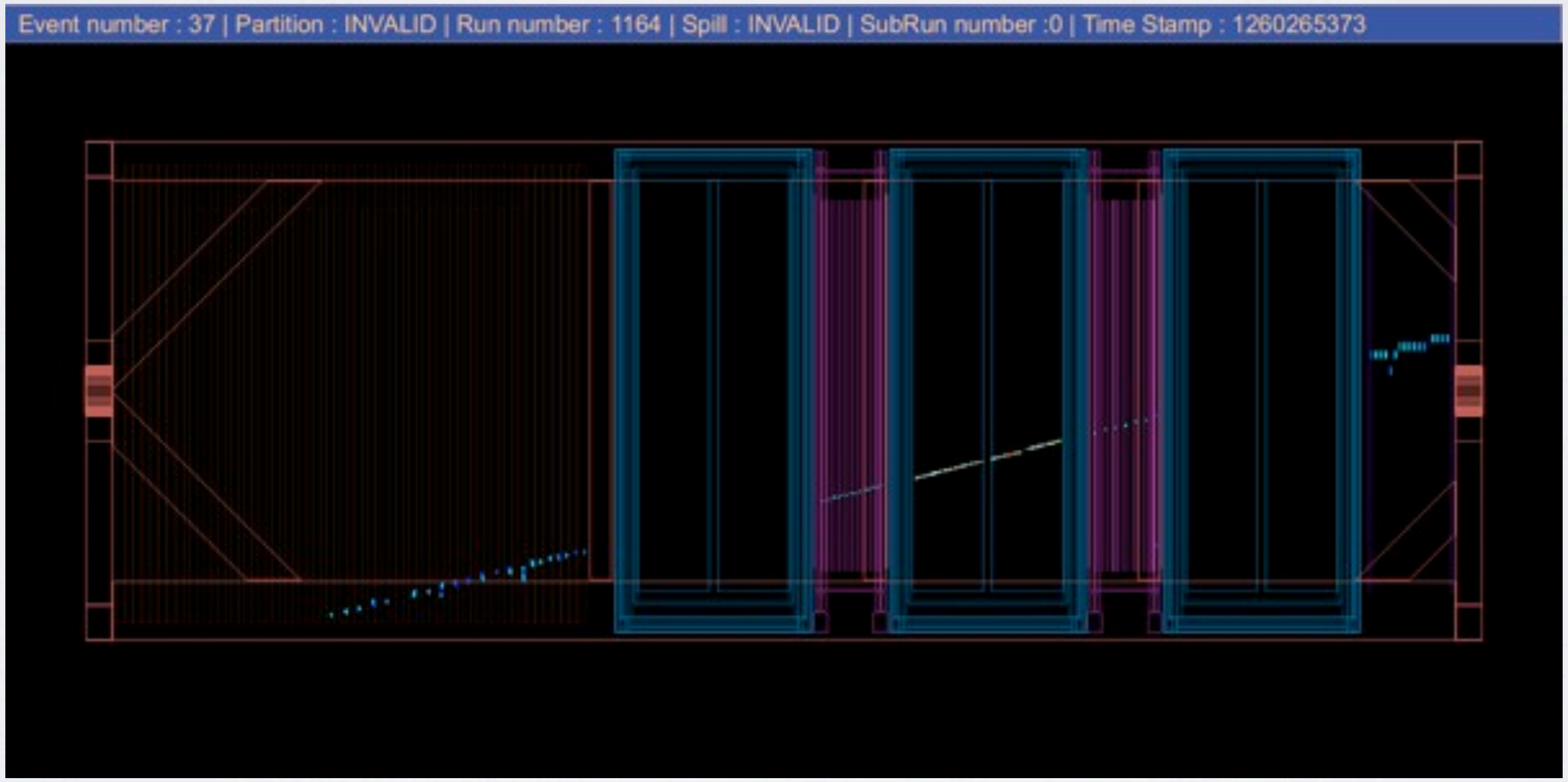
INSTITUTE OF
PARTICLE
PHYSICS

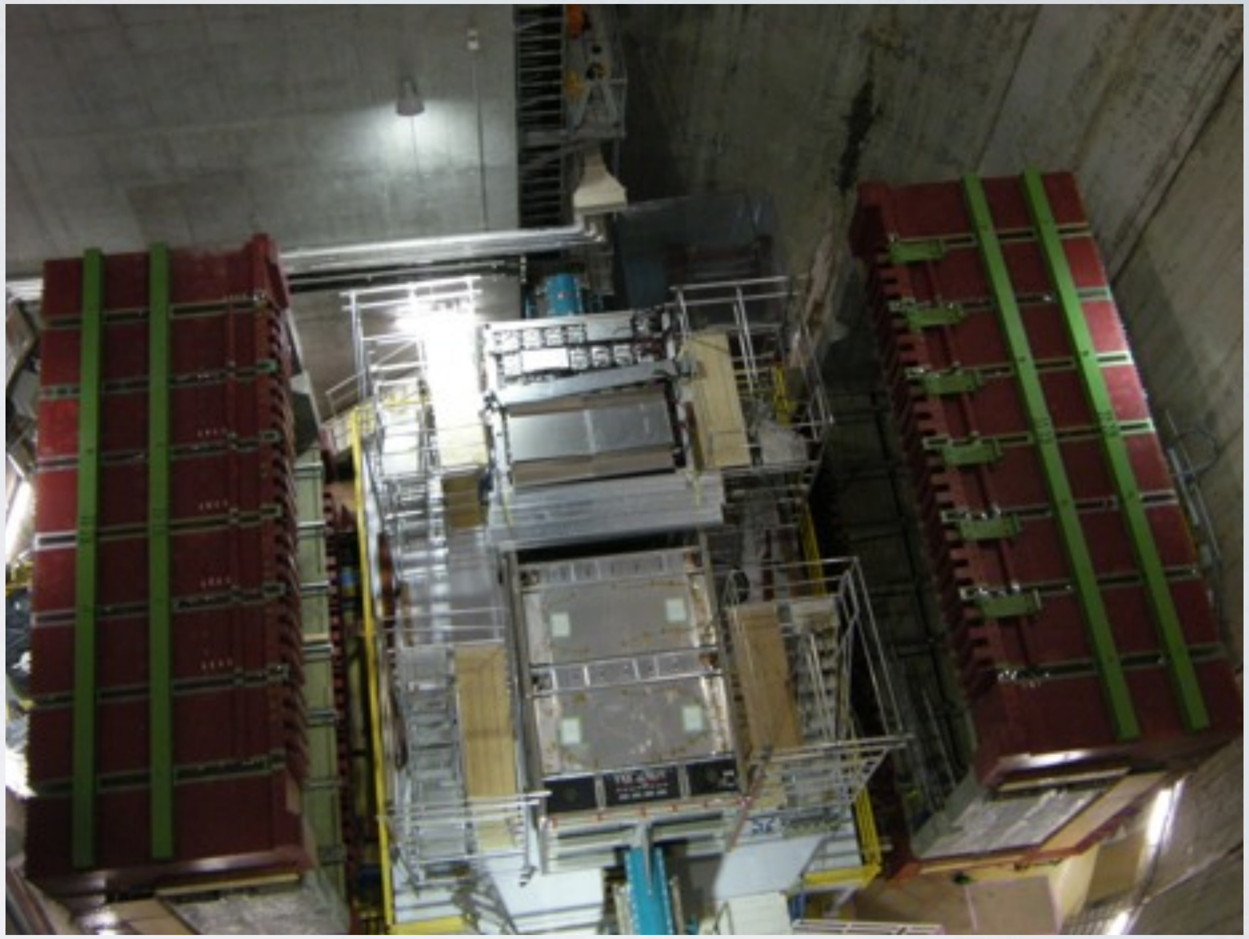
Achieving a High Sensitivity Neutrino Oscillation Search: MiniBooNE

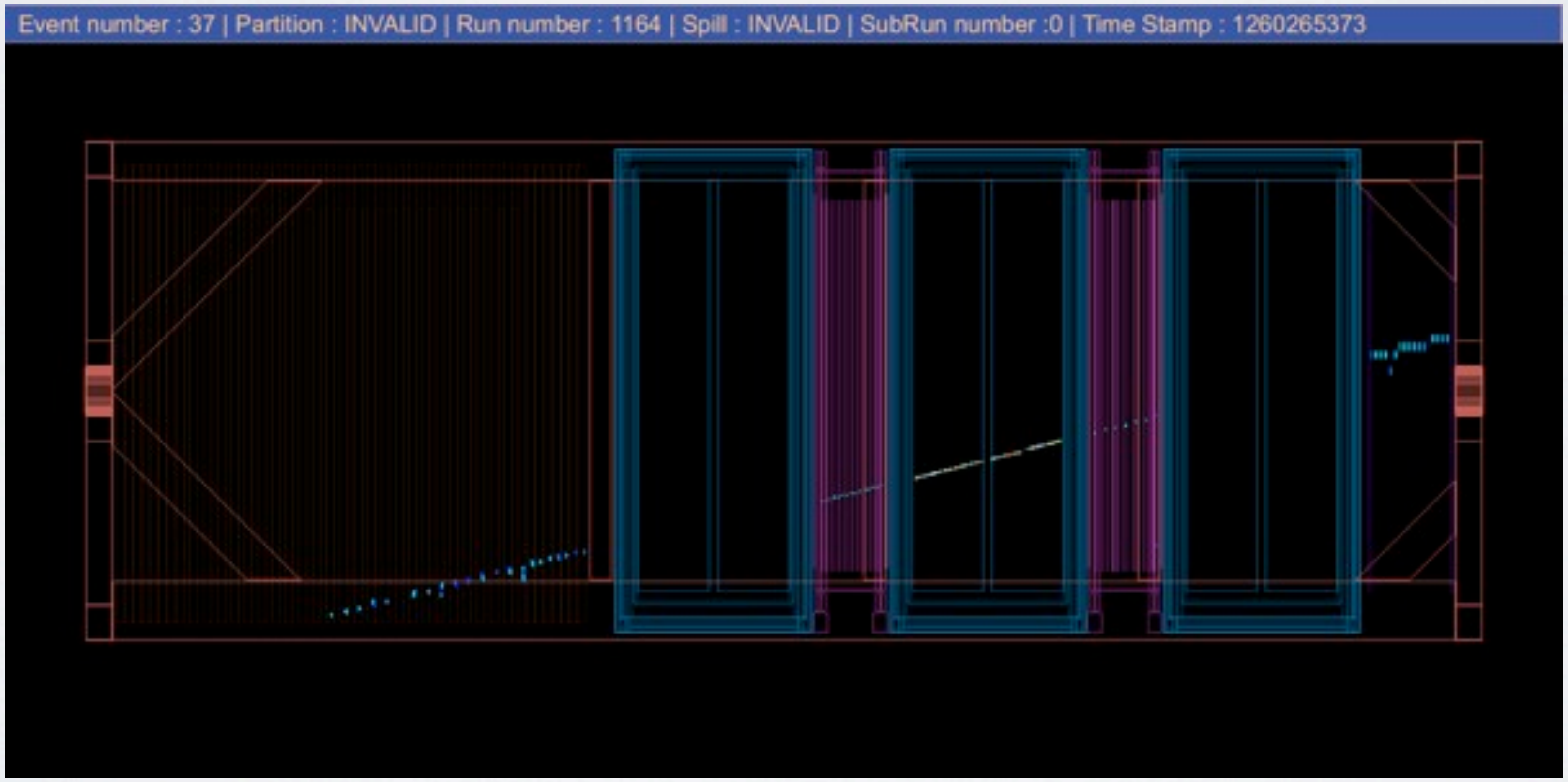
H. A. Tanaka



Event number : 37 | Partition : INVALID | Run number : 1164 | Spill : INVALID | SubRun number :0 | Time Stamp : 1260265373

Thank you for the opportunity to be here and participate!





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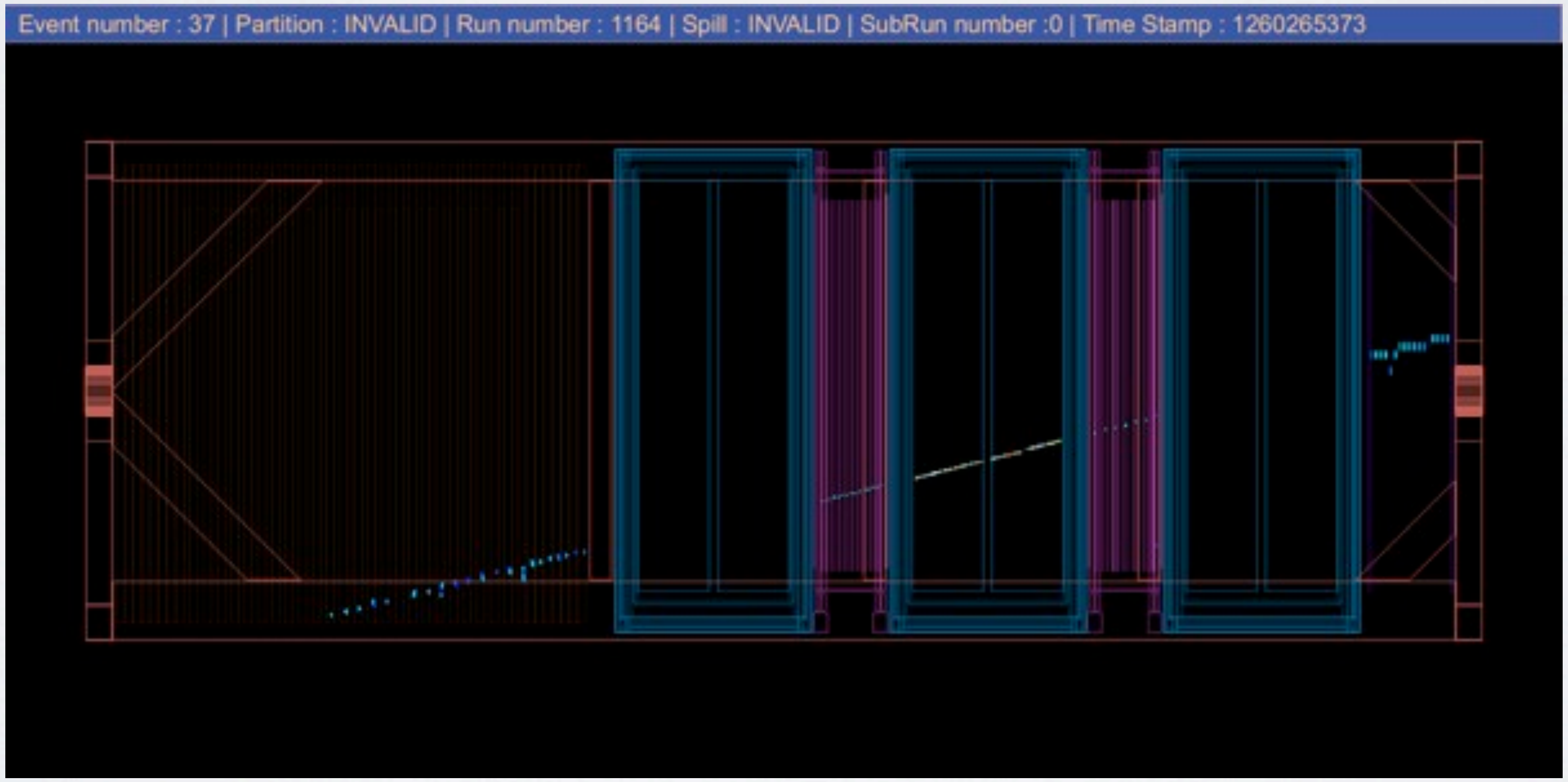

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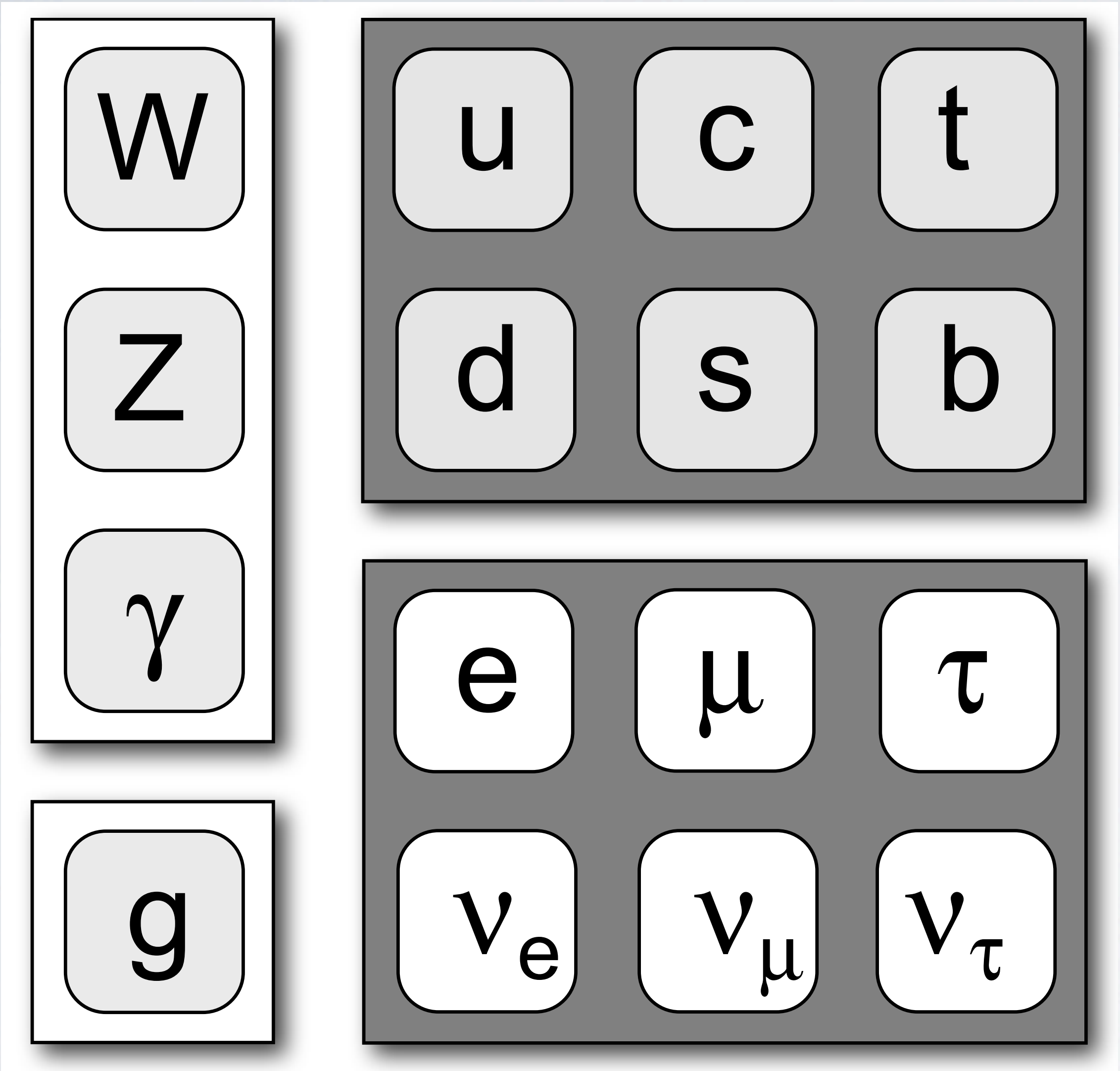
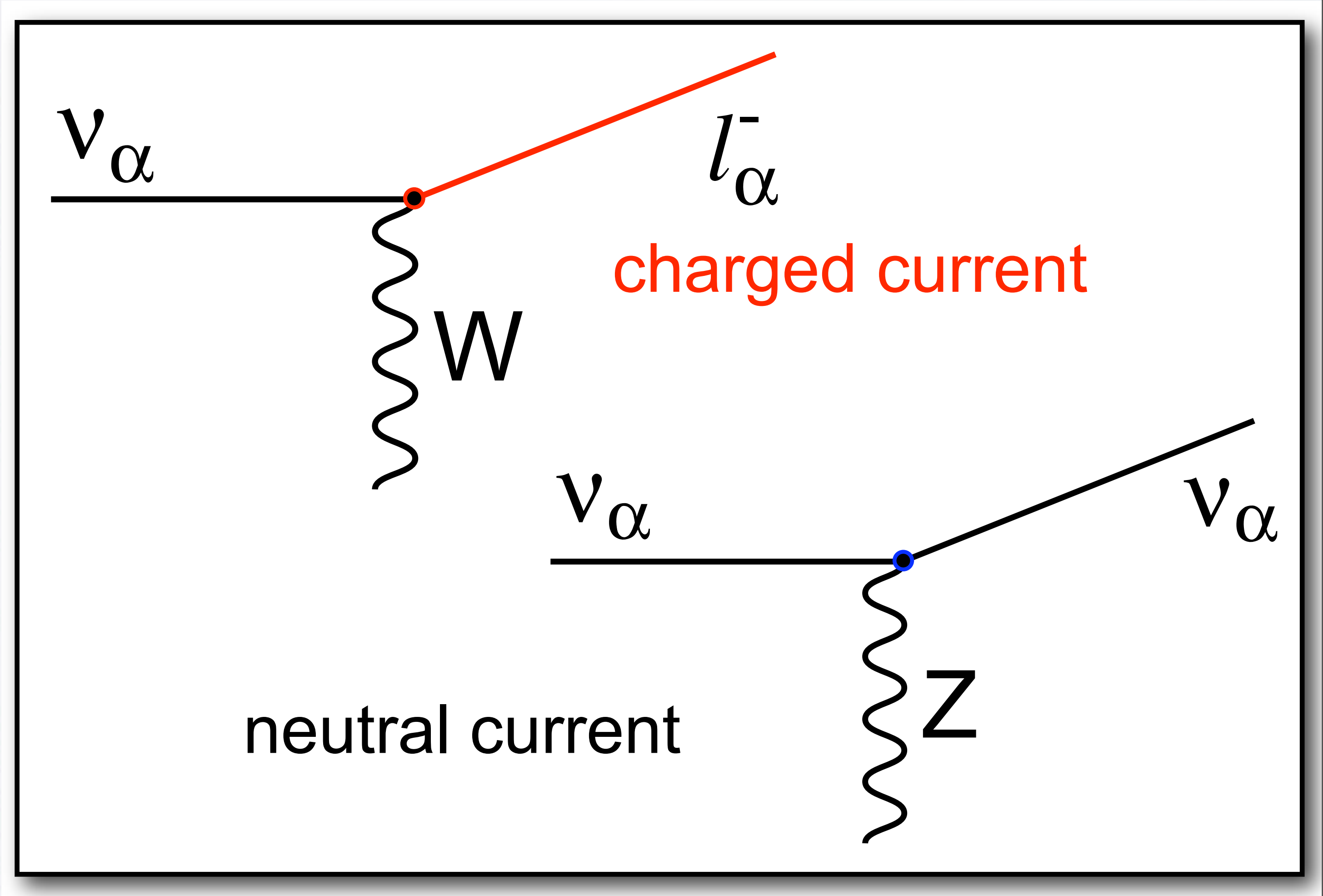
NEUTRINOS



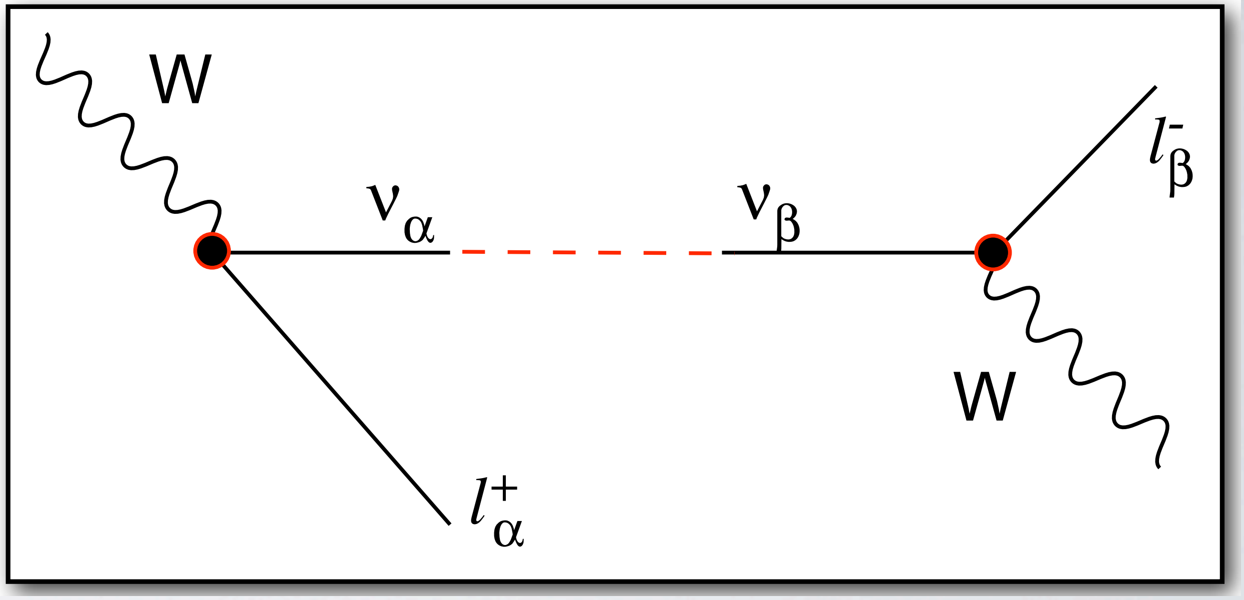
- 3 neutrinos associated with leptons
  - no color
  - no charge
  - interact only weakly (+gravity)

- Two forms of interaction
  - W exchange (CC)
  - Z exchange (NC)



NEUTRINO OSCILLATIONS

- Mass (E) eigenstates≠flavor eigenstates
  - Described by unitary transformation
  - Neutrinos created in flavor eigenstates will mix under time evolution (QM)
  - "neutrino oscillations"



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

"Amplitude"

"wavelength"

mass^2 difference

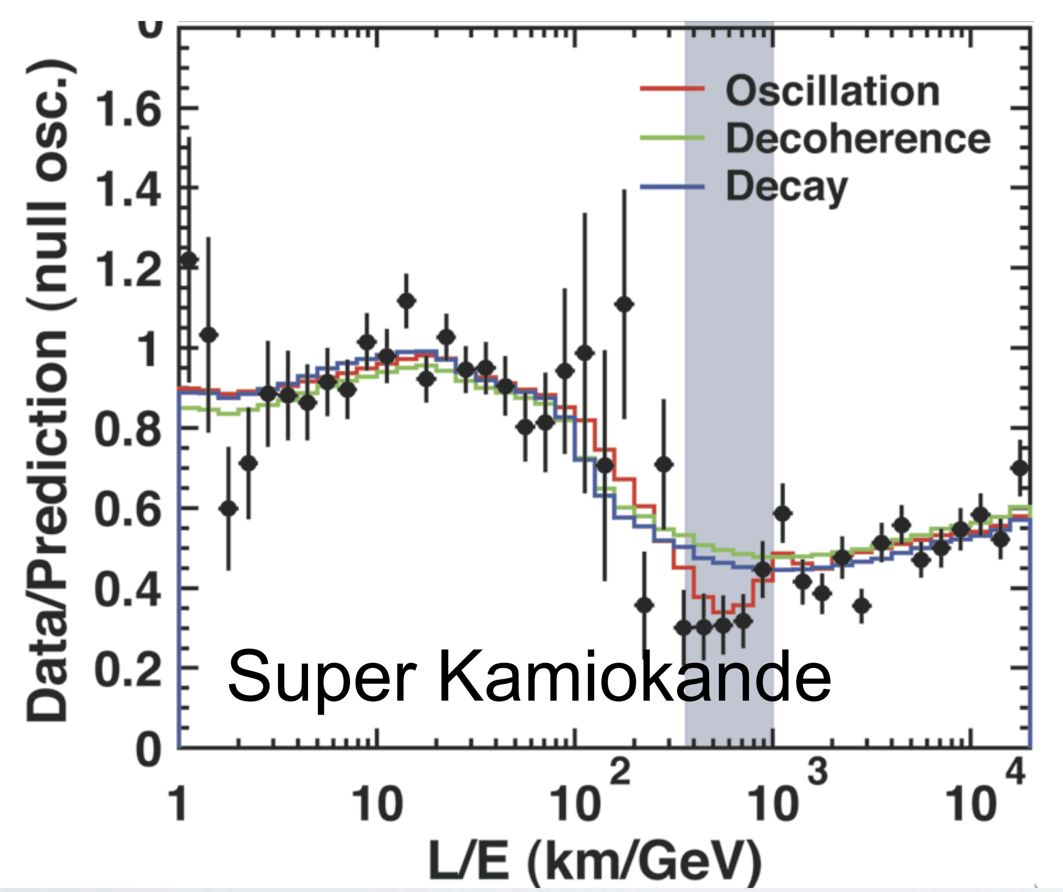
"baseline"

