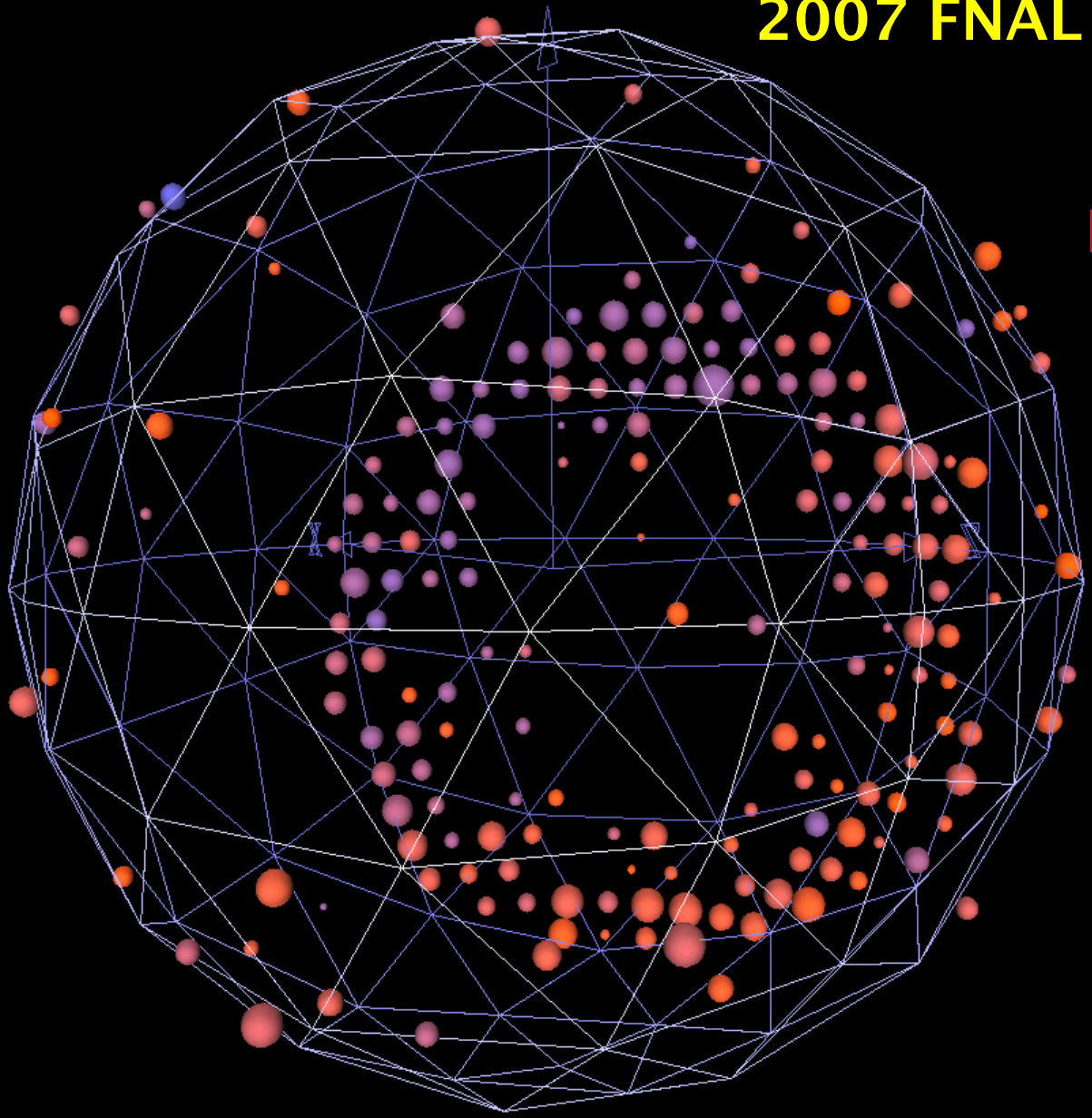
Results from MiniBooNE

2007 FNAL Users' Meeting

Chris Polly
Indiana University

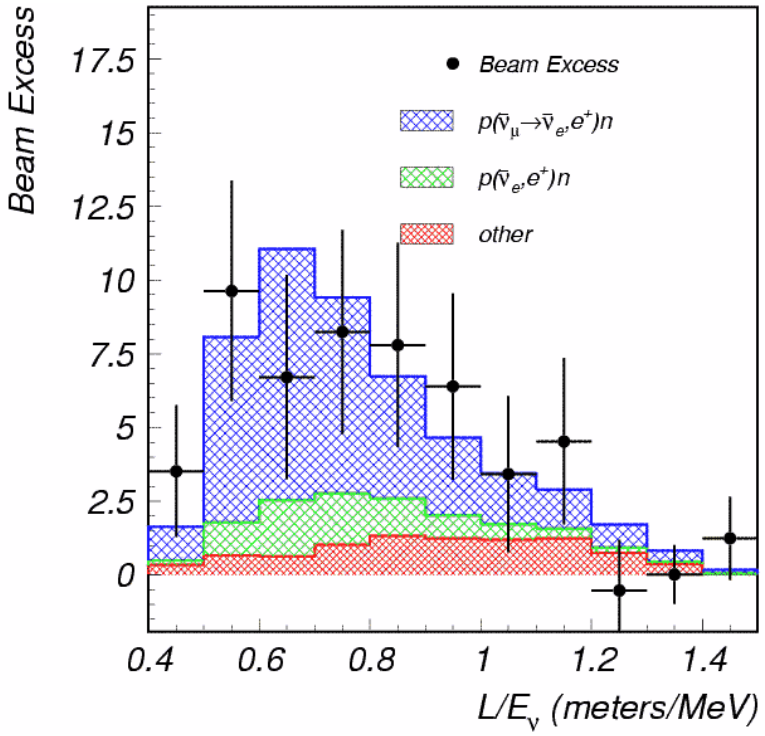


The MiniBooNE Collaboration

A. A. Aguilar-Arevalo, A. O. Bazarko, S. J. Brice, B. C. Brown, L. Bugel, J. Cao, L. Coney, J. M. Conrad, D. C. Cox, A. Curioni, Z. Djurcic, D. A. Finley, B. T. Fleming, R. Ford, F. G. Garcia, G. T. Garvey, J. A. Green, C. Green, T. L. Hart, E. Hawker, R. Imlay, R. A. Johnson, P. Kasper, T. Katori, T. Kobilarcik, I. Kourbanis, S. Koutsoliotas, J. M. Link, Y. Liu, Y. Liu, W. C. Louis, K. B. M. Mahn, W. Marsh, P. S. Martin, G. McGregor, W. Metcalf, P. D. Meyers, F. Mills, G. B. Mills, J. Monroe, C. D. Moore, R. H. Nelson, P. Nienaber, S. Ouedraogo, R. B. Patterson, D. Perevalov, C. C. Polly, E. Prebys, J. L. Raaf, H. Ray, B. P. Roe, A. D. Russell, V. Sandberg, R. Schirato, D. Schmitz, M. H. Shaevitz, F. C. Shoemaker, D. Smith, M. Sorel, P. Spentzouris, I. Stancu, R. J. Stefanski, M. Sung, H. A. Tanaka, R. Tayloe, M. Tzanov, M. O. Wascko, R. Van de Water, D. H. White, M. J. Wilking, H. J. Yang, G. P. Zeller, E. D. Zimmerman

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
Fermilab
Indiana University
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

MiniBooNE's Motivation: The LSND signal



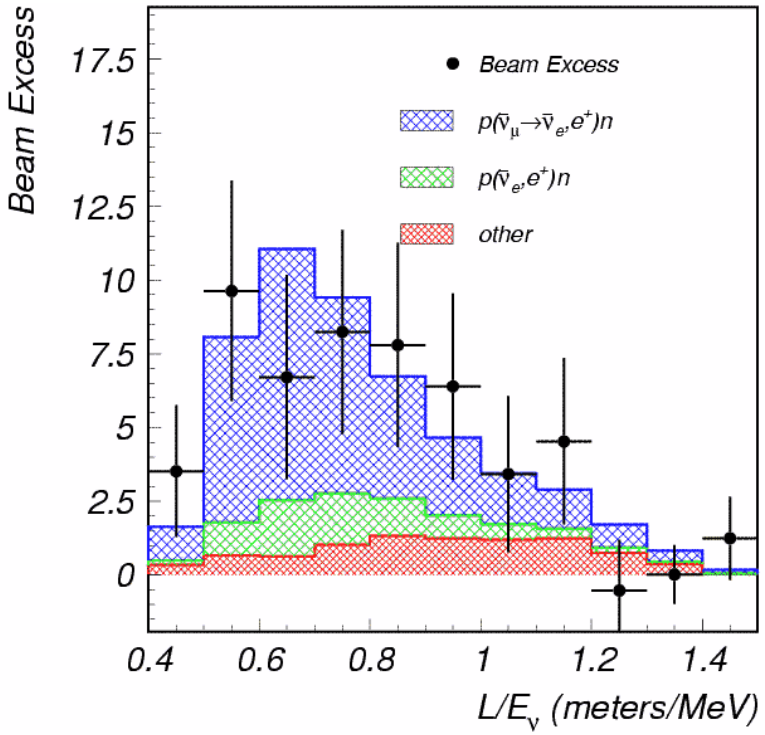
❋ See Gina Rameika's talk for a bigger picture

- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2ν mixing hypothesis:

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

MiniBooNE's Motivation: The LSND signal

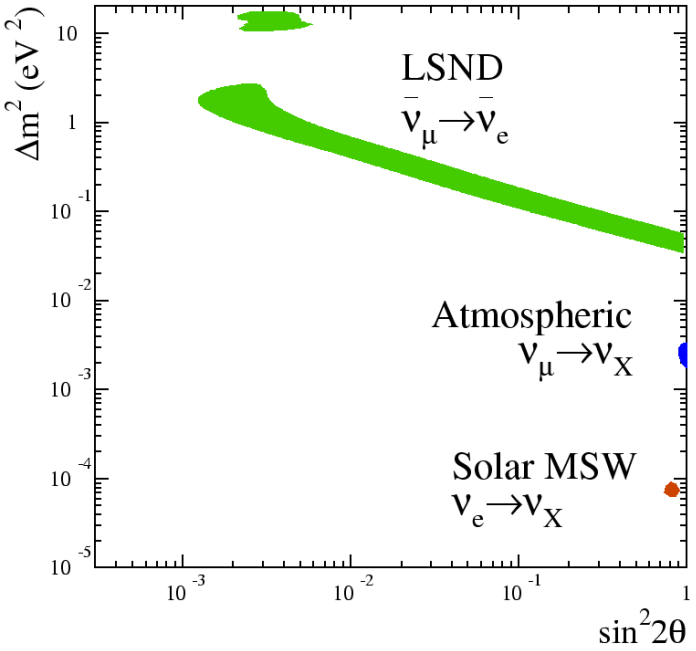
* For ν overview refer to Gina Rameika's talk from yesterday



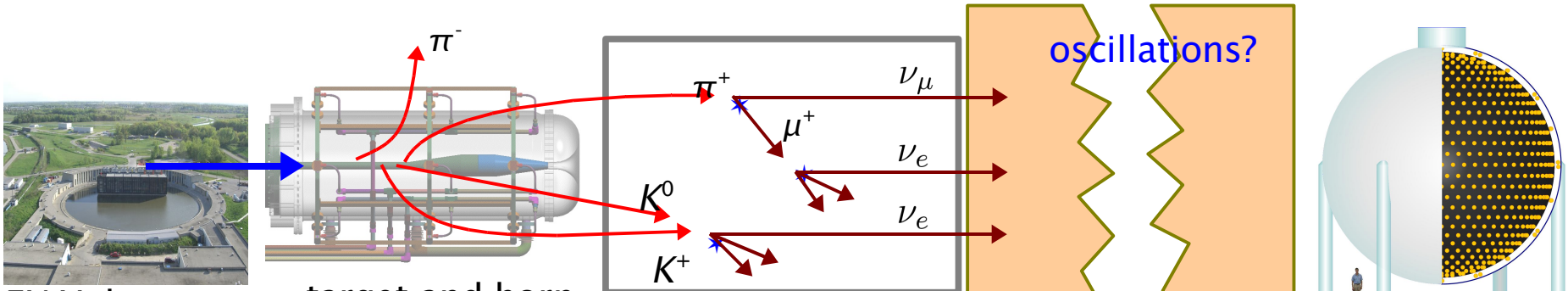
- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2ν mixing hypothesis:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

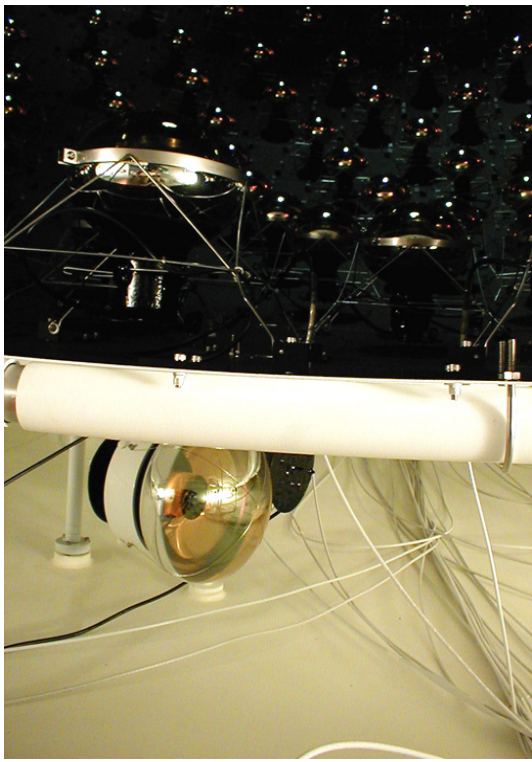
- LSND $\Delta m^2 \sim 1\ eV^2$ impossible to reconcile with other two measured mixings in 3ν world
- Requires extraordinary physics!
  - Sterile neutrinos *hep-ph/0305255*
  - Neutrino decay *hep-ph/0602083*
  - Lorentz/CPT violation *PRD(2006)105009*
  - Extra dimensions h*ep-ph/0504096*
- Unlike atmos and solar...LSND unconfirmed



The MiniBooNE design strategy

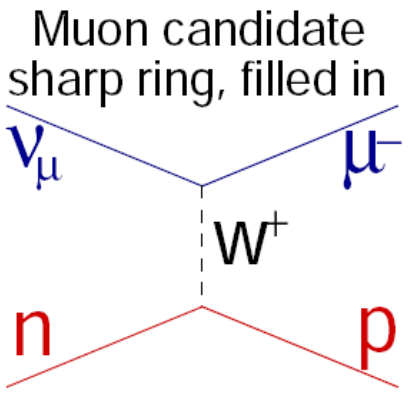


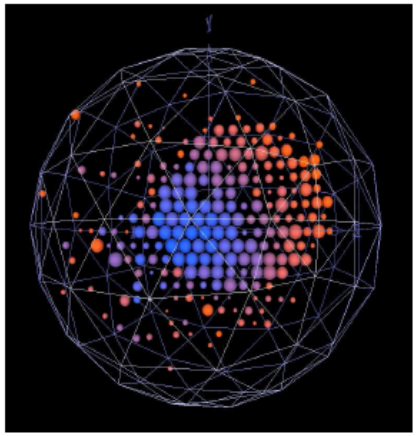
- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Requires running ν (not anti-ν) to get flux
- Pions decay to ν with E_ν in the 0.8 GeV range
- Place detector to preserve LSND L/E:
  - MiniBooNE: (0.5 km) / (0.8 GeV)
  - LSND: (0.03 km) / (0.05 GeV)
- Detect ν interations in 800T pure mineral oil detector
  - 1280 8" PMTs provide 10% coverage of fiducial volume
  - 240 8" PMTs provide active veto in outer radial shell

