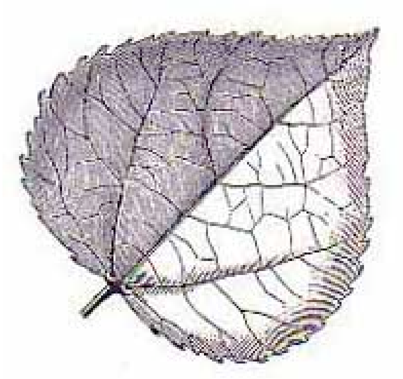


ν_e Oscillation Analysis Progress at MiniBooNE

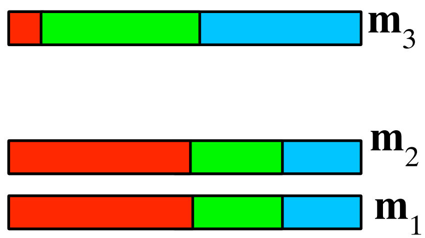
1. Motivation and Overview
2. Components of the Oscillation Analysis
3. Incorporating Constraints from ν_μ Data

Jocelyn Monroe, MIT

Aspen Winter Conference
January 11, 2007

MiniBooNE Motivation: LSND Result

ν Oscillations



weak eigenstates (ν_e, ν_μ, ν_τ) ≠ mass eigenstates (ν_1, ν_2, ν_3)
parameters $\Delta m_{i,j}^2 = |m_i^2 - m_j^2|$, $\sin^2 2\theta_{ij}$, i,j=1,3

2-ν oscillation probability:

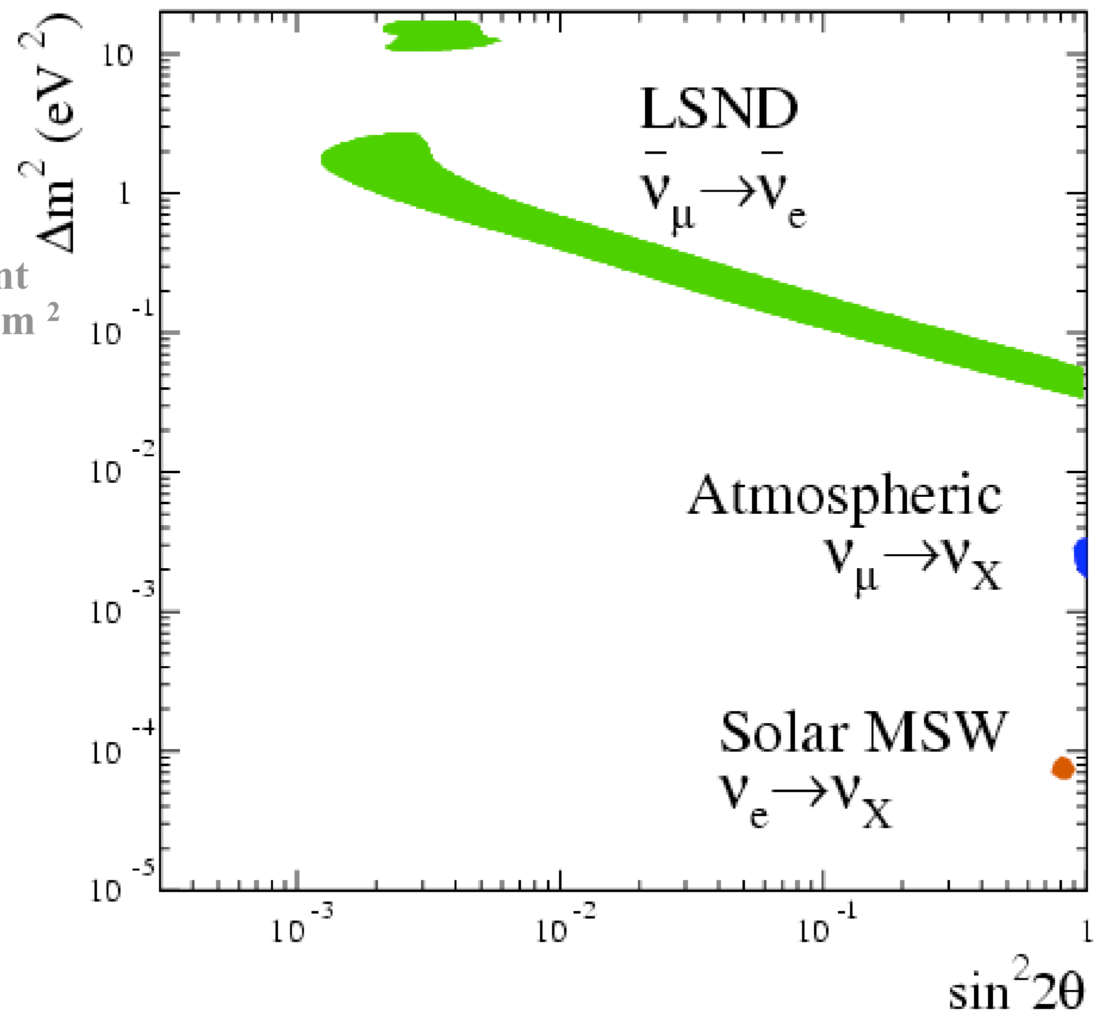
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Signals:
Solar: $\Delta m^2 \sim 10^{-5}$ eV ^{2}
(SNO, KamLAND, ...)

Atmospheric: $\Delta m^2 \sim 10^{-3}$ eV ^{2}
(Super-K, K, ...)

Accelerator: $\Delta m^2 \sim 10^{0}$ eV ^{2}
(LSND)

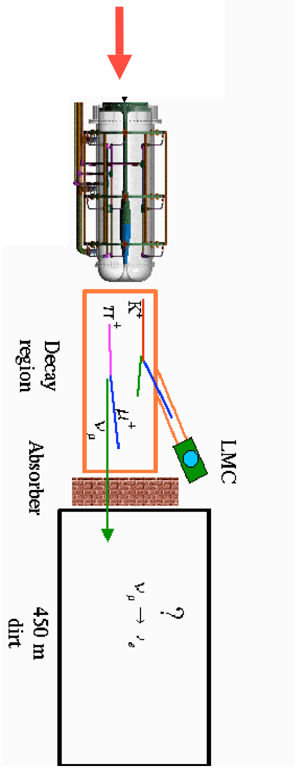
3 νs allow only 2 independent values of Δm^2

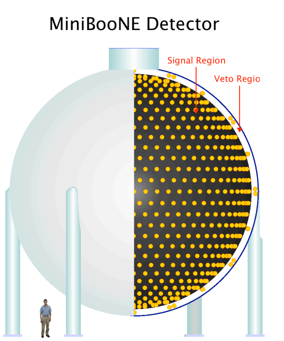


Explanation for Δm^2 problem?
1. LSND interpretation may be wrong
 -confirm or refute with MiniBooNE
2. Add sterile neutrinos: 1, 2, 3 ...
3. (More) exotic possibilities

MiniBooNE Overview: Beam and Detector

MiniBooNE is searching for an excess of ν_e in a ν_μ beam



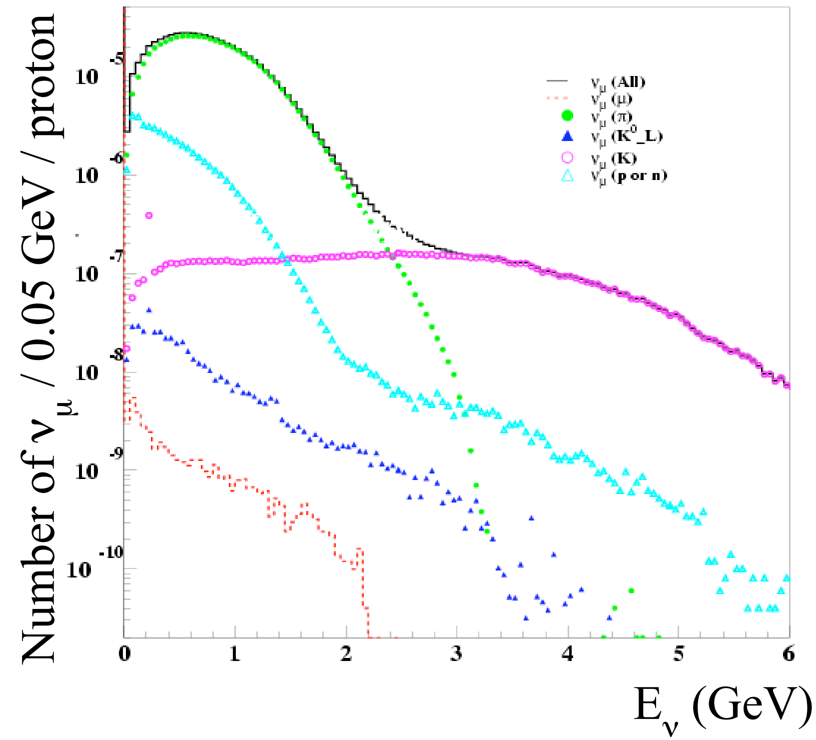


Protons*:* 4E12 protons per 1.6 μs pulse, at a rate of 3 - 4 Hz from Fermilab Booster accelerator, with E=8.9 GeV

Mesons*:* mostly π^+, produced in p-Be collisions, + signs focused in horn. 50m decay region.

