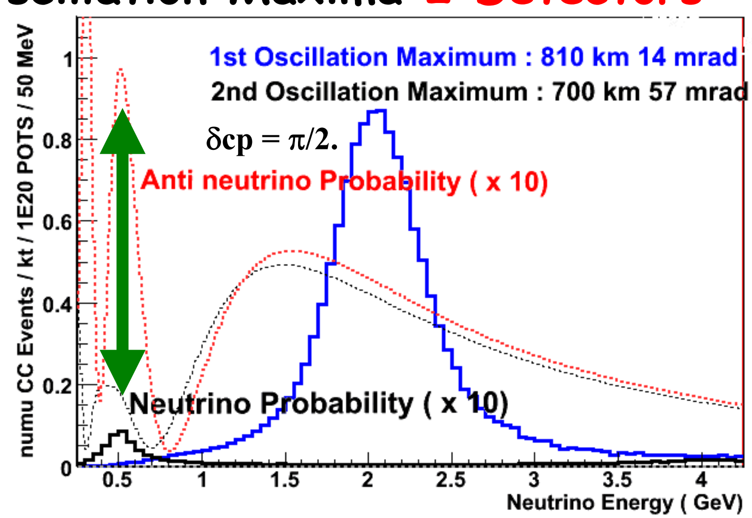
ON AXIS WBB : 1st and 2nd Oscillation Maxima 1 Detector





NUMI OFF AXIS : 1st and 2nd Oscillation Maxima 2 Detectors

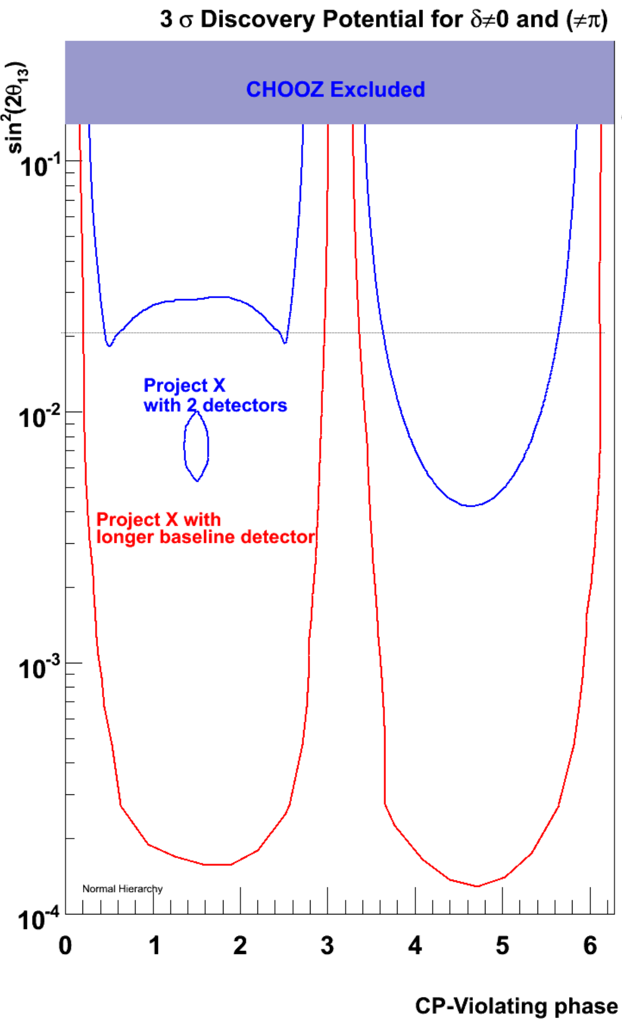


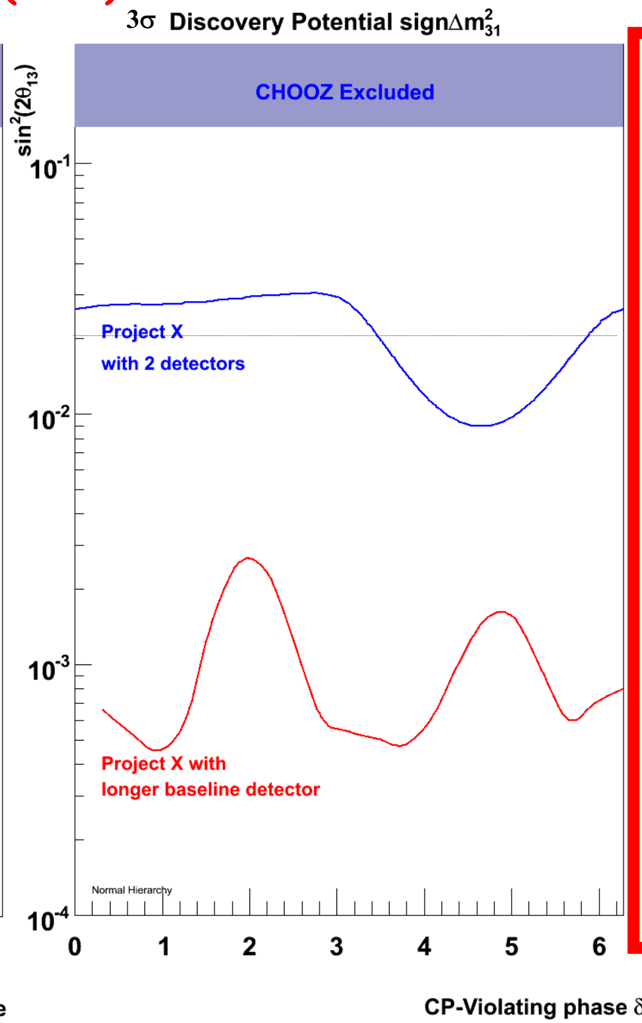


CP Violation and Neutrino Mass Hierarchy

Phase II with ProjectX

Same Detector (LAr) Different Beams





It all depends on the angle and the available Beam Power

For example if Project X is an option then:

If $\sin^2 2\theta_{13}$ > 0.02 Use NUMI Narrow Band Beam and upgraded detector (LAr)

If $\sin^2 2\theta_{13}$ < 0.02 Construct New Wide Band Beam and upgraded detector (LAr or Water Cerenkov) pointing to a detector at ~ 1300 km distance

W.Pauli
Nobel Prize 1945

But only the one who dare can win

Summary and Conclusions

- So far the behavior of the "little neutral one" has been full of many "big" surprises…
- Some of the questions in neutrino physics have been answered and are answered as we speak, but the remaining ones are more challenging.
- Running and future experiments worldwide aim to address many of these remaining important issues with respect to neutrino physics and neutrino oscillations.
- Stay tuned for the fascinating νews to come..

BACKUP SLIDES

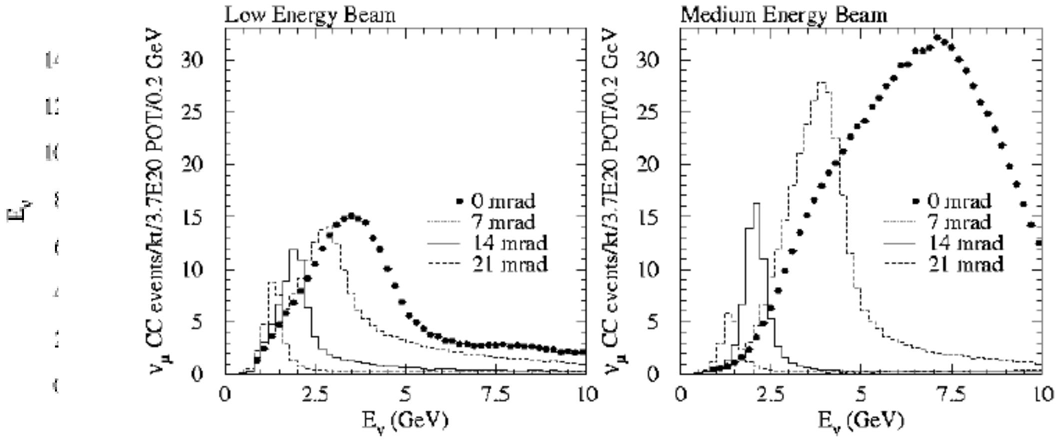
NuMI Neutrino Beam: Capabilities & Advantages

By using a conventional, albeit more intense, neutrino beam:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad < 1\% \nu_e$$

In an Off-Axis detector location

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

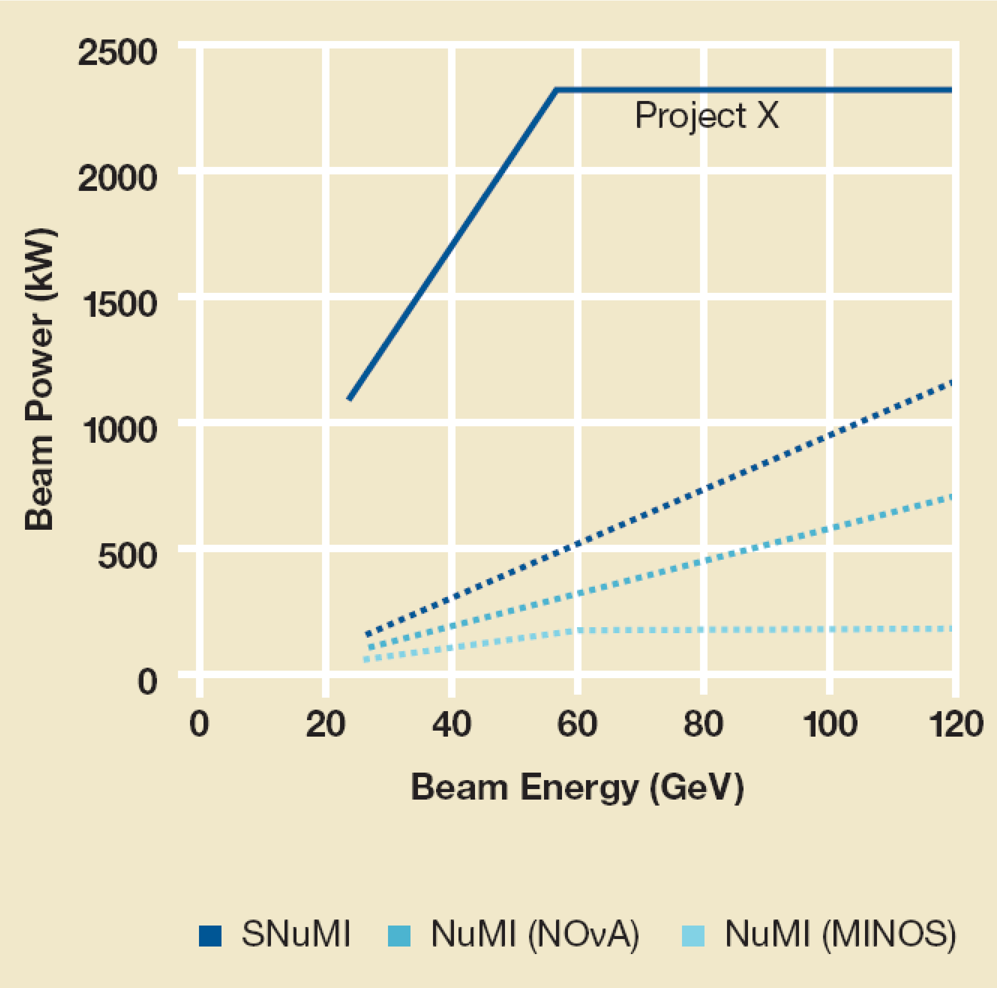


Advantages

- The Beam Exists and performs well (NUMI Beam took 6 years to be built and cost ~ 110M$)
- There is a well defined upgrade plan
- The off – axis idea of obtaining a NBB is attractive. It reduces the NC background resulting from high energy neutrinos.

