Neutrino Physics at MiniBooNE

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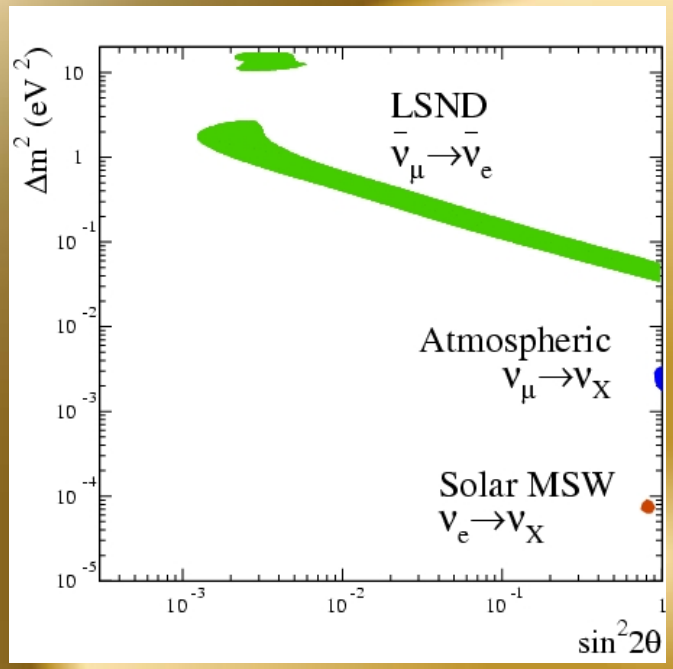
SLAC Summer Institute 2004

1. **Motivation**
   - LSND signal
2. **Overview**
   - experimental setup
   - first neutrino results
   - updated sensitivity

Motivation: Three Signal Regions

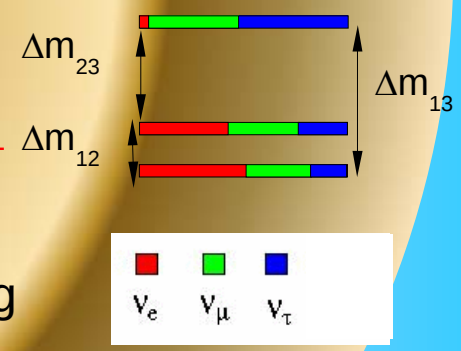


3 exp'l signatures for ν oscs point to 3 independent mass splittings

← LSND: $\Delta m^2 \sim 0.1\text{-}10$ eV^2

← Atmospheric: $\Delta m^2 \sim 10^{-3}$ eV^2

← Solar: $\Delta m^2 \sim 10^{-5}$ eV^2



3 ν 's allows only 2 indep values of Δm^2: $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

3 distinct oscillation signals with $\Delta m^2_{sol} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$

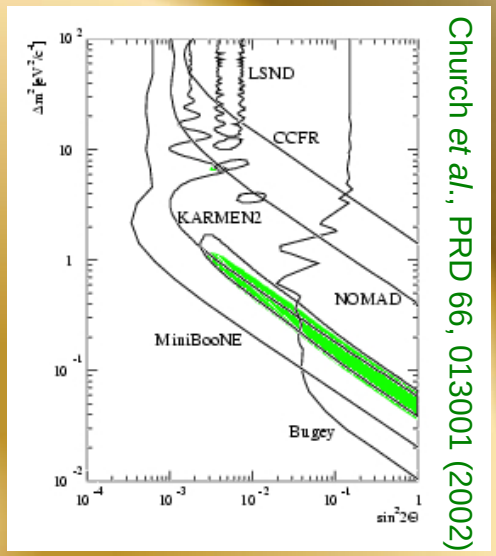
- one of the experimental measurements is wrong
  (or one or more are not seeing ν oscillations)
- additional sterile ν involved in the oscillation
  (>3 neutrinos gives 3 independent Δm^2 scales)
- or CPT is not a good symmetry
  (yields different mass scales for ν, $\bar{\nu}$)

Motivation: the LSND Result

* observed 3.8σ excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

87.9 ± 22.4 ± 6.0 excess
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ = (0.264 ± 0.067 ± 0.045) %

* unconfirmed by other experiments
but not excluded →

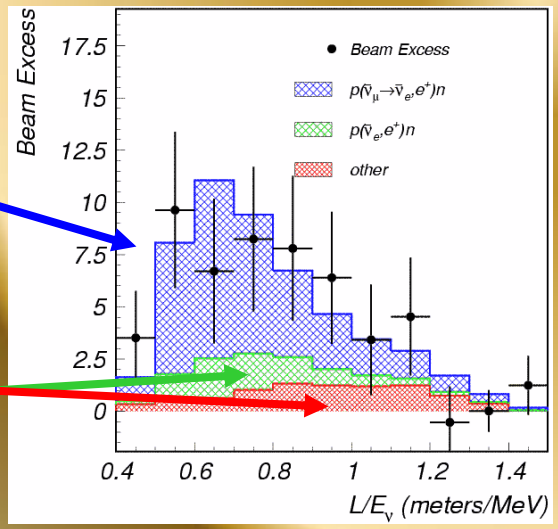


Church *et al.*, PRD 66, 013001 (2002)

joint LSND/KARMEN analysis leaves large **allowed region** compatible with both experiments

fit to oscillation hypothesis

beam-off and ν backgrounds



excess consistent w/ oscillations

To check LSND want:
* same L/E, but …
* higher statistics
* different systematics
* different signal signature & backgrounds

→ **MiniBooNE**
is that definitive test
search for $\nu_\mu \rightarrow \nu_e$ oscillations

MiniBooNE Collaboration

12 institutions, ~75 collaborators

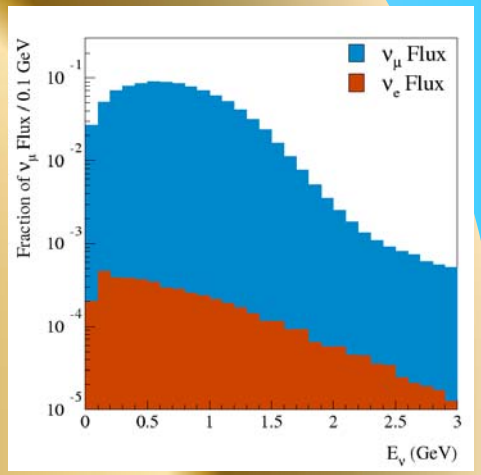
University of Alabama: Y.Liu, I.Stancu
Bucknell University: S. Koutsoliotas
University of Cincinnati: E.A.Hawker,R.Johnson,J.L.Raaf
University of Colorado: T.Hart,R.H.Nelson,M.Wilking, E.D.Zimmerman
Columbia University: A.A.Aquilar-Arevalo,L.Bugel,J.M.Conrad,J.Link, J.Monroe,D.Shmitz,M.H.Shaevitz,M.Sorel,G.P.Zeller
Embry Riddle Aeronautical University: D.Smith
Fermi National Accelerator Laboratory: L.Bartoszek,C.Bhat,S.J.Brice,B.C.Brown, D.A.Finley,R.Ford,F.G.Garcia,P.Kasper,T.Kobilarcik,A.Malensek, W.Marsh,P.Martin,F.Mills,C.Moore,P.Nienaber,E.Prebys, A.D.Russell,P.Spentzouris,R.Stefanski,T.Williams
Indiana University: D.Cox,A.Green,T.Katori,H.Meyer,R.Tayloe
Los Alamos National Laboratory: G.T.Garvey,C.Green,W.C.Louis,G.McGregor, S.McKenney,G.B.Mills,H.Ray,V.Sandberg,B.Sapp,R.Schirato, R.VandeWater,N.L.Walbridge,D.H.White
Louisiana State University: R.Imlay,B.Metcalf,S.Oeudraogo,M.Sung,M.O.Wascko
University of Michigan: J.Cao,Y.Liu,B.P.Roe,H.J.Yang
Princeton University: A.O.Bazarko,P.D.Meyers,R.B.Patterson,F.C.Shoemaker,H.A.Tanaka

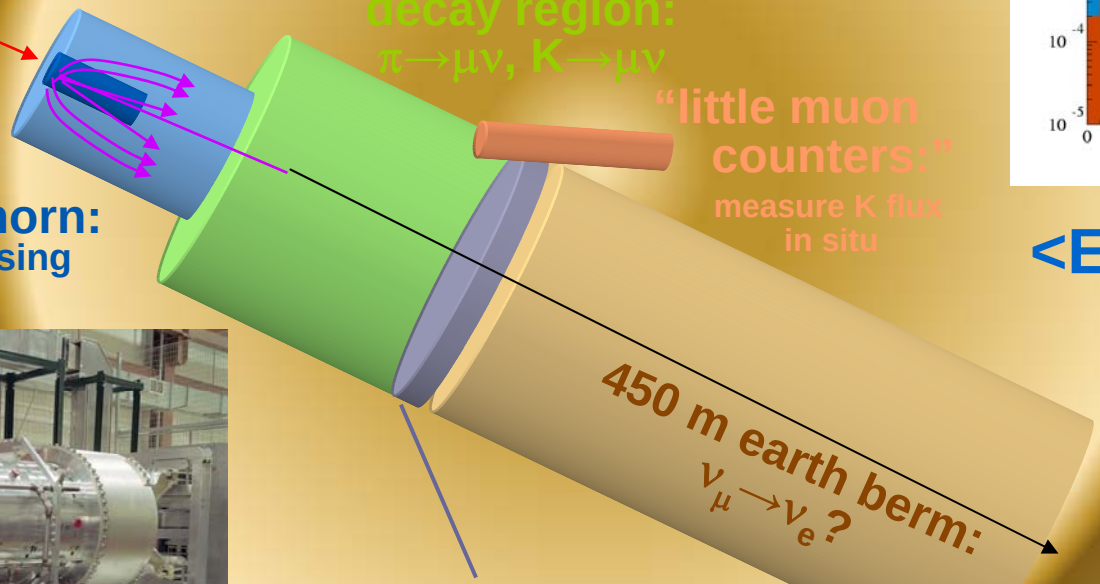
designed a beamline & detector optimized for this direct search …

