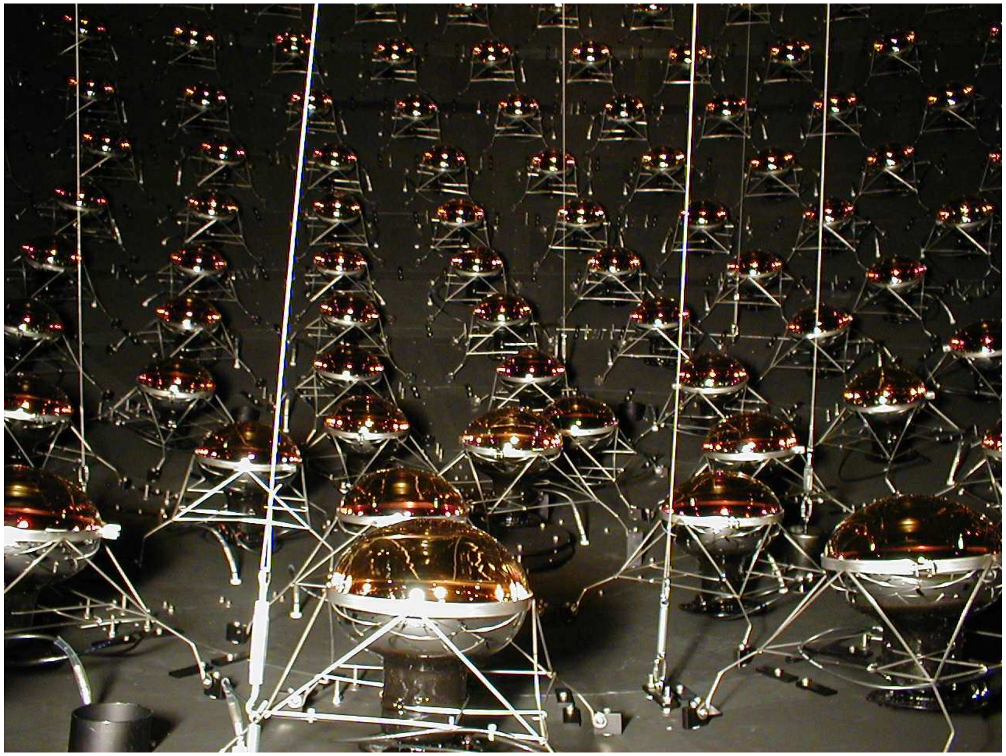
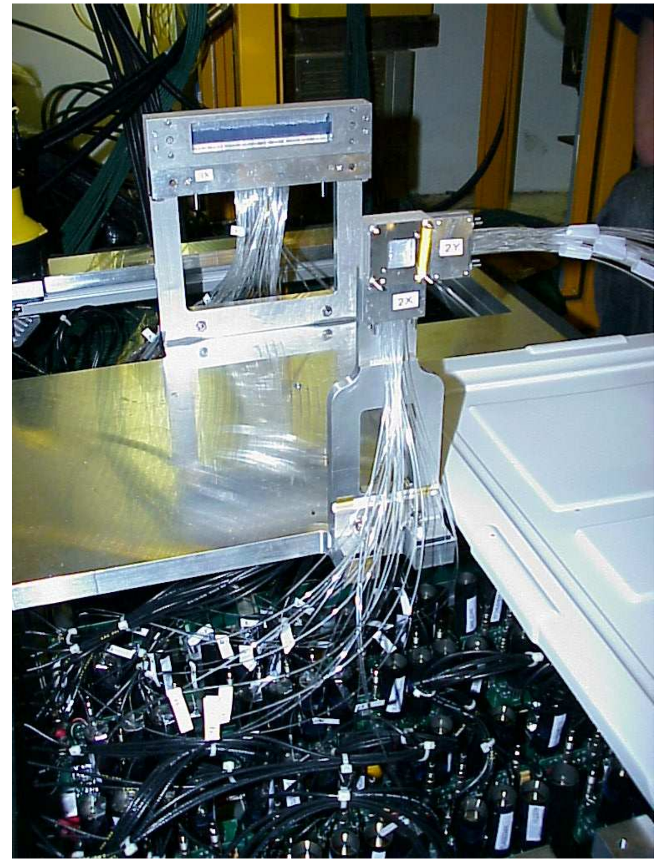
MiniBooNE Progress and Little Muon Counter Overview





- Neutrino Introduction and MiniBooNE Motivation
- MiniBooNE Detector and LMC Calibration and Performance
- Progress Toward Physics Results

Terry Hart,
University of Colorado,
IIT Physics Seminar,
August 12, 2005

Neutrino Characteristics

- Existence
  - Pauli postulated existence to explain beta decay energy spectrum (1930).
  - Reines and Cowan made first observation (1953).
- Neutrinos come in different flavors.
  - Discovery of ν_μ (neutrino associated with muon weak interactions) by Lederman, Schwartz, Steinberger, et al. at Brookhaven (1962).
  - Observation of ν_τ by DONUT experiment at Fermilab (2000).
- Neutrinos have mass contrary to previous assumptions.
  - Ray Davis detects solar neutrinos at Homestake and observes deficit in expected yield (1968).
  - IMB and Kamiokande experiments detect atmospheric neutrinos and observe deficit (1985).
  - Super-Kamiokande reports observation of neutrino oscillations establishing non-zero neutrino mass accounting for neutrino deficits (1998).
  - LSND, SNO, KamLAND, Super-Kamiokande provide latest neutrino oscillation measurements raising even more questions about the fundamental nature of neutrinos (1994 - present).

Positive Neutrino Oscillation Results

$\mathcal{P}(\nu_\alpha \rightarrow \nu_\beta) = (\sin^2 2\theta)(\sin^2\{1.27\Delta m^2 L/E\})$

θ is mixing angle between weak and mass eigenstates
$\Delta m^2 = m_2^{\,2} - m_1^{\,2}$ (eV^2)
L is travel distance of neutrino (km)
E is neutrino energy (GeV)

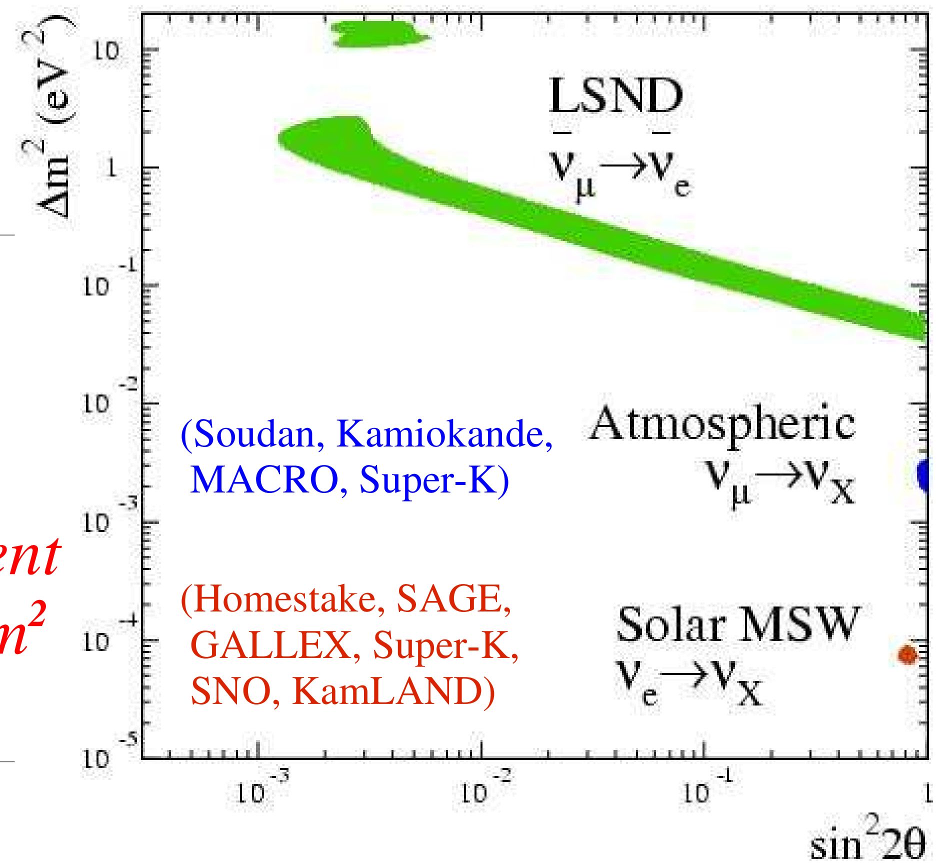
ν oscillation signals:

***LSND*:** $\Delta m^2 \sim 10^0$ eV^2

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

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

3 neutrinos allow only 2 independent values of Δm^2



What to do?

1. Some experiment is seeing something that's not oscillations.
2. Add more sterile neutrinos: 1, 2, 3 ...
3. Something else?

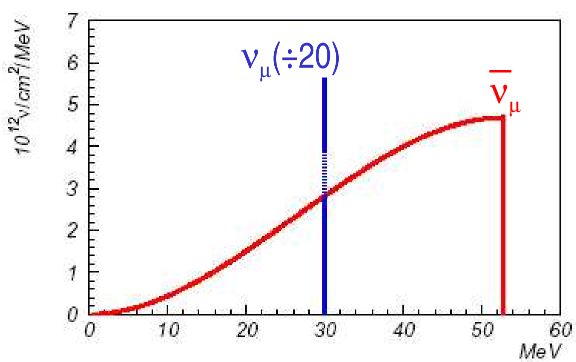
The LSND Experiment

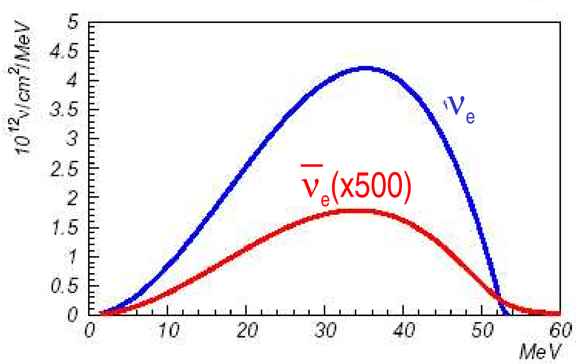
(Liquid Scintillator Neutrino Detector located at Los Alamos)

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance measurement

The neutrino source:

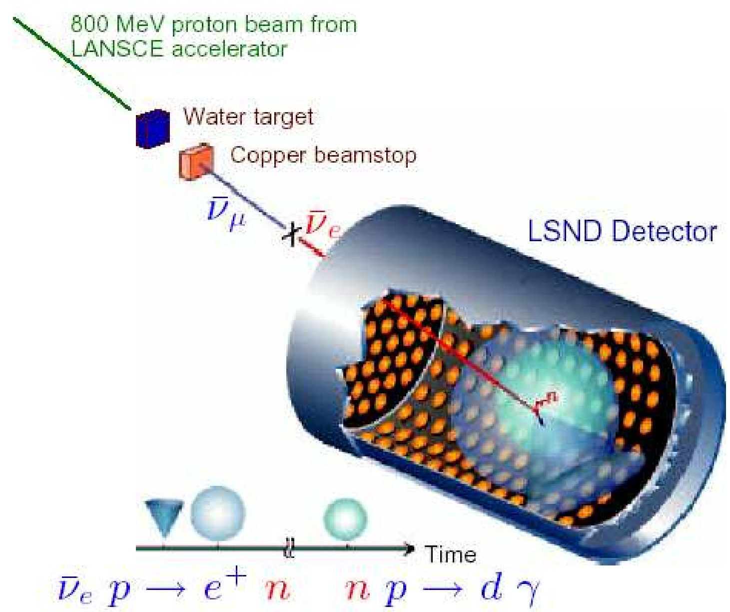
- $\bar{\nu}_\mu$ from: $\pi^+ \rightarrow \mu^+ \, \nu_\mu$
  $\hookrightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$
- E_ν = 20-53 MeV, L_ν = 25-35 m
- Almost no $\bar{\nu}_e$ at source





The detector:

- Liquid scintillator detects both Cherenkov and scintillation light. For $\bar{\nu}_e p \rightarrow e^+ n$:
  - Č+scintillation light from e^+
  - Scintillation light from n capture

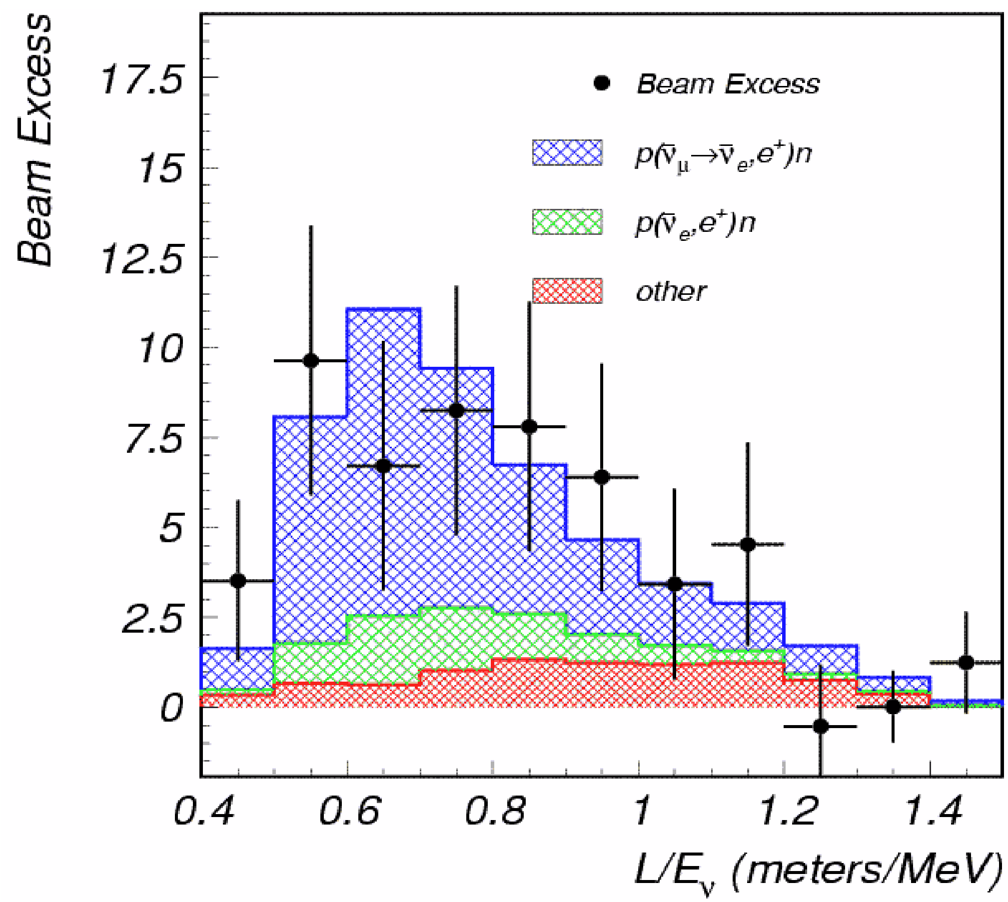


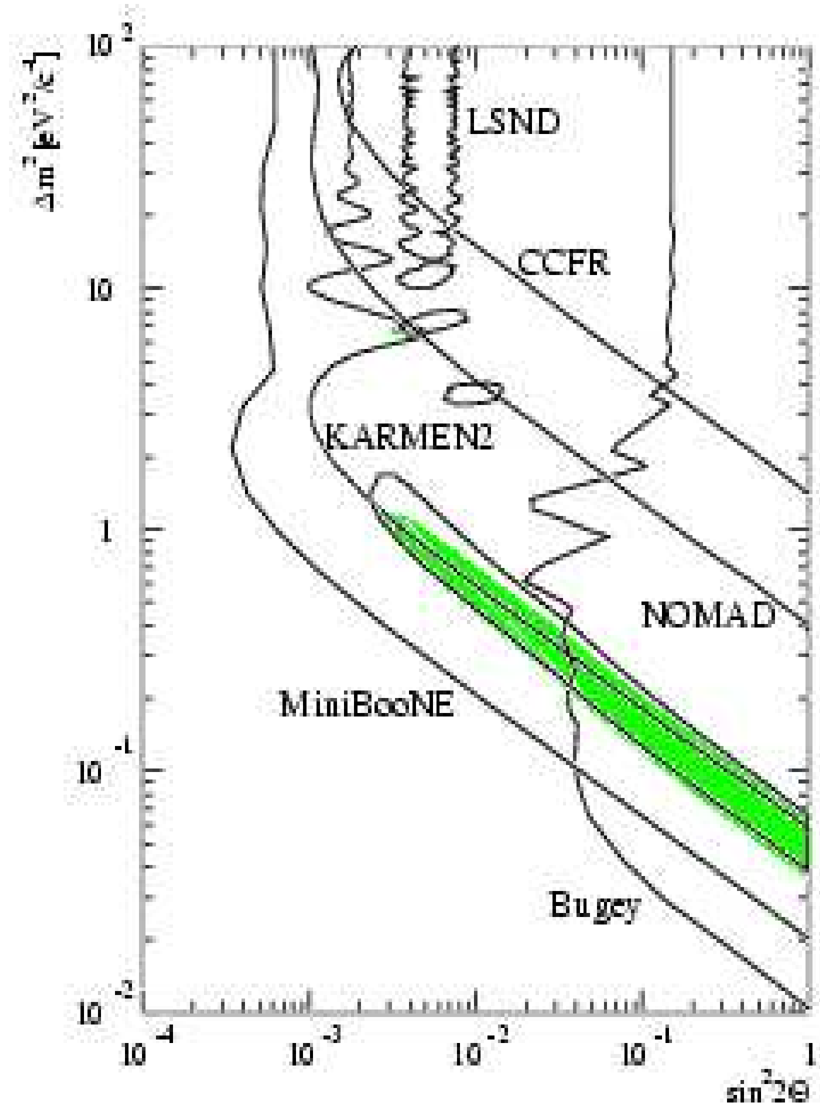
LSND Result

Excess ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, appearance): 87.9 ± 22.4 ± 6.0

Oscillation probability:
(0.264 ± 0.067 ± 0.045)% (muon decay at rest)

3.8 σ statistical significance of excess





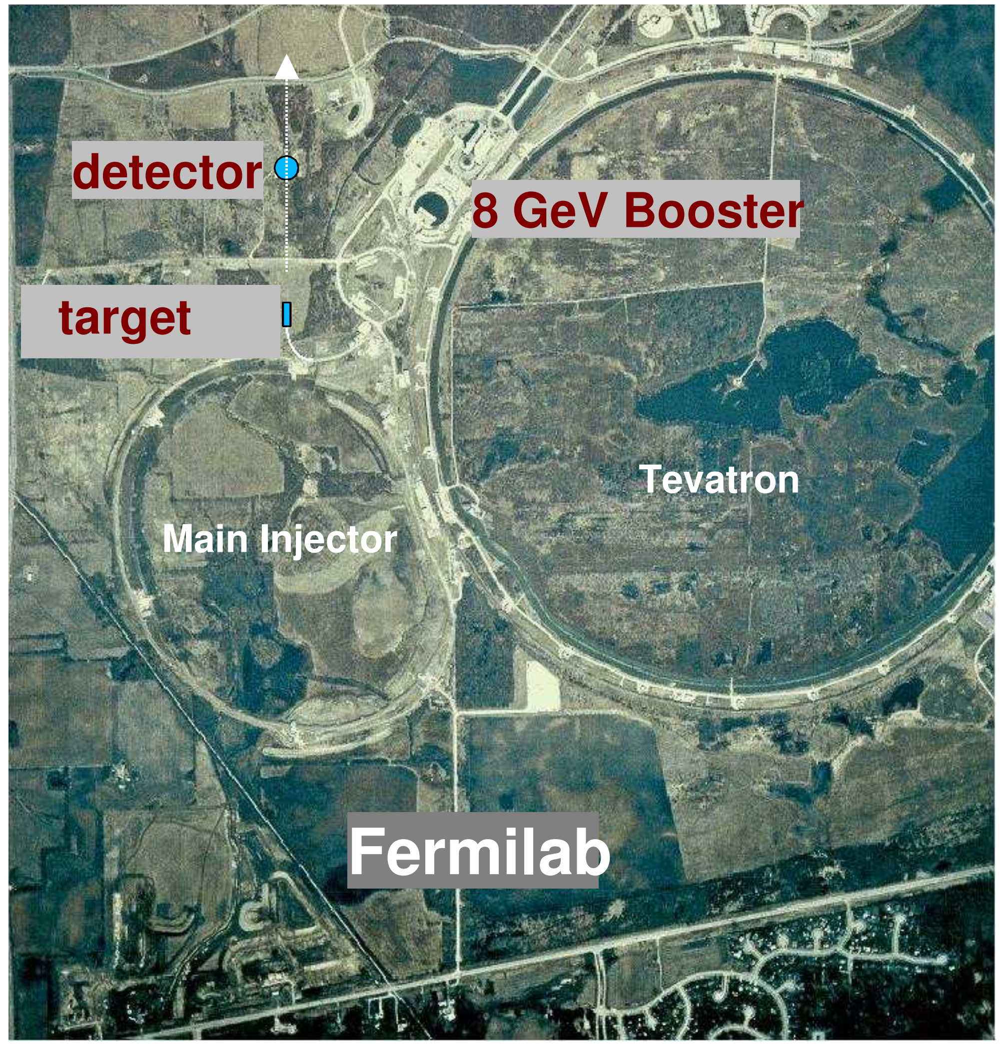
Combined analysis with KARMEN2 gives large allowed region. Confirmation is crucial!

