RESULTS OF THE MiniBooNE NEUTRINO OSCILLATION SEARCH

E. D. Zimmerman
University of Colorado

Brookhaven National Laboratory
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Search for Neutrino Oscillations

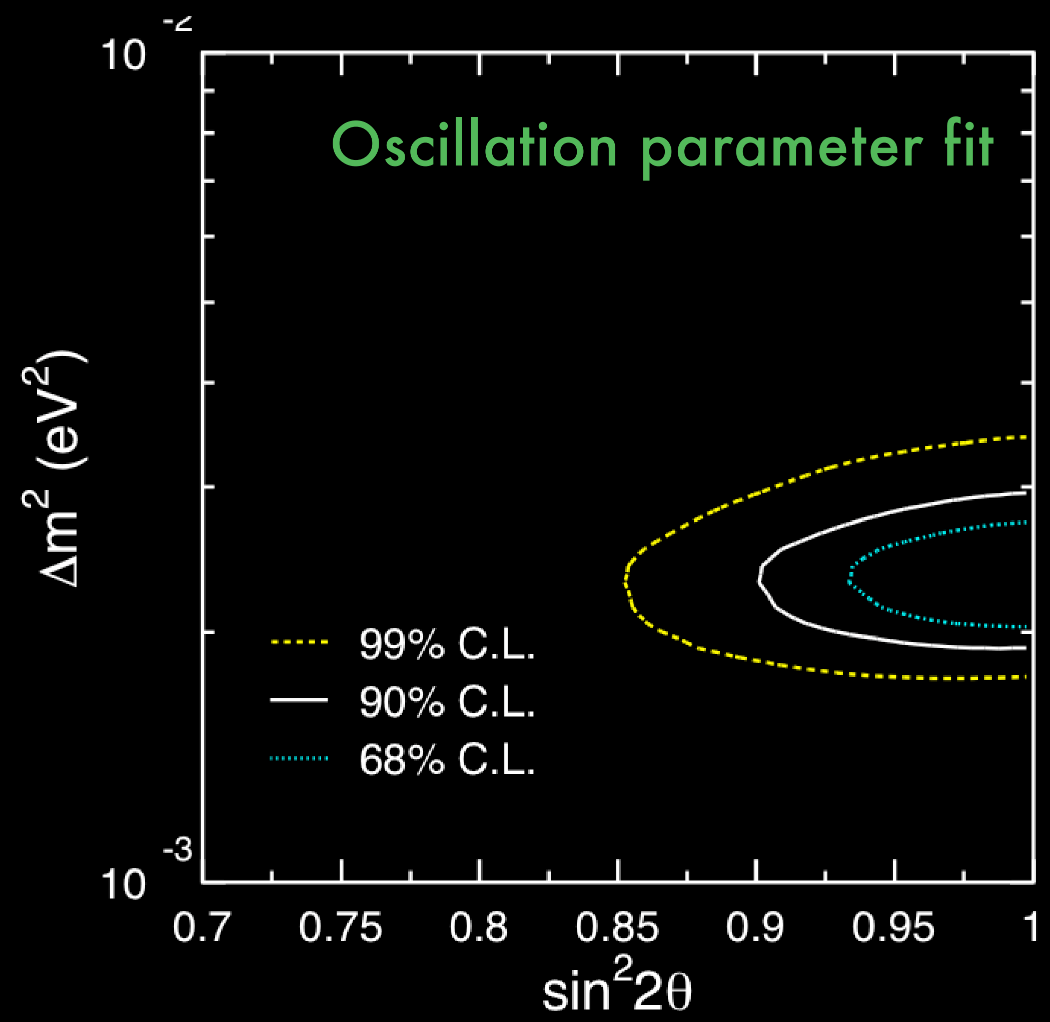
- Neutrino oscillations
- Introduction to MiniBooNE
- The oscillation analysis
- The initial results and their implications
- The next steps

Neutrino Oscillations: Experimental Evidence

- Atmospheric Neutrinos
- Solar Neutrinos
- LSND

Atmospheric Neutrinos

- Definitive discovery of oscillations, 1998 (muon disappearance only)
- ν_μ disappearance
- Disappearance confirmed in long-baseline accelerator experiments



$$\Delta m^2 \approx (2-3) \times 10^{-3} \mathrm{eV}^2/c^4$$

$$\sin^2 2\theta \approx 1$$

Assuming $\nu_\mu \to \nu_\tau$

Solar Neutrinos

- Experiments looking for solar ν_e have seen long-standing deficits in data compared to solar models
- Sudbury Neutrino Observatory (SNO) observed neutral/charged current ratio, confirming flavor mixing as the solution to solar neutrino "problem"
- KamLAND observed disappearance of reactor antineutrinos: confirmed oscillations and resolved an ambiguity in Δm^2.

$$\Delta m^2 \approx 10^{-4} \mathrm{eV}^2/c^4$$

ν_e disappearance

$$\sin^2 2\theta \approx 0.8$$

LSND

- Liquid Scintillator Neutrino Detector at Los Alamos Meson Physics Facility (LAMPF) accelerator
- Neutrino source: stopped pion and muon decays
- Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
- L = 30 m, E = 30-53 MeV

LSND

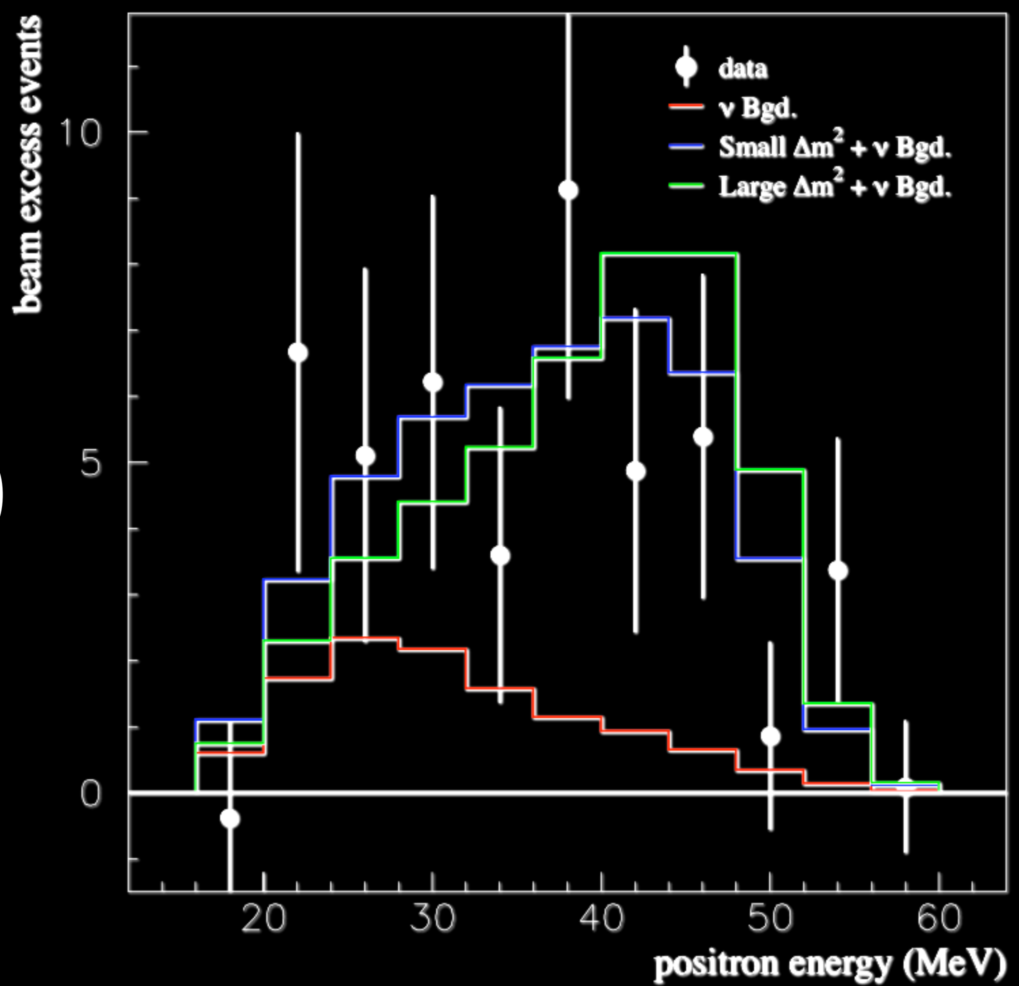
- Stopped π^+ beam at Los Alamos LAMPF produces ν_e, ν_μ, $\bar{\nu}_\mu$ but no $\bar{\nu}_e$ (due to π^- capture).

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

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

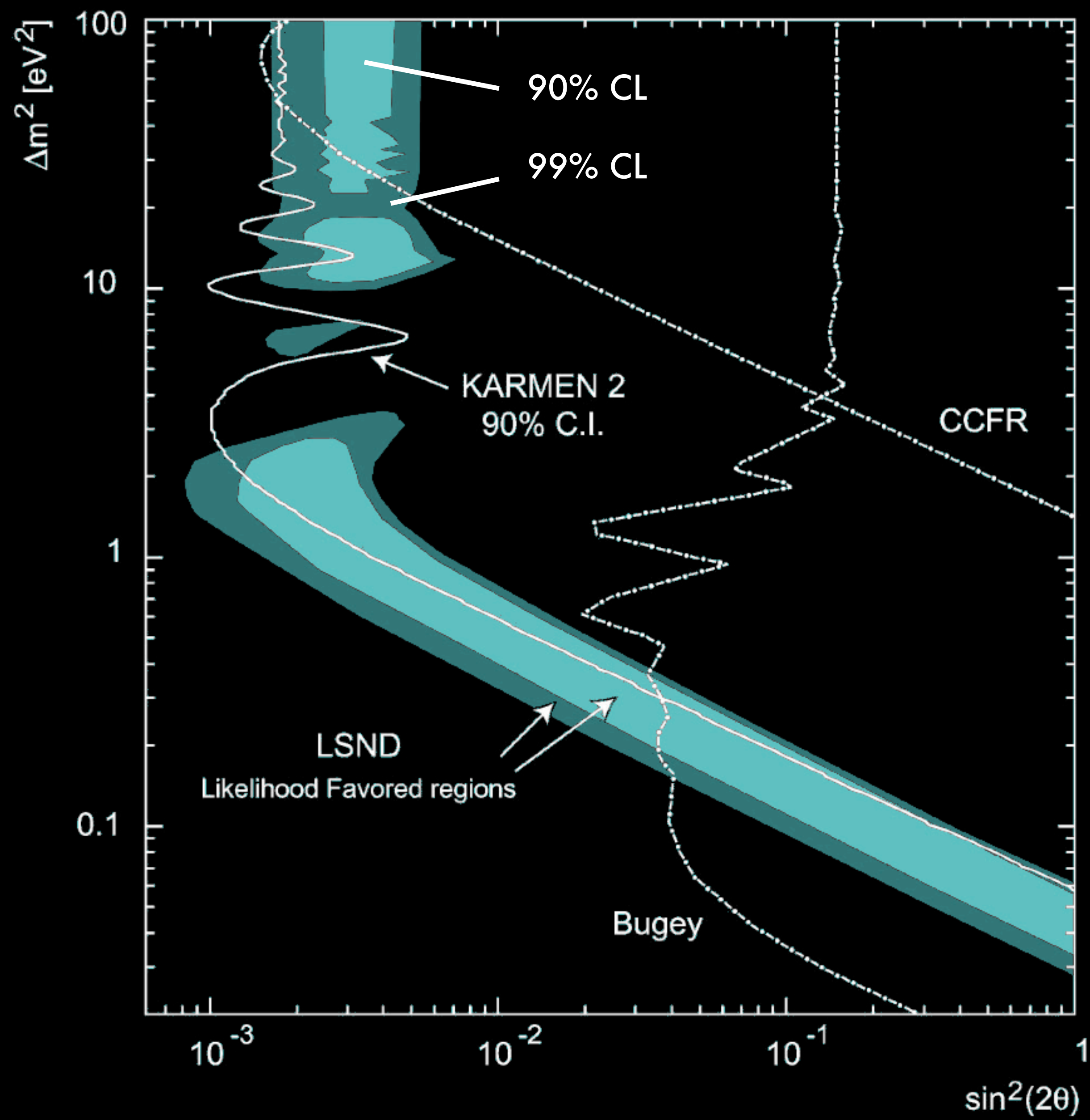
- Neutron thermalizes, captures ➨2.2 MeV γ-ray
- Look for the delayed coincidence.
- Major background non-beam (measured, subtracted)
- 4 standard dev. excess above background.
- Oscillation probability:

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



LSND oscillation signal

- LSND "allowed region" shown as band
- KARMEN2 is a similar experiment with a slightly smaller L/E; they see no evidence for oscillations. Excluded region is to right of curve.

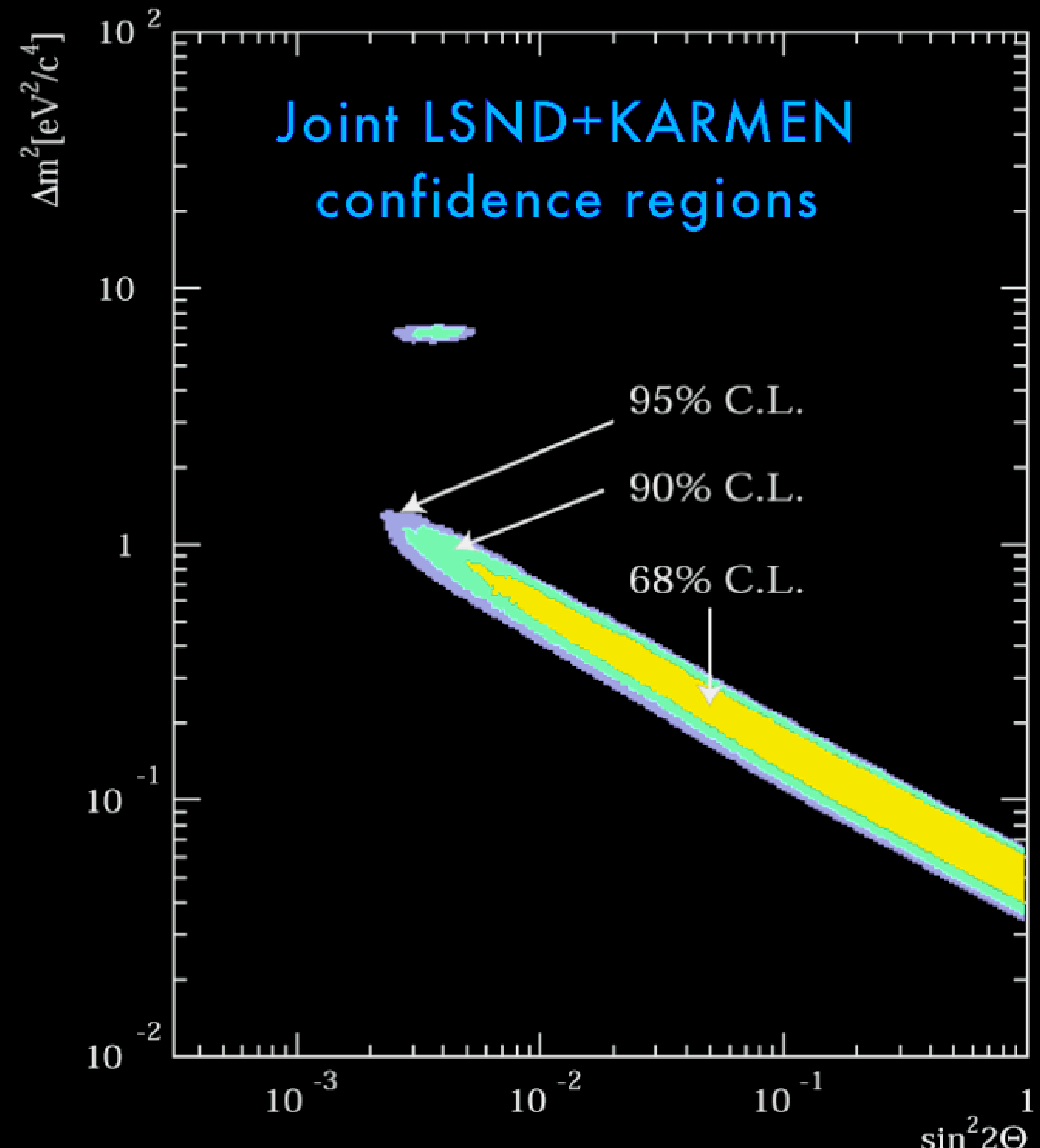


LSND Oscillation allowed region

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



The Overall Picture

$$\begin{array}{lcc} \text{LSND} & \Delta m^2 > 0.1\text{eV}^2 & \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e \\ \text{Atmos.} & \Delta m^2 \approx 2 \times 10^{-3}\text{eV}^2 & \nu_\mu \leftrightarrow \nu_? \\ \text{Solar} & \Delta m^2 \approx 10^{-4}\text{eV}^2 & \nu_e \leftrightarrow \nu_? \end{array}$$

With only 3 masses, can't construct 3 Δm^2 values of different orders of magnitude!

- Is there a fourth neutrino?
  - If so, it can't interact weakly at all because of Z^0 boson resonance width measurements consistent with only three neutrinos.
- We need one of the following:
  - A "sterile" neutrino sector
  - Discovery that one of the observed effects is not oscillations
  - A new idea

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.

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 two-flavor, appearance-only scenario
- Tests LSND in models where neutrinos and antineutrinos have same oscillations (and Lorentz invariance is respected)

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

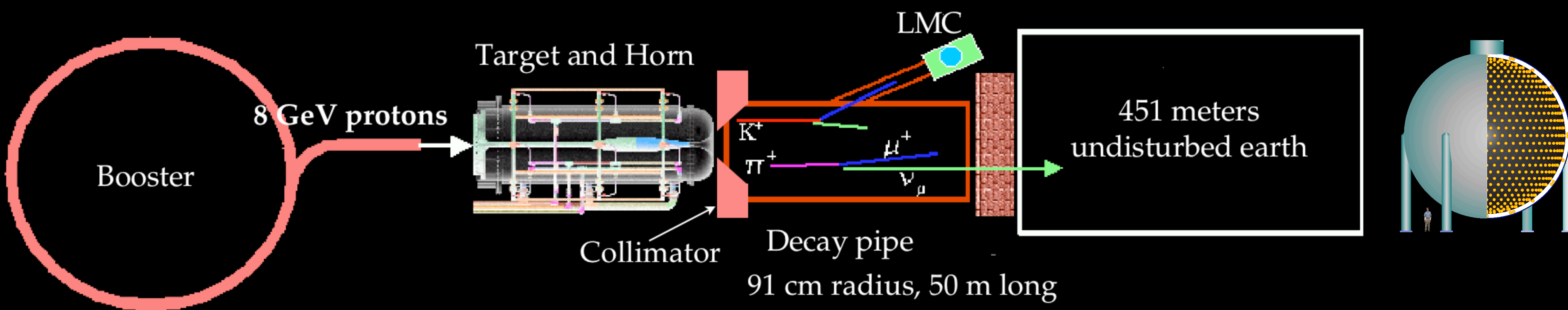
P.Nienaber
St. Mary's University of Minnesota

J. M. Link
Virginia Polytechnic Institute

E.Hawker
Western Illinois University

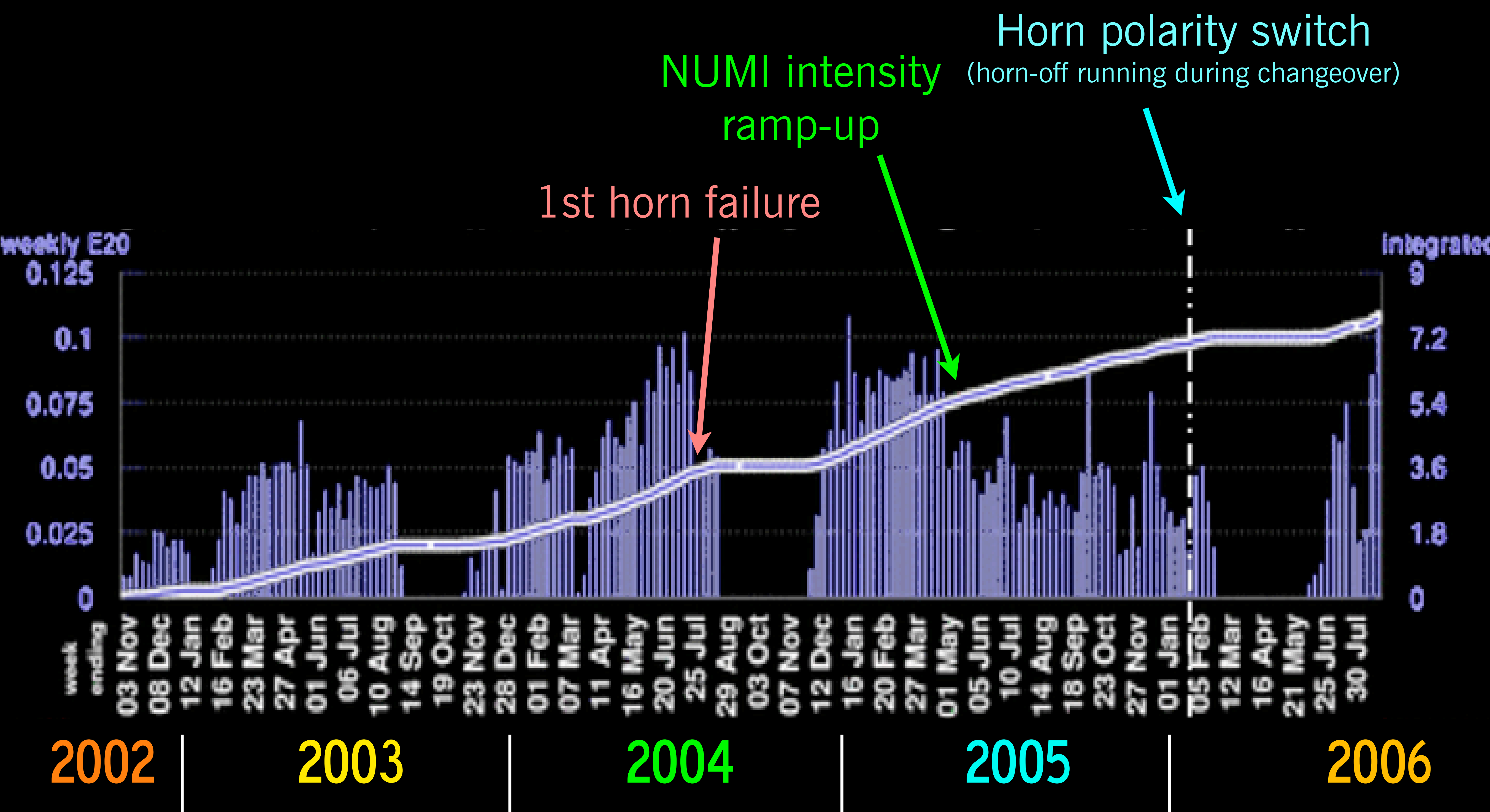
A.Curioni, B.T.Fleming
Yale University

MiniBooNE Beamline



- 8 GeV primary protons come from Booster accelerator at Fermilab
- Booster provides about 5 pulses per second, $5{\times}10^{12}$ protons per 1.6 μs pulse under optimum conditions

Beam Delivery Milestones

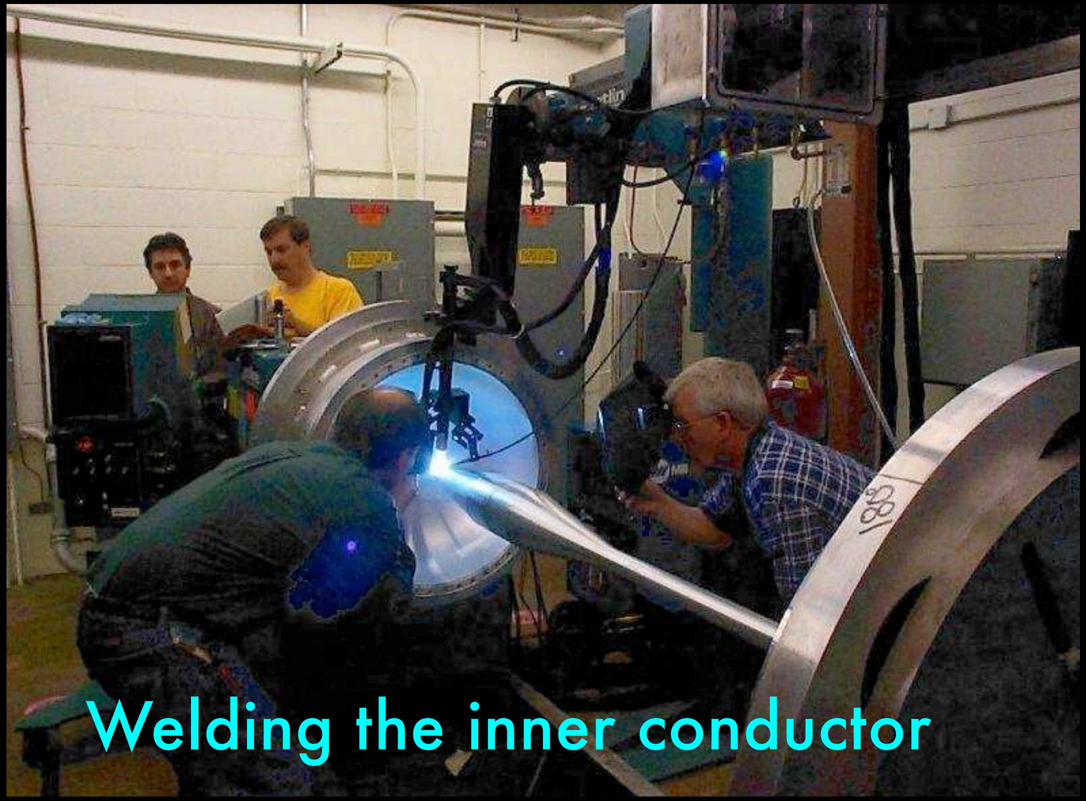


First oscillation result uses the 2002-2005 E898 data set (5.7E20 pot).

Secondary beam: horn and target

- Target is beryllium, 71 cm (1.7λ).
- Cooling tube and target are cantilevered into the neck of the horn.
- MiniBooNE horn runs at 174 kA, 140 μs pulse.
- This horn survived 96 million pulses -- a world record! -- before failing in July 2004.
- Replacement has already seen $>10^8$ pulses and shows no sign of deterioration.

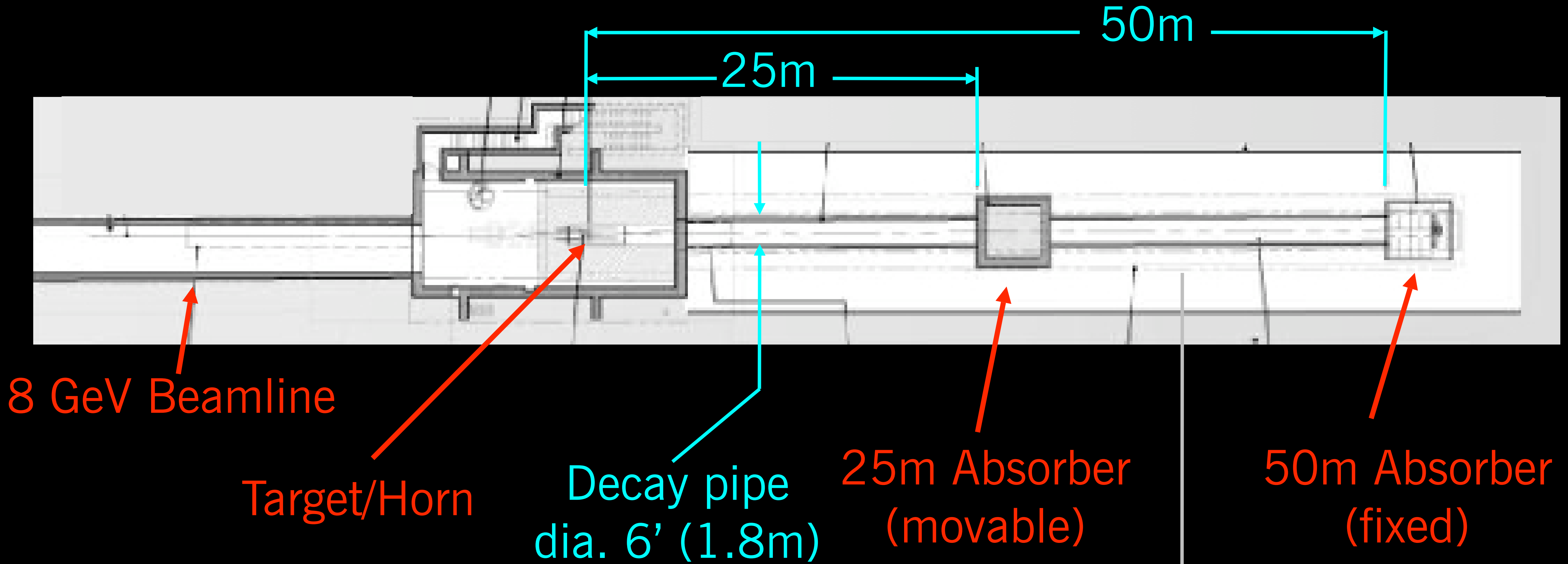
Target assembly



Welding the inner conductor

Assembled horn

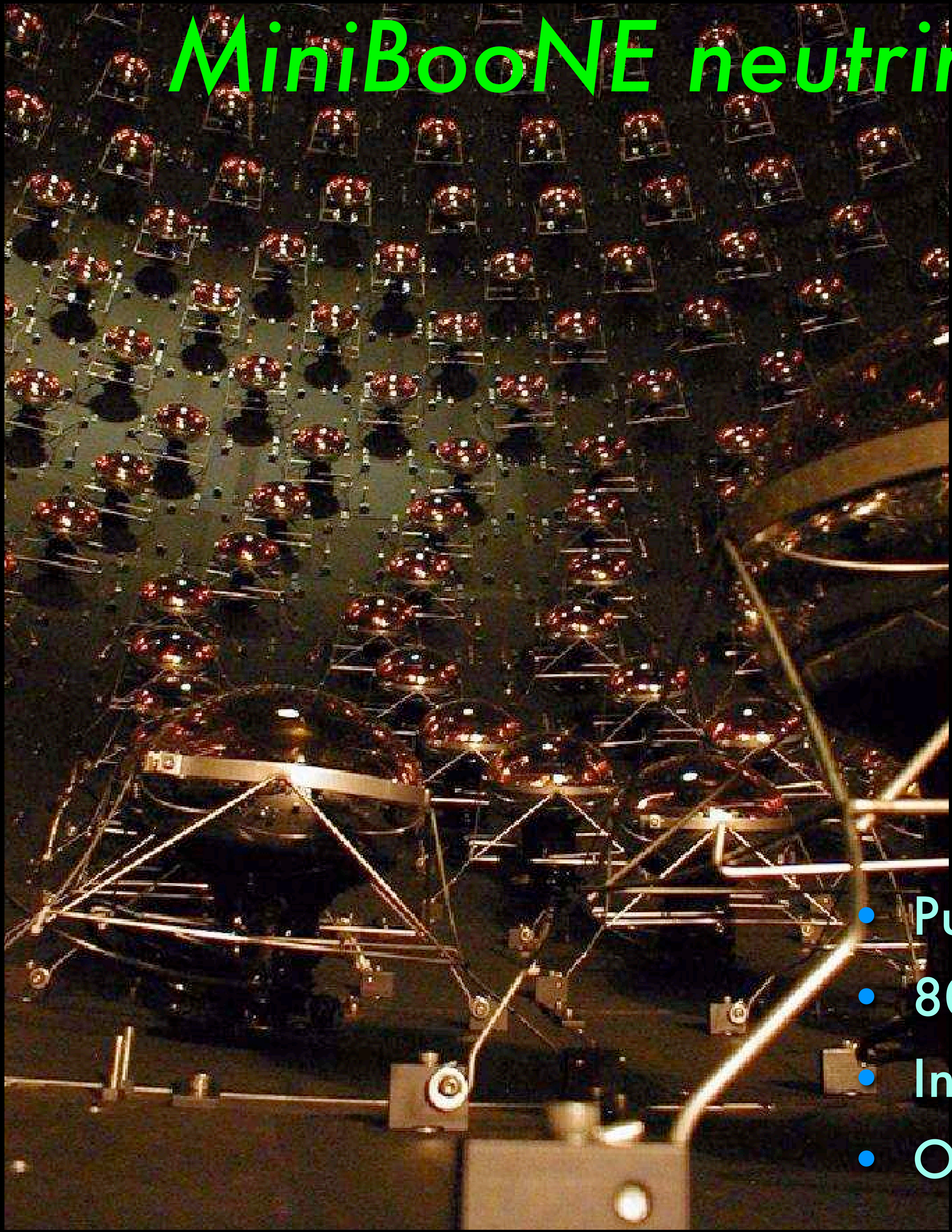
Decay Pipe and absorber

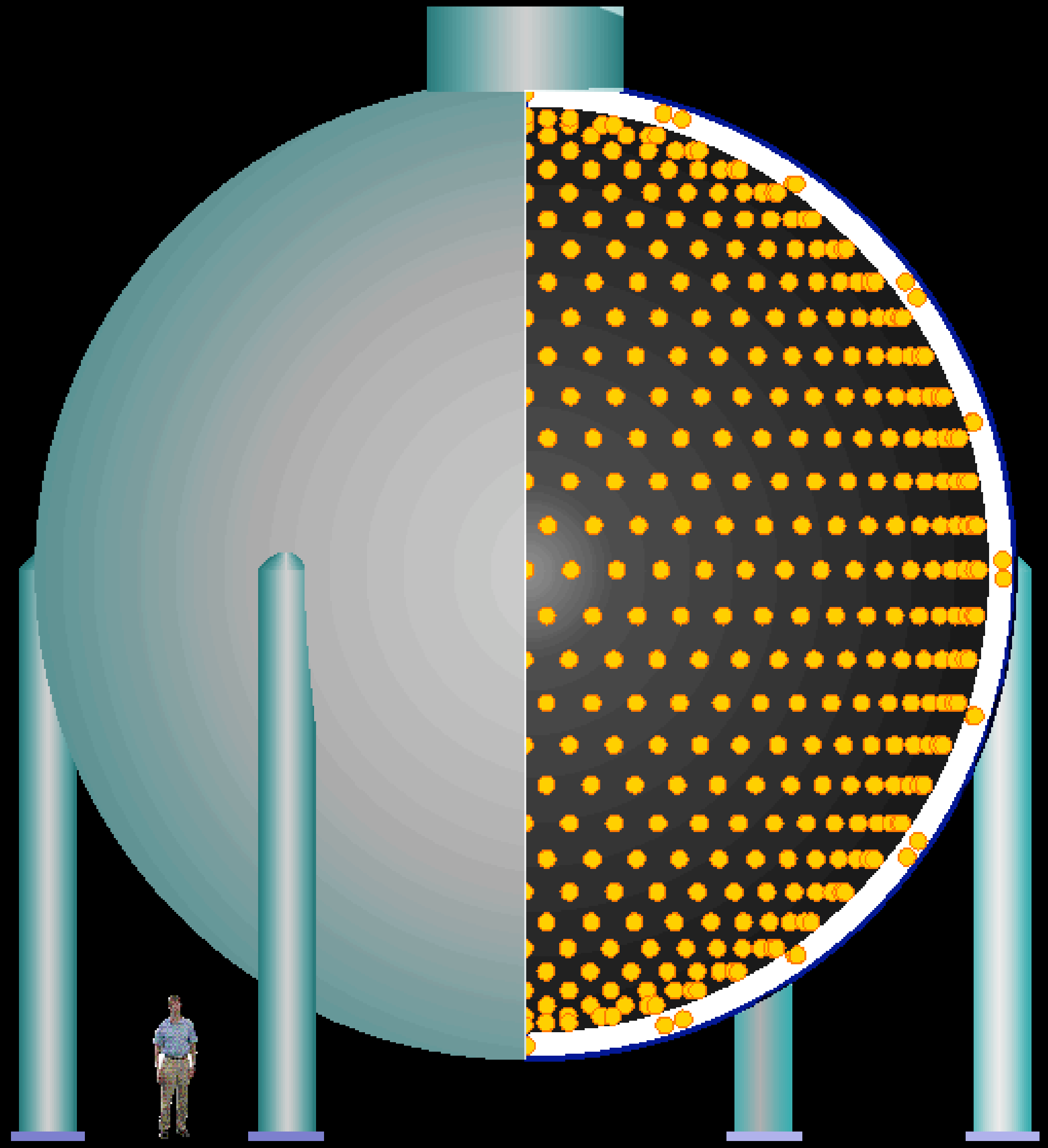


- Decay region is filled with stagnant air shared with target pile.
- The 25m Absorber is designed to be lowered in for cross-checks if MiniBooNE sees a signal.
- Both absorbers contain muon monitors.

