PANIC11 RUTHERFORD CENTENNIAL

Probing Neutrino Masses and Mixings with Accelerator and Reactor Neutrinos

Mike Shaevitz - Columbia University

Particles and Nuclei International Conference
(PANIC11) July, 2011

Outline

- Introduction to Neutrino Mass and Mixing
- Neutrino Oscillations among ν_e, ν_μ, and ν_τ
  - The "Hunt" for the Little Mixing Angle θ_{13}
    - New T2K and MINOS results
  - Plans and Prospects for Measuring CP Violation
- Possible Oscillations to Sterile Neutrinos
  - Current Hints and Anomalies
    - Updated MiniBooNE $\bar{\nu}_e$ appearance results
  - Ideas for Future Searches
- Final Comments

Absolute Mass Scale Determinations

Tritium β decay	$m_{\nu_e} = \left(\sum_i \lvert U_{ei} \rvert^2 m_i^2 \right)^{1/2}$
Neutrinoless double beta decay	$m_{ee} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$
Cosmology	$\sim \sum_i m_i$

$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

$$\left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

Current limit (Mainz):
$m_\nu < 2.2$ eV @ 95% CL
KATRIN Sensitivity:
$m_\nu < 0.2$ eV @ 90% CL
See J. Formaggio talk on Thurs.

If detect 0ν2β decay
⇒ Neutrinos are Majoranna particles
and information on m_ν at 0.1eV scale

Limits sum of neutrino masses:
$\Sigma m\nu < \sim 0.7 eV$

Neutrino Oscillations

The observation of neutrino oscillations where one type of neutrino can change (oscillate) into another type implies:

1. Neutrinos have mass

and

2. Lepton number (electron, muon, tau) is not conserved
   ($\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\tau$)

- The phenomena comes about because the mass and flavor states are different as parameterized by a mixing matrix

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$$P_{Osc}\left(\nu_a \rightarrow \nu_b\right) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$

More details on osc theory see Boris Kayser talk yesterday and J. Diaz on Thurs..

where $\theta =$ mixing angle; $\Delta m^2 = m_b^2 - m_a^2$; $L =$ travel distance; $E =$ neutrino energy

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- Two types of oscillation searches:
  - ***Appearance Experiment:***
    Look for appearance of ν_e or ν_τ in a pure ν_μ beam vs. L and E
  - ***Disappearance Experiment:***
    Look for a change in $\nu_{e/\mu}$ flux as a function of L and E

Oscillations Parameterized by 3x3 Unitary Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} Flavor \\ Eigenstate \end{pmatrix} = (Mixing\ Matrix) \begin{pmatrix} Mass \\ Eigenstate \end{pmatrix}$$

Three mass splittings: $\Delta m_{12}^2 = m_1^2 - m_2^2$, $\Delta m_{23}^2 = m_2^2 - m_3^2$, $\Delta m_{31}^2 = m_3^2 - m_1^2$

But only two are independent since only three masses

If $\delta \neq 0$, then have CP violation $\Rightarrow$ $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

solar atmospheric

Current Measurements: $\Delta m_{12}^2 = 8\times 10^{-5}\ \mathrm{eV}^2$, $\Delta m_{13}^2 \approx \Delta m_{23}^2 = 2.5\times 10^{-3}\ \mathrm{eV}^2$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

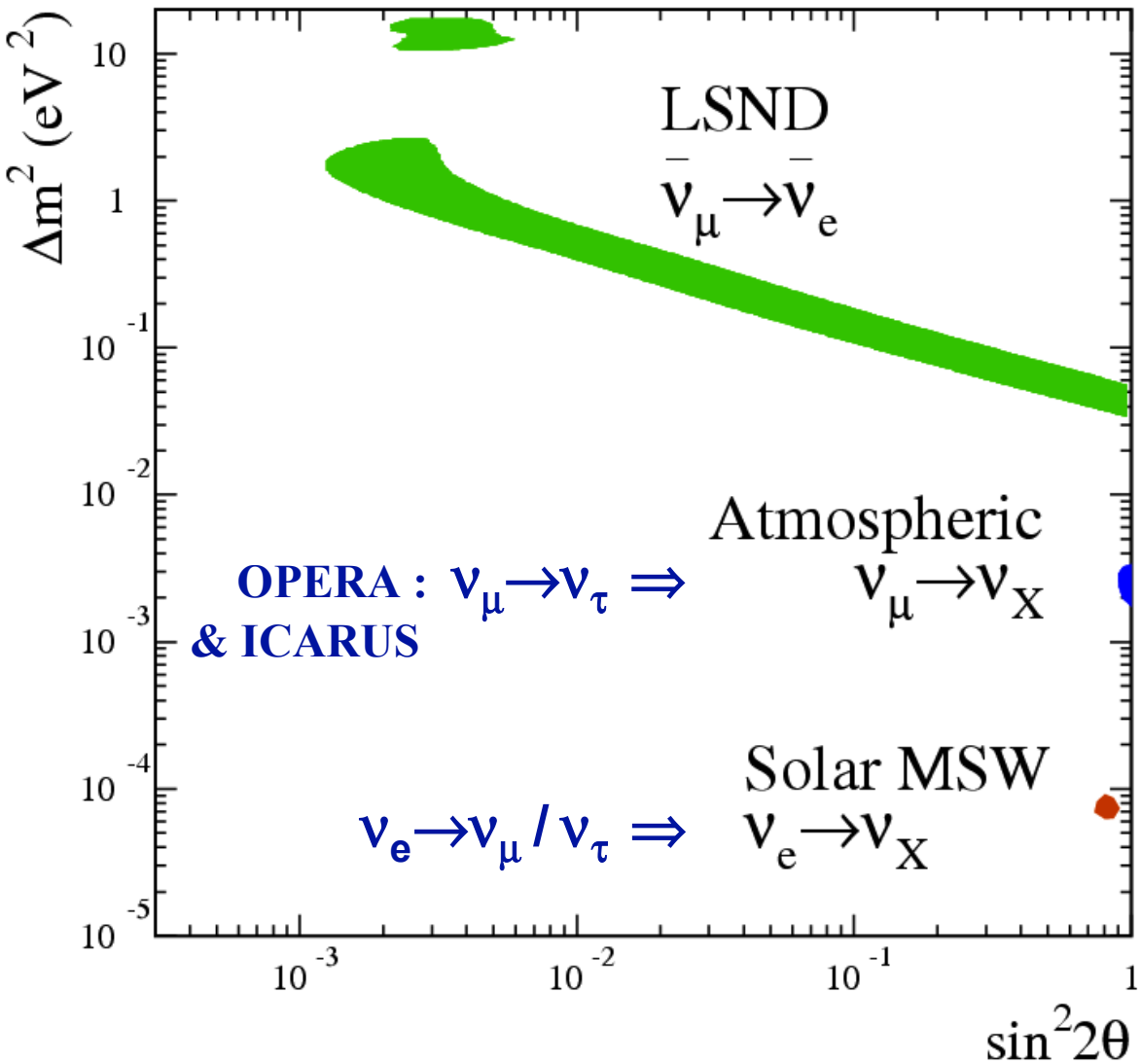
3-mixing angles

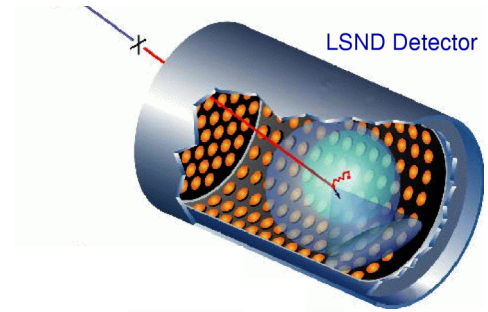
Solar: $\theta_{12} \sim 33°$

"Little mixing angle, θ_{13} "
$\sin^2 2\theta_{13} < 0.14$ at 90% CL
(or $\theta_{13} < 11°$) and δ = ??

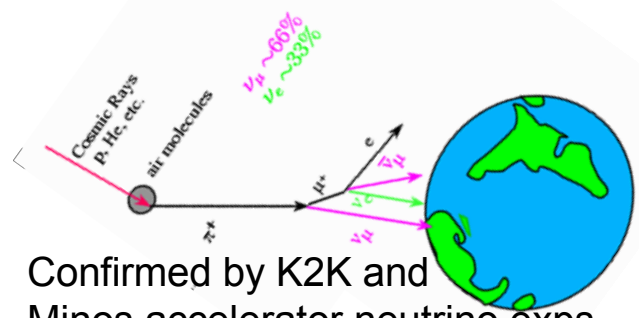
Atmospheric: $\theta_{23} \sim 45°$

Oscillation Summary Before PANIC11

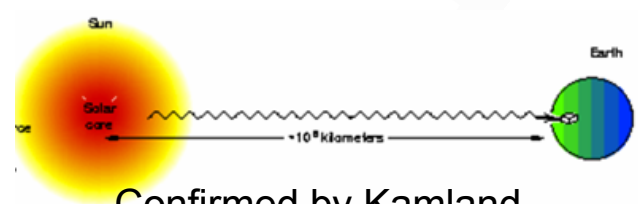




New MiniBooNE $\bar{\nu}_\mu$ consistent



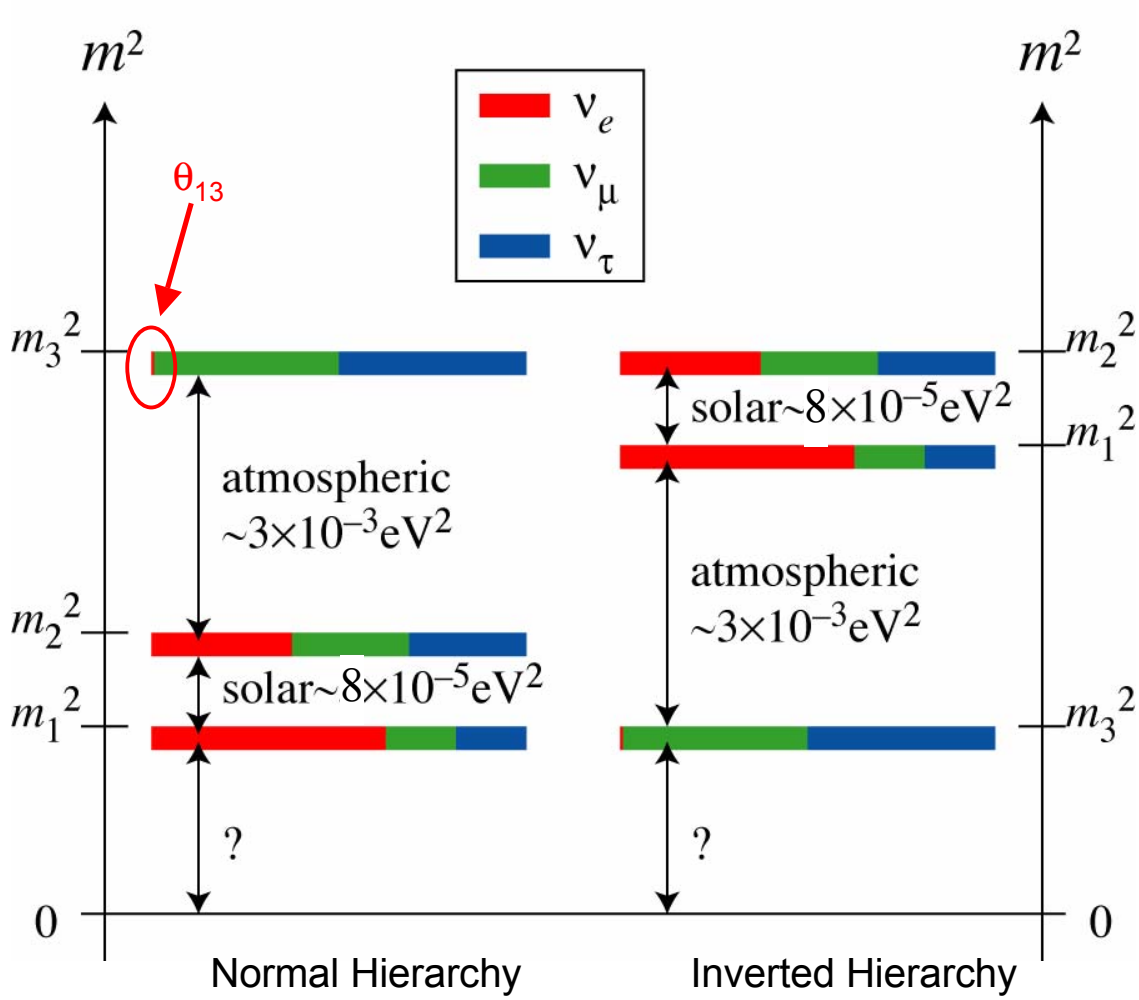
Confirmed by K2K and Minos accelerator neutrino exps



Confirmed by Kamland reactor neutrino exp

Big Questions in (3x3) Neutrino Mixing

1. What is ν_e component in the ν_3 mass eigenstate? $\Rightarrow$ The size of the "little mixing angle", θ_{13} ?
   - Only know $\theta_{13}<11^0$
2. What is the mass hierarchy?
   - Is the solar pair the least massive or not?
3. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?



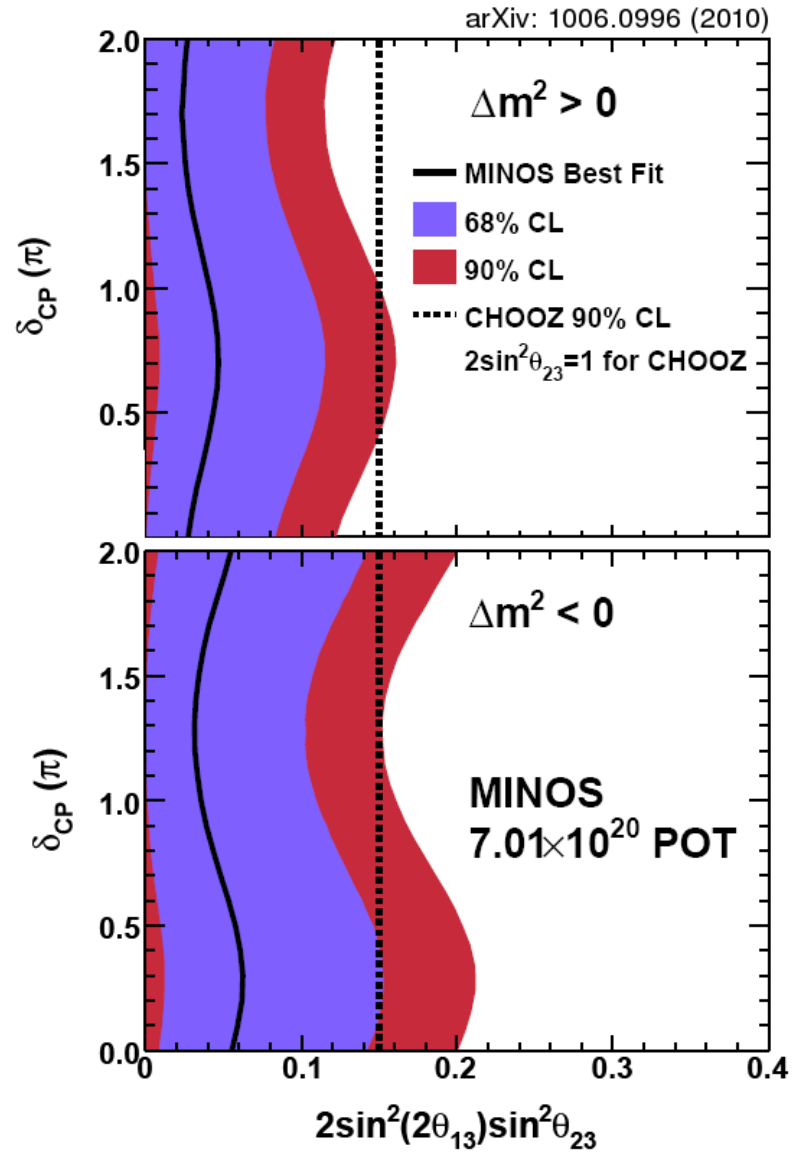
The Search for the "Little Mixing Angle" (θ_{13})

Experimental Limits before PANIC11 on θ_{13}

- Chooz Reactor Experiment
  - $\sin^2 2\theta < 0.14$ 90% CL
- MINOS previous longbaseline appearance limits
- Solar neutrino agreement including KAMLAND

Global Fits:

$$\sin^2 2\theta_{13} < 0.12 @ 95\% CL$$



Experimental Methods to Measure the "Little Mixing Angle", θ_{13}

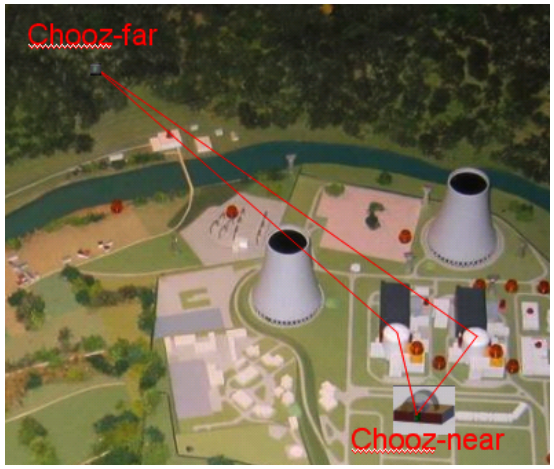
- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for appearance of ν_e in a pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

MINOS:
$\langle E_\nu \rangle = 3.0$ GeV
L = 735 km
NOνA:
$\langle E_\nu \rangle = 2.3$ GeV
L = 810 km
(See J. Nowak NOνA talk on Tuesday afternoon)

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
L = 295 km

- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for a change in $\bar{\nu}_e$ flux as a function of L and E
    - Look for a non- $1/r^2$ behavior of the ν_e rate
    - Use near detector to measure the un-oscillated flux

Double Chooz, RENO, Daya Bay:
$\langle E_\nu \rangle = 3.5$ MeV
L = ~1100 m



Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ_{13} but also:

1. CP violation parameter (δ)
2. Mass hierarchy (sign of Δm_{31}^2) "Matter Effects"
3. Size of $\sin^2\theta_{23}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& + 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)
\end{aligned}
$$

$\Rightarrow$ ***These extra dependencies are both a "curse" and a "blessing"***

Reactor Disappearance Experiments

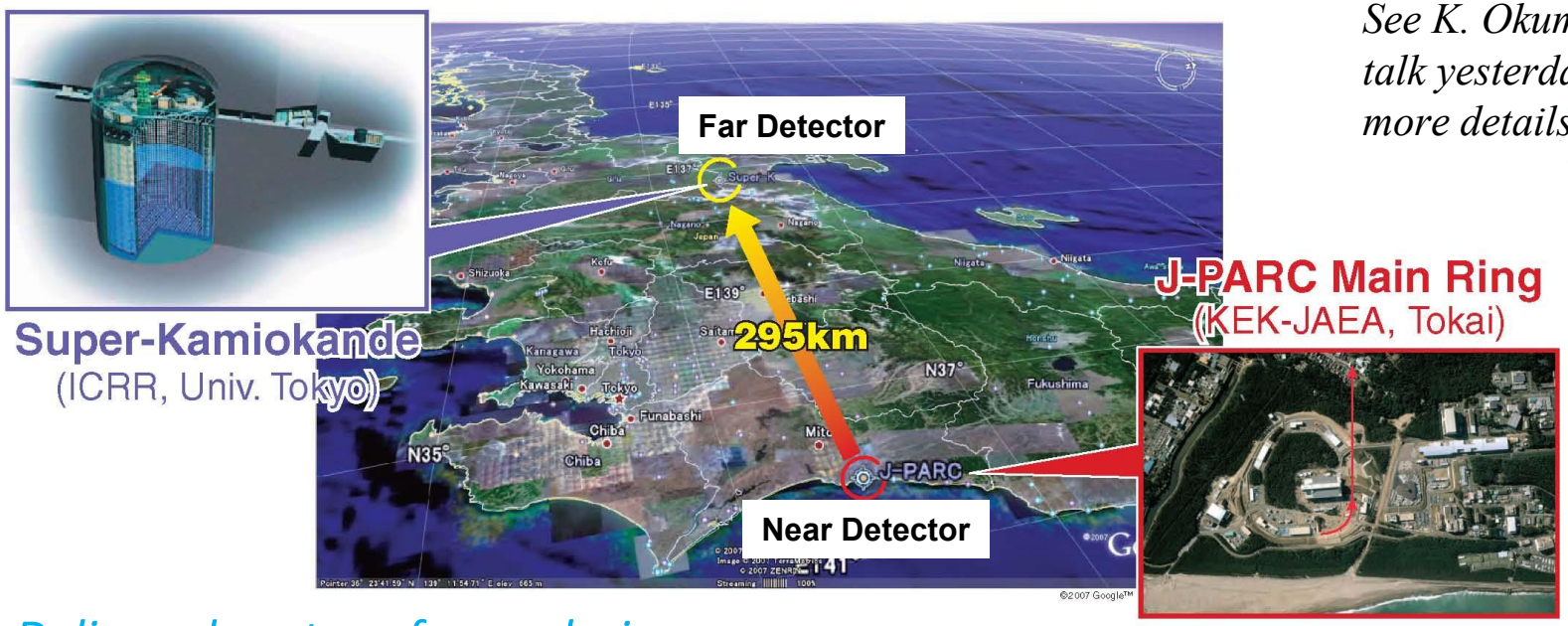
- Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + \textit{small terms}$$

Long-baseline ν_e Appearance Program

Big News: T2K Sees Indication of $\nu_\mu \rightarrow \nu_e$ Oscillations!

See K. Okumura talk yesterday for more details



Delivered protons for analysis

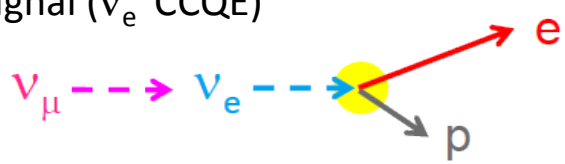
RUN1 (Jan. 2010 ~ Jun. 2010) 3.23 x 10^{19} p.o.t. achieved ave. 50 kW running

RUN2 (Nov. 2010 ~ Mar. 2011) 11.09 x 10^{19} p.o.t. achieved ave. 145 kW running

→ *RUN1+RUN2total 1.43 x 10^{20} p.o.t.* (2% of final goal)

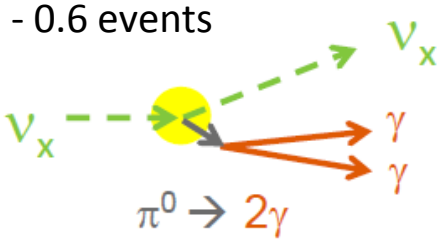
Select signal events and compare to 1.5 ± 0.3 event expected background

Signal (ν_e CCQE)



(Also intrinsic ν_e in beam - 0.8 events)

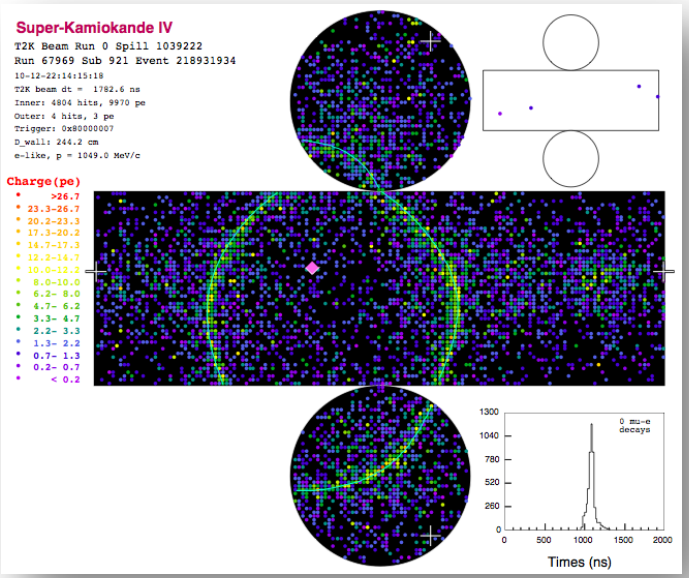
BG (NC π^0) - 0.6 events

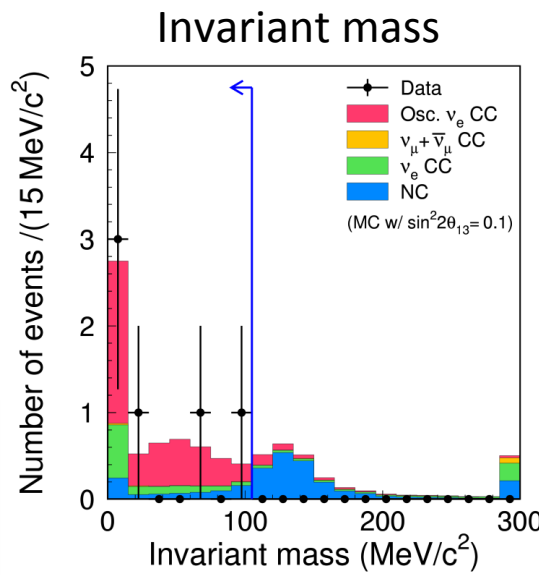


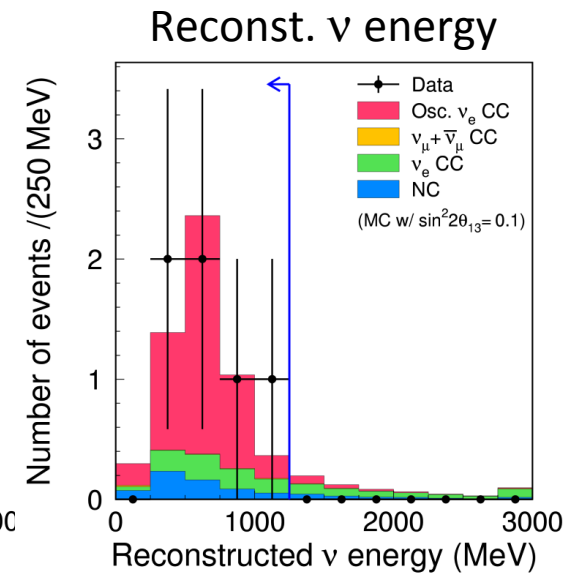
Observe Six Events with 1.5 ± 0.3 Background

