Recent Progress in the MiniBooNE Analysis

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on behalf of the *MiniBooNE Collaboration*

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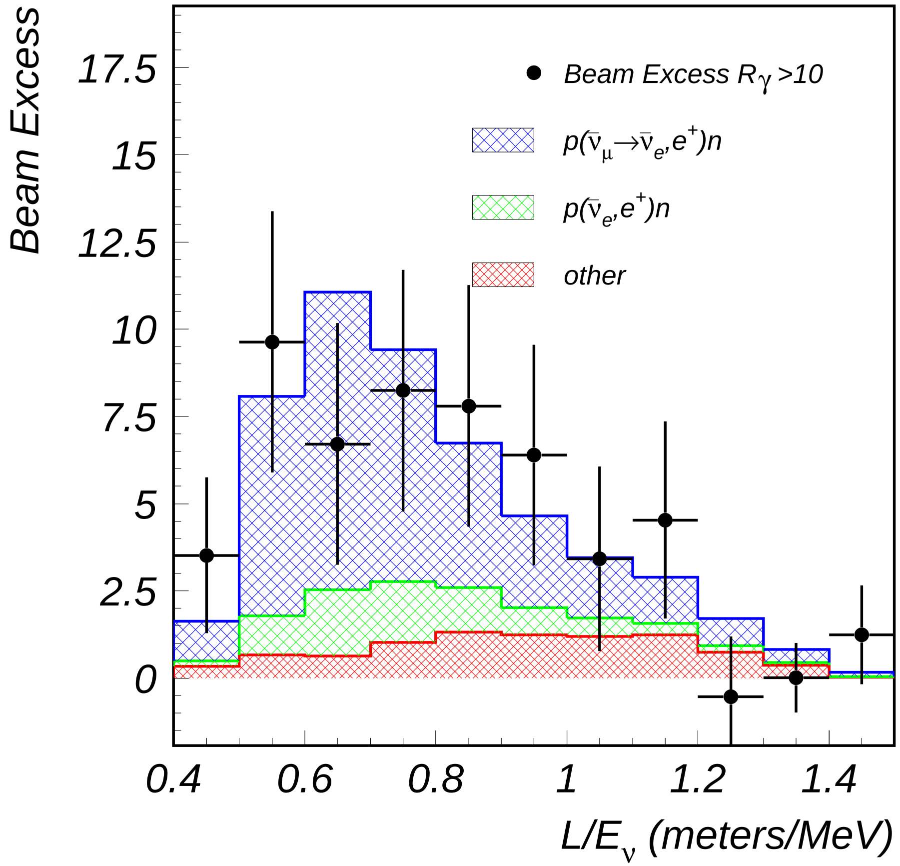
MiniBooNE goal: Verify/refute LSND signal.



- LSND found excess $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam.

  $N_{\text{excess}} = 87.9 \pm 22.4 \pm 6.0 \;\; (3.8\,\sigma)$

- Under a 2-neutrino mixing hypothesis:

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

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

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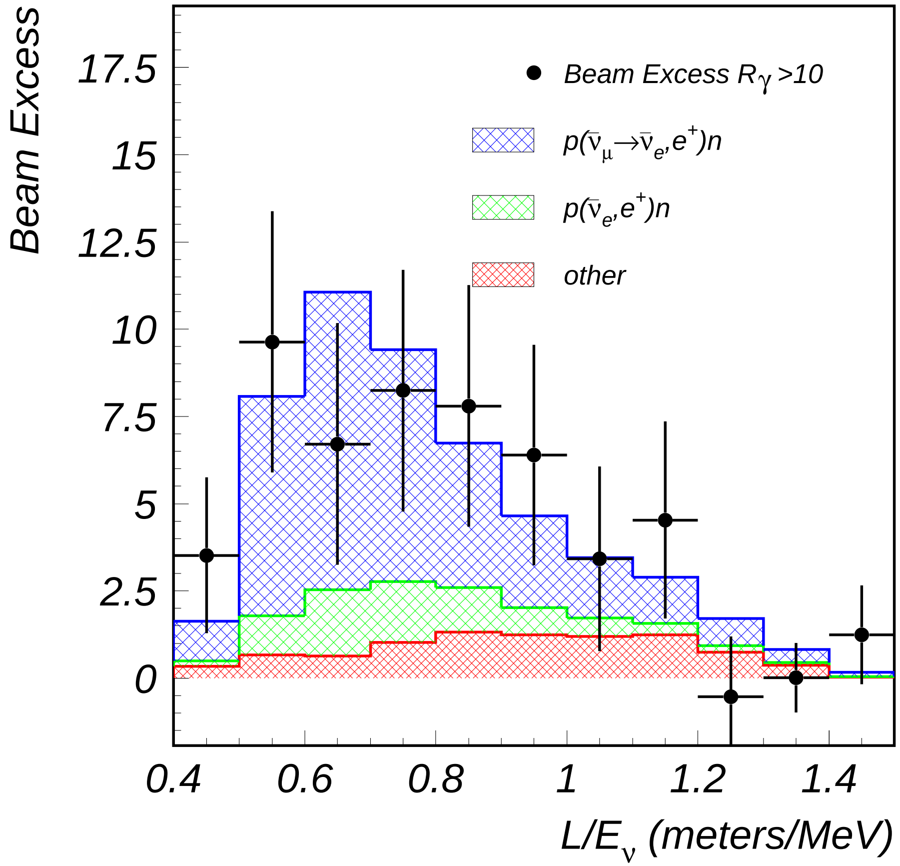

- ▷ Implies a mixing with $\Delta m^2 \approx 1\text{eV}^2$
- ▷ Not compatible with other Δm^2.
- ▷ Exciting possibilities for new physics!
  - ▷ Sterile neutrinos *hep-ph/0305255*
  - ▷ Neutrino decay *hep-ph/0602083*
  - ▷ Lorentz/CPT violation *hep-ex/0506067*

