Results from the MiniBooNE Experiment

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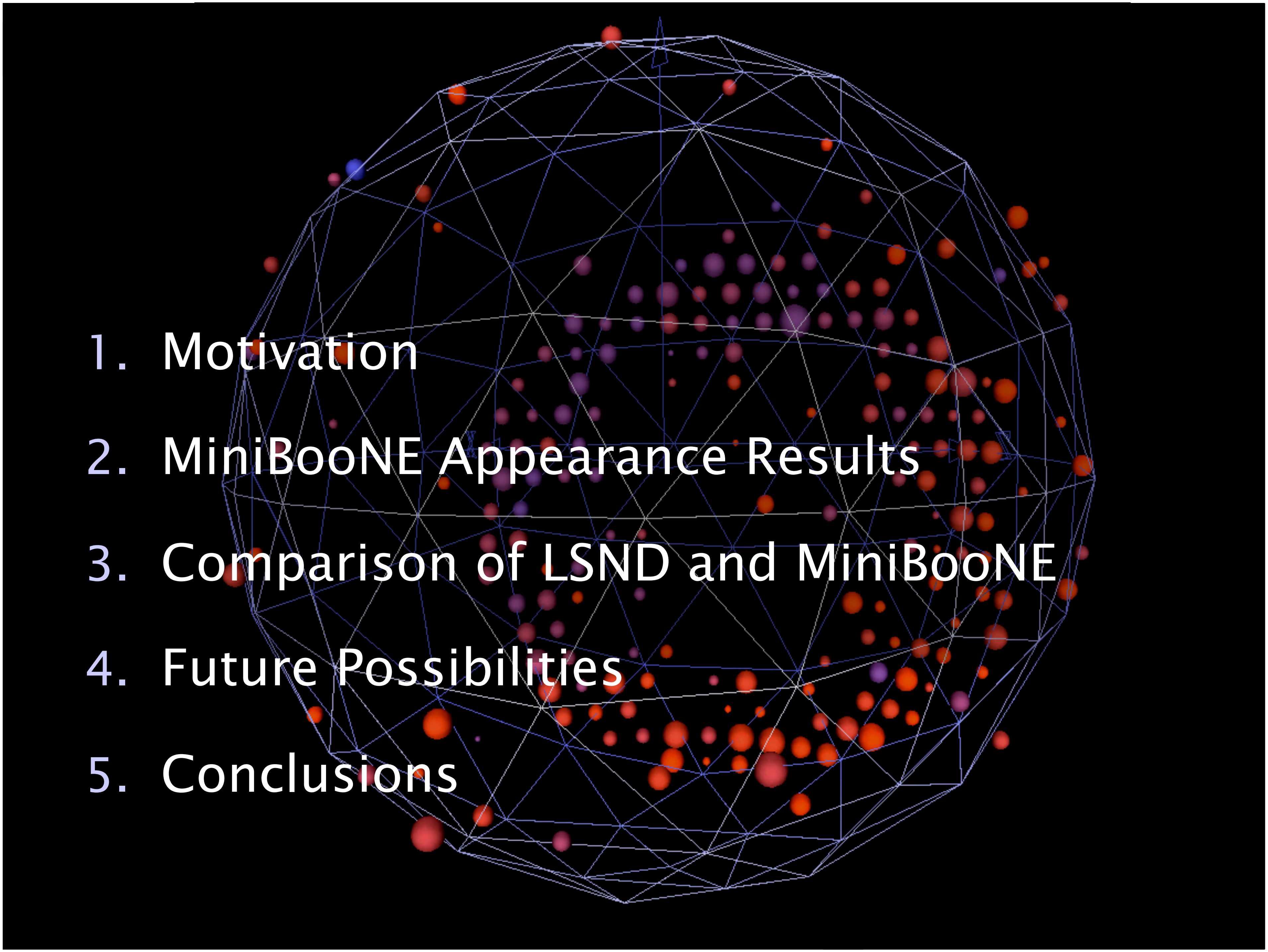
NeuTel2011
Venezia, Italia


1. Motivation
2. MiniBooNE Appearance Results
3. Comparison of LSND and MiniBooNE
4. Future Possibilities
5. Conclusions

Motivation....

Neutrino Oscillations

- The oscillation patterns between the 3 known active neutrino species have been demonstrated by a number of experiments over the last two decades:
  - SNO, Kamland
  - Super-K, K2K, MINOS
- Armed with that knowledge, measurements of neutrino behavior outside the standard 3 generations of active neutrinos indicate new physics:
  - LSND indicates that new physics may be operating
- Interpretations of such a non-standard result probe some deep theoretical issues, for example:
  - Light sterile neutrinos, neutrino decays, CP and/or CPT violation, Lorentz invariance, Extra dimensions

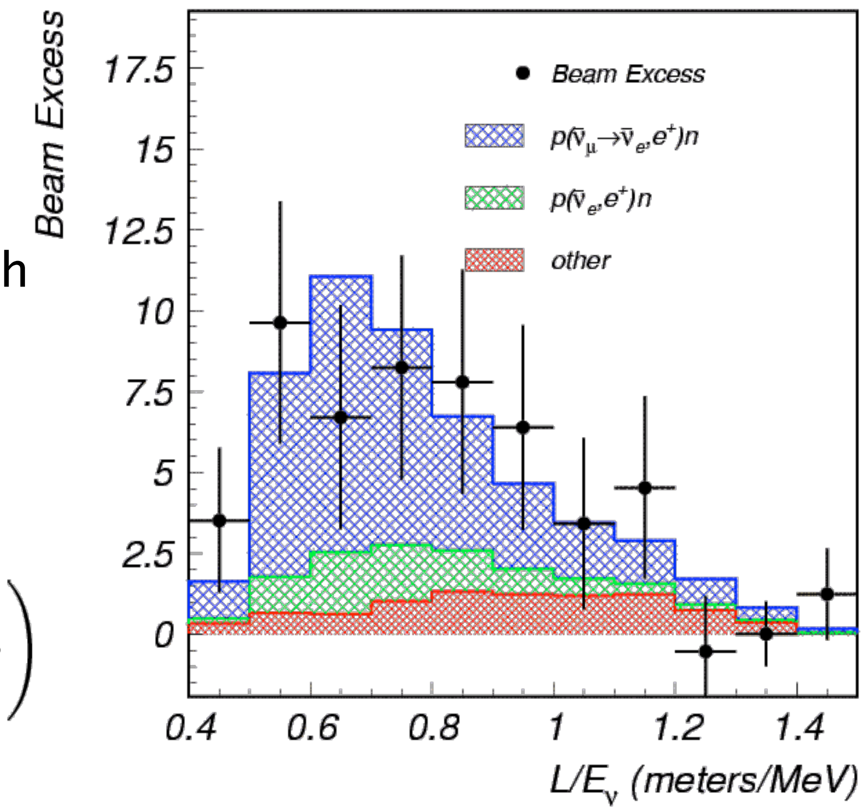
The investigation of neutrino oscillations at the <1% level is unique in its physics reach

Motivation….

Excess Events from LSND still remain:

- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8s)
- *The data was analysed under a two neutrino mixing hypothesis**

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$



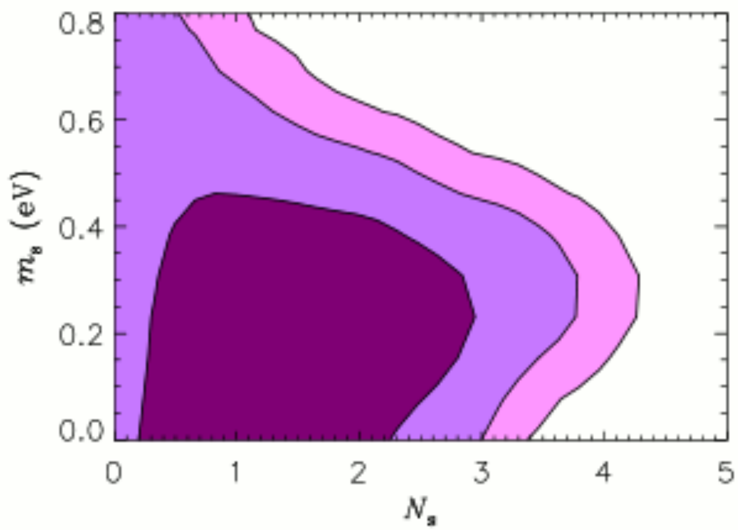
KARMEN at a distance of 17 meters saw no evidence for oscillations →low Δm^2

*3 active + ≥2 sterile vs needed to fit all appearance and disappearance

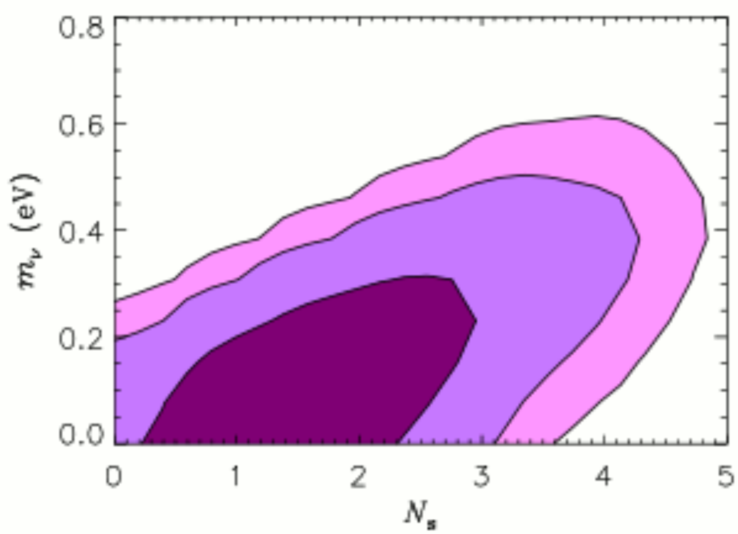
Motivation….