Beamline

FNAL 8 GeV Booster

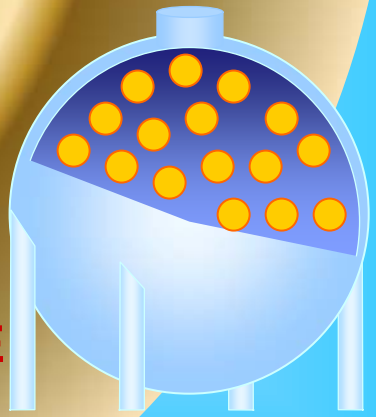
50 m decay pipe



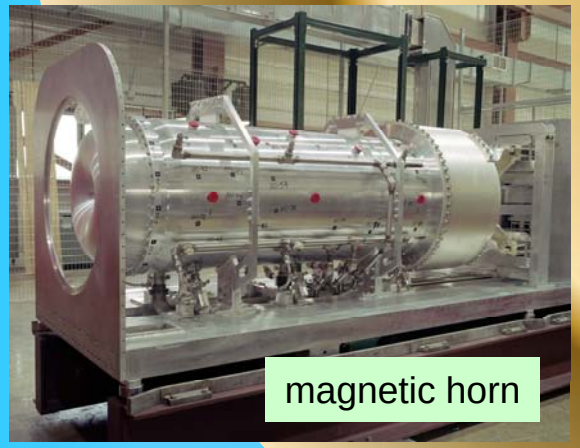


$\langle E_\nu \rangle \sim 700$ MeV

~0.5% ν_e



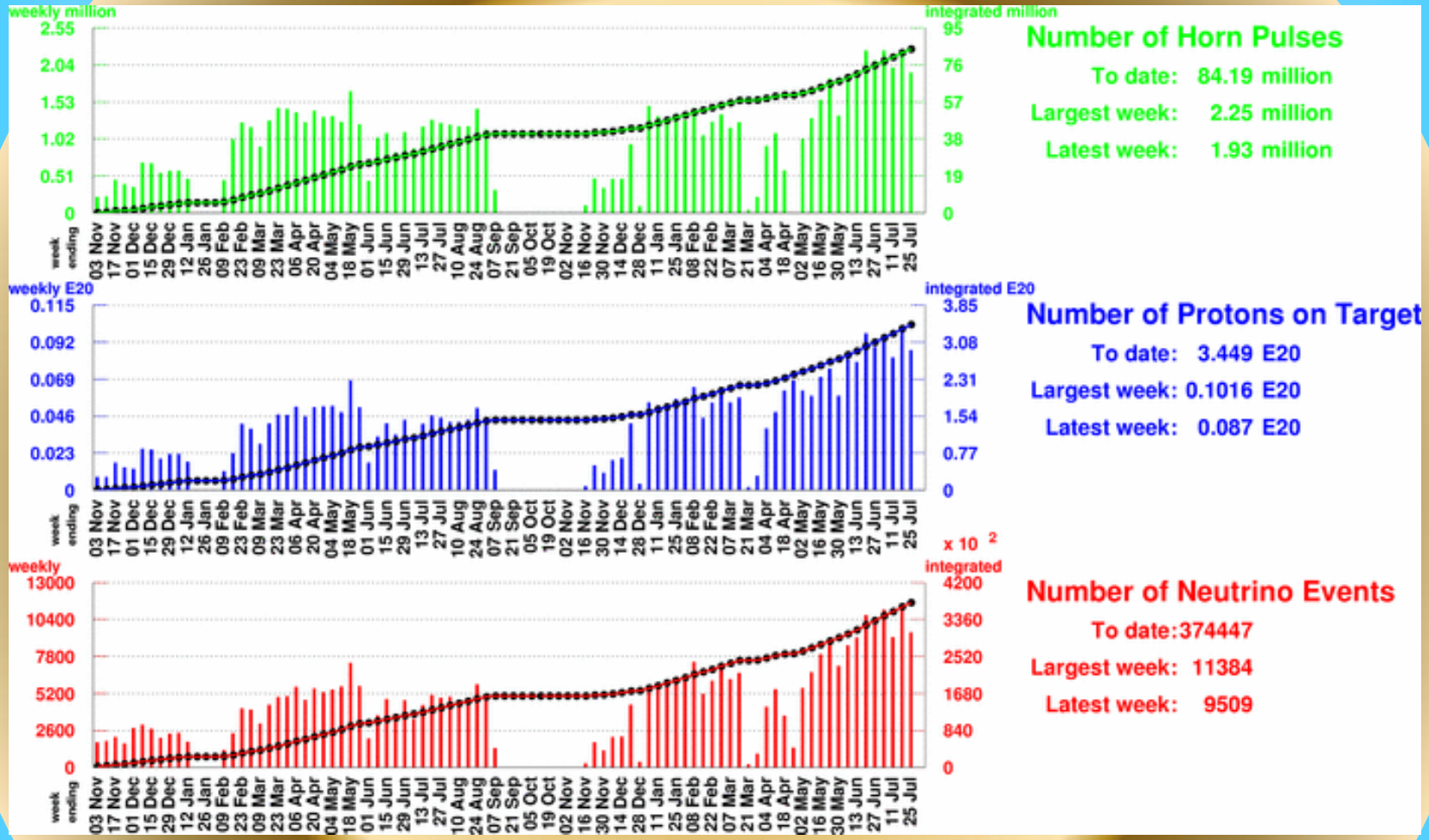
MiniBooNE detector



magnetic horn

technically the most impressive component of MiniBooNE

FNAL Booster Performance



- typically delivers (3-4) x 10^{16} p/hr, now (6-8) x 10^{16} p/hr due to recent Booster improvements
- collected 3.5 x 10^{20} POT, ~370,000 ν events

MiniBooNE Detector

- 12m diameter tank
- 800 tons ultra-pure mineral oil

  ν interactions in oil produce:

  - prompt ring of Cerenkov light
  - delayed isotropic scintillation light

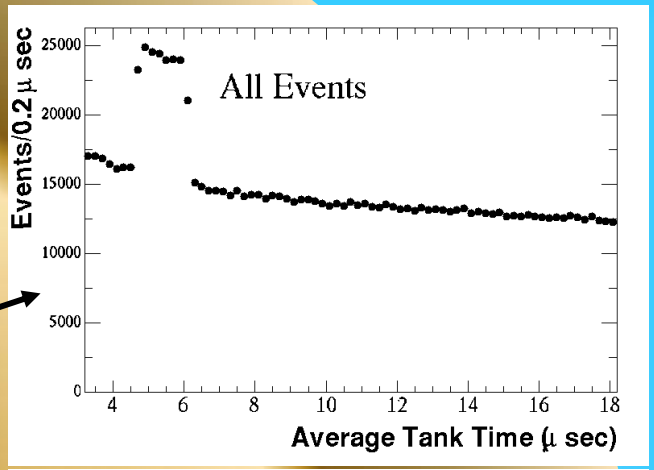
- 1280 8” phototubes in interior signal region

- 240 8” phototubes in outer veto region

  (> 99% veto efficiency)

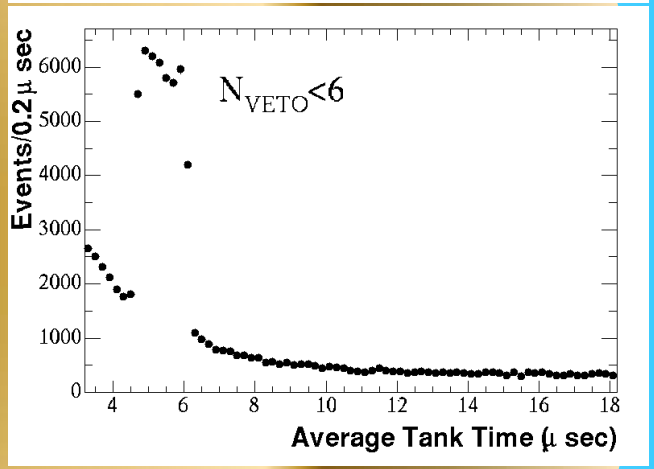
Neutrino Events

no high level analysis needed to see ν events over background

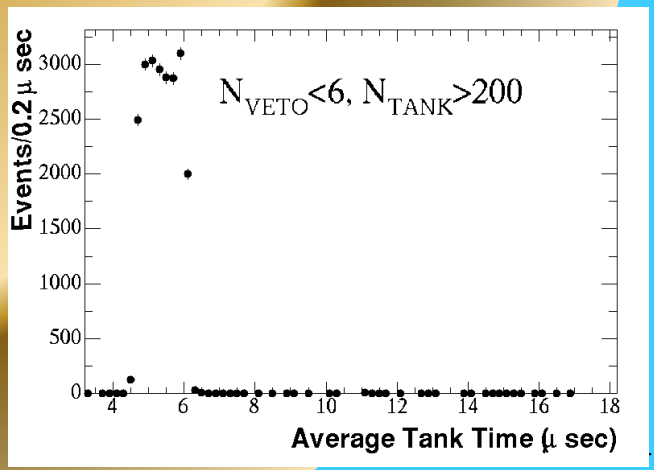


beam arrives in a 1.6 μs window

- clear beam excess with no selection
- N_{VETO}<6 eliminates cosmic muons
- N_{TANK}>200 removes Michel electrons (μ decay)



simple cuts reduce non-beam background to ~1/1000

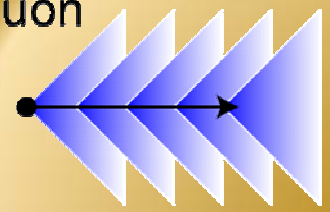


MiniBooNE Particle ID

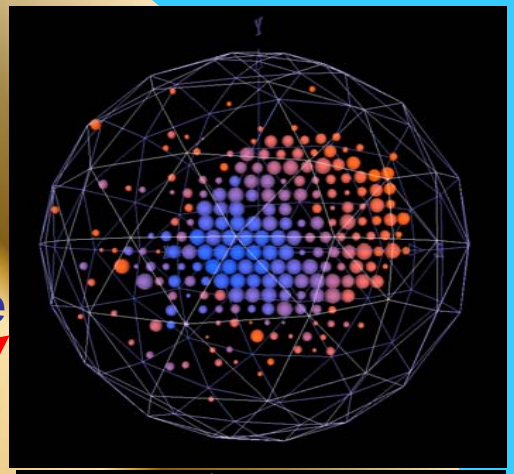
Cerenkov rings provide primary means of identifying products of ν interactions in the detector

ν_μ n → μ^- p

Muon

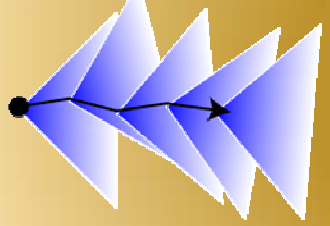


beam μ candidate

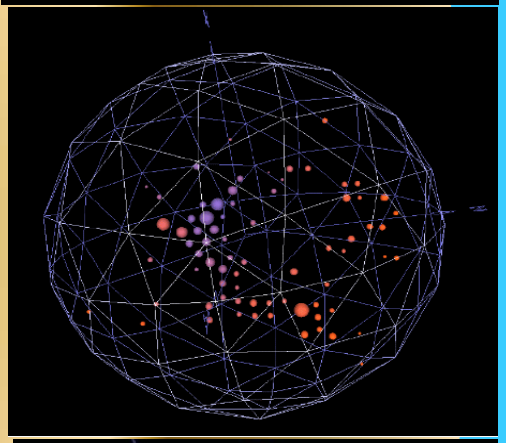


ν_e n → e^- p

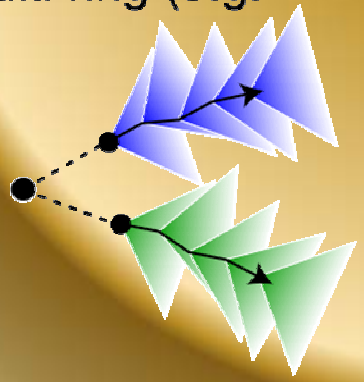
Electron



Michel e^- candidate



Multi-ring (e.g. $\pi^0 \rightarrow \gamma\gamma$)



beam π^0 candidate

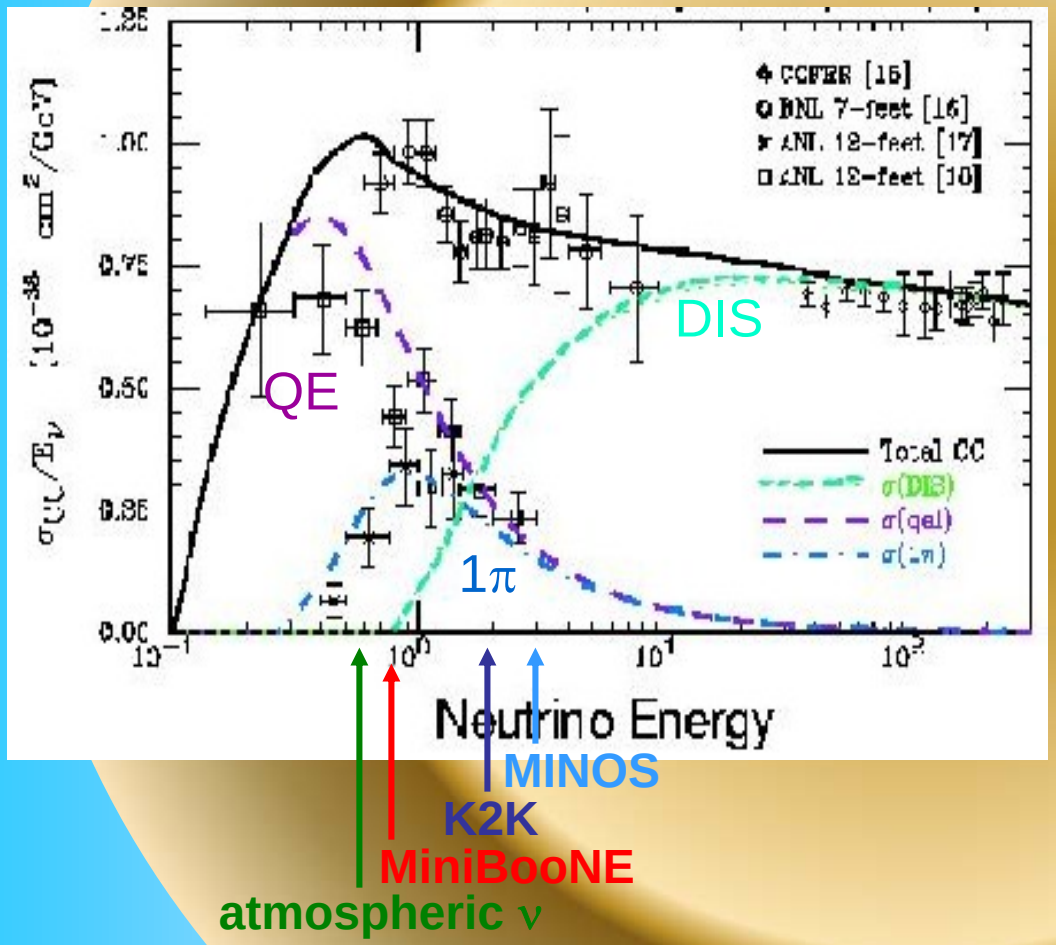
$\pi^0 \rightarrow \gamma\,\gamma$

On the Path to Oscillation Results

- MiniBooNE $\nu_\mu \rightarrow \nu_e$ appearance search is a blind analysis
- still in process of calibrating & understanding our detector, neutrino beam, and refining event reconstruction
- based on current understanding of these → 1st neutrino data
  - CC QE ← ν_μ disappearance analysis, ν flux
  - NC π^0 ← important background to $\nu_\mu \rightarrow \nu_e$
  - NC elastic ← understanding optical model
- not only are these physics samples specifically important for MiniBooNE, but ...

