Searching for Physics Beyond the Standard Model with Neutrinos

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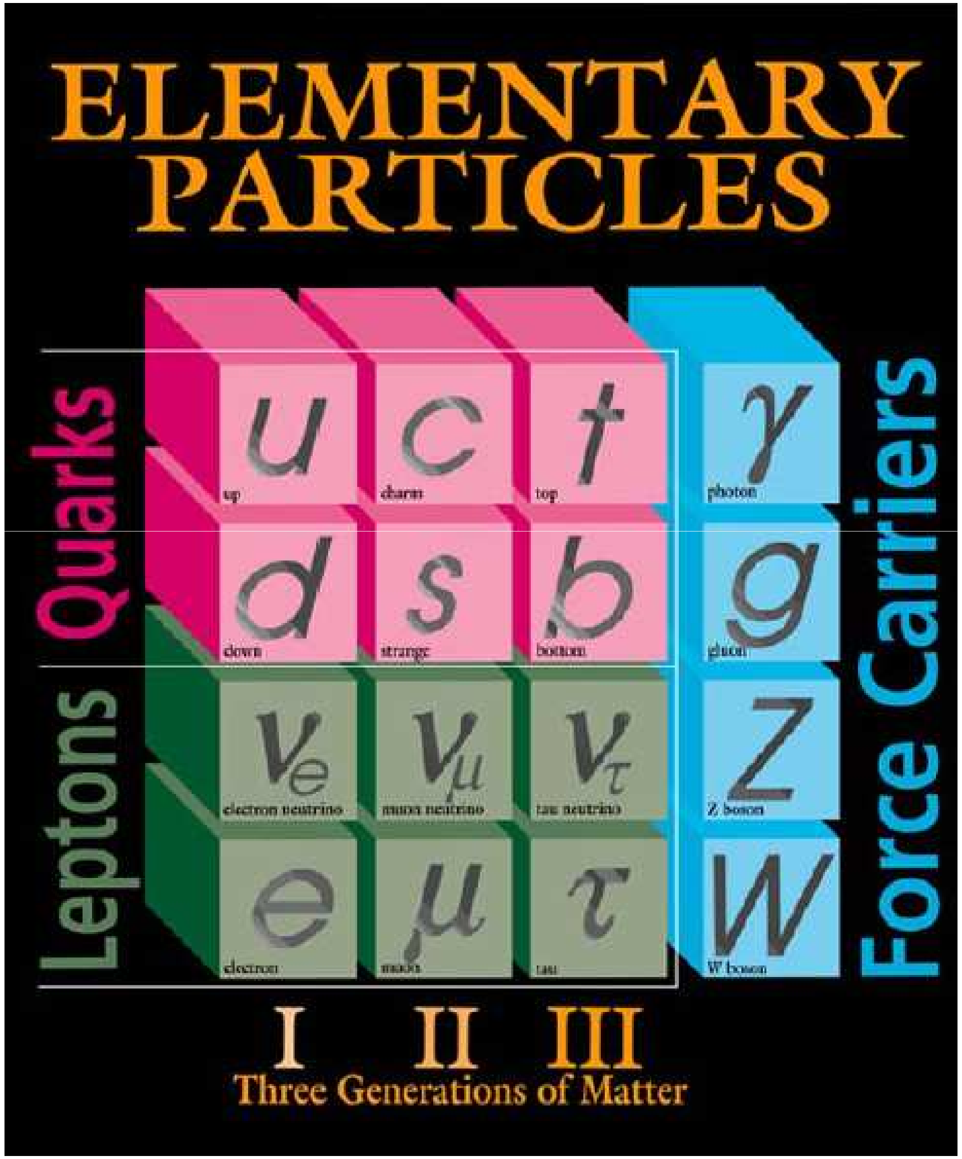
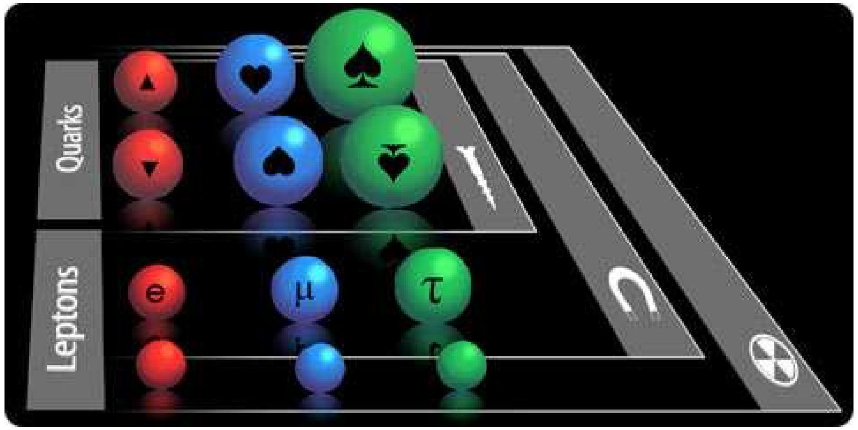
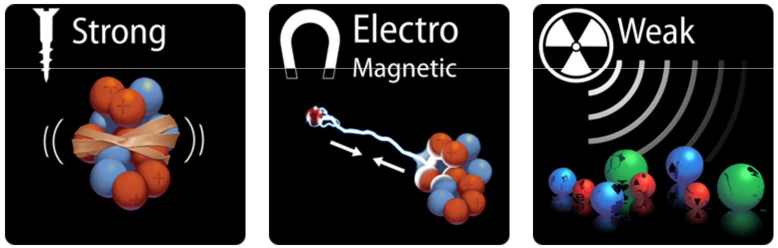
Outline

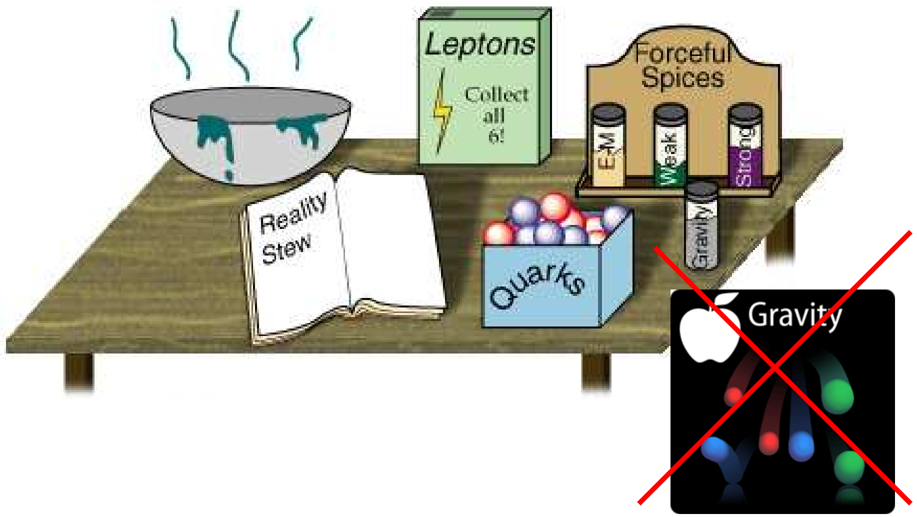
- Neutrinos in the Standard Model of Particle Physics
  - What are neutrinos?
  - Why the neutrinos are important?
  - Oscillations?
  - ν oscillation landscape
- Some of the Things I Worked on: MiniBooNE
  - Experiment Description
  - MiniBooNE's First Results
  - MiniBooNE's New Results!
  - What has MiniBooNE told us?
- Conclusions and Next Steps

Standard Model of Particle Physics



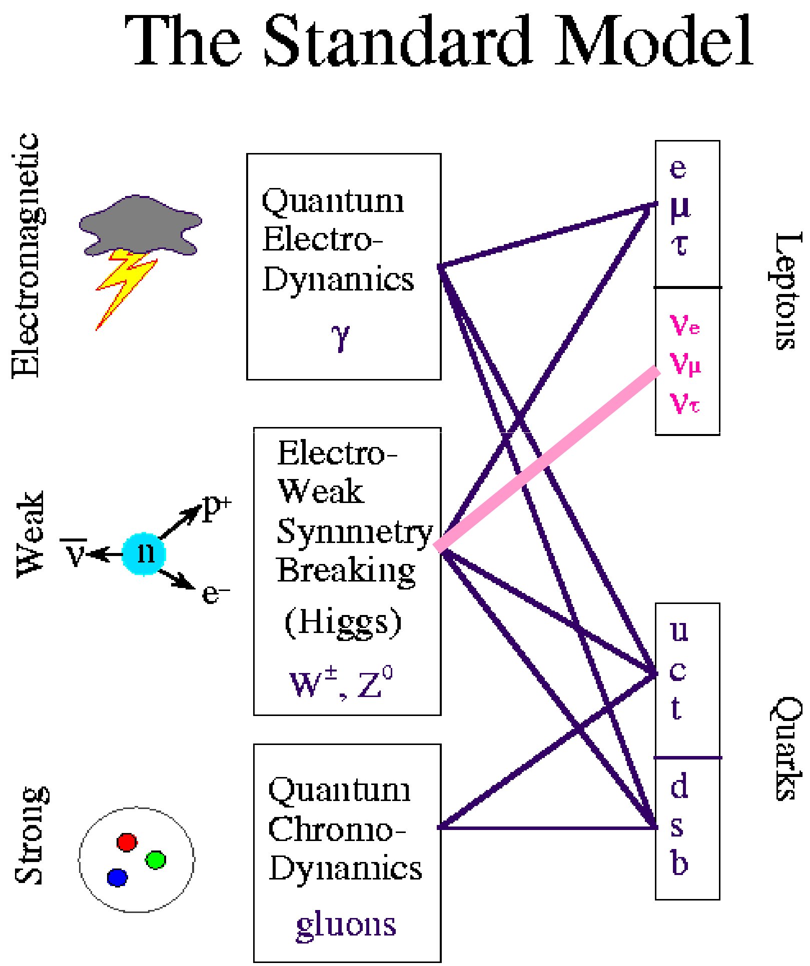






Neutrinos in the Standard Model

- Neutrinos are the only fundamental fermions with no electric charge
- Neutrinos only interact through the "weak force"
- Neutrinos are massless
- Neutrino interaction through W and Z bosons exchange is (V-A)
  - Neutrinos are left-handed (Antineutrinos are right-handed)
- Neutrinos have three types
  - Electron $\nu_e \to e$
  - Muon $\nu_\mu \to \mu$
  - Tau $\nu_\tau \to \tau$



How many neutrinos are there?

Experiment shows that the neutrinos produced in muon interactions are different from neutrinos involved in interactions with electrons.

A third kind of particle, the tau, is heavier version of muon which is itself a heavier version of the electron.

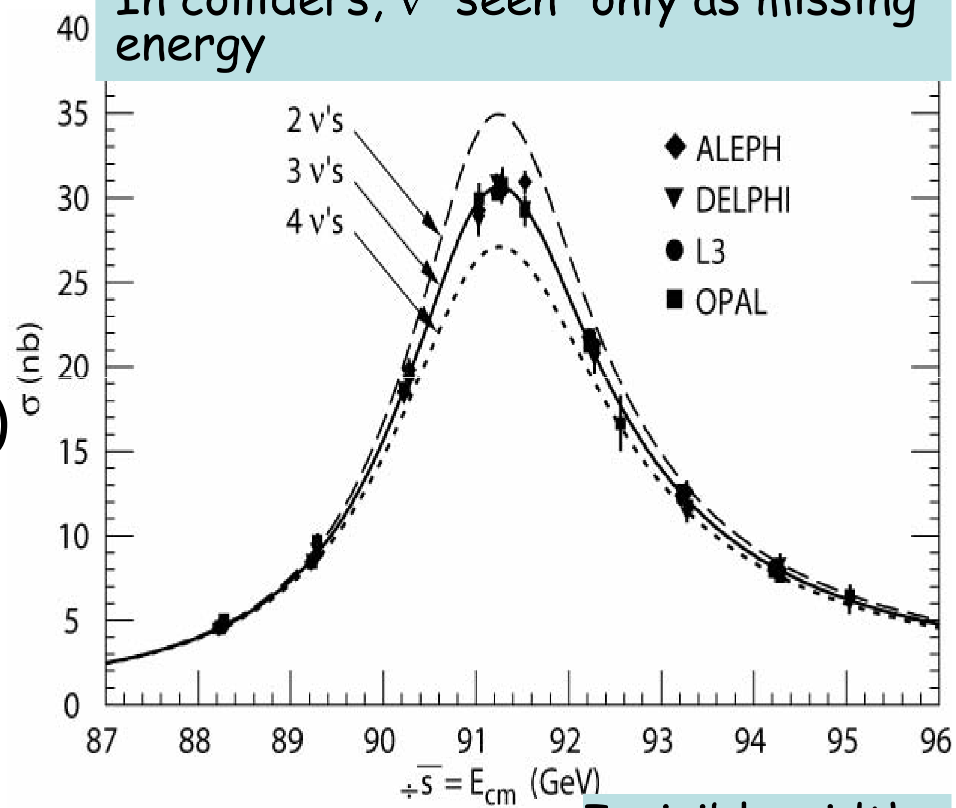
(It has its own neutrino as well.)

⇨ We have (at least) 3 kind of neutrinos:

the electron neutrino (ν_e), the muon neutrino (ν_μ), and the tau neutrino (ν_τ).

Sterile ν?

In colliders, ν "seen" only as missing energy



Invisible width of the Z^0 measured by LEP expts

Neutrino Cross Section: Very Small!

Weak interactions are weak because of the massive W and Z boson exchange

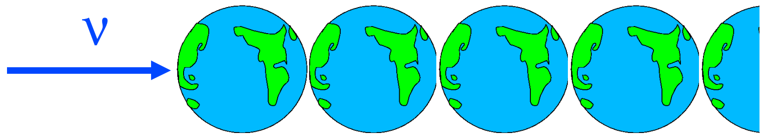
$\Rightarrow \sigma^{\text{weak}} \propto G_F^2 \propto (1/M_{W \text{ or } Z})^4$

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2 = 1.166\times10^{-5}/GeV^2 \quad (g_W \approx 0.7)$$

$M_W \sim 80$ GeV
$M_Z \sim 91$ GeV

For 100 MeV Neutrinos:

$\sigma(\nu e) \sim 10^{-42}$ and $\sigma(\nu n) \sim 10^{-39}$ cm^2
compared to $\sigma(pp) \sim 10^{-24}$ cm^2



A neutrino has a good chance of traveling through 3 million earths before interacting at all!

Mean free path length in steel $\sim 10^{13}$ meters!

Hundreds of billions of neutrinos from the sun pass through every square inch of you each second!

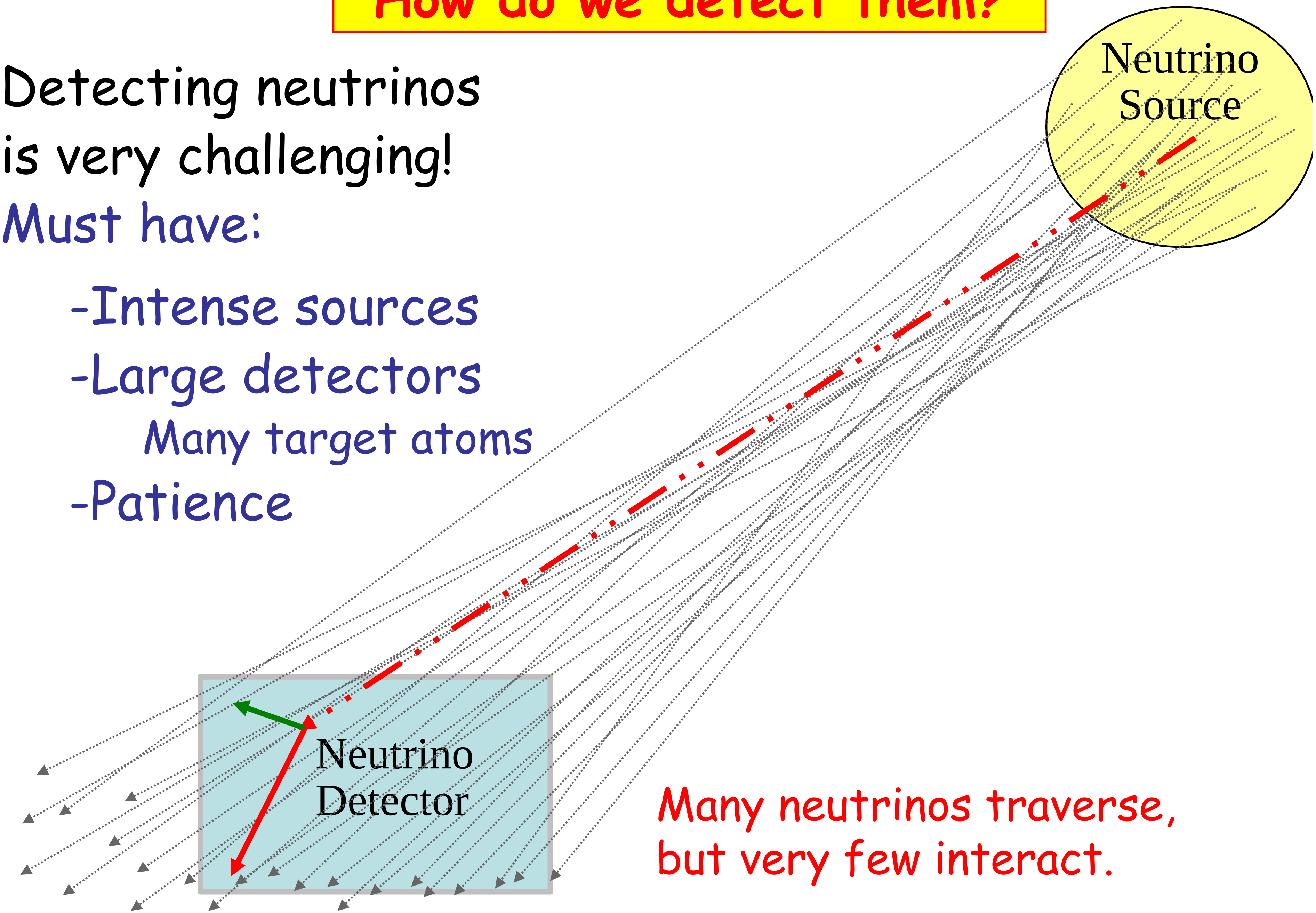
Need big detectors and lots of ν's!

How do we detect them?

Detecting neutrinos
is very challenging!

Must have:

- -Intense sources
- -Large detectors
  - Many target atoms
- -Patience



Many neutrinos traverse,
but very few interact.

Discovery of Neutrinos

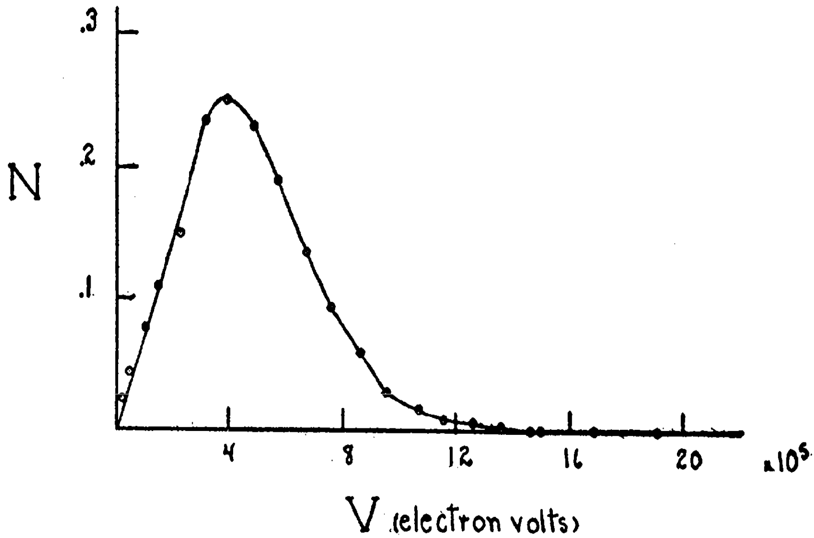


FIG. 5. Energy distribution curve of the beta-rays.

Continuous Beta Spectrum

- Continuous beta spectrum was the first hint that there is an extra particle in the beta decay reaction:

$n \rightarrow p + e^- + ?$

Bohr: At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations.

A Great...

...Pauli's Idea

4th December 1930

Dear Radioactive Ladies and Gentlemen,

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

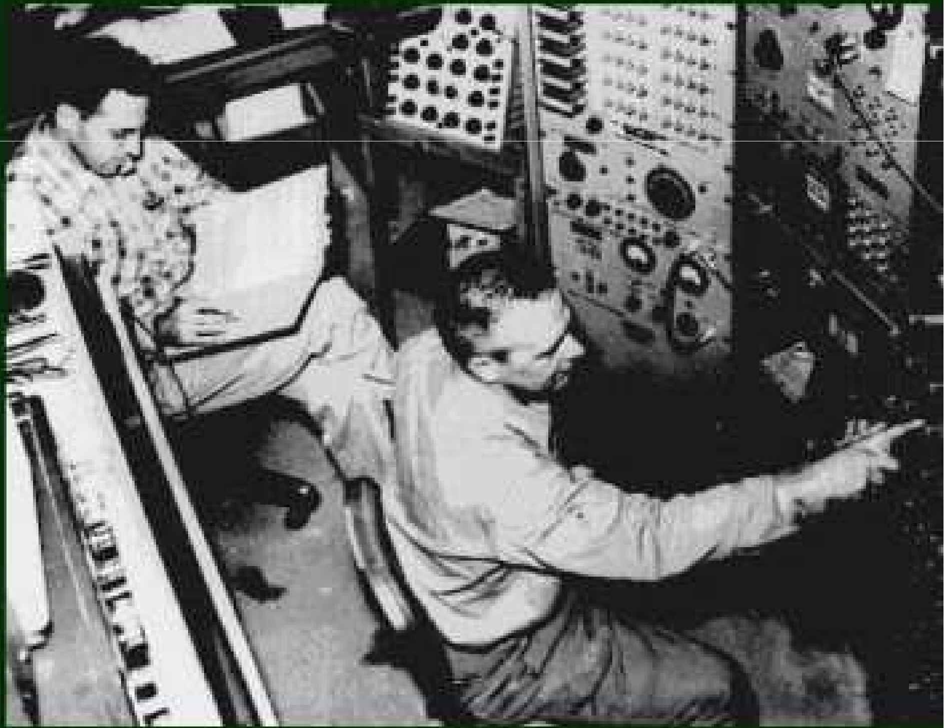
First Detection of (Reactor) Neutrinos


F. Reines and C. Cowan

detection process:
inverse β - decay:

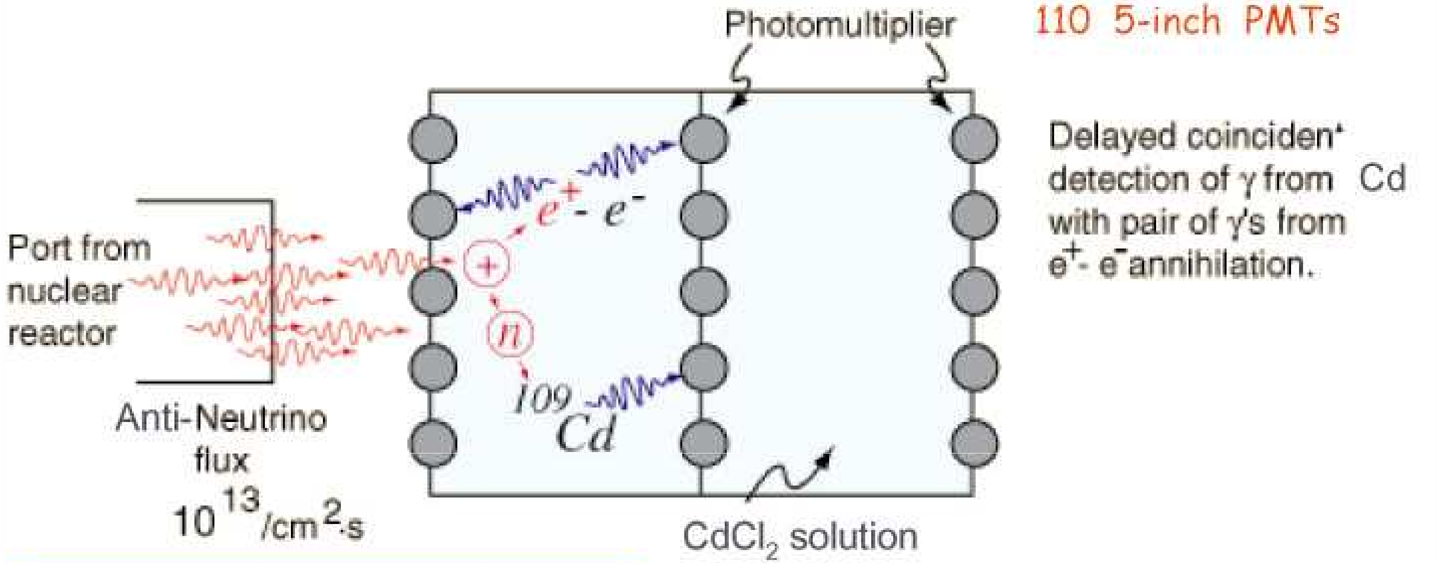
$$\bar{\nu}_e + p \rightarrow n + e^+$$

In 1953 Fred Reines and Clyde Cowan (LANL) in an experiment at Hanford nuclear reactor have detected anti-neutrinos from fission products. They confirmed their result in 1956 at Savannah River reactor where background conditions were much better.



F. Reines and C. Cowan at the Control Center of the Hanford Experiment (1953)

That was difficult experiment since cross section of anti-neutrino interaction with matter is incredibly small (~ $6 \cdot 10^{-44}$ cm^2 or ~ 10^{20} times smaller than typical nuclear cross sections)



$$\bar{\nu} + p \rightarrow e^+ + n$$

Detector was placed 11 m from the reactor and 12 m under the ground level. Neutrino interactions were observed by coincidence of prompt positron signal and delayed Cd(n,γ) capture with the rate of ~ 3 events / hour and with signal/background ratio of ~ 3/1

→ Nobel Prize to F. Reines for anti-neutrino detection in 1995

Discovery of the Neutrino: 26 years after predicted

- they collected data for ~ a year
- recording flashes of light produced by impact of neutrinos from the nearby reactor …

W E S T E R N   U N I O N

June 14, 1956

Dear Professor Pauli,

We are happy to inform you that we have definitely detected neutrinos. . .

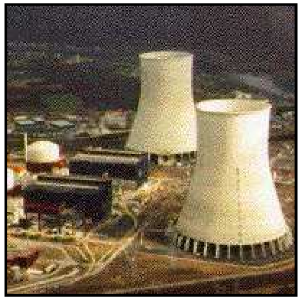
Fred Reines
Clyde Cowan

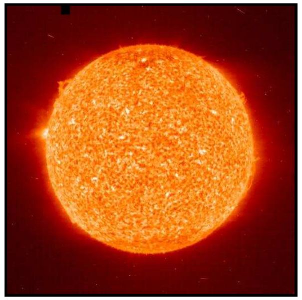
- ghostly particle (ν_e) had become a tangible reality
- this ground breaking experiment changed the role the ν_e was to play in physics
- ν_e not just the by-product of beta decay but would be used to expand our understanding of the subatomic world

won the Nobel Prize for detection of the ν_e (1995)

Sources of neutrinos: artificial and natural

✓ Nuclear Reactors (power stations, ships)



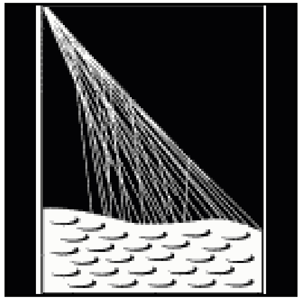


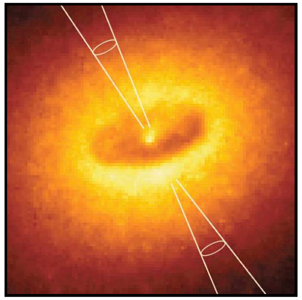
Sun ✓

✓ Particle Accelerator

Supernovae (star collapse)
SN 1987A ✓

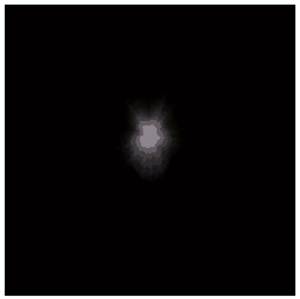
✓ Earth's Atmosphere (Cosmic Rays)





Astrophysical Accelerators
Soon ?

✓ Earth's Crust (Natural Radioactivity)



Big Bang (here 330 ν/cm^3)
Indirect Evidence

Neutrino Mass

In the standard model, neutrinos are massless.

But it's difficult to confirm this!

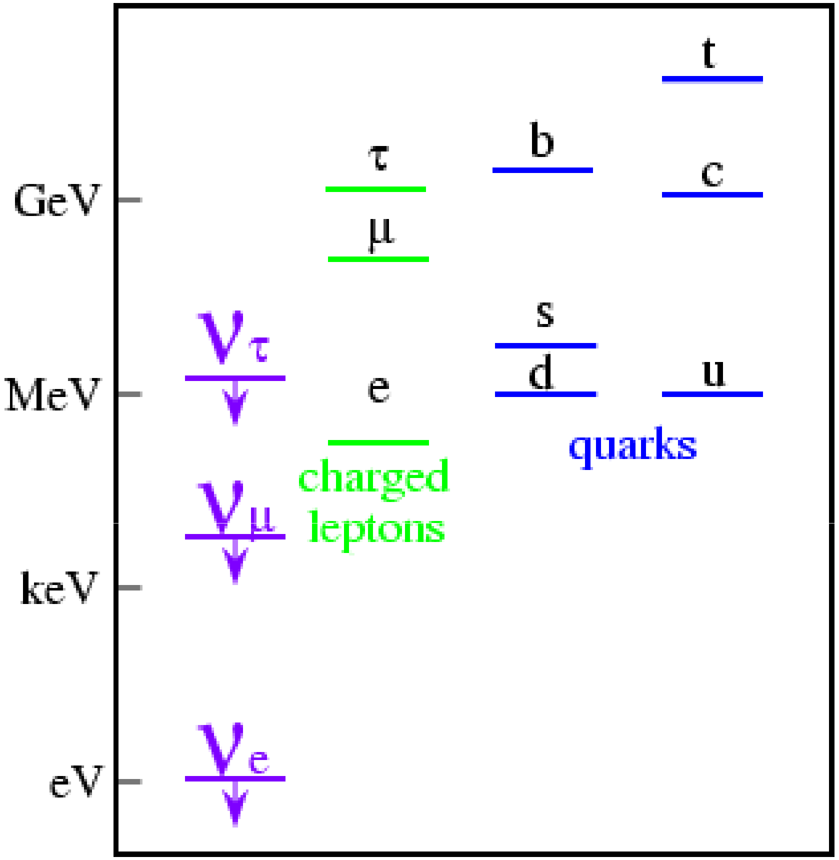
Direct mass searches yield limits:

- ν_e: tritium decay: m < 2 eV
- ν_μ: pion decay: m < 170 keV
- ν_τ: tau decay: m < 18.2 MeV

Compare to hadron masses:

(larger than neutrino mass limits)

- pions ~ 140 Mev
- kaons ~ 500 MeV
- protons ~ 1 GeV
- neutrons ~ 1 GeV



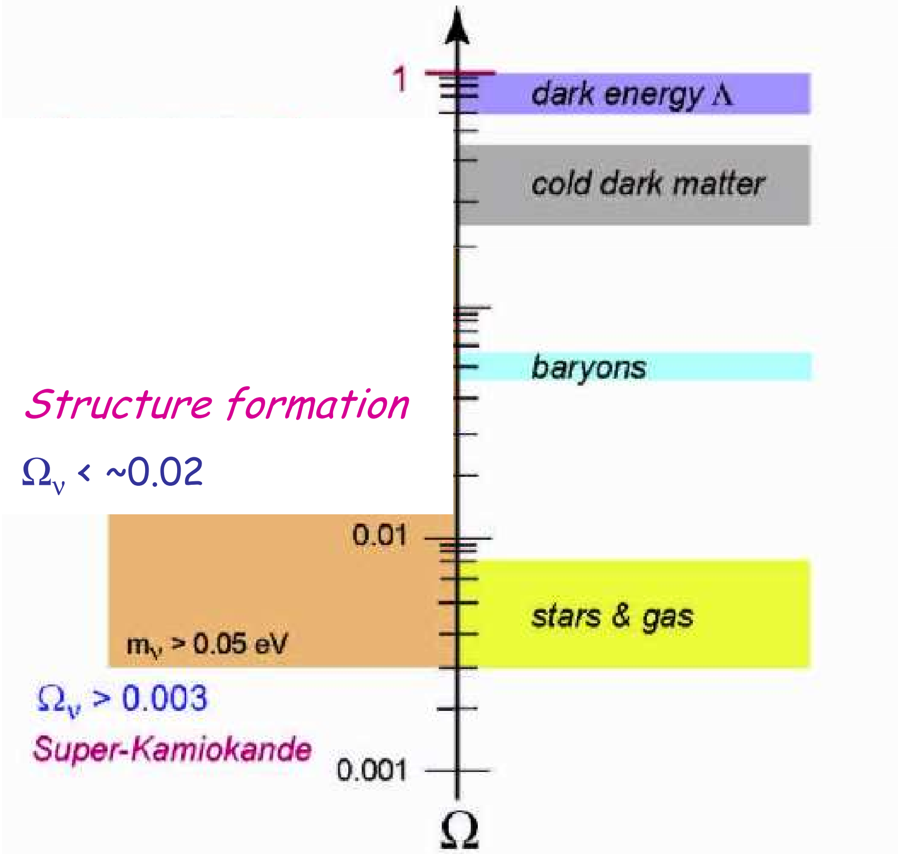
Can learn about neutrino mass with indirect searches.

