MiniBooNE

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MiniBooNE

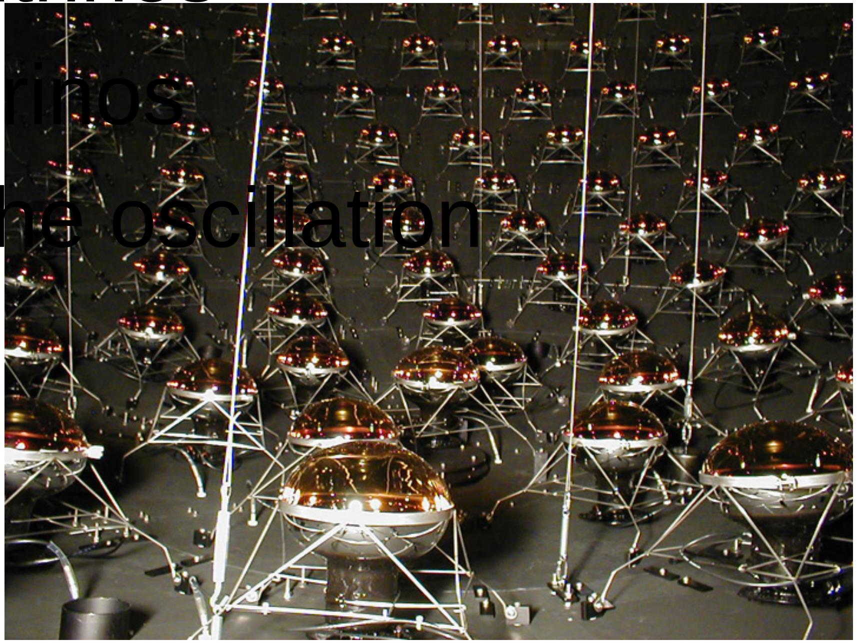
MiniBooNE Today

- MiniBooNE is performing a blind analysis (closed box)
  - Some of the info in all of the data
  - All of the info in some of the data
  - ~~All of the info in all of the data~~

- We haven't yet opened the box

Outline

- Oscillation Review
- MiniBooNE
  - How we get our neutrinos
  - How we detect neutrinos
  - What's needed for the oscillation analysis
  - Where we are now



Neutrino Oscillations

Weak state **Mass state**

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

Neutrino Oscillations

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$$|\nu_\mu(0)\rangle = -\sin\theta\, |\nu_1\rangle + \cos\theta\, |\nu_2\rangle$$

Neutrino Oscillations

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$$|\nu_\mu(t)\rangle = -\sin\theta\, |\underset{\uparrow}{\nu_1}\rangle + \cos\theta\, |\underset{\uparrow}{\nu_2}\rangle$$

$$e^{-iE1t} \qquad\qquad e^{-iE2t}$$

Neutrino Oscillations

$$P_{osc} = |\langle\nu_e | \nu_\mu(t)\rangle|^2$$

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

Neutrino Oscillations

Δm^2 is the mass squared difference between the two neutrino states

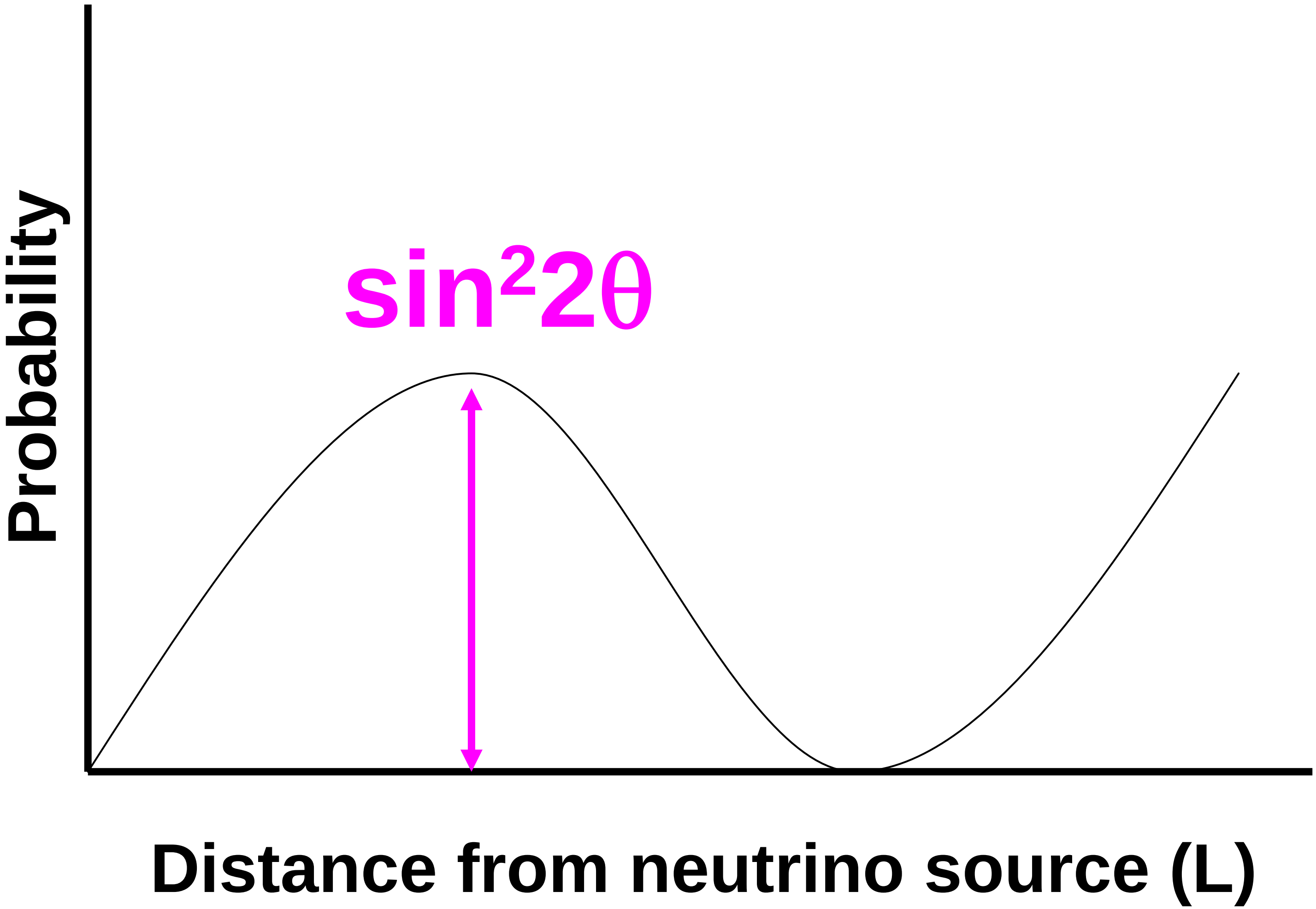
Distance from point of creation of neutrino beam to detection point

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

θ Is the mixing angle

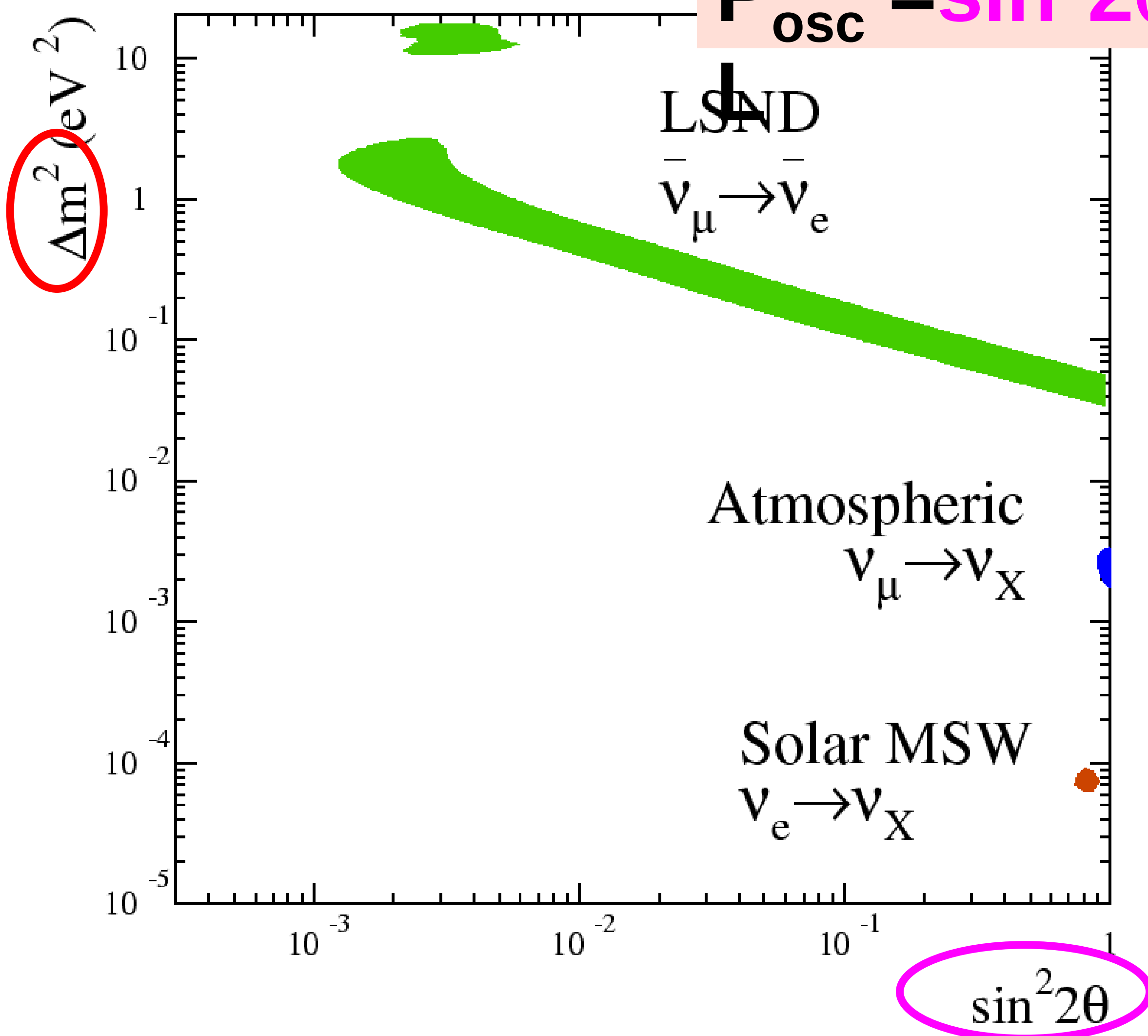
E is the energy of the neutrino beam

Neutrino Oscillations



Current Oscillation Status

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\,\Delta m^2\,L}{E}\right)$$



$$\Delta m^2 = m_a^2 - m_b^2$$

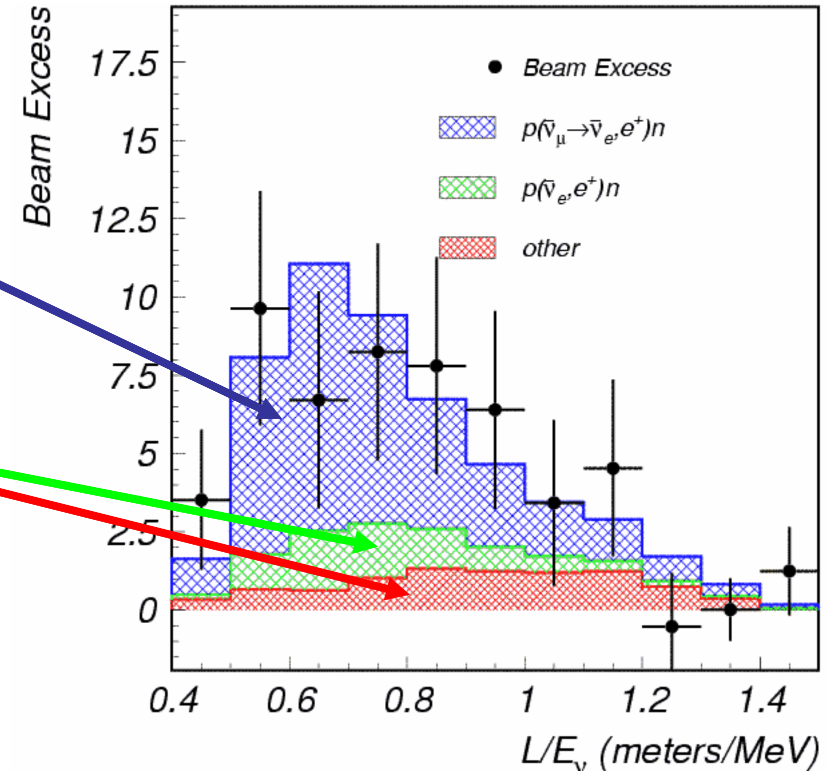
If there are only 3 :

$$\Delta m_{ac}^2 = \Delta m_{ab}^2 + \Delta m_{bc}^2$$

Confirming LSND

Fit to oscillation hypothesis

Backgrounds



- Want the same L/E
- Want higher statistics
- Want different systematics
- Want different signal signature and backgrounds