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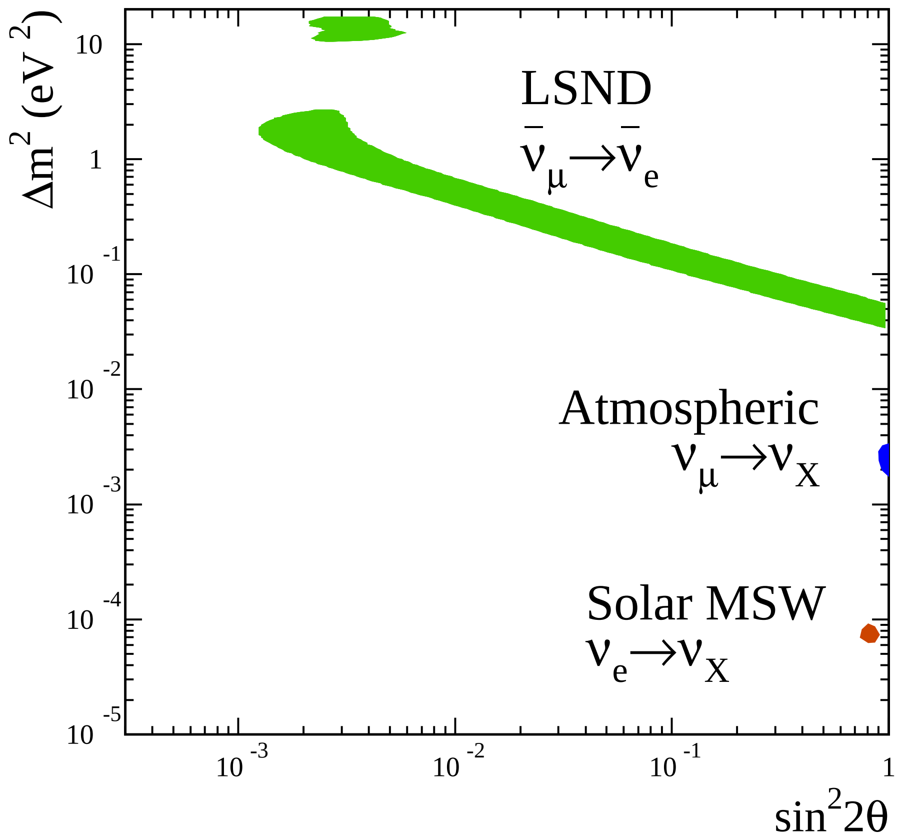
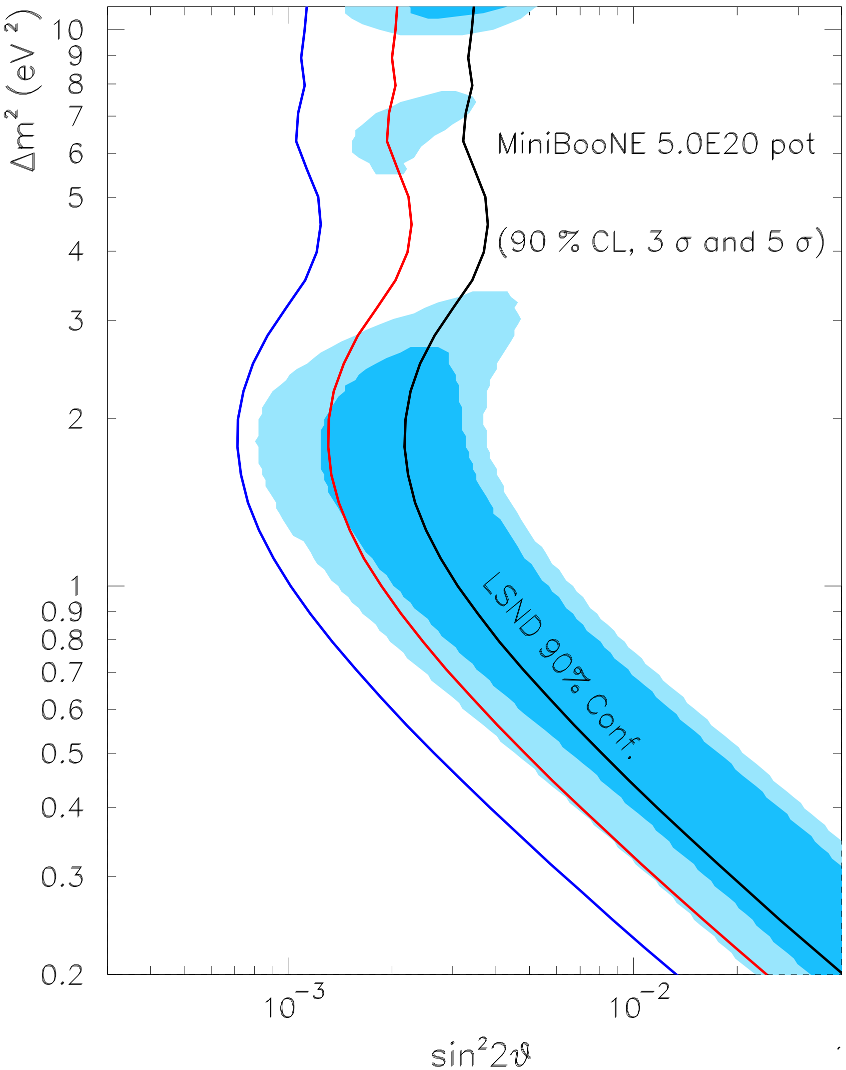


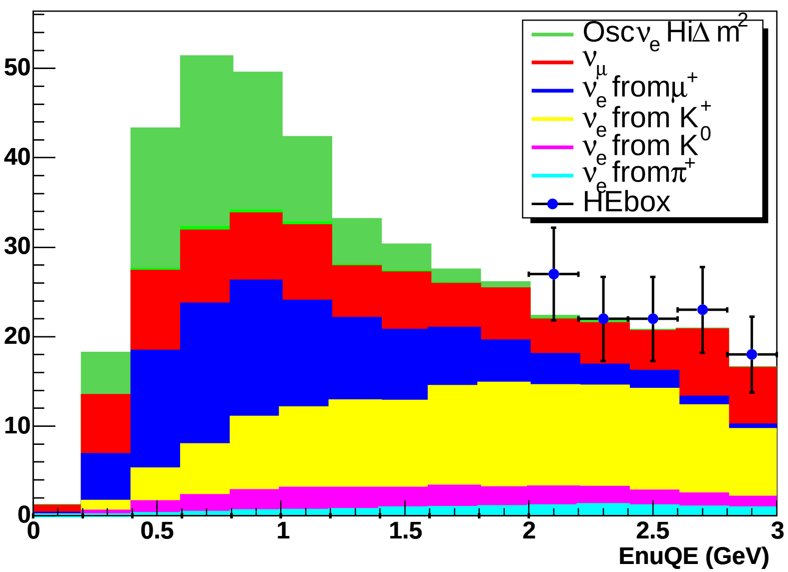
Projected sensitivity to the LSND signal in MiniBooNE.

With data already acquired...