Use quantum mechanics-> Neutrino Oscillations

Why Neutrino Mass Matters?

Cosmological Implications

- *Neutrinos important for heavy element production in supernova*
- *Light neutrinos affect galactic structure formation*



Window on Physics at High E Scales

The fact that neutrino masses are so much smaller than other particles
⇒ See-Saw Mechanism

$$\mathcal{L}^{D+M} = \mathcal{L}_L^M + \mathcal{L}_R^M + \mathcal{L}^D$$

$$= -\frac{1}{2}\begin{pmatrix}\overline{\nu_L^c} & \overline{\nu_R}\end{pmatrix}\begin{pmatrix} m_L & m_D \\ m_D & m_R\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix} + \text{h.c.}$$

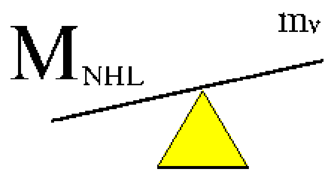
Heavy RH neutrino

Typical Dirac Mass

$$m_1 \simeq \frac{(m_D)^2}{m_R} \ll m_D\,,$$ Set of very light neutrinos

$$m_2 \simeq m_R\,,$$ Set of heavy sterile neutrinos

$$\tan\vartheta \simeq \frac{m_D}{m_R} \ll 1$$



Universe contains 330 active ν/cm³ (410 γ/cm³), from Big Bang (if sterile ν → most abundant Particle in the Universe).

Neutrino Oscillations?

Mass (objects with definitive mass plane wave) and flavor states (objects that participate in weak interaction) are not identical.

$$\left|\nu_\ell\right\rangle = \sum_i U_{\ell i} \cdot \left|\nu_i\right\rangle$$

Simplified Model: only two neutrino mix

Weak state **Mass state**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

A neutrino created as one specific flavor might later be detected as a neutrino of a different flavor.

Why? Neutrinos propagate as mass eigenstates.

Oscillation Probability

$$|\nu_\mu(t)\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

e^{-iE1t} e^{-iE2t}

Δm^2 is the mass squared difference between the two neutrino states

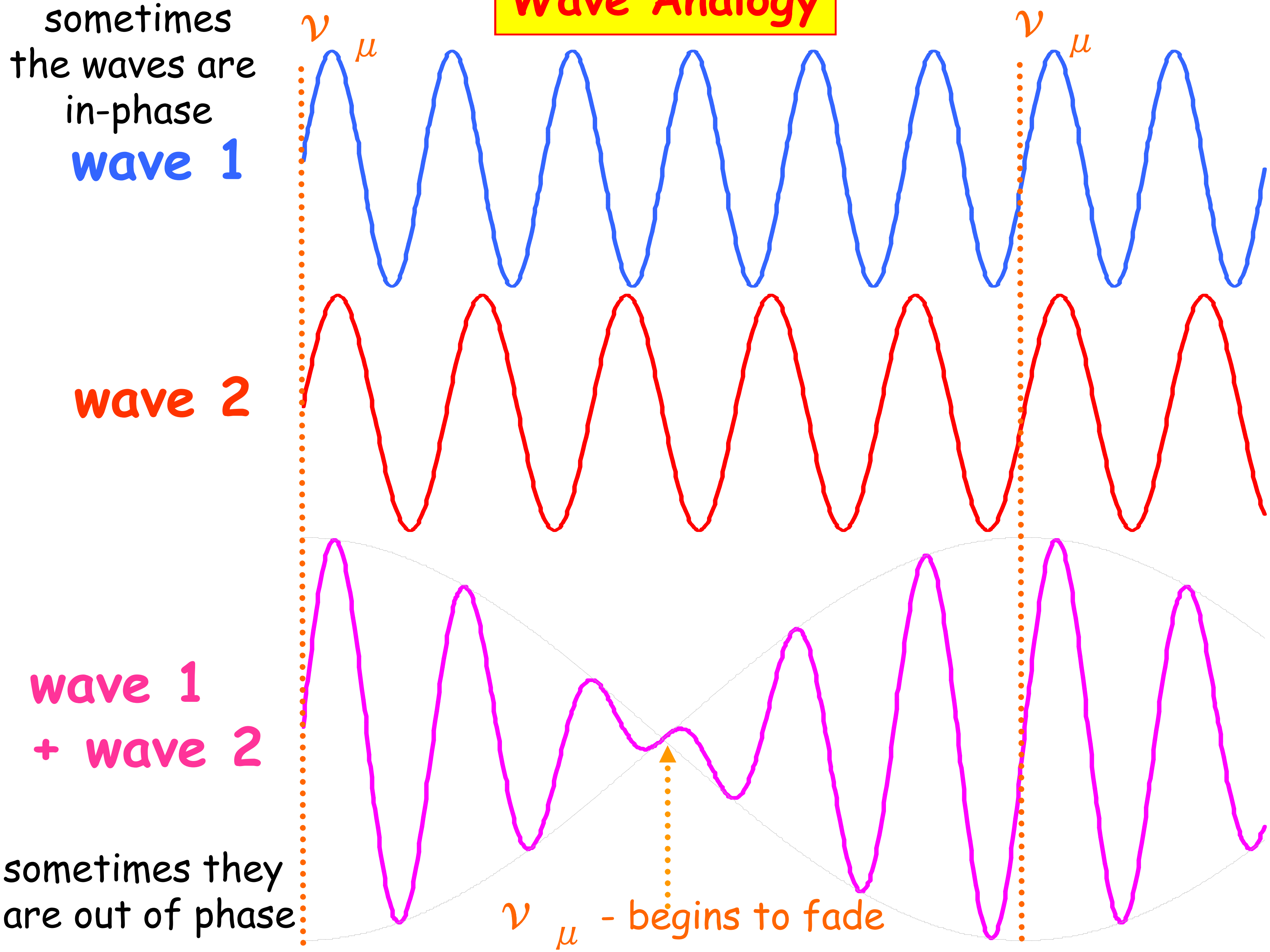
Distance from point of creation of neutrino beam to detection point

$$P_{osc} = |\langle\nu_e\,|\,\nu_\mu(t)\rangle|^2 = \sin^2 2\theta\,\sin^2 1.27\left[\frac{\Delta m^2 L}{E}\right]$$

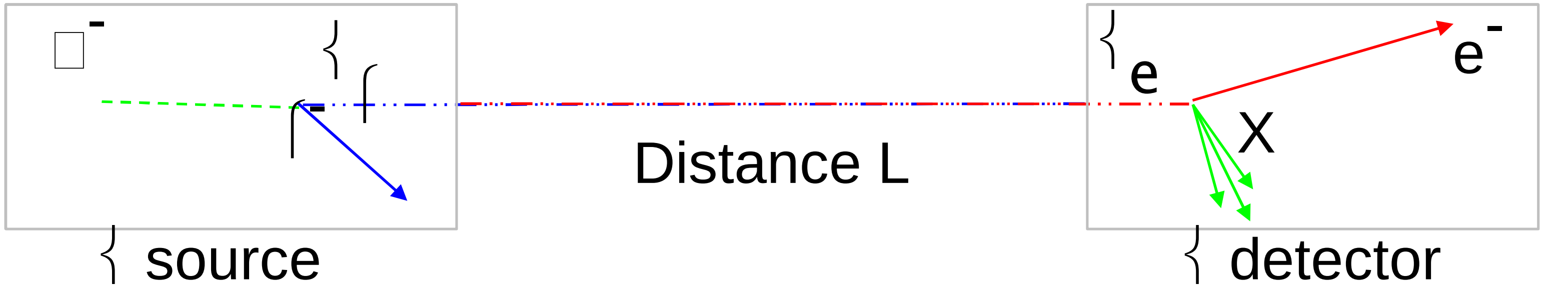
θ Is the mixing angle

E is the energy of the neutrino beam

Wave Analogy



Neutrino Oscillations



Example of quantum mechanics at work!

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 ($\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\tau$)

This phenomena cannot be explained within the Standard Model of particle physics

$\rightarrow$ Neutrino oscillations is the first indication of "new physics" outside the Standard Model.

Neutrino Mixing Matrix

In reality: 3 or more neutrinos! -> Neutrino mixing more compicated.

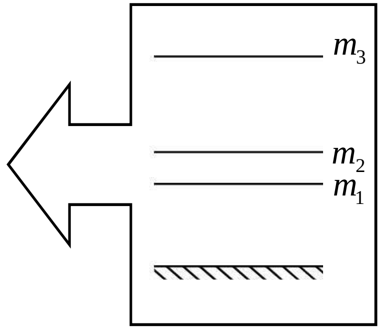
The case of only 3 neutrinos results is described by PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix :

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Standard Model states

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

Neutrino mass states



Can be parameterized as:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric angle | Reactor angle and CP phase | Solar angle | Majorana phases

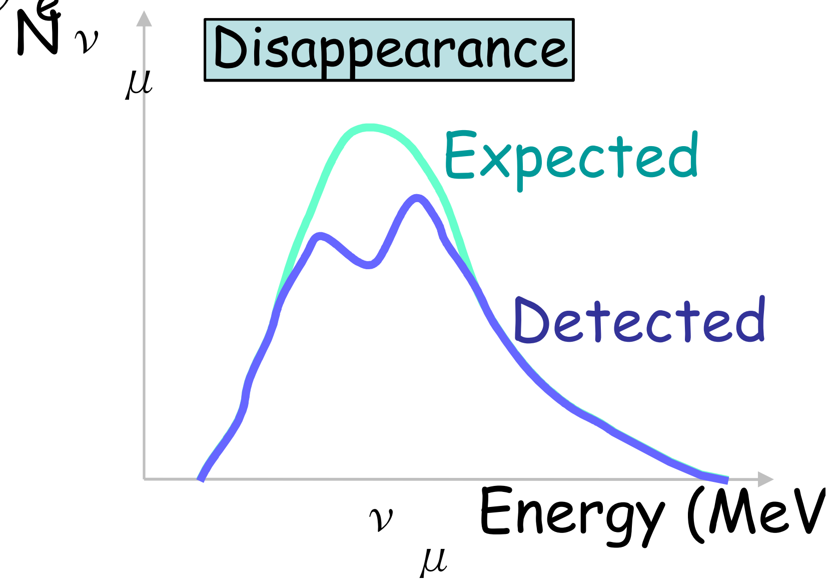
Detecting Oscillation

Consider searching for $\nu_\mu \rightarrow \nu_e$

Disappearance:

Detect fewer ν_μ events than expected.

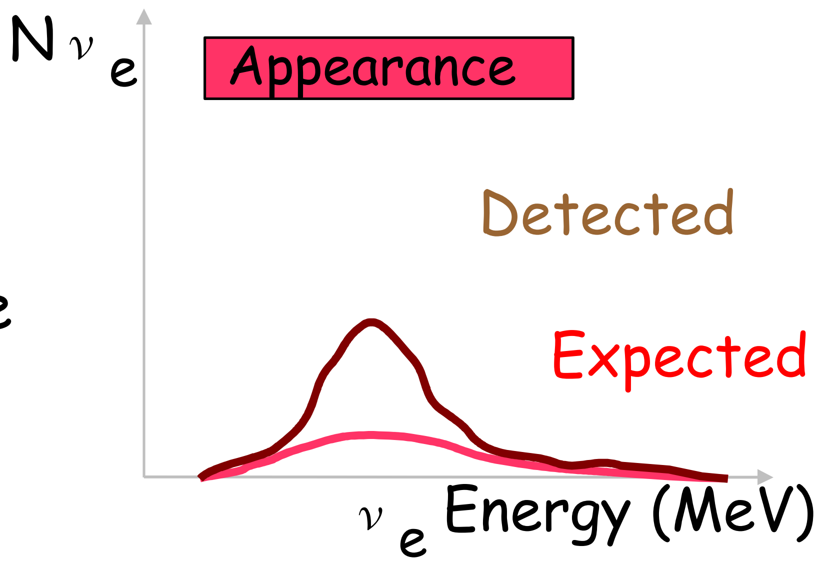
Should have a characteristic energy signature – oscillation probability depends on E!



Appearance:

Detect more ν_e events than expected.

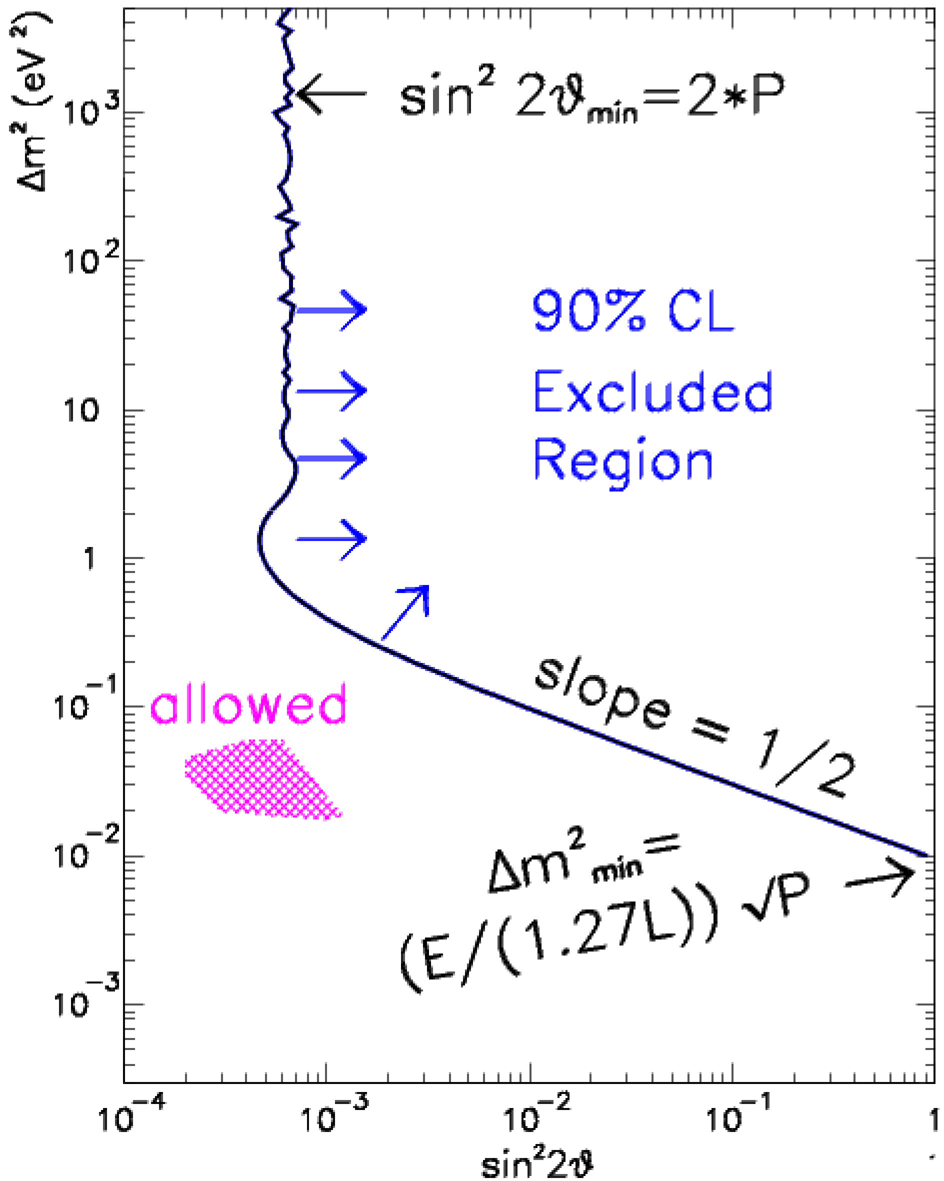
Oscillation depends on E: the events that disappeared in the blue plot are related to those appearing in the red plot.



Goal: Determine Δm^2, $\sin^2 2\Theta$

Oscillation Plots: Result of Experiment

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



- If you see an oscillation signal with

  $P_{osc} = P \pm \Delta P$

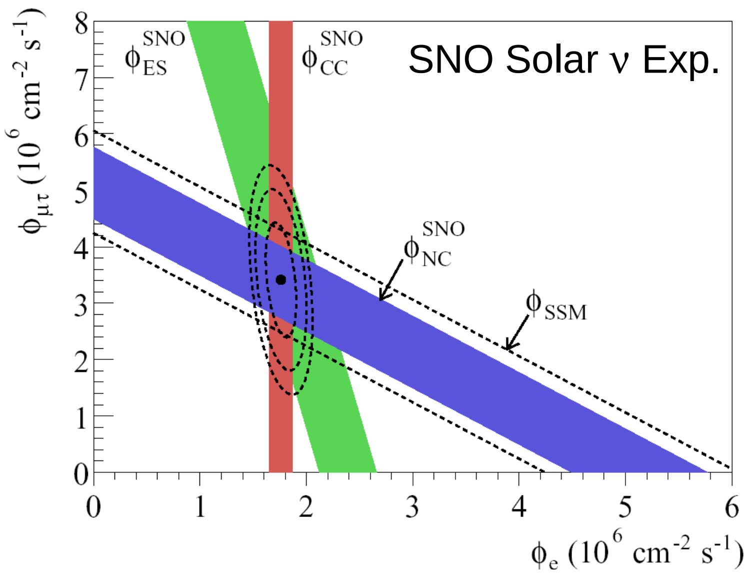
  then carve out an **allowed region** in $(\Delta m^2, \sin^2 2\theta)$ plane.
- If you see no signal and limit oscillation with

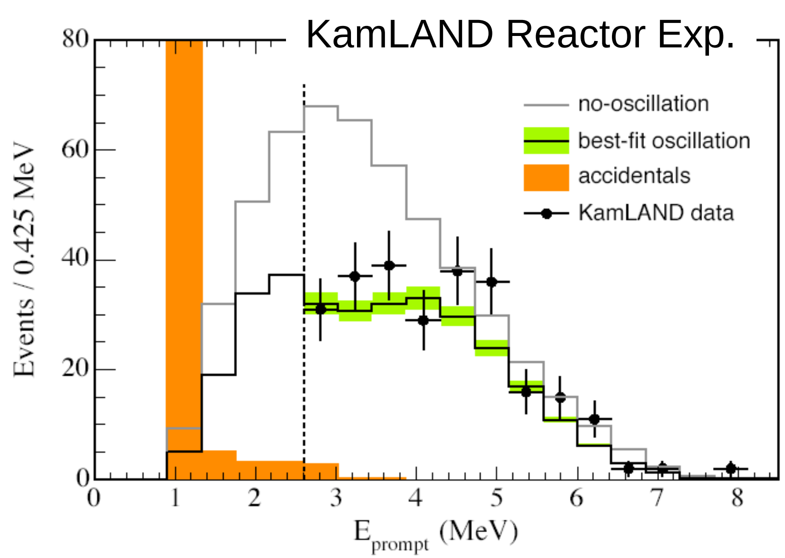
  $P_{osc} < P$ @90%CL

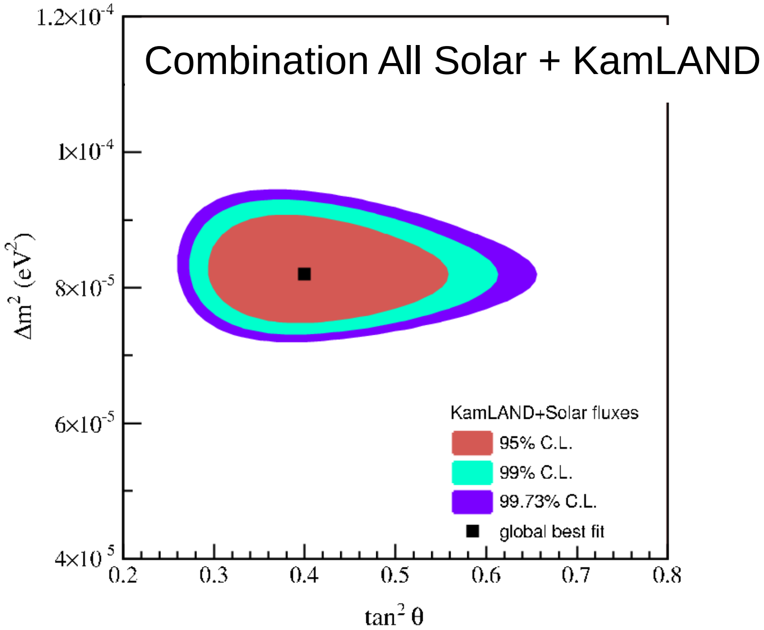
  then carve out an **excluded region** in the $(\Delta m^2, \sin^2 2\theta)$ plane.

Solar ν Results

- Solar Neutrino Oscillations Confirmed and Constrained
  - Many different exp's see deficit
  - SNO experiments sees that total neutrino flux correct from sun but just changing flavor
  - Kamland experiment using reactor neutrinos confirms solar oscillations
  - Combination of experiments
    ⇒ Large Mixing Angle MSW Solution



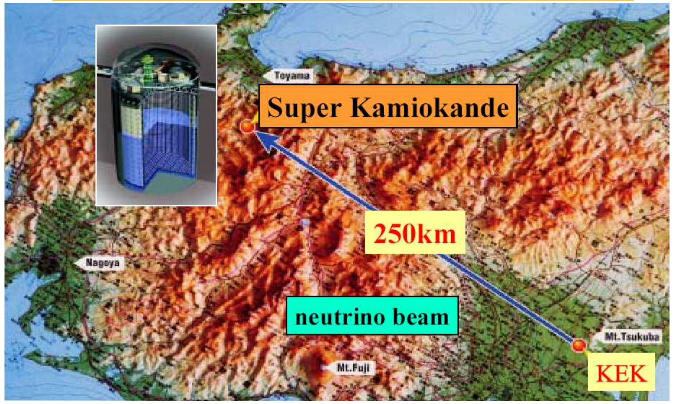




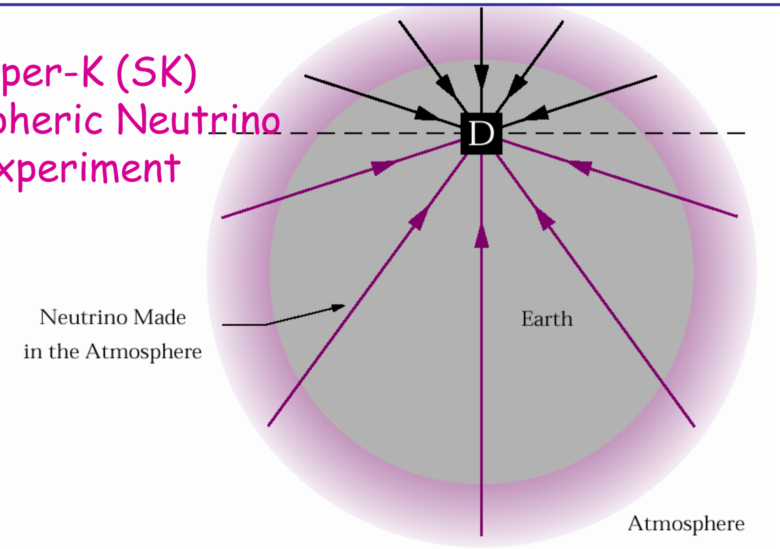
Atmospheric ν Results

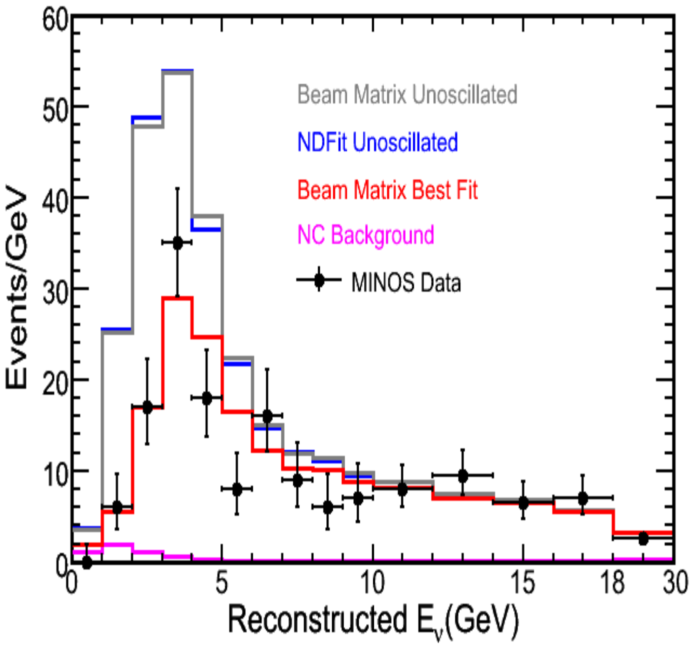
- Atmospheric neutrino oscillations definitively confirmed
  - "Smoking Gun" ⇒ Super-K flux change with zenith angle
  - Accelerator neutrino confirmation with KEK to Super-K exp. (K2K)
  - Confirmed by MINOS exp.
  - Value of Δm^2: 2.4×10^{-3} eV^2
  - Mixing angle~45° (Maximal!)

K2K Accelerator Neutrino Exp.



Super-K (SK) Atmospheric Neutrino Experiment





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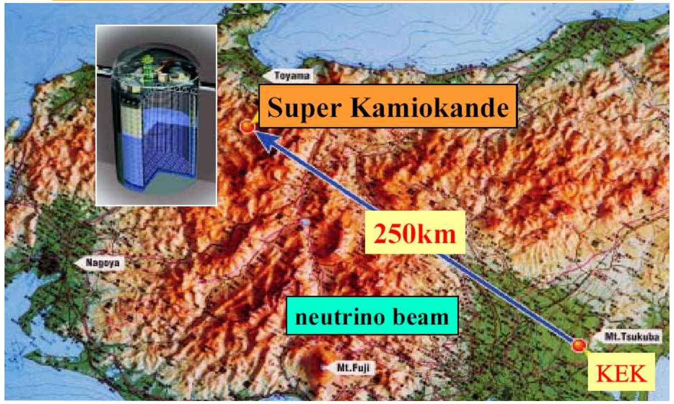

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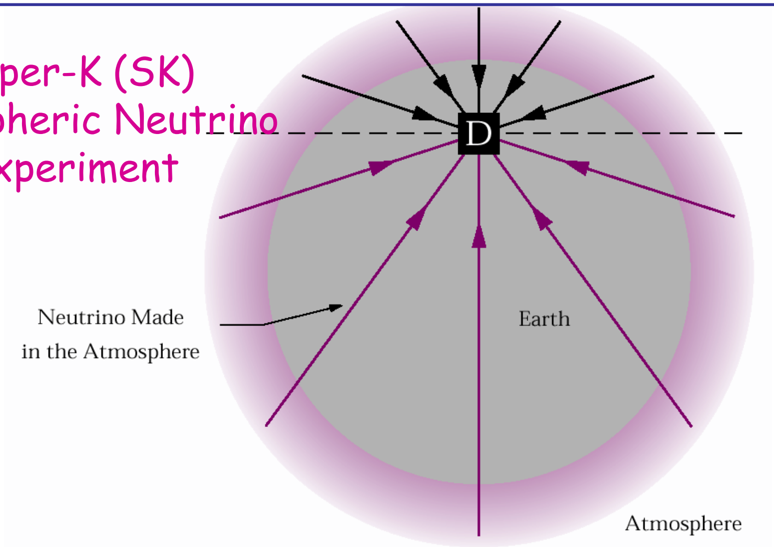
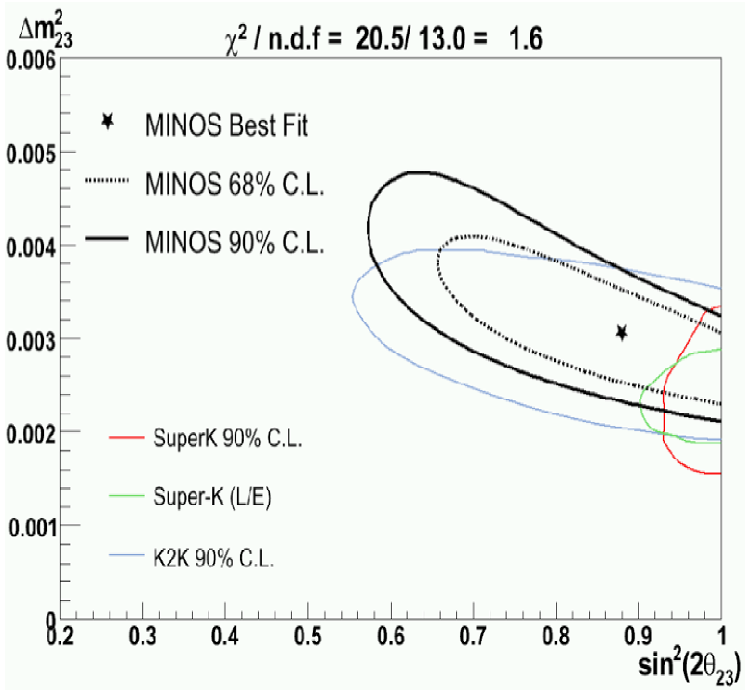
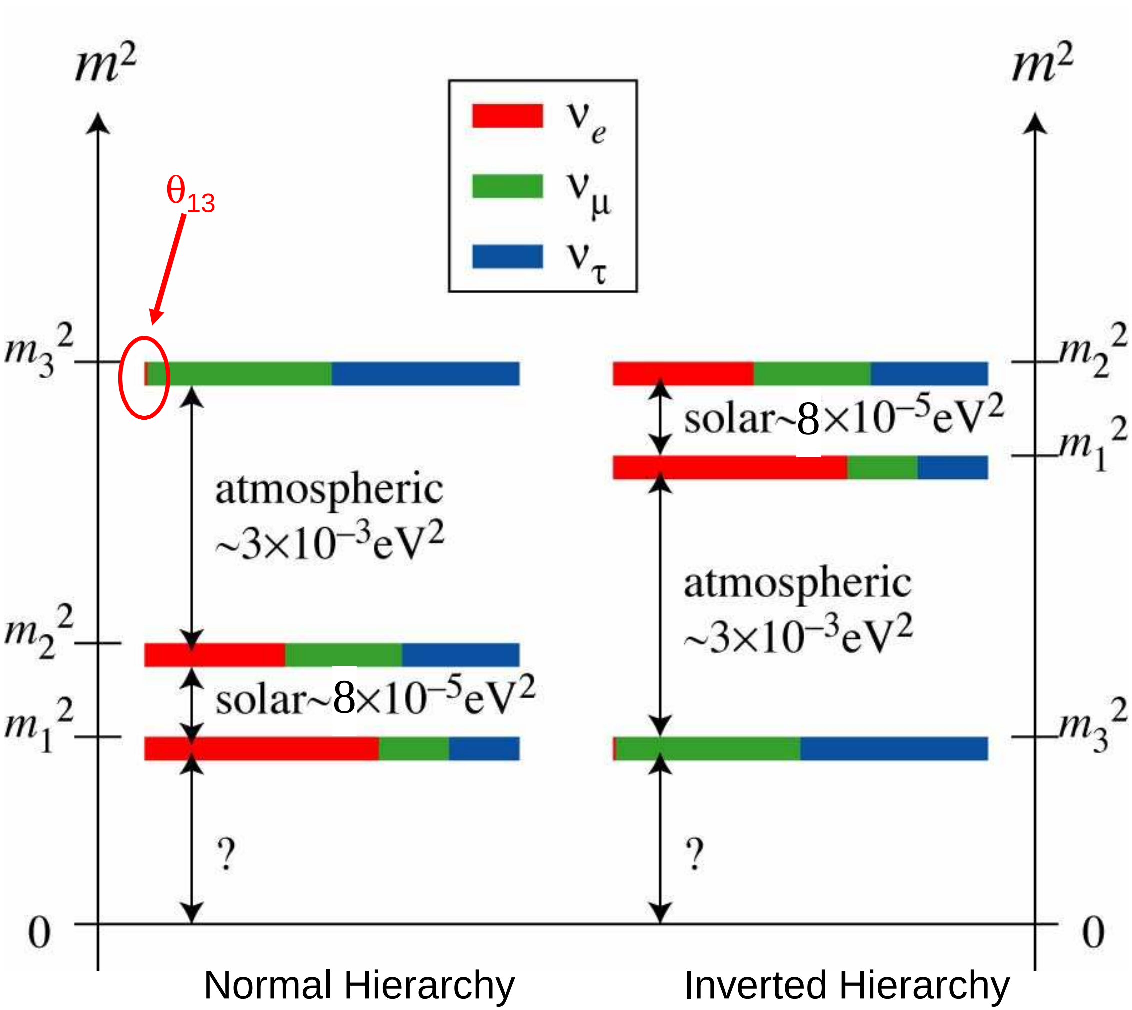




Neutrino Oscillations Results



Mixing angle Θ_{13} is not known ($\theta_{13} < 13^\circ$ @90% CL).