Neutrino Physics at ~1 GeV

there is a lot of interesting physics on the path to oscillation results …

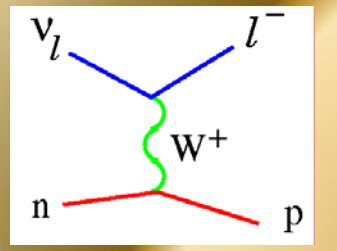


MiniBooNE data will help improve our understanding of low energy ν interactions

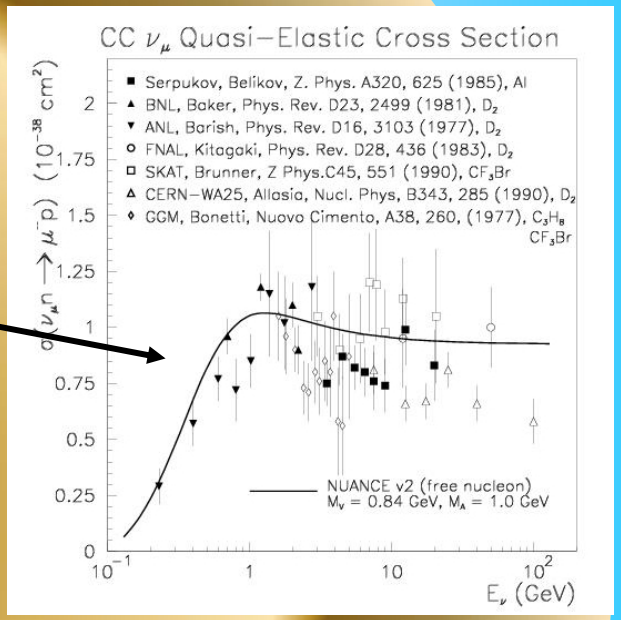
- imperative to ensure success of future ν osc exps
- MiniBooNE statistics will exceed any other exp in this energy range
- these analyses are interesting in their own right

Low Energy ν_μ Cross Sections

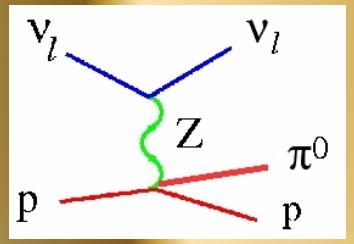
(1) charged current quasi-elastic (QE)



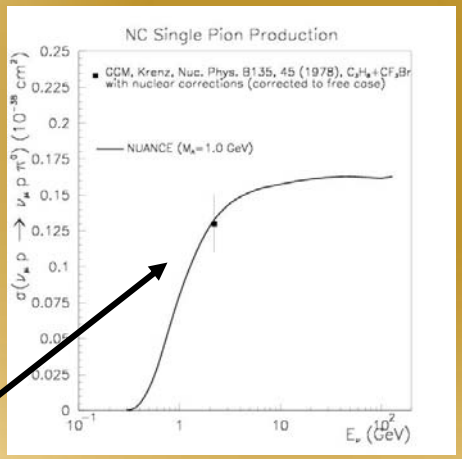
- highest statistics sample in previous bubble chamber data is **~2500** events



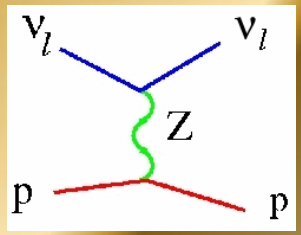
(2) neutral current π^0 events



- no NC π^0 data below ~2 GeV



(3) neutral current elastic scattering

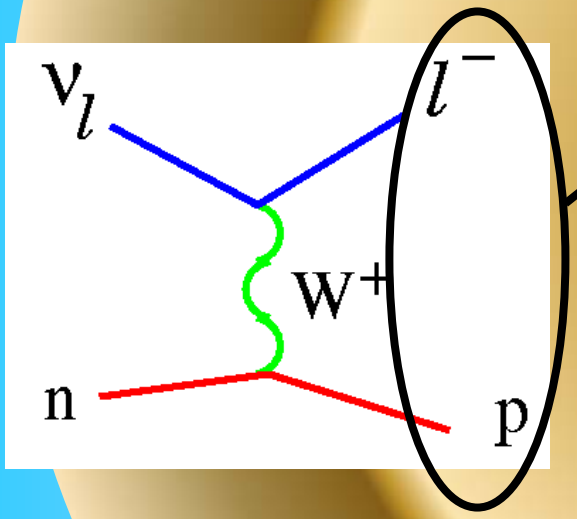


this situation is changing with new high statistics data from K2K and MiniBooNE

ν_μ CC Quasi-Elastic Events

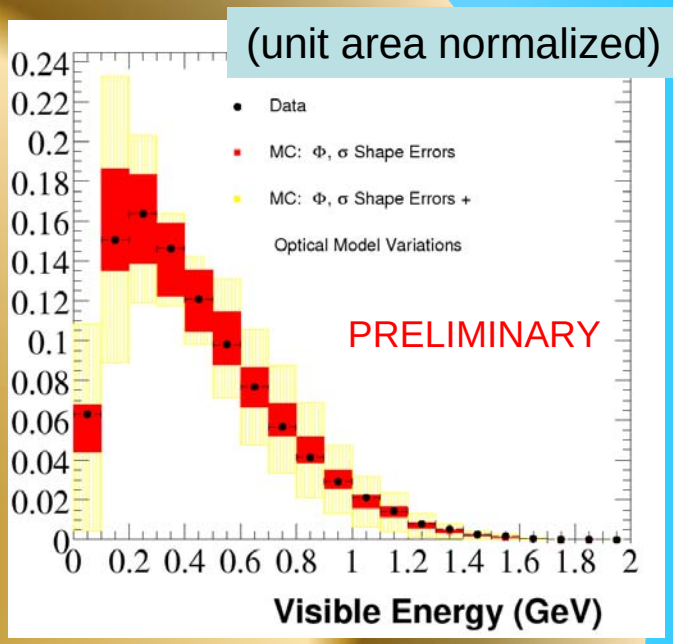
$\nu_\mu\, n \rightarrow \mu^-\, p$

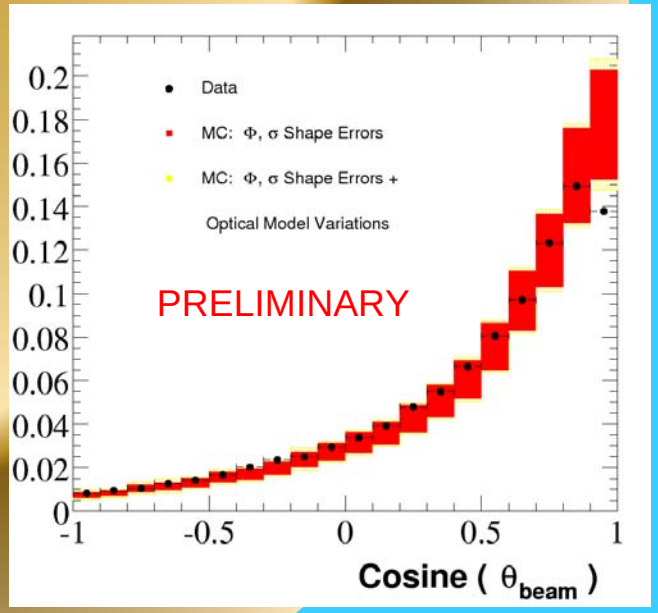
- QE processes are abundant
- simple two body kinematics



measure visible E and θ_μ from mostly Cerenkov (μ) + some scintillation light (*p*)

* 88% QE purity
* 30% efficiency





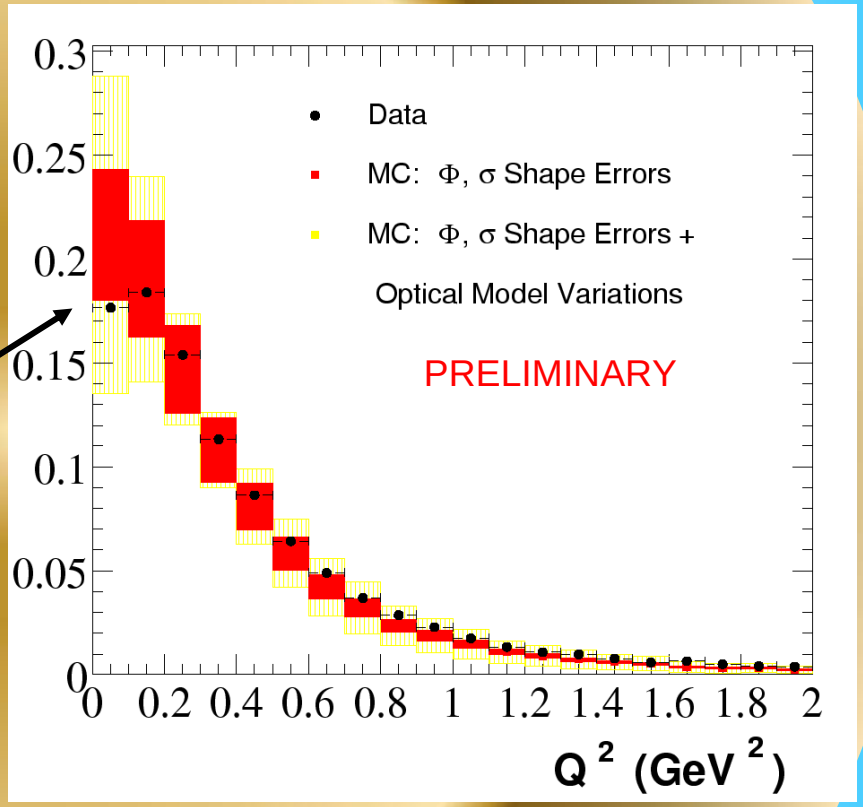
high statistics ~80,000 QE events now

measured dists agree well with expectations →

ν_μ CC Quasi-Elastic Events

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

$Q^2 = m_\mu^2 - 2E_\nu(E_\mu - p_\mu \cos\theta_\mu)$

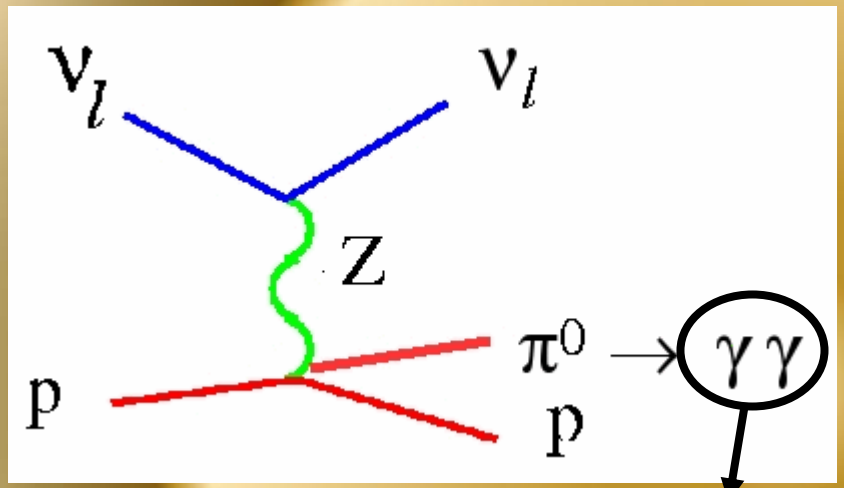


- nuclear effects depend strongly on Q^2, so low Q^2 region provides information on modeling of nuclear effects in carbon

- interesting roll-over in data not tracked by Monte Carlo; also seen in K2K near detector data
  - has received a lot of attention recently
  - points to a common model deficiency?

