

# *Physics of Short Baseline Accelerator Neutrino Experiments*

- ♦ SBL oscillations
  - ♦ LSND signal (sterile neutrinos?)
  - ♦ what to do about it
- ♦ Connections with other  $\nu$  sub-fields
  - ♦ nuclear physics (via precision CCQE  $\sigma$  measurements)
  - ♦ LBL, Atm. (via single  $\pi$  production  $\sigma$  measurements)
  - ♦ astrophysics (via SBL sterile neutrino searches)

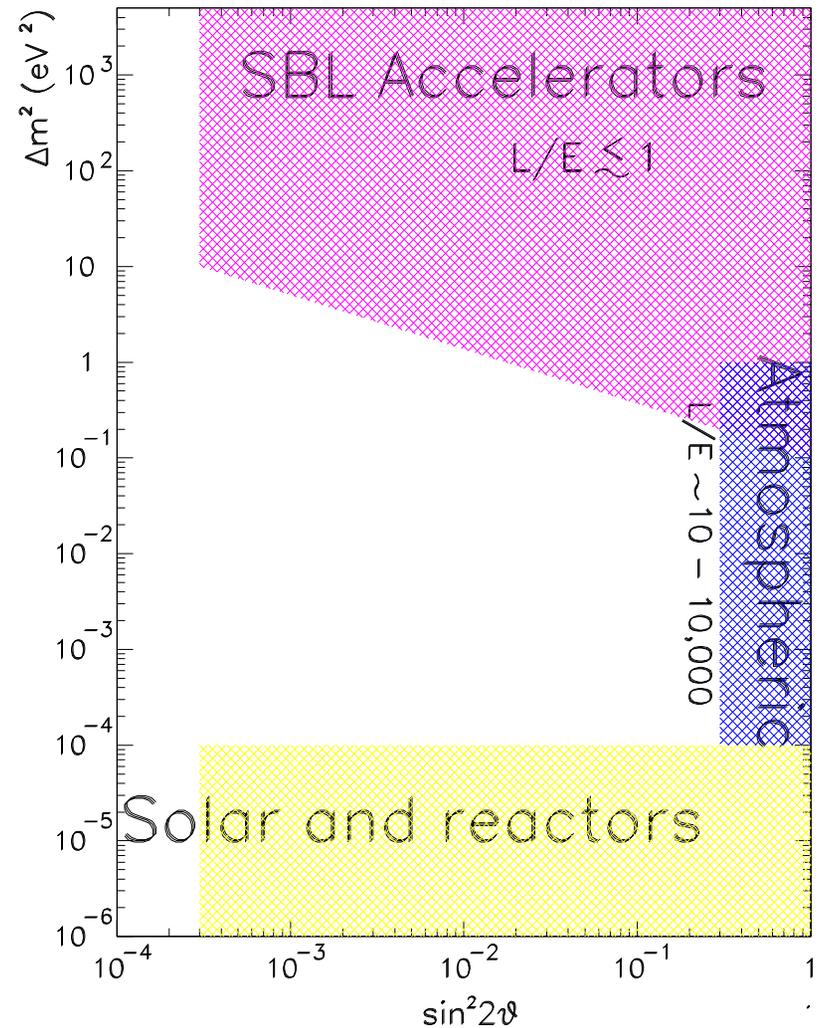


# SBL Oscillation Physics

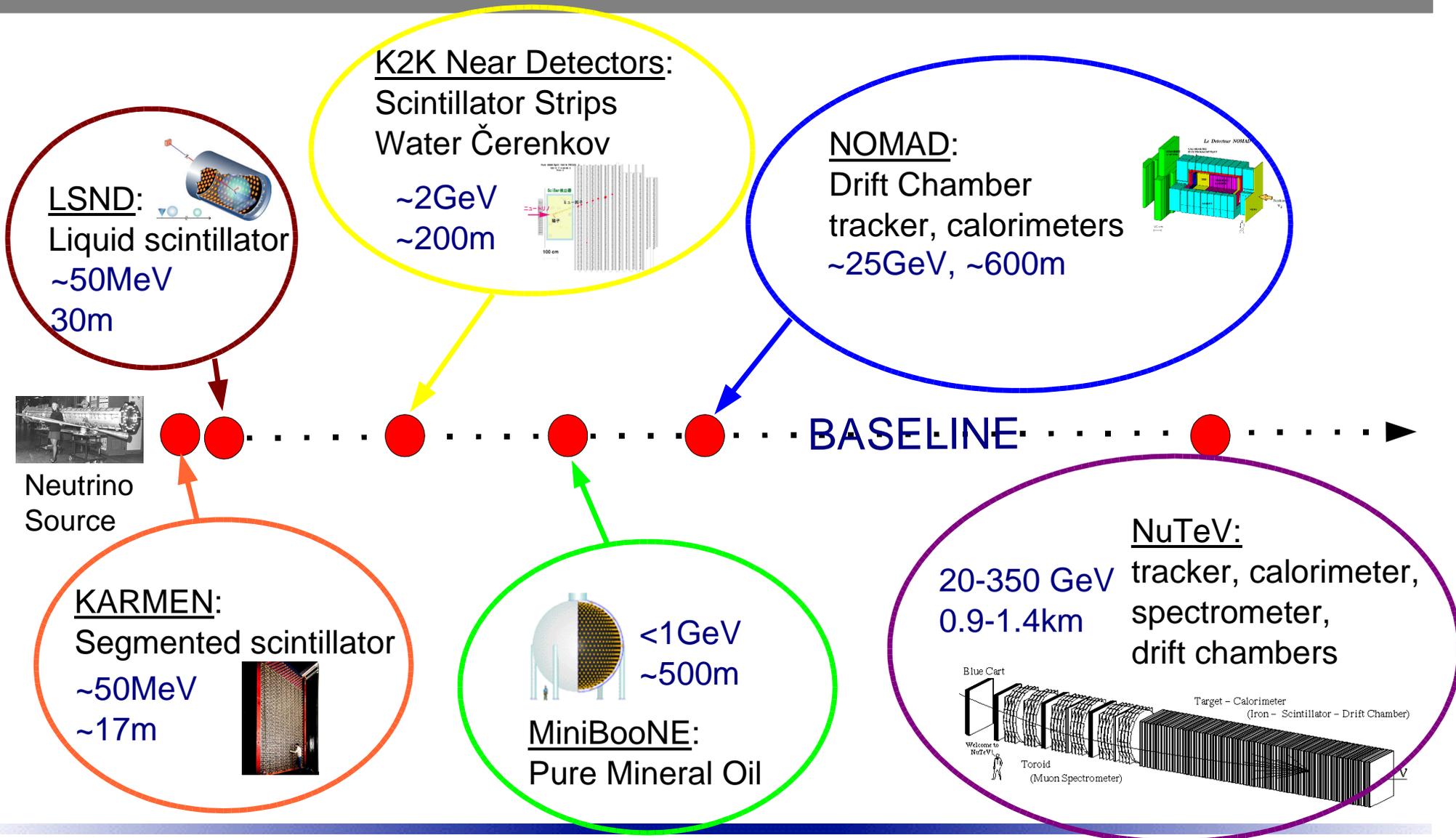
- Oscillation physics at high  $\Delta m^2$ ,

$$P(\nu_a \rightarrow \nu_b) \propto \sin^2(2\theta) \sin^2\left(1.27 \Delta m_{12}^2 \frac{L}{E}\right)$$

- $0.03 < E_\nu < 300 \text{ GeV}$ ,  $30\text{m} < L < 1.4\text{km}$
- low  $\sin^2 2\theta$  accessible with high statistics
- exciting prospects:
  - sterile  $\nu$ s
  - search for CPT violation
  - if LSND *is* oscillations, search for CP violation in  $\nu$ s at moderate baselines (30km)