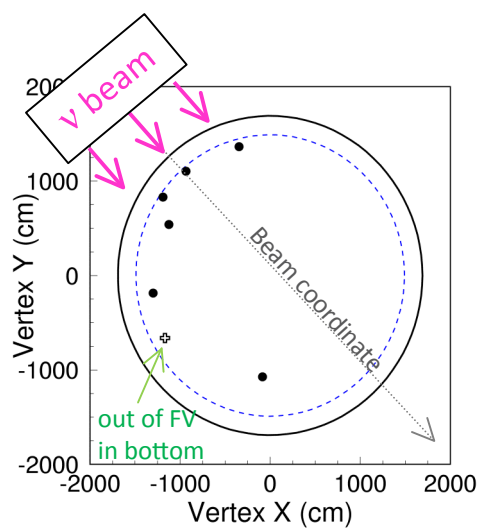
6 candidate events observed after all cuts

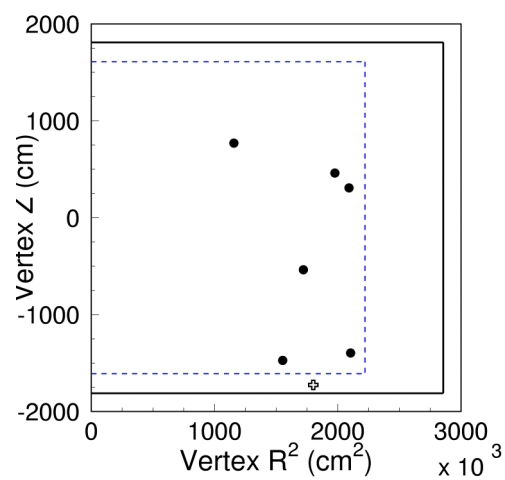
Null hypothesis (θ_{13}=0): 1.5 ±0.3 (syst.)
Null Prob. = 0.7% corresponding to 2.5σ



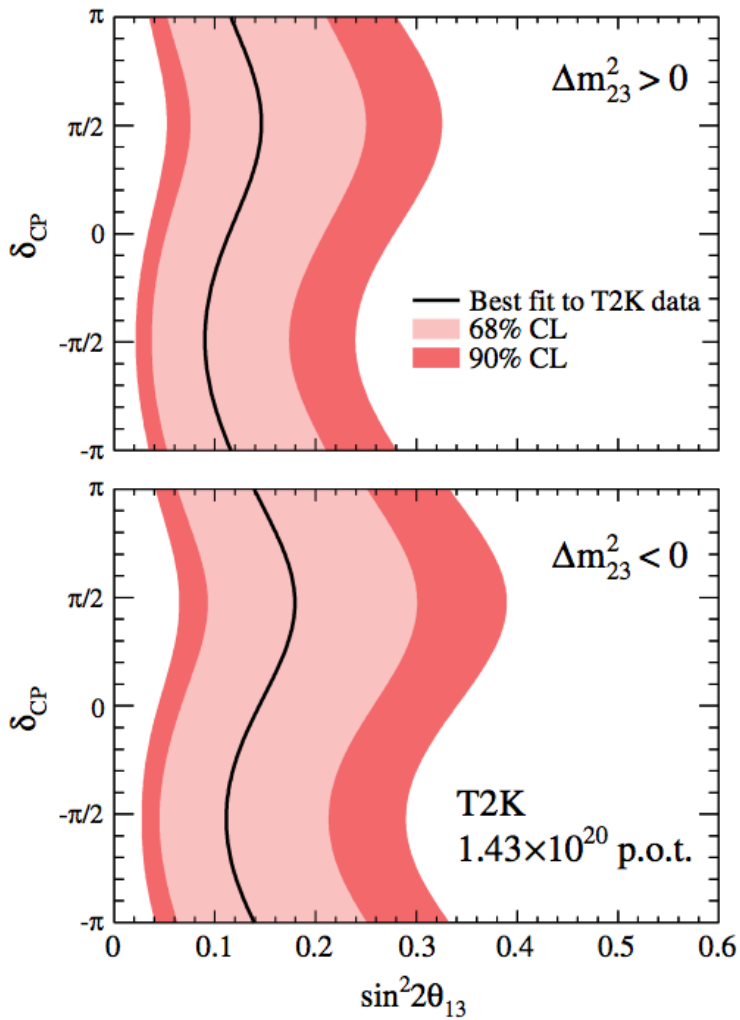








New T2K Results for $\sin^2 2\theta_{13}$



Published in Phys. Rev. Lett. 107, 041801 (2011)

From 6 events versus 1.5±0.3 backgnd (2.5σ)
90% C.L. allowed regions and best fit
(for Δm^2_{23}=2.4 x 10^{-3} eV^2, δ_{CP}=0)

$0.03 < \sin^2 2\theta_{13} < 0.28$
$\sin^2 2\theta_{13} = 0.11$
(normal hierarchy)

$0.04 < \sin^2 2\theta_{13} < 0.34$
$\sin^2 2\theta_{13} = 0.14$
(inverted hierarchy)

March 11 Earthquake caused damage to J-PARC but not too extensive (See K.Tanaka plenary talk)

Plan to resume J-PARC operation in Dec. 2011 and restart T2K data taking as soon as possible after that. Could triple data set by Summer 2012

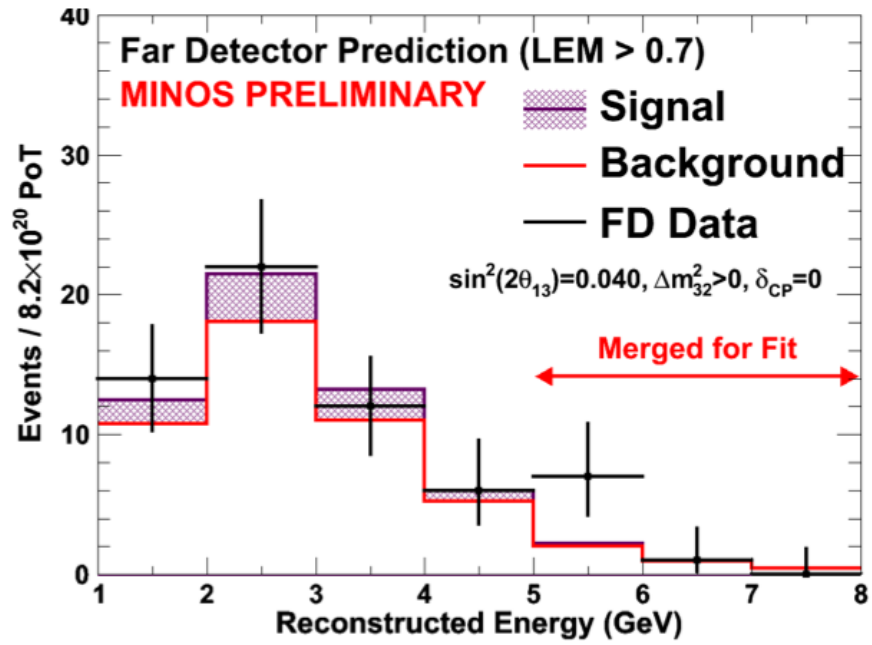
New MINOS $\nu_\mu \rightarrow \nu_e$ Oscillation Search and Results for $\sin^2 2\theta_{13}$

See L. Whitehead talk on Thurs. for more details

- New selection criteria for ν_e candidates
  - MINOS not optimized for isolating ν_e
  - Developed new type of "library event matching" technique
- Use nearly identical Near detector to make background prediction in Far detector.
  - Using Near detector is essential for the search
- Look for an excess of Far detector events over background
  - Use MC to predict Far/Near ratio

Expected background (θ_{13}=0):
49.5 +- 2.8 (syst) +- 7.0 (stat)

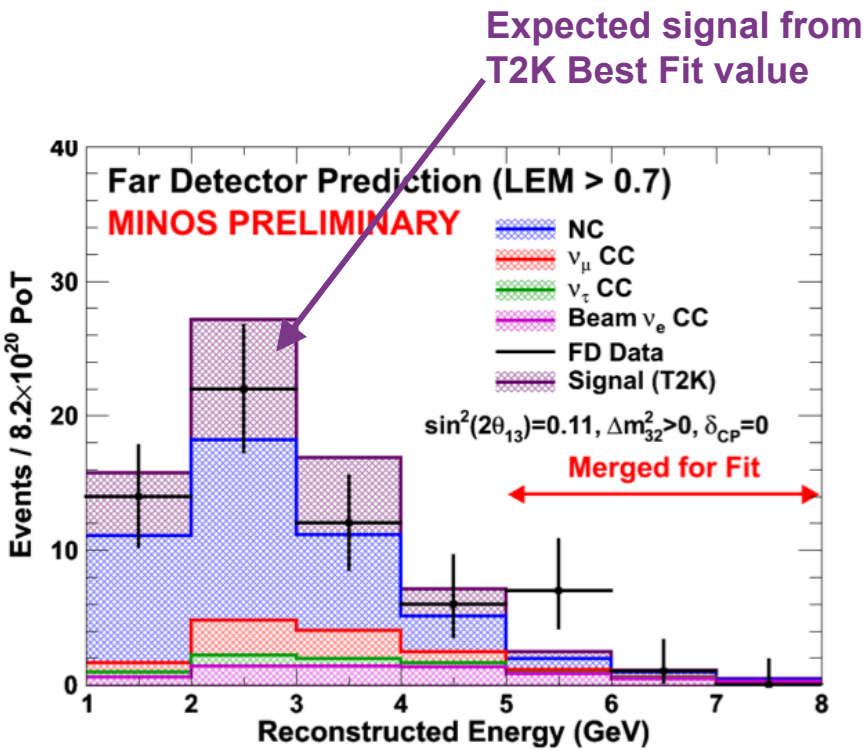
Observed data:
62

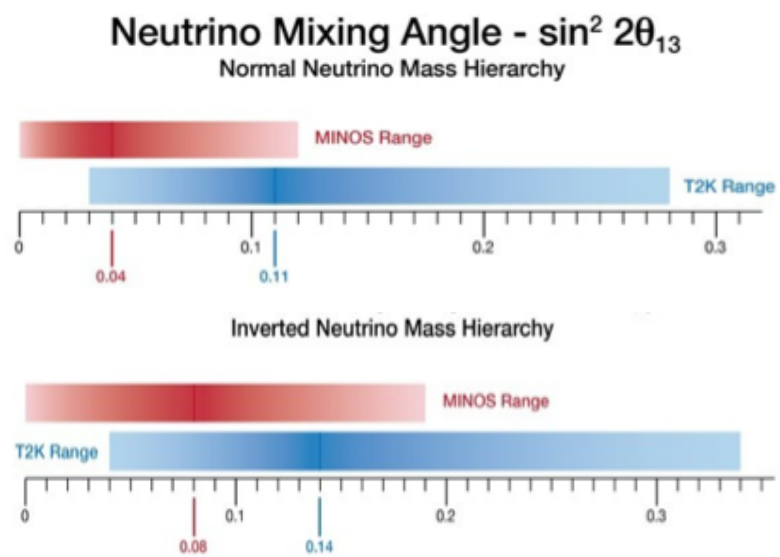


Best Fit: $\sin^2 2\theta_{13} = 0.04(0.08)$ for normal (inverted) hierarchy

Null ($\sin^2 2\theta_{13} = 0.0$) hypothesis excluded at 89% CL

Comparisons of T2K and MINOS $\sin^2 2\theta_{13}$ Results





- Good compatibility between two results:
  - MINOS consistent with T2K best fit value
  - MINOS upper limit cuts into T2K larger allowed values

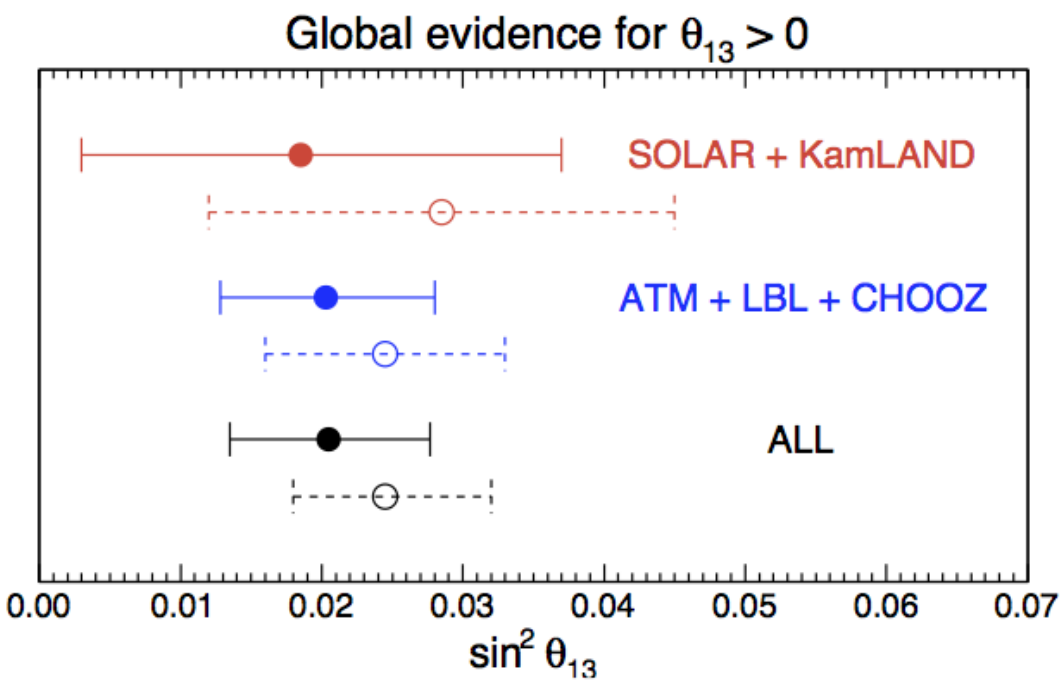
⇒ Need combined fit to establish the best $\sin^2 2\theta_{13}$ range

Global Fits with New T2K and MINOS Results

"Evidence of $\theta_{13} > 0$ from global neutrino data analysis",
Fogli et al. (arXiv:1106.6028v1 [hep-ph]))

Greater than 3σ evidence for $\theta_{13} > 0$

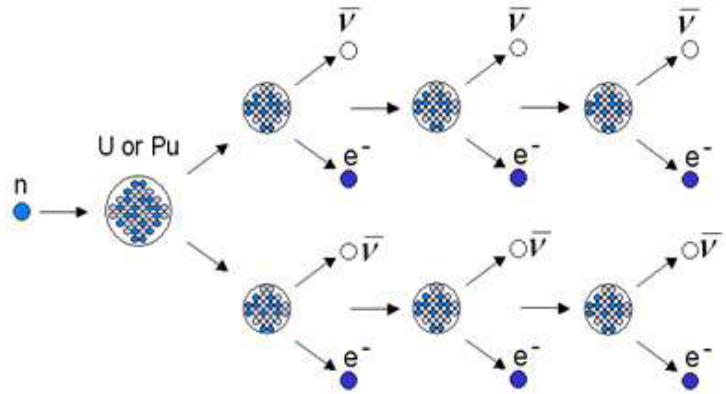
$$\sin^2 2\theta_{13} = \begin{cases} 0.084 \pm 0.028 \text{ , old reactor fluxes} \\ 0.100 \pm 0.028 \text{ , new reactor fluxes} \end{cases} \quad (1\sigma)$$

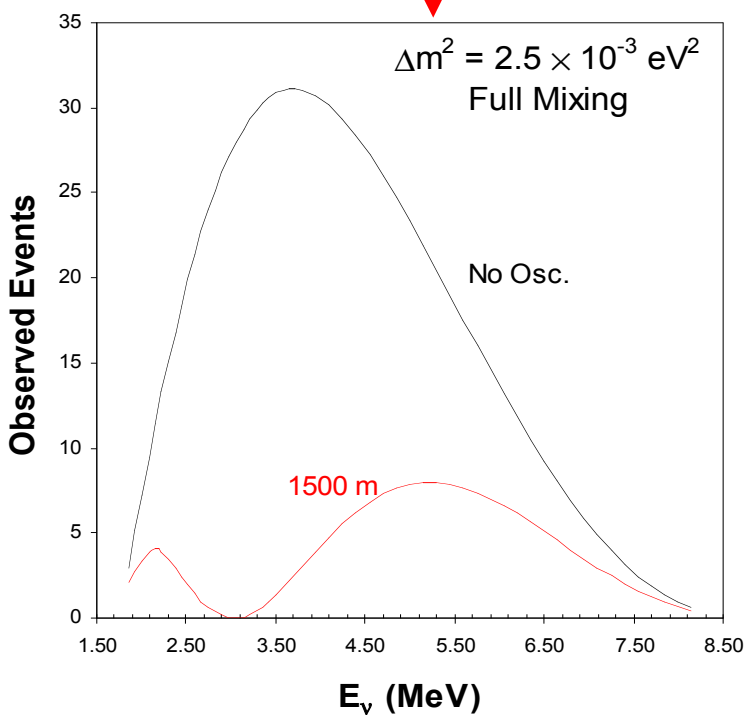


Reactor Neutrino Experiments

Reactor Measurements of θ_{13}

- Nuclear reactors are very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW → 6×10^{20} $\bar{\nu}_e$/s
    700 events / yr / ton at 1500 m away
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2=2.5\times10^{-3}$ eV^2 at L near 1500 m



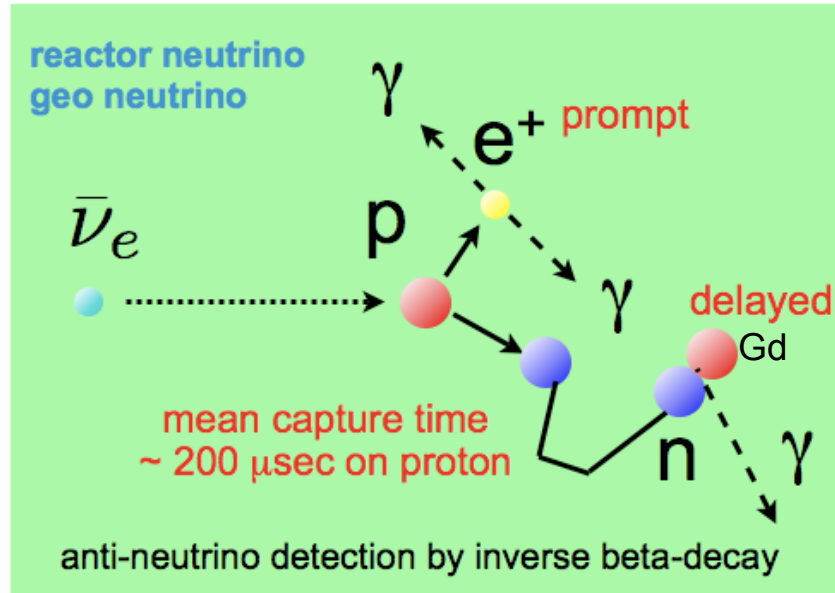


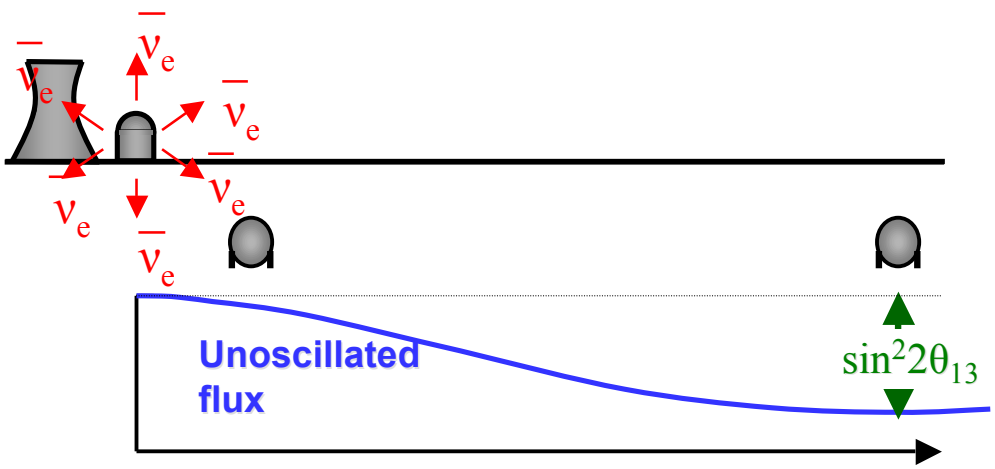
Disappearance Measurement:

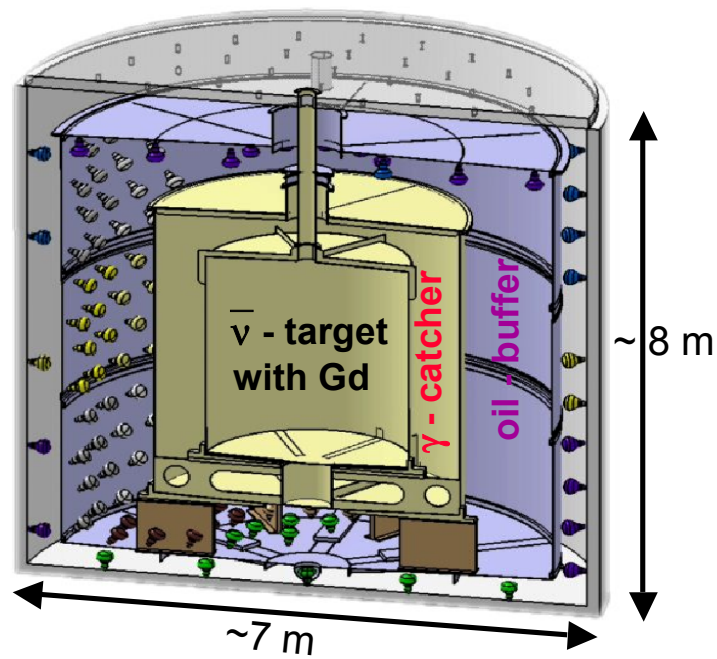
Look for small rate deviation from $1/r^2$ measured at near and far baselines

How to do better than previous CHOOZ reactor experiment?

- ⇒ **Better detectors with reduced systematic uncertainties**
- ⇒ **Use larger detectors**
- ⇒ **Reduce and control backgrounds**
- ⇒ **Use Near/Far Detectors**