- Shielding provided by gravel fill and earth berm above decay pipe

MiniBooNE neutrino detector



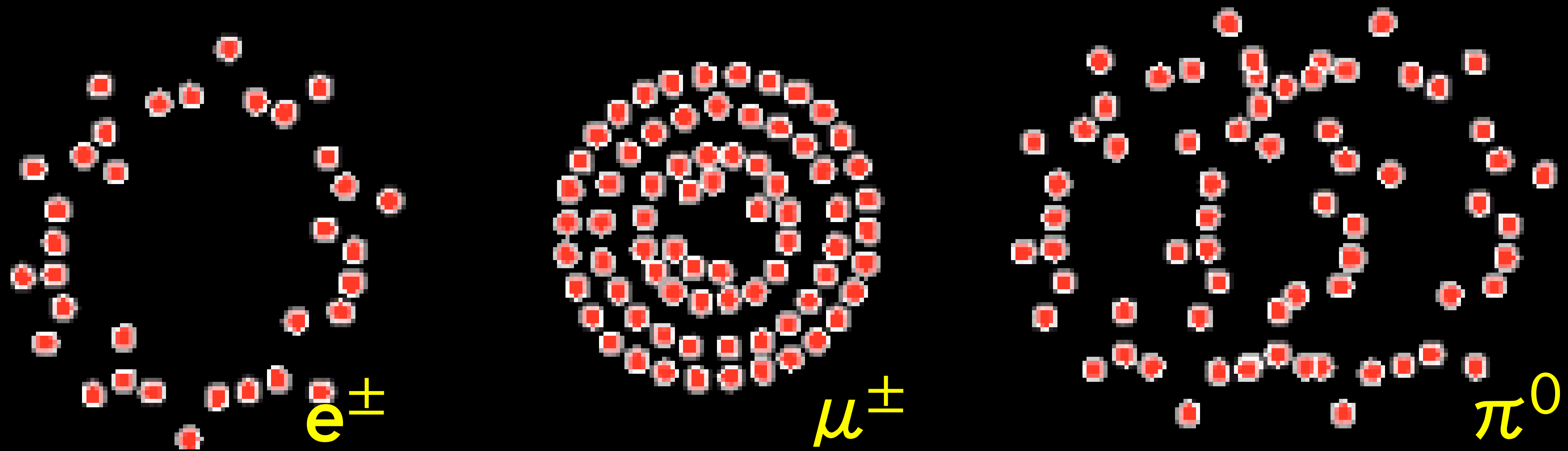


- Pure mineral oil
- 800 tons; 40 ft diameter
- Inner volume: 1280 8″ PMTs
- Outer veto volume: 240 PMTs

The detector records:

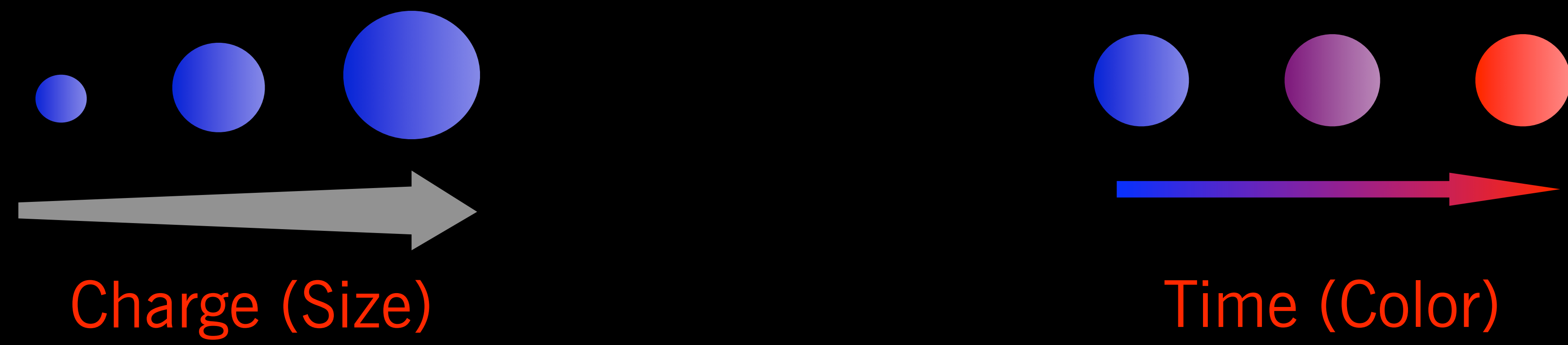
- Every 100 ns clock cycle:
  - Total charge on each PMT
    - Resolution ~1 photoelectron
  - Time of first hit on each PMT above threshold
    - Resolution ~1.5 ns
- Begin recording 4 μs before beam pulse
  - Able to check for earlier entering cosmic rays
- Stop recording 14 μs after beam pulse
  - Able to check for subsequent stopped muon decay ("Michel") electron

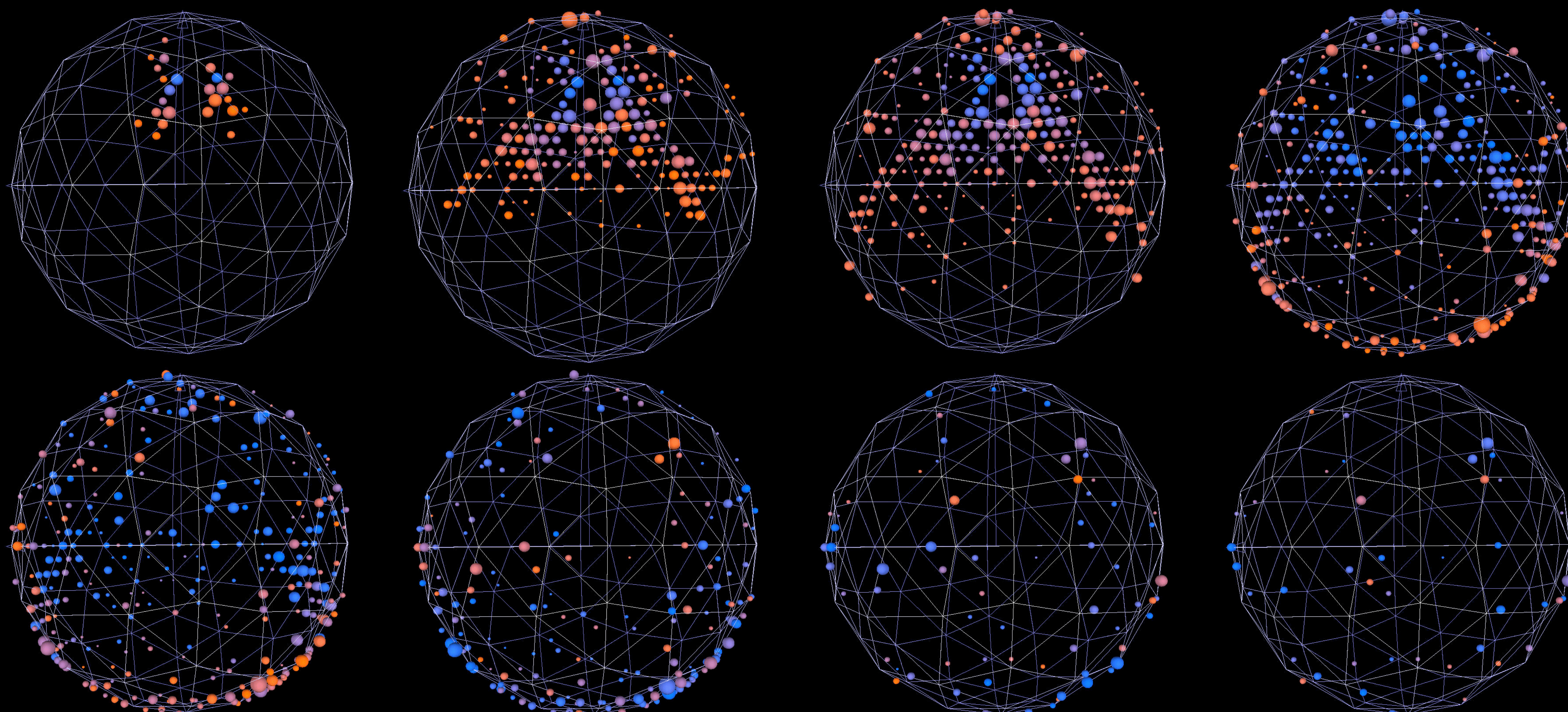
Event types:



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

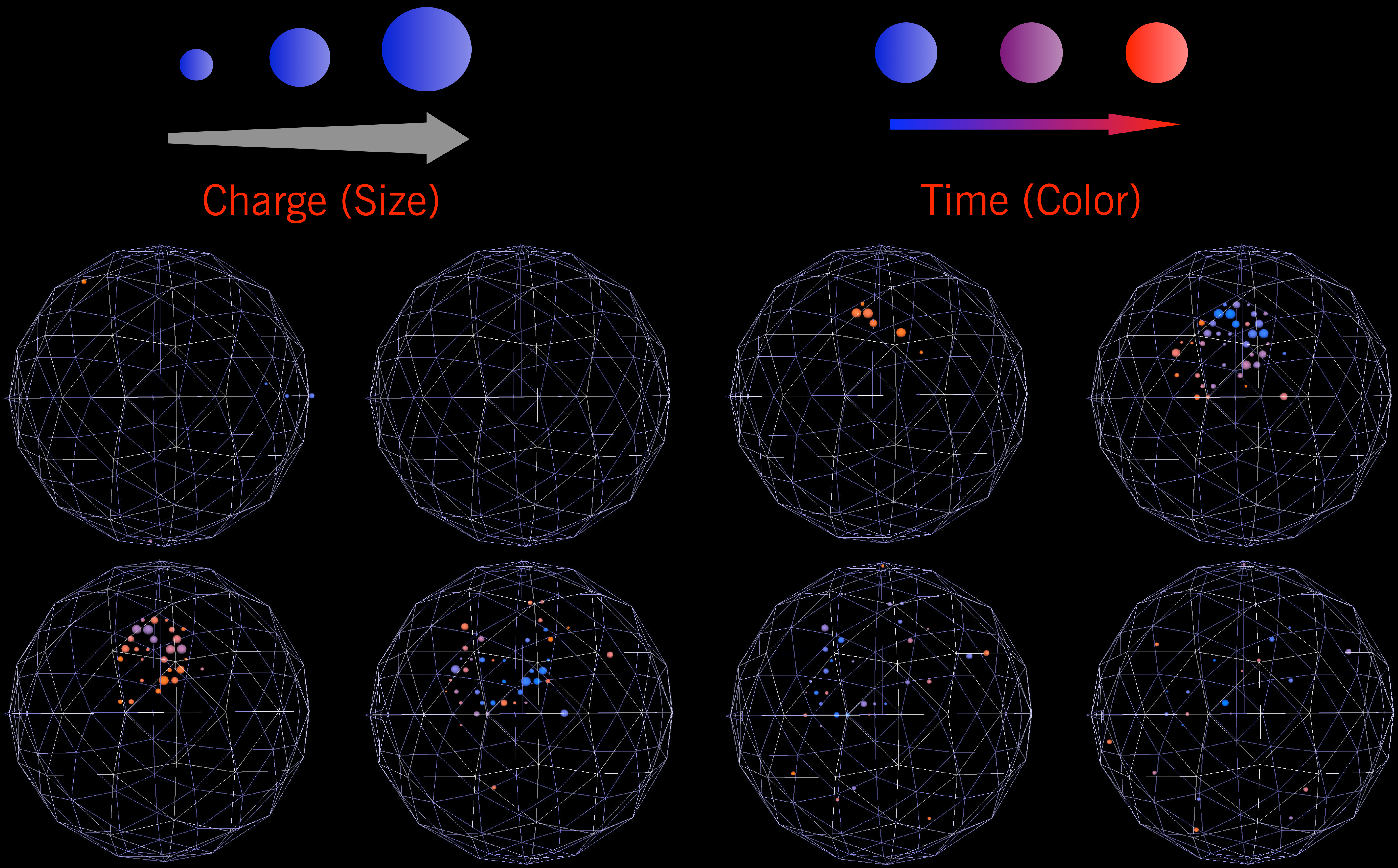
Event display: Cherenkov Rings





A cosmic-ray muon enters the tank and stops...

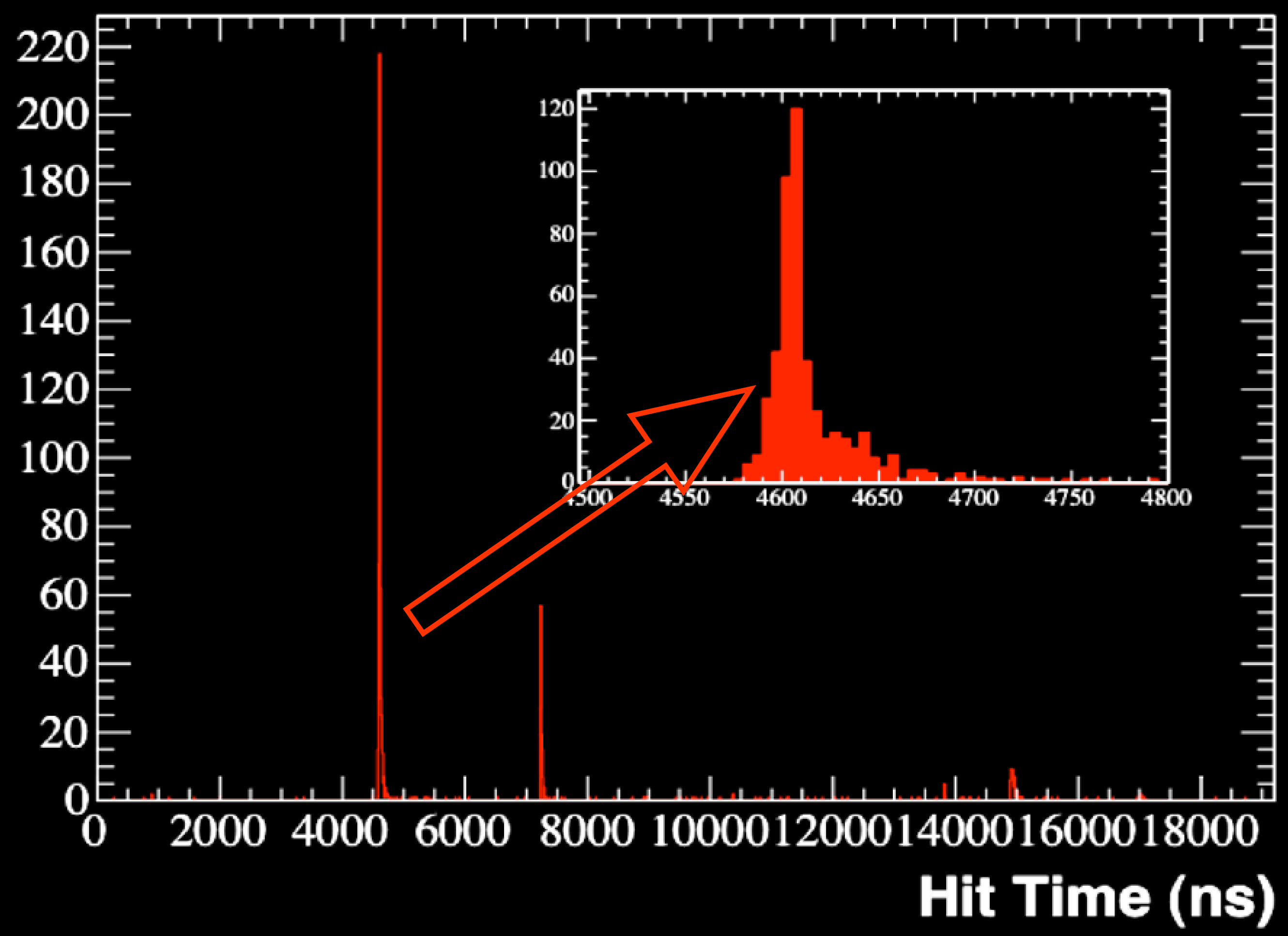
Event display: Cherenkov Rings



...then the Michel electron is observed a few μs later.

Subevents

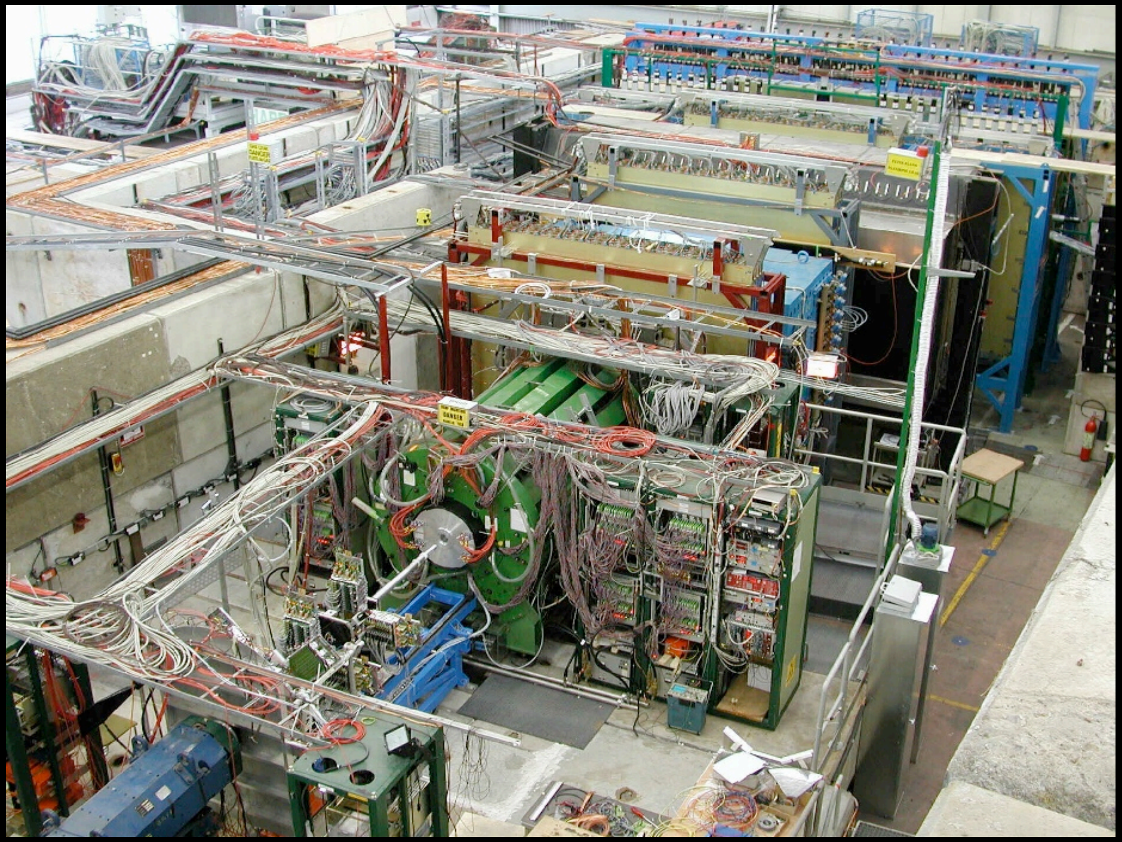
- We resolve the stopping muon and its Michel electron as two "subevents" (clusters of hits within ~100 ns).
- The Michel electron subevent provides muon tag as well as a very well-understood charge/energy calibration
- Muons capture on nucleus with 8% probability; these capture events cannot be tagged.

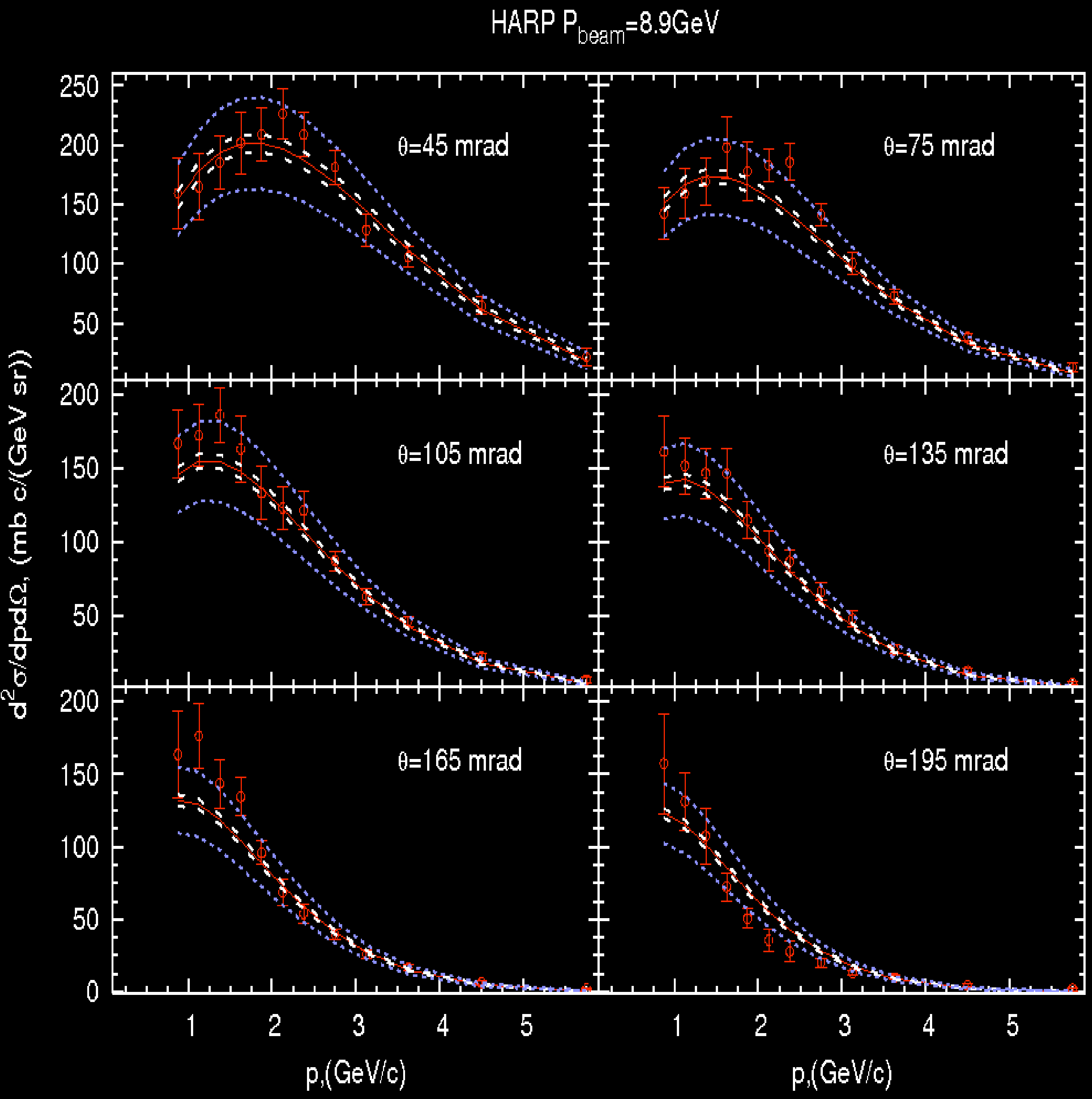


Oscillation Analysis

- 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

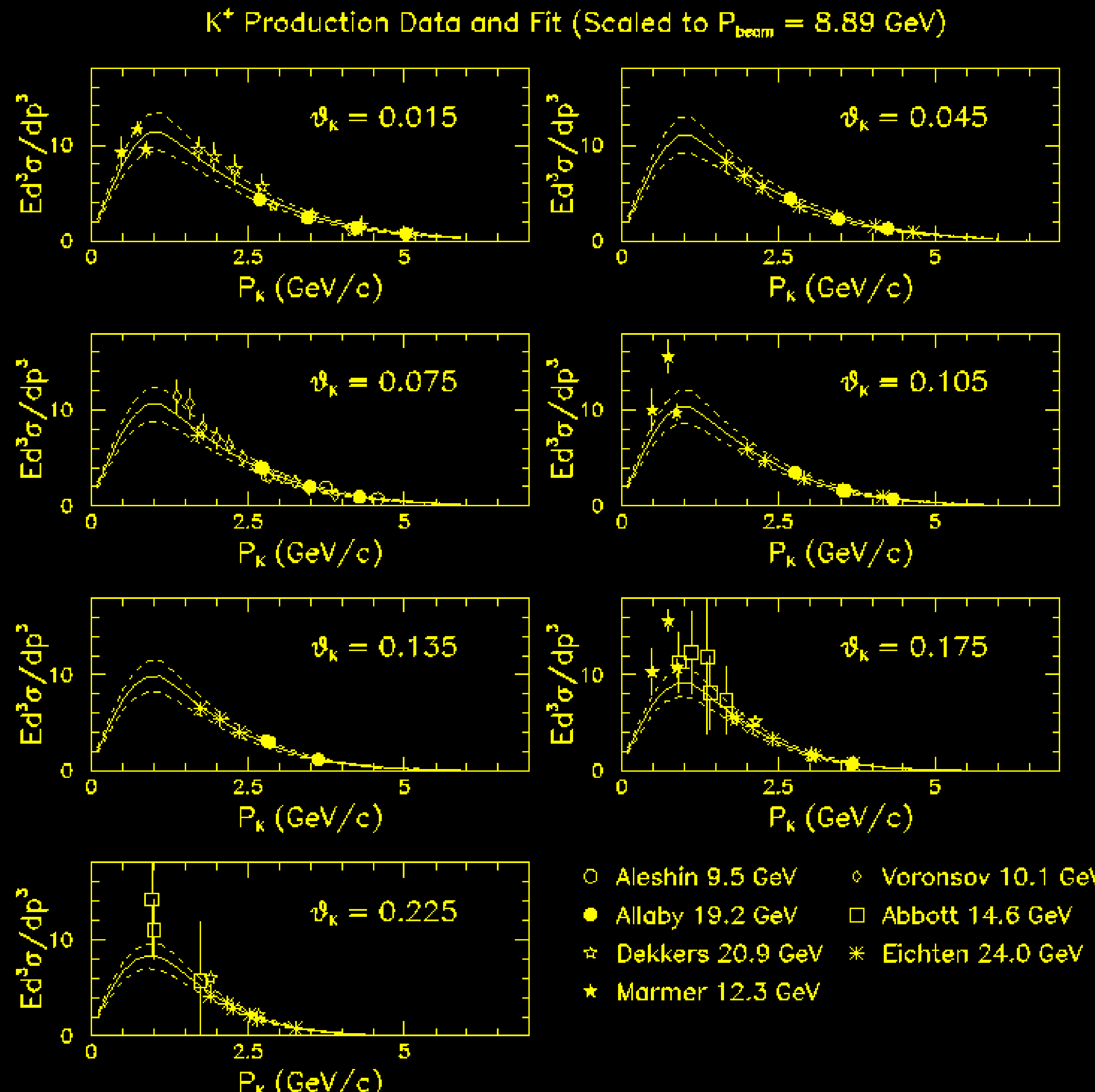




- Data from HARP experiment at CERN (taken with beryllium target at correct MiniBooNE beam momentum: hep-ex/0702024)
- Fit data to Sanford-Wang parametrization
- Sanford-Wang model used in GEANT4 beam Monte Carlo

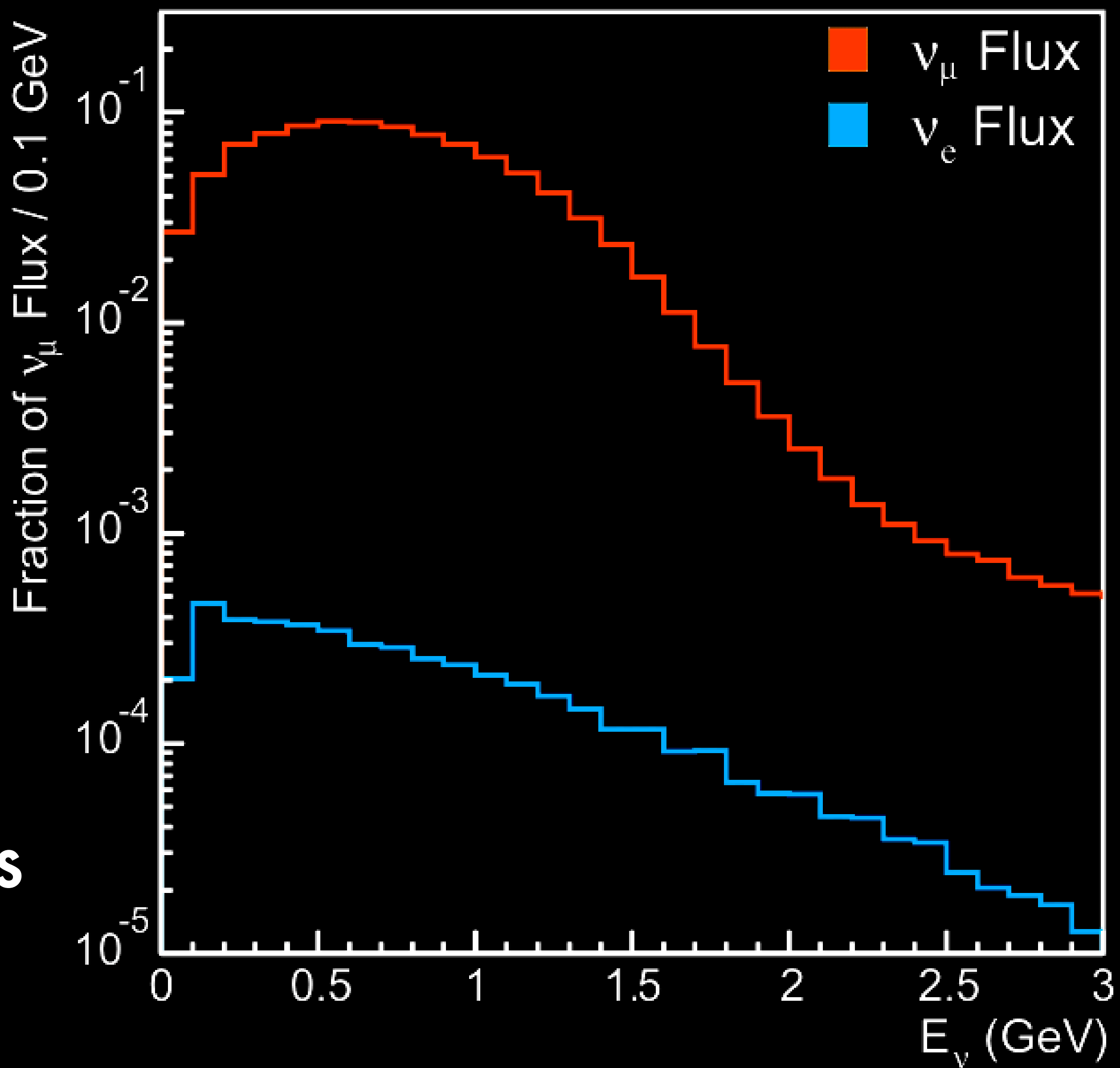
Flux model: kaon production

- 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

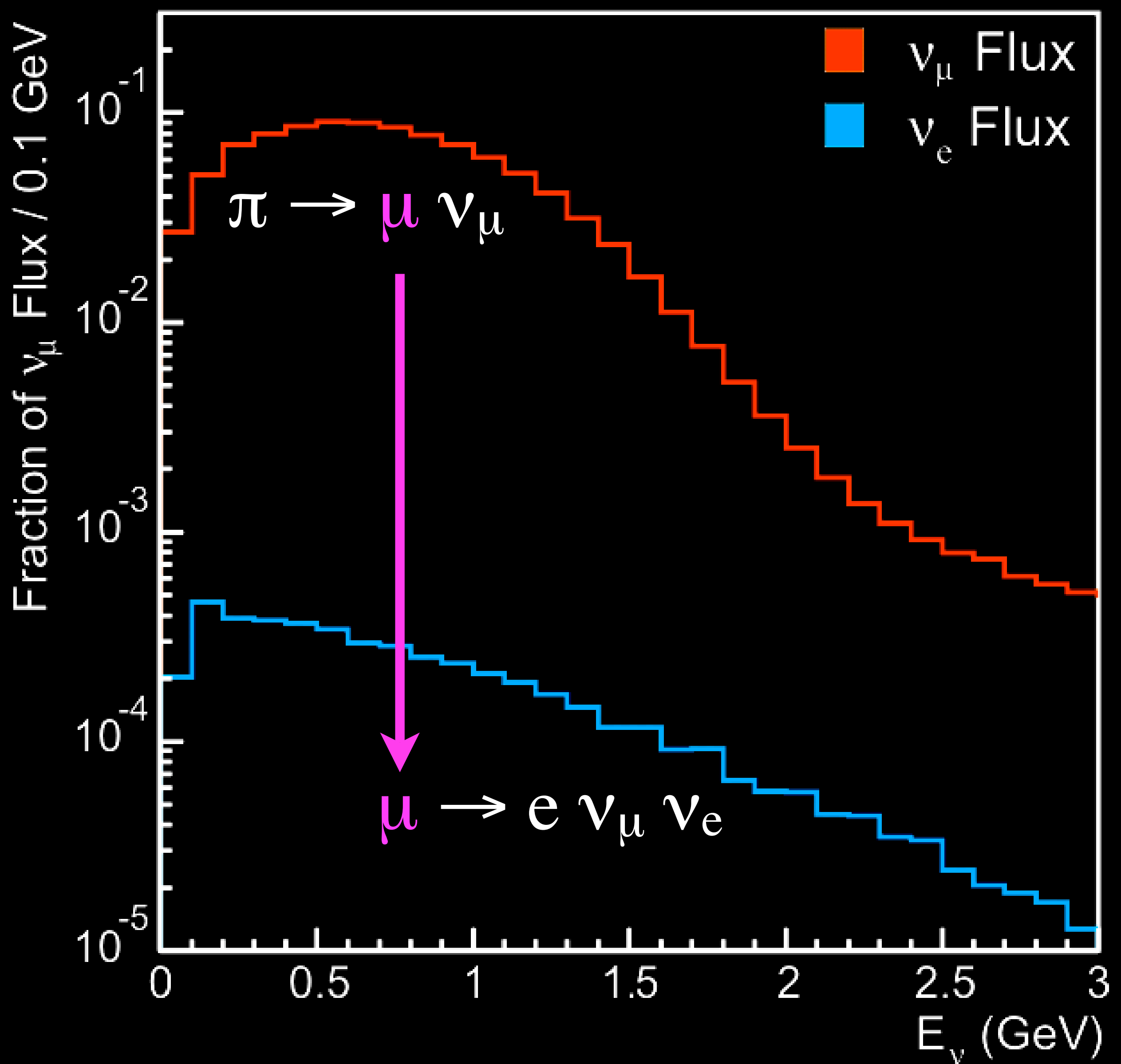


Predicted flux at detector

- 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)