Neutrinos*:* 450 m soil berm before the detector hall. Intrinsic ν_e flux ~ 0.4% x ν_μ flux.

Detector*:* 1280 PMTs, 250,000 gallons of mineral oil, Cherenkov and scintillation light. 240 PMTs in optically isolated veto region.



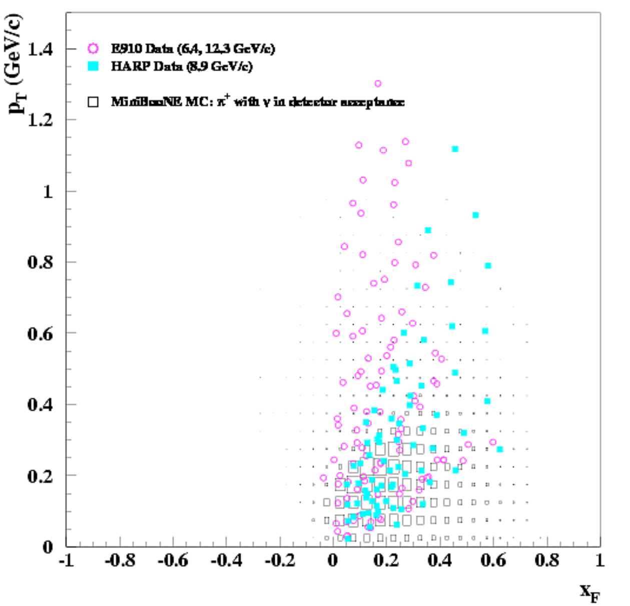
Beam ν_μs from:		(B.R.)
$\pi^+ \rightarrow$	$\mu^+ \nu_\mu$	(99.99%)
$K^+ \rightarrow$	$\mu^+ \nu_\mu$	(63%)
Beam ν_es from:		
$\mu^+ \rightarrow$	$e^+ \nu_e \bar{\nu}_\mu$	(99.99%)
$K^+ \rightarrow$	$\pi^0 e^+ \nu_e$	(5%)
$K^0_L \rightarrow$	$\pi^\pm e^\pm \nu_e$	(39%)

MiniBooNE Beam: **Pion Production**

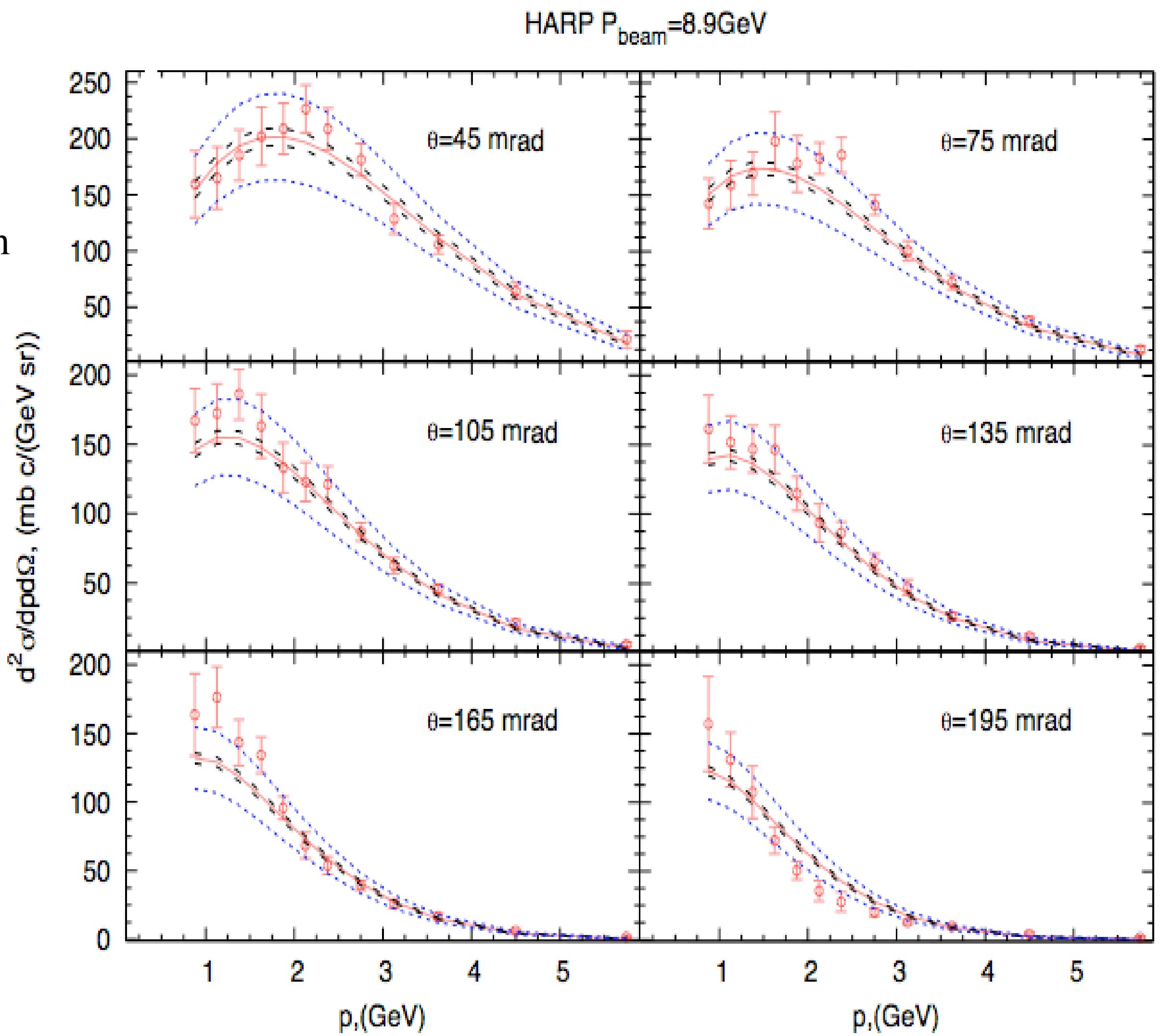
π^+ ***prediction*** *comes from a fit to* π^+ *production data from E910, HARP experiments* (p_p *= 6-12 GeV/c*)

Fit uses Sanford-Wang parameterization of inclusive meson production in p-Be collisions

HARP π^+ data at 8.9 GeV/c beam momentum shown (right) with prediction and error, data has excellent phase space coverage for MiniBooNE (below)



π^- similarly parameterized, but comprise negligible contribution to neutrino flux

