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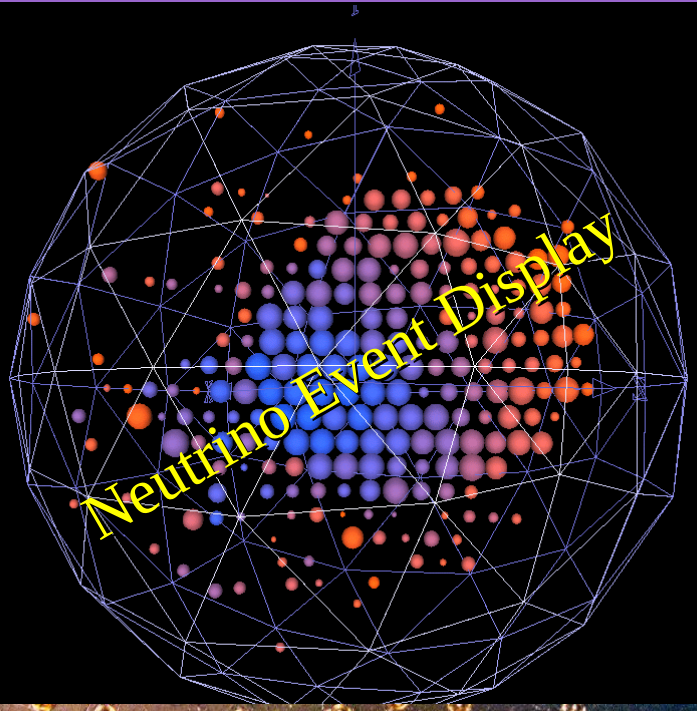
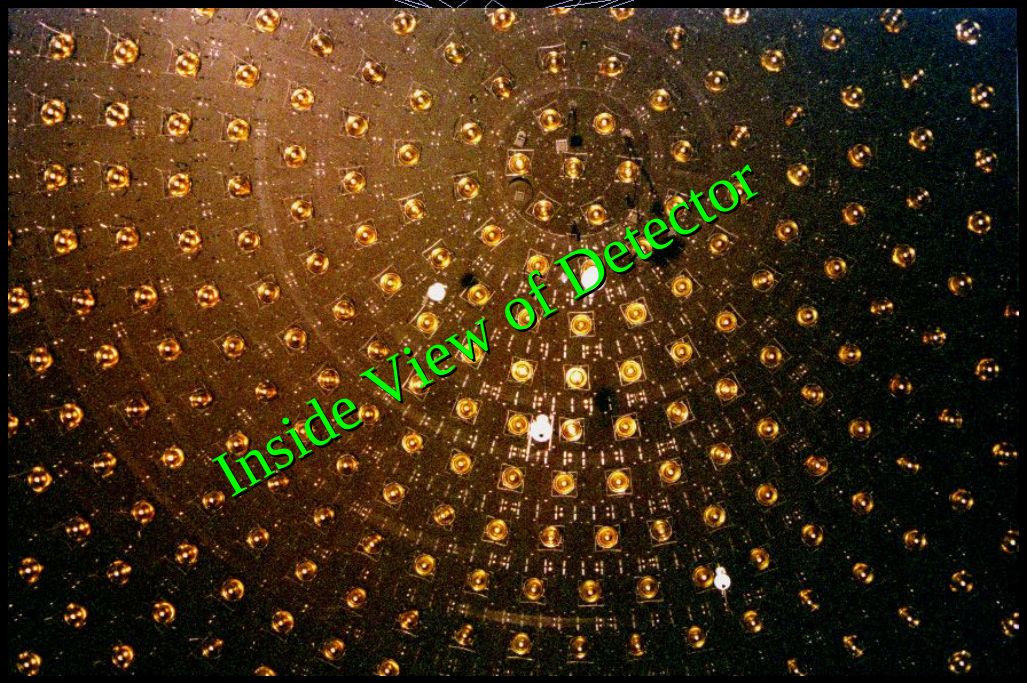
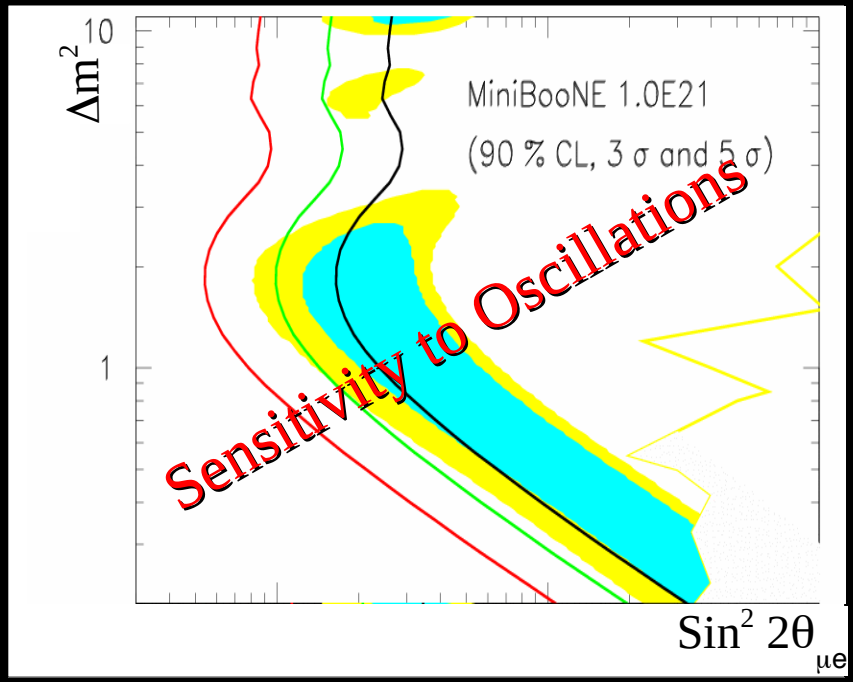
MiniBooNE and ν Oscillations







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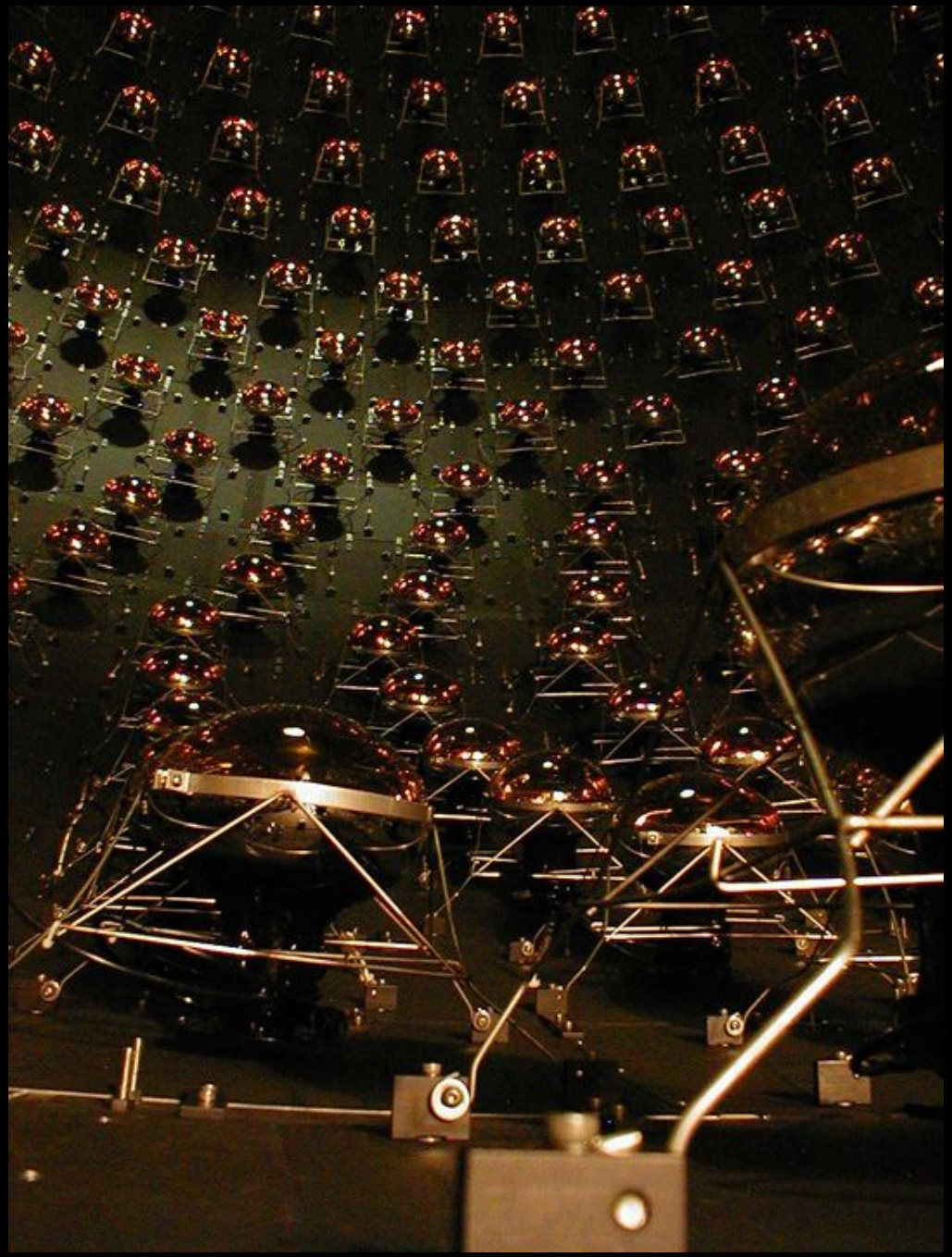
Outline

- A short course in the physics of ν oscillations
  - What are neutrinos? Oscillations?
  - ν oscillation landscape
    - Experimental results Neutrinos are surprising!
- MiniBooNE
  - An experiment in progress
  - Experiment description
  - Neutrino data
  - Oscillation sensitivity



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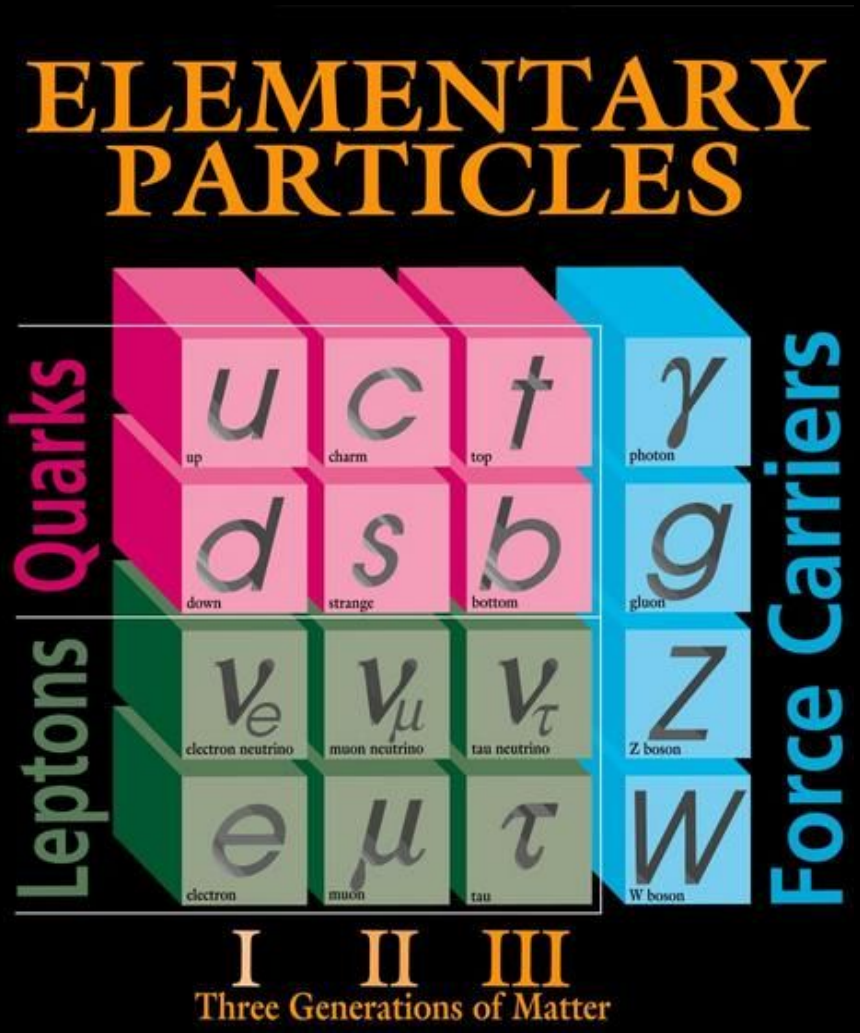
Neutrinos 101

- Particle physics is described by:
  - The Standard Model
- Matter: Fermions
  - Quarks and leptons
    - Doublets
    - Bound vs. free
  - Three generations of each
- Force Carriers: Bosons
  - EM: Photon
  - Strong force: Gluon
  - Weak force: W,Z
- Neutrinos are the lightest leptons
  - Massless in the standard model
  - Interact only via weak force



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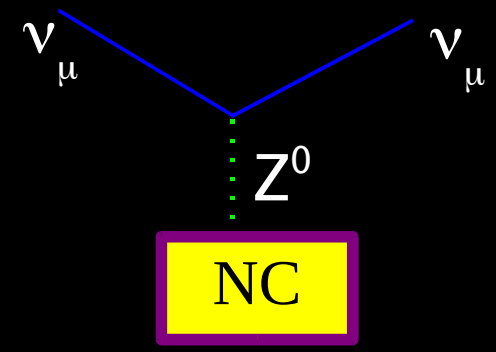
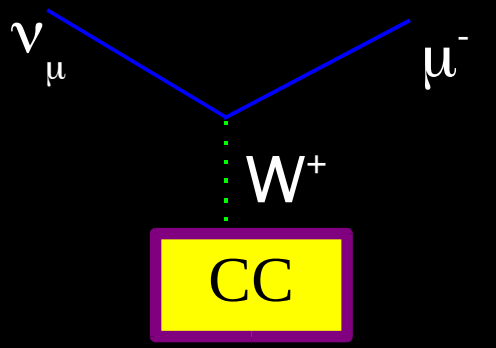
Neutrinos 102

- Neutrinos interact with other matter as weak-flavor eigenstates
  - e, μ, τ
- Neutral Current Interactions
  - Z exchange
  - Neutrino in, neutrino out
- Charged Current Interactions
  - W exchange
  - Mix within the doublets
  - Neutrino in, negative lepton out
    - Antineutrino in, positive lepton out
  - That's how we know a neutrino's flavor





Feynman Diagrams

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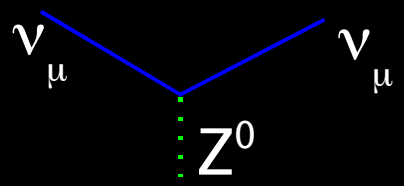
Neutrinos 111

- The weak force is weak
  - $\sigma(\nu\mathbf{e}) \sim 10^{-40}\text{cm}^2$
  - $\sigma(\nu\mathbf{N}) \sim 10^{-36}\text{cm}^2$
  - For comparison: $\sigma(\mathbf{pp}) \sim 10^{-25}\text{cm}^2$
    - 11-15 orders of magnitude difference!
  - Reason: W,Z are heavy:
    - 80, 91 GeV/c^2



- As an example:
  - A ~10 MeV neutrino from the sun has a mean free path of several light years in lead
  - Hundreds of billions of neutrinos from the sun pass through every square inch of you each second

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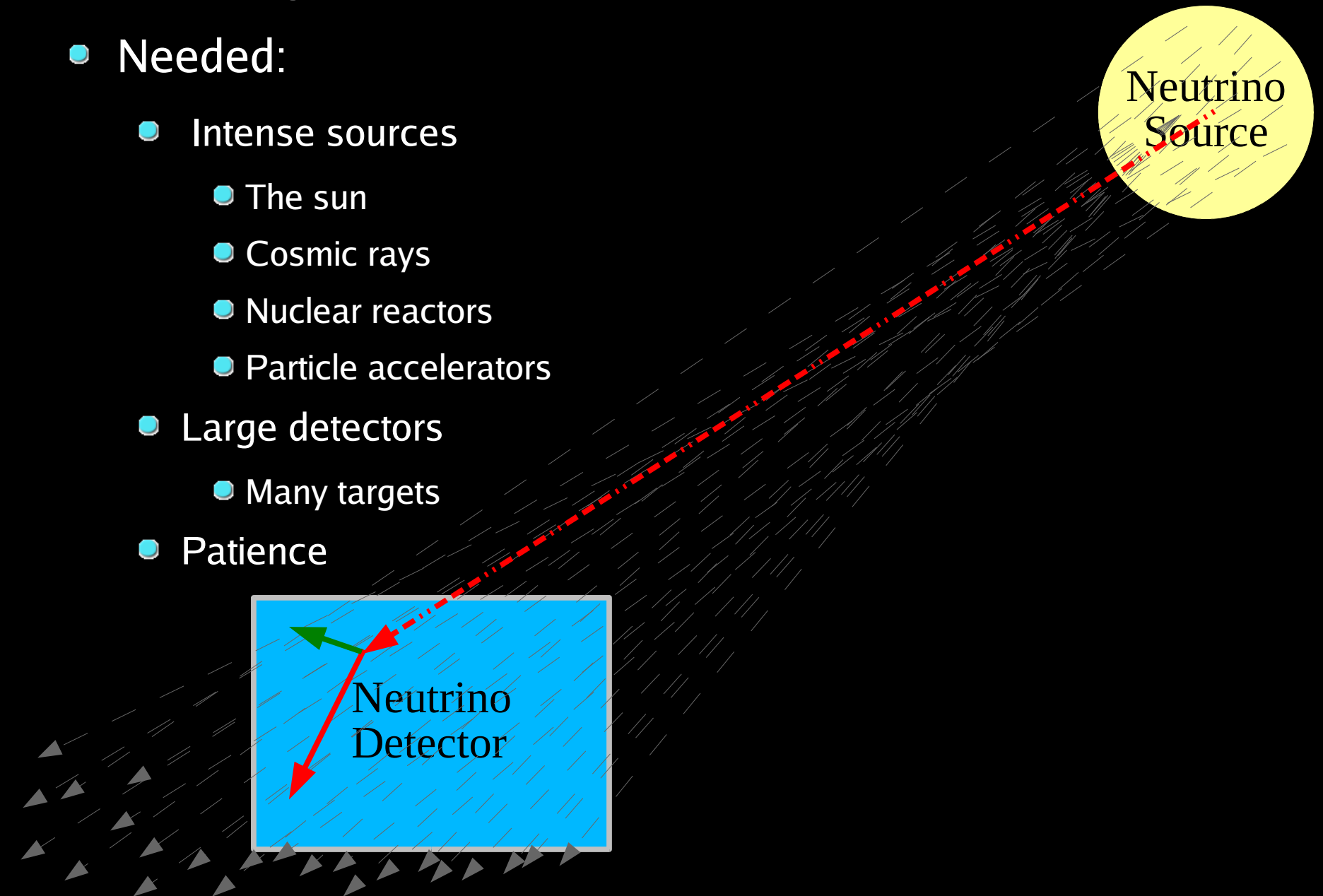
Neutrinos 112

- Detecting neutrinos is very difficult!
- Needed:
  - Intense sources
    - The sun
    - Cosmic rays
    - Nuclear reactors
    - Particle accelerators
  - Large detectors
    - Many targets
  - Patience



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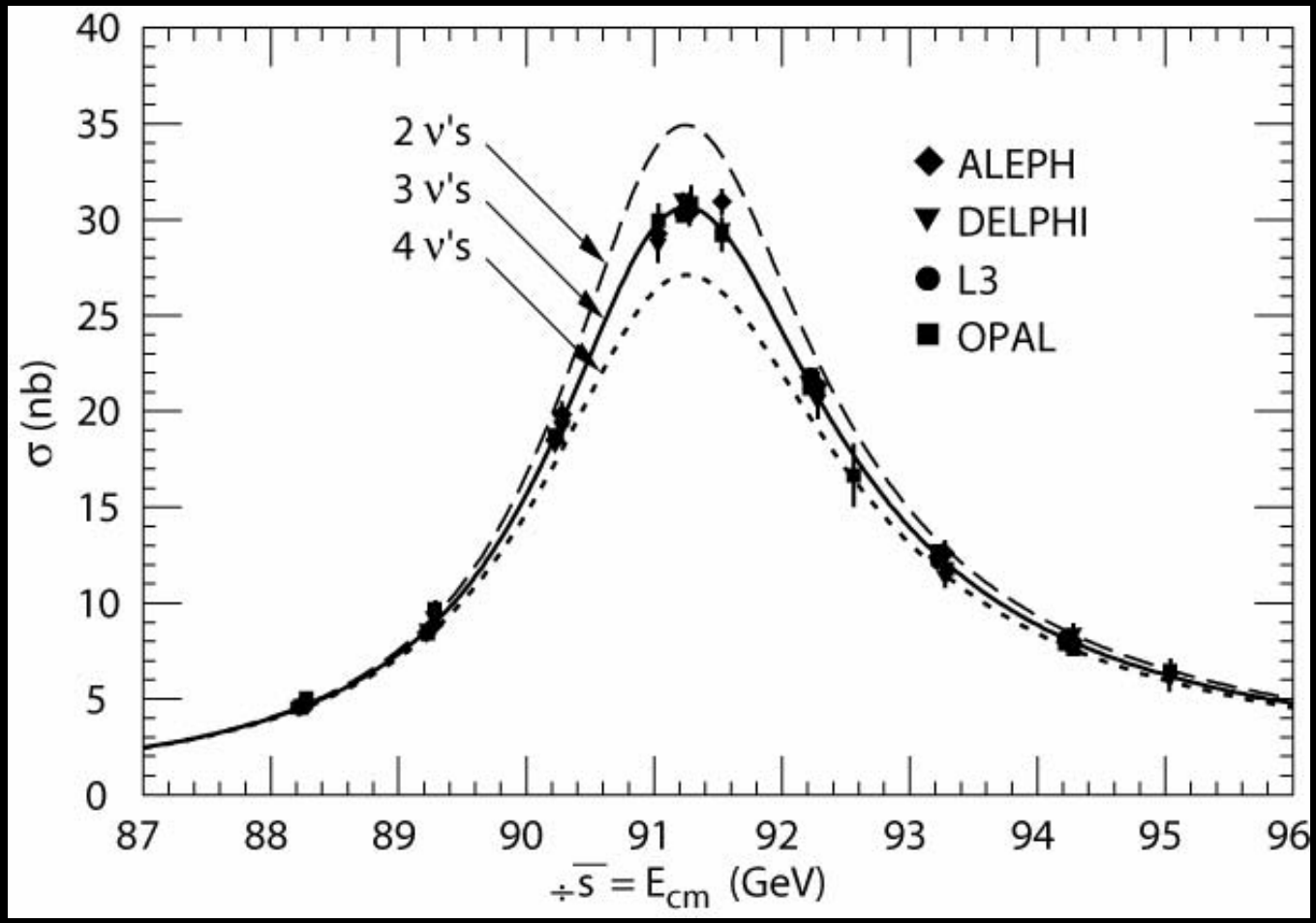
Neutrinos 121:

- Neutrinos are seen by collider expts only as missing energy



Invisible width of the Z^0 measured by LEP expts

- Careful analysis of missing energy in Z^0 decays reveals an interesting result:
  - Only three generations of light neutrinos!

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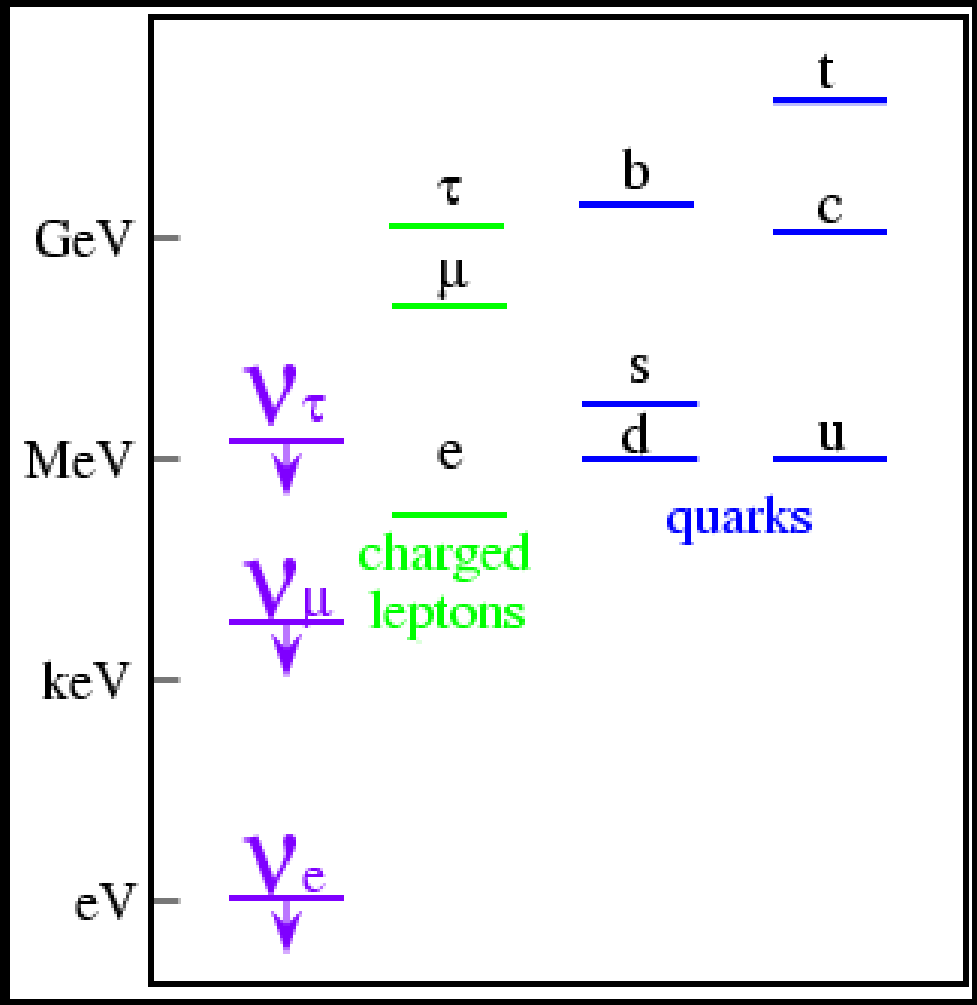
Neutrinos 122: Mass?

- In the standard model, neutrinos are massless
  - But it's difficult to confirm this
- Direct mass searches yield limits
  - ν_e: tritium decay: m < 3 eV
  - ν_μ: pion decay: m < 0.2 MeV
  - ν_τ: tau decay: m < 18 MeV
  - Compare to hadron masses:
    - pions ~ 140 Mev
    - kaons ~ 500 MeV
    - protons ~ 1 GeV
    - neutrons ~ 1 GeV
- Indirect mass searches use quantum mechanics ... and indicate non-zero neutrino mass!



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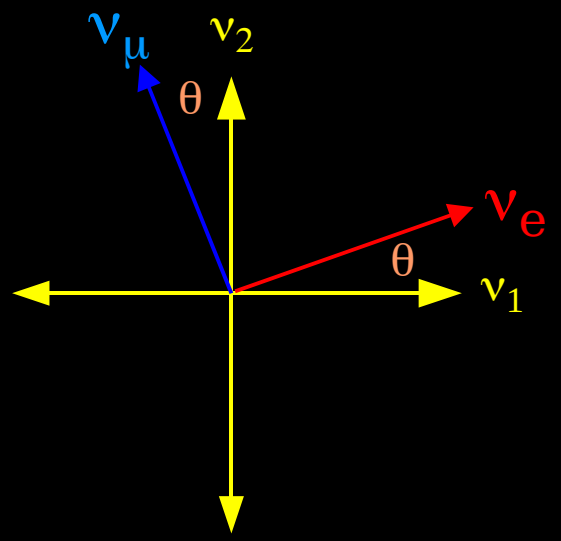
Neutrinos 201: Oscillations

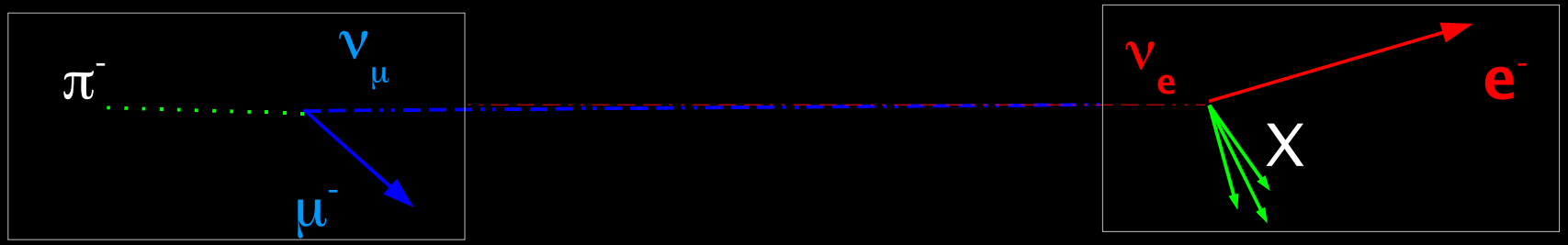
- IF:
  - Neutrinos have (different) masses

    Weak states are a mixture of the mass states

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



- THEN:
  - A neutrino created as one specific flavor may later be detected as a neutrino of a different flavor
  - Why? Neutrinos propagate as mass eigenstates



ν source

ν detector

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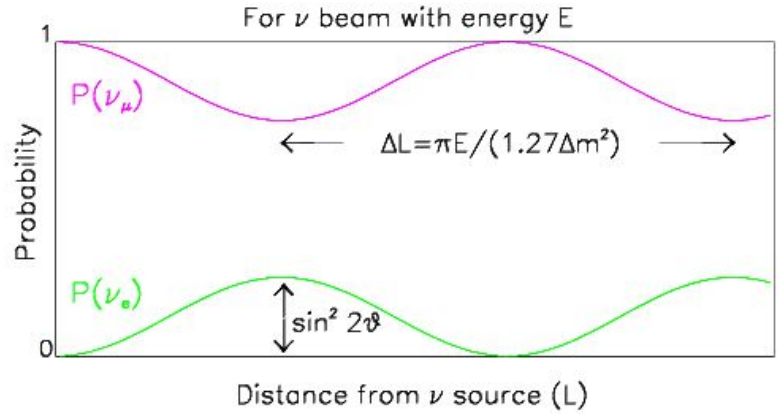
ν 202: Oscillation Probability

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

- Oscillation probability between 2 flavor states depends on:
  - Two fundamental parameters
    - $\Delta m^2 = m_1^2 - m_2^2$ - "period"
      - mass <u>difference</u> between states
    - $\sin^2 2\vartheta$ - "amplitude"
      - mixing between flavors
    - Oscillations don't measure the absolute mass scale
  - Two experimental parameters
    - L: distance from source to detector
    - E: neutrino energy



- Two possible experiments in this example:
- ν_μ <u>dis</u>appearance
  - $P(\nu_\mu \rightarrow \nu_\mu)$
- ν_e <u>a</u>ppearance
  - $P(\nu_\mu \rightarrow \nu_e)$

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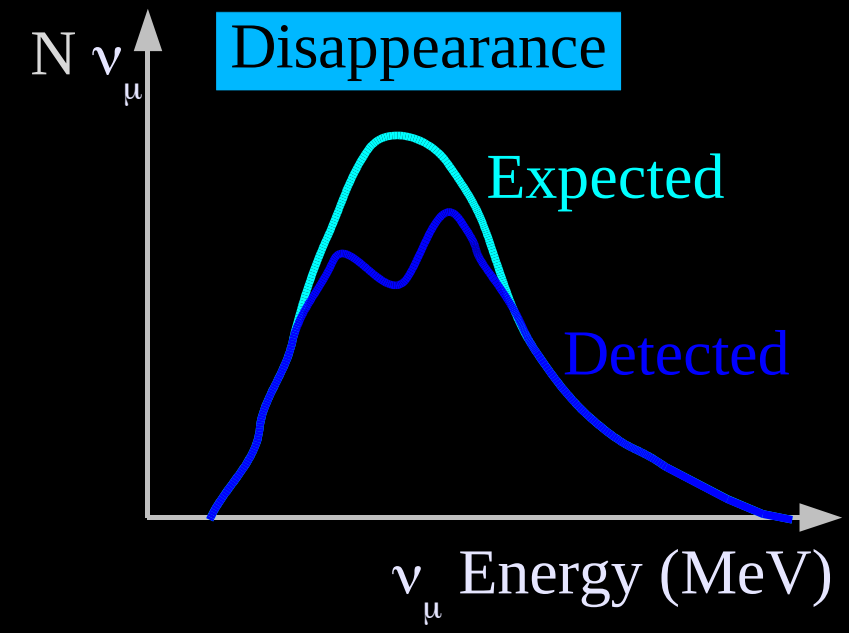
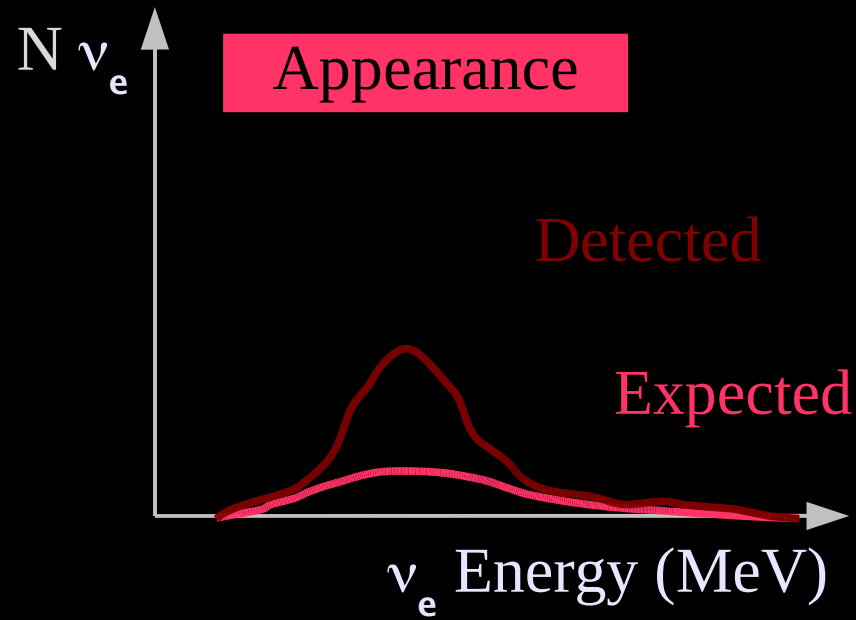
ν 203: Detecting Oscillations

- Consider $\nu_\mu \rightarrow \nu_e$ oscillations
- 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, $\sin^2 2\theta$





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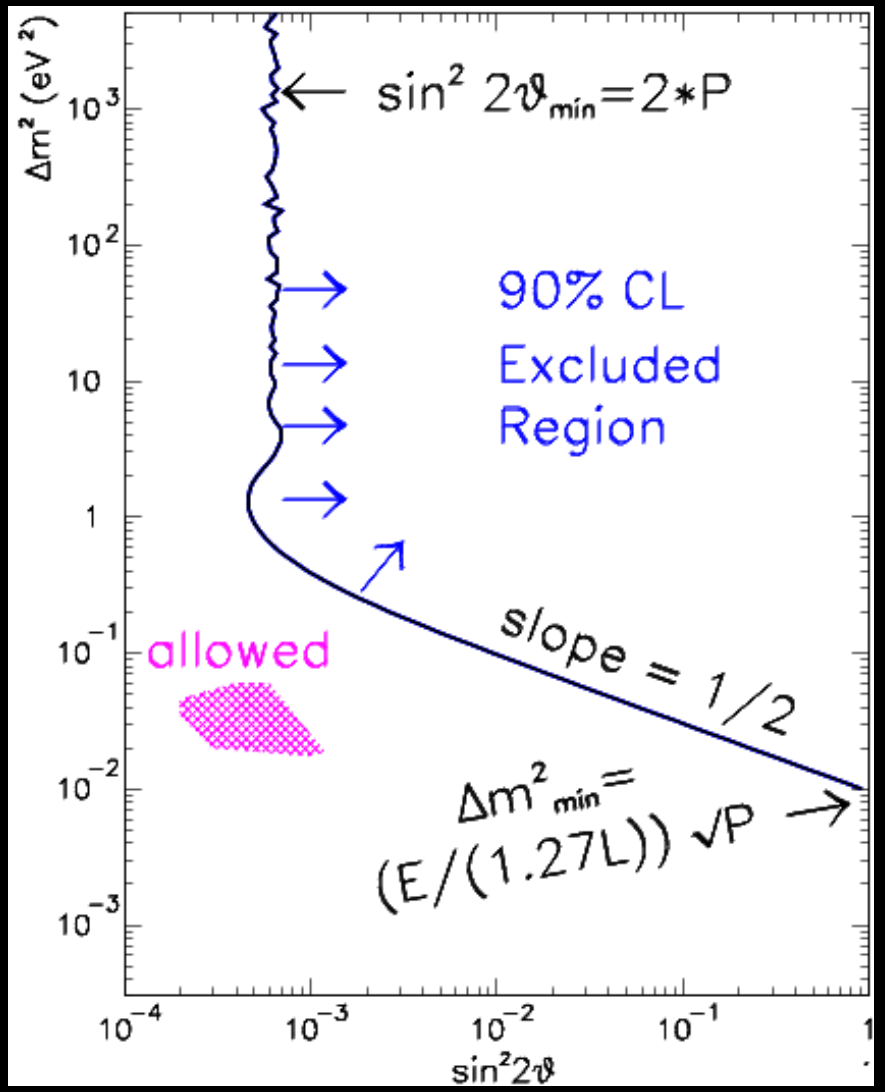
ν 204: Presenting Oscillations

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

- L and E determine the Δm^2 sensitivity region
- $\sin^2 2\theta$ gives amplitude of oscillations
- No signal: exclusion regions
  - Above and to the right excluded
  - Below and to the left cannot be ruled out
- Signal: allowed regions
  - Shown by shaded areas specifying Δm^2 and $\sin^2 2\theta$
  - Size of allowed region determined by experimental uncertainties



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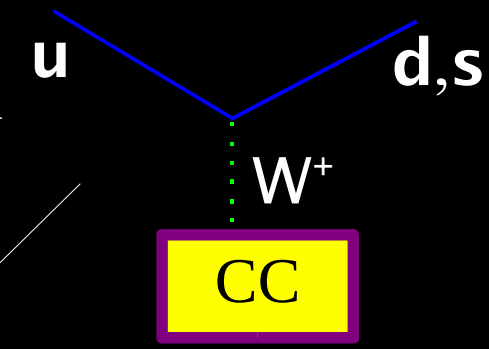
ν 205: 3 generations

- There are actually three generations of neutrinos that can oscillate into each other
- MNS matrix describes neutrino mixing
  - Analogous to CKM matrix for quarks
  - Except for the values of the matrix elements!