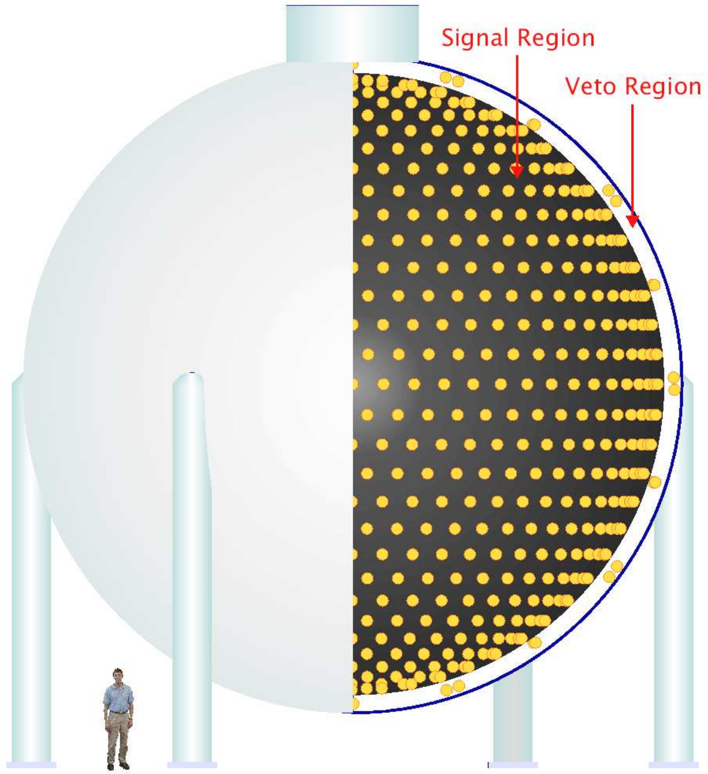


- Close to 3σ coverage of LSND 90% CL.
- MiniBooNE differs from LSND in several ways
  - $L = 540$ m ($\approx 10\times$ LSND)
  - $E \approx 500$ MeV ($\approx 10\times$ LSND)
  - ν_μ ($\overline{\nu}_\mu$ in LSND)
- Signal/background composition at:

$$\Delta m^2 = 1.0\text{eV}^2, \sin^2 2\theta = 0.004$$

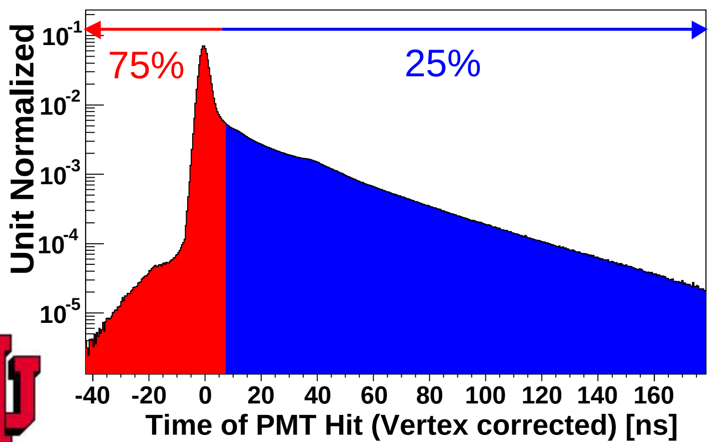


First ν detector to use pure mineral oil.



- Makes for a fairly complex optical model (OM).
  - In a water-detector, the Cerenkov light dominates (easy to calculate).
  - In a doped-detector, the scintillation dominates ((A_i, τ_i) well-known).
  - In pure mineral oil, natural absorption and emission are not as well-known.

Michel $e^{\pm}$ time distribution



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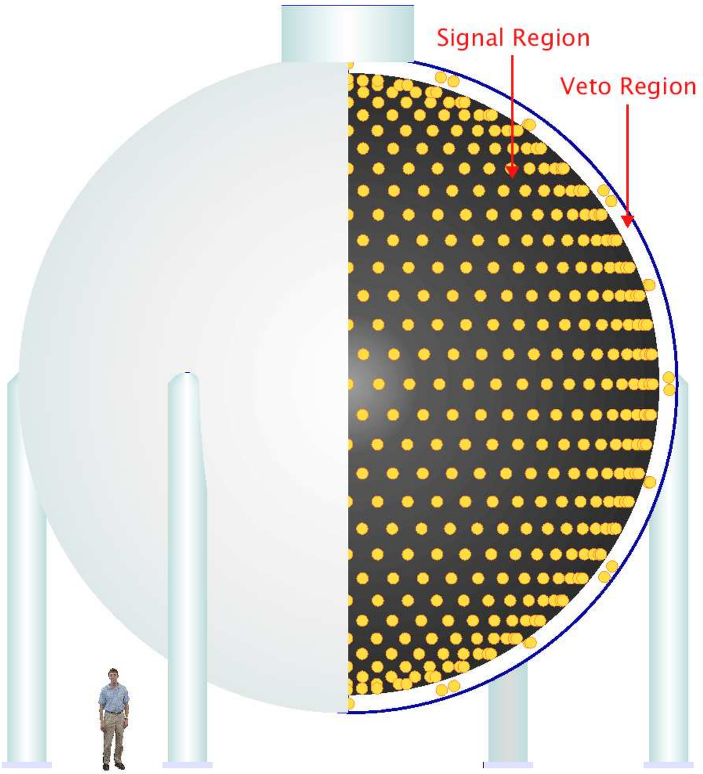

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- So, why use pure mineral oil?
  - Electrical insulator, not the "root of life".
  - $n = 1.47$ provides about 24% more Cerenkov light than water.
  - Primarily need clear Cerenkov ring for distinguishing ν_e from ν_μ.
  - A small amount of scintillation allows us to see nuclear recoils and neutral-current (NC) interactions.

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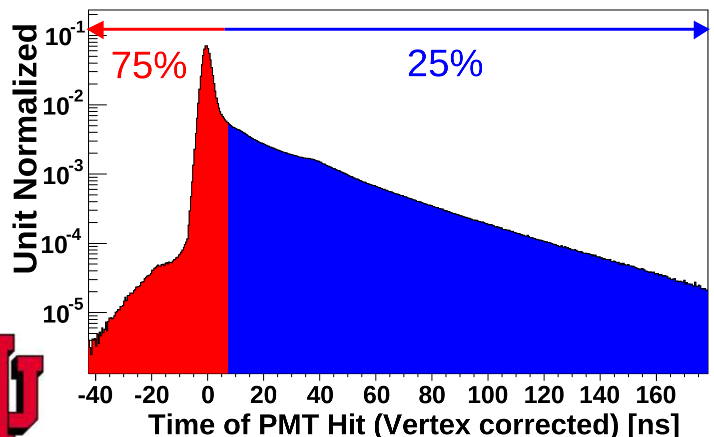
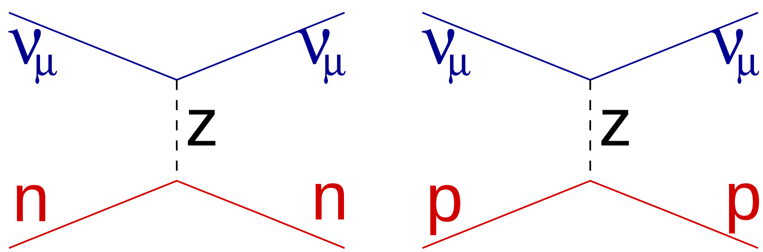