NC π^0 Sample

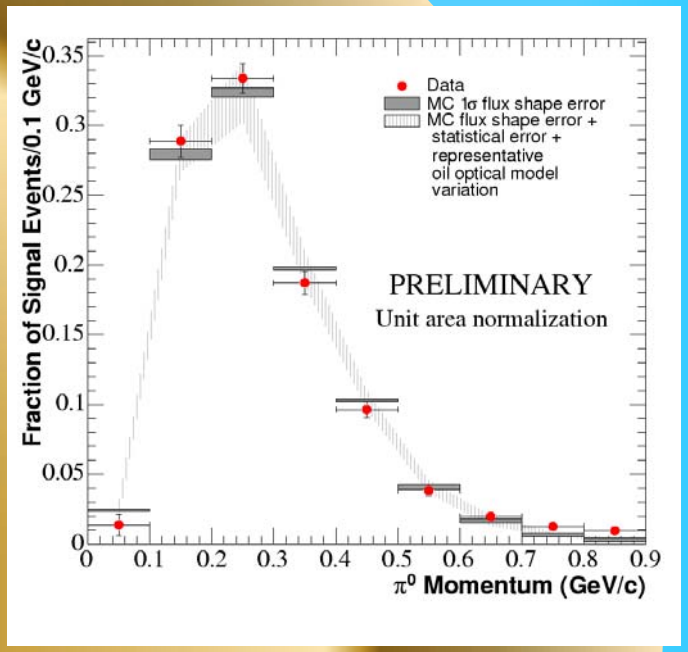
$\nu_\mu N \rightarrow \nu_\mu N \pi^0$

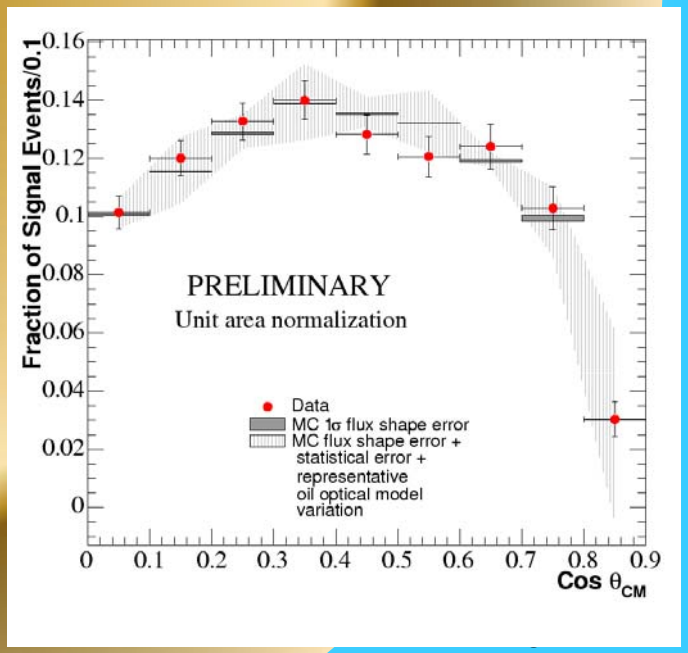


2 ring fit
determine E, direction
of each Cerenkov ring
→ decay kinematics

~7,000 NC π^0 events now

extracted signal π^0's in data & MC:



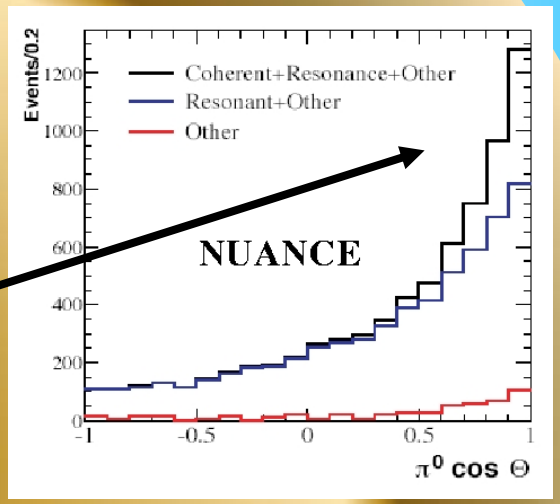


MC fits details of π^0 decays nicely →

NC Coherent π^0 Production

understanding rate & kinematics of π^0 production important because background to $\nu_\mu \rightarrow \nu_e$ search

π^0 angular distribution sensitive to mode of production



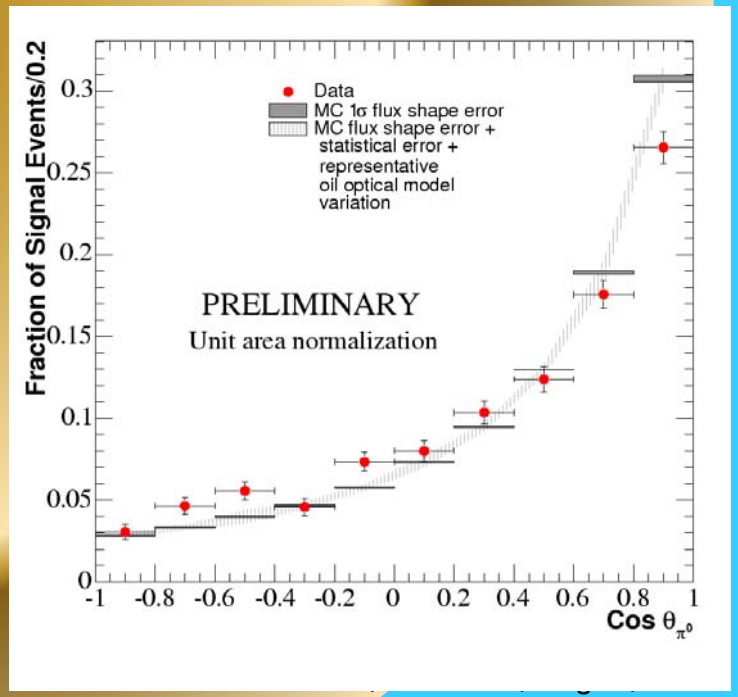
~ 80% **resonant** π^0 (Δ)

~ 20% **coherent** π^0 production

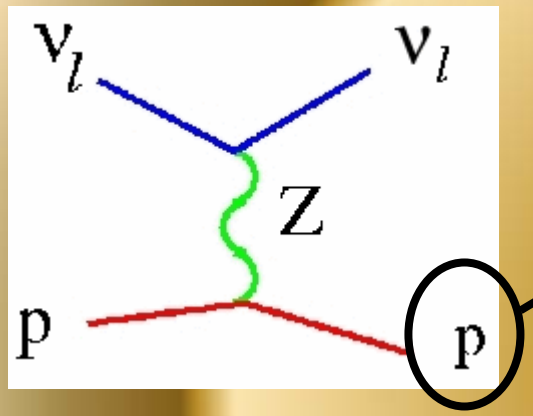
- scatter off entire nucleus
- forward scattered π (low Q^2)

- no coherent π data below 2 GeV
- competing models differ by large factors

- important to understand how strongly coherent production contributes to overall NC π^0 rate at low E with MiniBooNE & K2K near detector data



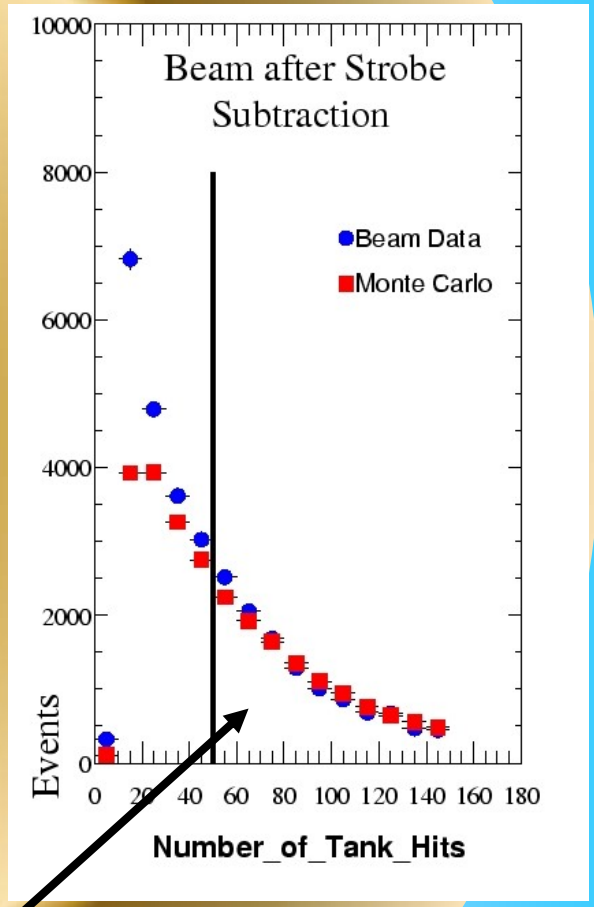
NC Elastic Scattering



$\nu_\mu\, p \rightarrow \nu_\mu\, p$

reconstruct proton E
from scintillation light

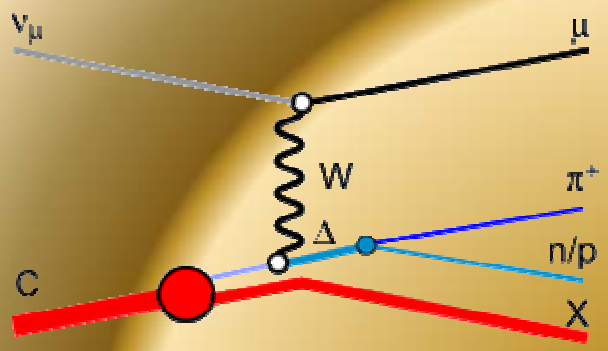
* 81% purity
* 68% efficiency



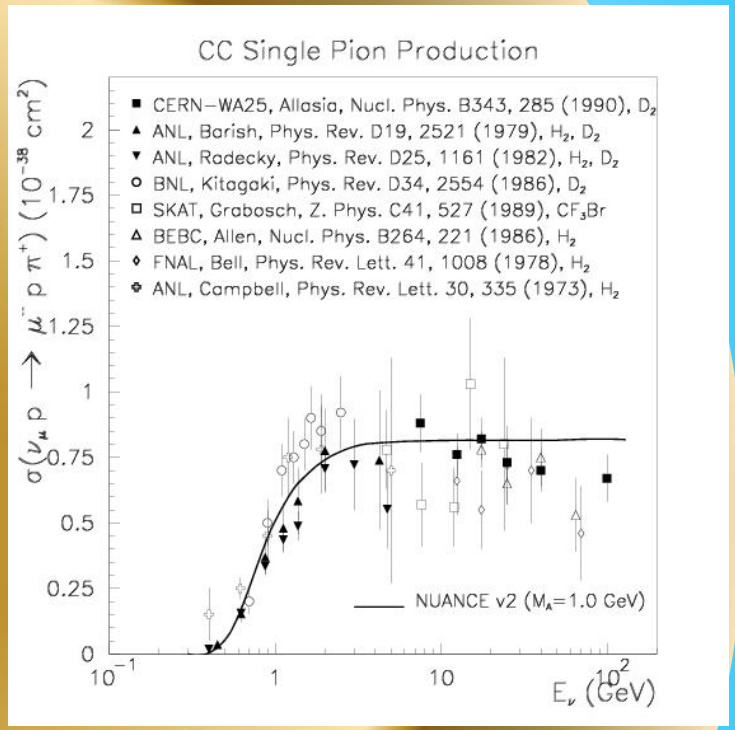
- low energy events (< 200 MeV)
- sensitive to optical model
  (useful for studying scintillation properties
  of oil & low energy response of detector)
- measure Δs (component of p spin carried by s quark)

Monte Carlo models data well down to ~60 tank hits = 150 MeV proton KE

CC π^+ Events



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



no previously published data on heavy targets at ~1 GeV

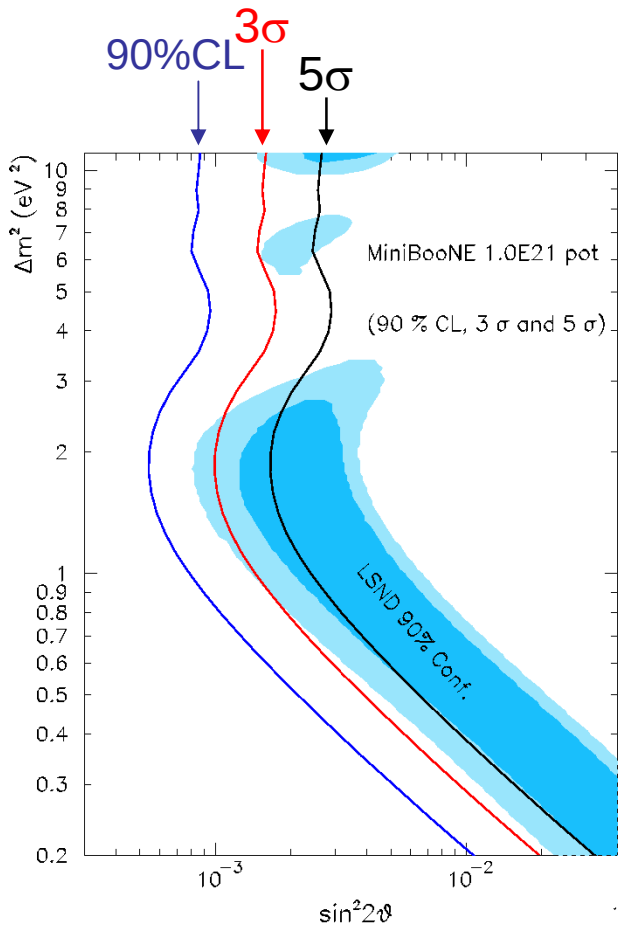
- newest ν sample
- large σ → ~1/2 rate of CC QE

- identify with 2 Michel electrons
- 85% pure selection of CC π^+

- use to study kinematics dists (Q^2, etc.) and coherent π production contributions

Updated MiniBooNE Sensitivity

detailed re-evaluation of ultimate sensitivity MiniBooNE can achieve



$\nu_\mu \rightarrow \nu_e$ oscillation search

contains our current best knowledge updated from MiniBooNE proposal

4-5 σ coverage of LSND 90% CL region with 1×10^{21} POT

to definitively exclude LSND in the event that MiniBooNE does not see a signal, we need 1×10^{21} POT

Conclusions

- **MiniBooNE will confirm/refute LSND evidence for ν oscillations**
  - confirmation would have dramatic implications for neutrino physics!