- Oscillation Review
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  - **How we get our neutrinos**
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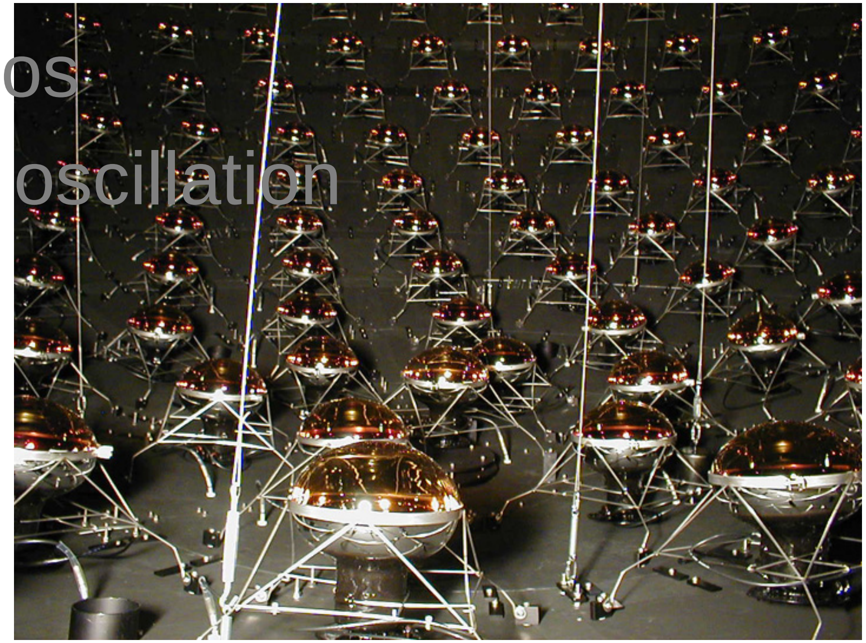
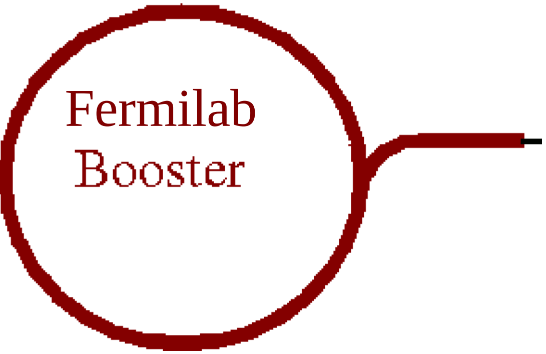
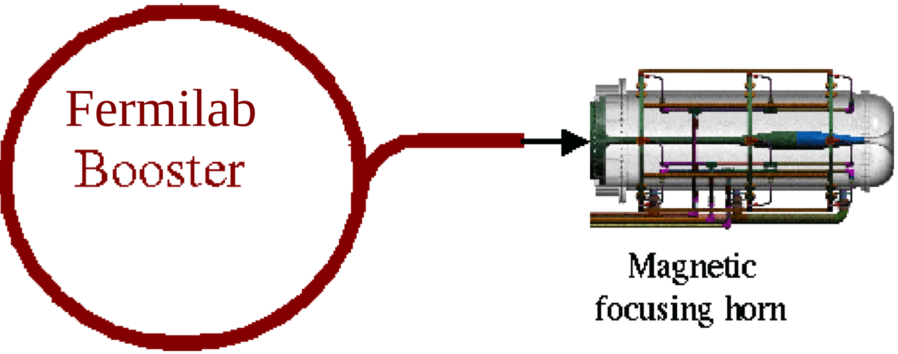


MiniBooNE Neutrino Beam



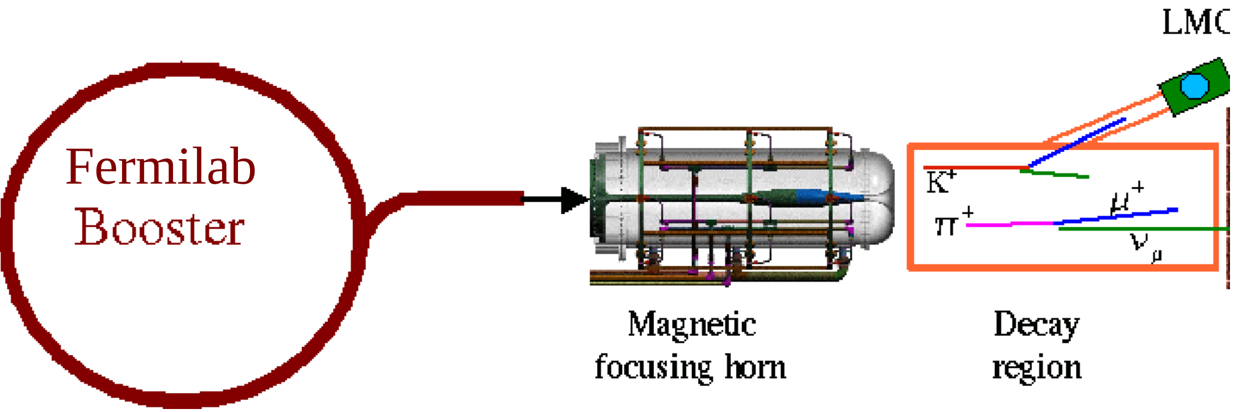
- Start with an 8 GeV beam of protons from the booster

MiniBooNE Neutrino Beam



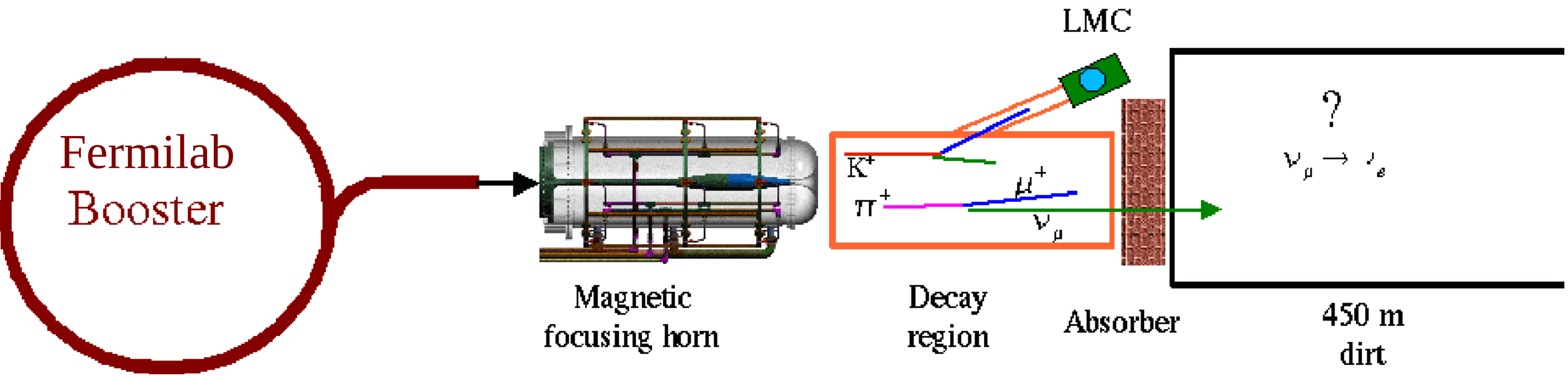
- The proton beam enters the magnetic horn where it interacts with a Beryllium target
- Focusing horn allows us to run in neutrino, anti-neutrino mode
  - Collected ~6x10^{20} POT, ~600,000 ν events
  - Running in anti- ν mode now, collected ~0.4x10^{20} POT

MiniBooNE Neutrino Beam



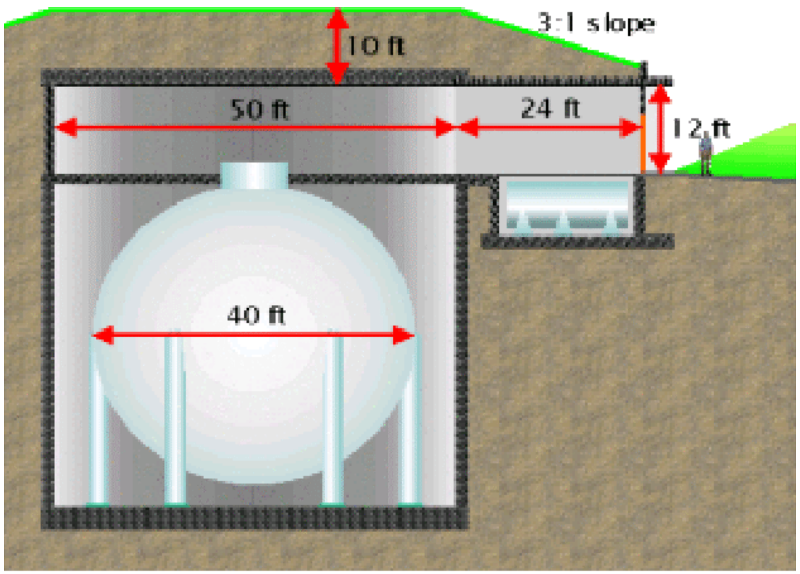
- p + Be = stream of mesons (π, K)
- Mesons decay into the neutrino beam seen by the detector
  - $K^+ / \pi^+ \rightarrow \mu^+ + \nu_\mu$
    - $\mu^+ \rightarrow e^+ + \nu_\mu + \overline{\nu}_e$

MiniBooNE Neutrino Beam

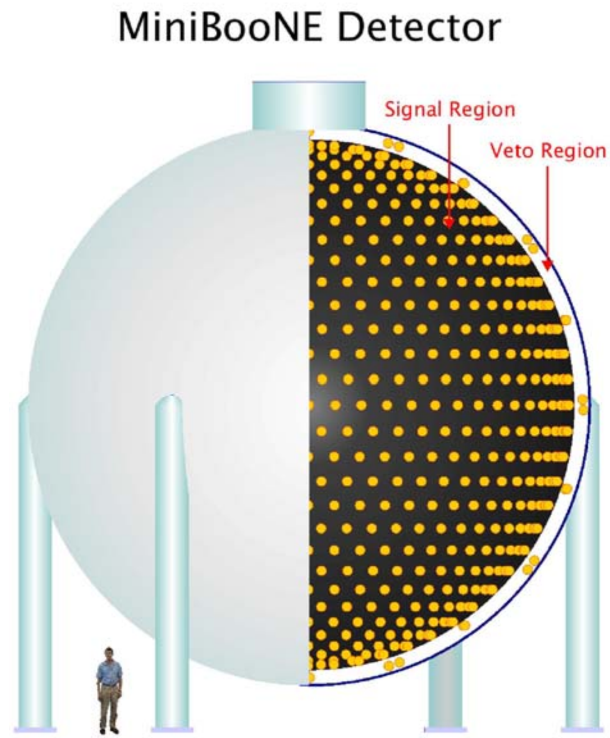


- An absorber is in place to stop muons and undecayed mesons
- Neutrino beam travels through 450 m of dirt

MiniBooNE Detector



Detector



- 12.2 meter diameter sphere
- **Pure** mineral oil
- 2 regions
  - **Inner light-tight region, 1280 PMTs (10% coverage)**
  - **Optically isolated outer veto-region, 240 PMTs**

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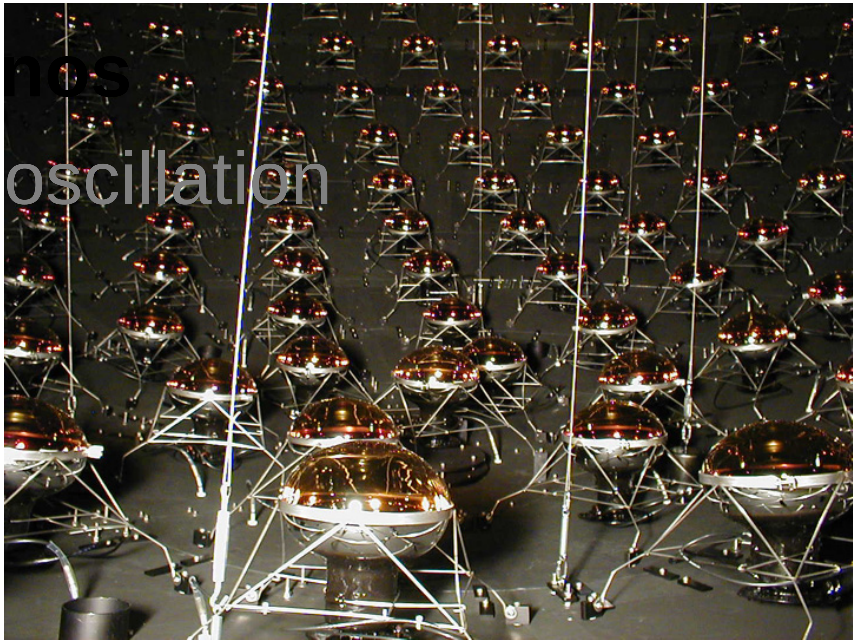
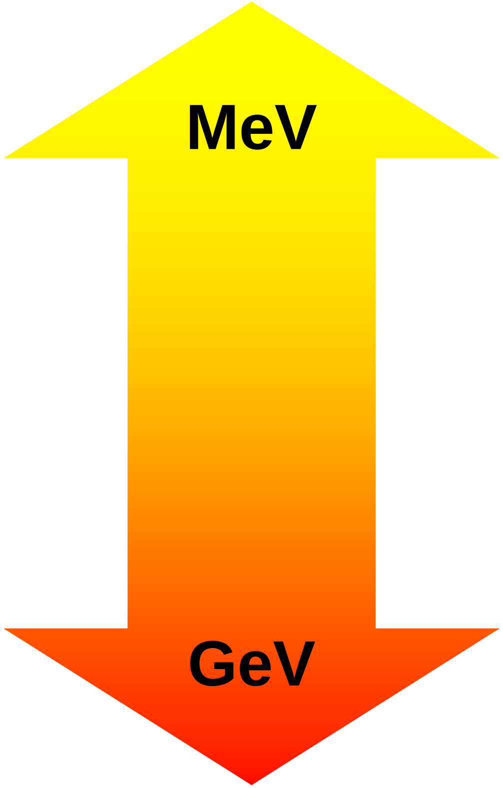


Detecting Neutrinos

- Neutrinos interact with material in the detector. It’s the outcome of these interactions that we look for
- Neutrinos can interact with :
  - Electron in the atomic orbit
  - The nucleus as a whole
  - Free proton or nucleon bound in nucleus
  - A quark

