MiniBooNE:

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Neutrinos in the Standard Model:

+antiparticles

g Color

Z W Weak charge

γ Electric charge

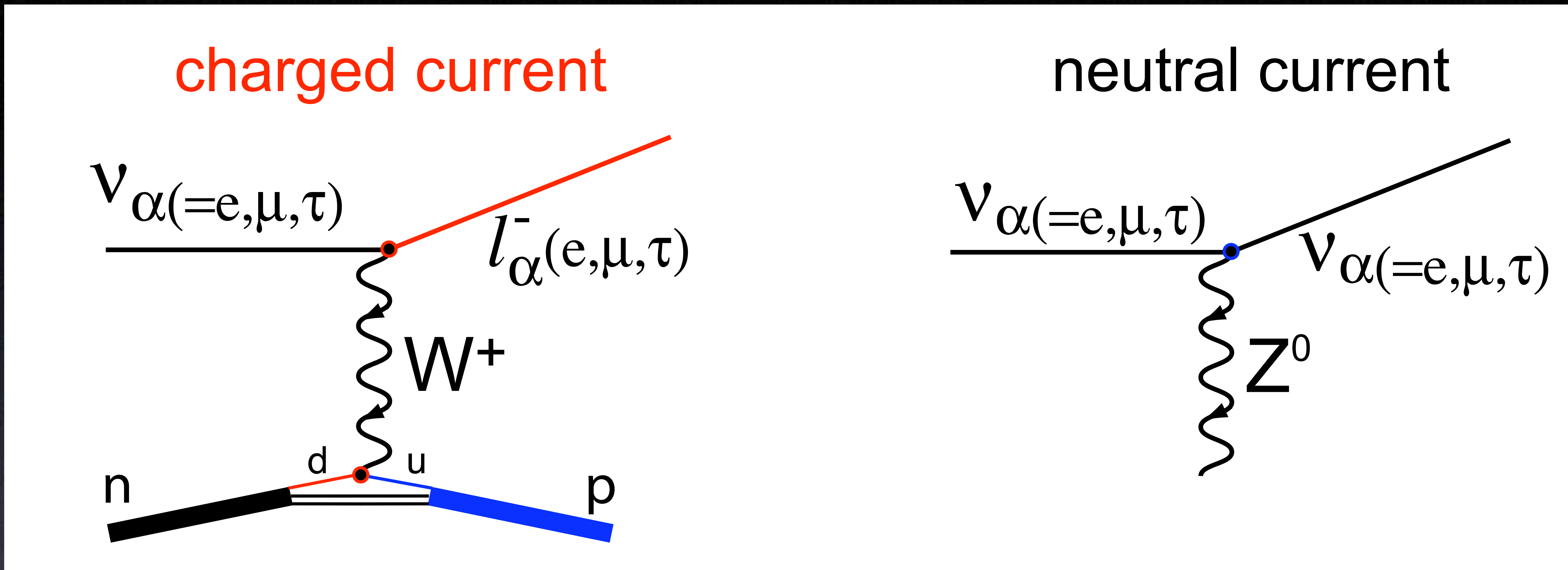
Quarks:
color, weak charge, electric charge

Charged Leptons:
~~color,~~ weak charge, electric charge

Neutrinos:
~~color,~~ weak charge, ~~electric charge~~

- Neutrinos interact only through the weak interactions (+ gravity)
- 1 GeV neutrino in lead has an interaction length $>10^9$ km
  Photon interaction length in lead: 0.56 cm

Neutrino Interactions:



- “CC”: neutrino converts to a charged lepton l_α
  - Defines flavor eigenstate of neutrino
  - Antineutrino produces positively charged lepton
  - Flavor of (anti)neutrinos also defined by decay (“tag” at production)
- “NC”: neutrino scatters off target, maintains identity

Mixing in Leptons and Quarks

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

$\alpha = (d, s, b)$

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

$\alpha = (e, \mu, \tau)$

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

Lepton Sector:

Neutrino oscillations

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

Quark Sector:

Flavor-changing decays
Mixing/oscillations
CP violation

Neutrino Oscillations:

$$|d_\alpha\rangle = \sum_i V^*_{\alpha i}|d_i\rangle$$
$\alpha = (d, s, b)$

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$
$\alpha = (e, \mu, \tau)$

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

Lepton Sector:

Neutrino oscillations

$\alpha = (e, \mu, \tau)$

Observe as: deficit of ν_α
appearance of ν_β

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

Neutrino Oscillations:

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

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- Mass eigenstates ≠ Flavor eigenstates
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- No theoretical guidance

Lepton Sector:

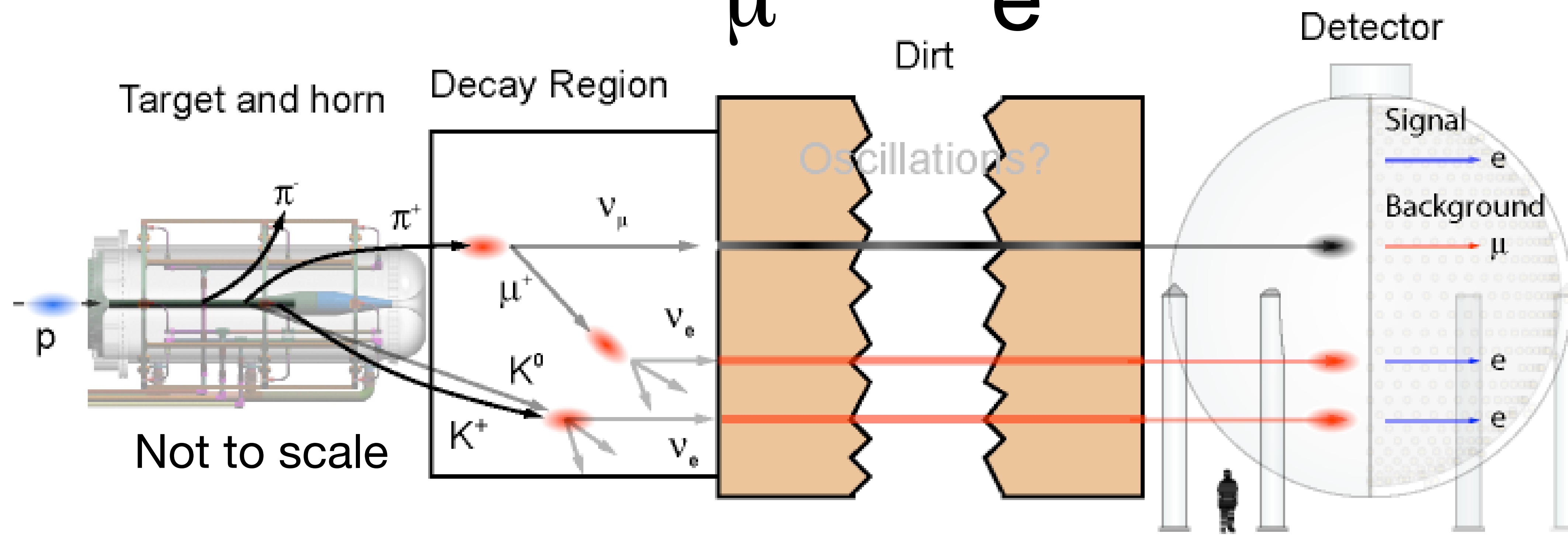
Neutrino oscillations

$$\sin^2 2\theta \times \sin^2\left[1.27\Delta m^2 \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

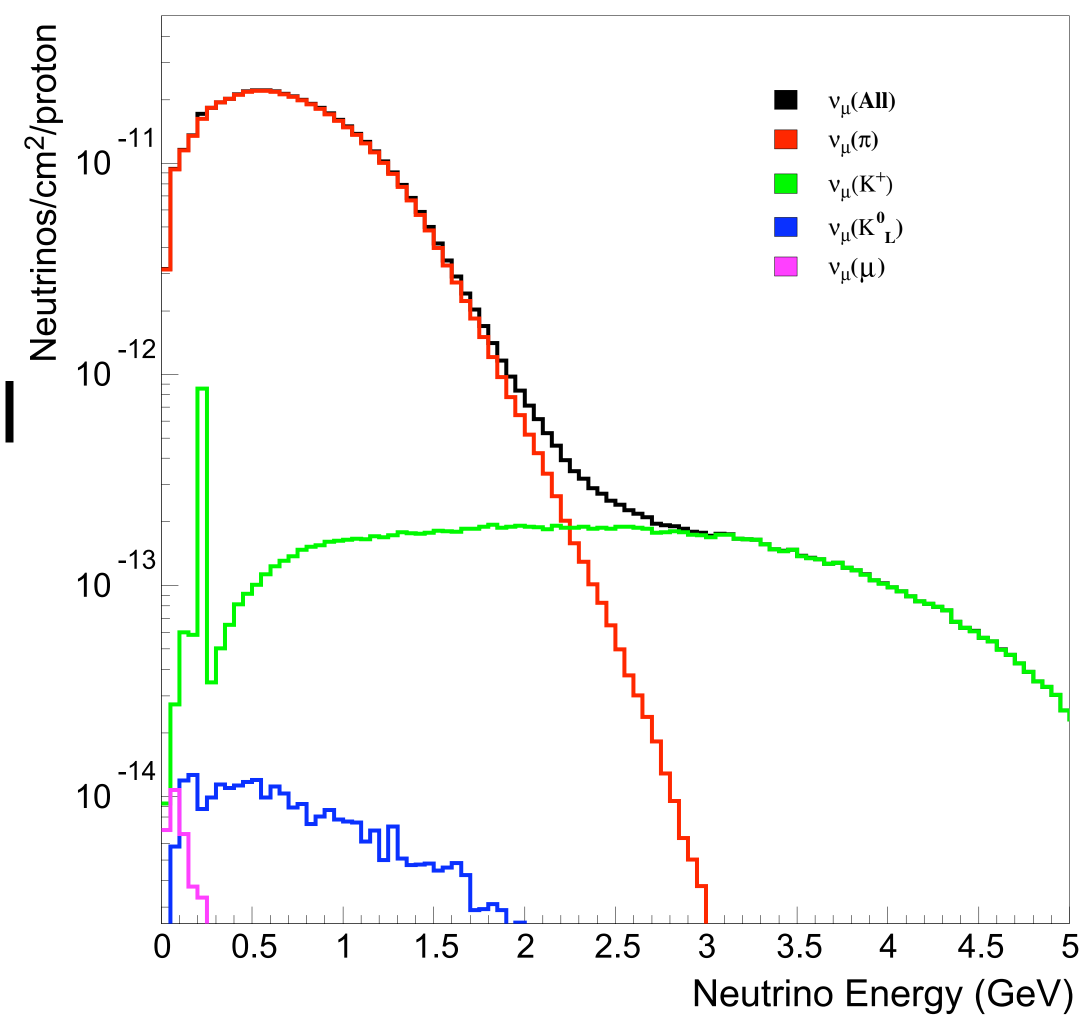
Two neutrinos

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

MiniBooNE: $\nu_\mu \rightarrow \nu_e$ search



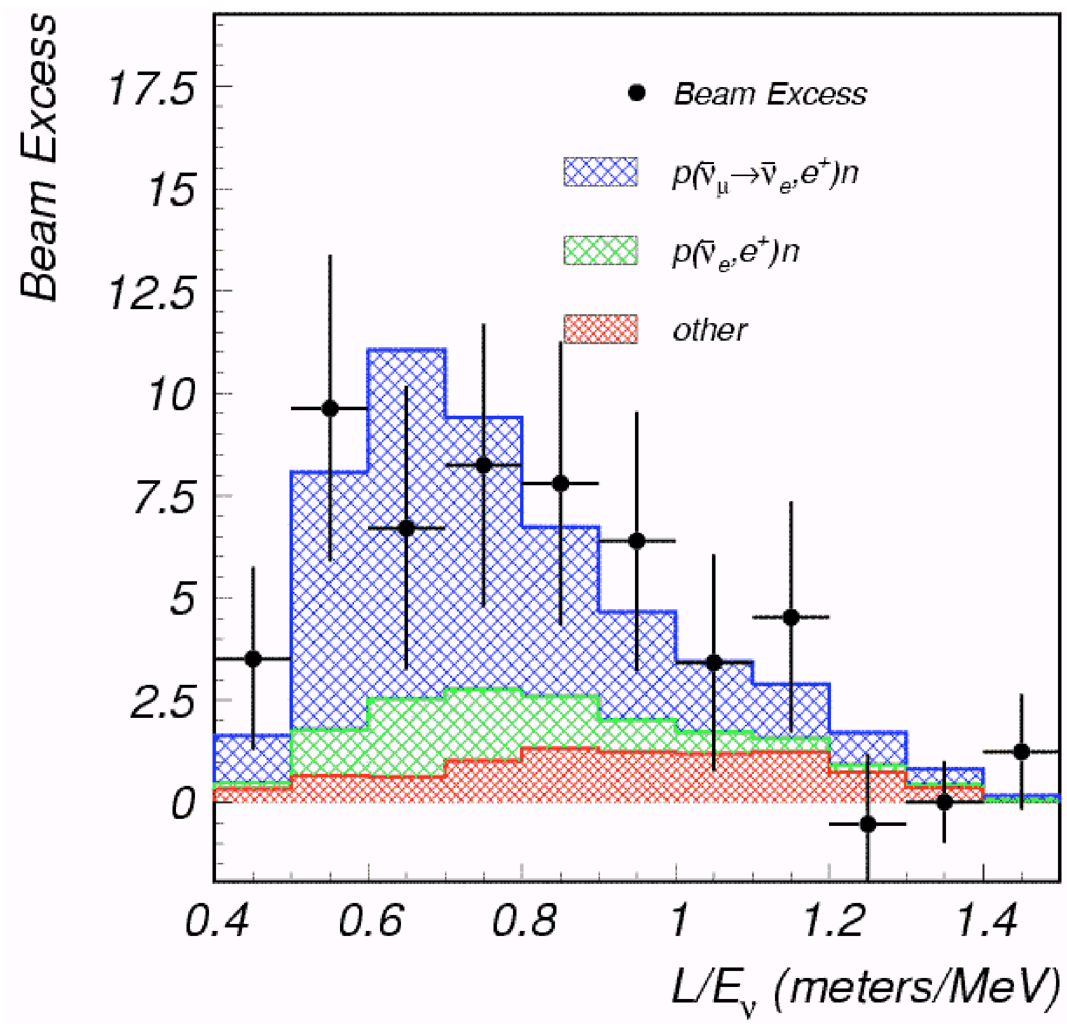
- Beam: 8 GeV protons on Be
  - Produce ~0.8 GeV ν_μ beam
  - 540 m baseline
  - 5.6 x 10^{20} POT for analysis
- Detector: 800 ton sphere of mineral oil
  - 550 cm inner "tank" region (1280 PMT)
  - Outer "veto" region (240 PMTs)



Detect ν interactions via Č/Scintillation

Search for $\nu_\mu \rightarrow \nu_e$, L/E~1 km/GeV

LSND Oscillations:

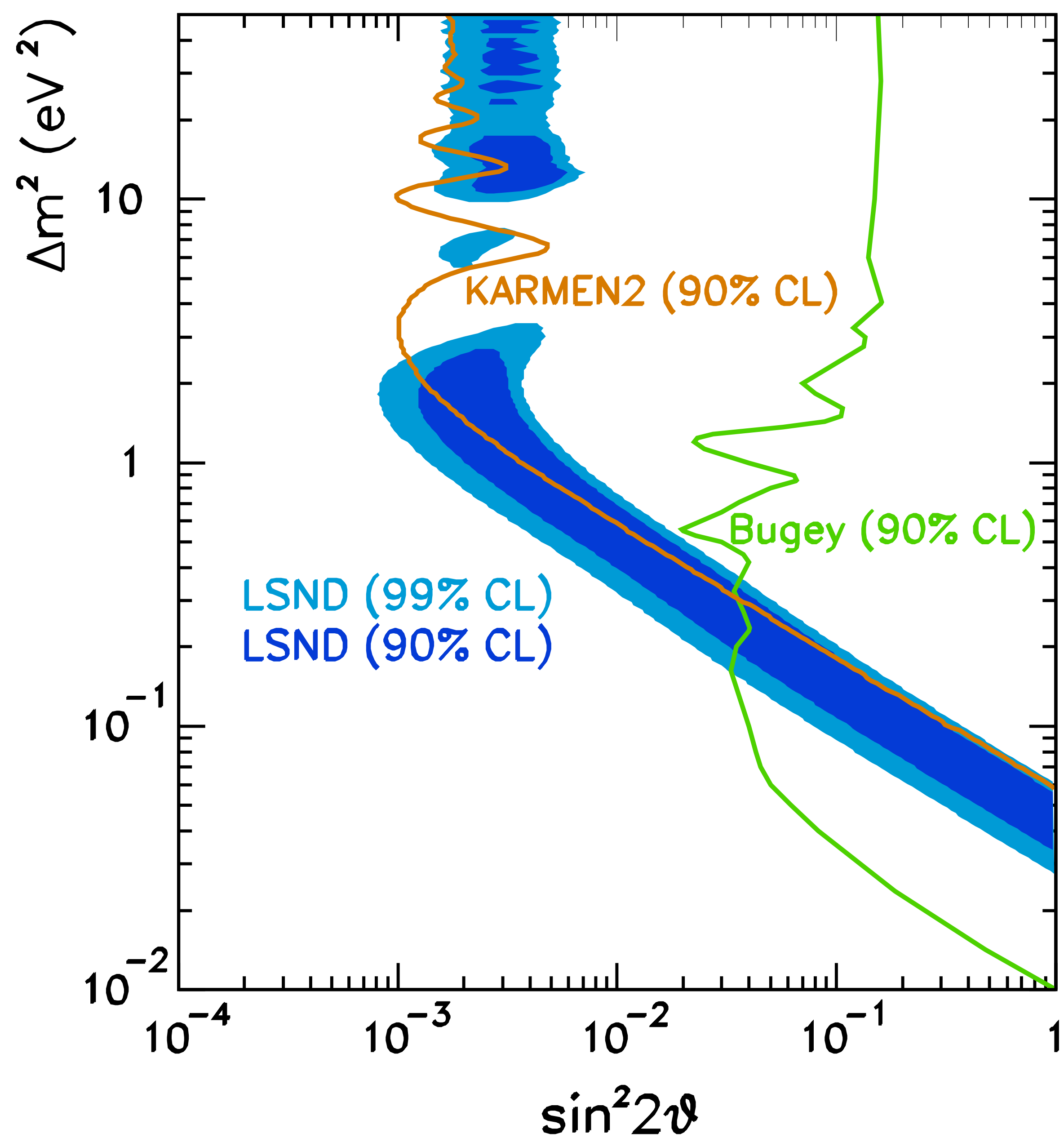


Evidence for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations

Stopped π^+ beam produces $\bar{\nu}_\mu$

Č/n-capture signature

Excess of 87.9 ±22.4 ±6.0 events



Neutrino oscillations with

$\Delta m^2 \sim 0.1$-$10\ \mathrm{eV}^2$ (L/E~ 1 km/GeV)