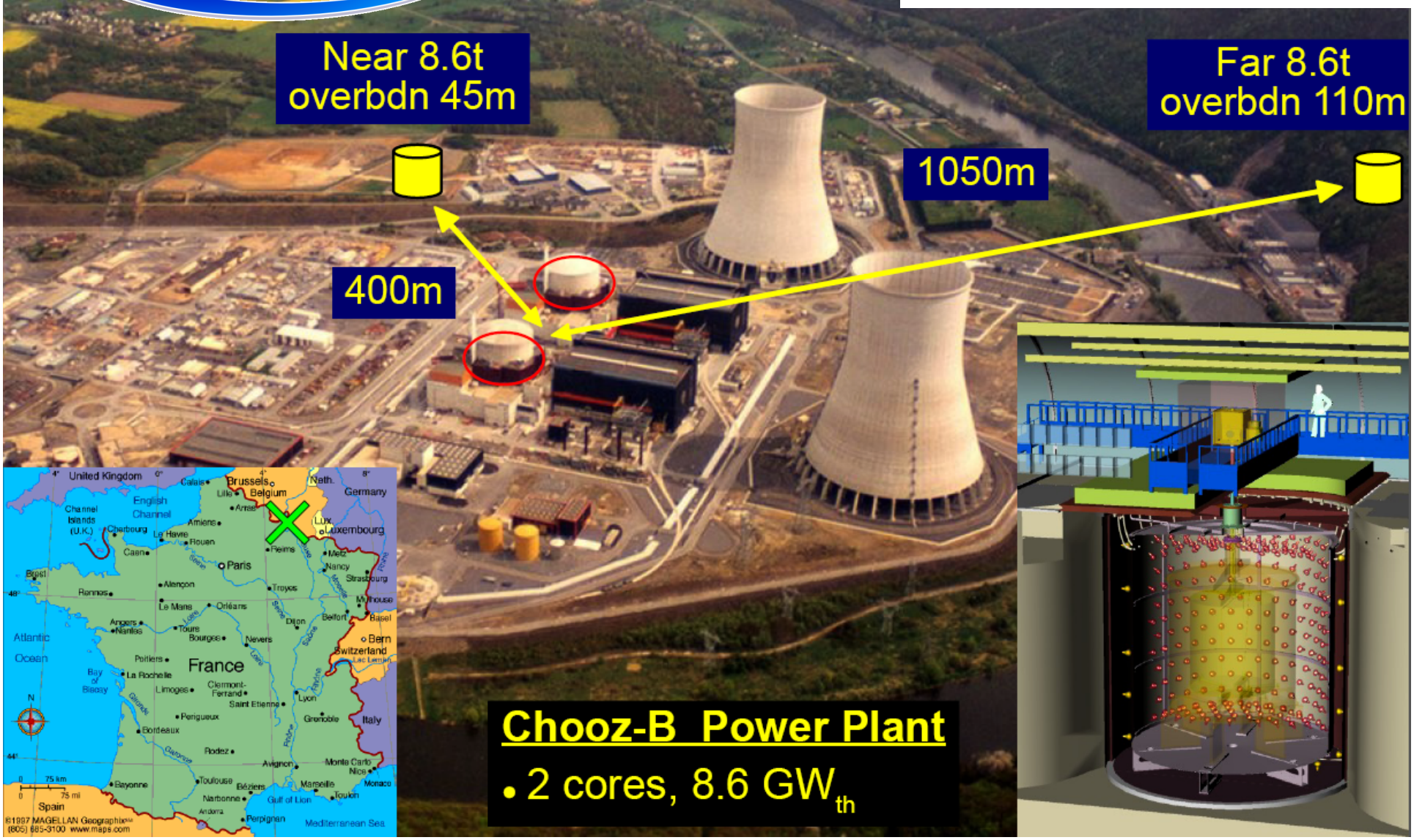


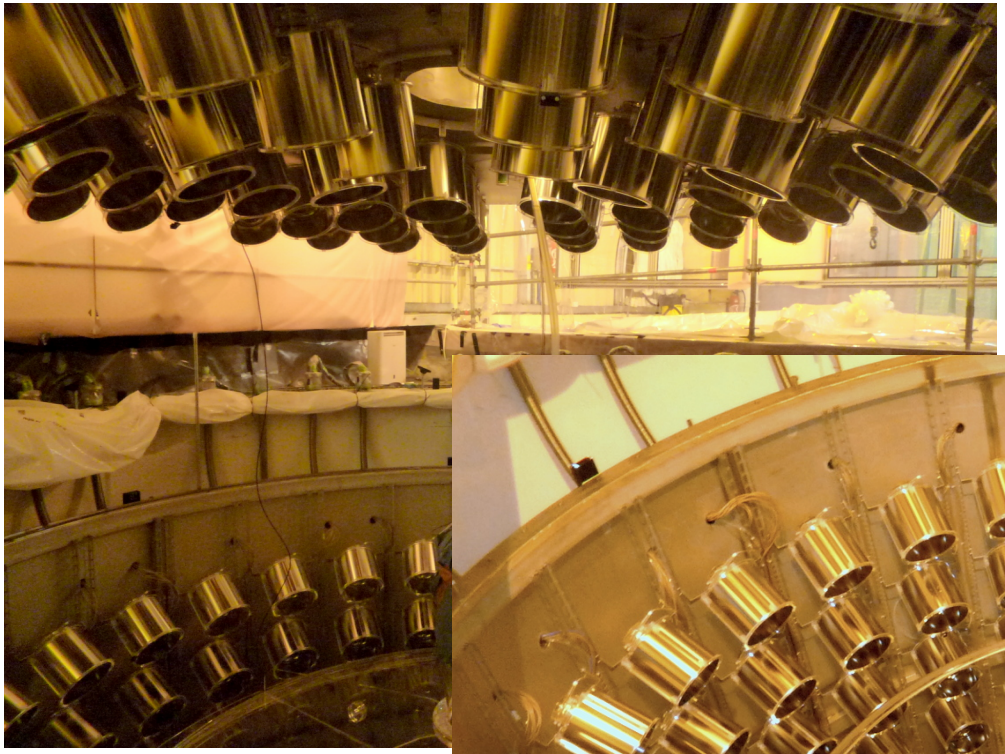


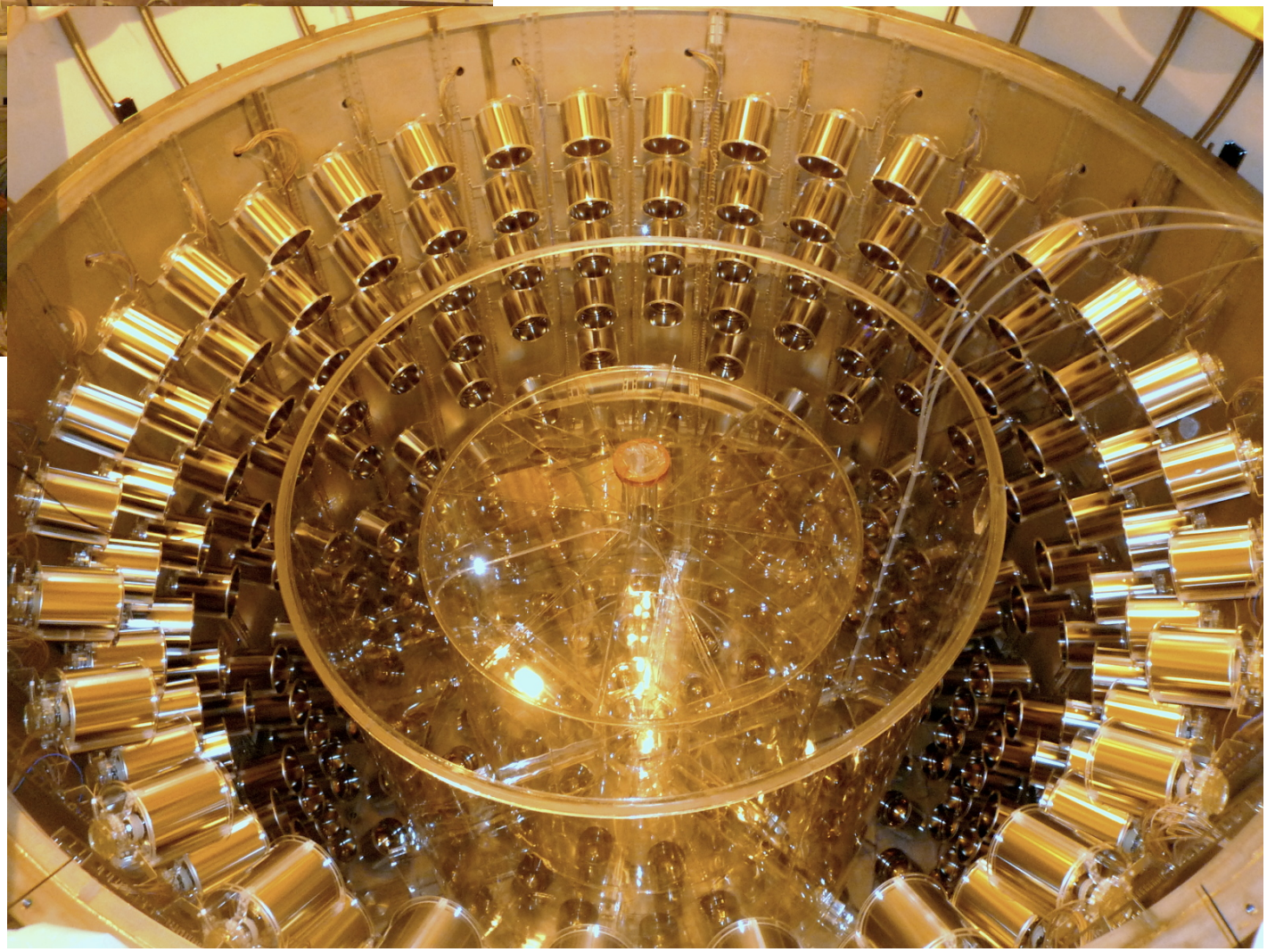


Double Chooz Reactor Experiment in Ardennes, France

See M. Kuse Talk yesterday for details

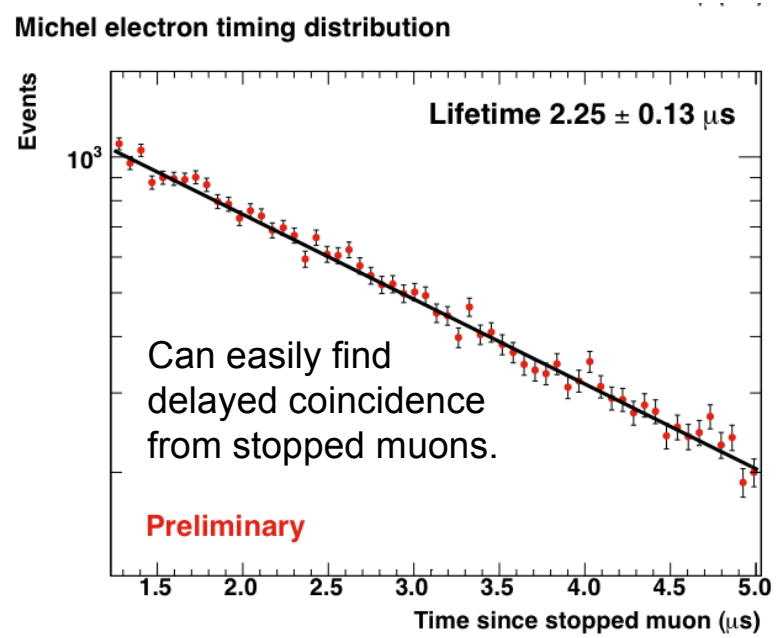


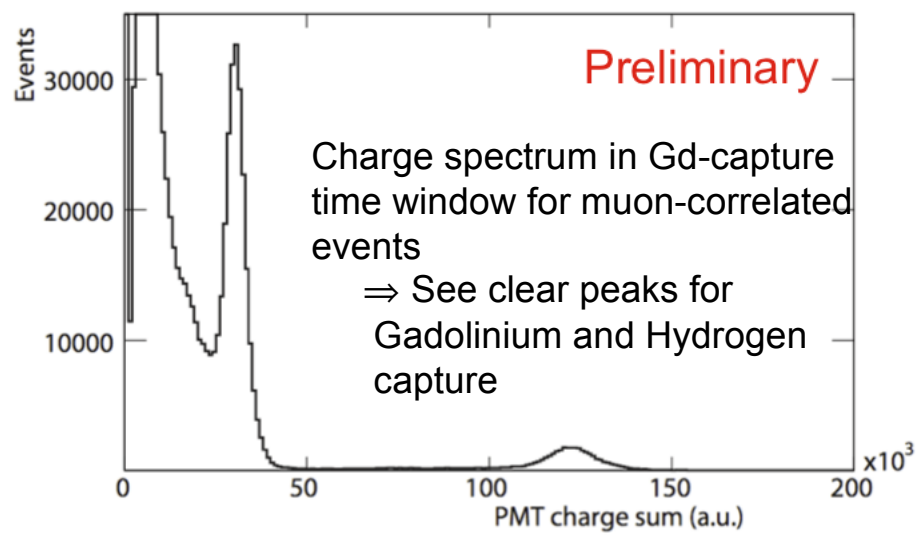




Double Chooz: Stable Data Taking since April 2011

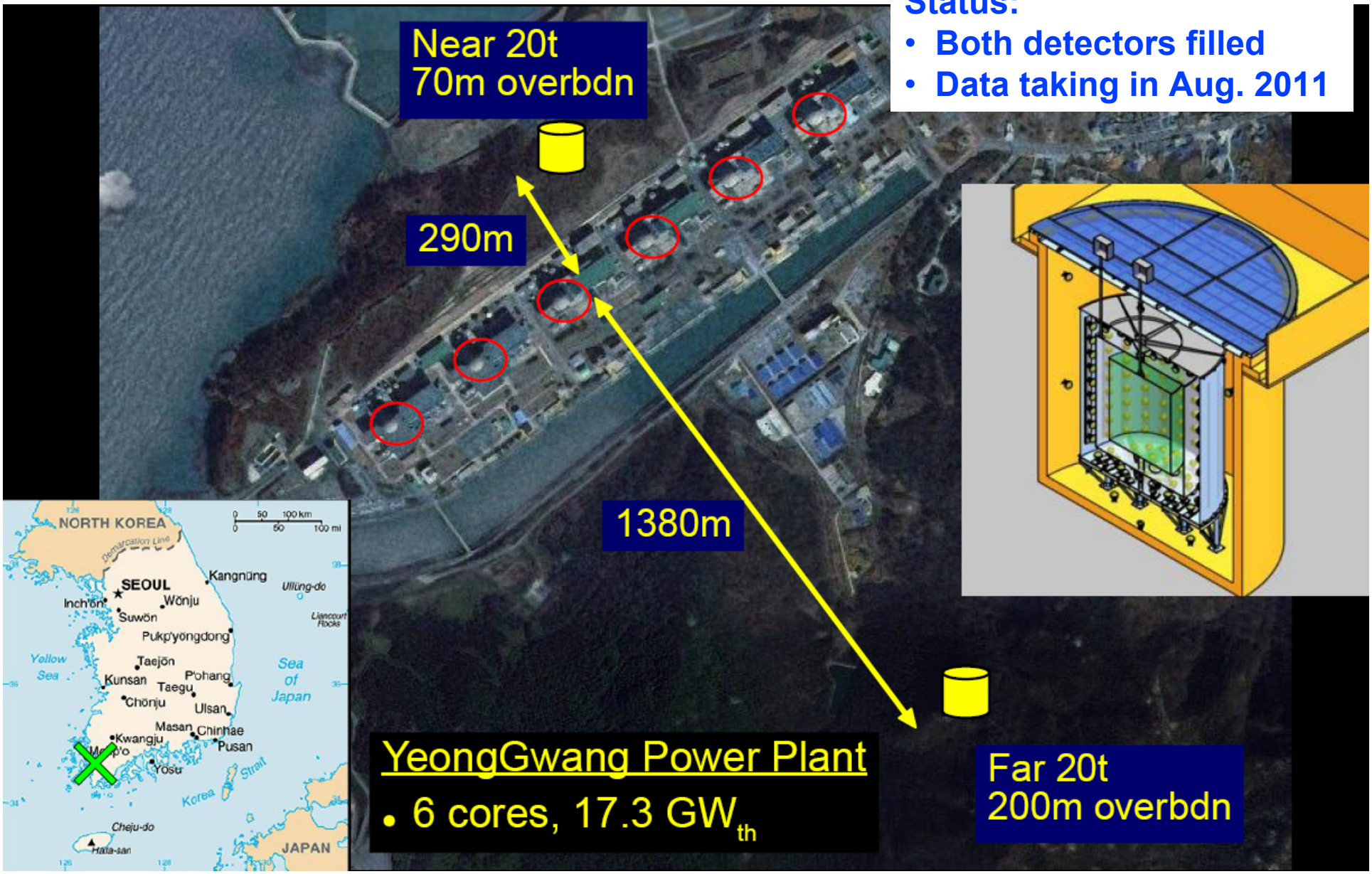
- Over 70 days of data already collected
- Rates of for prompt and delayed signals at or below expectation
  ⇒ Promising sign for low accidental rates
- Neutron-capture as expected on Gd (Target) & Hydrogen (T+GC)
- Initial data supports the prospects for DC to have a clean set of neutrino candidates soon
- The T2K central values can be addressed at 99% CL with 2011 data



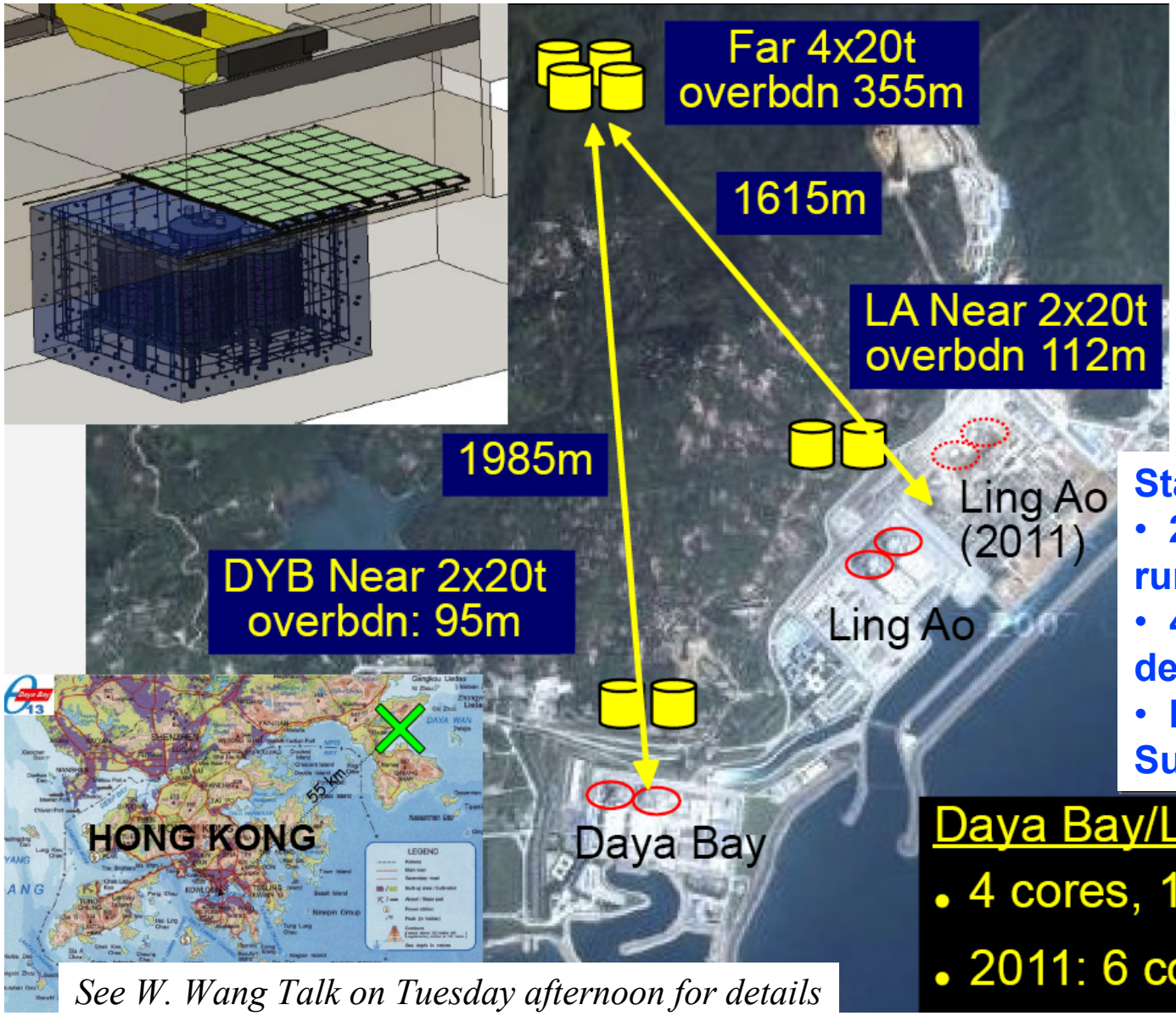


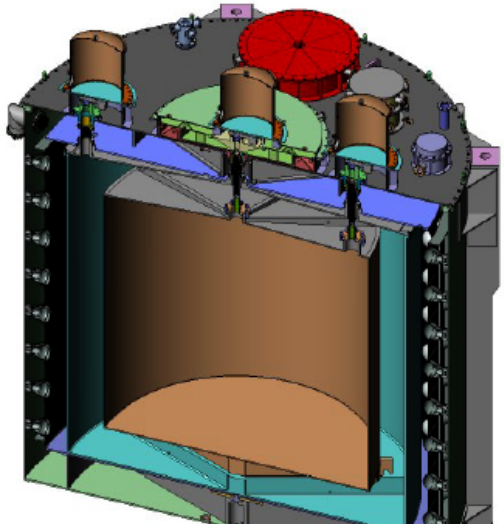
Reactor Experiment for Neutrino Oscillations at YoungGwang in Korea

Status:
- **Both detectors filled**
- **Data taking in Aug. 2011**



Daya Bay Experiment





Status:
- **2 near detectors running Summer 2011**
- **4 far detectors deployed in 2012**
- **Data taking to start in Summer 2012**

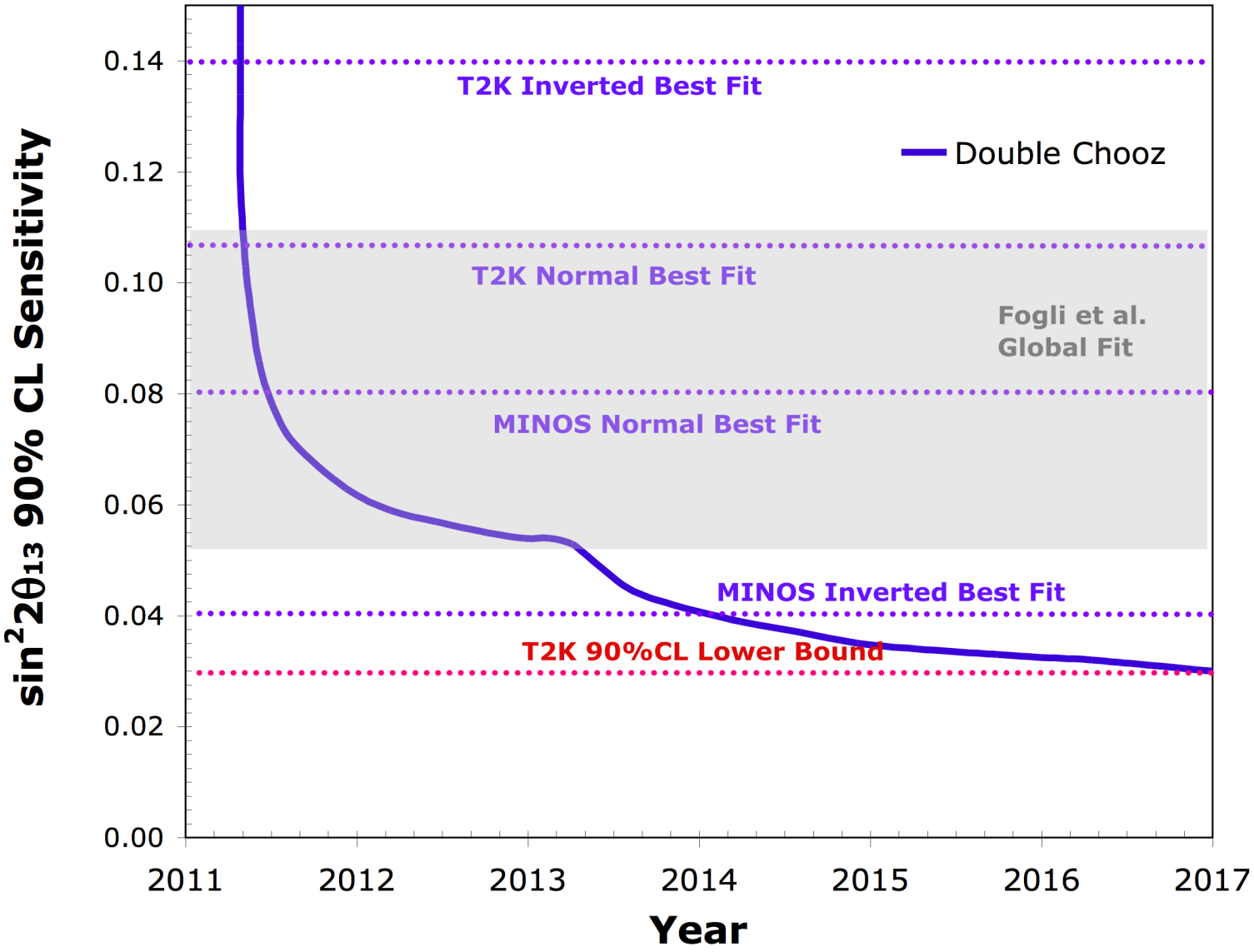
Daya Bay/Ling Ao Power Plant
- 4 cores, 11.6 GW_{th}
- 2011: 6 cores, 17.4 GW_{th}

See W. Wang Talk on Tuesday afternoon for details

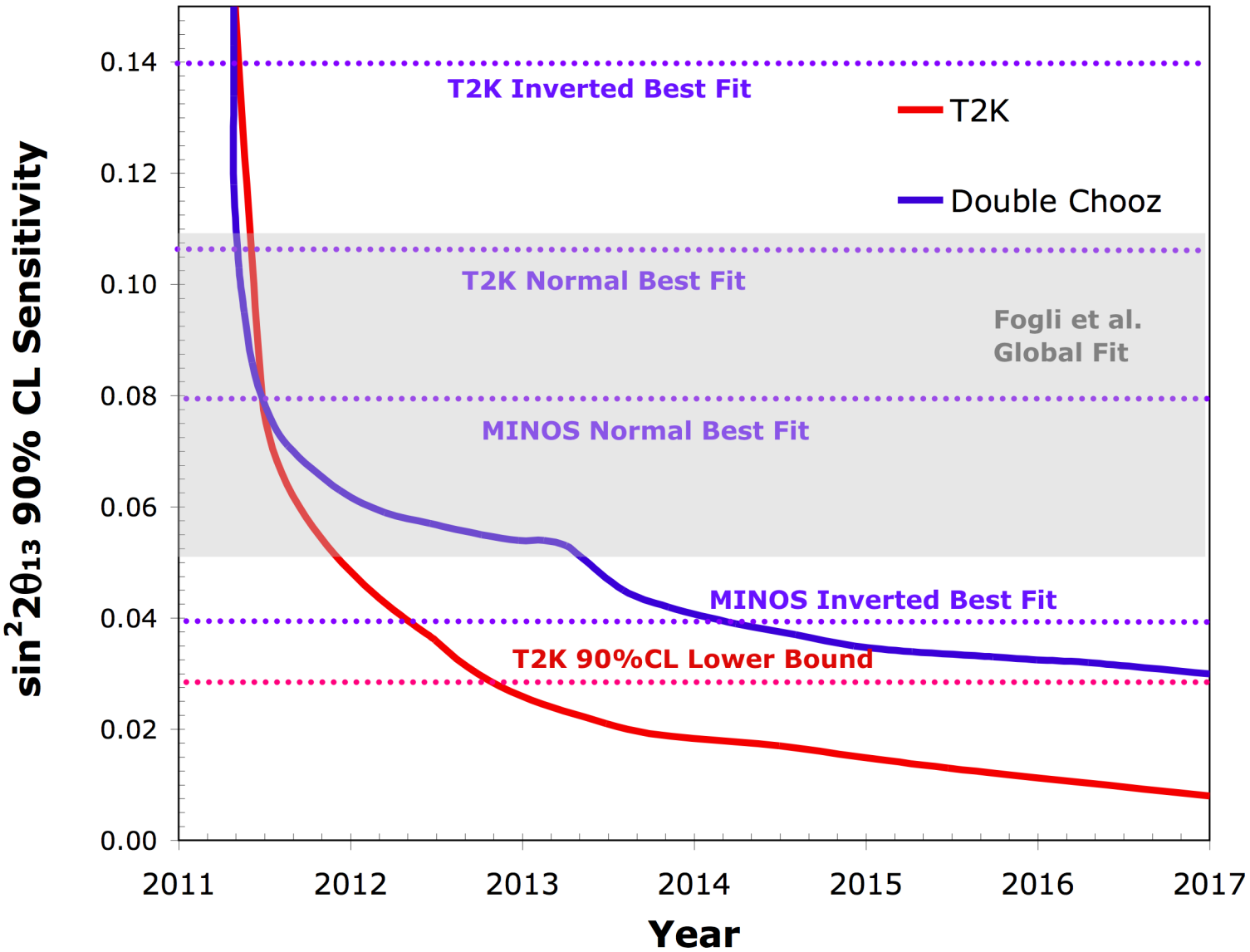
Expected Sensitivities

Expt	σ_{stat} [%]	σ_{syst} rel. [%]	$\sin^2 2\theta_{13}$ > (90% CL)
Double Chooz	0.5	0.6	0.03
RENO	0.3	0.5	0.02
Daya Bay	0.2	0.4	0.01

