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

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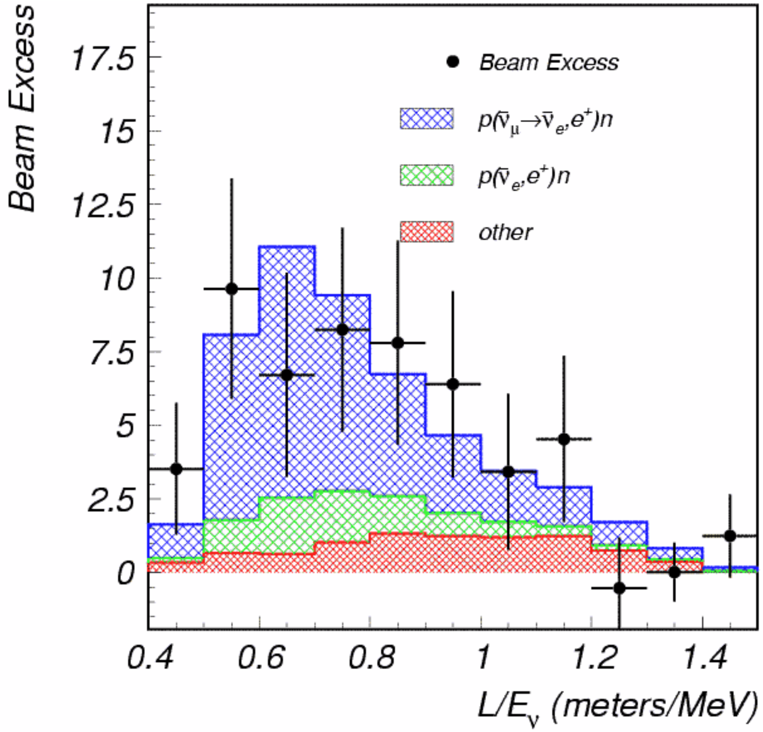
★ Thanks to organizers for squeezing this talk in...

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:

$$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$

$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

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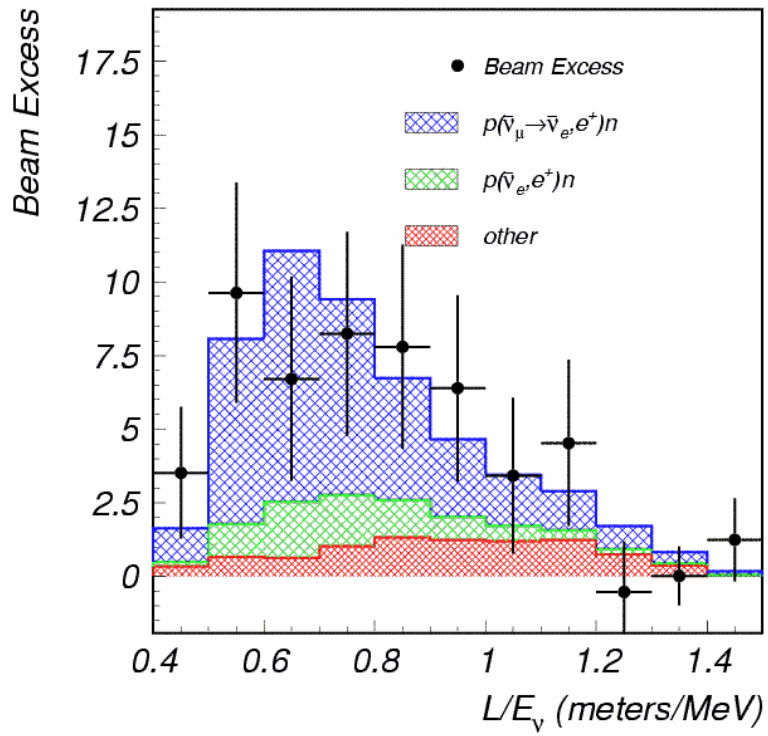

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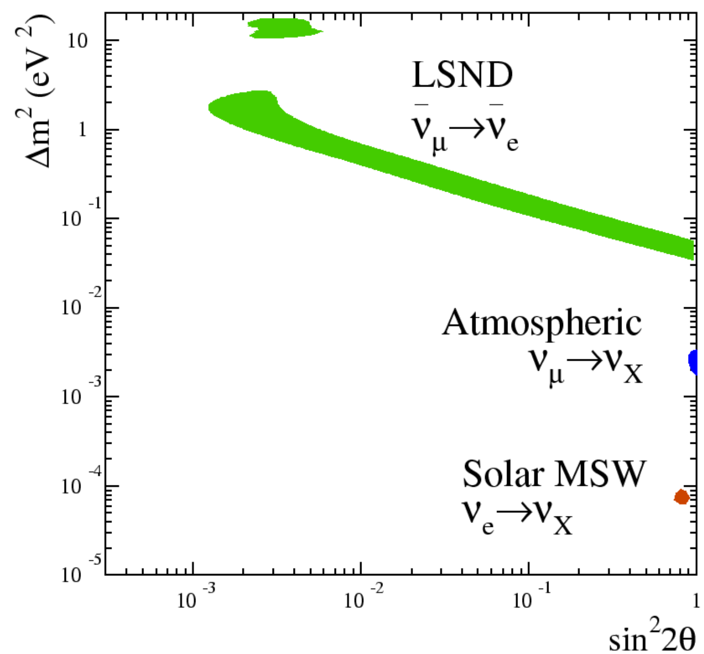
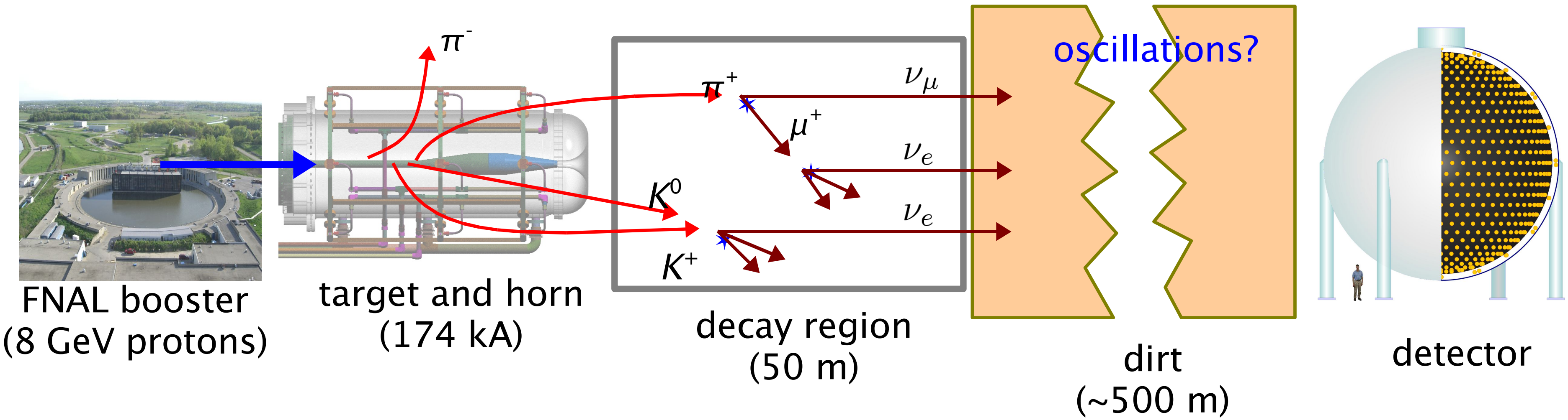
- LSND $\Delta m^2 \sim 1$ eV^2 impossible to reconcile with other two measured mixings in 3ν world
- Requires extraordinary physics!
  - Sterile neutrinos ***hep-ph/0305255***
  - Neutrino decay ***hep-ph/0602083***
  - Lorentz/CPT violation ***hep-ex/0506067***
  - Extra dimensions h***ep-ph/0504096***
- Unlike atmos and solar...LSND unconfirmed



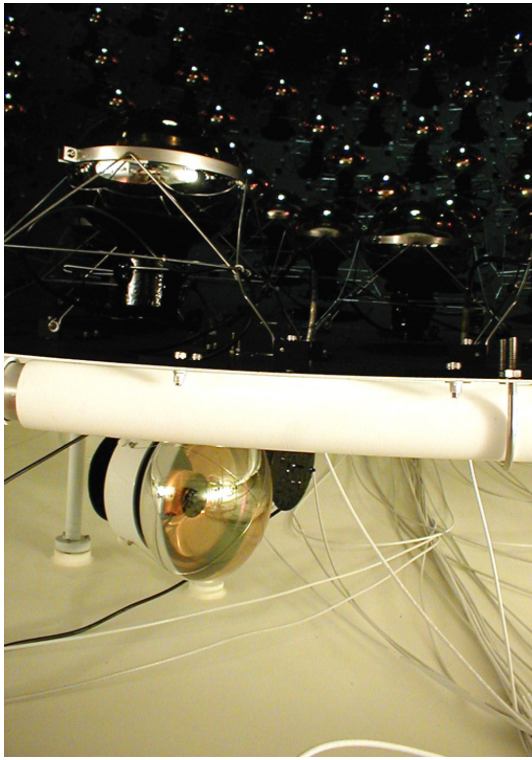
The MiniBooNE design strategy



- 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:

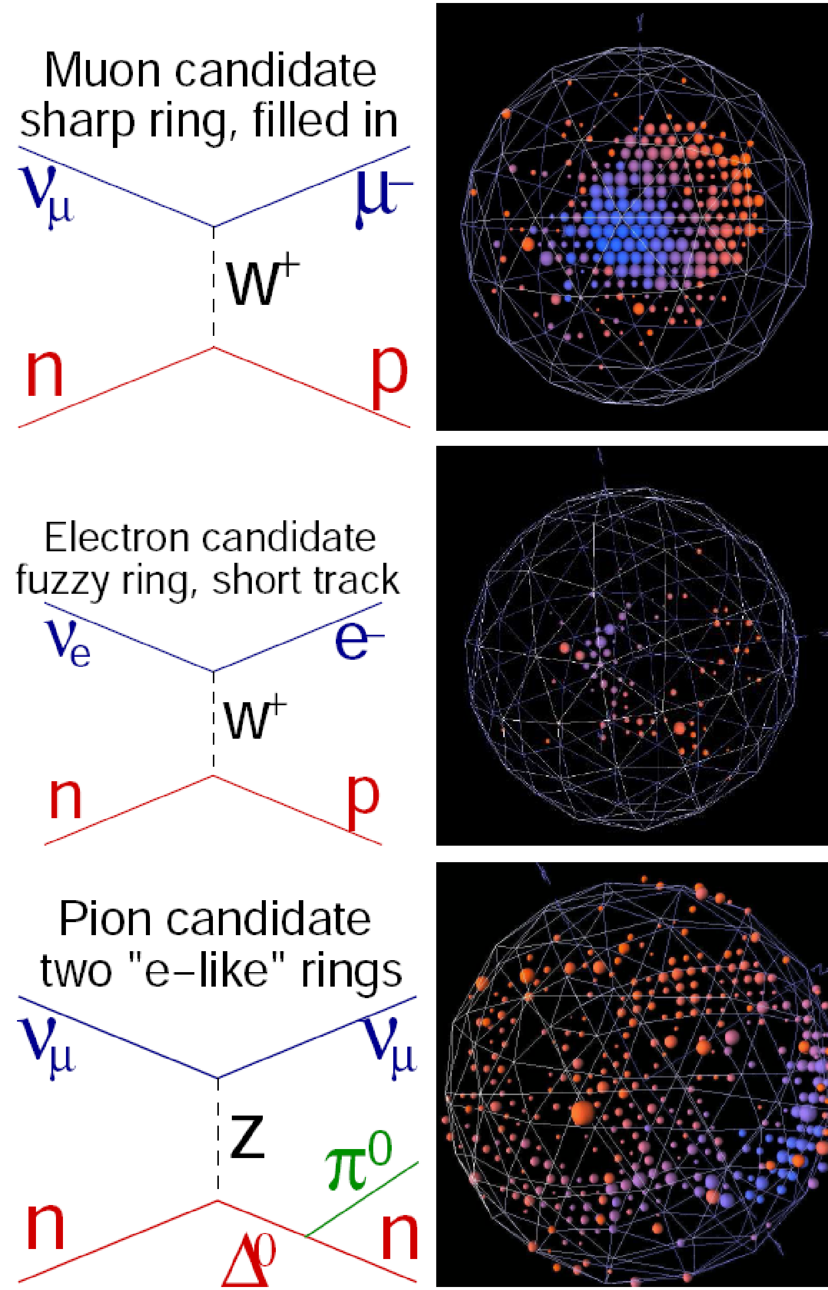
MiniBooNE:	(0.5 km) / (0.8 GeV)
LSND:	(0.03 km) / (0.05 GeV)

