MiniBooNE:

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Aspen Conference on Particle Physics February 2005

Mixing in Leptons and Quarks

$$|d_\alpha\rangle = \sum_i V^*_{\alpha i}|d_i\rangle$$

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

- Mass eigenstates ≠ Flavor eigenstates
- Allows flavor-changing interactions
- No theoretical guidance

Lepton Sector:

Neutrino oscillations

Quark Sector:

Flavor-changing decays
Mixing/oscillations
CP violation

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(\mathrm{U})\sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\sum_{i>j}\Im(\mathrm{U})\sin[2.54\Delta m^2_{ij}(L/E)]$$

sum over mass eigenstates

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Mixing in Leptons and Quarks

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Lepton Sector:

Neutrino oscillations

Neutrino of type α, energy E
Traverses distance L
Interacts as neutrino of type β

Observe as: deficit of ν_α
appearance of ν_β

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(\mathrm{U})\sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\sum_{i>j}\Im(\mathrm{U})\sin[2.54\Delta m^2_{ij}(L/E)]$$

Mixing in Leptons and Quarks

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$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

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- Allows flavor-changing interactions
- No theoretical guidance

Lepton Sector:

Neutrino oscillations

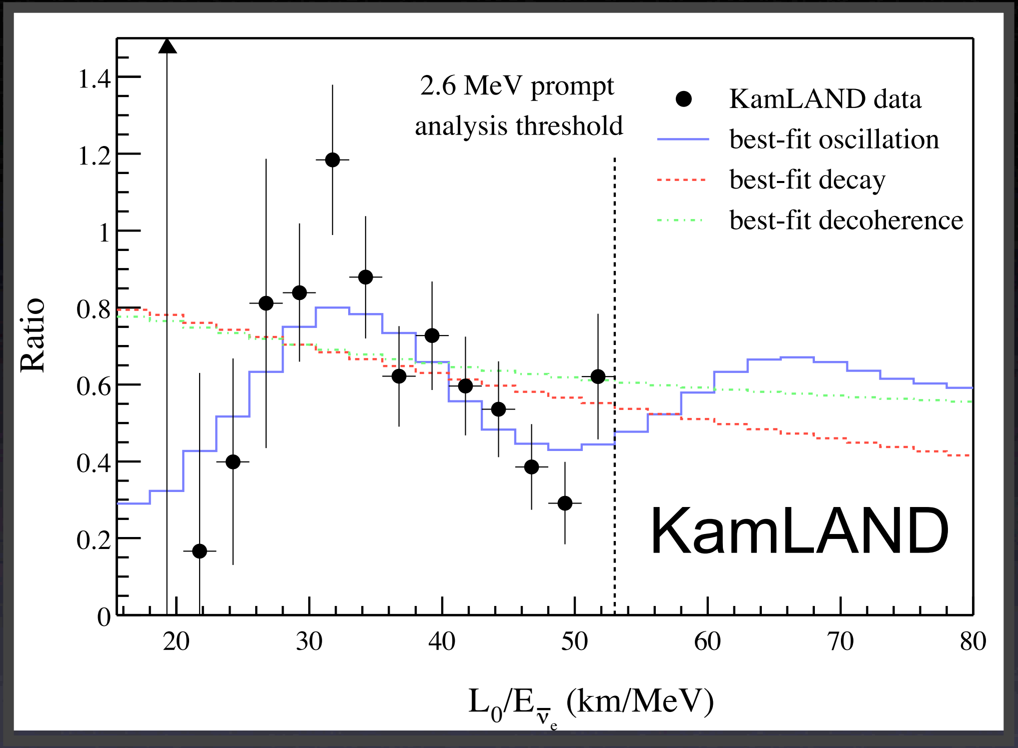
$$\sin^2 2\theta_{12} \sin^2[1.27\Delta m^2_{12}(L/E)]$$

Two flavor oscillations

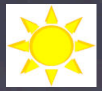
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(\mathrm{U}) \sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\sum_{i>j} \Im(\mathrm{U}) \sin[2.54\Delta m^2_{ij}(L/E)]$$

CP violation

Solar Neutrino Oscillations



$$\nu_e \longrightarrow \nu_x$$



$\Delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2$, $\sin^2 2\vartheta \sim 0.3$

Solar neutrinos, confirmed by reactor antineutrinos

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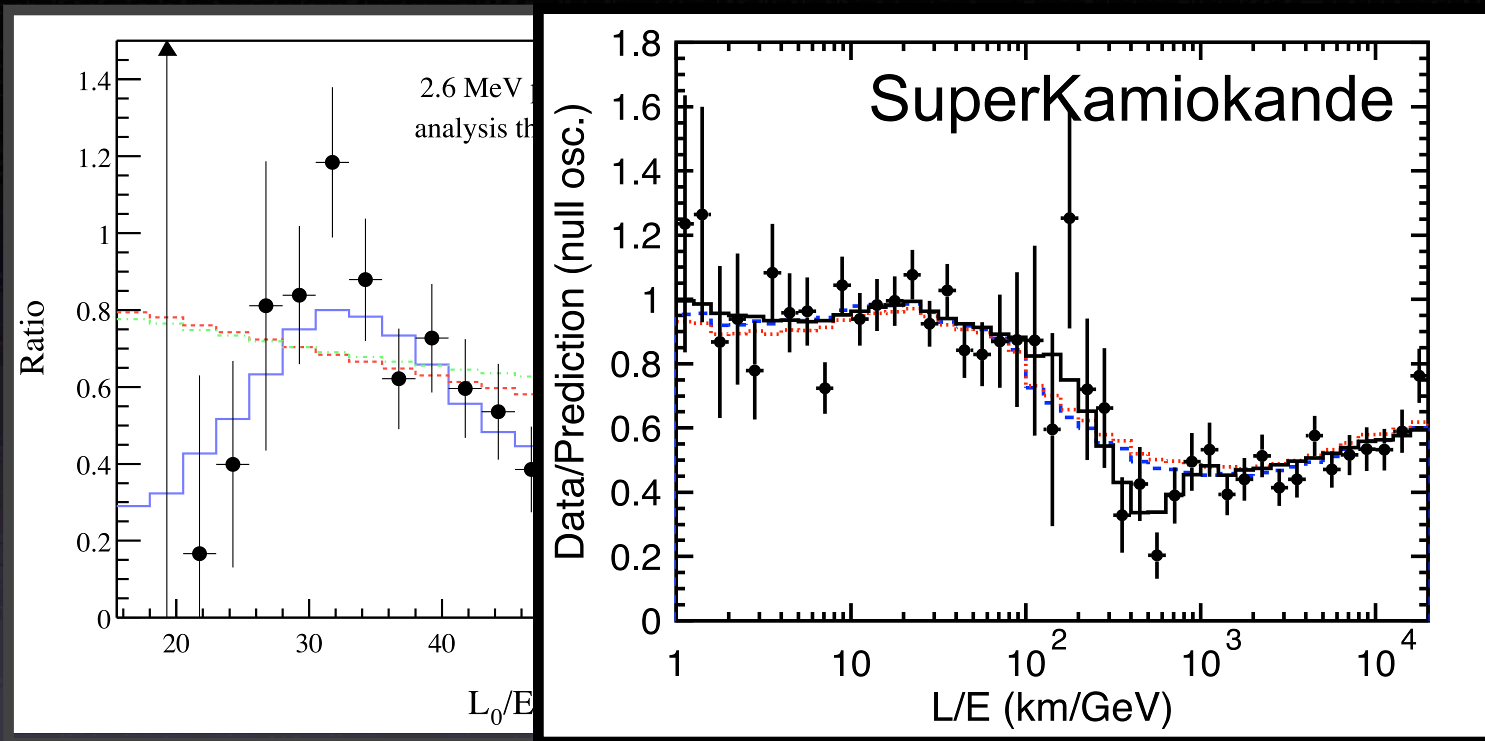
Atmospheric Neutrino Oscillations



$\nu_e \longrightarrow \nu_x$ $\nu_\mu \longrightarrow \nu_x$

$\Delta m^2 \sim 8 \times 10^{-5}\ eV^2$, $\sin^2 2\vartheta \sim 0.3$

$\Delta m^2 \sim 2.5 \times 10^{-3}\ eV^2$, $\sin^2 2\vartheta \sim 1.0$

Atmospheric ν, confirmed by accelerator ν

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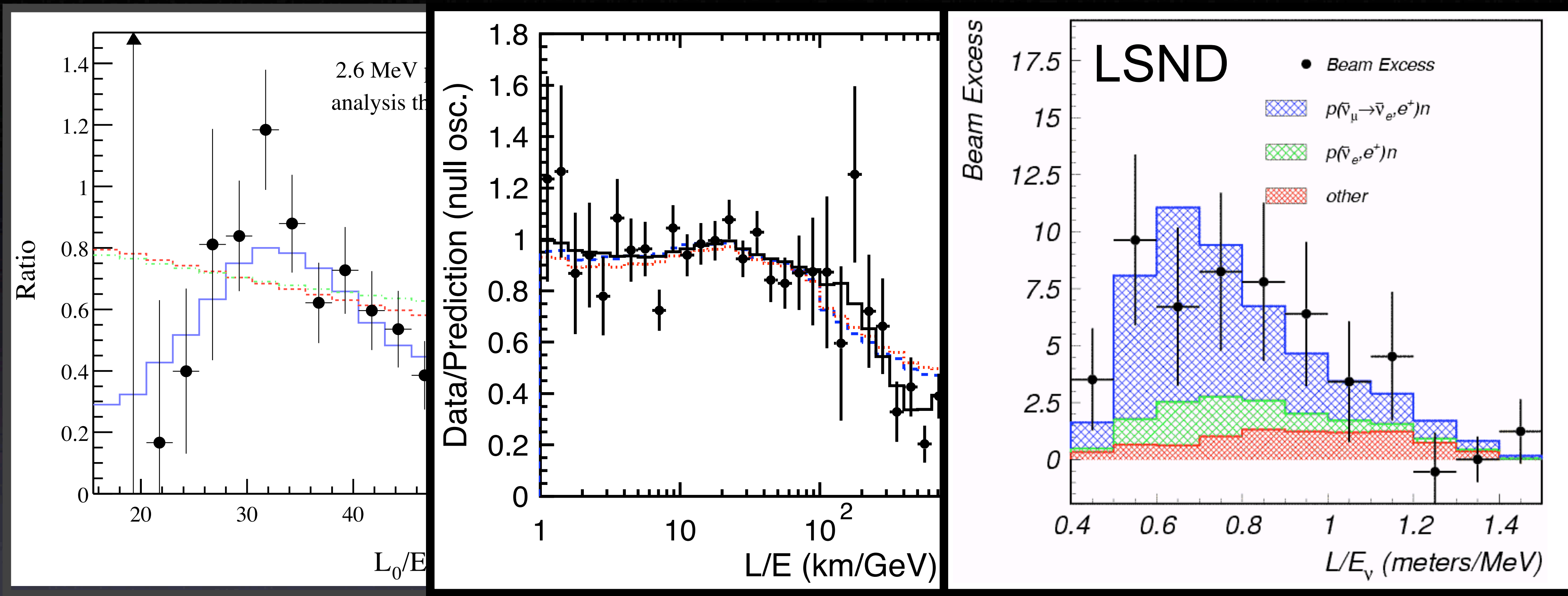
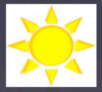
LSND Oscillations:



$\nu_e \longrightarrow \nu_x$ $\qquad$ $\nu_\mu \longrightarrow \nu_x$ $\qquad$ $\bar\nu_\mu \longrightarrow \bar\nu_e$

 $\Delta m^2 \sim 8\text{x}10^{-5}\ \text{eV}^2$, $\quad \sin^2 2\vartheta \sim 0.3$

 $\Delta m^2 \sim 2.5\text{x}10^{-3}\ \text{eV}^2$, $\quad \sin^2 2\vartheta \sim 1.0$

LSND $\Delta m^2 \sim 10^{-1}\text{-}10^{1}\ \text{eV}^2$, $\quad \sin^2 2\vartheta \sim 10^{-4}\text{-}10^{-2}$

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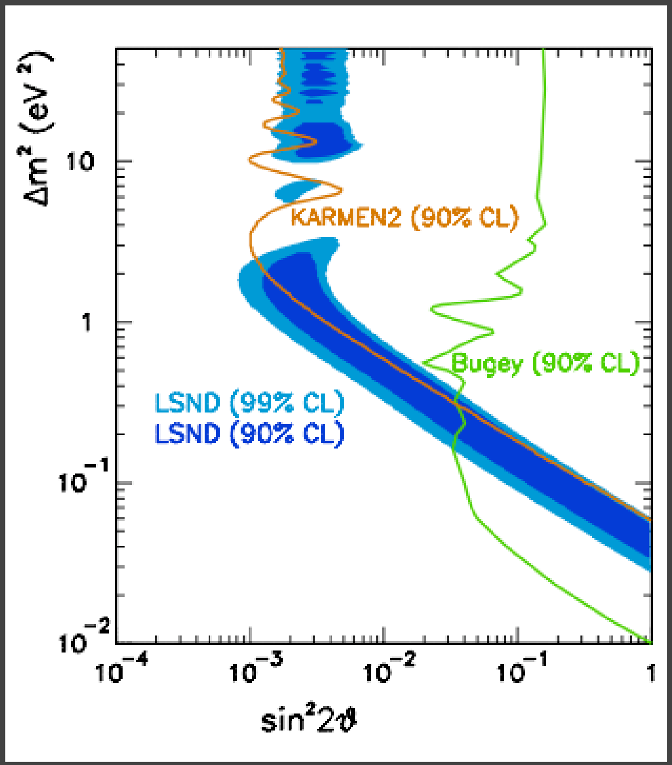
The LSND Result



Search for excess $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam

- Stopped pion beam produces pure $\bar{\nu}_\mu$

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \qquad O(10^{-4})\bar{\nu}_e$$

- Excess of 87.9 ±22.4 ±6.0 events
- Oscillation probability: (0.264±0.067±0.047)%

A challenge to the Standard Model:

$\Delta m^2 \sim 10^{-5}$, 10^{-3}, 10^{-1}eV^2 cannot result from three neutrinos
Cannot be explained by additional light active neutrinos
Fundamentally new physics (additional particles, broken symmetries) needed to explain all three modes.

