RESULTS OF THE MiniBooNE NEUTRINO OSCILLATION SEARCH

E. D. Zimmerman

University of Colorado

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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.

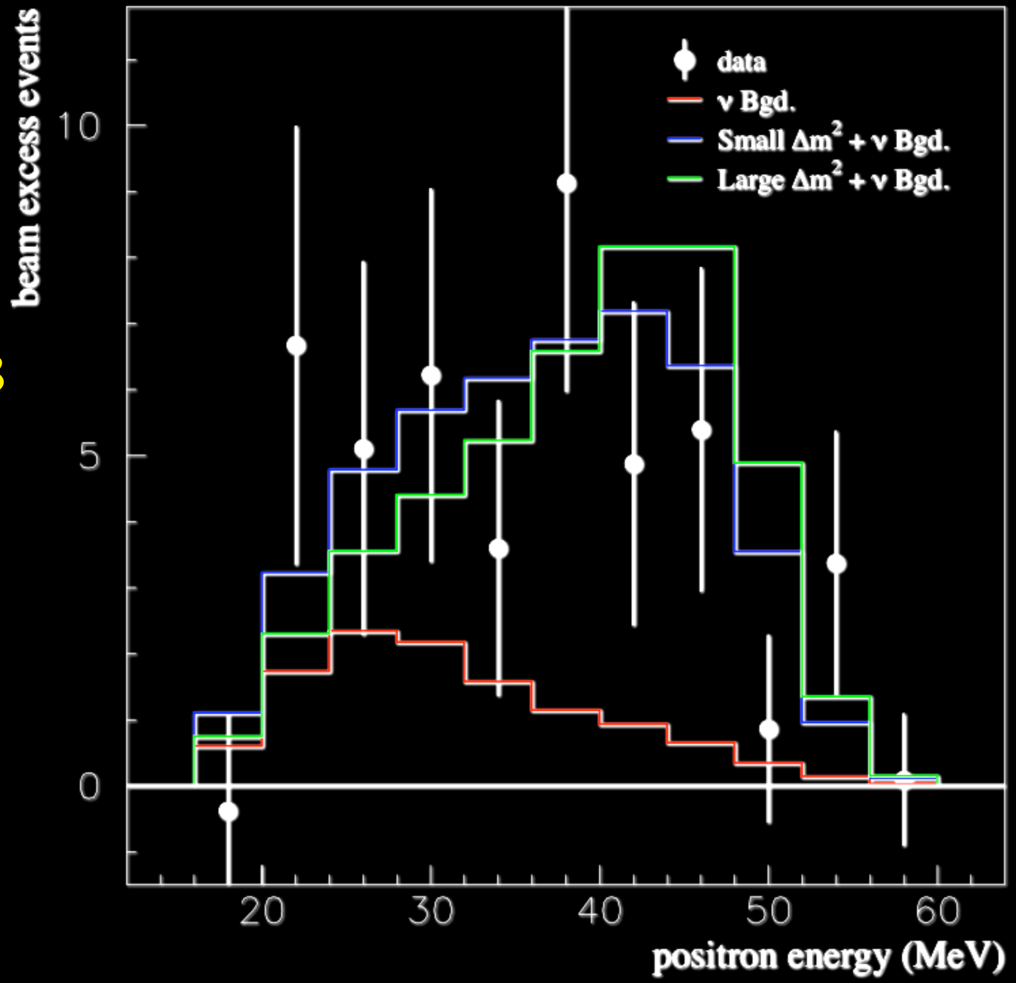
LSND

- 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:

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

- 4 standard dev. excess above background.
- Oscillation probability:

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

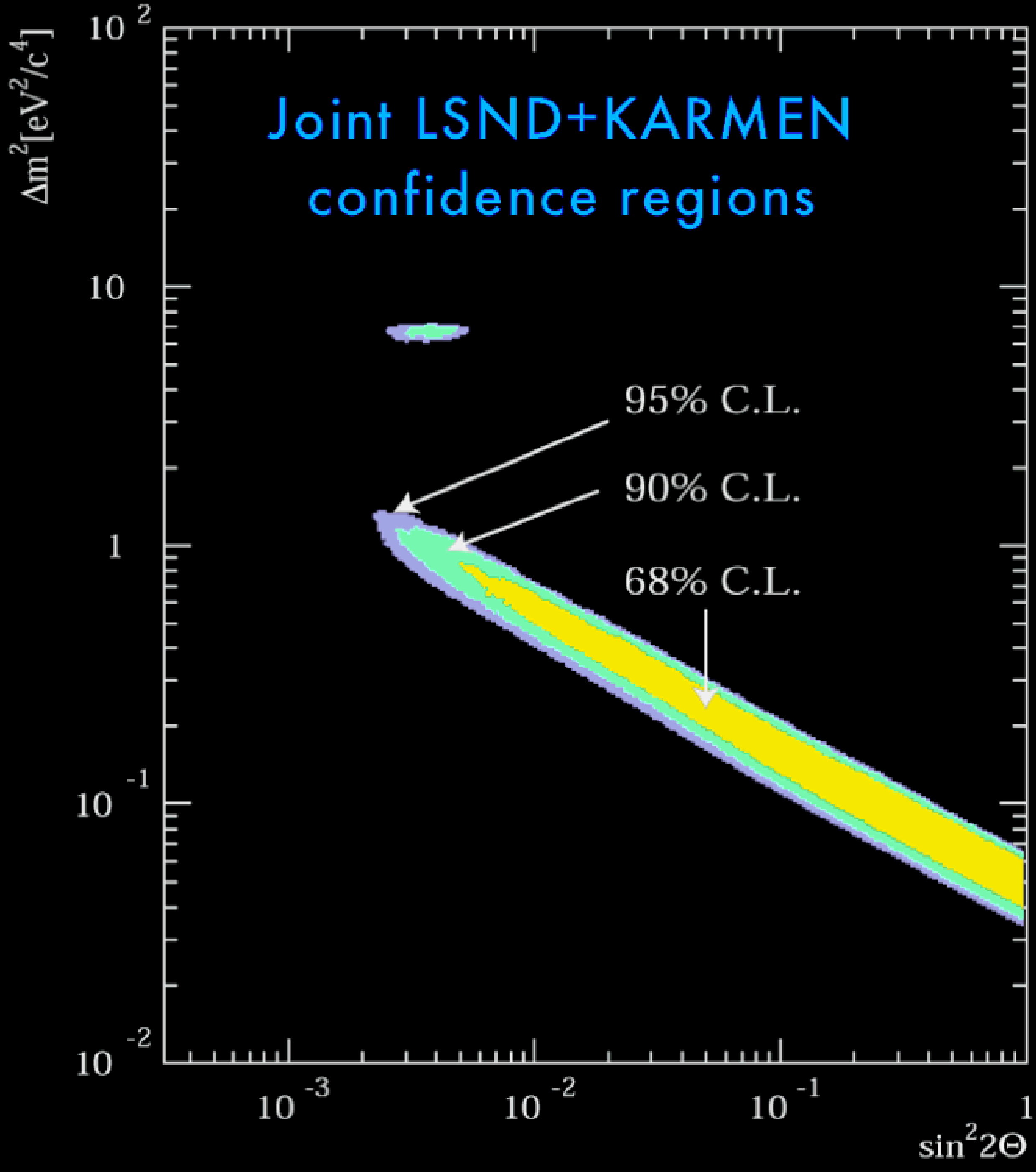


LSND Oscillation allowed region

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:

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

- 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

Y.Liu, D. Perevalov, I.Stancu
University of Alabama

S.Koutsoliotas
Bucknell University

R.A.Johnson, J.L.Raaf
University of Cincinnati

T.Hart, R.H.Nelson, M. Tzanov, M.Wilking,
E.D.Zimmerman
University of Colorado

A.A.Aguilar-Arevalo, L.Bugel, L.Coney, J.M.Conrad,
Z.Djurcic, J.Monroe, D.Schmitz, M.H.Shaevitz, M.Sorel,
G.P.Zeller
Columbia University

D.Smith
Embry Riddle Aeronautical University

S.J.Brice, B.C.Brown, D.A.Finley, R.Ford, F.G.Garcia, P.Kasper,
T.Kobilarcik, I.Kourbanis, A.Malensek, W.Marsh, P.Martin,
F.Mills, C.Moore, E.Prebys, A.D.Russell, P.Spentzouris, R.Stefanski
Fermi National Accelerator Laboratory

D.Cox, T.Katori, H.Meyer, C.C.Polly, R.Tayloe
Indiana University

G.T.Garvey, J.A.Green, C.Green, W.C.Louis, G.McGregor,
G.B.Mills, H.Ray, V.Sandberg, R.Schirato, R.Van de Water,
D.H.White
Los Alamos National Laboratory

R.Imlay, W.Metcalf, S.Ouedraogo, M.Sung, M.O.Wascko
Louisiana State University

J.Cao, Y.Liu, B.P.Roe, H.J.Yang
University of Michigan

A.O.Bazarko, P.D.Meyers, R.B.Patterson, F.C.Shoemaker,
H.A.Tanaka
Princeton University

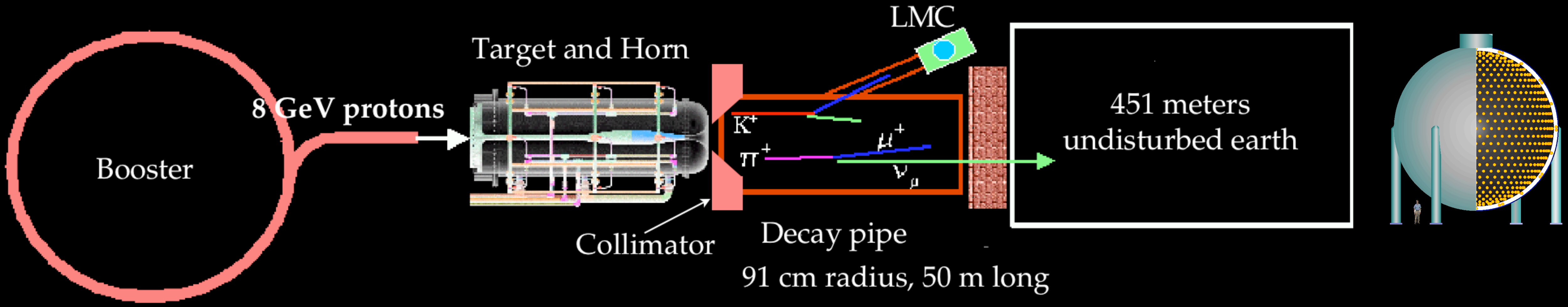
P.Nienaber
St. Mary's University of Minnesota

J. M. Link
Virginia Polytechnic Institute

E.Hawker
Western Illinois University

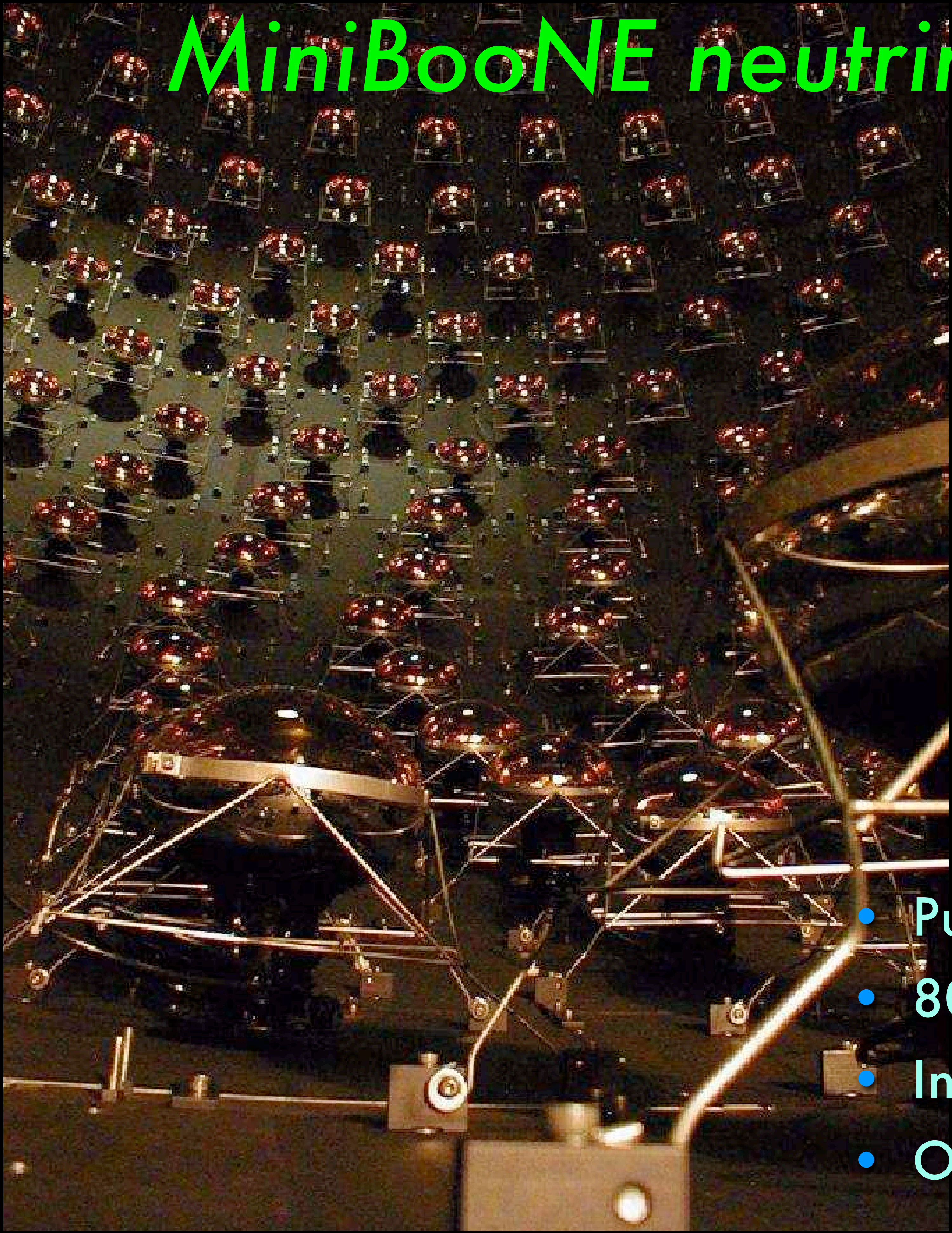
A.Curioni, B.T.Fleming
Yale University

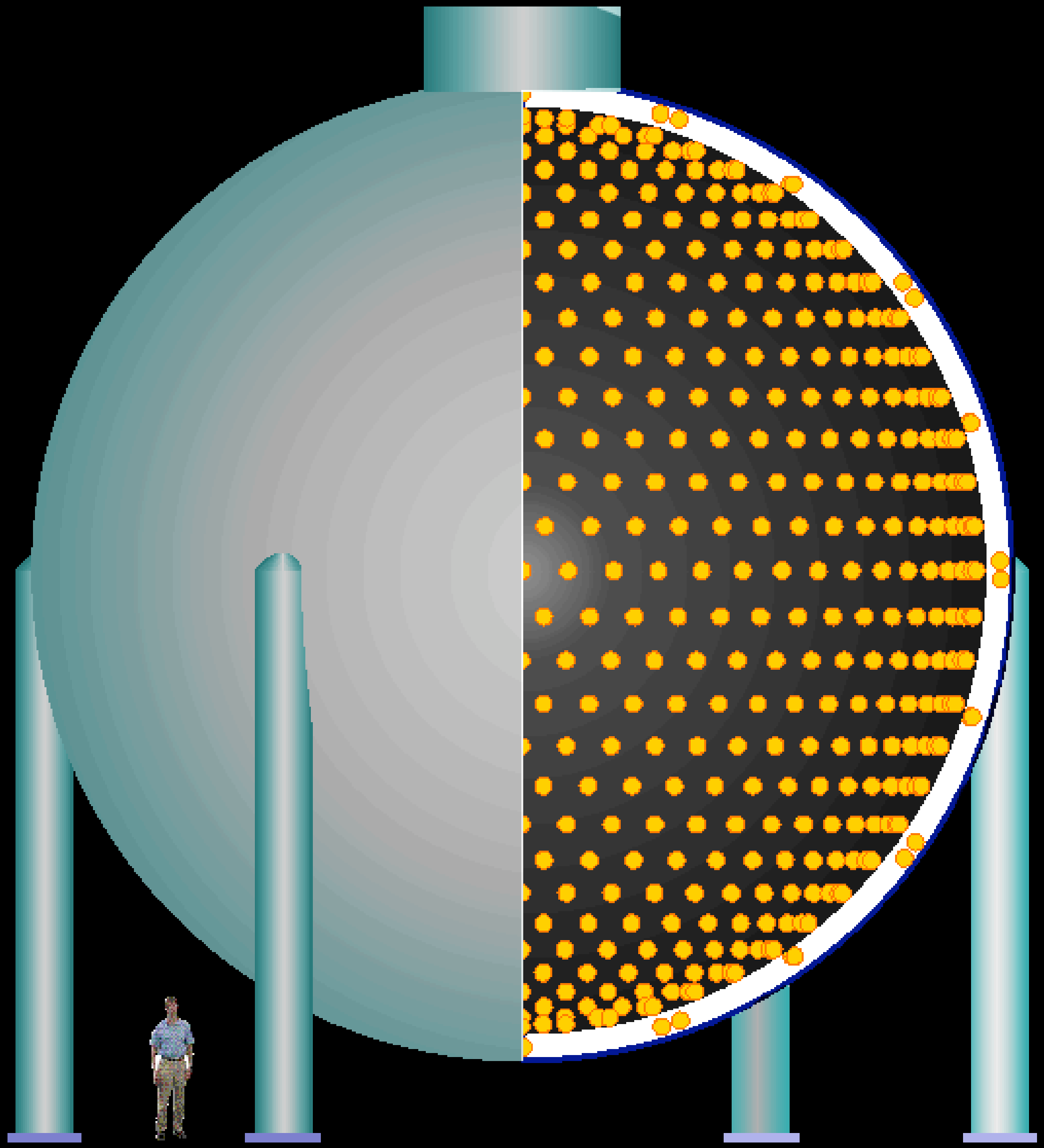
MiniBooNE Beamline



- 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



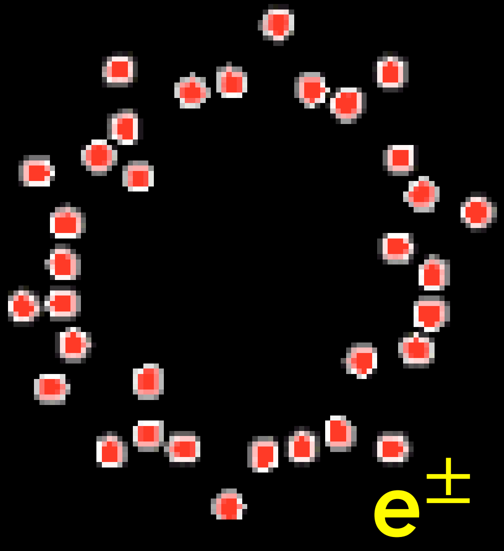


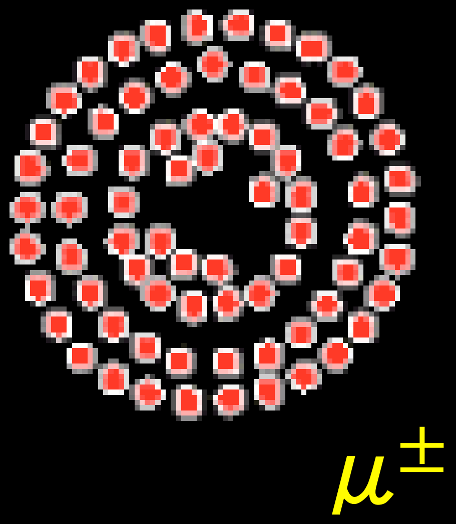
- Pure mineral oil
- 800 tons; 40 ft diameter
- Inner volume: 1280 8″ PMTs
- Outer veto volume: 240 PMTs

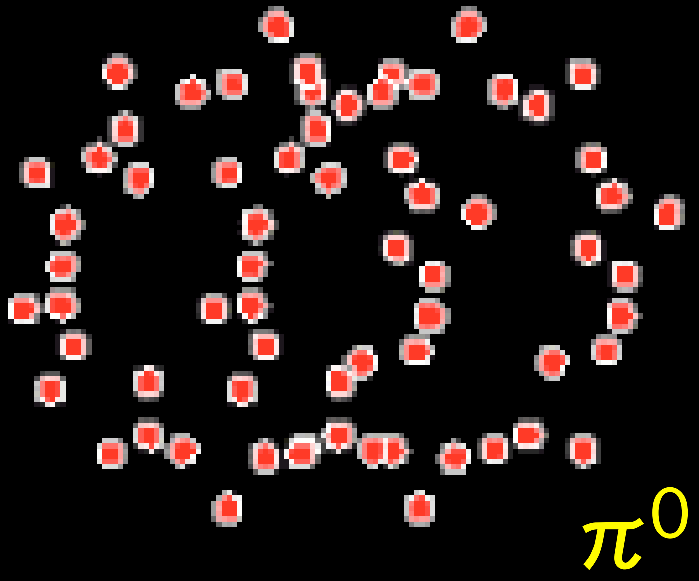
The detector records:

- 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:



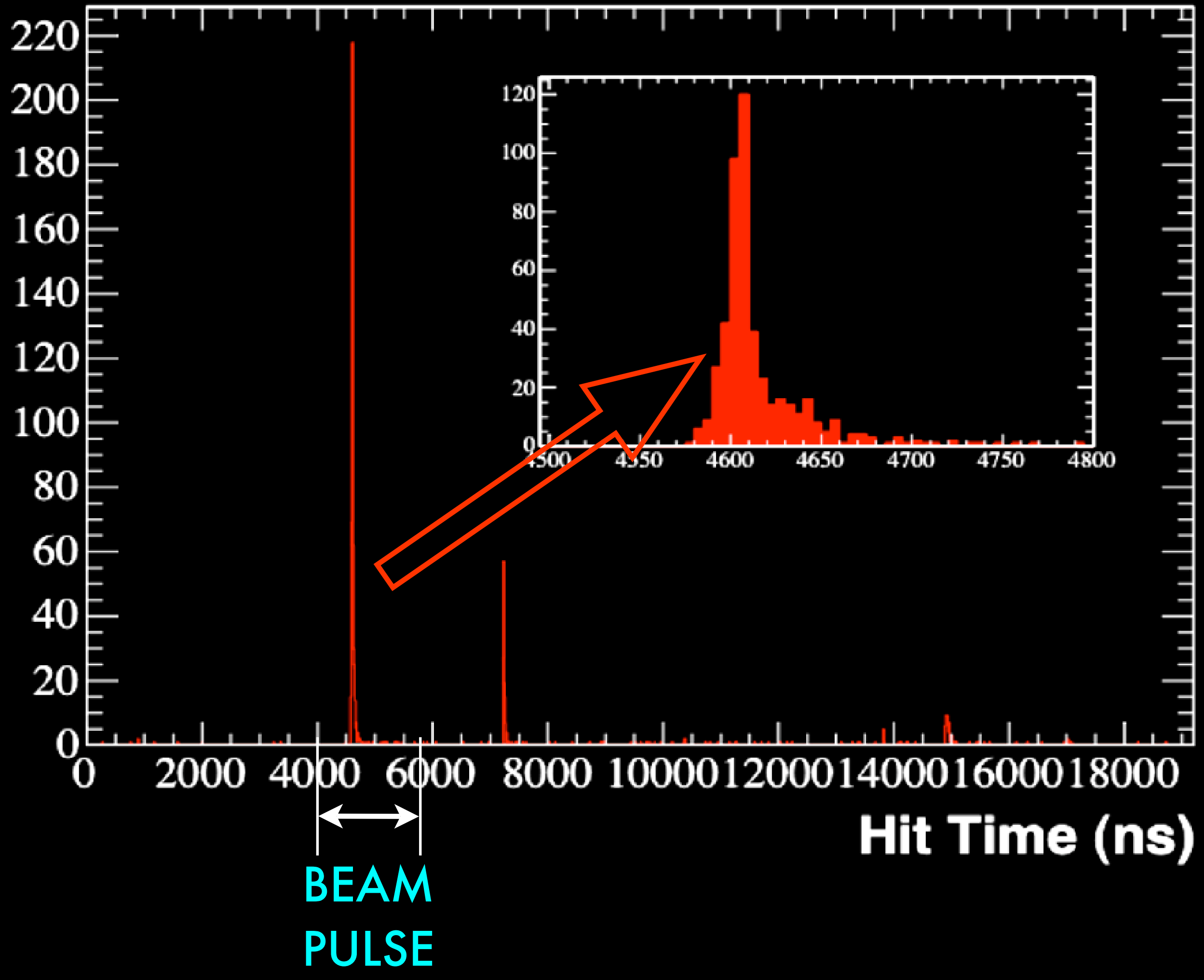




- Electrons: showers, scattering ⇒ “fuzzy” ring
- Muons: straight, long track ⇒ well-defined ring
- $\pi^0 \rightarrow \gamma\gamma$: two electron-like rings

Subevents

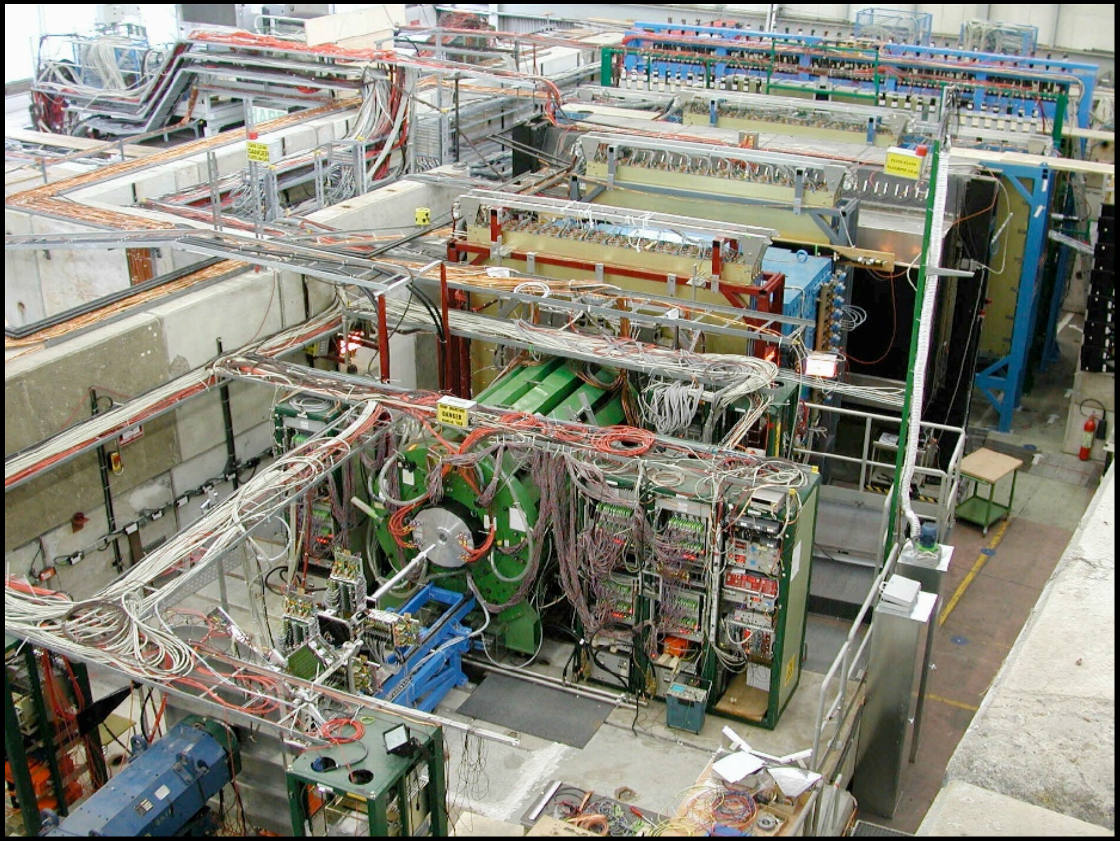
- All hits are recorded in a 20-μs window around the beam pulse.
- Able to check for subsequent stopped muon decay (“Michel”) electron: muon and its Michel electron resolved as two “subevents” (clusters of hits within ~100 ns).
- The Michel electron subevent provides muon tag as well as a very well-understood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

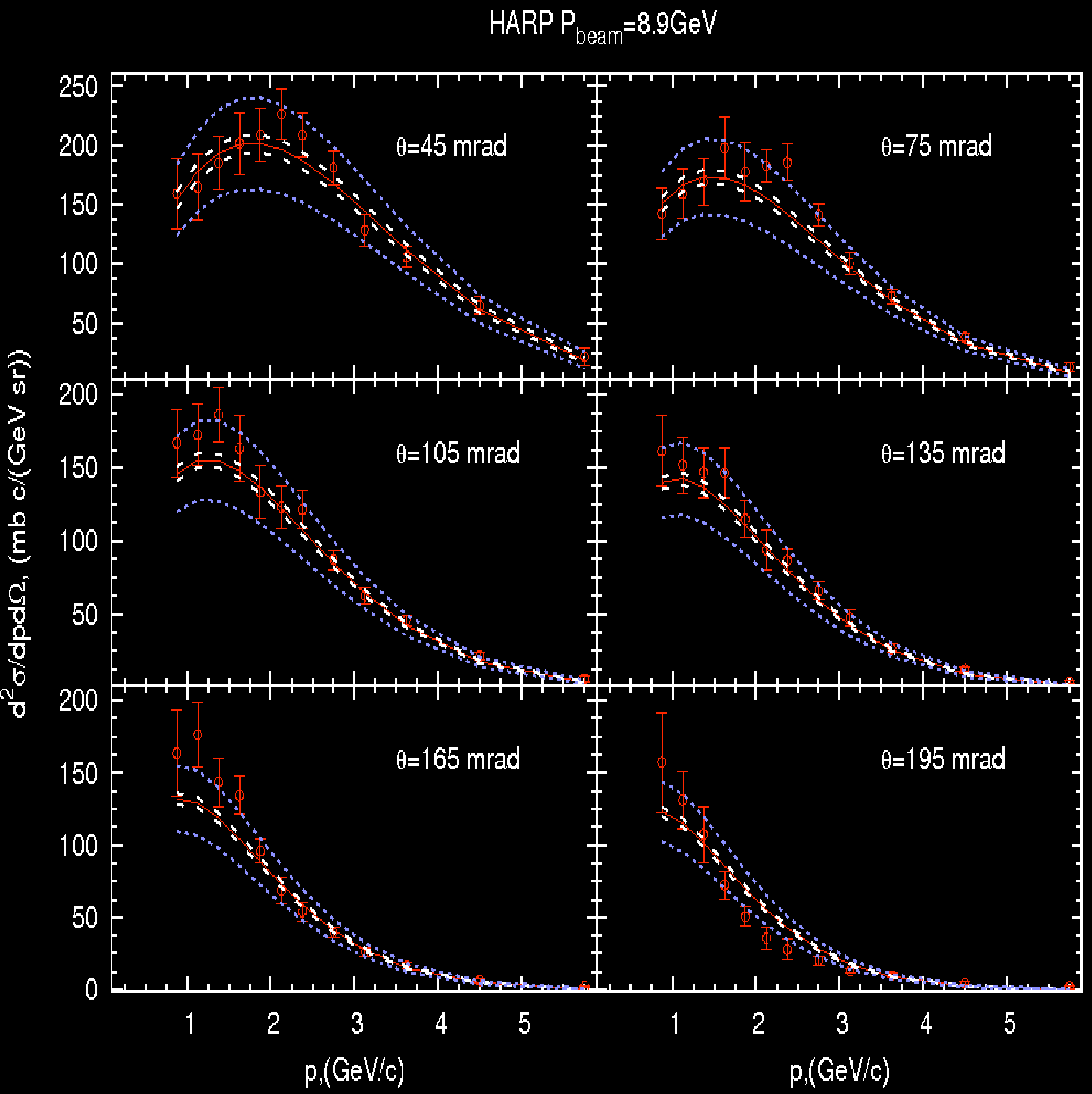


Oscillation Analysis

- 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

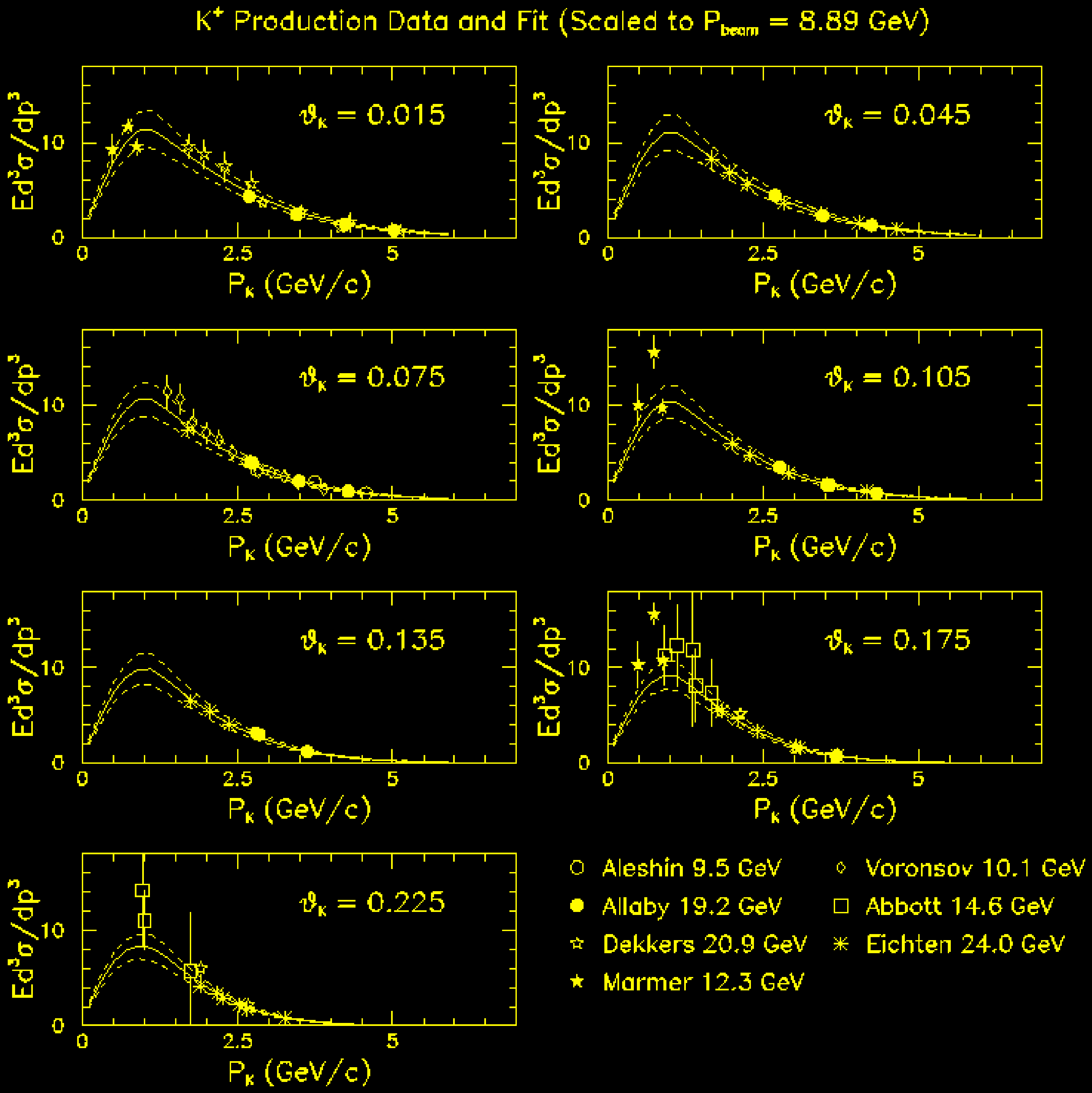




- Data from HARP experiment at CERN (taken with beryllium target at correct MiniBooNE beam momentum: hep-ex/0702024)
- Fit data to 9-parameter Sanford-Wang parametrization
- Sanford-Wang model used in GEANT4 beam Monte Carlo

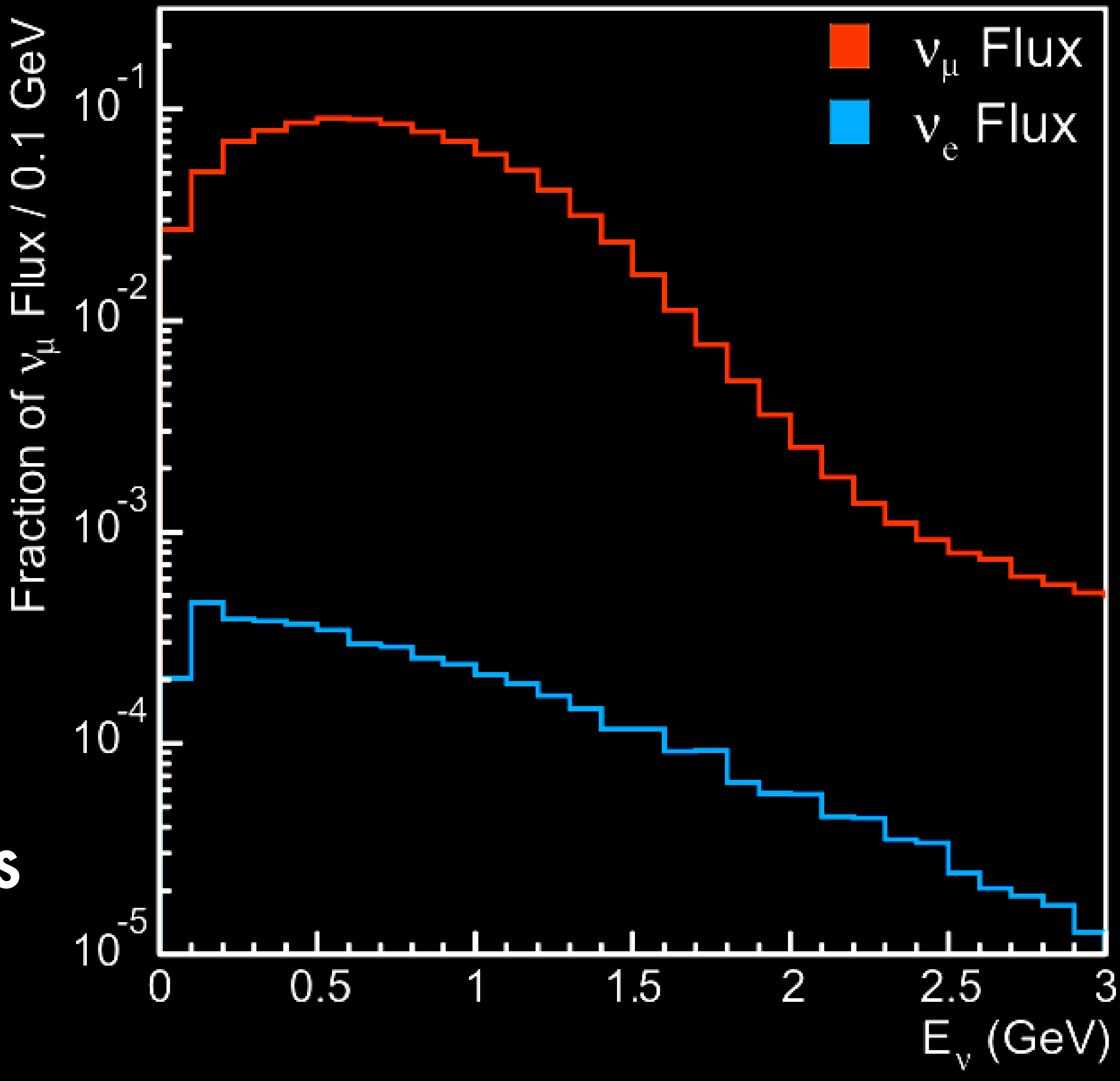
Flux model: kaon production

- 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



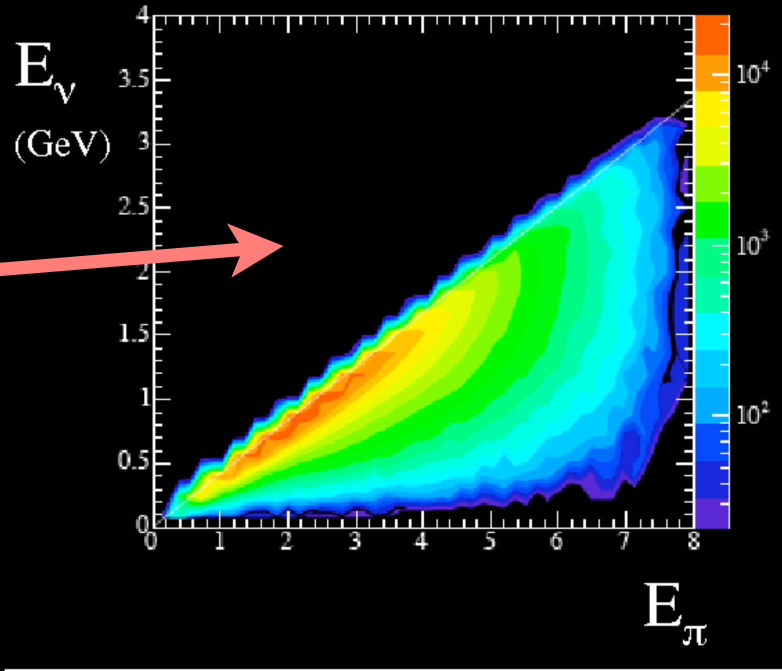
Predicted flux at detector

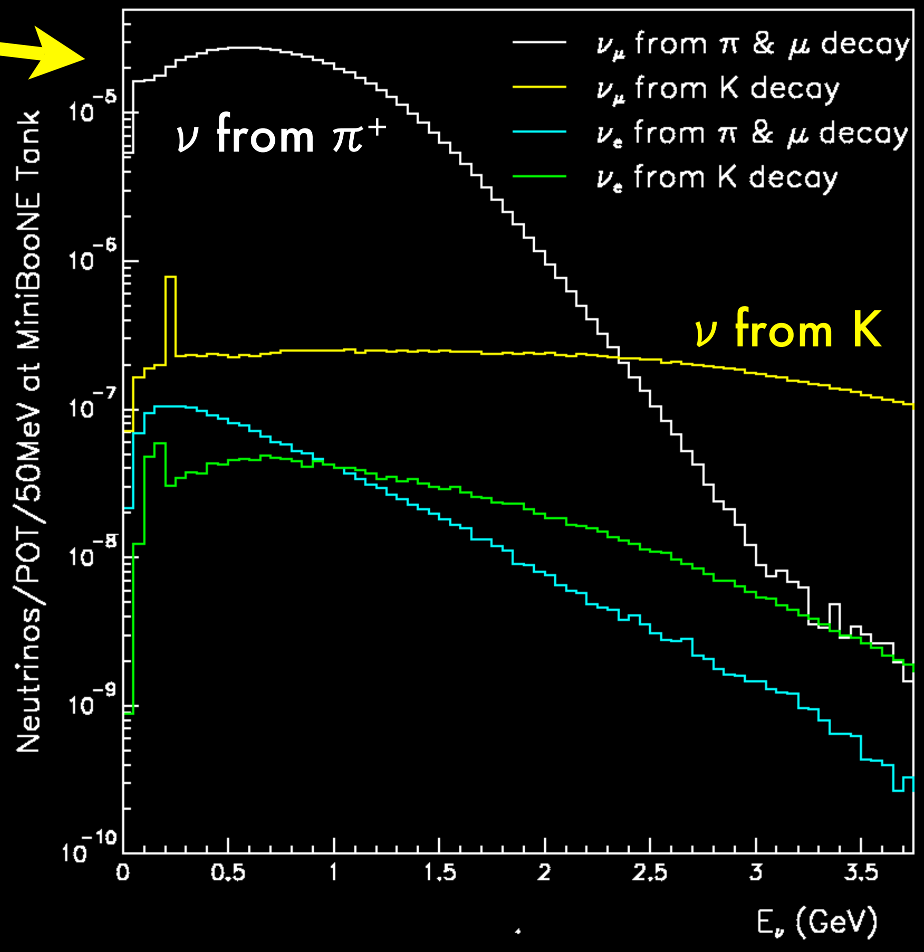
- Predicted flux:
  - 99.5% $\nu_\mu + \overline{\nu}_\mu$
  - 0.5% $\nu_e + \overline{\nu}_e$:
    - $\mu^+ \rightarrow e^+ \overline{\nu}_\mu \nu_e$ *(52%)*
    - $K^+ \rightarrow \pi^0 e^+ \nu_e$ *(29%)*
    - $K^0 \rightarrow \pi^+ e^- \overline{\nu}_e$ *(7%)*
    - $K^0 \rightarrow \pi^- e^+ \nu_e$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