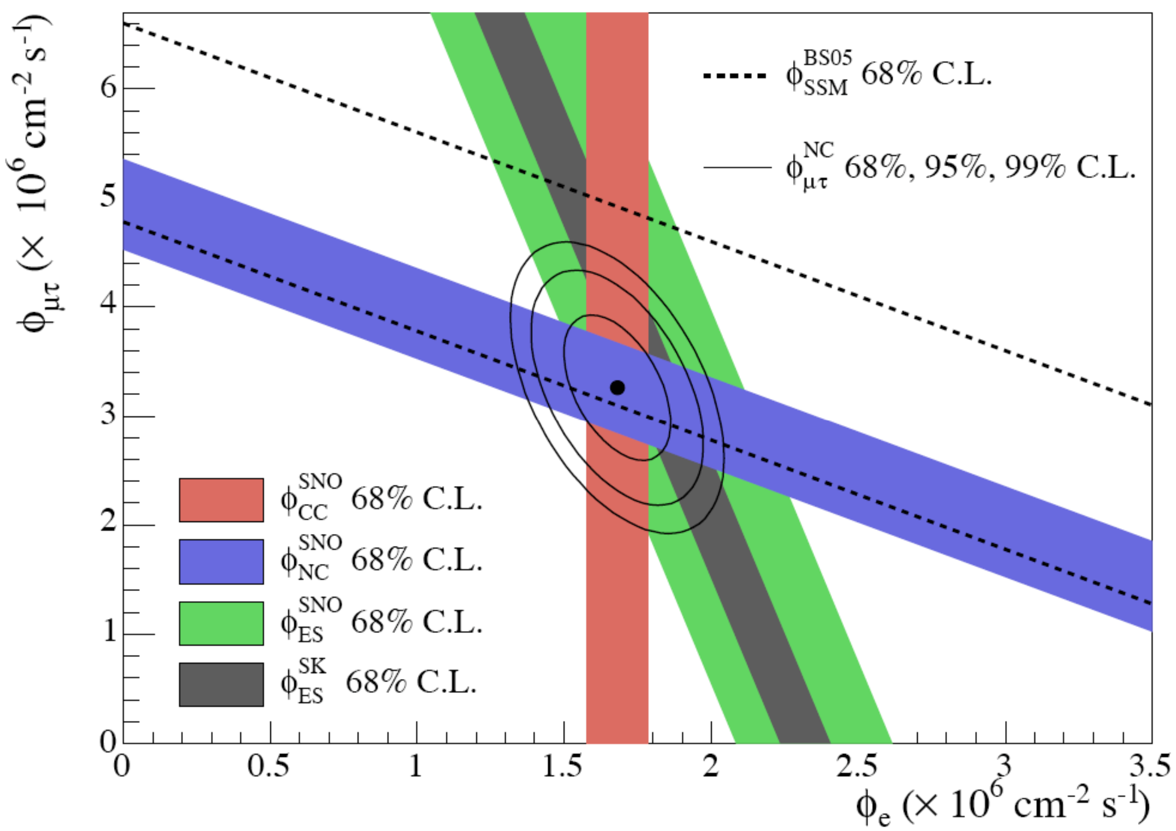
$\sin^2 2\theta \sim 0.001$-$0.04$

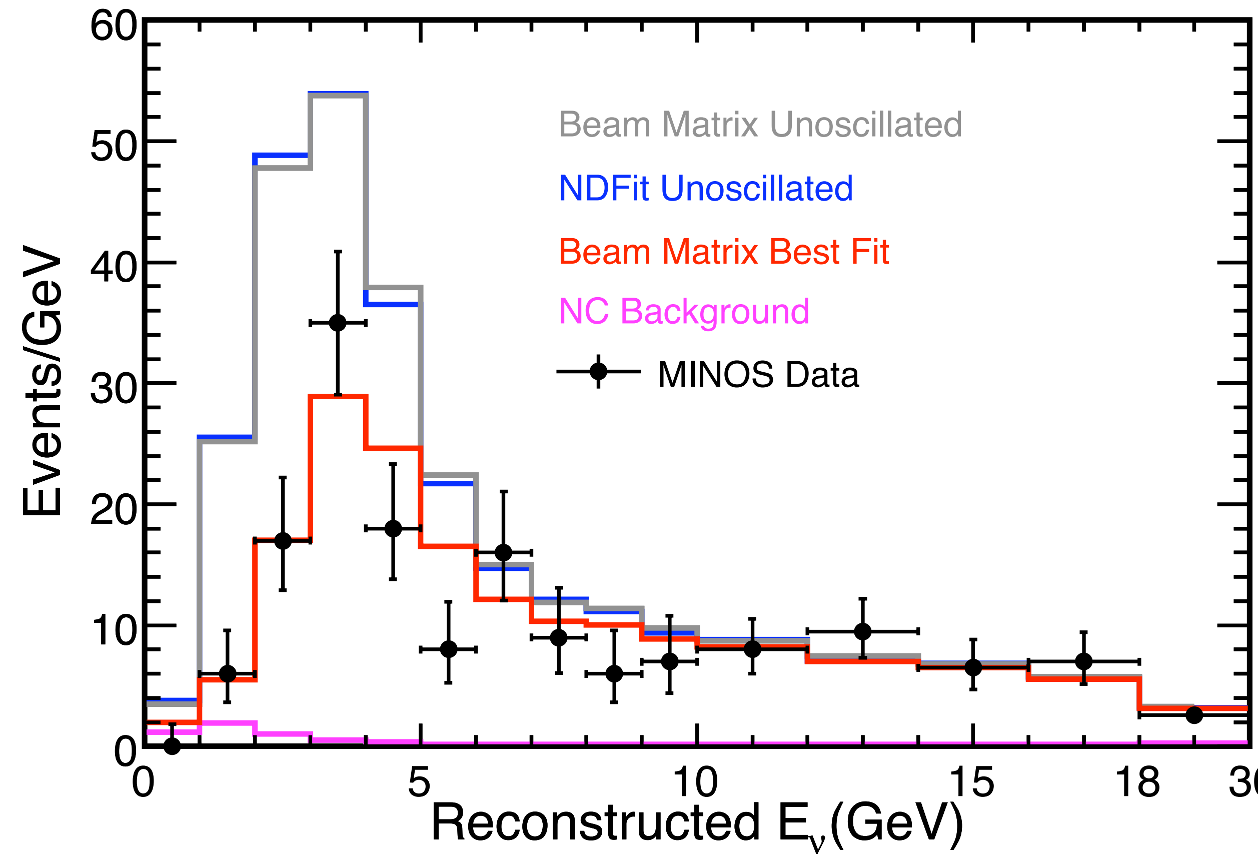
(includes constraints)

Unconfirmed by other experiments

Not ruled out, either

"Other" Oscillations:





Three Δm^2 with different orders of magnitudes:

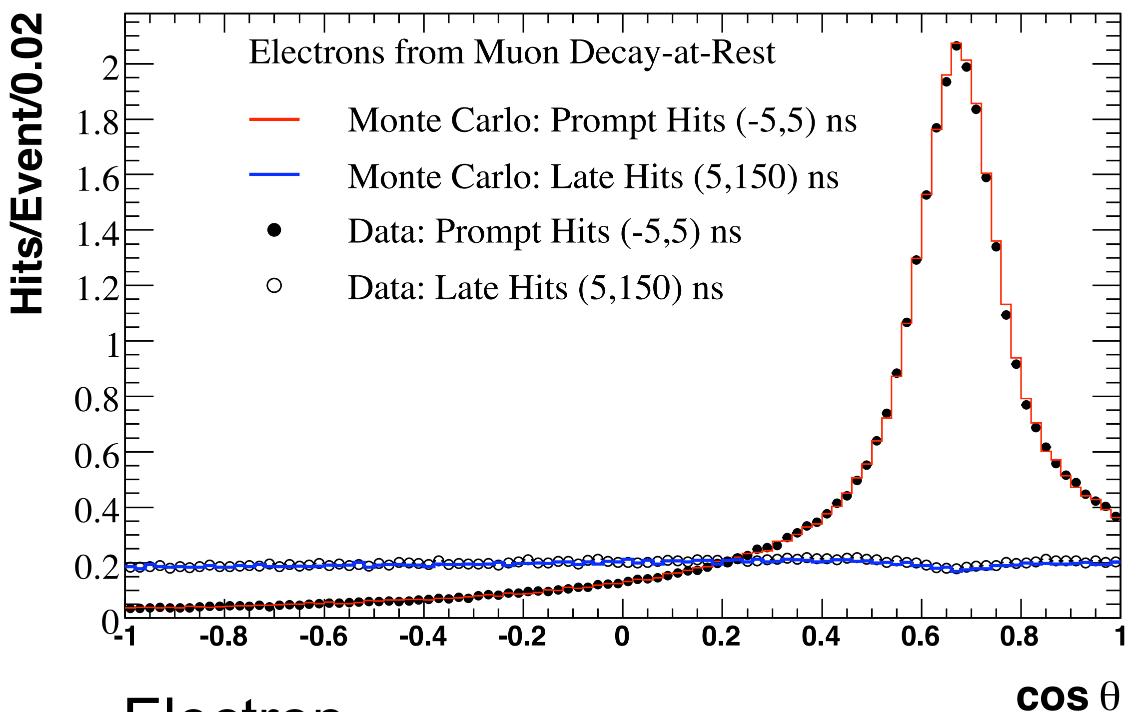
- "Solar": $\Delta m_{12}^2 \sim 8 \times 10^{-5}$ eV^2
- "Atmospheric": $\Delta m_{23}^2 \sim 2.5 \times 10^{-3}$ eV^2
- "LSND": $\Delta m^2 \sim 0.1$-10 eV^2

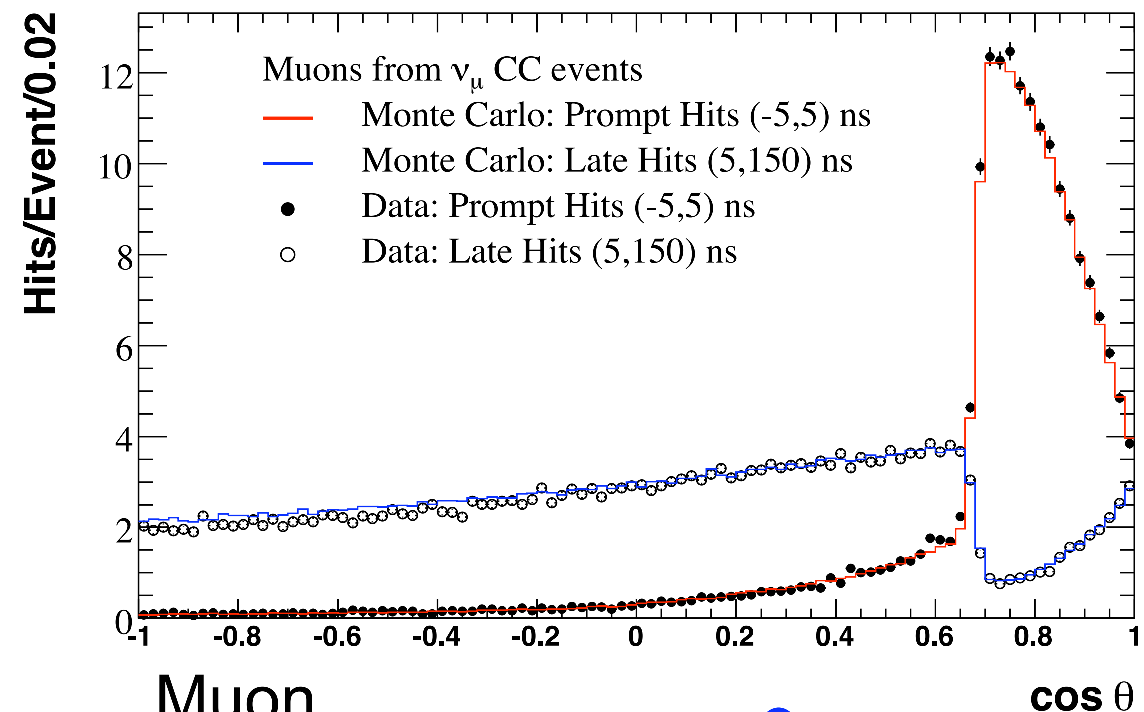
Incompatible with three neutrino model

New physics (sterile ν, CP(T) violation?) needed if confirmed

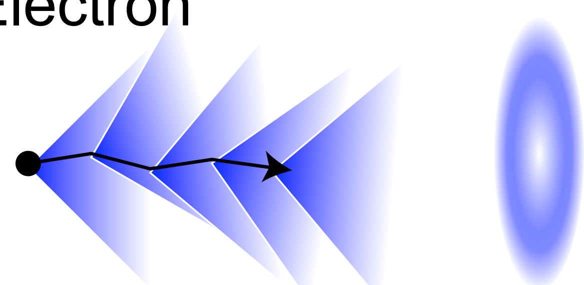
Identifying ν_e Events

Event Topology: Angular Profile

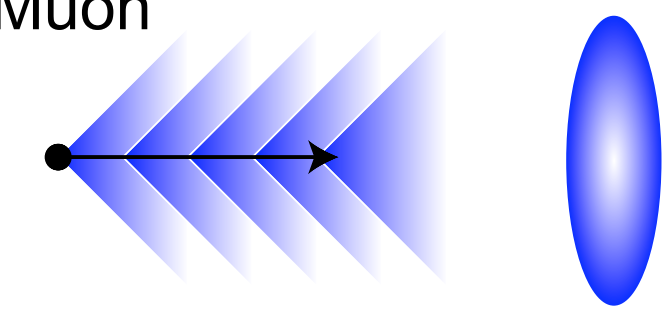




Electron

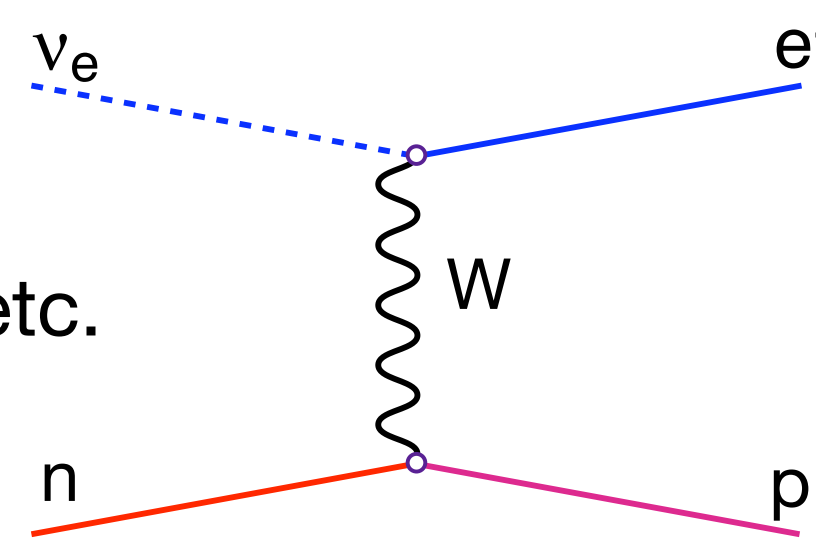


Muon



Signal Channel is ν_e CCQE ($\nu_e + n \rightarrow e^- + p$)

- Signature is one electron-like Č ring
  Proton is typically below Č threshold
- Isotropic light from scattering, fluorescence, etc.
- Neutrino energy from (E_e, θ_e)



The MiniBooNE Challenge:

Expect 0.25% oscillation probability:

- Identify $O(10^3)$ ν_e oscillation events in $O(10^6)$ ν_μ events

- Backgrounds:

Reducible:
Single ring muon events
NC π^0 (1 or 2 e-like rings)
$\Delta \rightarrow N\gamma$ decay (1 e-like ring)

Irreducible/Intrinsic:
Genuine ν_e events in beam
from kaon/muon decay

- Two approaches for reducible background

Track Likelihood:
Form ratio of fit
likelihoods under
different hypotheses

Algorithmic:
Use boosted decision tree
to find optimal combination
of many variables

In this talk I will focus on the **Track Likelihood** approach

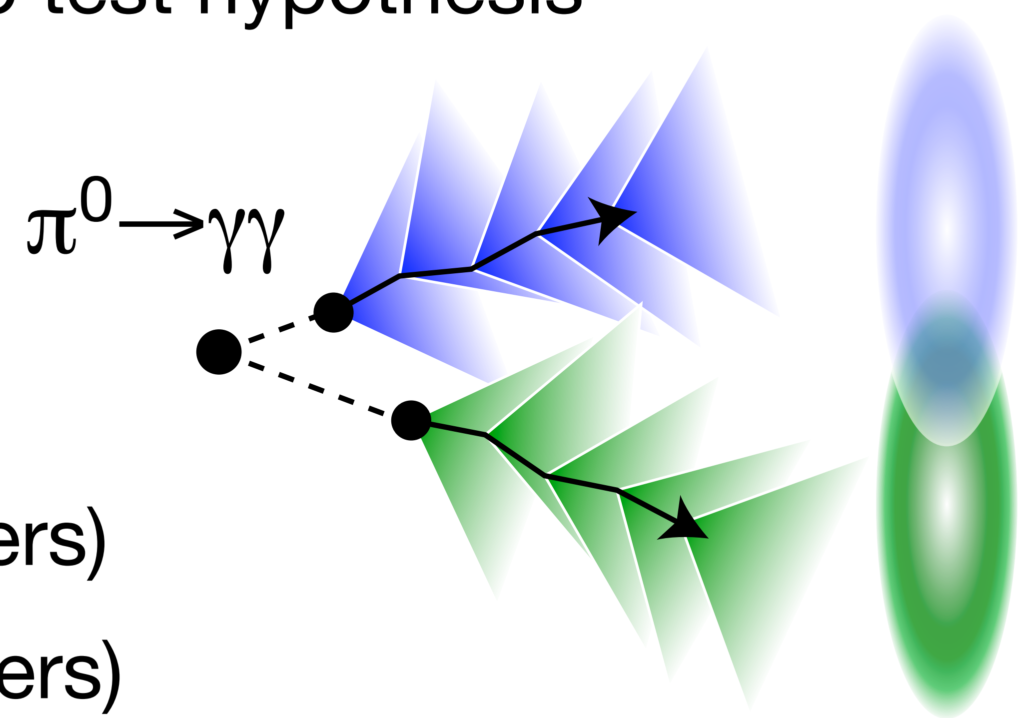
Likelihood Reconstruction:

Reconstructing one track events:

- Determine vertex, time, energy, direction of track (7 parameters)
- Fit model predicts light distribution to test hypothesis

Employ fits to four models:

- Single electron track
- Single muon track
- Two e tracks, free mass (12 parameters)
- Two e tracks, mass=m_{π^0} (11 parameters)



Use for parameter estimation and hypothesis testing

$\log(L_x/L_y) > 0$ if hypothesis x is preferred over y

Resolution/Discrimination dependent on quality of fit model

Analysis Strategy:

Boosted Decision Tree	Track Likelihood
“Fast” fits: vertex/energy/direction	“Full” fits:vertex/energy/direction
Calculate topology variables	Use track likelihoods
Many variables, maximize power	As few variables as possible
One BDT for all backgrounds	Staged background rejection “easiest → hardest”

- Independent methods, orthogonal goals lead to two event selections that serve as a meaningful crosscheck
- Comparable sensitivities

Background Suppression:

Precuts

Only 1 hit cluster

$N_{VETO} < 6$ hits

$N_{TANK} > 200$ hits

R<500 cm

Neutrino sample →

Supress:

- Cosmic background
- “Obvious” ν_μ CC
- Uncontained events

Fast fits
e/μ/2T

207 variables

Boosted Decision Tree

↓ ν_e sample

Signal extraction

Full fits
e/μ/2T/2Tπ

μ suppression
compare e/μ likelihoods

π^0 suppression I
Mass from 2T ~ M_{π^0}

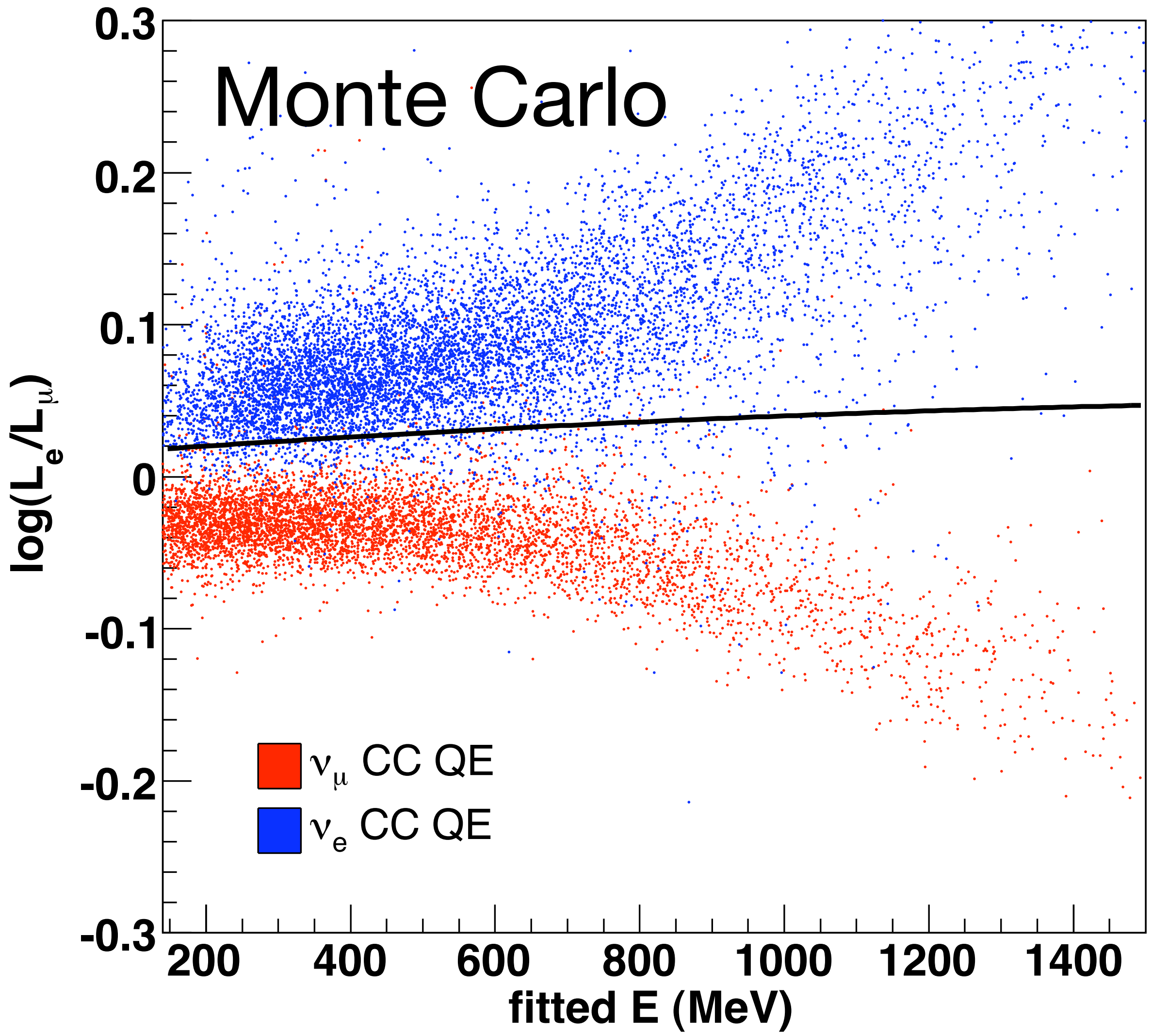
π^0 suppression II
compare e/2Tπ likelihoods

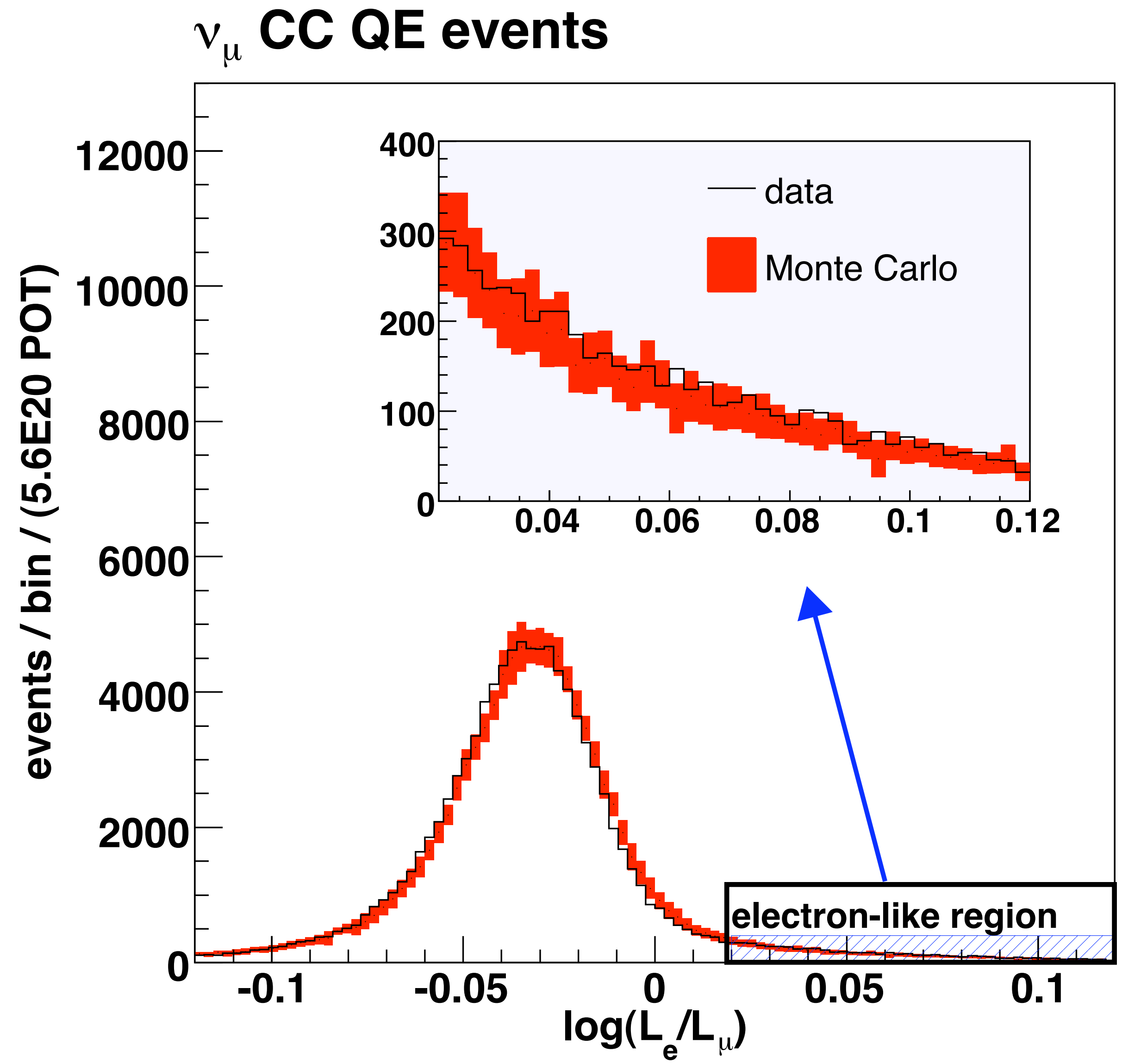
Uncontained π^0 cut
Additional E/R requirements

↓ ν_e sample

Signal extraction

Suppressing μ Events:

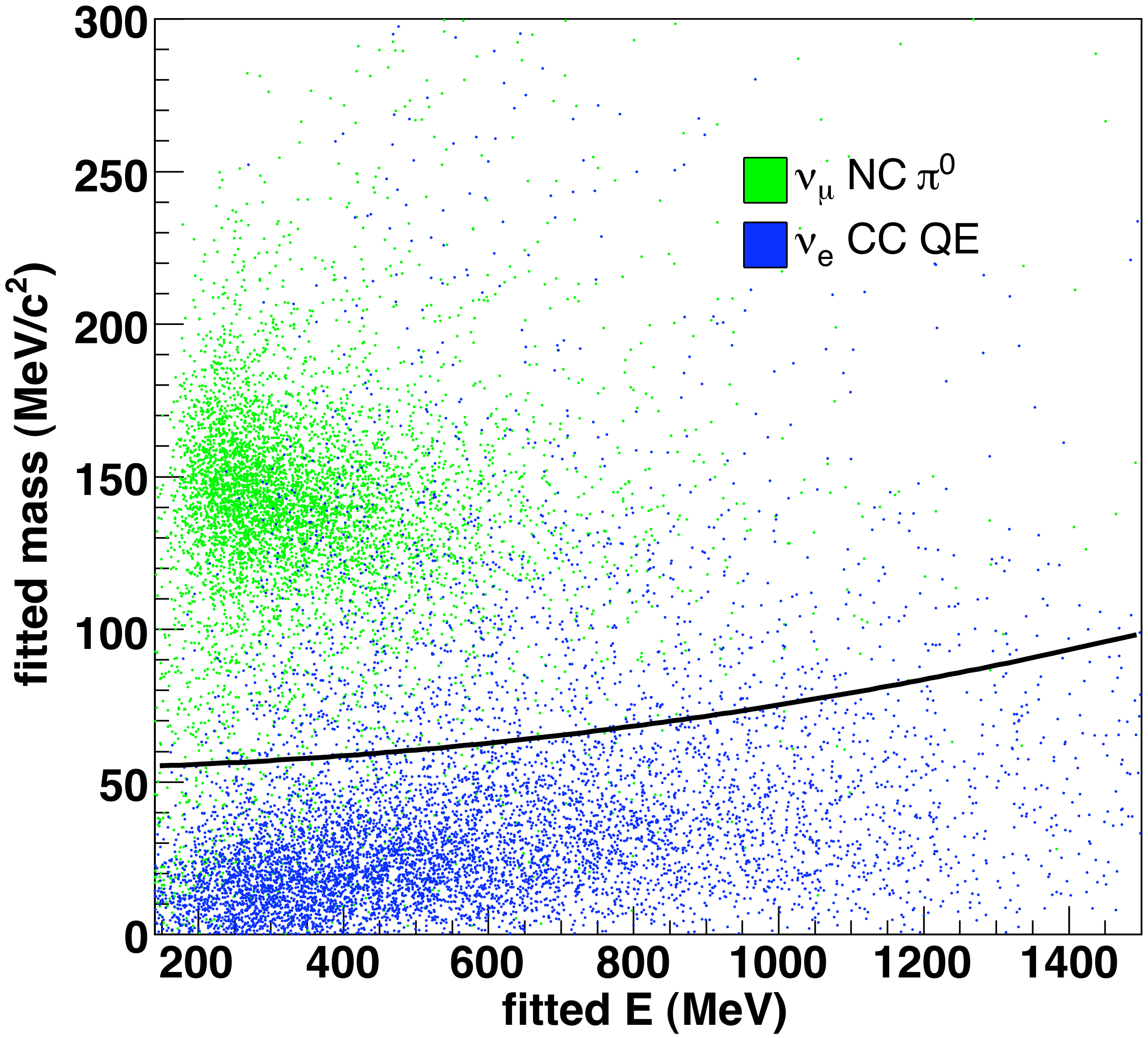


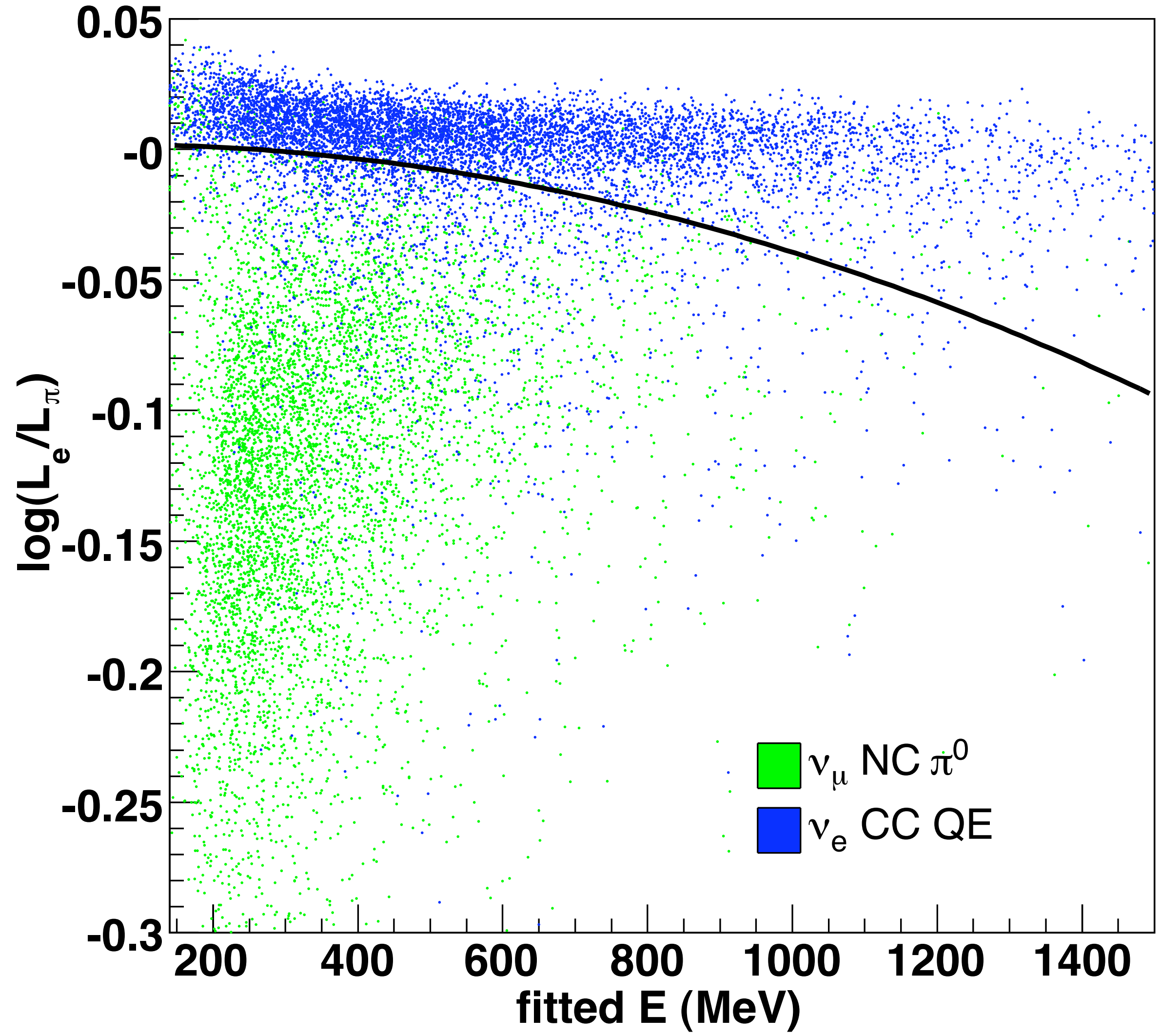


$\log(L_e/L_\mu)$: compare likelihoods returned by e and μ fits.

- $\log(L_e/L_\mu)>0$ indicates electron hypothesis is favored.
- Discrimination easier at higher energy (increasing μ tracklength)
- μ events cross checked with μ-DAR tagged sample

