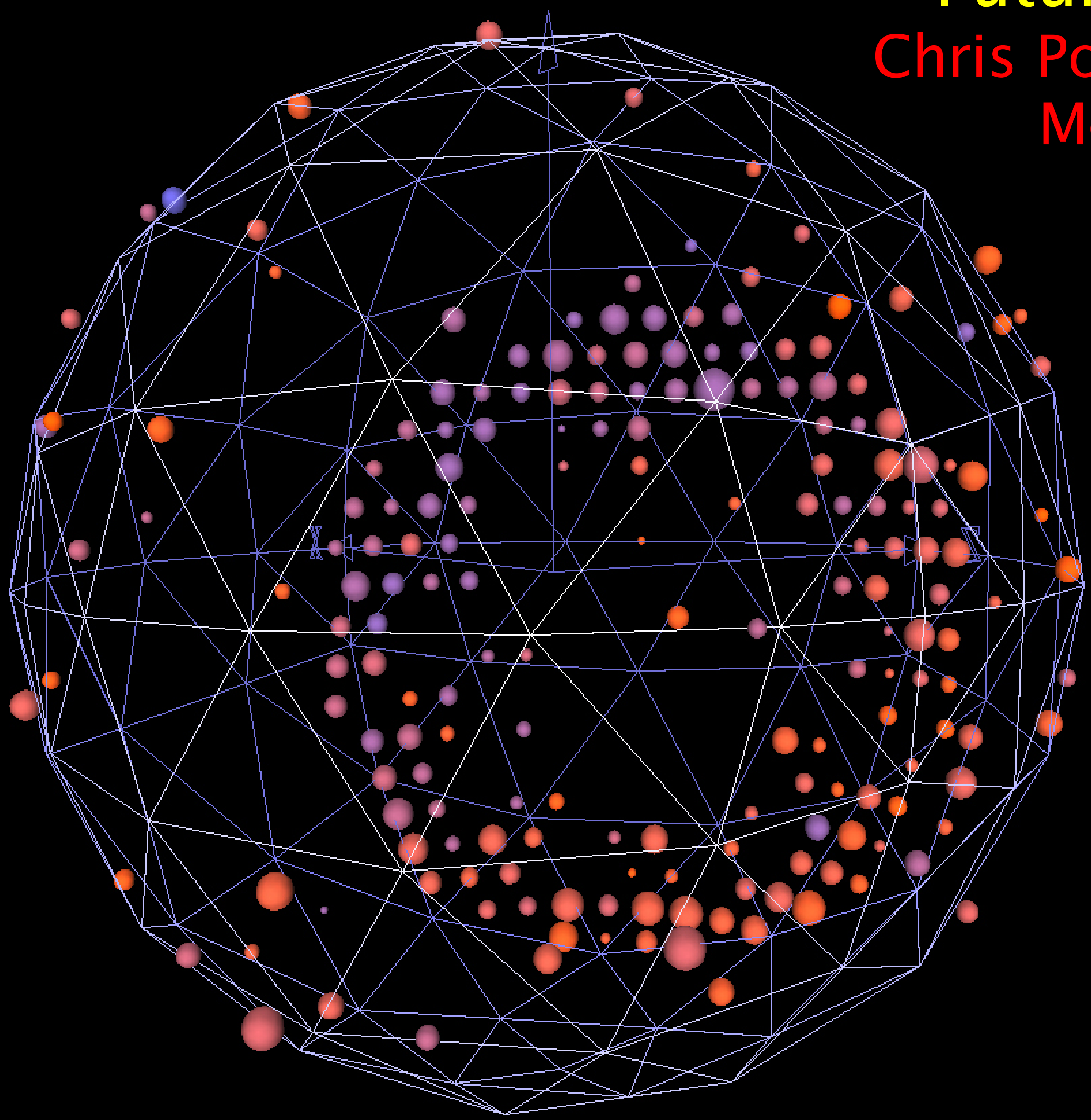
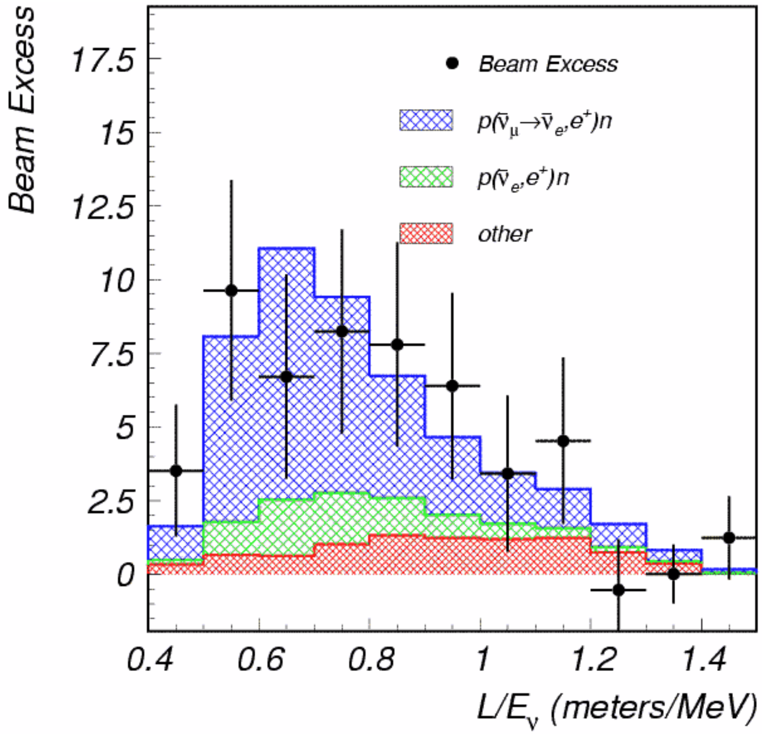
MiniBooNE Results and Future BNB Endeavors

Chris Polly, Indiana University

Moriond EW 2008



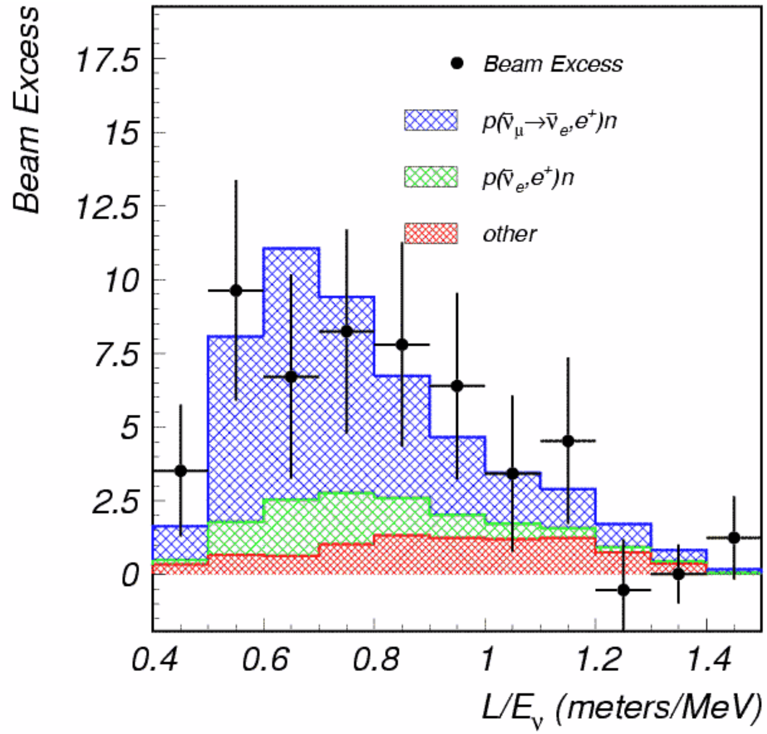
MiniBooNE's Motivation: The LSND signal



- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2ν mixing hypothesis:

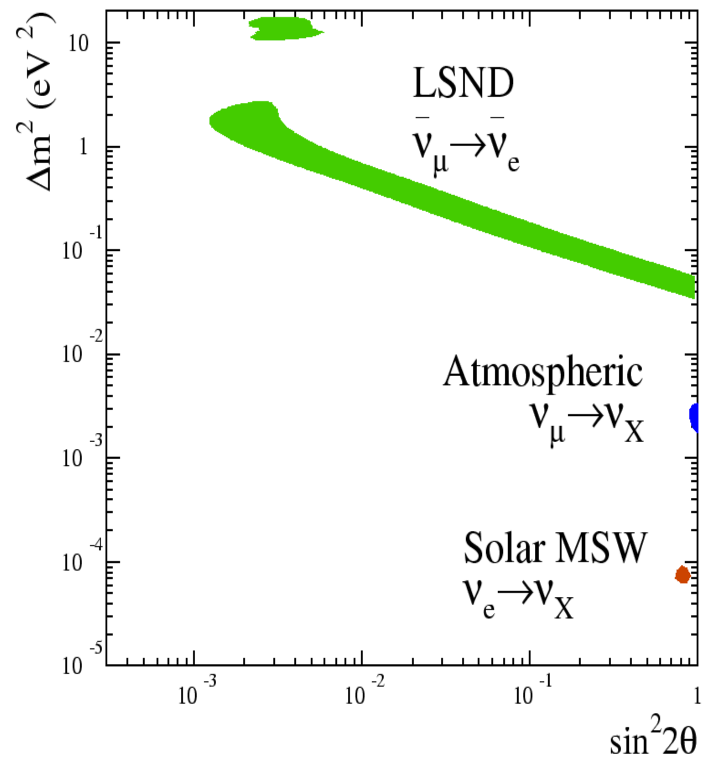
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

MiniBooNE's Motivation: The LSND signal



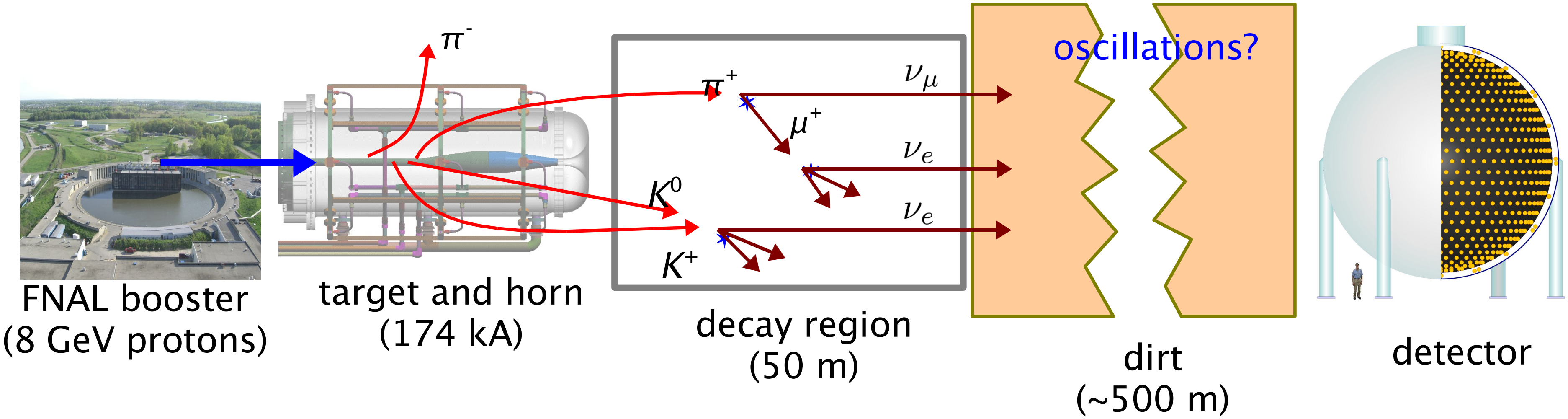
- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2ν mixing hypothesis:

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



- $\Delta m^2 \sim 1$ eV^2 impossible with only 3ν
- Requires extraordinary physics!
  - Sterile neutrinos *hep-ph/0305255*
    - Update from Thomas Schwetz later in session
  - Neutrino decay *hep-ph/0602083*
  - Lorentz/CPT viol. *PRD(2006)105009* (T. Katori here!)
  - Extra dimensions *hep-ph/0504096*
- Unlike atmos and solar...LSND unconfirmed

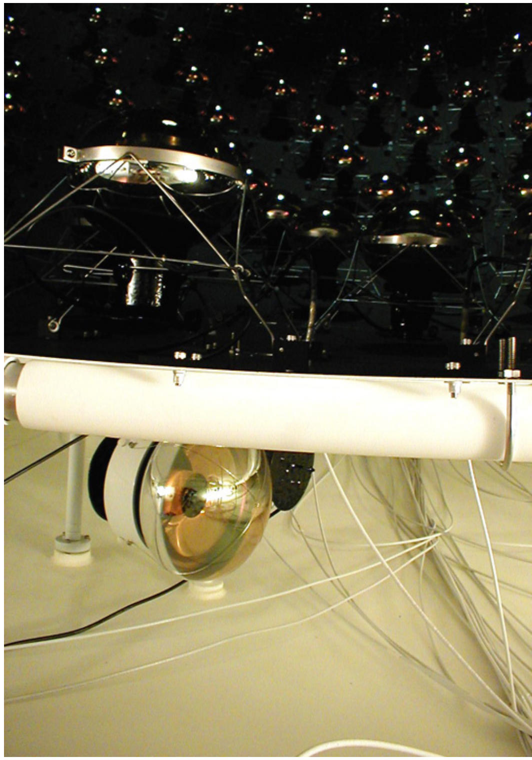
The MiniBooNE design strategy...must make ν_μ



- 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:

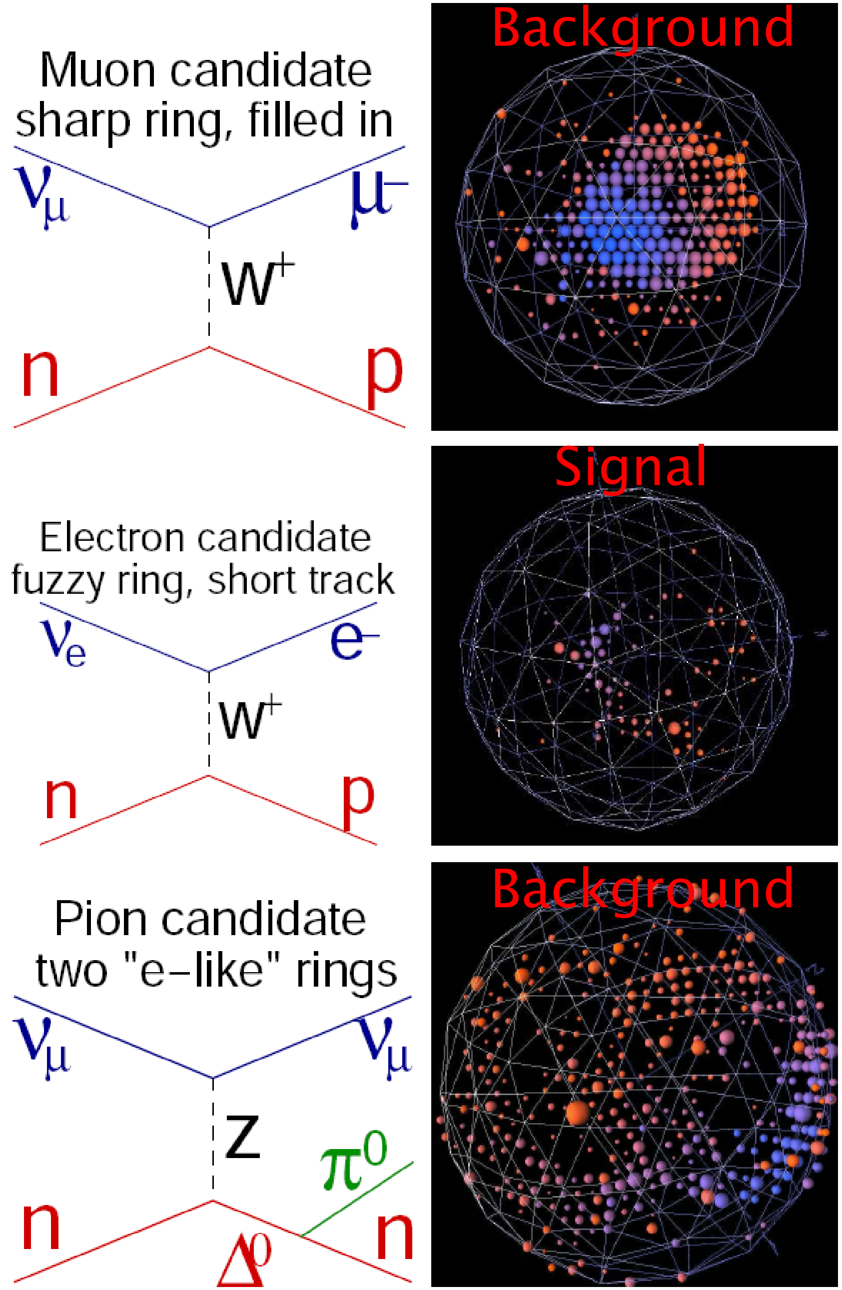
MiniBooNE:	(0.5 km) / (0.8 GeV)
LSND:	(0.03 km) / (0.05 GeV)

- 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

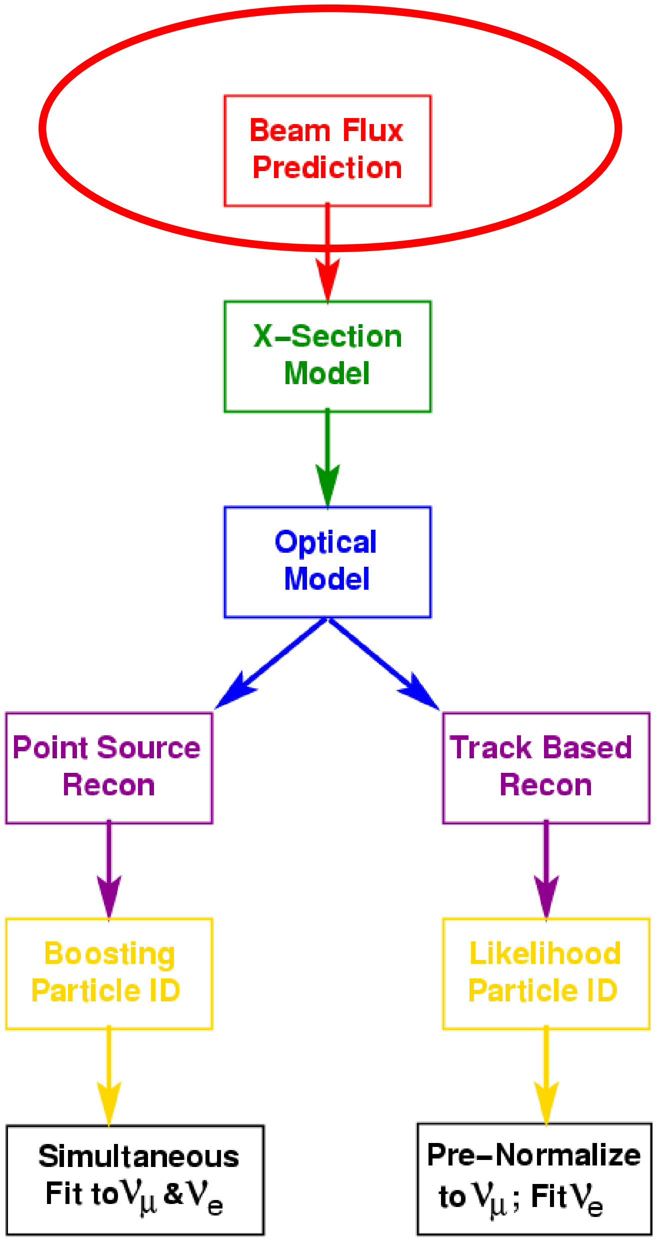


Key points about the signal

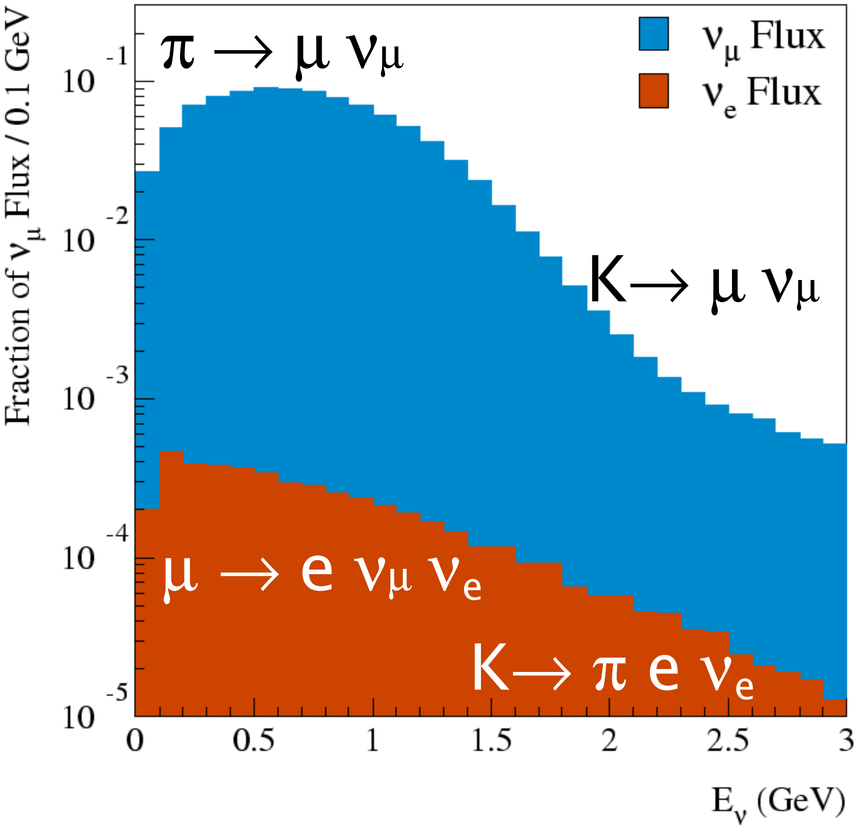
- LSND oscillation probability is < 0.3%
- After cuts, MiniBooNE has to be able to find ~300 ν_e CCQE interactions in a sea of ~150,000 ν_μ CCQE
- Intrinsic ν_e background
  - Actual ν_e produced in the beamline from muons and kaons
  - Irreducible at the event level
  - E spectrum differs from signal
- 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 more rare, but harder to separate
  - Can be reduced with better PID
- MiniBooNE is a ratio measurement with the ν_μ constraining flux X cross-section



Flux Prediction



Final neutrino flux estimation



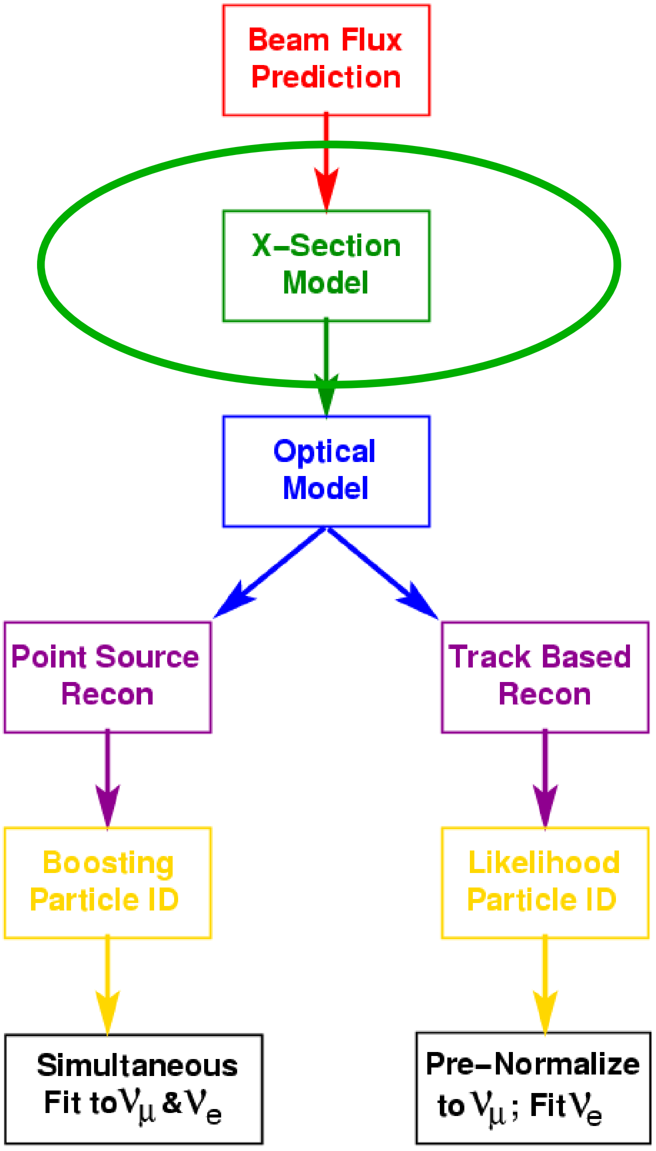
$\nu_e / \nu_\mu = 0.5\%$

"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%

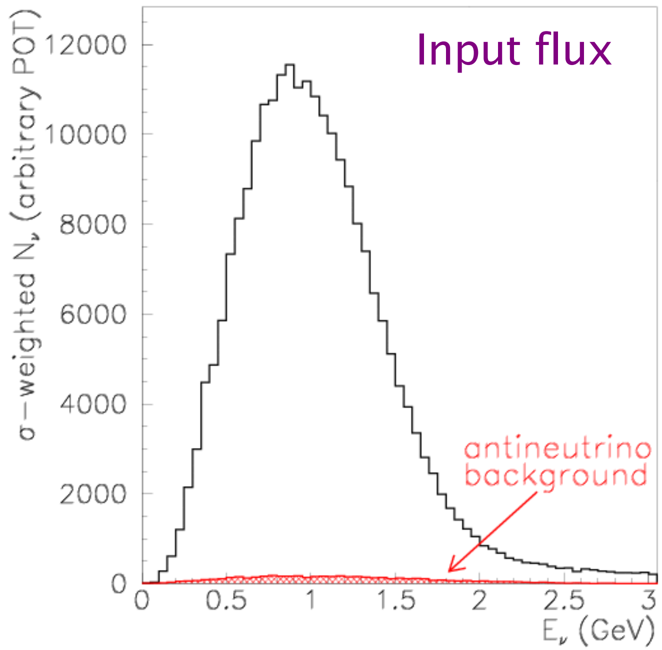
X–Section Model

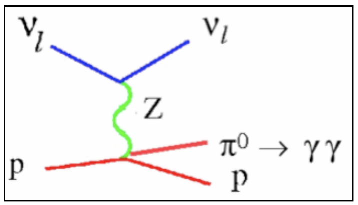


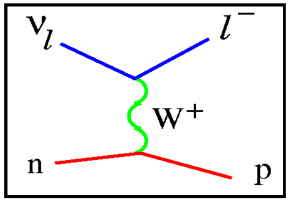
Nuance Monte Carlo

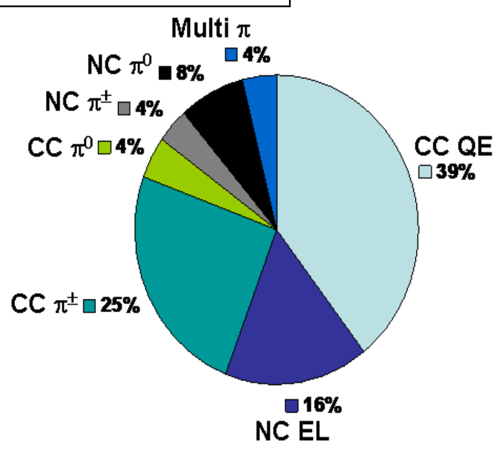
D. Casper, NPS, 112 (2002) 161

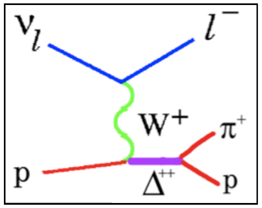
- Comprehensive generator, covers entire E_ν range
- Predicts relative rate of specific ν interactions from input flux
- Expected interaction rates in MiniBooNE (before cuts) shown below
- Based on world data, ν_μ CC shown below right

