RESULTS OF THE MiniBooNE NEUTRINO OSCILLATION SEARCH

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Results of the MiniBooNE Neutrino Oscillation Search

- Introduction to MiniBooNE
- The oscillation analysis
- The initial results and their implications
- The next steps

MiniBooNE: E898 at Fermilab

- Purpose is to test LSND with:
  - Higher energy
  - Different beam
  - Different oscillation signature
  - Different systematics
- L=500 meters, E=0.5−1 GeV: same L/E as LSND.

LSND

- Stopped π^+ beam at Los Alamos LAMPF produces ν_e, ν_μ, $\bar{\nu}_\mu$ but no $\bar{\nu}_e$ (due to π^- capture).

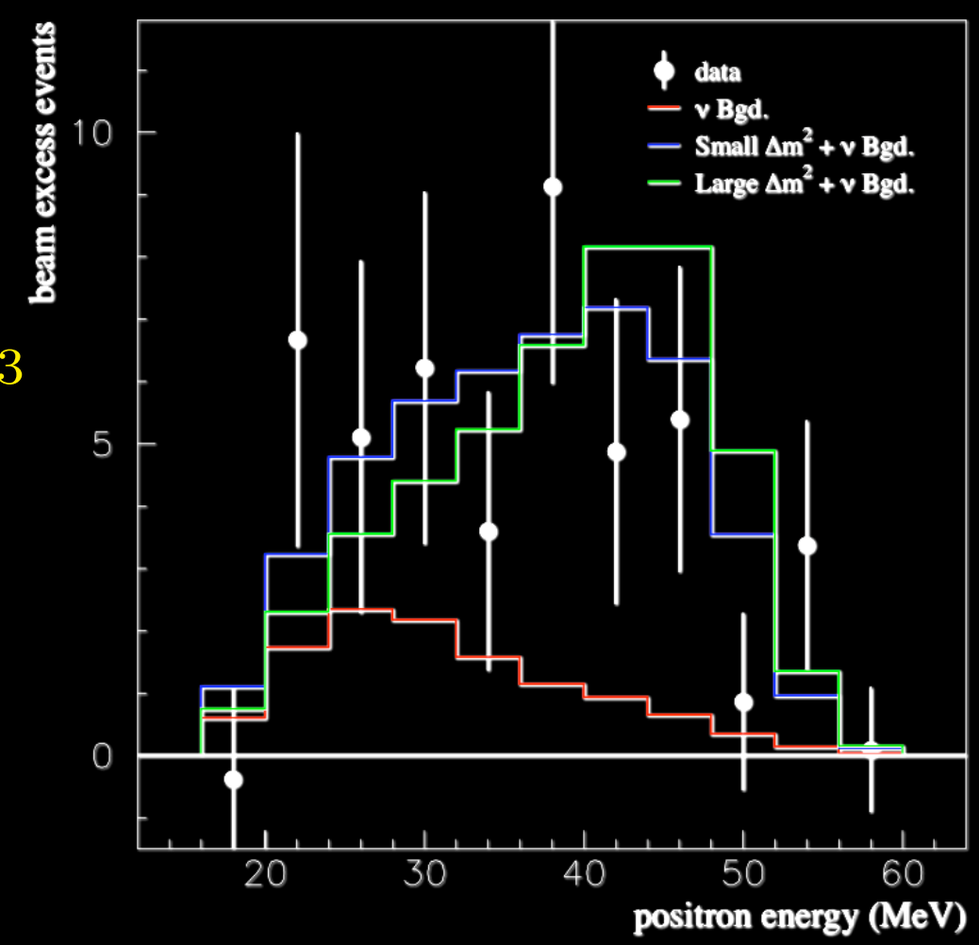
  Search for $\bar{\nu}_e$ appearance via reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- 4 standard dev. excess above background.

- Oscillation probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (2.5 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-3}$$

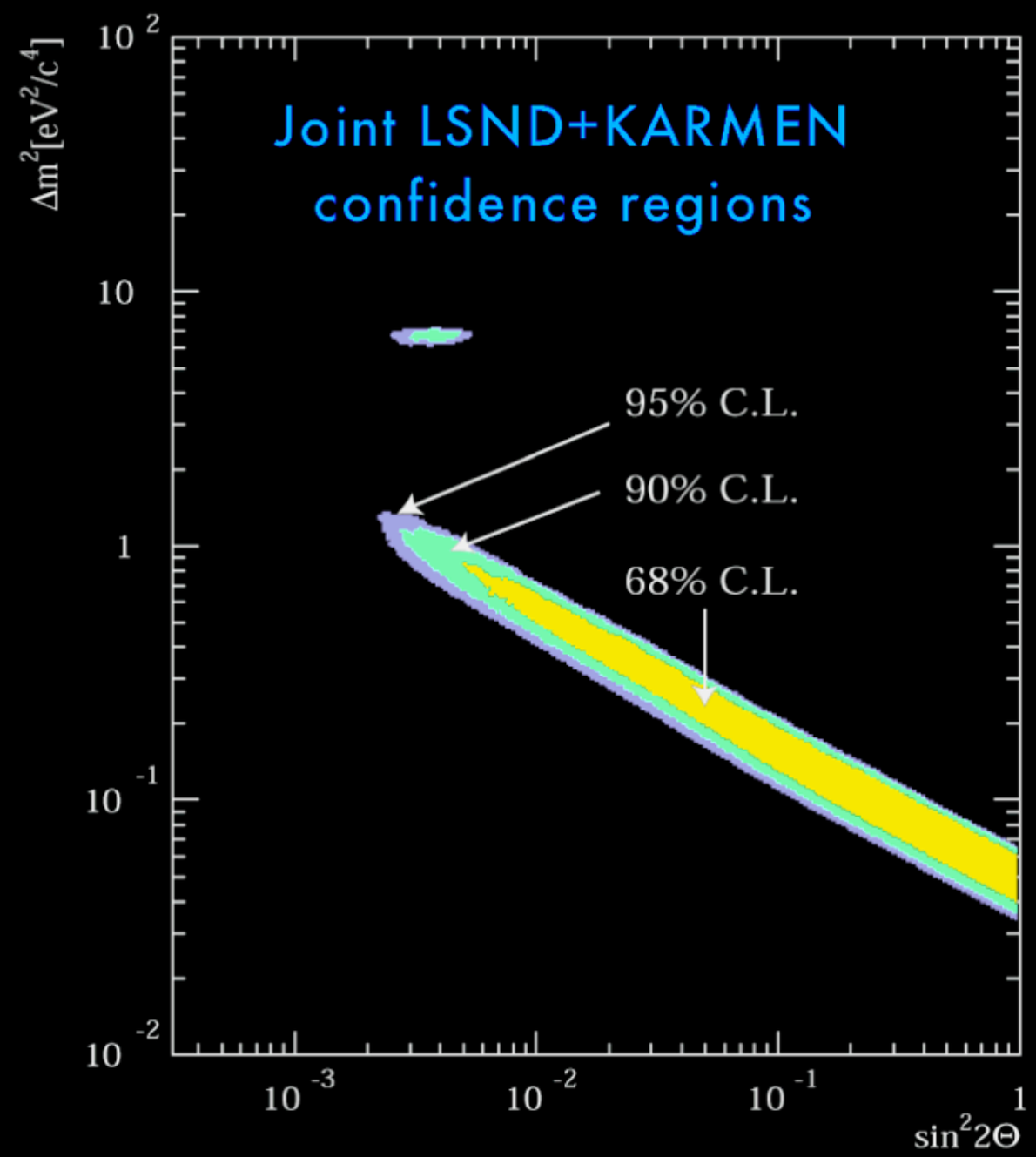


LSND Oscillation allowed region

Confidence regions from joint analysis of LSND and KARMEN2 data

E. Church *et al.*, *Phys. Rev.* **D66**, 013001 (2002)

- Combined analysis:
  - Consistency at 64% confidence level
  - Restricted parameter region



Oscillation Signature at MiniBooNE

- Oscillation signature is charged-current quasielastic scattering:

$$\nu_e + n \rightarrow e^- + p$$

- Dominant backgrounds to oscillation:
  - Intrinsic ν_e in the beam

    $\pi \rightarrow \mu \rightarrow \nu_e$ in beam

    $K^+ \rightarrow \pi^0 e^- \nu_e$, $K_L^0 \rightarrow \pi^0 e^\pm \nu_e$ in beam
  - Particle misidentification in detector

    Neutral current resonance:

    $\Delta \rightarrow \pi^0 \rightarrow \gamma\gamma$ or $\Delta \rightarrow n\gamma$, mis-ID as e

Results presented here

- A generic search for a ν_e excess in the ν_μ-dominated beam
- A fit for neutrino oscillations in a CP-conserving two-flavor, appearance-only scenario

The BooNE Collaboration

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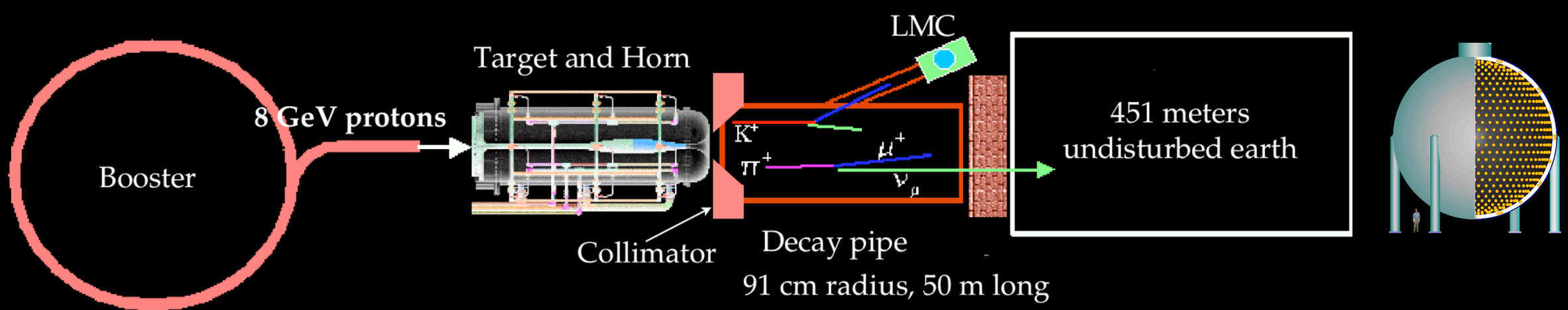
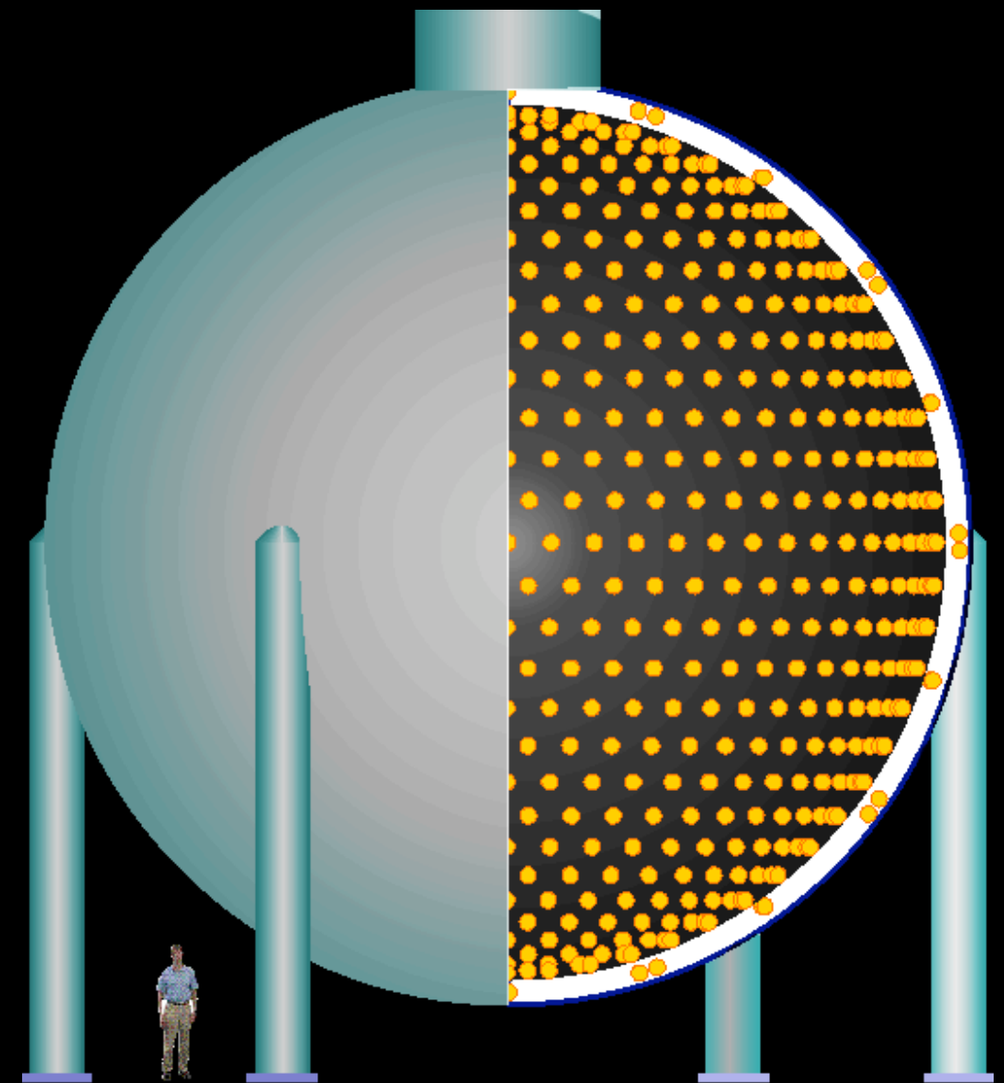
MiniBooNE Beamline



- 8 GeV primary protons come from Booster accelerator at Fermilab
- Booster provides about 5 pulses per second, 5×10^{12} protons per 1.6 μs pulse under optimum conditions
- Data collected September 2002-January 2006: 5.7×10^{20} POT in standard running configuration

MiniBooNE neutrino detector

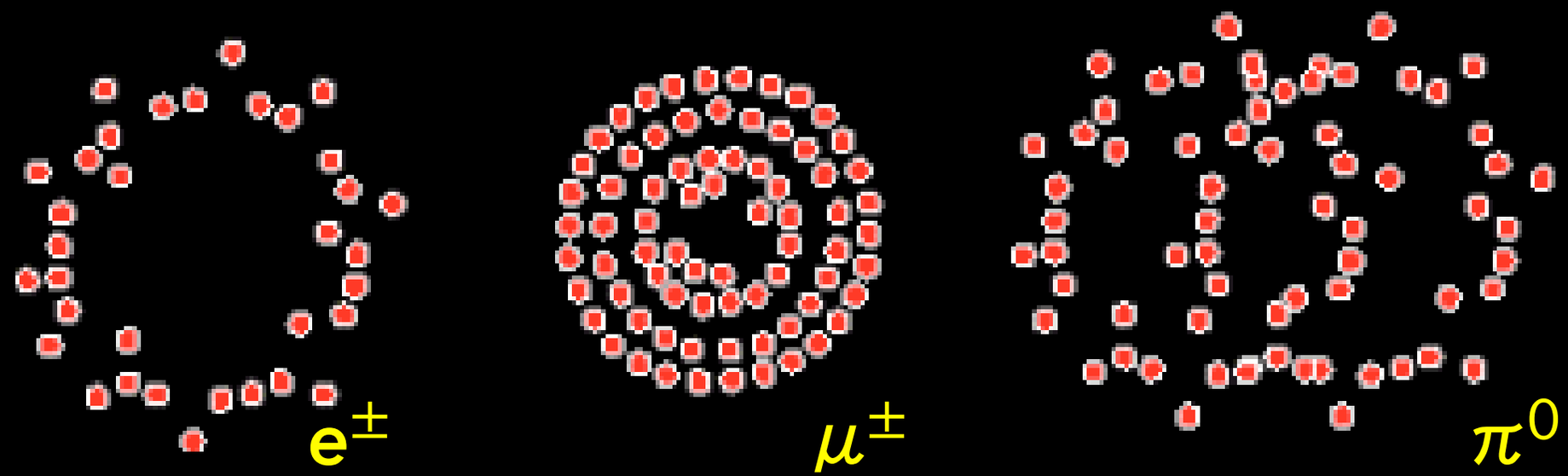


- Pure mineral oil
- 800 tons; 40 ft diameter
- Inner volume: 1280 8″ PMTs
- Outer veto volume: 240 PMTs

The detector records:

- Every 100 ns clock cycle:
  - Total charge on each PMT
    - Resolution ~1 photoelectron
  - Time of first hit on each PMT above threshold
    - Resolution ~1.5 ns

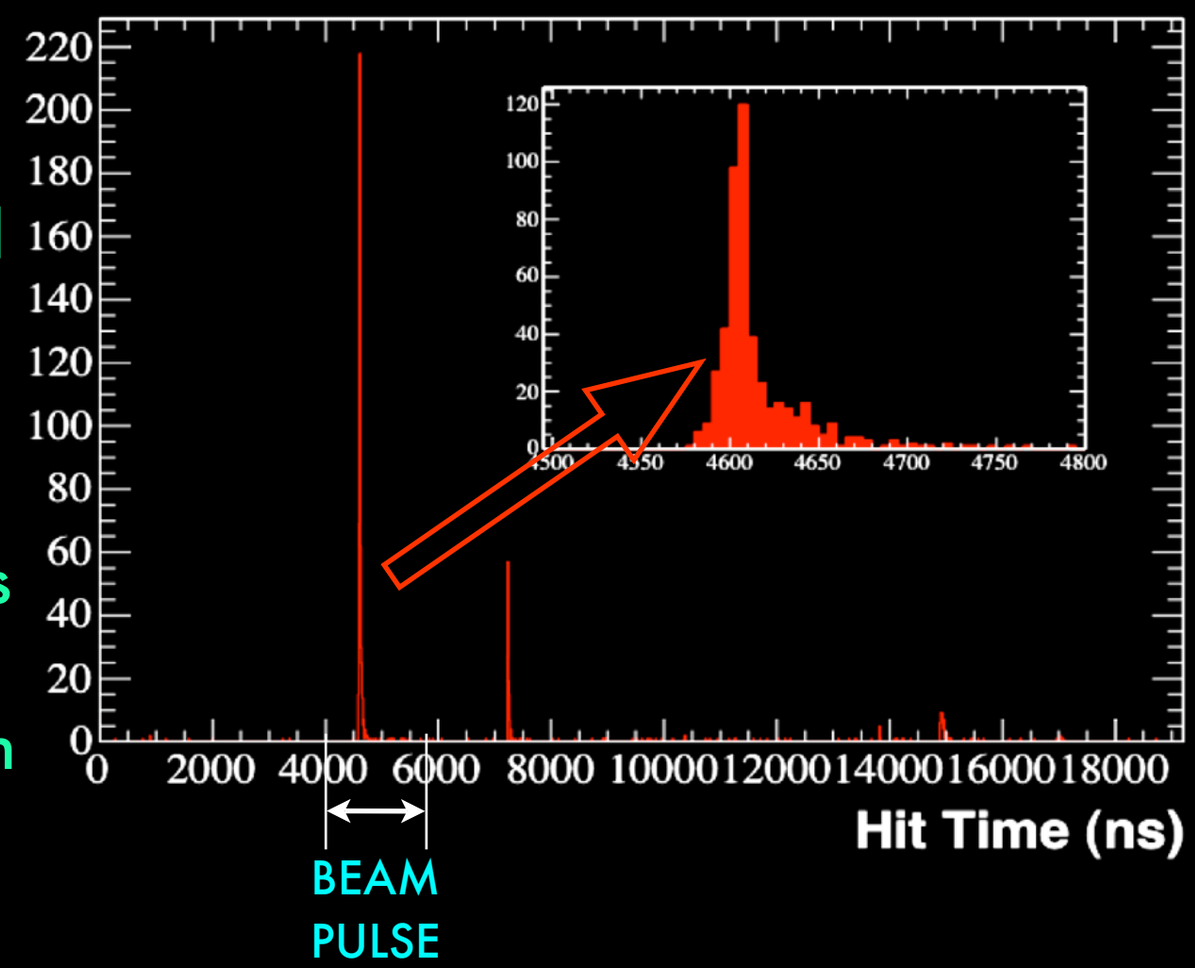
Event types:



- Electrons: showers, scattering ⇒ "fuzzy" ring
- Muons: straight, long track ⇒ well-defined ring
- $\pi^0 \rightarrow \gamma\gamma$: two electron-like rings

Subevents

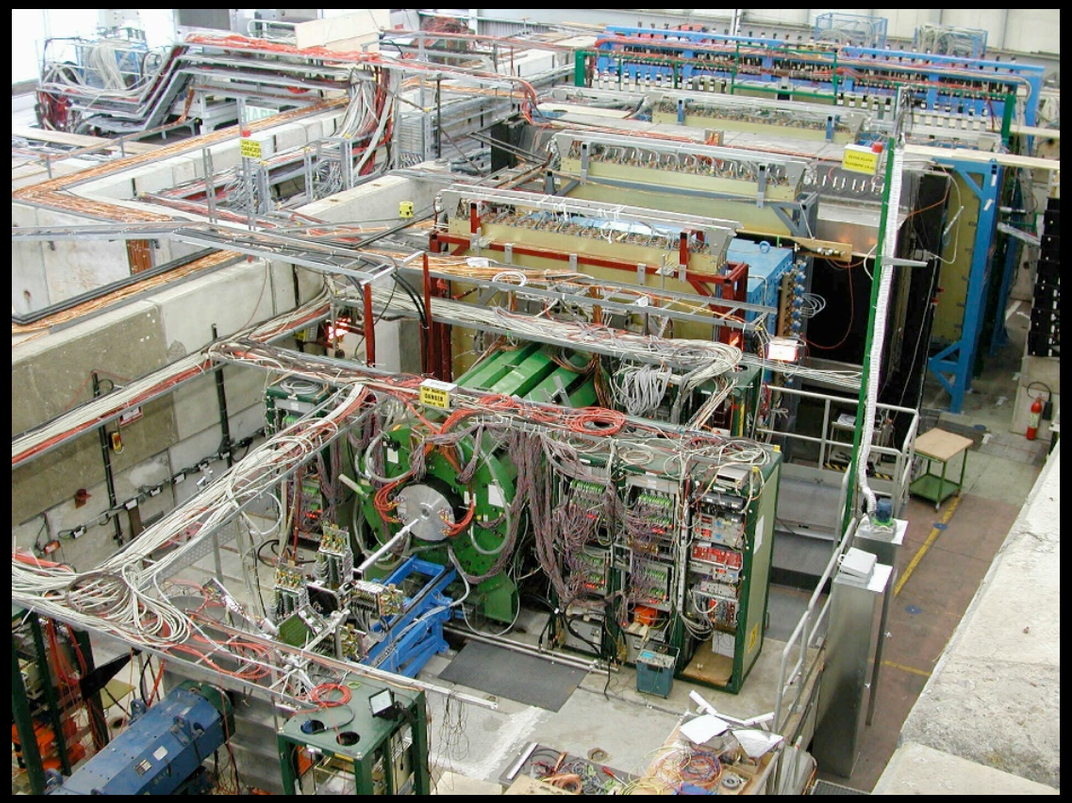
- All hits are recorded in a 20-μs window around the beam pulse.
- Able to check for subsequent stopped muon decay ("Michel") electron: muon and its Michel electron resolved as two "subevents" (clusters of hits within ~100 ns).
- The Michel electron subevent provides muon tag as well as a very well-understood charge/energy calibration
- Muons capture on nucleus with 8% probability; these capture events cannot be tagged.