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



$$\begin{bmatrix} \sim 1 & 0.2 & 0.006 \\ 0.2 & \sim 1 & 0.04 \\ 0.005 & 0.04 & \sim 1 \end{bmatrix}$$

CKM: small mixing angles

$$\begin{bmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix}$$

MNS: large mixing angles

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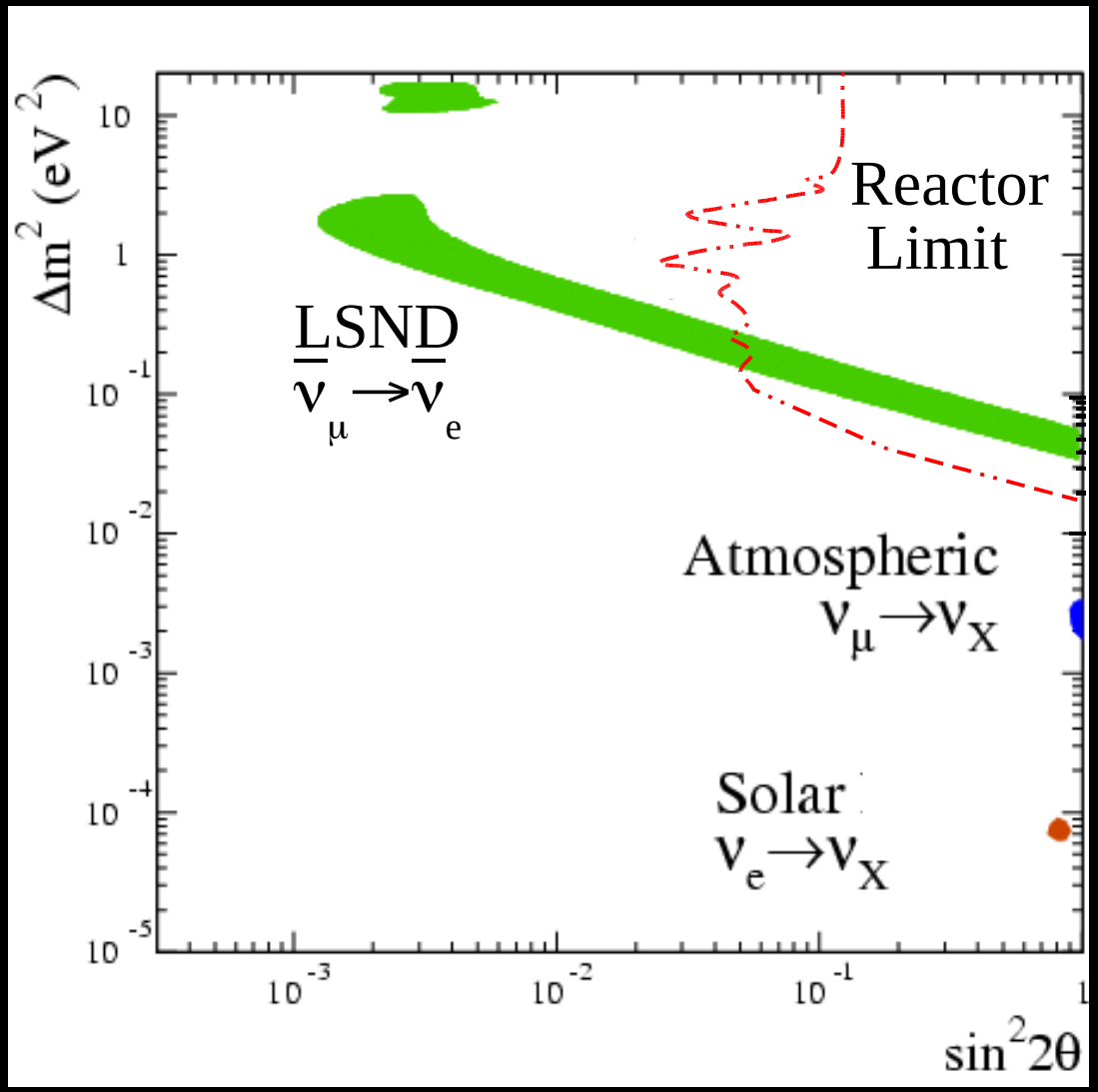
Current Oscillation Picture

- Three different oscillation signals observed (so far...)
- Allowed regions indicated
  - Note: The true answers are actually single points!
- Solar neutrinos: $\Delta m^2 \sim 10^{-5} eV^2$
- Atmospheric: $\Delta m^2 \sim 10^{-3} eV^2$
- LSND: $\Delta m^2 \sim 1 eV^2$
  - Yet to be confirmed
- Only mass differences, not absolute scale



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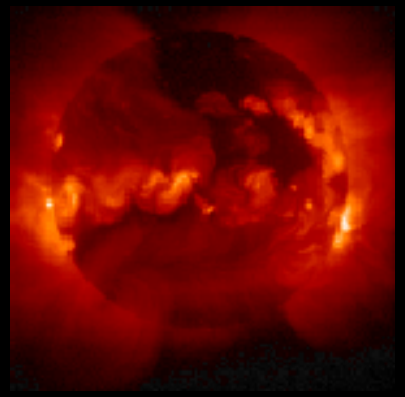
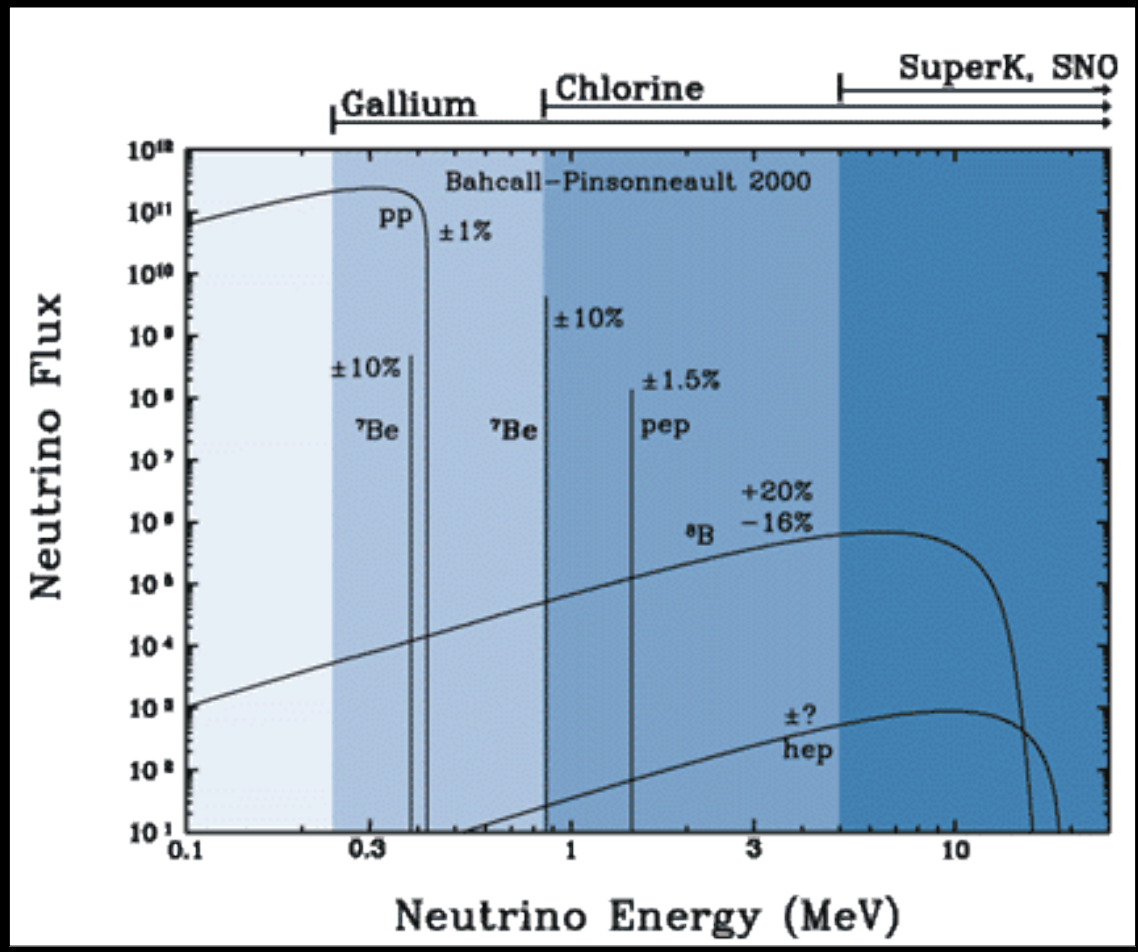
Neutrinos from the Sun

- The sun is fueled by fusion reactions
  - $4\,^{1}H + 2e^{-} \rightarrow {}^{4}He + 2\nu_e + 6\gamma$
  - More reaction chains follow...
- Neutrinos are produced copiously
  - Note all produce ν_e, below ~10MeV
- But when expts were built to search for them, they found too few!
  - Many techniques
  - All looking for CC reactions (ν_e)
- Many people thought the experiments were wrong





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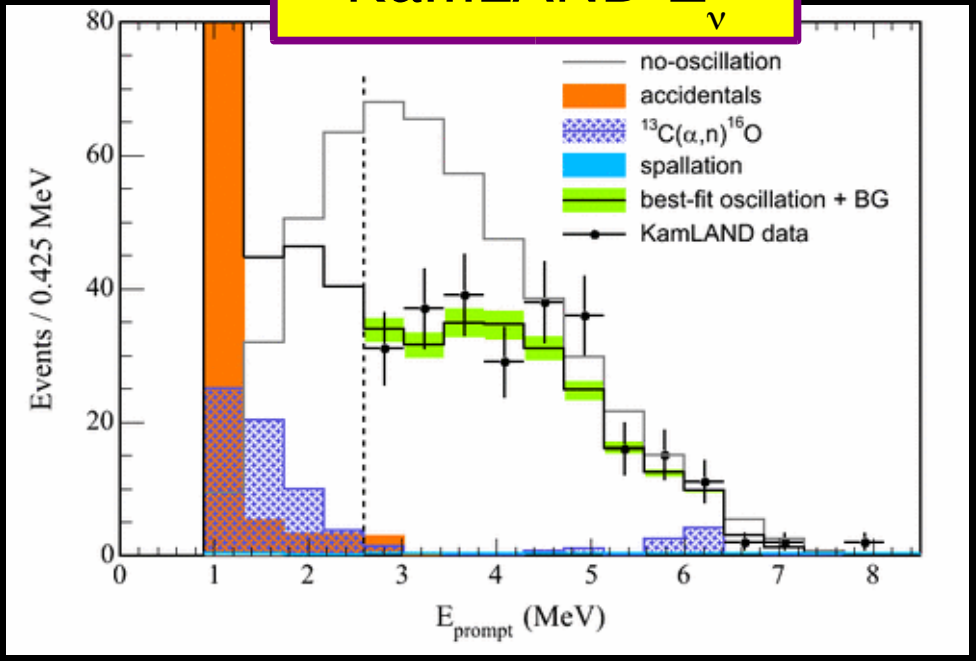
Solar ν Results

- SNO had the ability to see neutral current as well as charged current reactions
  - They can see all flavors---
  - Oscillations!
- Solution:
  - Mixing angle $\vartheta \simeq 32^\circ$
  - $\Delta m^2 = 8.2 \times 10^{-5} eV^2$
- KamLAND: reactor antineutrinos
- Confirm solar result
  - Spectral distortion!
- $\bar{\nu}$ vs. ν
- The experiments were right!

KamLAND E_ν



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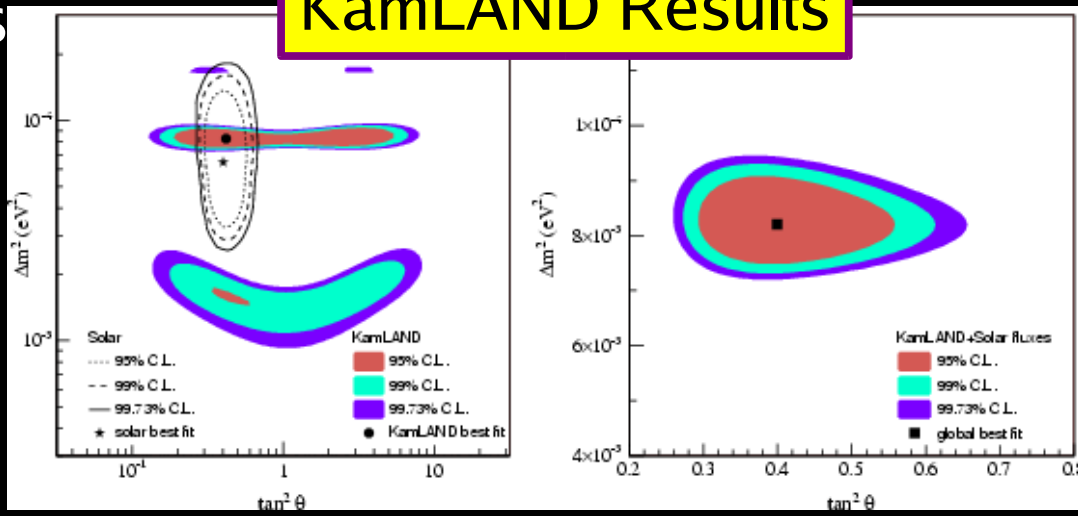
KamLAND Results



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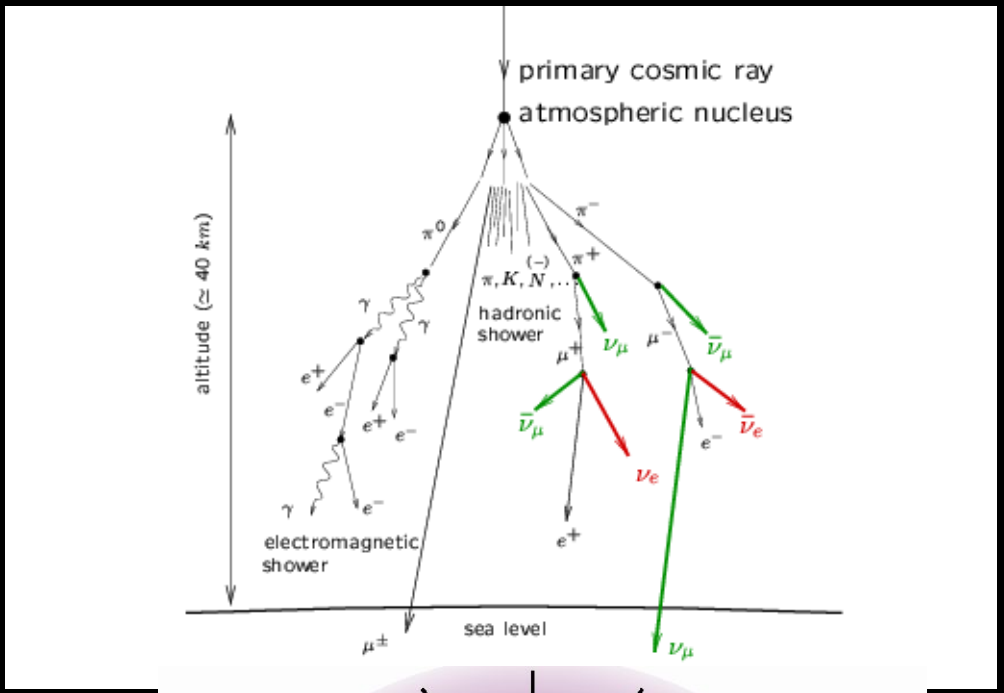
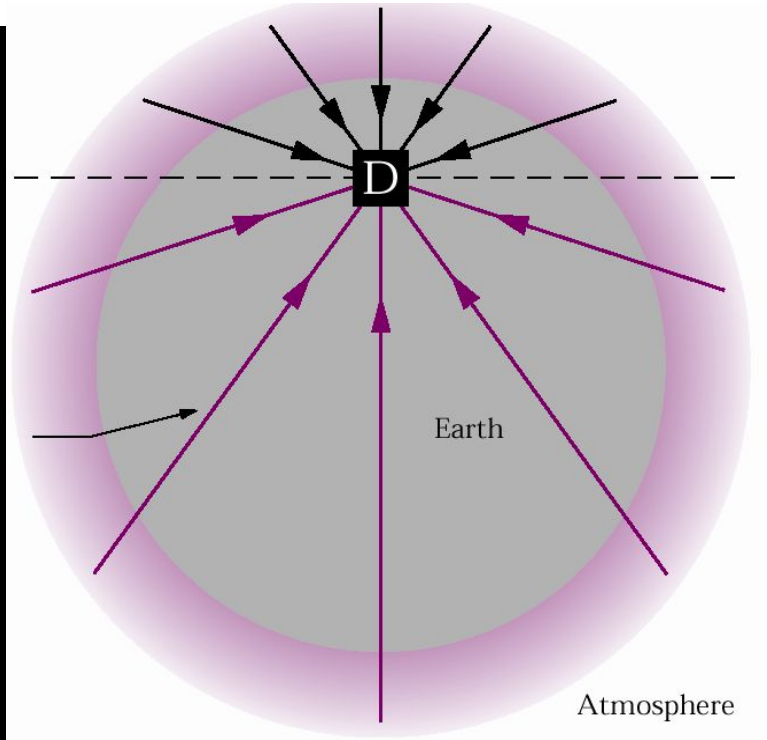
Atmospheric Neutrinos

- Neutrinos produced by cosmic ray induced air showers
  - $\bar{\nu}_\mu$ and ν_μ, $\bar{\nu}_e$ and ν_e
- High energy cosmic rays are isotropic
  - Same rates on this side of the earth as the other
- Super-K measures a difference in flux as a function of zenith angle
  - $\bar{\nu}_\mu$,ν_μ disappearance





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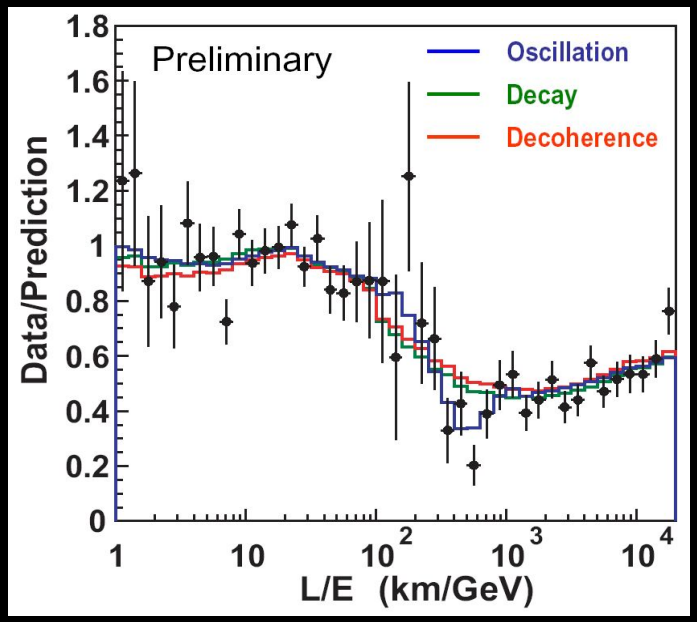
Atmospheric ν Oscillations



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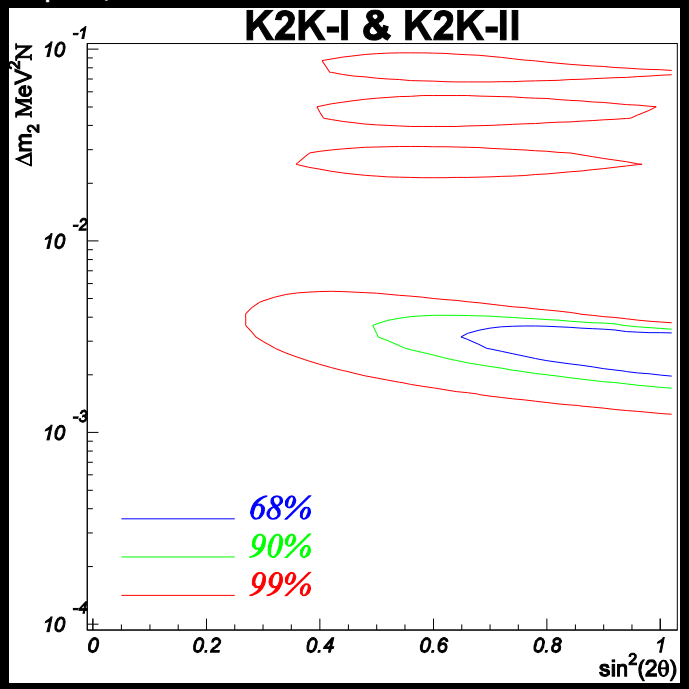

- L/E characteristic of oscillations
- Best fit to data:
  - Mixing Angle ~45° (Maximal!)
    - Quite unexpected!
  - $\Delta m^2 = 2.4 \times 10^{-3} eV^2$
- Mix of $\bar{\nu}$ and ν
- This result is confirmed by other experiments: Soudan, MACRO
- K2K send ν from KEK accelerator to Super-K
- Compare fluxes in near detectors (200m) to fluxes at Super-K (250km)

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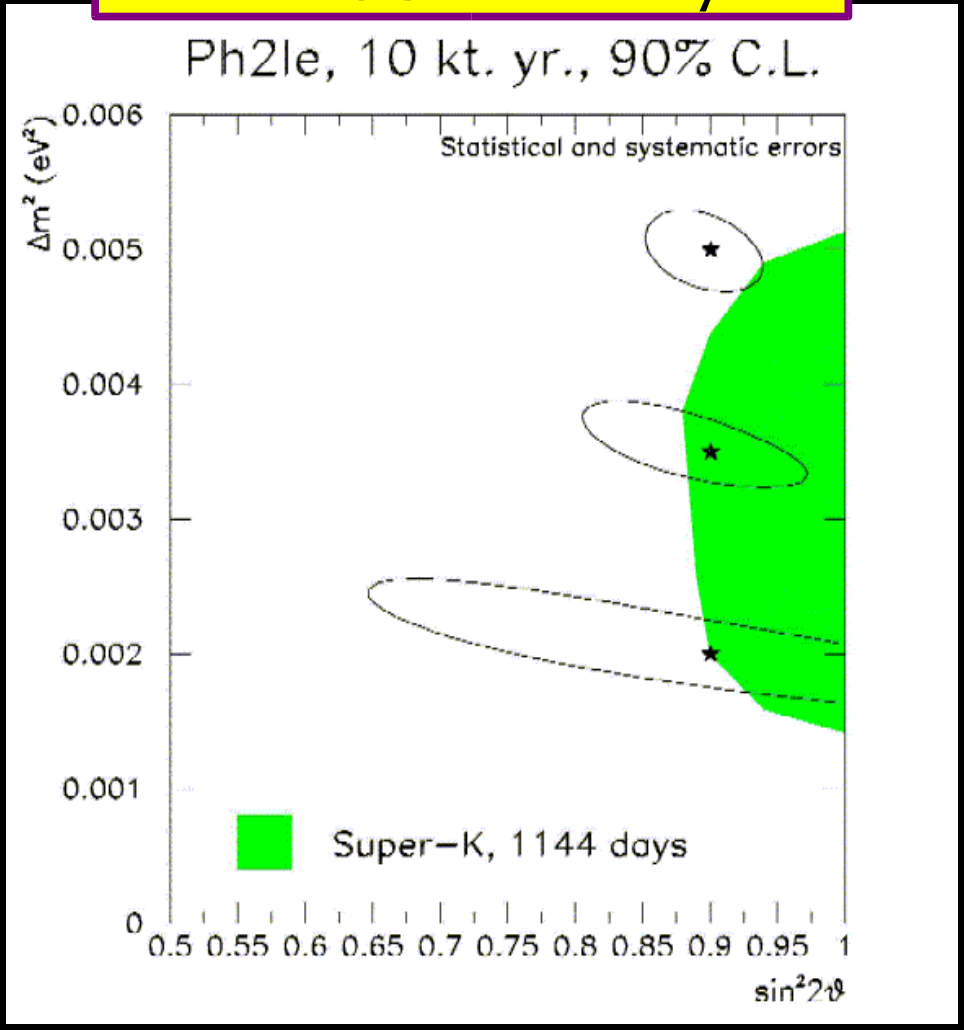
Atmos ν in the future

- MINOS will be able to measure the atmospheric oscillation parameters much better
- Can run in $\bar{\nu}$ and ν mode
- Taking data this winter!
- Names:
  - NuMI: Neutrinos from the Main Injector
    - Neutrino beam
  - MINOS: Main Injector Neutrino Oscillation Search
    - Neutrino detectors

MINOS sensitivity



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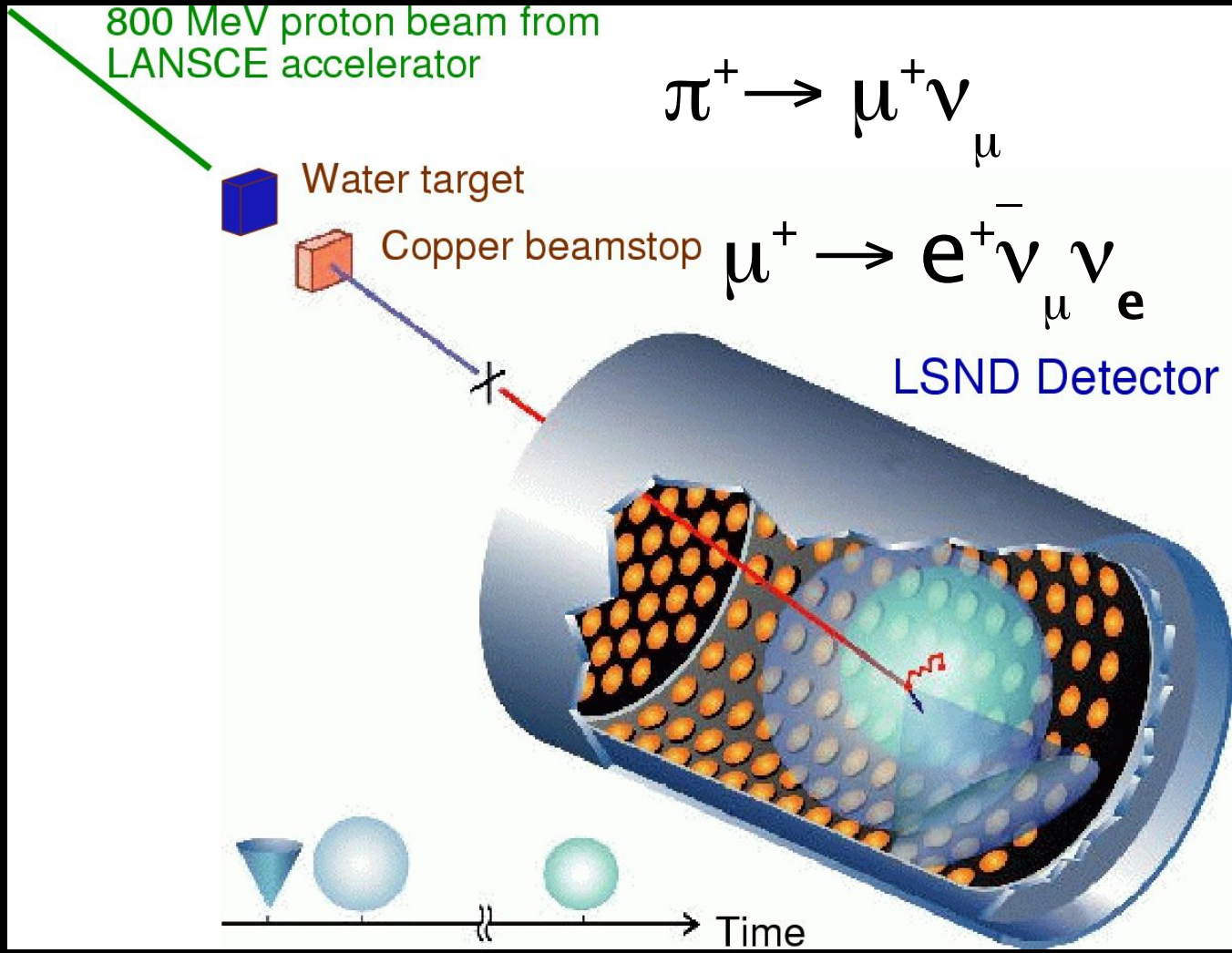
Accelerator Neutrinos

- Many null result accelerator neutrino experiments
- Positive result: LSND Experiment at LANL
- Beam: μ^+ decay at rest
- L/E ~ 1m/MeV
  - L ~ 30m
  - $20 < E_\nu < 55$ MeV
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?
  - Appearance search