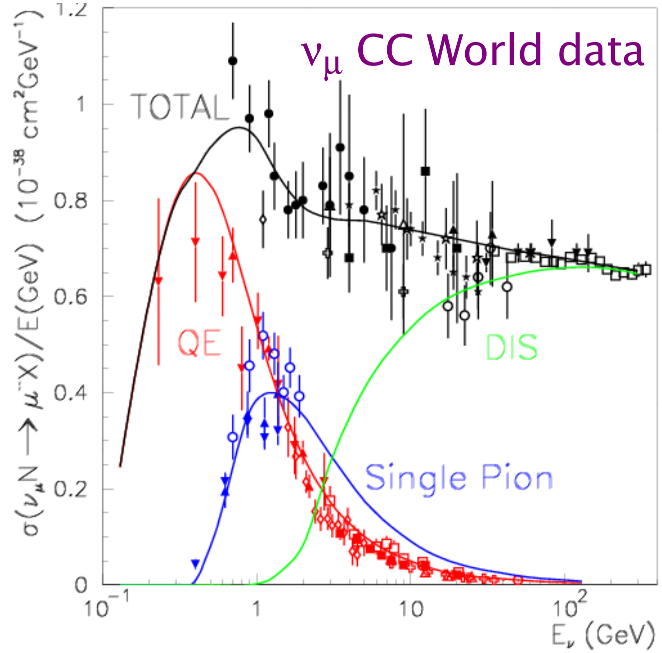








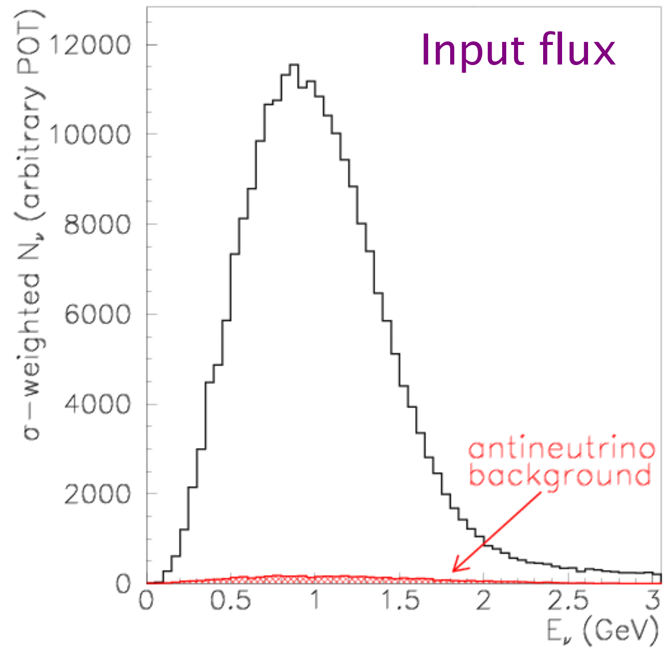


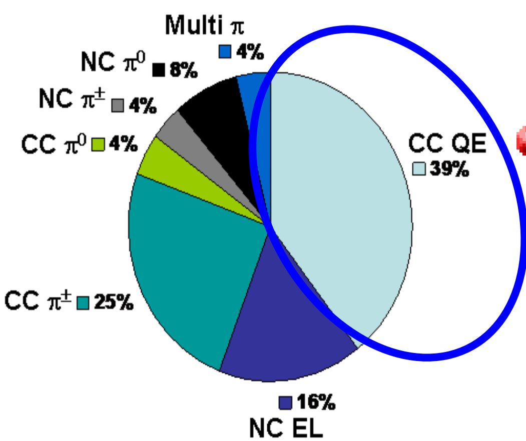


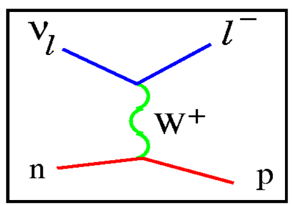
Nuance Monte Carlo

D. Casper, NPS, 112 (2002) 161

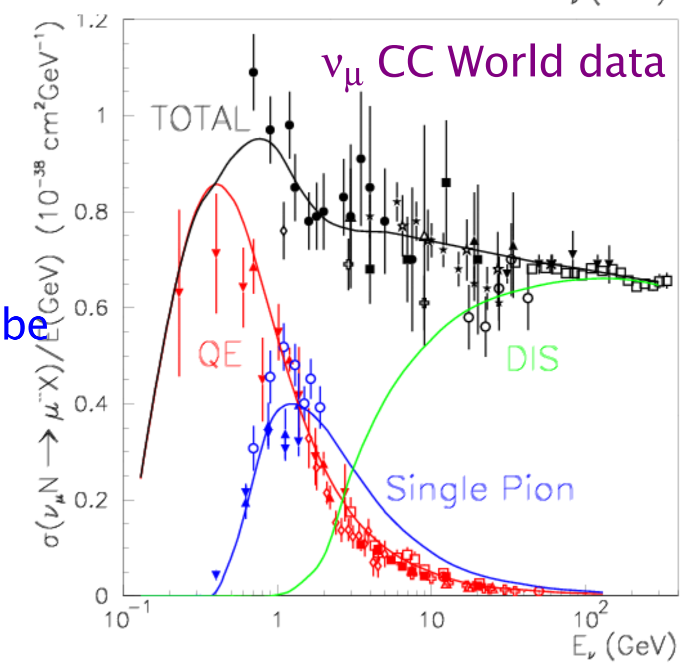
- Comprehensive generator, covers entire E_ν range
- Predicts relative rate of specific ν interactions from input flux
- Expected interaction rates in MiniBooNE (before cuts) shown below
- Based on world data, ν_μ CC shown below right
- Also tuned on internal data







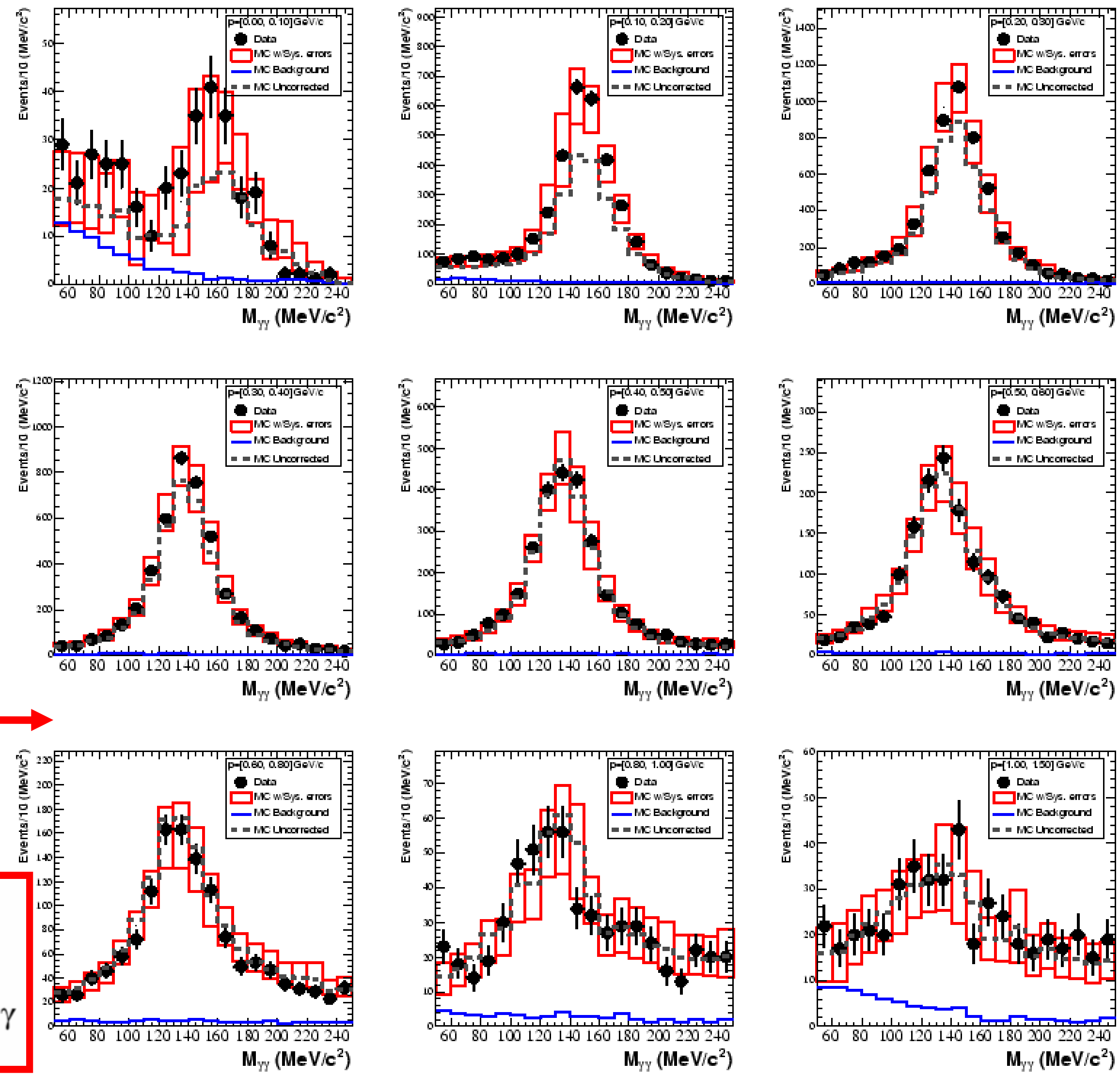
- Teppei Katori will describe later in the session

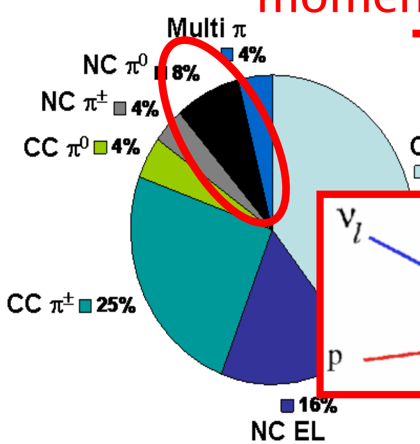


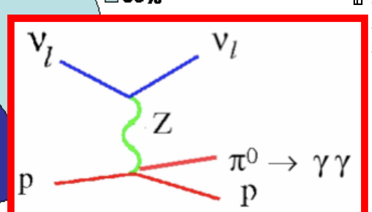
Tuning Nuance on internal NC π^0 data

- NC π^0 important background
- 90%+ pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)...see Van Nguyen's YS2 talk
- Measure rate as function of π momentum
- Default MC underpredicts rate at low momentum
- $\Delta \rightarrow N\gamma$ also constrained

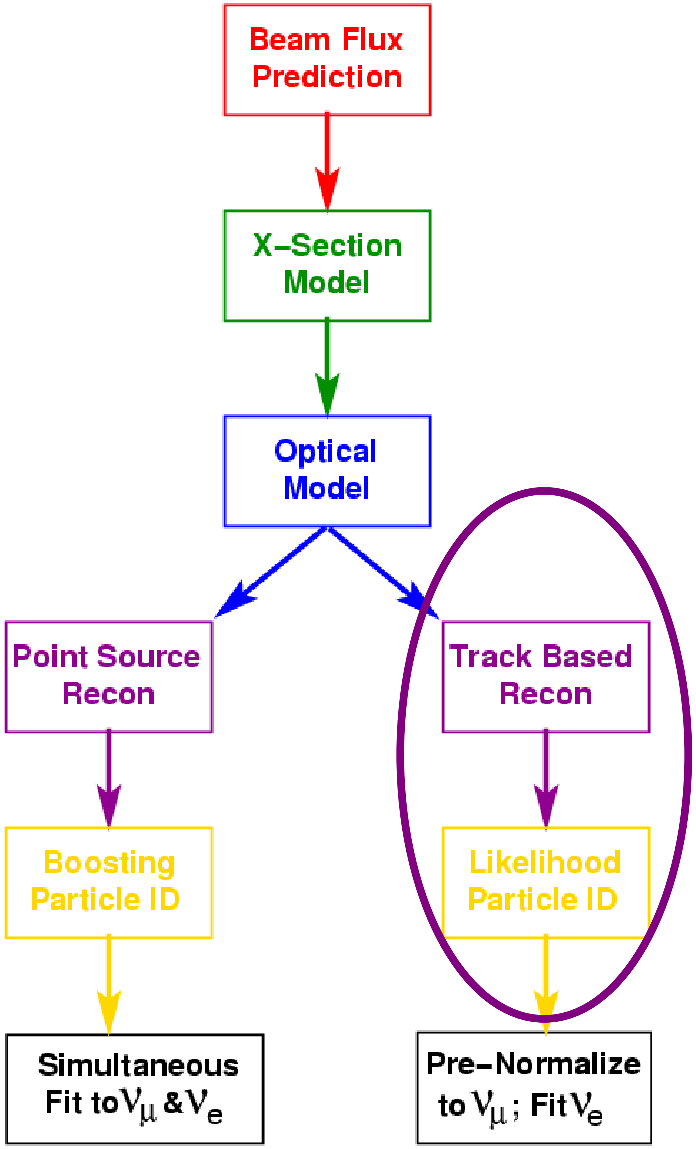
Invariant mass distributions in momentum bins





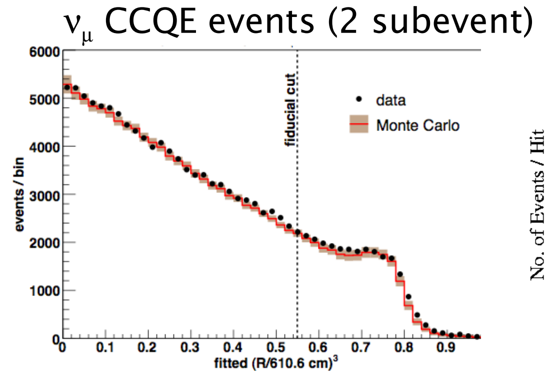


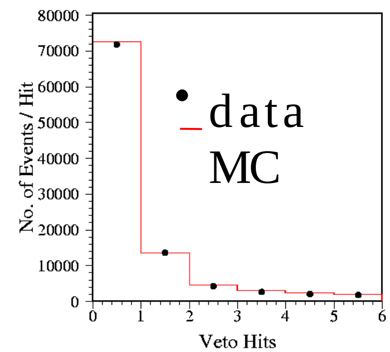
Track-Based Likelihood (TBL) Reconstruction and Particle ID

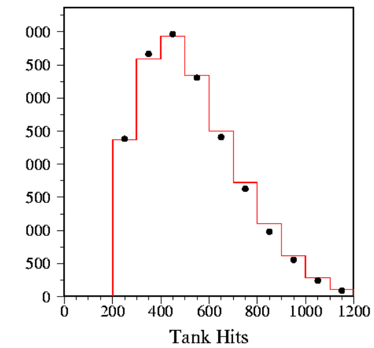


TBL Analysis: Separating e from μ

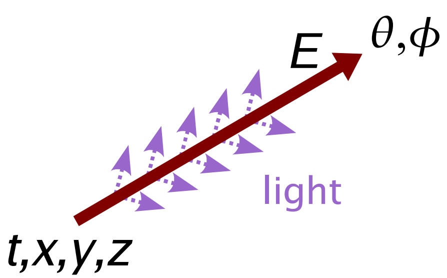
- Analysis pre-cuts
  - Only 1 subevent
  - Veto hits < 6
  - Tank hits > 200
  - Radius < 500 cm

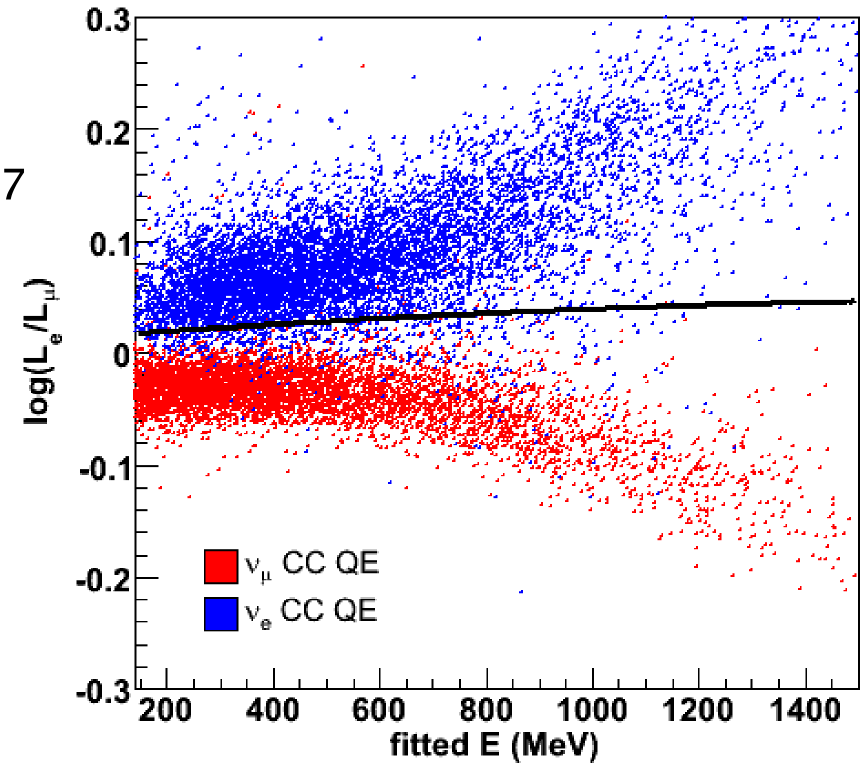






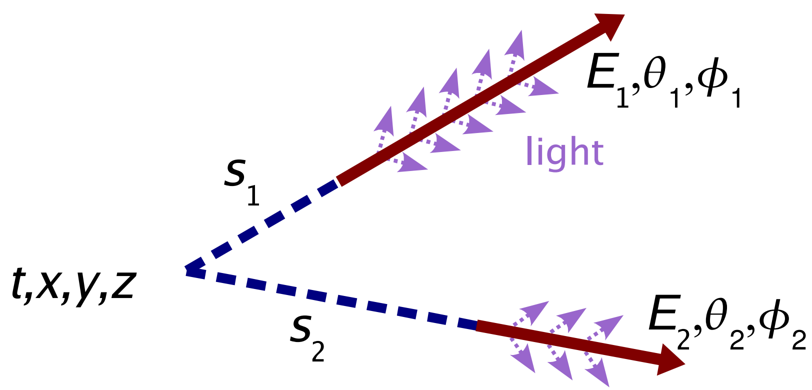
- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

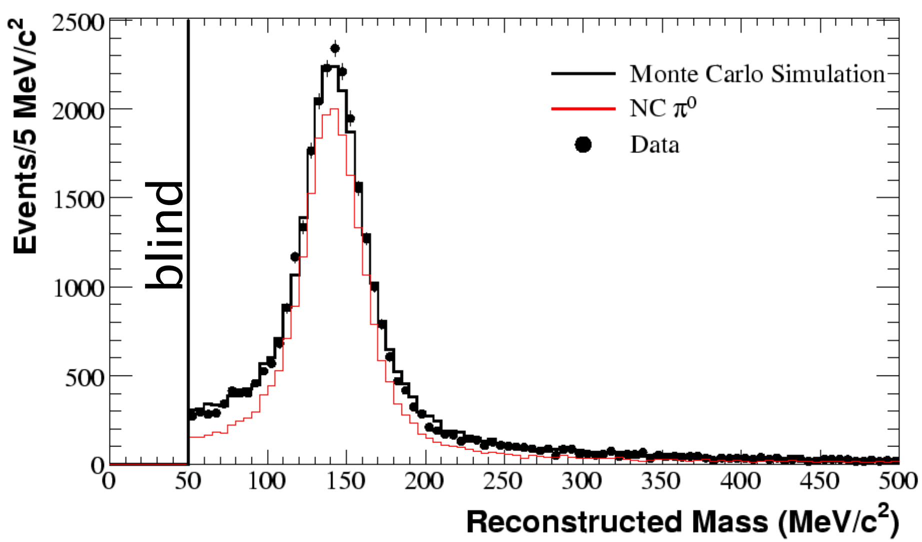


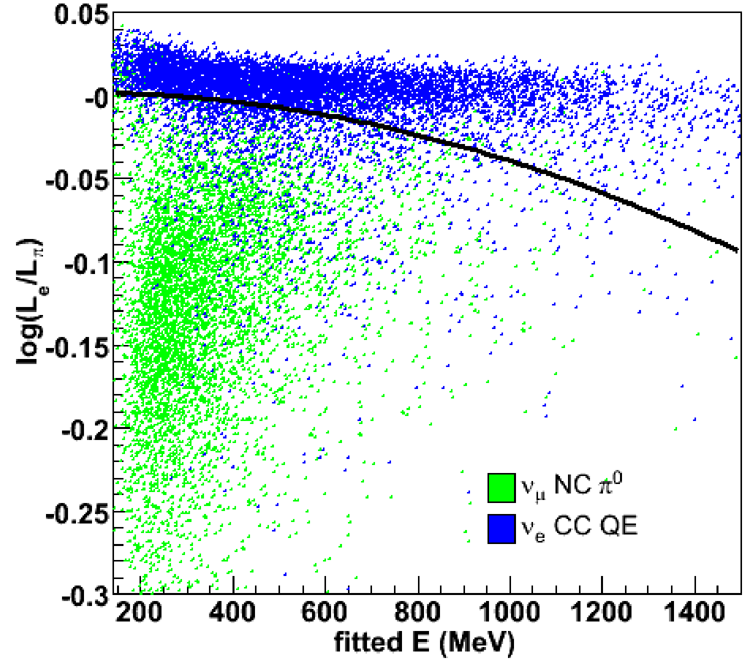


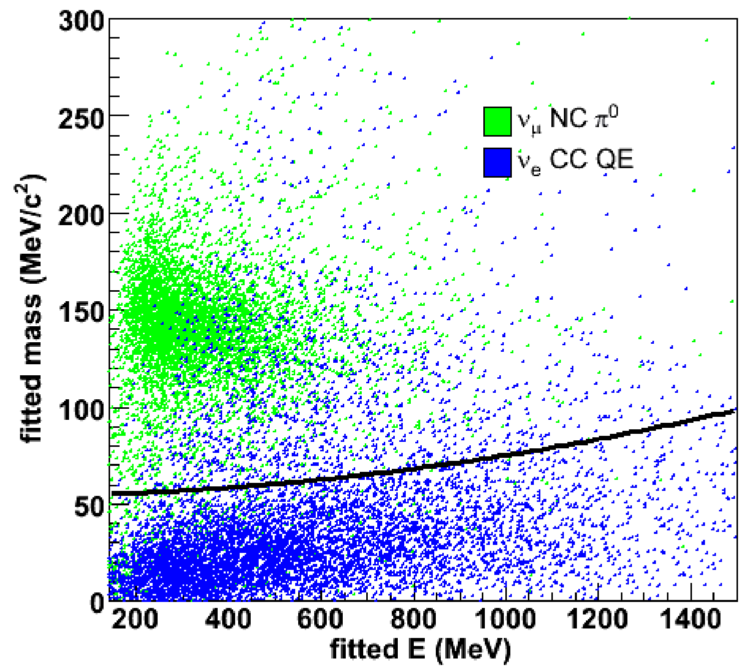
Separating e from π^0

- Extend fit to include two e-like tracks
- Very tenacious fit…8 minutes per event
- Nearly 1M CPU hours used (thanks OSG!)

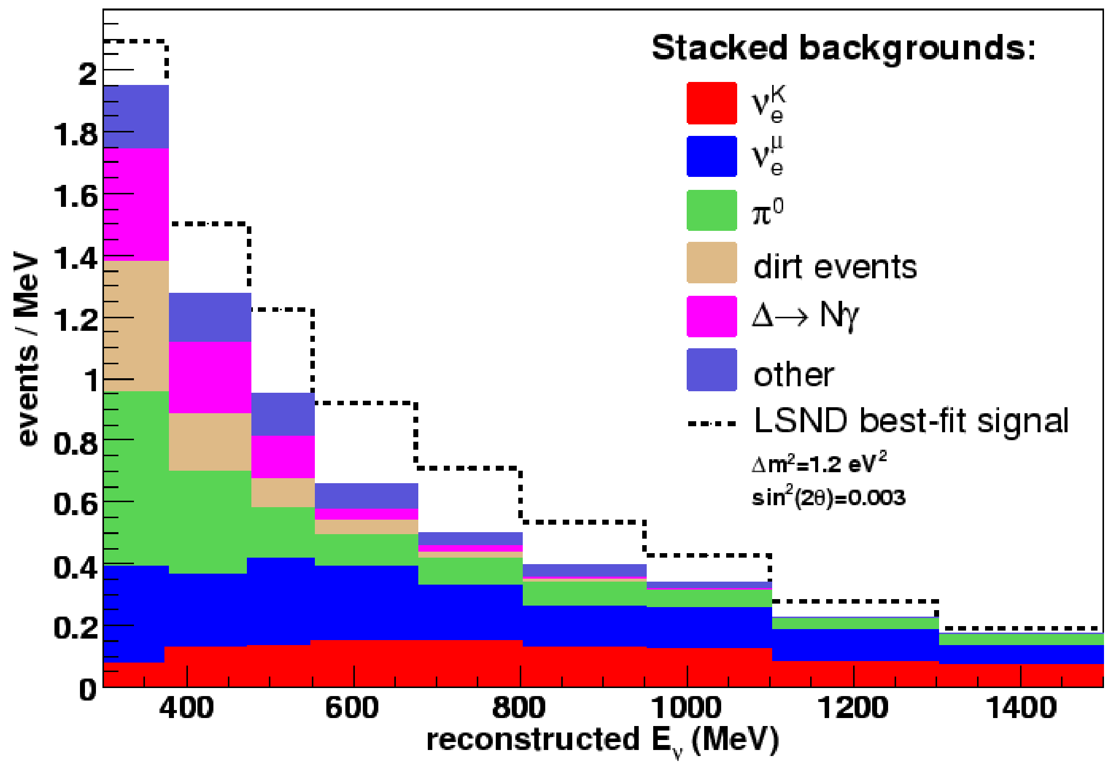








TBL Analysis: Expected event totals

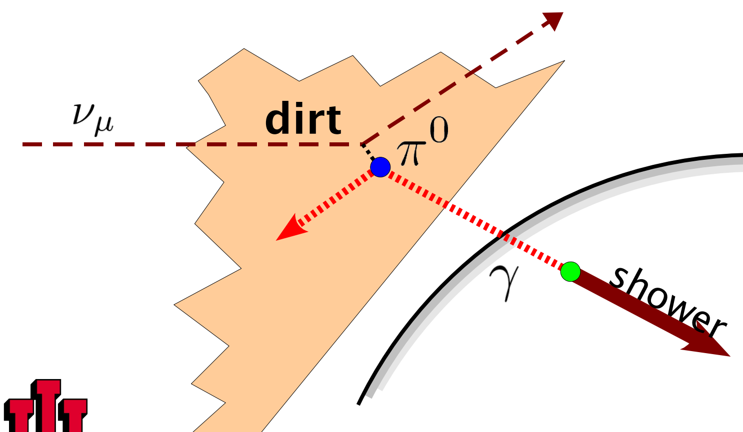


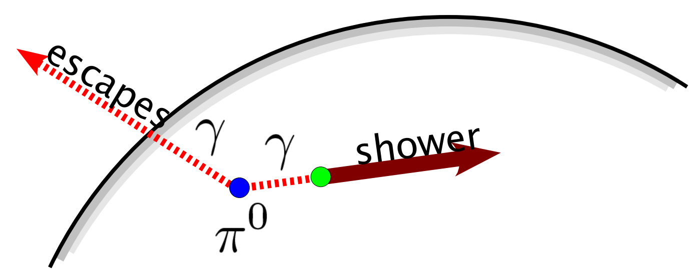
475 MeV – 1250 MeV

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

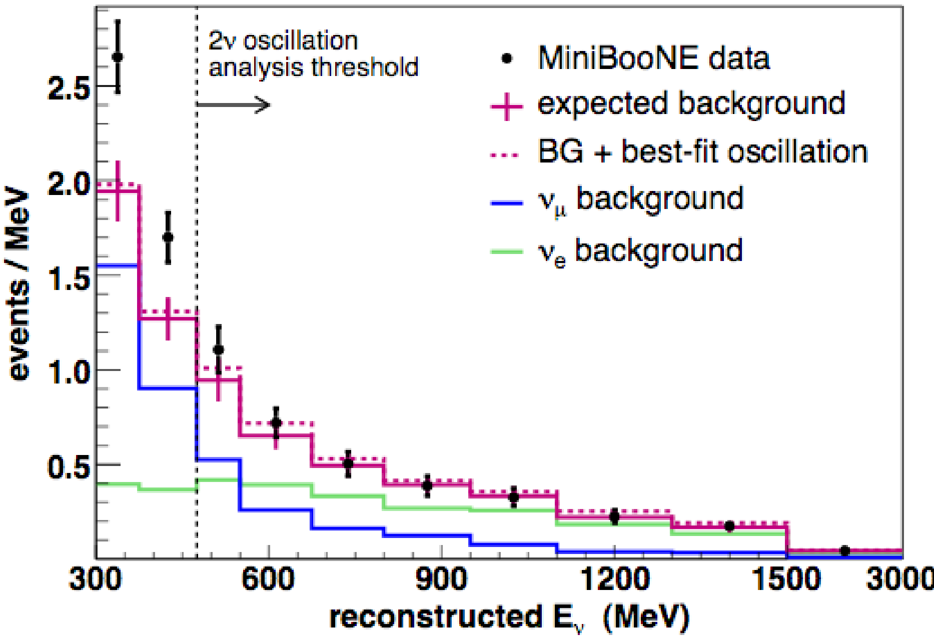
LSND best-fit $\nu_\mu \to \nu_e$ 126

S/sqrt(B)=6.8

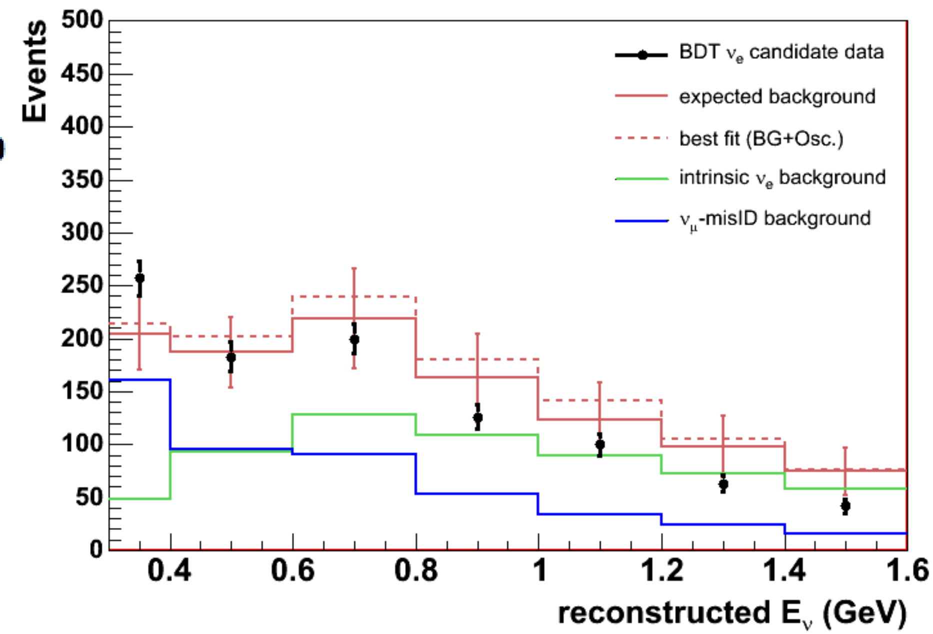




Looking at the data in the signal region...



