Review of Accelerator Neutrino Results

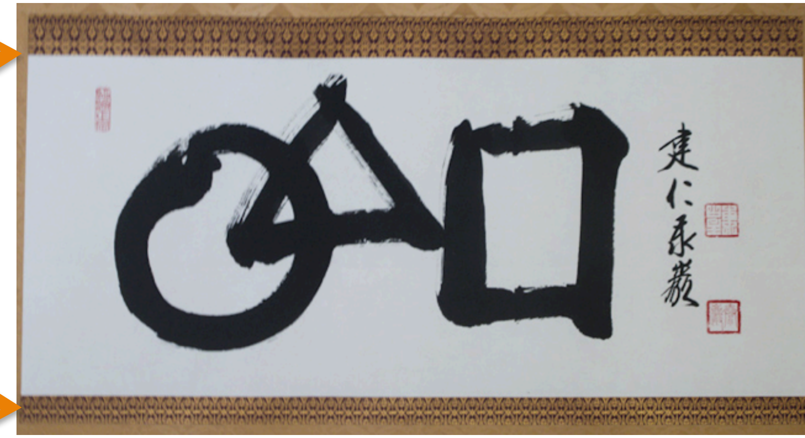
CHRIS WALTER, DUKE UNIVERSITY

Sidereus Nuncius - Galileo (1610)

GGI Neutrino Conference
June 25th 2012

June 2012: Where do we stand?

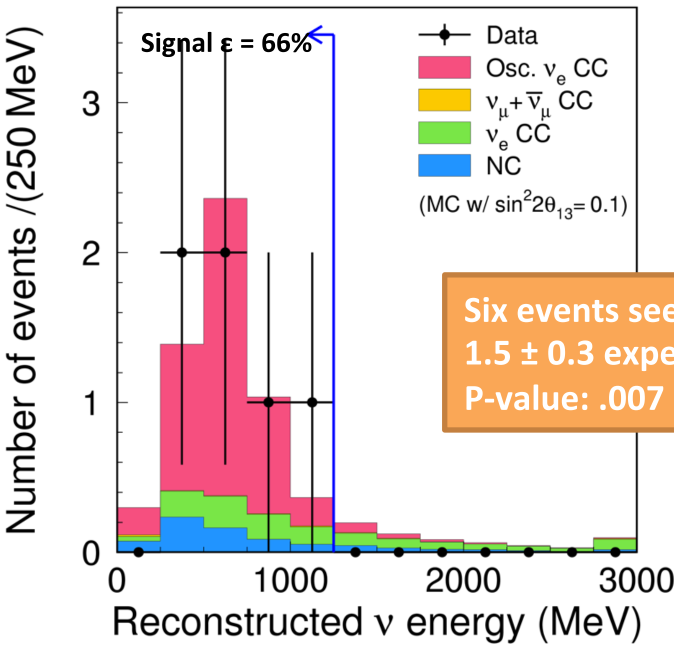
Neutrino 2010: Athens



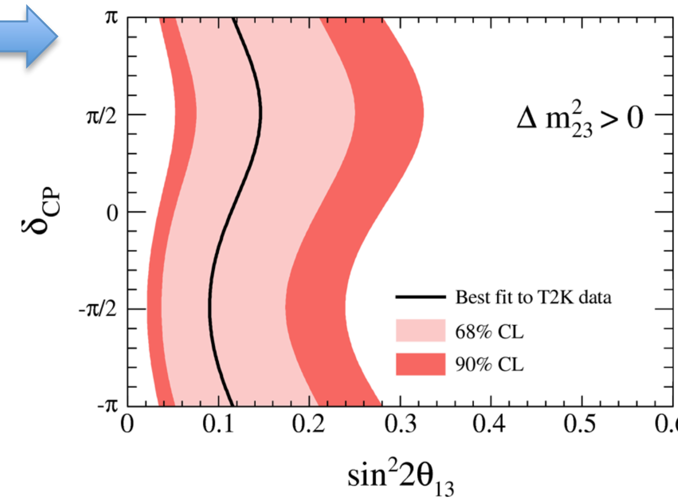
Neutrino 2012: Kyoto

- <u>The measurement of non-zero θ_{13} has changed the nature of discussions and presentations about the current experiments.</u>
- I'll concentrate on results from the neutrino conference.
- Emphasis on Long-baseline: T2K, MINOS, OPERA, with some Miniboone and a bit of atmospheric neutrinos also.
- I'll go over some experimental issues related to the accelerator experiments.

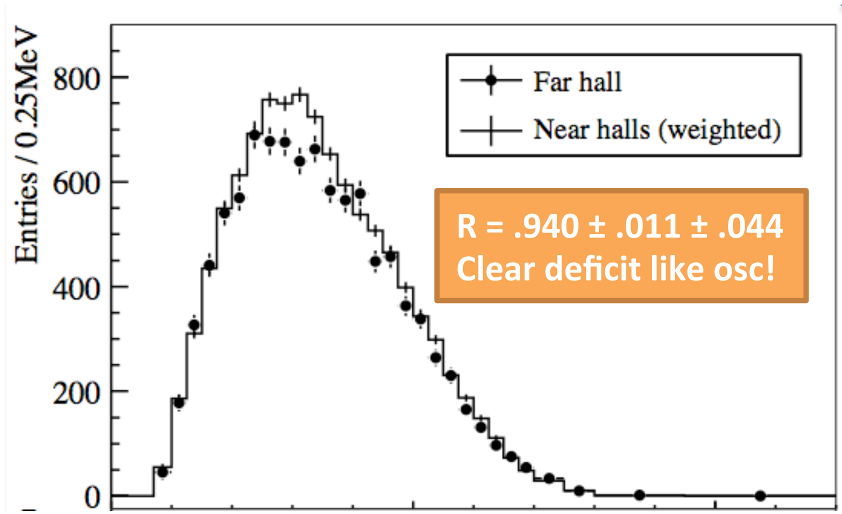
The θ_{13} Story



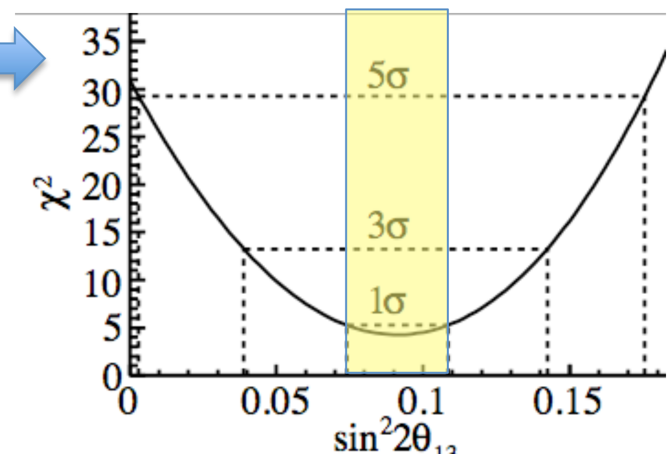
Six events seen
1.5 ± 0.3 expected
P-value: .007



T2K + Minos + Double Chooz (θ_{13}≠0)

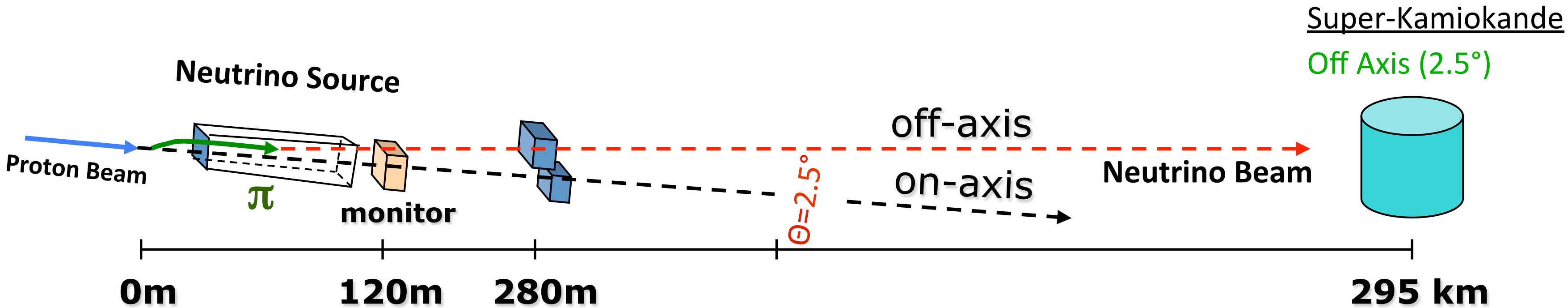


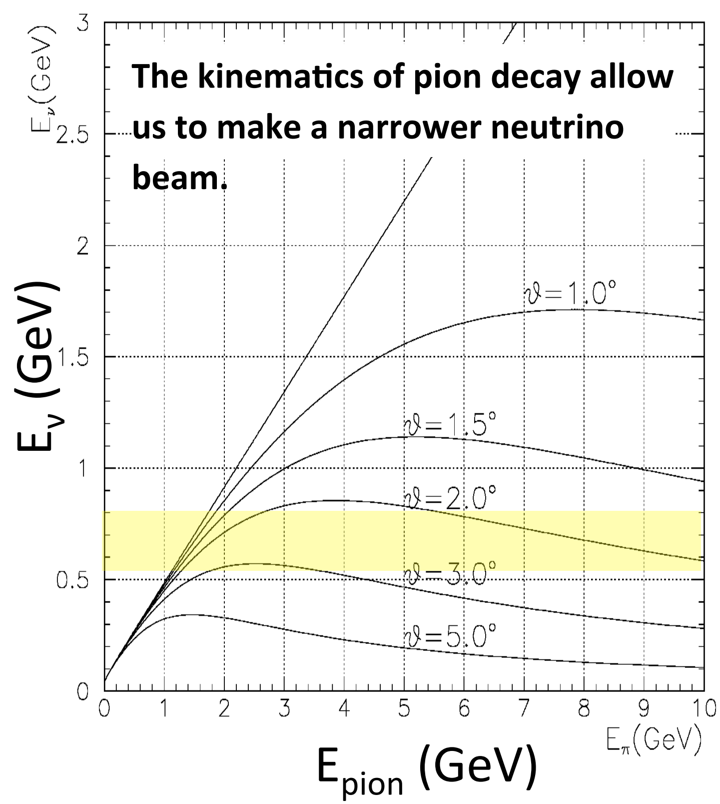
R = .940 ± .011 ± .044
Clear deficit like osc!

