First MiniBooNE Oscillation Results

Chris Polly, Indiana University

Pheno 07 Madison, WI

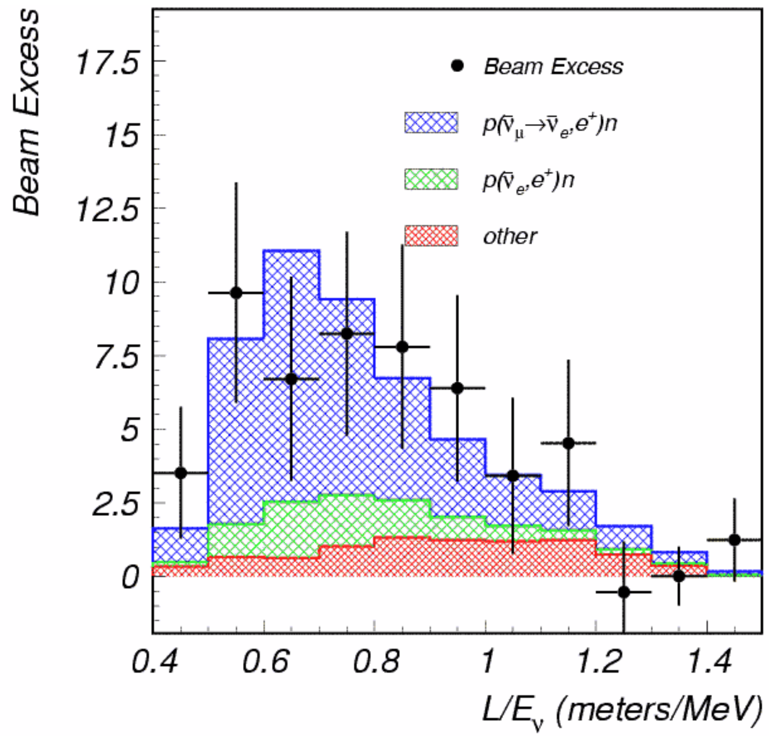
The MiniBooNE Collaboration

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

★ Thanks to organizers for squeezing this talk in...

MiniBooNE's Motivation: The LSND signal

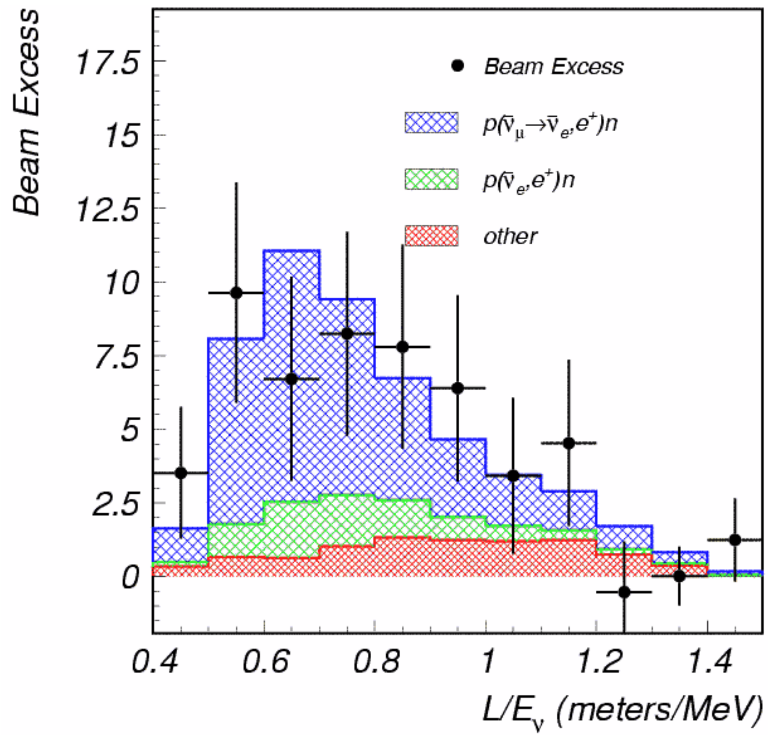


* For ν overview see Andre and Bonnie's talks later this morning

- 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

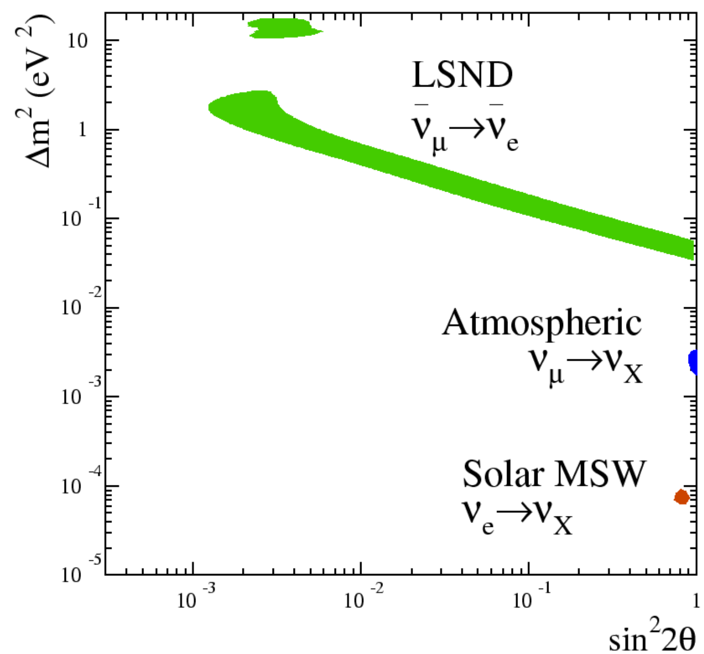


* For ν overview see Andre and Bonnie's talks later this morning

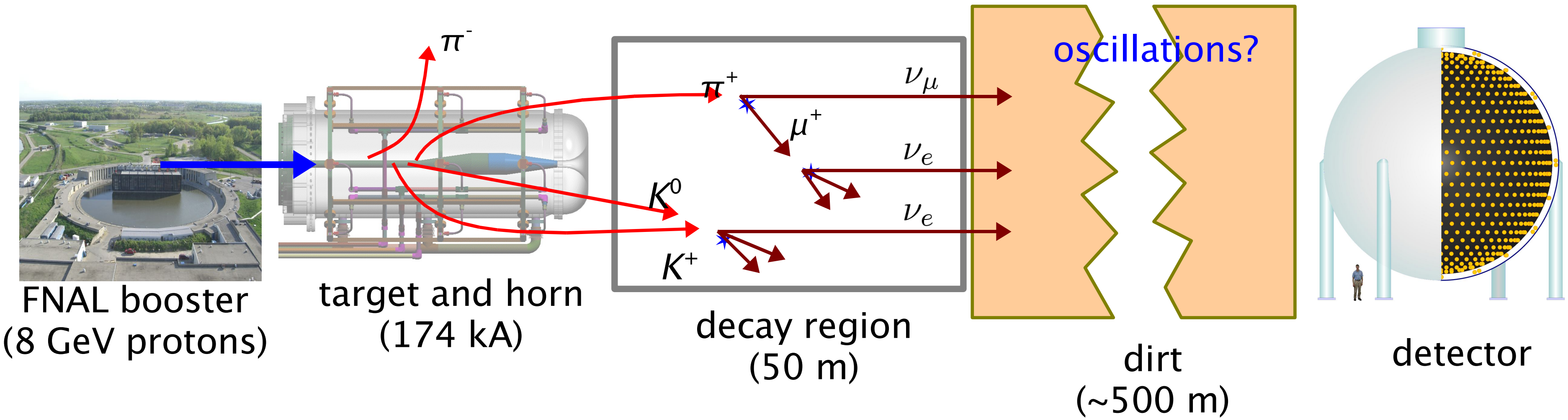
- LSND found an excess of $\overline{\nu_e}$ in $\overline{\nu_\mu}$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2ν mixing hypothesis:

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

- 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 ***hep-ex/0506067***
  - Extra dimensions ***hep-ph/0504096***
- Unlike atmos and solar...LSND unconfirmed



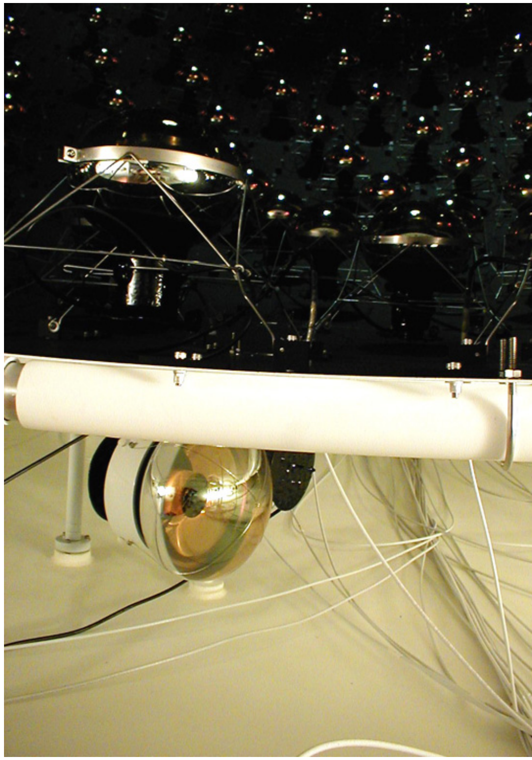
The MiniBooNE design strategy



- 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:

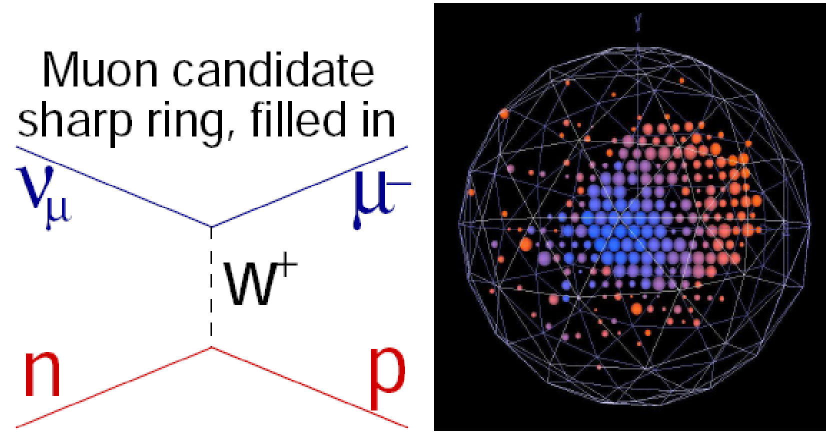
MiniBooNE:	(0.5 km) / (0.8 GeV)
LSND:	(0.03 km) / (0.05 GeV)

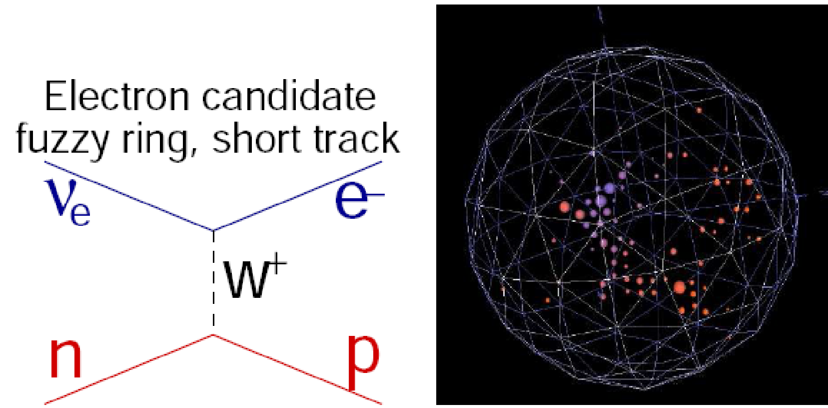
- Detect ν interations in 800T pure mineral oil detector
  - 1280 8” PMTs provide 10% coverage of fiducial volume
  - 240 8” PMTs provide active veto in outer radial shell