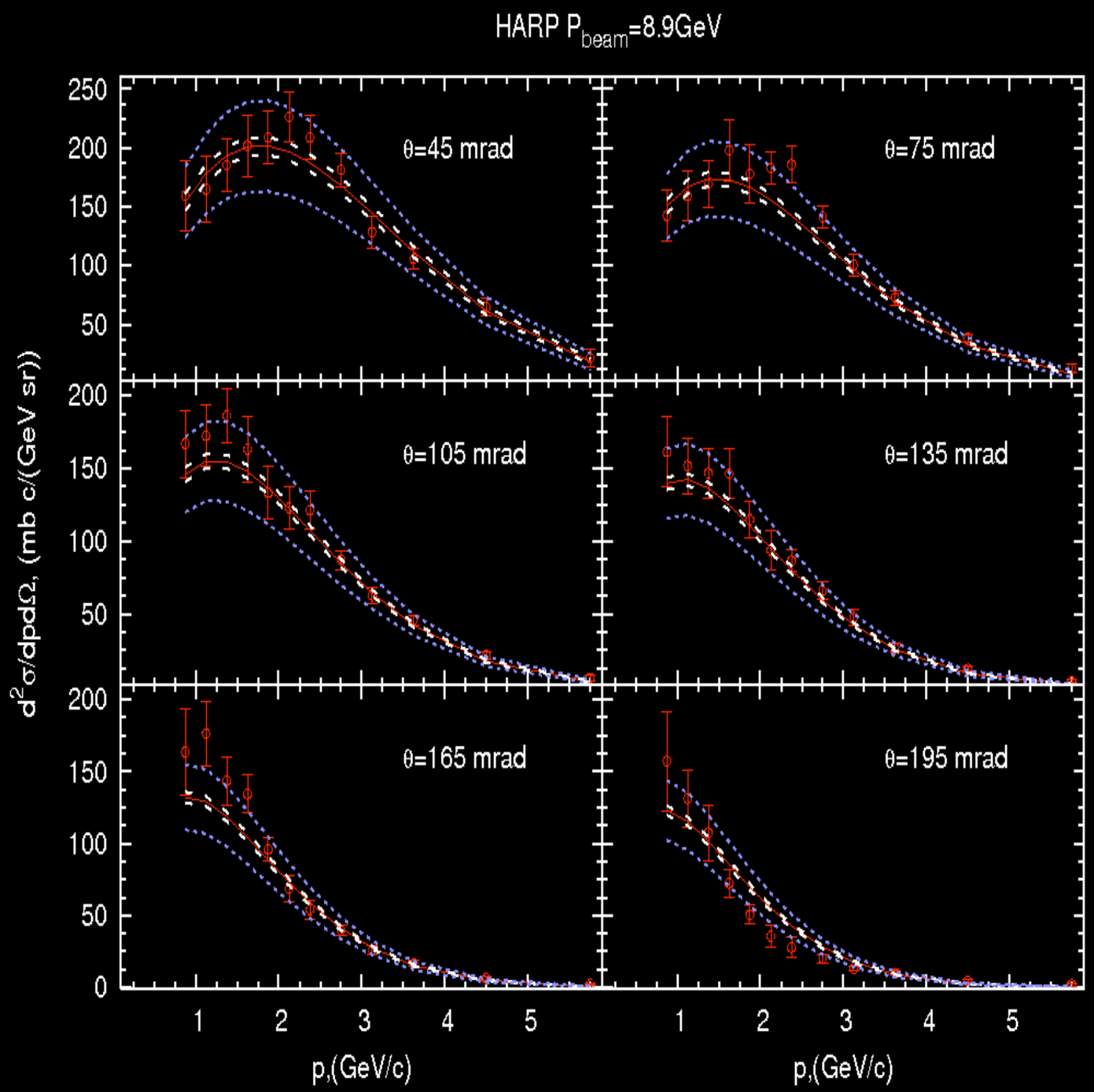


Oscillation Analysis

- Steps to an oscillation result:
  - Predict flux
  - Model neutrino interactions in detector
  - Model detector response
  - Reconstruct events; particle ID
  - Oscillation fit

Flux model: Pion production

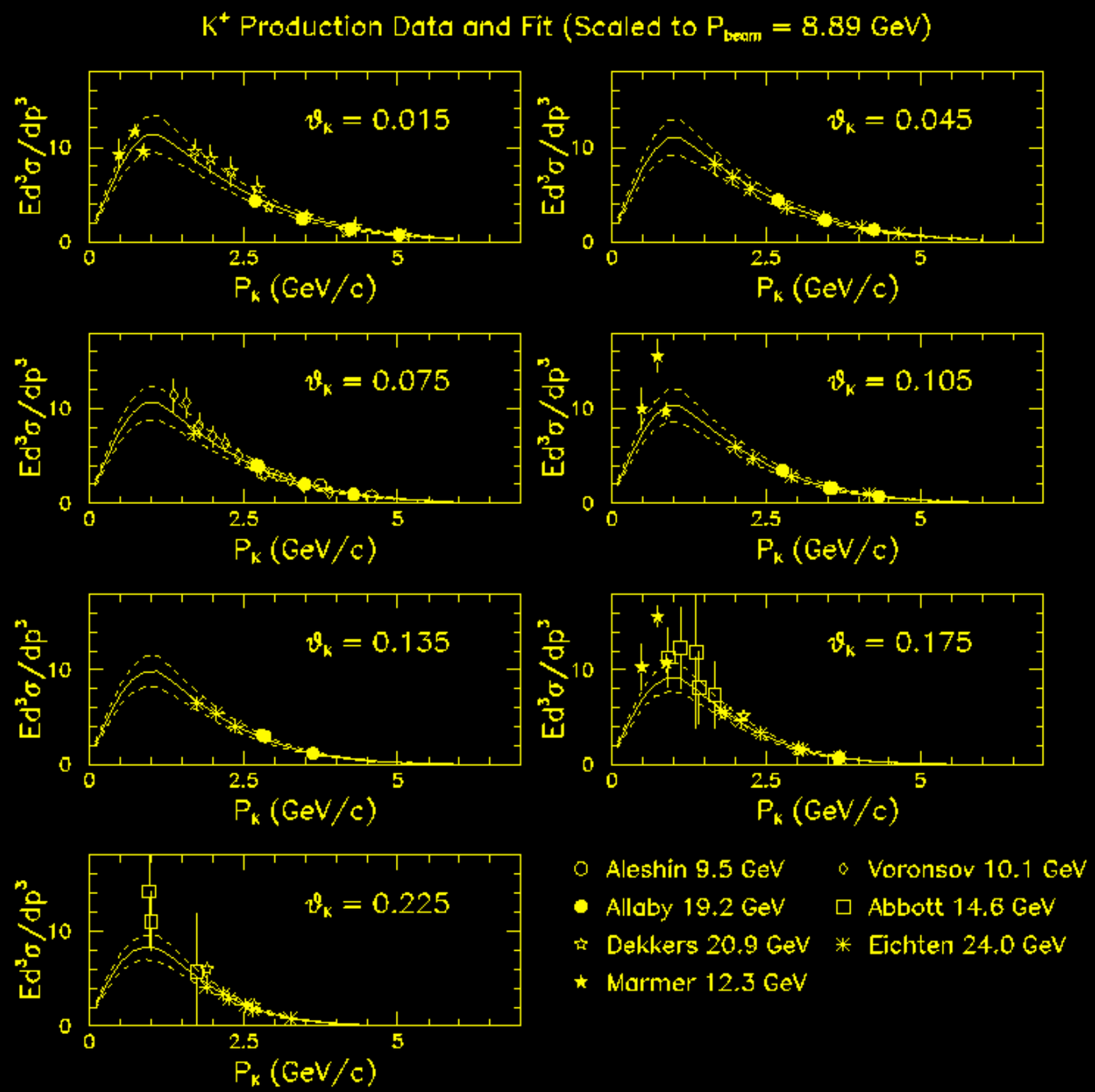




- Data from HARP experiment at CERN (taken with beryllium target at correct MiniBooNE beam momentum: hep-ex/0702024)
- Fit data to 9-parameter Sanford-Wang parametrization
- Sanford-Wang model used in GEANT4 beam Monte Carlo

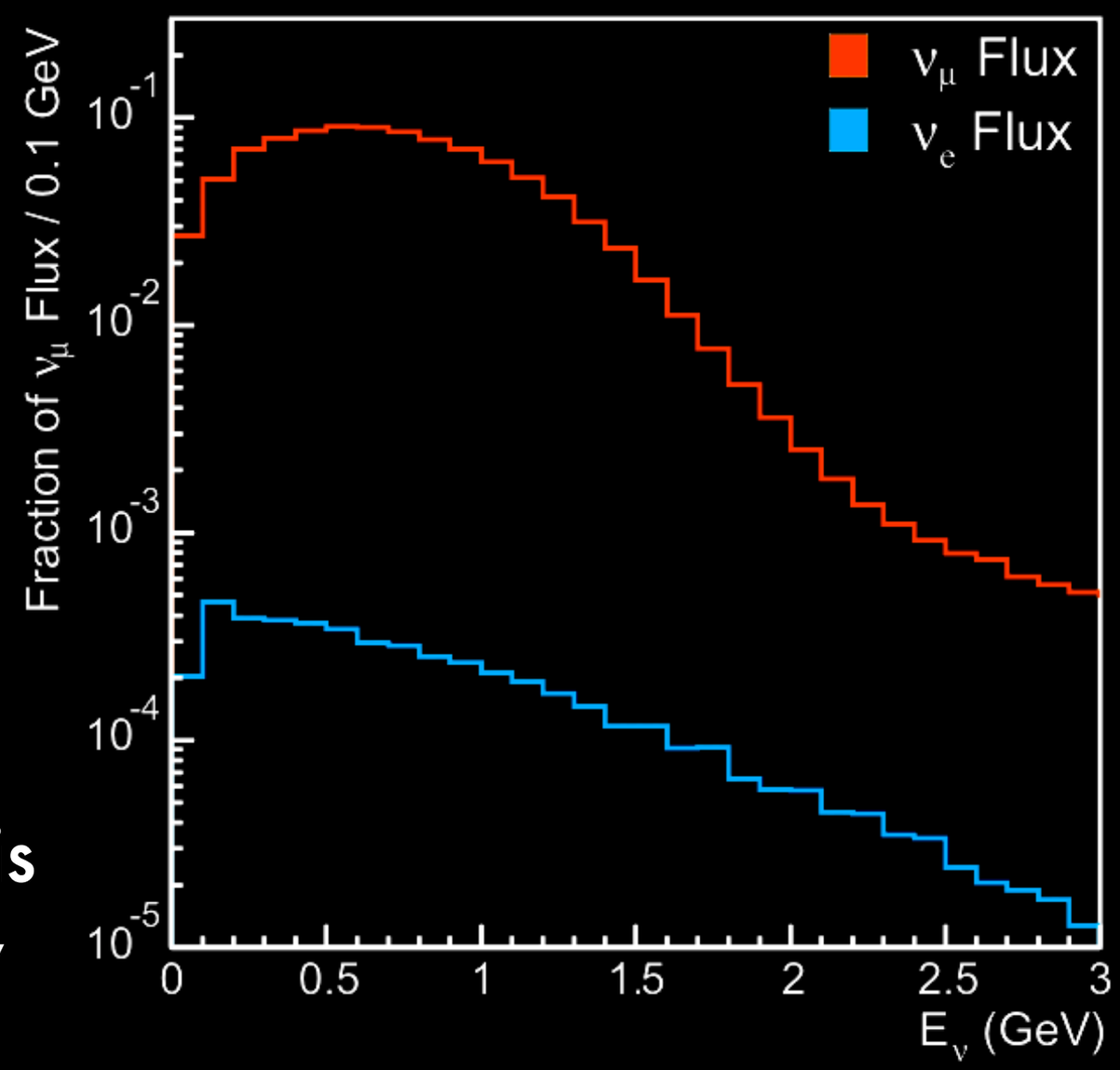
Flux model: kaon production

- Kaon production data from many experiments, with primary beam momentum 9→24 GeV
- Fit data to a Feynman scaling parametrization
- Sanford-Wang model used as well; errors cover the differences in flux predictions for MiniBooNE



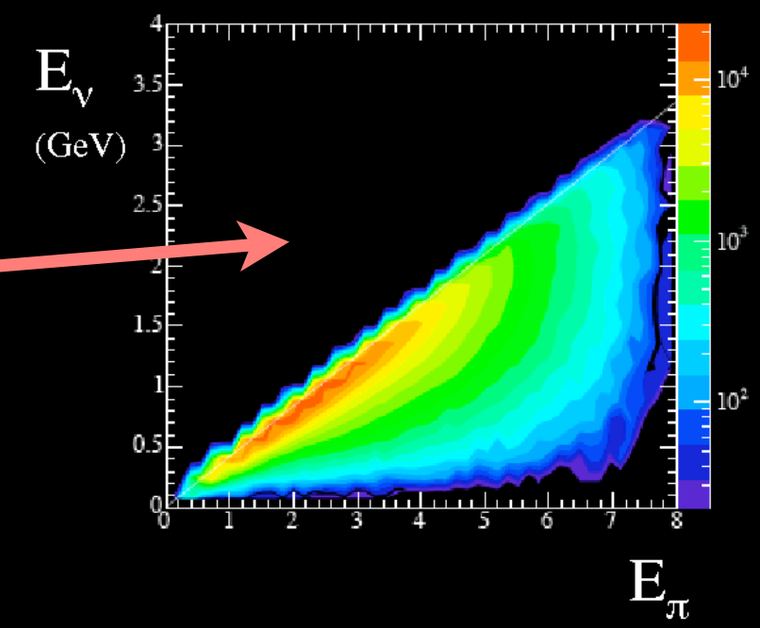
Predicted flux at detector

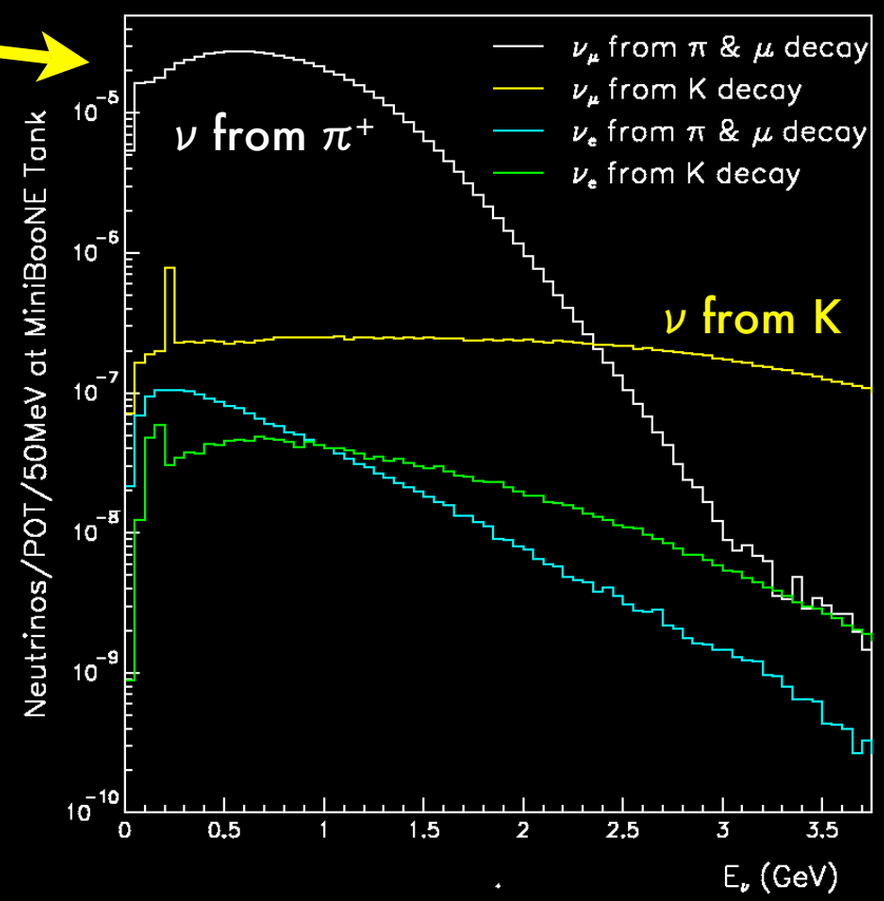
- Predicted flux:
  - 99.5% $\nu_\mu + \bar{\nu}_\mu$
  - 0.5% $\nu_e + \bar{\nu}_e$:
    - $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ *(52%)*
    - $K^+ \rightarrow \pi^0 e^+ \nu_e$ *(29%)*
    - $K^0 \rightarrow \pi^+ e^- \bar{\nu}_e$ *(7%)*
    - $K^0 \rightarrow \pi^- e^+ \nu_e$ *(7%)*
    - $\pi^+ \rightarrow e^+ \nu_e$ *(4%)*
    - *Other* *(<1%)*
- Total antineutrino content is 6% (much of it at very low energy)

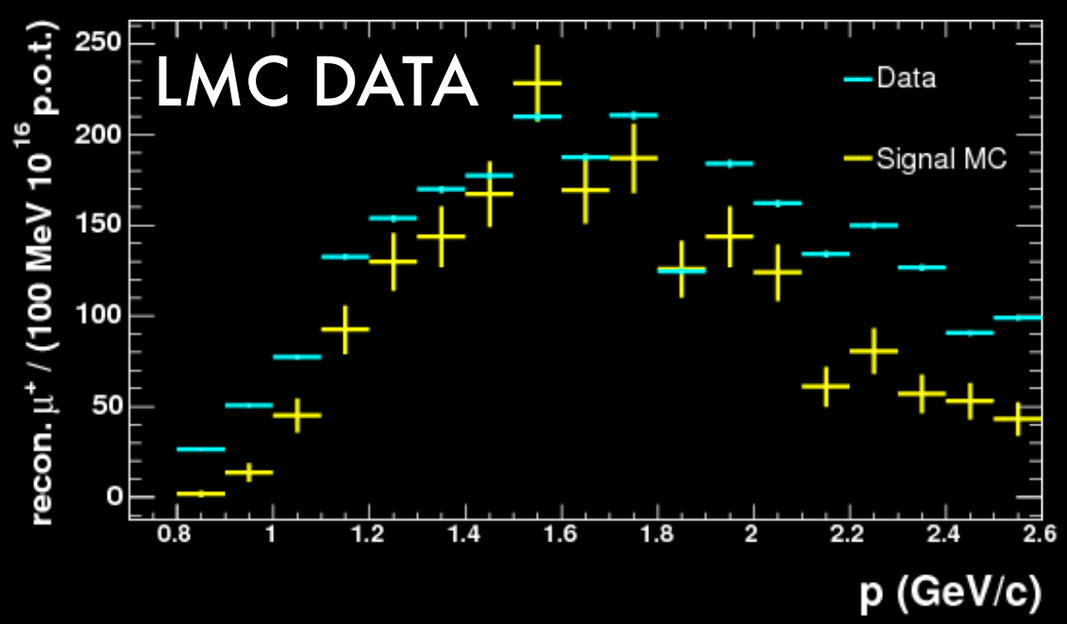


Further constraints on flux components

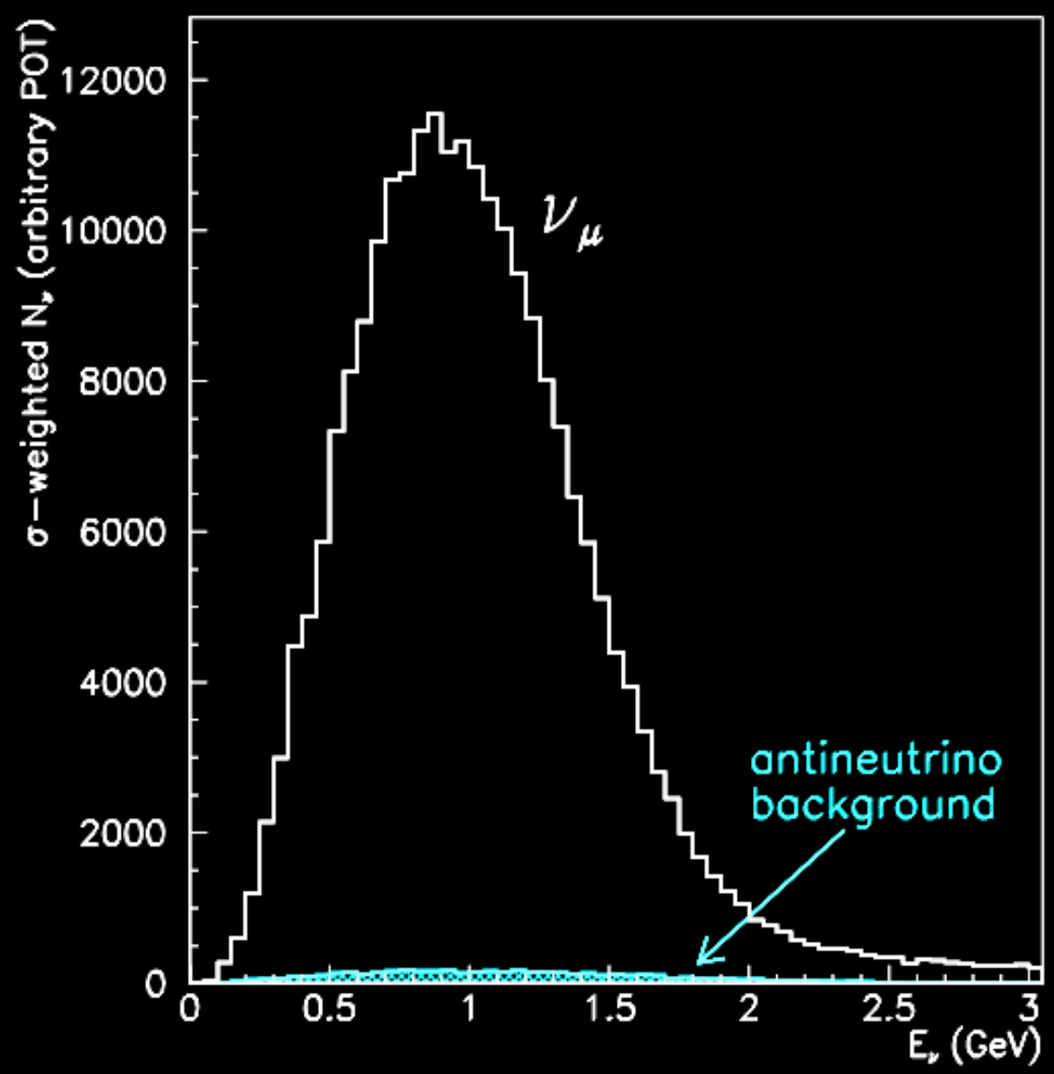
- Muons originate predominantly from pion decays in secondary beam:
  - These pions also produce most ν_μ in detector, which are easily observed
  - Kinematic correlation allows tight constraint on $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ chain
- Kaon decay has much higher Q-value than pion decay. Several ways to take advantage of this:
  - Kaons produce higher energy ν_μ: use the high energy events to constrain the kaon flux that produces ν_e background
  - Off-axis "Little Muon Counter" views high-p_T muons in the secondary beam

