Neutrino 6

S J Parke ,
in Neutrino Oscillations,World Scientific 2008

3-flavor mixing

- 3 light (m_i <1 eV) Neutrinos: only 2 independent Δm^2 ($\Delta m^2_{ij} = m^2_i - m^2_j$)
- Three active neutrino flavors (no steriles): $\nu_e,\ \nu_\mu,\ \nu_\tau$
- Unitary Mixing Matrix: 3 angles ($\theta_{12},\ \theta_{23},\ \theta_{13}$), 1 Dirac phase ($\delta$), 2 Majorana phases ($\alpha, \beta$)

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

$$\times \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix} \quad \text{where } s_{ij} = \sin\theta_{ij} \text{ and } c_{ij} = \cos\theta_{ij}$$

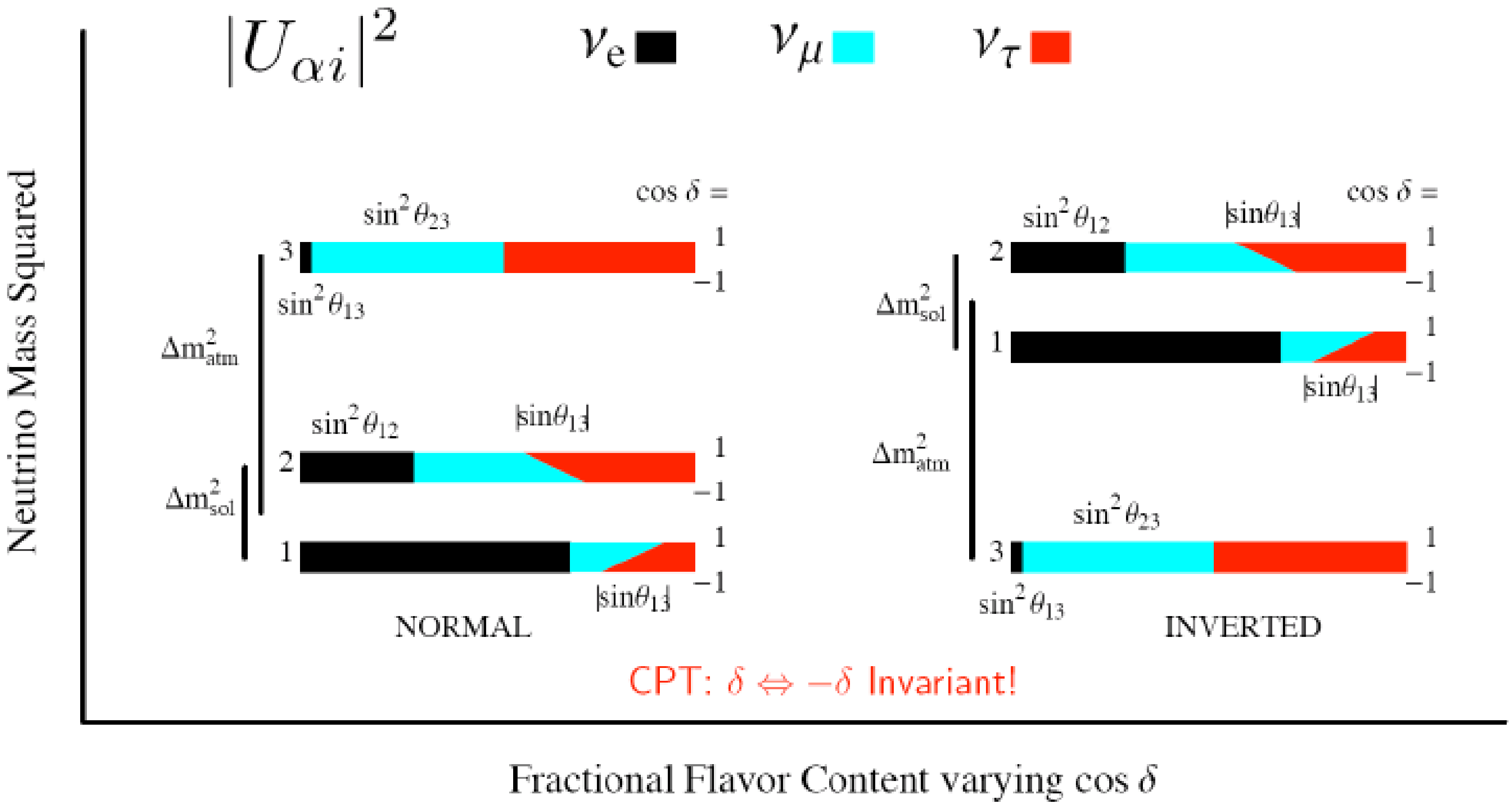
$$|\Delta m^2_{32}| = 2.7 \pm 0.4 \times 10^{-3}\mathrm{eV}^2 \quad \text{and} \quad \Delta m^2_{21} = +8.0 \pm 0.4 \times 10^{-5}\mathrm{eV}^2$$

$$U = \overbrace{\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}}^{\text{atmosferici}} \overbrace{\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix}}^{?} \overbrace{\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}}^{\text{solari}}$$

$$\times \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

$$\sin^2\theta_{12} = 0.31 \pm 0.03$$
$$\sin^2\theta_{23} = 0.50 \pm 0.15$$
$$\sin^2\theta_{13} < 0.04$$
$$0 \leq \delta < 2\pi$$

$$\sin^2\theta_{13} = |U_{e3}|^2 \ll 1,\ \sin^2\theta_{23} \approx |U_{\mu 3}|^2 \text{ and } \sin^2\theta_{12} \approx |U_{e2}|^2$$


$|U_{\alpha i}|^2$
ν_e ■
ν_μ 🟦
ν_τ 🟥
Neutrino Mass Squared
cos δ =
$\sin^2\theta_{23}$
3
1
−1
$\sin^2\theta_{13}$
$\Delta m^2_{\rm atm}$
$\sin^2\theta_{12}$
$|\sin\theta_{13}|$
2
1
−1
$\Delta m^2_{\rm sol}$
1
1
−1
$|\sin\theta_{13}|$
NORMAL
cos δ =
$\sin^2\theta_{12}$
$|\sin\theta_{13}|$
2
1
−1
$\Delta m^2_{\rm sol}$
1
1
−1
$|\sin\theta_{13}|$
$\Delta m^2_{\rm atm}$
$\sin^2\theta_{23}$
3
1
−1
$\sin^2\theta_{13}$
INVERTED
CPT: $\delta \Leftrightarrow -\delta$ Invariant!
Fractional Flavor Content varying cos δ

Questions

- What is the size of $|U_{e3}|^2$? i.e $\sin^2\theta_{13} = ?$
- Hierarchy: Is $m_3^2 >$ OR $< m_1^2$? i.e. what is the sign of Δm_{31}^2?
- Is there CP violation? i.e. $\sin\delta \neq 0$?
- Is $|U_{\mu 3}|^2 = |U_{\tau 3}|^2$? i.e. $\sin^2\theta_{23} = \frac{1}{2}$?
  If not, is $|U_{\mu 3}|^2 >$ or $< |U_{\tau 3}|^2$? i.e. $\sin^2\theta_{23} >$ or $< \frac{1}{2}$?

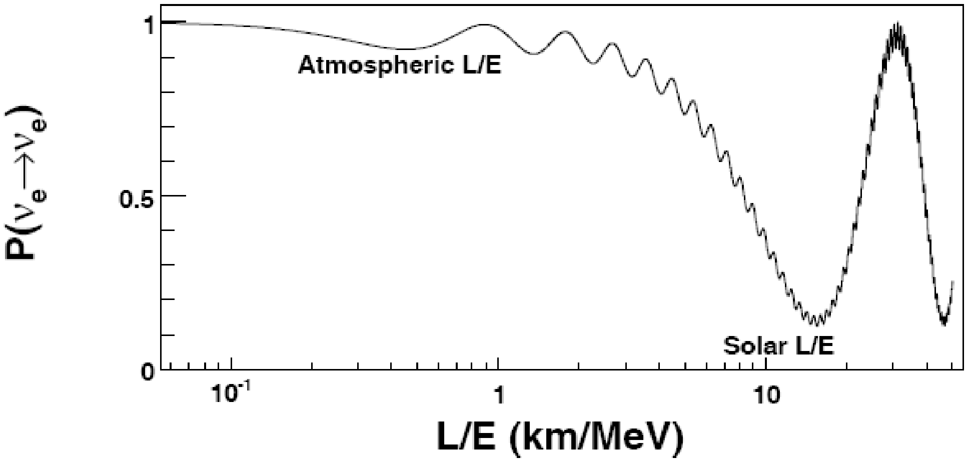
- What is the mass of the lightest neutrino?
- Are Neutrinos Majorana or Dirac?
- Are there more than three neutrinos? Are there sterile neutrinos?
- Do exotic neutrinos interactions exist?

Inaccessibili agli esperimenti di oscillazione

ν_e disappearance

$$\boxed{\begin{aligned} P(\nu_e \to \nu_e) = 1 &- 4|U_{e3}|^2|U_{e1}|^2 \sin^2 \Delta_{31} \\ &- 4|U_{e3}|^2|U_{e2}|^2 \sin^2 \Delta_{32} \\ &- 4|U_{e2}|^2|U_{e1}|^2 \sin^2 \Delta_{21} \end{aligned}}$$

$$\Delta_{jk} \equiv \frac{\Delta m_{jk}^2 L}{4\hbar c E} = 1.2669\cdots \left(\frac{\Delta m_{jk}^2}{eV^2}\right)\left(\frac{L}{km}\right)\left(\frac{GeV}{E}\right)$$



assuming

$$\sin^2\theta_{13} = 0.02$$

Reattori nel regime delle oscillazioni solari (KamLAND)

$$\begin{aligned} P(\nu_e \to \nu_e) = 1 &- 4|U_{e3}|^2|U_{e1}|^2 \boxed{\sin^2\Delta_{31}} \\ &- 4|U_{e3}|^2|U_{e2}|^2 \boxed{\sin^2\Delta_{32}}\ 1/2 \\ &- 4|U_{e2}|^2|U_{e1}|^2 \sin^2\Delta_{21} \end{aligned}$$

$$\begin{pmatrix} \boxed{c_{13}c_{12}} & \boxed{c_{13}s_{12}} & \boxed{s_{13}e^{-i\delta}} \\ -c_{23}s_{12} - s_{13}c_{12}s_{23}e^{+i\delta} & c_{23}c_{12} - s_{13}s_{12}s_{23}e^{+i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{12}c_{23}e^{+i\delta} & -s_{23}c_{12} - s_{13}s_{12}c_{23}e^{+i\delta} & c_{13}c_{23} \end{pmatrix}$$

$$P(\bar\nu_e \to \bar\nu_e) = c_{13}^4(1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}) + \xcancel{s_{13}^4}.$$

trascurabile

L'unico effetto di un valore non nullo di theta13 è la riduzione della probabilità di sopravvivenza (non facile da misurare!)

Reattori nel regime delle oscillazioni atmosferiche

- For L/E~500m/MeV (CHOOZ, Palo Verde, Double-CHOOZ, Daya-Bay):

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee} + \mathcal{O}(\Delta_{21}^2)$$

where $\Delta_{ee} = \Delta m^2_{ee} L/4E$, and Δm^2_{ee} is the effective atmospheric Δm^2 for the ν_e oscillation channel, given by

$$\Delta m^2_{ee} \equiv c^2_{12}|\Delta m^2_{31}| + s^2_{12}|\Delta m^2_{32}|.$$

- Double-CHOOZ e Daya-Bay: measure (or improve bounds on) theta13

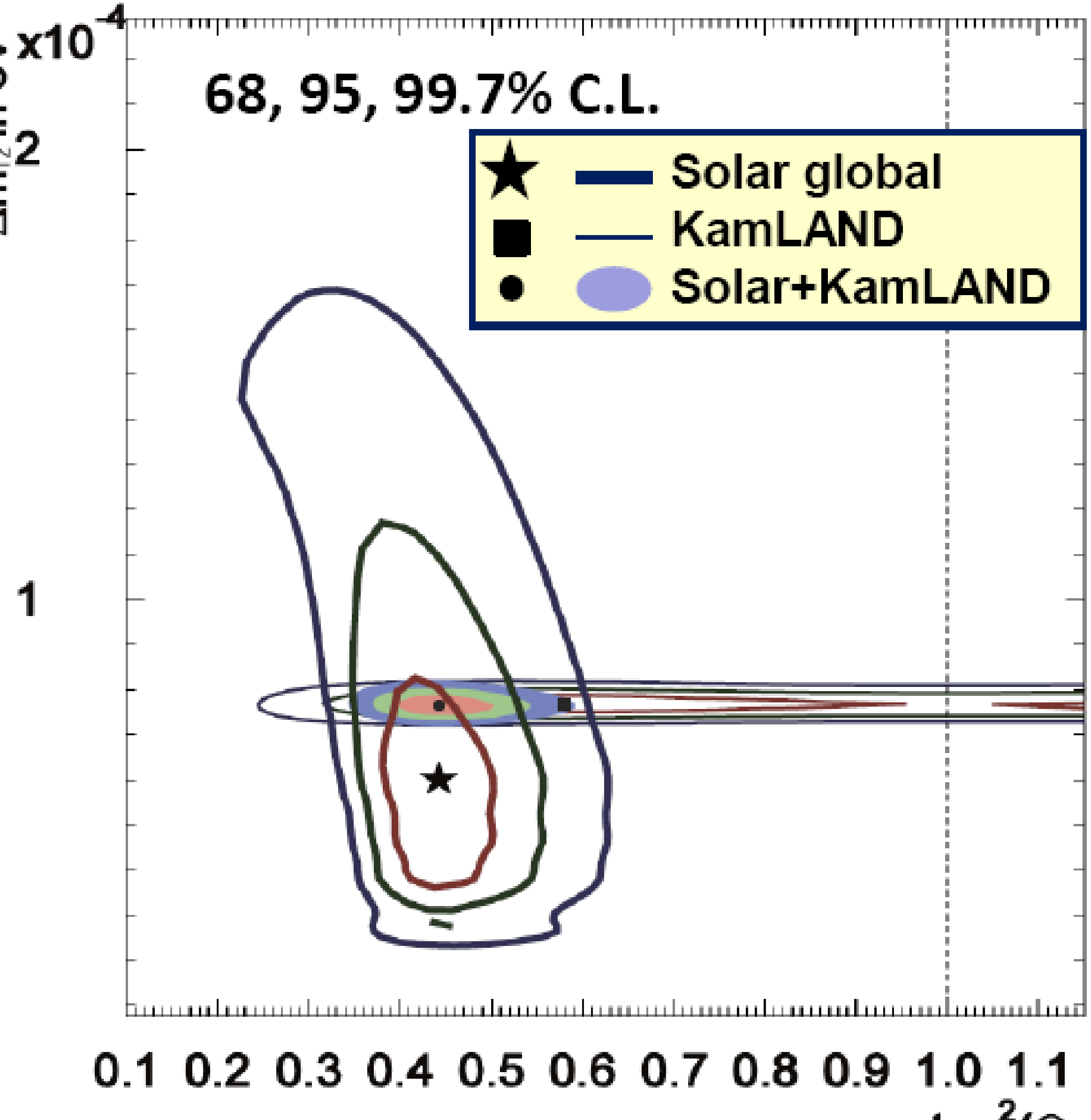
Neutrini solari

- Salto la trattazione analitica che è complicata…
- Comunque i risultati più recenti vengono analizzati nell’ambito dell’oscillazione a tre famiglie fornendo indicazioni indirette anche su theta13