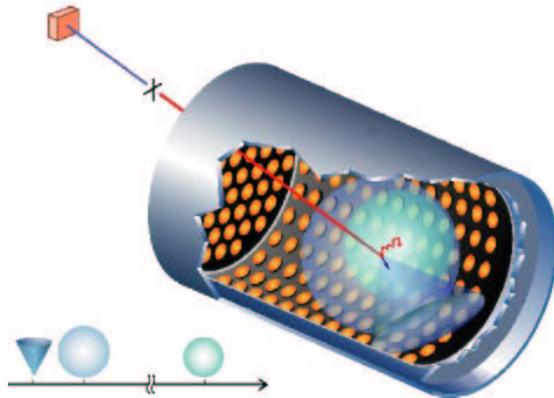


# SBL: The Experiments



# The LSND Signal

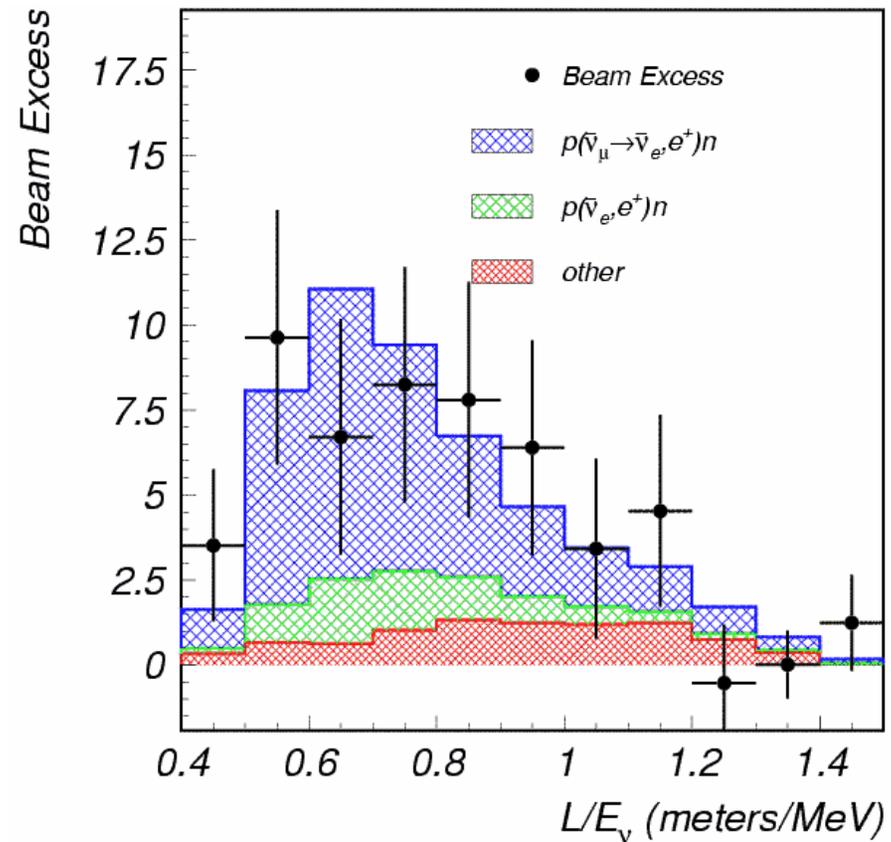
Observed:  
 $87.9 \pm 22.4 \pm 6.0$   
 $\bar{\nu}_e$  events



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

$n p \rightarrow d \gamma(2.2\text{MeV})$

3.8 $\sigma$  excess, 3.3 $\sigma$  oscillation, probability:  $(0.264 \pm 0.067 \pm 0.045)\%$ .



# Current SBL $\nu_{\mu} \rightarrow \nu_e$ Oscillation Picture

• L/E range:  $10^{-2}$ -10:  $\Delta m^2 > 0.1 \text{eV}^2$

• Positive Result:

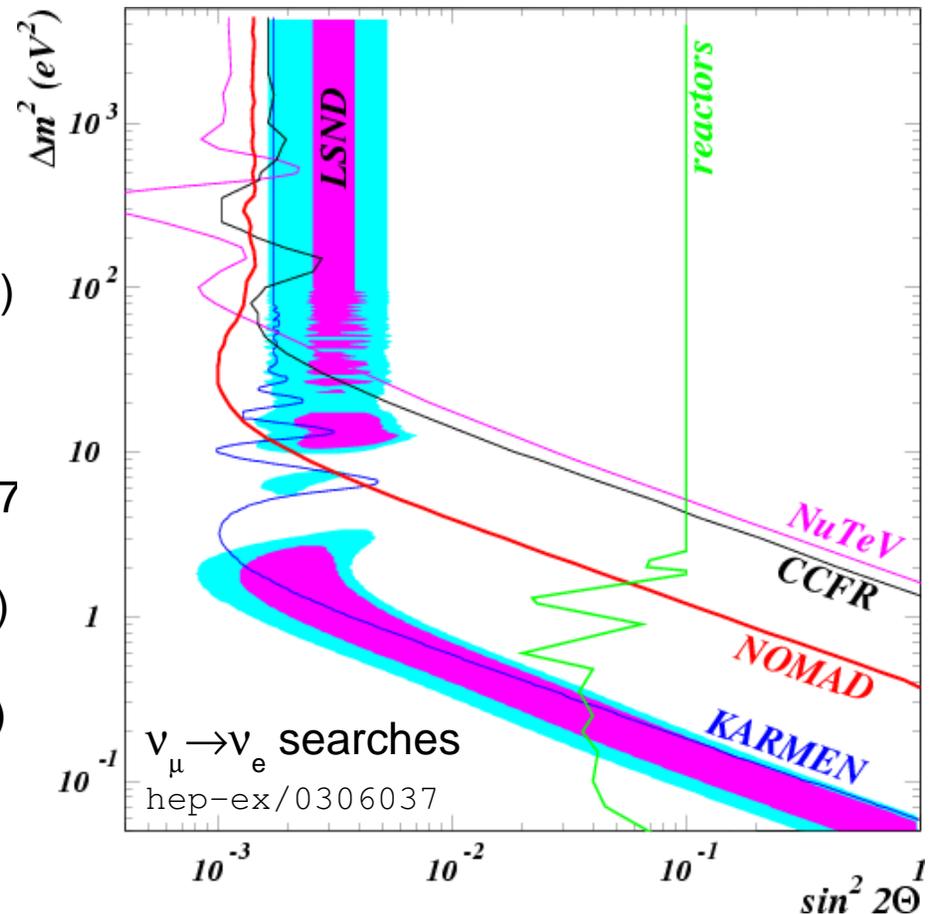
• LSND:  $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$  (1993-1998)

• SBL oscillation NULL results:

• NuTeV, CCFR:  $\nu_{\mu} \rightarrow \nu_{e,\tau}$  (1985→1997)

• NOMAD:  $\nu_{\mu} \rightarrow \nu_{e,\tau}$  (1994-1998)

• KARMEN:  $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$  (1992-1999)