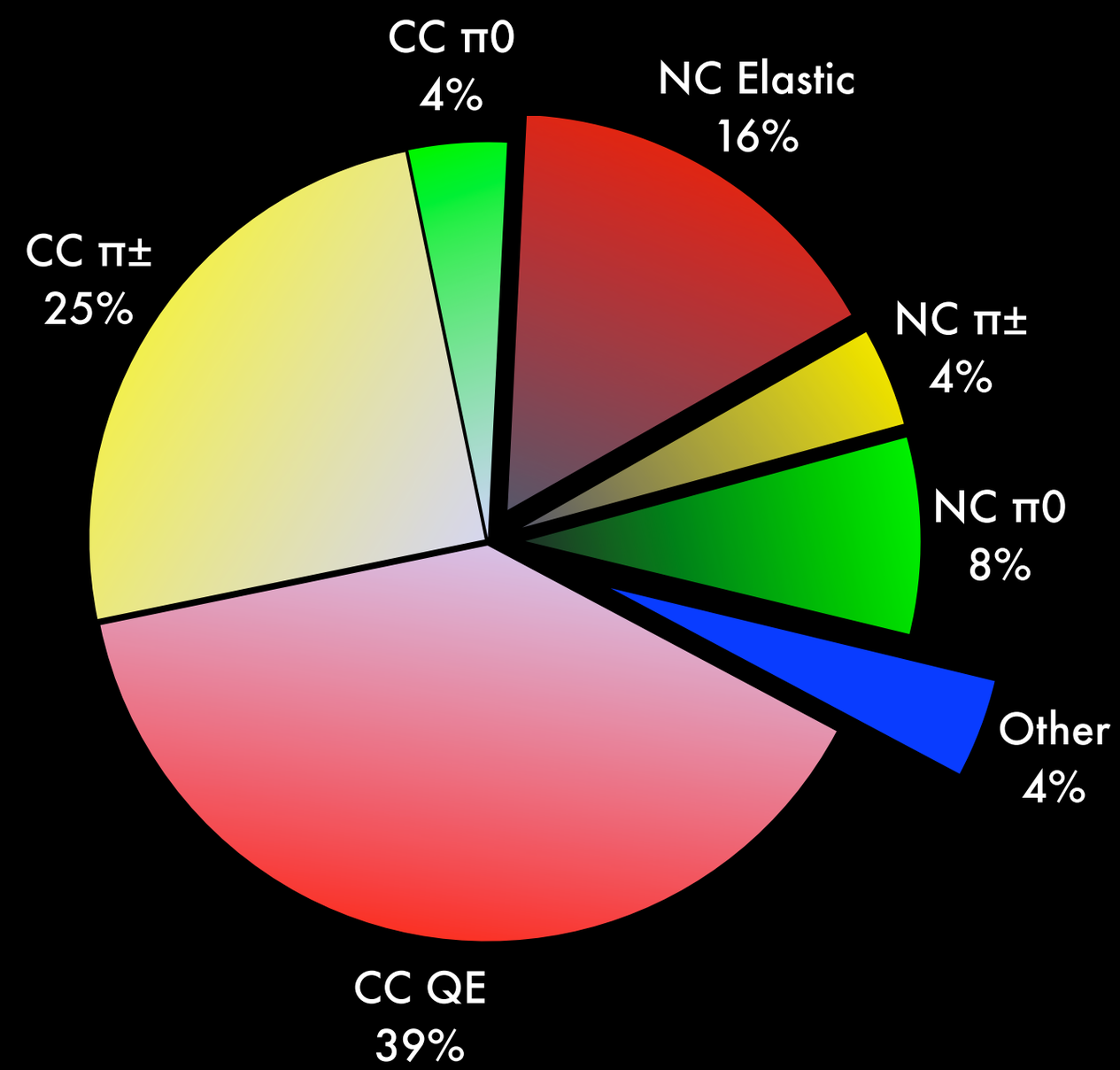






Neutrino Interactions in MiniBooNE





Predicted event spectrum, fractions before cuts
(NUANCE Monte Carlo)

D. Casper, NPS, 112 (2002) 161

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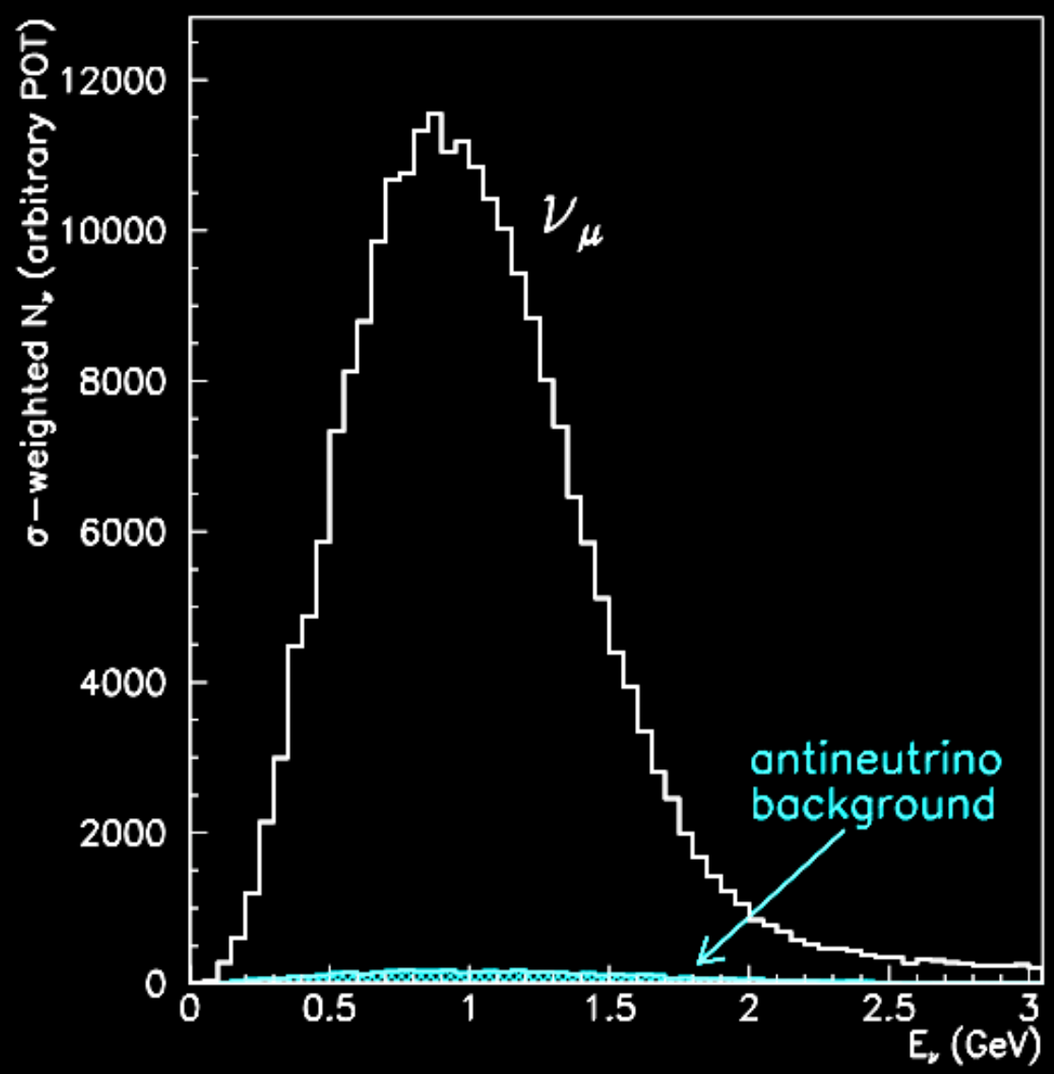

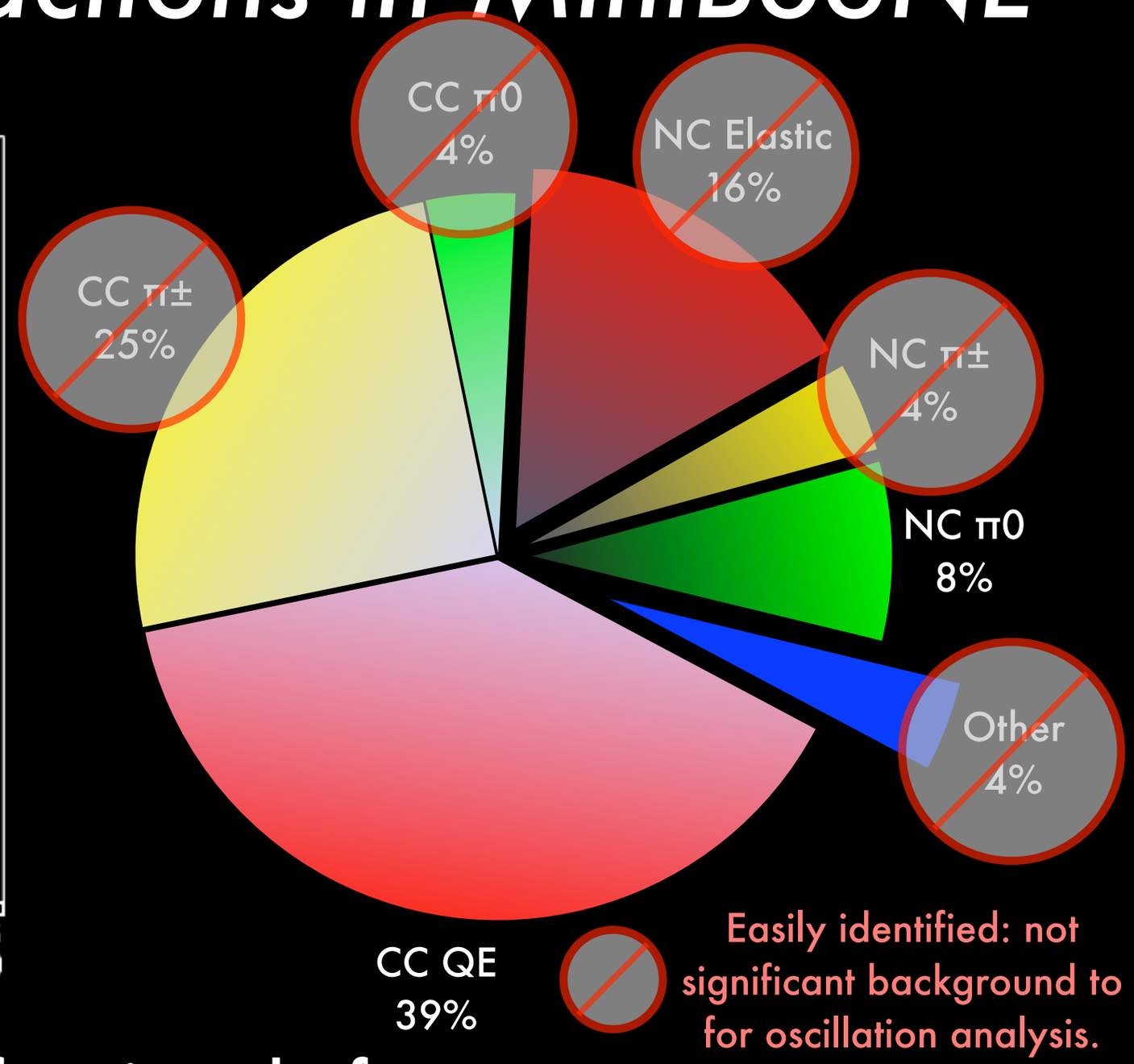

Predicted event spectrum, fractions before cuts (NUANCE Monte Carlo)

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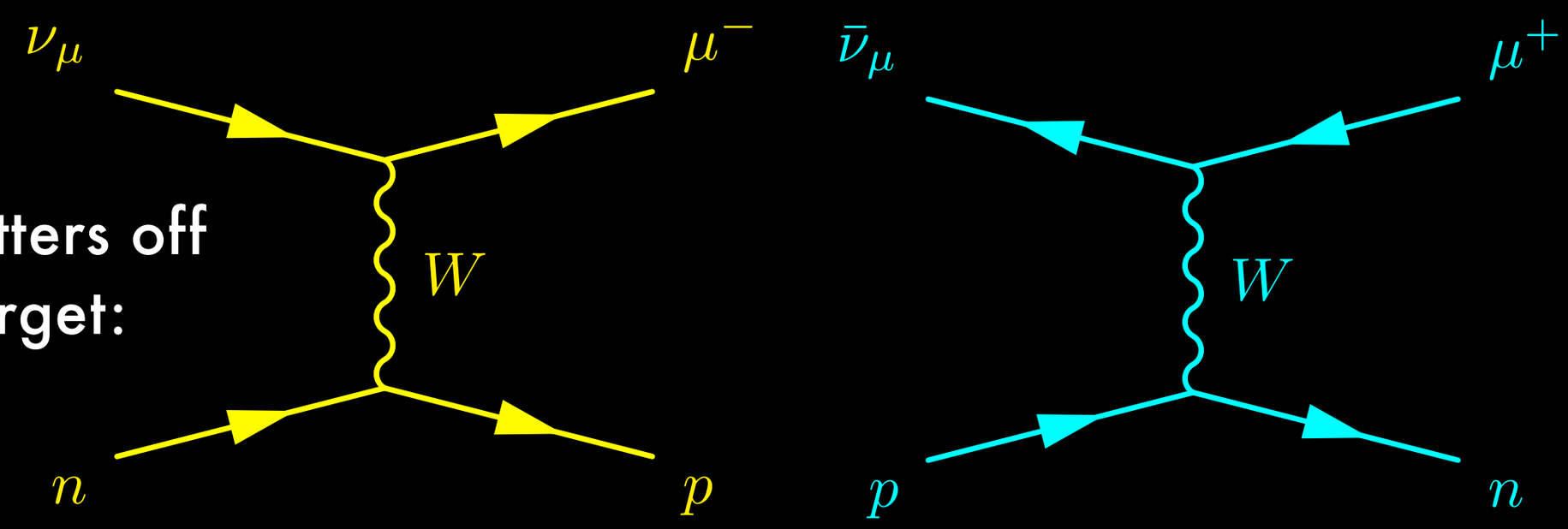
Charged-current quasielastic (CCQE)

Neutrino scatters off nucleon in target:

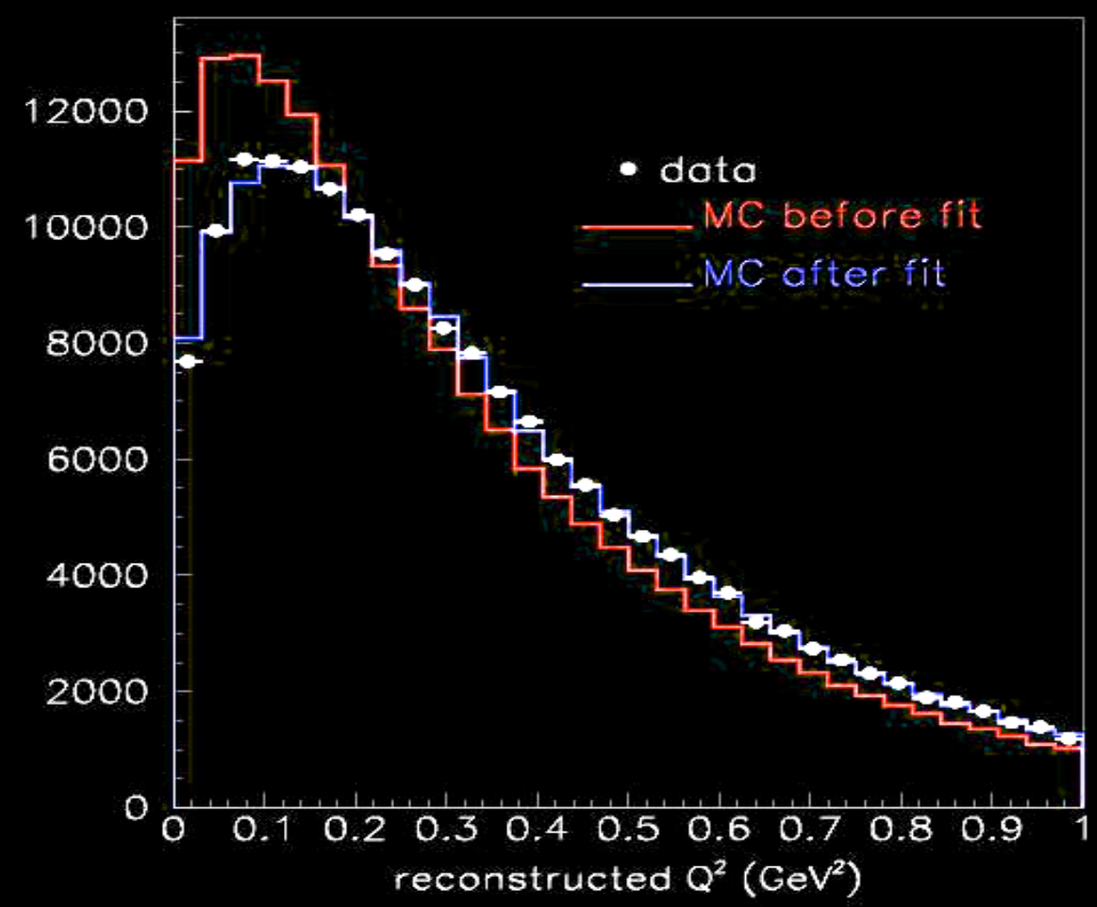


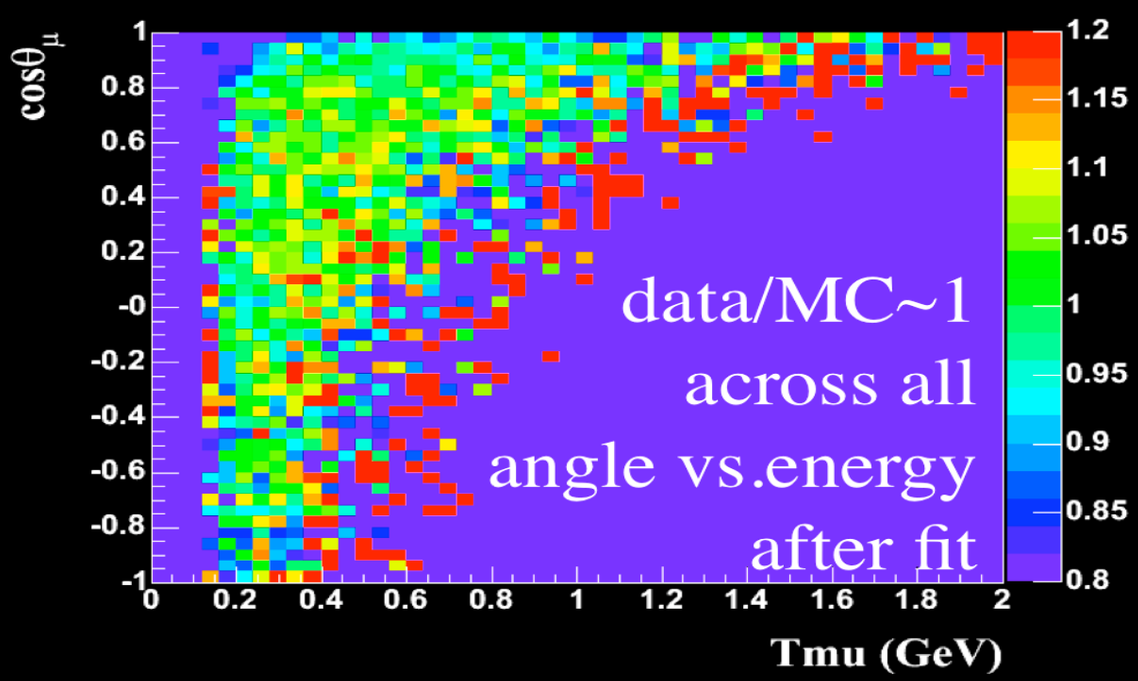
- Golden signal mode for oscillation search: clean events; neutrino energy can be calculated given known neutrino direction:

$$E_\nu^{\mathrm{CCQE}} = \frac{m_N E_\ell - \frac{1}{2} m_\ell^2}{m_N - E_\ell + p_\ell \cos\theta_\ell}; \qquad Q^2 = -2E_\nu(E_\nu - p_\ell \cos\theta_\ell) + m_\ell^2$$

- Nucleus may break up
- Final state nucleon not excited: no resonance, no pion, no (hard) gamma

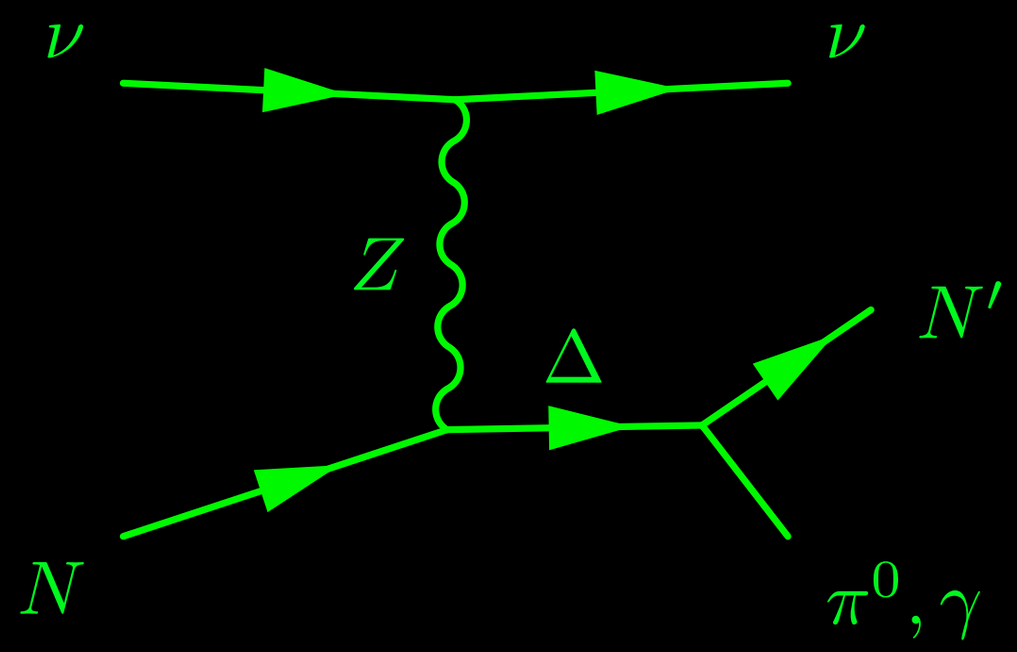
Cross-section parameters need tuning





- From Q^2 fits to MiniBooNE ν_μ CCQE data:
  - M_A^{eff}: effective axial mass
  - E_{lo}^{SF}: Pauli-blocking parameter
- From electron scattering data:
  - E_b -- binding energy
  - p_F -- Fermi momentum