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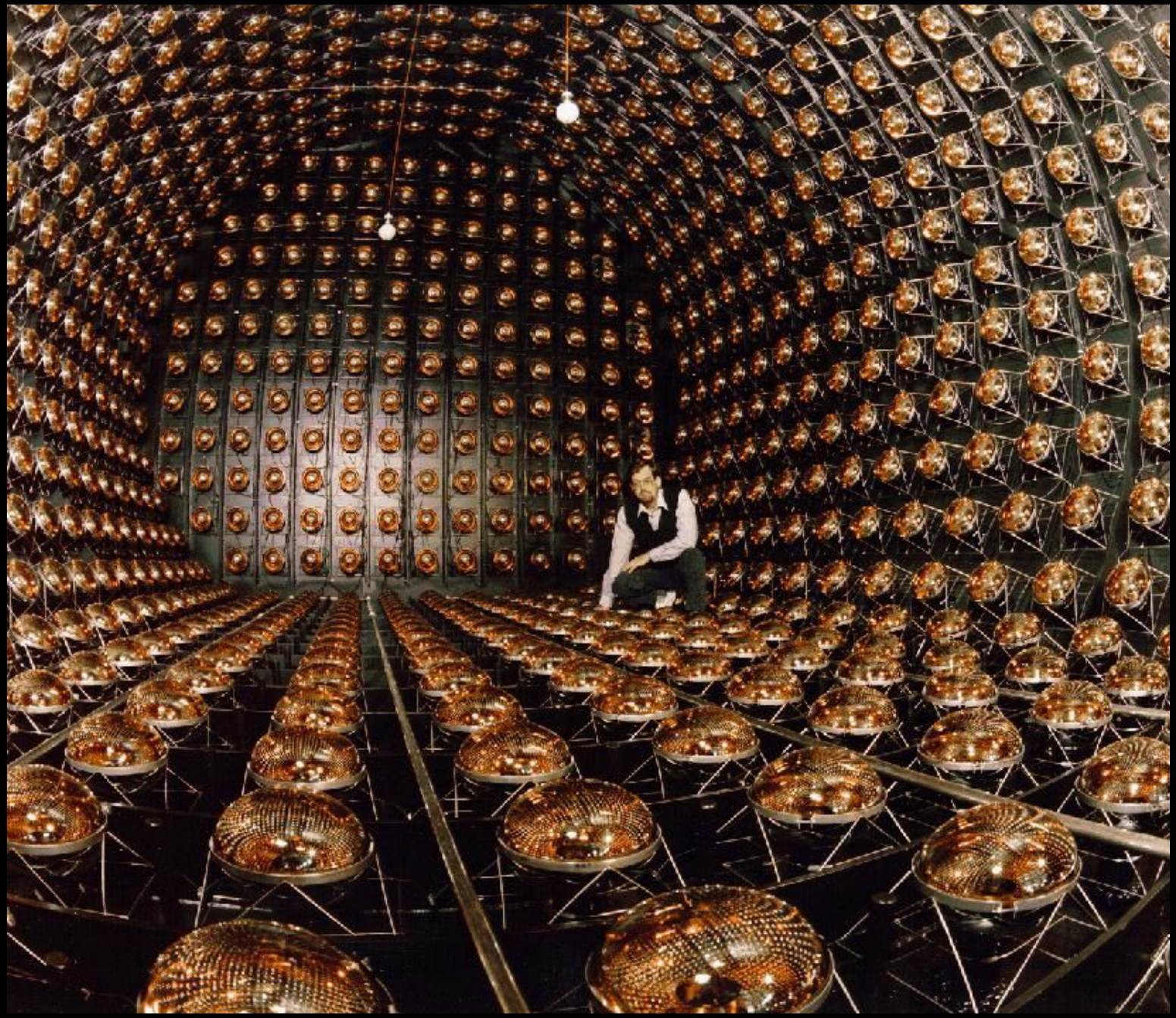
Inside LSND



Remember these PMTs! (photo-multiplier tubes)

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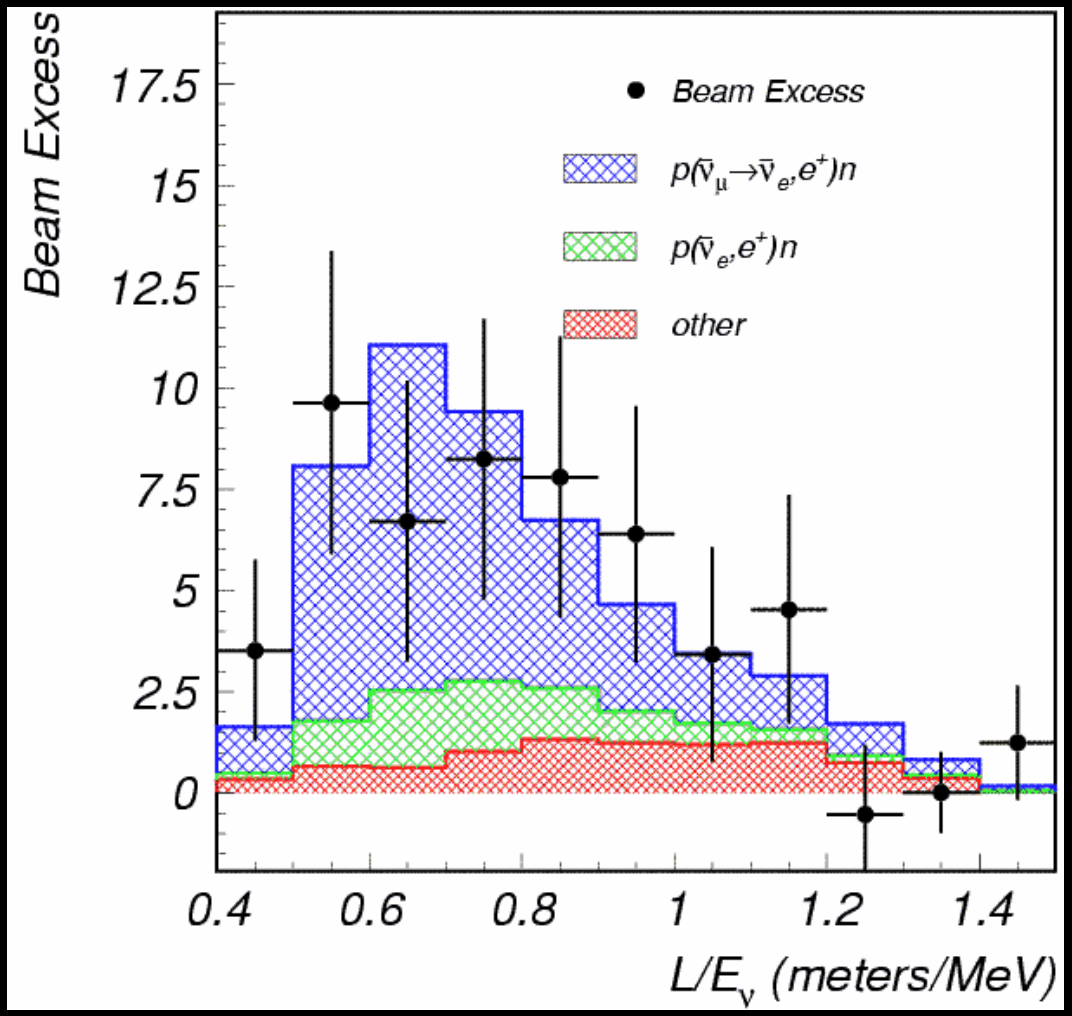
The LSND signal

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability:
  0.264±0.067±0.045%



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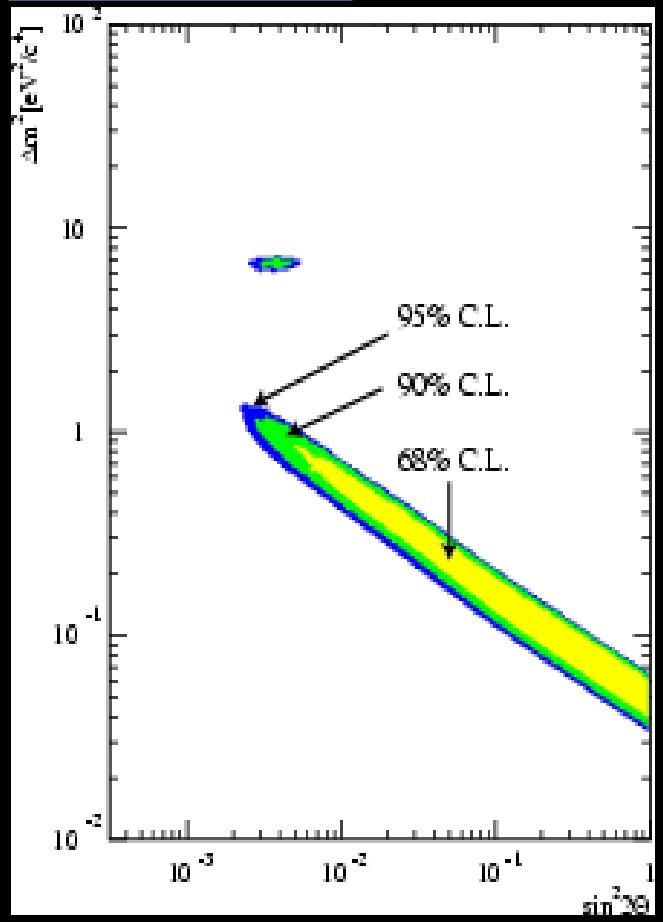
3.8σ excess!



hep-ex/0203023

- KARMEN2 and LSND collaborators performed joint analysis on both data sets - allowed regions remain!
- $\Delta m^2 \sim 1 eV^2$, $\theta \sim 2°$

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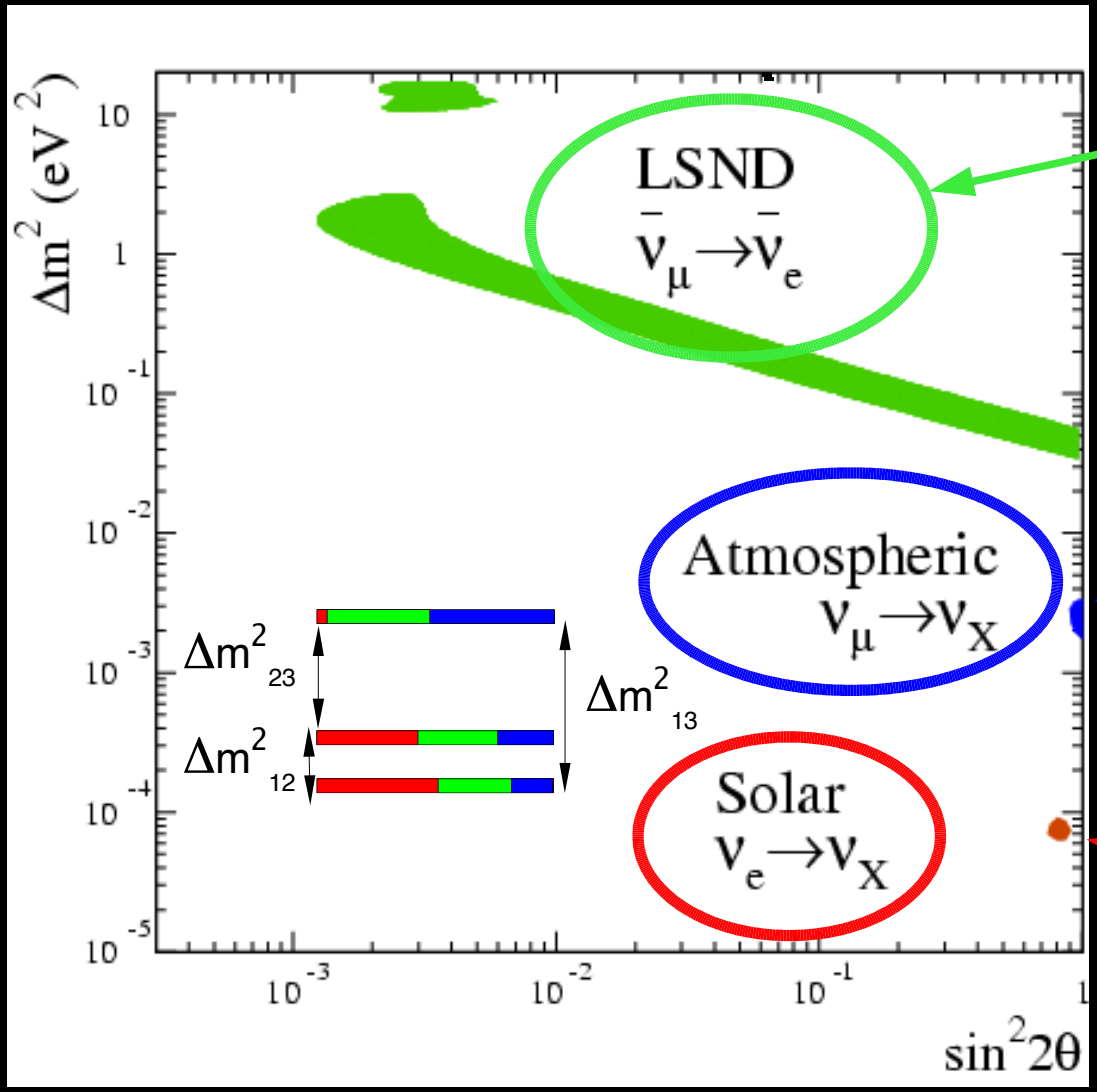
Current Oscillation Summary



LSND
$\Delta m^2 \sim 1 eV^2$
$\theta \sim 2°$

Atmospheric oscillations
$\Delta m^2 \sim 10^{-3} eV^2$
$\theta \sim 45°$

Solar oscillations
$\Delta m^2 \sim 10^{-5} eV^2$
$\theta \sim 32°$

- Problem: That's too many Δm^2 regions!
  - Should find: $\Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13}$

$10^{-5} + 10^{-3} \neq 1$

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The 3 Δm^2 Problem

- LSND signal not oscillations?
  - Anomalous muon decay: $\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu$
    - New TWIST result rules out
- If it is oscillations, it indicates that our model is incomplete
- Sterile Neutrinos
  - $\nu_\mu \rightarrow \nu_s$, $\nu_s \rightarrow \nu_e$
    - LEP results require these extra νs have no weak coupling
- LSND needs to be confirmed experimentally!

NEW physics beyond the standard model

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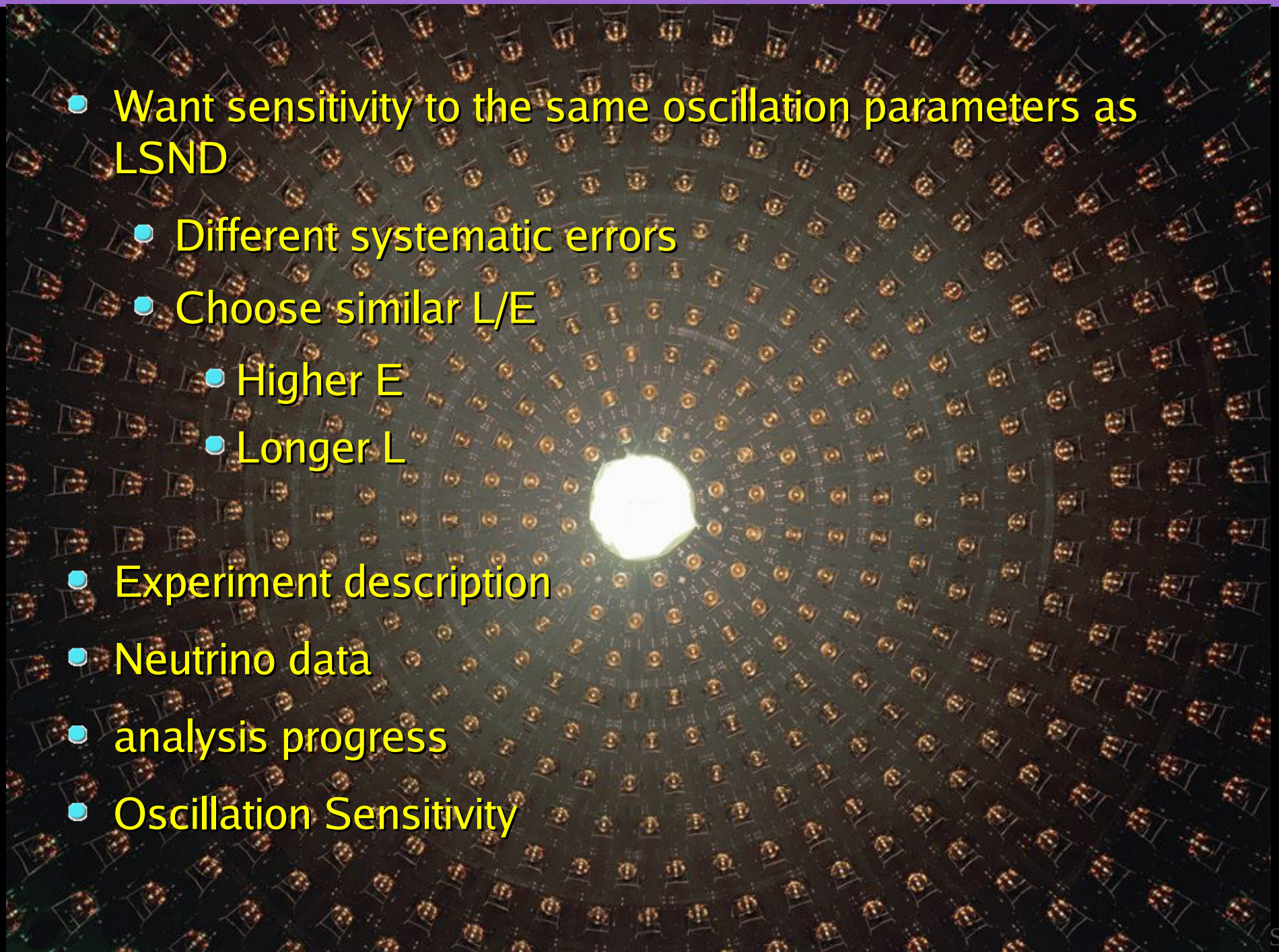
Resolving LSND: MiniBooNE



- Want sensitivity to the same oscillation parameters as LSND
  - Different systematic errors
  - Choose similar L/E
    - Higher E
    - Longer L
- Experiment description
- Neutrino data
- analysis progress
- Oscillation Sensitivity

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MiniBooNE Collaboration

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L.Bartoszek, C. Bhat, S J. Brice, B.C. Brown, D.A. Finley, R. Ford, F.G.Garcia, P. Kasper, T. Kobilarcik, I. Kourbanis, A. Malensek, W. Marsh, P. Martin, F. Mills, C. Moore, P. Nienaber, E. Prebys, A.D. Russell, P. Spentzouris, R. Stefanski, T. Williams *Fermilab*

D. C. Cox, T. Katori, H.-O. Meyer, C. Polly, R. Tayloe *Indiana*

G.T. Garvey, A. Green, C. Green, W.C. Louis G.McGregor, S.McKenney, G.B. Mills, H. Ray, V.Sandberg, B. Sapp, R. Schirato, R.G.VandeWater, D.H. White *Los Alamos*

R. Imlay, W. Metcalf, S.A. Ouedraogo, M. Sung, M.O. Wascko *Louisiana State University*

J. Cao, Y. Liu, B.P. Roe, H. Yang *Michigan*

A.O. Bazarko, P.D. Meyers, R.B. Patterson, F.C. Shoemaker, H.A.Tanaka *Princeton*

P.J. Nienaber *St. Mary's of Minnesota*

E.A. Hawker *Western Illinois*

A. Curioni, B.T. Fleming *Yale*

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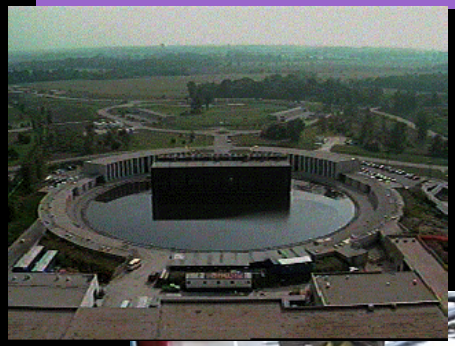
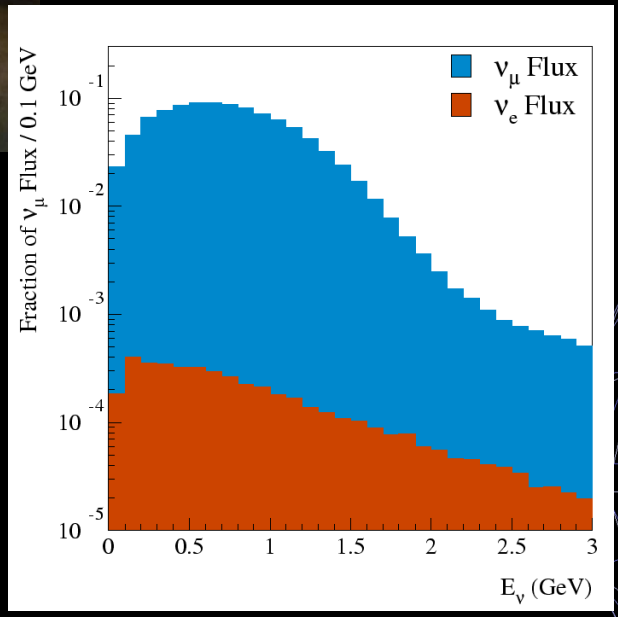
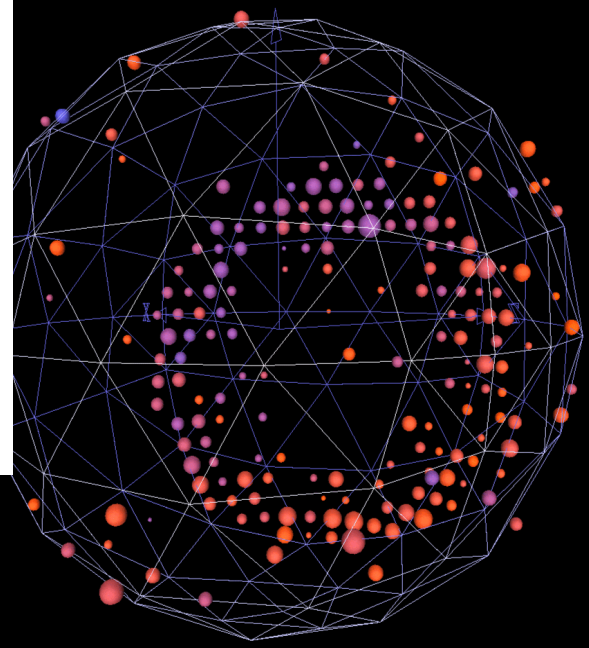
MiniBooNE Overview



- 8 GeV protons from Fermilab Booster
- Beryllium target

- Magnetic horn to focus mesons
  - Over 96M pulses - a world record!
  - Reversible polarity - $\bar{\nu}$ mode





- 50 m decay region
  - >99% pure ν_μ,$\bar{\nu}_\mu$ beam
- ~500 m dirt
  - $\nu_\mu \rightarrow \nu_e$?
- 800 ton mineral oil detector
  - 1520 PMTs (1280+240 veto)

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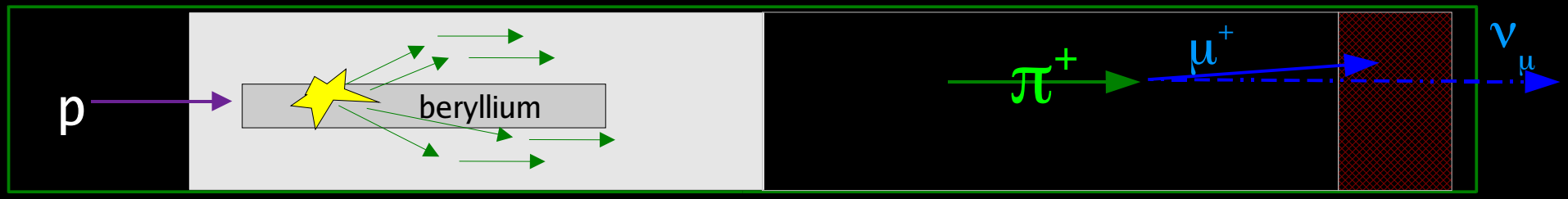
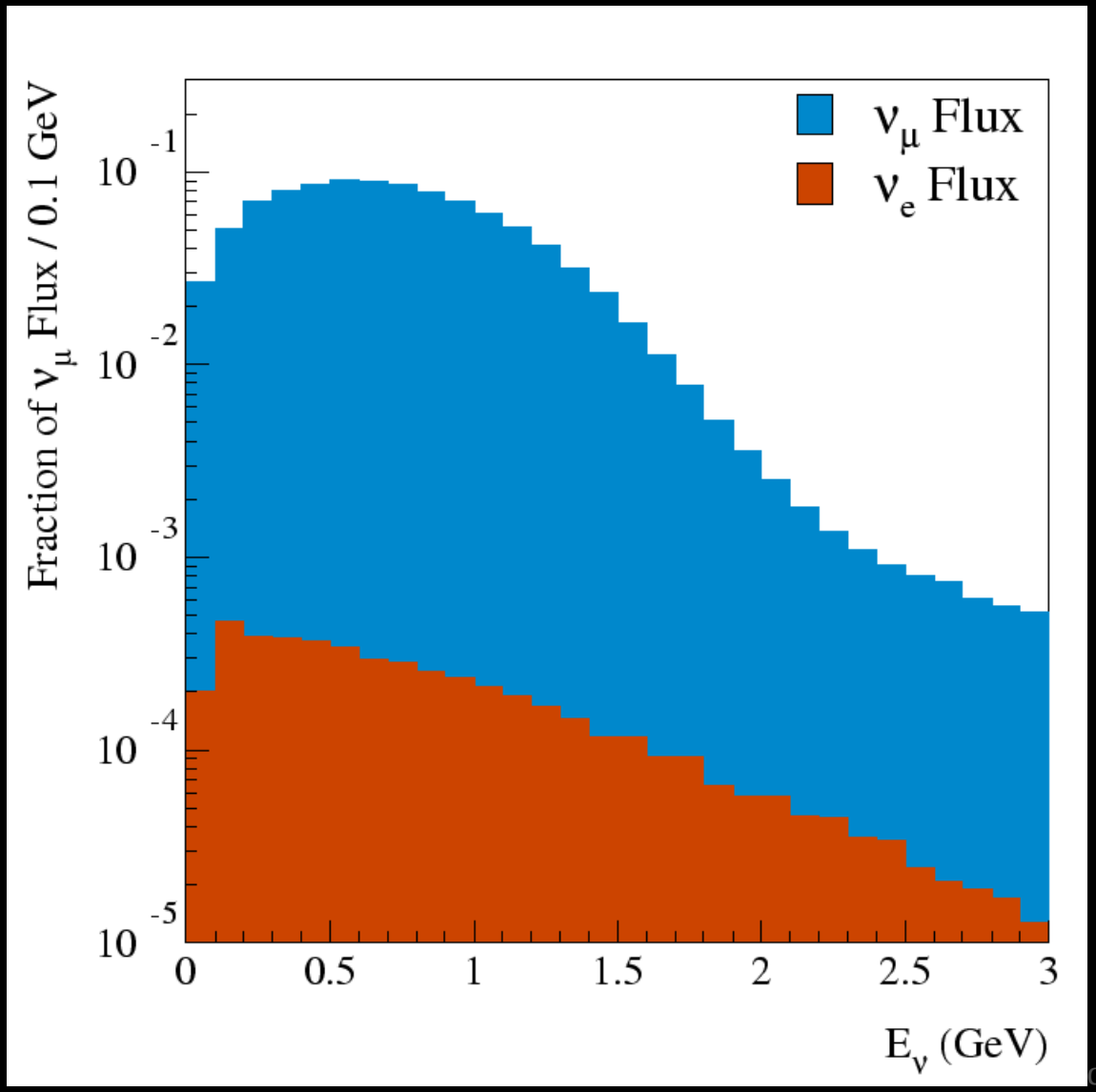
Neutrino Flux



$$\pi^+/K^+ \rightarrow \mu^+ \nu_\mu$$
$$\pi^-/K^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$K^+/K^0_L \rightarrow \pi e \nu_e$$
$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

- Use external meson production data to predict rates
- Accelerator neutrino jargon: POT = proton on target
- 99.5% are muon neutrinos



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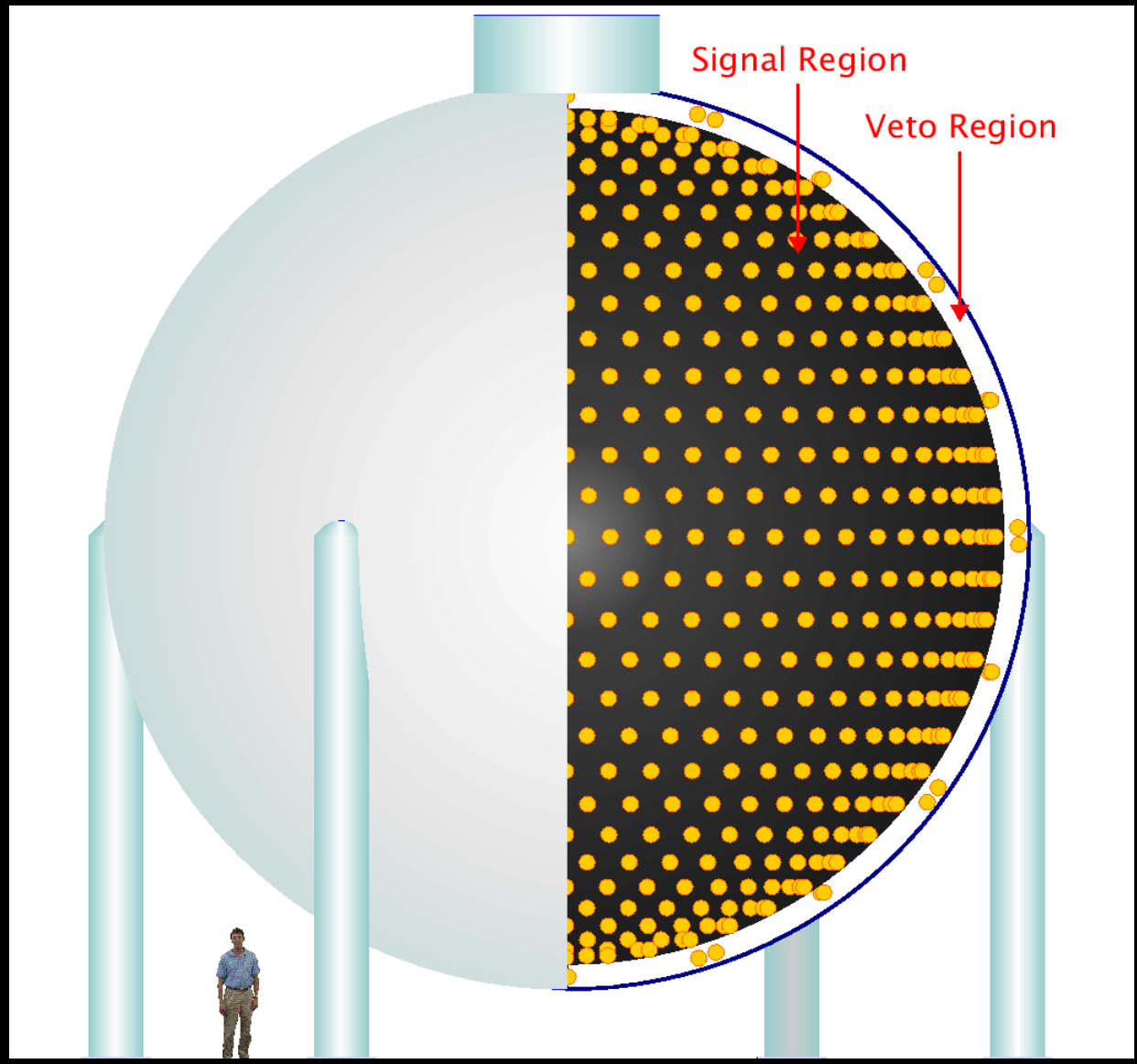
MiniBooNE Detector

- 800 tons of pure mineral oil
- 6m radius steel sphere
- ~2m earth overburden
- 1520 8" PMTs
  - 1280 in main tank (sphere)
  - 240 in veto region (shell)
  - LSND PMTs/New PMTs
- DAQ records t,Q
  - “Hits”



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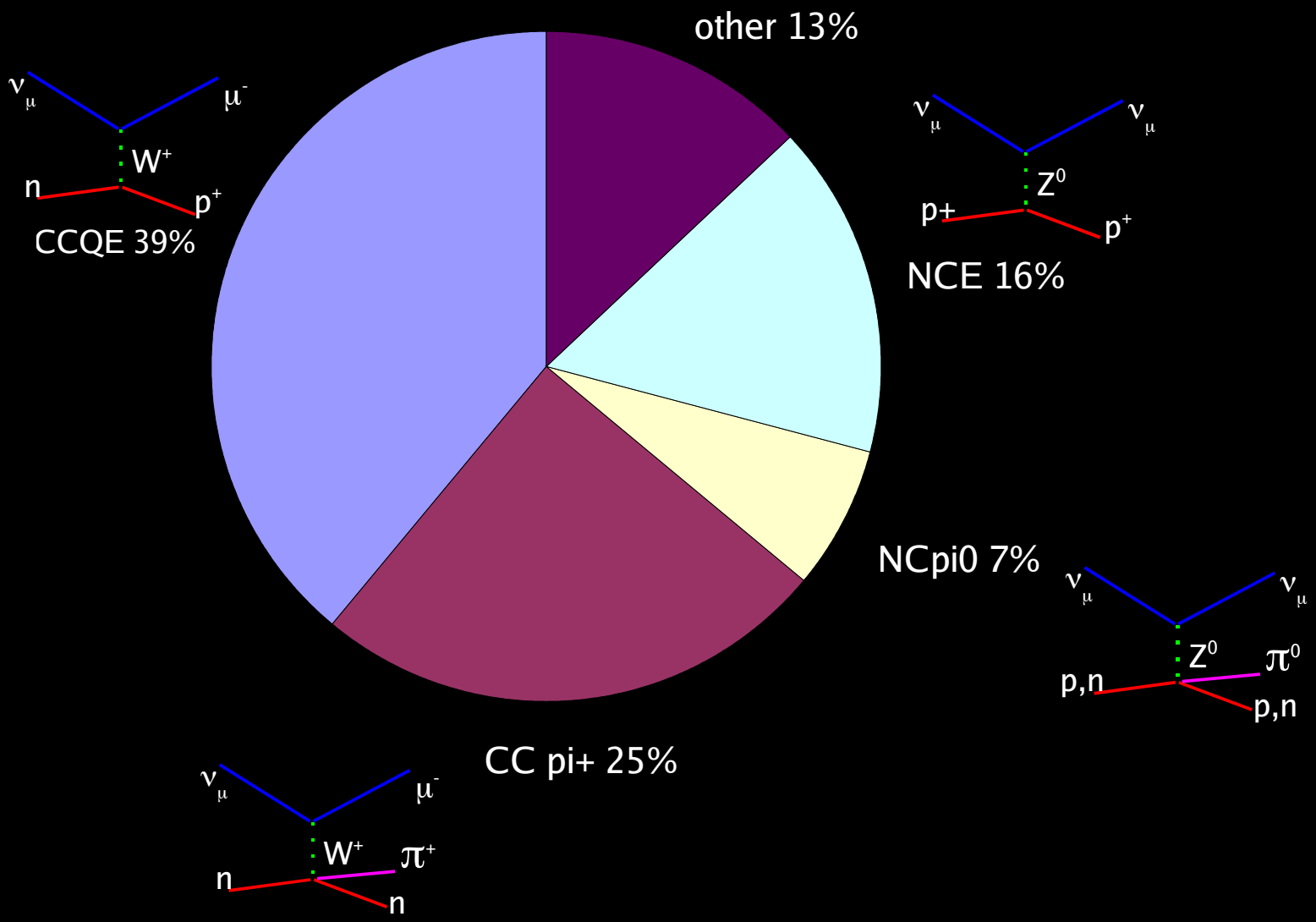
Neutrinos in oil