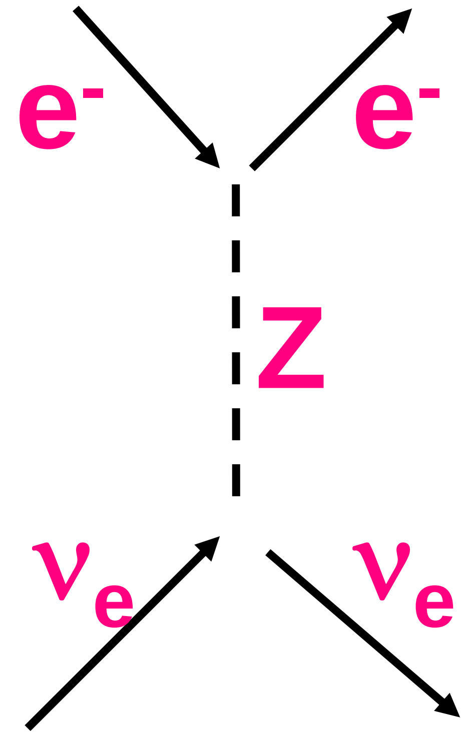
Neutrino Interactions

- Elastic Scattering
- Quasi-Elastic Scattering
- Single Pion Production
- Deep Inelastic Scattering



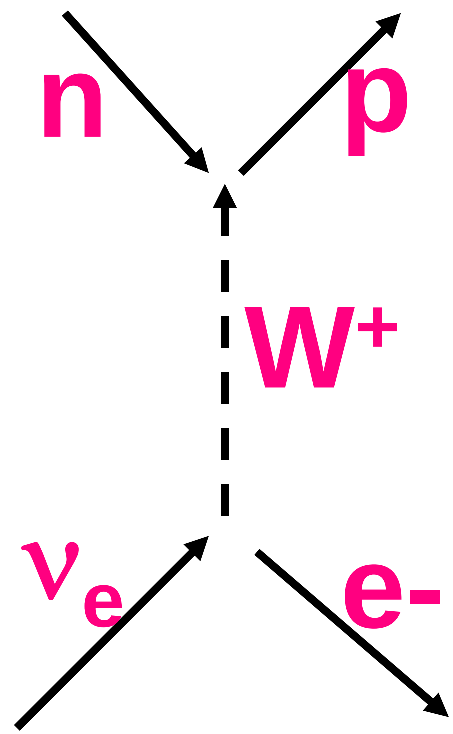
Elastic Scattering

- Target left intact
- Neutrinos can elastic scatter from any particle (electrons, protons)
- Neutrino imparts recoil energy to target = how we observe these interactions



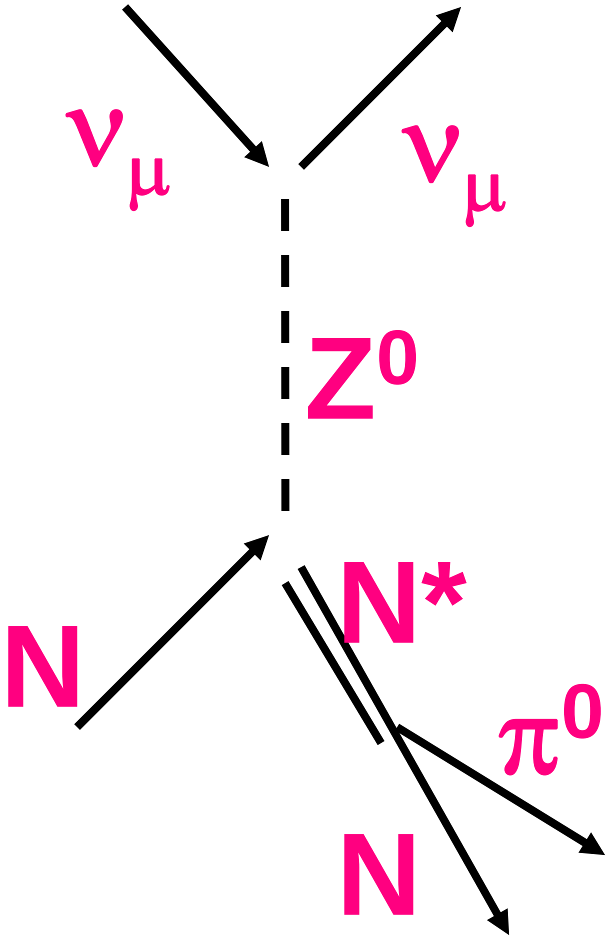
Quasi-elastic Scattering

- Neutrino in, charged lepton out
- Target changes type
- Need to conserve electric charge at every vertex
- Need minimum neutrino E
  - Need enough CM energy to make the two outgoing particles



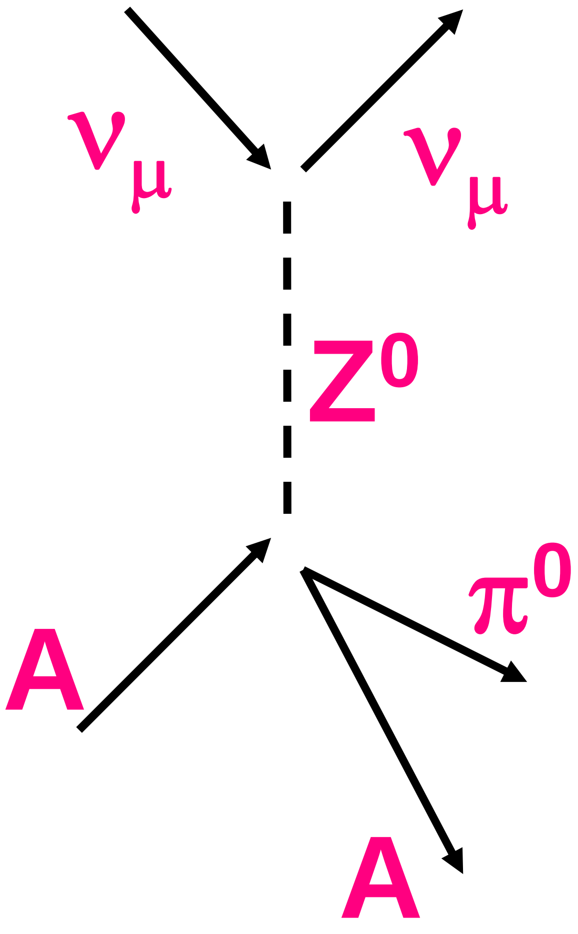
Single Pion Production

- Resonant
  - neutrino scattering from a nucleon
  - Nucleon resonance is excited, decays back into it's ground state nucleon
  - Emits one or more mesons in the de-excitation process



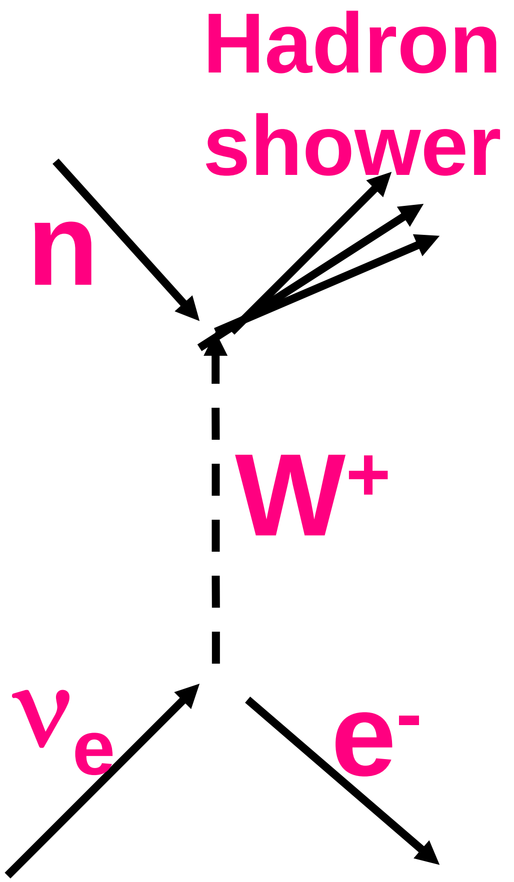
Single Pion Production

- Coherent
  - neutrino scatters from entire nucleus
  - nucleus does not break up / no recoil nucleon
  - Requires low momentum transfer (to keep nucleus intact)
  - No transfer of charge, quantum numbers



Deep Inelastic Scattering

- Scattering with very large momentum transfers
- Incoming neutrino produces a W boson, turns into partner lepton
- W interacts with quark in nucleon and blows it to bits (ie inelastic)
- Quarks shower into a variety of hadrons, dissipating the E carried by the W boson (ie deep)

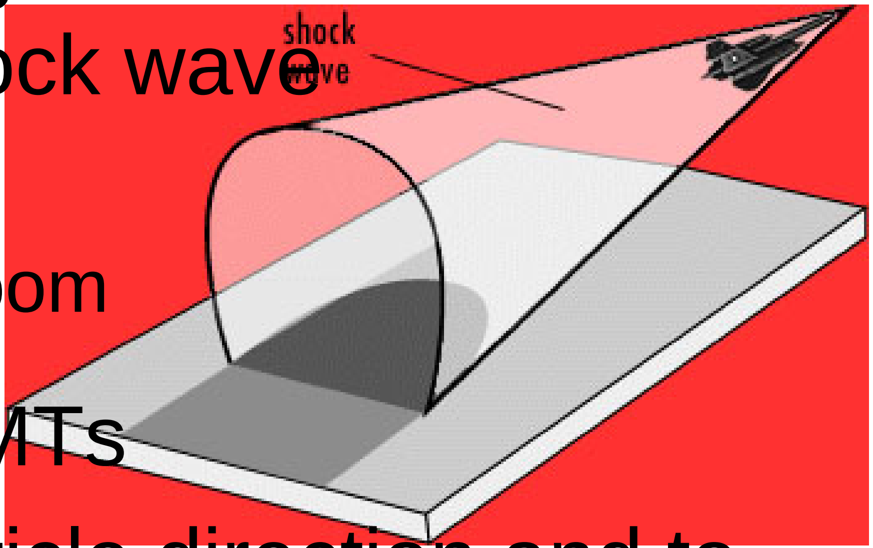


Observing Neutrino Interactions

- Find products of neutrino interactions
- Passage of charged particles through matter leaves a distinct mark
  - **Cerenkov effect / light**
  - **Scintillation light**

Cerenkov Light

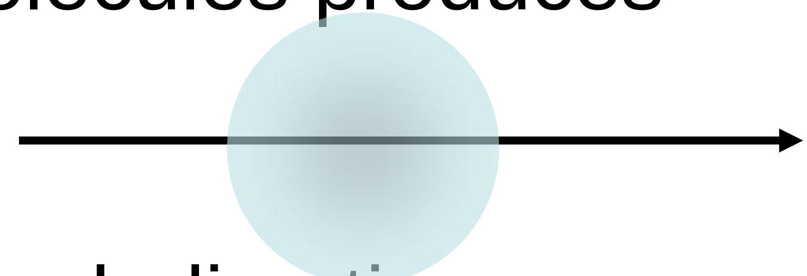
- Charged particles with a velocity greater than the speed of light * in the medium* produce an E-M shock wave
  - $v > 1/n$
  - Similar to a sonic boom



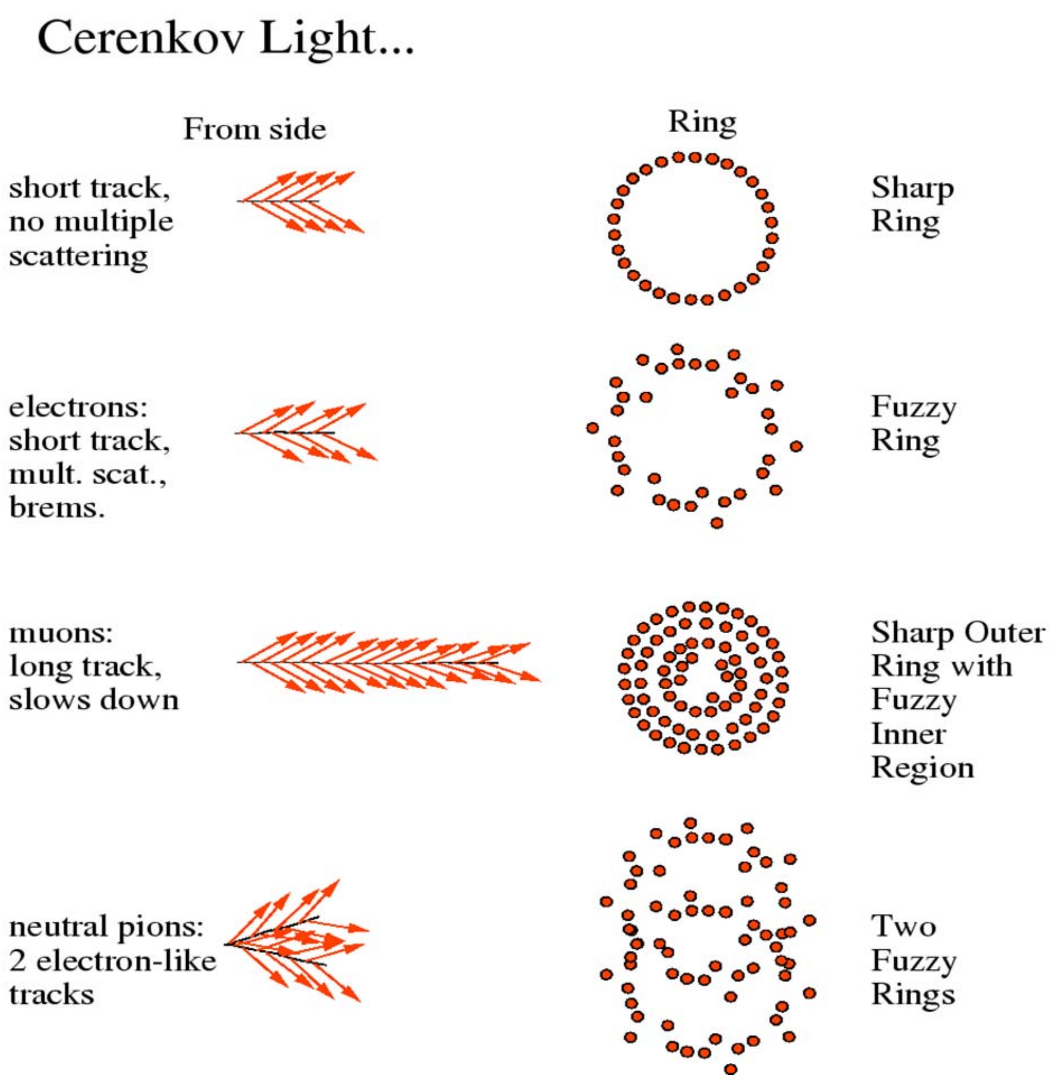
- Light detected by PMTs
- Use to measure particle direction and to reconstruct interaction vertex
- Prompt light signature