Wide Band Neutrino Beam

: Capabilities & Advantages



- A wide band neutrino beam aimed at a longer baseline experiment has advantages we will discuss shortly.

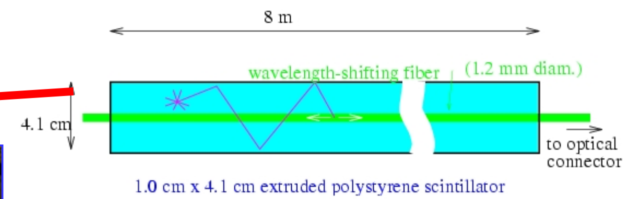
- This type of neutrino beam might require optimization at lower proton energies in order to reduce NC backgrounds (necessary depending on detector technology)

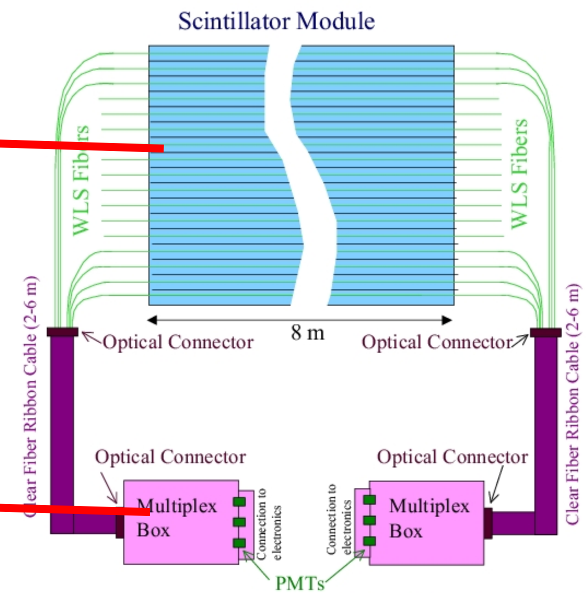
- Without Project X a wide band neutrino beam at <120 GeV proton power is not an option.

Detector Technology

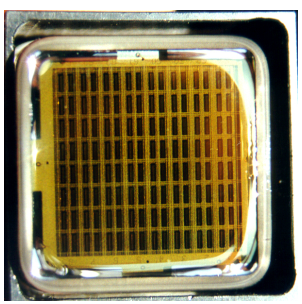
MINOS Near and Far detectors are functionally identical: share same detector technology and granularity:

Scintillator strip

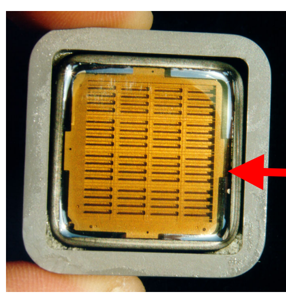




Objects not to scale

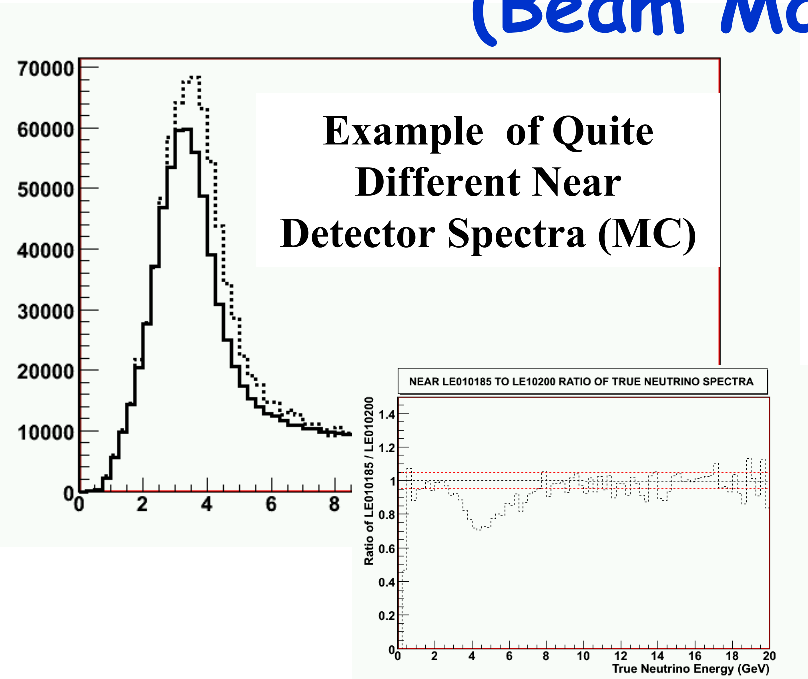


M64 PMT



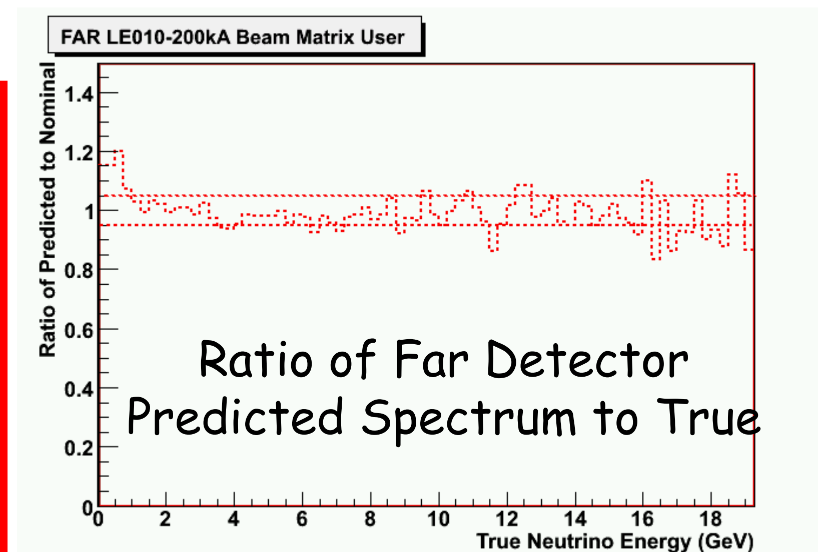
M16 PMT

Why Beam Modeling uncertainties Cancel (Beam Matrix Method)



Beam Matrices that correspond to quite different near detector spectra are very similar (spread in each column determined primarily by the geometry of the beamline)

NOTE :Red dotted bands are ± 5%.



Method: Use instead of LE010 185 kA Beam transfer Matrix the LE010 200kA Beam transfer Matrix

These different matrices correspond to quite different "beams" as evident from the Near Detector Spectra.

However, Far Detector Prediction is quite accurate to within < 5%

Why Cross Section Uncertainties Cancel (Beam Matrix Method)

ND Spectrum — **Beam Matrix** — **FD Spectrum**

$$\begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \times \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix}^{-1} \times \begin{pmatrix} b_1 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & b_3 \end{pmatrix} \times \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix} = \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix} \Rightarrow$$

ND Flux → **FD Flux**

Cross Section matrices & Beam Matrix almost diagonal=>They Commute!

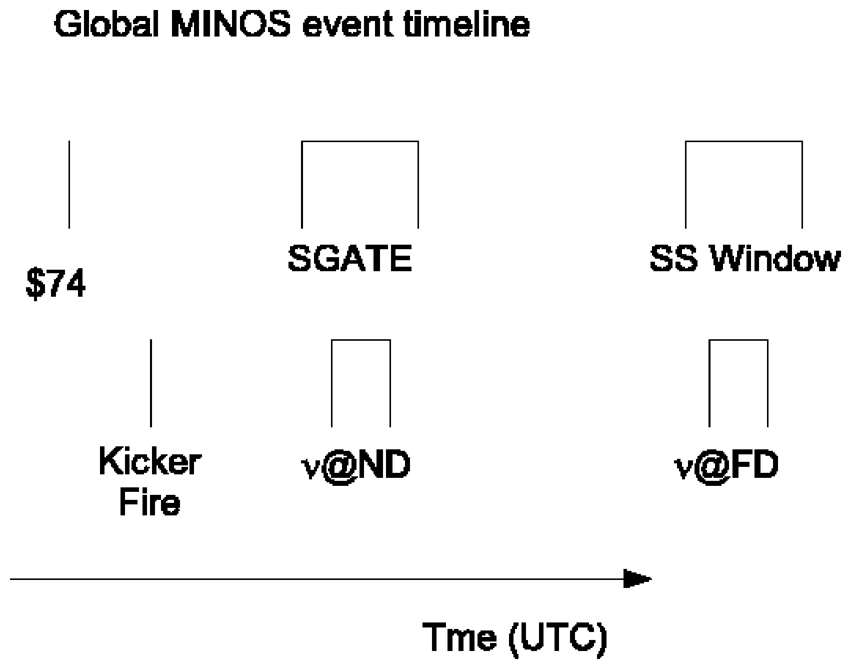
$$\Rightarrow \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} \times \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix}^{-1} \begin{pmatrix} \sigma_a & 0 & 0 \\ 0 & \sigma_b & 0 \\ 0 & 0 & \sigma_c \end{pmatrix} \begin{pmatrix} b_1 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & b_3 \end{pmatrix} = \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}$$

Their Product is I regardless of their values!