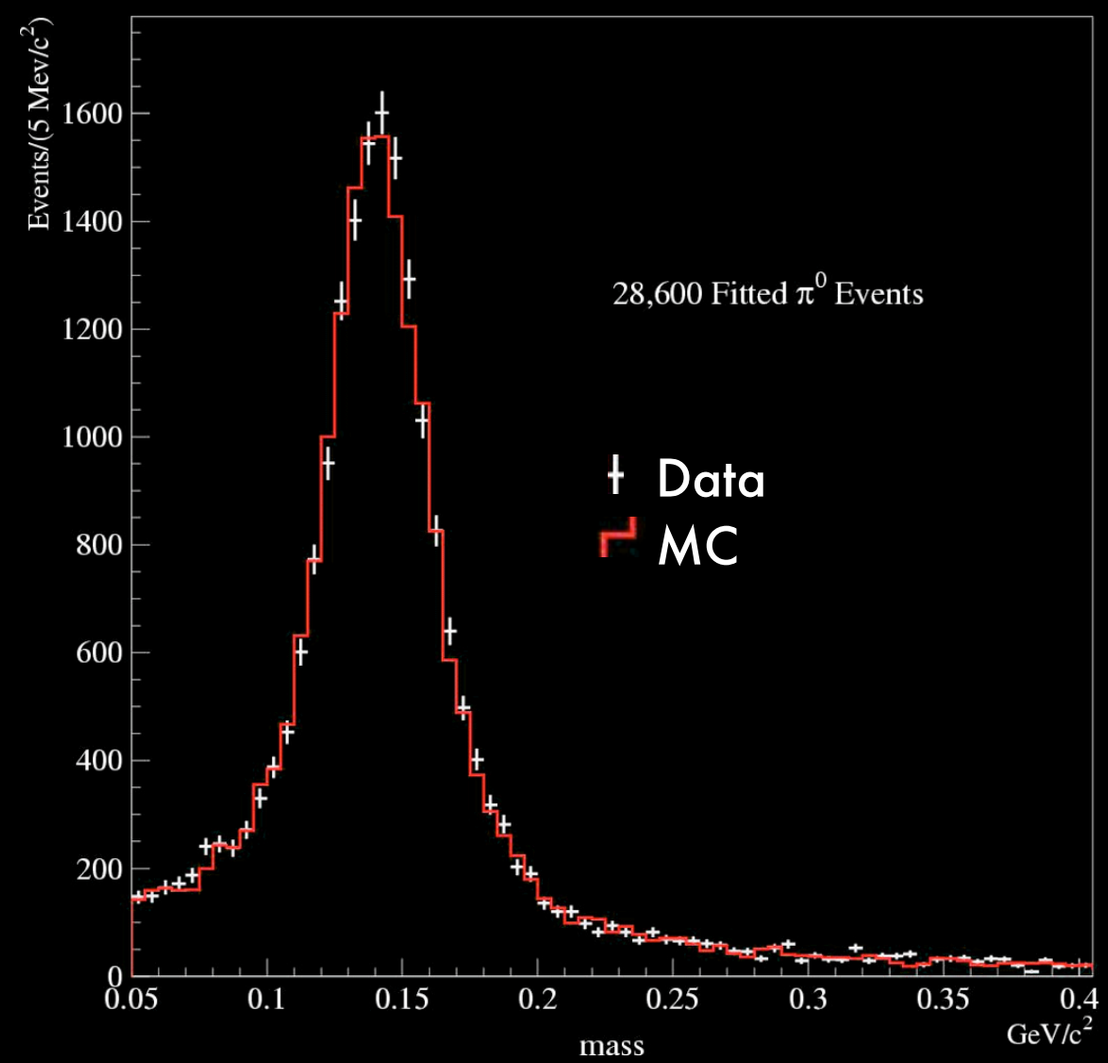
Neutral Current Δ Resonances



- No Michel electron to tag events
- Gamma rays, electrons indistinguishable in the detector
- $\Delta \rightarrow N\pi^0$: large decay branching ratio, but can usually detect both gammas
- $\Delta \rightarrow N\gamma$ radiative decay: small branching ratio (<1%), softer photon, but looks exactly like electron.
- Neutral current Δ resonance production is our largest source of particle misidentification background.

Neutral Current Δ Resonances

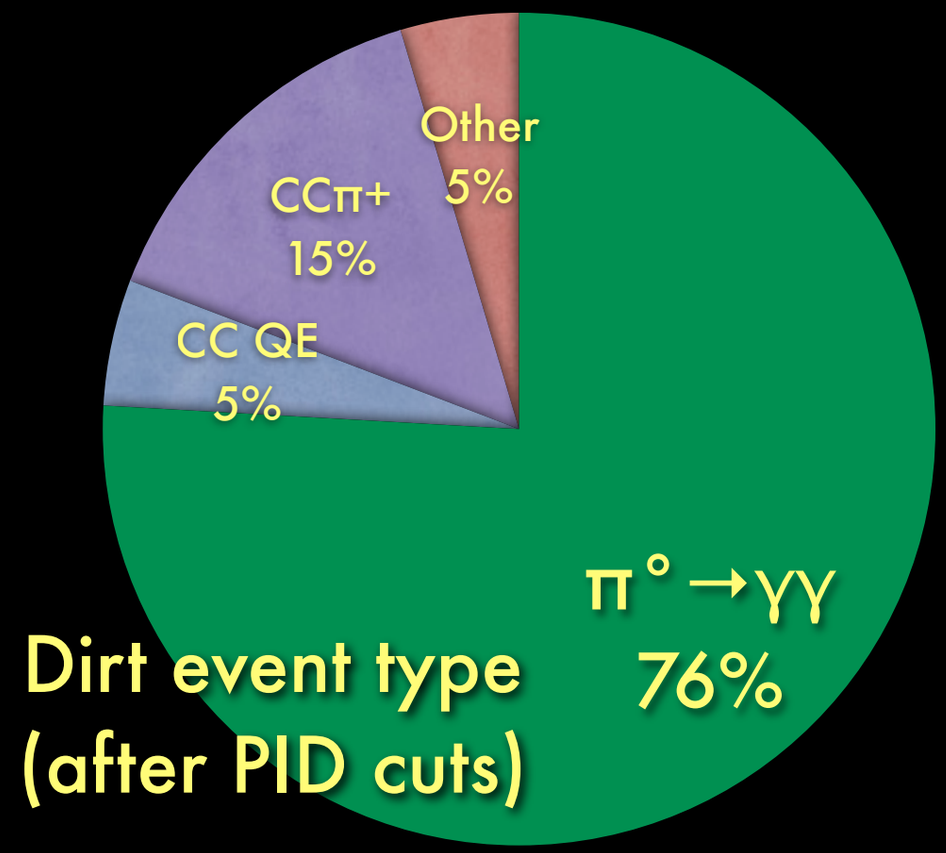
- π^0 events
  - Most π^0 events have two reconstructible photon rings.
  - Mass peak identifies neutral pions



- Total NC Δ rate is measured from these fully-reconstructed π^0 events.
- Use measured π^0 total rate and momentum spectrum to reweight the Δ Monte Carlo
- Reduces error on unreconstructed/misidentified π^0 and radiative decays

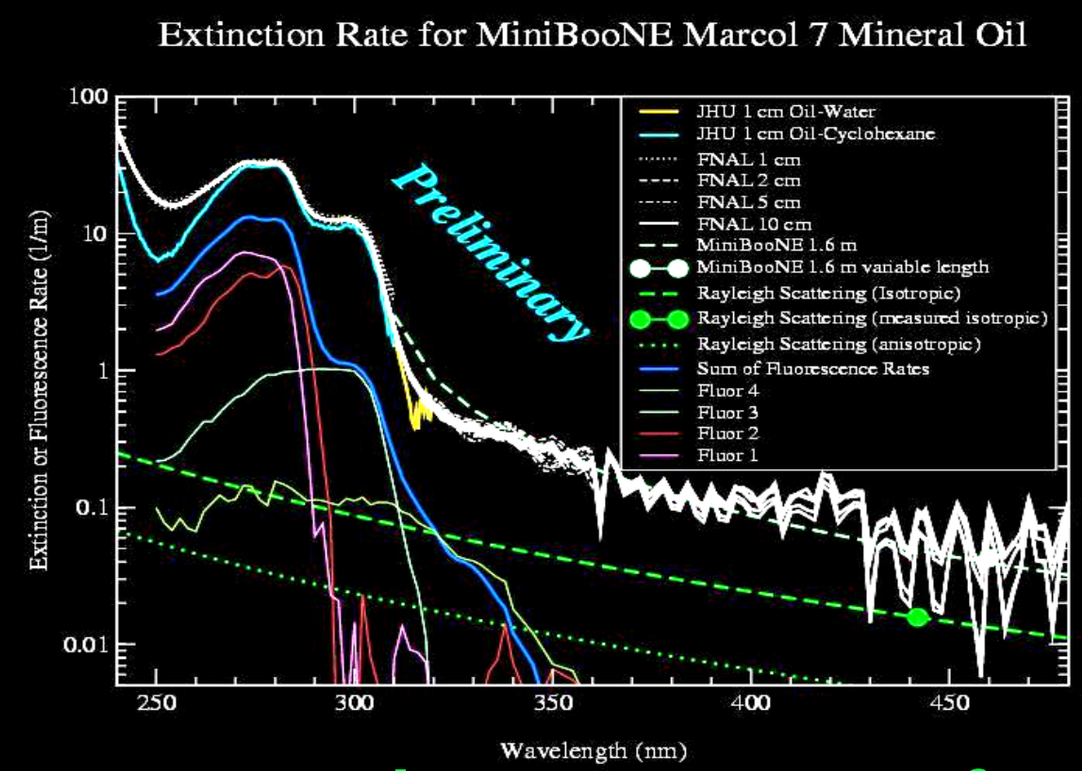
External backgrounds: "Dirt"

- "Dirt" events: neutrino interactions outside the detector
- Most events are cut by veto
- Background is dominated by π^0 where only one photon enters detector
- Cosmic/other beam-unrelated background is very small: 2.1±0.5 events, measured with beam-off data



Neutrino detector modeling: "optical" issues

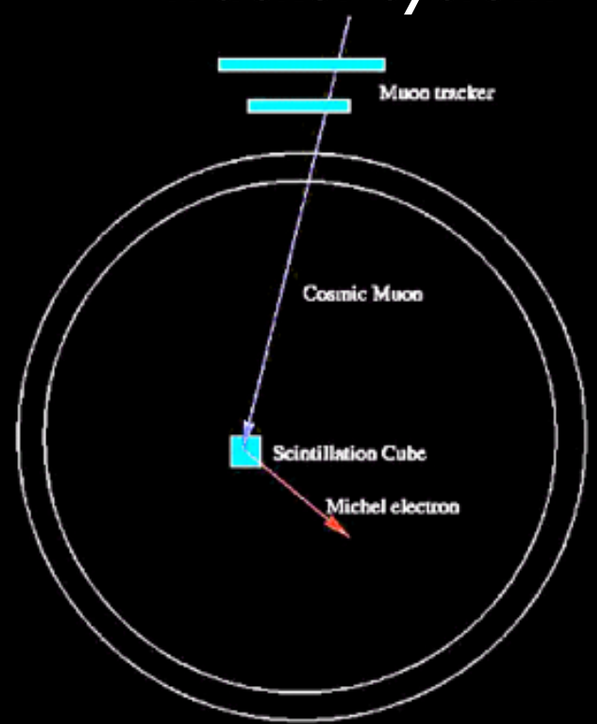
- Primary light sources
  - Cherenkov
    - Emitted promptly, in cone
    - known wavelength distribution
  - Scintillation
    - Emitted isotropically
    - Several lifetimes, emission modes
    - Studied oil samples using Indiana Cyclotron test beam
    - Particles below Cherenkov threshold still scintillate

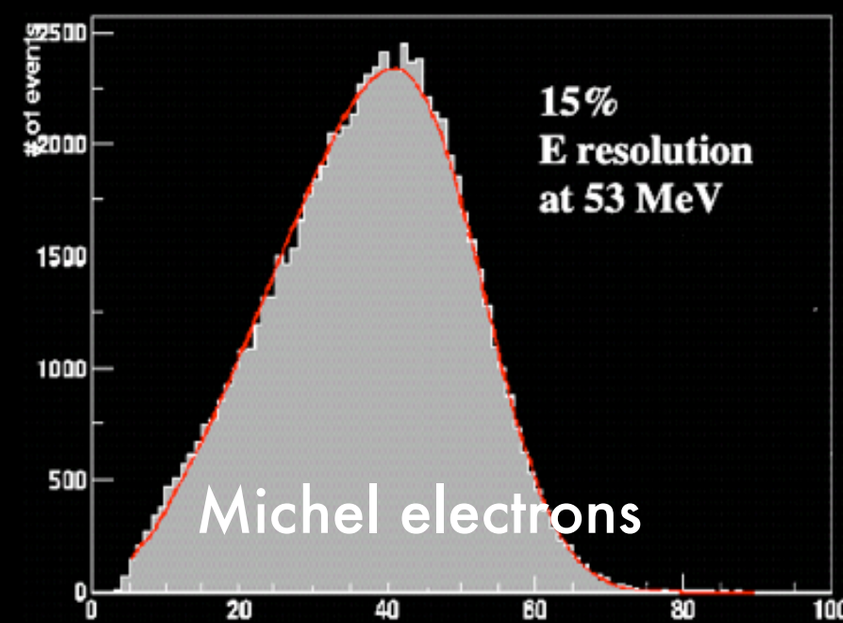


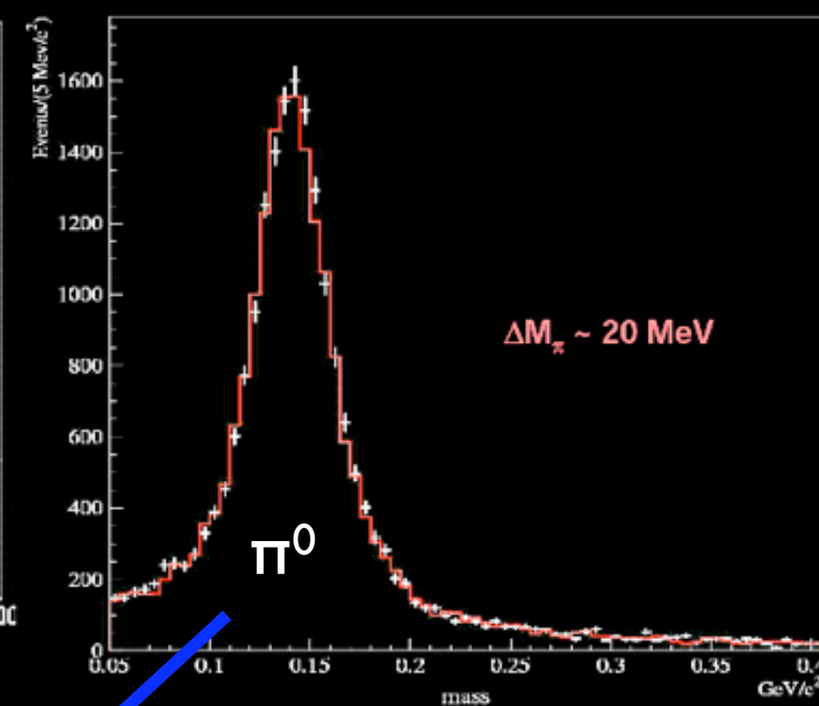
- Optical properties of oil, detectors:
  - Absorption (attenuation length >20m at 400 nm)
  - Rayleigh and Raman scattering
  - Fluorescence
  - Reflections
  - PMT response

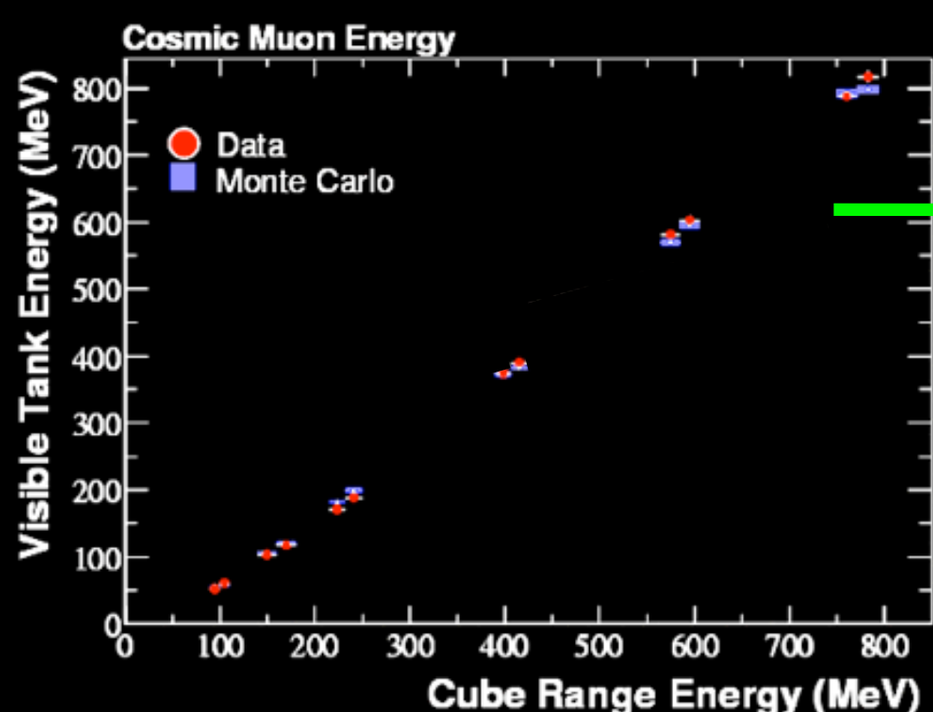
Calibration Sources

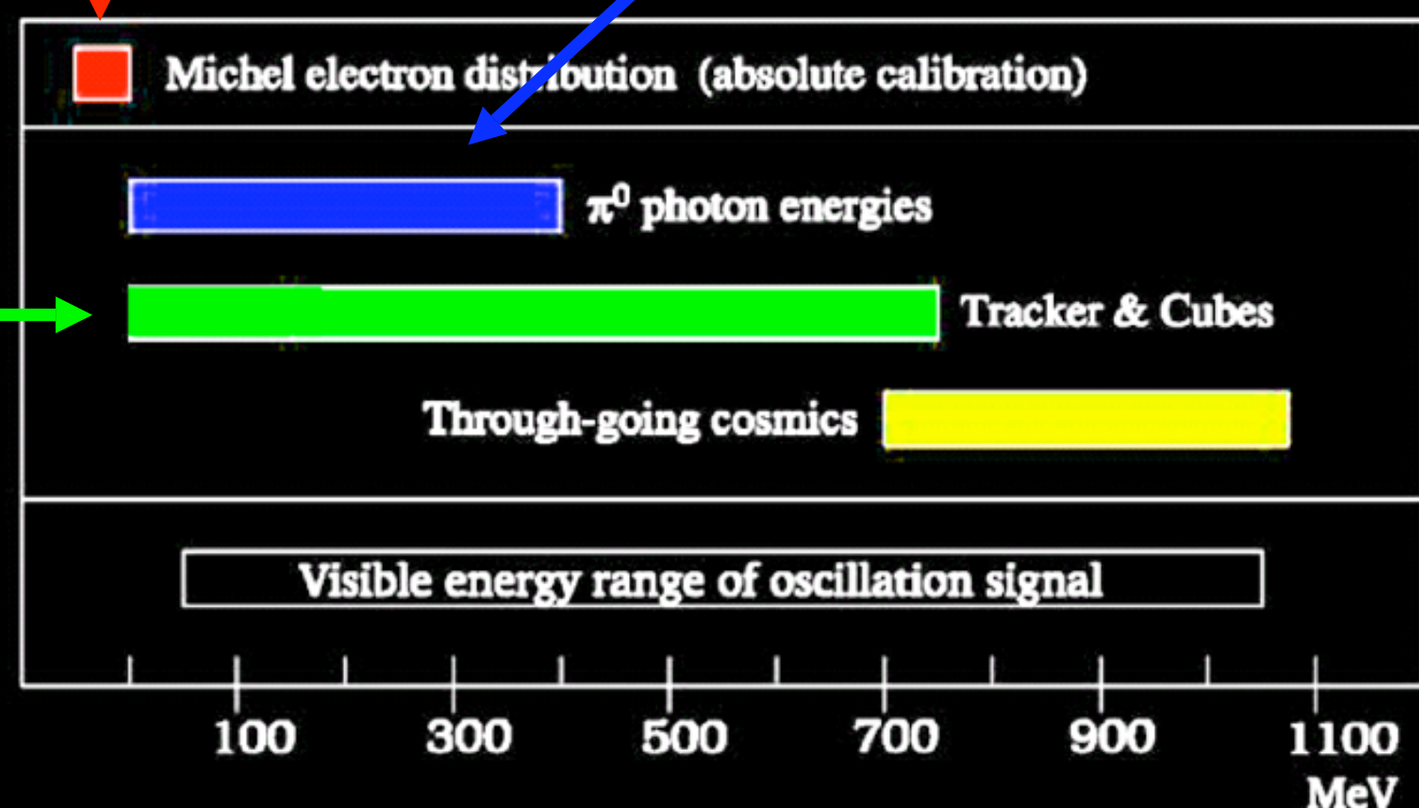
Tracker system











Event Reconstruction and Particle ID

- Parallel approaches to analysis: independent event reconstructions and PID algorithms
  - Track/likelihood-based (TB) analysis: detailed reconstruction of particle tracks; PID from ratio of fit likelihoods for different particle hypotheses. Less vulnerable to detector modeling errors.
  - Boosted decision trees (BDT): algorithmic approach, able to extract particle ID information from larger set of lower-level event variables. Better signal/background, but more sensitive to detector modeling.

The Blindness Procedure

- Philosophy: hide any event that could be an oscillation candidate from detailed analysis, while allowing aggregate or low-level information on all events to be examined.
- Early stages: highly restrictive, as particle ID was being developed: neutrino events closed by default. to open a sample of events for study, must show it is (nearly) oscillation-free.
- Later stages: MC and algorithms become more stable and trustworthy. Look in regions closer and closer to the signal; eventually all data open by default, and only the signal "box" (1% of events) was closed.
- Final stages: Open box in a series of steps, starting with fit quality values only, ending in full spectrum and oscillation fit.