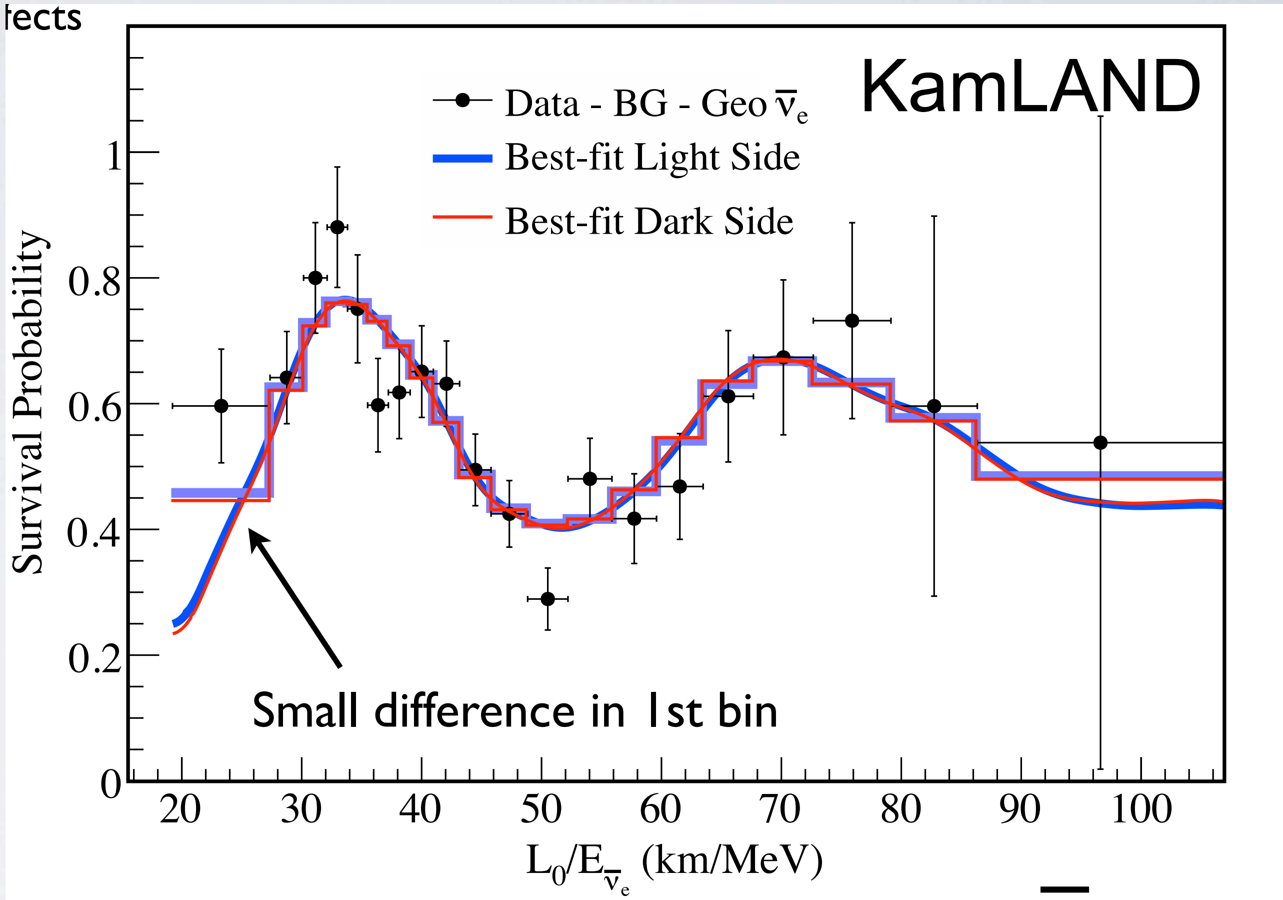
energy

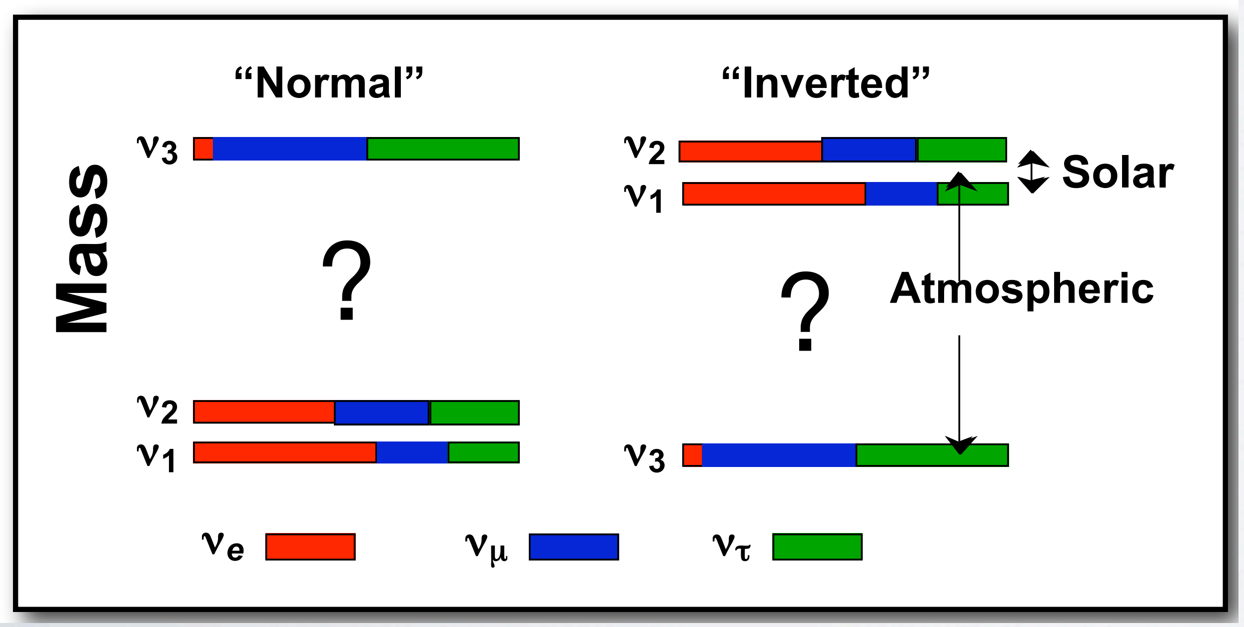
$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) = \quad & \delta_{\alpha\beta} \\ & -4\Sigma_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}(L/E)] \\ & +2\Sigma_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[2.54\Delta m^2_{ij}(L/E)] \end{aligned}$$

Switches sign for neutrino ↔ antineutrino (CP violation)

NEUTRINOS OSCILLATE





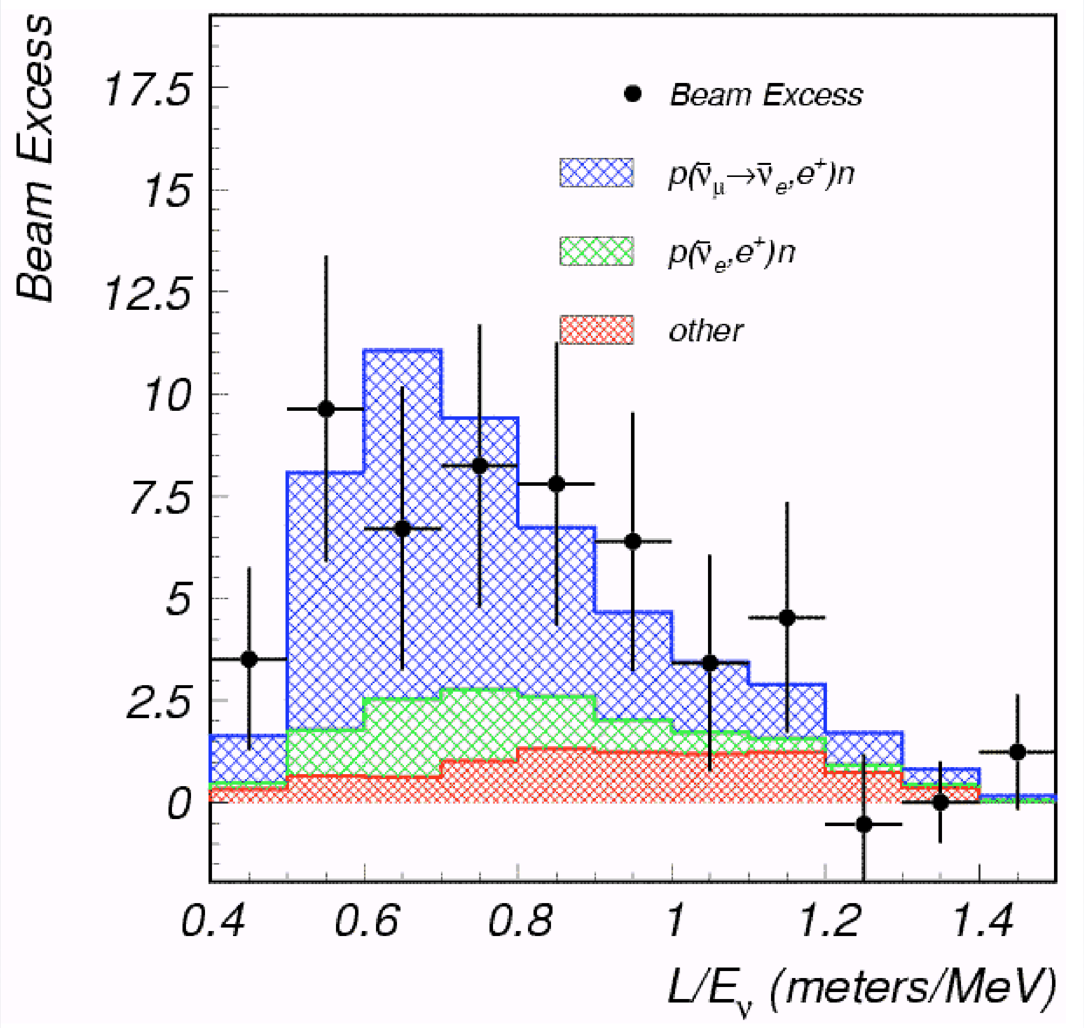


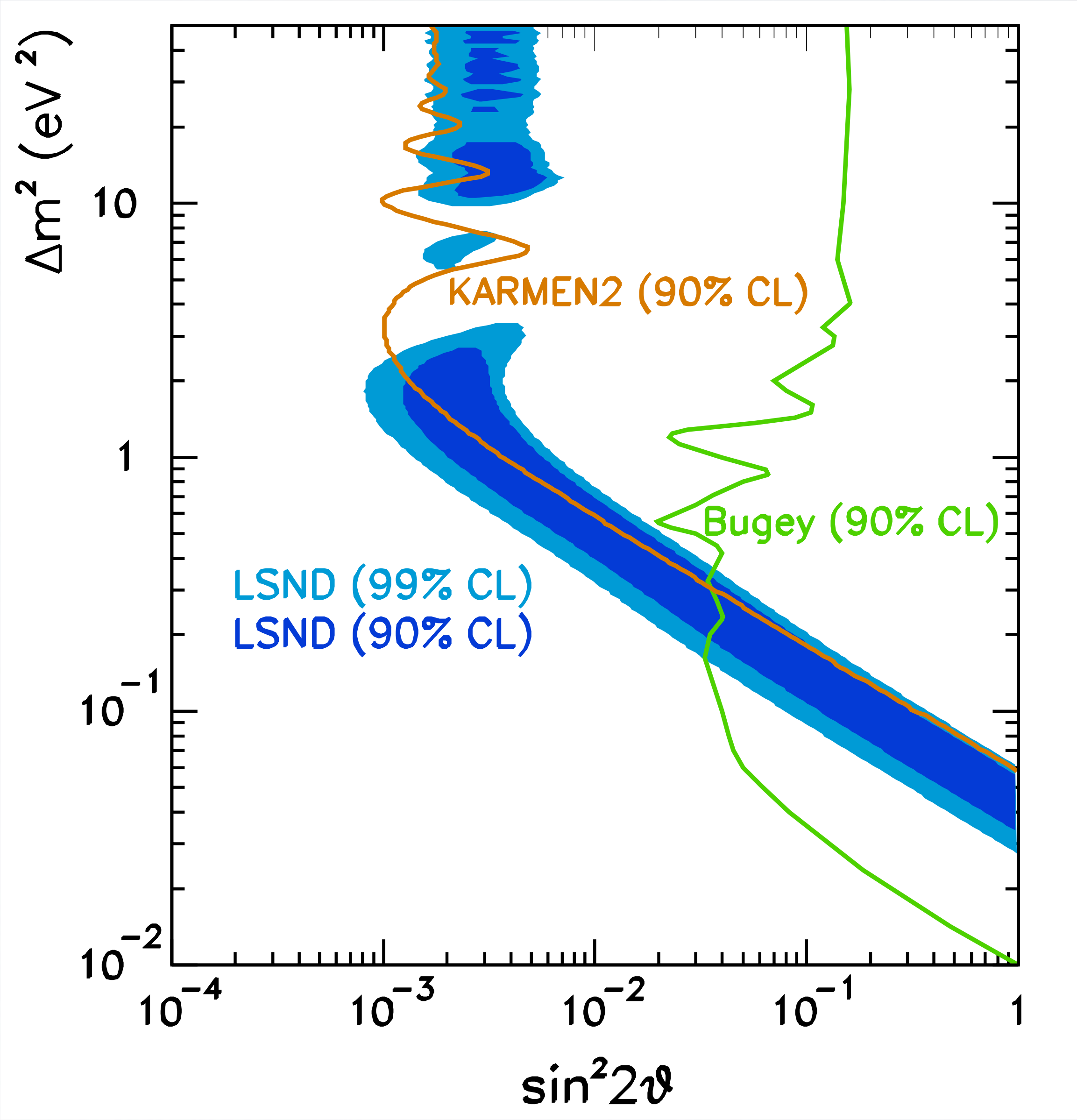
- After many years of hints, we now know that neutrinos oscillate (a lot)
  - Δm^2_{23} ~2.5×10^{-3} eV^2
  - Δm^2_{12} ~7.6×10^{-5} eV^2

Neutrinos have mass and mix

LSND

"Liquid Scintillator Neutrino Detector"





- Search for excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

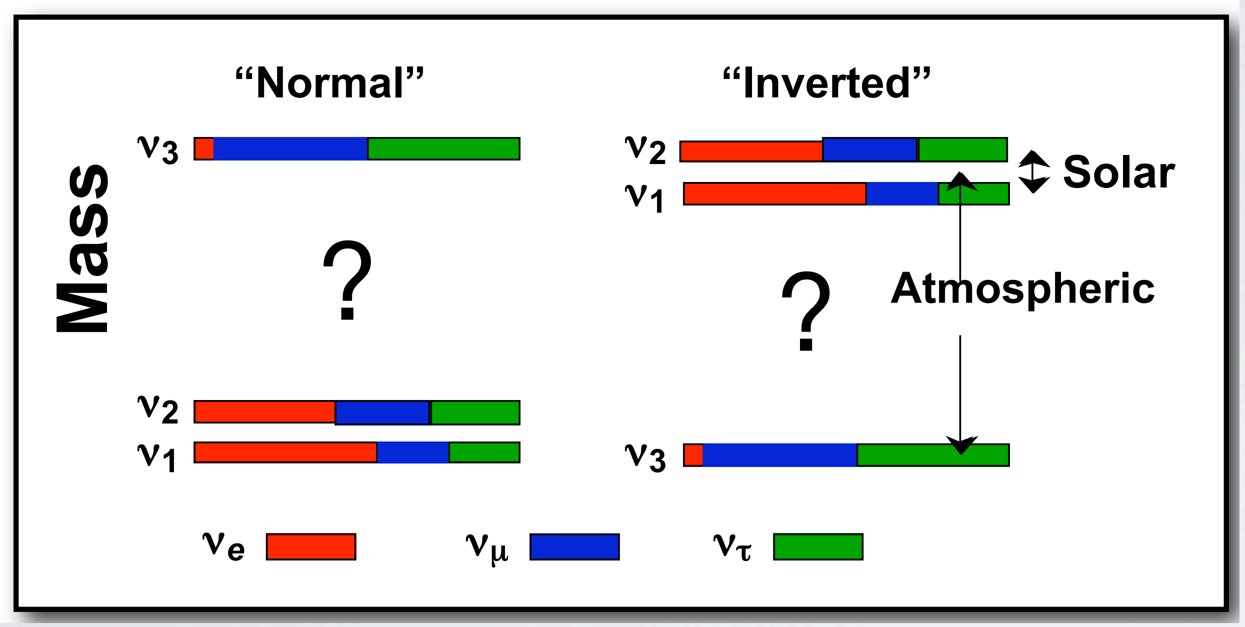
- Signal observed via CC + n capture

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

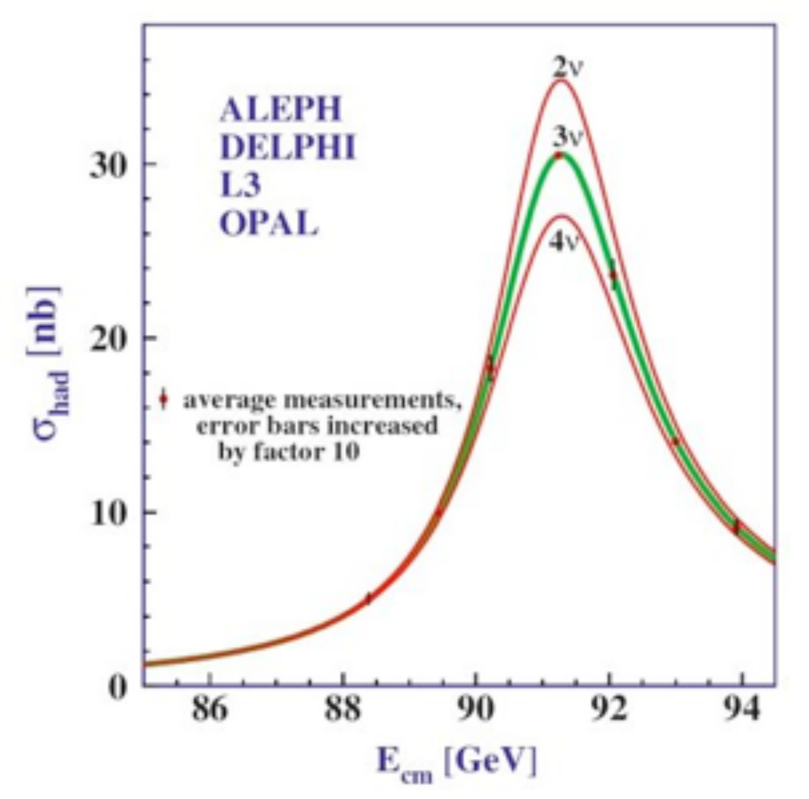
$$n + p \to d + \gamma(2.2\ \mathrm{MeV})$$

Excess of 87.9±22.4±6.0 $\bar{\nu}_e$ candidates interpreted as neutrino oscillations with $\Delta m^2 \sim 1$ eV^2

INTERPRETATION



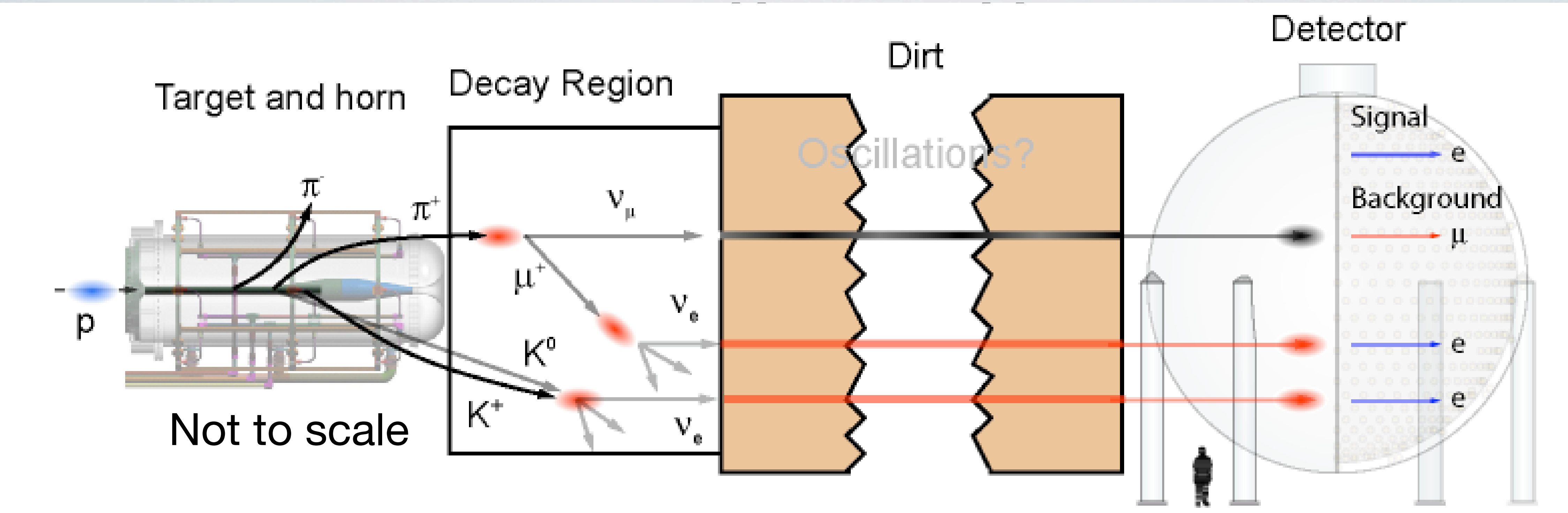
- 2 Δm^2 already measured
  - ~2.5×10^{-3} eV^2
  - ~7.6×10^{-4}eV^2
  - Impossible to accommodate Δm^2~1eV^2 without another (4th or more) neutrino



- Z decays probe particles coupling to it (i.e. those that participate in weak NC)
  - Additional neutrinos affect decay rate
  - LEP data: $N_\nu = 2.984 \pm 0.008$
  - Additional neutrino must be "sterile" or very heavy

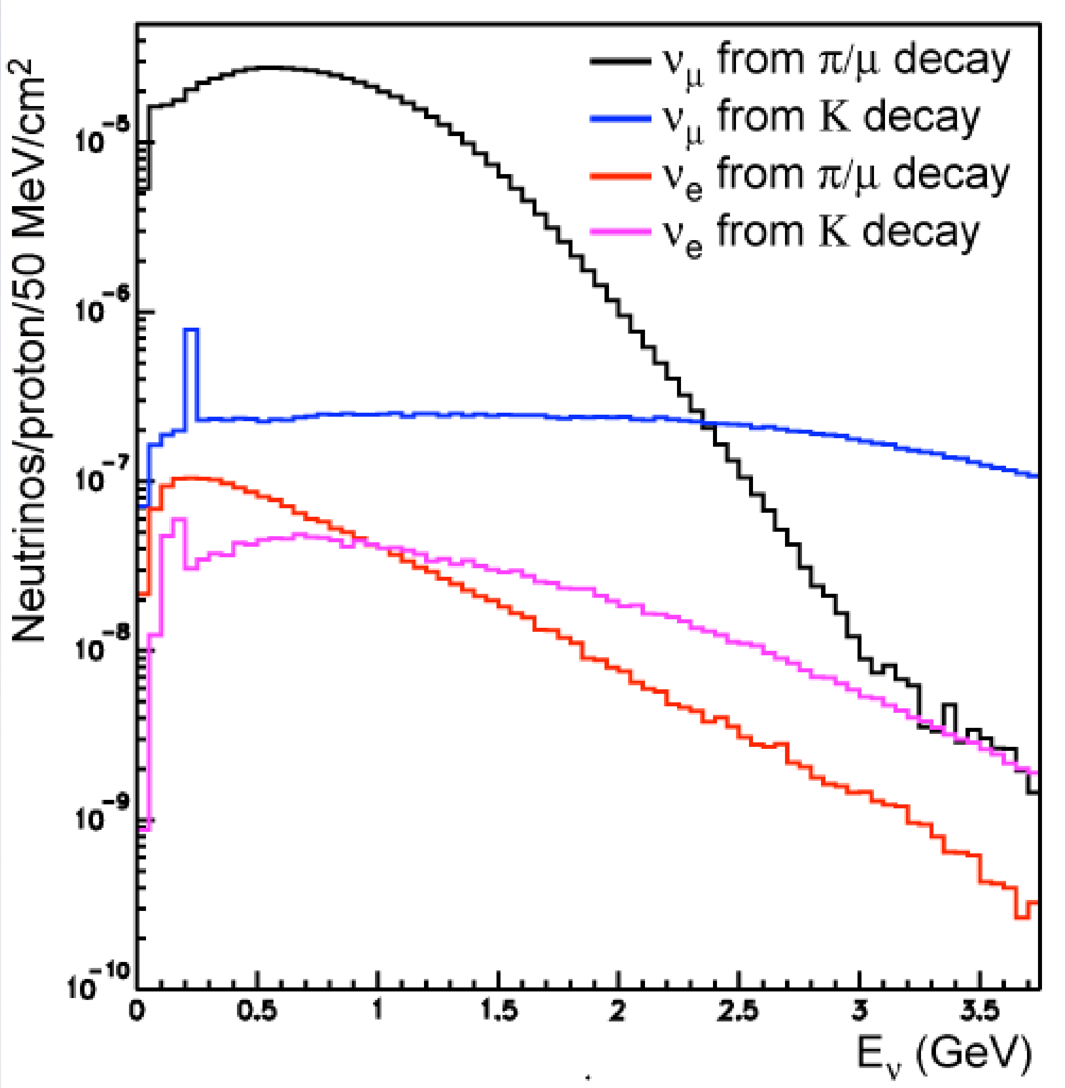
New physics is necessary to explain LSND excess

MINIBOONE



- Confirm/refute LSND evidence with a new experiment
  - Generate ~1 GeV ν_μ with FNAL booster (8 GeV primary protons)
  - Look for the appearance of ν_e ~0.5 km later (same L/E as LSND)
  - Use "large" Cherenkov detector to identify, reconstruct and classify neutrino interactions