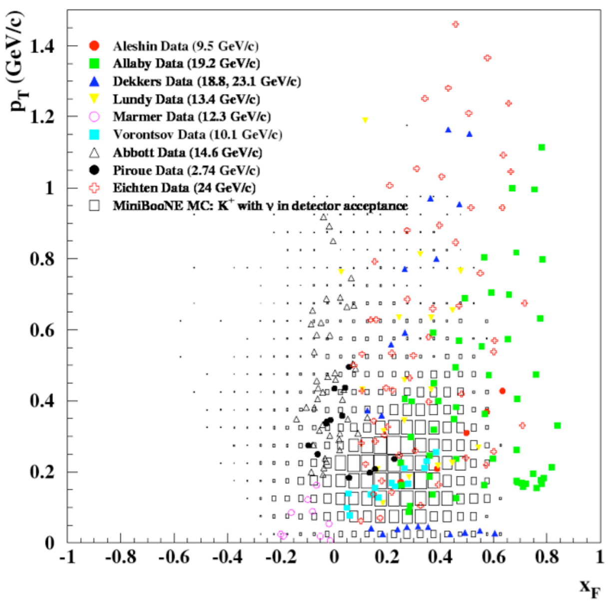


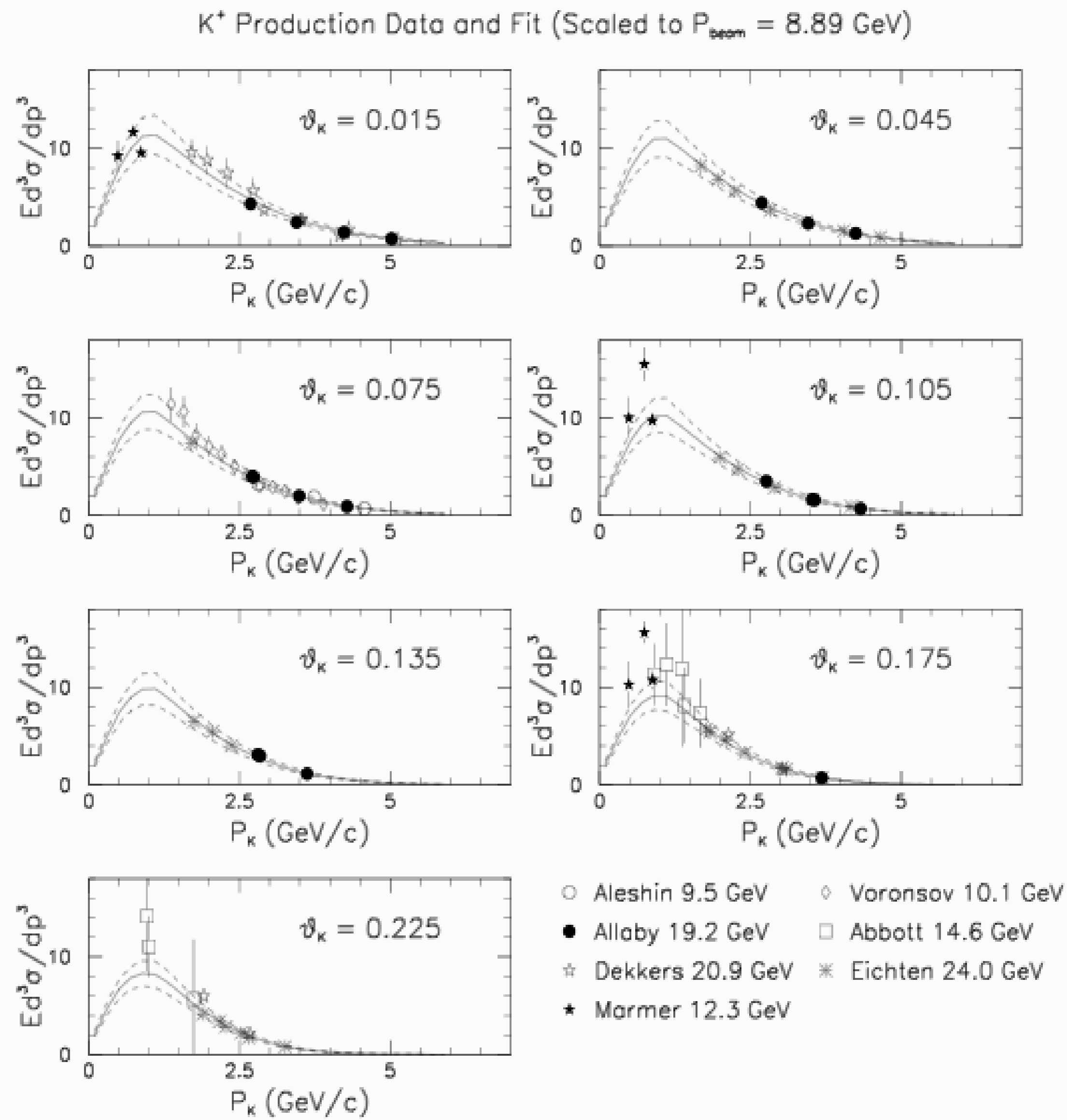
MiniBooNE Beam: **Kaon Production**

***K^+ prediction** comes from a fit to K^+ production data from past experiments (= 10-24 GeV/c)*

Fit uses a parameterization based on Feynman scaling (developed by MiniBooNE)

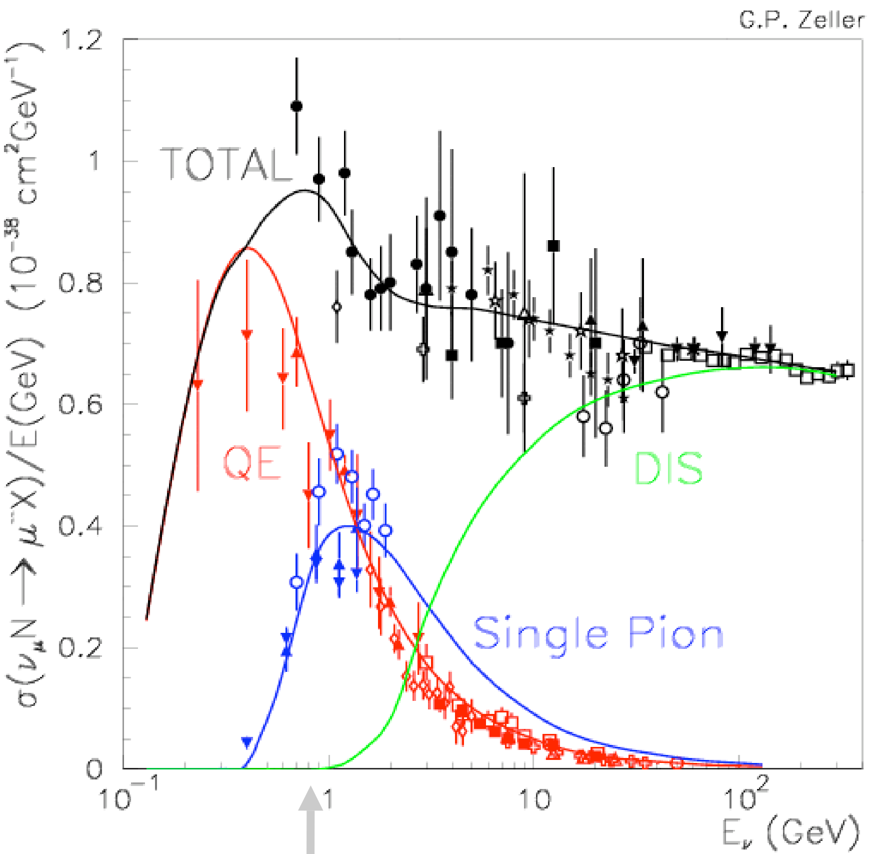
K^+ data from past experiments, scaled to 8.9 GeV/c beam momentum, shown with prediction and error (right), data has reasonable phase space coverage for MiniBooNE (below)





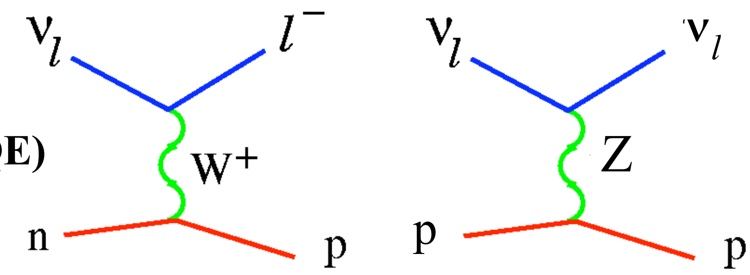
K^0 similarly parameterized, but comprise much smaller background than K^+

MiniBooNE Detector: Neutrino Cross Sections

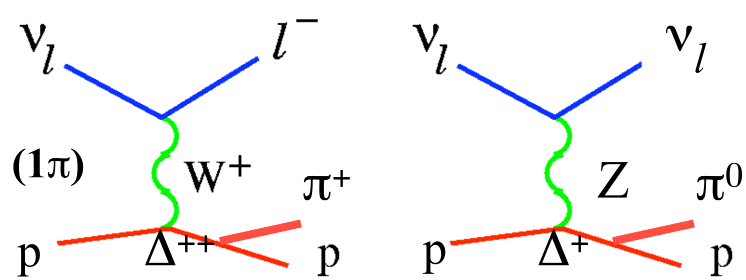


MiniBooNE is here,
has world's largest data set,
will publish σs in all of these channels

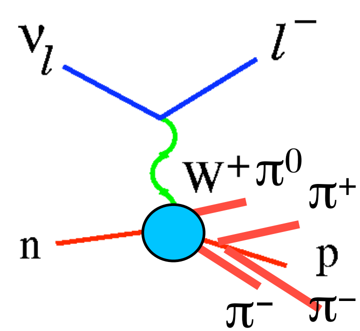
- **CC / NC quasi-elastic scattering (QE) 42% / 16%**