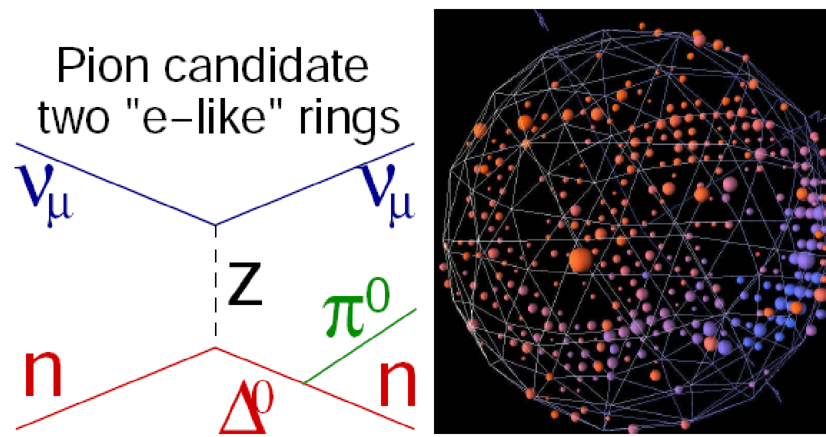


Key points about the signal

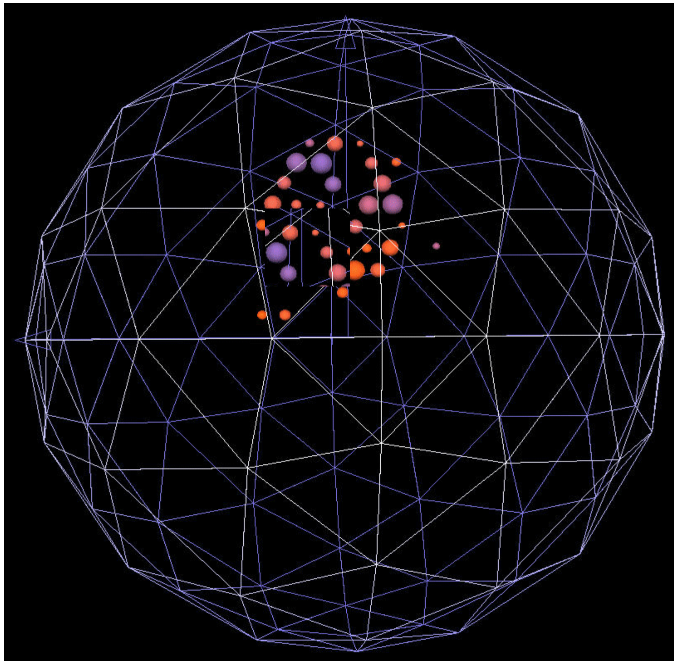
- LSND oscillation probability is 0.3%
- After cuts, MiniBooNE has to be able to find ~300 ν_e CCQE interactions in a sea of ~150,000 ν_μ CCQE
- Intrinsic ν_e background
  - Actual ν_e produced in the beamline from muons and kaons
  - Irreducible at the event level
  - E spectrum differs from signal
- 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

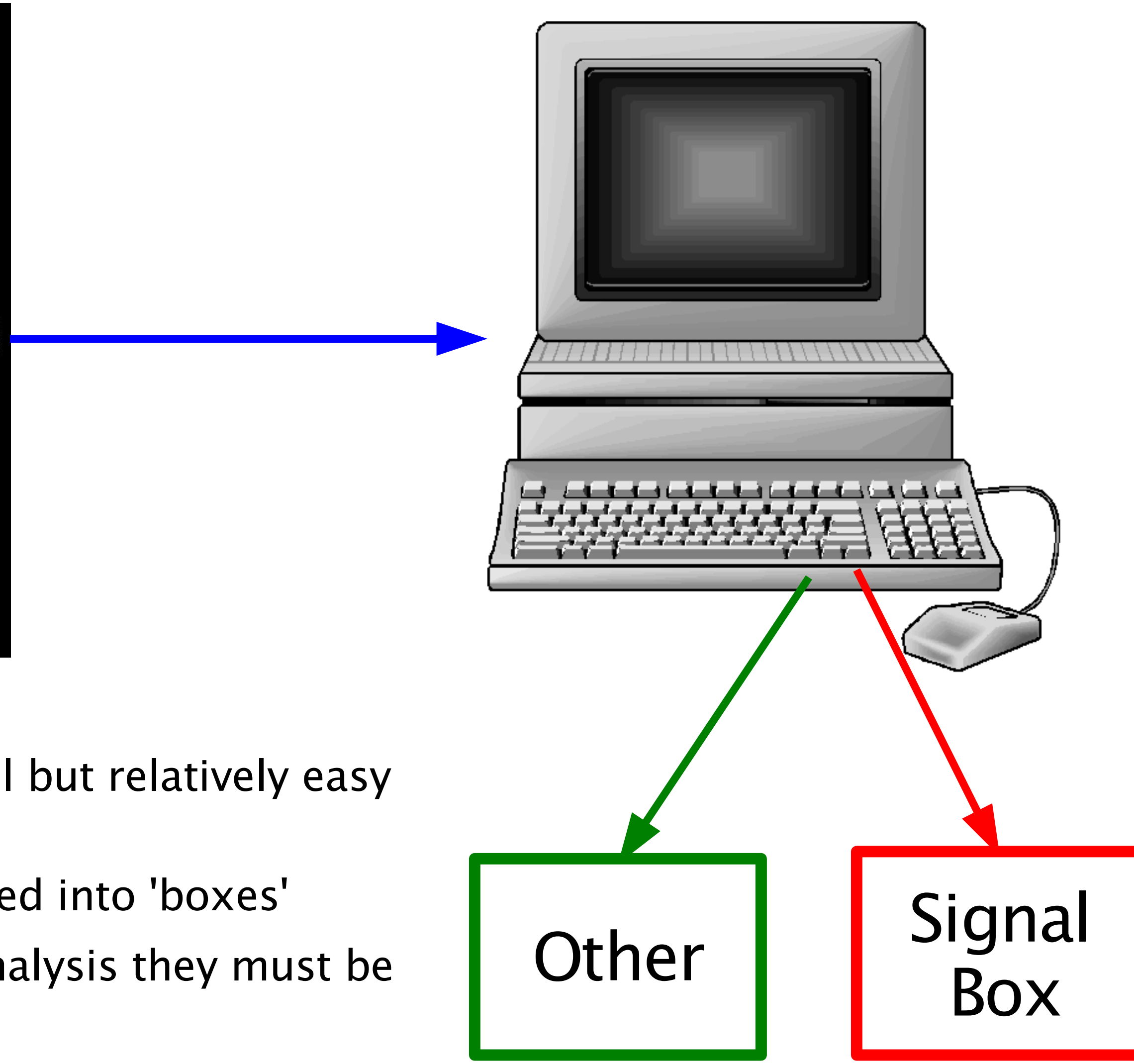






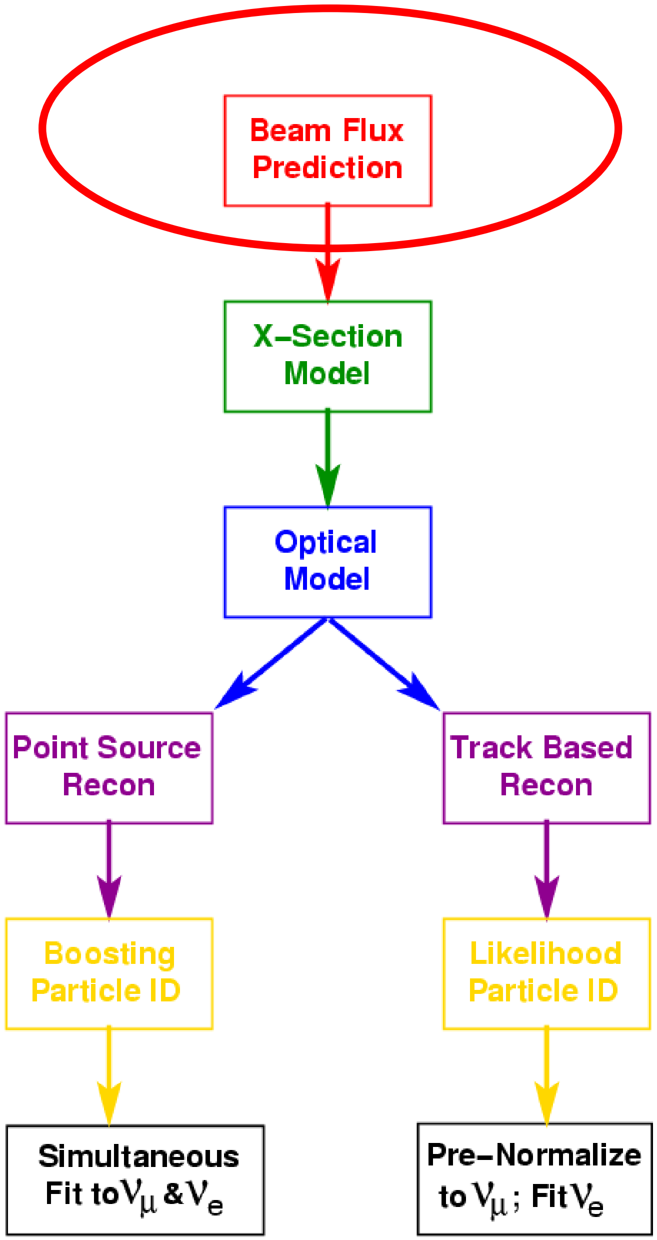
Blind analysis in MiniBooNE





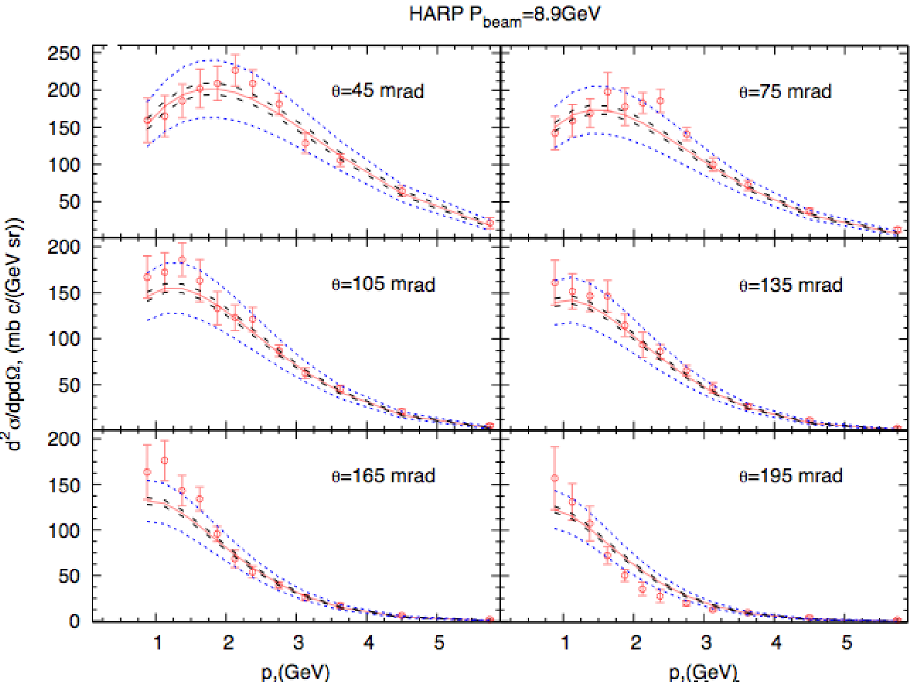
- The MiniBooNE signal is small but relatively easy to isolate
- As data comes in it is classified into 'boxes'
- For boxes to be opened to analysis they must be shown to have a signal $< 1\sigma$
- In the end, 99% of the data were available prior to unblinding...necessary to understand errors