Cosmology Fits for the Number of Sterile Neutrinos

(J. Hamann, et. al. arXiv:1006.5276)

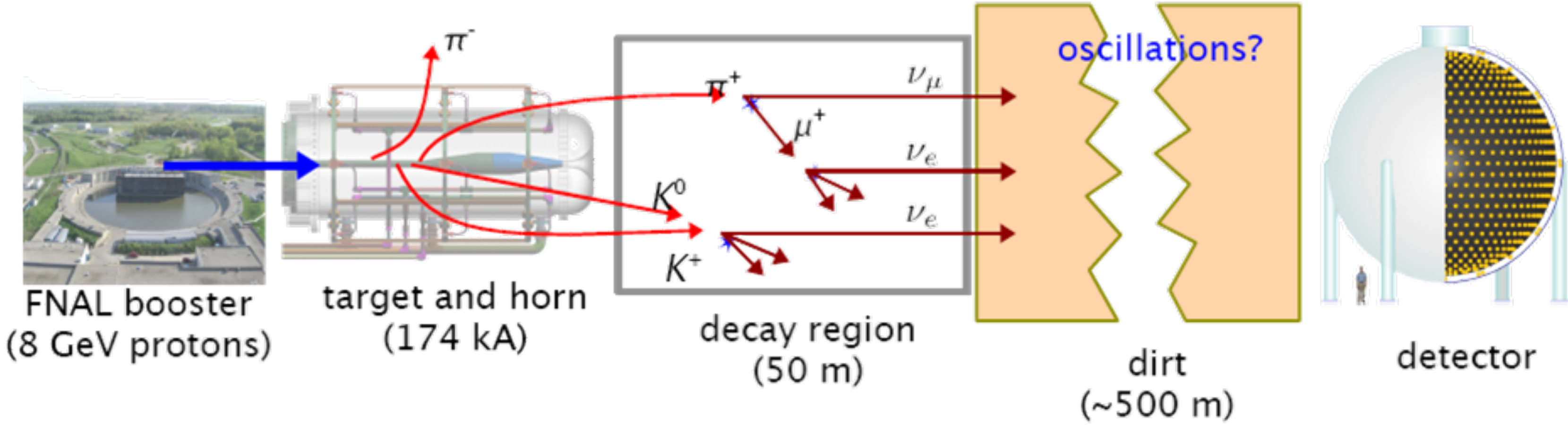


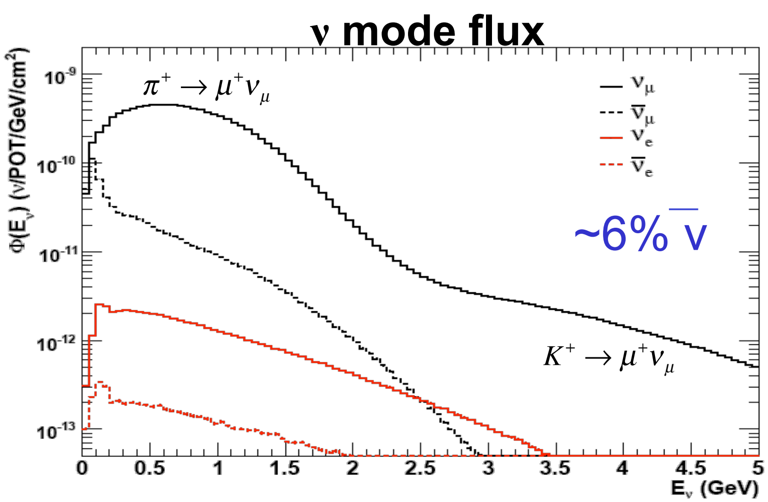
$3 + N_s$
$m_\nu = 0$

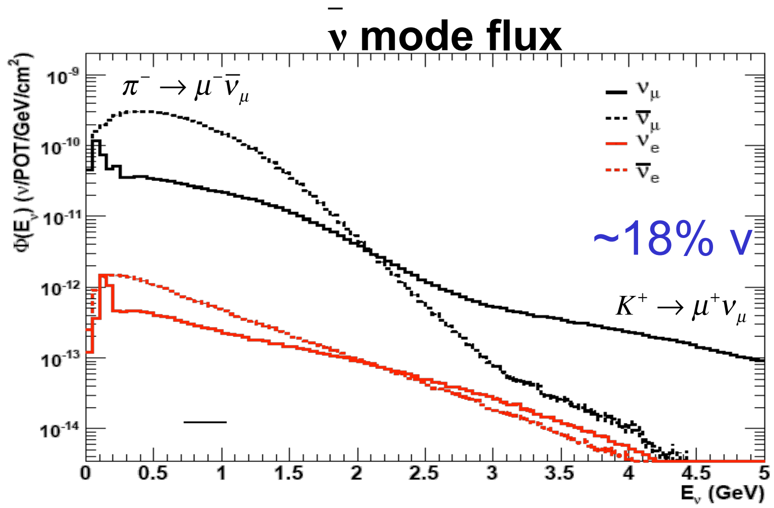


$3 + N_s$
$m_s = 0$

MiniBooNE looks for an excess of electron neutrino events in a predominantly muon neutrino beam





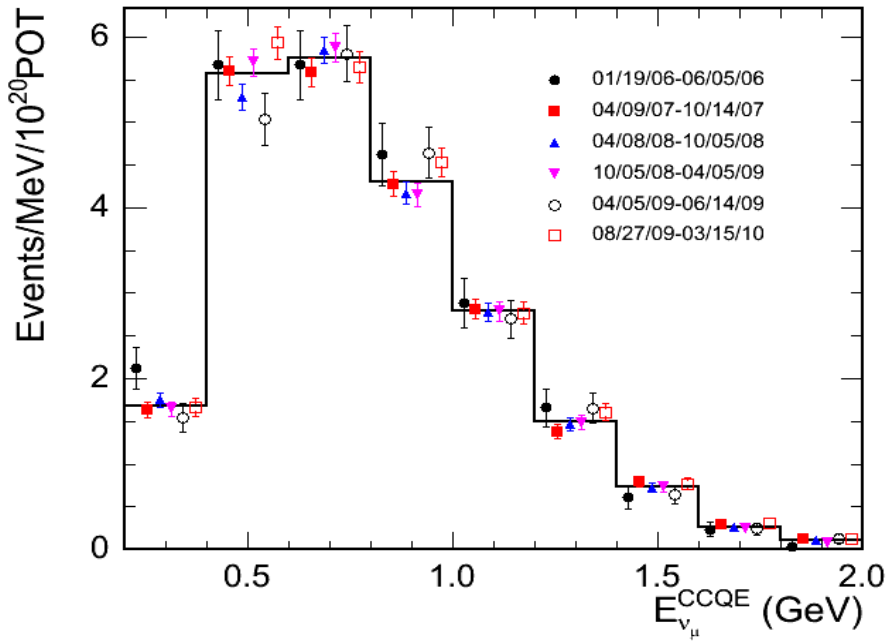


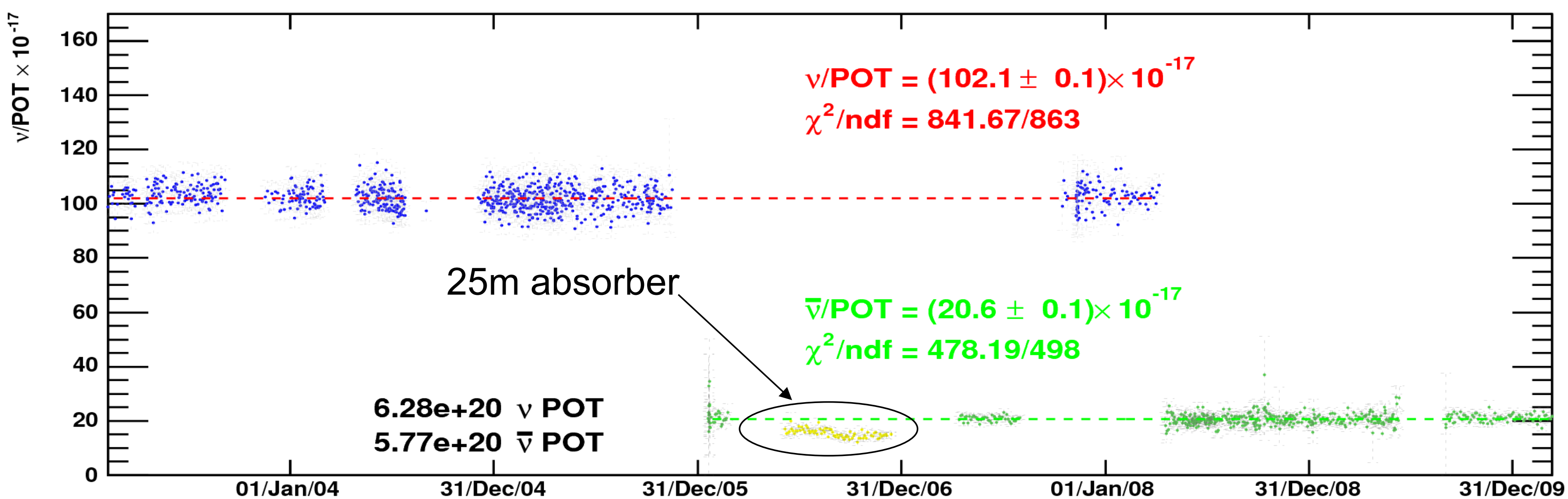
neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