(In the limit where the Beam Matrix is diagonal)

Event catching: Timing and Triggering

- The elements of the timing system are as follows:
  - $74 signal from Main Injector – tells kicker magnet (which extracts protons to NuMI) that it is in the queue to fire (which it does ~220 us later).
  - $74 signal sent to clock controller at ND & a spill gate (SGATE) window is opened (in hardware) for 13us around the time neutrinos hit the ND (with an offset of –1.5us)
  - SpillServer process at FD informed when most recent spill occurred.
  - FD trigger farm queries SpillServer process every second. If a spill signal has been received and the Spill Trigger is enabled, the DAQ reads out 100us of previously buffered data around the predicted time that the neutrinos should have hit the FD



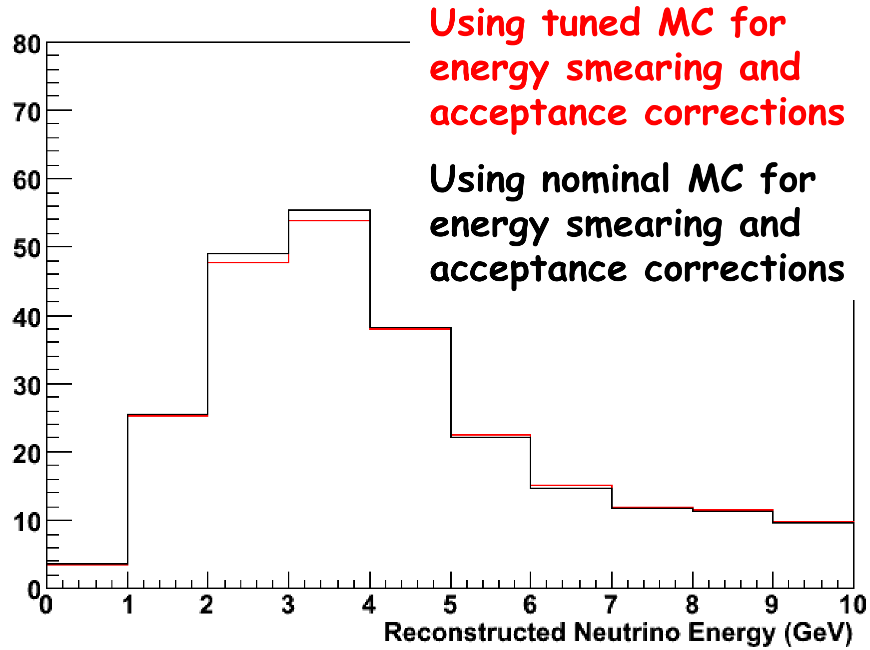
NuMI Alignment

Align the center of ν beam to the Far Detector in the Soudan mine. Goal is within 12 m.

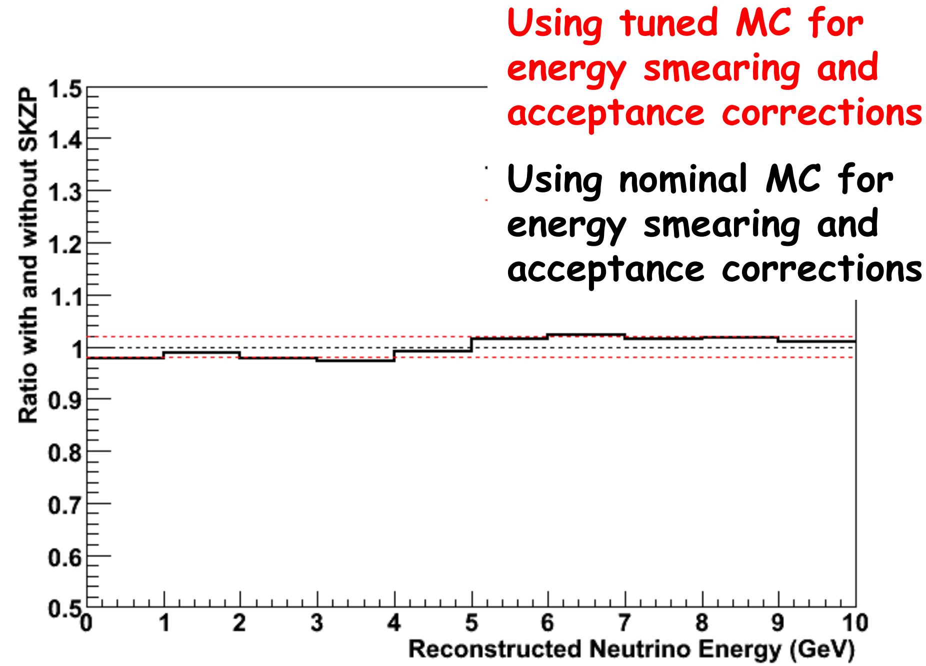
- Fermilab to Soudan surface done using GPS
  - determined vector to 0.01 m horiz., 0.06 m vertical
- Soudan surface to 27th level
  - 0.7 m per coordinate
- Fermilab surface to underground
  - gyrotheodolite with 0.015 mrad precision
  - 11 m at Soudan
- Transverse alignment of baffle, target and horn at 0.5 mm

Effect of MC tuning on the measurement

Far Predicted Spectra using the Beam Matrix and with/without hadron production tuning

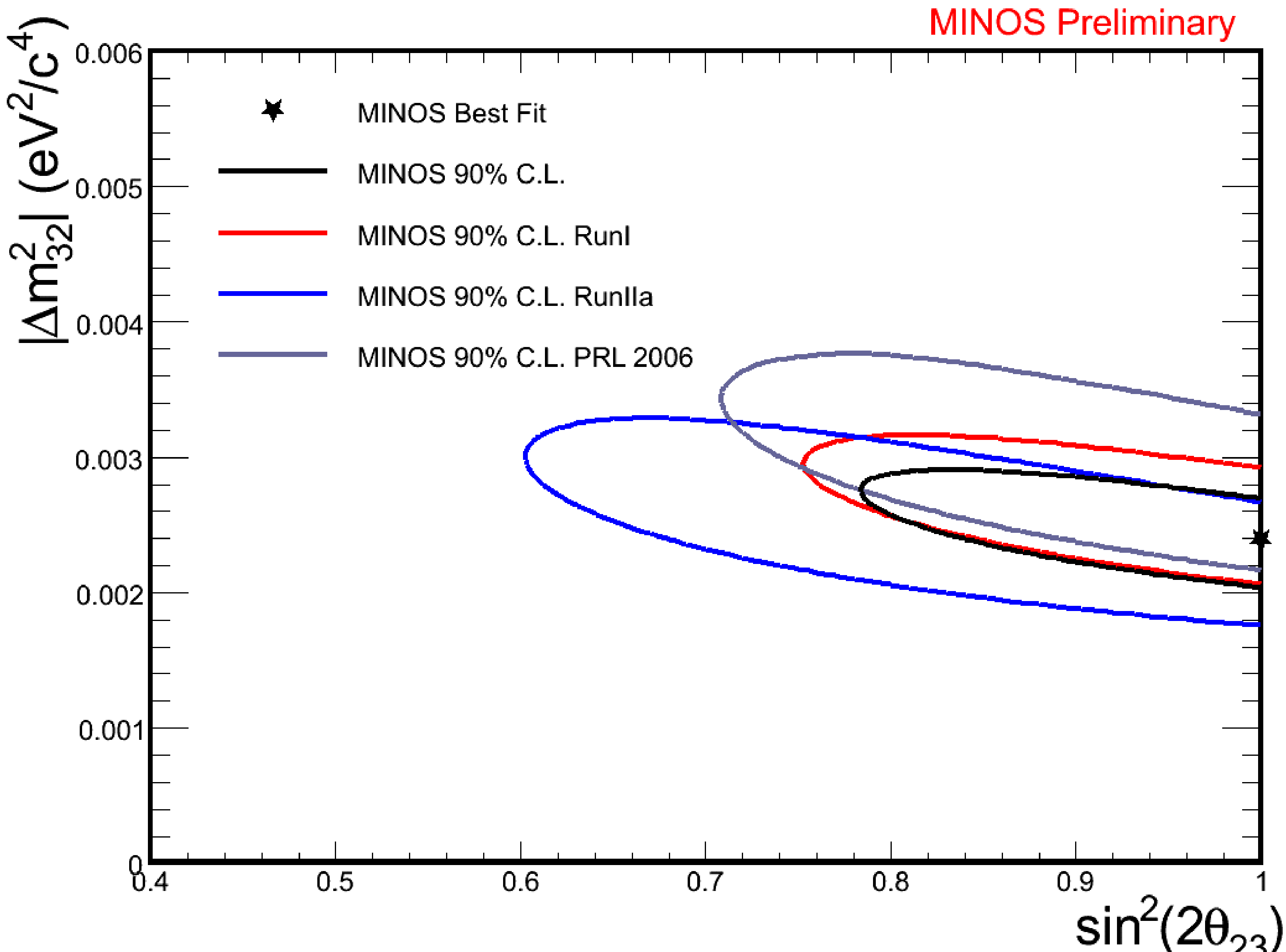


Ratio of Far Prediction using the Beam Matrix and with/without hadron production tuning