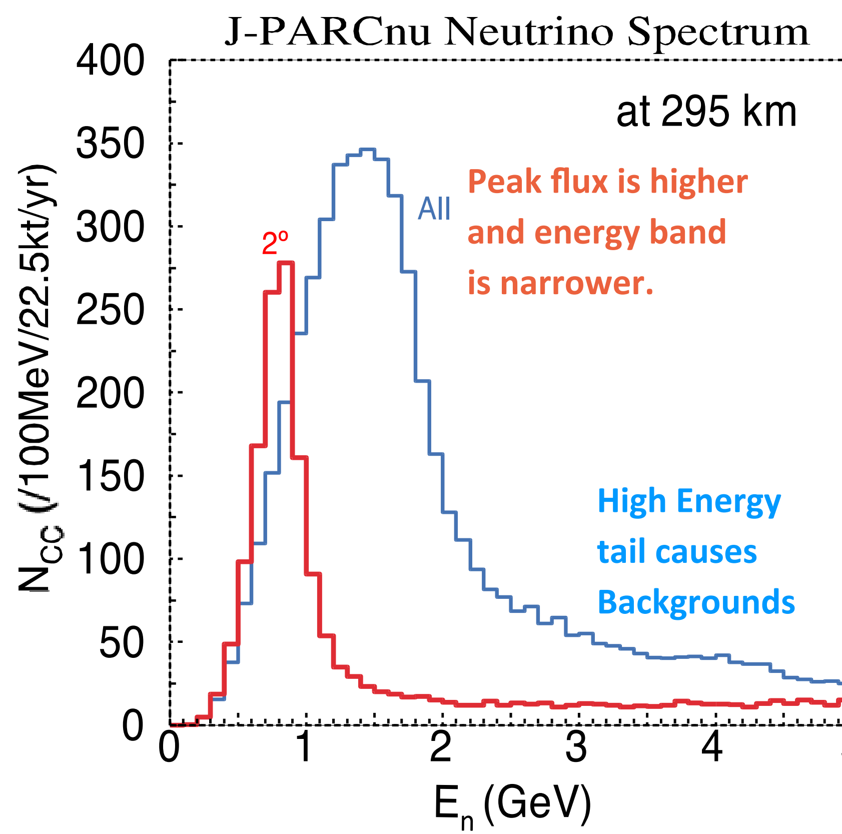


Daya Bay + Reno precision measurement
(θ13≠0 at 5σ!)

On and Off-Axis Beams

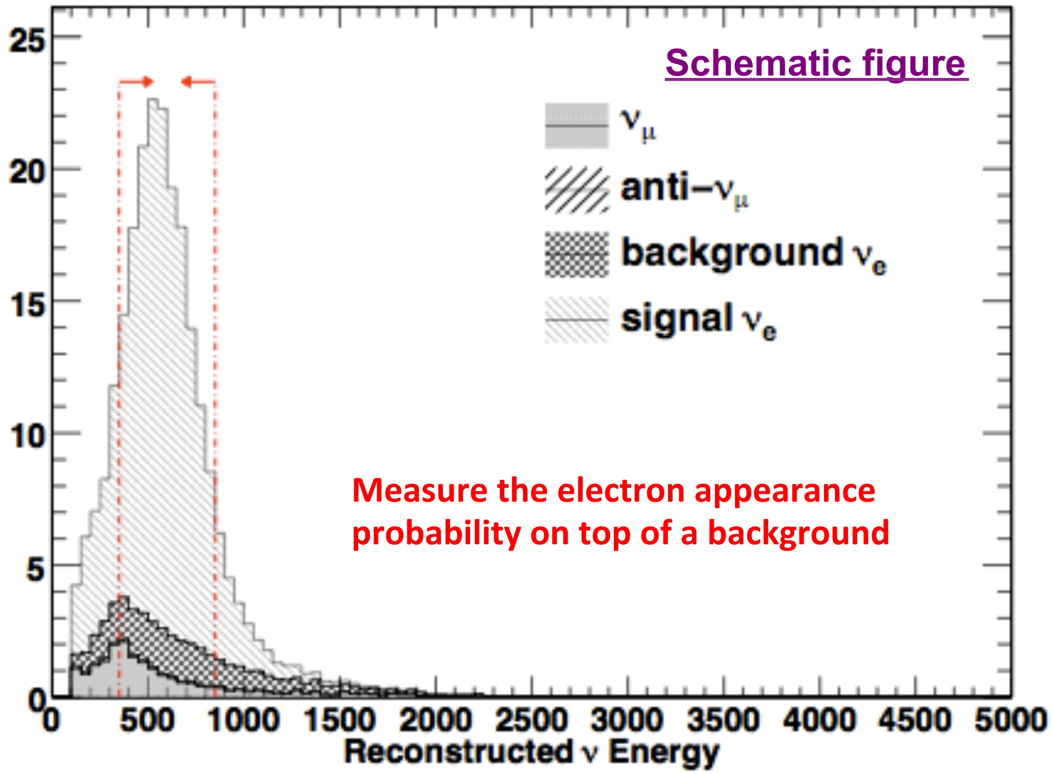






How do we measure $\theta_{13?}$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E_\nu} + sub\text{-}leading\ terms$$

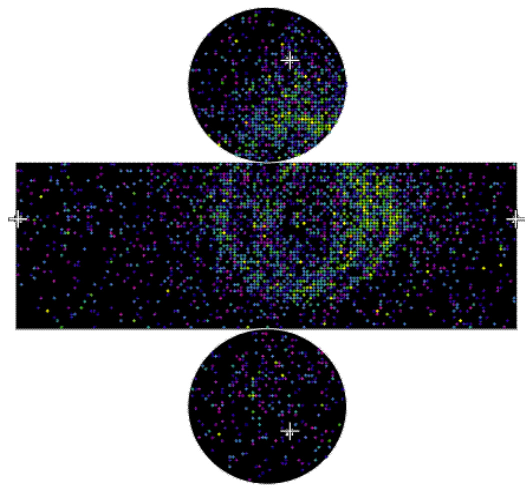
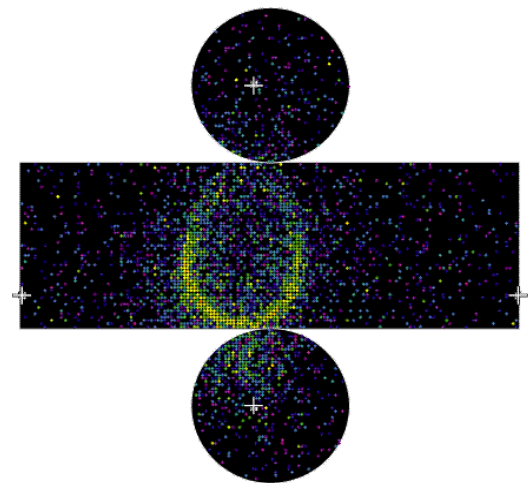
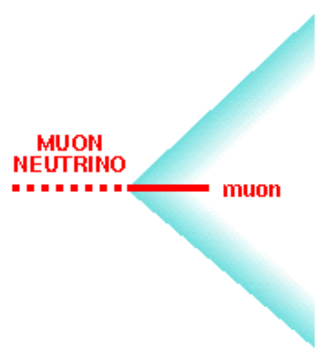
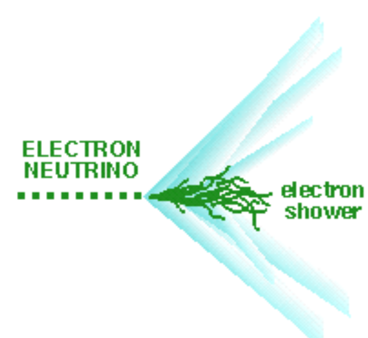


ν_e appearance is crucial for studying the MH and CPV!

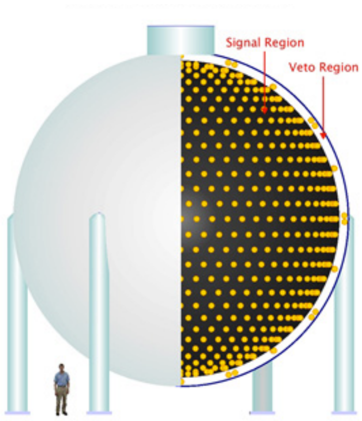
For appearance three main types of background:
intrinsic ν_e, misidentified π^0, mis-identified charged μ

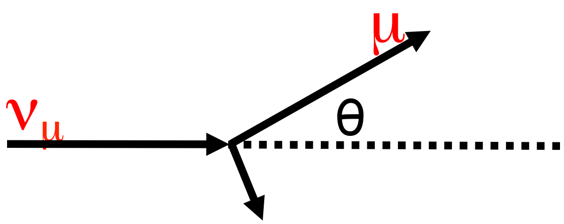
We need a very high intensity beam and a large target. Make a pure neutrino beam and look for electrons to appear.

Main ν_e Appearance backgrounds

Intrinsic ν_e contamination	$\pi^+ \to \mu^+ \nu_\mu$, $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ $K^+ \to \pi^0 e^+ \nu_e$ $K^0_L \to \pi^+ e^- \nu_e$ DECAY PIPE
Confuse $\pi^0 \to \gamma\gamma$ with ν_e	 
Confuse ν_μ with ν_e	 

E_ν Reconstruction (assuming QE)





$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos(\theta_\mu)}$$

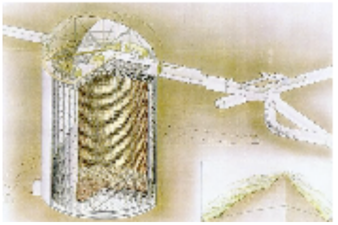
In Cherenkov detectors not every particle is above Cherenkov threshold. Luckily, in a Quasi-Elastic reaction, even if only the muon is visible we can reconstruct the neutrino energy!