NEUTRINO FLUX

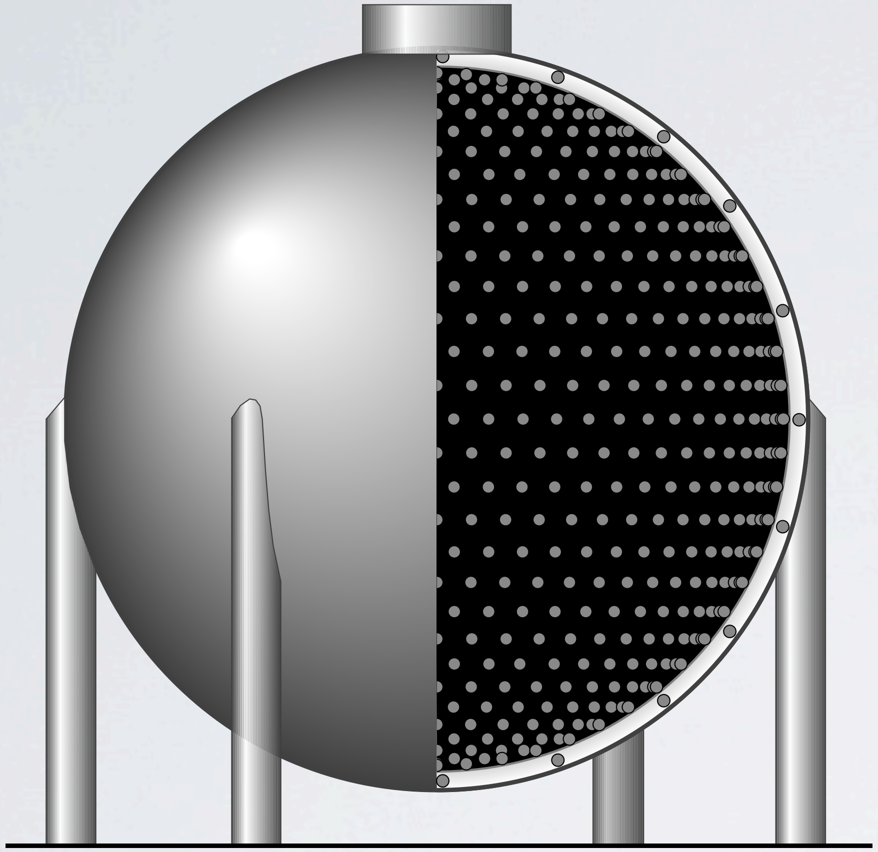


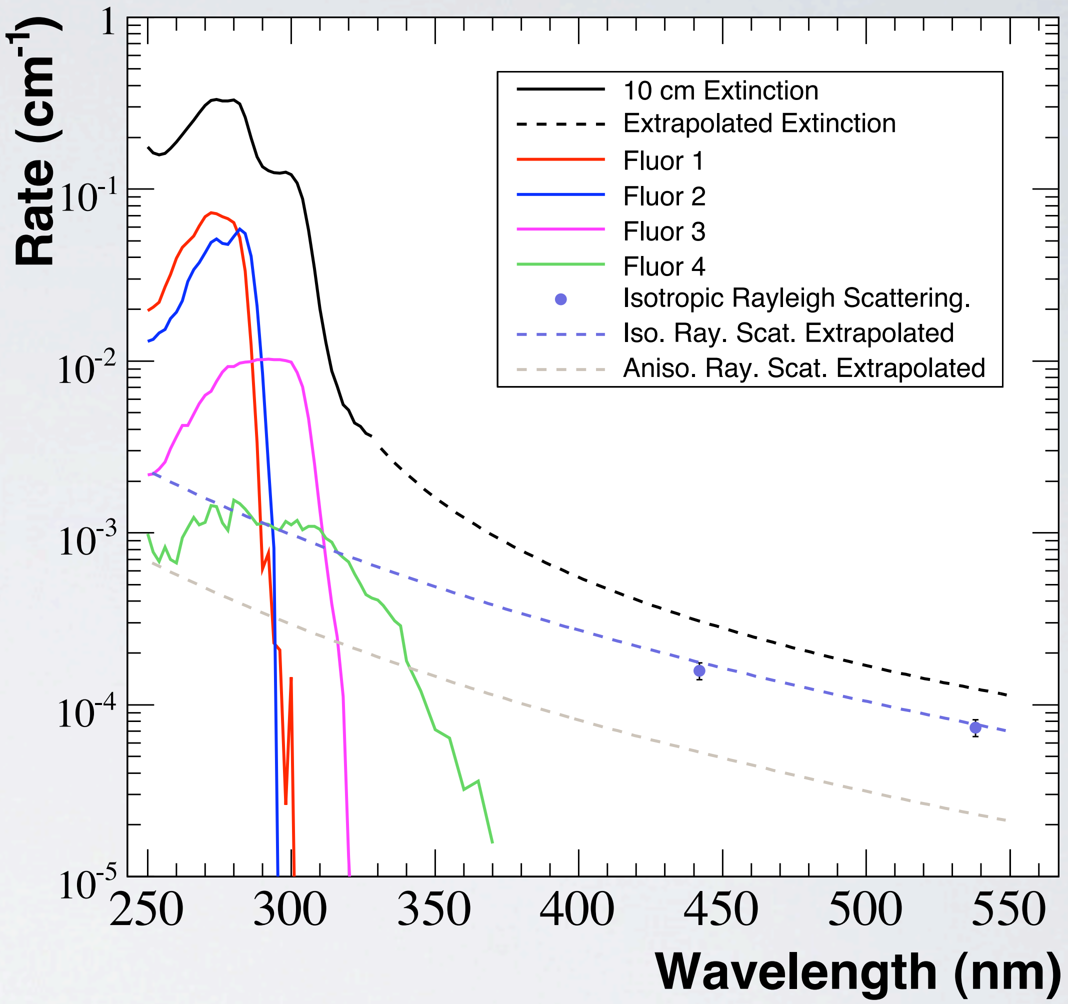
- Primary contribution to neutrino flux is from pion decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - note that this necessarily produces a contribution of ν_e
    - $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- Kaons also contribute to the ν_μ flux via 2- and 3-body decays
  - This has a higher energy spectrum
  - also produces ν_e flux via 3-body decay

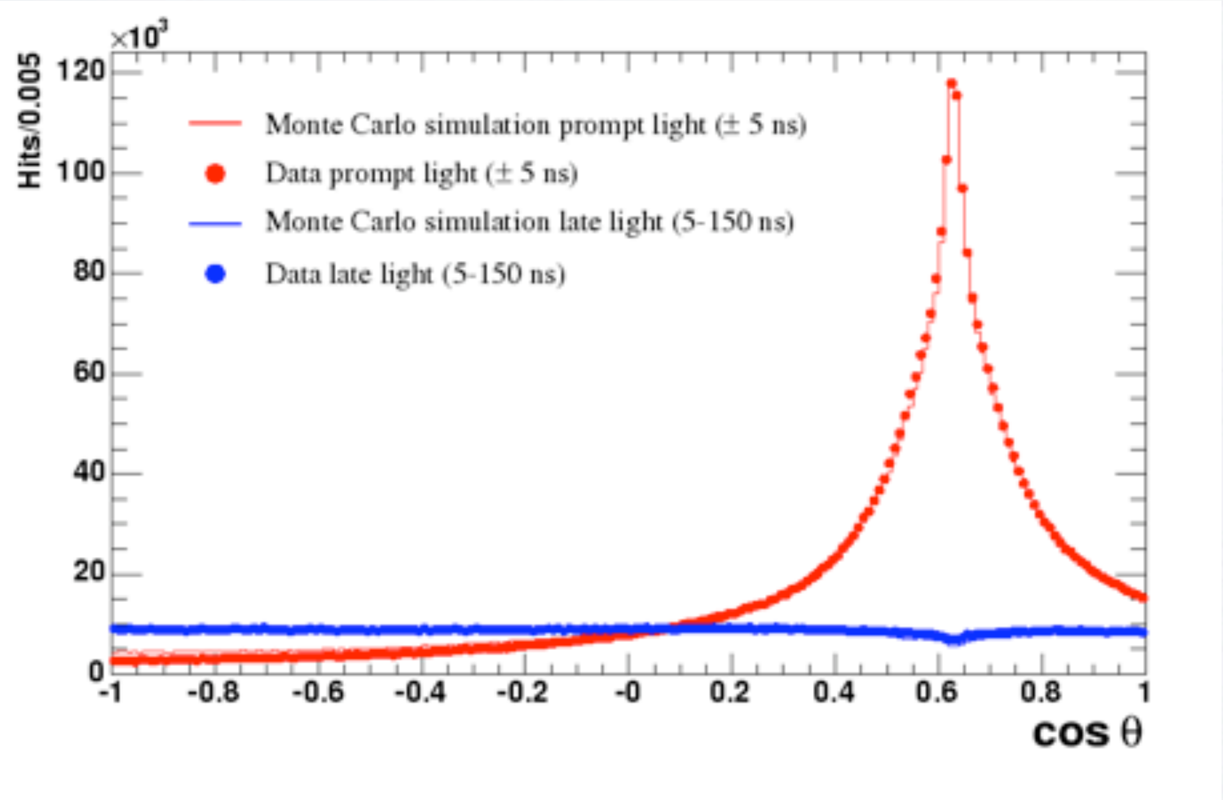
$$K \rightarrow \pi + e + \nu_e$$

We must account for irreducible background of ν_e in background estimate

THE DETECTOR

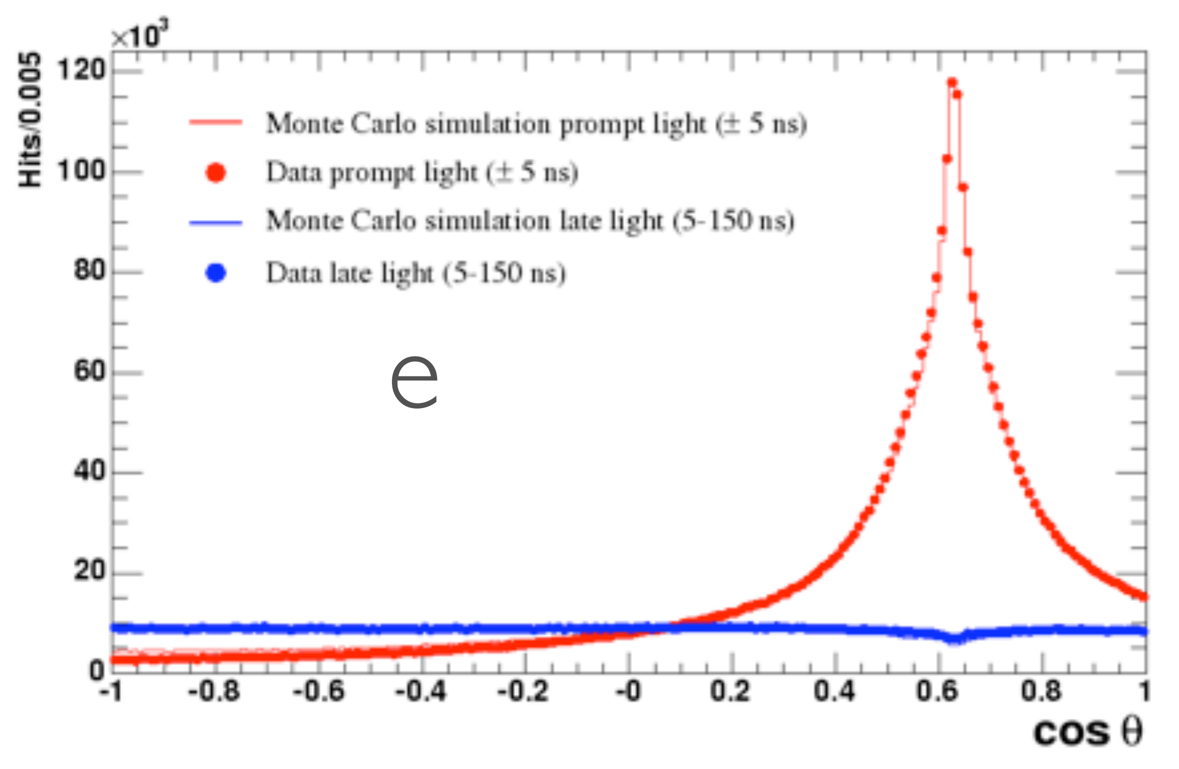


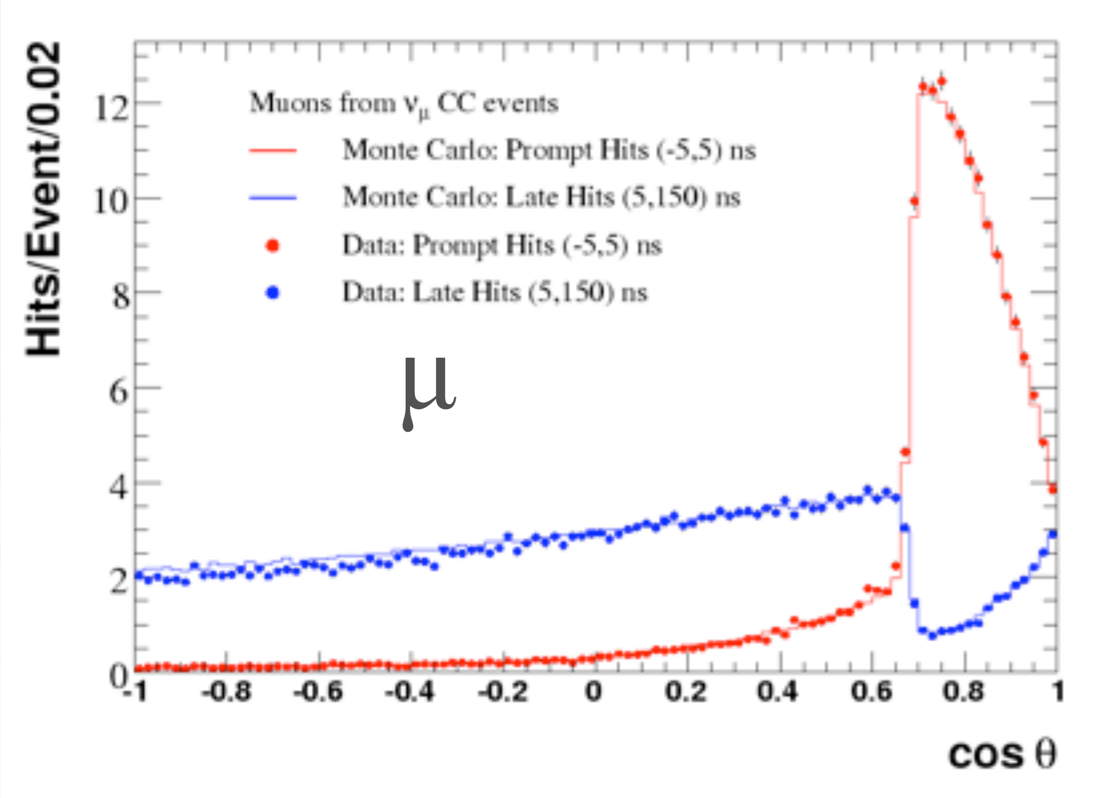


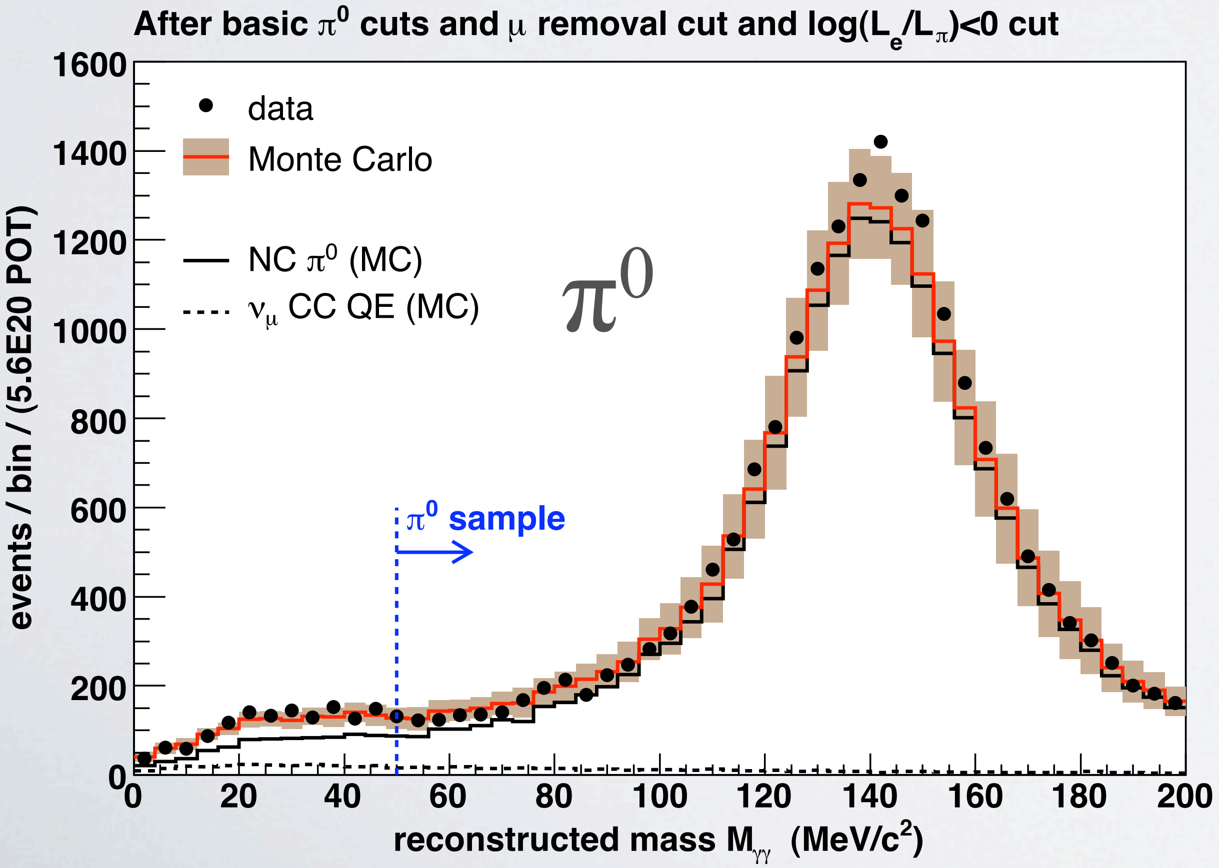


- 800 tons of mineral oil
  - n~1.47 (Č light), scintillates weakly.
  - "rich" optical phenomenology
- 1280 PMTs view inner volume
- Outer shell with 240 PMT: veto for incoming cosmic rays, outgoing particles

PARTICLE IDENTIFICATION

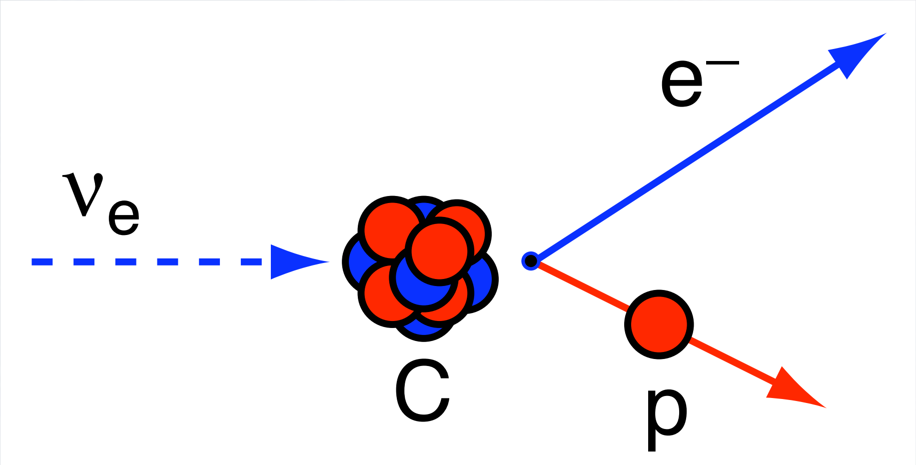






- Č profile can provide particle identification information
  - showering electrons (e-like)
  - MIP muons (μ-like)
- π^0 events produce second e-like ring that can usually be reconstructed
  - otherwise, it is background

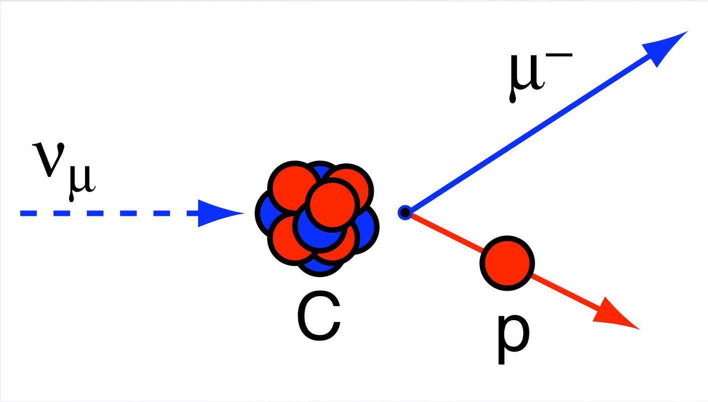
SIGNAL AND BACKGROUND

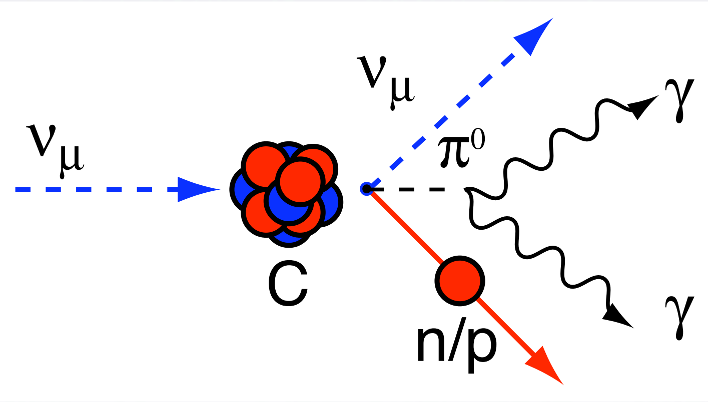


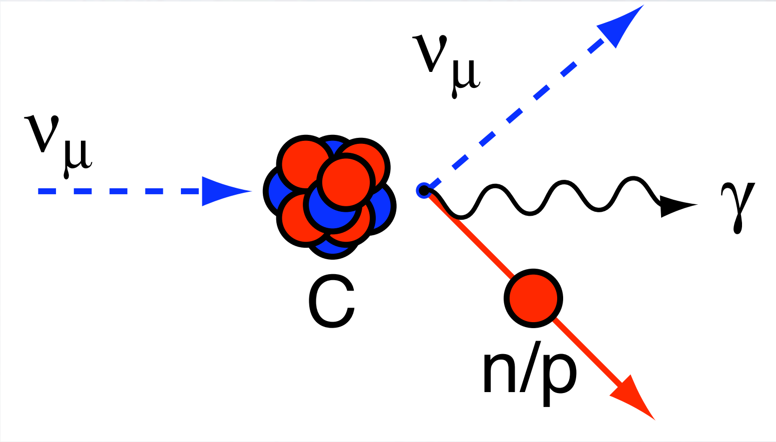
- Signal
  - O(10^3) ν_e events identified mainly as ν_e CCQE events with 1 e-like ring

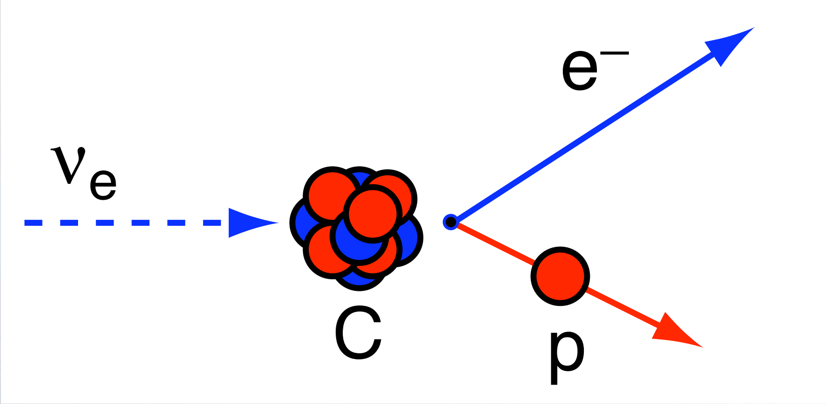
$$\nu_e + n \rightarrow e^- + p$$

- O(10^6) ν_μ CCQE events which produce 1 μ-like ring
- O(10^4) NC π^0 events produce 2 e-like rings
- O(10^2) $\Delta \rightarrow$ (n/p)+γ produce 1 e-like ring (effectively irreducible)





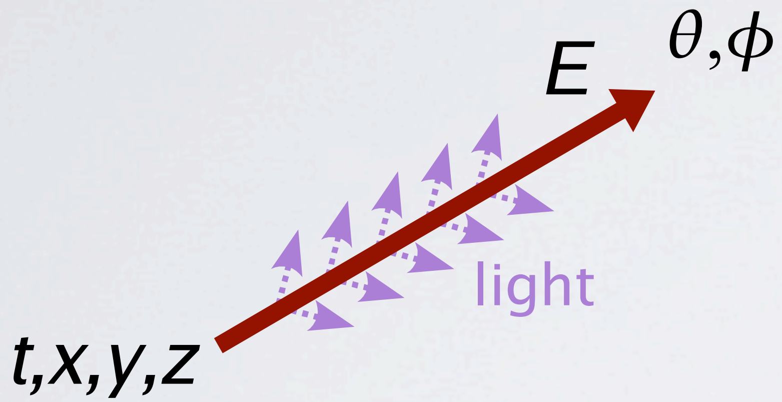




O(10^3)irreducible background from ν_e in the beam

RECONSTRUCTION

- The event reconstruction is based on a likelihood fit



- For a single track, the expected response of each PMT is predicted
- A PDF is formed based on seven parameters (**x**) and a particle hypothesis (e.g. e, μ)

- The likelihood functions involve:
  - predicted charge response
  - predicted time response
- For each PMT in data:
  - hit: q,t information
  - no hit: q information only
- Likelihood calculated:

$$F_q(\mathbf{x}) = -\sum_{\text{unhit}} \log P(i\ \text{unhit}; \mathbf{x}) - \sum_{\text{hit}} \log(P(i\ \text{hit}; \mathbf{x}) f_q(q_i; \mathbf{x}))$$

$$F_t(\mathbf{x}) = -\sum_{\text{hit}} \log(f_t(t_i; \mathbf{x}))$$

- Maximized by varying **x**

OPTIMIZATION:

- Balance:
  - Accurate modeling gives better (in principle best) performance
  - Practical computational limits (CPU)
- Defining optimal strategy is a case-by-case endeavor
- Factorize charge likelihood into:
  - "predicted charge" at PMT: light production, propagation (from MC)
    - various parameterizations to tabulate integrals, etc.
  - "charge response": PDF of PMT response (from data)

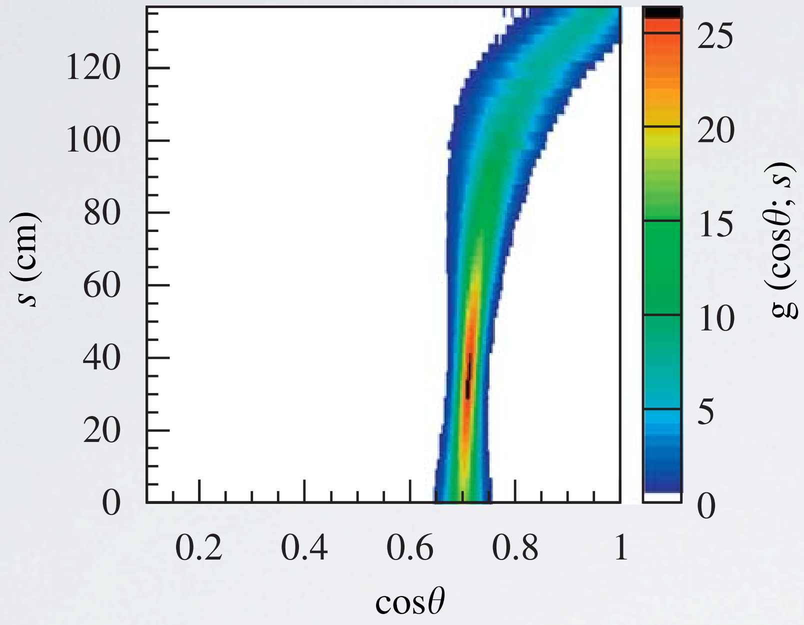
$$F_q(\mathbf{x}) = -\sum_{\text{unhit}} \log P(i \text{ unhit}; \mathbf{x}) - \sum_{\text{hit}} \log(P(i \text{ hit}; \mathbf{x}) f_q(q_i; \mathbf{x})) \qquad \mathbf{x} \rightarrow \mu$$

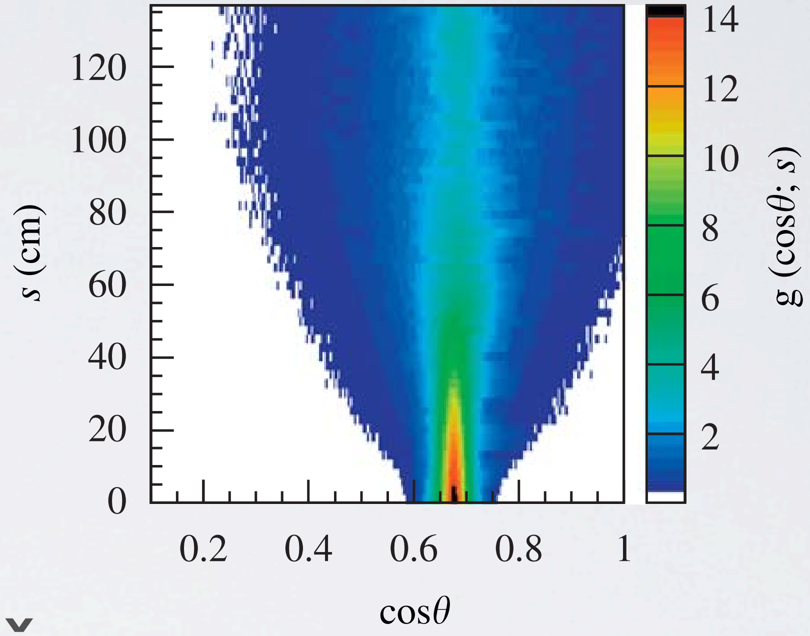
- Time likelihood: incorporate assumptions about
  - spread of arrival times at PMT due to spread of light emission points
  - time response dominated by "first hit"