Data stability

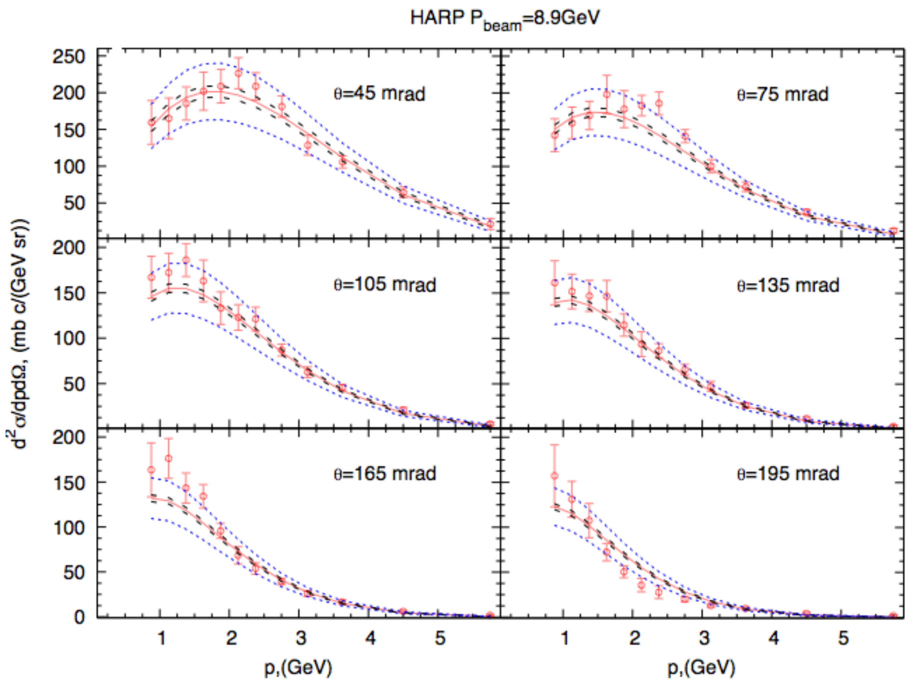
- Very stable throughout the run





Meson production at the Proton Target

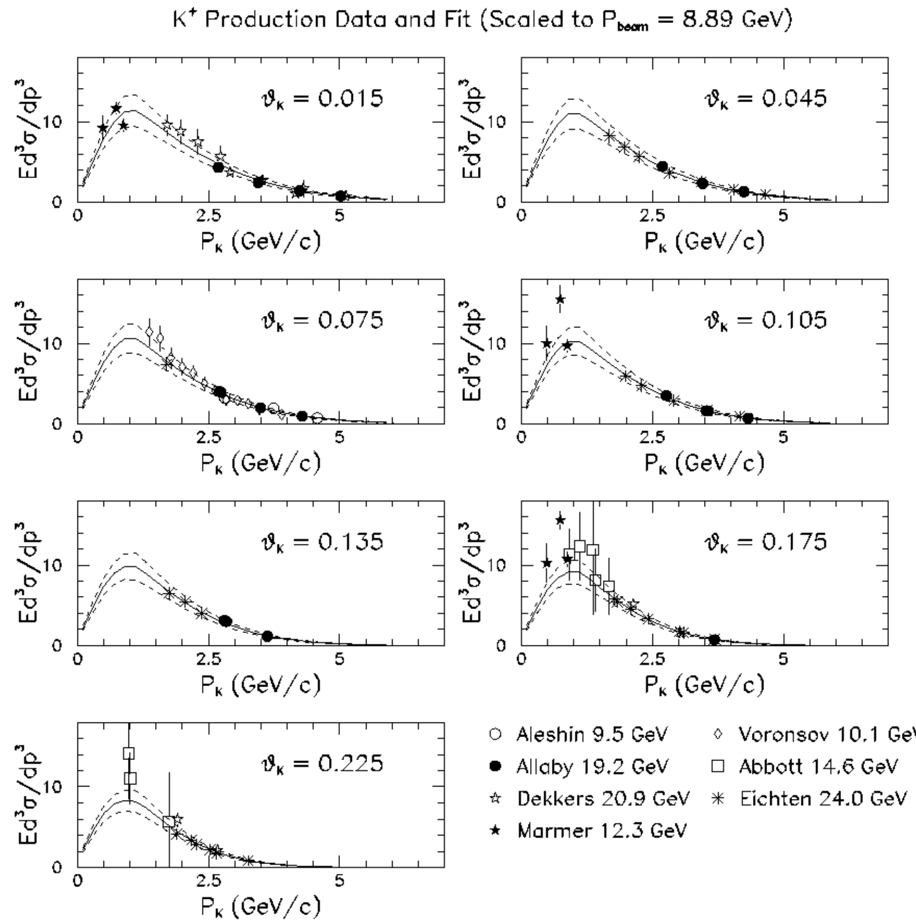
Pions(+/-):



HARP collaboration,
hep-ex/0702024

- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% Beryllium target
- Spline fits were used to parameterize the data.

Kaons:

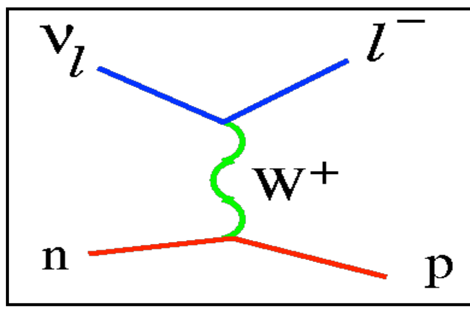


- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

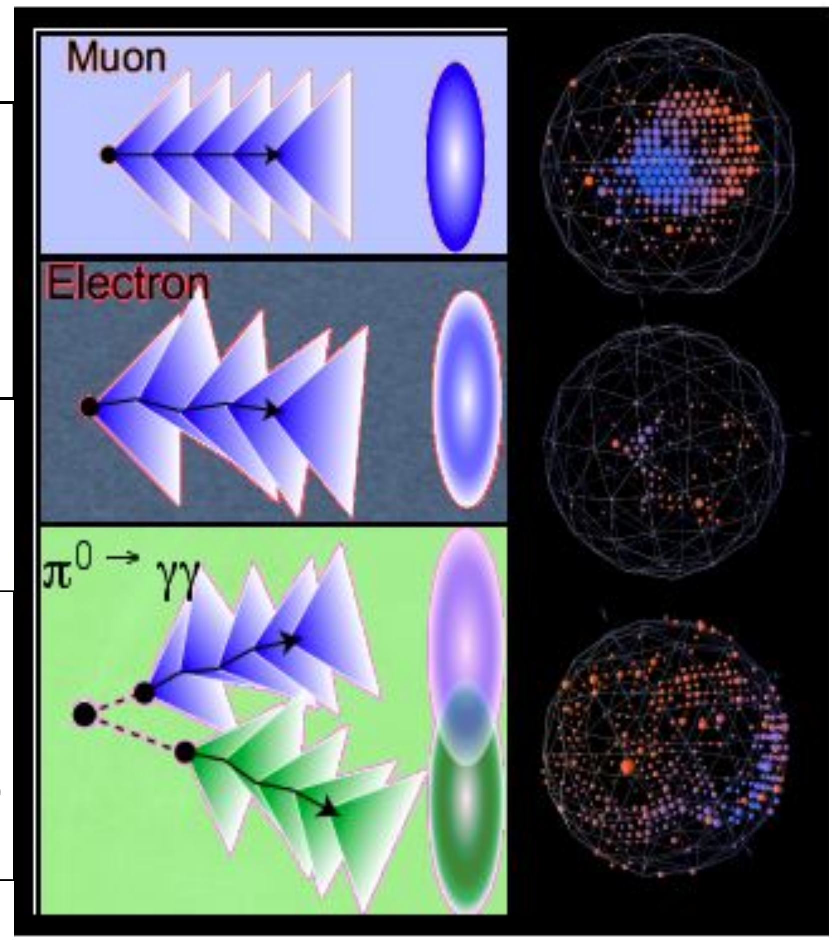
Pattern of Cerenkov Light Gives Event Type

The main types of particles neutrino events produced:

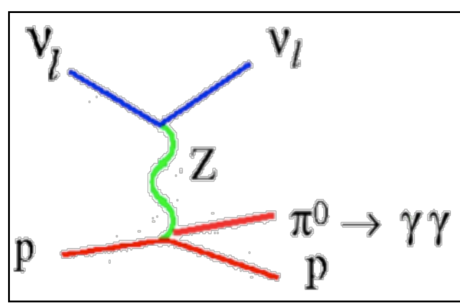
Background Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents
or exiting through veto.