3-flavor analysis: θ_{12} - Δm_{12}^2

Preliminary

May 2010



Solar global:

Min $\chi^2 = 52.8$
$\Delta m^2 = 6.0 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.44$
$\sin^2\theta_{13} = 0.010$
$\Phi_{B8} = 0.92 \times \Phi_{B8,SSM}$

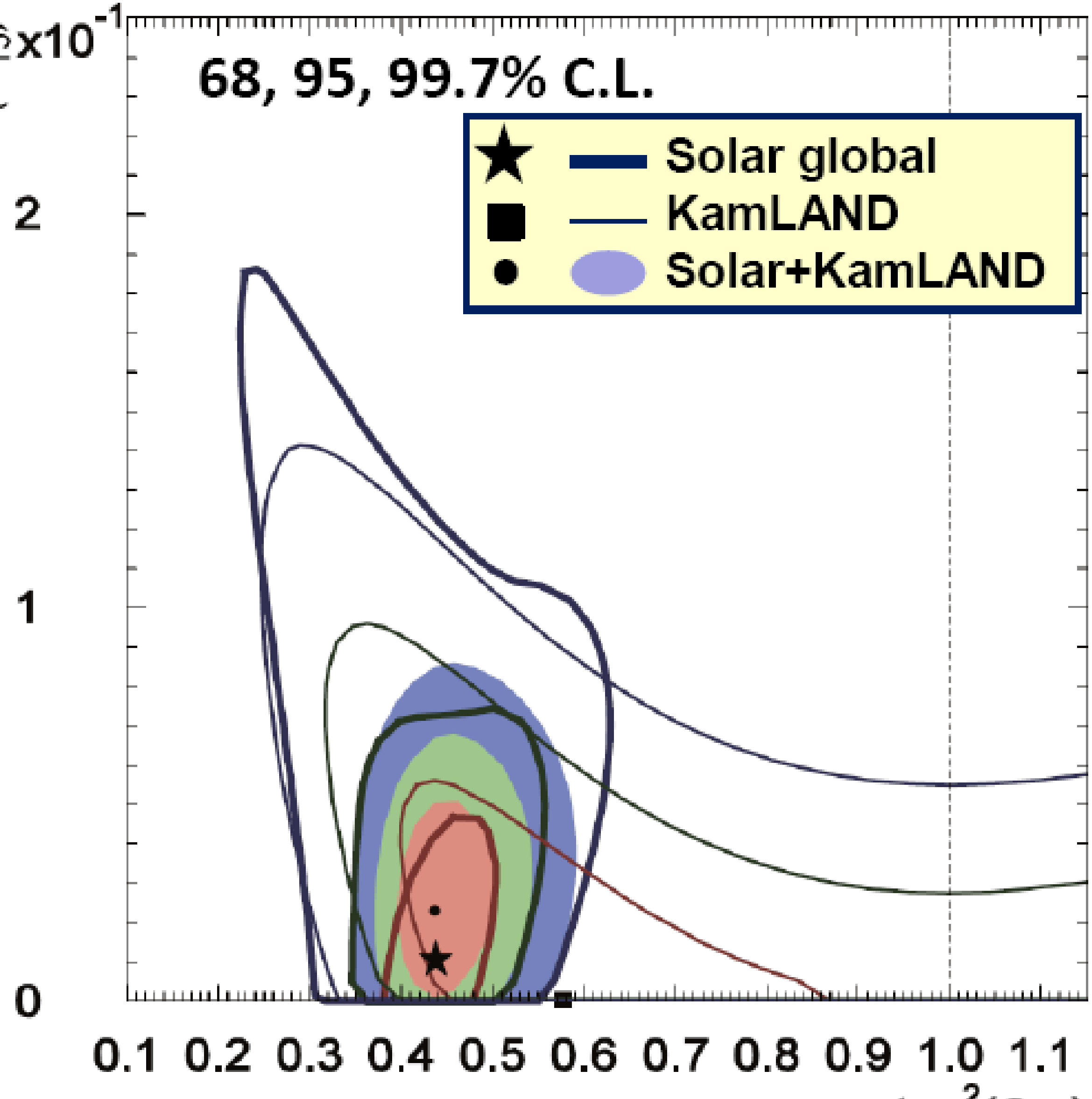
Solar global + KamLAND:

Min $\chi^2 = 71.2$
$\Delta m^2 = 7.7 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.44$
$\sin^2\theta_{13} = 0.025$
$\Phi_{B8} = 0.91 \times \Phi_{B8,SSM}$

3-flavor analysis: θ_{12} - θ_{13}

Preliminary

May 2010



Solar global:

$\sin^2\theta_{13}<0.060$

@95%C.L.

Solar global + KamLAND:

$\sin^2\theta_{13}=0.025^{+0.018}_{-0.016}$

(<0.059 @95%C.L.

Cf. PRC81, 055504 (2010

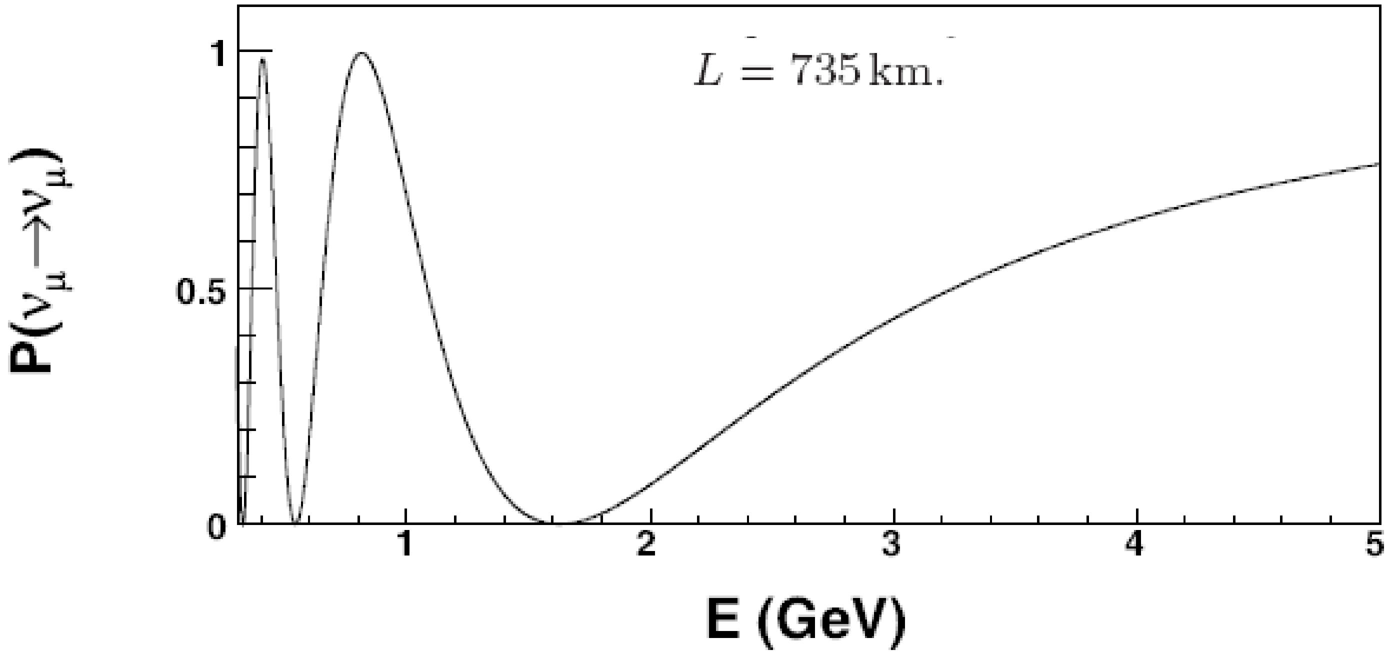
$\sin^2\theta_{13}=0.020+0.021-0.01$

(<0.057 @95%C.L.)

⇨ Poster-54 Byeongsu Yang

Scomparsa di ν_μ

$$\begin{aligned}P(\nu_\mu \to \nu_\mu) = 1 &- 4|U_{\mu 3}|^2|U_{\mu 1}|^2 \sin^2 \Delta_{31} \\ &-4|U_{\mu 3}|^2|U_{\mu 2}|^2 \sin^2 \Delta_{32} \\ &-4|U_{\mu 2}|^2|U_{\mu 1}|^2 \sin^2 \Delta_{21}.\end{aligned}$$



$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)\sin^2\Delta_{\mu\mu} + \mathcal{O}(\Delta_{21}^2)$$

$$\text{where } |U_{\mu 3}|^2 = c_{13}^2 s_{23}^2 \text{ and } \Delta_{\mu\mu} = \Delta m_{\mu\mu}^2 L/4E$$

$$\Delta m_{\mu\mu}^2 \equiv \frac{|U_{\mu 1}|^2|\Delta m_{31}^2| + |U_{\mu 2}|^2|\Delta m_{32}^2|}{(|U_{\mu 1}|^2 + |U_{\mu 2}|^2)}$$

for $\theta_{13} \to 0$

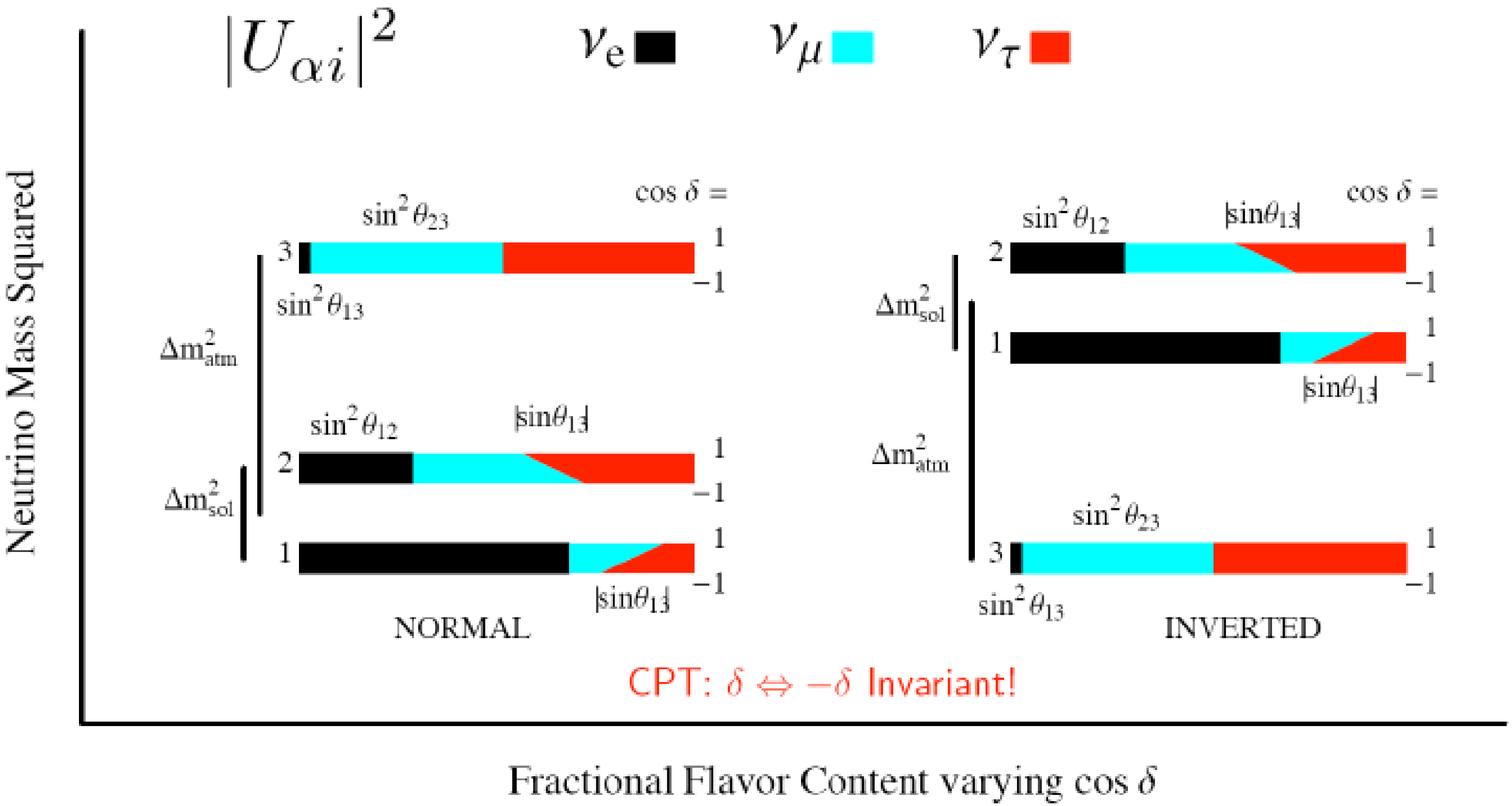
$$4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) = \sin^2 2\theta_{23}$$

$$\text{and} \quad \Delta m_{\mu\mu}^2 = s_{12}^2|\Delta m_{31}^2| + c_{12}^2|\Delta m_{32}^2|$$

The difference between $\Delta m_{\mu\mu}^2$ and $|\Delta m_{32}^2|$ is given by $\pm s_{12}^2 \Delta m_{\overset{31}{21}}^2$ which is approximately a 1% shift whose sign depends on the hierarchy.