PREDICTED CHARGE

- To obtain the predicted charge, we must know how much light is expected to arrive on the PMT

μ Č emission profile vs. path





e Č emission profile vs. path

- Light sources: direct/indirect **Č** light, direct/indirect scintillation

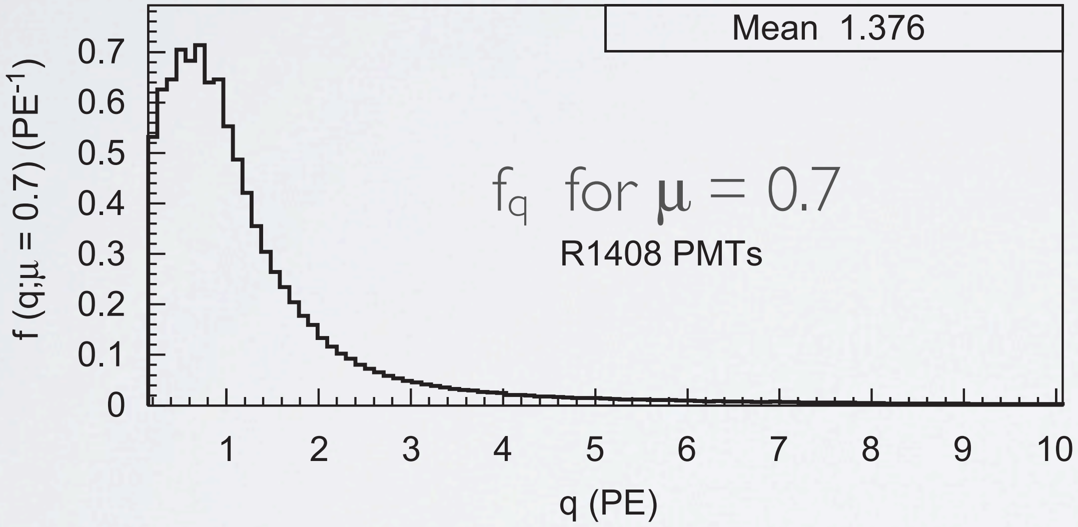
- Contribution from each source is obtained by integrating over path and parameterized

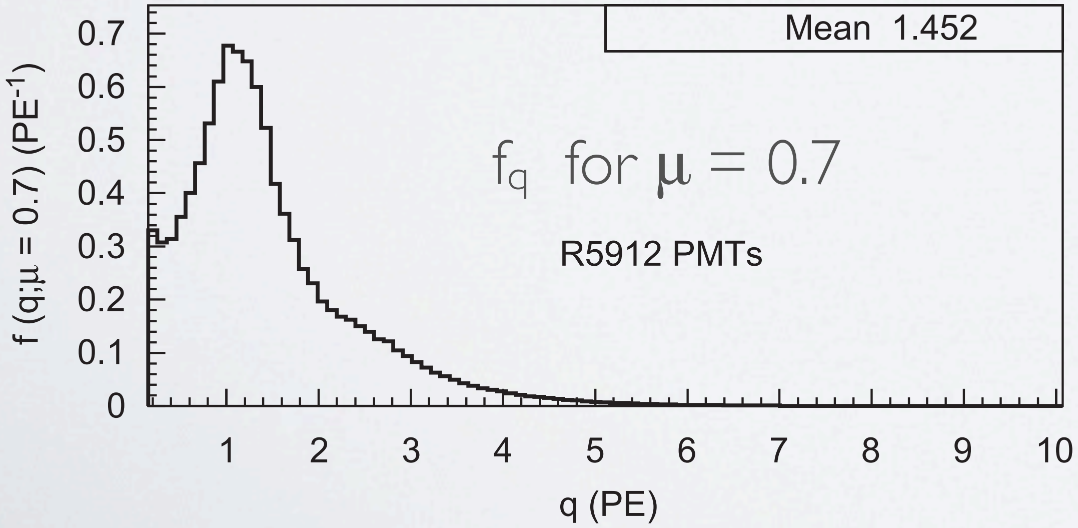
angle, distance to PMT parameterized as a function of *s*

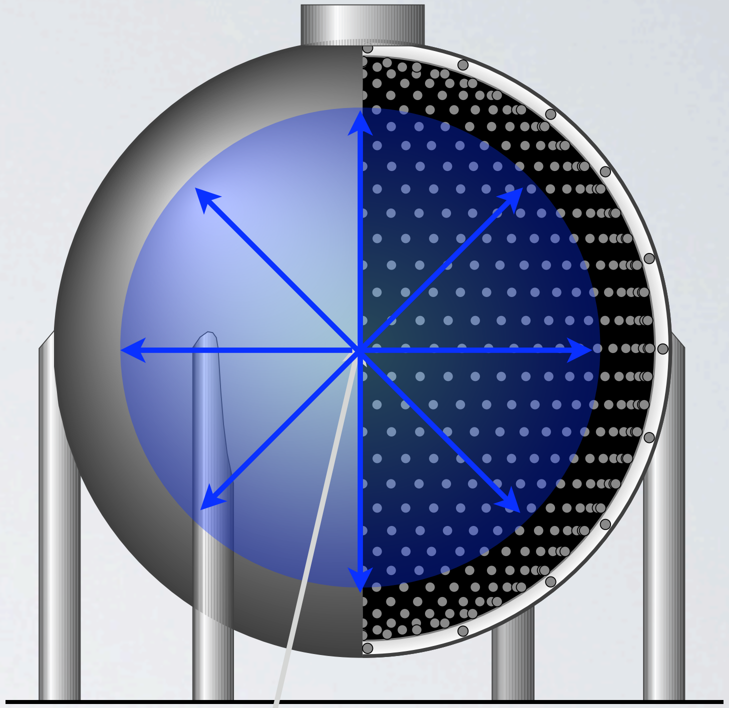
$$\mu_{\check{C}} = \overset{\overset{\text{Č overall strength}}{\downarrow}}{\phi_{\check{C}}} \times \int_{-\infty}^{\infty} ds\; \underset{\underset{\text{Č emission}}{\uparrow}}{\rho_{\check{C}}(s)}\; \overset{\overset{\text{Solid angle}}{\downarrow}}{\Omega(s)}\; \underset{\underset{\text{Transmission}}{\uparrow}}{T_{\check{C}}(s)}\; \overset{\overset{\text{efficiency}}{\downarrow}}{\epsilon(s)}\; \underset{\underset{\text{angular profile}}{\uparrow}}{g(\cos\theta(s); s)}$$

CHARGE RESPONSE

- Charge response of PMT vs μ (predicted charge) is measured by laser data ($f_q(\mu)$)
  - Pulses of 397 nm light flashed ~isotropically through detector with varying intensity
  - q measured by occupancy of PMT hits.







laser flask

CORRECTED TIME

- Express arrival time of light at the PMT in "corrected time":

time at PMT

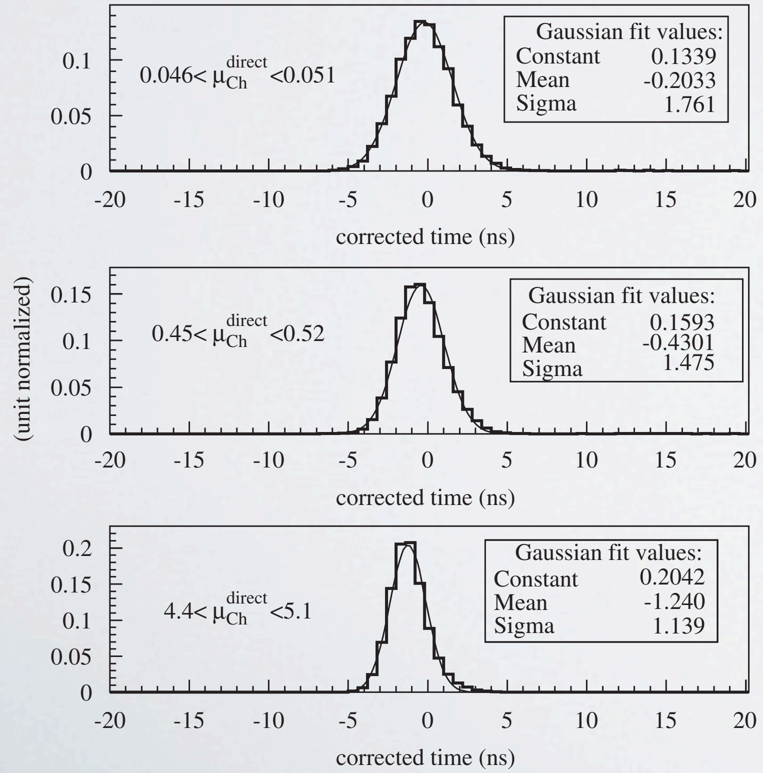
time of light from midpoint to PMT

$$t^c = t - t_0 - r\frac{\Delta s_{\text{mid}}}{c_n} - \frac{\Delta s_{\text{mid}}(E_0)}{c}$$

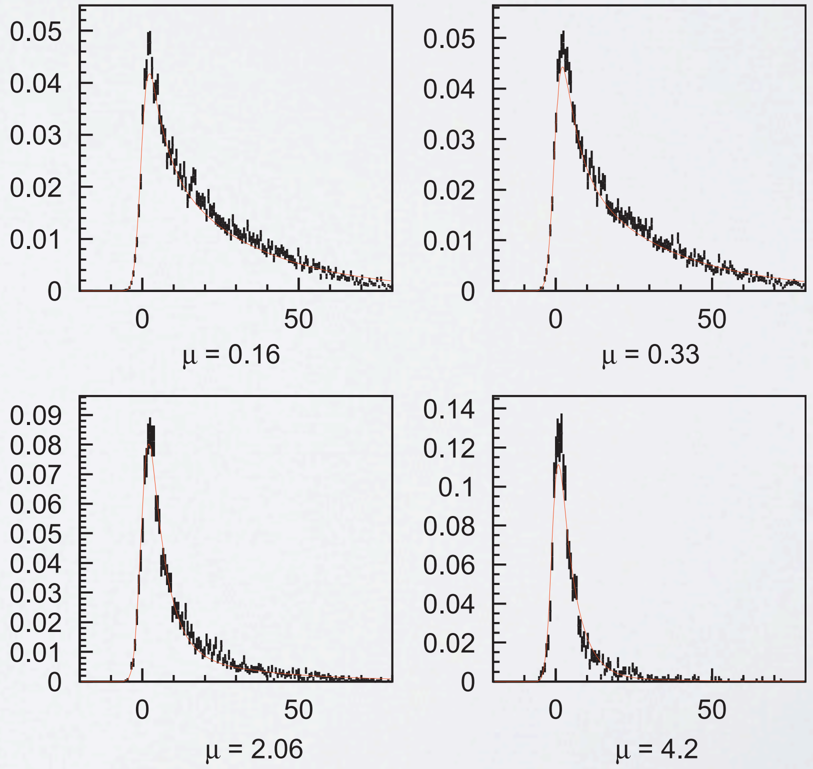
time at starting point of track

time of track from start to midpoint

- Approximation: corrected time spread is dominated by;
  - Extent of track (light emitted from different places)
  - prompt vs. delayed light (scintillation, scattering, fluorescence)



prompt light

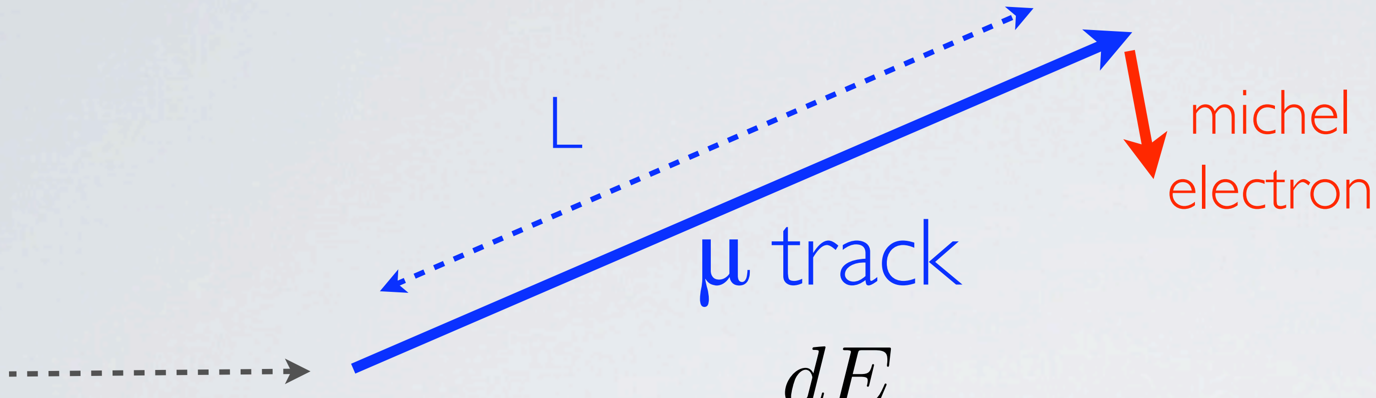


late light

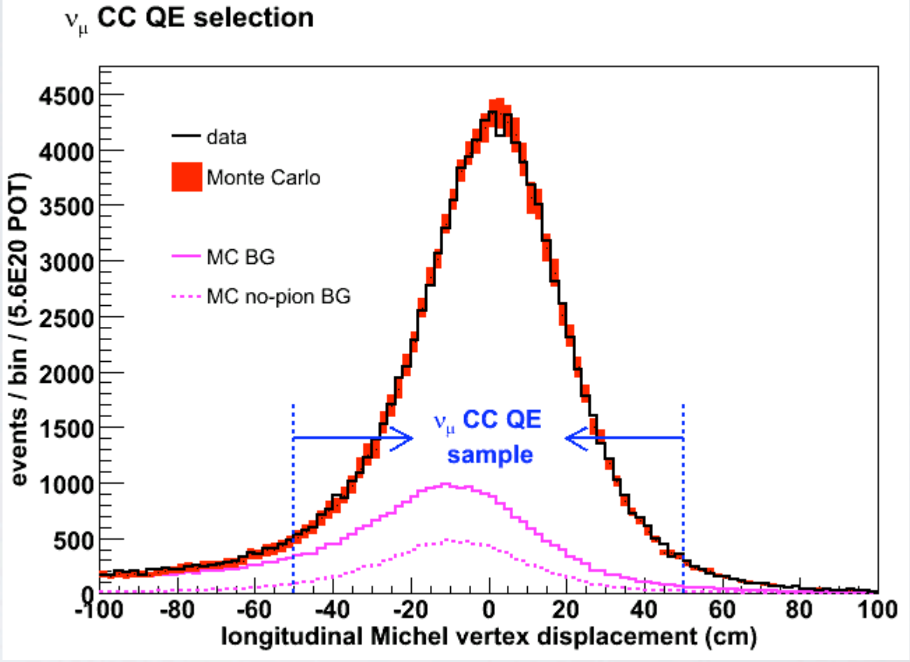
TIME LIKELIHOOD

- time likelihood is modeled as a function of
  - amount of prompt light (gaussian)
  - amount of late light (scintillation, scattering, reflection, etc.)
    - gaussian convoluted with exponentials
  - energy (spread of track, hence spread of light production)
- PMT timing reflects first hit to trigger the PMT
  - Assume that prompt PDF is representative of response if there is prompt light regardless of amount of late light.
  - weight prompt and delayed PDFs accordingly based on predicted amount of prompt and delayed light.

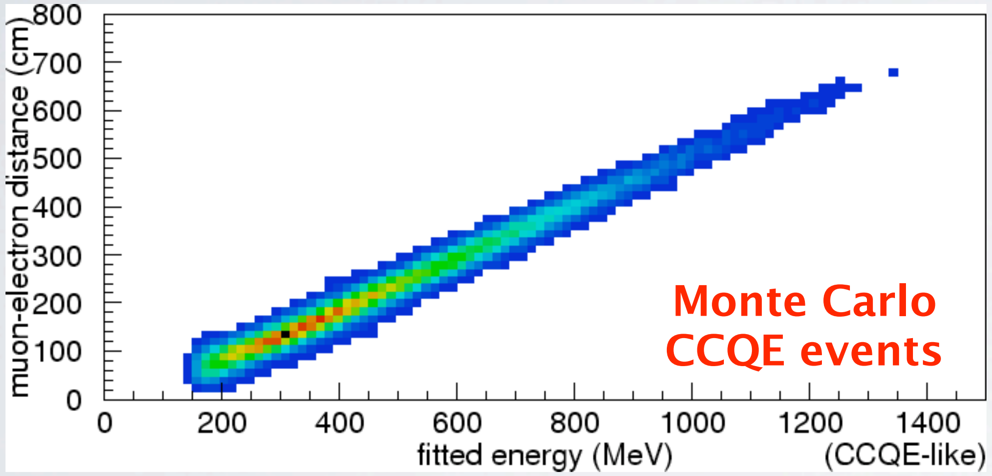
ON NEUTRINO EVENTS

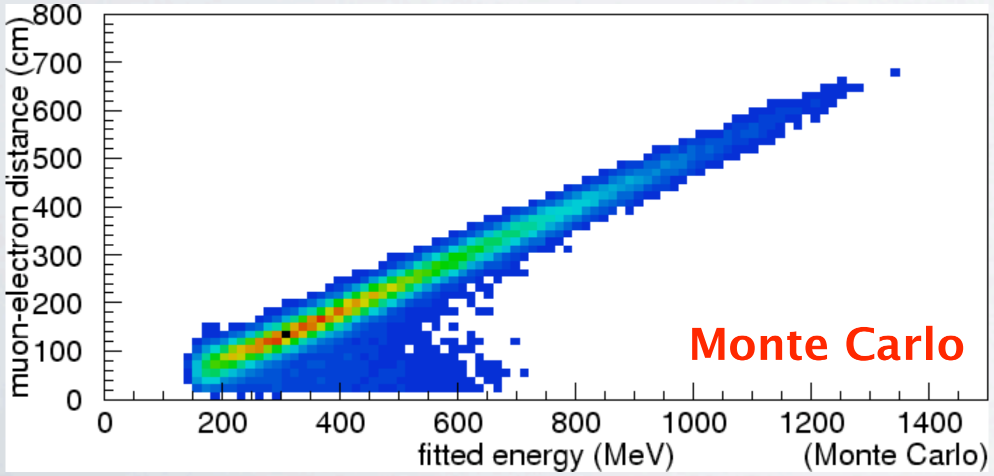


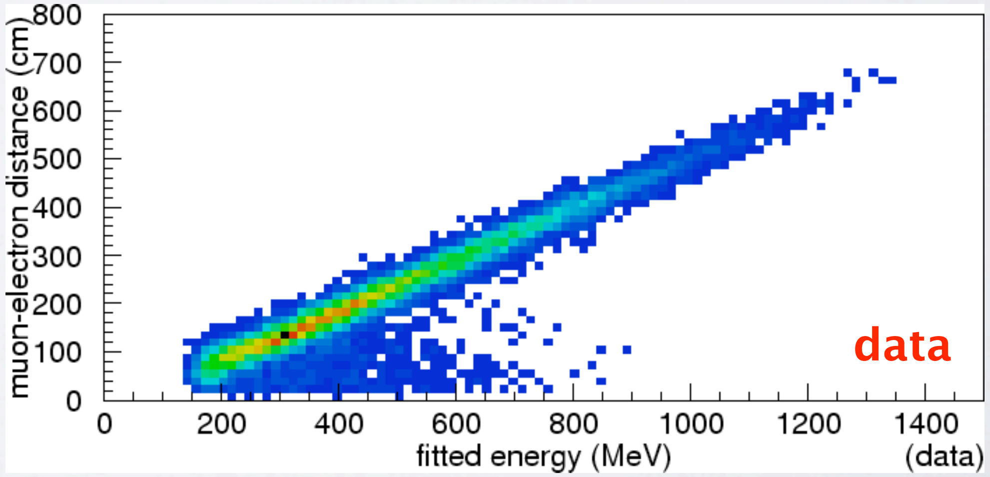
$$E \sim \frac{dE}{dx} \times L$$



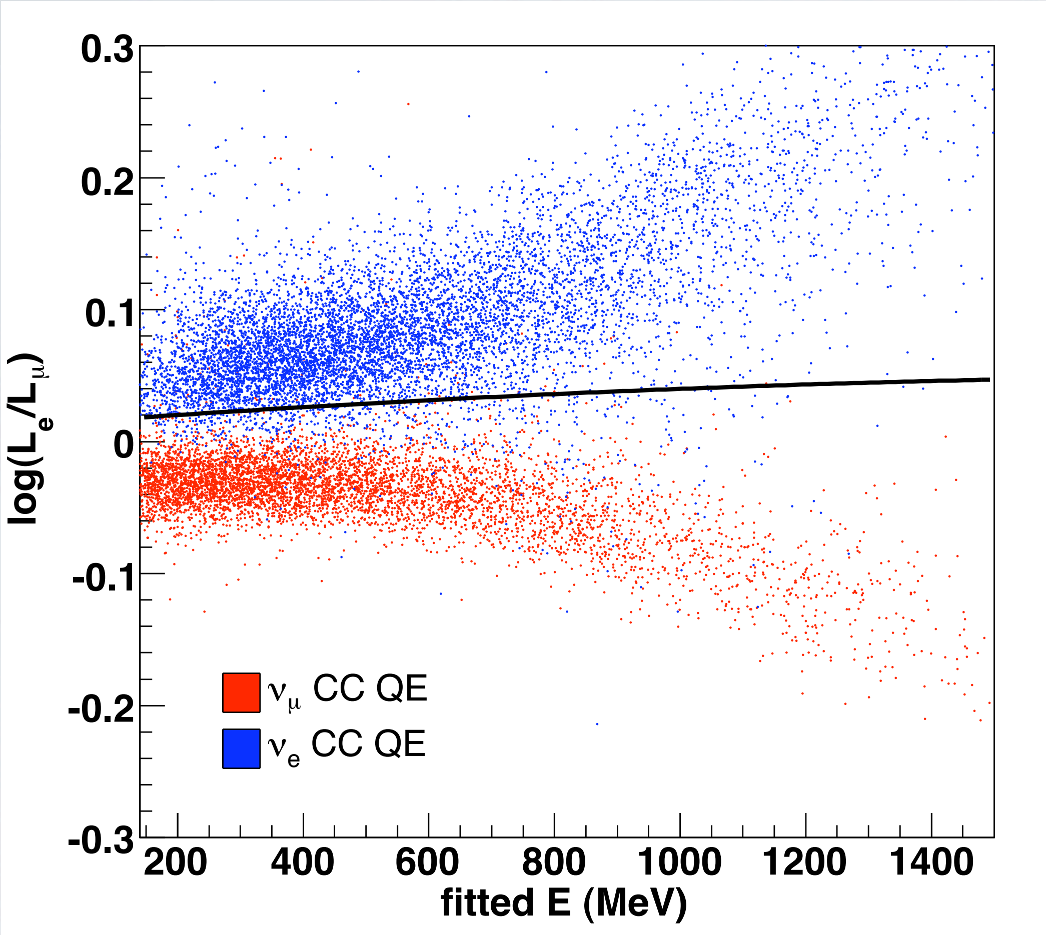
- Two ways of measuring energy for Michel-tagged events
  - track length of muon (μ, e vertex)
  - reconstruction (E is free parameter)

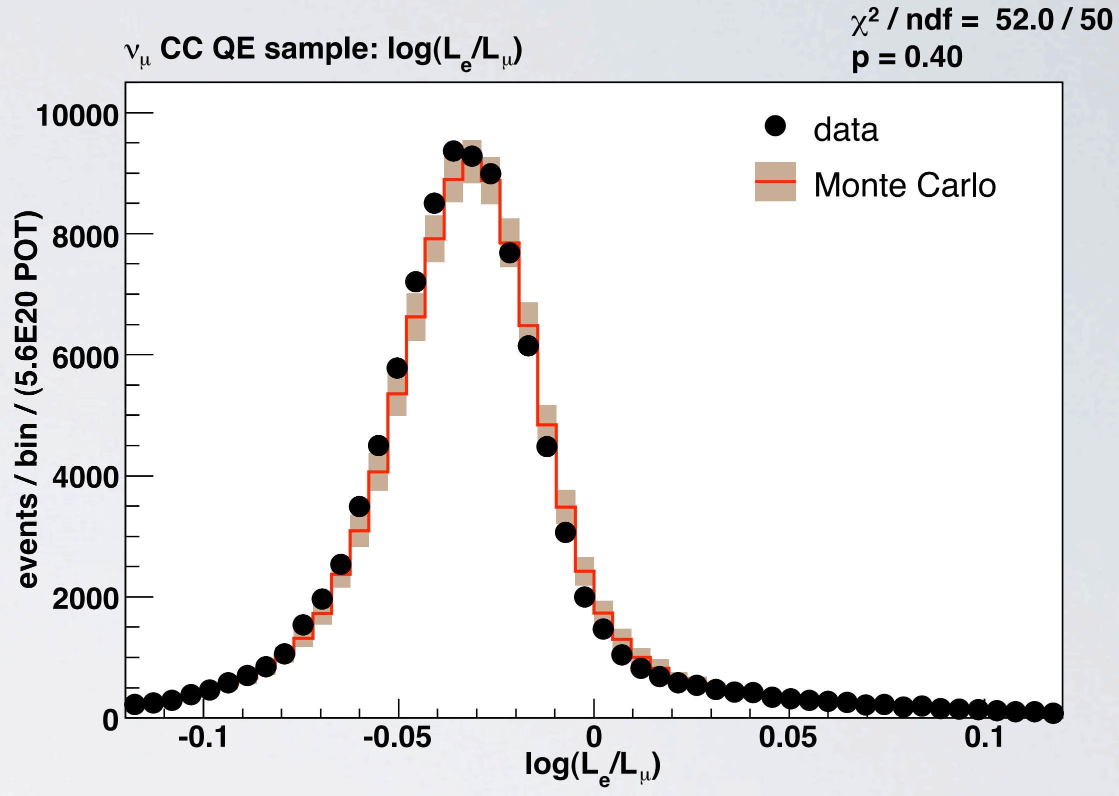


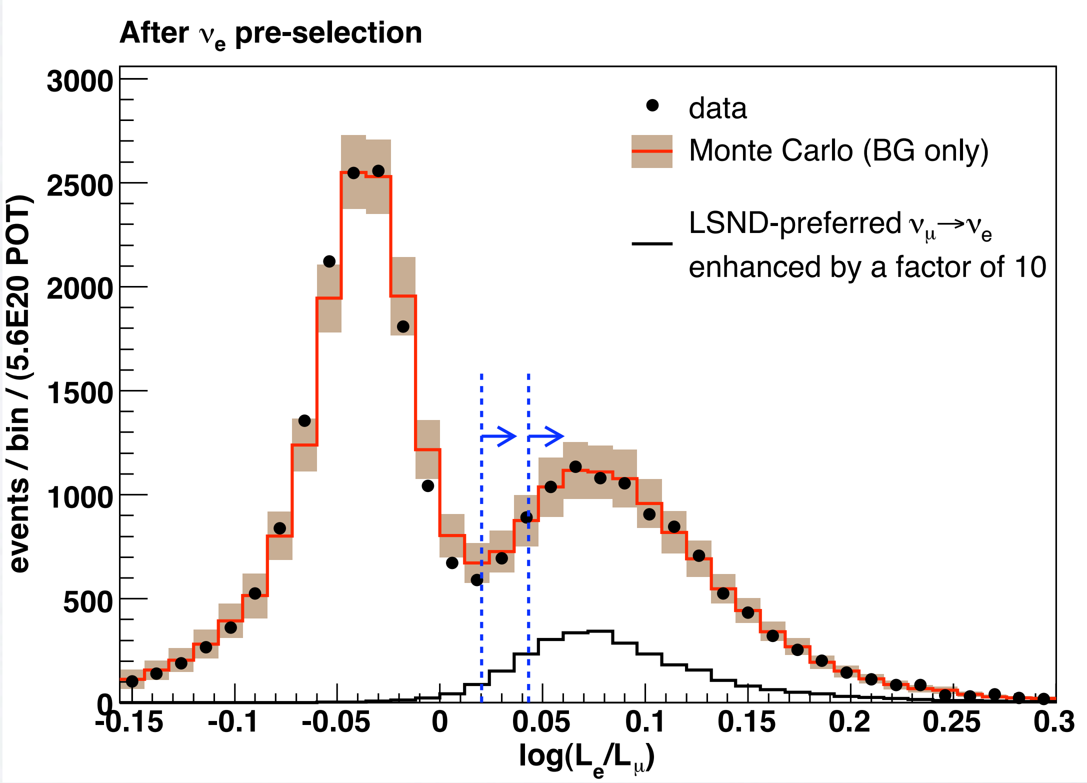




e/μ IDENTIFICATION



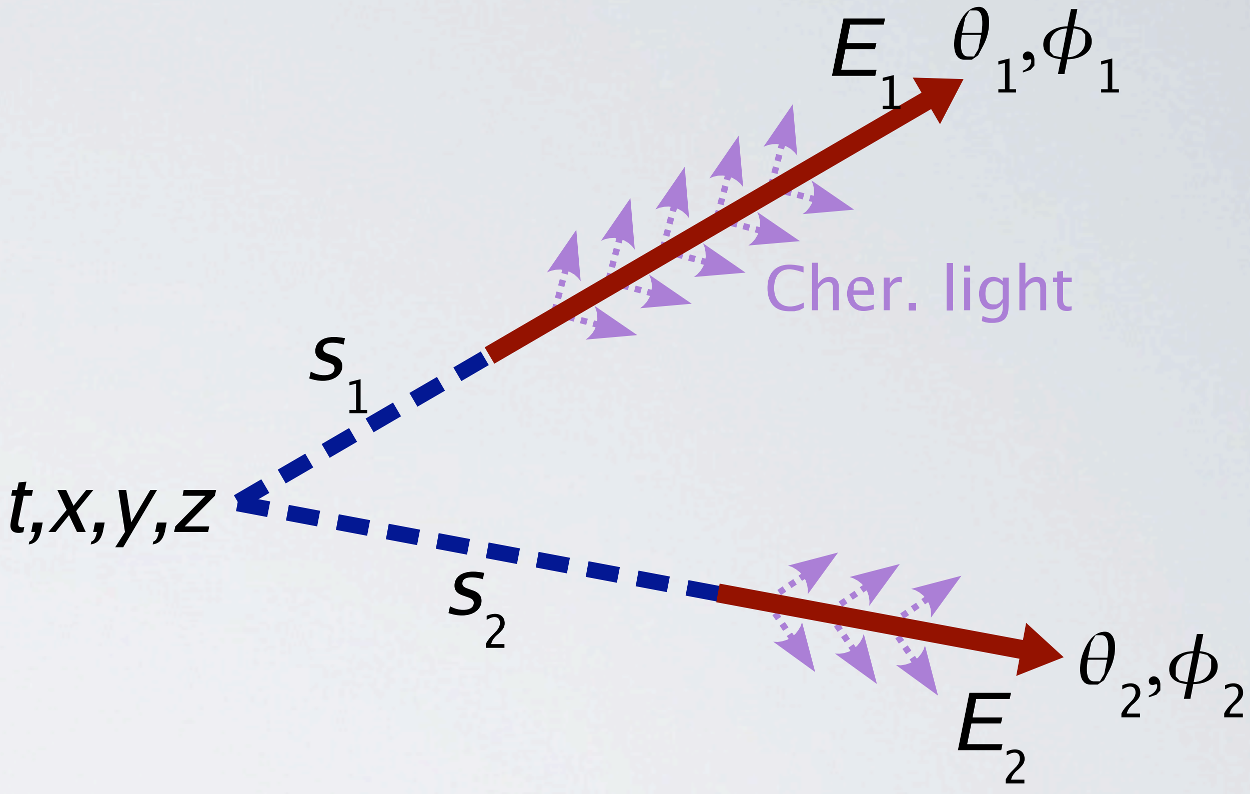




- Fit event once with e hypothesis, once with μ hypothesis
- Compare likelihoods via ratio
- "Did track fit better as e or μ?"