Signal and Background
Electrons (or single photon):
Tag for :$\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent



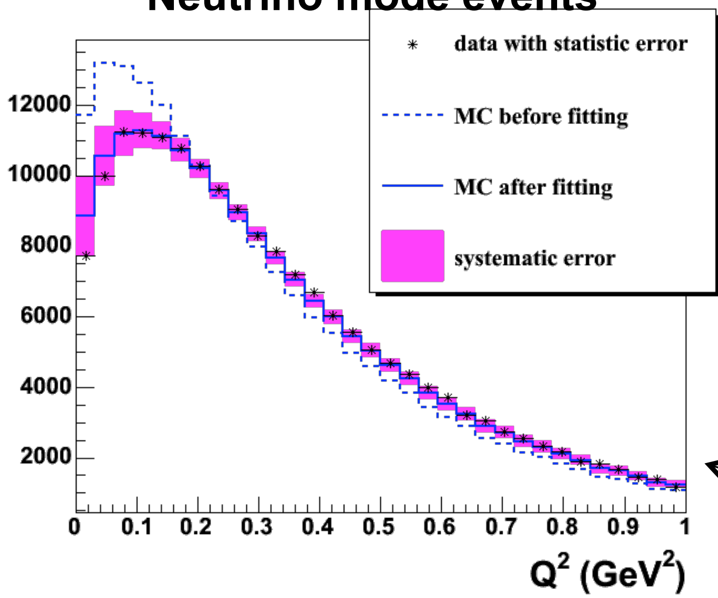
Background π^0s:
Can form a background if one
photon is weak or exits tank.
In NC case, 1 subevent.

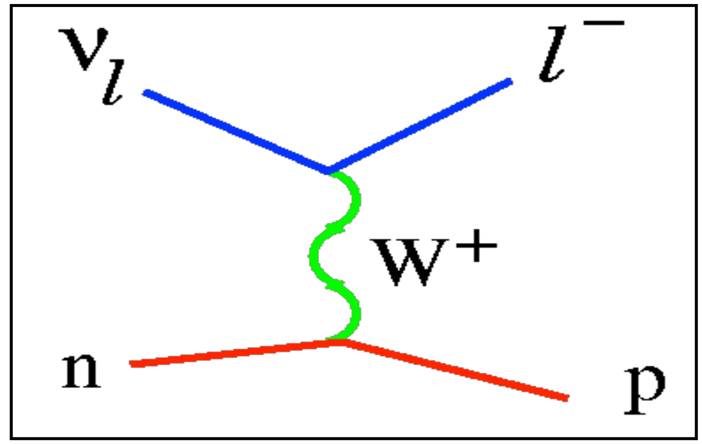


Benchmark Reaction: Charged Current Quasi Elastic (CCQE)

Normalizes our (flux ***x*** cross section)

Neutrino mode events





We adjust the parameters of a Fermi Gas model to match our observed Q^2 Distribution.

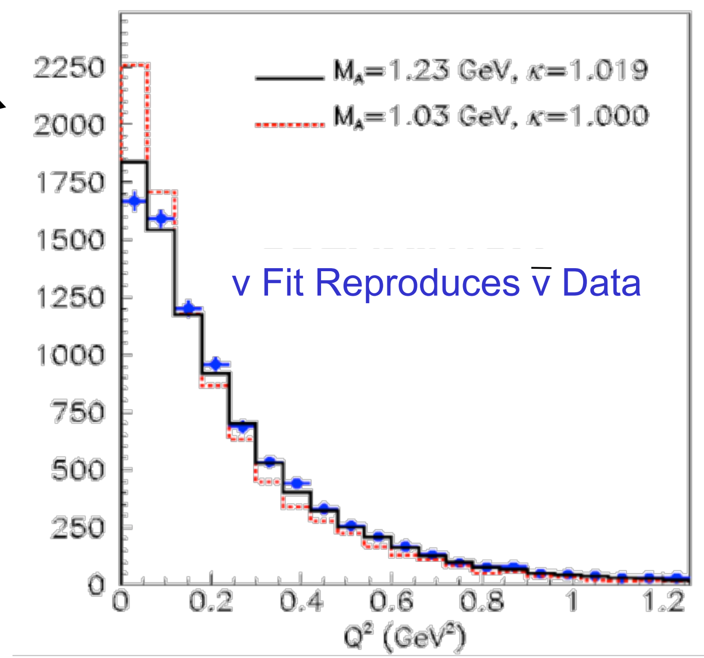
Describes CCQE ν_μ and $\overline{\nu_\mu}$ data well