[Case for most events in T2K/MiniBooNE Energies]

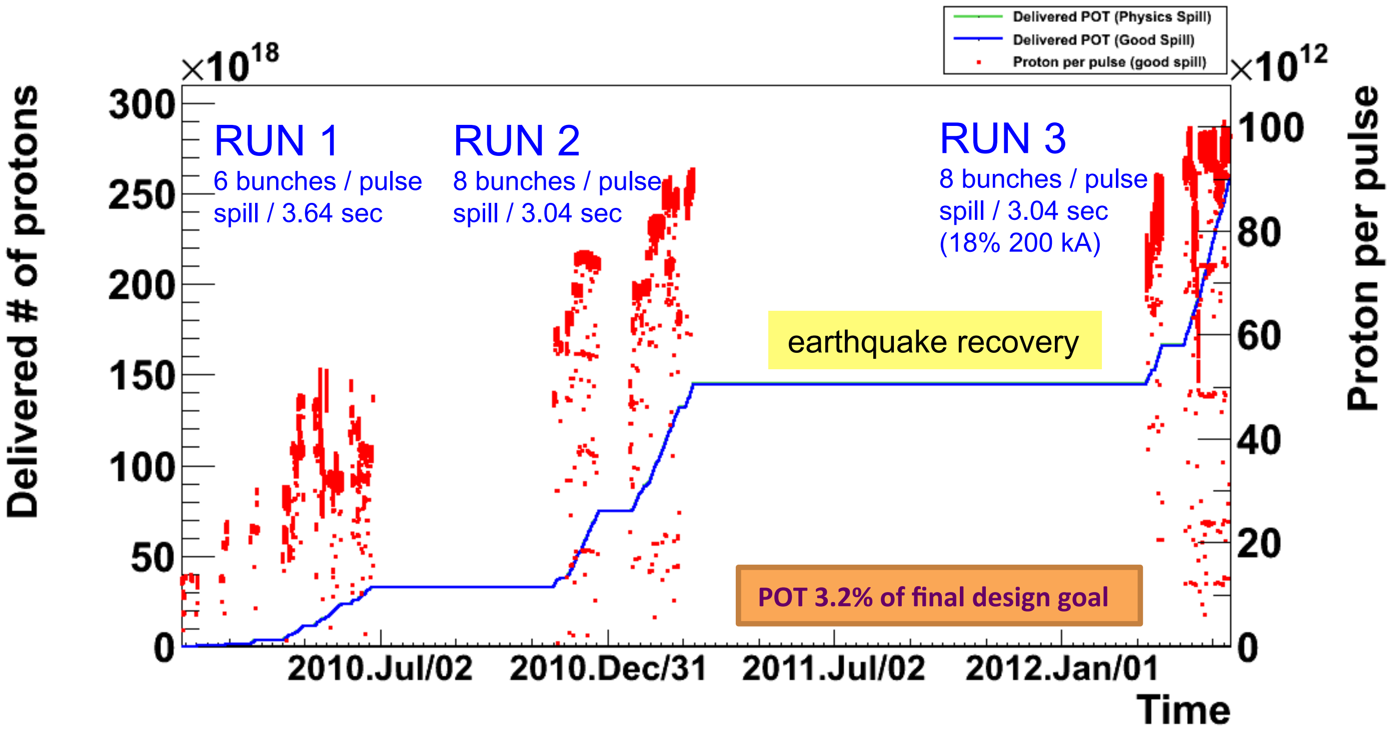
m_N = Neutron Mass
E_μ = Muon Energy
m_μ = Muon mass
p_μ = Muon momentum
θ_μ = Muon angle wrt beam

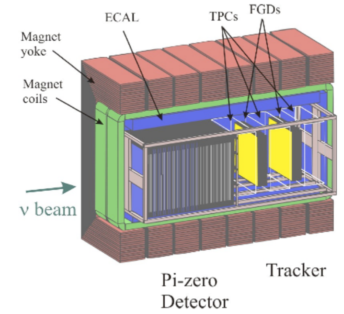
If the interaction is non Quasi-Elastic then the reconstructed energy will be incorrect.

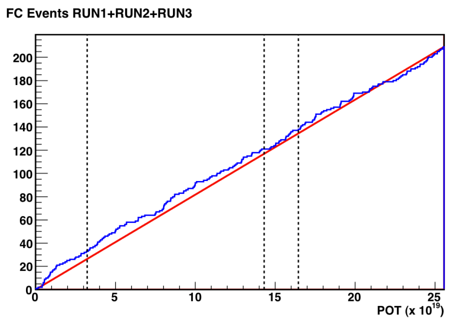
T2K Experiment (Analysis Update)

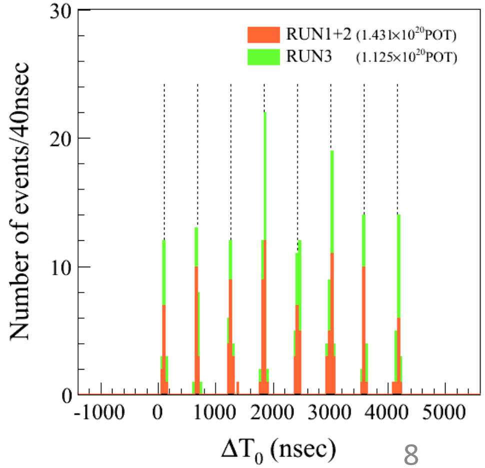


Super-K water Cherenkov detector as far detector.
Uses the JPARC accelerator complex 295 km away





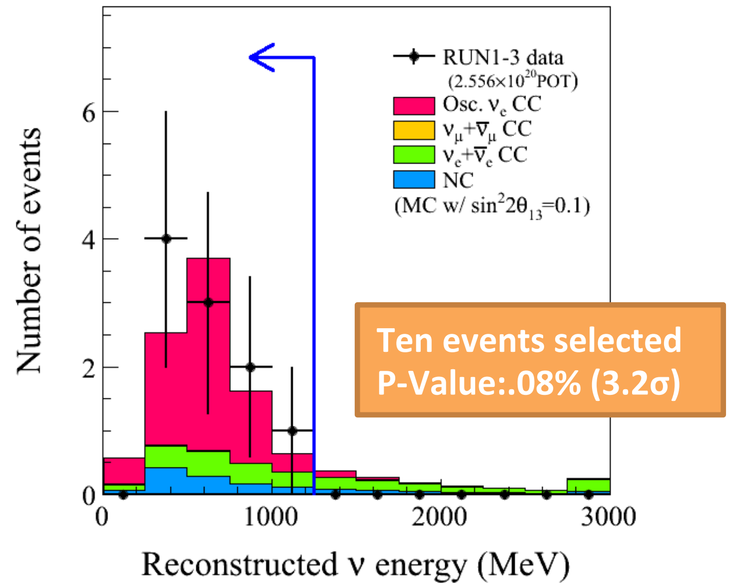




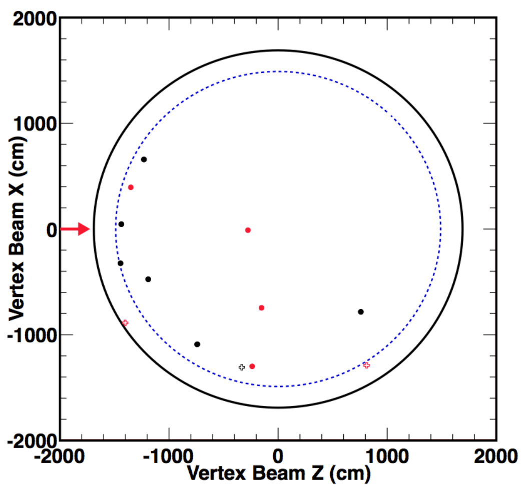
- Run 1-3 data set contain 2.56×10^{20} POT (1.8 × previous result)
- Run 1 (2) instantaneous power reached 50 kW (145 kW)
- Earthquake March 11. JPARC restarted in Jan. T2K in March
- Run 3 stable power reached **190 kW**

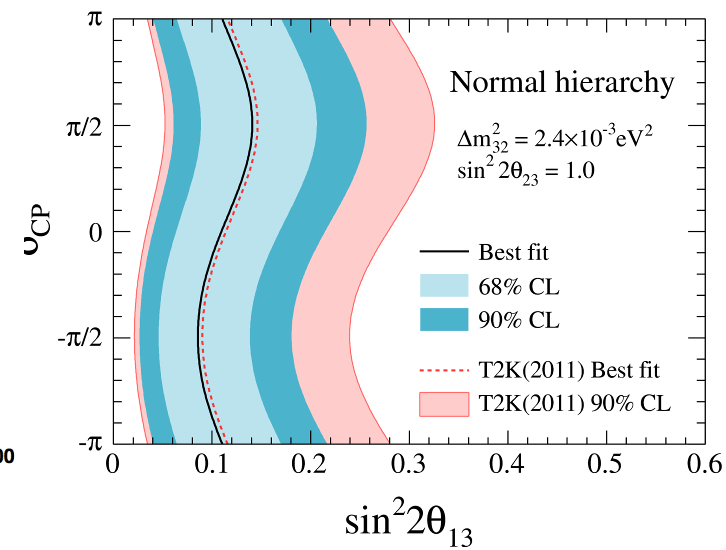
T2K Evidence of ν_e Appearance

RUN1+2+3 2.556×10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}$=0.1					Data
	$\nu_\mu+\nu_\mu$ CC	$\nu_e+\nu_e$ CC	NC	BG total	Signal	
True FV	130.99	6.82	112.61	250.41	10.89	-
FCFV	99.43	6.51	34.31	140.26	10.46	151
One-ring	56.27	4.09	9.78	70.15	8.81	74
e-like	2.30	4.07	6.86	13.23	8.70	19
E_{vis}>100MeV	1.49	4.03	5.94	11.47	8.50	18
No decay-e	0.28	3.19	5.09	8.56	7.31	13
POLfit mass	0.07	2.21	1.39	3.67	6.82	10
E_ν^{rec}<1250MeV	0.05	1.36	1.06	2.47	6.61	10
Efficiency [%]	0.0	20.0	0.9	1.0	60.7	-



