# MiniBooNE:
# Latest Results & Updated Sensitivity

1. Motivation and Overview
2. Latest results
3. Updated $\nu_\mu \rightarrow \nu_e$ sensitivity

*Jocelyn Monroe, Columbia University*
*Moriond Electroweak, 2004*

# Motivation: LSND Result

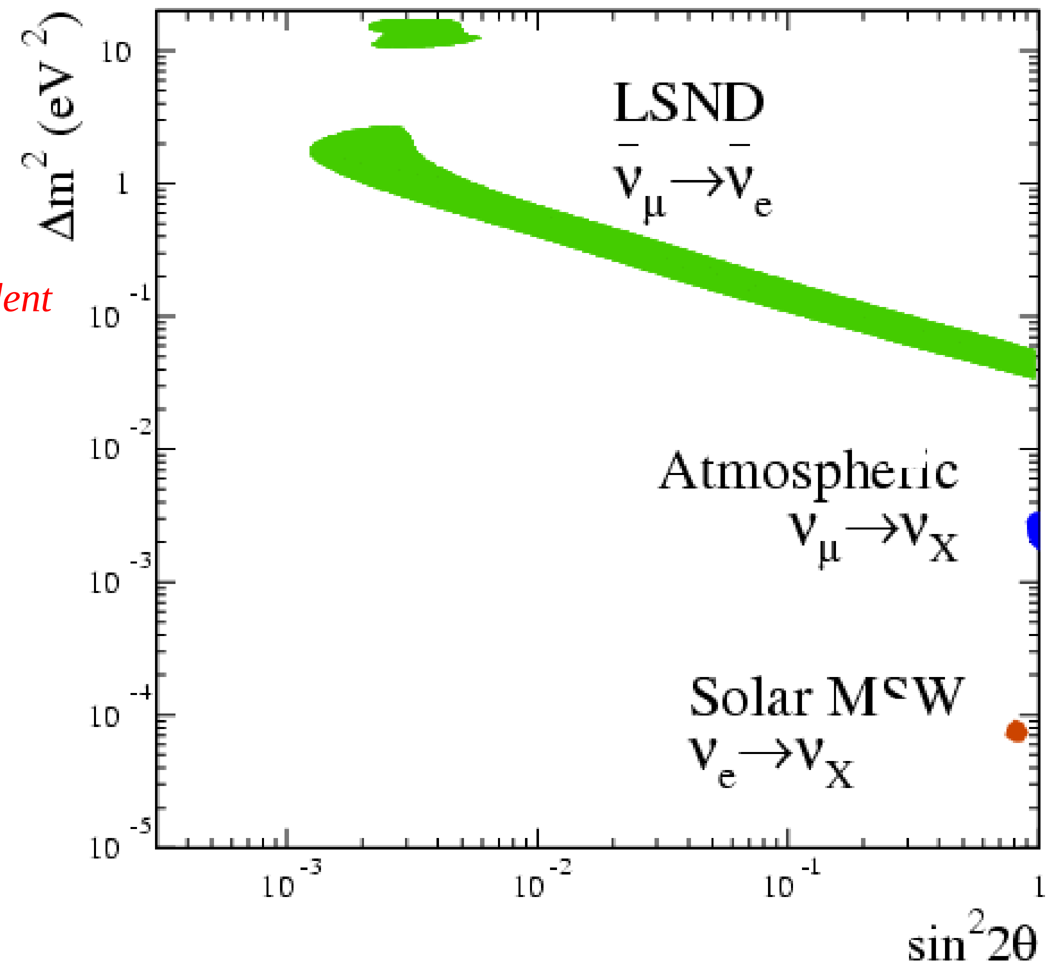
- **ν oscillation signals:**

  ***Solar***: $\Delta m^2 \sim 10^{-5}$ eV $^2$
  (SNO, KamLAND, ...)

  ***Atmospheric***: $\Delta m^2 \sim 10^{-3}$ eV $^2$
  (Super-K, K, ...)

  ***Accelerator***: $\Delta m^2 \sim 10^{0}$ eV $^2$
  (LSND)

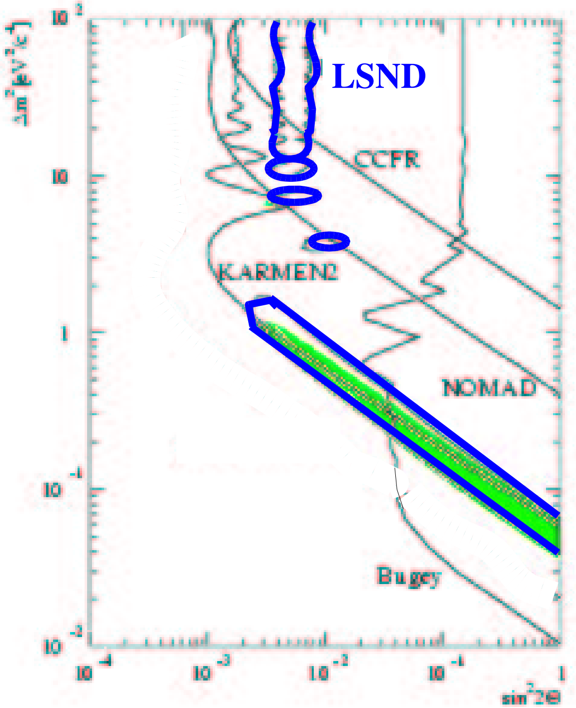
*3 vs allow only 2 independent values of $\Delta m^2$*

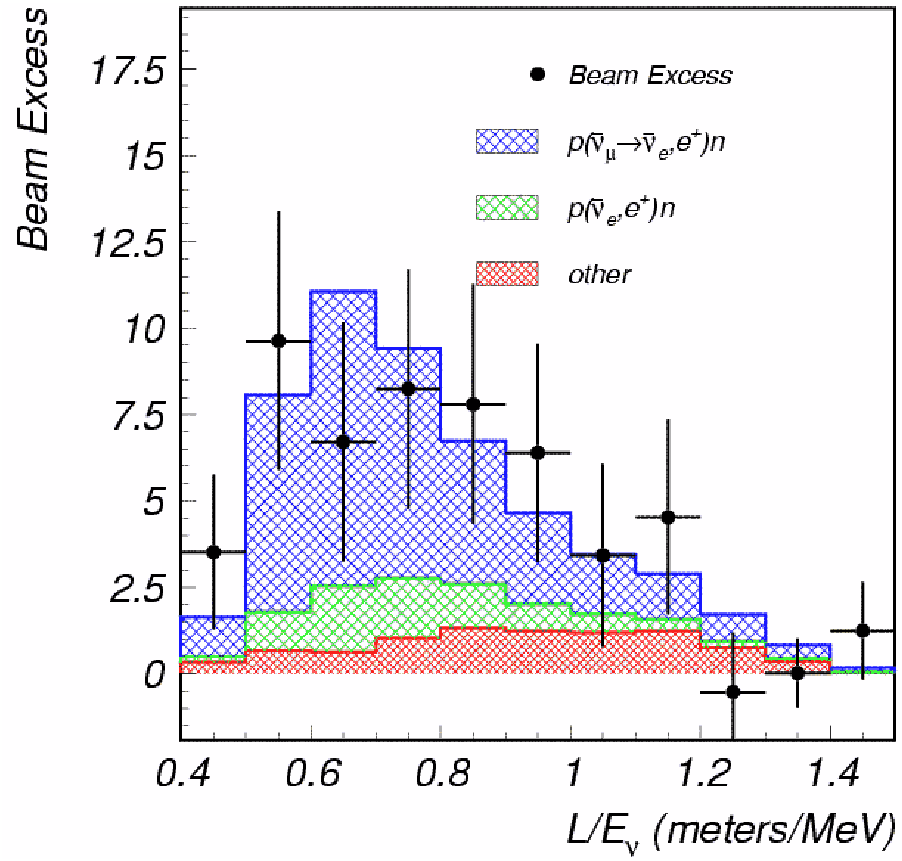



- **What to do?**
  1. An experiment or interpretation is wrong
  2. Add sterile neutrinos: 1, 2, 3 ...
  3. Violate CPT

# Motivation: LSND Result

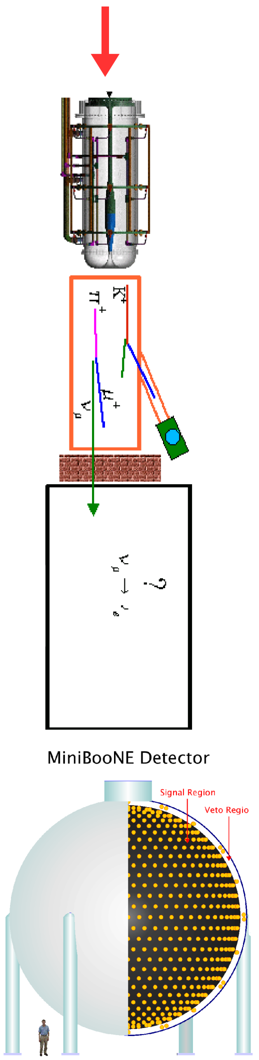
- ***Excess*** $(\bar{\nu}_\mu \rightarrow \bar{\nu}_e$***, appearance):*** 87.9 ± 22.4 ± 6.0
- ***Oscillation probability:***
  (0.264 ± 0.067 ± 0.045)% (DAR)
  (0.10 ± 0.16 ± 0.04)% (DIF)
- **3.8 σ statistical significance of excess,**
  **3.3 σ significance of oscillation hypothesis**