Flux Prediction



Meson production at the target

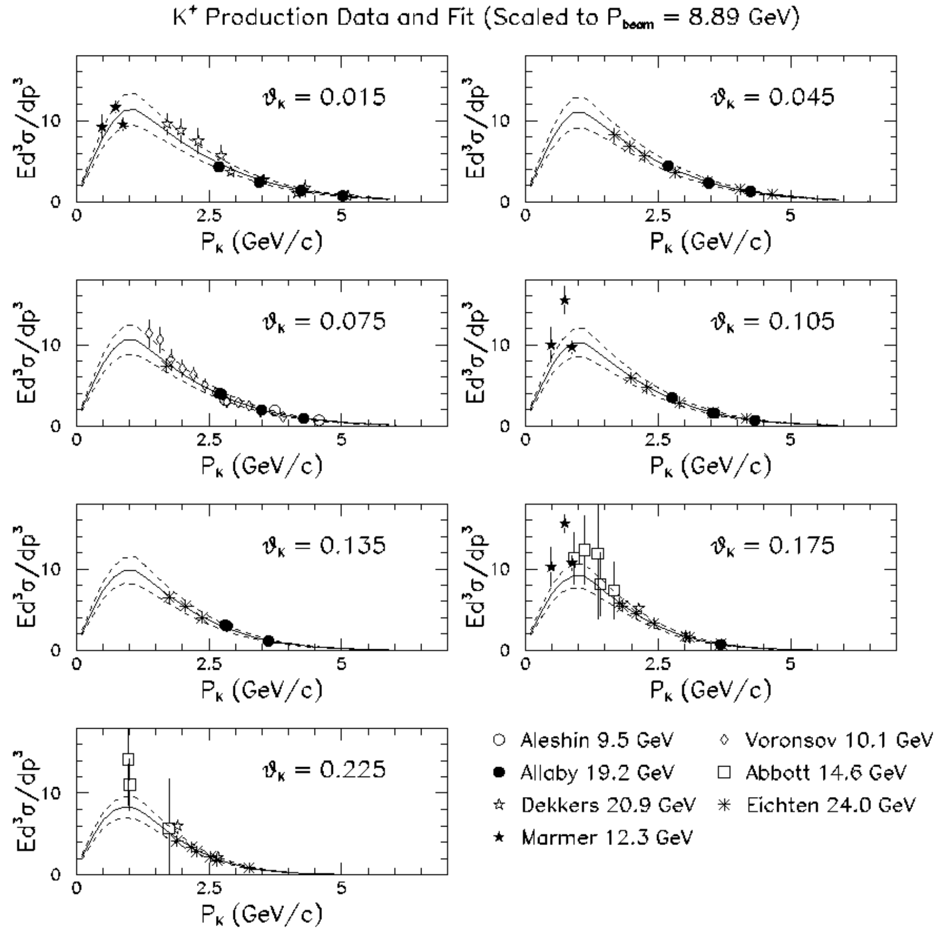
Pions:



HARP collaboration, hep-ex/0702024

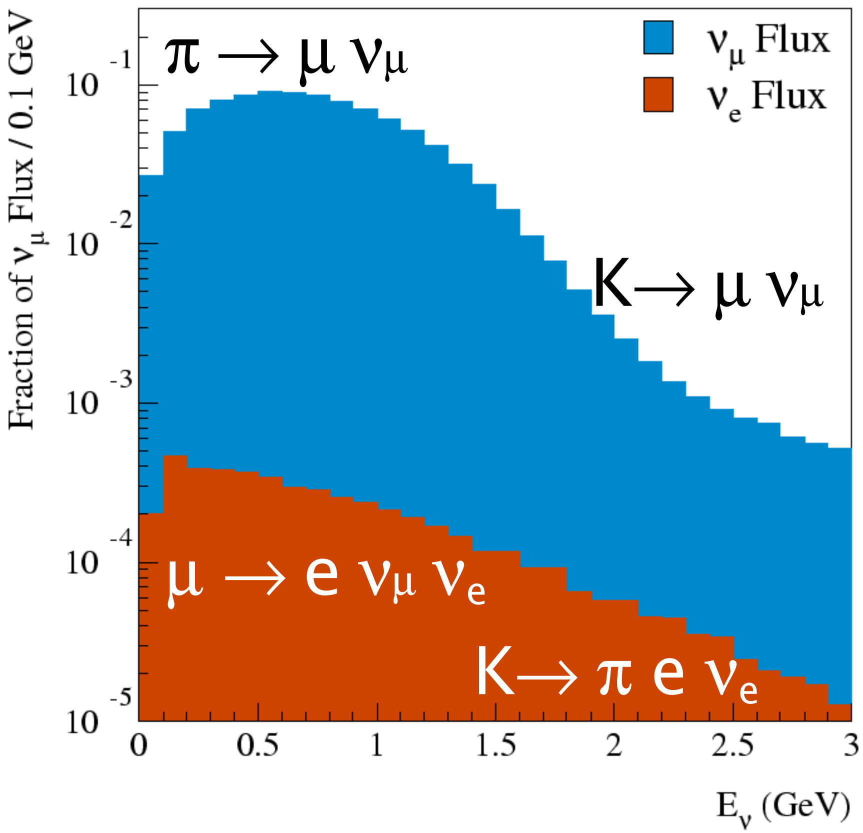
- MiniBooNE members joined the HARP collaboration (* see L. Coney talk later today!)
  - 8 GeV proton beam
  - 5% λ Beryllium target
- Data were fit to Sanford-Wang parameterization

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



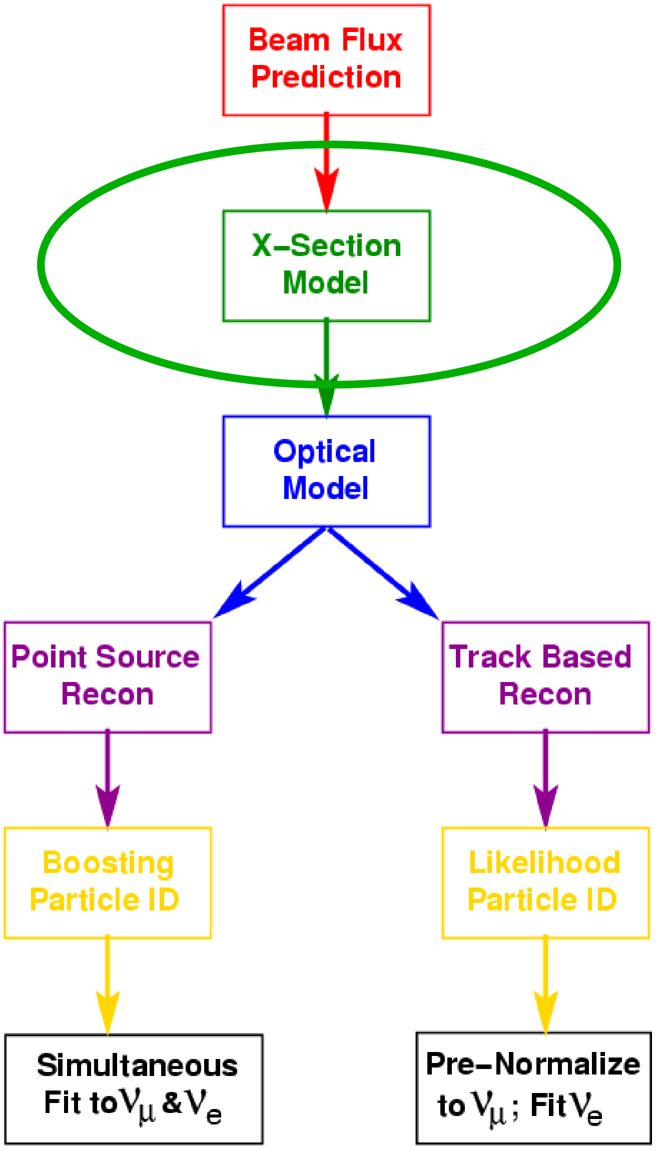
$\nu_e / \nu_\mu = 0.5\%$

"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%

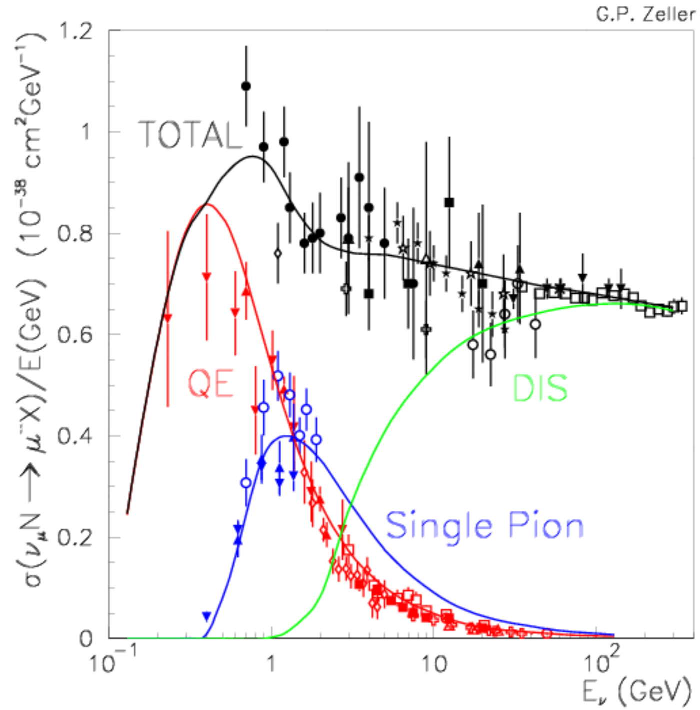
X–Section Model

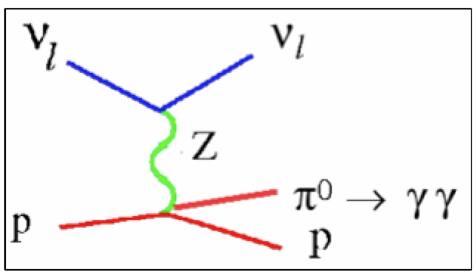


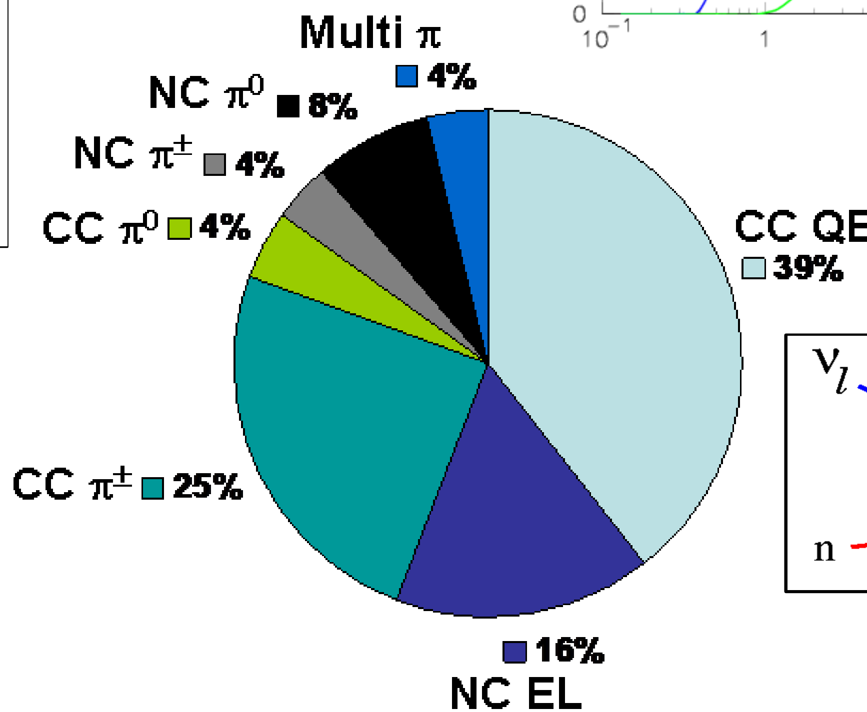
Nuance Monte Carlo

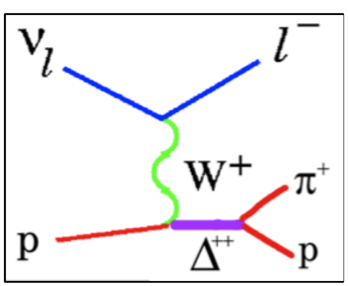
D. Casper, NPS, 112 (2002) 161

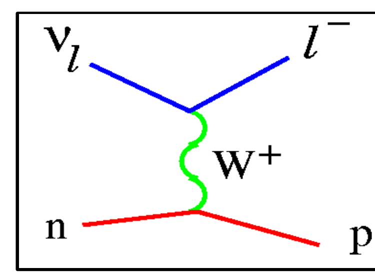
- Used to predict rate of specific ν interactions
- World data for various channels shown at right
- Expected interaction rate in MiniBooNE (before cuts) shown below