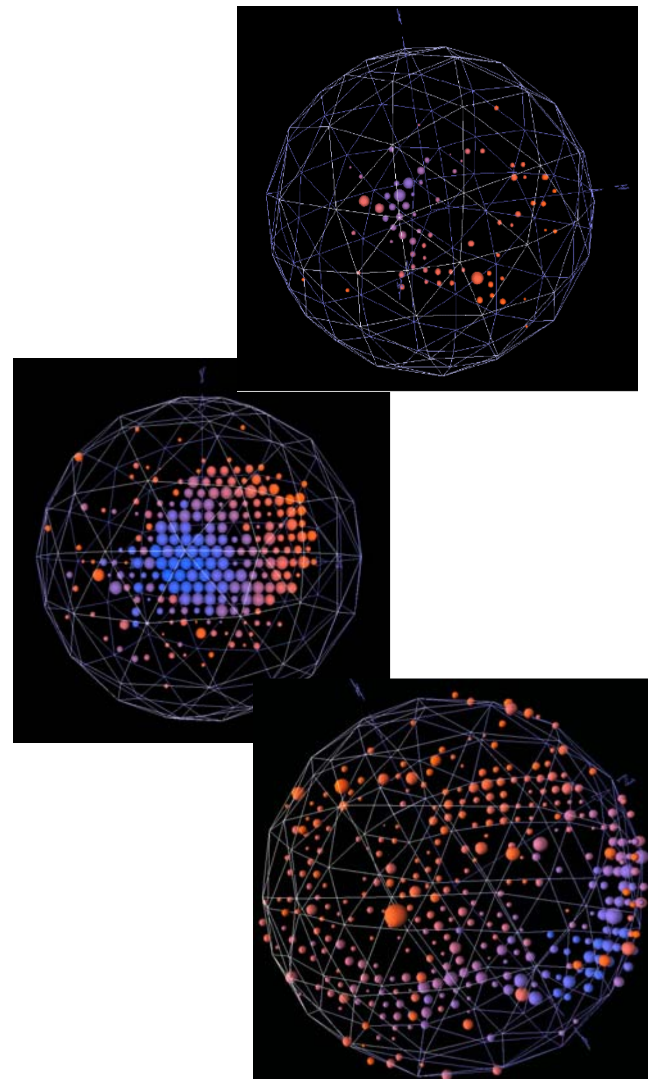
Scintillation Light

- Charged particles moving through a material deposit energy in the medium, which excites the surrounding molecules
- The de-excitation of molecules produces scintillation light
- Isotropic, delayed
- No information about track direction
- Can use PMT timing information to locate interaction point



Event Signature





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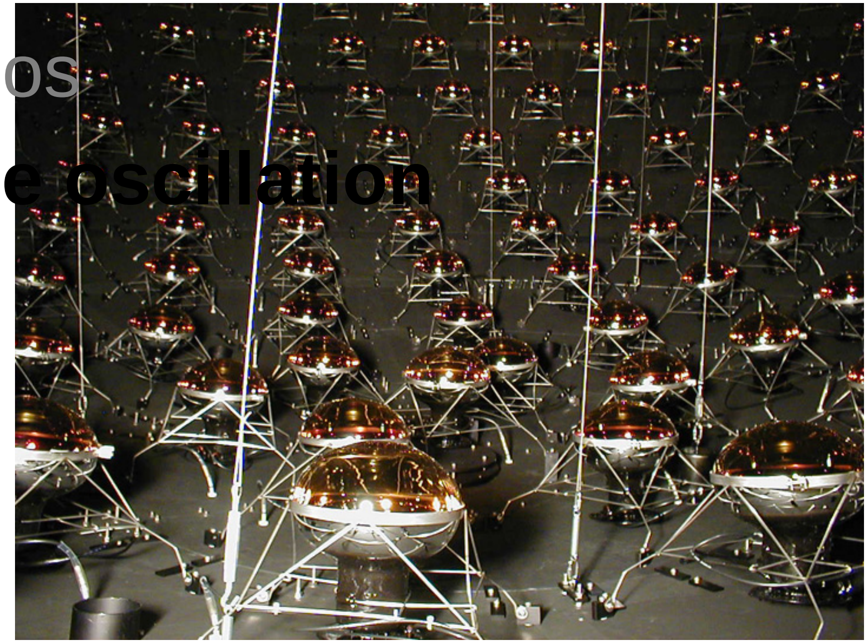
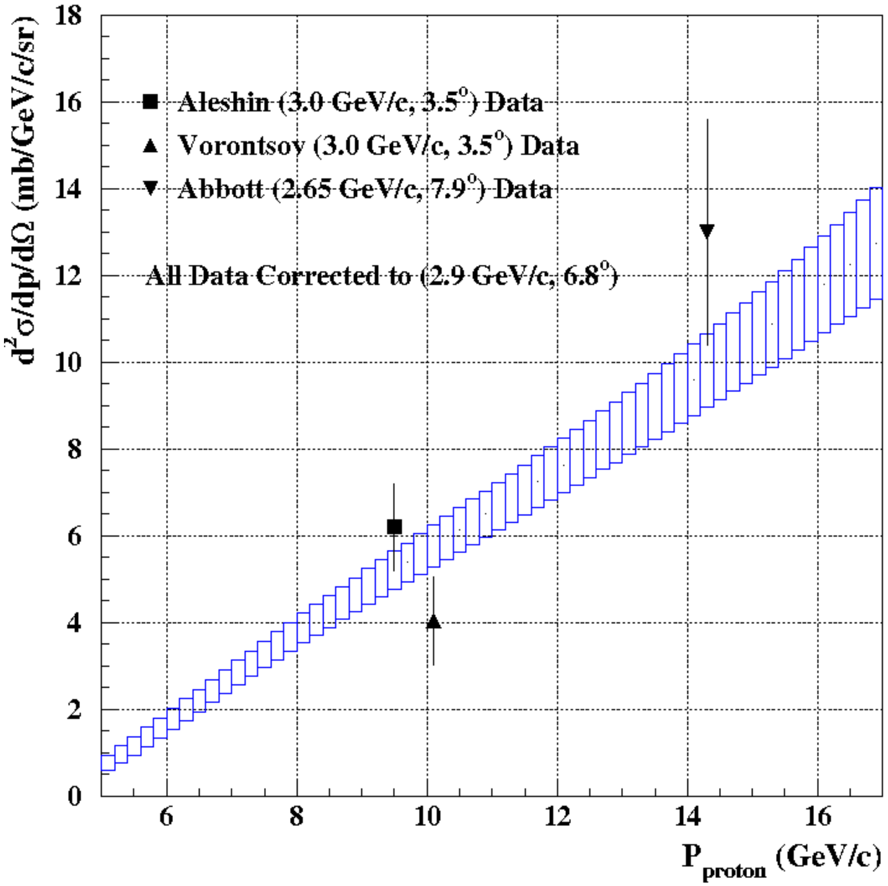


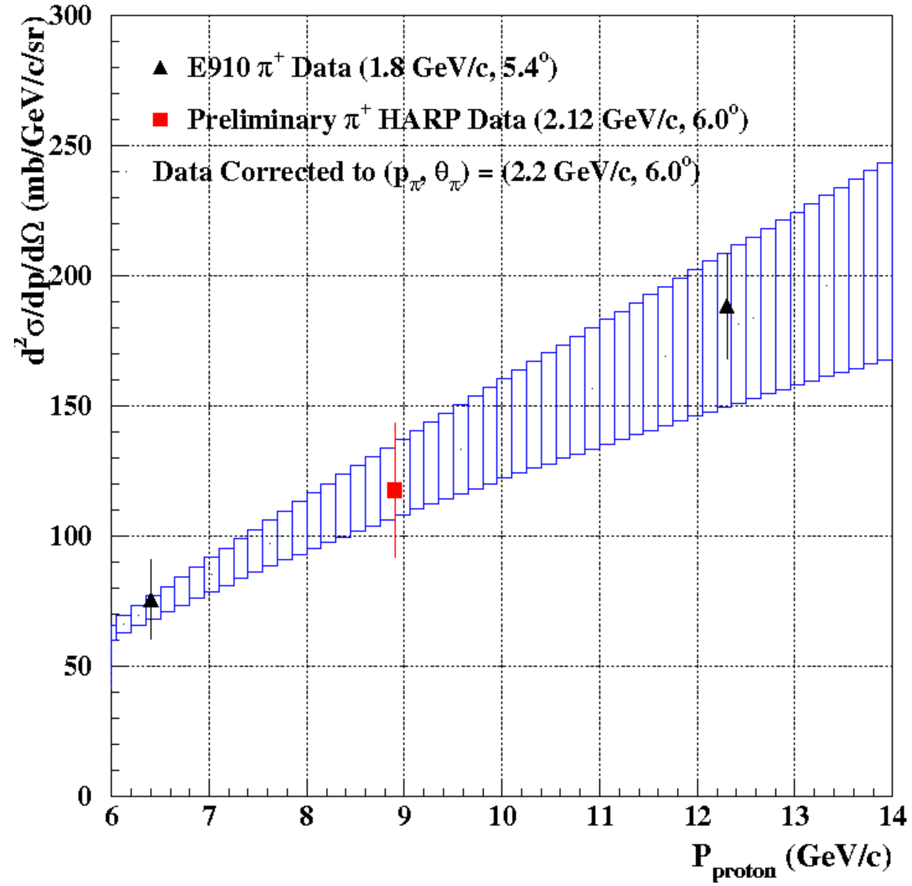
Analysis Components

- We are performing a blind analysis
- The oscillation signal is expected to be small
  - Probability for LSND oscillations = ~0.26%!
- Requires very precise knowledge of
  - **Event rate / neutrino flux**
  - **Detector response**
  - **Backgrounds to the oscillation search**
- Requires **well developed Particle ID algorithm**

Event Rate / Neutrino Flux

World P+Be Measurements



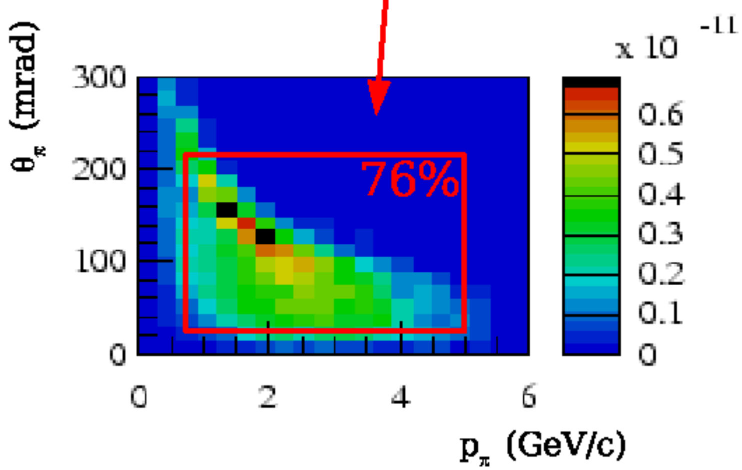


Event Rates & Flux Predictions

New!