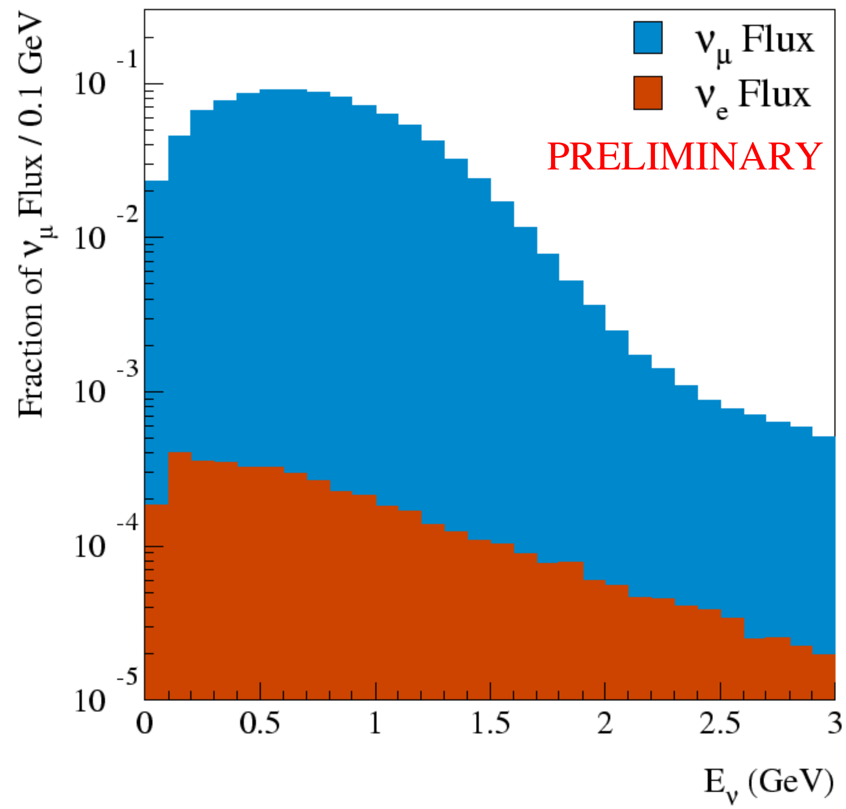




Combined analysis with KARMEN2 gives large allowed region. Confirmation is crucial!
***Enter MiniBooNE***

# MiniBooNE Overview: Beam and Detector




- ***Protons:*** 4E12 protons per 1.6 μs pulse, at a rate of 3 - 4 Hz from Fermilab Booster accelerator
- ***Mesons:*** produced in p-Be collisions, + signs focused in horn. 50m decay region.
- ***Neutrinos:*** 450 m soil berm before the detector hall. Intrinsic $\nu_e$ flux ~ 0.4% x $\nu_\mu$ flux.
- ***Detector:*** 1280 PMTs, 250,000 gallons of mineral oil, Cherenkov and scintillation light. 240 PMTs in optically isolated veto region.



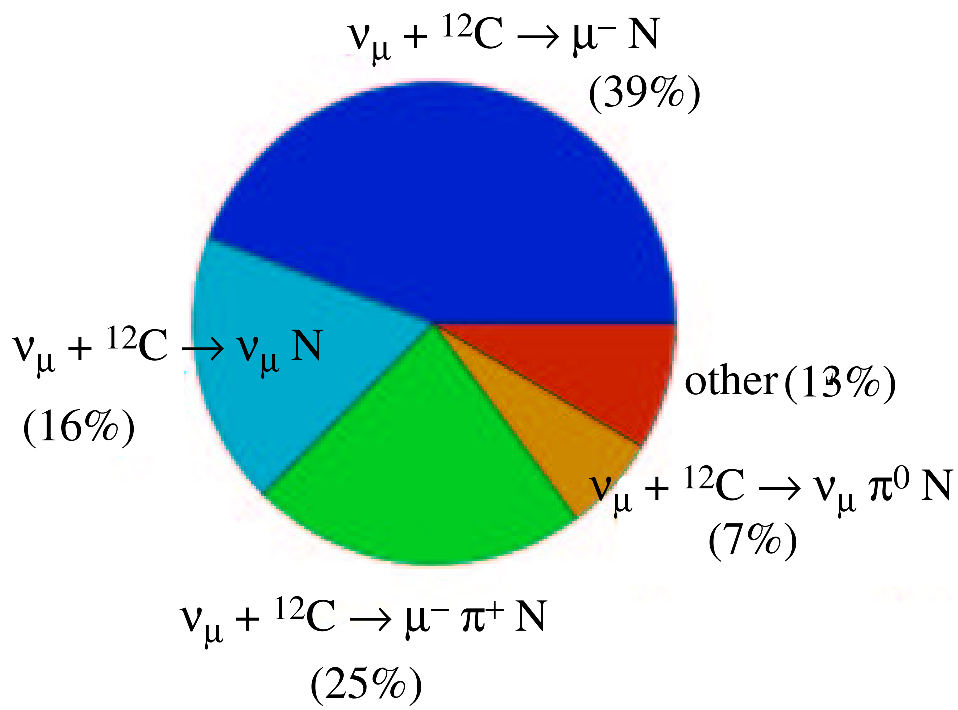

- Beam background $\nu_e$s from:

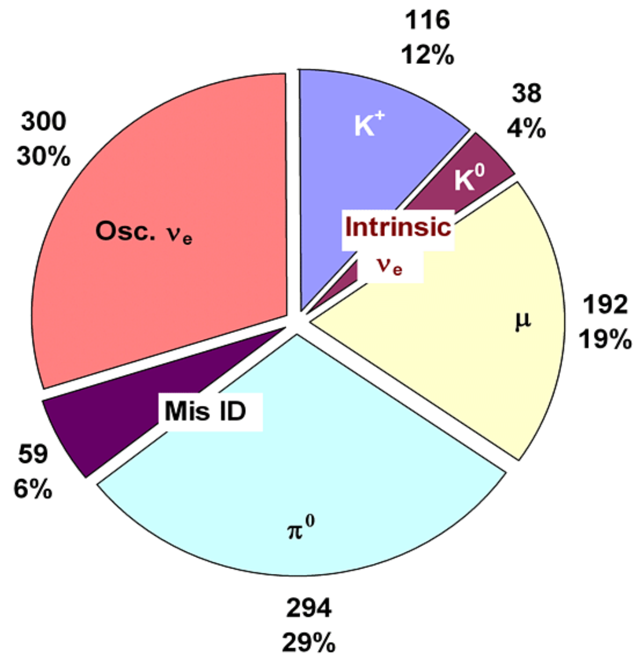
| | |
|---|---|
| $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ | (99.99% B.R.) |
| $K^+ \rightarrow \pi^0 e^+ \nu_e$ | (5% B.R.) |
| $K^0_L \rightarrow \pi^\pm e^\pm \nu_e$ | (39% B.R.) |

# MiniBooNE Overview: Event Rate Prediction

- **Beam Monte Carlo:** parametrization of p Be $\rightarrow \pi^+$ X data for p interaction, GEANT4 for everything else

- **Cross Section Monte Carlo:** NUANCE (K2K, SuperK): Llewellyn-Smith free nucleon QE $\sigma$, Rein-Sehgal coherent, Smith & Moniz Fermi gas model, $m_A = 1.03$, Carbon FSI




- **Electron Neutrino Events:** important backgrounds are beam $\nu e$ (35%), $\pi^0$ mis-ID (29%), and $\mu$ mis-ID (6%)

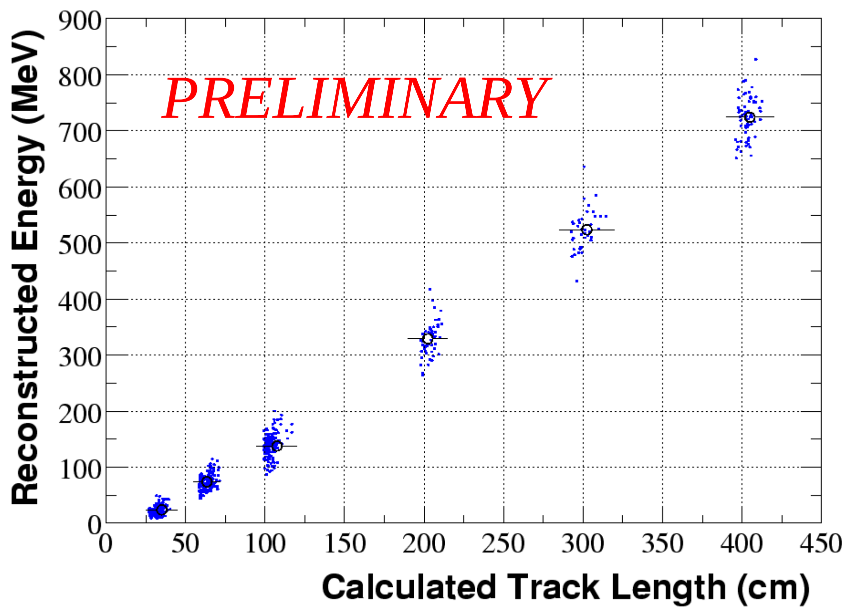
- **Signal:** for LSND average ($\Delta m^2$, $\sin^2 2\theta$) 30% of $\nu e$ events are signal $\nu e\ p \rightarrow e^-\ n$