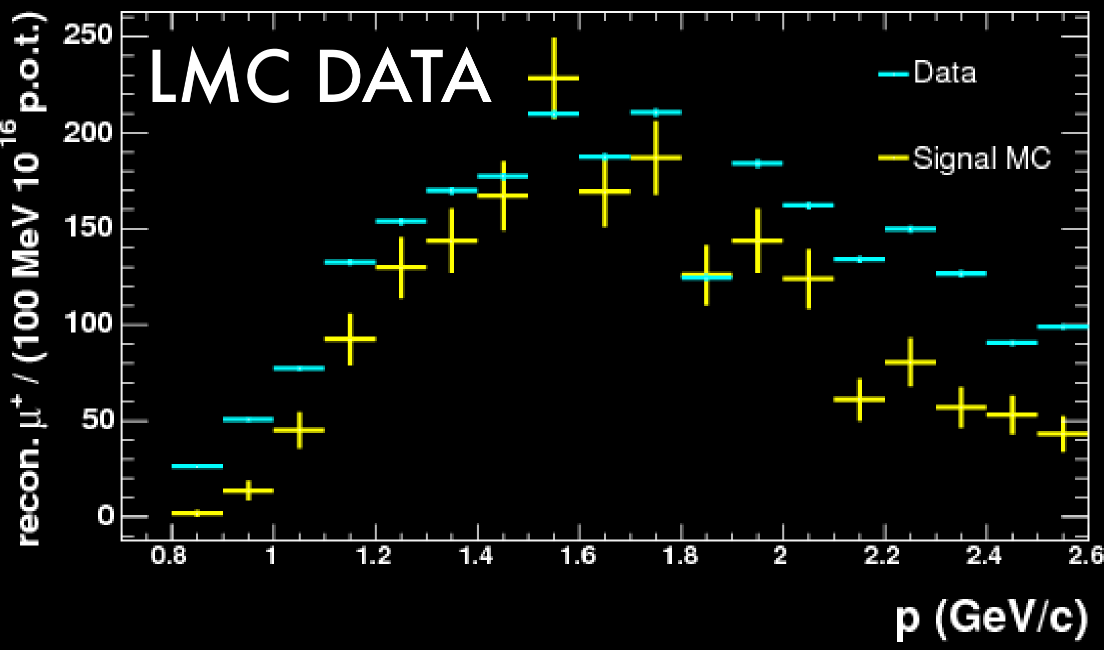


Further constraints on flux components

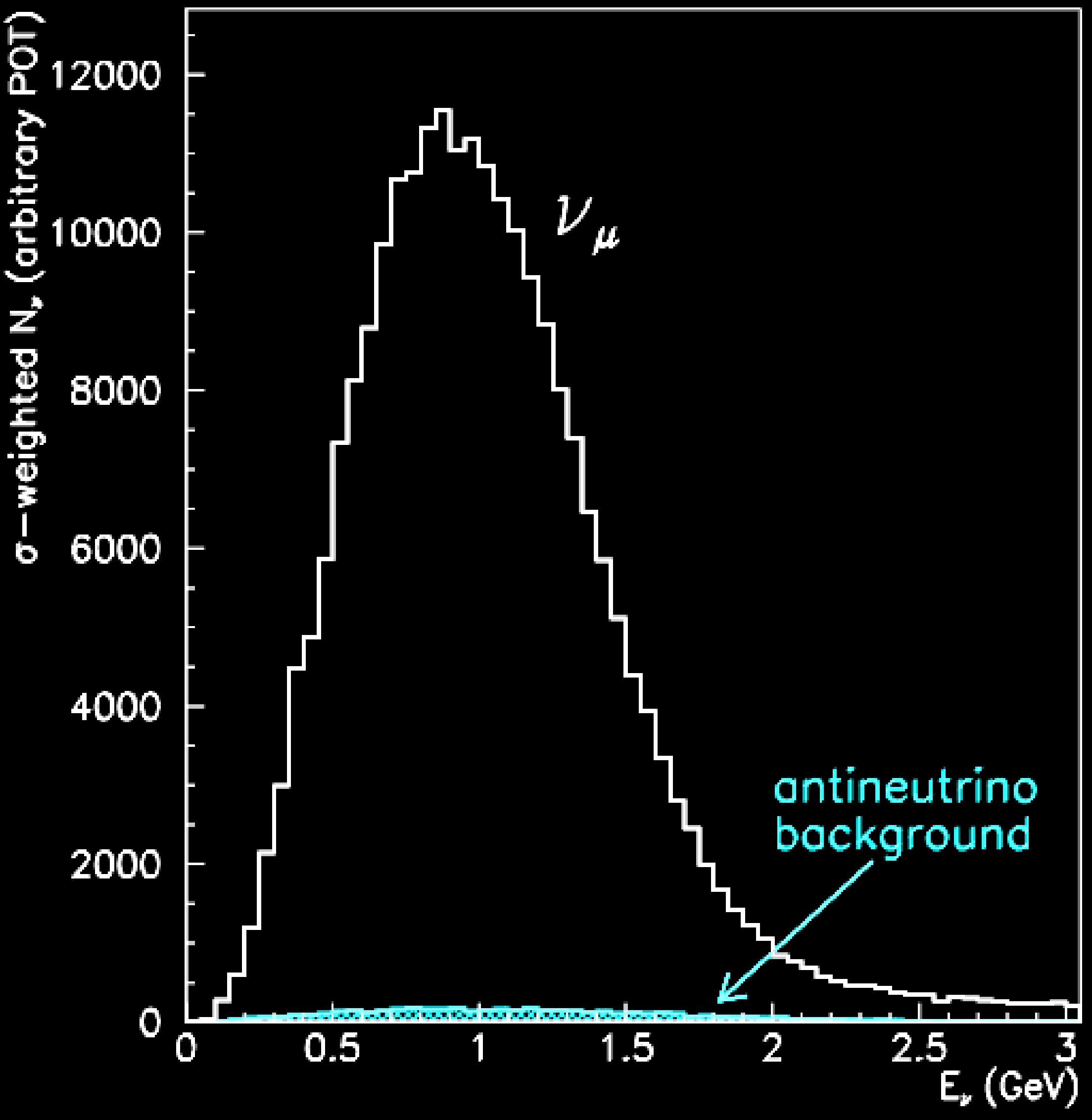
- Muons originate predominantly from pion decays in secondary beam:
  - These pions also produce most ν_μ in detector, which are easily observed
  - Kinematic correlation allows tight constraint on $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ chain
- Kaon decay has much higher Q-value than pion decay. 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

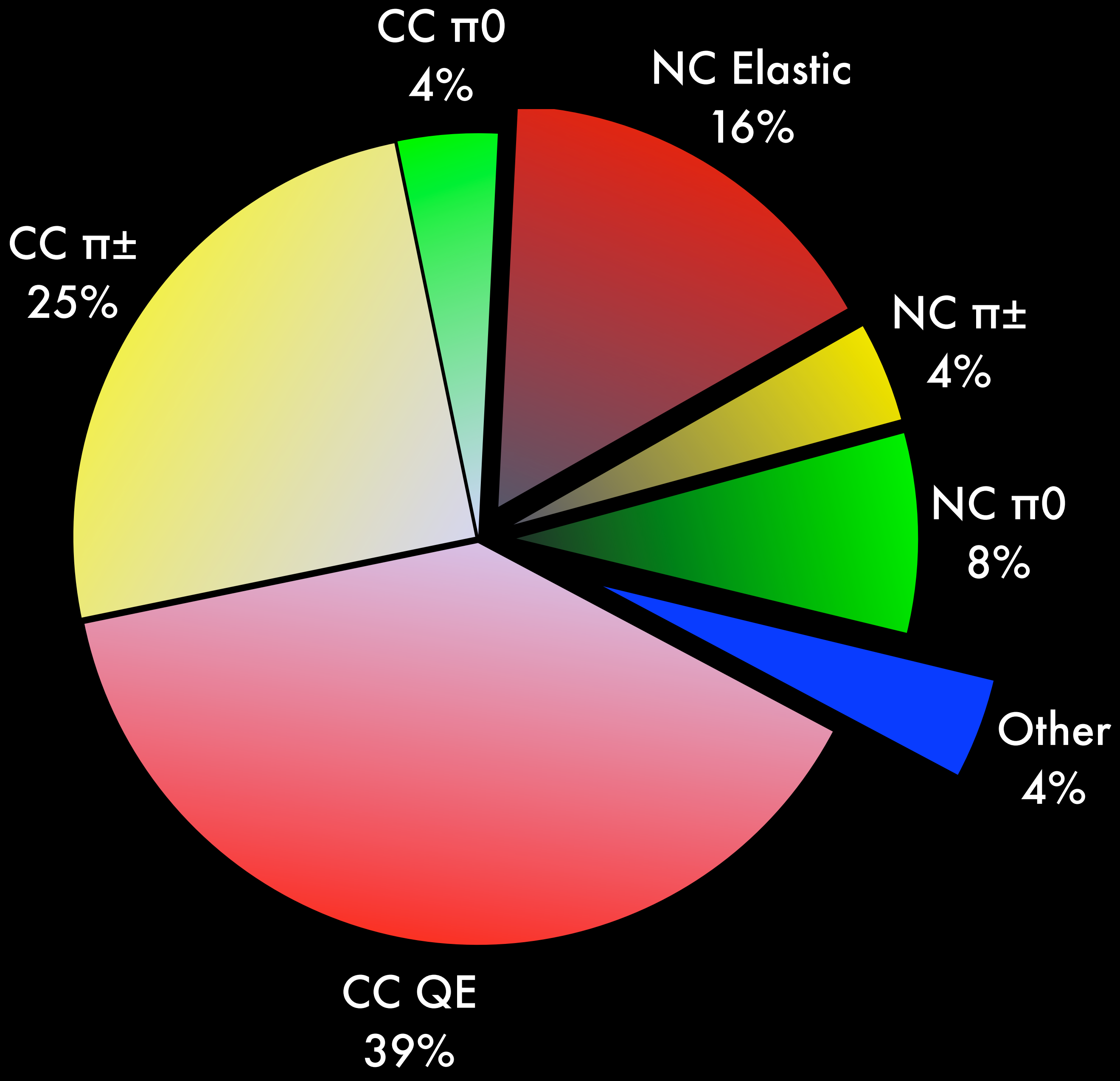






Neutrino Interactions in MiniBooNE

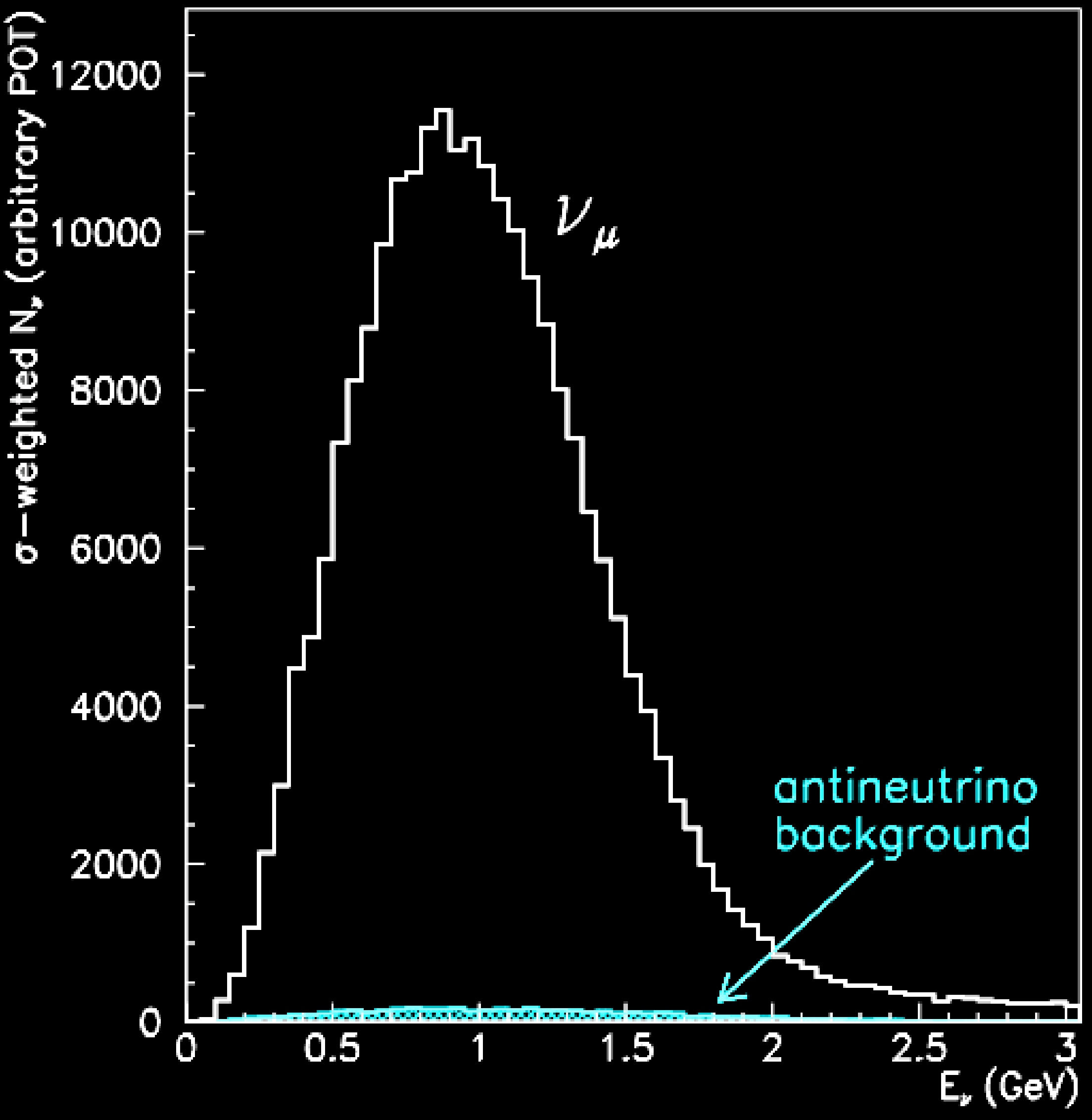


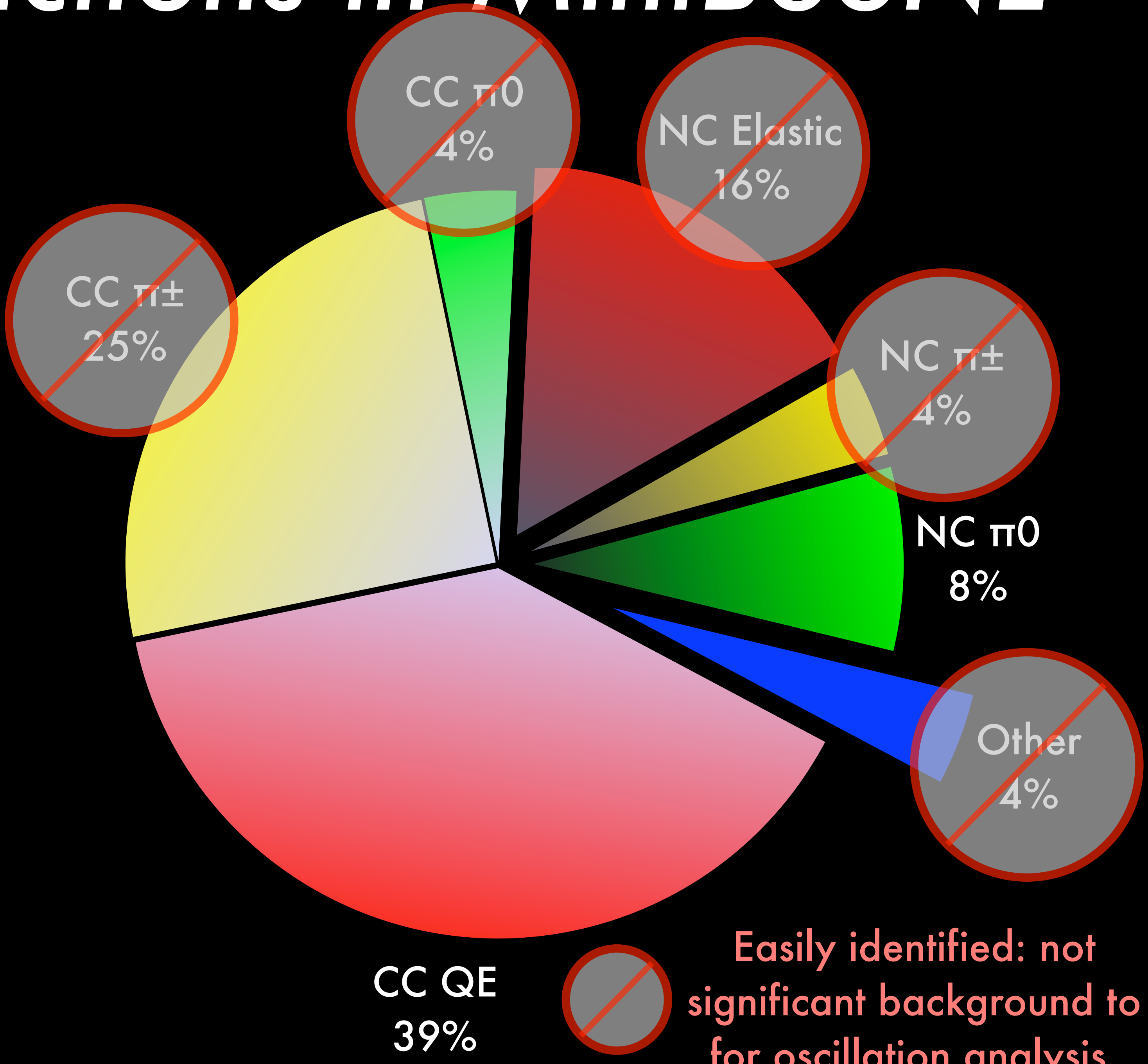


Predicted event spectrum, fractions before cuts
(NUANCE Monte Carlo)

D. Casper, NPS, 112 (2002) 161

Neutrino Interactions in MiniBooNE





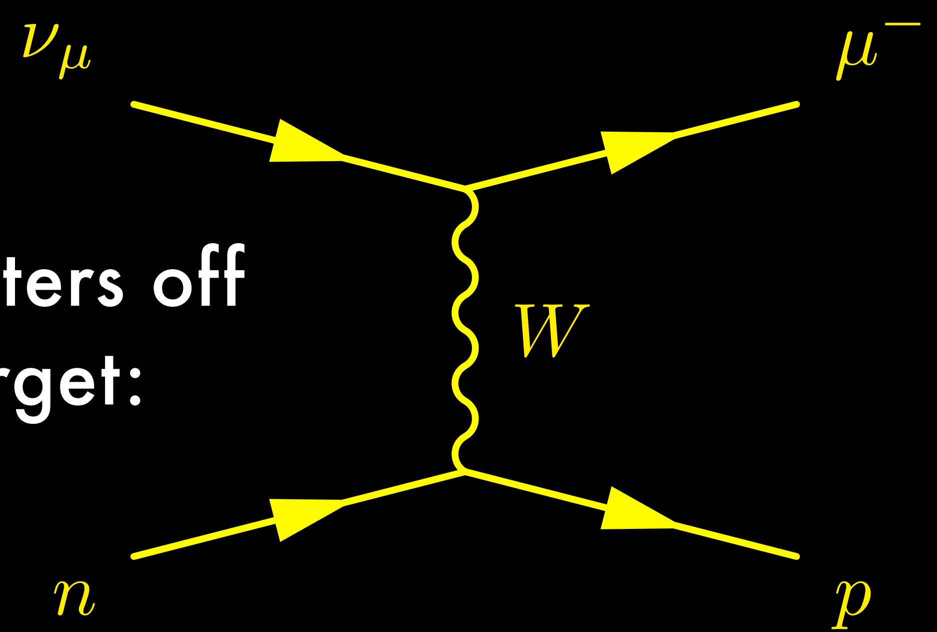
Easily identified: not significant background to for oscillation analysis.

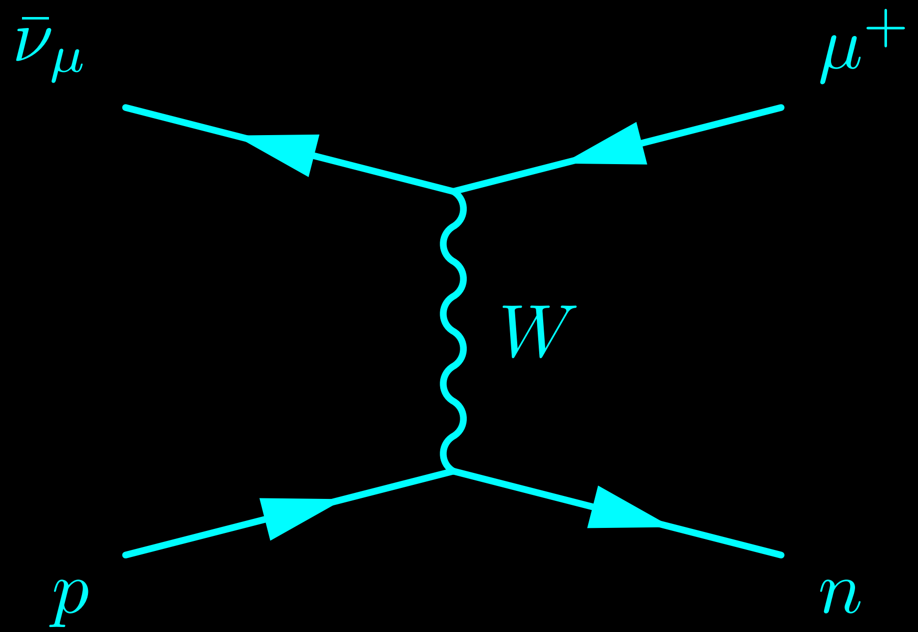
Predicted event spectrum, fractions before cuts (NUANCE Monte Carlo)

D. Casper, NPS, 112 (2002) 161

Charged-current quasielastic (CCQE)

Neutrino scatters off nucleon in target:



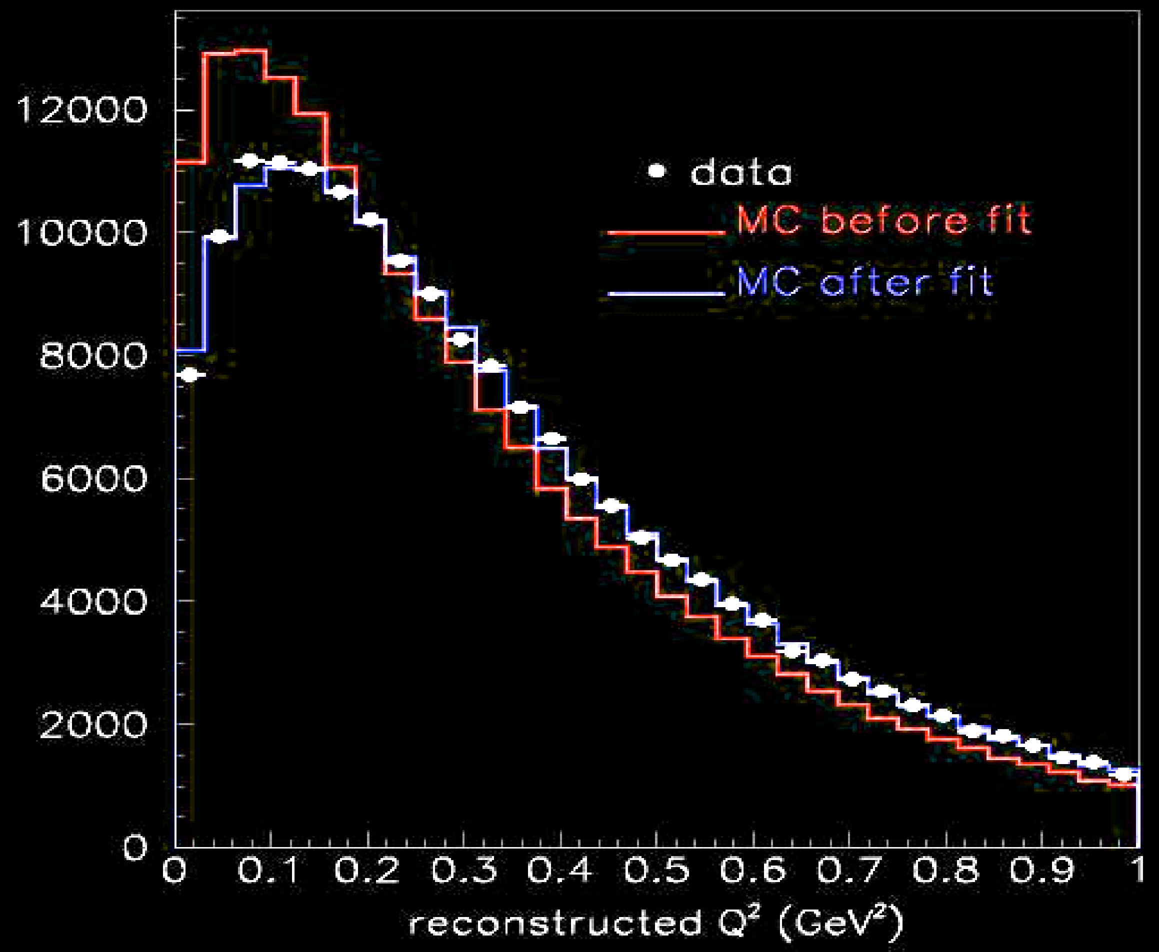


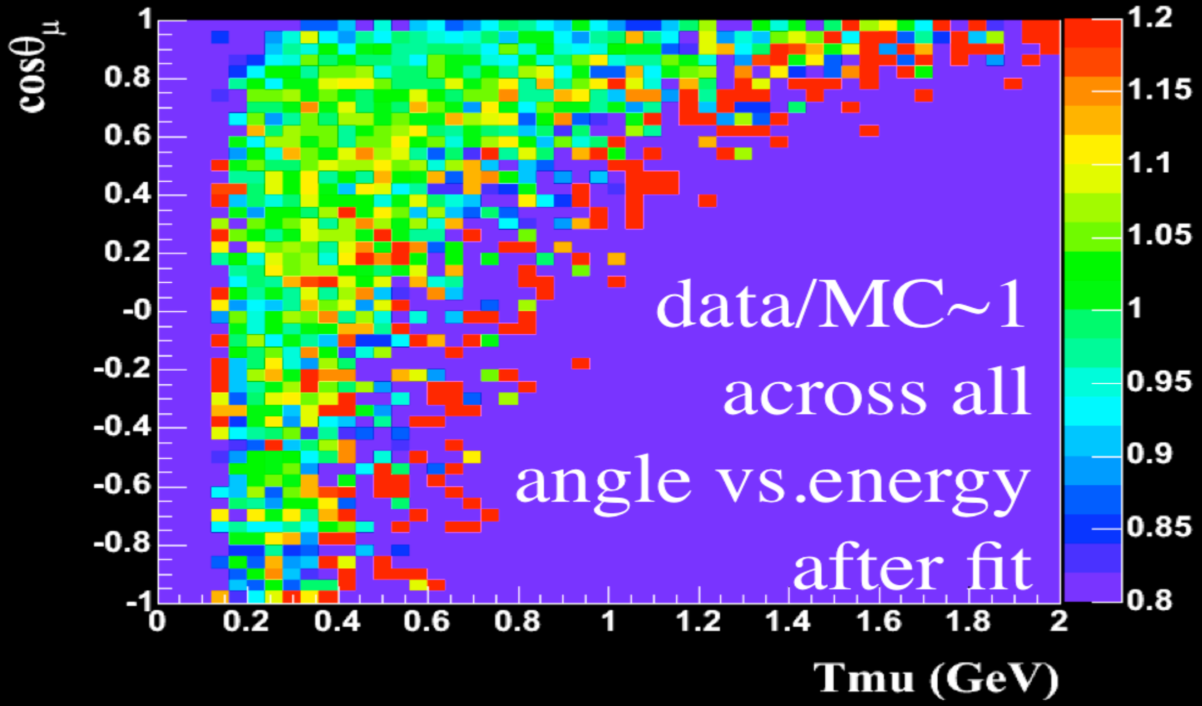
- Golden signal mode for oscillation search: clean events; neutrino energy can be calculated given known neutrino direction:

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

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

Cross-section parameters need tuning

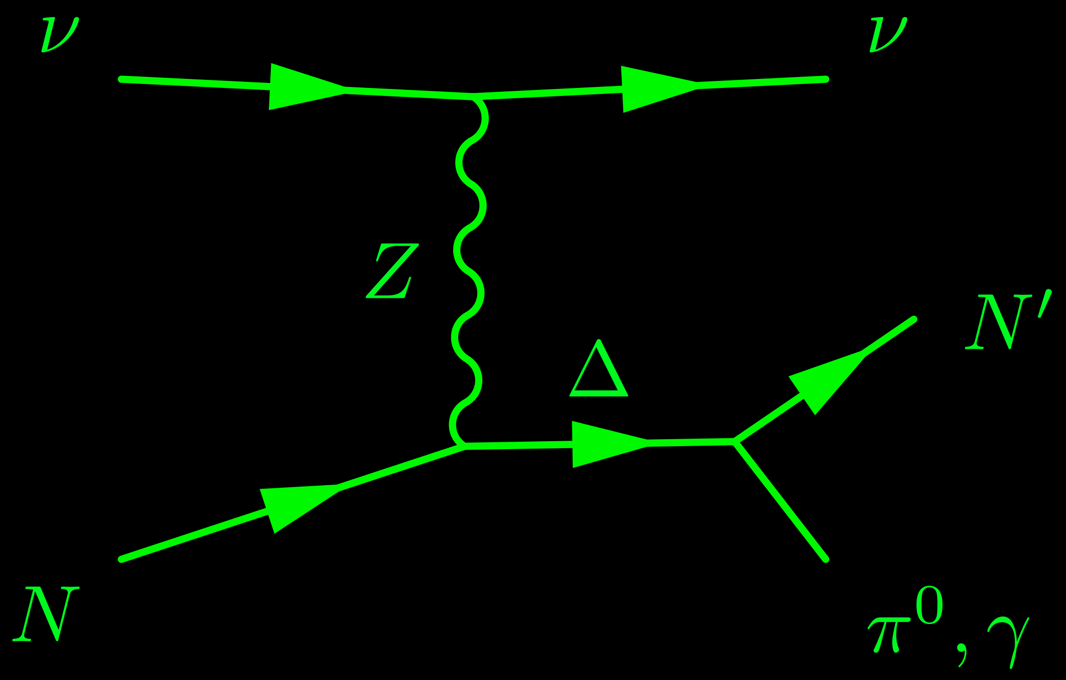




- From Q^2 fits to MiniBooNE ν_μ CCQE data:
  - M_A^{eff}: effective axial mass
  - E_{lo}^{SF}: Pauli-blocking parameter

- From electron scattering data:
  - E_b -- binding energy
  - p_F -- Fermi momentum

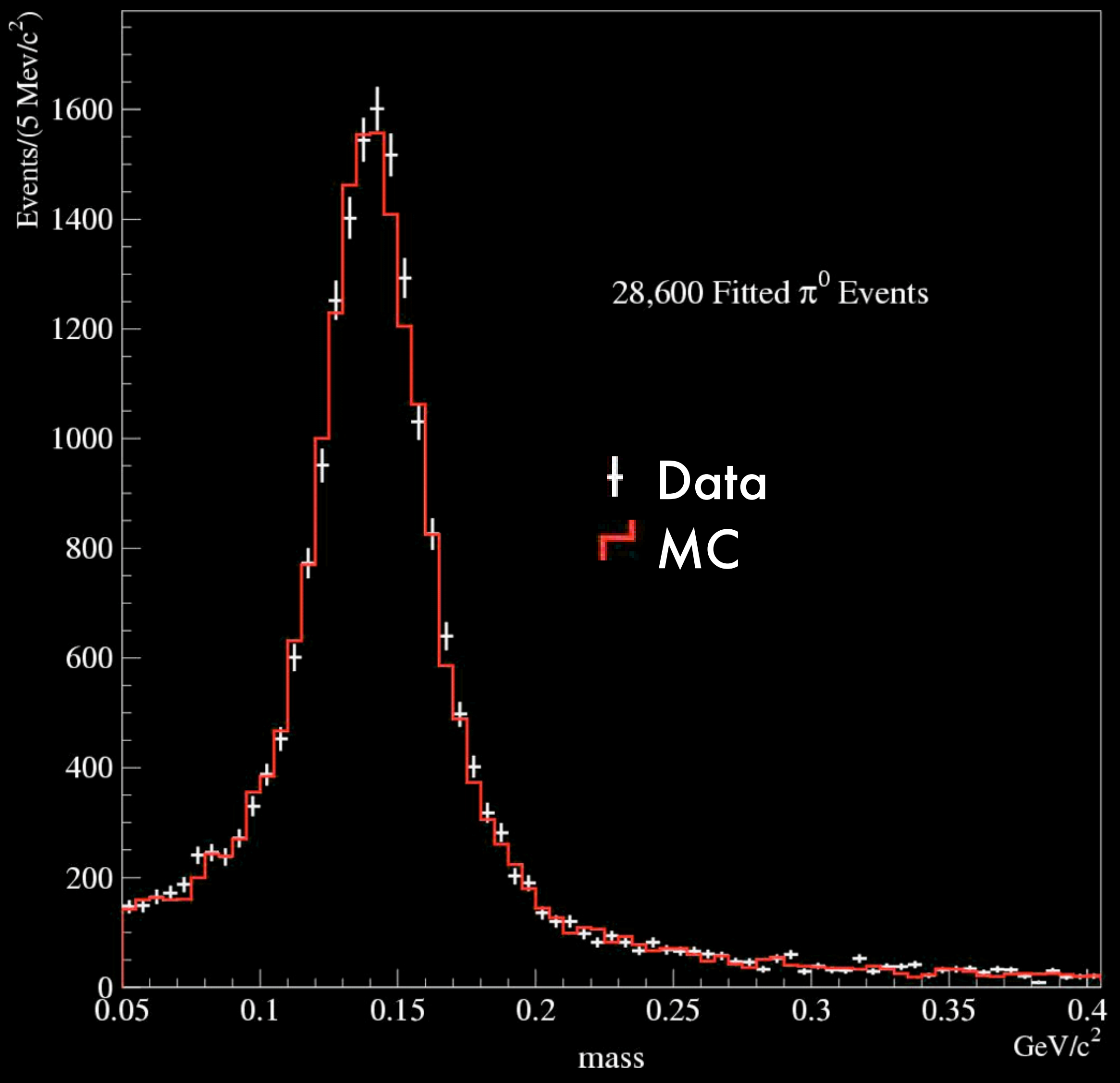
Neutral Current Δ Resonances



- 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

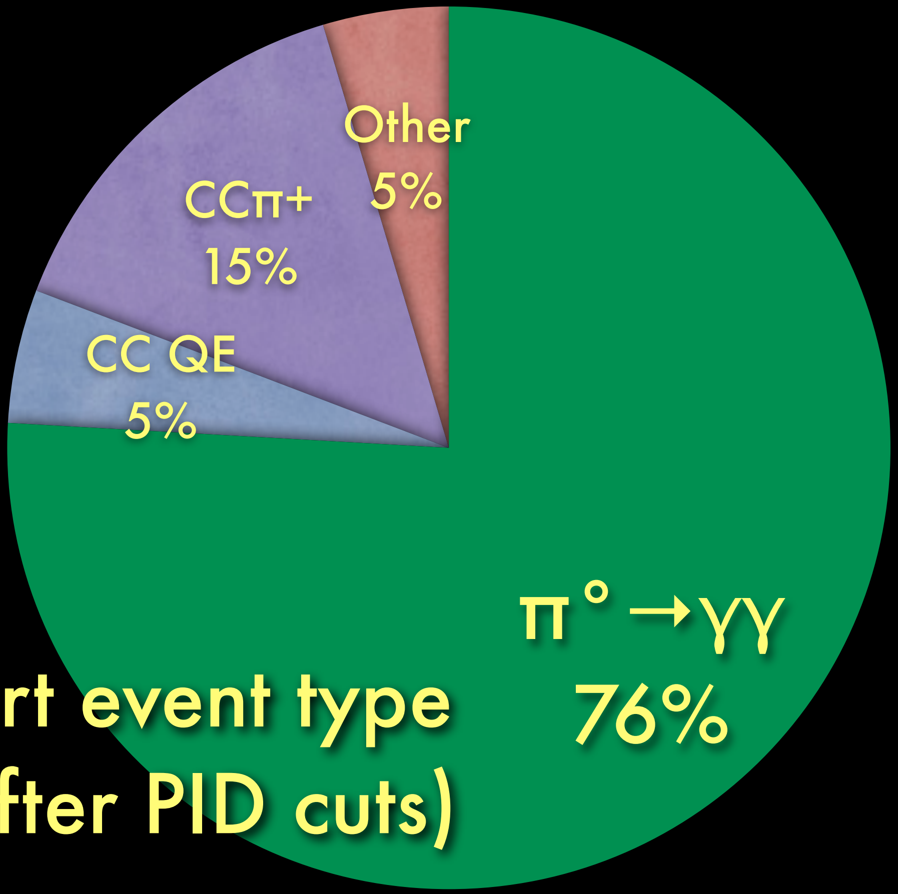
- π^0 events



- 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"

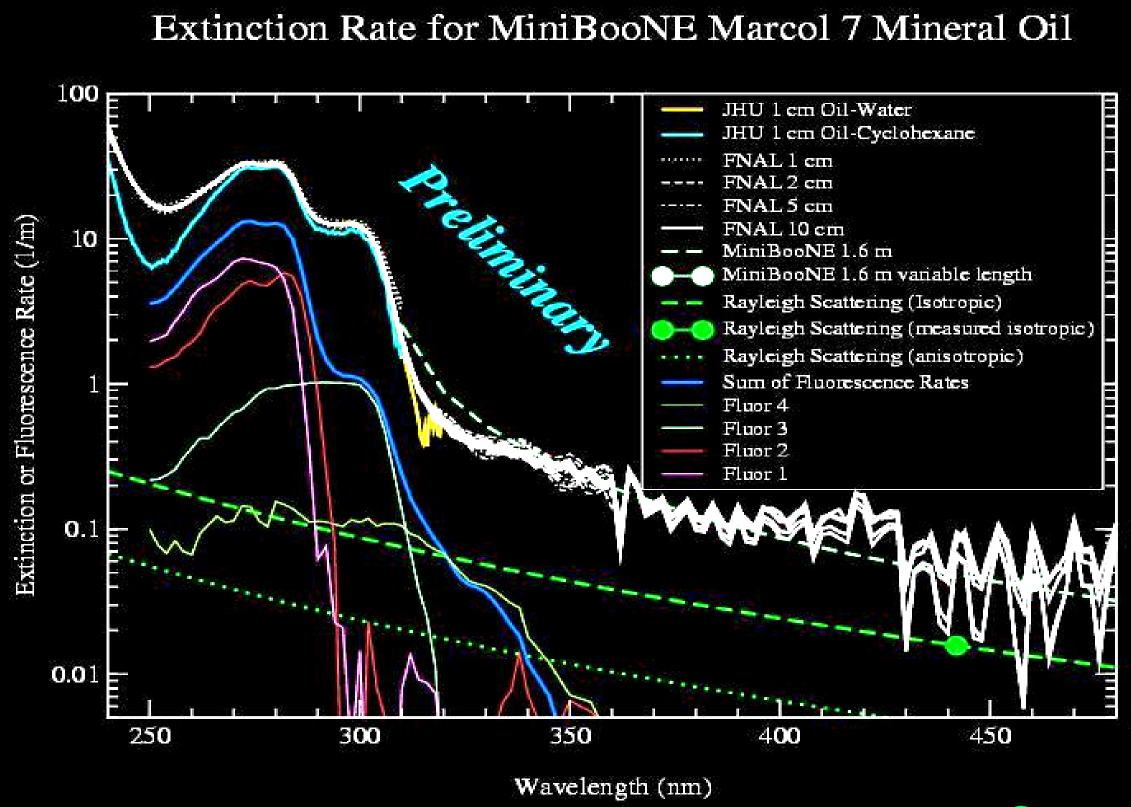
- "Dirt" events: neutrino interactions outside the detector
- Most events are cut by veto
- Background is dominated by π^0 where only one photon enters detector
- Cosmic/other beam-unrelated background is very small: 2.1±0.5 events, measured with beam-off data



Dirt event type (after PID cuts)

Neutrino detector modeling: "optical" issues

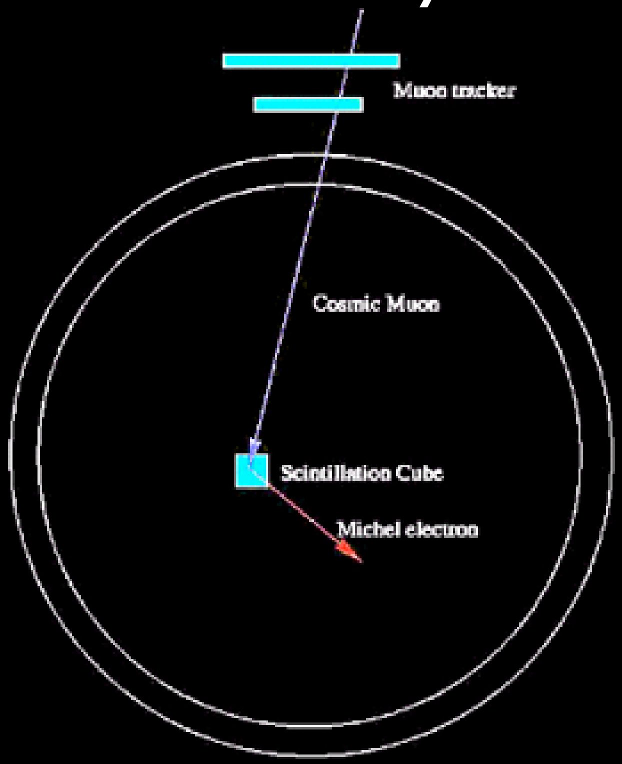
- Primary light sources
  - Cherenkov
    - Emitted promptly, in cone
    - known wavelength distribution
  - Scintillation
    - Emitted isotropically
    - Several lifetimes, emission modes
    - Studied oil samples using Indiana Cyclotron test beam
    - Particles below Cherenkov threshold still scintillate

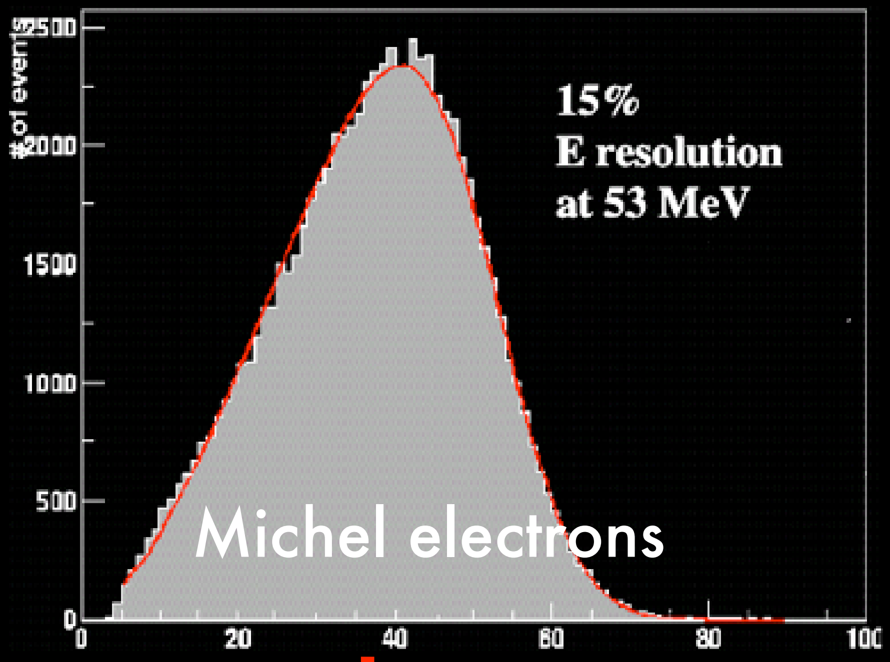


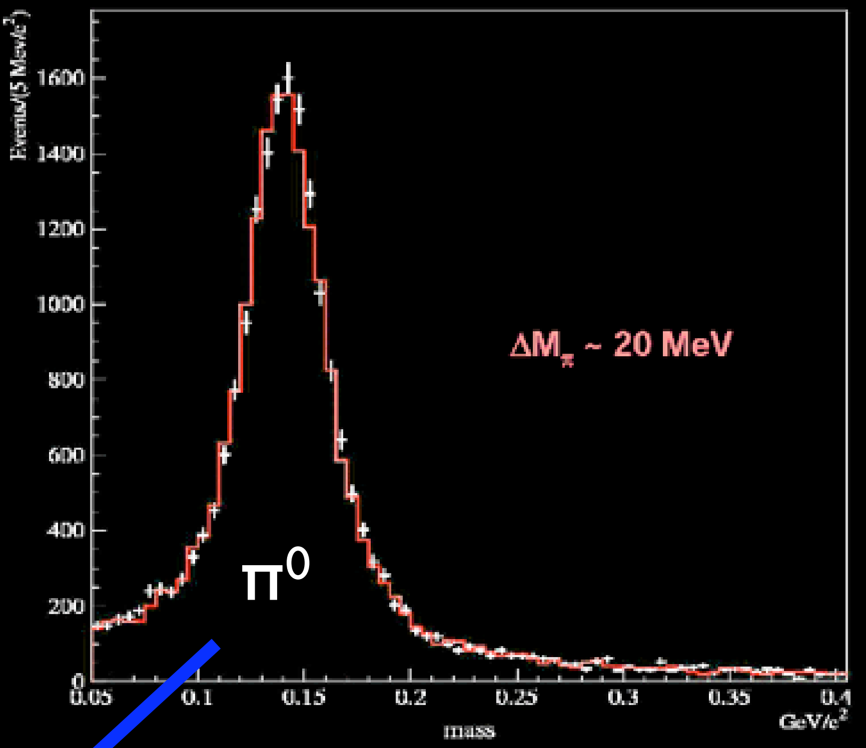
- Optical properties of oil, detectors:
  - Absorption (attenuation length >20m at 400 nm)
  - Rayleigh and Raman scattering
  - Fluorescence
  - Reflections
  - PMT response