First experiment to address Θ_{13} : Double Chooz(France 09).

The Standard Model ...

… fails with respect to neutrinos!

We now know:

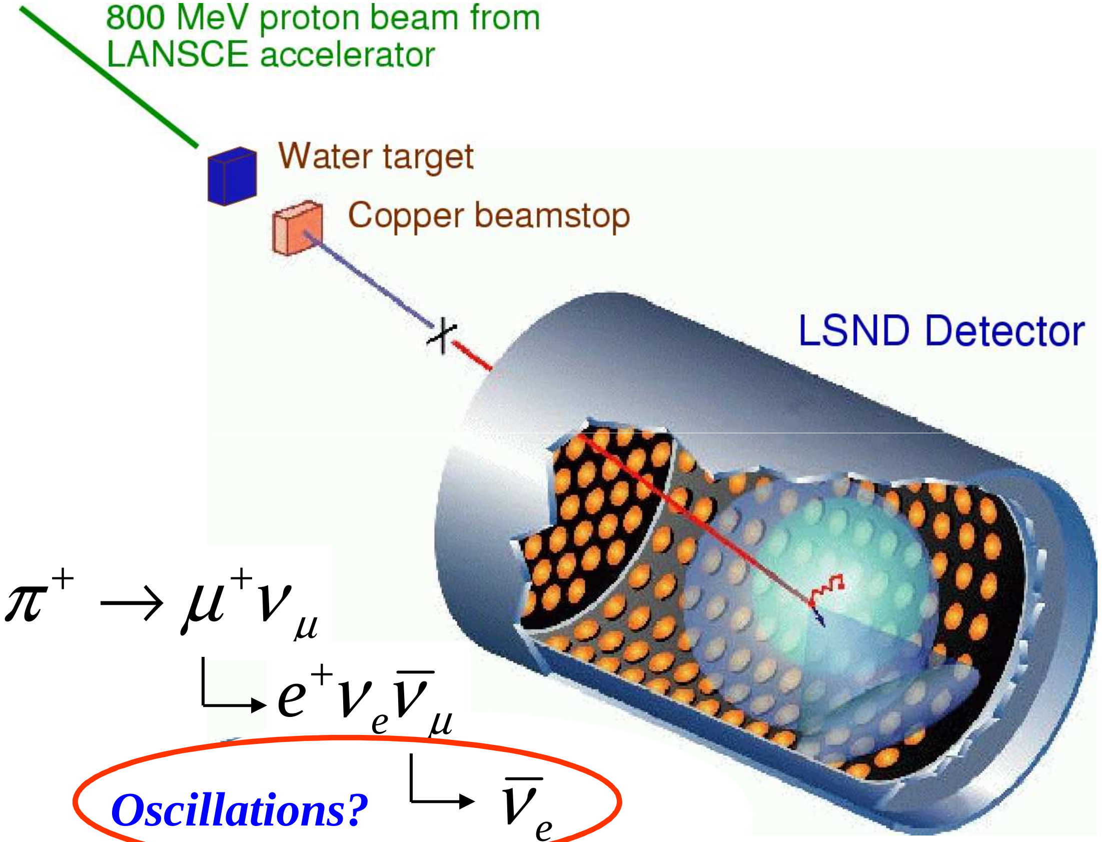
1. **Neutrinos have tiny masses**

2. **The neutrino types mix**

We did see that there were multiple experiments confirming each other.

However, one experiment produced an evidence for oscillations that stayed unconfirmed...

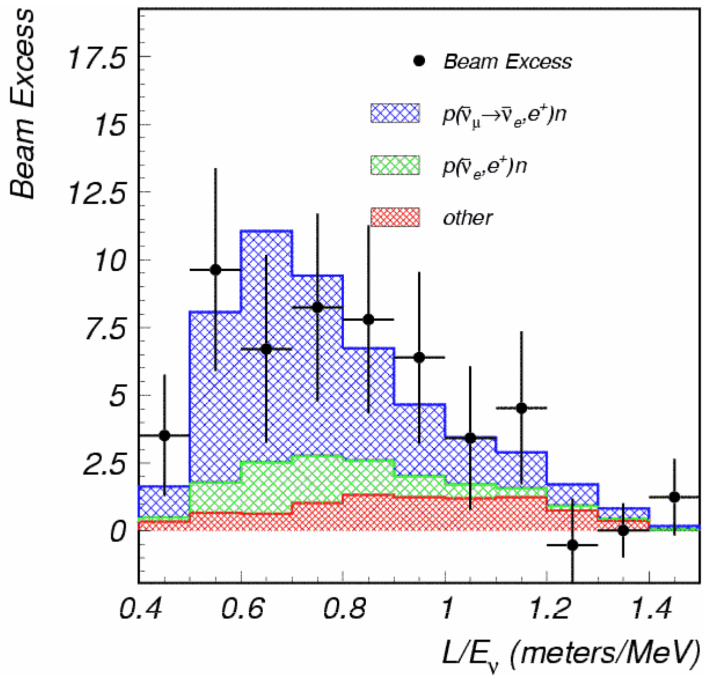
The LSND Experiment



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
Oscillations? $\hookrightarrow \bar{\nu}_e$

Signal: $\bar{\nu}_e$ p $\rightarrow$ e^+ n

n p $\rightarrow$ d γ(2.2MeV)



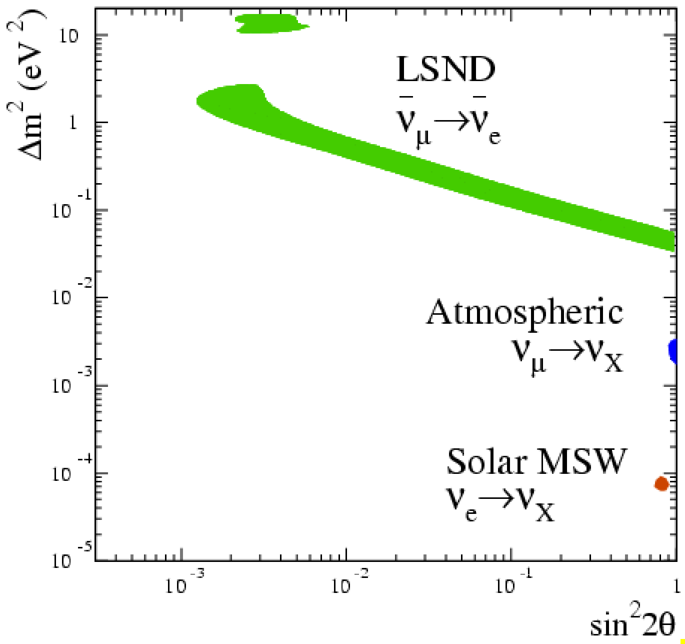
LSND took data from 1993-98
- 49,000 Coulombs of protons
- L = 30m and 20 < E_ν < 53 MeV

Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

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

3.8 σ significance for excess.

Oscillation Status After LSND



This signal looks very different from the others...

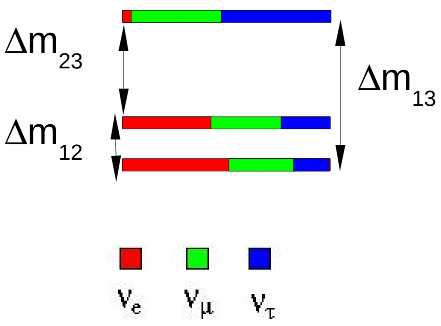
- Much higher $\Delta m^2 = 0.1 - 10$ eV^2
- Much smaller mixing angle
- Only one experiment!

Kamioka, IMB, Super K, Soudan II, Macro, K2K
$\Delta m^2 = 2.4 \times 10^{-3}$ eV^2

Homestake, Sage, Gallex, Super-K SNO, KamLAND
$\Delta m^2 = 8.2 \times 10^{-5}$ eV^2

- Three distinct neutrino oscillation signals, with $\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- For three neutrinos, expect $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

In SM there are only 3 neutrinos

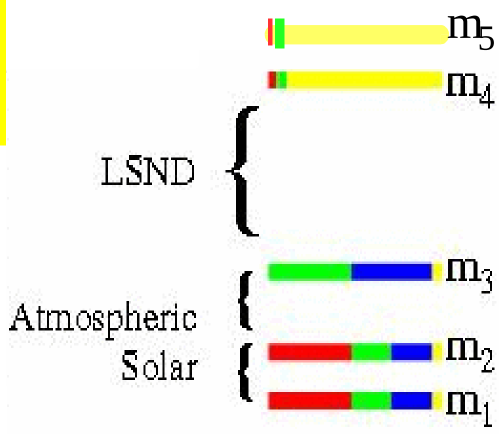


LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 ν's

⇒ Models developed with 2 sterile ν's or

⇒ Other new physics models

3+2 models



How can one get 3 distinct Δm^2 ?

- One of the experimental measurements is wrong
- One of the experimental measurements is not neutrino oscillations
  - Neutrino decay
  - Neutrino production from flavor violating decays
- Additional "sterile" neutrinos involved in oscillations
- CPT violation (or CP viol. and sterile ν's) allows different mixing for ν's and $\bar{\nu}$'s

MiniBooNE

(Booster Neutrino Experiment)

Search for ν_e appearance in ν_μ beam

FNAL 8 GeV Beamline

50 m decay pipe

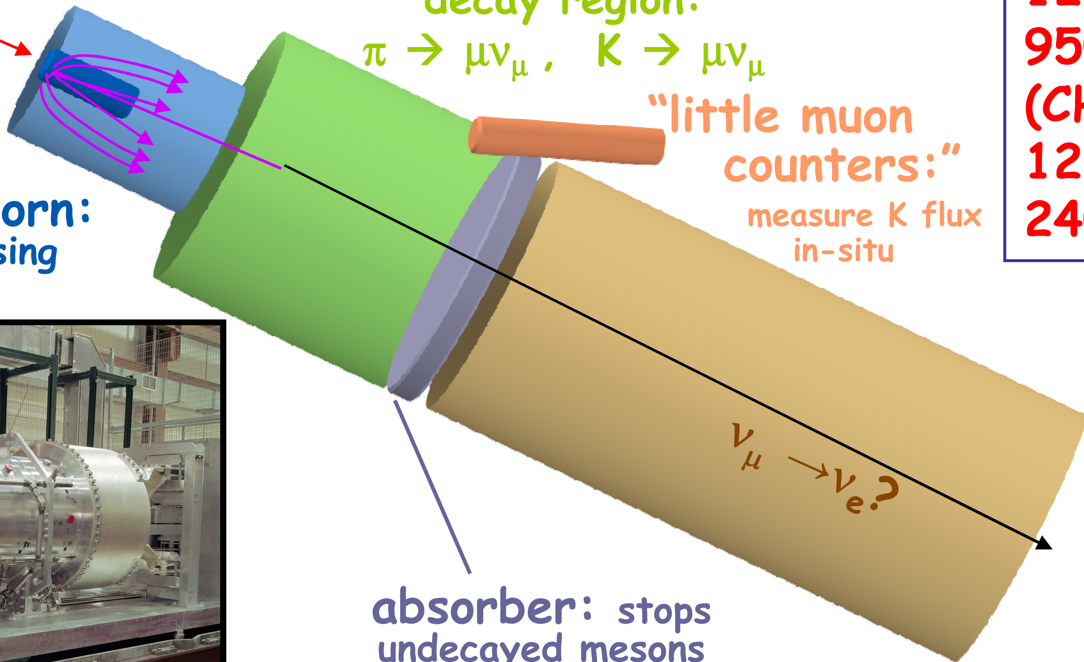
Use protons from the 8 GeV booster
$\Rightarrow$ Neutrino Beam
$\langle E_\nu \rangle \sim 0.7$ GeV

MiniBooNE Detector:
12m diameter sphere
950000 liters of oil (CH_2)
1280 inner PMTs
240 veto PMTs

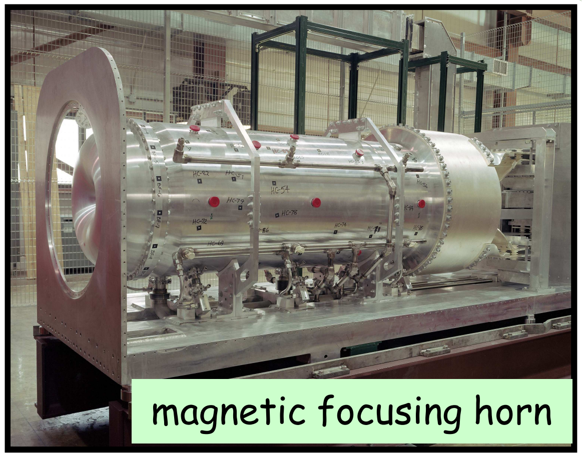
decay region:
$\pi \rightarrow \mu\nu_\mu$, $K \rightarrow \mu\nu_\mu$

"little muon counters:"
measure K flux in-situ

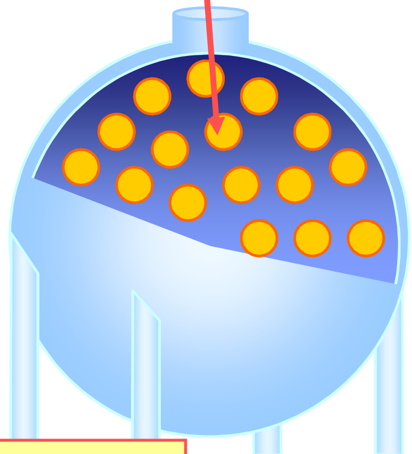
magnetic horn: meson focusing



absorber: stops undecayed mesons



magnetic focusing horn



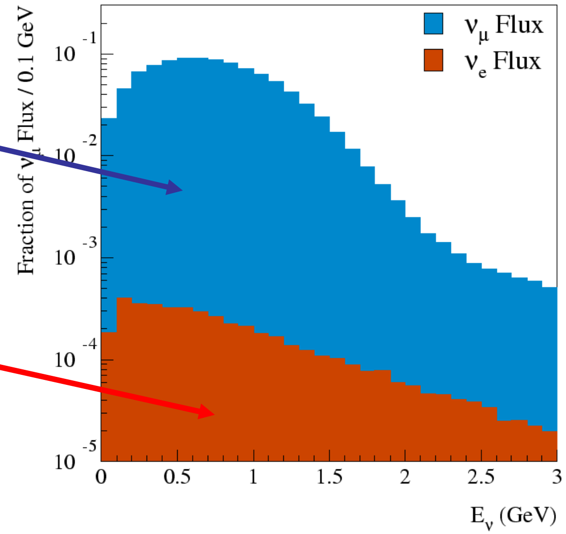
Same L/E~0.8m/MeV as LSND !

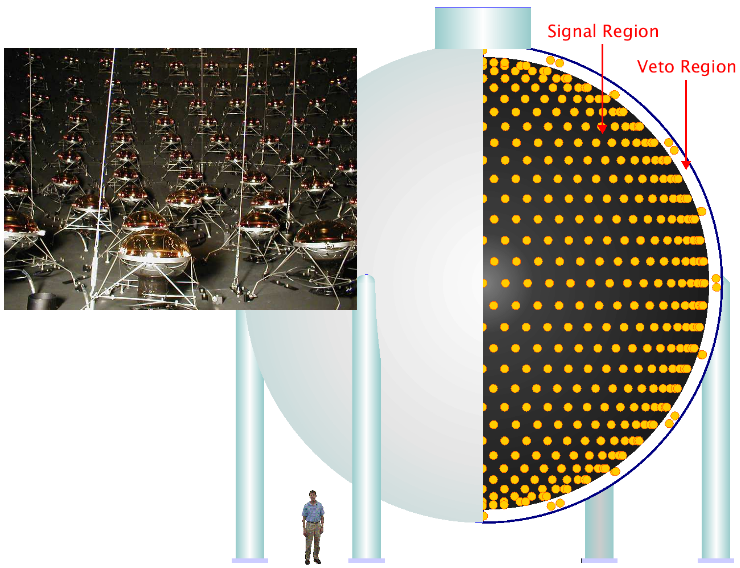
$\nu_\mu \rightarrow \nu_e$???

$\nu_\mu \rightarrow \nu_e$ Oscillation Search

- Main ν_μ flux from $\pi^+ \rightarrow \mu^+ \ \nu_\mu$
- Intrinsic ν_e flux from
  - $\mu^+ \rightarrow \nu_\mu \ e^+ \ \nu_e$
  - $K^+ \rightarrow \pi^0 \ e^+ \ \nu_e$
  - $K^0_L \rightarrow \pi^- \ e^+ \ \nu_e$

$\Rightarrow \nu_e / \nu_\mu \approx$ **0.5%**





MiniBooNE Detector:
- 12m diameter sphere
- 950000 liters of oil(CH_2)
- 1280 inner PMTs
- 240 veto PMTs

Detector Requirements:
- Detect and Measure Events: Vertex, E_ν …
- Separate ν_μ events from ν_e events.

$\nu_\mu \rightarrow \nu_e$ Oscillation Signal…

… is an excess of ν_e events above expectation.

Understanding the expected events is therefore the key!

Need to know the neutrino fluxes:

- Electron neutrinos from μ, K^+, and K^0 decay.
- Muon neutrinos can make background or oscillate to give a signal.

Need to know the $\nu_{\mu/e}$ neutrino cross section vs. energy:

- Events = flux $\times$ cross section.

Need to know the ν_e reconstruction efficiency vs energy:

- Observed events = efficiency $\times$ events.

Need to know the probability for ν_μ events to be mis-identified as ν_e events. Events with single EM showers look like ν_e events in MiniBooNE:

- Neutral current (NC) π^0 events are the main mis-id background.
- NC Δ production followed by radiative decay, $\Delta \rightarrow N\gamma$.
- Photons entering from outside detector ("Dirt" background).

MiniBooNE's Principle is to understand and calibrate the expected events from the observed non-signal events.

Analysis Structure

Start with a Geant4 flux prediction for the ν spectrum from π and K produced at the target.

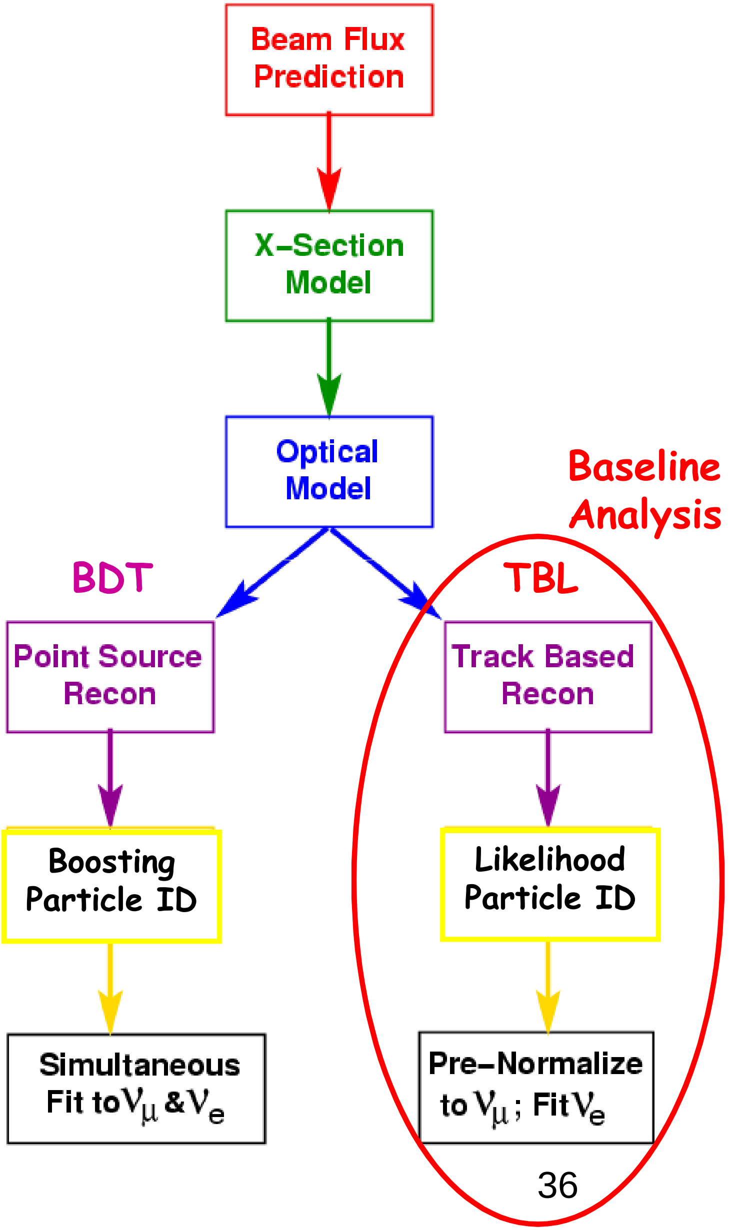
Predict ν interactions using the Nuance cross section parameterization.

Pass final state particles to Geant3 to model particle and light propagation in the tank.

Starting with event reconstruction, independent analyses:
- Boosted Decision Tree (BDT) .
- Track Based Likelihood (TBL).

Develop particle ID/cuts to separate signal from background.

Fit reconstructed E_ν spectrum for oscillations.



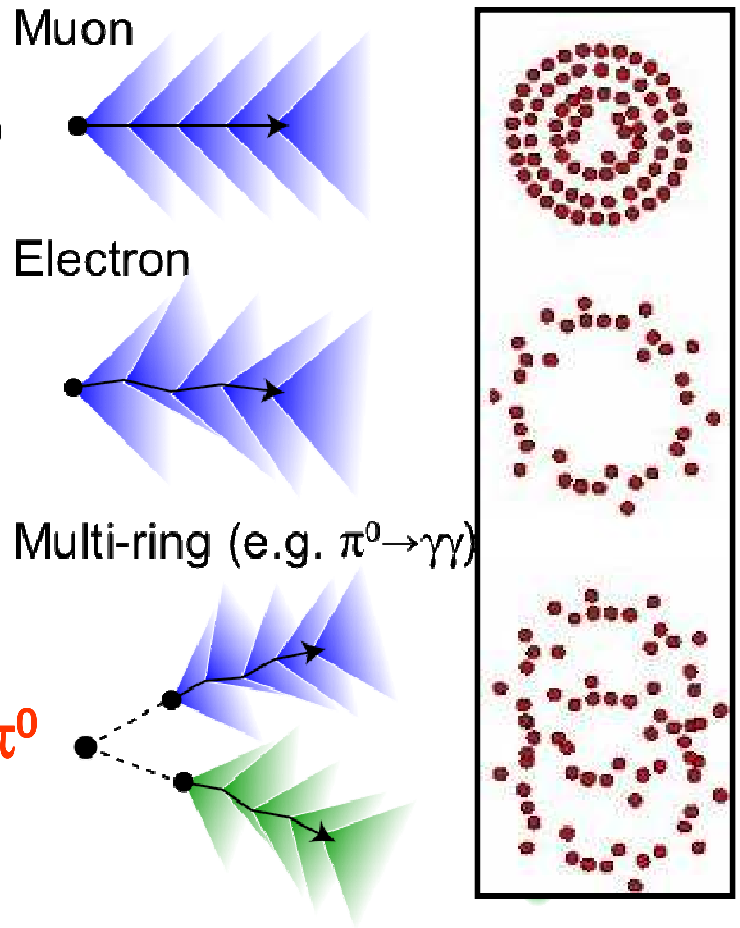
Particle Identification

Čerenkov rings provide primary means of identifying products of ν interactions in the detector

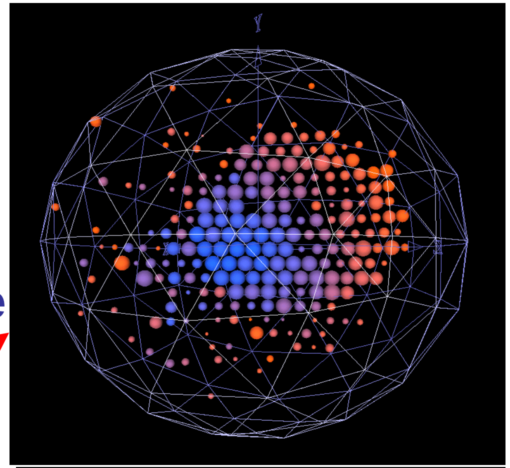
$\nu_\mu\, n \rightarrow \mu^-\, p$

$\nu_e\, n \rightarrow e^-\, p$

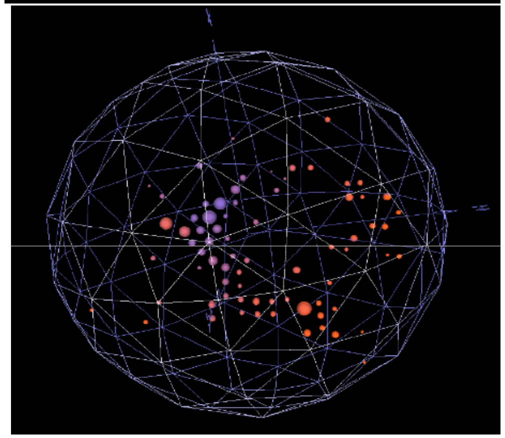
$\nu_\mu\, p/n \rightarrow \nu_\mu\, p/n\, \pi^0$



beam μ candidate

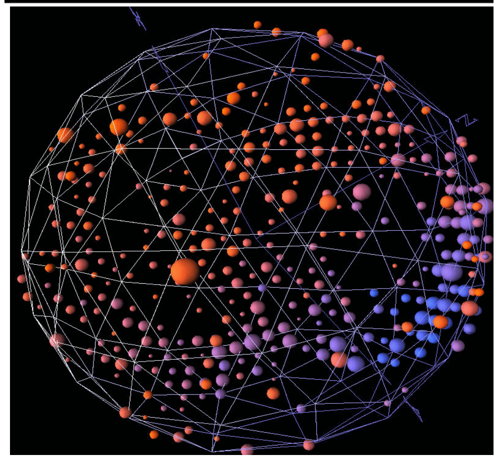


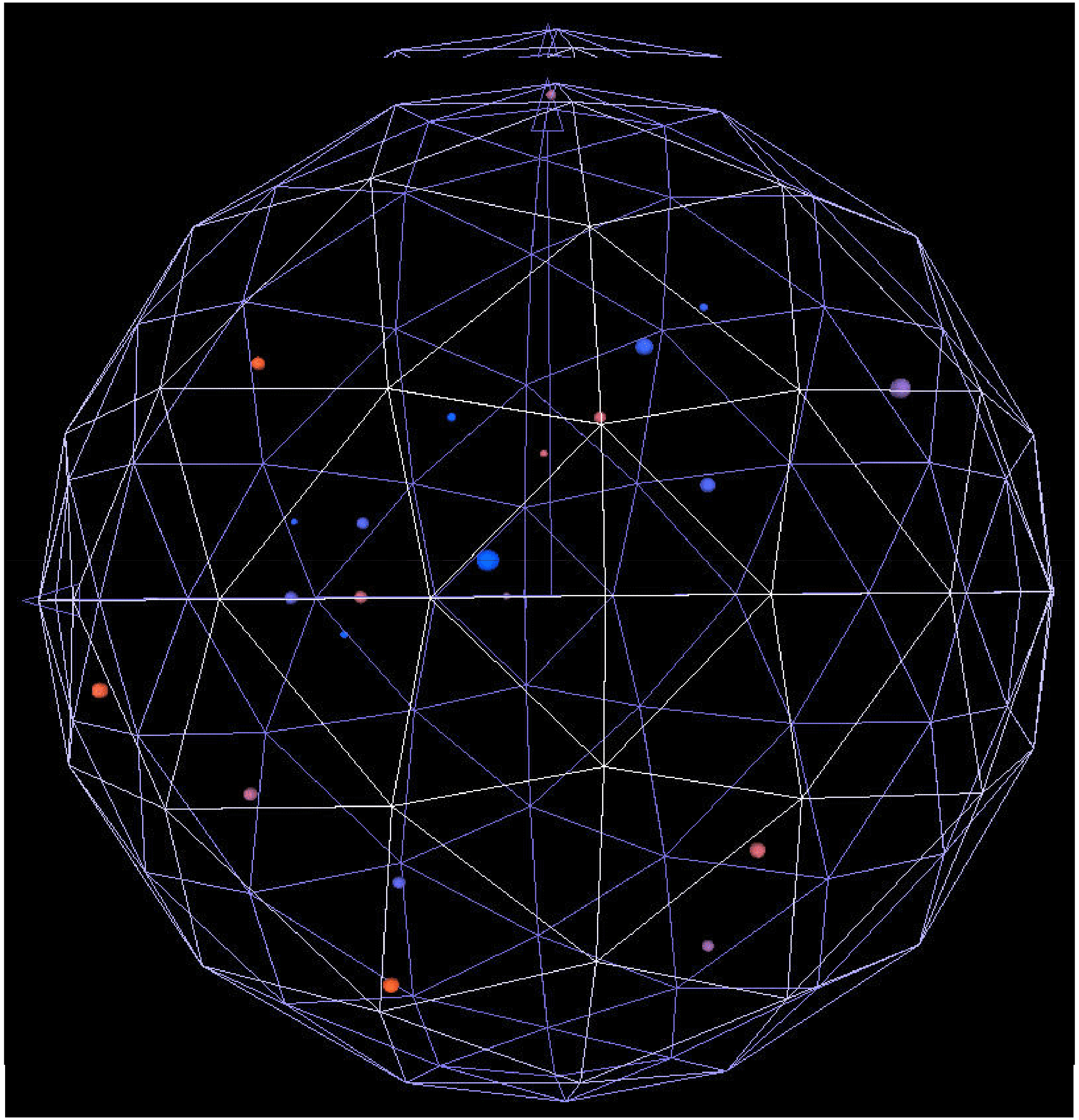
Michel e⁻ candidate



beam π^0 candidate

$\pi^0 \rightarrow \gamma\gamma$





Muon Identification Signature:

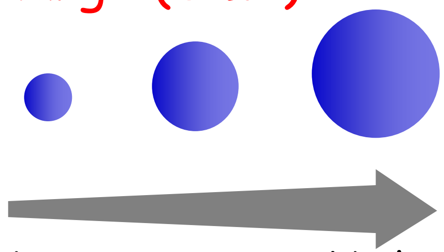
$\mu \rightarrow e\, \nu_\mu\, \nu_e$

after ~2μsec

[Animation]

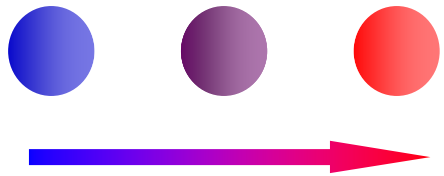
Each frame is 25 ns with 10 ns steps.

Charge (Size)



Low High

Time (Color)



Early Late

Analysis Method

Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles.

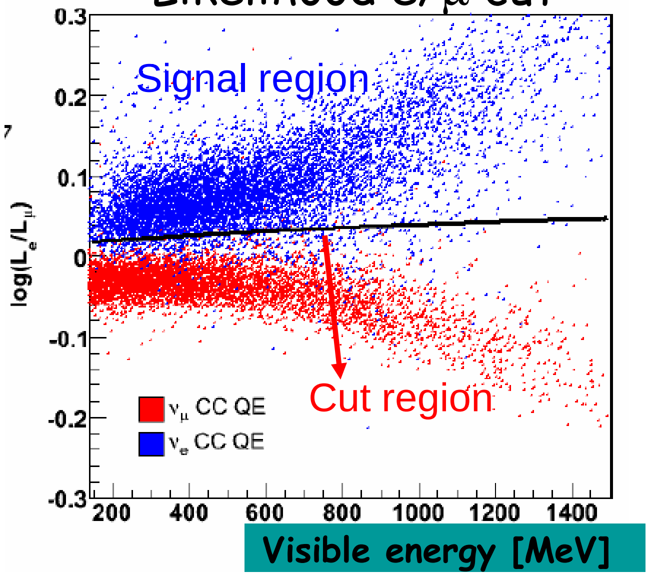
Apply likelihood fits to three hypotheses:
- single electron track
- single muon track
- two electron-like rings (π^0 event hypothesis)

Compare observed light distribution to fit prediction:

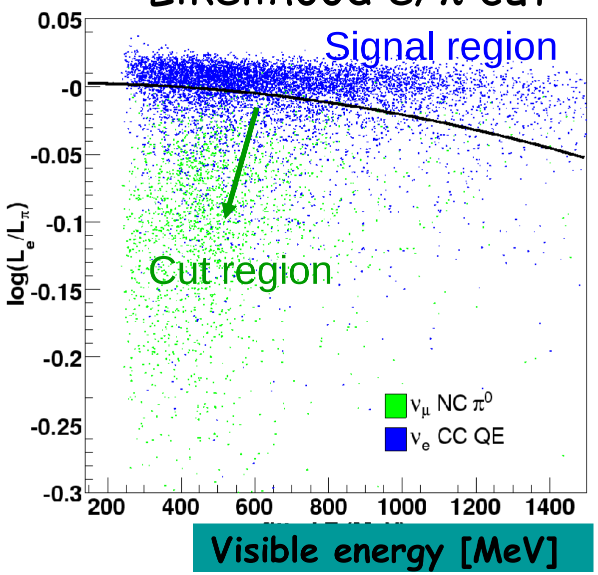
Does the track actually look like an electron?