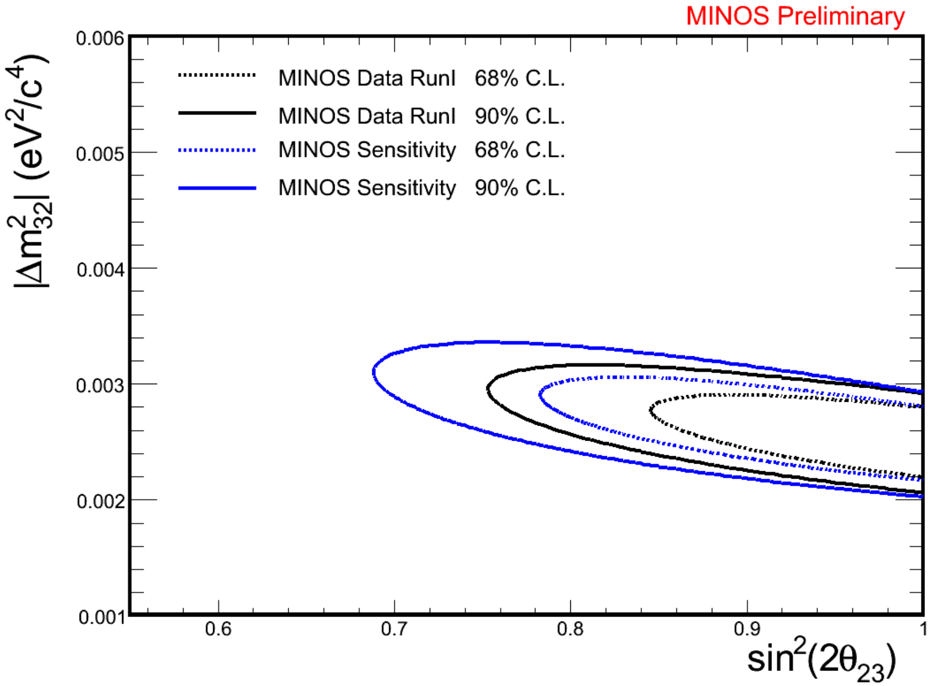


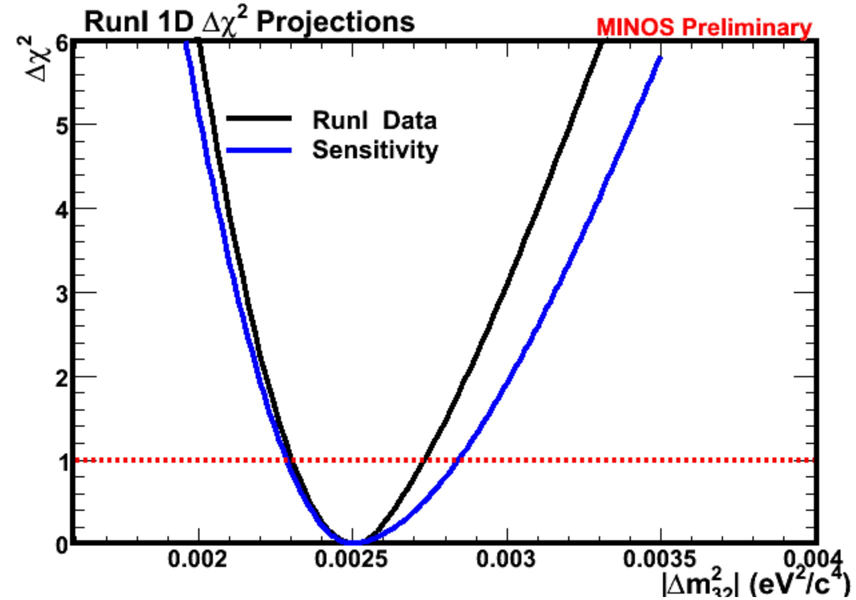
- Using Beam Matrix Method, hadron production tuning does not affect the Unoscillated prediction (obtained from the ND data) by more than 1-2%.
- However, its use improves the MC (make it more similar to the data) and therefore uncertainties due to energy smearing-unsmearing and acceptance become smaller.