- 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

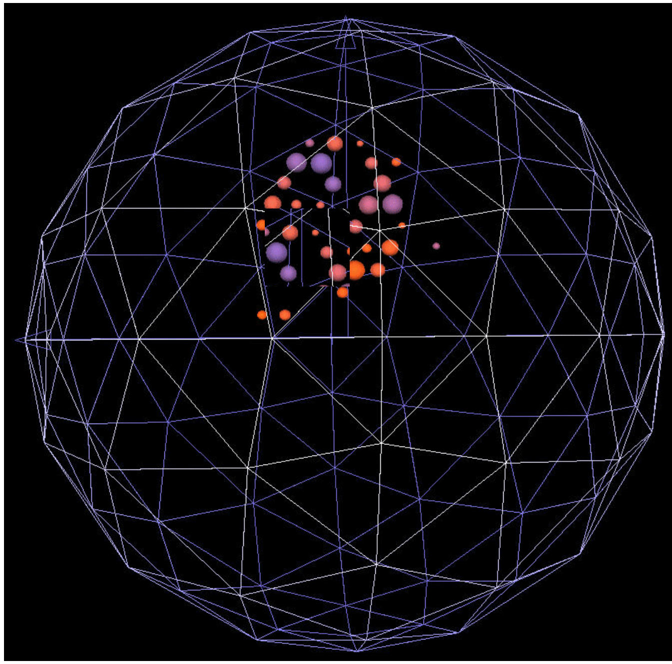


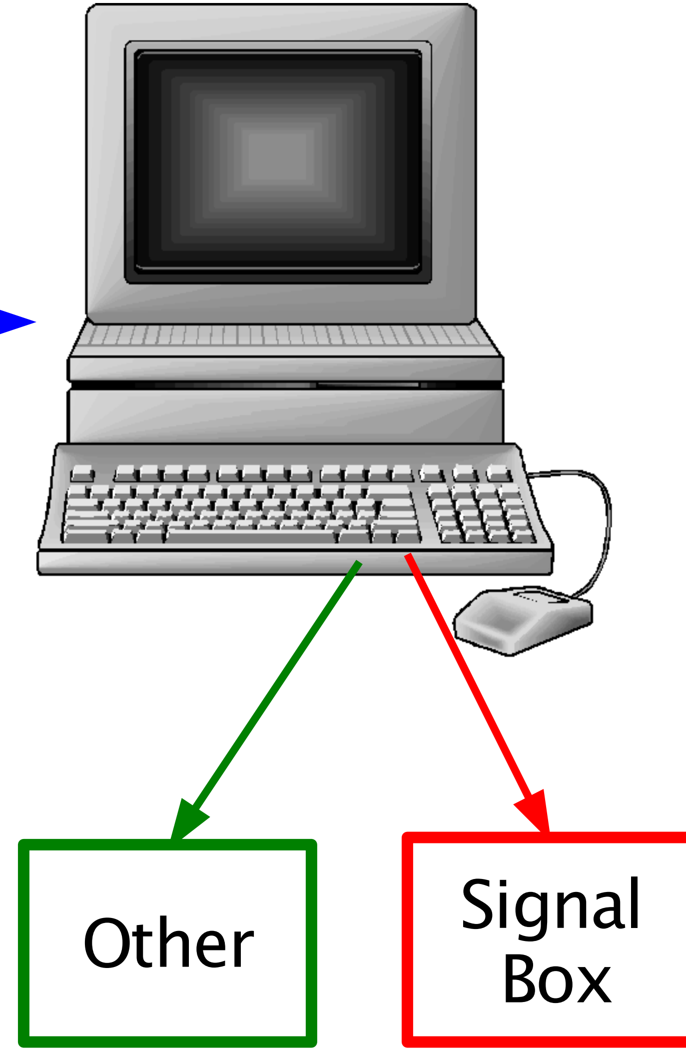
Key points about the signal

- LSND oscillation probability is < 0.3%
- 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



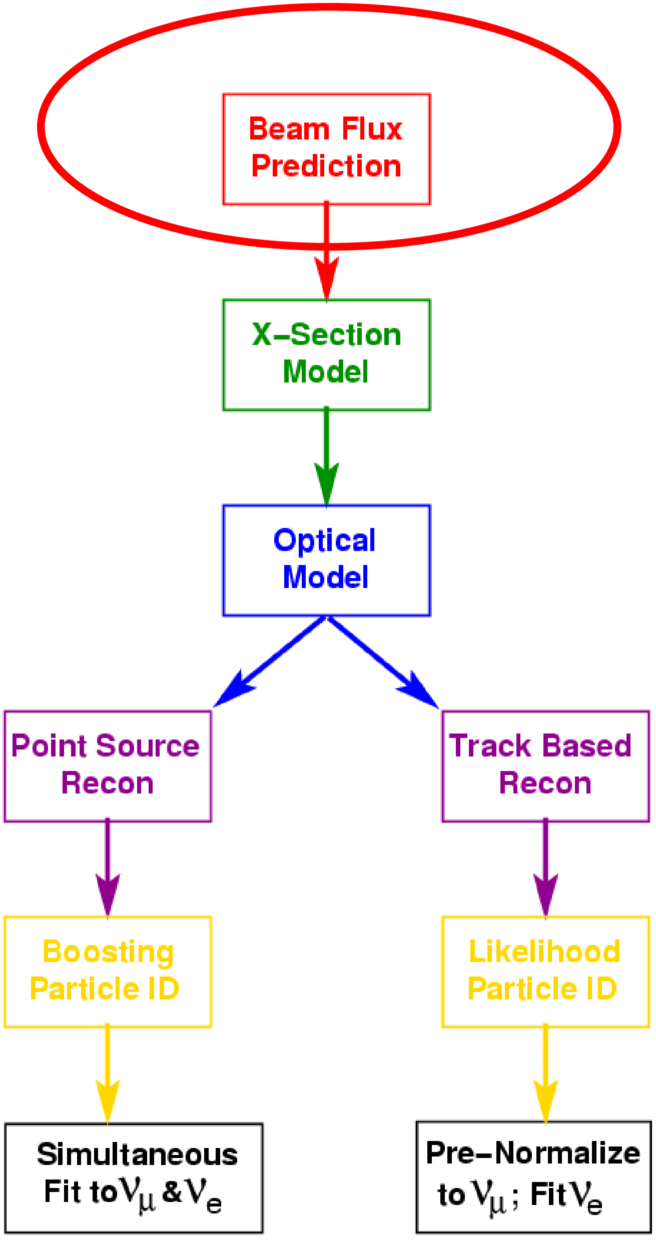
Blind analysis in MiniBooNE





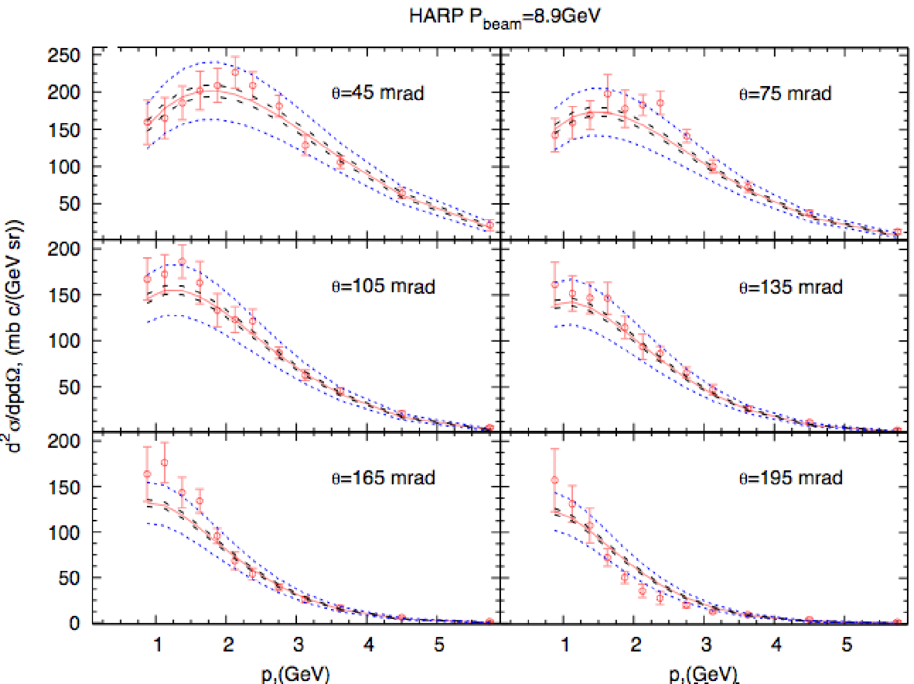
- The MiniBooNE signal is small but relatively easy to isolate
- As data comes in it is classified into 'boxes'
- For boxes to be opened to analysis they must be shown to have a signal < 1σ
- In the end, 99% of the data were available prior to unblinding...necessary to understand errors

Flux Prediction



Meson production at the target

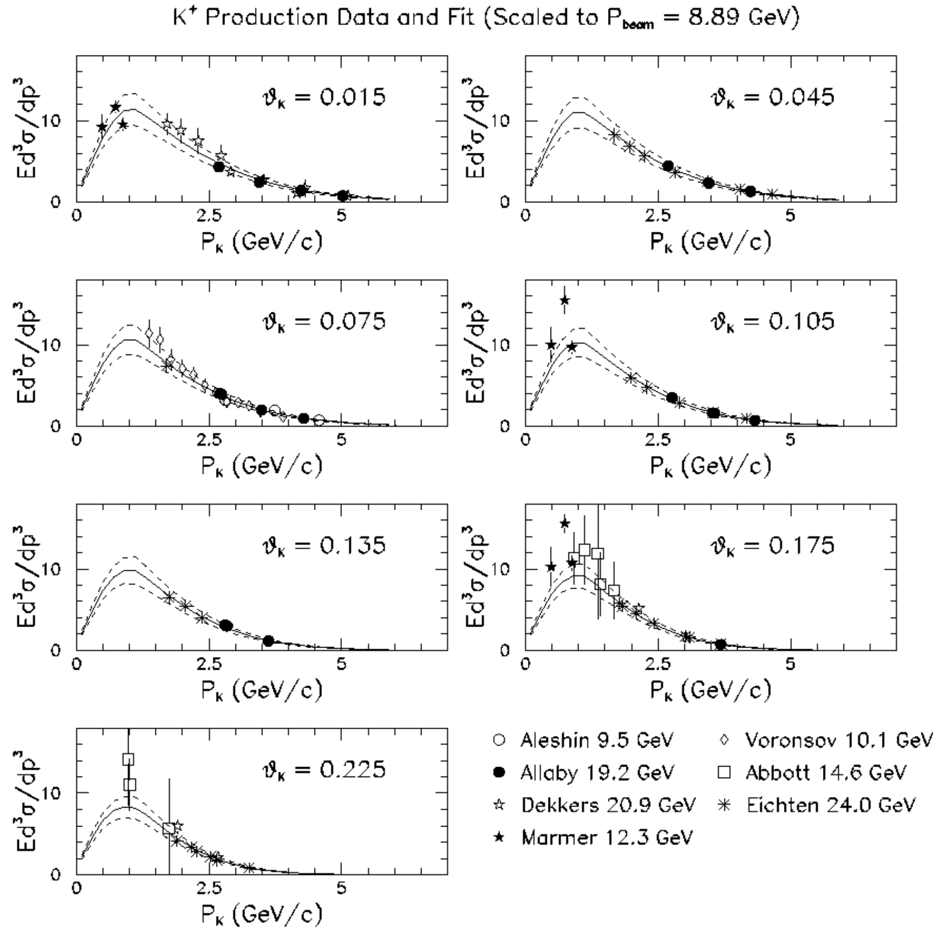
Pions:



HARP collaboration, hep-ex/0702024

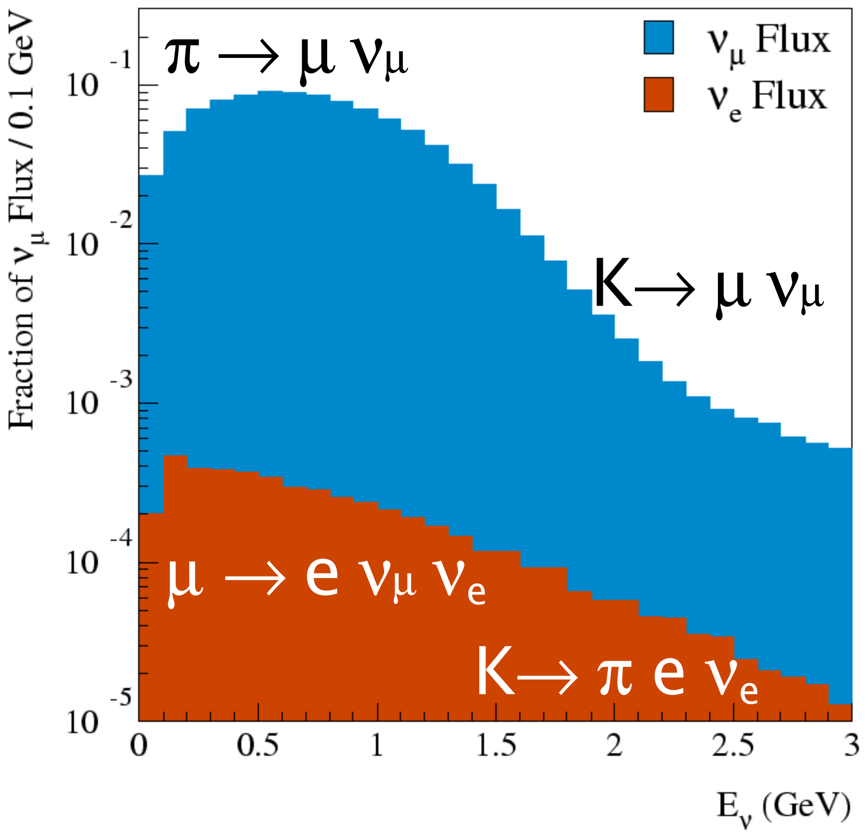
- MiniBooNE members joined the HARP collaboration (* see L. Coney talk later today!)
  - 8 GeV proton beam
  - 5% λ Beryllium target
- Data were fit to Sanford-Wang parameterization

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



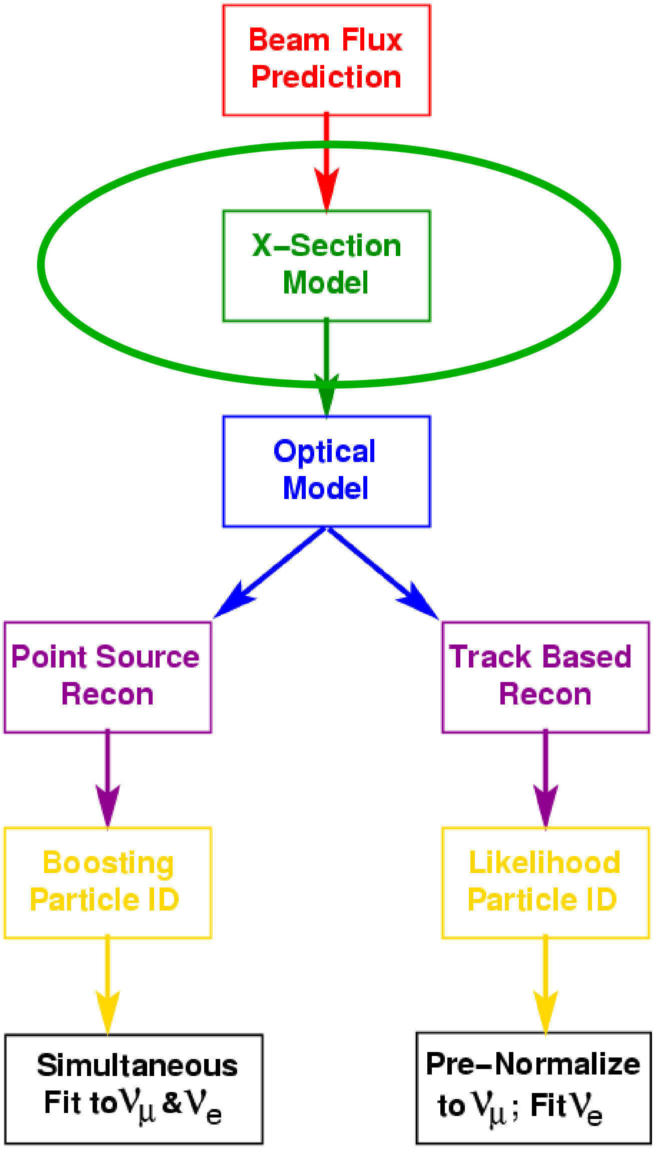
$\nu_e / \nu_\mu = 0.5\%$

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

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

Antineutrino content: 6%

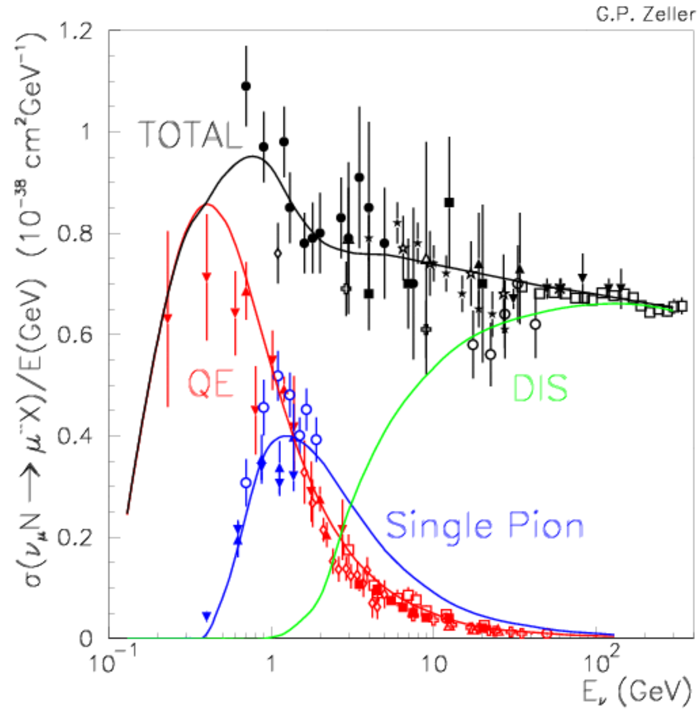
X–Section Model

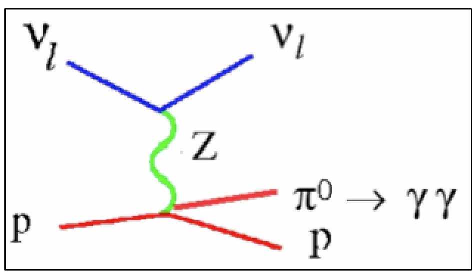


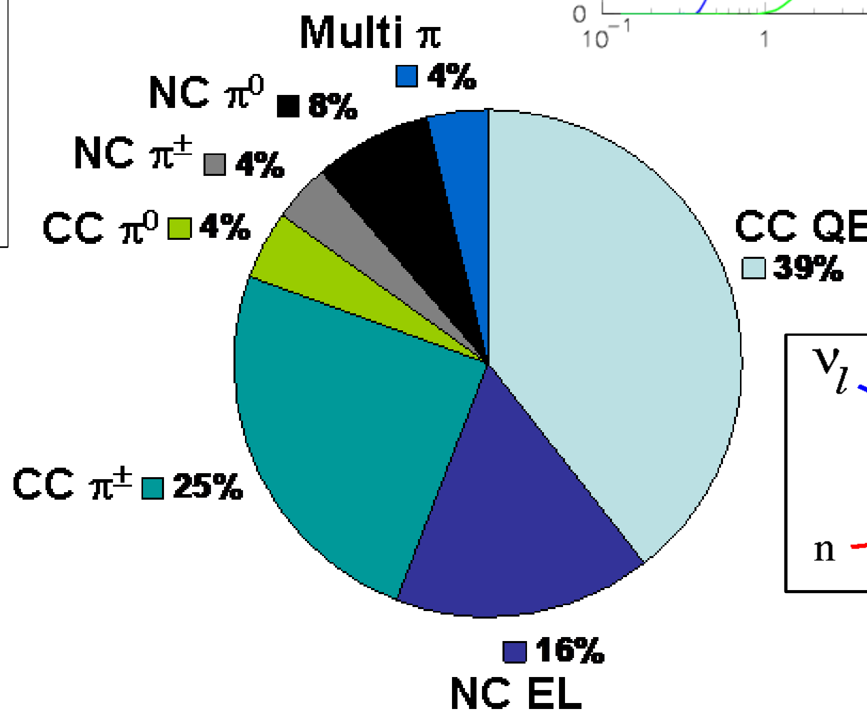
Nuance Monte Carlo

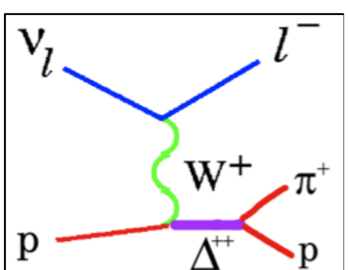
D. Casper, NPS, 112 (2002) 161

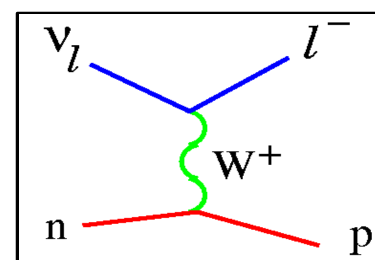
- Used to predict rate of specific ν interactions
- World data for various channels shown at right
- Tuned on external and internal data
- Expected interaction rate in MiniBooNE (before cuts) shown below