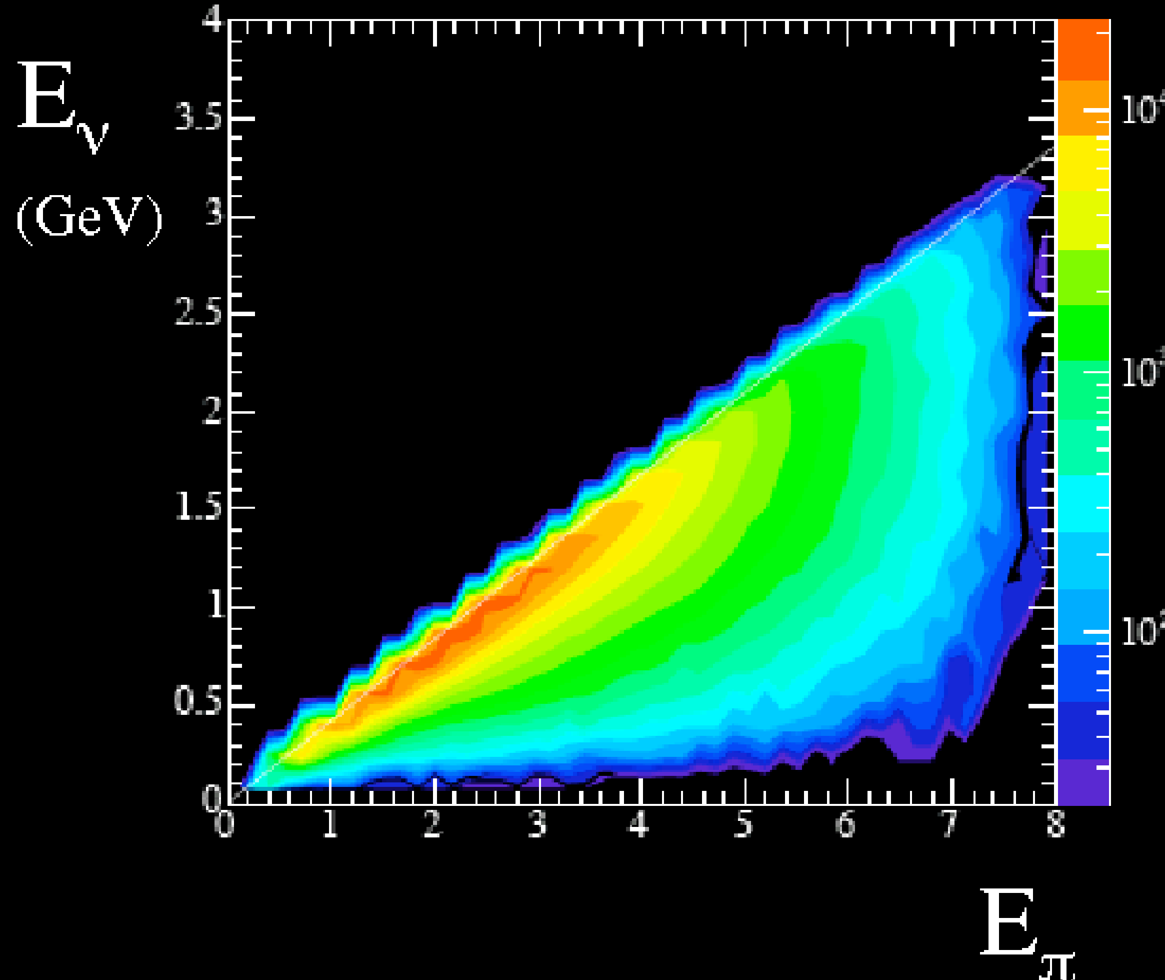


Further constraint on muon-decay ν_e

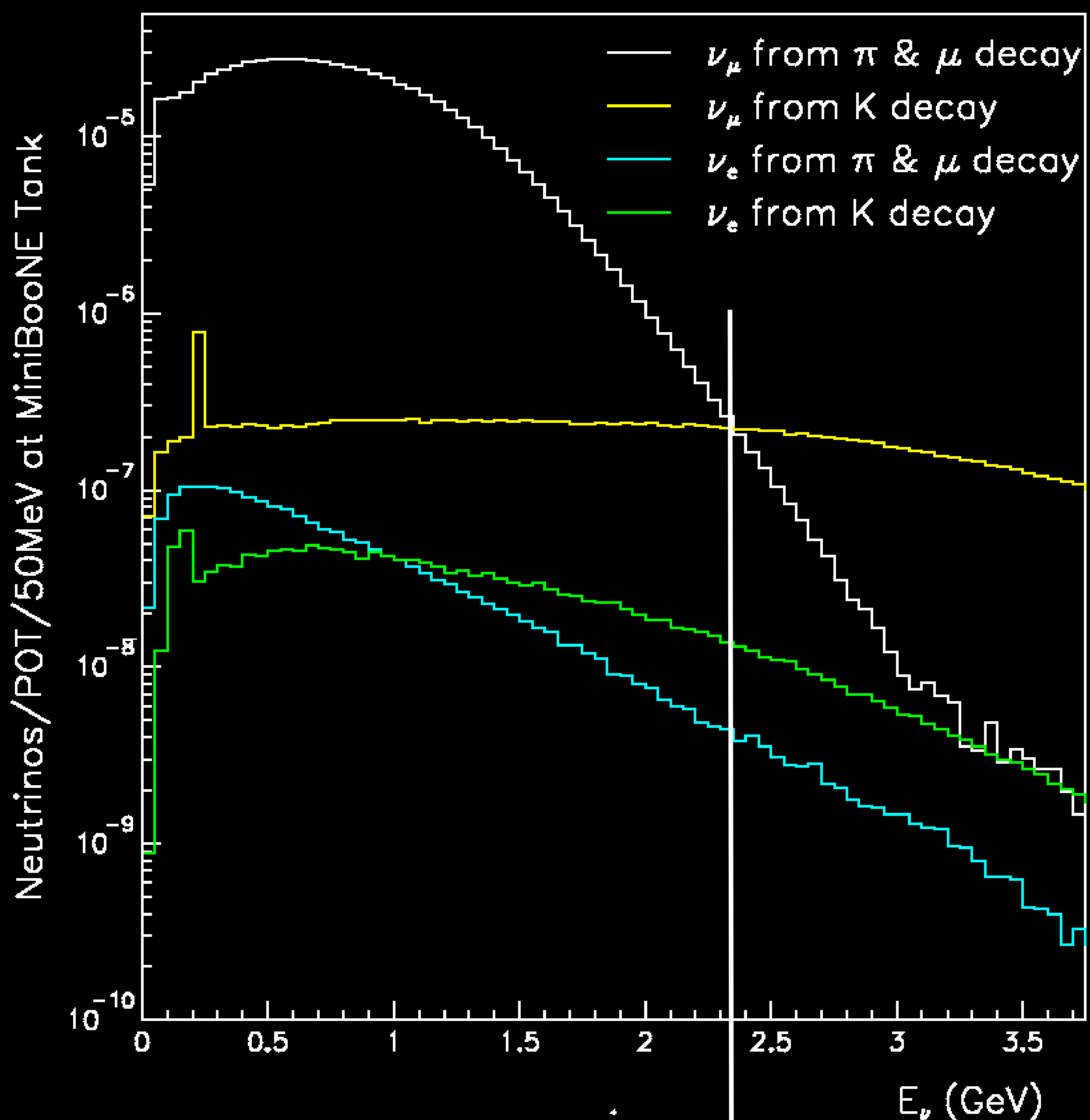


Muons originate predominantly from pion decays in secondary beam

- These pions also produce ν_μ in detector, which are easily observed
- Kinematic correlation allows tight constraint on $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ chain



High energy events constrain kaon decay flux



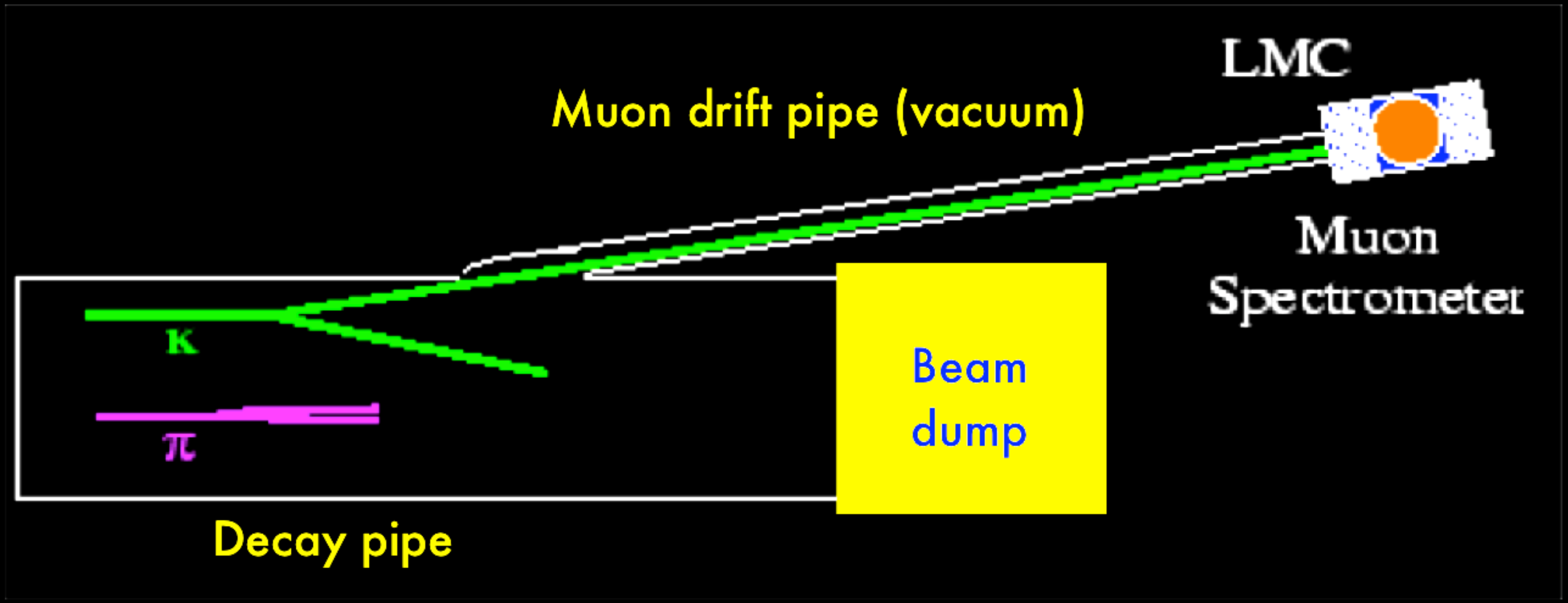
Dominated by π decay

Dominated by *K* decay

- Kaon decay has much higher Q-value than pion decay
- Kaons produce higher energy neutrinos
- Particularly true for two-body $K^+ \rightarrow \mu^+ \nu_\mu$
- Use the high energy ν_μ events to constrain the kaon flux that produces ν_e background

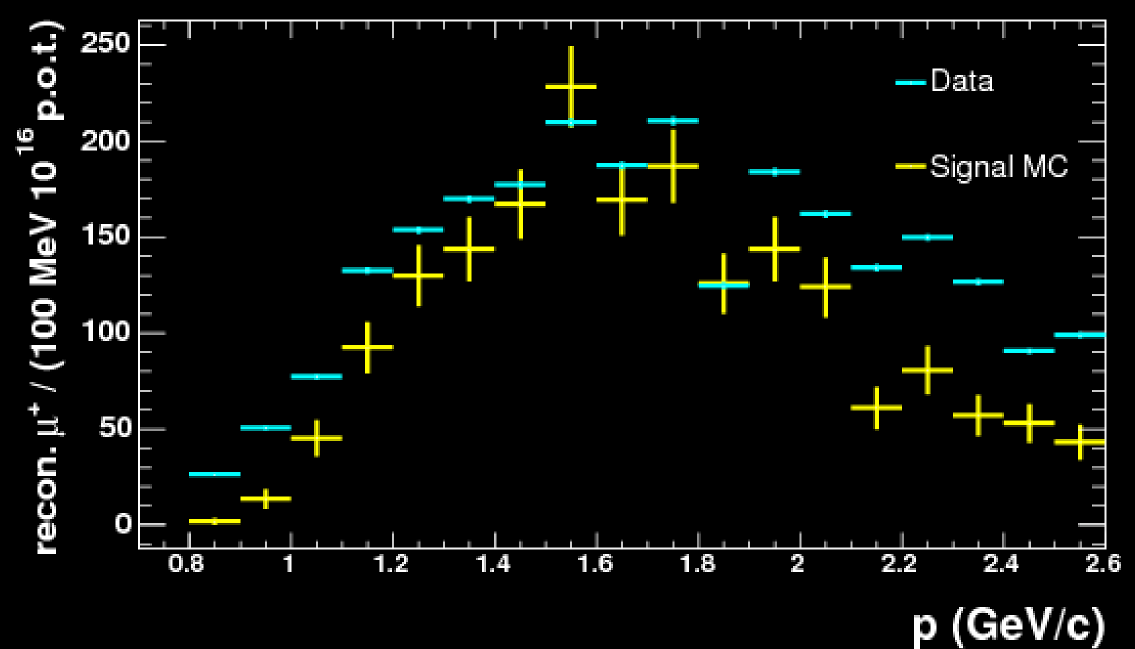
In-situ cross-check on kaon flux: Little Muon Counter (LMC)

Use kinematics of the muons in the decay pipe to isolate kaon-decay contribution



- Phase space in two-body decays limits the accessible kinematic region of the products:
- High-p_T μ's come from K^+ decay (mostly)
- Select off-axis decay muons by collimation, to turn p_T separation into an effective |p| separation.
- Scintillating fiber tracker / magnetic spectrometer measures muon spectrum

In-situ cross-check on kaon flux: Little Muon Counter (LMC)

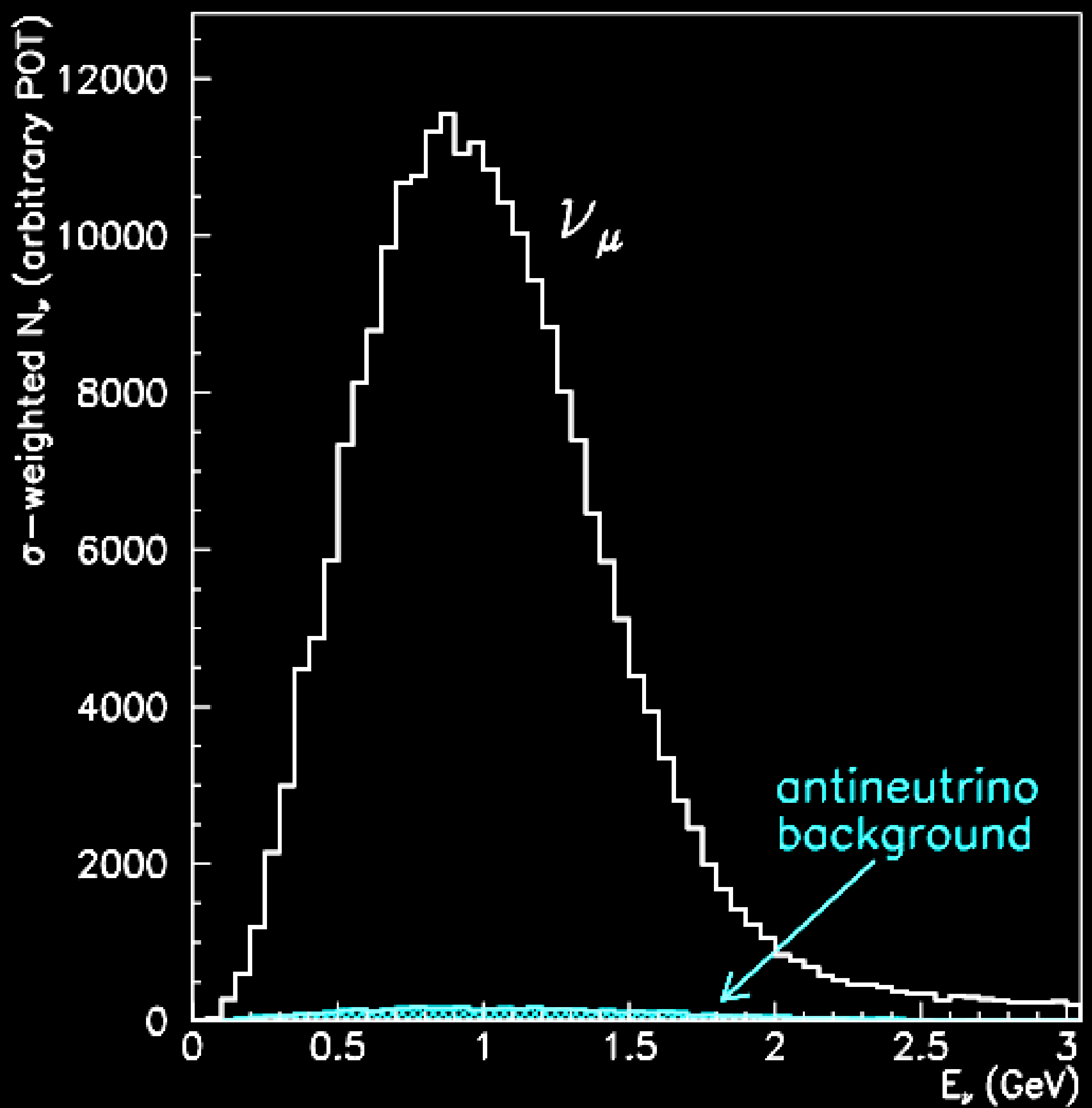


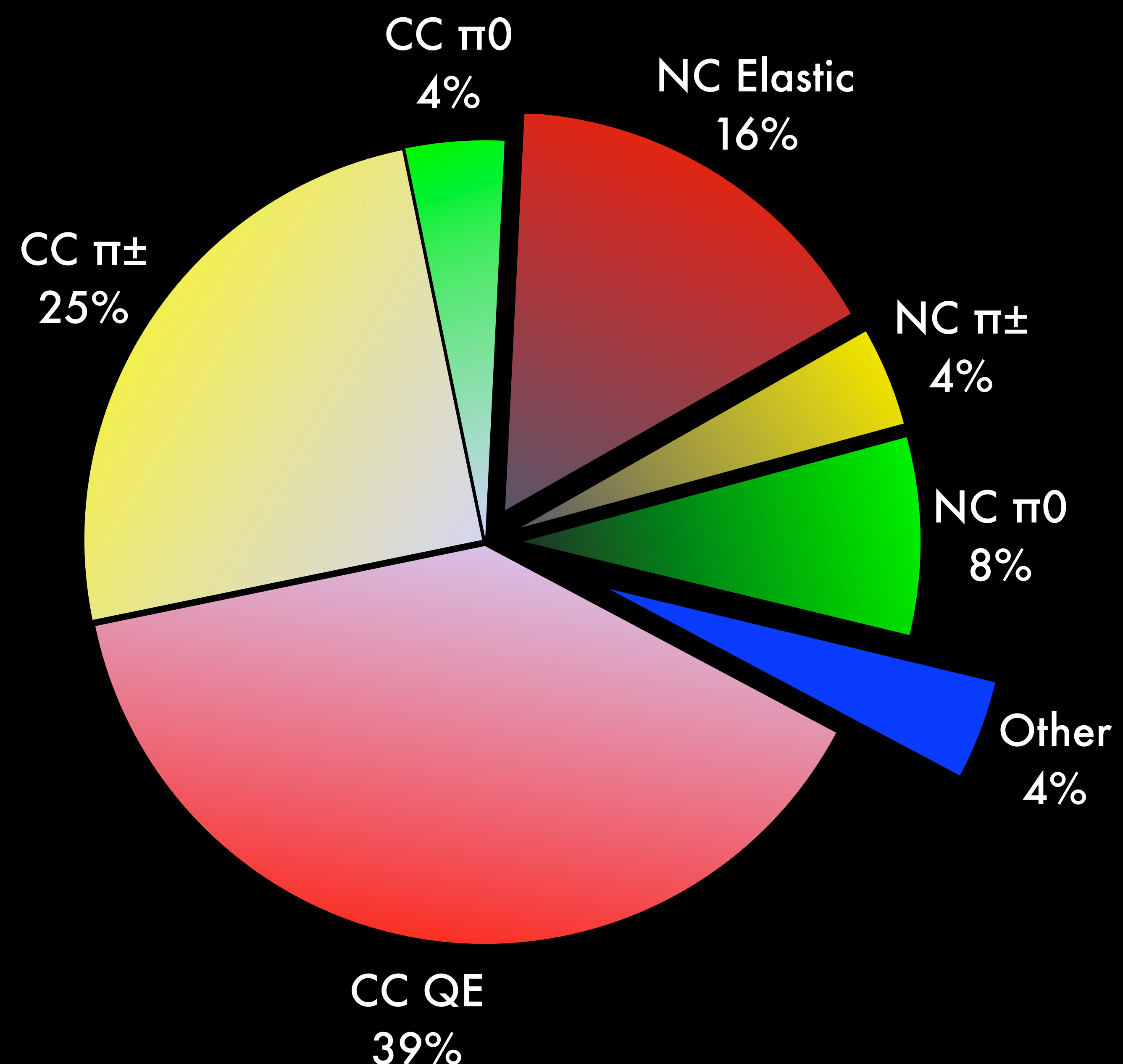
Data/MC ratio is constraint on the K^+ flux normalization:

- MC simulates π and K decays.
- No hadronic interaction backgrounds simulated yet.
- Plot shows data vs MC for well-identified muons in a region where we expect lower backgrounds.

Upper limit on the K^+ flux normalization is 1.32 (~1σ on the Feynman scaling fit).

Neutrino Interactions in MiniBooNE

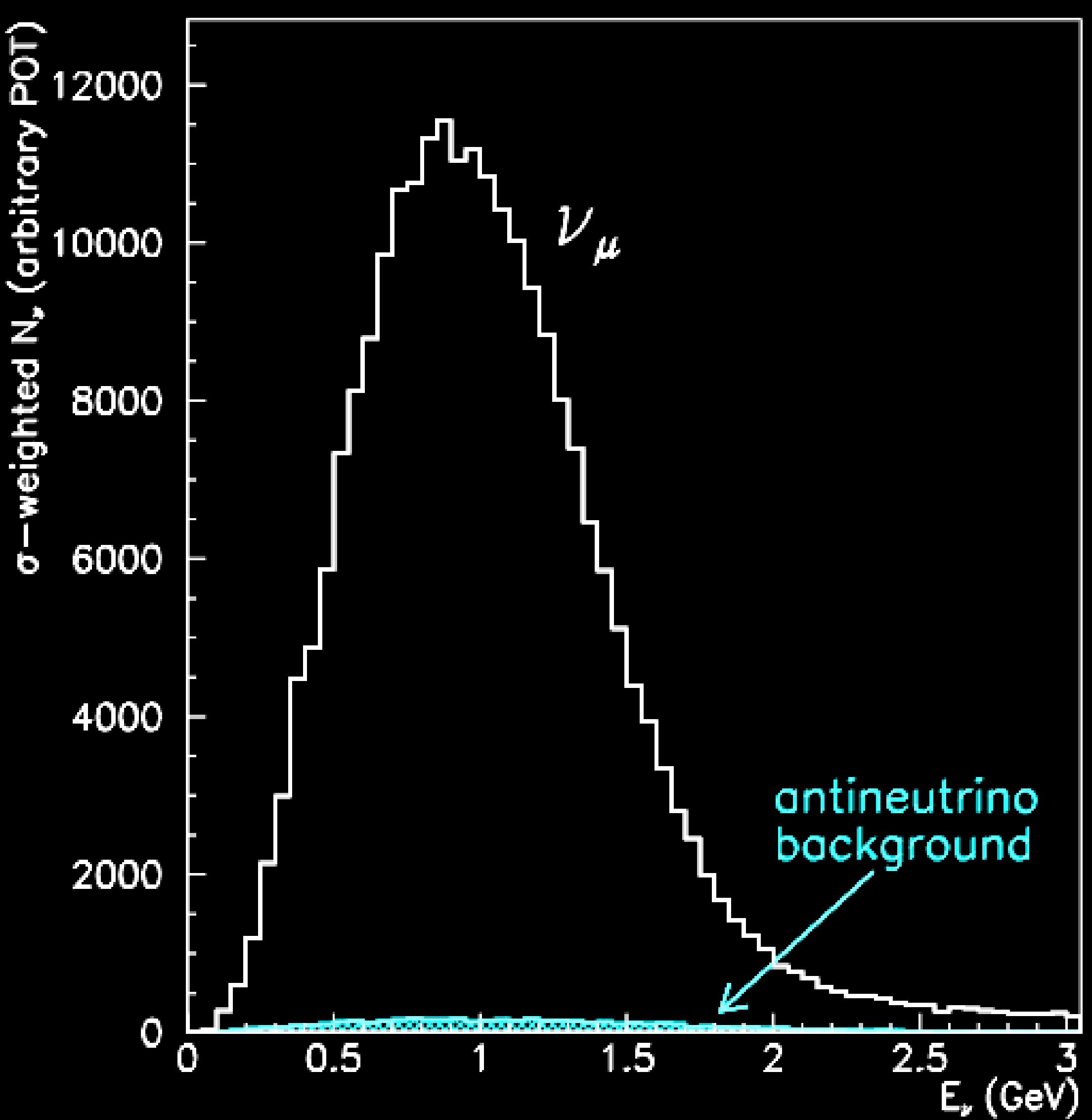


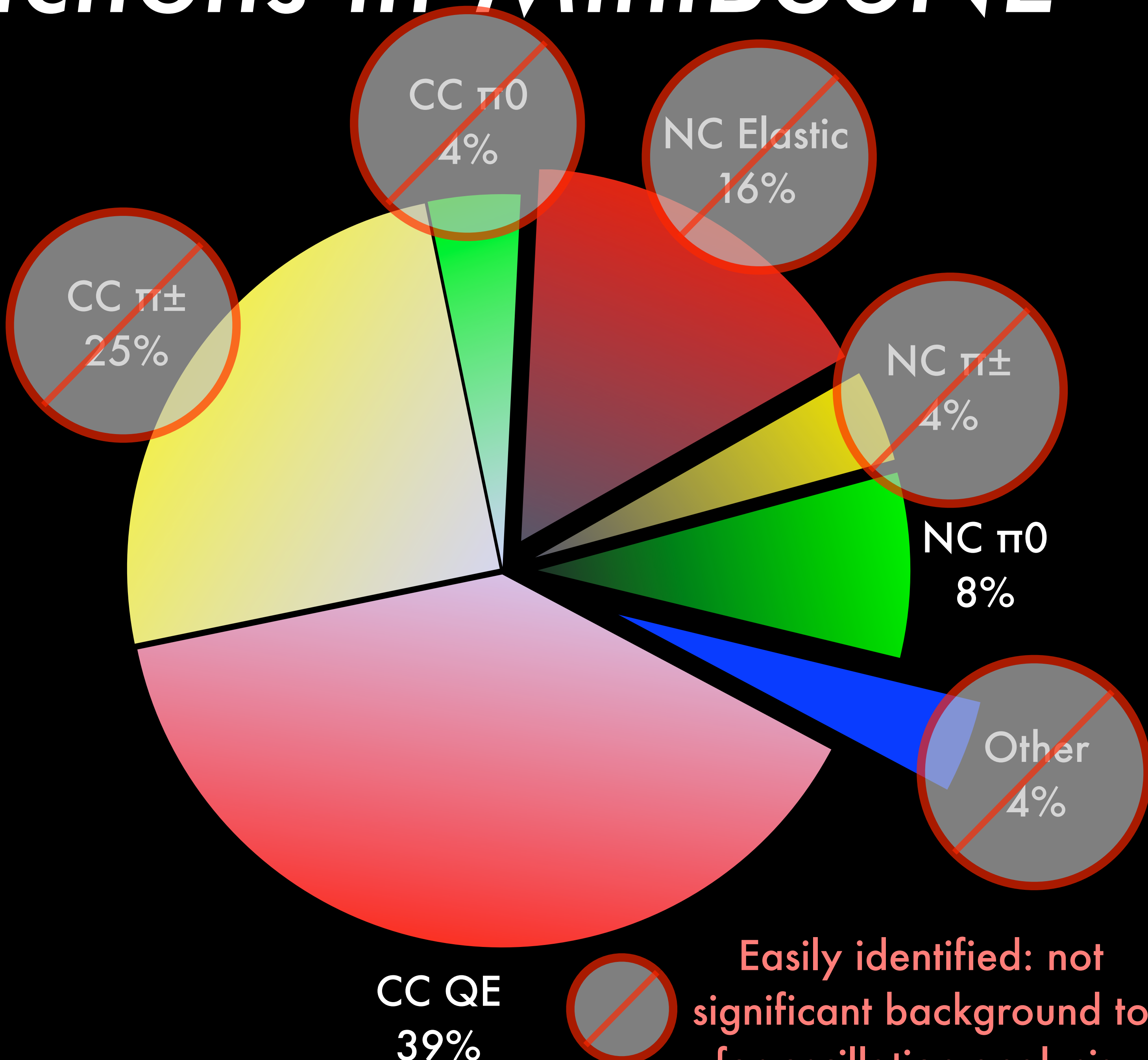


Predicted event spectrum, fractions before cuts
(NUANCE Monte Carlo)