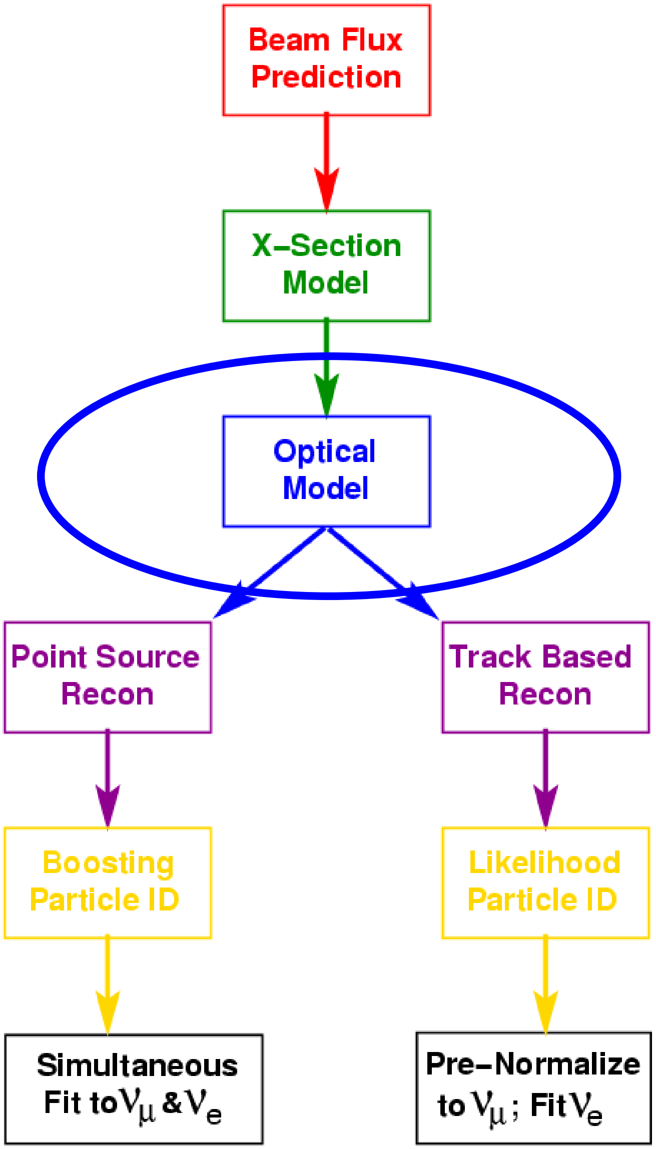




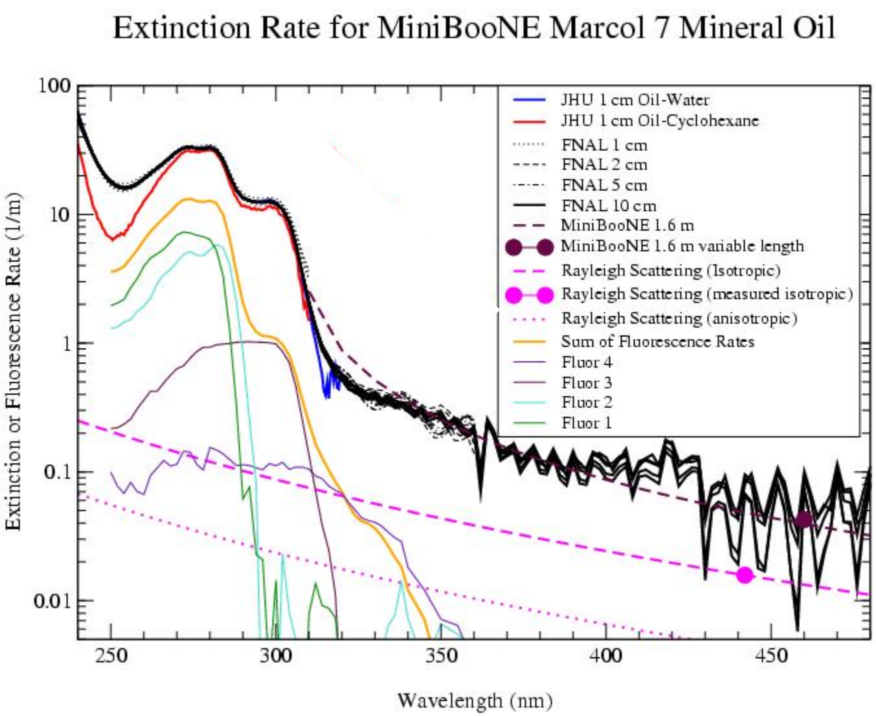


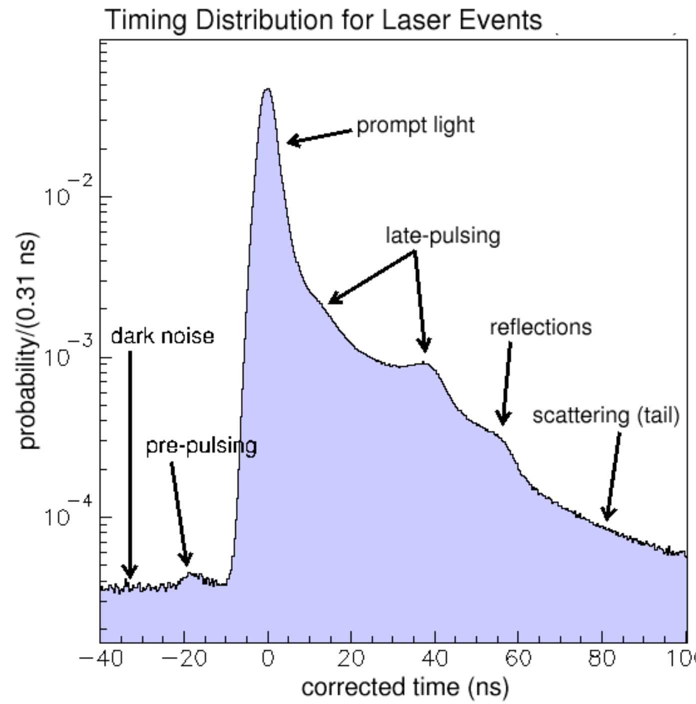


Optical Model



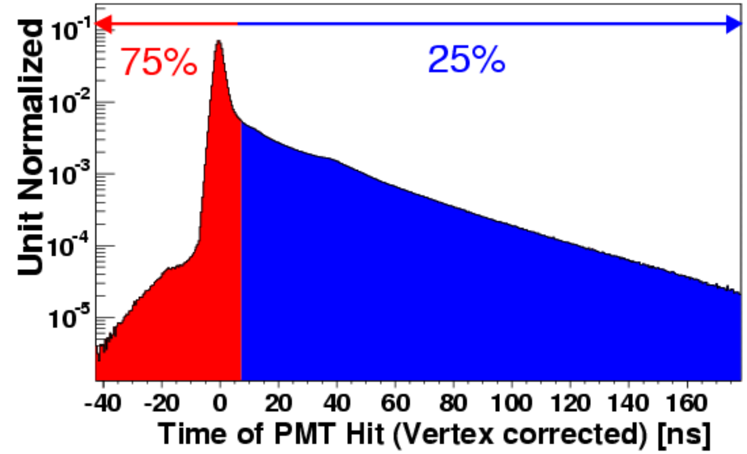
Light propagation in the detector





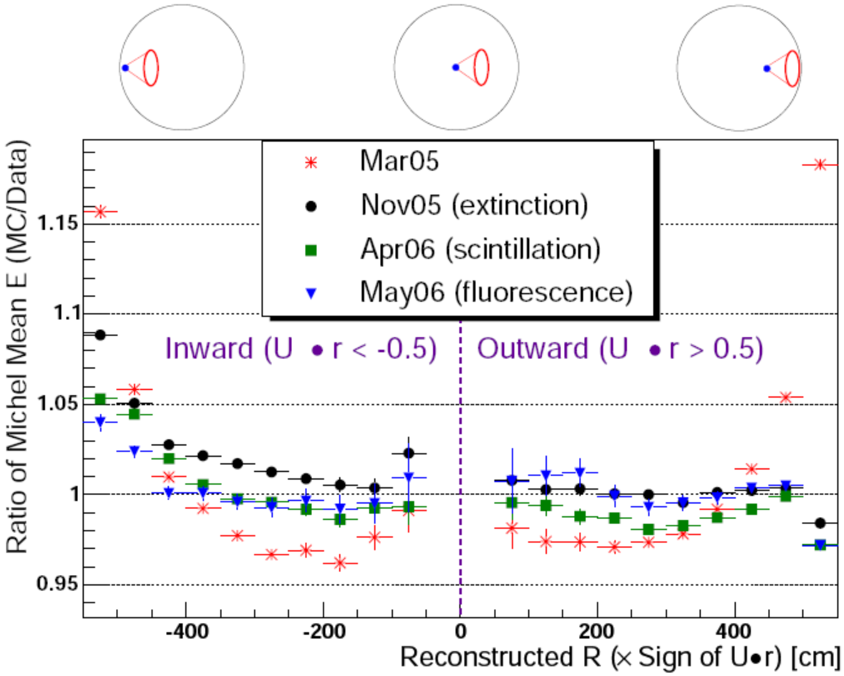
- Optical model is very complex
  - Cerenkov, scintillation, fluorescence
  - PMT Q/t response
  - Scattering, reflection, prepulses
- Overall, about 40 parameters

Michel electron t distribution

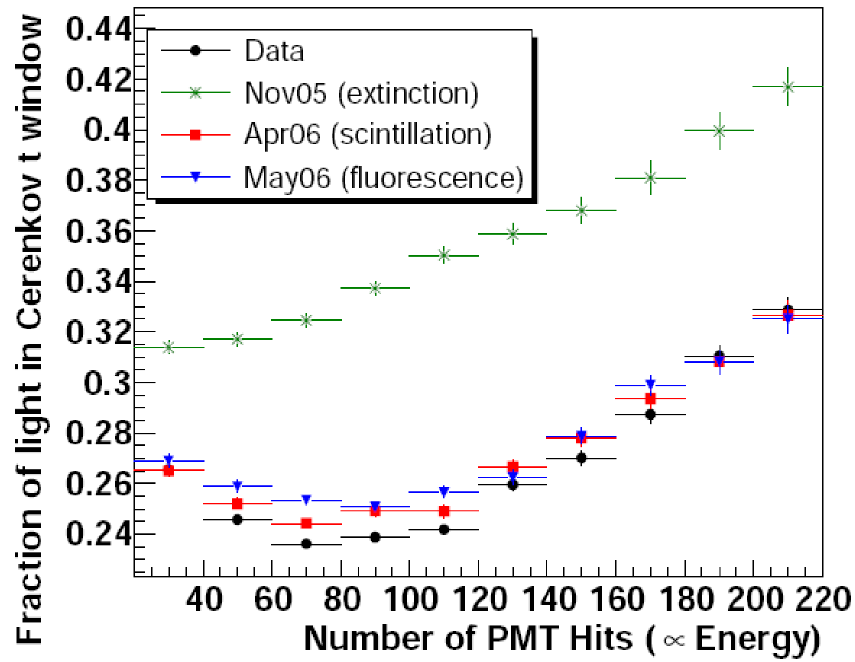


Tuning the optical model

Using Michel electrons...