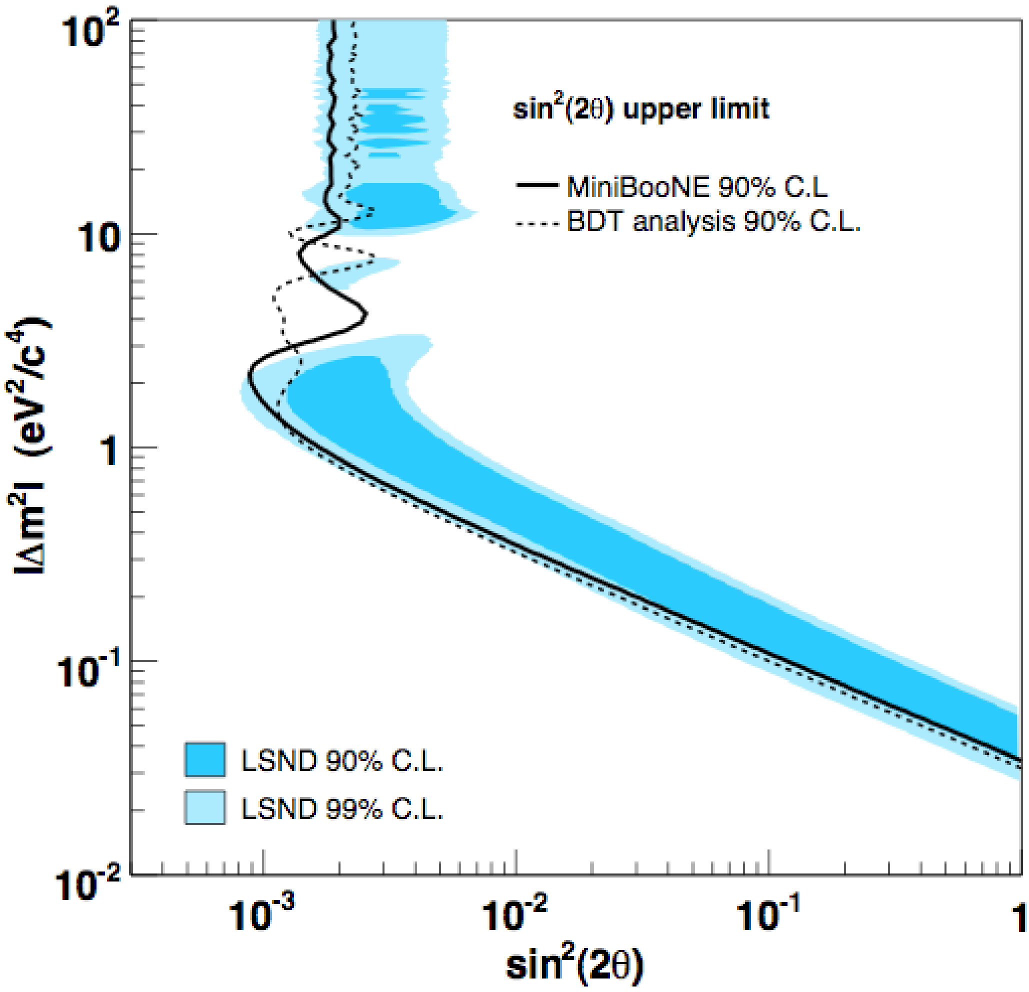
- TBL shows no sign of an excess in the analysis region (where the LSND signal is expected for the 2ν mixing hypothesis)
- Visible excess at low E



- The Boosted-Decision Tree started out with higher S/B, but lost ground to TBL when systematic errors were quantified
- Good fit to null, also sees excess in lowest bin, but obscured by larger systmetics

Neither analysis shows an evidence for $\nu_\mu \rightarrow \nu_e$ appearance at LSND's L/E

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



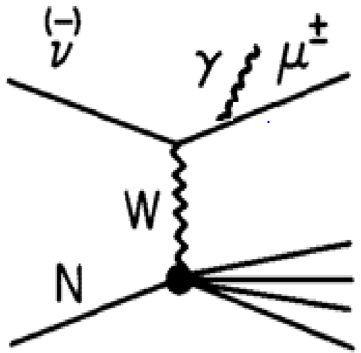
- What does it all mean? There are a few possiblities...
  - LSND was wrong
  - The physics causing the excess in LSND doesn't scale with L/E
  - Difference between neutrinos and antineutrinos?

Exploring the Low E Excess

The low E excess has fueled much speculation...

Commonplace

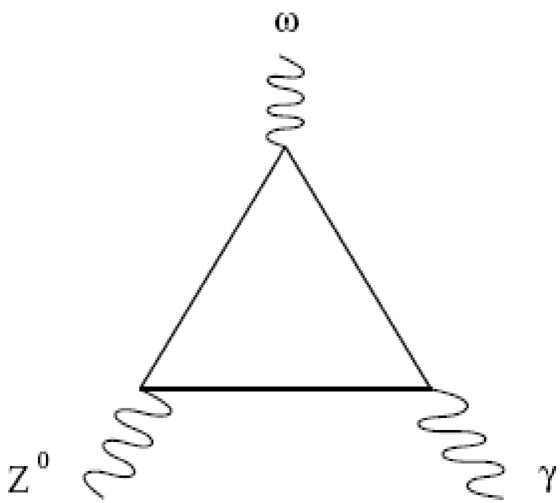
- Muon bremstrahlung
  (Bodek, 0709.4004)



- Proved negligible in 0710.3897

SM, but neglected

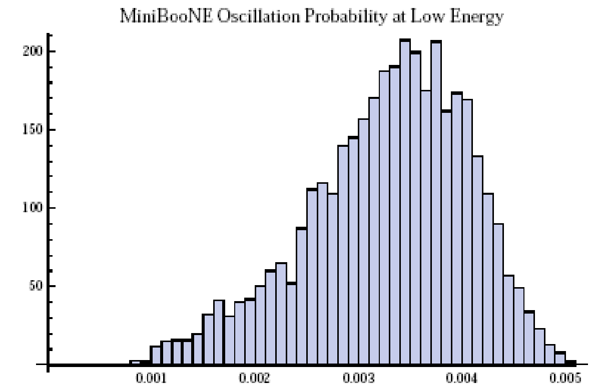
- Anomaly-mediated γ
  (Harvey, Hill, Hill, 0708.1281)



- Will hear from Richard Hill next!

Beyond the SM

- New gauge boson
  (Nelson, Walsh,0711.1363)



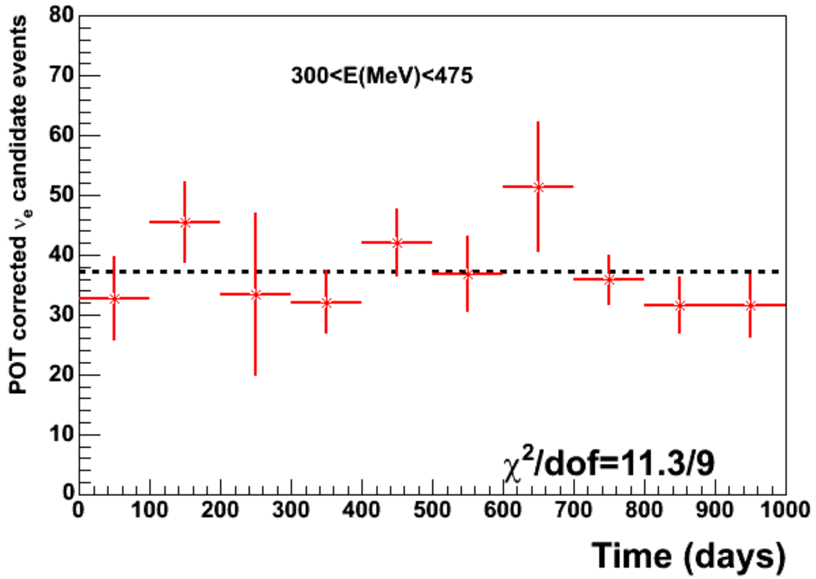
- Will hear from Ann Nelson next-to-next!

Signal events have no obvious pathologies

No Detector anomalies found

– Example: rate of electron candidate events is constant (within errors) over course of run

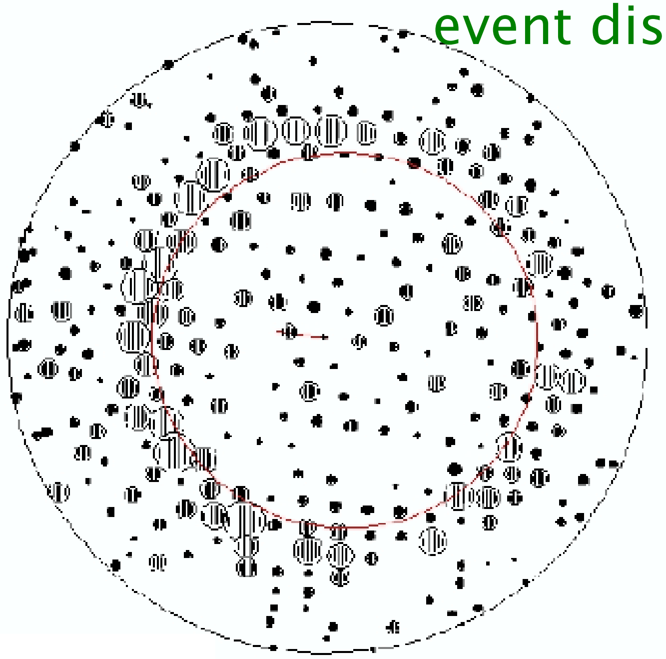
event/POT vs day, 300<Enu<475 MeV



No Reconstruction problems found

– All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

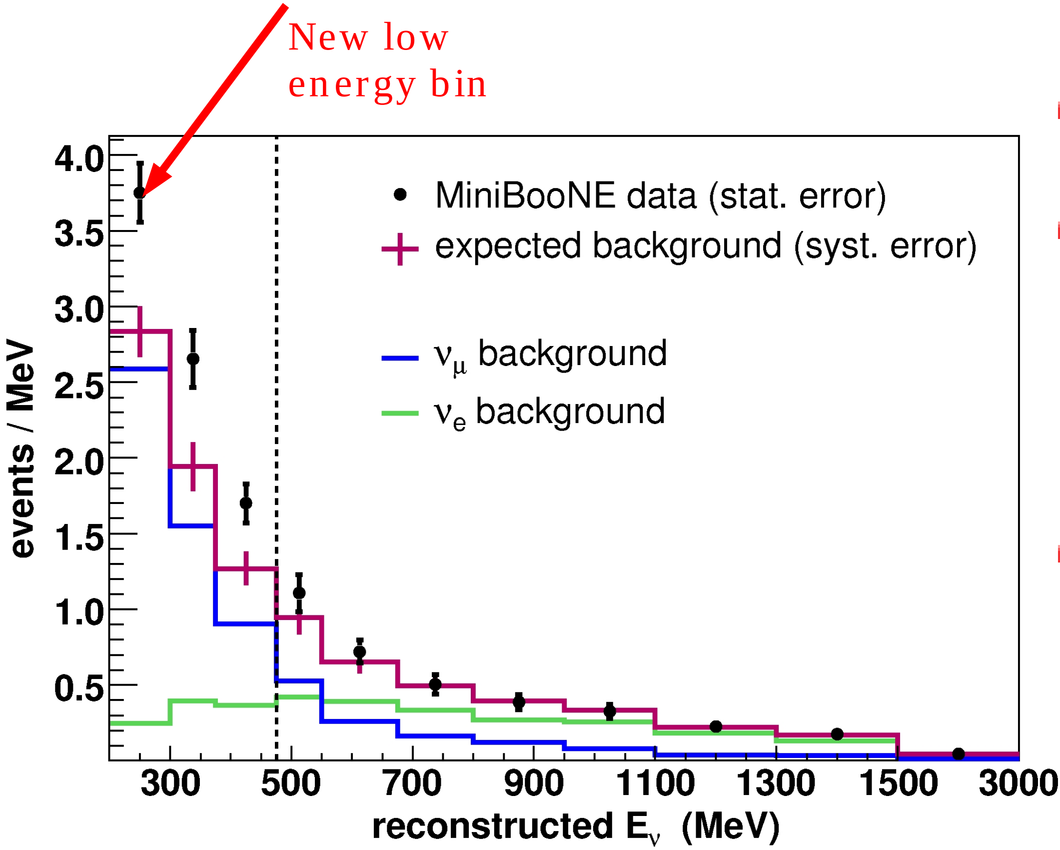
example signal-candidate event display



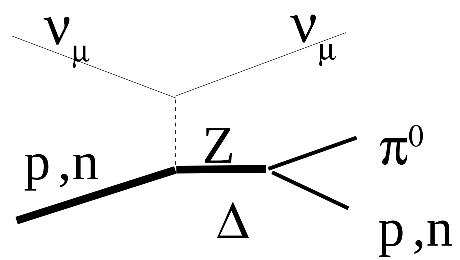
Signal candidate events are consistent with single-ring neutrino interactions

– But could be either electrons or photons

Extending the analysis to lower energies



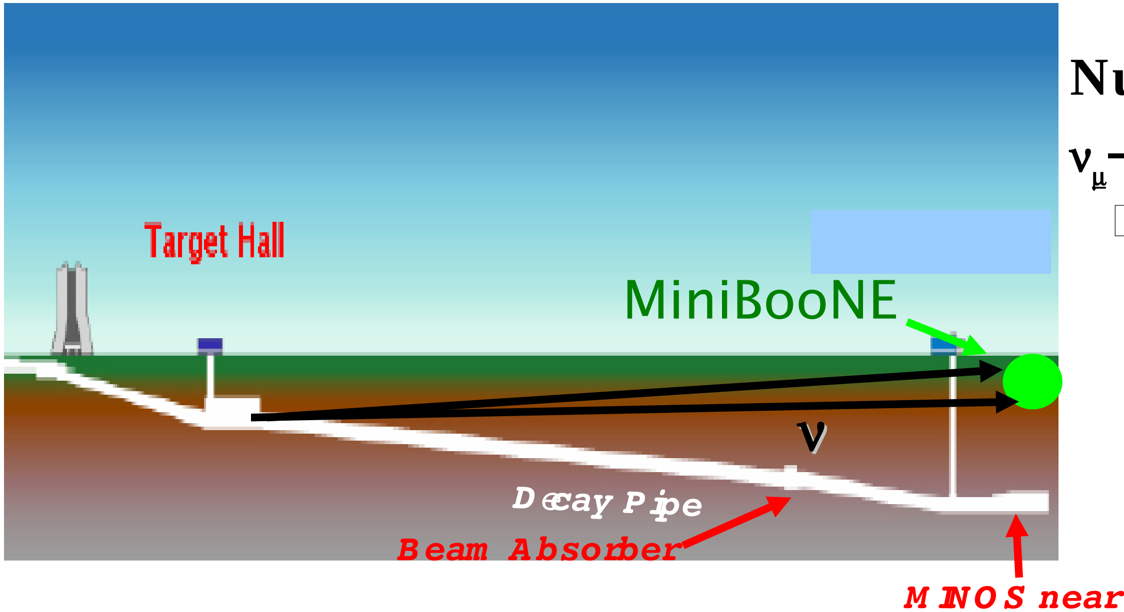
$$\nu_\mu(p,n) \rightarrow \nu_\mu(p,n)\pi^0, \pi^0 \rightarrow \gamma\gamma$$



- Excess persists in 200–300 MeV bin
- Significance (stat + syst error)
  - 475–1250 MeV, 22 ± 40
  - 300–475 MeV, 95 ± 28
  - 200–300 MeV, 91 ± 31
- Looking to bring out a full update for the summer conferences
  - 15–20% more data
  - Additional cut to remove dirt bkg
  - Flux-fit extended to high angle π production data from HARP
  - Refined hadronic model
    - π^- radiative capture
    - Inter and intra-nucleus charge exchange
    - Photonuclear disintegration

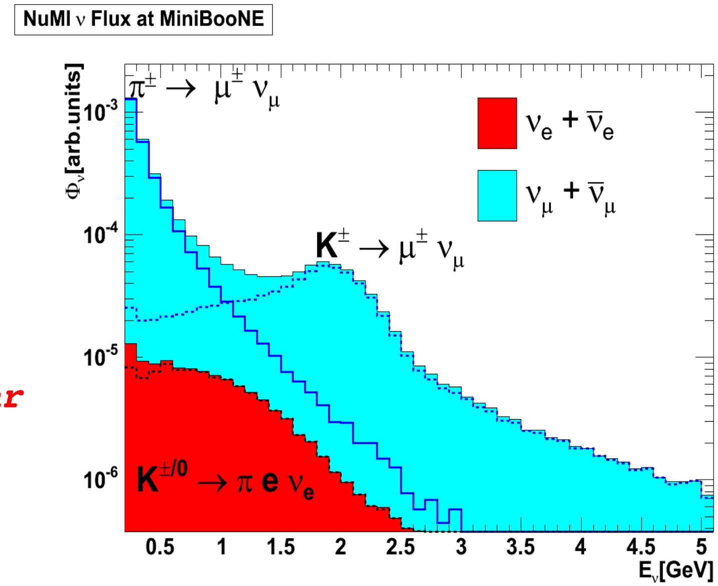
NuMI neutrinos in the MB detector

NuMI neutrinos in the MB detector...

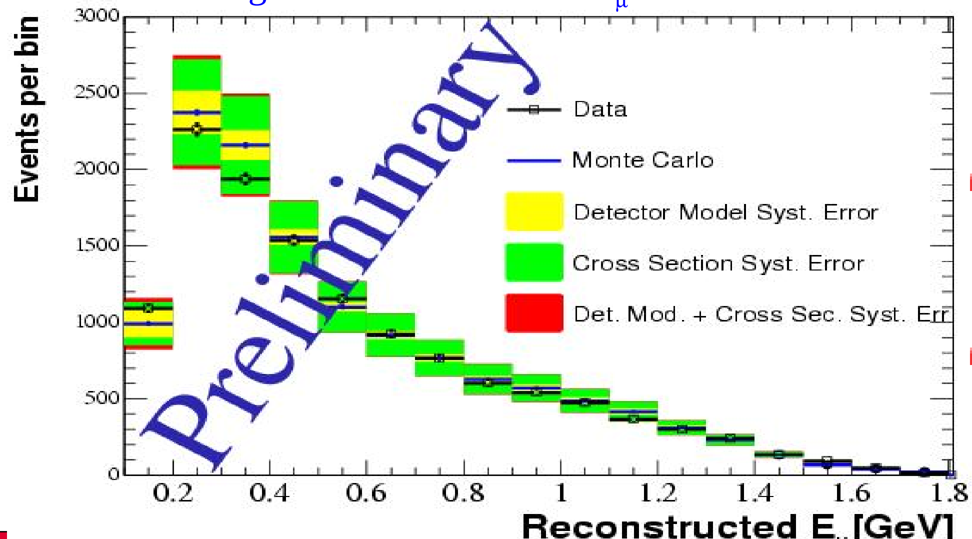


NuMI event composition:

ν_μ - 81%, ν_e - 5%, $\bar{\nu}_\mu$ - 13%, $\bar{\nu}_e$ - 1%

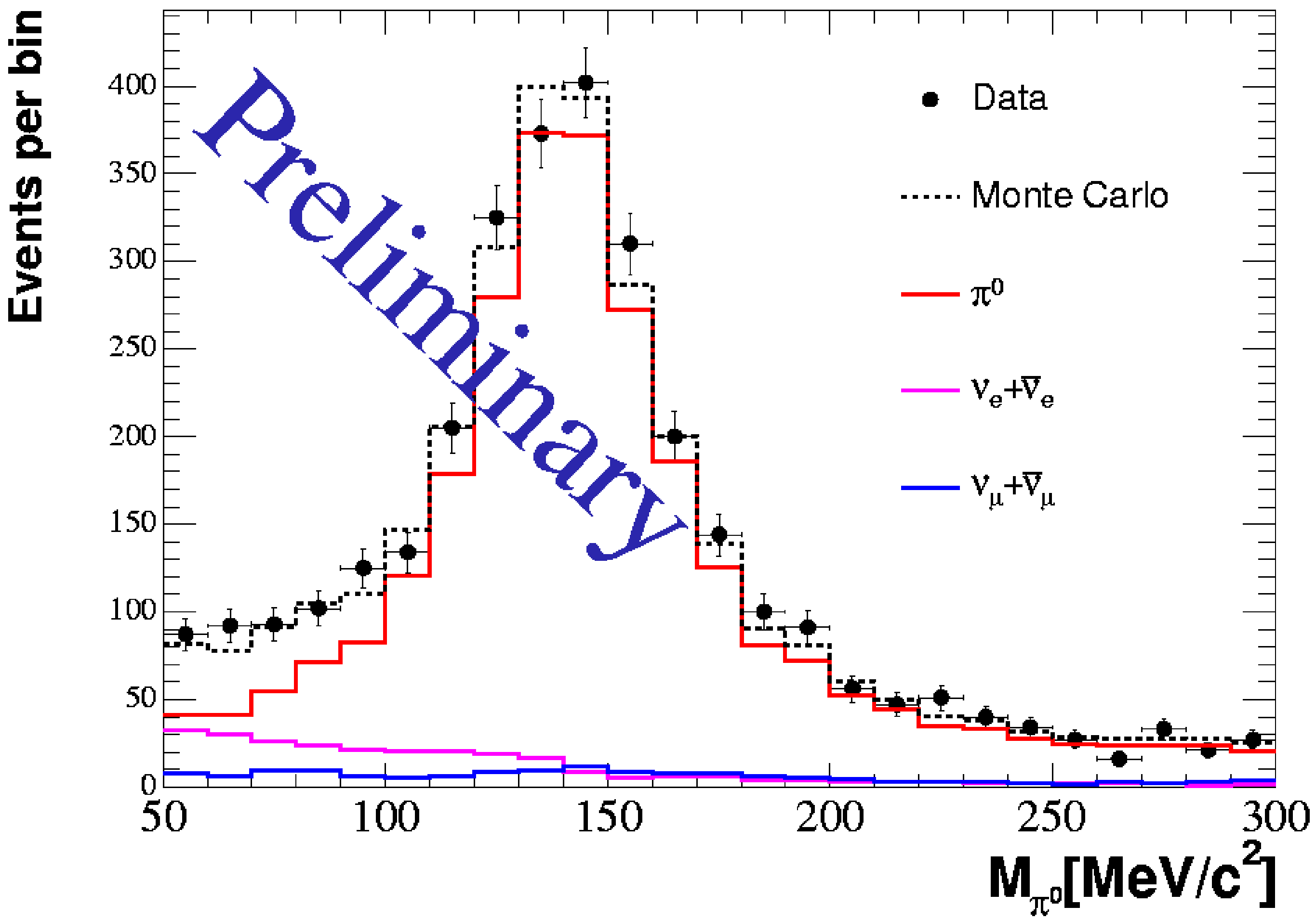


Data vs MC Agreement for NuMI ν_μ events in MiniBooNE



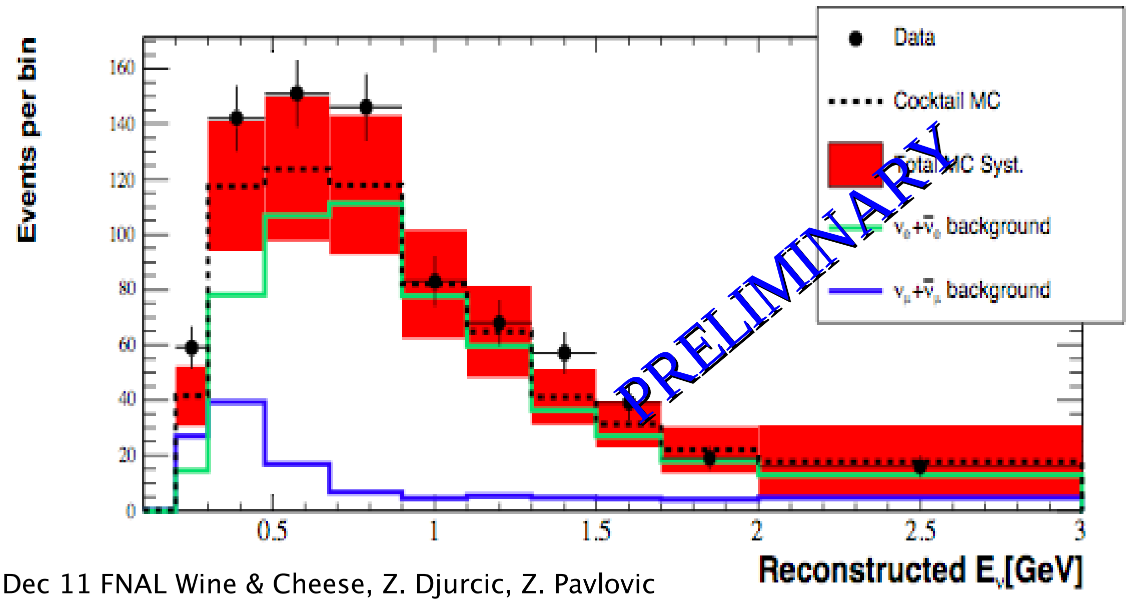
- MiniBooNE detector is 110 mrad off-axis from NuMI beamline (NOVA @ 14.5 mrad/T2K @ 35 mrad)
- Significantly enhanced in ν_e from K decay because of the off-axis position.