D. Casper, NPS, 112 (2002) 161

Neutrino Interactions in MiniBooNE





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

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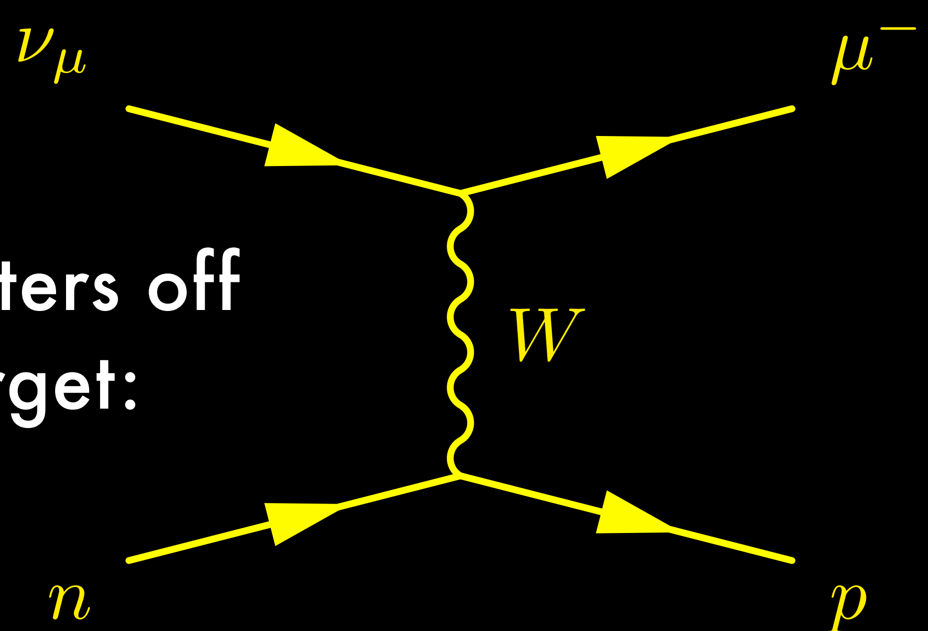
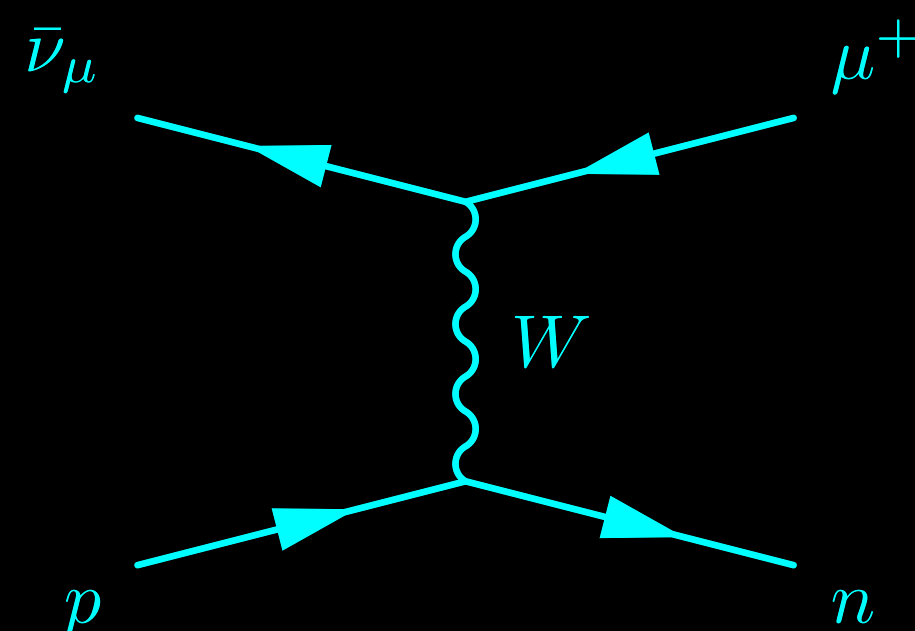
Charged-current quasielastic (CCQE)

Neutrino scatters off nucleon in target:



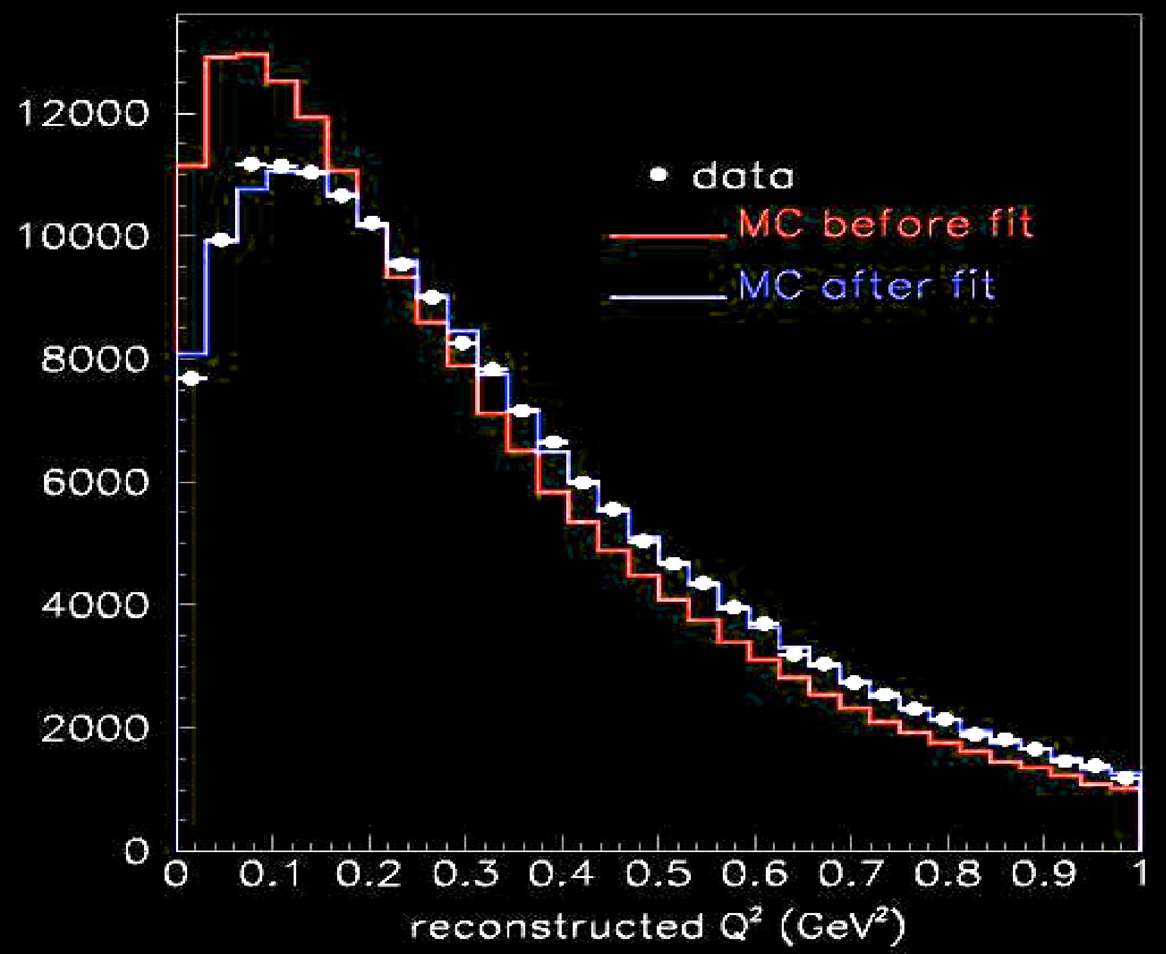


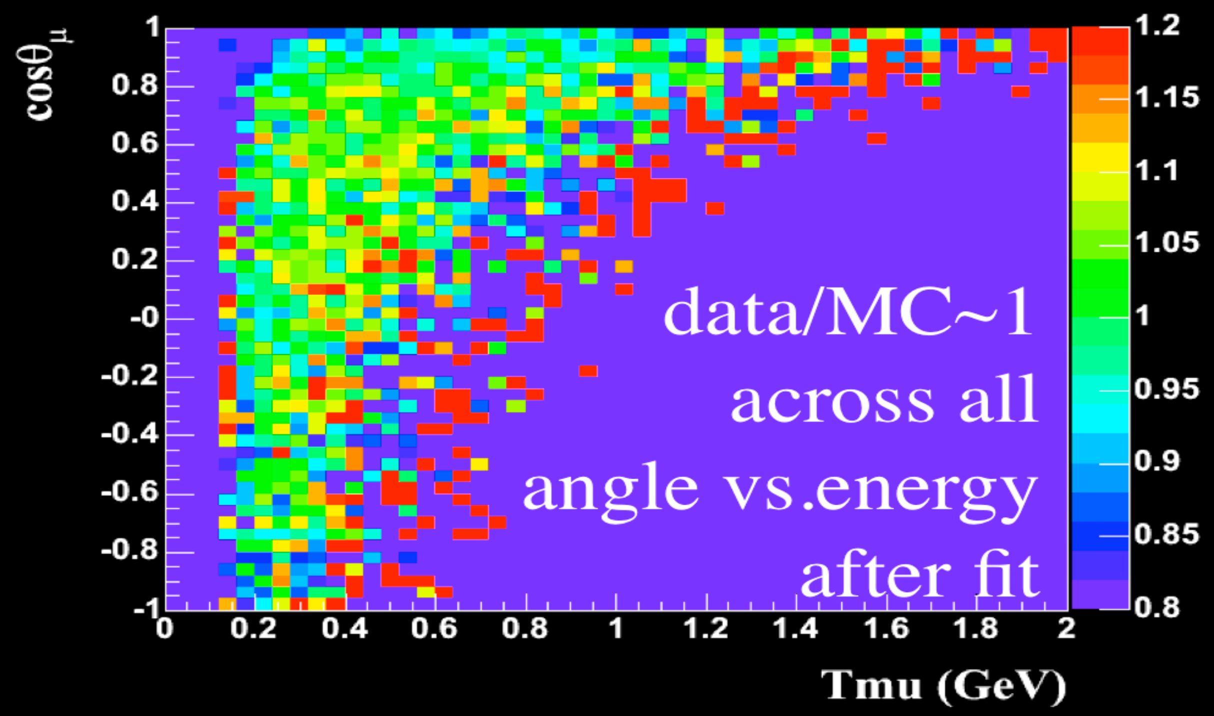
- Golden signal mode for oscillation search: clean events; neutrino energy can be calculated given known neutrino direction:

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

- Nucleus may break up
- Final state nucleon not excited: no resonance, no pion, no (hard) gamma
- Physics to measure: axial form factor F_A, parametrized by M_A (axial mass)

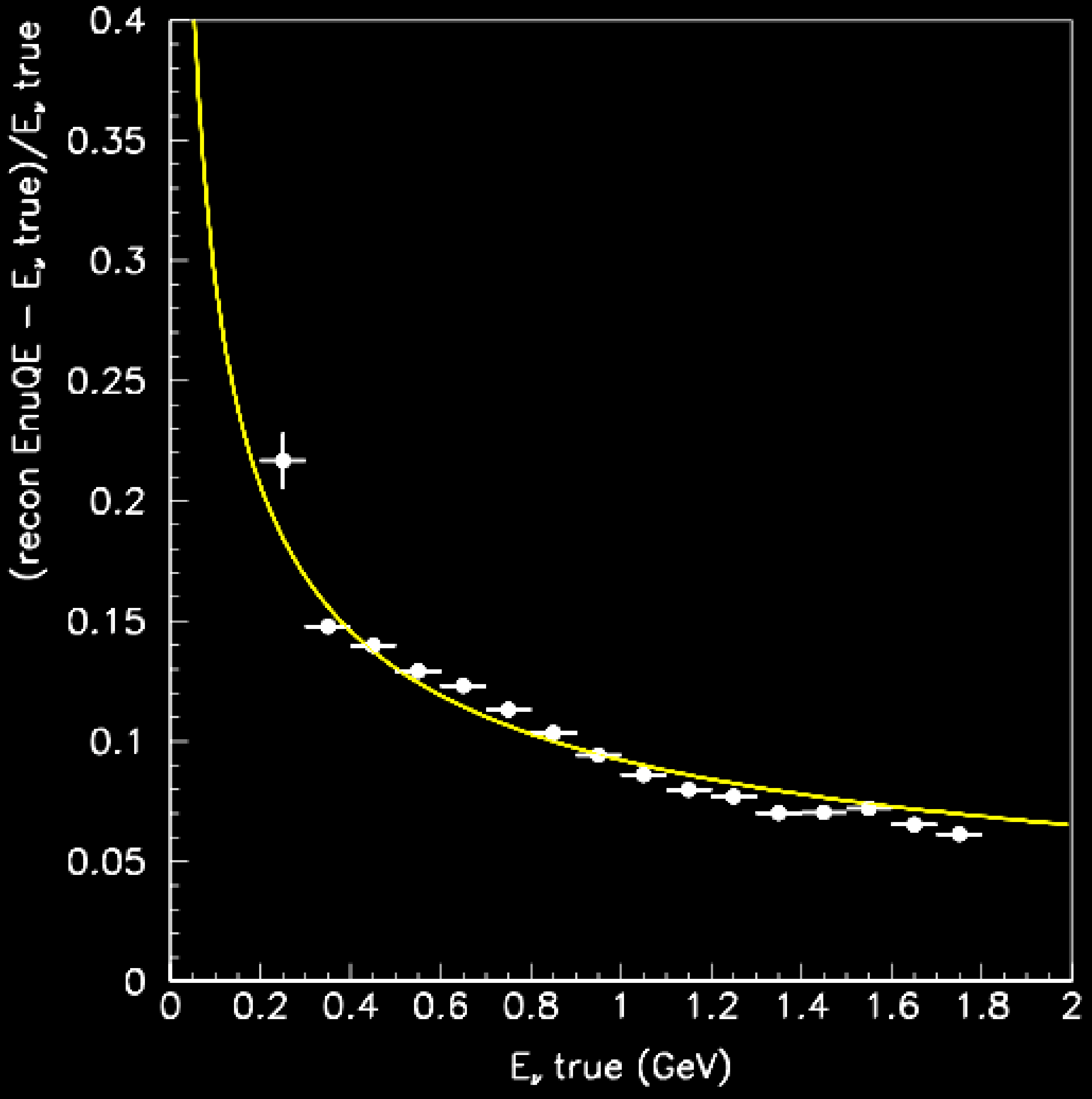
Cross-section parameters need tuning





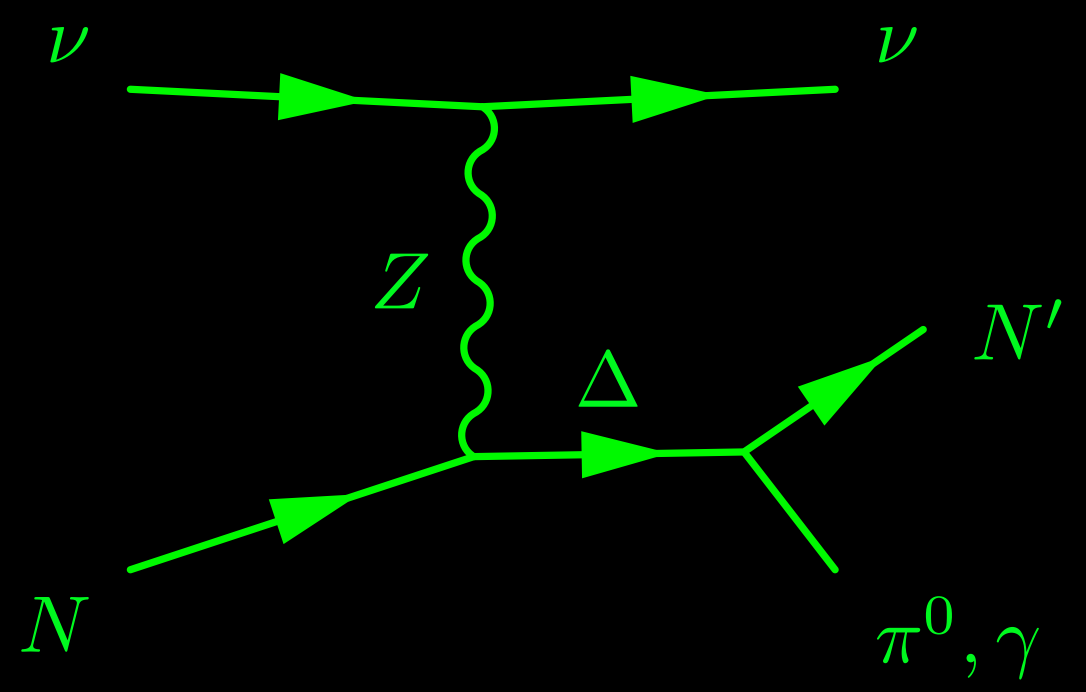
- From Q^2 fits to MiniBooNE ν_μ CCQE data:
  - M_A^{eff}: effective axial mass
  - E_{lo}^{SF}: Pauli-blocking parameter
- From electron scattering data:
  - E_b -- binding energy
  - p_F -- Fermi momentum

Charged-current quasielastic (CCQE)



- MiniBooNE E_ν^{CCQE} Reconstruction
- Resolution 8-15% in region of interest (300-1200 MeV)

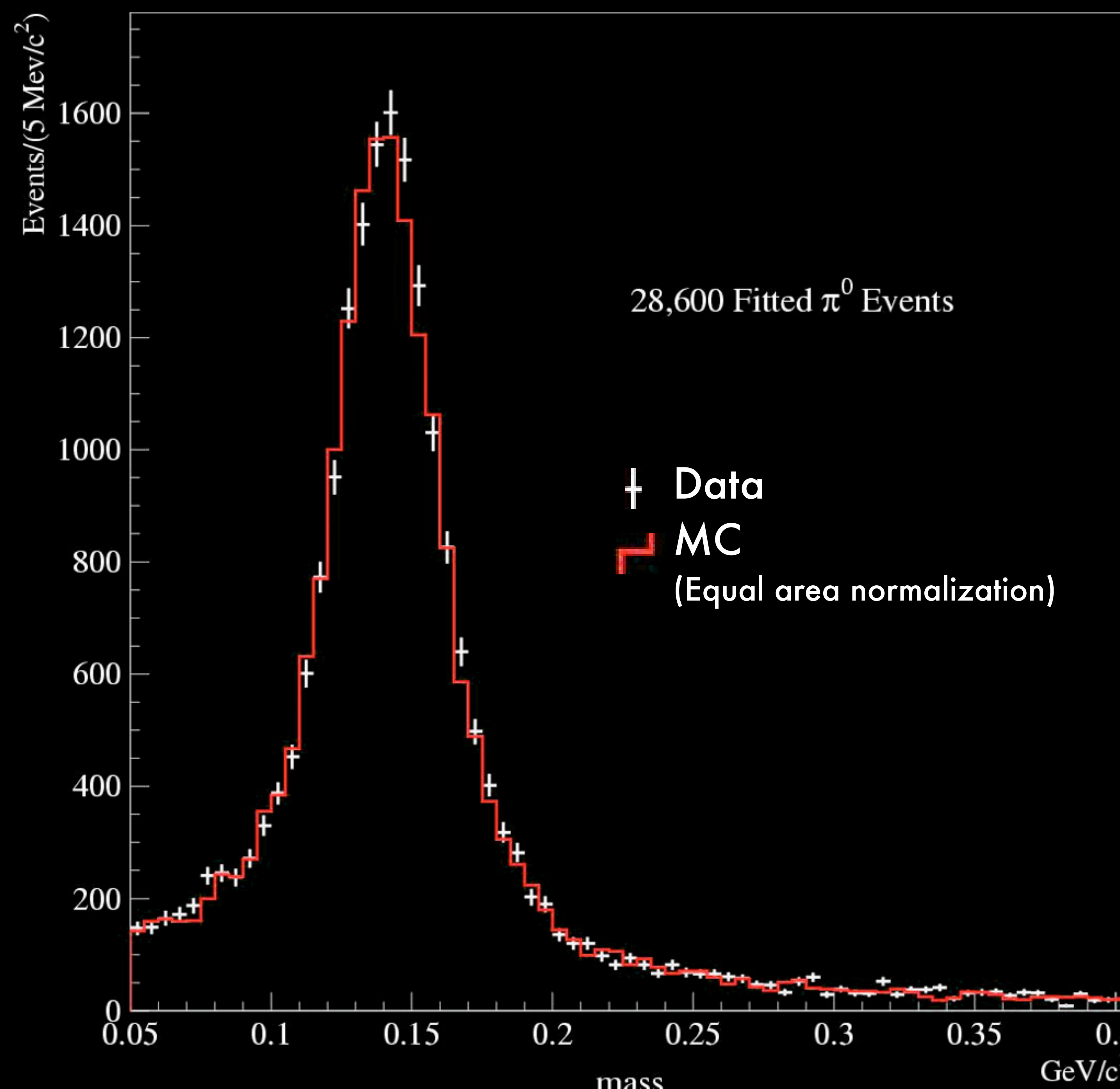
Neutral Current Δ Resonances



- 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.

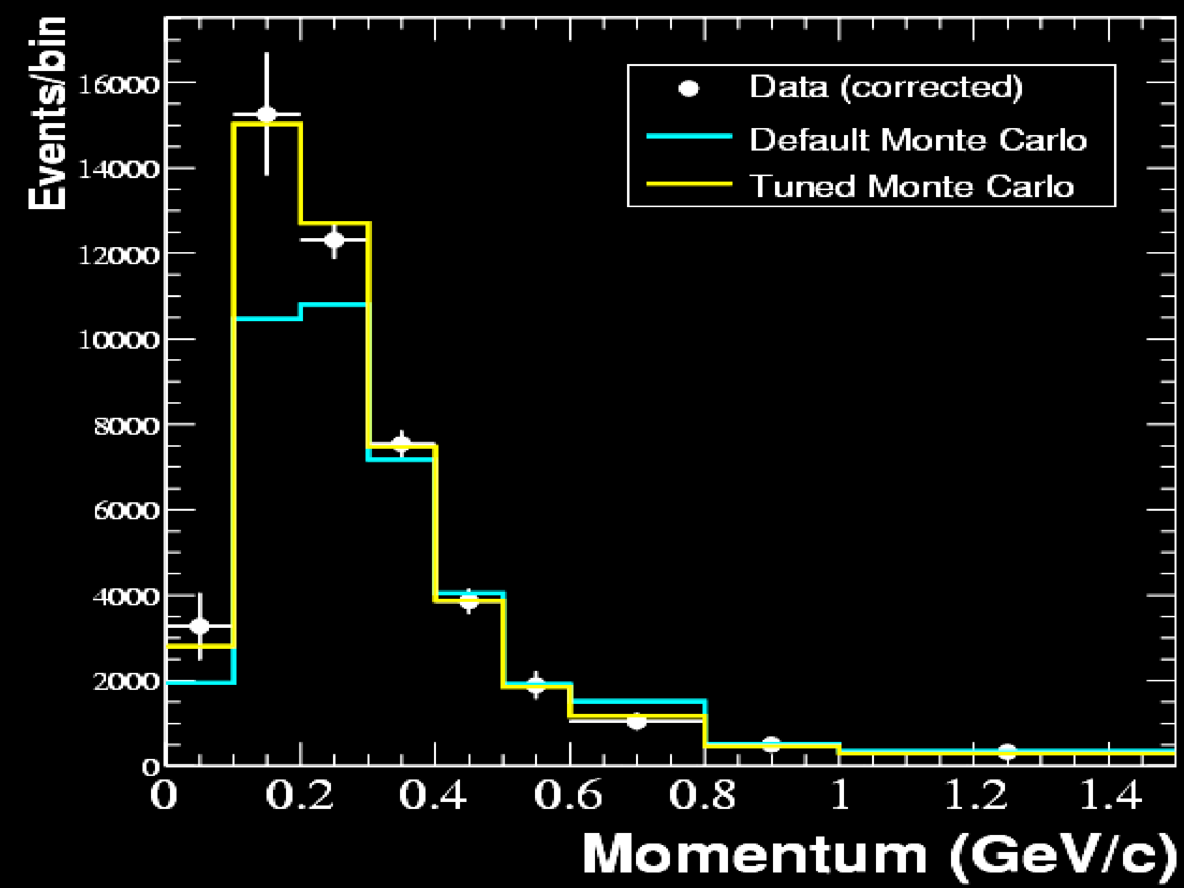
Neutral Current Δ Resonances

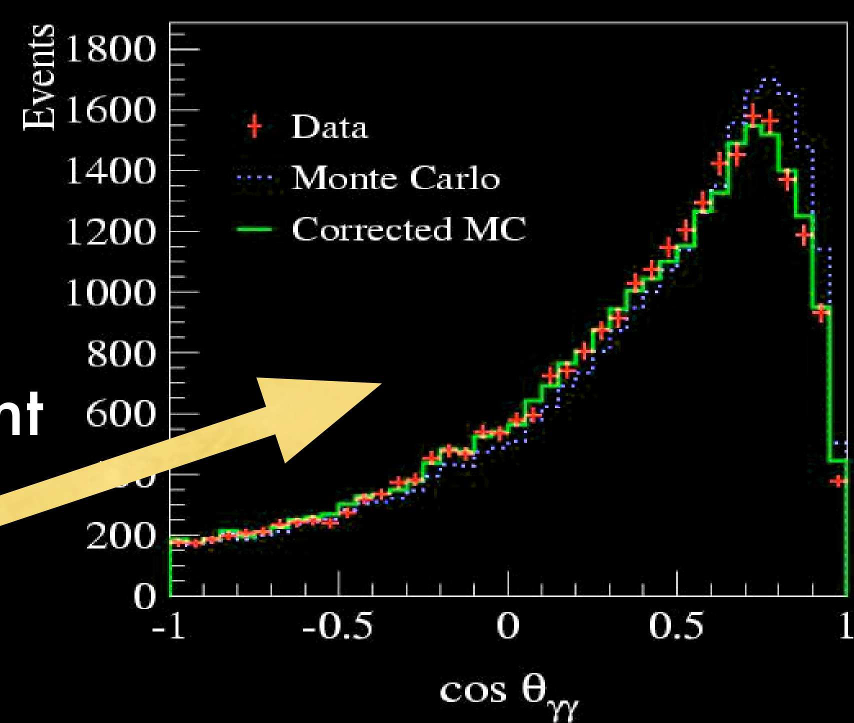
- π^0 **events**
  - Most π^0 events have two reconstructible photon rings.
  - Mass peak identifies neutral pions

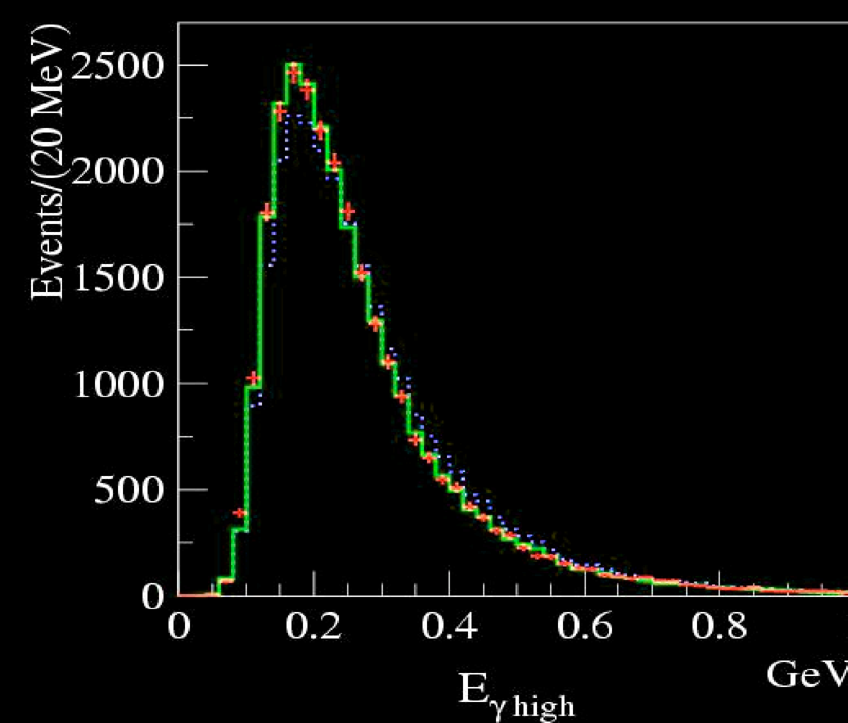


Neutral Current Δ Resonances

- 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
- Also improves agreement in other distributions:

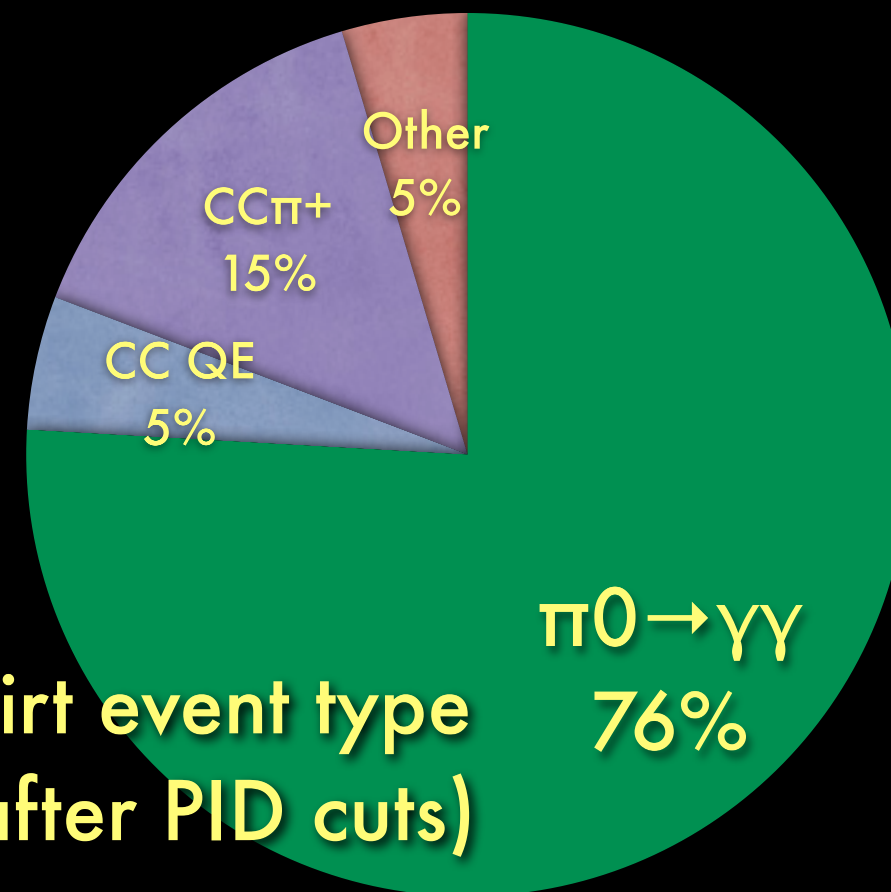






External backgrounds

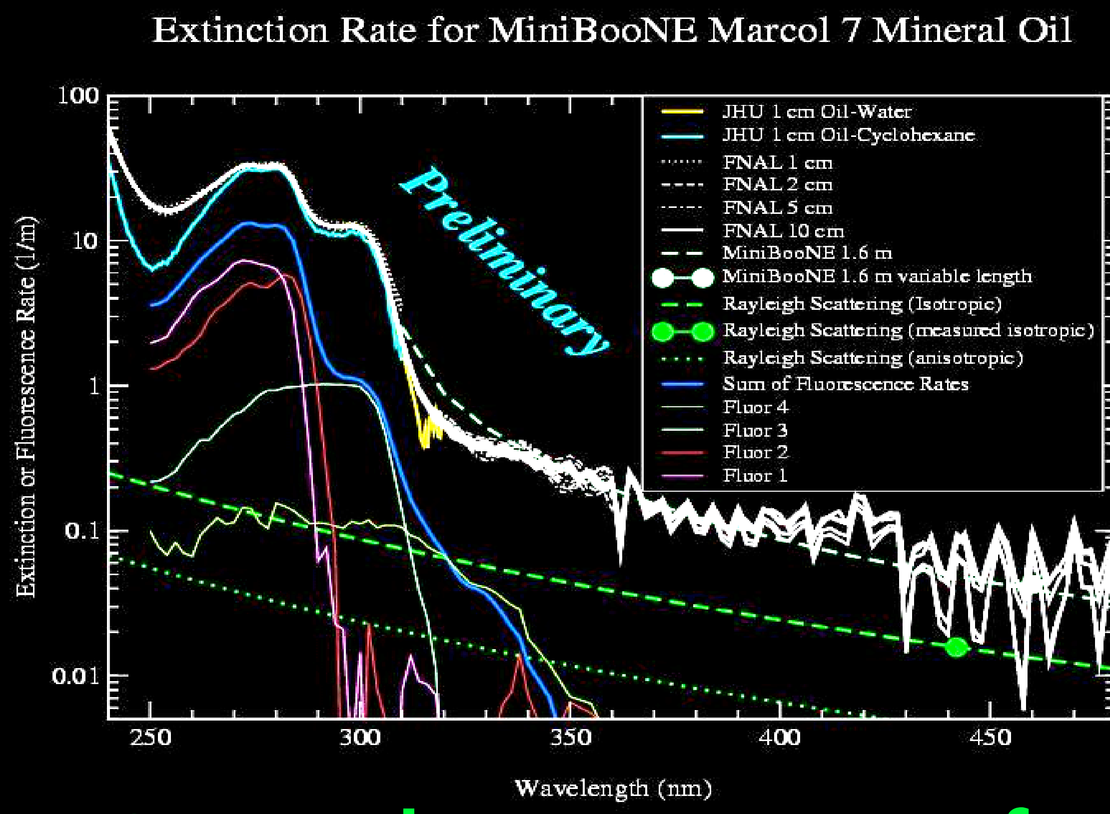
- "Dirt" events: neutrino interactions outside the detector
- Most events are cut by veto
- Background is dominated by π^0 where only one photon enters detector
- Cosmic/other beam-unrelated background is very small: 2.1±0.5 events, measured with beam-off data



Dirt event type
(after PID cuts)