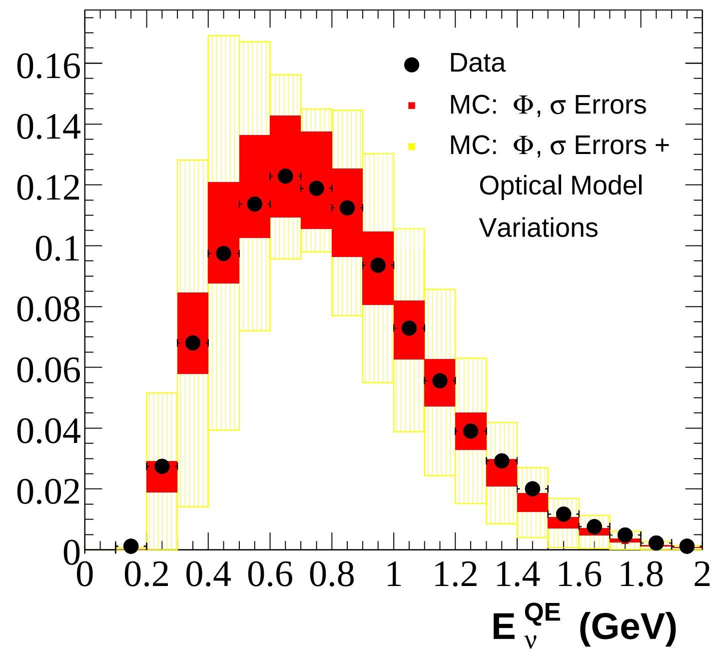


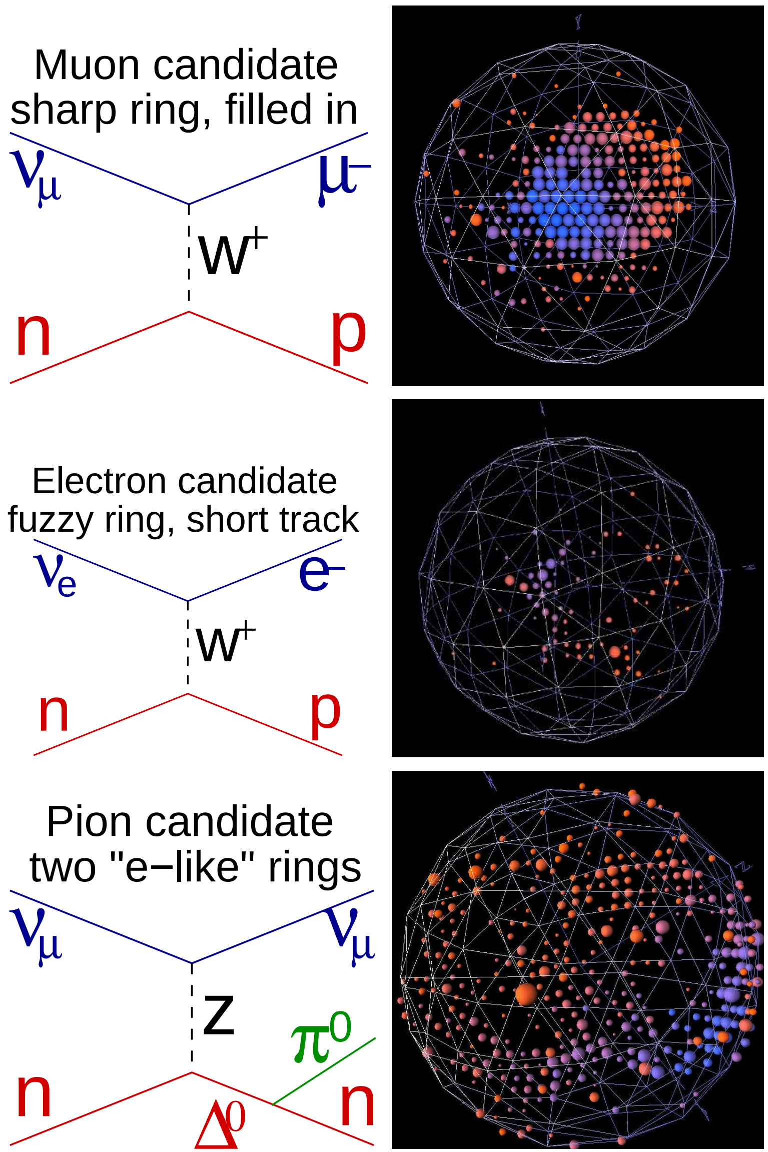
NC Elastic Interactions

A correct OM is important for robust PID.

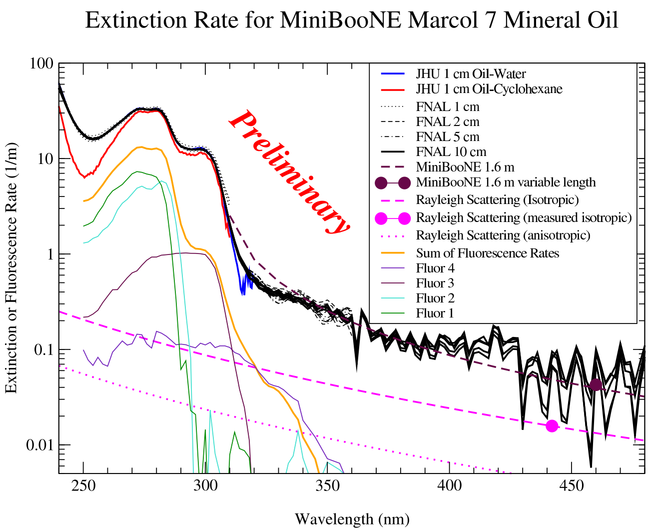
- We have to identify a handful of $\nu_e n \rightarrow e^- p$ in a sea of $\nu_\mu n \rightarrow \mu^- p$.
- Also have mis-ids from $\nu_\mu n \rightarrow \nu_\mu \Delta^0 \rightarrow \pi^0 n$
- Because of residual uncertainties in the optical model, prior physics results have been reported with large systematic errors.
- Should be possible to make the OM systematic errors a small part of the overall error.

ν_μ Charged-Current Quasi-Elastic (CCQE)
Relative Cross-section

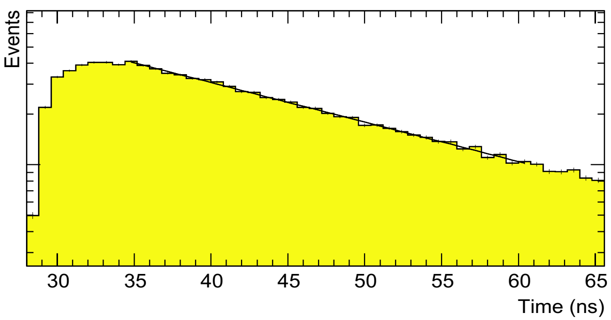




Initial optical properties defined by external measurement.