Analysis of π^0 events from NuMI beam



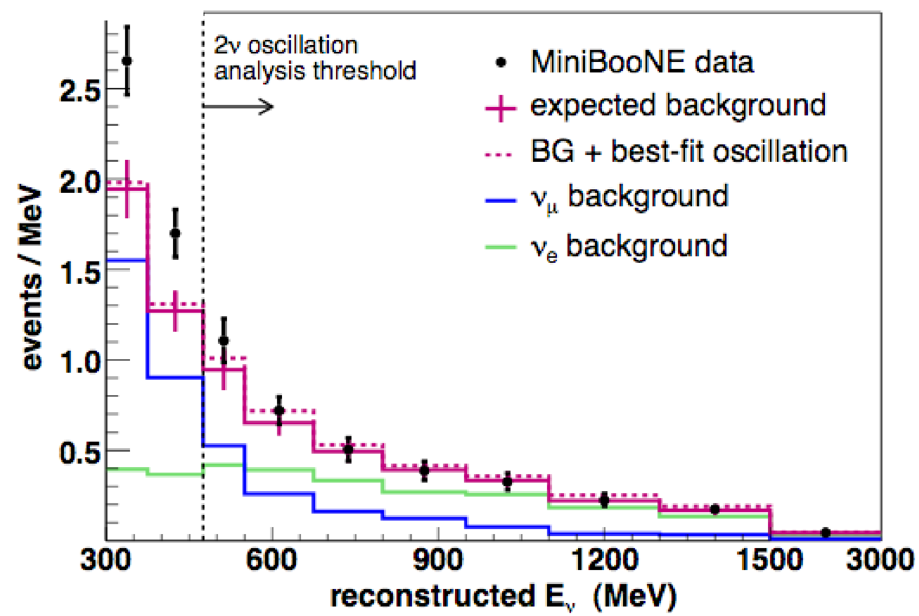
- Good data/MC agreement for π^0 events
- Ready to finalize background predictions/systematics
- Final step: Look for ν_e oscillation or excess

Analysis of ν_e–like events from NuMI beam



Dec 11 FNAL Wine & Cheese, Z. Djurcic, Z. Pavlovic

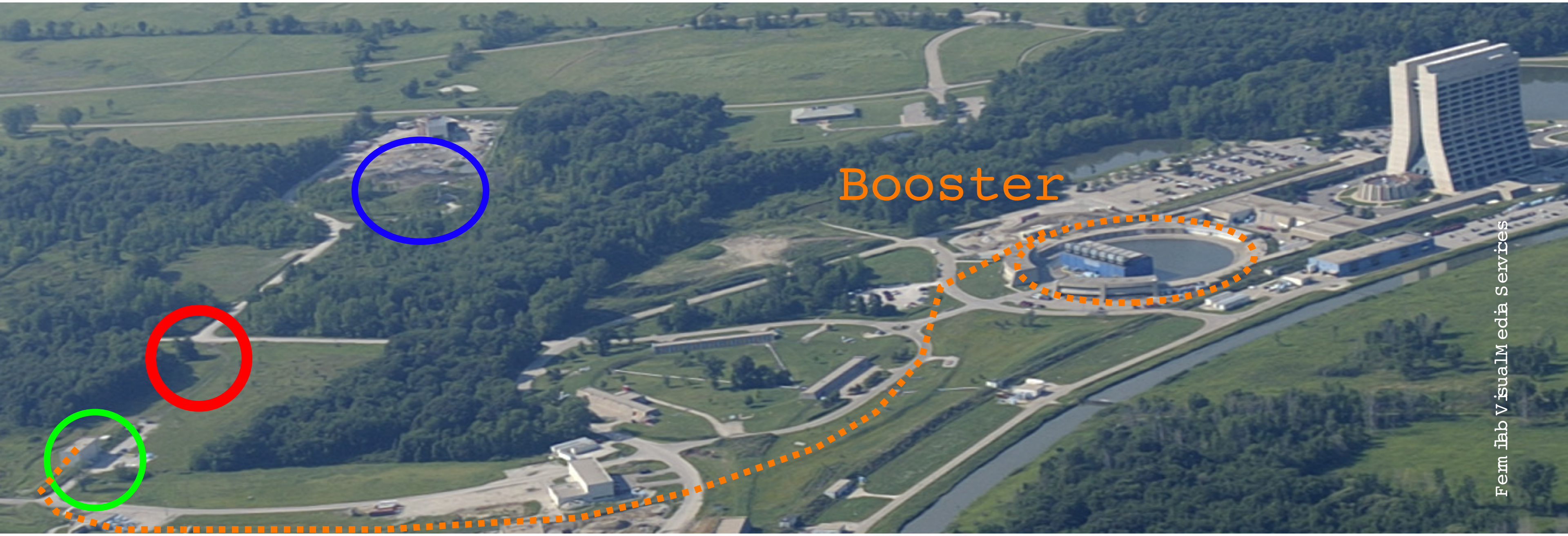
- Can see a visible excess at low energy
- Errors should be reduced when internal constraints on flux x cross-section are applied

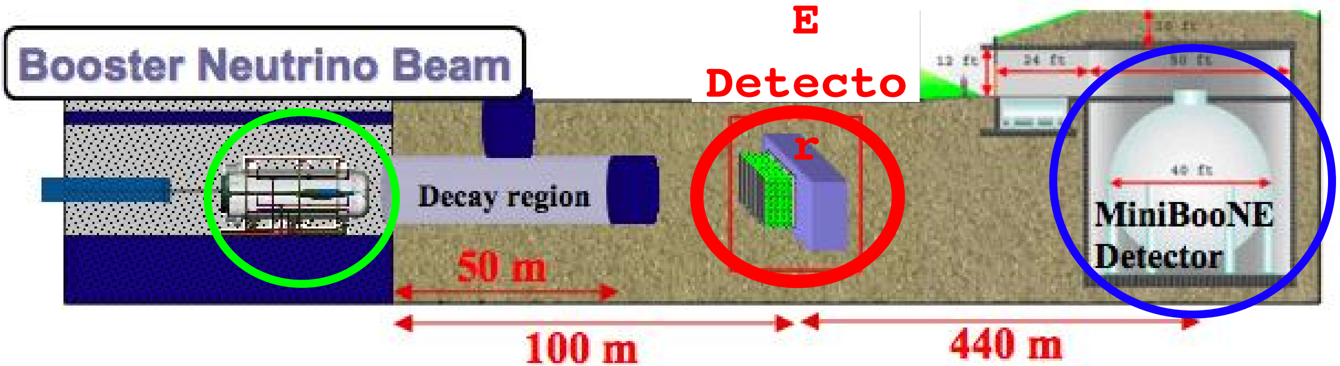


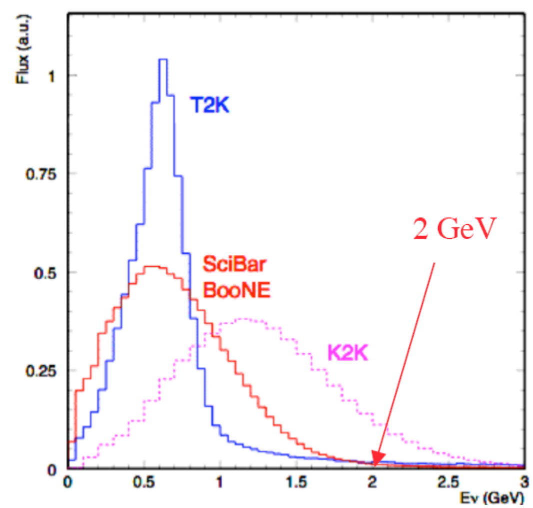
- However, can already use NuMI data to eliminate error in ν_e CCQE cross-section as source of excess
  - MB would require ν_e cross-section to be 2.5 times higher
  - Not supported by NuMI

The SciBooNE near detector experiment

SciBooNE installed and taking data at near location

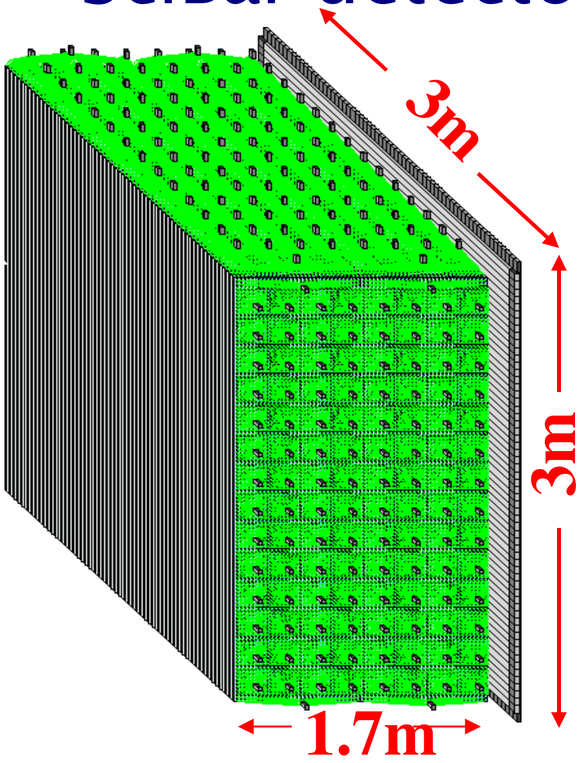




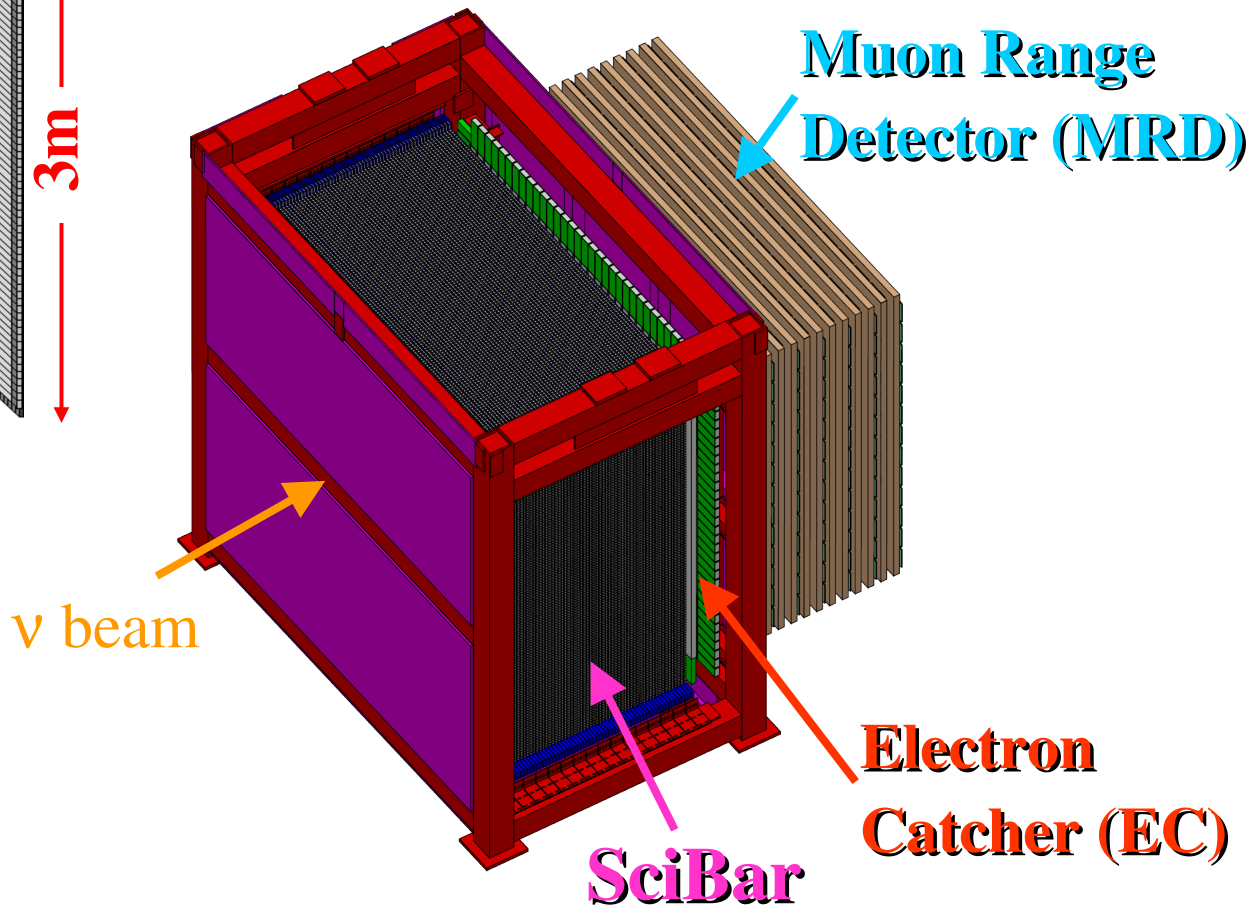


- Primary motivation: Cross-sections for T2K

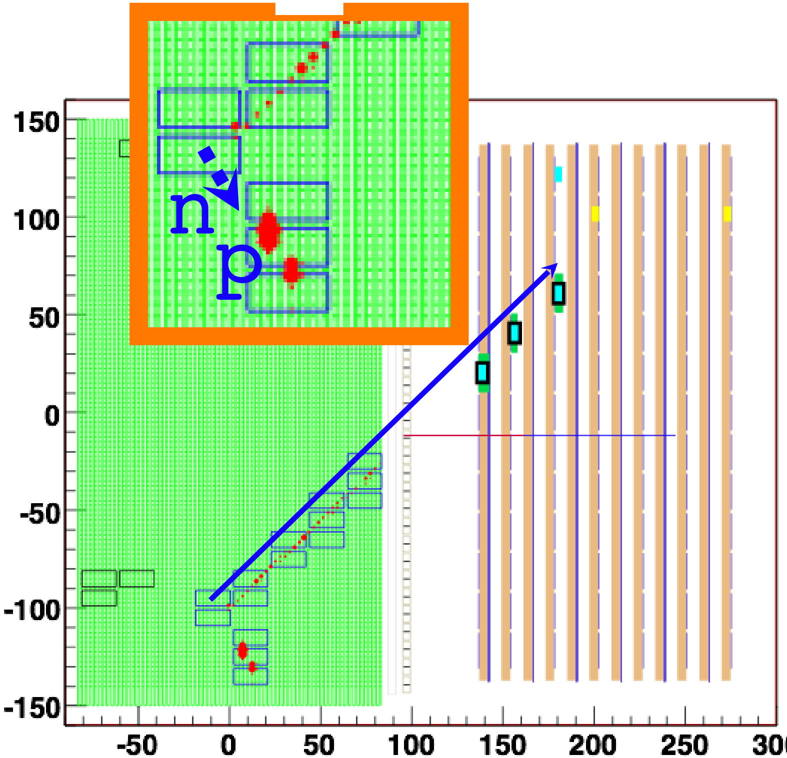
SciBar detector brought from K2K to FNAL



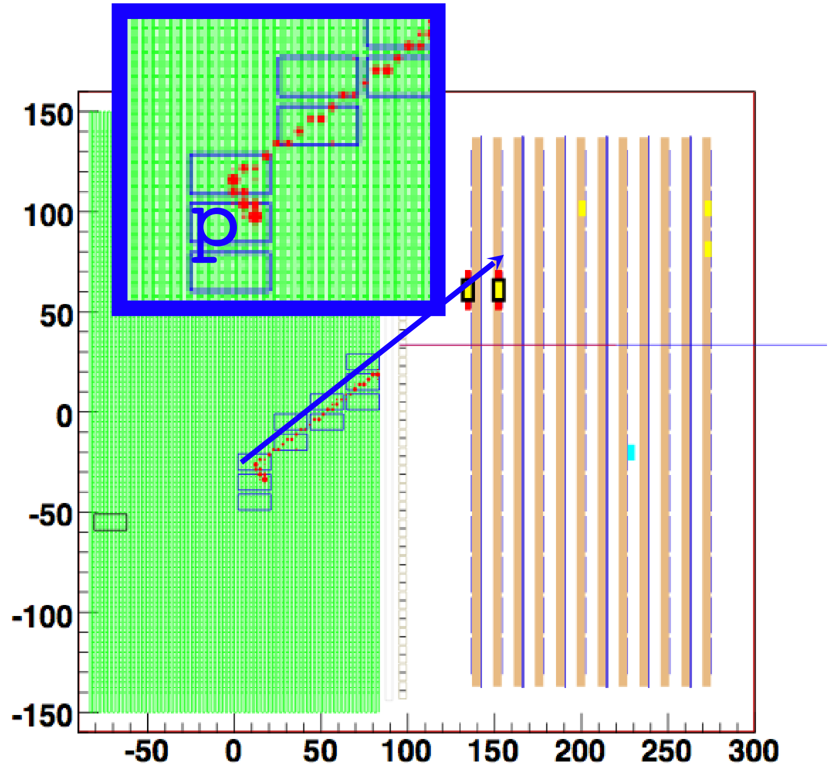
- 15 ton, 14,800 channels
- 2.5 cm x 1.3 cm x 300 cm extrusions



Neutrino interactions in SciBooNE data



$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$



$\nu_\mu + n \rightarrow \mu^- + p$

- In addition to providing generally useful cross-section information, some MB-specific analyses are in progress
  - Possibility of distinguishing e from γ $\Rightarrow$ understand low E excess
  - SciBooNE (near)/MiniBooNE (far) ν_μ CCQE ratio will give best disappearance limit for $\Delta m^2 \sim 0.3 - 60\ eV^2$

Anti–neutrinos in MiniBooNE

Antineutrinos in MiniBooNE

- Data acquired to date:

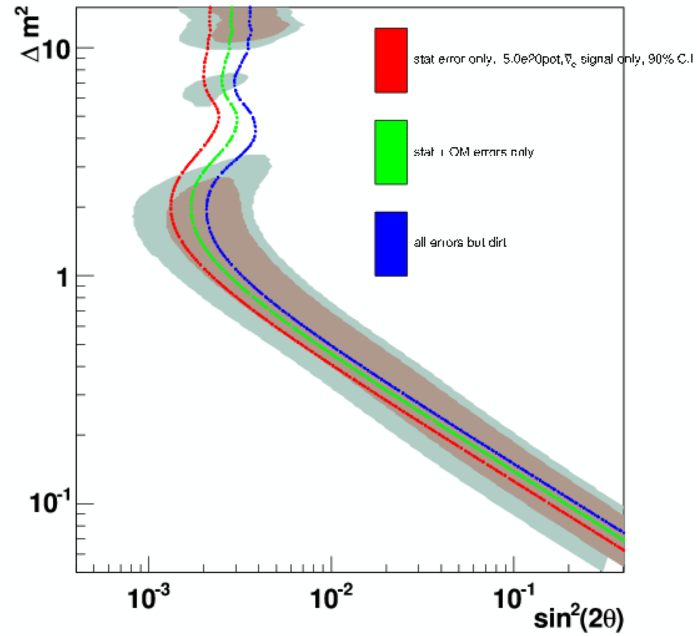
ν channel	events
all channels	810k
CC quasielastic	340k
NC elastic	150k
CC π^+	180k
CC π^0	30k
NC π^0	48k
NC $\pi^{+/-}$	27k
CC/NC DIS, multi-π	35k

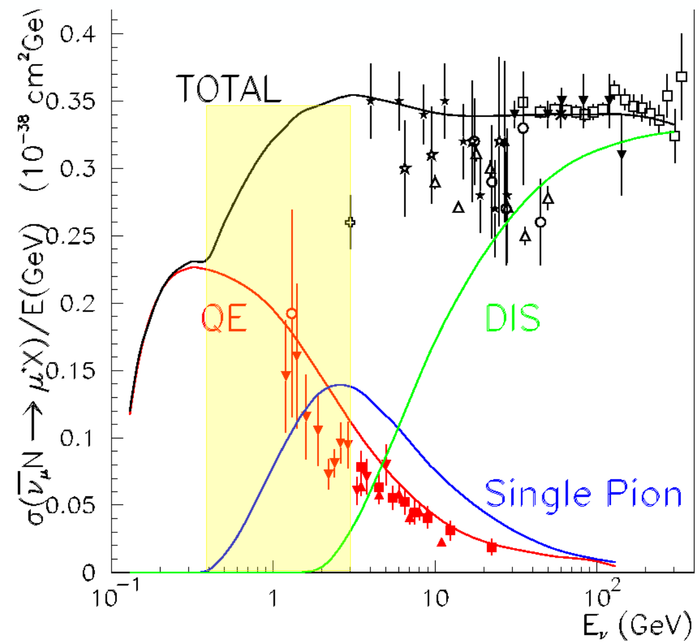
6×10^{20} POT
ν mode

$\bar{\nu}$ channel	events
all channels	54k
CC quasielastic	24k
NC elastic	10k
CC π^-	8.9k
CC π^0	1.7k
NC π^0	4.9k
NC $\pi^{+/-}$	1.8k
CC/NC DIS, multi-π	1.9k

2×10^{20} POT
$\bar{\nu}$ mode

- In November, PAC recommended MB run for two more years to triple the antineutrino statistics
  - Direct check of LSND result
  - Understanding low E excess
  - Cross-sections measurements





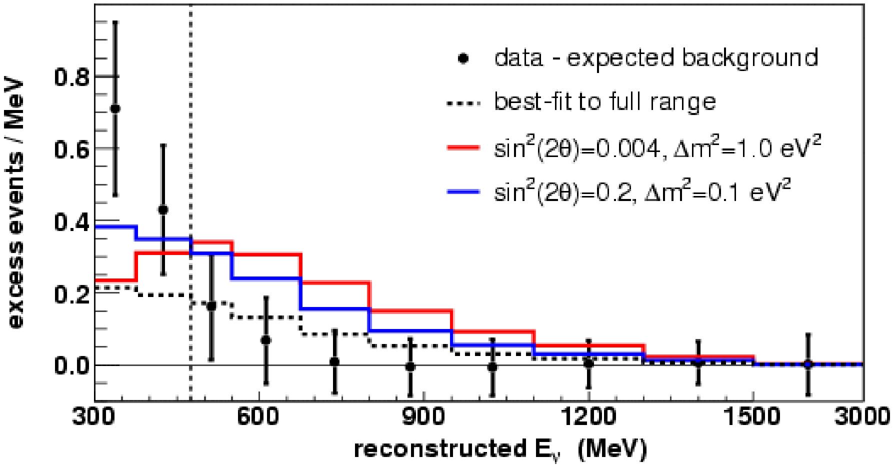
Conclusions

- MiniBooNE did not find any evidence for ν_e appearance in the energy region expected if the LSND signal scales as L/E

- A significant excess is observed at low energy and is still under study
  - Finalized predictions from an improved hadronic model coming soon

- MiniBooNE is approved to run 2 more years of anti-ν running in the BNB
  - Unique cross-section measurements
  - Partial coverage of the LSND signal region with an anti-neutrino beam

- Lots of exciting possibilities
  - NuMI events in MiniBooNE
  - SciBooNE near detector
  - ν/anti-ν xsecs for T2K/NOVA



Extra slides

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

~80 physicists from ~18 institutions

- Motivation
- Recap of the neutrino oscillation result
- Current and future efforts:
  - Exploring the observed ν_e excess at low energy
  - Utilizing NuMI neutrino events in MiniBooNE
  - Applications using SciBooNE as a near detector
  - Anti-neutrinos at the BNB

Neutrino Oscillations

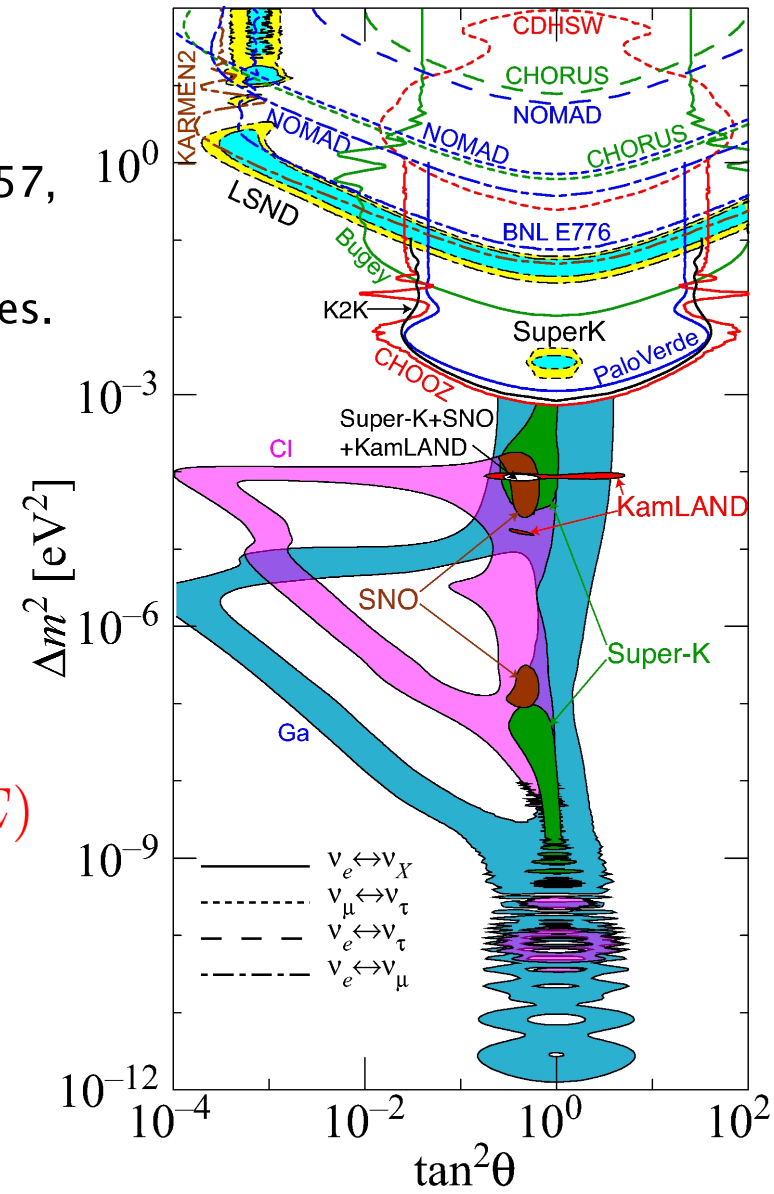
- ν oscillations first postulated by Pontecorvo in 1957, based on analogy to kaons.
- A non-zero ν mass allows for lepton flavor changes.
- mass eigenstates ≠ flavor eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \qquad \alpha = (e, \mu, \tau)$$

- Flavor composition changes as ν propagates.
- Reducing to simple 2-neutrino mixing:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

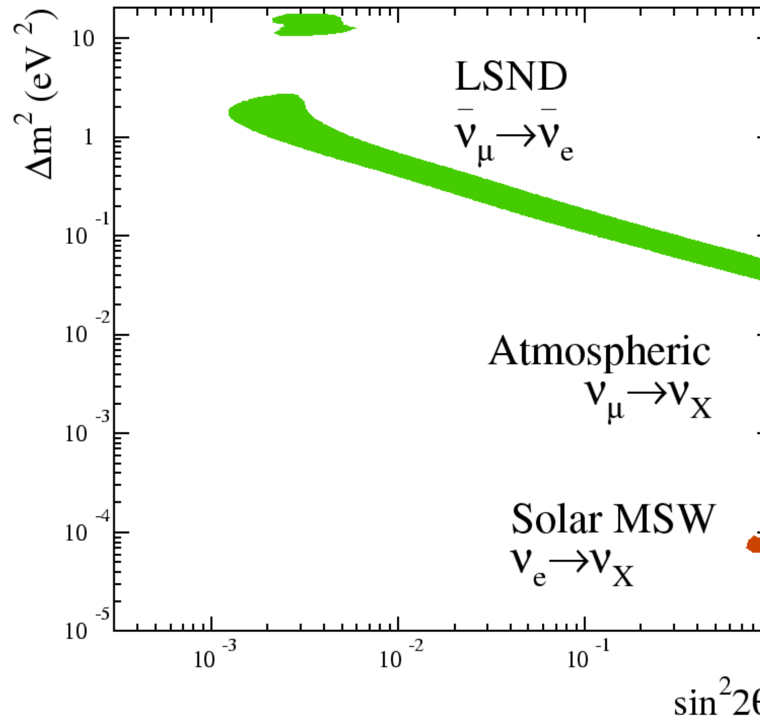
- Many experiments have hunted for ν oscillations, some have found them!

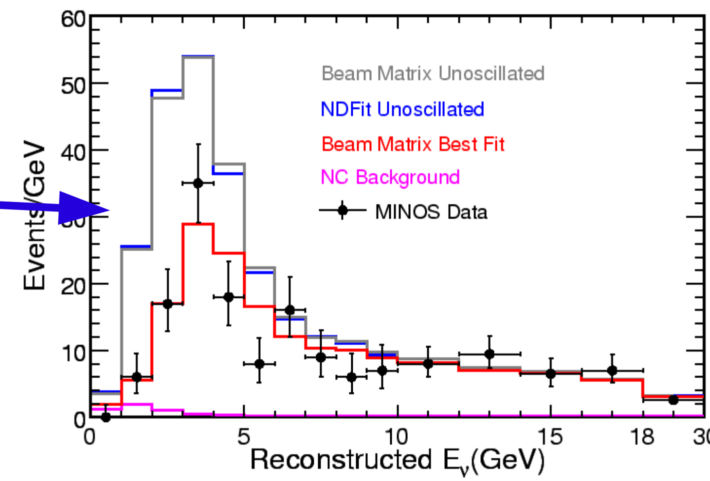


http://hitoshi.berkeley.edu/neutrino

Evidence for ν oscillations

- First evidence came in 1968 from Davis' solar ν_e experiment
  - found 1/3 of the expected ν_e from sun
  - disappearance $\nu_e \rightarrow \nu_x$
  - $\Delta m_{12}^2 \sim 8\times10^{-5}$ eV^2, $\sin^2(2\theta) \sim 0.8$
  - Confirmed by SNO, Super-K, Kamland
- New mixing found by Super-K through atmospheric ν_μ oscillations
  - found 1/2 as the upward ν_μ as downward
  - disappearance $\nu_\mu \rightarrow \nu_x$
  - $\Delta m_{23}^2 \sim 2\times10^{-3}$ eV^2, $\sin^2(2\theta) \sim 1.0$
  - Confirmed by IMB, Soudan, K2K, and most recently MINOS
- **Only one unconfirmed observation!**

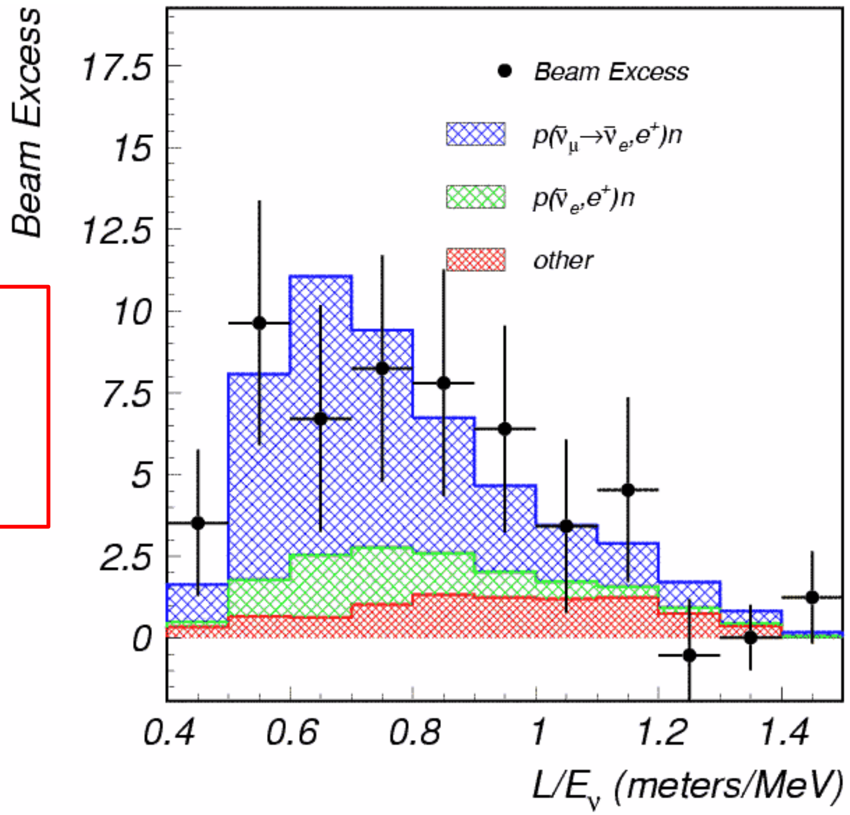




MiniBooNE's motivation...LSND

- 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:

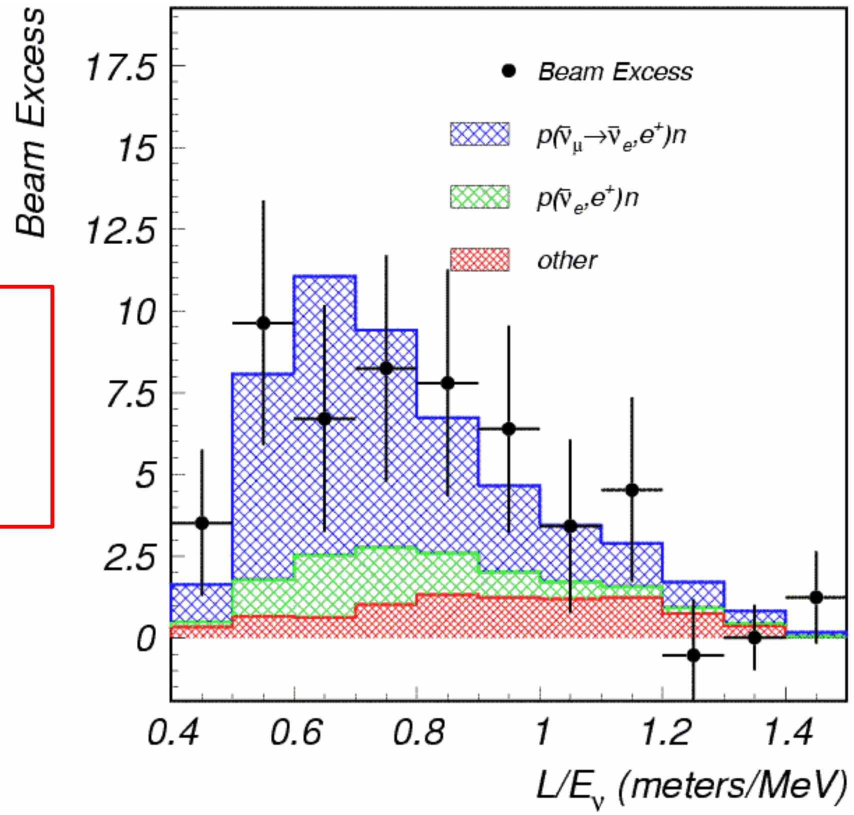
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

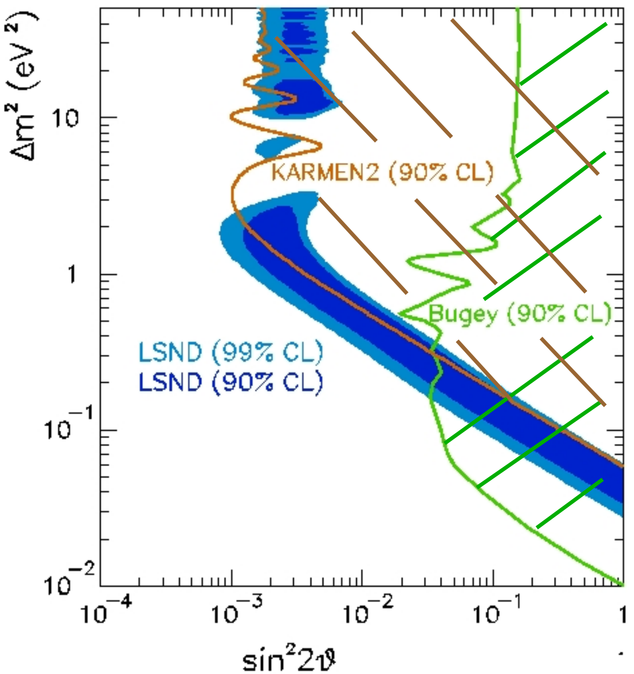


MiniBooNE's motivation...LSND

- 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:

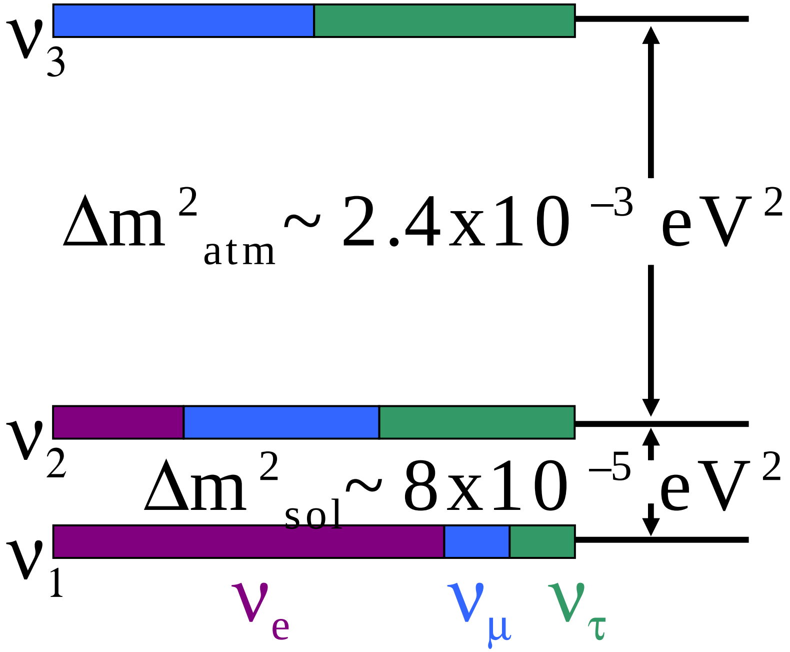
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$





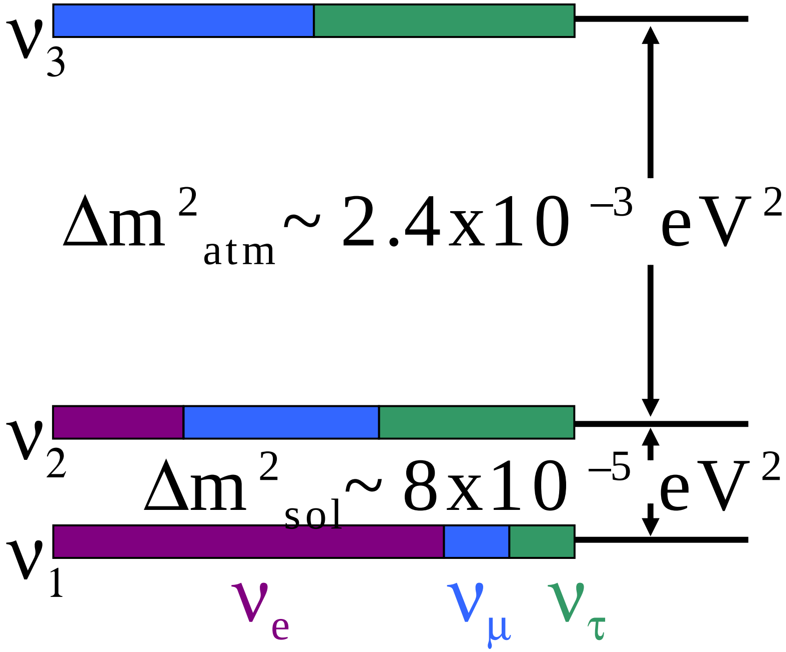
- Other experiments, i.e. Karmen and Bugey, have ruled out portions of the LSND signal
- MiniBooNE was designed to cover the entire LSND allowed region

Interpreting the LSND signal



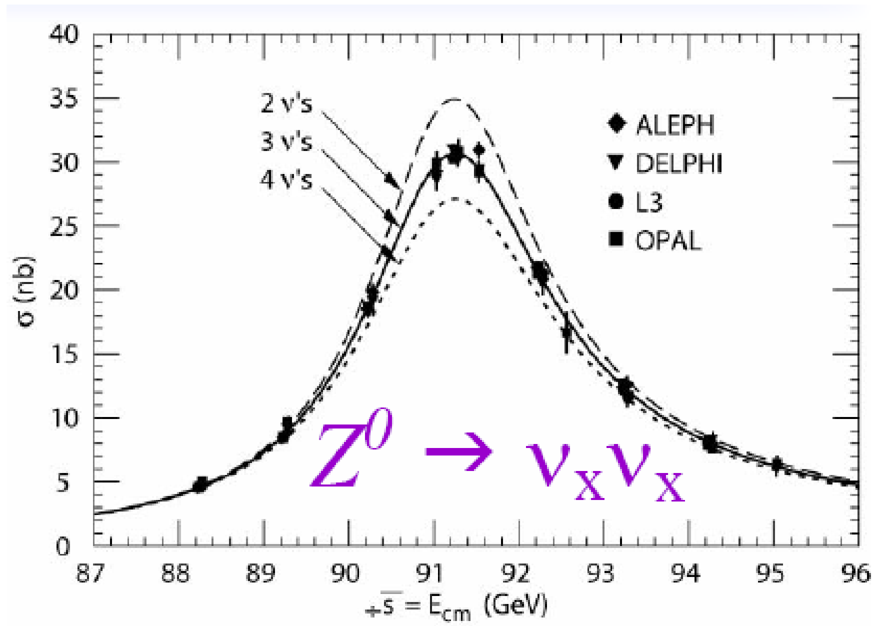
- The other two measured mixings fit conveniently into a 3-neutrino model
- With $\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$, the LSND $\Delta m^2 \sim 1\ eV^2$ does not fit
- 'Simplest' explanation...a 4th neutrino

Interpreting the LSND signal

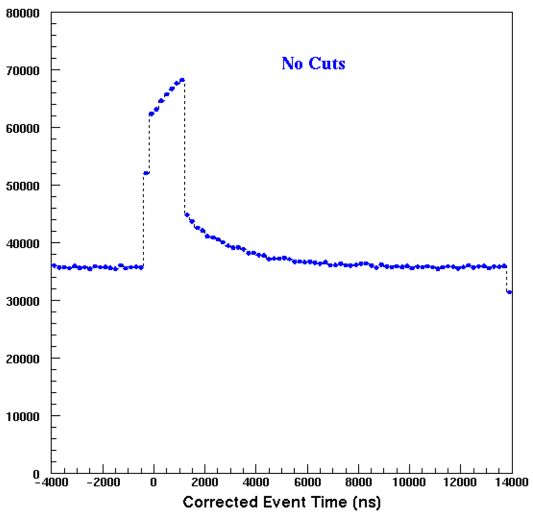


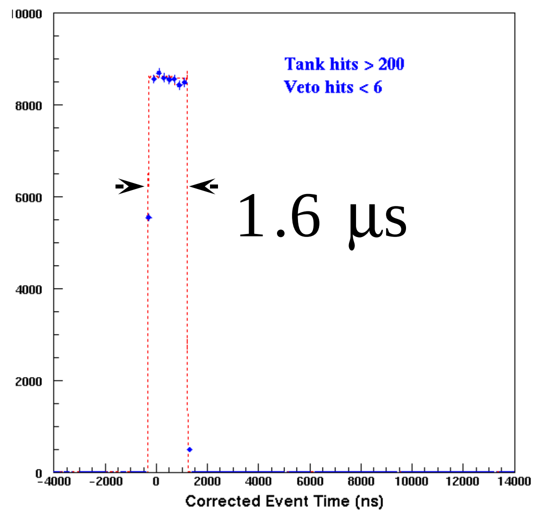
- The other two measured mixings fit conveniently into a 3-neutrino model
- With $\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$, the LSND $\Delta m^2 \sim 1\ eV^2$ does not fit
- 'Simplest' explanation...a 4^{th} neutrino

- Width of the Z implies 2.994 + 0.012 light neutrino flavors
- Requires 4^{th} neutrino to be 'sterile' or an even more exotic solution
  - Sterile neutrinos *hep-ph/0305255*
  - Neutrino decay *hep-ph/0602083*
  - Lorentz/CPT violation *PRD(2006)105009*
  - Extra dimensions *hep-ph/0504096*



Simple cuts eliminate random backgrounds

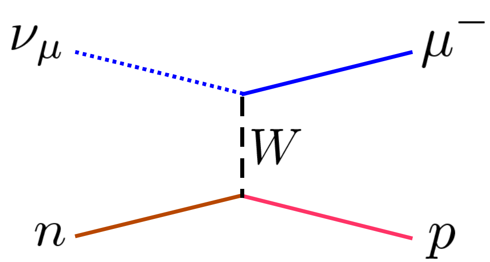


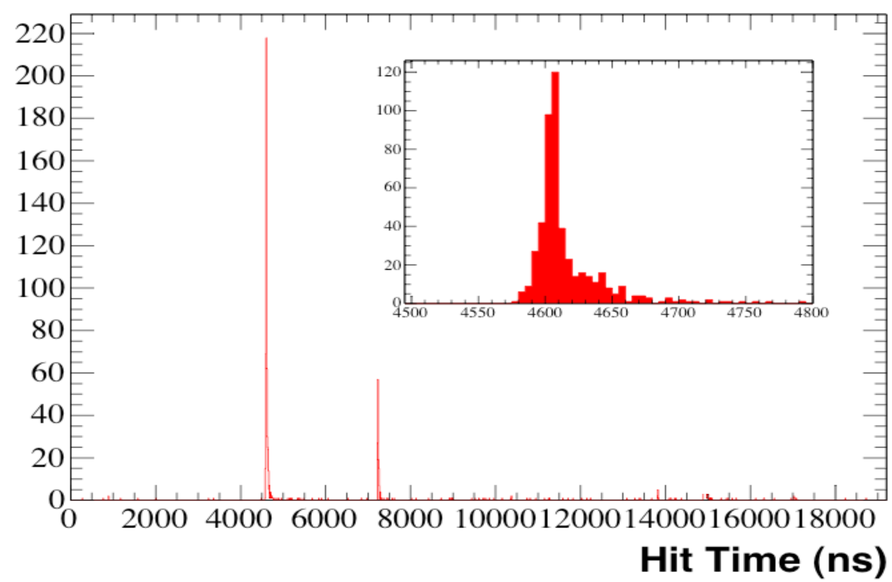


- Left: trigger window, no cuts
- Right: Simple cuts applied PMT hits in veto < 6 and tank > 200 show clean beam window
- Removes cosmic μ and their decay electrons

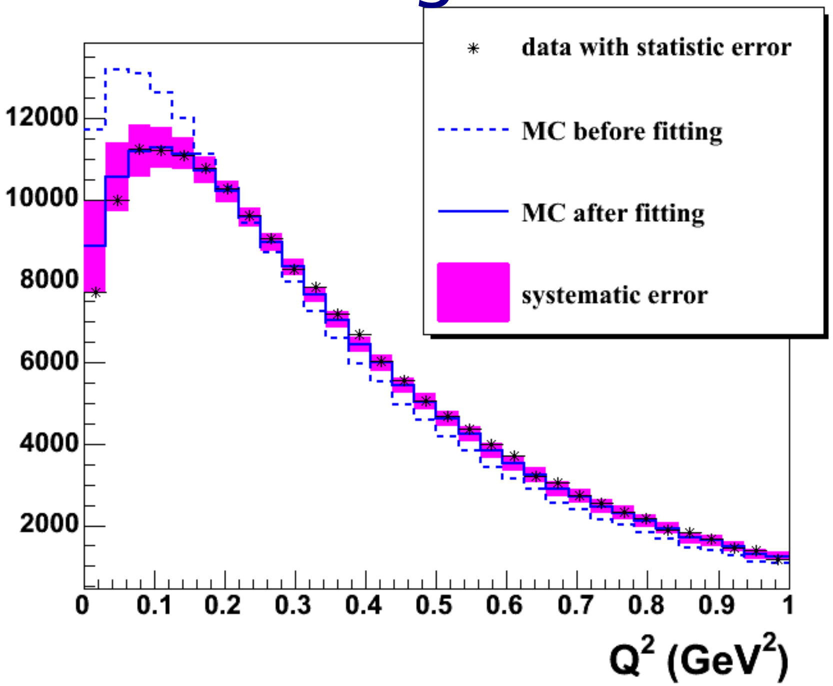
- Subevent structure (clusters in time) can be used for particle identification (PID)
- 2 subevent time structure expected for most common ν interaction in MB:

ν_μ CCQE (charged-current quasi-elastic)

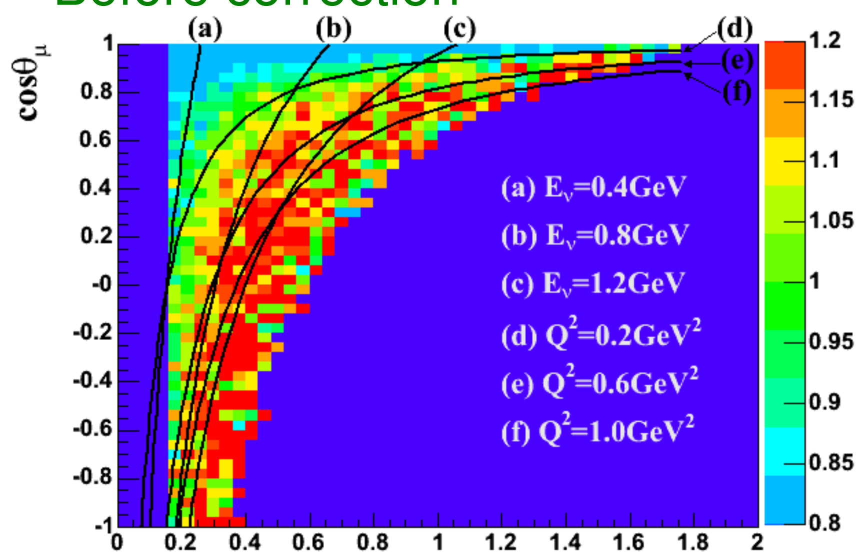




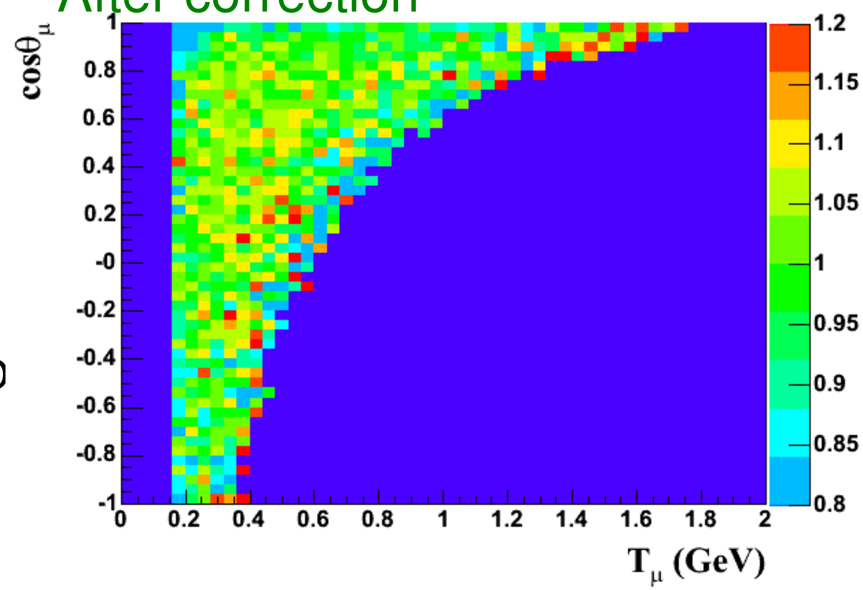
Tuning Nuance on internal ν_μ CCQE data



Before correction



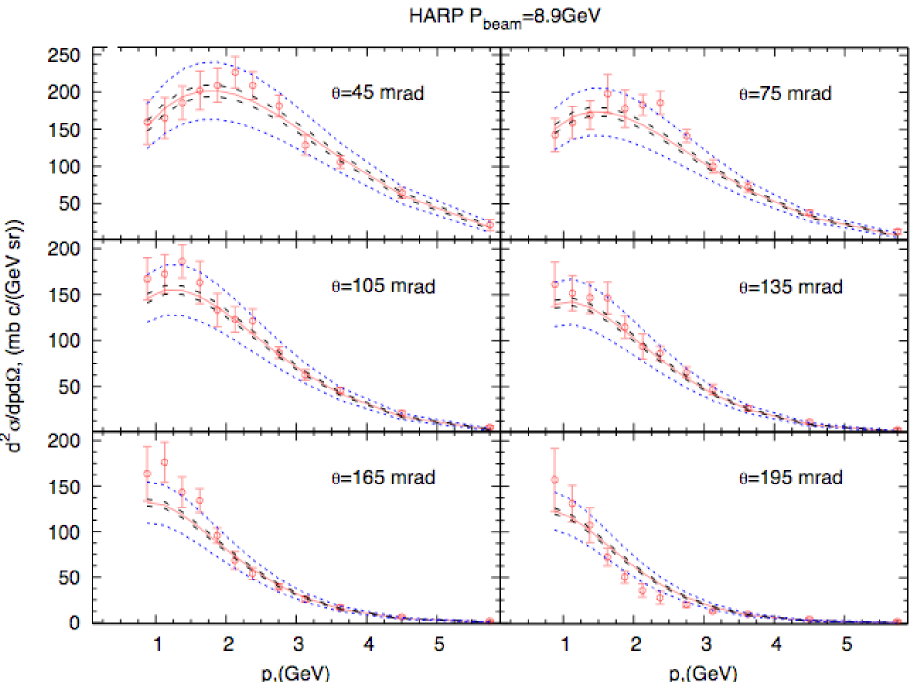
After correction



- Poor agreement at low Q^2
- From Q^2 fits to MB ν_μ CCQE data extract:
  - M_A^{eff} -- effective axial mass
  - E_{lo}^{SF} -- Pauli Blocking parameter
- Beautiful agreement after Q^2 fit, even in 2D
- Ability to make these 2D plots is unique due to MiniBooNE's high statistics

Meson production at the target

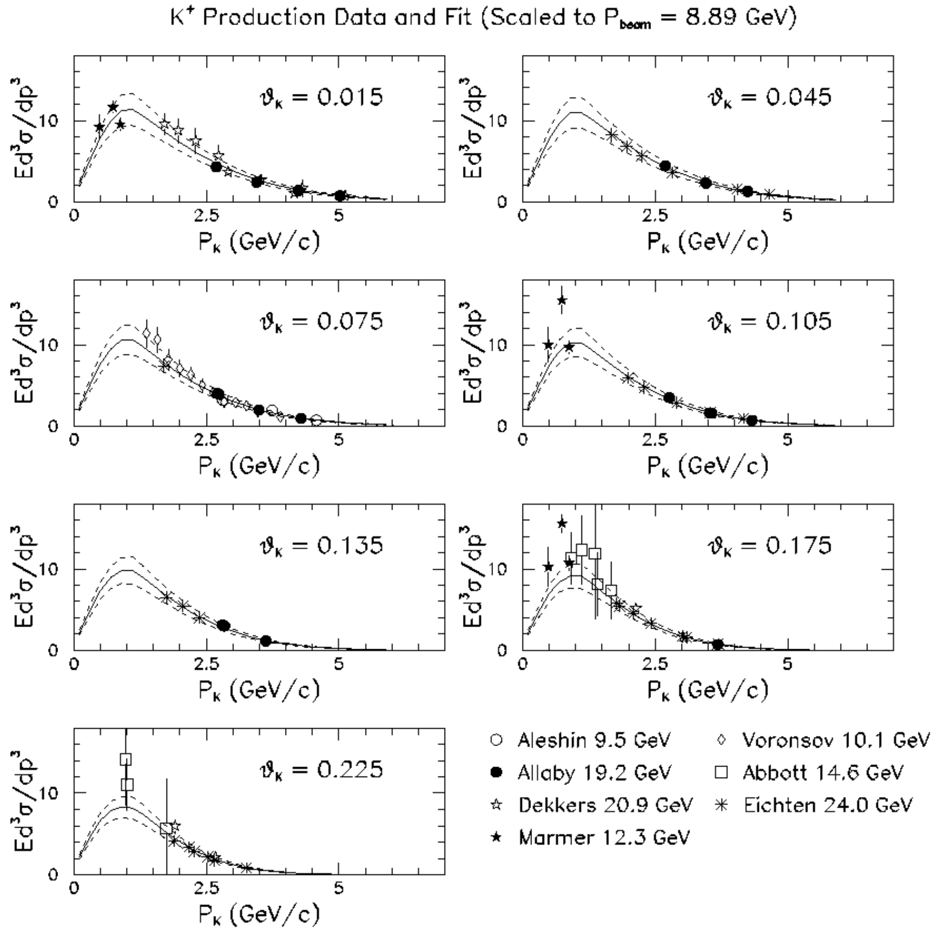
Pions:



HARP collaboration,
hep-ex/0702024

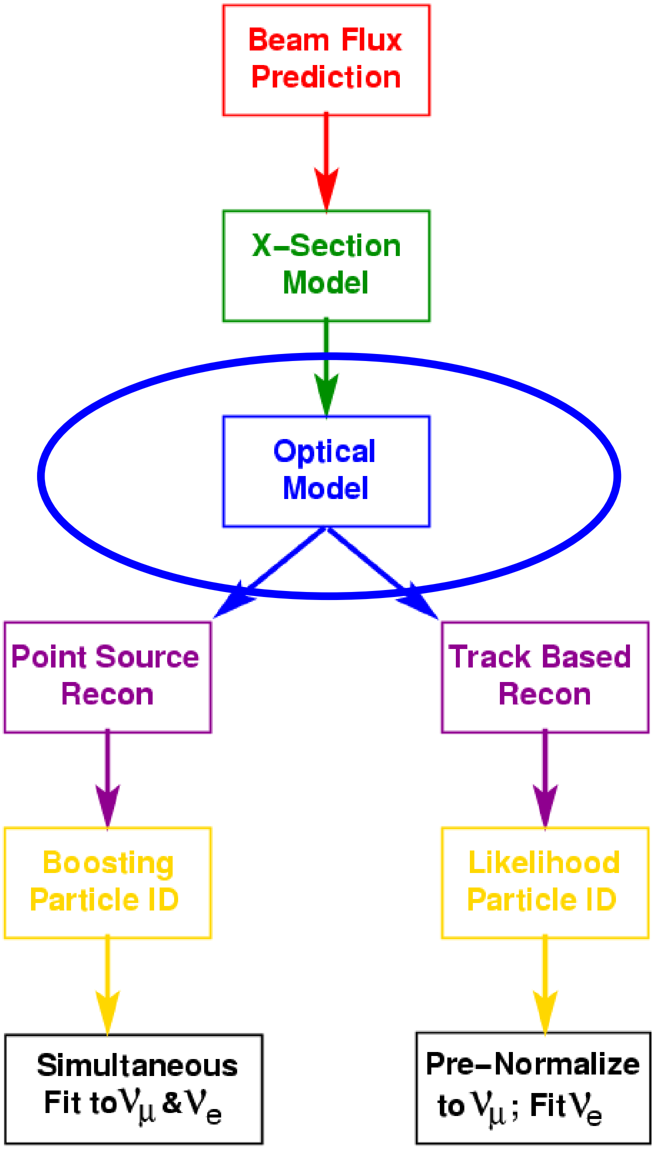
- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% λ Beryllium target
- Data were fit to Sanford-Wang parameterization

Kaons:

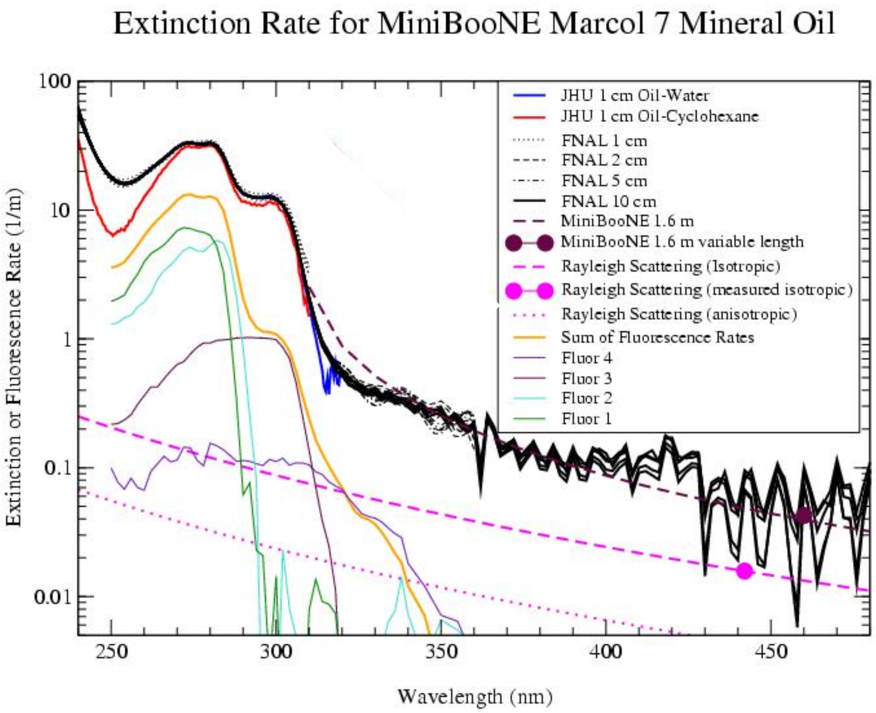


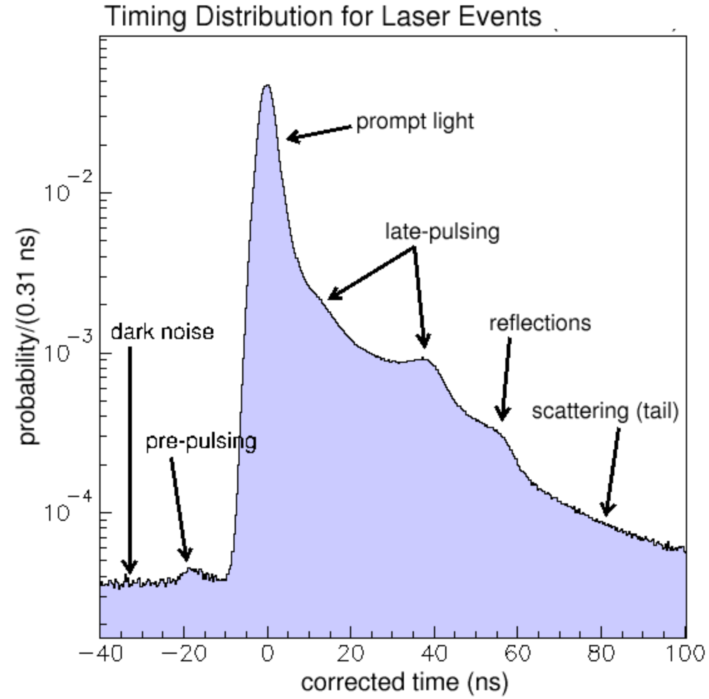
- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

Optical Model

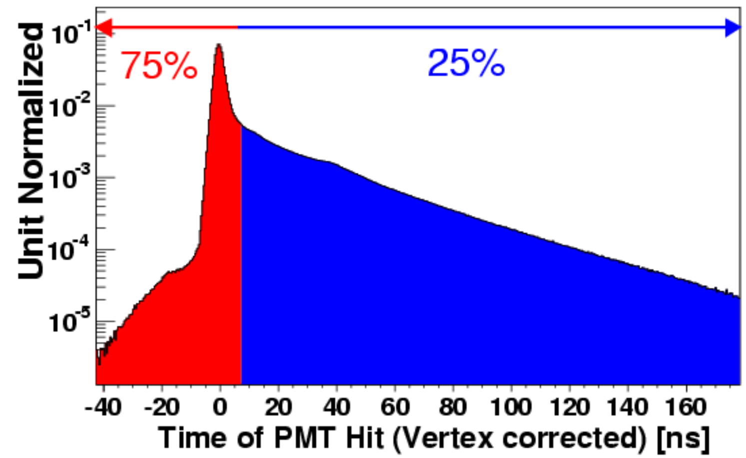


Light propagation in the detector



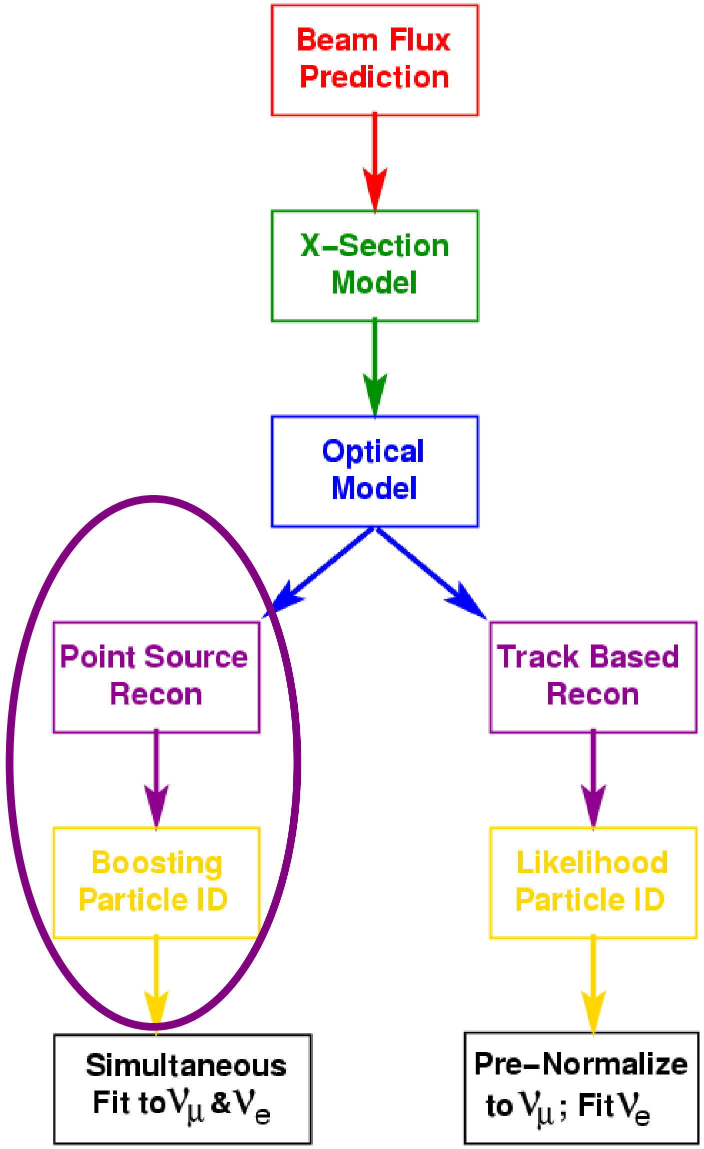


Michel electron t distribution



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

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, but runs 10 x faster
- To make up for the simple fit, the BDT analysis relies on a form of machine learning, the boosted decision tree.