Systematic errors now of order 10%, 3 analyses



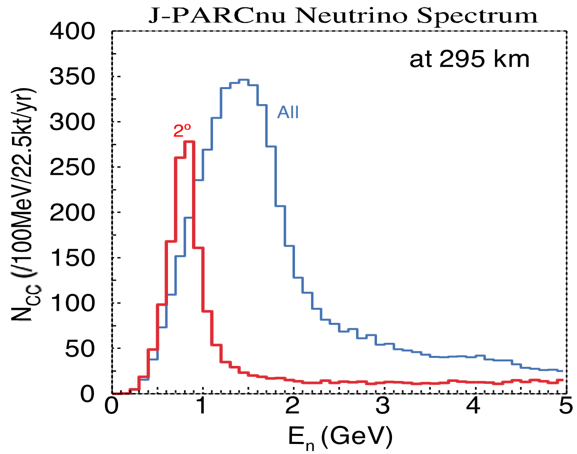


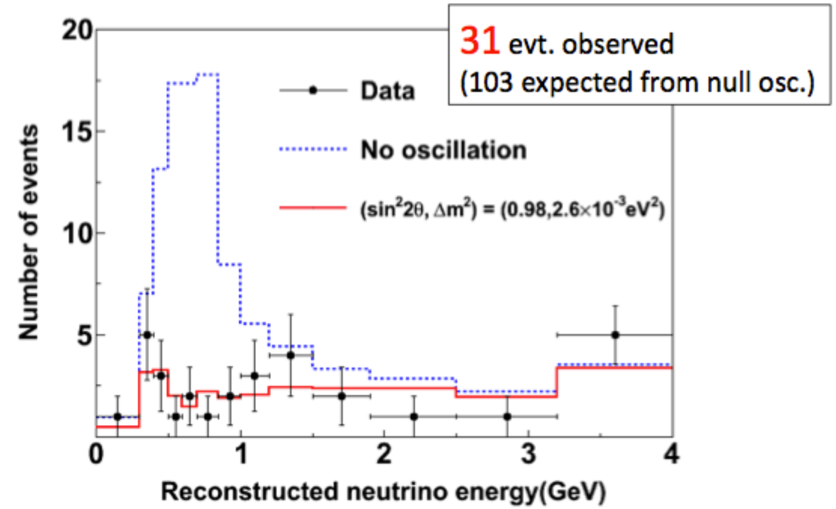
$\sin^2 2\theta_{13}$ 68% CL @ δ=0

NH: $0.104^{+0.060}_{-0.045}$

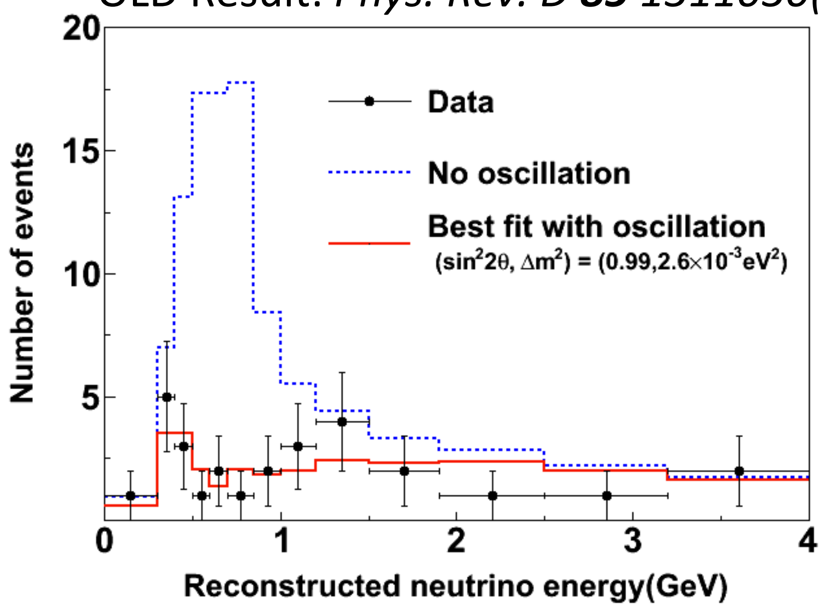
IH: $0.128^{+0.070}_{-0.055}$

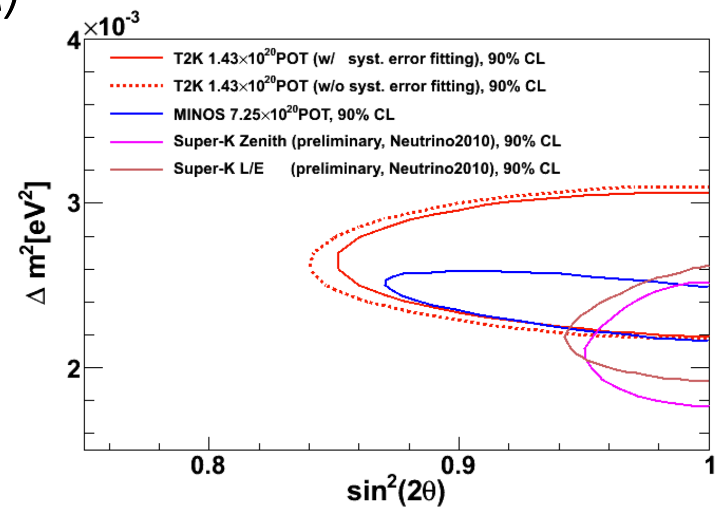
T2K ν_μ Results





OLD Result: *Phys. Rev. D* ***85*** *1311030(R)*



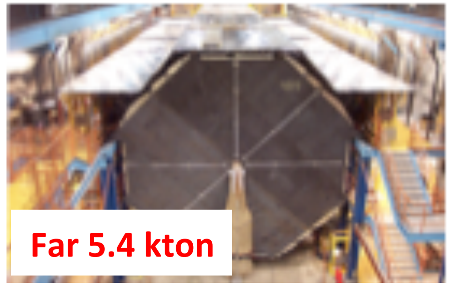


Even with limited statistics, shows the power of the off-axis technique.

06/25/12
10

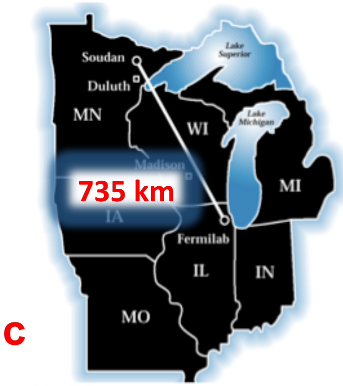
R.NICHOL (UCL)

"Final" MINOS Results



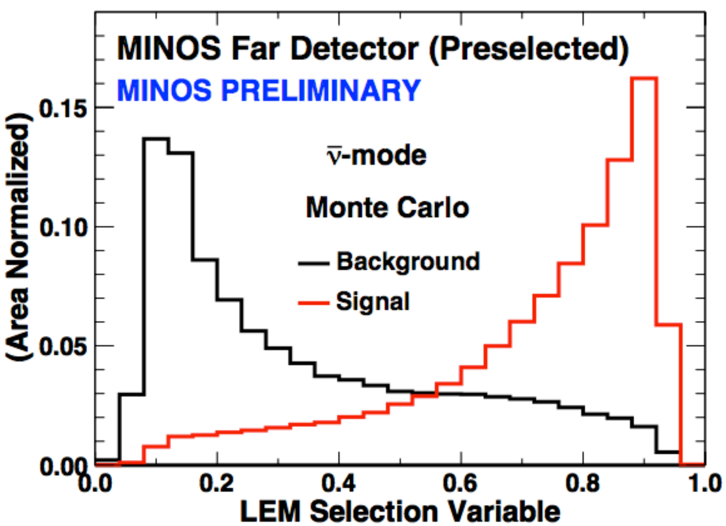
Updated results:

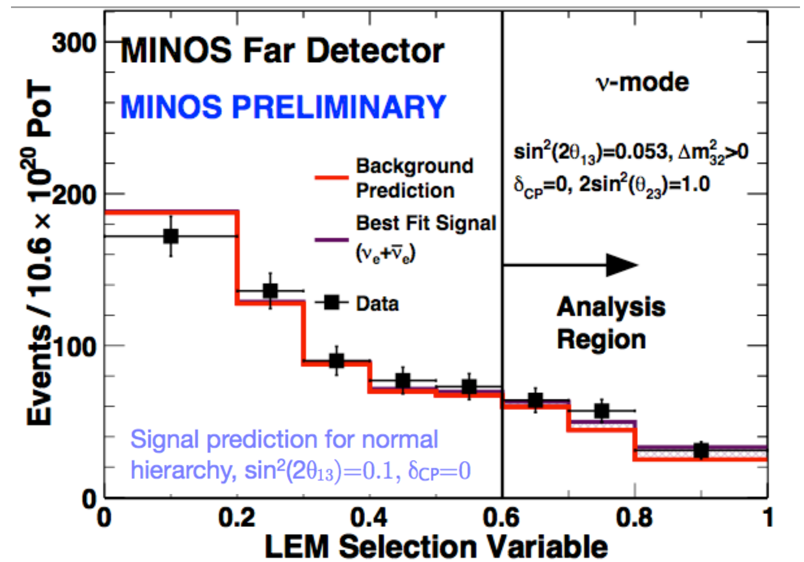
10.71×10^{20} pot neutrino
3.36×10^{20} pot anti-neutrino
37.9 kton-years atmospheric



Appearance:

Use statistical separation based on a pattern matching library





Neutrino beam

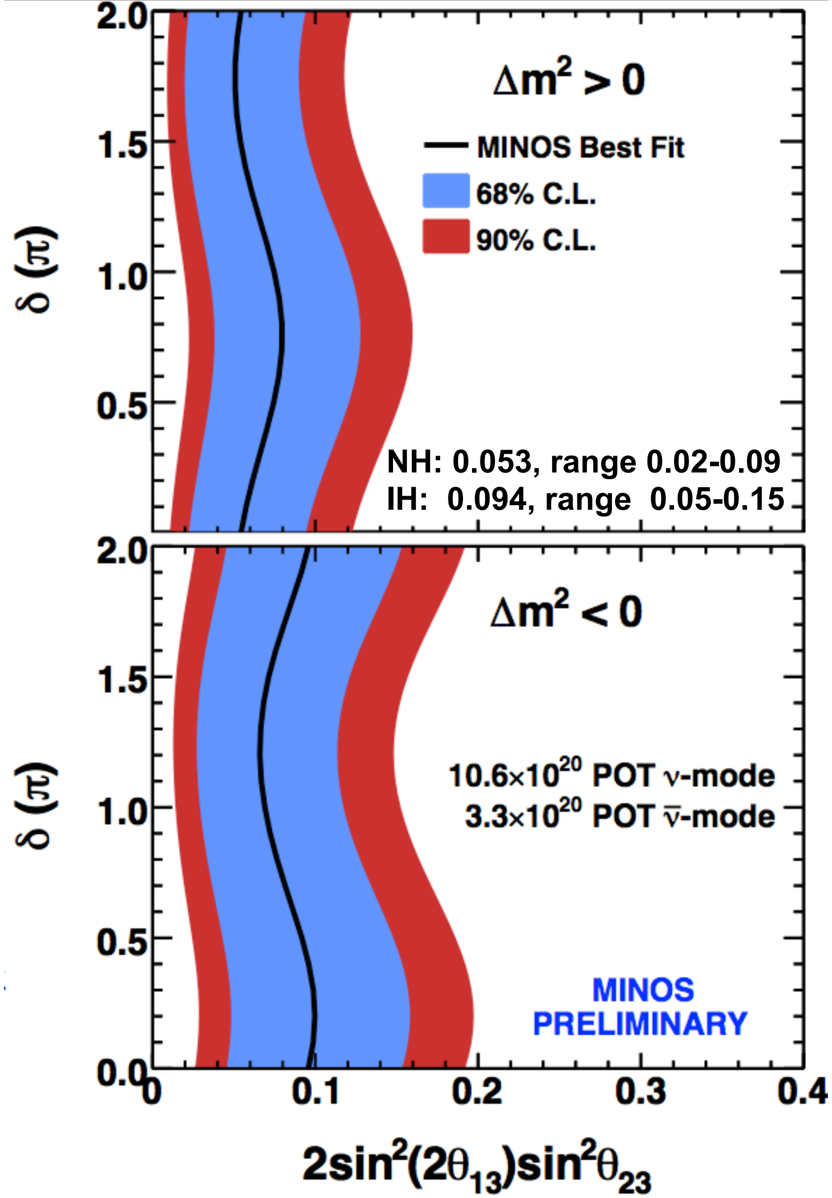
- Expect: 128.6(+32.5) events
- Observe: 152 Events