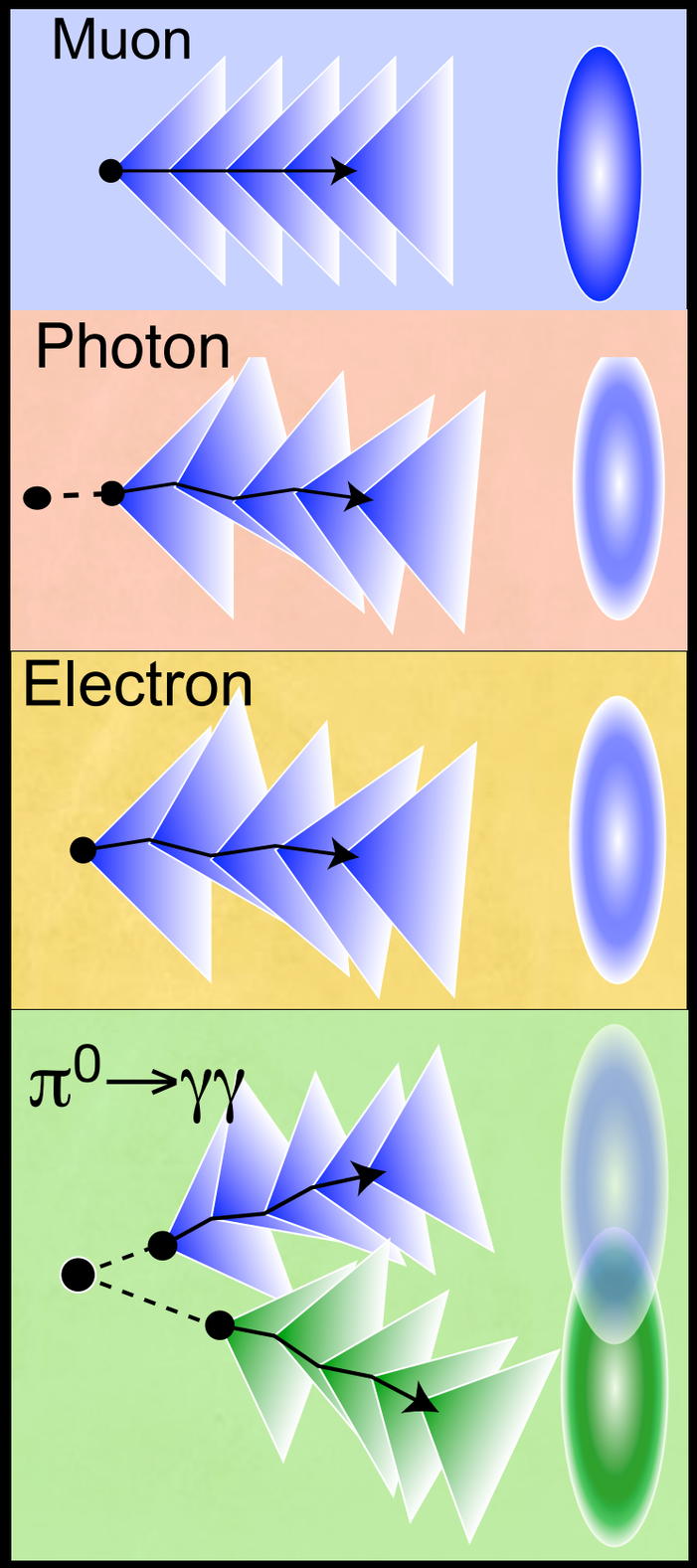
The Track-based Analysis: Reconstruction

- A detailed analytic model of extended-track light production and propagation in the tank predicts the probability distribution for charge and time on each PMT for individual muon or electron/photon tracks.
- Prediction based on seven track parameters: vertex (x,y,z), time, energy, and direction $(\theta,\varphi)\Leftrightarrow(U_x, U_y, U_z)$.
- Fitting routine varies parameters to determine 7-vector that best predicts the actual hits in a data event
- Particle identification comes from ratios of likelihoods from fits to different parent particle hypotheses

The Track-based Analysis:

Reconstruction

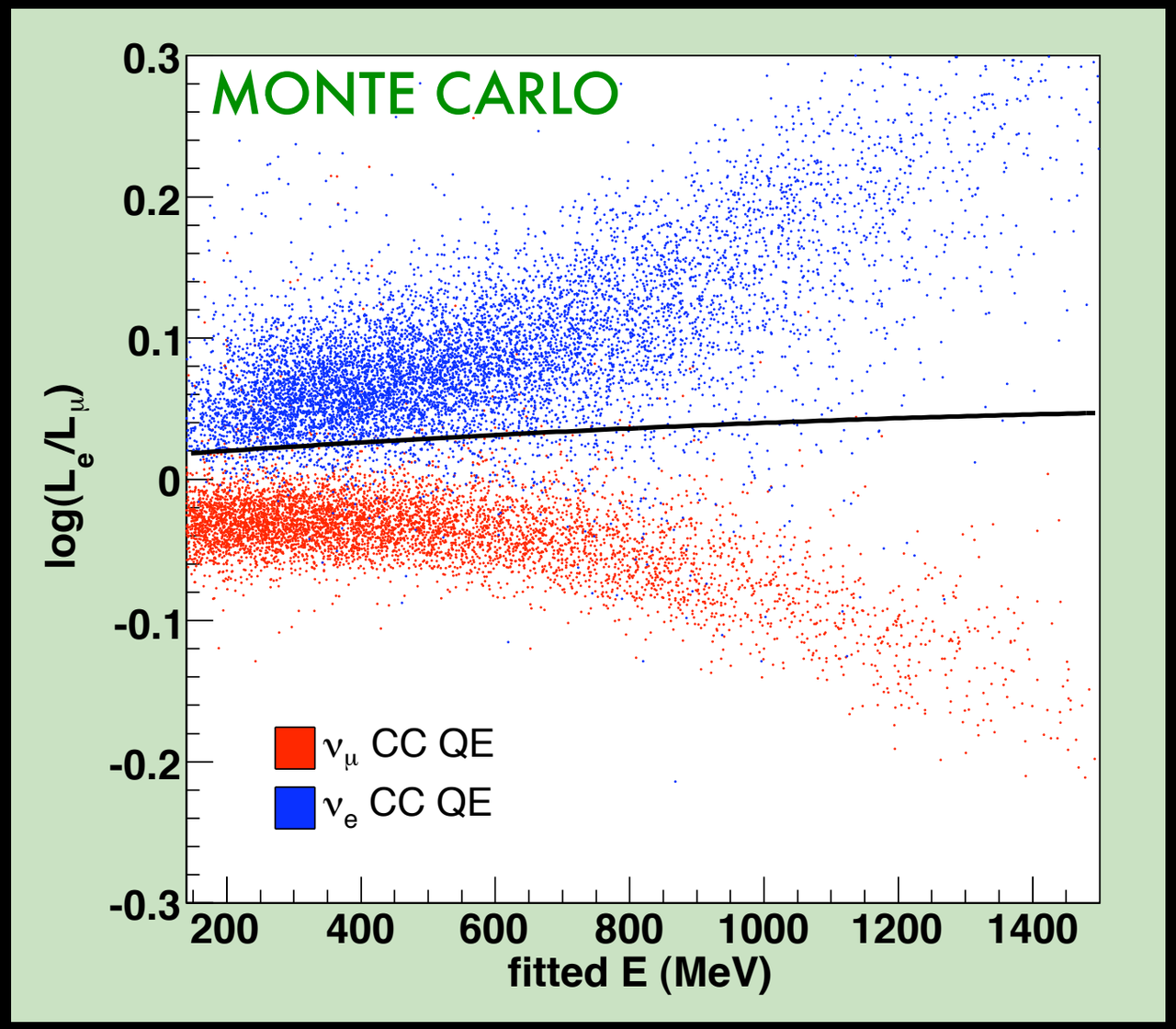
FIT HYPOTHESIS	NUMBER OF PARAMETERS
Single muon	7
Single electron/photon	7
Two photons from common vertex, mass unconstrained	12
Two photons from common vertex, mass constrained to $m(\pi^0)$	11



The Track-based Analysis:
Event Selection

- Start with events that pass "precuts:"
  - Exactly one subevent during spill
  - NVETO < 6 hits
  - NTANK > 200 hits
- Perform all four fits: electron; muon; two-track, with and without π^0 mass constraint
- Fiducial cuts:
  - Radius must be less than 500 cm (calculated from electron fit)
- Make track energy-dependent cuts on likelihood ratios, to reject specific backgrounds in order from easiest to hardest

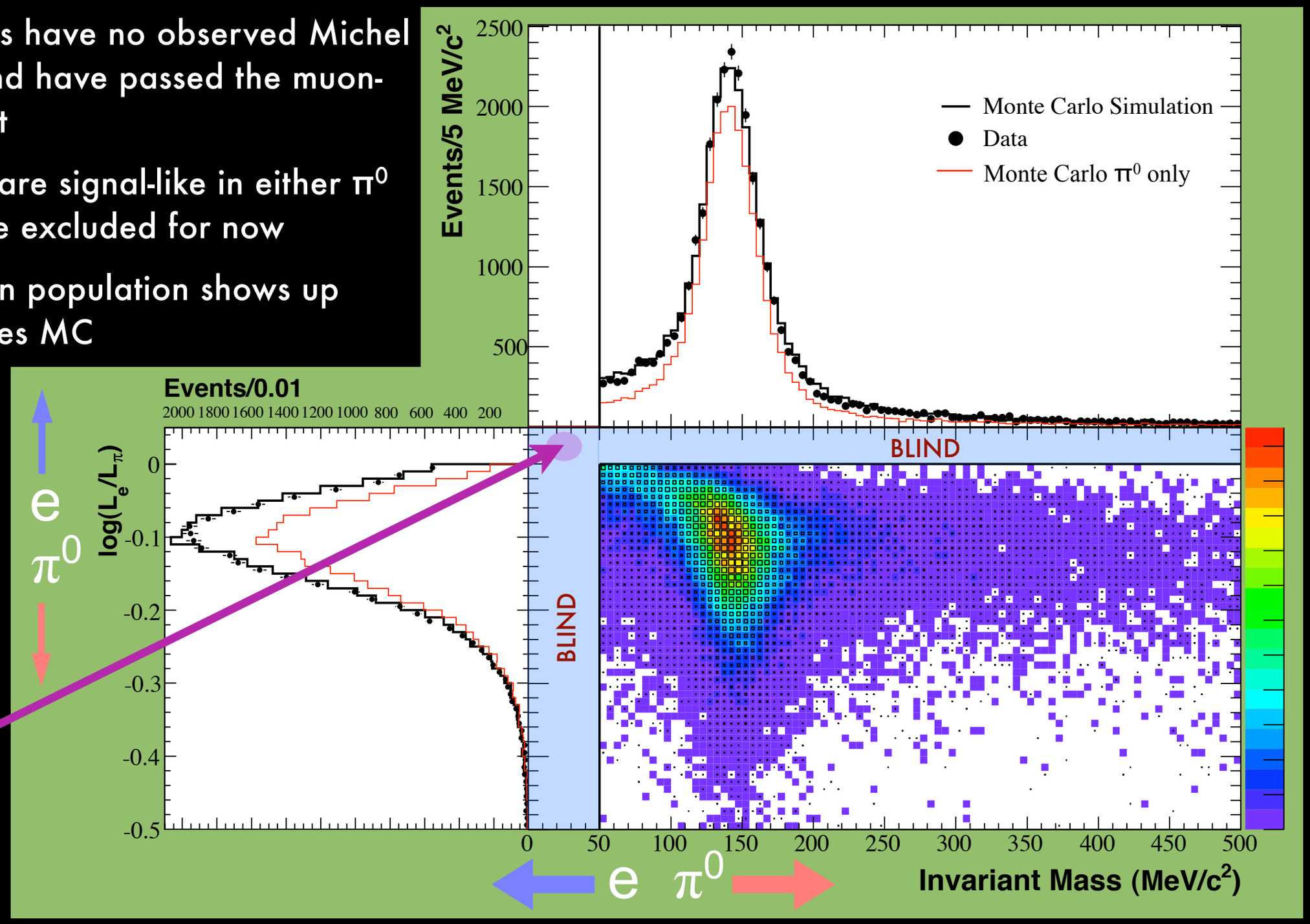
The Track-based Analysis:
Muon rejection



- $\log(L_e/L_\mu)$: compare likelihoods returned by e and μ fits.
- $\log(L_e/L_\mu)>0$ indicates electron hypothesis is favored.
- Analysis cut is parabola whose parameters selected to optimize oscillation sensitivity
- Discrimination easier at higher energy (increasing muon track length)

The Track-based Analysis:
Neutral pion rejection

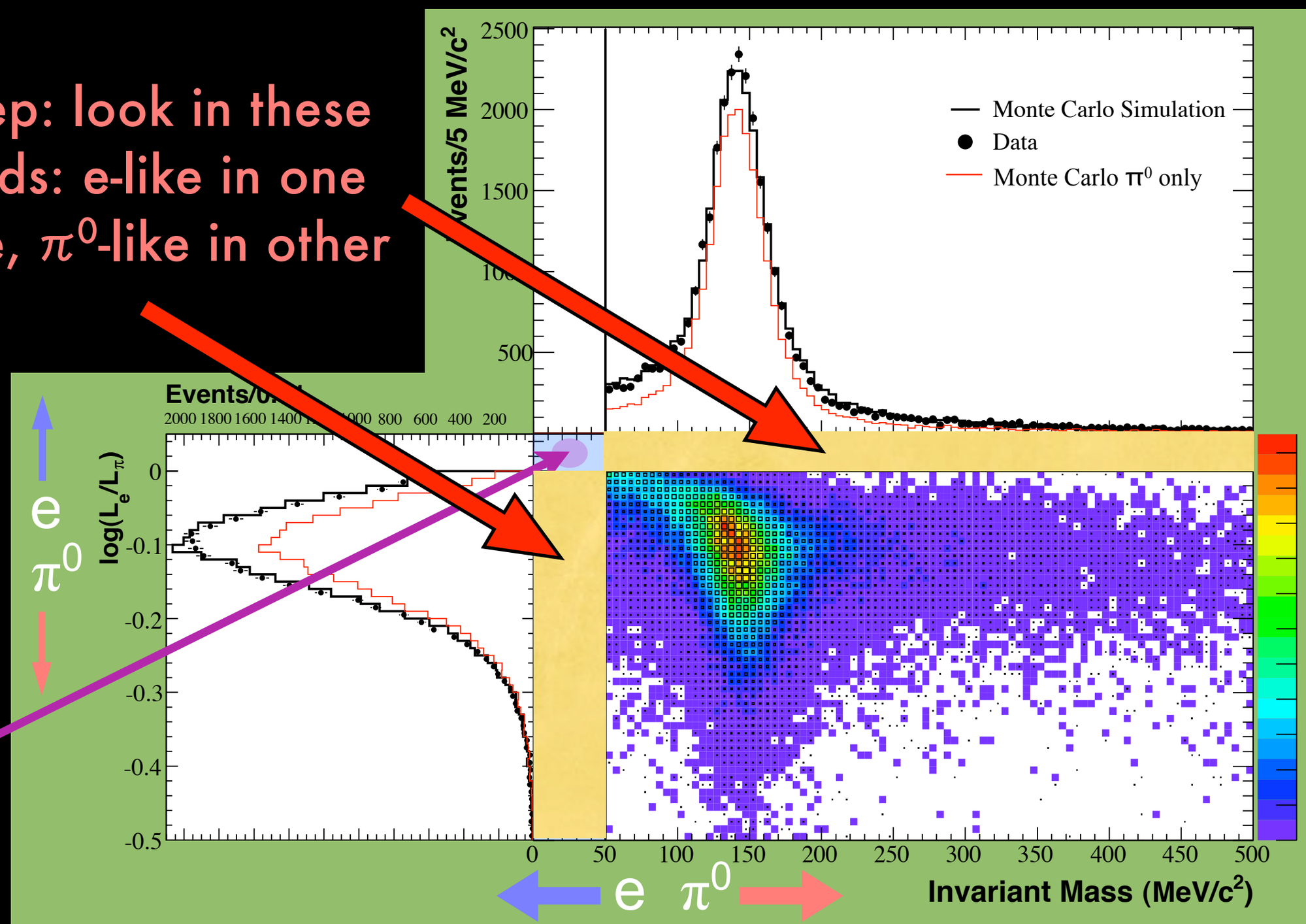
- These events have no observed Michel electron, and have passed the muon-rejection cut
- Events that are signal-like in either π^0 variable are excluded for now
- Neutral pion population shows up well, matches MC



ν_e signal region

The Track-based Analysis:
Neutral pion rejection

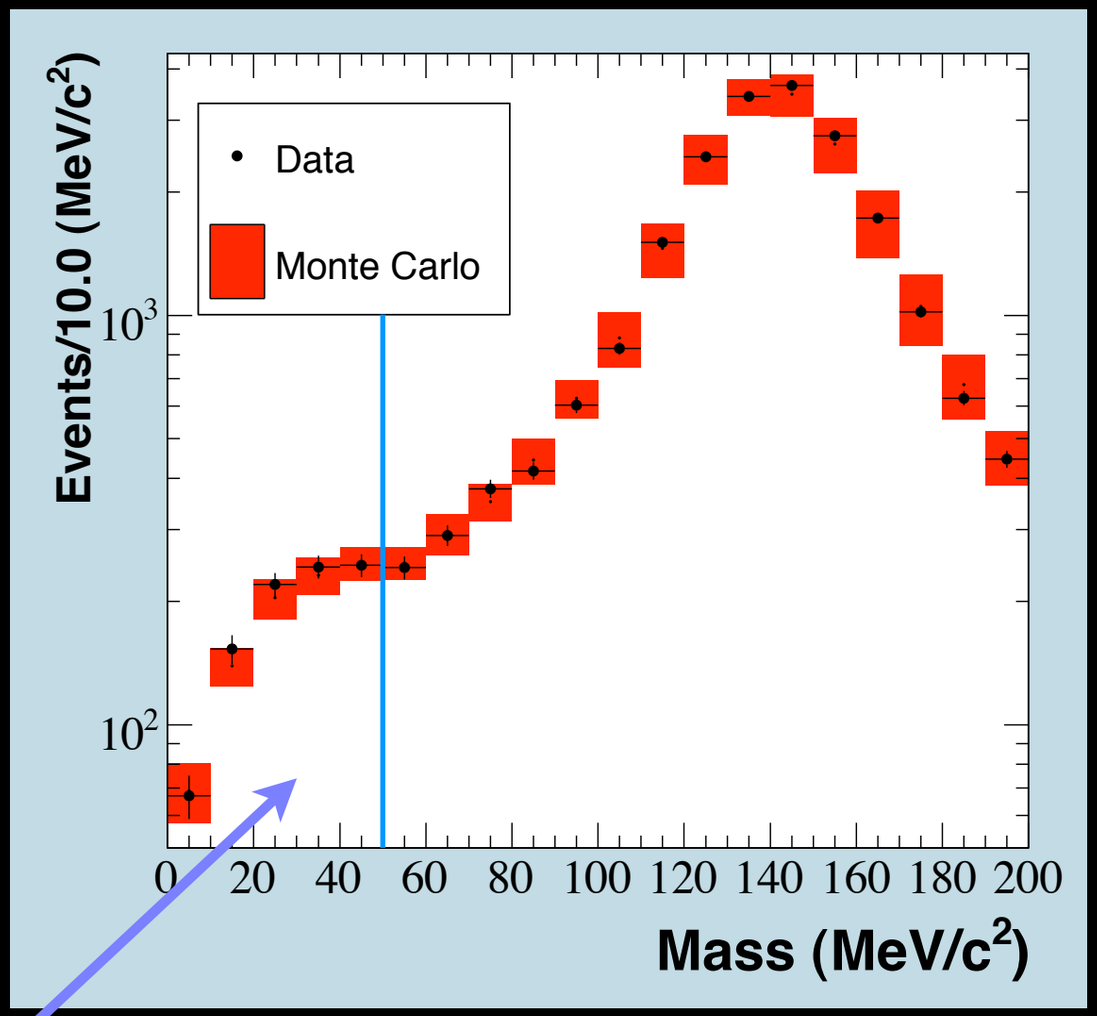
- Next step: look in these sidebands: e-like in one variable, π^0-like in other



ν_e signal region

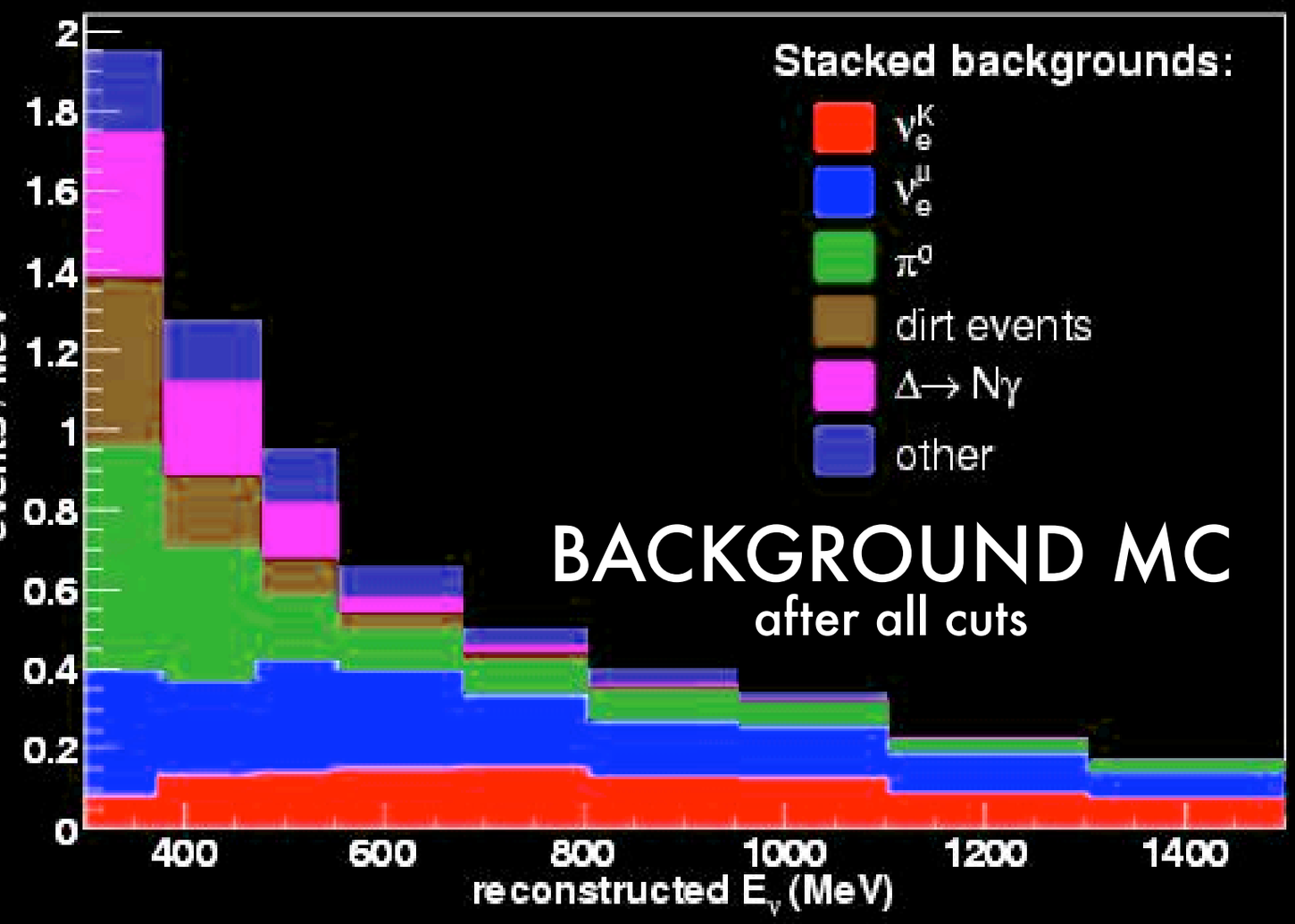
The Track-based Analysis:
Looking in the sidebands