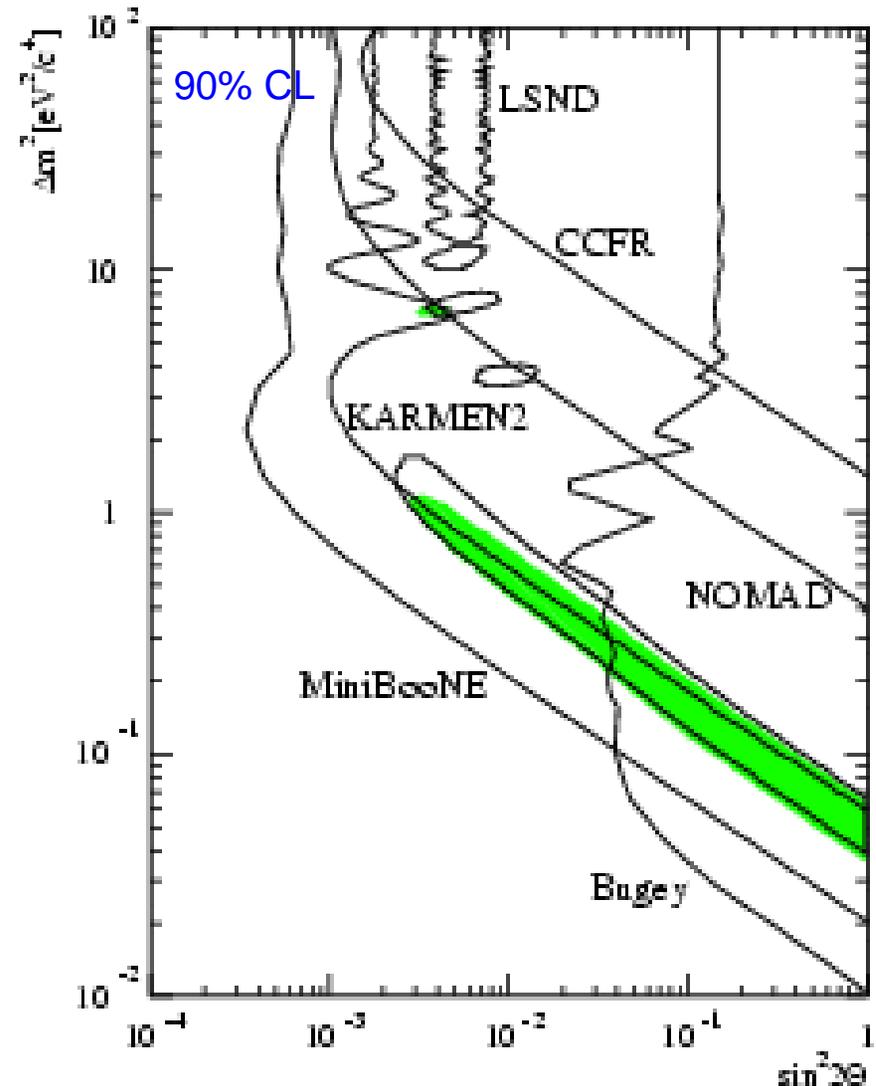


# LSND and KARMEN

## KARMEN/LSND Joint Analysis:

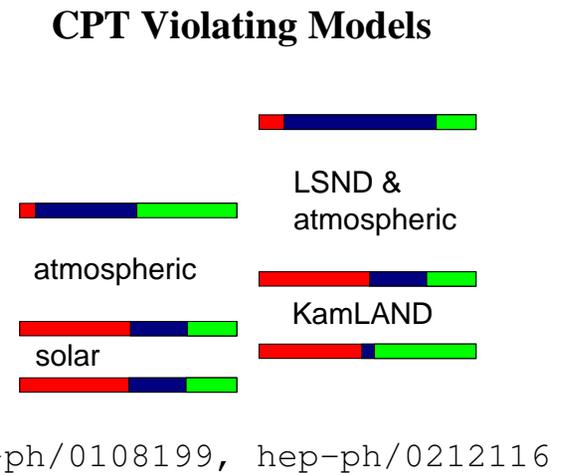
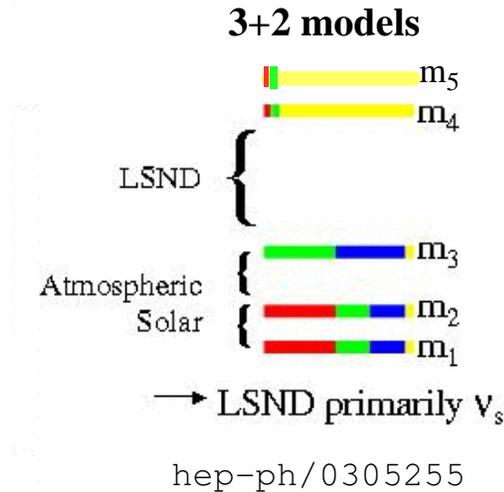
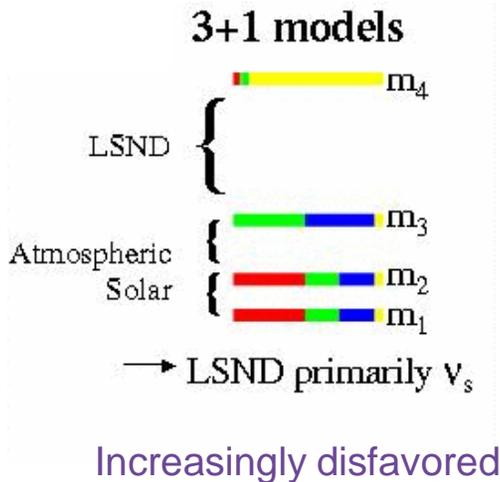
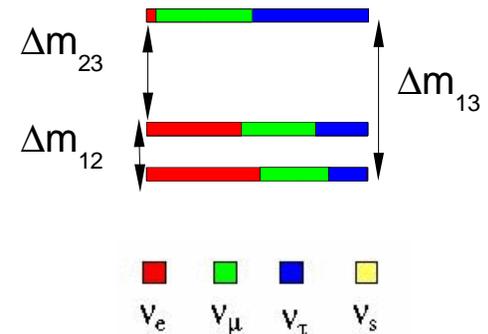
hep-ex/0203023

- ◆ KARMEN and LSND collaborators performed a combined analysis of both data sets
- ◆ Relatively low statistical power of KARMEN's data cannot cover all of LSND allowed region
  - ◆  $3.8 \sigma$  is a strong signal!



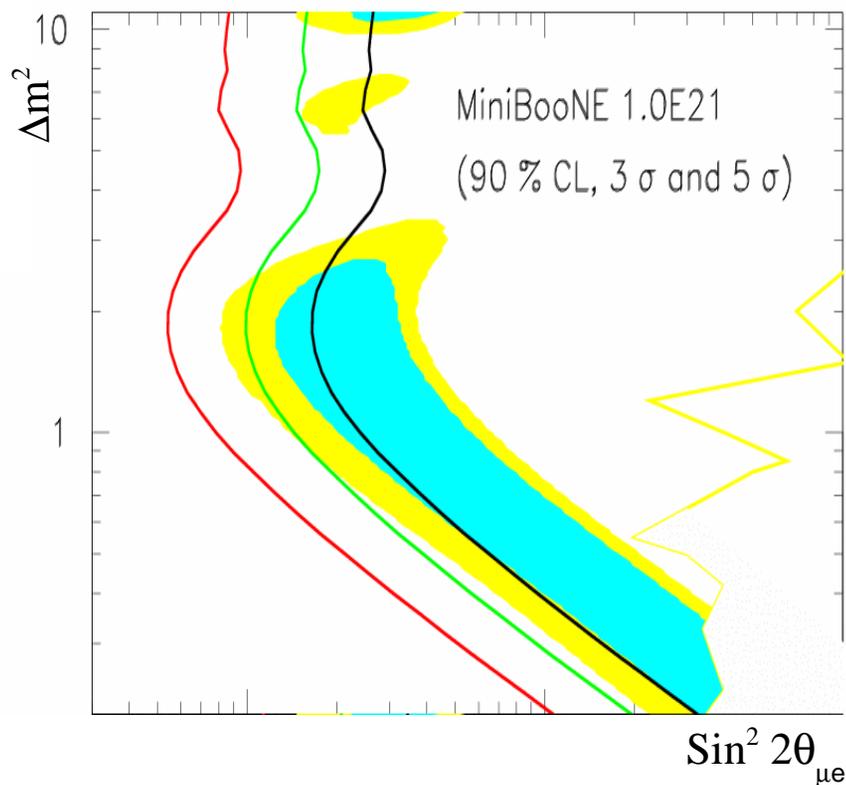
# Interpretations of the LSND Signal

- Not oscillations?
  - Anomalous muon decay? Ruled out by KARMEN2 at 90%CL (hep-ex/0302017)
- $10^{-5} + 10^{-3} \neq 1$  (Solar + Atmospheric  $\neq$  LSND)
- Sterile Neutrinos? (No weak coupling  $\Leftarrow$  invisible Z width)
- CPT Violation?



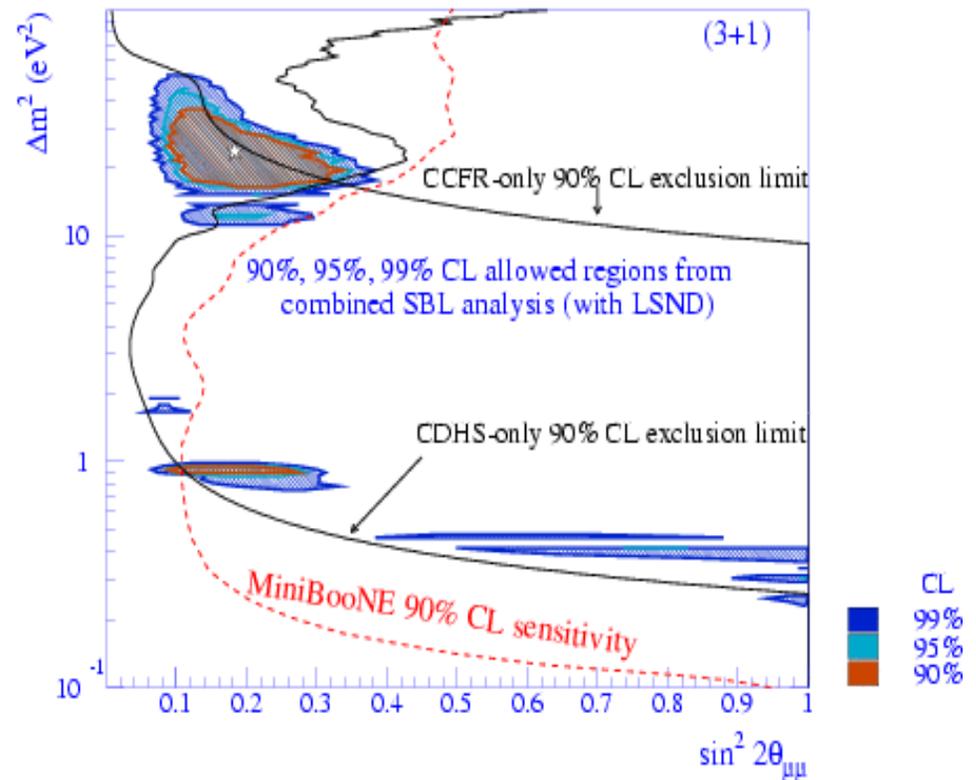
# MiniBooNE Sensitivity

- MiniBooNE can cover LSND region at 4-5 $\sigma$  level with 1.0E21 p.o.t.
- $\nu_\mu$  disappearance is *larger* than  $\nu_e$  appearance in models with steriles



$\nu_\mu \rightarrow \nu_e$ : first results in 2005

<http://www-boone.fnal.gov/publicpages/news.html>

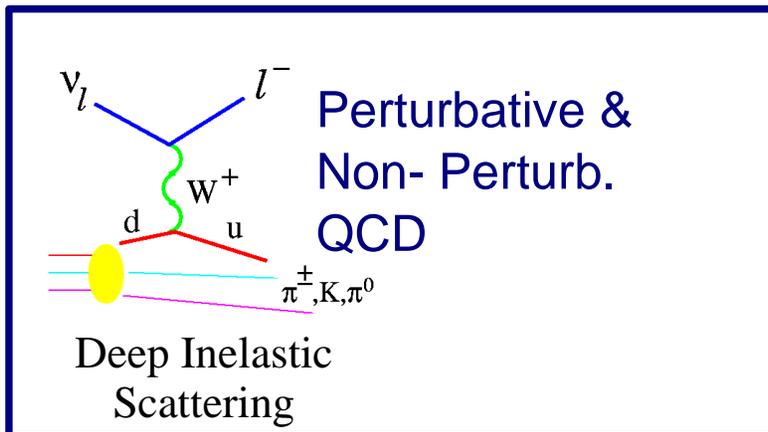
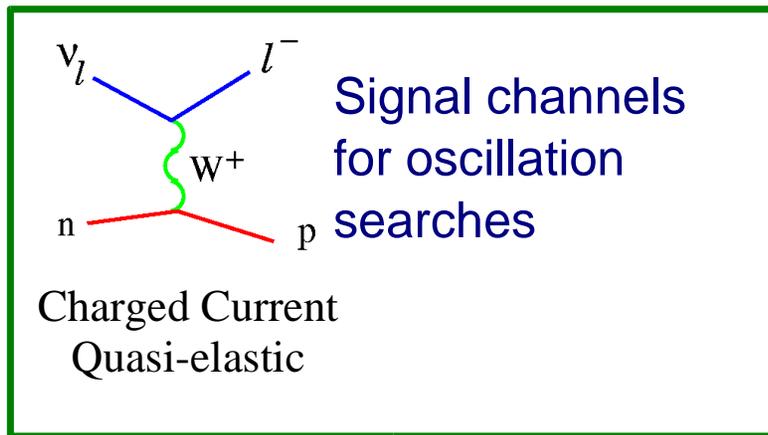