$M_{A,carbon}$ = 1.35+-0.20 GeV

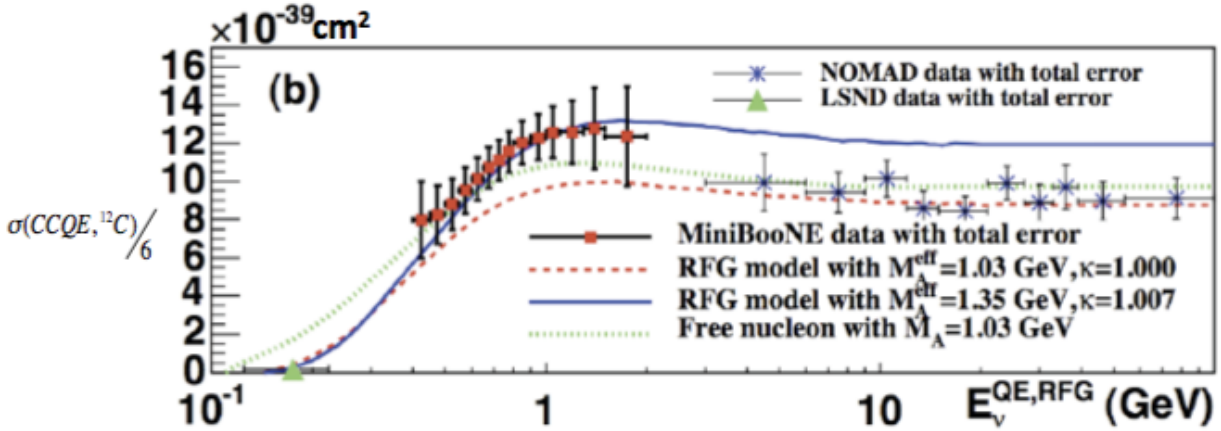
$\varkappa$ = 1.007+-0.011

Also used to model ν_e and $\overline{\nu_e}$ interactions

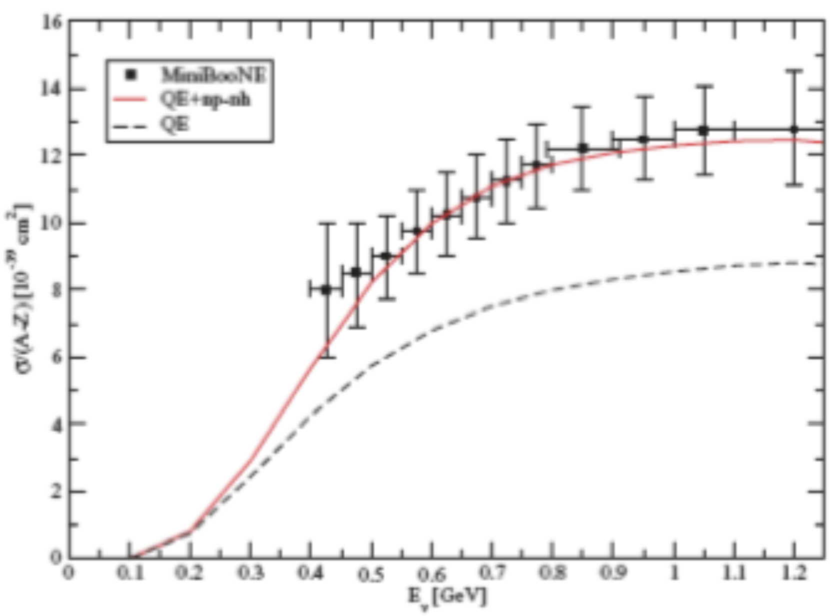
Antineutrino mode events



Charged Current Quasi Elastic Cross Section



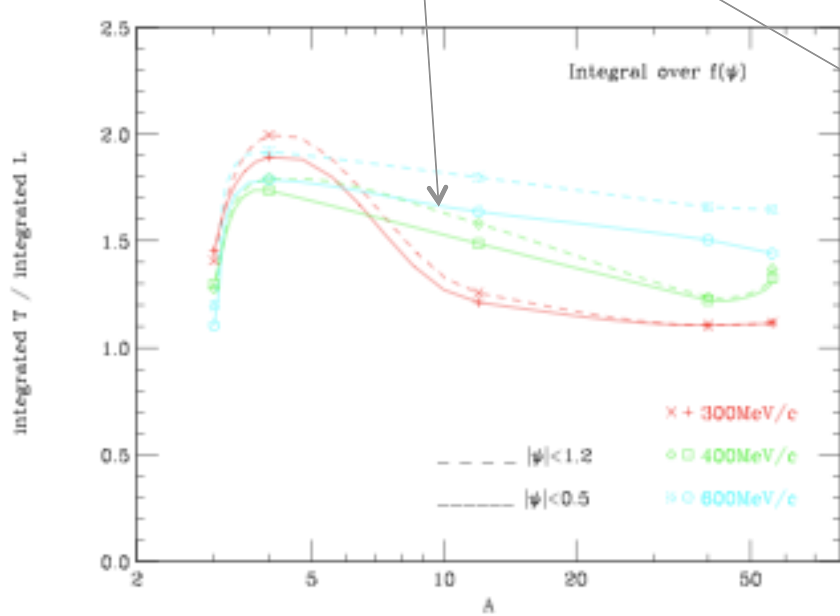
M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PHYS. REV. **C 80**, 065501 (2009)

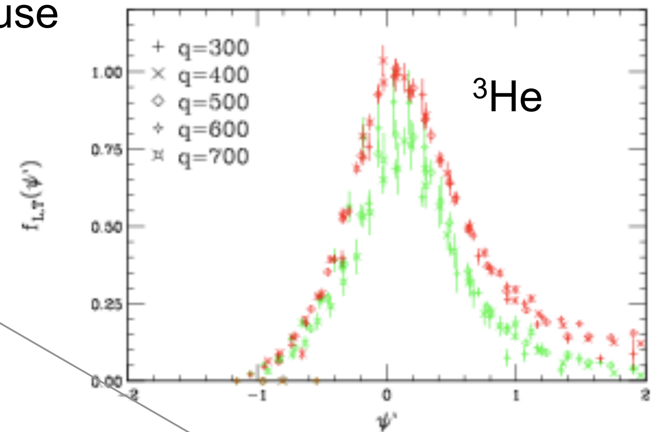


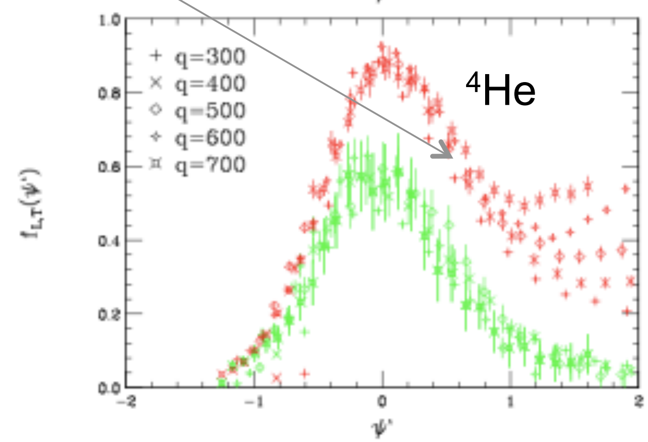
"We suggest that the proposed increase of the axial mass from the standard value to a larger one to account for the quasielastic data, reflects the presence of a polarization cloud, mostly due to tensor interaction, which surrounds a nucleon in the nuclear medium. It translates into a final state with ejection of two nucleons, which in the present stage of the experiments is indistinguishable from the quasielastic final state."

Scaled Quasi Elastic Cross Section in Electron Scattering

The reason is now becoming understood (Garvey + others):
• large increase in transverse component of cross section
• due largely to 2-body current effects in the nucleus because of the presence of amplitudes containing pions and Δs
• requires full treatment of nucleus







J. Carlson et al, Phys.Rev. C65 (2002) 024002:

- Euclidian response function calculations
- Green's function Monte Carlo techniques
- Reproduces data and explains the source of the extra strength

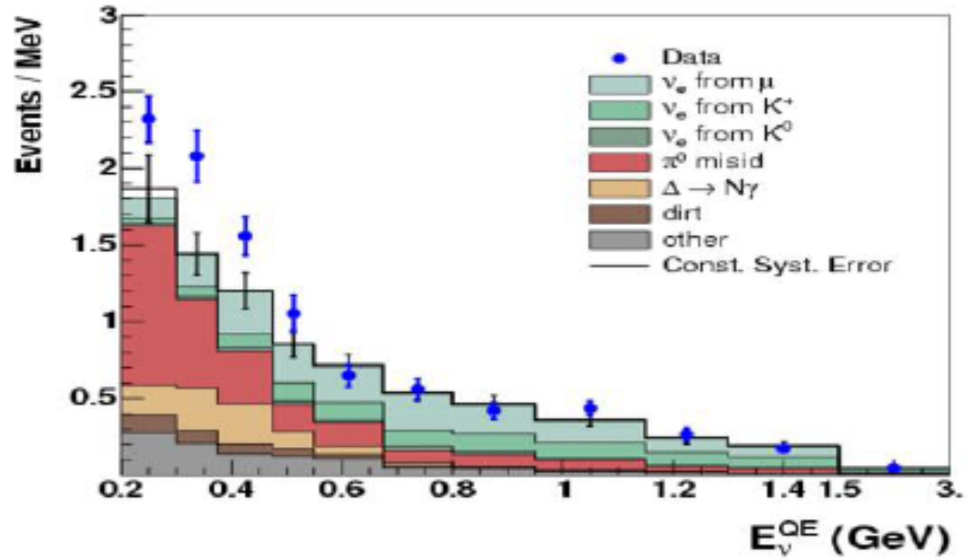
Crucial for oscillation interpretation, provides neutrino energy!!

MiniBooNE Oscillation Searches

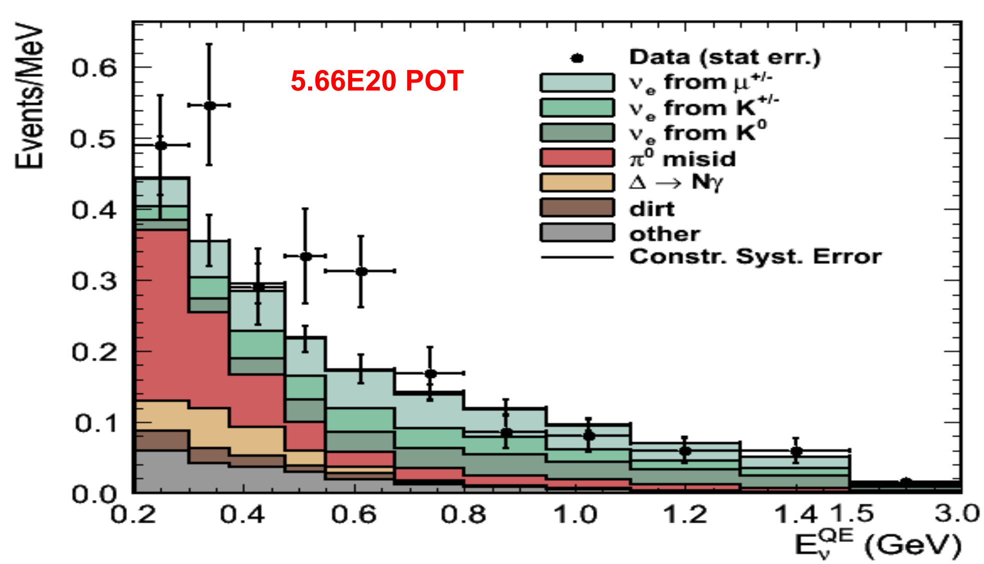
- Neutrino mode ν_e appearance: $\nu_\mu \longrightarrow \nu_e$
  - Seach for excess events above expected background
  - Pure sample of neutrinos
- Antineutrino mode $\bar{\nu}_e$ appearance: $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$
  - Search for excess $\bar{\nu}_e$ events above expected background
  - *Contamination from large amount of neutrinos in antineutrino mode*

MiniBooNE ν_e and $\bar{\nu}_e$ Data

ν Mode



$\bar{\nu}$ Mode



$\bar{\nu}_e$ Background Uncertainties

Uncertainty (%)	200-475MeV	475-1100MeV
p^+	0.4	0.9
p^-	3	2.3
K^+	2.2	4.7
K^-	0.5	1.2
K^0	1.7	5.4
Target and beam models	1.7	3
Cross sections	6.5	13
NC pi0 yield	1.5	1.3
Hadronic interactions	0.4	0.2
Dirt	1.6	0.7
Electronics & DAQ model	7	2
Optical Model	8	3.7
Total	13.4%	16.0%

- Unconstrained $\bar{\nu}_e$ background uncertainties
- Propagate input uncertainties from either MiniBooNE measurement or external data

(ν_μ constrained error ~10%)

Recent Progress in the Appearance Analysis

- SciBooNE analysis of its ν_μ CCQE data
  - Effectively a “near detector” although not identical to MiniBooNE and not sensitive to ν_e component
  - Constraint on K^+ component of the beam
- Have now collected >8x10^{20} pot (published data: 5.66x10^{20})
  - Plan to release new data in May or June

Model Independent Views of Oscillations
Why L/E?