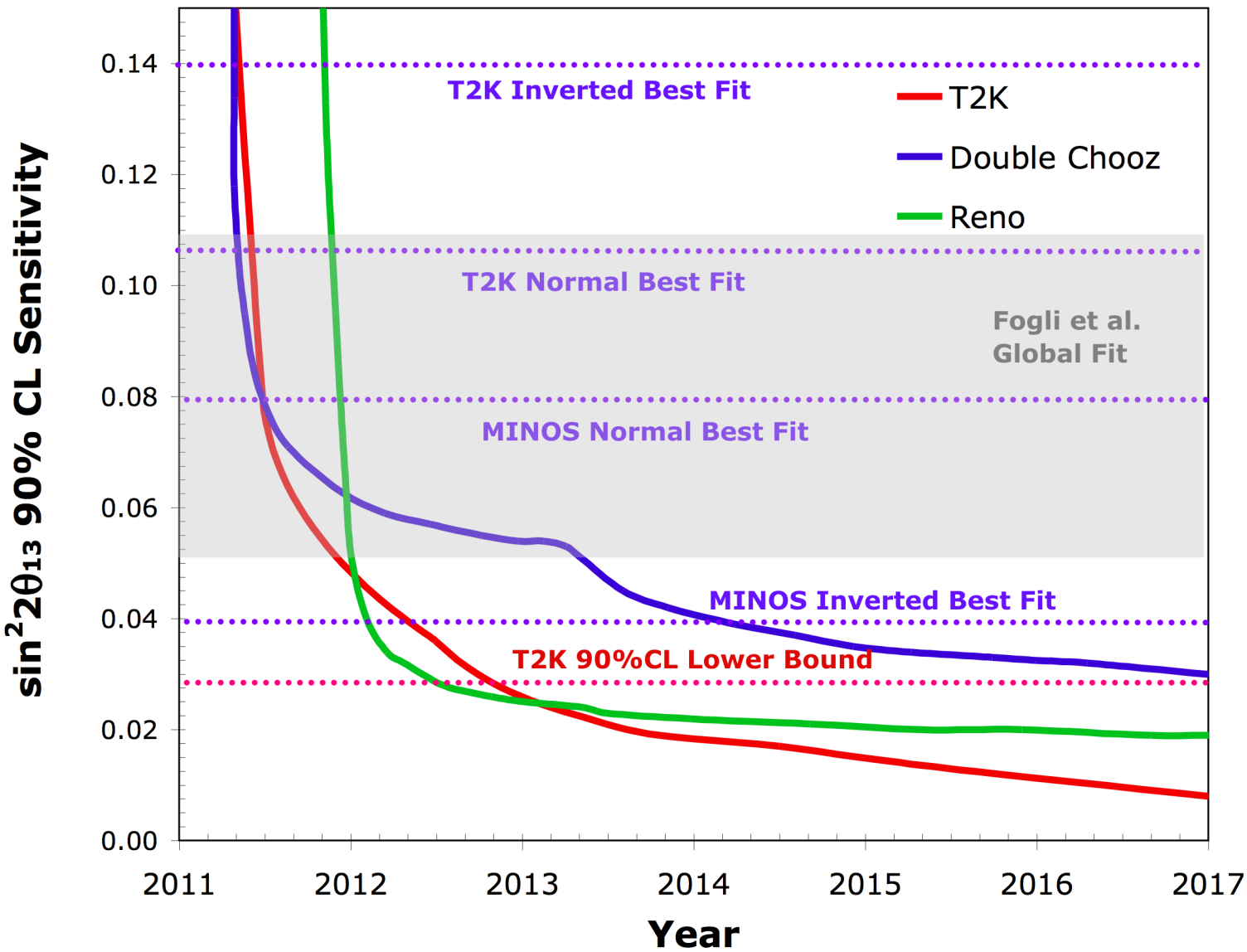
90%CL Sensitivity Estimates vs Year



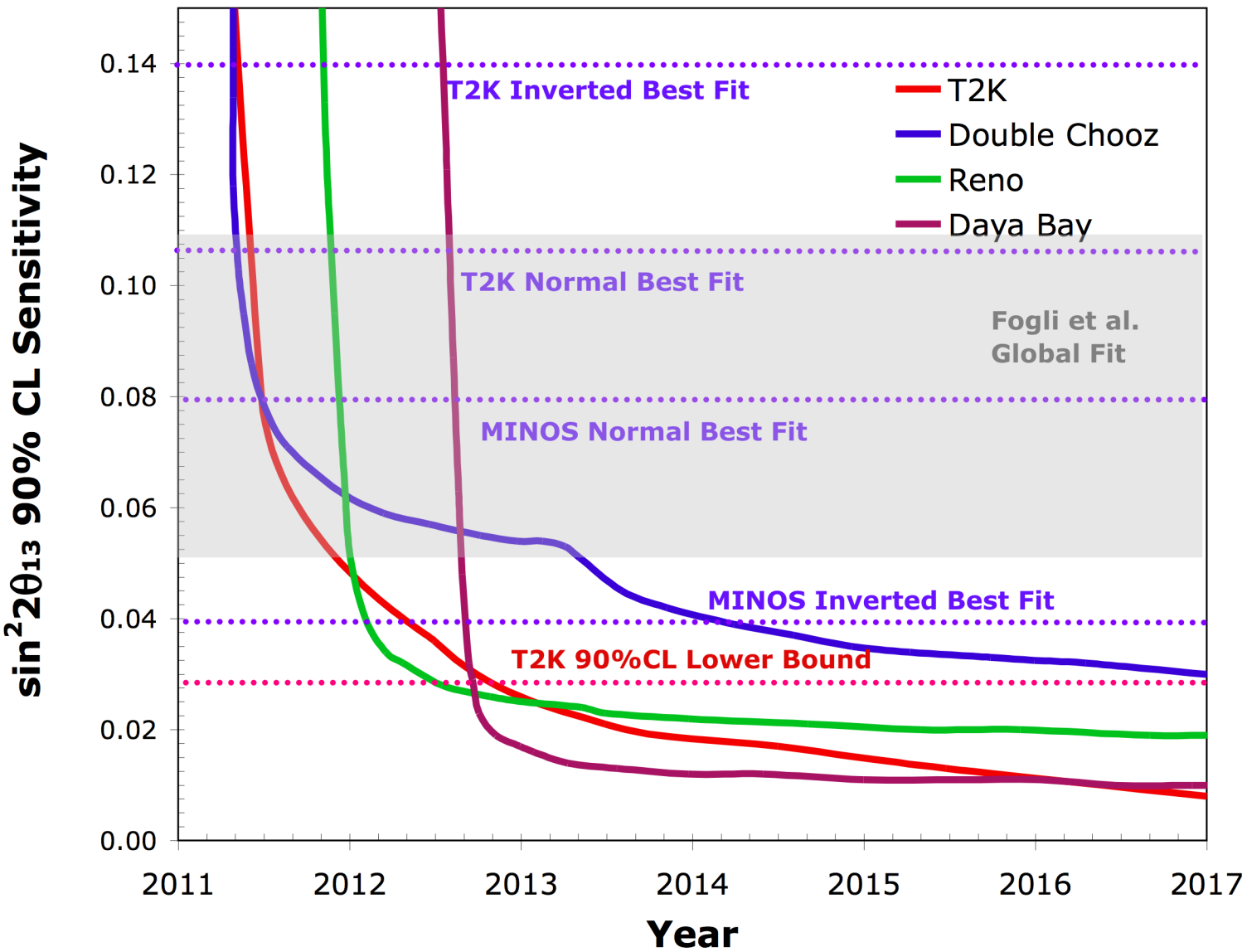
90%CL Sensitivity Estimates vs Year



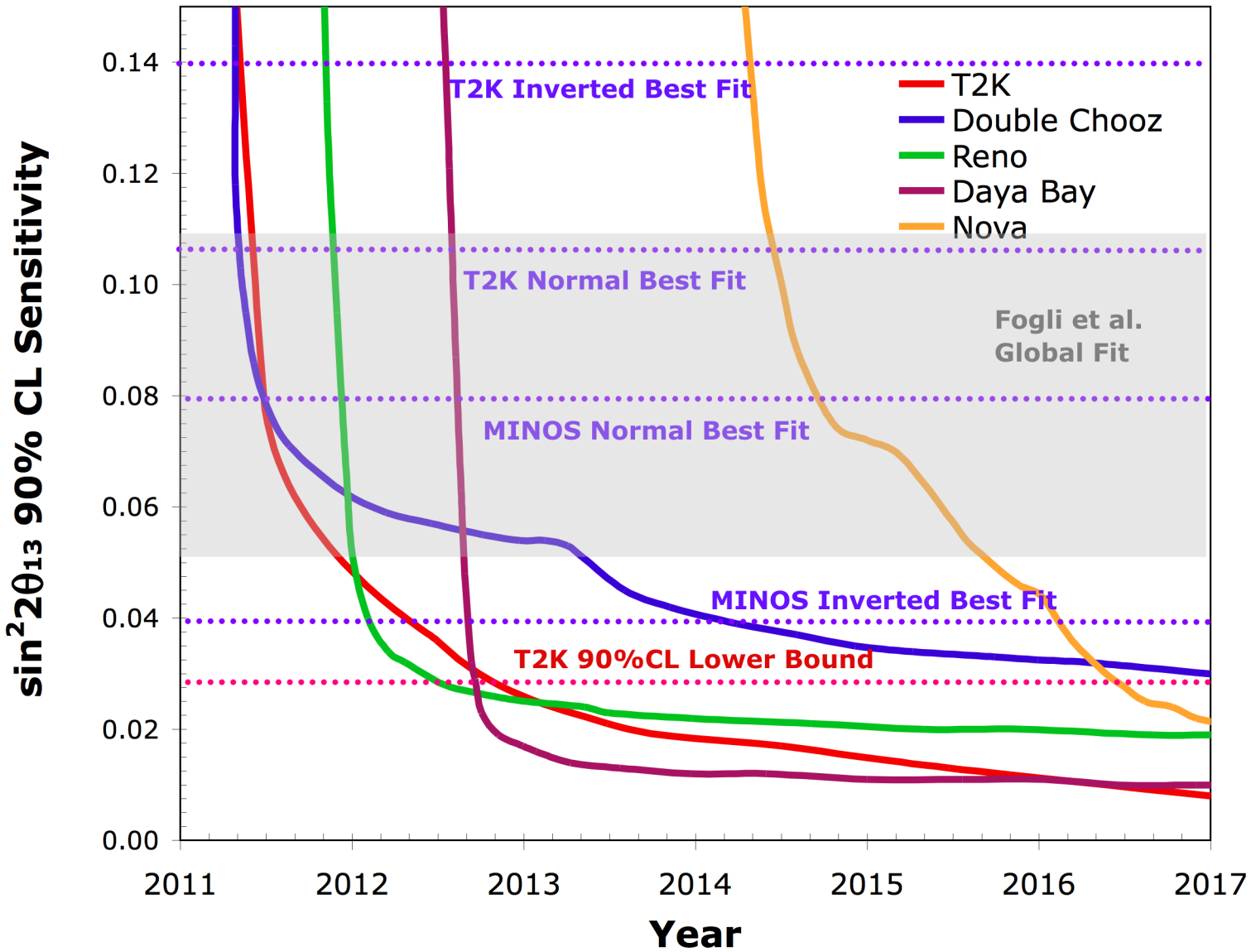
90%CL Sensitivity Estimates vs Year



90%CL Sensitivity Estimates vs Year



90%CL Sensitivity Estimates vs Year



Moving on to Measuring the Mass Hierarchy and CP Violation

Measure CP Violation by Comparing $\nu_\mu \to \nu_e$ versus $\bar{\nu}_\mu \to \bar{\nu}_e$

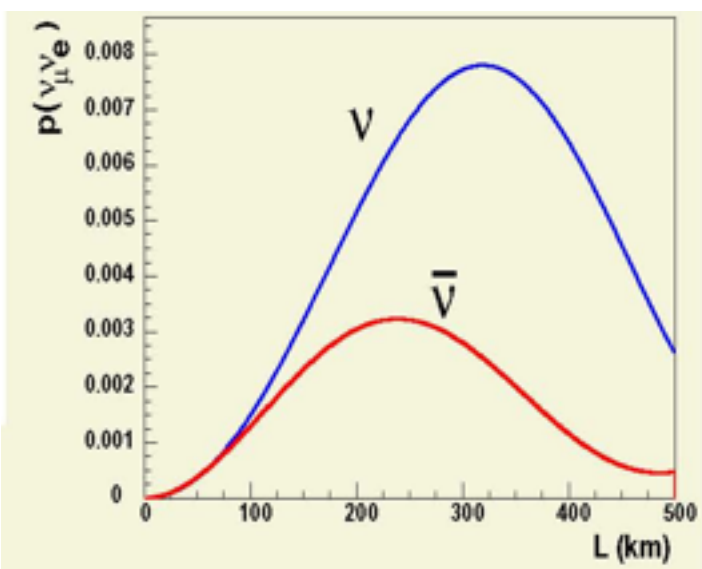
$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CPeven}$$

$$\pm 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$\pm 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) \qquad \text{matter effect (CP odd)}$$



Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \neq 0$$

Opportunities with Current Program Data

Combine T2K, NOvA, and Reactor Data

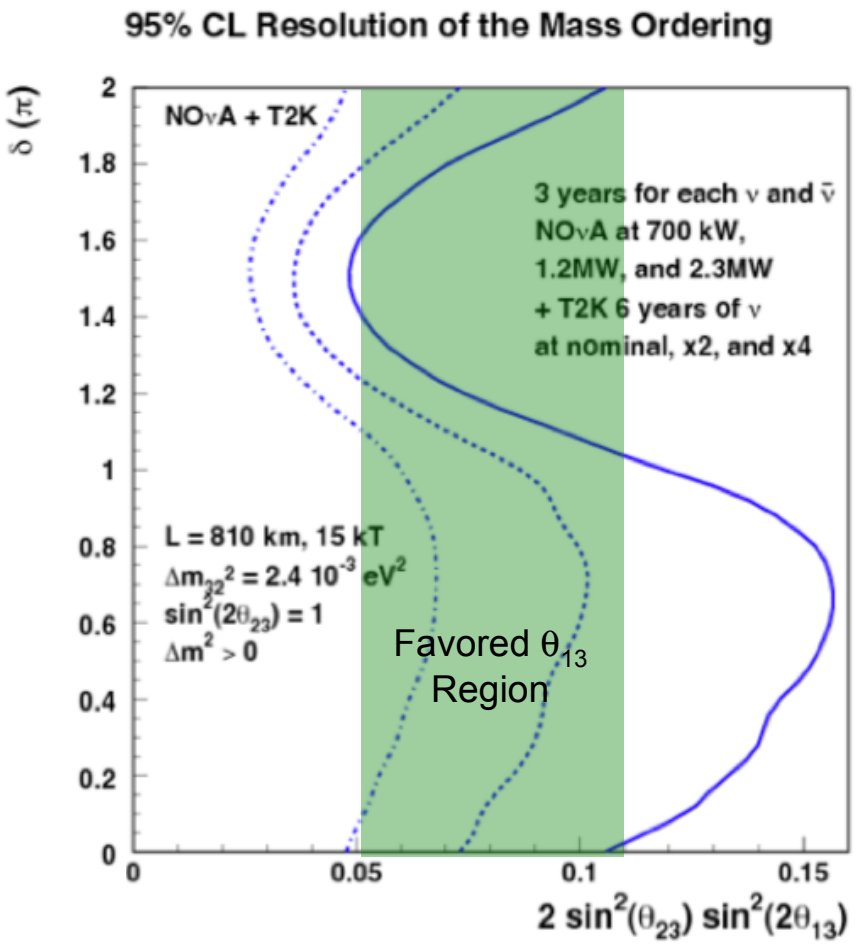
Examples:

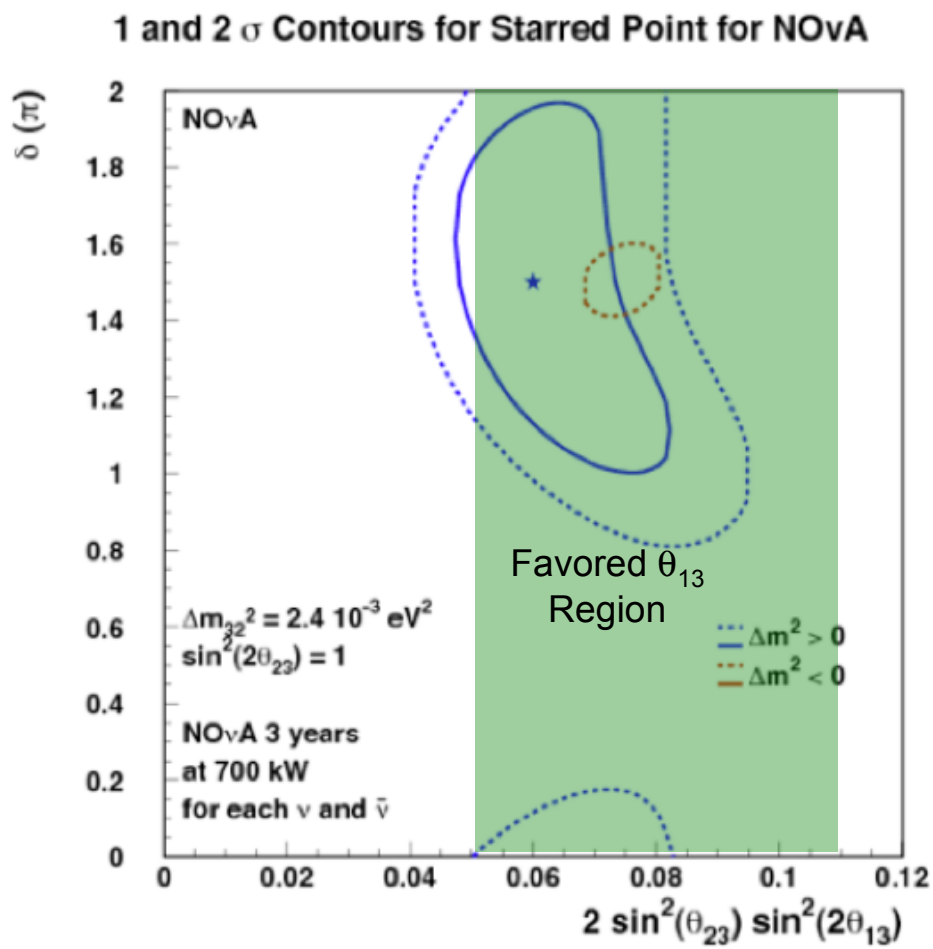
Measuring the mass hierarchy:

Compare NOvA appearance with matter effects to T2K appearance measurement without matter effects

Measuring CP violation:

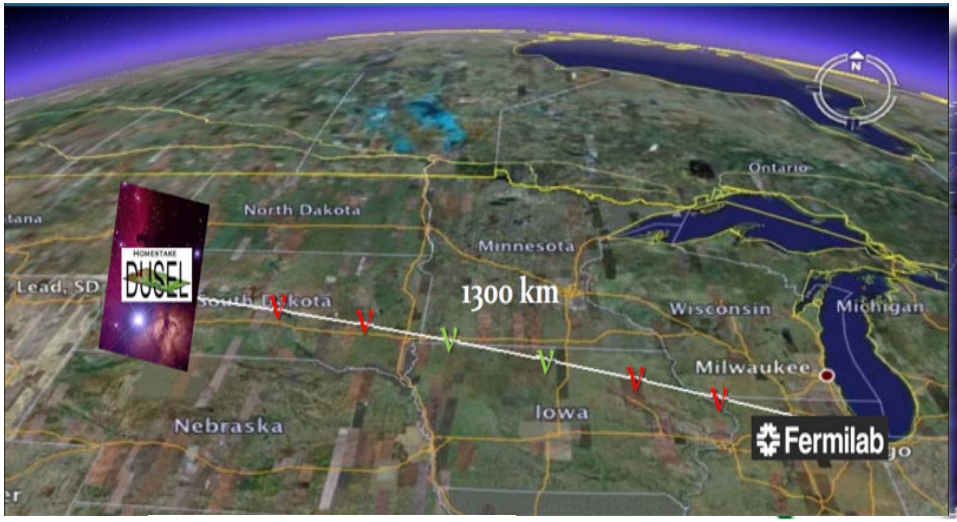
Compare NOvA neutrino and antineutrino appearance measurements.



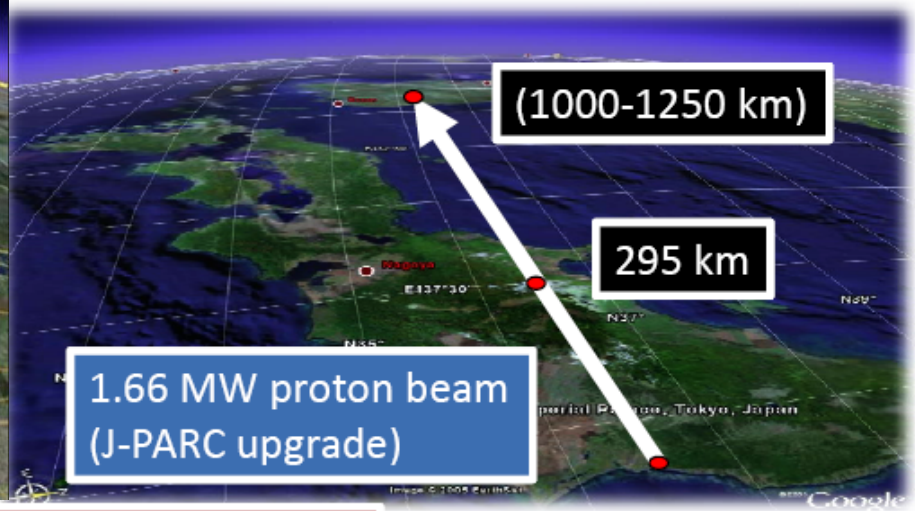


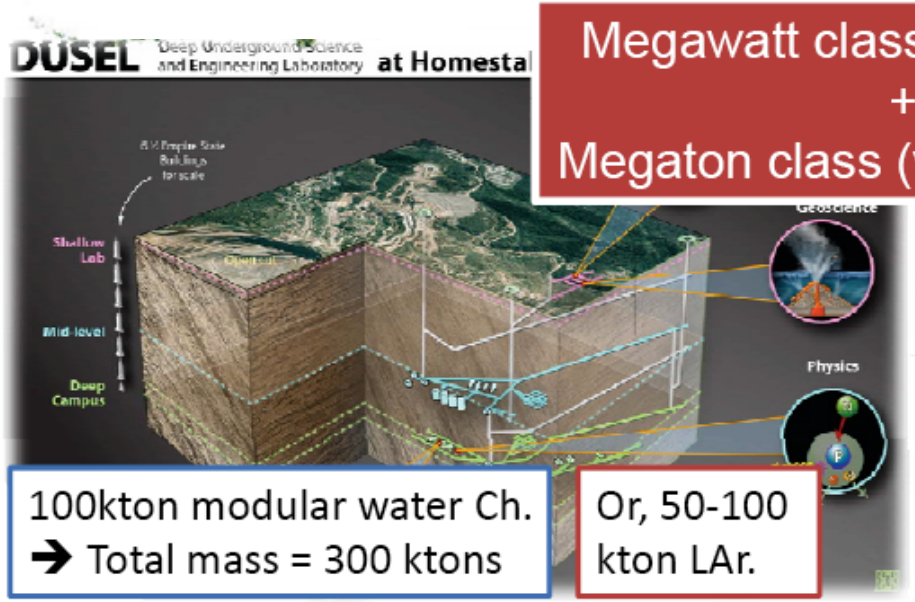
Future Longbaseline Experiments

Homestake Long Baseline Experiment

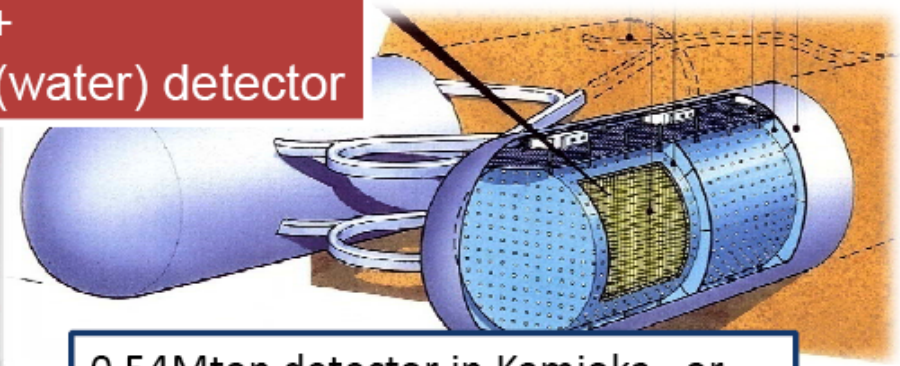


HyperK Long Baseline Experiment





Megawatt class super-beam
+
Megaton class (water) detector



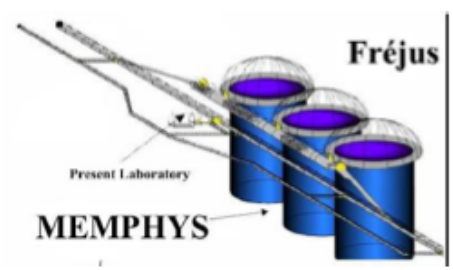
100kton modular water Ch.
➔ Total mass = 300 ktons

Or, 50-100 kton LAr.

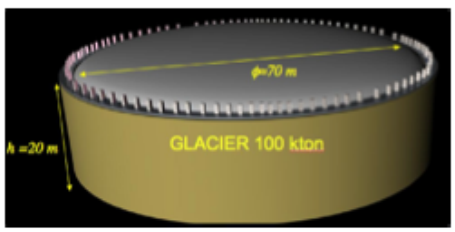
0.54Mton detector in Kamioka, or 0.27 Mton water Cherenkov detector in Kamioka and Korea.