$\nu_\mu \rightarrow \nu_\chi$ : first results this year

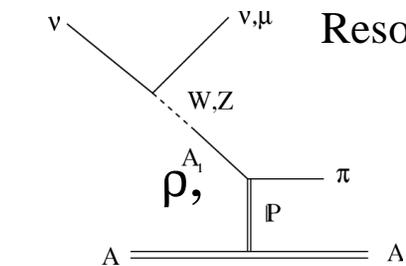


# Cross Section Physics

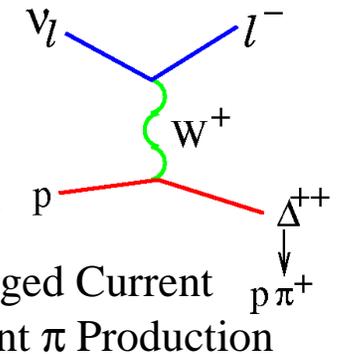
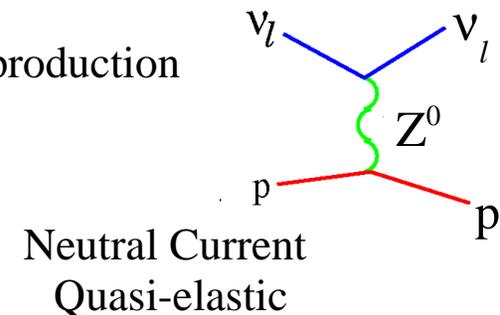
- Cross section measurements key to improving oscillation sensitivity
- much exciting physics accessible with SBL neutrino scattering data!



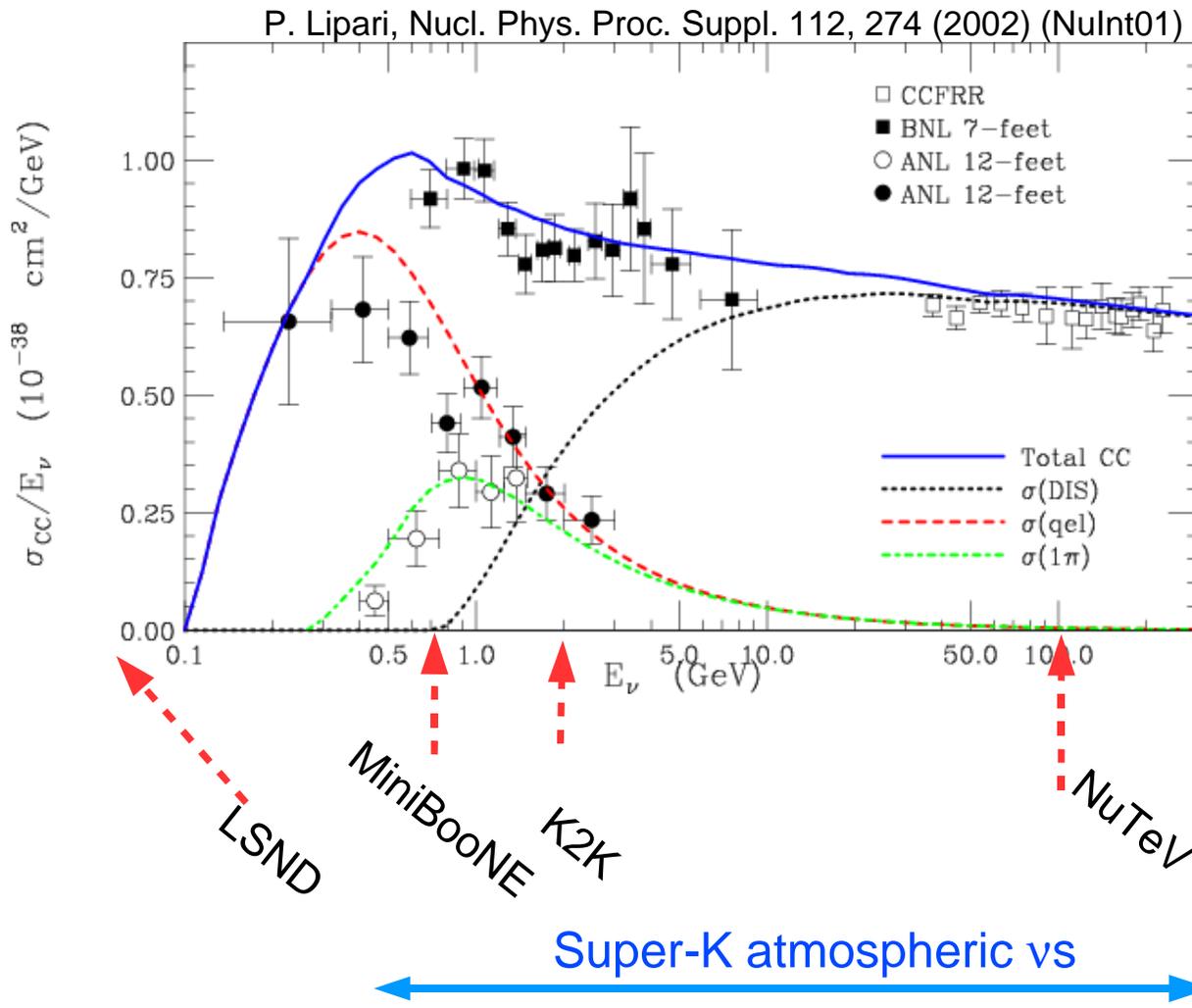
Background channels for oscillation searches and probes of nuclear structure



Coherent  $\pi$  production



# Current Cross Section Measurements

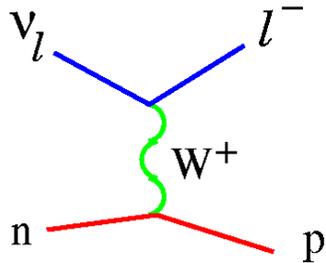


## Cross section uncertainties

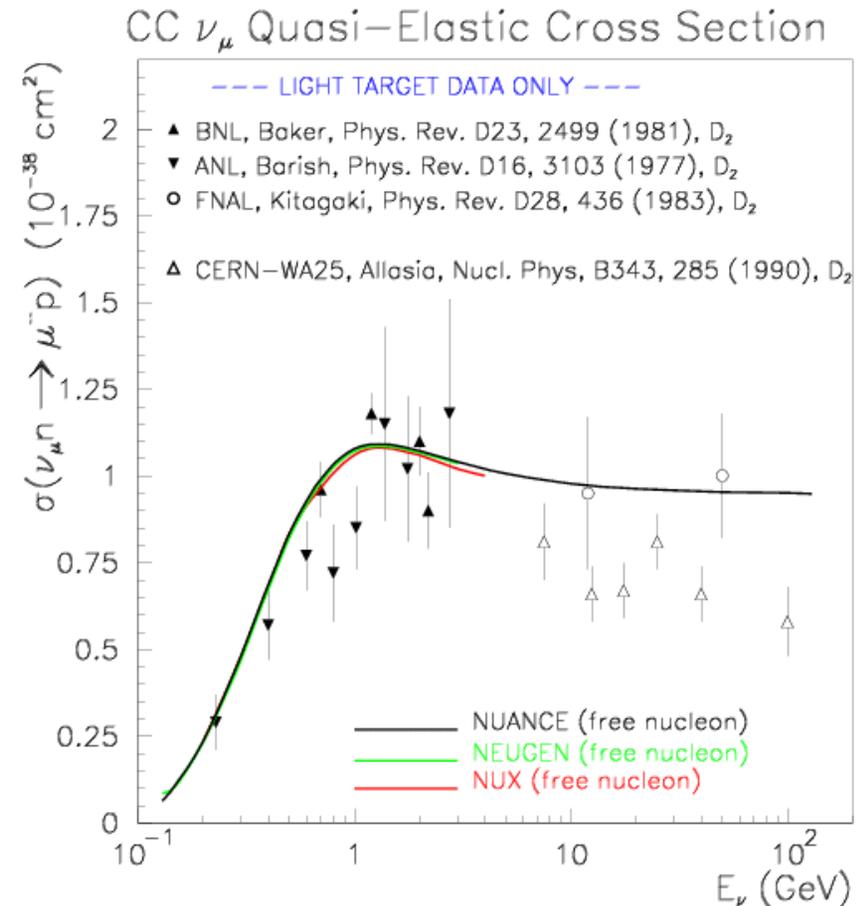
- ◆ DIS ~2%
- ◆ CCQE ~ 20%+
- ◆ Res. Single Pion ~ 20%
- ◆ Neutral Pion Production
  - ◆ Resonant ~ 40%
  - ◆ Coherent ~100%