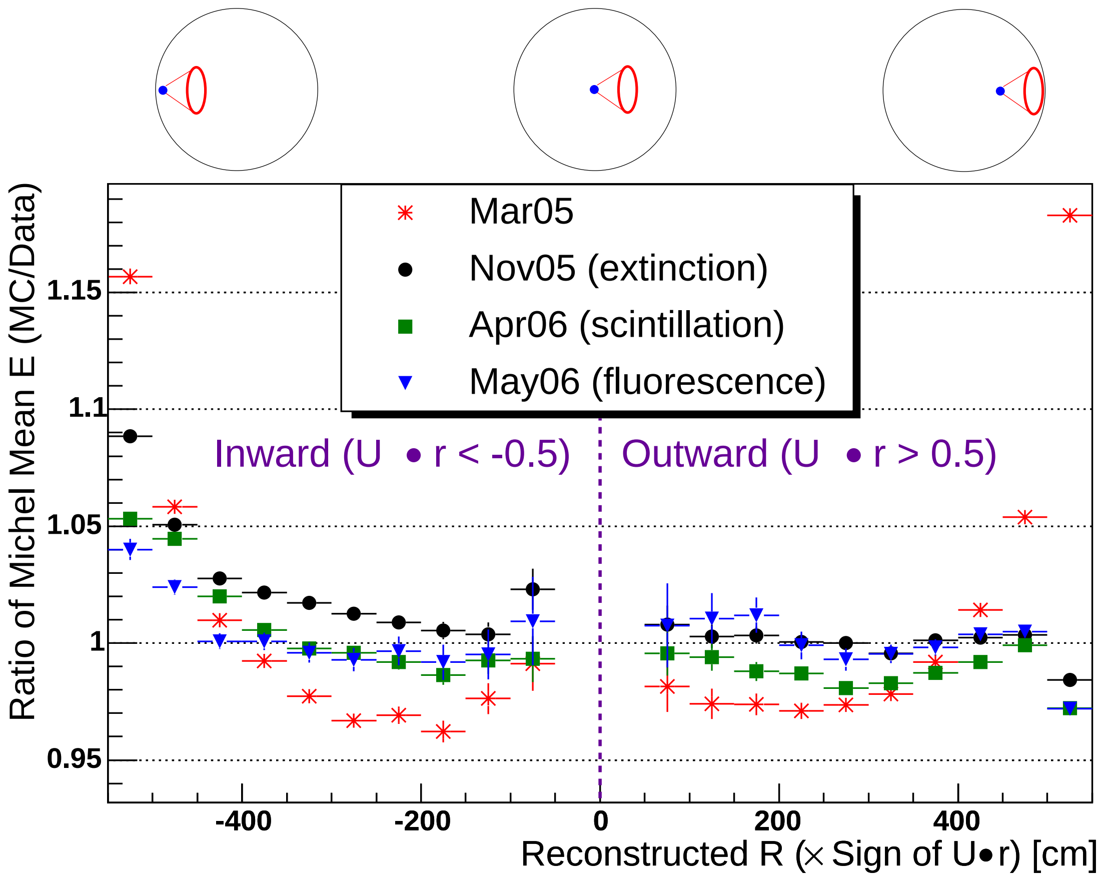
Time response to 200 MeV protons



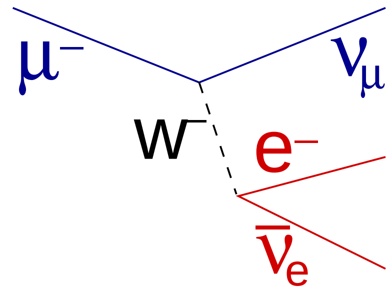
- Sources of light
  - Cerenkov light produced by particles with $v/c_{\text{medium}} > 1$.
  - Scintillation light from charged-particles stimulating the mineral oil
  - Fluorescence from Cerenkov light that is absorbed and re-emitted.
- Tank effects
  - Reflection from tank walls, PMT faces, etc.
  - Scattering (Raman and Rayleigh) off the mineral oil.
  - PMT properties
    - Single pe charge response
    - Charge linearity
    - Time distributions

- External measurements were made for almost all of the various properties.
  - Sometimes hard to set relative amplitudes between measurements.
  - Some measurements in conflict...worry about contamination of oil, etc.
  - All measurements have some residual uncertainty.
- Solution: Build as complete an OM as possible and turn to tank calibration data to refine oil properties.

Refining the OM using *in situ* calibration sources.



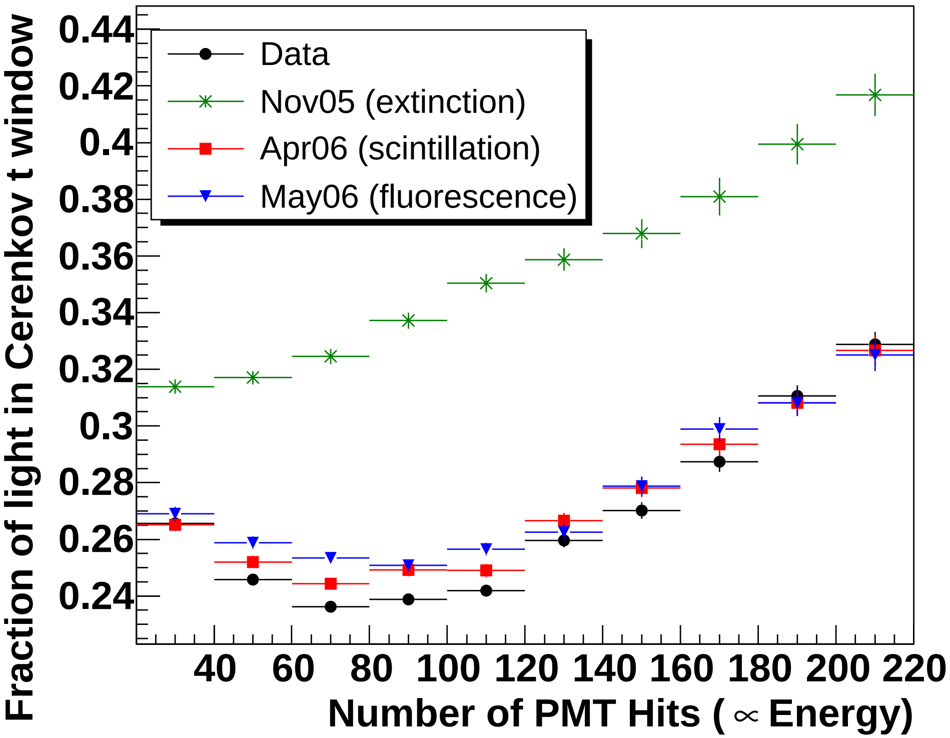
- Stopping cosmic muons provide an abundance of Michel decay electrons.



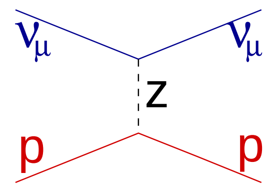
- We are able to quickly simulate many Michel decays.
- We run MC excursions of 1 OM parameter ("unisim") and use the derivatives with central-value MC to fit tank data.

- Monte Carlo simulation proceeds in "baselines" where the code is updated to include all improvements and new samples are run for analyzers.
- From Mar05 to Nov05 the dominant OM change was to the extinction length.
- As a function of R and $U \cdot r$, the data/MC energy distribution is now flat to within 2% in a 5 m fiducial volume..