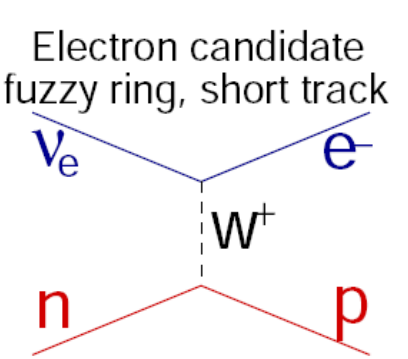


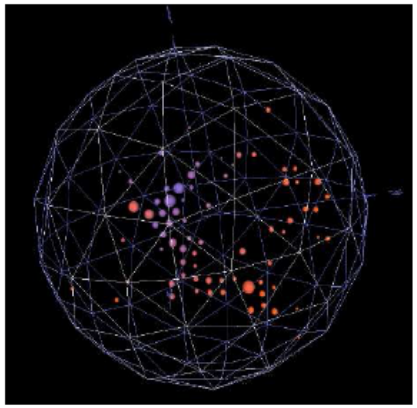
Key points about the signal

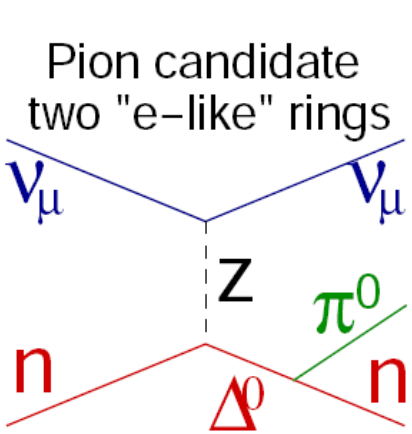
- LSND oscillation probability is < 0.3%
- MiniBooNE has to distinguish ~200 ν_e CCQE interactions in a sea of ~200,000 ν_μ CCQE
- Intrinsic ν_e background
  - Actual ν_e produced in the beamline from muons and kaons
  - Irreducible at the event level
  - E spectrum differs from signal
- Mis-identified events
  - ν_μ CCQE easy to identify, i.e. 2 "subevents" instead of 1. However, lots of them.
  - Neutral-current (NC) π^0 and radiative Δ are rarer, but harder to separate
  - Can be reduced with better PID
- MiniBooNE is a ratio measurement with the ν_μ constraining flux X cross-section

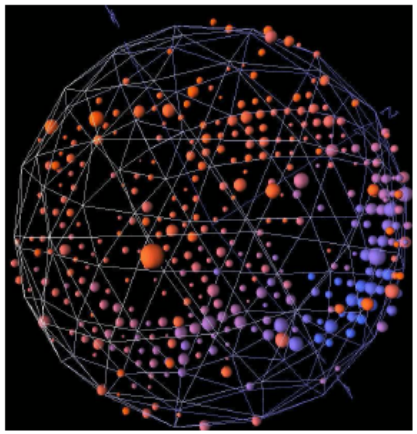




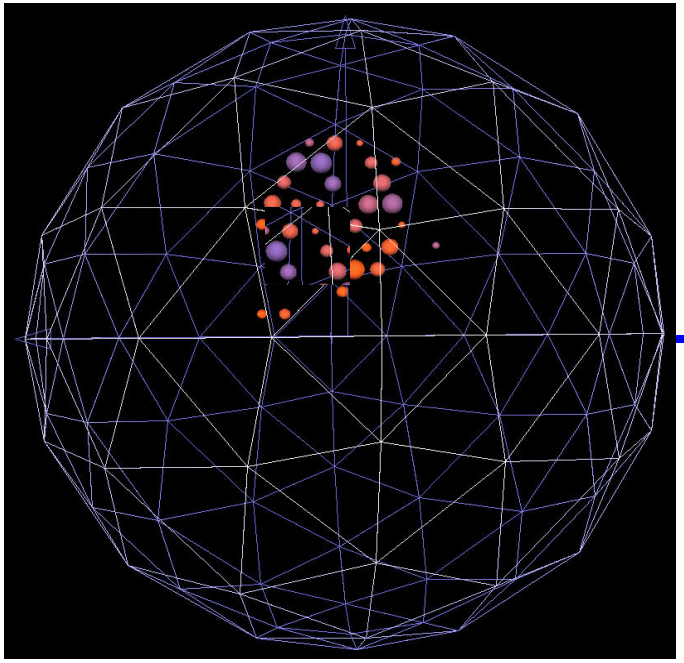


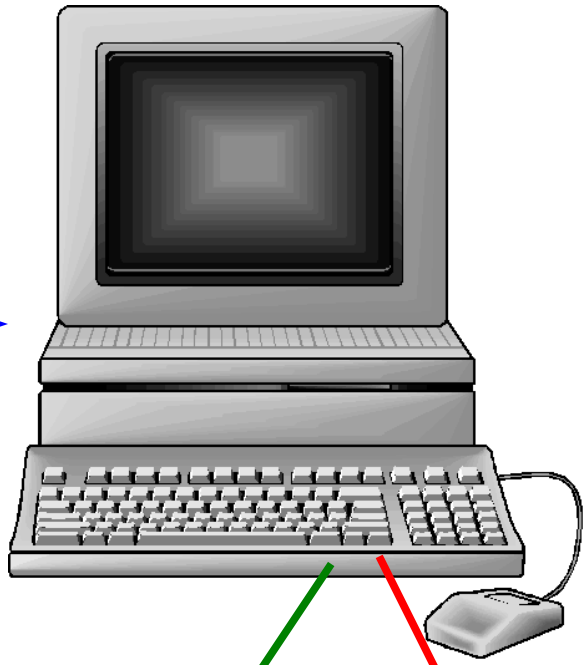


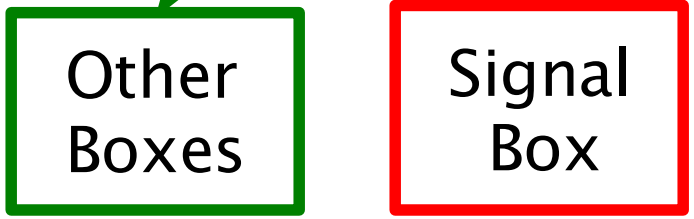




Blind analysis in MiniBooNE

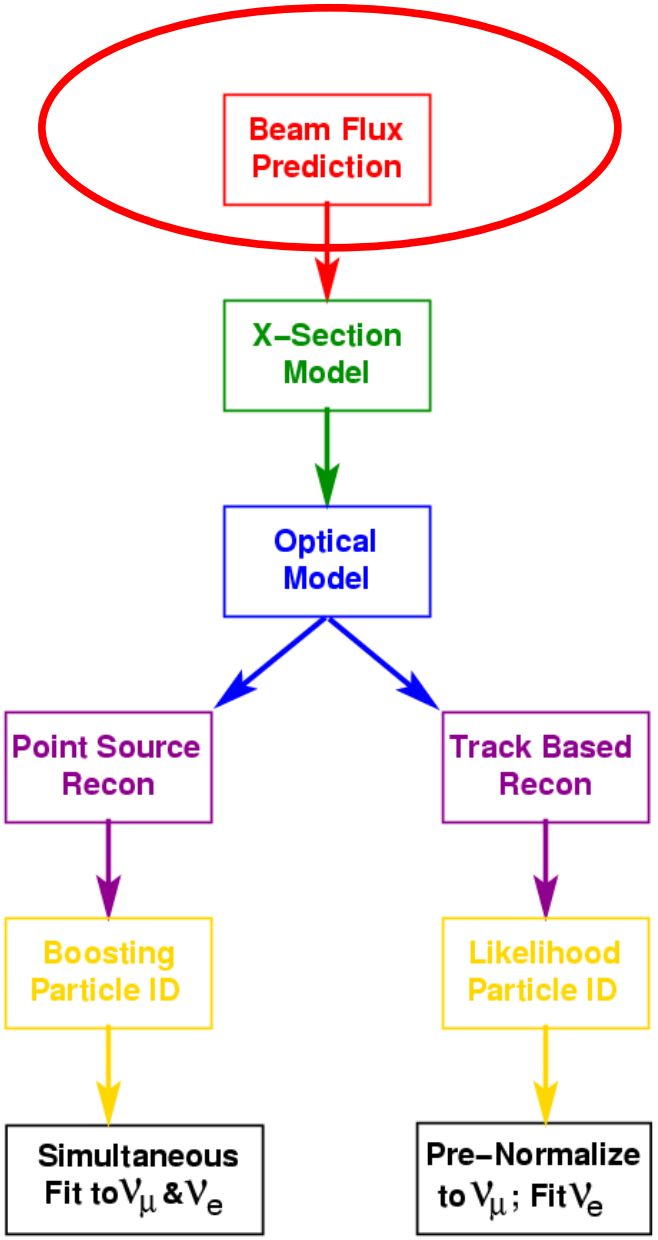






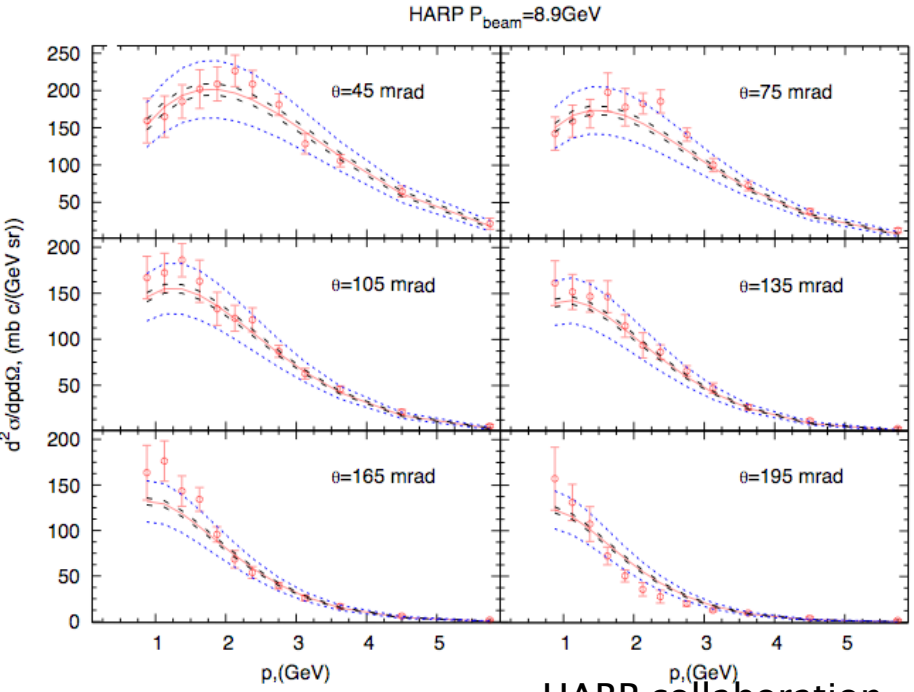
- The MiniBooNE signal is small but relatively easy to isolate
- As data comes in it is classified into 'boxes'
- For boxes to be opened to analysis they must be shown to have a signal < 1σ
- In the end, 99% of the data were available prior to unblinding...necessary to understand errors

Flux Prediction



Meson production at the target

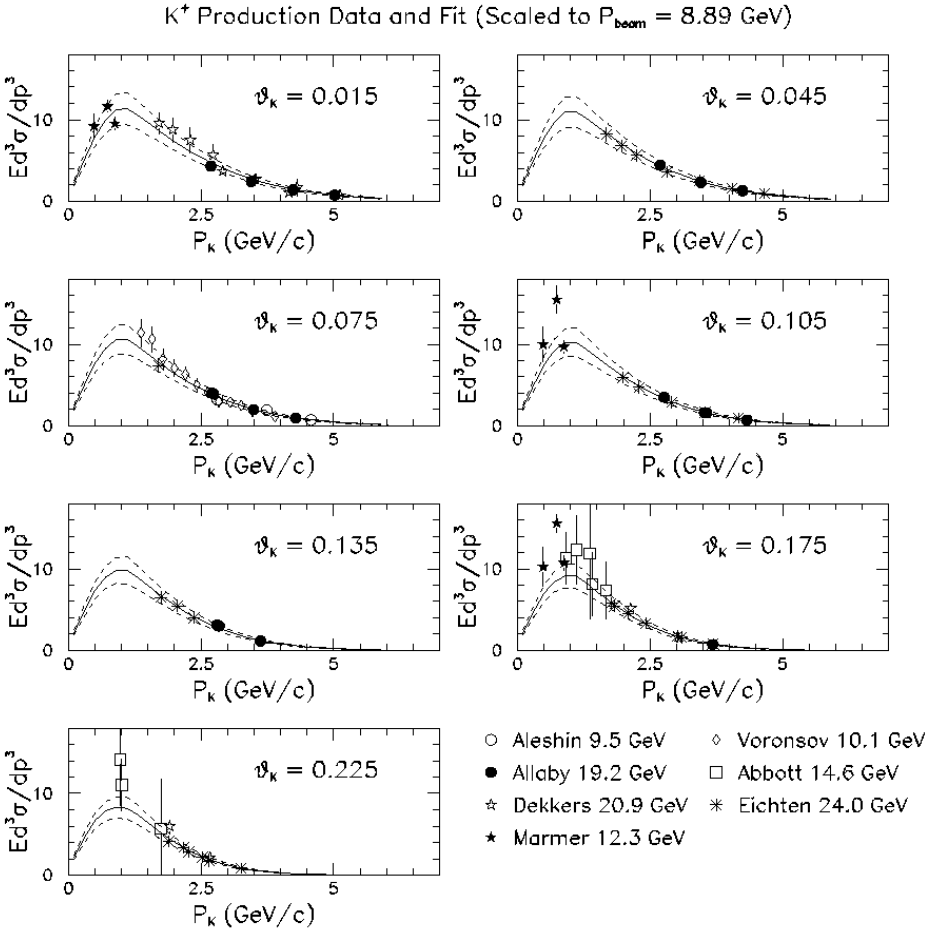
Pions:



HARP collaboration, hep-ex/0702024

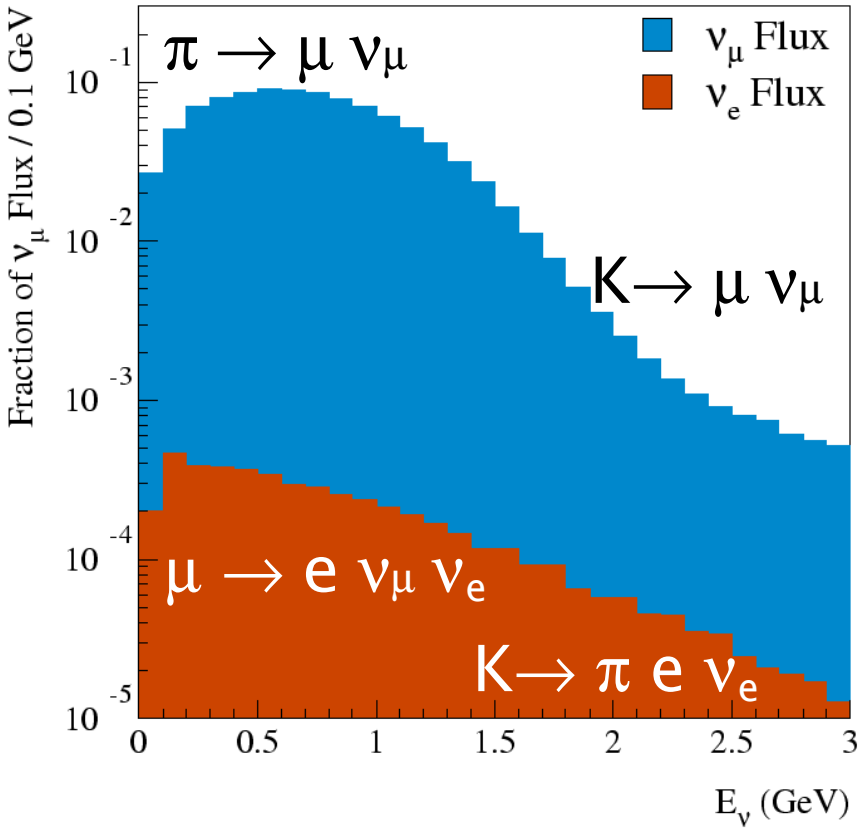
- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% λ Beryllium target
- Data were fit to Sanford-Wang parameterization

Kaons:



- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

Final neutrino flux estimation



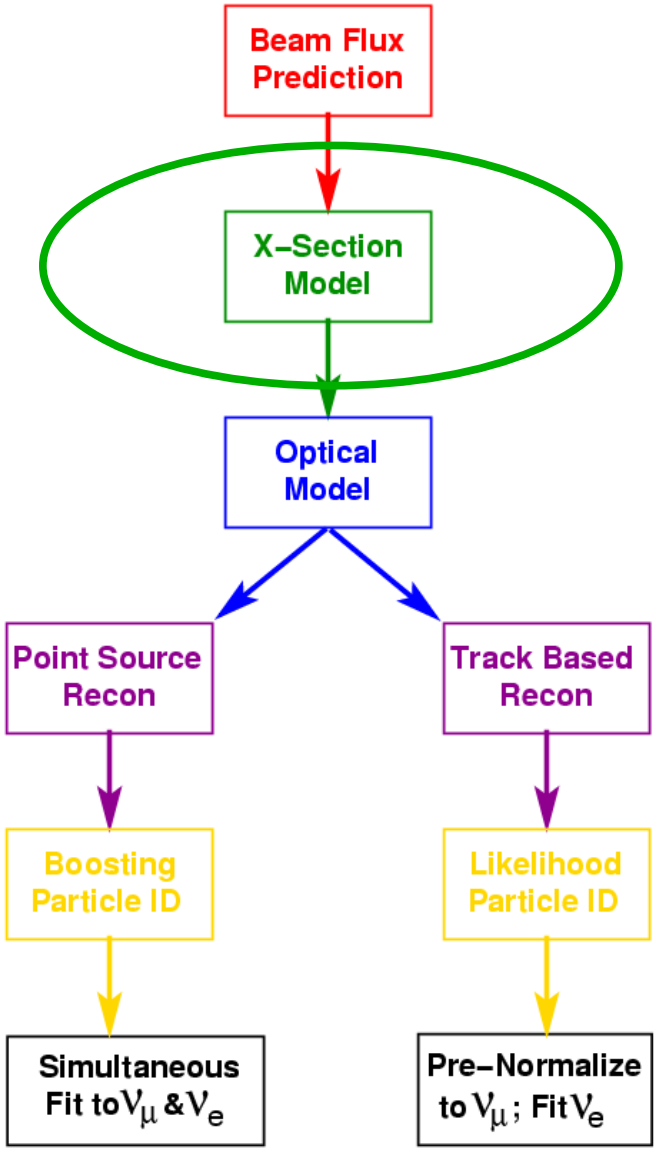
$\nu_e / \nu_\mu = 0.5\%$

"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

$\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\ \nu_e$	(52%)
$K^+ \rightarrow \pi^0\ e^+\ \nu_e$	(29%)
$K^0 \rightarrow \pi\ e\ \nu_e$	(14%)
Other	(5%)

Antineutrino content: 6%

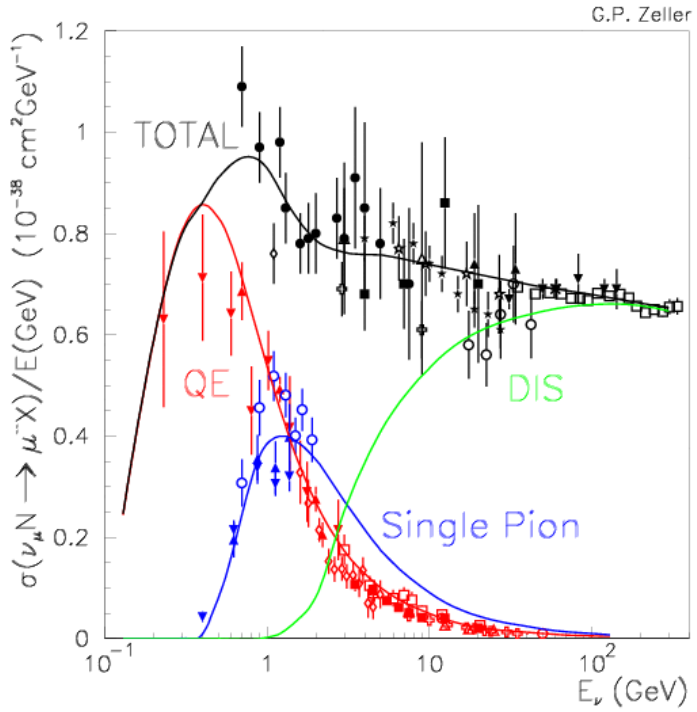
X-Section Model

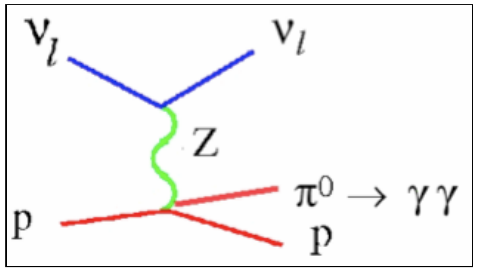


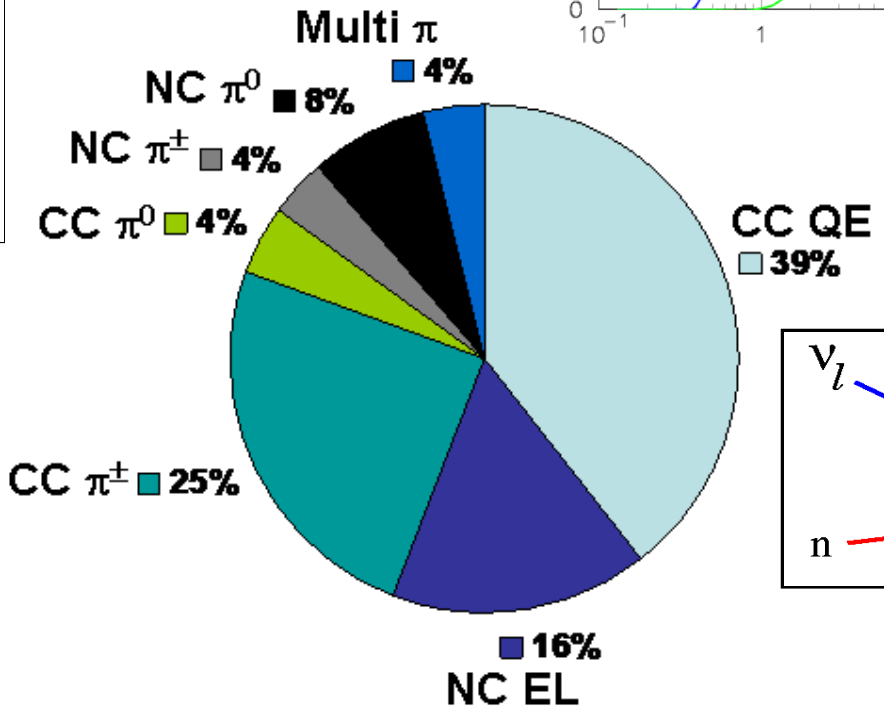
Nuance Monte Carlo

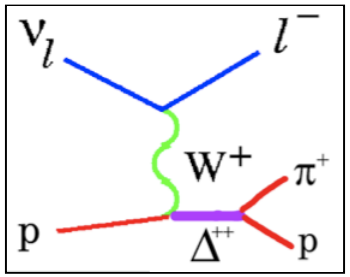
D. Casper, NPS, 112 (2002) 161

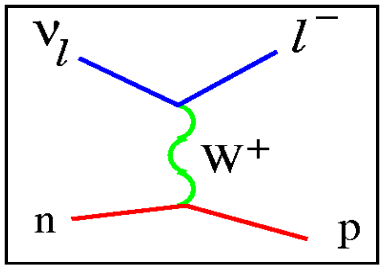
- Used to predict rate of specific ν interactions
- World data for various channels shown at right
- Tuned on external and internal data
- Expected interaction rate in MiniBooNE (before cuts) shown below



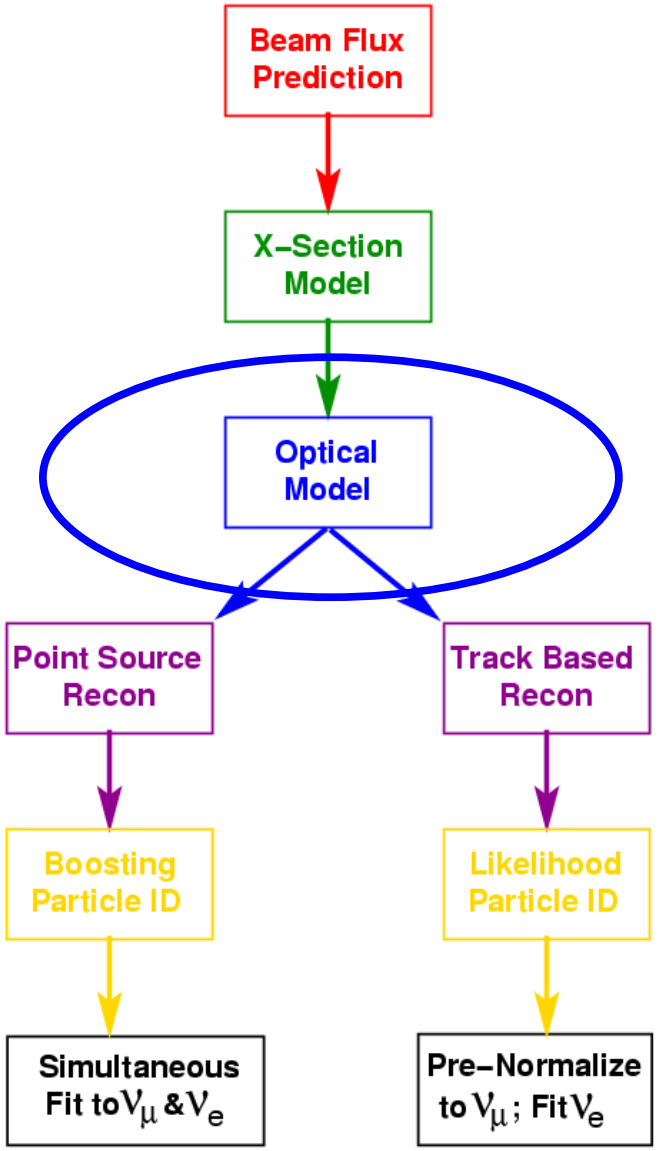




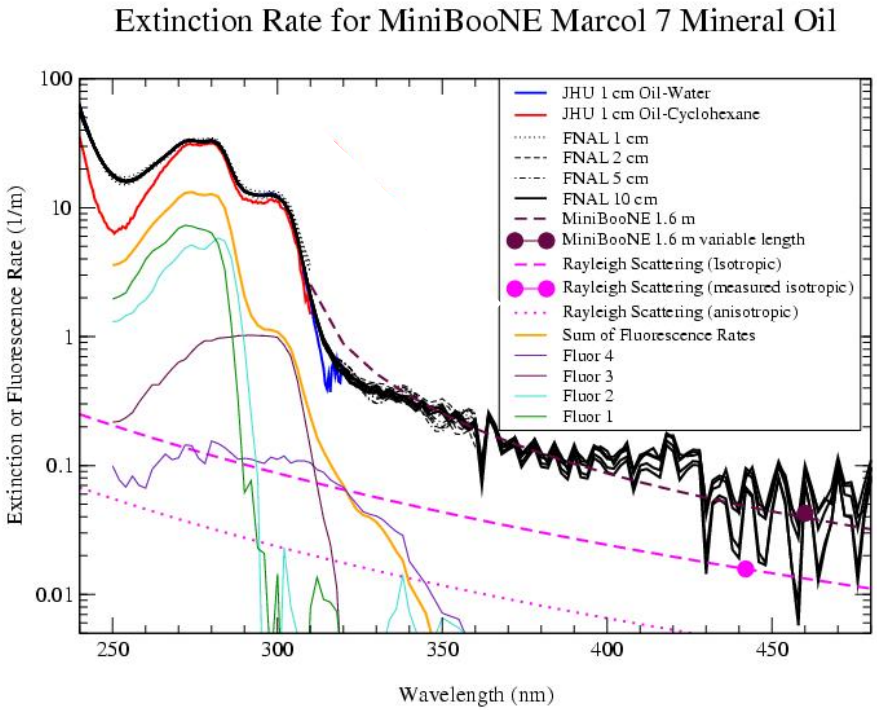


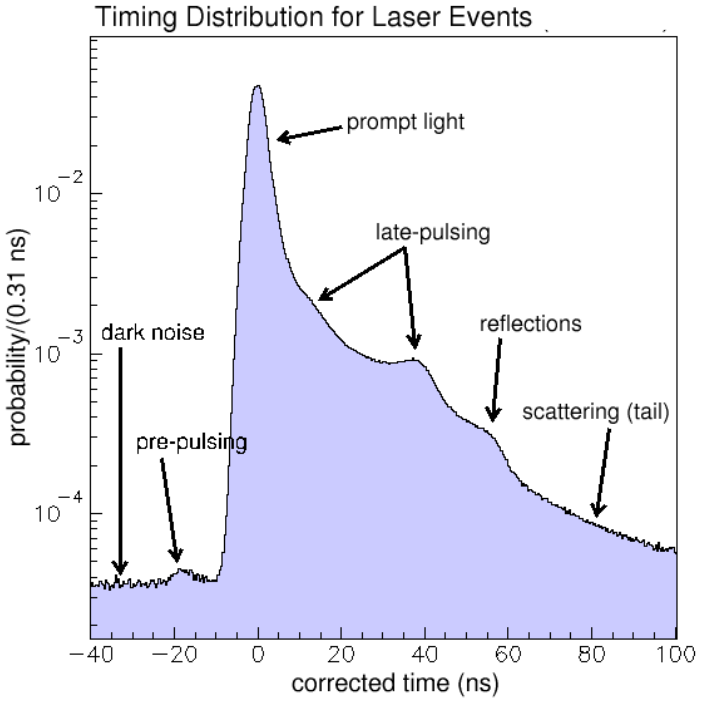


Optical Model



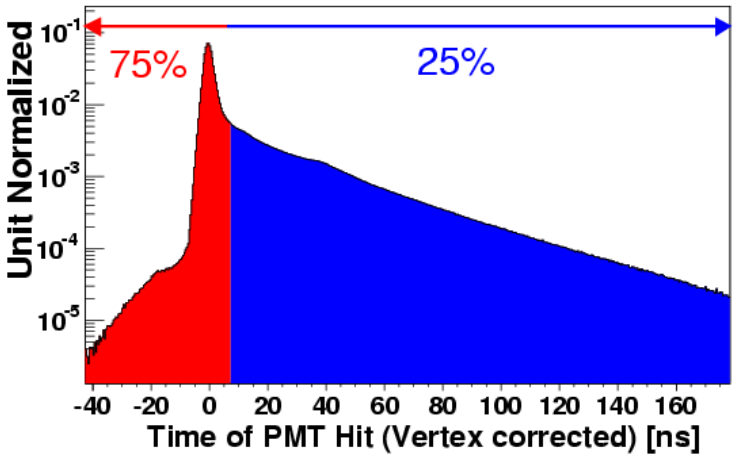
Light propagation in the detector



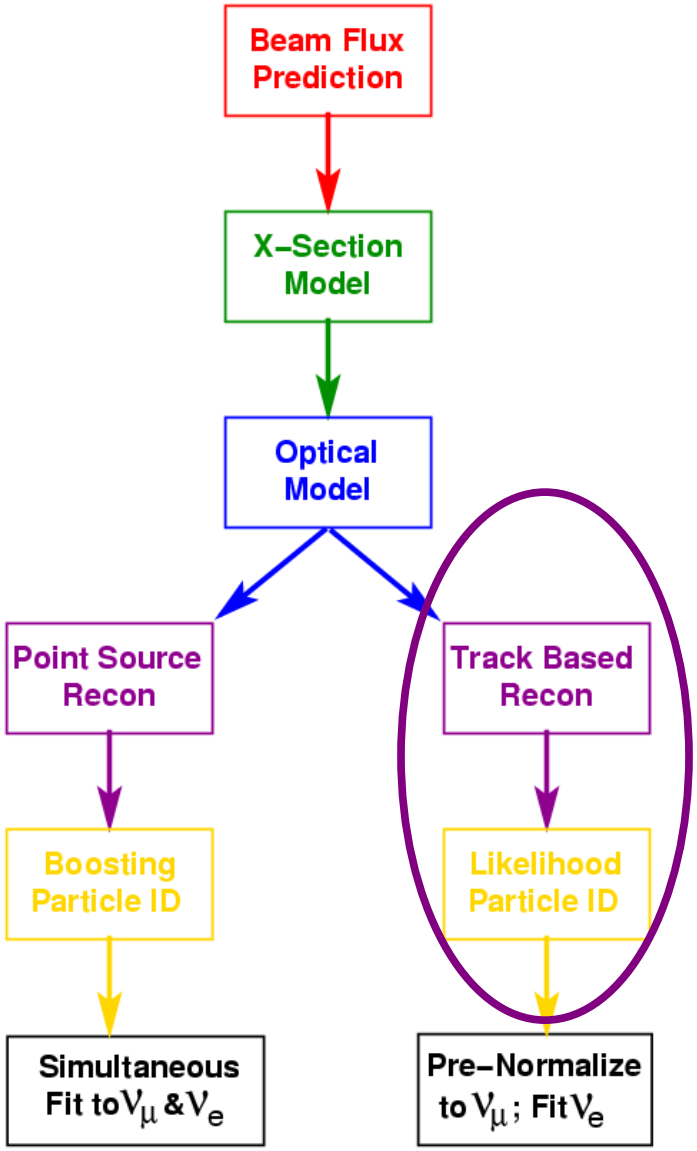


- Optical model is very complex
  - Cerenkov, scintillation, fluorescence
  - PMT Q/t response
  - Scattering, reflection, prepulses
- Overall, about 40 parameters