Suppressing π^0 Events





Free mass 2-track fit (2T) employed to reconstruct mass

- Background π^0 reconstruct near m_{π^0}, signal ν_e have smaller mass

Fixed mass 2-track fit (2Tπ) used to form $\log(L_e/L_\pi)$

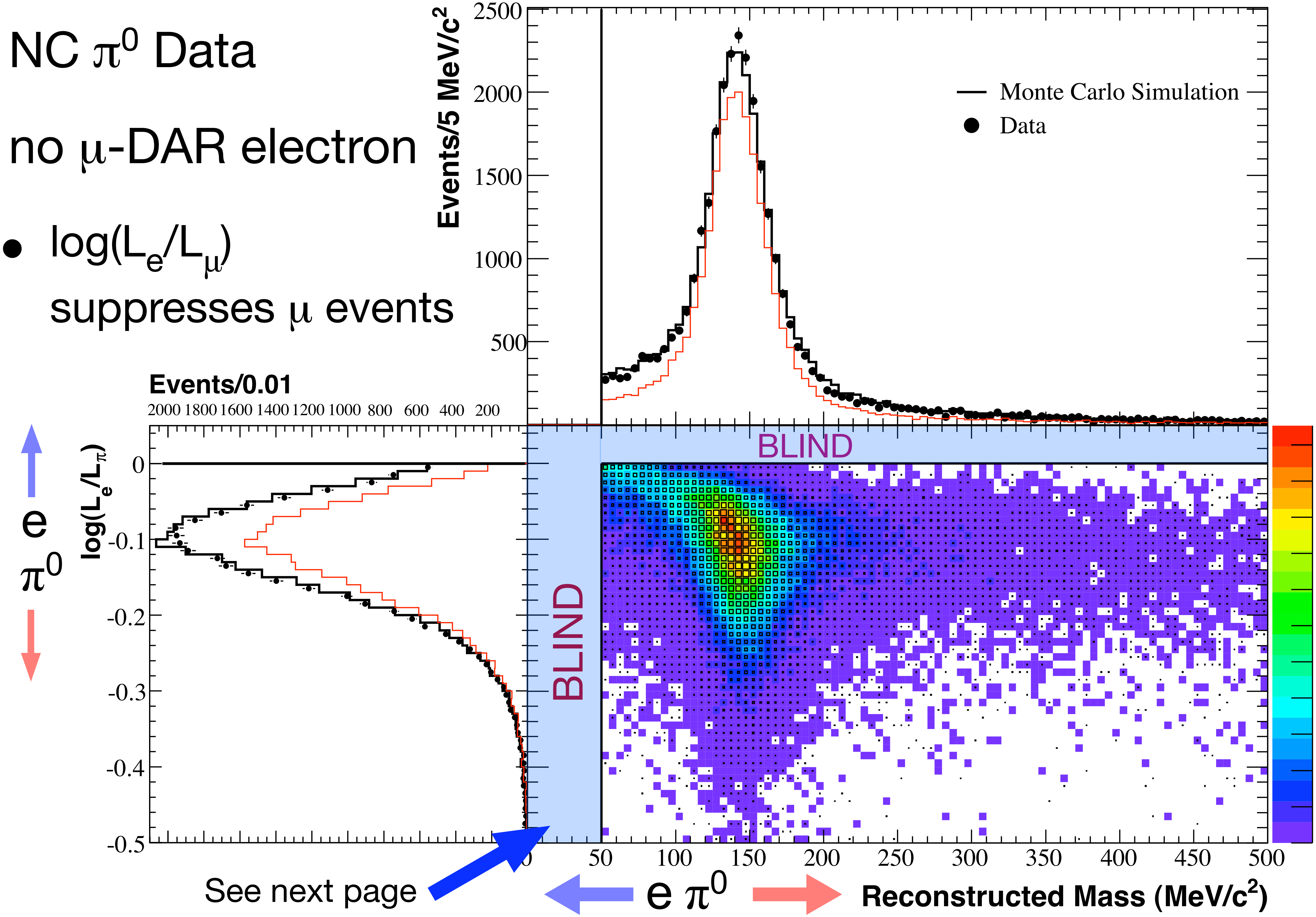
- $\log(L_e/L_\pi)>0$ for signal ν_e

Suppressing π^0 Events

NC π^0 Data

no μ-DAR electron

- $\log(L_e/L_\mu)$ suppresses μ events



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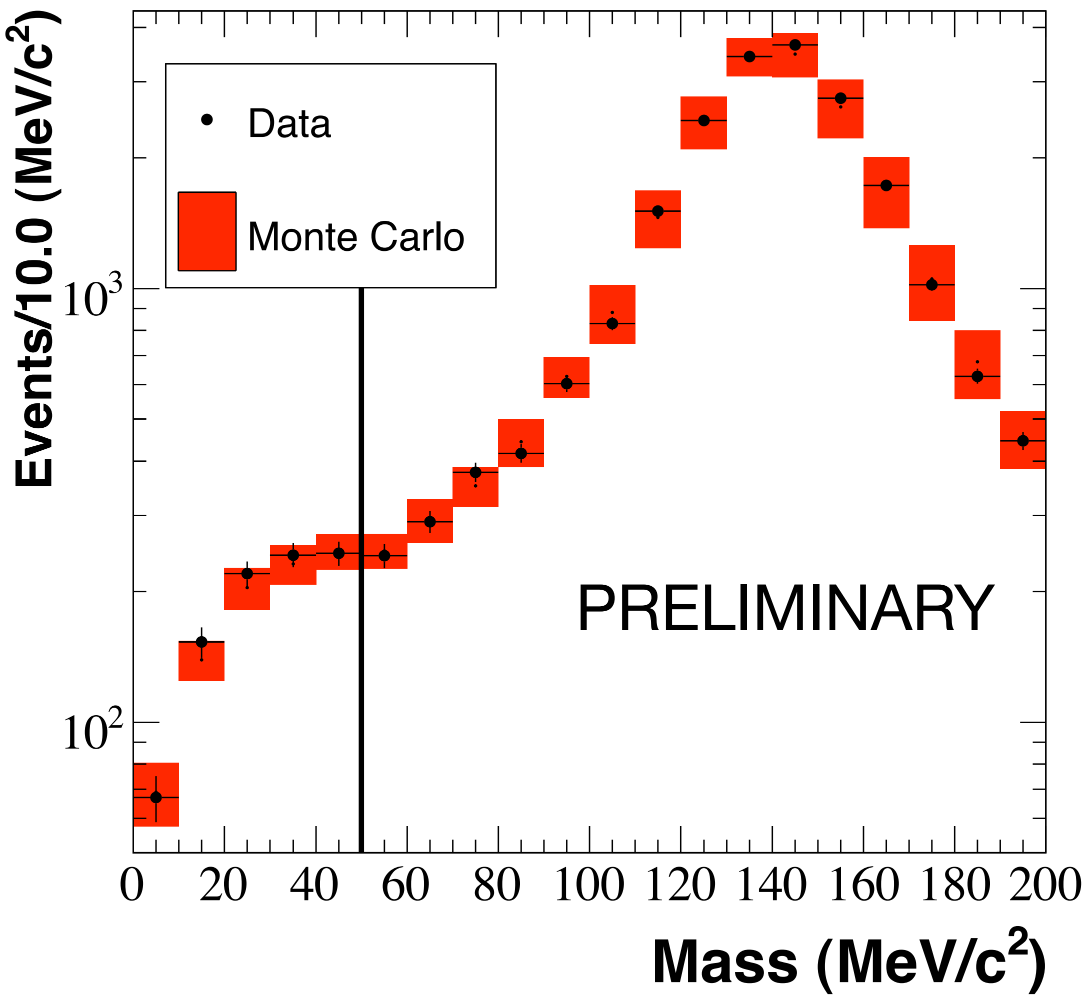
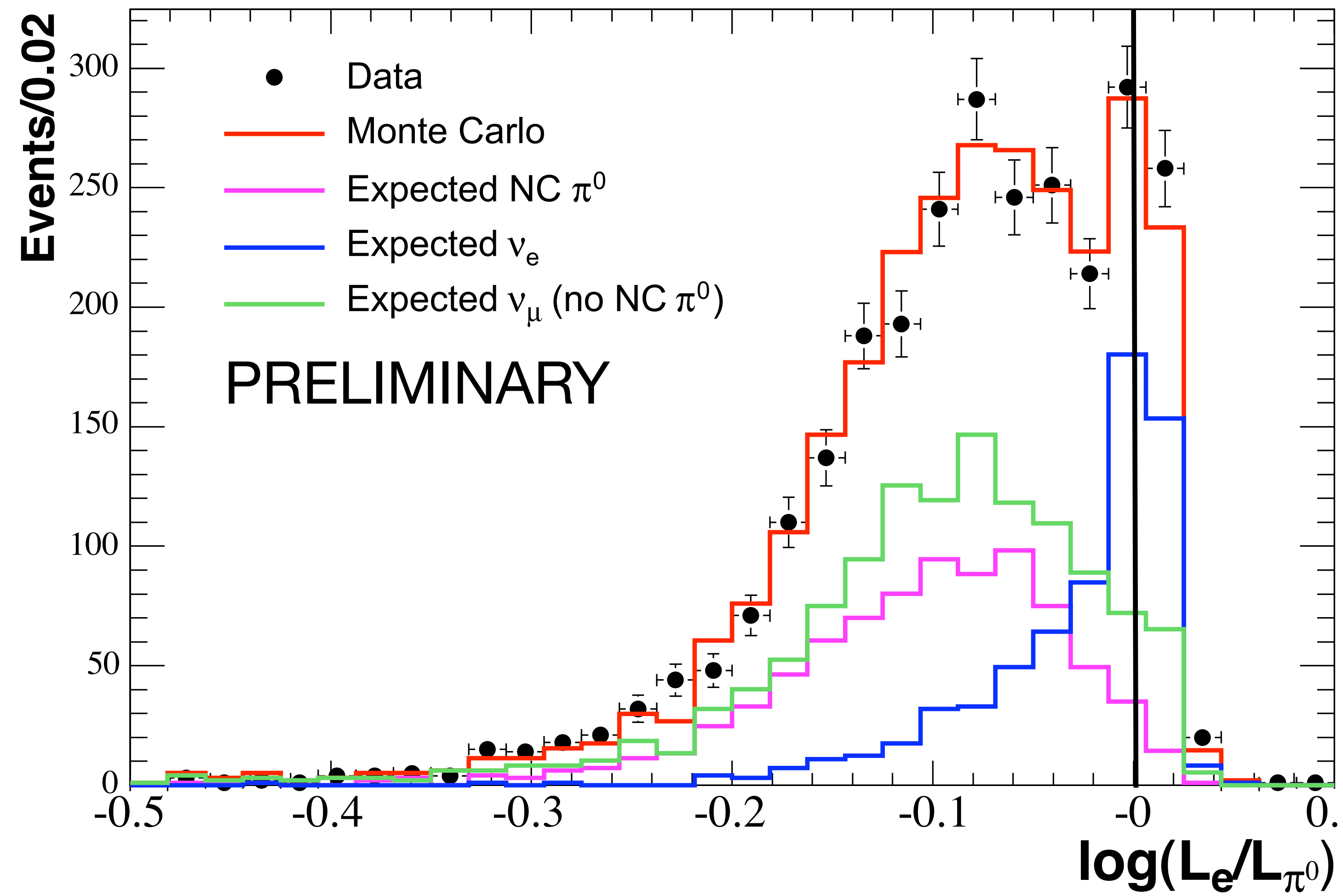
Towards the Signal Region





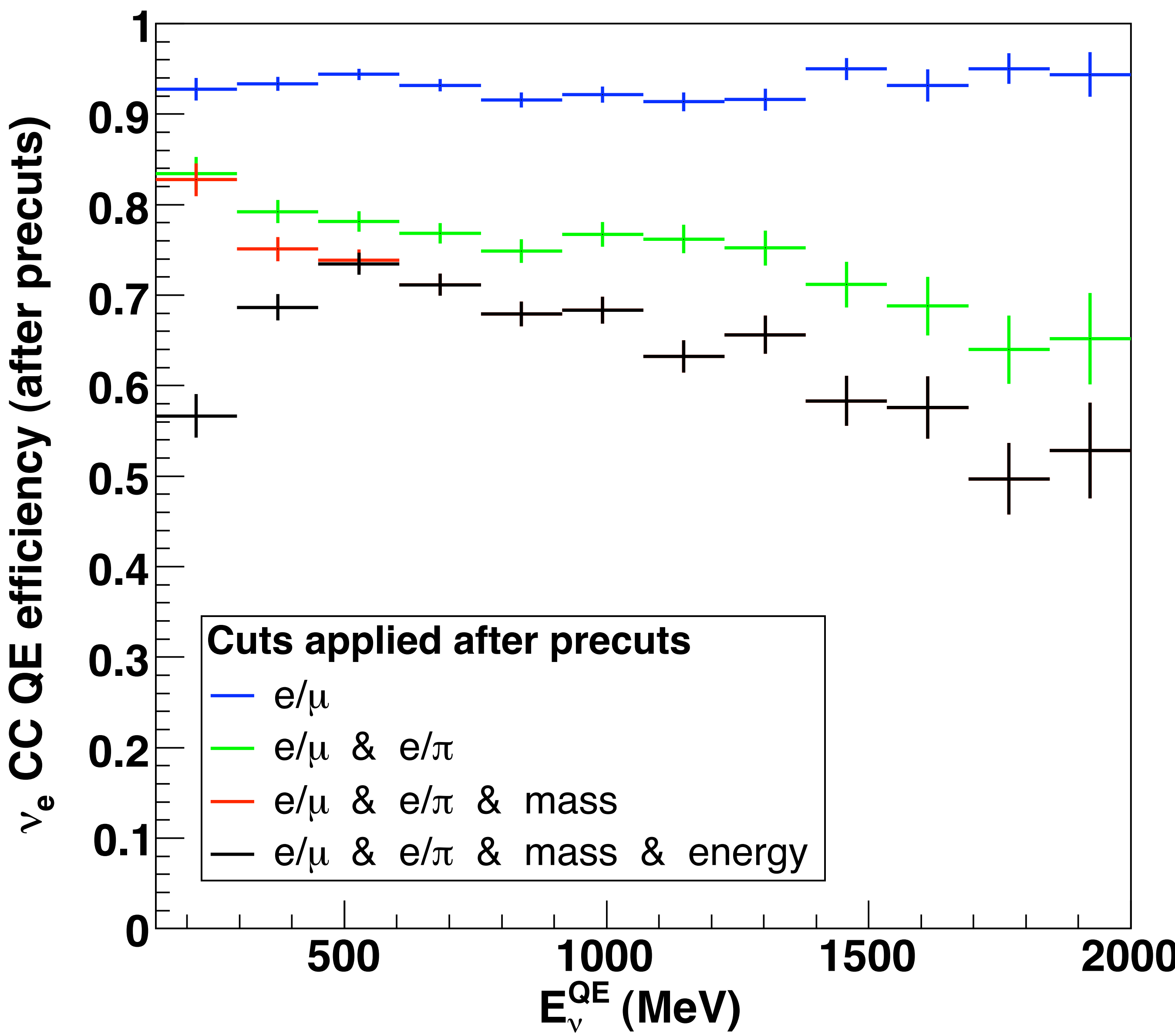
Look at mass for $\log(L_e/L_{\pi^0}) < 0$ events:

- Signal-like in mass, background like in $\log(L_e/L_{\pi^0})$

Off-axis flux from NuMI: Enhanced in three body decays $\Rightarrow \nu_e$

- Probe signal region of $\log(L_e/L_{\pi^0})$

Selection Efficiency:



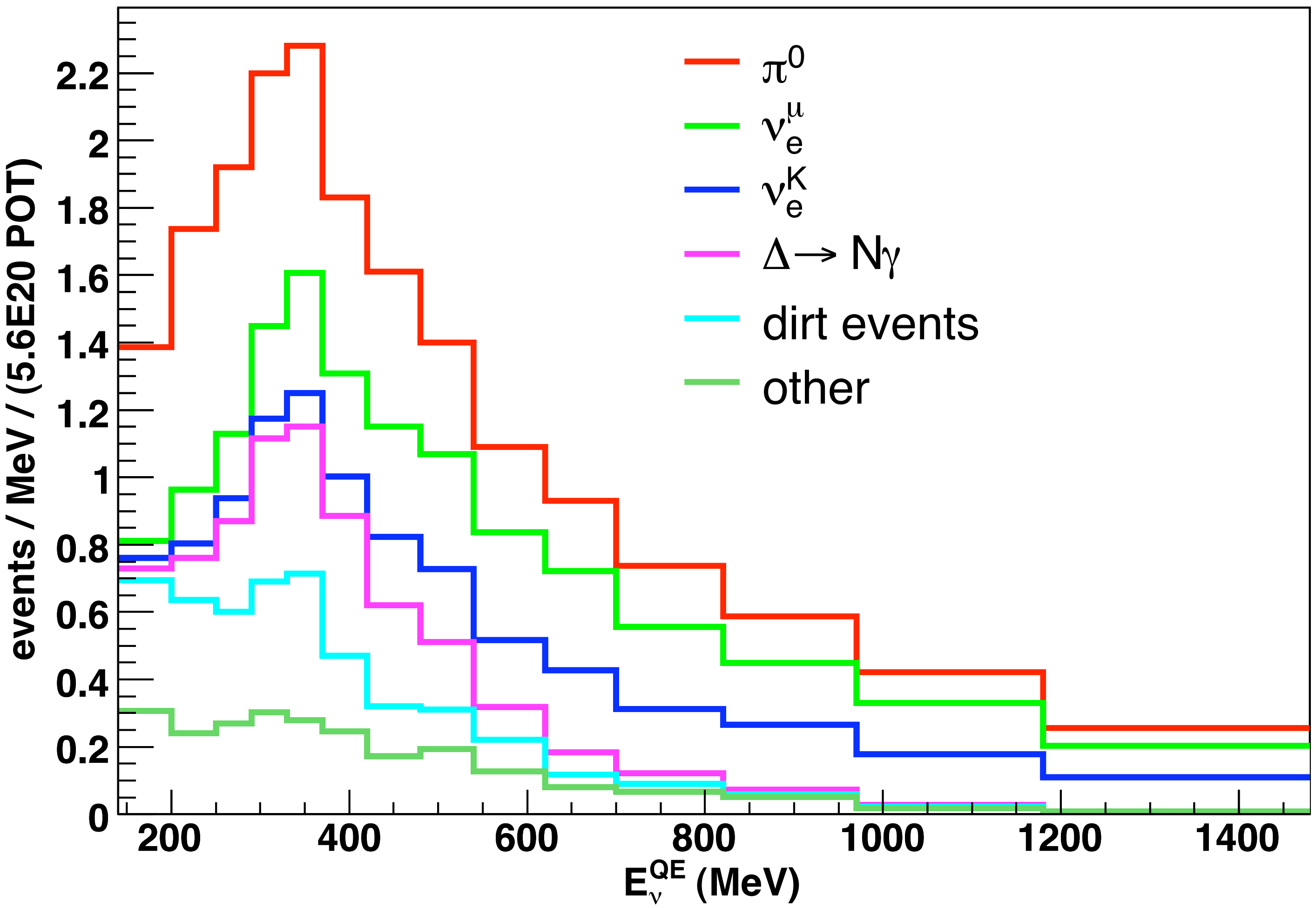
Energy spectrum used for signal extraction

- $\log(L_e/L_\mu)$: ~flat
- $\log(L_e/L_\pi)$, mass

ν_e/π^0 separation more difficult at higher energy

>50% efficiency after precuts across signal region

Expected Background

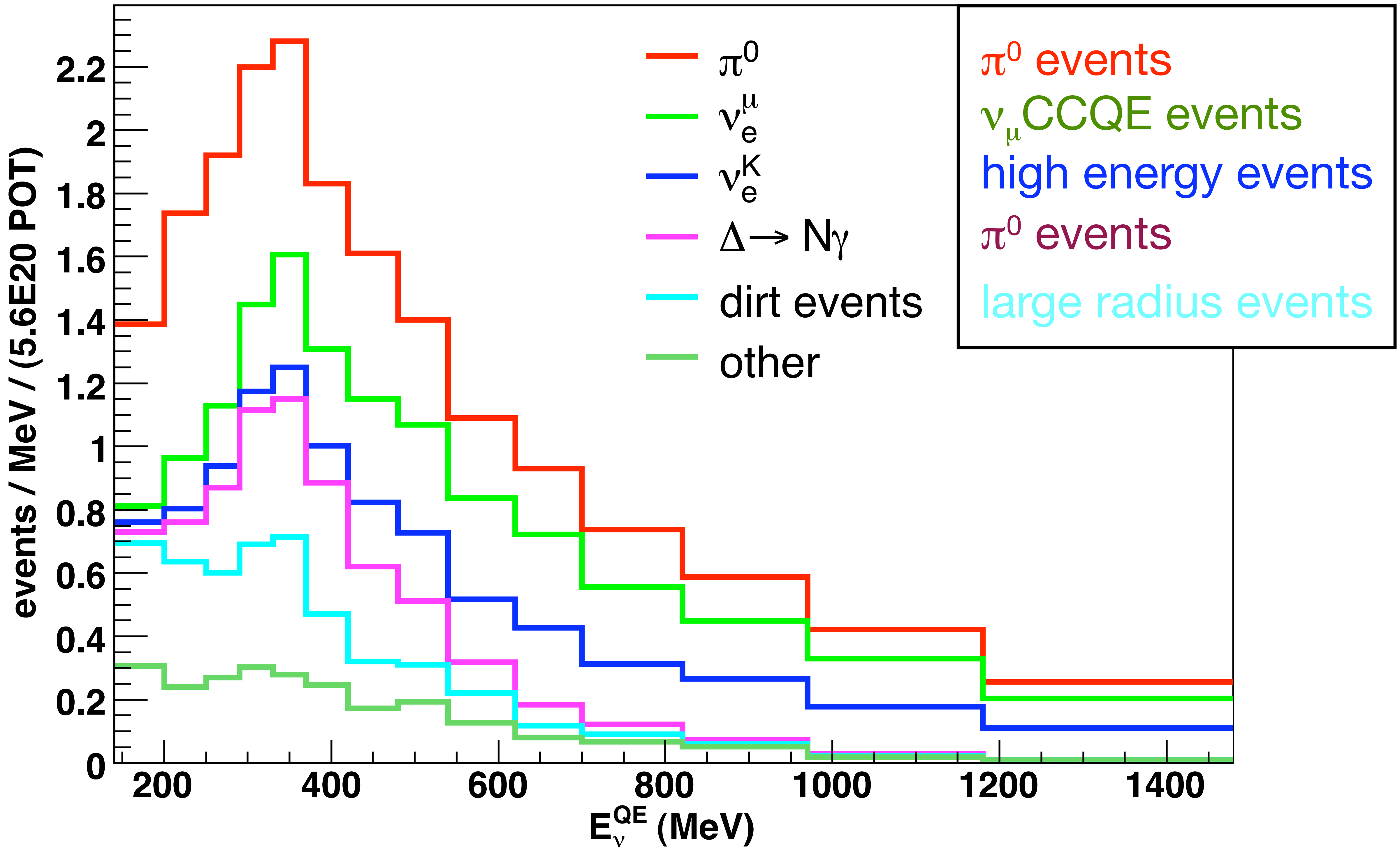


Signal:

(Δm^2=0.4eV^2, $\sin^2 2\theta$=0.017) = 315

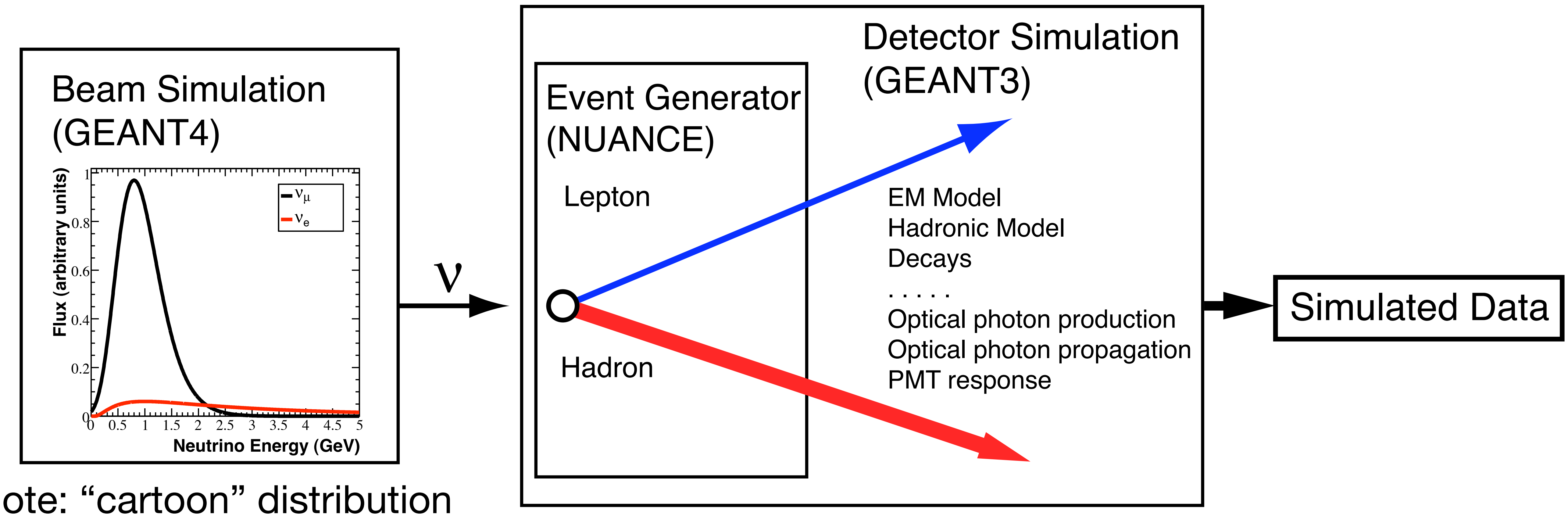
- Signal/Background ~1/4 at LSND central value
- Comparable contributions from intrinsic/reducible background

Constraining/Cross-checking Backgrounds



Monte Carlo Simulation
and
Constraints/Cross checks

Monte Carlo Simulation:

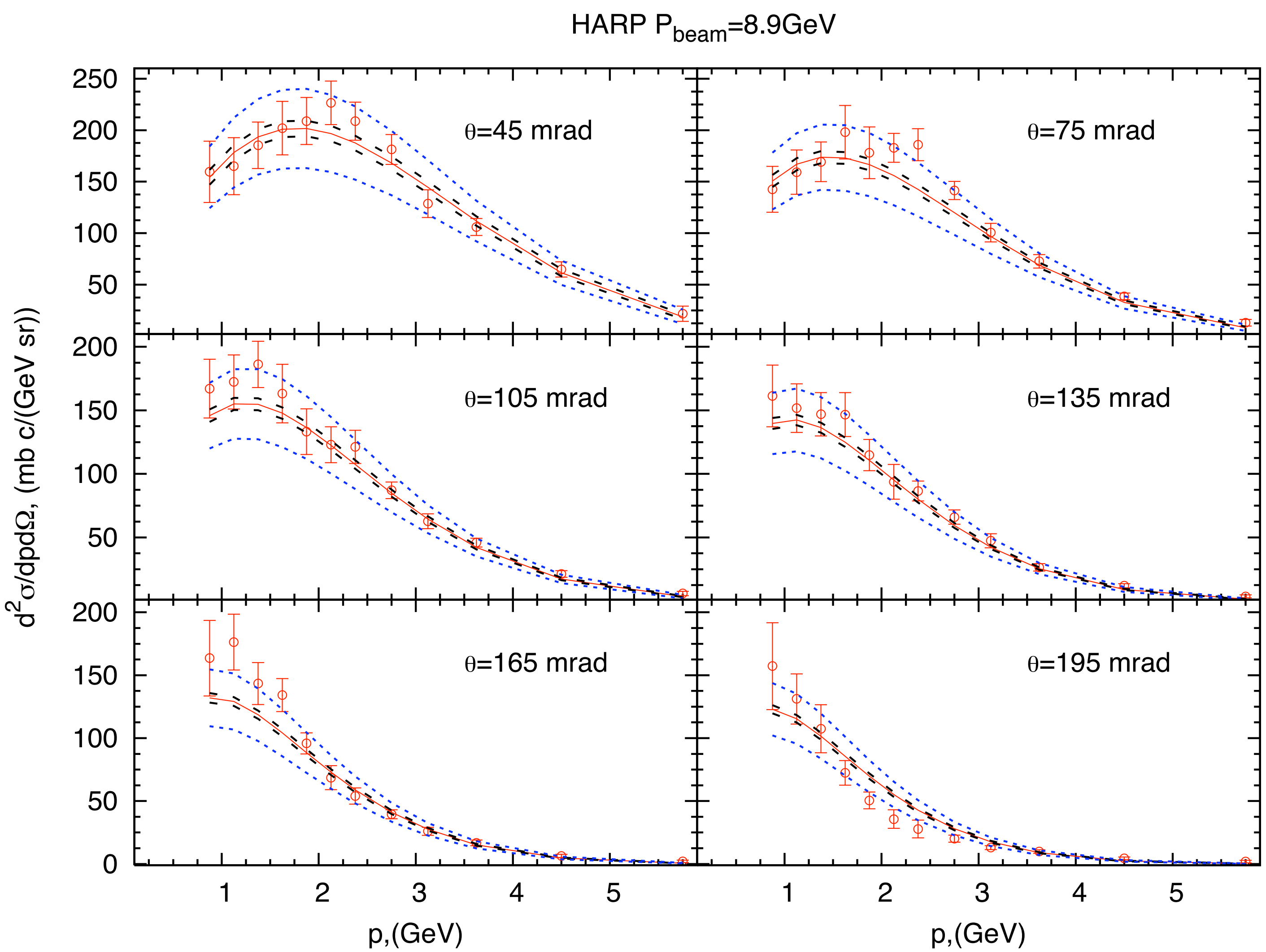


note: “cartoon” distribution

- Beam simulation: meson production propagated through beam line, decayed to produce neutrinos
- Neutrino Event Generator:

  NUANCE: comprehensive ν-(H/C/O) event generator
- Detector simulation propagates final state particles.

Flux prediction



HARP 8 GeV p-Be π^+ production measurements

Tune π/K production model to external production data

Pions:

- HARP (8 GeV)
- BNL E910 (6/12 GeV)

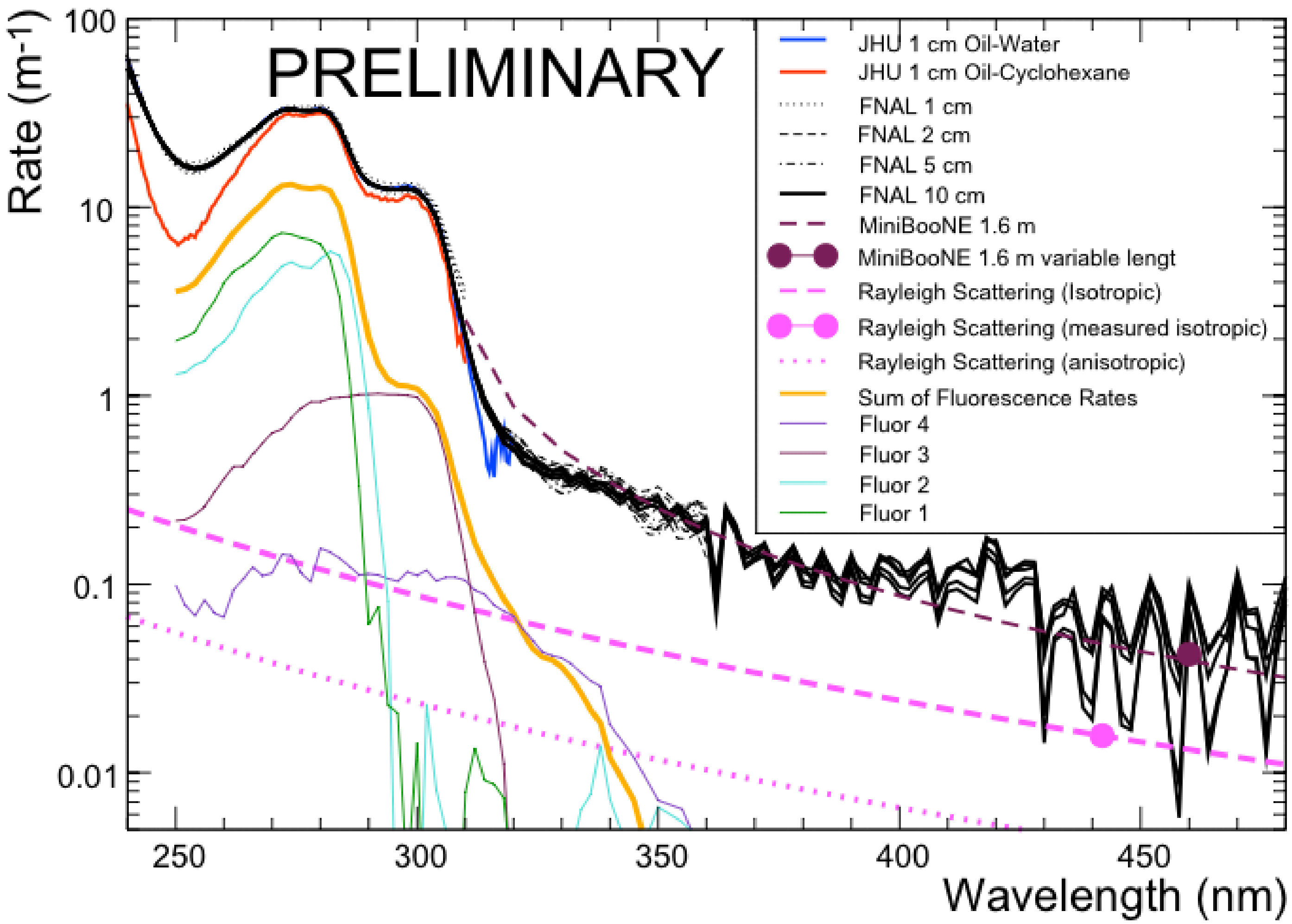
Kaons:

- Data sets at 9.5-24 GeV
- 12 GeV E910 K^0 analysis

Other uncertainties

- Hadronic cross sections (tuned to external data)
- Horn EM model
- Proton counting

Detector Model Uncertainties



μ-Decay-at-Rest electrons

- Well-know spectrum
- Abundant (cosmic μ)
- Fast simulation

Start with externally measured parameters and errors

- Constrain parameters with observed distributions of energy, Č ring profile, time distribution, etc.
- Propagate uncertainties by varying parameters according to constraints

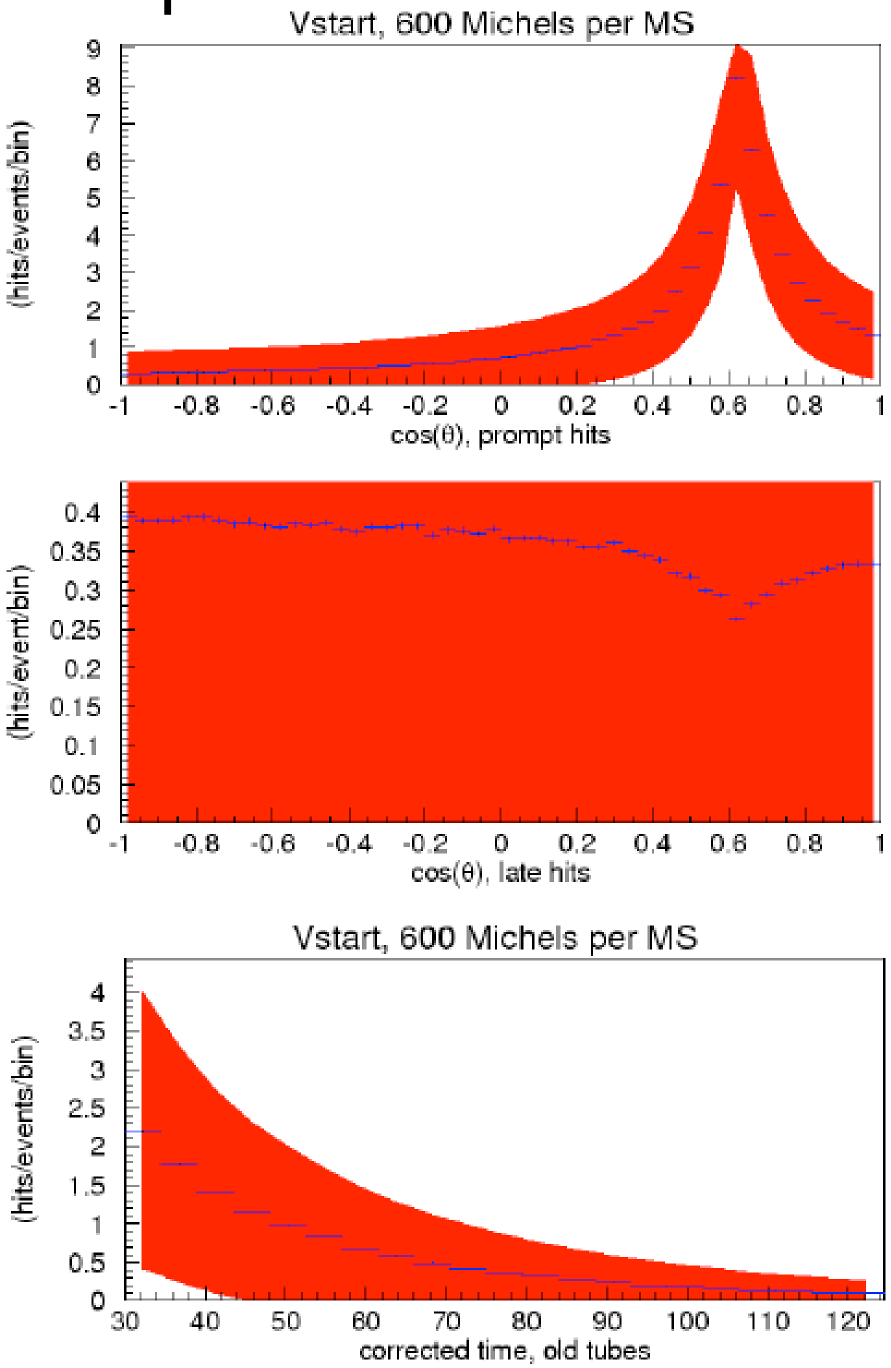
Dominated by “Optical Model”

Production, transport and detection of Č and scintillation light.