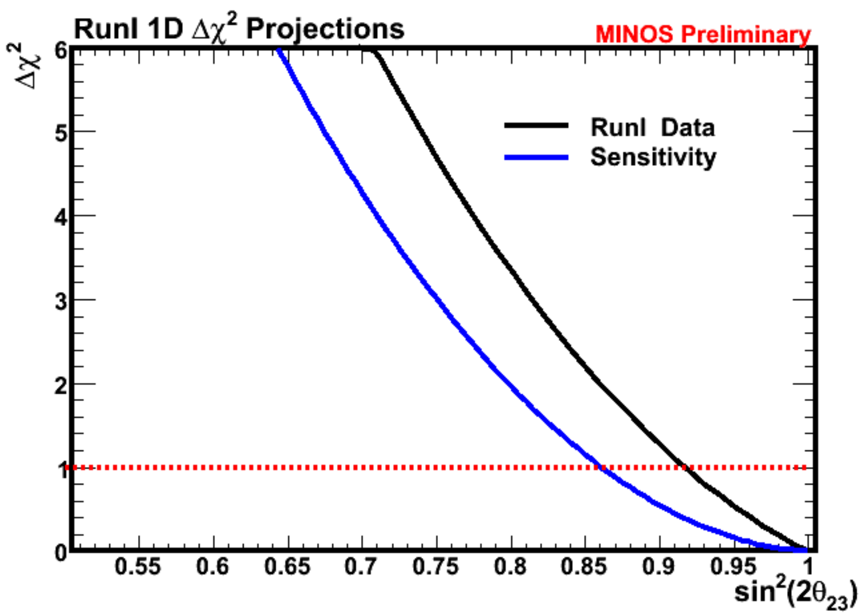
MINOS Data Samples



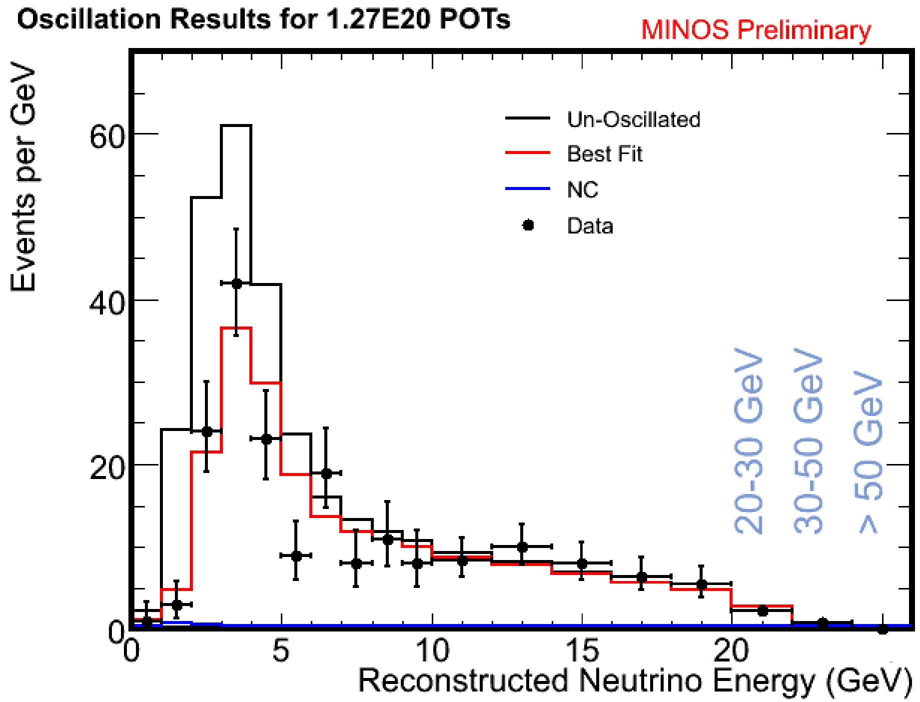
Beam Matrix Results RunI

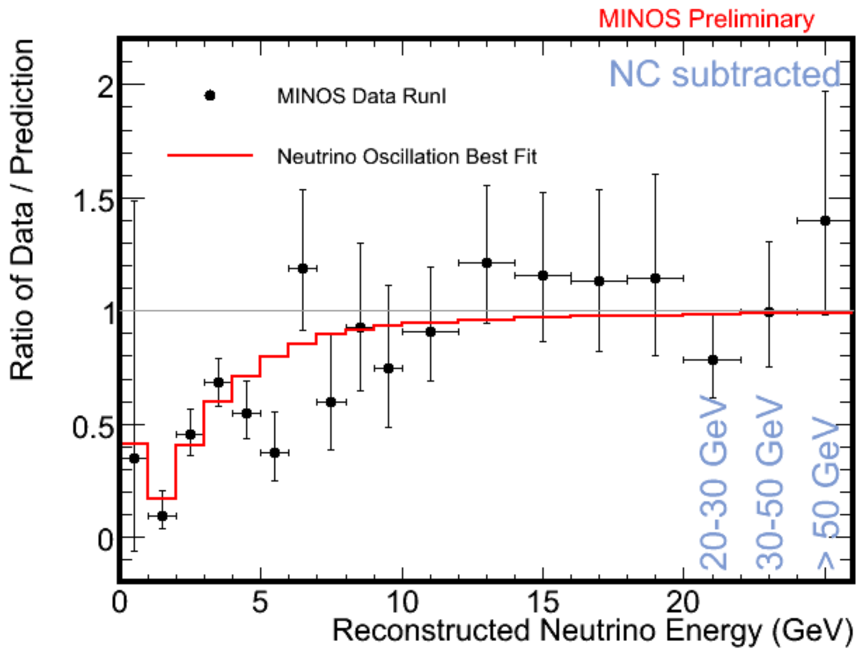




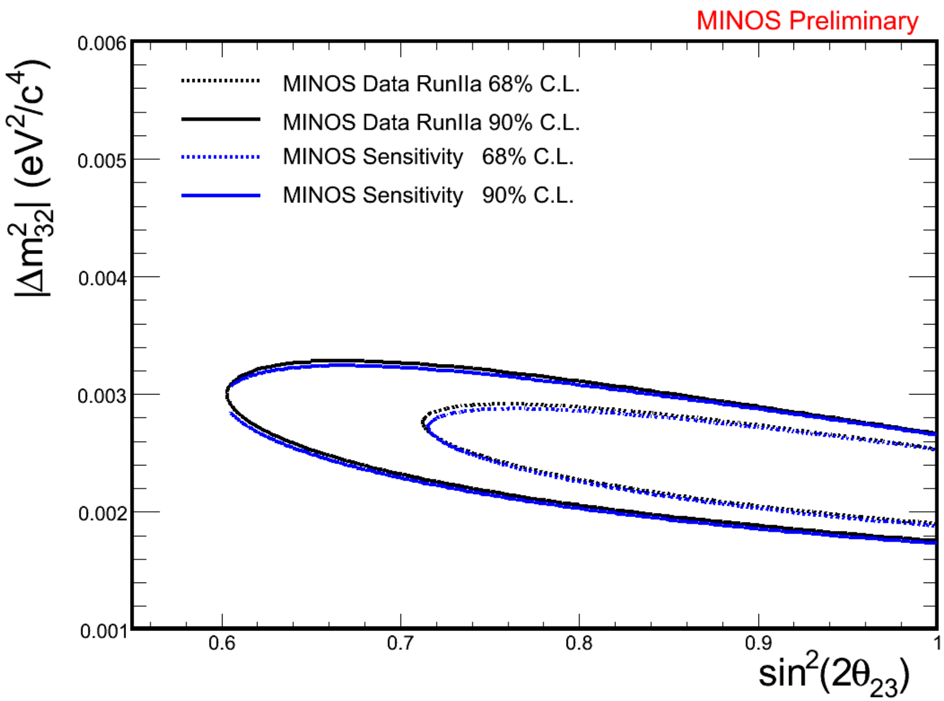


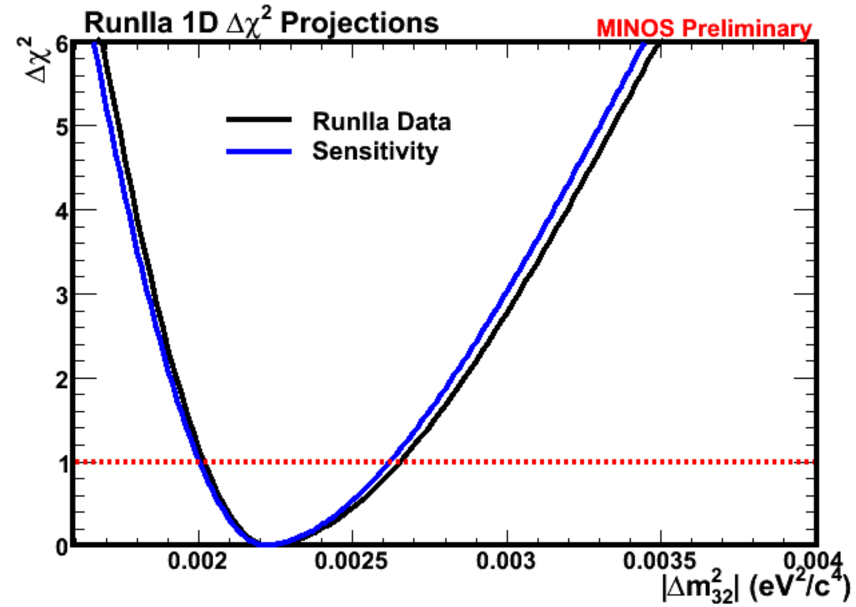
Beam Matrix Results RunI

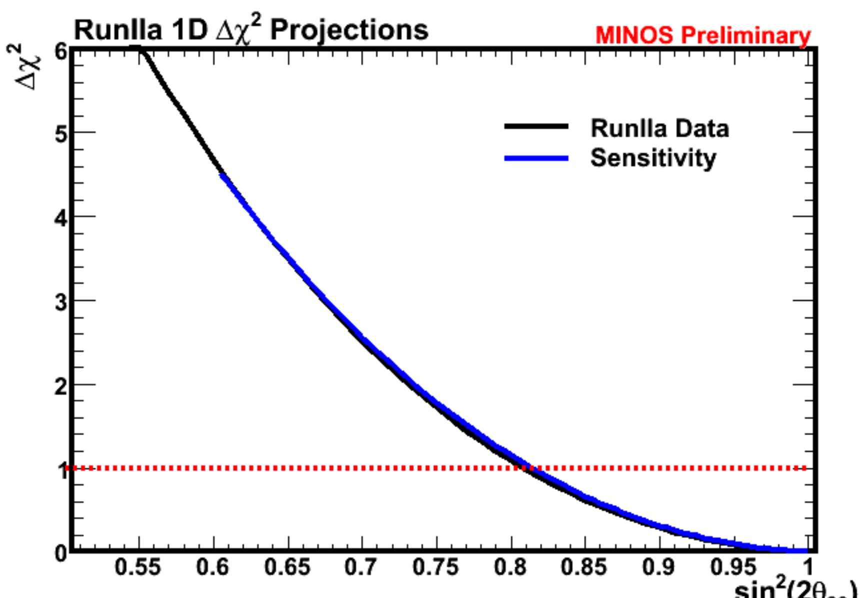




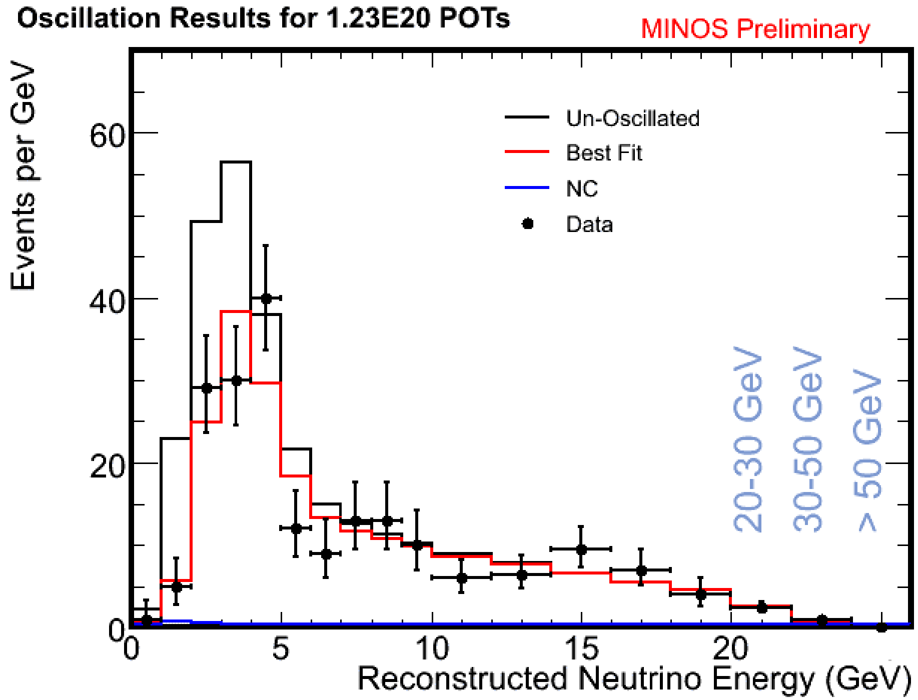
Beam Matrix Results RunIIa

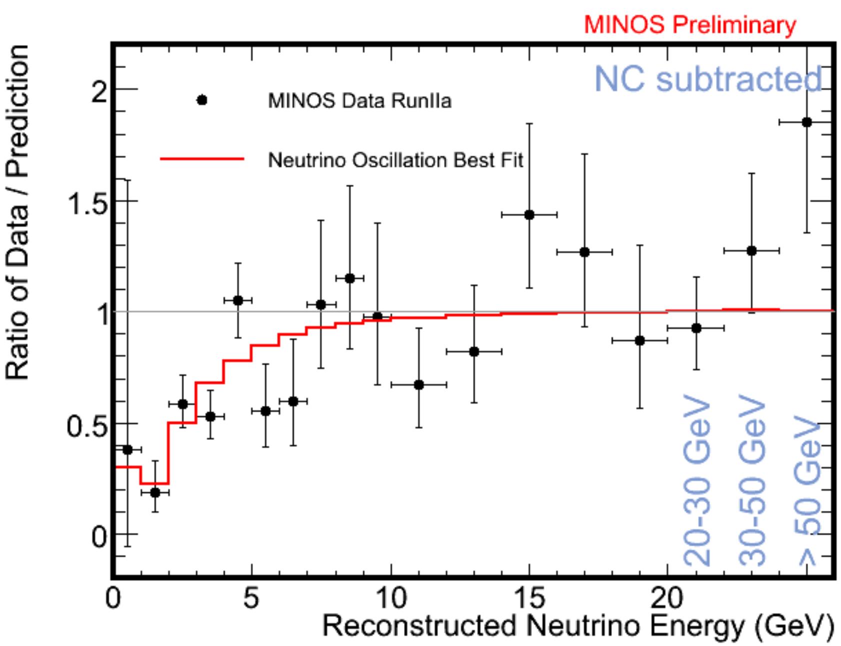






Beam Matrix Results RunIIa





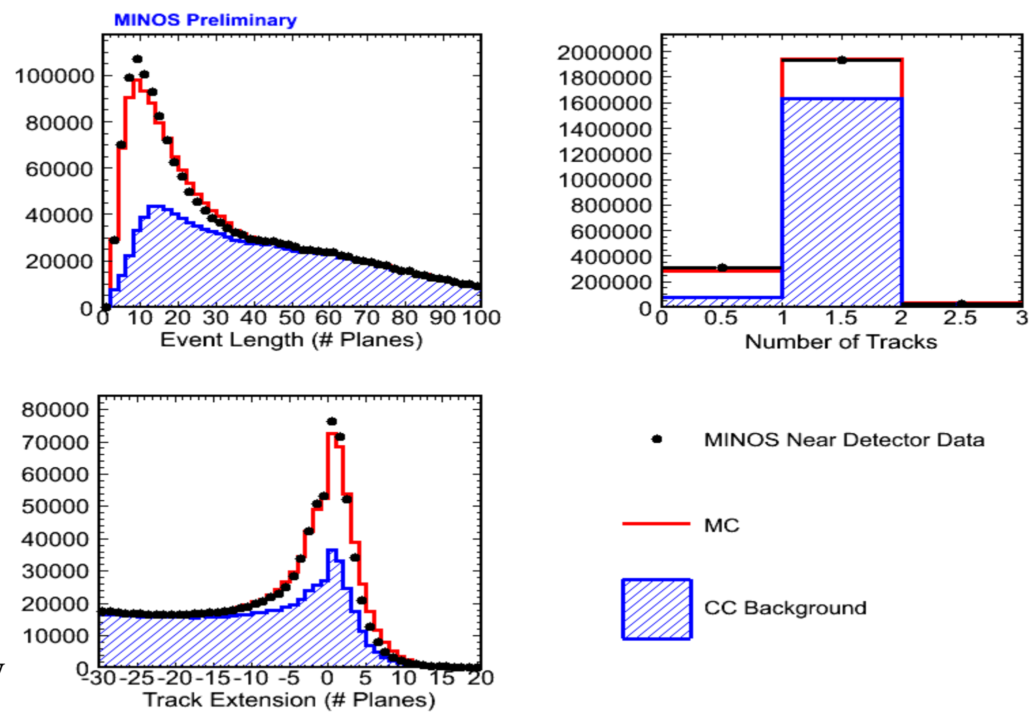
Neutral Current Analysis : Near Detector NC-like Spectrum

- *Goal is a NC spectrum measurement in the FD which is* **Sensitive to $\nu_\mu \rightarrow \nu_{sterile}$, ν decay signatures…**

  -First step of this analysis is a measurement of the NC spectrum in the Near Detector.