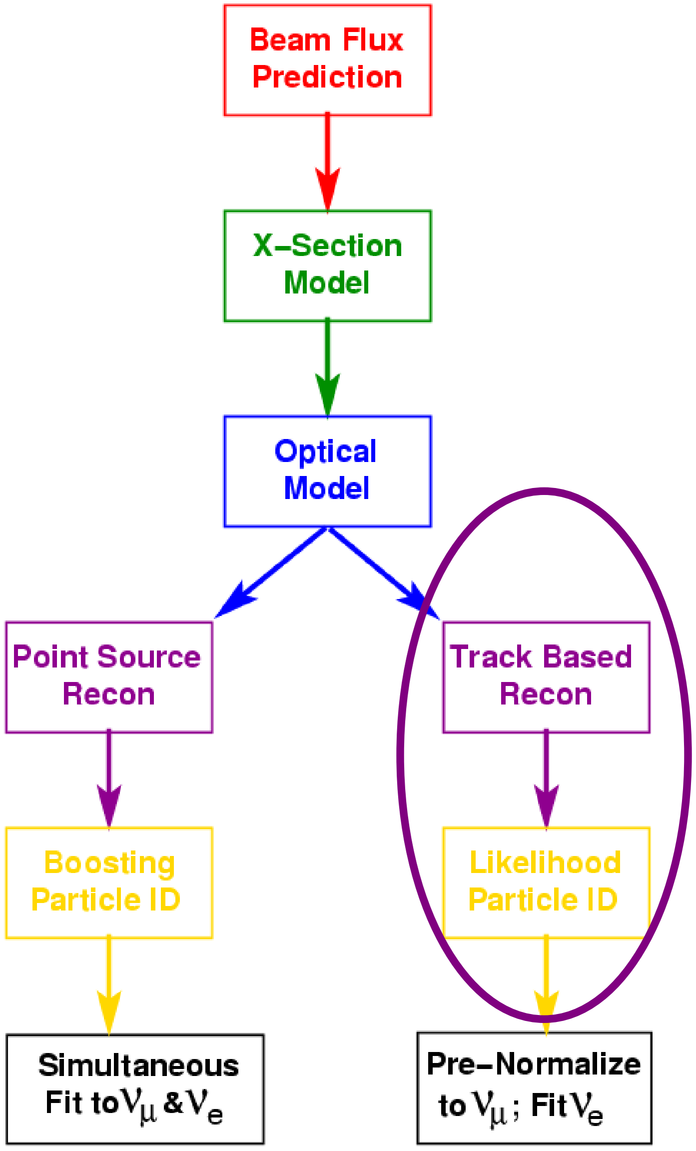


Using NC elastic ν interactions...



- 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

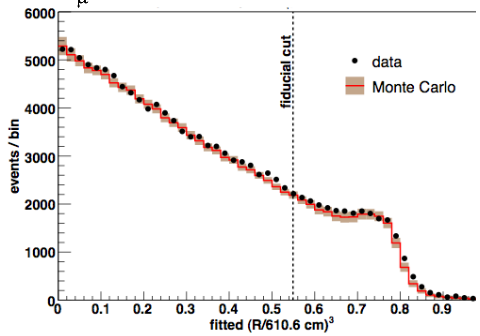
Track–Based Likelihood (TBL) Reconstruction and Particle ID

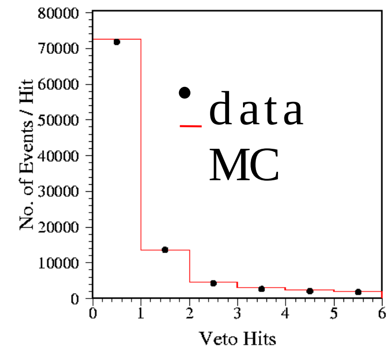


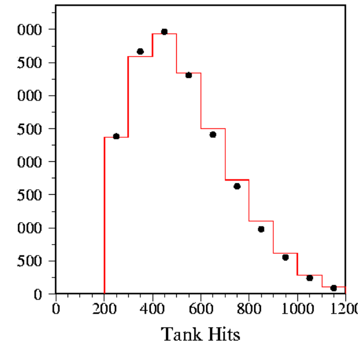
TBL Analysis: Separating e from μ

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

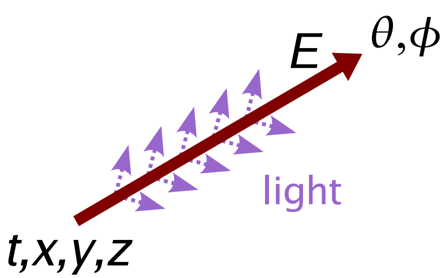
ν_μ CCQE events (2 subevent)

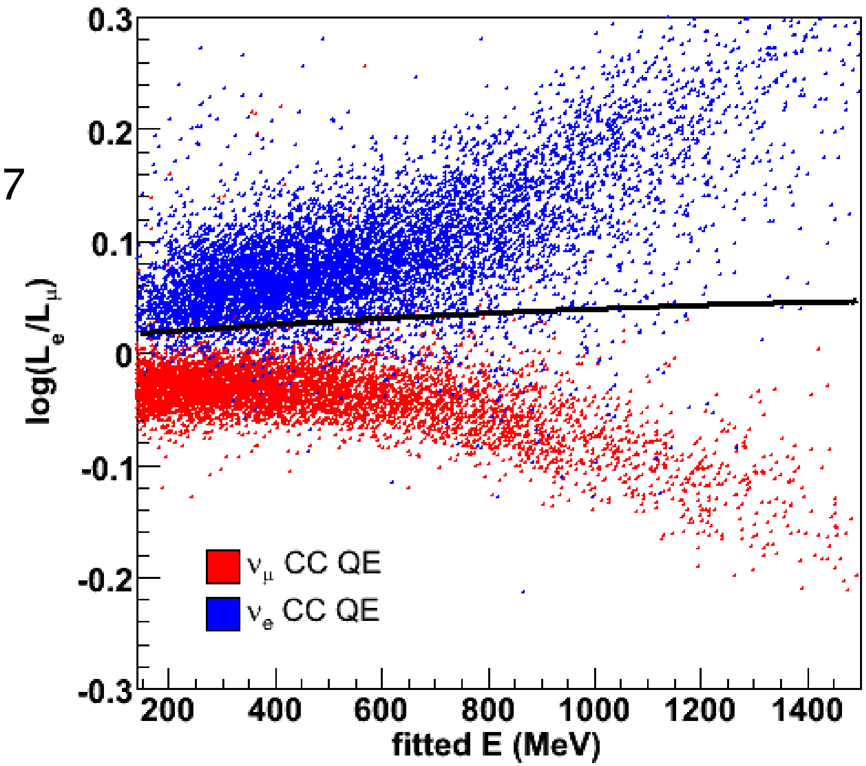






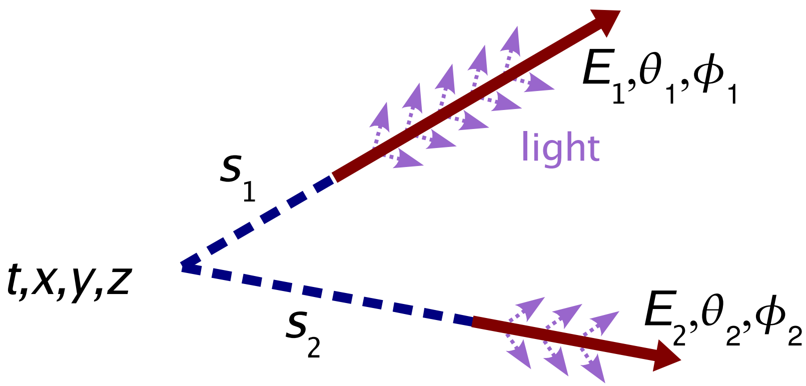
- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