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MiniBooNE

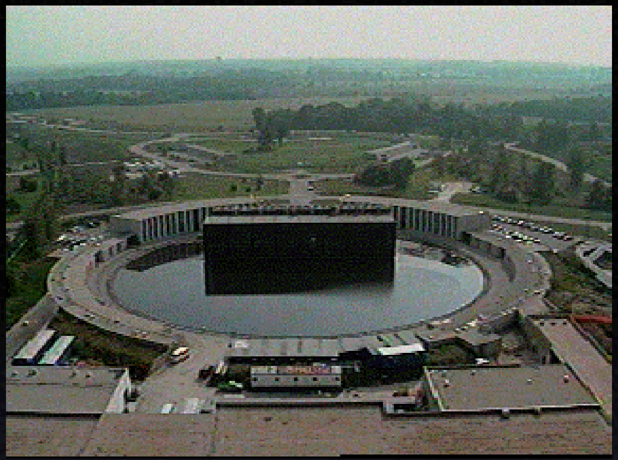
Confirm/refute LSND evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

LSND vs. MiniBooNE

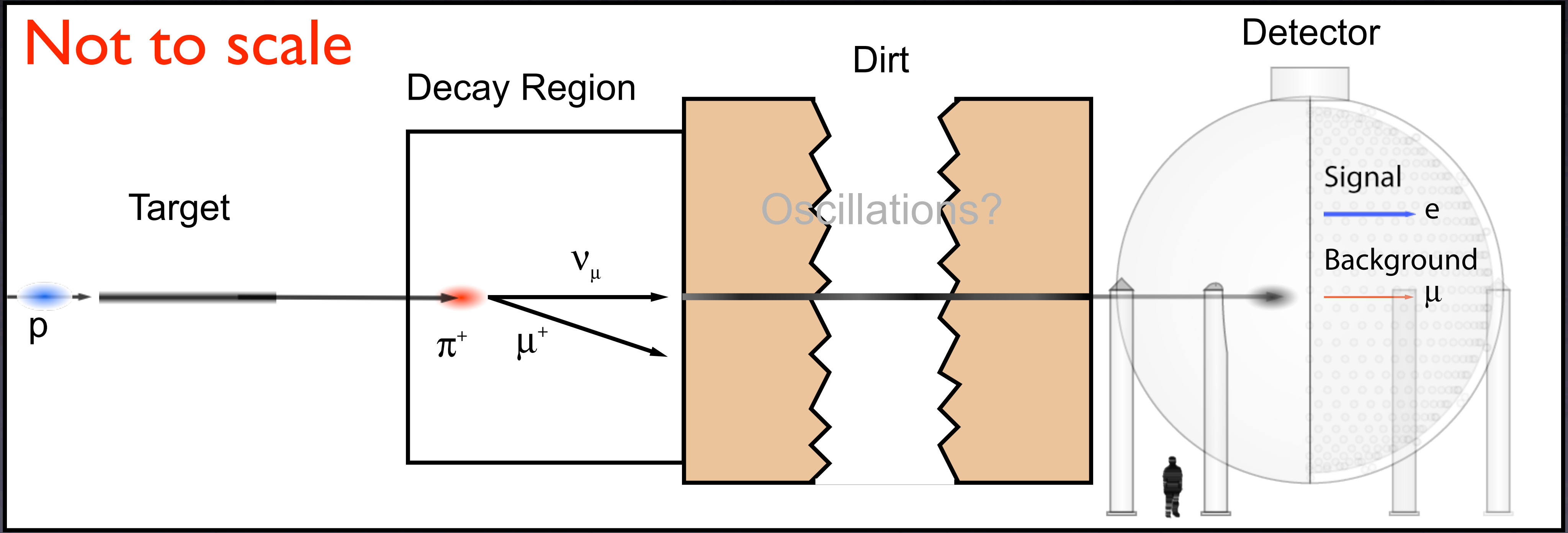
	LSND	MiniBooNE
Neutrino Energy	~40 MeV	~800 MeV
Baseline	30 meters	540 meters
Signal Process	inverse β decay	ν_e CC quasi-elastic
Signal Identification	Double coincidence (e^+, n capture)	Č ring, Sci. profile
Backgrounds	π^- wrong sign decay	ν_e from μ/K NC π^0
S/B Yield	~88/30	~300/800

- Sensitive to same parameters with different method

Overview of MiniBooNE



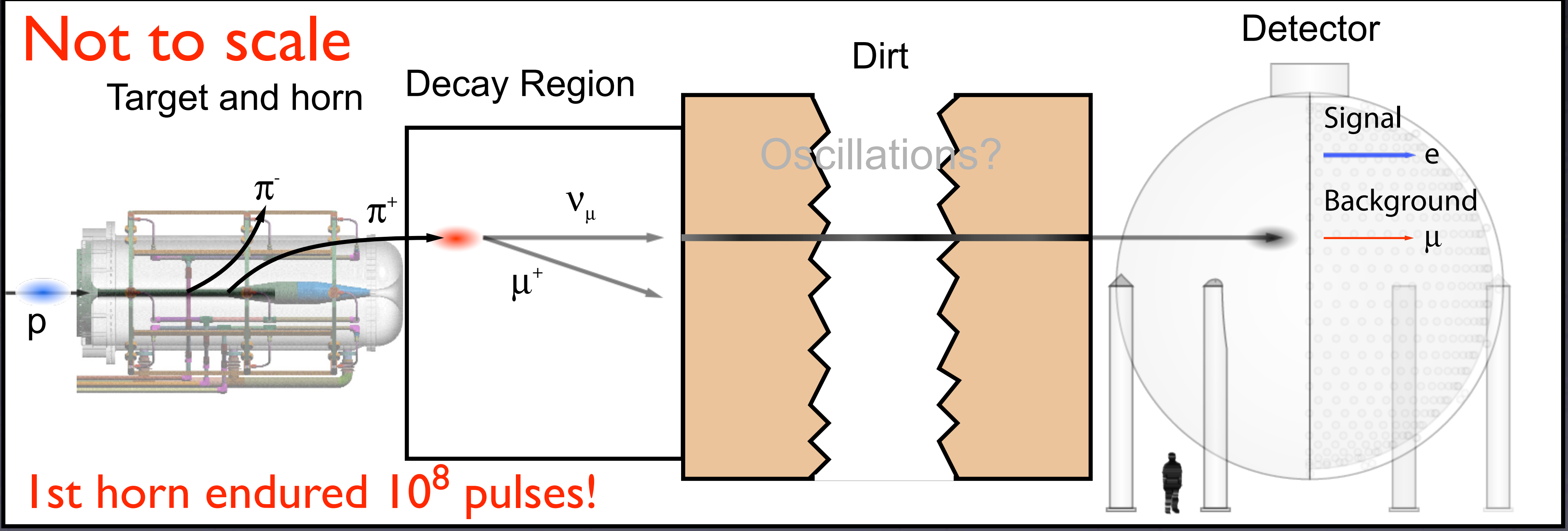
- Produce a pure beam of ν_μ
  - proton interactions on Be produce π^+
  - $\pi^+ \rightarrow \mu^+\nu_\mu$ in decay region
- 8 GeV Protons delivered by FNAL Booster
- Look for ν_e interactions in the detector



Focussing the Beam

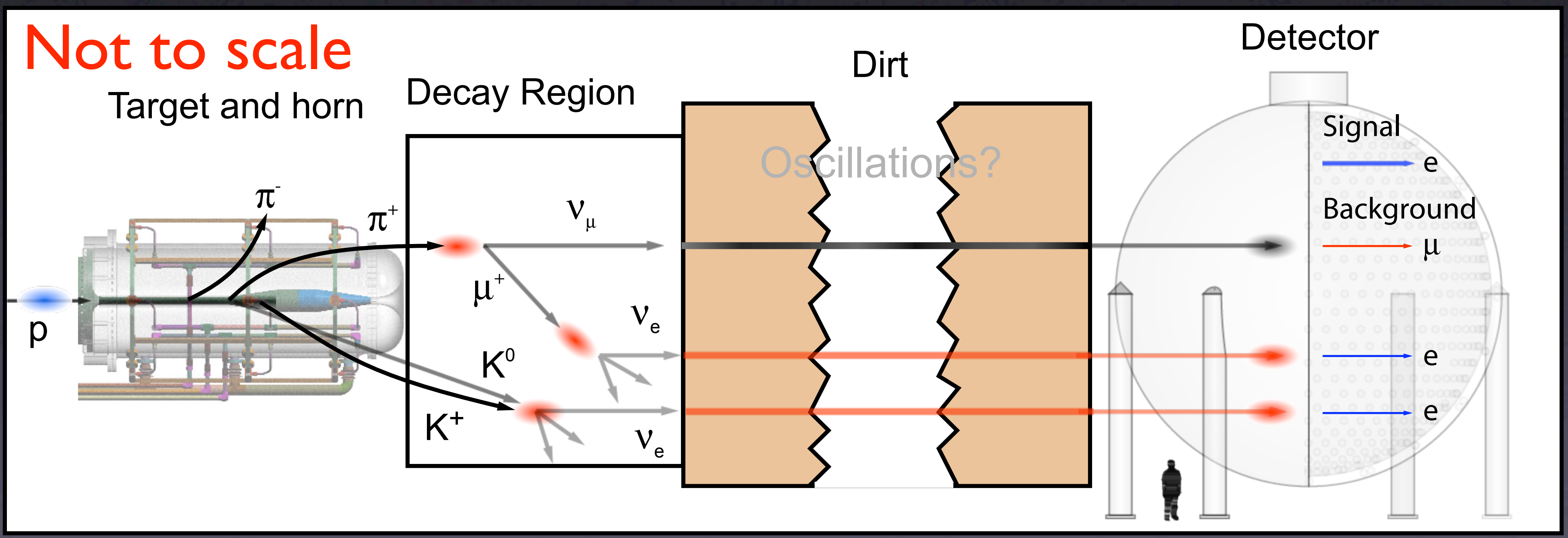
- Electromagnetic focussing horn
  - 170 kA pulse
  - focuses positive secondaries
- x5 enhancement in neutrino flux
  - Polarity can be reversed to focus negative secondaries

New horn installed and working well

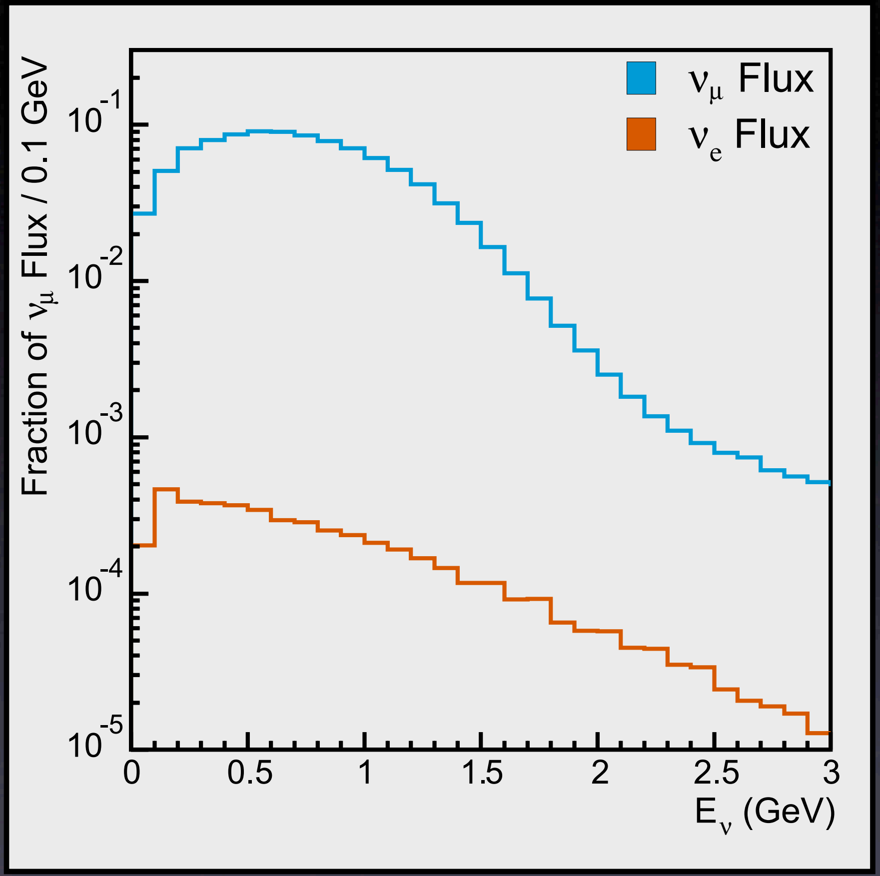


"Intrinsic" Background (II)

- Sources of ν_e not due to neutrino oscillations
  - μ^+ produced from π^+ decay can also decay
  - Kaons are produced in p-Be interactions and decay via K_{e3}
- Source of irreducible ν_e background

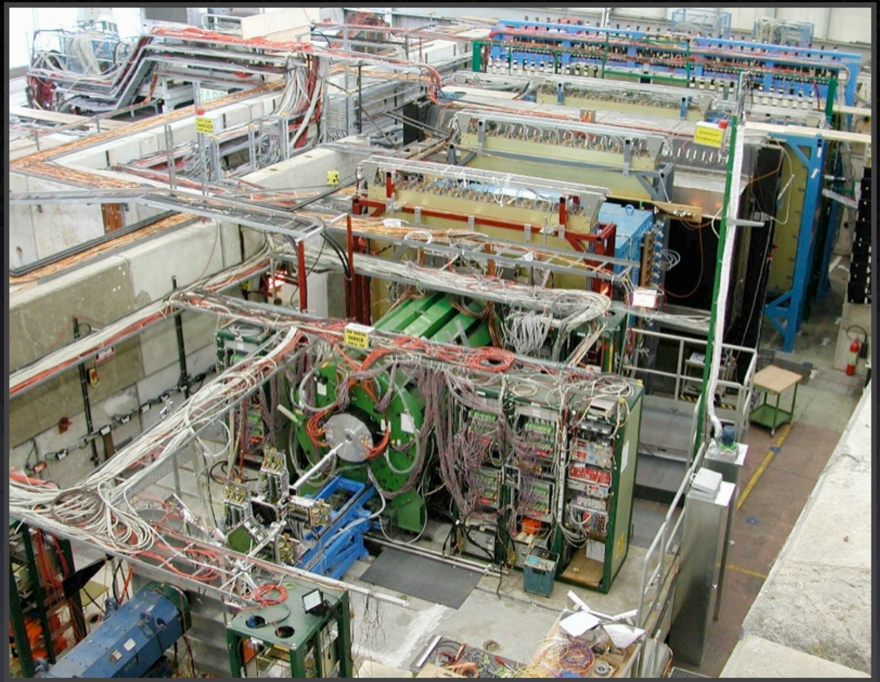


The Neutrino Beam



- Primary p-Be interaction:
  - $\pi^\pm$ from global fit to available data
  - K^+ from global fit
  - K^0 scaled according to GFLUKA
  - Use existing data including E910
- High purity ν_μ beam
  - ~0.5% ν_e contamination from:
  - Kaons produced at target (K_{e3})
  - μ decays from pion decay
- 540 m baseline to detector

HARP (Hadron Production)



Dedicated Measurement:

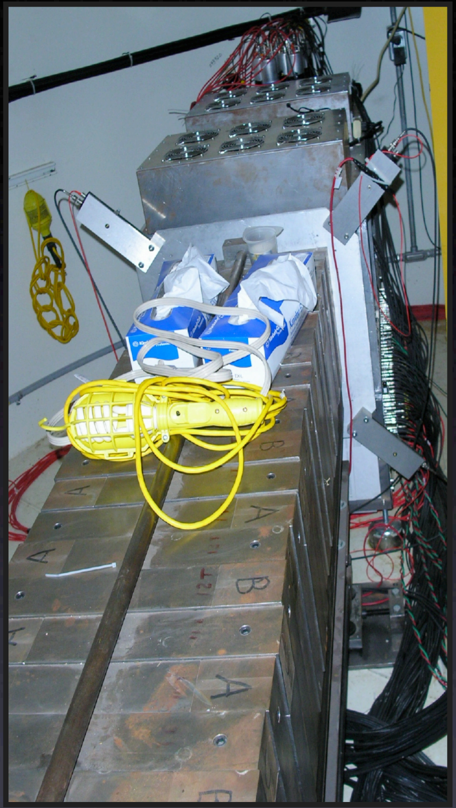
- 8 GeV protons on Be
  - Replica targets
    0.1, 0.5 and 1 interaction length
- Tracking (TPC, Drift Chambers)
  Particle ID (TOF and Cherenkov)