  - Second step is the use of similar techniques to the CC analysis to extrapolate measured spectrum to the Far Detector and compare with the data

Use simple cuts to select NC events with high (93%) efficiency (CC contamination ~50%)



The agreement of NC Selection Variables between Data and MC is good.

Neutral Current Analysis : Near Detector NC-like Spectrum

• Unlike the Far Detector our Near Detector "sees" a lot of neutrinos per beam spill (event overlapping).

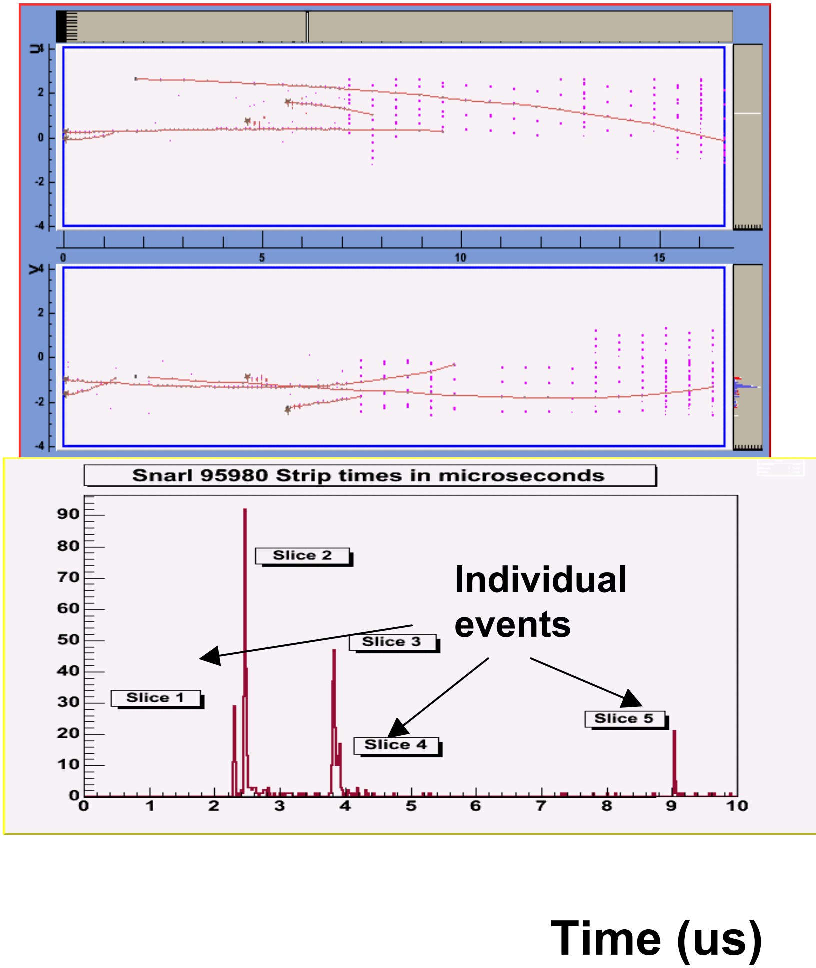
• To ensure that event overlapping is not affecting the NC-like spectrum we reconstruct we developed two independent methods to obtain clean samples of events for data/MC comparisons in the Near Detector :

-Both are designed to reject events that overlap in time and space and/or are not well-reconstructed:

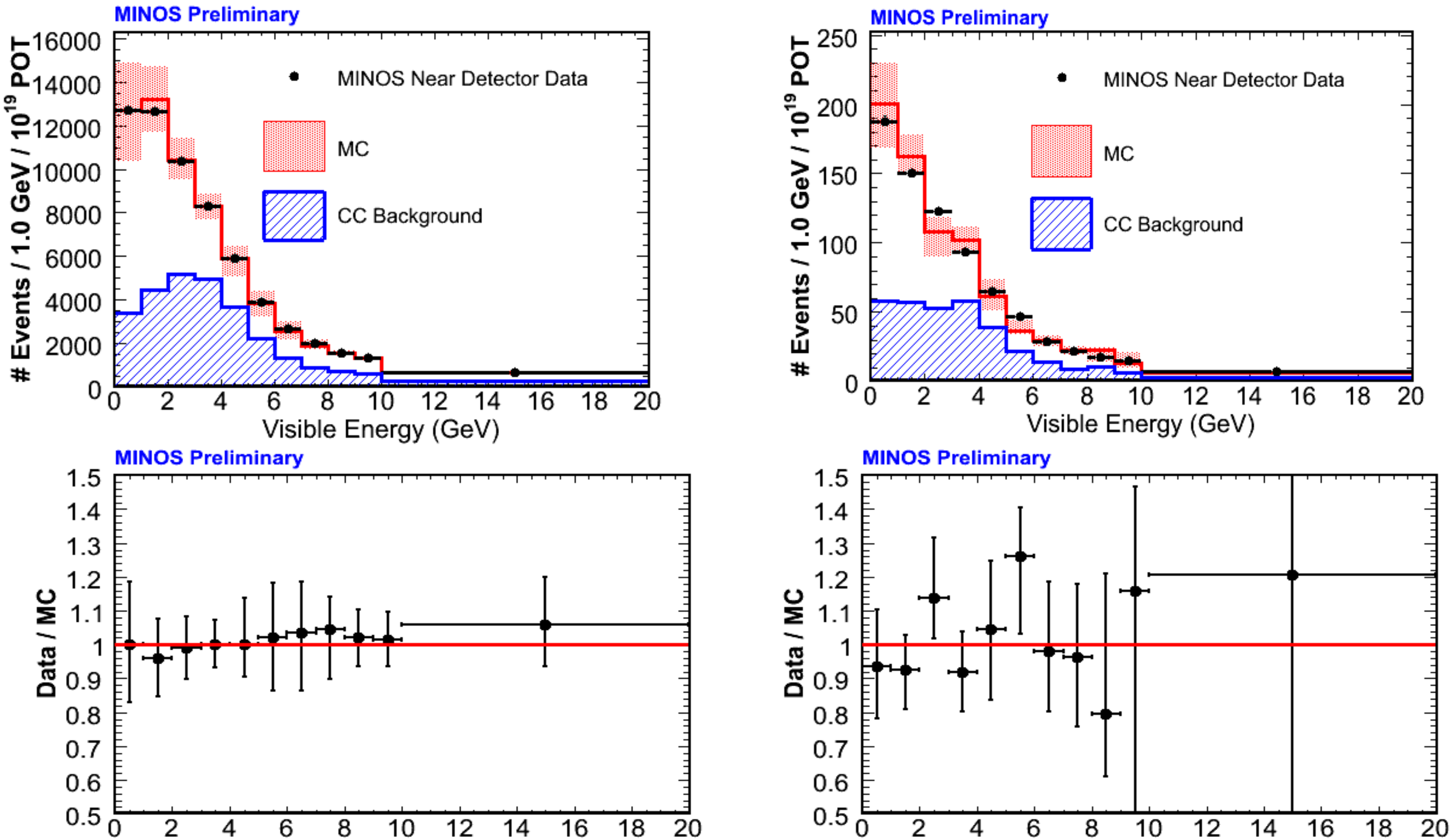
1) High multiplicity selection: Uses timing & topological cuts (selects 860K NC-like events for 1.23e20 pot)

2) Low multiplicity selection: Use only spills with 1 or 2 reconstructed events (selects 10472 NC-like events for 1.23e20 pot)

One near detector spill



Neutral Current Analysis : Near Detector NC-like Spectrum cont'd

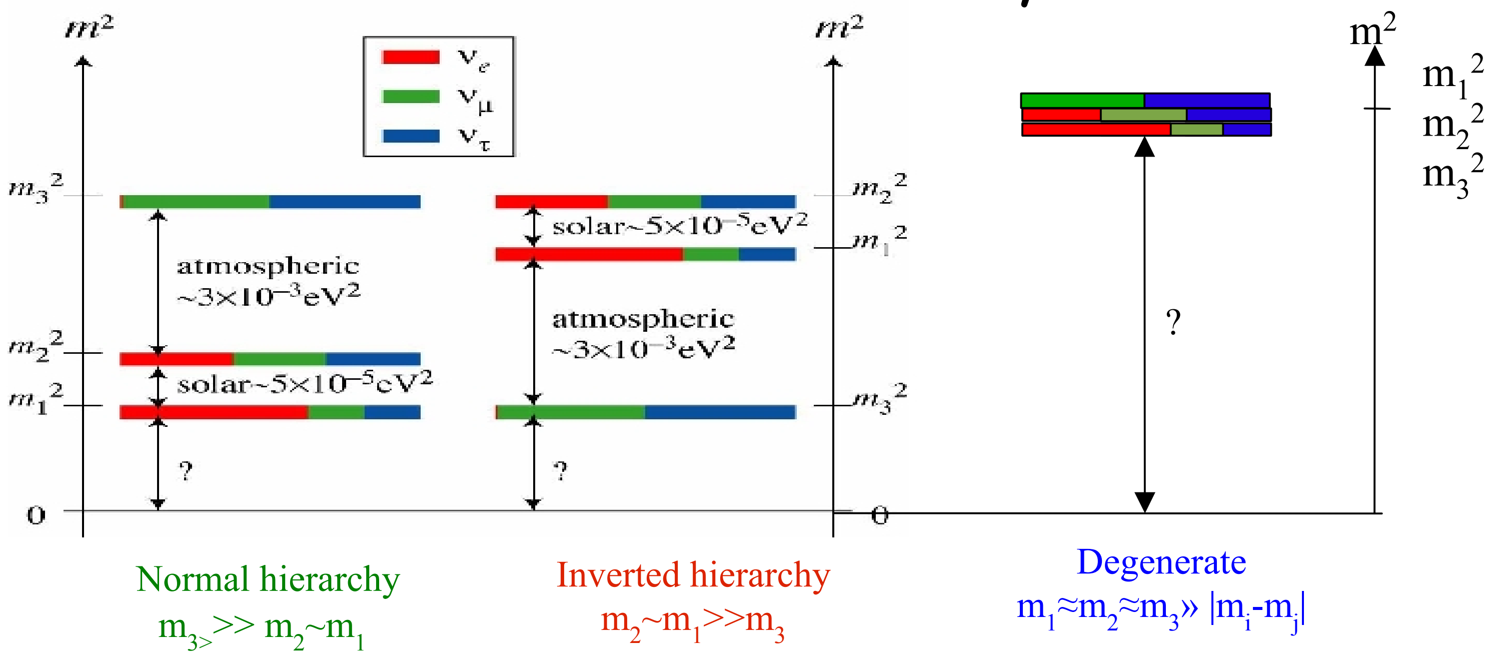


- MC error band includes contributions from beam, cross-section and energy scale uncertainties
- Both methods (high and low multiplicity data cleaning) give results consistent with each other and with expectations.