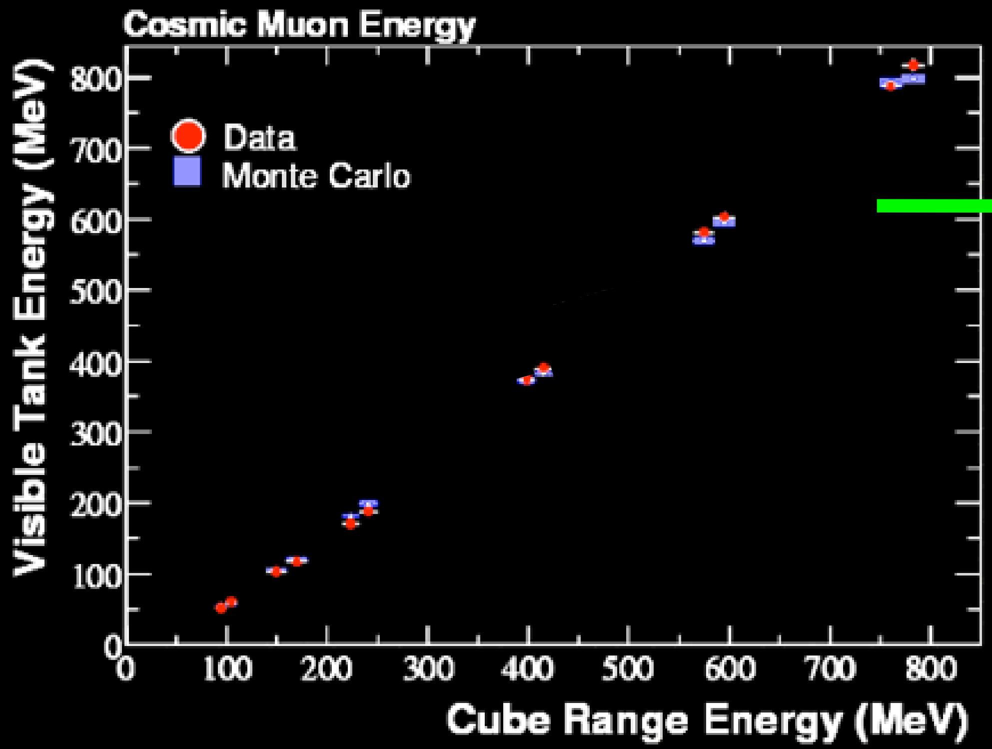
Calibration Sources

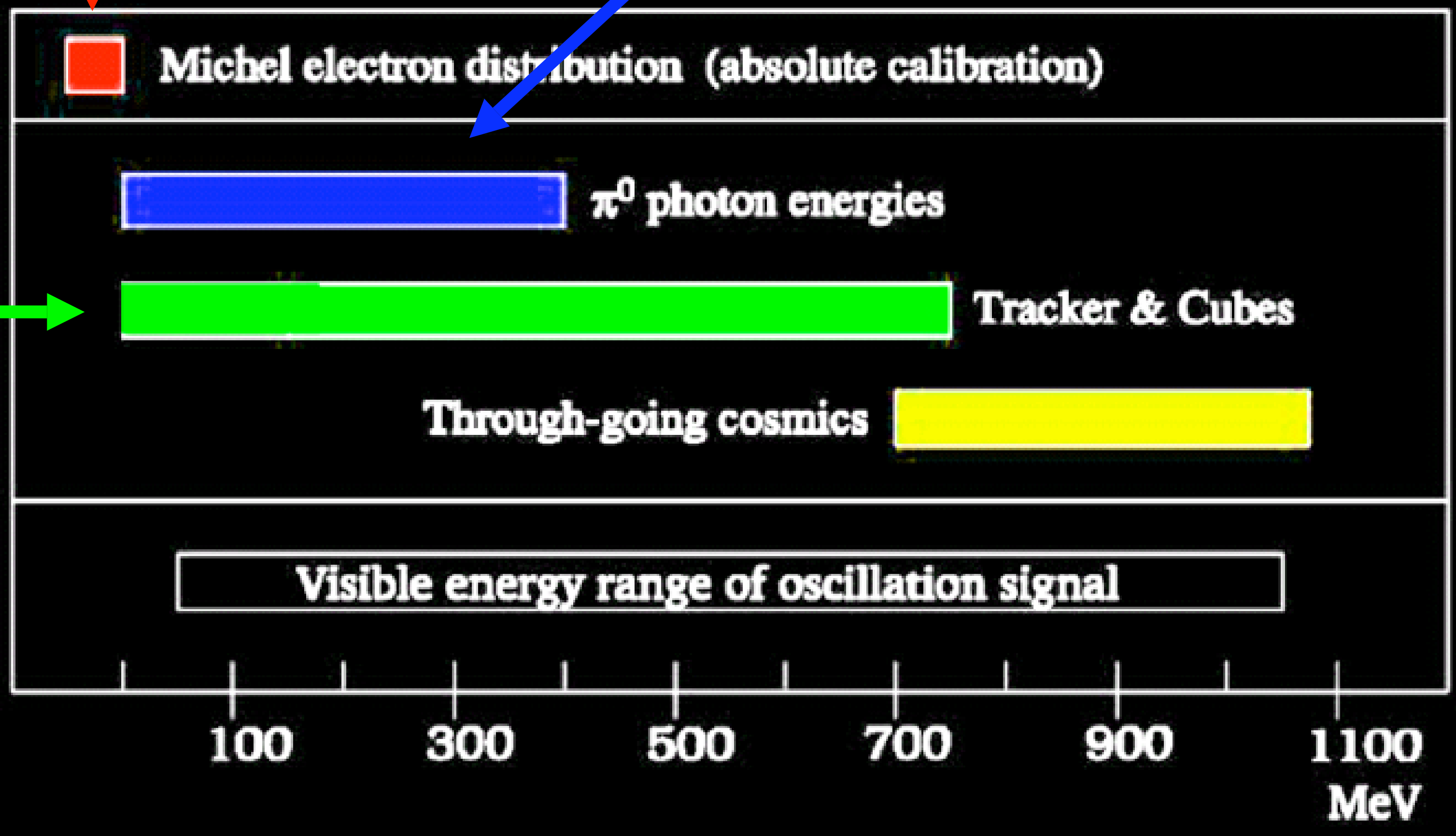
Tracker system











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.

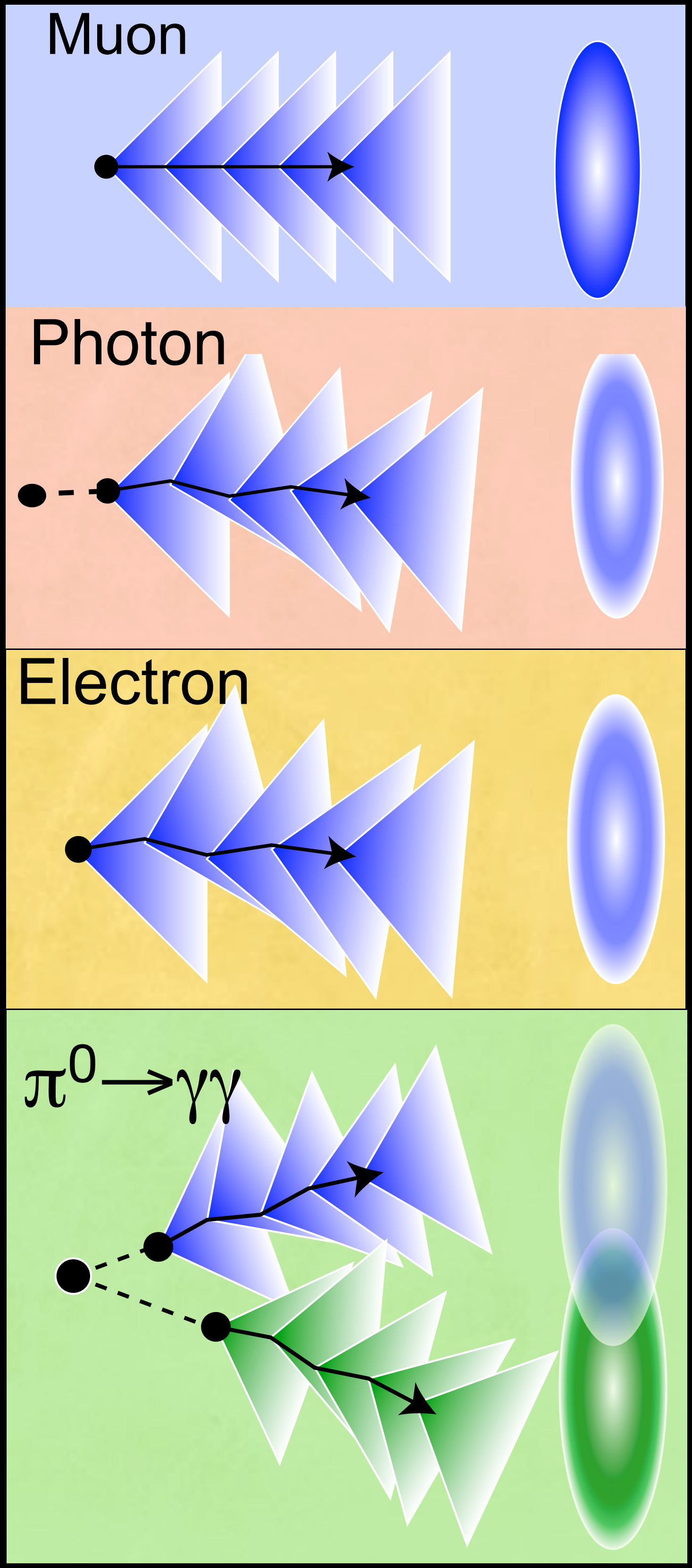
The Track-based Analysis:
Reconstruction

- 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(π^0)	11

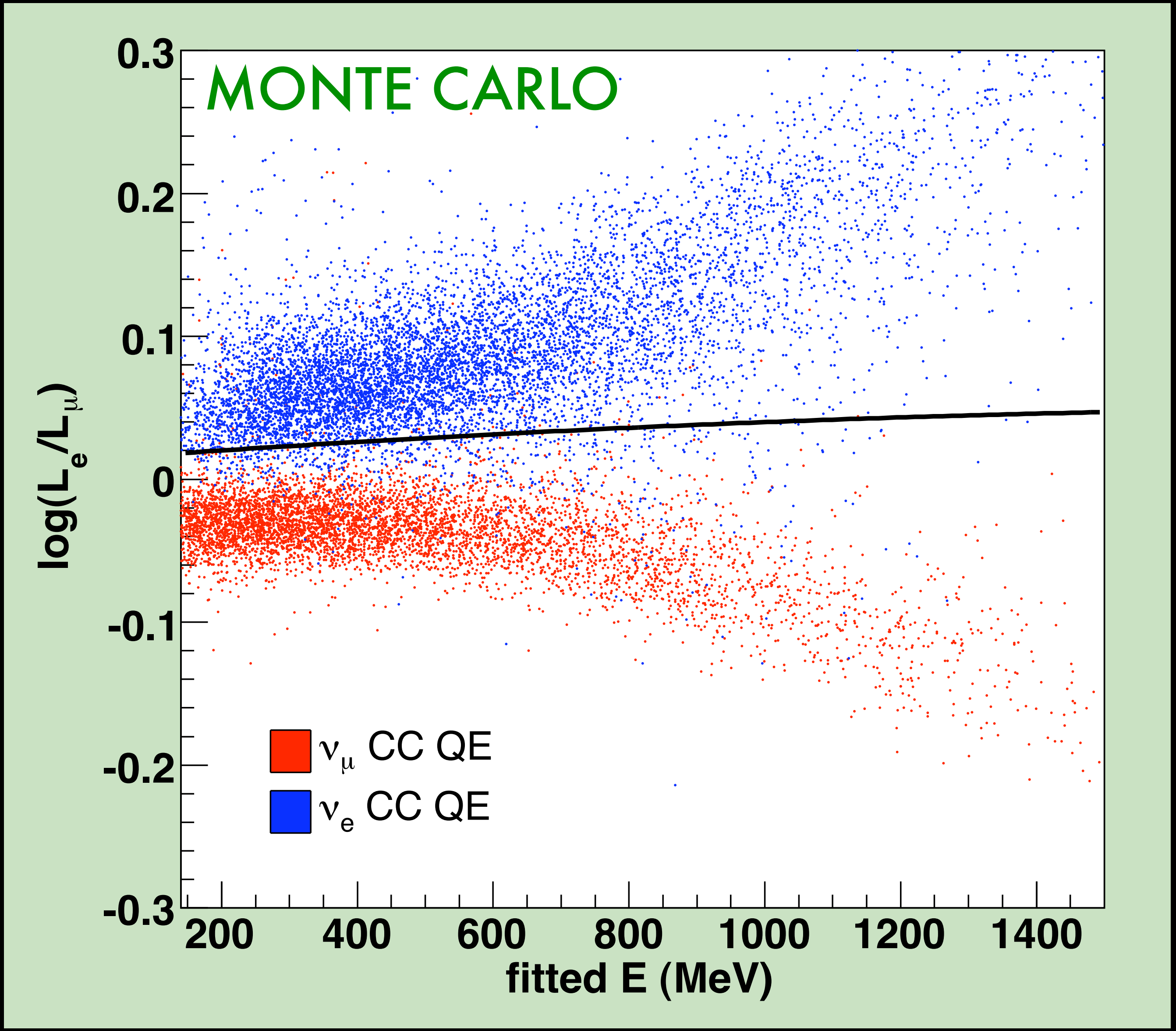


The Track-based Analysis:

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

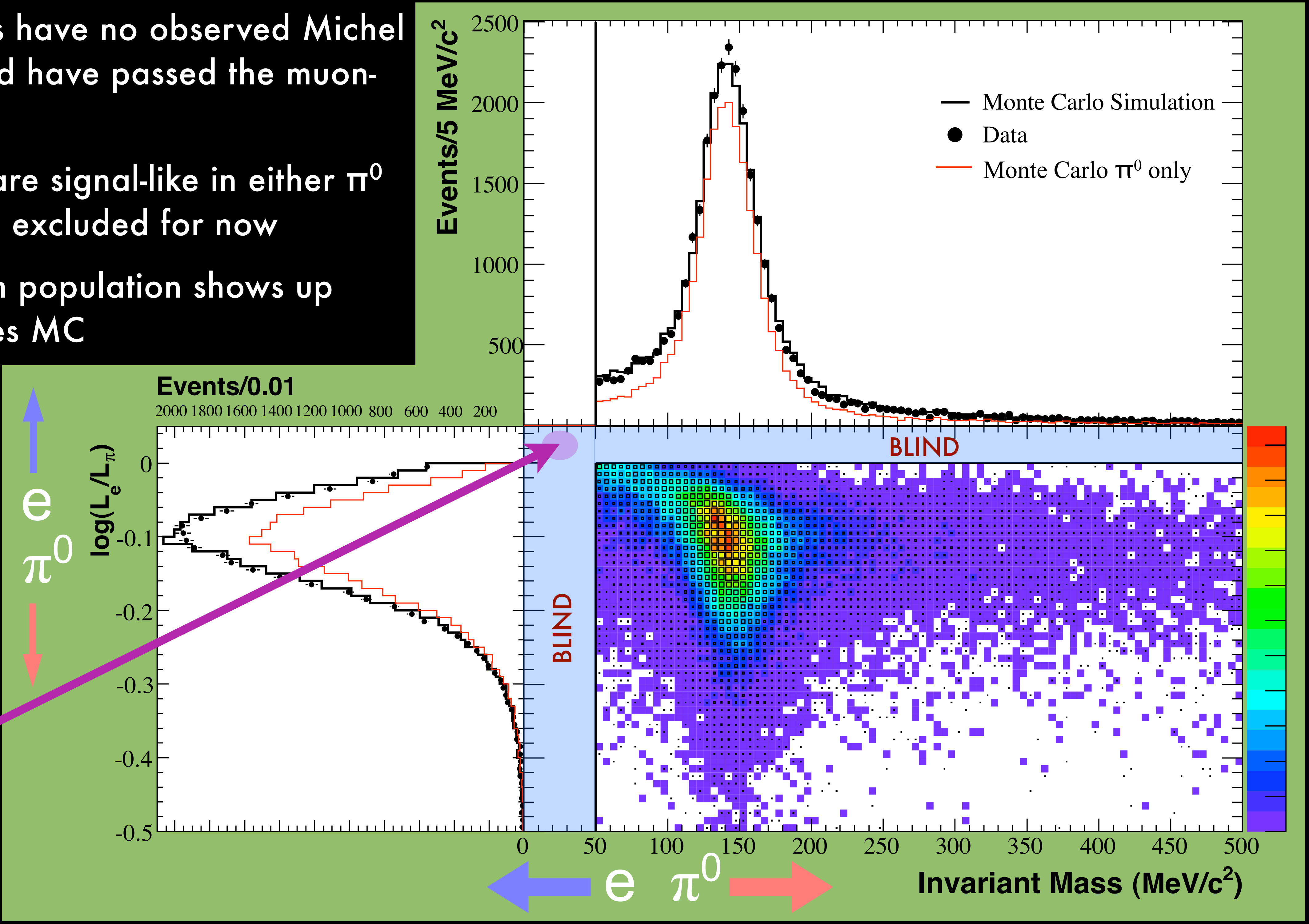


- $\log(L_e/L_\mu)$: compare likelihoods returned by e and μ fits.
- $\log(L_e/L_\mu)>0$ indicates electron hypothesis is favored.
- Analysis cut is parabola whose parameters selected to optimize oscillation sensitivity
- Discrimination easier at higher energy (increasing muon track length)

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

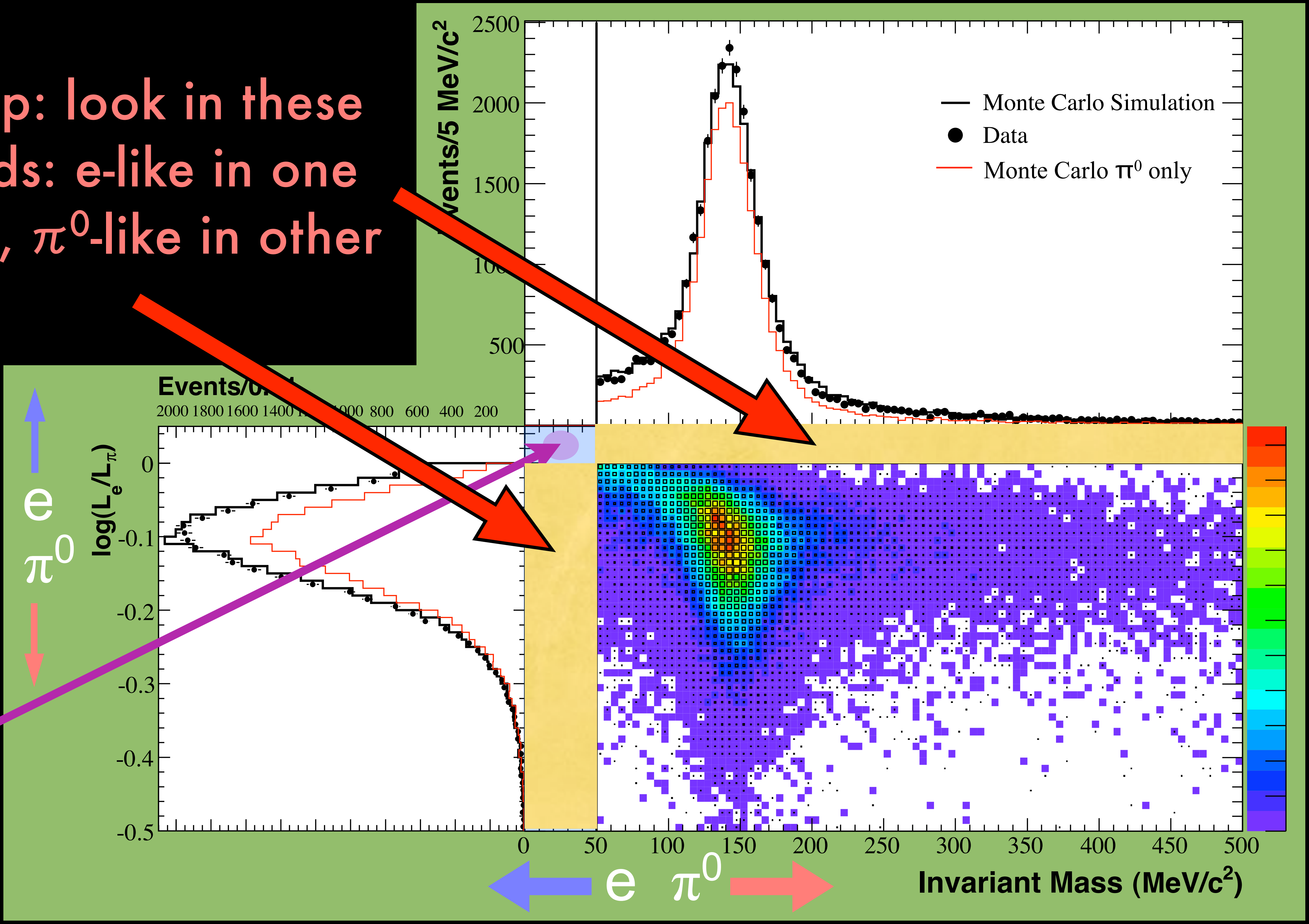


ν_e signal region

The Track-based Analysis:

Neutral pion rejection

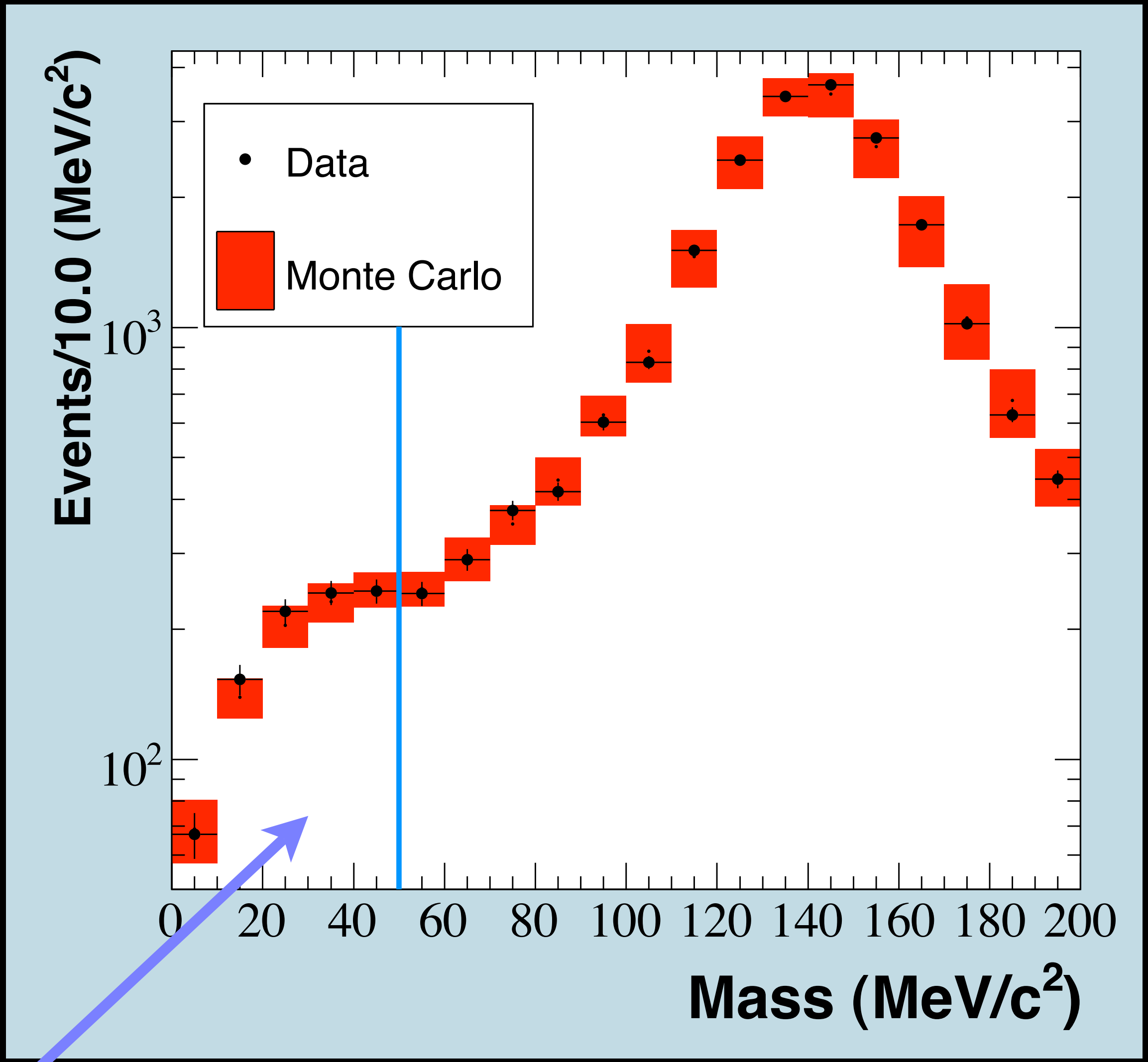
- Next step: look in these sidebands: e-like in one variable, π^0-like in other