Tuning the scintillation components (A_i, t_i)



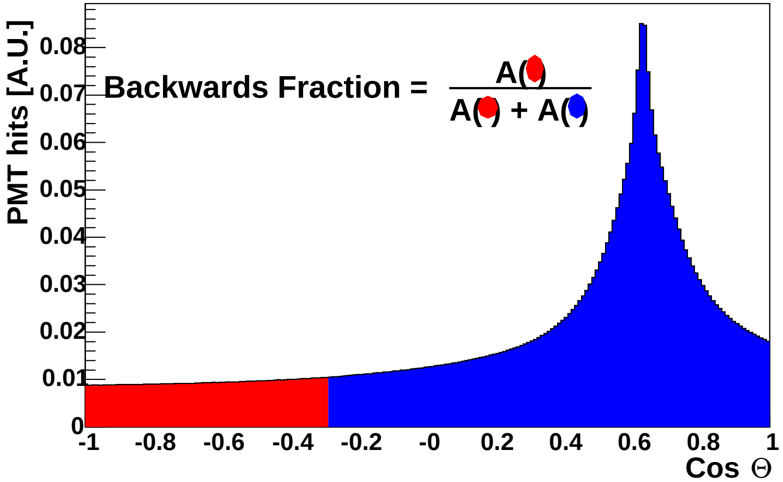
- As a general rule, we do not tune the OM with ν data.



- The exception: NC elastic interactions
  - NC not a significant part of the oscillation signal/background.
  - Sub-Cerenkov *p* produce only scintillation

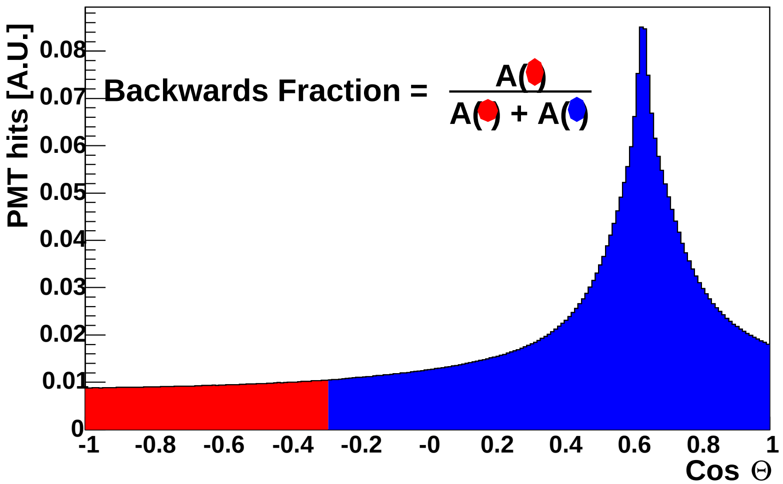
- The plot shows the fraction of light emitted in the Cerenkov time window vs number of PMT hits (energy).
- As the energy of the ν interaction increases, the recoil proton becomes more Cerenkov-like resulting in the rising fraction.
- Large improvement between the Nov05 and Apr06 baselines.

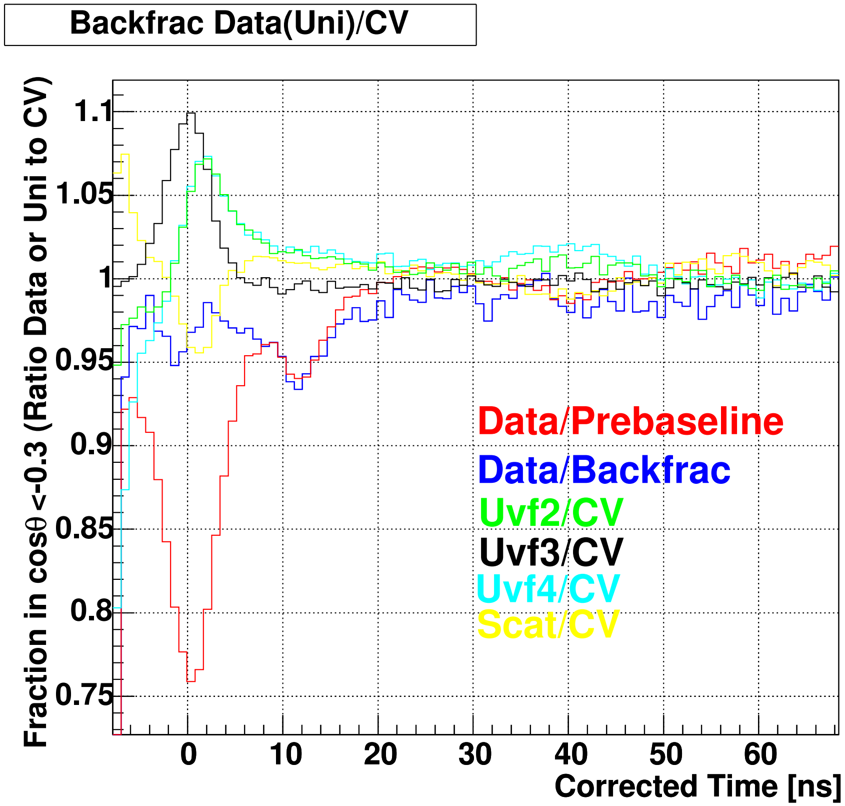
Back to Michels for constraints from topology



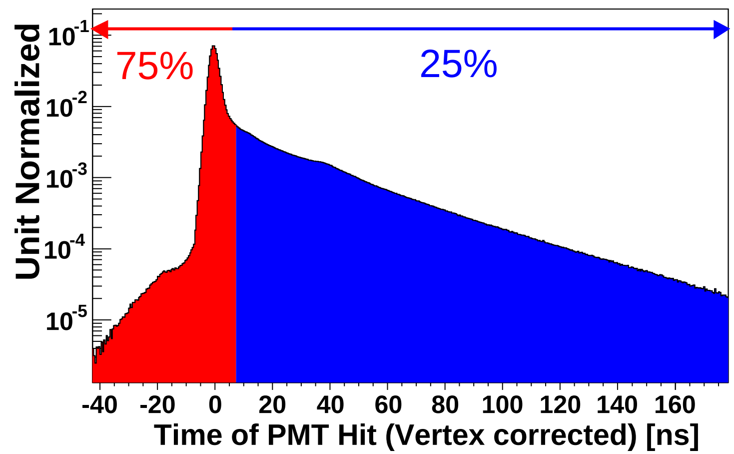
- "Backwards fraction" is the fraction of light detected opposite of the Cerenkov cone.
- This fraction is sensitive to scintillation, fluorescence, and scattering.