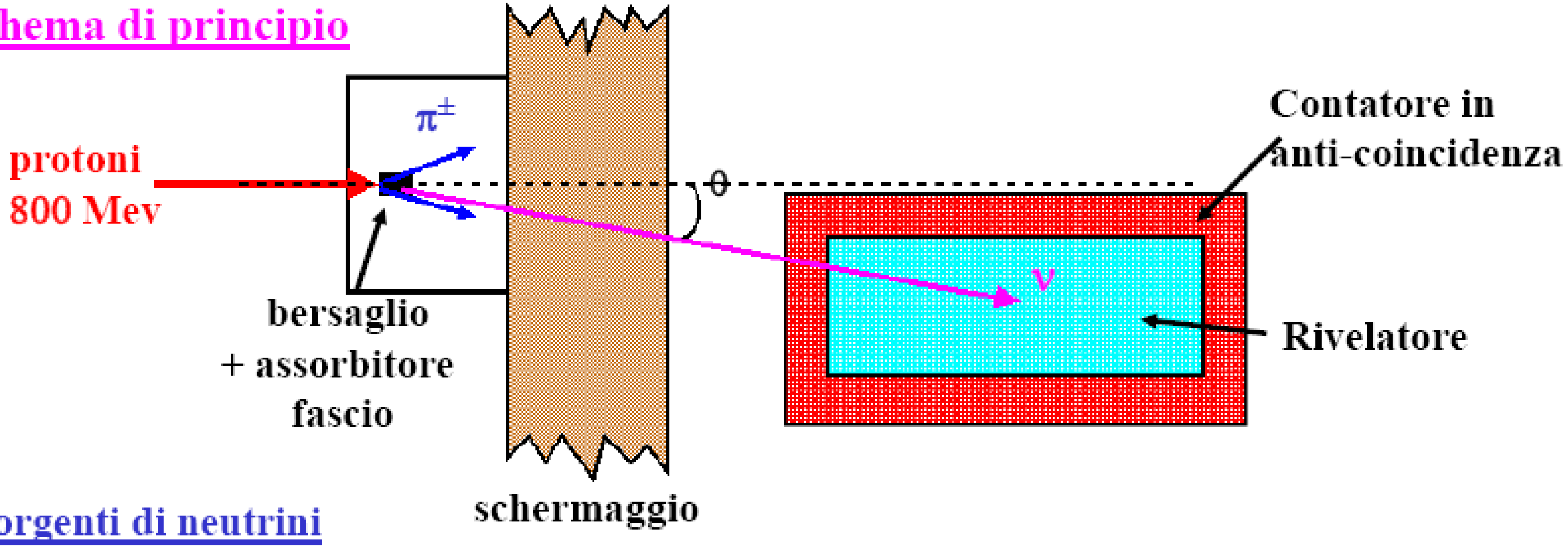
⇨ The survival probability is essentialy 1 - the oscillation involving 2 and 3

Modello con 3 neutrini ➔ sono possibili solo due valori indipendenti di Dm2

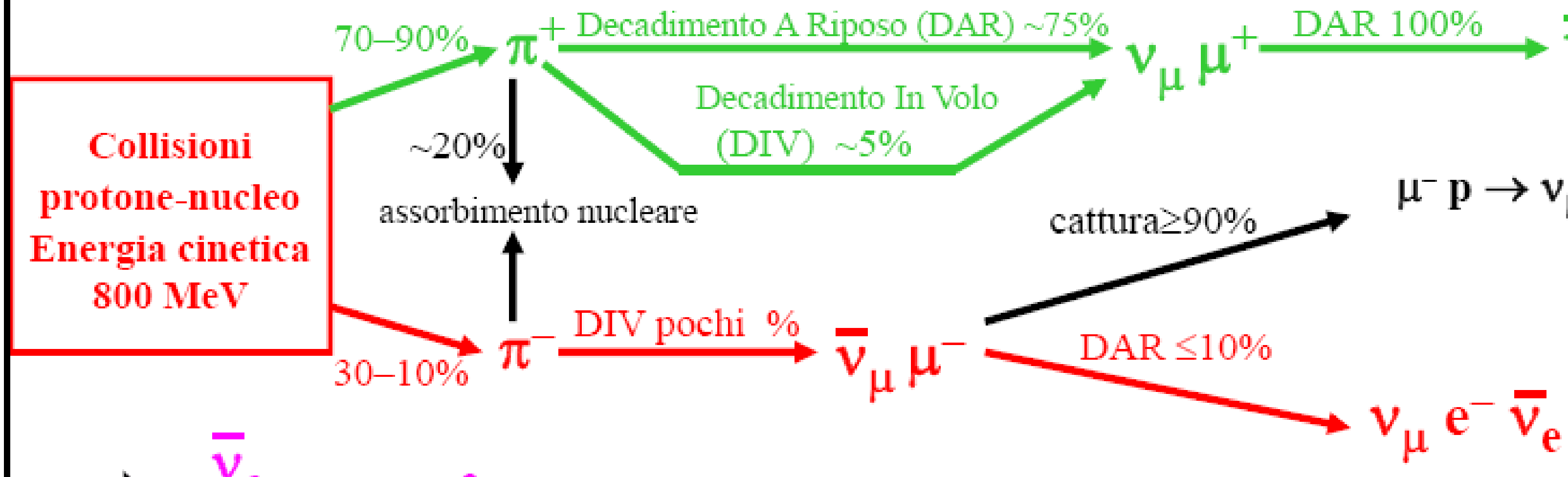


Esperimenti LSND e KARMEN : ricerca di oscillazioni $\bar{\nu}_\mu - \bar{\nu}_e$

Schema di principio



Sorgenti di neutrini



Collisioni protone-nucleo Energia cinetica 800 MeV

70–90% π^+

π^+ Decadimento A Riposo (DAR) ~75% → $\nu_\mu\ \mu^+$

π^+ Decadimento In Volo (DIV) ~5% → $\nu_\mu\ \mu^+$

μ^+ DAR 100% → $\bar{\nu}_\mu\ e^+\ \nu_e$

~20% assorbimento nucleare

30–10% π^-

π^- DIV pochi % → $\bar{\nu}_\mu\ \mu^-$

μ^- cattura≥90% → $\mu^- p \rightarrow \nu_\mu n$

μ^- DAR ≤10% → $\nu_\mu\ e^-\ \bar{\nu}_e$

L'unica sorgente di $\bar{\nu}_e$

$$\Rightarrow \frac{\bar{\nu}_e}{\nu_e} \leq 10^{-3}$$

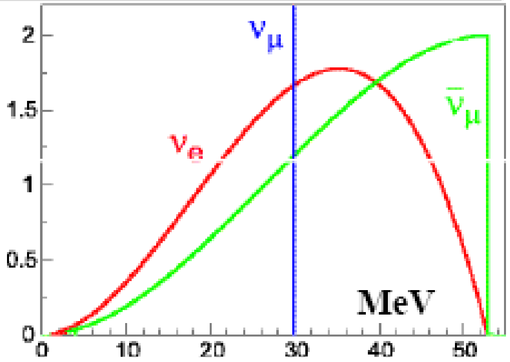
Parametri degli esperimenti LSND e KARMEN

	LSND	KARMEN
Acceleratore	Los Alamos Neutron Science Centre	Neutron Spallation Facility ISIS , R.A.L. (U.K.)
Energia cin. protoni	800 MeV	800 MeV
Corrente protoni	1000 μA	200 μA
Rivelatore	Cilindro riempito di scintillatore liquido Luce di scintillazione e luce Čerenkov	512 celle indipendenti riempite di scintillatore liquido
Massa rivelatore	167 tonn.	56 tonn.
Localizzazione evento	misura tempo PMT	dimensione cella
Distanza dalla sorgente ν	29 m	17 m
Angolo θ tra direzione fascio protoni e neutrini	11°	90°
Presa - dati	1993 – 98	1997 – 2001
Protoni su bersaglio	4.6×10^{23}	1.5×10^{23}

Spettri d'energia dei neutrini dal decadimento a riposo

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$$



Esperimento LSND: evidenza di oscillazioni $\overline{\nu}_\mu - \overline{\nu}_e$

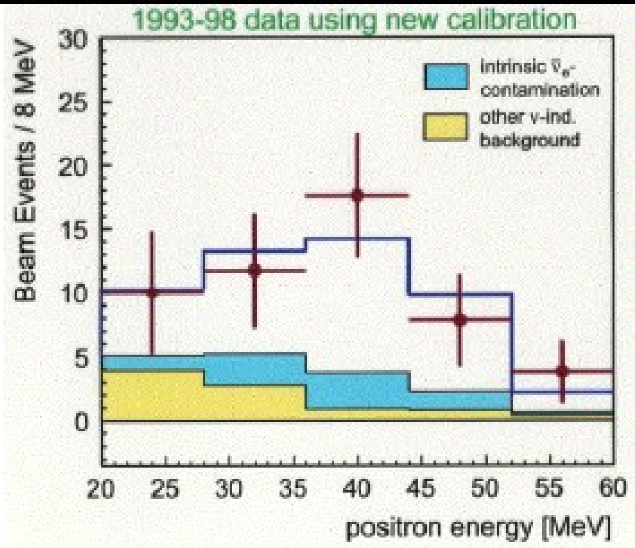
Positroni con $20 < E < 60$ MeV

N(beam-on) – N(beam-off) = 49.1 ± 9.4 eventi

Fondo da neutrini = 16. 9 ± 2.3

Segnale $\overline{\nu}_e = 32.2 \pm 9.4$ eventi

$\mathscr{P}_{osc} = (0.264 \pm 0.067 \pm 0.045) \times 10^{-2}$

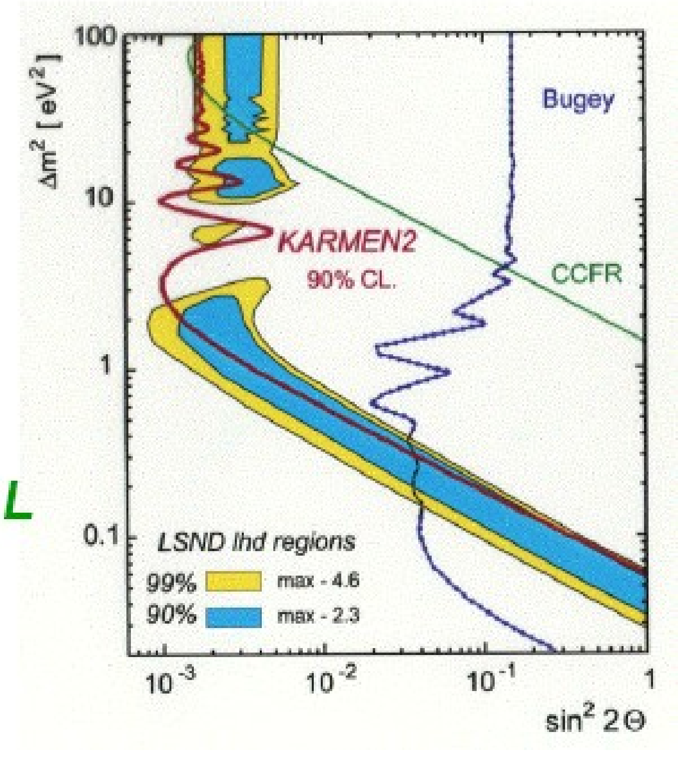


Esperimento KARMEN: nessuna evidenza di oscillazioni $\nu_\mu - \nu_e$

Positroni con $16 < E < 50$ MeV selezionati : 15

Fondo previsto totale: 15.8 ± 0.5 eventi

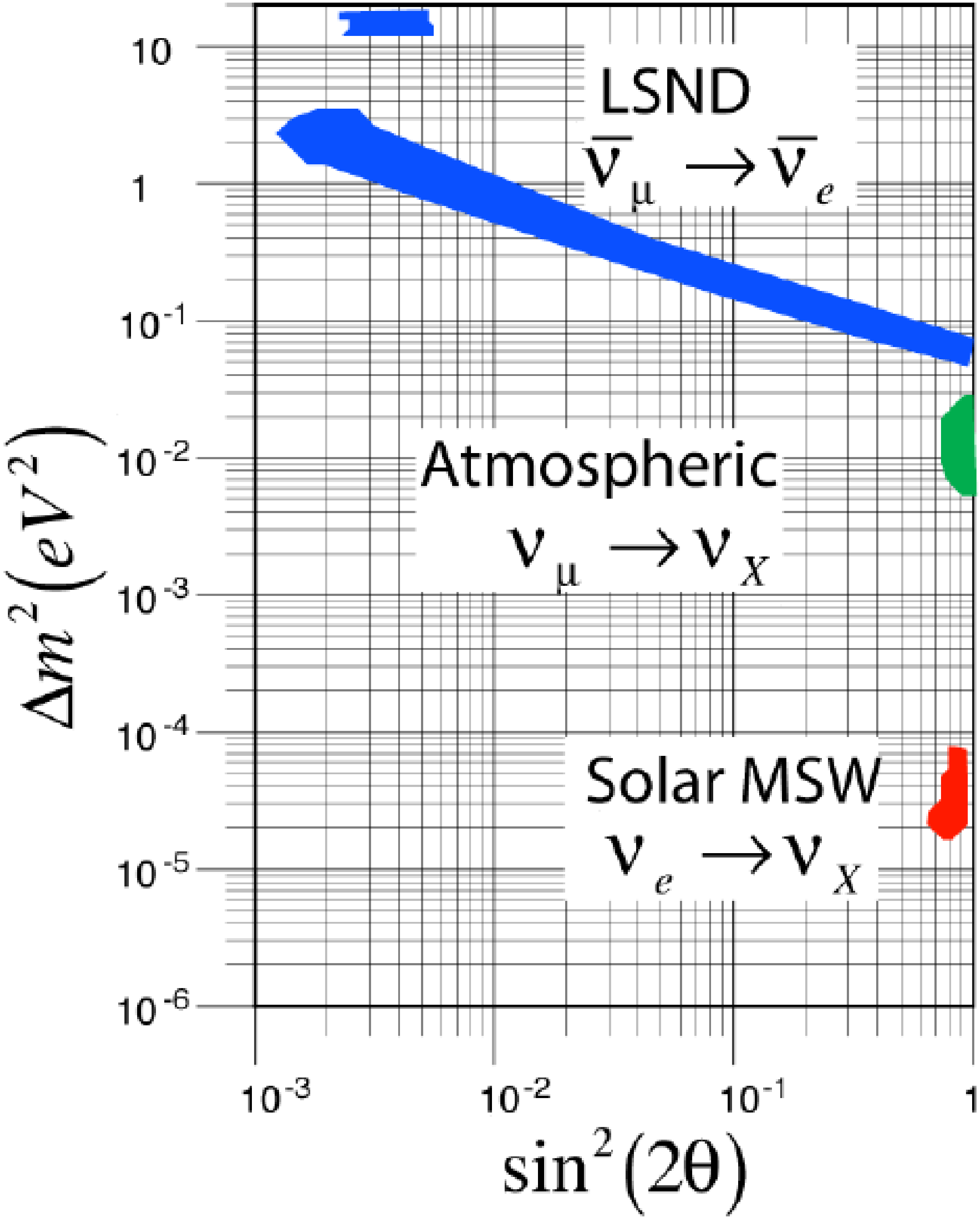
$\mathscr{P}_{osc} < 0.085 \times 10^{-2}$ (livello conf. 90%)



Compatibilità tra KARMEN e LSND possibile soltanto in una regione limitata dei parametri di oscillazione perchè la distanza L è diversa per i due esperimenti:

L = 29 m (LSND);

L = 17 m (KARMEN)



LSND
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Atmospheric
$\nu_\mu \rightarrow \nu_X$
Solar MSW
$\nu_e \rightarrow \nu_X$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\Delta m^2 (eV^2)$
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\theta)$

Segnale di oscillazione $\bar{\nu}_\mu - \bar{\nu}_e$ in LSND : un problema serio

Definizione: $\Delta m_{ik}{}^2 = m_k{}^2 - m_i{}^2$ (i,k = 1, 2, 3)

➡ $\Delta m_{12}{}^2 + \Delta m_{23}{}^2 + \Delta m_{31}{}^2 = 0$

Segnali di oscillazione:

- Neutrini solari: $\Delta m_{12}{}^2 \approx 7.6 \times 10^{-5}$ eV^2
- Neutrini atmosferici: $\Delta m_{23}{}^2 \approx 2.5 \times 10^{-3}$ eV^2
- LSND: $|\Delta m_{31}{}^2| = 0.2 — 2$ eV^2

➡ $| \Delta m_{12}{}^2 + \Delta m_{23}{}^2 + \Delta m_{31}{}^2 | = 0.2 — 2$ eV^2

L'interpretazione dei tre risultati richiede almeno quattro neutrini.