Form likelihood differences using minimized −logL quantities: $\log(L_e/L_\mu)$ and $\log(L_e/L_\pi)$

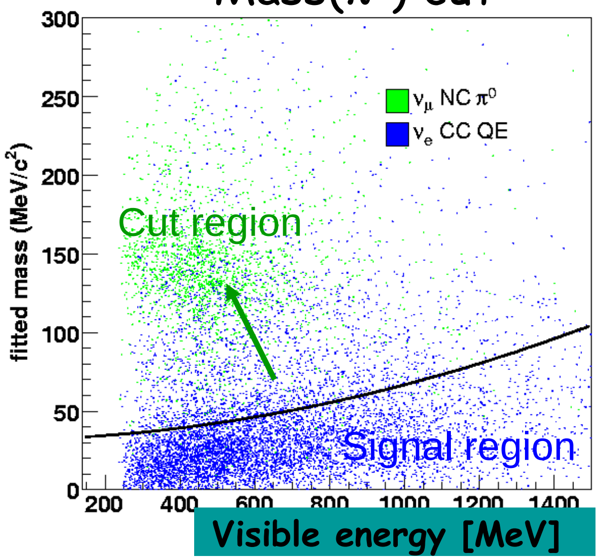
Likelihood e/μ cut



Likelihood e/π cut



Mass(π^0) cut



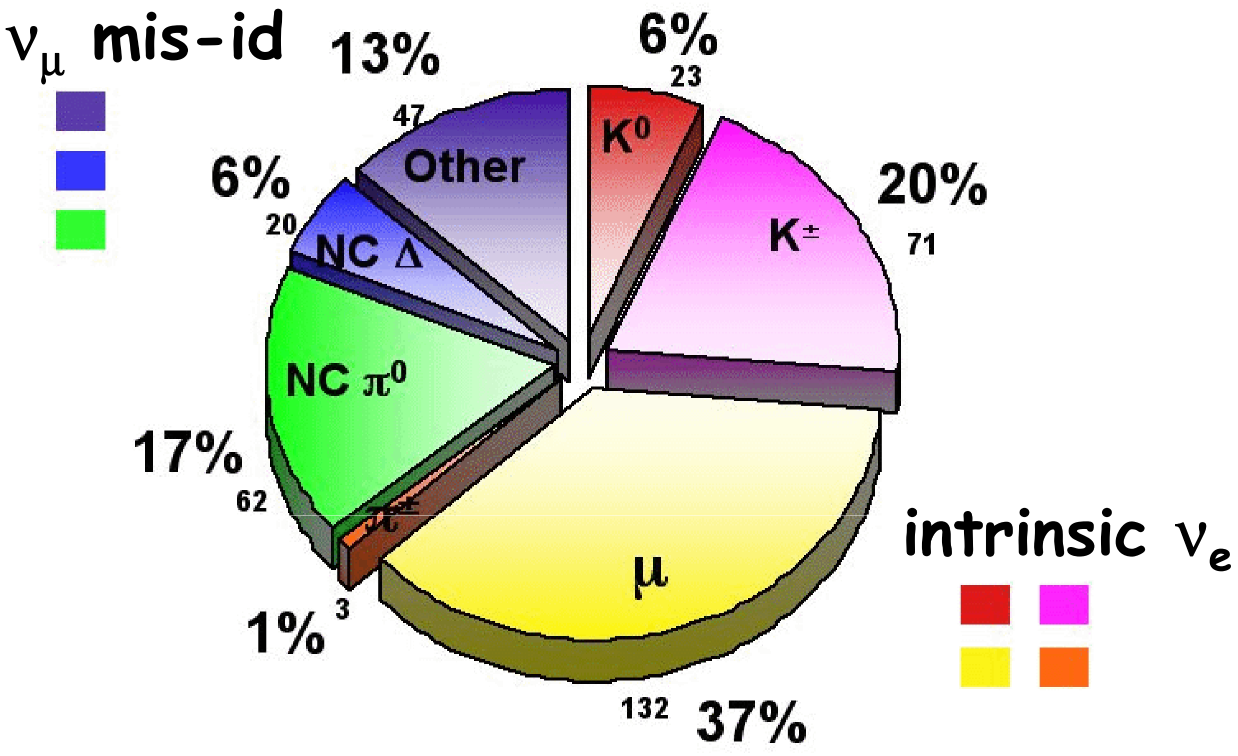
Blue points are signal ν_e events.

Red points are background ν_μ CCQE events.

Green points are background ν_μ NC π^0 events.

Expected Background Events

Two main categories of backgrounds: ν_μ mis-ids and intrinsic ν_e



→ Events with ν_e Selection requirements

$475 < E_\nu < 1250$ MeV

TBL analysis predicted backgrounds:

Total Expected Background = 358 events.

Example LSND Osc Signal = 163 events
($\Delta m^2 = 0.4\ eV^2$, $\sin^2 2\theta = 0.017$).

The Box Opening: What we found

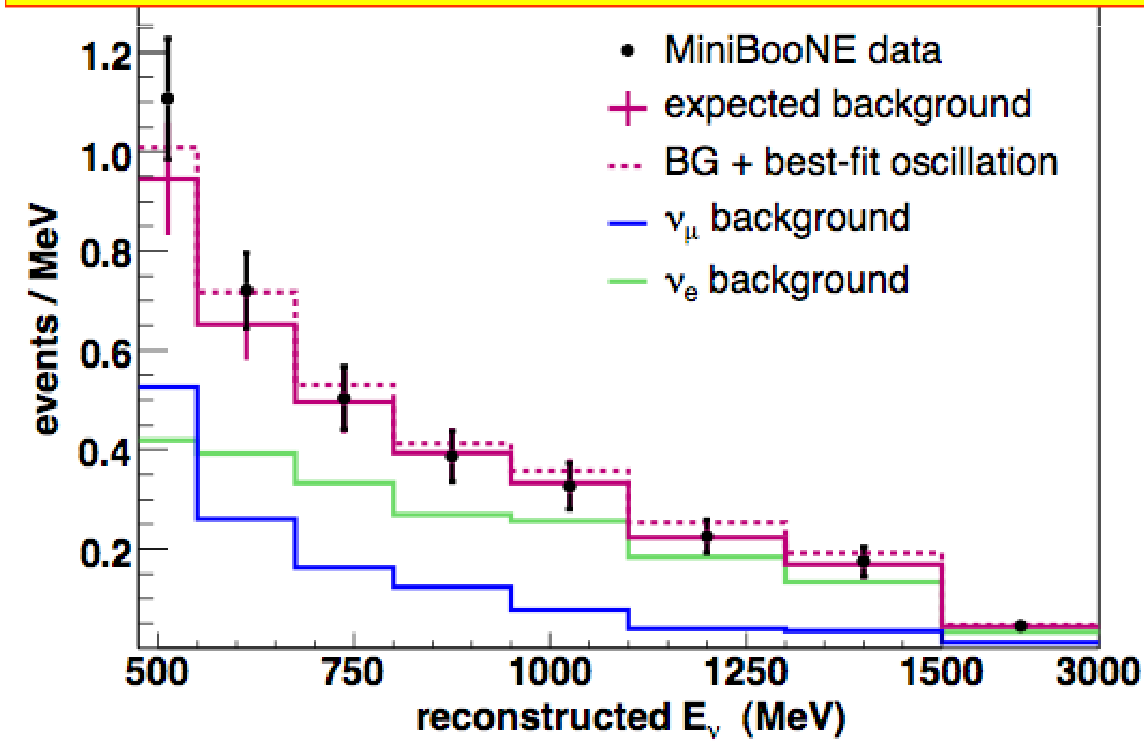
Open the box and look into E_ν^{QE} :Return the fit parameters.

Is there an oscillation signal?

The Track-based $\nu_\mu \rightarrow \nu_e$ **appearance-only** result:

Counting Experiment: $475 < E_\nu^{QE} < 1250$ MeV
Data: 380 events
Expectation: 358 ±19 (stat) ± 35 (sys) events

Significance: 0.55 σ

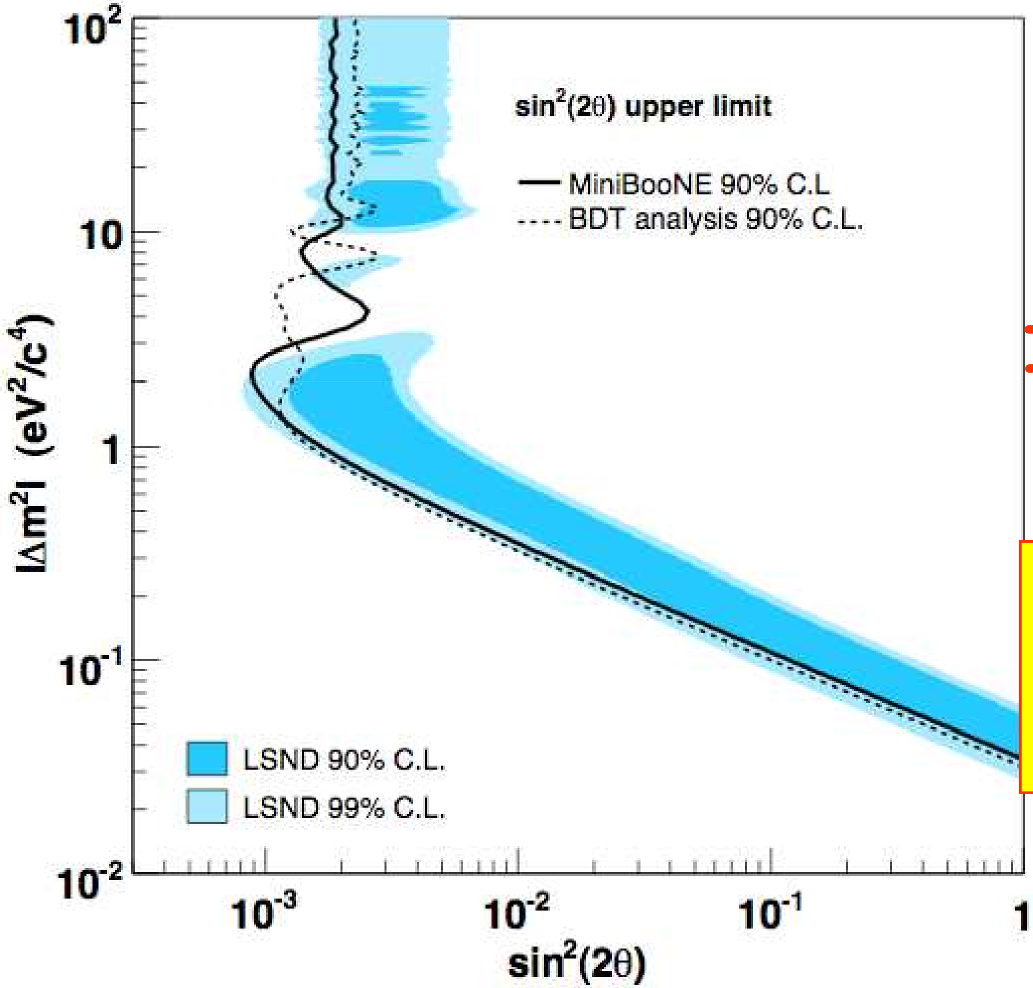


Best Fit (dashed):
$(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ eV^2)$

Probability of Null Fit: 93%
Probability of Best Fit: 99%

Analysis Results

Main Conclusion: The observed reconstructed energy distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ 2-neutrino model.



Energy-fit analysis:
Solid: Analysis I
Dashed: Analysis II

Independent analyses are in good agreement.

The result of the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis is a limit on oscillations.

Energy fit: $475 < E_\nu^{QE} < 3000$ MeV

Details:

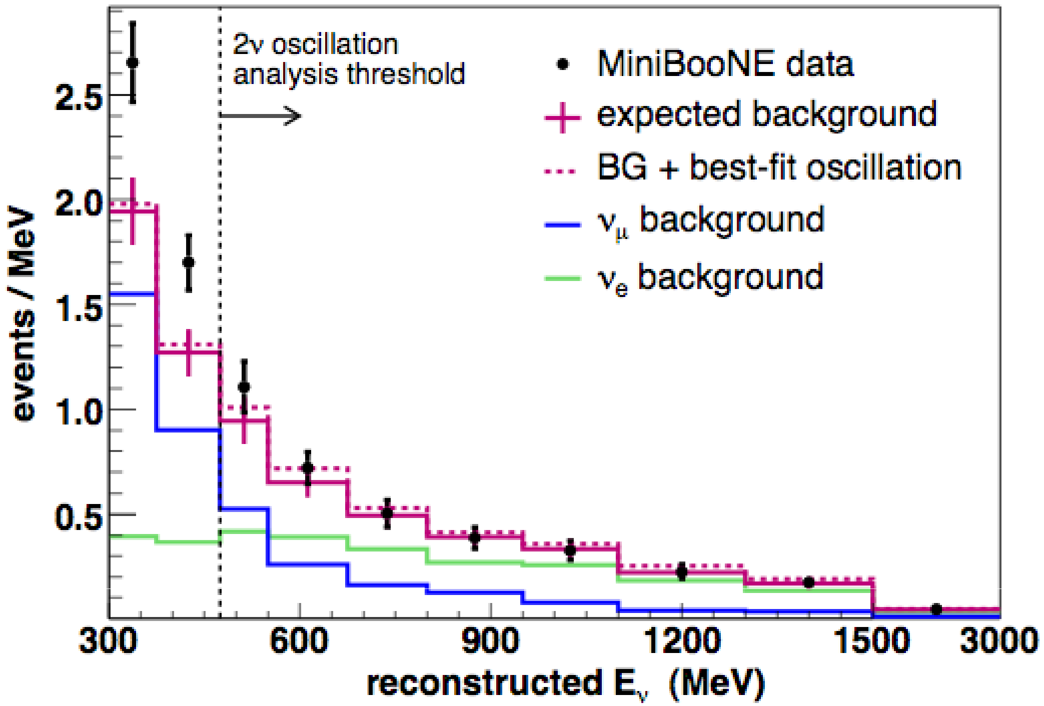
Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex]

Full Energy Range: Found Low E excess!

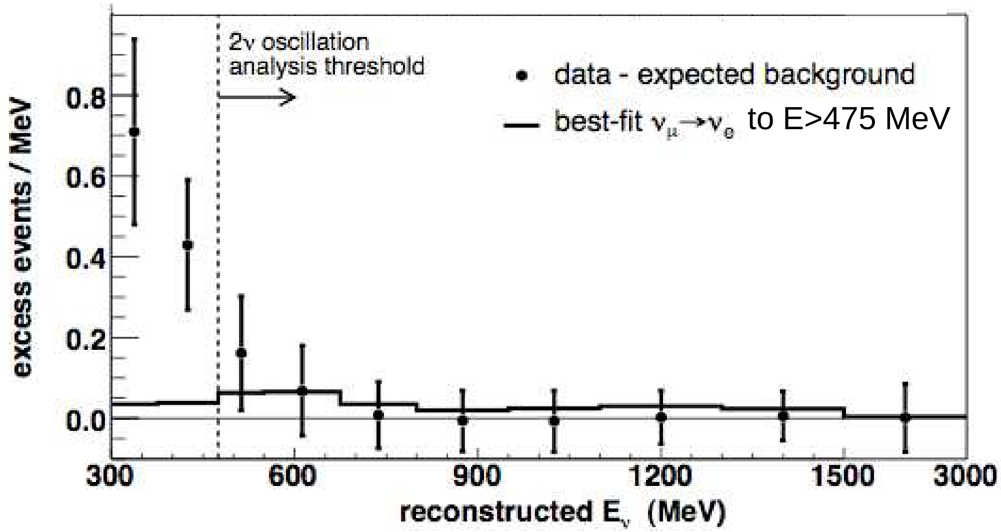
Report the full range:
$300 < E_\nu^{QE} < 3000$ MeV

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

Deviation: 3.7 σ

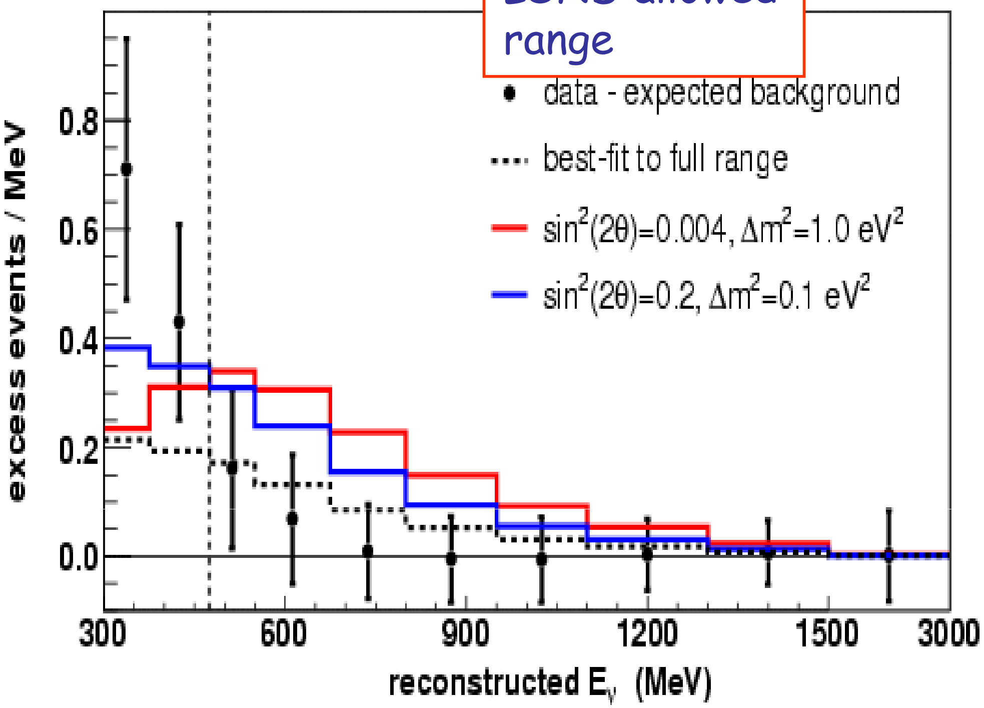


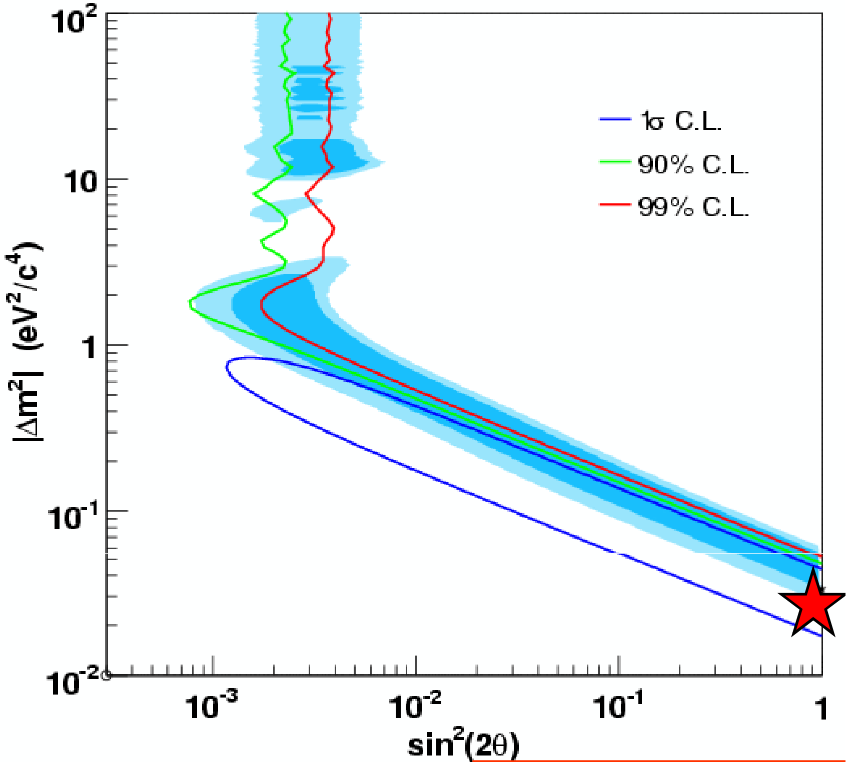
Background-subtracted:



Full Energy Range Fit 300< E_ν^{QE}< 3 GeV

Examples in LSND allowed range





Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03 \text{ eV}^2)$
χ^2 Probability: 18%

The best falls into region excluded by other Experiments (i.e. Bugey)

Therefore …

…the simplest models which would produce similar signals in LSND and MiniBooNE are ruled out.

There is a low energy excess observed: we are analyzing it vigorously.

The simplest explanation: it is some type of Standard Model background.

Alternative: it is a more complicated oscillation signal than originally expected.

Remember that LSND was an anti-neutrino experiment and MiniBooNE measurement was done with neutrinos.
If neutrinos oscillate differently from anti-neutrinos, one might be able to explain difference between the MiNibooNE and LSND signal → "CP Violation".
It is of great interest right now because of …

Leptogenesis

Neutrinos may hold the key to the Matter-Antimatter asymmetry in the Universe:

Hard to generate a baryon asymmetry ($\Delta B \neq 0$) using quark matrix CP violation.

-> Use Heavy Sterile Neutrinos and Neutrino CP Violation.

Generate $\Delta L \neq 0$ in the early universe from CP (or CPT) violation in heavy neutrino N decays (only needs to be at the 10^{-6} level).

If ν oscillation violates CP, then quite likely so does N decay.
In the See-Saw, these two CP violations have a common origin.

$N \rightarrow L^- + \ldots$ and $N \rightarrow L^+ + \ldots$

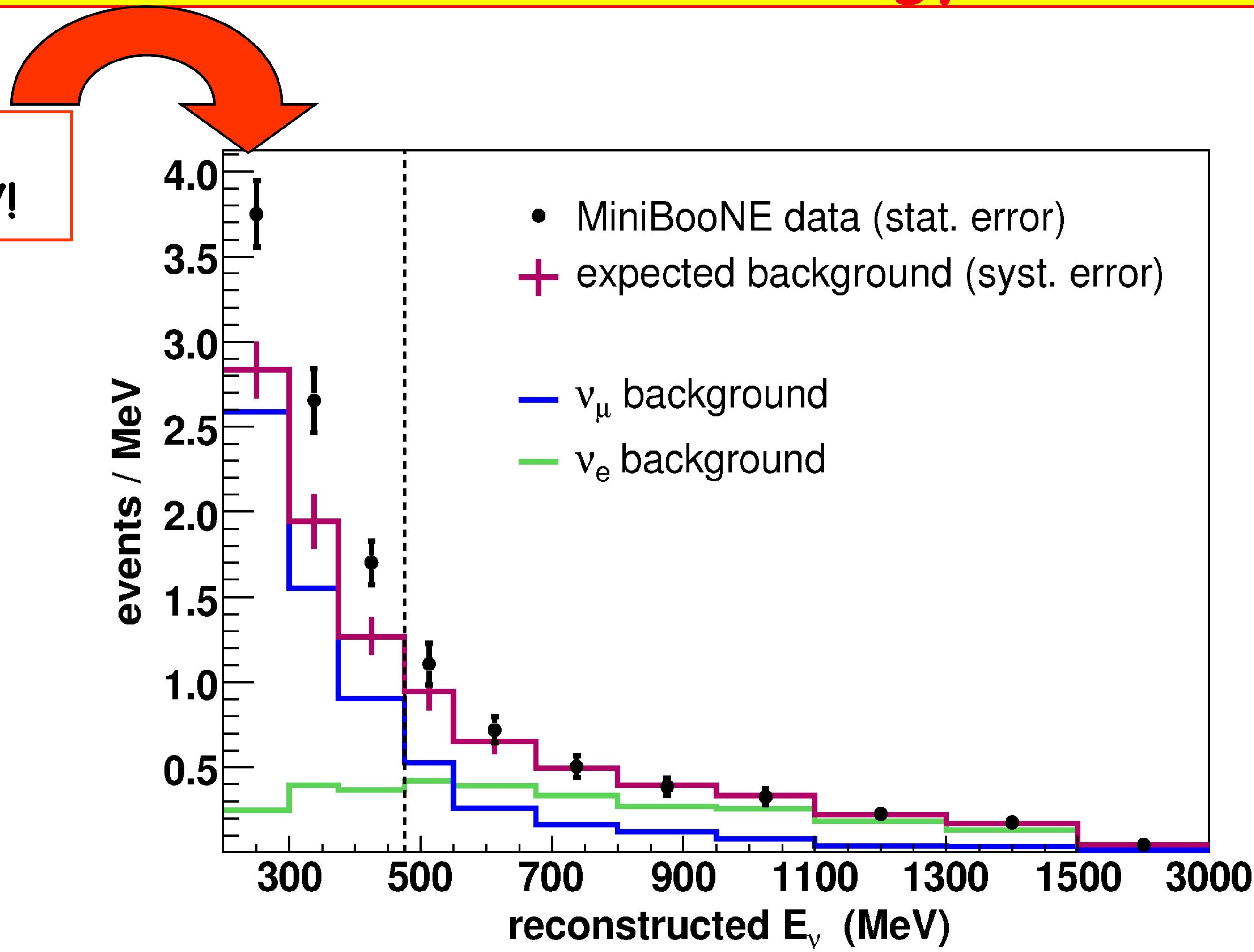
Results: unequal number of leptons and anti-leptons.

B-L processes then convert neutrino excess to baryon excess.
Sign and magnitude ~correct to generate baryon asymmetry in the universe with $m_N > 10^9$ GeV and $m_\nu < 0.2$ eV.

Low Energy Excess

Investigation of observed low-energy excess

Lower the energy:
to E_ν^{QE} = 200 MeV!



Reconstructed E_ν^{QE}: from E_{lepton} ("visible energy") and lepton angle wrt neutrino direction

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$

Summary of estimated backgrounds vs data

E_ν^{QE} [MeV]	200-300	300-475	475-1250
total background	284±25	274±21	358±35
ν_e intrinsic	26	67	229
ν_μ induced	258	207	129
NC π^0	115	76	62
NC $\Delta \rightarrow N\gamma$	20	51	20
Dirt	99	50	17
other	24	30	30
Data	375±19	369±19	380±19
Data-MC	91±31	95±28	22±40

- Low Energy: largest backgrounds a are ν_μ-induced, in particular:
    - NC π^0
    - NC $\Delta \rightarrow N\gamma$
    - Dirt

-High Energy: no significant excess with ν_e bkgd dominant

Thoroughly Re-checked these processes last 6 months.

In addition, new processes being considered:

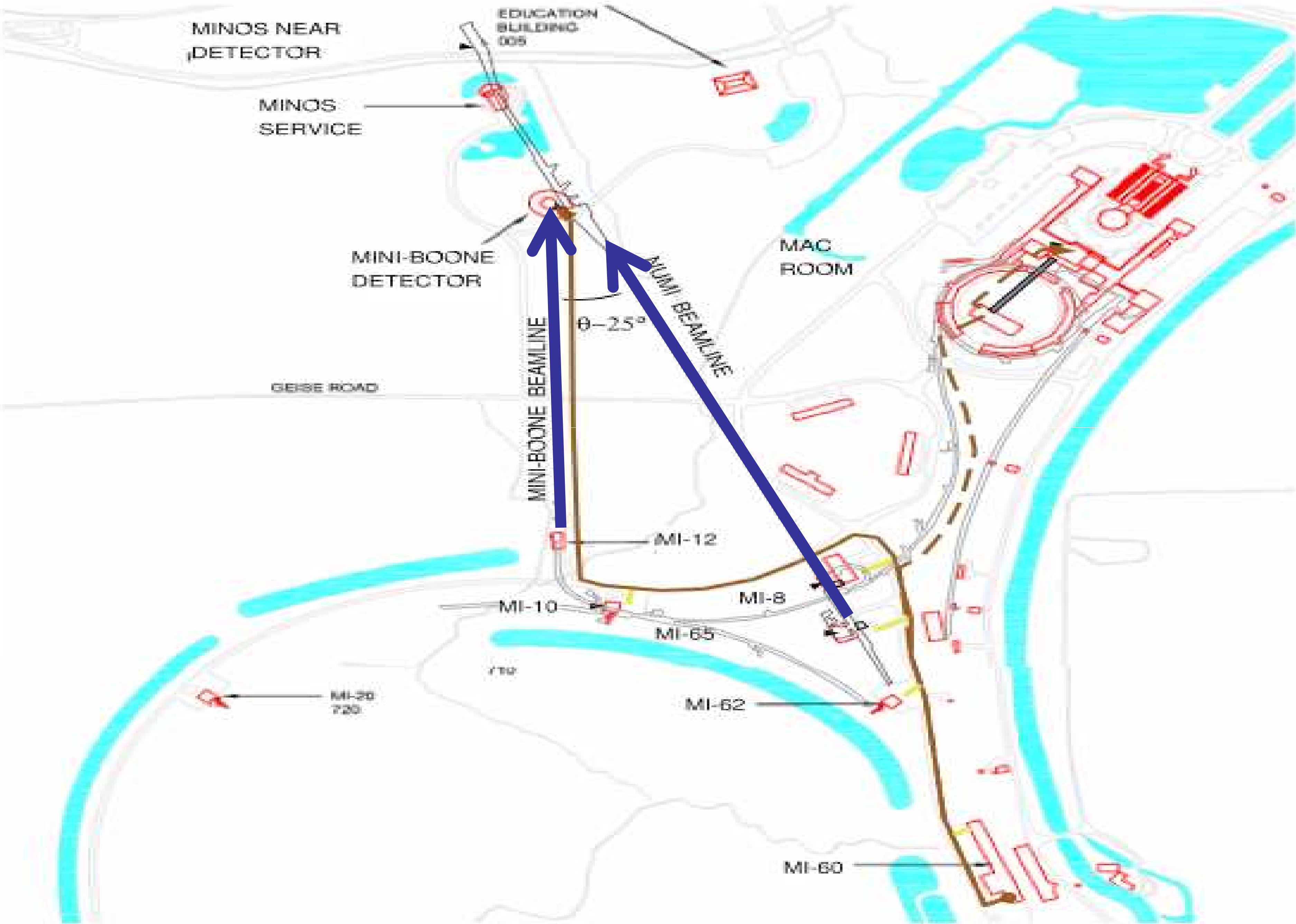
- ν_μ-induced NC π^0 with photonuclear absorption of π^0 photon

-new ν_μ-induced NC photon production (eg: hep-ex:0708.1281v2)

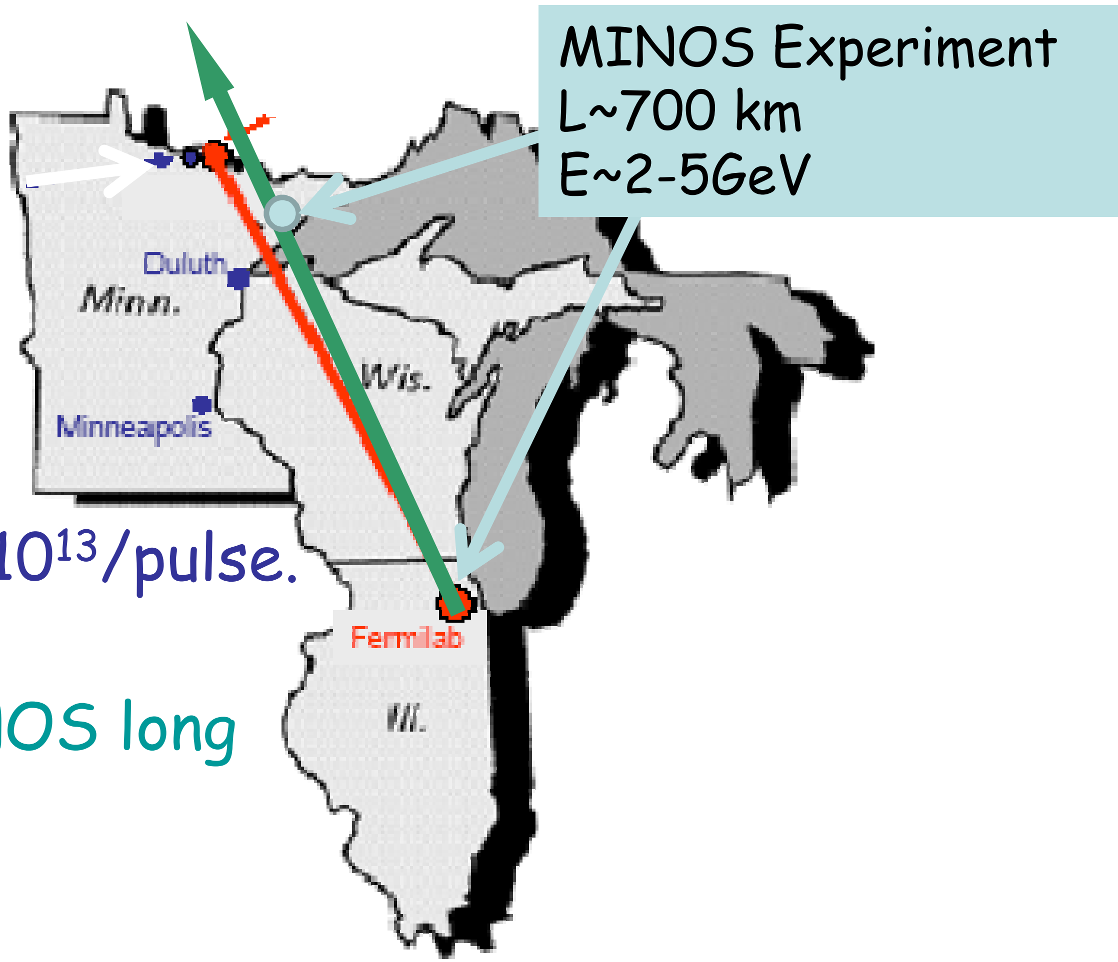
-new physics?