Back to Michels for constraints from topology

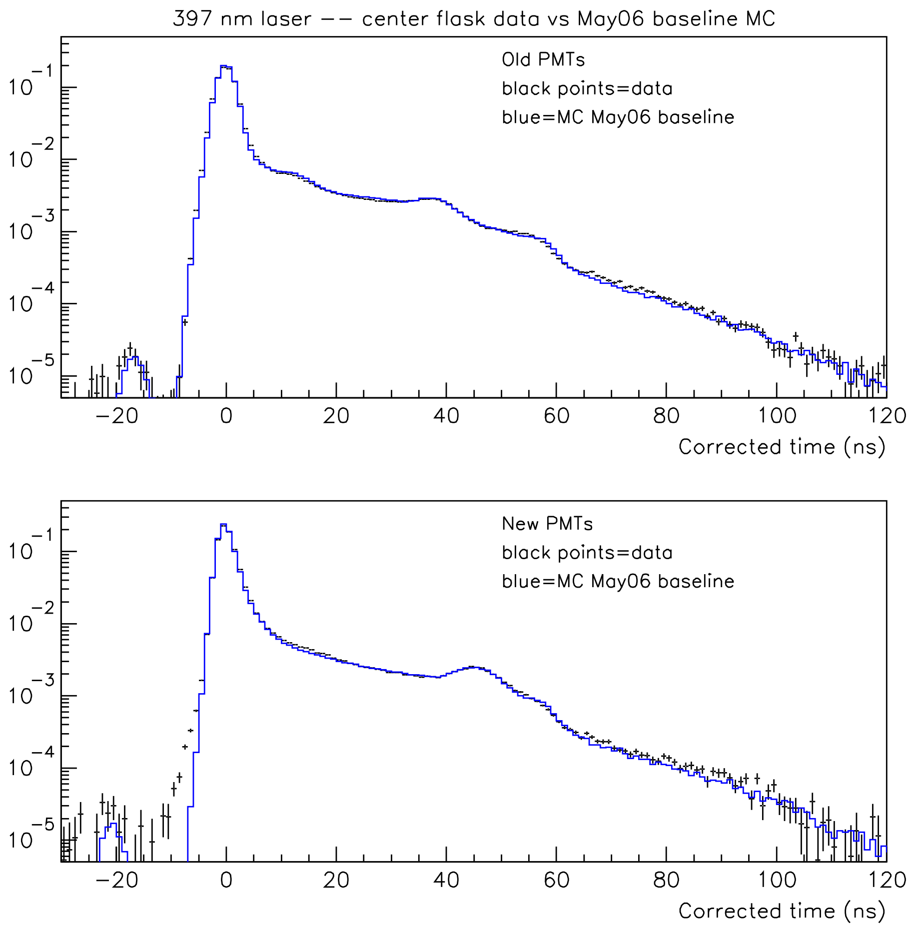




- "Backwards fraction" is the fraction of light detected opposite of the Cerenkov cone.
- This fraction is sensitive to scintillation, fluorescence, and scattering.
- Plotted as a function of corrected time it is sensitive to various time components of the OM.
- The ratio of data to MC shows a 25% deficit of isotropic light in the Cerenkov window.
- Large improvement from Apr06(red) to May06 baseline(blue).



Check OM with independent calibration source.

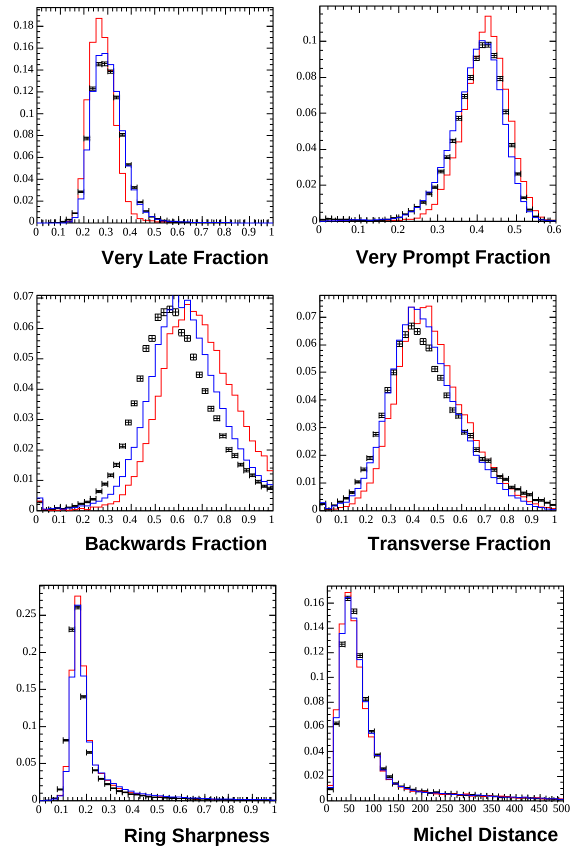


- Laser light of a fixed $\lambda = 398$ nm emitted from laser flasks suspended in tank.
  - No Cerenkov, scintillation, or fluorescence.
  - Tests reflection, scattering, and PMT response.
- Data/MC agreement in the May06 baseline is spectacular.

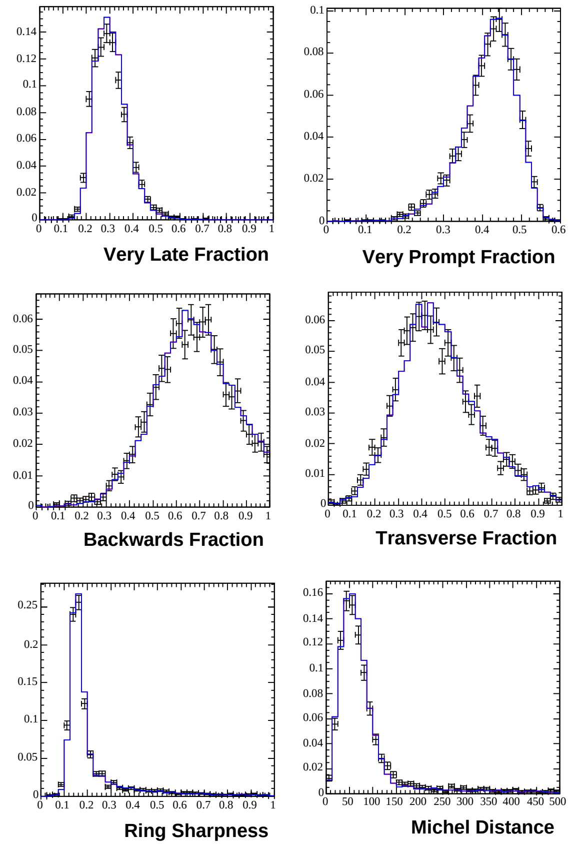
The improvement in the OM is apparent in the ν analyses.