- *Neutrino oscillations usually appear as simple trigonometric functions of L/E*

$$P\left(\nu_\alpha \to \nu_\beta\right) = \delta_{\alpha\beta} - 4\sum_{i>j}^{N} \Re\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin^2(\Delta m_{ij}^2 \frac{L}{E}) + 2\sum_{i>j}^{N} \Im\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin(2\Delta m_{ij}^2 \frac{L}{E})$$

$$(\text{antineutrinos}: U \to U^*)$$

- *Experiments can be compared directly to each other in L/E to look for the interference of mass states and oscillations*

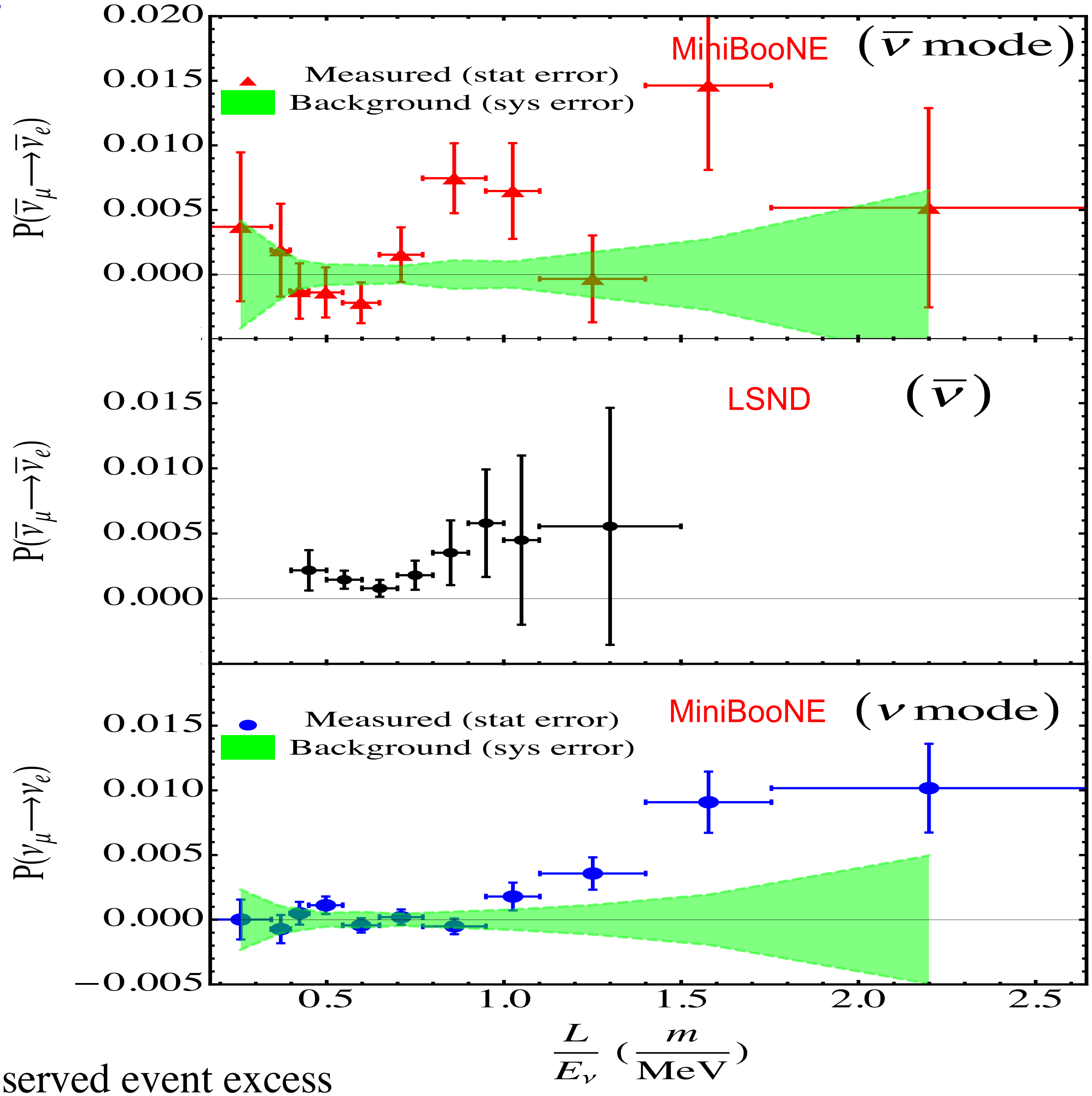
- *The next plots show P(osc) vs L/E:*

$$P\left(\alpha \to \beta\right) \equiv \frac{\text{observed event excess}}{\text{number expected for full transmutation of } \nu_\mu \text{ or } \bar{\nu}_\mu}$$

$$\left(\Delta m^2 \frac{L}{E_\nu}\right) \text{ is just the phase difference of the two states}$$