Antineutrino beam

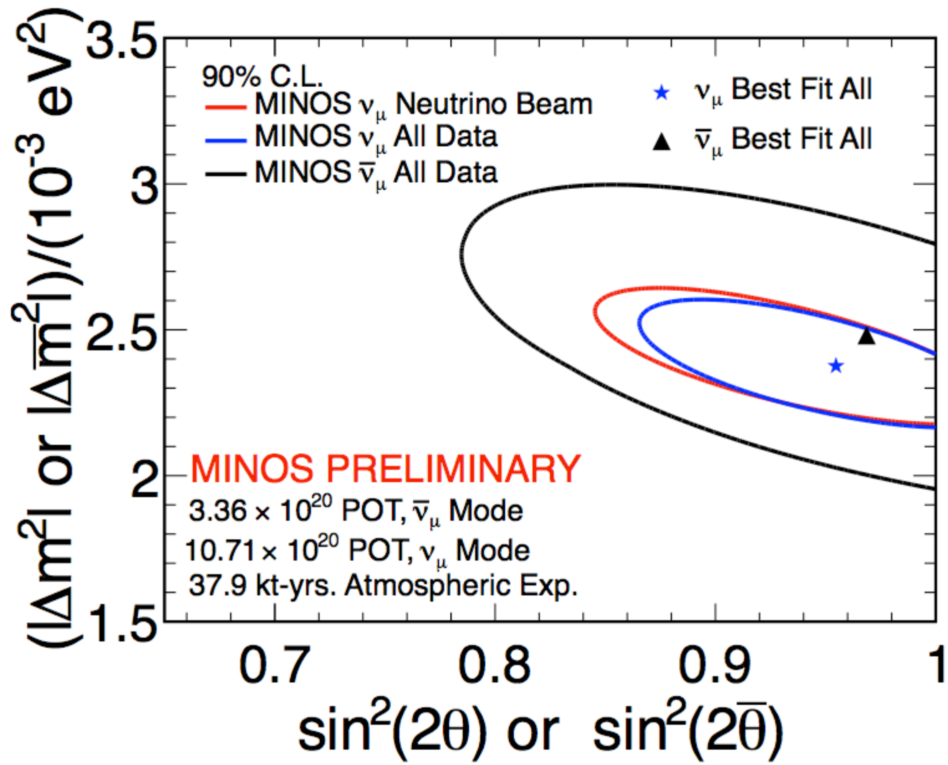
- Expect 17.5(+3.7) events
- Observe 20 events

Now disfavour $\theta_{13}=0$ at 96% C.L. for normal hierarchy, $\delta_{CP}=0$

MINOS anti-ν

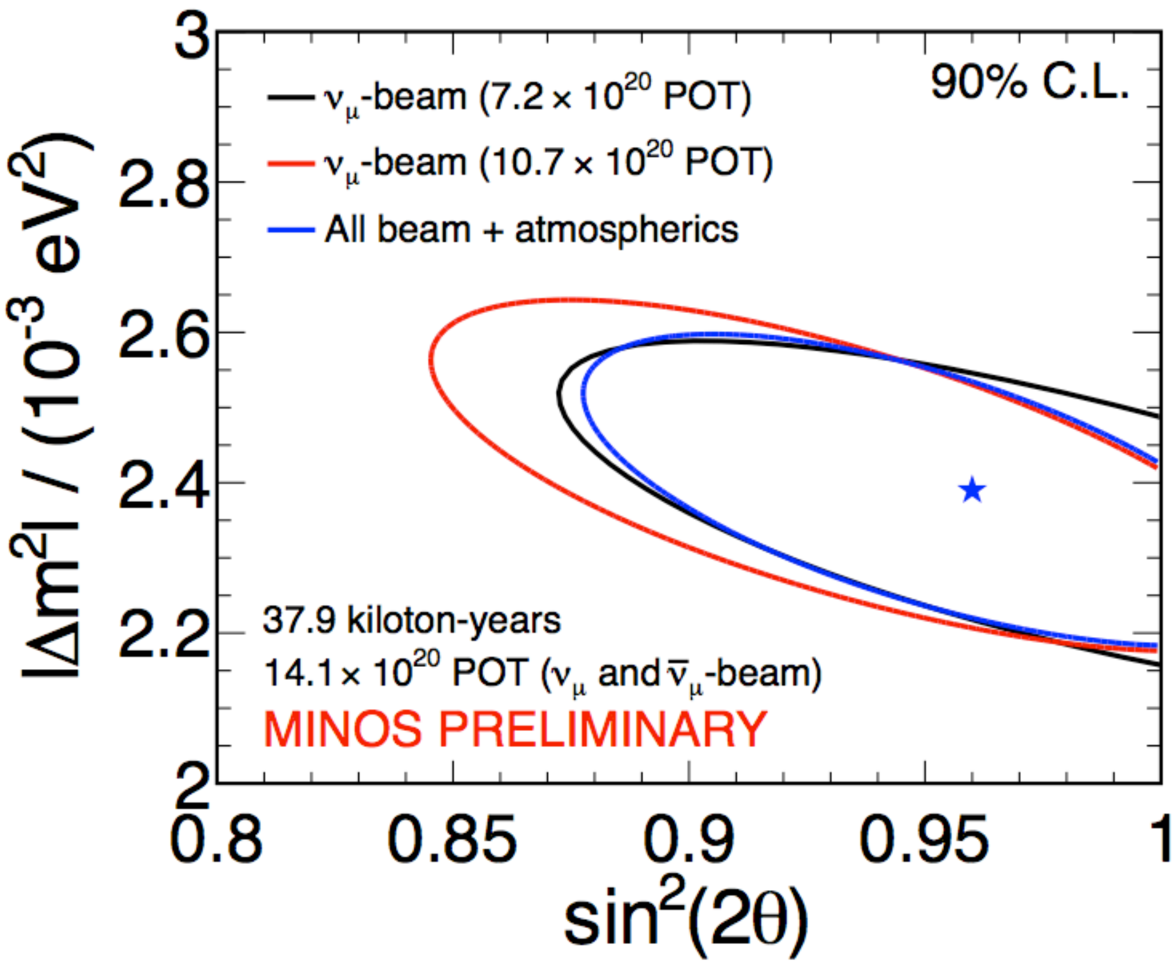


The anti-neutrino / neutrino tension shown and neutrino 2010 has disappeared with data.



MINOS Atmospheric Parameters

New MINOS neutrino oscillation parameters:

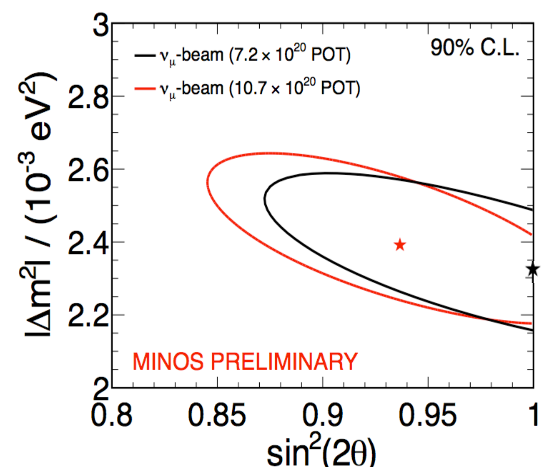


Beam + Atmo.

$$|\Delta m^2| = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$

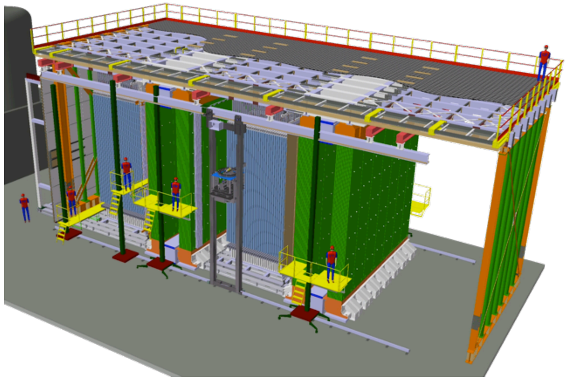
$$\sin^2(2\theta) > 0.90 \text{ at } 90\% \text{ C.L.}$$

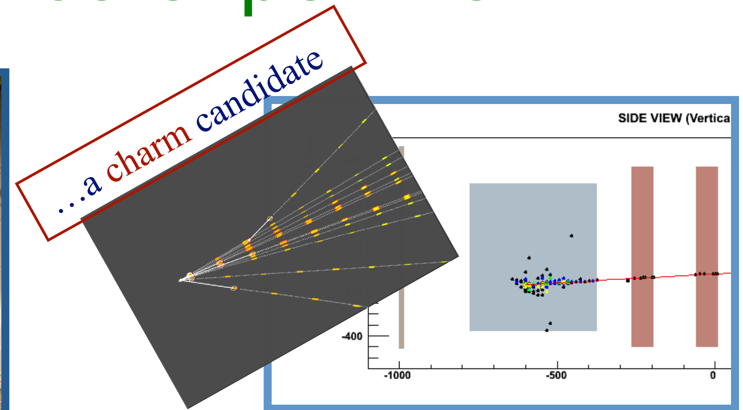


Shift caused by new neutrino beam data

M. NAKAMURA (NAGOYA)

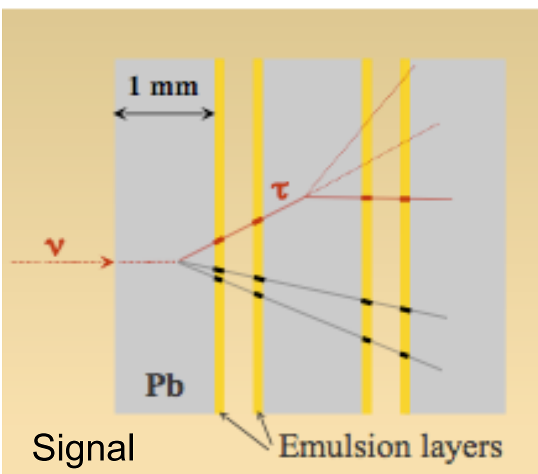
OPERA tau appearance experiment





Electronic trackers point
Back to bricks.