Michel electron t distribution



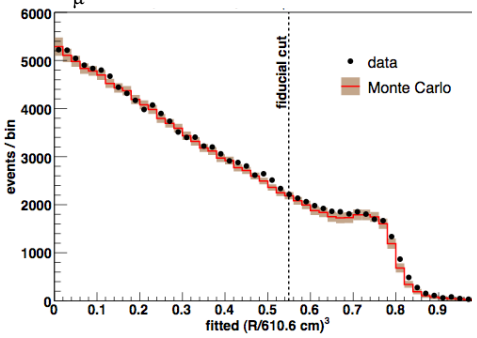
Track-Based Likelihood (TBL) Reconstruction and Particle ID

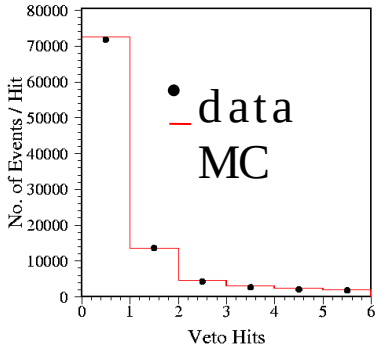


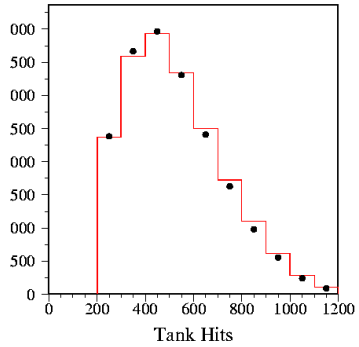
TBL Analysis: Separating e from μ

- Analysis pre-cuts
  - Only 1 subevent
  - Veto hits < 6
  - Tank hits > 200
  - Radius < 500 cm

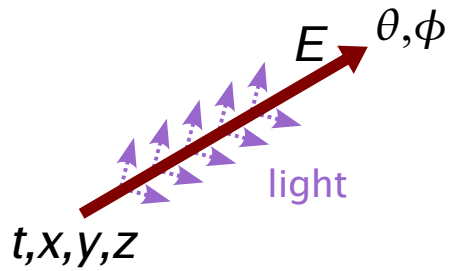
ν_μ CCQE events (2 subevent)

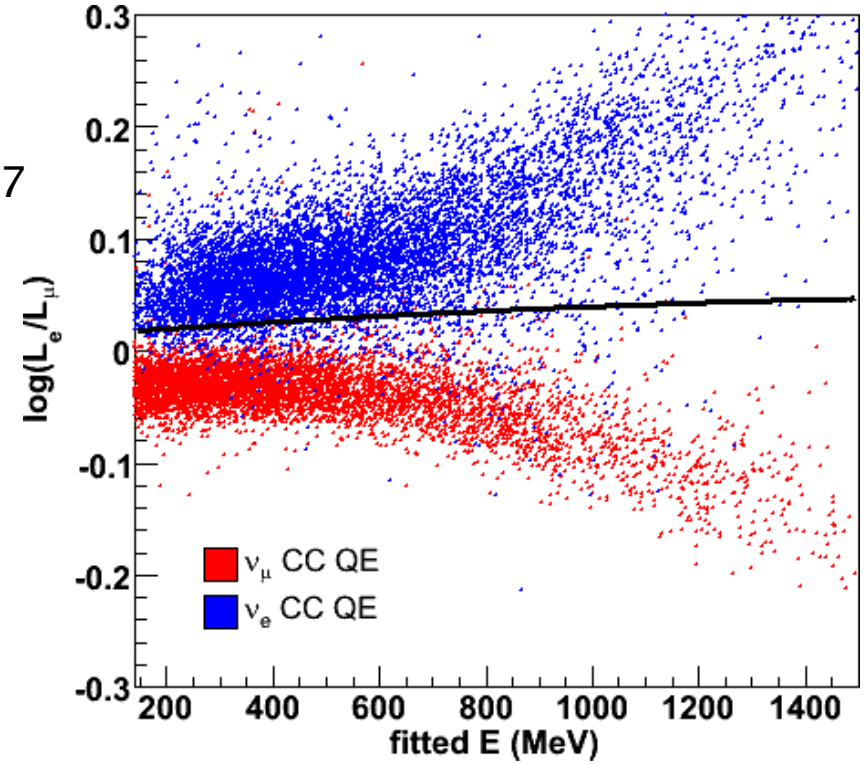






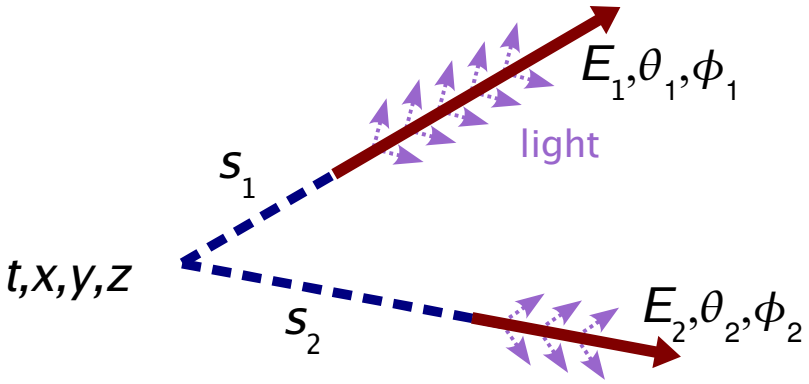
- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

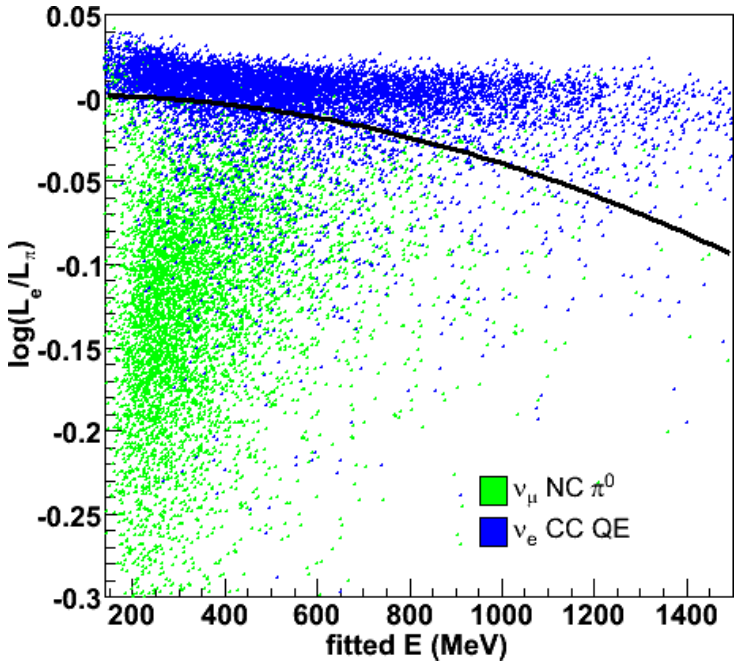


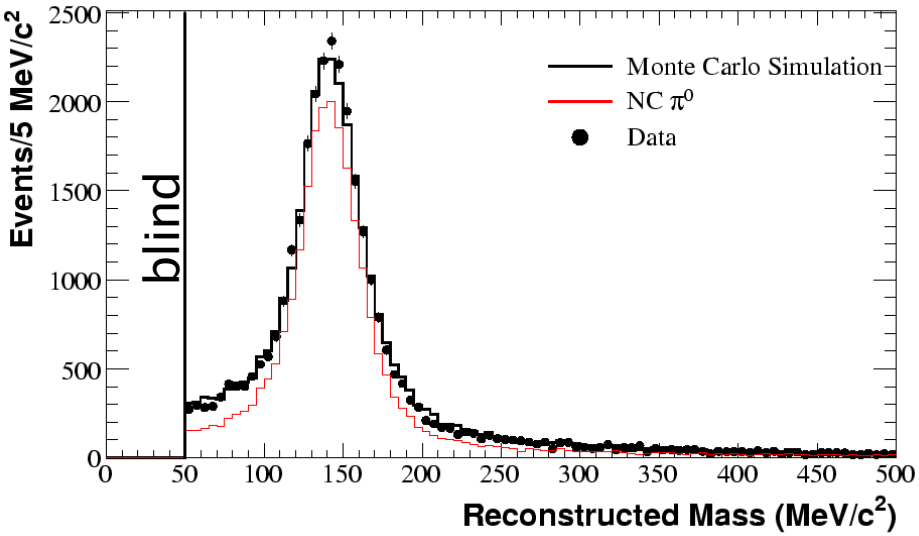


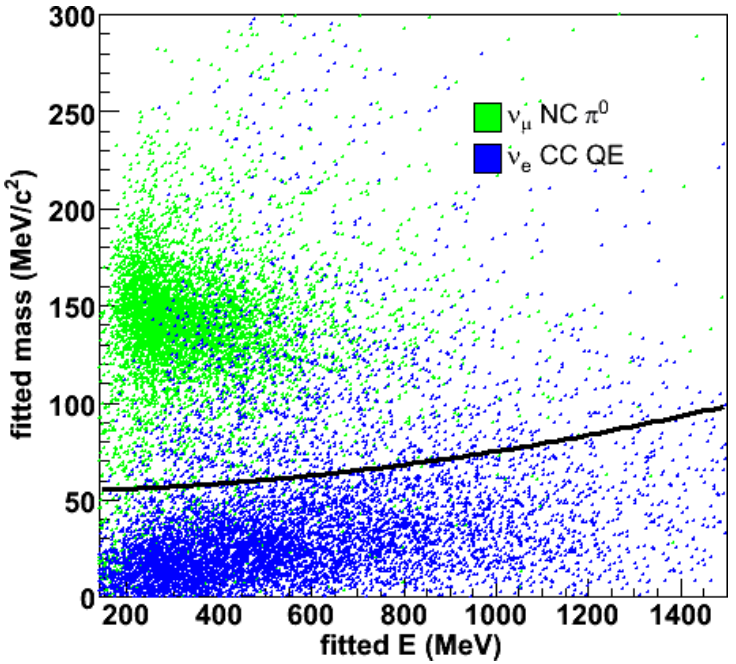
Separating e from π^0

- Extend fit to include two e-like tracks
- Very tenacious fit...5 minutes per event
- Nearly 500k CPU hours used

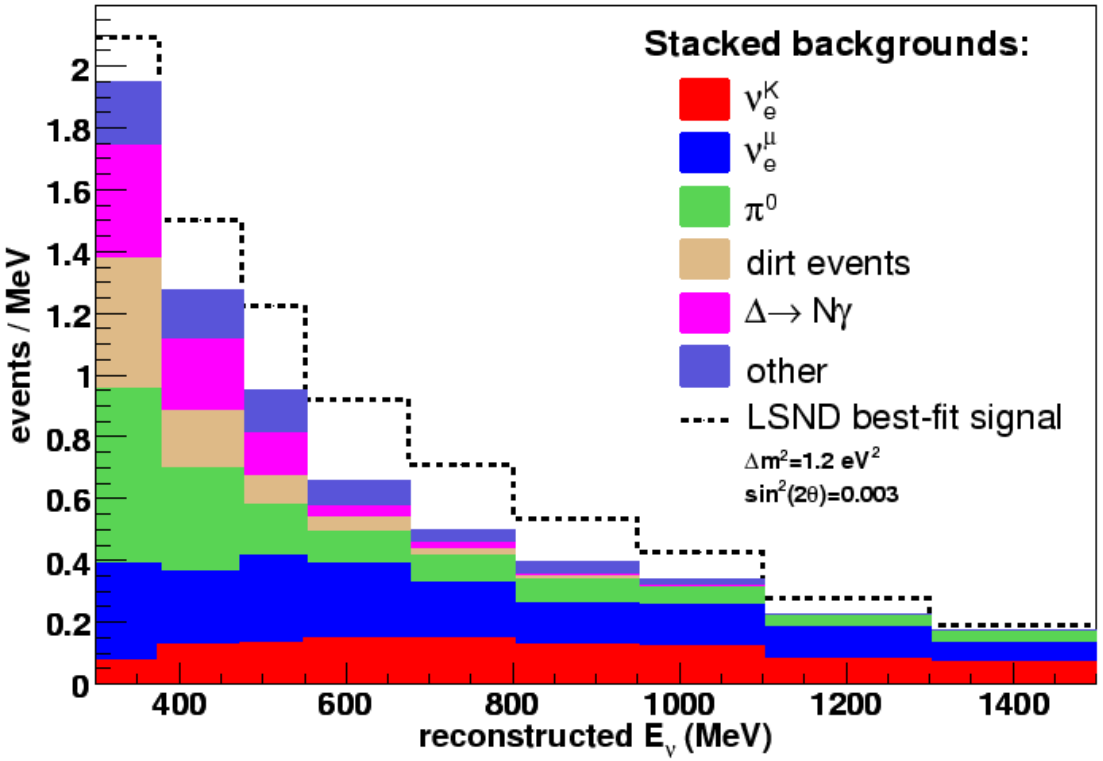








TBL Analysis: Expected event totals

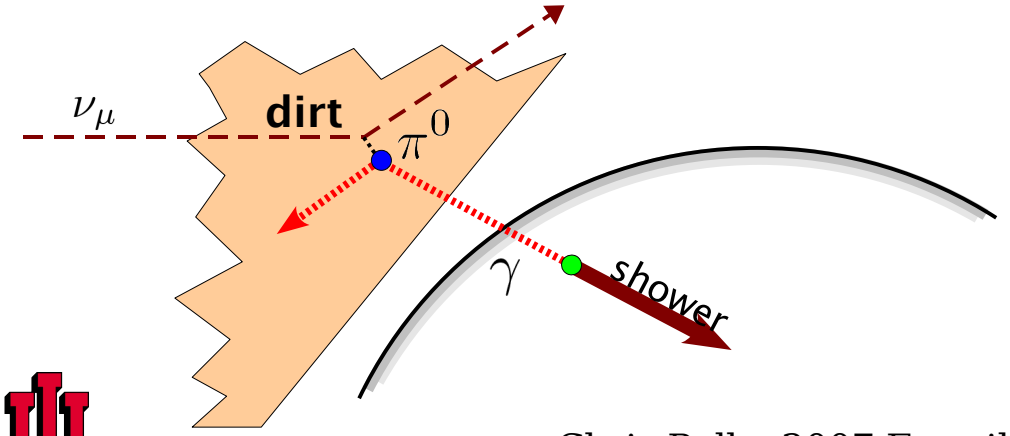


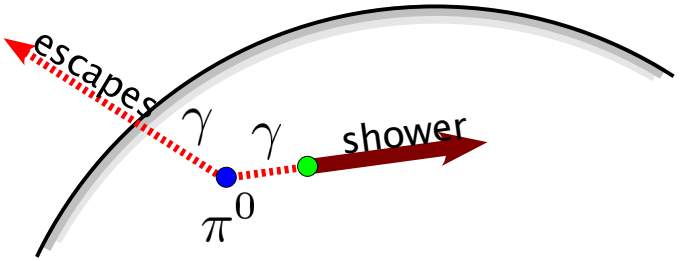
475 MeV – 1250 MeV

ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

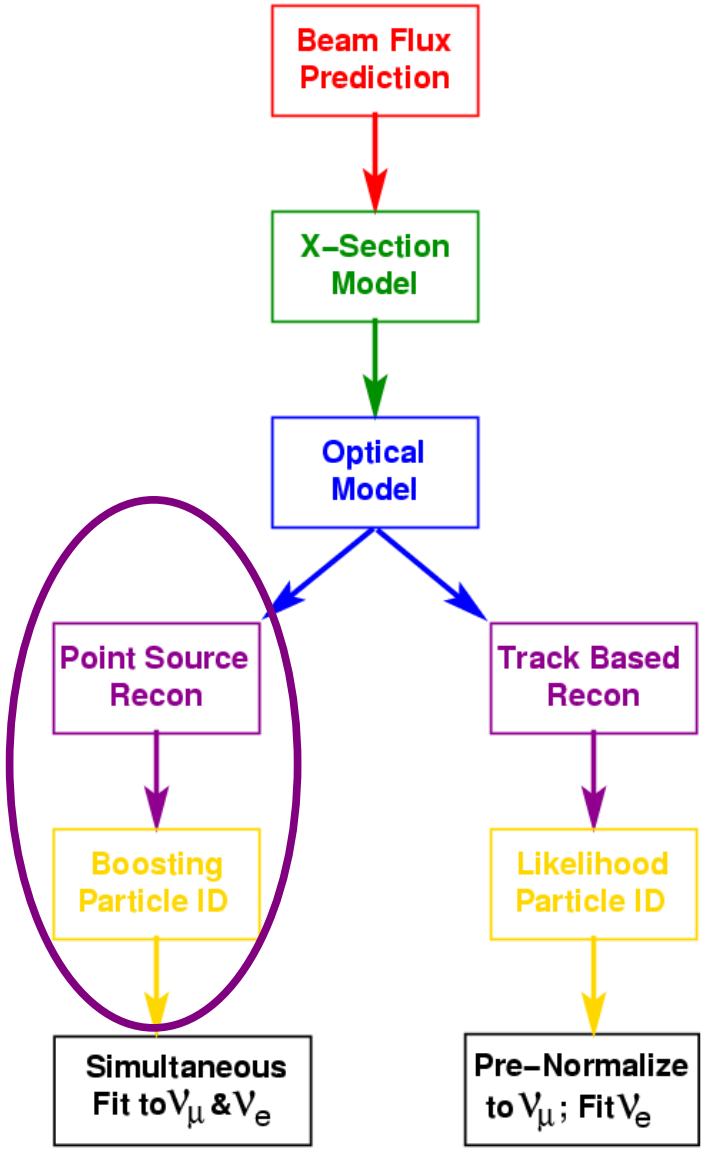
LSND best-fit $\nu_\mu \rightarrow \nu_e$ 126