Enter MiniBooNE

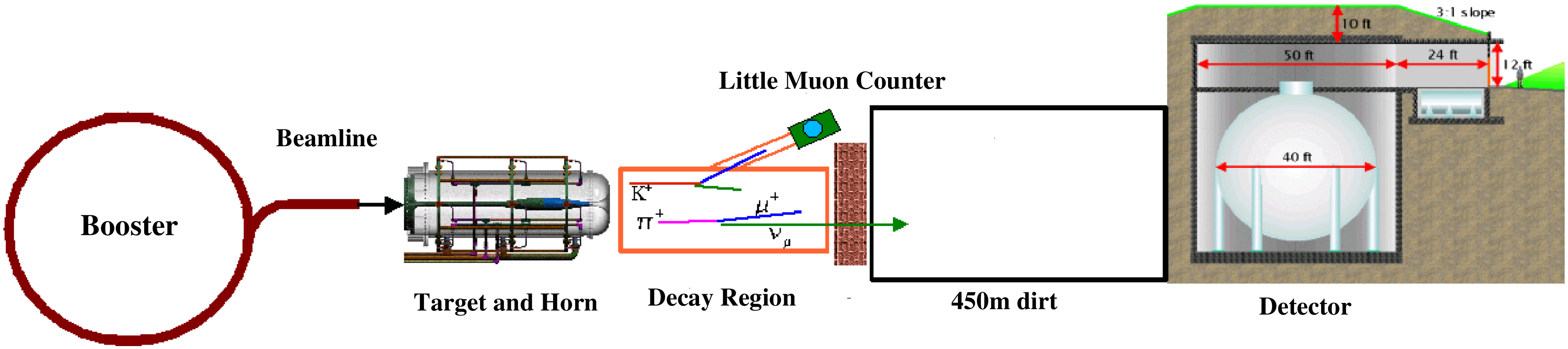
Goal: Test LSND with 5 σ sensitivity over whole allowed range.

- Higher statistics
- Different signature
- Different backgrounds
- Different systematics

MiniBooNE!



MiniBooNE Layout at Fermilab



Proton Beam

- 8 GeV protons from Booster
- Into MiniBooNE beamline

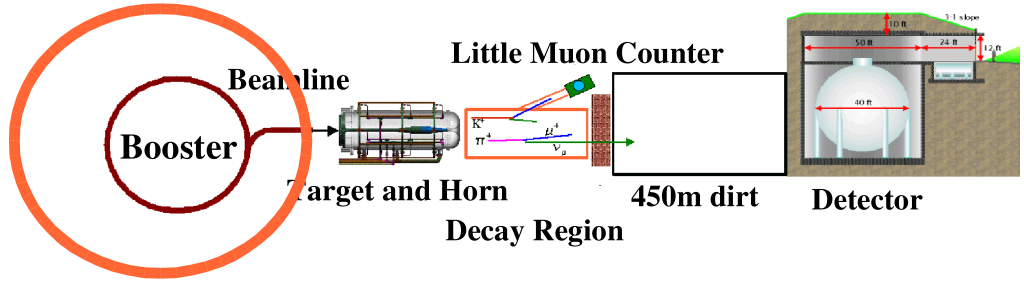
Secondary Beam

- Mesons from protons striking Be target
- Focused by horn and monitored by Little Muon Counter

Neutrino Beam

- Neutrinos from meson decay in 50 m pipe
- Pass through 450 m dirt (and oscillate?) to reach detector

The Booster

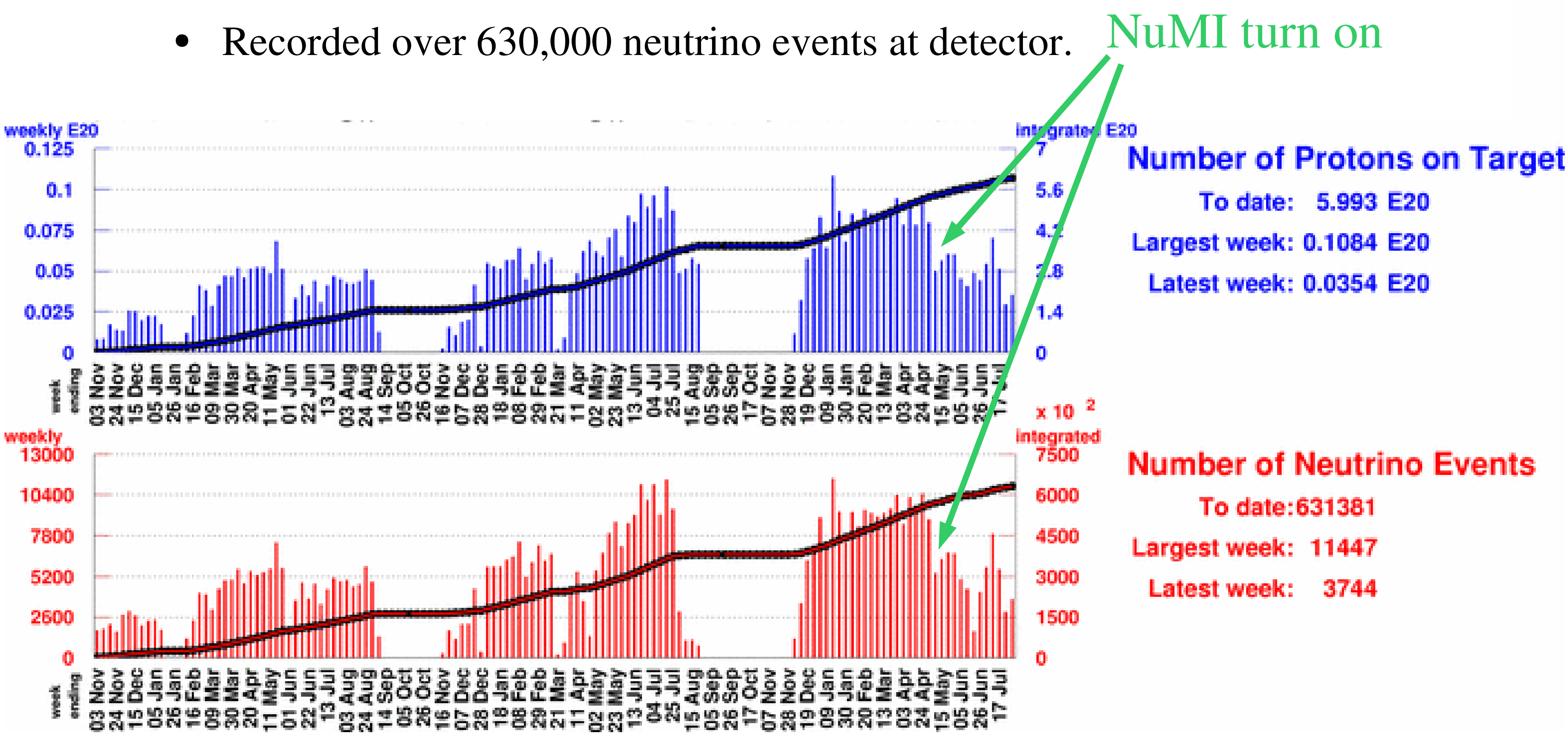


- 8 GeV proton accelerator supplies beam to all Fermilab experiments.
- To meet demands of all experiments the Booster runs at record intensity.
- MiniBooNE runs simultaneously with collider program with negligible impact on their operations.

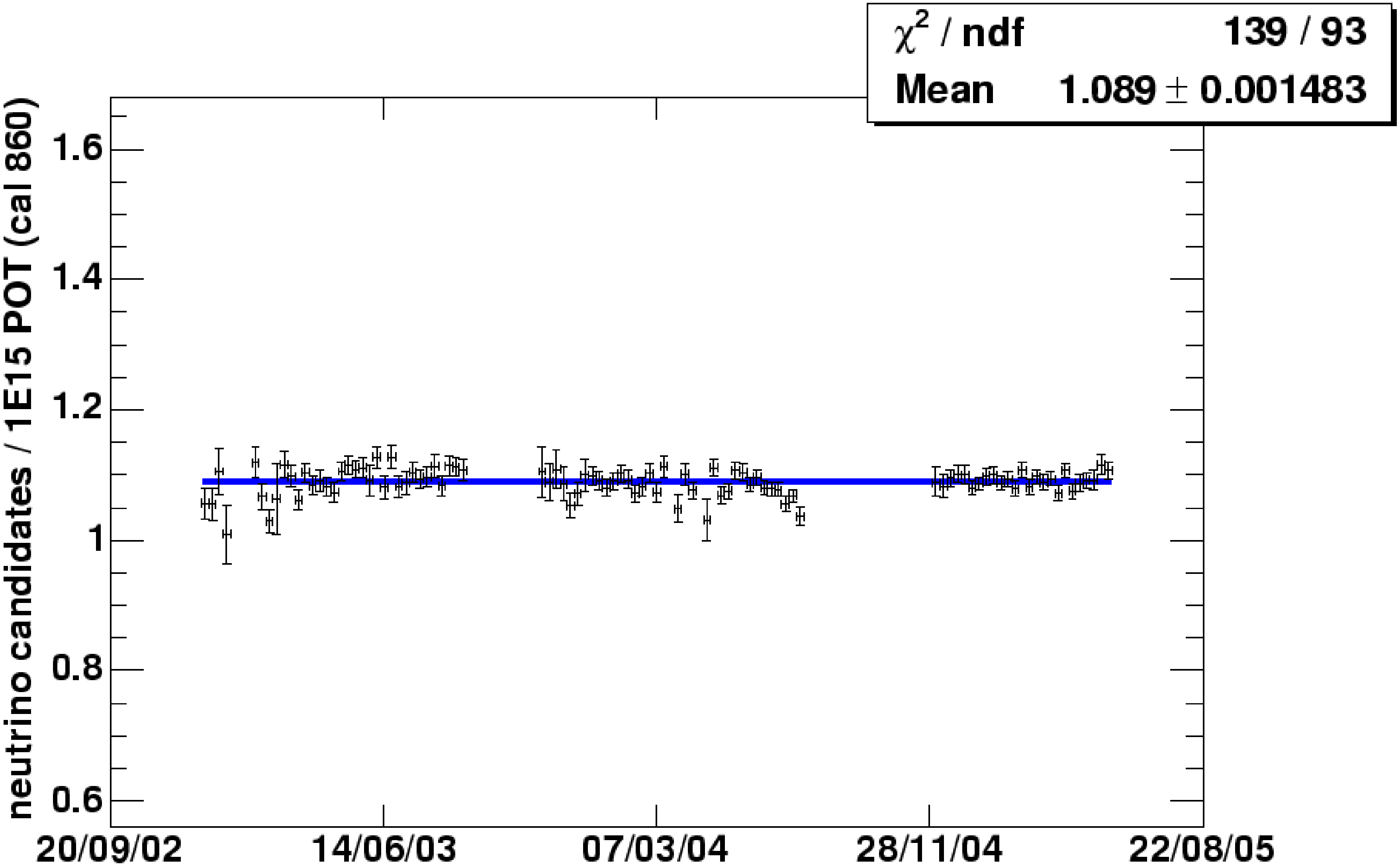
Booster → MiniBooNE
Booster → Main Injector → antiproton source
Main Injector → TeVatron
Main Injector → NuMI
Main Injector → 120 GeV fixed target

Protons and Neutrinos to MiniBooNE

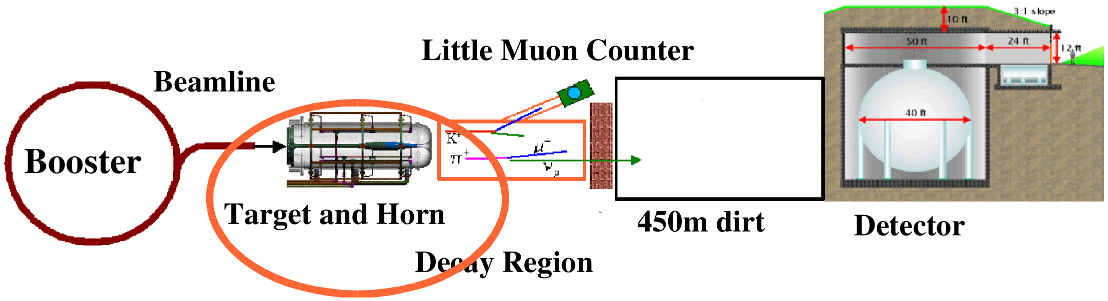
- MiniBooNE has been taking data for a little over 2 ½ years.
- Note that MiniBooNE has
  - Received 6×10^{20} protons on target
  - Recorded over 630,000 neutrino events at detector.



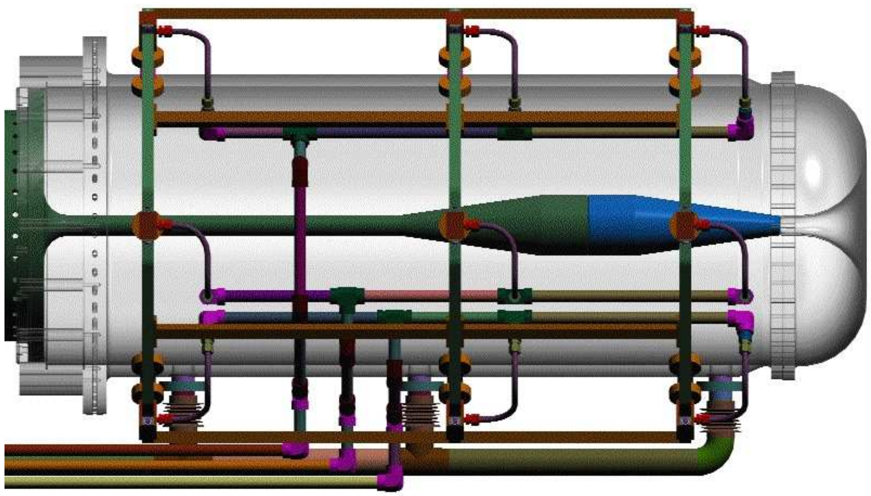
Neutrino Candidates/Protons on Target



Magnetic Focusing Horn Basics



- A horn focuses charged particles through a magnetic field.
- The MiniBooNE horn generates a toroidal magnetic field between its conductors through an electric current going
  - along the inner conductor
  - back down the outer conductor along the opposite direction
- Focusing the neutrino parents increases the neutrino flux at the downstream detector.

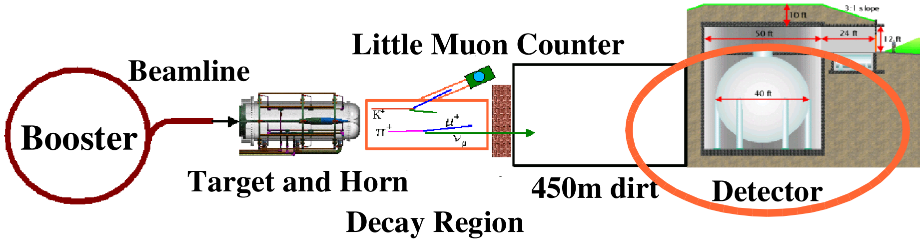


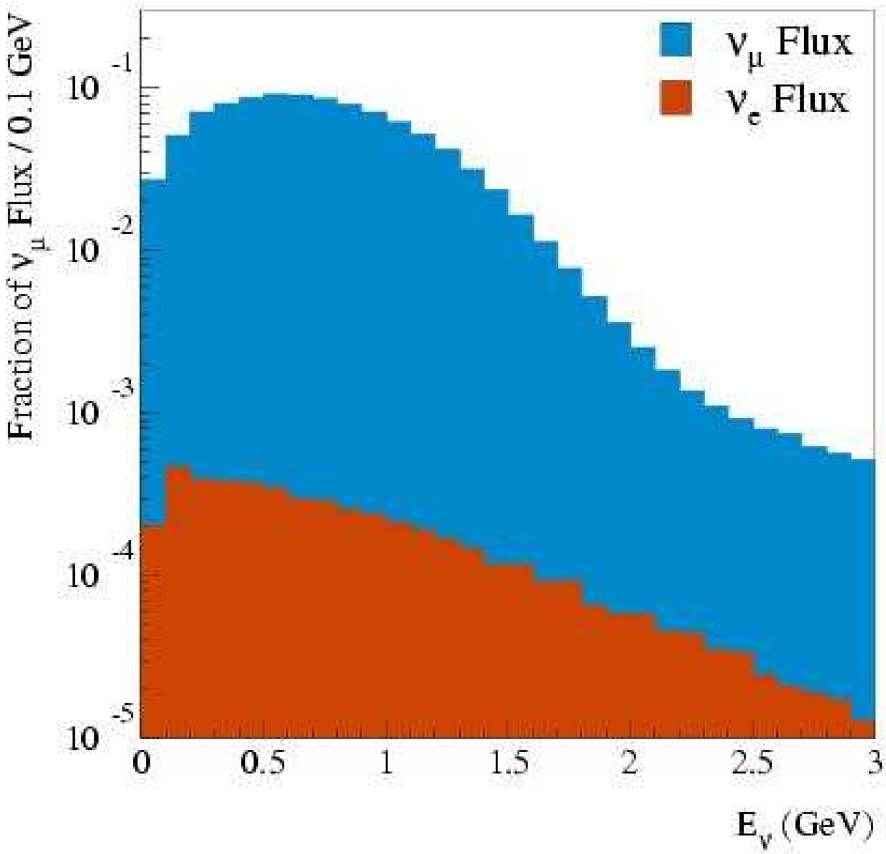
Target and Magnetic Focusing Horn

- Protons impinge on 71cm long, air cooled beryllium target embedded in horn.
- Horn focusing of secondary beam increases ν flux by factor of ~7.
- Horn current can be reversed to select $\bar{\nu}$.
- $\bar{\nu}$ running possible for 2006.
- 170 kA pulses, 143 μs long at ~5 Hz.

- First horn lasted over 90 million pulses.
- Current horn has received over 35 million pulses.