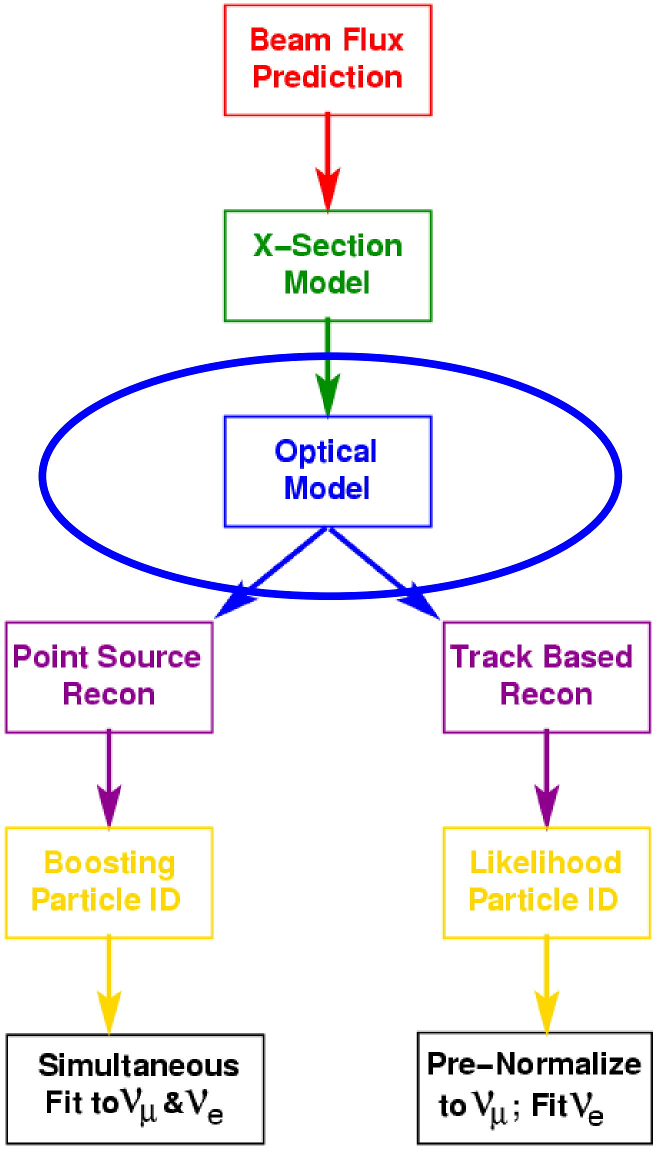




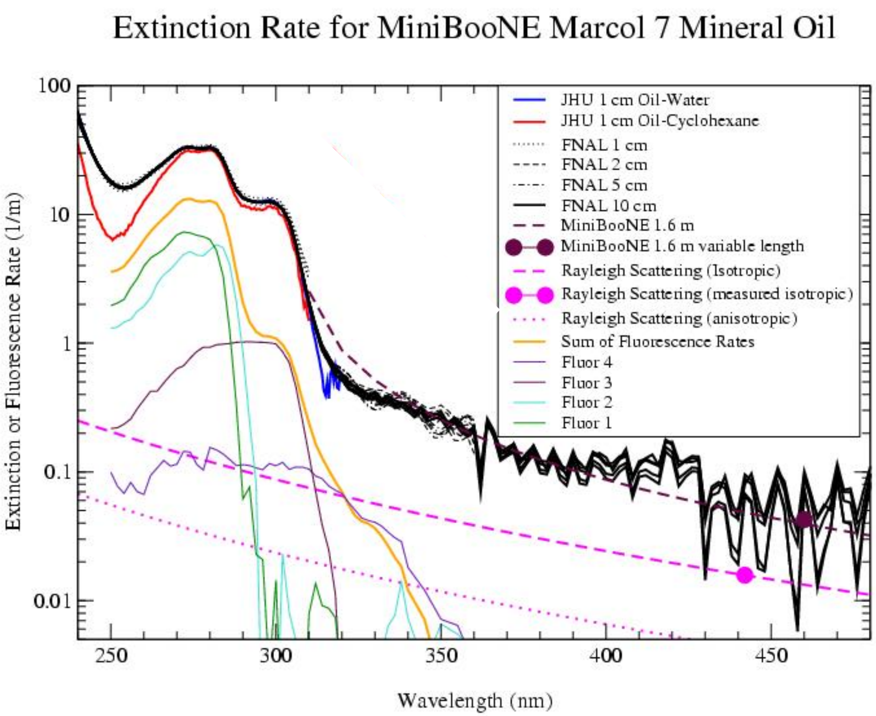


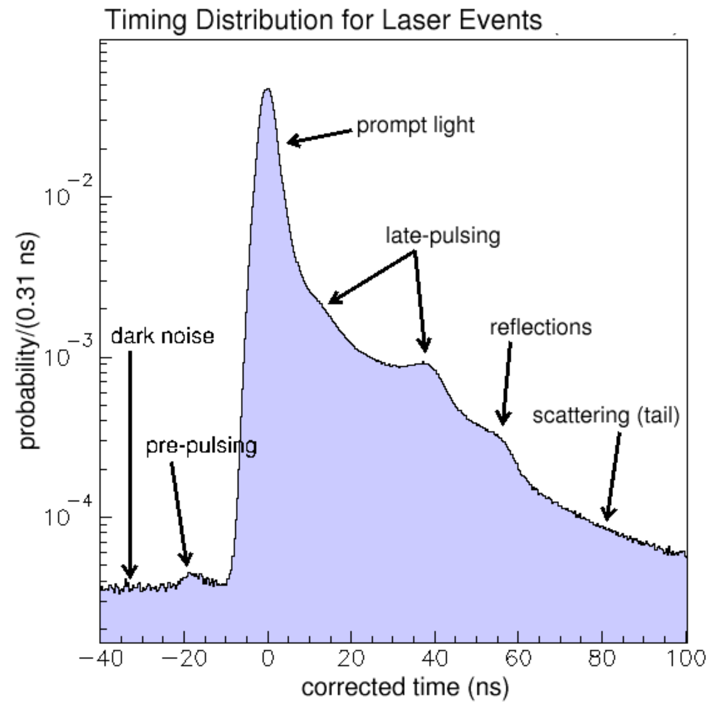


Optical Model



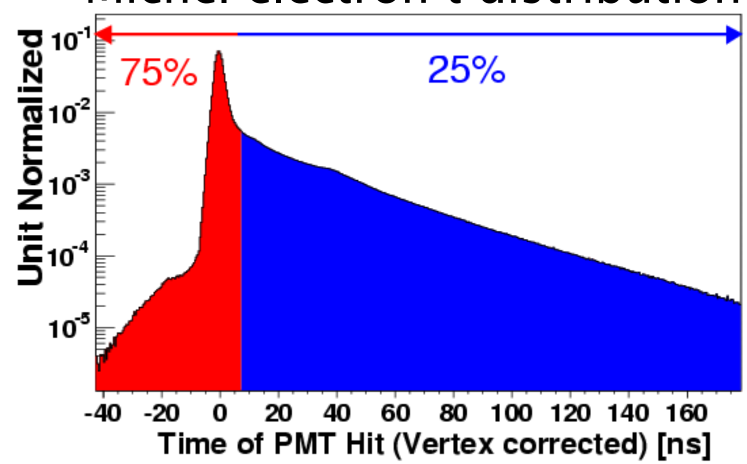
Light propagation in the detector



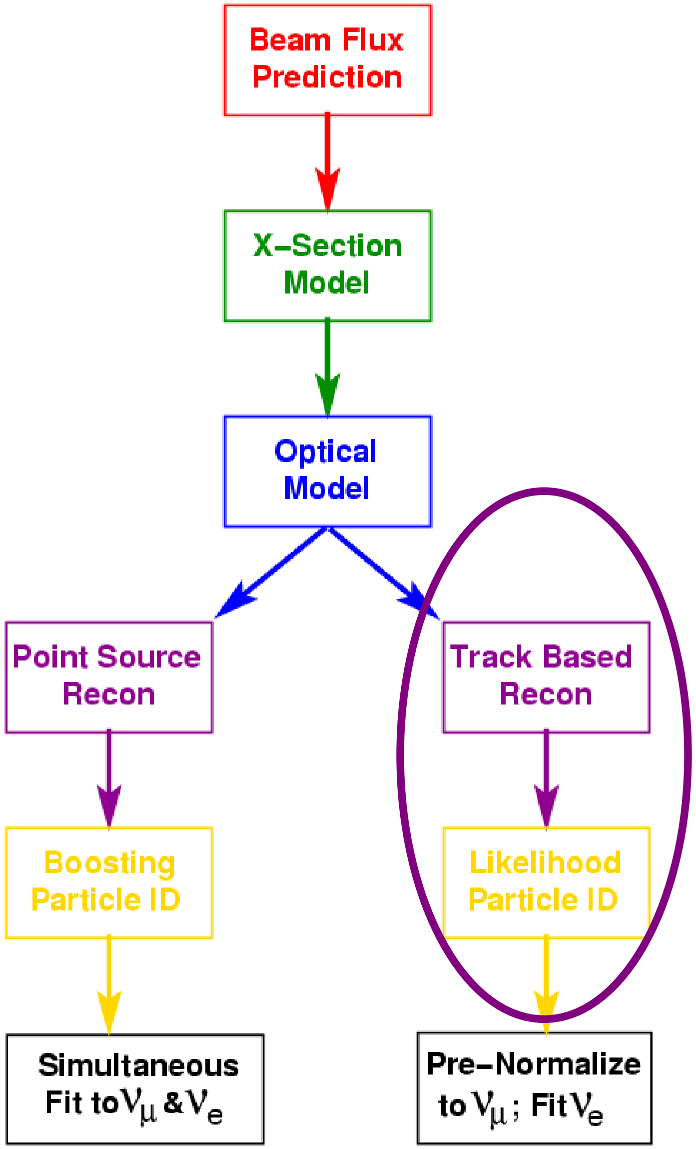


- Optical model is very complex
  - Cerenkov, scintillation, fluorescence
  - PMT Q/t response
  - Scattering, reflection, prepulses
- Overall, about 40 parameters

Michel electron t distribution



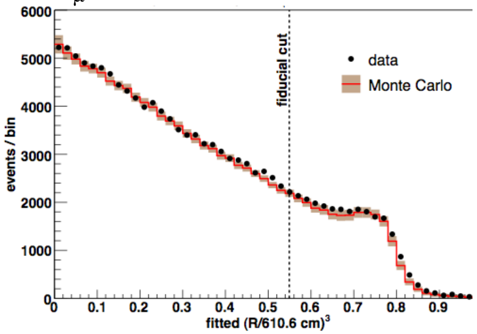
Track–Based Likelihood (TBL) Reconstruction and Particle ID

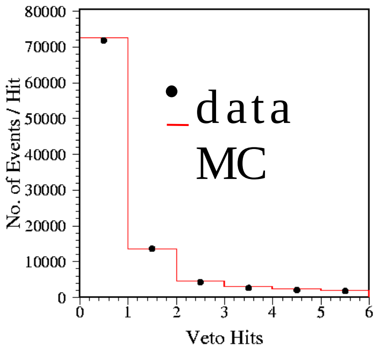


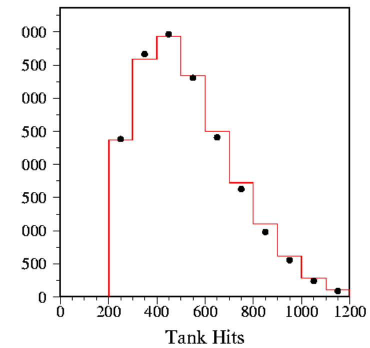
TBL Analysis: Separating e from μ

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

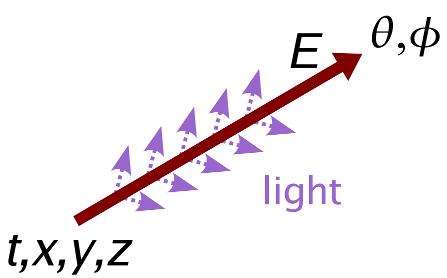
ν_μ CCQE events (2 subevent)