European Design Study - LAGUNA

(Large Apparatus for Grand Unification and Neutrino Astrophysics)



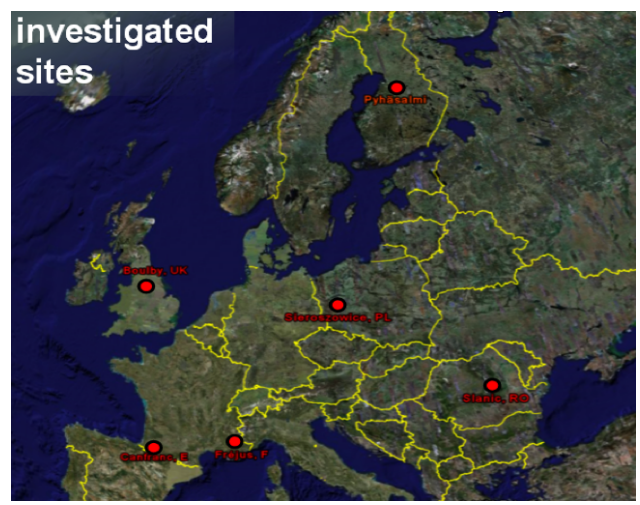
- MEMPHYS - MEgaton Mass PHYSics
  - tanks of 60 m heigth ×65 m ∅
  - ∼440 kt water Cherenkov detector



- GLACIER - Giant Liquid Argon Charge Imaging ExpeRiment
  - 20 m heigth ×70 m ∅
  - ∼ 100 kt liquid Ar TPC

- LENA - Low Energy Neutrino Astronomy
  - 100 m long × 30 m ∅
  - ∼ 50 kt liquid scintillator

Possible sites for a program with a neutrino beam from CERN

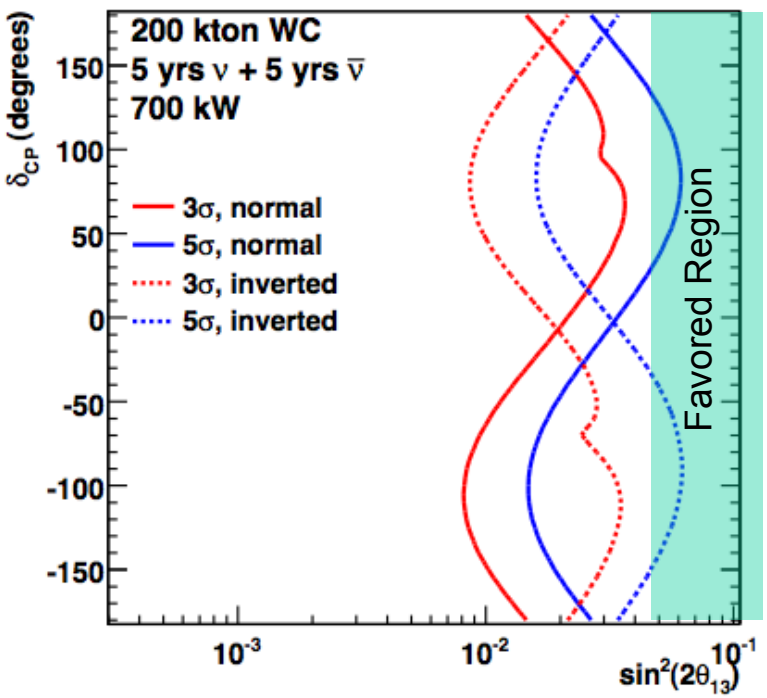


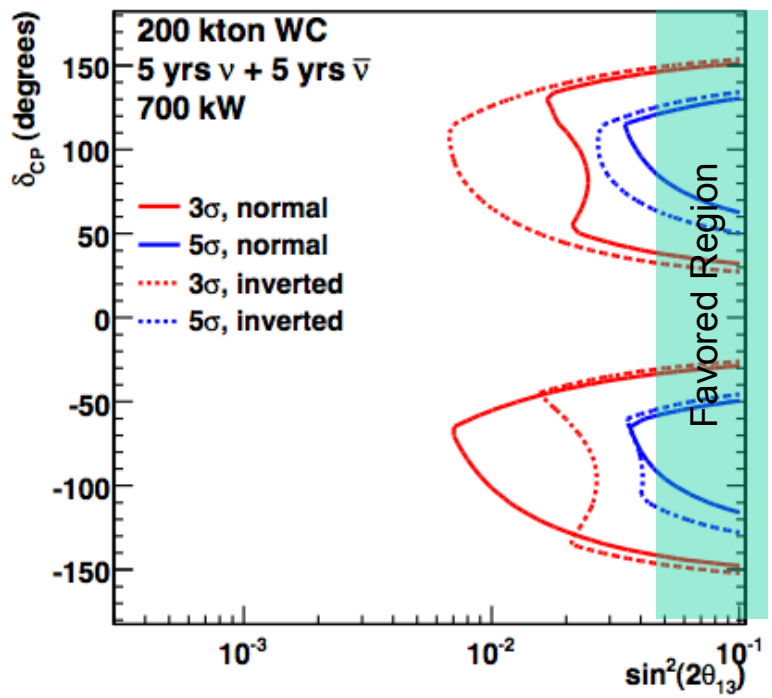
Sensitivity for Determining Mass Hierarchy and CP

Homestake (DUSEL) Long Baseline Experiment (LBNE)

200 kt WCD detector and 5 yrs of ν + 5 yrs of $\bar{\nu}$ running with 700kW:

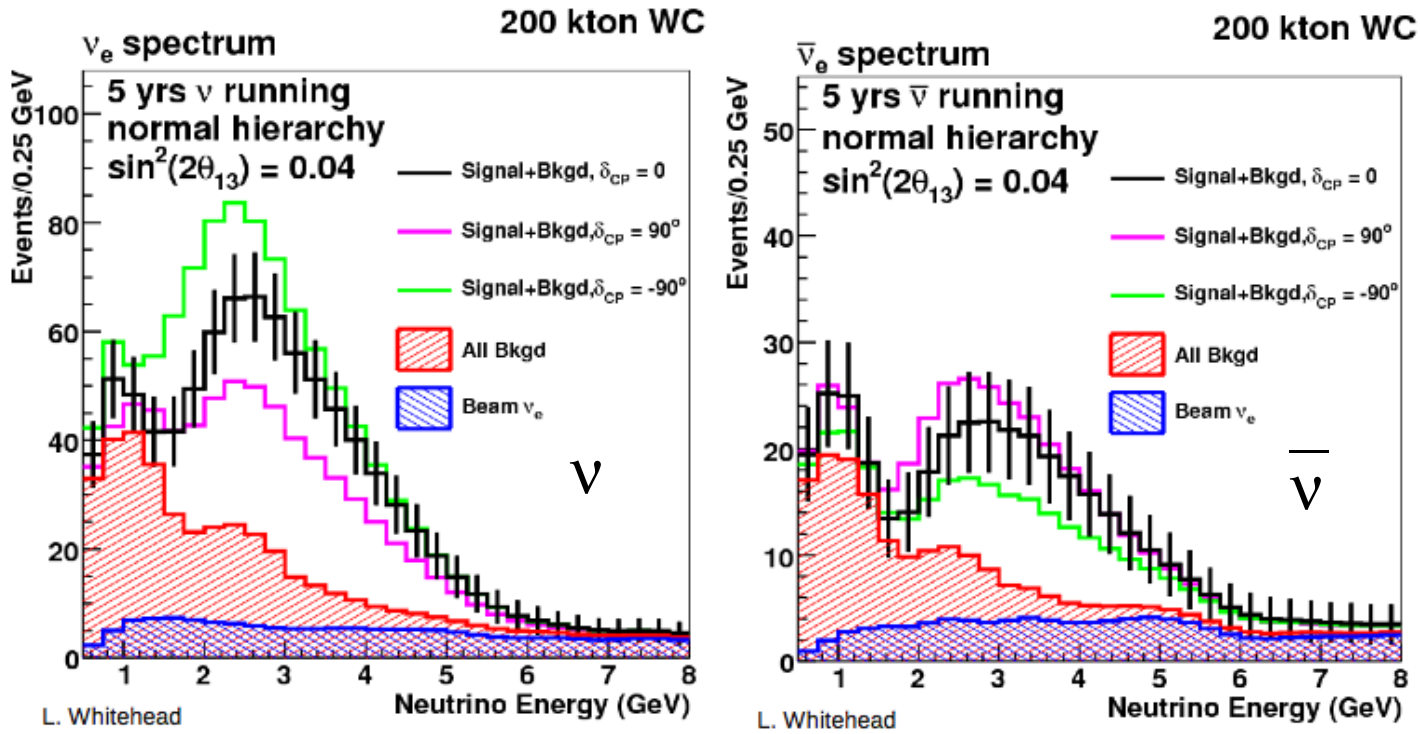
Mass Hierarchy **CP Violation**





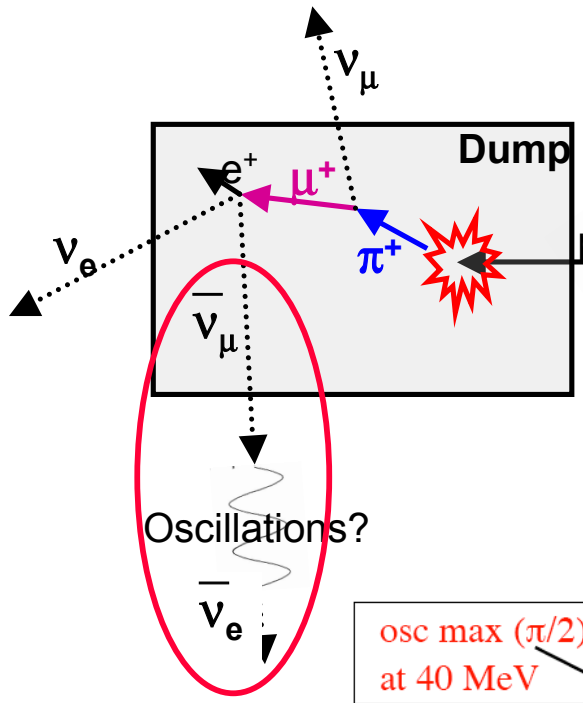
Limitations of LBNE Approach

Long Baseline experiments are usually low in antineutrino statistics
→ due to lower π^- production and $\bar{\nu}$ cross section

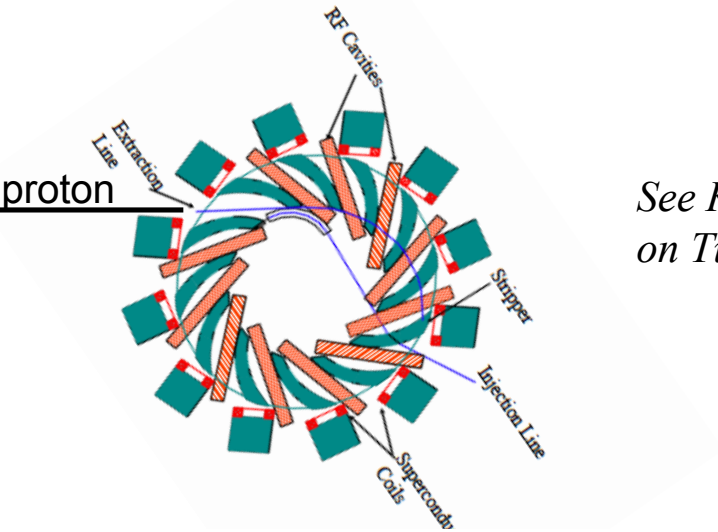


… and the backgrounds are large compared to signal

Daedalus Experiment: Antineutrino Source for CP Measurements

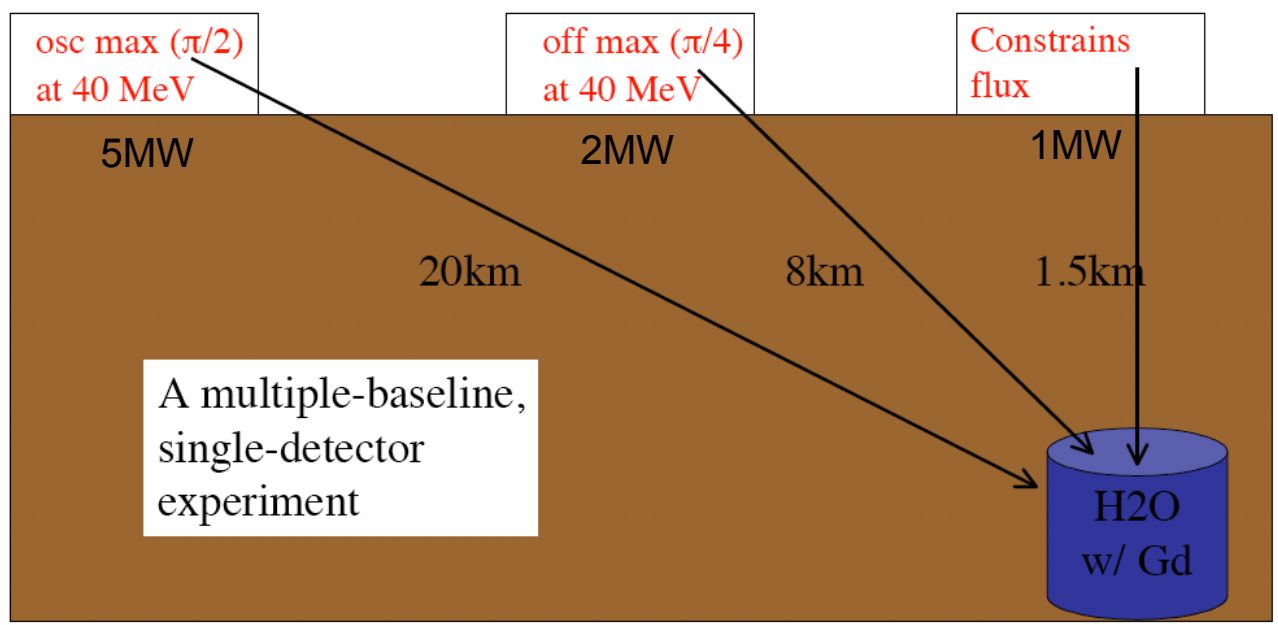


Cyclotron (~800 MeV KE proton)



See K. Scholberg talk on Tues. afternoon

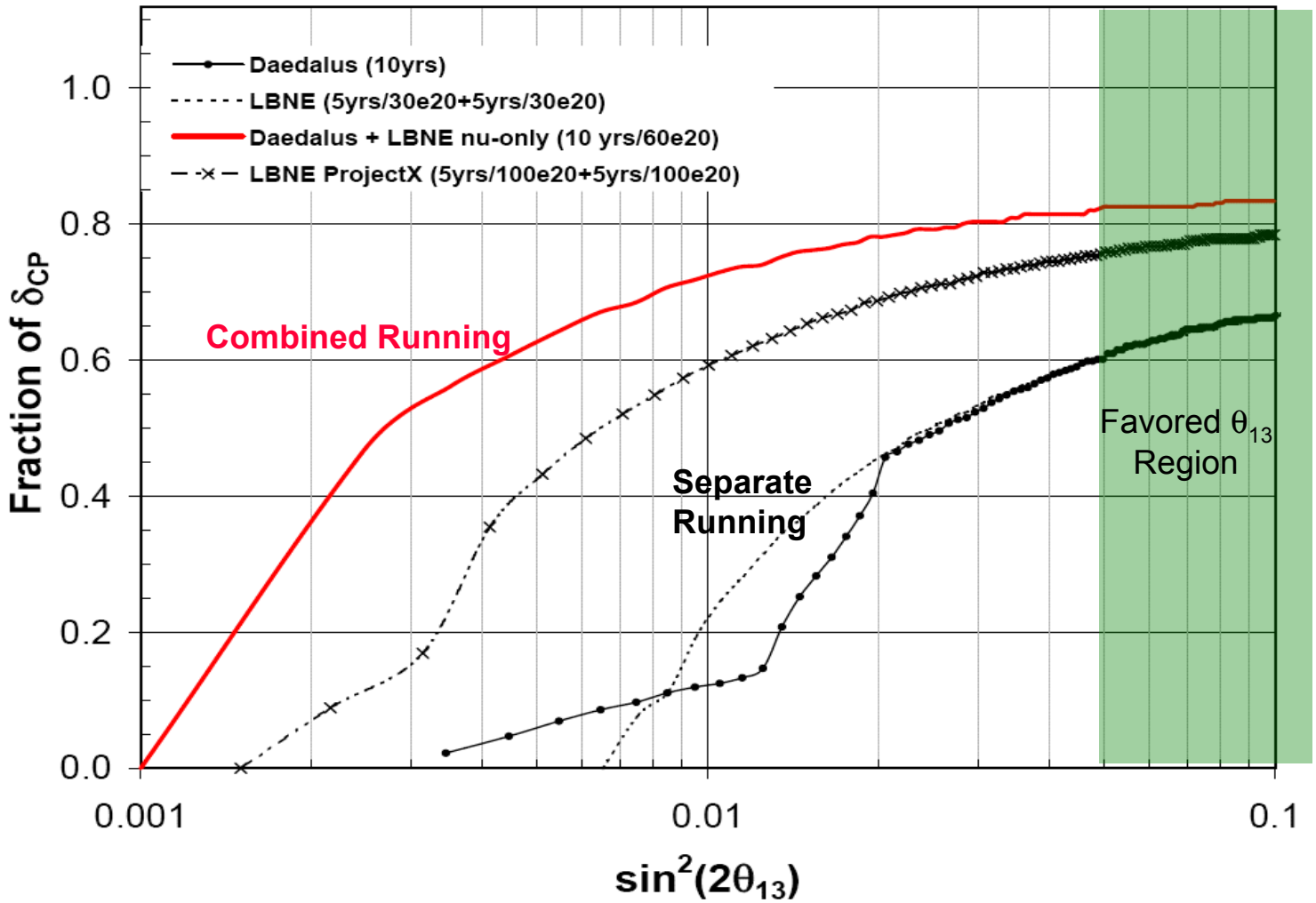
- Combine:
  - High statistics Daedalus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - High statistics Longbaseline $\nu_\mu \rightarrow \nu_e$



(Described in: Conrad/Shaevitz, PRL104,141802 (2010), Alonso et al., arXiv:1006.0260 [physics.ins-det] and 1008.4967 [hep-ex])

Exclusion of δ_{CP}= 0^0 or 180^0 at 3σ

Combined running LBNE plus Daedalus gives best sensitivity

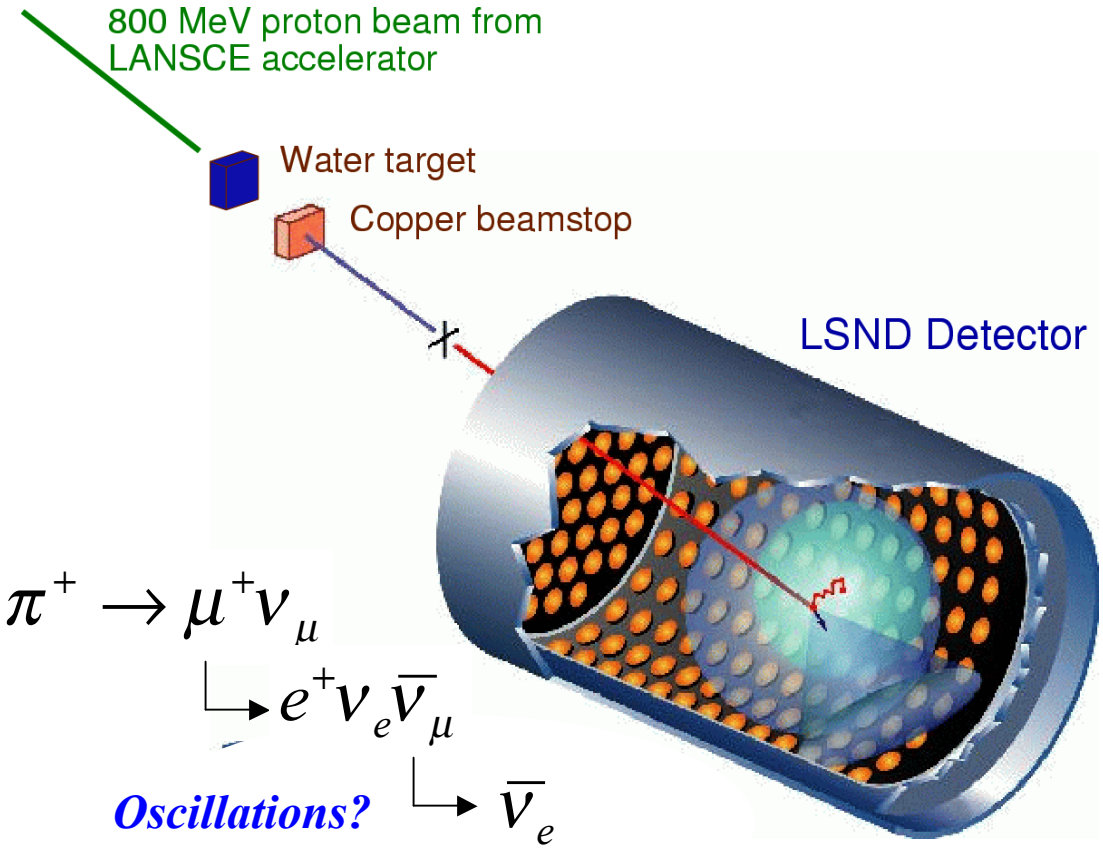


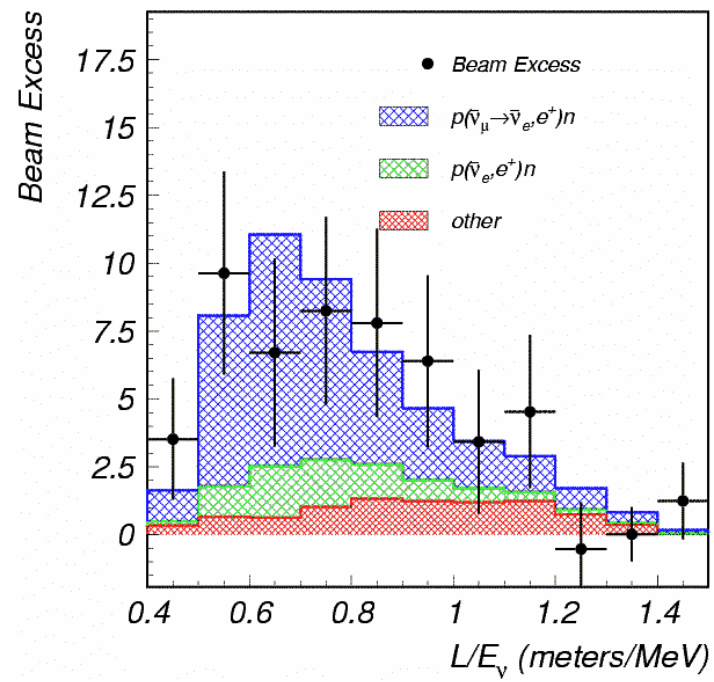
Possible Oscillations to Sterile Neutrinos

Sterile neutrinos

- Have no weak interactions (through the standard W/Z bosons)
- Would be produced and decay through mixing with the standard model neutrinos
- Can affect oscillations through mixing

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Signal





Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

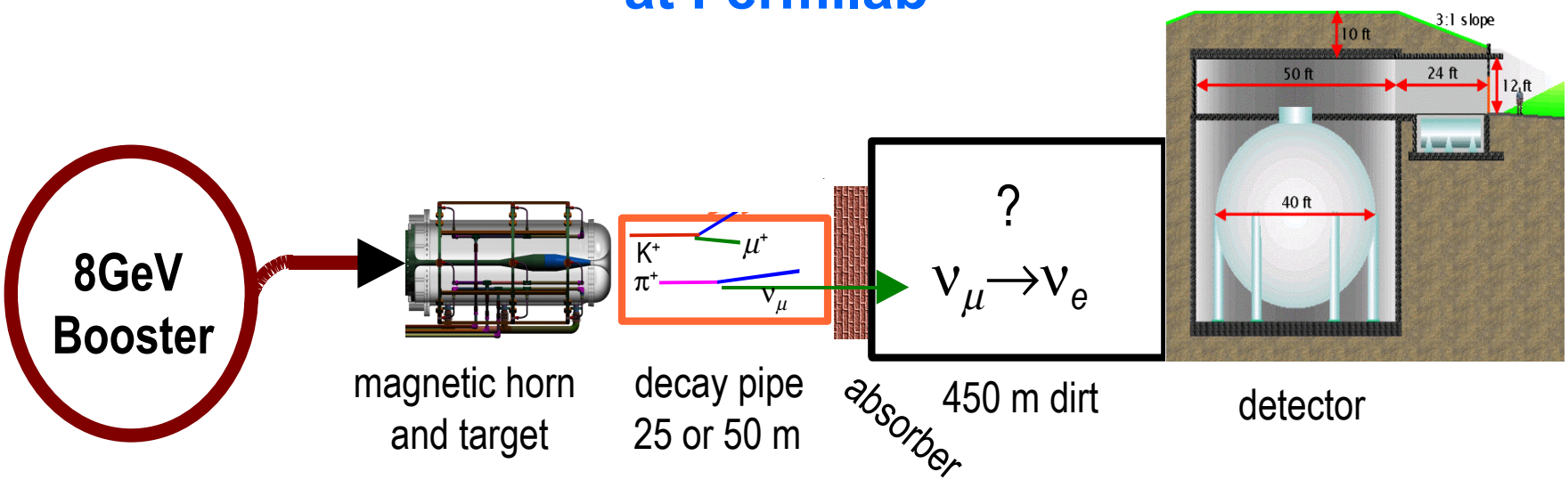
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

LSND in conjunction with the atmospheric and solar oscillation results needs more than 3 ν's

⇒ Models developed with 1 or 2 sterile ν's

The MiniBooNE Experiment at Fermilab

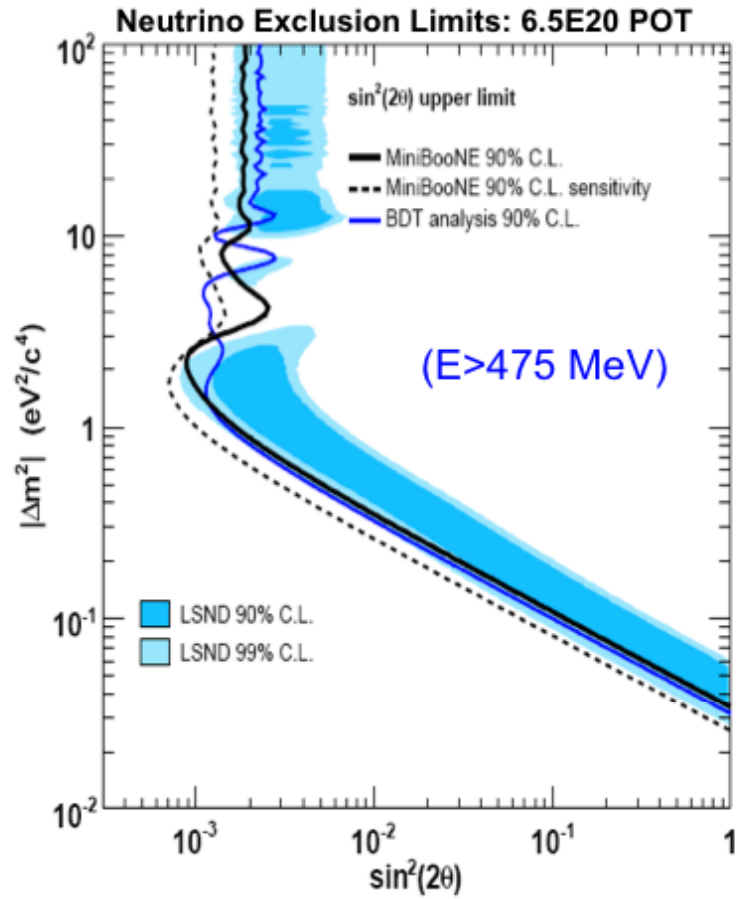


- Goal to confirm or exclude the LSND result - Similar L/E as LSND
  - Different energy, beam and detector systematics
  - Event signatures and backgrounds different from LSND