Double differential π^+ production cross sections from the Be 5% target

$0.75 < p_\pi < 5$ GeV/c
$30 < \theta_\pi < 210$ mrad

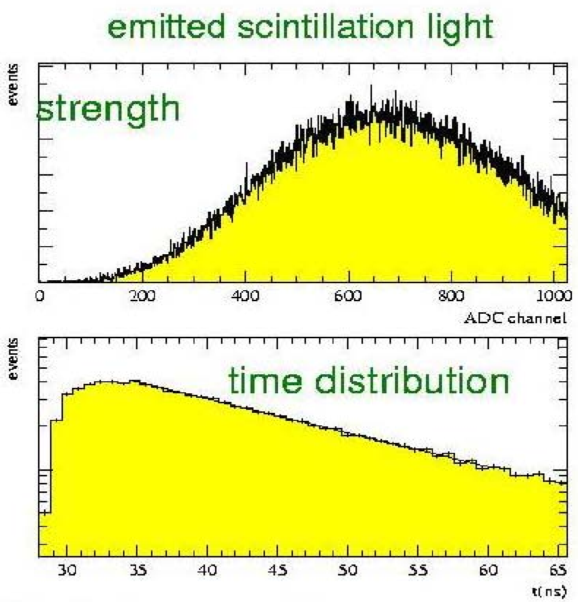


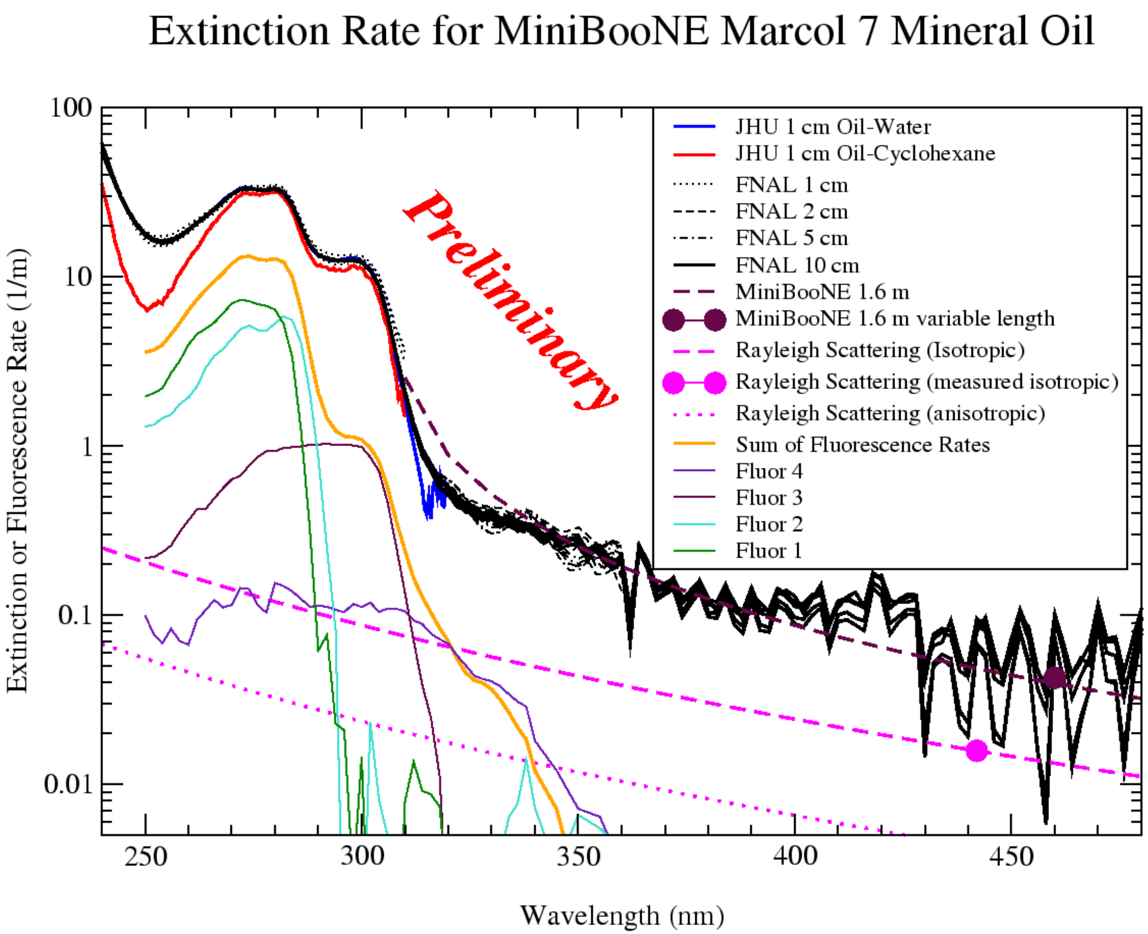
Momentum and Angular distribution of pions decaying to a neutrino that passes through the MB detector.

- E910
  - π, K production @ 6, 12, 18 GeV w/thin Be target
- HARP
  - π, K production @ 8 GeV w/ 5, 50, 100% λ thick Be target
  - **Thin target results just added! (Apr 06)**

Detector Response

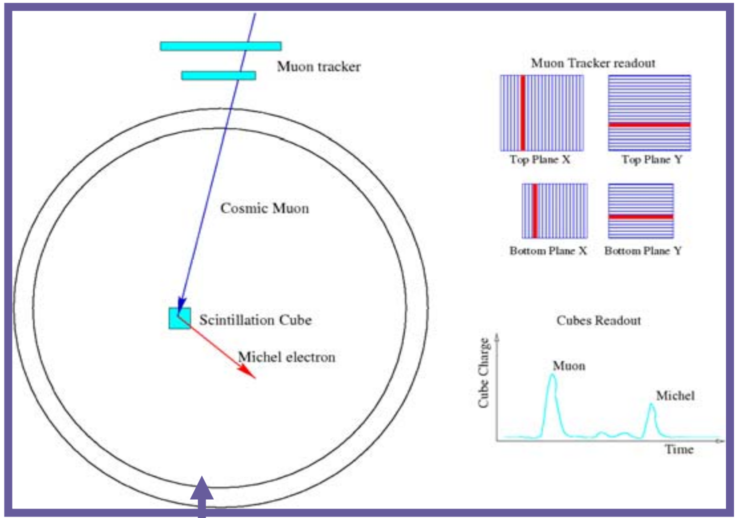
External Measurements

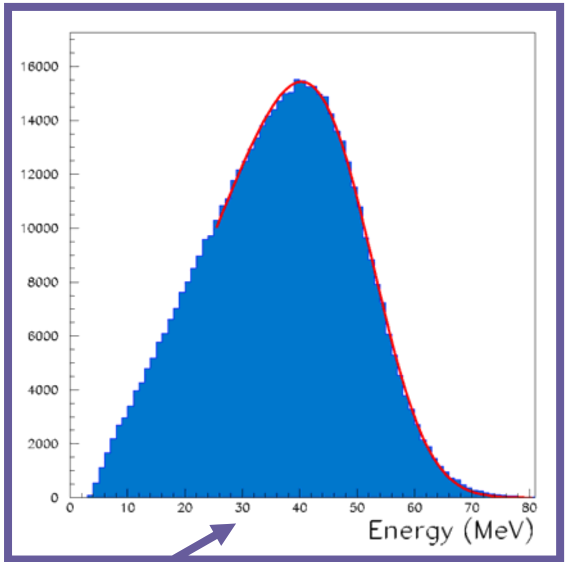




- Variety of stand-alone tests which characterize separate components of mineral oil

Internal Calibration Sources





- Muon tracker + cubes : provides μ and Michel e^- of known position and direction in tank, key to understanding E and reconstruction
- Laser flasks (4) : used to measure tube charge, timing response
- Neutral Current Elastic sample : provides neutrino sample, protons below Cerenkov threshold == isolate scintillation components, distinguish from fluorescence of detector

The Optical Model Chain

External Measurements and Laser Calibration

First Calibration with Michel Data

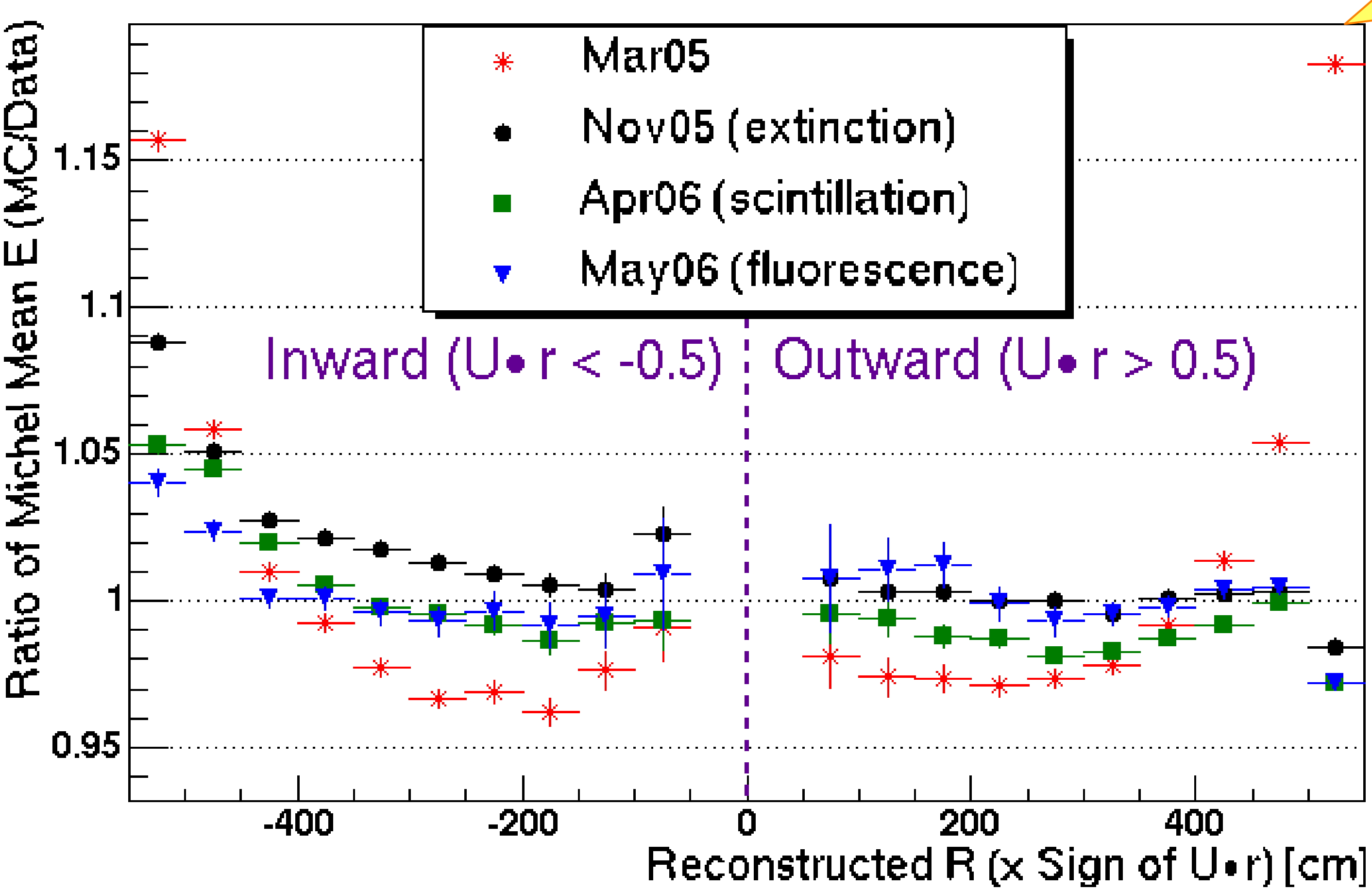
Calibration of Scintillation Light with NC Events

Final Calibration with Michel Data

Validation with Cosmic Muons, ν_μ CCQE, ν_e NuMI, etc.

Recent Improvements

New!



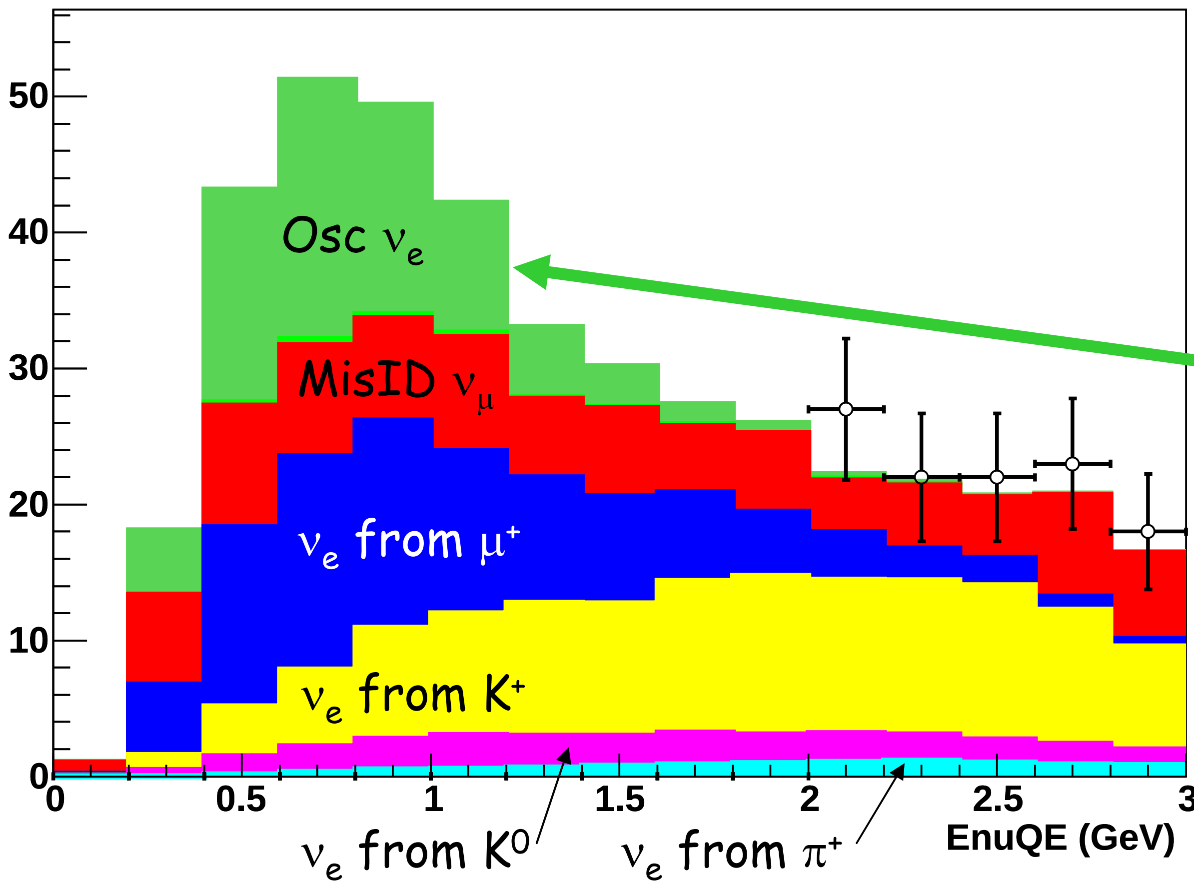
Improvements to OM greatly improve Michel electron E as a function of location in our detector

Backgrounds

Backgrounds

- Backgrounds are determined from our own data using
  - ν_μ CCQE events for intrinsic ν_e from μ^+
  - Single π^0 events for π^0 mis-ID
  - High energy ν_e events for intrinsic ν_e from K^+