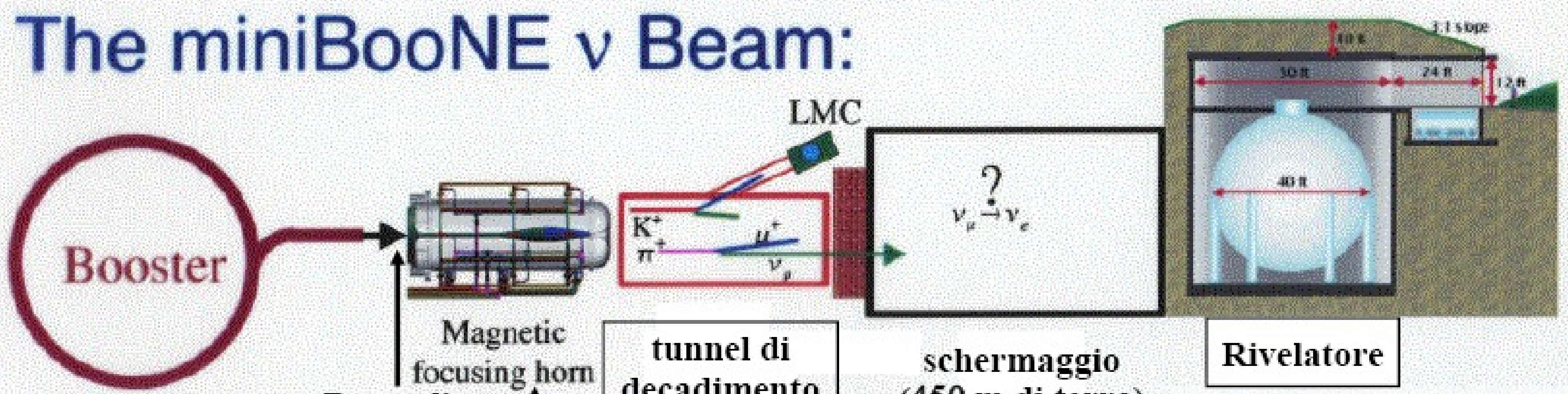
Risultati degli esperimenti LEP: numero di neutrini leggeri = 3

$\Rightarrow$ altri neutrini, se esistono, devono essere "sterili":
costante di accoppiamento ai bosoni W e Z = 0
$\Rightarrow$ nessuna interazione con la materia

MiniBooNE

Scopo: conferma del segnale LSND

- fase iniziale: ricerca di oscillazioni $\nu_\mu - \nu_e$;
- fase successiva: ricerca di oscillazioni $\overline{\nu}_\mu - \overline{\nu}_e$;
- in caso di conferma del segnale LSND, installazione di un secondo rivelatore a *L* diverso



Sincrotrone a protoni (8 GeV) al Fermilab

Bersaglio in Berillio

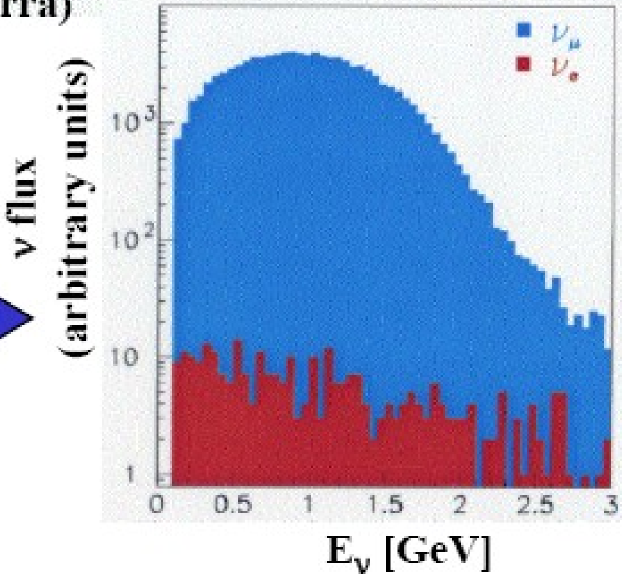
focalizzazione dei π^+ in un fascio parallelo

tunnel di decadimento (50 m)

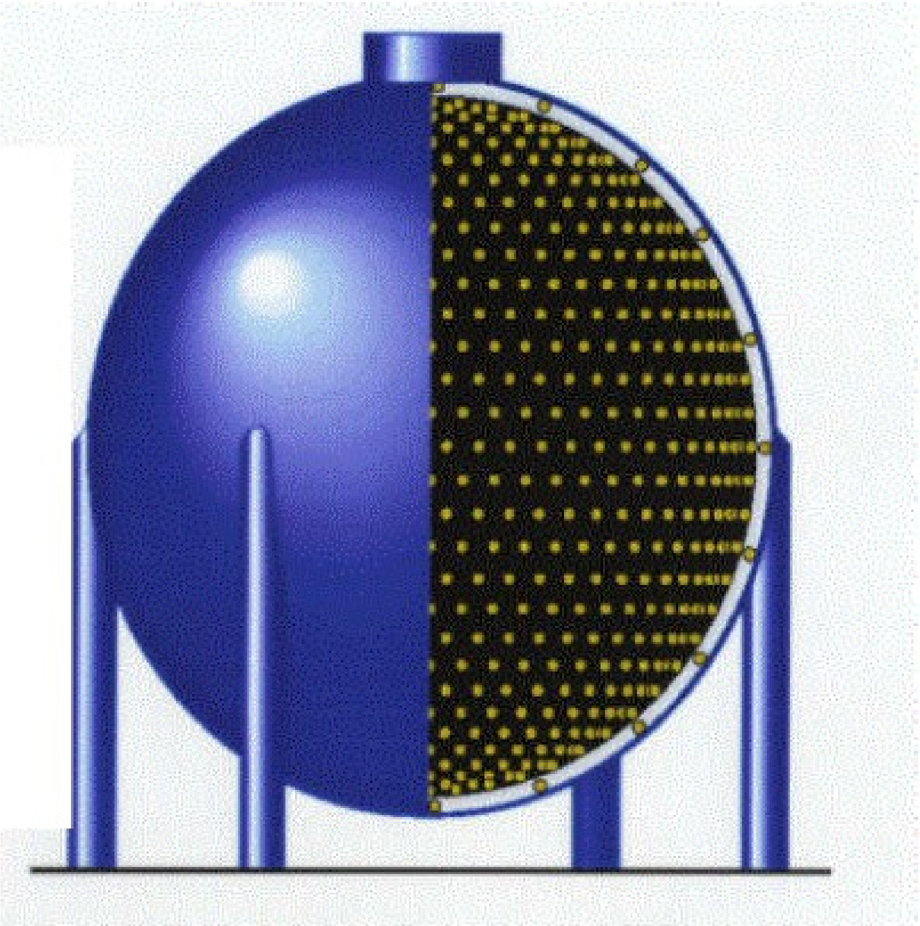
schermaggio (450 m di terra)

Rivelatore

Flussi ν (calcolati)



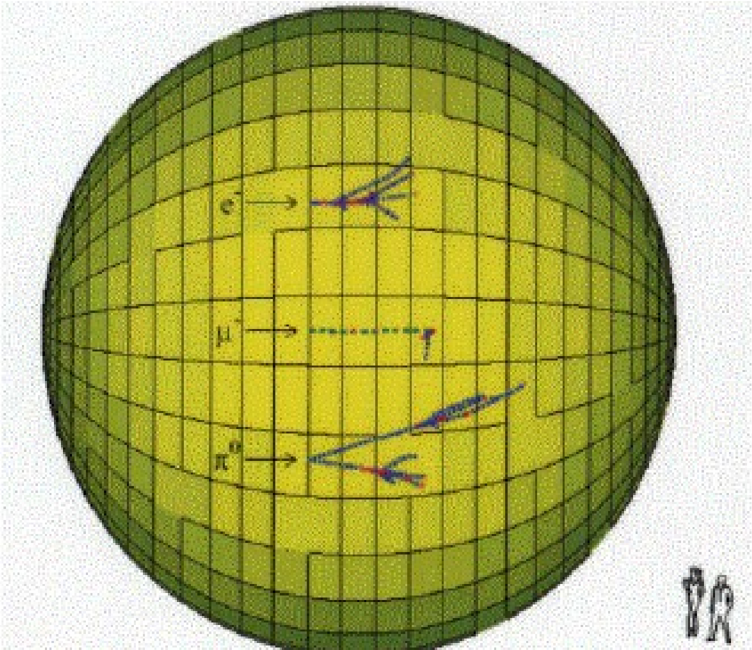
Rivelatore MiniBooNE



- Contenitore sferico, diametro 12 m
  807 tonn. olio minerale poco scintillante.
- Raccolta della luce Čerenkov (direzionale)
  e della luce da scintillazione.
- Massa fiduciale 445 tonn.
- Regione interna isolata otticamente
  (1280 fototubi, diam. 20 cm)
- Regione esterna in anticoincidenza
  (240 fototubi)

Identificazione delle particelle secondarie

basata sul comportamento diverso di elettroni, muoni, pioni e sulla configurazione degli anelli di luce Čerenkov



http://beyond3nu.lngs.infn.it/

- Workshop on Beyond Three Family Neutrino Oscillations
- May 3-4, 2011 - Laboratori Nazionali del Gran Sasso - Assergi, Italy
- What is the status of sterile neutrinos? Possible hints, theoretical explanations and new experimental tests.

MiniBooNE/LSND Neutrino Oscillation Results

M. Sorel (IFIC - CSIC & U.Valencia)

Workshop on Beyond Three Family Neutrino Oscillations
May 3-4, 2011, LNGS (Italy)

1. LSND $\bar{\nu}_\mu \to \bar{\nu}_e$
(1993-2001)

2. MiniBooNE $\nu_\mu \to \nu_e$
(2001-2007)

3. MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$
(2006-2010)

4. MiniBooNE $\nu_\mu \to \nu_\mu$
and $\bar{\nu}_\mu \to \bar{\nu}_\mu$
(2001-2011)

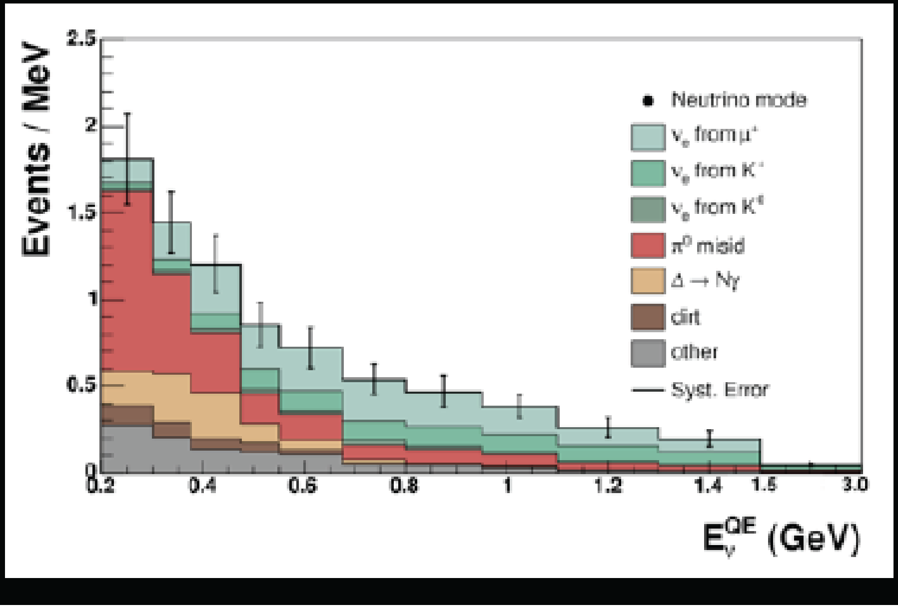
5. Light sterile neutrino oscillations: where we stand
(2011)

Two Searches: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

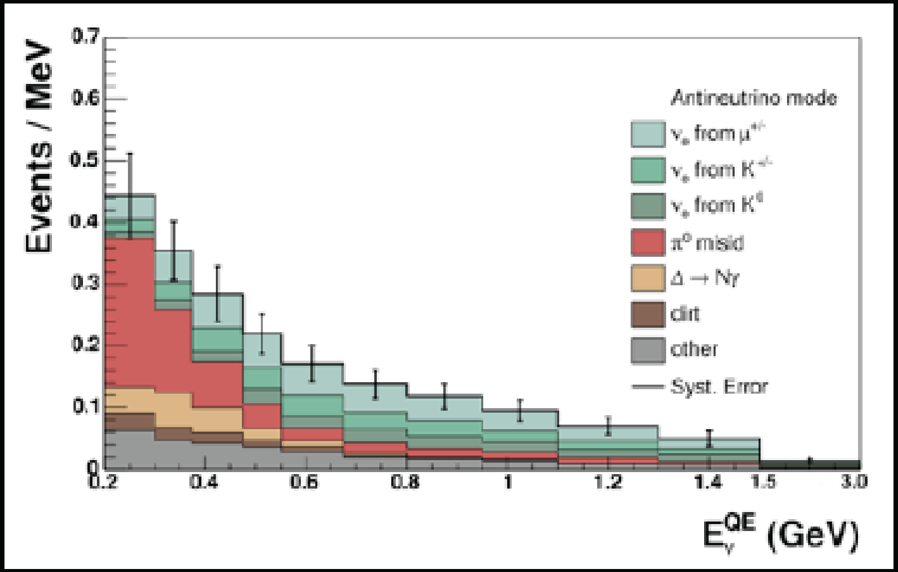
Two separate searches, one in neutrino mode and one in antineutrino mode

Look for appearance of ν_e or $\bar{\nu}_e$ events above background expectations versus energy, and see if described by a two-neutrino oscillation hypothesis

Expected background neutrino mode



Expected background antineutrino mode



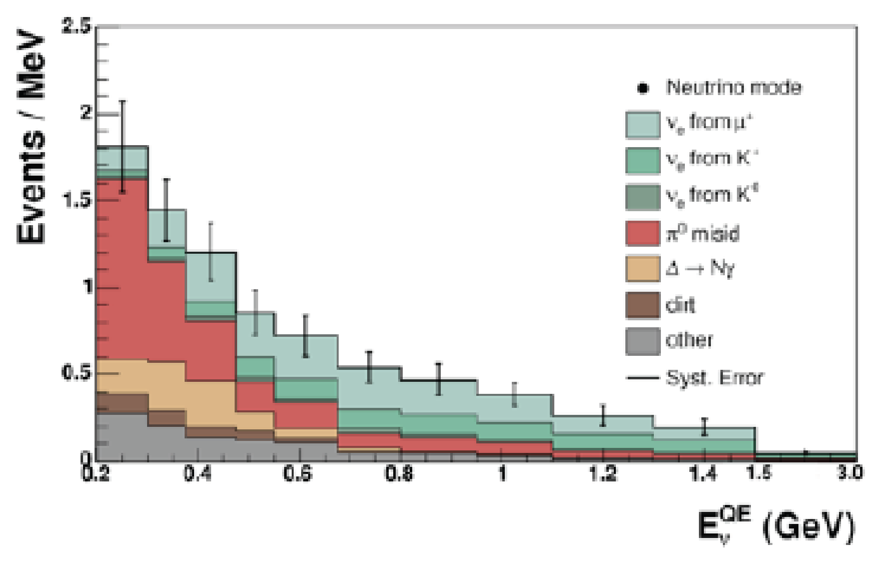
Two Searches: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Two separate searches, one in neutrino mode and one in antineutrino mode