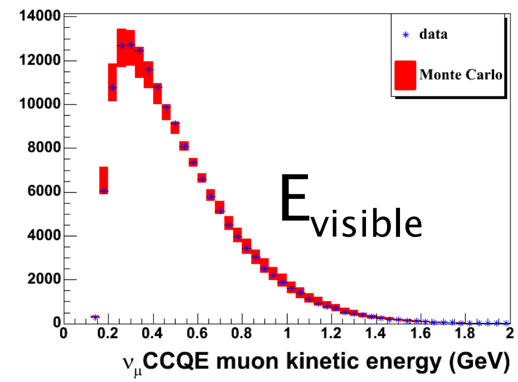
Byron P. Roe, *et al.*, NIM A543 (2005) 577.

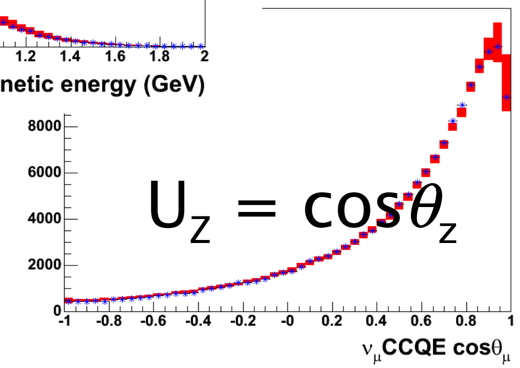
BDT Resolution:
vertex: 24 cm
direction: 3.8°
energy 14%

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

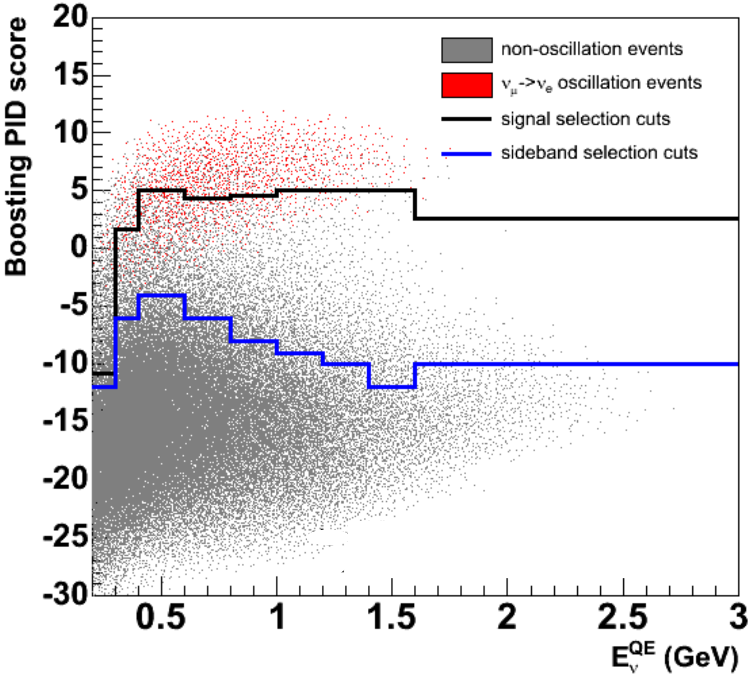
- Boosting Input Variables:
  - Low-level (# tank hits, early light fraction, etc.)
  - High-level (Q2, U_z, fit likelihoods, etc.)
  - Topology (charge in annuli, isotropic light, etc.)
- A total of 172 variables were used
- All 172 were checked for agreement within errors in 5 important 'boxes' (ν_μ CCQE, NC π^0, NC-elastic, Michel decay e, 10% closed)
- Boosting Output: Single 'score', + is signal-like

ν_μ CCQE Examples



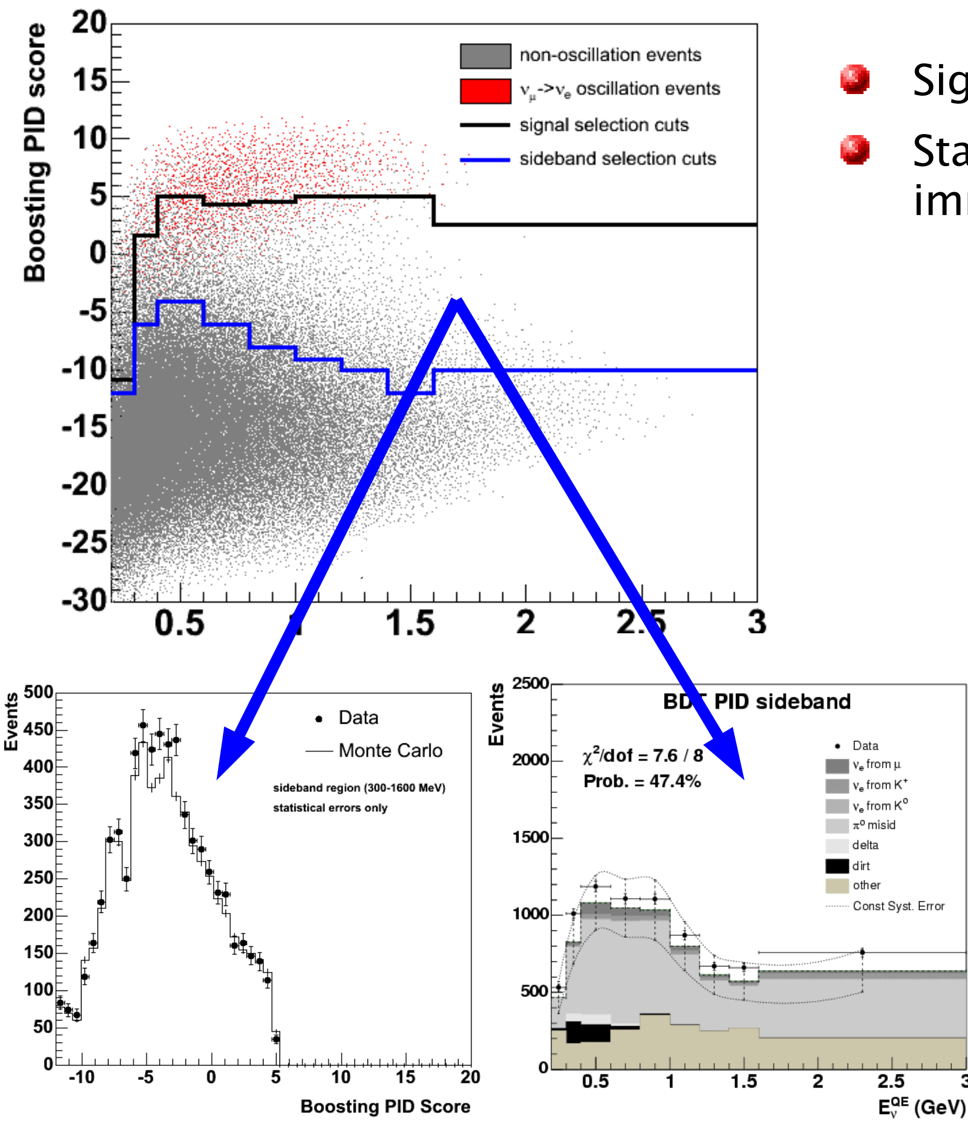


BDT Analysis: Signal/background regions



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

BDT Analysis: Signal/background regions

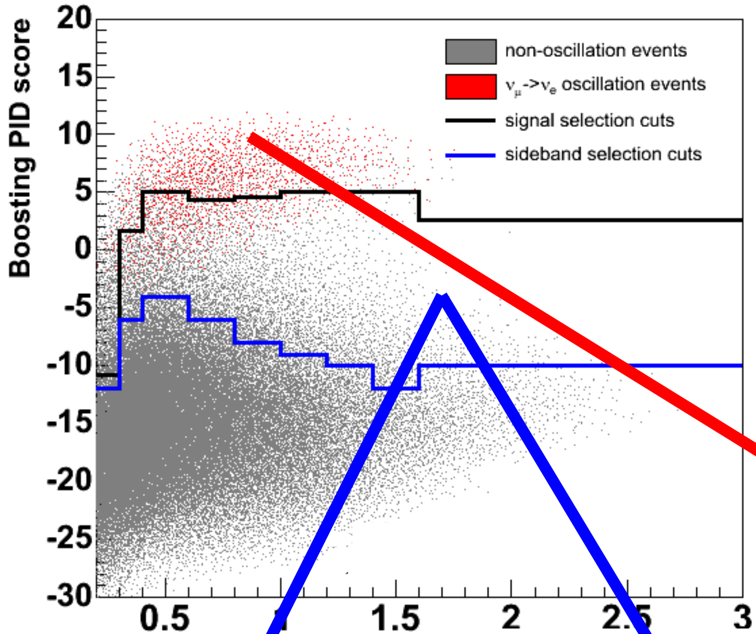


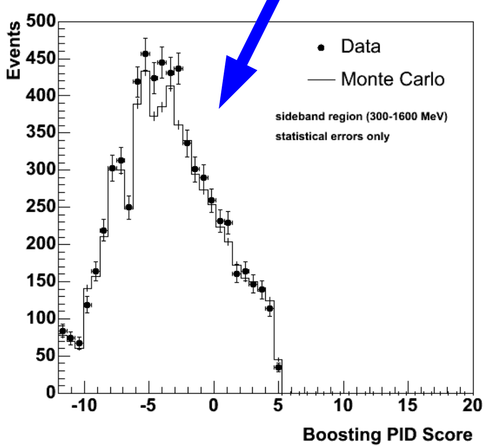
- Signal prediction (red) versus all bkgs (gray)
- Start by looking at data in 'sideband'...region immediately adjacent to signal region

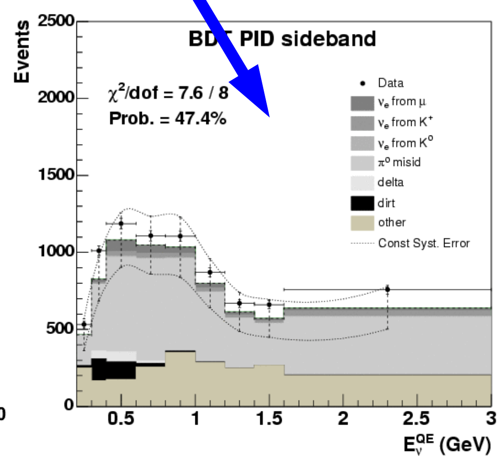
BDT Analysis: Signal/background regions

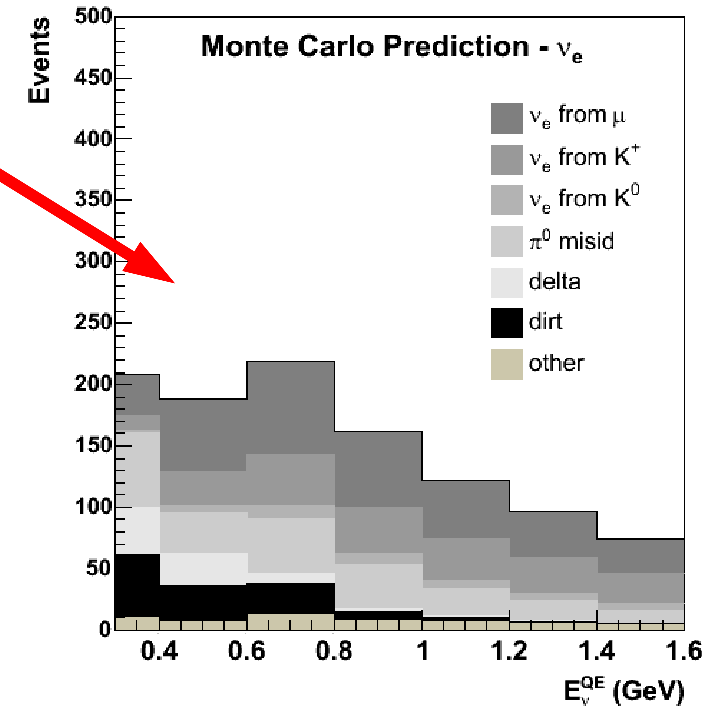
- Signal prediction (red) versus all bkgs (gray)
- Start by looking at data in 'sideband'...region immediately adjacent to signal region
- Satisfied with agreement? Finalize background prediction
- In 500-1200 MeV range: 603 bkg, LSND best-fit $\nu_\mu \rightarrow \nu_e$ 203

S/sqrt(B)=8.3





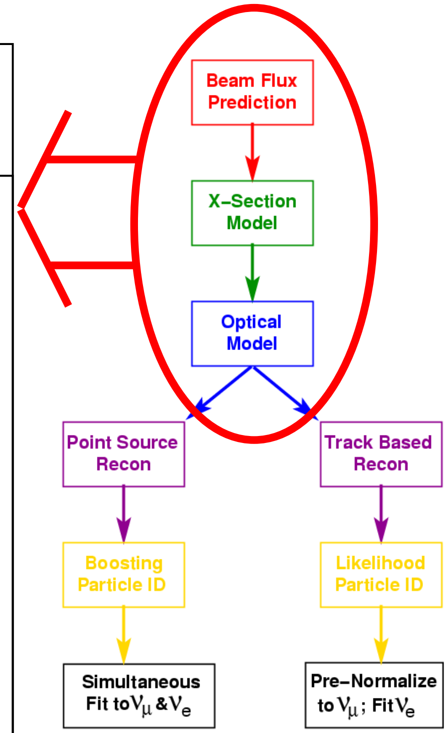




Systematic Error Analysis and Results

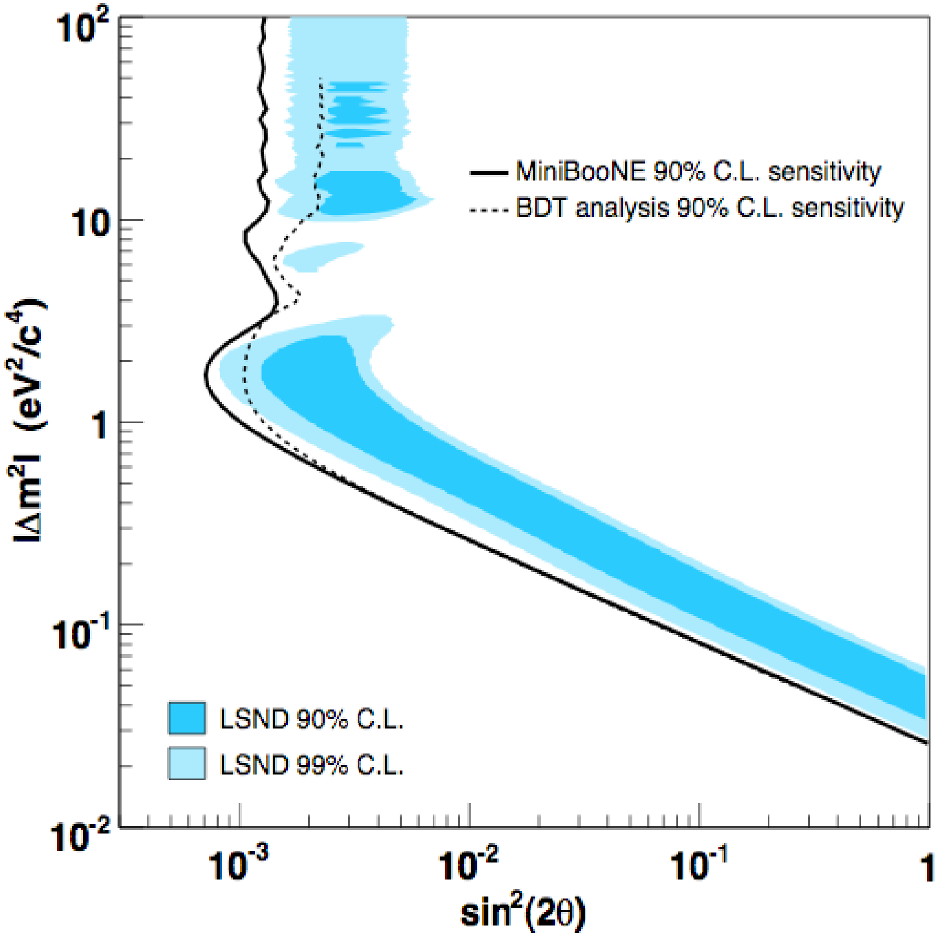
Final error budget (diagonals only...greatly simplified)

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



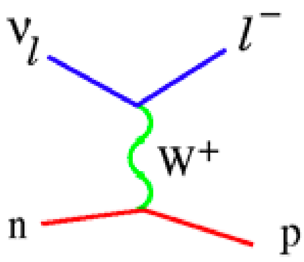
- Sensitivity is determined from simulation only (no data yet!)
- Decided before unblinding:
  - Final PID cuts
  - Region of E_ν to fit
  - Analysis with higher sensitivity would be the final MB result
- TBL (solid) is better at high Δm^2
- 90% CL defined by $\Delta\chi^2 = 1.64$

Analysis/publication status

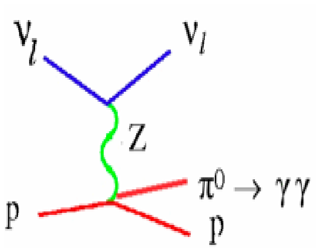
- New analysis structure
  - 2 analysis coordinators
  - 10 analysis teams
- 4 Papers coming out in support of the oscillation analysis
  - NC π^0 background measurement
  - ν_μ CCQE analysis
  - flux NIM
  - detector NIM
  - reconstruction NIM
- 12 other analyses being finalized
  - NC elastic x-section
  - Combine 2 oscillation analyses
  - Combination with Karmen/LSND/Bug
  - NuMI events in MiniBooNE
  - $CC\pi+/CCQE$ x-section ratio
  - ν_μ disappearance limit
  - Extending to lower E_ν
  - ν_μ e- elastic scattering
  - Coherent/resonant π production
  - Reconstructing the Δ
  - Anti-neutrino oscillations
  - Tandem LV model after MB

MB cross-section analyses from NuInt07...

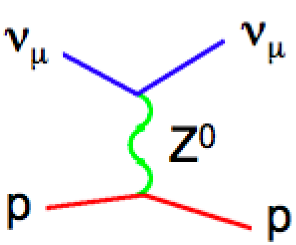
- ν_μ CCQE



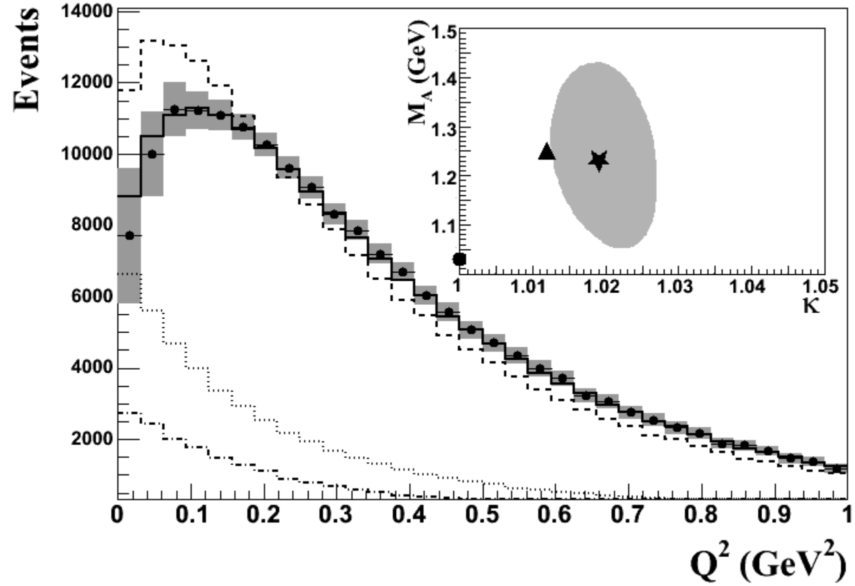
- NC π^0



- NC elastic



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

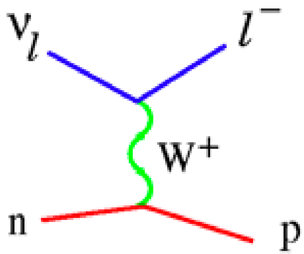


- 198,000 events allows for detailed 1 and 2d kinematic views
- Agreement between data (points) and MC (solid) after fitting for modified Fermi gas parameters
- 'Golden channel' for normalizing flux X xsec in oscillation analysis

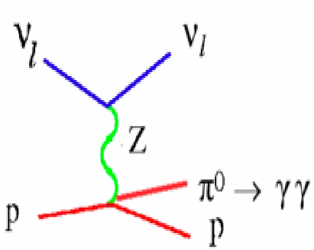
T. Katori, NuInt07

MB cross-section analyses from NuInt07...

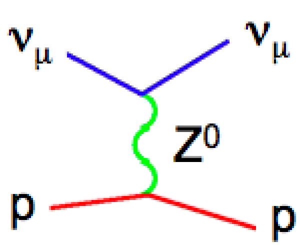
- ν_μ CCQE



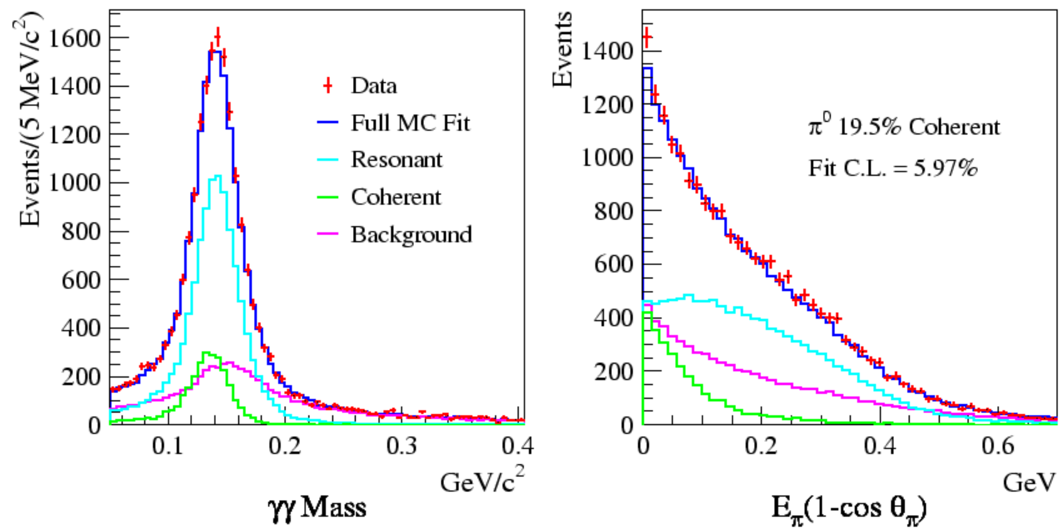
- NC π^0



- NC elastic



NC π^0 fits to resonant/coherent fractions

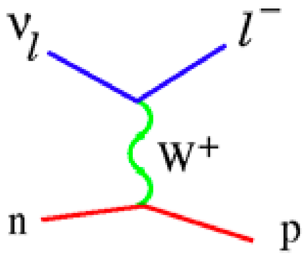


- 28,600 events, largest sample to date
- For MB flux and Nuance model we find that (19.5±1.1)% of exclusive NC π^0 production is coherent
- Very important background for oscillation analysis

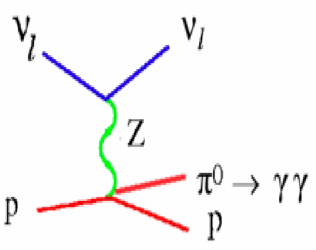
J. Link, NuInt07

MB cross-section analyses from NuInt07...