ν(less)(2)β Decay Experiments : Physics Goals

- What is the absolute ν mass ?
- What is the ν mass hierarchy (normal-inverted)?

ν Mass hierarchy



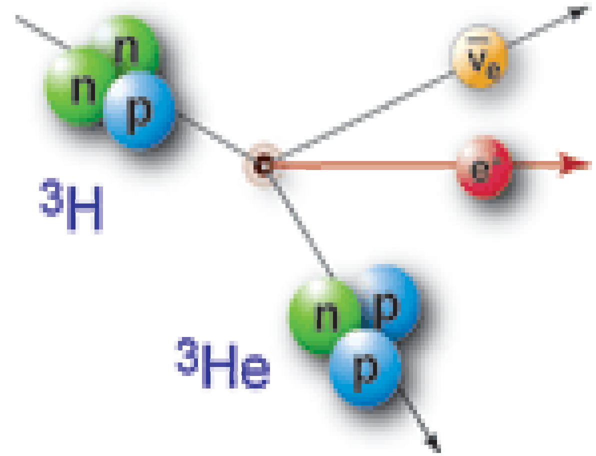
- Is neutrino a Dirac ($\nu \neq \bar{\nu}$) or Majorana Particle ($\nu = \bar{\nu}$) ?

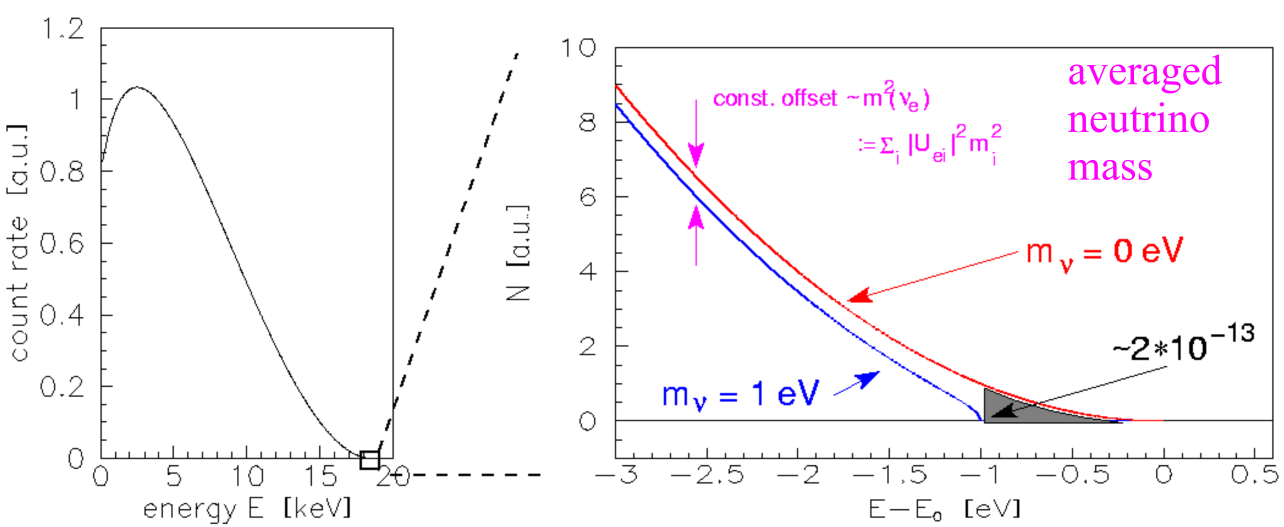
$\nu\beta$ Decay Experiments : absolute ν mass

(A,Z) → (A,Z+1) + e$^-$ + ν_e

$$\frac{dN}{dE} \sim \sqrt{\left[(E_o - E_e)^2 - m^2{}_{\nu i}\right]}$$

$$m^2{}_{\nu_e} = \sum_{i=1}^{3} |U_{ei}|^2 \, m^2{}_i$$



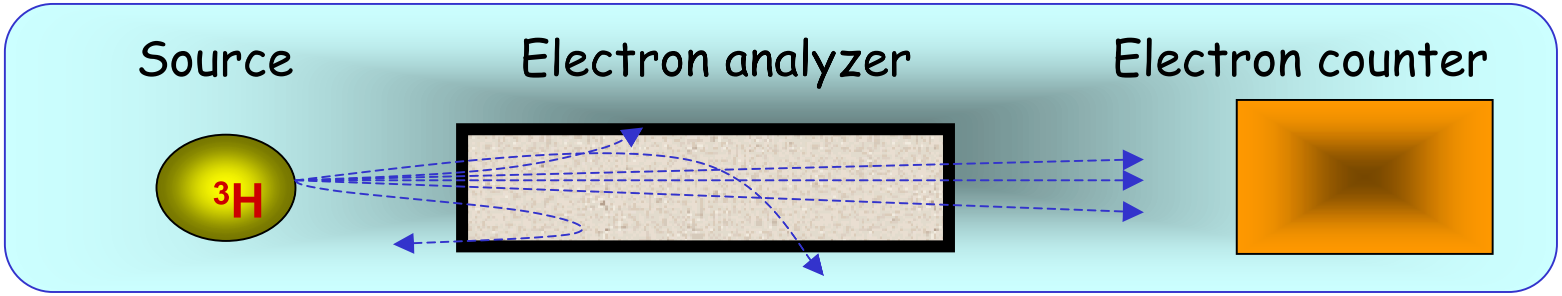


νβ Decay Experiments : absolute ν mass

MAINZ: $m^2_\nu = -0.6 \pm 2.2 \pm 2.1$ eV^2 $m_\nu < 2.3$ eV (95% C.L.)

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

Troisk: $m^2_\nu = -2.3 \pm 2.5 \pm 2.0$ eV^2 $m_\nu < 2.05$ eV (95% C.L.)

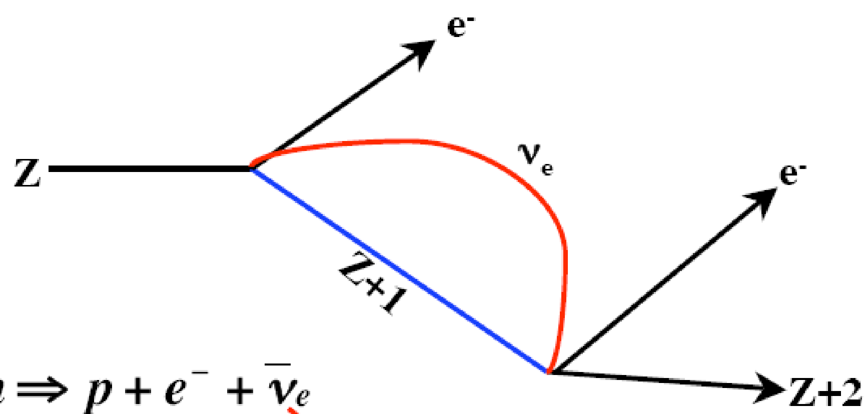


Sensitivity $m_\nu < 0.2$ eV

Improvement of ΔE: 0.93 eV
(4.8 eV for Mainz)
Larger acceptance
Statistics 100 days → 1000 days

Commissioning and start : 2010

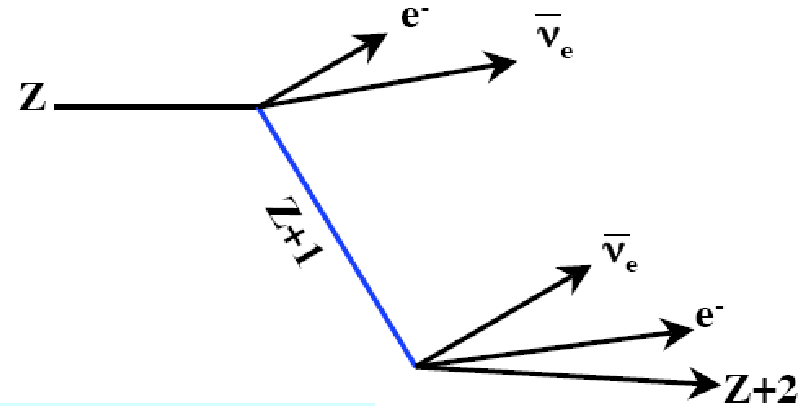
$\beta\beta(0)\nu$ Decay Experiments :