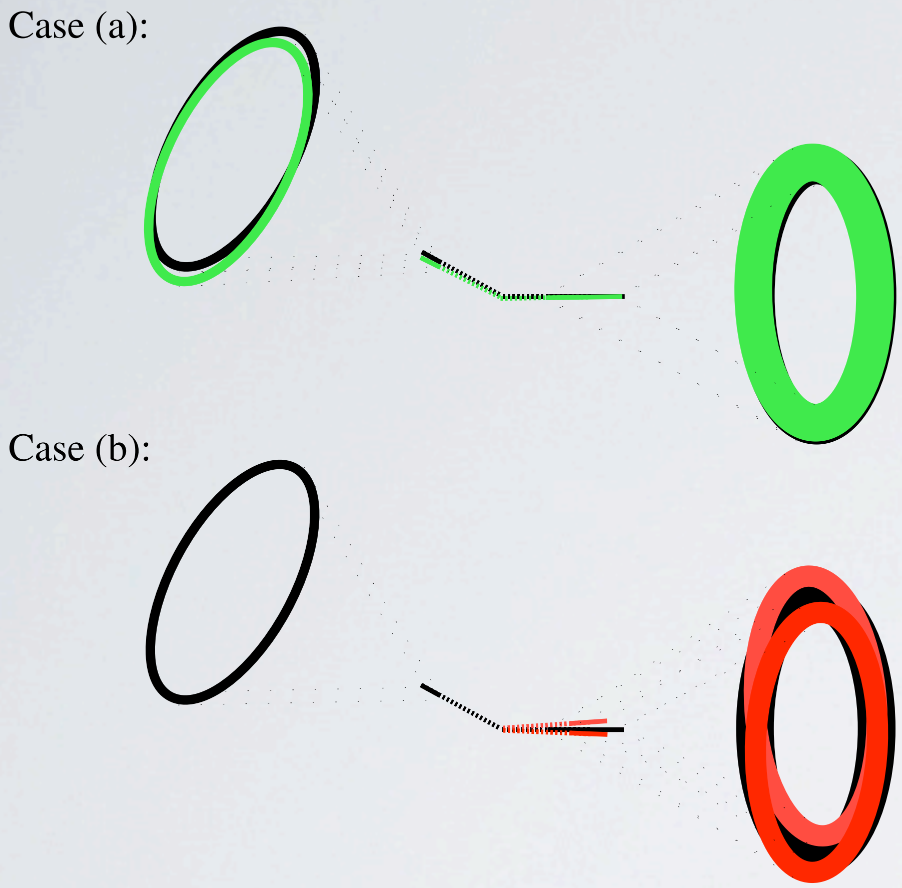
π^0 FITTER:

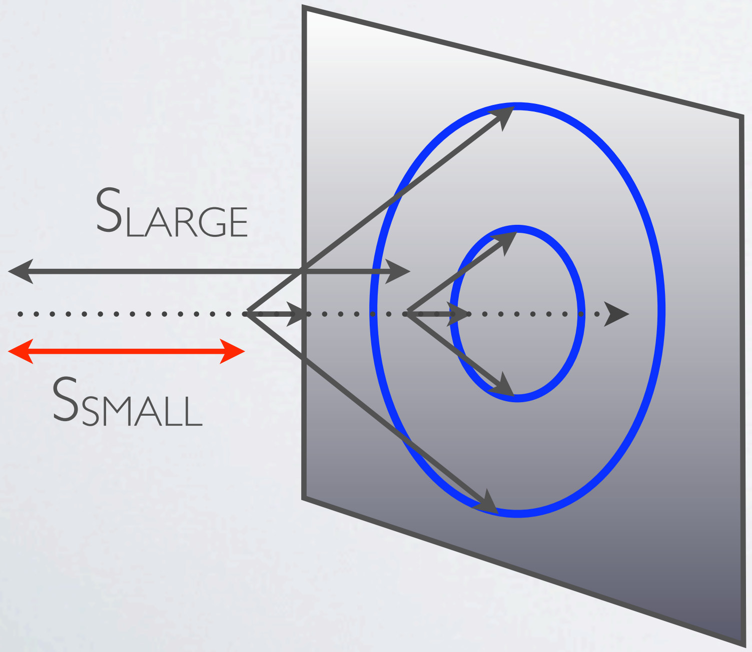
- Introduce a second ring to the hypothesis with geometric constraints (12 parameters):
  - Common vertex from which two photons are emitted (4)
  - Conversion distance (2)
  - Energy, direction of photons (2x3)
- Our likelihood formalism generalizes (somewhat) straightforwardly
  - Add the predicted charge from each track and obtain a new charge PDF
  - Time is a bit more complicated . .
    - basic assumption: PDF is dominated by first photon to arrive



- Seeding the algorithm (choice of starting parameters is tricky
  - Many local minima in 12D space
  - Easy for MINUIT to get trapped
  - Need to use some "physics"

TRAPS





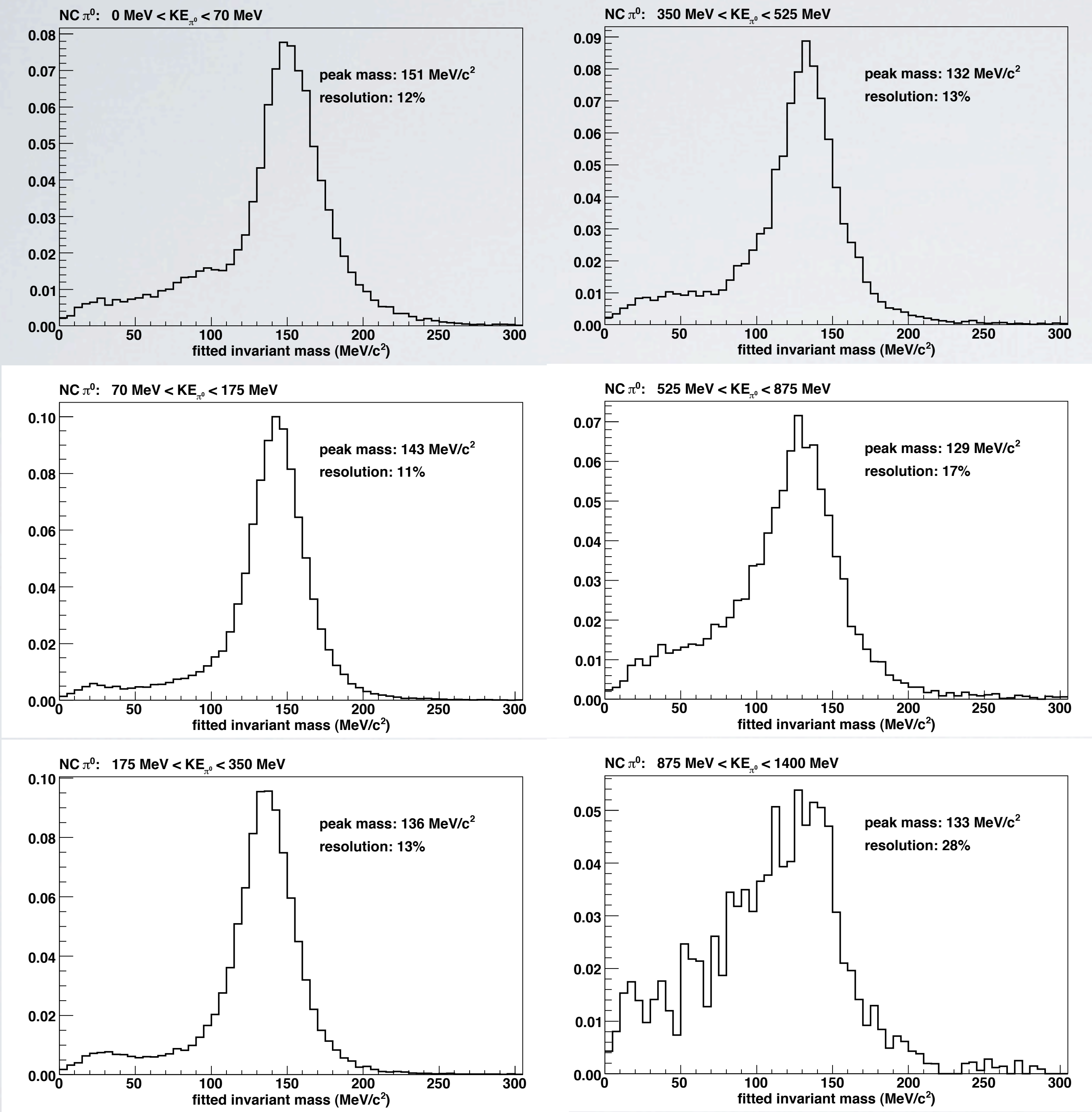
- If parameters are far from the true configuration, it can be difficult for the minimization to find the true solution
- Opening Angle: (left)
  - Rings are actually well separated but the fitter is exploring small opening angle parameters
  - The true solution is "disconnected" from the current parameters
- Conversion distance:
  - If a photon converts far from the wall it appears "big", if it is close, it is "small"
  - If the conversion distance is far from actuality, it could be difficult for algorithm to converge to true solution

solution: seed algorithm several times with configurations which are discretely different

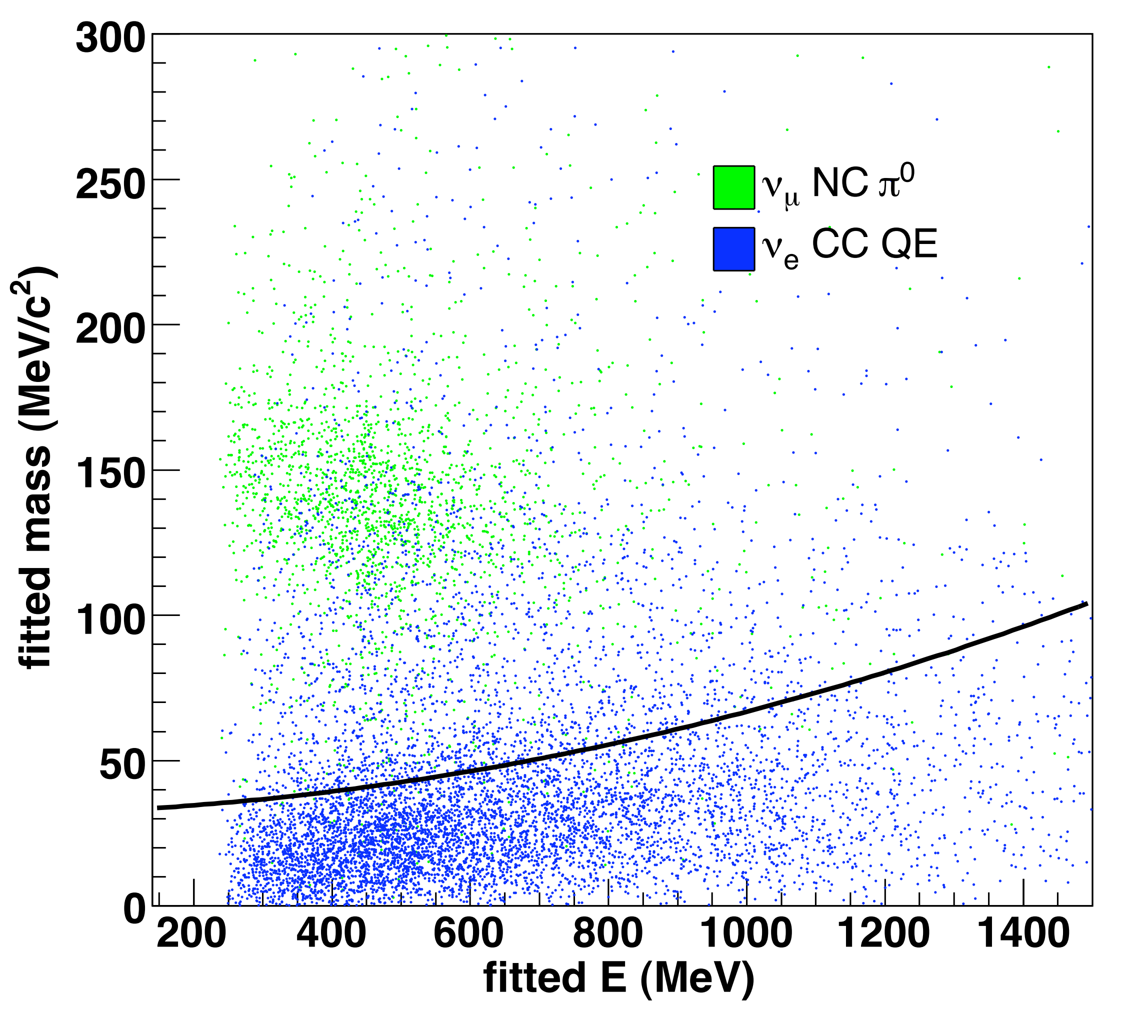
SEEDING

- Explore several starting configurations to try to cover all cases
- Select starting vertex by using 1-ring e fit
  - shift back to account for conversion by 50/250 cm (2 cases)
  - Perturb the direction slightly (1+8 cases)
- Explore a 24x12 or 50x25 grid of second photon directions
  - Set starting energy to make $M_{\gamma\gamma} = m_{\pi^0}$
- Select starting parameters with:
  - Best, 2nd best total likelihood
  - Best, 2nd best charge likelihood with "symmetric" E_1,E_2
  - Best 2nd best charge likelihood with "asymmetric" E_1, E_2
- Forward these to MINUIT for fit and report best result

PERFORMANCE

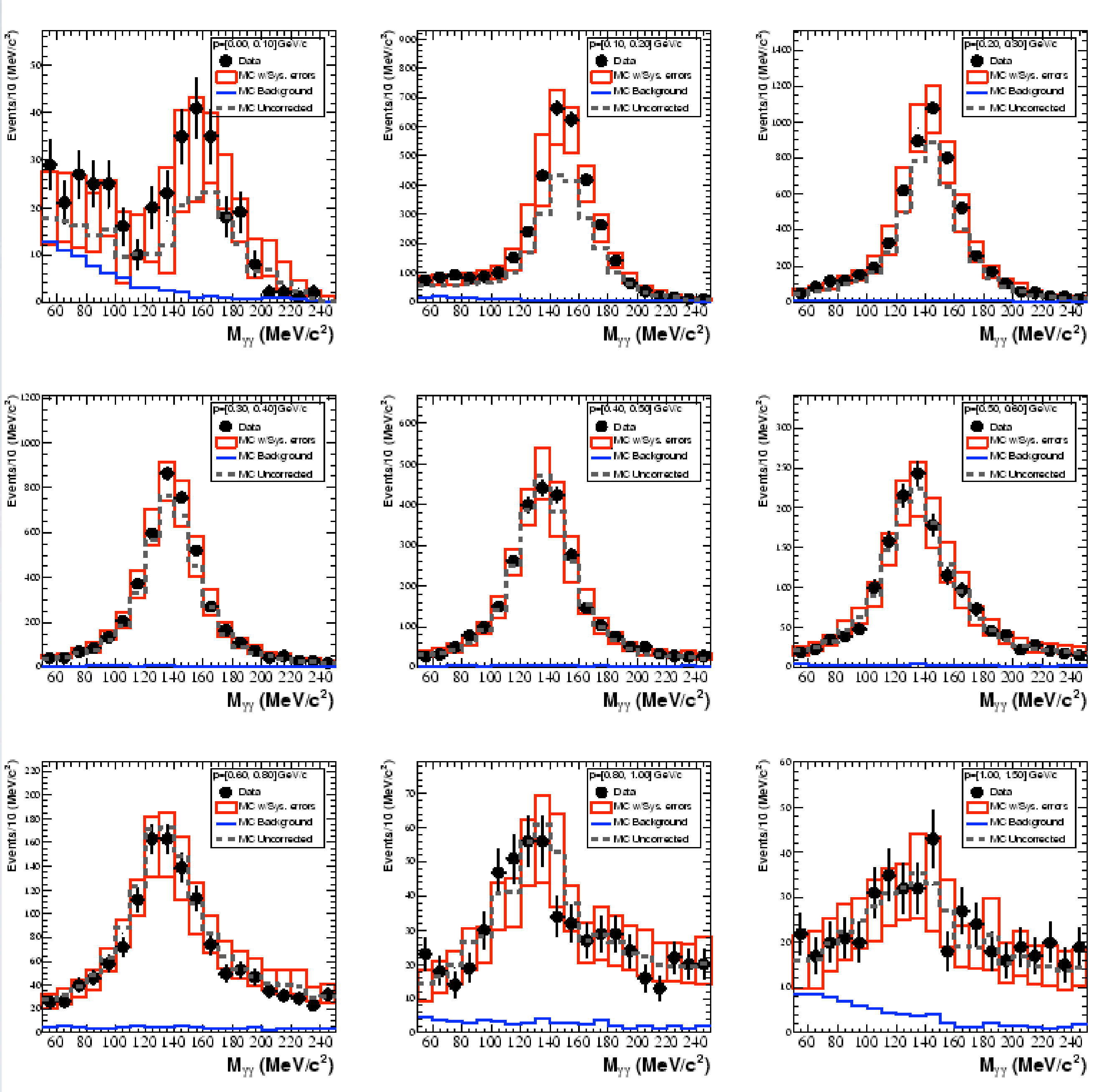


MC



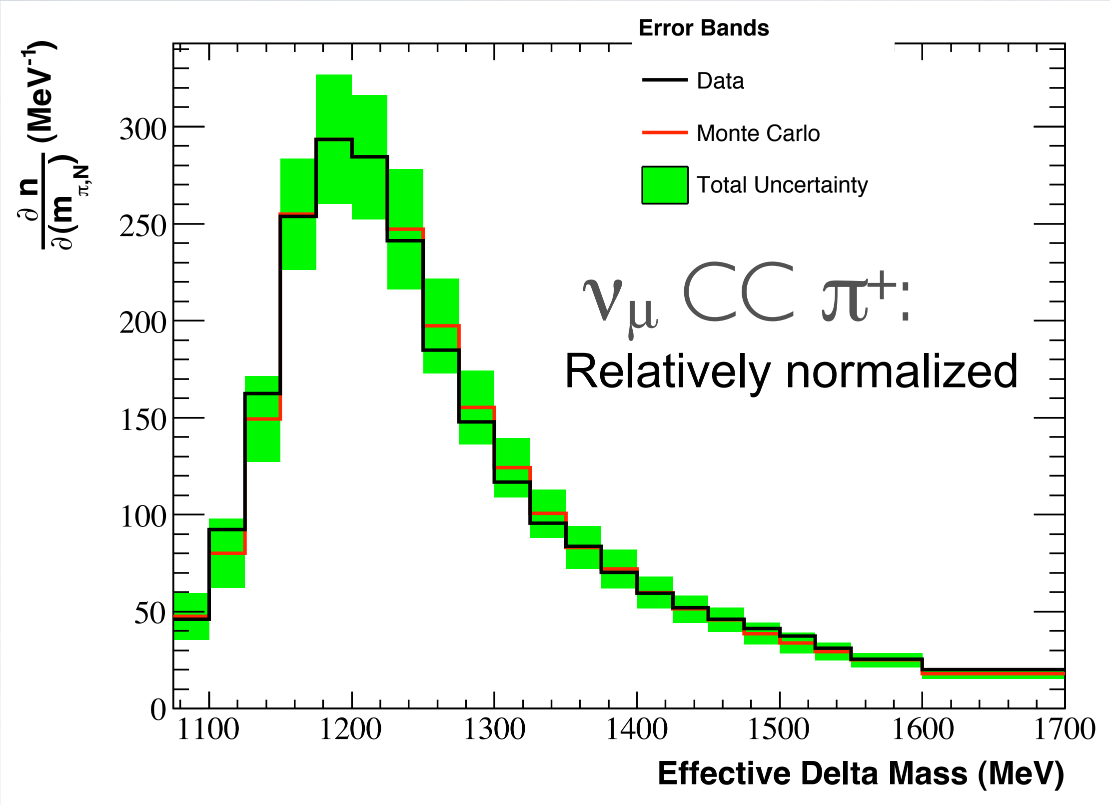
- No artificial peak in ν_e events from seeding (assumes π^0 mass)
- Mass peak visible even at 1 GeV/c momentum

MEASURING π^0 RATE:

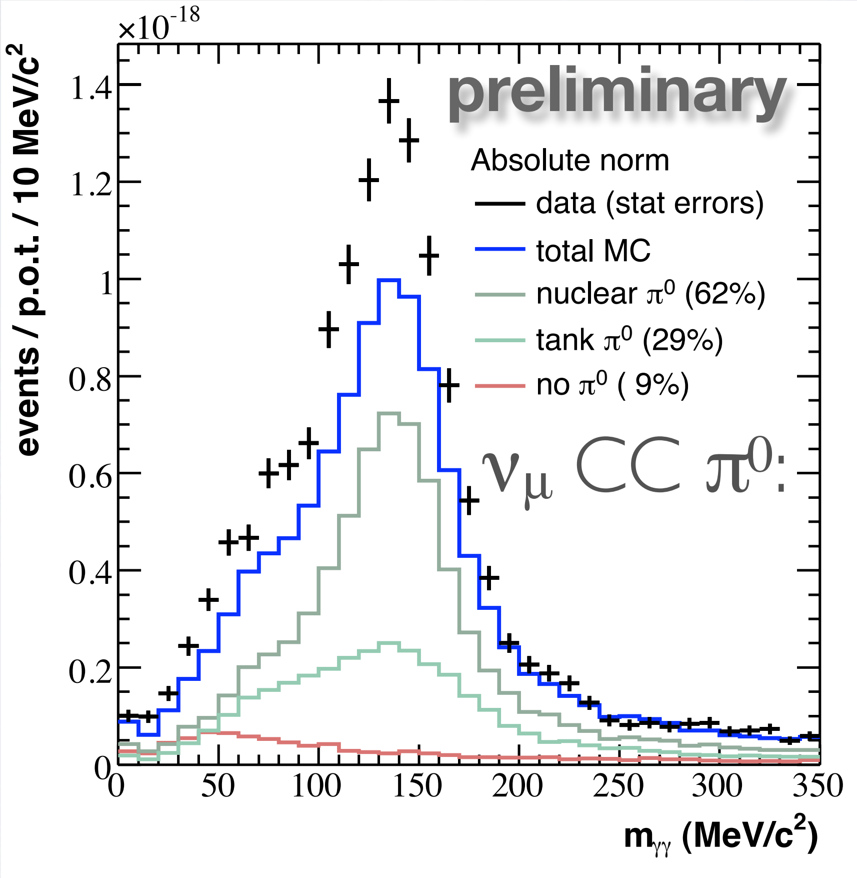


- In addition to e/π separation, the algorithms are used to identify π^0 events
- Measure the momentum distribution and correct background prediction
- Model dependence (cross section uncertainties) pushed to higher order.

ν_μ CC π RECONSTRUCTION



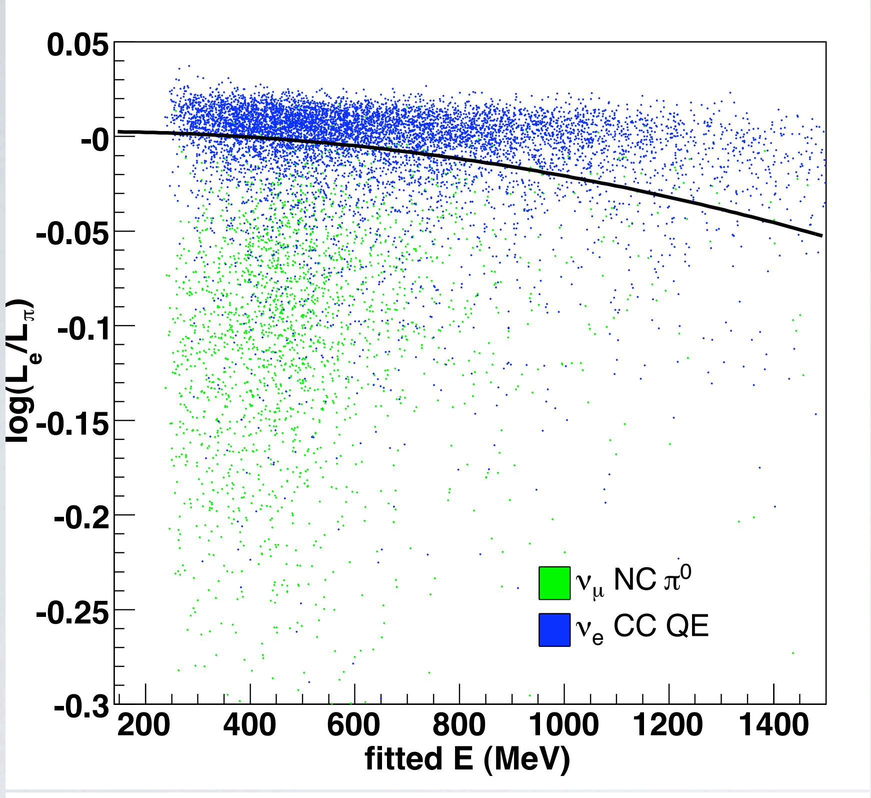
ν_μ CC π^+:
Relatively normalized



ν_μ CC π^0:

- The methodology has been extended towards:
  - ν_μ CC π^+:
    - $\mu+$ π^+ final state = 2 μ like rings, no conversion distance)
  - ν_μ CC π^0: $\mu+\gamma+\gamma$ final state = μ ring, 2 e rings with conversion distance
- Seeding the algorithm is always tricky .... but solutions have been found!