Expected ν Flux at MiniBooNE Detector



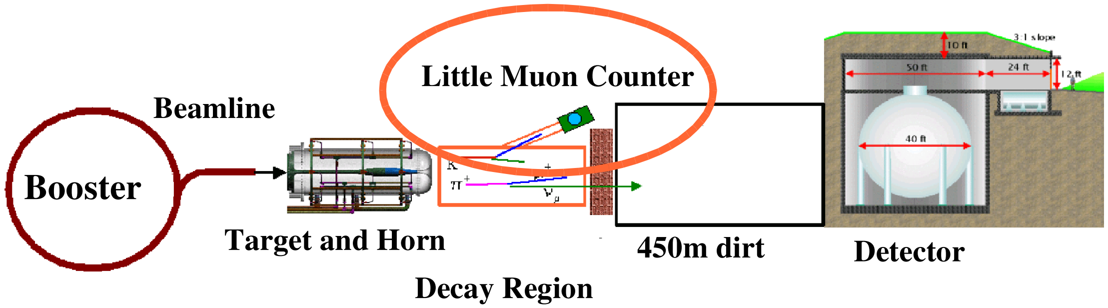


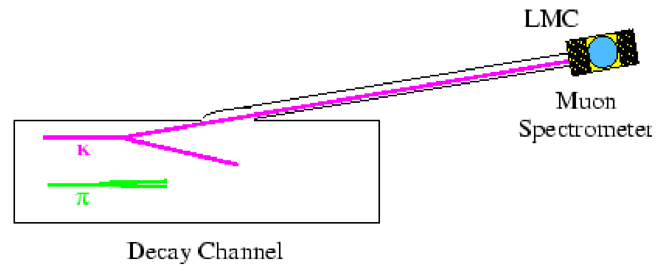
Signal ν_e's: ν_e's from ν_μ oscillations

Intrinsic ν_e's: ν_e's from kaon and muon decay

- Fluxes generated with GEANT4-based beam Monte Carlo.
- Intrinsic ν_e flux about 3 orders of magnitude smaller than ν_μ flux but ν_e flux from kaons not well measured.
- Intrinsic ν_e flux is comparable to ν_e's from oscillations.
- Sources of intrinsic ν_e's will be constrained through
  - Observed ν_μ (from μ decay) rate at detector
  - Absorbers at 25 m and 50 m from target.
  - Improved particle production modeling.
  - Cross section measurements from HARP and Brookhaven E910.
  - In situ kaon monitoring with the Little Muon Counter.

Little Muon Counter





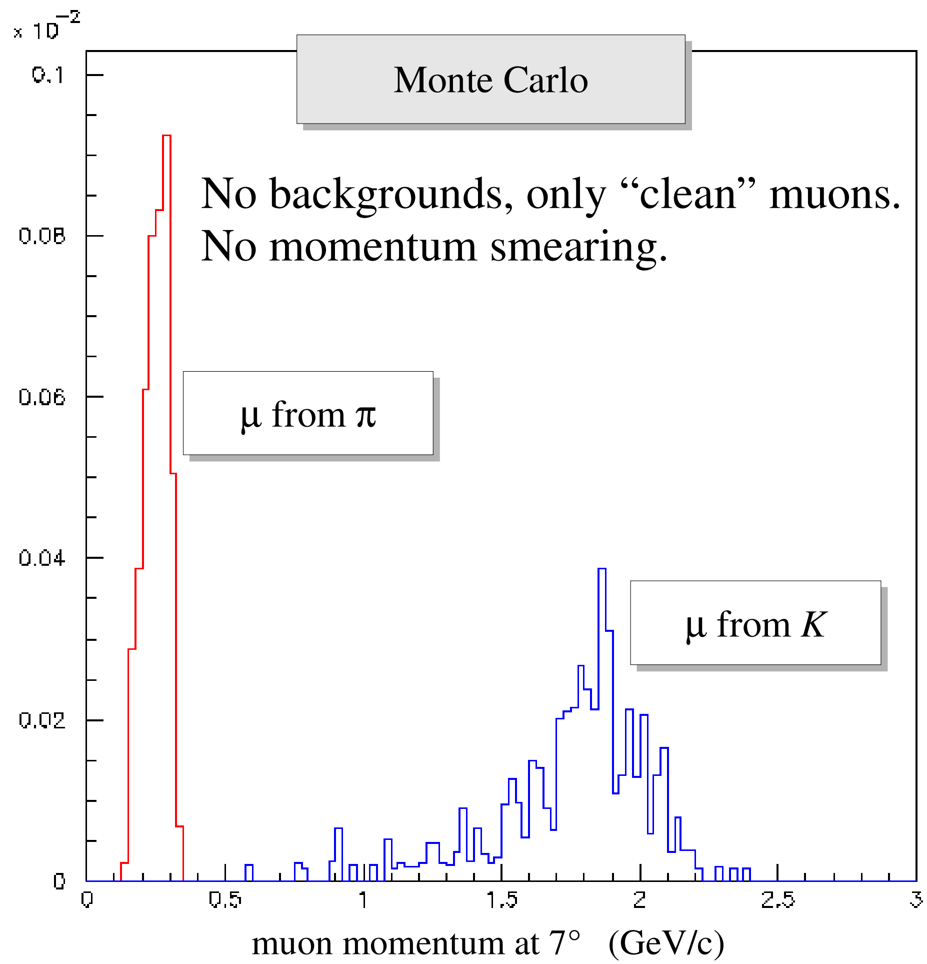
- The LMC will measure momenta of muons from

  $K \rightarrow \mu\,\nu,\ \pi\,\mu\,\nu$ ($p_{T,max}$ = 236 MeV/c, 216 MeV/c)

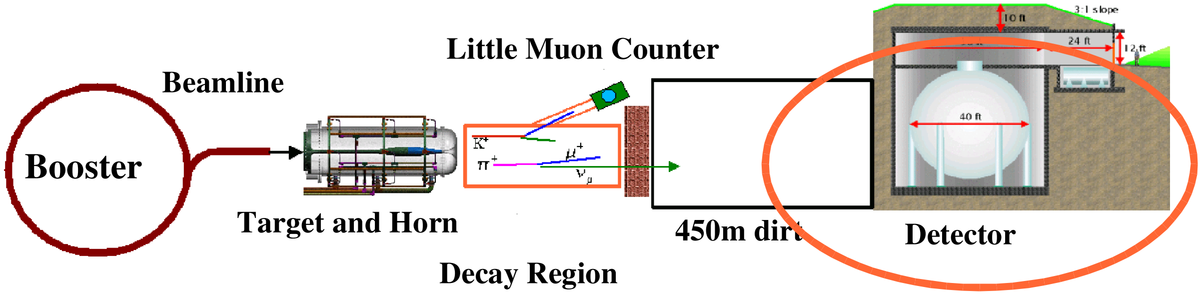
  $\pi \rightarrow \mu\,\nu$ ($p_{T,max}$ = 30 MeV/c)

- At large angles, high momentum muons come from kaons.

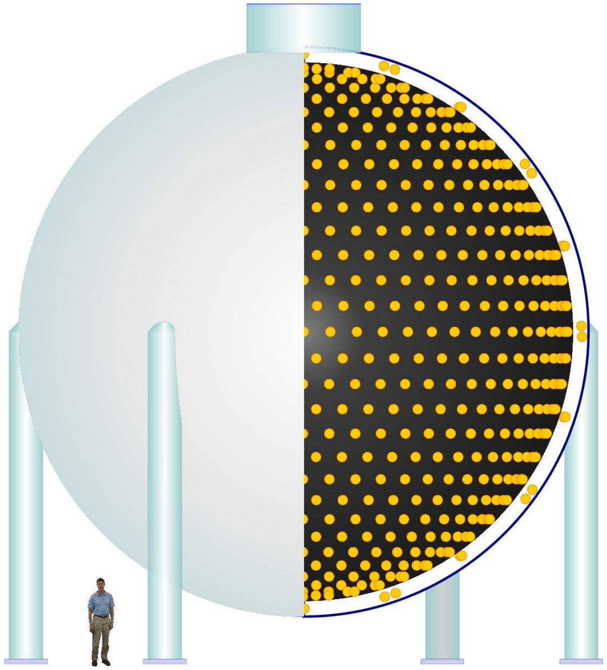
- Goal: Determine the rate of ν_e's from kaons to less than 10% uncertainty.



The Neutrino Detector



- 40' (12 m) diameter sphere
- 250,000 gallons of pure mineral oil
  (3:1 Cherenkov:scintillation light output)
- Optically isolated inner region with 1280 PMT's (10% coverage)

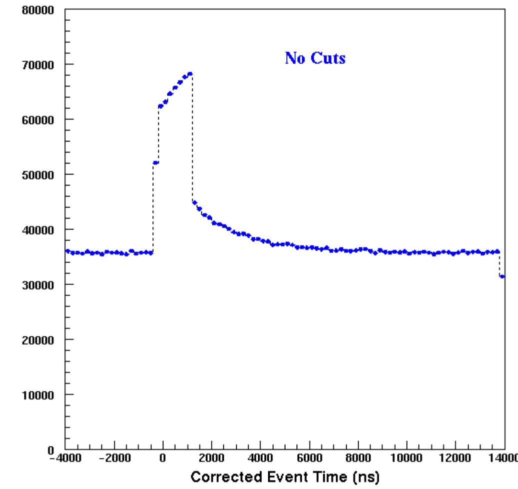


- Veto region (240 PMT's)
- Muon tracker for cosmic rays

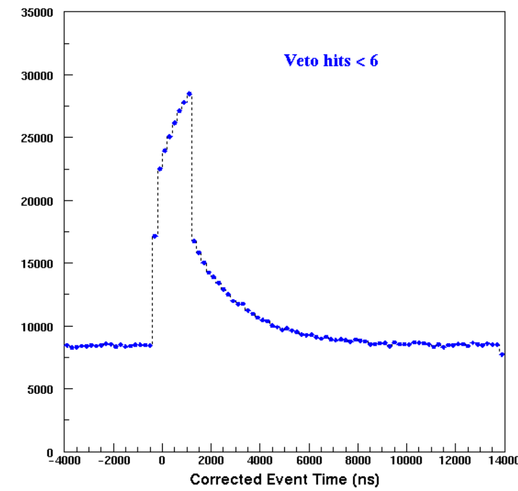
Selecting Beam Events

- MiniBooNE DAQ collects data during 20 μs window starting just before beam pulse.
- Even with no cuts, the 1.6 μs beam pulse is clearly visible.
- With 2 simple cuts, our signal-to-noise ratio is about 1000/1.
- Unlike LSND, non-beam backgrounds aren't a concern for MiniBooNE.

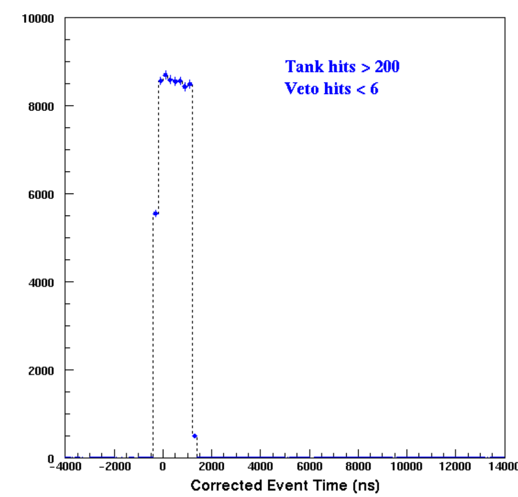
No Cuts



Veto hits < 6



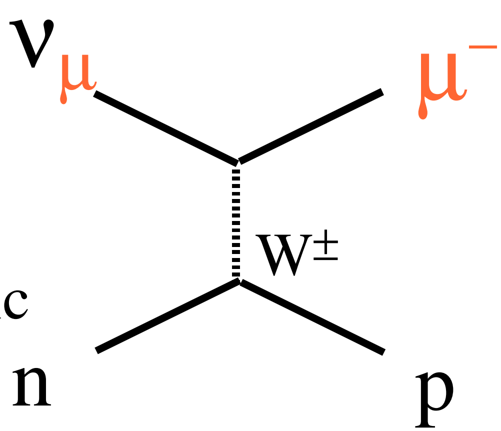
Veto hits < 6
Tank hits > 200

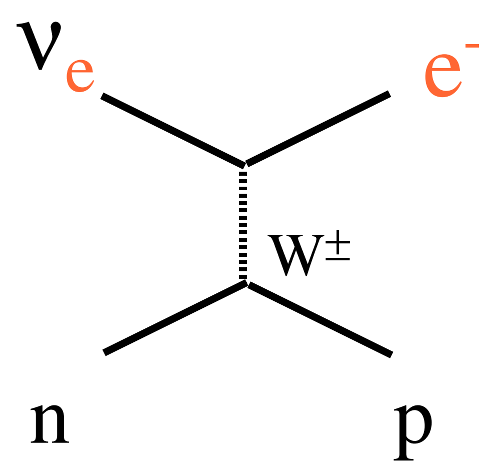


Seeing ν_μ and ν_e Interactions in the Detector

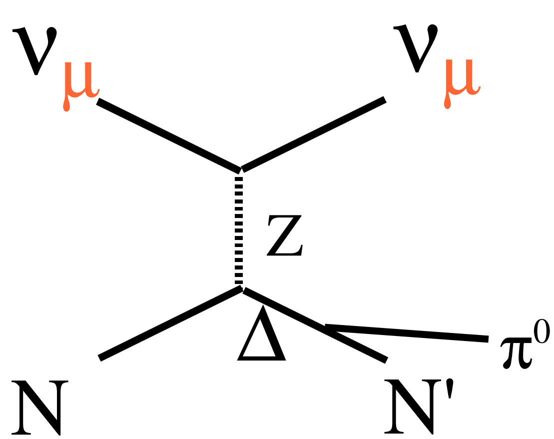
Look for outgoing charged particles produced with no activity in the veto.

charged current quasi-elastic

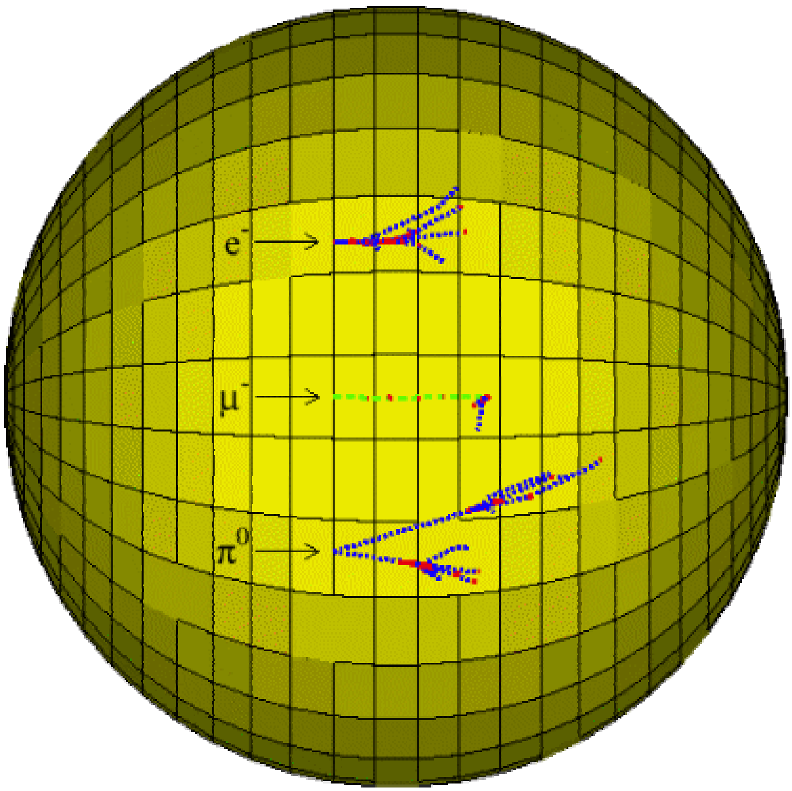


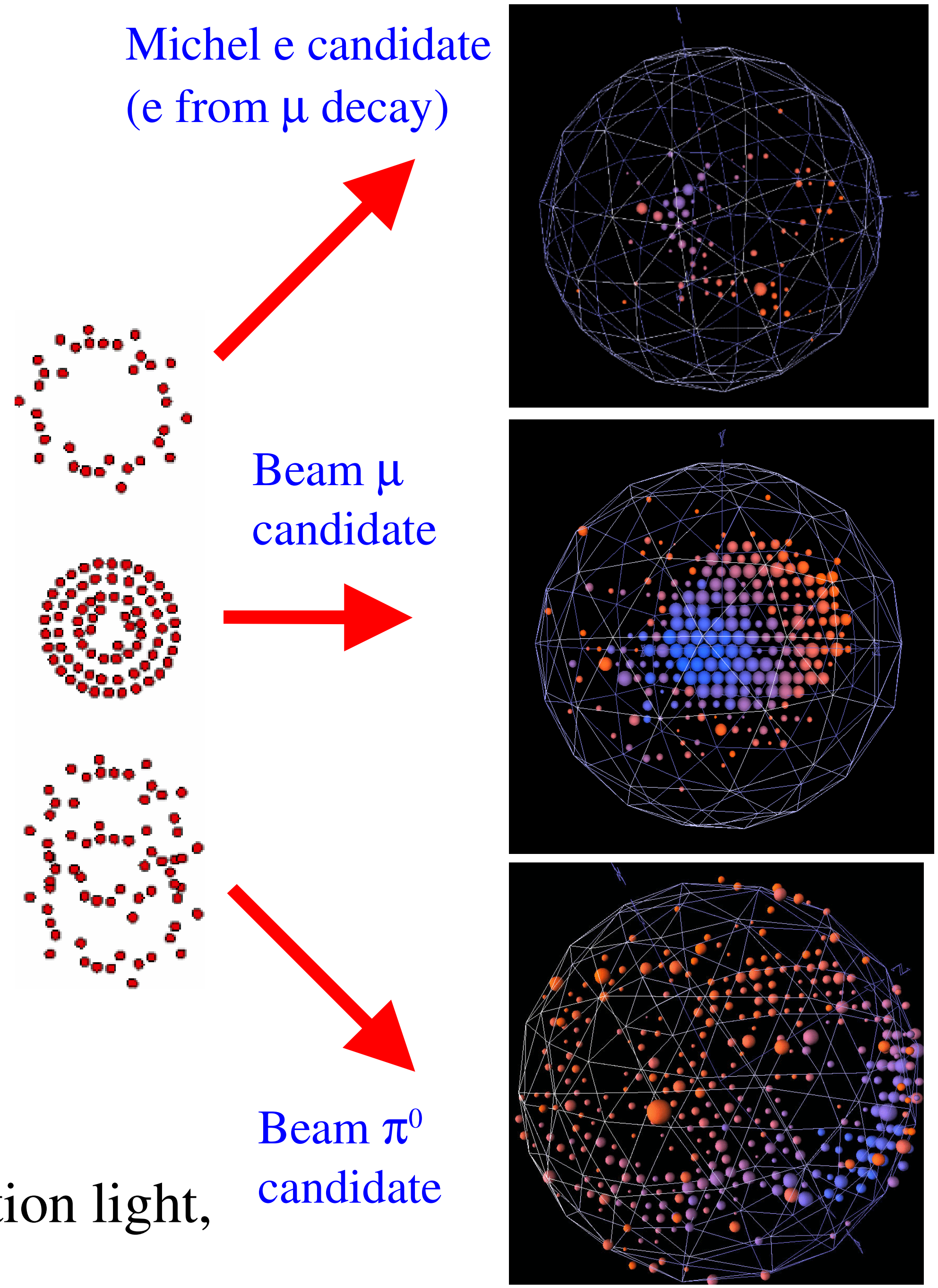


single pion production



Particle ID

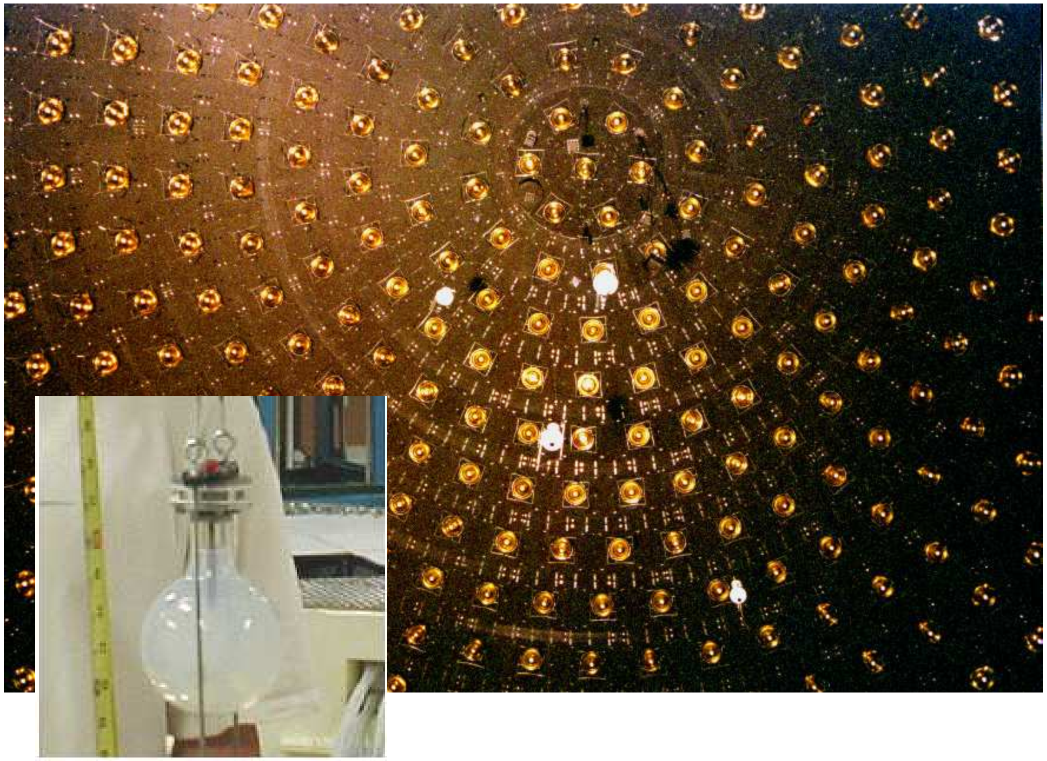




PMT's measure:

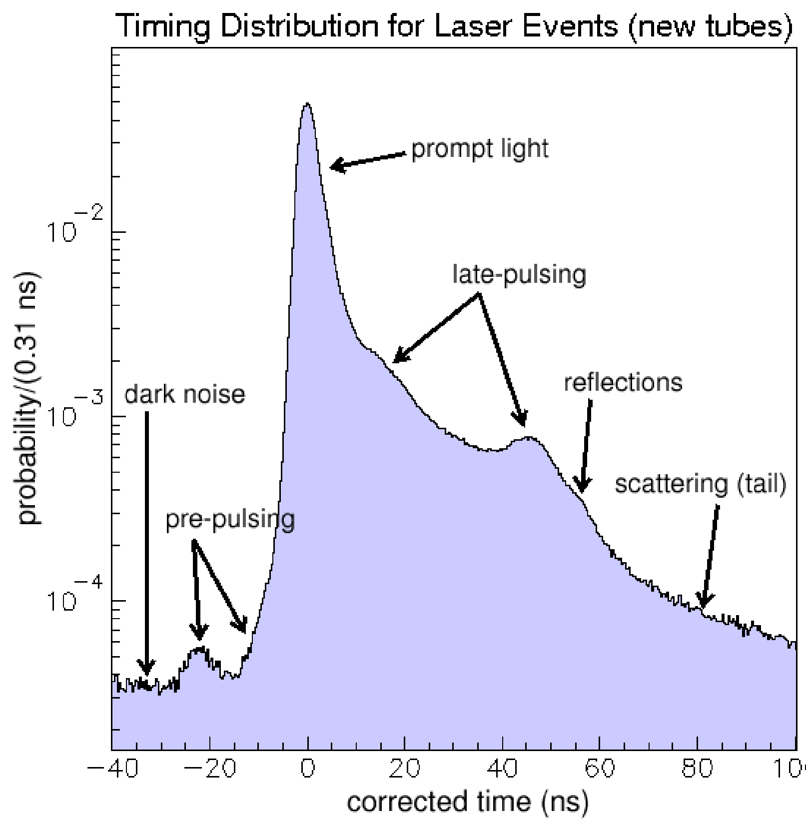
- Charge (Cherenkov and scintillation light, light output ∝ size.)
- Times (Red is early, Blue is late.)

Understanding the Detector



Laser Flasks

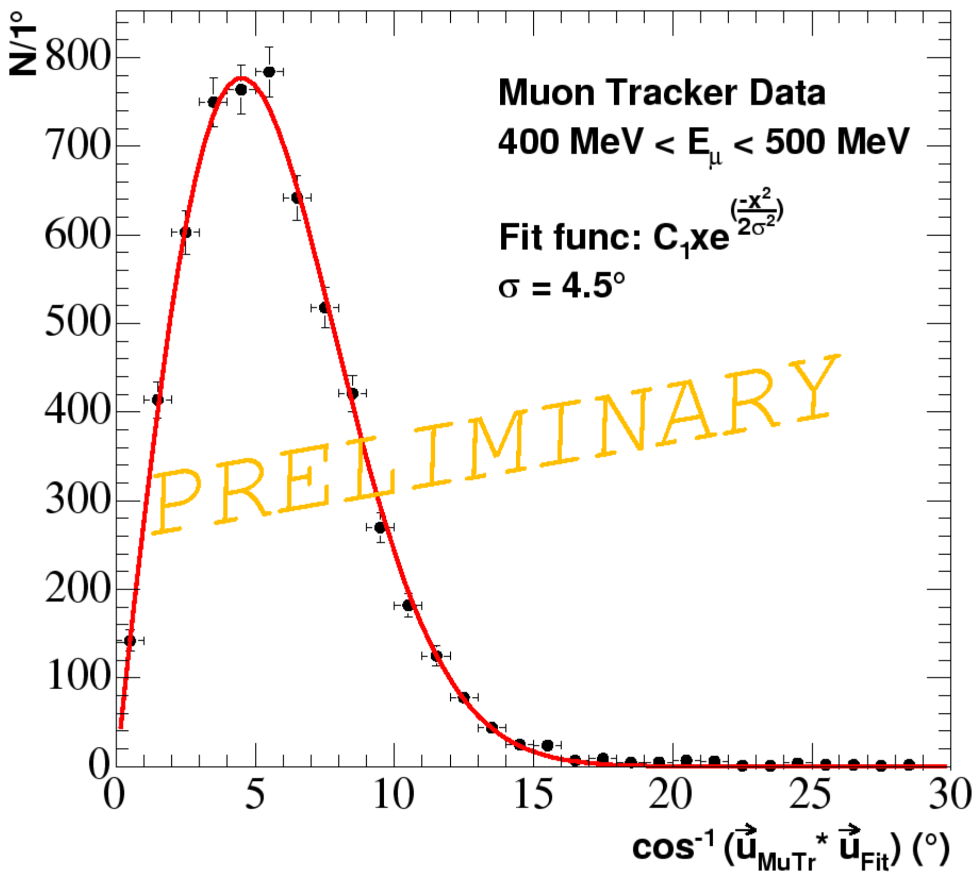
- 397 nm laser light
- Four Ludox-filled flasks fed by optical fiber from laser



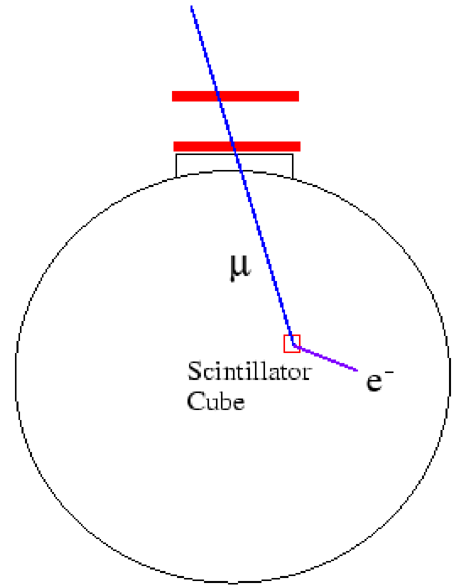
To calibrate PMT's, we measure

- PMT charge
- Timing response
- Oil attenuation length

Stopping Muon Calibration System



Scintillator tracker above the tank



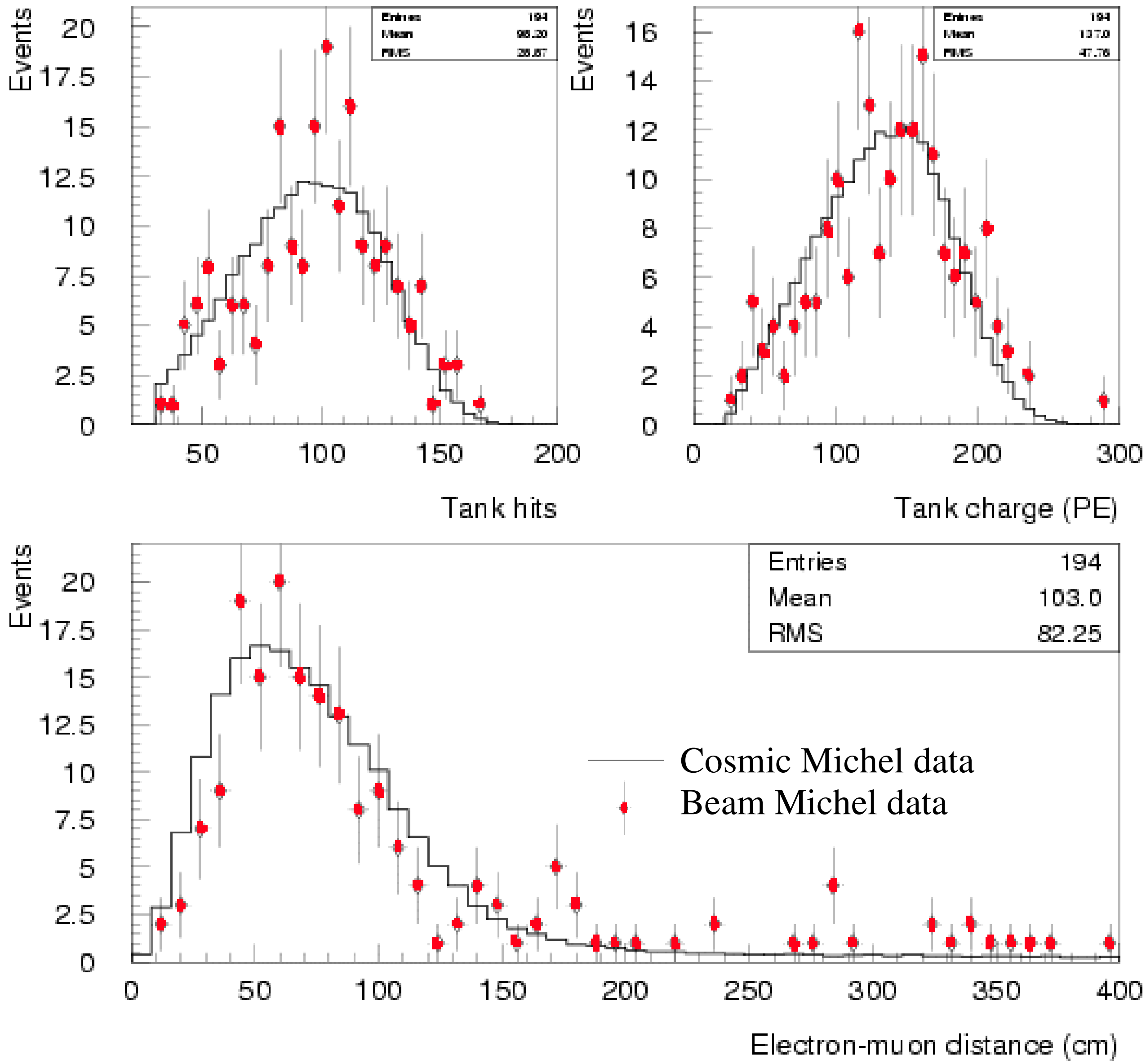
Sample consists of muons with energies up to 700 MeV. This sample calibrates
- energy measurements
- vertex reconstruction
- angle reconstruction

Optically isolated scintillator cubes in tank:

- six 2-inch (5 cm) cubes
- one 3-inch cube

Cosmic Ray/Beam Data Agreement

Cosmics and beam data agree $\Rightarrow$ cosmics good for calibration

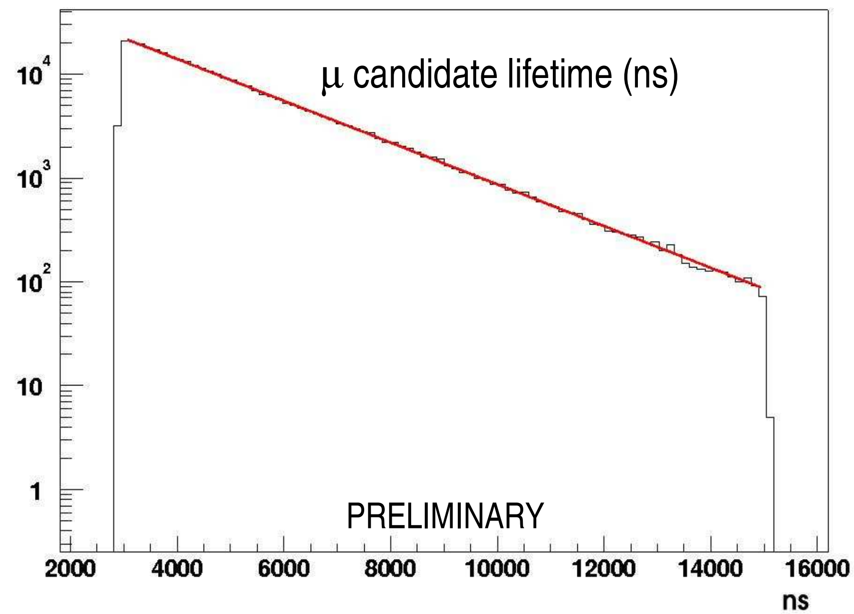


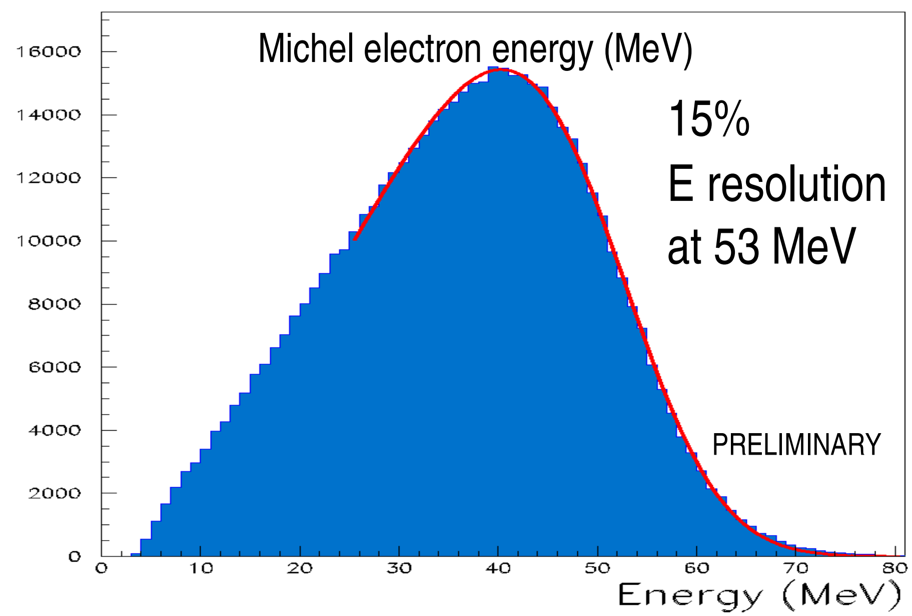
Michel Electron Measurements

(electrons from the decay of stopped muons)

- Michel electrons from cosmic rays and beam-induced muons
- Cosmic ray muon lifetime in oil
  - measured: $\tau = 2.15 \pm 0.02\ \mu s$
  - expected: $\tau = 2.13\ \mu s$

  ($8\%\ \mu^-$ capture)
- Energy scale and resolution at Michel endpoint (53 MeV)

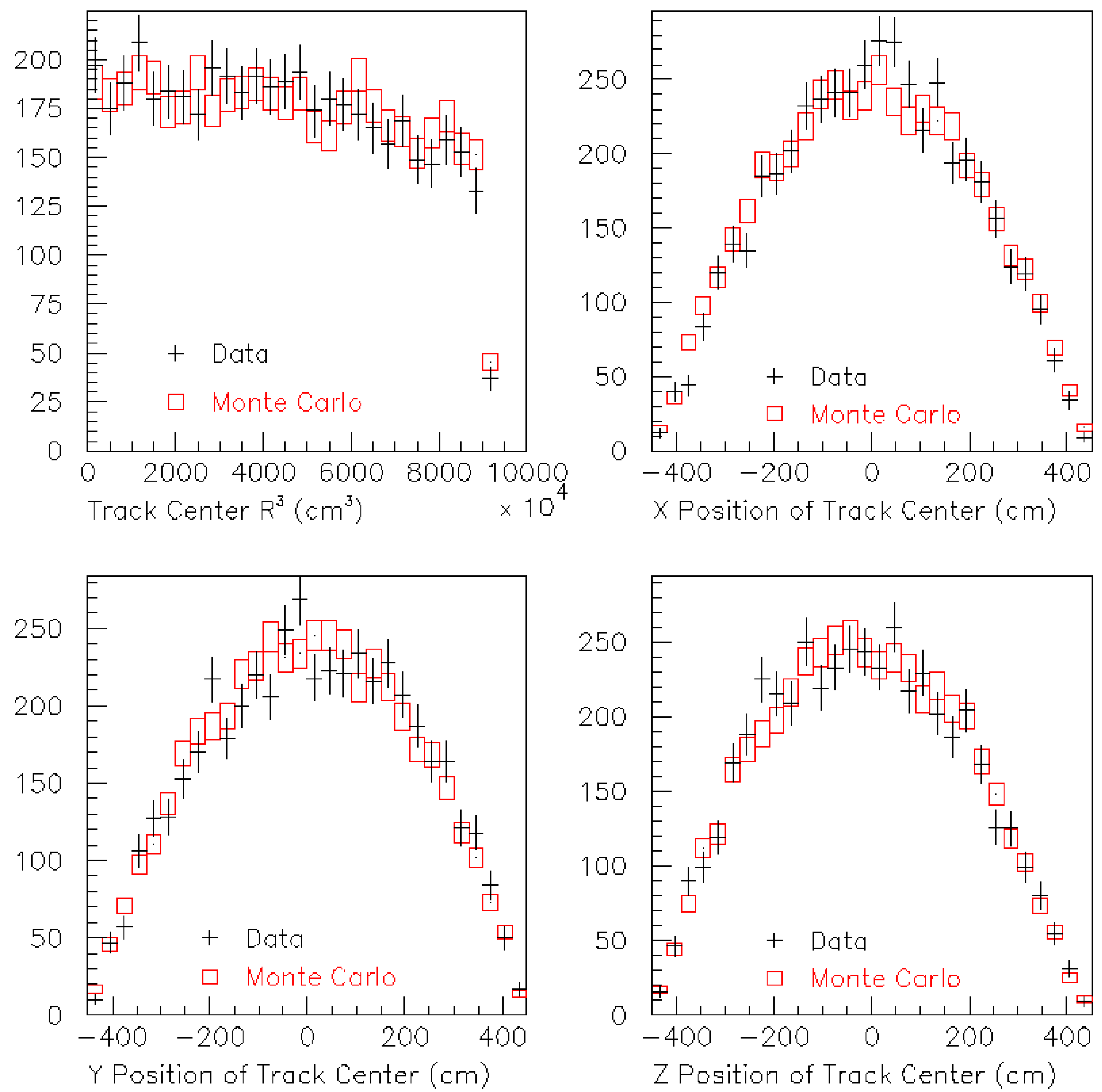




Data/MC Agreement in Vertex Reconstruction

Beam events:

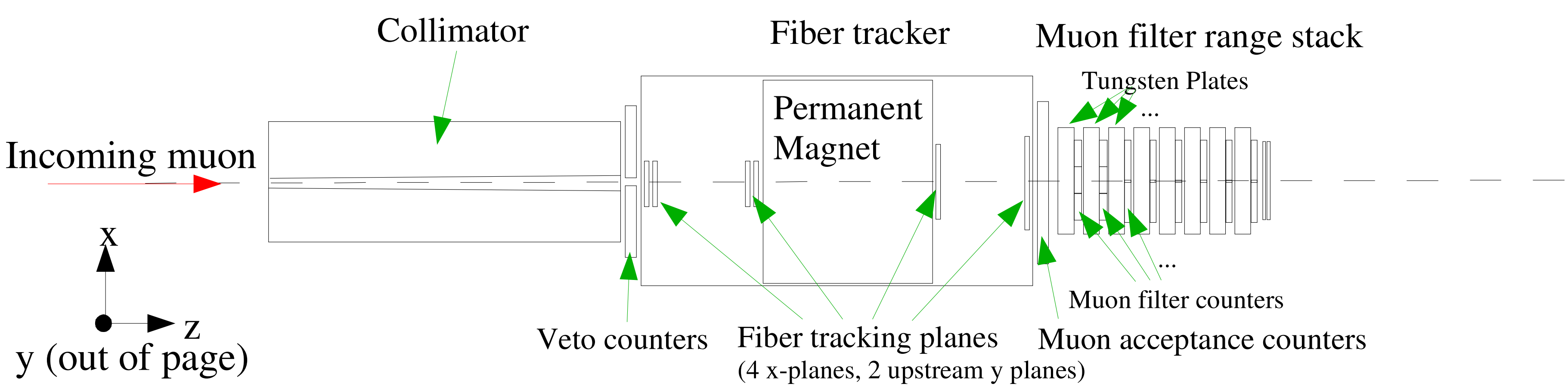
- NHIT > 200
- NVETO < 6
- r < 450cm
- Timing



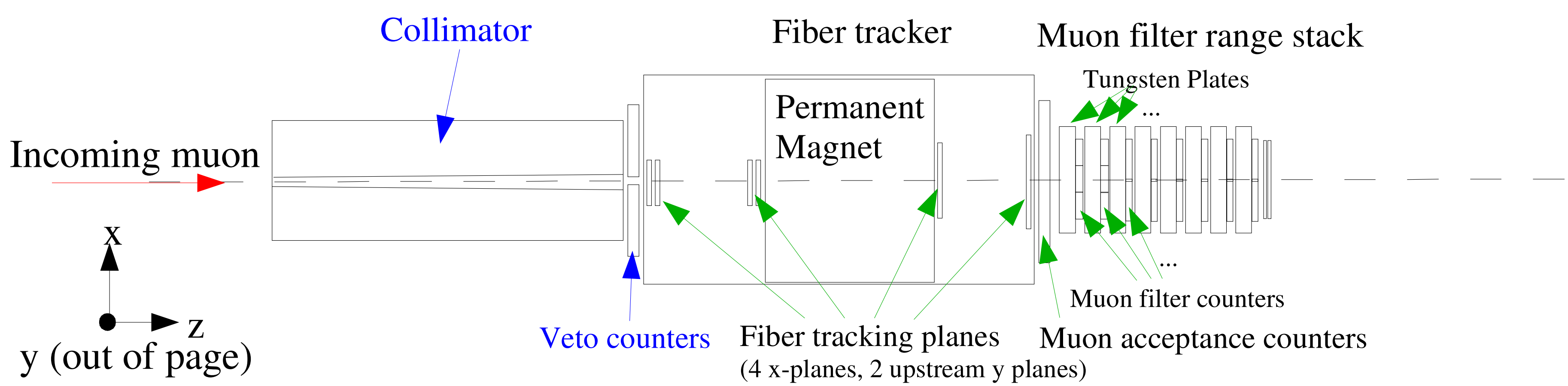
Little Muon Counter Analysis

- Description of components
- LMC event reconstruction and data
- Preliminary muon spectrum

Little Muon Counter Schematic Drawing



Little Muon Counter Collimator and Veto Counters

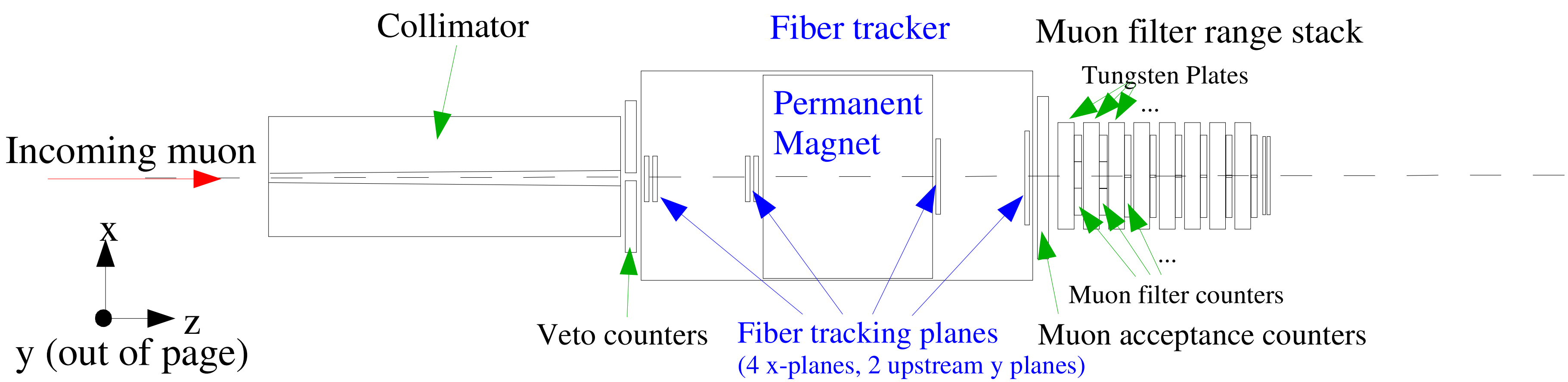


Collimator

- 81 inches long consisting of steel with inner tungsten core.
- Inner hole tapered so that tracks traveling down the hole must have originated from MiniBooNE secondary beam.
- Downstream hole diameter is 6 mm and upstream hole diameter is 10 mm.

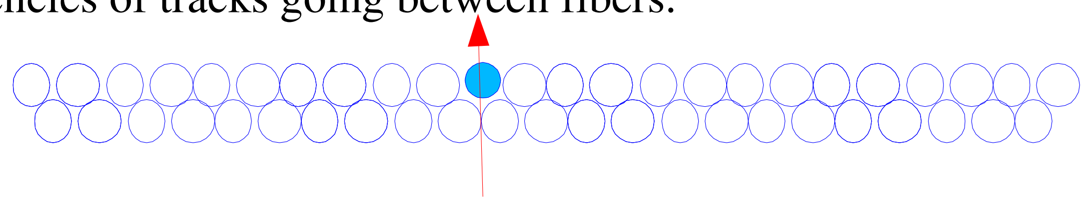
Veto counters – 4 scintillation counters between the collimator and fiber tracker surrounding downstream hole of collimator.

LMC Fiber Tracker



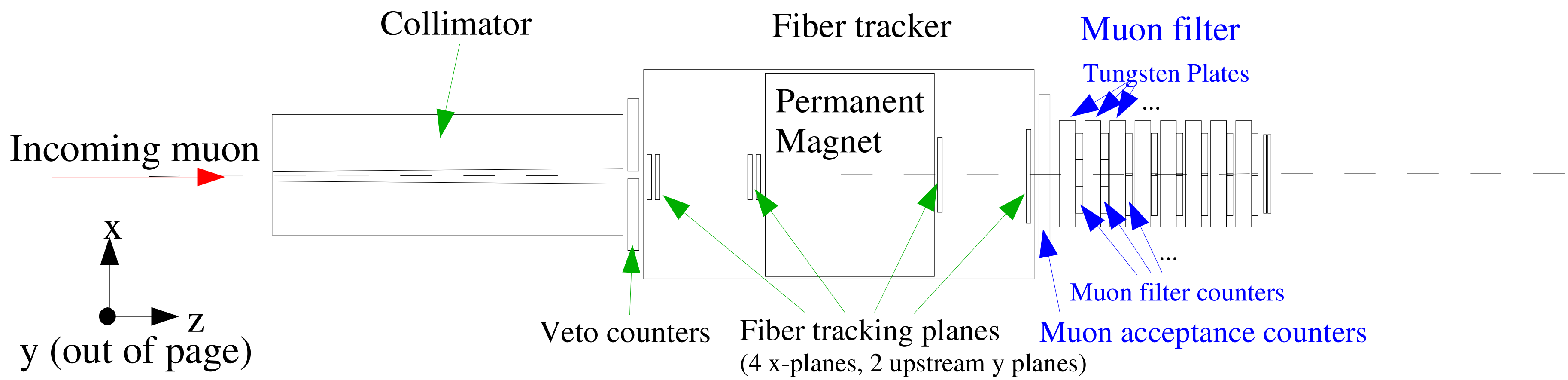
Fiber Tracker Spectrometer

- Permanent magnet provides 2.27 kgauss magnetic field over 23 cm.
- 6 planes of 1 mm diameter scintillating fibers.
  - Each of 6 planes consists of 2 parallel subplanes staggered by ½ fiber diameter to remove inefficiencies of tracks going between fibers.



  - 4 planes instrumented along magnetic field bend direction, 2 upstream of the magnet and 2 downstream of the magnet.
  - 2 planes instrumented along direction perpendicular to both bend direction and beam direction, both upstream of the magnet.

Little Muon Counter Muon Acceptance Counter and Muon Range Stack

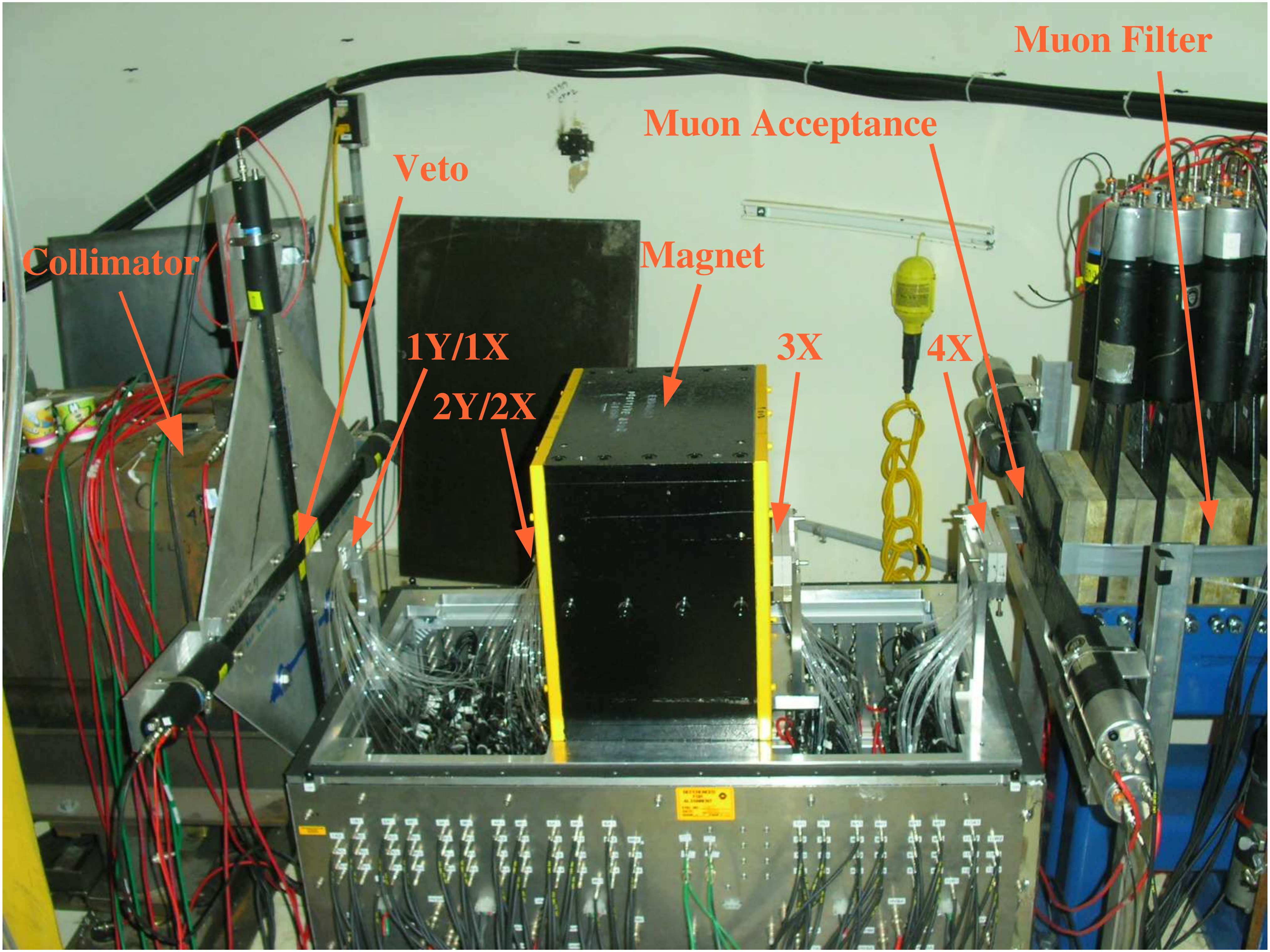


Muon Acceptance Counters – 4 scintillation counters after tracker

- 2 counters in LMC beamline
- 1 counter above beamline and 1 below beamline

Muon Filter – Range stack to identify muons

- 8 layers of alternating tungsten sheets and scintillation counters.
- Each tungsten layer is 2 inches thick.
- 1.3 GeV/c and higher muons will penetrate all 8 layers.

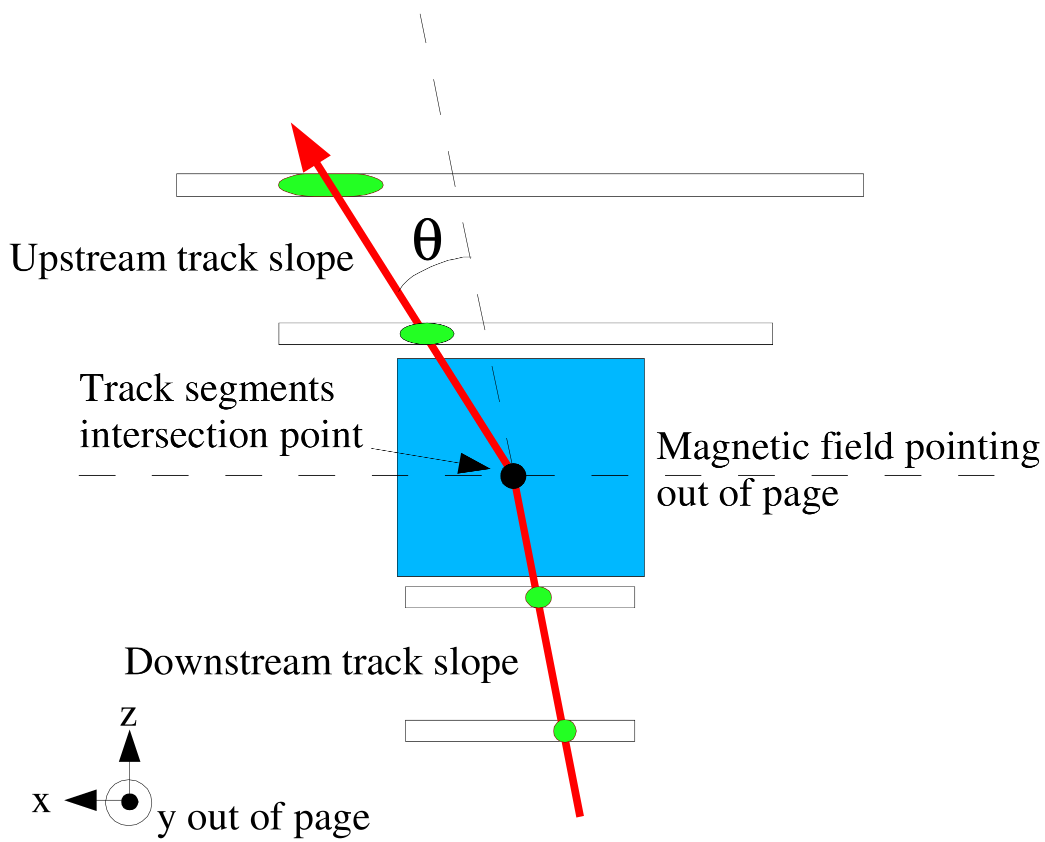


Muon Filter
Muon Acceptance
Veto
Magnet
Collimator
1Y/1X
2Y/2X
3X
4X

LMC Event Reconstruction

- Coincidences from 6 layers of the scintillating fiber tracker are formed.
  - All hits within 5 ns of the mean time of hits are kept.
  - We allow for multiple hit combinations in a coincidence.
- For each 6-fold coincidence, a tracking algorithm determines
  - momentum
  - momentum uncertainty
  - a track reconstruction χ^2 for the 4 x-hits (magnet field bend coordinate) coming from a single charged track bent by the magnetic field.
- All hits from the filter, veto counters, and muon acceptance counters within 5 ns of the tracker coincidence mean time are added to the event.
- A filter penetration range is determined from the filter hits
  - Muon momentum is proportional to range while hadrons will penetrate only one or two layers.
  - One inefficient layer is allowed in the range determination.
- LMC analysis is being done on data events and Monte Carlo samples.

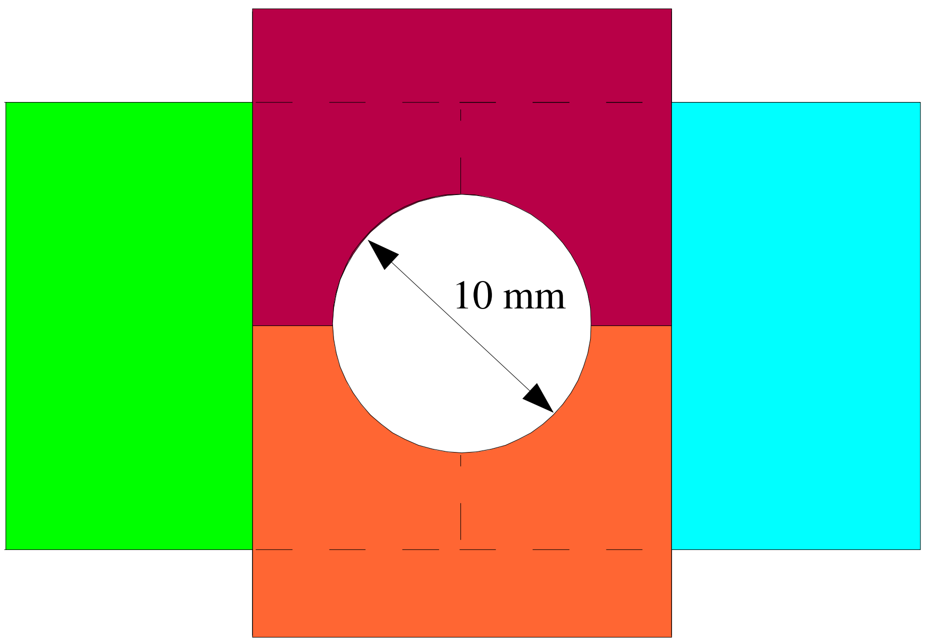
Determining Momentum With the Fiber Tracker



$p = q\,B\,L\,\cot(\theta)$
$B = 2.27$ kgauss,
$L = 23$ cm

- Small angle approximation allows track trajectory to be taken as two line segments connected at middle of magnet.
- From the locations and location uncertainties of the 4 x hits, the optimum upstream slope, downstream slope, and intersection point can be determined analytically by minimizing a χ^2.
  - 4 x hits
  - 2 slopes
  - 1 intersection point
  - $\Rightarrow \chi^2$ with one degree of freedom
- Optimization provides p, σ_p, and χ^2.