Precision Pion and Kaon production measurement

- Spectrum and rate of incident neutrino flux
- Backgrounds from intrinsic ν_e (Kaon decay)

First measurements of pion production released

Little Muon Counter (LMC)

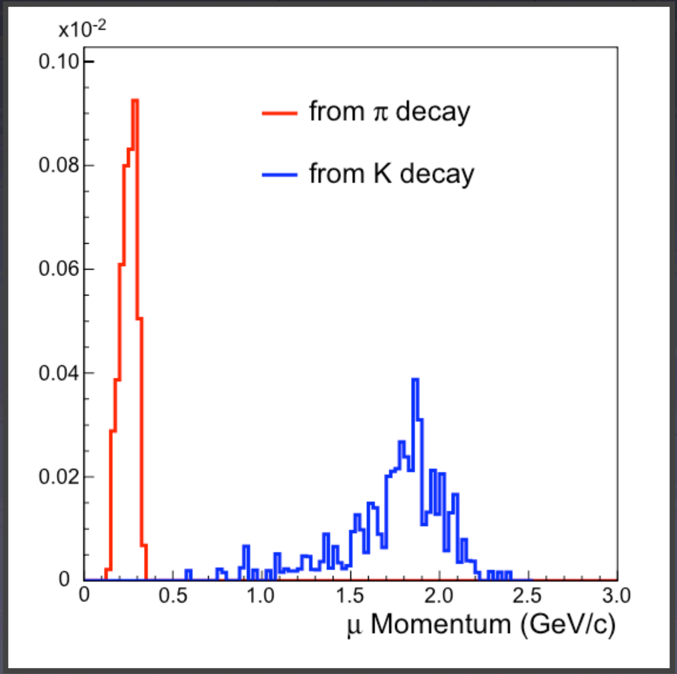


Decay Region Monitor:

- Wide angle (7º), high *p* (2 GeV/c) muons
- Kaon decays in the decay pipe.

Detector:

- Collimator to select angle range
- Fiber tracker/magnet
- Range stack

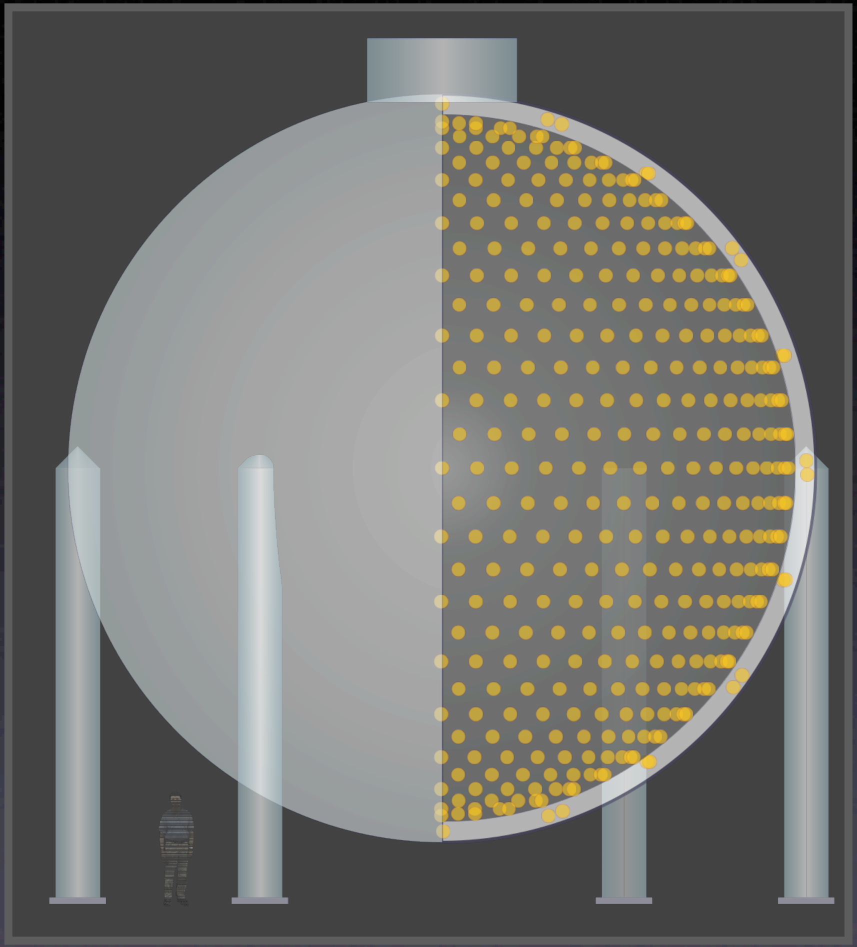


Detector installed:

Analysis in progress

The MiniBooNE Detector

- 800 ton mineral oil target
- 610 cm radius
- Optical barrier at 575 cm
  - Inner “tank” volume
    1280 photomultipliers
  - Outer “veto” region
    240 photomultipliers

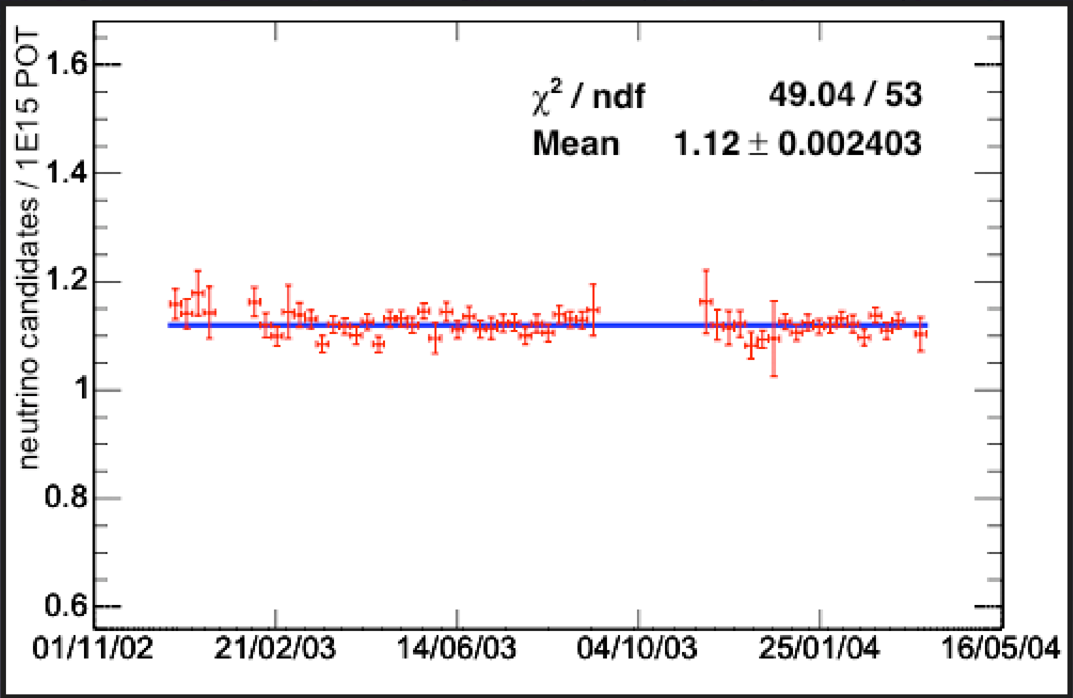


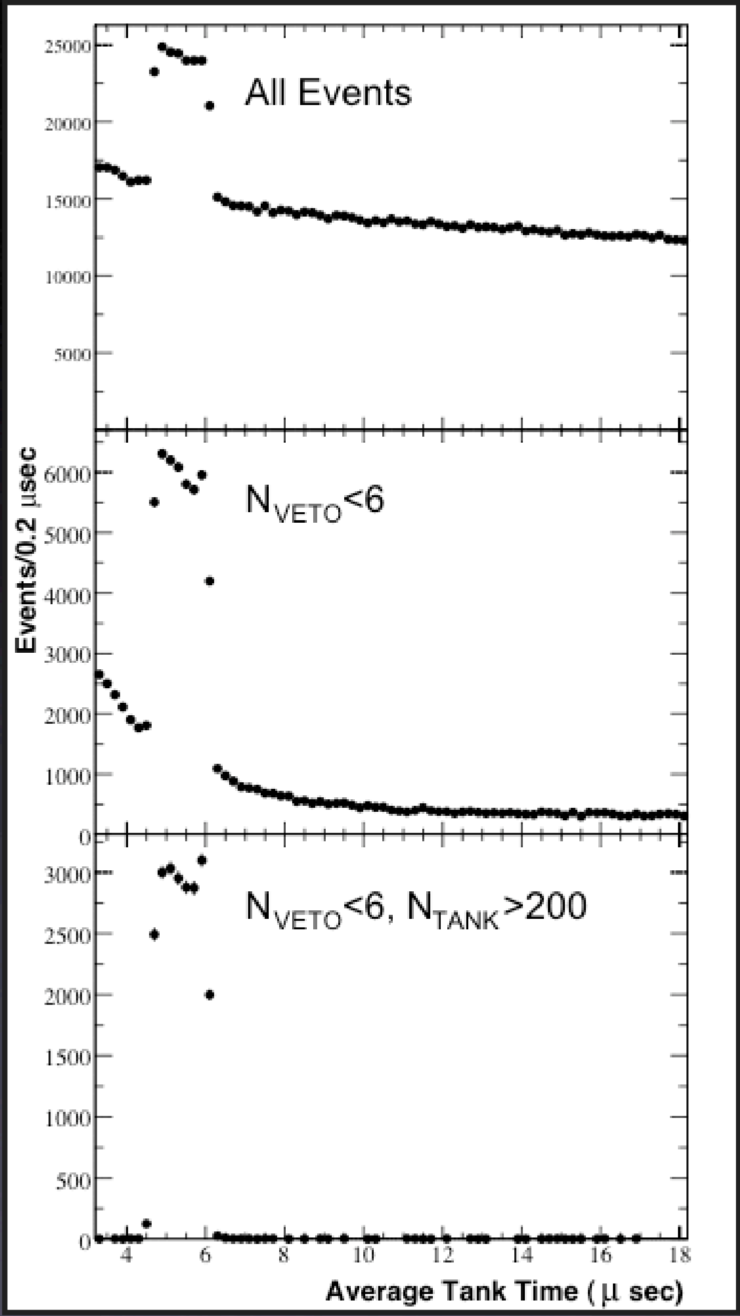
Detect neutrino interactions via Č and scintillation light

Neutrino Events

Beam arrives in 1.6 μsec window

- Clear beam excess without any cuts
- N_{VETO}<6 eliminates cosmic muons
- N_{TANK}>200 eliminates (μ DAR)

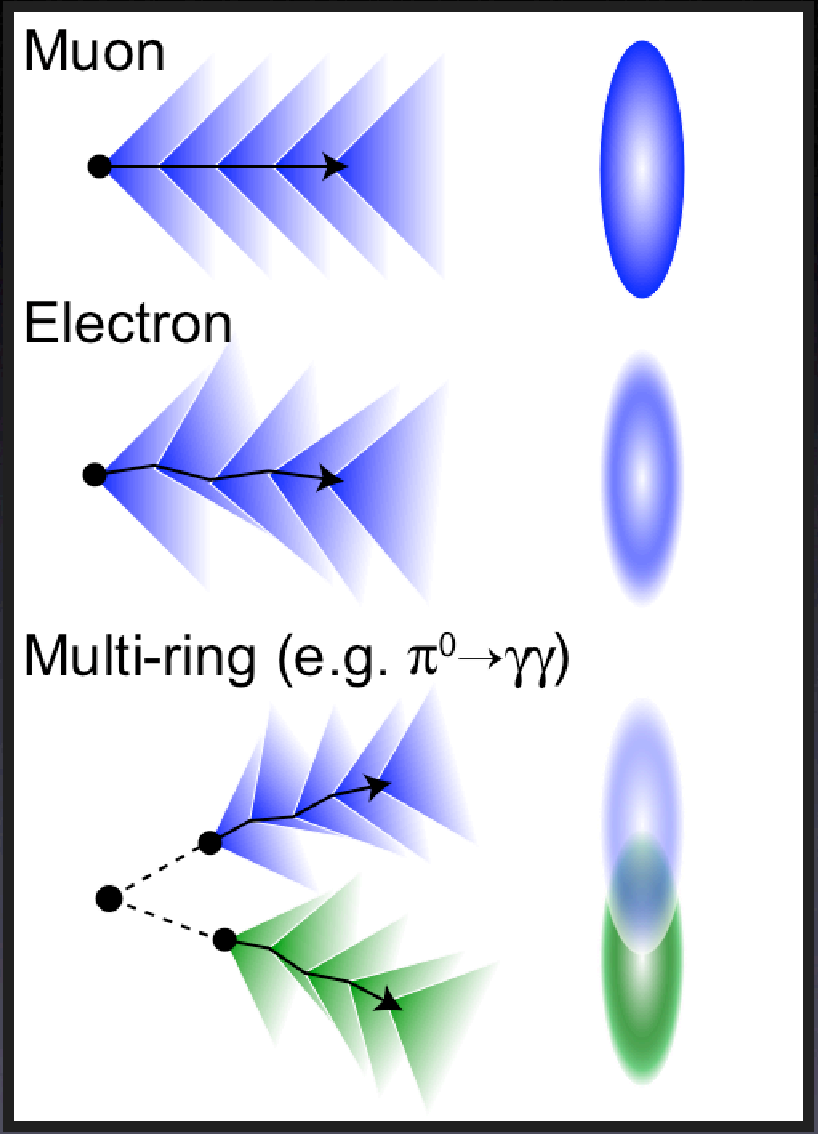




Particle Identification:

Cherenkov radiation:

- Charged particles with produce cone of radiation
- Minimum ionizing particles (muons) sharp-edged rings
- Electrons (photons) scatter, shower, convert, etc. →more diffuse rings
- Multiple particles: reconstruct by identifying rings