ν_e signal region

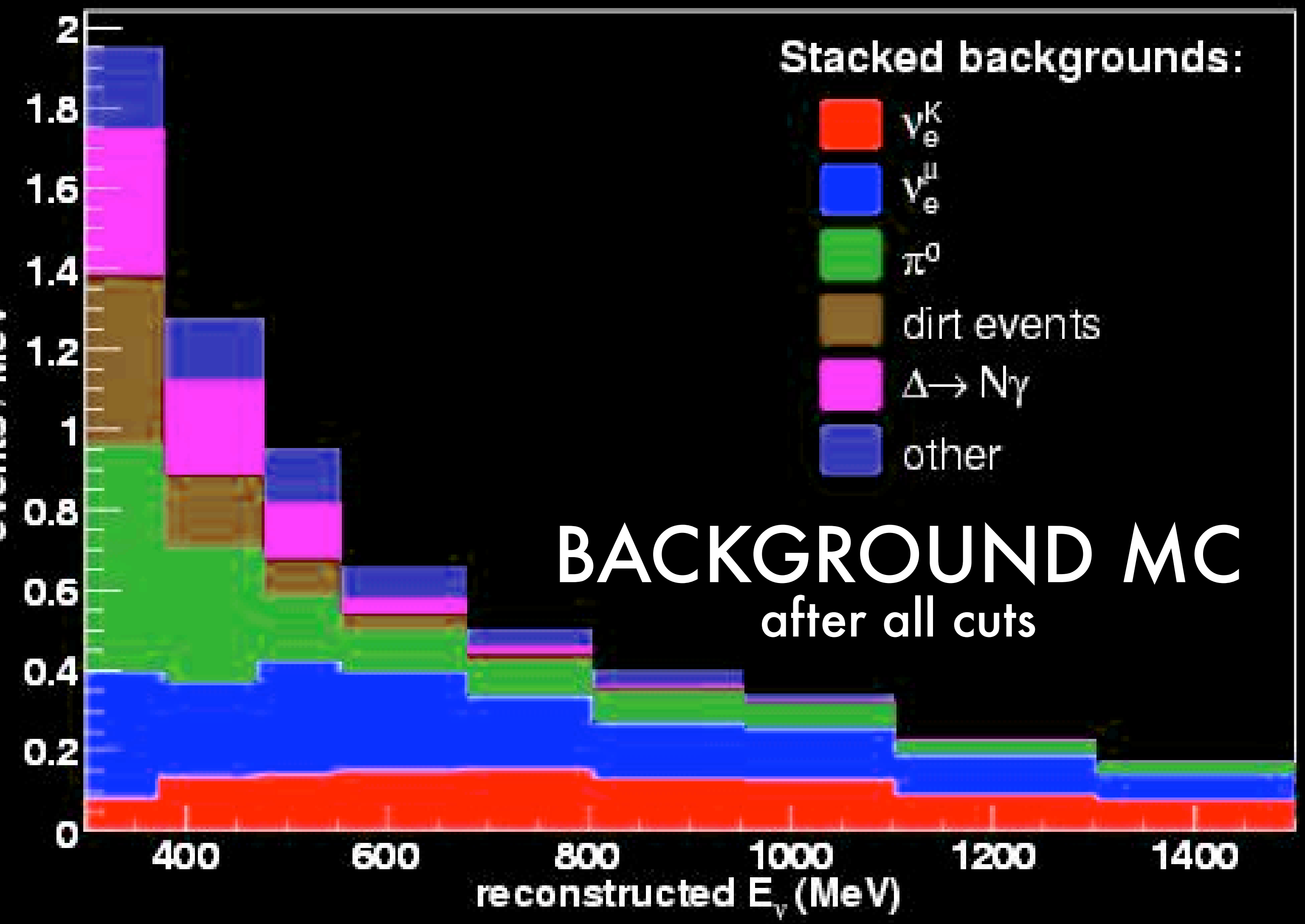
The Track-based Analysis:
Looking in the sidebands

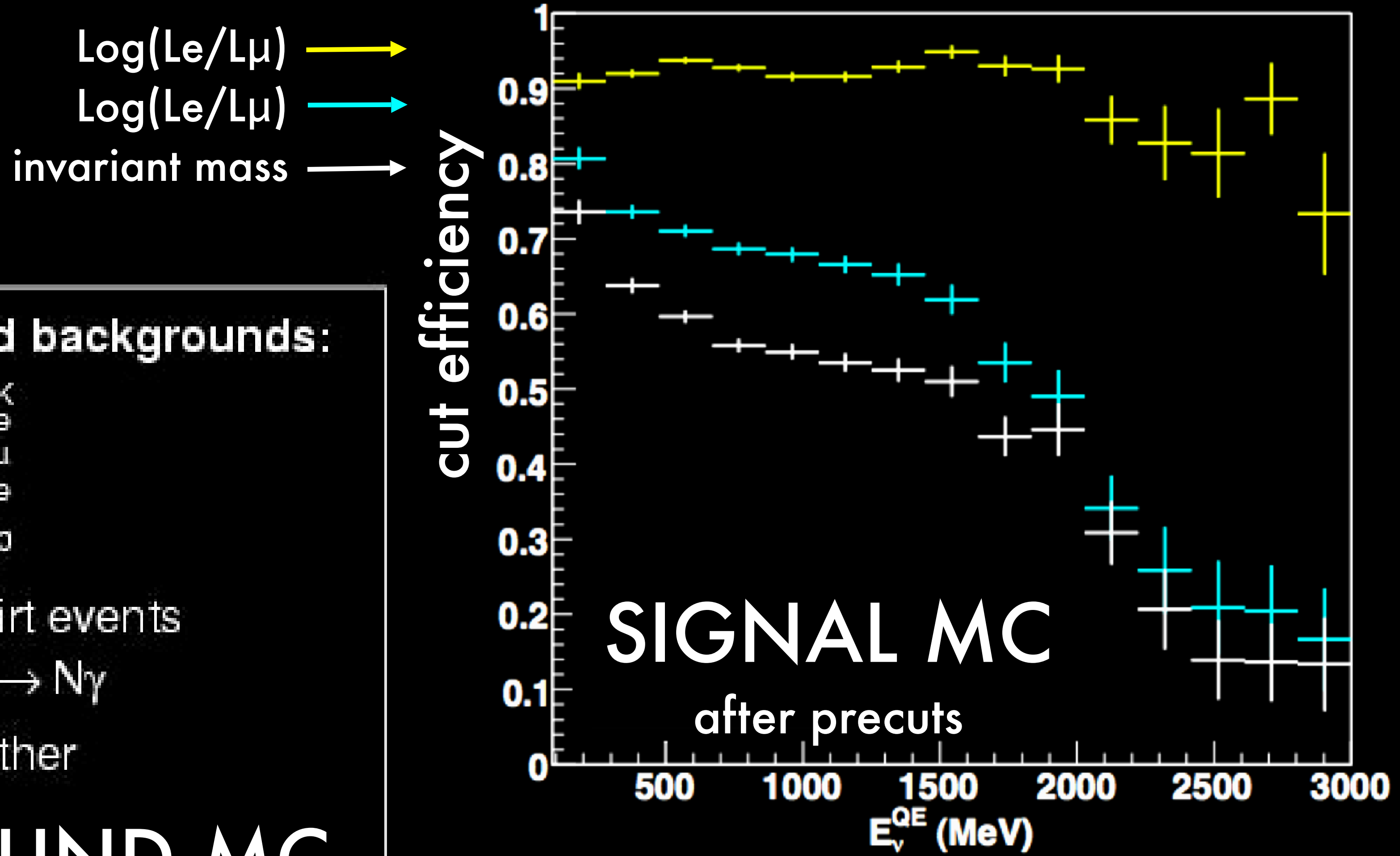
- Look at full mass range for events with $\log(L_e/L_\pi) < 0$
- These are signal-like in mass, but background-like in $\log(L_e/L_\pi)$
- Nice data/MC agreement



sideband

The Track-based Analysis:
Efficiency and backgrounds





x1500 μ rejection

x200 π^0 rejection

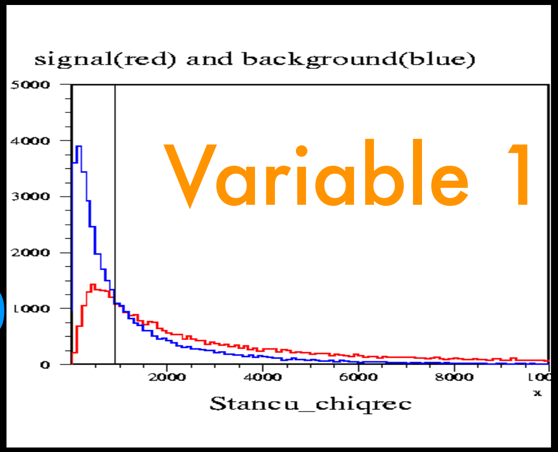
Boosted Decision Trees (BDT)

- 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

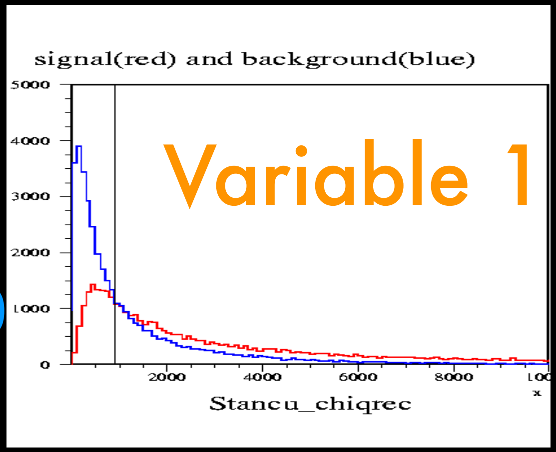
A Decision Tree

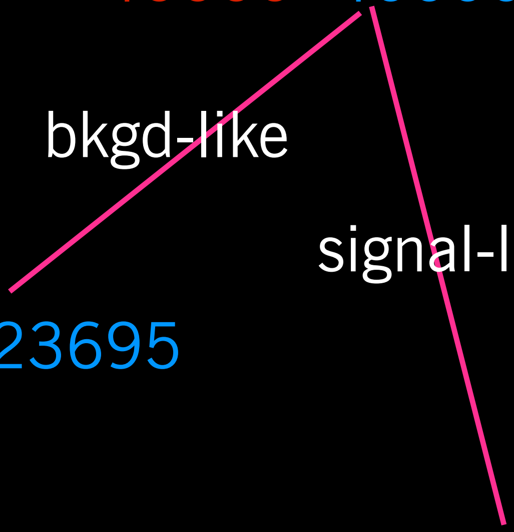
N_{signal} 40000

N_{bkgd} 40000



A Decision Tree





N_{signal} N_{bkgd}

40000 40000

bkgd-like

signal-like

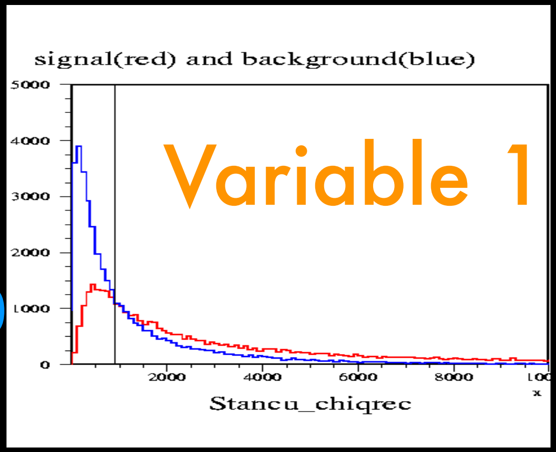
9755 23695

30,245 16,305

A Decision Tree

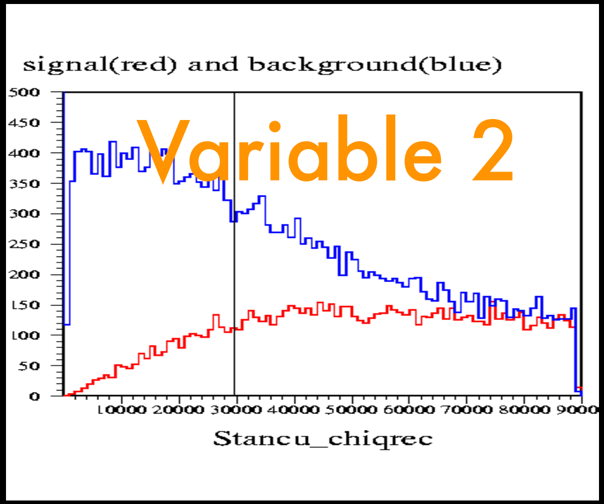
N_{signal} N_{bkgd}

40000 40000



bkgd-like

signal-like



9755 23695

30,245 16,305

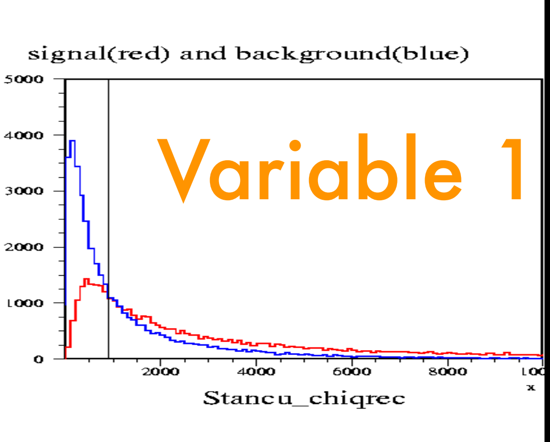
bkgd-like

signal-like

1906 11828

7849 11867

A Decision Tree

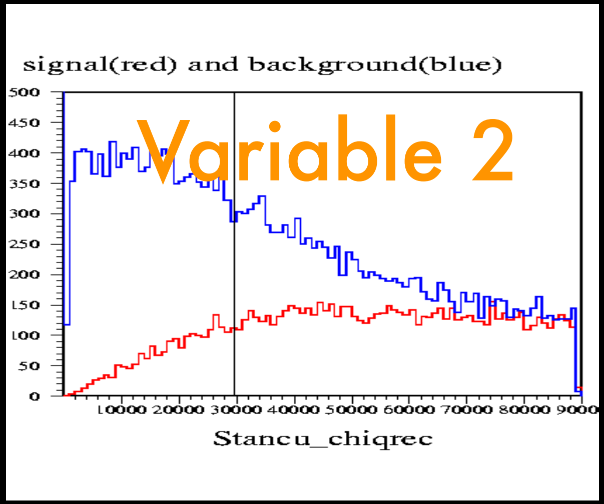


N_{signal} N_{bkgd}

40000 40000

bkgd-like

9755 23695



bkgd-like

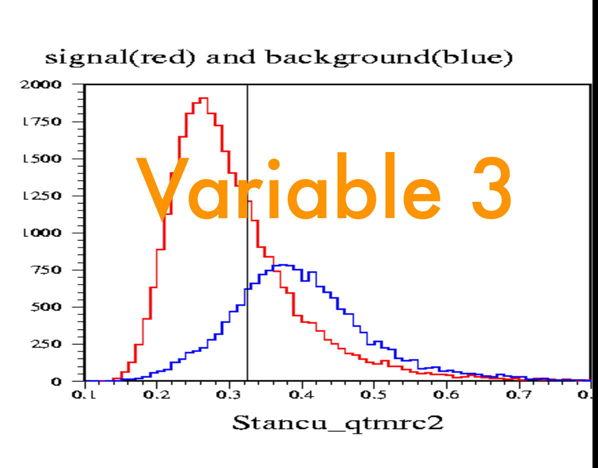
1906 11828

signal-like

7849 11867

signal-like

30,245 16,305



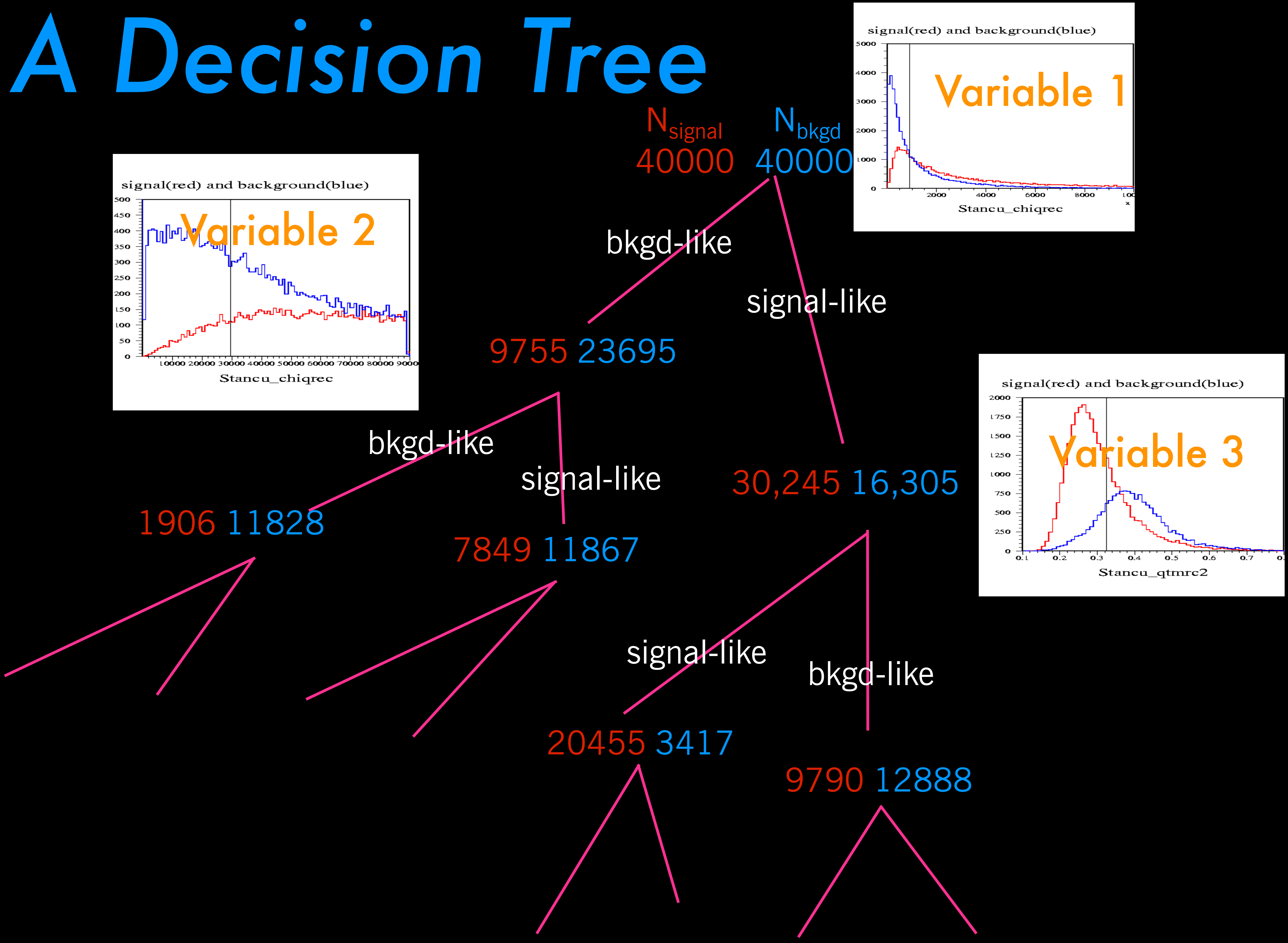
signal-like

20455 3417

bkgd-like

9790 12888

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

signal-like

bkgd-like

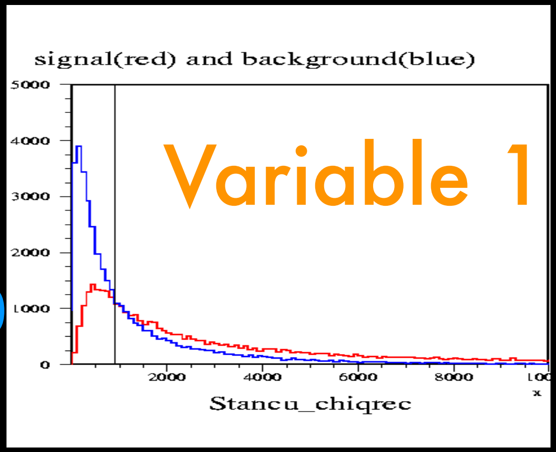
20455 3417

9790 12888

A Decision Tree

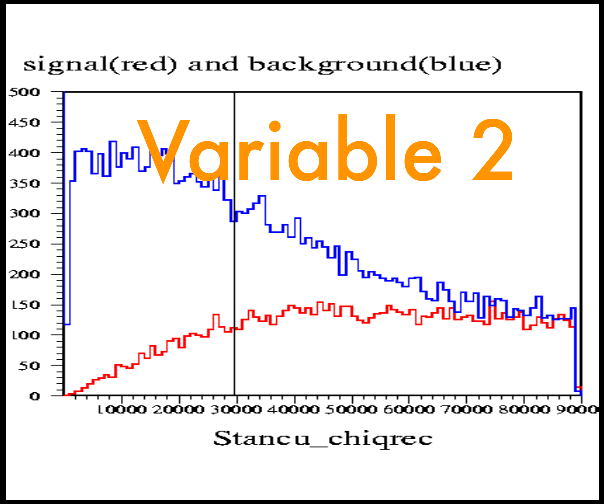
N_{signal} N_{bkgd}

40000 40000



bkgd-like

signal-like



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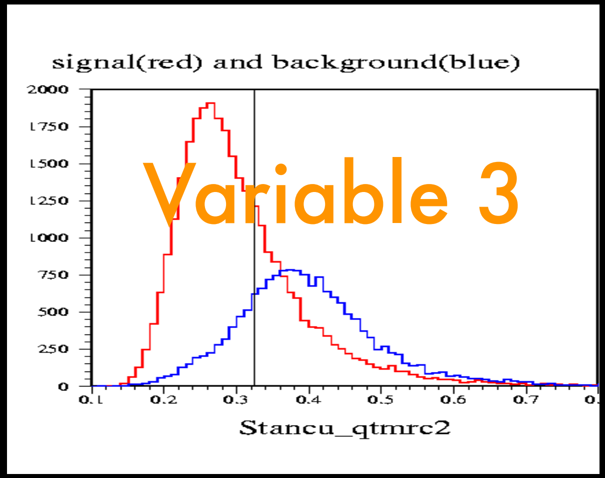