- A neutrino can do many things in mineral oil...
- About 75% CC, 25 % NC



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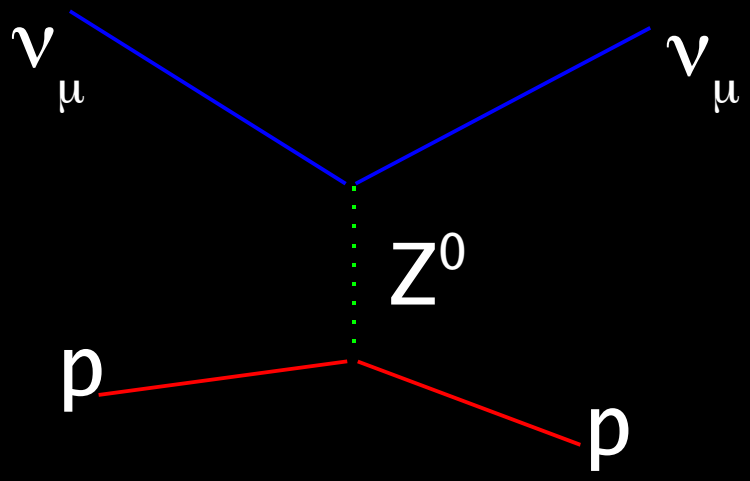
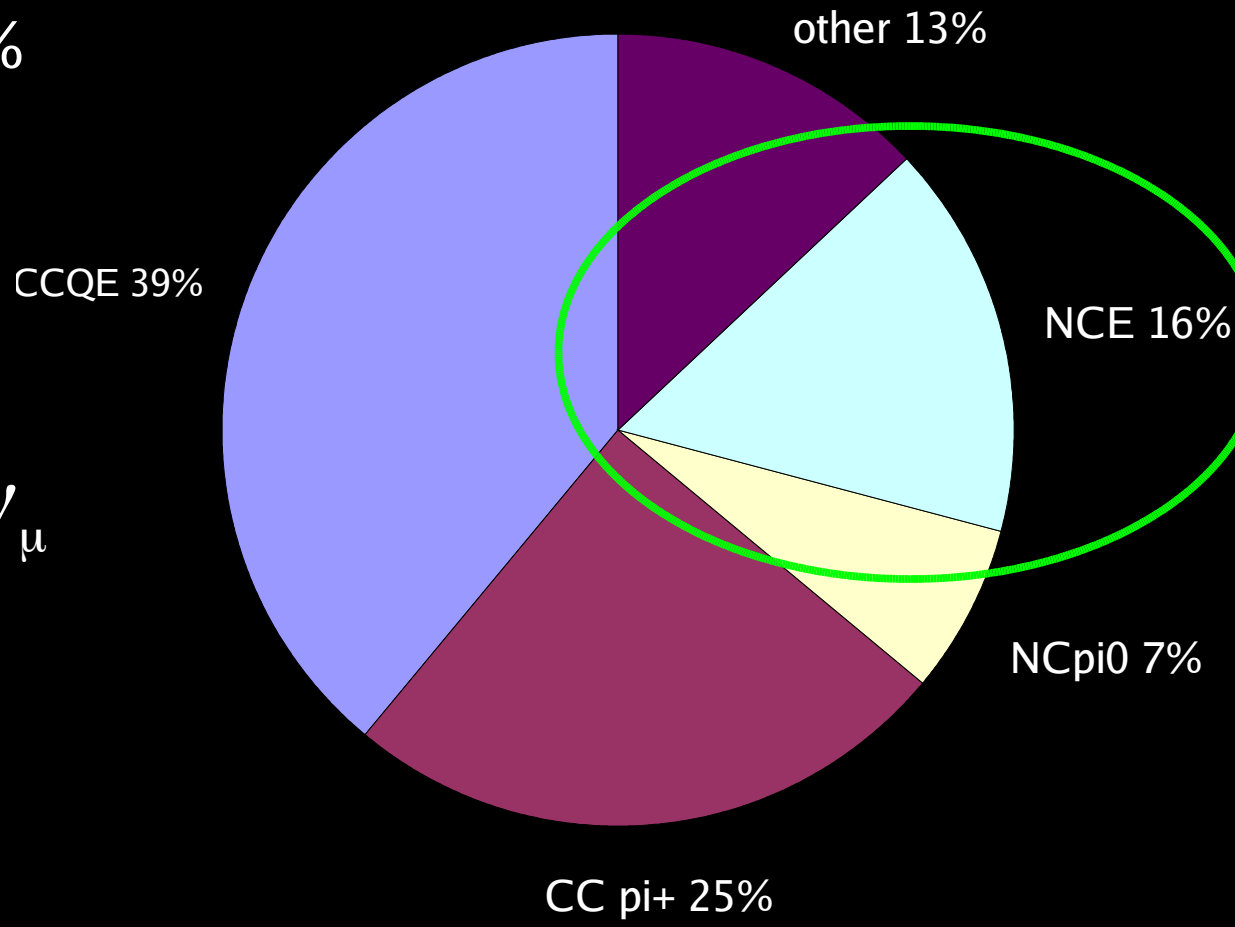
Neutrinos in oil

- A neutrino can do many things in mineral oil...
- It can bounce off a nucleus and:
  - Eject a proton
- NC elastic events ~ 16%





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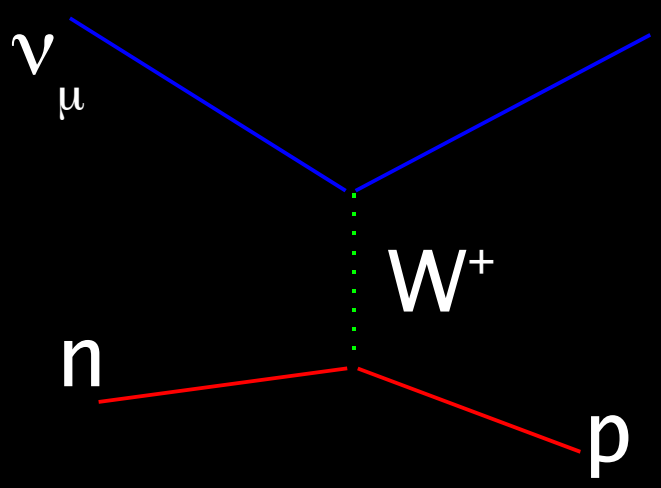
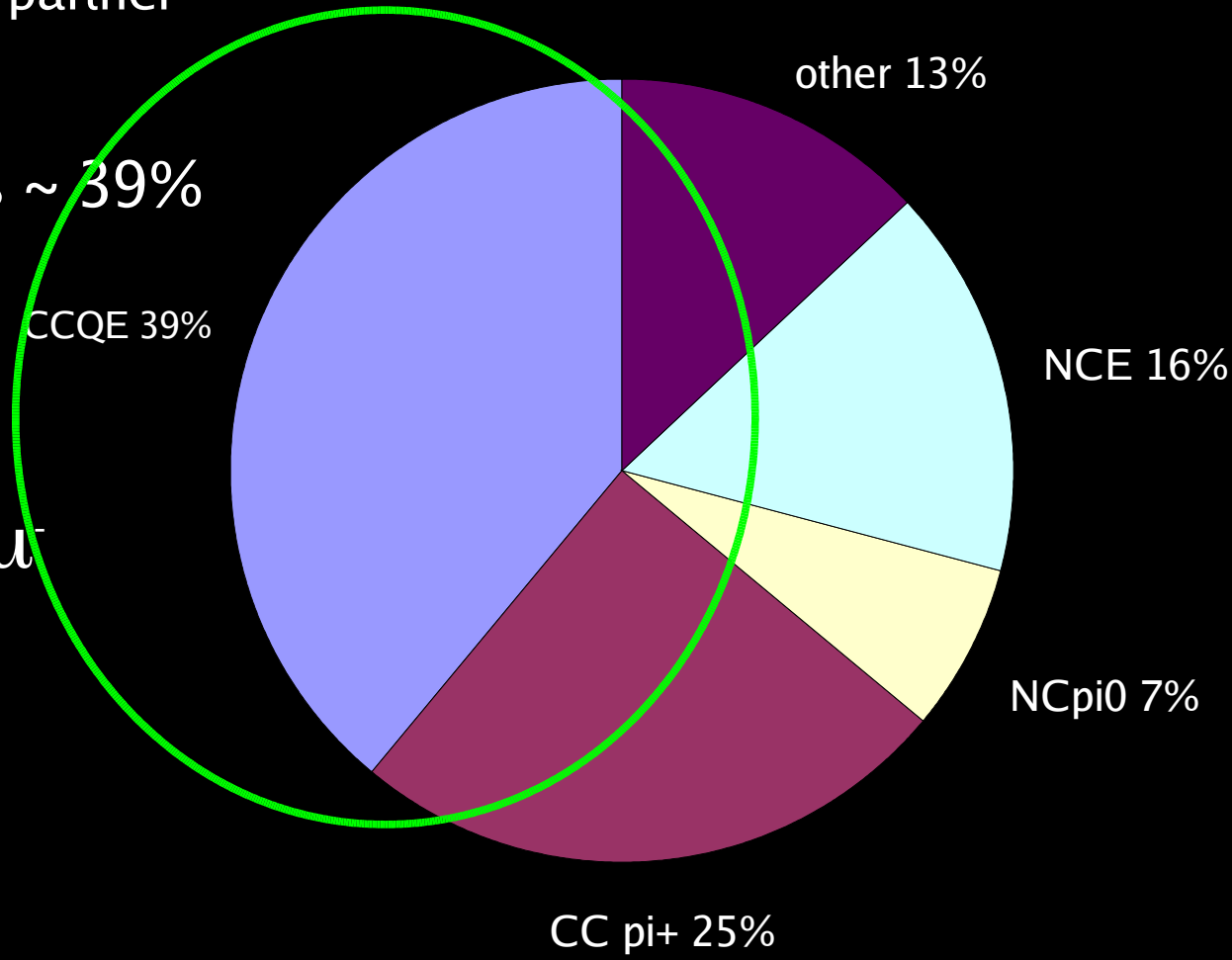
Neutrinos in oil

- A neutrino can do many things in mineral oil...
- It can bounce off a nucleus and:
  - Change into its charged partner
  - Eject a proton
- CC quasi elastic events ~ 39%





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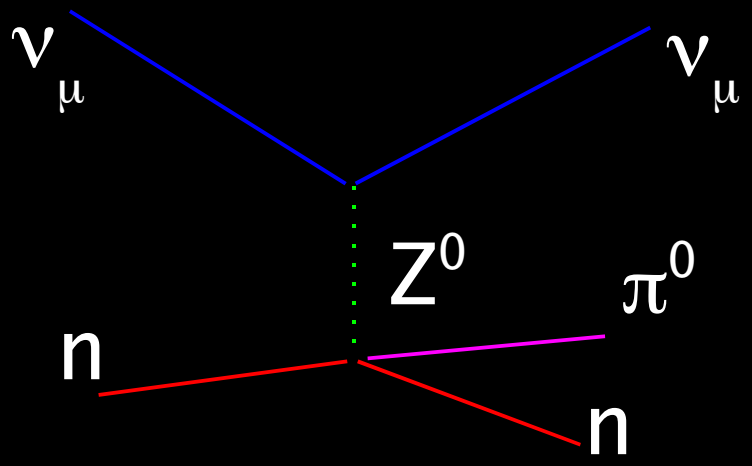
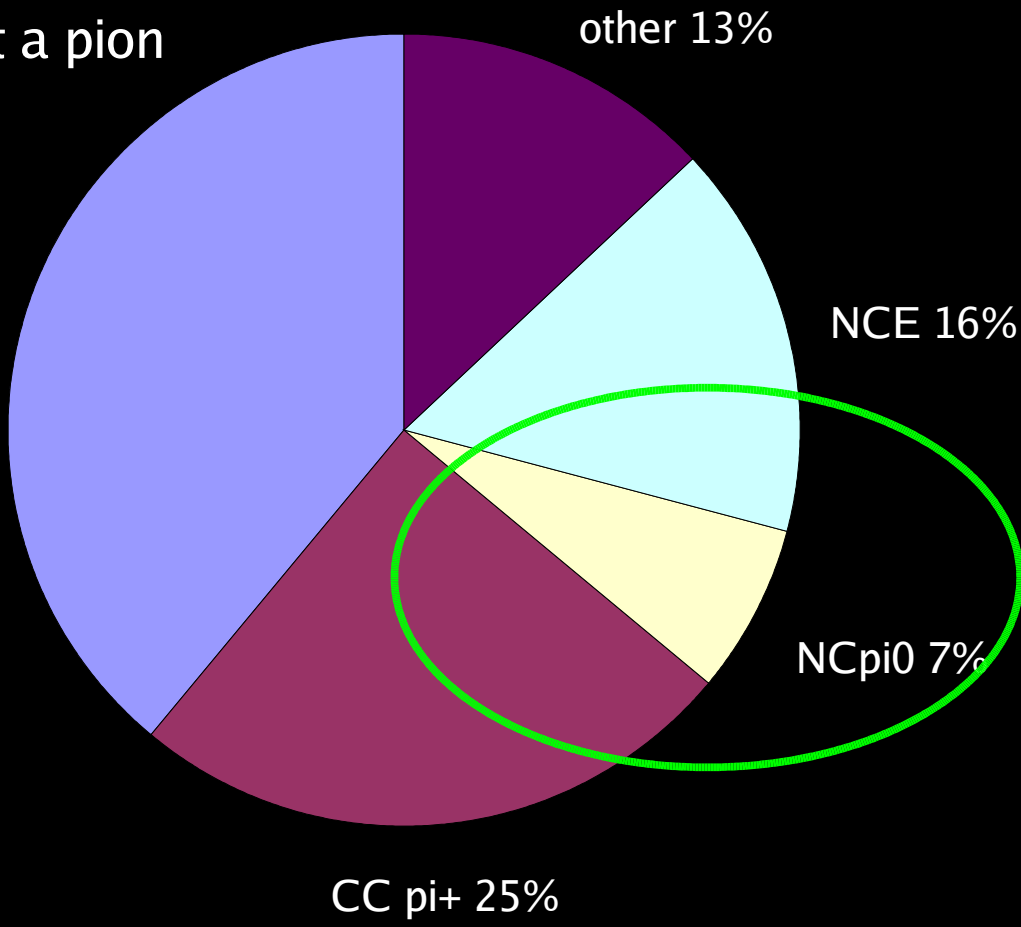
Neutrinos in oil

- A neutrino can do many things in mineral oil...
- It can bounce off a nucleus and:
  - Eject an excited nuleon state
  - Or it can tickle a nucleus and emit a pion
- NC single pion events ~ 7%





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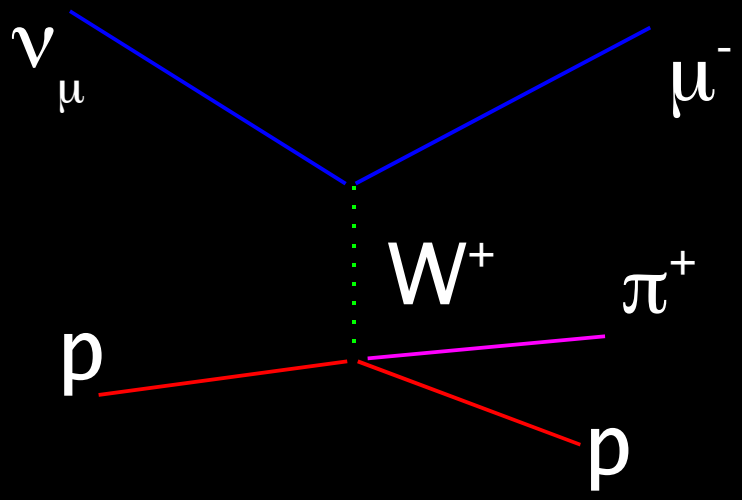
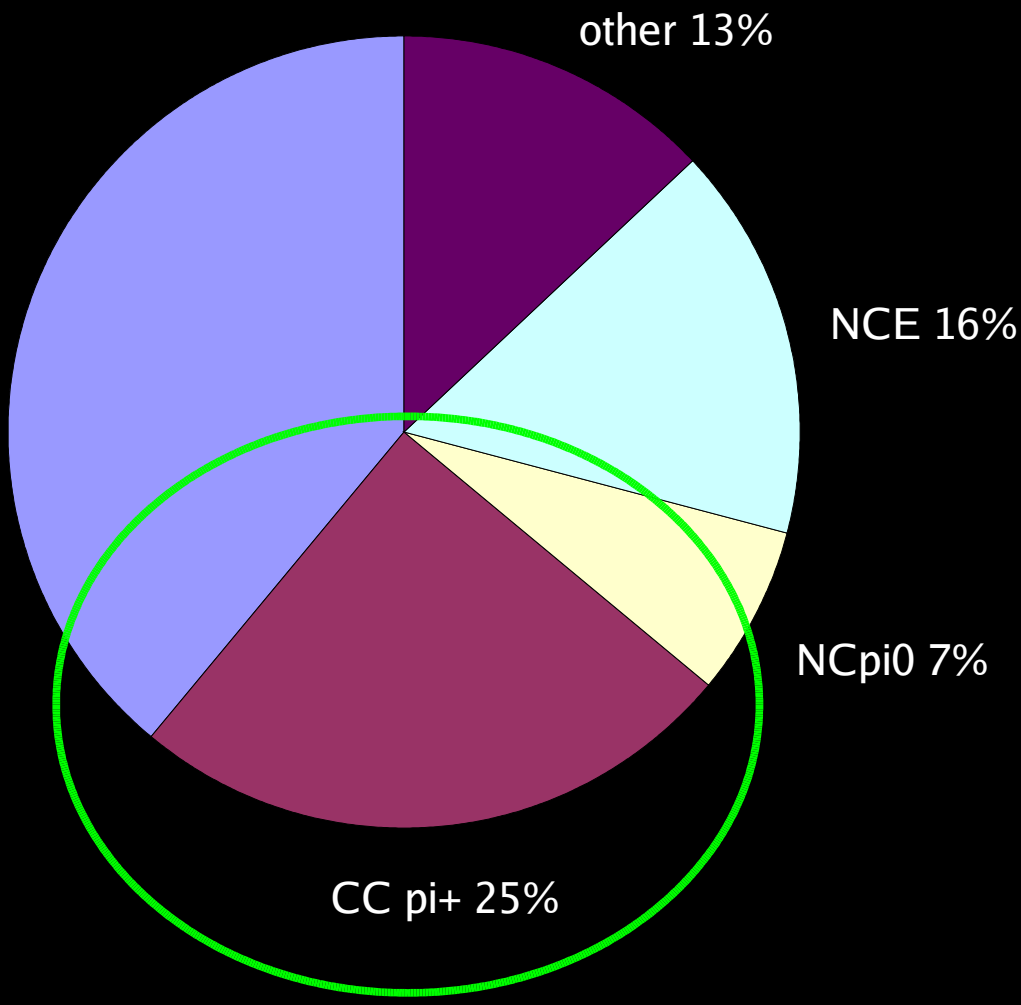
Neutrinos in oil

- A neutrino can do many things in mineral oil...
- It can bounce off a nucleus and:
  - Change into its charged partner
  - Eject an excited nucleon
- CC single pion events ~ 25%





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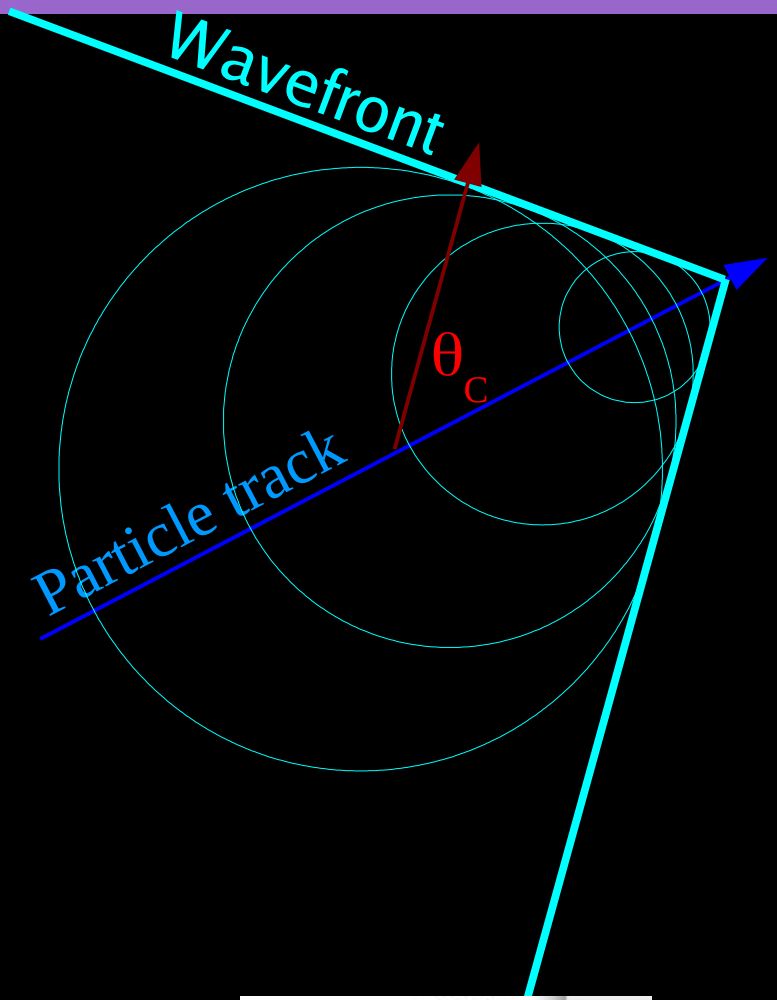
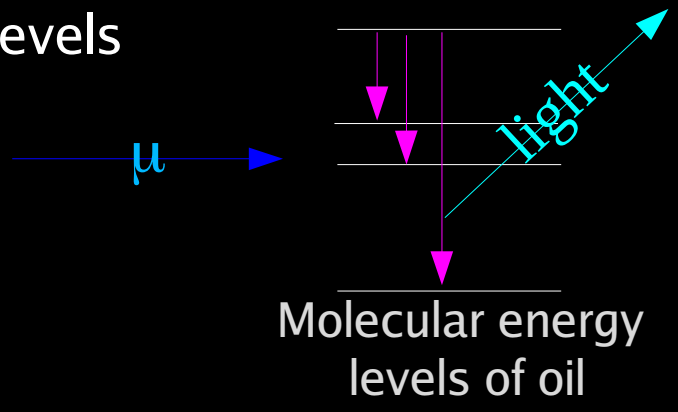
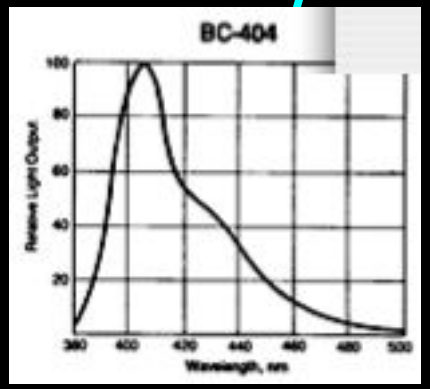
Enlightening Mineral Oil

- Charged particles passing through mineral oil produce visible light in two ways
- Cherenkov radiation
  - Light emitted by oil if particle v > c/n
  - Similar to a sonic boom
- Scintillation
  - Excited/ionized molecules emit light when electrons drop to lower E levels







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Optics of Mineral Oil

Creation

- Cherenkov light
  - proportional to β
- Scintillation
  - dE/dx
  - time delay

Propagation

- Scattering (Rayleigh)
  - prompt
  - $1+\cos^2\theta$
  - λ^4
- Fluorescence
  - isotropic
  - time delay
  - spectrum
- Absorption

In Situ

- Michel electrons
- Cosmic muons
- Laser: diffuse light
- Laser: pencil beam

Ex Situ

- Scintillation (IUCF) w/p^+
- Scintillation (FNAL) w/**m**
  - repeated w/p^+ (IUCF)
- Goniometry (Princeton)
- Fluorescence spectroscopy (FNAL)
- Time resolved spectroscopy (JHU)
- Attenuation (FNAL)
  - multiple devices

Work nearing completion...

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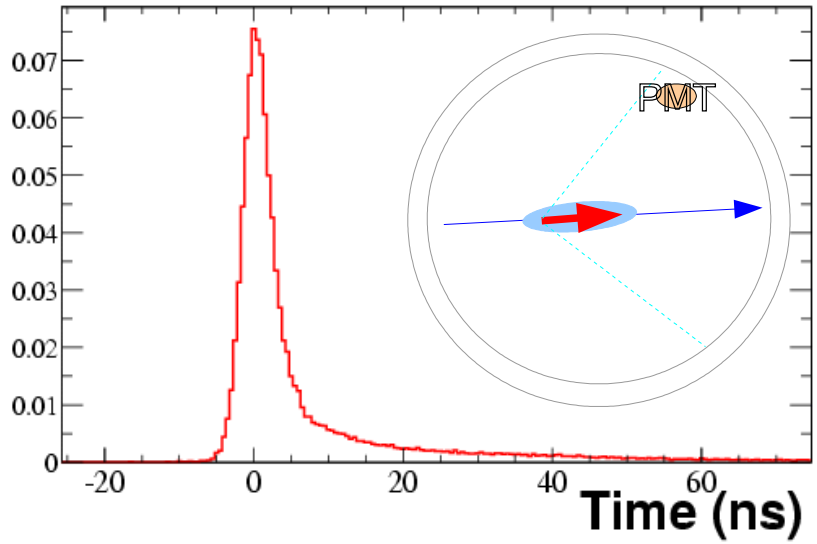
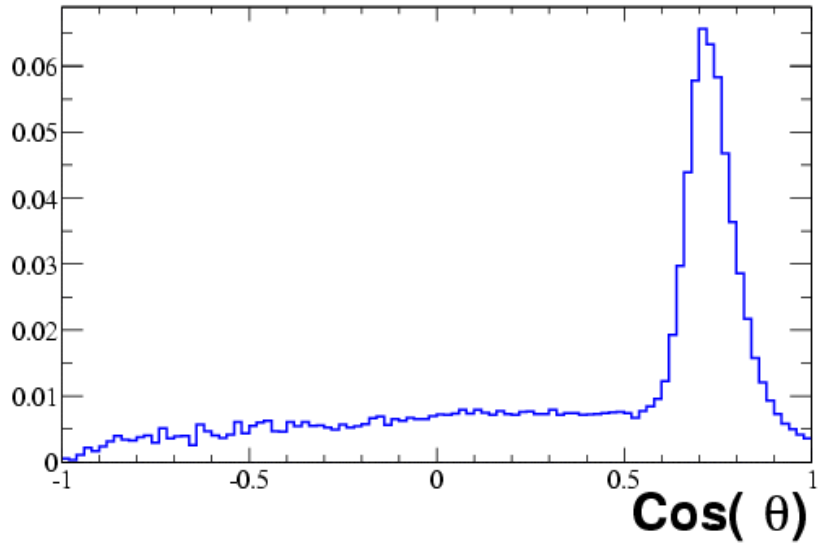
MiniBooNE Detector

- PMTs collect photons, record t,Q
- Reconstruct tracks by fitting time and angular distributions

- Energetic charged particles in oil cause Cherenkov and scintillation light emission in oil





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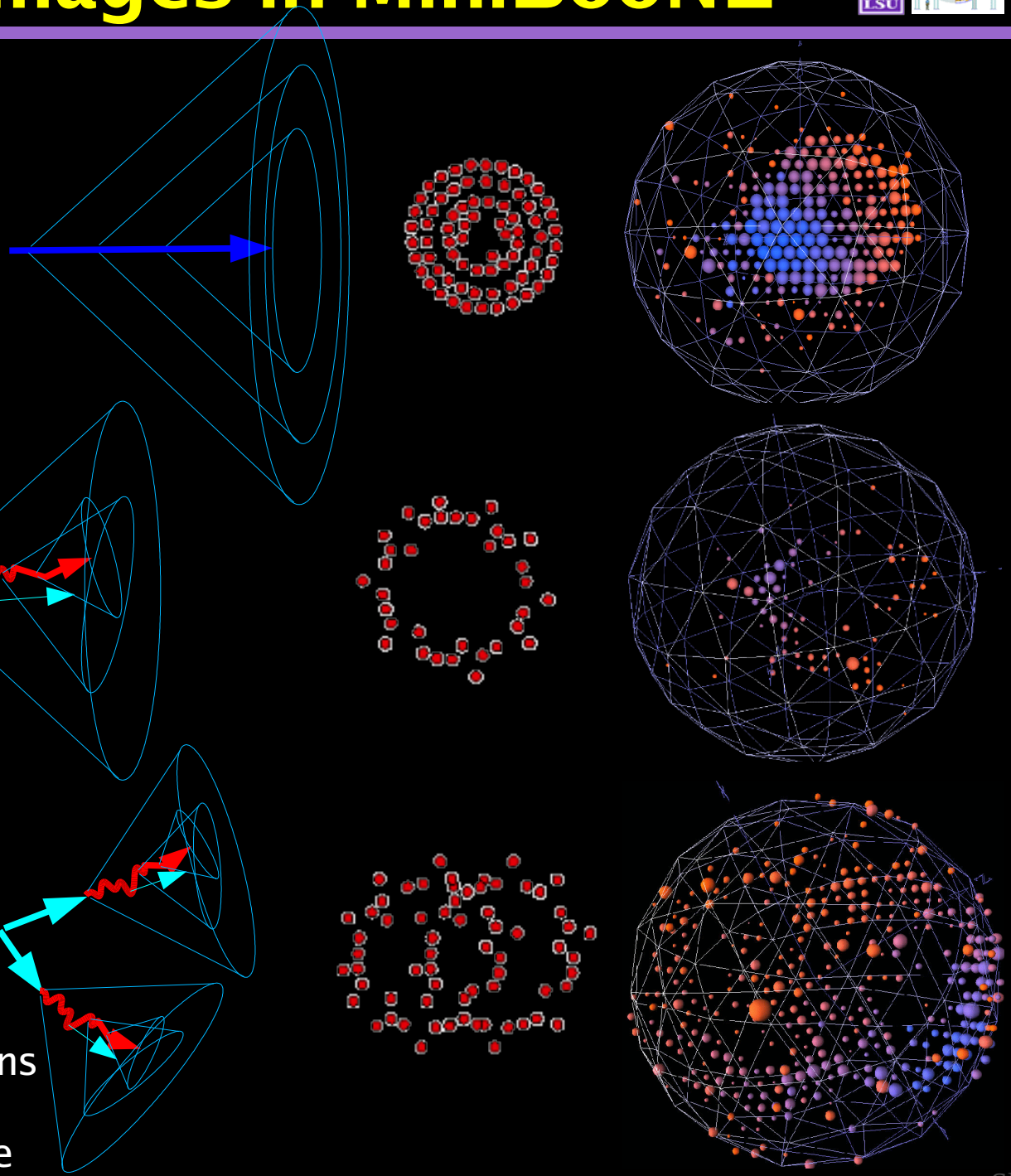
Particle Images in MiniBooNE

- Muons
  - Sharp, clear rings
    - Long, straight tracks
- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes
- Neutral Pions
  - Double rings
    - Decays to two photons
    - Photons pair produce