Data plotted vs L/E

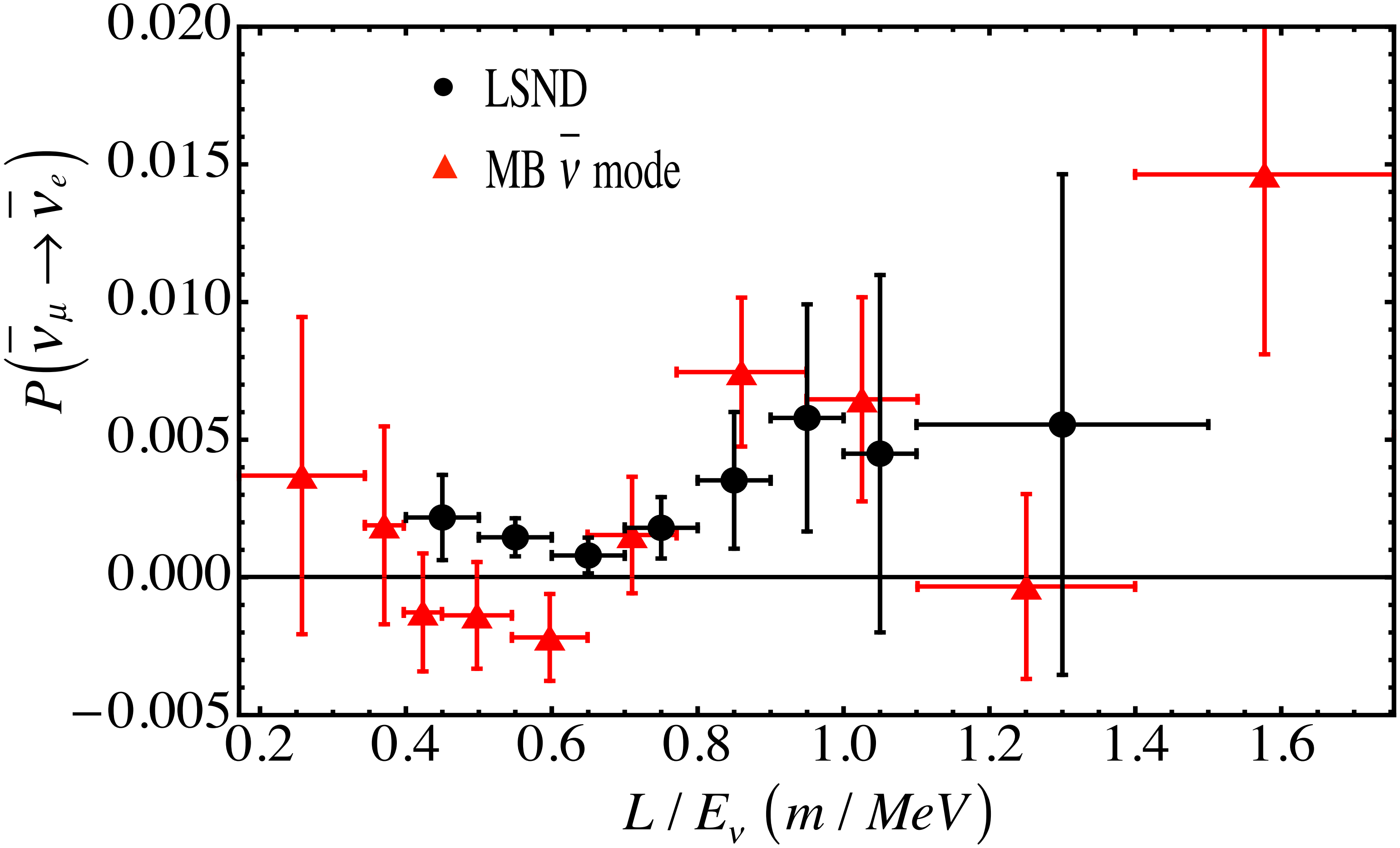
5.66E20 POT



- MiniBooNE L/E bins match the standard MB energy bins, just recast in L/E

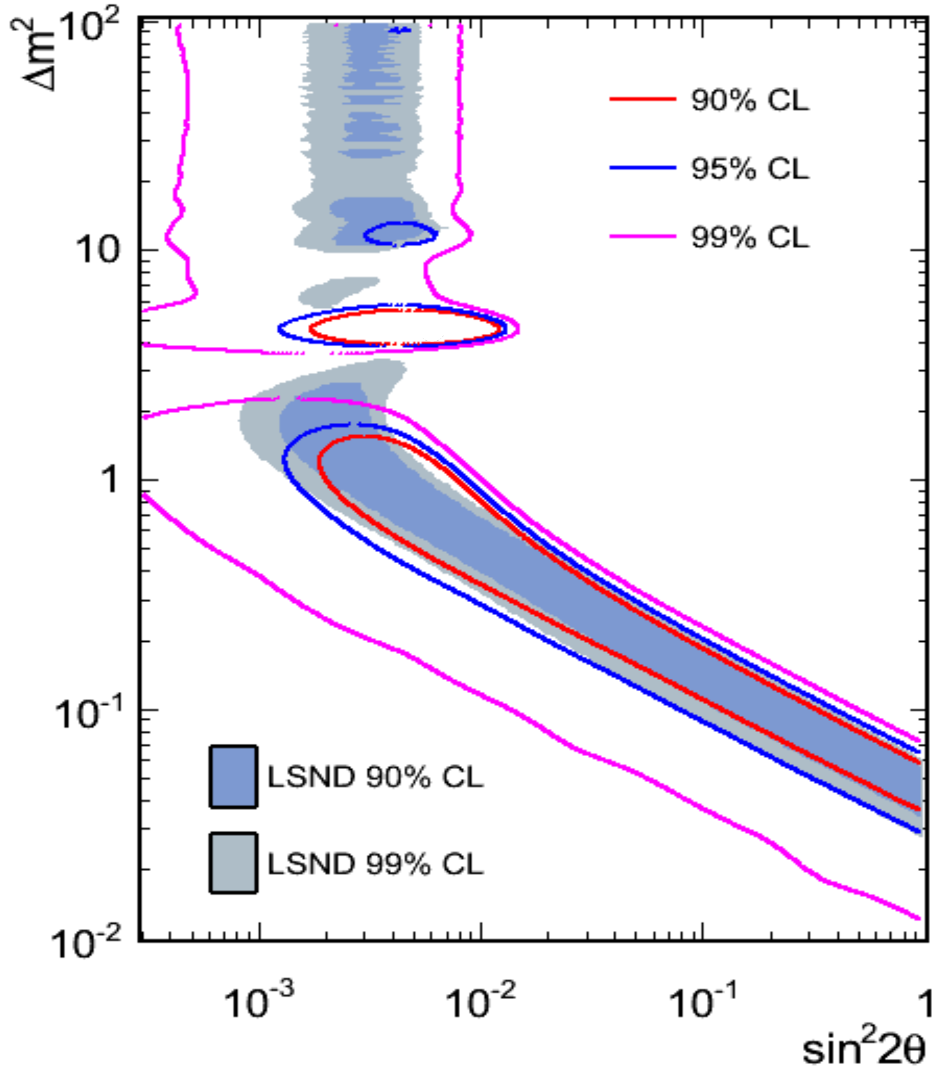
$$P(\alpha \to \beta) \equiv \frac{\text{observed event excess}}{\text{number expected for full transmutation of } \nu_\mu \text{ or } \bar{\nu}_\mu}$$

Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data



Antineutrino mode MB results Full Energy Range

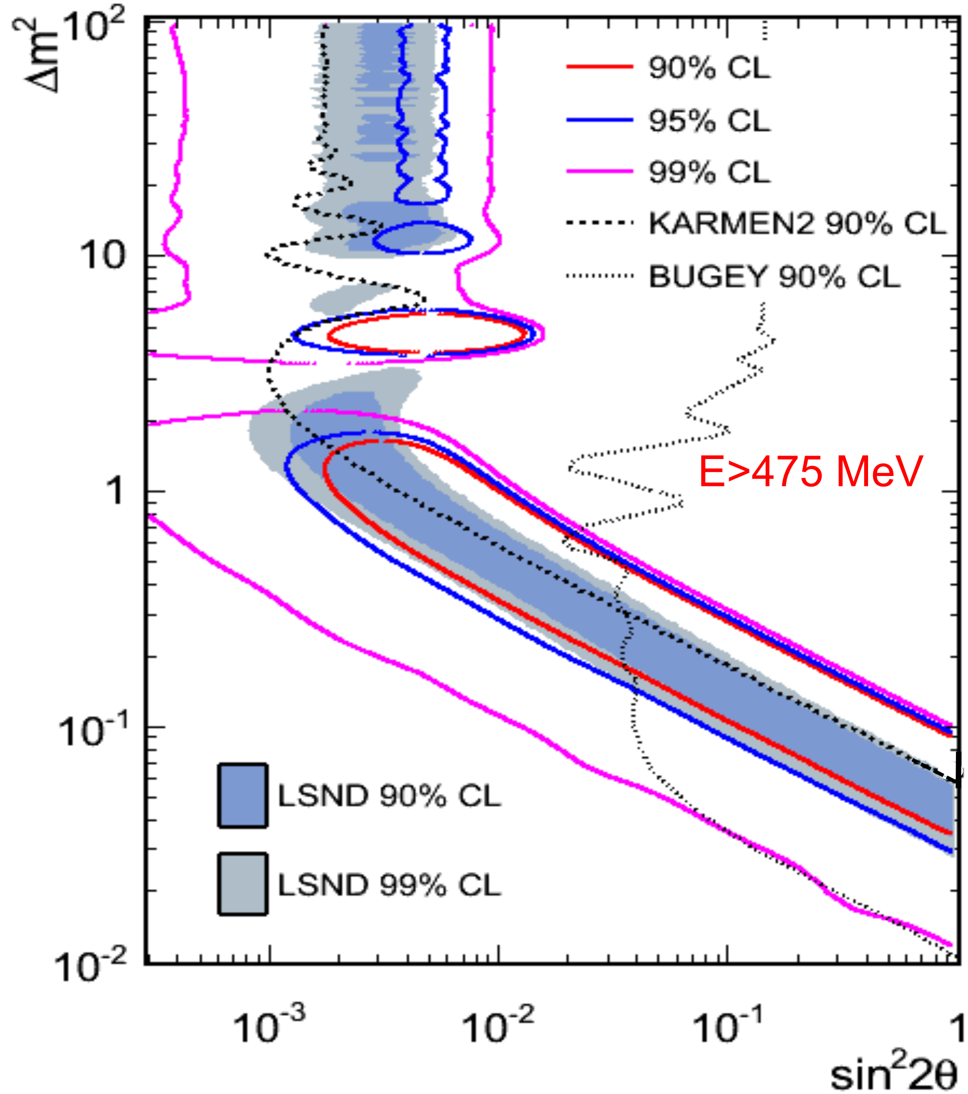
- Results for **5.66E20 POT**
- Maximum likelihood fit in *simple 2 neutrino model*
- Null excluded at 99.5% with respect to the two neutrino oscillation fit



Antineutrino mode MB results for E>475 MeV

(E>475 avoids question of low energy excess in nu-mode)

- Results for **5.66E20 POT**
- Maximum likelihood fit for *simple two neutrino model*
- Null excluded at 99.4% with respect to the two neutrino oscillation fit.
- Signal bins only:
  - $P_{\chi 2}$(null)= 0.5%
  - $P_{\chi 2}$(best fit)= ~10%



Analysis of All Short Baseline Data
Karagiorgi et. al. (Laguna Meeting March 3-5 2011)

Updated fits: (3+2)

Dataset	CP	χ^2 (ndf)	gof	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	ϕ_{45}
all SBL+ atm	CPC	186.1 (193)	62%	0.92	23.8	0.13	0.13	0.083	0.14	0
	CPV	182.6 (192)	67%	0.92	26.6	0.14	0.14	0.077	0.15	1.7π

Overall χ^2 quite reasonable and compatibility of data sets is acceptable

Preliminary

NEW: includes updated MiniBooNE antineutrino appearance dataset, and new reactor flux predictions

Best fit parameters essentially unchanged. Small improvements in χ^2.