New Analysis:
Events from NuMI beamline

Fermilab Neutrino Beams



NuMI Beam



120 GeV protons ~ $3x10^{13}$/pulse.

Primarily for the MINOS long baseline experiment.

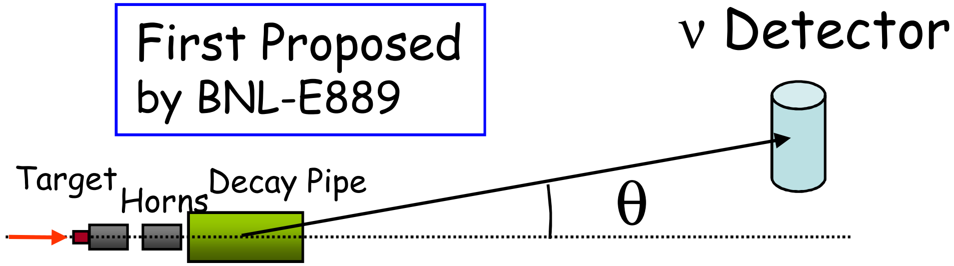
Off-axis Beam

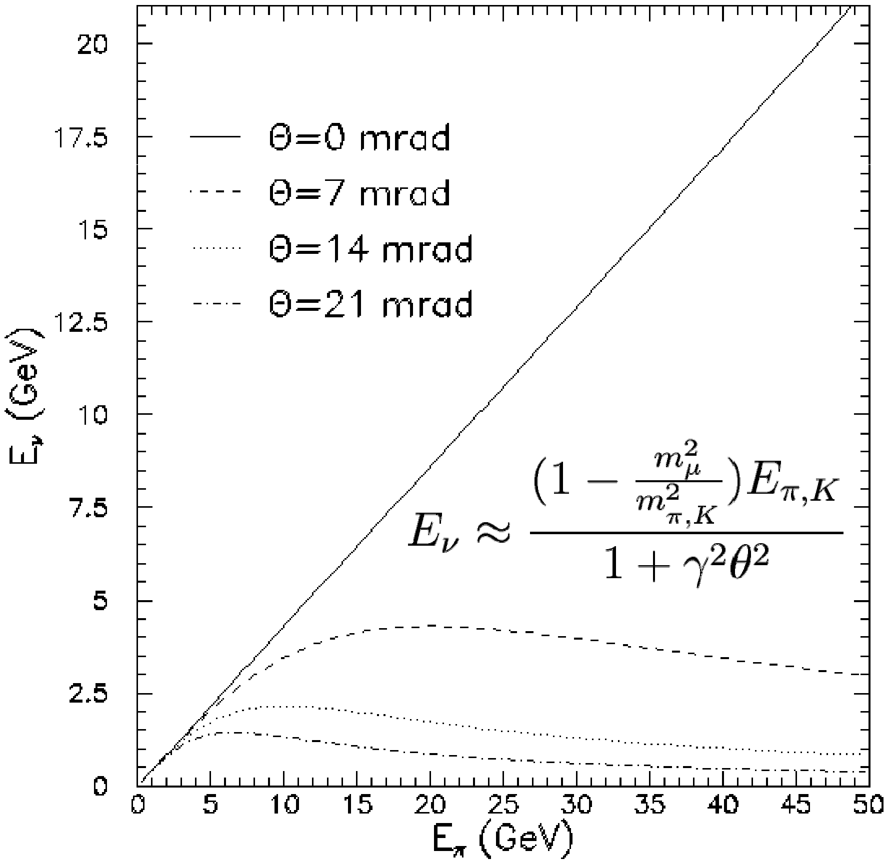
On-axis, neutrino energy more tightly related to hadron energy.

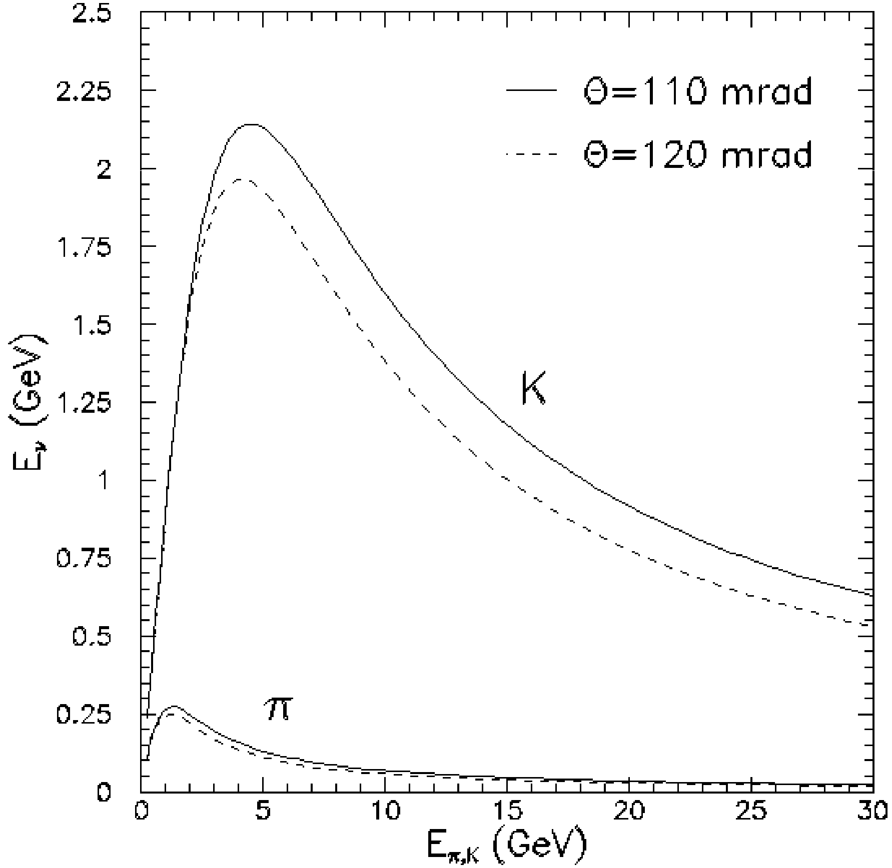
Off-axis, neutrino spectrum is narrow-band and 'softened'.

Easier to estimate flux correctly: all mesons decay to same energy ν.

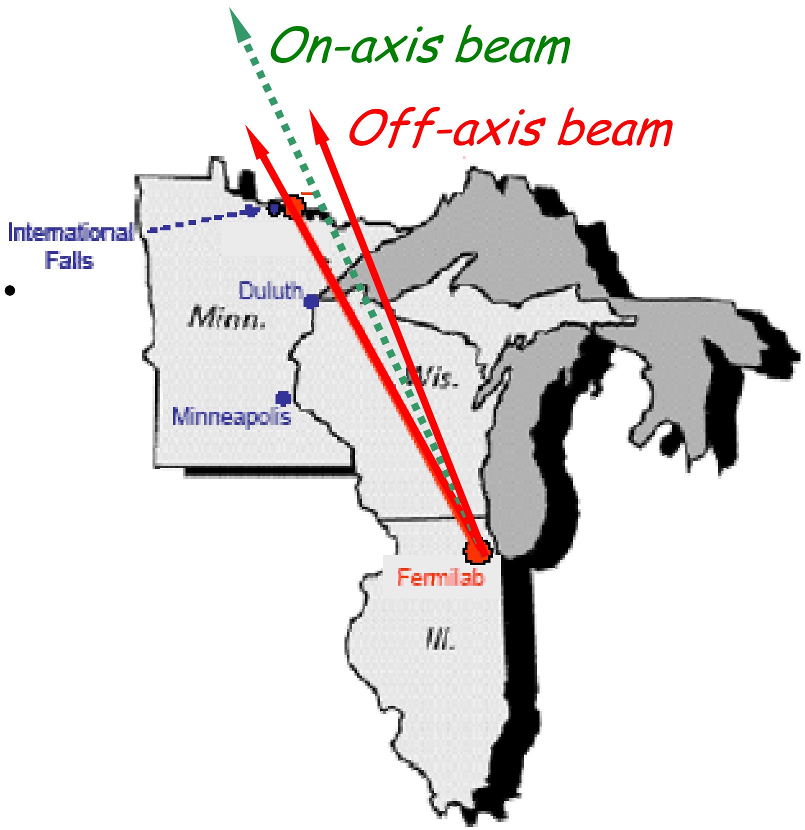
First Proposed by BNL-E889







Future off-axis Neutrino Experiments



Use off-axis trick for optimized $\nu_\mu \to \nu_e$ search.

NOvA:

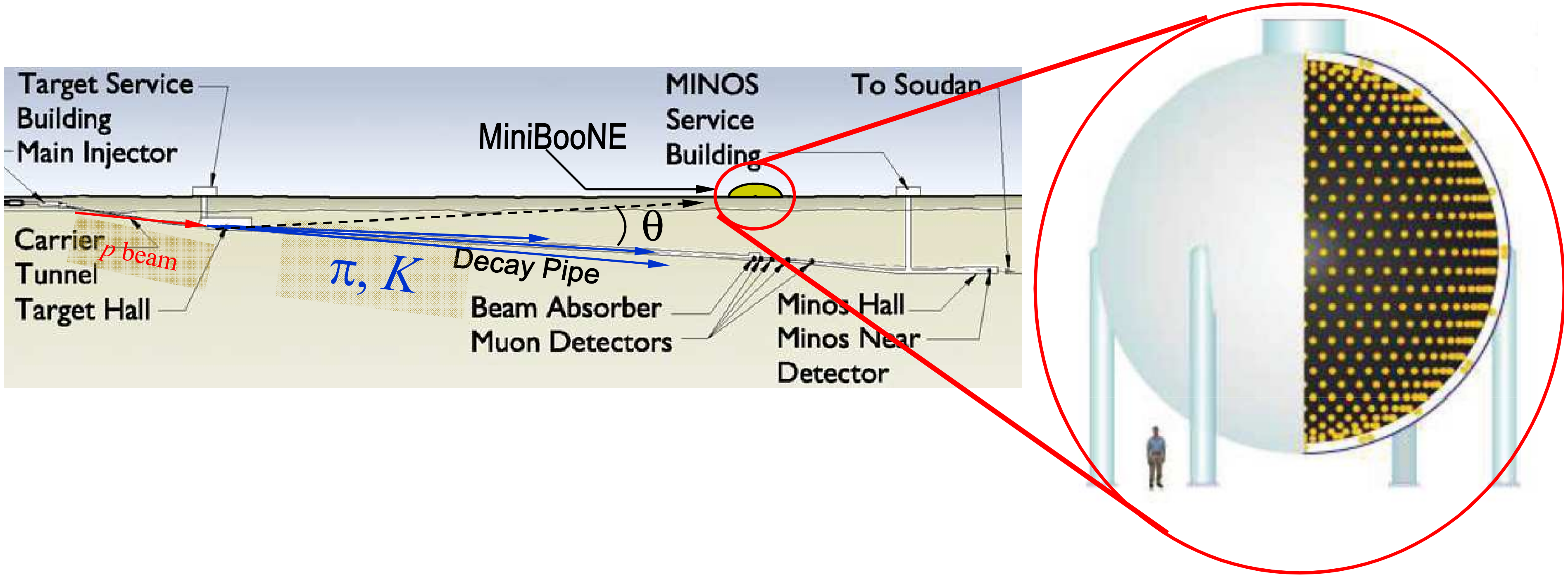
- NuMI off-axis beam
- 810km baseline
- 14.5mrad; E_ν~2GeV

T2K:

- J-PARC 50GeV proton beam
- Use SK as Far detector 295km away
- 35 mrad; E_ν~0.6GeV

NuMI Beam and MiniBooNE Detector

NuMI events (for MINOS) detected in MiniBooNE detector!



MiniBooNE detector is 745 meters downstream of NuMI target.
MiniBooNE detector is 110 mrad off-axis from the target along NuMI decay pipe.

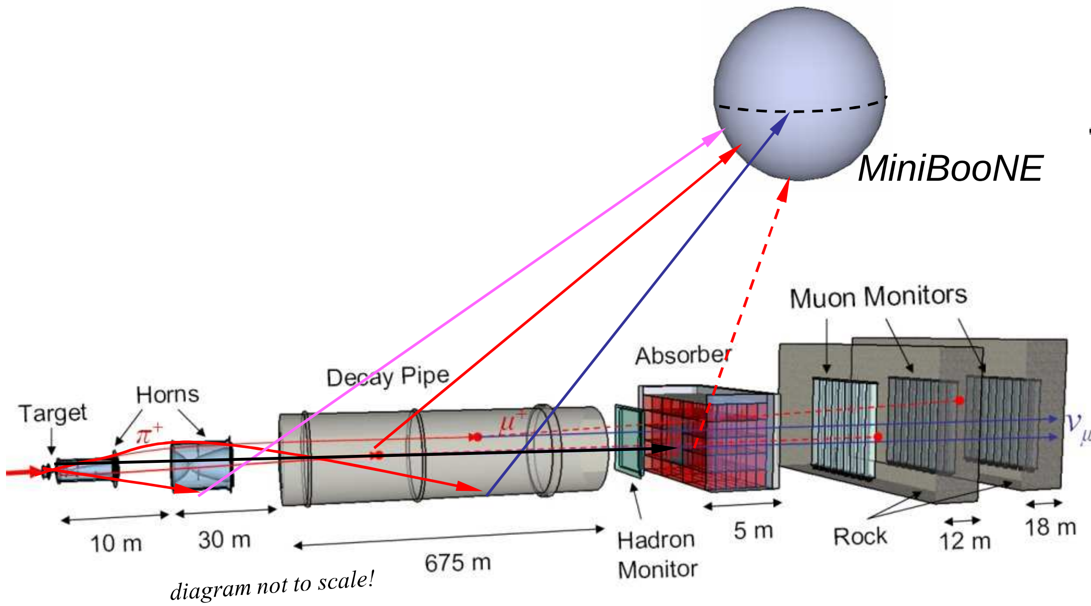
Main trigger is an accelerator signal indicating a beam spill.
Information is read out in 19.2 μs interval covering arrival of beam.

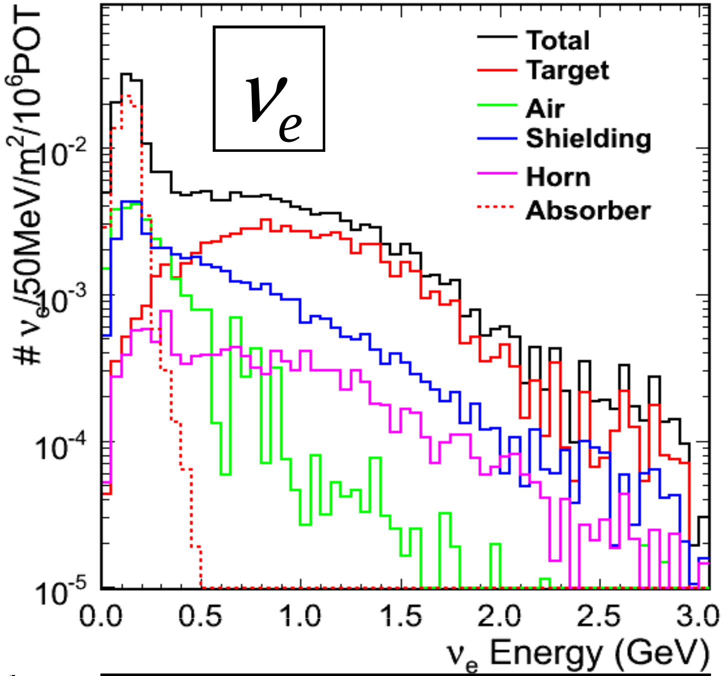
Neutrino Origin Along NuMI Beam Line

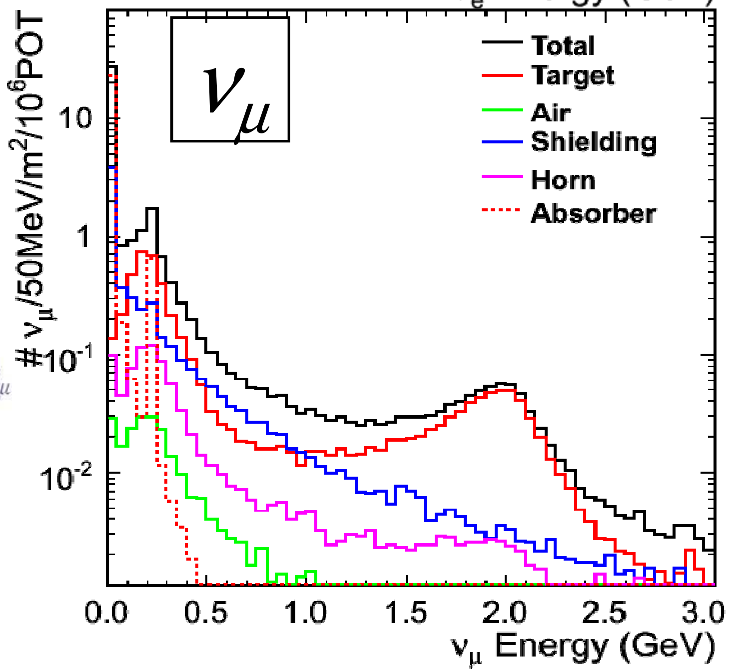
Higher energy neutrinos mostly from particles created in target.

Interactions in shielding and beam absorber contributes in lowest energy bins.

Plots show where the parent was created.







MiniBooNE

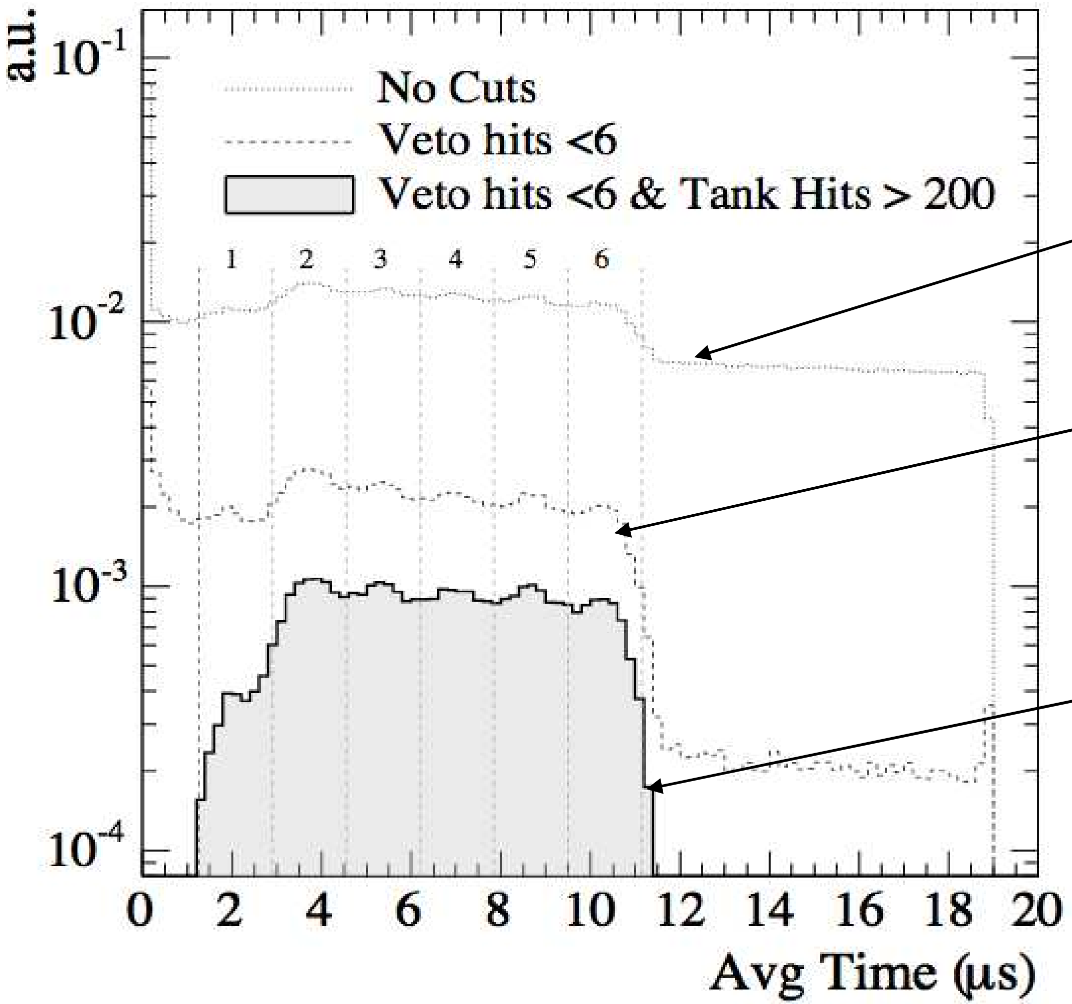
(Booster Neutrino Experiment)

becomes

An off axis neutrino experiment using Main Injector

Detector Operation and Event reconstruction

No high level analysis needed to see neutrino events



Events in DAQ window:no cuts

Removed cosmic ray muons:
PMT veto hits < 6

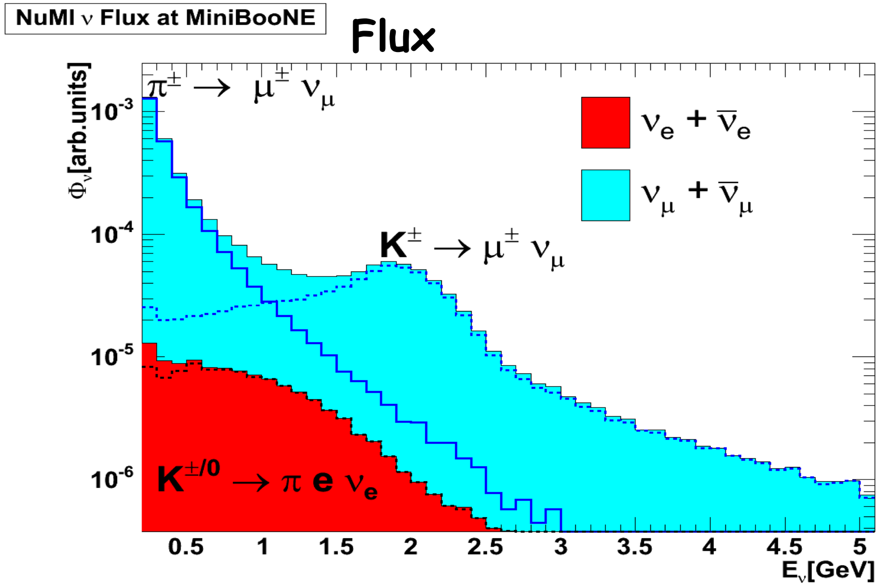
Removed cosmic ray muons and μ-decay electrons:
PMT veto hits < 6 and
PMT tank hits > 200

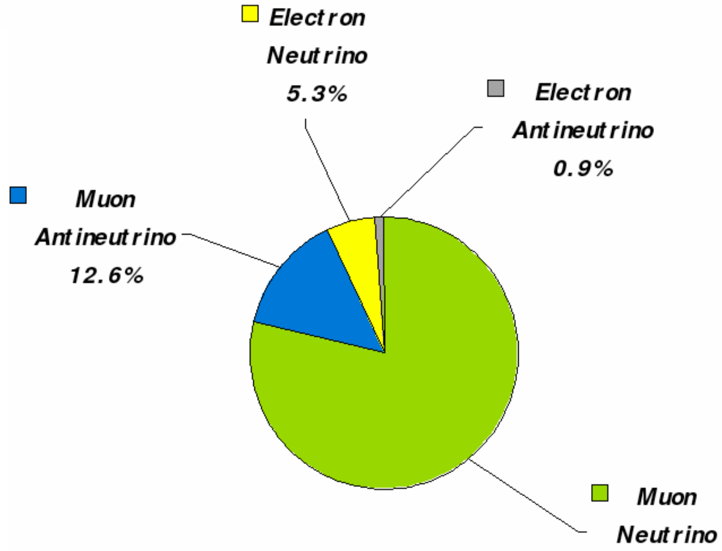
6-batch structure of MI about 10 μs duration reproduced.

Backgrounds: cosmic muons and decay electrons

->Simple cuts reduce non-beam backgrounds to ~10^{-5}

Events from NuMI detected at MiniBooNE

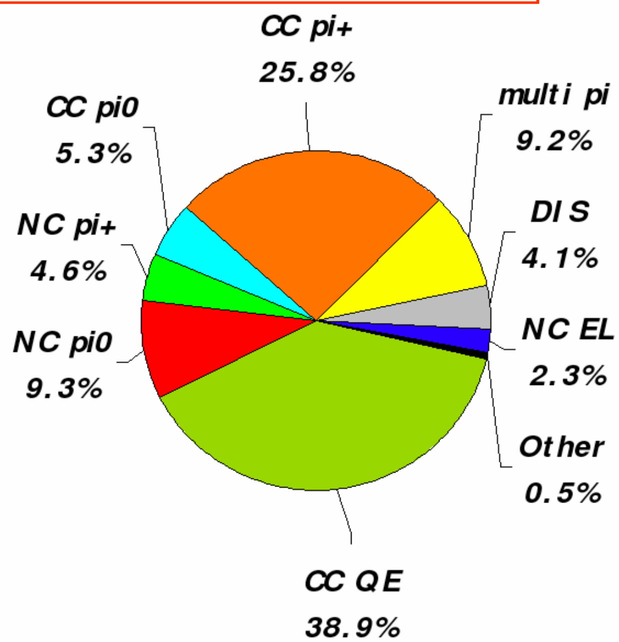




Event rates

NuMI event composition at MB
ν_μ-81%, ν_e-5%, $\bar{\nu}_\mu$-13%, $\bar{\nu}_e$-1%

Neutrino interactions at carbon simulated by NUANCE event generator: neutrino flux converted into event rates.



Event rates

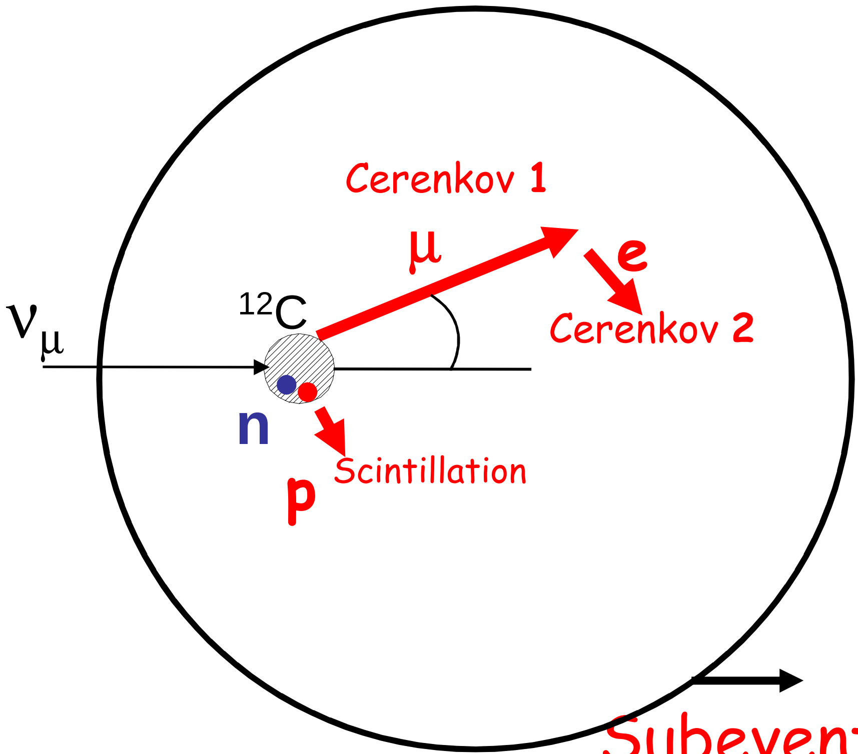
CCQE	39%
CC π^+	26%
NC π^0	9%

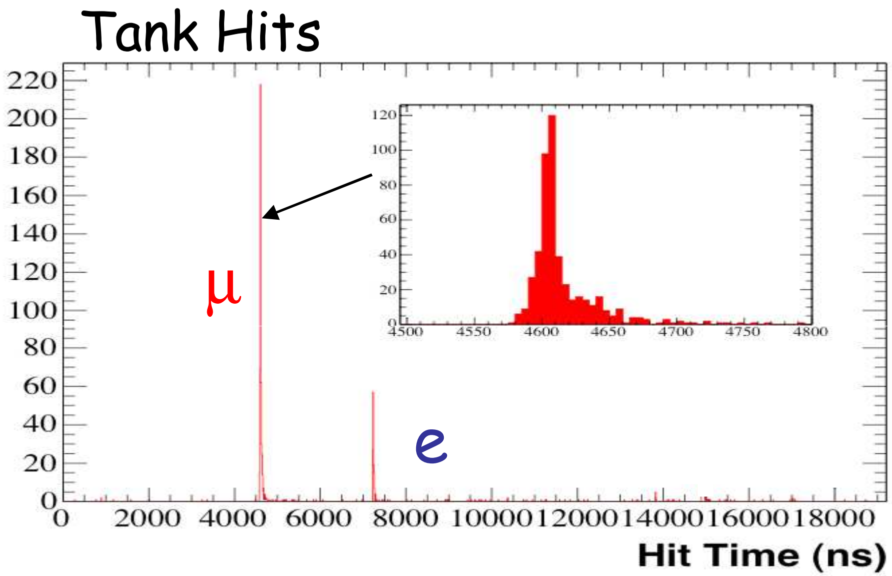
ν_μ CCQE Analysis

Analysis of the ν_μ CCQE events from NuMI beam

ν_μ CCQE ($\nu+n \rightarrow \mu+p$) has a two "subevent" structure

(with the second subevent from stopped $\mu \rightarrow \nu_\mu \nu_e e$)





Event Selection:

Subevent 1:

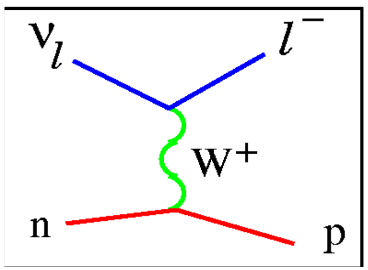
Thits>200, Vhits<6

R<500 cm

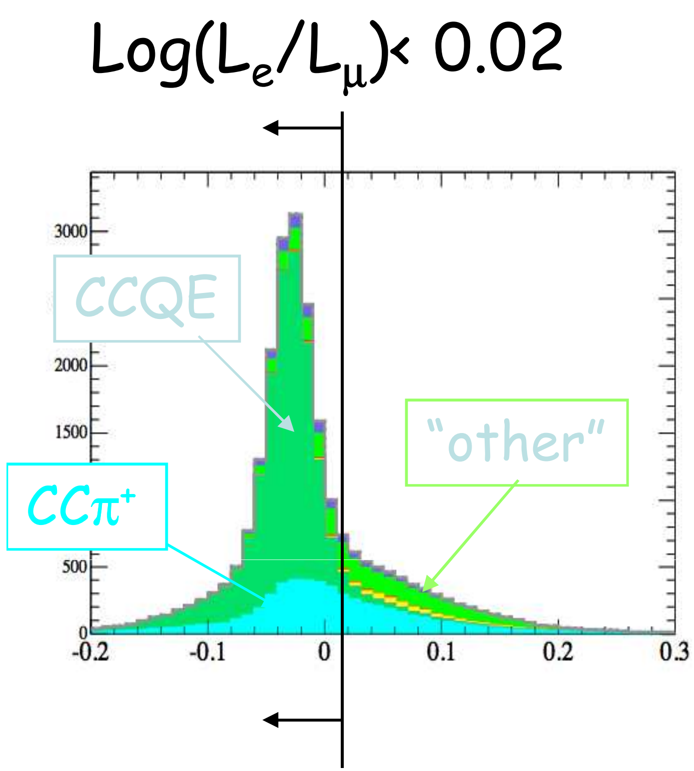
$L_e/L_\mu < 0.02$

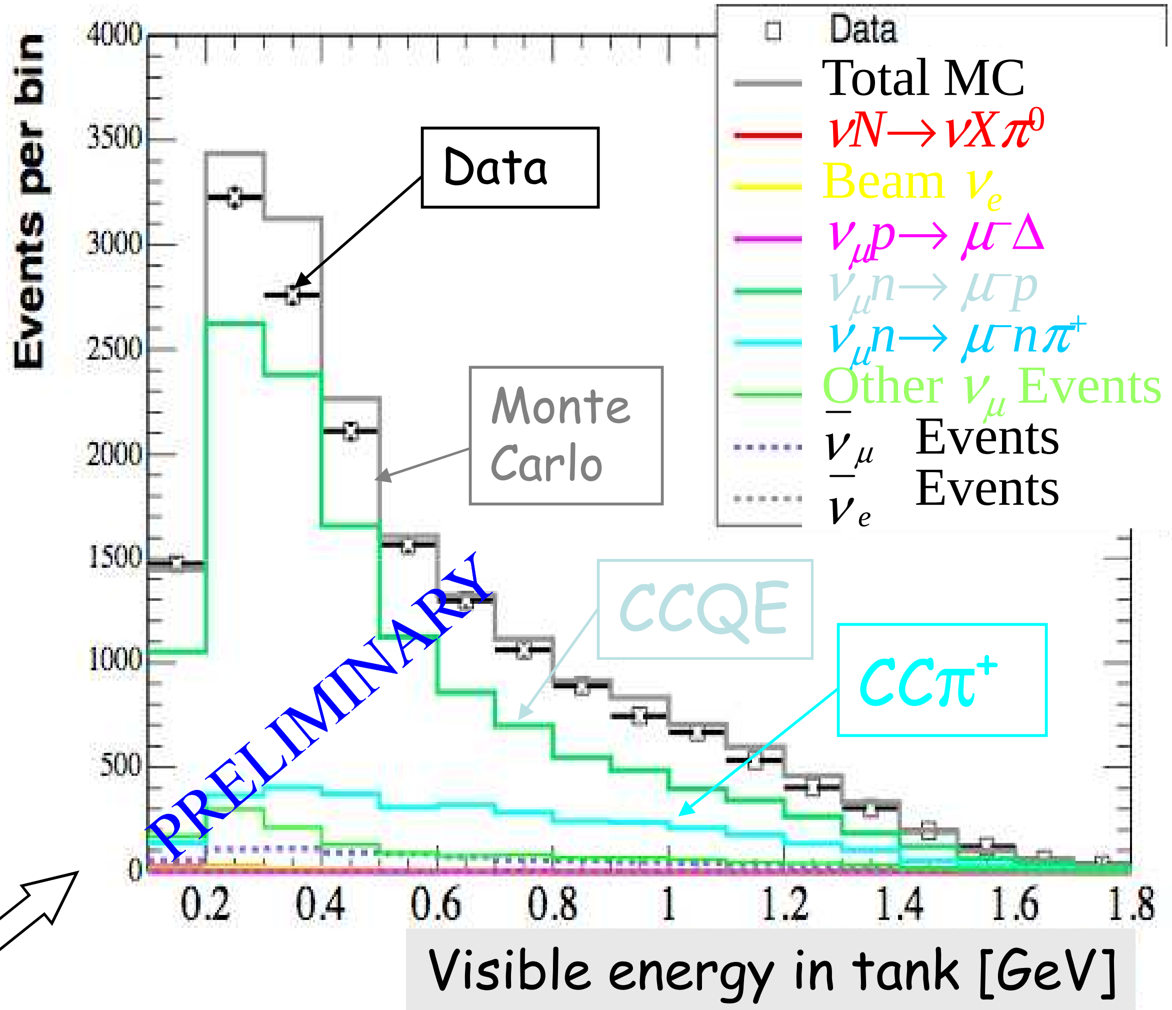
Subevent 2:

Thits<200, Veto<6



Visible E of μ: final state interactions in ν_μ CCQE sample

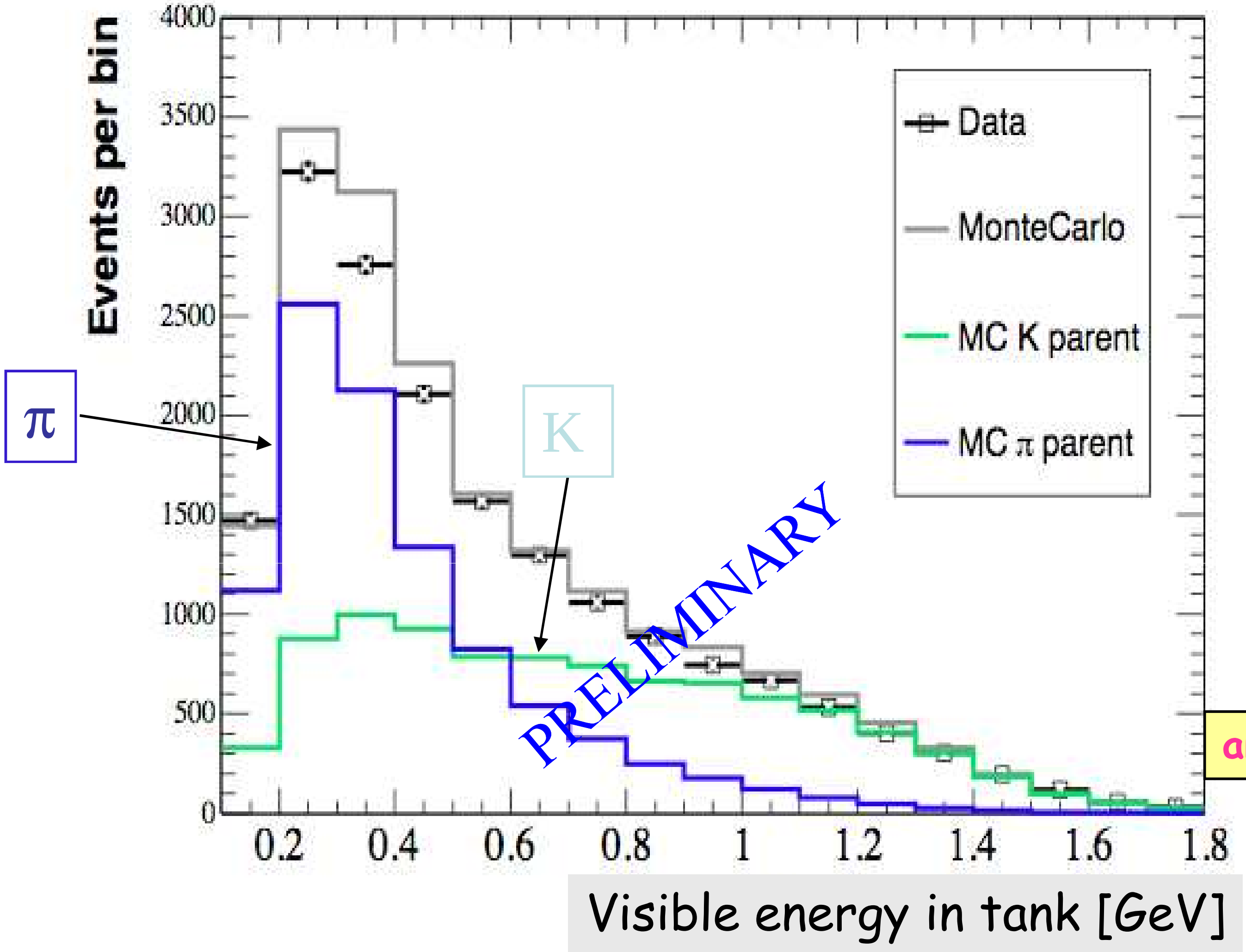




Data (stat errors only) compared to MC prediction for visible energy in the tank.

This sample contains 18000 events of which 70% are CCQE's.

Compare ν_μ CCQE MC to Data:Parent Components



Beam MC tuned with MINOS near detector data.

Cross-section Monte Carlo tuned with MB measurement of CCQE pars M_A and κ.

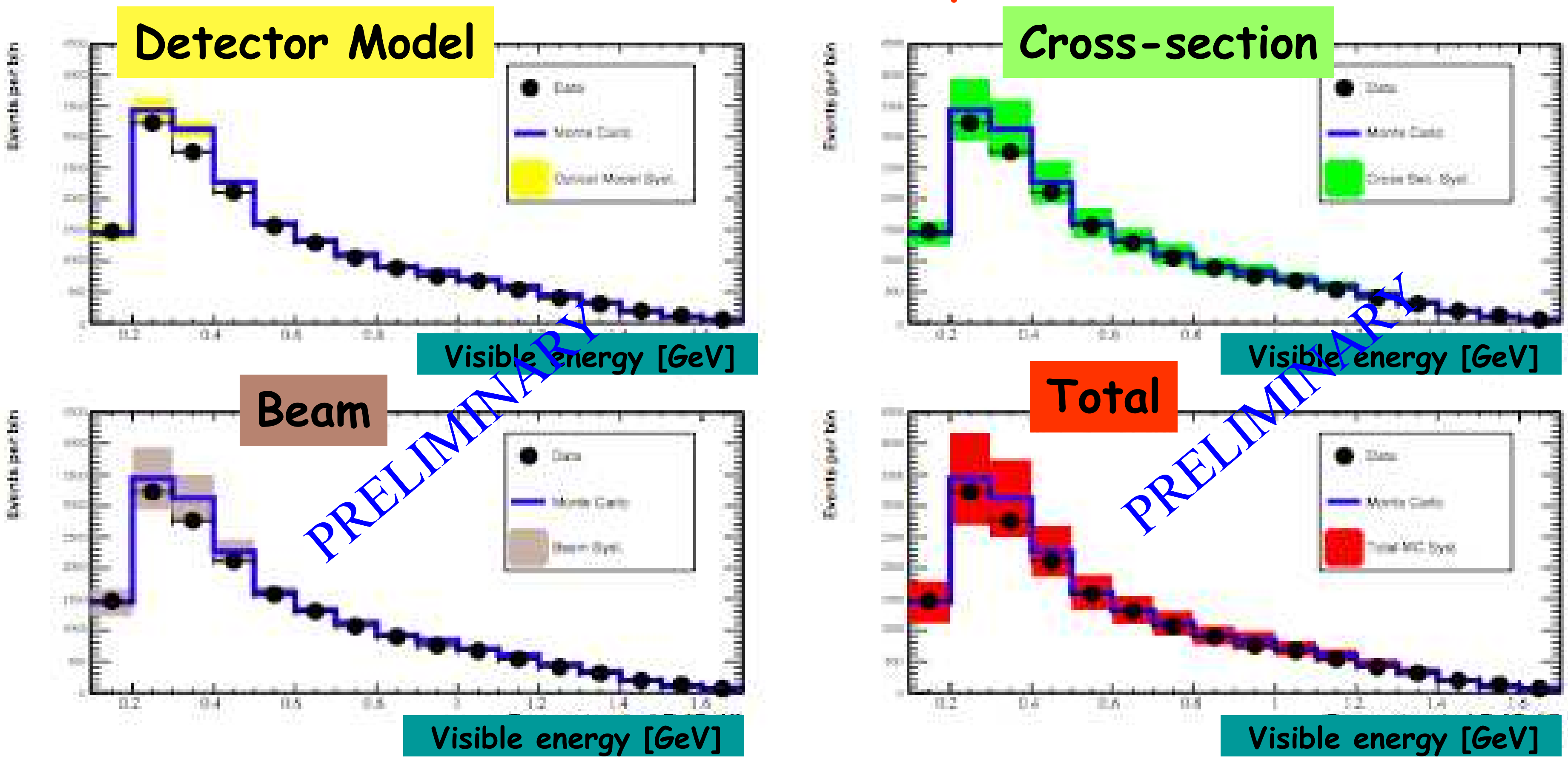
arXiv:0706.0926 [hep-ex]

MC is normalized to data POT number!

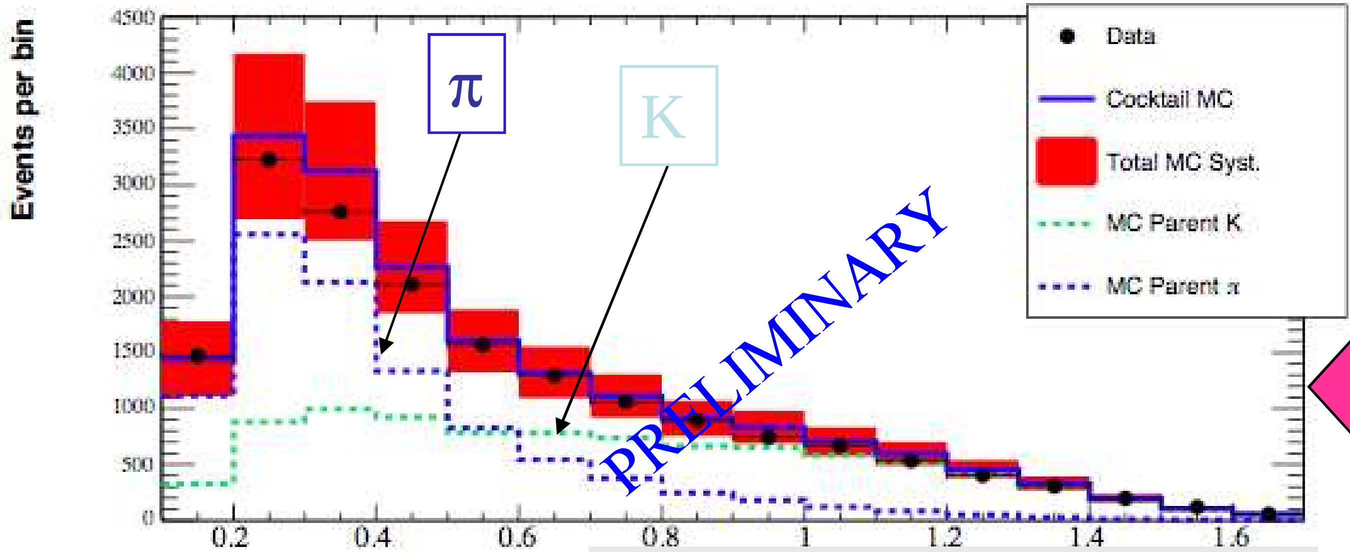
Systematic Uncertainties in ν_μ CCQE analysis

To evaluate Monte Carlo agreement with the data need estimate of systematics from three sources:

-Beam modeling: flux uncertainties.
-Cross-section model: neutrino cross-section uncertainties.
-Detector Model:describes how the light emits, propagates, and absorbs in the detector (how detected particle looks like?).



Add Systematic uncertainty to ν_μ CCQE Monte Carlo

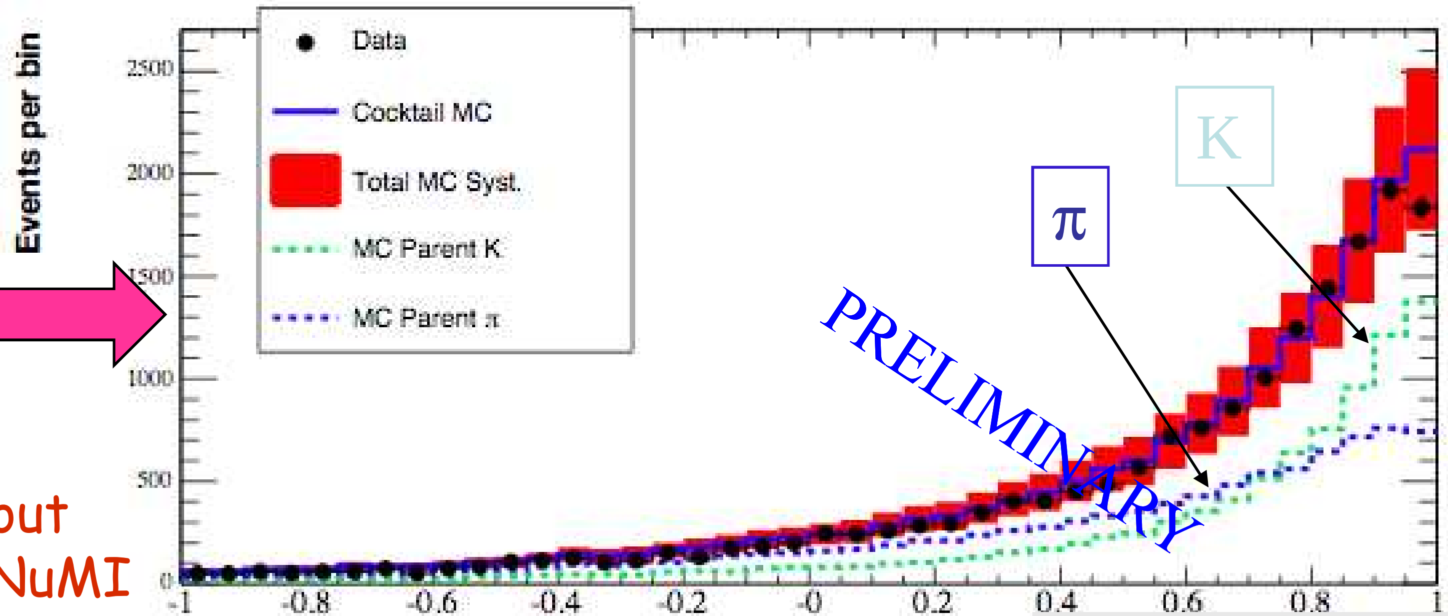


Visible energy in tank [GeV]

Predicted Pions are matching the data within systematics!

μ visible energy distribution

Outgoing μangular distribution



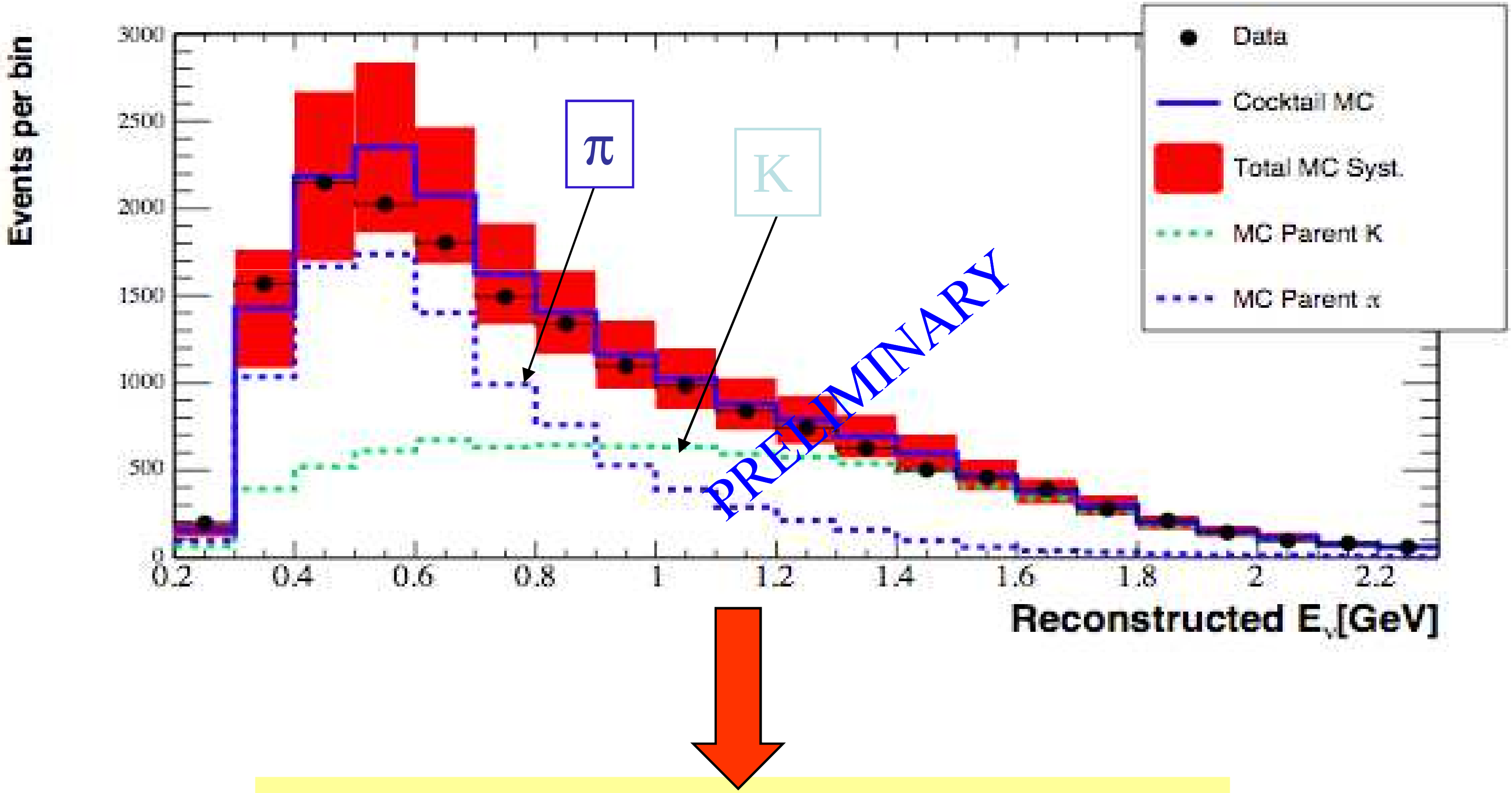
cos θ_μ

Information about incoming ν:wrt NuMI target direction.

ν_μ CCQE sample: Reconstructed energy E_ν of incoming ν

Reconstructed E_ν^{QE}:from E_{lepton} ("visible energy") and lepton angle wrt neutrino direction

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$



Understanding of the beam demonstrated:

MC is normalized to data POT number !

Conclusion from ν_μ CCQE analysis section

This is the first demonstration of the off-axis principle.

There is very good agreement between data and Monte Carlo:the MC tuned well.

Because of the good data/MC agreement in ν_μ flux and because the ν_μ and ν_e share same parents the beam MC can now be used to predict:

ν_e rate, and

mis-id backgrounds for a ν_e analysis.

ν_e CCQE Analysis

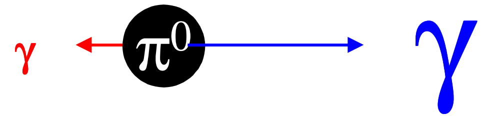
Backgrounds to ν_e CCQE sample

ν_e CCQE (ν+n $\rightarrow$ e+p)

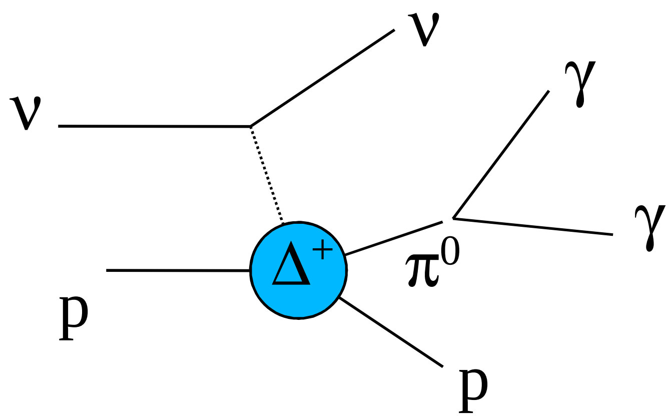
When we try to isolate a sample of ν_e candidates we find background contribution to it:
-π^0 ($\pi^0 \rightarrow \gamma\gamma$) and radiative Δ ($\Delta \rightarrow N\gamma$) events

Therefore, before analyzing ν_e CCQE we constrain the backgrounds by measurement in our own data.

Analysis of π^0 events from NuMI beam

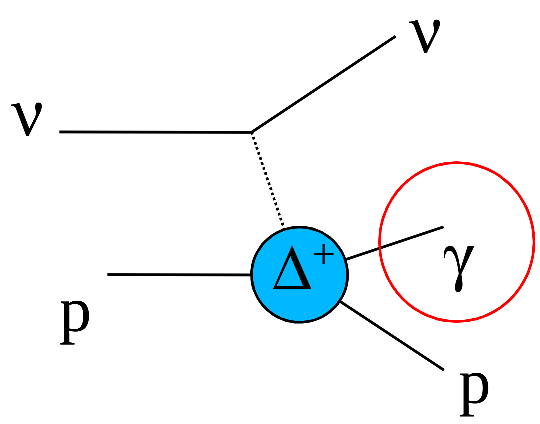


Among the e-like mis-ids, π^0 decays which are boosted, producing 1 weak ring and 1 strong ring is largest source.



Strategy: Don't try to predict the π^0 mis-id rate, **measure it!**
Measured rates of reconstructed π^0… tie down the rate of mis-ids

Δ decays to a single photon: with 0.56% probability:

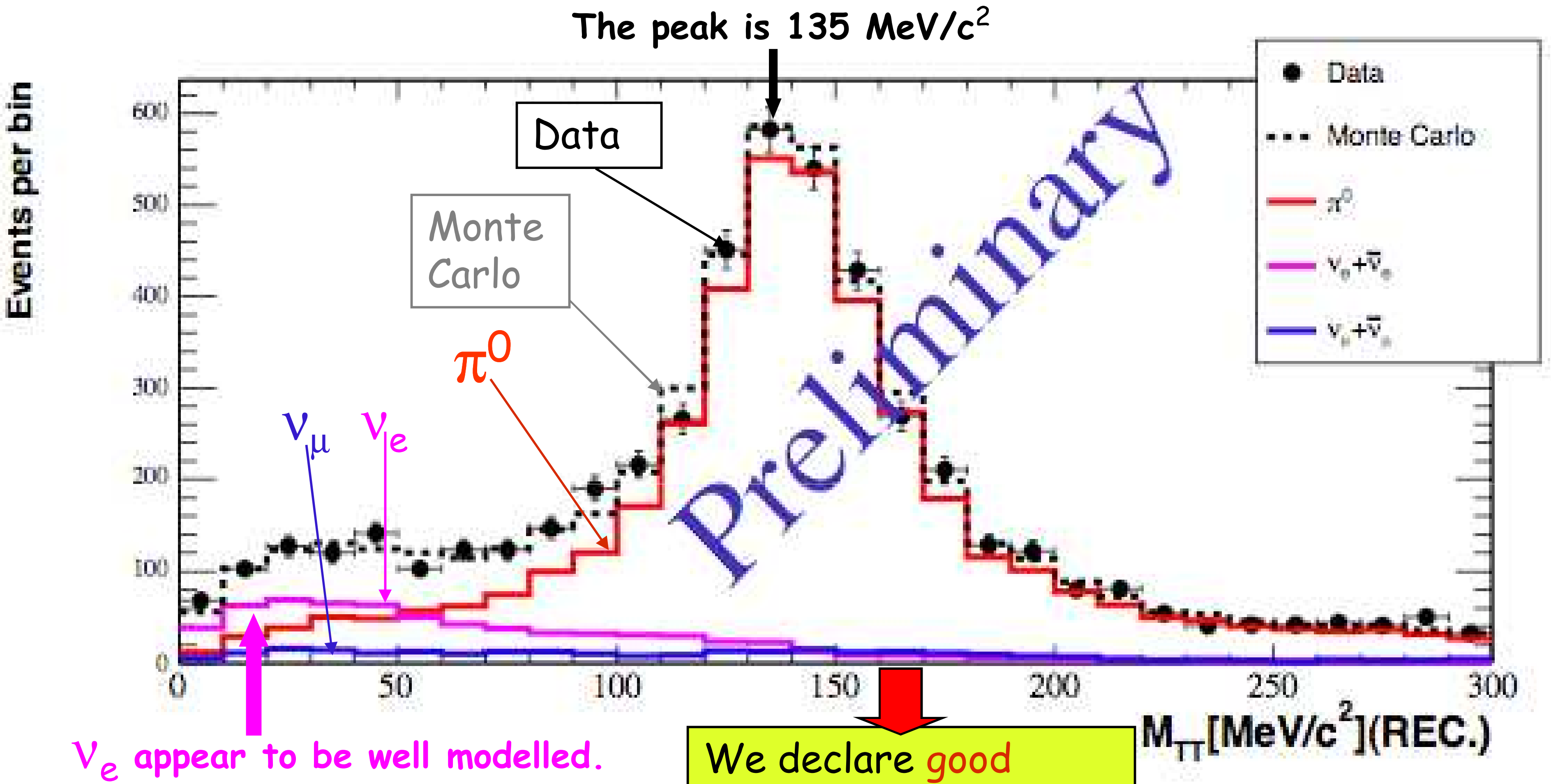


What is applied to select π^0s

Event pre-selection:
1 subevent
Thits>200, Vhits<600
R<500 cm

$\log(L_e/L_\mu)>0.05$ (e-like)
$\log(L_e/L_\pi)<0$ (π^0-like)

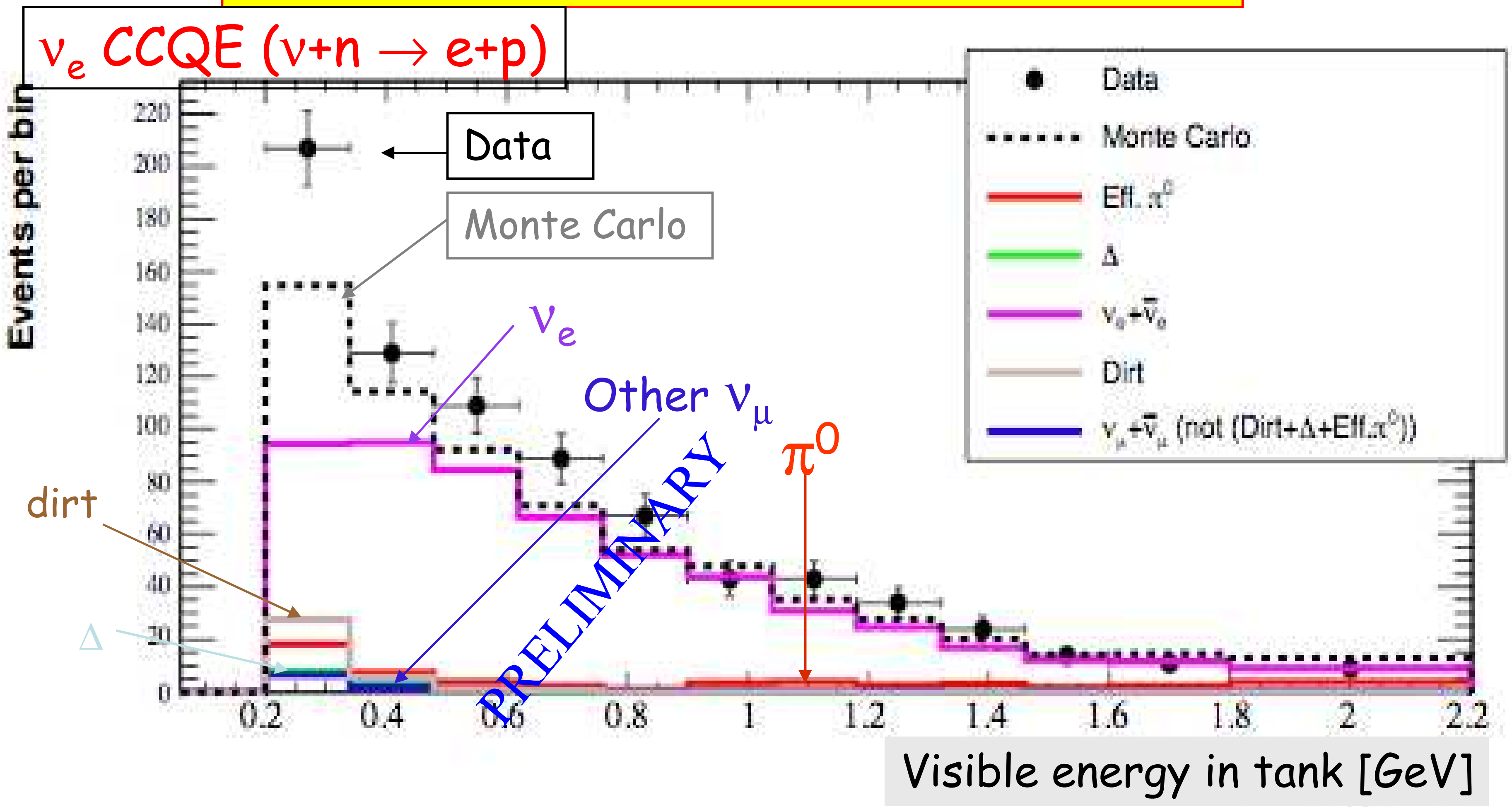
Analysis of π^0 events from NuMI beam: π^0 mass



This sample contains 4900 events of which 81% are π^0 events: **world second largest π^0 sample!**

We declare good MC/Data agreement for π^0 sample going down to low mass region where ν_e candidates are showing up!