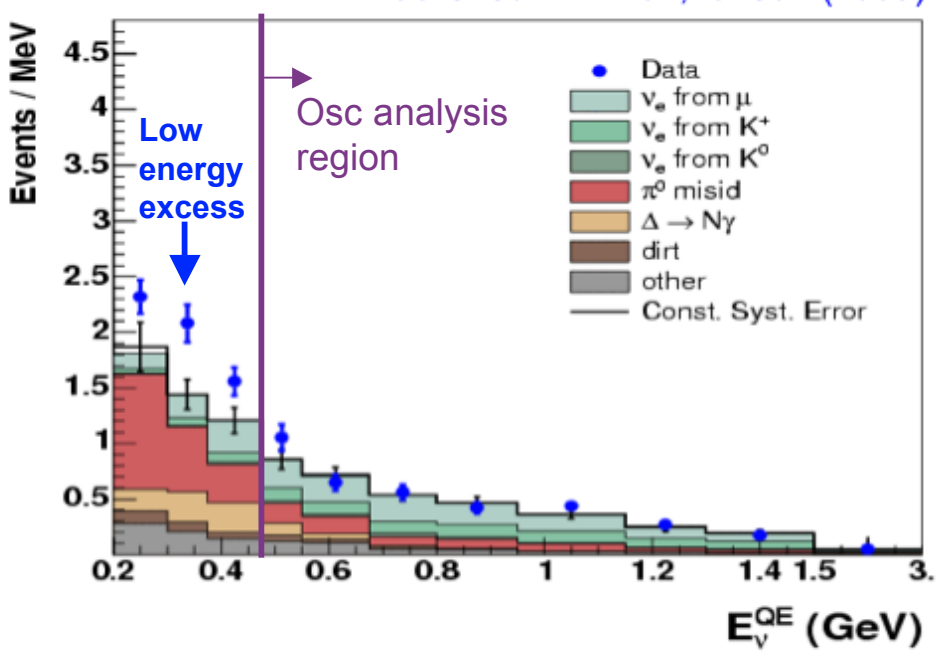
- Since August 2002 have collected data:
  - 6.5×10^{20} POT ν
  - 8.6×10^{20} POT $\bar{\nu}$

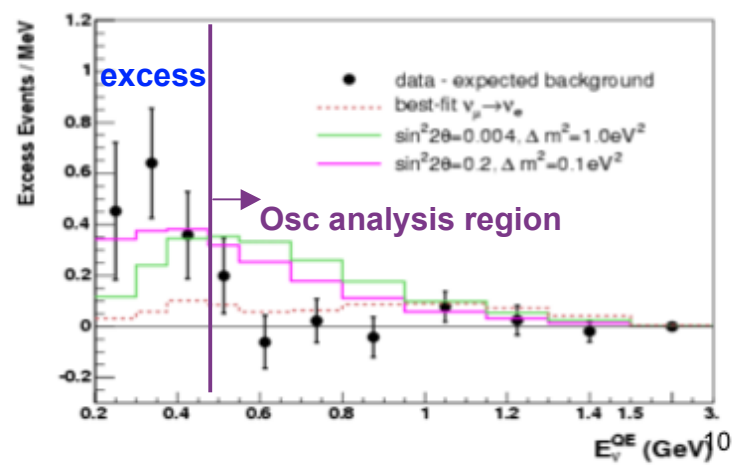
MiniBooNE neutrino-mode results (2009)

- E > 475 MeV data in good agreement with background prediction.
  - A two neutrino fit is inconsistent with LSND at the 90% CL assuming CP conservation.
- E < 475 MeV shows a 3σ excess at low enegy
  - The total excess of 129 ± 43 (stat+syst) is consistent with magnitude of LSND signal



Published PRL 102,101802 (2009)

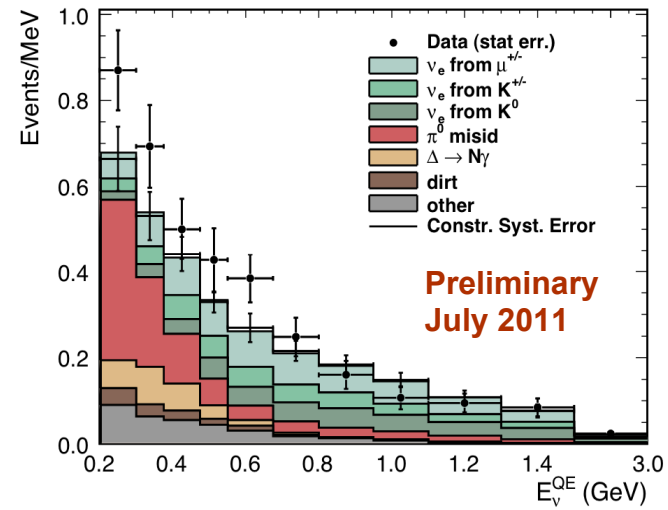


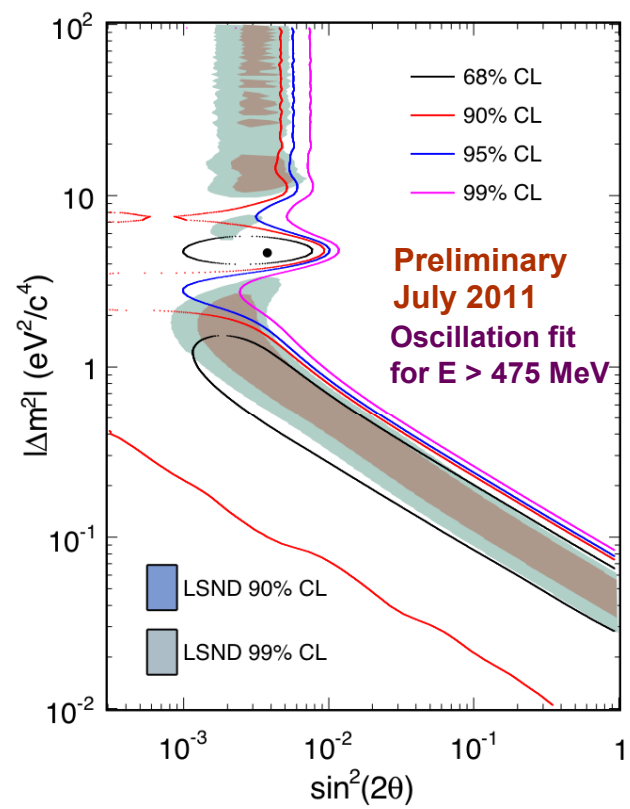


See E. Zimmerman talk yesterday for details

Updated MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Result

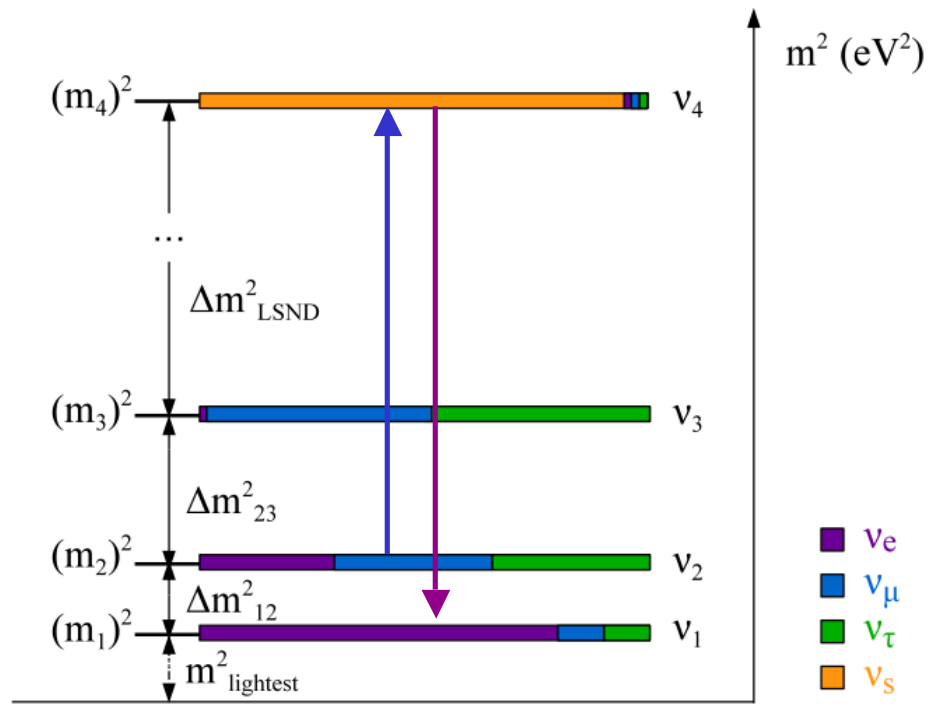
- Updated result from previous publication
  - 5.66E20 ⇒ 8.58E20 protons-on-target (x1.5)
  - Reduced systematic uncertainties especially backgrounds from beam K^+ decays
- For E > 475 MeV (>200 MeV), oscillations favored over background only (null) hypothesis at the 91.1% CL (97.6% CL)
  - Consistent with LSND but less strong than previous result (99.4%)
  - Best fit: χ^2 prob. = 35.5% (51%)
    Null: χ^2prob. = 14.9% (10%)
- Low energy excess now more prominent for antineutrino running than previous result
  - For E< 475 MeV, excess = 38.6 ± 18.5
    (For all energies, excess = 57.7 ± 28.5)
  - Neutrino and antineutrino results are now more similar.
- MiniBooNE will continue running through spring 2012 (at least) towards the request of 15E20 pot (~x2 from this update)
  - Full data set will probe LSND signal at the 2-3 sigma level





Phenomenology of Oscillations with Sterile Neutrinos (3+1 Models)

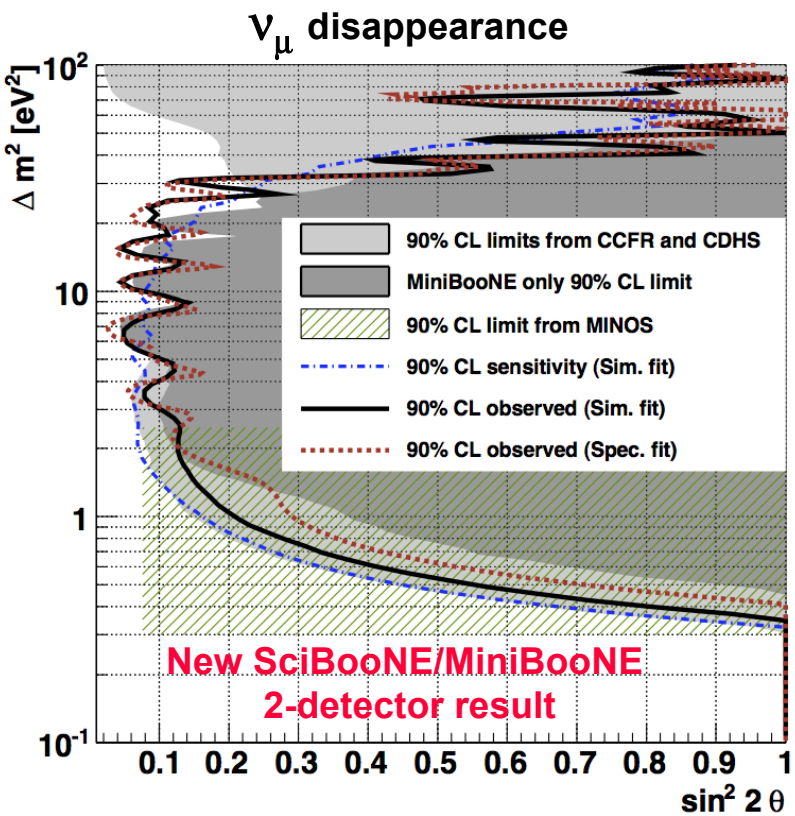
- In sterile neutrino (3+1) models, high Δm^2 ν_e appearance comes from oscillation through ν_s
  - $\nu_\mu \rightarrow \nu_e = (\nu_\mu \rightarrow \nu_s) + (\nu_s \rightarrow \nu_e)$
- This then requires that there be ν_μ and ν_e disappearance oscillations
  - Limits on disappearance then restrict any (3+1) models



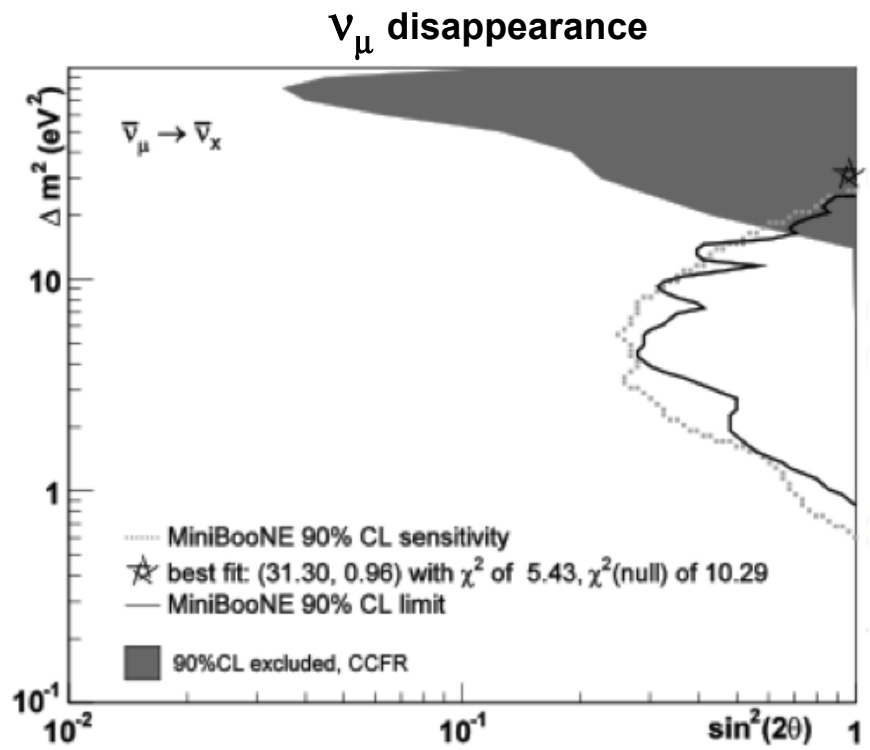
Stringent limits on ν_μ disappearance from experiments

- New SciBooNE/MiniBooNE ν_μ disappearance limit event stronger
- Less stringent limits for $\bar{\nu}_\mu$ Disappearance
- CPT conservation implies ν_μ and $\bar{\nu}_\mu$ disappearance are the same

$\Rightarrow$ **Restricts application of 3+1 since ν_μ constrains $\bar{\nu}_\mu$ disappearance.**



Mahn et al. arXiv:1106.5685 [hep-ex], submitted to PRL



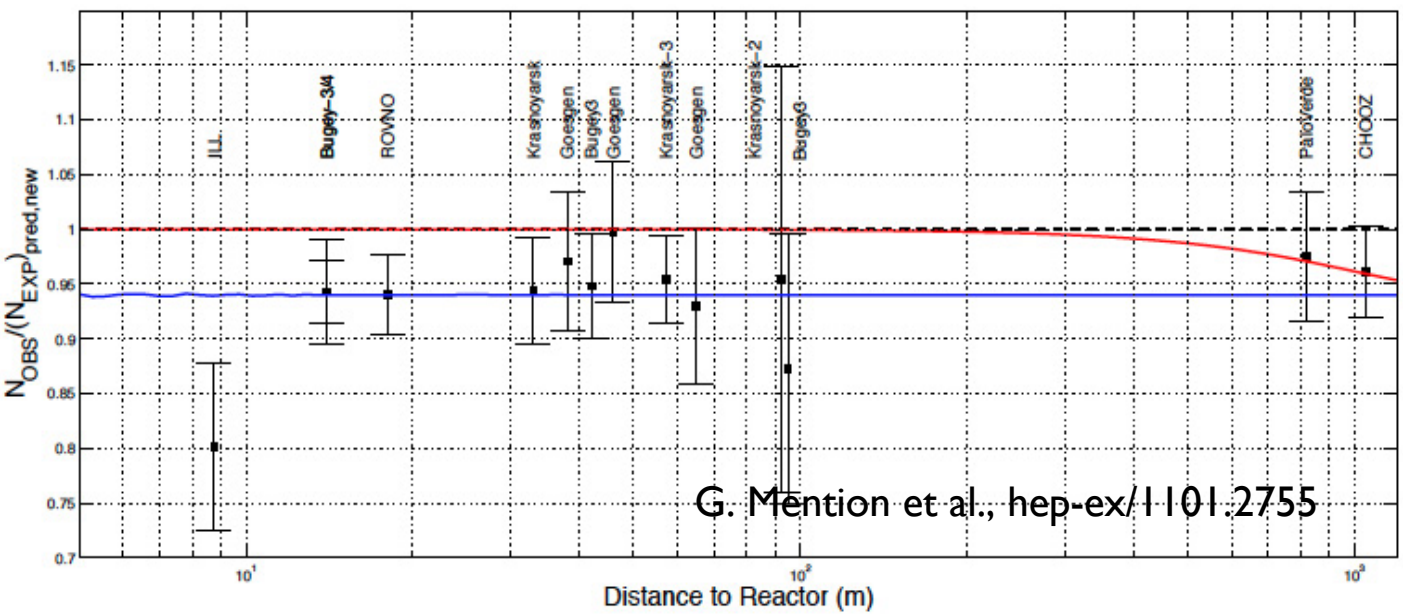
Aguilar-Arevalo et al., Phys. Rev. Lett. 103, 061802 (2009)

Possible Indication of $\bar{\nu}_e$ Disappearance

Reactor Antineutrino Anomaly

Re-analysis of predicted reactor fluxes based on a new approach for the conversion of the measured electron spectra to anti-neutrino spectra.

- Reactor flux prediction increases by 3%.
- Re-analysis of reactor experiments show a deficit of electron anti-neutrinos compared to this prediction – at the 2.14σ level
- Could be oscillations to sterile with $\Delta m^2 \sim 1 eV^2$ and $\sin^2 2\theta \sim 0.1$



Red line: Oscillations assuming 3 neutrino mixing

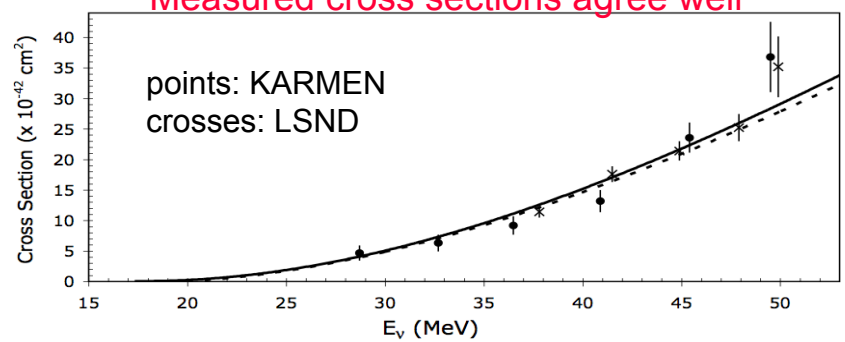
Blue line: Oscillations in a 3 + 1 (sterile neutrino) model

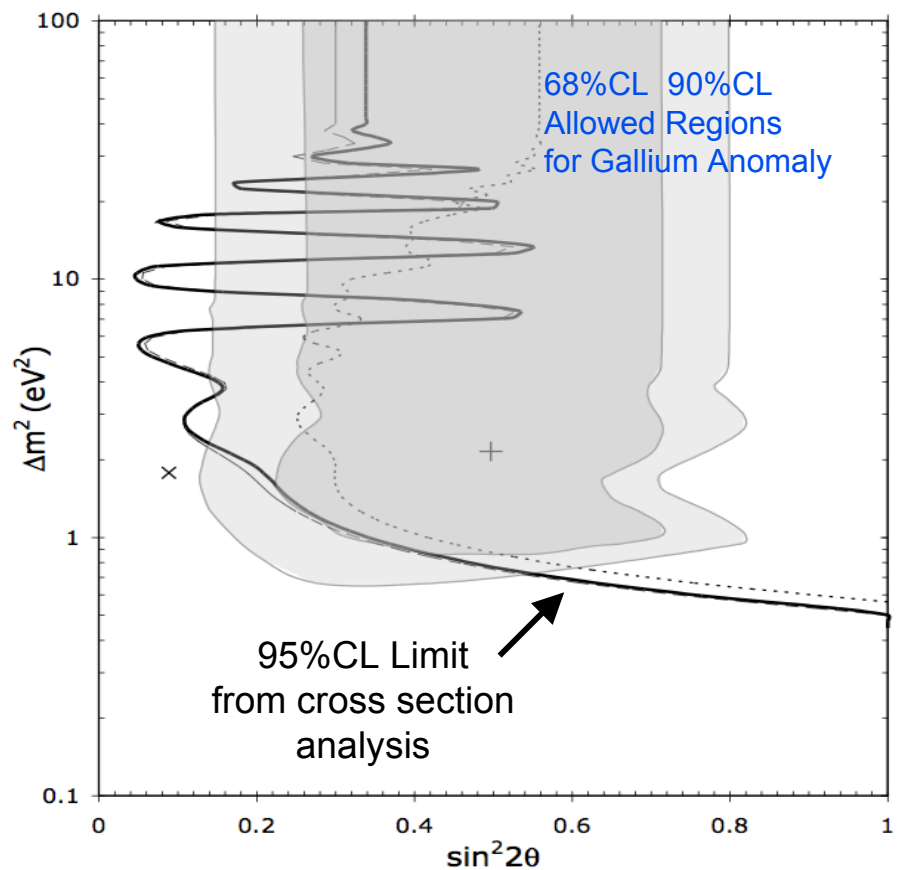
Gallium Anomaly: ν_e Disappearance?

- Gallium SAGE and GALLEX solar neutrino experiments used MCi ^{51}Cr and ^{37}Ar sources to calibrate their detectors
  - A recent analysis claims a significant (3σ) deficit
    (Giunti and Laveder, 1006.3244v3 [hep-ph])
    - Ratio (observation/prediction) = 0.76 ± 0.09
    - An oscillation interpretations gives $\sin^2 2\theta > 0.07, \Delta m^2 > 0.35 eV^2$

- Such an oscillation would change the measured ν_e-Carbon cross section since assumed flux would be wrong
  - Comparing the LSND and KARMEN measured cross sections restricts possible ν_e disappearance.
    (Conrad and Shaevitz, 1106.5552v2 [hep-ex])
    - Experiments at different distances: LSND (29.8m) and KARMEN (17.7m)

Measured cross sections agree well

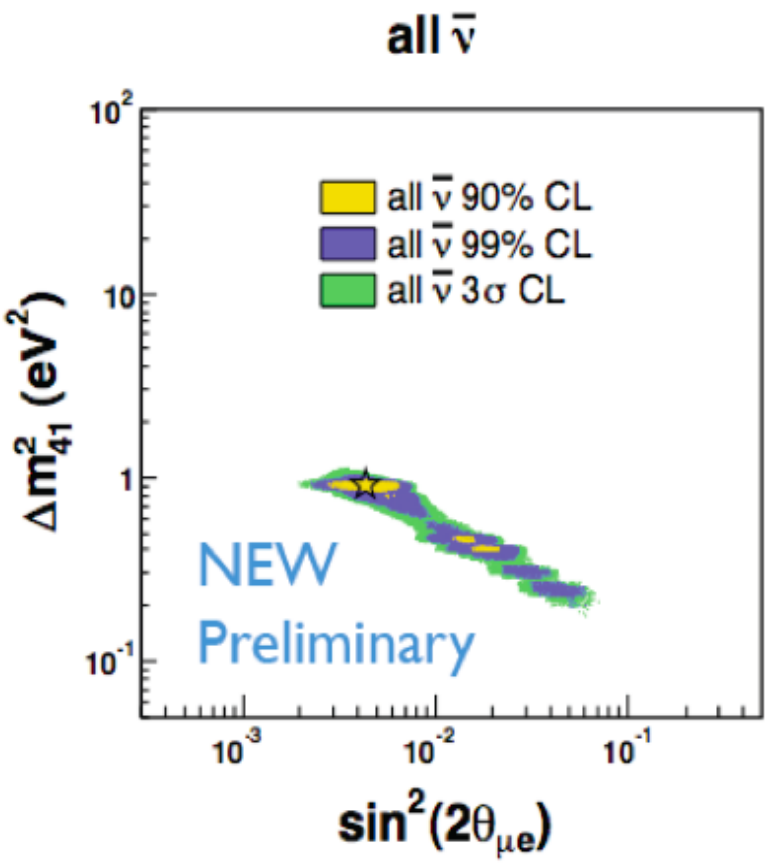




$\bar{\nu}$ – Only Data: Good 3+1 Fits with Sterile Neutrinos

- $\bar{\nu}$ Data from LSND, MiniBooNE, Karmen, Reactor
- Good fits and compatibility for antineutrino - only data.
- MiniBooNE ν_e appearance and CDHS ν_μ disappearance do not fit

  $\Rightarrow$ Need CP (and maybe CPT) violation $\Rightarrow$ 3+2 Model



From Georgia Karagiorgi
Columbia University

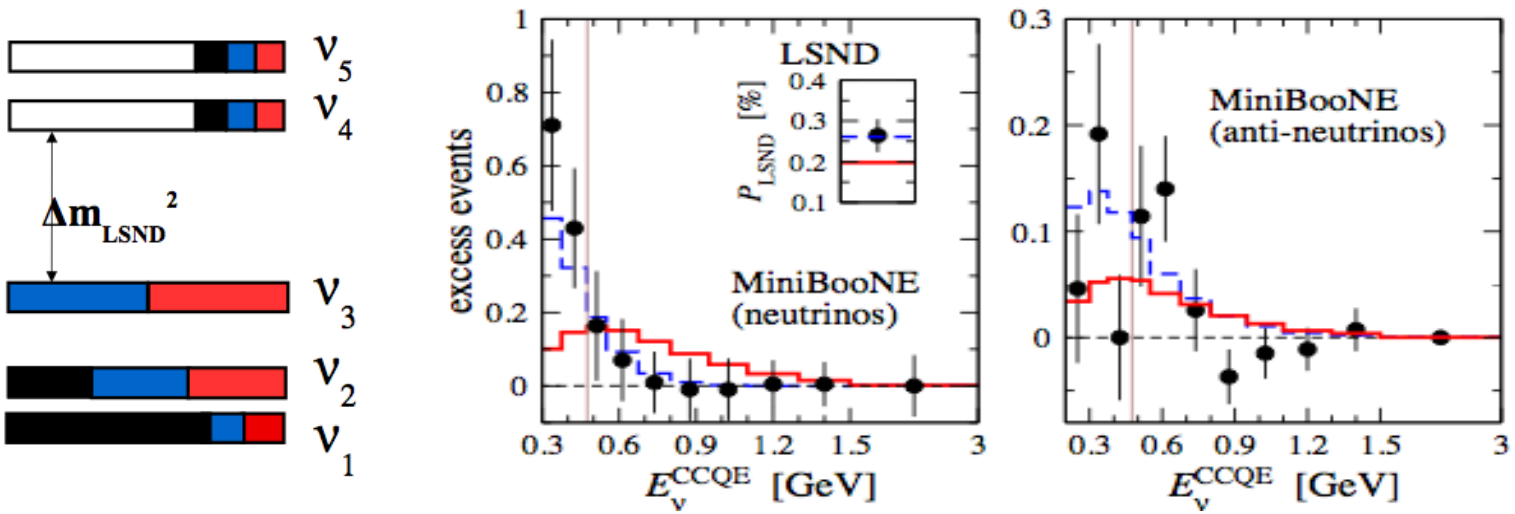
Global 3+2 Fits with Sterile Neutrinos

- In 3+2 fits, CP violation allowed so $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130

(Kopp et al. - hep-ph:1103.4570)

- But still hard to fit appearance and disappearance simultaneously



Red: Fit to Disapp + App
Blue: Fit to App Only

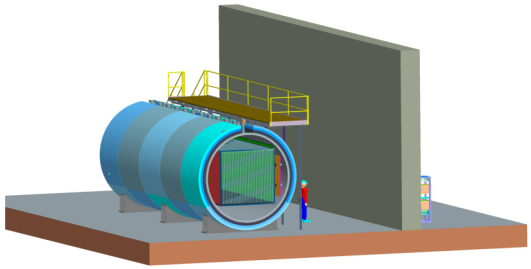
- Compatibility between data sets better but still not very good
  - LSND+MB ($\bar{\nu}$) vs Rest = 0.13%
  - Appearance vs Disappearance = 0.53%

Future Plans and Prospects

Approved program:

1. Should reach x2 the current MiniBooNE $\bar{\nu}$ data over the next year
   $\Rightarrow$ Address the LSND region at the 2 to 3 σ level

2. New MicroBooNE Exp in front of MiniBooNE (2013)
   Liquid Argon TPC detector which can address the low-energy excess:
   - Reduced background levels
   - Can determine if low-energy excess due to single electron or photon events?