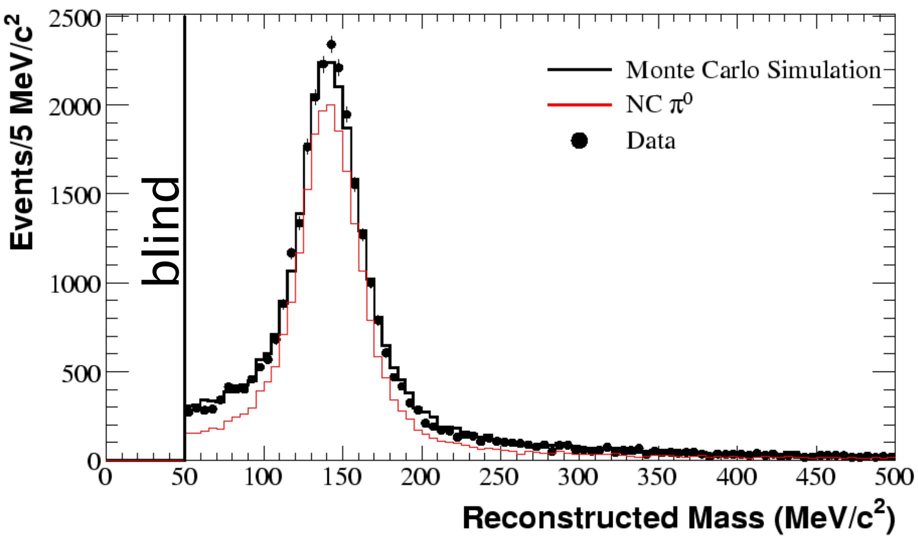


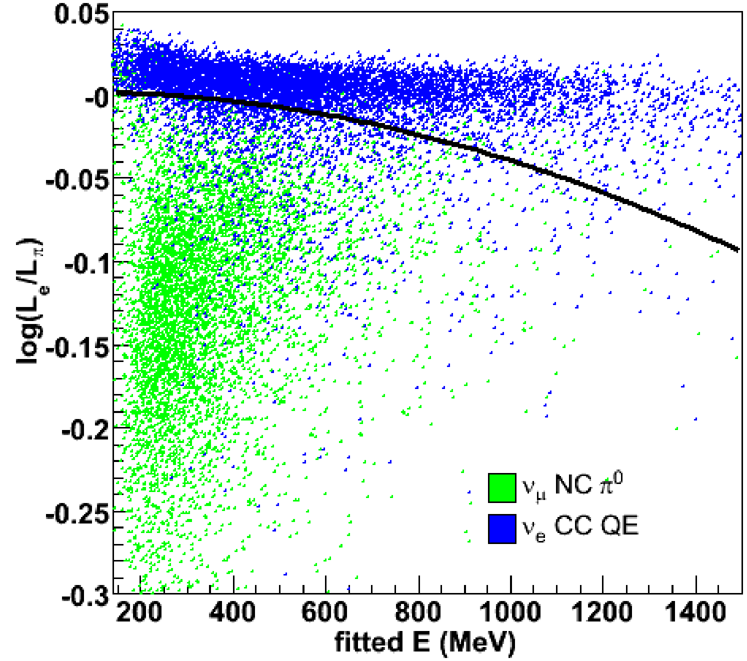


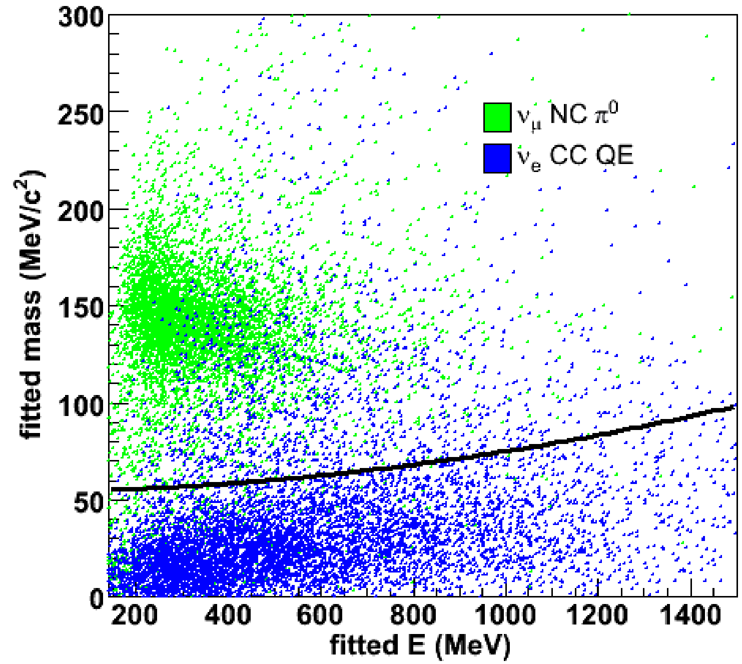
Separating e from π^0

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

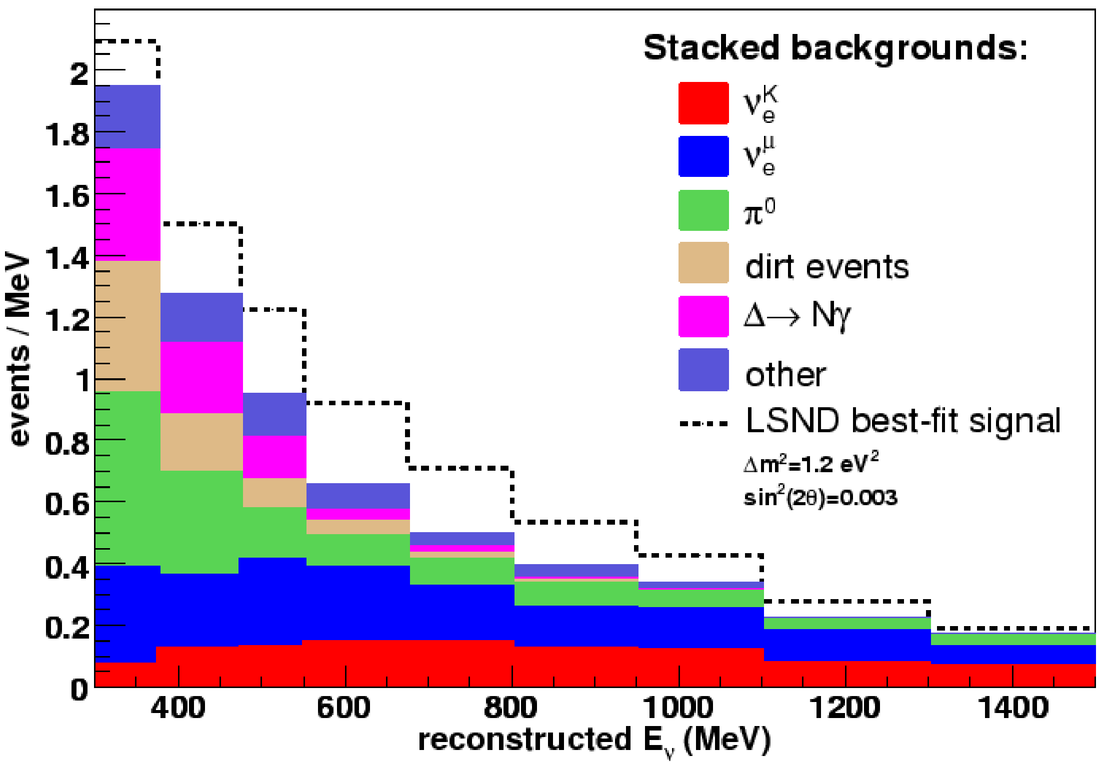








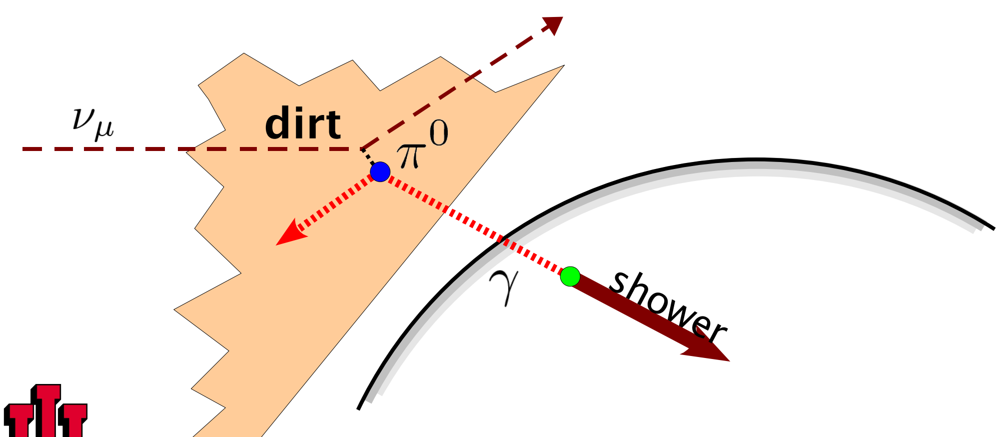
TBL Analysis: Expected event totals

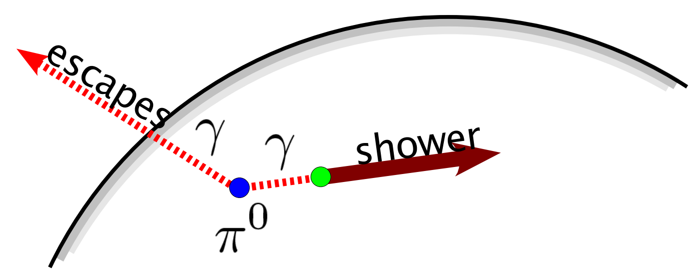


475 MeV – 1250 MeV

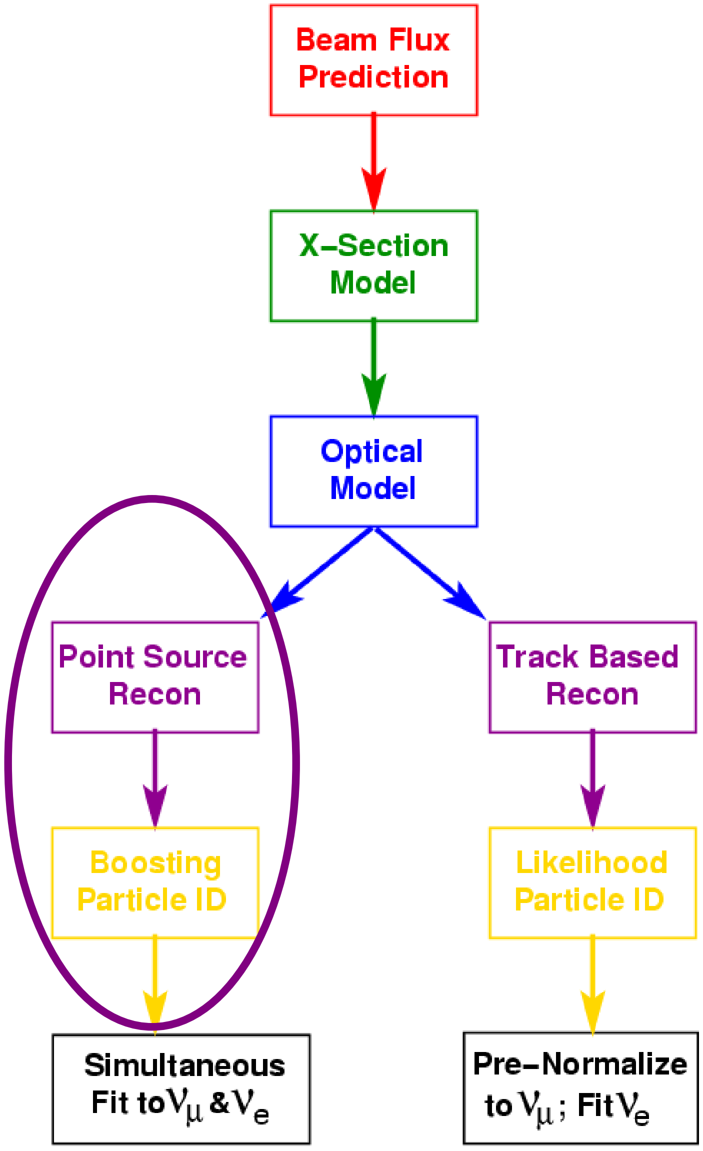
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \to N\gamma$	20
other	33
total	358

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





Boosted Decision Tree (BDT) Reconstruction and Particle ID



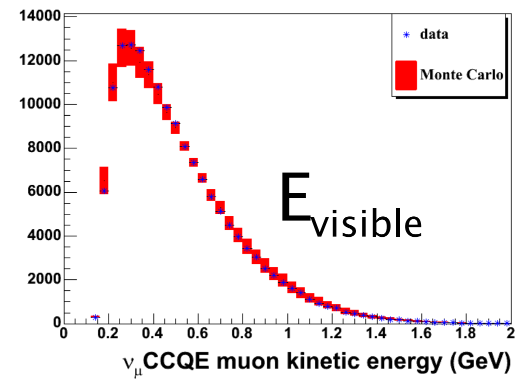
BDT Reconstruction

- 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.

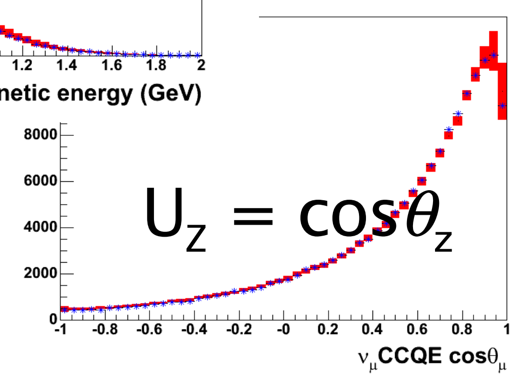
BDT Resolution:
vertex: 24 cm
direction: 3.8°
energy 14%

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

- Boosting Step 1: Define input variable
  - 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)