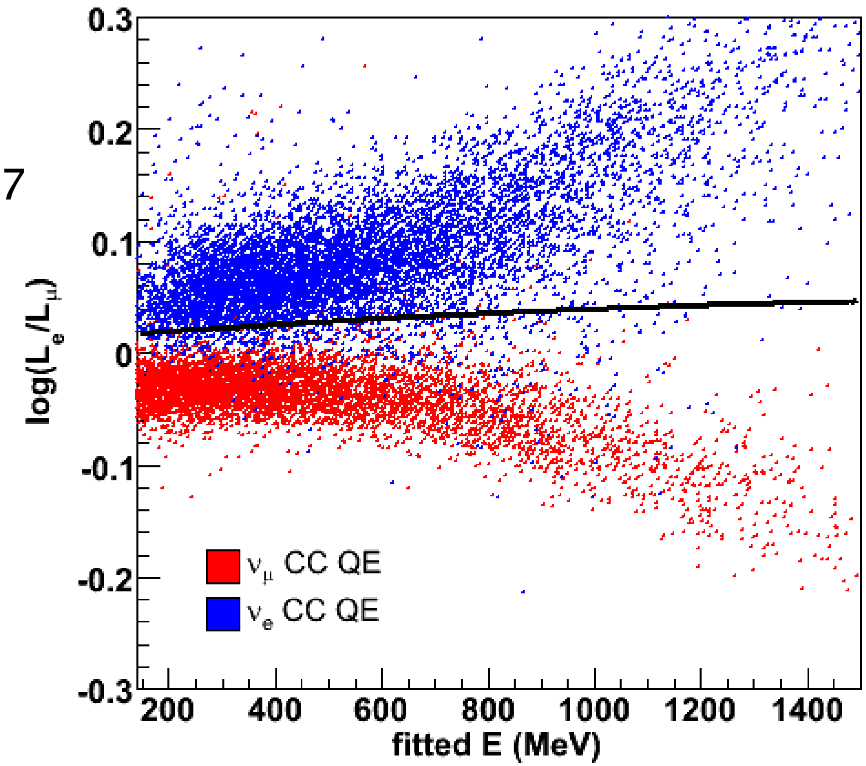






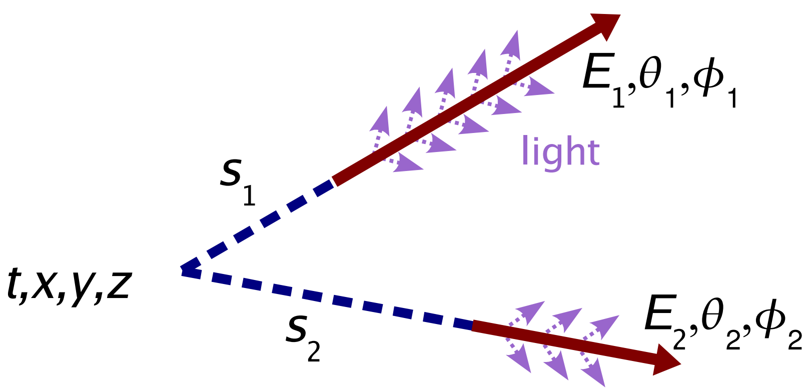
- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