Reducible Backgrounds

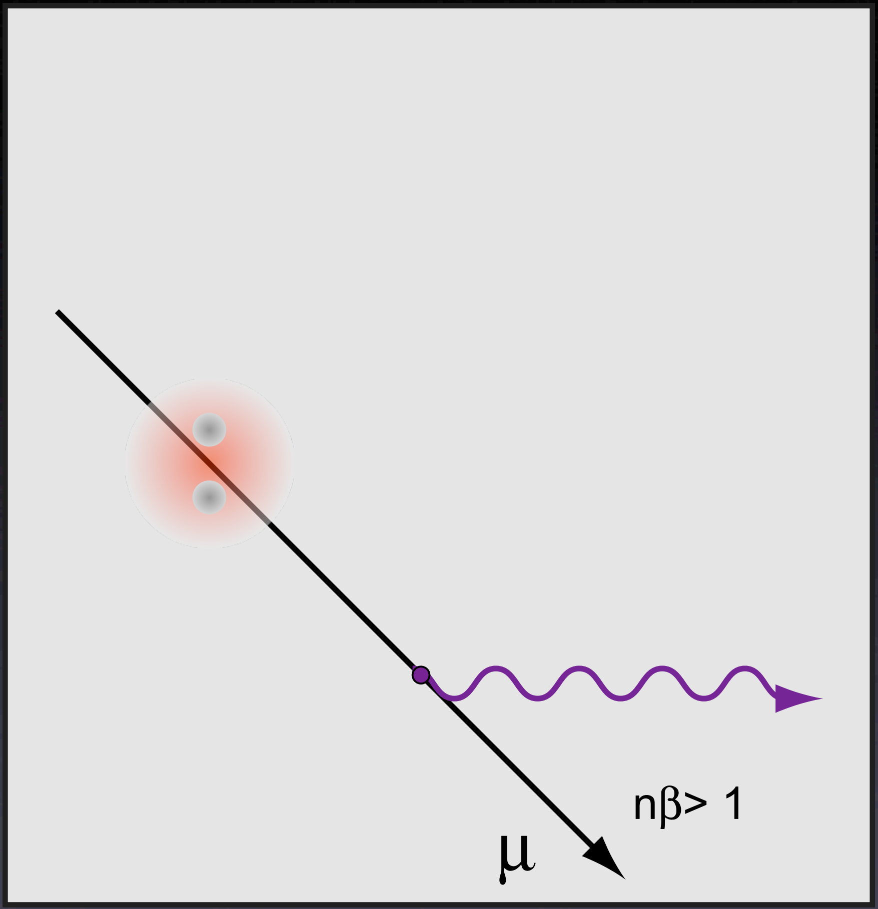
- Signal Process: ν_e CCQE
  - $\nu_e + n \rightarrow p + e^-$
  - proton typically under threshold
  - single electron-like ring
- Backgrounds from high energy photons
  - NC π^0 production: $\nu + (n/p) \rightarrow \nu + \pi^0 + (n/p)$

    $\pi^0 \rightarrow \gamma\gamma$
  - NC radiative Δ decays: $\nu + (n/p) \rightarrow \nu + \Delta$

    $\Delta \rightarrow (n/p) + \gamma$
- Background rejection by topology of PMT hits

Highly sensitive to photon propagation in mineral oil

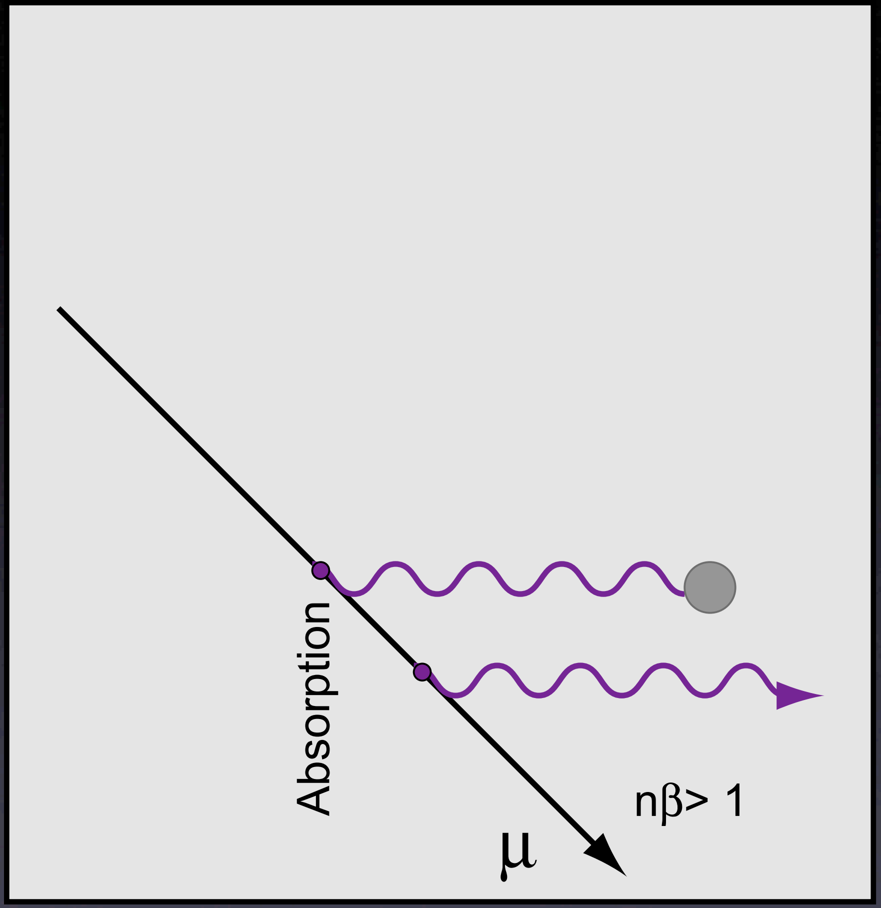
Primary light production



- Č light production
  - Occurs when $n\beta > 1$ ($n \sim 1.47$)
  - Emitted in cone
  - $1/\lambda^2$ wavelength distribution
- Scintillation light
  - Emission from molecular excitations from ionization
  - Emits isotropically
  - Several lifetime, emission modes
  - λ = 270-340 nm

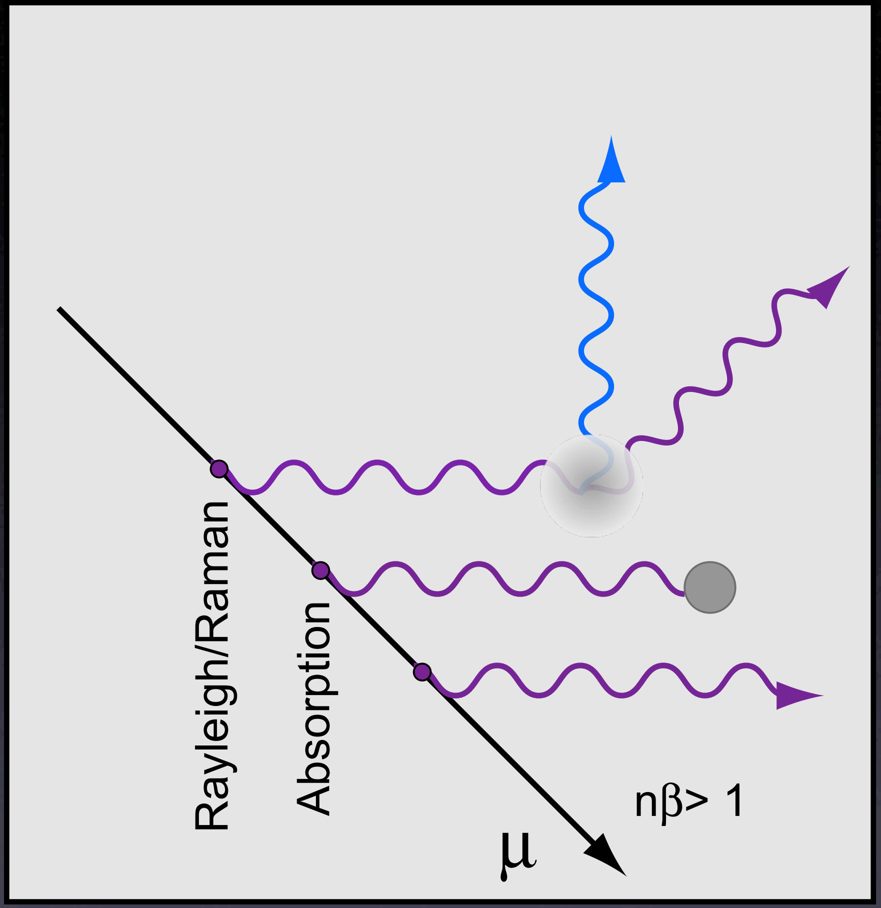
Optical properties of light change dramatically over wavelength range

Absorption



- Photon disappears:
  - Thermally dissipated

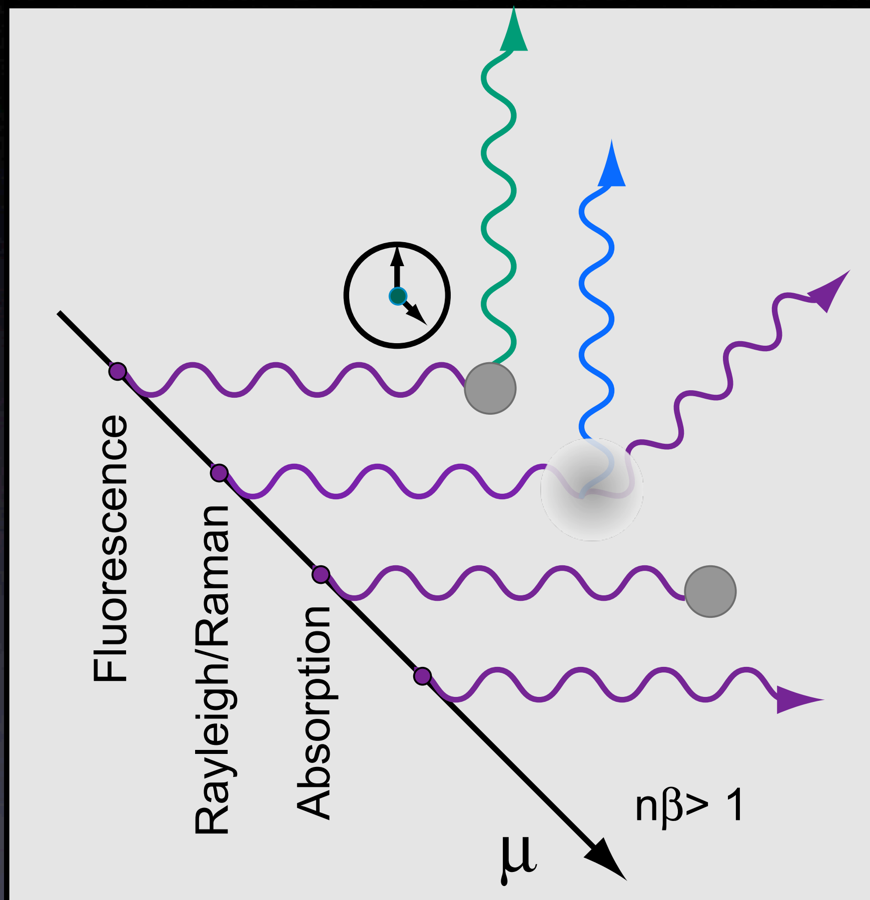
Rayleigh/Raman Scattering



- Rayleigh Scattering:
  - Density pertubations
  - Prompt, no λ shift
- Raman scattering
  - Excitation of vibrational states
  - Prompt with λ shift

Dominant process at λ>350 nm

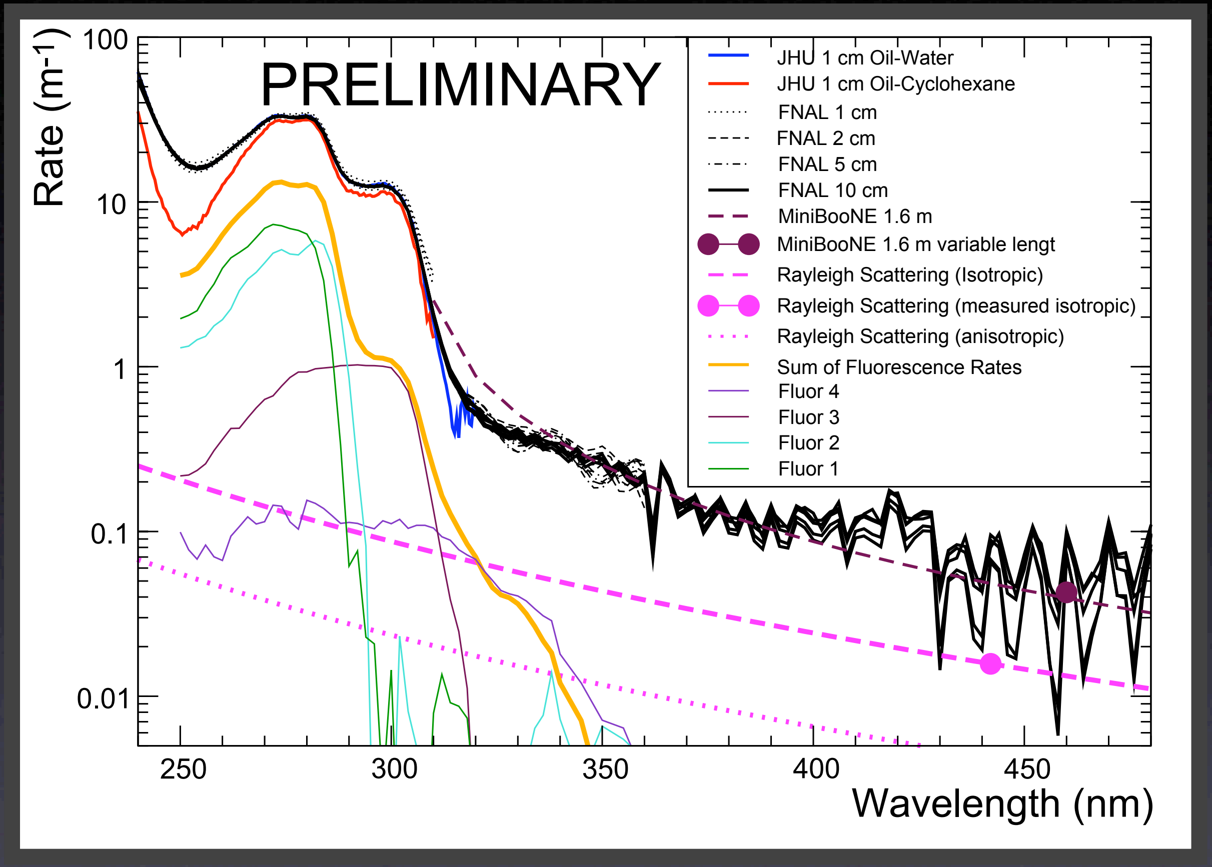
Fluorescence



- Excite molecular states
  - Emission at different wavelength
  - Decay lifetime
- Multiple components
  - Different lifetimes (0.35-33 ns)
  - Different emission (270-340 nm)
- Stokes Shift:
  - UV photons red-shifted to visual

Dominant process in UV region (<300 nm)