Uses ECC (Emulsion Cloud Chamber)
With automatic scanning
+ Magnetic spectrometer.



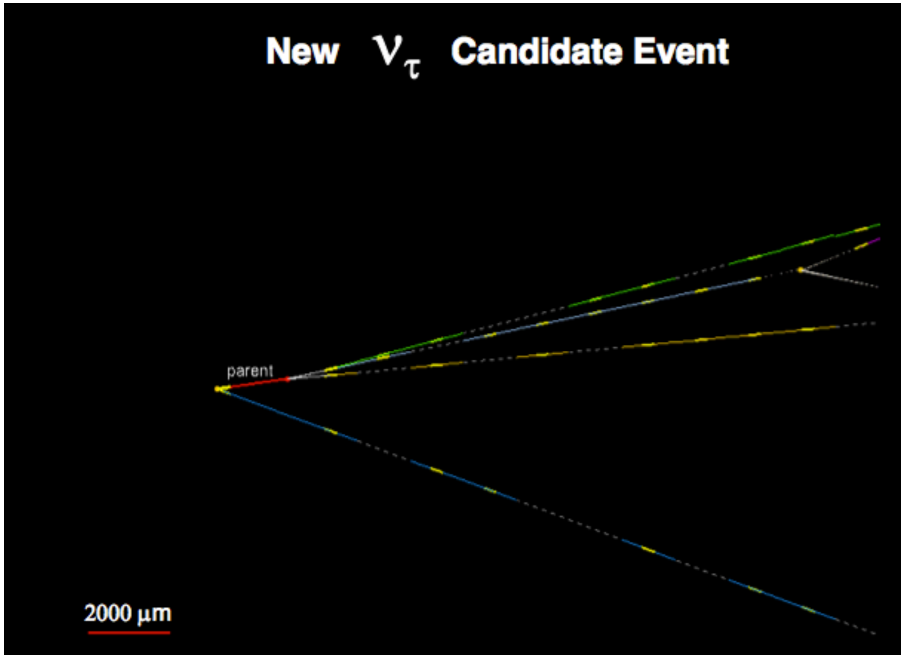
(also reported on nue search)

For 22.5x10^{19} POT → Expected Events 7.6 Signal, 0.8 Background
Ref: New Journal of Physics 14(2012)033017

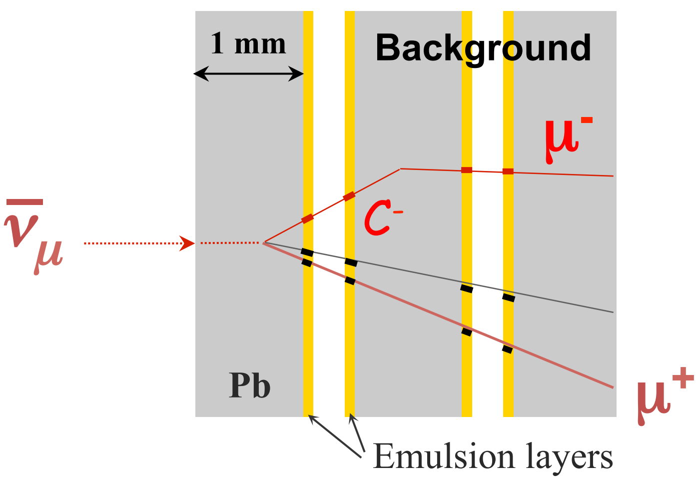
Year	Proton On Target POT	Number of Neutrino Interactions	Integrated POT / Proposal Value
2008	1.78x10^{19}	1698	7.9%
2009	3.52x10^{19}	3557	23.6%
2010	4.04x10^{19}	3912	41.5%
2011	4.84x10^{19}	4210	63.0%
2012	(~4.7x10^{19})	(~4050)	(~84%)

- 14.2 x 10^{19} POT up to 2011

Opera – New Tau Event

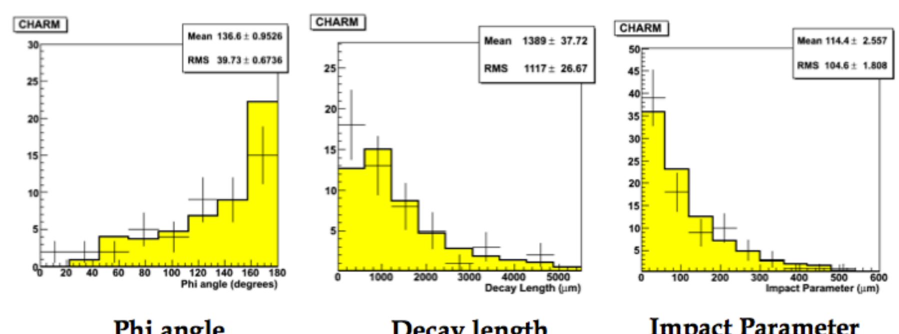


Years	Status	# of events for Decay search	Expected ν_τ (Preliminary)	Observed ν_τ Candidate Events	Expected BG for ν_τ (Preliminary)
2008-2009	Finished	2783		1	
2010-2011	In analysis	1343 Background and efficiency still under study		1	
2012	Started	Analyzing now			
Total		4126	2.1	2	0.2



Detected : 49 events ⇔ Expected 51±7.5 events

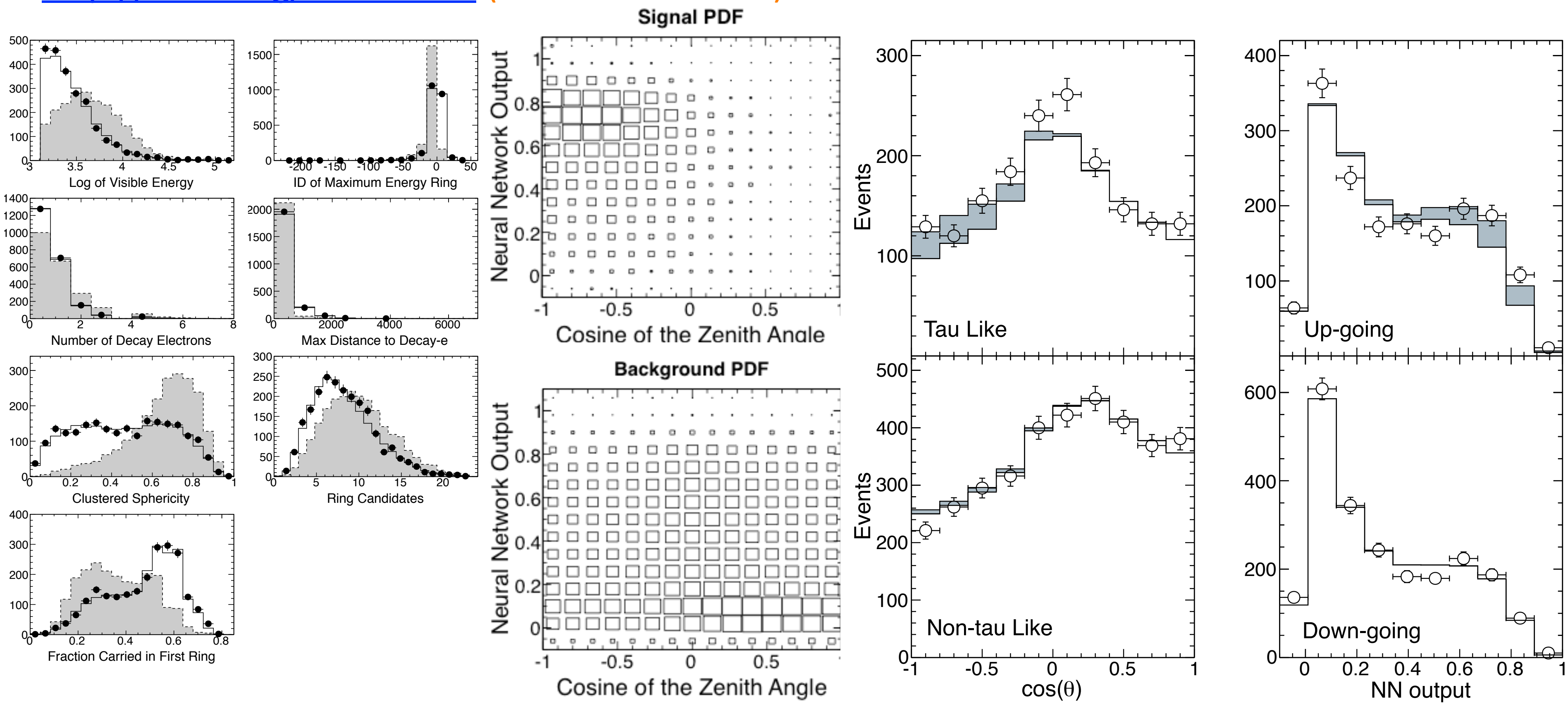
Charm background is well modeled



Super-K Evidence for Tau Appearance

New data + perform 2D un-binned likelihood fit of signal and background.

http://arxiv.org/1206.0328 (submitted to PRL)



$$\text{Norm}_{Tau} = 1.42 \pm 0.35_{(stat)} \begin{matrix} +0.14 \\ -0.12 \end{matrix} (sys)$$

➔ We can reject the no-appearance hypothesis.