S/sqrt(B)=6.8





Boosted Decision Tree (BDT) Reconstruction and Particle ID

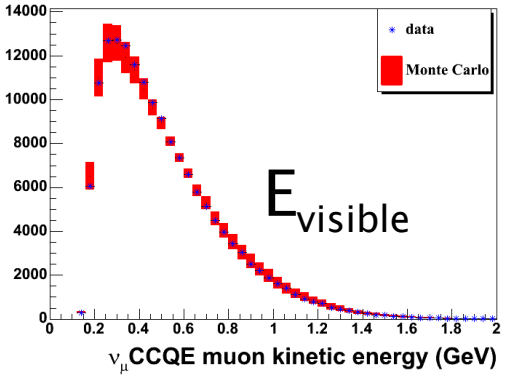


BDT Reconstruction

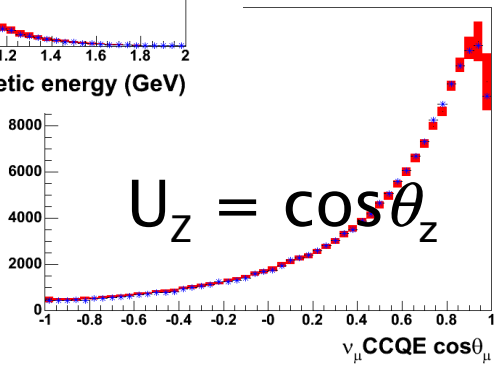
- Same pre-cuts as TBL (taking R from different reconstruction)
- Different reconstruction:
  - Treats particles more like point sources, *i.e.* not as careful about dE/dx
  - Not as tenacious about getting out of local minima, particularly with pion fit
  - Reconstruction runs nearly 10 times faster
- To make up for the simple fit, the BDT analysis relies on a form of machine learning, the boosted decision tree. Byron P. Roe, *et al.*, NIM A543 (2005) 577.
- Boosting Input Variables:
  - Low-level (# tank hits, early light fraction, etc.)
  - High-level (Q2, U_z, fit likelihoods, etc.)
  - Topology (charge in anuli, isotropic light, etc.)
- A total of 172 variables were used
- All 172 were checked for agreement within errors in 5 important 'boxes' (ν_μ CCQE, NC π^0, NC-elastic, Michel decay e, 10% closed)
- Boosting Output: Single 'score', + is signal-like

BDT Resolution:
vertex: 24 cm
direction: 3.8°
energy 14%

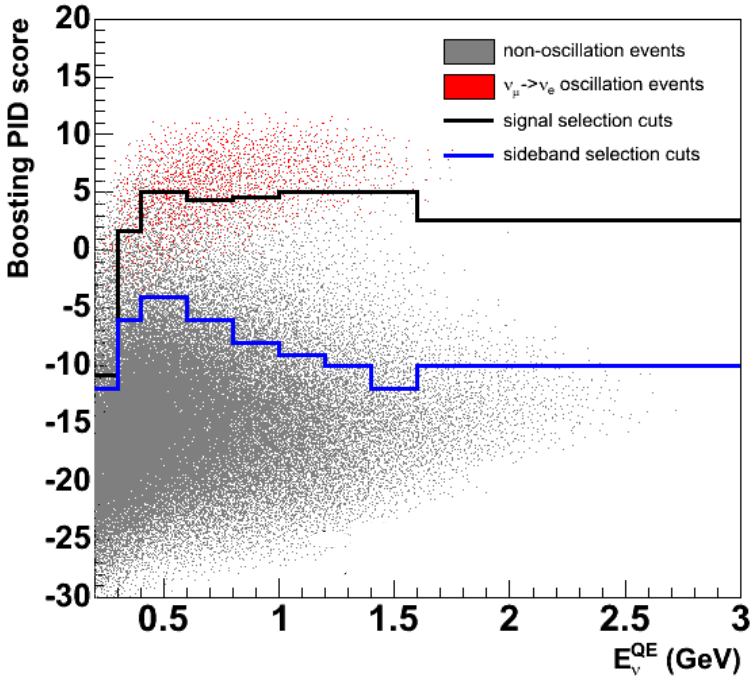
TBL Resolution:
vertex: 22 cm
direction: 2.8°
energy 11%



ν_μ CCQE Examples

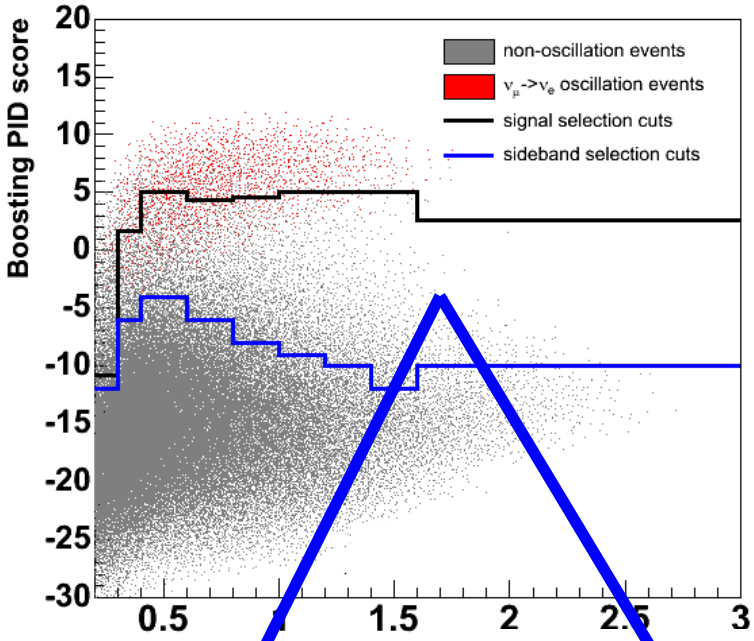


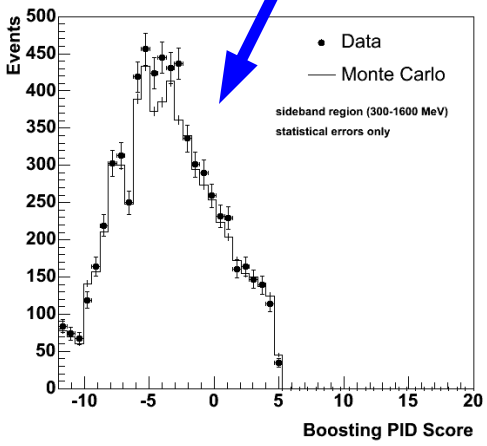
BDT Analysis: Signal/background regions

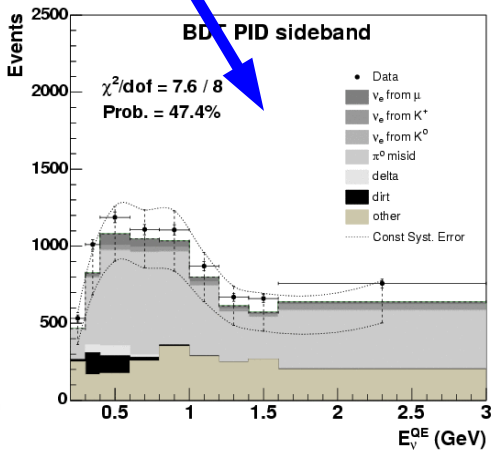


- Signal prediction (red) versus all bkgs (gray)

BDT Analysis: Signal/background regions

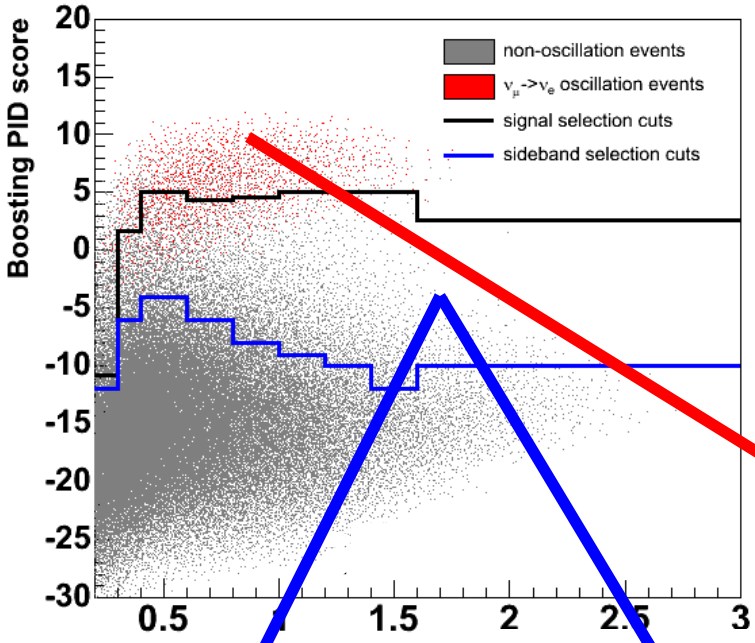






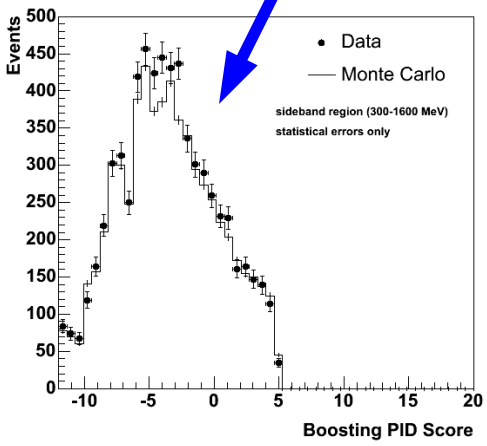
- Signal prediction (red) versus all bkgs (gray)
- Start by looking at data in 'sideband'...region immediately adjacent to signal region

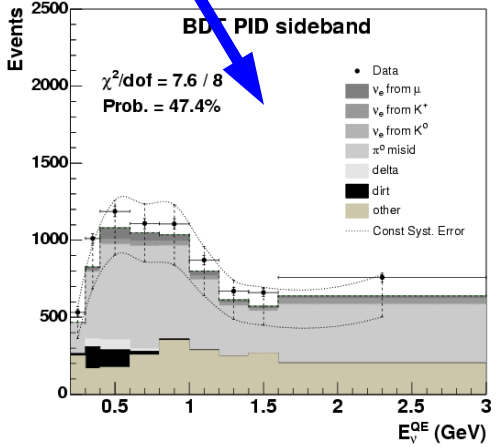
BDT Analysis: Signal/background regions

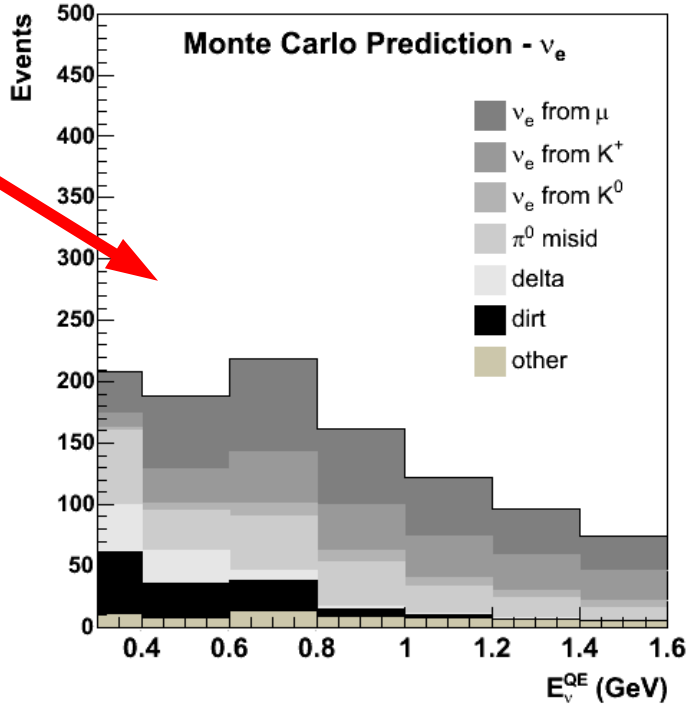


- Signal prediction (red) versus all bkgs (gray)
- Start by looking at data in 'sideband'...region immediately adjacent to signal region
- Satisfied with agreement? Finalize background prediction
- In 500–1200 MeV range: 603 bkg, LSND best-fit $\nu_\mu \rightarrow \nu_e$ 203

S/sqrt(B)=8.3



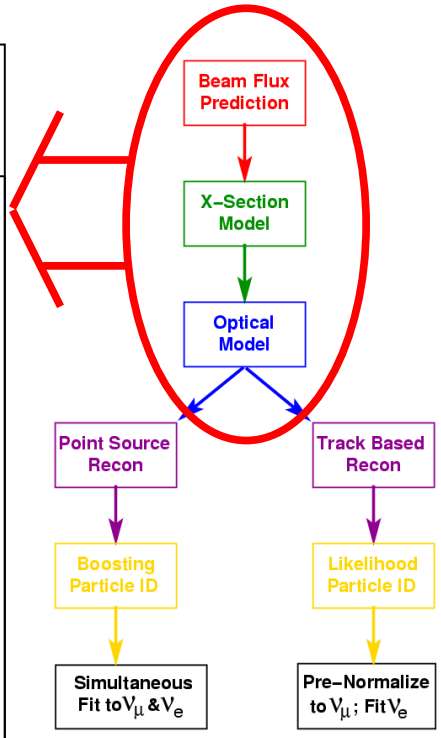




Systematic Error Analysis and Results

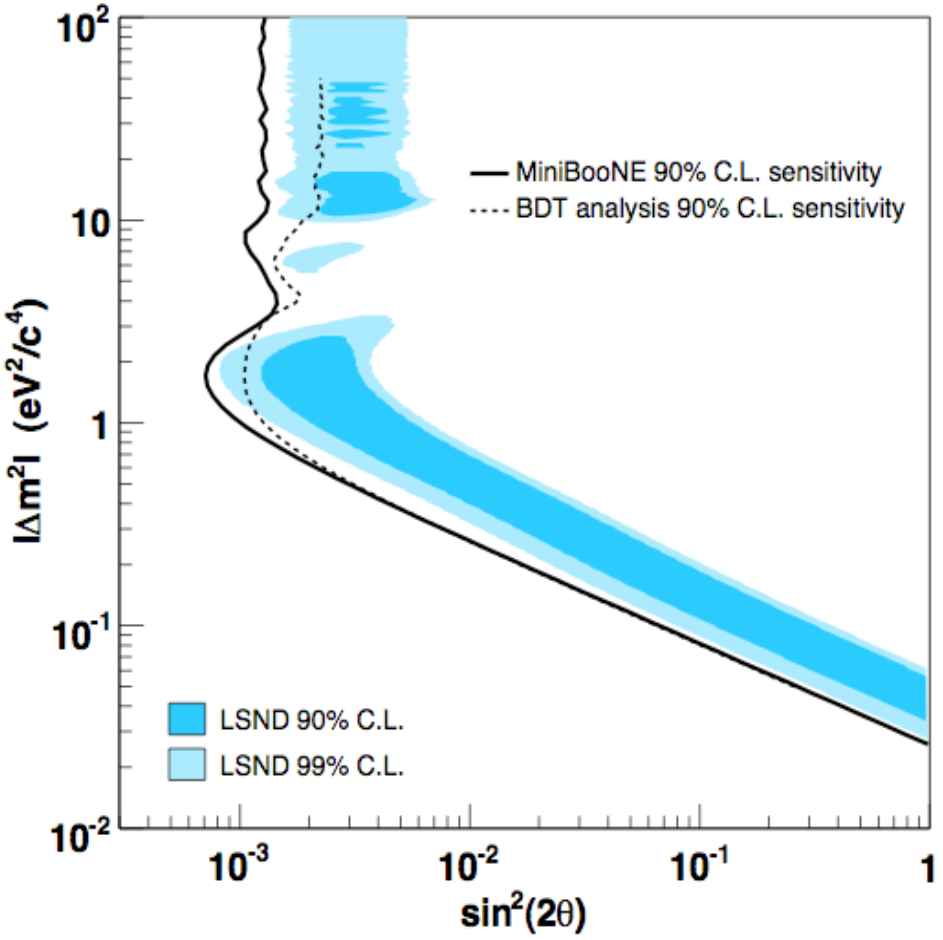
Final error budget (diagonals only...greatly simplified)