Summary of Processes



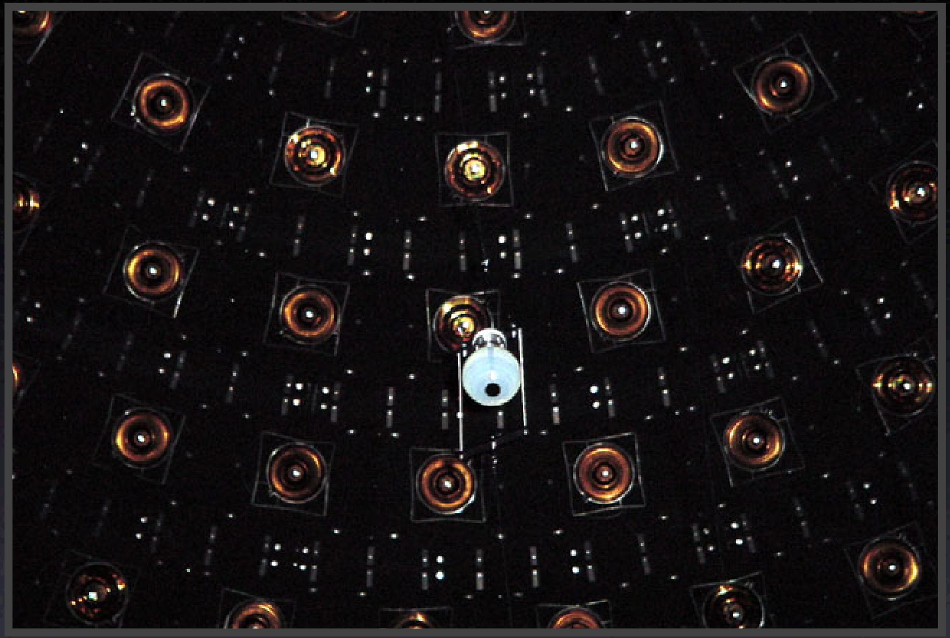
Measurements of

- Index of refraction
- Raman/Rayleigh
- Fluorescence
  - time-resolved
  - steady state
- Overall rate (extinction)
- Scintillation

Complement "test beam" measurements with *in-situ* calibrations

Recent "push" propagating through analyses

Calibration Systems

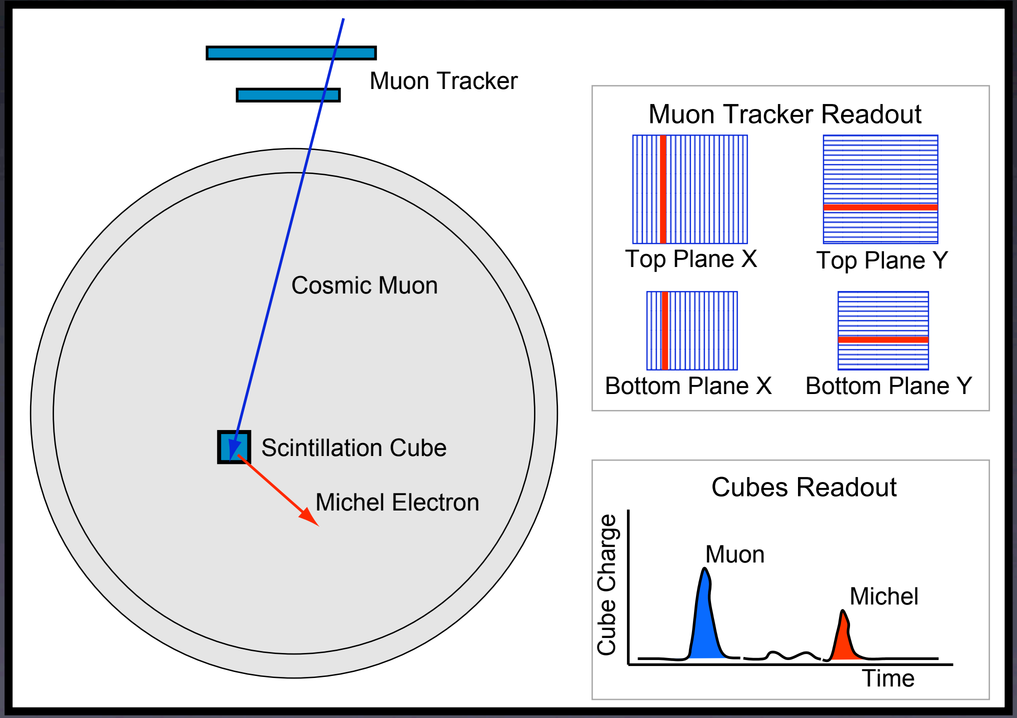


Laser Flask System:

397 and 438 nm pulsed lasers

4 Ludox flasks scatter light

1 bare fiber (collimated light)

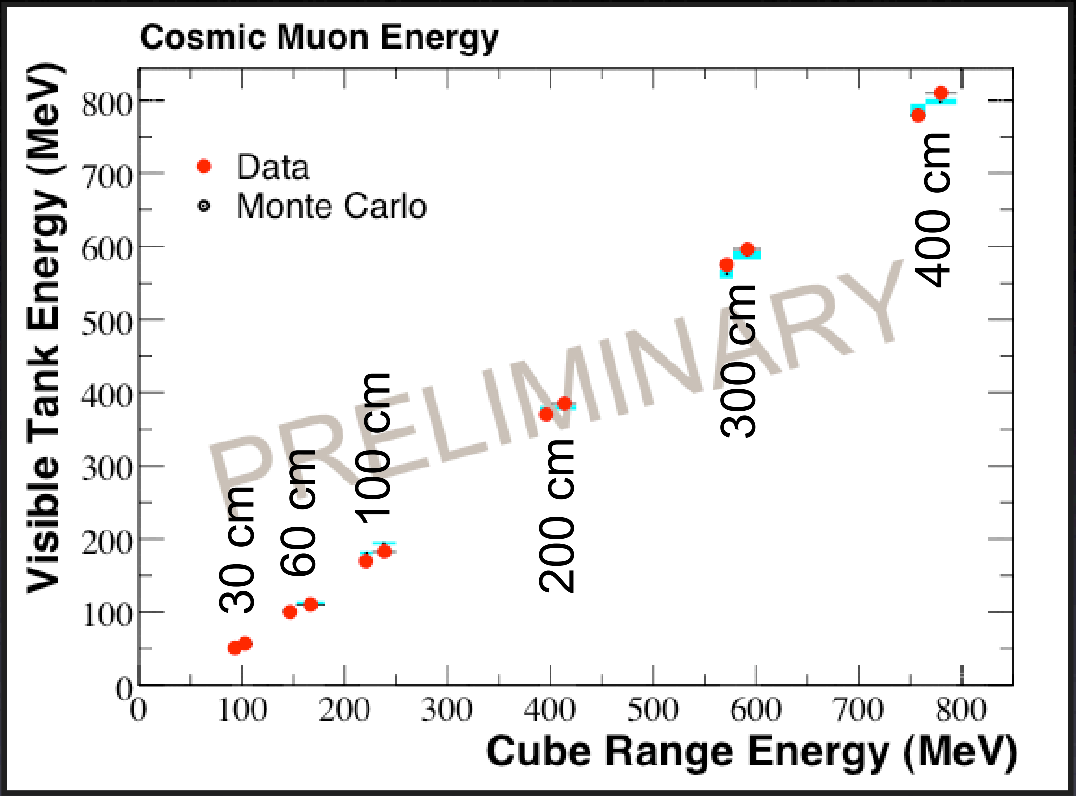


Tracker/Cube System

- Scintillator hodoscope
- Seven scintillator cubes at various depths (15 cm-6 m)

Muons with well-known pathlength

Calibration Systems

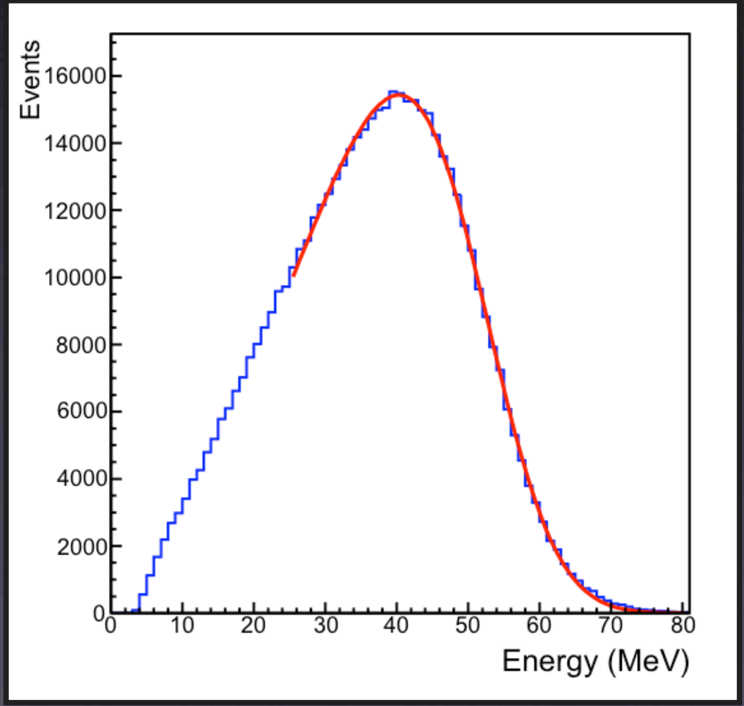


Michel electrons:

Decay of stopped muons

Well-defined energy spectrum

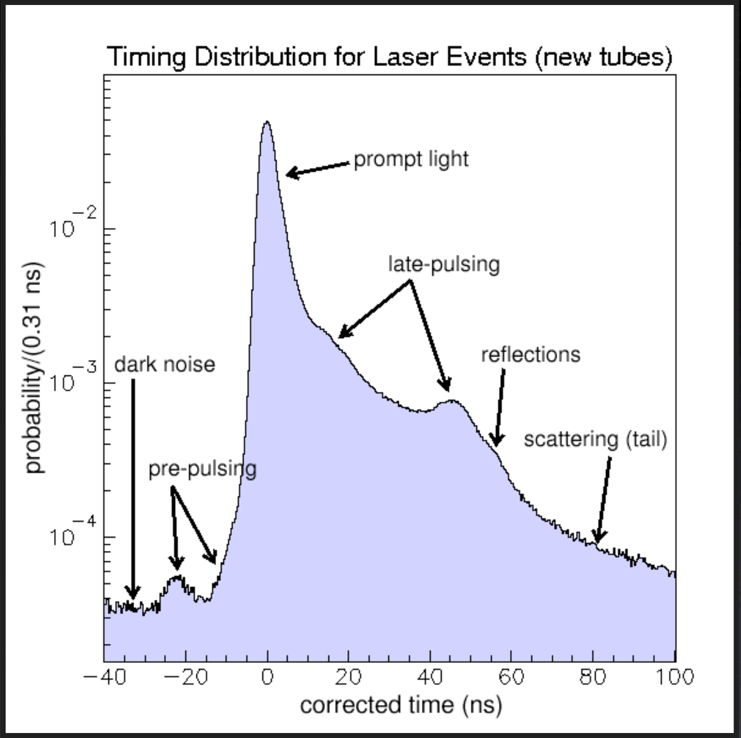
Reconstructed energy compared with theory and resolution model

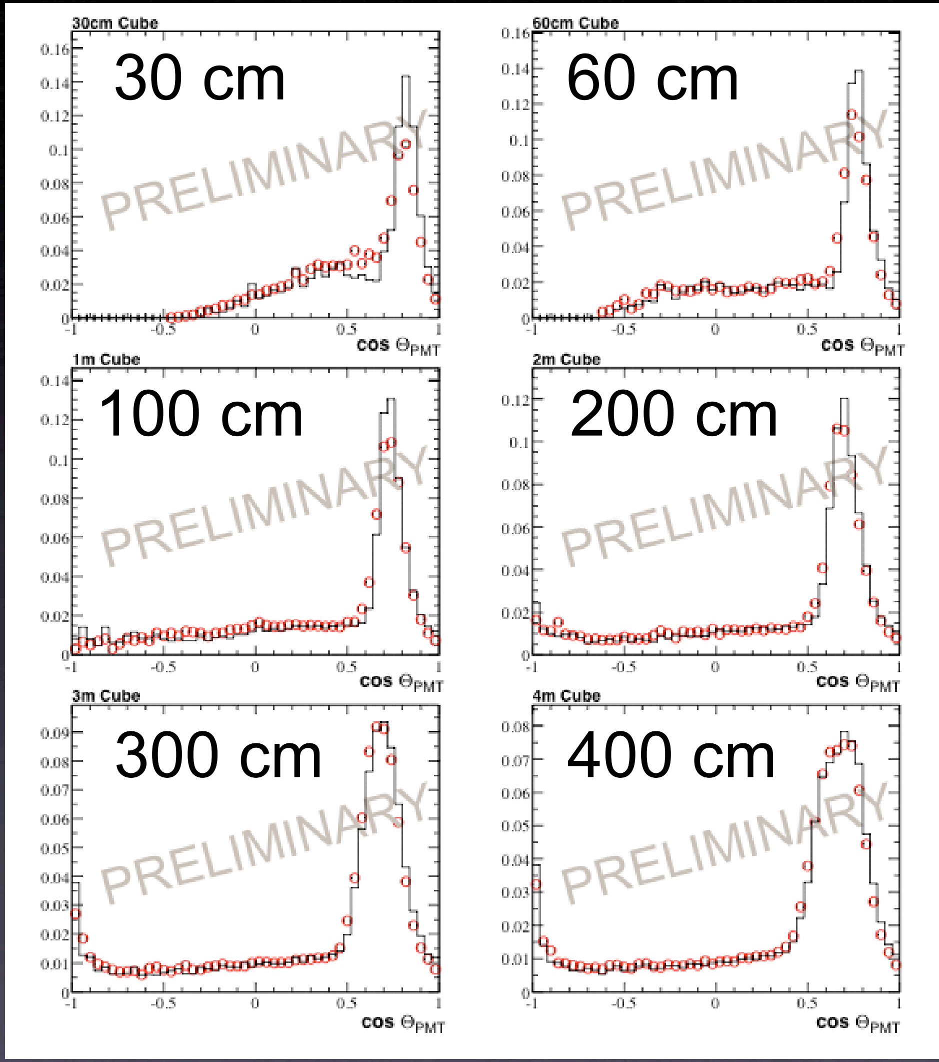


Tracker/Cube reconstructed muons

- Energy estimate from pathlength and dE/dx
- Compare with reconstructed energy

Space/Time Distributions





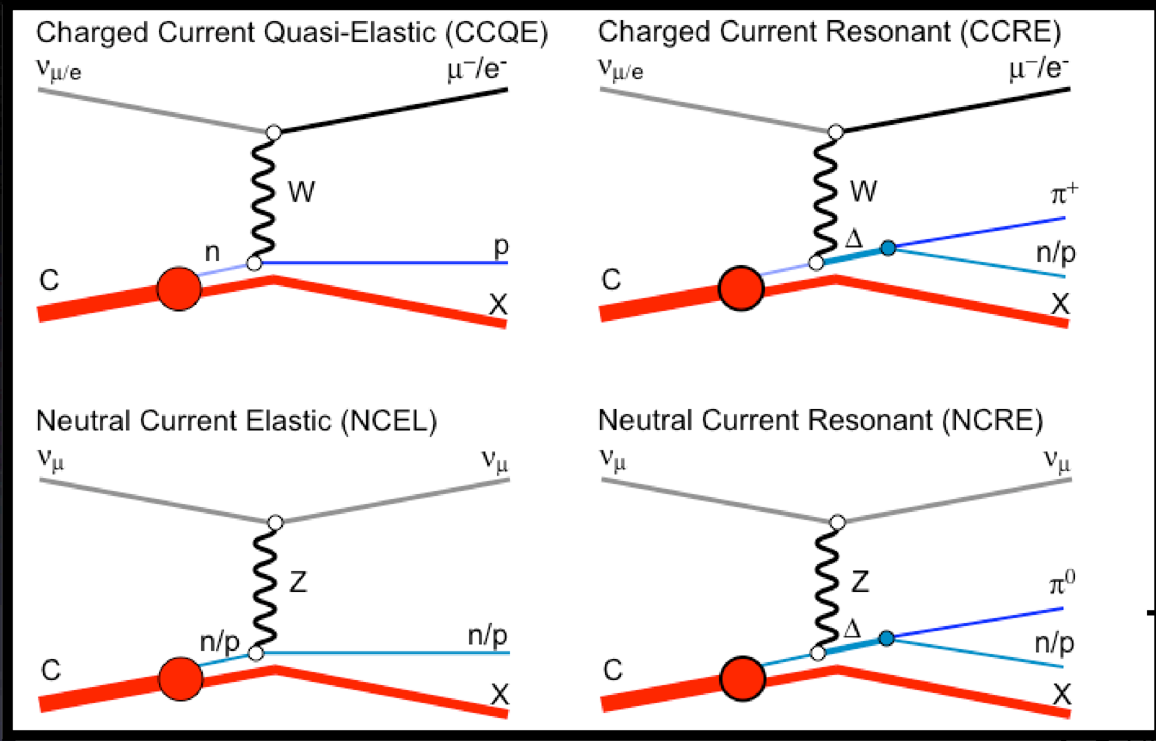
Laser data:

- Scattering/absorption from time profile

Tracker/Cube Muons:

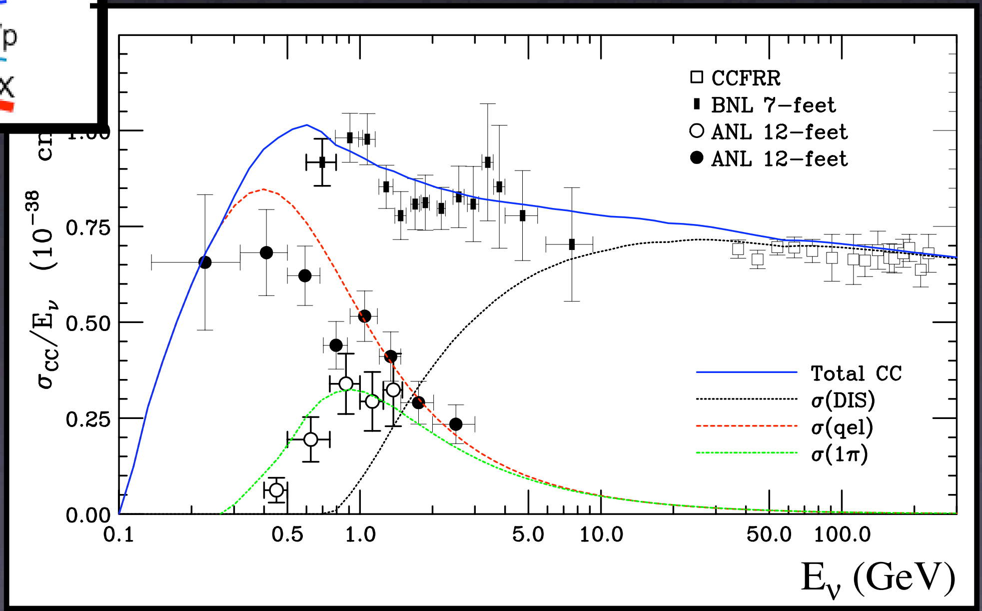
- Scintillation/Fluorescence from time and angular distribution

Neutrino Interactions at O(1GeV)



Primary Interactions:

- CC Quasi-Elastic (40%)
- NC Elastic (15%)
- CC Resonance (25%)
- NC Resonance (10%)



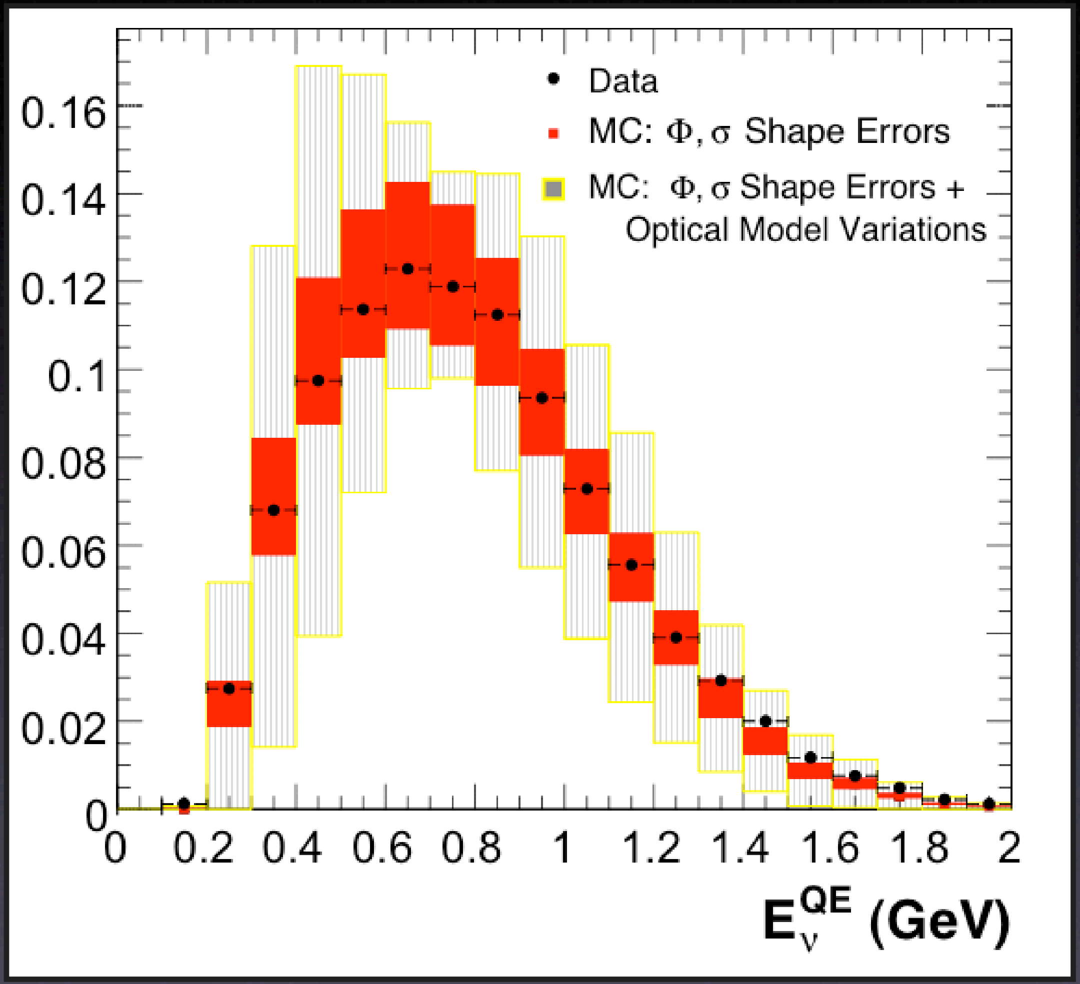
Other Interactions:

Multi pion production

Deep-inelastic scattering

Coherent pion production

ν_μ CCQE events



Selected based on:

Ring profile

Time profile of hits

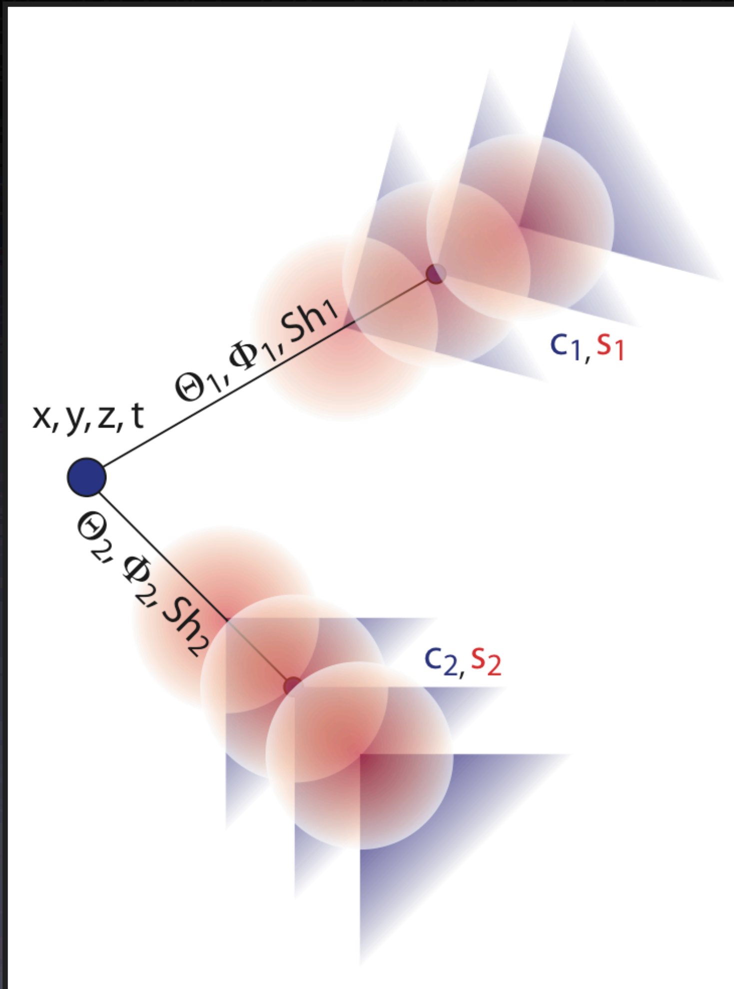
80% purity

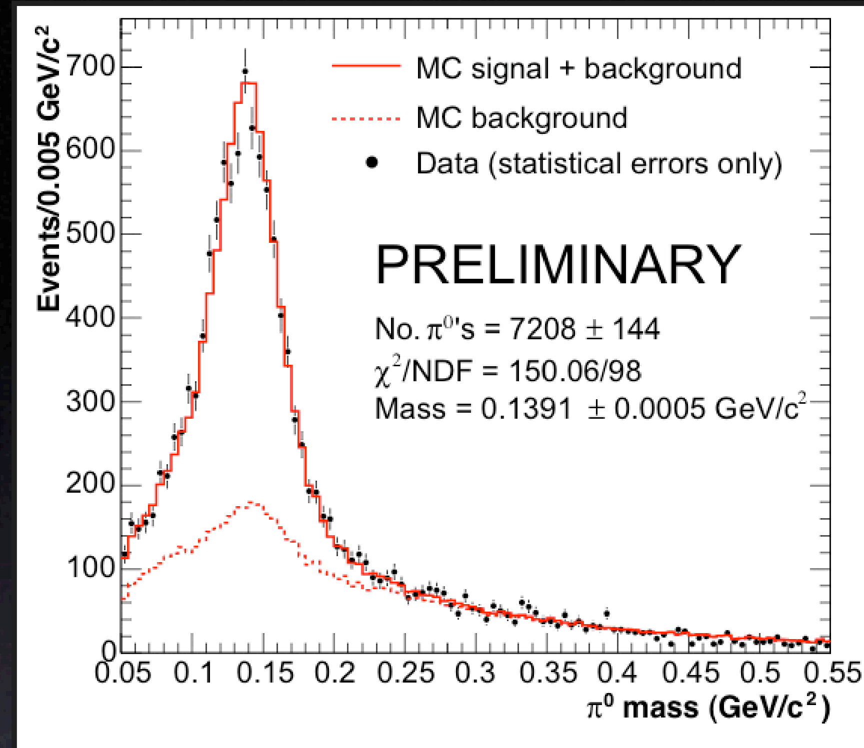
Neutrino energy based on

- Energy, angle of muon
- Two body kinematics

28K events selected

NC π^0 Events:

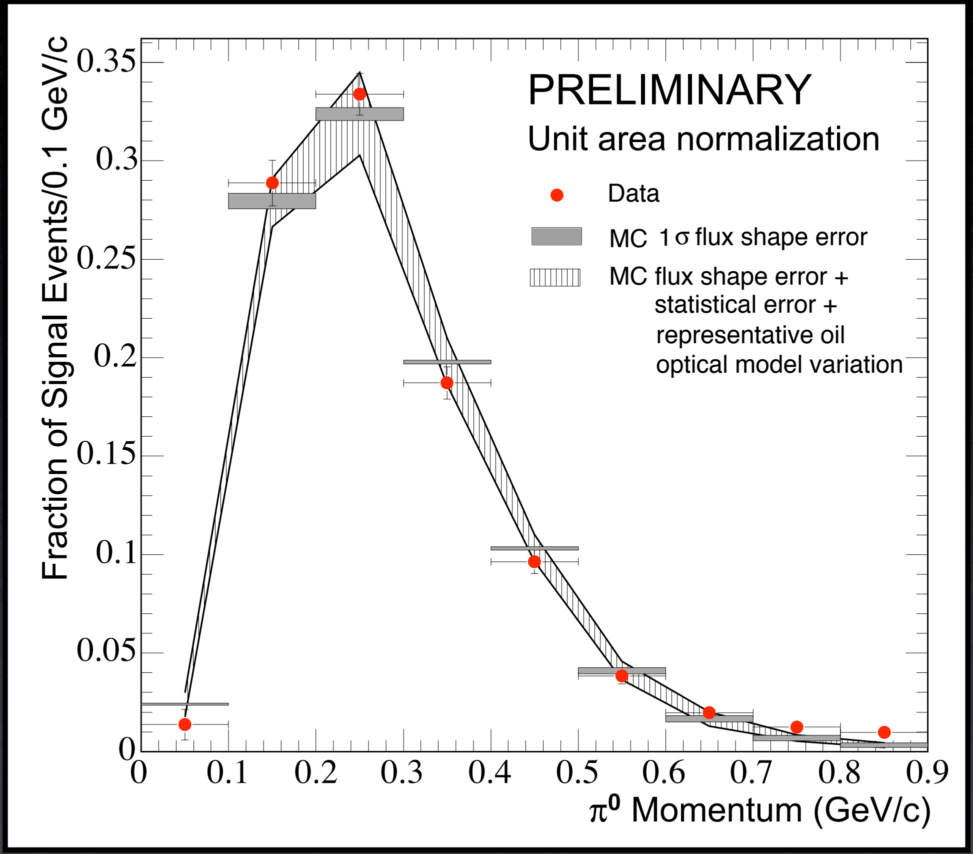


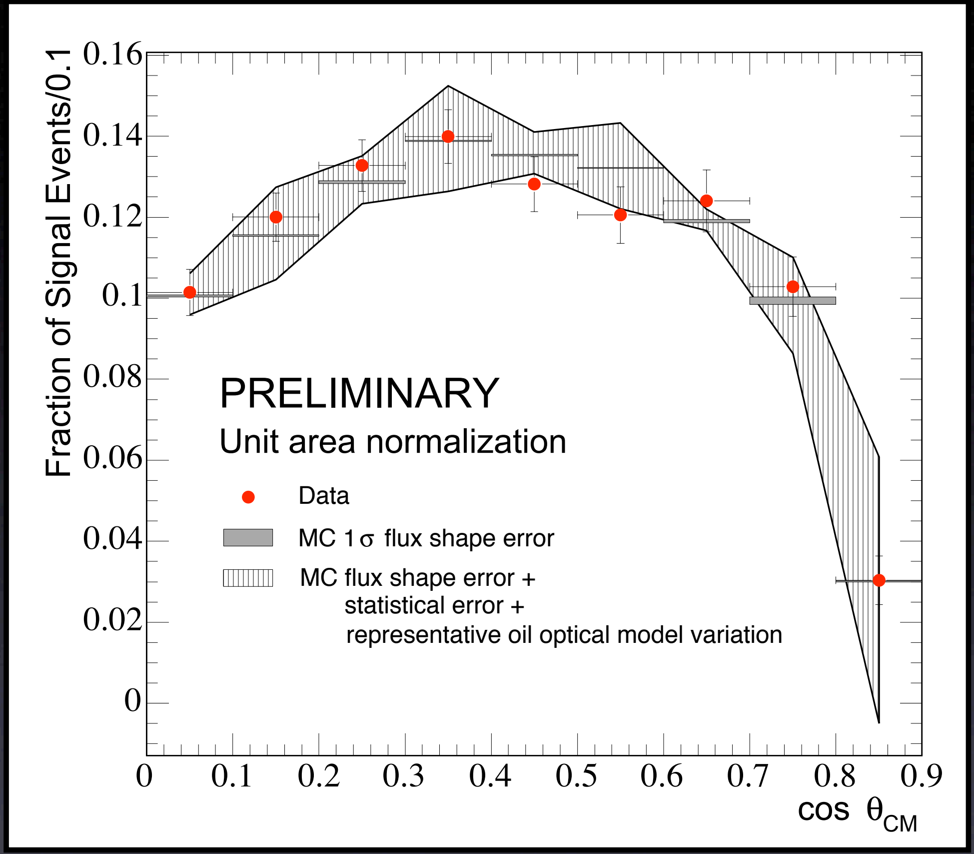


- Two ring fit for each event
  - Č/Sci light from each
  - Direction
  - Mean shower point