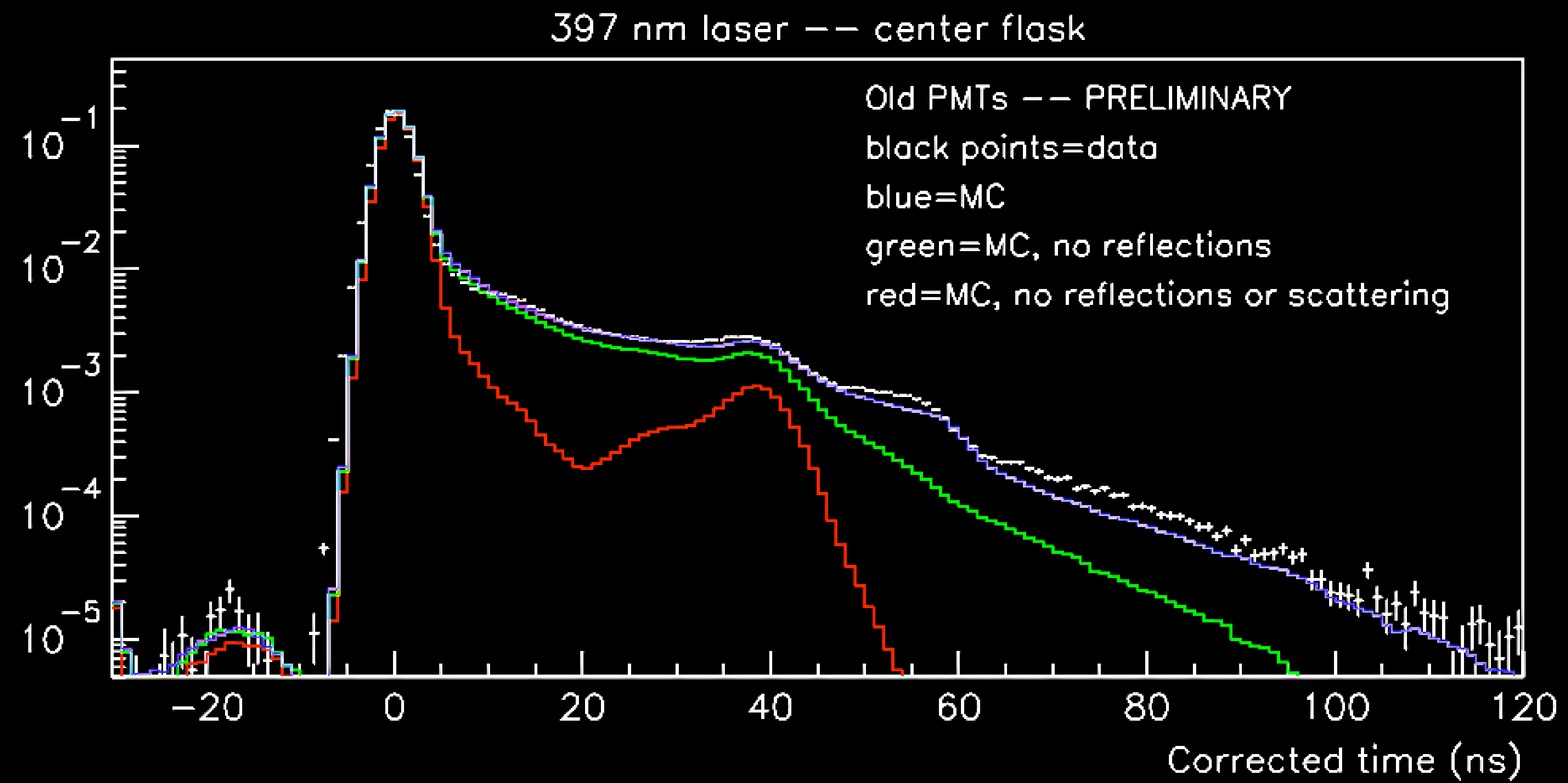
Neutrino detector modeling: "optical" issues

- 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



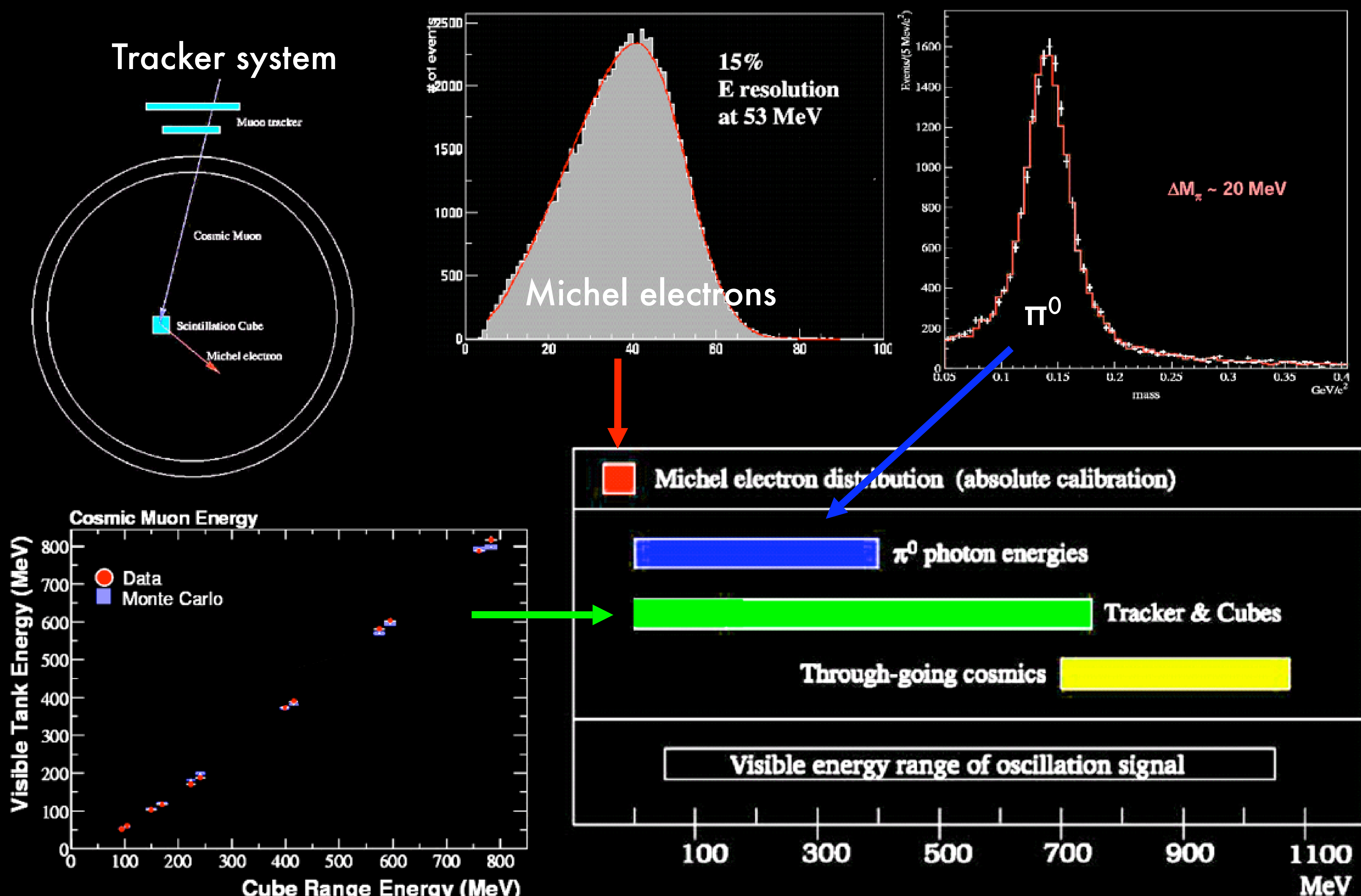
- Optical properties of oil, detectors:
  - Absorption (attenuation length >20m at 400 nm)
  - Rayleigh and Raman scattering
  - Fluorescence
  - Reflections
  - PMT response

Neutrino detector: "optical" issues



- Timing distribution for PMT hits
  - Calibration laser source inside tank
  - Monte Carlo with full optical model describes most of the timing structure

Calibration Sources



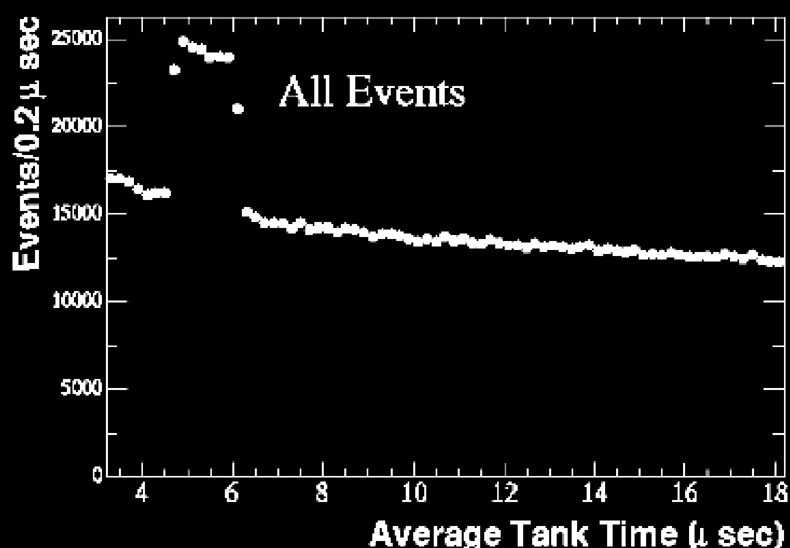
Event Reconstruction and Particle ID

- 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.

Start with "precuts" to find neutrino-like subevents:

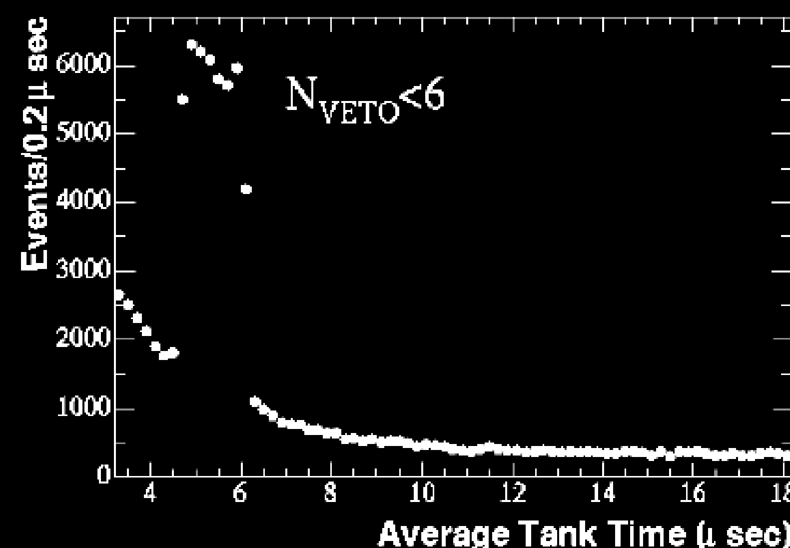
First subevent arrival time (μs).

Beam pulse is from 4.5 to 6 μs.



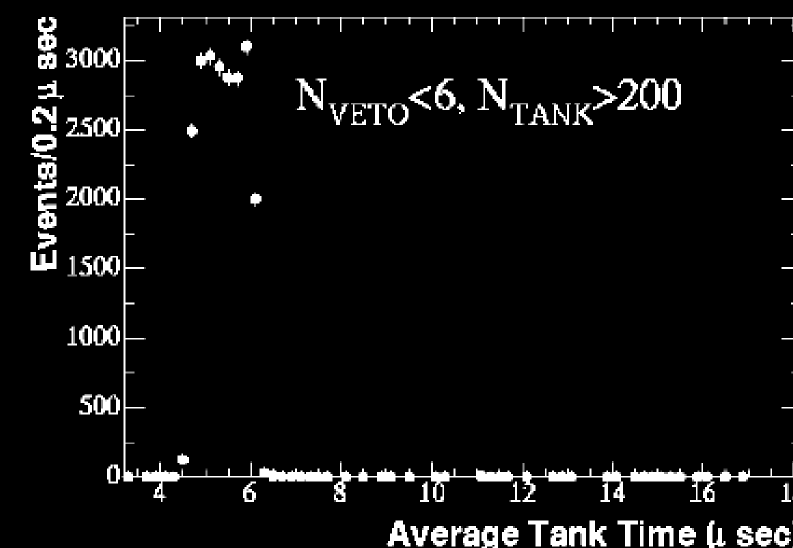
ALL SUBEVENTS

Cosmic rays dominate



<6 VETO HITS

Cosmic rays reduced (except for Michel electrons)



>200 TANK HITS

Cosmic rays nearly eliminated; only beam neutrinos survive

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.

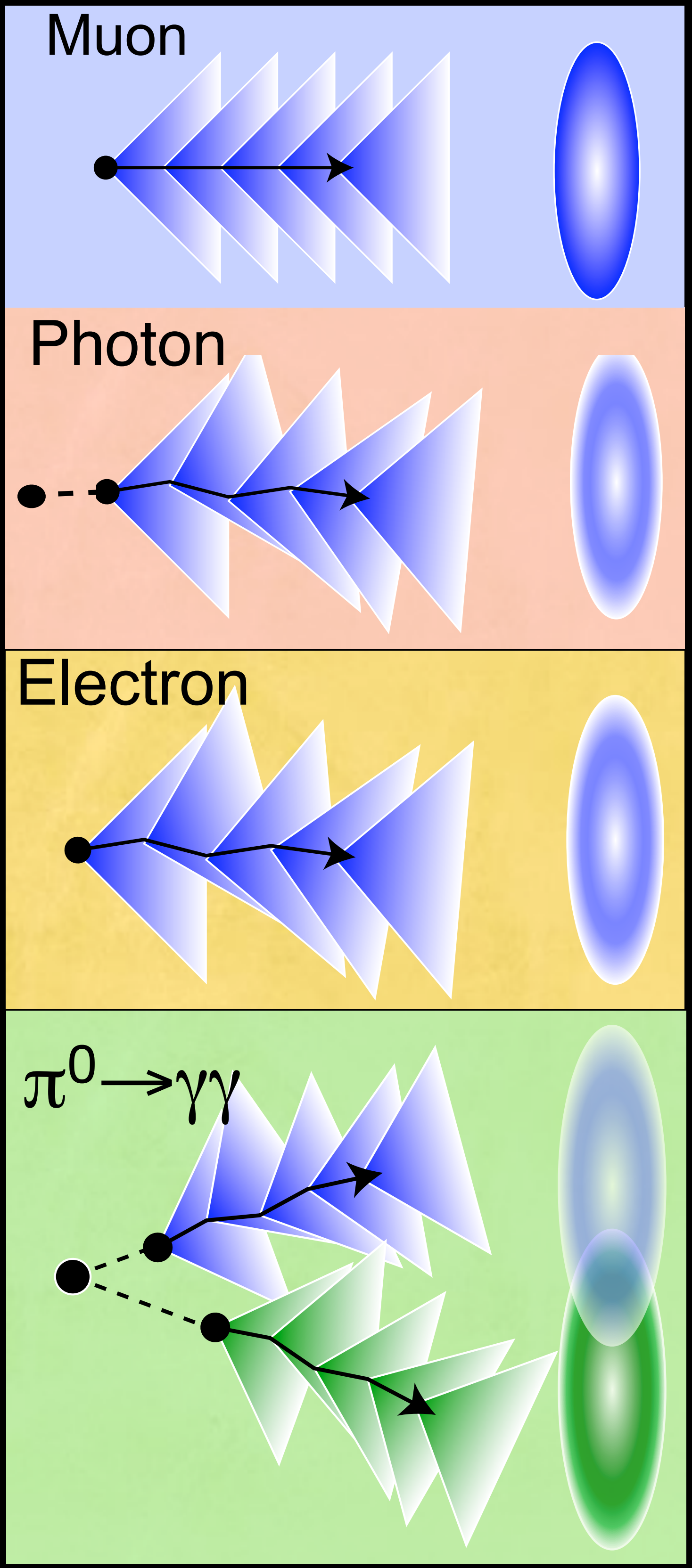
The Track-based Analysis: *Reconstruction*

- 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

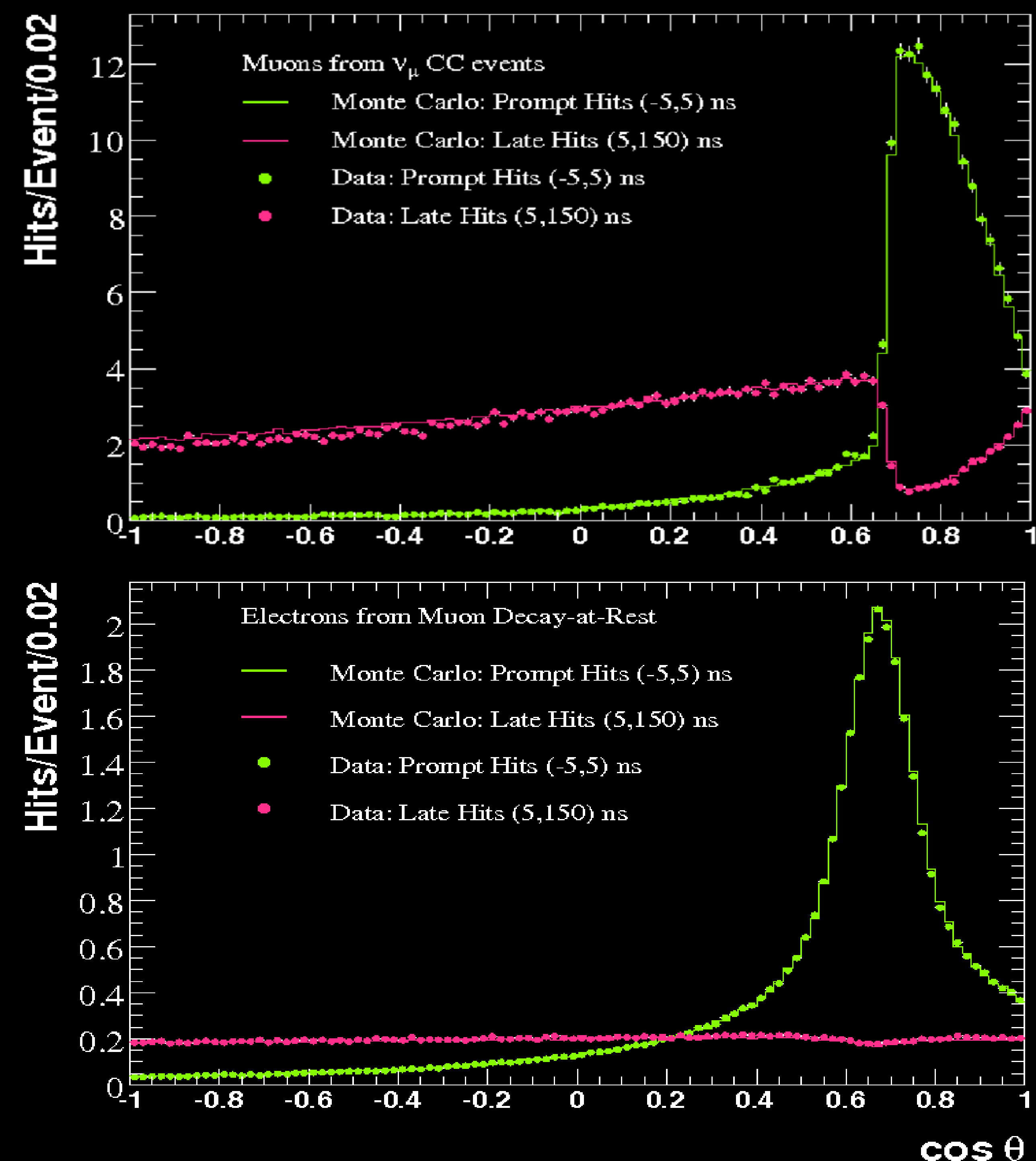
FIT HYPOTHESIS	NUMBER OF PARAMETERS
Single muon	7
Single electron/photon	7
Two photons from common vertex, mass unconstrained	12
Two photons from common vertex, mass constrained to m(π^0)	11



The Track-based Analysis: Reconstruction

The track-based reconstruction accounts for:

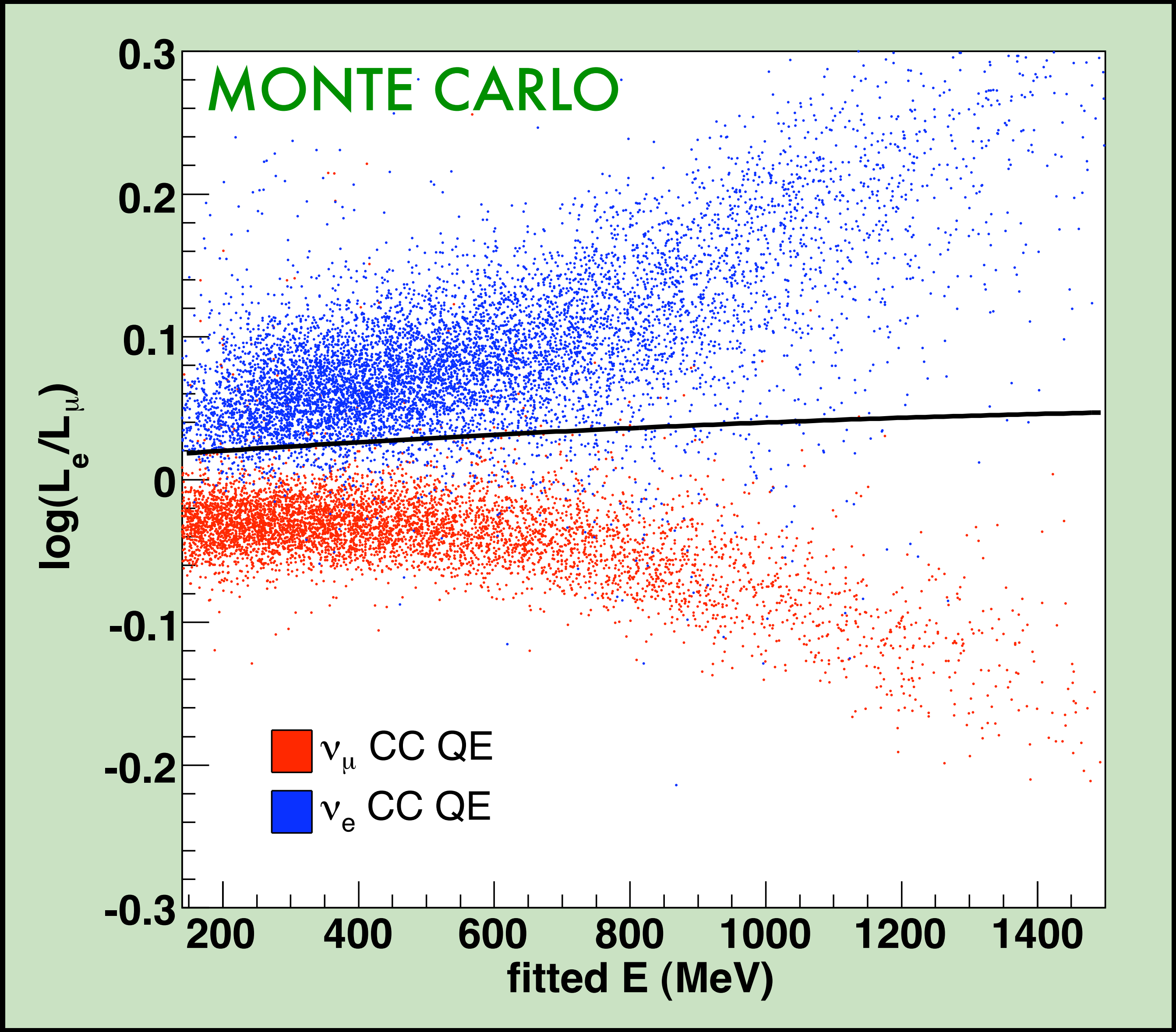
- Extended source of light ("track")
- Scattering, absorption of light
- Prompt light (cherenkov, scattering, somc scintillation)
- Delayed light (scintillation, fluorescence)
- Angular distribution of light from particles (due to showers, MCS)
- PMT efficiency and geometry
- dE/dx



The Track-based Analysis:
Event Selection

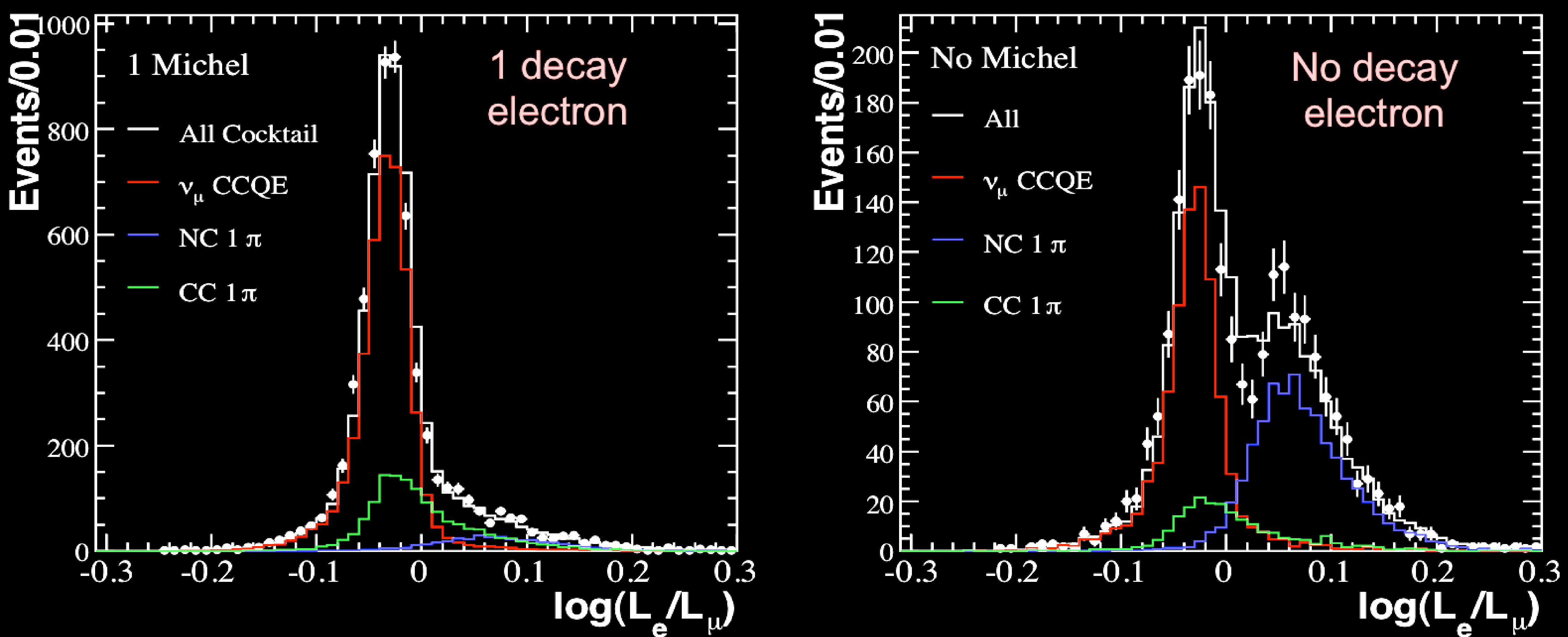
- Start with events that pass "precuts:"
  - Exactly one subevent during spill
  - NVETO < 6 hits
  - NTANK > 200 hits
- Perform all four fits: electron; muon; two-track, with and without π^0 mass constraint
- Fiducial cuts:
  - Radius must be less than 500 cm (calculated from electron fit)
- Make track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

The Track-based Analysis: Muon rejection



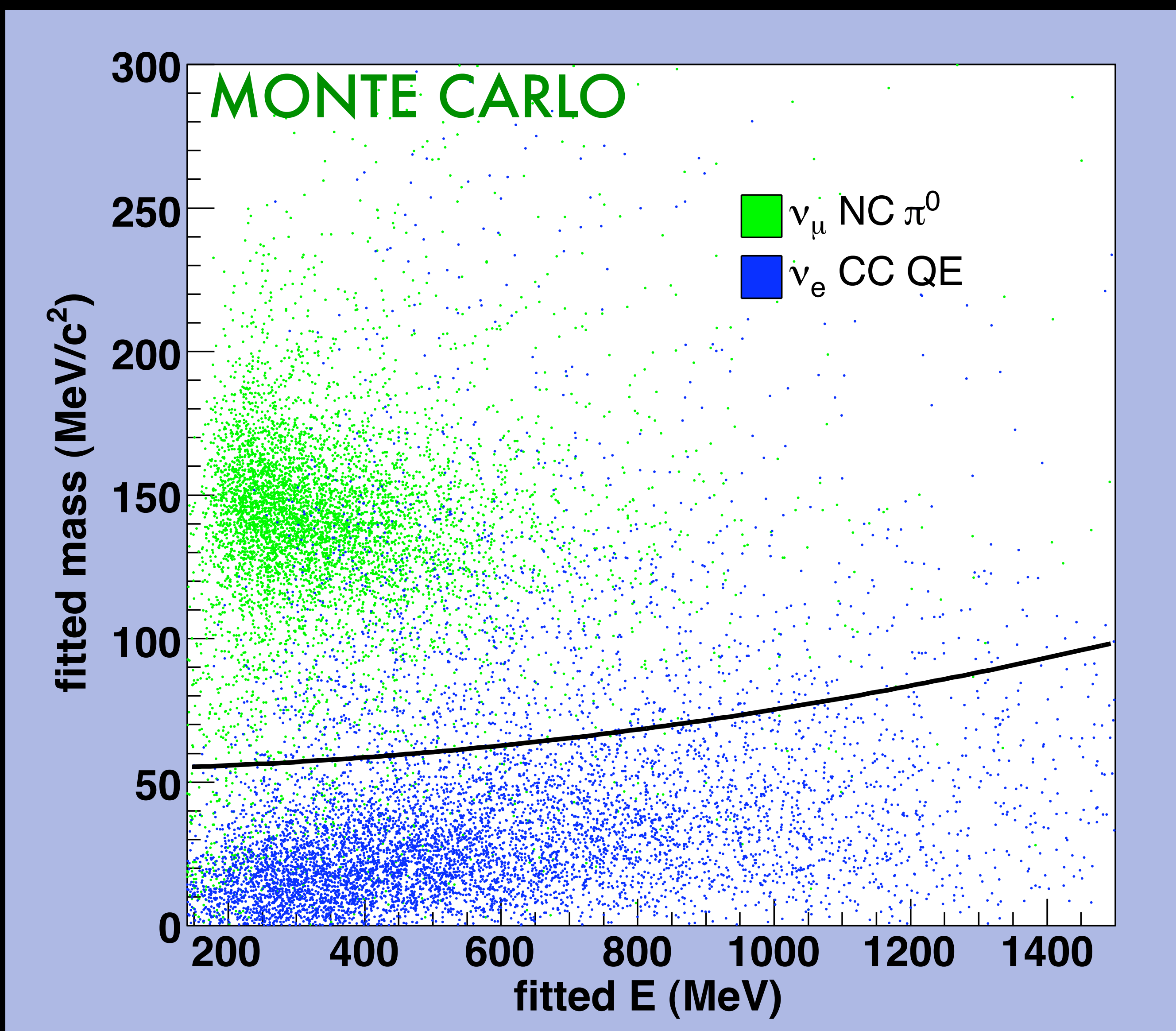
- $\log(L_e/L_\mu)$: compare likelihoods returned by e and μ fits.
- $\log(L_e/L_\mu)>0$ indicates electron hypothesis is favored.
- Analysis cut is parabola whose parameters selected to optimize oscillation sensitivity
- Discrimination easier at higher energy (increasing muon track length)

The Track-based Analysis: Muon rejection



- Can tag muons independently of particle ID by observing decay of stopped muon
- Valuable cross-check on data-Monte Carlo agreement
- In this variable, electrons and π^0 are indistinguishable
- Electrons have been removed by selecting background-like π^0 fit

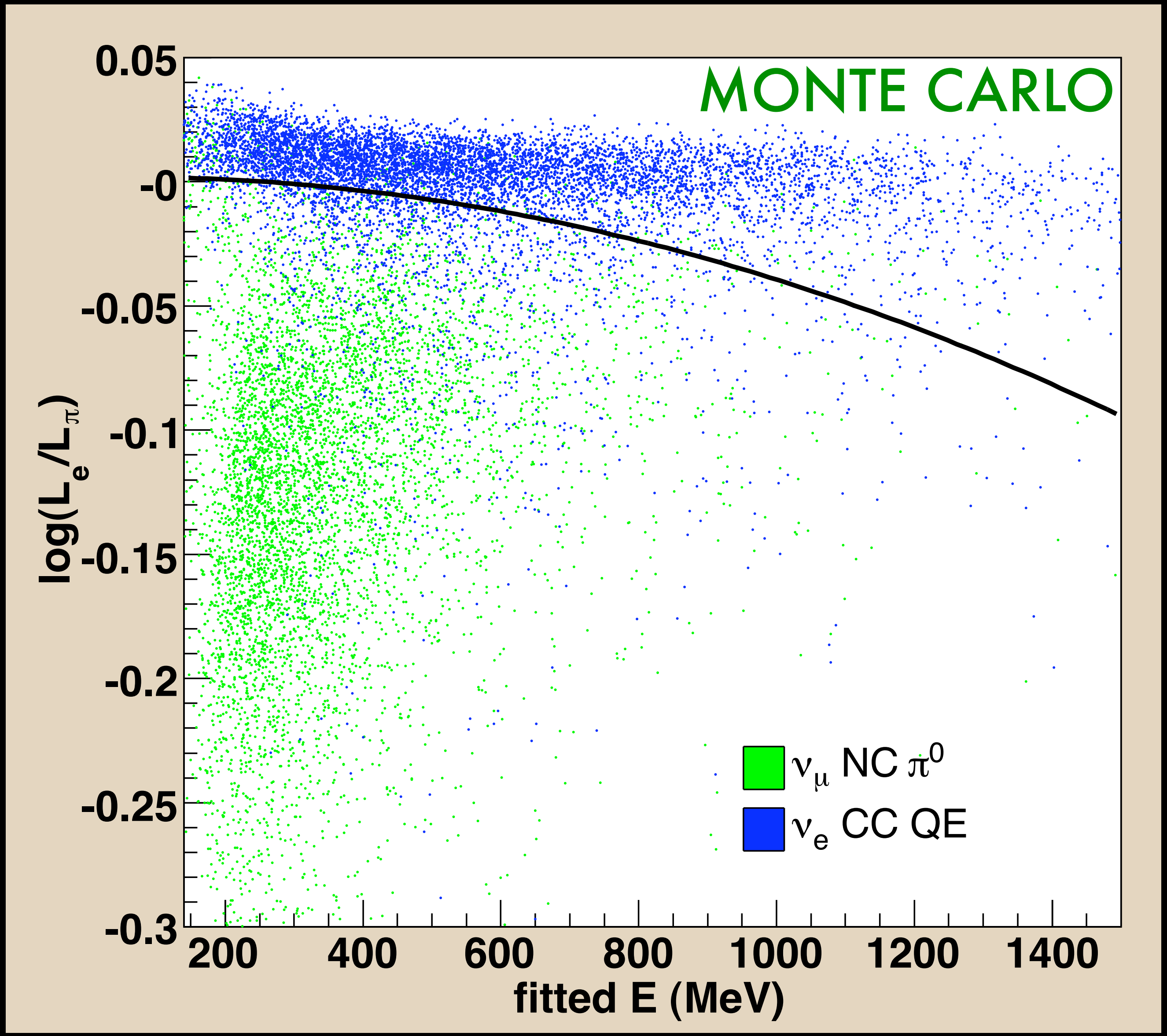
The Track-based Analysis: Neutral pion rejection