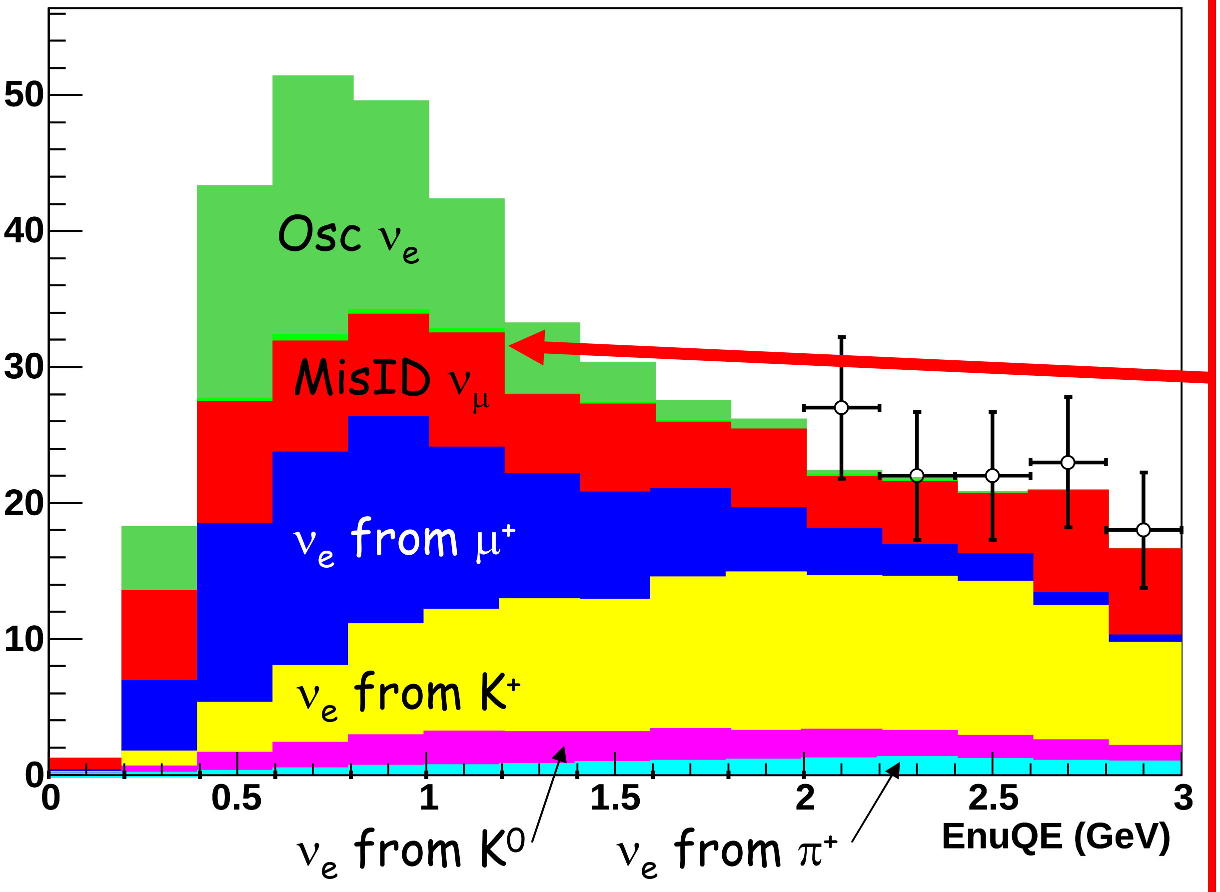
Backgrounds



Osc ν_e

- Example oscillation signal
  - $\Delta m^2 = 1\ eV^2$
  - $\sin^2 2\theta = 0.004$
- Fit for excess as a function of reconstructed ν_e energy

Mis-ID Backgrounds

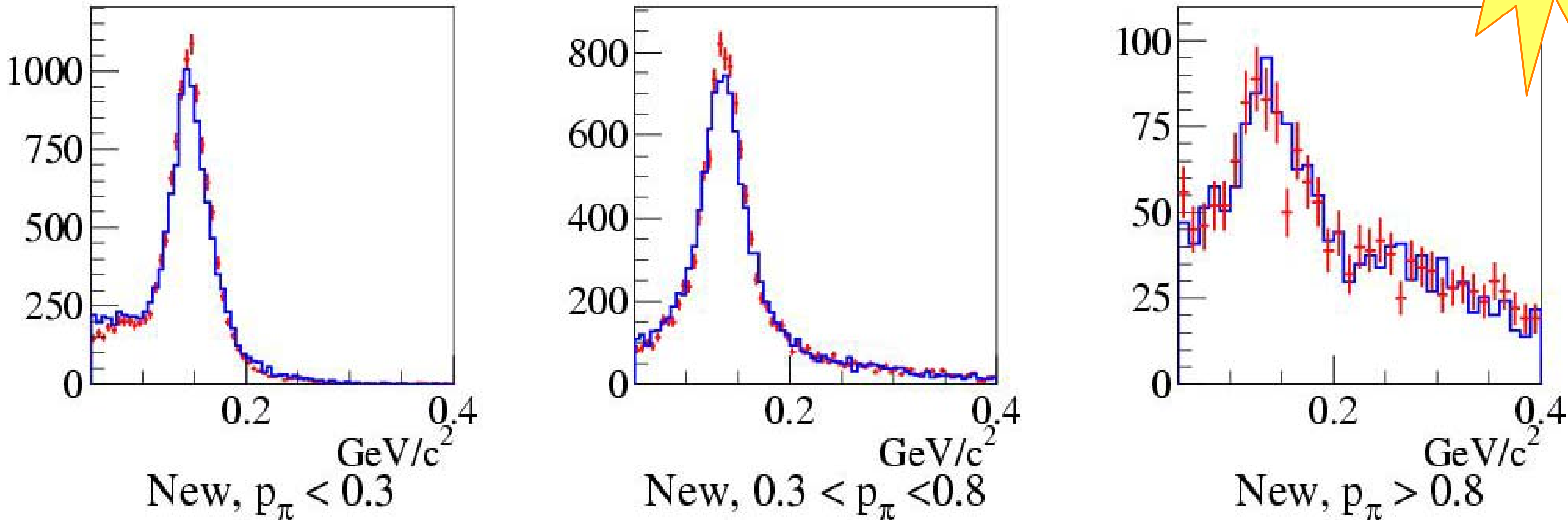


Mis-ID ν_μ

- ~83% π^0
  - Determined by clean π^0 measurement
- ~7% Δ decay
- ~10% other
  - Use ν_μ CCQE rate to normalize and MC for shape

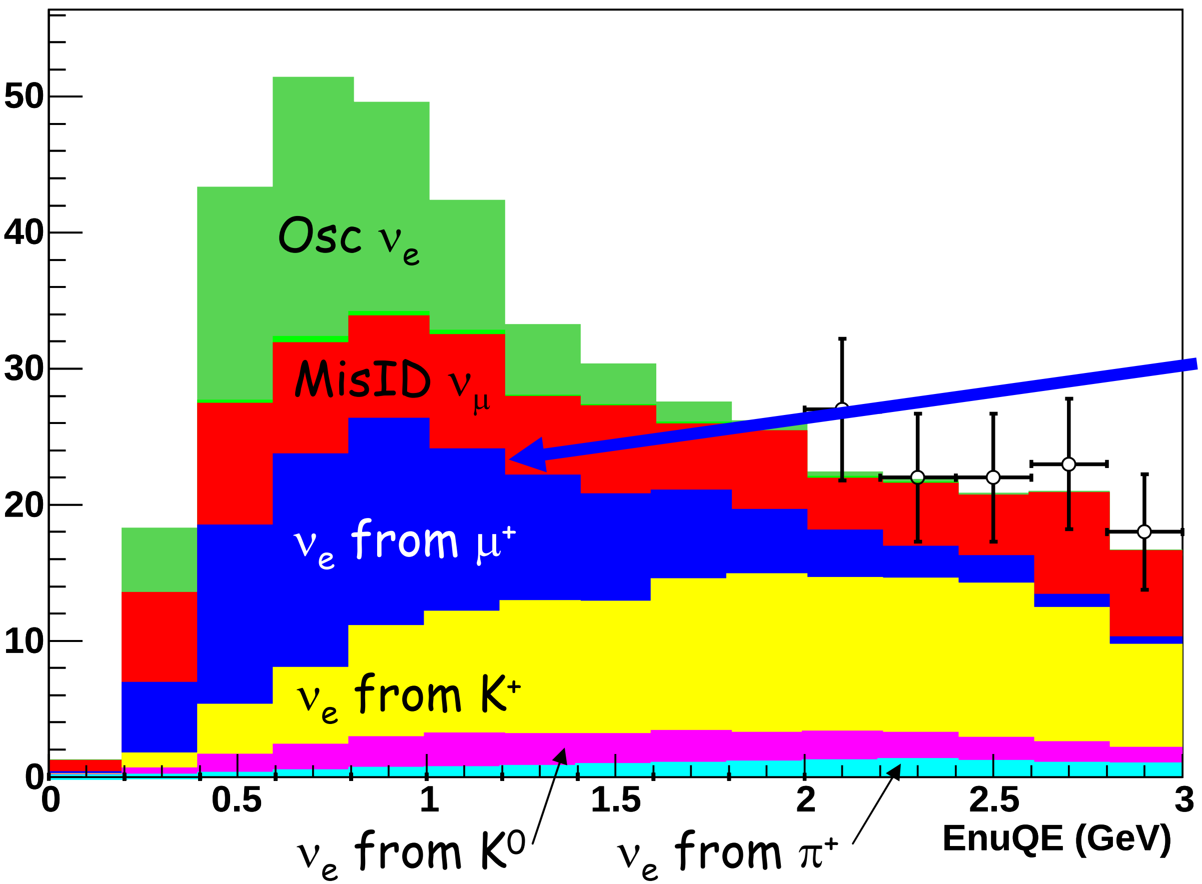
Mis-ID Backgrounds

New!

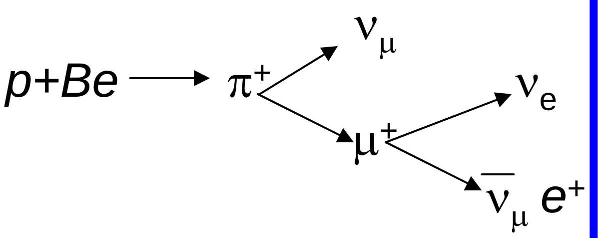


- Need sample of pure π^0 to measure rate as f(momentum)
- High-P region very important to get a handle on high-E ν_e background from K^+

Intrinsic ν_e Backgrounds

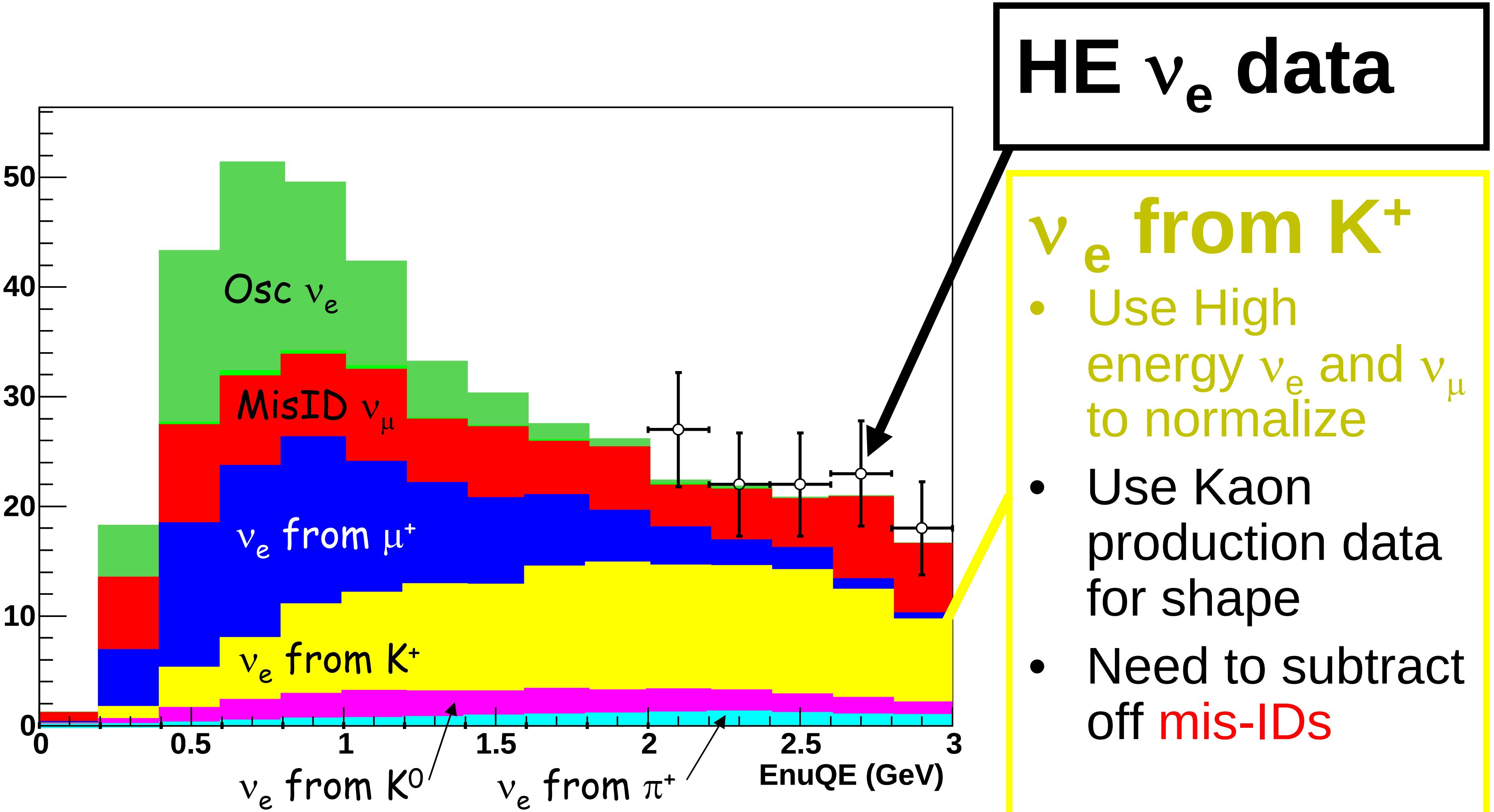


ν_e from μ^+



- Measured with ν_μ CCQE sample
  - Same parent π^+ kinematics
- Most important background
- Very highly constrained (a few percent)