Source of uncertainty on ν_e background	TBL/BDT error in %	Constrained by MB data	Reduced by tying ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2 / 4.3	√	√
Flux from K^+ decay	3.3 / 1.0	√	√
Flux from K^0 decay	1.5 / 0.4	√	√
Target/beam models	2.8 / 1.3	√	
ν–cross section	12.3 / 10.5	√	√
NC π^0 yield	1.8 / 1.5	√	
Dirt interactions	0.8 / 3.4	√	
Optical model	6.1 / 10.5	√	√
DAQ electronics model	7.5 / 10.8	√	



- Every checkmark in this table could easily consume a 30 minute talk
  - All error sources had some *in situ* constraint
  - Some reduced by combined fit to ν_μ and ν_e
- Errors arise from common uncertainties in flux, xsec, and optical model
- Reconstruction and PID unique
  - BDT had higher signal-to-background
  - TBL more impervious to systematics
  - About 50% event overlap

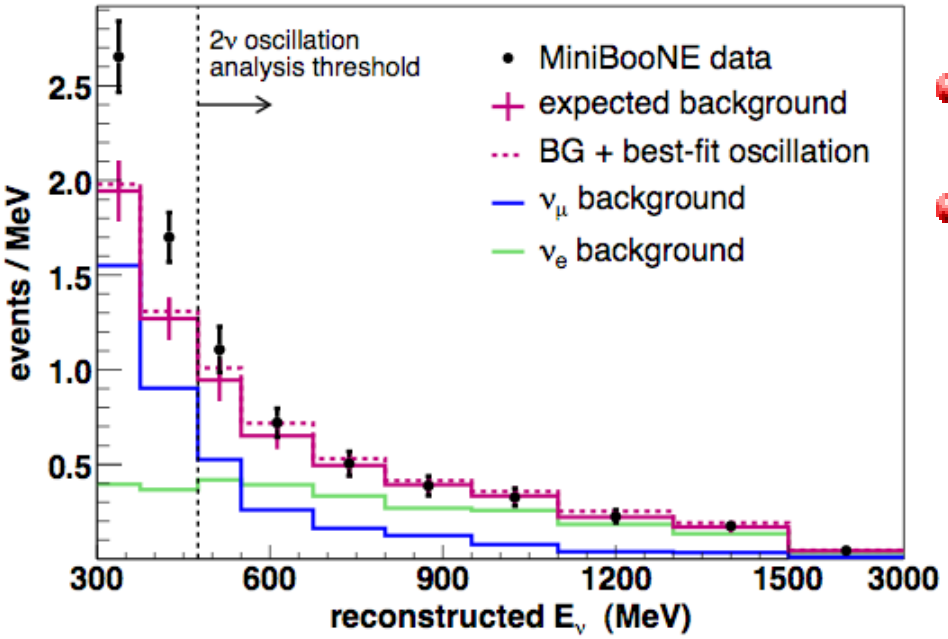
BDT/TBL sensitivity comparison



- Sensitivity is determined from simulation only (no data yet!)
- Decided before unblinding:
  - Final PID cuts
  - Region of E_ν to fit
  - Analysis with higher sensitivity would be the final MB result
- TBL (solid) is better at high Δm^2
- 90% CL defined by $\Delta\chi^2 = 1.64$

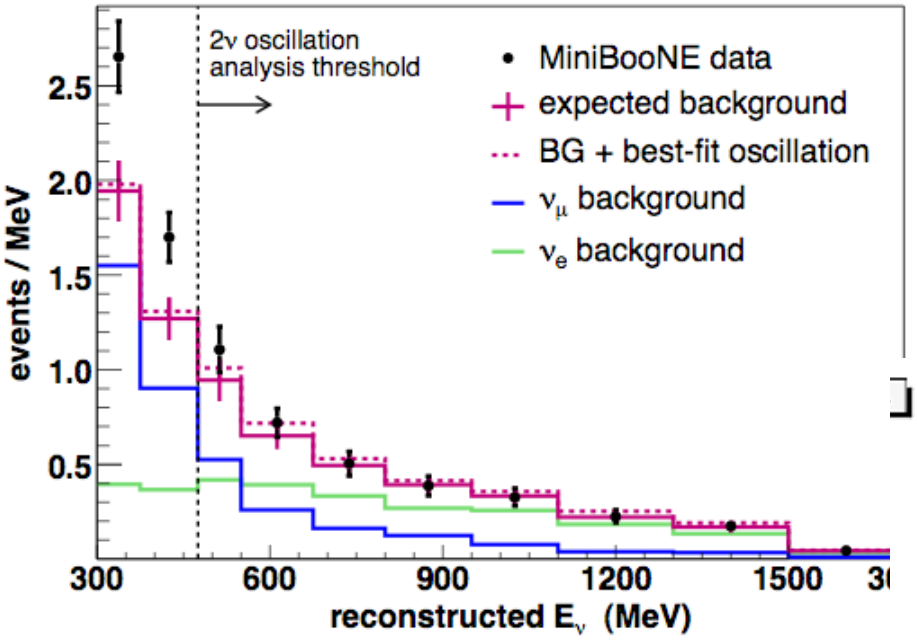
After many people-years (not to mention CPU-hours)...

Finally we see the data in the signal region...

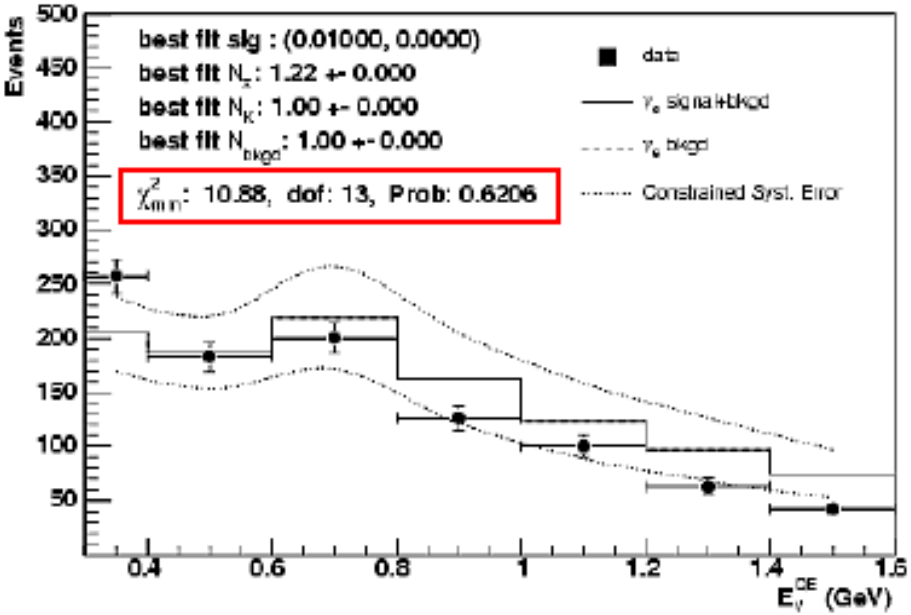


- TBL shows no sign of an excess in the analysis region
- Visible excess at low E that cannot be described based on LSND and a simple 2ν mixing hypothesis

Finally we see the data in the signal region...

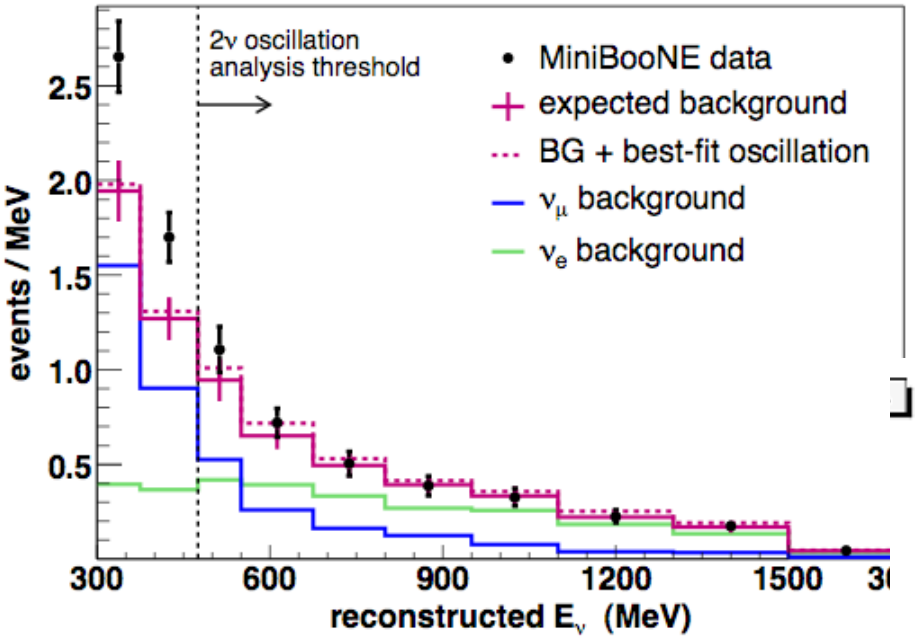


- TBL shows no sign of an excess in the analysis region
- Visible excess at low E that cannot be described based on LSND and a simple 2ν mixing hypothesis

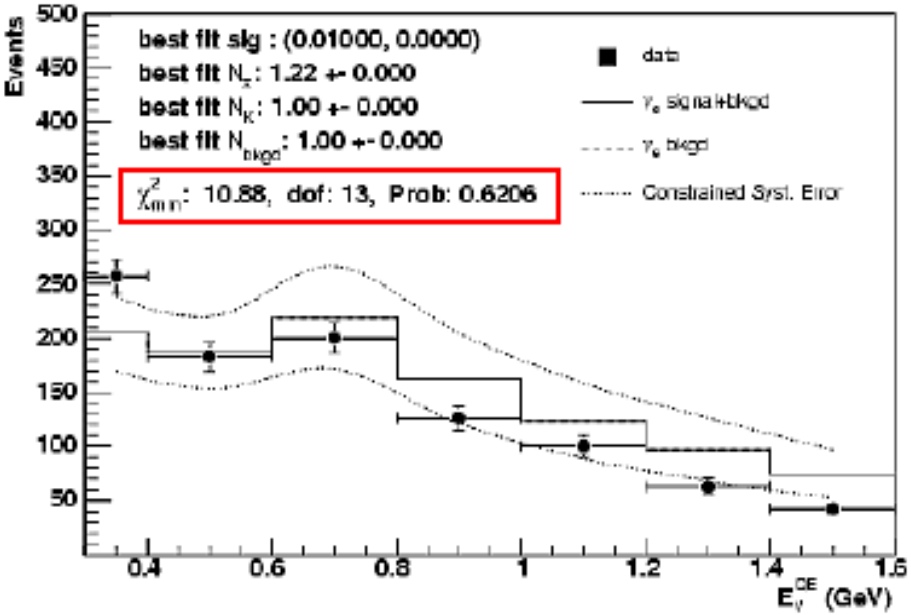


- BDT has a good fit and no sign of an excess, in fact the data is low relative to the prediction
- Also sees an excess at low E, but larger normalization error complicates interpretation

Finally we see the data in the signal region...



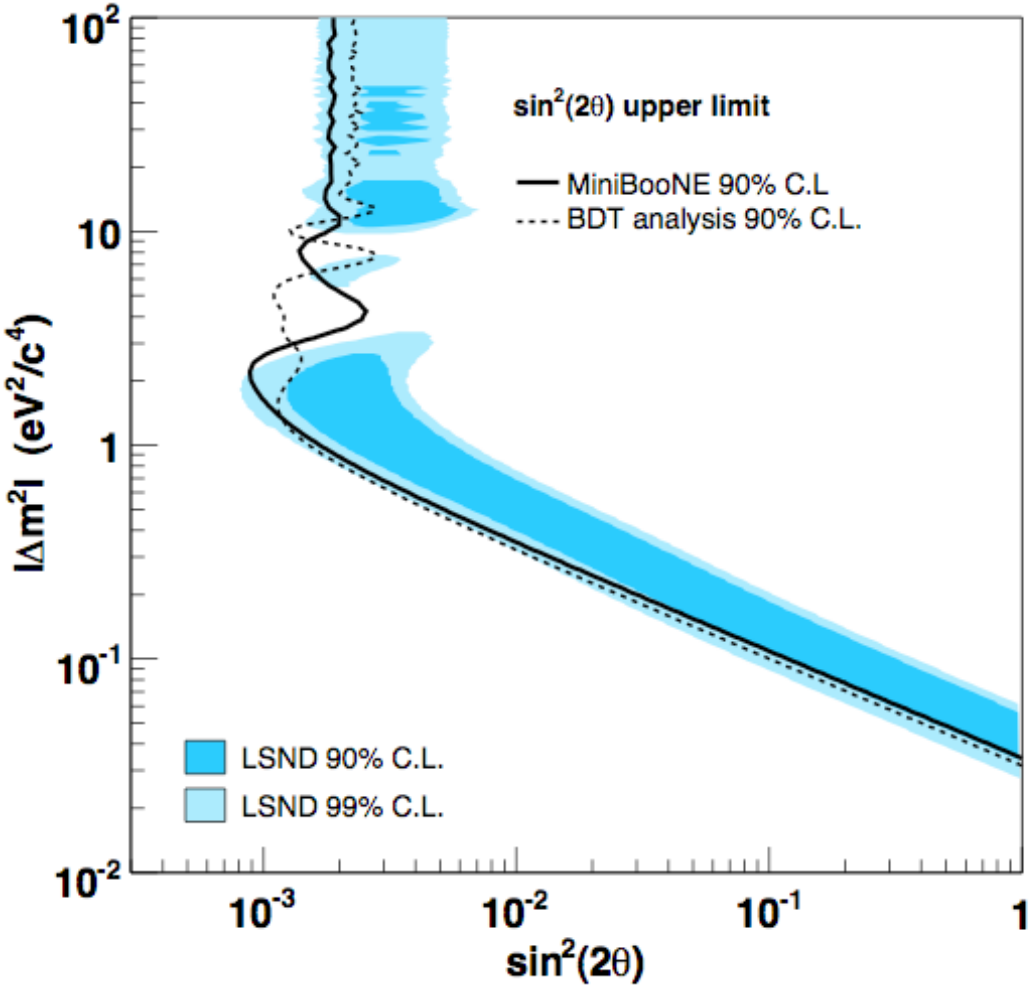
- TBL shows no sign of an excess in the analysis region
- Visible excess at low E that cannot be described based on LSND and a simple 2ν mixing hypothesis



- BDT has a good fit and no sign of an excess, in fact the data is low relative to the prediction
- Also sees an excess at low E, but larger normalization error complicates interpretation

Neither analysis shows an evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region

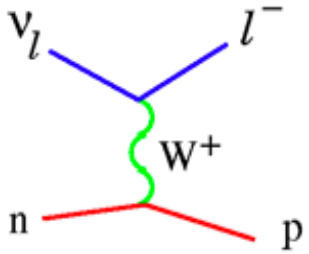
Fit results mapped into $\sin^2(2\theta)$ Δm^2 plane



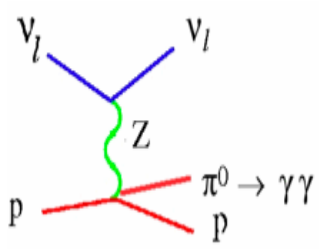
- Energy-fit analysis:
  - solid: TBL
  - dashed: BDT
- Independent analyses in good agreement
- Looks similar to sensitivity because of the lack of a signal
- Had there been a signal, these curves would have curled around and closed into contours
- MiniBooNE and LSND incompatible at a 98% CL for all Δm^2 under a 2ν mixing hypothesis

MB cross-section analyses from NuInt07...