- Free mass 2-track fit (2T) employed to reconstruct invariant mass
- Background π^0 reconstruct near $m(\pi^0)$; signal ν_e have smaller mass

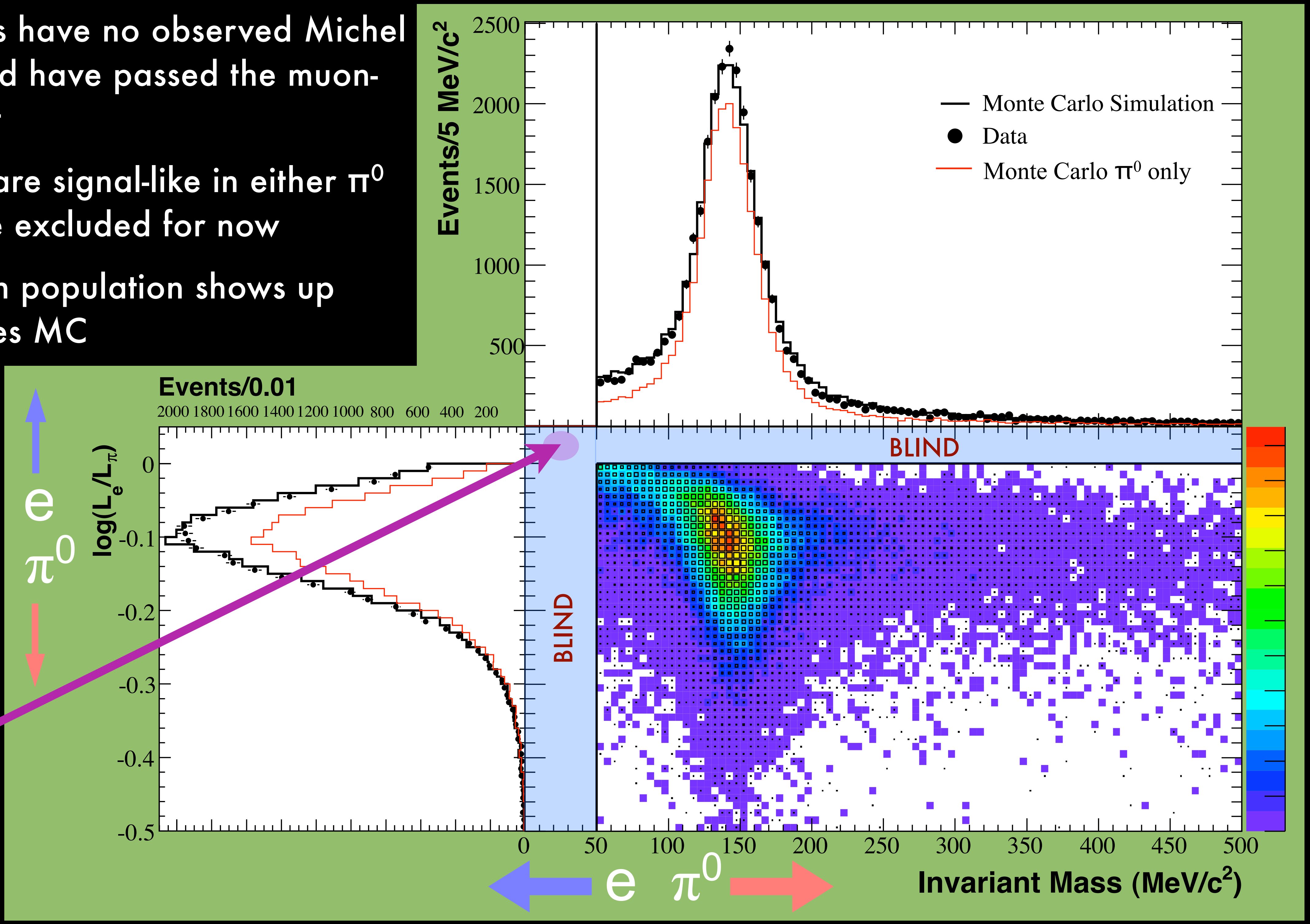
The Track-based Analysis: Neutral pion rejection

- Fixed mass 2-track fit used to form L_π
- $\log(L_e/L_\pi) > 0$ indicates electron hypothesis produces a better fit



The Track-based Analysis:
Neutral pion rejection

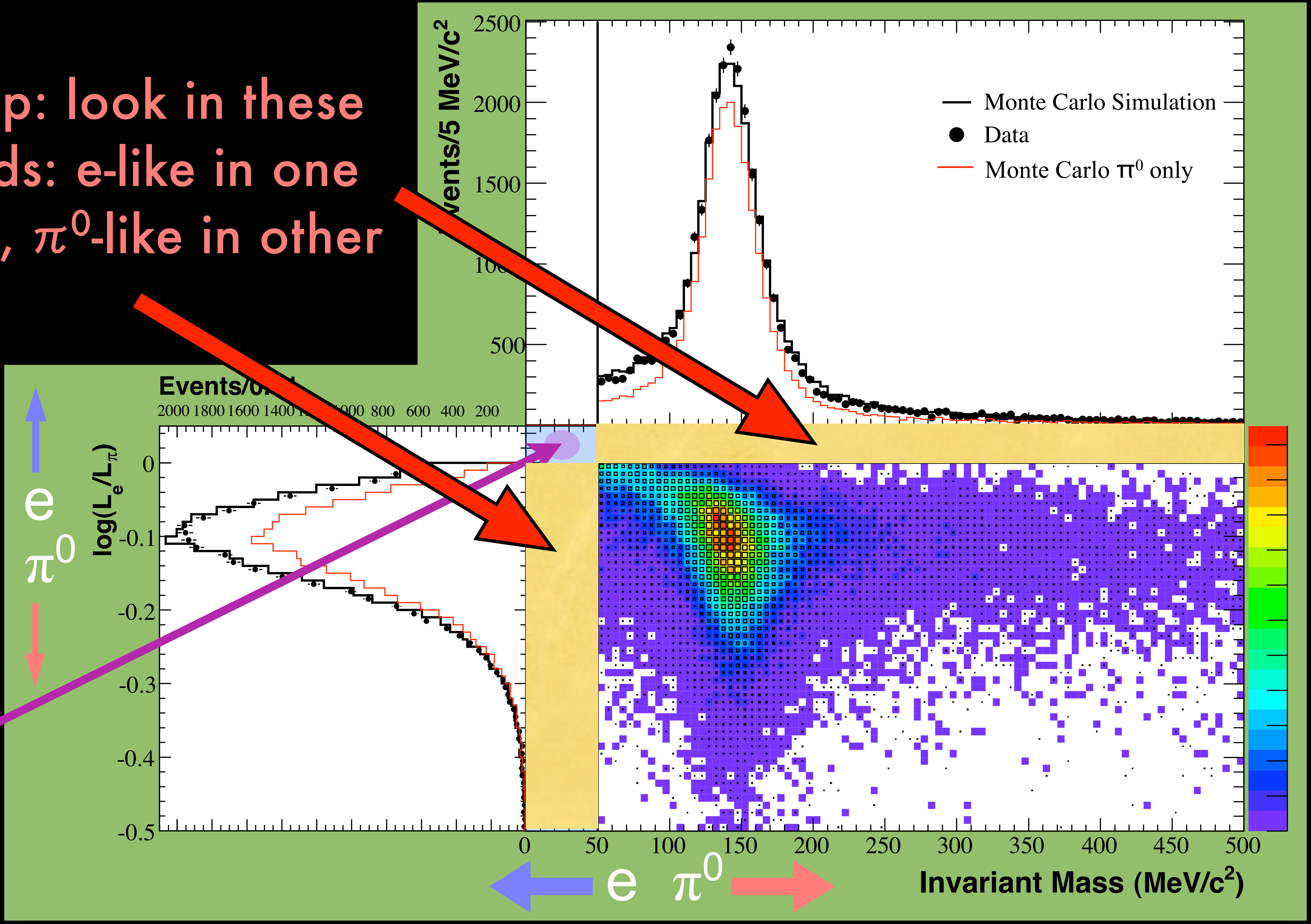
- These events have no observed Michel electron, and have passed the muon-rejection cut
- Events that are signal-like in either π^0 variable are excluded for now
- Neutral pion population shows up well, matches MC



ν_e signal region

The Track-based Analysis: Neutral pion rejection

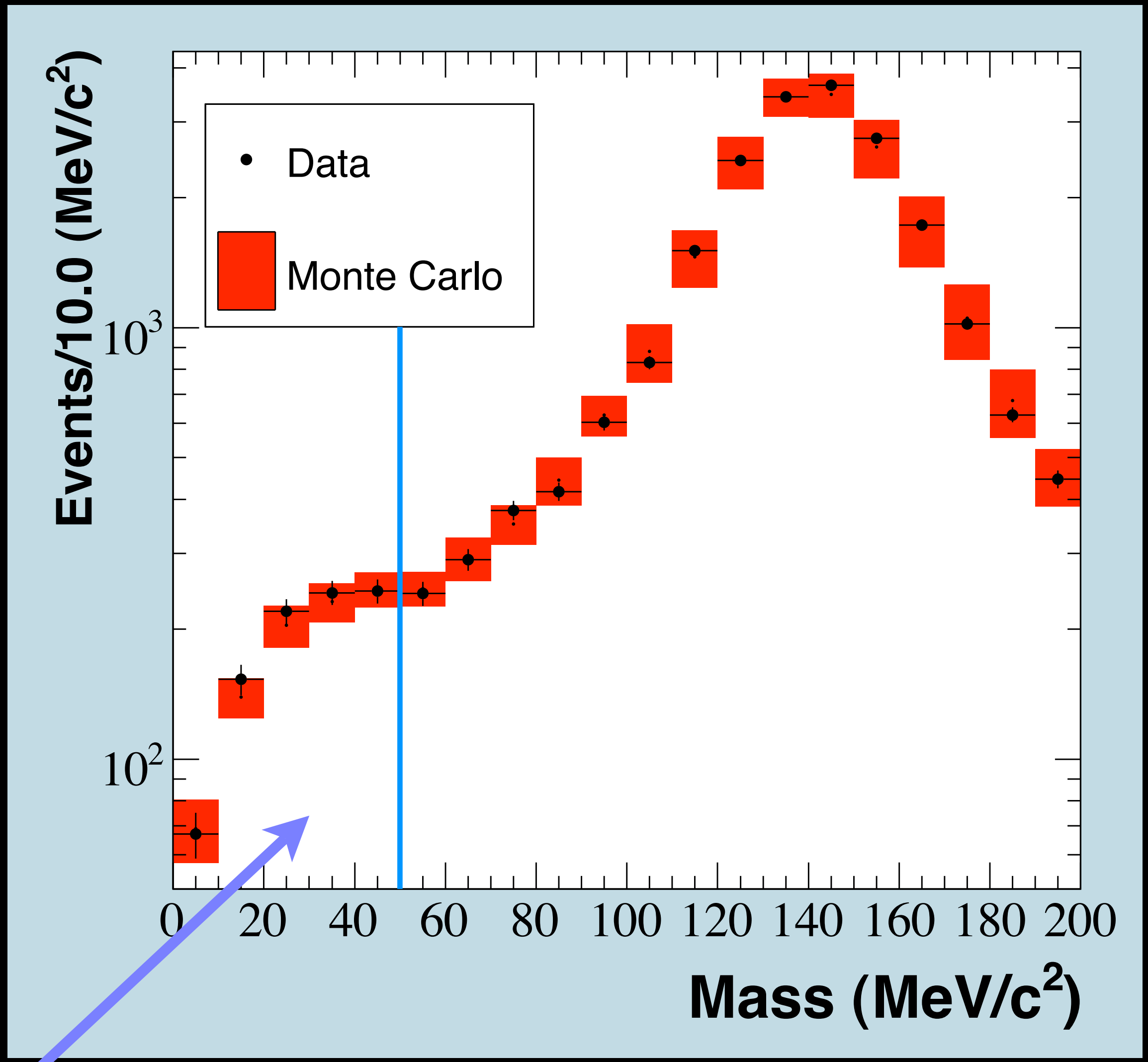
- Next step: look in these sidebands: e-like in one variable, π^0-like in other



ν_e signal region

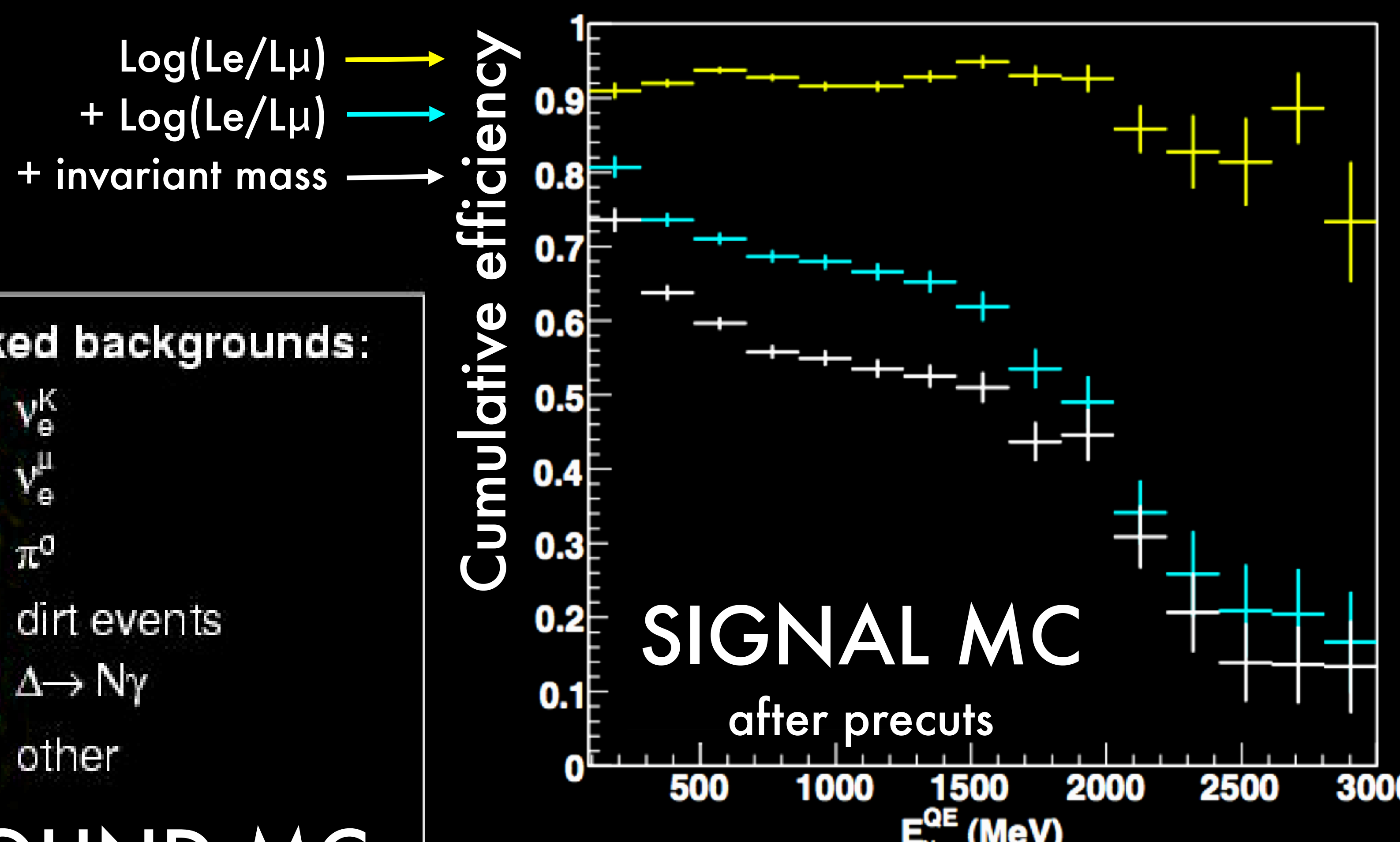
The Track-based Analysis:
Looking in the sidebands

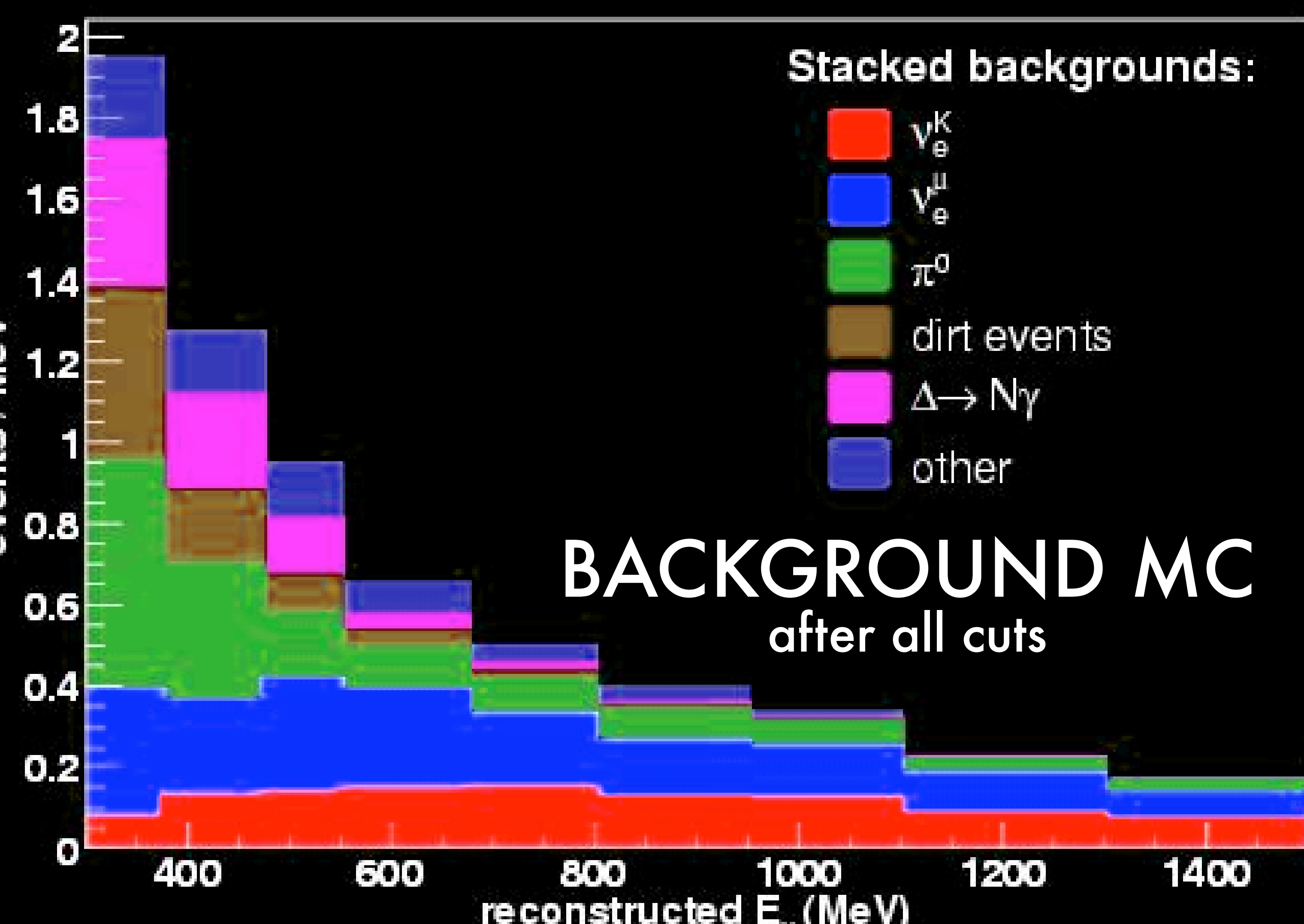
- Look at full mass range for events with $\log(L_e/L_\pi) < 0$
- These are signal-like in mass, but background-like in $\log(L_e/L_\pi)$
- Nice data/MC agreement



sideband

The Track-based Analysis: Efficiency and backgrounds





x1500 μ rejection

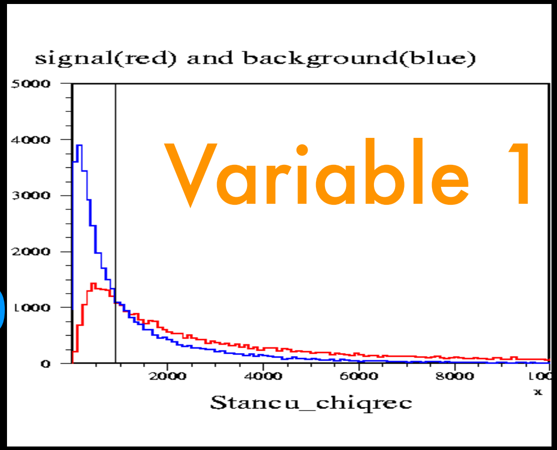
x200 π^0 rejection

Boosted Decision Trees (BDT)

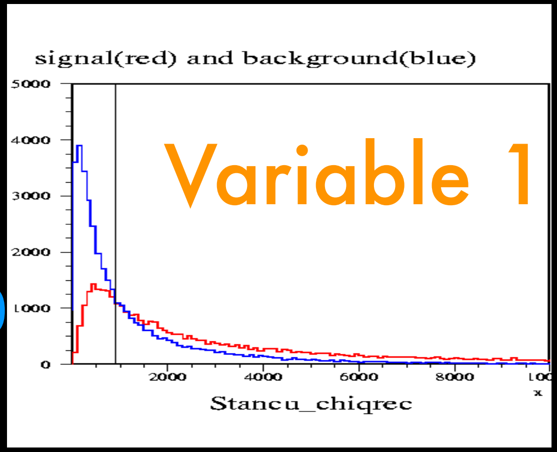
- An algorithm optimized to combine many weakly discriminating variables into one that provides powerful separation
- B. Roe *et al.*, *Nucl. Inst. Meth.* **A543** *577* (2005)
- Idea: Go through all analysis variables and find best variable and value to split a Monte Carlo data set.
  - For each of 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