P-Value: 6.16×10^{-5} = **3.8 sigma**

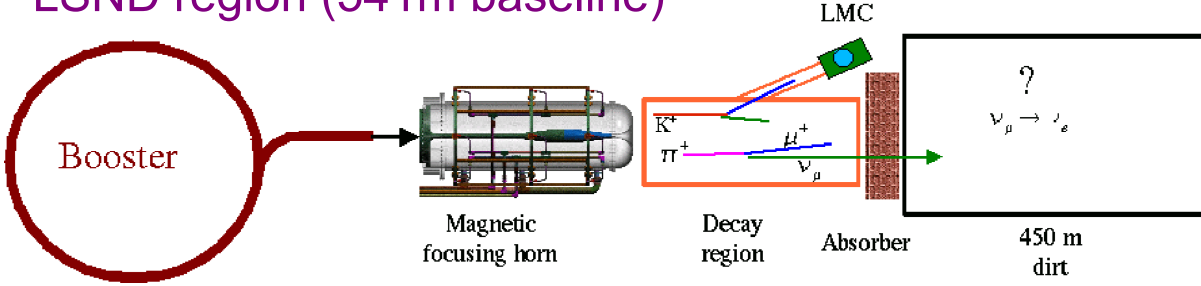
Corresponds to observed signal:

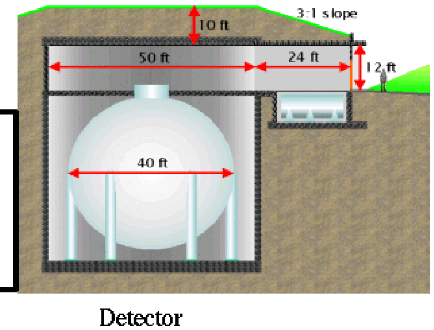
180.1 +- 44.3 (stat) +17.8 -15.2

C. POLLY (FNAL)

MiniBooNE RESULTS

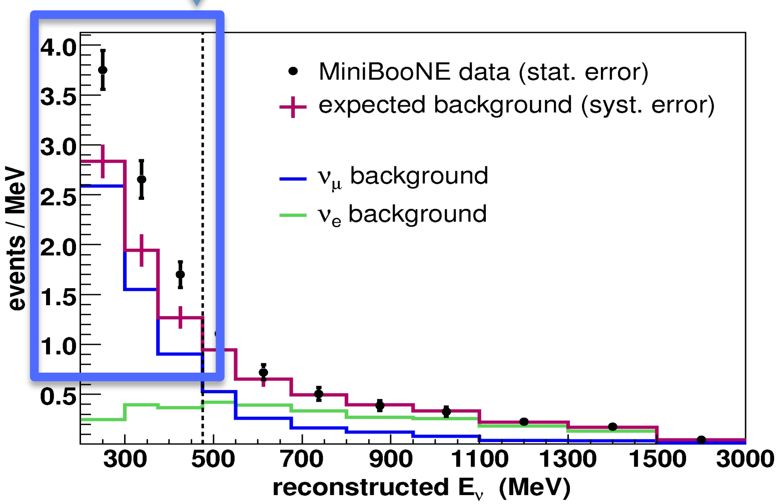
Search for electron appearance in the LSND region (541m baseline)





What's going on here?

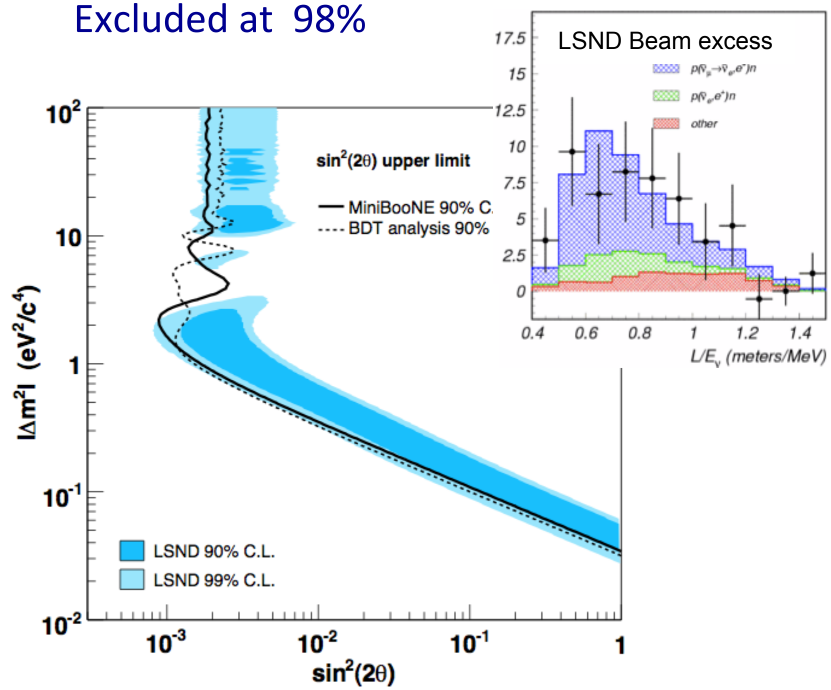
475 < E_ν < 1250 MeV
380 events Exp: 358±19±35 events
0.55 σ Difference



Phys. Rev. Lett. 98, 231801 (2007),
arXiv:0704.1500 [hep-ex]

HISTORY ~2008

2 neutrino oscillation in the LSND region
Excluded at 98%

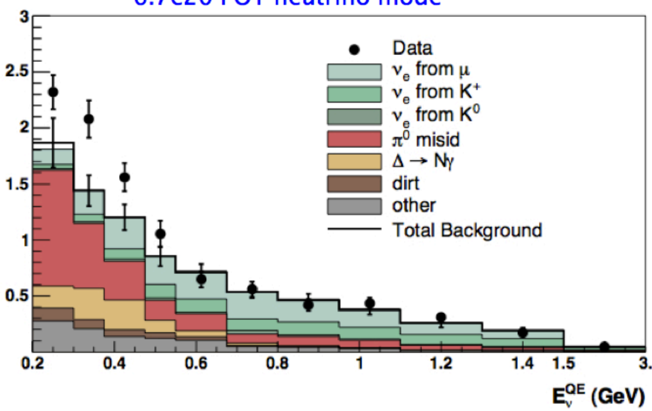


MiniBooNE with doubled anti-νs

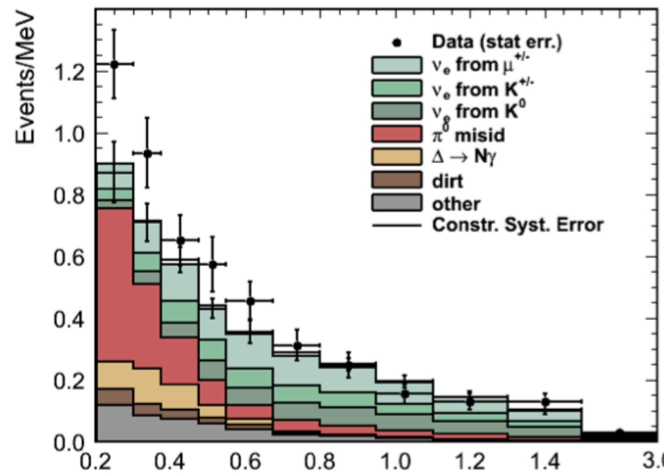
With new statistics ν and anti-ν look very similar.

REMOVE the energy cut.

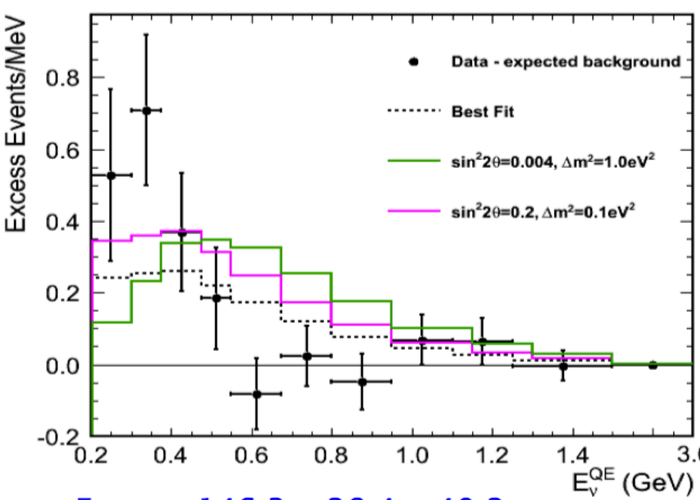
6.7e20 POT neutrino mode



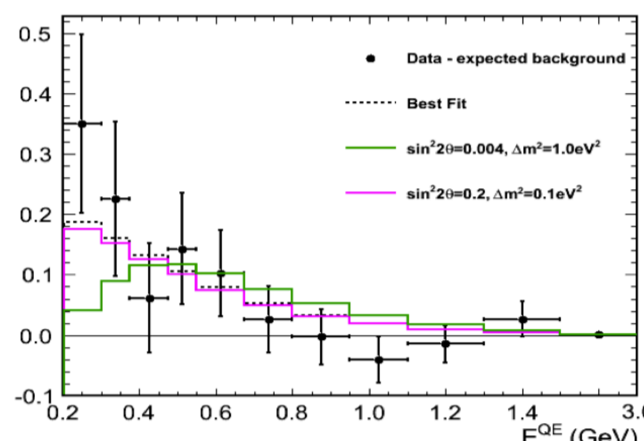
11.3e20 POT anti-neutrino mode



Neutrinos:
Fit > 200 MeV &
Fit > 450 MeV
Inconsistent
(allowed region
vs limit)



Excess: 146.3 ± 28.4 ± 40.2

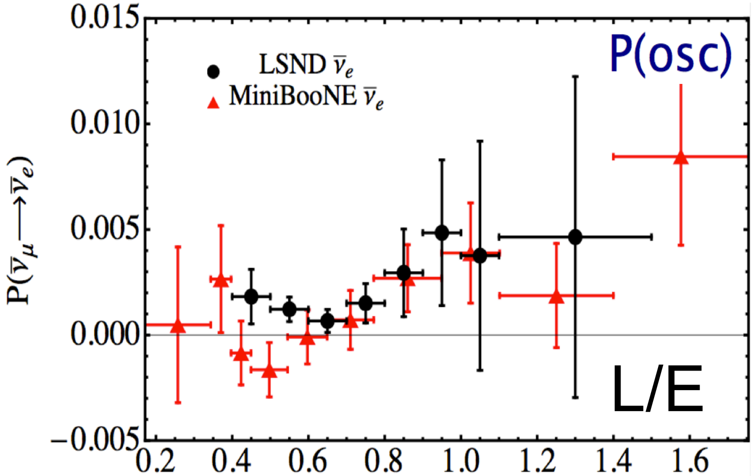


Excess: 77.8 +/- 20.0 +/- 23.4

Anti-Neutrinos:
Fit > 200 MeV &
Fit > 450 MeV
consistent (both
allowed region)