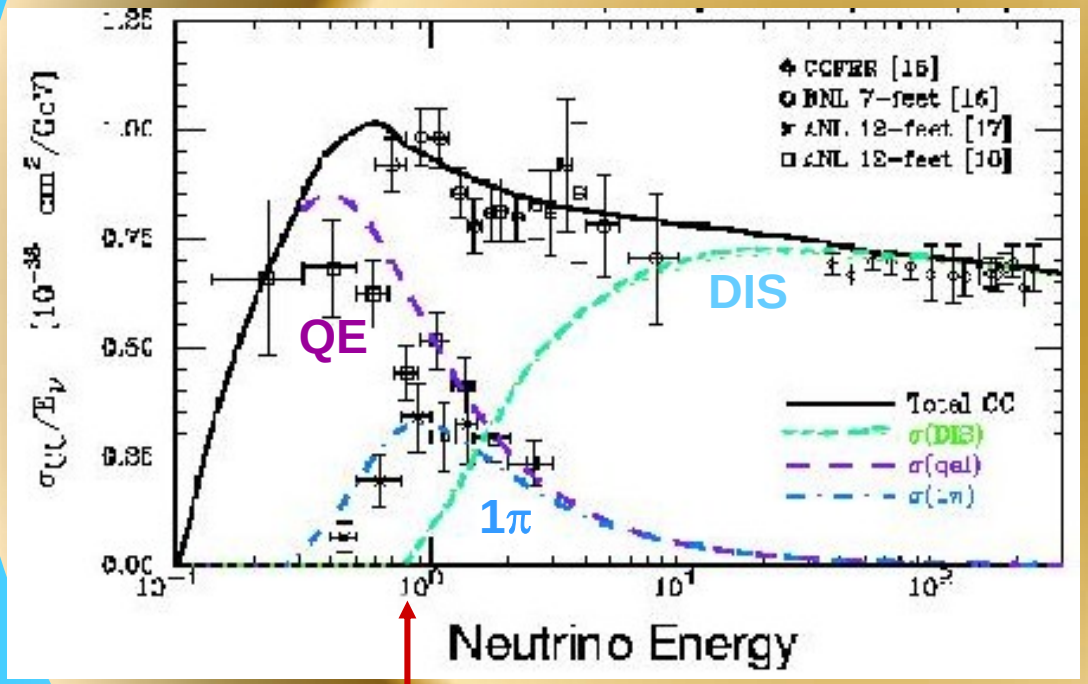
- **collected 3.5 x 10^{20} POT to date**
  - detector and beamline functioning well
  - accumulating data at rate of ~1,000 ν events/day
    - 370,000 neutrino interactions recorded thus far

- **currently:**
  - working to improve our understanding of beam & detector
  - first results on QE, NC π^0, NC elastic samples (CC π^+ soon)
    - already have > order of magnitude more data than previous bubble chamber based measurements
    - part of larger effort to gain a better understanding of low E ν interactions (important input to ν osc experiments)

- **outlook on anticipated oscillation results:**
  - ν_μ disappearance: expect results later this year
  - $\nu_\mu \rightarrow \nu_e$ plan is to "open the box" sometime in 2005

Backup Slides

Neutrino Event Fractions

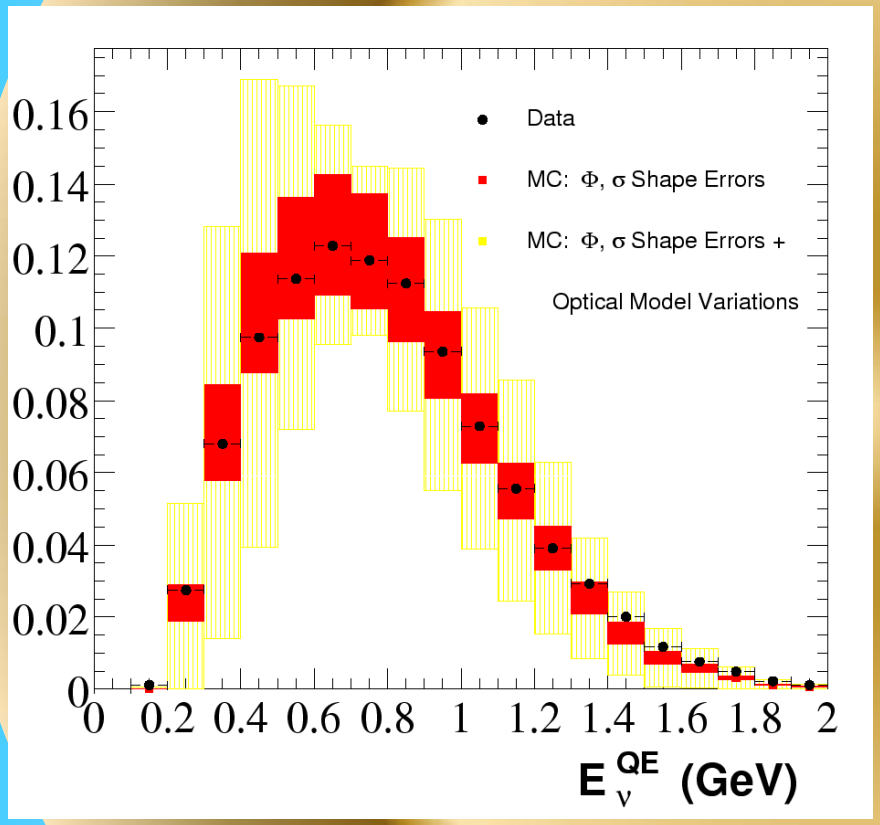


MiniBooNE flux-averaged event composition:

- 40% QE
- 25% CC π^+
- 16% NC elastic
- 8% NC π^0
- 4% CC π^0
- 2% NC π^+
- 2% NC π^-
- 1% DIS

MiniBooNE $\langle E_\nu \rangle \sim 700$ MeV

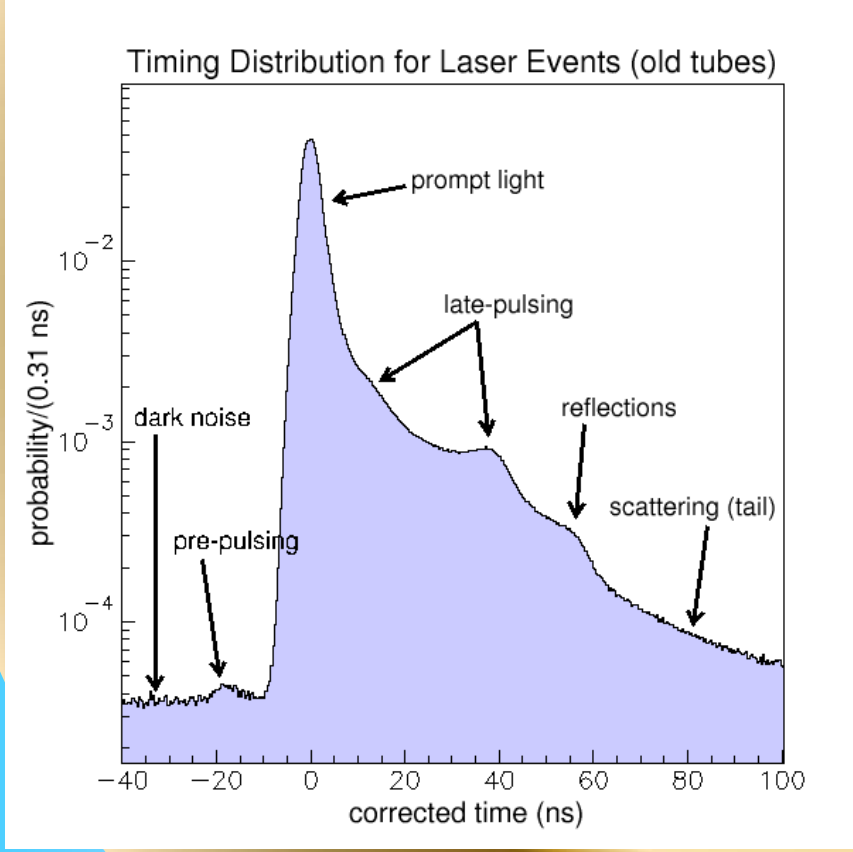
MiniBooNE QE Data



$$E_\nu^{QE} = \frac{2ME_\mu - m_\mu^2}{2(M - E_\mu + p_\mu \cos\Theta_\mu)}$$

Laser Calibration

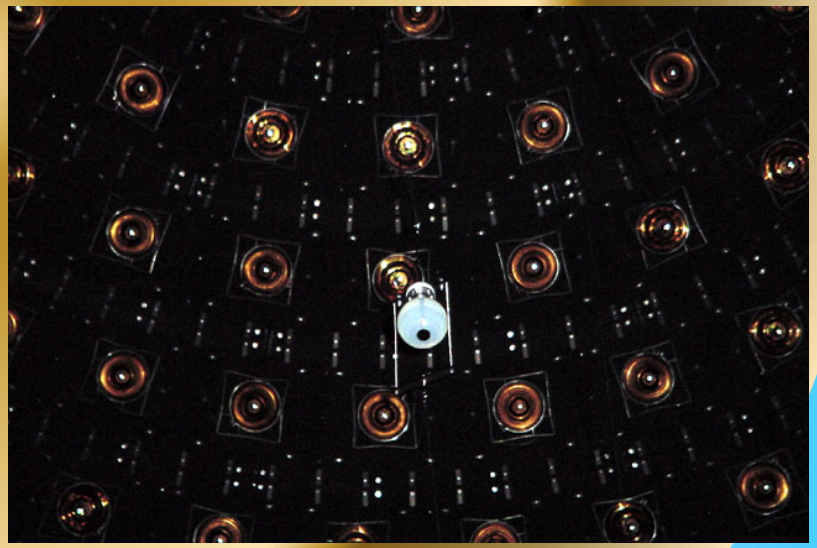
laser system is main tool for understanding PMT response



corrected time distribution for old tubes in laser events

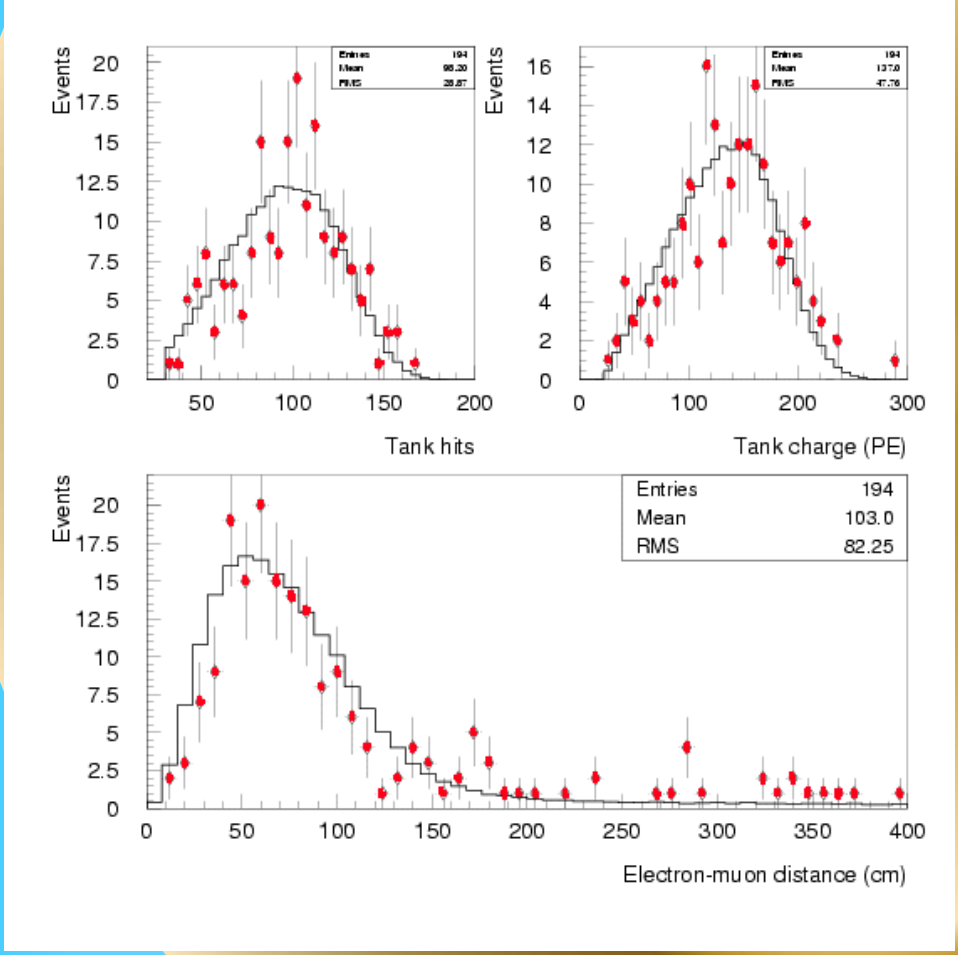
Laser flask system:

- laser light (397 and 438 nm)
- sent to 1 of 4 Ludox filled flasks (scatter light)



Cosmic vs. Beam Michels

cross-check on using Michel electrons from cosmic ray μ's for calibration



← comparison between Michel electrons from cosmic rays (line) and beam interactions (points)