Intrinsic ν_e Backgrounds

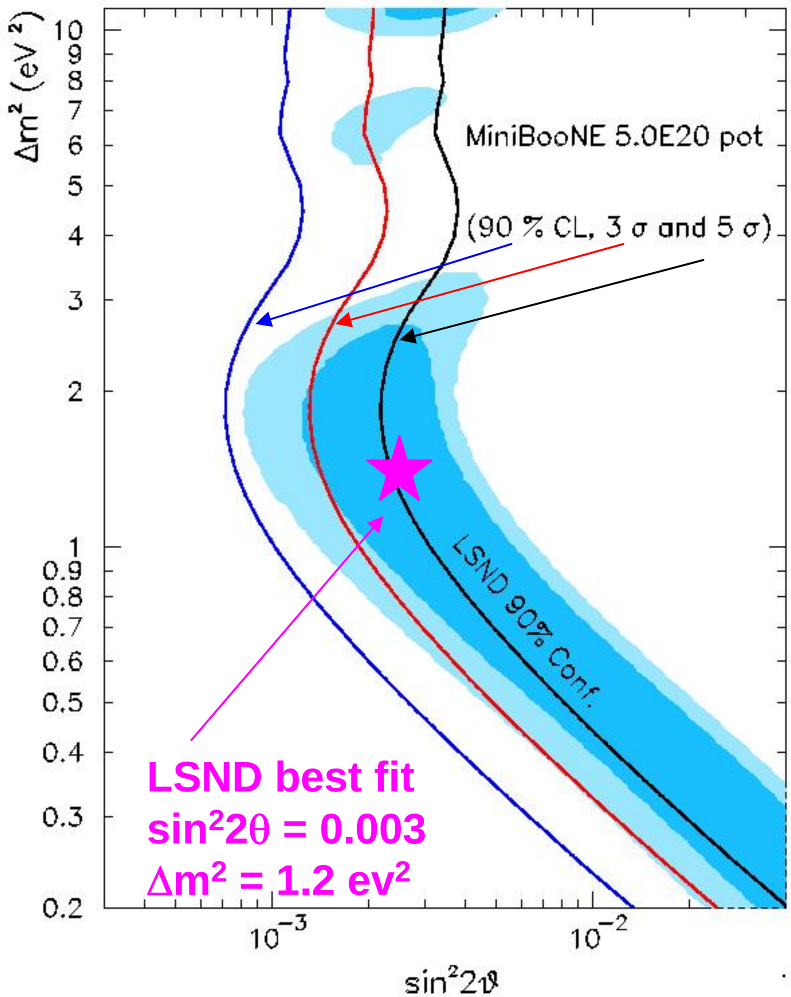


ν_e from K^+

- Use High energy ν_e and ν_μ to normalize
- Use Kaon production data for shape
- Need to subtract off mis-IDs

Particle ID

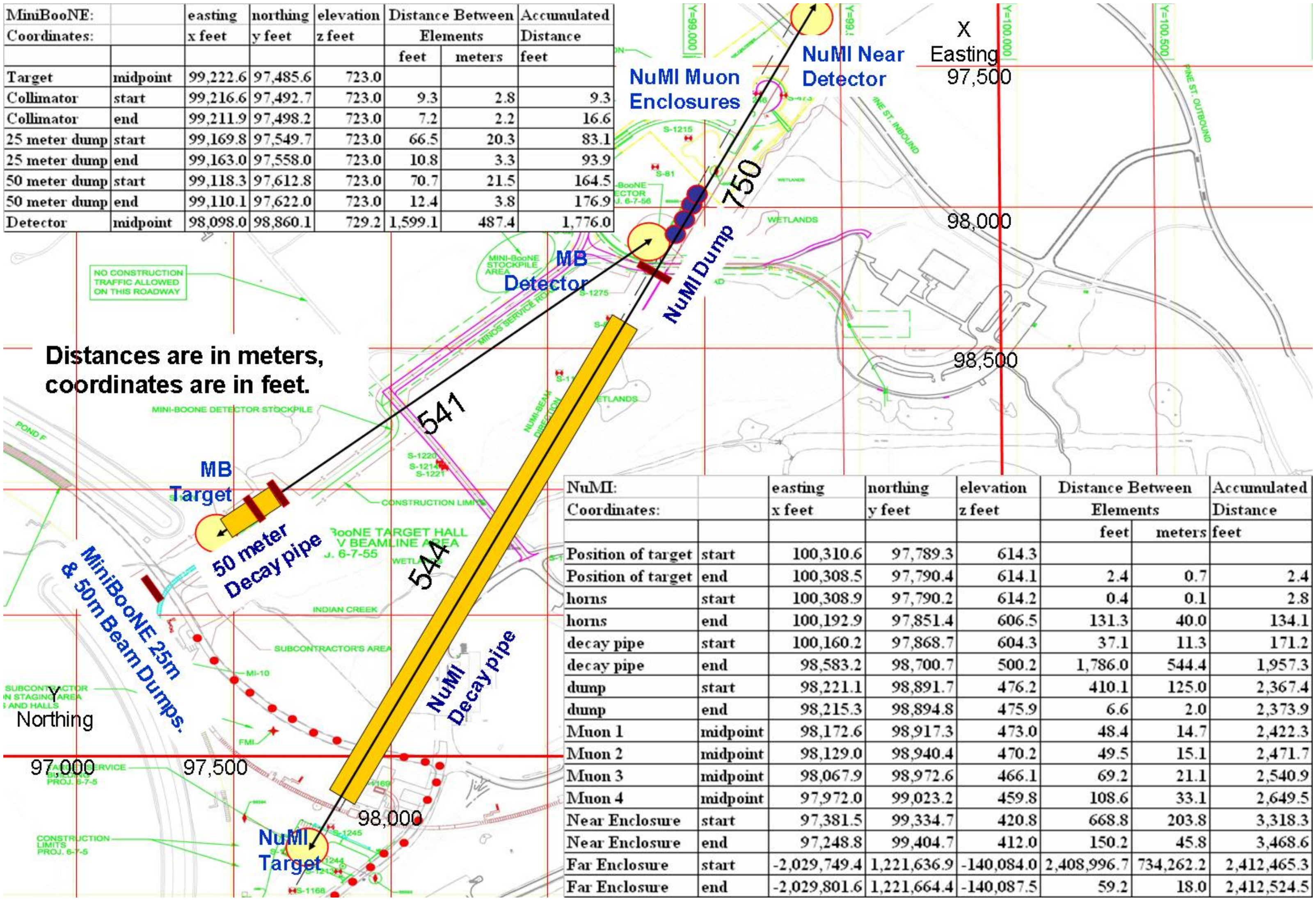
Sensitivity Estimate



- Good sensitivity requires PID
  - Remove ≈ 99.9% of ν_μ CC interactions
  - Remove ≈ 99% of all NC π^0 producing interactions
  - Maintain ≈ 30-60% efficiency for ν_e interactions

NuMI and MiniBooNE

MiniBooNE: Coordinates:		easting x feet	northing y feet	elevation z feet	Distance Between Elements feet	Distance Between Elements meters	Accumulated Distance feet
Target	midpoint	99,222.6	97,485.6	723.0			
Collimator	start	99,216.6	97,492.7	723.0	9.3	2.8	9.3
Collimator	end	99,211.9	97,498.2	723.0	7.2	2.2	16.6
25 meter dump	start	99,169.8	97,549.7	723.0	66.5	20.3	83.1
25 meter dump	end	99,163.0	97,558.0	723.0	10.8	3.3	93.9
50 meter dump	start	99,118.3	97,612.8	723.0	70.7	21.5	164.5
50 meter dump	end	99,110.1	97,622.0	723.0	12.4	3.8	176.9
Detector	midpoint	98,098.0	98,860.1	729.2	1,599.1	487.4	1,776.0

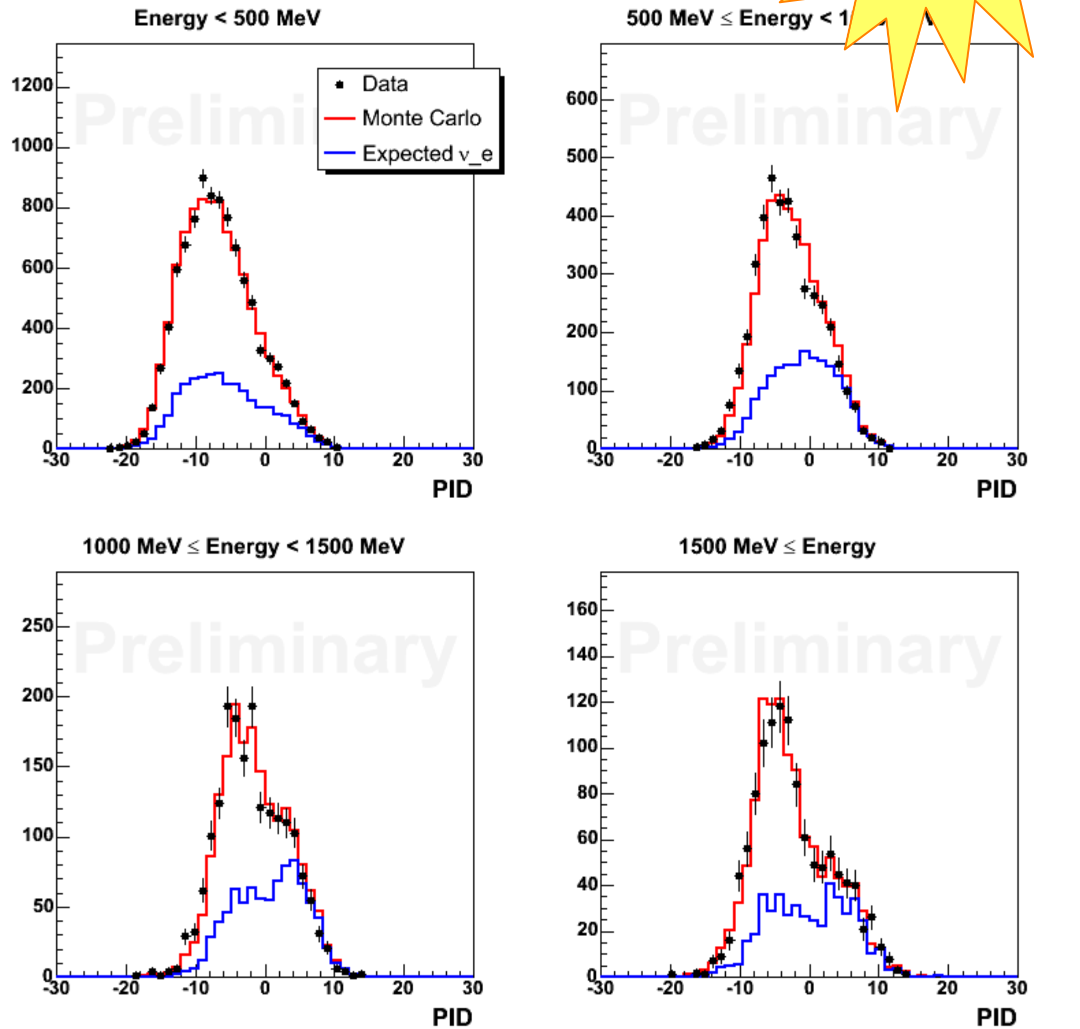


NuMI: Coordinates:		easting x feet	northing y feet	elevation z feet	Distance Between Elements feet	Distance Between Elements meters	Accumulated Distance feet
Position of target	start	100,310.6	97,789.3	614.3			
Position of target	end	100,308.5	97,790.4	614.1	2.4	0.7	2.4
horns	start	100,308.9	97,790.2	614.2	0.4	0.1	2.8
horns	end	100,192.9	97,851.4	606.5	131.3	40.0	134.1
decay pipe	start	100,160.2	97,868.7	604.3	37.1	11.3	171.2
decay pipe	end	98,583.2	98,700.7	500.2	1,786.0	544.4	1,957.3
dump	start	98,221.1	98,891.7	476.2	410.1	125.0	2,367.4
dump	end	98,215.3	98,894.8	475.9	6.6	2.0	2,373.9
Muon 1	midpoint	98,172.6	98,917.3	473.0	48.4	14.7	2,422.3
Muon 2	midpoint	98,129.0	98,940.4	470.2	49.5	15.1	2,471.7
Muon 3	midpoint	98,067.9	98,972.6	466.1	69.2	21.1	2,540.9
Muon 4	midpoint	97,972.0	99,023.2	459.8	108.6	33.1	2,649.5
Near Enclosure	start	97,381.5	99,334.7	420.8	668.8	203.8	3,318.3
Near Enclosure	end	97,248.8	99,404.7	412.0	150.2	45.8	3,468.6
Far Enclosure	start	-2,029,749.4	1,221,636.9	-140,084.0	2,408,996.7	734,262.2	2,412,465.3
Far Enclosure	end	-2,029,801.6	1,221,664.4	-140,087.5	59.2	18.0	2,412,524.5

Checking PID with NuMI Events

New!