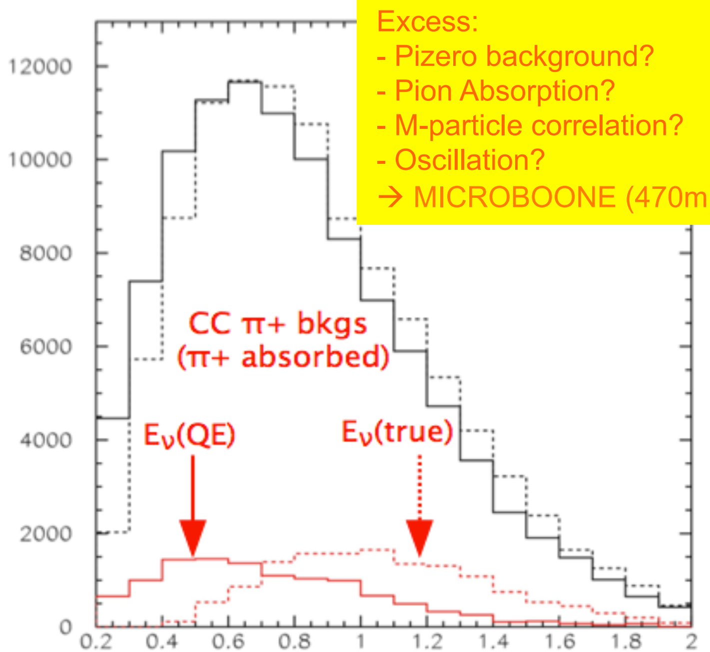
MiniBooNE: New Oscillation Results

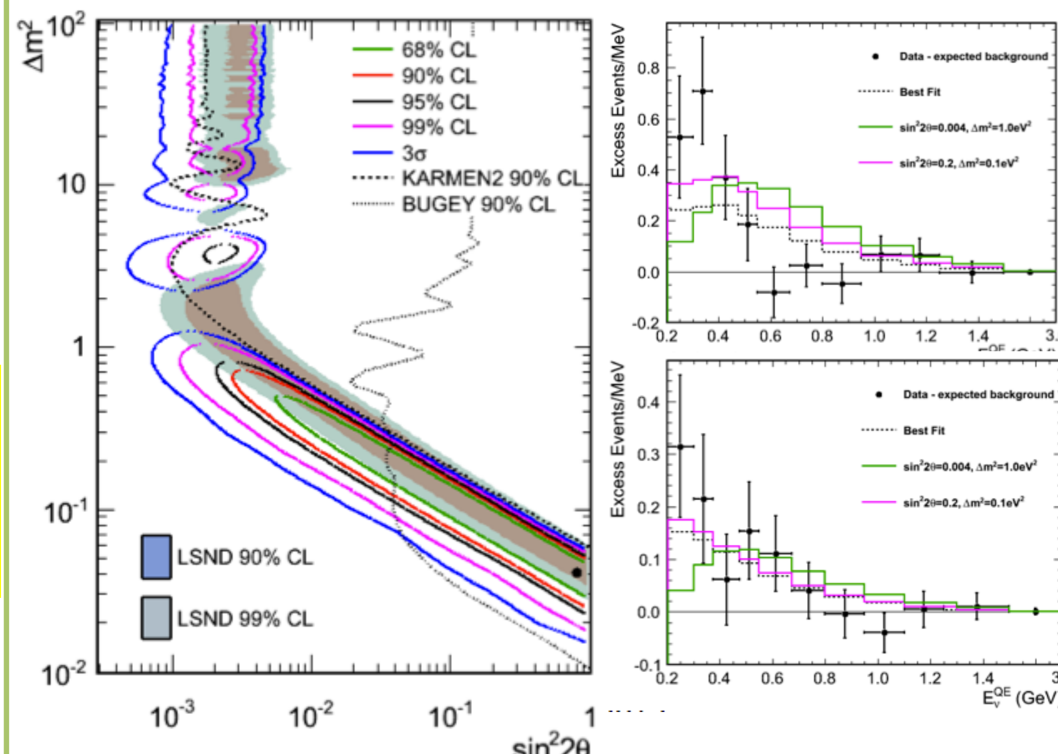
Wait! Isn't the peak supposed to be at L/E ~ 0.6??!



Excess:
- Pizero background?
- Pion Absorption?
- M-particle correlation?
- Oscillation?

→ MICROBOONE (470m)

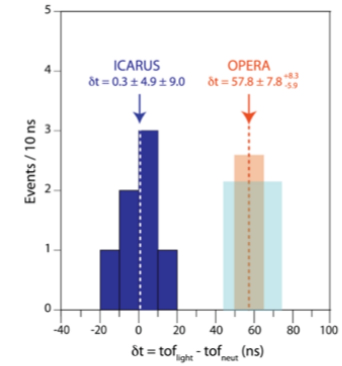




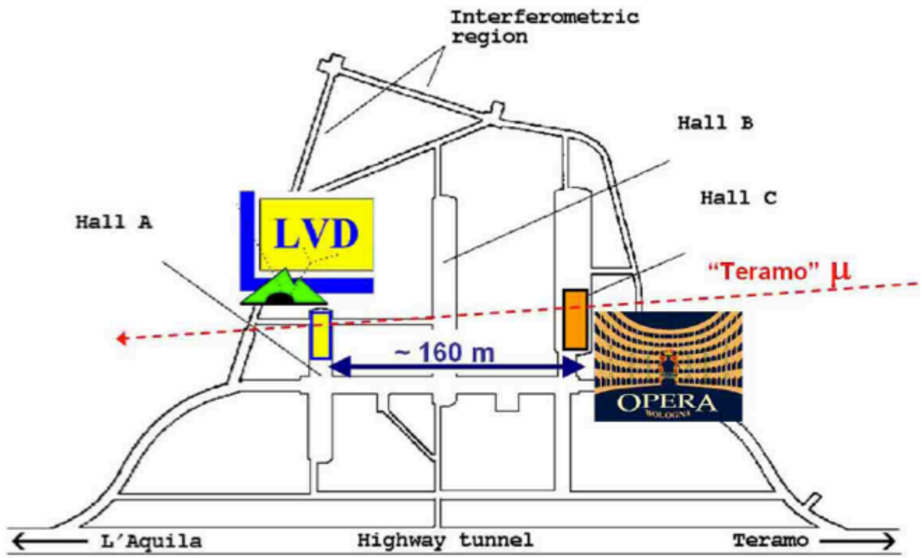
➔ So, fit together with no cut (3+1). This gives the 3.6 σ preference against the null hypothesis.

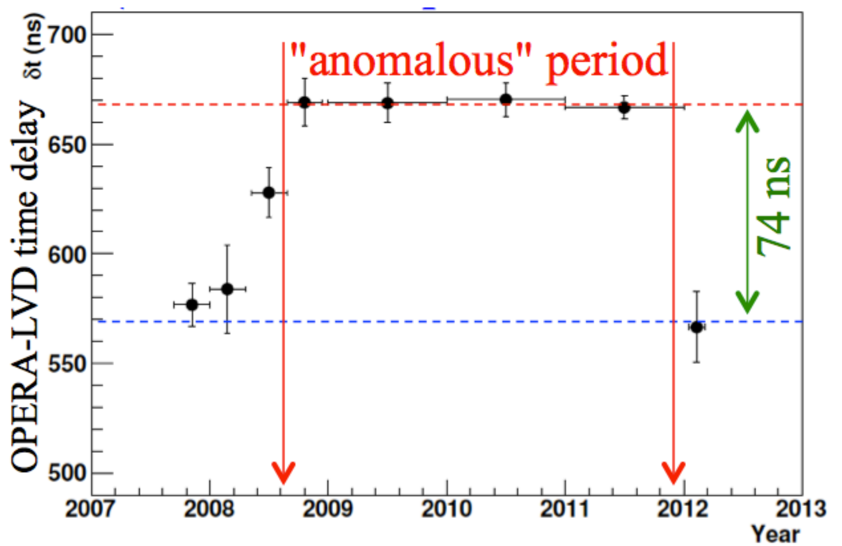
➔ Note: no muon disappearance in these fits!

Neutrino Velocity



OPERA anomaly is now resolved (two issues found)

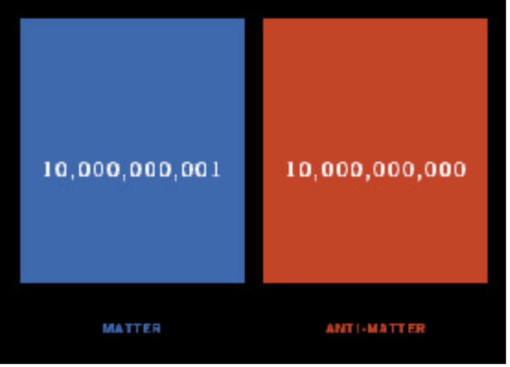




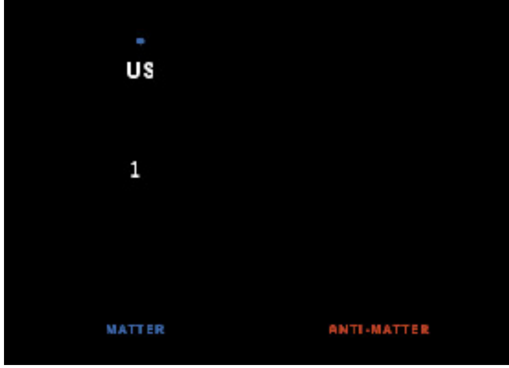
CERN made a special beam structure to facilitate tests.

- **Borexino:** $\delta t = 2.7 \pm 1.2$ (stat) ± 3(sys) ns
- **ICARUS:** $\delta t = 5.1 \pm 1.1$(stat) ± 5.5(sys) ns
- **LVD:** $\delta t = 2.9 \pm 0.6$(stat) ± 3(sys) ns
- **OPERA:** $\delta t = 1.6 \pm 1.1$(stat) [+ 6.1, -3.7](sys) ns
- **MINOS:** $\delta t = -11.4 \pm 11.2$(stat) ± 29 (sys) ns **[new hardware and analysis coming]**

Now: $(v-c)/c \approx 10^{-6}$



Conclusion



$\sin^2 2\theta_{13}$ is now known to be non-zero! Accelerator experiments have measured an appearance signal. Values will get even more precise.

Now we can check the full consistency of our models using accelerators, atmospheric neutrinos and reactors. Some hints of inconsistency remain, so: let's resolve those, keep working hard, and and try to measure CPV!