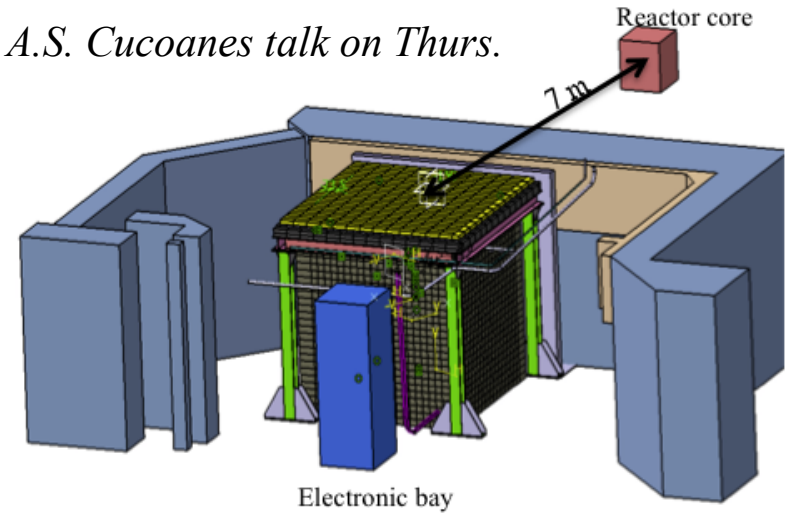
Other ideas:

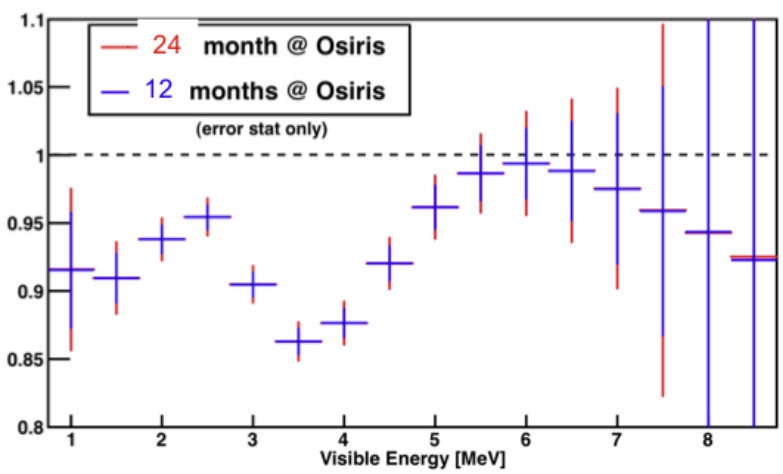
- New two detector experiments for appearance and disappearance
  - At Fermilab using using new detectors in MiniBooNE beamline
  - CERN PS neutrino beam with Icarus style detectors at 130m/850m
- Very short baseline (VSBL) ν_e disappearance and $\bar{\nu}_e$ appearance exps
  - Use high rate radioactive sources in Borexino (or other) detector
  - Small detector close (<10m) to nuclear reactor
  - Decay-at-rest beam close to a large detector (Nova, LAr_1kton)

Examples: Very-short Baseline Exps

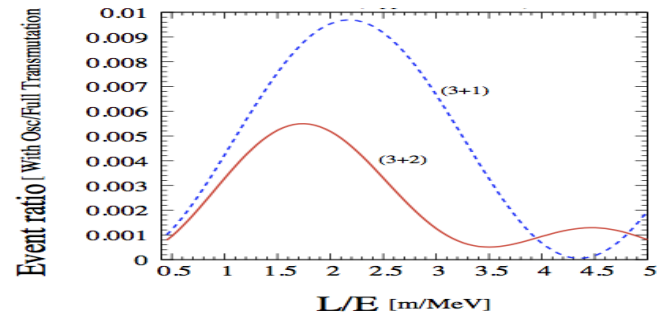
- NUCIFER Proposed Experiment
  - Osiris Research Reactor: Core Size: 57x57x60 cm
  - 1.2m x 0.7m detector 7m distance from core

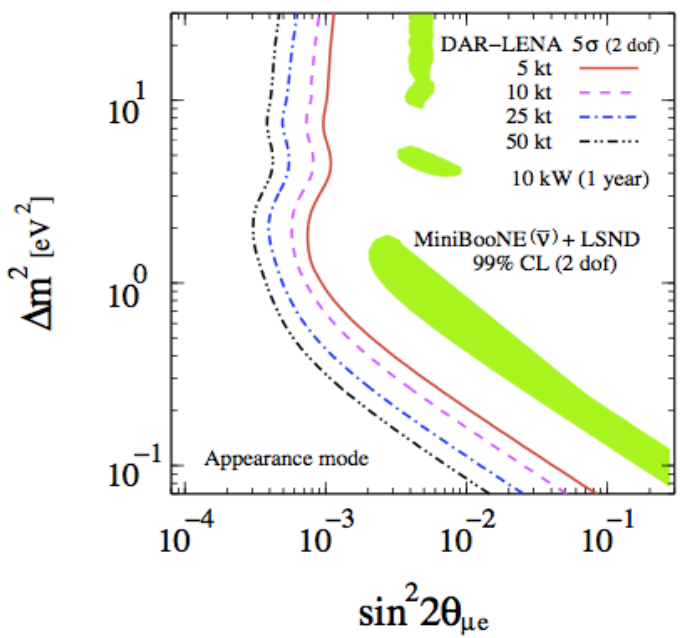
See A.S. Cucoanes talk on Thurs.





- Small (10 kW) decay-at-rest source (like Daedalus) near a large liquid scintillator detector (ala LENA)
  - Detect $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance





Agarwalla, Conrad, and Shaevitz,1105.4984 [hep-ph]

Final Comments

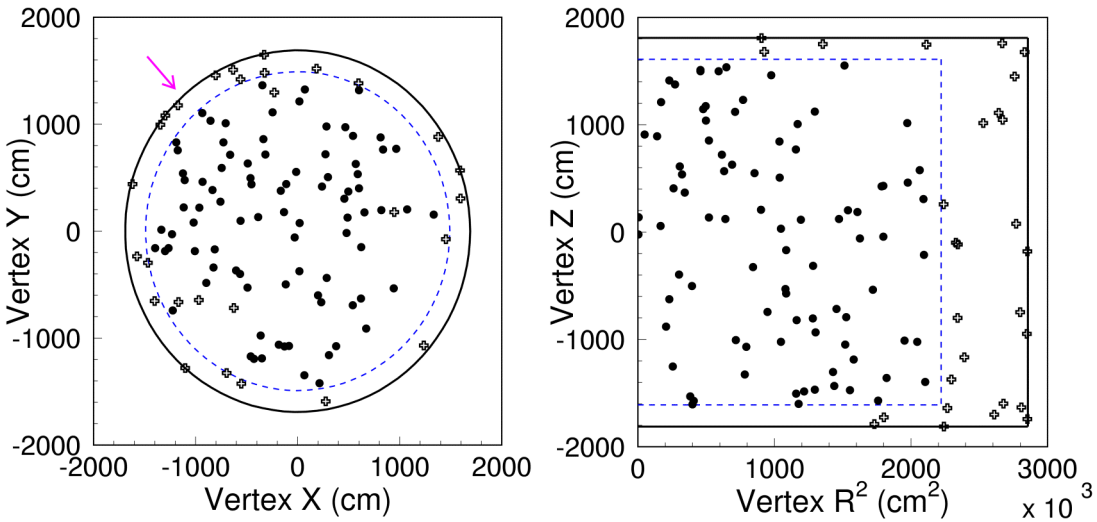
- Recent results from T2K and MINOS suggest that $\theta_{13} > 5°$ ($\sin^2 2\theta_{13} > 0.03$)
  - Such a large value would open up a large window for near-term reactor and longbaseline experiments.
    - Better measurements of θ_{13} and θ_{23}
    - Possible resolution of the mass hierarchy and, if lucky, hints of CP violation
  - This would give the next generation longbaseline experiments a rich program of neutrino oscillation physics with precision mass hierarchy and CP violation measurements.
- There are a number of results and hints that suggest that there may be oscillations to sterile neutrinos in the $\Delta m^2 \sim 1$ eV^2 region
  - Further running and new experiments are being planned to address this possibility
    $\Rightarrow$ Establishing the existence of sterile neutrinos would be a major result

$\Rightarrow$ These are certainly exciting times for neutrino physics

Backup

Event Vertex Distribution

Fully-contained (FC) sample
(w/o ν_e selection and fiducial volume cuts)



Fiducial volume cut is 2m top, bottom, and radius

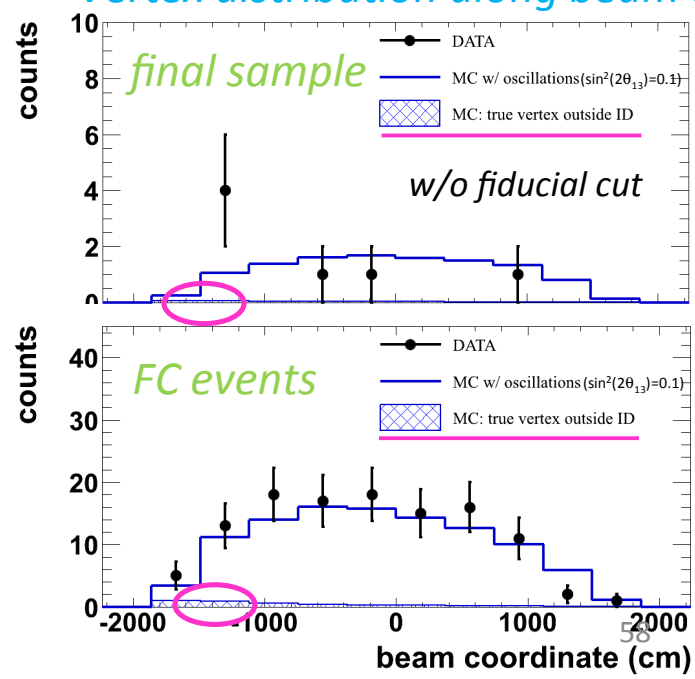
⇒ Corresponds to > 5 rad. lengths

Vertex of these six events are located near fiducial volume edge

K-S test of R^2 event distribution

→ 3% probability

Vertex distribution along beam dir.



Check distribution of events outside FV
Check distribution of OD events

→ No indication of BG contamination

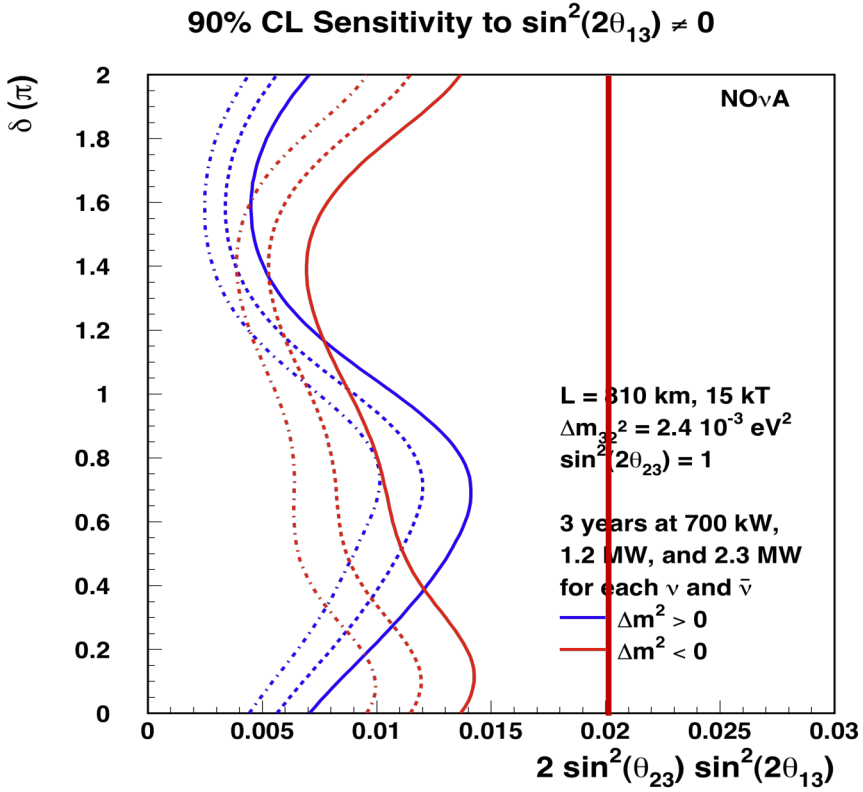
Simulation study of beam-induced BG from mis-ID μ, π^0 photon, neutron, K

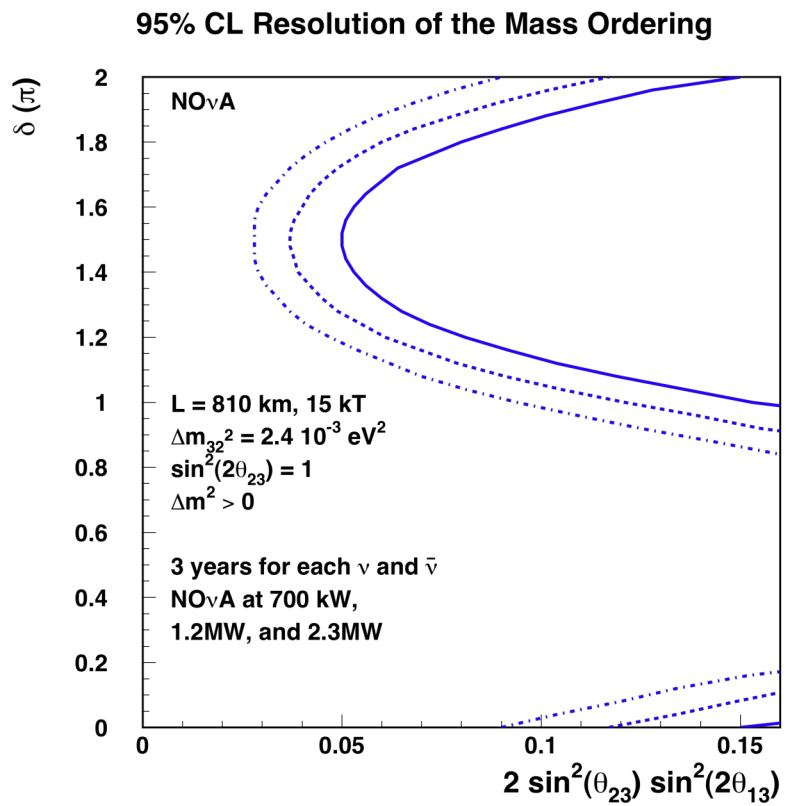
→ very small (3×10^{-3}) events estimated in FV

NOvA Longbaseline Experiment

- Beam:
  - Accelerator shutdown to install upgrades for 700kW beam: March 2012
  - Horn1 and target design complete
  - Kicker for Booster-Recycler in use
  - First recycler injector magnet installed
- Far Detector:
  - Start construction: Jan 2012
  - 1 block ready by start of shutdown
  - 50% detector by end of shutdown
  - Complete by early 2014
- Near Detectro:
  - Cavern excavation during shutdown
  - Prototype in operation at FNAL on the surface

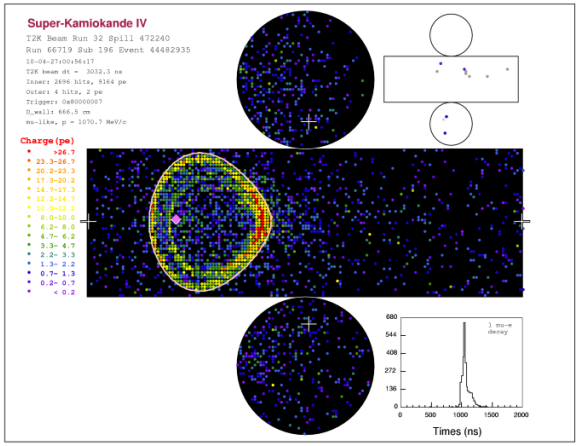
NOvA Sensitivities





T2K New ν_μ Disappearance Result: Measuring Δm_{23}^2

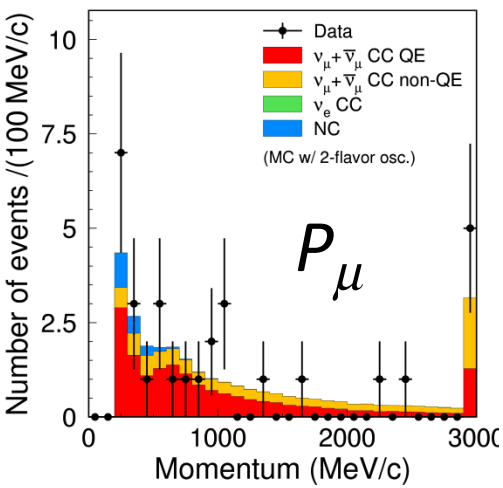
A selected single-ring μ-like event

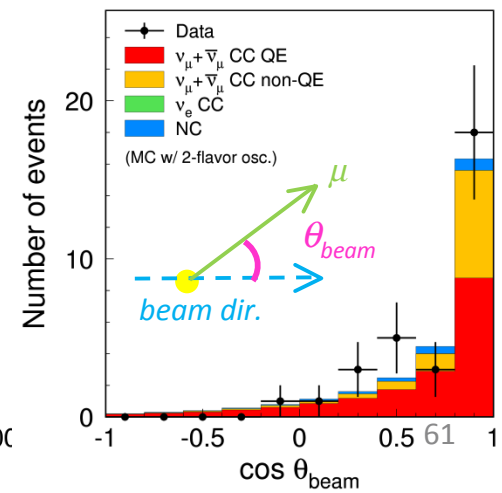


See K. Okumura
Talk yesterday

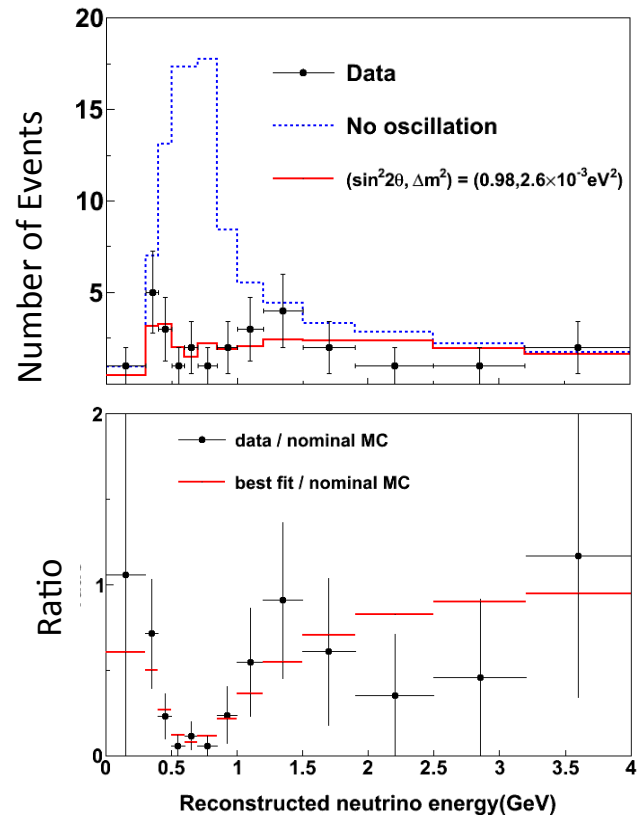
- Observe 31 events for single-ring muon-like
  - (104 events expected w/o osc.)

Pμ and cosθ_{beam} dist. for selected events





Measured energy distribution



Fit with 2-flavor oscillation assumption

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

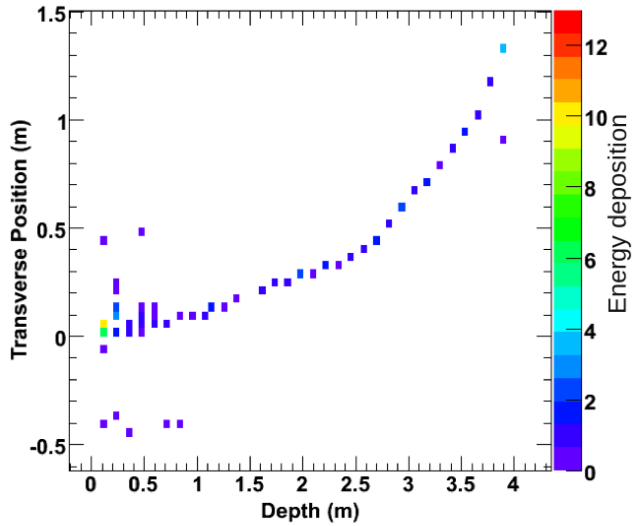
90% C.L. allowed region:

– $2.1\times10^{-3} < \Delta m^2 < 3.1\times10^{-3}$ eV^2

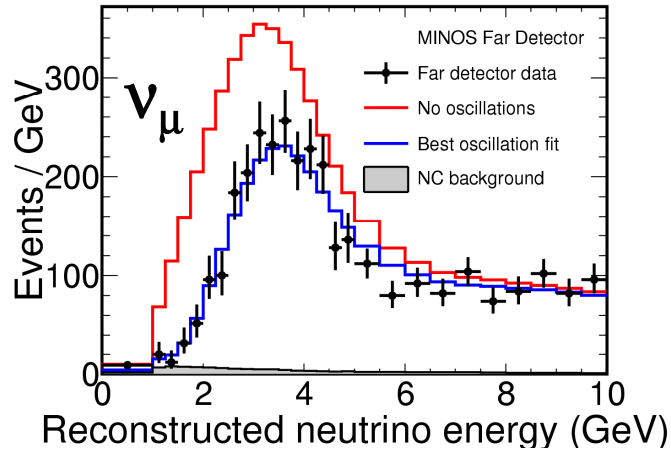
– $\sin^2 2\theta > 0.85$

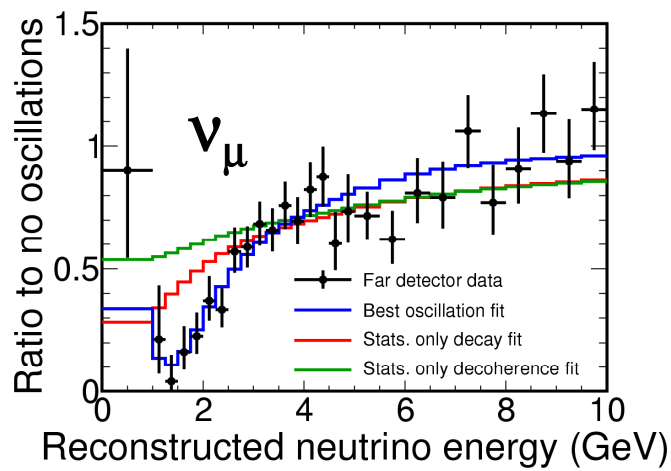
New MINOS ν_μ and $\bar{\nu}_\mu$ Disappearance Results

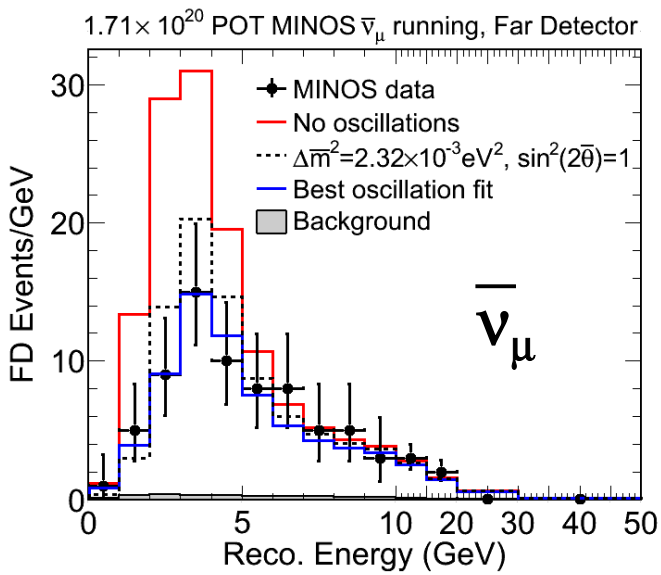
ν_μ and $\bar{\nu}_\mu$ Charged Current Events using neutrino or antineutrino mode running (magnetized target ⇒ muon sign)