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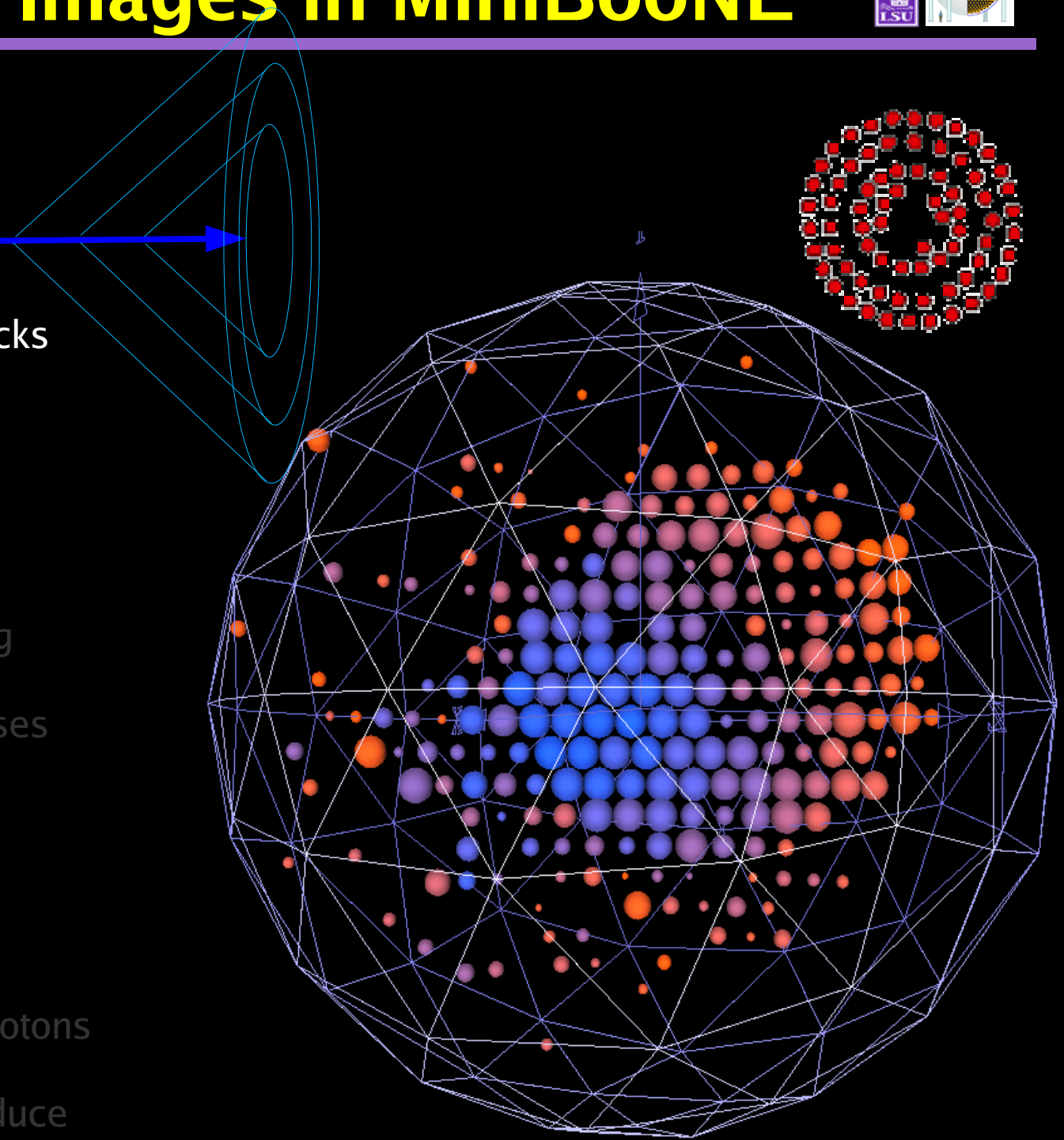

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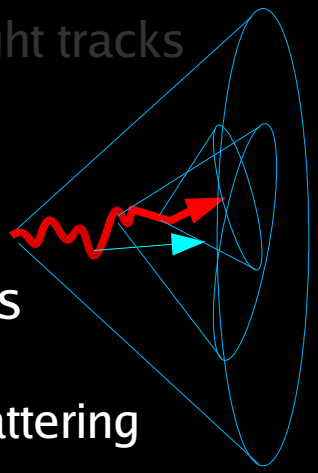

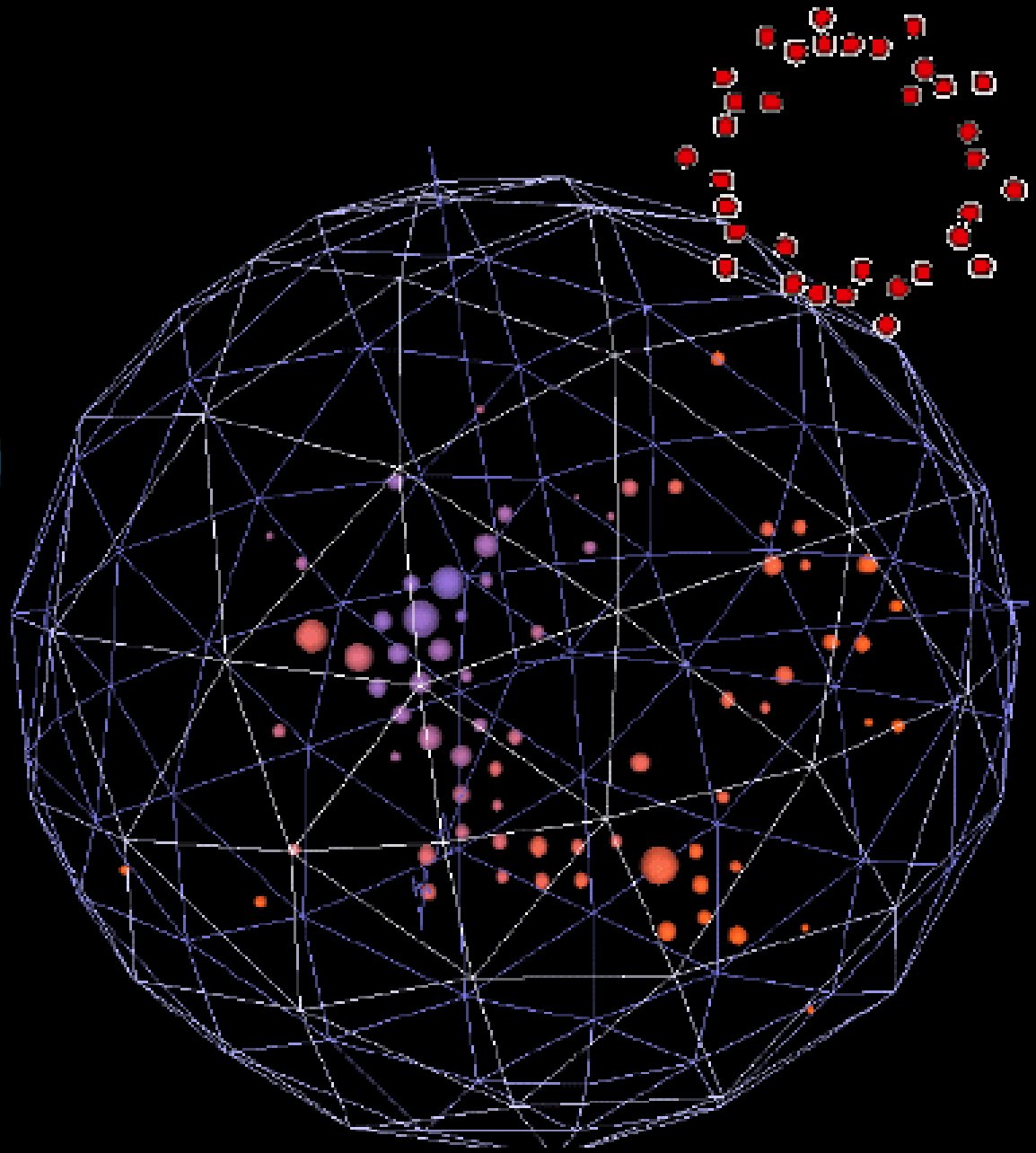

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Particle Images in MiniBooNE

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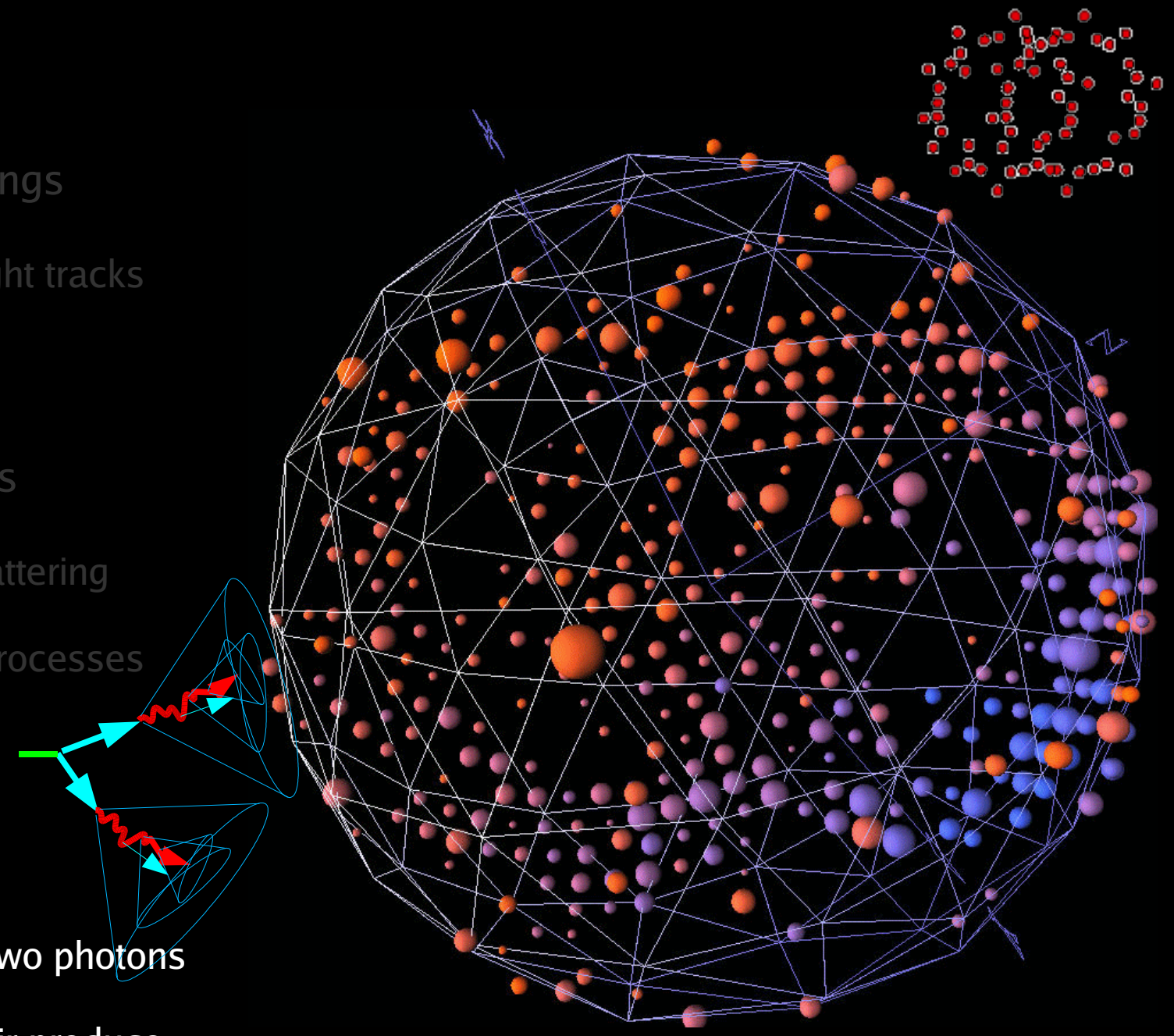

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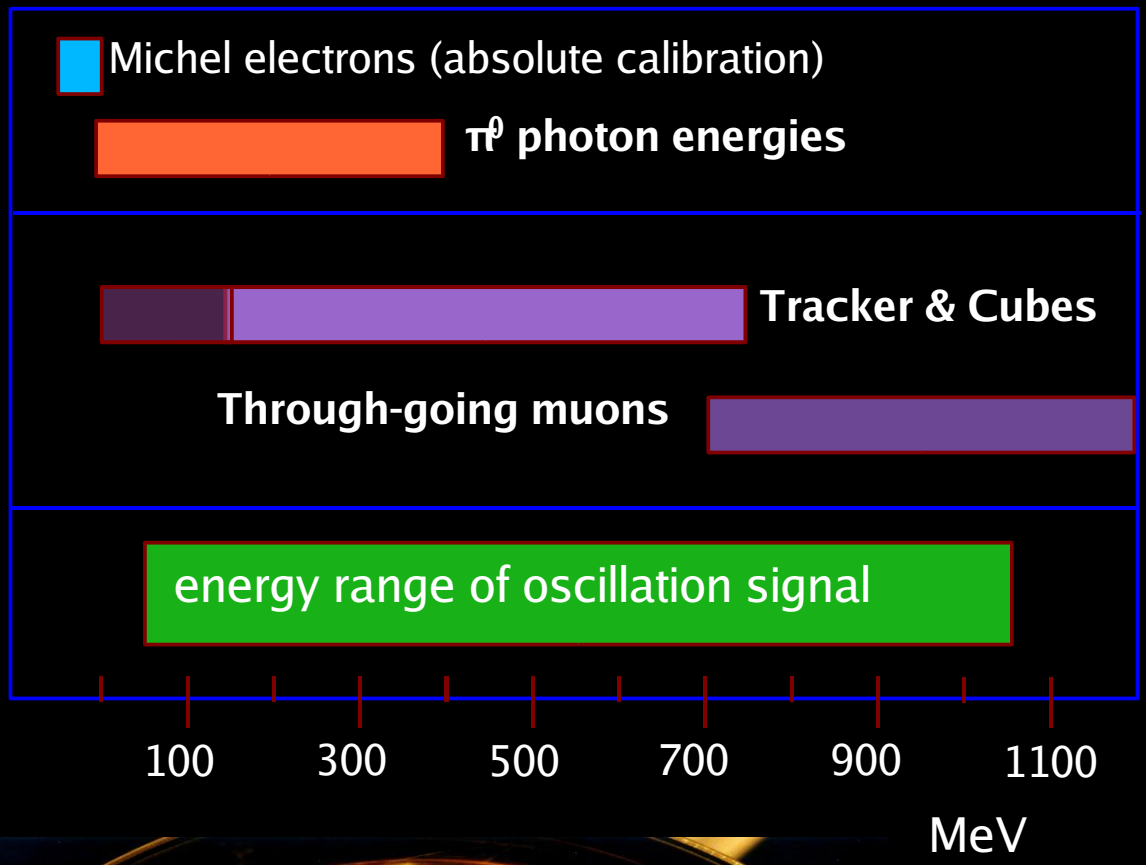
Detector Calibration



- Why we think we understand the detector ...
- PMTs calibrated with laser system
- Calibration data samples span oscillation signal energy range
- Electron data samples
  - Michel electrons
  - π^0 photons
- Cosmic Muons
  - Stopping, through-going
  - Very important: most neutrino events have muons

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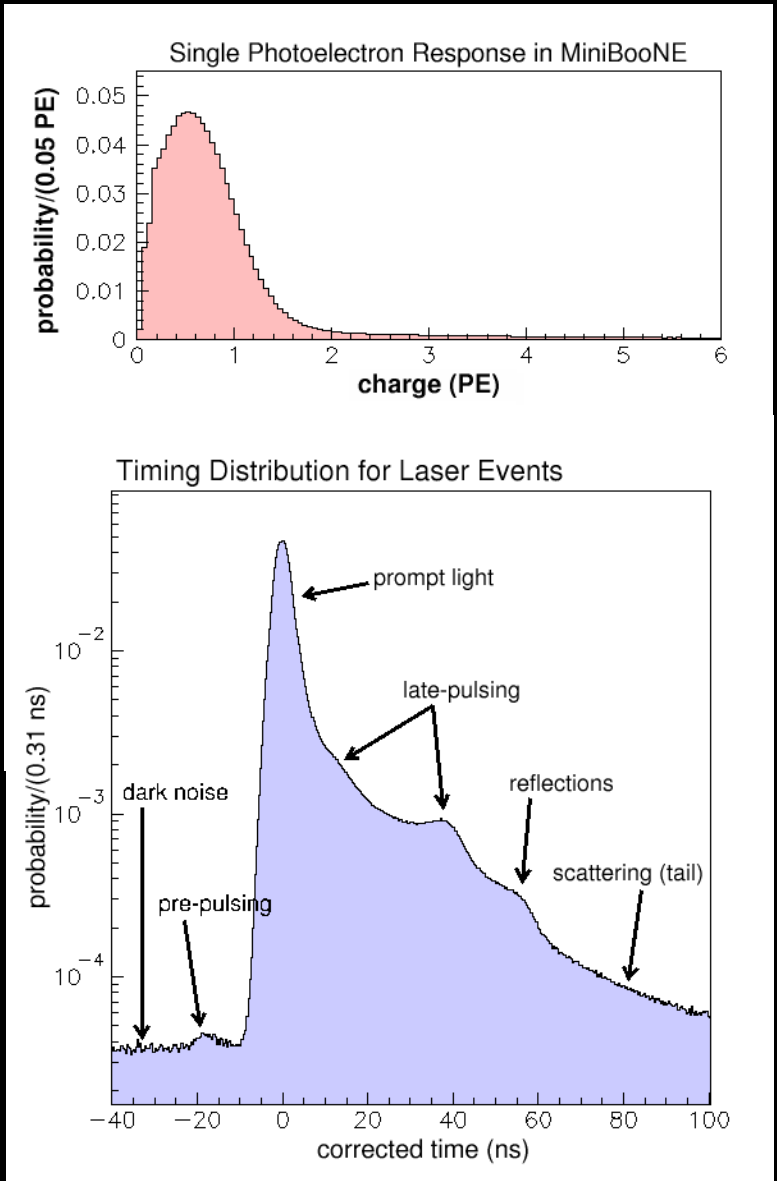
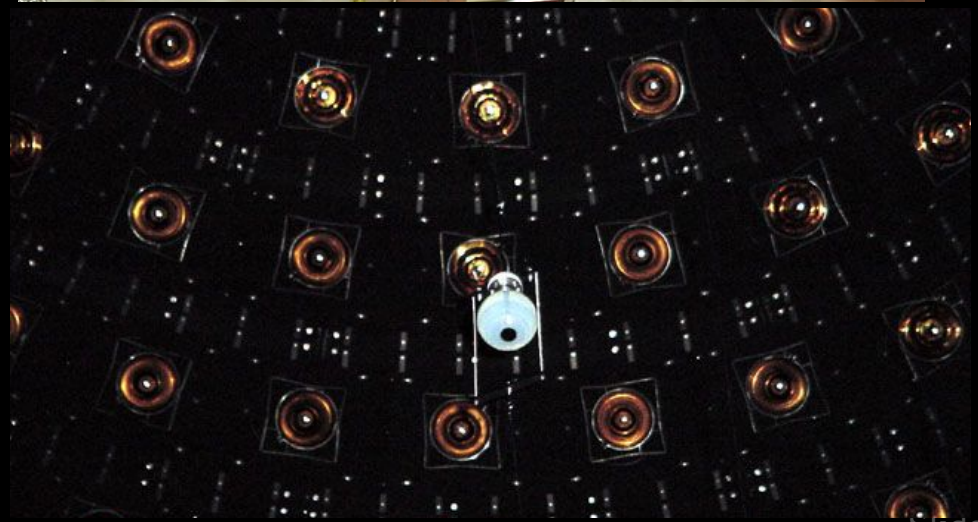
PMT Calibration

Laser light distributed to 4 flasks throughout the detector

Known light source position, known light emission time





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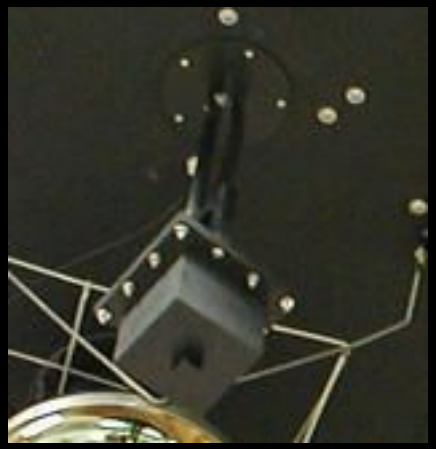
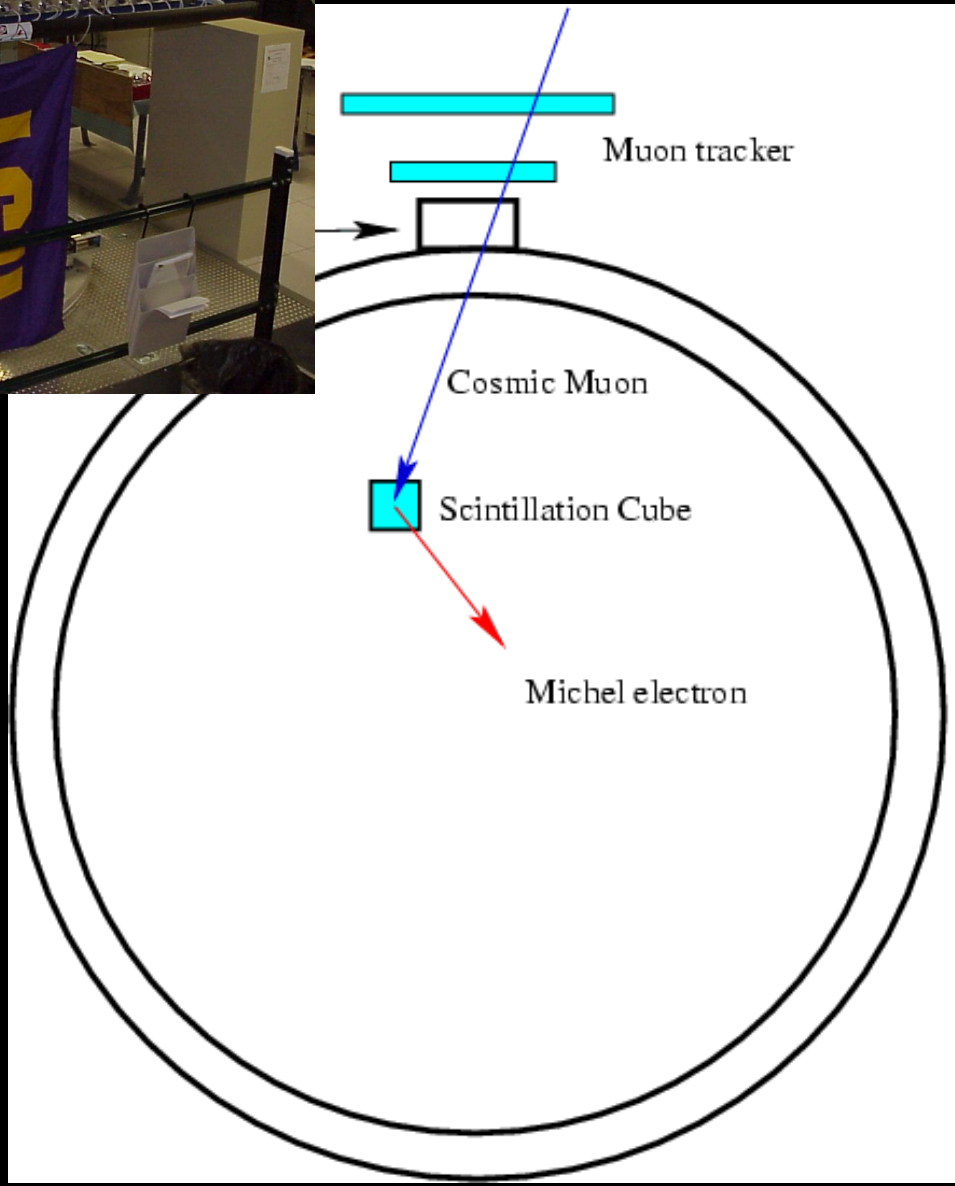
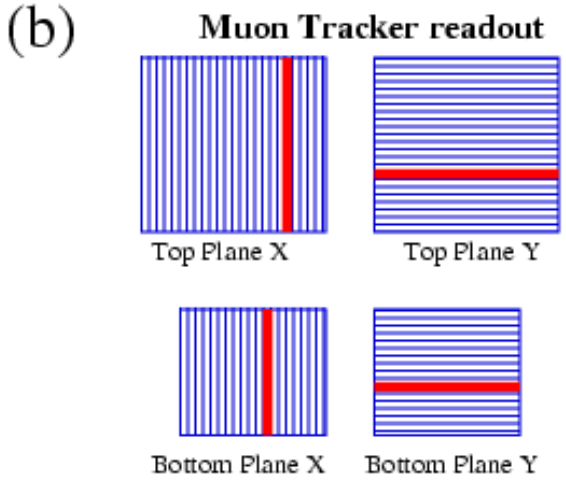
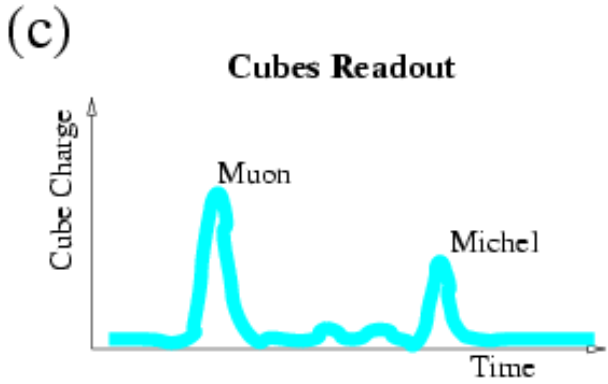
Cosmic Muon Calibration









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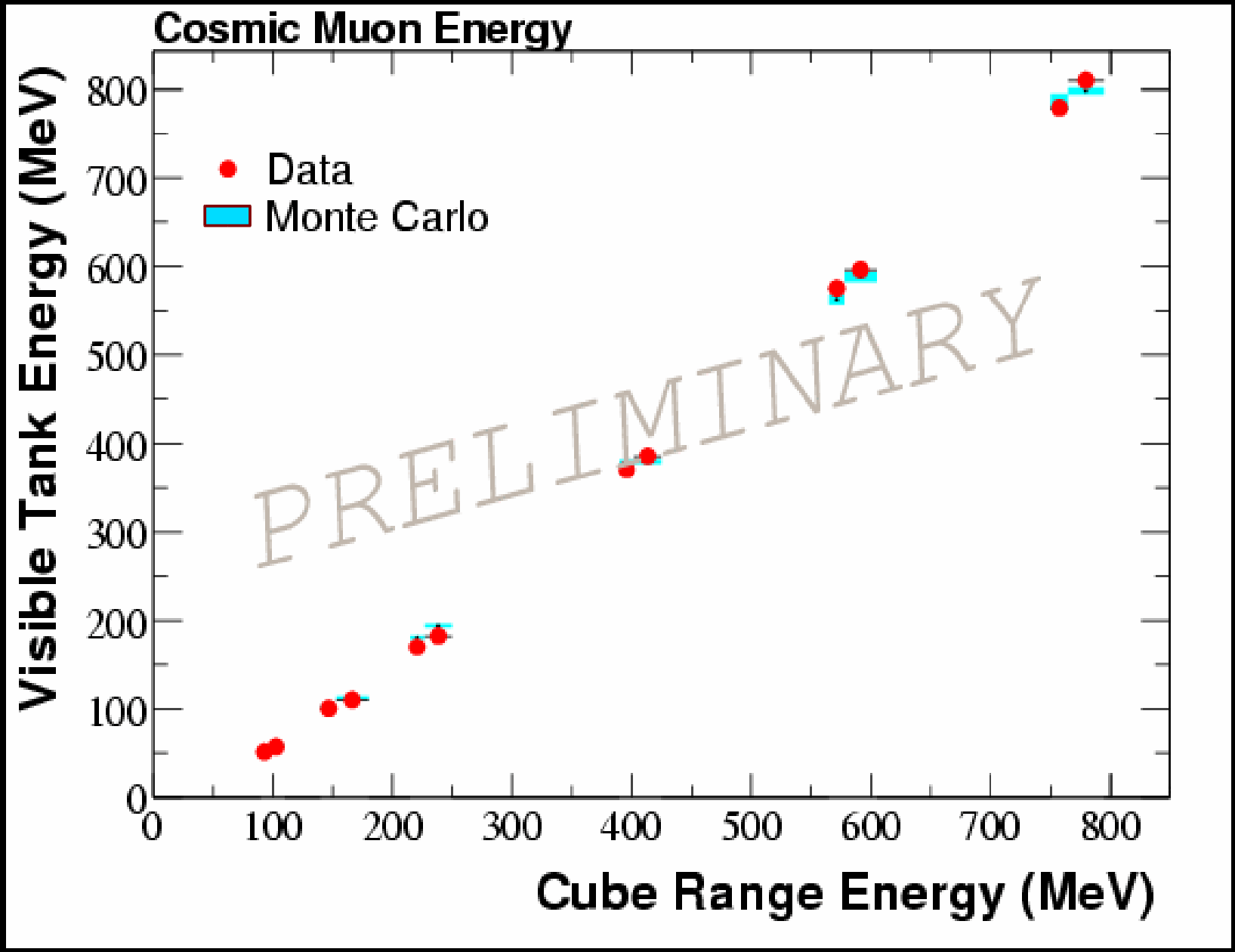
Muon Energy Calibration



- Visible energy: electron equivalent energy

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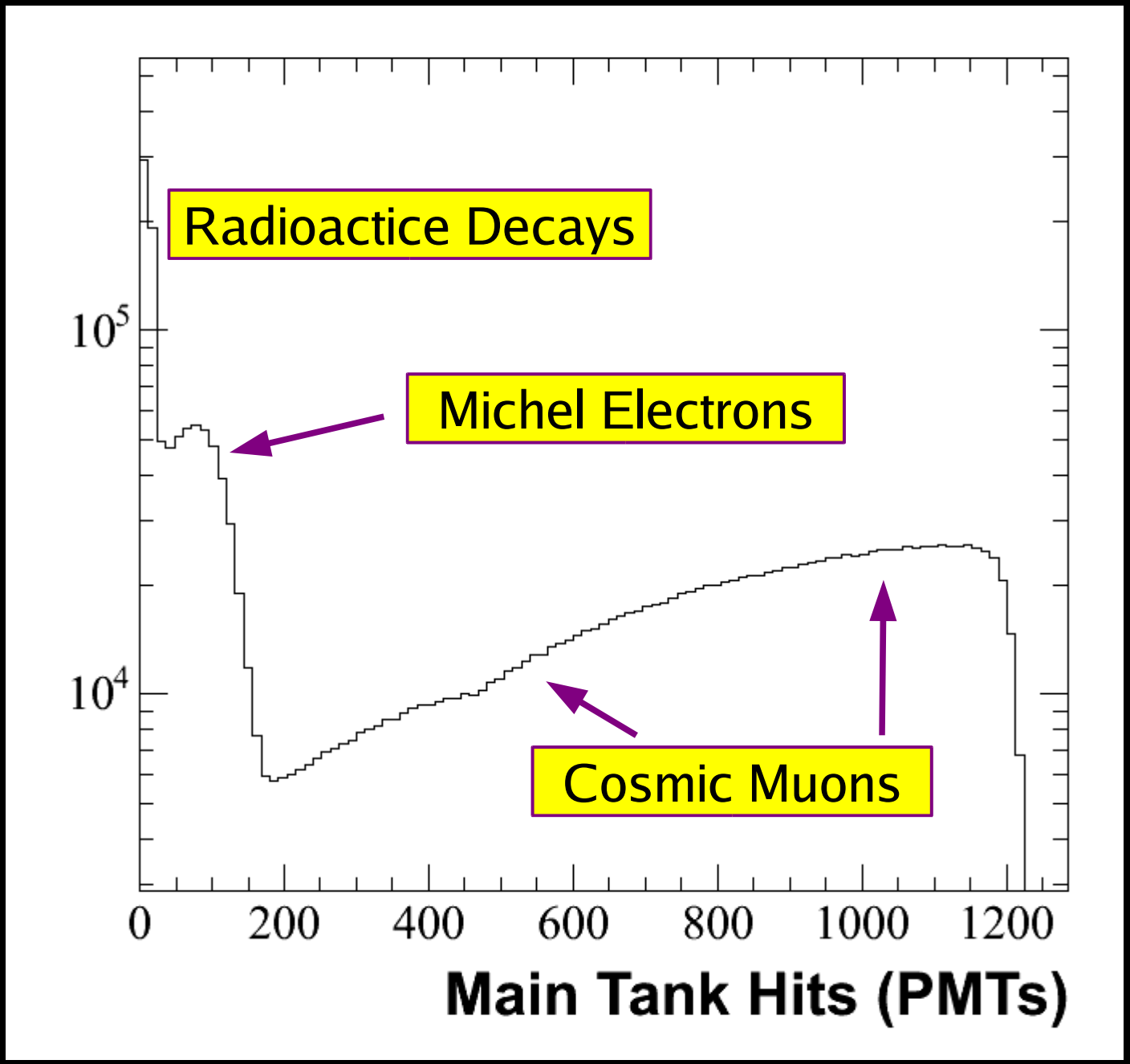
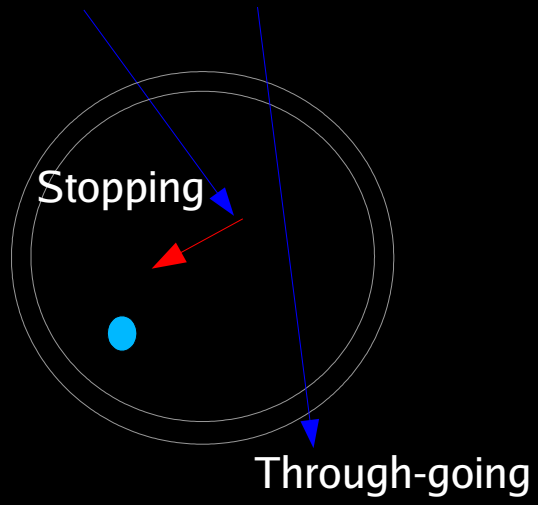
Looking at Tank Data



- Putting it all together...