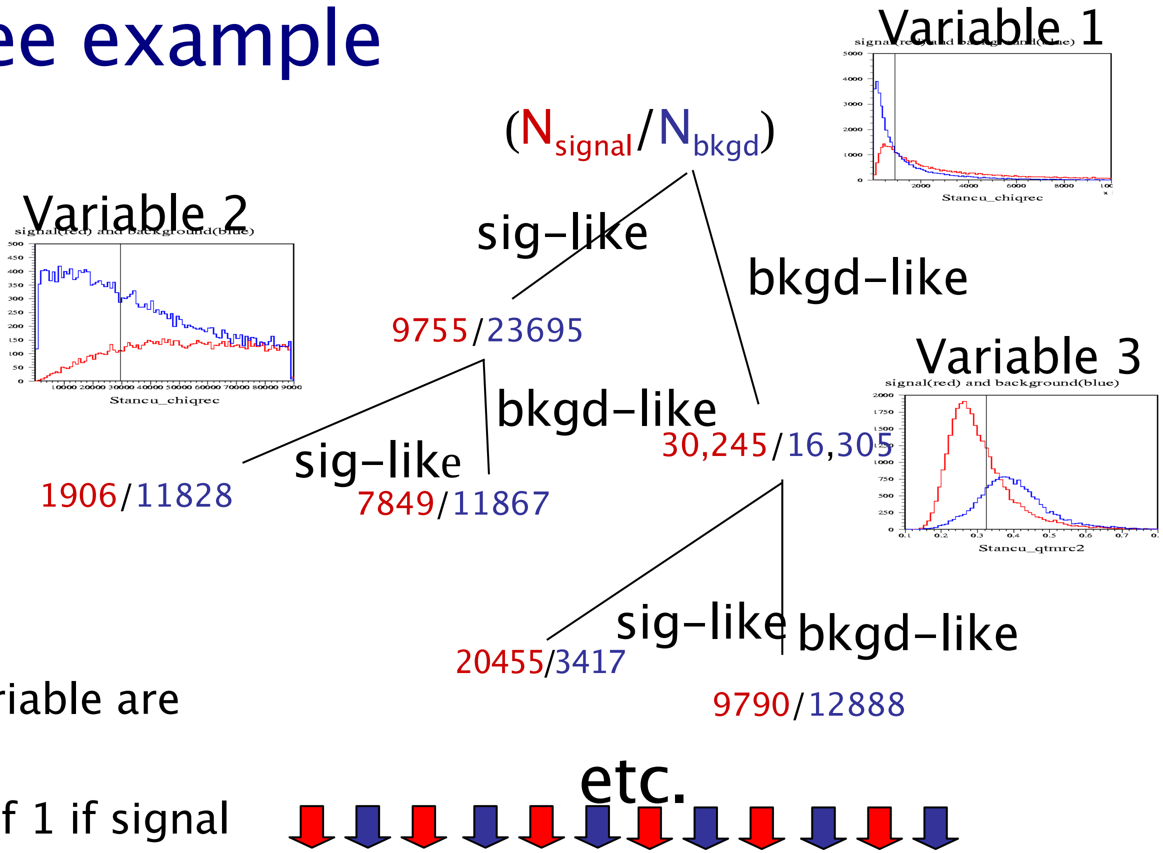


ν_μ CCQE Examples



Decision tree example

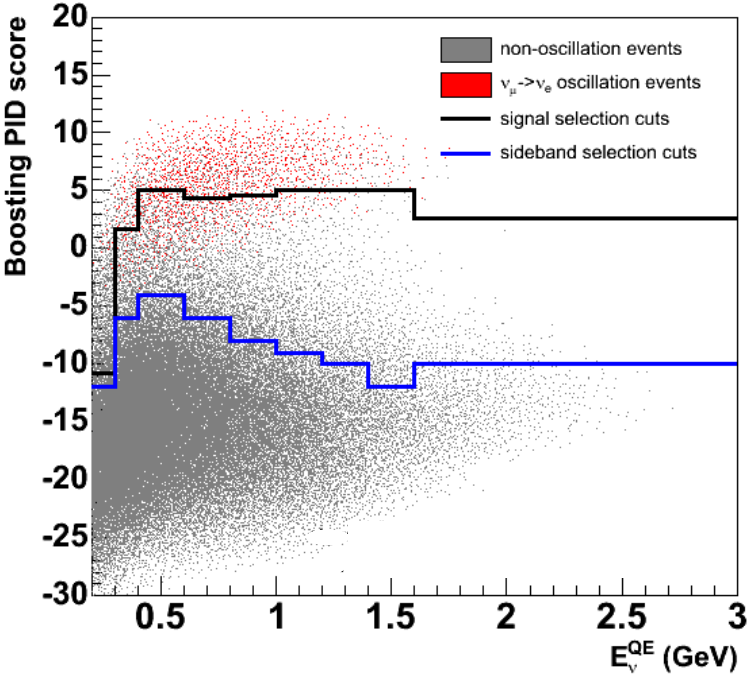
(sequential series of cuts based on MC study)



This tree is one of many possibilities...

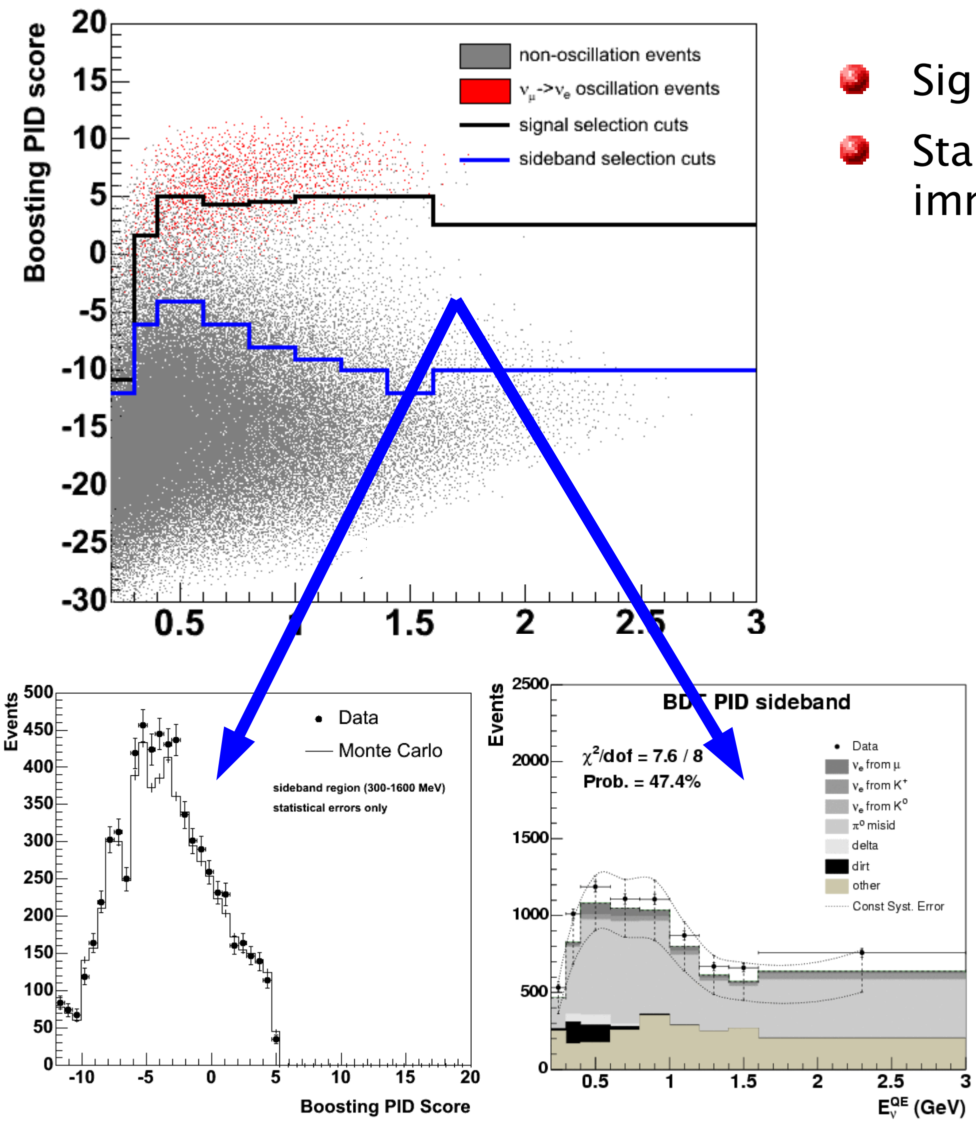
- Optimal cuts on each variable are determined
- An event gets a weight of 1 if signal -1 if background
- Hard to identify backgrounds are iteratively given more weight
- Many trees built
- PID 'score' established from ensemble

BDT Analysis: Signal/background regions



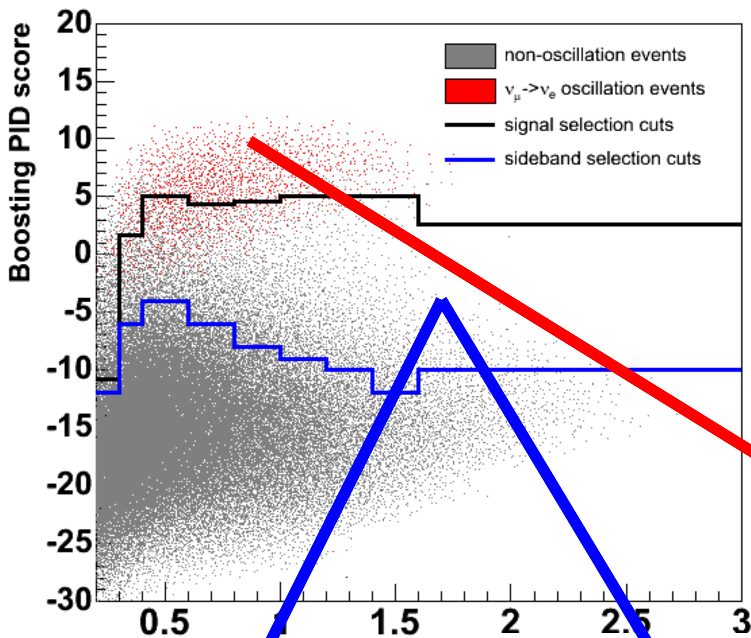
- Signal prediction (red) versus all bkgs (gray)

BDT Analysis: Signal/background regions

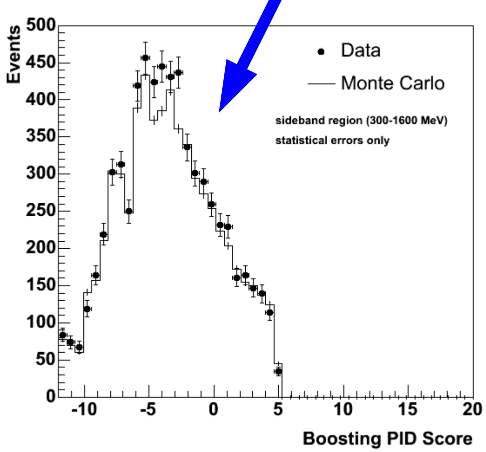


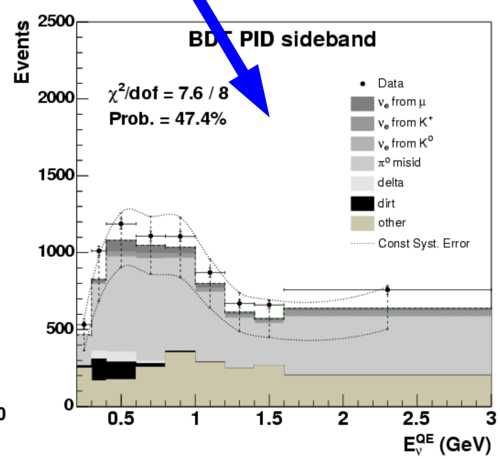
- Signal prediction (red) versus all bkgs (gray)
- Start by looking at data in 'sideband'...region immediately adjacent to signal region