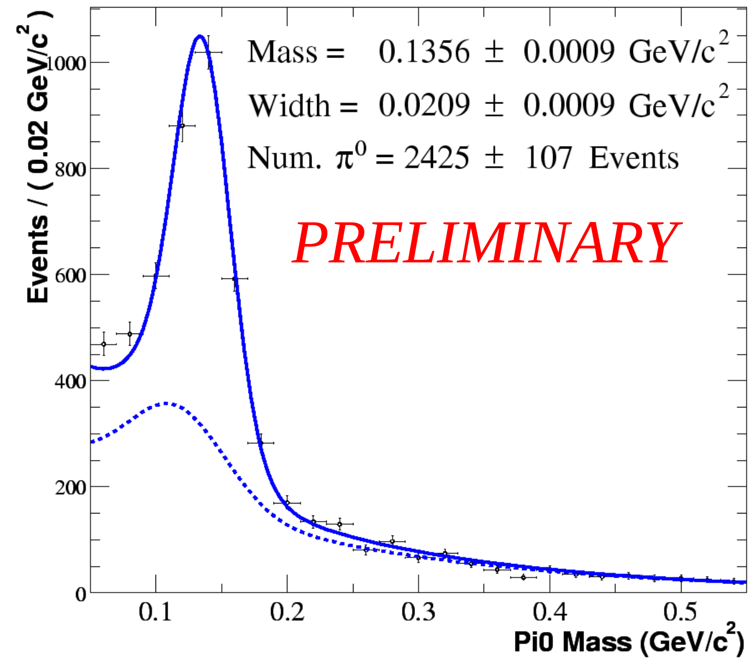
***Updated event rate predictions and sensitivities!***

# MiniBooNE Overview: Calibration

*Many calibration sources ...*

- **Laser + Flasks:** PMT gains, timing resolution, vertex reconstruction cross-check
- **Cosmic Rays + Tracker + Cubes** ($\nu_\mu$'s): energy scale and resolution at high (GeV) energy and track reconstruction cross-check

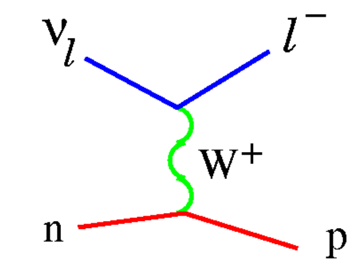



- **Michel Electrons**: low energy (50 MeV) scale and resolution, electron particle ID
- $\pi^0$ **mass peak**: energy scale and resolution at medium energy (135 MeV), reconstruction
- **FNAL Debuncher ($\nu_e$'s):** electron particle ID at high energy (GeV), expect ~50 total

# Latest MiniBooNE results

***Lots of interesting physics on the way to the $\nu_e$ appearance result...***




- **$\nu_\mu$ charged current quasi-elastic events**

  $\nu_\mu \rightarrow \nu_s$ oscillations? ($\nu_\mu$ disappearance)

  measure flux shape (and rate)

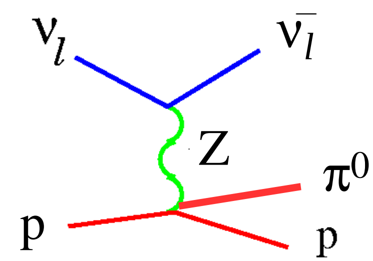
  measure / extrapolate beam $\nu_e$ backgrounds

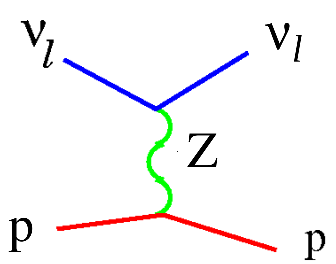
- **$\pi^0$ events**

  coherent vs. resonant production

  (tests PCAC, also relevant for SK $\nu_\mu \rightarrow \nu_s$ limit)

  measure / extrapolate $\pi^0$ background




- **Neutral current elastic scattering events**

  study optical properties of $\nu$ target (oil)

  measure $\sigma(\nu\, p \rightarrow \nu\, p)$

  measure strange spin of the nucleon:

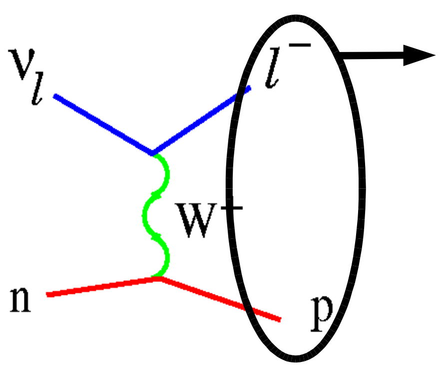
  $\Delta s \sim \sigma\,(\nu\, p \rightarrow \nu\, p)\,/\,\sigma\,(\nu_\mu\, n \rightarrow \mu^-\, p)$

# Latest MiniBooNE results: $\nu_\mu$ CCQE

**event selection:** $\nu_\mu$ **n** $\rightarrow \mu^-$ **p** ....... $\mu^- \rightarrow e^- \nu_\mu \nu_e$

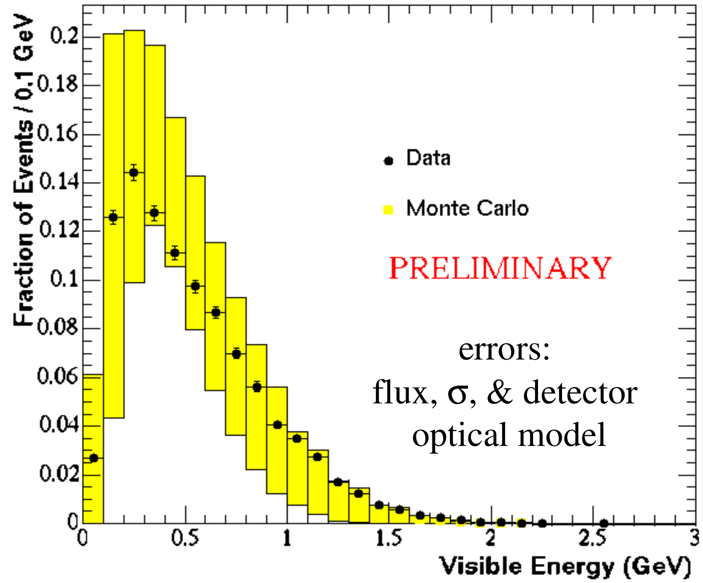
- cut cosmic rays & ensure good reconstruction
  - event in time with beam spill
  - # Tank hits > 100 & # Veto hits < 6
  - Radius < 500 cm
- cut events with > 1 $\mu$ in final state (e.g. resonant 1$\pi$ events)
  - 0 < # Sub-events < 3
- ID CCQE event topology (Fisher discriminant)
  - on- and off-ring hits
  - early (Čerenkov) vs. late (scintillation) light
  - dE/dx consistent with $\mu$

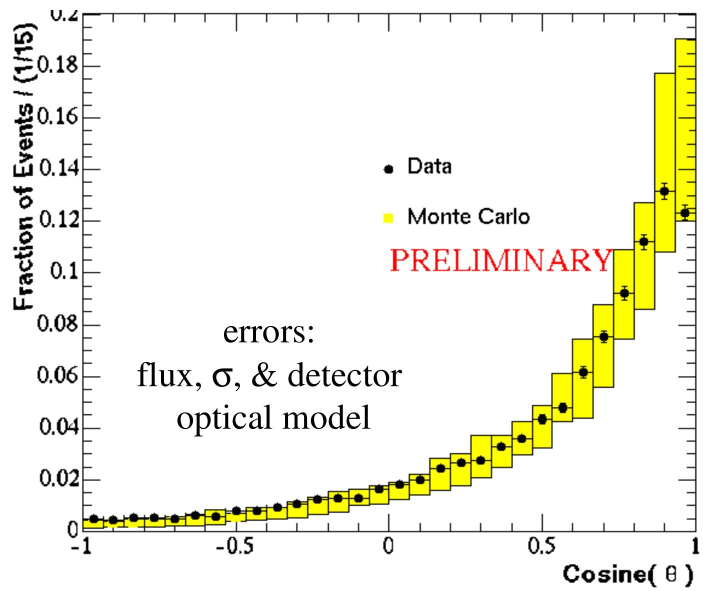
**reconstruction:**




measure visible energy and θ
mostly Čerenkov ($\mu$),
+ a little scintillation light (p)

**result:**
88% purity,
30% efficiency



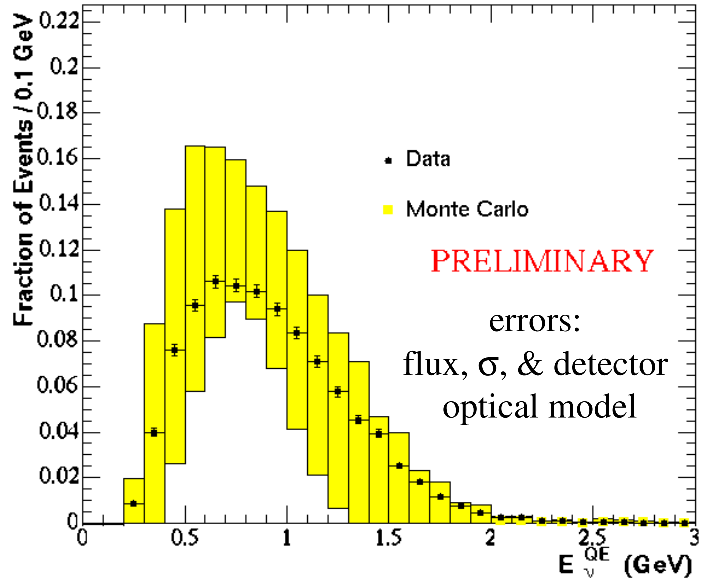
# Latest MiniBooNE results: $\nu_\mu$ CCQE