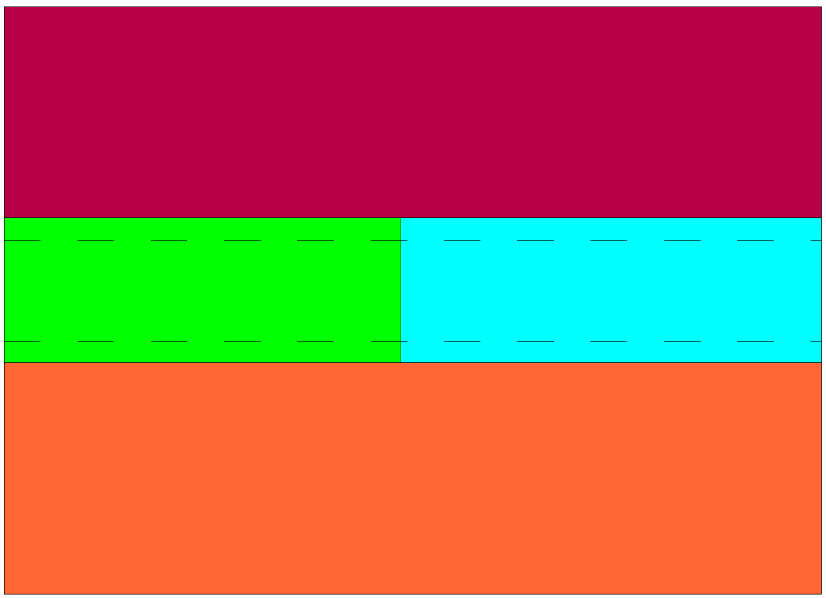
Veto Counter Arrangement



4 veto counters are between collimator and spectrometer.

The 10 mm diameter hole is the same as the downstream collimator hole diameter, and is designed to be the defining aperture of reconstructed tracks.

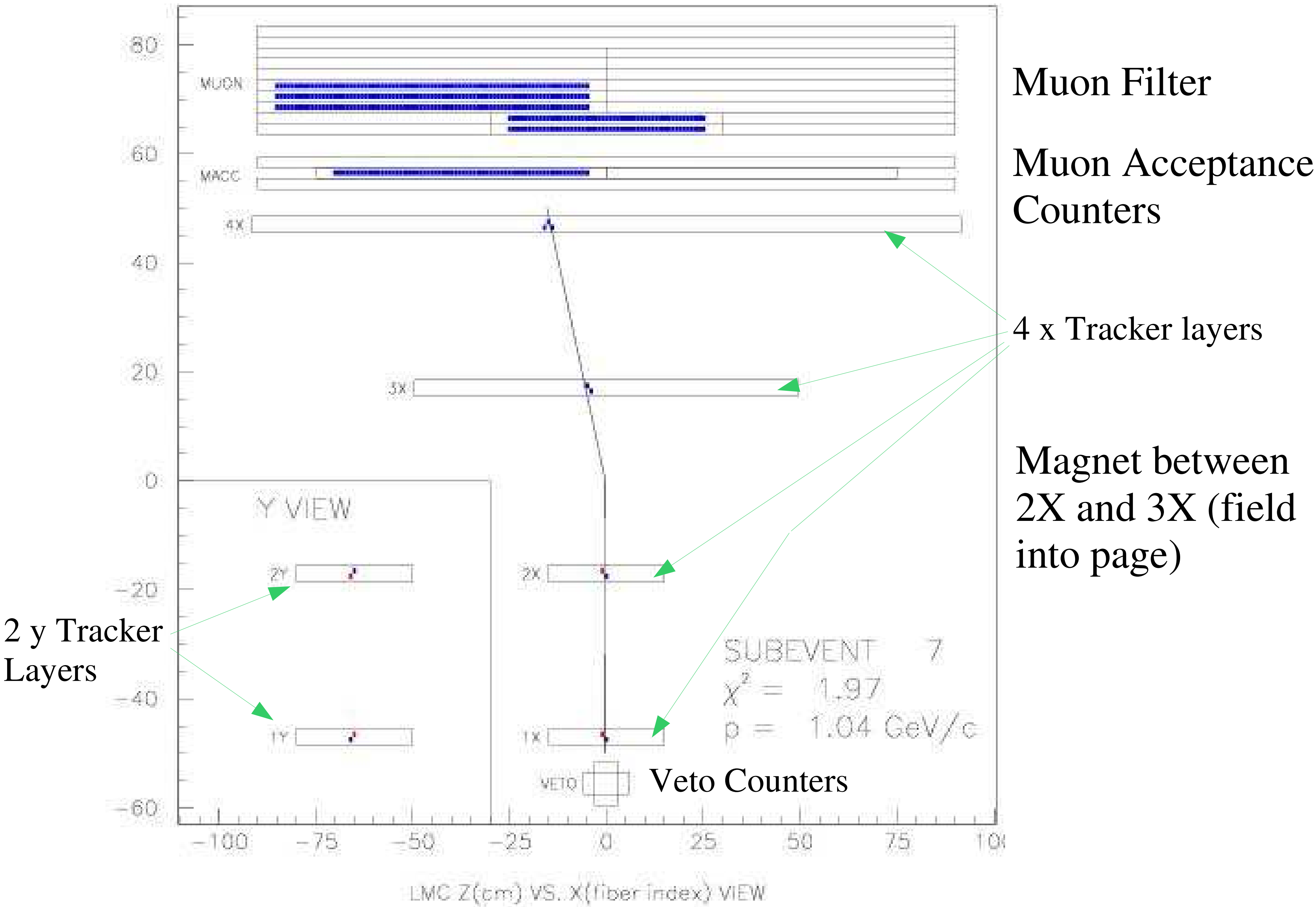
Muon Acceptance Counter Arrangement



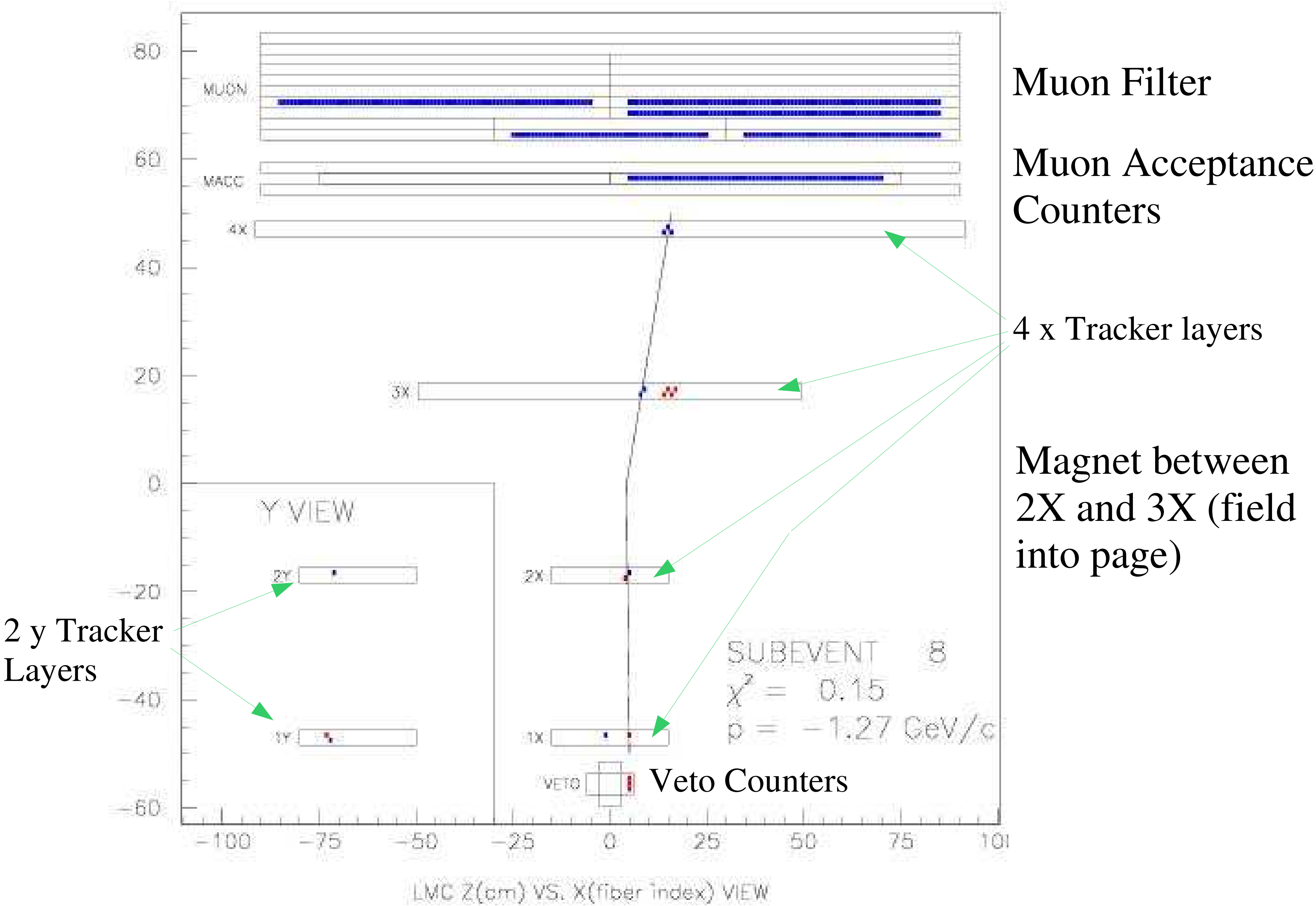
4 scintillator counters located between fiber tracker and muon range stack.

Middle two counters may be helpful in selecting tracks which went through all 6 tracker layers.

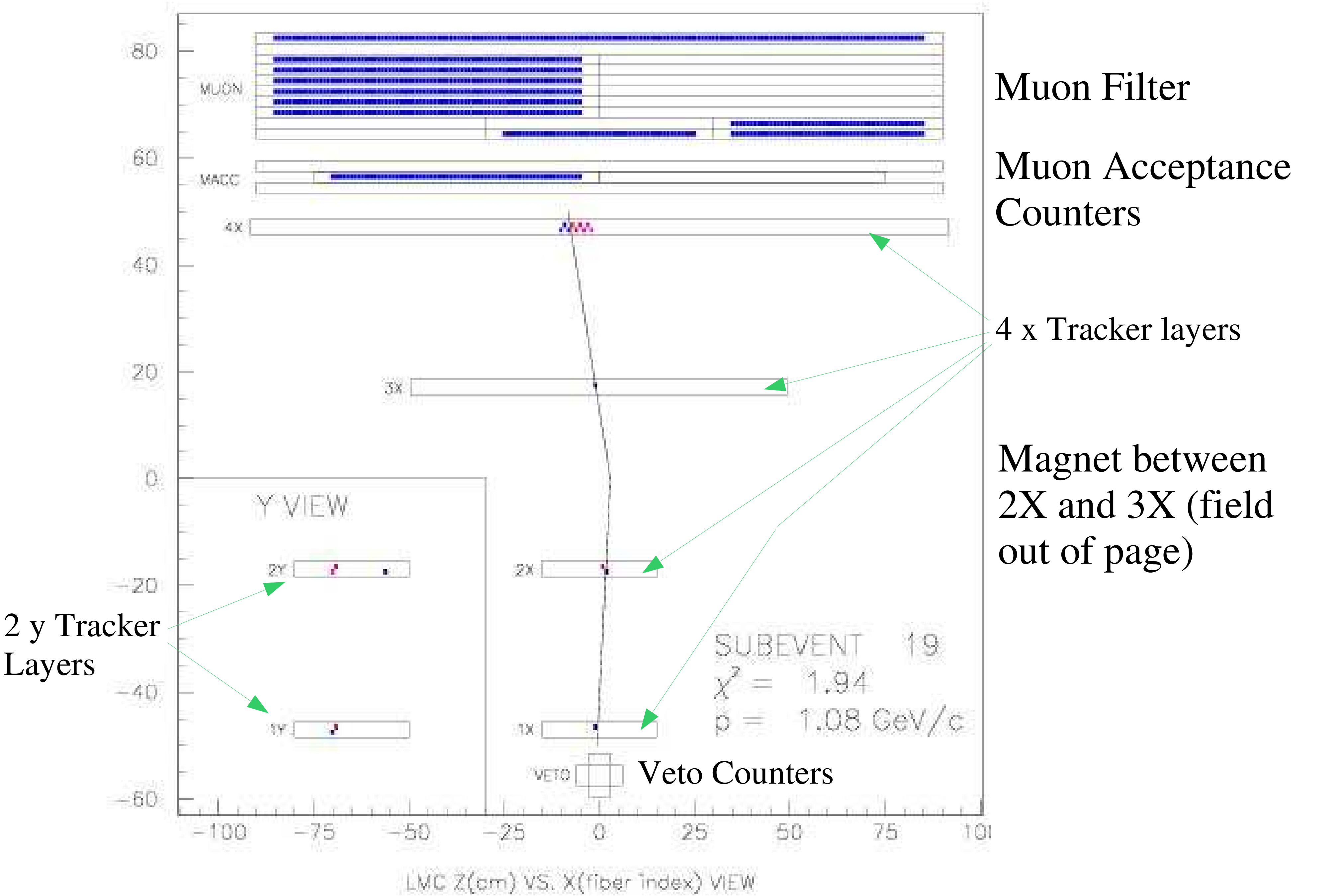
LMC Event Displays – Monte Carlo 1 GeV/c Muon



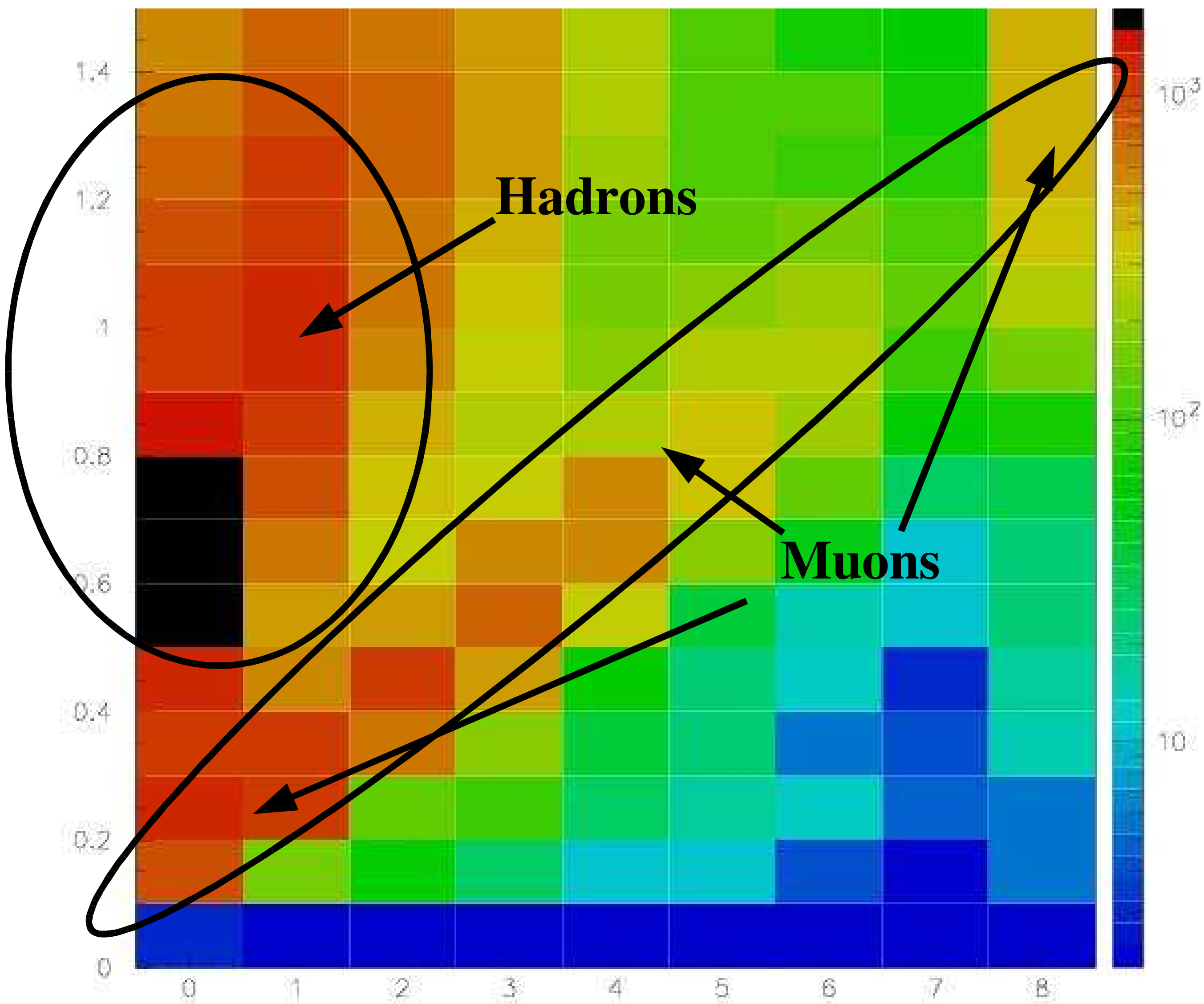
LMC Event Displays – Data Pion Candidate



LMC Event Displays – Data Muon Candidate



Momentum/Muon Range Correlation, Data

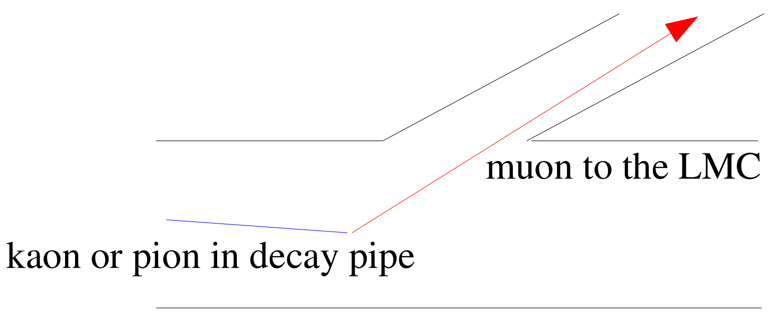


Momentum (GeV/c) vs. Range

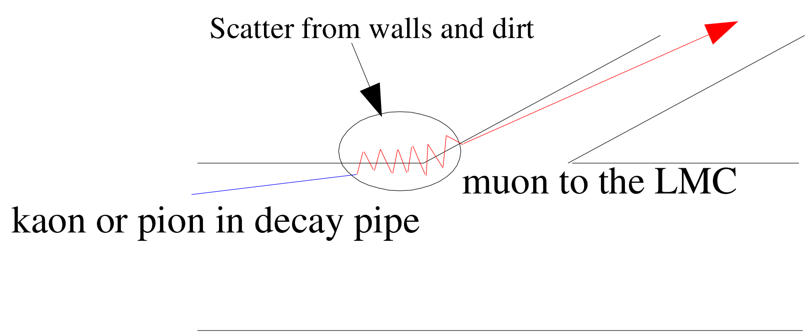
- Range (x coordinate) from muon filter.
- Momentum (y coordinate) from tracker.
- Expected distributions:
  - Muons: Momentum proportional to penetration depth.
  - Hadrons: Penetrate up to about 2 layers.
- Muon and hadron populations demonstrate
  - Momenta are well-measured by tracker.
  - Muon filter is identifying muons.

Preliminary Muon Spectrum at the LMC, Signal and Background Muons

Clean muons: Signal for muon spectrum.



Dirt muons: Background to muon spectrum.