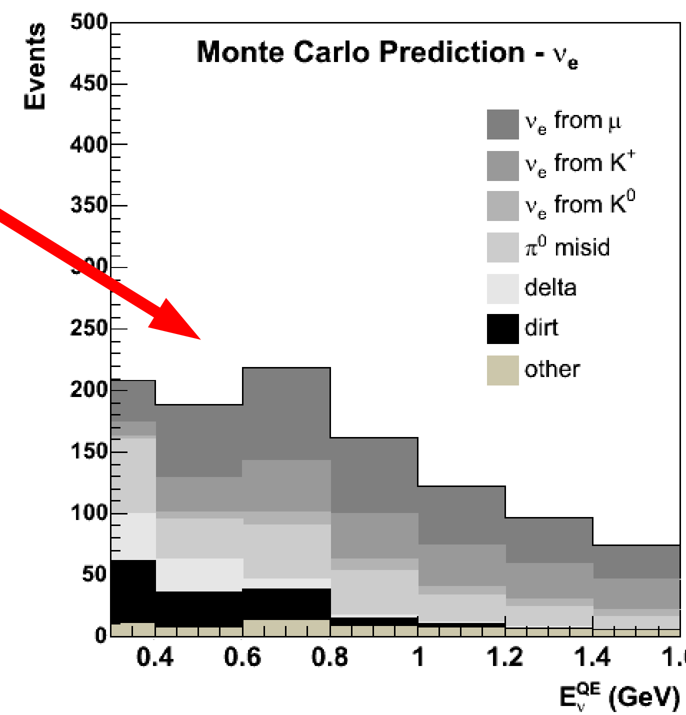
BDT Analysis: Signal/background regions



- 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



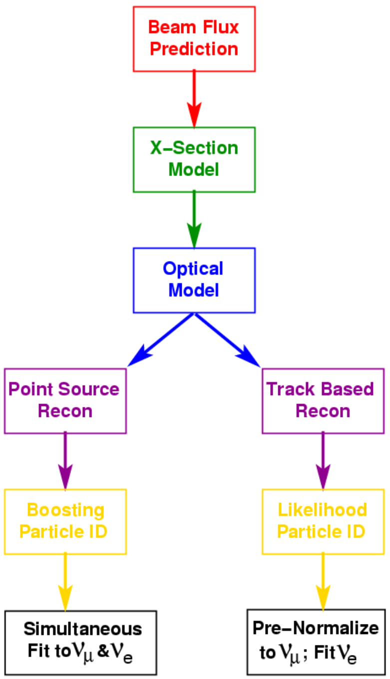




Systematic Error Analysis and Results

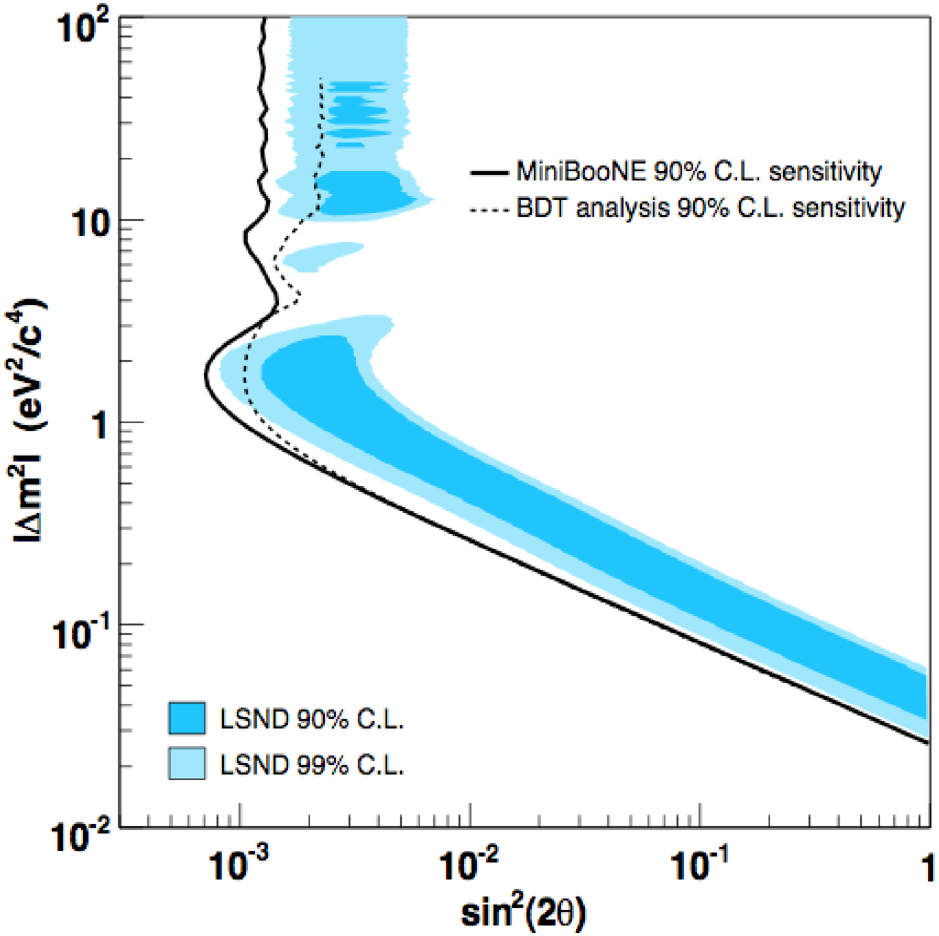
Final error budget (diagonals only...greatly simplified)

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

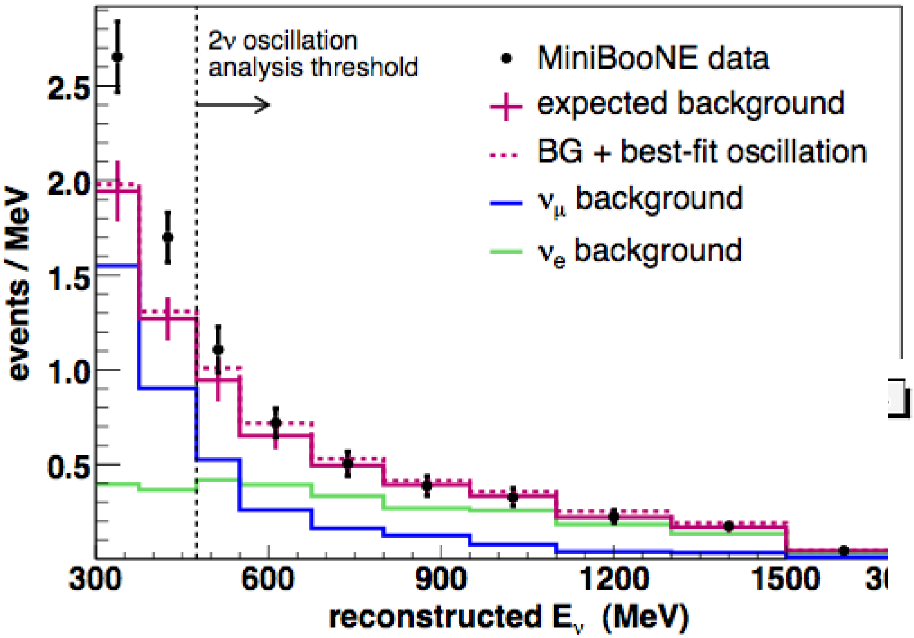
BDT/TBL sensitivity comparison



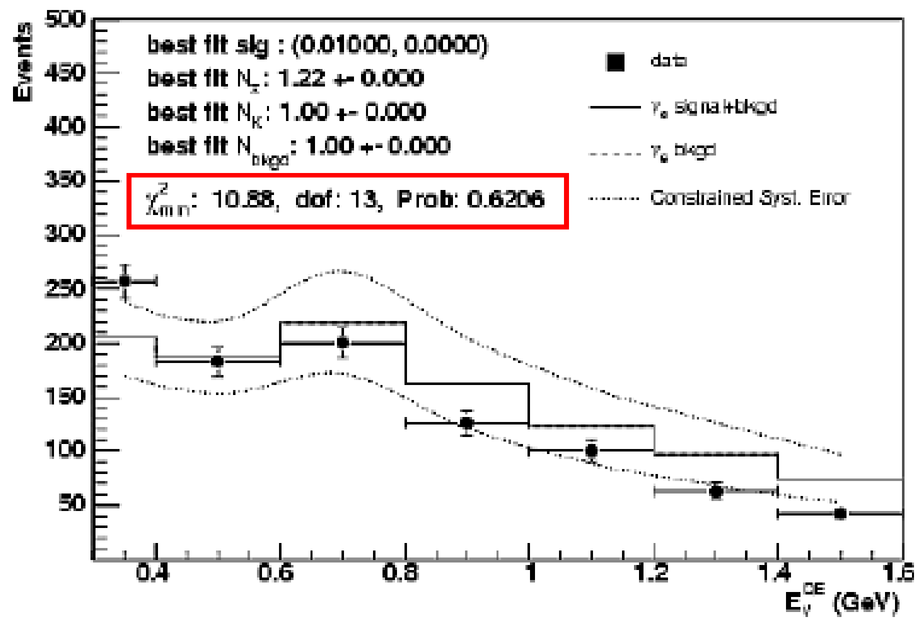
- Sensitivity is determined from simulation only (no data yet!)
- Decided before unblinding that the analysis with higher sensitivity would be the final analysis
- TBL is better at high Δm^2
- 90% CL defined by $\Delta\chi^2 = 1.64$

After many man-years and CPU-hours...

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



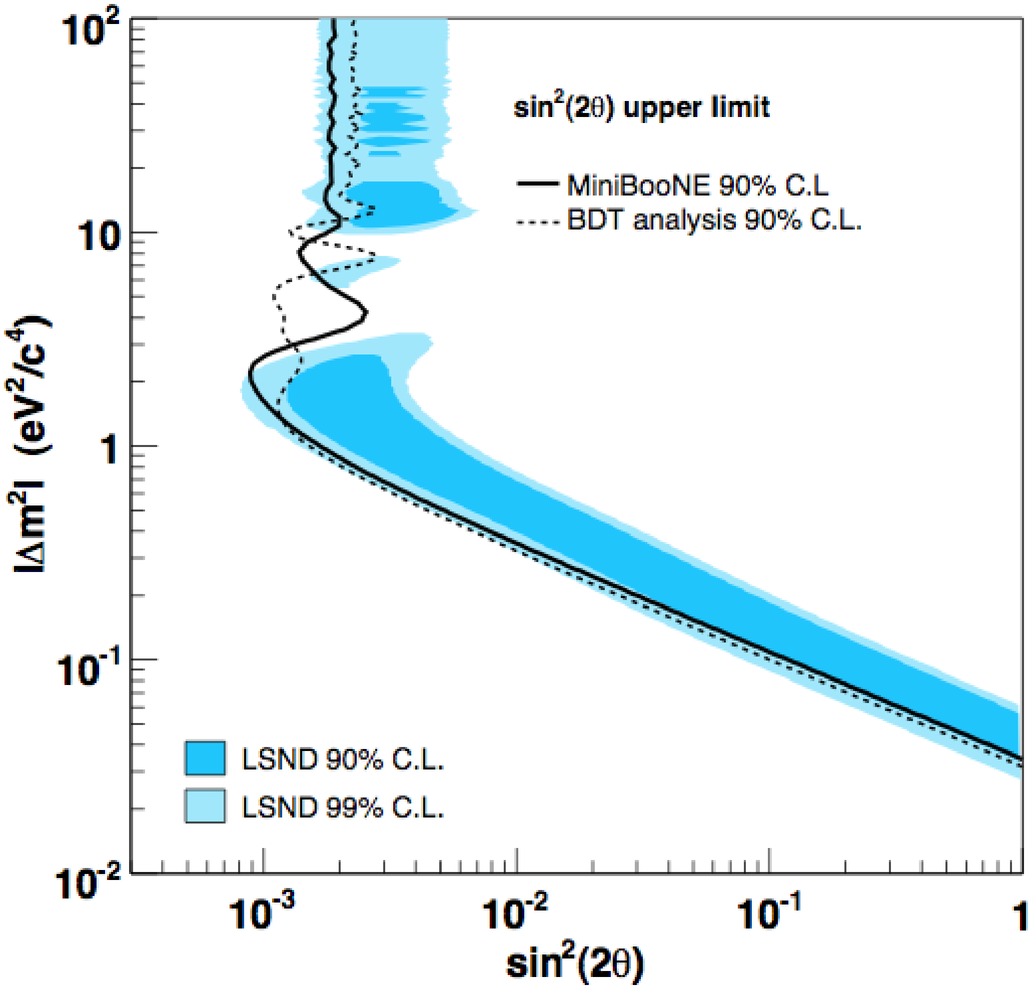
- TBL shows no sign of an excess in the analysis region (where the LSND signal is expected for the 2ν mixing hypothesis)
- Visible excess at low E



- 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

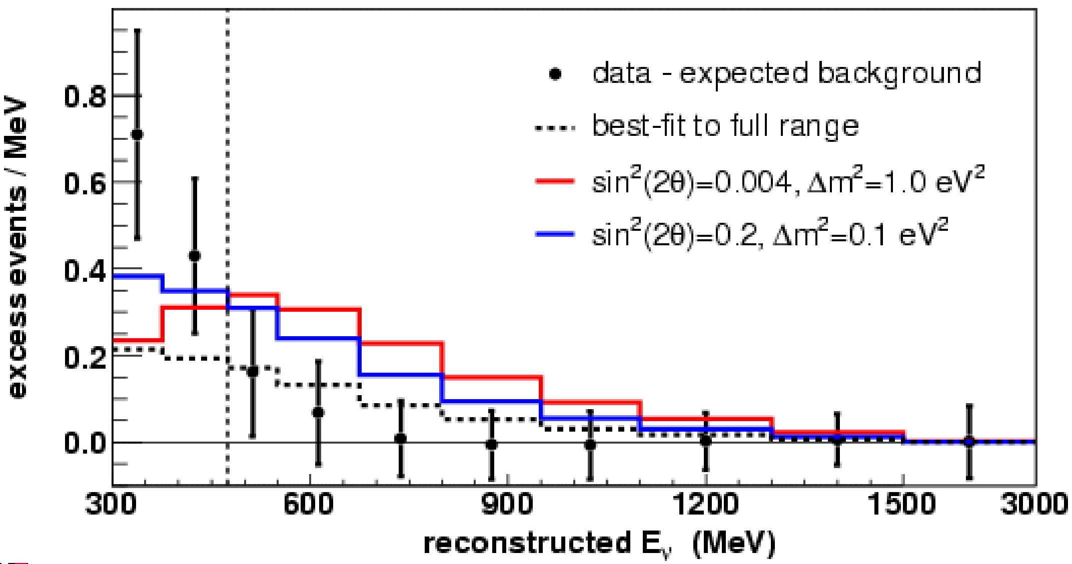
Fit results mapped into $\sin^2(2\theta)$ Δm^2 plane



- 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.

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
NC π^0	48k
NC $\pi^{+/-}$	27k

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