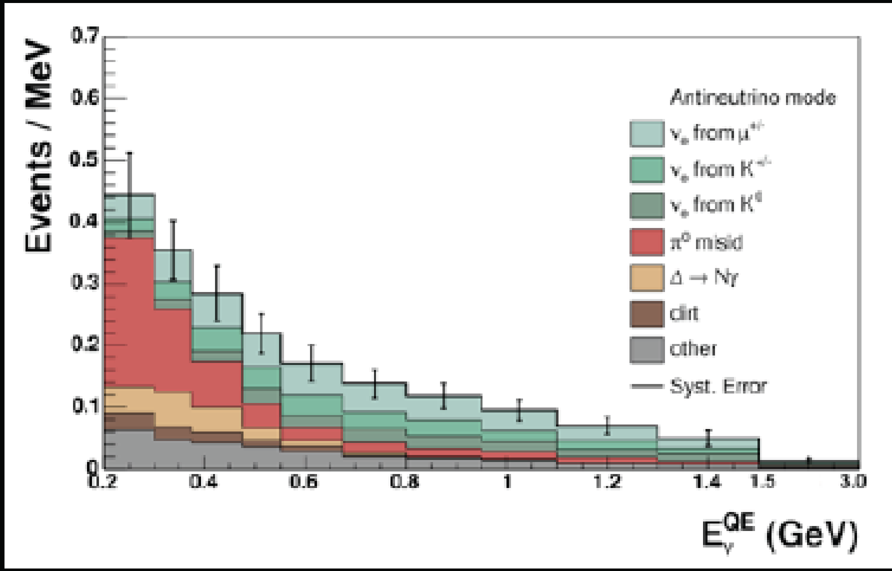
High statistics, powerful test of LSND's simplest interpretation

Lower statistics (less powerful), but direct test of LSND excess

Expected background neutrino mode



Expected background antineutrino mode



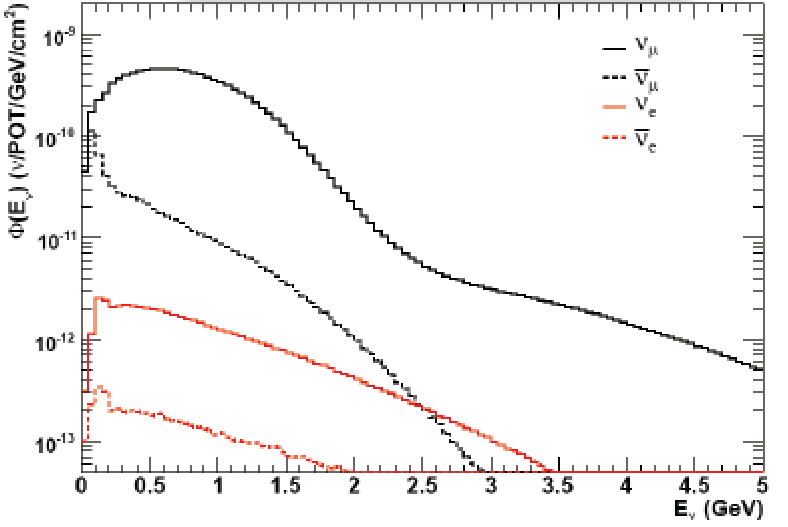
The MiniBooNE Recipe For Appearance Searches

Ingredients:

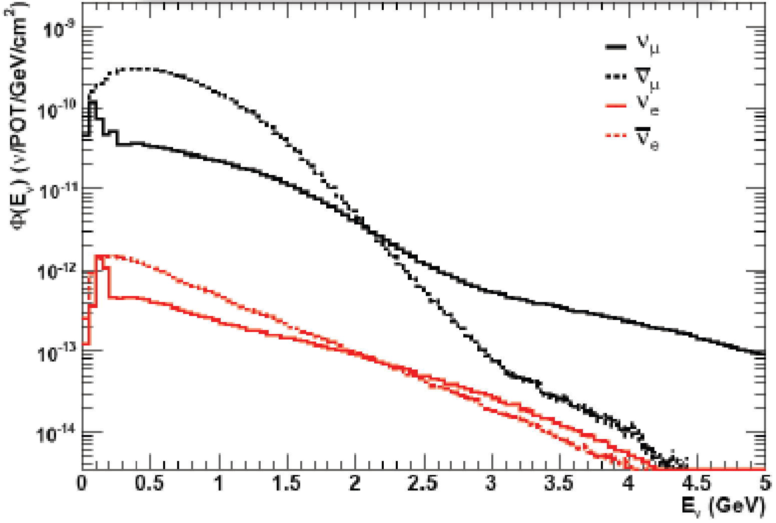
- Same L/E as LSND
- High intensity ν_μ beam with low intrinsic ν_e contamination
- Powerful neutrino flavor tagging (ν_μ .vs. ν_e interaction)
- Information about neutrino energy spectrum
- Patience (& data stability)

- ☑ Same L/E as LSND
- ☑ High intensity ν_μ beam with low intrinsic ν_e contamination

Neutrino mode flux prediction



Antineutrino mode flux prediction

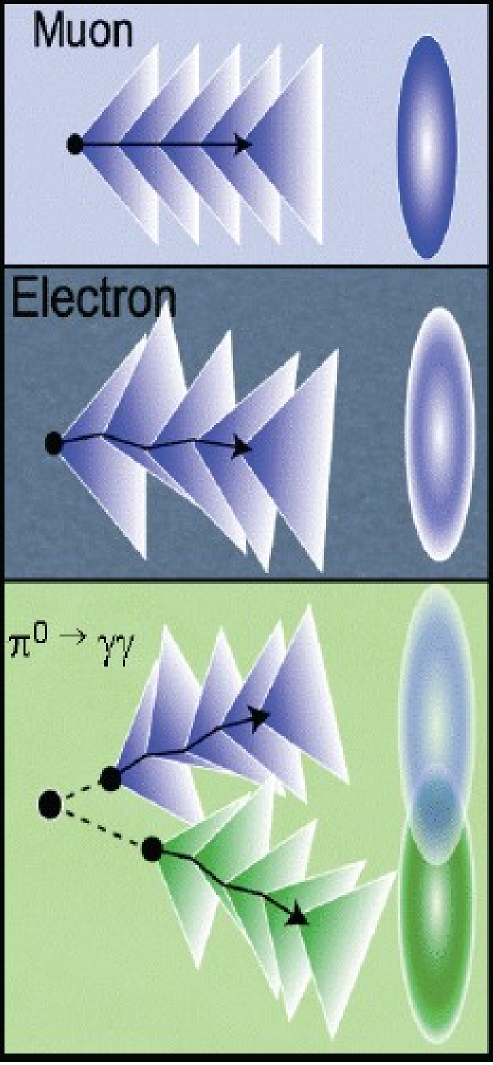


☑ Powerful neutrino flavor tagging (ν_μ .vs. ν_e interaction)

Muons:
- long tracks
- sharp Cherenkov ring
- ~80% with decay electron tag

Electrons:
- short tracks
- fuzzy Cherenkov ring
- single subevent

$\pi^0 \rightarrow \gamma\gamma$:
- disconnected short tracks
- typically two fuzzy rings with $m_{\gamma\gamma} \sim m_\pi$
- single subevent



Results (Oscillation Fit Region)

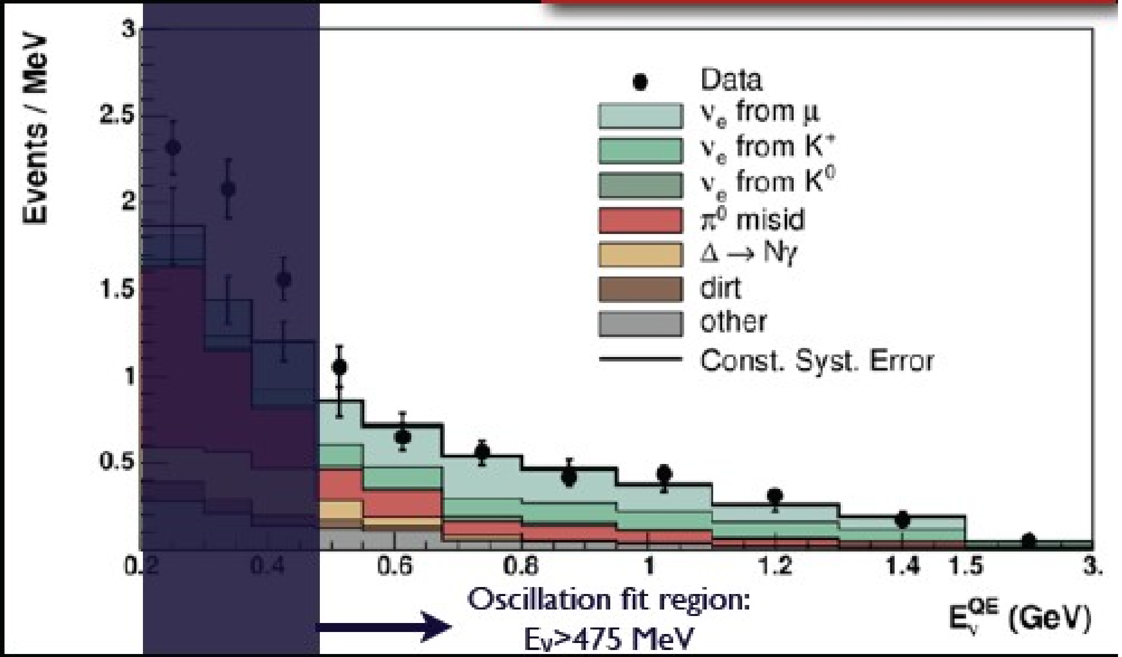
475 < E_ν < 1250 MeV counts:

- 22.1 ± 35.7 excess events
- No evidence for oscillations

E_ν > 475 MeV energy fit:

- null: χ^2/dof = 9.1/15 (87%)
- best-fit: χ^2/dof = 7.2/13 (89%)

PRL 102, 101802 (2009), $6.46 \cdot 10^{20}$ POT

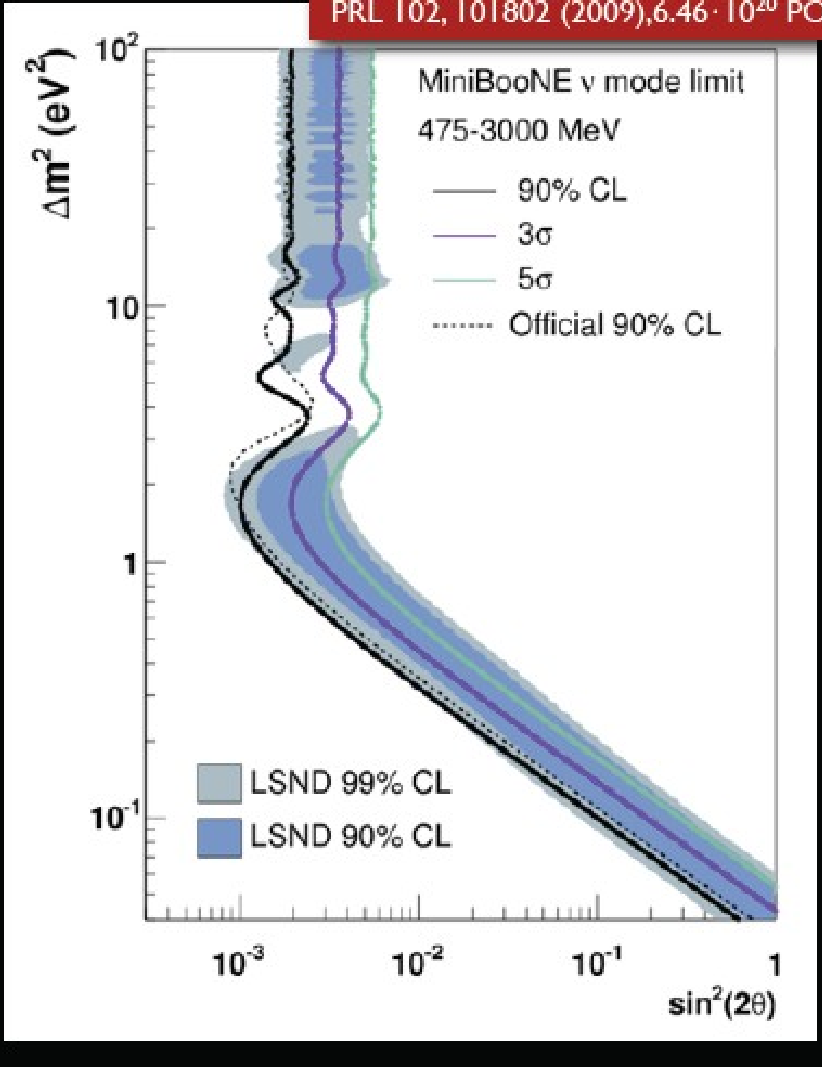


- Assume no ν_μ/ν_e disappearance

Results (Oscillation Fit Region)

- **MiniBooNE rules out the LSND two-neutrino oscillation interpretation (assuming no CP or CPT violation)**

PRL 102, 101802 (2009),6.46·10^{20} POT

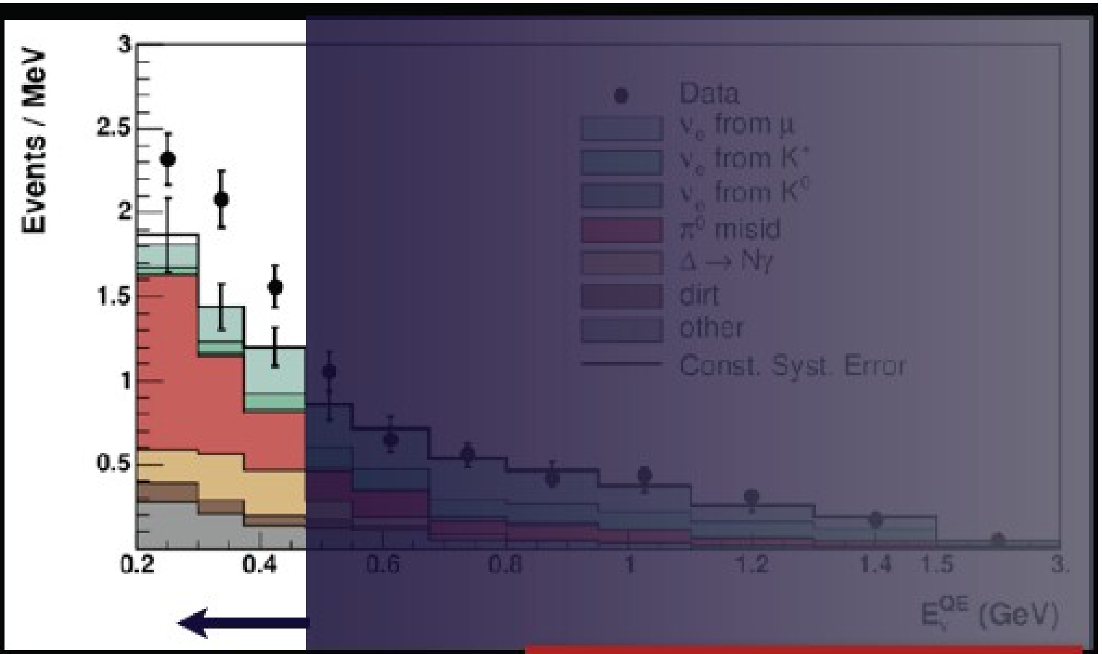


Results (Low Energies)