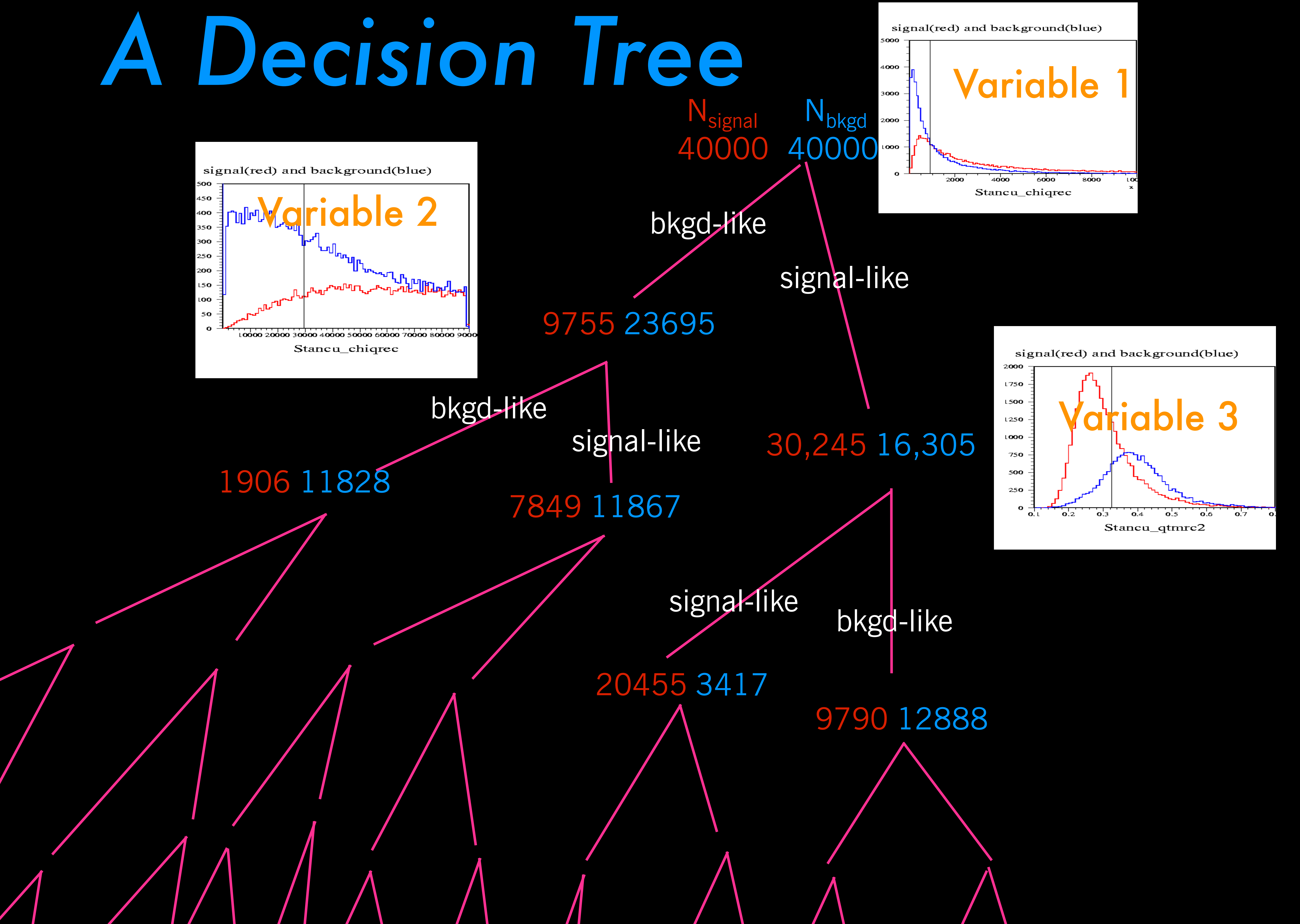
signal-like

bkgd-like

20455 3417

9790 12888

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

signal-like

bkgd-like

20455 3417

9790 12888

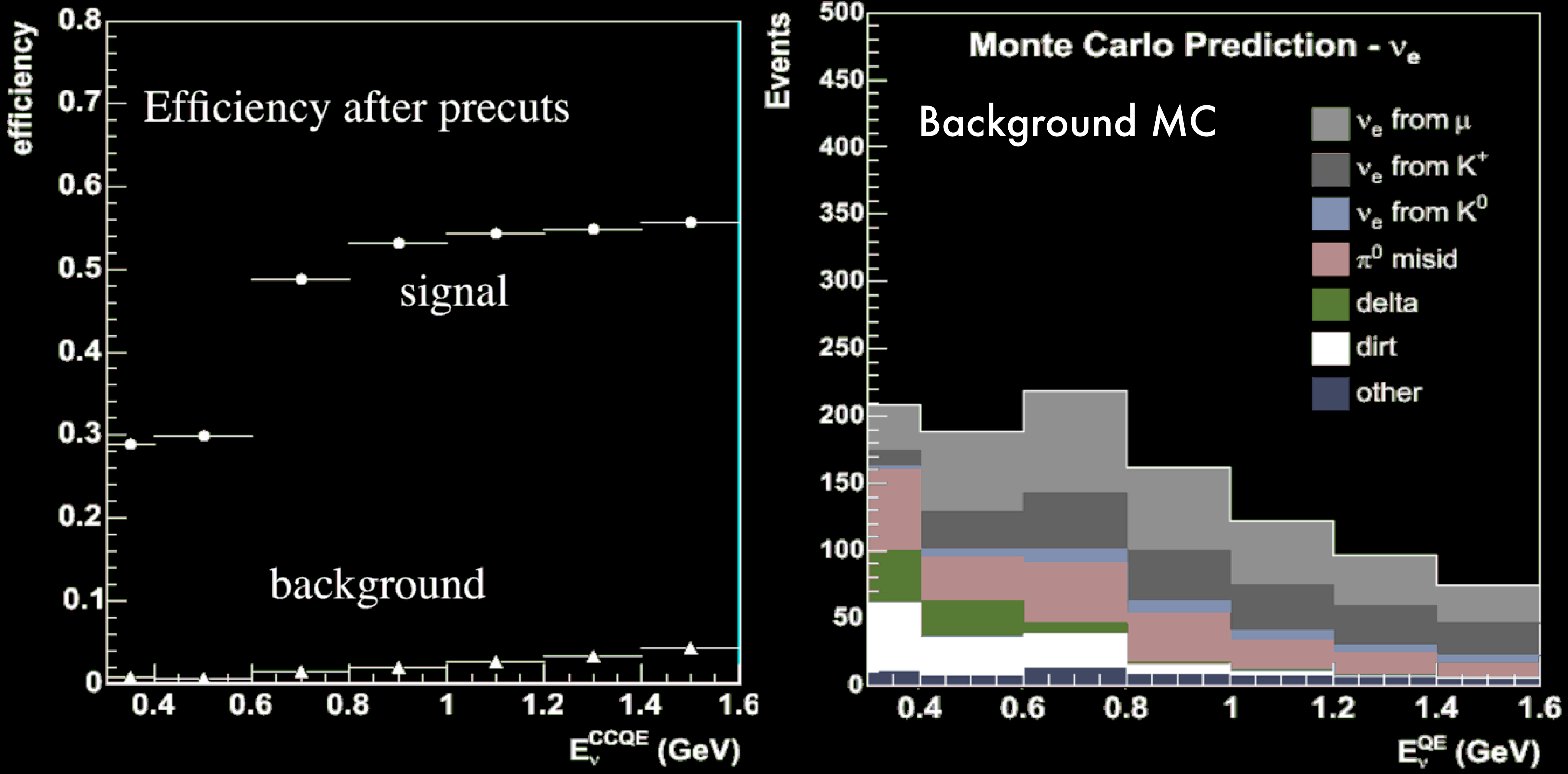
Boosted Decision Trees (BDT)

- 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

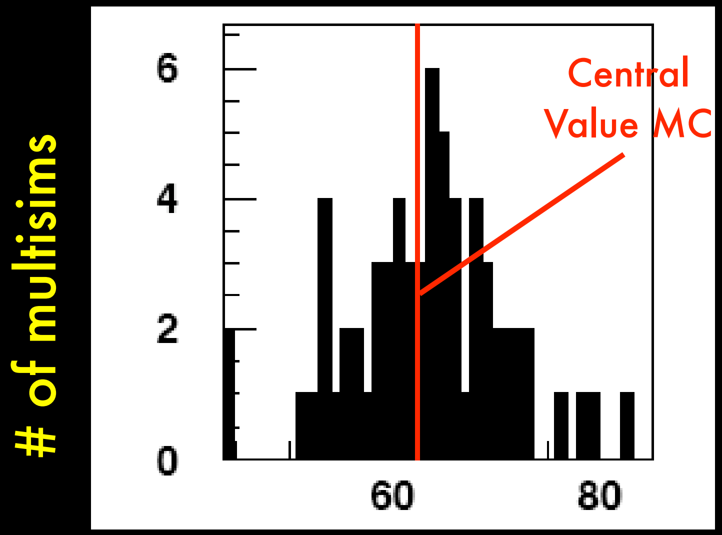
Parameter	Error/Value	Source
M_A^{QE}, E_{lo}^{SF}	6%, 2% (stat+bkg)	MiniBooNE ν_μ CCQE
QE σ norm	10%	MiniBooNE ν_μ CCQE
NC π^0 rate	few % (depends on p_π)	MiniBooNE NC π^0 data
$\Delta \rightarrow N\gamma$ rate	$\sim$ 10%	MiniBooNE NC π^0 data, $\Delta \rightarrow N\gamma$ BR
E_B, p_F	9 MeV, 30 MeV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



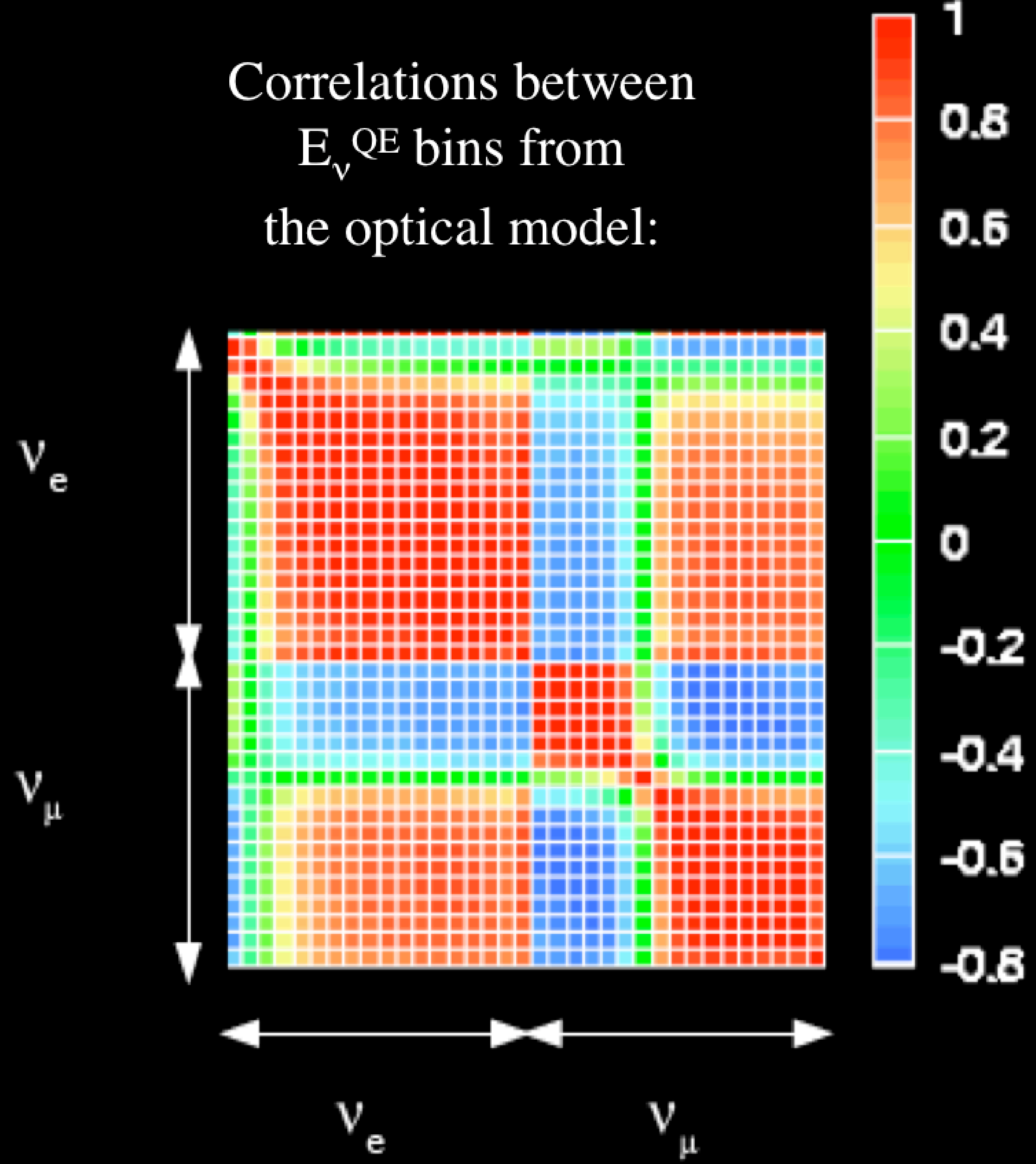
events passing signal cuts in bin $500<E_\nu^{QE}<600$ MeV

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



Correlations between E_ν^{QE} bins from the optical model:

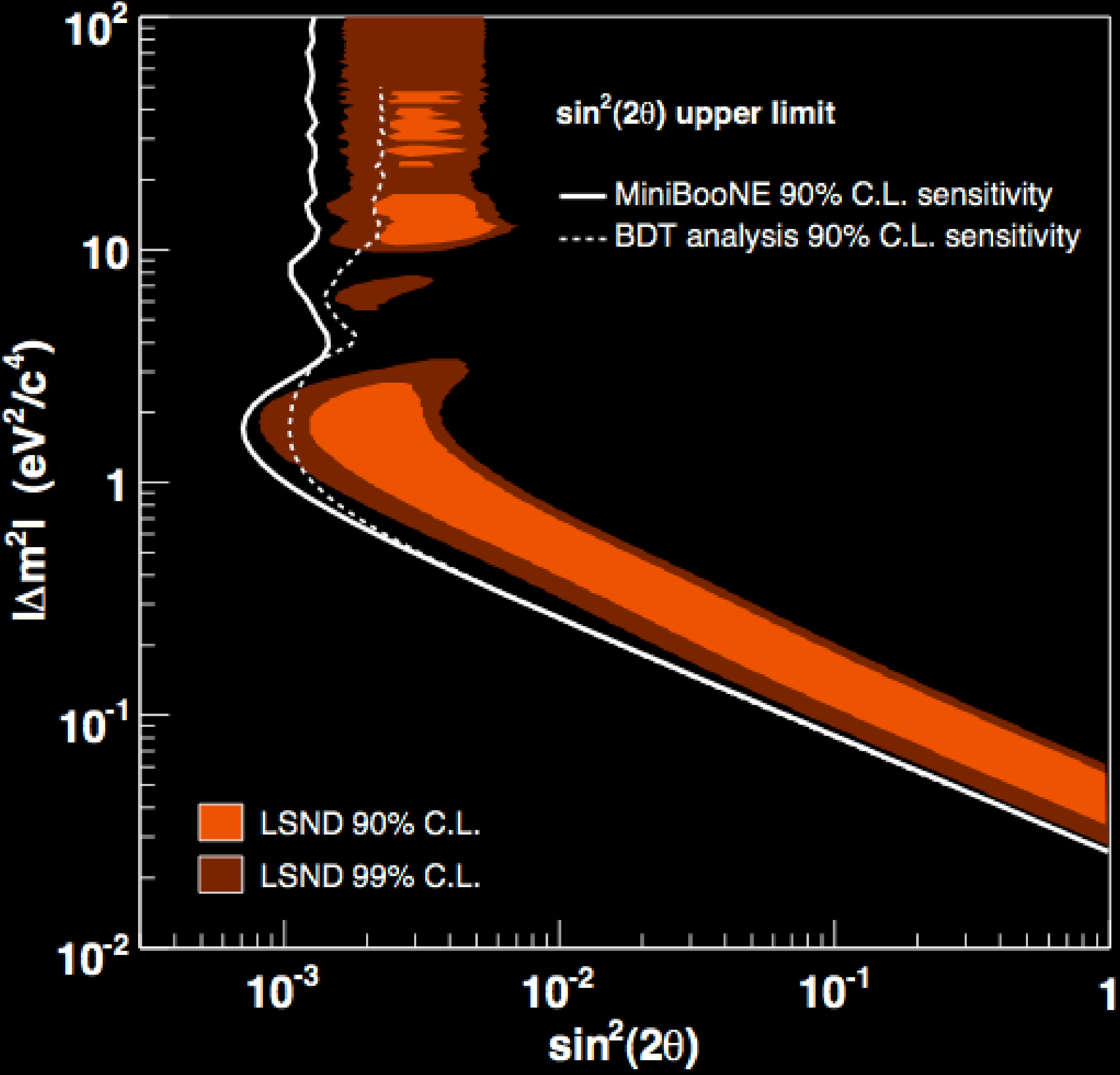
Expected background events by source (Track-based analysis)

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

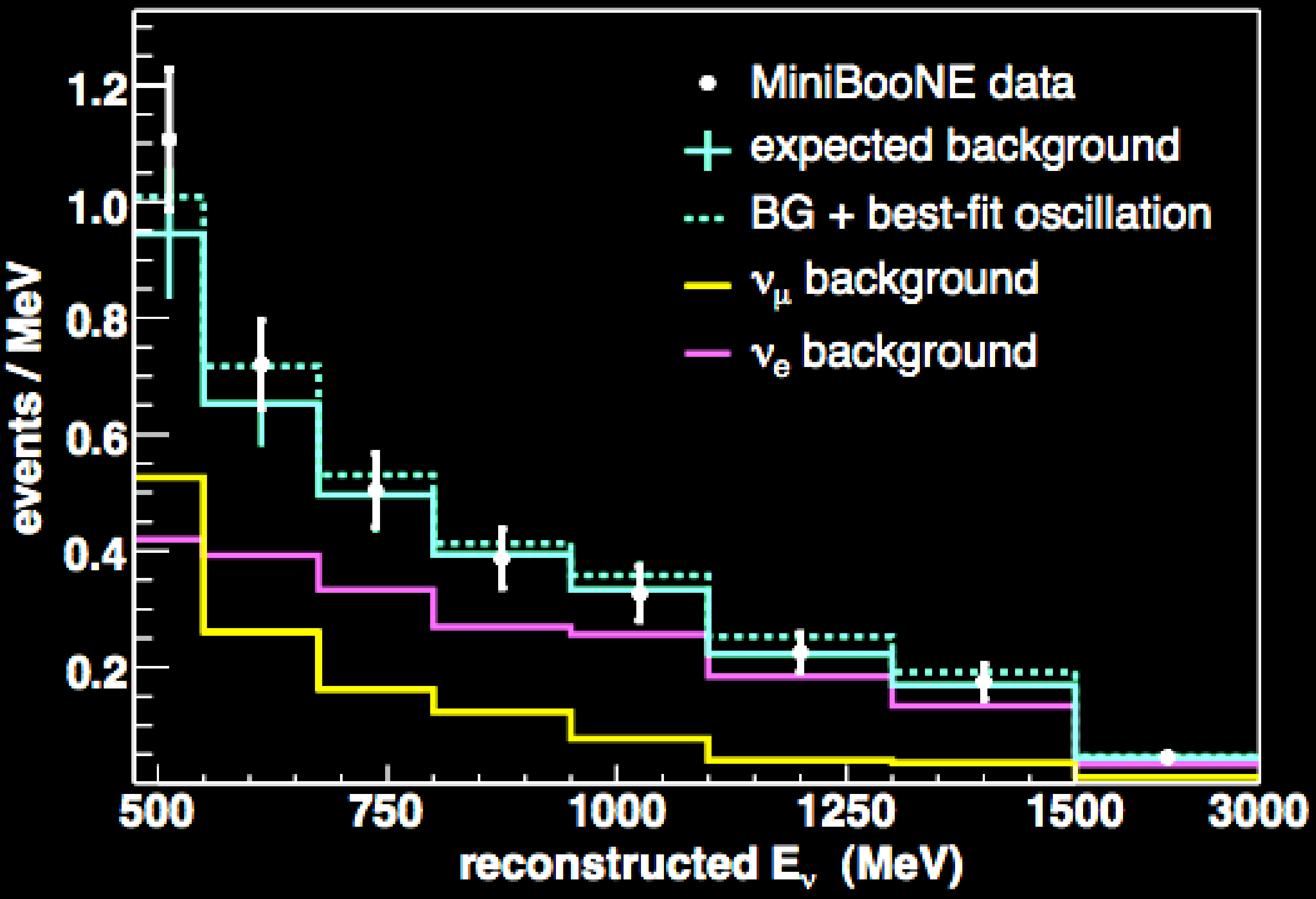
- First step:
    - Perform fit, but do not report results
    - Return χ^2 probability for a set of diagnostic variables, *not* including the quasielastic energy on which the fit is performed, compared to Monte Carlo *with (still hidden) best-fit signal*
        - One distribution poor (1% CL): two 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