# CCQE Cross Section

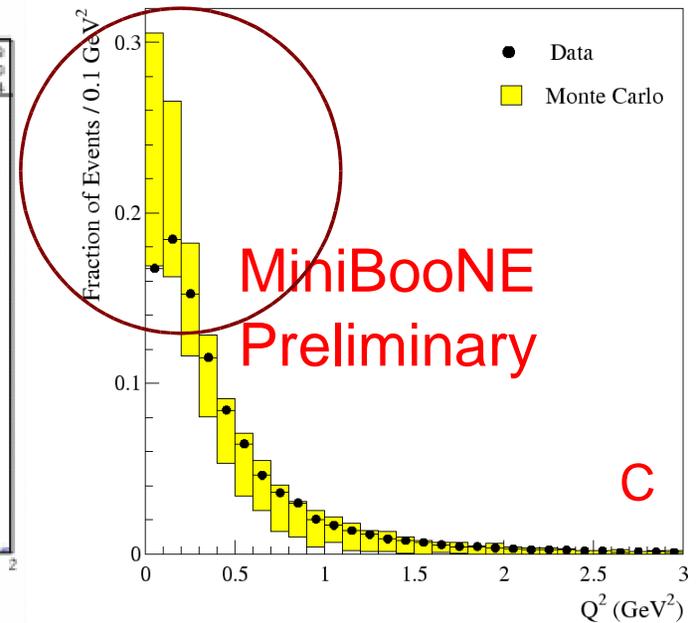
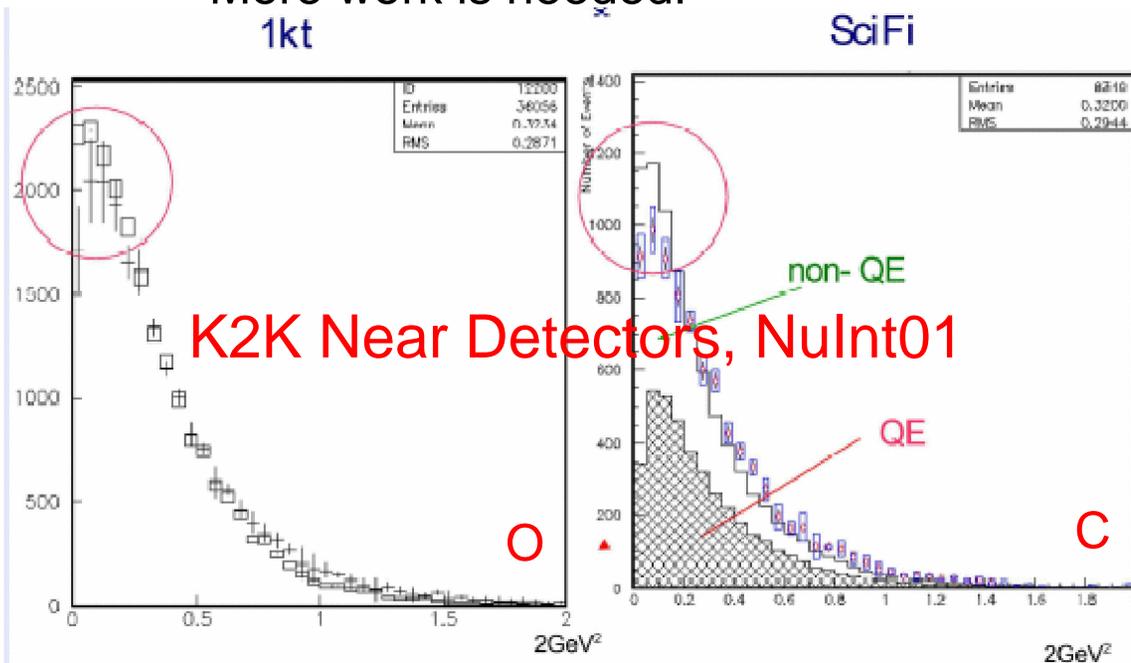
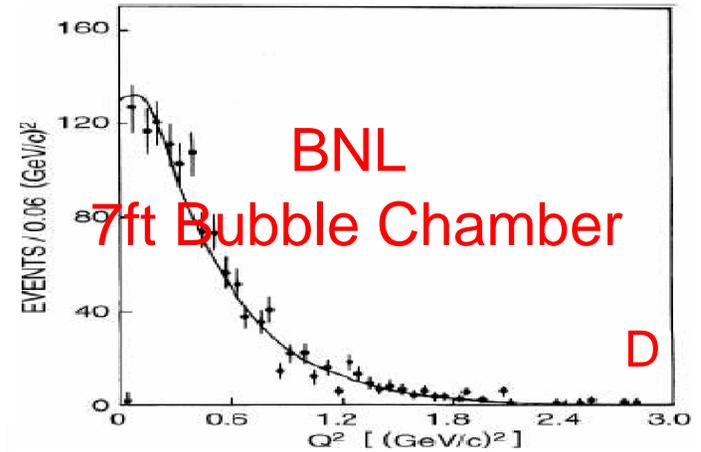


- CCQE reaction is used to search for oscillations
- Cross section industry is booming
- Data is pouring in from expts
- Monte Carlo Generators
  - NUANCE, NEUGEN, NEUT, NUX ...
- Low energy  $\sigma_\nu$  soon to be included in Durham database

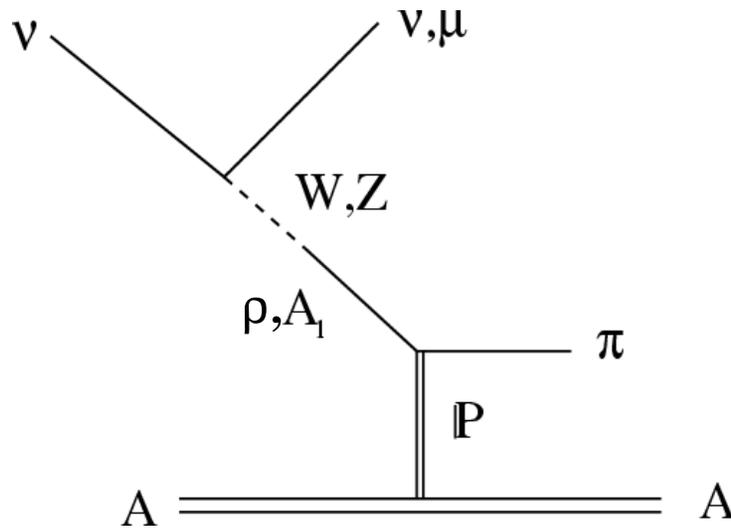


# CCQE Low $Q^2$ : Model Deficiencies?

- Larger than expected rollover at low  $Q^2$
- Pauli blocking expected, accounted for
- Nuclear Effects
  - Seen in DIS data by BEBC – shadowing
  - More work is needed!