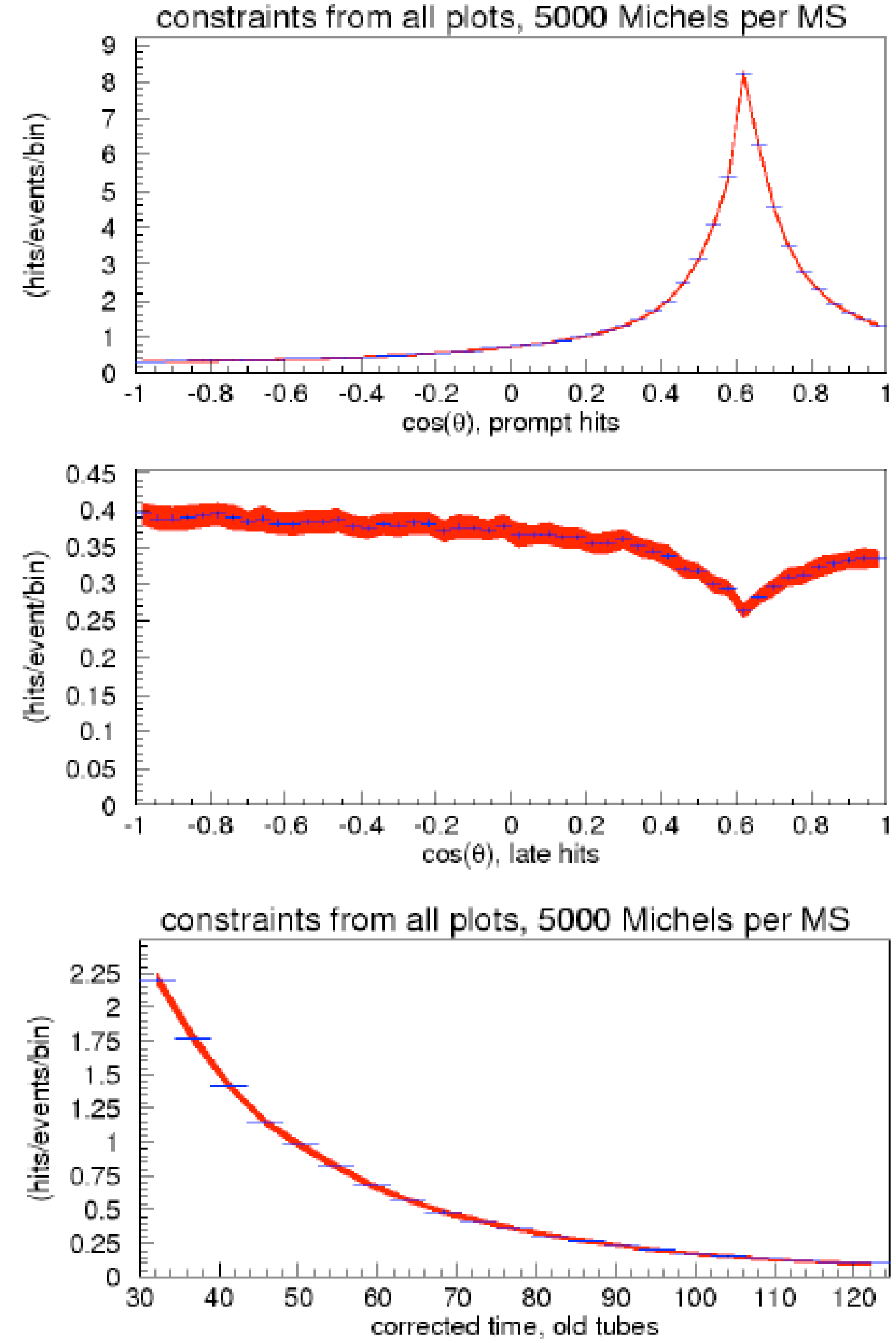
Account for Rayleigh/Raman scattering, absorption, fluorescence

Optical Model Constraints

A priori uncertainties

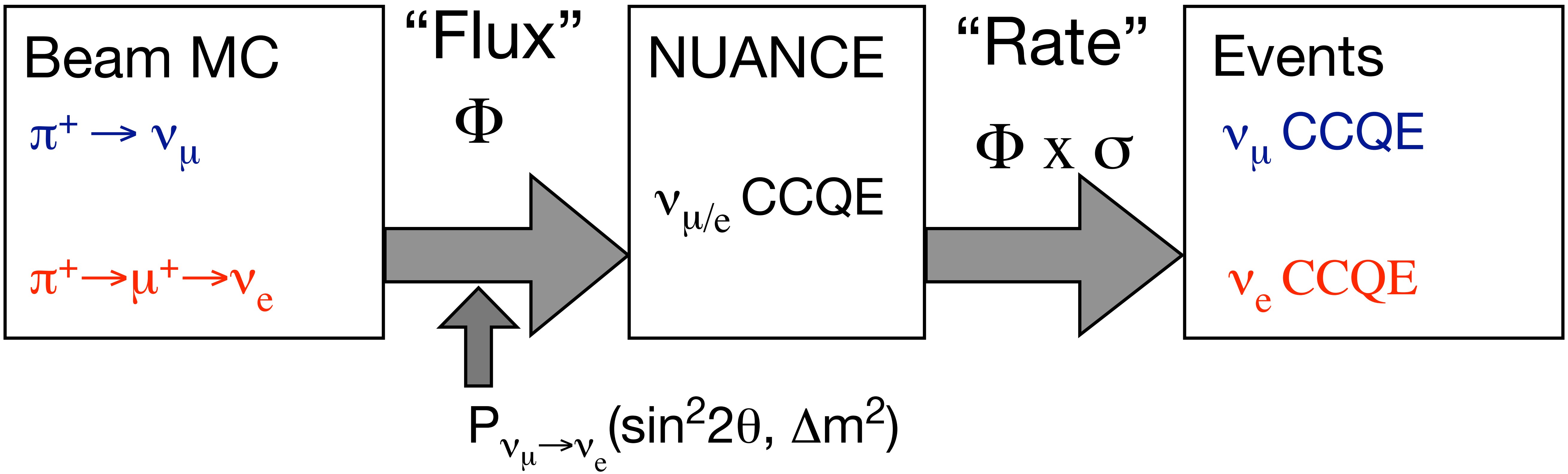


Constrained Parameters



- Spread represents uncertainties propagated to distribution
- NC elastic scattering (protons) used to constrain scintillation

Internal Constraints: ν_μ CCQE:



If we measure the rate of ν_μ CCQE in the detector:

The $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ background

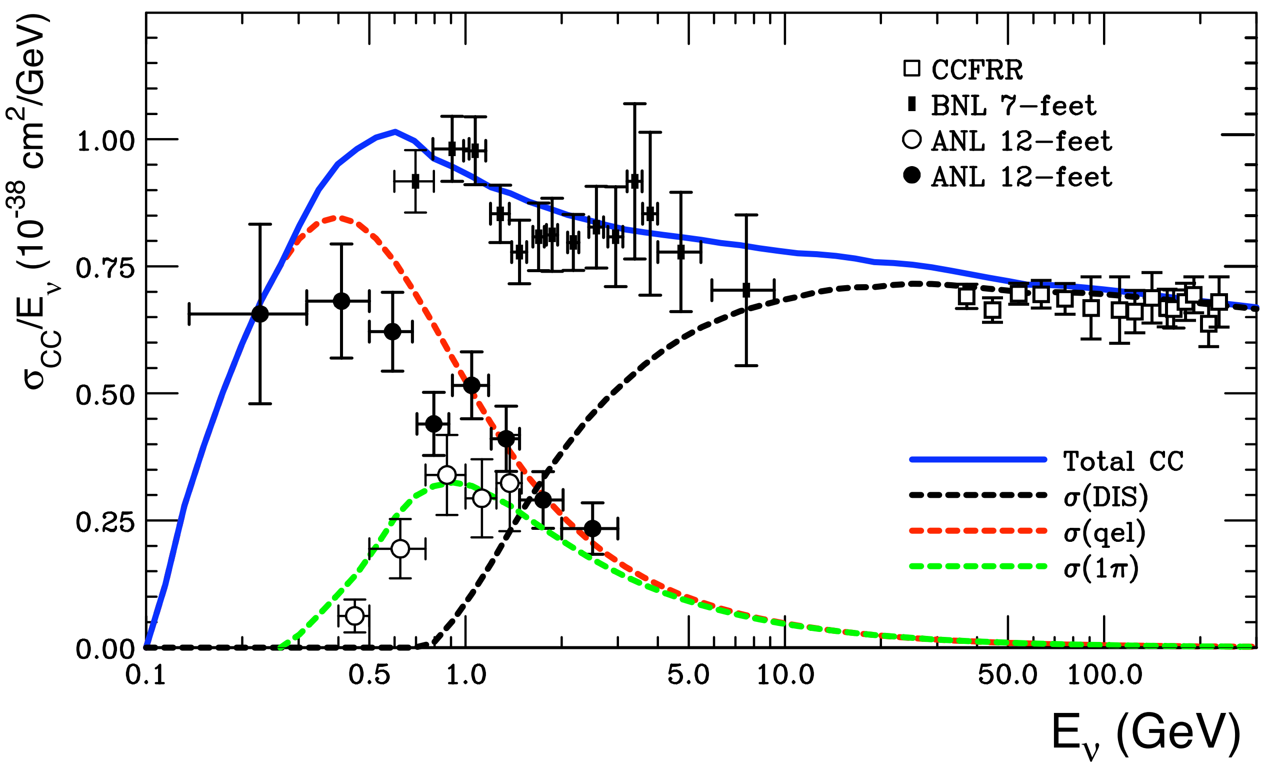
- comes from the same π^+ that produced ν_μ CCQE
- interacts with the same cross section (CCQE)
- Uncertainties in π^+ production/cross section at higher order

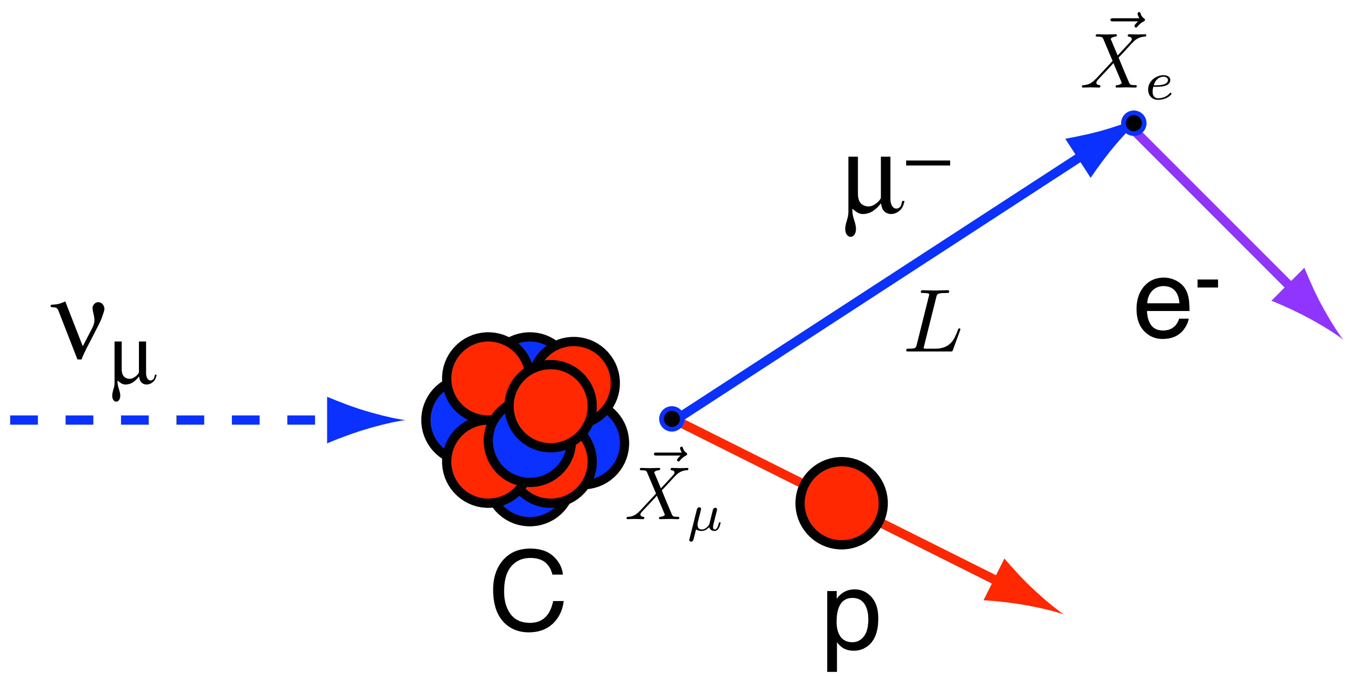
Oscillation signal: same neutrinos/cross section

ν_μ CCQE:

Why ν_μ CCQE?

- Largest (and well-known) cross sections at these energies
- Simple one-ring muon topology
- Two-body kinematics allows determination of $E_\nu(E_\mu,\theta_\mu)$





Identifying ν_μ CCQE

92% of μ^- decay, producing e^-

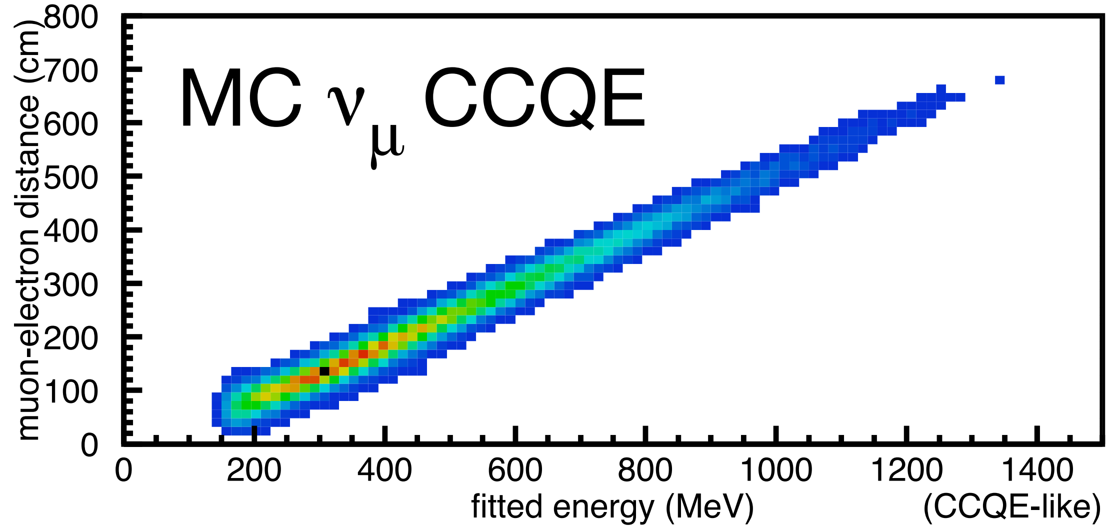
X_μ, X_e determines L (=μ tracklength)

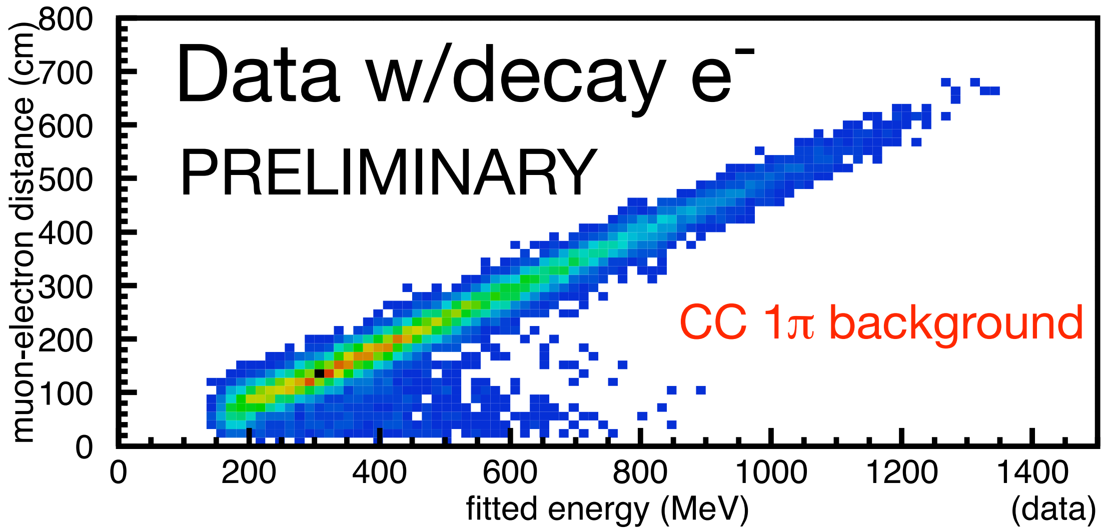
For single μ, $L \propto E_\mu$

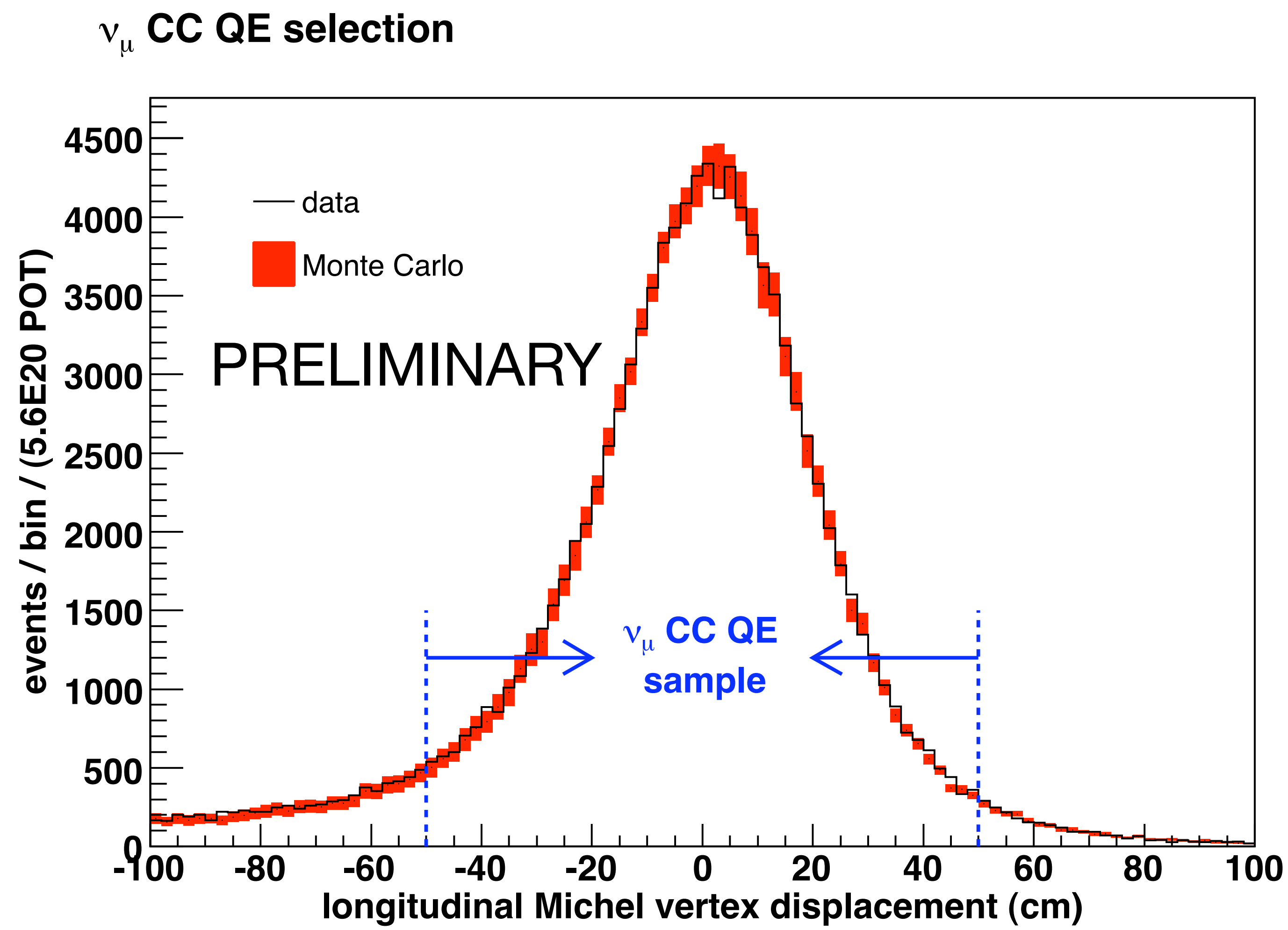
Presence of other particles will disrupt this relation

“Clean muon” selection

Identifying ν_μ CCQE:



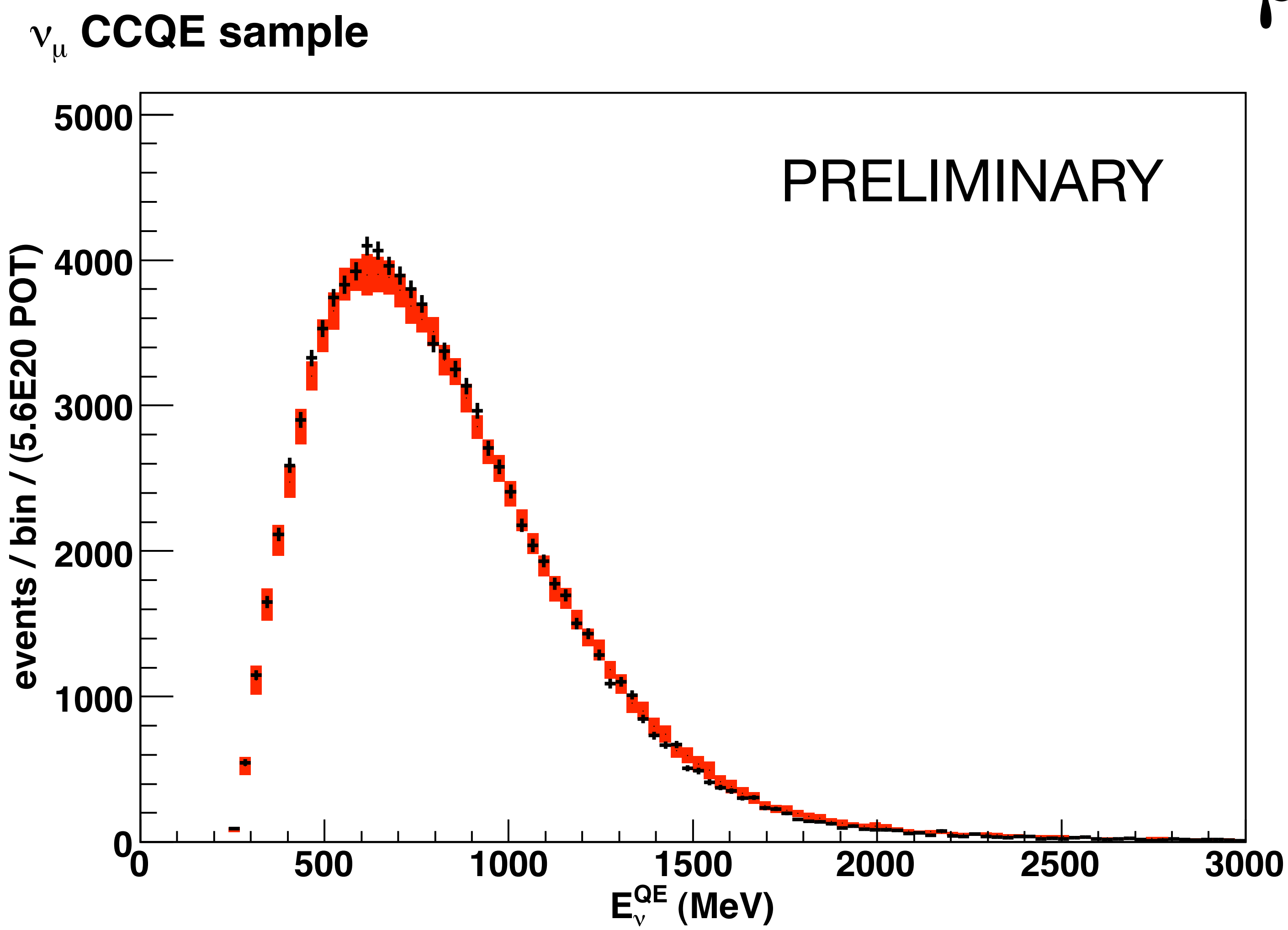


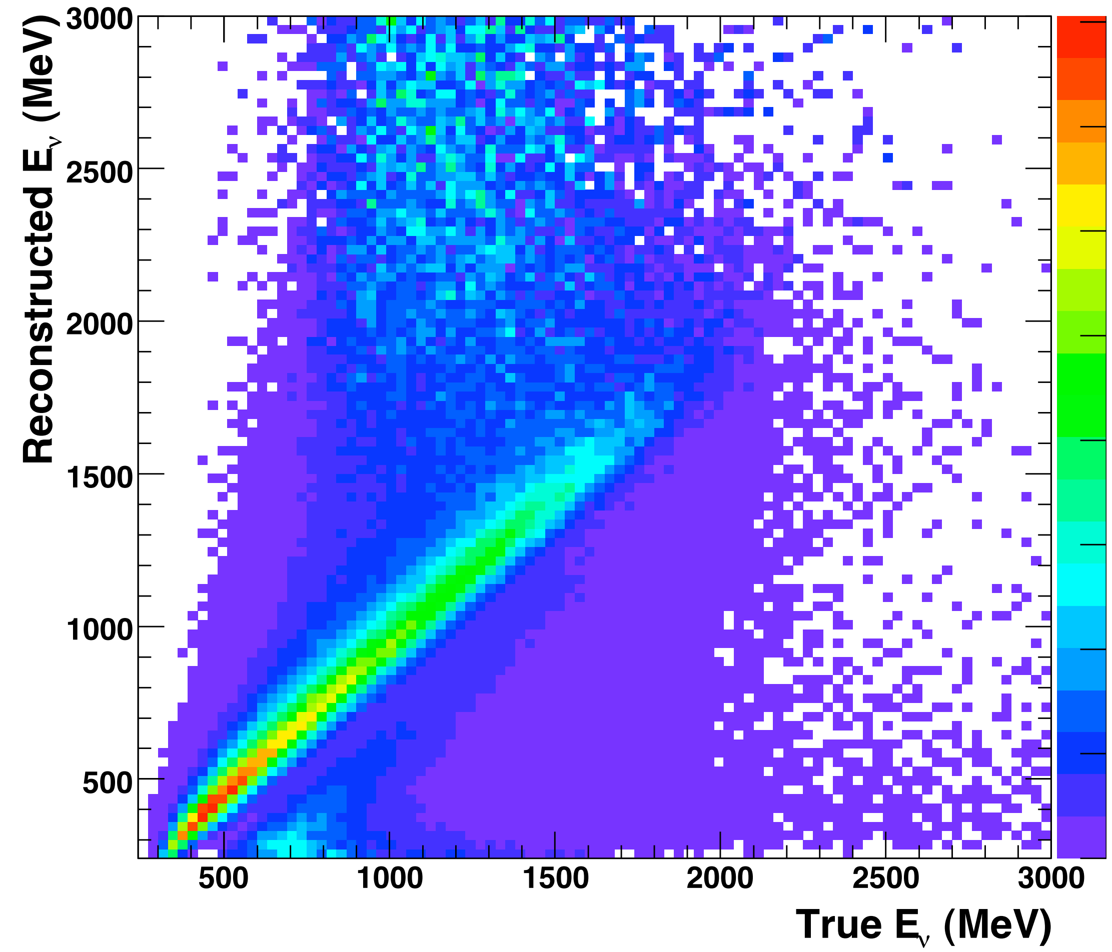


L(E) relationship predicts μ/e distance for a given E_μ

- Compare predicted/reconstructed decay electron position
- Brought to you by excellent position, energy, angular resolution

Measuring the ν_μ Spectrum:

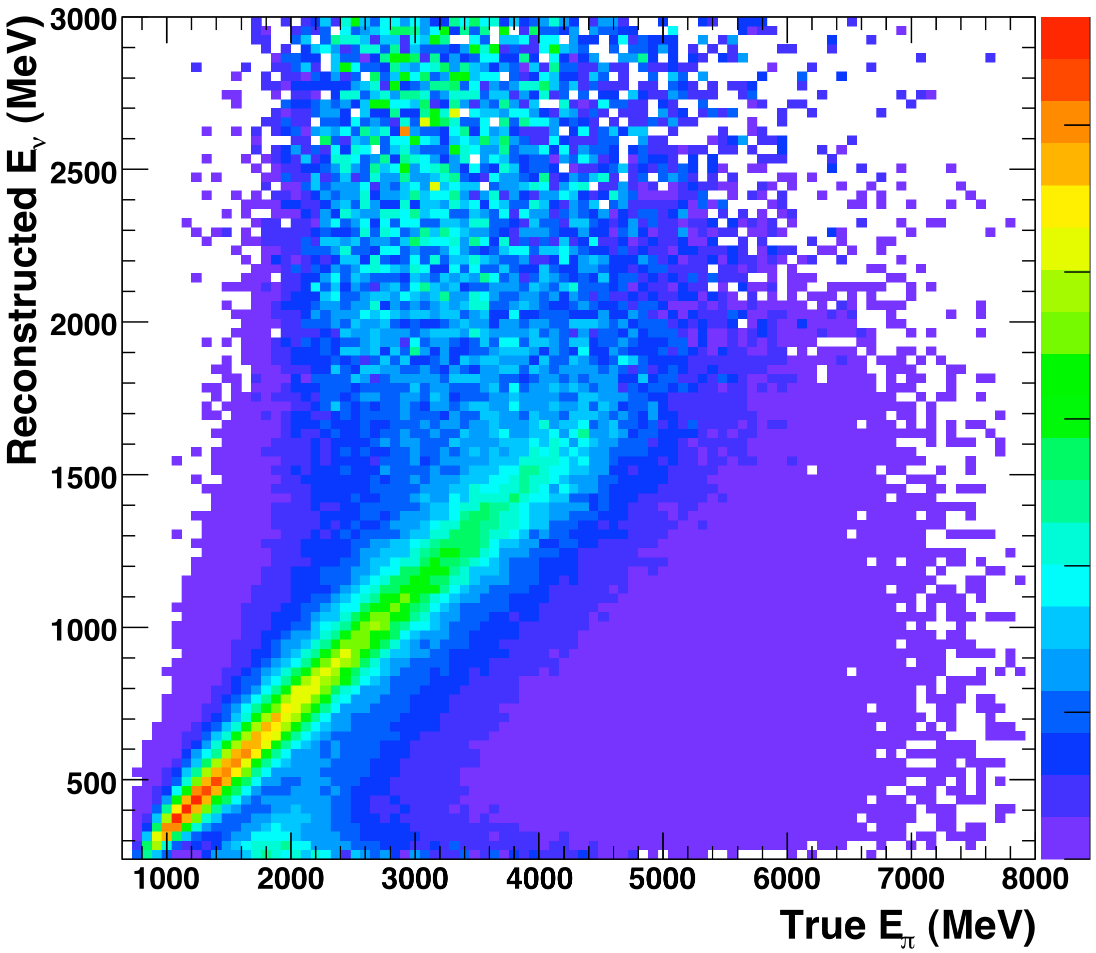




Determine E_ν using two-body kinematics

- MC-based template gives true spectrum
- Push uncertainties (flux, ν xsec, etc.) to higher order for predicted signal $\nu_\mu \rightarrow \nu_e$ oscillation events

ν_e from μ decay:



Geometry selects narrow phase space of forward $\pi \rightarrow \mu + \nu_\mu$ decays

$$E_\nu \sim \gamma \frac{m_\pi^2 - m_\mu^2}{2m_\pi}(1+\beta)$$

$$\sim 0.38 E_\pi$$

ν_e from μ decay background:

- Measuring ν_μ spectrum measures π spectrum
- Same π decays give $\pi \rightarrow \mu \rightarrow \nu_e$ background
- Correct π spectrum to match data

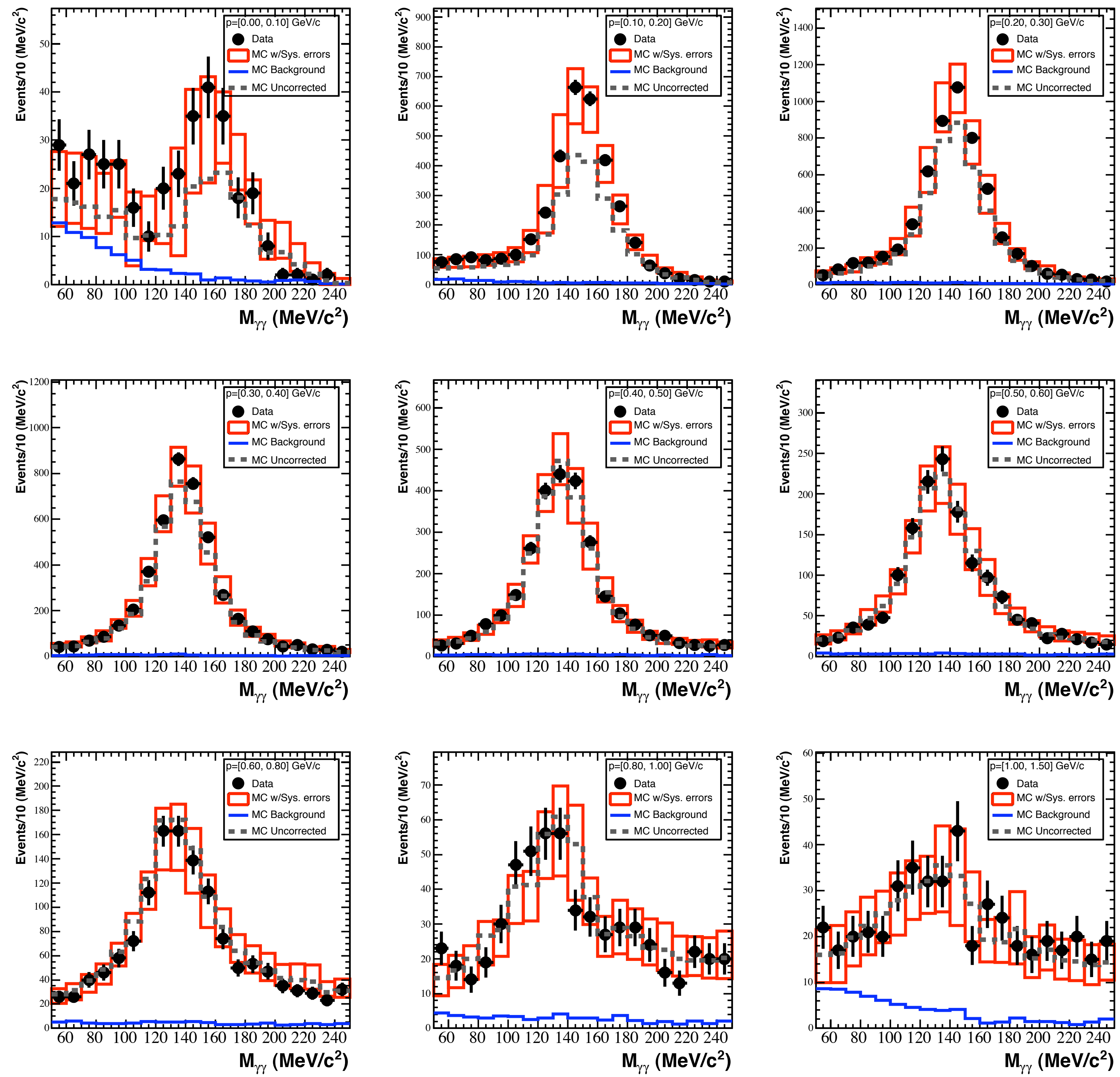
Flux, ν cross section uncertainties pushed to higher order

π^0 Rate and Spectrum

Momentum spectrum

- $\log(L_e/L_\mu)$ suppresses μ
- Purity ~90% or greater
- Default MC underpredicts π^0 at low momentum
- Range of analysis