Updated MiniBooNE Sensitivity

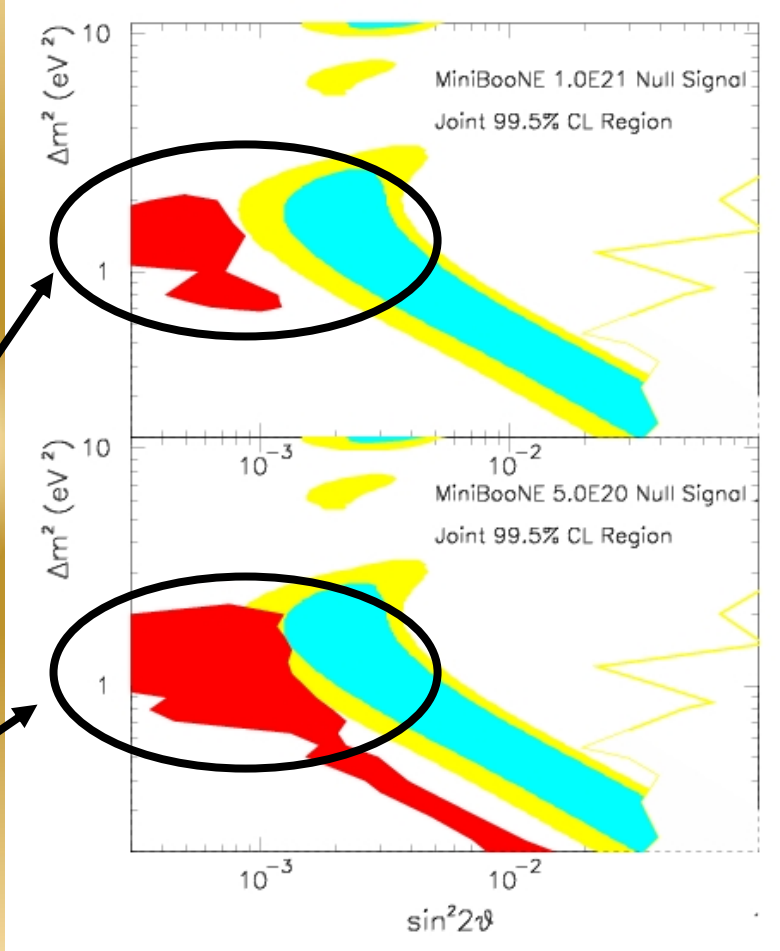
$$\nu_\mu \rightarrow \nu_e$$

Converting to an allowed region…

shows 3σ allowed region
from a joint
MiniBooNE/LSND analysis

1x10^{21} POT: lack of overlap
shows two experiments
are inconsistent

5x10^{20} POT: allowed region is larger
and overlaps LSND

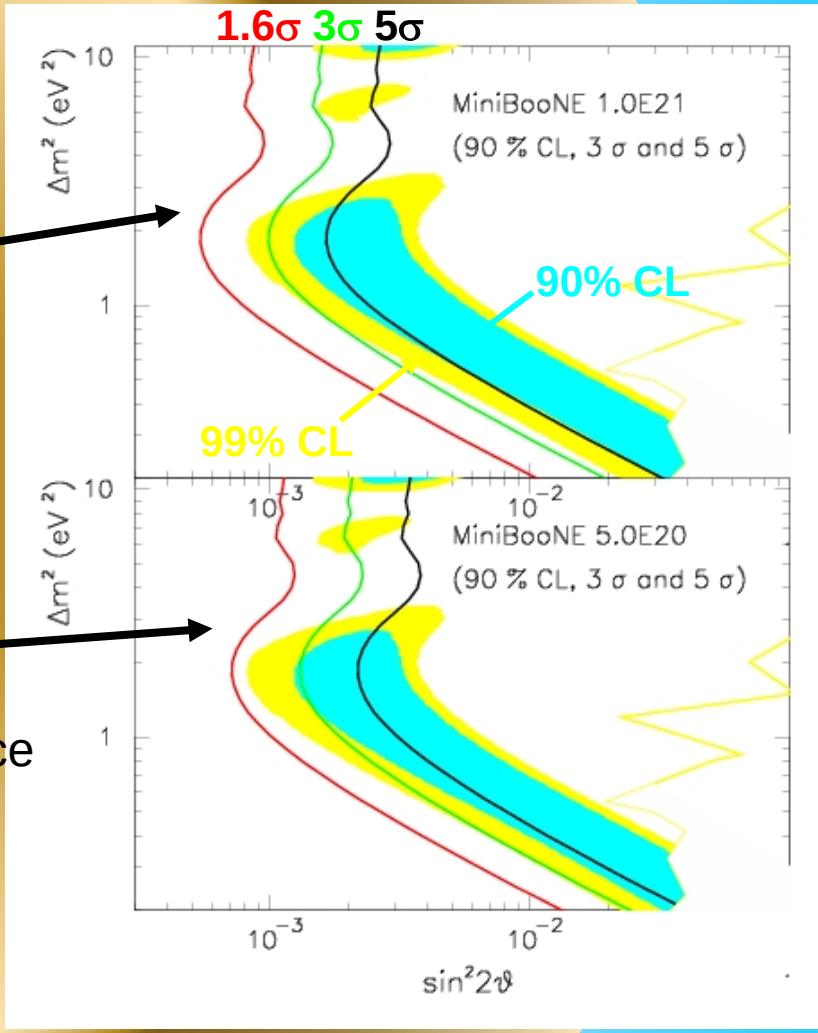


LSND Coverage

if MiniBooNE doesn't see a signal …

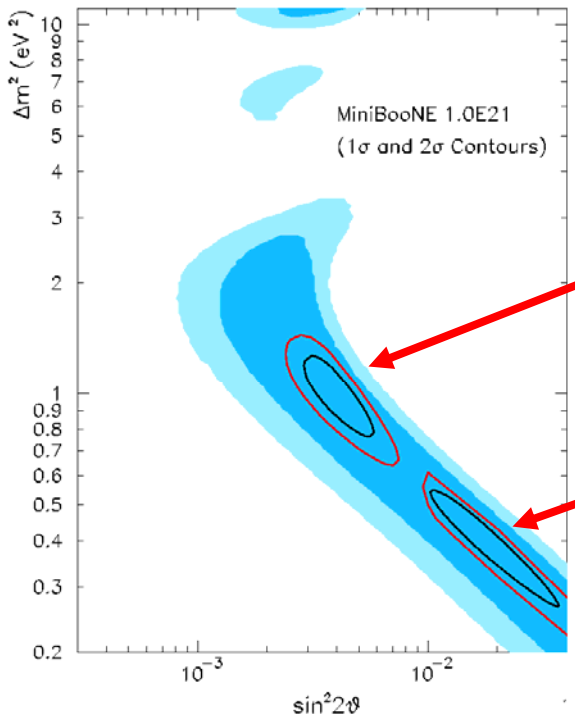
$1x10^{21}$ POT:
good coverage
90% CL LSND excluded at > 4σ confidence

$5x10^{20}$ POT:
90% CL LSND excluded at only 3σ confidence



Differentiating High vs. Low Δm^2

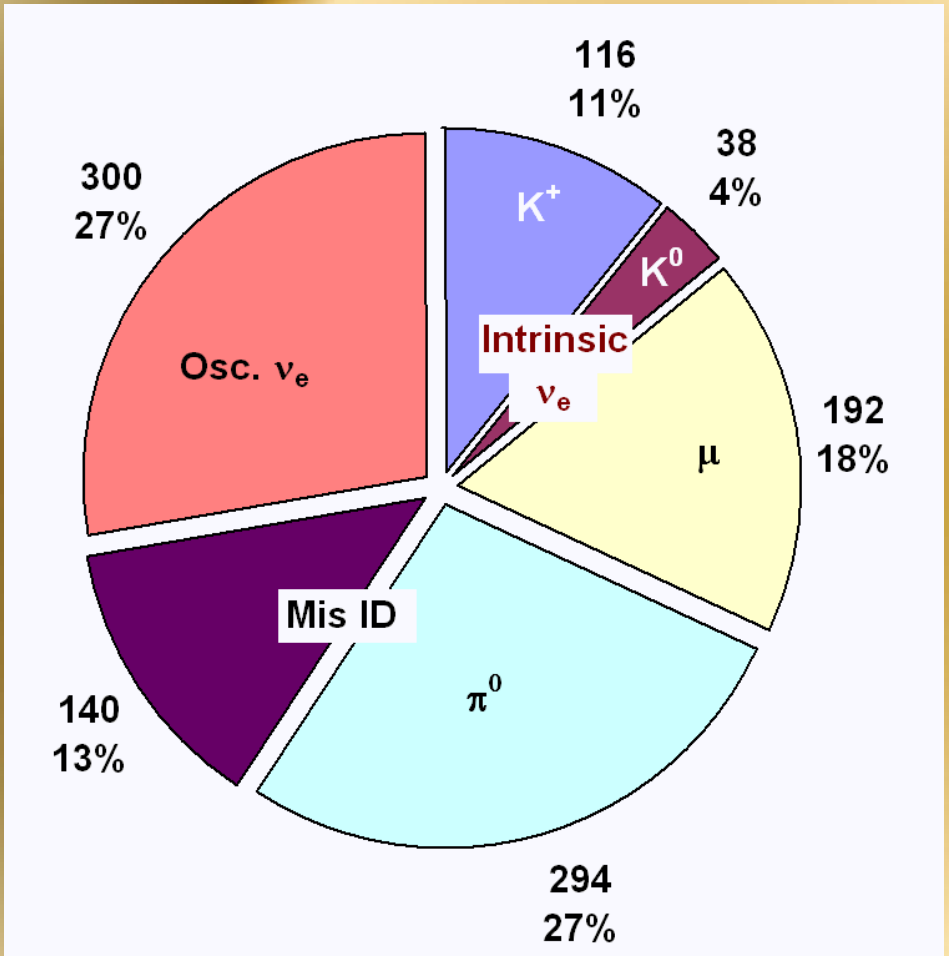
with 1×10^{21} POT, can clearly separate a high from low Δm^2 signal
(however, two measurement regions overlap with 5×10^{20} POT)



$\Delta m^2 = 1\ eV^2$

$\Delta m^2 = 0.4\ eV^2$

Electron Neutrino Events



numbers are for 1×10^{21} POT

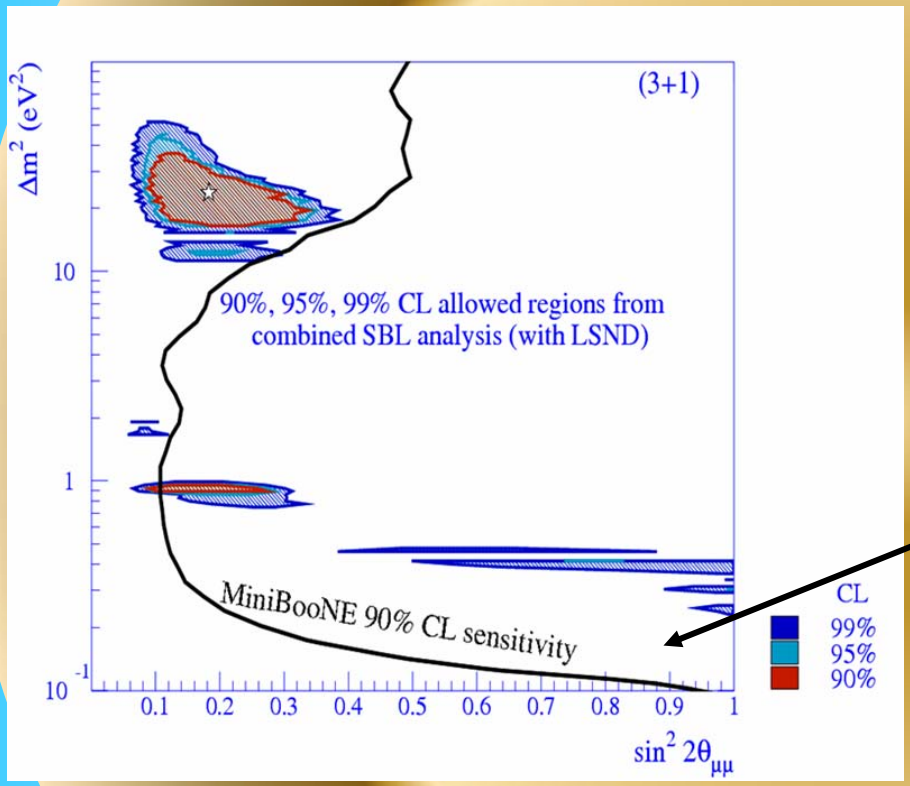
important backgrounds include:

- beam ν_e (33%)
- π^0 mis-ID (27%)
- μ mis-ID (13%)

signal events:

- 30% are ν_e signal (for average LSND Δm^2 and $\sin^2 2\theta$)
- expected to differ by ~20% between $\Delta m^2 = 0.4 \rightarrow 1$ eV^2