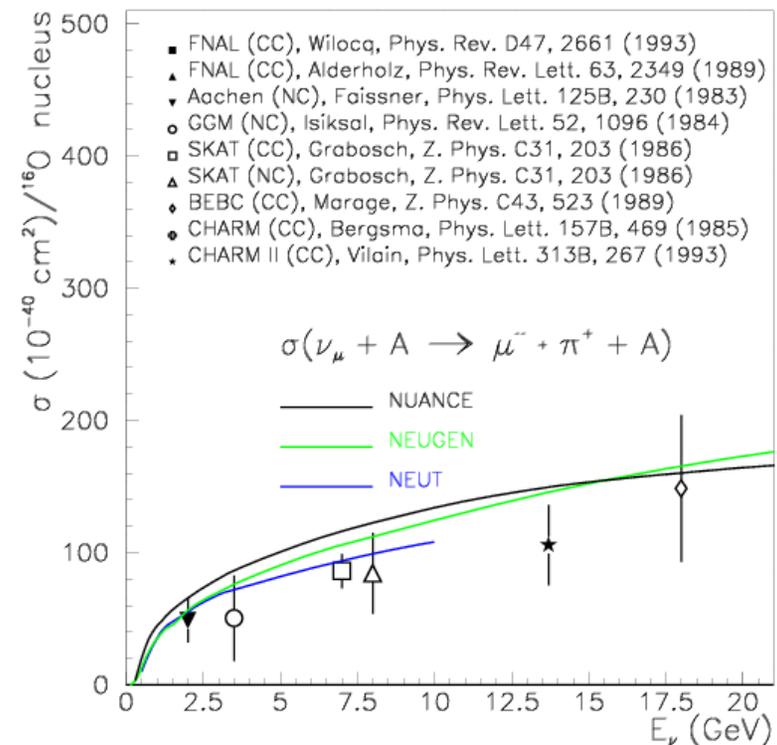


# Coherent Pion Production



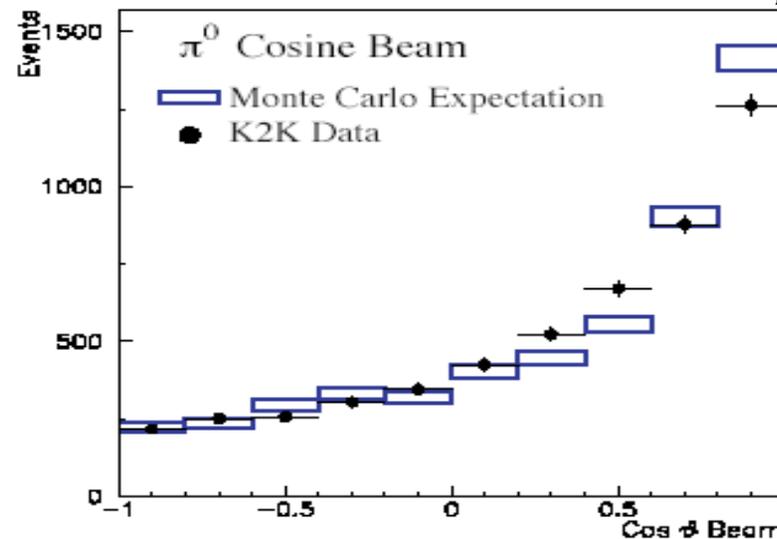
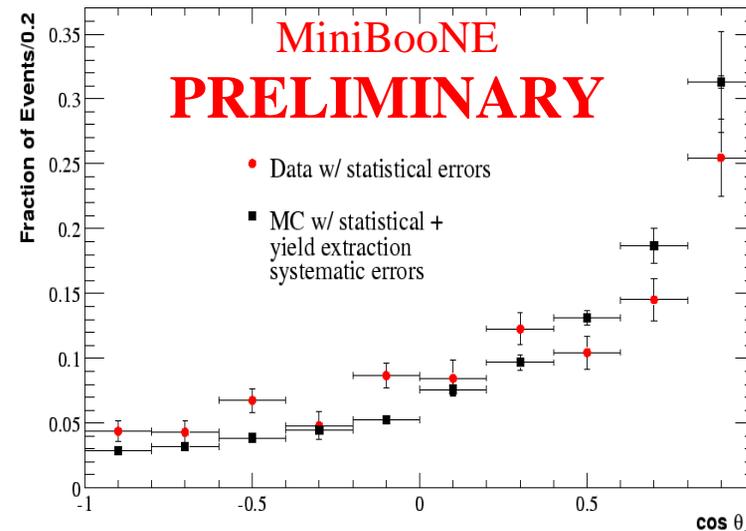
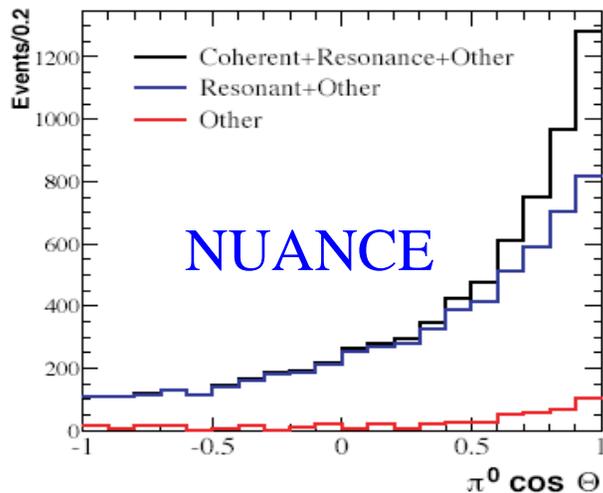
- Super-K BG for  $\nu_{\mu} \rightarrow \nu_s$  vs.  $\nu_{\mu} \rightarrow \nu_{\tau}$
- No data below 2 GeV!

- Neutrino scatters with whole nucleus
- diffractive scattering (Pomeron)
- Clear signature: forward-peaked
- $\sim 20\%$  of  $\sigma(\nu_{\mu} N \rightarrow X\pi^0)$  at 1 GeV



# Coherent Pion Production: Data

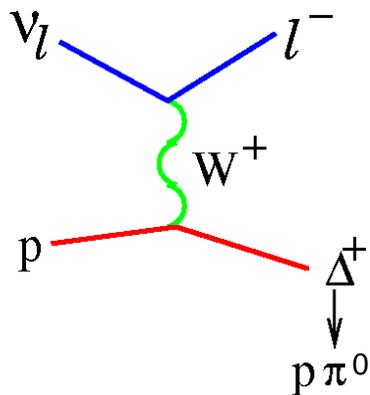
- K2K Near and MiniBooNE both suggest a reduction in forward peaked NC  $\pi^0$  events cf MC
- Competing models
  - Rein – Sehgal (NUANCE), Paschos (1/6 x NUANCE)
- Distinct kinematics



(C. Mauger, NuInt01)

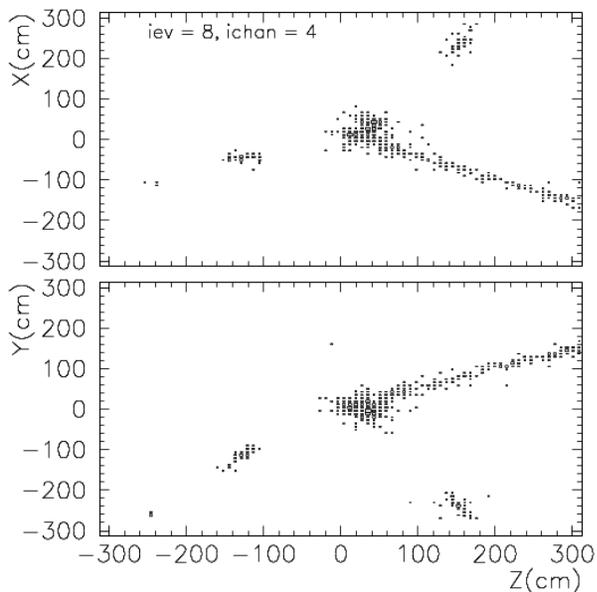


# High Precision Cross Sections: New SBL detectors wanted!



... for recoil nucleon energy measurement,  
complex final state ID, large active volume

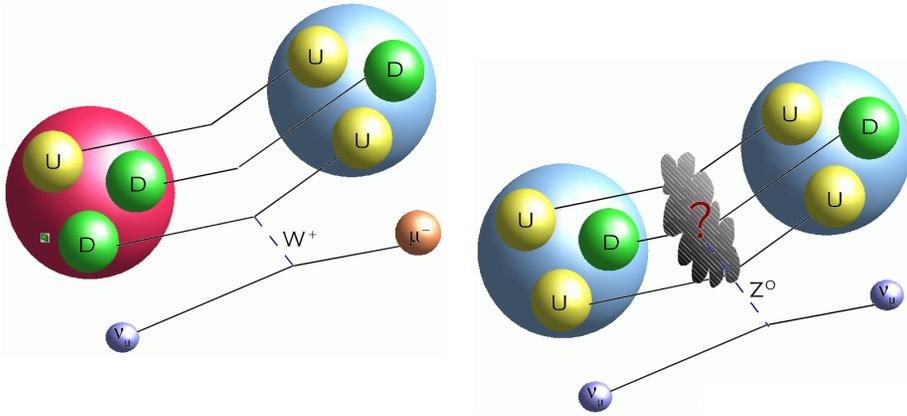
- ◆ FINEsSE (MiniBooNE beamline)
  - ◆ <http://home.fnal.gov/~bfleming/finese.html>
  - ◆ New detector technology: SciBath
  - ◆ Resonant CC  $\pi^0$  event:  $\nu_{\mu} n \rightarrow \mu^- p \pi^0$  (left)
- ◆ MINERvA (NuMI beamline)
  - ◆ <http://www.pas.rochester.edu/~ksmcf/minerva/>
  - ◆ Finely grained scintillator strips
  - ◆ DIS  $\sigma$ , form factors + ...