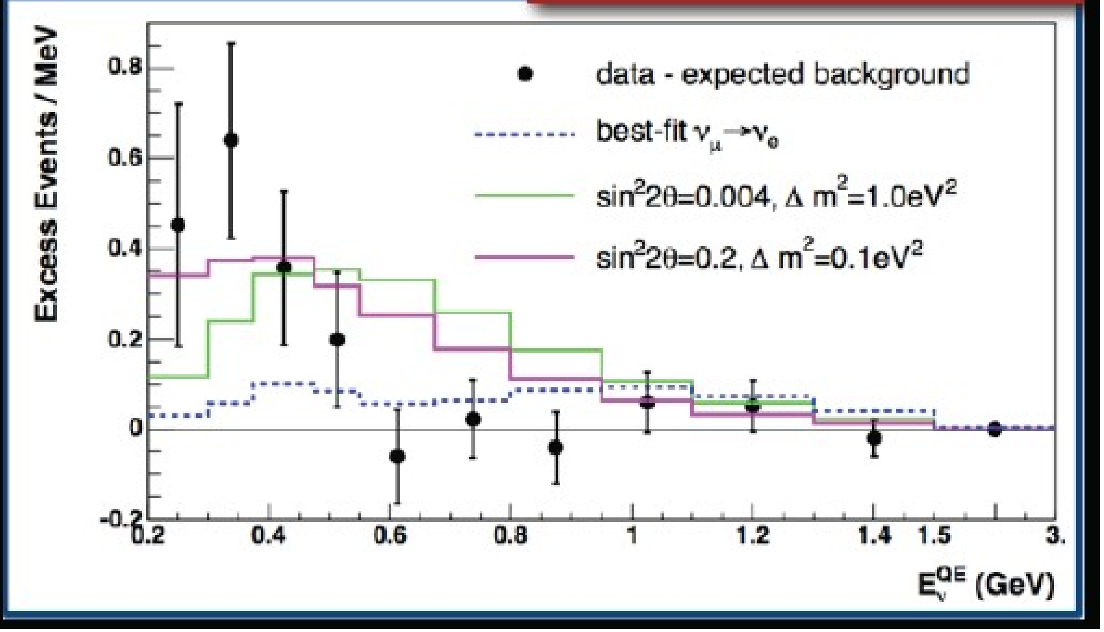
- 200 < E_ν < 475 MeV counts:
  - 128.8 ± 20.4 ± 38.3 excess events
  - 3.0σ significance

- Shape inconsistent with 2ν oscillations

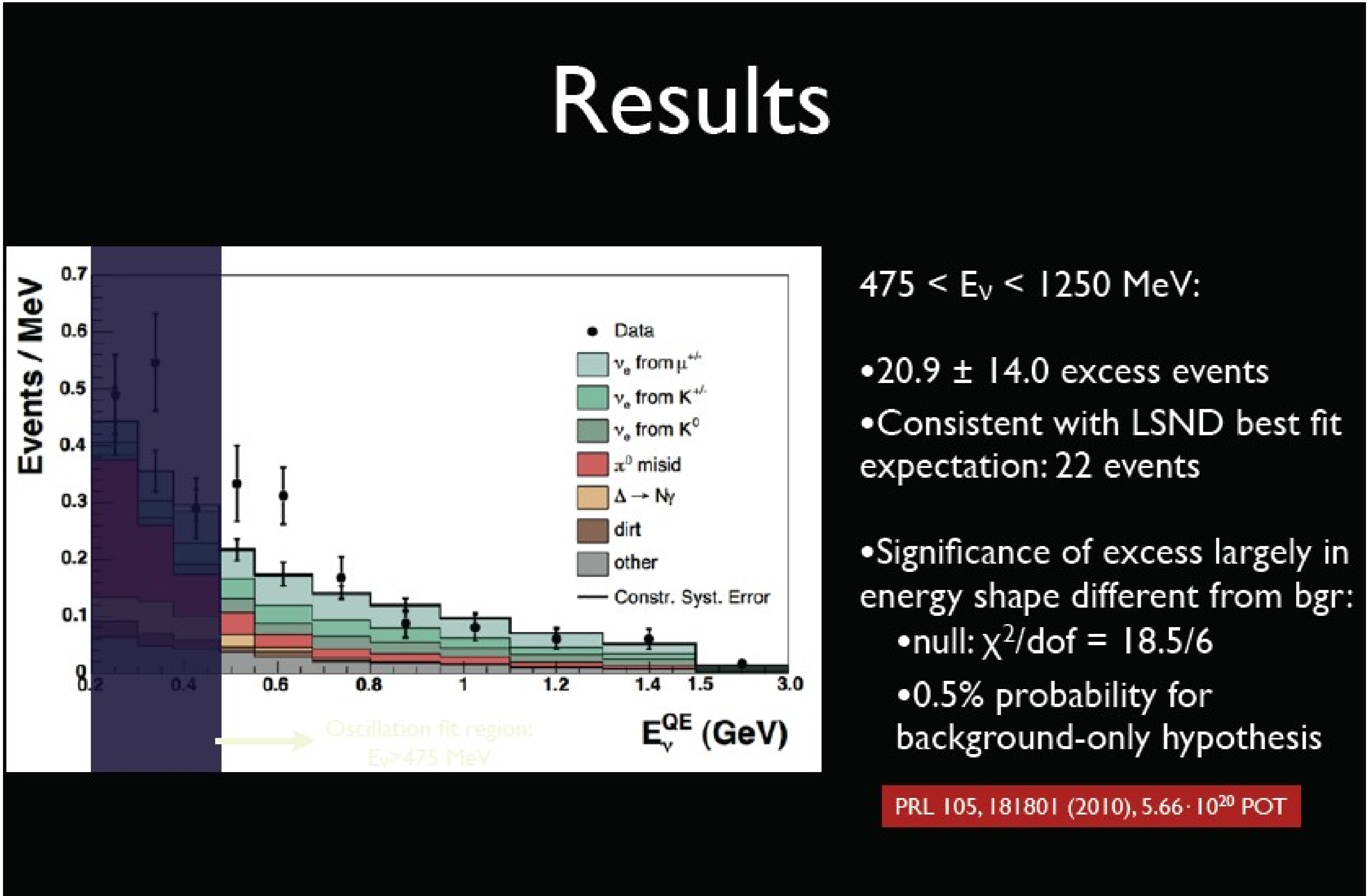
- Excess remains unexplained



PRL 102, 101802 (2009),6.46·10^{20} POT



Anti-neutrino channel



Results

$475 < E_\nu < 1250$ MeV:

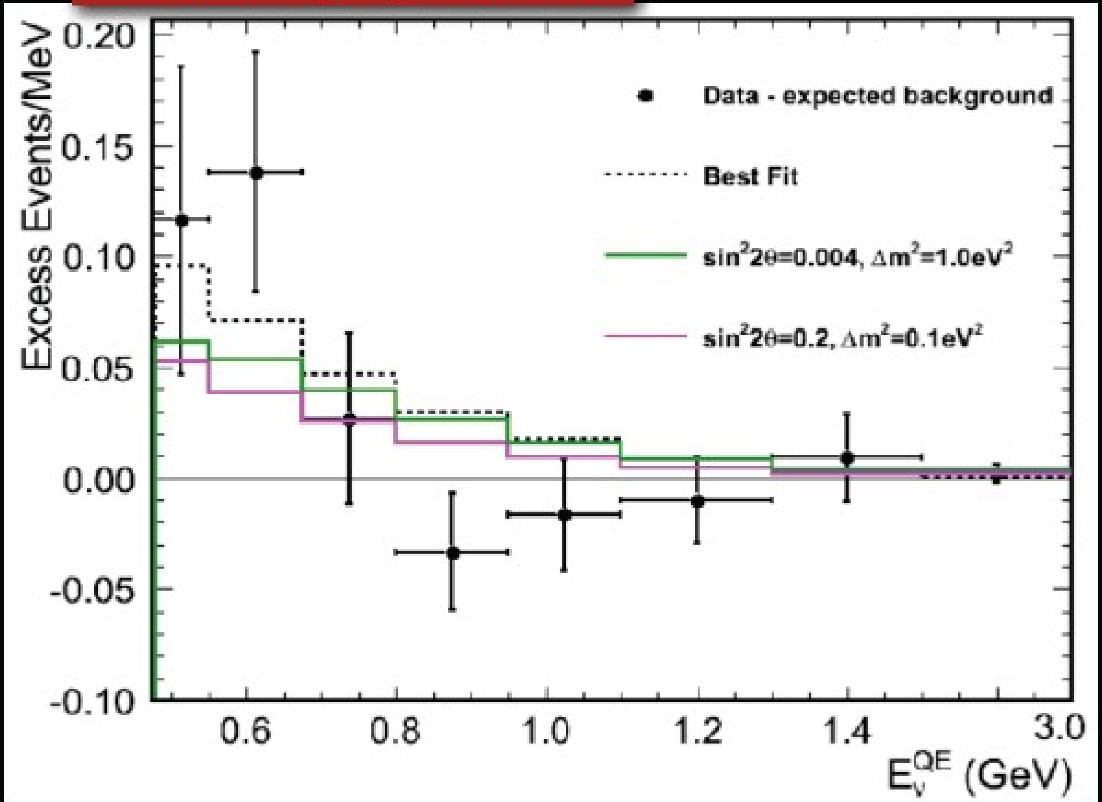
- 20.9 ± 14.0 excess events
- Consistent with LSND best fit expectation: 22 events

- Significance of excess largely in energy shape different from bgr:
  - null: χ^2/dof = 18.5/6
  - 0.5% probability for background-only hypothesis

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT

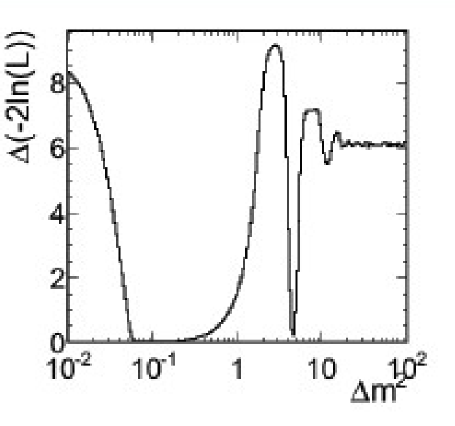
Results

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT



E-dependent fit to oscillations:

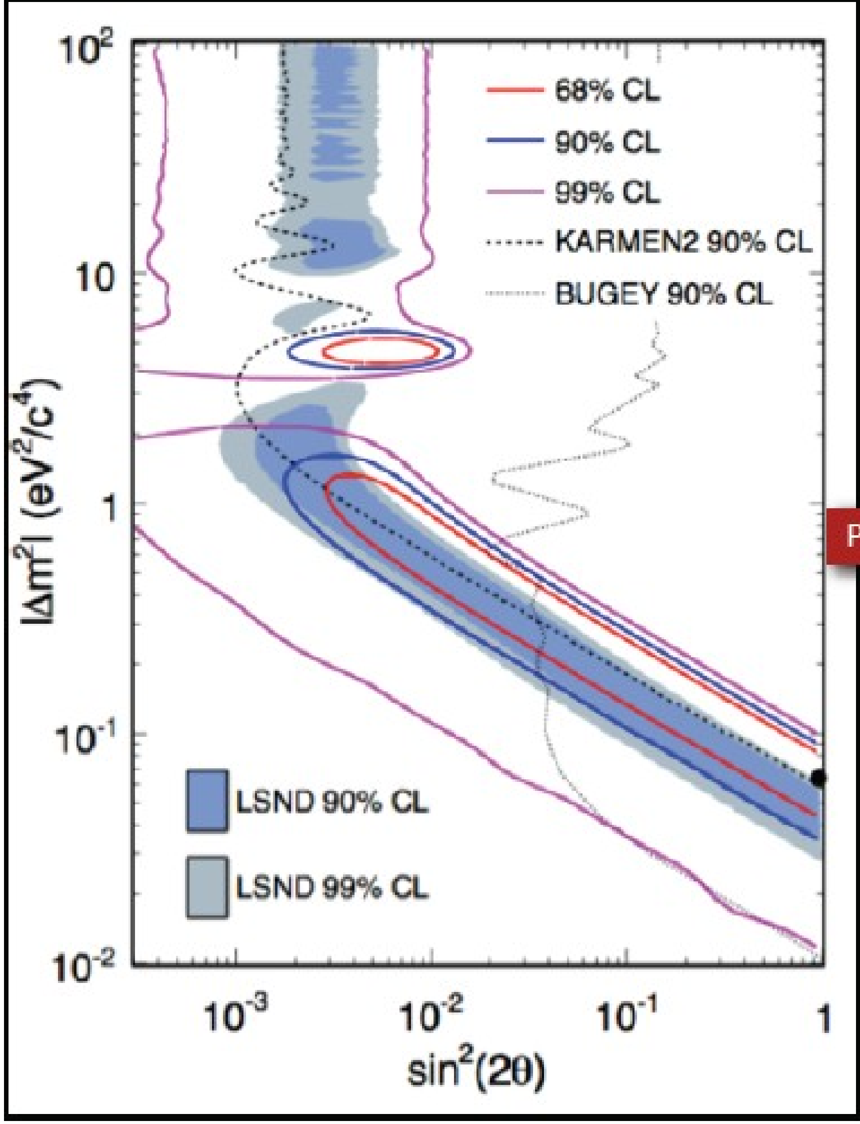
- Assume no ν_μ/ν_e disappearance
- Assume only antineutrinos oscillate
- Best fit:
  $(\sin^2 2\theta, \Delta m^2) = (0.96, 0.064\ \mathrm{eV}^2)$



$475 < E_\nu < 1250$ MeV:

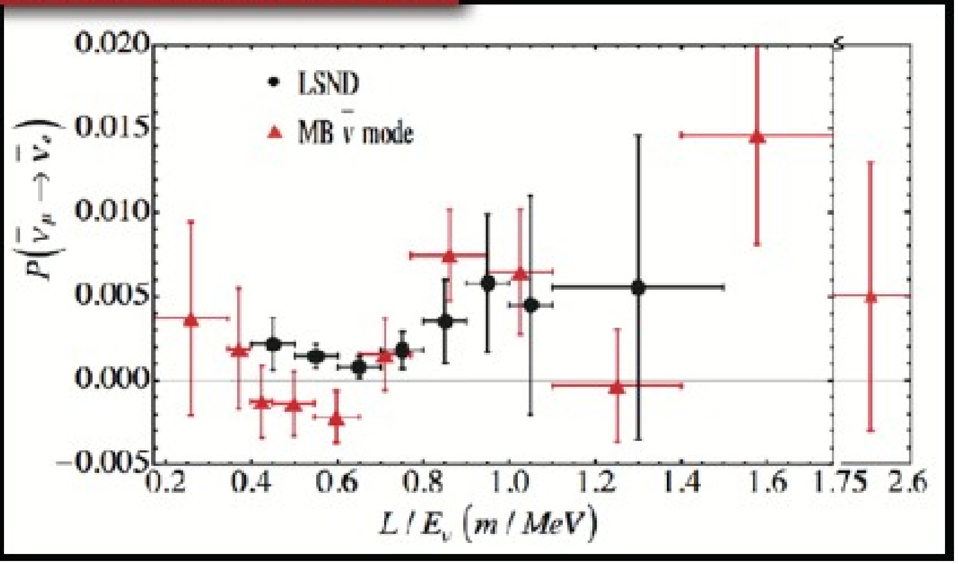
- Best fit: $\chi^2/\mathrm{dof} = 8.0/4$ (8.7%)
- Consistent with 2ν oscillations
- Oscillations favored over background hypothesis at 99.4% CL

Results



- Consistent with oscillation interpretation of LSND
  - Overlap in oscillation parameters allowed regions
  - Consistent L/E trend for excess-inferred oscillation probabilities

PRL 105, 181801 (2010), $5.66 \cdot 10^{20}$ POT



Confused? Here's a Summary of MiniBooNE Appearance Claims

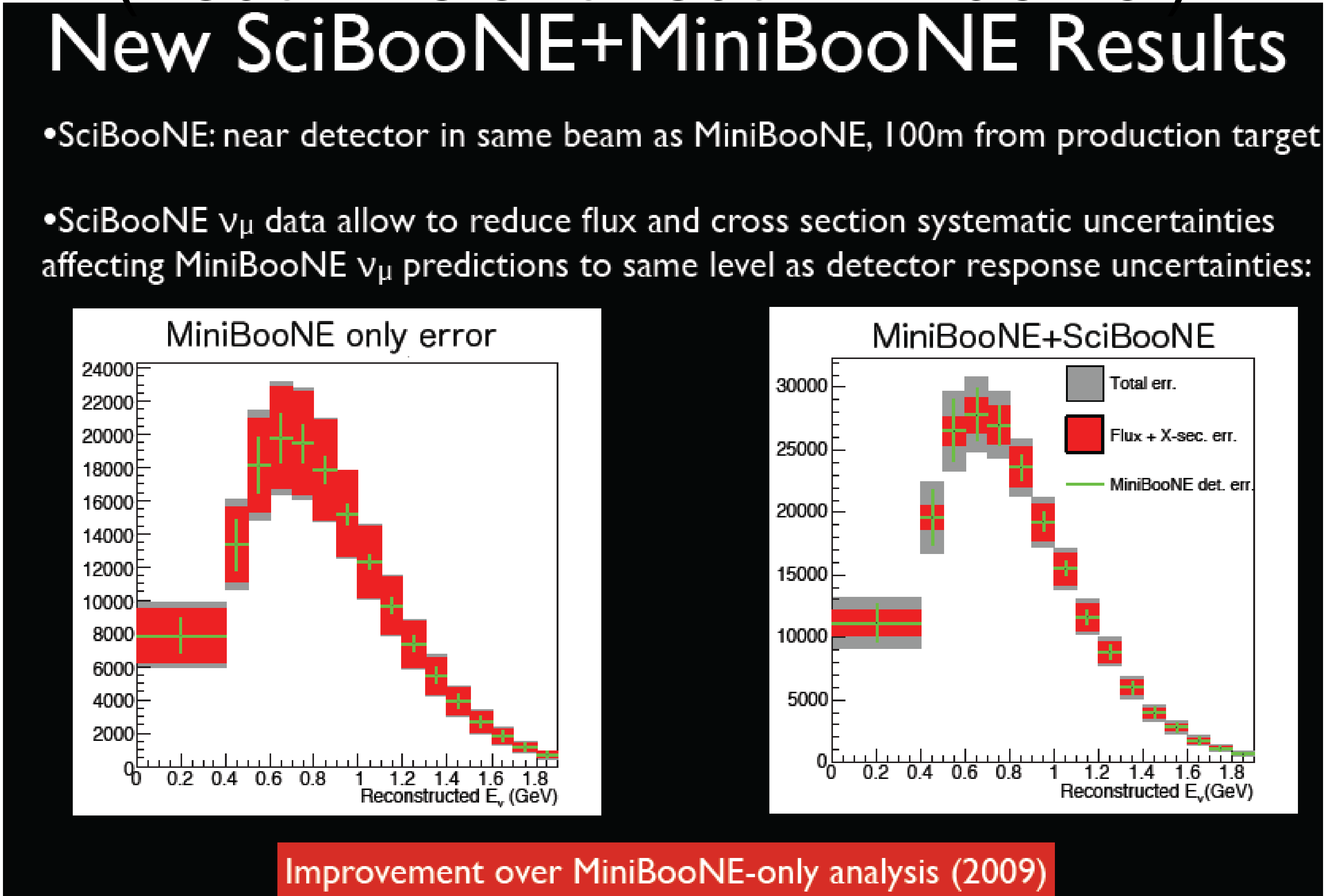
1. In a ν_μ beam above 475 MeV, we see no evidence for an excess of ν_e-like events

2. In a ν_μ beam below 475 MeV, we see a 3σ excess (128 + 43) of ν_e-like events that does not fit well a 2ν oscillation hypothesis

3. In a $\bar{\nu}_\mu$ beam below 475 MeV, we see (18 ± 14) events, consistent with both no excess and LSND + ν-only low-E excess. This rules out some explanations of the ν_μ beam low-E excess

4. In a $\bar{\nu}_\mu$ beam above 475 MeV, we see an excess of events. The null hypothesis in the 475-1250 MeV region is only 0.5% probable. A 2ν fit prefers an LSND-like signal at 99.4% CL

Scomparsa (neutrini e antineutrini muonici)



New SciBooNE+MiniBooNE Results

- SciBooNE: near detector in same beam as MiniBooNE, 100m from production target
- SciBooNE ν_μ data allow to reduce flux and cross section systematic uncertainties affecting MiniBooNE ν_μ predictions to same level as detector response uncertainties:

MiniBooNE only error

MiniBooNE+SciBooNE

Improvement over MiniBooNE-only analysis (2009)

New SciBooNE+MiniBooNE Results

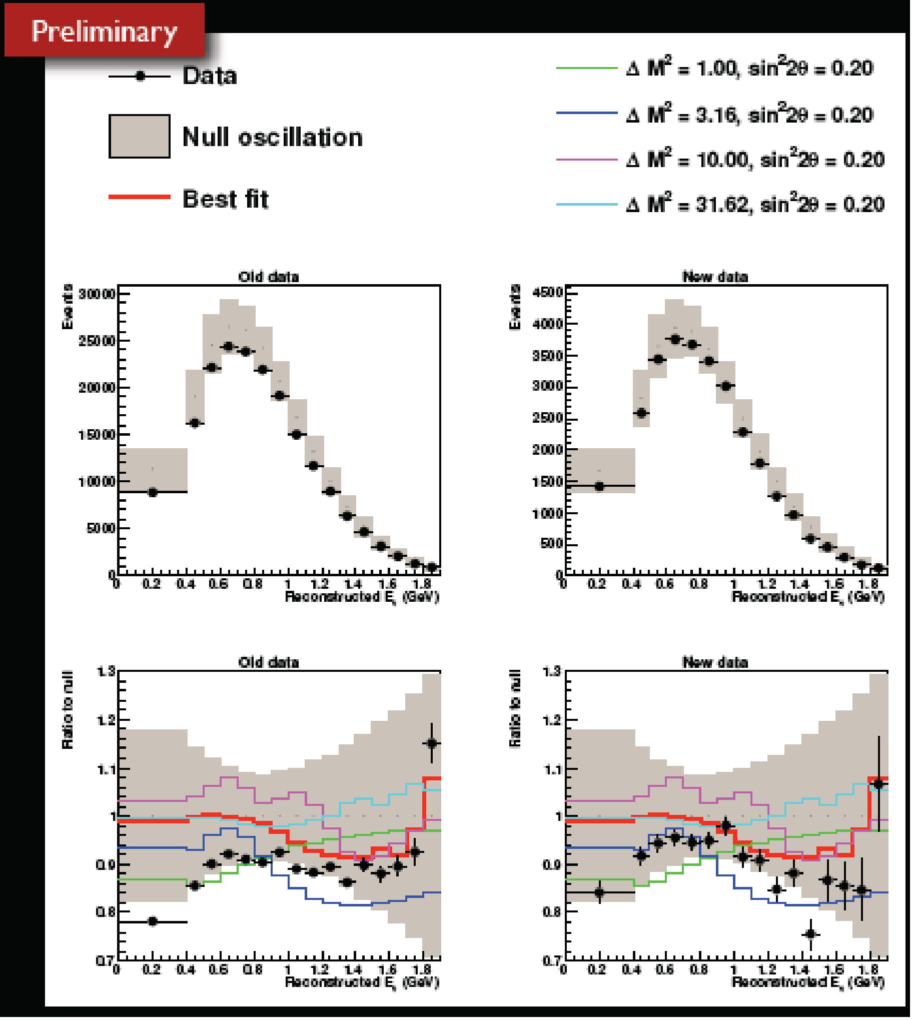
- Use MiniBooNE neutrino mode data taken both prior to (“old”) and together with (“new”) SciBooNE

- Best fit: Δm^2=42 eV^2, $\sin^2 2\theta$=0.51

- Null: χ^2/dof = 41.5/32
- Best: χ^2/dof = 35.6/30

- $\Delta\chi^2$(observed)=5.9
- Simulations: $\Delta\chi^2$(90% CL, null)=8.4

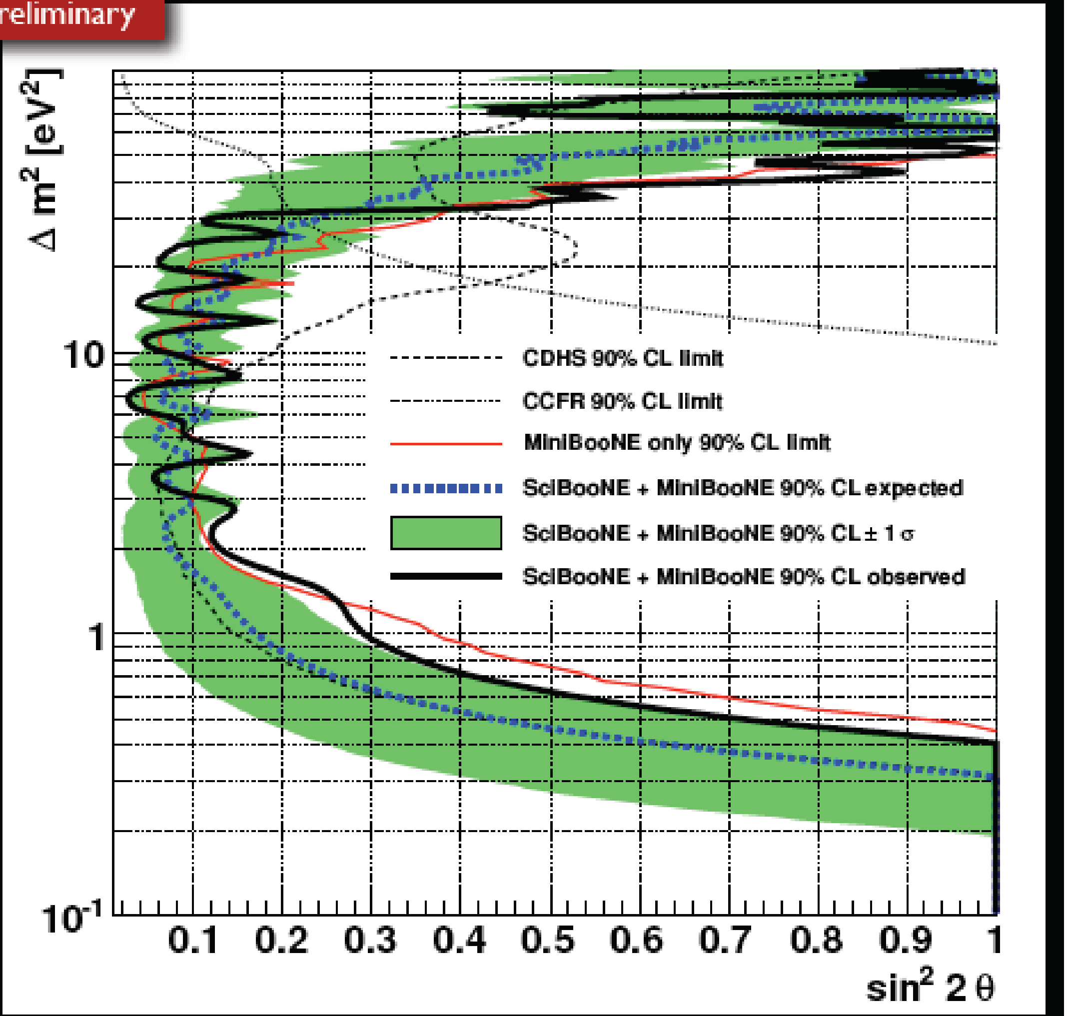
- **No significant ν_μ disappearance observed**



Preliminary

New SciBooNE+MiniBooNE Results

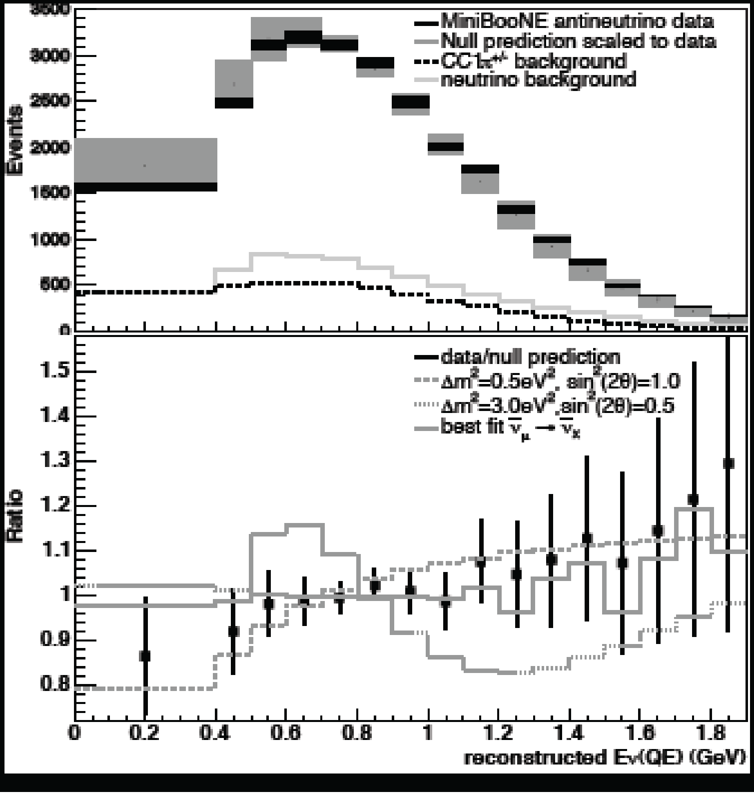
- World's strongest limit for $10 < \Delta m^2 < 30$ eV^2
- Limit weaker than sensitivity for $\Delta m^2 < 30$ eV^2 because of small data deficit observed
- Constrains sterile neutrino mixing models