- Certain variables can be constructed that are useful for extracting a particular interaction in the tank.
- Here are a few from the ν_μ CCQE analysis:

Black-Nov05 Data,
Red-Nov05 MC,
Blue-Apr06 MC

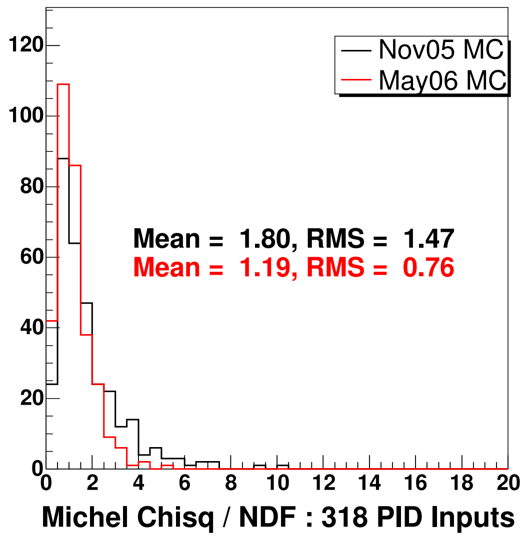


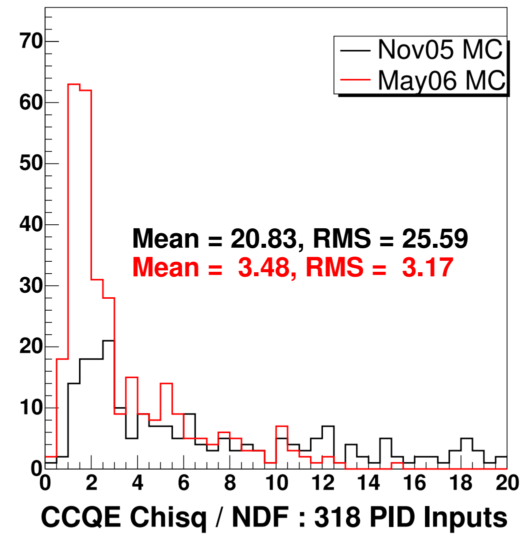
Black-May06 Data,
Blue-May06 MC

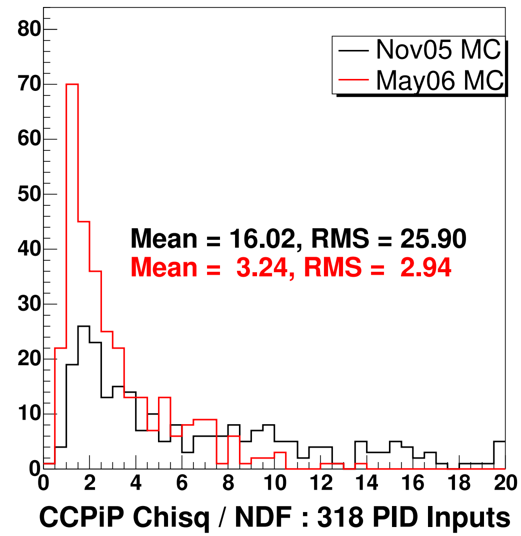


- You can imagine calculating a “χ^2” between data and MC...

χ^2 distribution for an ensemble of 318 variables.





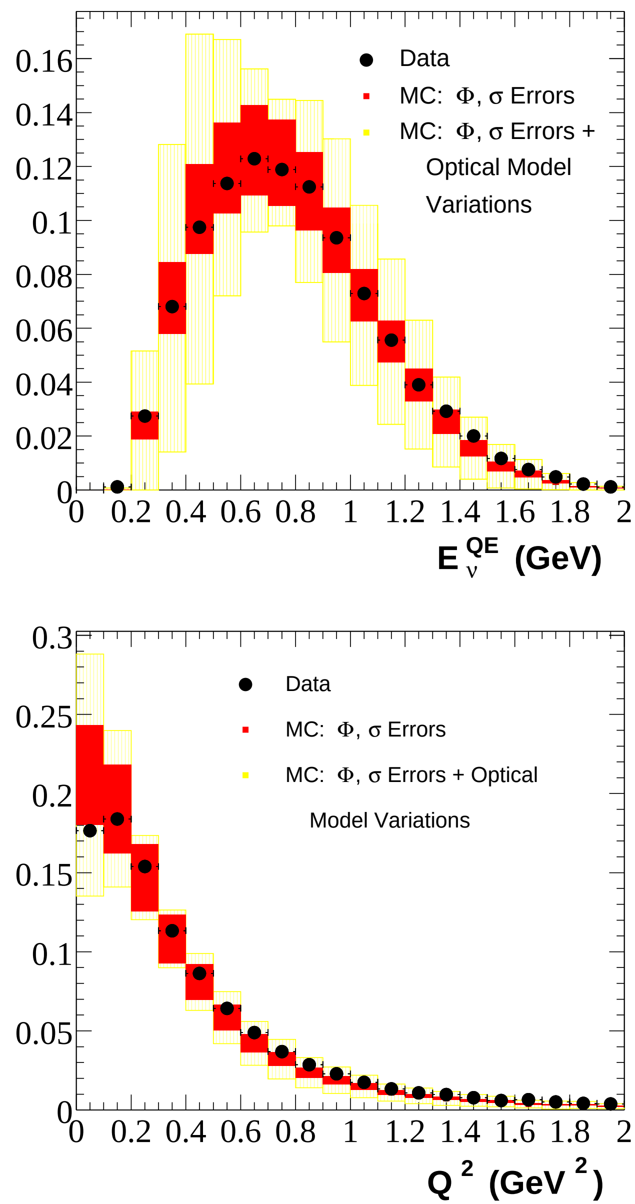


- The same 318 variables were used to produce each of the χ^2 distributions.
- Each plot is made only from a subset of events with cuts that prefer:
  - Michel decay electrons from beam events
  - Charged-current, quasi-elastic ν_μ interactions.
  - Charged-current interaction with a π^+ in the final state.
- All sample show a remarkable improvement in the simulation.

Outlook for MiniBooNE

- I hope I have demonstrated substantial improvements that have been made over the course of the last year.
- The optical model is not the only area of the analysis that has progressed.
  - Recent improvements in understanding the absolute normalization, largely due to new HARP results.
  - Development of two analyses
    - Likelihood-based (simple to understand).
    - Boosted-decision tree (maximum sensitivity).
  - Progress in understanding how to propagate a full statistical and systematic error.
- We are sensitive to the desire of the community to see our result, but the payoff for the wait can really be measured in sensitivity and the ultimate errors on our cross-sections.

ν_μ CCQE Relative Cross-Section



Normalization

- The MiniBooNE Run Plan reported we were seeing 1.5 times as many events as the Monte Carlo predicted.
  - For an inclusive ν sample.
- This normalization difference is now 1.2
- Major changes in rate prediction since Run Plan (not complete list) ...
  - -3.5% from better ν cross-section modeling
  - +17.5% from better modeling of incoming proton beam
  - +5.2% from CCQE cross-section tuning (MA extraction)
  - -6.0% from better modeling of secondary beam interactions
  - +16.2% from HARP π^+ + horn current + better modeling of primary proton interactions
- After a huge amount of cross-checking the agreement between data and MC ν rates is now far less of an issue