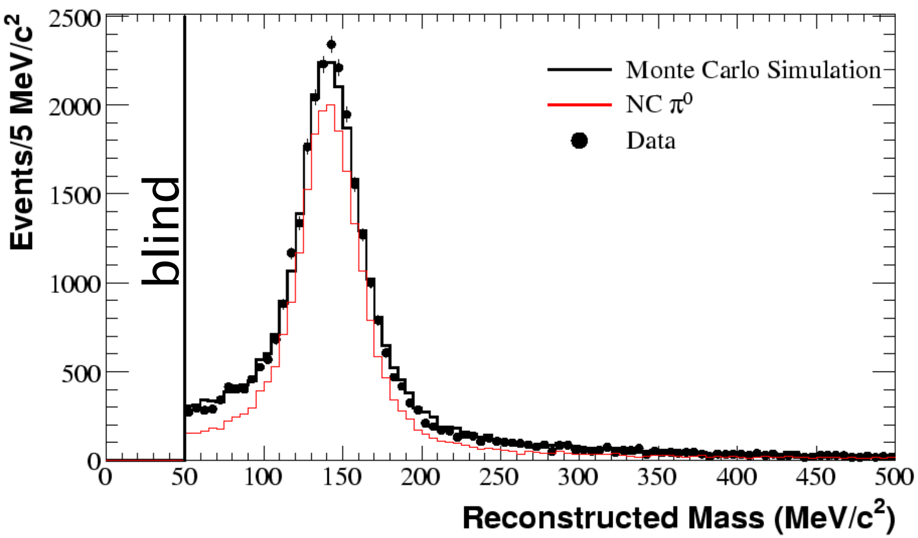


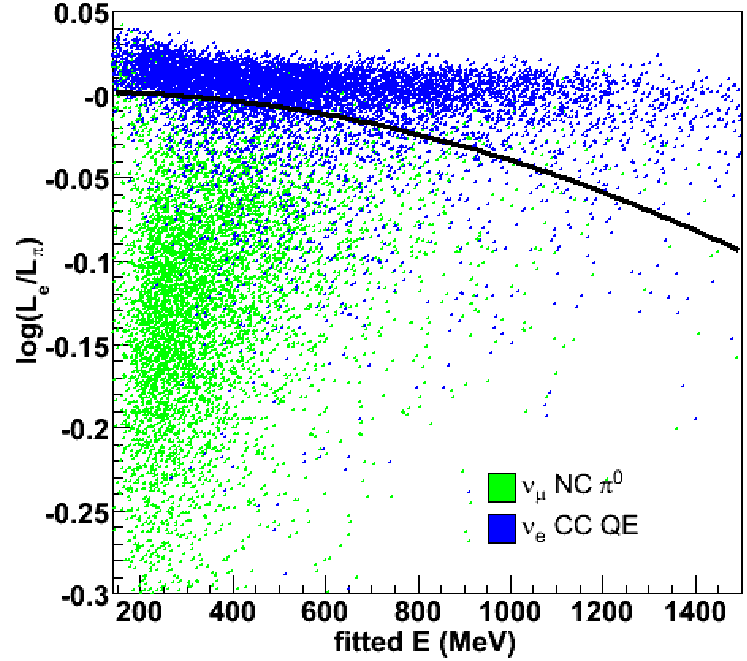


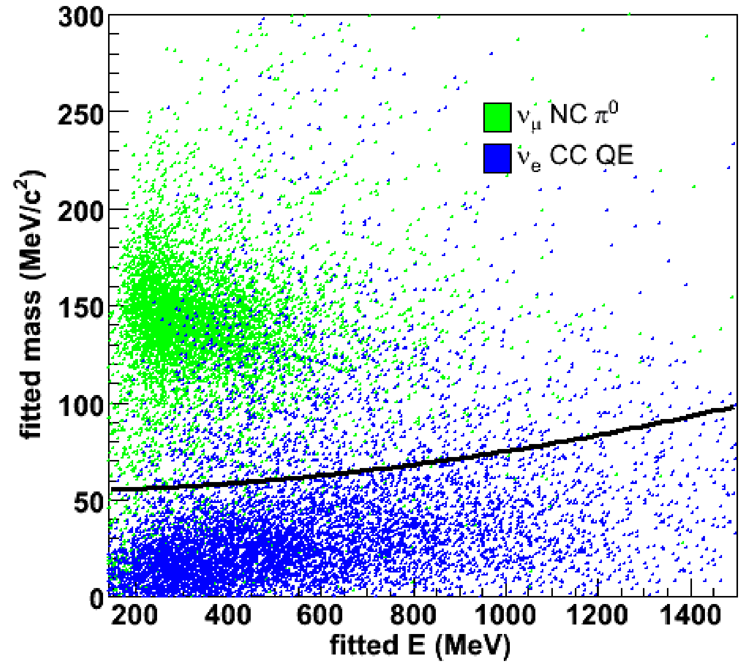
Separating e from π^0

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

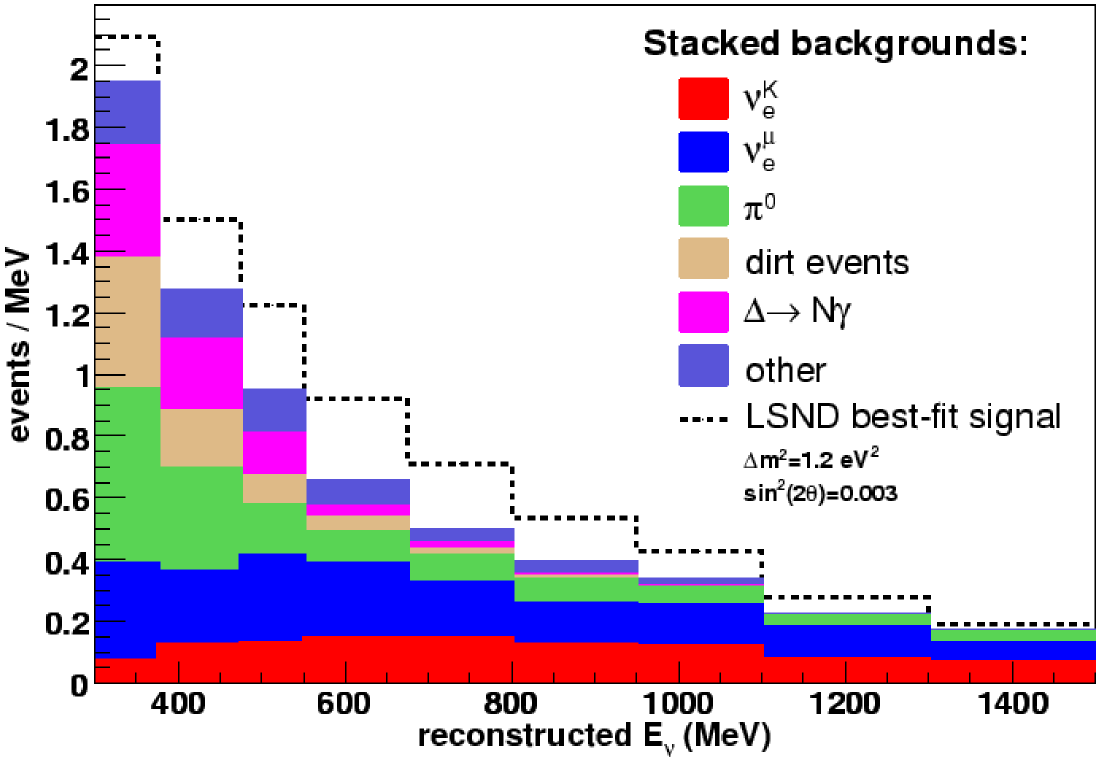








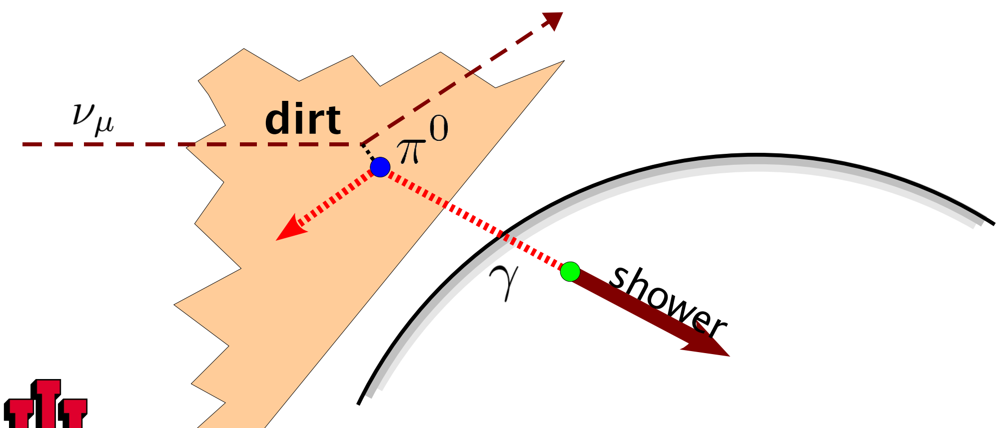
TBL Analysis: Expected event totals

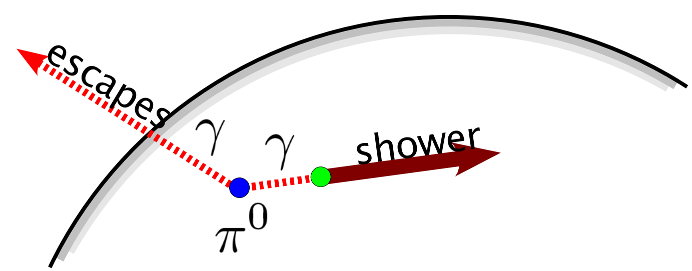


475 MeV – 1250 MeV

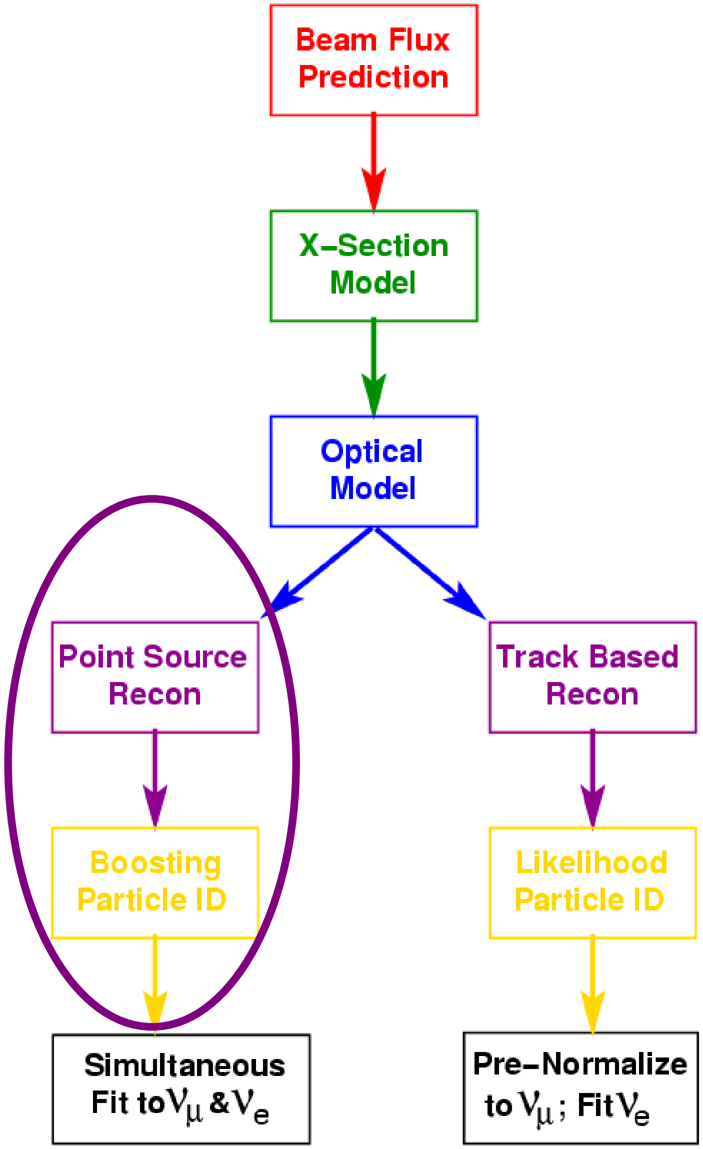
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

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





Boosted Decision Tree (BDT) Reconstruction and Particle ID



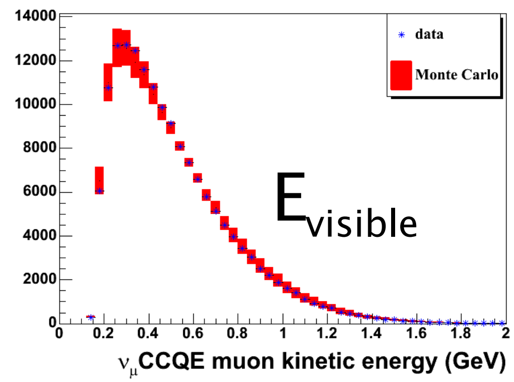
BDT Reconstruction

- 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.

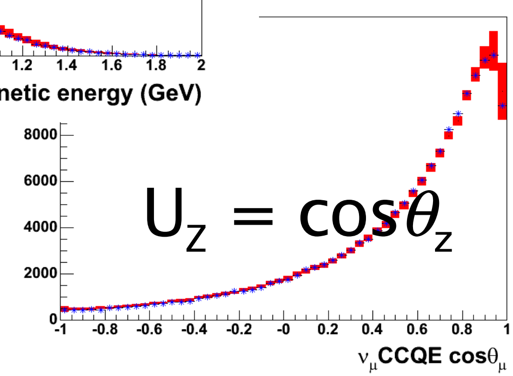
BDT Resolution:
vertex: 24 cm
direction: 3.8°
energy 14%

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

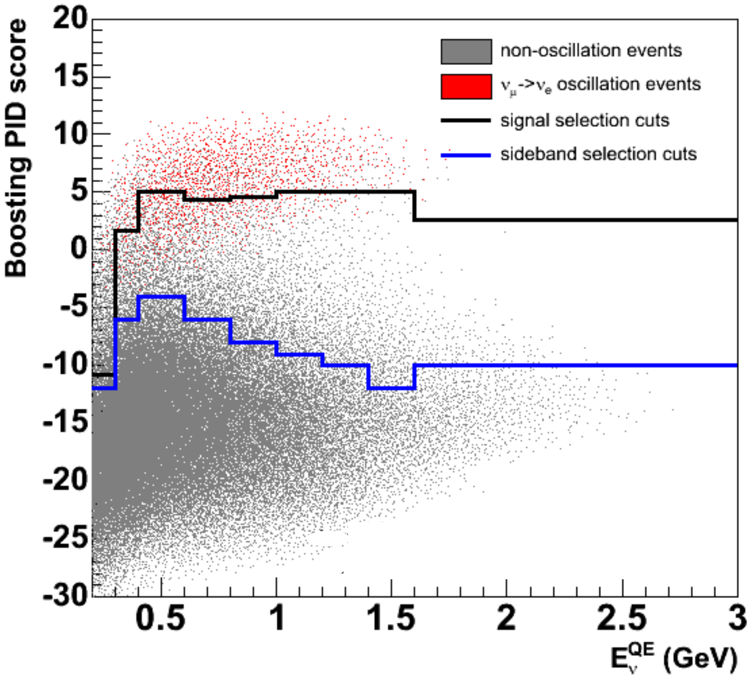
- Boosting Input Variables:
  - Low-level (# tank hits, early light fraction, etc.)
  - High-level (Q2, U_z, fit likelihoods, etc.)
  - Topology (charge in anuli, isotropic light, etc.)
- A total of 172 variables were used
- All 172 were checked for agreement within errors in 5 important 'boxes' (ν_μ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



ν_μ CCQE Examples

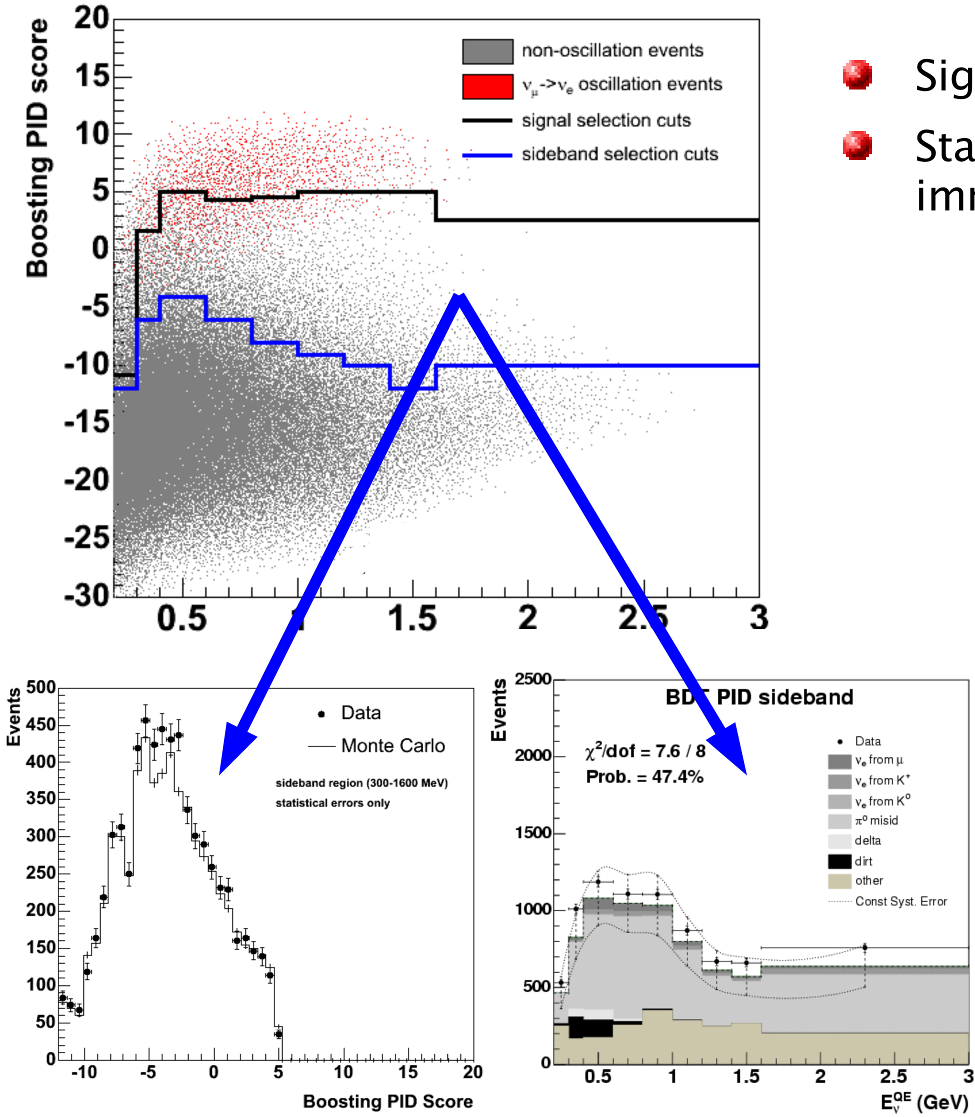


BDT Analysis: Signal/background regions



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

BDT Analysis: Signal/background regions



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- Start by looking at data in 'sideband'...region immediately adjacent to signal region