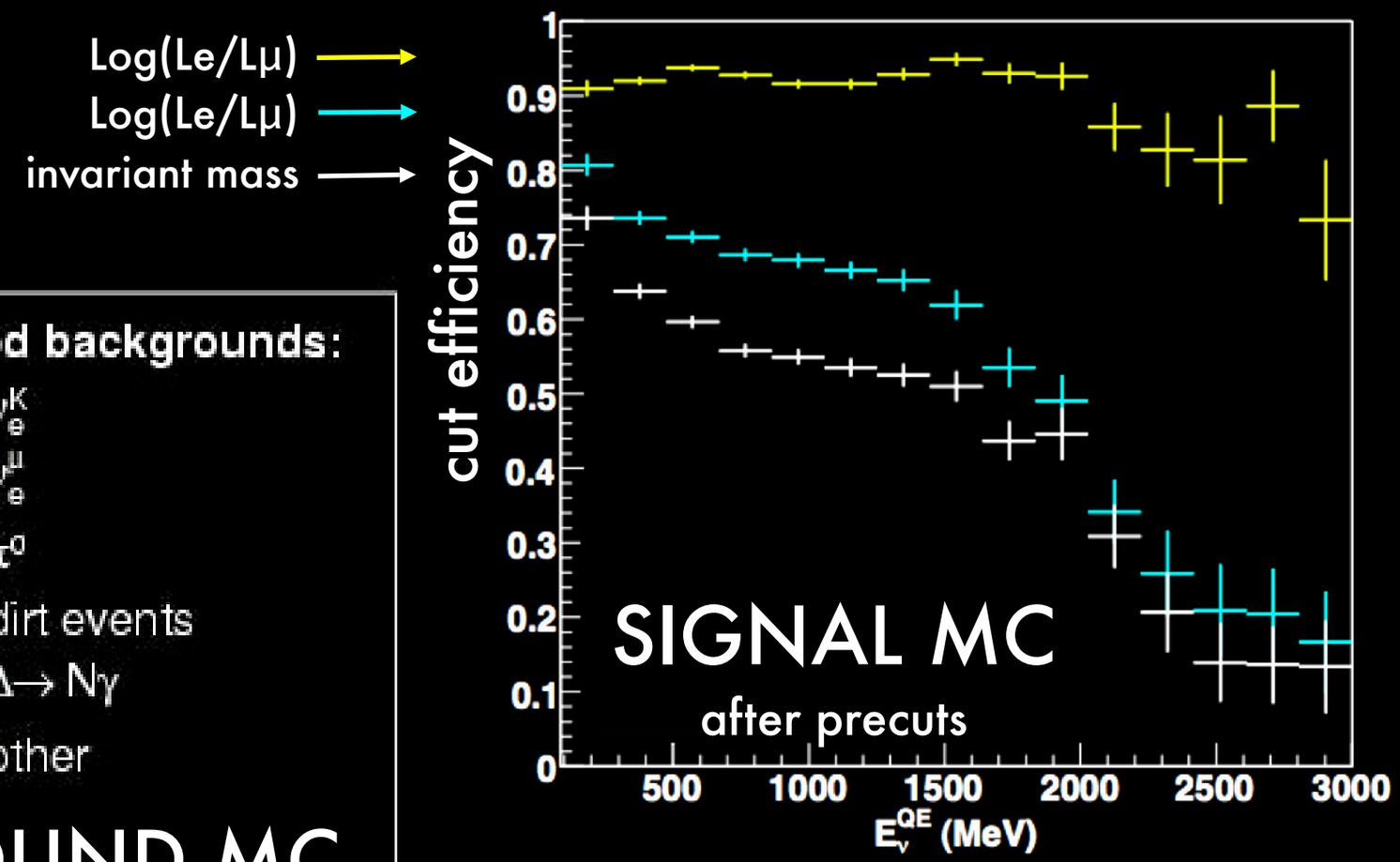
- Look at full mass range for events with $\log(L_e/L_\pi) < 0$
- These are signal-like in mass, but background-like in $\log(L_e/L_\pi)$
- Nice data/MC agreement



sideband

The Track-based Analysis:
Efficiency and backgrounds





x1500 μ rejection

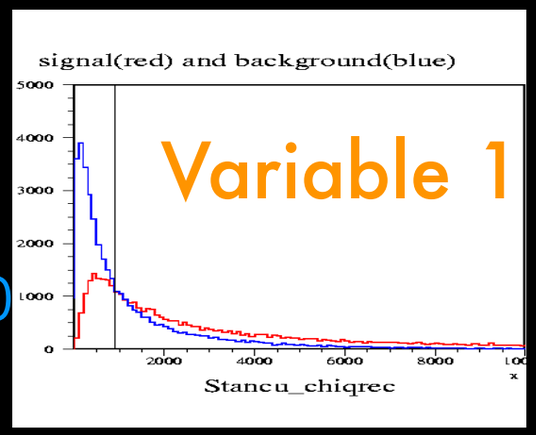
x200 π^0 rejection

Boosted Decision Trees (BDT)

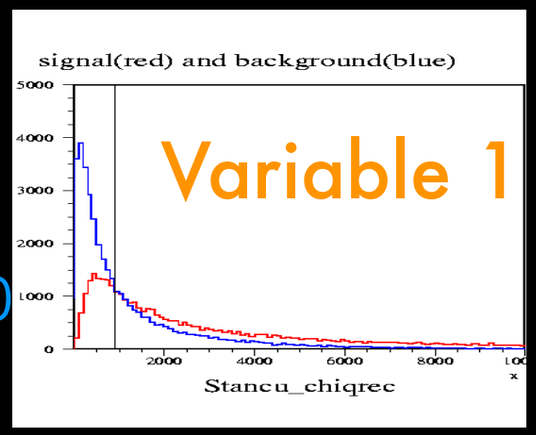
- An algorithm optimized to combine many weakly discriminating variables into one that provides powerful separation
- B. Roe *et al., Nucl. Inst. Meth.* **A543** *577* (2005)
- Idea: Go through all analysis variables and find best variable and value to split a Monte Carlo data set.
  - For each of the two subsets repeat the process
  - Proceeding in this way, a "decision tree" is built, whose final nodes are called leaves

A Decision Tree

N_{signal} 40000 N_{bkgd} 40000



A Decision Tree



N_{signal} 40000 N_{bkgd} 40000

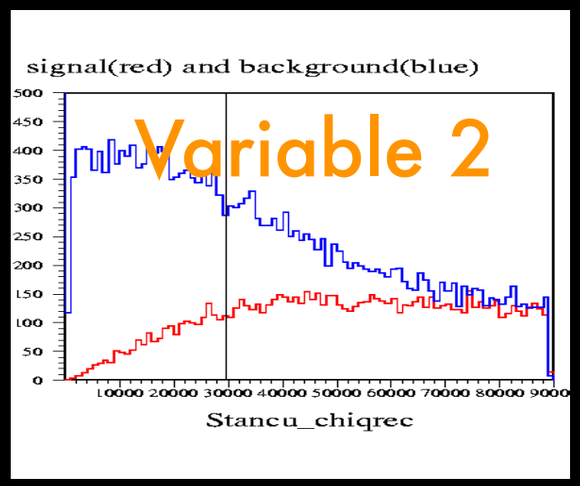
bkgd-like

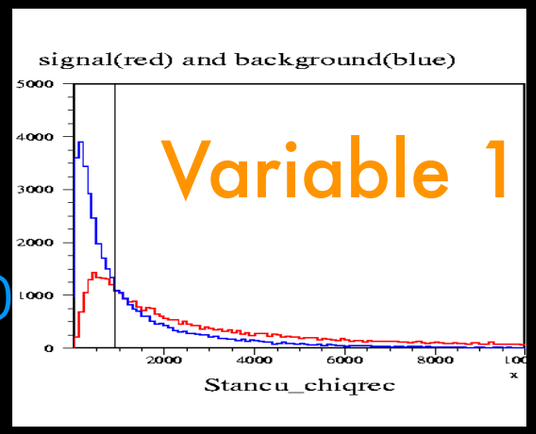
signal-like

9755 23695

30,245 16,305

A Decision Tree





N_{signal} N_{bkgd}

40000 40000

bkgd-like

signal-like

9755 23695

bkgd-like

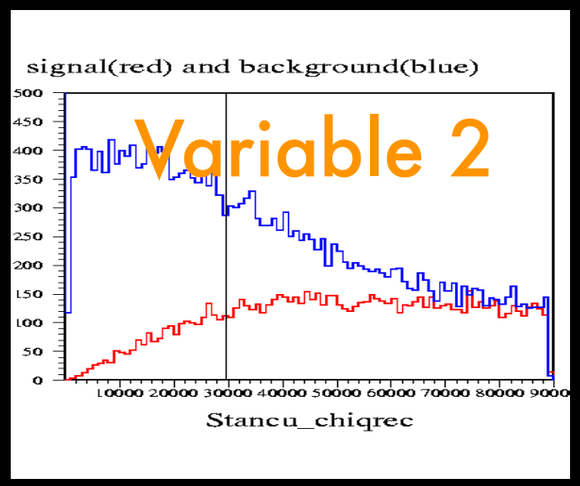
signal-like

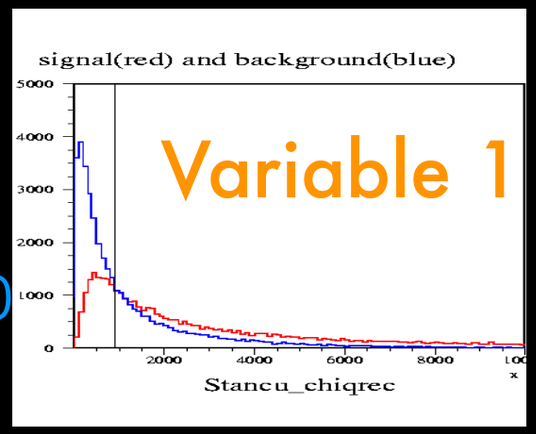
30,245 16,305

1906 11828

7849 11867

A Decision Tree





N_{signal} N_{bkgd}

40000 40000

bkgd-like

signal-like

9755 23695

bkgd-like

signal-like

1906 11828

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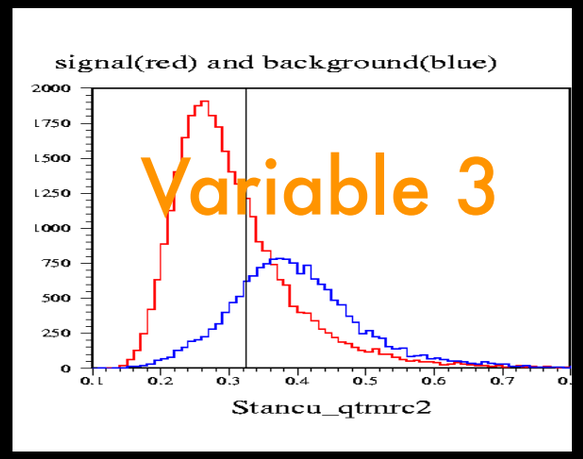
30,245 16,305



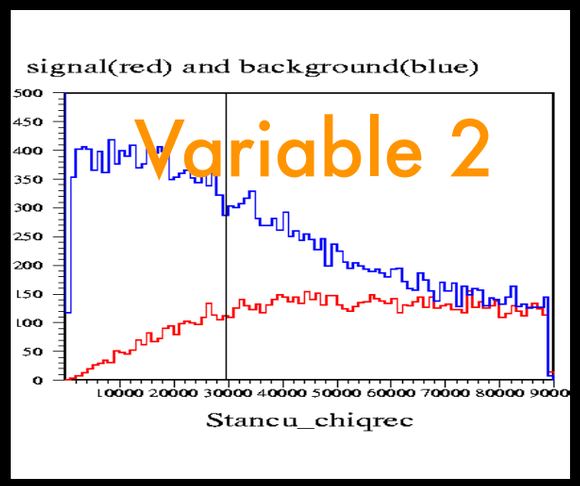
signal-like

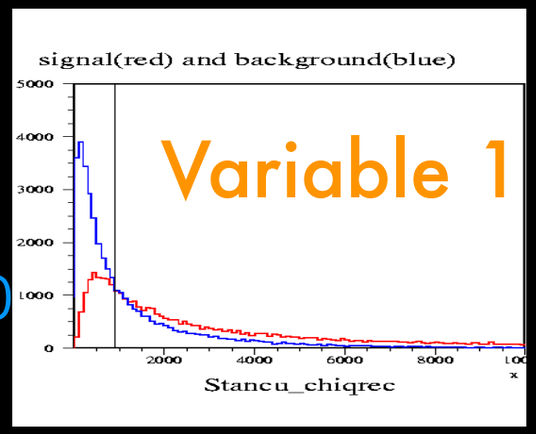
bkgd-like

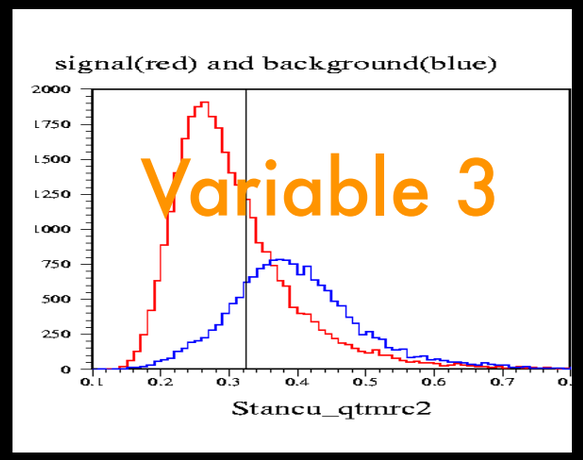
20455 3417

9790 12888

A Decision Tree







N_{signal} 40000 N_{bkgd} 40000

bkgd-like

signal-like

9755 23695

bkgd-like

signal-like

30,245 16,305

1906 11828

7849 11867

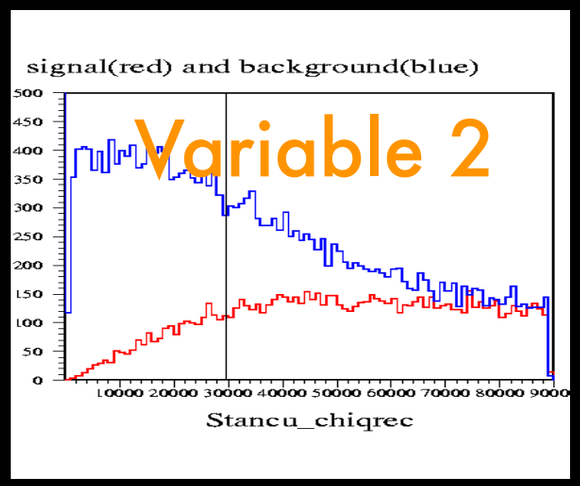
signal-like

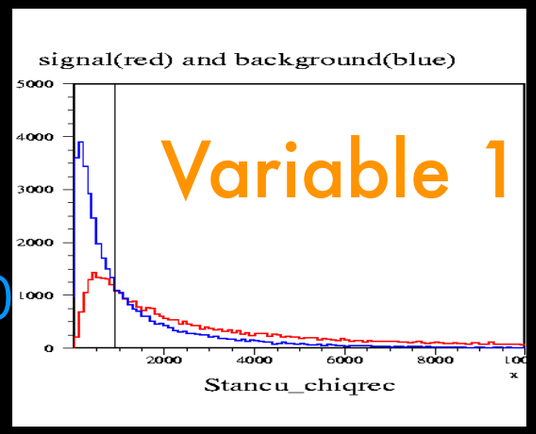
bkgd-like

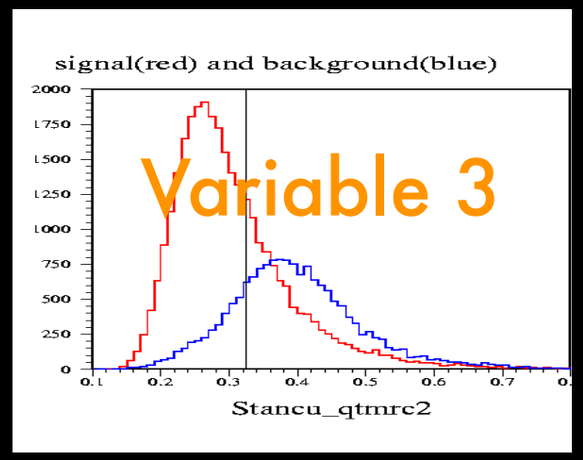
20455 3417

9790 12888

A Decision Tree







N_{signal} 40000 N_{bkgd} 40000

bkgd-like

signal-like

9755 23695

bkgd-like

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30,245 16,305

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bkgd-like

20455 3417

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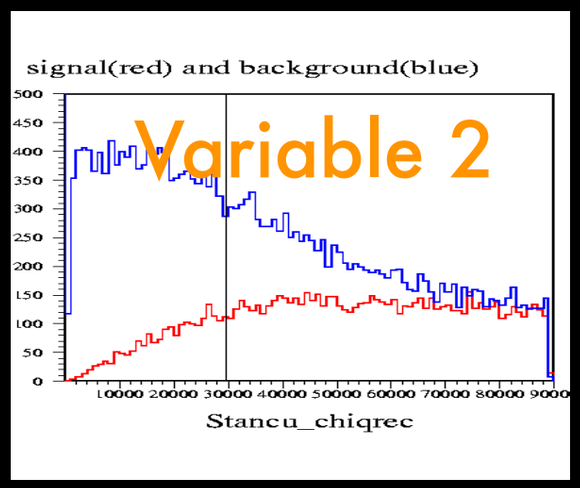
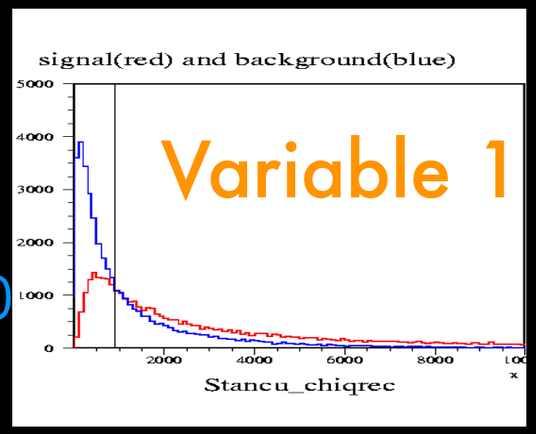
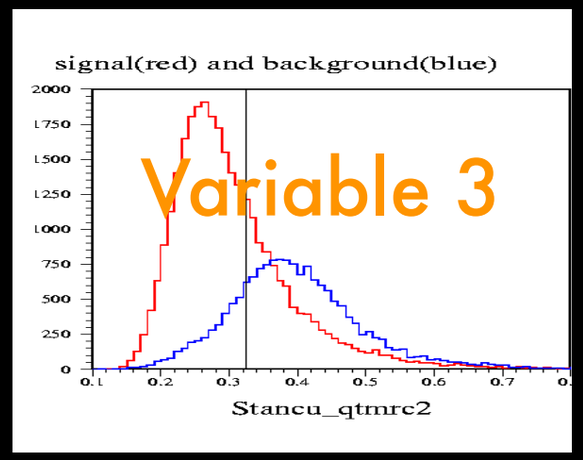
A Decision Tree







N_{signal} 40000 N_{bkgd} 40000

bkgd-like

signal-like

9755 23695

bkgd-like

signal-like

30,245 16,305

1906 11828

7849 11867

signal-like

bkgd-like

20455 3417

9790 12888

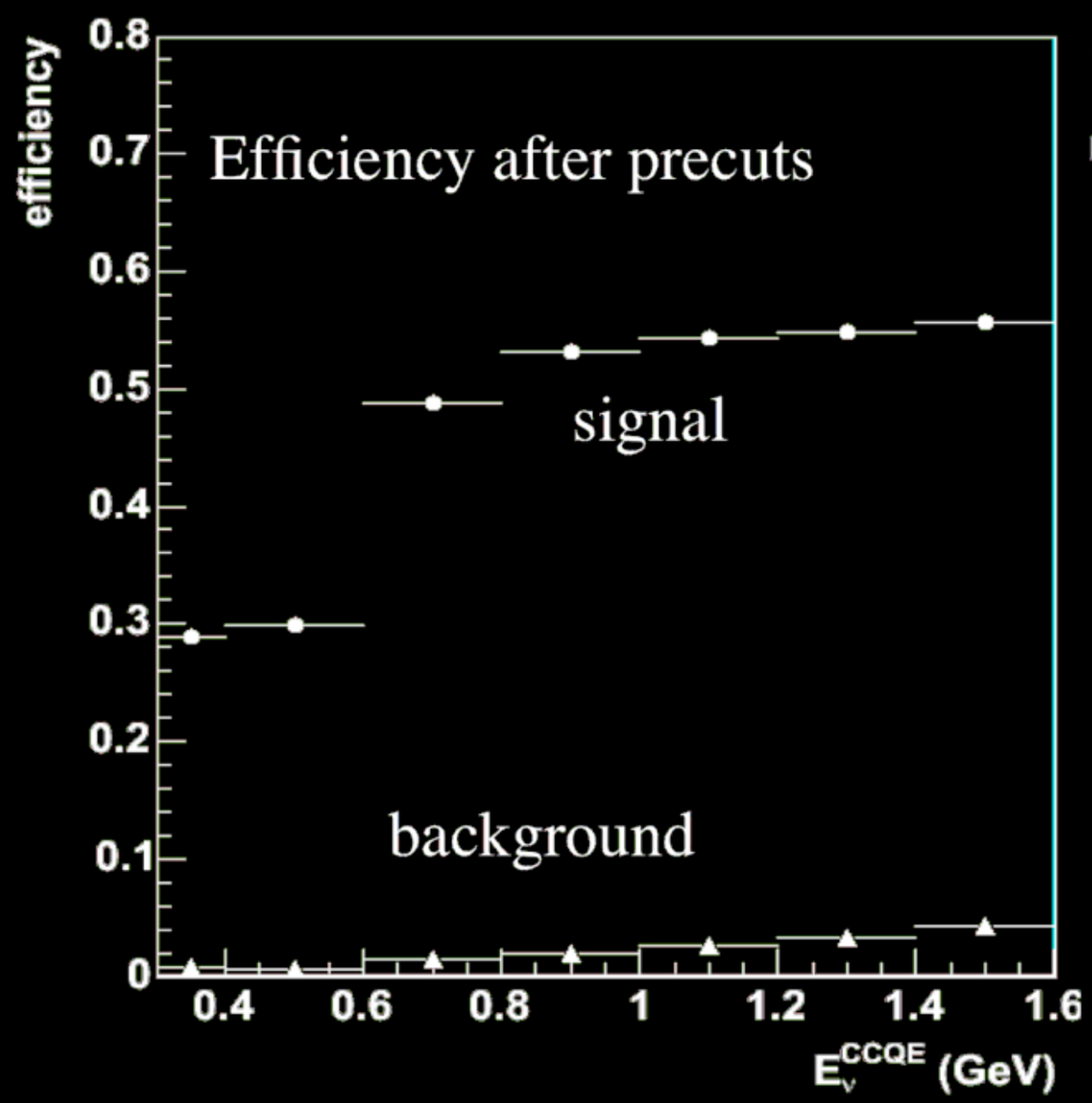
Boosted Decision Trees (BDT)