Kinematic reconstruction of $\pi^0 \rightarrow \gamma\gamma$ decay

NC π^0 Kinematic Distributions





π^0 misidentification driven by

- Collimation of photons, energy asymmetry of photons
- Momentum, CM decay axis

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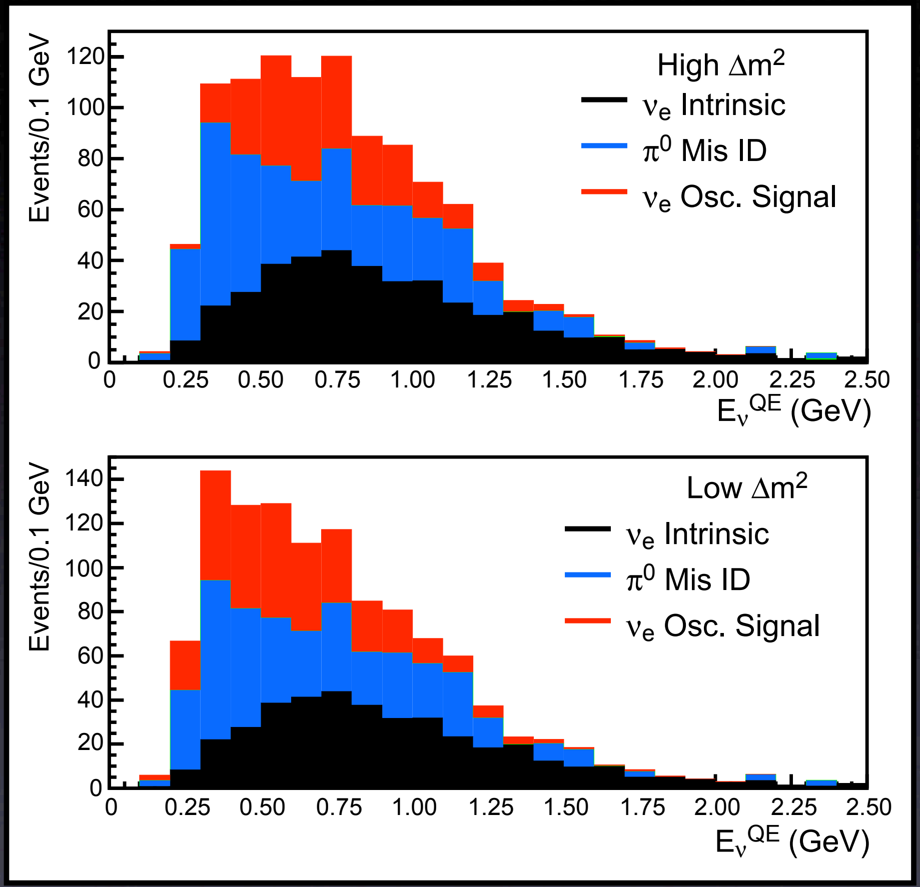
Expected Signal/Background

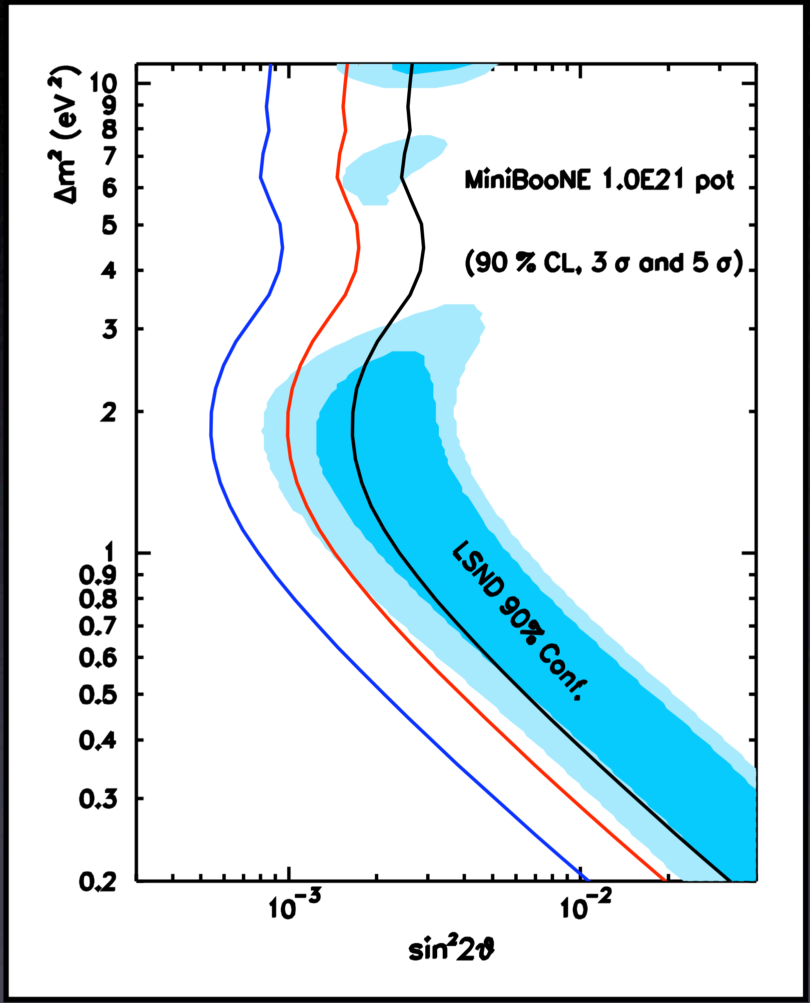
Process	All Events	After Selection
ν_μ CC quasi-elastic	553,000	8
ν_μ NC π^0	110,000	290
Radiative Δ decay	1,080	80
Intrinsic ν_e	2,500	350
Oscillation Signal	1,500	300
Signal/Background		300/780=0.38

For 10^{21} protons-on-target

NC π^0 is dominant reducible background

Expected Sensitivity





- Energy distribution fit to extract signal, background yield

Looking ahead: FY 2006

- MiniBooNE approved for FY06 running
- FY06 running may be in antineutrino mode: Studies of O(1 GeV) $\bar{\nu}_\mu$ interactions
  - Challenge: wrong-sign (ν_μ) contamination (30%)
    - Angular distributions
    - Muon lifetime (μ^+ vs. μ^- with capture)
    - CC π^+ events (from ν_μ events only)
- Prepare for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation search

Summary and Outlook

MiniBooNE:

Confirm/refute LSND evidence for neutrino oscillations

- ! Confirmation has dramatic implications for neutrino physics

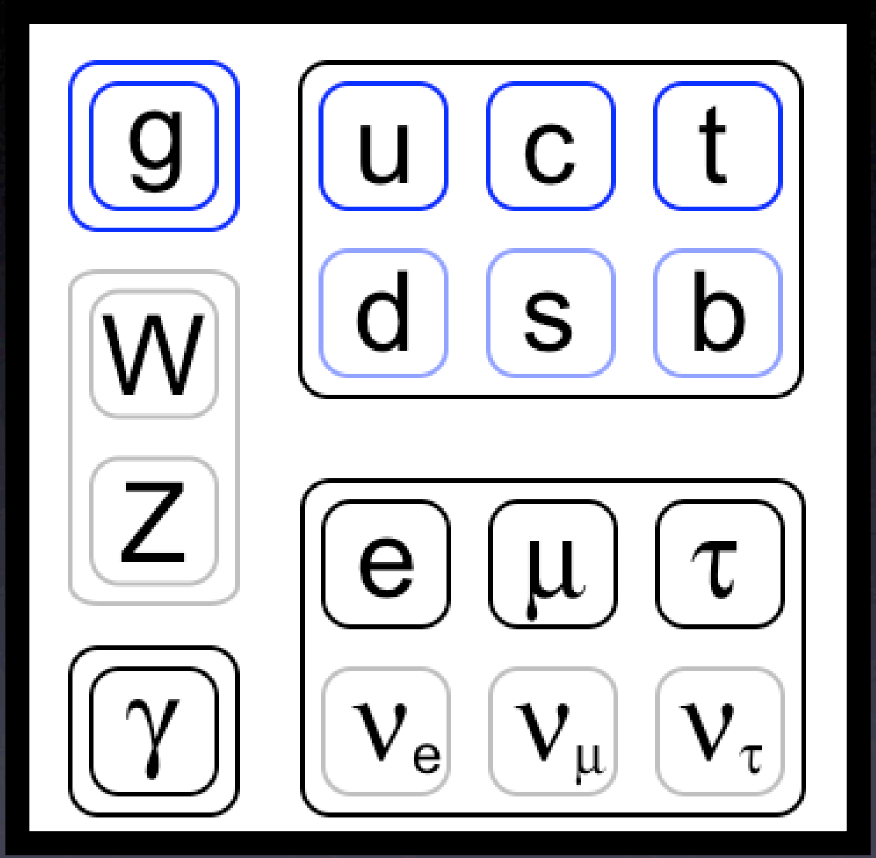
Accumulated $4x10^{20}$ pot (400K neutrino interactions)

- Detector/reconstruction functioning well
- Beamline functioning well
  (>100 million horn pulses with 1st horn, new horn installed)

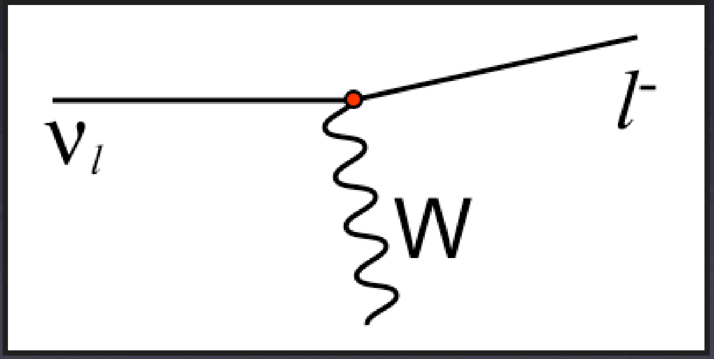
Current Activities

- Systematic studies:
  - Bring offline measurements and in-situ into agreement
  - For both beam and detector
- Accumulating data towards 10^{21} pot goal

Neutrinos in the Standard Model



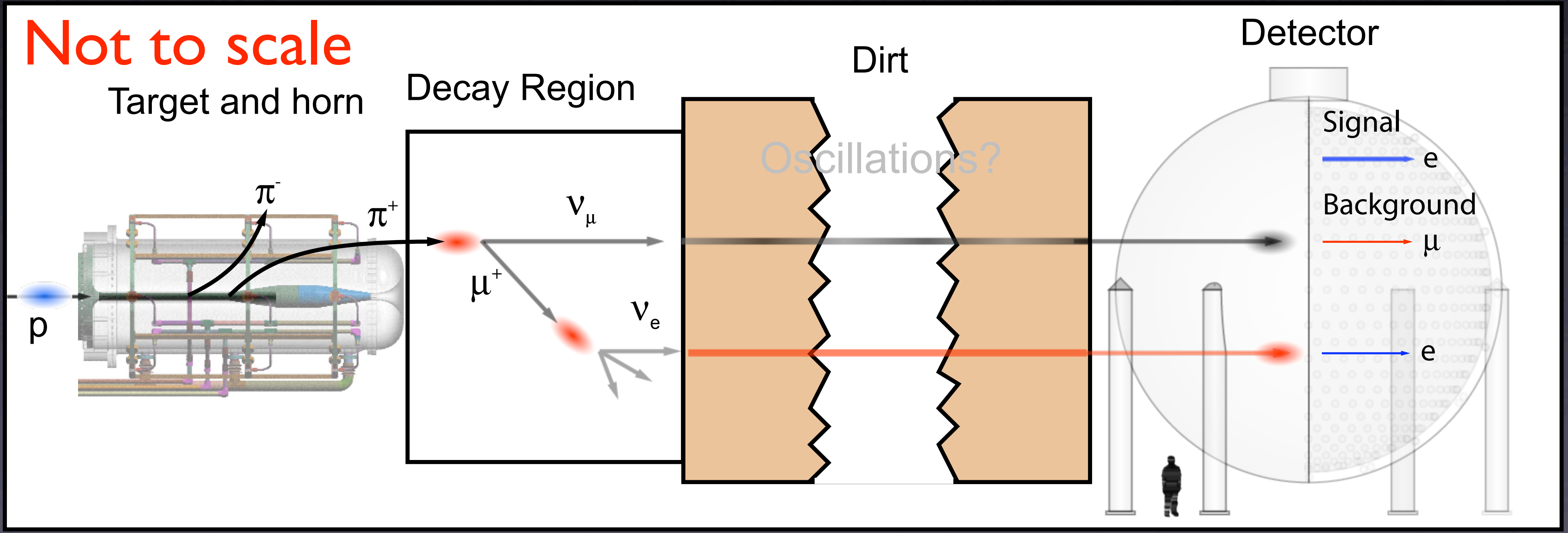
- Lepton sector has
  - charged leptons
  - neutrinos
- Neutrinos identified by flavor