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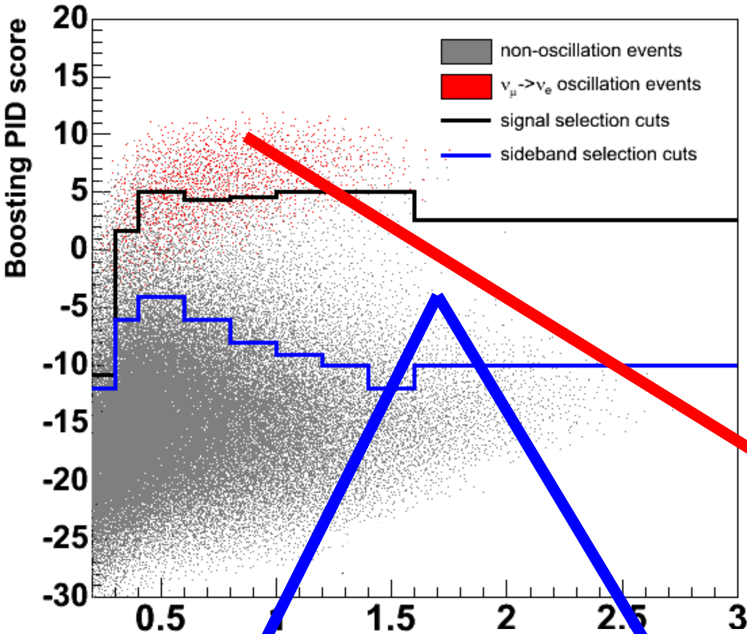
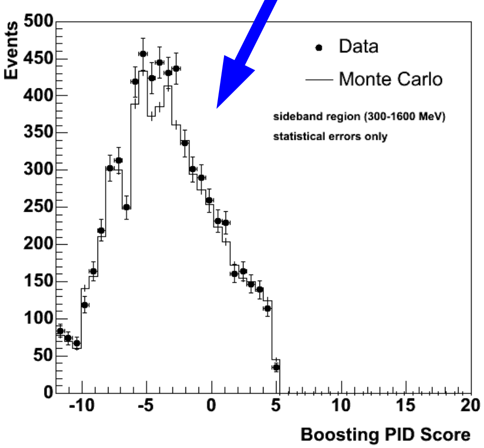
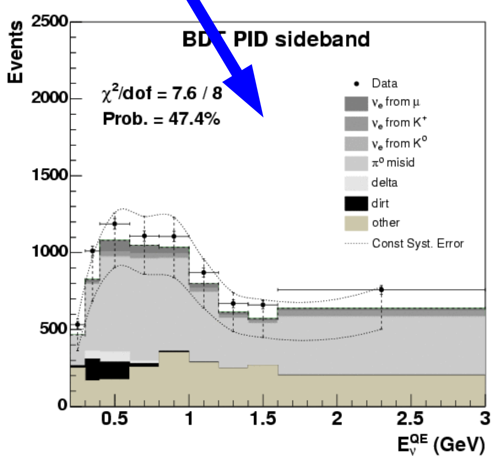
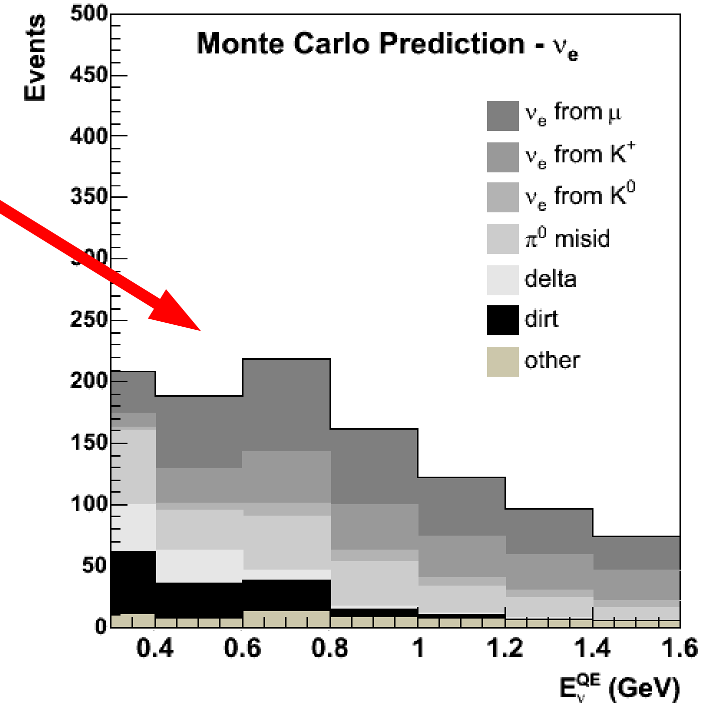


- Signal prediction (red) versus all bkgs (gray)
- Start by looking at data in 'sideband'...region immediately adjacent to signal region
- Satisfied with agreement? Finalize background prediction



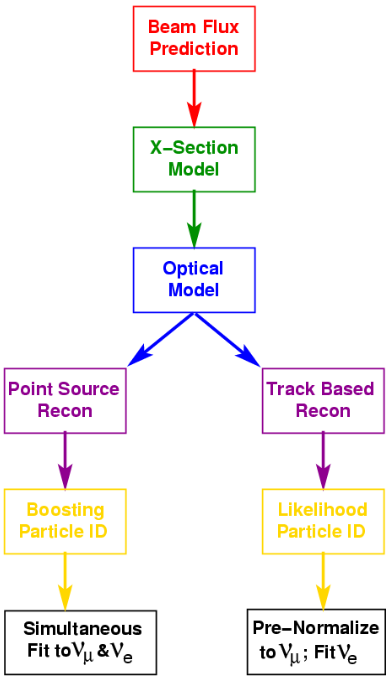




Systematic Error Analysis and Results

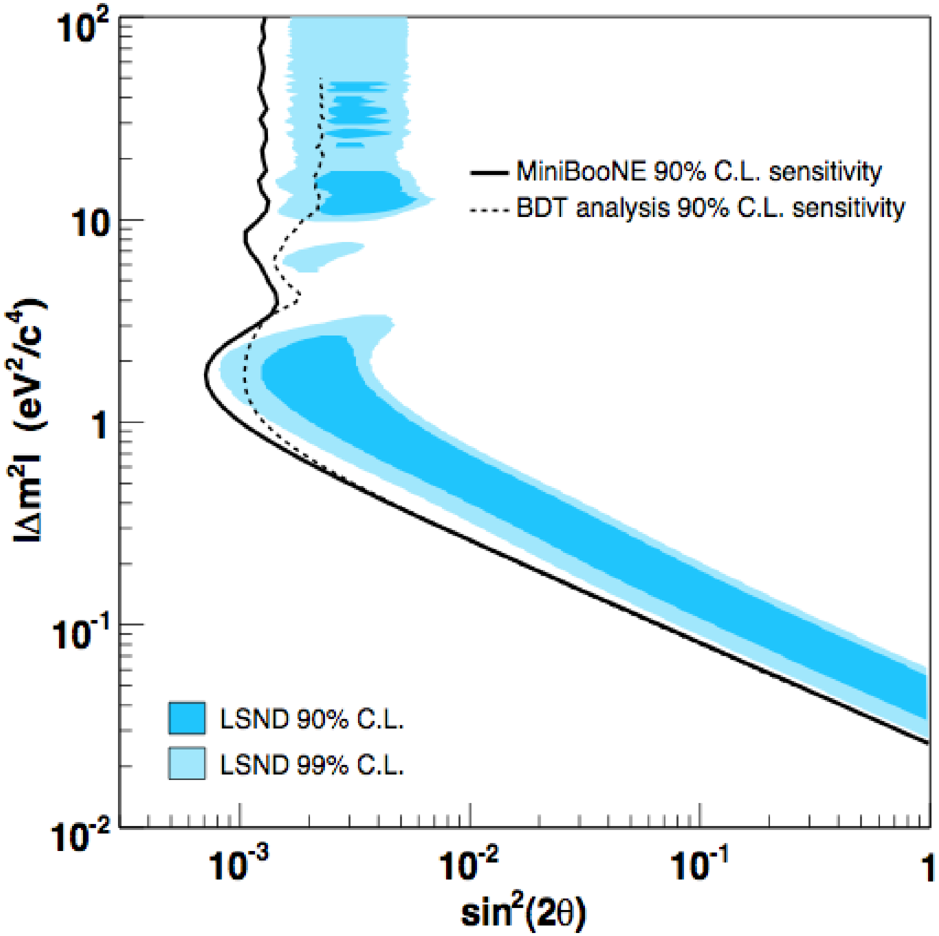
Final error budget (diagonals only...greatly simplified)

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

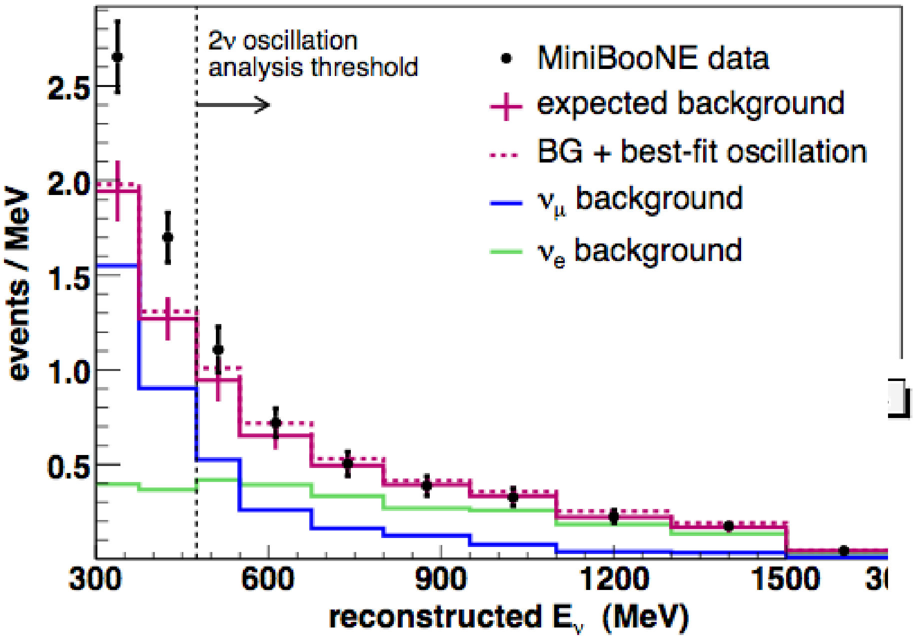
BDT/TBL sensitivity comparison



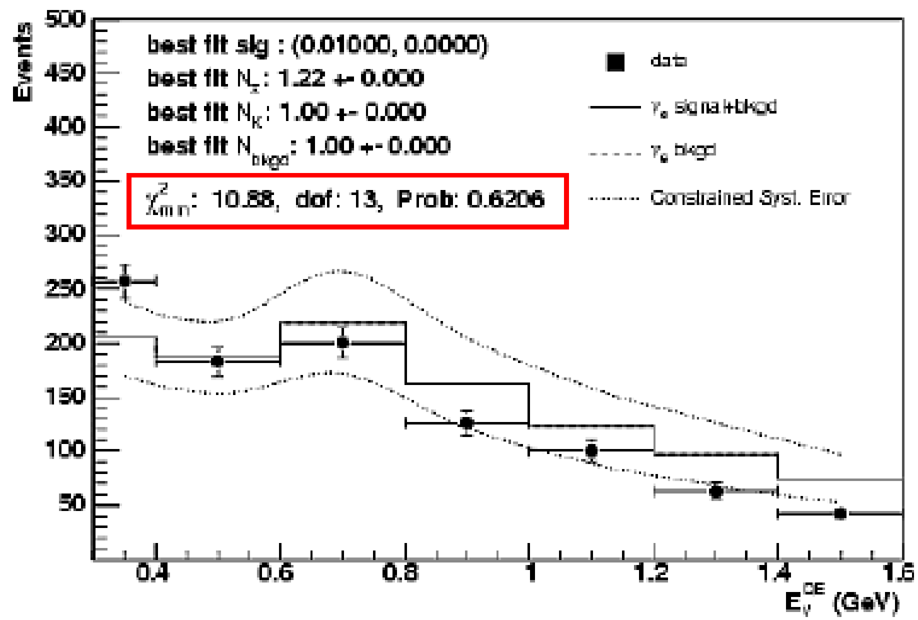
- Sensitivity is determined from simulation only (no data yet!)
- Decided before unblinding that the analysis with higher sensitivity would be the final analysis
- TBL (solid) is better at high Δm^2
- 90% CL defined by $\Delta\chi^2 = 1.64$