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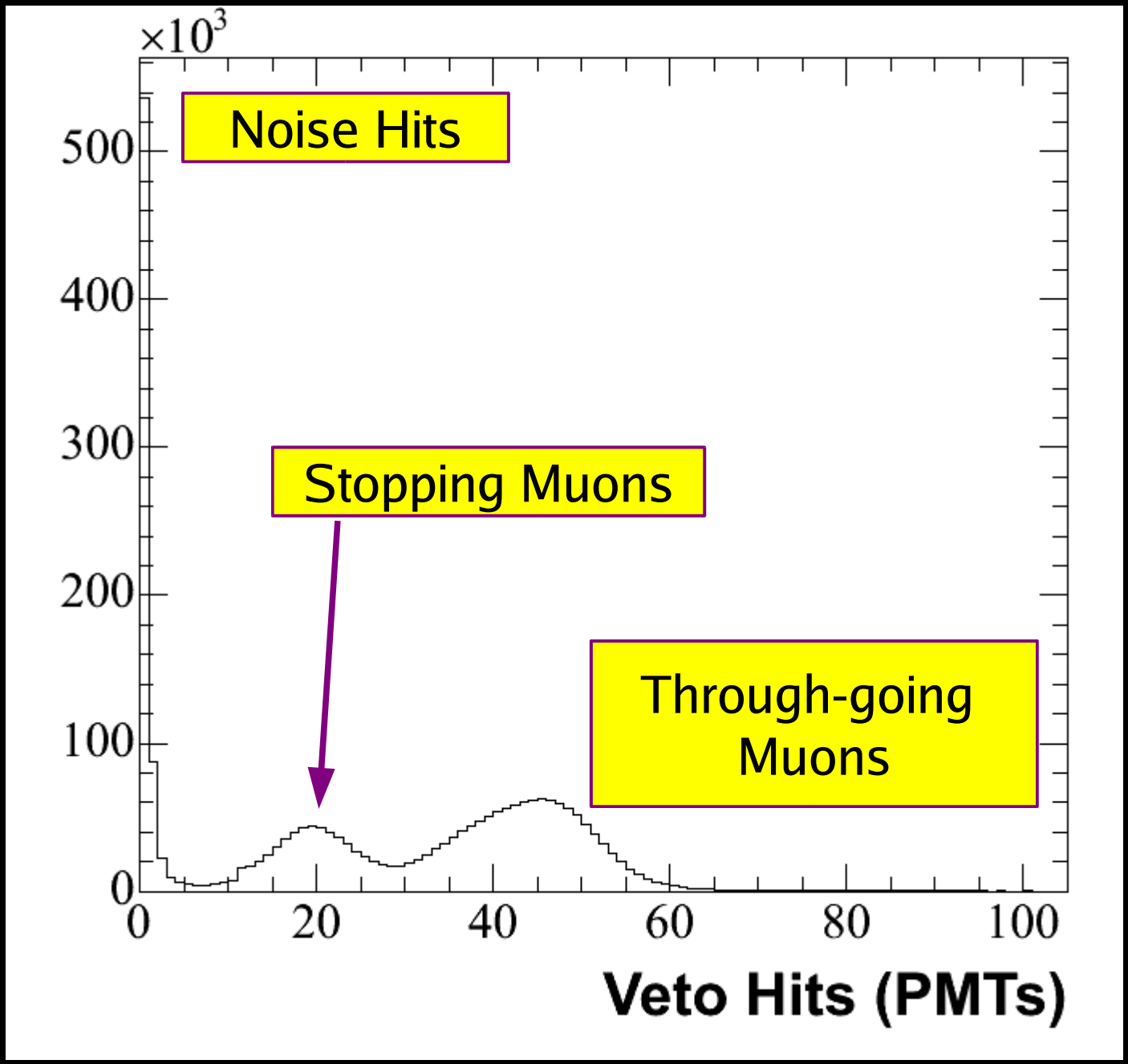
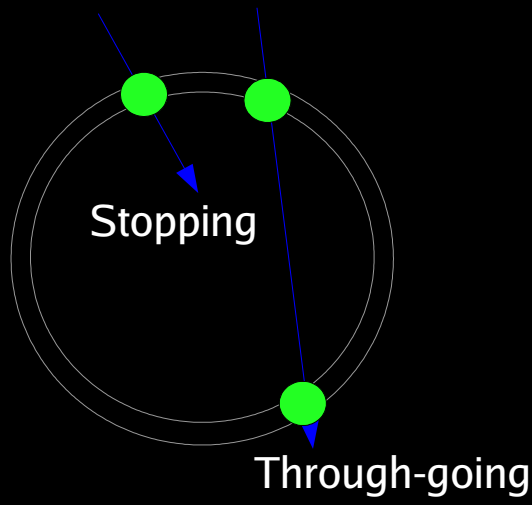
Looking at Tank Data





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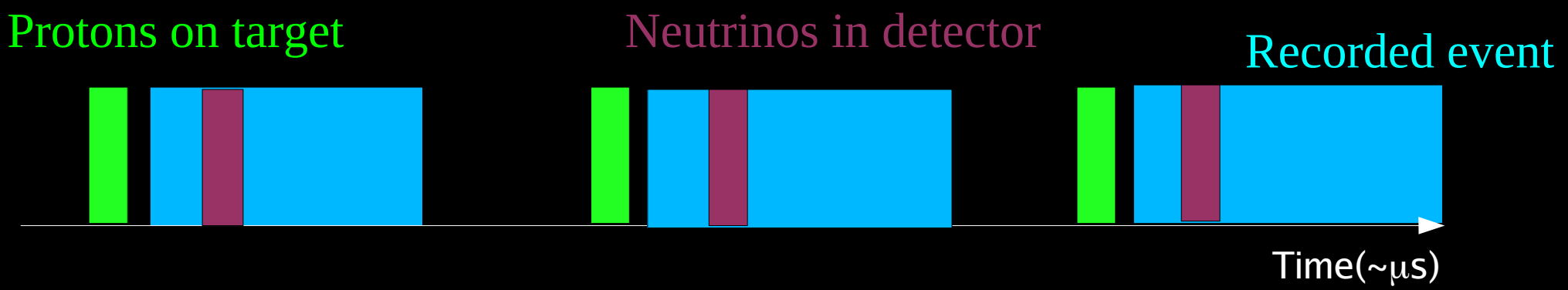
Triggering on Neutrinos

- MiniBooNE's neutrino trigger is unbiased
- The Booster dumps protons onto our target in 1.6μs intervals, several times per second
  - "Beam spill"
- When this happens, we record all detector activity in a 20μs interval around the beam spill
  - We know exactly when neutrinos from the beam could be passing through the detector



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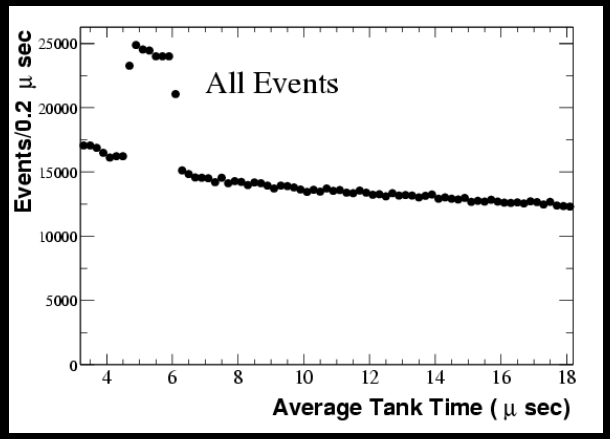
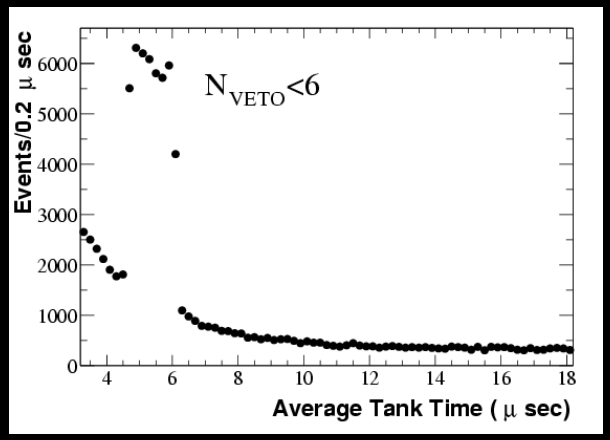
Picking out Neutrinos

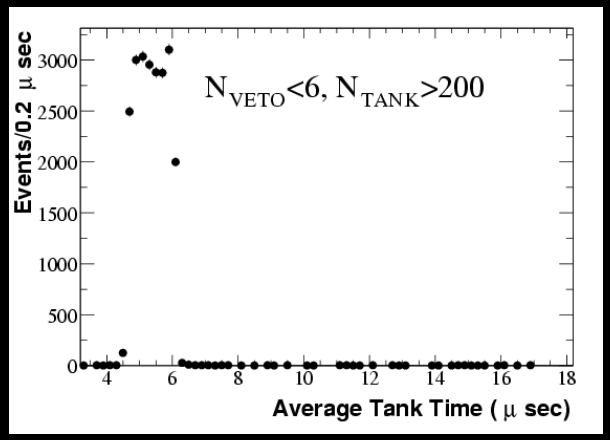
- Times of hit-clusters (sub-events)
- Beam spill (1.6μs) is clearly evident in all
  - simple cuts eliminate cosmic backgrounds
- Neutrino Candidate Cuts
  - <6 veto PMT hits
  - >200 tank PMT hits



Beam and Cosmic BG



Beam and Michels



Beam only

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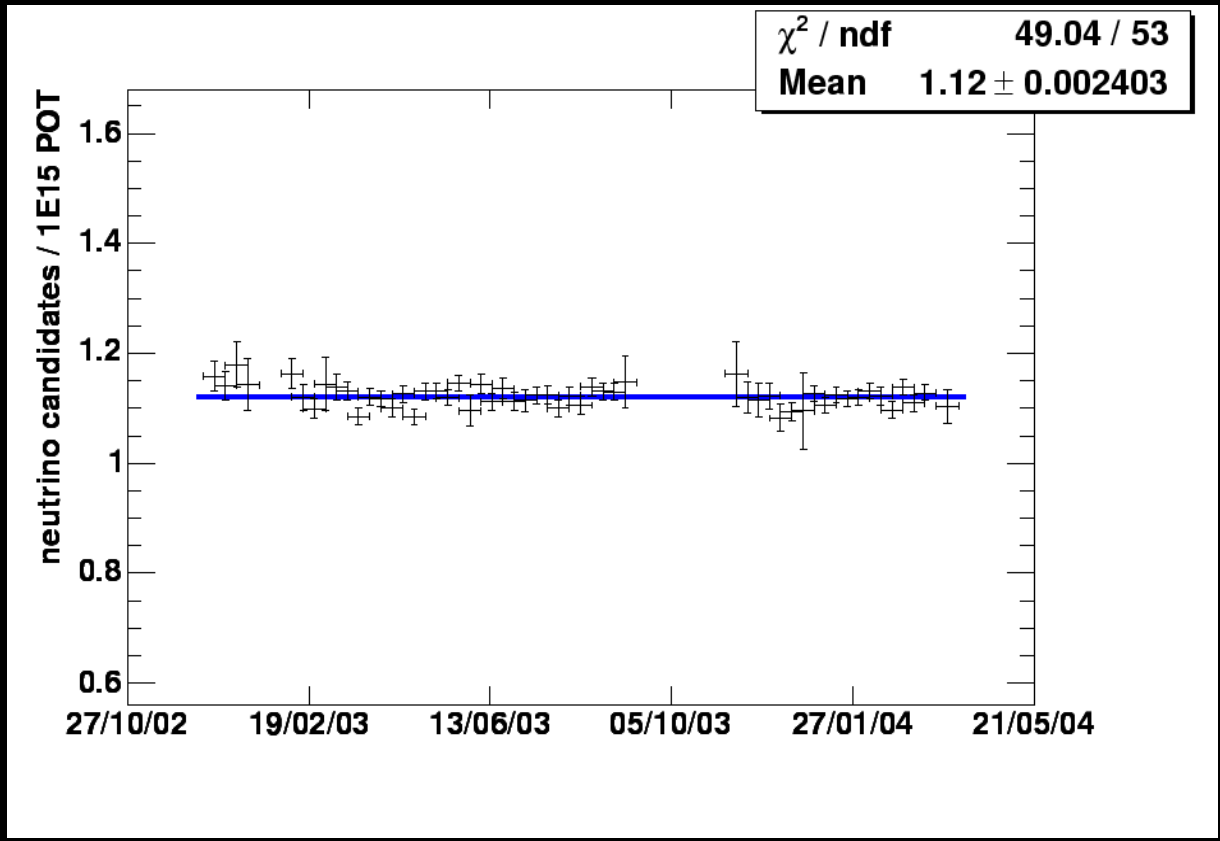
Neutrinos keep coming!

- Measured rate of neutrino candidates (per 1E15 protons!)
  - Neutrino candidates≡
    - >200 tank hits
    - <6 veto hits
- Constant rate over time
  - χ^2/d.o.f. = 49/53
- Tests performance of:
  - Tank DAQ
  - Calibration stability
  - Data processing chain



- >380,000 neutrino events recorded so far...
  - 3.7×10^{20} POT

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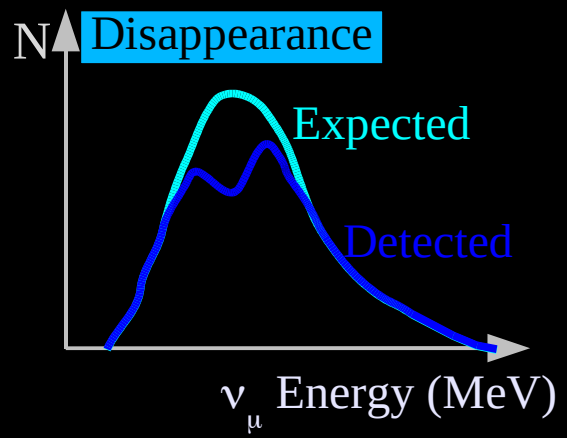
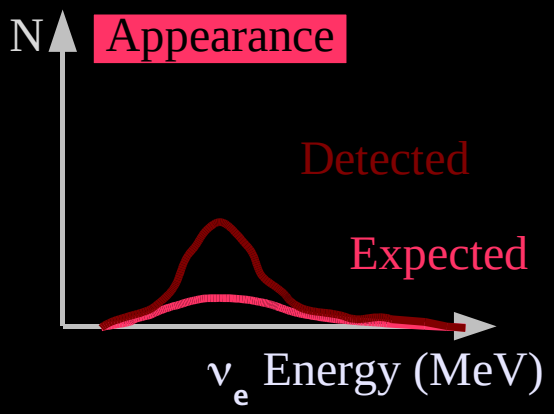
Reconstructing Oscillations

- To search for oscillations, need neutrino energy
  - Reconstruct neutrino energy from particle tracks in detector
- Develop neutrino energy reconstruction with ν_μ data, check with muon calibration data
  - apply to $\nu_\mu \rightarrow \nu_e$ appearance search
- CCQE: $\nu_\mu n \rightarrow \mu^- p$
  - Largest event sample, simplest kinematics
  - Fit for single muon Cherenkov ring
- CCπ^+: $\nu_\mu p \rightarrow \mu^- \pi^+ p$
  - Search for events with two Michel electrons
  - Fit for dominant Cherenkov rings





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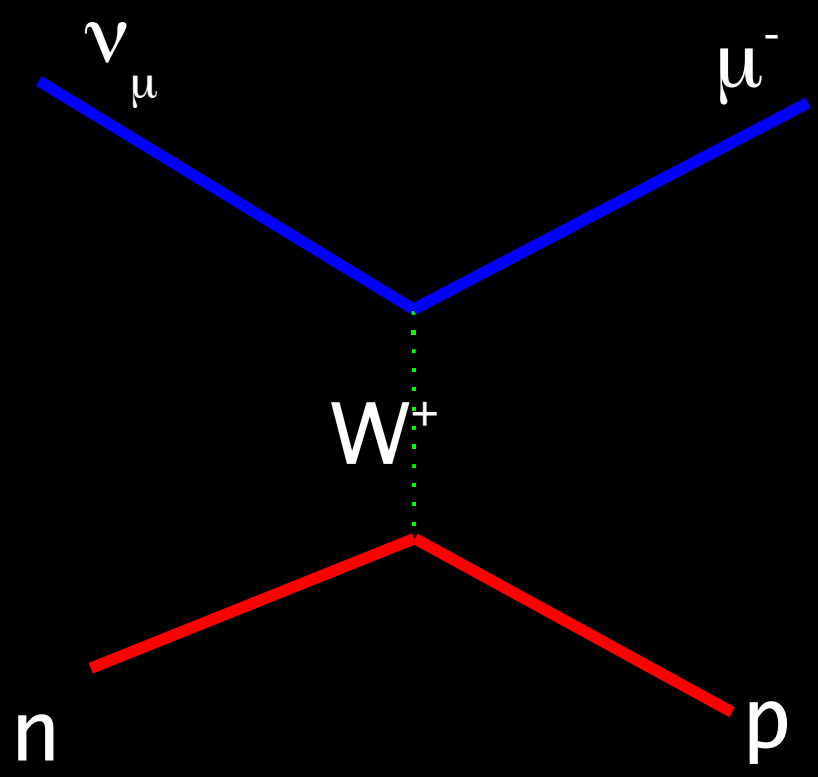
Charged Current Quasi-Elastics

Reconstruct E_ν to search for oscillations



Measure energy and angle from visible light: prompt Cherenkov, delayed scintillation

Fermi motion of target nucleon, binding energy

isotropic scintillation light, nuclear interactions

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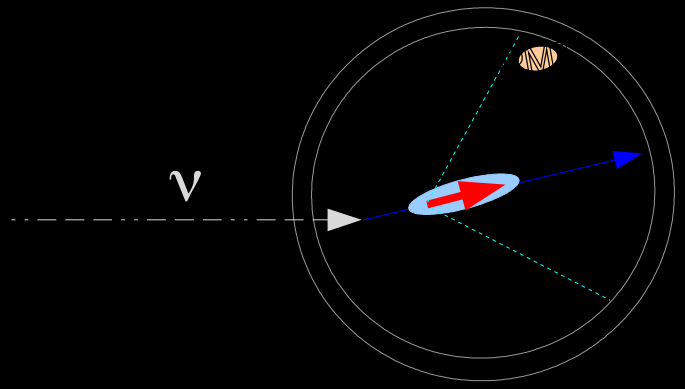
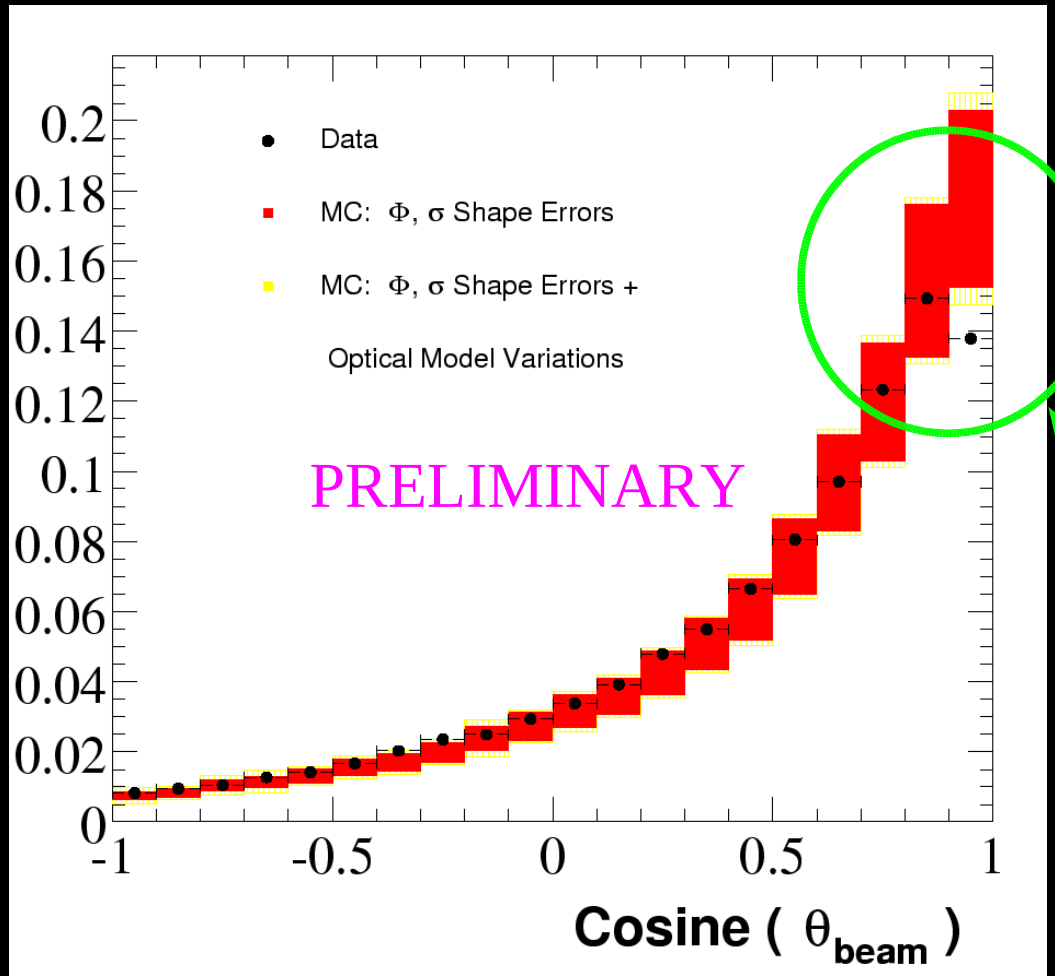
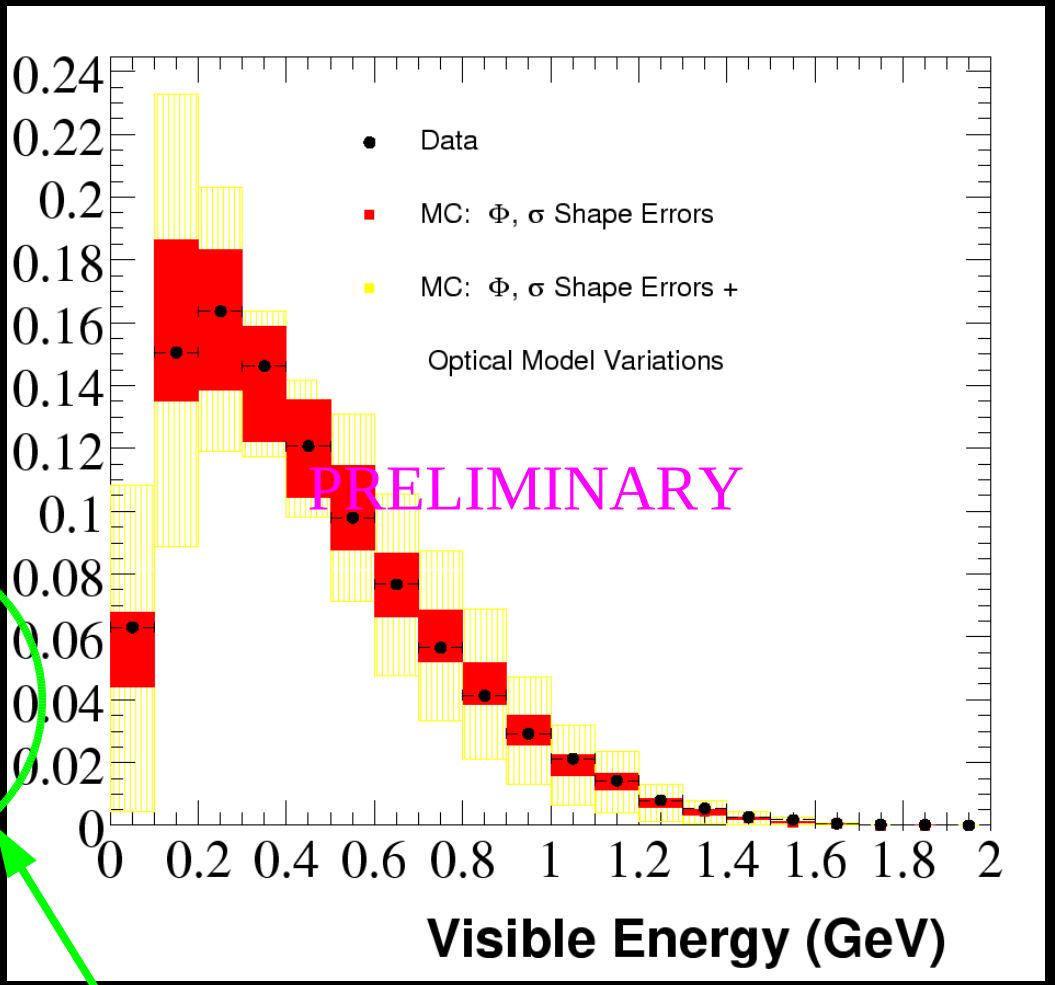
Reconstructed Tracks







Discrepancy between data and Monte Carlo --- not a reconstruction effect, as we know from the cosmic muon analysis

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CCQE ν Energy

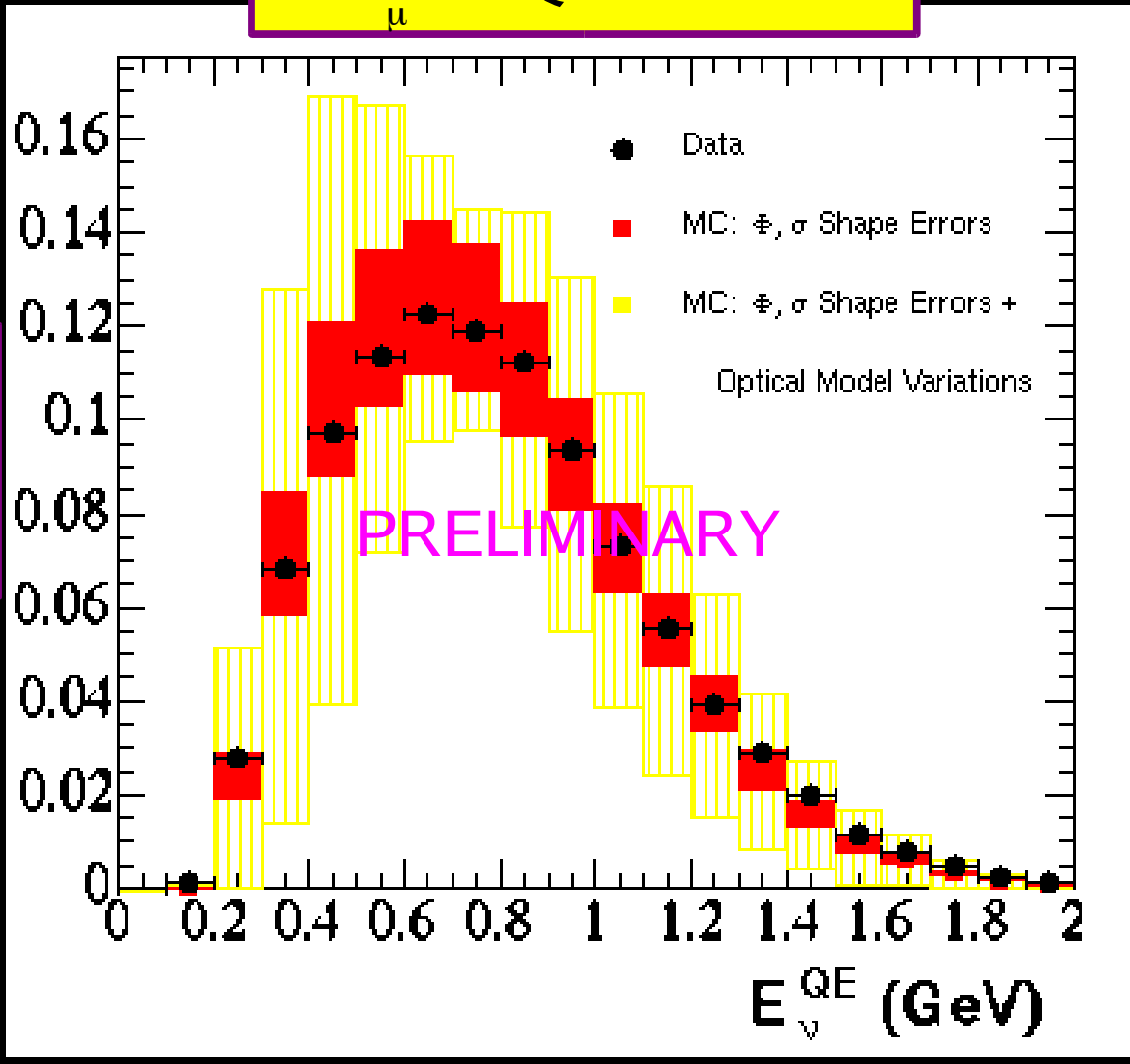
Can reconstruct the neutrino energy with just the energy and direction of the outgoing muon.

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

Neutrino energy resolution 15-20%

Will use this distribution to search for ν_μ disappearance. The deficit could be anywhere from 1% to 10%.

ν_μ CCQE Events



Note: both curves unit area normalized

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Oscillations at MiniBooNE

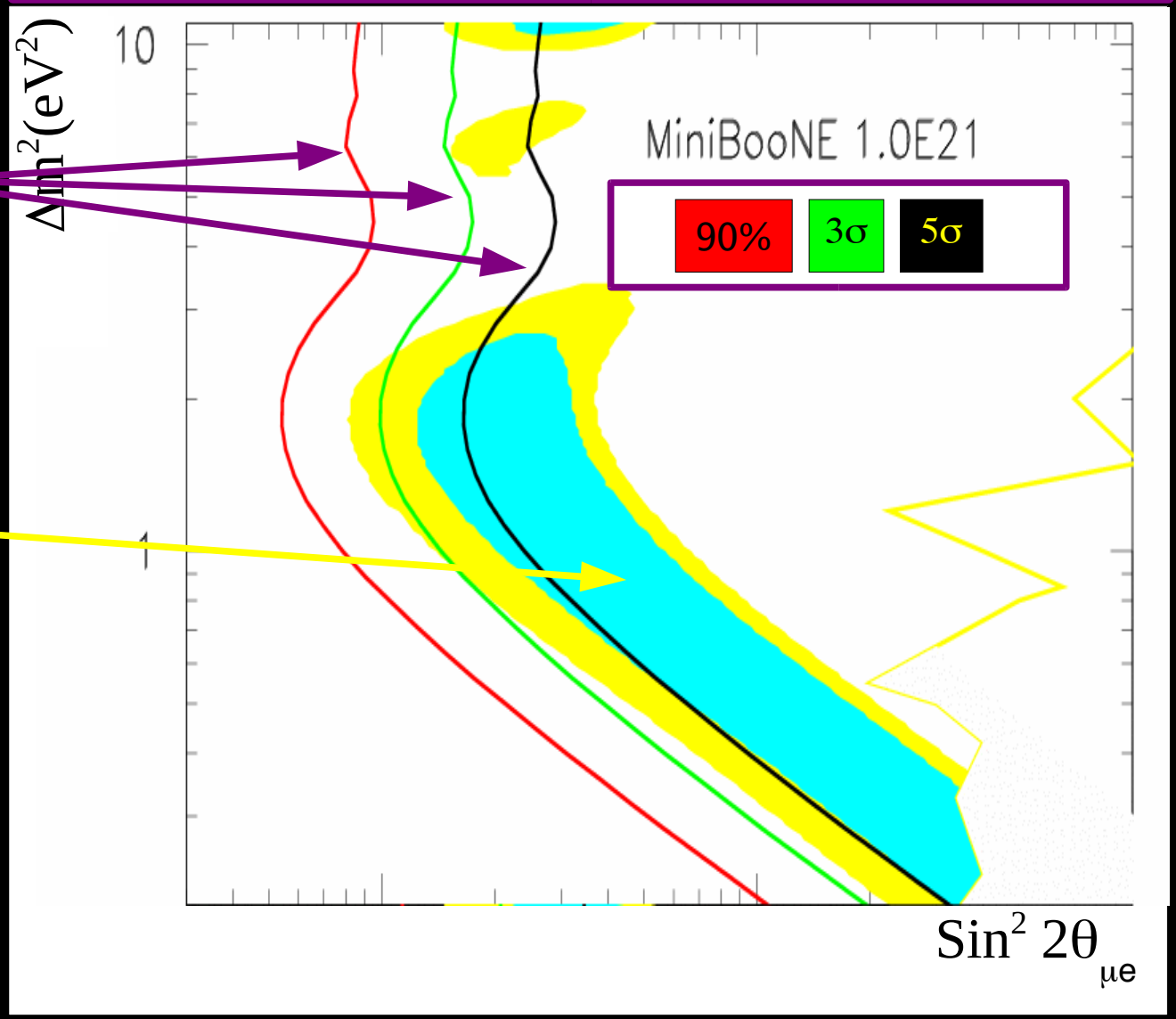
MiniBooNE sensitivity curves

LSND allowed region

Statistics Limited until 2×10^{21} POT

Can we improve our statistics?

Sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations



www-boone.fnal.gov/publicpages/news.html

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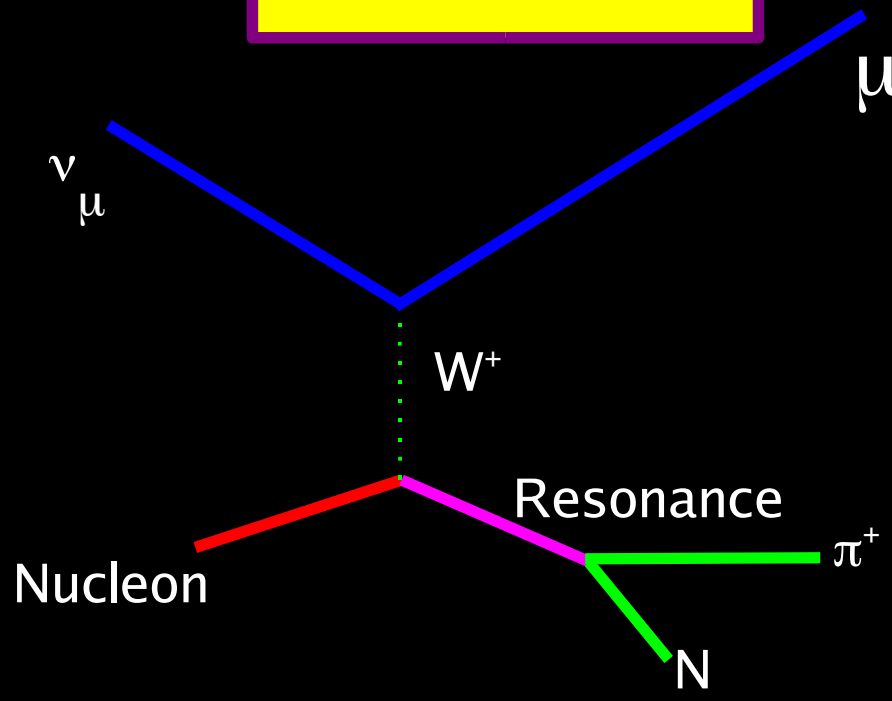
CCπ^+ Events

- ν_μ:
  - Goal: reconstruct E_ν

Recall: 25% of MiniBooNE events are CCπ^+



- μ^-:
  - Reconstruct Cherenkov ring to get energy, momentum vector
  - Michel electron
- Resonance:
  - Decays promptly
    - Nucleon
      - Scint. only
    - Pion
      - Cherenkov ring
      - Michel electron

Eventual goal of this analysis is a search for oscillations using single pion events

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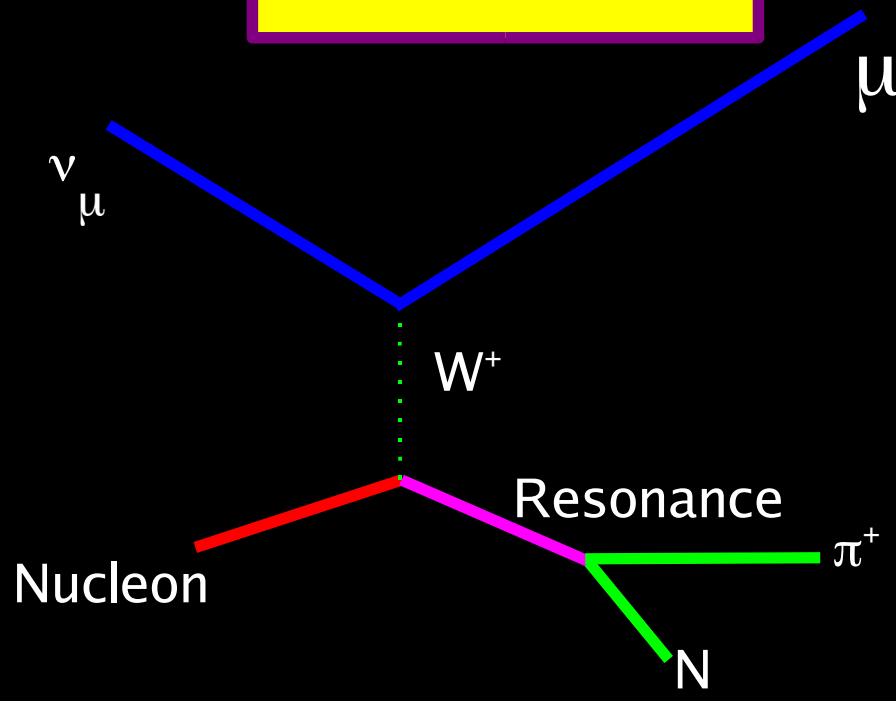
CCπ± Events

- ν_μ:
  - Goal: reconstruct E_ν

Recall: 25% of MiniBooNE events are CCπ^+



- μ^-:
  - Reconstruct Cherenkov ring to get energy, momentum vector
  - Michel electron

- Resonance:
  - Decays promptly
    - Nucleon
      - Scint. only
    - Pion
      - Cherenkov ring
      - Michel electron

Multiple ring events:
Complex event topologies
Hard to reconstruct!

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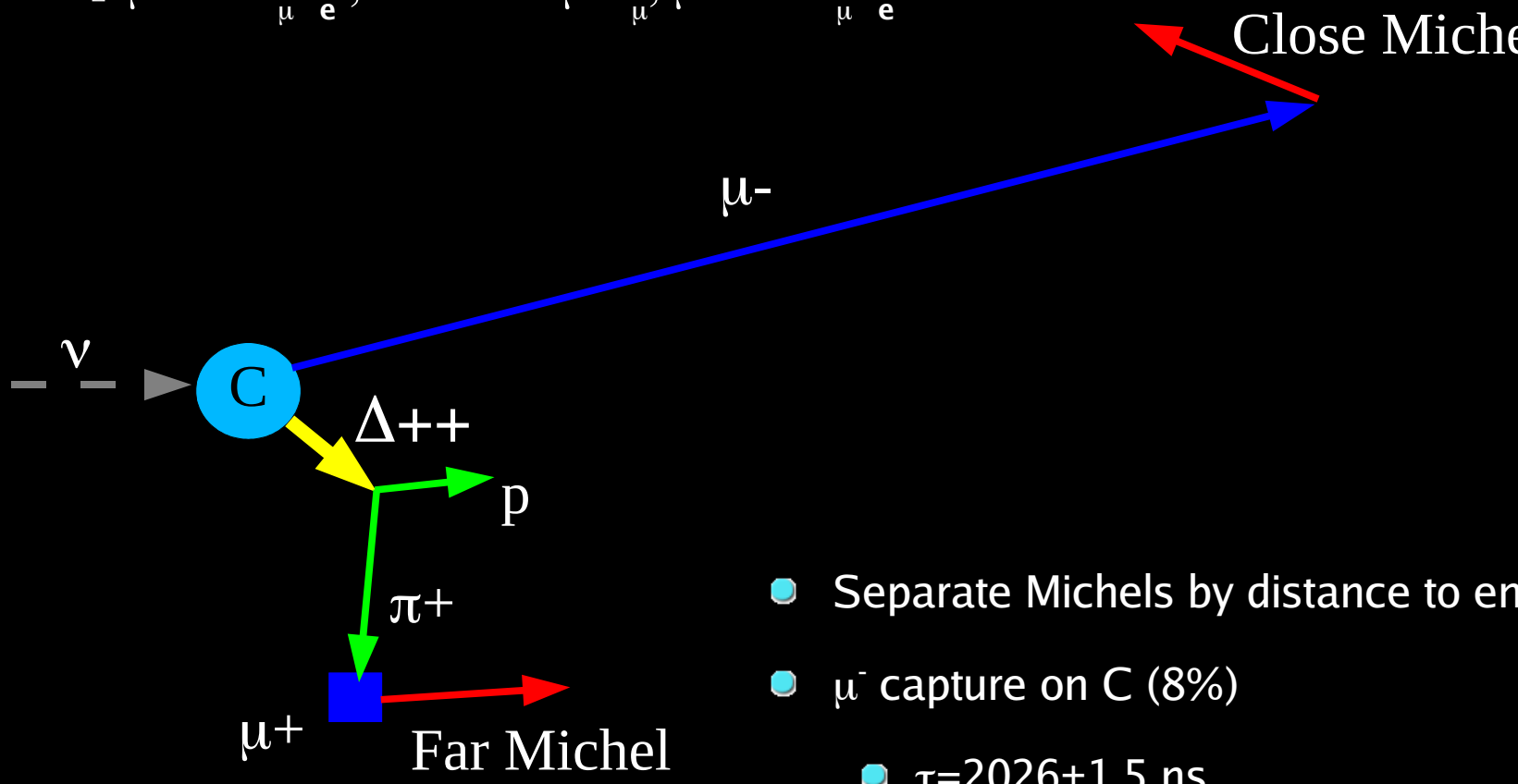
Using the Michel Electrons

- Neutrino events with 2 Michels:
  - $\nu_\mu C \rightarrow \mu^- \pi^+ p X$
    - $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$, and $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$



- Separate Michels by distance to end of μ^- track
- μ^- capture on C (8%)
  - τ=2026±1.5 ns
- μ^+ do not capture
  - τ=2197.03±0.04 ns

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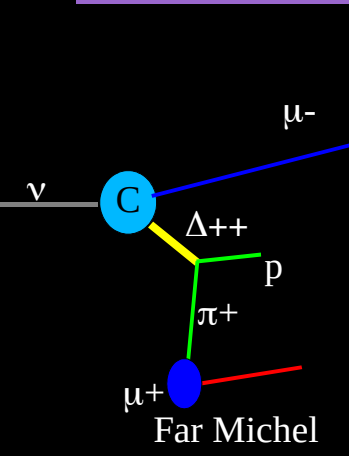
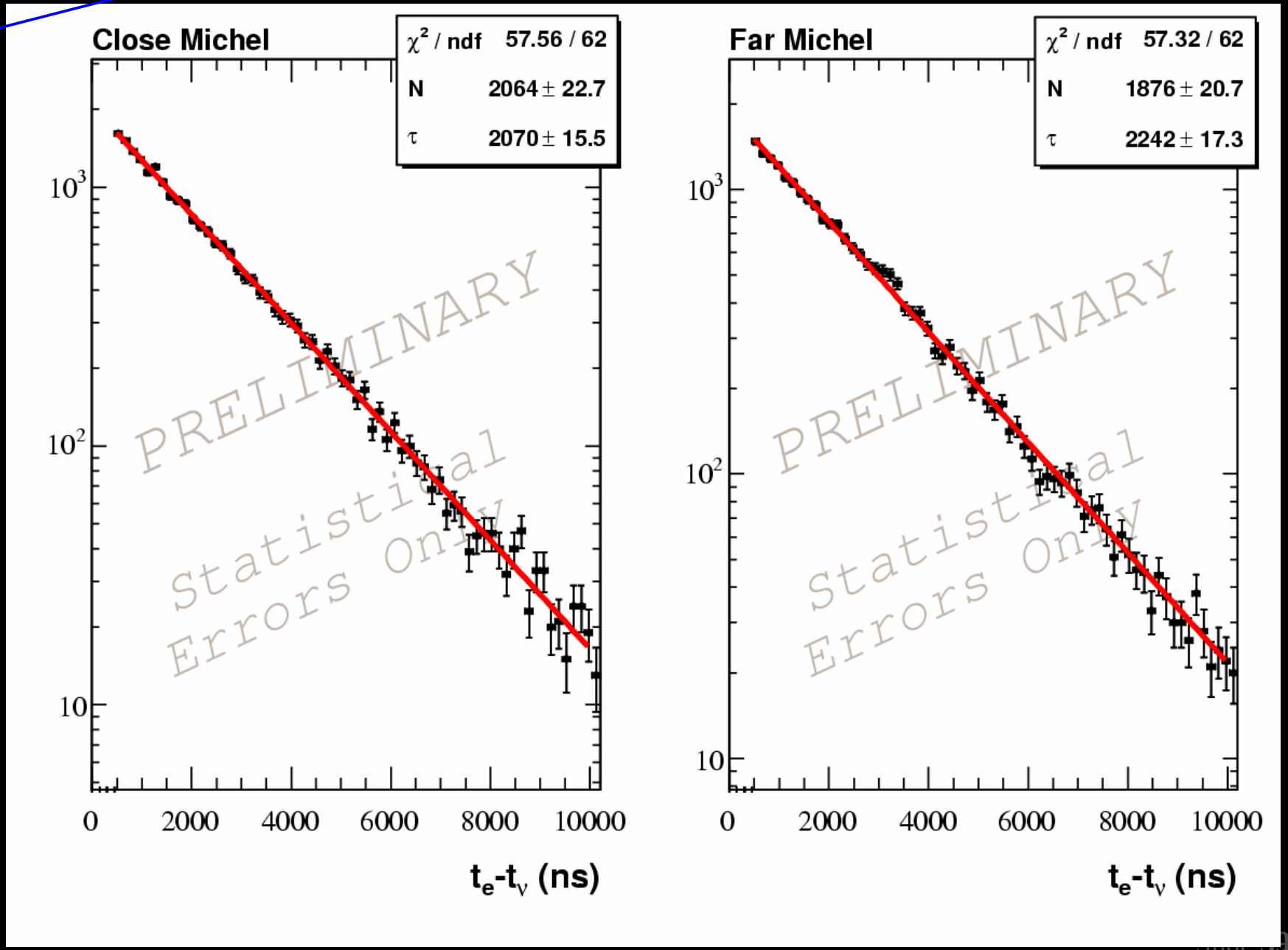
CCπ⁺: Muon Lifetimes





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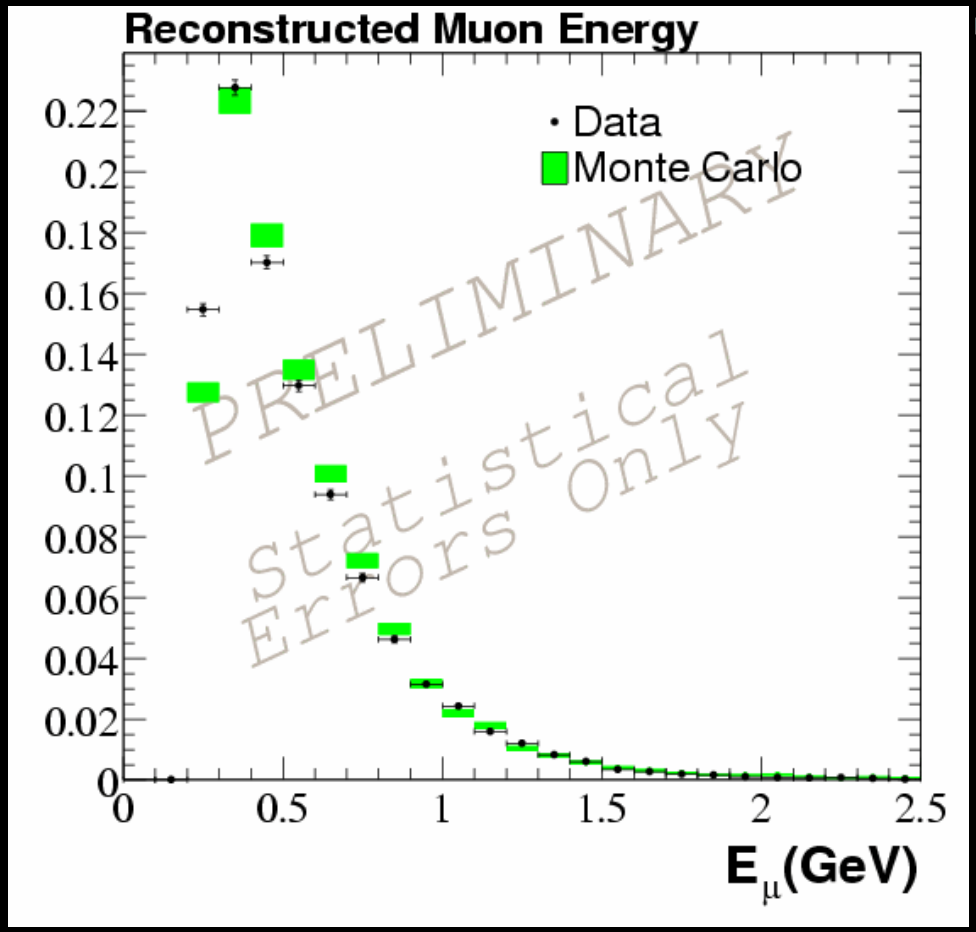
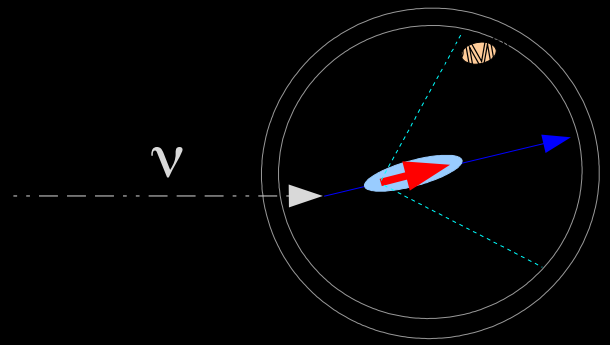
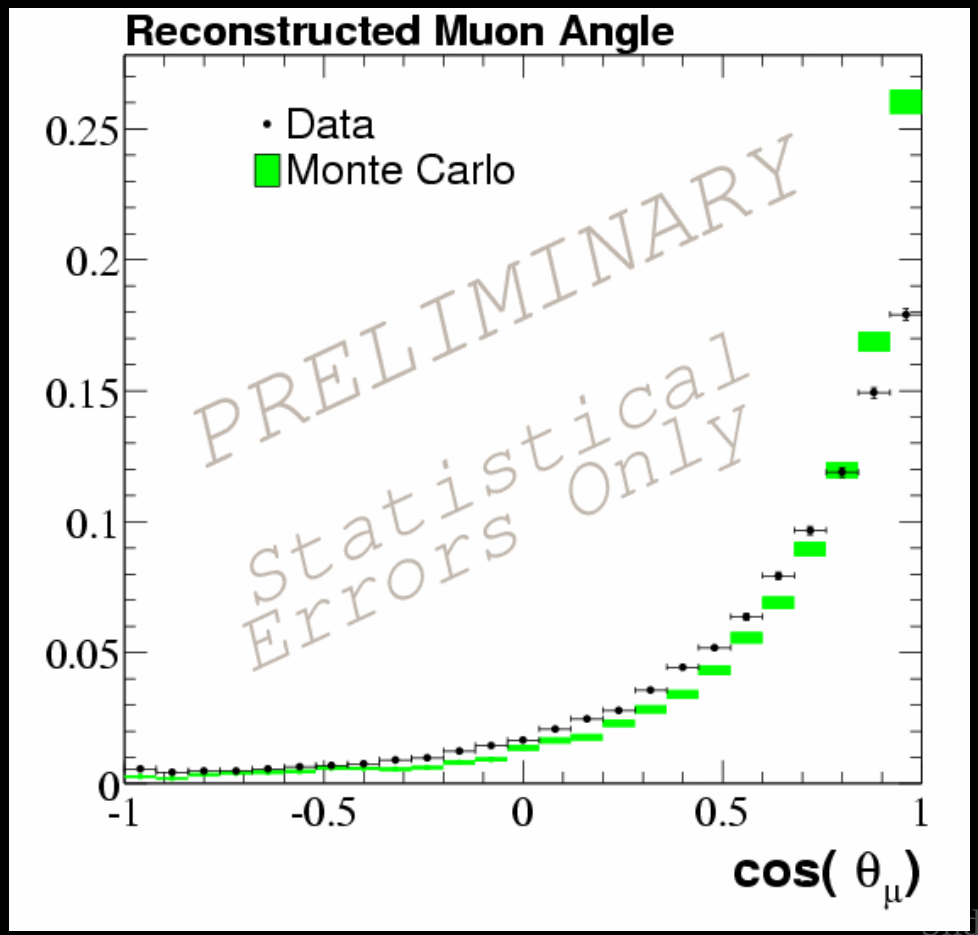
Detector Observables



- Energy in Cherenkov ring only





- statistical errors only on data and MC!
- Reasonable agreement in muon energy
- Discrepancy in angle, as in CCQE

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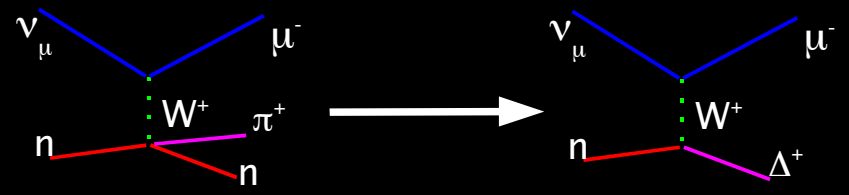
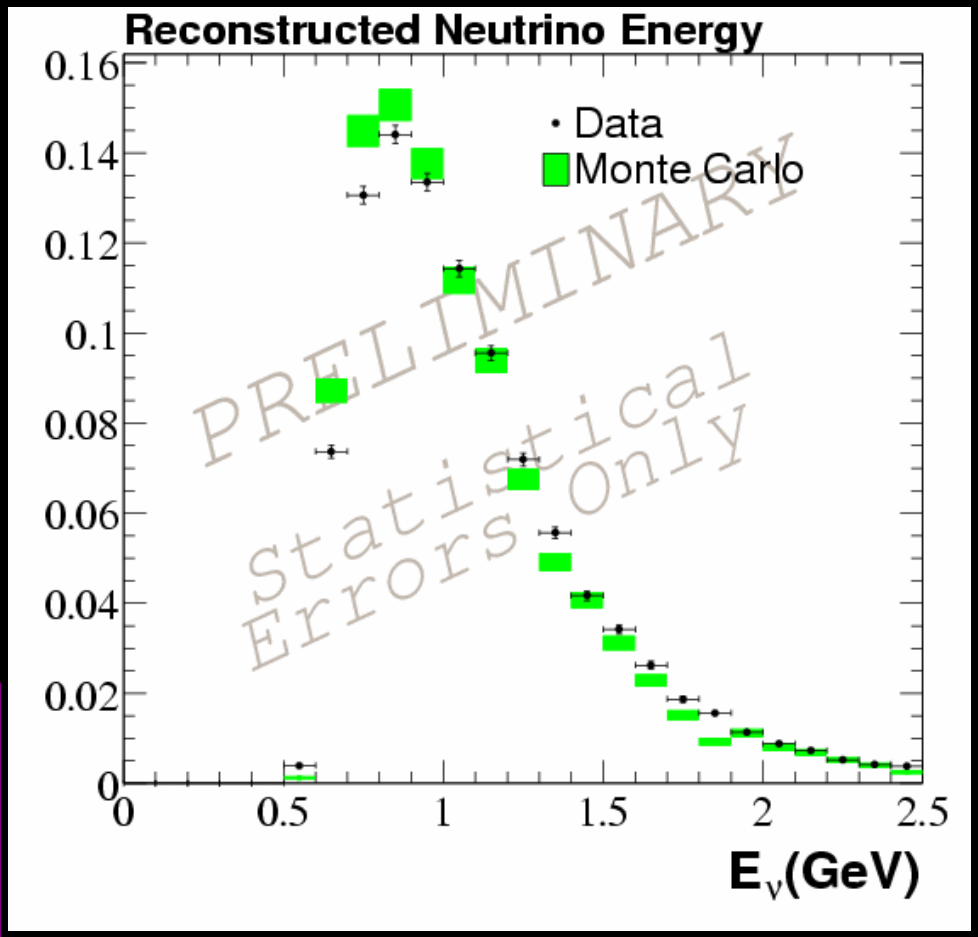
Reconstructing ν Energy

- Starting out with simplest possible assumptions
- Reconstruct CCπ^+ interaction as quasi-elastic, with a resonant state instead of a recoil nucleon
  - Assume target nucleon is at rest
  - Assume resonance is Δ(1232 MeV)
  - Assume the single ring fitter picks out the muon
    - MC: this is true ~75%





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

- Working toward oscillation search

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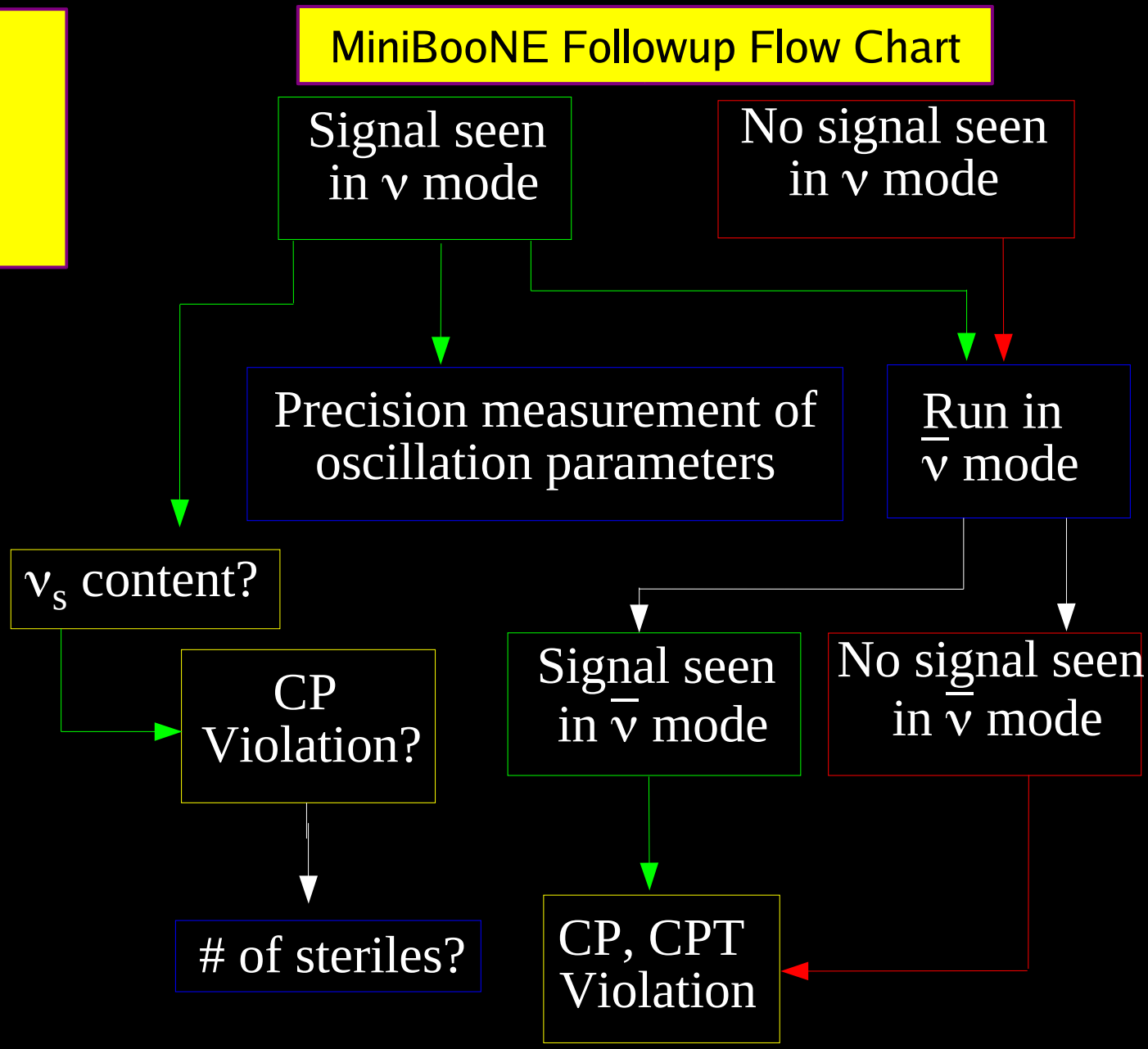
Next steps for MiniBooNE

First MiniBooNE oscillation results in 2005

Approved for running in 2006

NEW physics beyond Standard Model!



www.aps.org/neutrino/index.html

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Conclusions

- Open Questions:
  - Are there sterile neutrinos?
  - How many generations?
  - What is the absolute mass scale for neutrinos?
  - Why are neutrino mixing angles so different from quark sector?
- Parting Thoughts
  - Historically, neutrinos have been surprising
  - It's a field where experiments have led theories
  - This is an exciting time to be working with neutrinos

Stay tuned ...
(most likely for something unexpected!)

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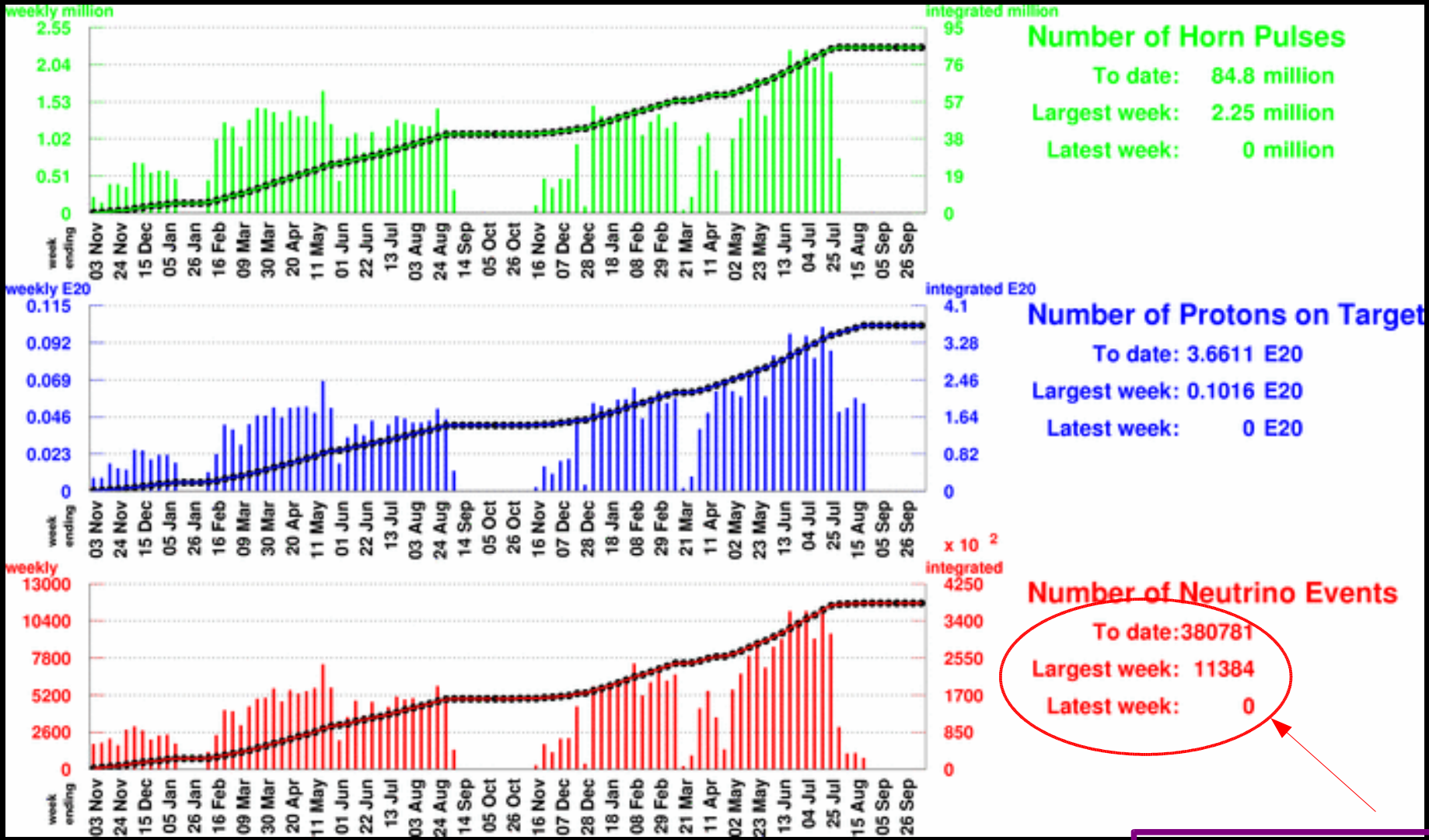
Proton Delivery



http://www-boone.fnal.gov/publicpages/progress_monitor.html

Already the largest data set at these energies - ever!