# Precision $\nu$ scattering with FINeSSE

$\Delta s$ : component of nucleon spin carried by strange quarks

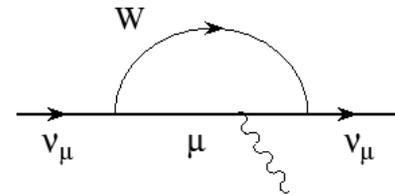
$$\frac{d\sigma}{dQ^2} \sim G_A^2 = (-g_a + G_A^s)^2$$



• Measure NC/CC ratio:

$$\bullet R_{\text{NC/CC}} = \sigma(\nu p \rightarrow \nu p) / \sigma(\nu n \rightarrow \mu p)$$

$\nu$  magnetic moment

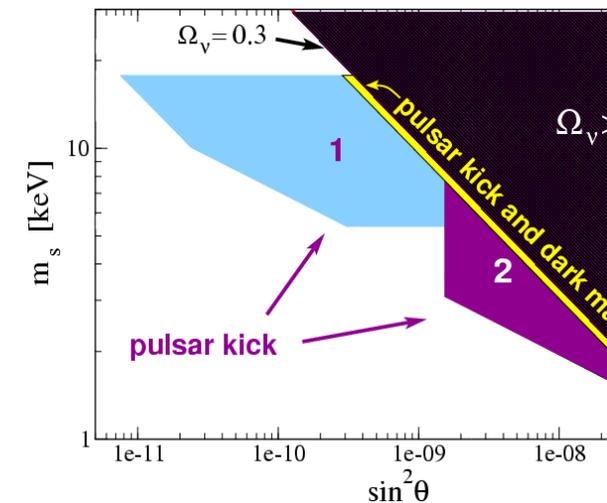
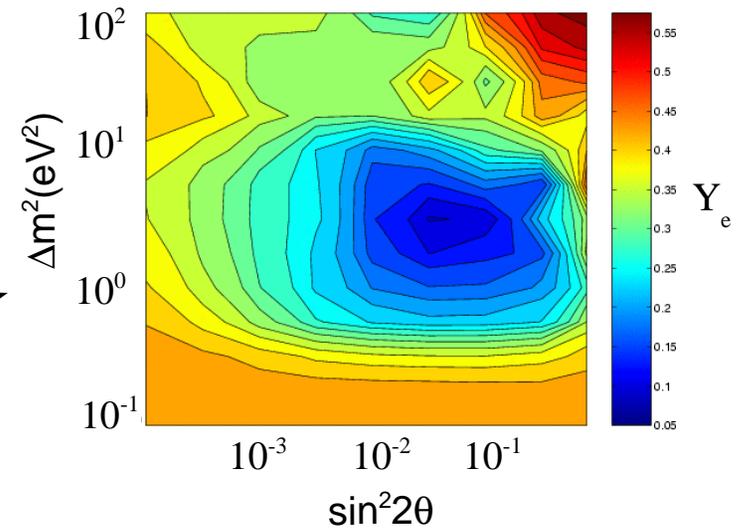


- Minimal Extension of SM:  
(Massive Dirac  $n$ ):  $\mu_{\nu} \sim 3 \times 10^{-19} \mu_B$
- SUSY:  $\mu_{\nu\mu} \sim 1 \times 10^{-(12-13)} \mu_B$
- Current best limit set by LSND:
  - $\mu_{\nu\mu} \sim 6.8 \times 10^{-10} \mu_B$
- Excess  $e-\nu_{\mu}$  scattering via EM
- MiniBooNE can improve LSND limit by factor of 2, FINeSSE even better!



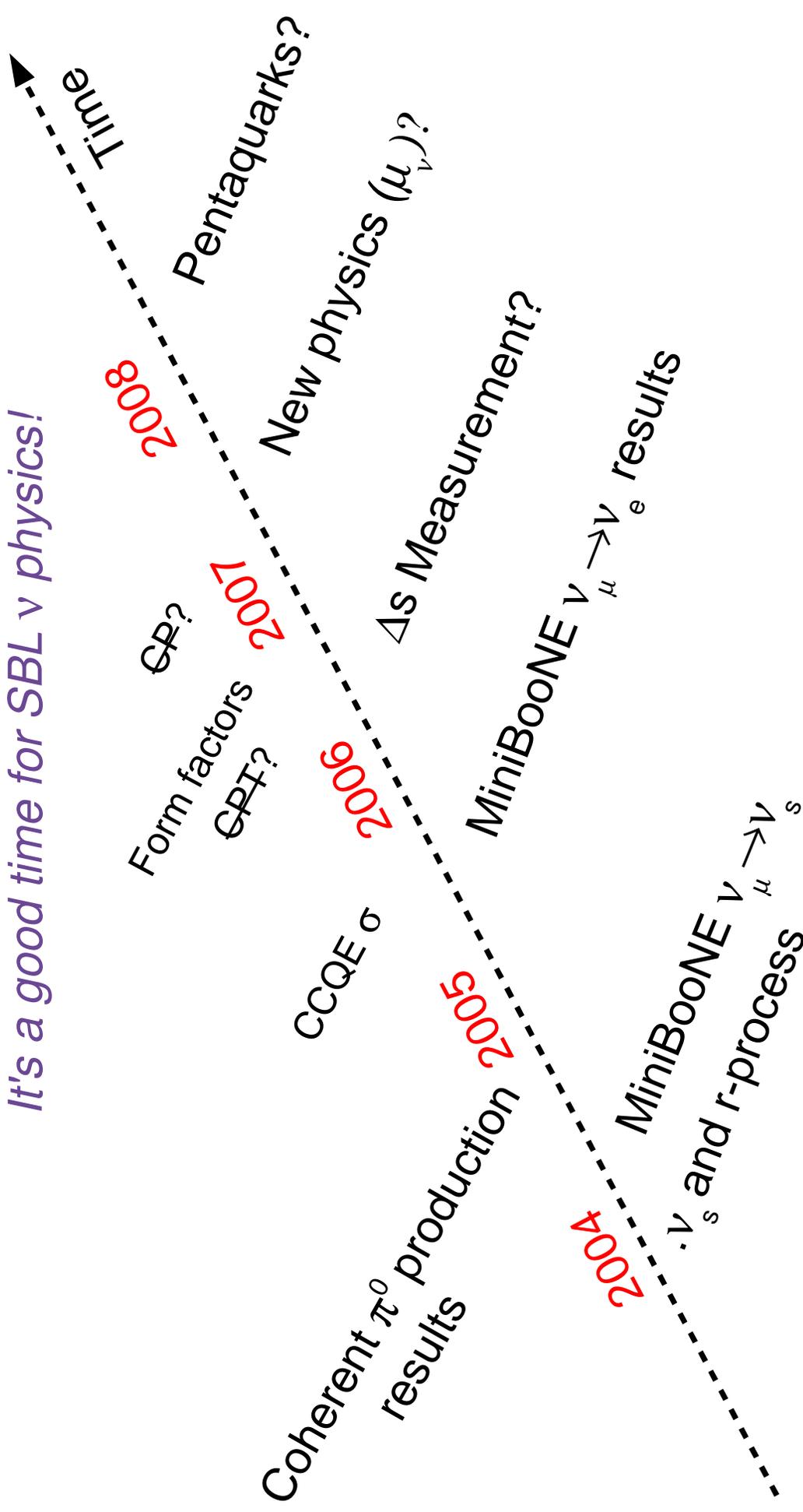
# SBL Interactions with Astrophysics

- Already
  - SN 1987A & LSND data rule out 3+1 inverted hierarchy: [hep-ph/0112214](#)
- Currently
  - SBL sterile  $\nu$  limits impact r-process models (heavy element production in supernovae) [hep-ph/0003034](#)
- Future
  - Sterile  $\nu$  oscillations and neutron star kicks: (may explain anomalous velocity distribution) [astro-ph/0307267](#)
  - Other cosmological implications?



# Future SBL Opportunites

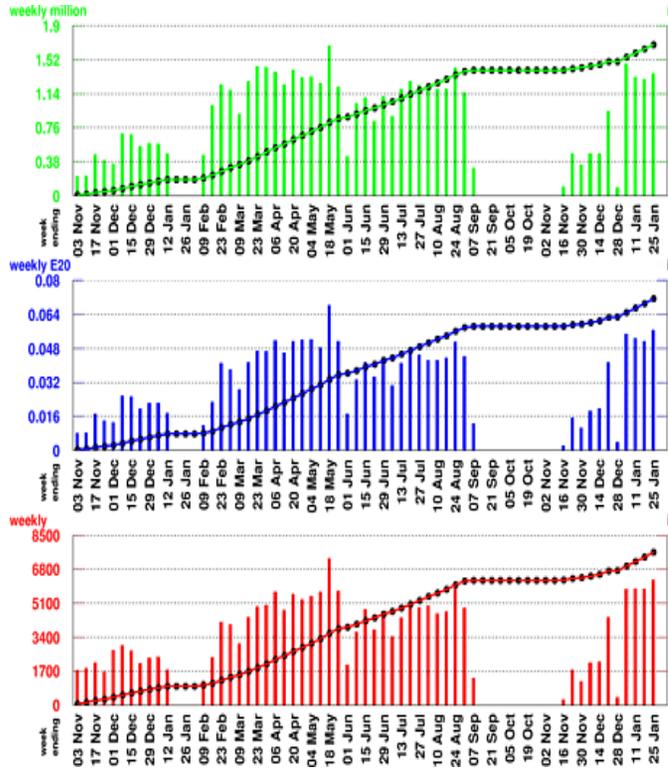
*It's a good time for SBL  $\nu$  physics!*