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

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



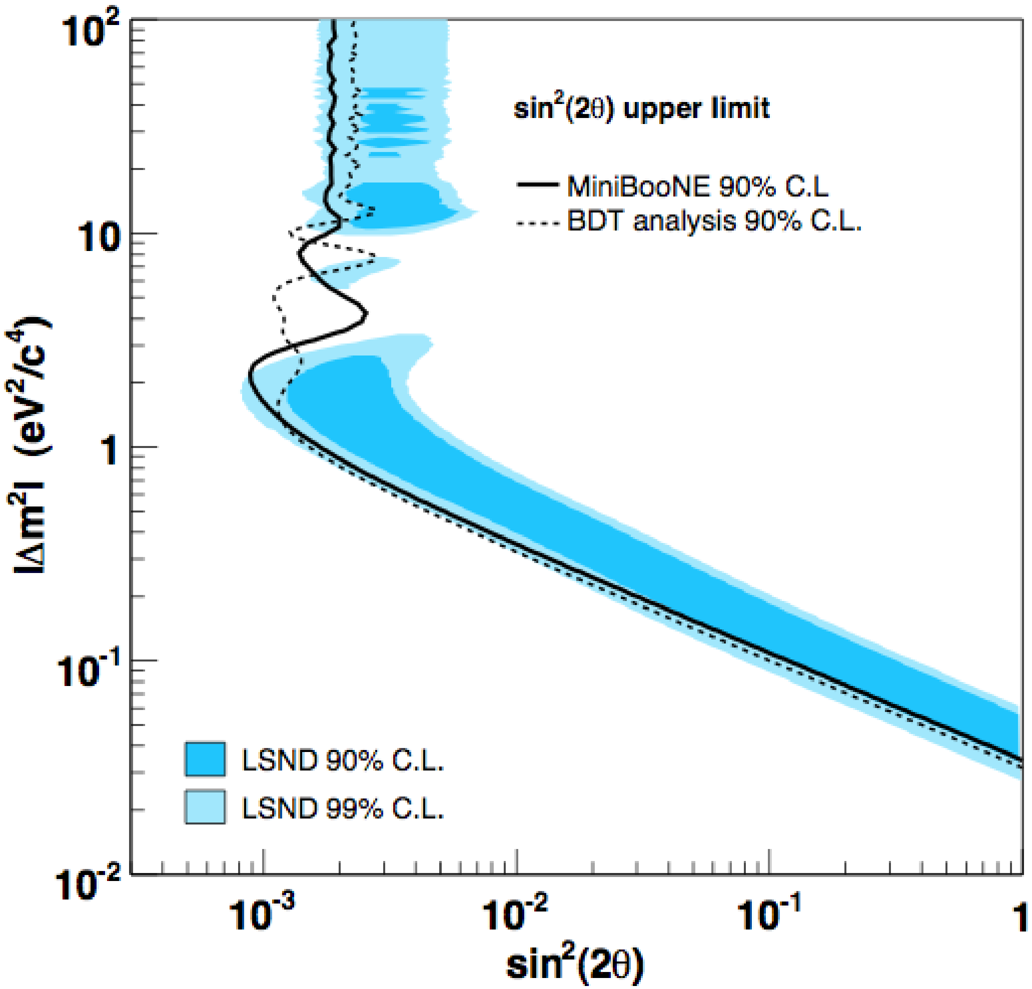
- TBL shows no sign of an excess in the analysis region (where the LSND signal is expected for the 2ν mixing hypothesis)
- Visible excess at low E



- 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

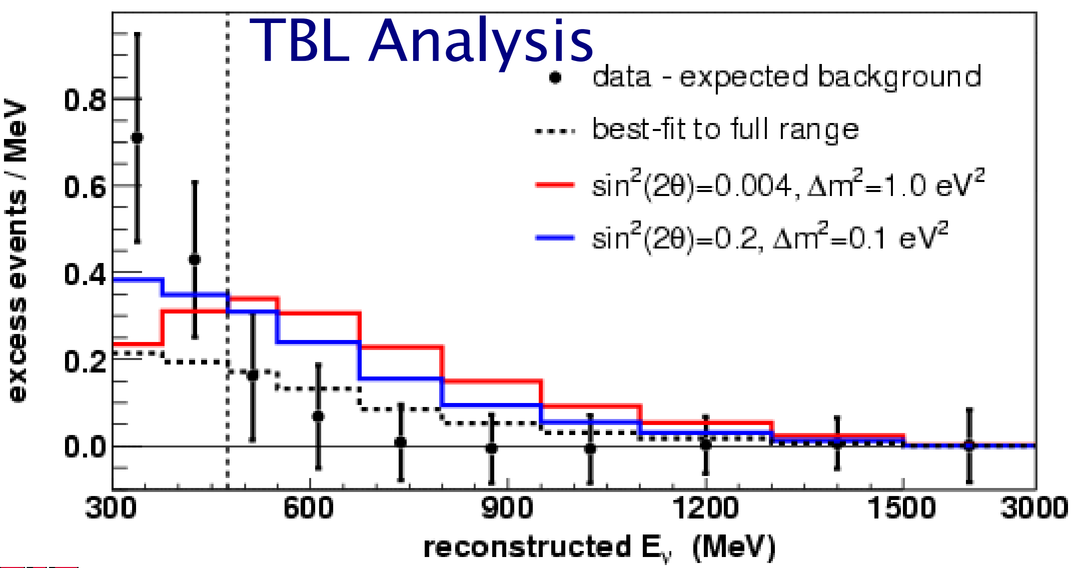
Fit results mapped into $\sin^2(2\theta)$ Δm^2 plane



- 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:

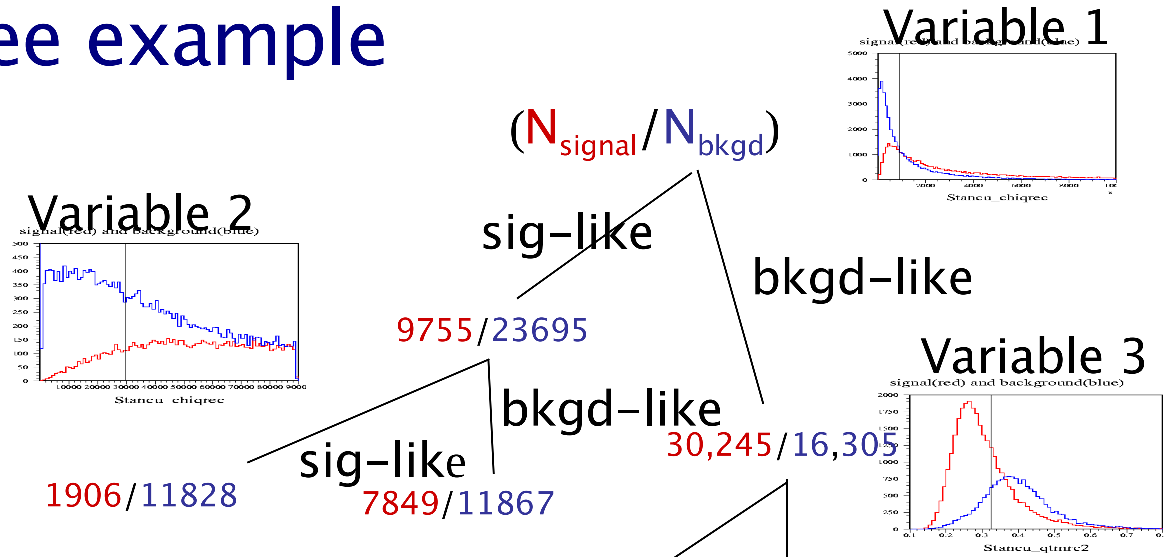
ν channel	events
all channels	810k
CC quasielastic	340k
NC elastic	150k
CC π^+	180k
CC π^0	30k
NC π^0	48k
NC $\pi^{+/-}$	27k

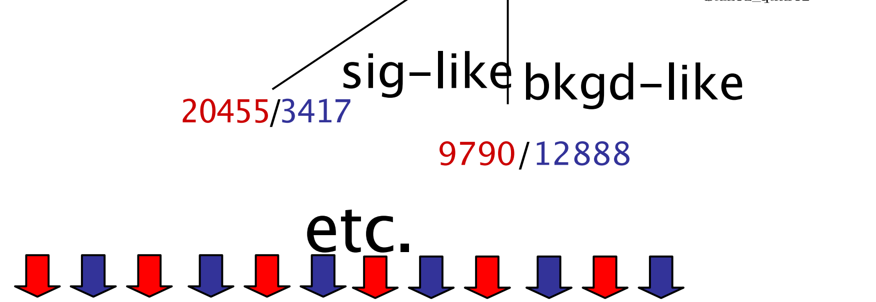
- Currently running in anti-ν mode for anti-ν cross sections

* For 3+1 and 3+2 interpretations see B. Fleming and G. Karagiorgi talks

Decision tree example

(sequential series of cuts based on MC study)



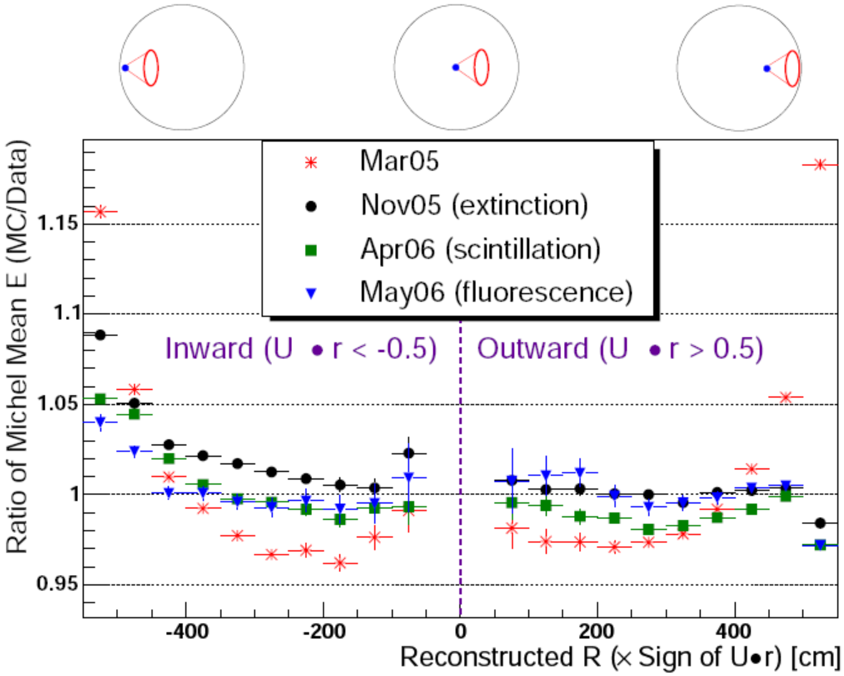


This tree is one of many possibilities...

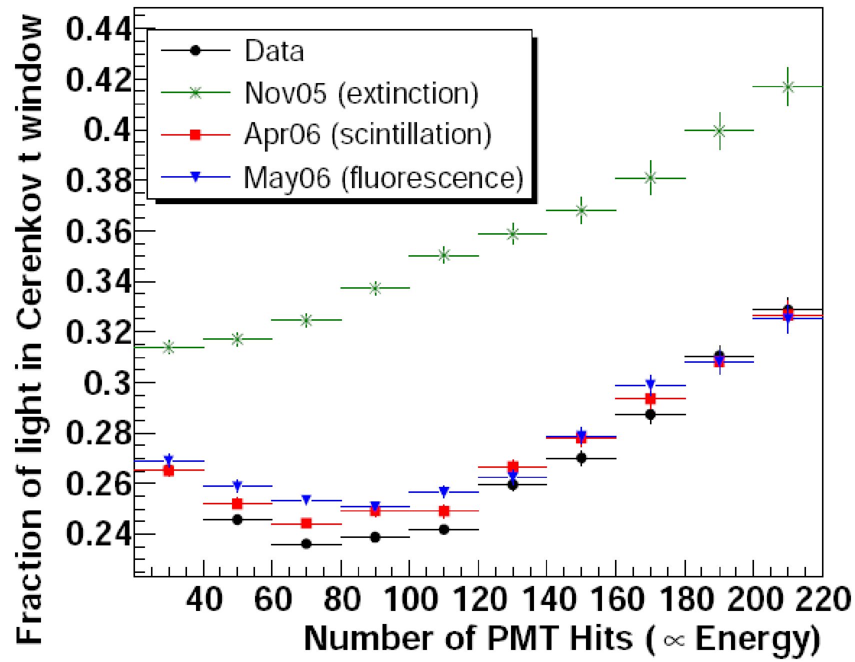
- Optimal cuts on each variable are determined
- An event gets a weight of 1 if signal –1 if background
- Hard to identify backgrounds are iteratively given more weight
- Many trees built
- PID 'score' established from ensemble

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