- Because of the off-axis angle, the beam at MiniBooNE from NuMI is significantly enhanced in ν_e from K^+
- Enables a powerful check on the Particle ID

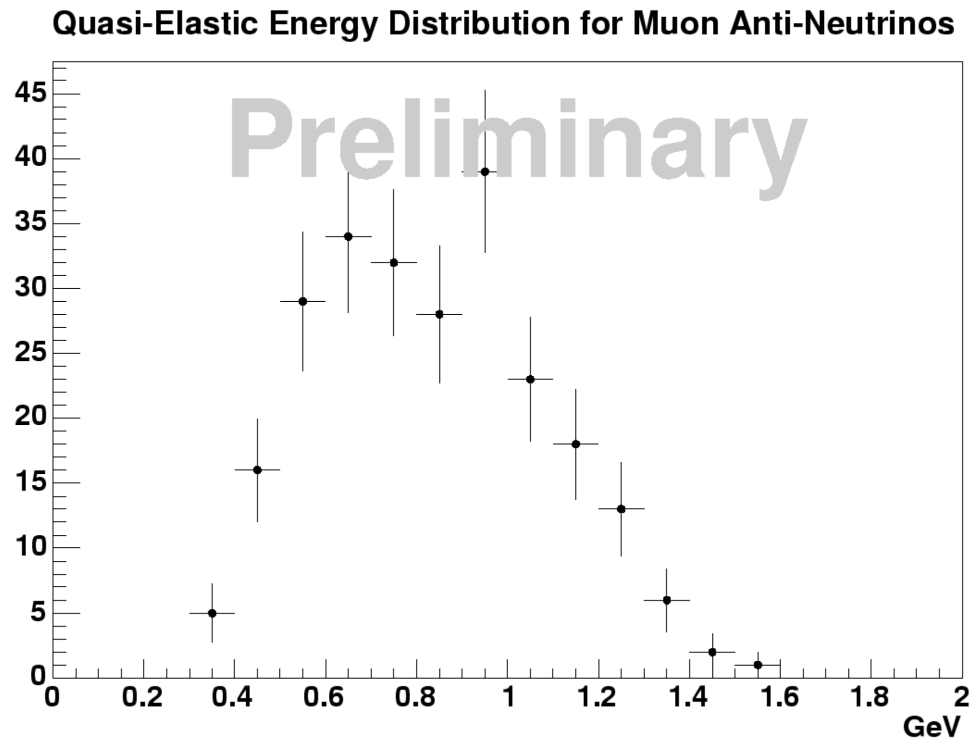


MiniBooNE Summary

- **Checking and double-checking our systematic errors**

Anti-neutrino Data

- We have several summer students working with the anti-neutrino data
  - $\overline{\nu_\mu}$ CCQE free-proton cross section
  - NC pion analysis



Backup Slides

Sampling Neutrino Theories

AKA : explaining the three oscillation results

Explaining LSND

- Sterile Neutrinos
  - RH neutrinos that don't interact (Weak == LH only)
- CPT Violation
  - 3 neutrino model, $\Delta m_{\text{anti-}\nu}^2 > \Delta m_{\nu}^2$
  - Run in neutrino, anti-neutrino mode, compare measured oscillation probability
- Mass Varying Neutrinos
  - Mass of neutrinos depends on medium through which it travels
- Lorentz Violation
  - Oscillations depend on direction of propagation
  - Oscillations explained by small Lorentz violation
  - Don't need to introduce neutrino mass for oscillations!
  - Look for sidereal variations in oscillation probability

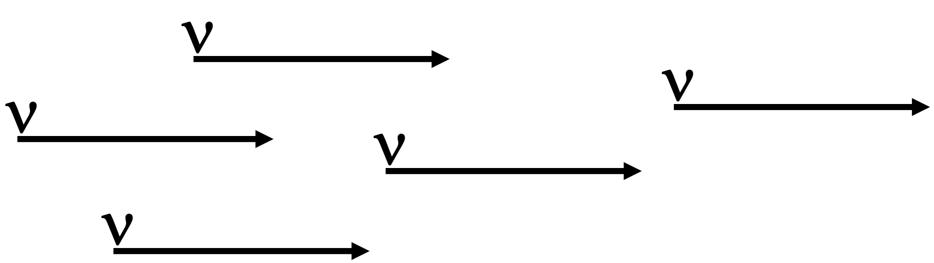
How often do these interactions occur?

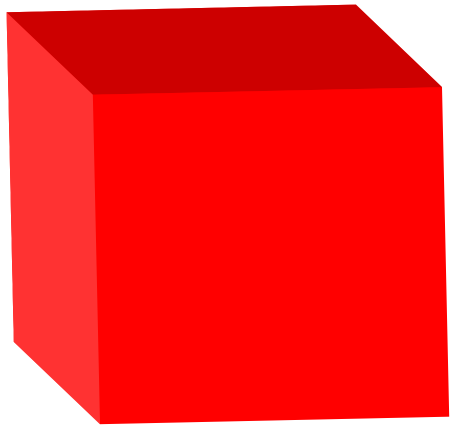
Cross Sections

- Cross section = probability that an interaction will take place

Volume of detector = V (m^3)
Density of nucleons = n ($1/m^3$)

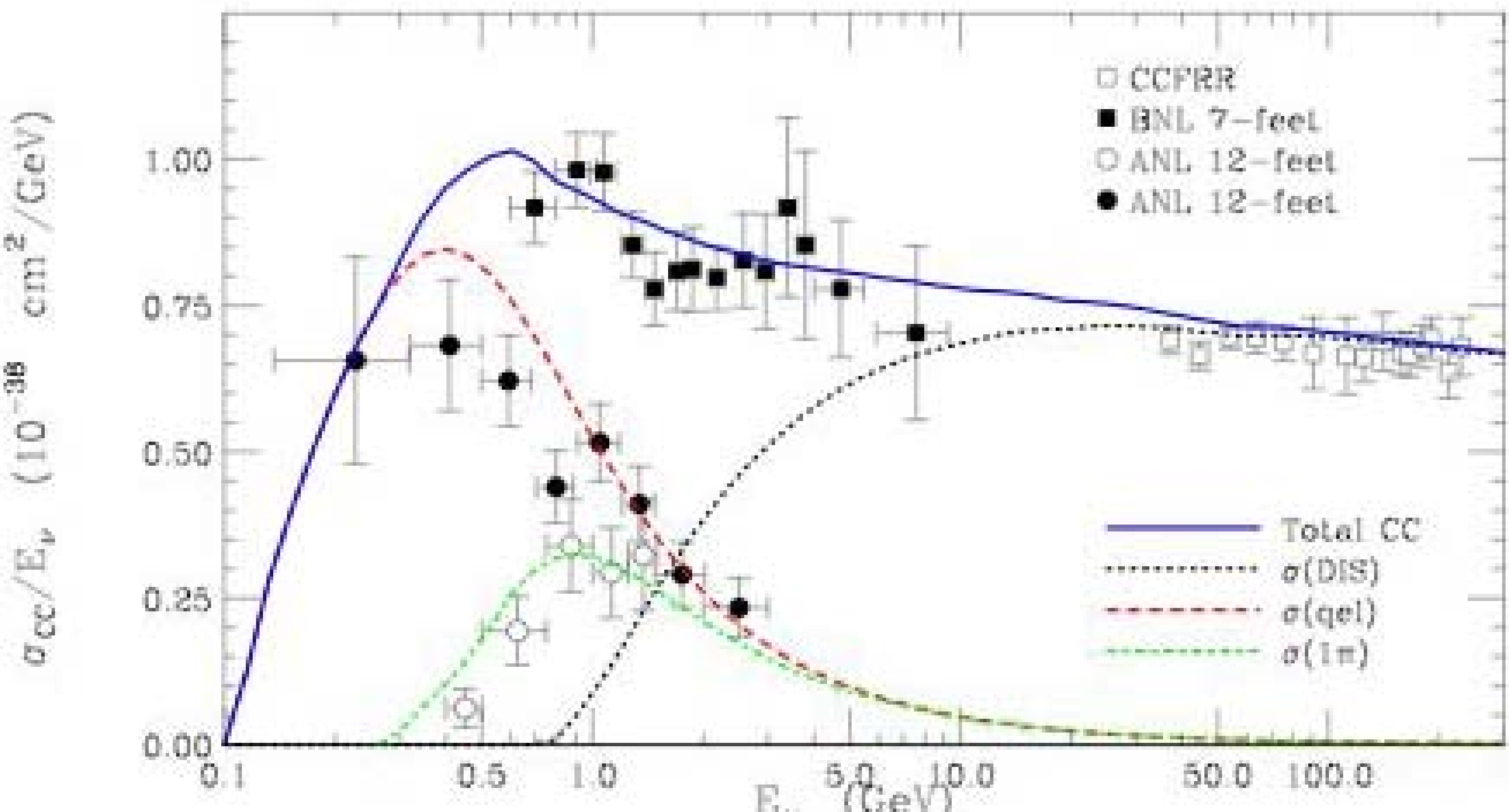
Neutrino flux = ϕ ($1/m^2s$)





$$\textbf{Cross Section } \sigma \ (m^2) = \frac{\text{\# neutrino interactions per second}}{\text{Flux} \ * \underbrace{\text{Density} * \text{Volume}}_{\text{\# of targets}}}$$

Neutrino Cross Sections

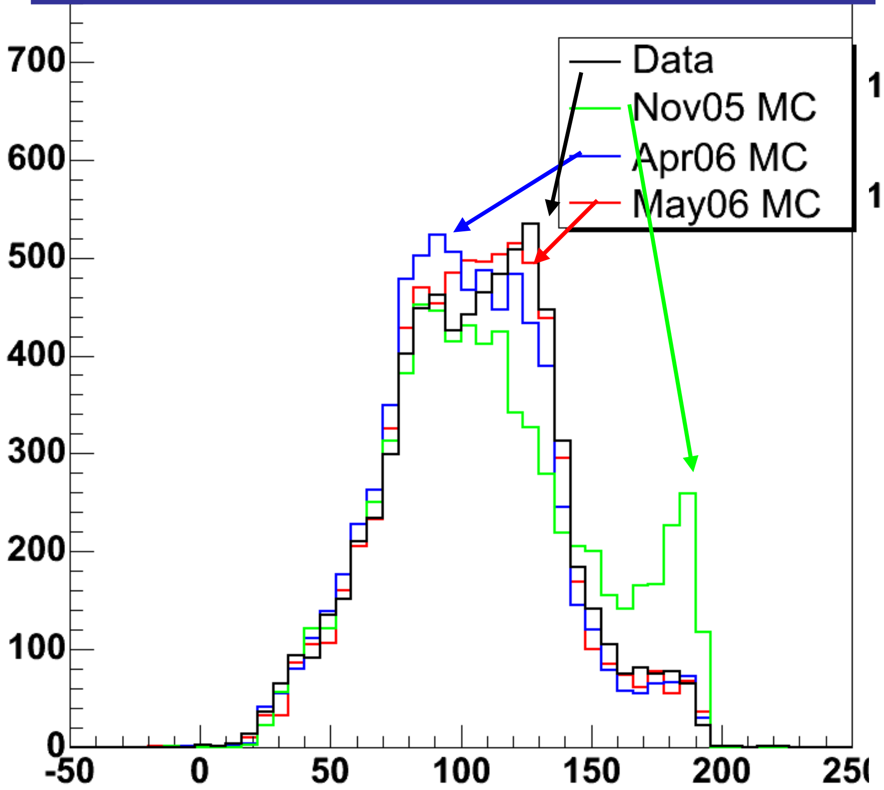


Neutrino has to produce a charged lepton = need enough E to produce this extra mass

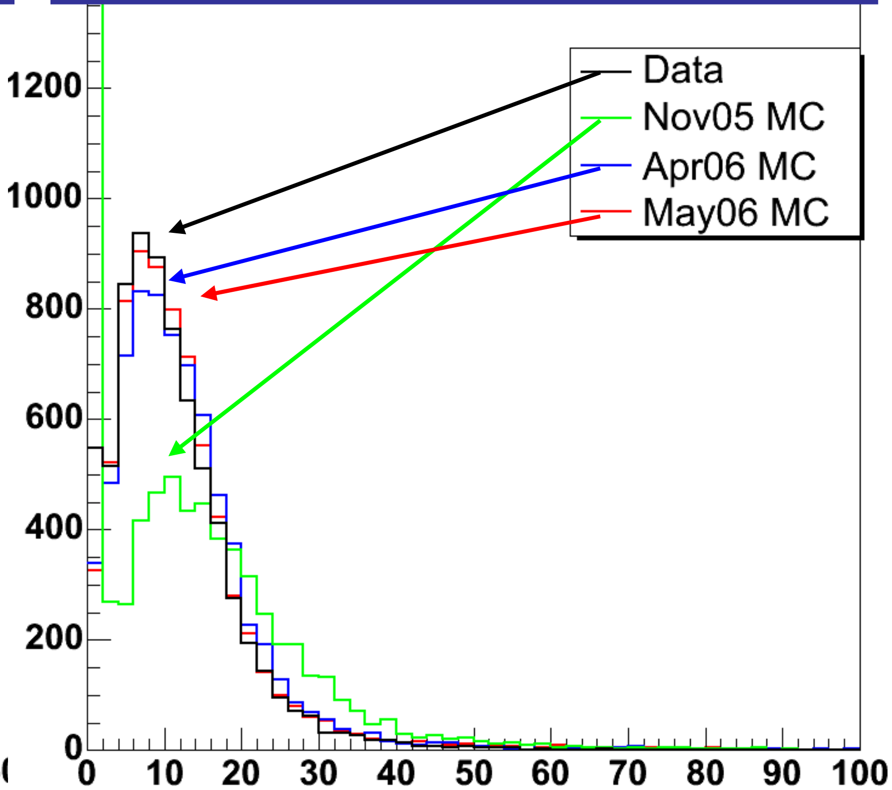
Impact of Improved OM

New!

Distance between pi0 vertex and 1st gamma conversion point



Scintillation light in 1st gamma in pi0 fitter



Particle ID Algorithm

- Using a boosted decision tree
  - Similar to a neural net, but better
  - Needs to be trained on a set of variables
  - Want vars which are powerful at distinguishing between signal, background event types
- Have a large list of potential inputs
- Require data & MC shapes to agree for an input to be considered for training
- The more vars with agreement, the larger set of powerful vars we'll have to draw from, thus providing a more powerful PID algo

Nuc.Inst.Meth.A 543 (2005) 557-584
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PID Inputs

New!