***Backup slides follow***



# MiniBooNE Outlook



## Number of Horn Pulses

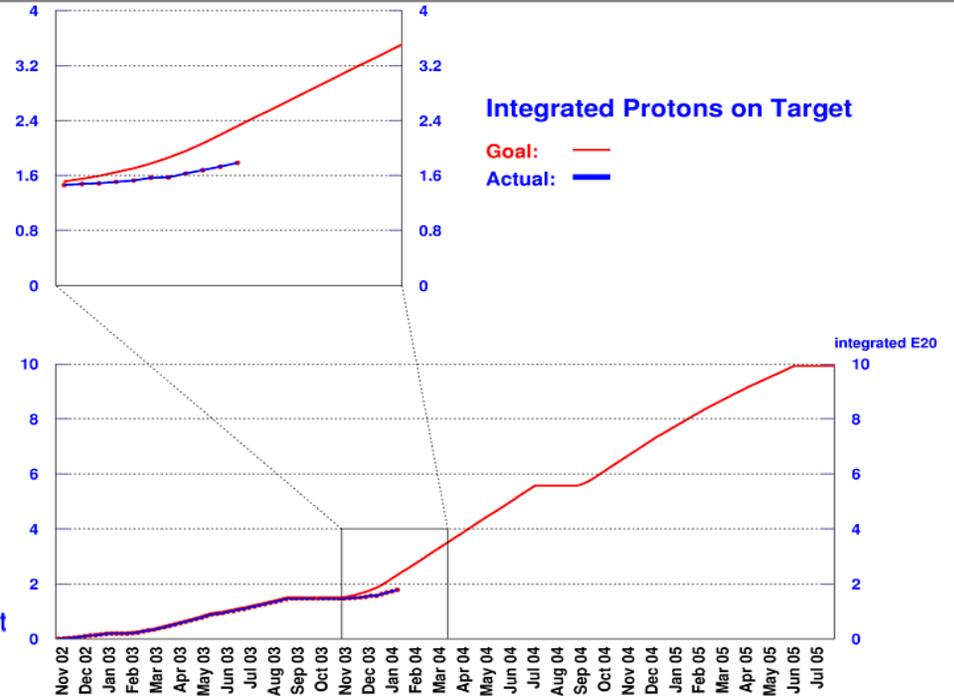
To date: 48.89 million  
 Largest week: 1.67 million  
 Latest week: 1.37 million

## Number of Protons on Target

To date: 1.7855 E20  
 Largest week: 0.0682 E20  
 Latest week: 0.0566 E20

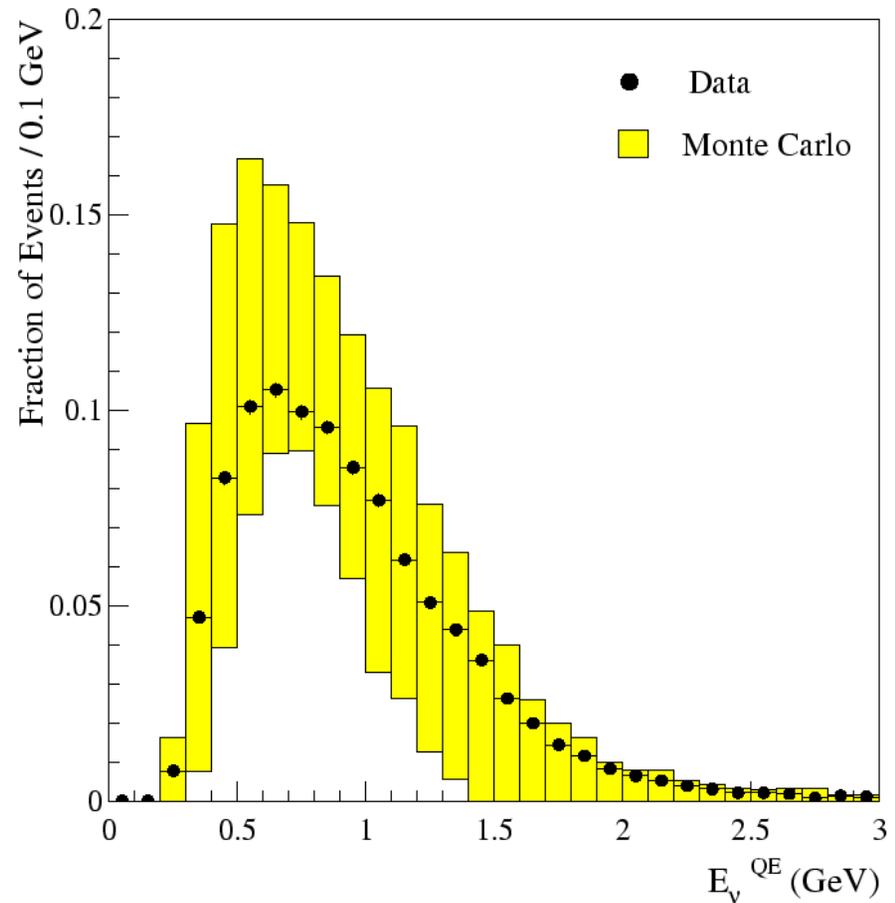
## Number of Neutrino Events

To date: 197849  
 Largest week: 7334  
 Latest week: 6256



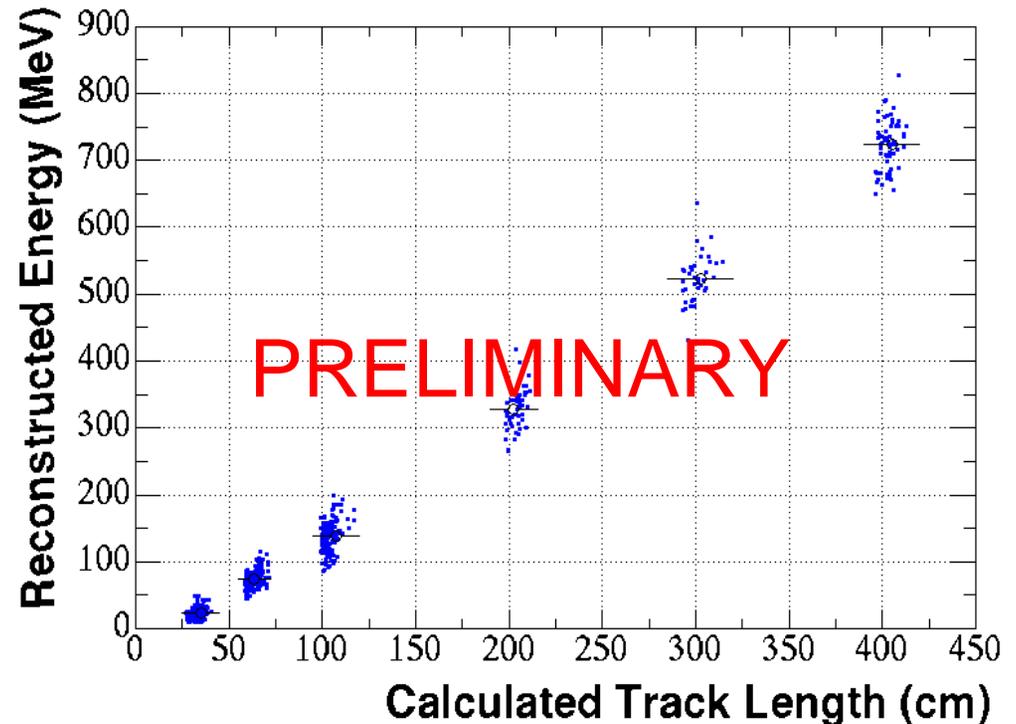
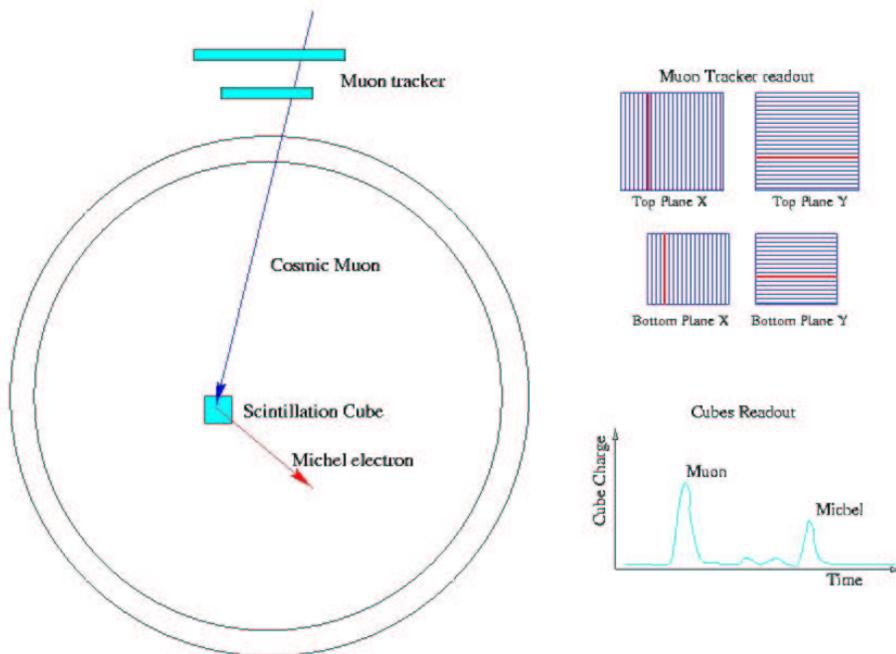
# MiniBooNE $\nu_{\mu}$ Energy Spectrum

- $\nu_{\mu}$  CCQE energy reconstruction
- QE energy reconstruction depends on accurate angular reconstruction
- Muon Tracker studies are crucial!



# MiniBooNE Cosmic Muon Reconstruction

- Muon Tracker tags entering cosmic muon
- Cubes capture stopping muons



- Calculated path length (range) of muon gives energy deposited in detector

# MiniBooNE Reconstructed $\pi^0$ Mass

- NC  $\pi^0$ : simple event topology
- Invariant mass recon. assumes 2  $\gamma$ s converting 2 Čerenkov rings
- 40 MeV cut on energy of each  $\gamma$
- BG channels also have  $\pi^0$  content