**neutrino energy reconstruction:**

- use CCQE kinematics + measured $E_\mu$ & $\cos(\theta)_\mu$

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

- energy resolution ~15 - 20% now, will improve

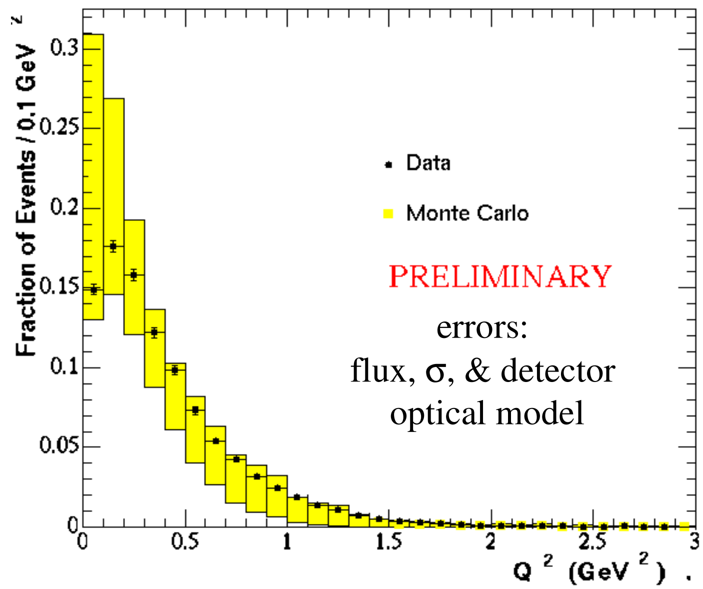



**$Q^2$ reconstruction:**

- use measured $E_\mu$, $\cos(\theta)_\mu$ & $E_\nu$

$$Q^2 = 2E_\nu E_\mu(1 - \beta_\mu \cos\theta_\mu) - m_\mu^2$$

- low $Q^2$ sensitive to nuclear effects
  Pauli blocking
  nuclear shadowing (observed at BEBC)



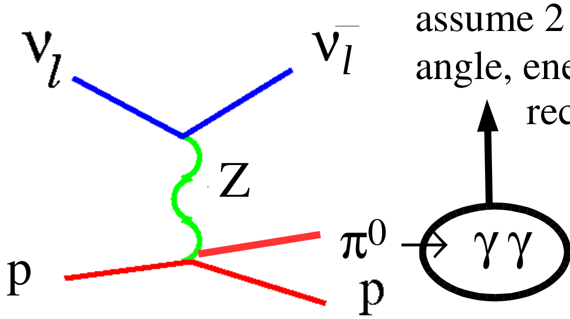

***next: compare observed with expected $E_\nu$ spectrum, fit for $\nu_\mu$ disappearance ($\nu_\mu \rightarrow \nu_s$ oscillations)***

# Latest MiniBooNE results: NC $\pi^0$

**event selection:** $\nu_\mu\, n \rightarrow \nu_\mu\, n\, \pi^0$ ... $\pi^0 \rightarrow \gamma\ \gamma$

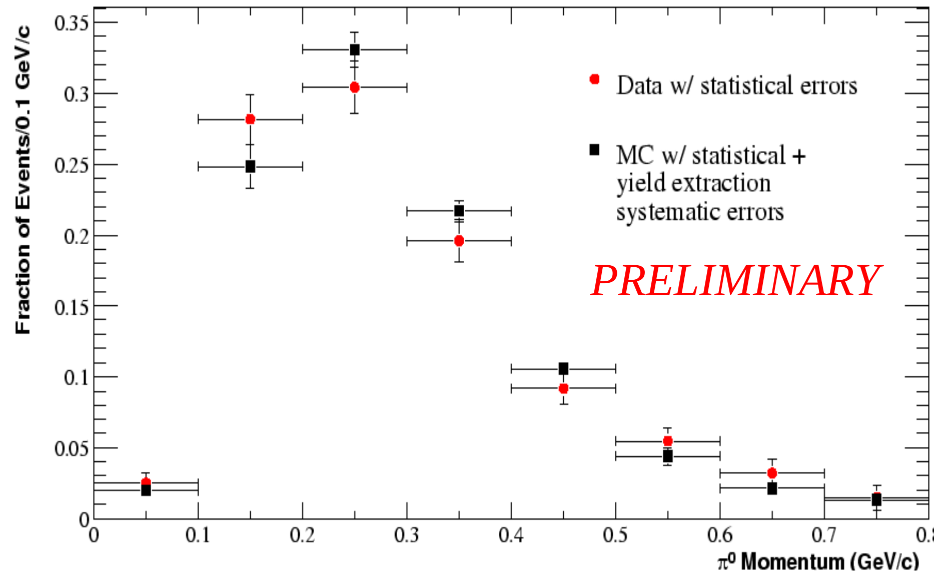
- cut cosmic rays & ensure good reconstruction
  - event in time with beam spill
  - # Tank hits > 200 & # Veto hits < 6
  - Radius < 500 cm
- cut $\nu_\mu$ CCQE events:
  - # Sub-events = 1
- ID $\pi^0 \rightarrow \gamma\ \gamma$ event topology
  - require 2 rings with > 40 MeV each
  - invariant mass > 50 MeV
- EML fit signal extraction

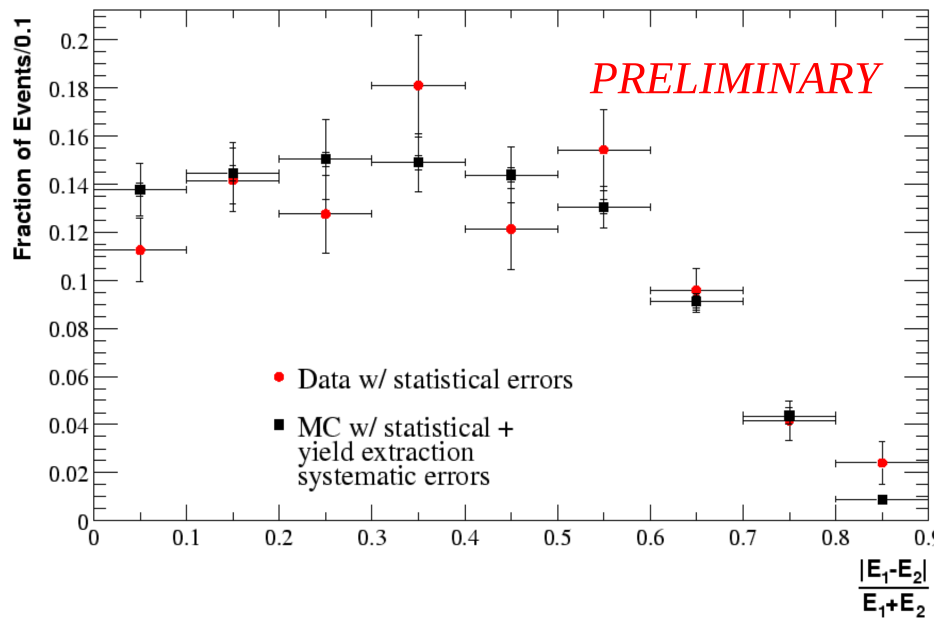
**reconstruction:**




assume 2 rings, fit for $\gamma$ opening angle, energy, vertex, direction, reconstruct W