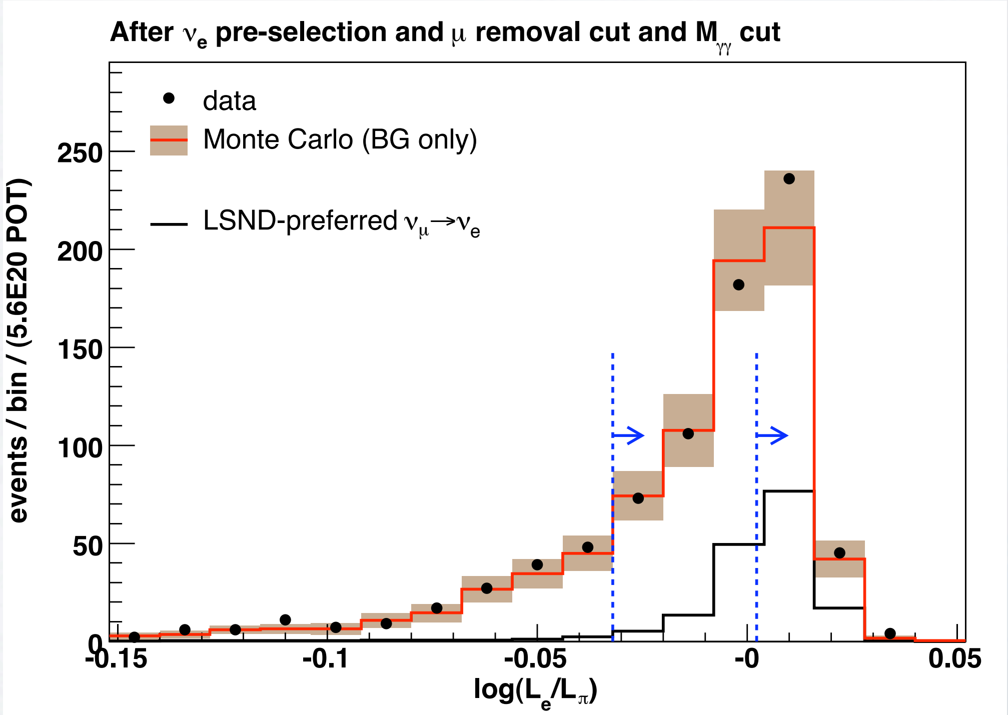
e/π LIKELIHOOD RATIO



- Related but additional information can be obtained by requiring $M_{\gamma\gamma} = m_{\pi^0}$
  - $M_{\gamma\gamma}$ (E_2) is no longer a free parameter
  - Refit the event with this constraint
- We can use the likelihood ratio between electron and π^0 (with fixed mass) to distinguish events
  - Is fit better with 1 e-ring or 2 e-rings with $M_{\gamma\gamma} = m_{\pi^0}$
  - Note: without this, the event will always fit better with 2 e-rings.

In previous case, $M_{\gamma\gamma} = m_{\pi^0}$ was used to make initial guesses to seed fit.

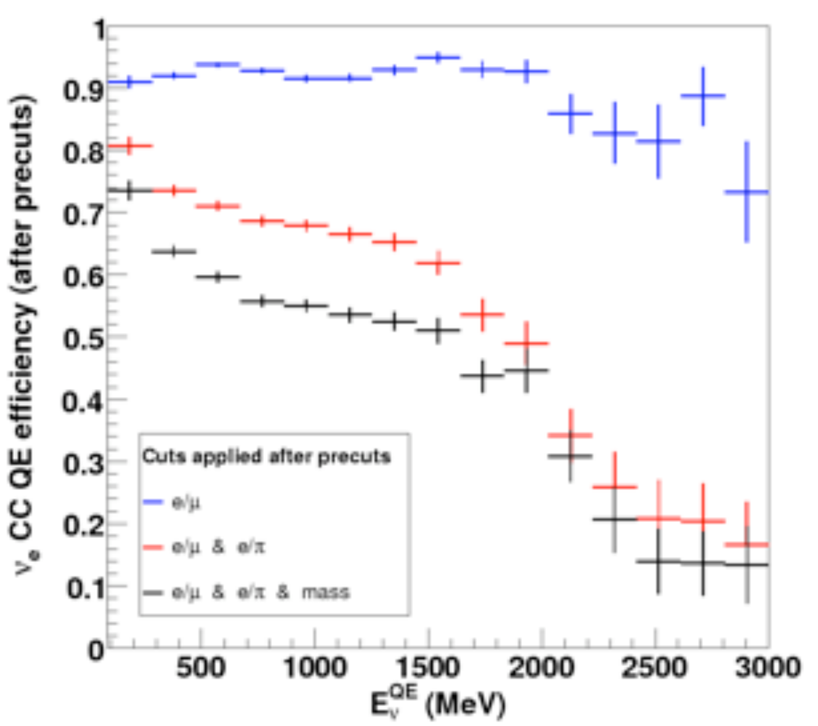
Now, this constraint is used throughout the fit process to calculate L(e/π)



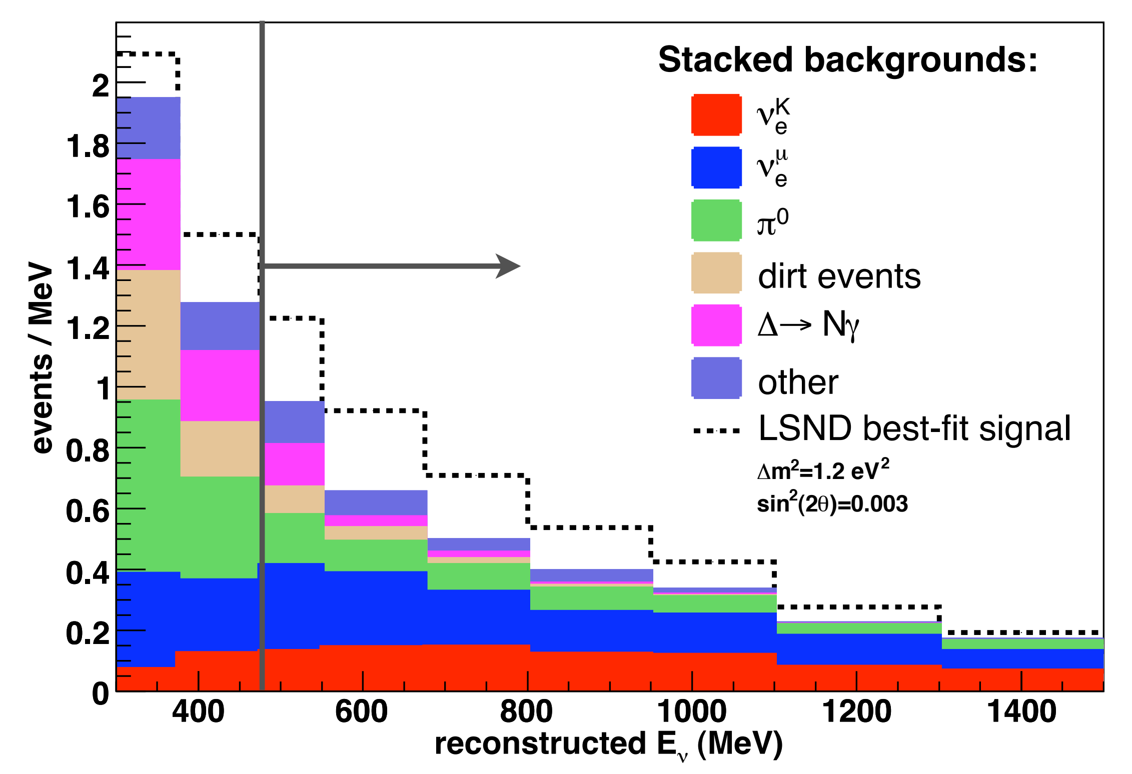
OVERALL SELECTION

- No decay electron (suppress ν_μ CC)
- No veto activity (suppress cosmics)
- >200 Inner detector PMTs hit (above Michel electron)
- Fiducial volume (5 m)
- Likelihood ratios:
  - more e-like than μ-like
  - more e-like than π^0-like
- $M_{\gamma\gamma}$ small (not consistent with π^0)
- Neutrino energy window (475-3000 MeV)

OVERALL PERFORMANCE



- Through most of signal region (<2 GeV) 50% or better efficiency
  - NC π^0 reduced to <1% of original rate

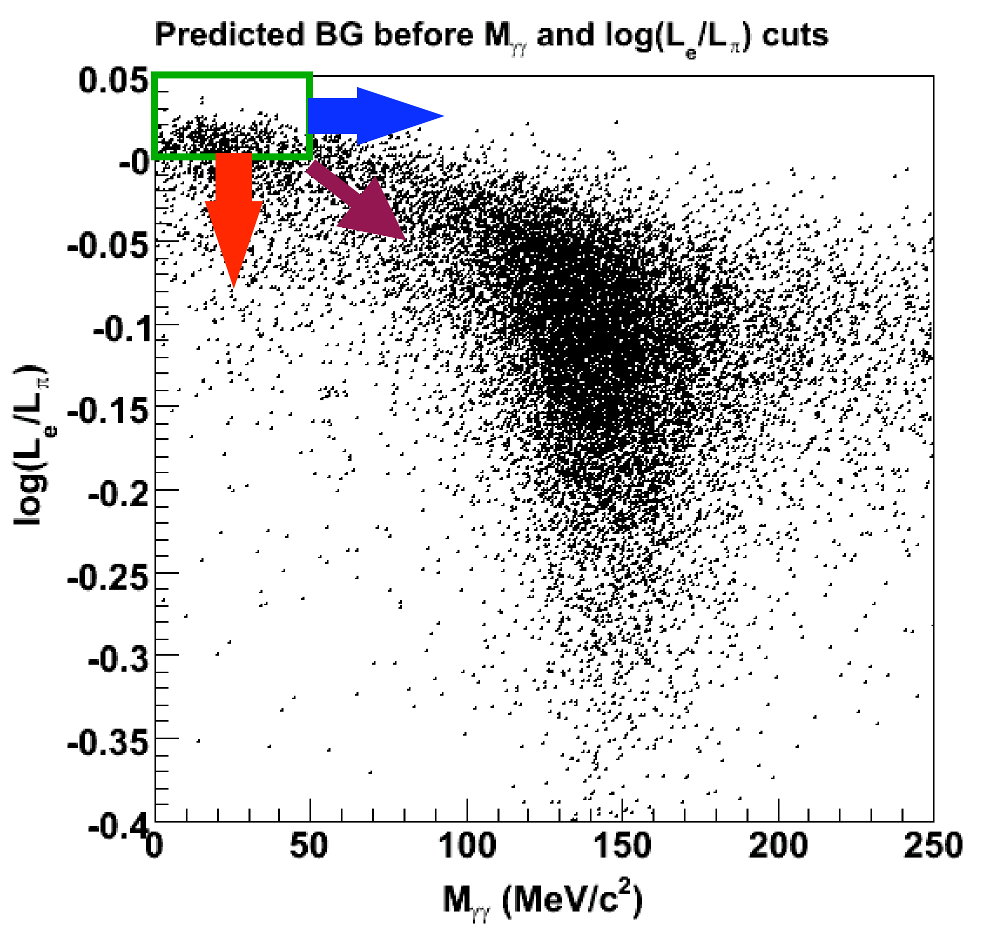


Process	Predicted Yield
ν_μ CCQE	10±2
$\nu_\mu + e \rightarrow \nu_\mu + e$	7±2
NC π^0	62±10
NC $\Delta \rightarrow N\gamma$	20±4
dirt events	17±3
other ν_μ events	13±5
ν_e from μ decay	132±10
ν_e from K^+ decay	71±26
ν_e from K^0_L decay	23±7
ν_e from π decay	3±1
Total	358±35
LSND best fit	126±16

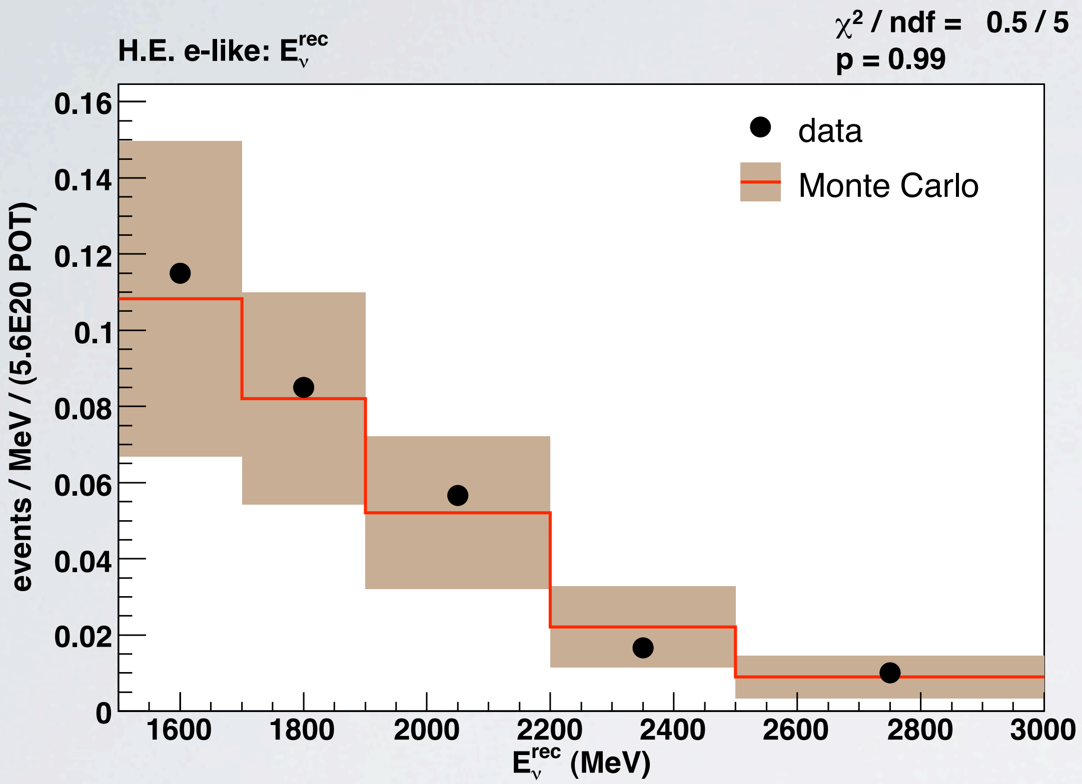
BACKGROUND CHECKS

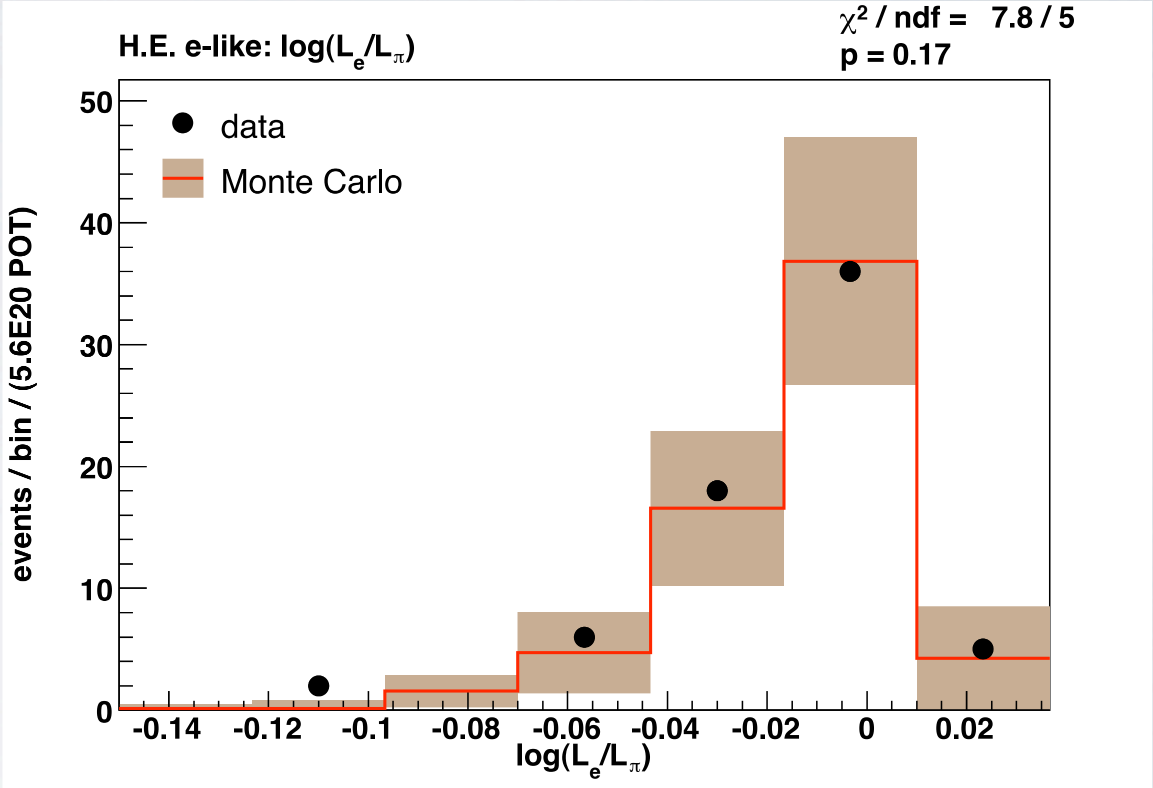
- We defined 4 "sideband" regions near the signal regio
  - None are ideal, but if should agree if our background modeling is correct
- High Energy ν_e: all selected events with E_ν>1500 MeV

- π^0 sidebands
  - L(e/π) sideband: events which are π^0 like in L(e/π) but ν_e-like in $M_{\gamma\gamma}$
  - $M_{\gamma\gamma}$ sideband: events which are ν_e like in L(e/π) but π^0-like in $M_{\gamma\gamma}$
  - A little bit "background like" in both

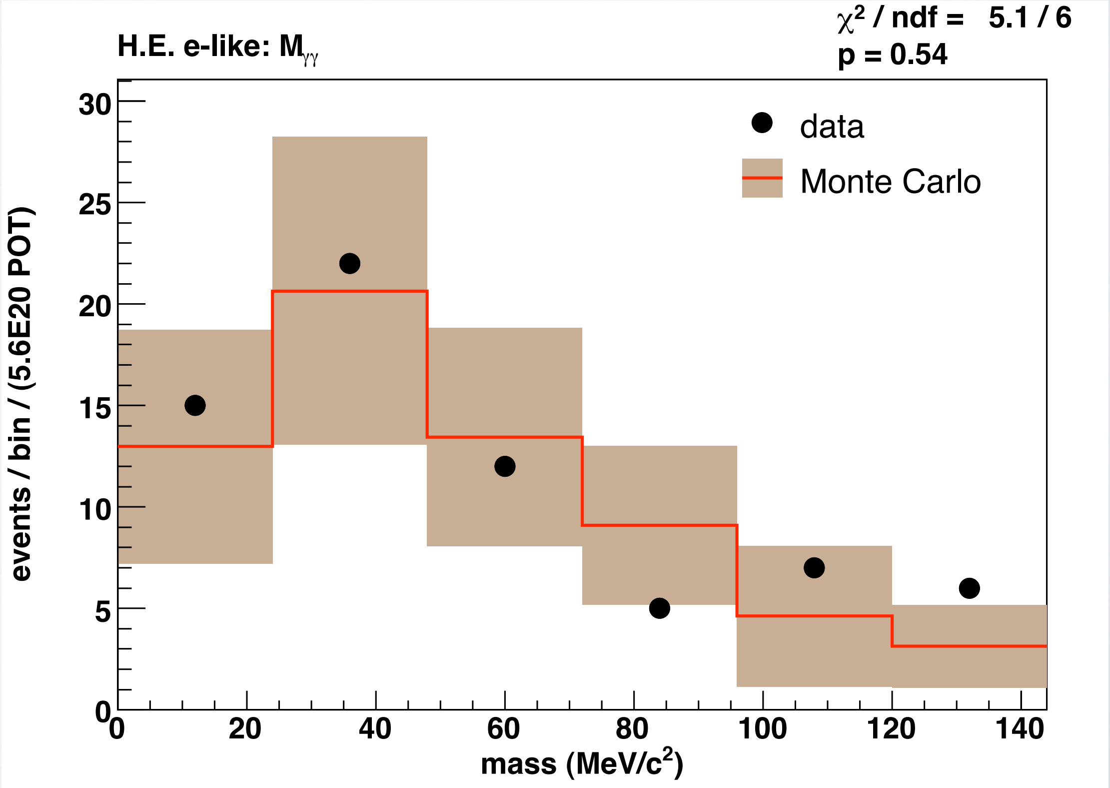


CHECKS: HIGH ENERGY ν_e

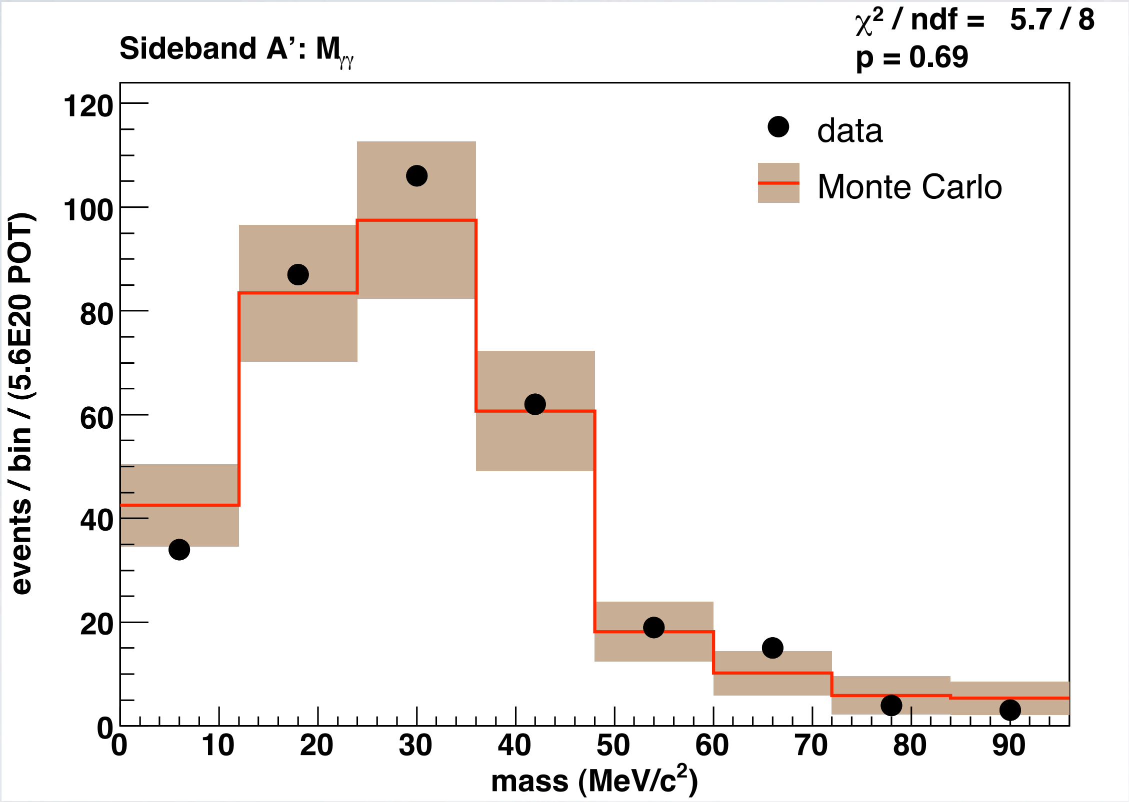




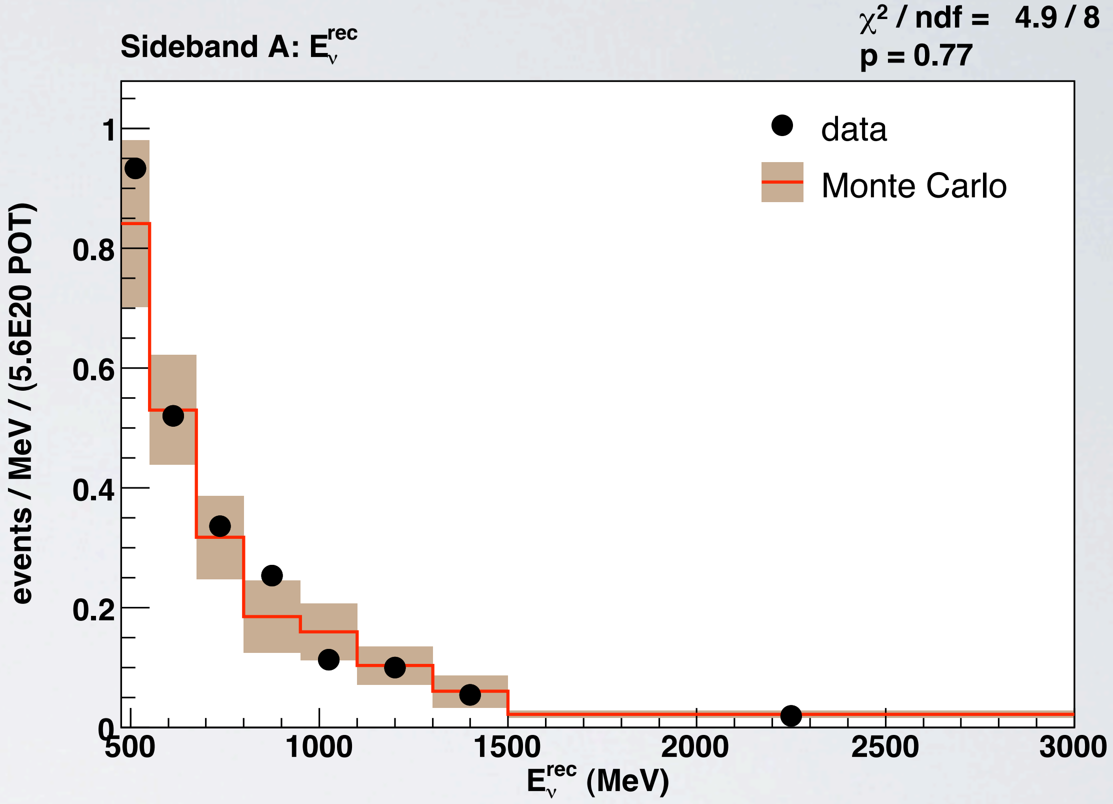
- Both kinematic and particle identification quantities look okay.