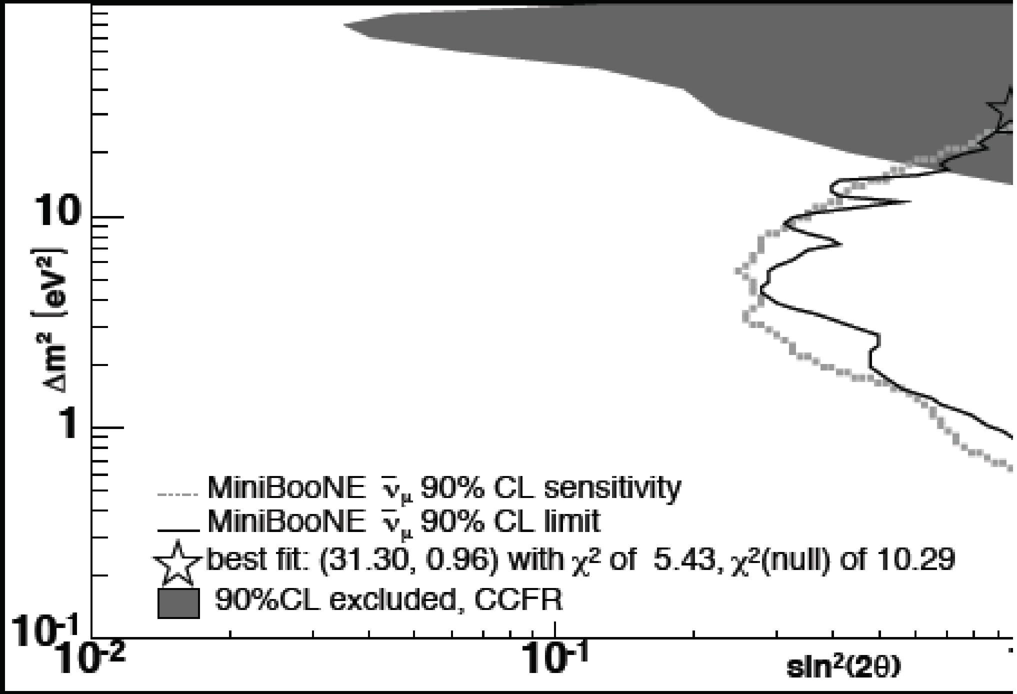


Preliminary

MiniBooNE ν_μ Disappearance

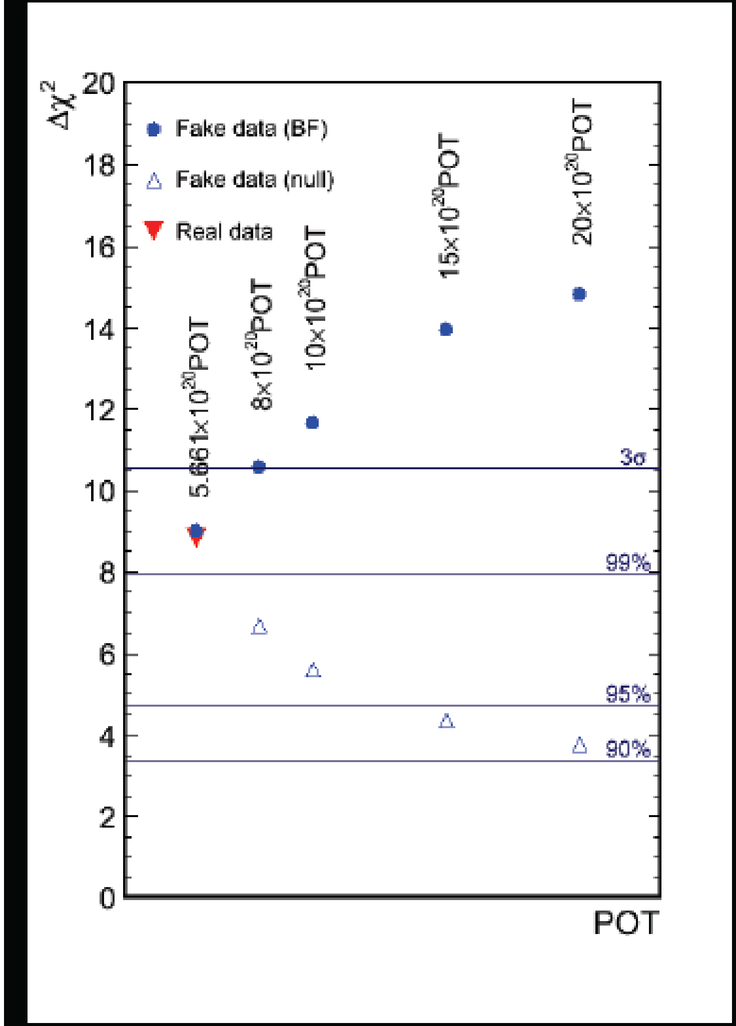
- 2009 results: no $\bar{\nu}_\mu$ disappearance observed, but limited sensitivity
- Current antineutrino mode data statistics (x3 2009 result) + SciBooNE near detector constraint will allow for a more sensitive search
- Particularly interesting now, given MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results!





PRL 103, 061802 (2009)

Conclusions:



- 15 years after first first LSND claim for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, the issue is still not settled

- At such small oscillation probabilities, not an easy measurement to make!

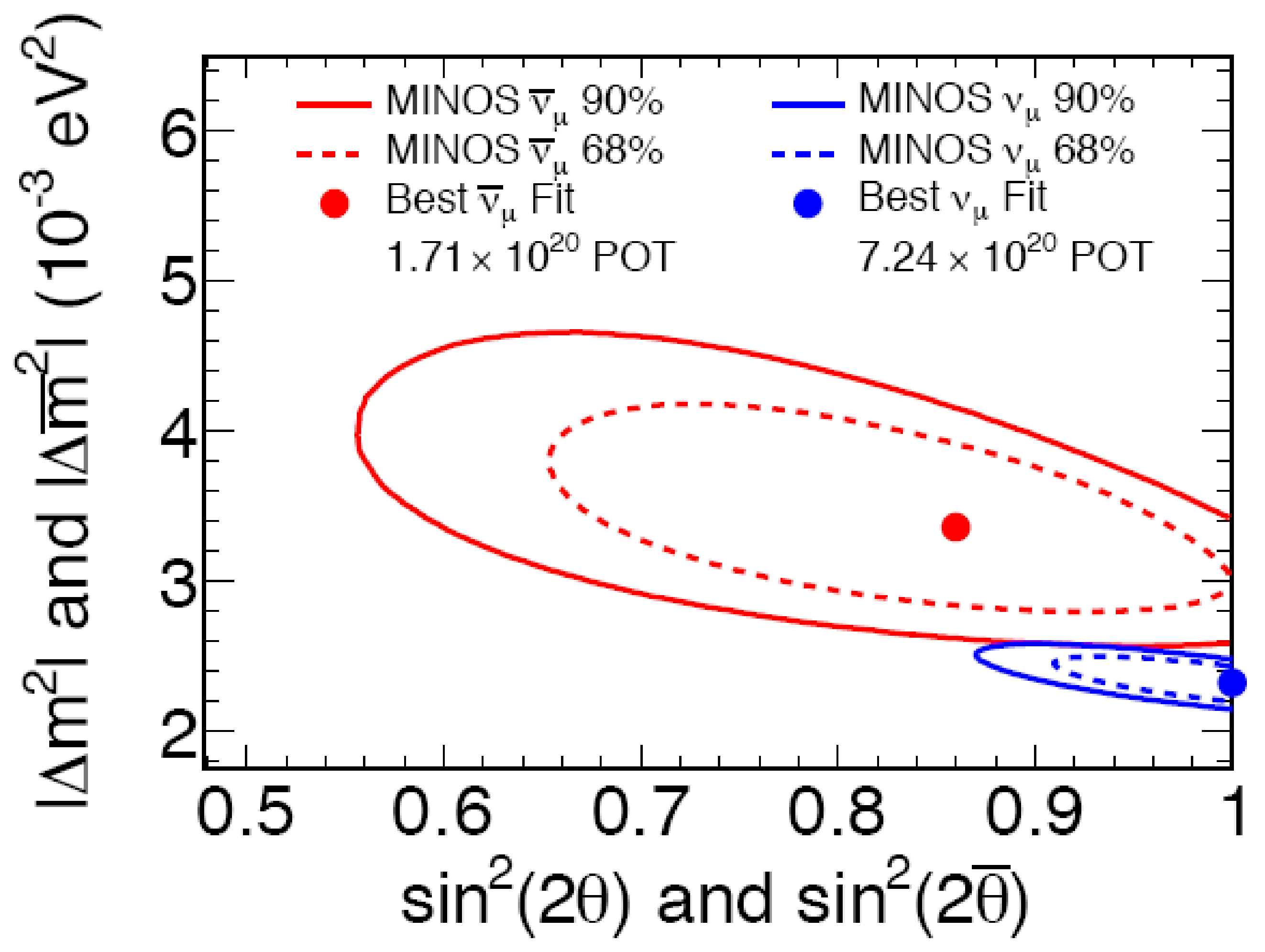
- MiniBooNE is exploring four oscillation channels and a large L/E range covering LSND, but no clear picture (invoking steriles or otherwise) has emerged so far

- More MiniBooNE data needed:
  - New $\bar{\nu}_\mu \to \bar{\nu}_e$ results this summer ($9 \cdot 10^{20}$ POT)
  - Continue $\bar{\nu}$ mode data-taking until March 2012 ($12 \cdot 10^{20}$ POT)
  - Plan to submit proposal this fall for 2nd identical detector at 200m

- More eperimental efforts definitely needed:
  - See talks at this workshop

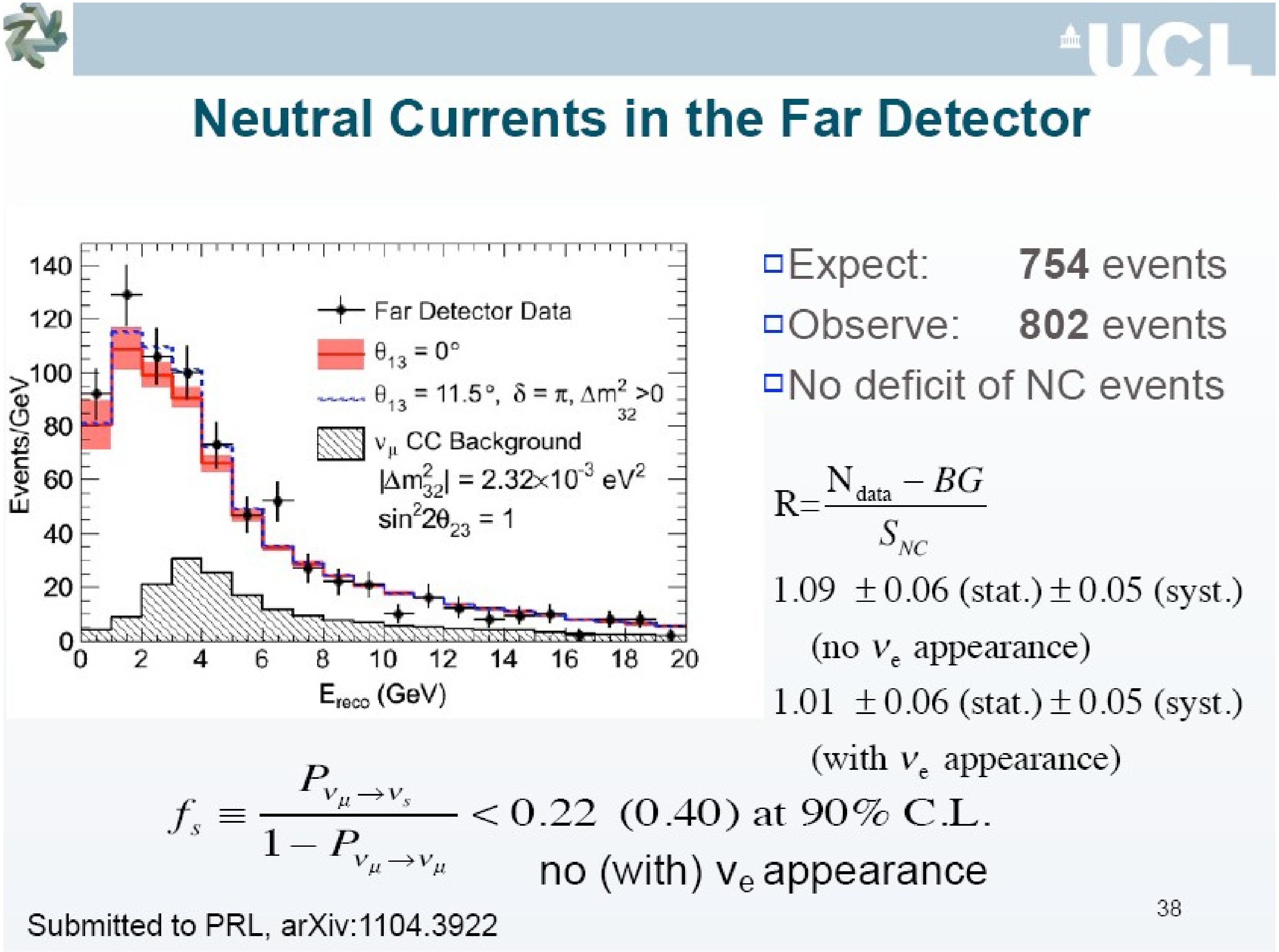
MINOS: neutrini vs antineutrini

Comparisons to Neutrinos



A 2% chance of seeing such a discrepancy if the underlying parameters are the same

MINOS: update su neutrini sterili



Neutral Currents in the Far Detector

- Expect: **754** events
- Observe: **802** events
- No deficit of NC events

$$R = \frac{N_{data} - BG}{S_{NC}}$$

$$1.09 \pm 0.06\ (\text{stat.}) \pm 0.05\ (\text{syst.})$$

(no ν_e appearance)

$$1.01 \pm 0.06\ (\text{stat.}) \pm 0.05\ (\text{syst.})$$

(with ν_e appearance)

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ \ (0.40)\ \text{at}\ 90\%\ \text{C.L.}$$

no (with) ν_e appearance

Submitted to PRL, arXiv:1104.3922

conclusioni

- Ci sono chiare indicazioni di un diverso comportamento tra neutrini ed anti-neutrini
- Le oscillazioni osservate da LSND e MiniBOONE non possono rientrare in uno schema a tre soli neutrini
- La non osservazione di un quarto neutrino leggero lascia presumere che serva includere almeno un neutrino sterile o comunque che serva ricorrere a nuova fisica