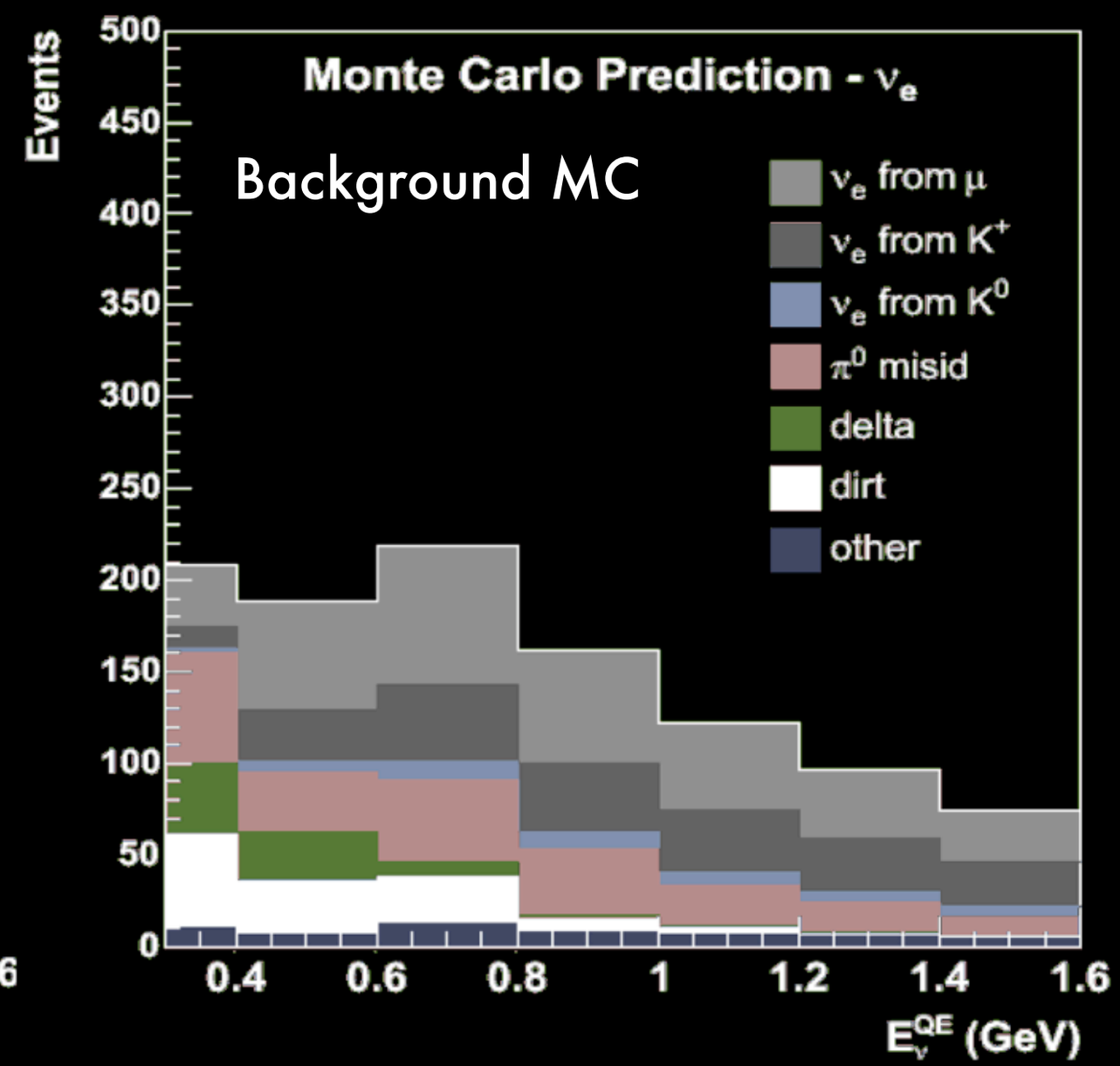
- After the tree is built, additional trees are built with the leaves re-weighted to emphasize the previously misidentified events (since those are hardest to classify). This is "boosting."
- Each data event is sent through every tree, and in each tree is assigned a value:
  - +1 if the event ends up on a signal leaf
  - −1 if the event ends up on a background leaf.
- PID output variable is a sum of event scores from all trees: background at negative values, signal at positive values.

Analysis variables used in BDT:

- Low-level functions of fundamental variables like hit time, charge, etc.
- Examples of analysis variables:
  - Physics reconstruction variables ($\cos\theta_\mu$, vertex radius, ...)
  - Lower-level quantities (charge in theta range, etc)

Efficiency of BDT PID cut





Cross-checks and Systematic Errors

- Constraints from CCQE sample
- Cross-sections
- Optical model
- Error propagation
- Final estimate of errors and backgrounds

Neutrino cross-section errors for oscillation analysis

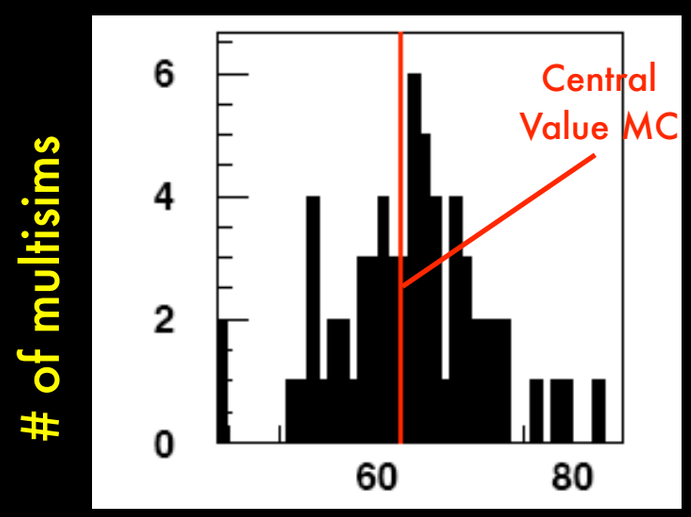
Parameter	Error/Value	Source
M_A^{QE}, E_{lo}^{SF}	6%, 2% (stat+bkg)	MiniBooNE ν_μ CCQE
QE σ norm	10%	MiniBooNE ν_μ CCQE
NC π^0 rate	few % (depends on p_π)	MiniBooNE NC π^0 data
$\Delta \to N\gamma$ rate	$\sim 10\%$	MiniBooNE NC π^0 data, $\Delta \to N\gamma$ BR
E_B, p_F	9 MeV, 30 MeV	External data
σ_{DIS}	25%	External data

These cross-sections and several others will be the subject of upcoming dedicated MiniBooNE analyses.

Optical model uncertainties

- Optical model depends on 39 parameters such as absorption, scintillation, fluorescence behavior.
- Use "Multisim" technique to estimate error: vary the parameters according to a full covariance matrix, and run 70 full GEANT Monte Carlo "experiments" to map the space of detector responses to the parameters.
- Space of output results is used to produce error matrix for the oscillation candidate histogram
- Non-optical model errors evaluated using "mock multisims" generated by reweighting a single high-statistics MC data set
- Example of multisim outputs in a single osc. bin:

70 Optical Model multisims



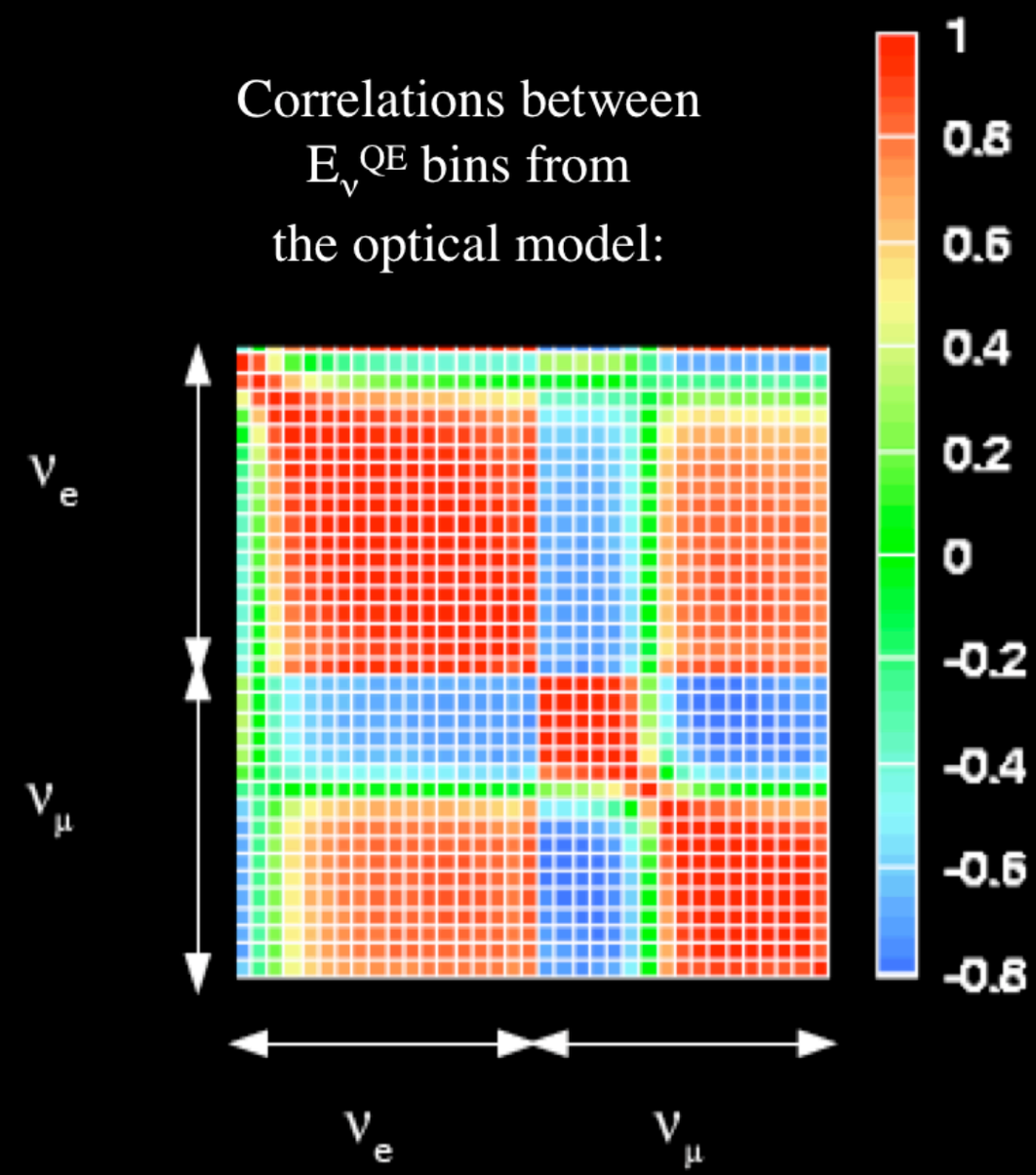
events passing signal cuts in bin $500<E_{\nu}^{QE}<600$ MeV

The error matrix

$$E_{ij} = \frac{1}{M} \sum_{\alpha=1}^{M} \left(N_i^{\alpha} - N_i^{MC}\right) \left(N_j^{\alpha} - N_j^{MC}\right)$$

- N: Number of events passing cuts
- MC: Central value Monte Carlo
- α: index represents a given multisim
- M: total number of multisims
- i, j: E_ν^{QE} bins

- Brings in correlations among the input parameters, and the resulting correlations among the data bins
- Total error matrix is sum from nine sources (optical model, K production, QE cross-section, etc...)
- Track-based: uses error matrix in ν_e E_ν^{QE} only (ν_μ CCQE information comes in reweighting instead of fit)
- Boosting: uses combined error matrix in ν_μ+ν_e E_ν^{QE} bins



Expected background events by source

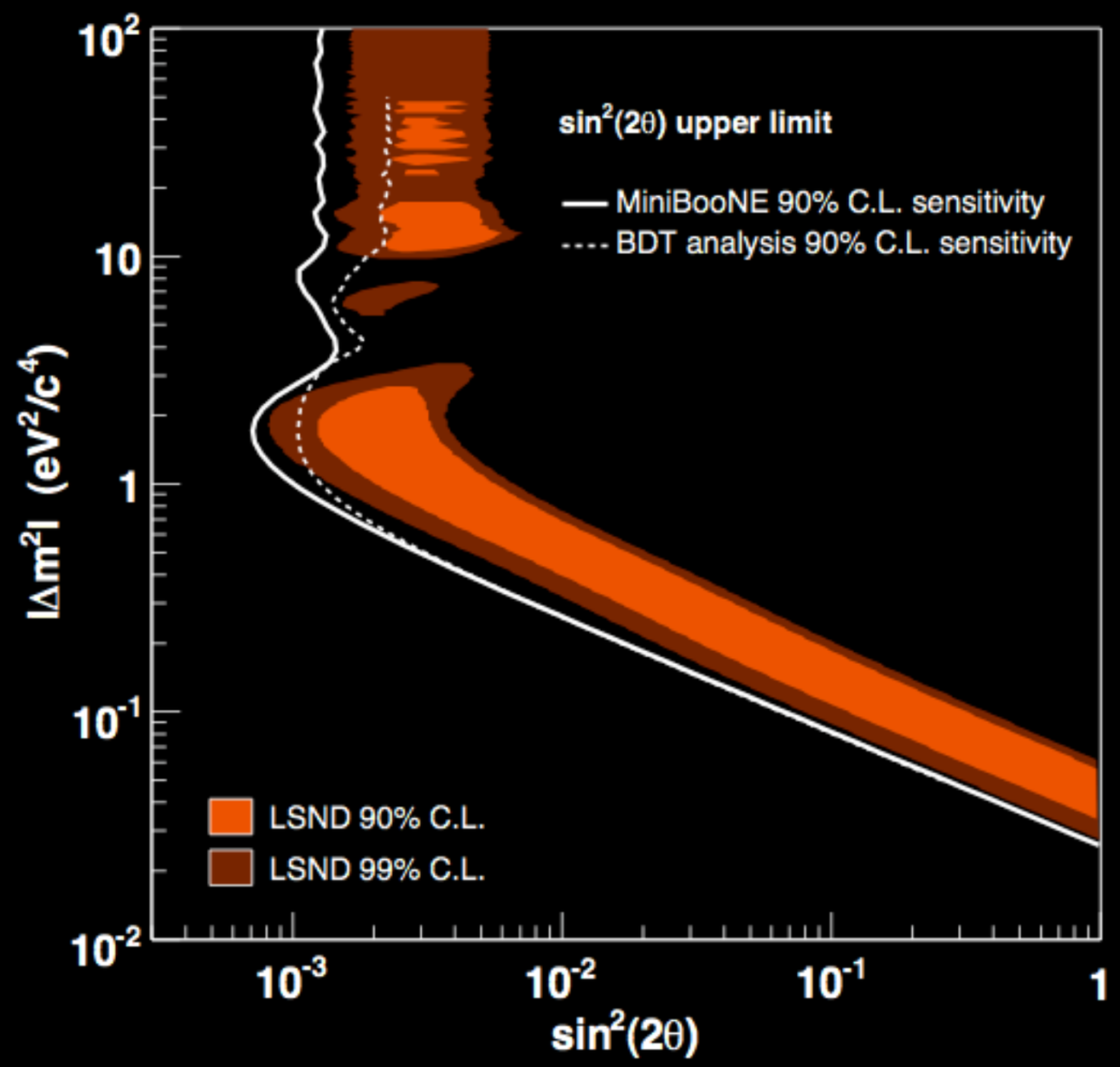
(Track-based analysis)

PROCESS	EVENTS AFTER SELECTION
BEAM UNRELATED	2
DIRT	17
NEUTRAL CURRENT π^0	62
NC RADIATIVE Δ DECAY	20
NC COHERENT AND RADIATIVE	<1
ν_μ QUASIELASTIC	10
NEUTRINO-ELECTRON ELASTIC	7
OTHER ν_μ	13
INTRINSIC ν_e FROM MUONS	132
INTRINSIC ν_e FROM K^+	71
INTRINSIC ν_e FROM K^0	23
INTRINSIC ν_e FROM $\pi^+ \rightarrow e^+ \nu_e$	3
TOTAL BACKGROUND	358 ± 35(syst)
0.26% $\nu_\mu \rightarrow \nu_e$	163

If LSND correct

Oscillation sensitivity

- Track-based algorithm has slightly better sensitivity to 2-neutrino oscillations
- This will therefore be our primary result (decided before unblinding)



Unblinding

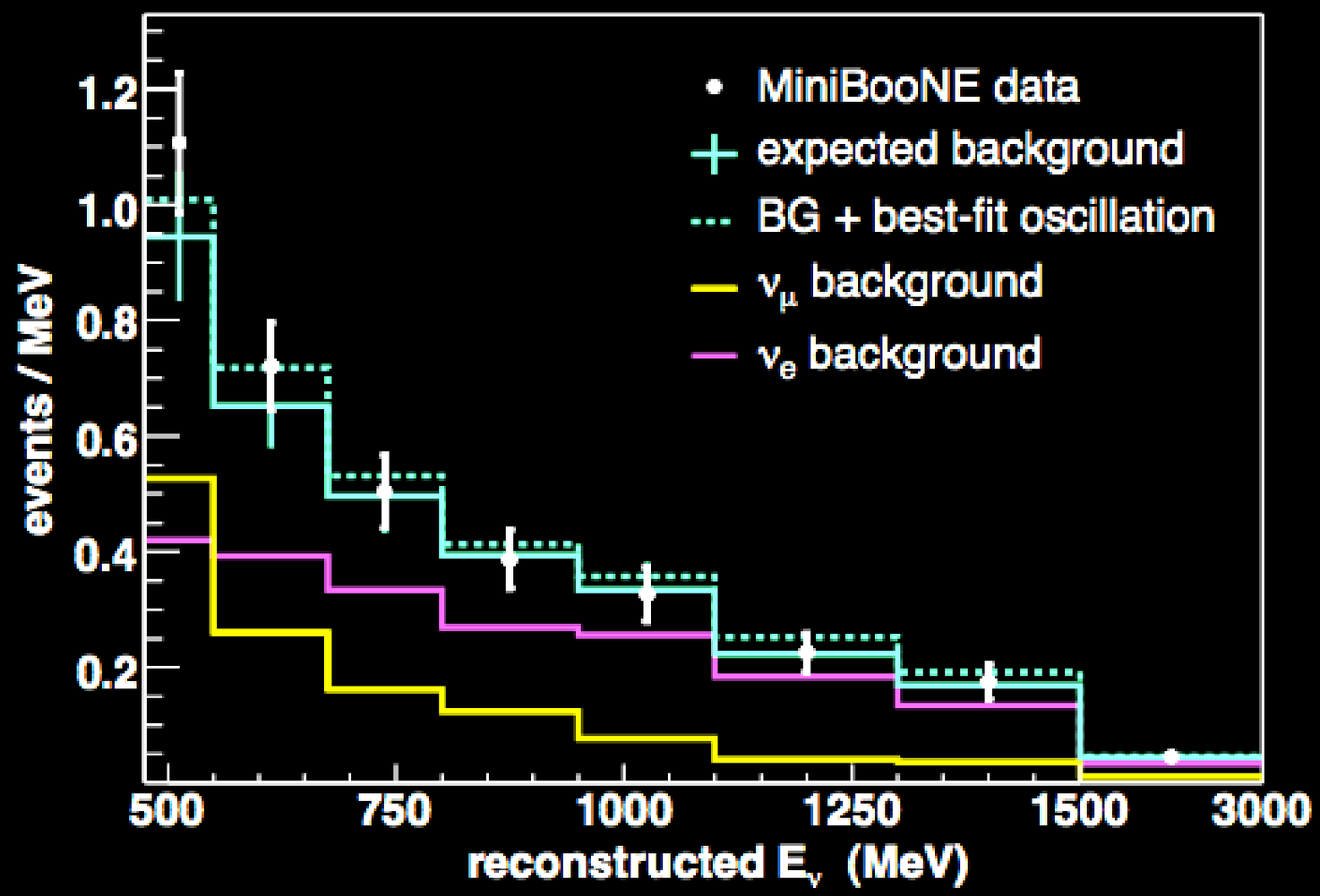
- First step:
  - Perform fit, but do not report results
  - Return χ^2 probability for a set of diagnostic variables, *not* including the quasielastic energy on which the fit is performed, compared to Monte Carlo *with (still hidden) best-fit signal*
    - One distribution poor (1% CL): two background-dominated low-energy bins removed from Track-Based fit
- Second step:
  - Compare these plots directly, with no normalization info
- Third step:
  - Report the χ^2 for the oscillation parameter fit
- Final step:
  - Report the results of the fit and the full energy distribution

Results

- Track based analysis: $475 < E_\nu^{QE} < 1250$ MeV
  - Expected background: 358 ±19 (stat) ± 35 (syst)
  - Observed: 380 Discrepancy: 0.55 σ

NO EVIDENCE FOR OSCILLATIONS IN COUNTING ANALYSIS

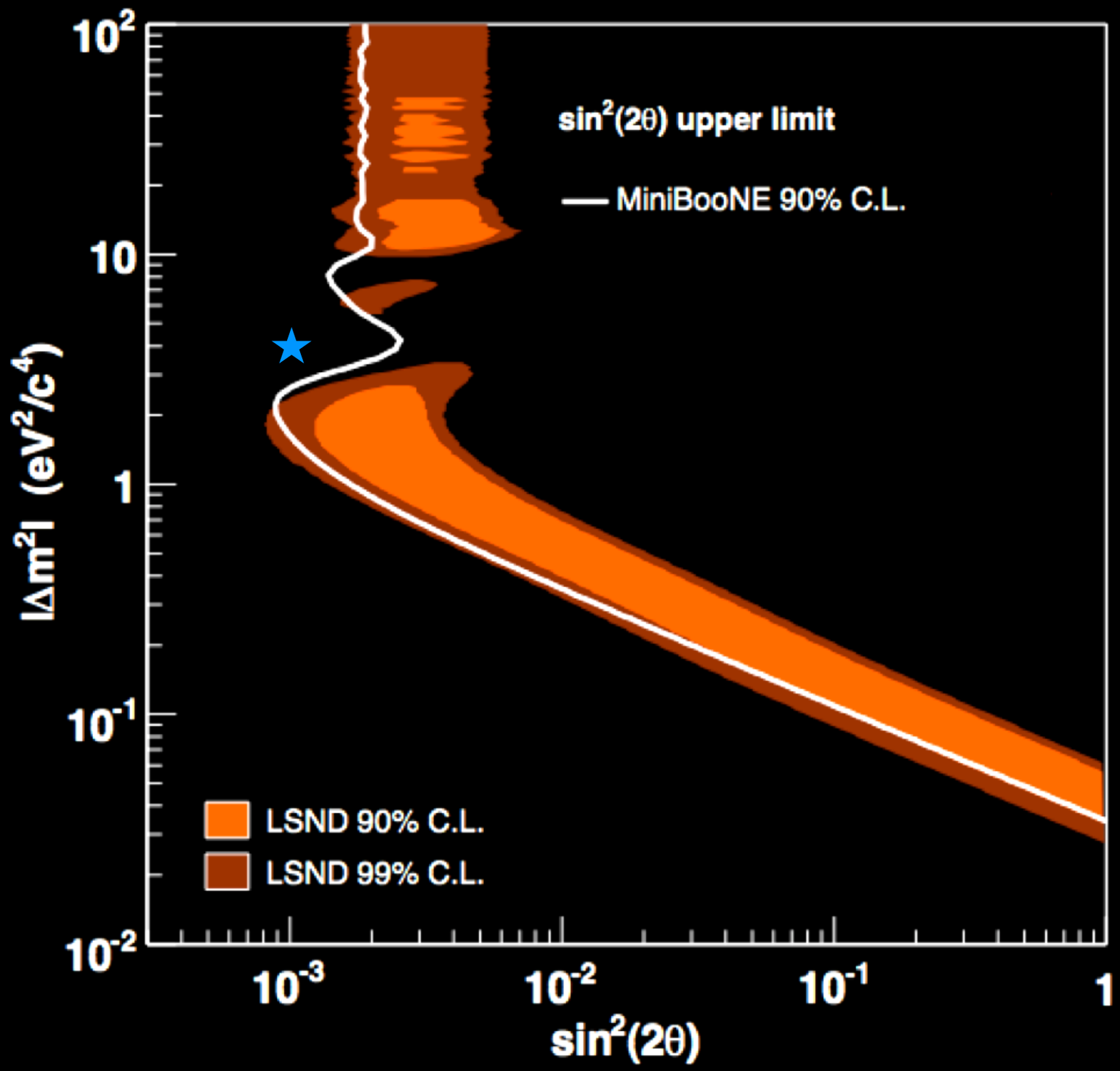
Energy fit and spectrum



- Good agreement with background only (93% CL)
- Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ \mathrm{eV}^2)$, 99% fit CL