ν_l produces lepton l (e, μ, τ)
in the weak charged current interaction

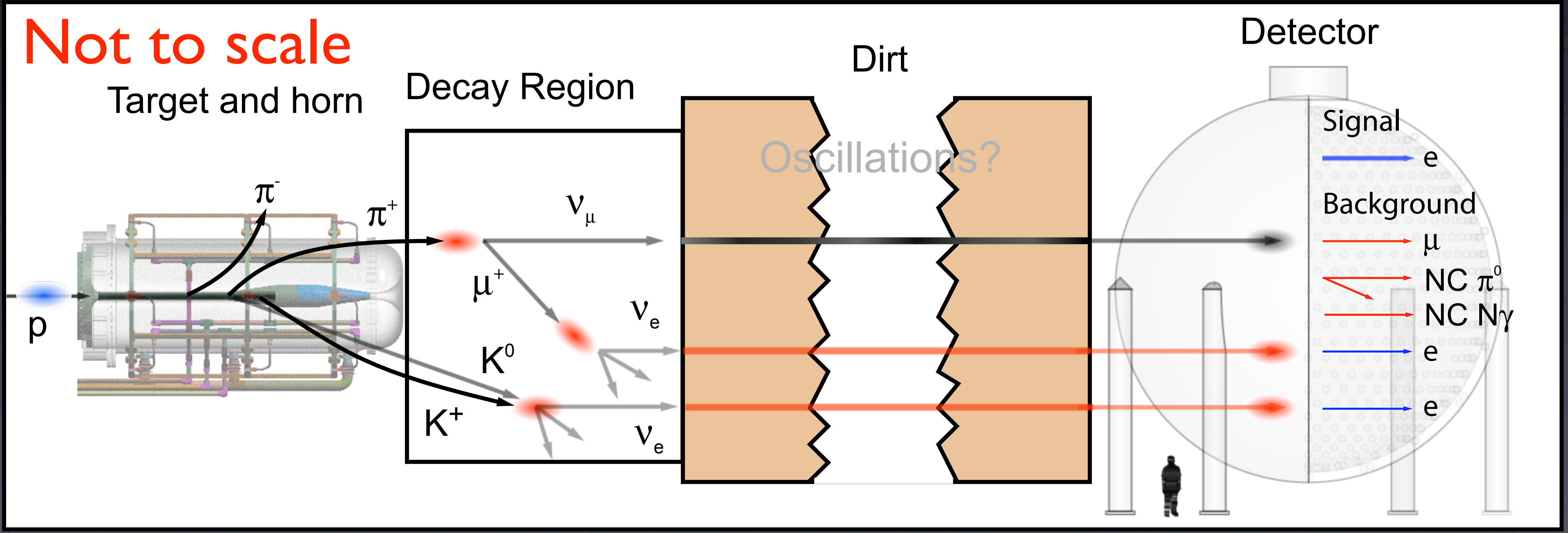
"Intrinsic" Background (I)

- μ^+ produced from π^+ decay can also decay
  - Produce ν_e in detector not due to oscillations
  - Irreducible "intrinsic" ν_e background
- μ^+ intrinsic background $\propto$ decay region length



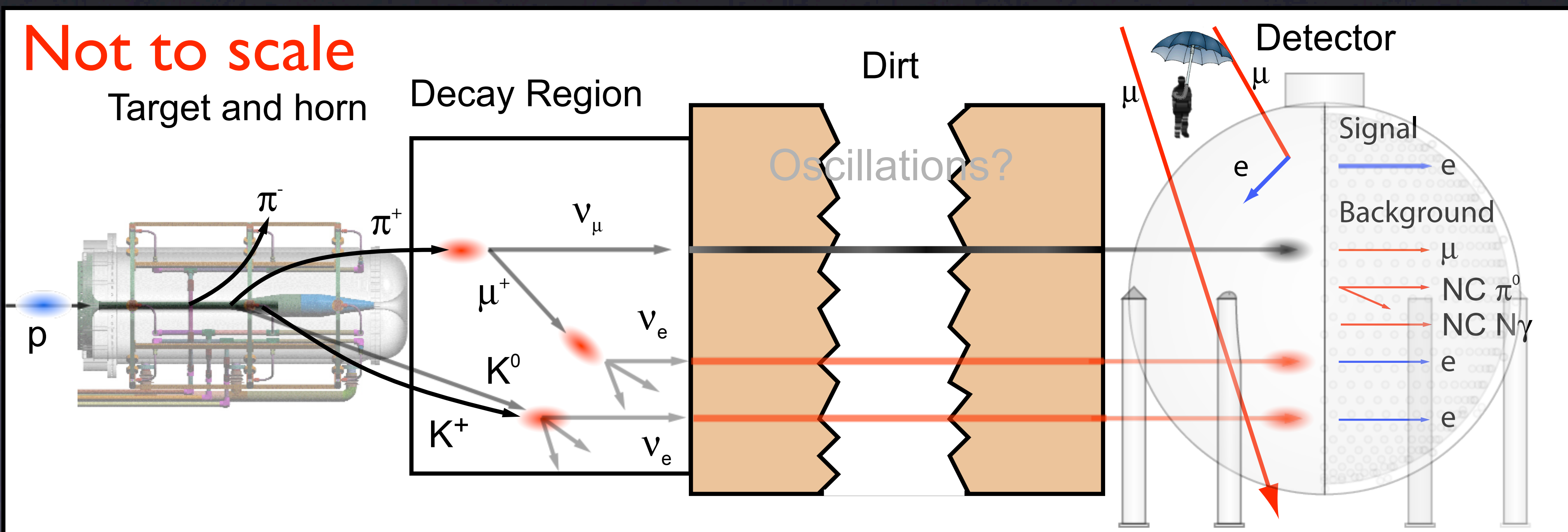
“MisID” Background

- Some ν_μ interactions produce high energy γs
  - π^0 production
  - Radiative Delta decays ($\Delta \rightarrow N\gamma$)
- γ conversions produces e^+e^- pairs
  - Reducible by analyzing topology of event

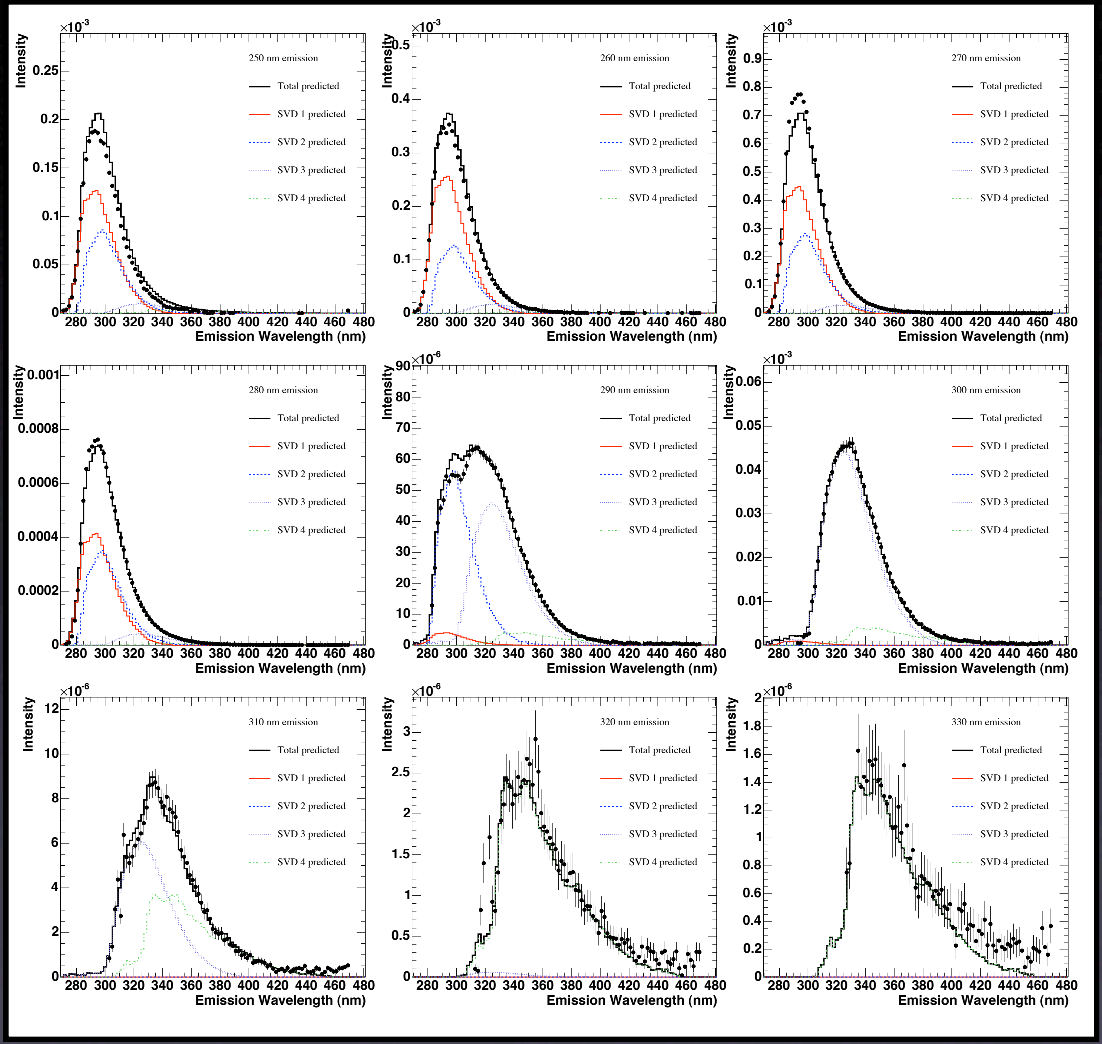


Cosmic Rays

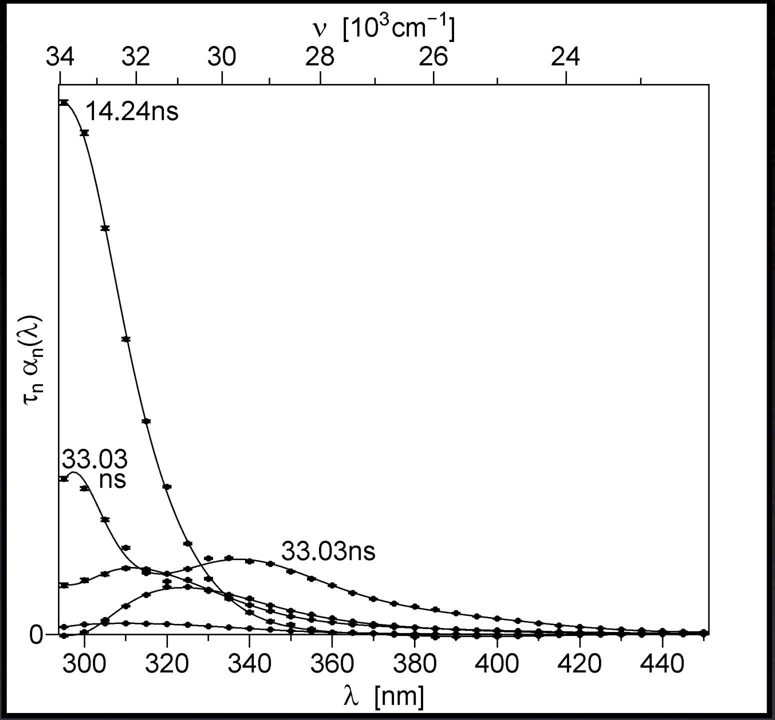
- Shallow overburden reduces rate to 10 kHz
  - Use combination of active veto, beam timing
- e from stopped μ provide valuable calibration



Fluorescence



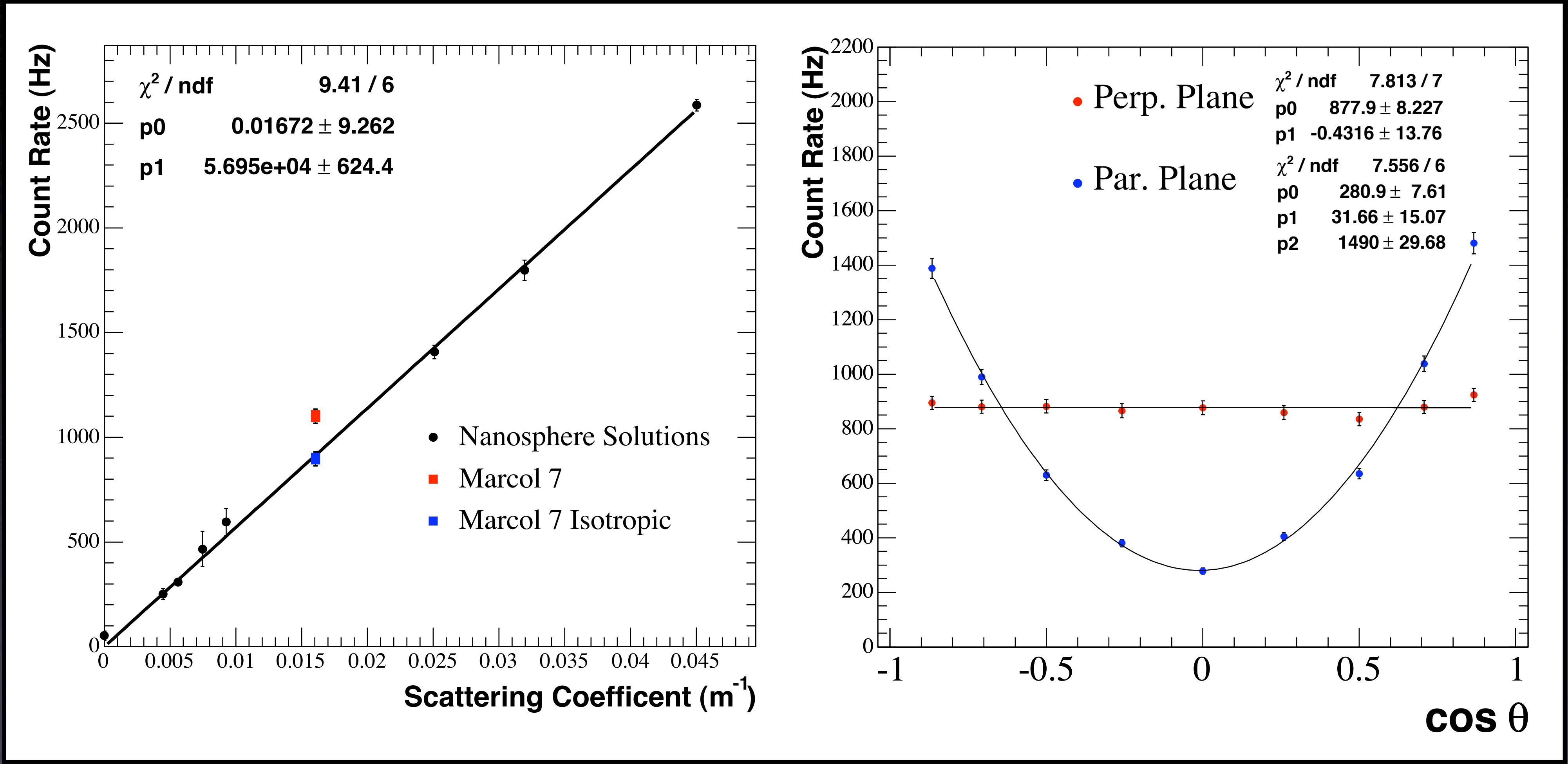
Emission from 250-330 nm vs. model



1 cm cell:

- Time-resolved (285, 300 nm excitation)
- Steady-state excitation/emission matrix

Cosmic Rays



- Rate and angular distribution of Rayleigh scattering

ν_μ CCQE Kinematics