- **CC / NC resonance production (1π) 25% / 7%**



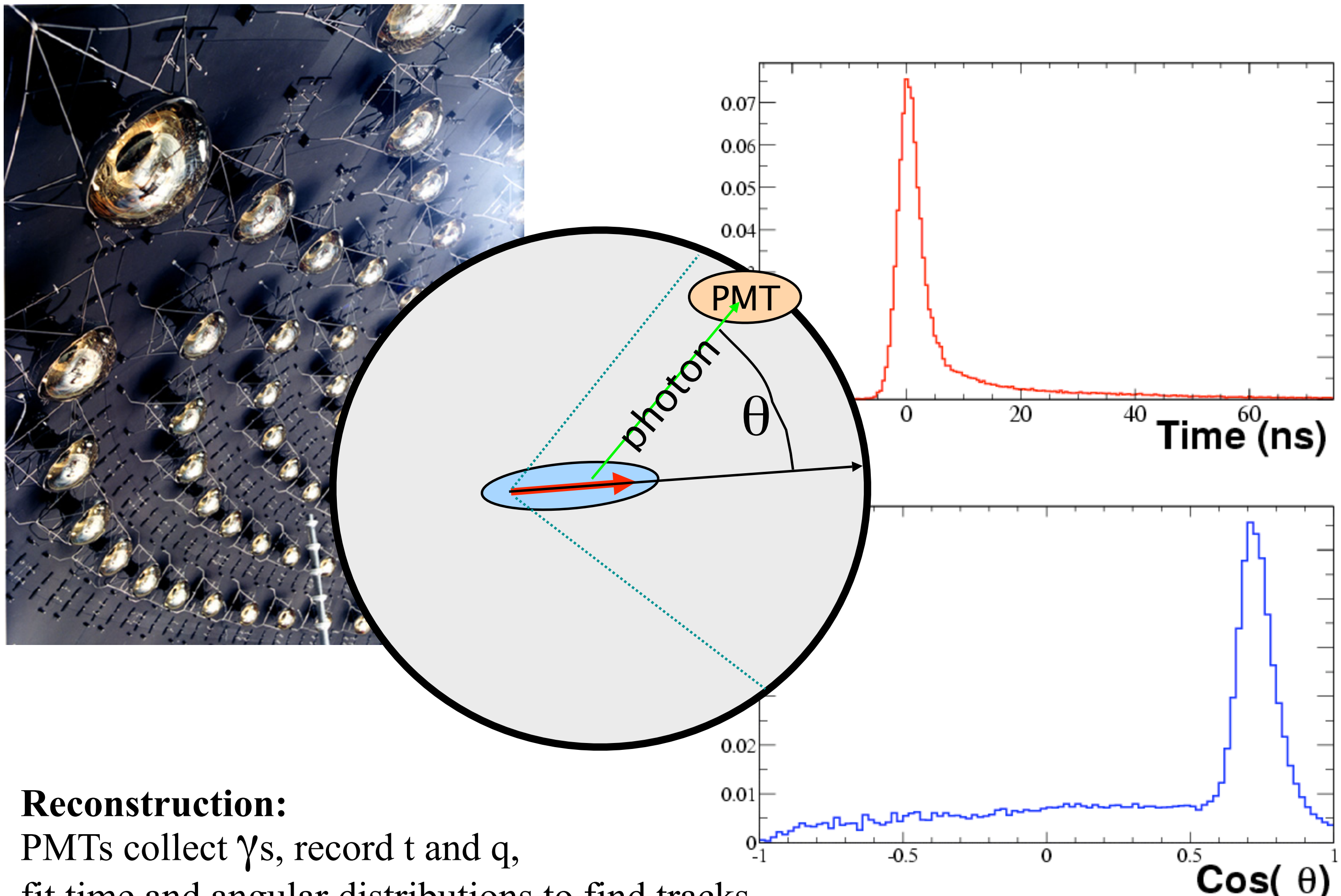
- **multi-π /DIS production ~13%**

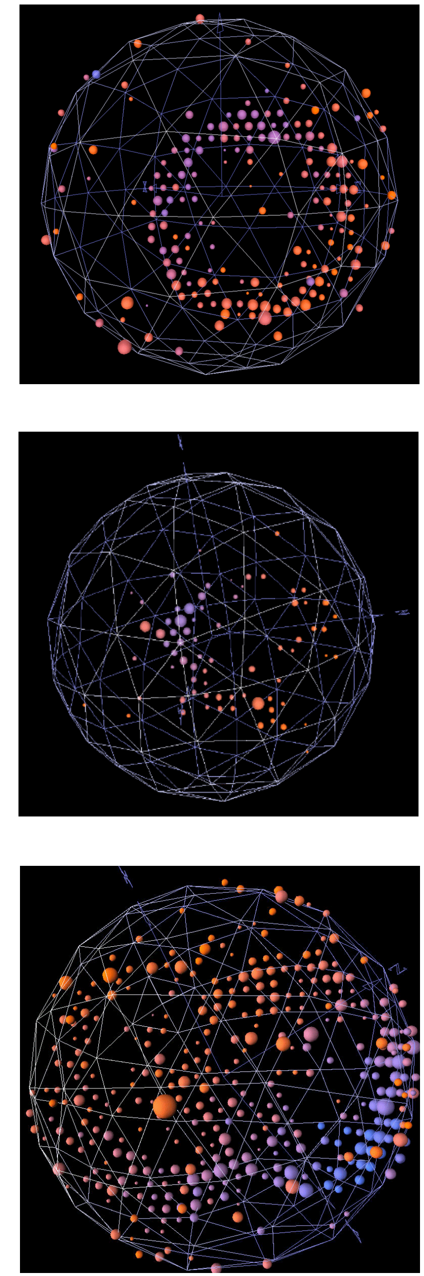


Cross Section Predictions from NUANCE Monte Carlo event generator:
variety of theoretical models for exclusive processes, joined smoothly to reproduce the total CC cross section data, with model parameters tuned on free-nucleon data

Use CCQE events for oscillation analysis signal channel: $E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$

MiniBooNE Detector: Reconstruction and Particle ID





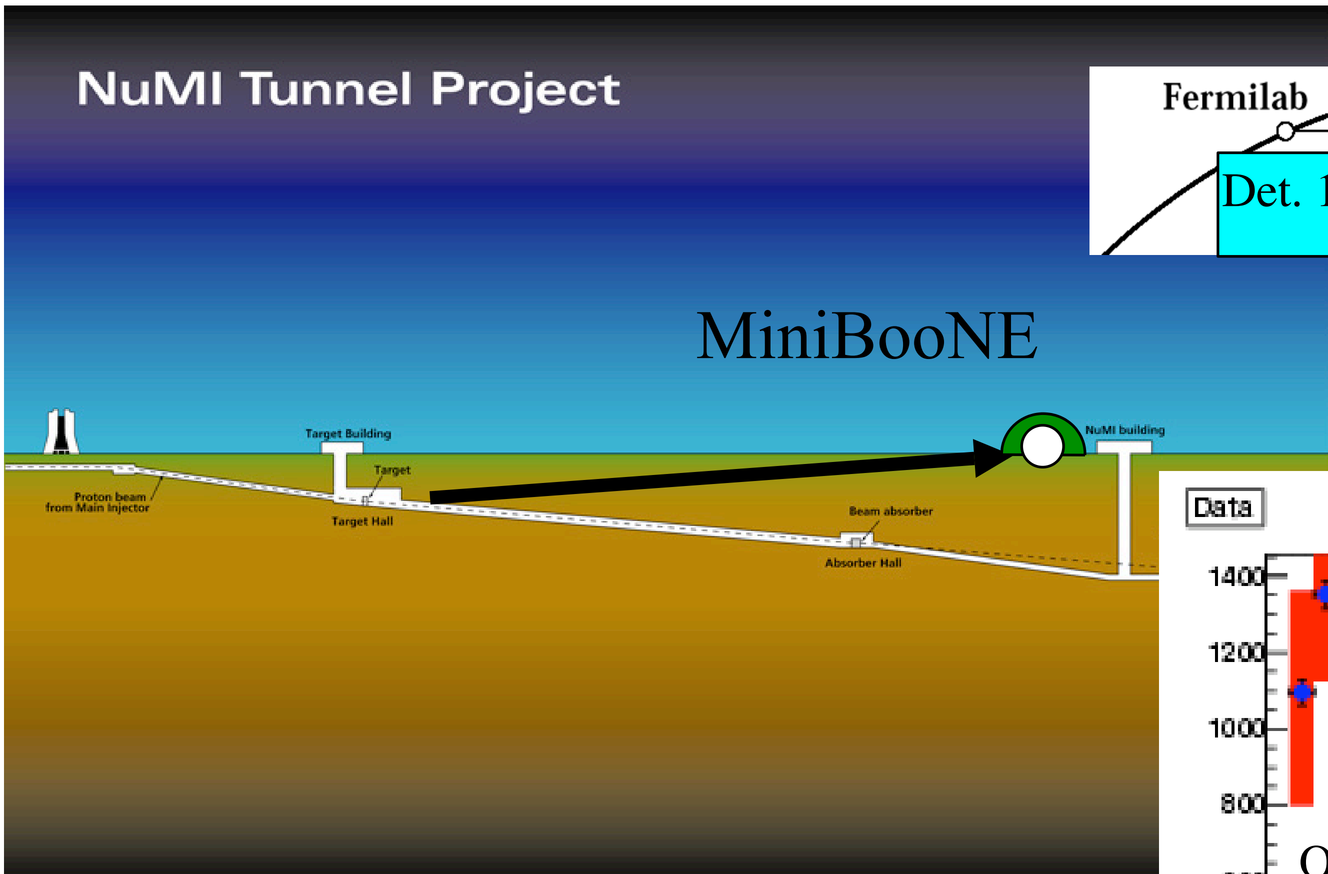
Reconstruction:
PMTs collect γs, record t and q,
fit time and angular distributions to find tracks

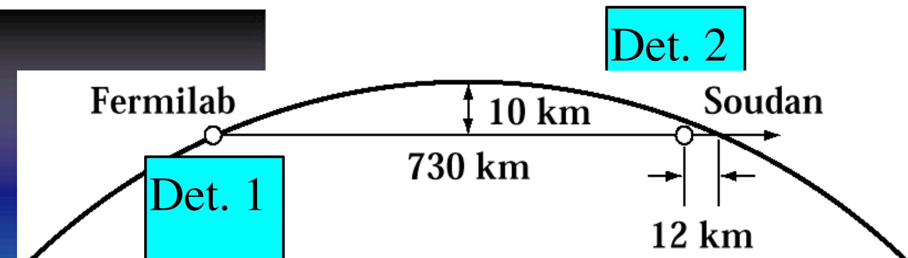
Final State Particle Identification:
muons have sharp rings due to Cherenkov emission, long tracks
electrons have fuzzy rings, from multiple scattering, and short tracks
neutral pions decay to 2 γs, which convert and produce two fuzzy rings,

easily mis-identified as electrons if one ring gets lost!