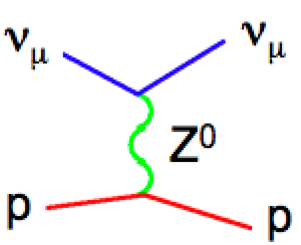
- ν_μ CCQE



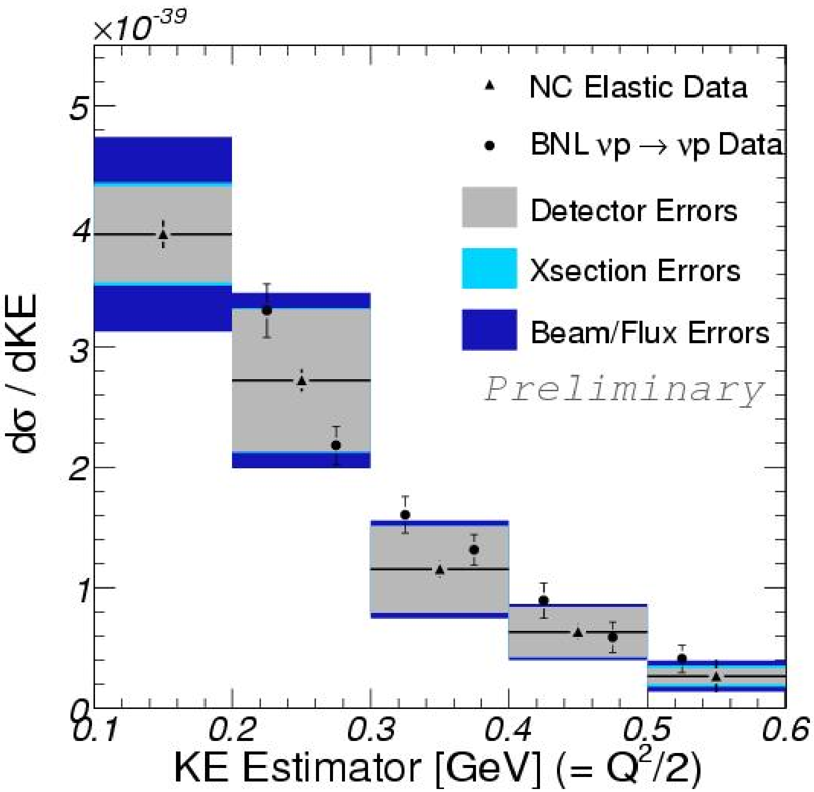
- NC π^0



- 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

Update on the low E excess…

E_ν^{QE} [MeV]	200–300	300–475	475–1250	
total background	284±25	274±21	358±35	(syst. error)
ν_e intrinsic	26	67	229	
ν_μ induced	258	207	129	
NC π^0	115	76	62	
NC $\Delta \rightarrow N\gamma$	20	51	20	
Dirt	99	50	17	
other	24	30	30	
Data	375±19	369±19	380±19	(stat. error)
Data-MC	91±31	95±28	22±40	(stat+syst)

- NC π^0 largest
- Dirt background significant
- NC $\Delta \rightarrow N\gamma$ falling off
- Intrinsic ν_e negligible

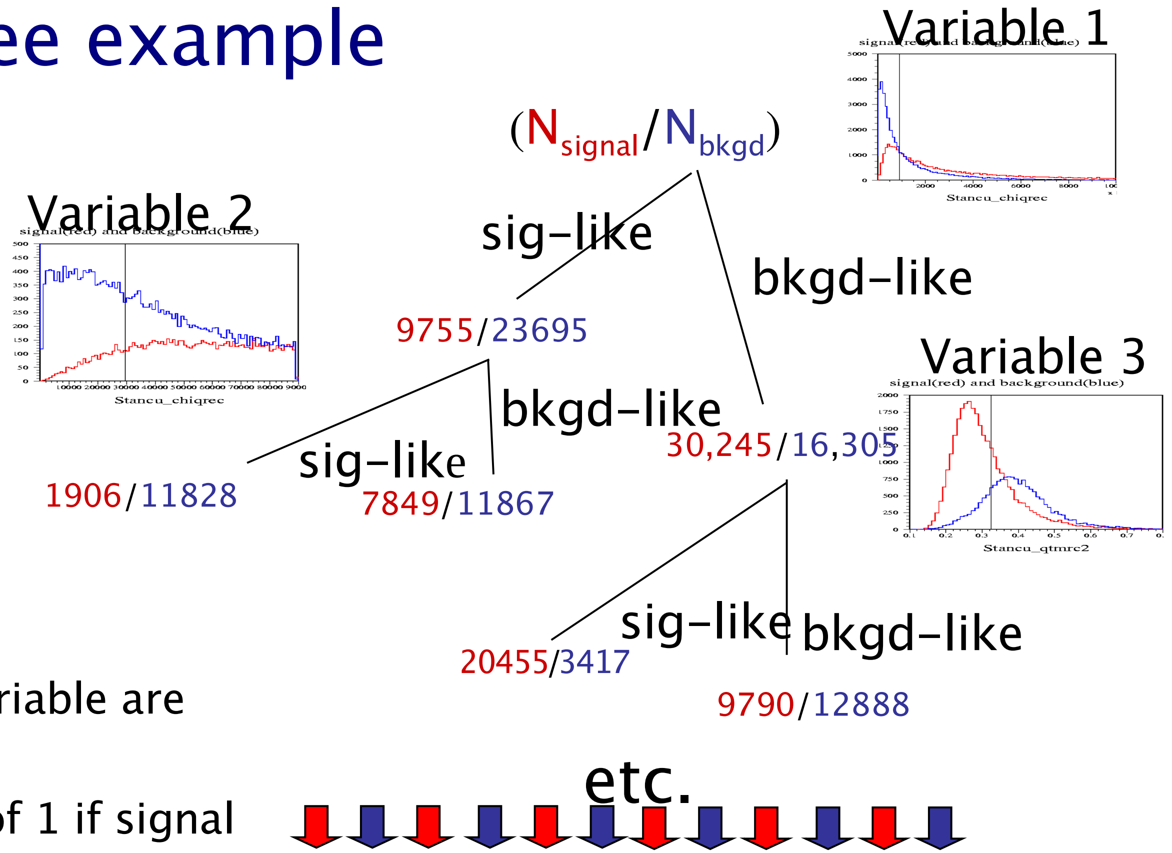
- Three main:
  - NC π^0
  - Dirt bkgnd
  - NC $\Delta \rightarrow N\gamma$
- Intrinsic ν_e small

- Intrinsic ν_e largest
- NC π^0 significant
- Others small

★ Systematics/backgrounds at low E still under study…

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

Incorporating the ν_μ constraint into the errors

Two Approaches

TBL: Reweight MC prediction to match measured ν_μ result
(accounting for systematic error correlations)

BDT: include the correlations of ν_μ to ν_e in the error matrix:

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

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

Systematic (and statistical) errors are included in $(M_{ij})^{-1}$,
where *i, j* are bins of E_ν^{QE}

Example: Underlying X-section parameter errors

(Many are common to ν_μ and ν_e and cancel in the fit)

M_A^{QE}, e_{lo}^{sf}	6%, 2% (stat + bkg only)	determined from MiniBooNE ν_μ QE data
QE σ norm	10%	
QE σ shape	function of E_ν	
ν_e/ν_μ QE σ	function of E_ν	

NC π^0 rate	function of π^0 mom	determined from MiniBooNE ν_μ NC π^0 data
M_A^{coh}, coh σ	$\pm$25%	
$\Delta \rightarrow N\gamma$ rate	function of γ mom + 7% BF	

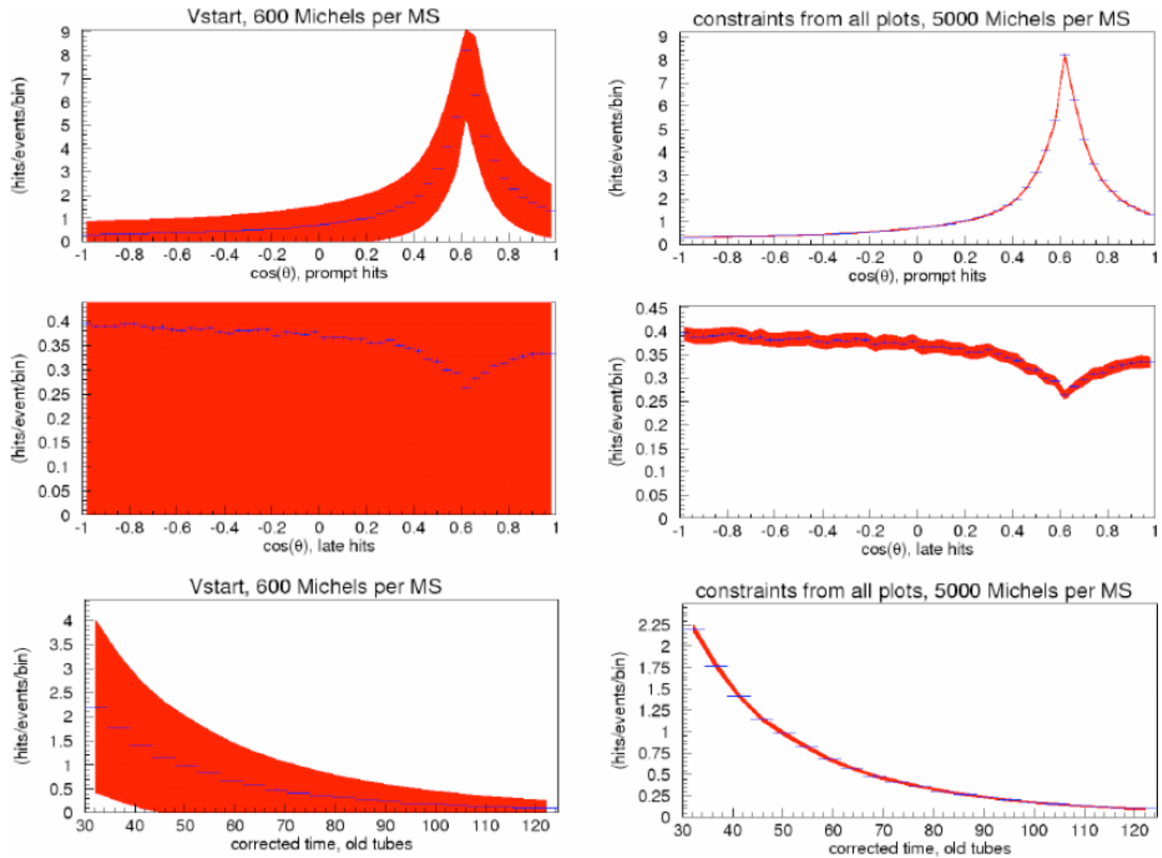
E_B, p_F	9 MeV, 30 MeV	determined from other experiments
Δs	10%	
$M_A^{1\pi}$	25%	
$M_A^{N\pi}$	40%	
DIS σ	25%	

Extracting the OM systematic error

- external measurements essential

- **finish with μ decay events (low-energy electrons)**
  (~unlimited supply and fast to simulate)

- use a Monte Carlo method to reduce uncertainty:
- compare data/MC events in relevant distributions for many allowed models
- de-weight disallowed regions of model space
- NC elastic events help out with scintillation

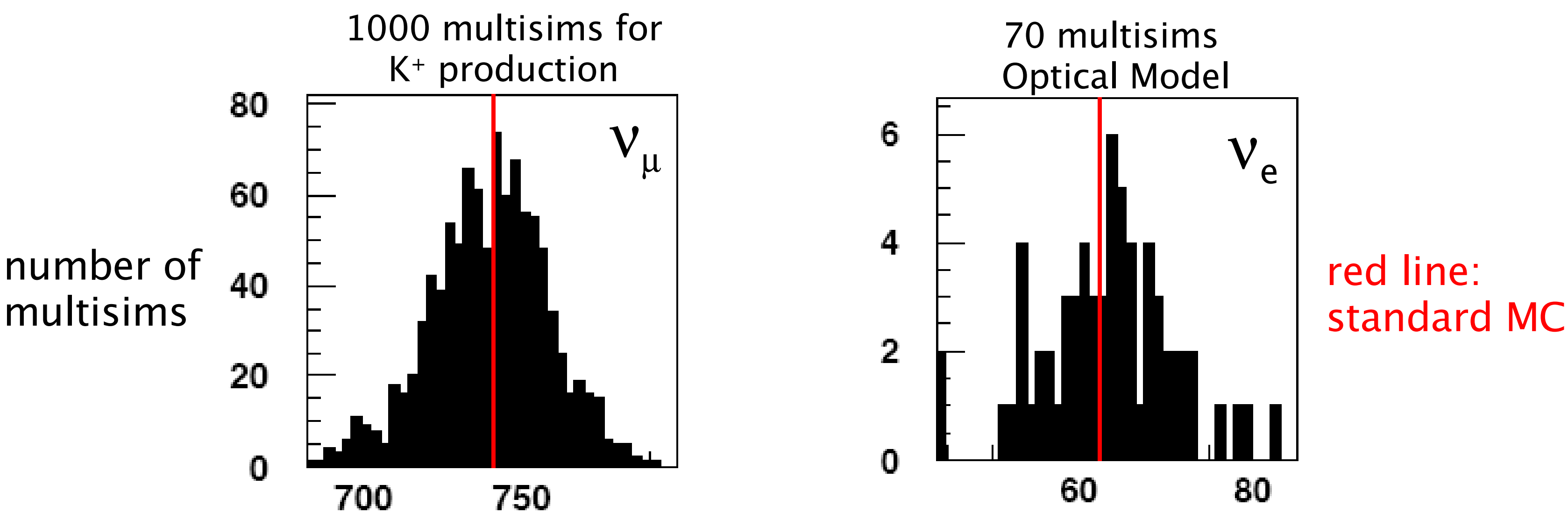


starting uncertainties in three of the distributions

(near) ending uncertainties

"Multisim" approach to assessing systematics

- A multisim is defined as a random draw from the underlying parameter that is considered allowed
- Allowed means the draw does not violate internal or external constraints
- Draws are taken from covariance matrices that dictate how parameters are allowed to change in combination, imagine Cerenkov and scintillation as independent sources of light but requiring the Michel energy to be conserved
- For flux and X-section multisims can be done via reweighting, optical model requires running hit level simulation



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

Optical model error matrix

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

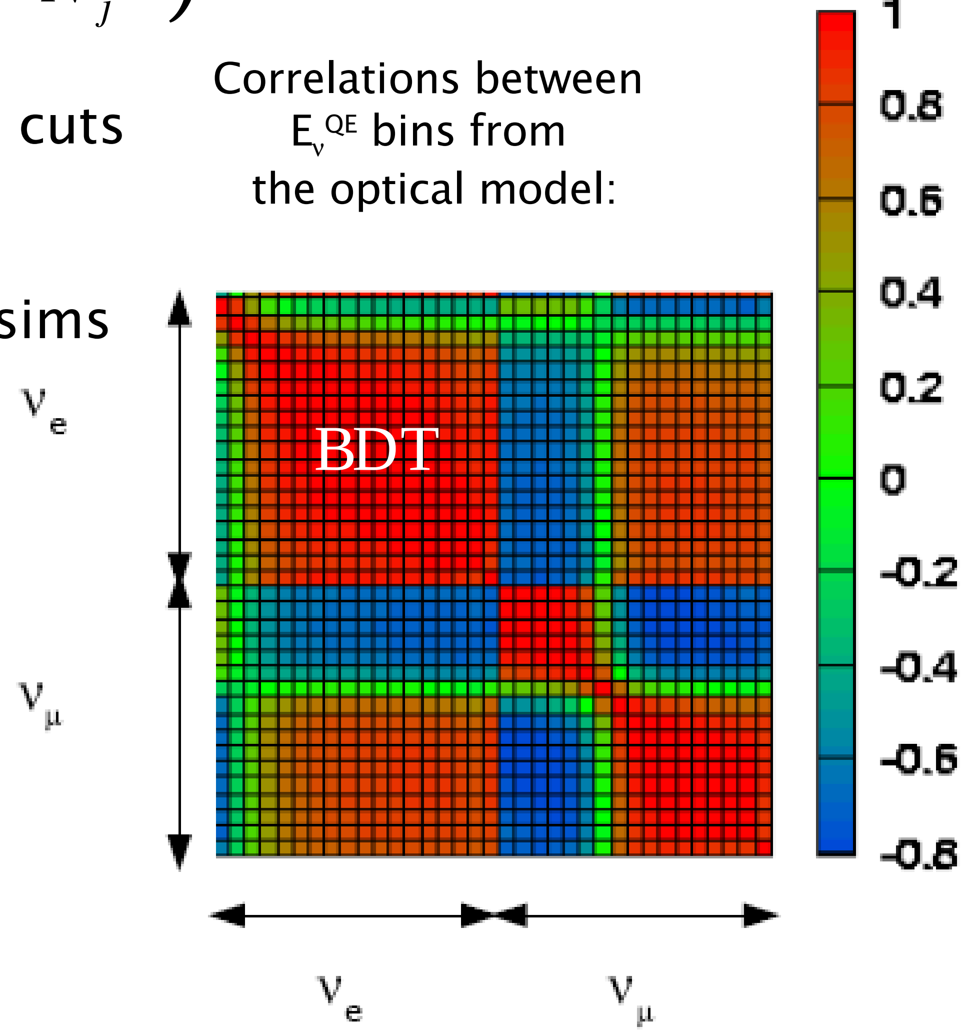
- N is number of events passing cuts
- MC is standard monte carlo
- α represents a given multisim
- M is the total number of multisims
- i,j are E_ν^{QE} bins

Total error matrix is calculated from the sum of 9 independent sources

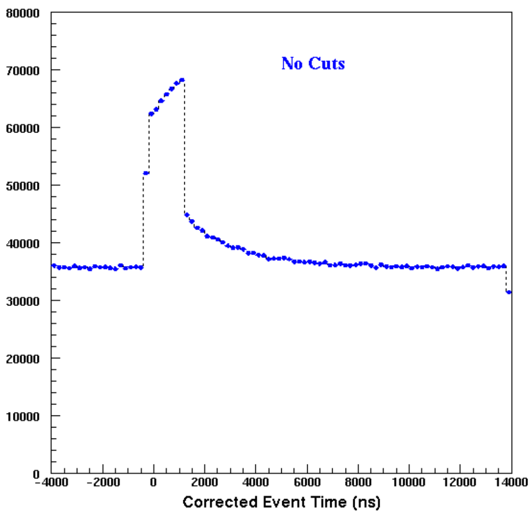
TB: ν_e–only total error matrix

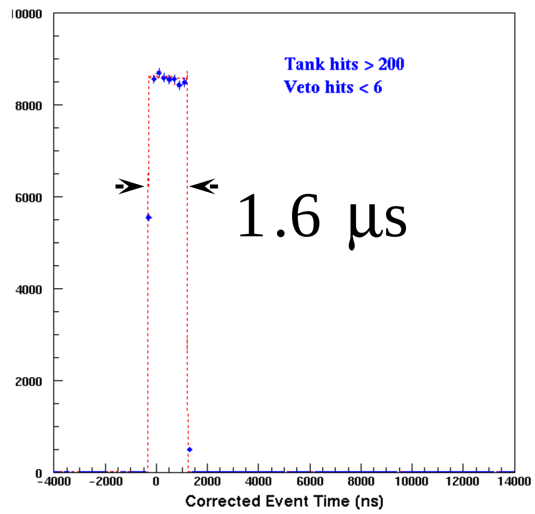
BDT: ν_μ–ν_e total error matrix

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



Simple cuts eliminate random backgrounds

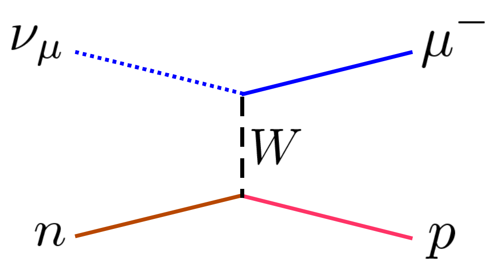


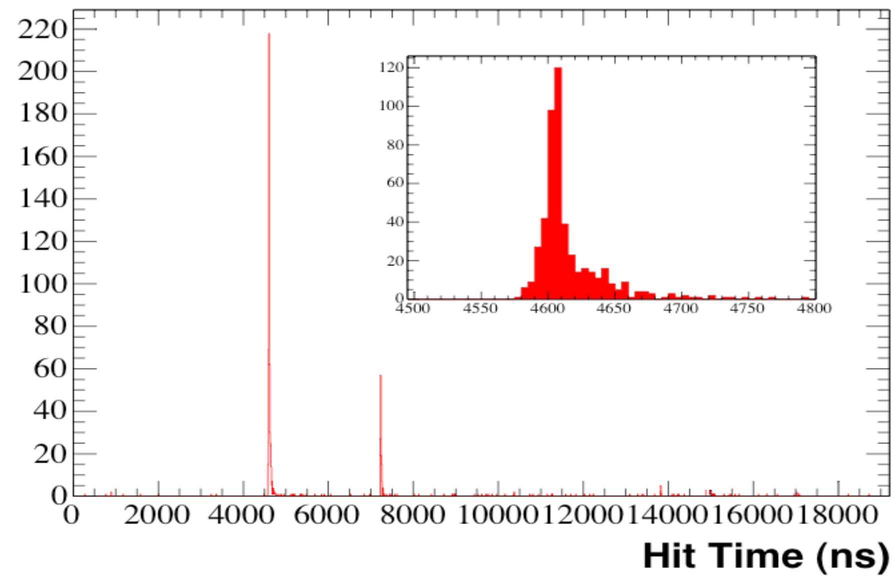


- Left: trigger window, no cuts
- Right: Simple cuts applied PMT hits in veto < 6 and tank > 200 show clean beam window
- Removes cosmic μ and their decay electrons

- Subevent structure (clusters in time) can be used for particle identification (PID)
- 2 subevent time structure expected for most common ν interaction in MB:

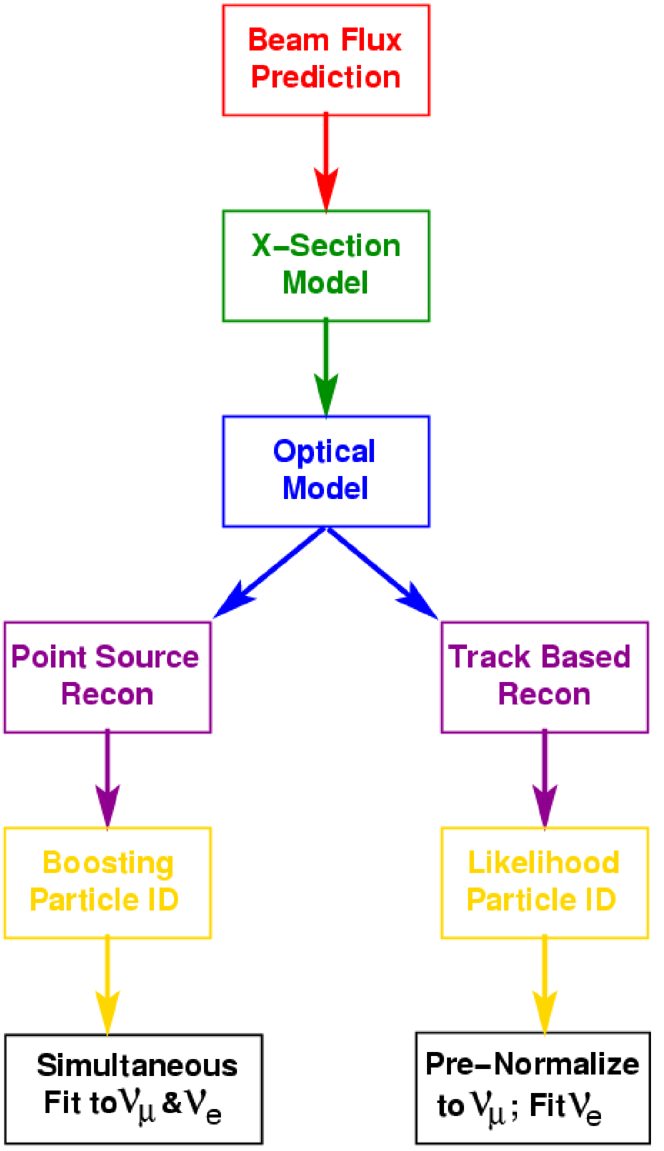
ν_μ CCQE (charged-current quasi-elastic)





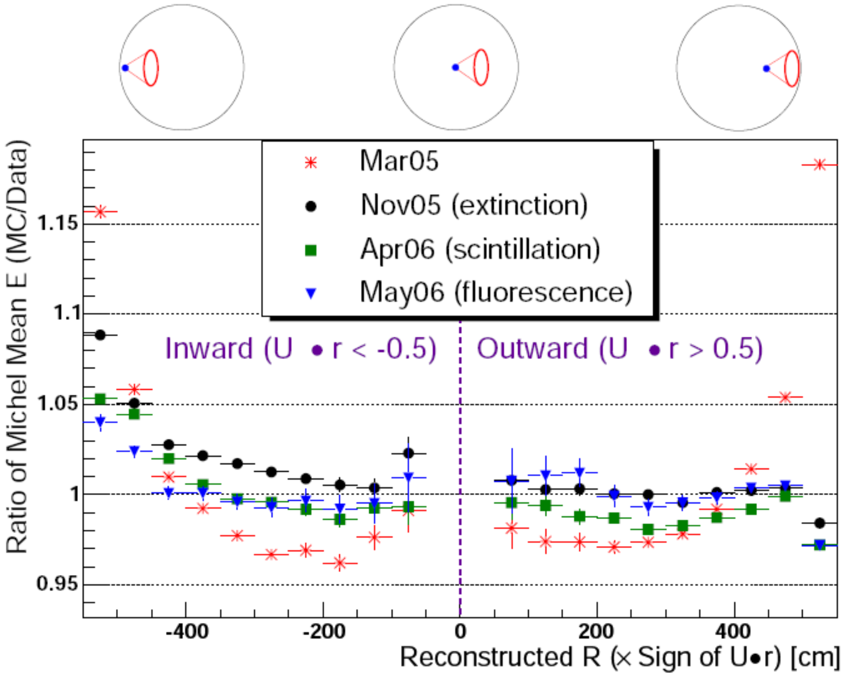
MiniBooNE analysis structure

- ✔ Start with a Geant 4 flux prediction for the ν spectrum from π and K produced at the target
- ✔ Predict ν interactions using Nuance
- ✔ Pass final state particles to Geant 3 to model particle and light propagation in the tank
- ✔ Starting with event reconstruction, independent analyses form: Boosted Decision Tree (BDT) and Track Based Likelihood (TBL)
- ✔ Develop particle ID/cuts to separate signal from background
- ✔ Fit reconstructed E_ν spectrum for oscillations

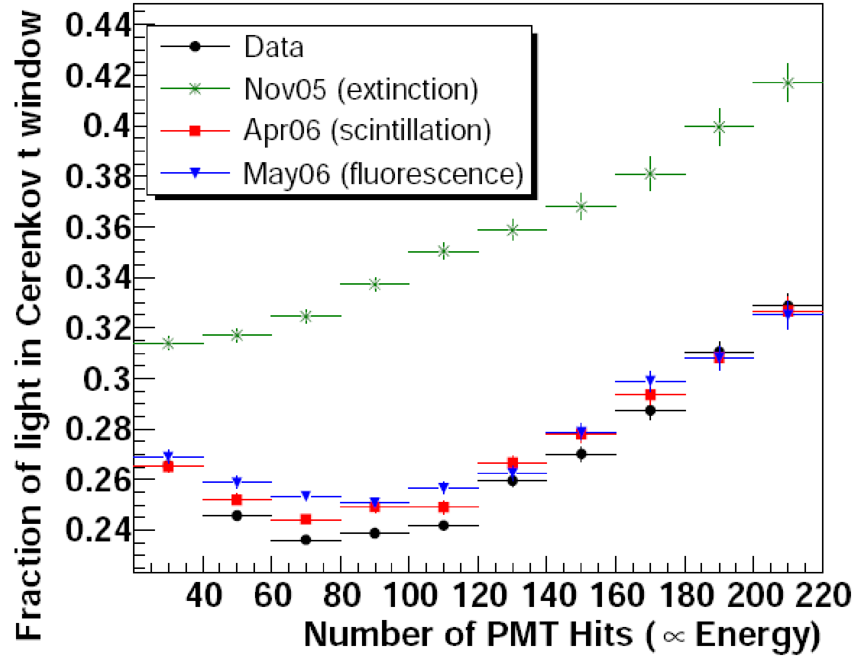


Tuning the optical model

Using Michel electrons...



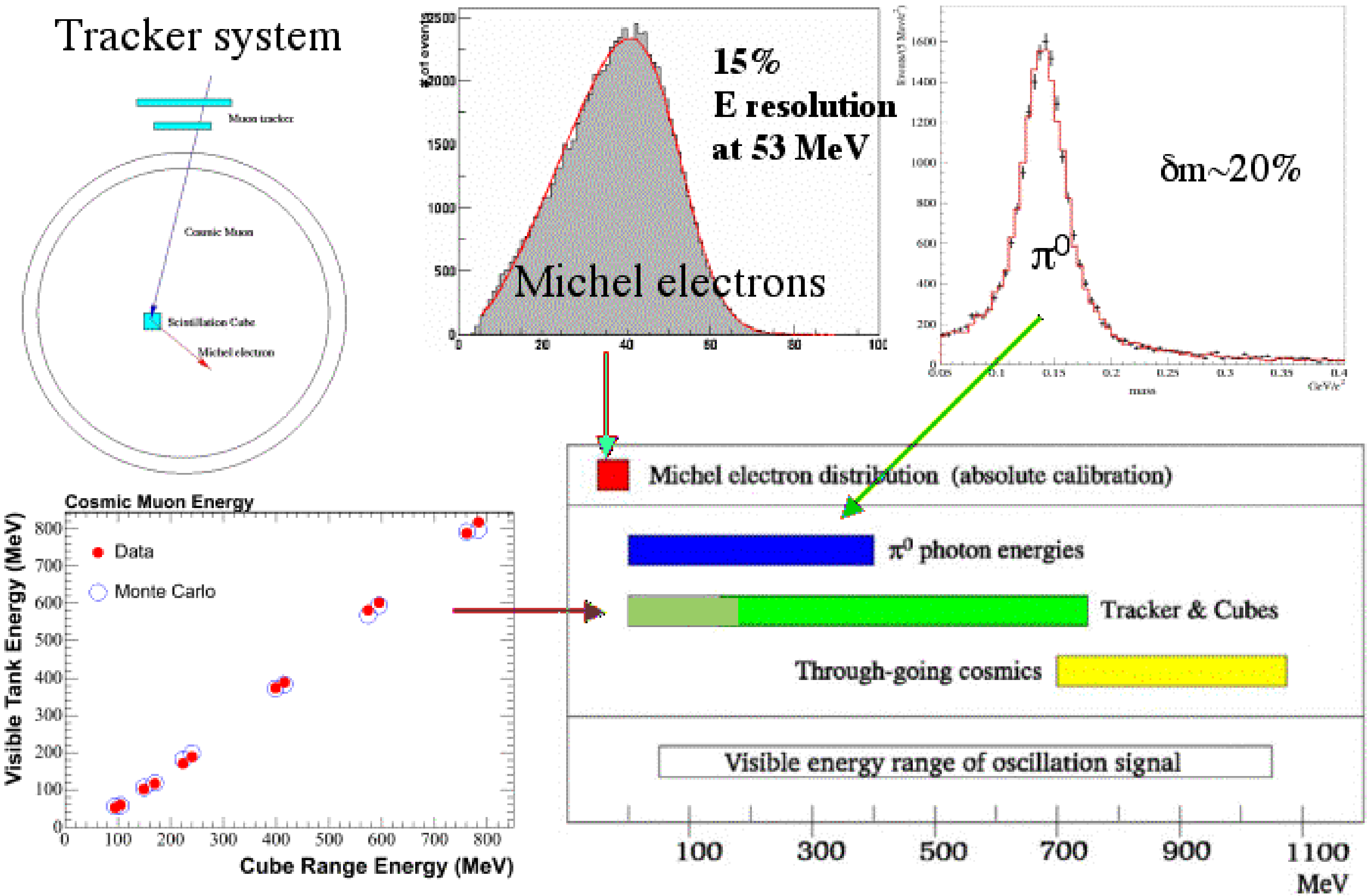
Using NC elastic ν interactions...