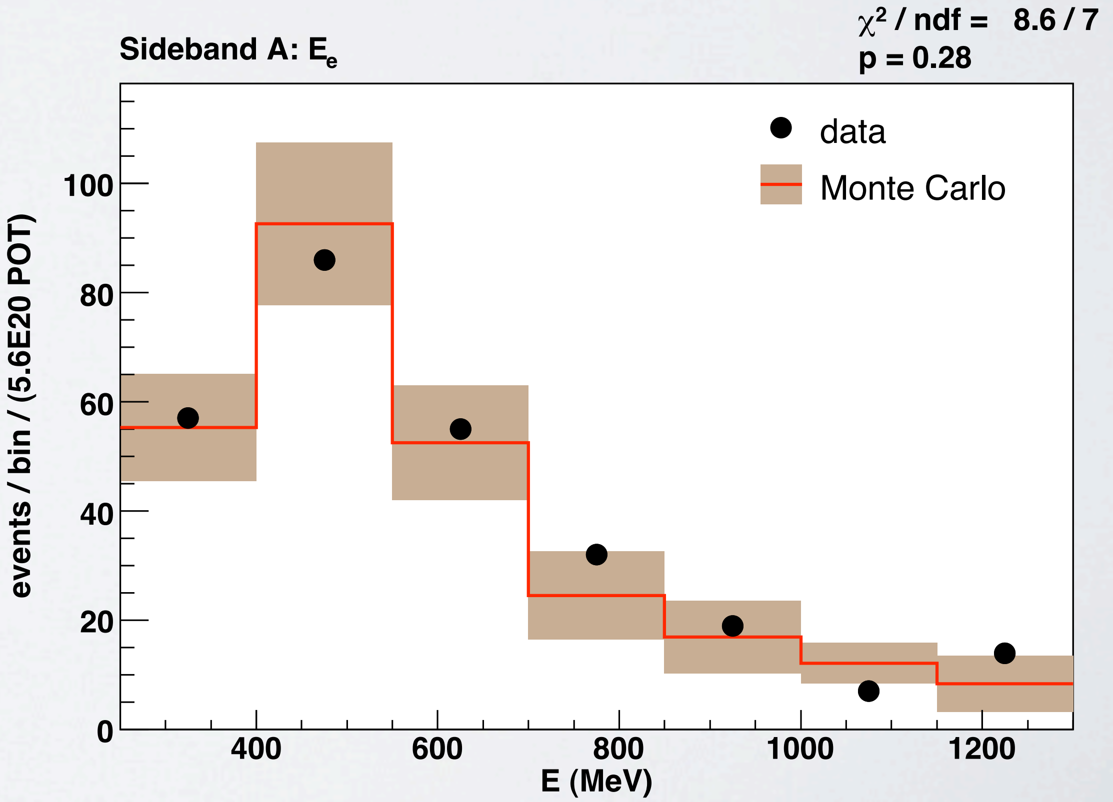


CHECKS L(e/π) SIDEBAND

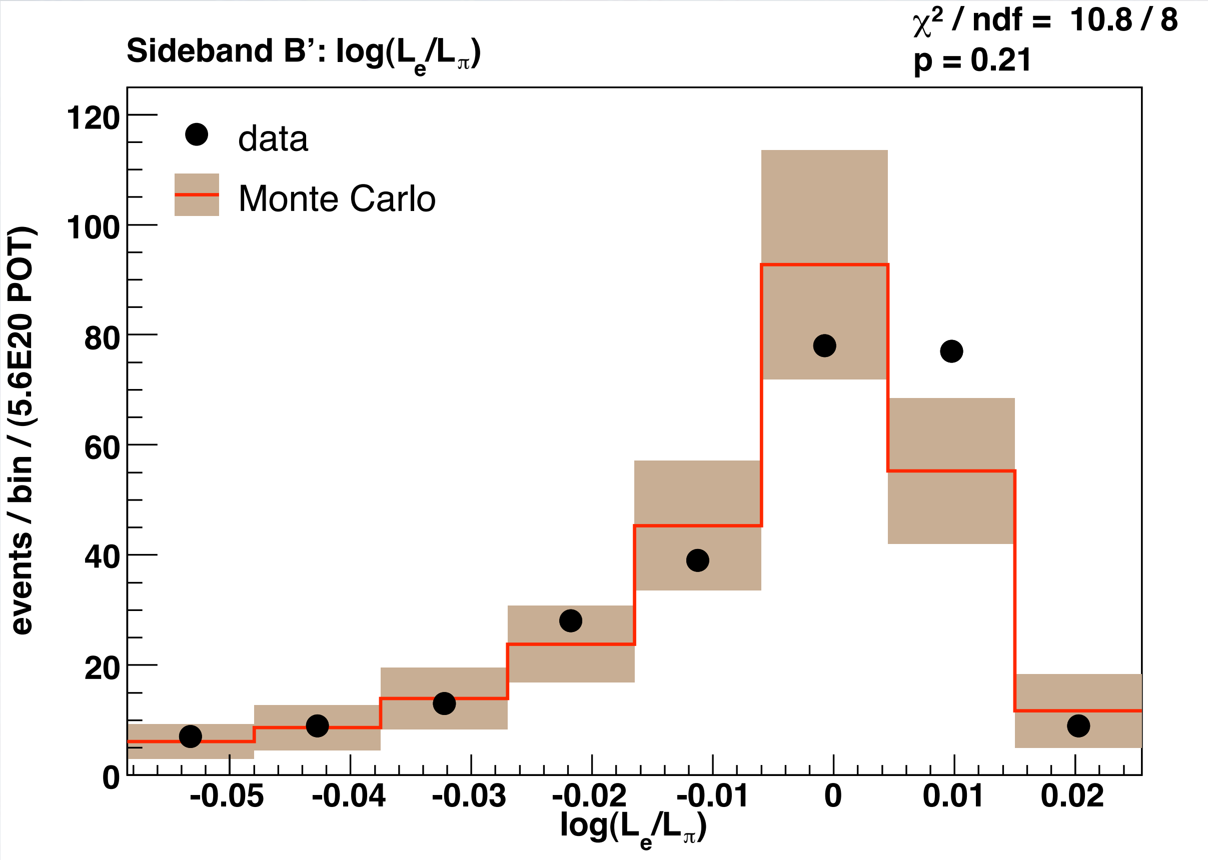


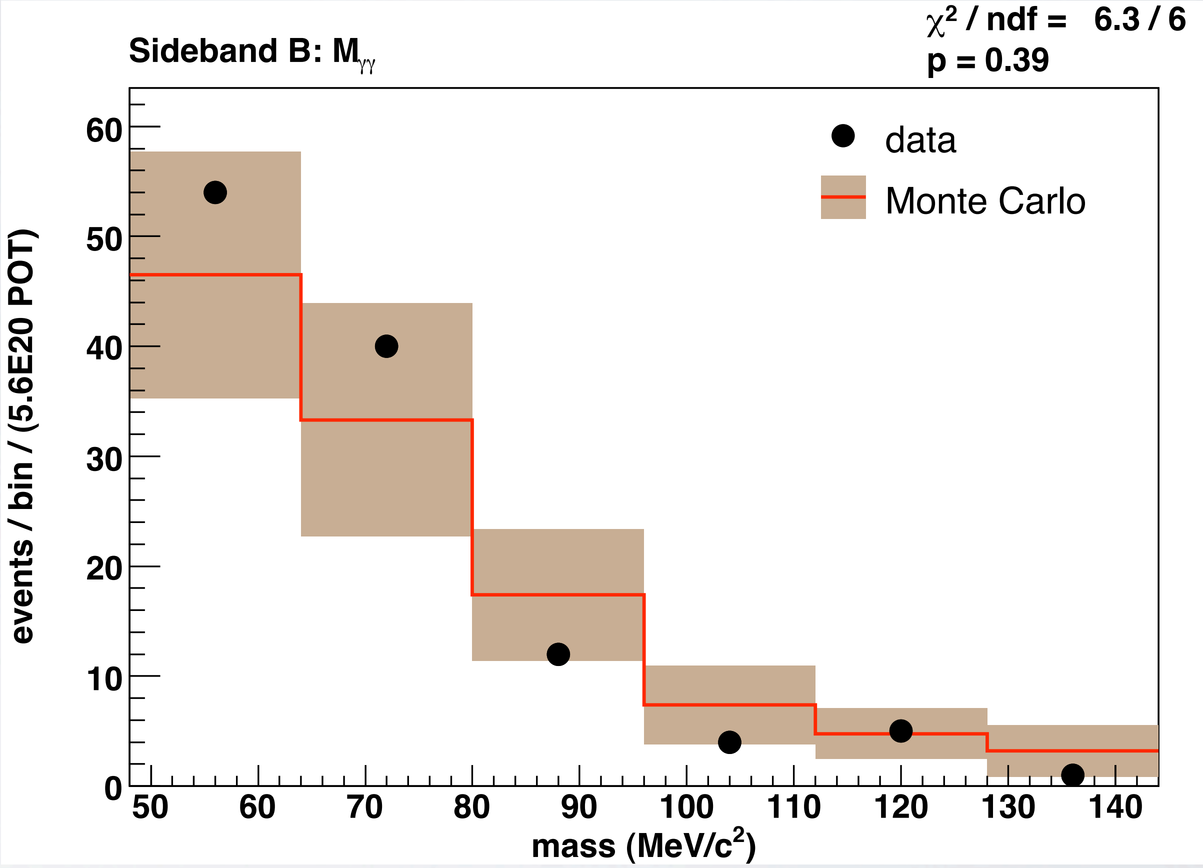
- Looks okay!
- $M_{\gamma\gamma}$ cut removed for $M_{\gamma\gamma}$ plot

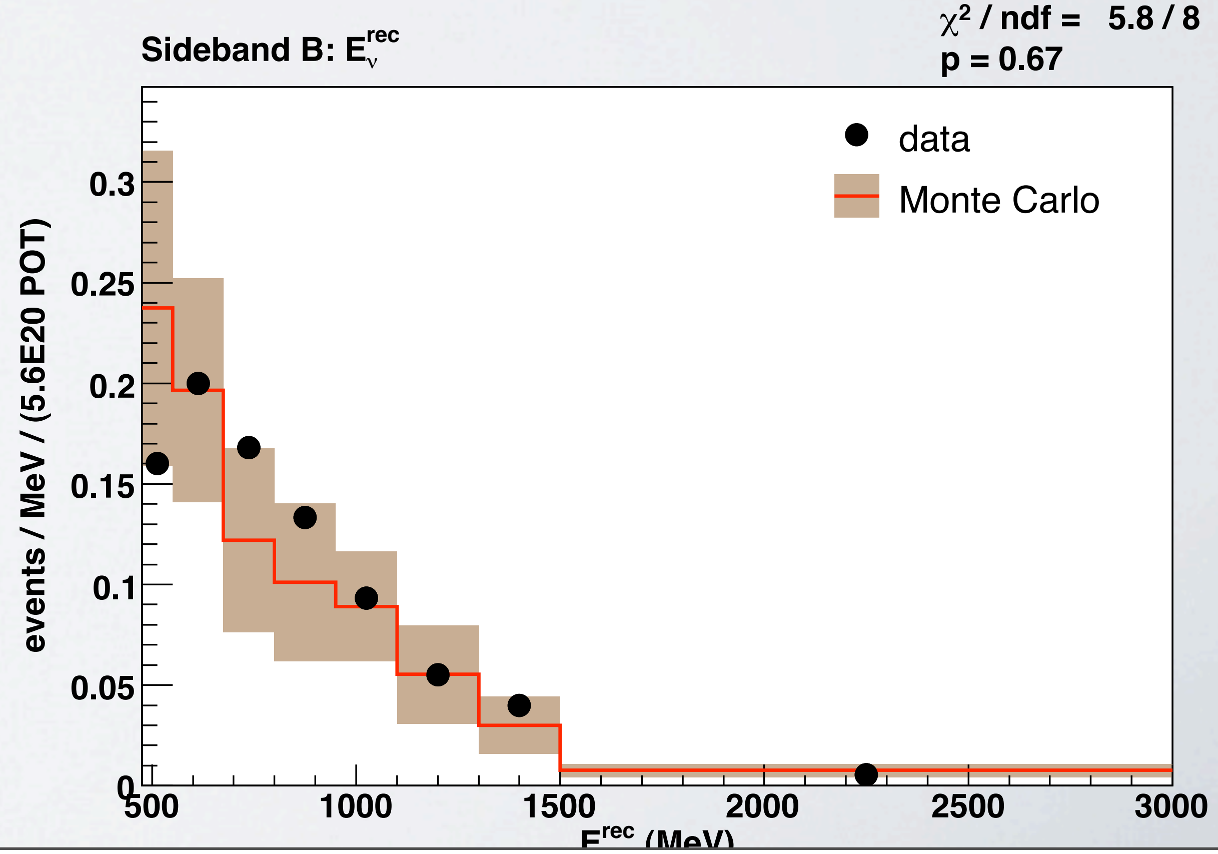




$M_{\gamma\gamma}$ SIDEBAND

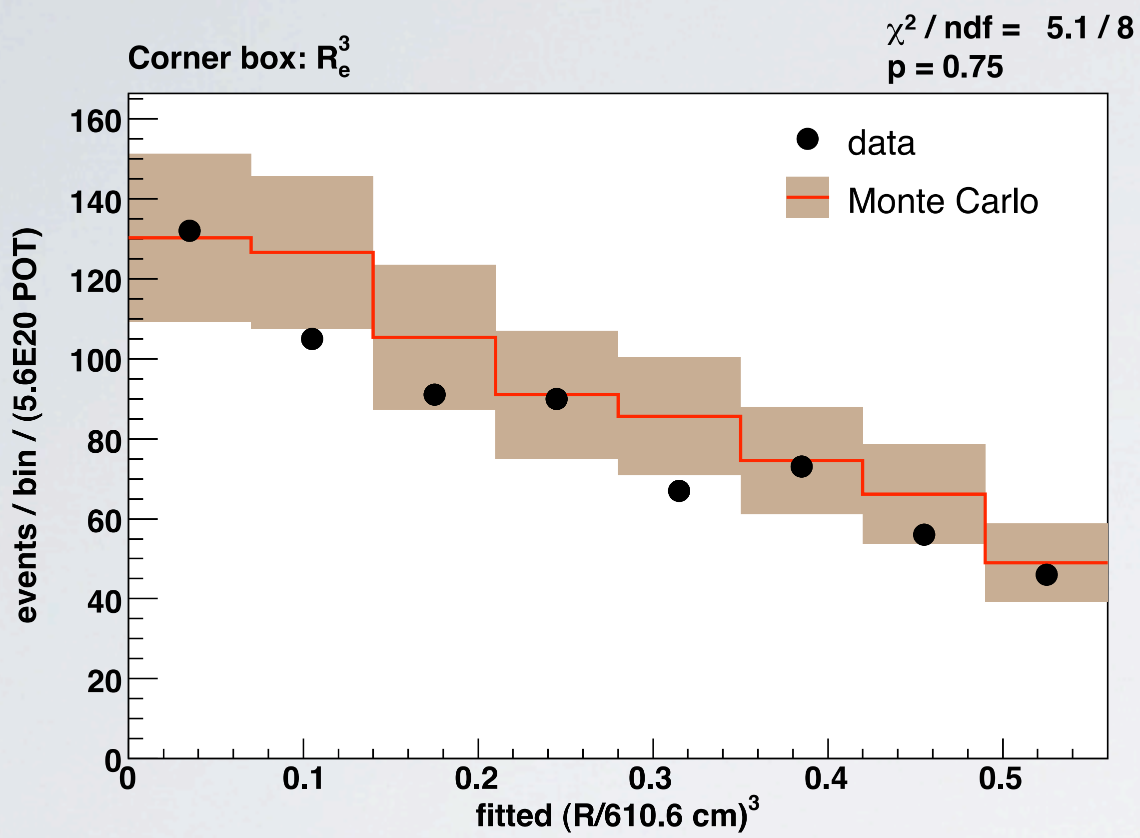


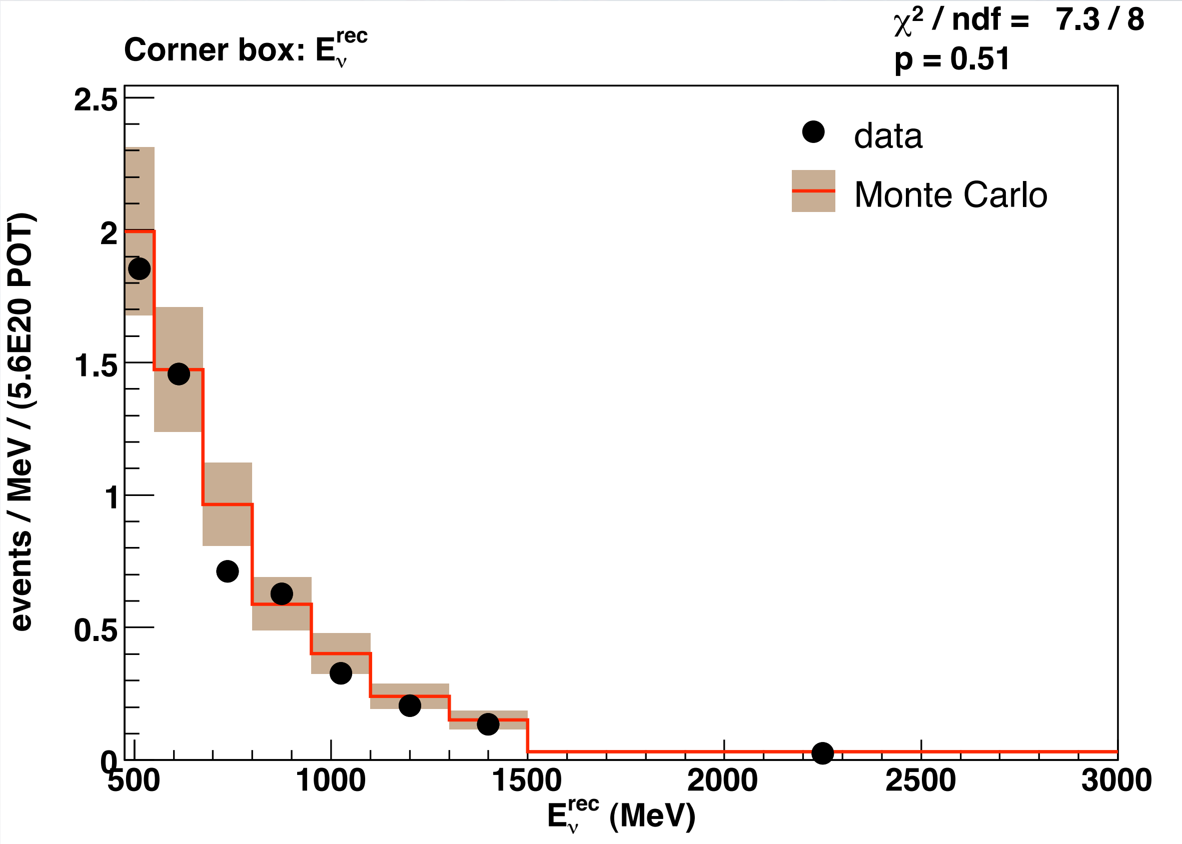




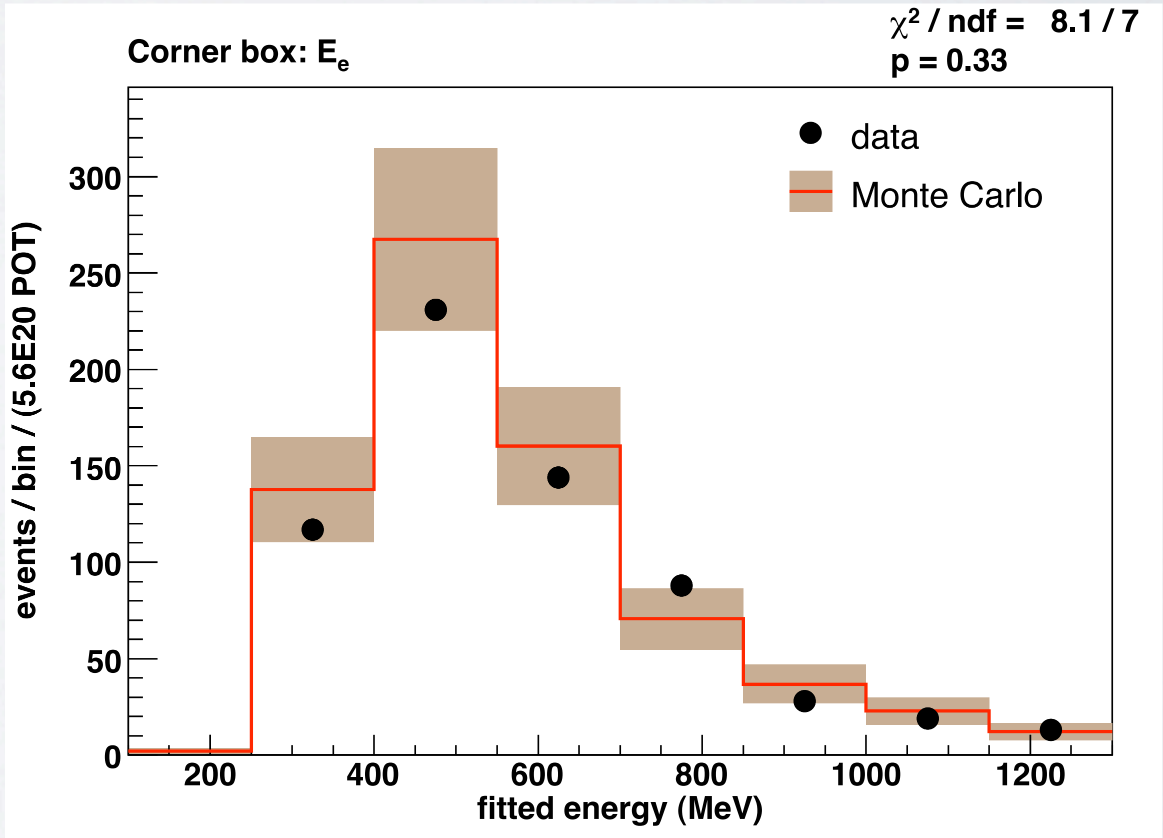
- Looks okay!
  - L(e/π) cut removed for L(e/π) plot

“CLOSE” IN BOTH

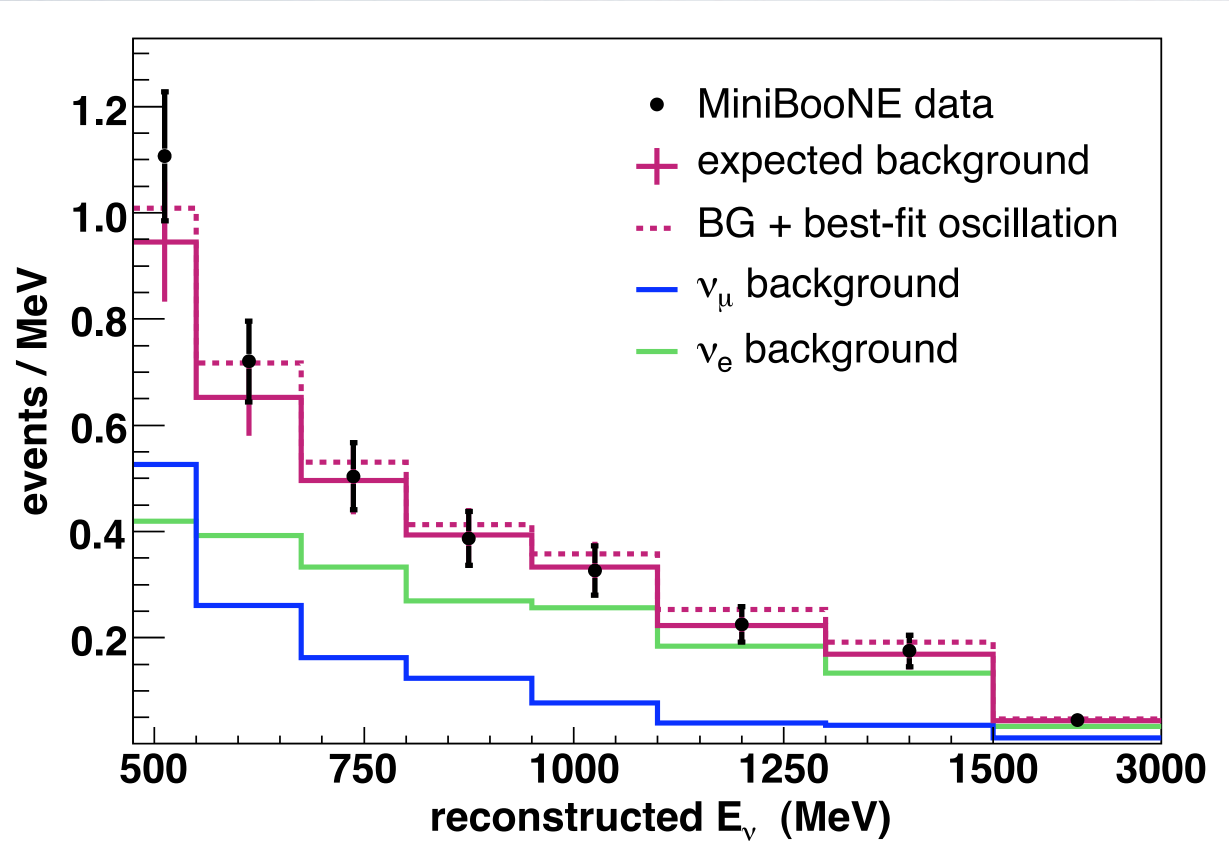


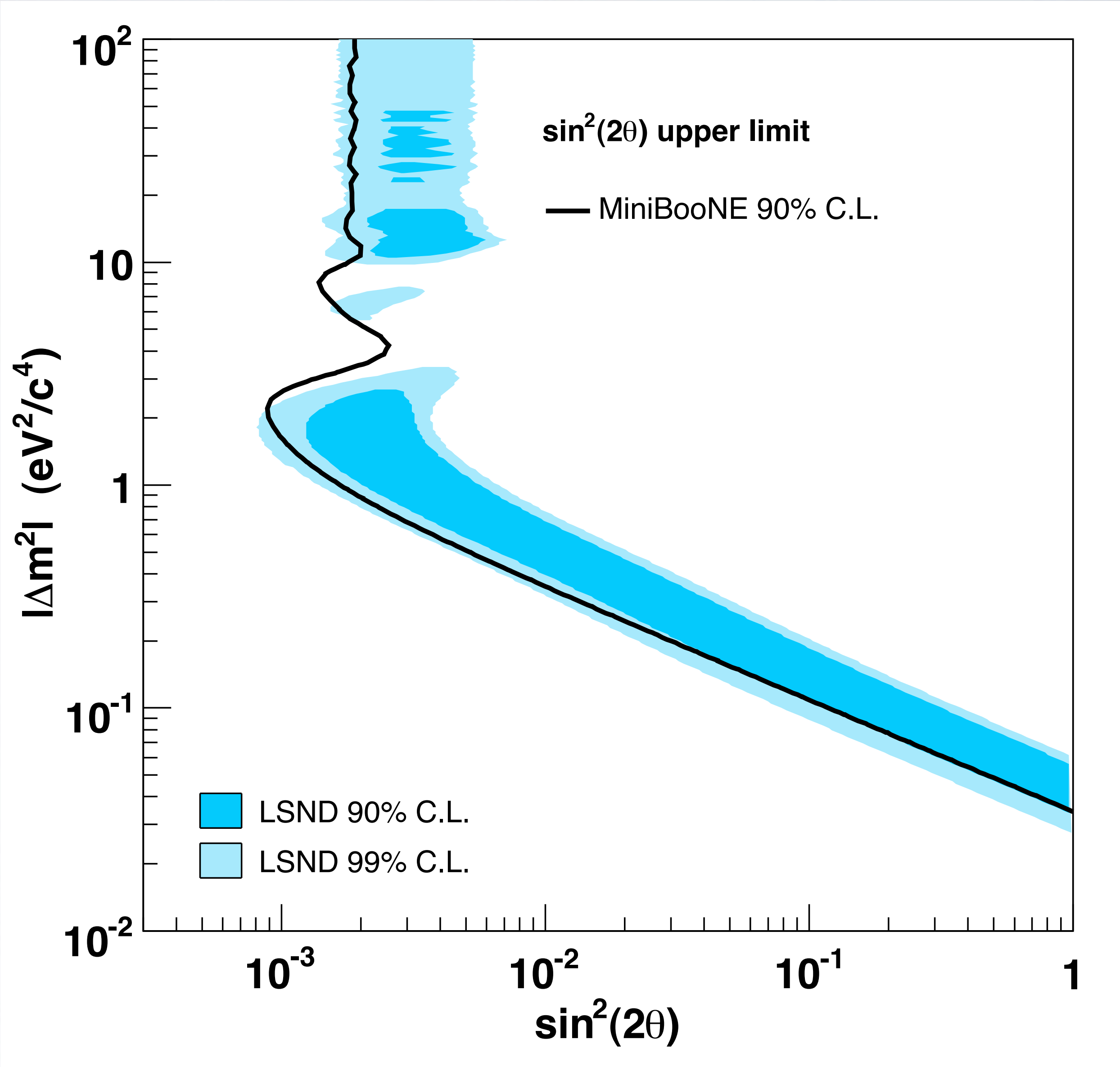


- Looks okay!
- Conclusion:
  - background rejection variables, kinematics agree in control samples “near” the signal region.