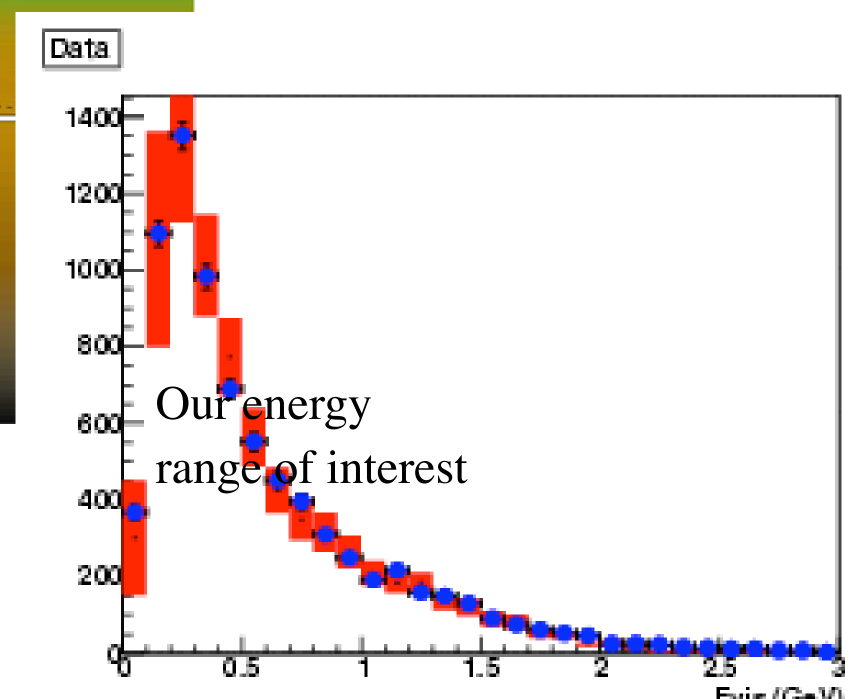
MiniBooNE Detector: **NuMI "Calibration Beam"**

We need to verify our PID with ν_e in the signal energy range, but we are doing a blind analysis.
Solution: use someone else's beam!





The NuMI beam to MINOS in Minnesota



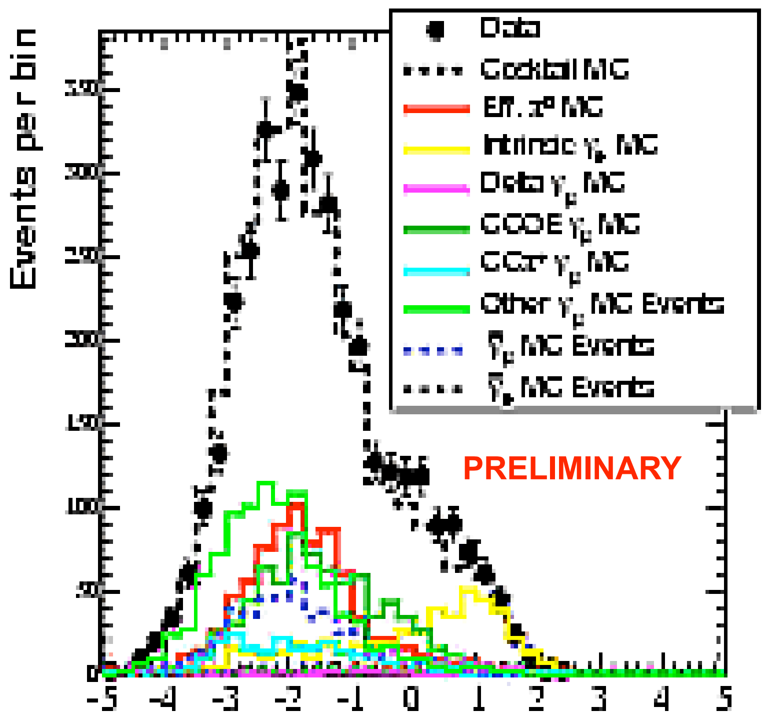
Sitting off axis, we see a beam which is enhanced in ν_e and is in a useful energy range.

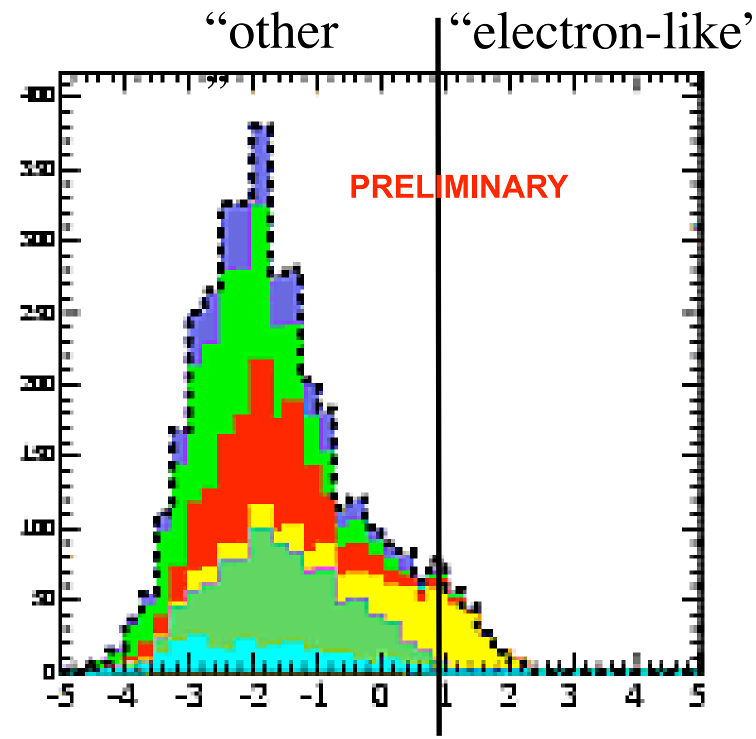
Oscillation Search: Signal Event Selection #1

Method #1: to find ν_e CCQE final state:

1. apply simple cuts on event time and number of hit PMTs to eliminate cosmics
2. eliminate muons by requiring 1 sub-event in time
3. employ Boosted decision tree discriminant ***or*** cut on e-μ and e-π likelihood variables to eliminate mis-IDs

   placement of cut determined by requiring 99.9% rejection of ν_μ CC, 99% rejection of π^0, ~50% ν_e CC efficiency





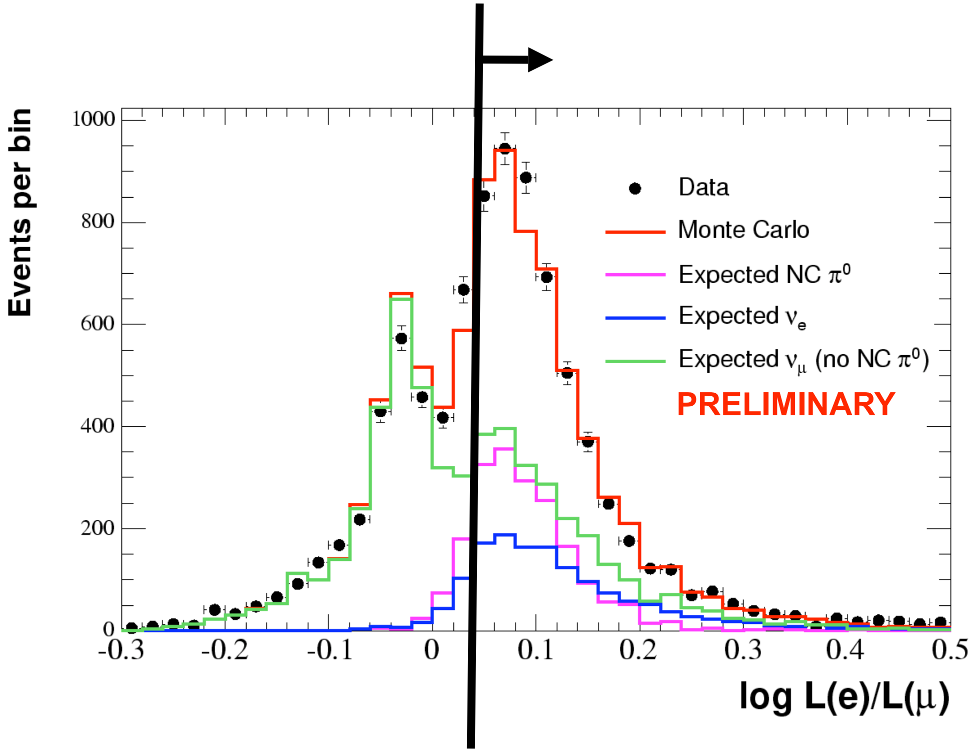
"calibration beam" data shown here is from the MiniBooNE detector and the NuMI beam, which is out of time, off-axis, enhanced in ν_e, and spans the relevant energy range