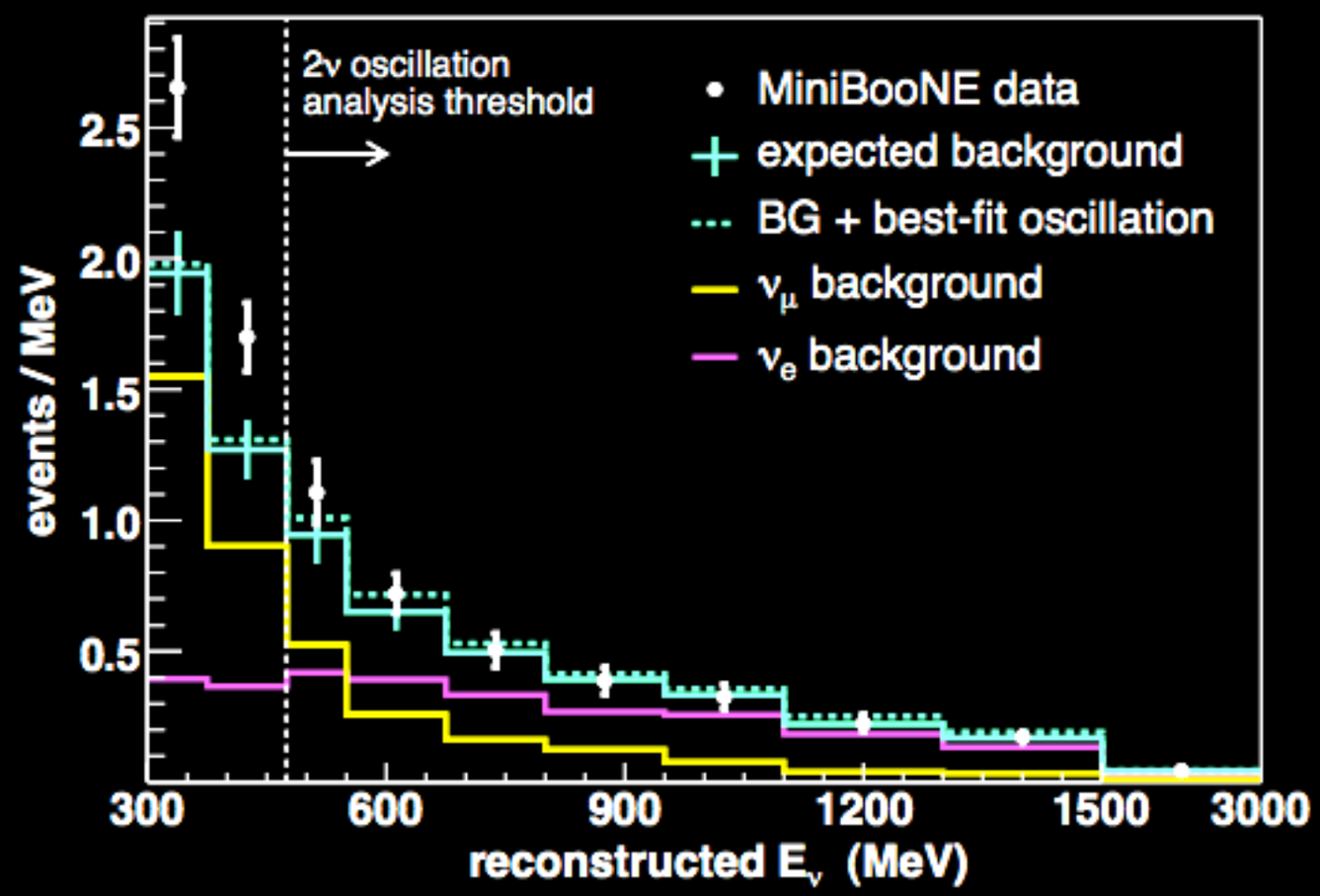
Oscillation Limit

- Single-sided 90% confidence limit
- Best fit (star): $(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ eV^2)$



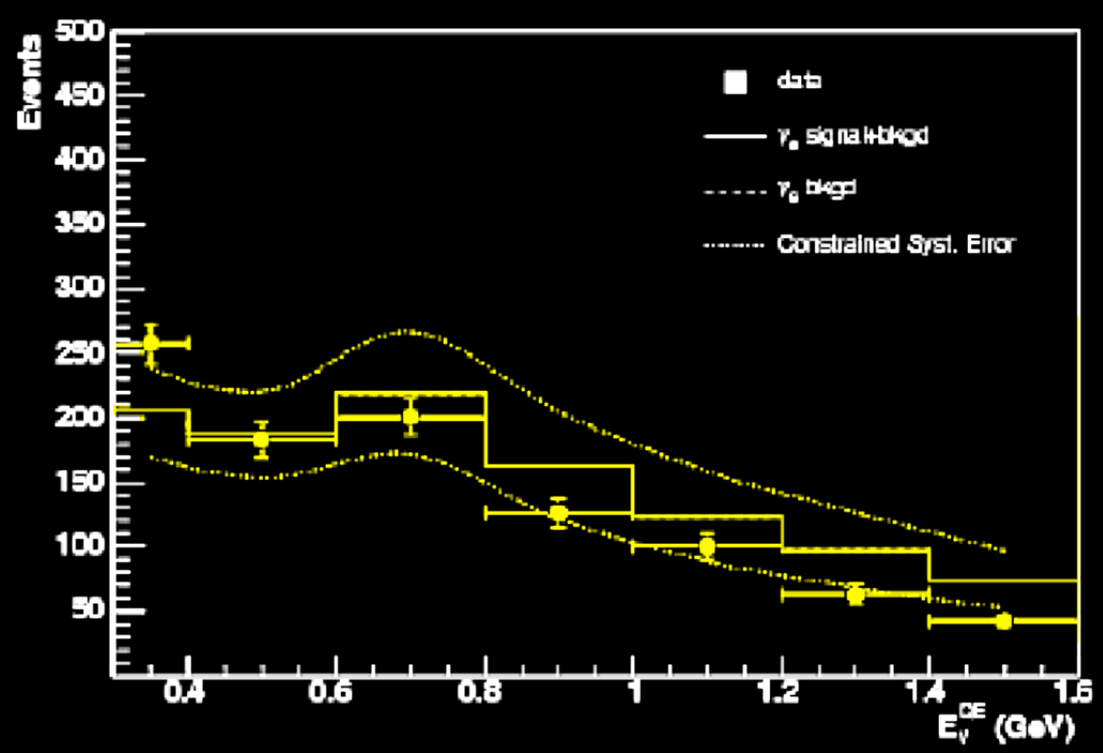
The full spectrum

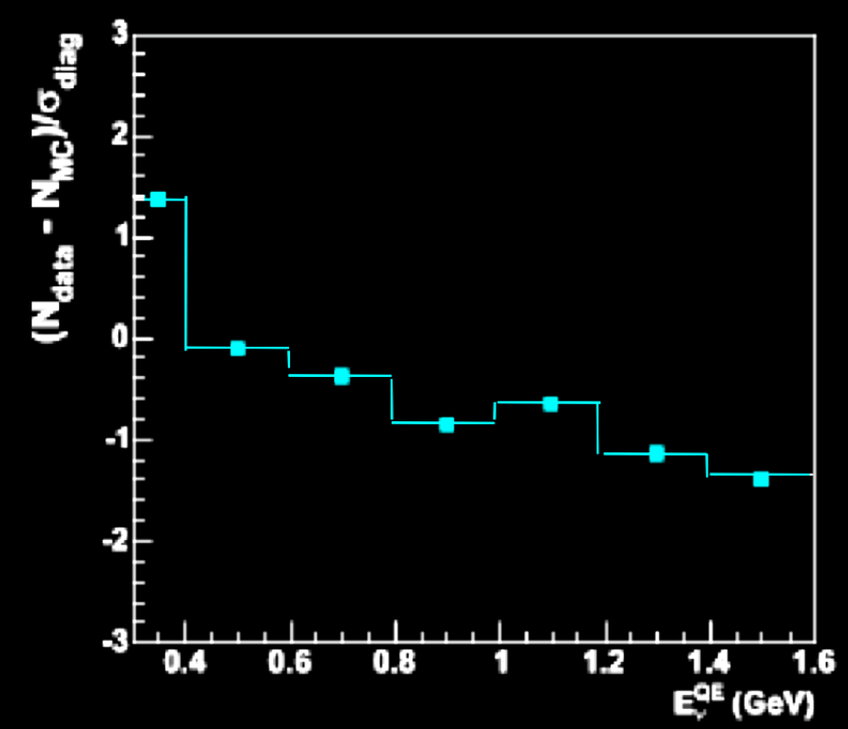
- Extending the plot down to the 300 MeV threshold
- A significant data/MC discrepancy exists in the lower bins



Oscillation fit in Boosting Analysis

- Best fit probability is 62%
- Less significant excess at low energy (but larger normalization error)
- Only diagonal errors shown – fit uses full error matrix
- Counting Experiment: $300<E_\nu^{QE}<1600$ MeV
  - Data: 971 events
  - Background expectation: 1070 ±33 (stat) ±225 (sys) events
  - Overall counting significance: −0.38 σ

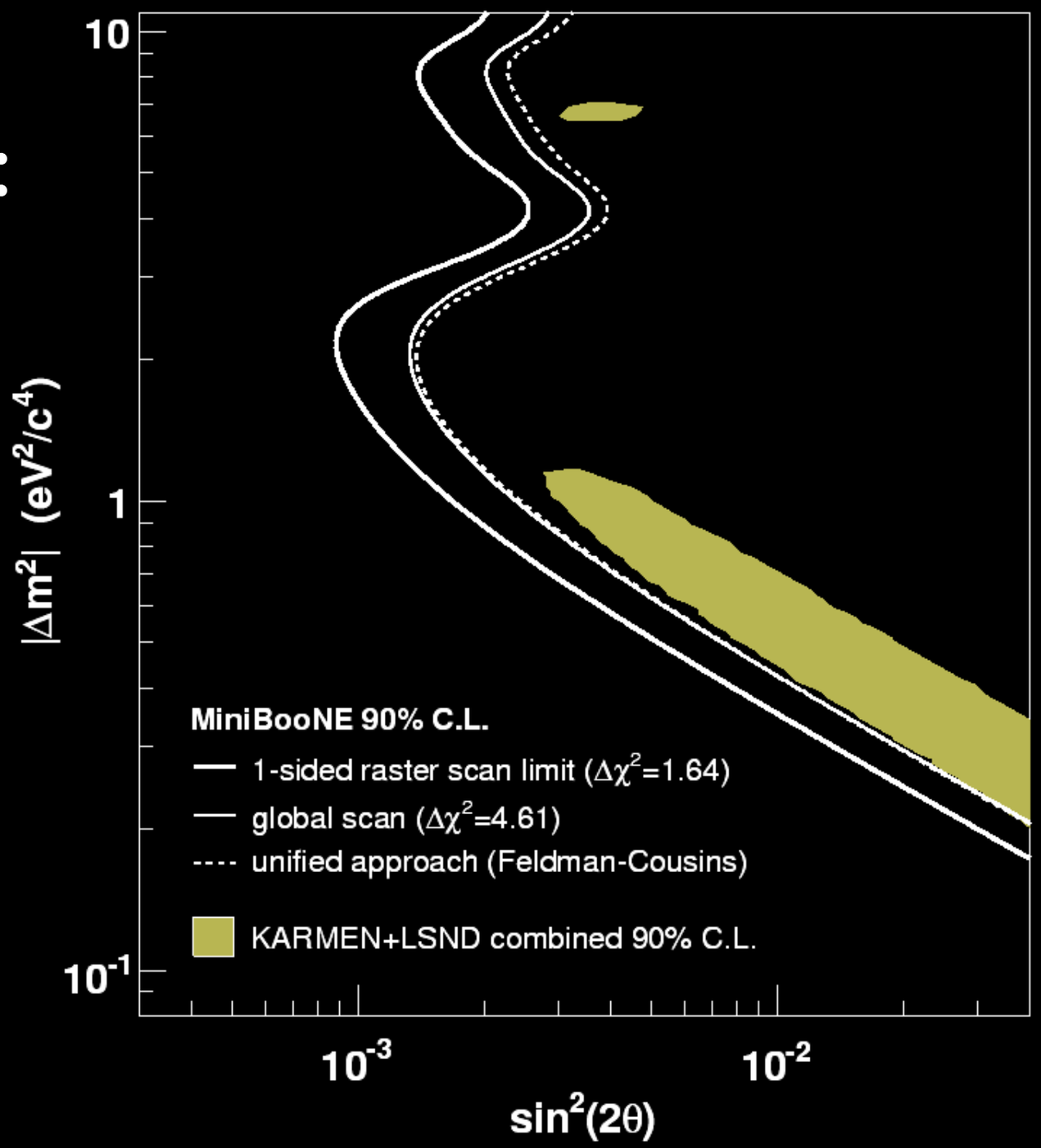




Limit curves under different confidence bound options

Ways to present limits:

- Single sided raster scan (historically common, our default)
- Global χ^2 scan
- Unified approach (Feldman-Cousins)



MiniBooNE vs. LSND: A simple compatibility test

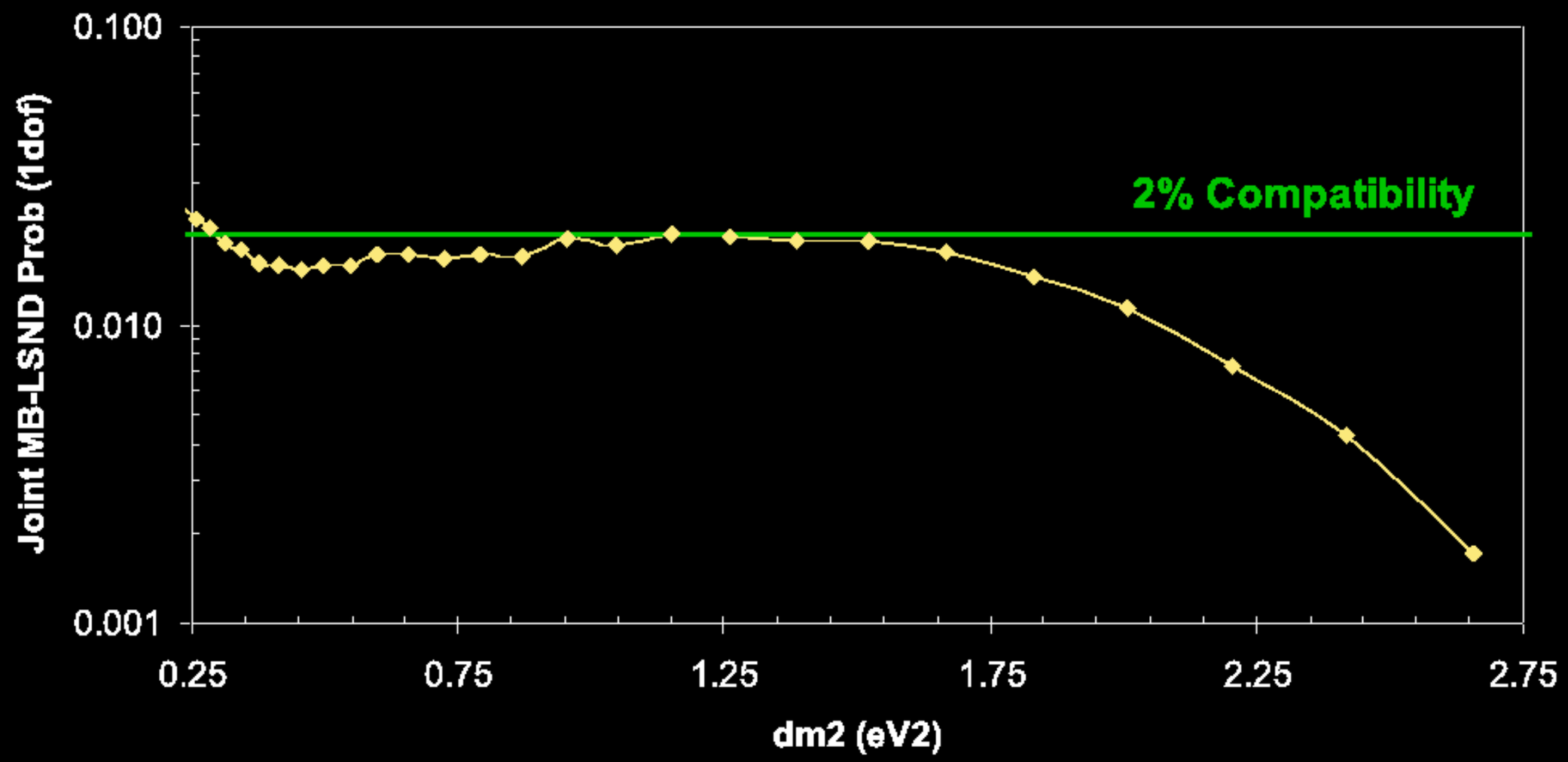
- For each Δm^2, determine the MiniBooNE *(M)* and LSND *(L)* measurement of $\sin^2(2\theta)$:
  - $z_M \pm \sigma_M$, $z_L \pm \sigma_L$ where $z \equiv \sin^2(2\theta)$ and σ_M, σ_L evaluated at that Δm^2
- For each Δm^2, form χ^2 between MiniBooNE and LSND measurement:

$$\chi_0^2 = \frac{z_M - z_0}{\sigma_M^2} + \frac{z_L - z_0}{\sigma_L^2}$$

- *M:* MiniBooNE
- *L:* LSND

- Find z^0 that minimizes χ^2 (weighted average of two measurements of $\sin^2(2\theta)$); this gives χ^2_{min}
- Find probability of χ^2_{min} for 1 dof; this is the joint probability at this Δm^2 if the two experiments are measuring the same thing.

LSND-MiniBooNE compatibility

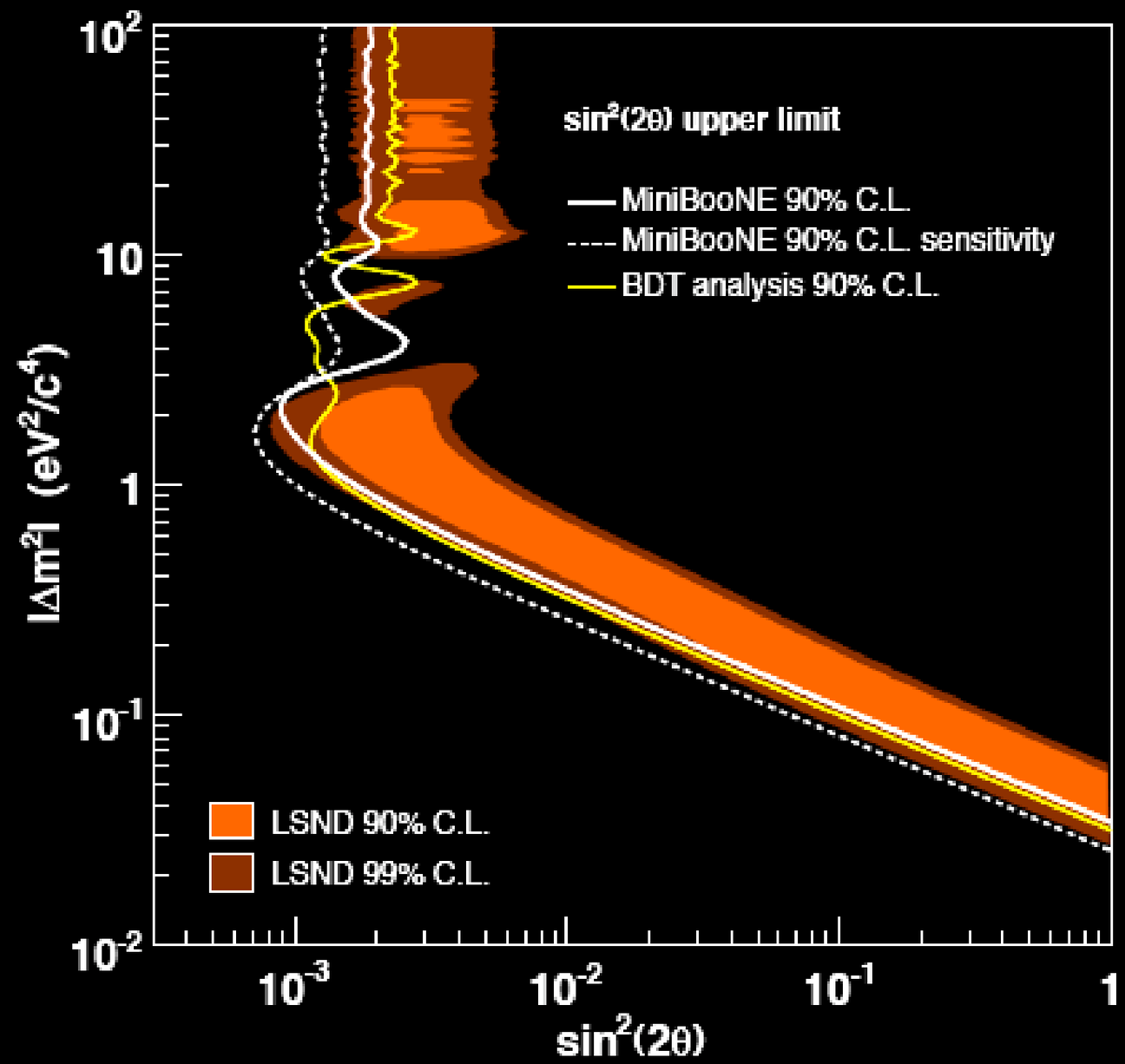


- MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance-only interpretation of LSND at 98% CL

Next Steps

- Further investigation of low-energy excess
  - See next talk
- Further interpretation of oscillation limit
  - Full MiniBooNE+LSND+KARMEN joint analysis
  - Combined track-based and boosting analysis

Conclusions



- MiniBooNE sets a limit on $\nu_\mu \rightarrow \nu_e$ oscillations. We strongly exclude LSND in a CP-conserving two-neutrino model.
- Data show discrepancy vs. background at low energies, but spectrum inconsistent with two-neutrino oscillation.

Ackowledgments

Our thanks to DOE, NSF,
and Fermilab