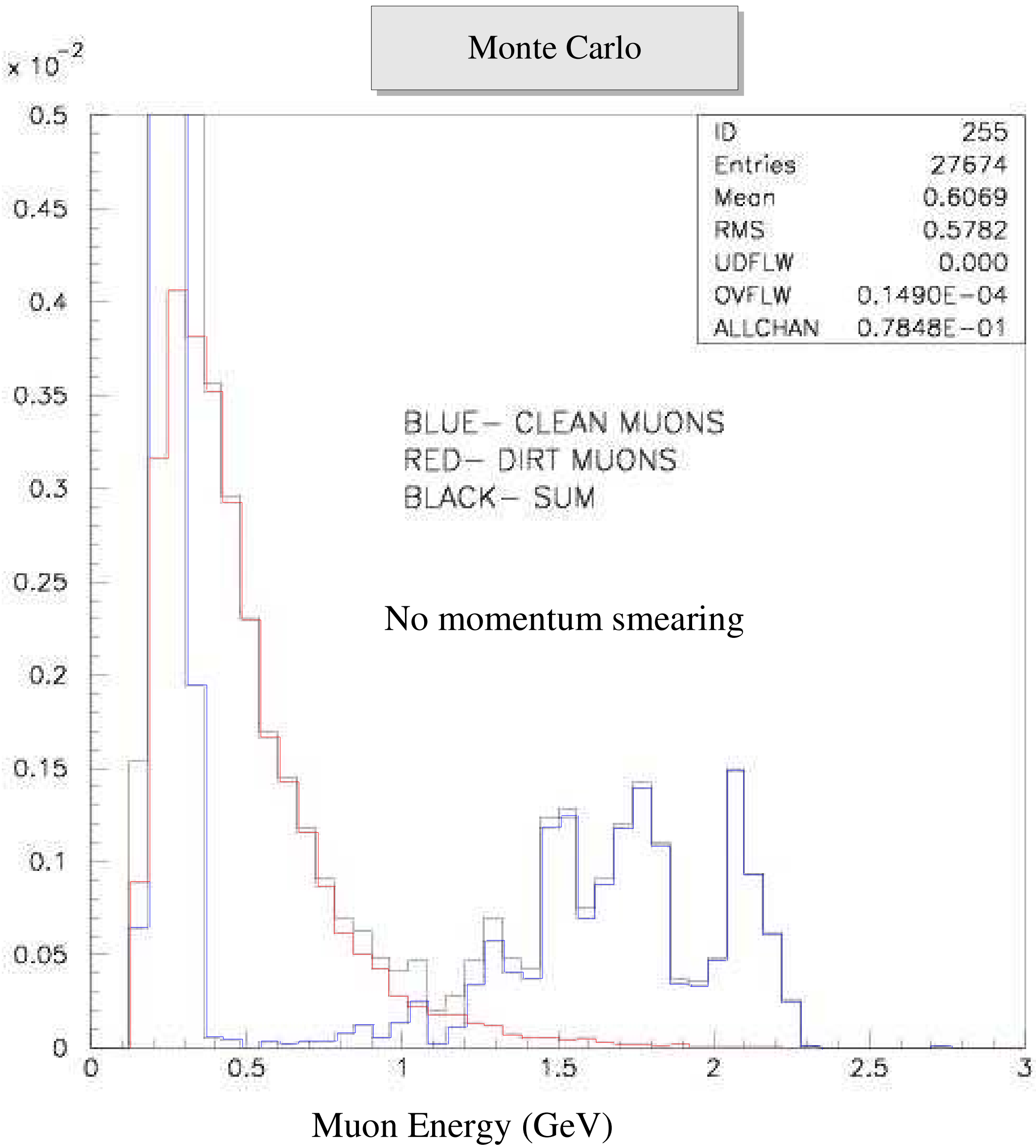


LMC collimator designed to let in clean muons and reject dirt muons.

Muon Spectrum Procedure

- Use the tracker for momentum measurements and the filter for muon range.
- Apply the following tracker cuts:
  - Good track reconstruction.
  - Track must project to active areas of all 6 tracker planes.
  - Track must project to upstream hole of LMC collimator. This is to keep clean muons and reject dirt muons. This cut is loose for now.
- Plot all events whose momentum and range are consistent with correlation expected for muons.

Monte Carlo Expectation of Muon Spectrum at the LMC



Fluctuations in distributions caused by low Monte Carlo statistics.

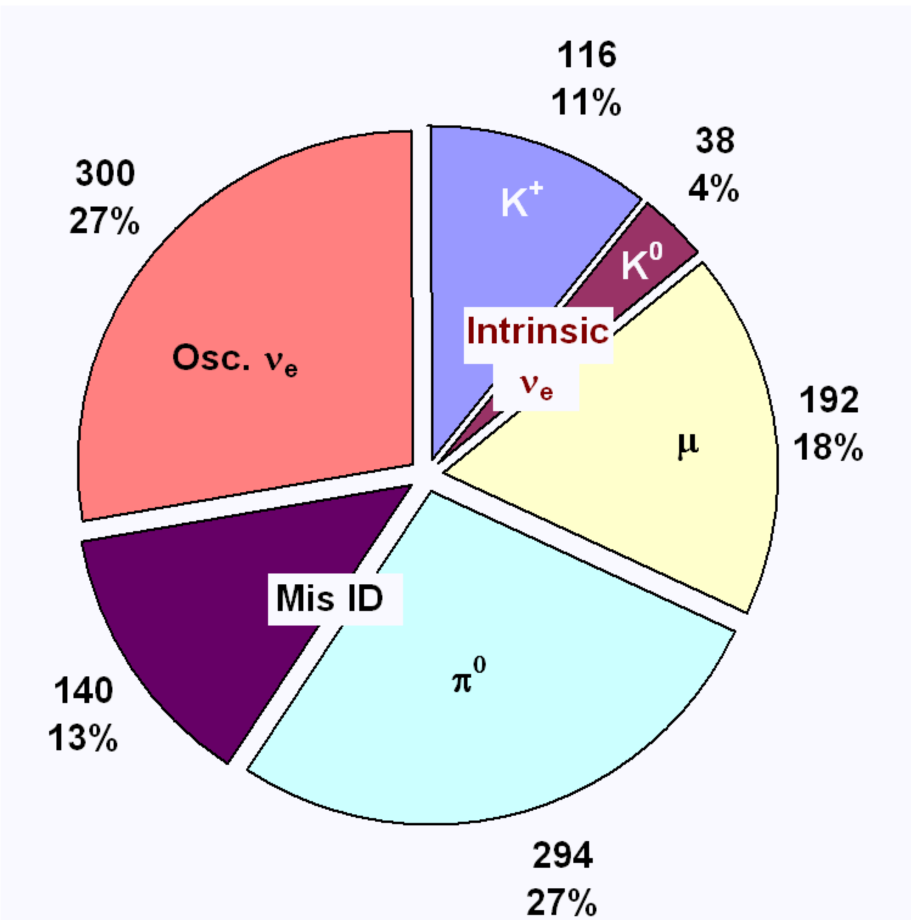
Data muon spectrum looks roughly like this MC simulation, but plot is not yet approved for posting on public web pages.

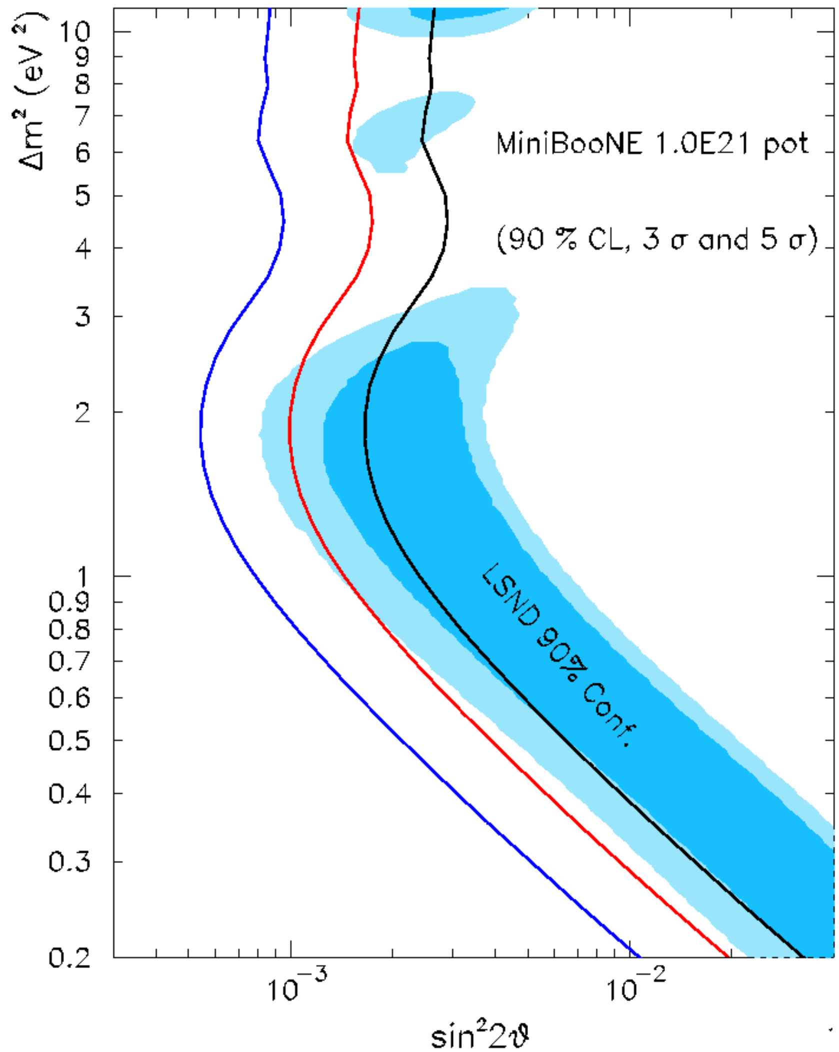
Next Steps for LMC Momentum Spectrum

- Refine and develop muon spectrum measurement
  - Understand dirt muon background
  - Determine amount of non-muon backgrounds
  - Account for tracker and filter efficiencies
  - Incorporate momentum uncertainties
- Possible special data runs with collimator at different positions to understand alignment issues and which may be helpful for understanding dirt muon contributions.
- Determine kaon content of MiniBooNE secondary beam to 10% uncertainty.

ν_e Appearance Sensitivity

Preliminary estimates of backgrounds and signal based on 10^{21} protons on target



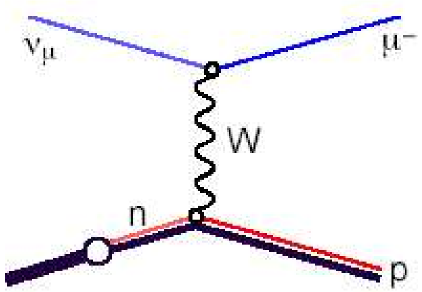


Cover LSND allowed region at 5 σ.

Currently expect results in 2005.

MiniBooNE Non-Oscillation Physics

CC quasi-elastic



abundance ~40%

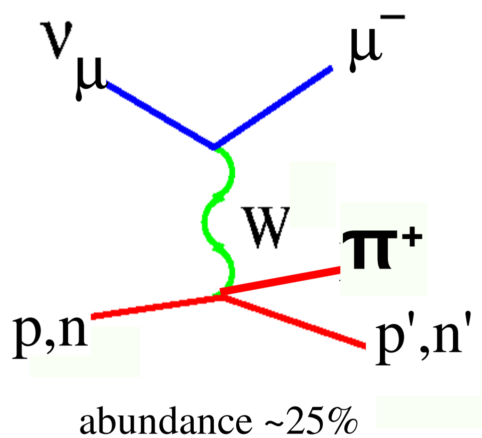
simple topology
one muon-like ring
proton rarely above
Cherenkov threshold

~88% purity

kinematics:
E_μ, θ_μ, E_ν, Q^2

relatively well-known
cross-section and will be
used for oscillation analysis

CC π^+



abundance ~25%

proton rarely above
Cherenkov threshold: only muon
ring reconstructed in primary event

π^+ and primary μ^- both leave stopped
μ-decay electrons.

kinematics:
E_μ, θ_μ, E_ν, Q^2

Measure (CC π^+/CC quasi-elastic)
cross-section ratio.

NC π^0 production

resonant:

$$\nu + (p/n) \rightarrow \nu + \Delta$$
$$\Delta \rightarrow (p/n) + \pi$$

coherent:

$$\nu + \mathrm{C} \rightarrow \nu + \mathrm{C} + \pi^0$$

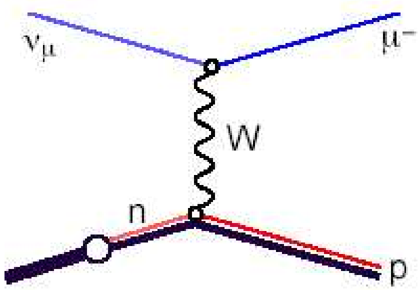
abundance ~7%

$\pi^0 \rightarrow \gamma\gamma$ two rings
E_1, E_2 from Cherenkov
intensities

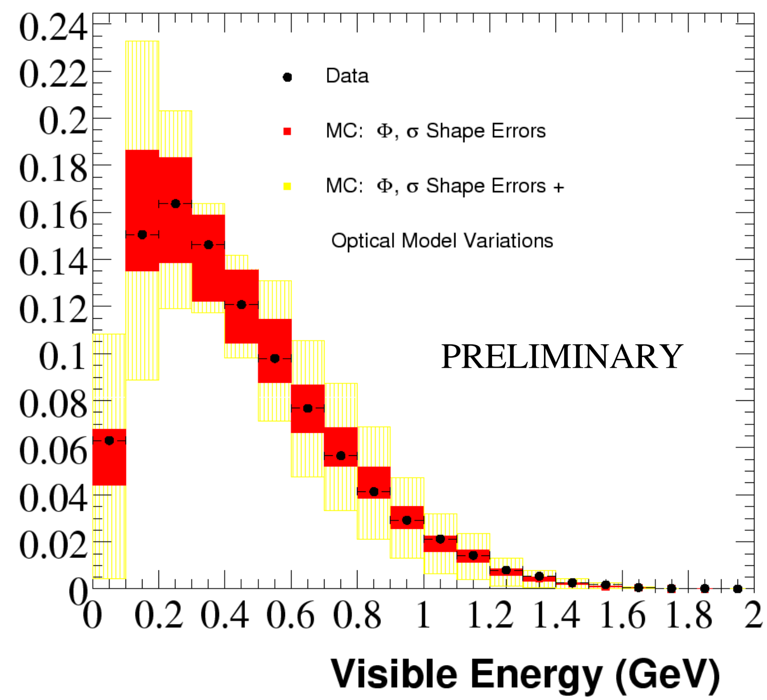
reconstruct invariant
mass of two photons

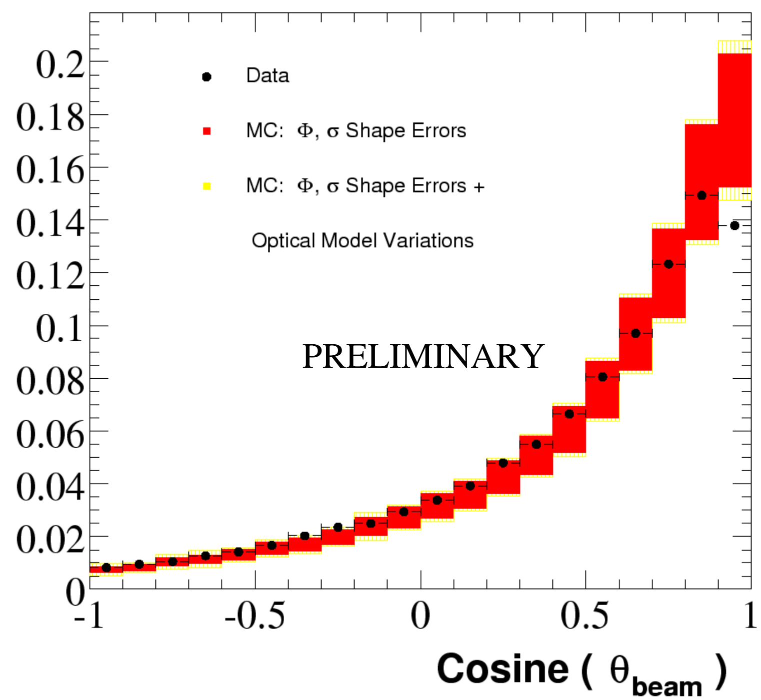
background to ν_e appearance
and limits on sterile ν

CC ν_μ Quasi-Elastic Events



- Event selection
  - Topology
    - Ring sharpness
    - on- vs. off-ring hits
  - Timing
    - Single μ-like ring
    - Prompt vs. late light
- Variables combined in a Fisher discriminant
- Data and MC relatively normalized
- Red Band: MC with current uncertainties from
  - Flux prediction
  - σ_{CCQE}
- Yellow Band: MC with current uncertainties from
  - Flux prediction
  - σ_{CCQE}
  - Optical property variations



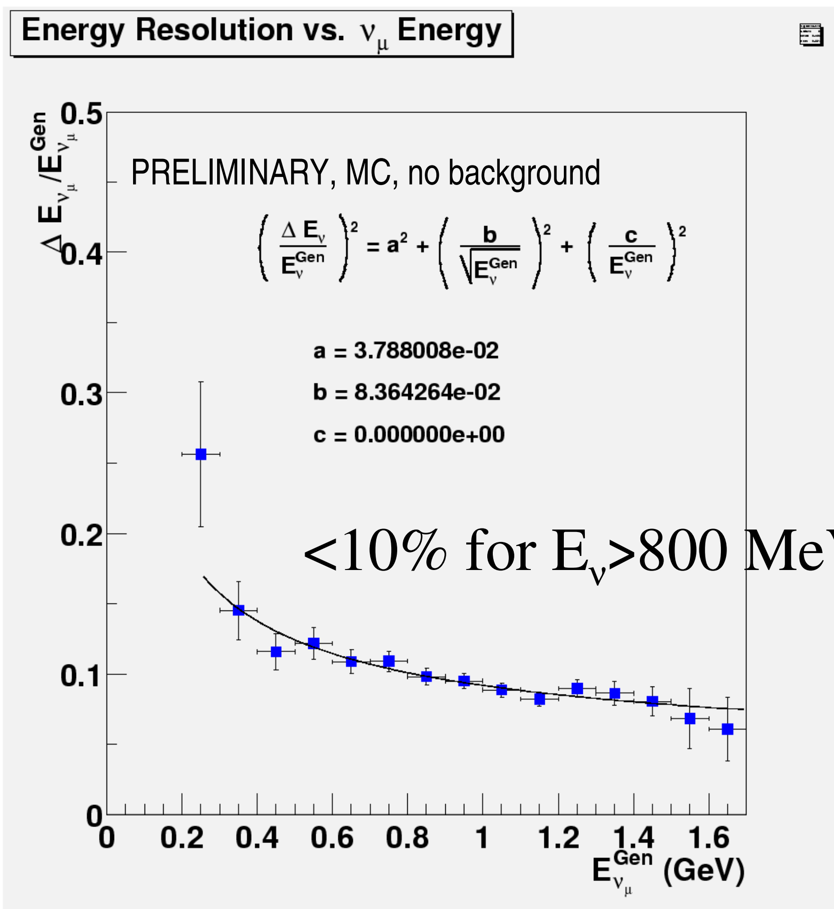


CC ν_μ Quasi-Elastic Events

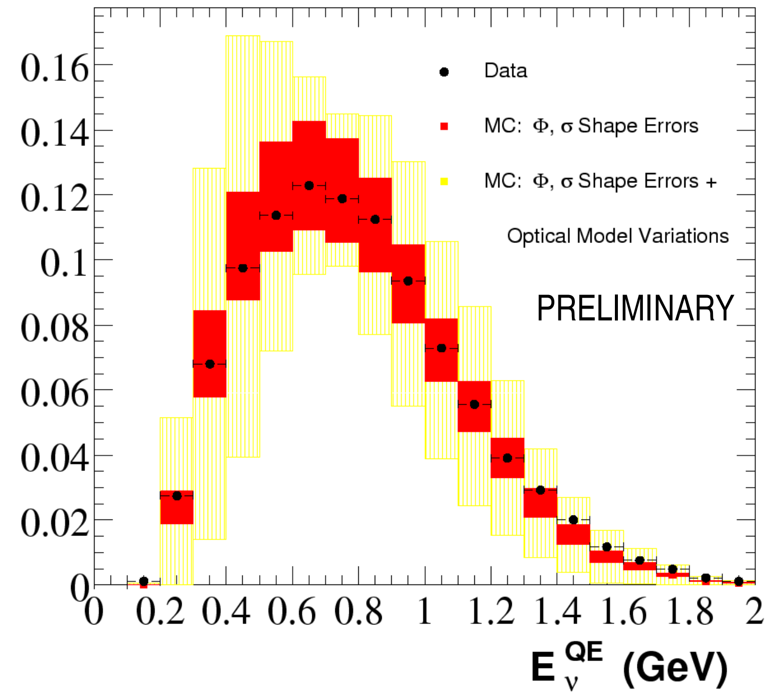
(used for oscillations analysis)

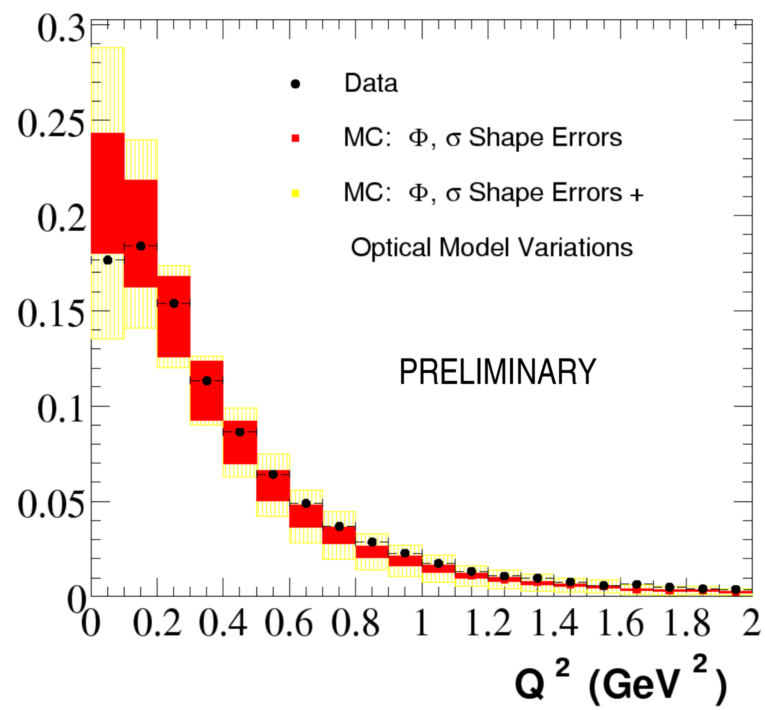
E_ν reconstruction:

- Assume $\nu_\mu n \rightarrow \mu^- p$.
- Use E_μ, θ_μ, to get E_ν.