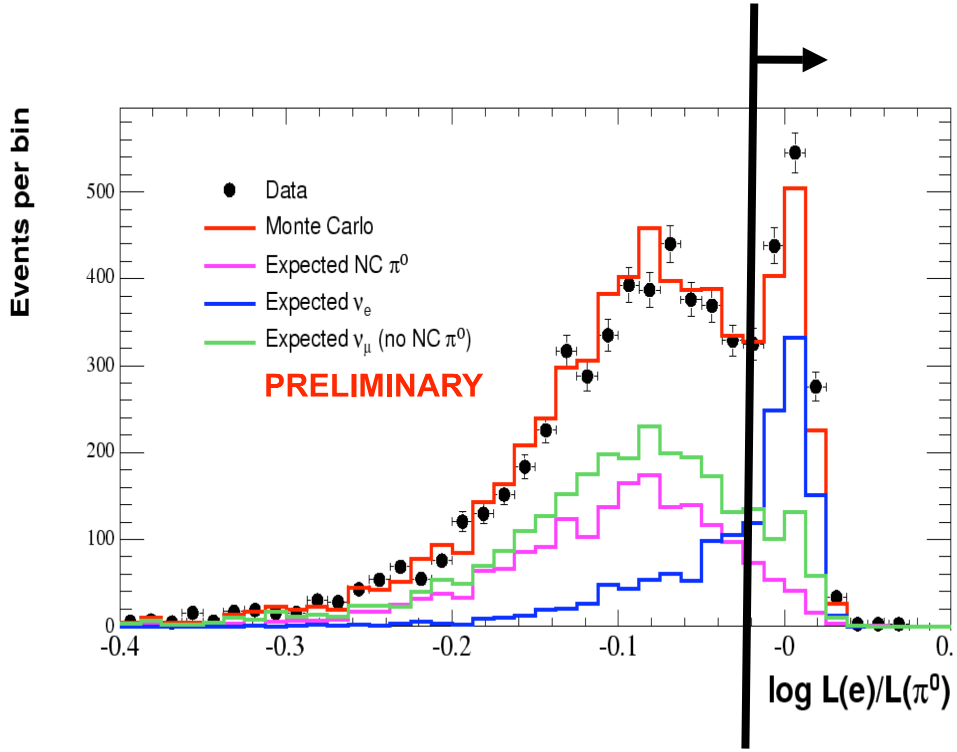
Oscillation Search: Signal Event Selection #2

Method #2: to find ν_e CCQE final state:

1. apply simple cuts on event time and number of hit PMTs to eliminate cosmics
2. eliminate muons by requiring 1 sub-event in time
3. employ Boosted decision tree discriminant ***or*** cut on e-μ and e-π likelihood variables to eliminate mis-IDs

   placement of cuts determined by requiring 99.9% rejection of ν_μ CC, 99% rejection of π^0, ~50% ν_e CC efficiency





"calibration beam" data shown here is from the MiniBooNE detector and the NuMI beam, which is out of time, off-axis, enhanced in ν_e, and spans the relevant energy range

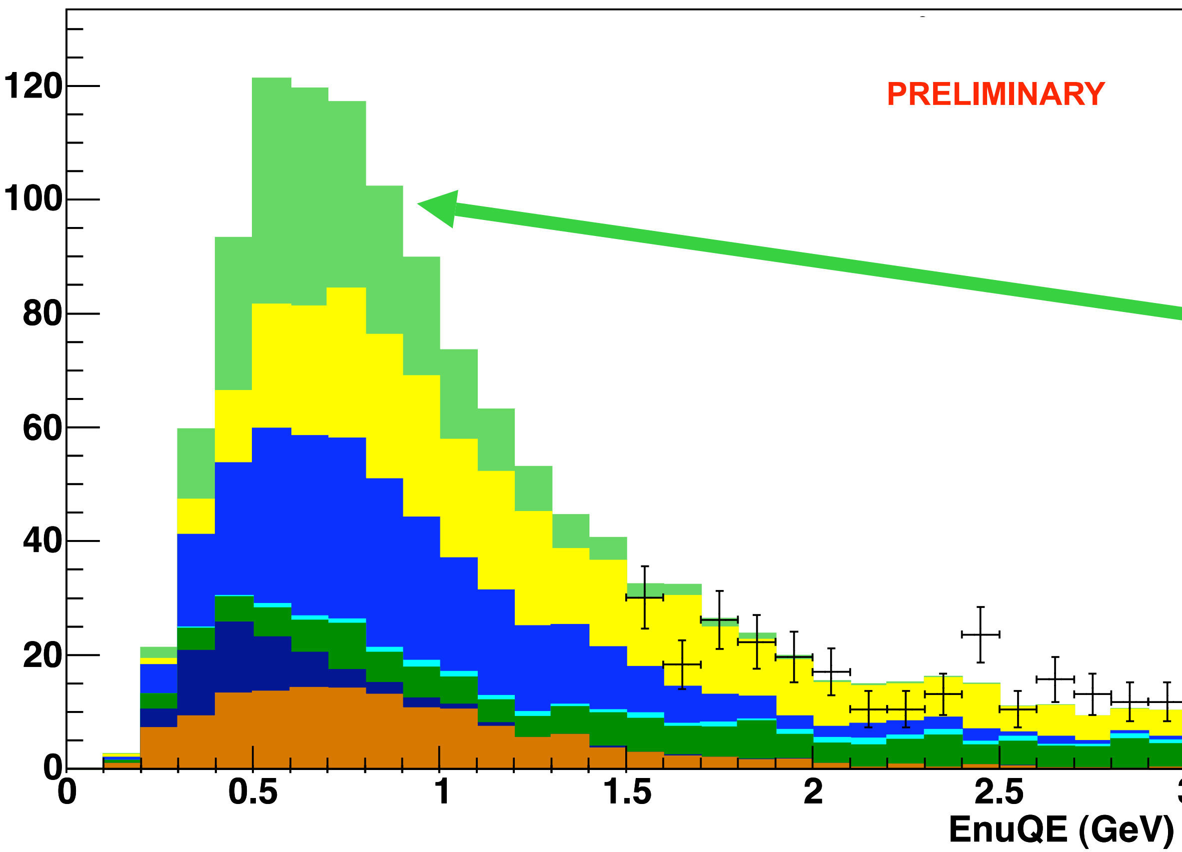
Oscillation Search: Signal Extraction

Raster scan in (Δm^2, $\sin^2 2\theta$), calculate

$$\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} (m_i - t_i)\, \mathcal{M}_{ij}^{-1}\, (m_j - t_j)$$

m_i = Number of measured data events in bin i
t_i = Number of predicted events in bin i
(t_i events are a function of Δm^2, $\sin^2 2\theta$,
M_{ij}^{-1} = Inverse of the covariance matrix

what we predict for the existing data set (5.3E20 protons on target)...