p=[0.0,1.5] GeV/c

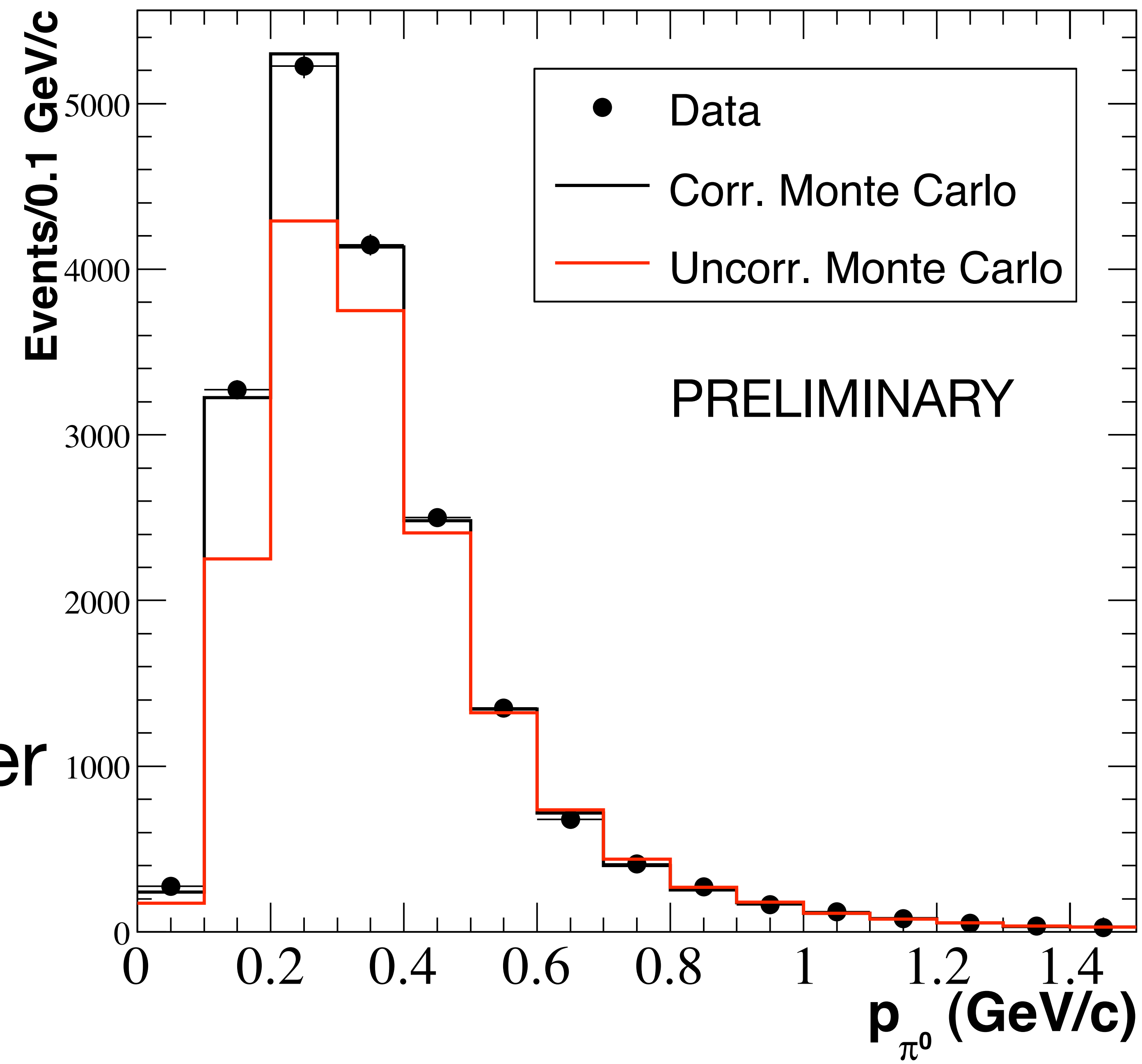


Mass spectra in momentum bins

π^0 Spectrum

MC templates used to to extract true p_{π^0} distribution

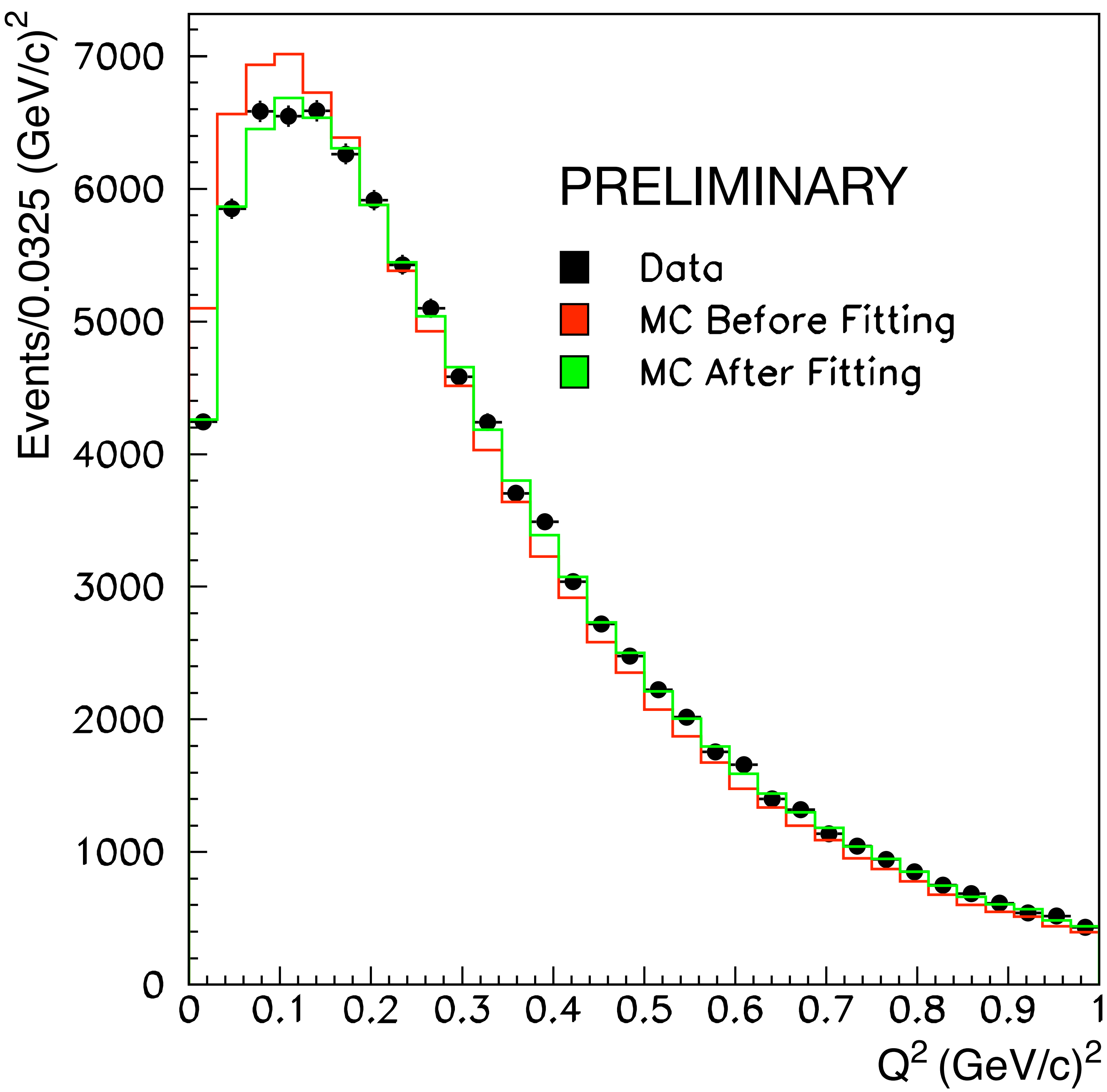
- MC prediction corrected to match data
- Flux/ν xsec uncertainties in π^0 rate now higher order



π^0 dominated by resonant Δ production

⇒ $\Delta \rightarrow N\gamma$ decays also constrained

ν Cross section Uncertainties



CCQE Tuning

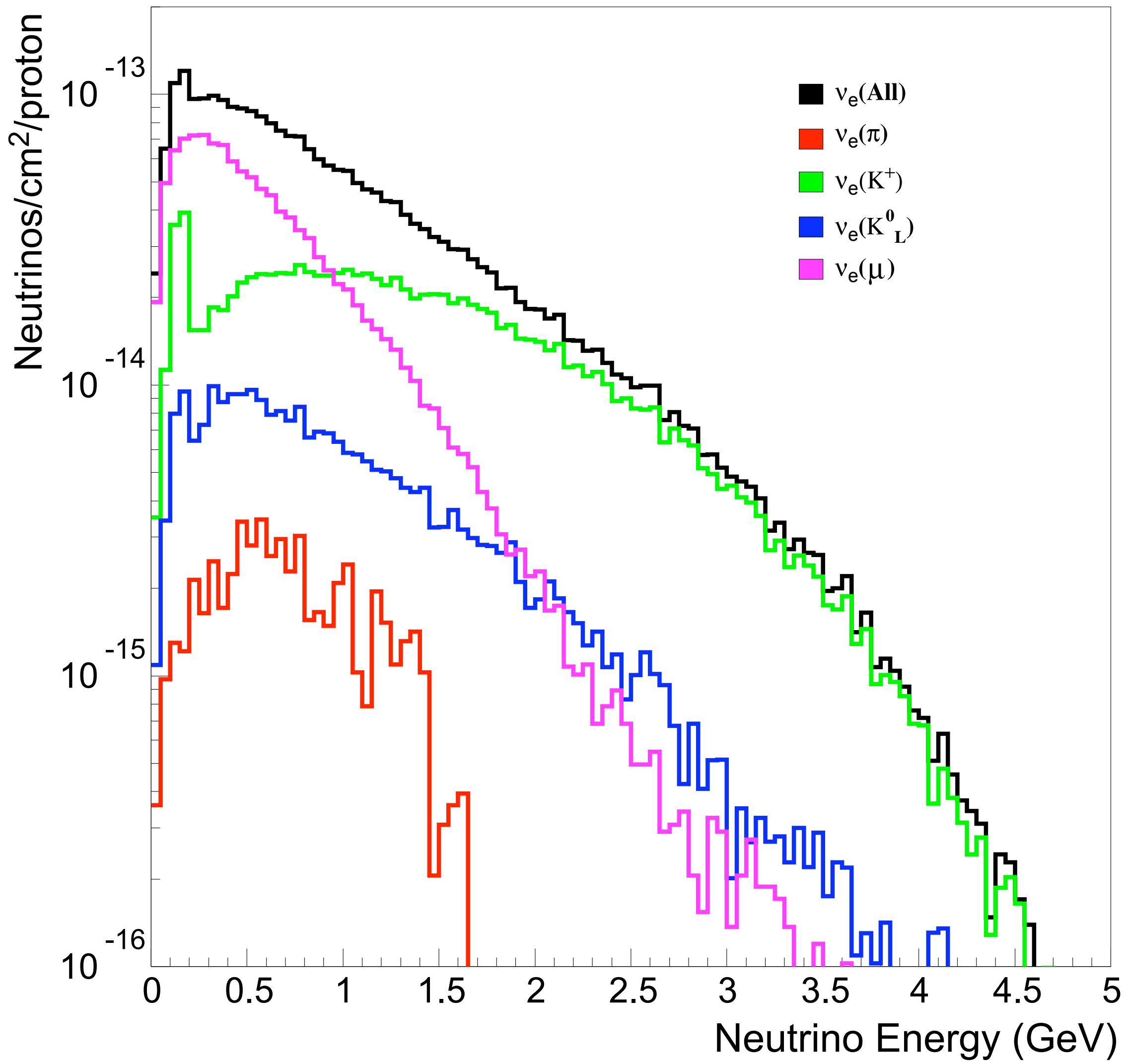
- Q^2 distribution used to tune nuclear parameters
- Brings other related kinematic quantities into agreement.

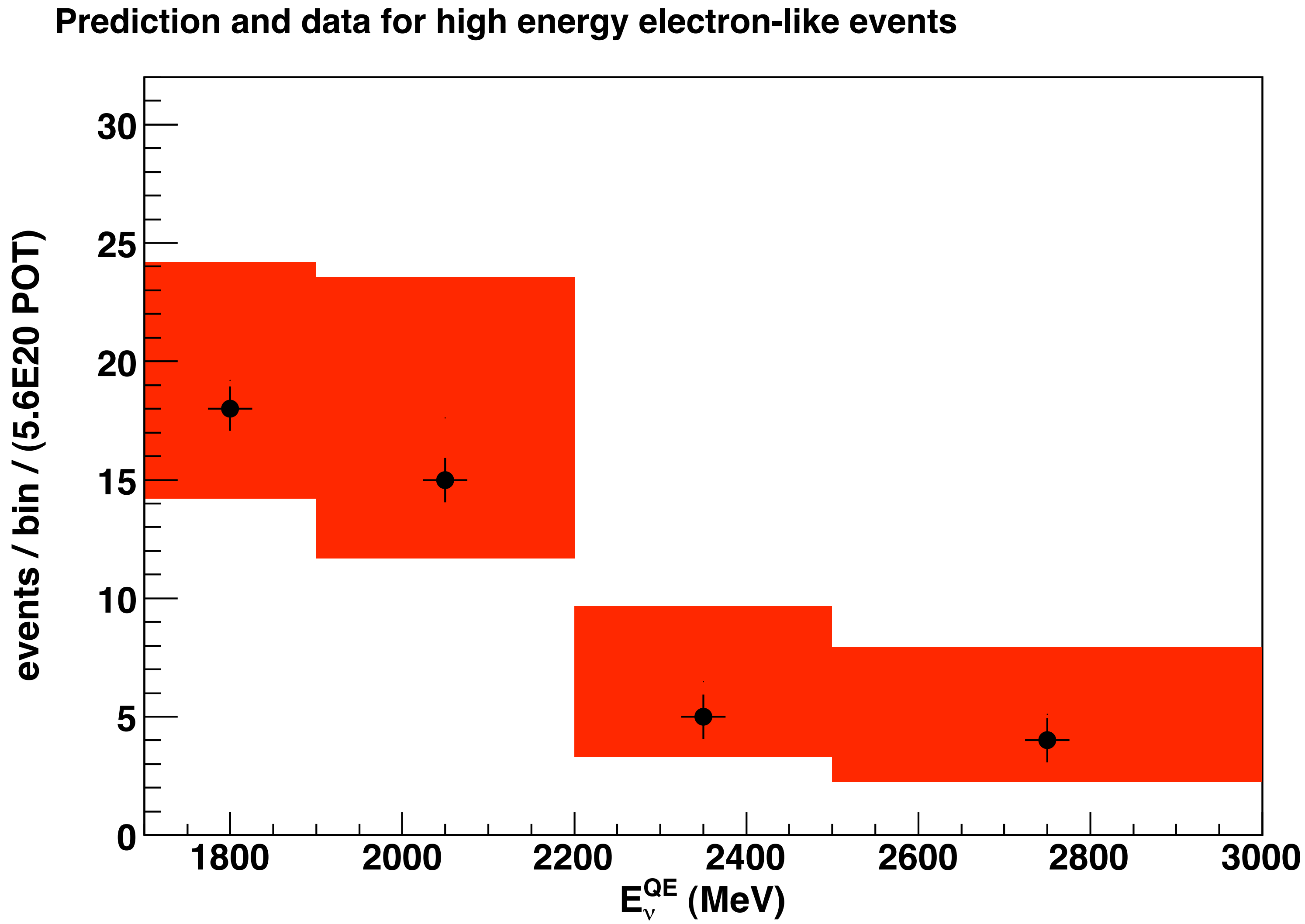
Other uncertainties are taken from "historical" data

(Important) low energy cross sections have large uncertainties

Internal data constraints/measurements critical for analysis

High Energy Data

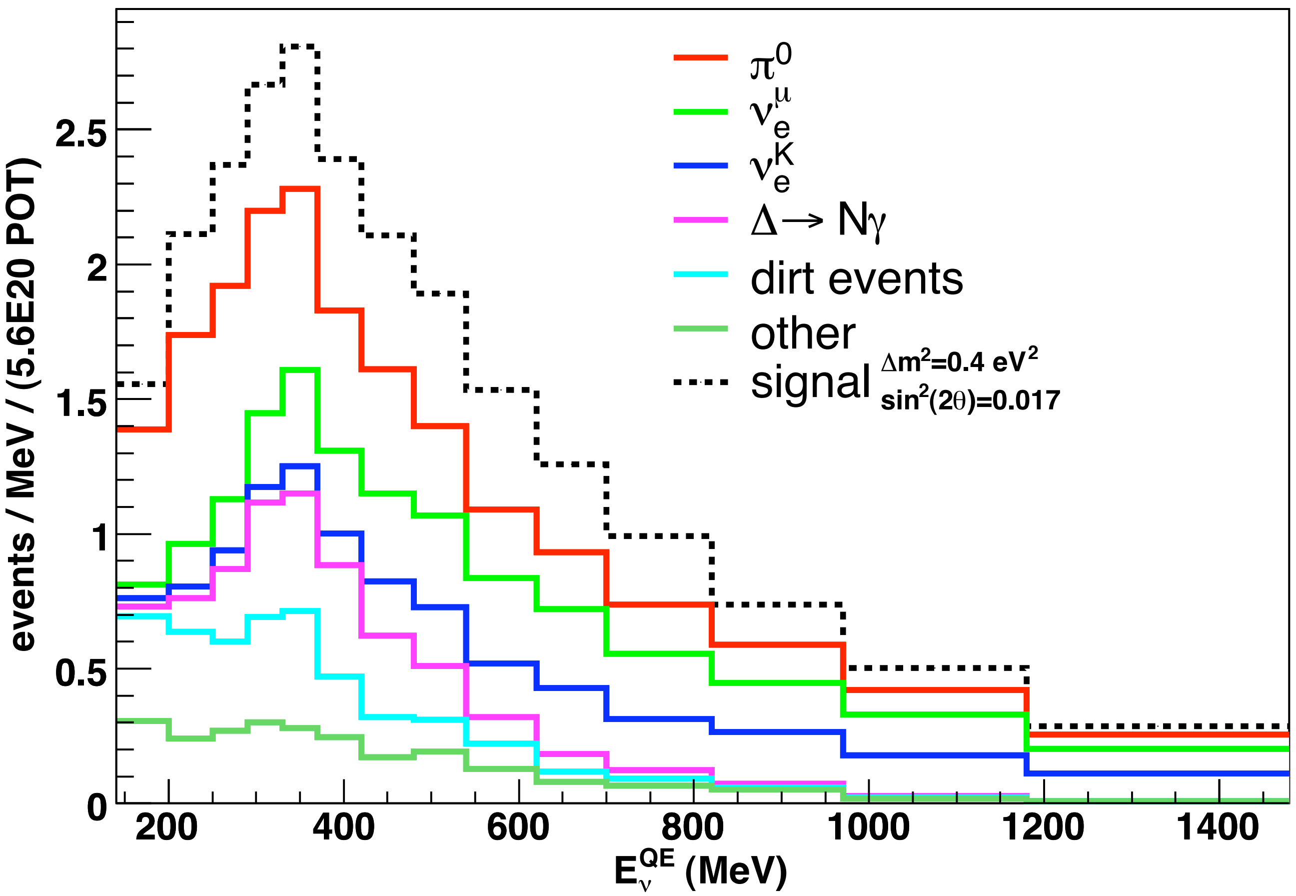


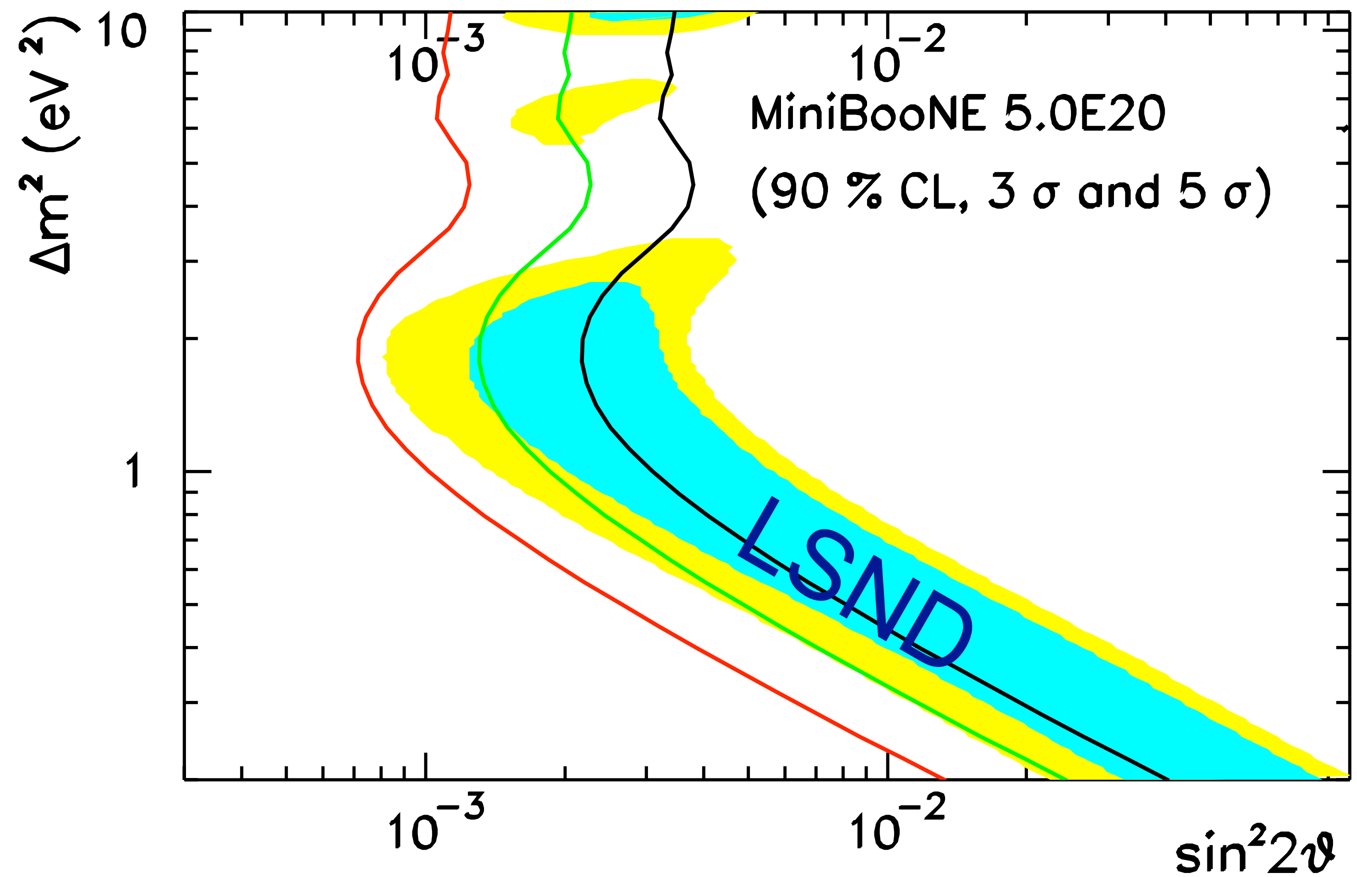


High energy ν_e flux dominated by K decay

- Constraint incorporated in signal extraction fit
- Small contribution from possible signal

Signal and Sensitivity:





S/B ~ 300/1200 for LSND central values

- Signal extracted in χ^2 fit (2 methods) incorporating systematic/statistical uncertainties.
- Comparable to 2002 run plan sensitivity

Conclusions and Outlook:

MiniBooNE:

Confirm/refute the LSND evidence for neutrino oscillations

Two parallel analyses for the $\nu_\mu \rightarrow \nu_e$ search

- Event likelihood ratio based on likelihoods returned from reconstruction algorithms
- Boosted decision tree with 207 variables optimized for maximum S/B separation

- Dominant background rates measured/constrained

Analyses are in final stages

- event selection finalized
- systematics and signal extraction being finalized