**result:**
42% purity,
22% efficiency

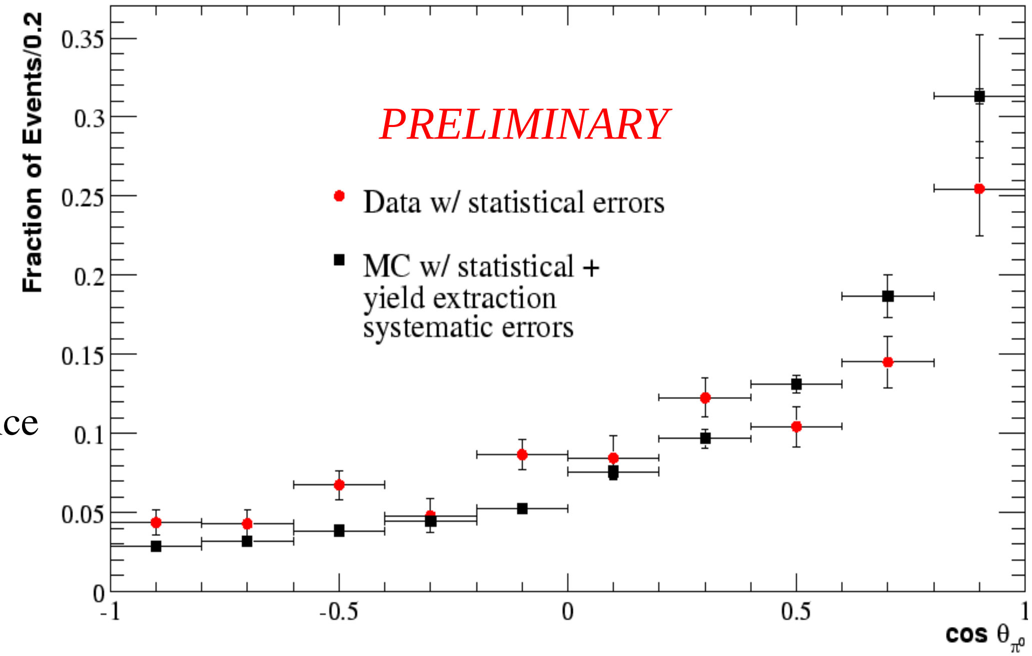


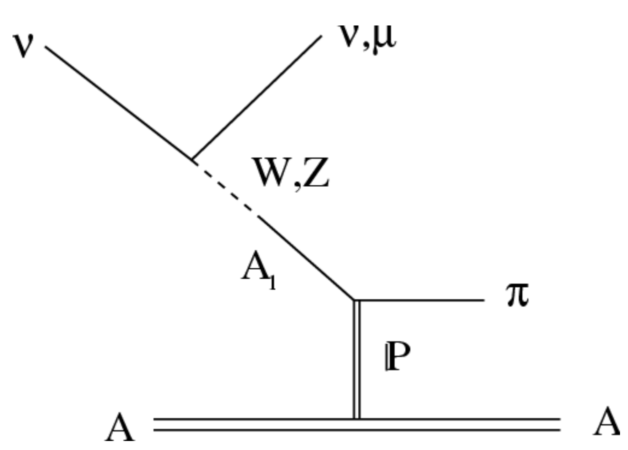
# Latest MiniBooNE results: NC $\pi^0$

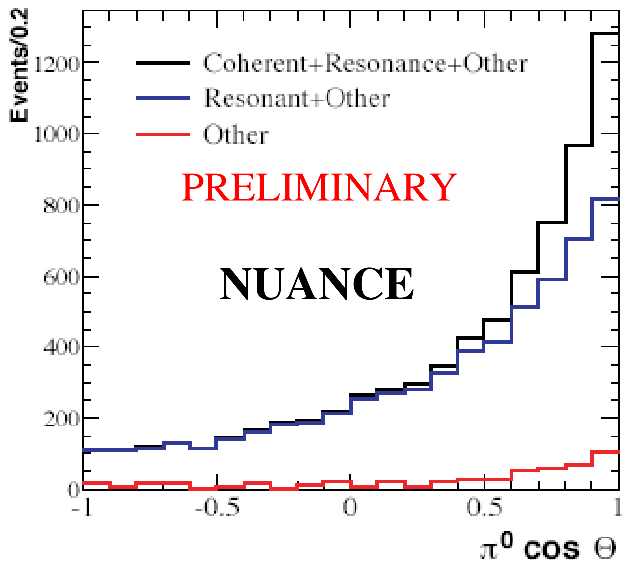
**Coherent $\pi^0$ events:**

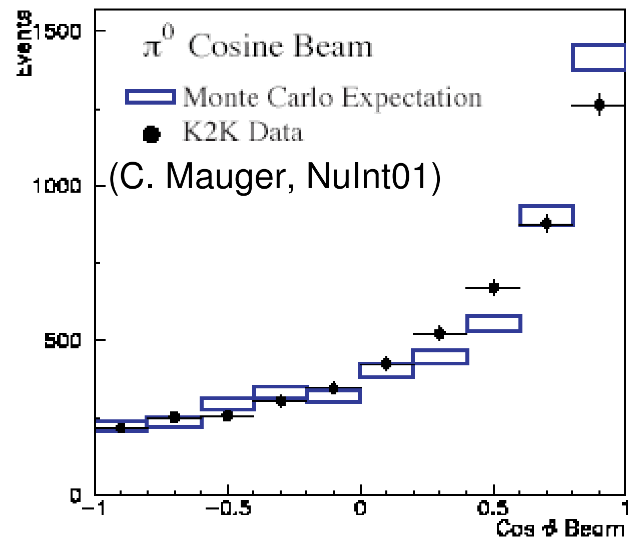
- diffractive scattering from whole C nucleus, low $Q^2 \rightarrow$ distinctive kinematics
- important background to $\nu_\mu \rightarrow \nu_e$ search (20%)
- competing models differ by 6x
- Impacts atmospheric oscillations to $\nu_s$: NC rate + cross- section bounds sterile content of disappearance




***next, NC $\pi^0$ cross sections***



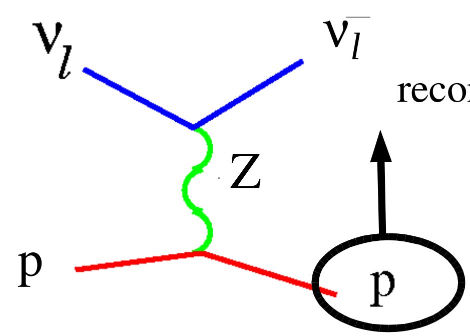
# Latest MiniBooNE results: NC elastic

**event selection:** $\nu_\mu$ **p** $\rightarrow$ $\nu_\mu$ **p**

- cut cosmic rays & beam induced backgrounds
  - event in time with beam spill
  - # Veto hits < 6
  - Radius < 500 cm
- cut $\nu_\mu$ CCQE events:
  - # Sub-events = 1
  - # Tank hits < 150