Oscillation ν_e

Example oscillation signal

- $\Delta m^2 = 1\ eV^2$
- $SIN^2 2\theta = 0.004$

Fit for excess as a function of reconstructed ν_e energy

Oscillation Search: Signal Extraction

Raster scan in (Δm^2, $\sin^2 2\theta$), calculate

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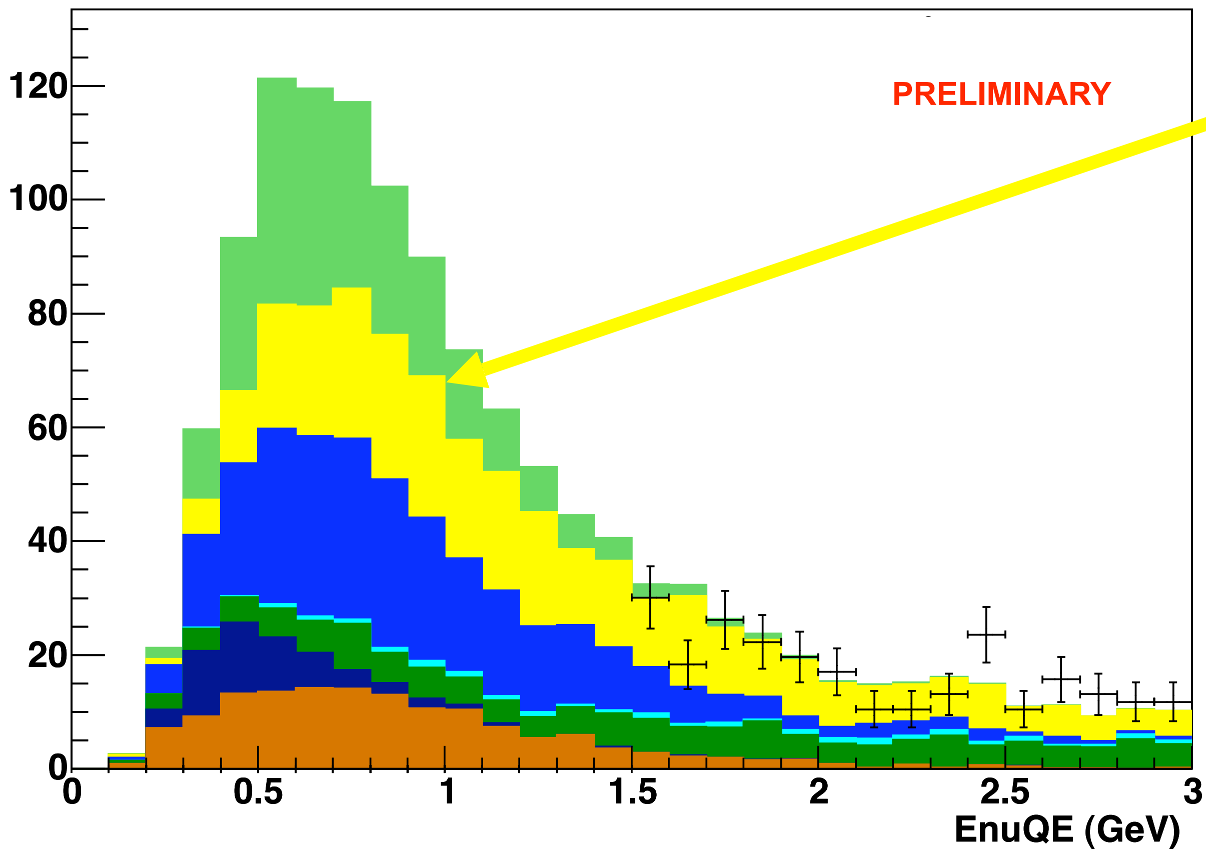

ν_e from K^+ and K^0

Use High energy ν_e and ν_μ for normalization

Use fit to kaon production data for shape

Oscillation Search: **Signal Extraction**

Raster scan in (Δm^2, $\sin^2 2\theta$), calculate

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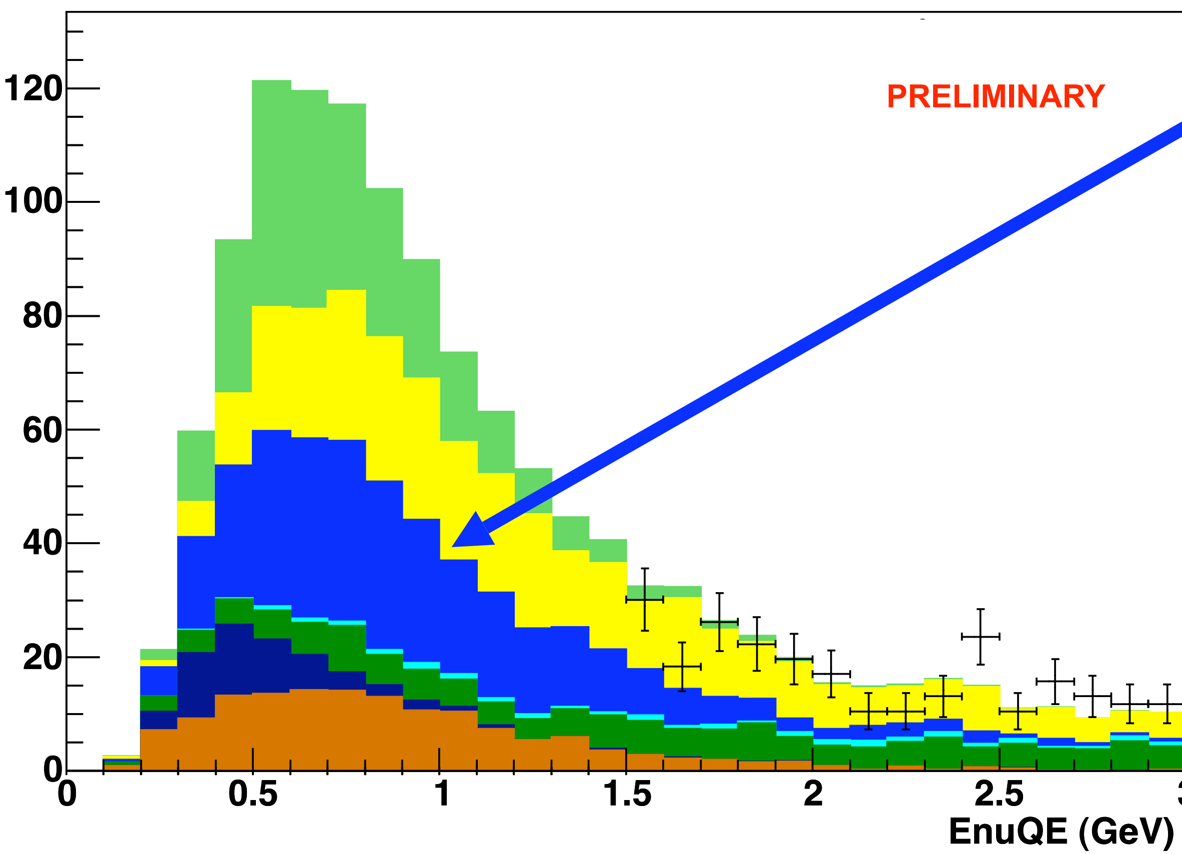
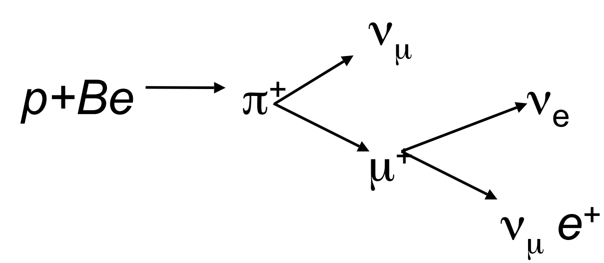


ν_e from μ^+



Measured with ν_μ CCQE sample

- Same ancestor π^+ kinematics

Most important background

- Constrained to a few %

Oscillation Search: Signal Extraction

Raster scan in (Δm^2, $\sin^2 2\theta$), calculate

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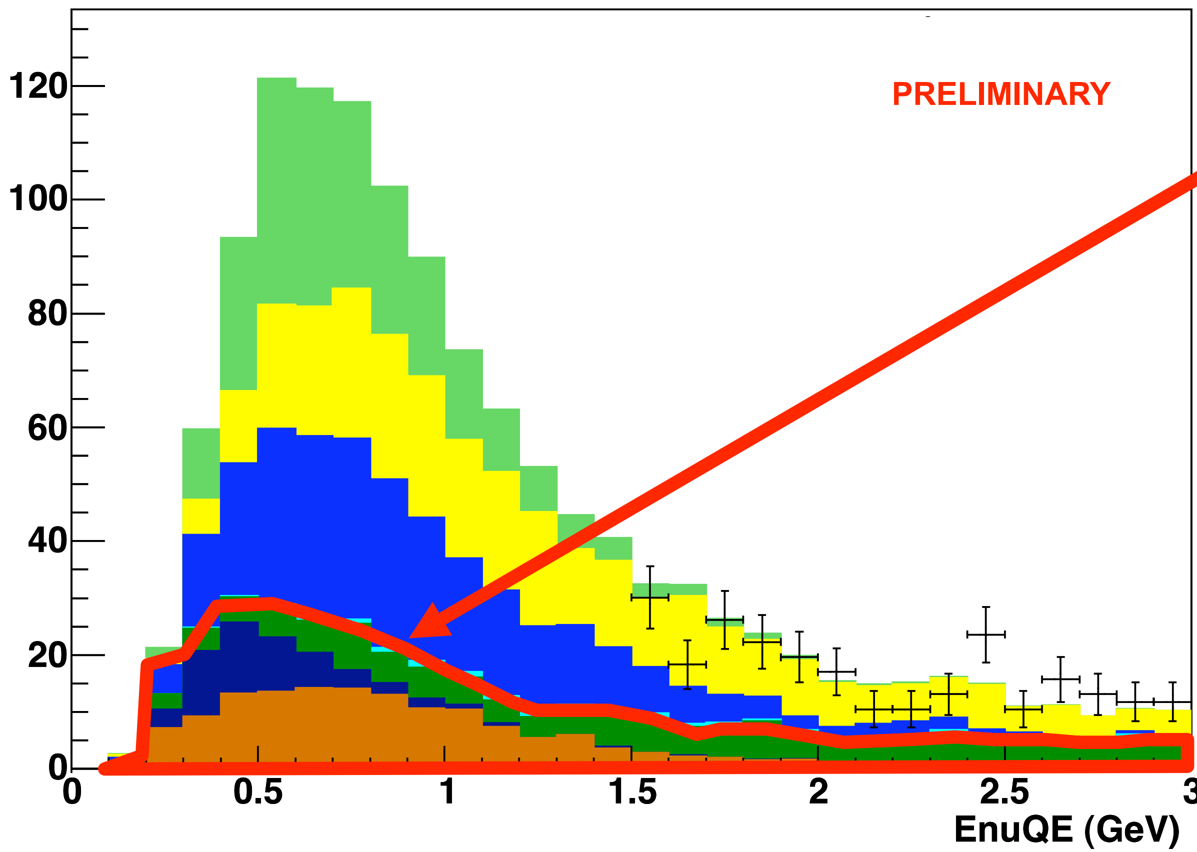
what we predict for the existing data set (5.3E20 protons on target)...