Visible energy of ν_e CCQE events

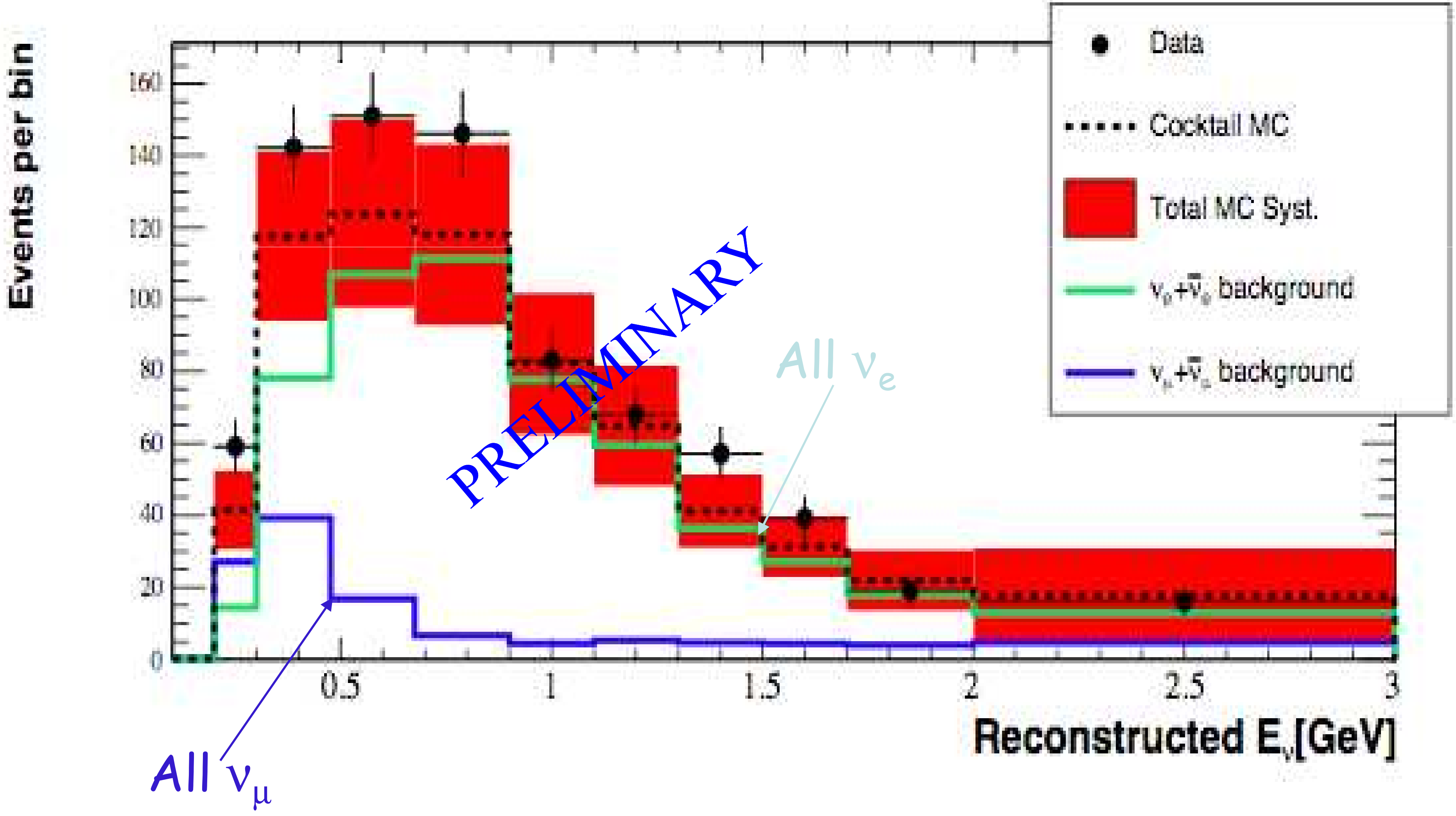


Data = 783 events.
Monte Carlo prediction = 662 events.

Before we further characterize data/MC agreement we have to account for the systematic uncertainties.

ν_e CCQE sample: Reconstructed energy E_ν of incoming ν

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$



Summary of estimated backgrounds vs data ν_e CCQE sample

Looking quantitative into low energy and high energy region:

E_ν^{QE} [MeV]	200-900	900-3000
total background	401±66	261±50
ν_e intrinsic	311	231
ν_μ induced	90	30
NC π^0	30	25
NC $\Delta \rightarrow N\gamma$	14	1
Dirt	35	1
other	11	3
Data	498±22	285±17
Data-MC	97±70	24±53
Significance	1.40 σ	0.45 σ

At this point systematic errors are large: we cannot say much about the difference between low and high-E regions.

In the future we will reduce ν_e CCQE sample systematics constraining it with our large statistics ν_μ CCQE sample.

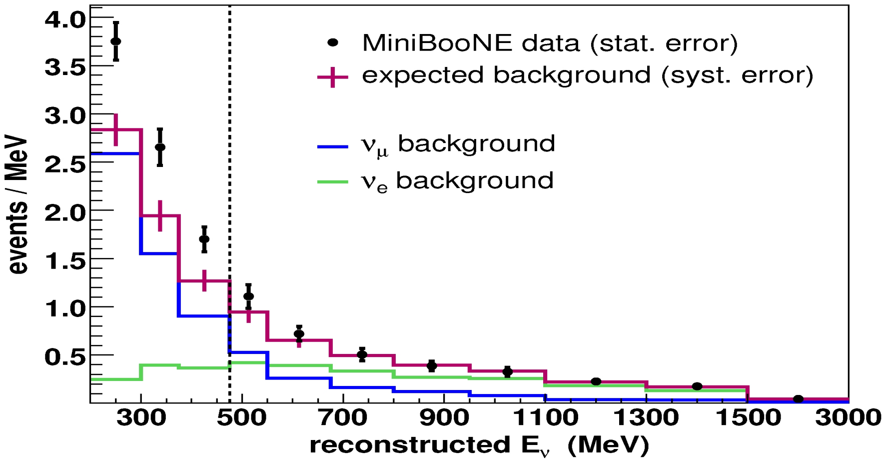
NuMI vs Booster Beam at MiniBooNE

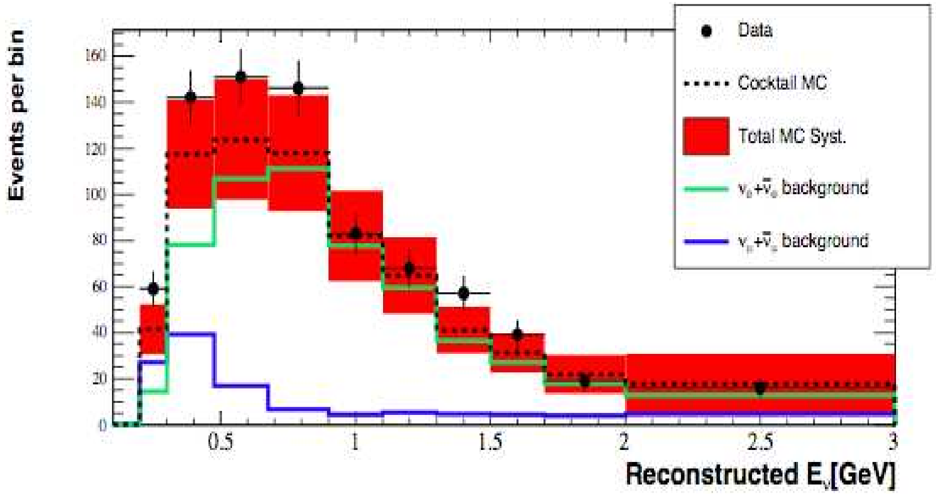
Recall:

1) Distance to MiniBooNE:
L (from NuMI source) ≈ 1.4 L (from Booster beam source).

2) Neutrino Oscillation depends on L and E through L/E ratio.

Therefore, if an anomaly seen at some L in Booster beam data is due to oscillation it should appear at 1.4E in the NuMI beam data at MiniBooNE.

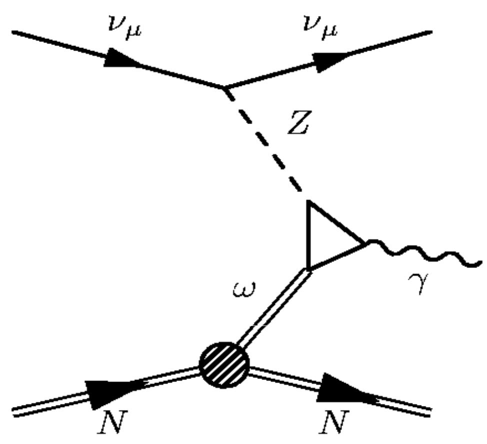




Will be published soon!

Is there a physics?

- Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density (arXiv:0708.1281: Jeffrey A. Harvey, Christopher T. Hill, Richard J. Hill)
- CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107
- Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017
- Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009
- CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303
- New Light Gauge Boson: Nelson & Walsh, arXiv:0711.1363



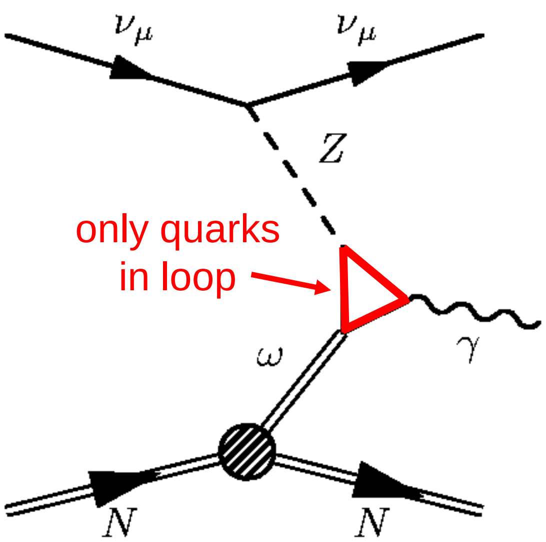
Possible Sources of Single Gamma Backgrounds

Since MiniBooNE cannot tell an electron from a single gamma, any process that leads to a single gamma in the final state will be a background.

Example: "Anomaly mediated neutrino-photon interactions at finite baryon density."
No quark vs. lepton cancellation in loop since only quarks can contribute
(Under active investigation)
(Harvey, Hill, and Hill, hep-ph0708.1281)

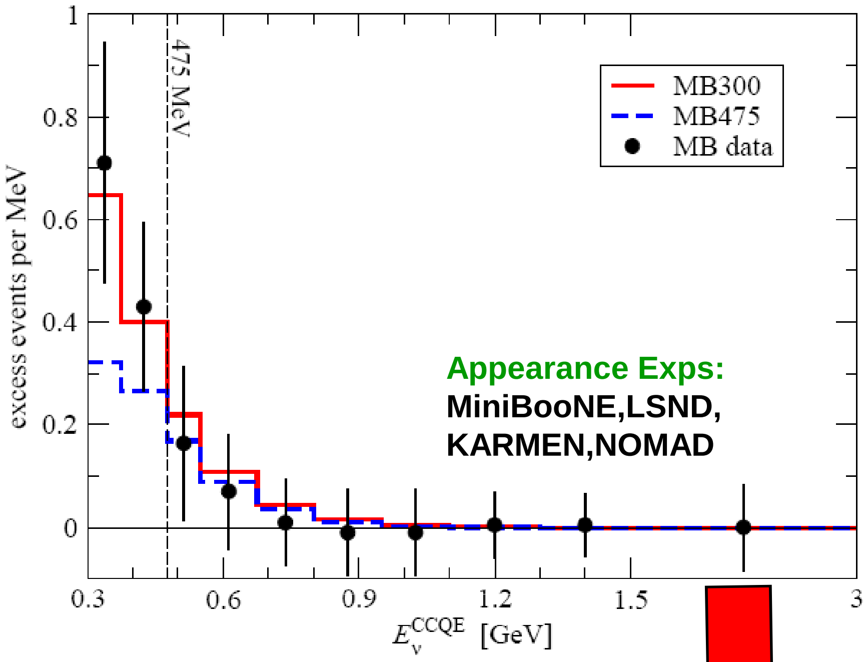
$$\sigma = \frac{\alpha g_\omega^4 G_F^2 E_\nu^6}{480\pi^6 m_\omega^4} \simeq 2.2 \times 10^{-41} (E_\nu/\text{GeV})^6 (g_\omega/10.0)^4 \text{cm}^2$$

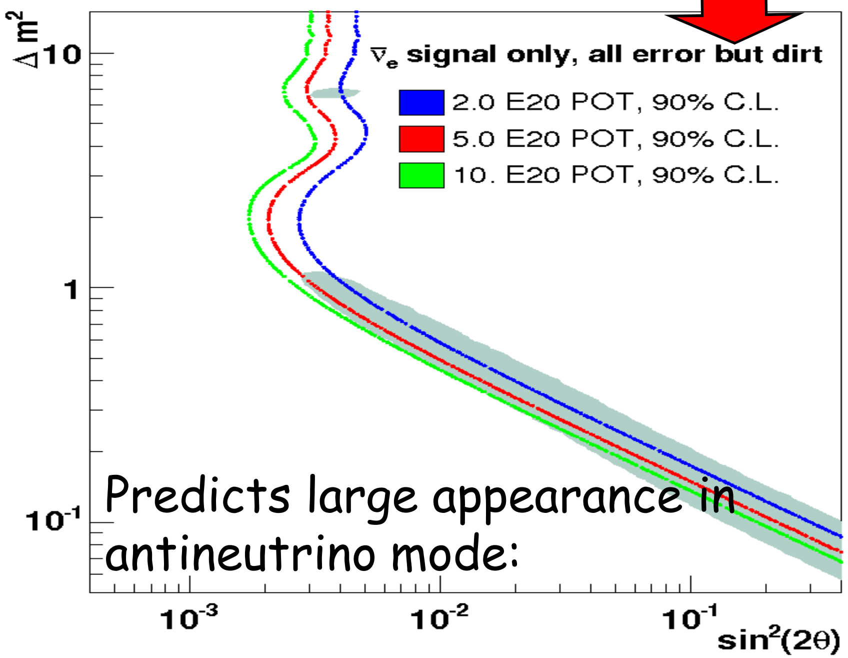
if g_w~10, and E_ν were 700 MeV
this would produce a 115 event excess…
About the right level….



New Physics: Models With Sterile Neutrinos

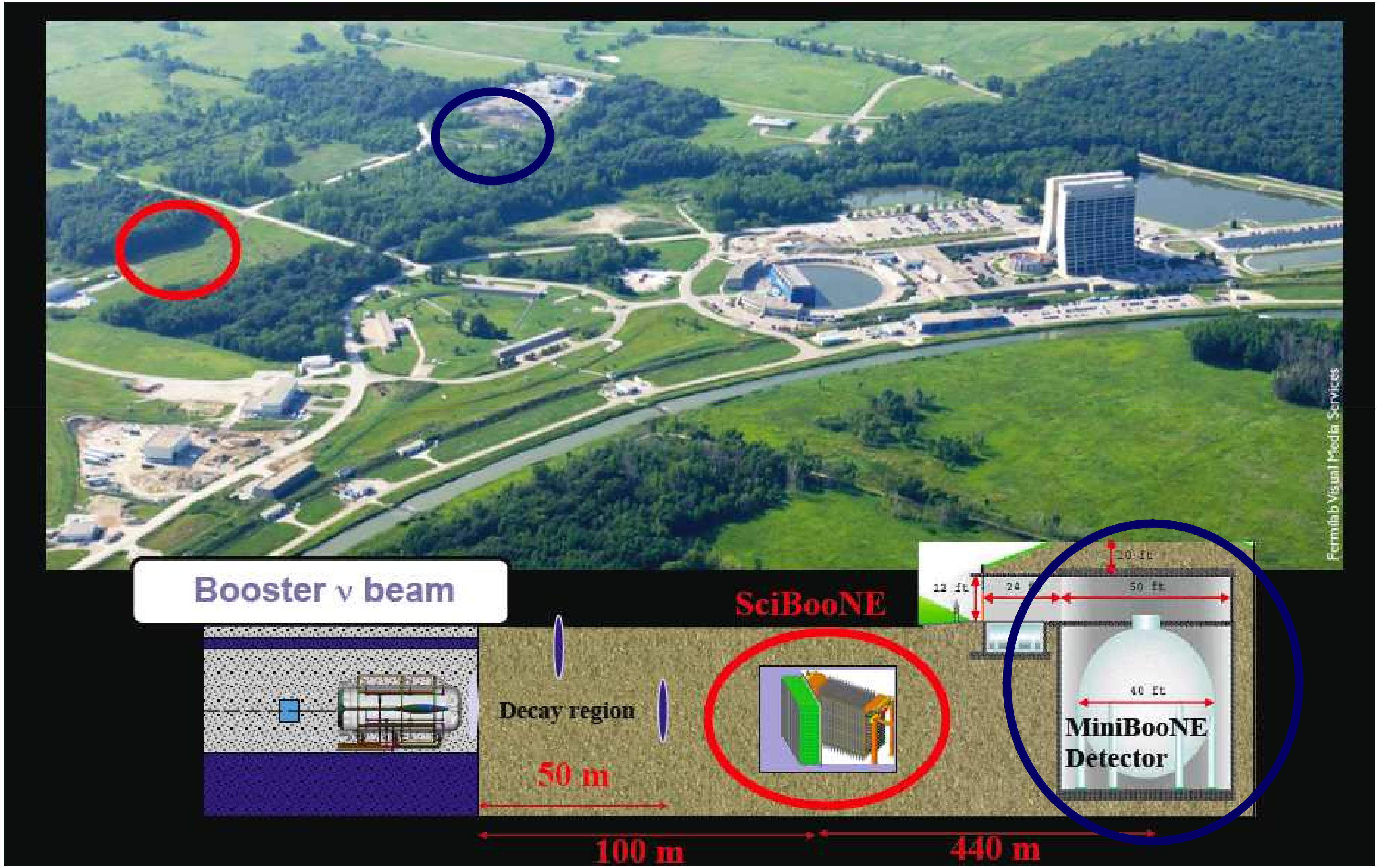
- Models with 3 active and 1 sterile neutrino (3+1) are excluded by various ν_e and ν_μ disappearance measurements
- 3+2 models can give a good fit to appearance data but fit is discrepant with the disappearance results: Bugey,Chooz,PaloVerde,CDHS. (Appearance and disappearance incompatible at the 4σ level) (Maltoni and Schwetz, hep-ph0705.0107
- 3+2 models may also produce measurable effects in the Double Chooz experiment especially for the near detector (Bandyopadhyay and Choubey, hep-ph0707.2481)



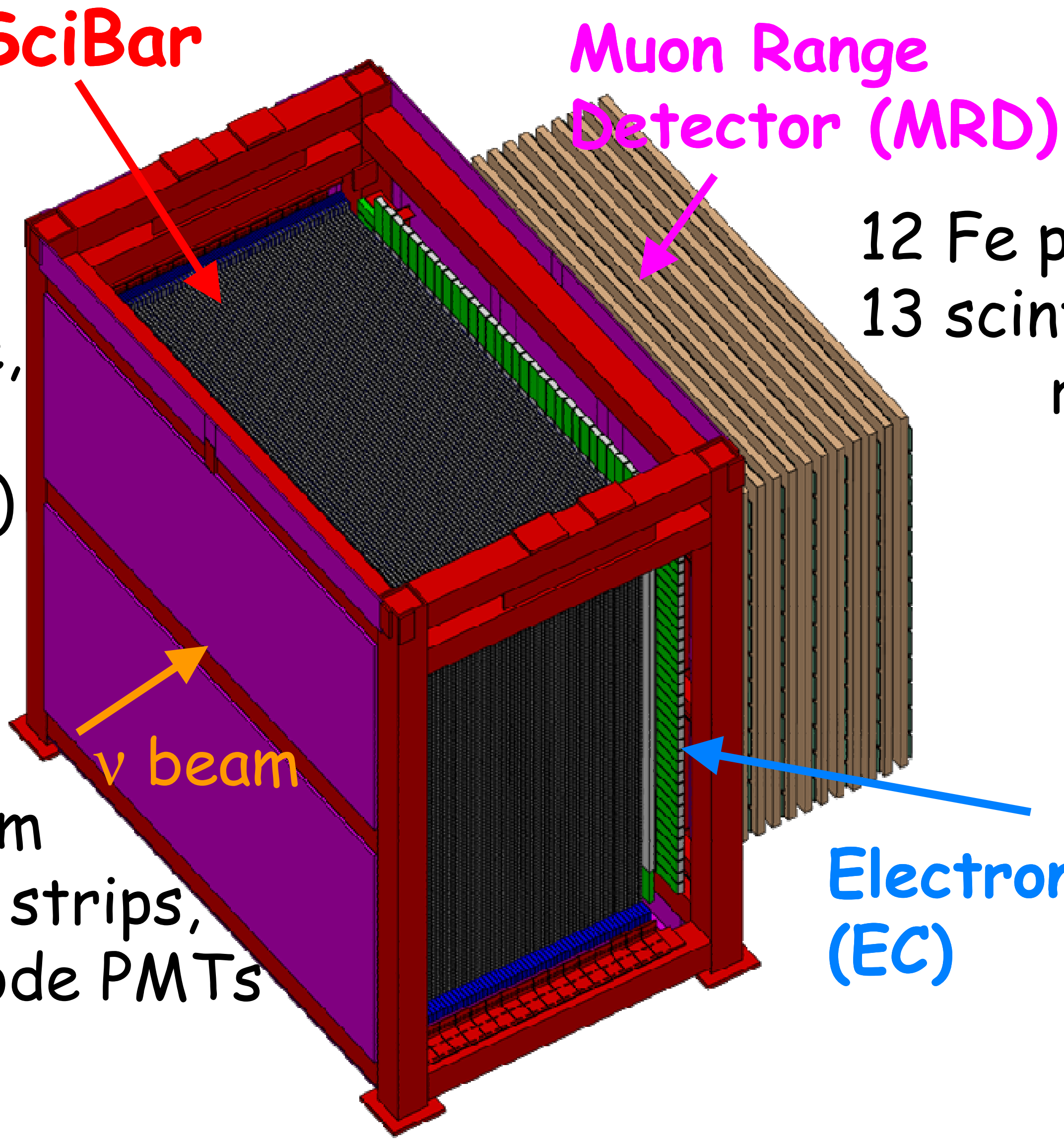


But Wait, Here is More:
SciBooNE

New Experiment on the Booster Neutrino Beamline



The SciBooNE detector: used at K2K in Japan



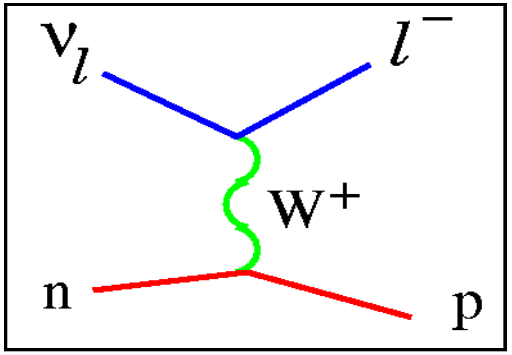
12 Fe plates,
13 scintillator planes
range ~ 1 GeV

Fully active,
CH_2 target
(ran in K2K)

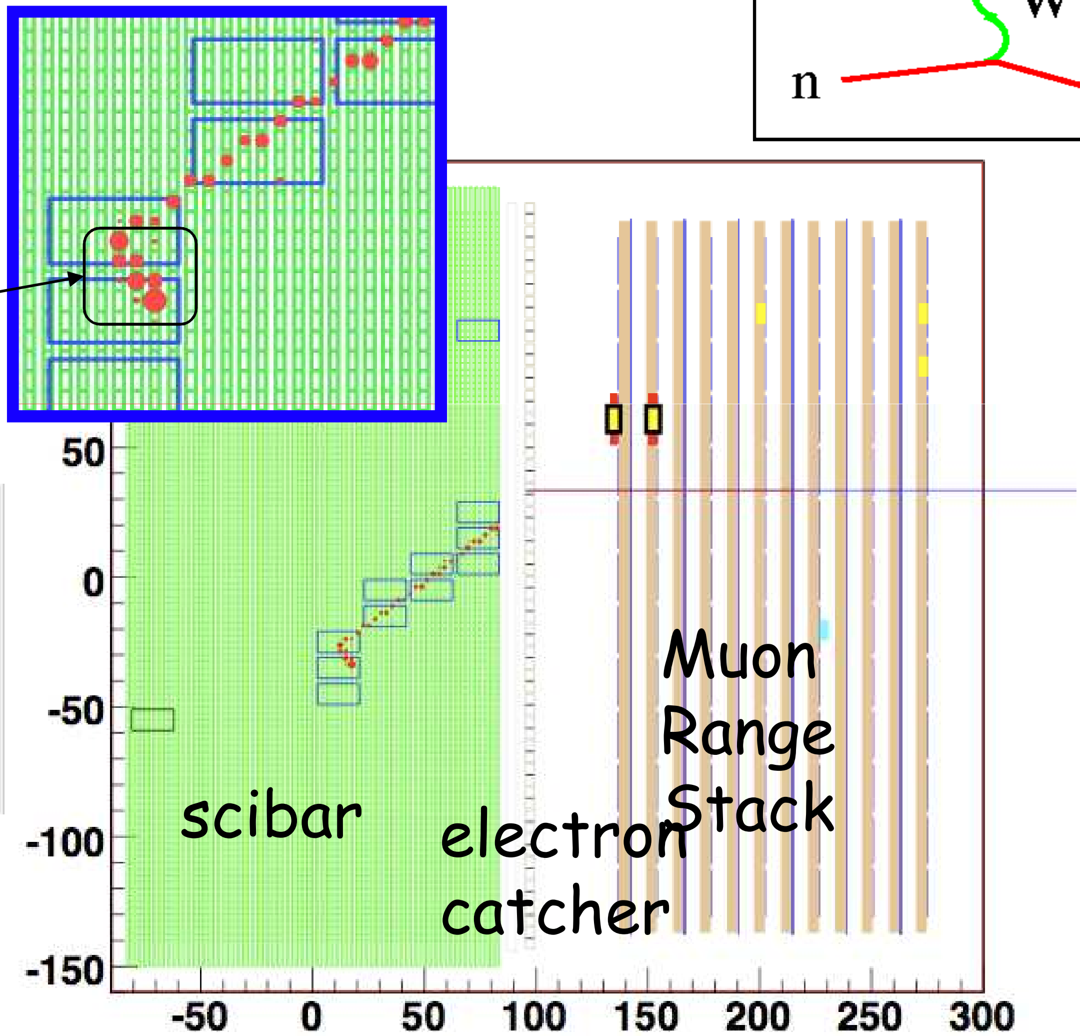
2.5 cm x 3 m
scintillator strips,
w/ multianode PMTs

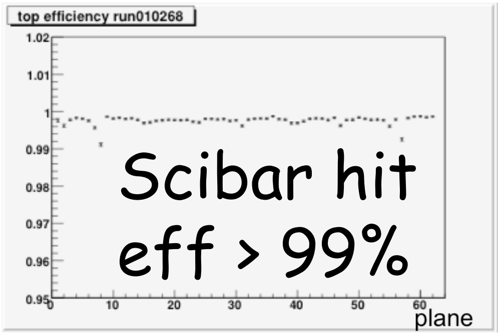
The SciBooNE sees what MiniBooNE cannot

A CCQE event in SciBooNE:

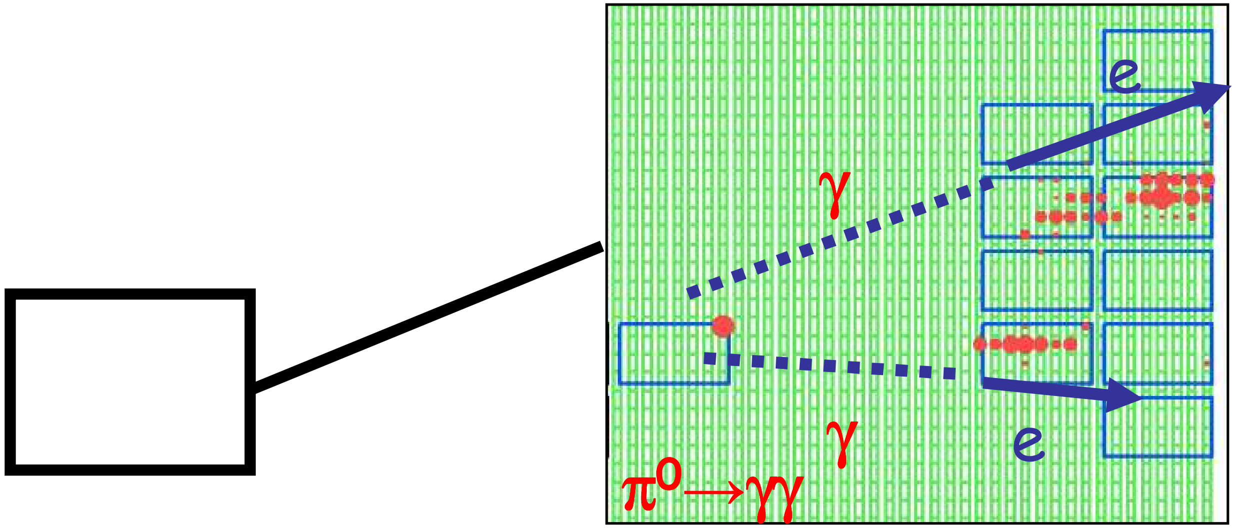


Proton ID via dE/dx





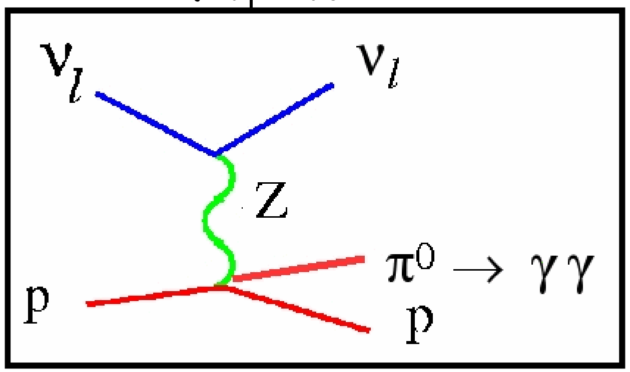
The SciBooNE has good $\pi^0 \to \gamma\gamma$ resolution



TIFFÅiL
Ç™Ç±ÇÃÉsÉNÉ`É

vertex

NC-π^0



SciBooNE is helpful for measuring beam content and cross sections…

Useful for both T2K, and MiniBooNE: new handle in low energy region $\to$ first analysis later this year

Summary and Outlook

MiniBooNE is currently running with Booster antineutrino beam and is granted to run antineutrinos for several more years.

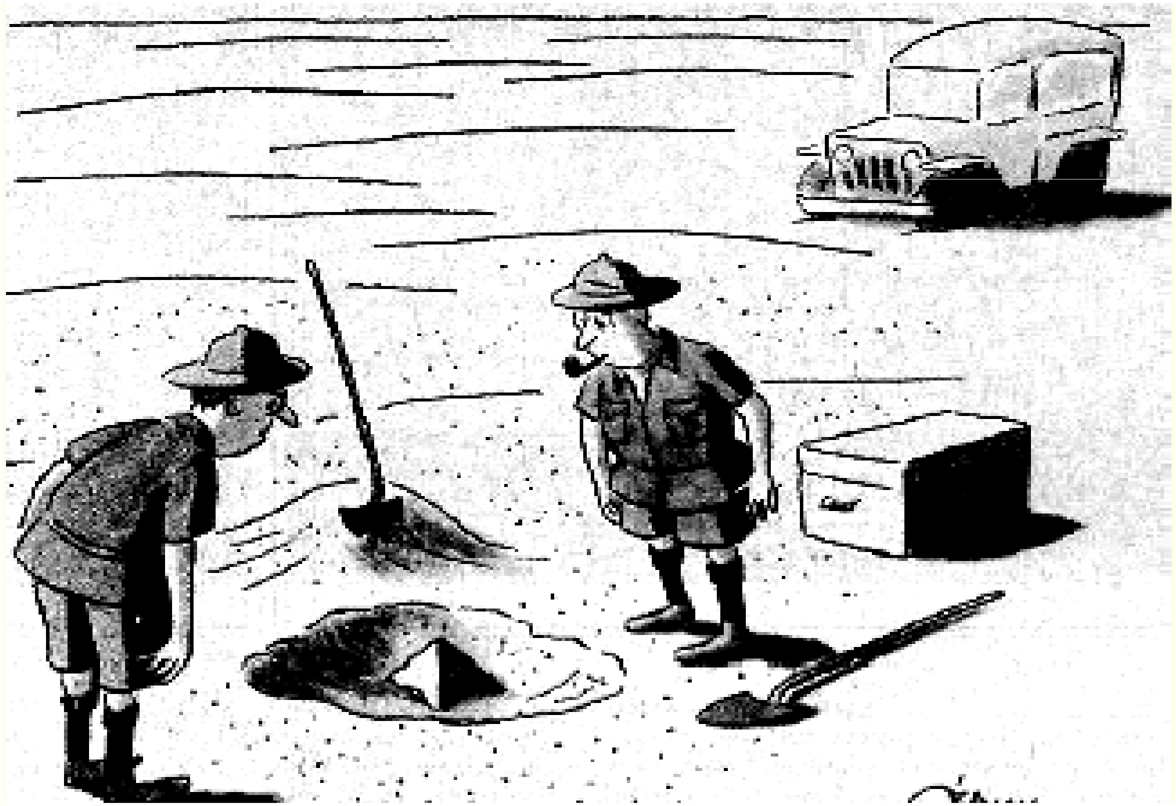
- Provides another low E data set and directly checks LSND.