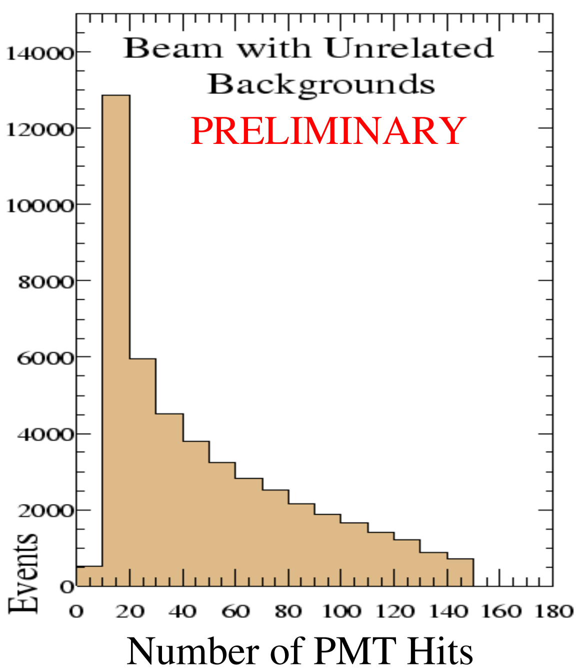
**result:**
81% purity,
68% efficiency

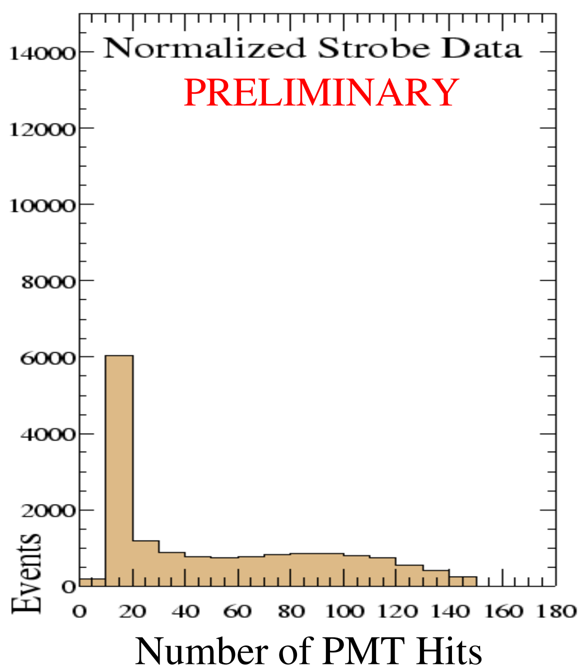
**reconstruction:**

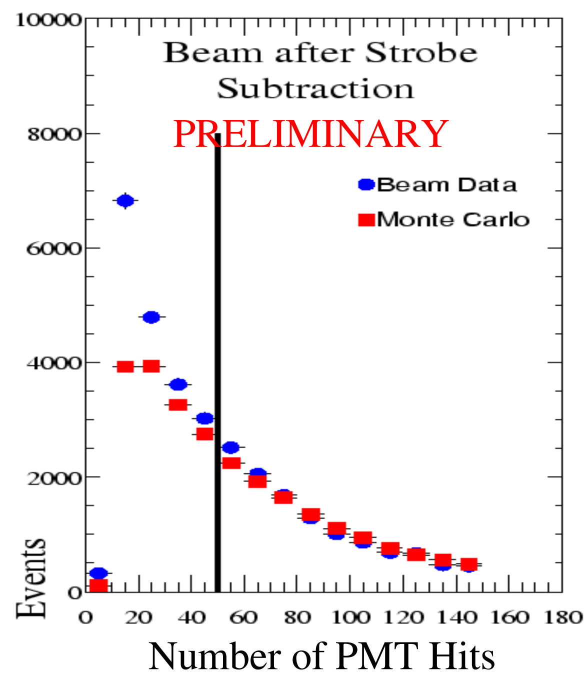



reconstruct proton energy from scintillation light

*MC models data well down to 60 tank hits*    *150 MeV proton kinetic energy*



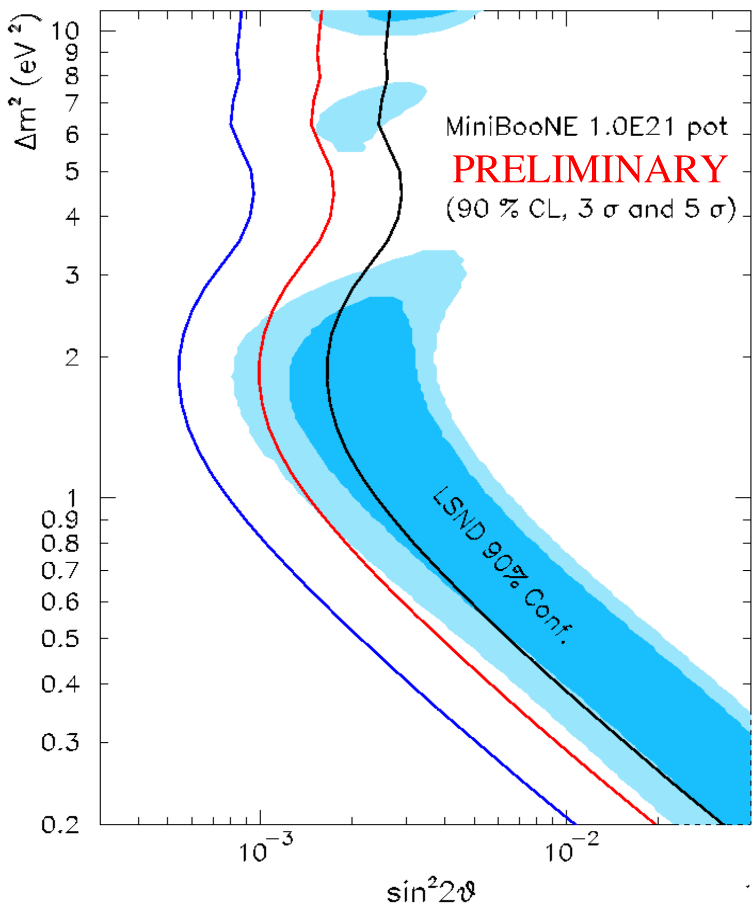



# Updated MiniBooNE Sensitivity

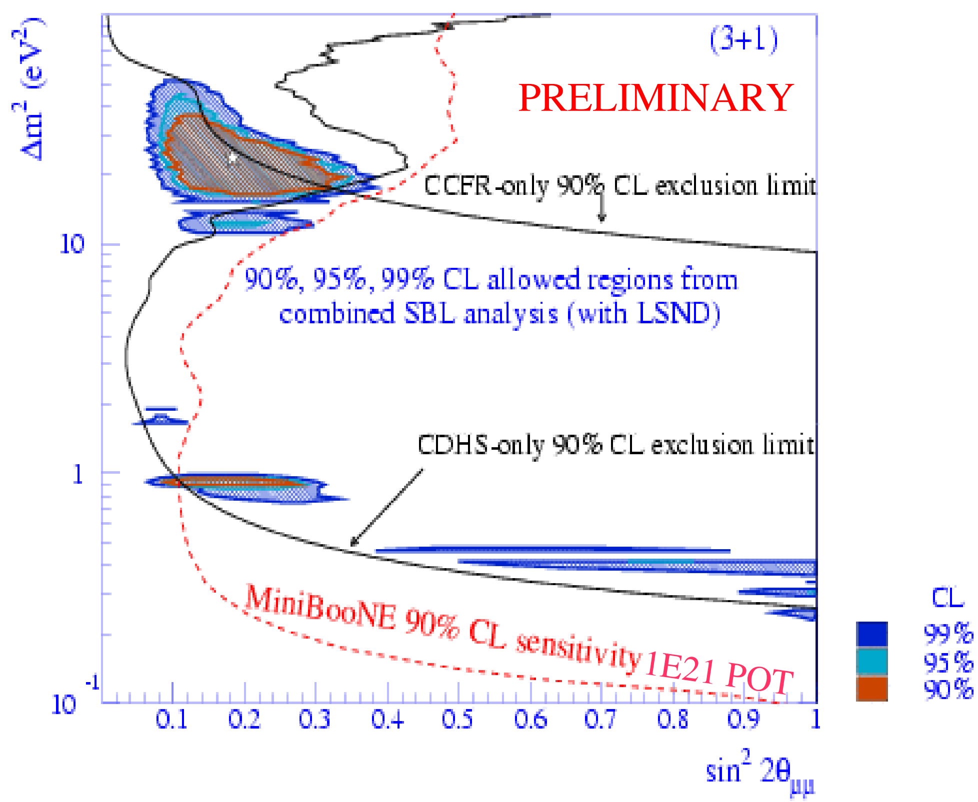
**$\nu_\mu \rightarrow \nu_e$ oscillation search:**

4 -5 σ coverage of the LSND 90% CL region
with 1 x $10^{21}$ protons on target
analysis target date: ~ 2005




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

90% CL coverage of low $\Delta m^2$ 3+1 allowed regions
from combined fit of all short baseline experiments
analysis target date: ~ 2004



# Summary & Outlook

*summary:*

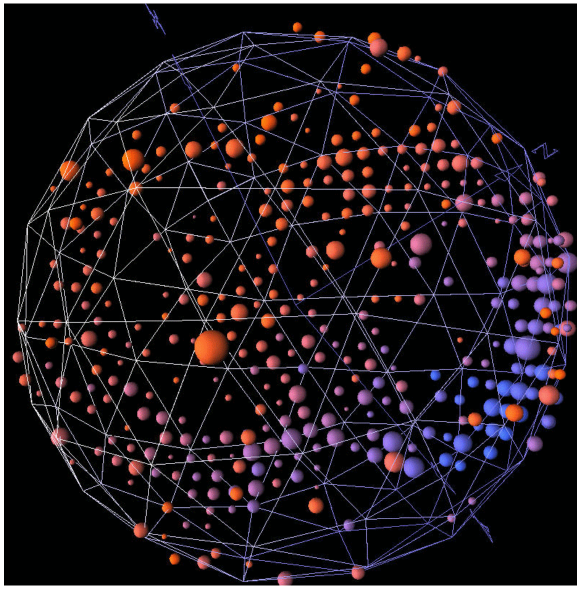
- PMT calibrations done, energy scale calibrations & reconstruction cross-checks in progress

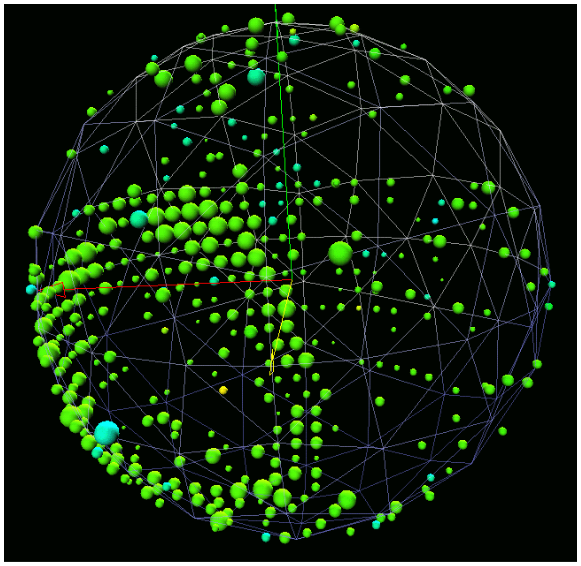
$\nu_\mu$ **CCQE**:
- first data MC comparisons of neutrino energy spectrum
- working to reduce errors & on absolute normalization
- interesting disagreement in data / MC $Q^2$, model deficiencies?
- big effort to compare $\sigma$ MC s with each other and data

**NC $\pi^0$**:
- first kinematic distributions
- interesting $\pi^0$ angular distribution (probes coherent / resonant)

**NC elastic**:
- high purity and efficiency sample ID'd & reconstructed
- studying scintillation properties of oil & low energy response of detector

*outlook (2004):*
- NC $\pi^0$ cross sections
- $\nu_\mu$ disappearance analysis

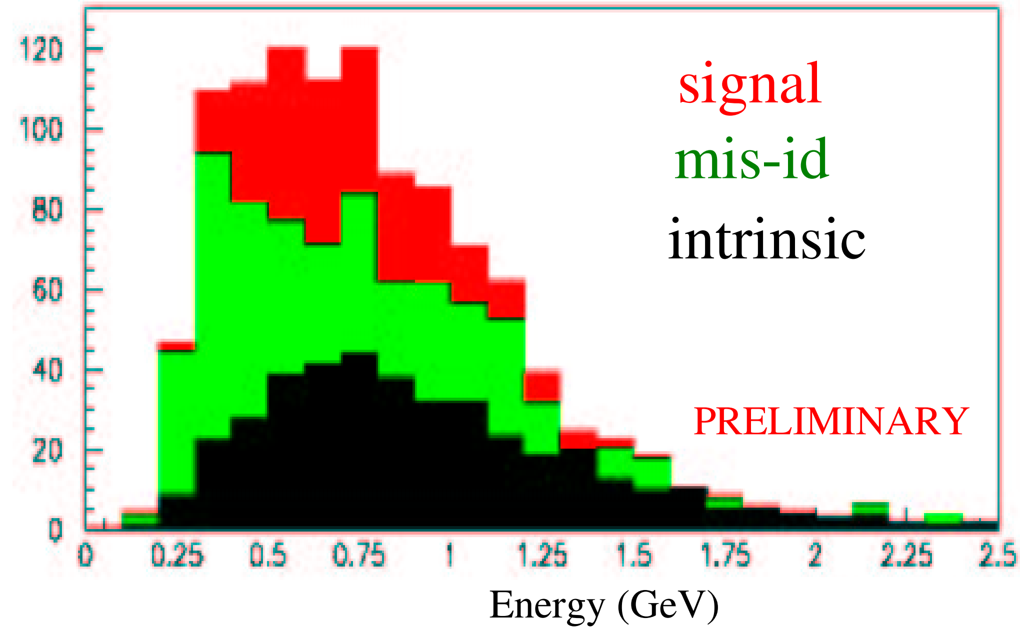




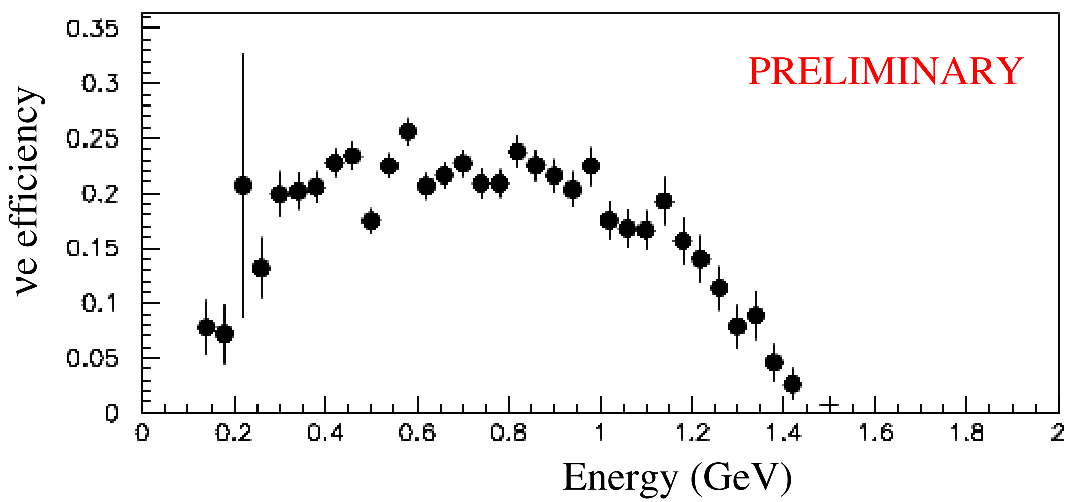
# BACKUP SLIDES ....