Future of CCπ^{+} Analysis

- Develop multi-ring fitters
  - Use different Cherenkov profiles for muons, pion
  - Hough transform?
- Use Michel positions to check fitter results
- Assess systematic errrors
- Cross section measurement
- Identify ν_e CCπ^{+} events
- Oscialltion searches
  - Appearance
  - Disappearance

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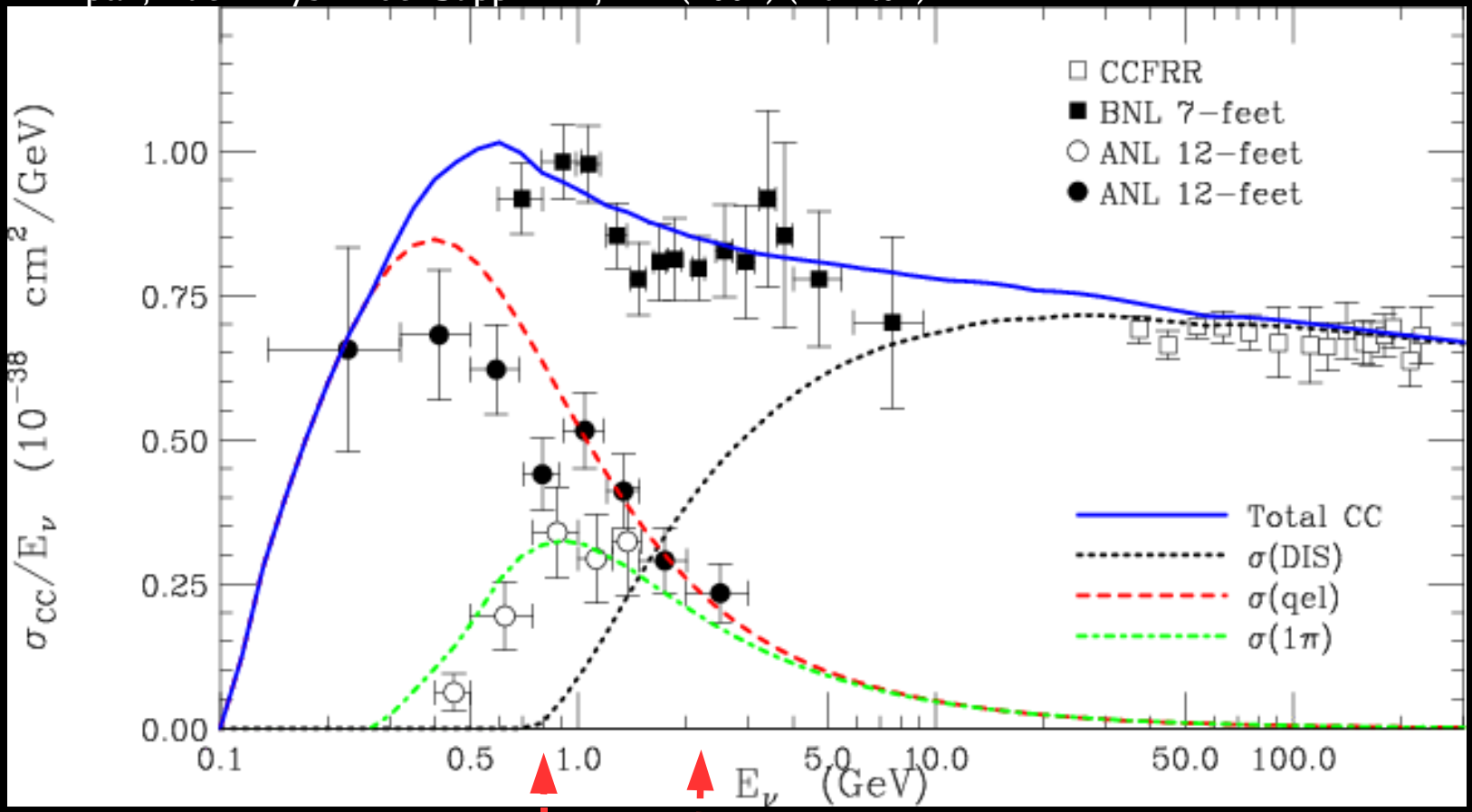
Charged Current Events

P. Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002) (NuInt01)



MiniBooNE

K2K

Super-K atmospheric **ν**s

Range of NuMI Possibilities

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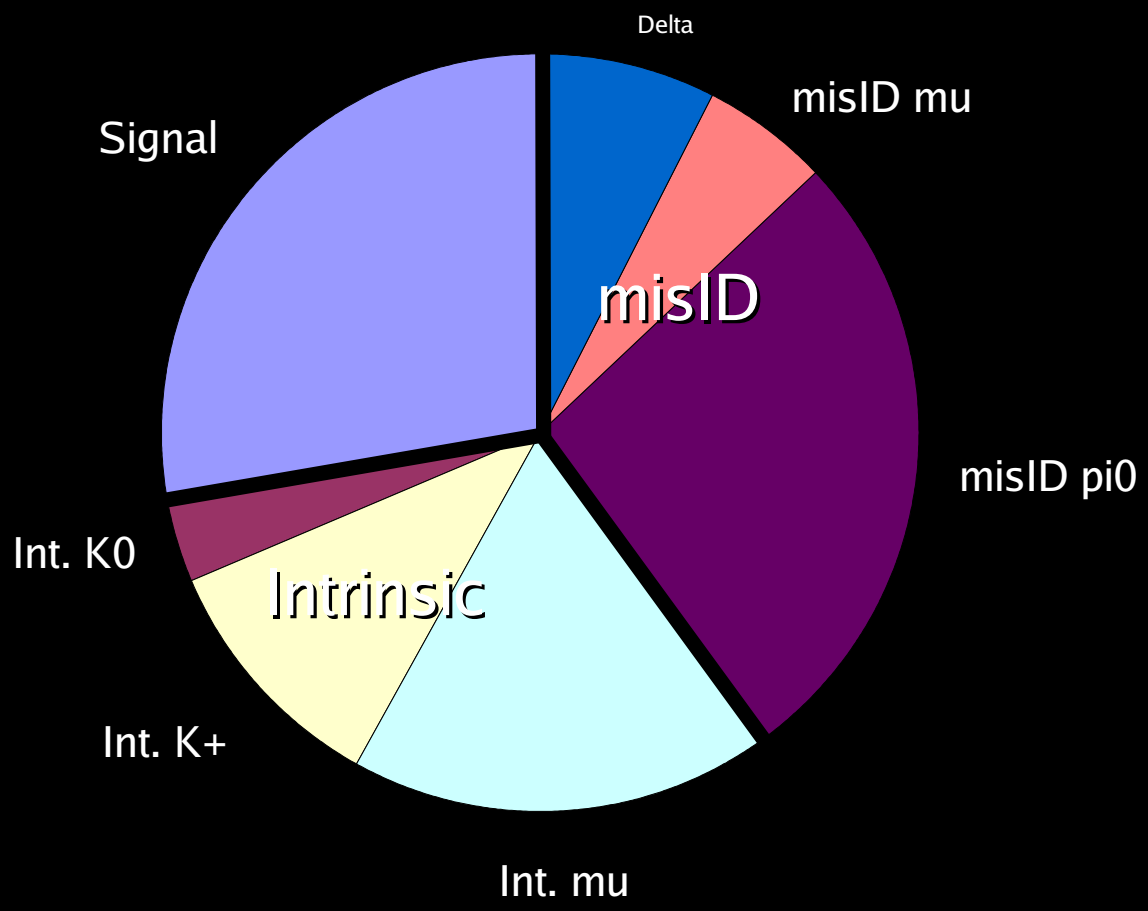
ν_e Event Rates

- ν_e Appearance Analysis, 1E21 pot
- Expect to see ~1000 ν_e CC QE
  - 300 oscillation signal events
  - 350 Intrinsic ν_e in beam
    - K^+, K^0, **m** decay
  - 430 misID events
    - μ, π^0,Δ



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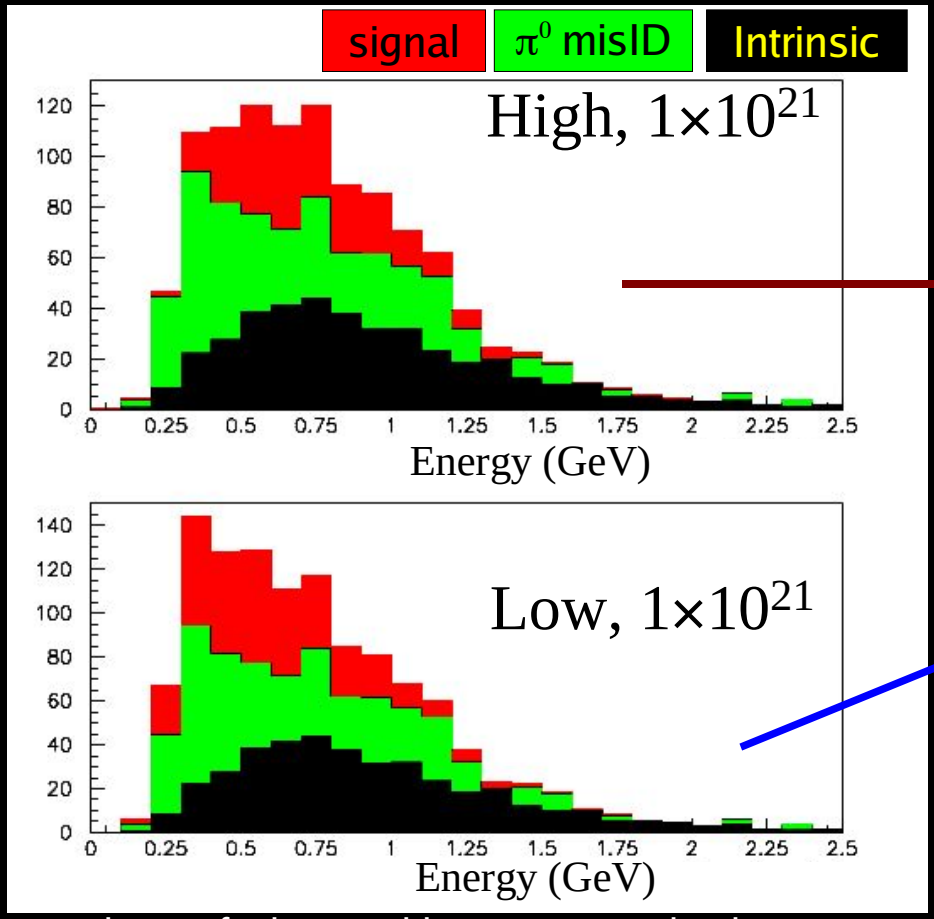
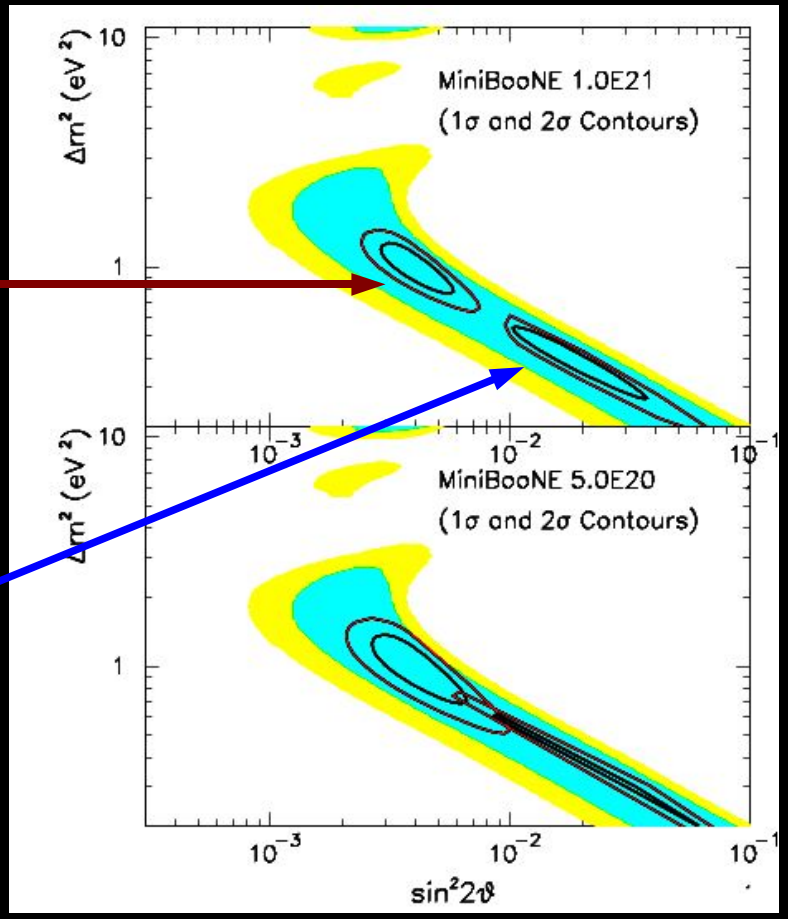
Measuring Δm^2





www-boone.fnal.gov/publicpages/news.html

- Can differentiate high and low Δm^2 regions with 1E21 POT
- High vs. low Δm^2 is important for near future experiments

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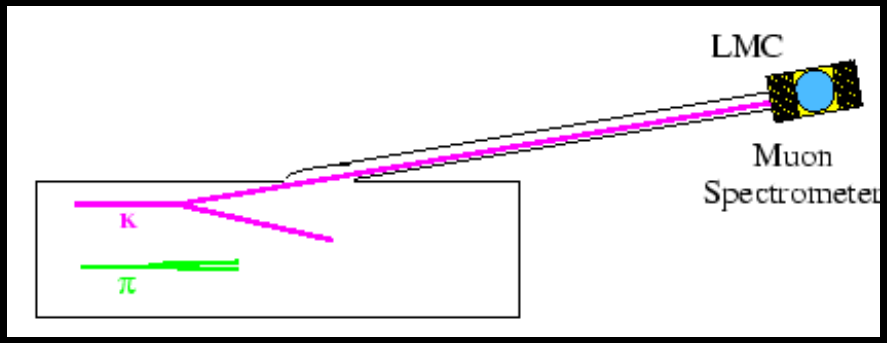
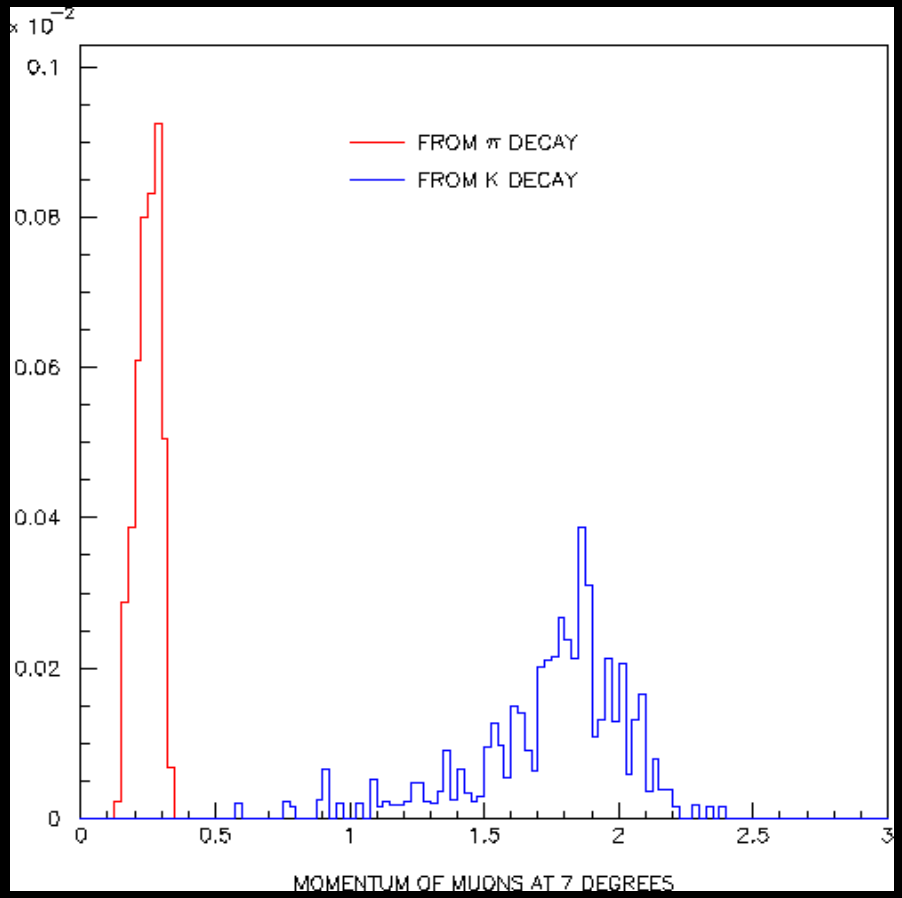
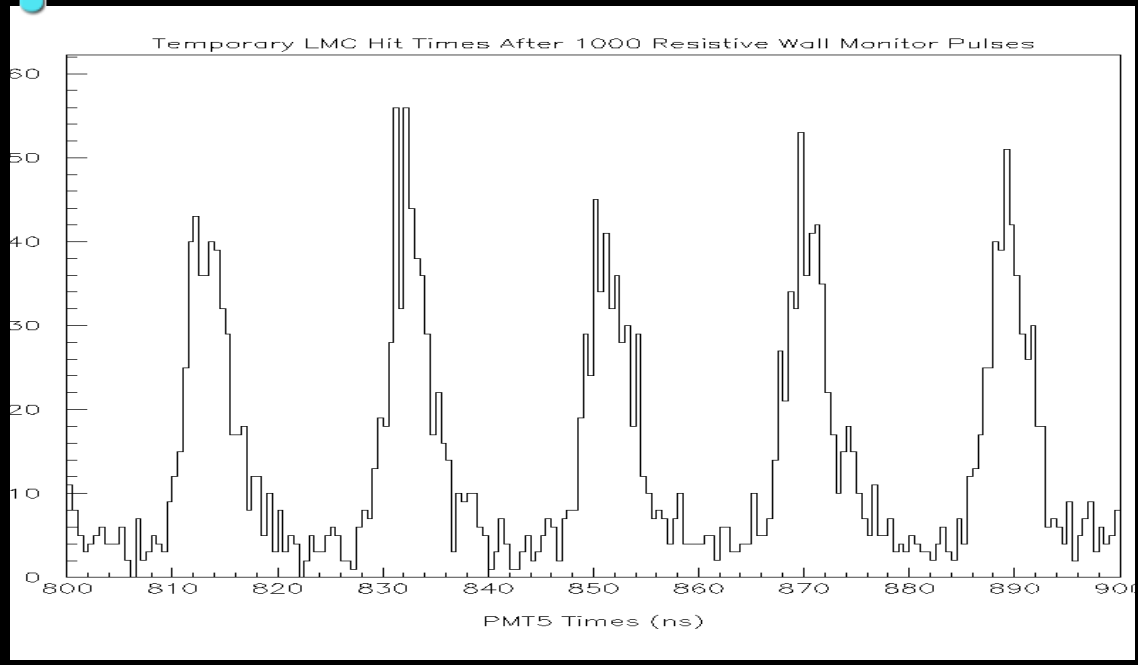
Little Muon Counter





- Pions and kaons both decay to muons (99.9%, 63.4%)
- Different rest masses give pion and kaon decays different energy spectra
- LMC should accept only muons from kaon decay, not pion decay



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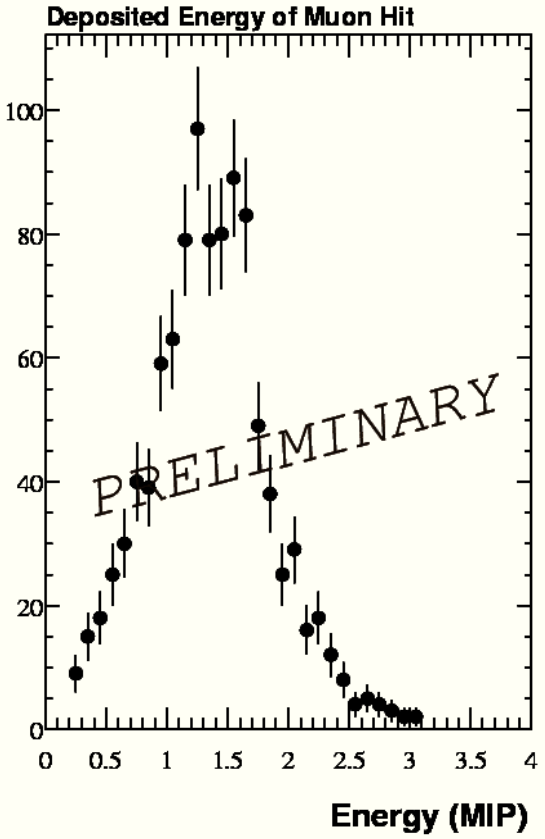
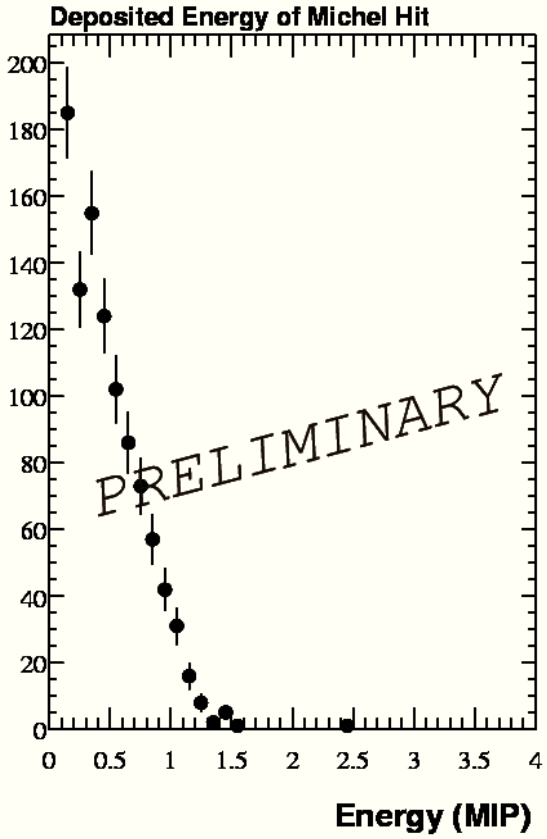
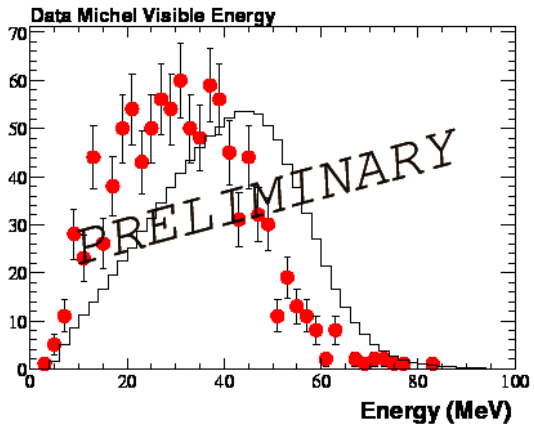
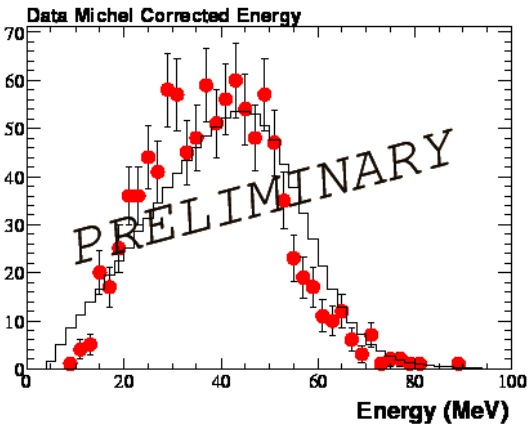
Muon Calibration Checks









- Through-going muons calibrate correction for energy lost in cube
- Amount of charge seen by cube PMT converted to energy deposited (MIPs)
- Use Michels to verify that the energy correction works
- Applying correction to Michels from cubes gives a much better match to Michels in oil

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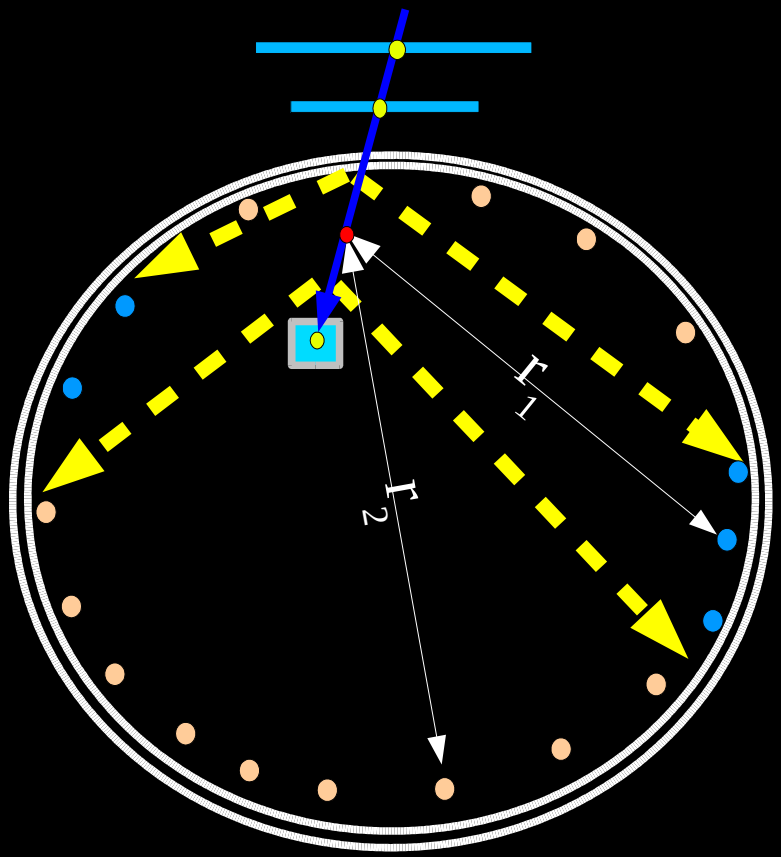
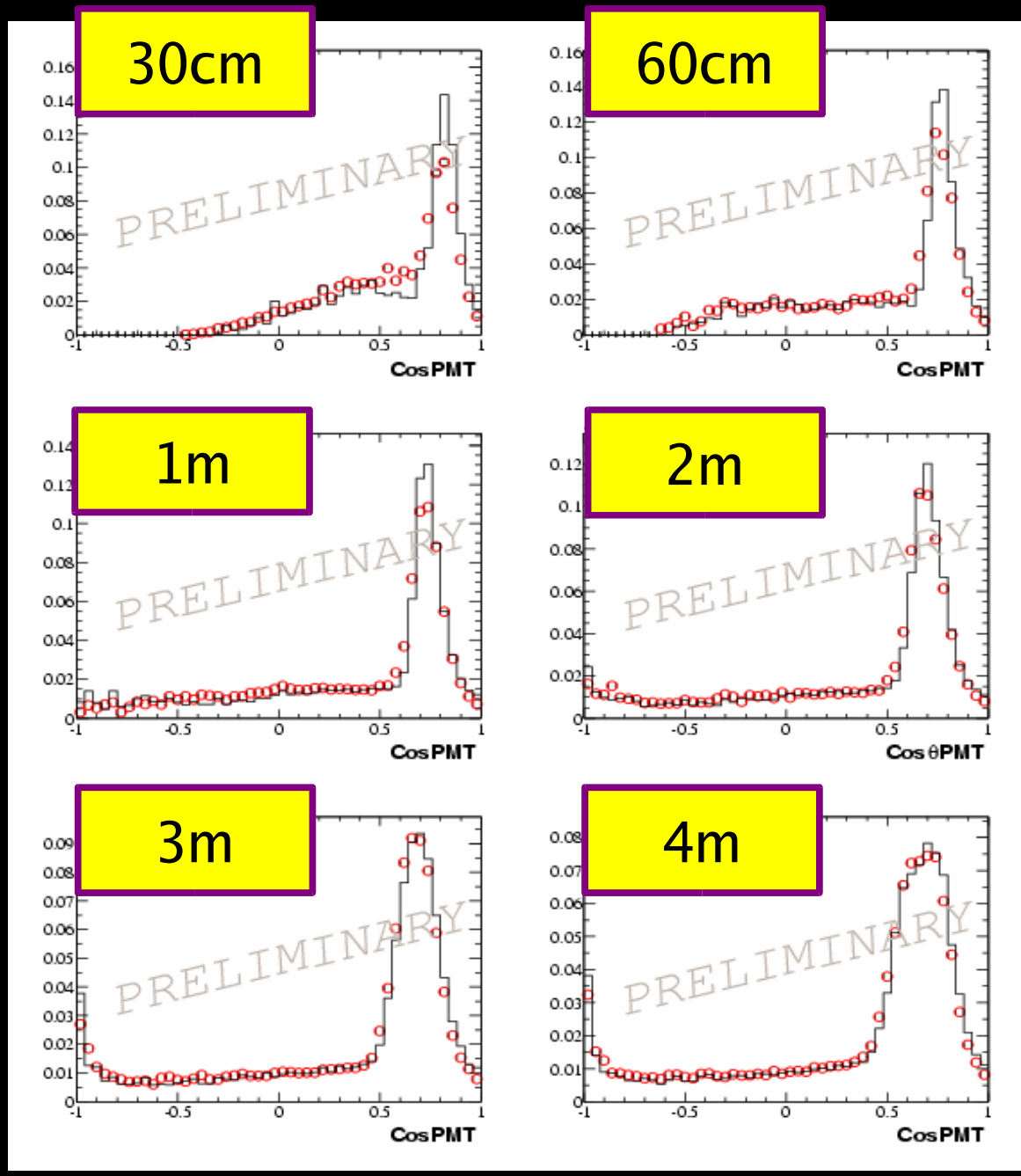
Muons in the Oil

- Use calibration hardware to determine the event paramters (x, t, u)
- Assemble corrected times, angles using known track center
- Find Cherenkov rings and time peaks, isotropic and delayed emission





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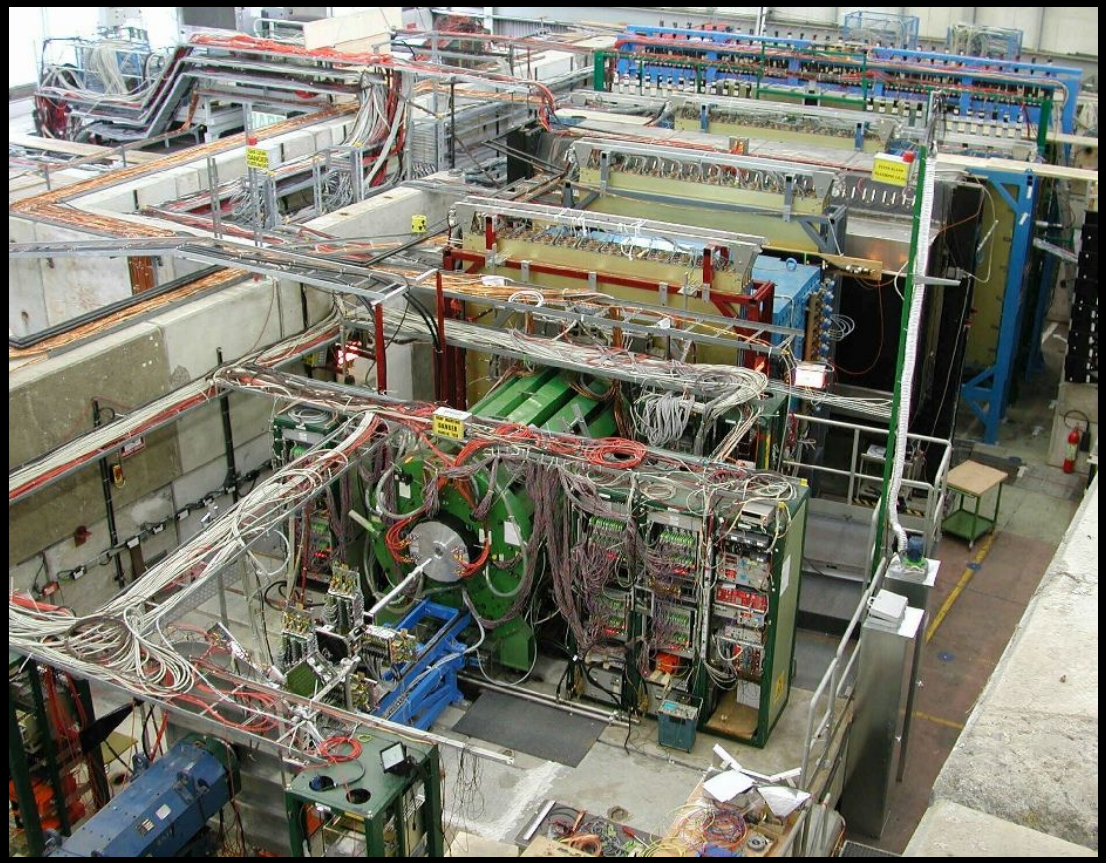
HARP

- Experiment at CERN designed to measure pion and kaon momentum spectra from proton Beryllium interactions
- Used MiniBooNE replica target slugs (5%λ, 100%λ)
- Protons at 8.9 GeV/c
  - Exactly like the Booster
- Pion flux distributions within six months, kaon within a year



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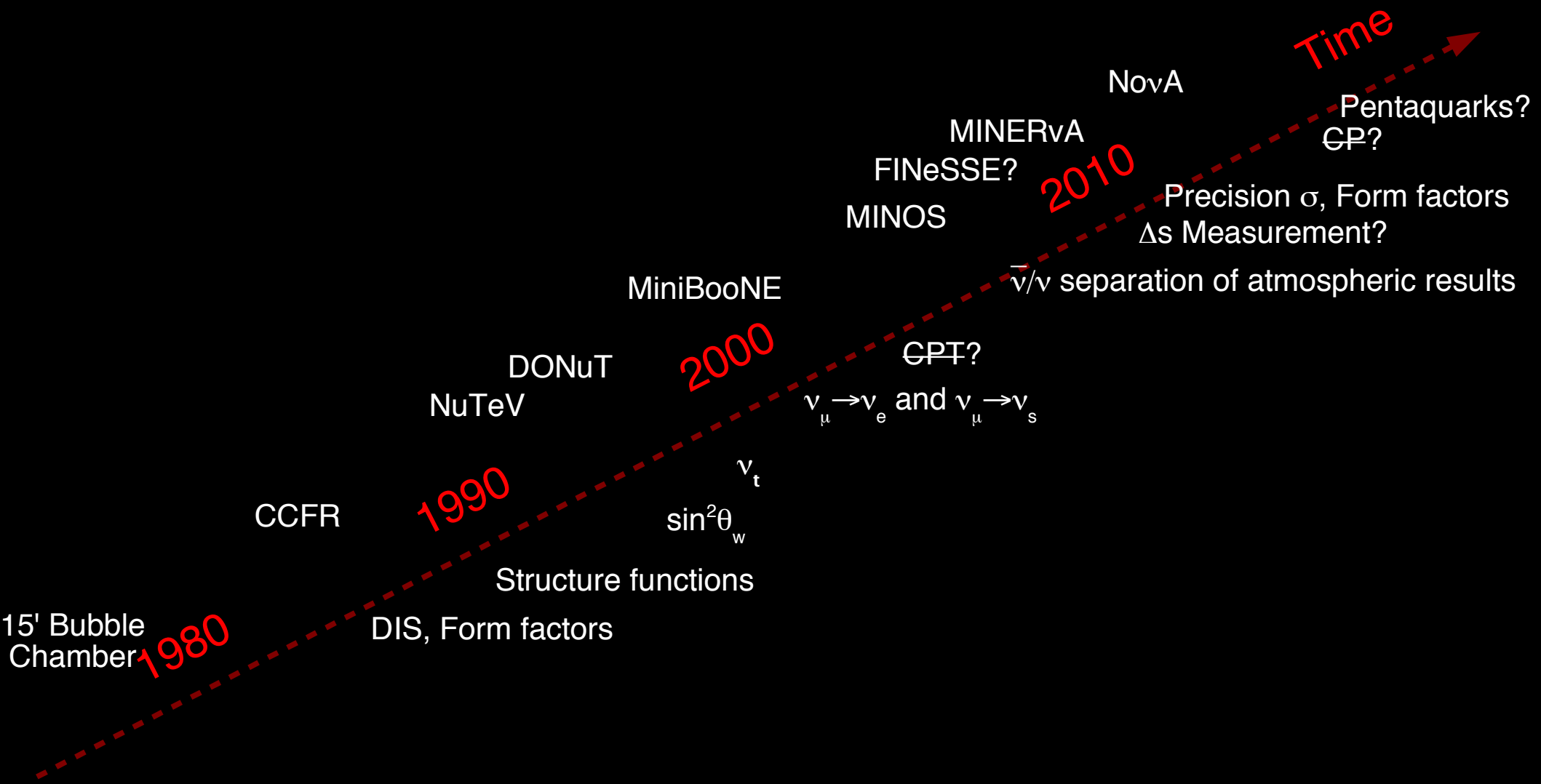
Parting Thought

MiniBooNE is one in a long line of great **n** physics experiments at FNAL



We're working hard to ensure that the future matches our great past