MiniBooNE is collecting more data from NuMI beamline (different beam, another Low E data set).

SciBooNE is a near detector experiment now running that should make a (independent) cross check measurements.

Much interest in MiniBooNE results (New Physics Beyond Standard Model?).

More results Shortly…

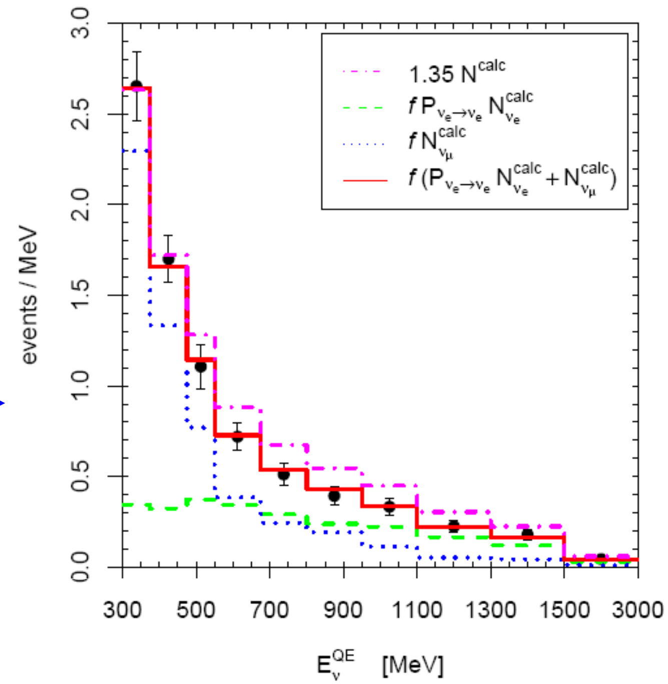


"This could be the discovery of the century. Depending, of course, on how far down it goes"

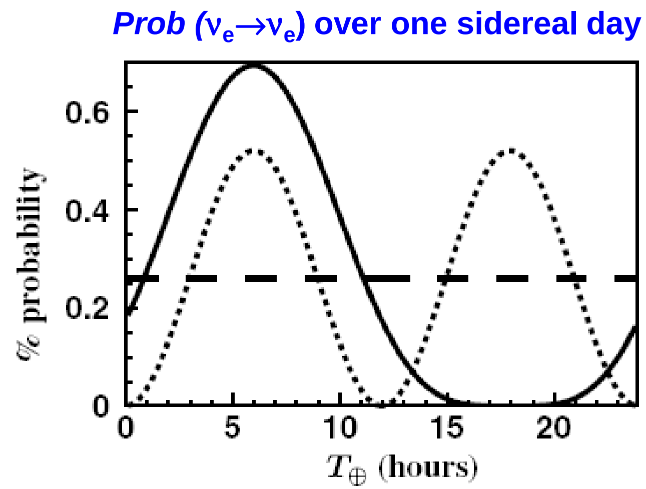
Backups

Other New Physics Models

- Electron neutrino disappearance (Giunti and Laveder, hep-ph 0707.4593)
- Prompted by the deficit seen in the Ga exp's source calibrations
- To fit the MiniBooNE data, postulate that the neutrino flux is off by x1.48 and that electron neutrino disappearance probability is 0.59
- This model disagrees with the MiniBooNE constraints on the measured p0 background



- Lorentz Invariance Violation (Katori, Kostelecký, Tayloe, PRD 74,1050009)
- Adding Lorentz invariance violating terms in the Hamiltonian that depend on neutrino flavor can produce interference terms for the neutrino propagation
- New oscillation phenomenology
- Osc length dependence on E*L
- Variation with sidereal position



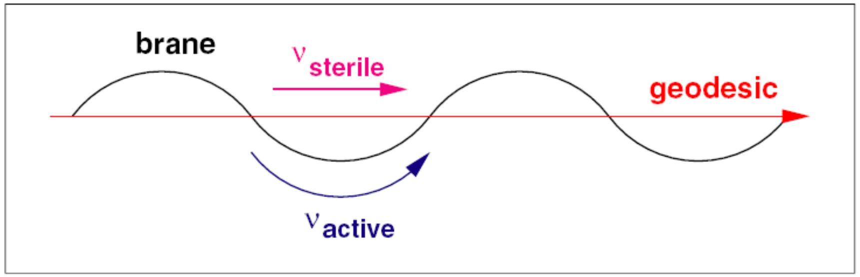
Sterile Neutrinos That Take Shortcuts in Extra Dimensions

- Prior to MiniBooNE's first result, it was put forward that sterile neutrinos can take shortcuts in extra dimensions.

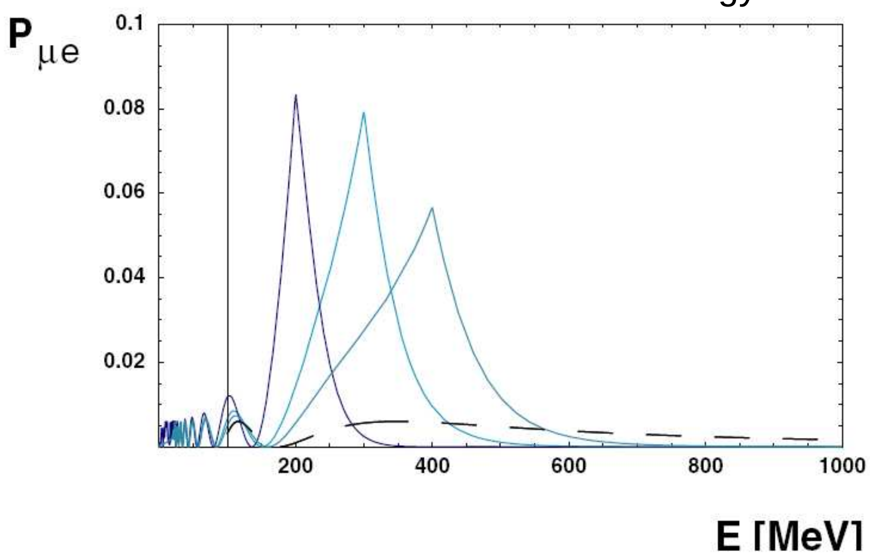
(Päs, Pakvasa, Weiler, Phys.Rev. D72 095017, 2005)

  - A resonance in active-sterile neutrino oscillations arises from an increase in the path-length of active neutrinos relative to sterile neutrinos in the bulk.
    - Below the resonance, the standard oscillation formulas apply.
    - Above the resonance, active-sterile oscillations are suppressed.
    - A resonance energy in the range of 30– 400 MeV allows an explanation of all neutrino oscillation data, including LSND data in a 3+1 model
    - And this model can evade the problems with the Bugey and CDHS limits.
  - This paper predicted that a significant oscillation signal would only be seen in MiniBooNE at low

Schematic representation of a periodically curved brane in Minkowski spacetime.



Oscillation probabilities for MiniBooNE as a function of the neutrino energy.



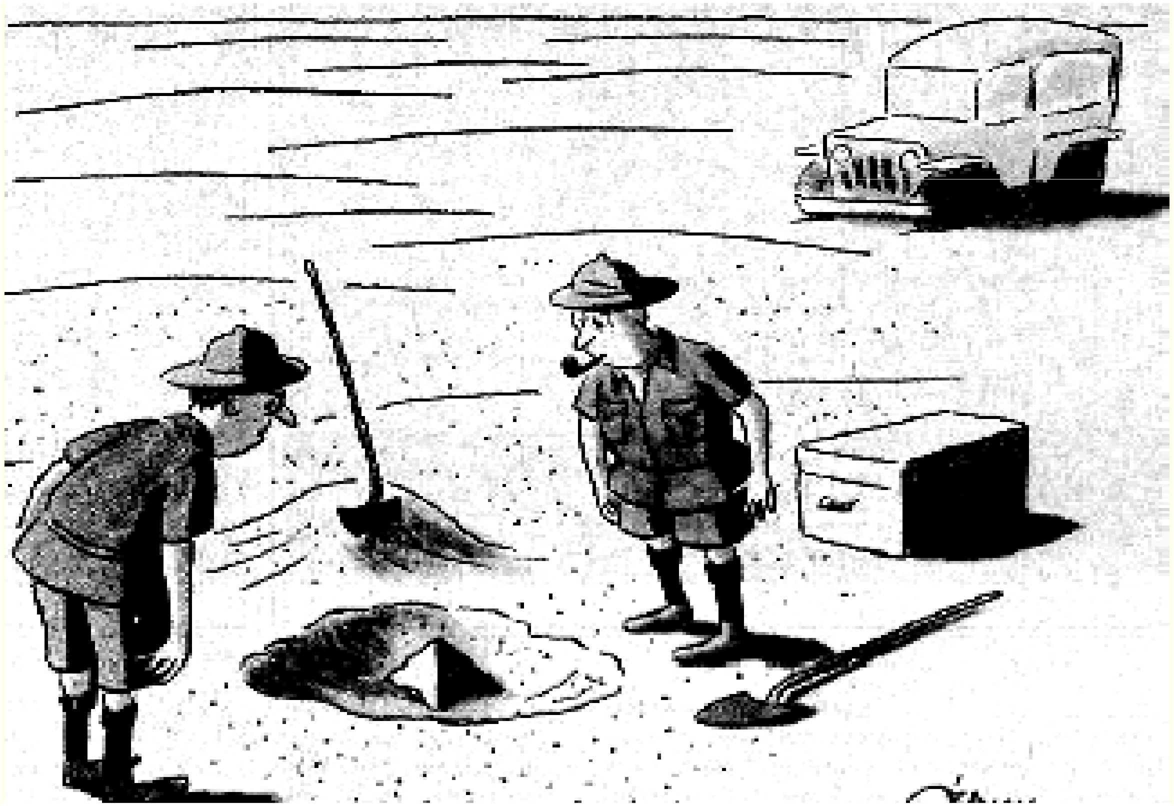
Future Steps

MiniBooNE has been running with Booster antineutrino beam and is granted to run antineutrinos for several more years.

- Statistics are less but background are smaller and somewhat different.
- Provides another low E data set and directly checks LSND.

MiniBooNE is collecting more data from NuMI beamline

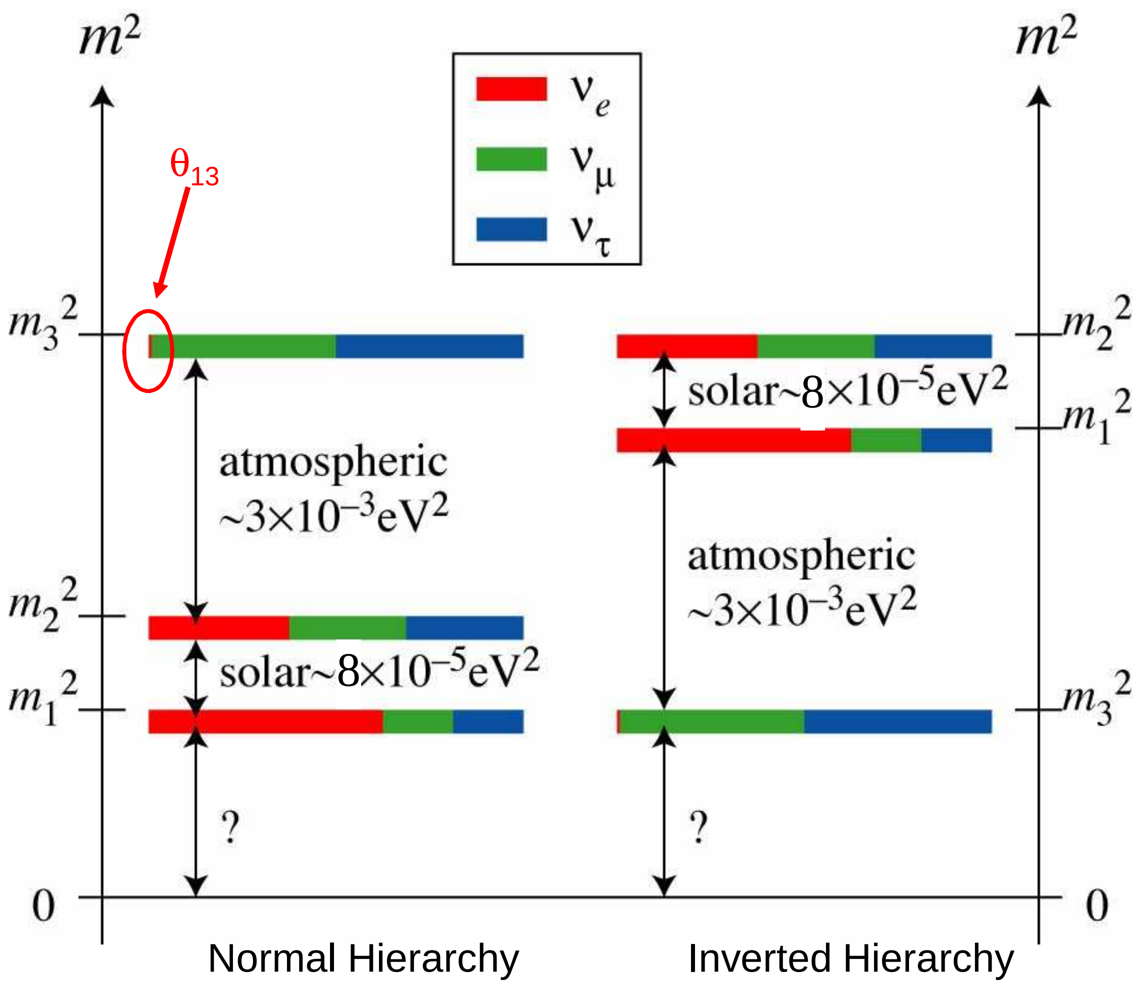
SciBooNE is a near detector experiment now running that should be able to make a cross check of the intrinsic ν_e's from kaon decay.



"This could be the discovery of the century. Depending, of course, on how far down it goes"

Big Questions in Neutrino Oscillations

1. What is ν_e component in the ν_3 mass eigenstate?
   $\Rightarrow$ The size of the "little mixing
   angle", θ_{13} ?
   Only know $\theta_{13}<13^0$
2. Is the μ - τ mixing maximal?
   $35^0 < \theta_{23} < 55^0$
3. What is the mass hierarchy?
   Is the solar pair the most massive or not?
4. What is the absolute mass scale for neutrinos?
   We only know Δm^2 values
5. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?

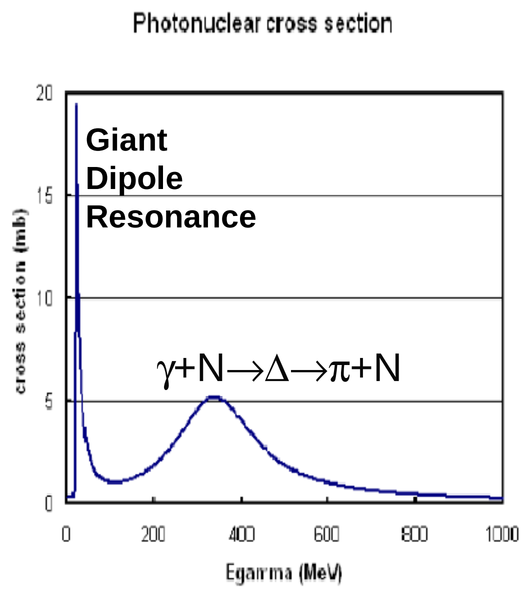


Possible Sources of Single Gamma Backgrounds

Since MiniBooNE cannot tell an electron from a single gamma, any process that leads to a single gamma in the final state will be a background

Processes that remove/absorb one of the gammas from a ν_μ-induced NC $\pi^0 \rightarrow \gamma\gamma$

- These processes should be in the GEANT detector Monte Carlo but there might be exceptions or inaccurate rates
- Example: photonuclear absorption
- But tends to give extra final state particles

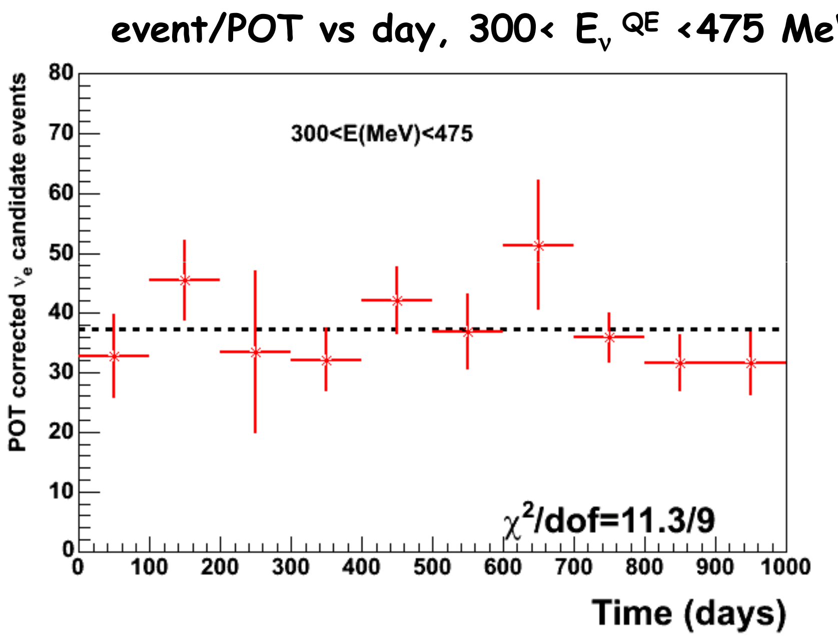


Explains some, but far from all of the excess.

Investigation of detector anomalies or problems

No Detector anomalies found

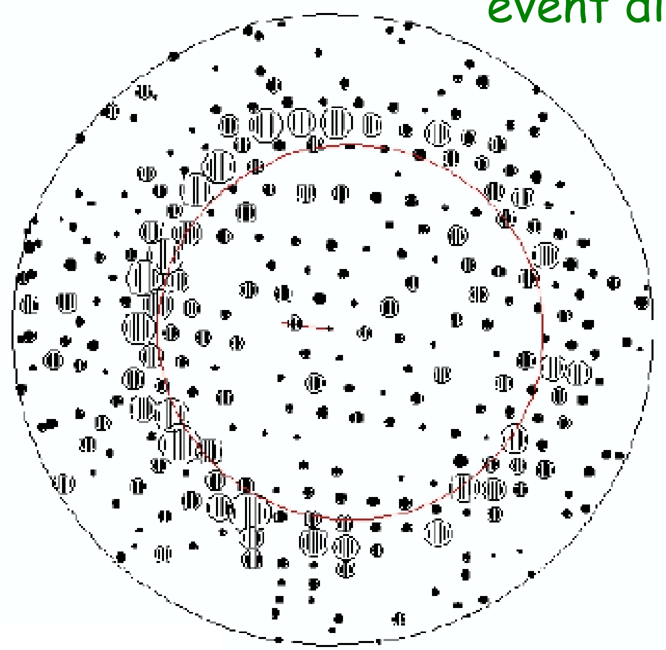
Example: rate of electron candidate events is constant (within errors) over course of run



No Reconstruction problems found

All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

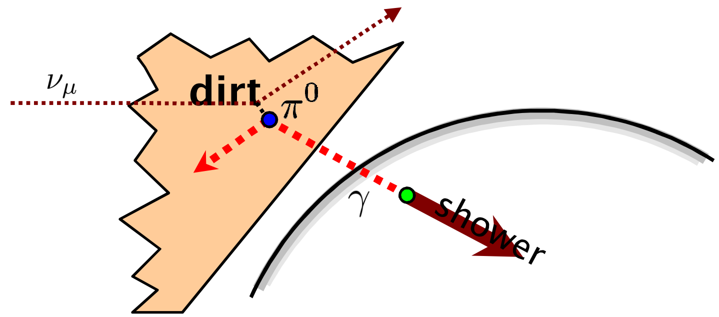
example signal-candidate event display



Signal candidate events are consistent with single-ring neutrino interactions

$\Rightarrow$ ***But could be either electrons or photons***

Analysis of dirt events from NuMI beam



- "Dirt" background is due to ν interactions outside detector. Final states (mostly neutral current interactions) enter the detector.

- **Measured** in "dirt-enhanced" samples:
    - we tune MC to the data selecting a sample dominated by these events.

- "Dirt" events coming from outside deposit only a fraction of original energy closer to the inner tank walls.
- -Shape of visible energy and event vertex distance-to-wall distributions are well-described by MC: good quantities to measure this background
- component.

Selecting the dirt events

Event pre-selection:
1 subevent
Thits>200, Vhits<600
R<500 cm

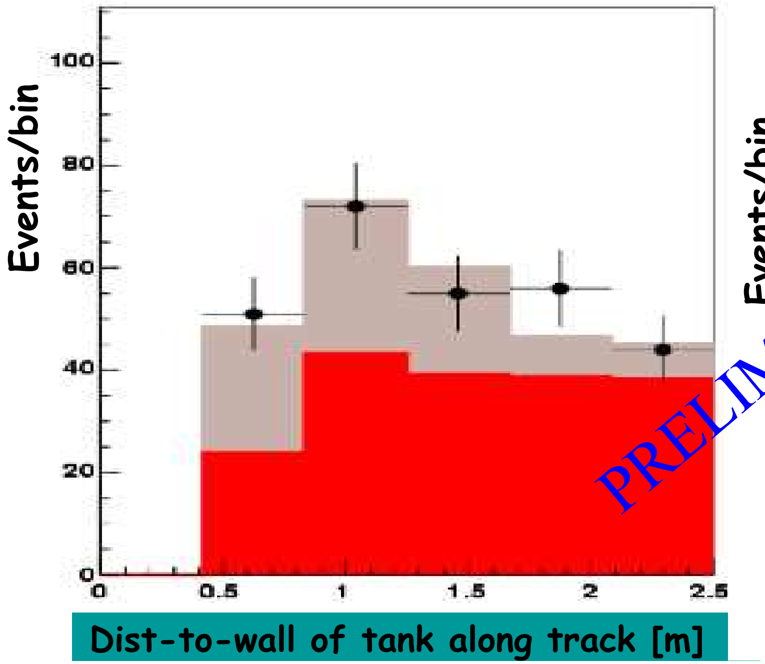
$\log(L_e/L_\mu)>0.05$ (e-like)

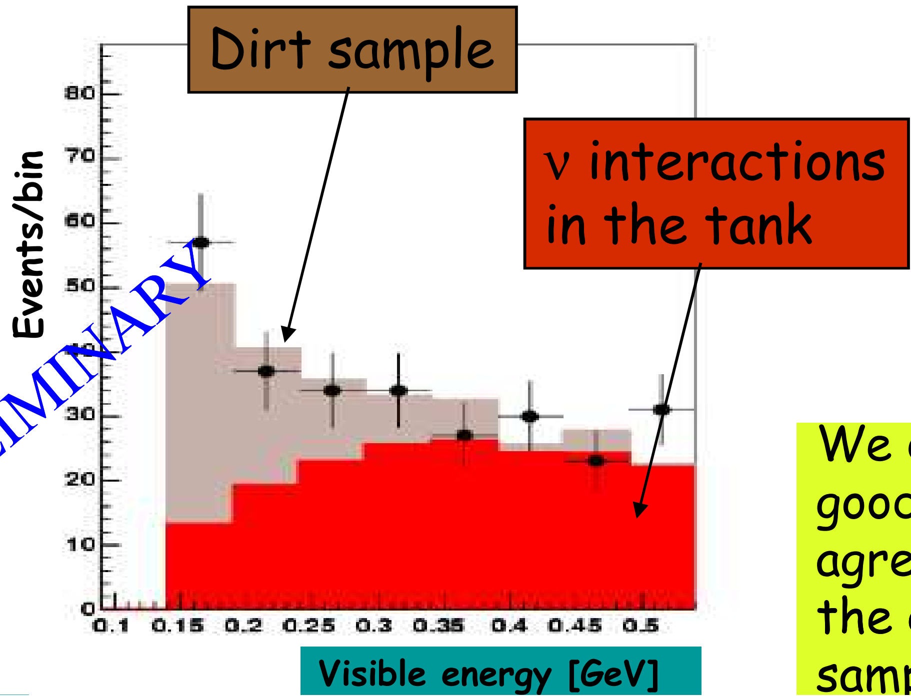
E_e <550 MeV

Distance-to-wall <250 cm

m_π<70 MeV/c^2 (not π^0-like)

Fits to dirt enhanced sample: Uncertainty in the dirt rate is less than 20%.





We declare good MC/Data agreement for the dirt sample.

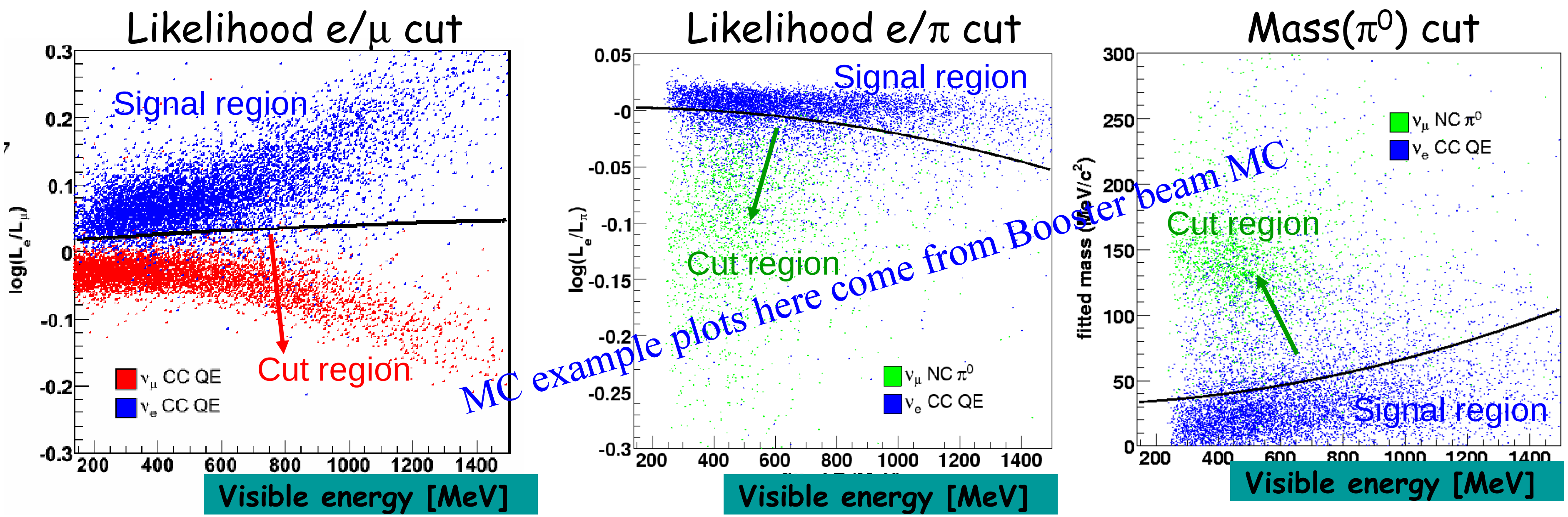
Analysis of the ν_e CCQE events from NuMI beam

ν_e CCQE (ν+n $\rightarrow$ e+p)

1 Subevent
Thits>200, Vhits<6
R<500 cm, E_e>200MeV

\+ Likelihood cuts as the as shown below

E_e>200MeV cut is appropriate to remove ν_e contribution from the dump that is hard to model.

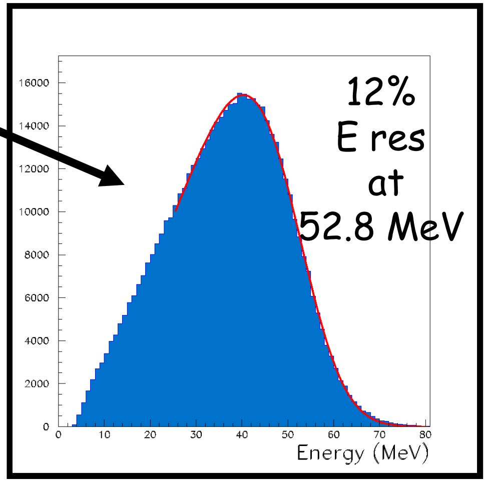


Analysis of ν_e events: do we see data/MC agreement?

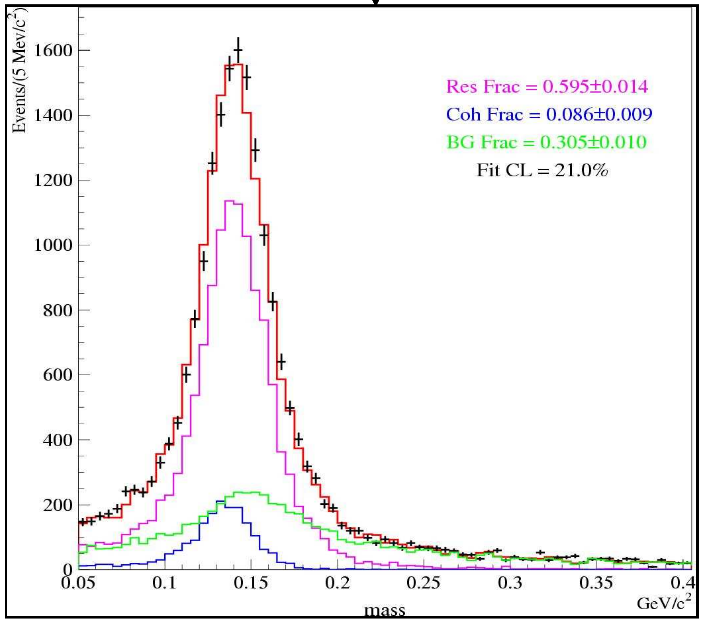
Energy Calibration

We have calibration sources spanning wide range of energies and all event types !

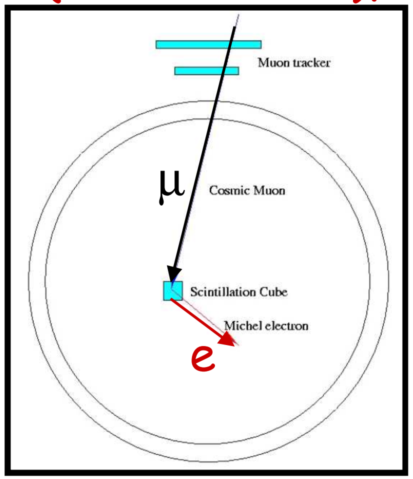
Michel electrons from μ decay:
provide E calibration at low energy **(52.8 MeV)**,
good monitor of light transmission, electron PID



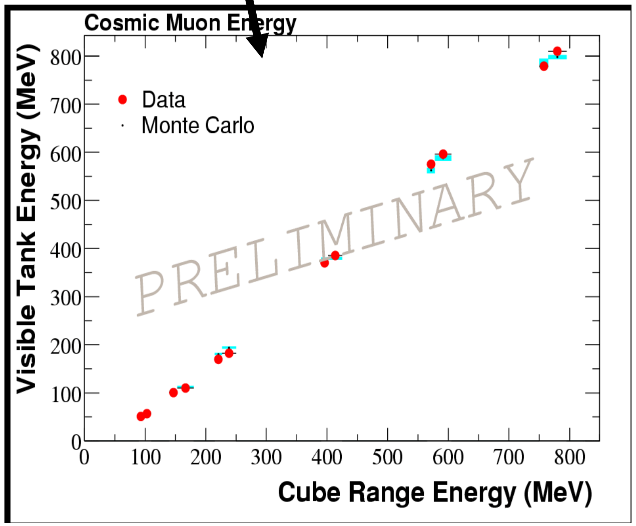
π^0 mass peak: energy scale & resolution
at medium energy **(135 MeV)**, reconstruction



cosmic ray μ + tracker + cubes:
energy scale & resolution at high energy
(100-800 MeV), cross-checks track reconstruction



provides μ tracks of
known length → E_μ



Analysis Motivation

Observation and analysis of an off-axis beam.

Measurement of π/K components of the NuMI beam.

The NuMI beam provides MiniBooNE with an independent set of neutrino interactions.

Enables a comparison of the Booster Neutrino Beam (BNB) with the NuMI neutrino beam (off axis):
- -Similar energy spectrum.
- -Proton target is further away (~746 m vs. 550 m)
- -Very different background composition.
- -Rich in ν_e flux $\rightarrow$can study ν_e reactions in greater detail.