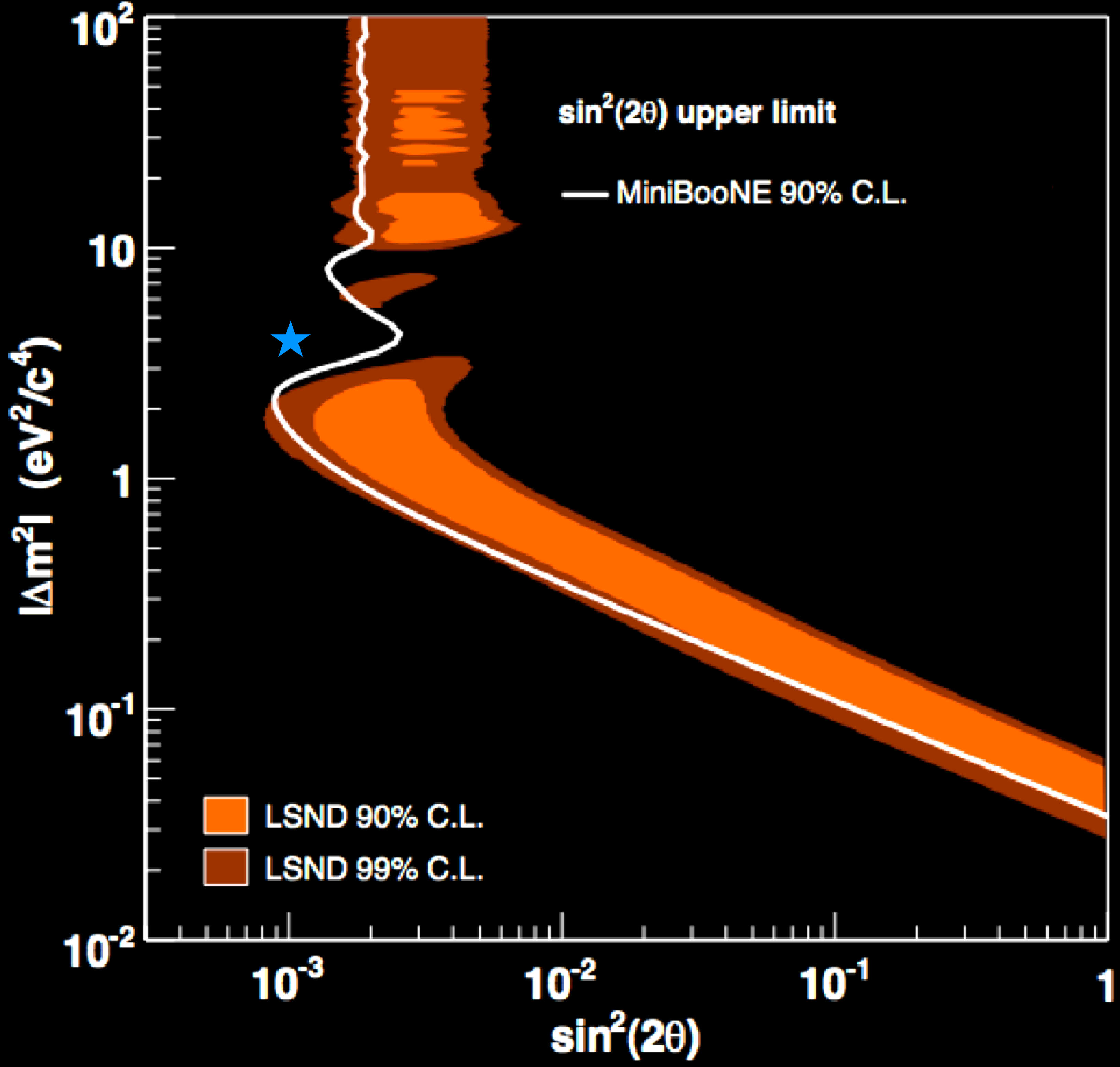
Energy fit and spectrum



- 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

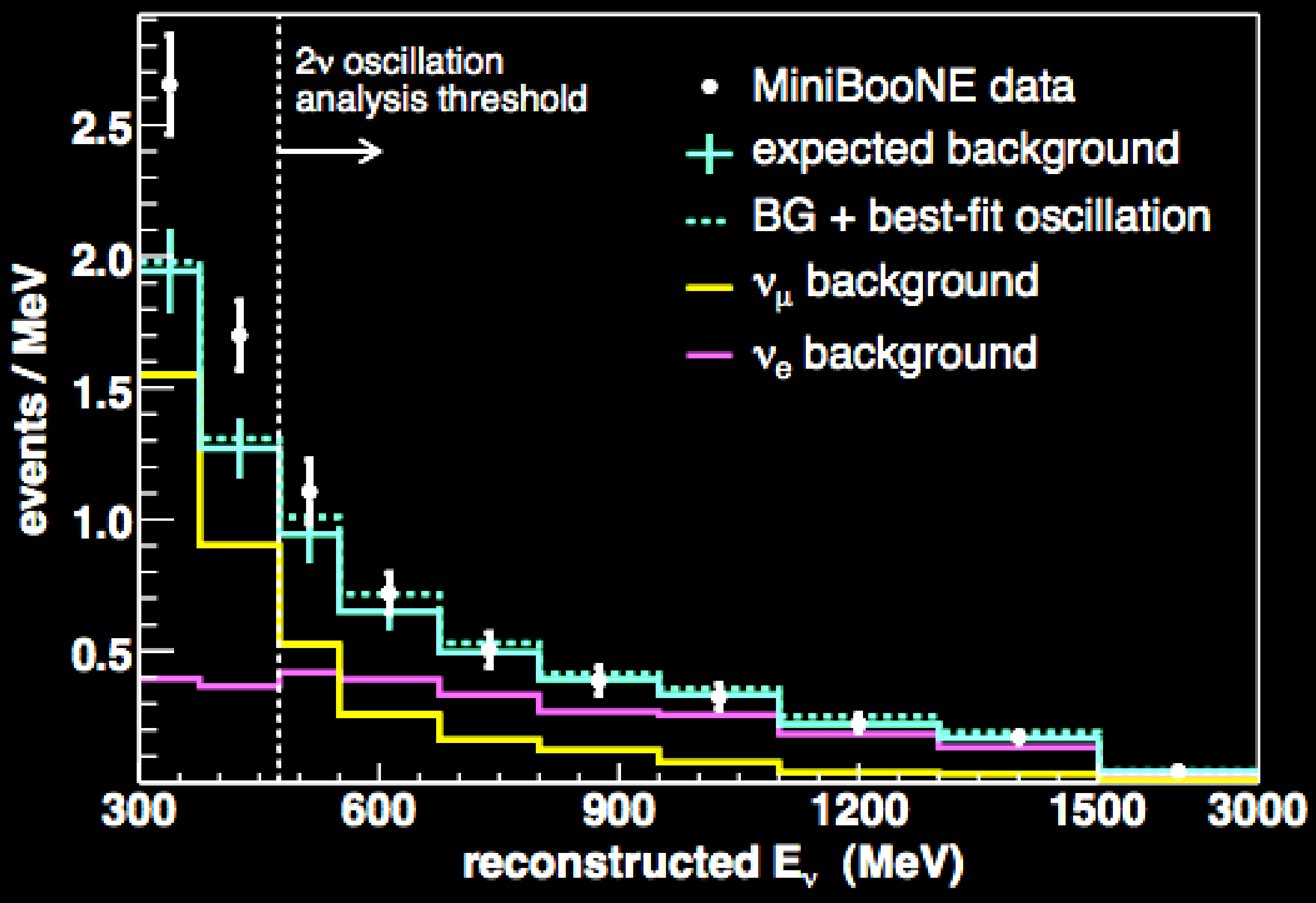
Oscillation Limit

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



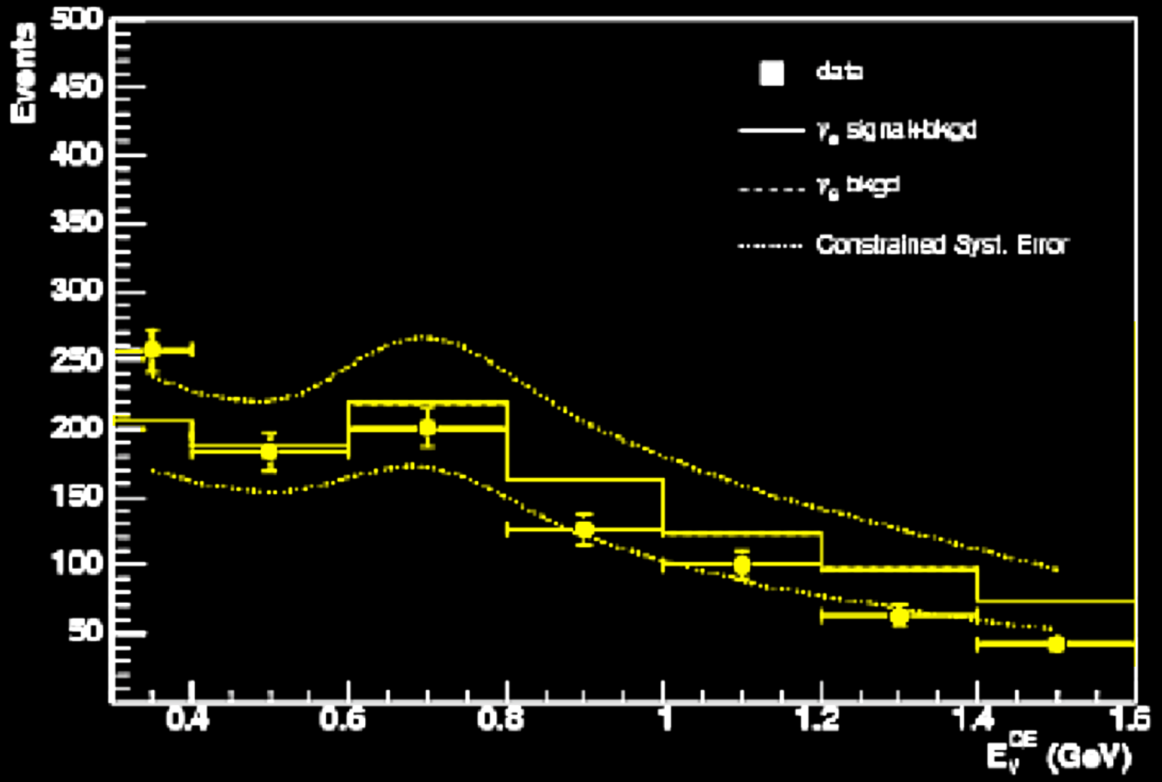
The full spectrum

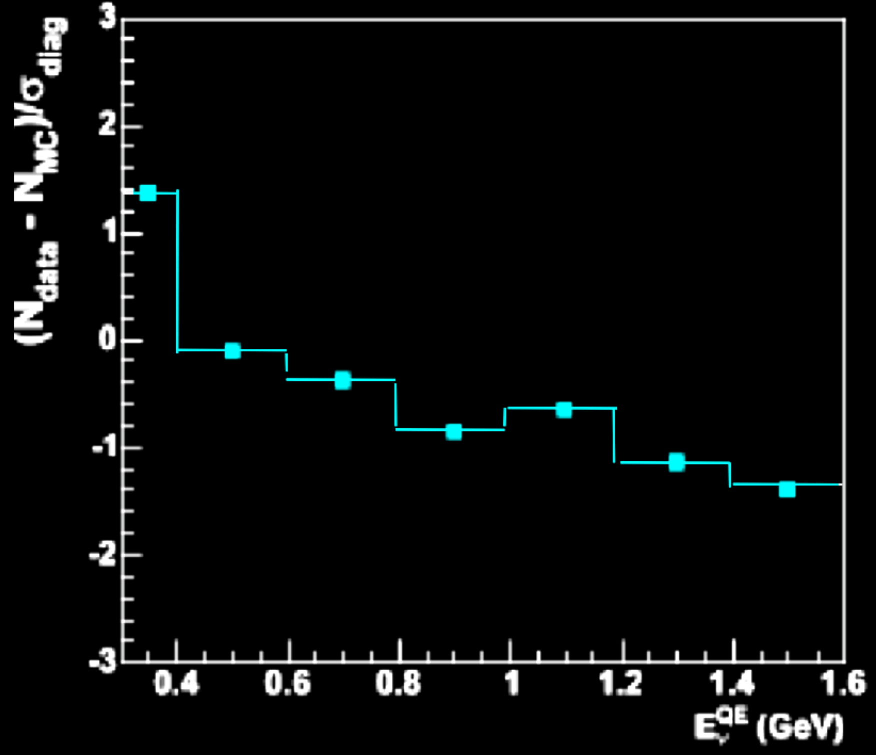
- Extending the plot down to the 300 MeV threshold
- A significant data/MC discrepancy exists in the lower bins



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: $-0.38\ \sigma$

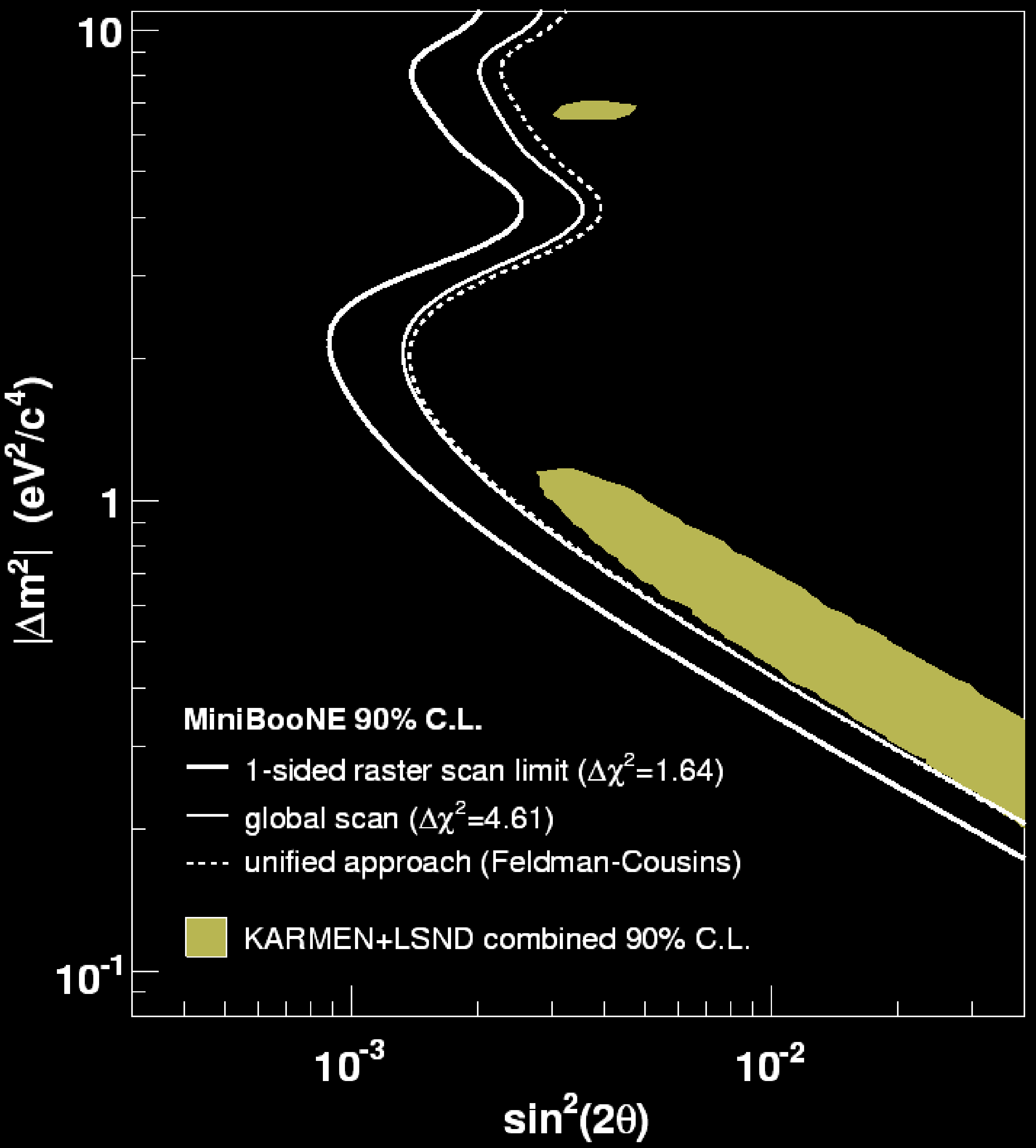




Limit curves under different confidence bound options

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:

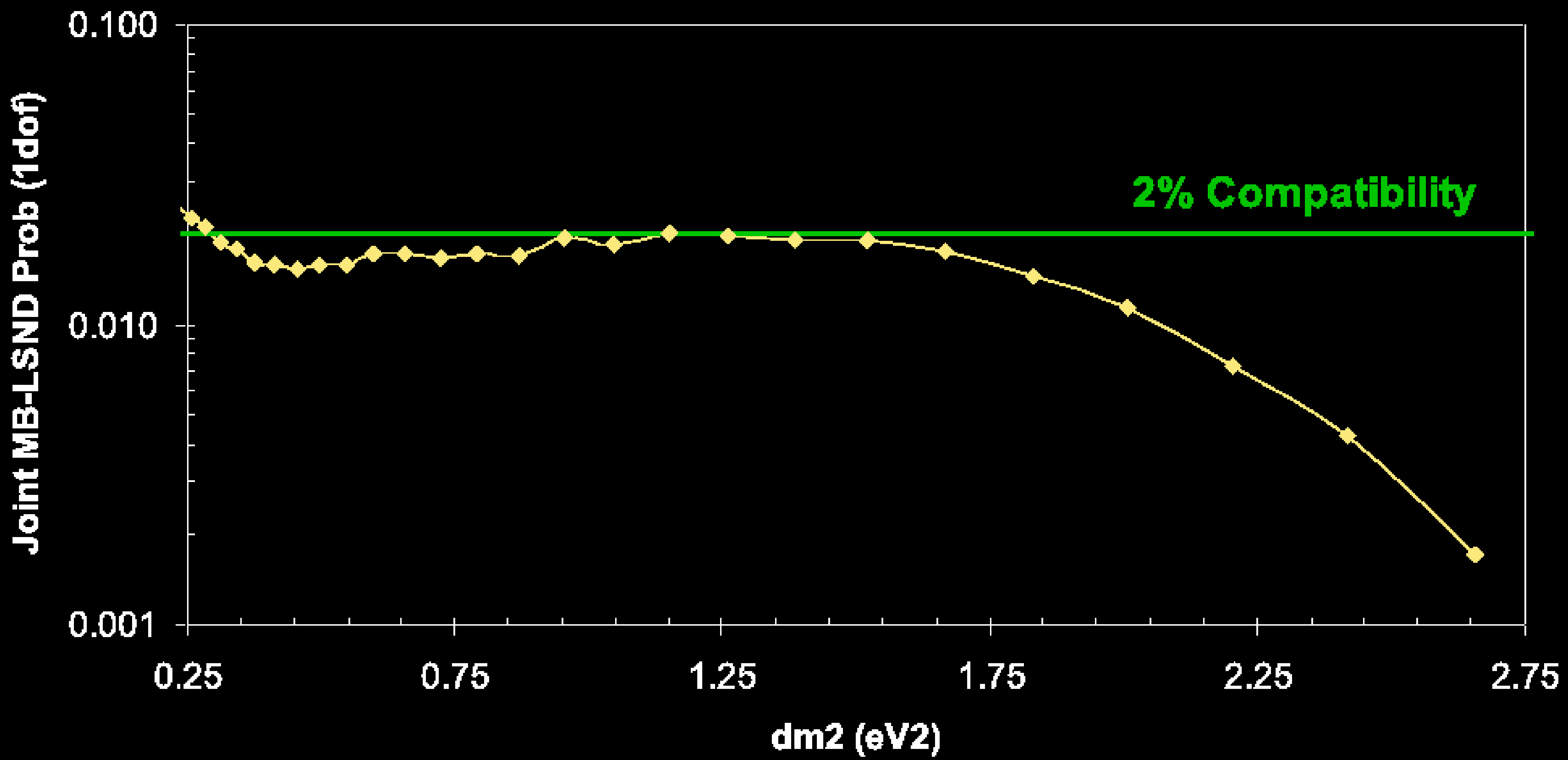
$$\chi_0^2 = \frac{z_M - z_0}{\sigma_M^2} + \frac{z_L - z_0}{\sigma_L^2}$$

- *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

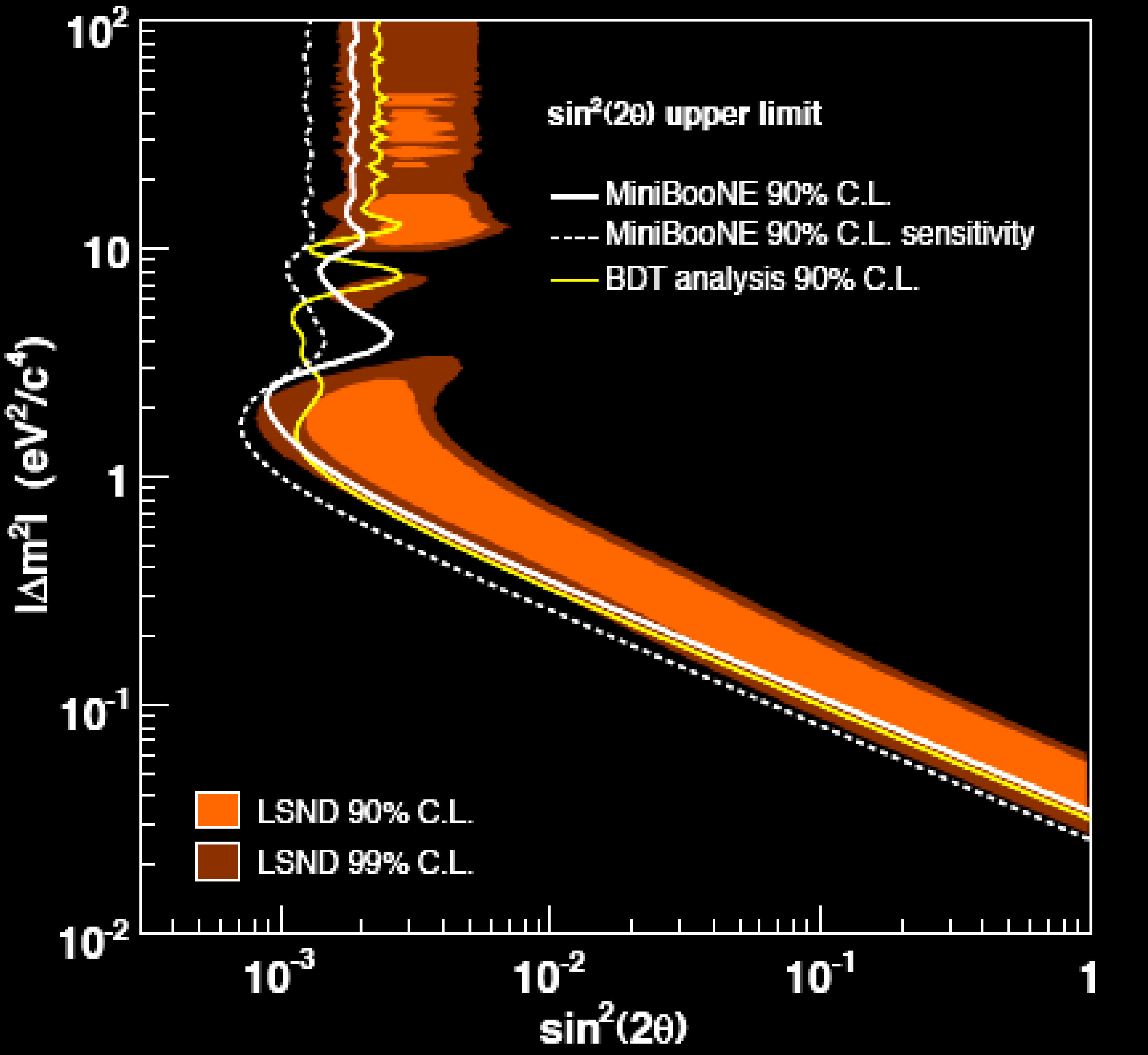


- MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance-only interpretation of LSND at 98% CL

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 $\nu_\mu \to \nu_e$ 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

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and Fermilab