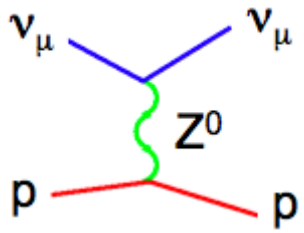
- ν_μ CCQE



- NC π^0

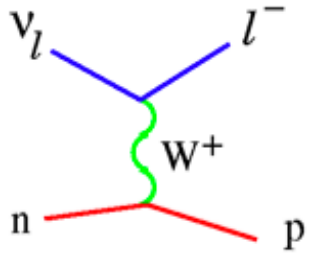


- NC elastic

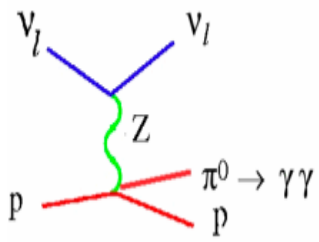


MB cross-section analyses from NuInt07...

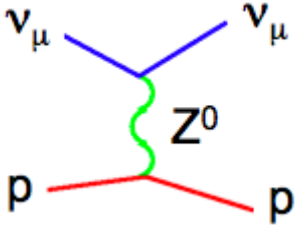
- ν_μ CCQE



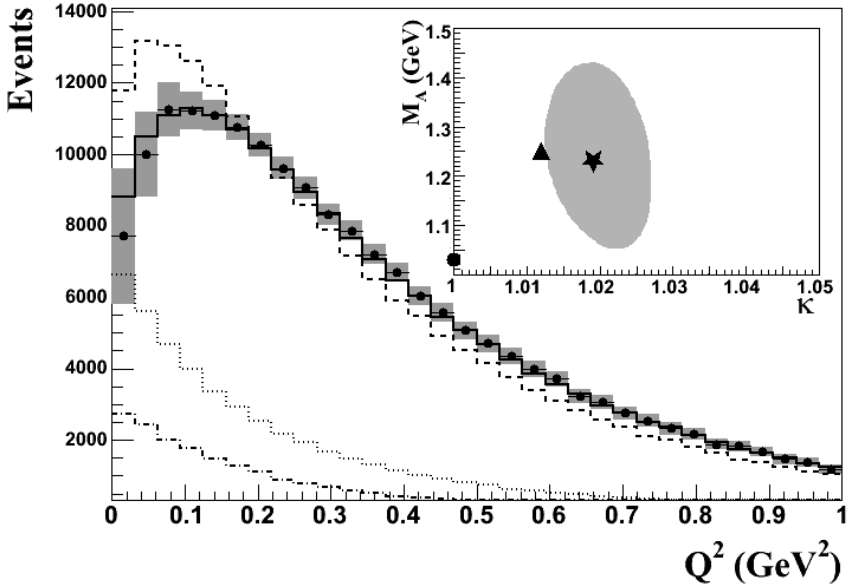
- NC π^0



- NC elastic



ν_μ CCQE Q^2 distribution (hep-ex/0706.0926)

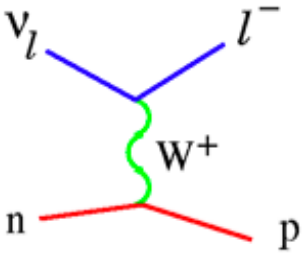


- 198,000 events allows for detailed 1 and 2d kinematic views
- Agreement between data (points) and MC (solid) after fitting for modified Fermi gas parameters
- 'Golden channel' for normalizing flux X xsec in oscillation analysis

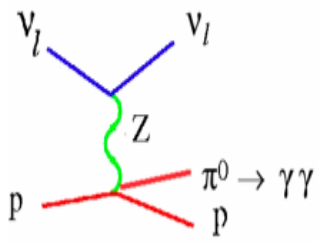
T. Katori, NuInt07

MB cross-section analyses from NuInt07...

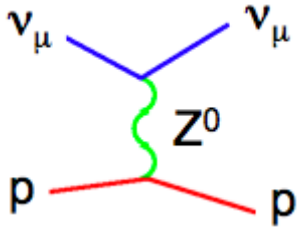
- ν_μ CCQE



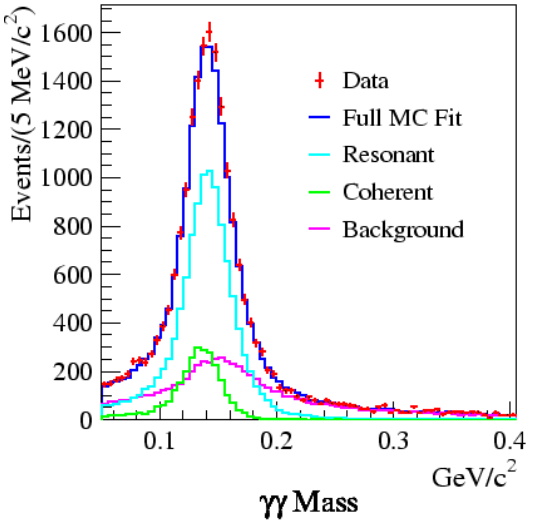
- NC π^0

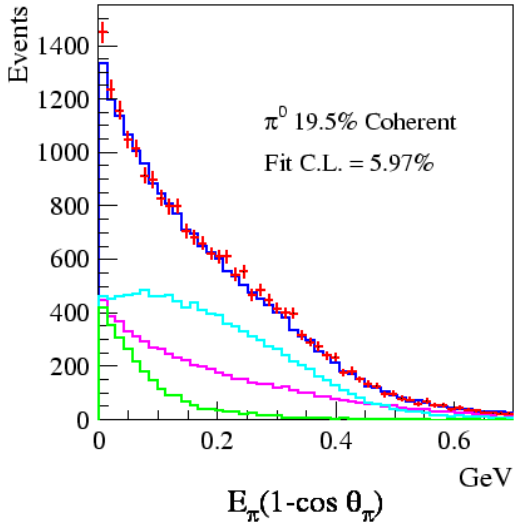


- NC elastic



NC π^0 fits to resonant/coherent fractions



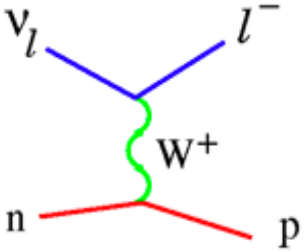


- 28,600 events, largest sample to date
- For MB flux and Nuance model we find that (19.5±1.1)% of exclusive NC π^0 production is coherent
- Very important background for oscillation analysis

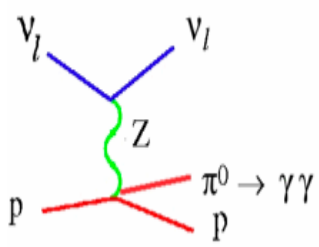
J. Link, NuInt07

MB cross-section analyses from NuInt07...

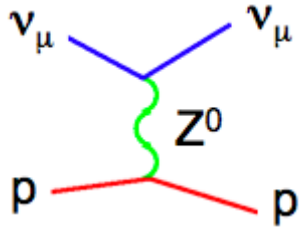
- ν_μ CCQE



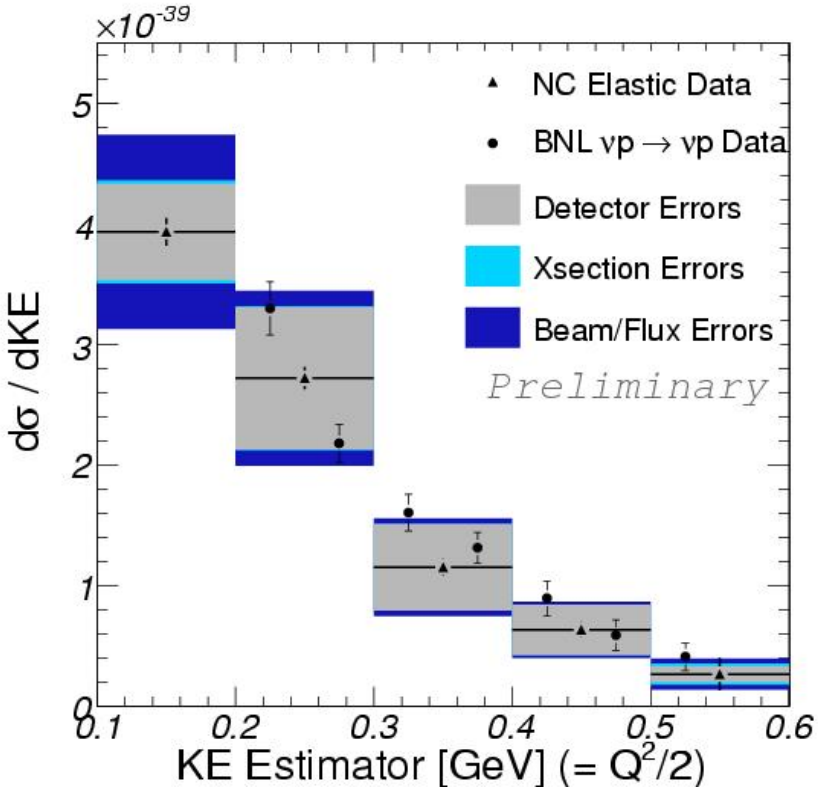
- NC π^0



- NC elastic



NC elastic absolute cross section



- Data shown is 10% of total sample
- Comparison to BNL E734
- First differential cross section from MB

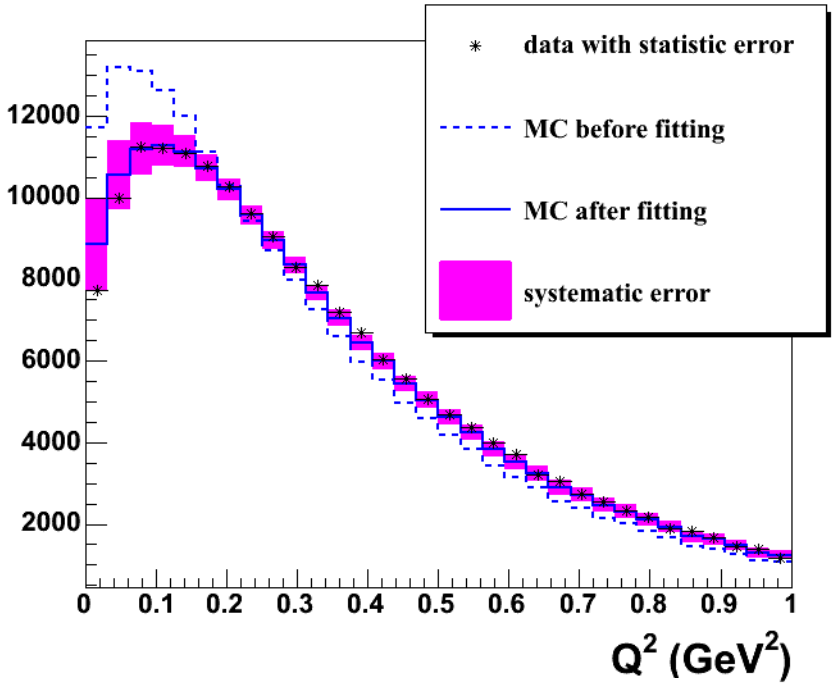
D. Cox, NuInt07

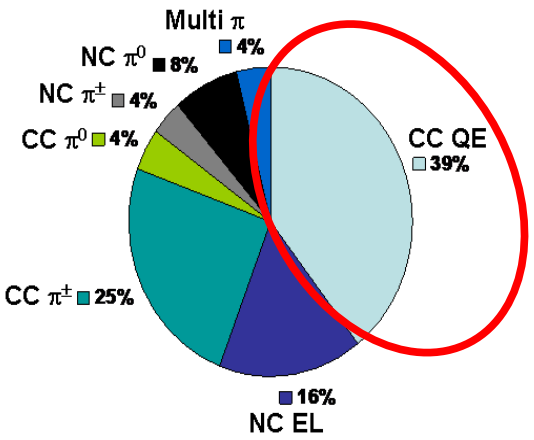
Conclusions

- Two systematically different analyses show no evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region
- Excess at low E_ν is currently under investigation
- Look for lots of papers over the next year from cross-sections, further oscillation analysis, and interpretation

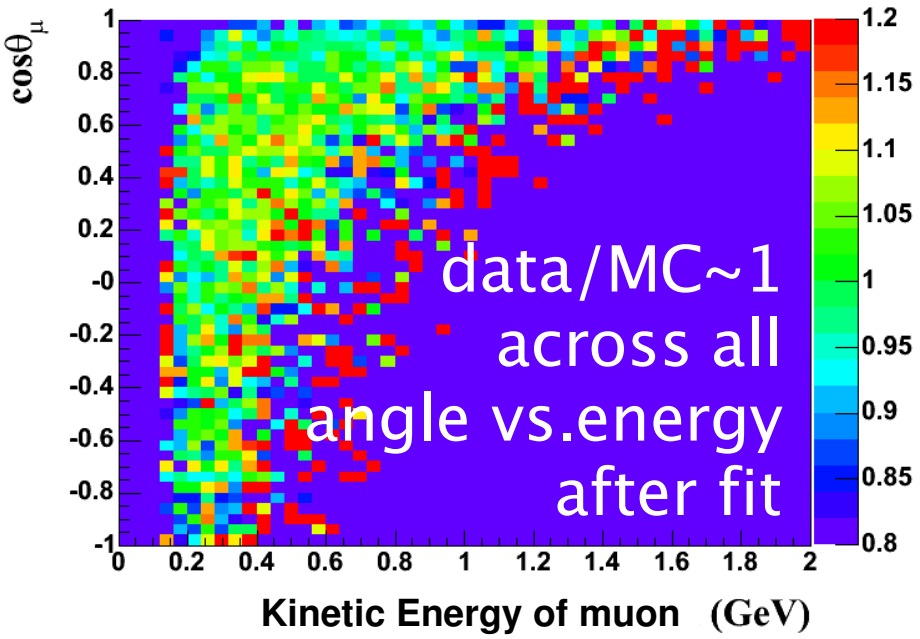
Backup Slides

Tuning Nuance on internal ν_μ CCQE data





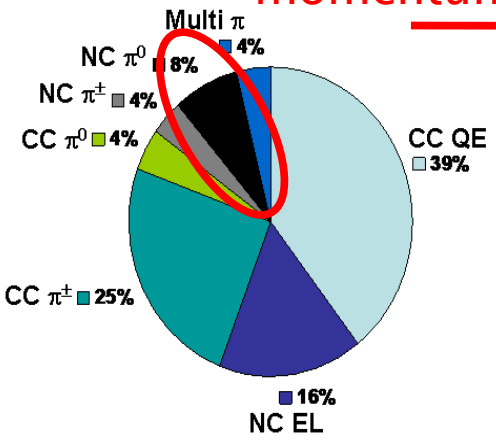
- From Q^2 fits to MB ν_μ CCQE data:
  - M_A^{eff} -- effective axial mass
  - E_{lo}^{SF} -- Pauli Blocking parameter
- From electron scattering data:
  - E_b -- binding energy
  - p_f -- Fermi momentum
- Model describes CCQE ν_μ data well