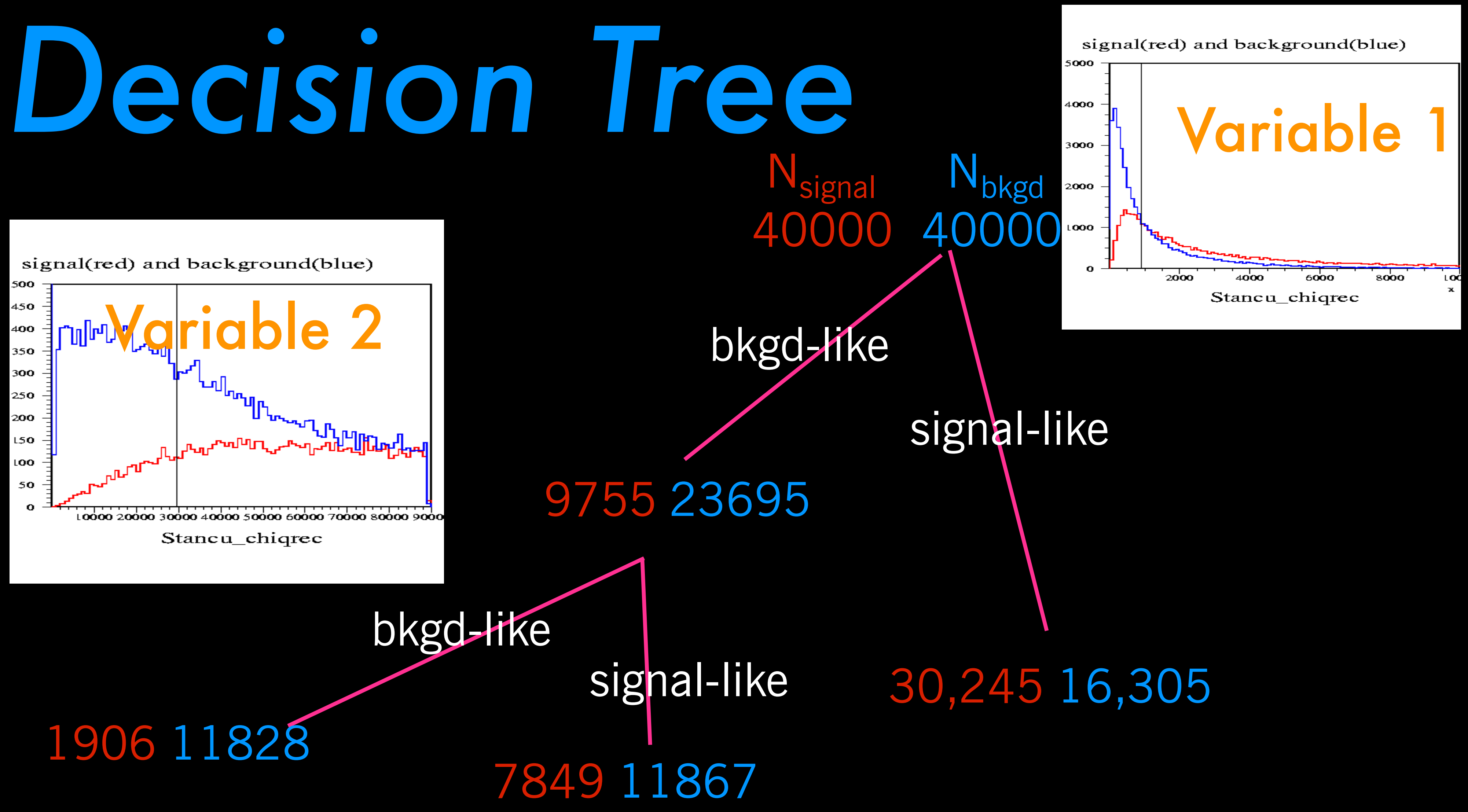
bkgd-like

9755 23695

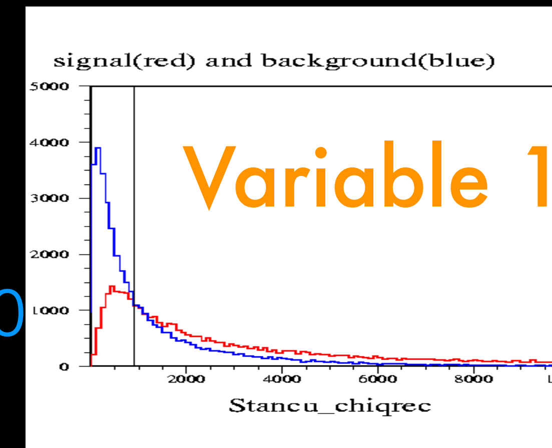
signal-like

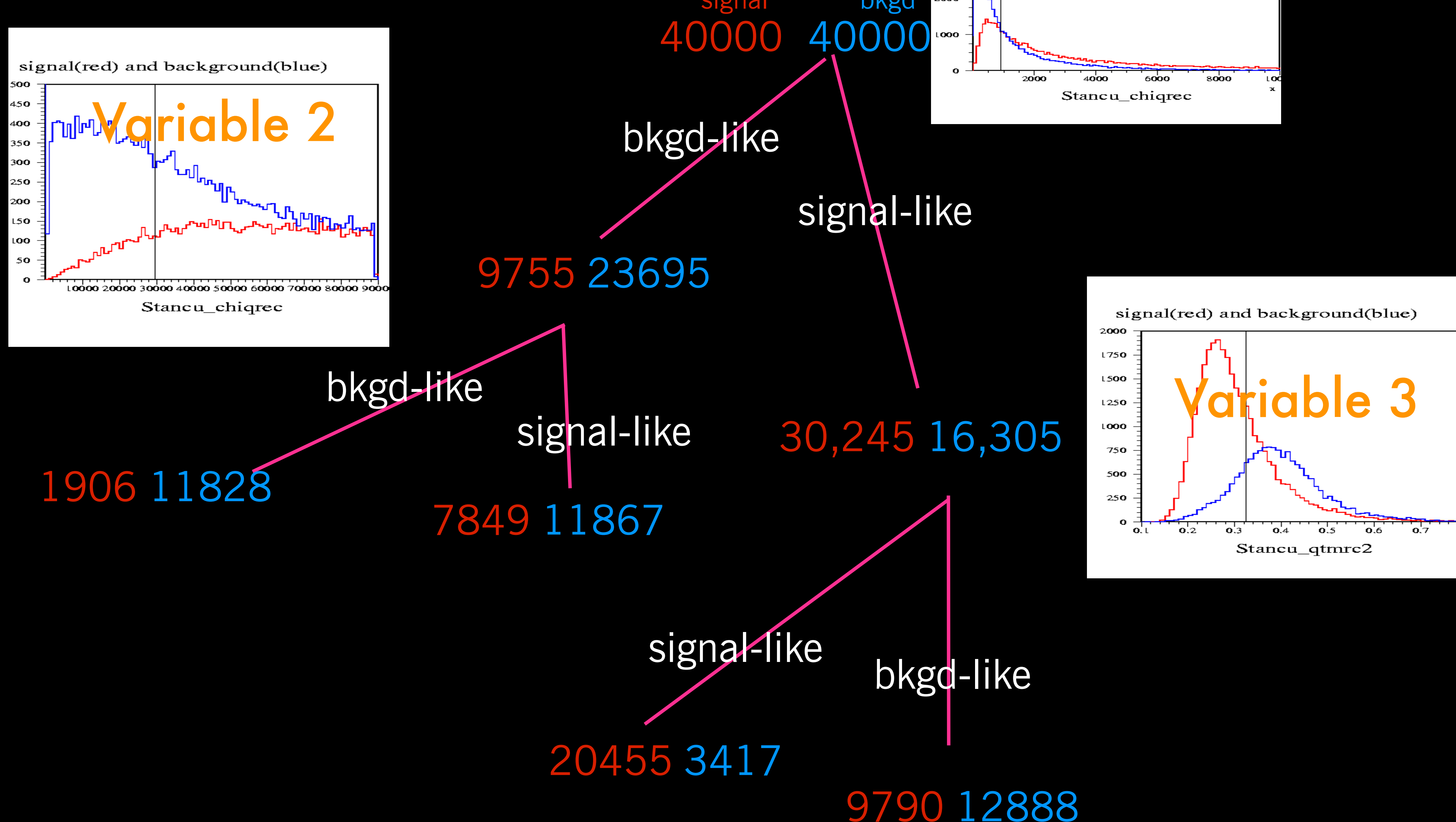
30,245 16,305

A Decision Tree

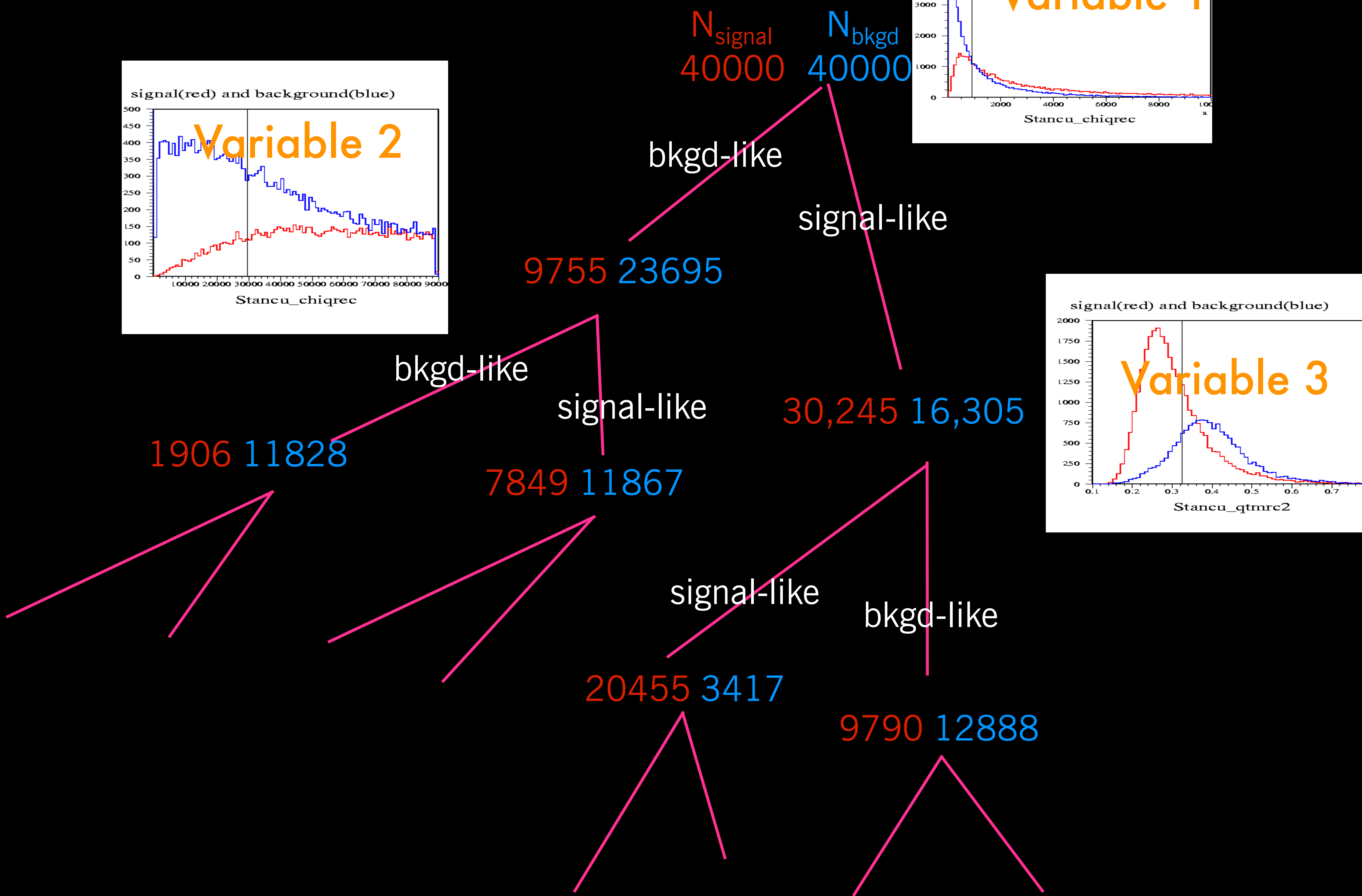


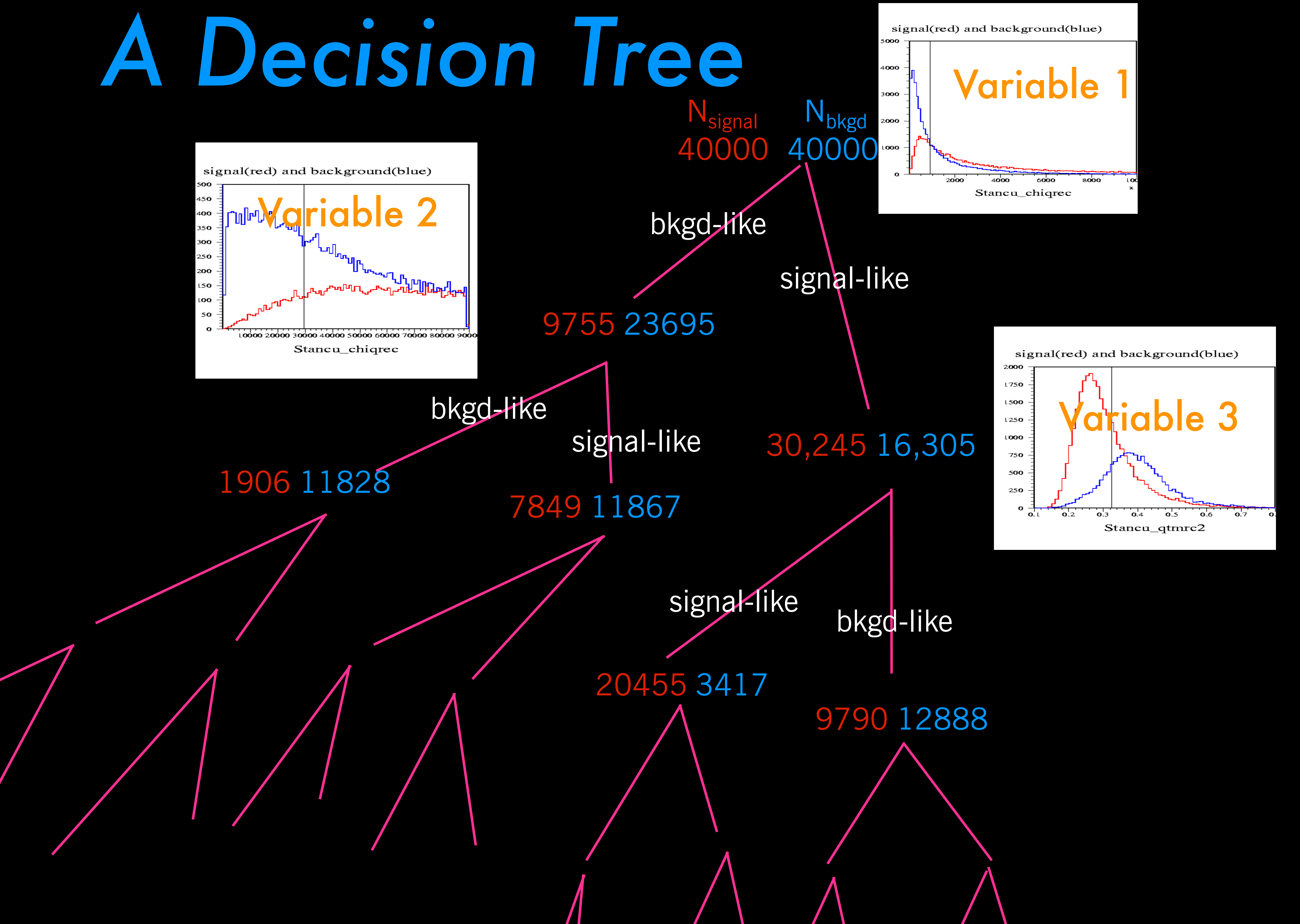
A Decision Tree



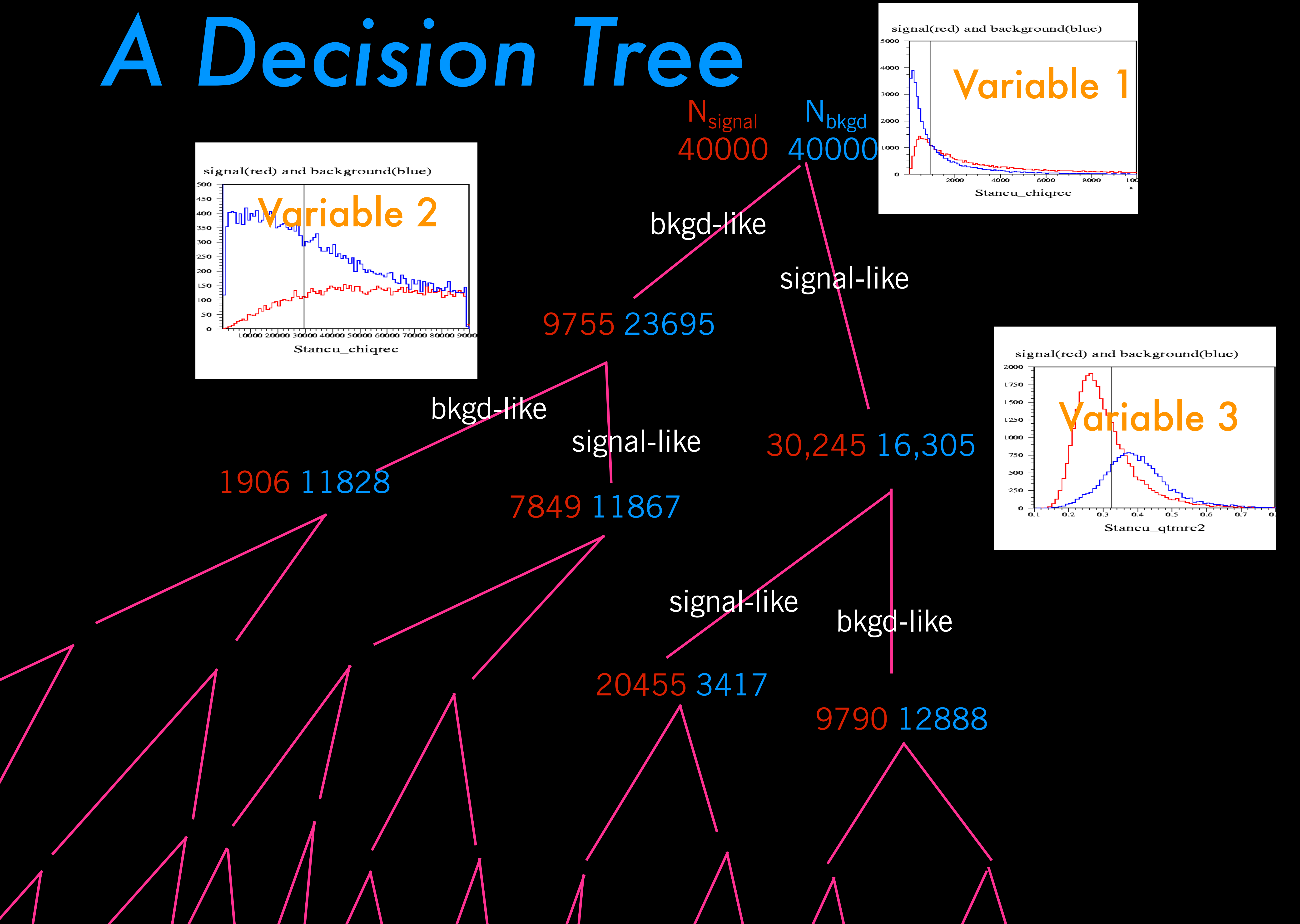


A Decision Tree




A Decision Tree
signal(red) and background(blue)
Variable 1
Stancu_chiqrec
N signal
N bkgd
40000 40000
bkgd-like
signal-like
signal(red) and background(blue)
Variable 2
Stancu_chiqrec
9755 23695
bkgd-like
signal-like
1906 11828
7849 11867
30,245 16,305
signal(red) and background(blue)
Variable 3
Stancu_qtmrc2
signal-like
bkgd-like
20455 3417
9790 12888

A Decision Tree



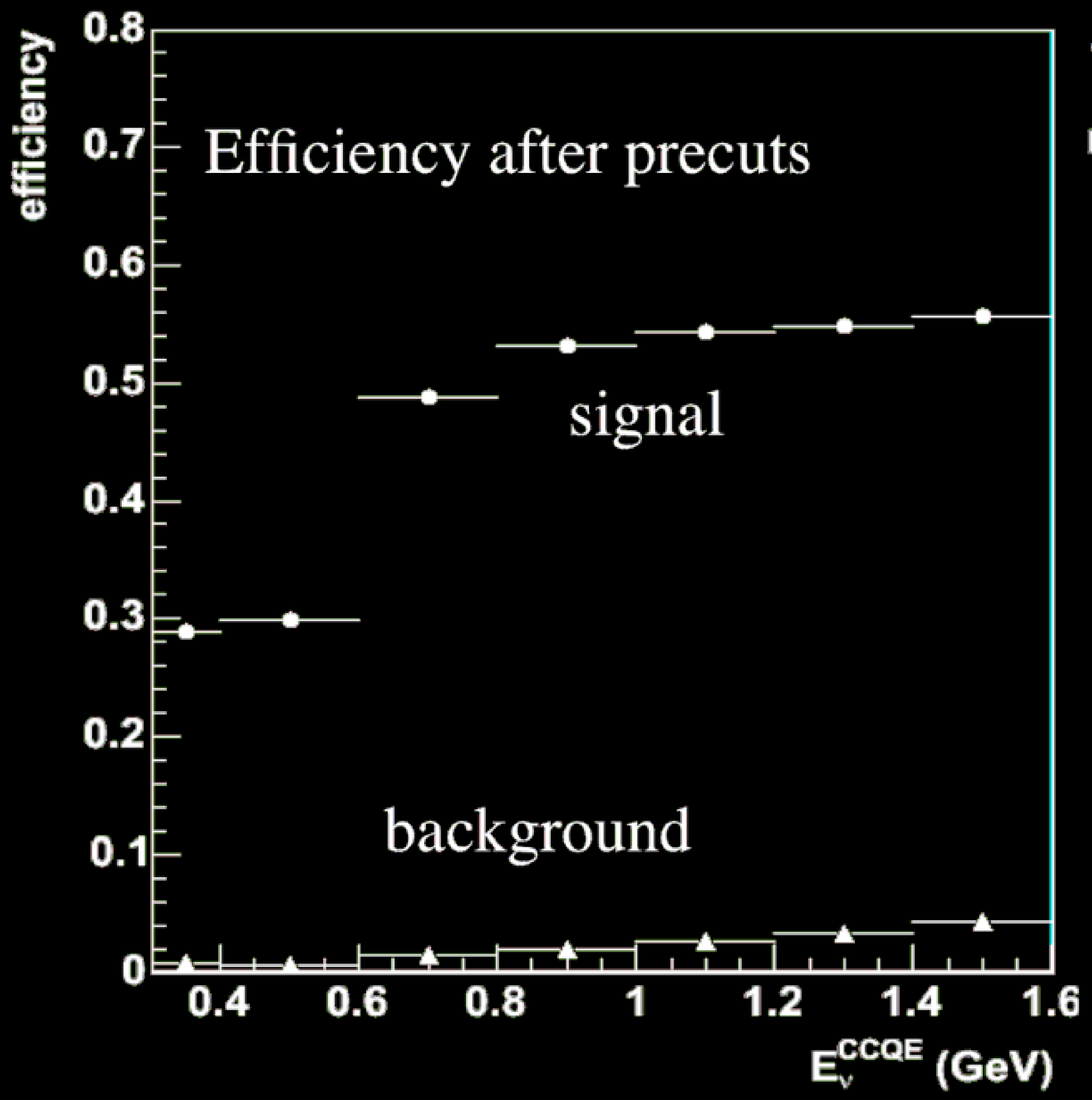
Boosted Decision Trees (BDT)

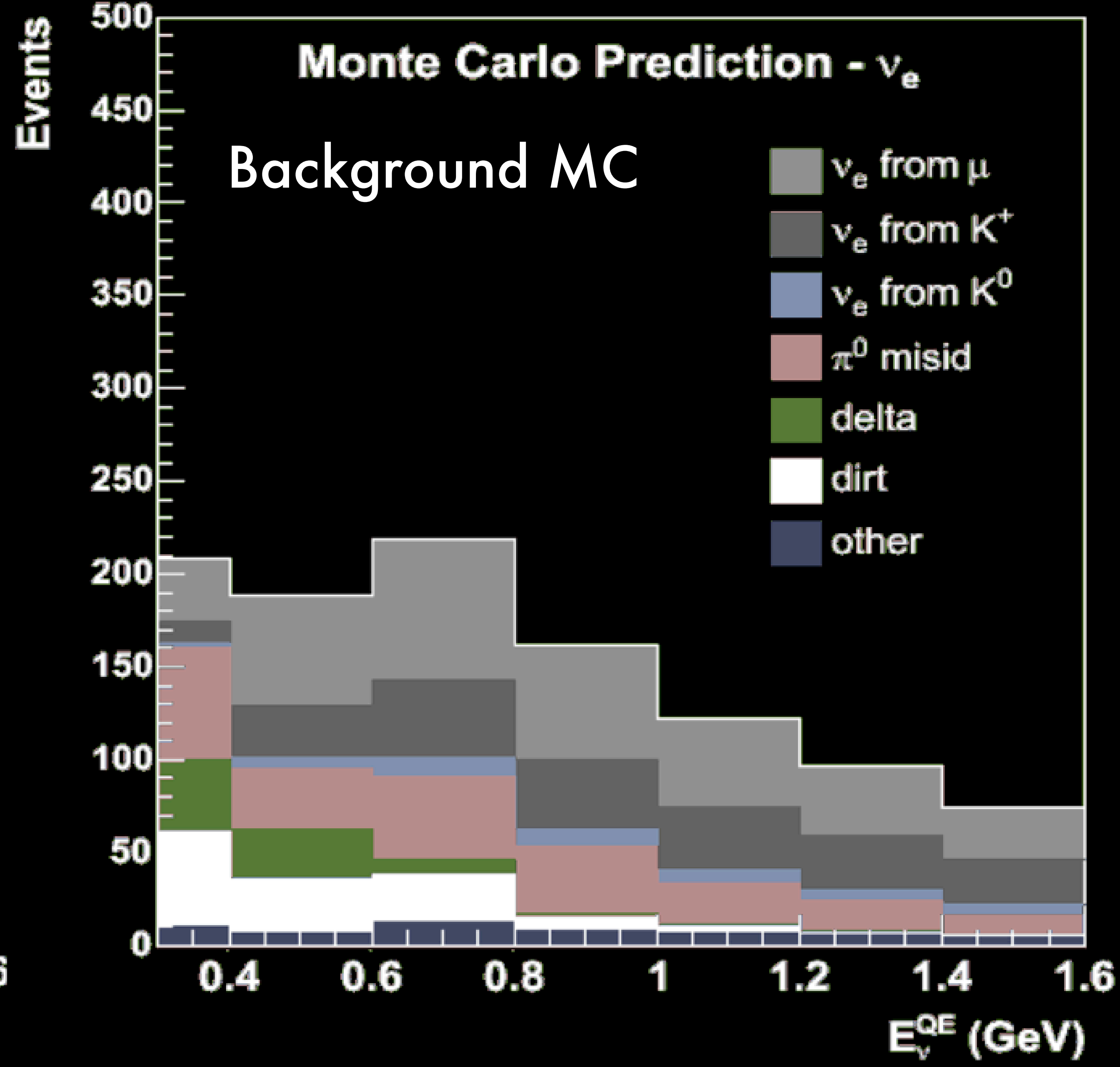
- A tree is not unique
- After the tree is built, additional trees are built with the leaves re-weighted to emphasize the previously misidentified events (since those are hardest to classify). This is "boosting."
- Each data event is sent through every tree, and in each tree is assigned a value:
  - +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

Constraints from ν_μ CCQE sample

Event rate normalization

- Total ν_μ CCQE rate compared to Monte Carlo: appearance-only search will tie electron rate to this normalization
- Track-based: 1.32 ± 0.26
- Boosting: 1.22 ± 0.29

Constraints from ν_μ CCQE sample

- Each analysis approaches this differently:
- Track-based: Reweight MC prediction to match measured ν_μ result
- Boosting: include the correlations of ν_μ to ν_e in the error matrix of a combined ν_μ+ν_e fit:

$$\chi^2 = \begin{pmatrix} \Delta_i^{\nu_e} & \Delta_i^{\nu_\mu} \end{pmatrix} \begin{pmatrix} M_{ij}^{e,e} & M_{ij}^{e,\mu} \\ M_{ij}^{\mu,e} & M_{ij}^{\mu,\mu} \end{pmatrix}^{-1} \begin{pmatrix} \Delta_j^{\nu_e} \\ \Delta_j^{\nu_\mu} \end{pmatrix}$$

$$\text{where } \Delta_i^{\nu_e} = \text{Data}_i^{\nu_e} - \text{Pred}_i^{\nu_e}(\Delta m^2, \sin^2 2\theta) \text{ and } \Delta_i^{\nu_\mu} = \text{Data}_i^{\nu_\mu} - \text{Pred}_i^{\nu_\mu}$$

  - Systematic (and statistical) uncertainties are included in $(M_{ij})^{-1}$

Neutrino cross-section errors for oscillation analysis

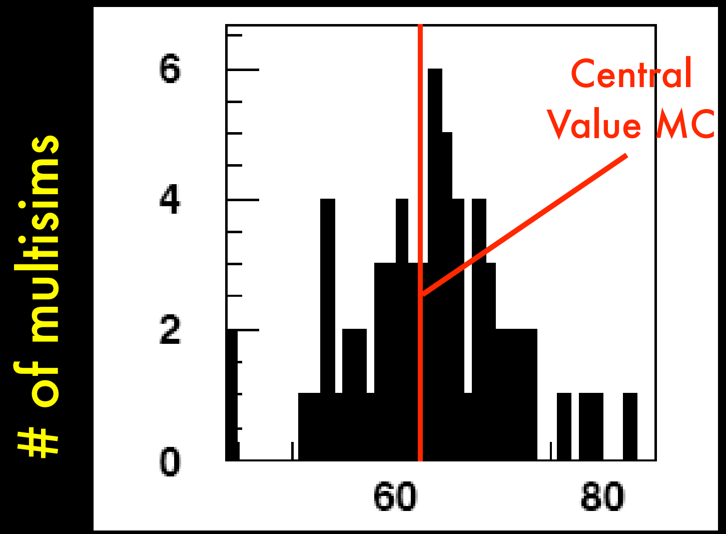
Parameter	Error/Value	Source
M_A^{QE}, E_{lo}^{SF}	6%, 2% (stat+bkg)	MiniBooNE ν_μ CCQE
QE σ norm	10%	MiniBooNE ν_μ CCQE
NC π^0 rate	few % (depends on p_π)	MiniBooNE NC π^0 data
$\Delta \rightarrow N\gamma$ rate	$\sim$ 10%	MiniBooNE NC π^0 data, $\Delta \rightarrow N\gamma$ BR
E_B, p_F	9 MeV, 30 MeV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

70 Optical Model multisims

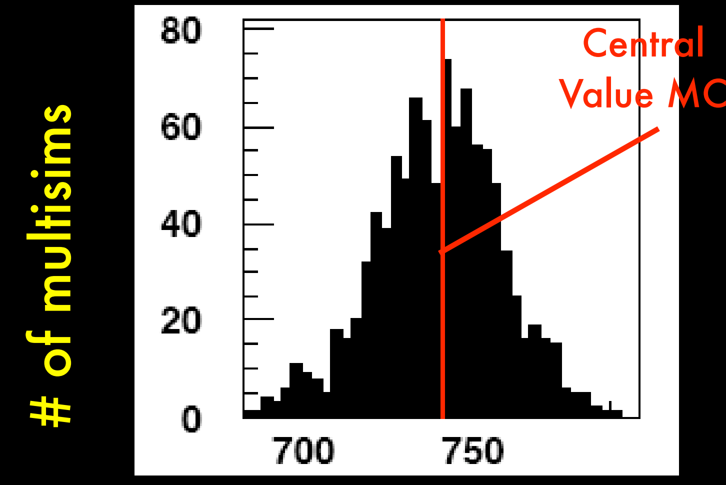


events passing signal cuts in bin $500 < E_\nu^{QE} < 600$ MeV

Handling other uncertainties

- Flux and neutrino cross-section parameter variations do not affect the hit distributions for a given event, only the probability of that event occurring in the first place
- Rather than repeating hit-level MC, determine effect of varying by mocking up 1000 multisims by reweighting the same MC events: reduced MC statistics error and greatly reduced CPU usage.
- Similar procedure to produce error matrix for the oscillation candidate histogram
- Example of multisim outputs in a single osc. bin:

1000 K+ reweighting multisims



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

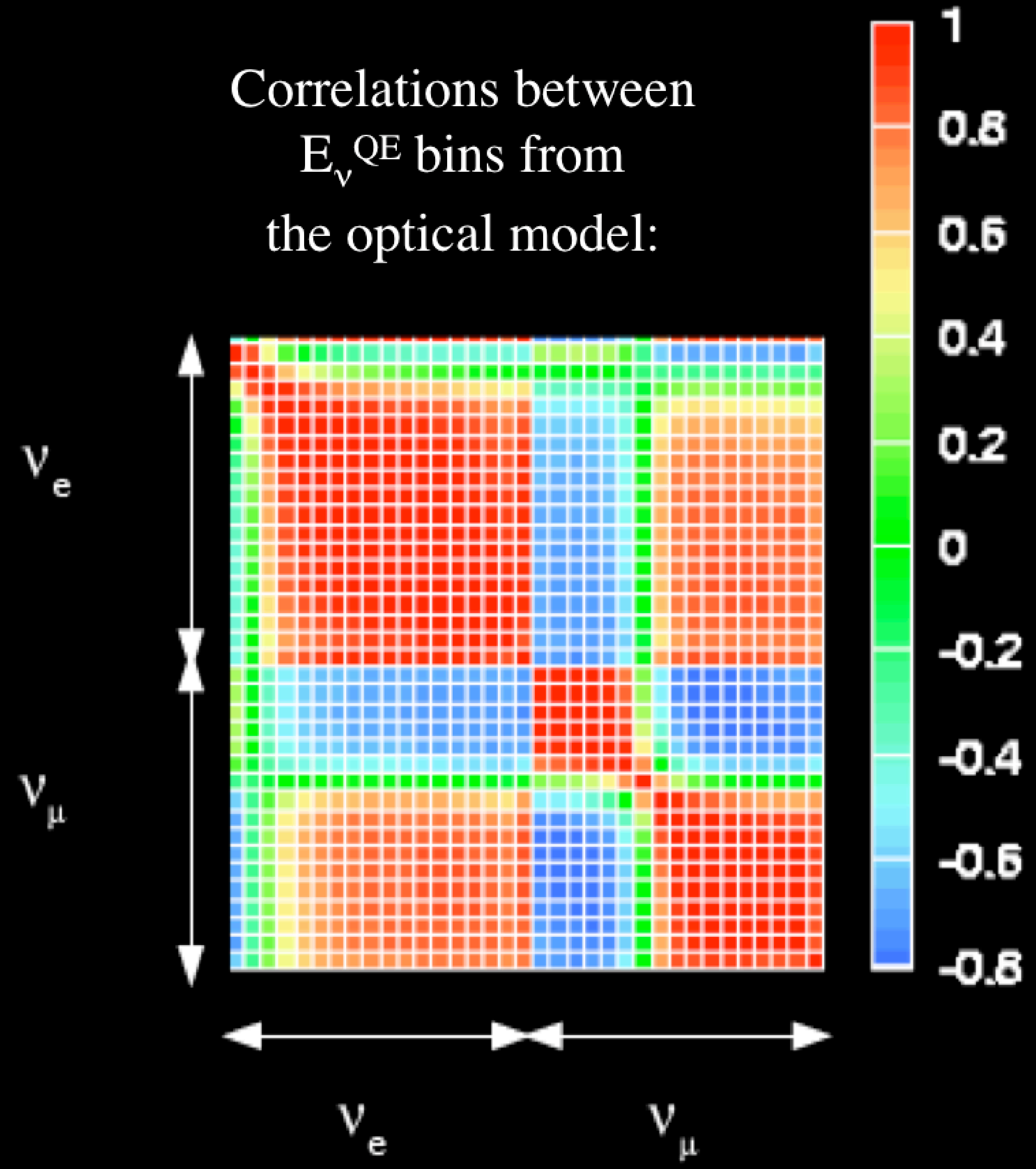
The error matrix

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

- 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 each source (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:



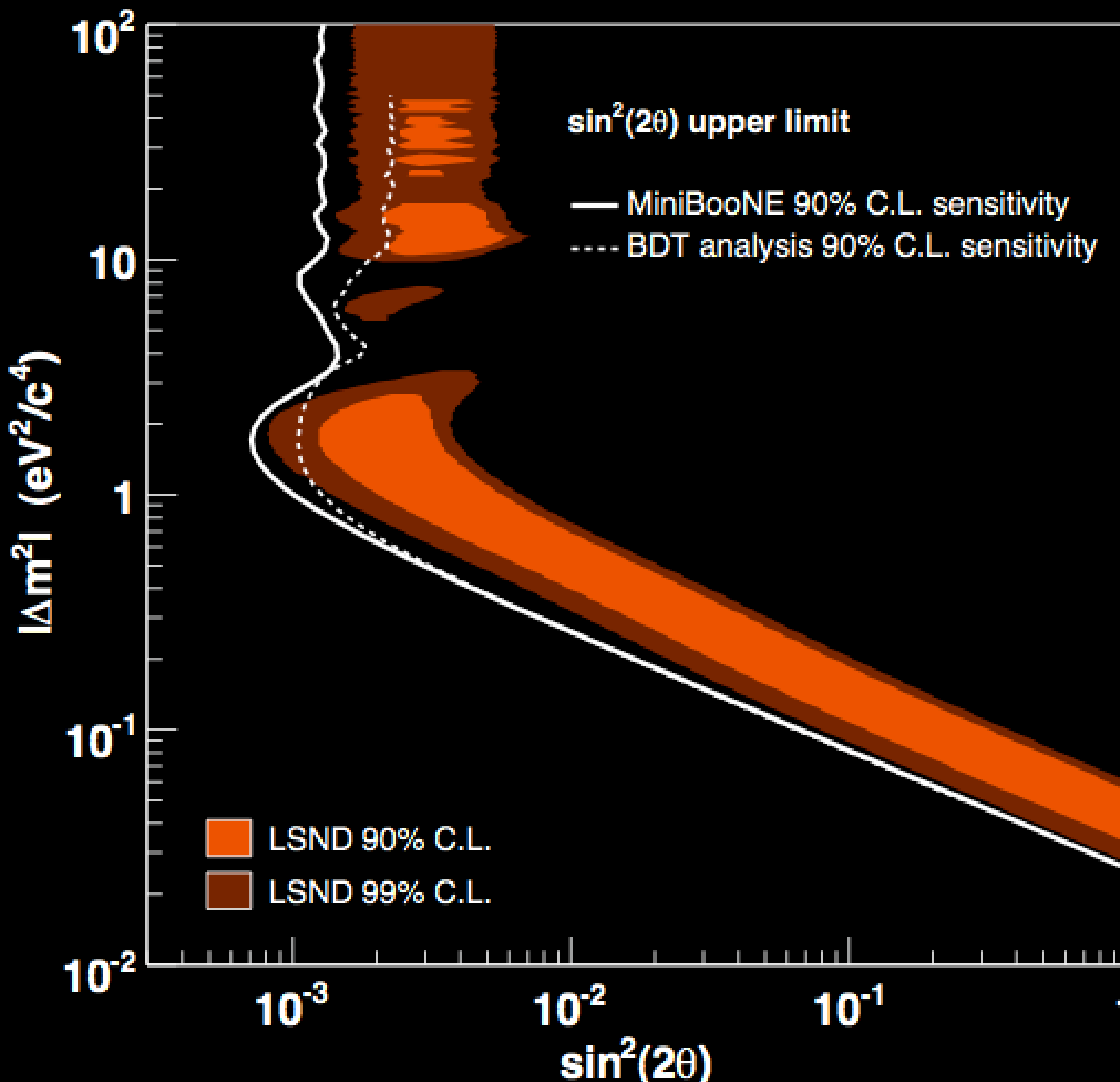
Expected background events by source

PROCESS	EVENTS AFTER SELECTION
BEAM UNRELATED	2
DIRT	17 ± 3
NEUTRAL CURRENT π^0	62 ± 10
NC RADIATIVE Δ DECAY	20 ± 4
NC COHERENT AND RADIATIVE	<1
ν_μ QUASIELASTIC	10 ± 2
NEUTRINO-ELECTRON ELASTIC	7 ± 2
OTHER ν_μ	13 ± 5
INTRINSIC ν_e FROM MUONS	132 ± 10
INTRINSIC ν_e FROM K^+	71 ± 26
INTRINSIC ν_e FROM K^0	23 ± 7
INTRINSIC ν_e FROM $\pi^+ \rightarrow e^+ \nu_e$	3 ± 1
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



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*
- 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

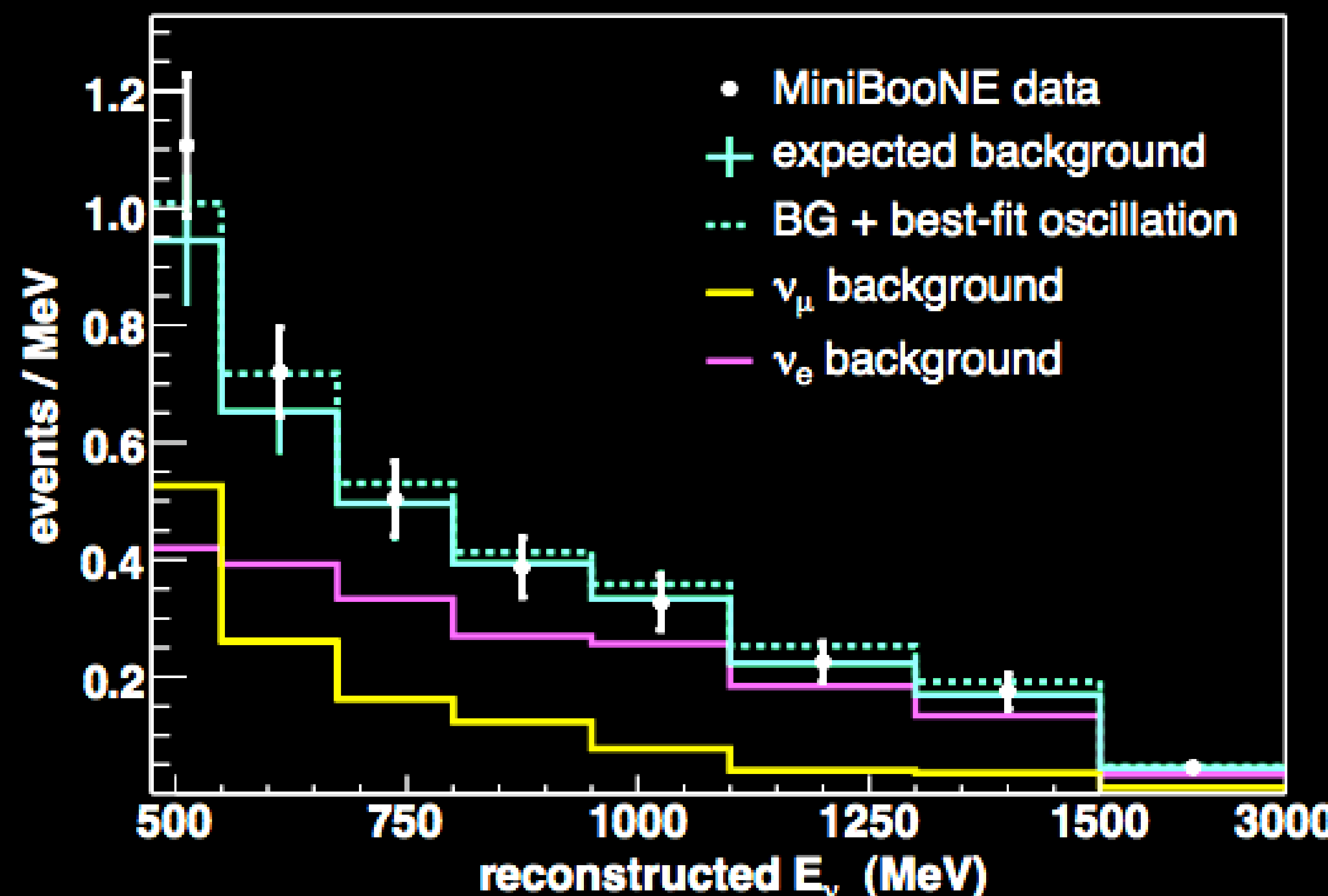
- Step 1 (χ^2 probability for a set of diagnostic variables):
  - Only probabilities revealed, not full histograms
  - 12 variables for track-based analysis: 11 look good
  - 46 variables for boosting analysis: all look good
- $E_{visible}$ (not E_ν^{QE}) distribution in track-based analysis returned a probability of <1%:
  - Track-based analysis revised to limit oscillation fit range to E_ν^{QE} >475 MeV, eliminating two low-energy bins where backgrounds known to rise.
  - New sensitivity almost identical to old
  - No change to the Boosting analysis