Updated MiniBooNE Sensitivity



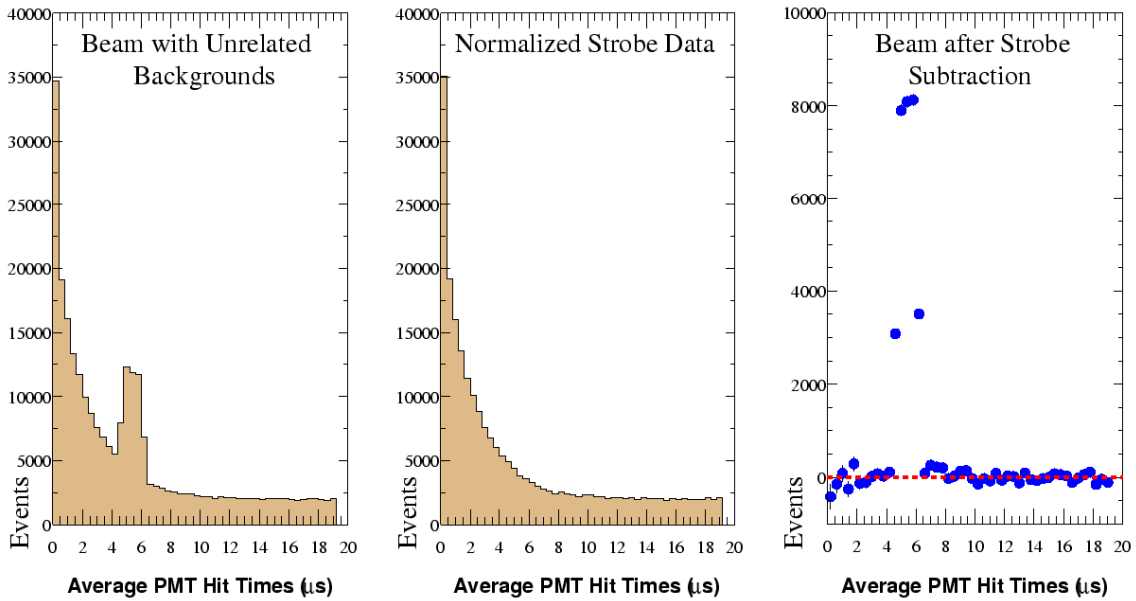
$\nu_\mu \rightarrow \nu_s$ oscillation search:

sensitivity to ν_μ disappearance through shape of E_ν distribution

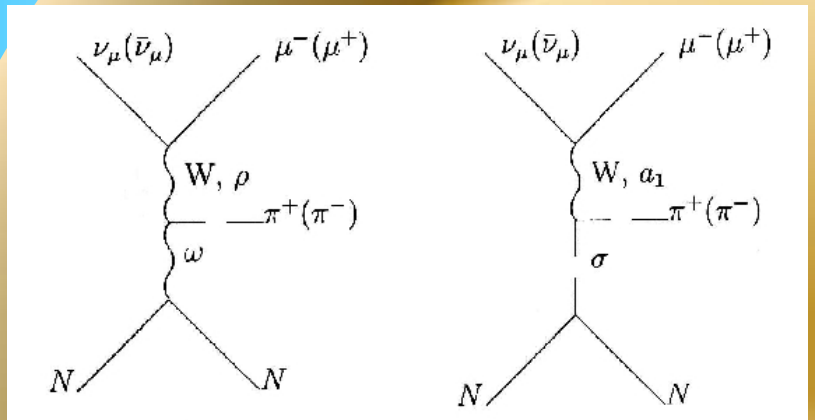
estimated 90% CL coverage of low Δm^2
3+1 allowed regions from combined fit to all SBL experiments (with 1×10^{21} POT)

NC Elastic Scattering Events

events with only 1 subevent, Thits < 150, Vhits <6



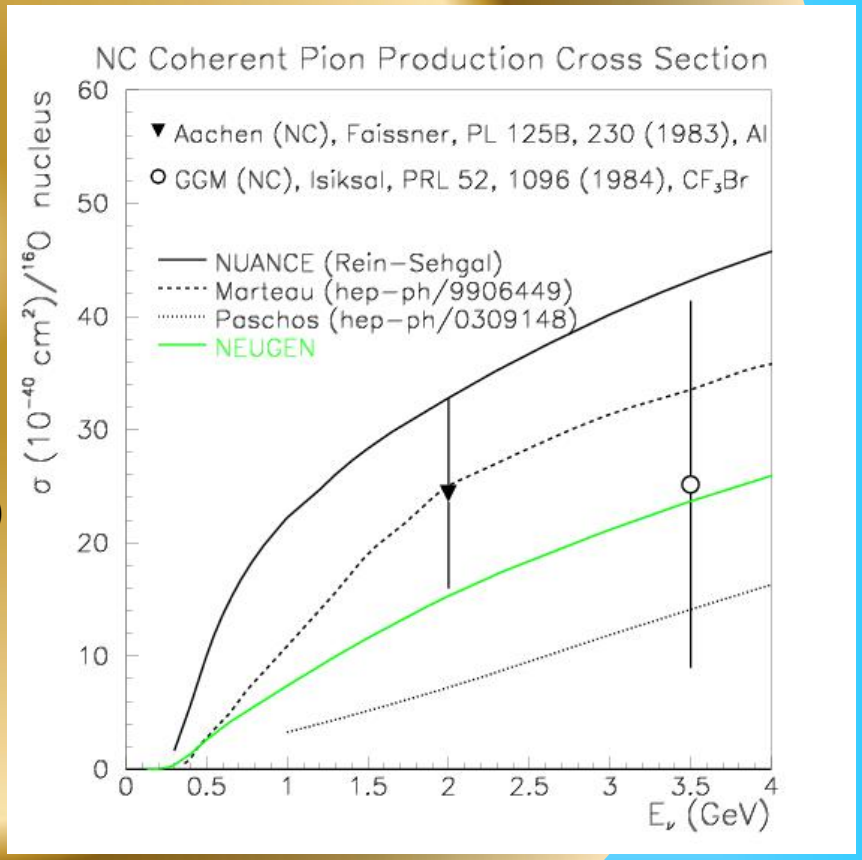
Coherent Pion Production



Paschos & Kartavtsev, hep-ex/0309148

$\nu_\mu A \rightarrow \nu_\mu A \pi^0$ ← **NC**

$\nu_\mu A \rightarrow \mu^- A \pi+$ ← **CC**

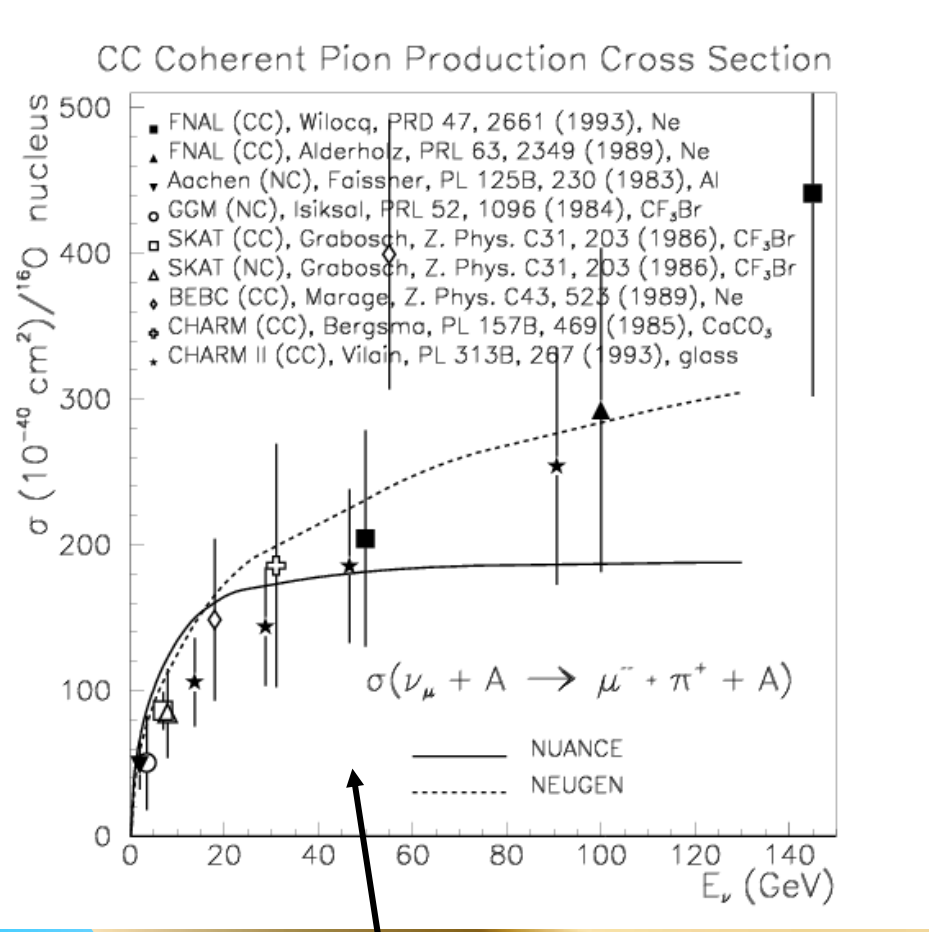


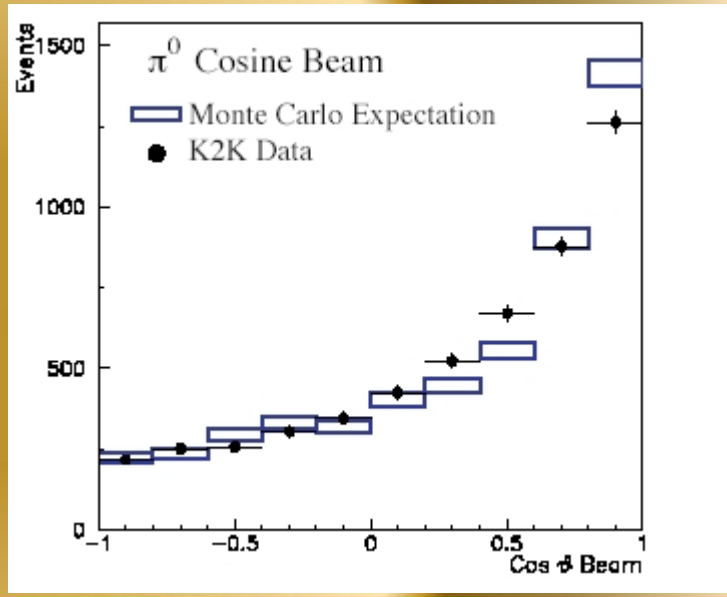
* coherently scatter off entire nucleus rather than its constituents

* distinct kinematics:
  - negligible E transfer to target (low Q^2)
  - forward scattered π

* largely a ν specific process as dominated by the axial current
  - no e^- scattering analogue exists to constrain this process

Coherent Pion Production

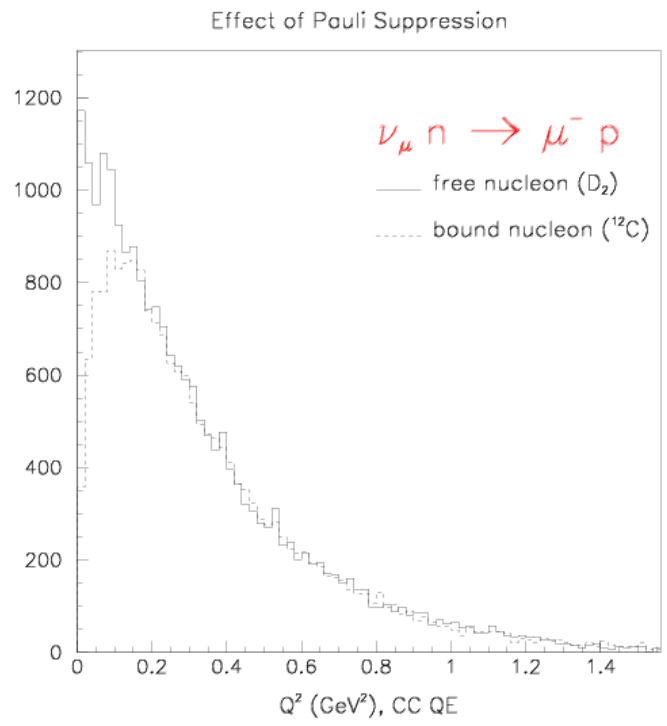




C. Mauger thesis (K2K)

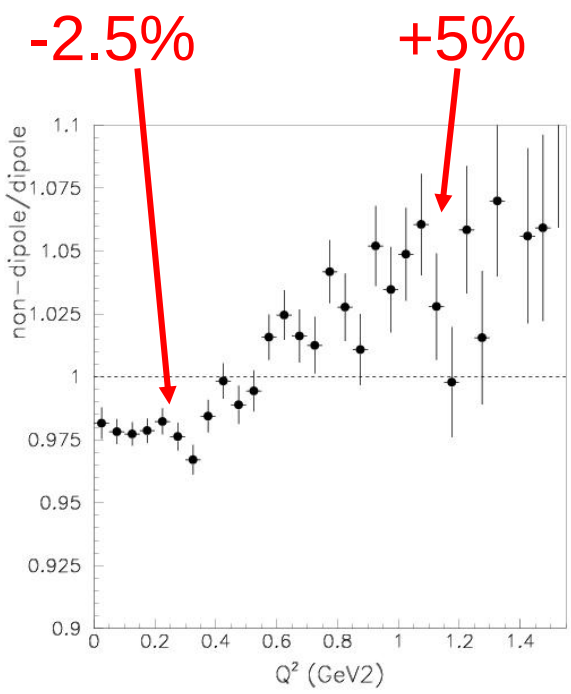
of course, there is much more coherent data at higher energy