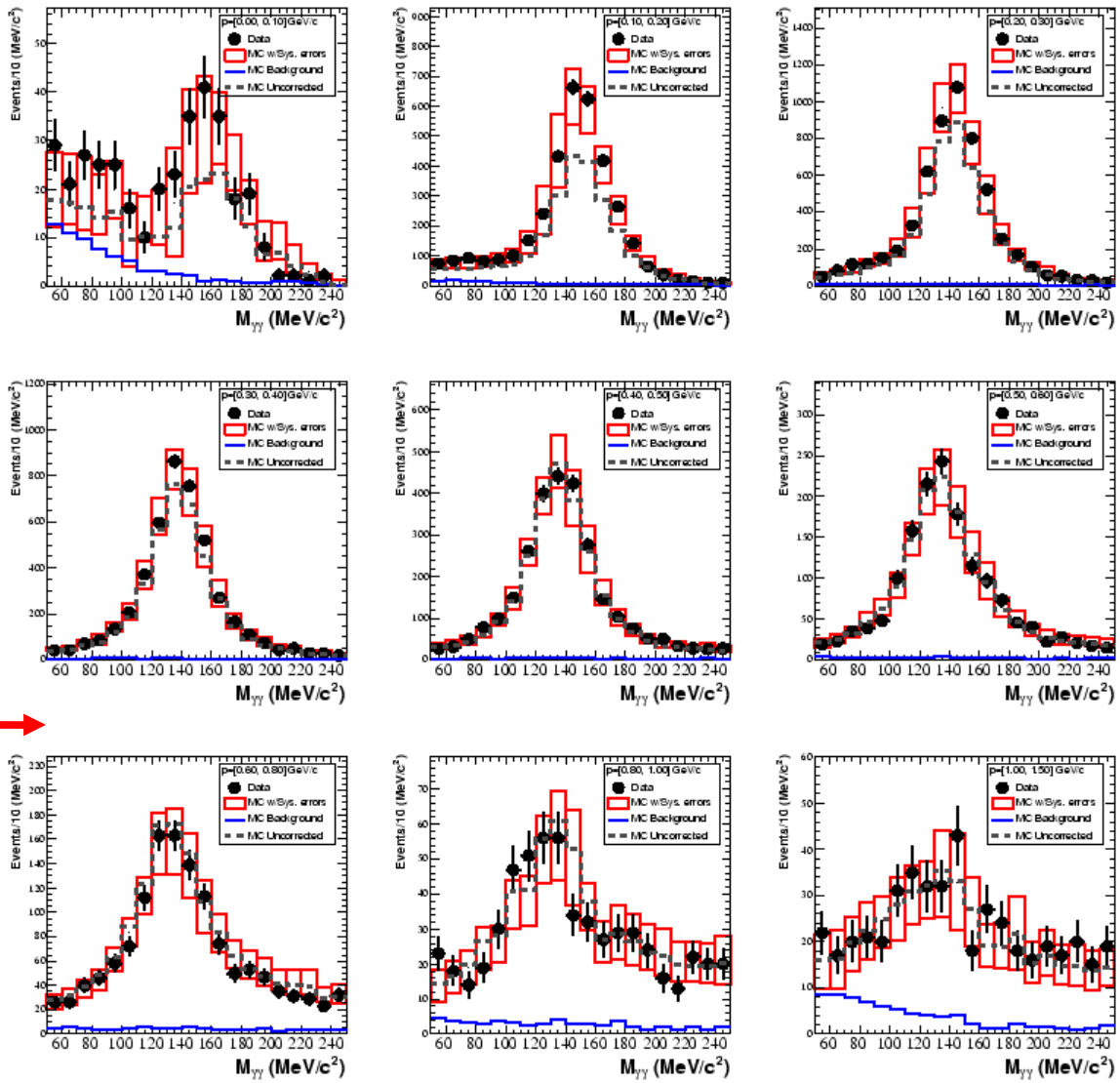


Tuning Nuance on internal NC π^0 data

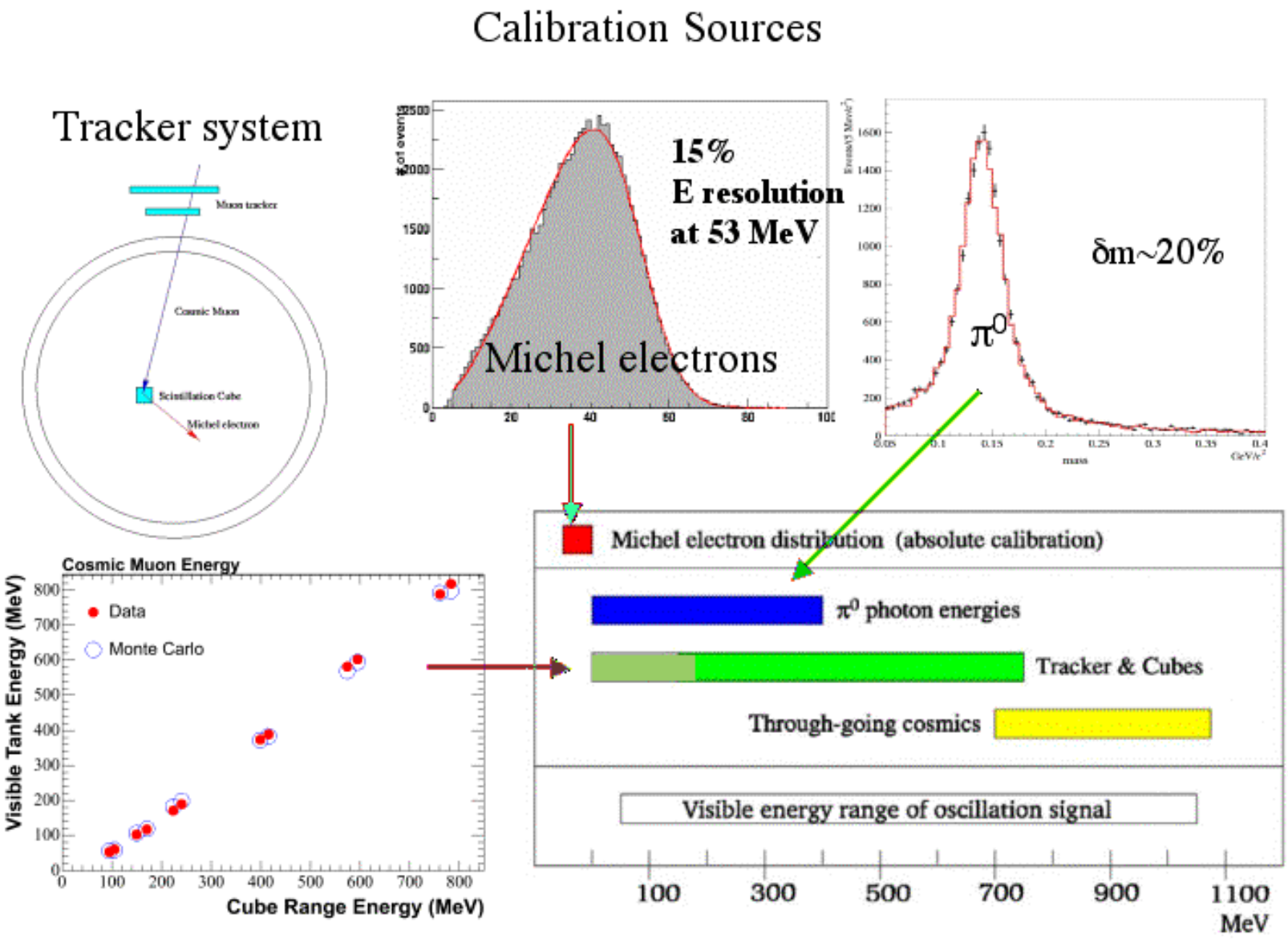
- 90%+ pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)
- Measure rate as function of momentum
- Default MC underpredicts rate at low momentum
- analysis reaches 1.5 GeV
- $\Delta \rightarrow N\gamma$ also constrained (though to a lesser extent)

Invariant mass distributions in momentum bins



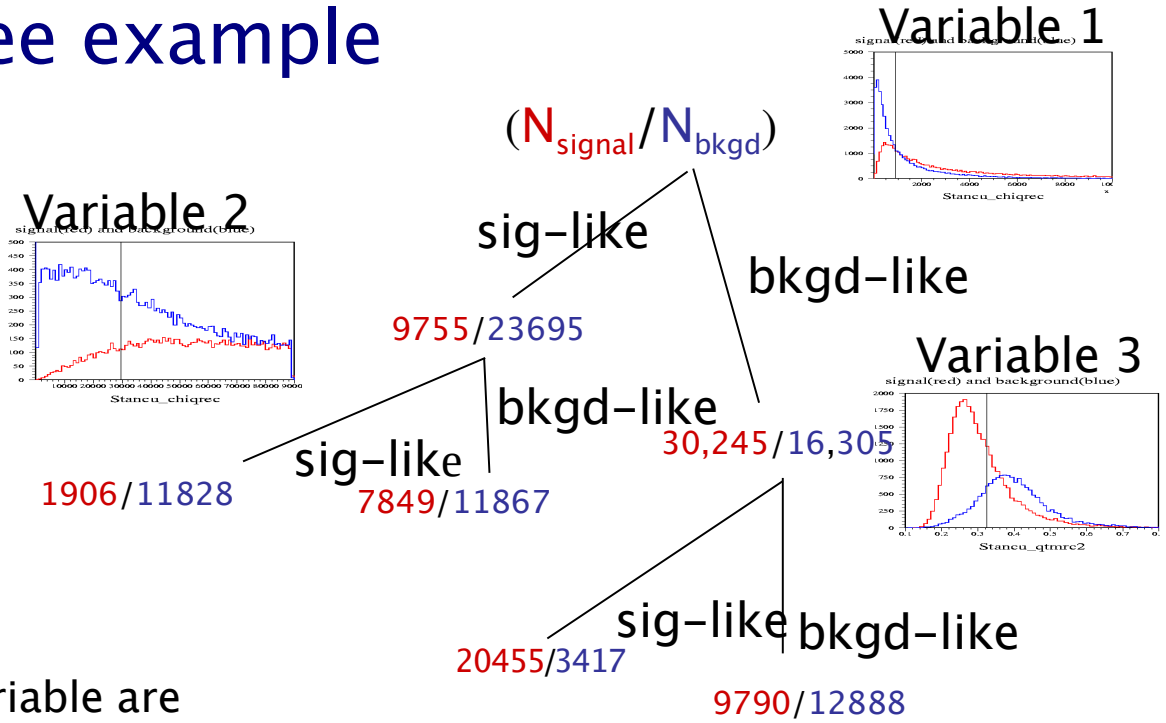


Calibration sources span various energies



Decision tree example

(sequential series of cuts based on MC study)

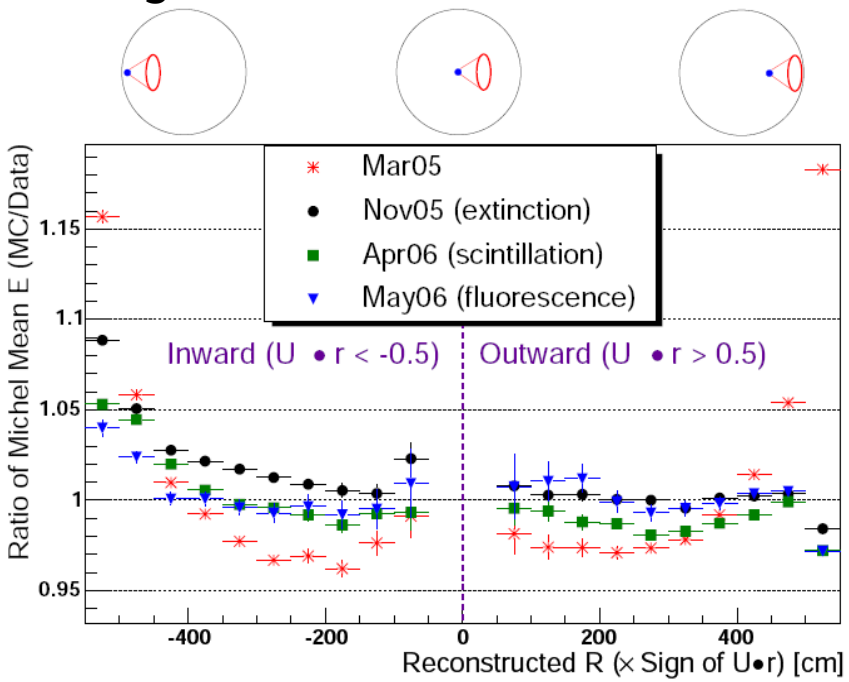


- Optimal cuts on each variable are determined
- An event gets a weight of 1 if signal -1 if background
- Hard to identify backgrounds are iteratively given more weight
- Many trees built
- PID 'score' established from ensemble

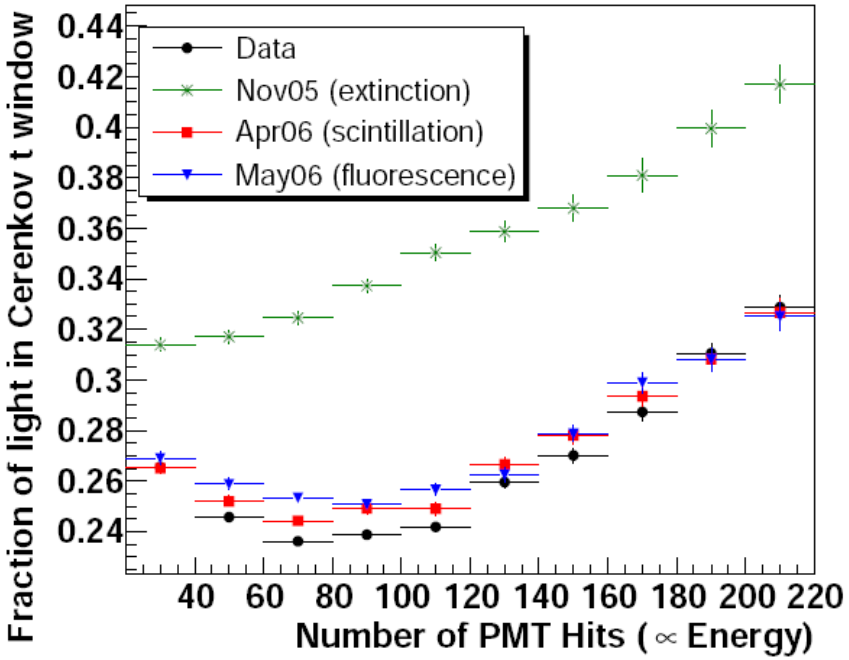
This tree is one of many possibilities...

Tuning the optical model

Using Michel electrons...



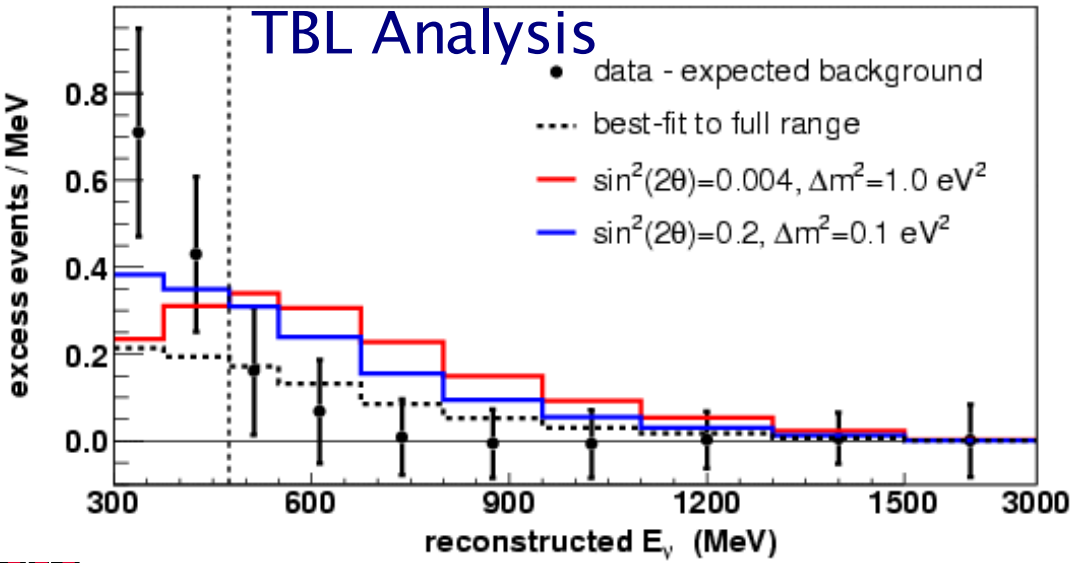
Using NC elastic ν interactions...



- Initial optical model defined through many benchtop measurements
- Subsequently tuned with *in situ* sources, examples
  - Left: Michel e populate entire tank, useful for tuning extinction
  - Right: NC elastic n interactions below Cerenkov threshold useful for distinguishing scintillation from fluorescence

Future work for MiniBooNE

- Papers in support of this analysis
  - NC π^0 background measurement
  - ν_μ CCQE analysis
- Continued improvements of the ν oscillation analysis
  - Combined BDT and TBL
  - More work on reducing systematics
- Re-examine low E backgrounds and significance of low E excess



- Lots of work on cross-sections
- MiniBooNE has more ν_μ interactions than any prior experiment and they are in an energy range relevant to future ν experiments.
- Event count before cuts:

ν channel	events
all channels	810k
CC quasielastic	340k
NC elastic	150k
CC π^+	180k
CC π^0	30k

- Currently running in anti-ν mode for anti-ν cross sections