Change in χ^2 OLD→NEW	CPC:	5.4/0 dof
	CPV:	6.7/0 dof
Change in χ^2 CPC→CPV	NEW:	3.5/1 dof
	OLD:	2.2/1 dof

Compatibility among all SBL+atm: 7% → 6% (decrease is due to MiniBooNE($\overline{\nu}$))

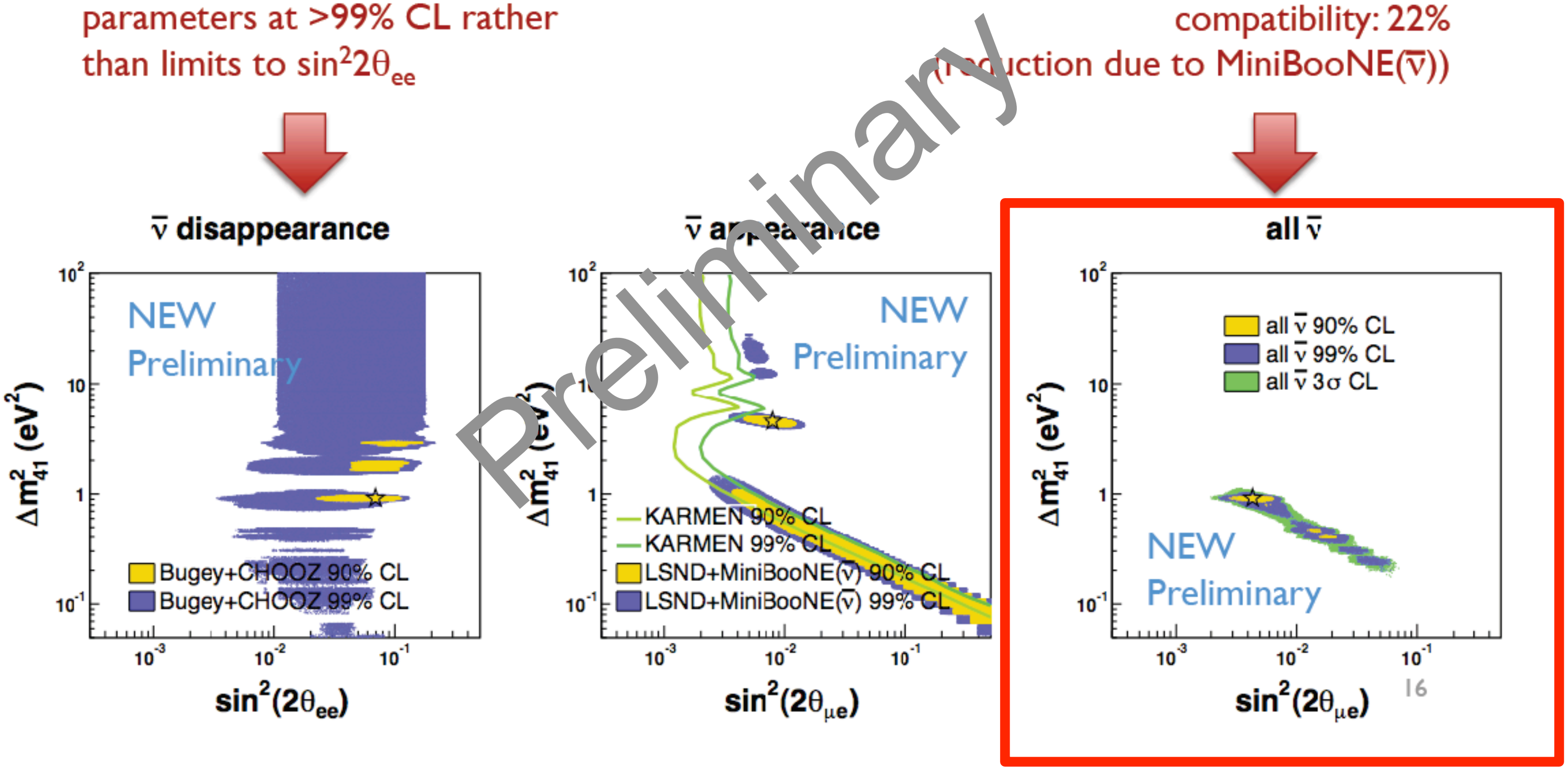
Karagiorgi et. al. cont.

Updated fits: (3+1), antineutrino-only

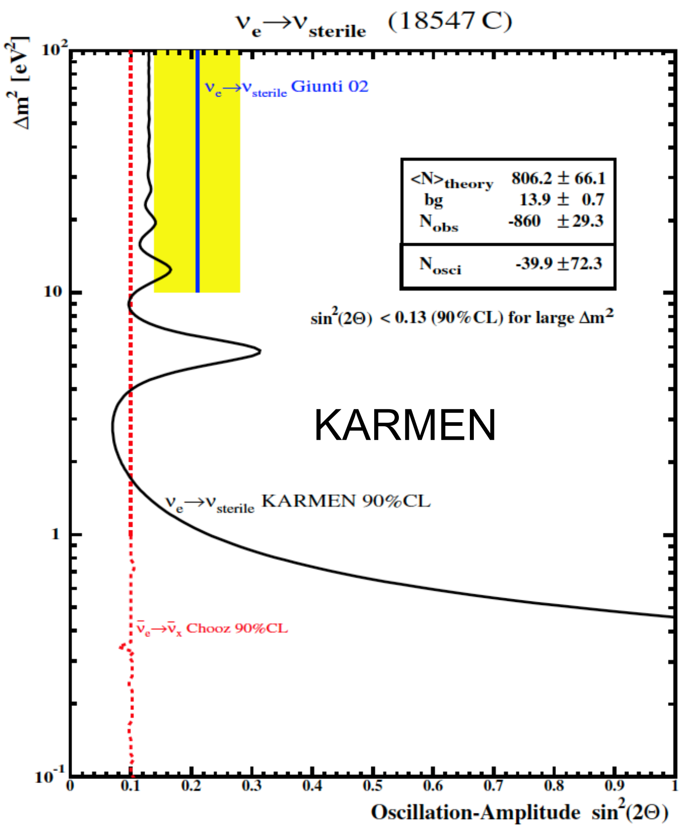
CPT Violating!

Now, reactor data from CHOOZ and Bugey yield allowed parameters at >99% CL rather than limits to $\sin^2 2\theta_{ee}$

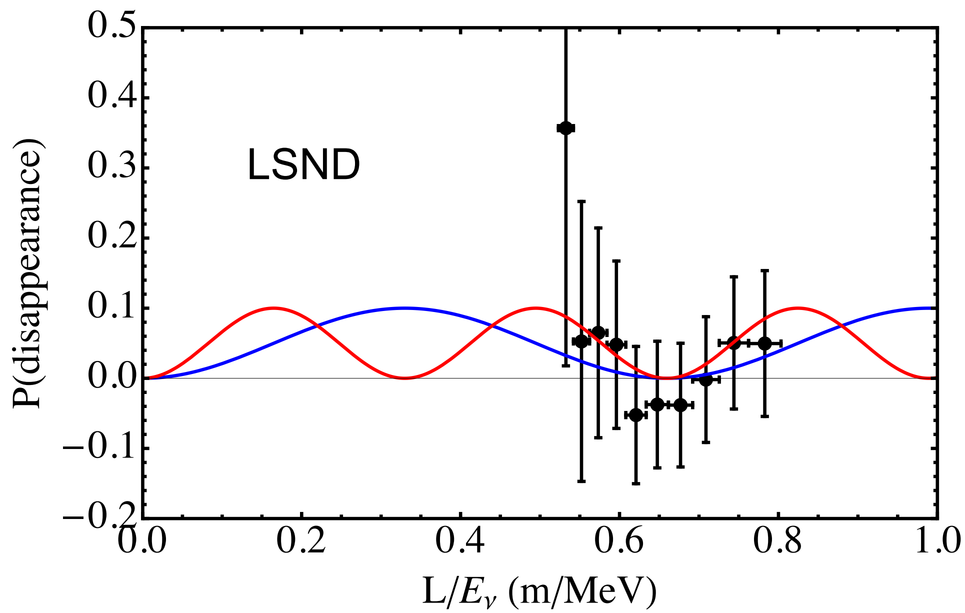
Antineutrino SBL compatibility: 22% (reduction due to MiniBooNE($\bar{\nu}$))



Other data: KARMEN & LSND ν_e Disappearance Limit



$^{12}C(\nu_e,e^-)\ ^{12}N_{GS}$



Not usually included in global fits

Conclusions

- Significant ν_e (~3 σ) and $\bar{\nu}_e$ (~2.8 σ) excesses above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE

- MiniBooNE $\bar{\nu}_e$ data are consistent with an oscillation interpretation of the LSND appearance data

- Neutrino mode systematic errors dominate (near detector?)

- Antineutrino mode statistical errors dominate (more data?)

- MiniBooNE plans to accumulate data until the goal of 10^{21} protons on target is reached (0.8×10^{21} so far)

Outlook

- Additional experiments under consideration or design:
  - Moving MiniBooNE to a near position following the $\bar{\nu}$ run
    - High statistics (1 year run)
  - MicroBooNE
    - 70 ton Liquid Argon TPC
    - Good electron-gamma separation
    - Construct "Super"MicroBooNE (LAr1kT)
  - ICARUS @PS
    - 600 ton Liquid Argon TPC running at Grand Sasso
    - Move to CERN PS beam and augment with small near detector (~<100 tons)
    - Good electron-photon separation
  - Repeat LSND:
    - SNS (OscSNS) is running now at 1 MW
(neutrinos are going to waste as we speak!!)

Workshop on Short Baseline Neutrinos

- May 12-14 at Fermilab
- https://indico.fnal.gov/event/sbnw2011
- Agenda:
  - Experimental Short-Baseline Neutrino Data
  - Theoretical Interpretation of Short-Baseline Neutrino Data
  - Future Neutrino Facilities
  - Future Short-Baseline Experiments