# Updated MiniBooNE $\nu_\mu \rightarrow \nu_e$ Sensitivity

*What we are looking for:*
- events with a single electron
- $0 < E < 1.25$ GeV (high $\Delta m^2$ LSND out)




*Isolating the signal:*
Pre-cuts: # tank & veto hits,
fiducial region, 1 sub-event
ID cuts: neural net variables (e-mu & e-pi)
Kinematic cuts: E<1.25 GeV,
scattered lepton angle <0.956,
$\pi^0$ mass fit < 72 MeV




Cutting Hard on Backgrounds
Hurts the Signal Efficiency:
- this is about ×2 lower than the proposal
- improving the efficiency is a top priority

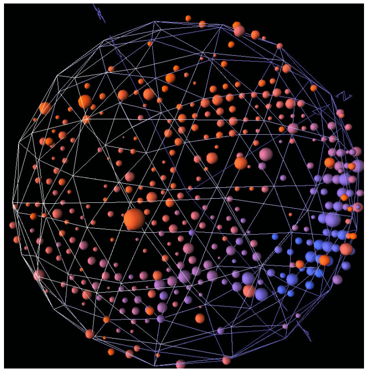
# Updated MiniBooNE $\nu_\mu \rightarrow \nu_e$ sensitivity

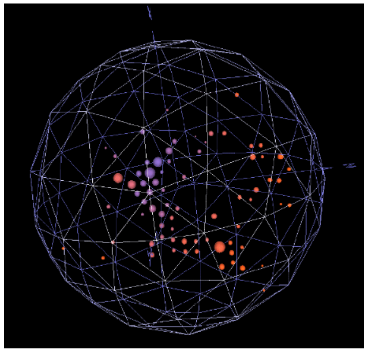
Systematic Error from Mis-identified $\pi^0$'s:

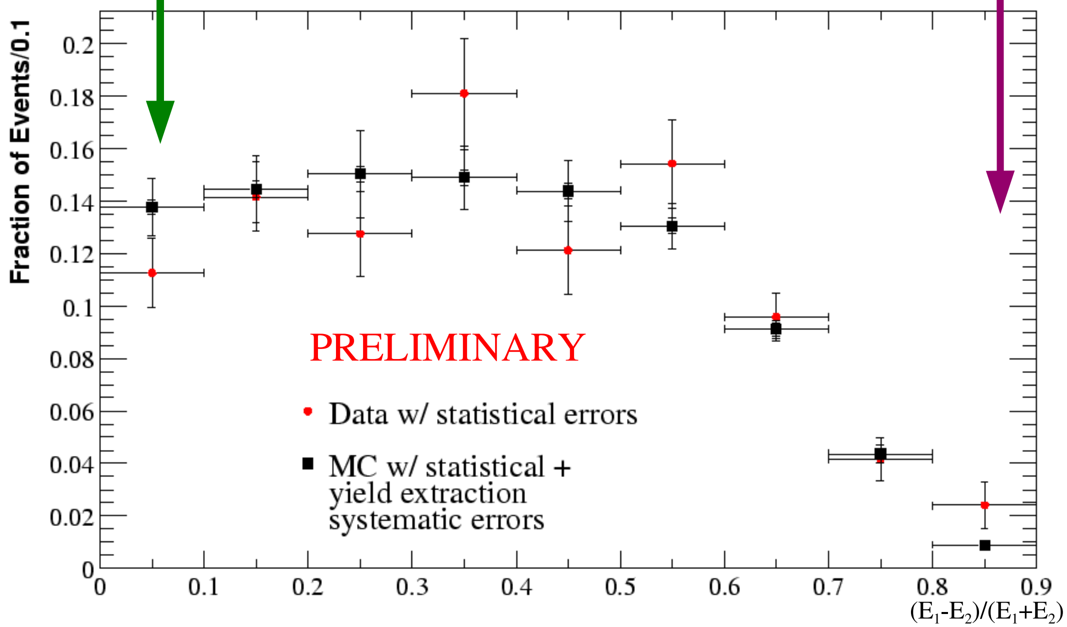
1) Asymmetric decay only reconstruct one ring
2) high momentum events -- overlapping rings

Extrapolate from measured $\pi^0$'s

*(needs full statistics!)*



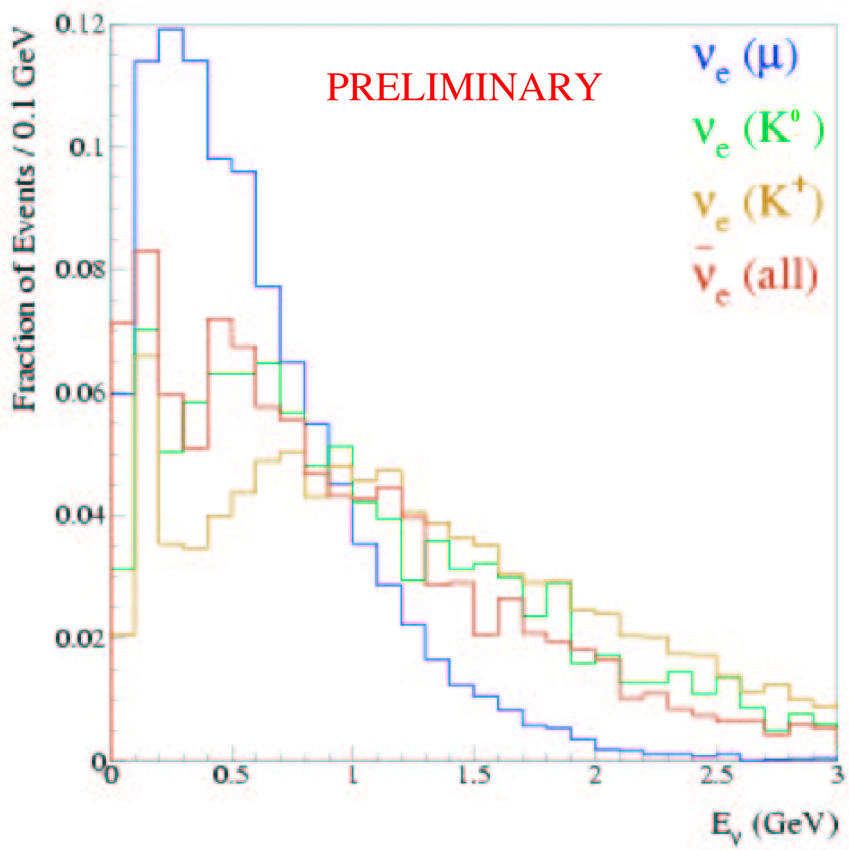





***with full statistics, 5% systematic error from pion mis-id***

# Updated MiniBooNE $\nu_\mu \to \nu_e$ Sensitivity

Systematic Error on Intrinsic $\nu_e$ Events:




From kaons:

- data from HARP & BNL E910 on production
- high energy νe(μ) events in detector
- events in the LMC detector

5% for $K^\pm$

6% for $K^0$

From muons:

- detector picks out very forward decays

  strong correlation $E\nu \Rightarrow E\pi$

  From $E\pi$, $\Rightarrow E\mu$

  From $E\mu \Rightarrow E\nu e$

5% for muons

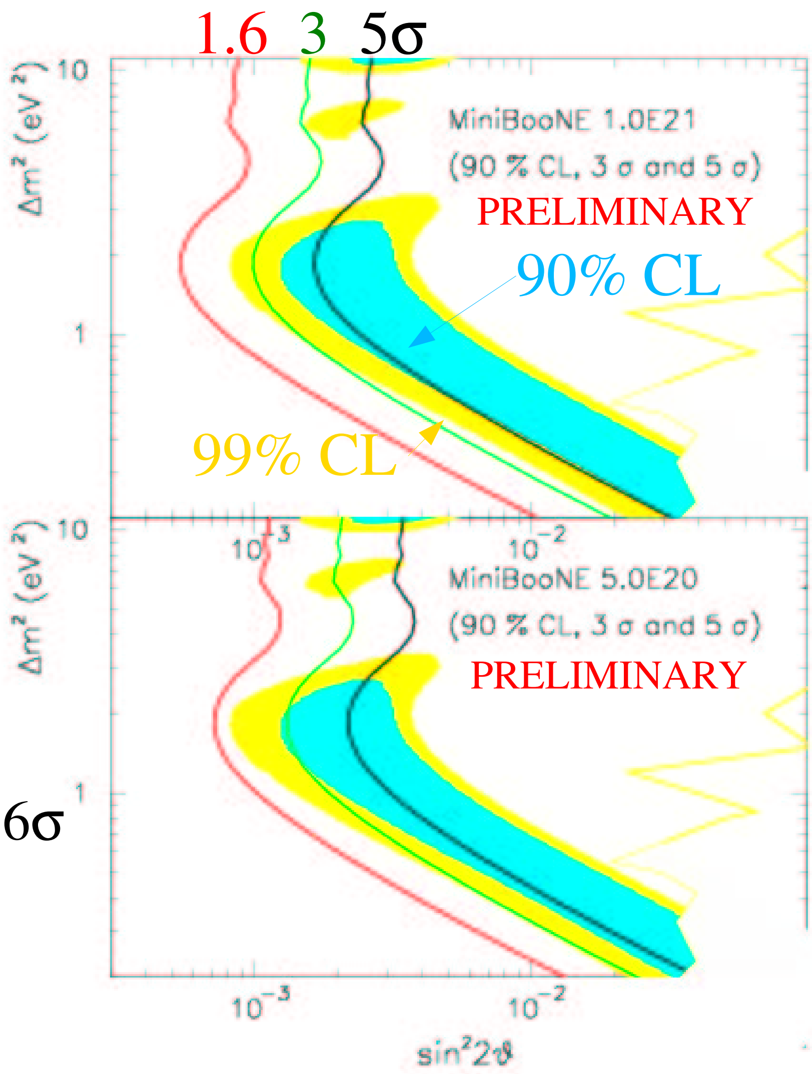
***with full statistics, 5% systematic error from intrinsic νe***

# Updated MiniBooNE $\nu_\mu \rightarrow \nu_e$ Sensitivity

Coverage of LSND:

$1\times10^{21}$ POT:
Good coverage:
90% LSND allowed at > 4σ

$5\times10^{20}$ POT:
90% CL LSND @ ~3σ
Only just covers at LSND 99% CL at <1.6σ



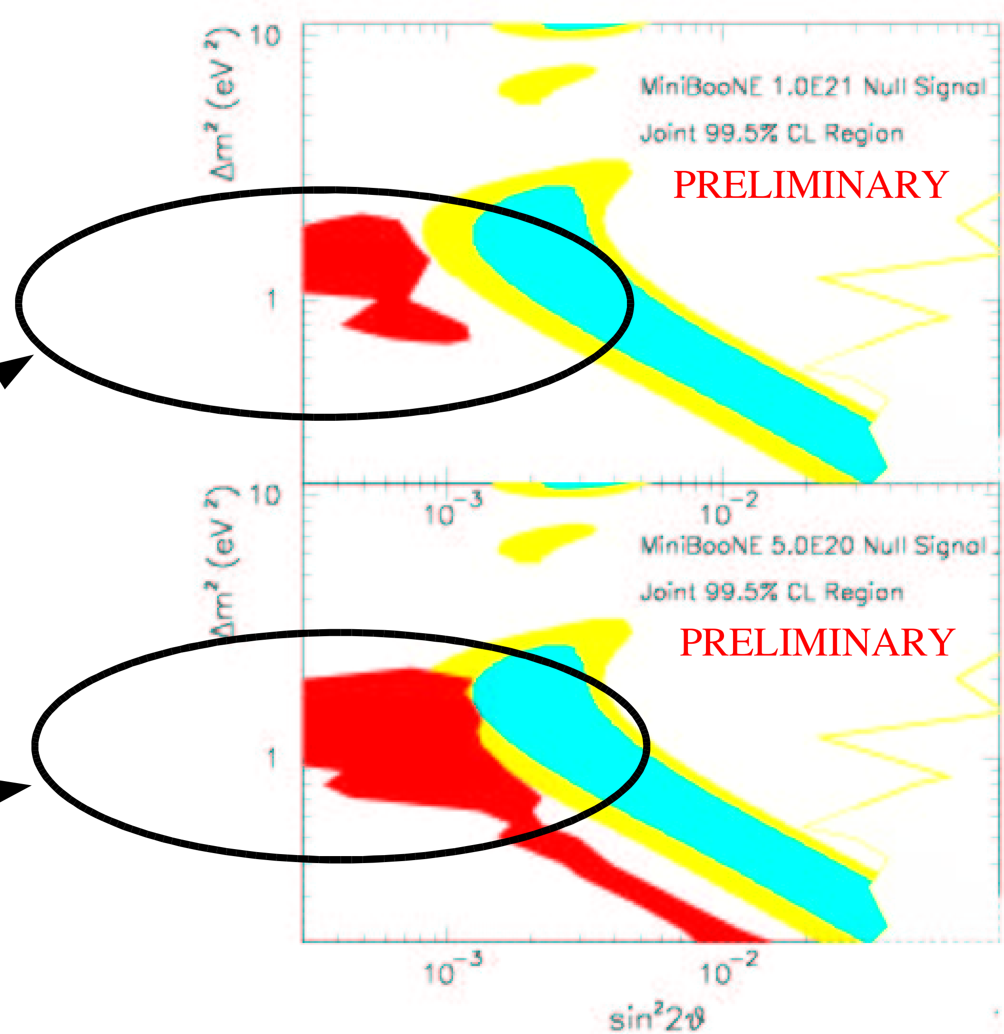
# Updated MiniBooNE $\nu_\mu \rightarrow \nu_e$ Sensitivity

Converting to an allowed region:

The ~3σ
allowed region
from a joint analysis

The lack of overlap shows
the two experiments are inconsistent

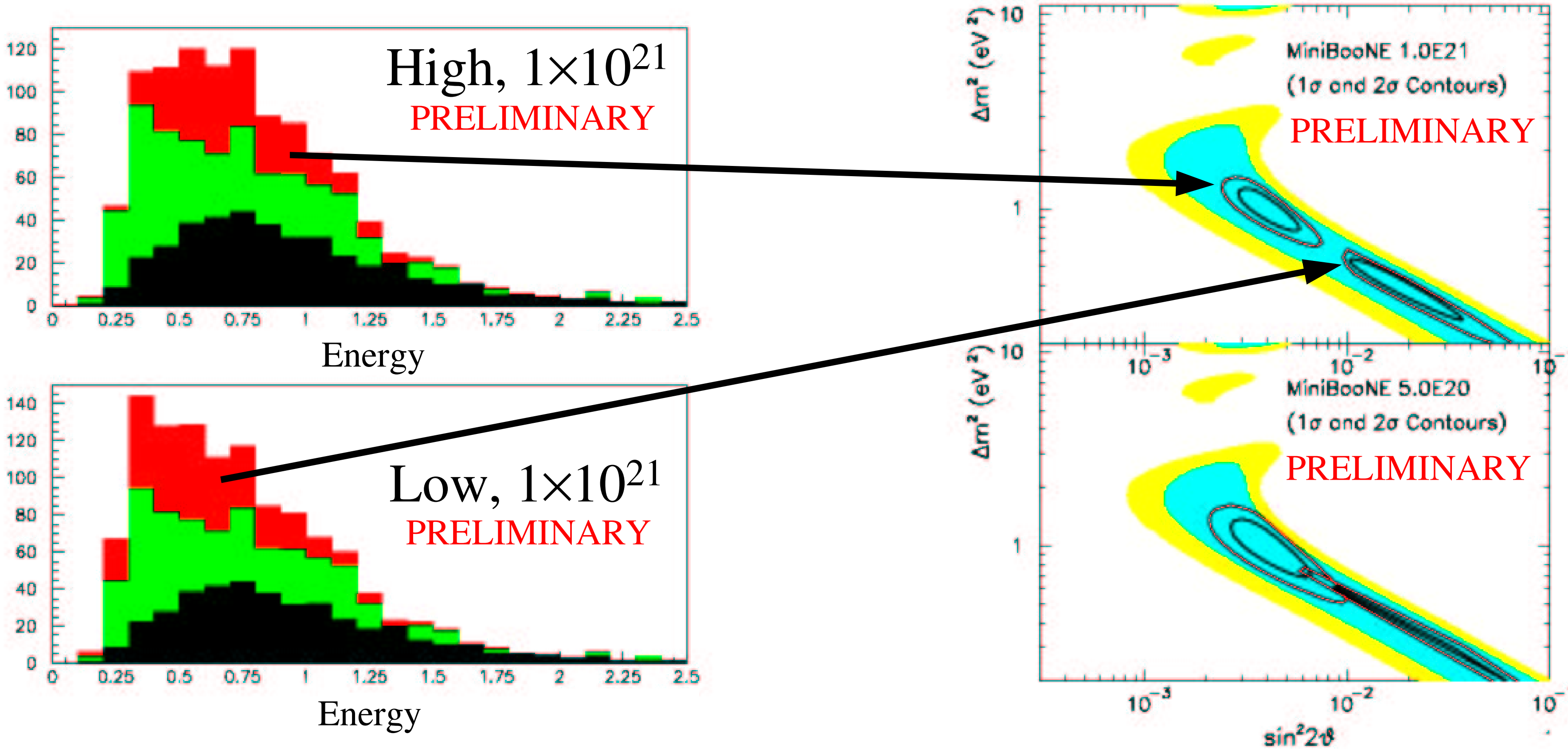
At $5\times10^{20}$ POT, an overlap
region remains!




***to completely exclude LSND in the event of no MiniBooNE signal,***
***we need $1\times10^{21}$ protons on target***

# Updated MiniBooNE $\nu_\mu \rightarrow \nu_e$ Sensitivity

Differentiating high vs low $\Delta m^2$:




***at $1\times10^{21}$ POT, we can observe the distinctive shape of an oscillation signal, and resolve high vs low $\Delta m^2$***