Effect of Pauli Suppression

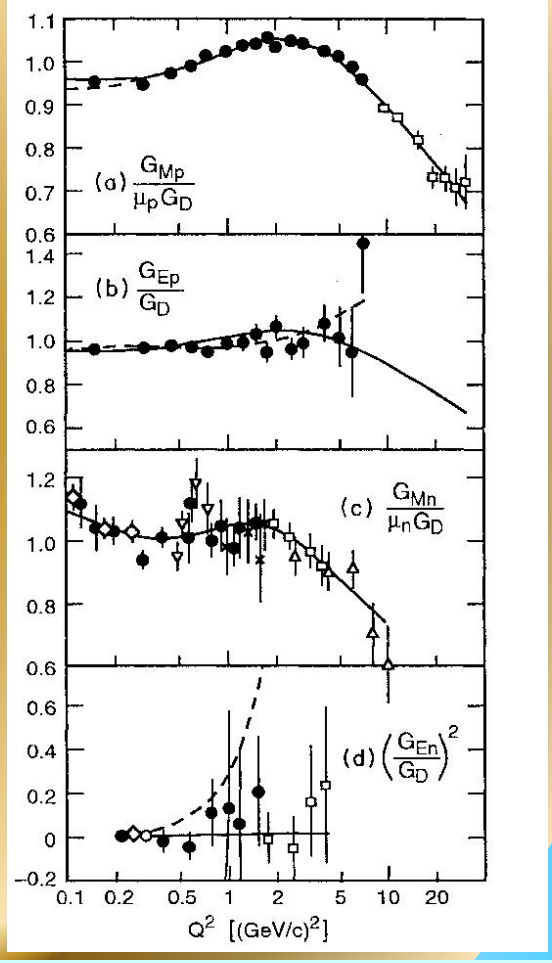


NUANCE-predicted Pauli suppression
(QE event sample)

Effect of Non-Dipole Vector Form Factors on QE Kinematics

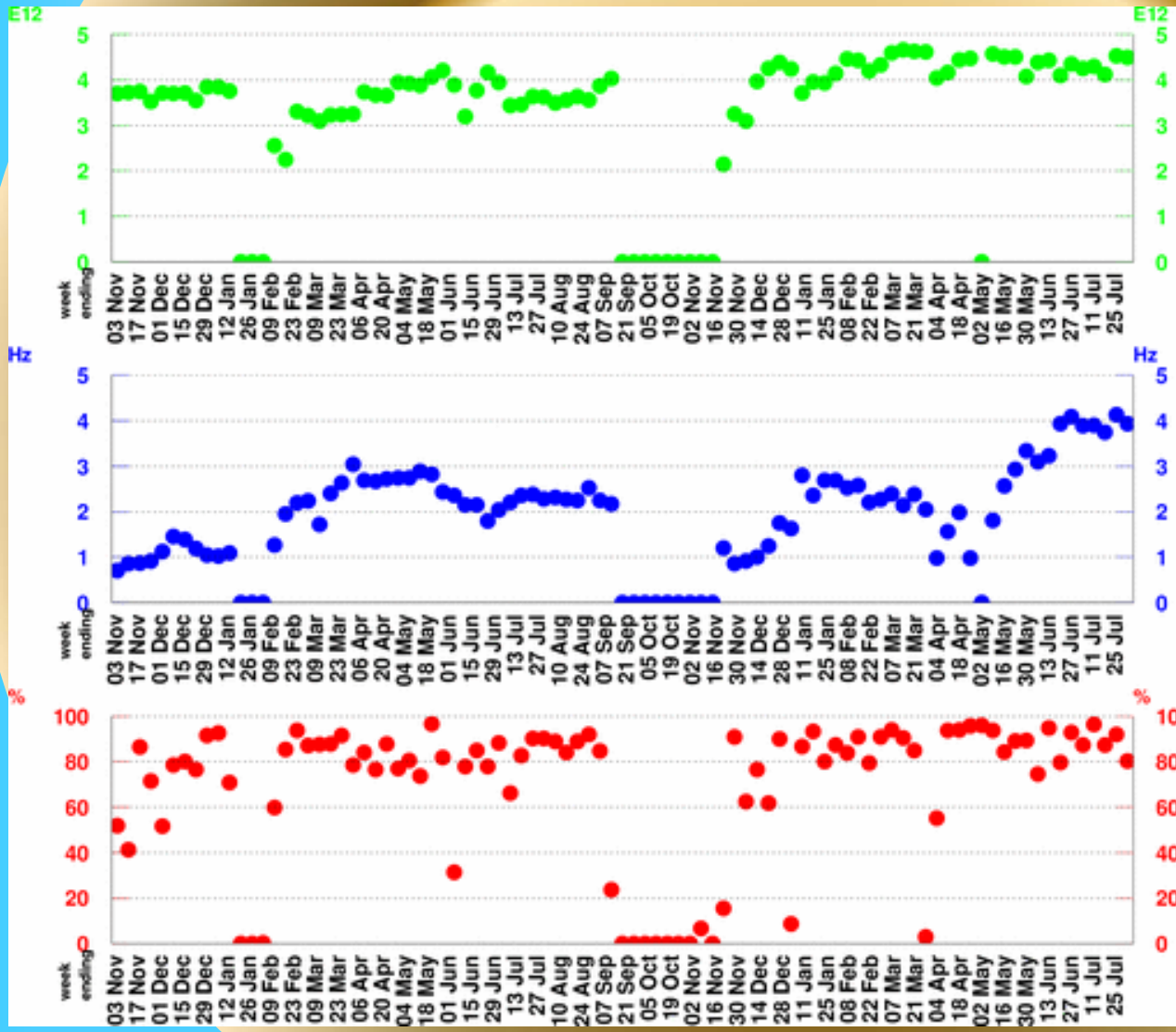


Q^2 distribution of QE events



P.E. Bosted, Phys. Rev, **C51**, 409 (1995)

Beam Performance to MiniBooNE



POT per Horn Pulse

Largest week: 4.66 E12

Latest week: 4.5 E12

Horn Rate

(for time periods with beam)

Largest week: 4.13 Hz

Latest week: 3.94 Hz

Beam Uptime Fraction

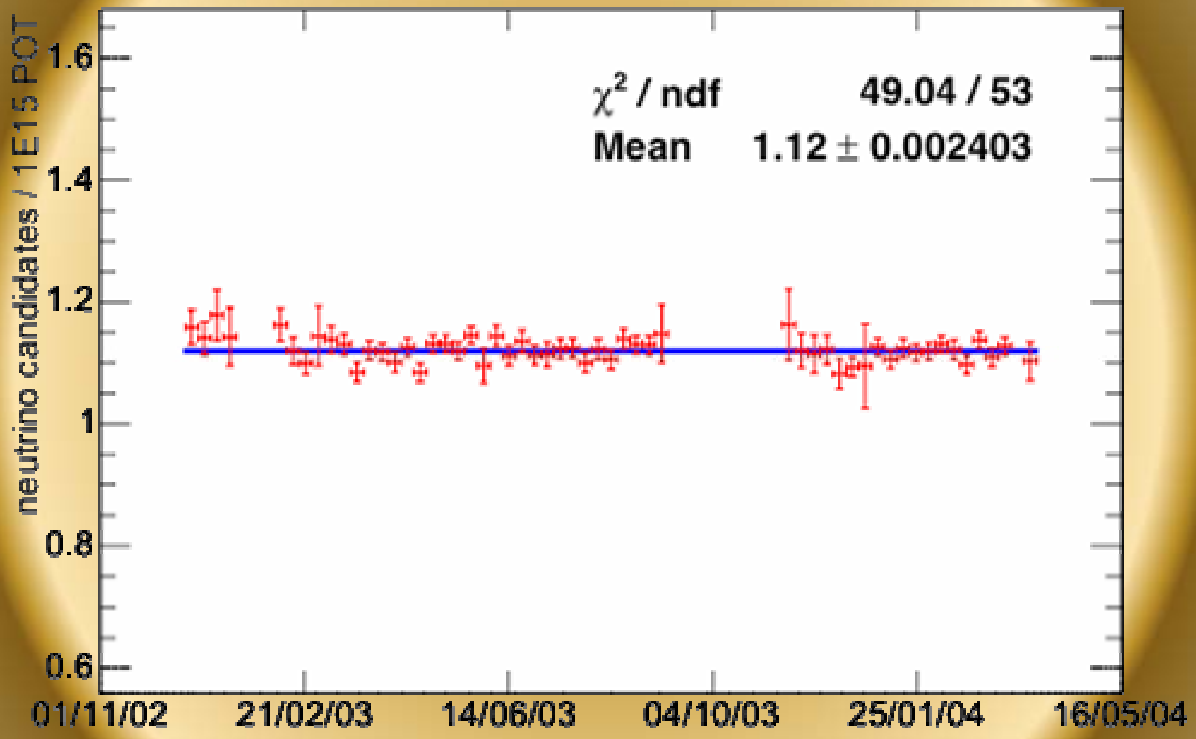
(fraction of time with beam)

Largest week: 96.7 %

Latest week: 80.3 %

Sam Zeller, SSI 2004, Aug. 3, 2004

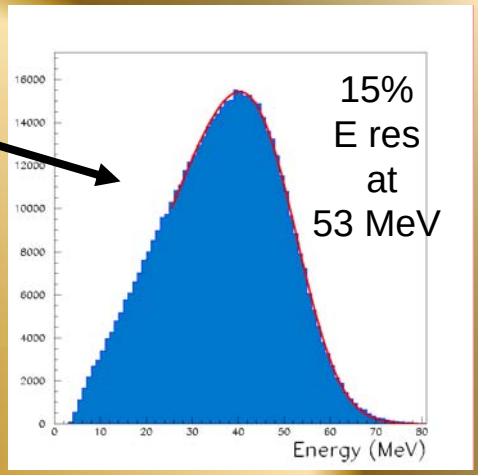
Neutrinos/POT Stable Over Time



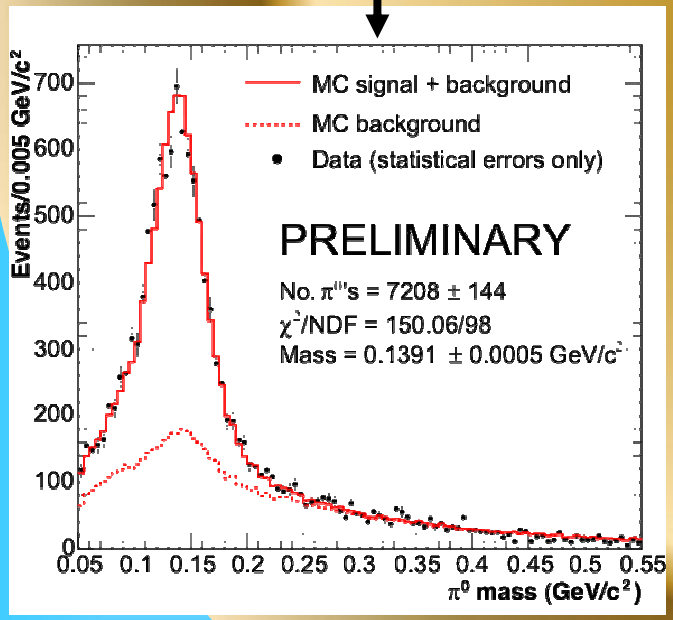
Several Calibration Sources

have calibration sources spanning wide range of energies

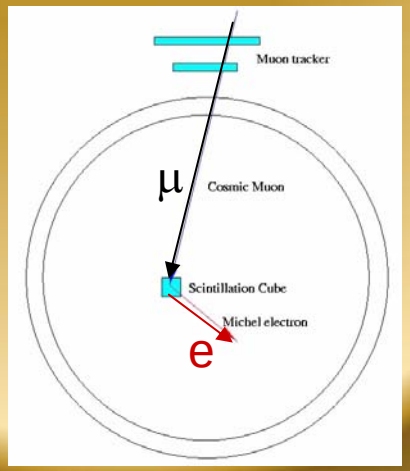
Michel electrons prod from μ decay:
provide E calibration at low energy **(50 MeV),**
good monitor of light transmission, electron PID

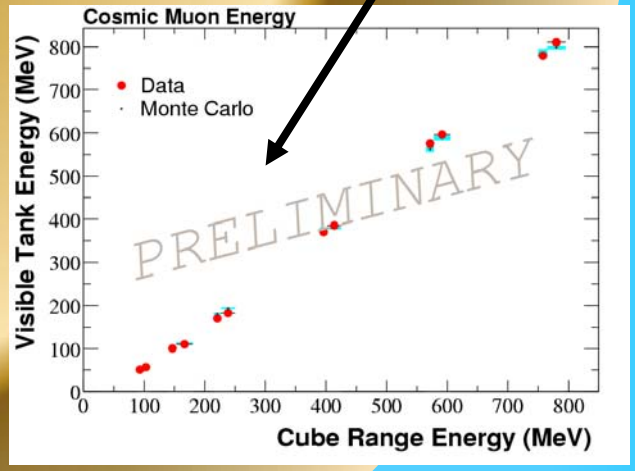


π^0 mass peak: energy scale & resolution
at medium energy **(135 MeV),** reconstruction



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