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

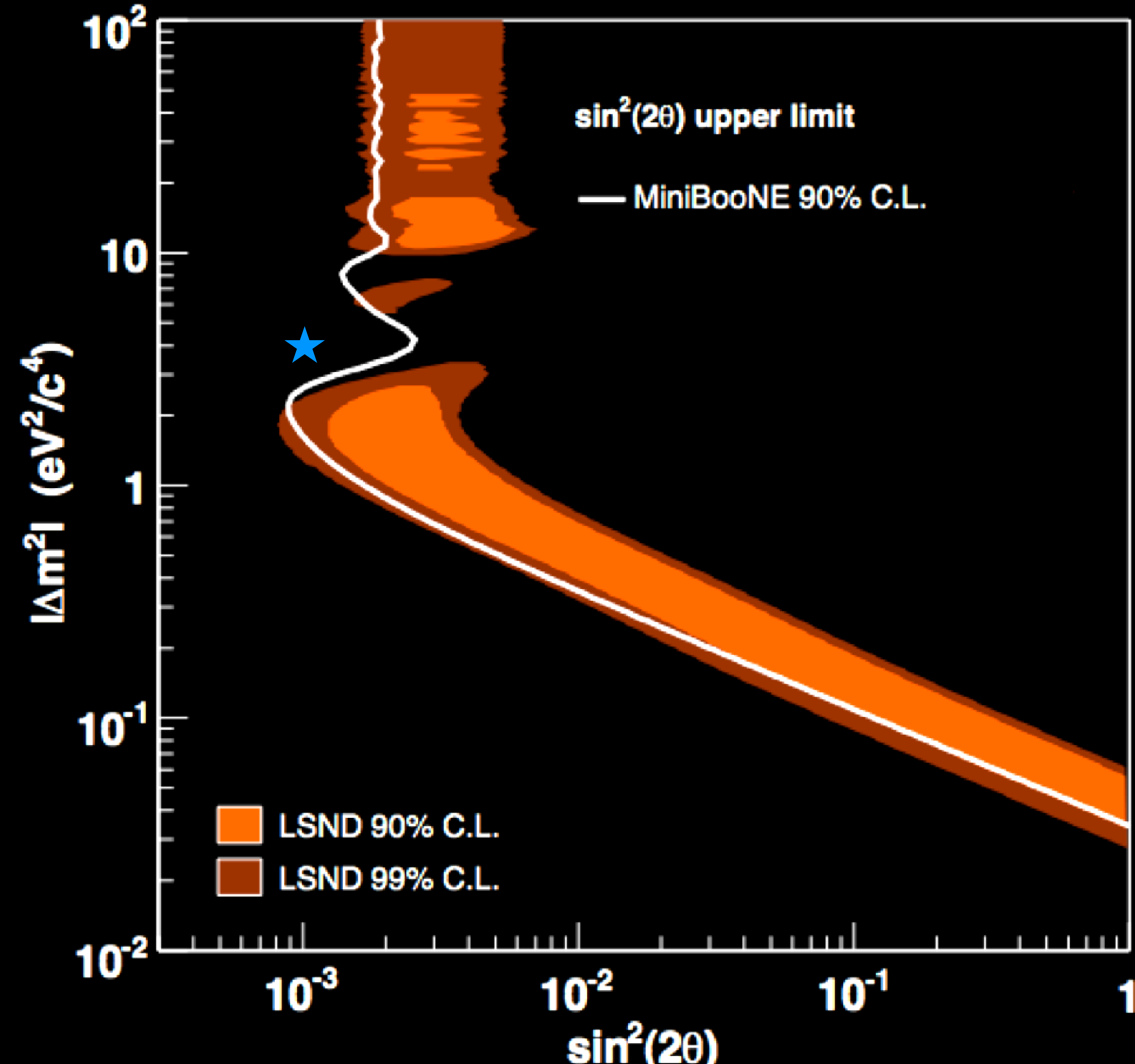
Energy fit and spectrum



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

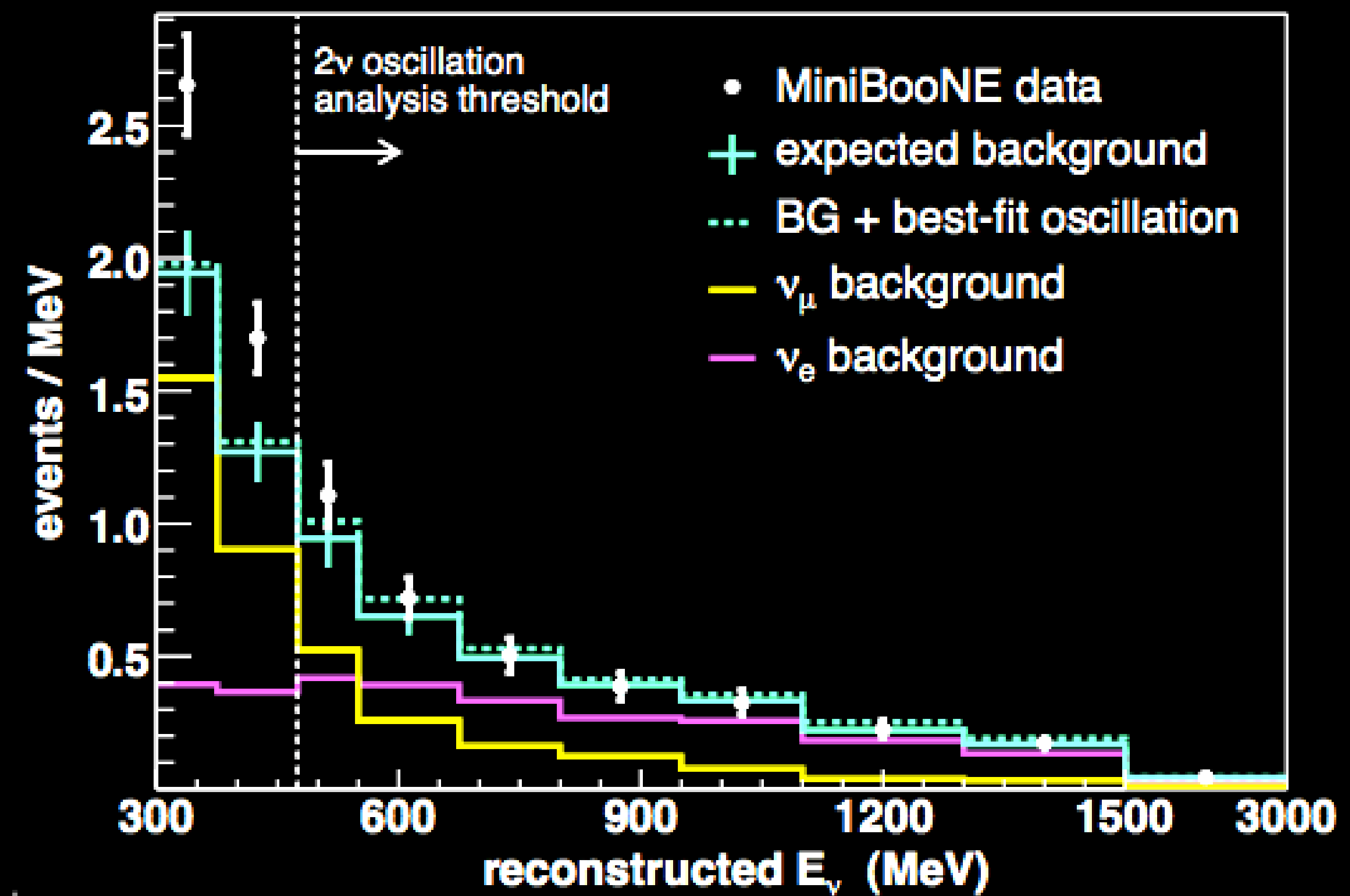
Oscillation Limit

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

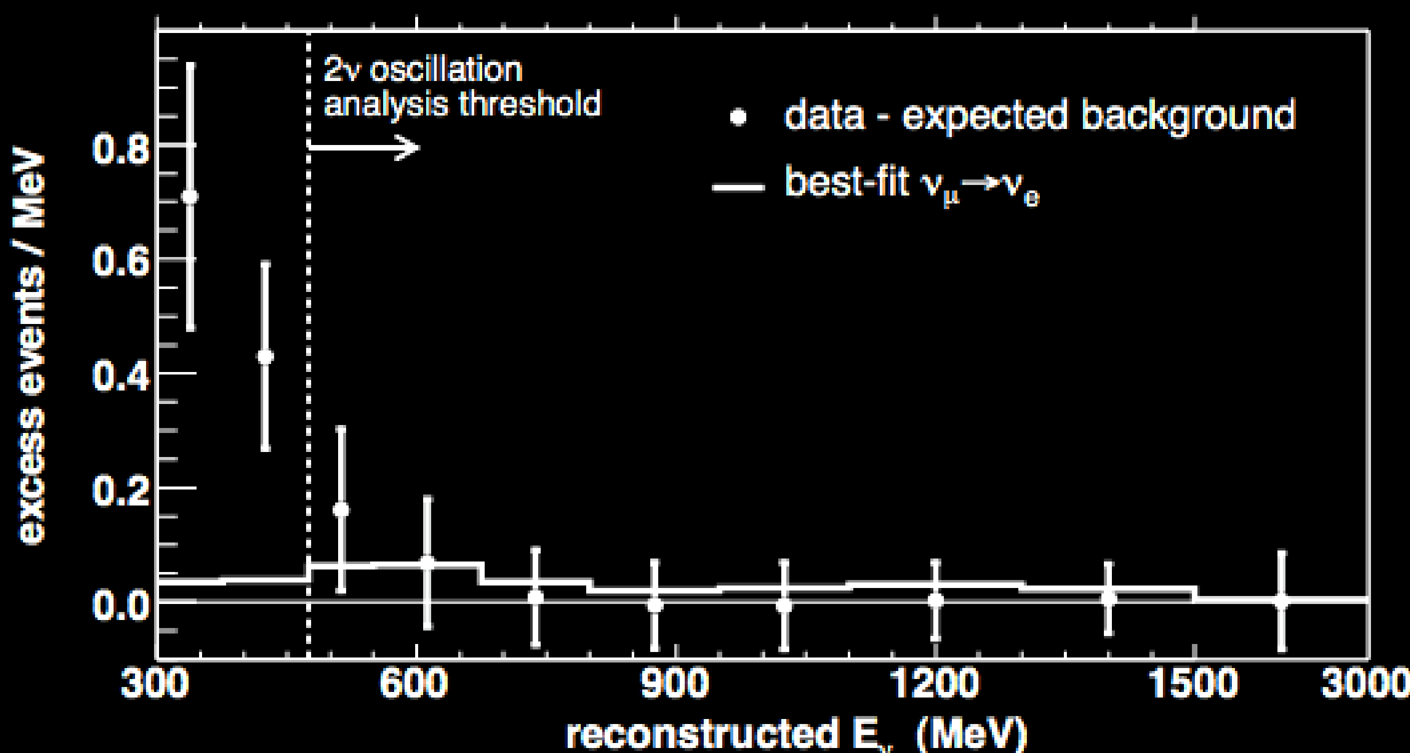


The full spectrum

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



BACKGROUND SUBTRACTED

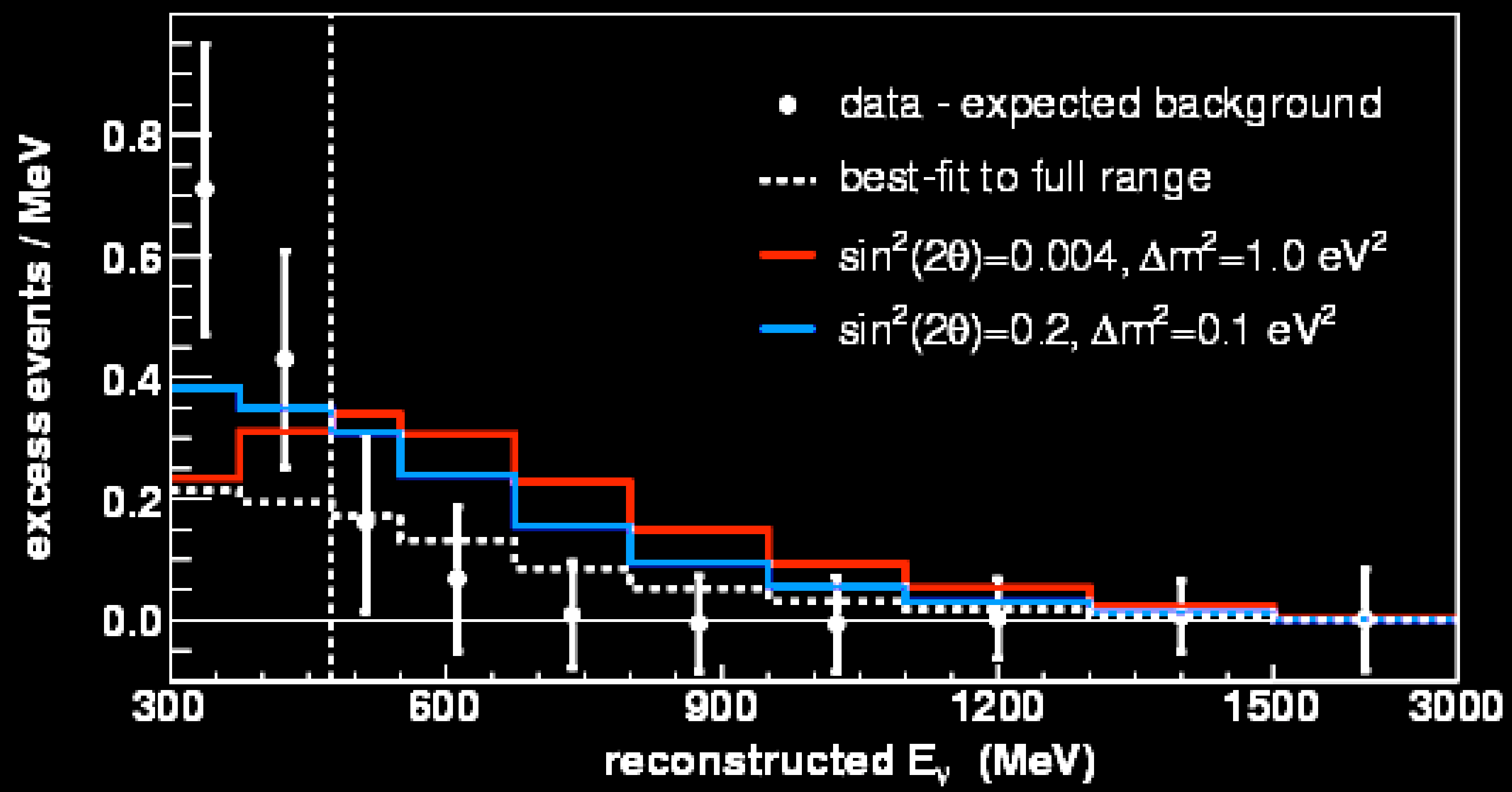


Focusing on the lowest two bins only:

- Excess is 96±17±20 events

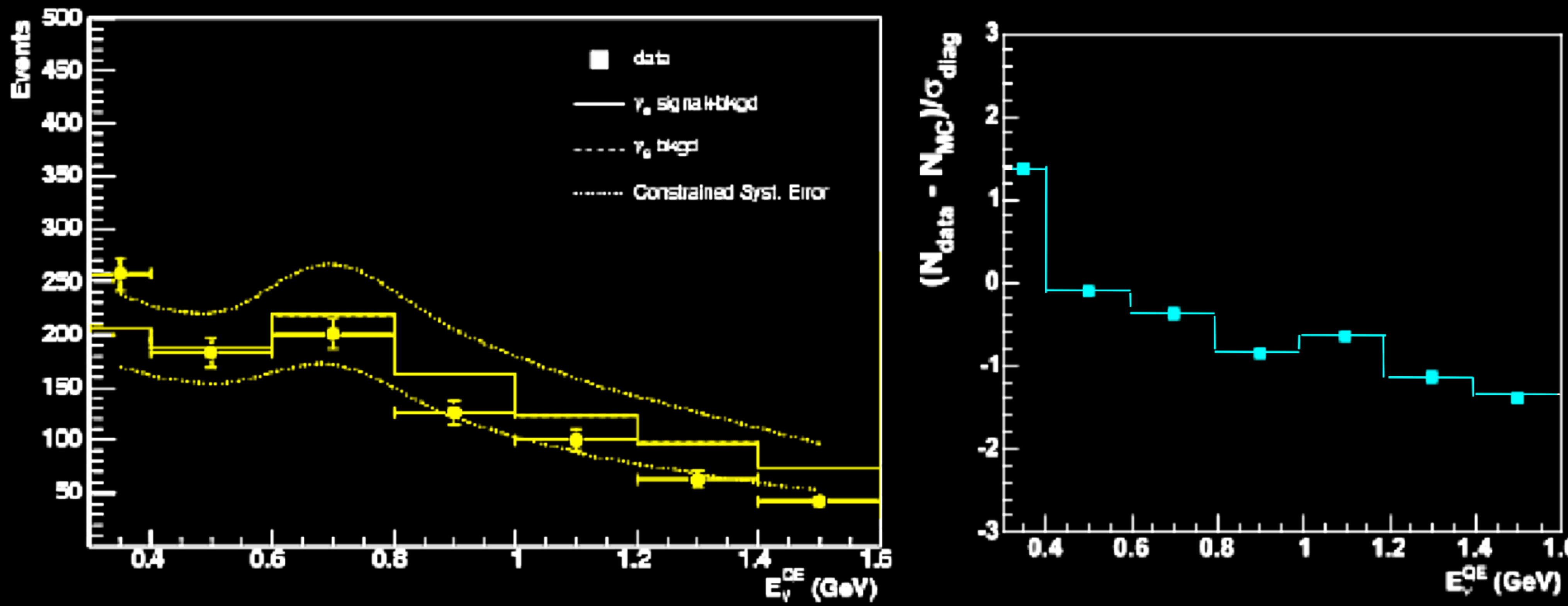
2-neutrino fit to full spectrum

- Best fit has 18% probability
  - $(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03\ eV^2)$
  - These parameters are completely excluded by reactor experiments in 2-nu model
- Null hypothesis has 3% probability
- Spectrum does not resemble LSND-type oscillations



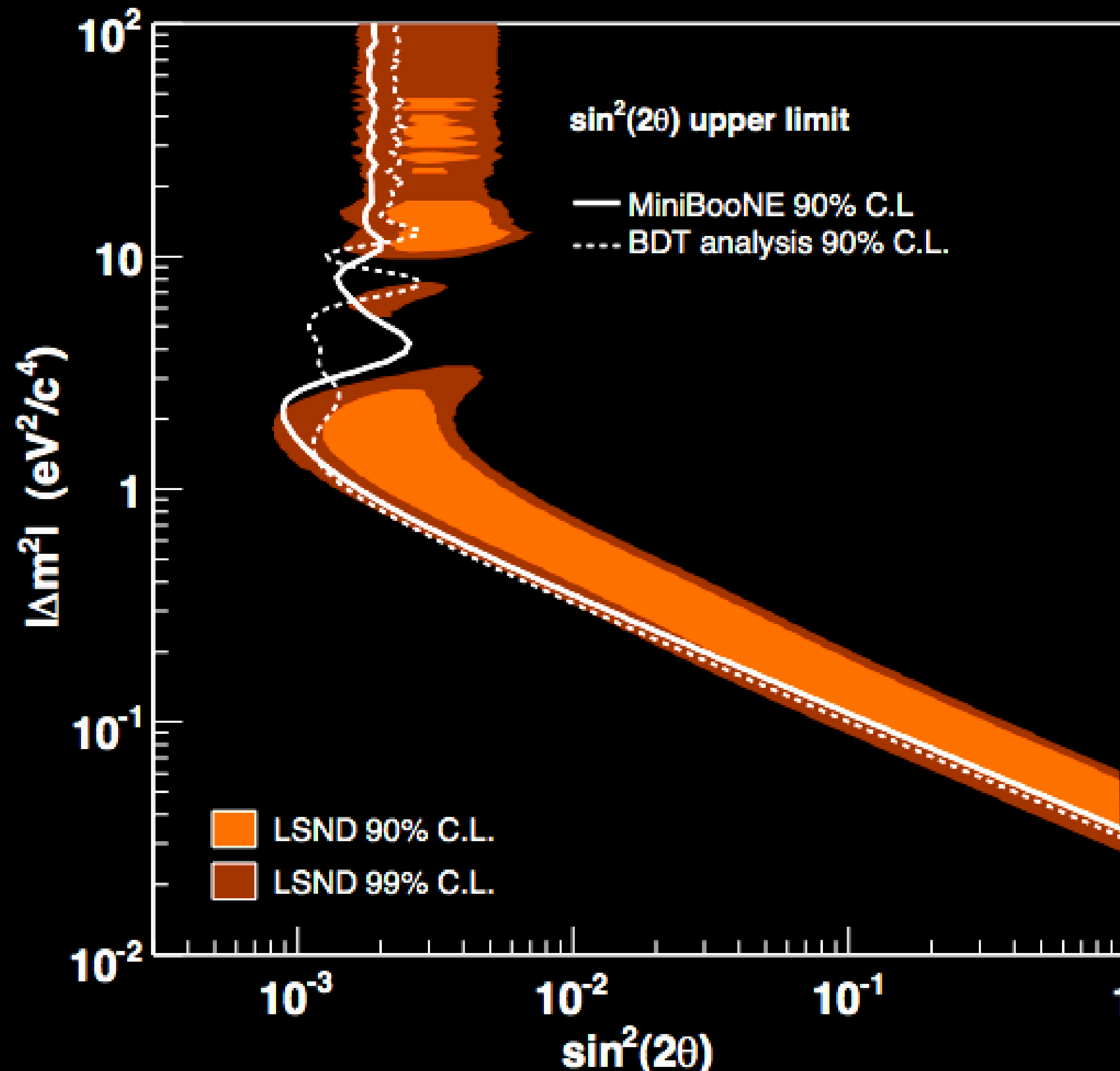
Oscillation fit in Boosting Analysis

- 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_ν^{QE}<1600 MeV
  - Data: 971 events
  - Background expectation: 1070 ±33 (stat) ±225 (sys) events
  - Overall counting significance: −0.38 σ



Comparing the limits

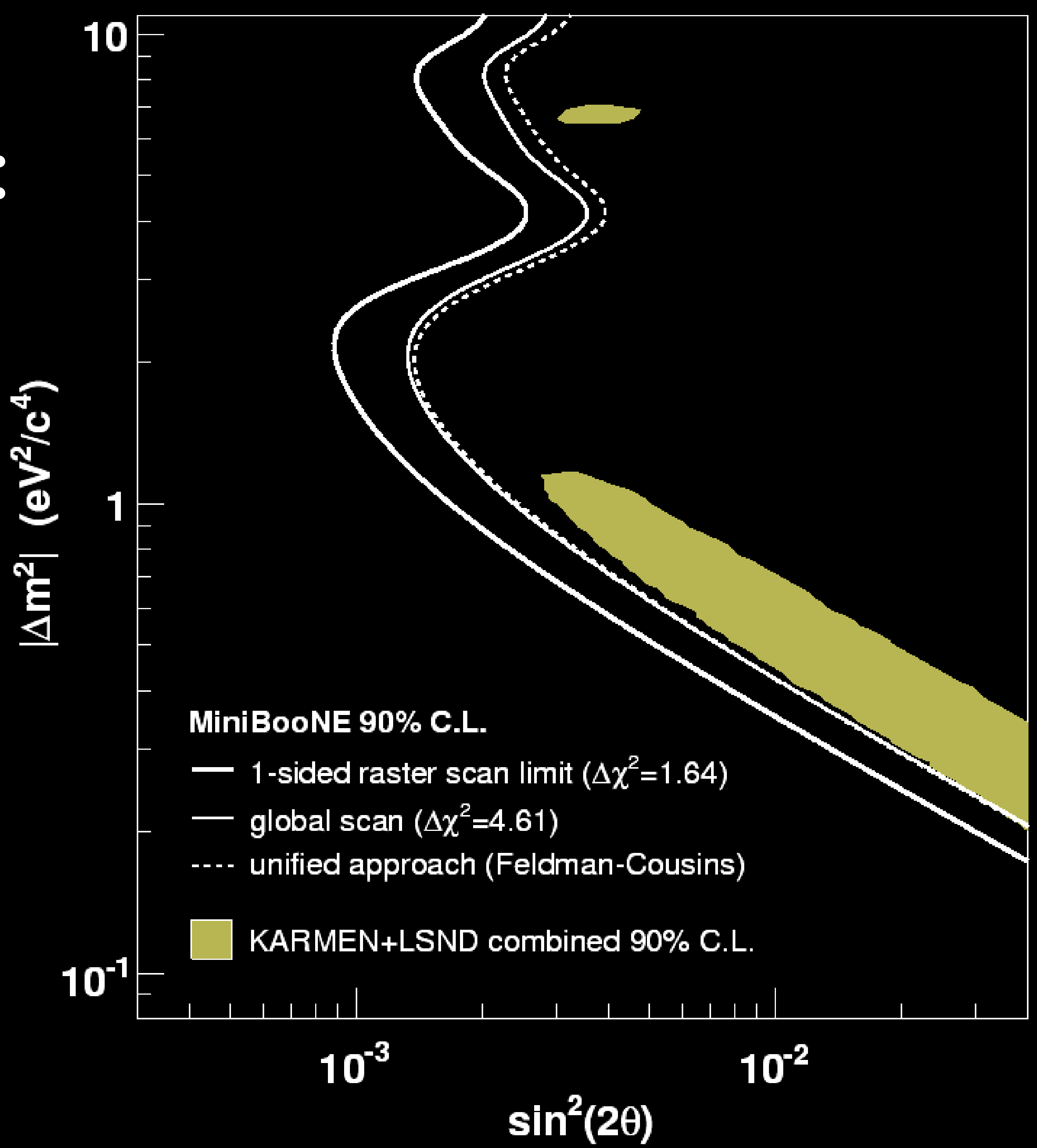
- Solid: Track-based
- Dashed: Boosting
- The two analyses have very consistent fit results.
- Track-based fit remains our primary result.



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

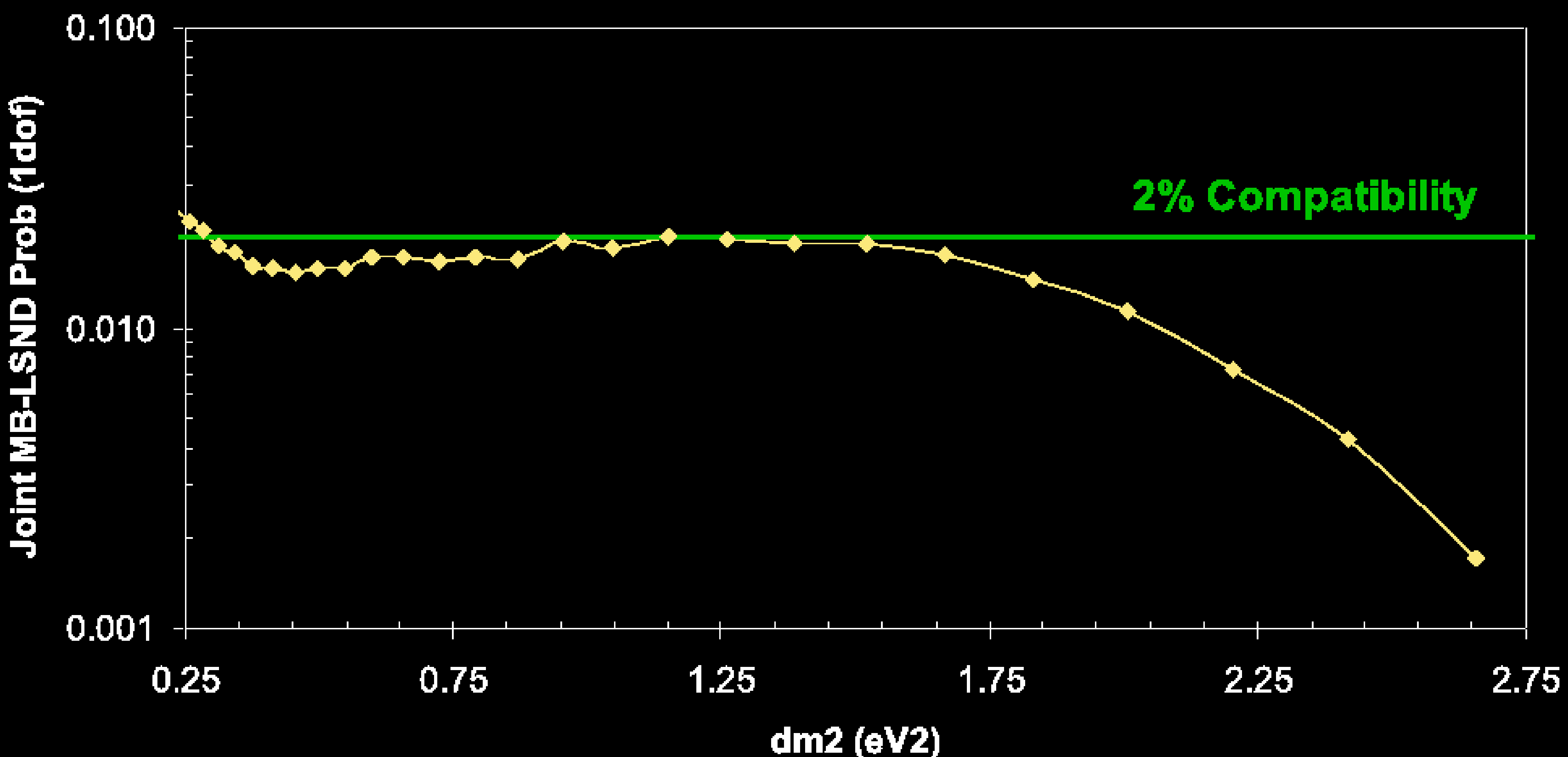
- For each Δm^2, determine the MiniBooNE *(M)* and LSND *(L)* measurement of $\sin^2(2\theta)$:
  - $z_M \pm \sigma_M$, $z_L \pm \sigma_L$ where $z \equiv \sin^2(2\theta)$ and σ_M, σ_L evaluated at that Δm^2
- For each Δm^2, form χ^2 between MiniBooNE and LSND measurement:

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

- *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

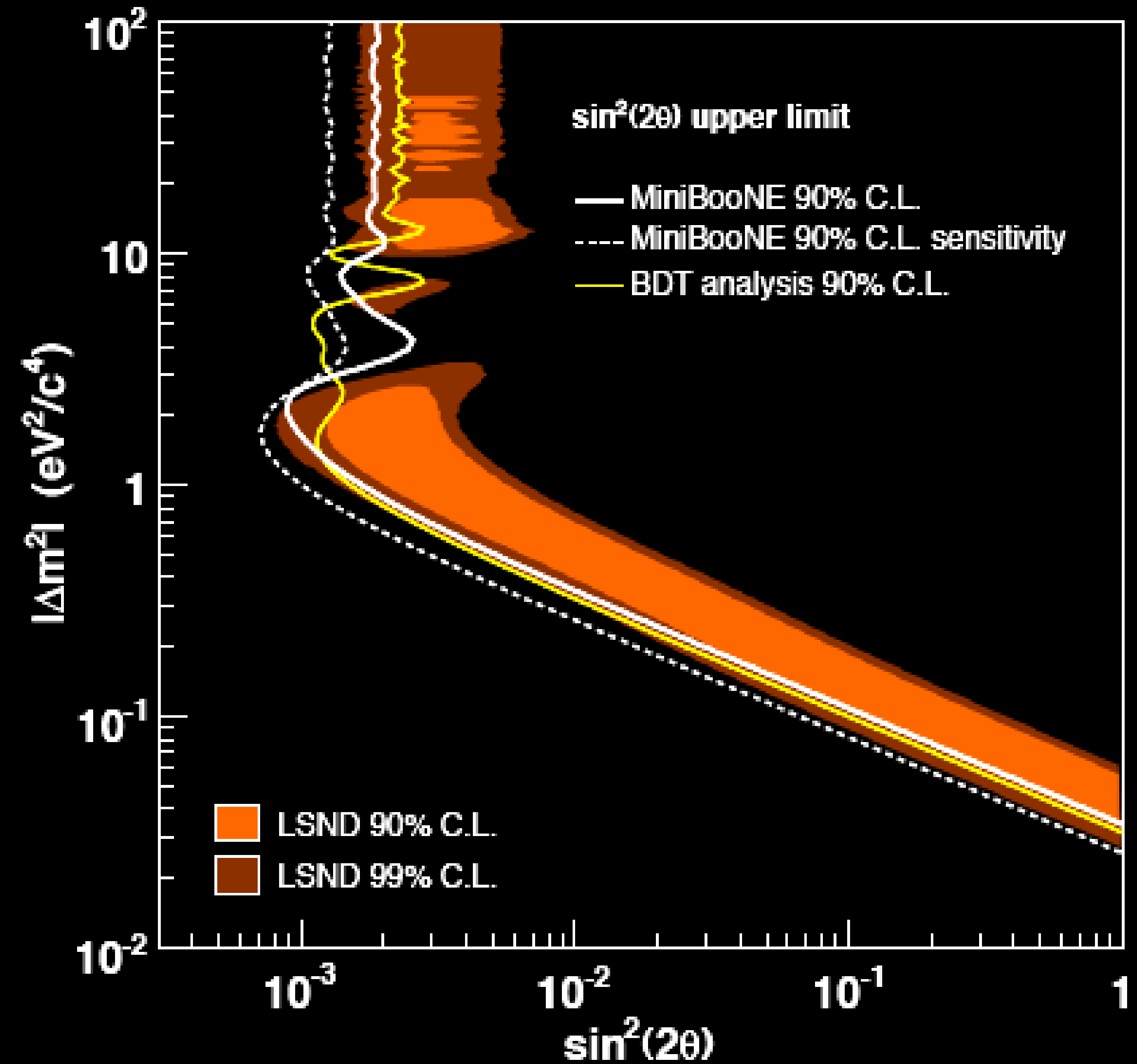


- MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance-only interpretation of LSND at 98% CL

Next Steps

- Further investigation of low-energy excess
  - Cross-sections? (Further MiniBooNE, SciBooNE studies)
  - Other non-oscillation effects?
- 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 wiith two-neutrino oscillation.