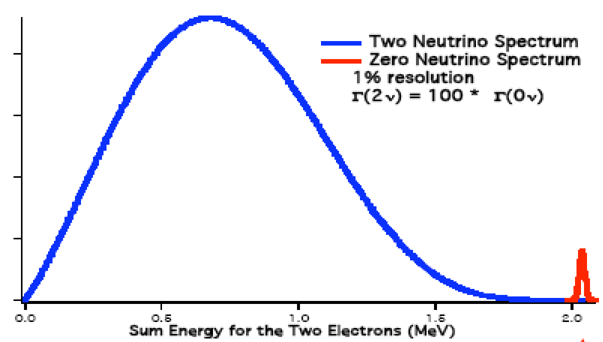
$$n \Rightarrow p + e^- + \bar{\nu}_e$$

(RH $\bar{\nu}_e$) (LH ν_e)

$$\nu_e + n \Rightarrow p + e^-$$



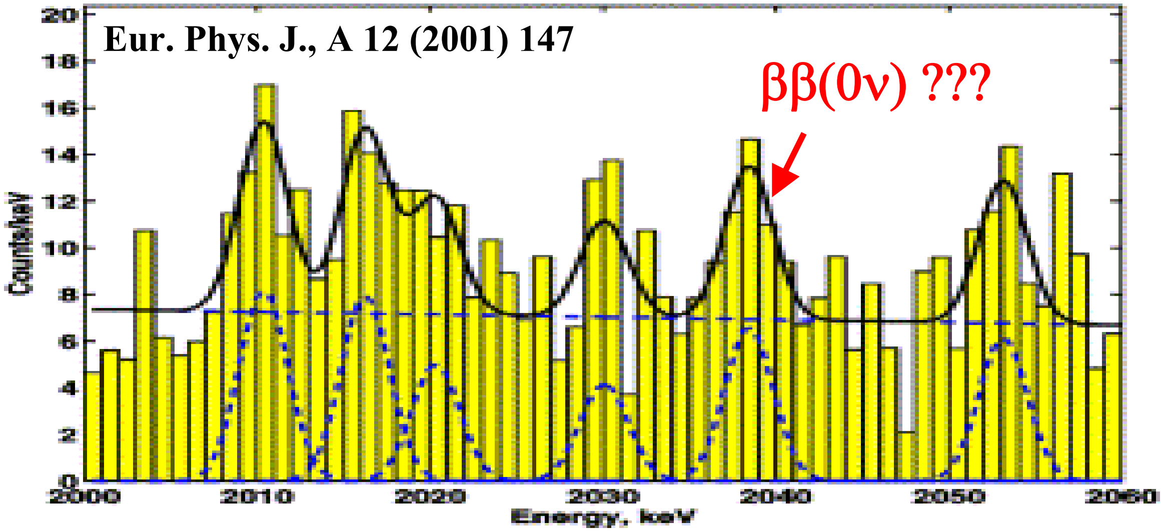
$$2n \Rightarrow 2p + 2e^- + 2\bar{\nu}_e$$



Endpoint Energy

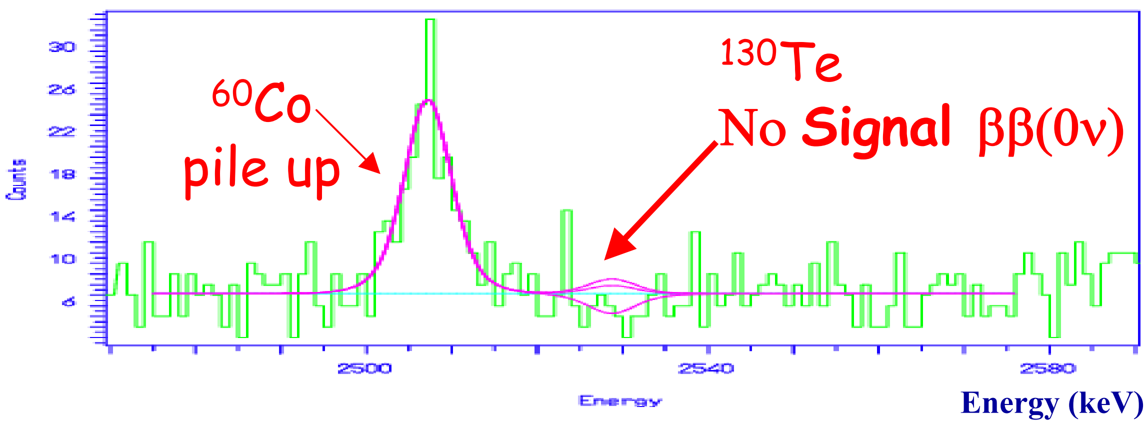
$\beta\beta0\nu$ Decay Experiments : Dirac Or Majorana Particle??

2006 new PSA analysis: 6 σ effect



Heidelberg-Moscow
~11 kg of enriched Ge diodes in ^{76}Ge (86%)

$<m_\nu> = 0.32 \pm 0.03$ eV



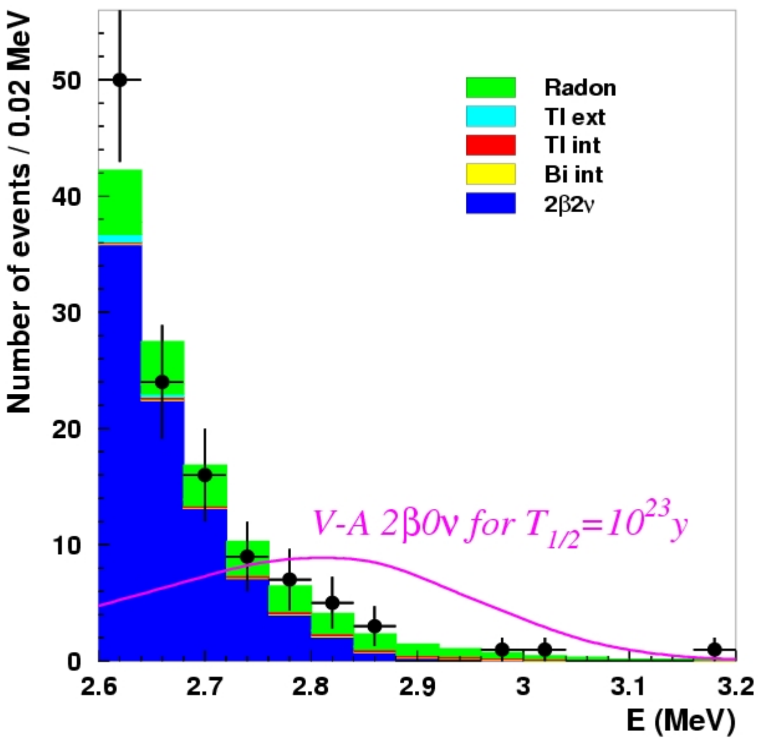
Cuoricino (bolometer)
~41 kg of TeO_2

$<m_\nu> < 0.2 - 1$ eV (90% CL)

$\beta\beta0\nu$ Decay Experiments : Dirac Or Majorana Particle??

NEMO Experiment

Phase I + II
13.3 kg.yr

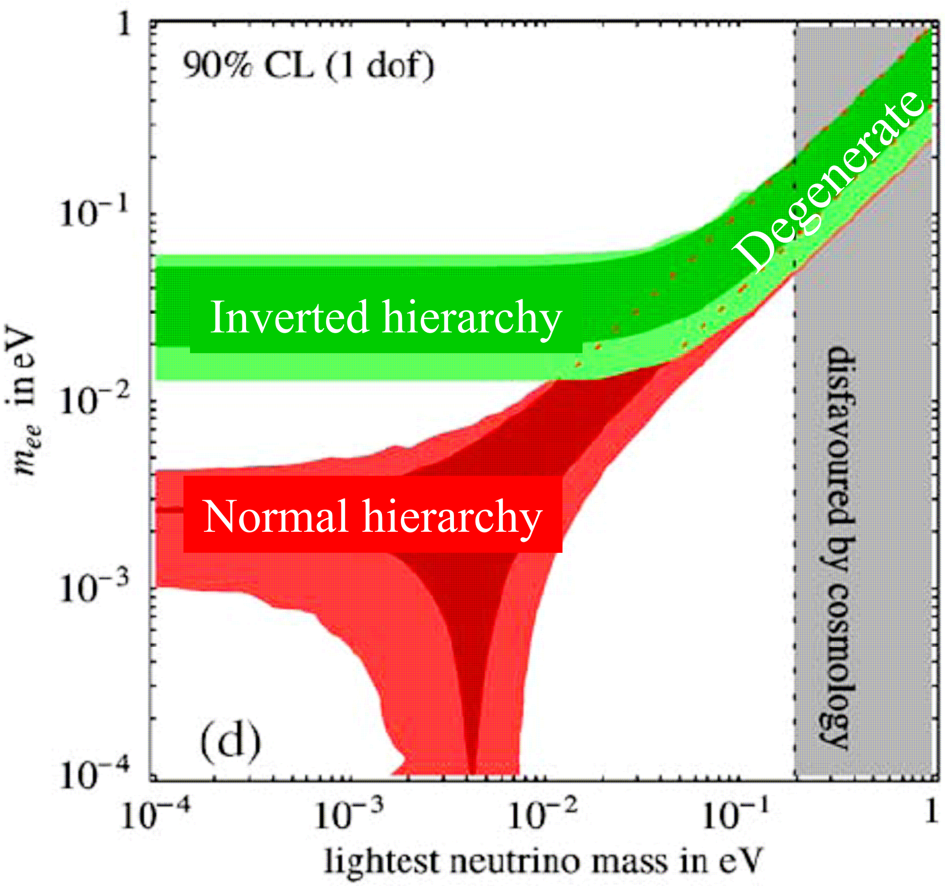


Results on ^{100}Mo -> no $\beta\beta0\nu$ **Signal…**

$T_{1/2}(\beta\beta0\nu) > 5.8\ 10^{23}$ yr (90 % C.L.)

$\langle m_\nu \rangle < 0.8 - 1.3$ eV

ββ0ν Decay Experiments : Neutrino Mass Hierarchy



Degenerate: can be tested !!

Inverted hierarchy: tested by the next generation of ββ experiments…

Normal hierarchy: inaccessible

$\beta\beta0\nu$ Decay Experiments : Future

Experiment	Isotope	Enriched isotope mass (kg)	$T_{1/2}$ (yr)	$<m_\nu>$ (eV)	Start	Status
CUORE	^{130}Te	203	2.1 10^{26}	0.03 - 0.07*	2011	Funded
GERDA phase I phase II	^{76}Ge	17.9 40	3. 10^{25} 2. 10^{26}	0.2 – 0.5* 0.07 – 0.2*	2009 2011	Funded Funded
Majorana	^{76}Ge	30 - 60	1.10^{26}	0.1 – 0.3*	2011	Funded
EXO-200	^{136}Xe	200	6.4 10^{25}	0.2 - 0.7*	2008	Funded
SuperNEMO	^{82}Se ^{150}Nd	100 100	2. 10^{26} 10^{26}	0.05- 0.09* 0.07	2011	R&D
CANDLES	^{48}Ca	0.5		~0.5	2008	Funded
MOON II	^{100}Mo	120		0.09 – 0.13	?	R&D
DCBA	^{150}Nd	20			?	R&D
SNO++	^{150}Nd	500				R&D
COBRA	116Cd, ^{130}Te	420				R&D

* Calculation with NME from Rodim et al., Suhonen et al., Caurier et al. PMN07