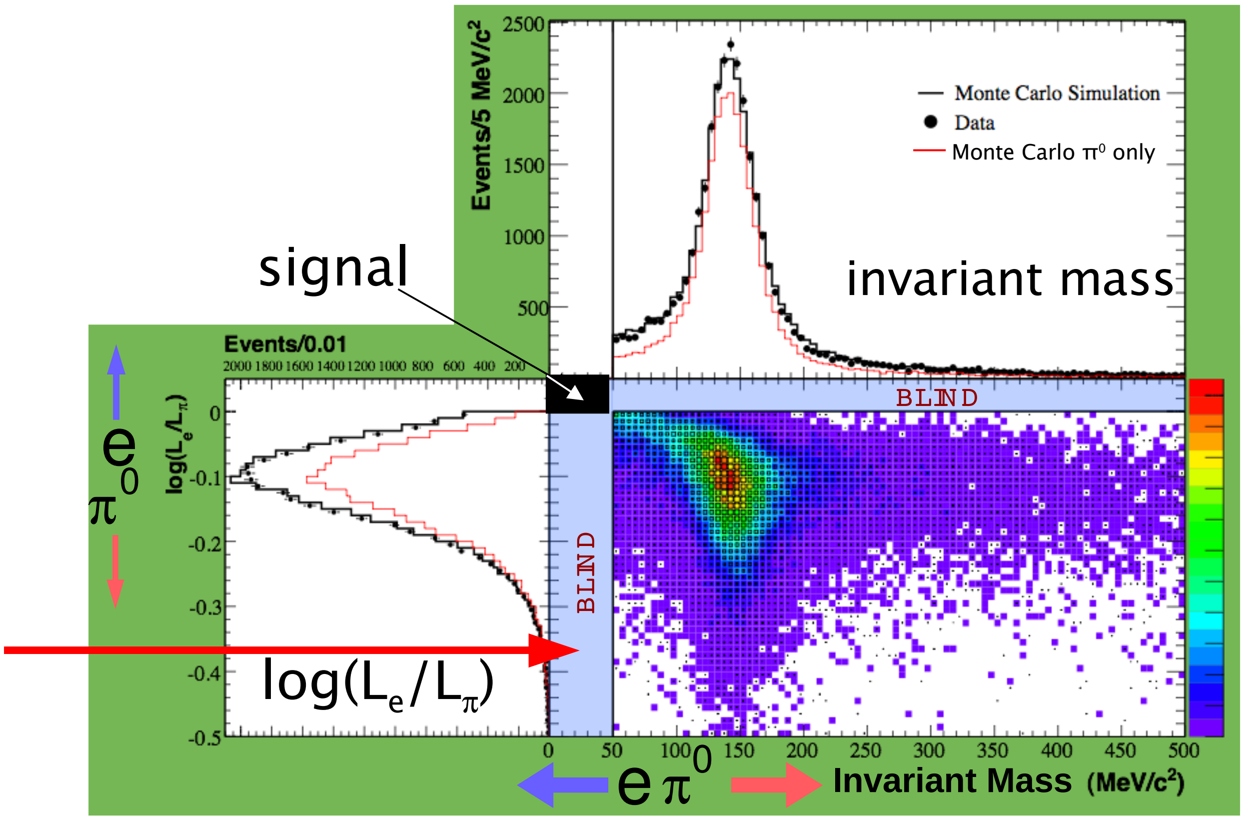
- Initial optical model defined through many benchtop measurements
- Subsequently tuned with *in situ* sources, examples
  - Left: Michel e populate entire tank, useful for tuning extinction
  - Right: NC elastic n interactions below Cerenkov threshold useful for distinguishing scintillation from fluorescence

Calibration sources span various energies

Calibration Sources

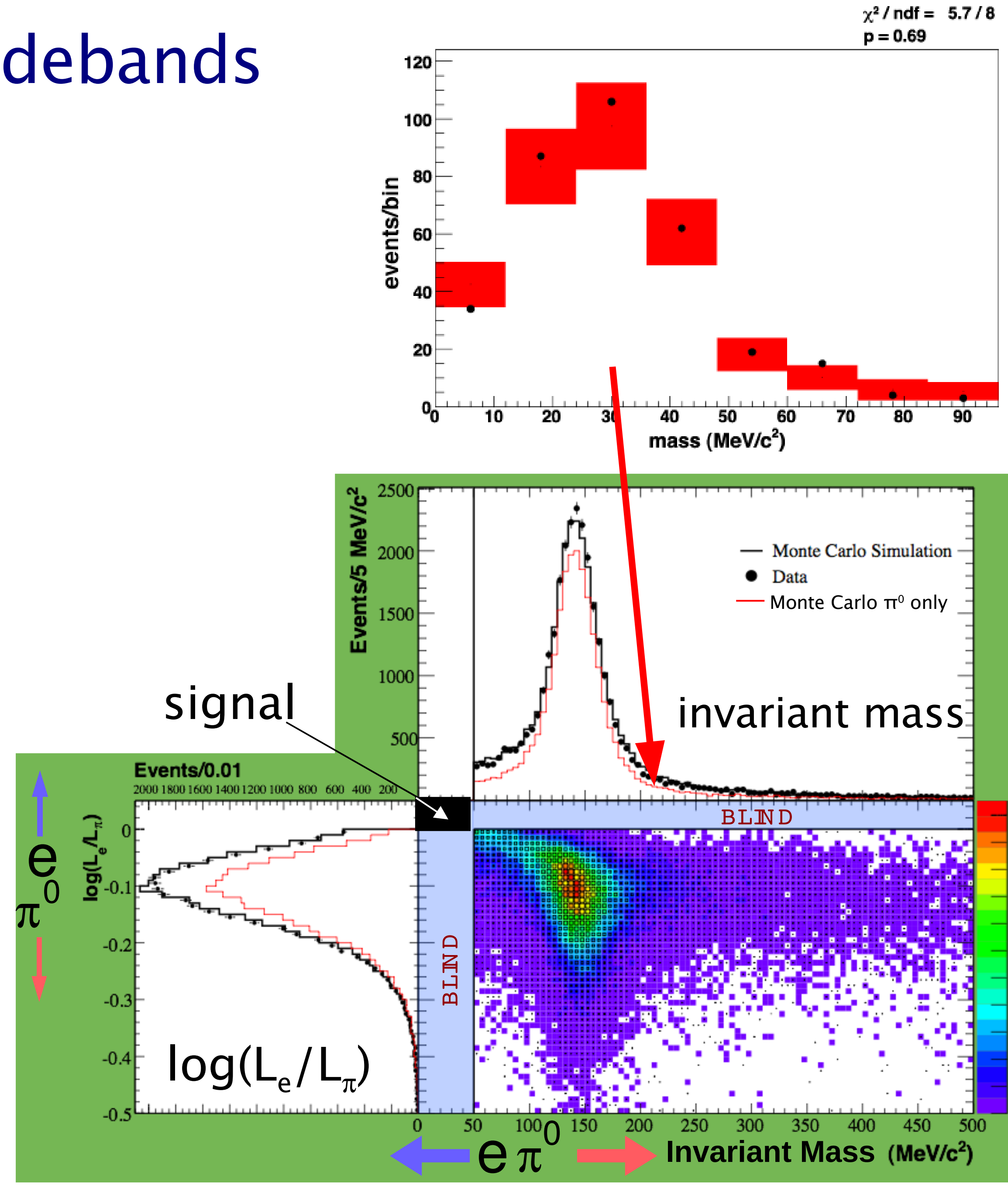


Checking signal sidebands



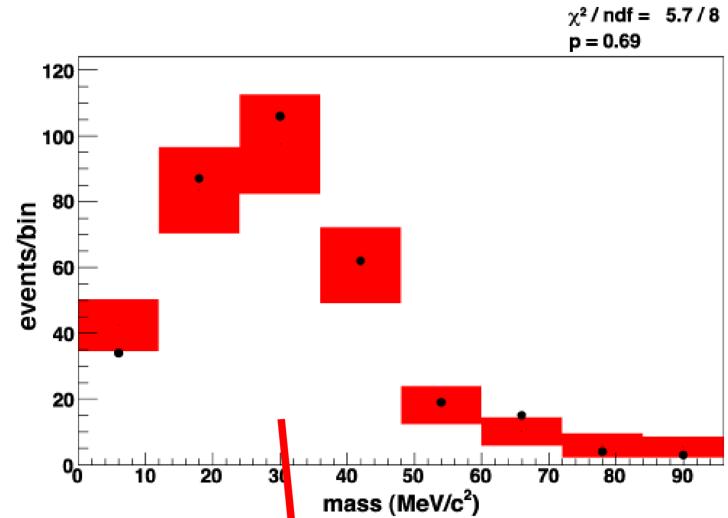
Checking signal sidebands

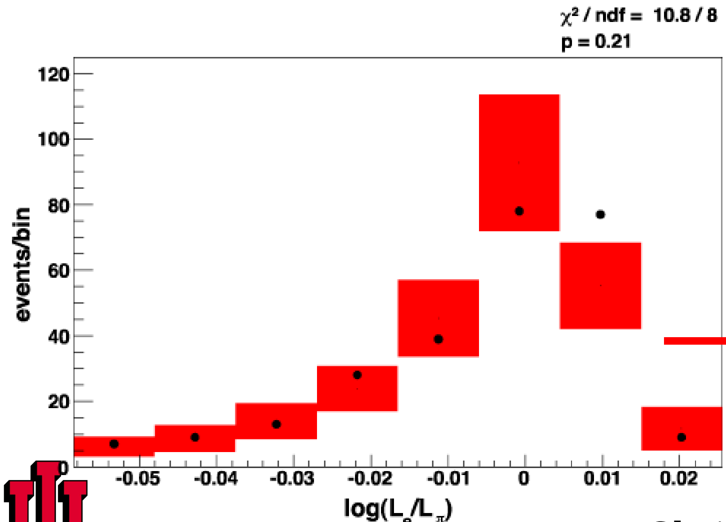
- Region at low $\log(L_e/L_\pi)$

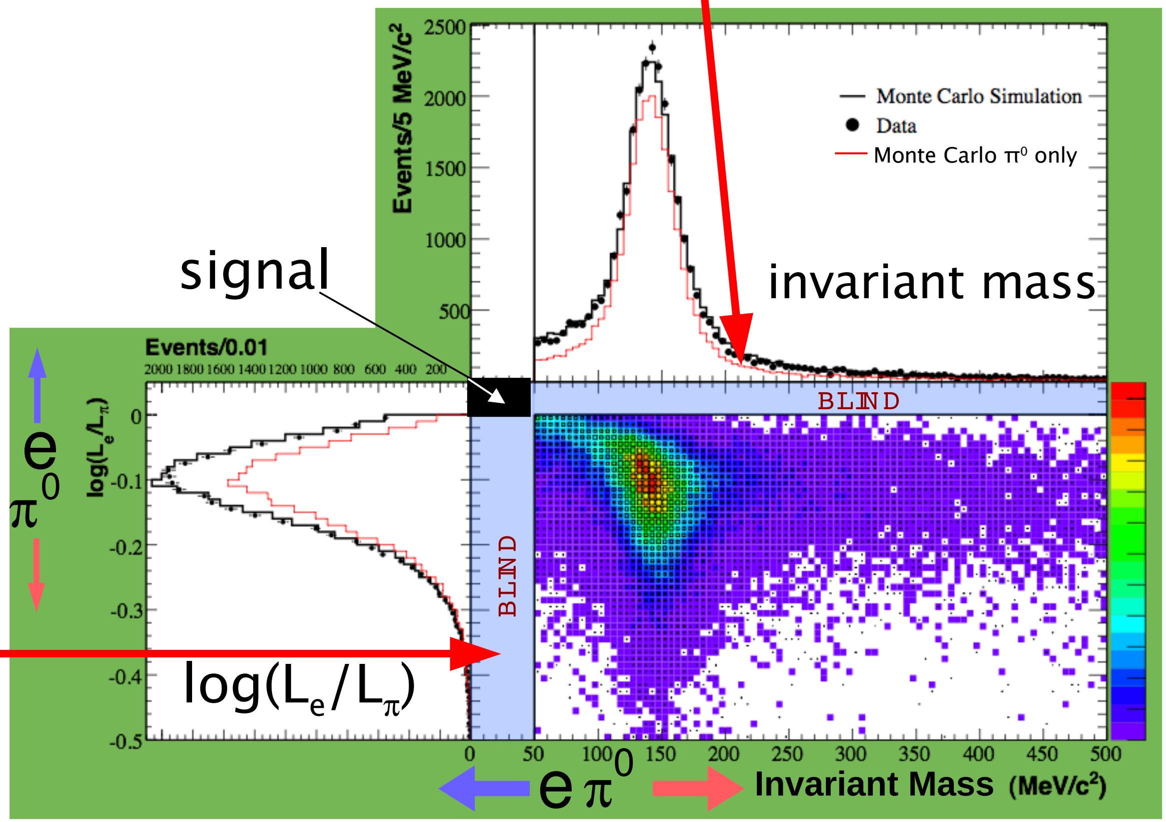


Checking signal sidebands

- Region at low $\log(L_e/L_\pi)$
- Region at low invariant mass

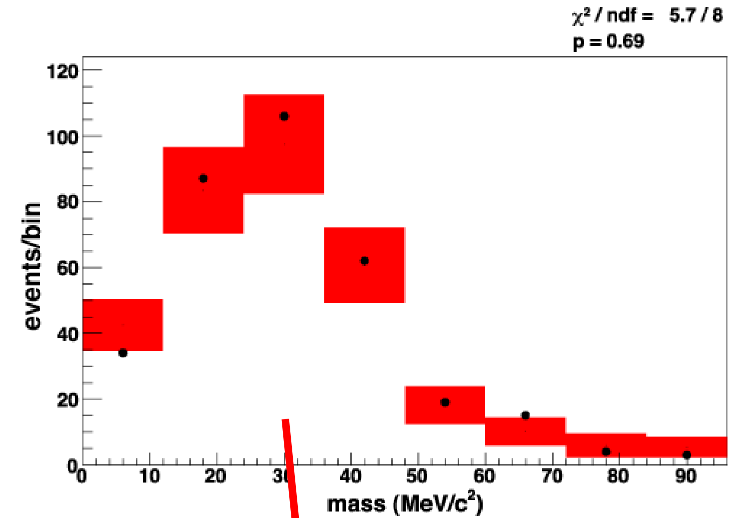


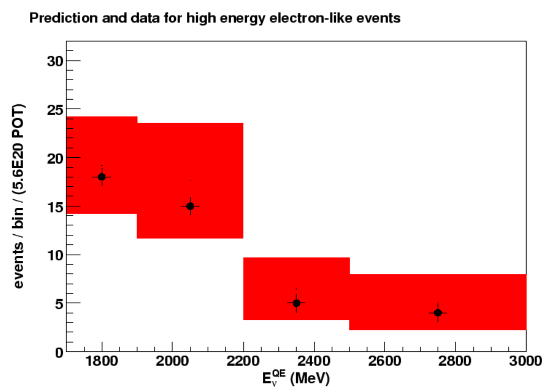


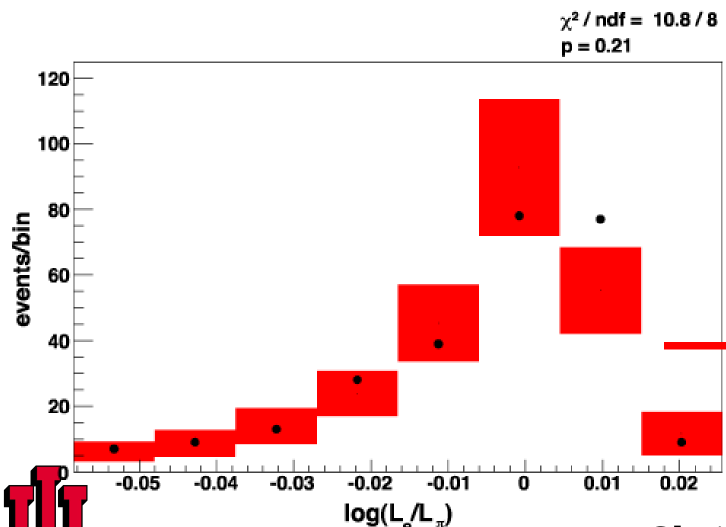


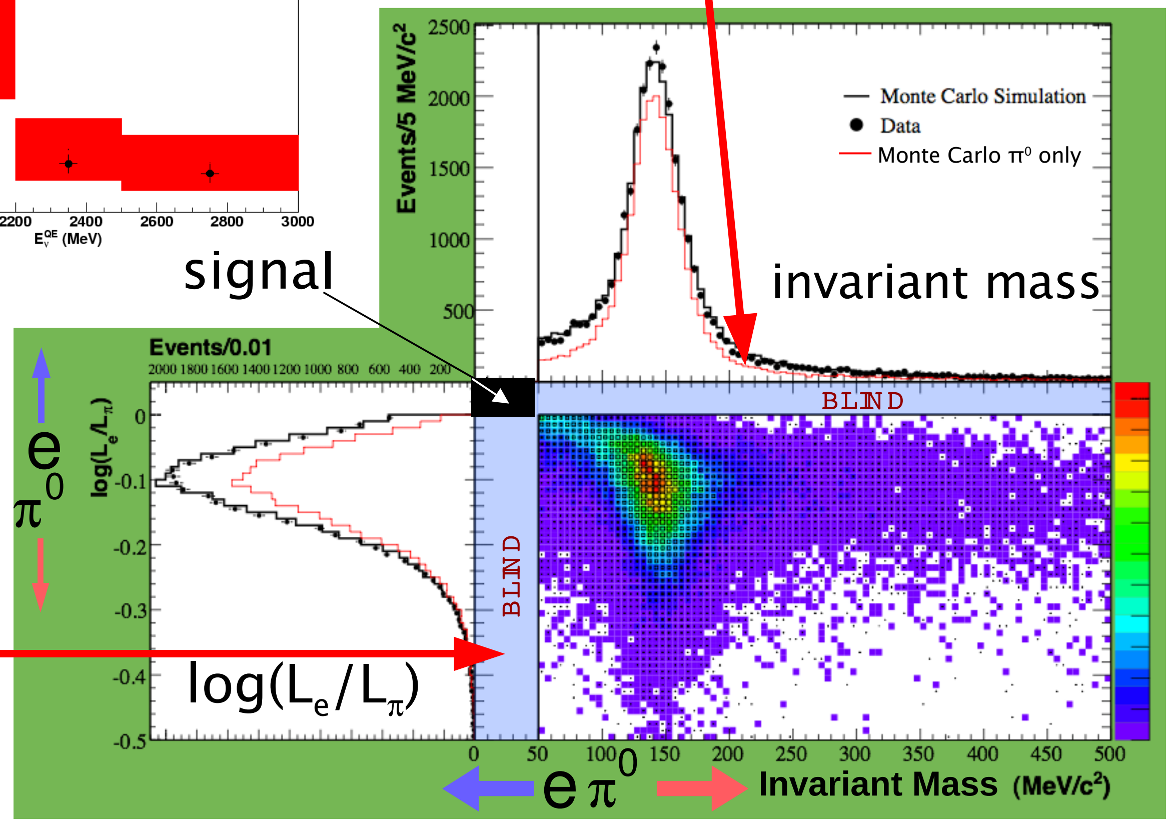
Checking signal sidebands

- Region at low $\log(L_e/L_\pi)$
- Region at low invariant mass
- Region in signal, but at high E_ν

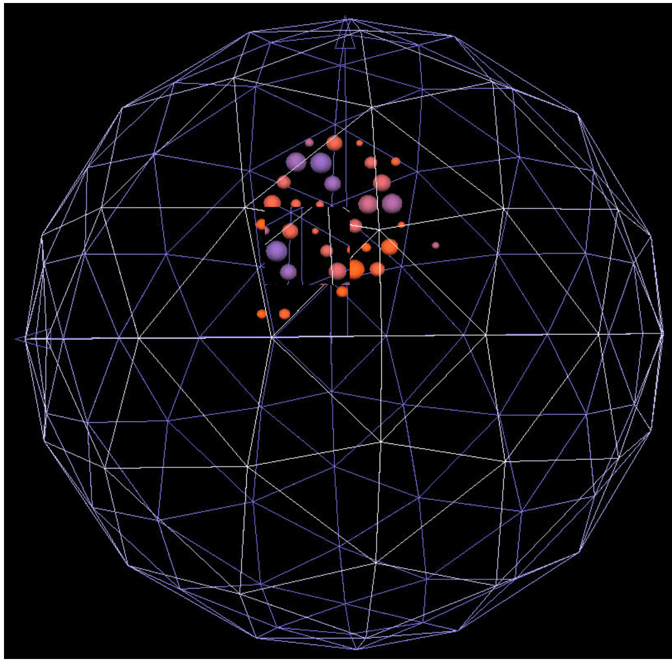


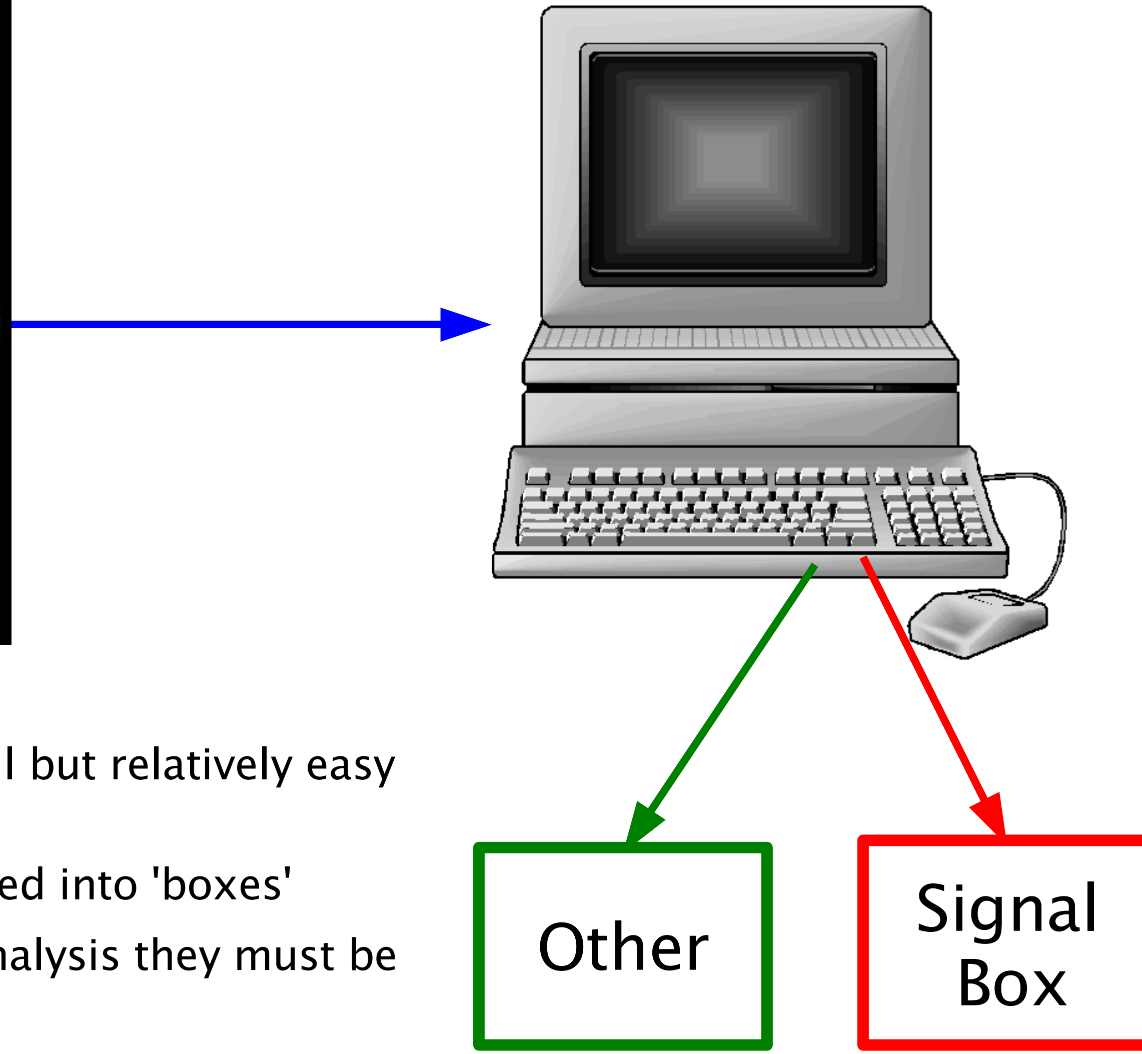






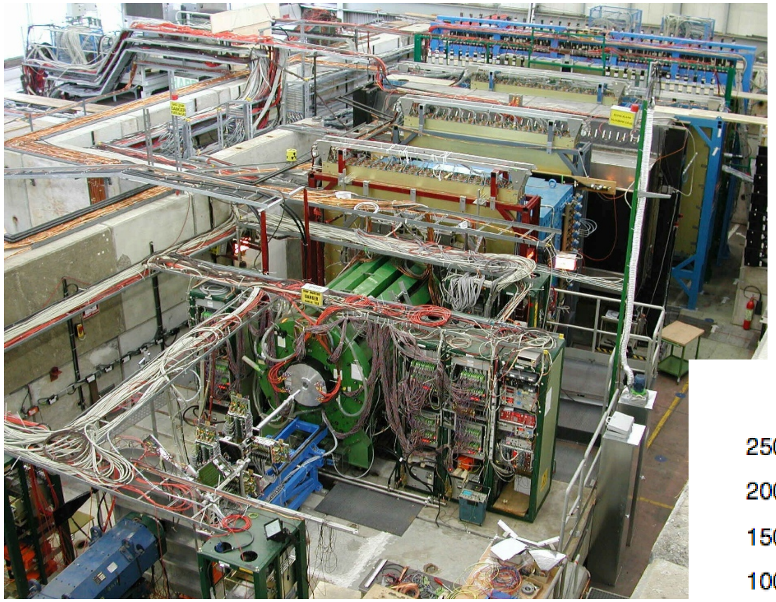
Blind analysis in MiniBooNE



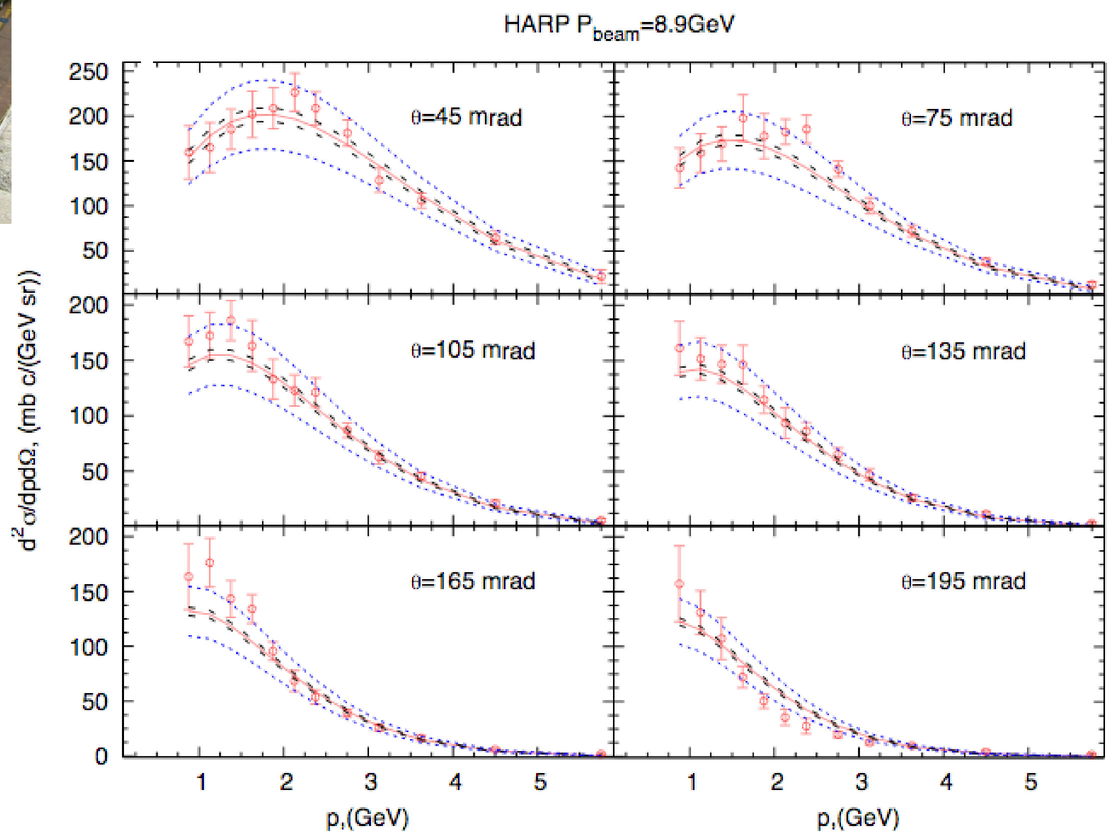


- The MiniBooNE signal is small but relatively easy to isolate
- As data comes in it is classified into 'boxes'
- For boxes to be opened to analysis they must be shown to have a signal $< 1\sigma$
- In the end, 99% of the data were available prior to unblinding...necessary to understand errors

Modeling pion production



- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV/c proton beam momentum



Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024