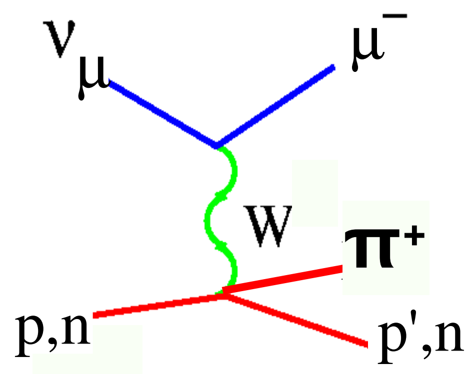


<10% for E_ν>800 MeV



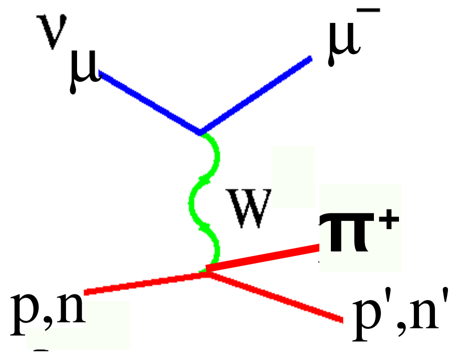


CC π^+ Analysis, Muon Reconstruction



- Reconstruct CC π^+ events from events with μ^- and μ-decay electrons from π^+ and μ^-.
- Data and Monte Carlo samples are relatively normalized.
- Monte Carlo uncertainties are from
  - Neutrino cross section
  - light extinction
  - light scattering length uncertainties
  - Uncertainties from flux predictions are not included as cross-section is measured relative to CC quasi-elastic cross-section.
- Reconstructed muon angle and energy distributions not yet approved for posting on public web pages.

CC π^+ Analysis, Neutrino Reconstruction



- Reconstruct neutrino energy from measured muon energy and direction.
- Assume 2-body quasi-elastic kinematics and that π^+ and p' parent is $\Delta^{++}(1232)$.
- Monte Carlo uncertainties are from
  - Neutrino cross section
  - light extinction
  - light scattering length uncertainties
- Reconstructed neutrino energy distribution not yet approved for posting on public web pages.

CC π^+ Analysis, Relative Cross Section Measurement

- Normalize CC π^+ cross section to CC quasi-elastic cross section as a function of neutrino energy.
- Cross section ratio cut efficiency corrections from
  - High energy CCQE degradation from exiting muon.
  - Low energy cut-off by kinematic threshold.
- Systematic errors from
  - Neutrino cross section uncertainties
  - Photon extinction and scattering length uncertainties
  - Energy scale uncertainty

NC π^0 Production – Mass

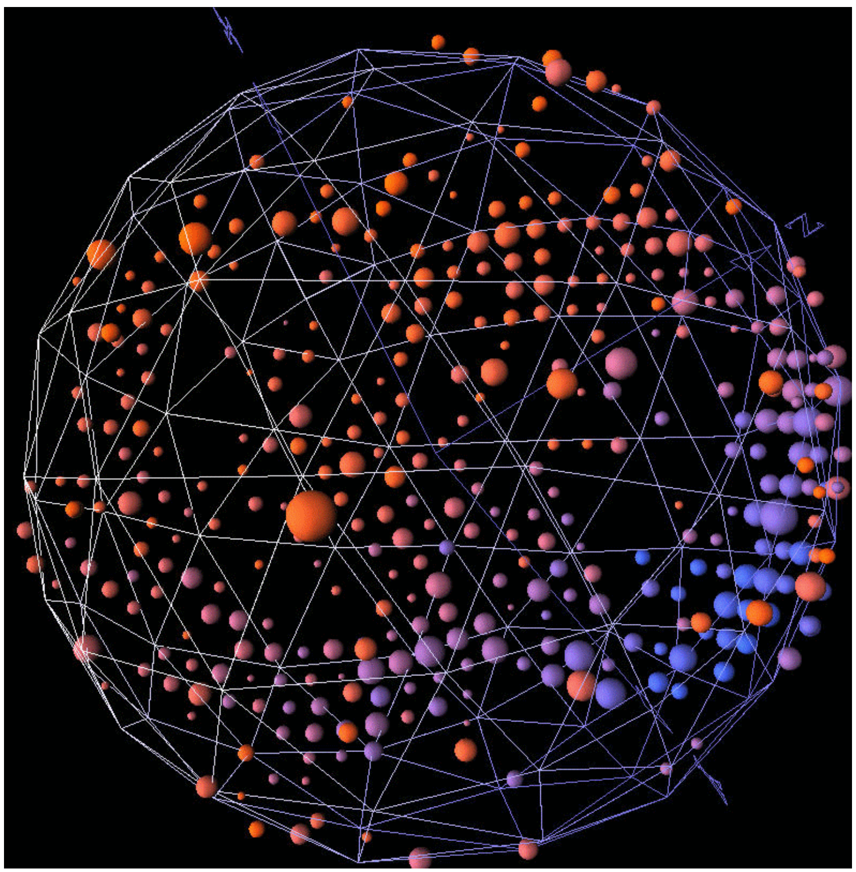
- $N_{TANK} > 200$, $N_{VETO} < 6$, no decay electron
- Perform two-ring fit on ALL events.
- Ring energies > 40 MeV
- Fit mass peak to extract signal yield including background shape from MC.

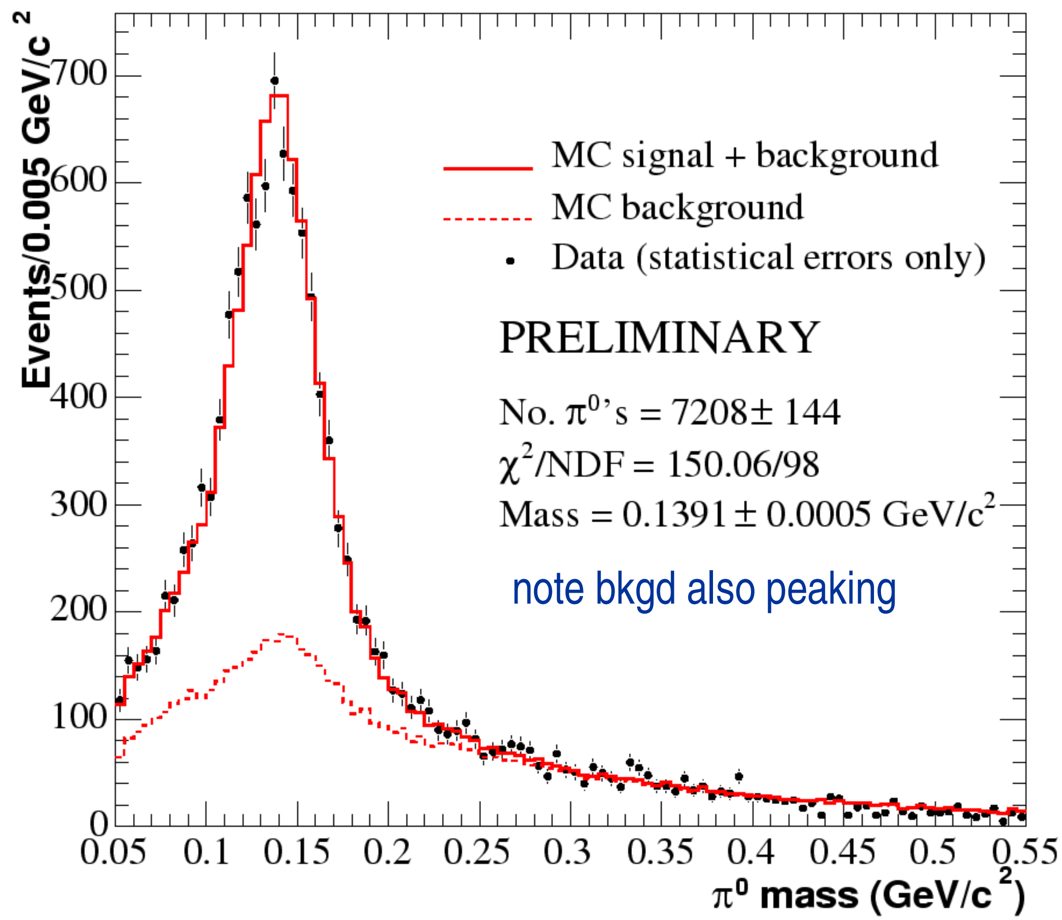
resonant:

$$\nu + (p/n) \rightarrow \nu + \Delta$$
$$\Delta \rightarrow (p/n) + \pi$$

coherent:

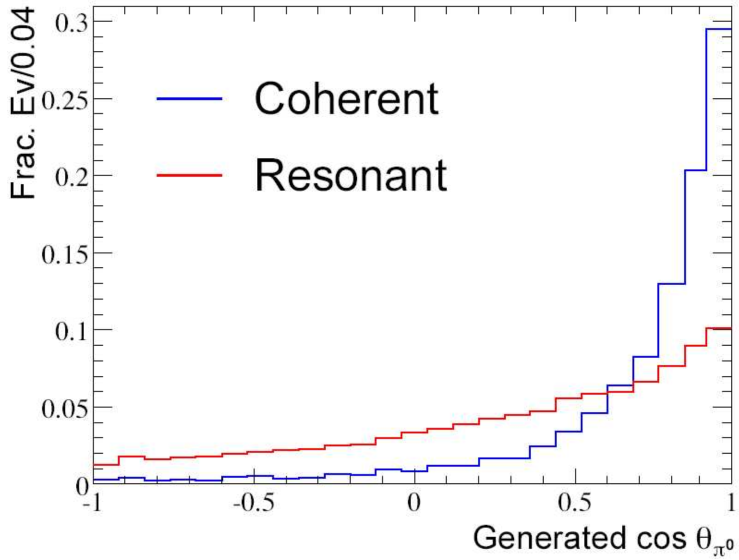
$$\nu + \mathrm{C} \rightarrow \nu + \mathrm{C} + \pi^0$$

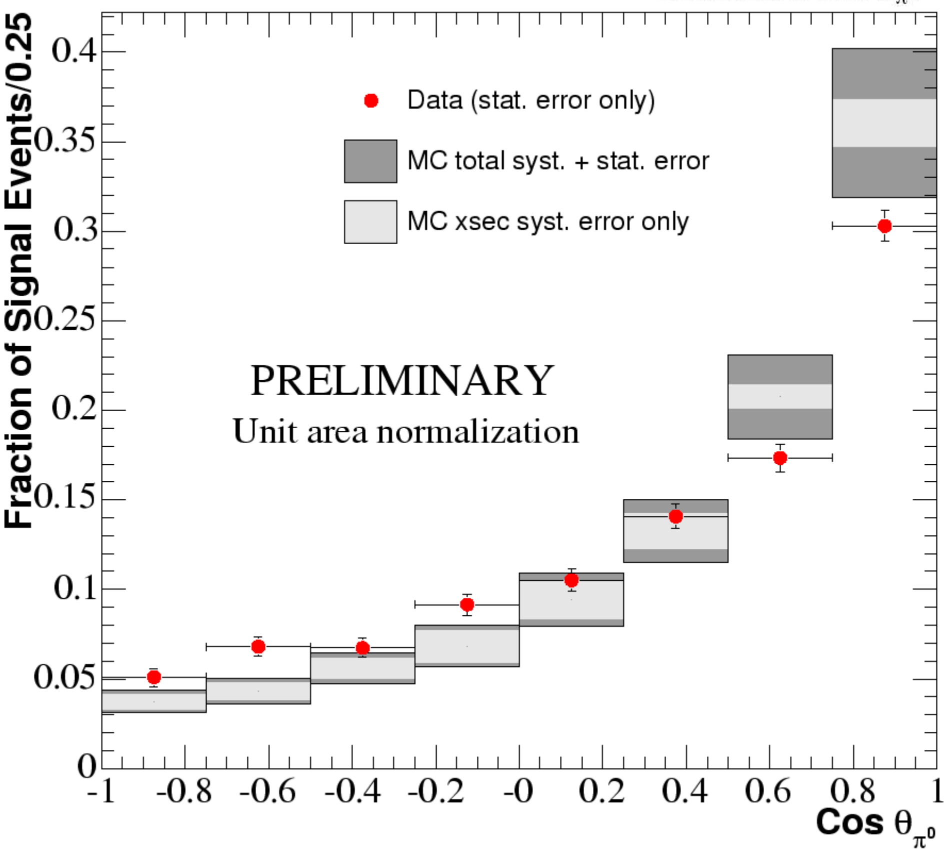




NC π^0 Production – Production Angle

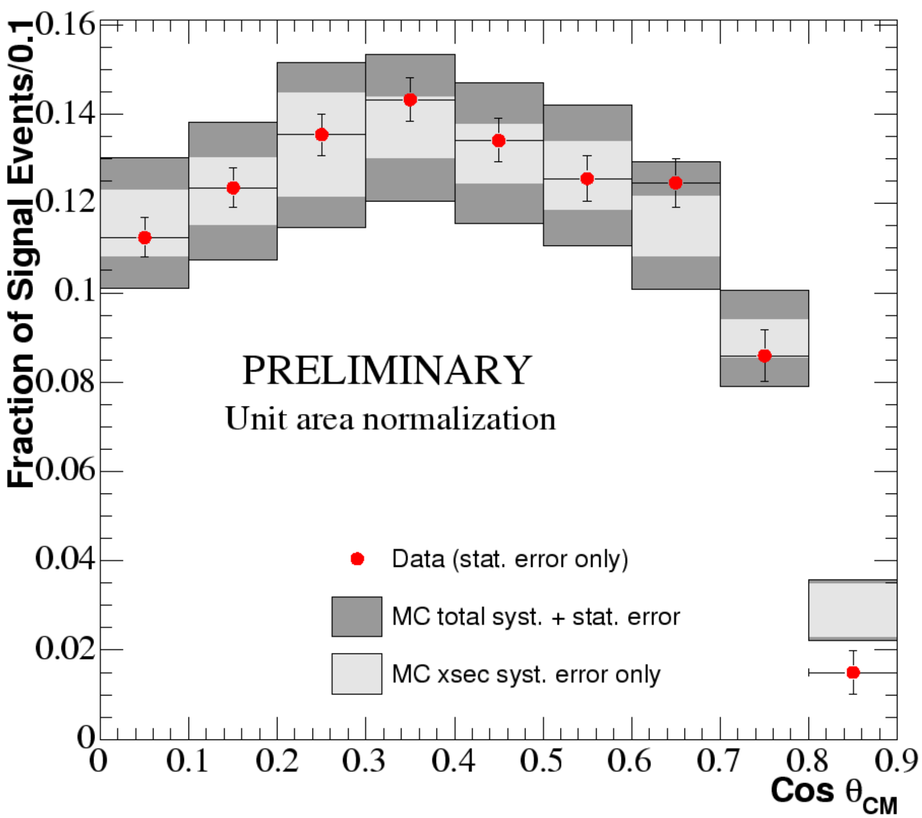
- Production angle is sensitive to production mechanism: coherent is highly forward-peaked.
- Data and MC are relatively normalized.
- MC shape assumes Rein-Sehgal cross-sections.
- Discrepancy near $\cos(\theta_{\pi^0}) = 1$ may indicate that coherent cross-section is lower than expected.

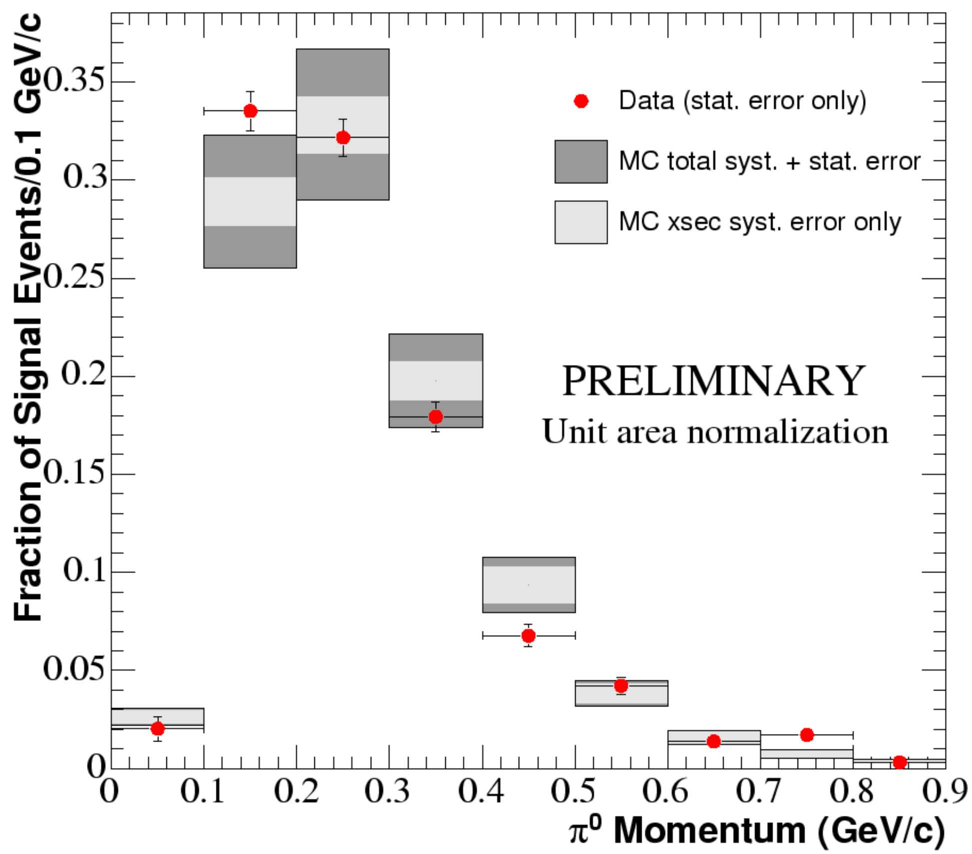




NC π^0 Production – Decay Angle and Momentum

θ_{CM} is angle of π^0 decay photons in π^0 rest frame with respect to neutrino direction.





Conclusions

- All detector and reconstruction algorithms are working and are providing our first physics results.
- MiniBooNE has made important preliminary measurements of neutrino interaction processes important for the oscillation analysis.
  - CC quasi-elastic cross-section
  - CC π^+ cross-section
  - NC π^0 cross-section
- $\nu_\mu \rightarrow \nu_e$ oscillation measurement is expected in late 2005.