RESULTS:





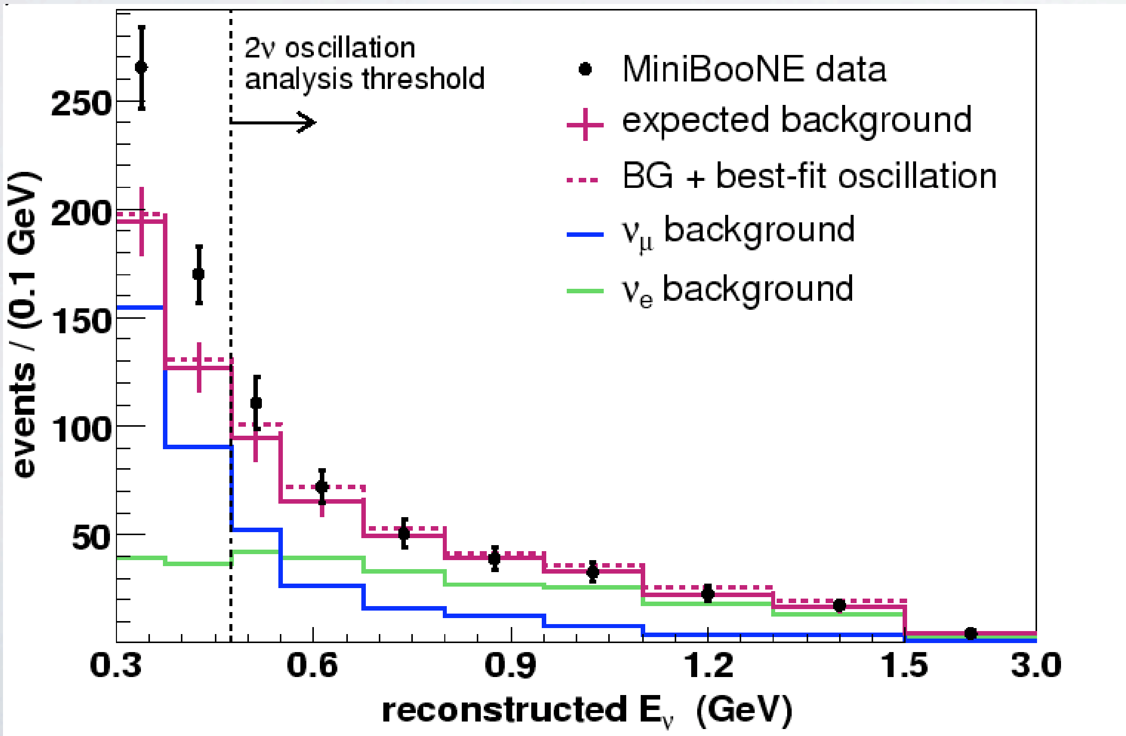
- No significant excess of events above 475 MeV threshold

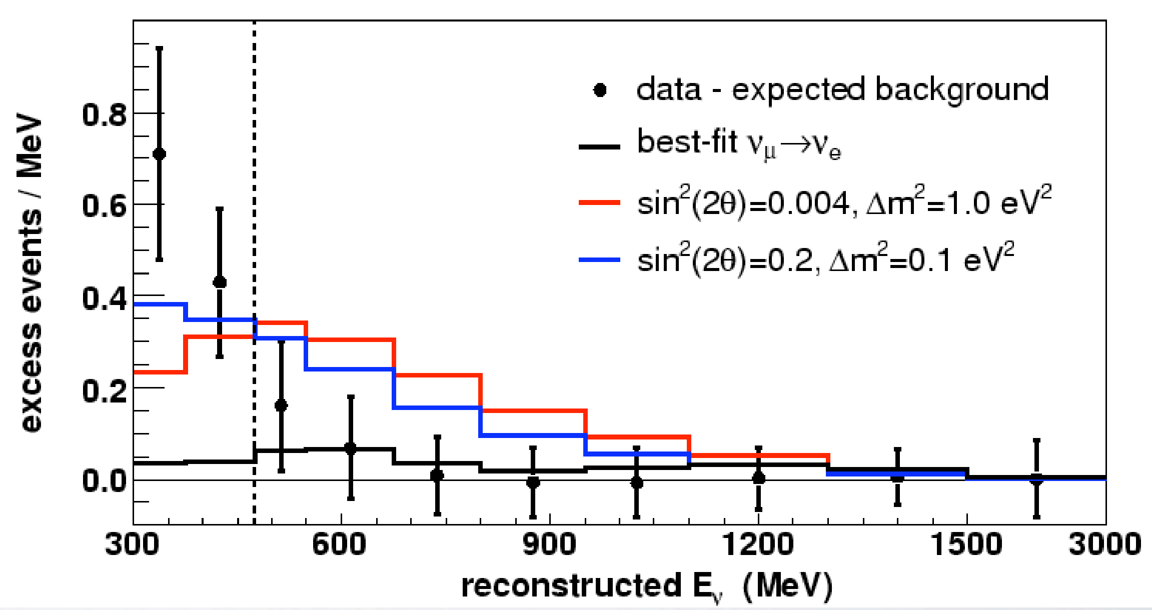
Expect: 358 ± 19(stat) ± 35(sys) Events

Observe: 380 Events

LOW ENERGY EXCESS

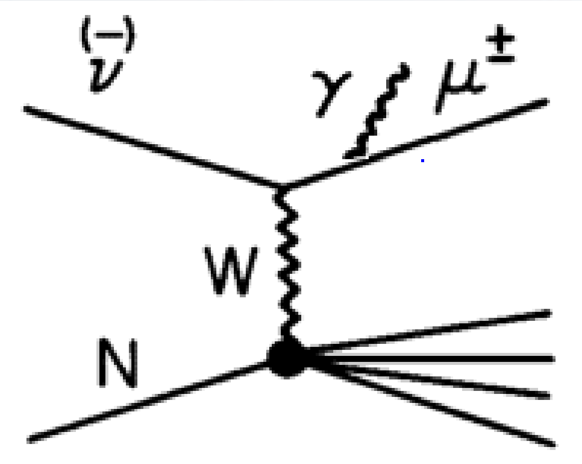
- We knew there was an issue:
  - Prior to "opening the box", a blind χ^2 test on the E_ν^{QE} distribution revealed a bad χ^2.
  - Since the test fits for an oscillation signal, there is a discrepancy that cannot be explained by background, signal, systematic uncertainties
  - After a few studies, we found that we could increase threshold to 475 MeV without compromising the sensitivity
  - The previous results are based on this threshold.



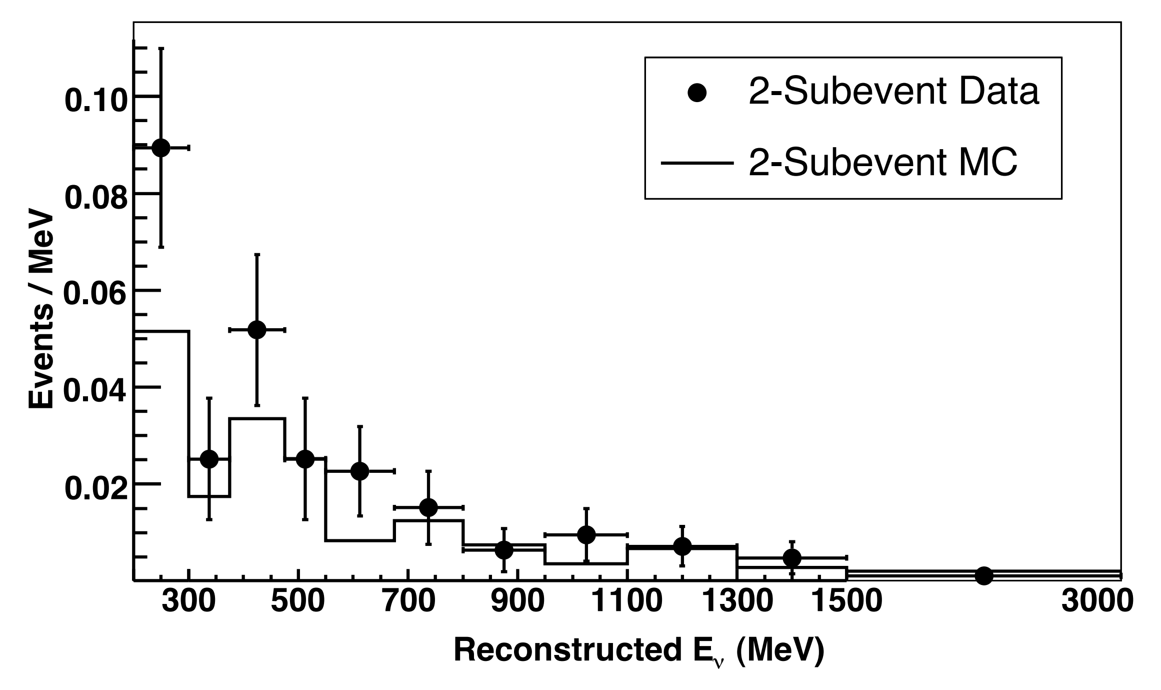


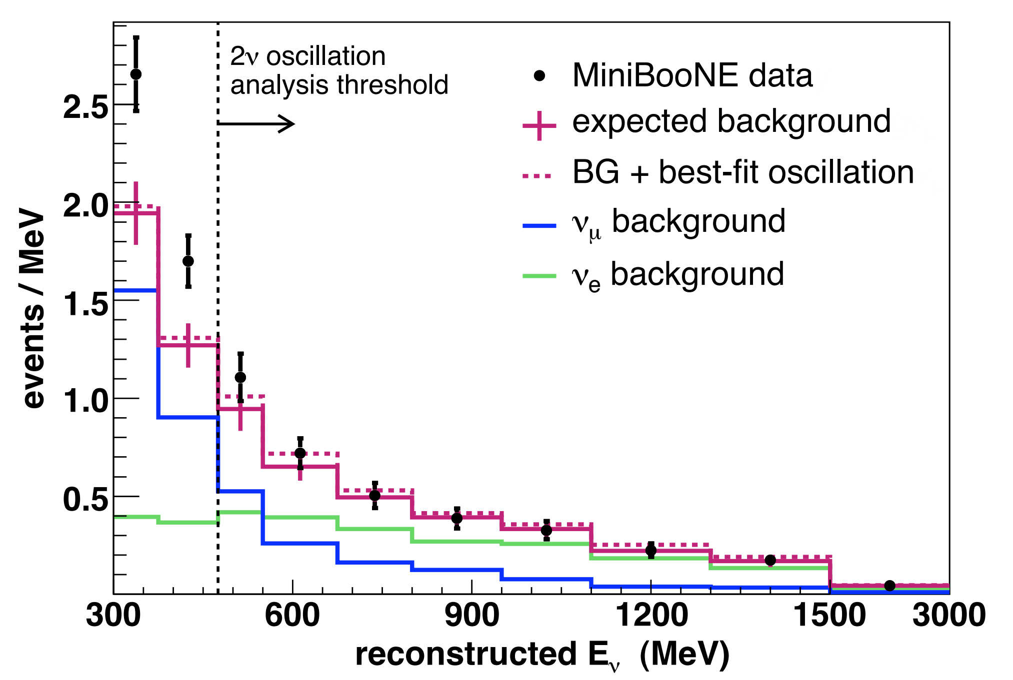
MUON BREMSSTRAHLUNG?

- Suggested by A. Bodek (arxiv: 0709.4004v2)
  - Initial state radiation from muon creates e-like ring
  - New source of signal-like single e-rings not modeled in event generator



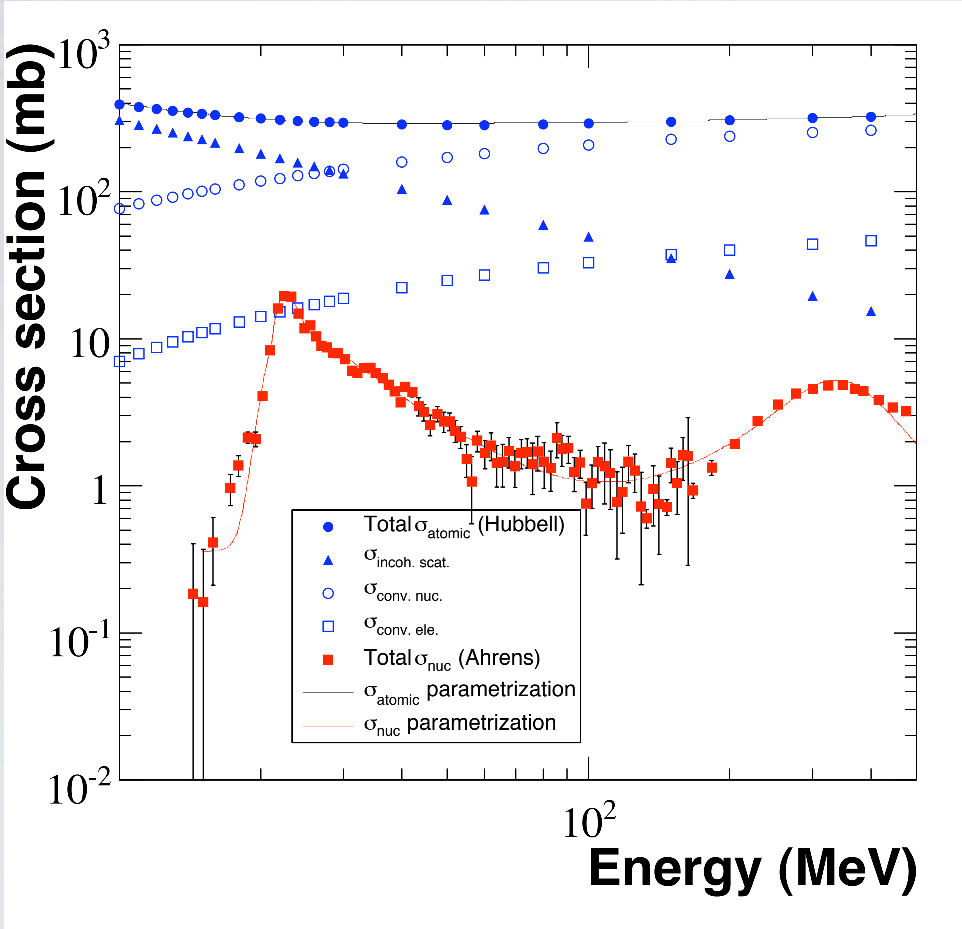
Radiative process is independent of muon decay signature (Michel electron tag)
Tag events independently by requiring Michel electron see how many pass the other cuts





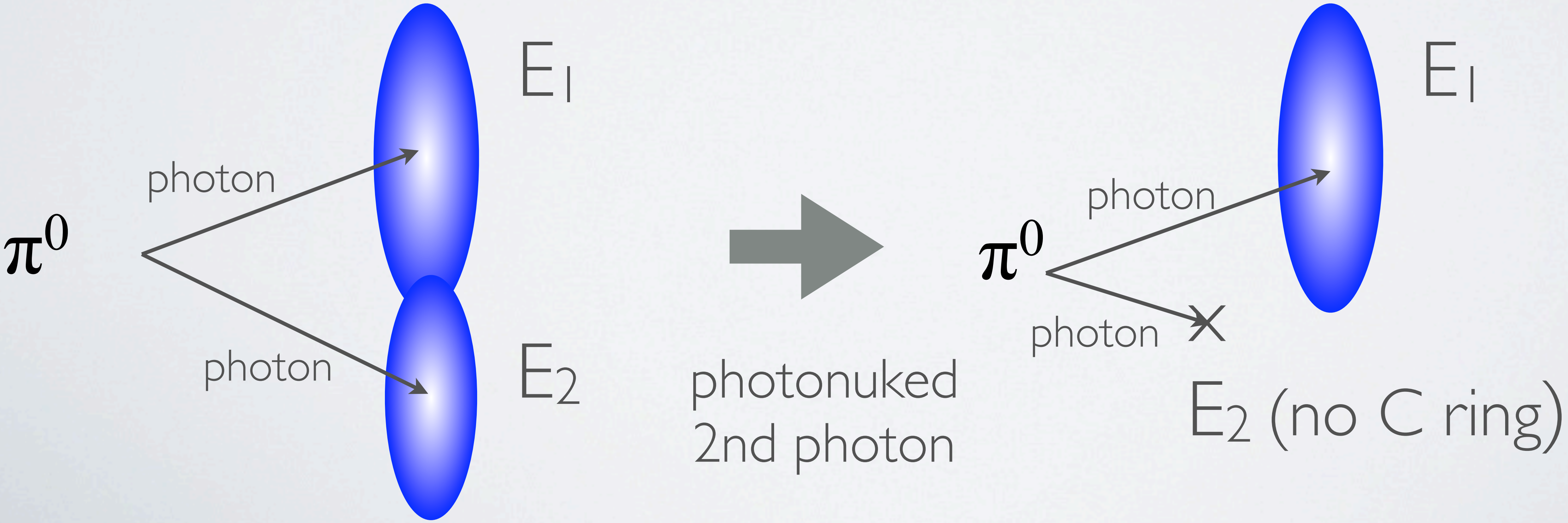
excess but far too small to explain discrepancy

PHOTONUCLEAR



- In addition to “standard” EM processes like pair production, Compton scattering, photons can undergo “photonuclear interactions”
- At low energy (~20-30 MeV), the photon can “shake” the nucleus after absorption
- This eliminates the photon from the event.

Additional source of single e rings



π^0

photon

photon

E_1

E_2

photonuked
2nd photon

π^0

photon

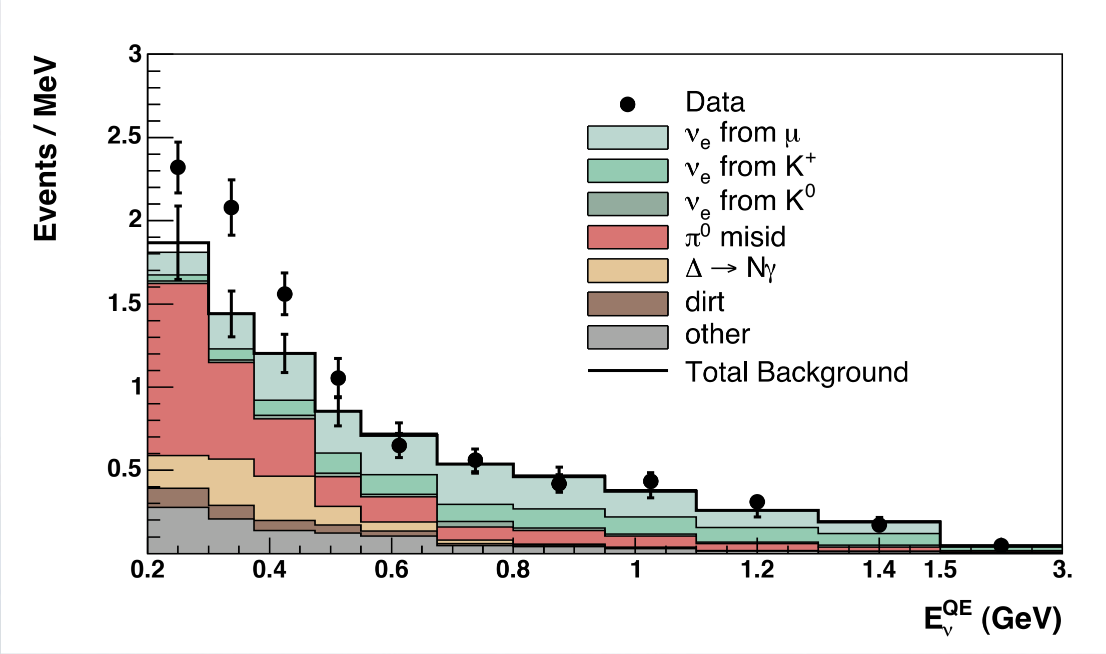
photon

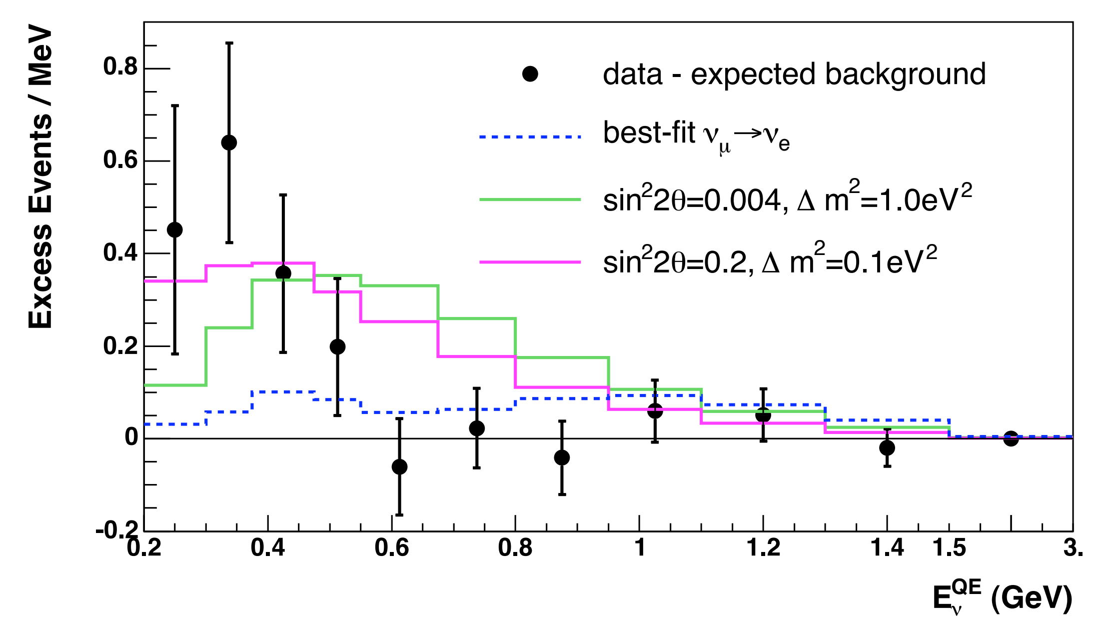
E_1

E_2 (no C ring)

REVISED ESTIMATES

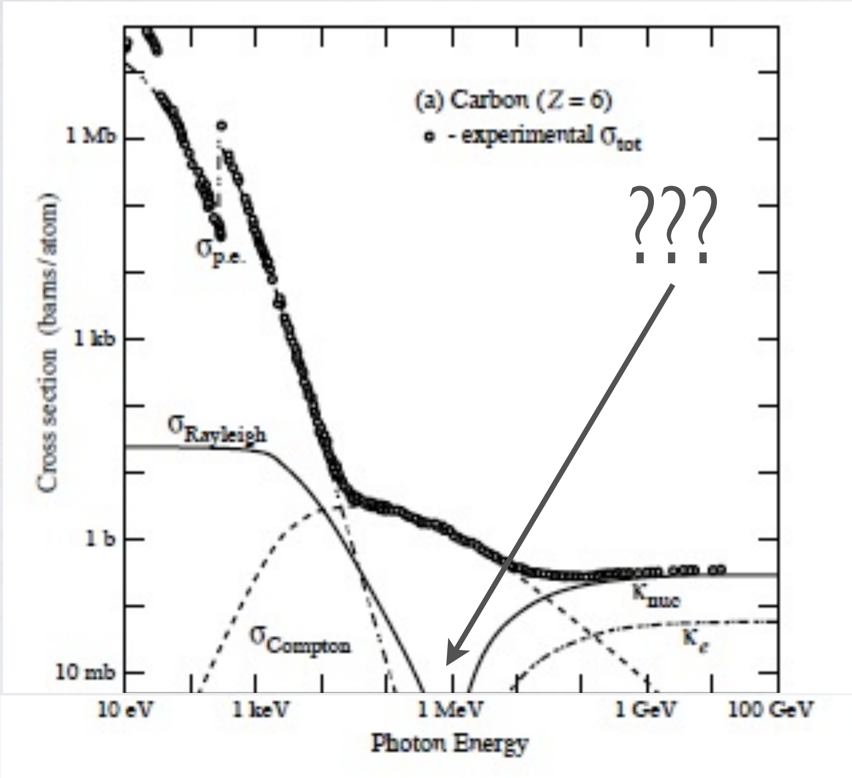
- More data (6.5×10^{20} POT vs. 5.6×10^{20} POT)
  - Better flux estimate and uncertainties
  - additional cuts to reduce “dirt” backgrounds
  - slight changes to π^0 model (also affects $\Delta \rightarrow N+\gamma$)
- New background processes
  - photonuclear processes
    - increases π^0 background by 30% in E_ν=[200,475] MeV region
  - Radiative π^- capture, radiative decays from π-C interactions
    - Not a significant effect

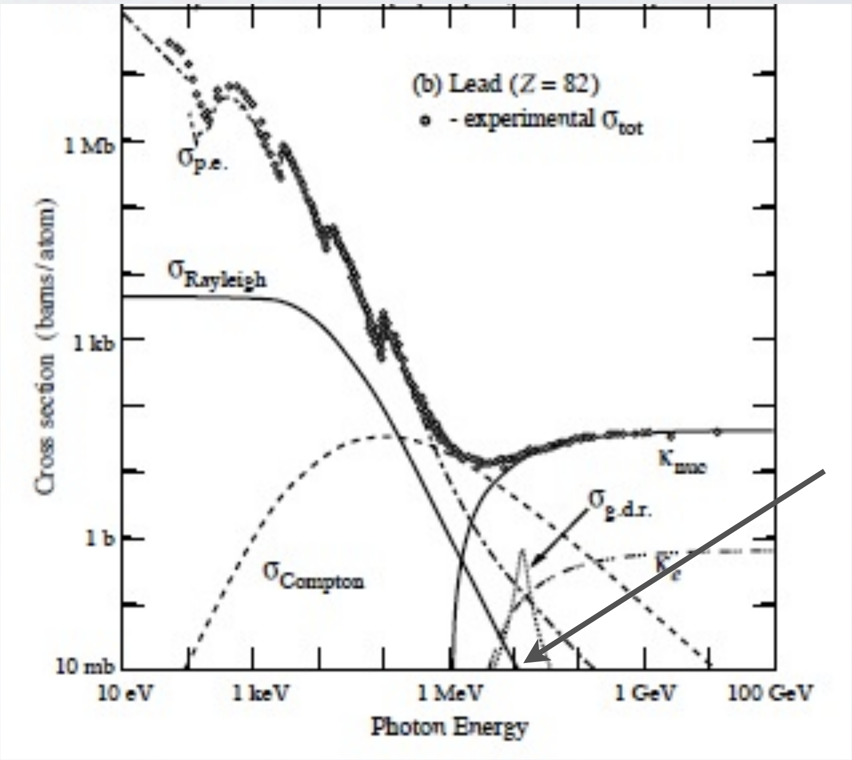




HINDSIGHT:

- Photonuclear interactions turned out to be a significant effect
  - oversight in initial analysis
  - could we have known in advance .....





Here!

- Be prepared to make your own judgement!!!

Different editions of the PDG show/don't show the GDR in C/Pb.

SUMMARY OF LOW ENERGY

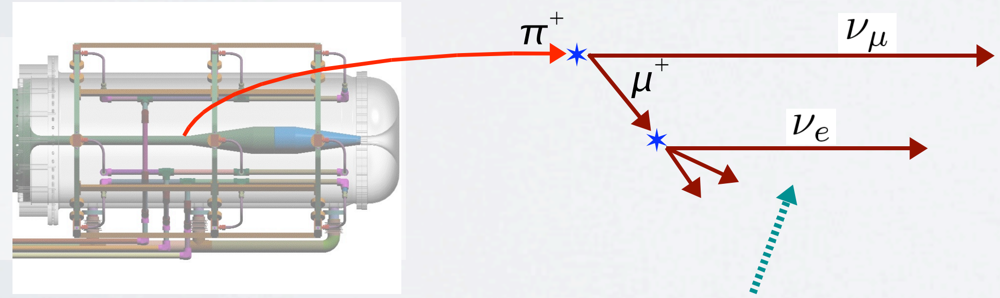
- After revision of background estimates, improved selection, more data, discrepancy persists:
  - Between 200-475 MeV, it is 3 σ above expectation
  - Antineutrino data does not show excess but statistics is low
- Lots of theoretical work has been pursued:
  - SM processes: axial anomaly, more study of
  - New physics ….
- Critical input: is the excess due to ν_e or photons?
  - Unfortunately, MiniBooNE cannot really say
  - New generation of tracking detectors (LAr) may provide some answers.

CONCLUSIONS

- We developed powerful e/μ and e/π separation tools for the MiniBooNE $\nu_\mu \rightarrow \nu_e$ oscillation search
  - Required commensurate effort on the detector MC
  - Cross check performance and distributions on control samples
- Search didn't reveal neutrino oscillations consistent with LSND neutrino oscillations
  - Excess in low energy bins observed (but not later in antineutrinos)
  - Revised background estimates found significant sources of new backgrounds
  - Future experiments may reveal whether the excess is photons or electrons and guide theoretical developments

A measure of the ν_μ E_ν spectrum...

... is a measure of the π^+ spectrum...



... which provides the $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ flux.