Long μ track with hadronic activity at vertex







$\bar{\nu}_\mu$ Result

$\Delta m^2 = 3.36 \pm 0.43 \times 10^{-3}\ eV^2$

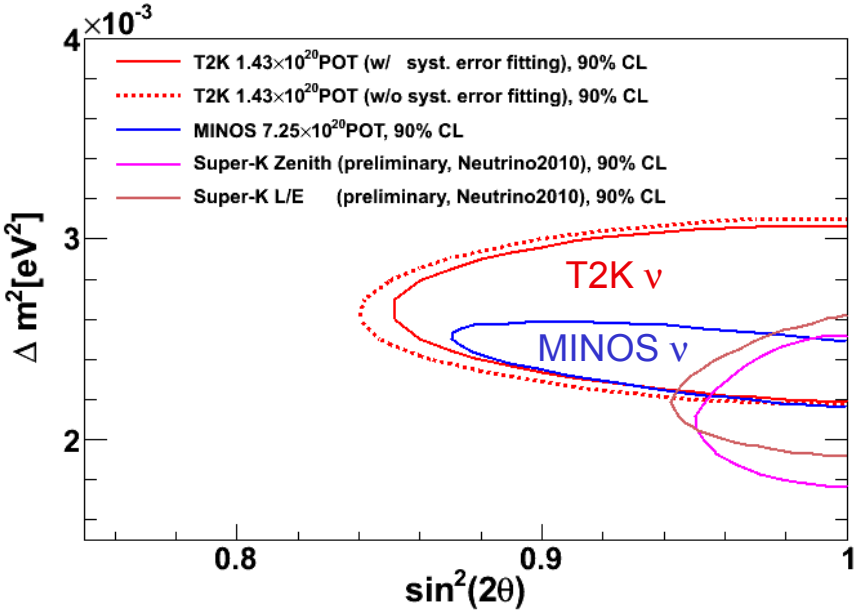
$\sin^2 2\theta_{23} = 0.86 \pm 0.12$

$$\Delta m^2 = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ eV^2$$

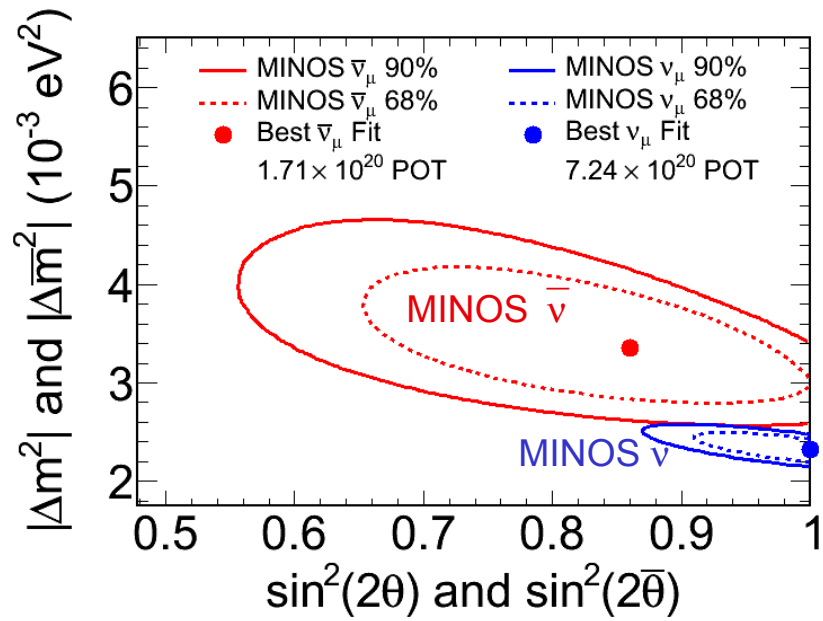
$$\sin^2 2\theta_{23} > 0.9 \ @\ 90\%CL$$

Comparisons of Δm^2 Measurements

Good agreement for T2K and MINOS neutrino measurements



MINOS ν and $\bar{\nu}$ measurements only consistent at the 2% conf. level.

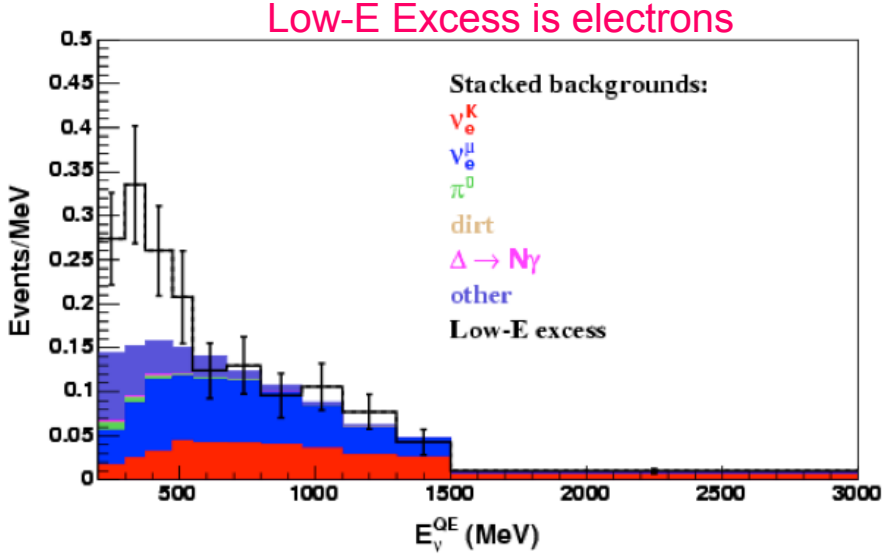


- Questions:
  - Is there a real difference for the ν and $\bar{\nu}$ Δm^2 values? (CPT invariance demands them to be the same.)
  - Is the $\sin^2 2\theta_{23}$ mixing angle maximal? If so, why?

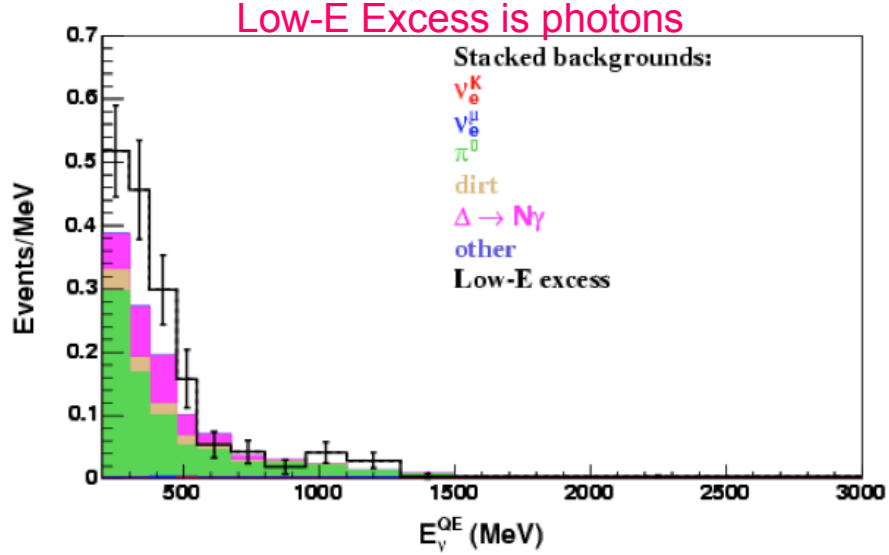
MicroBooNE can resolve Low-E Excess

- MicroBooNE can separate events as to outgoing electrons or photons
  - Therefore, can determine what the excess is due to
- Backgrounds are very different
  - Much better sensitivity for electrons than photons - but either ok

Low-E Excess is electrons



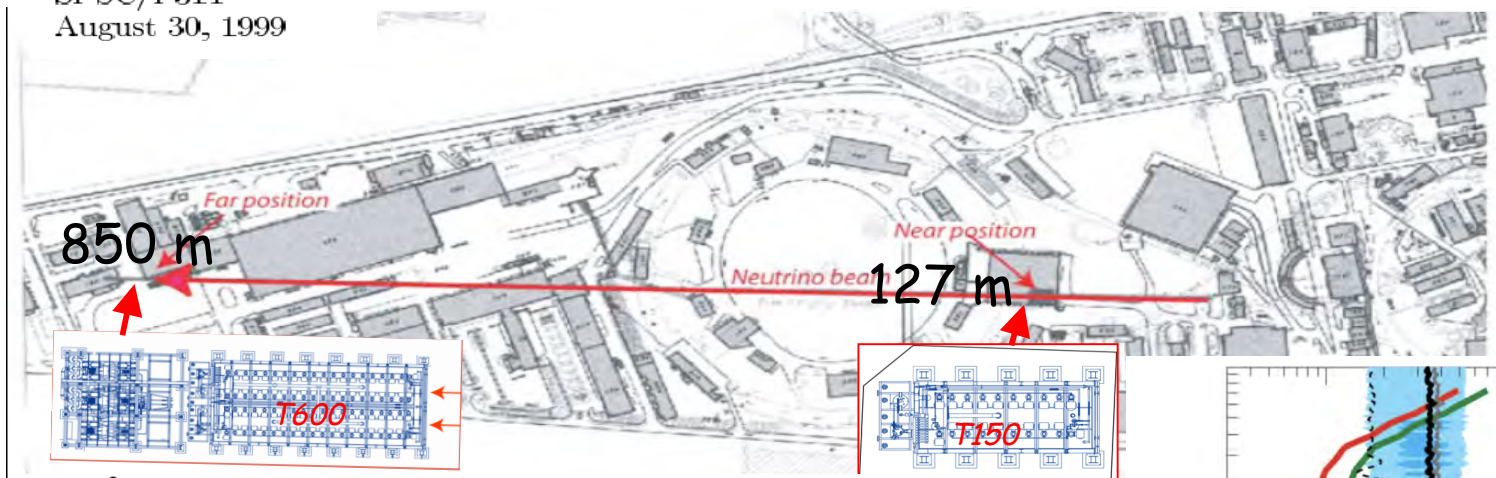
Low-E Excess is photons

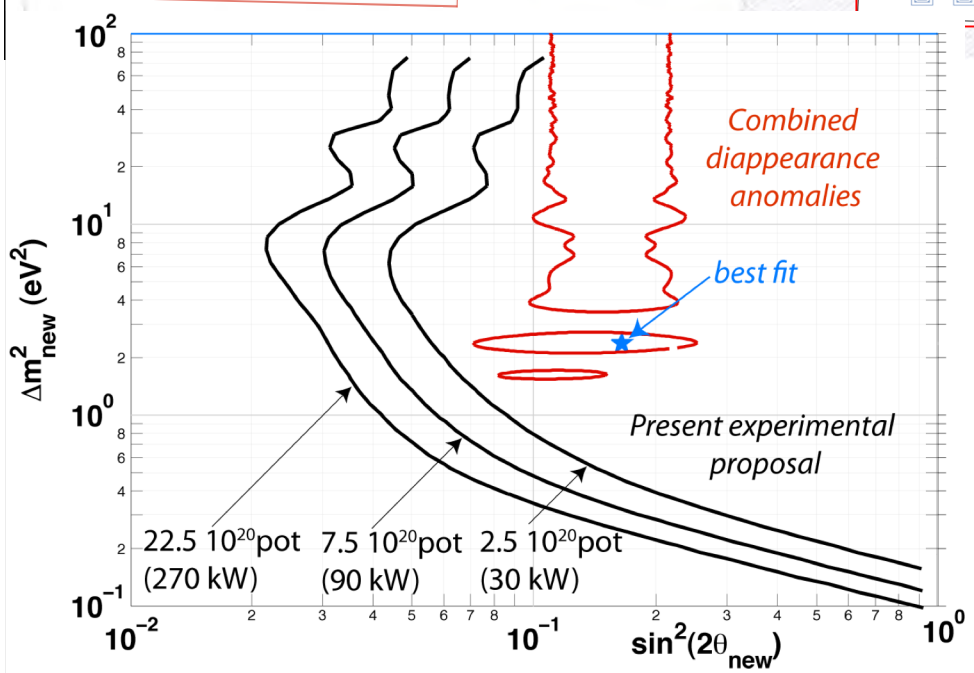


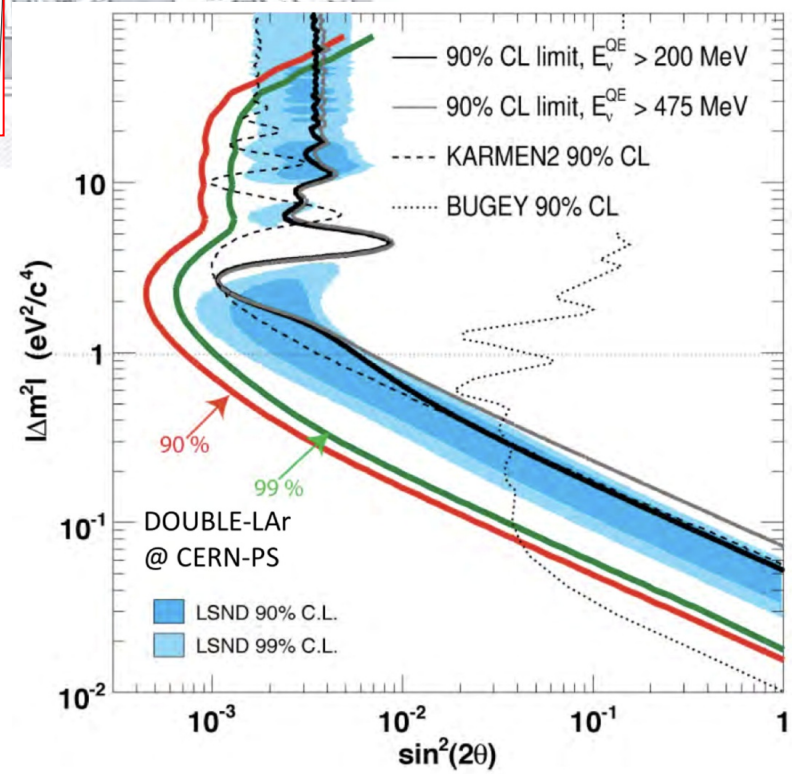
CERN Low Energy (~1GeV) Two Detector Experiment (C. Rubbia)

CERN-SPSC/99-26
SPSC/P311
August 30, 1999

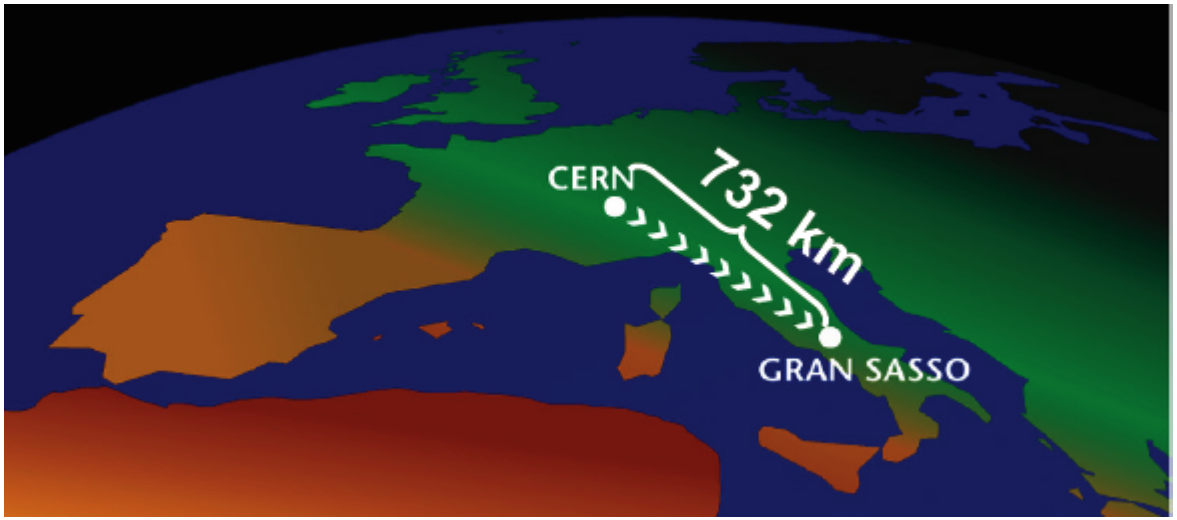
SEARCH FOR $\nu_\mu \to \nu_e$ OSCILLATION AT THE CERN PS



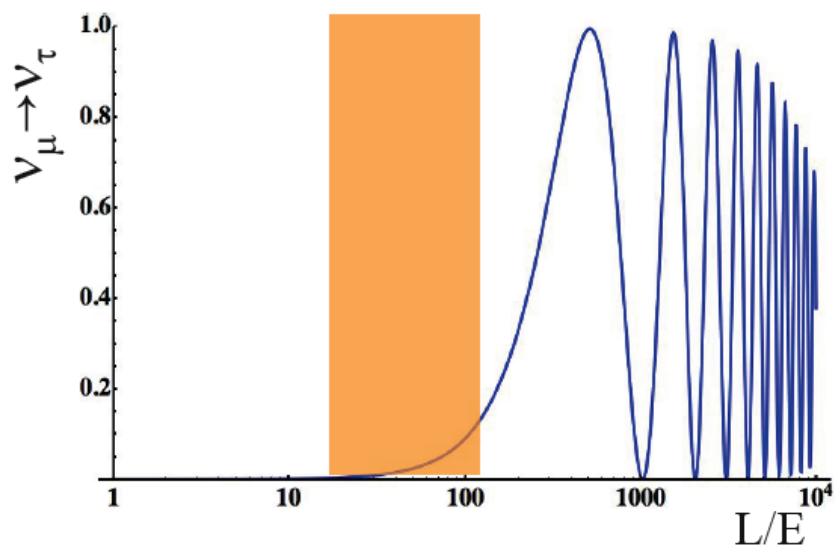




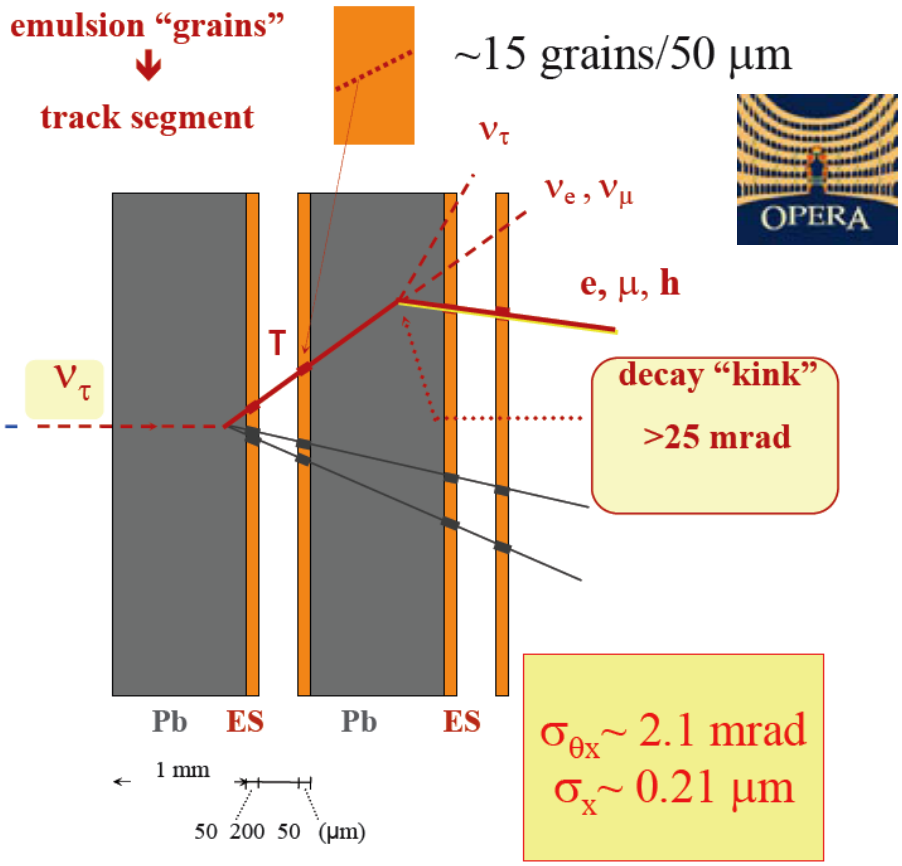
OPERA and ICARUS: ν_τ Appearance Search



- Uses 400 GeV protons to produce neutrino beam $\langle E_\nu \rangle \approx$ 17 GeV
- $\langle E_\nu \rangle$ above threshold to produce τ leptons from ν_τ
- $\langle L/E \rangle \approx 43$ so oscillation probability for Δm^2_{atm} is small



OPERA: Nuclear Emulsion plus Lead

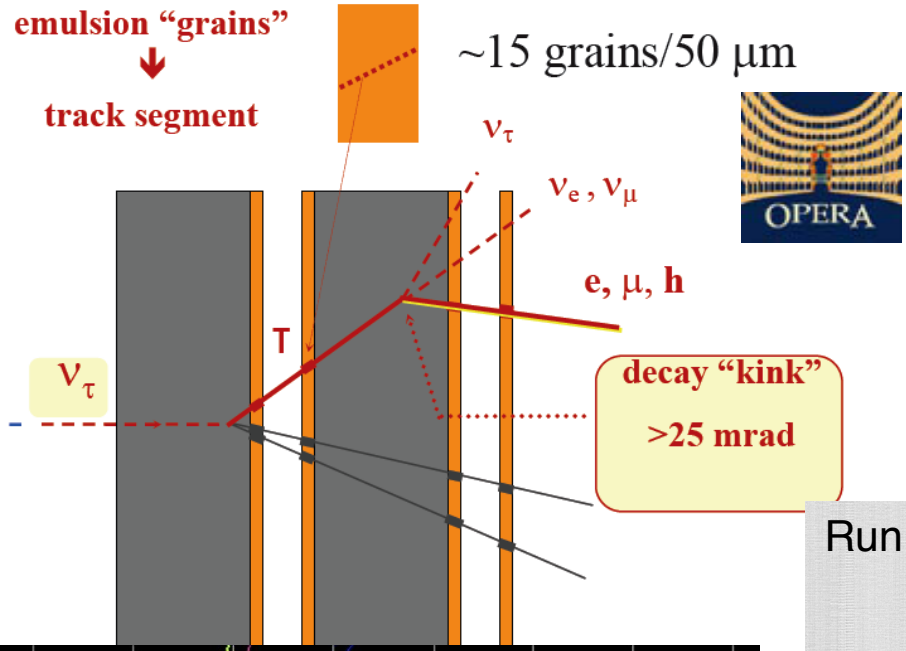


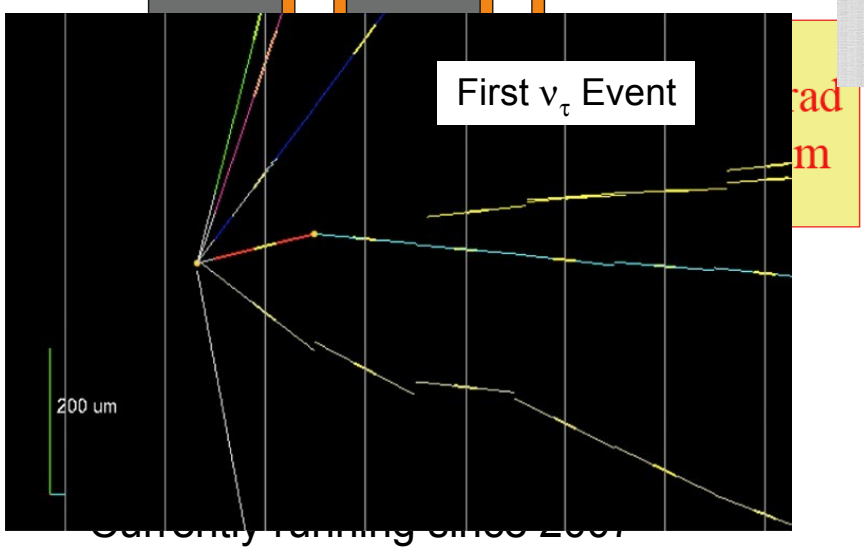
- Scintillator Strips isolate emulsion brick with an event
- Robot then picks out brick to be scanned.
- Currently running since 2007
- Expect about 15 ν_τ events in 5 years

ICARUS: Liquid Argon TPC 600 Tons

- Will use kinematic reconstruction to isolate ν_τ-events.

OPERA: Nuclear Emulsion plus Lead





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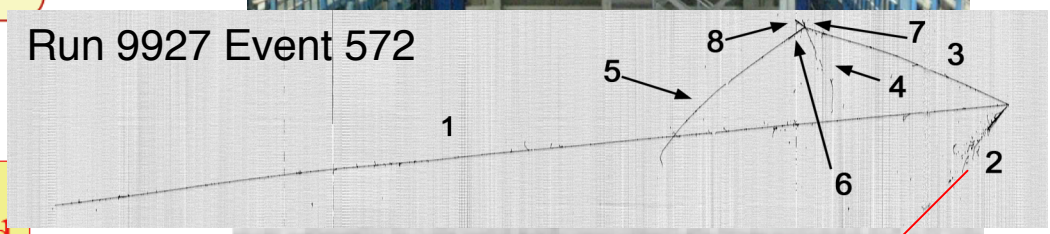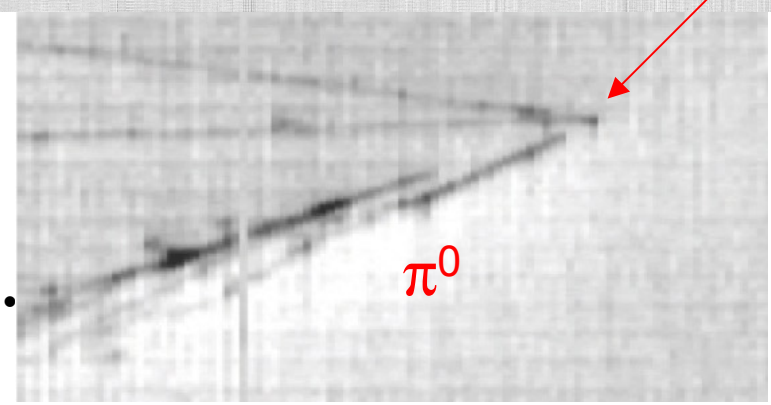
ICARUS: Liquid Argon TPC 600 Tons