MisID ν_μ

~83% π^0

- Only ~1% of all π^0s are misIDed
- Determined by clean π^0 measurement

~7% $\Delta\ \gamma$ decay

- Use clean π^0 measurement to estimate Δ production

~10% other

- Use ν_μ CCQE rate to normalize and MC for shape

Oscillation Search: Signal Extraction

Raster scan in (Δm^2, $\sin^2 2\theta$), calculate

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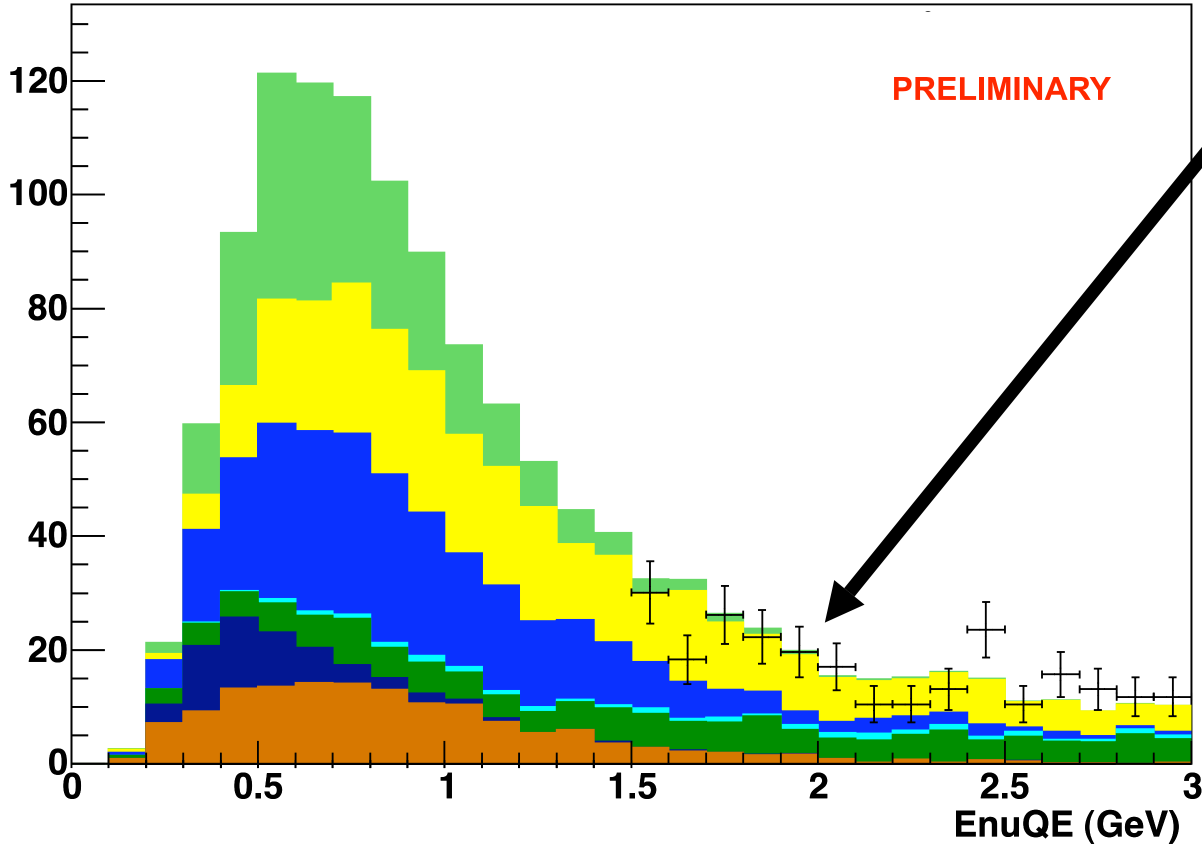
what we see for the existing data set (5.3E20 protons on target)...



High energy ν_e data

(relatively normalized)

Events below ~1.5 GeV still "in the box"

we are doing a "closed box" analysis in order to obtain the most convincing result!

- isolate data with the signature for $\nu_\mu \rightarrow \nu_e$
- use the rest (99%) to calibrate and constrain

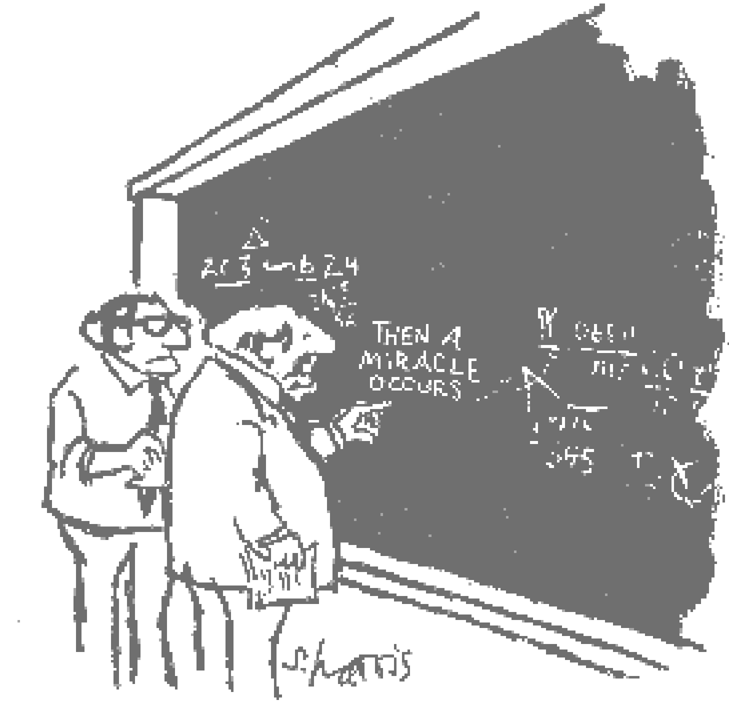
Oscillation Search: Analysis Strategy

in-situ data is incorporated wherever possible...

0. MC tuning with calibration data
   - energy scale
   - PMT response
   - optical model of light propagation in the detector

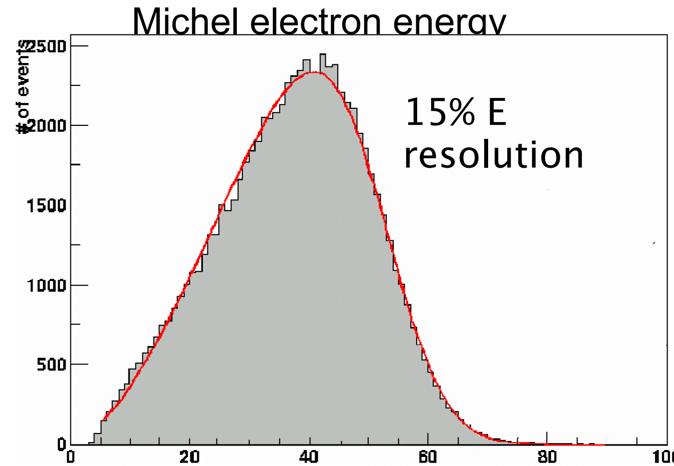
1. MC fine-tuning with neutrino data
   - neutrino cross section nuclear model parameters
   - π^0 rate constraint

2. constraining systematic errors with neutrino data
   - combined oscillation fit to high-statistics ν_μ data set and ν_e oscillation data set
   - example: ν_e from μ decay background



"I think you should be more explicit here in step two."

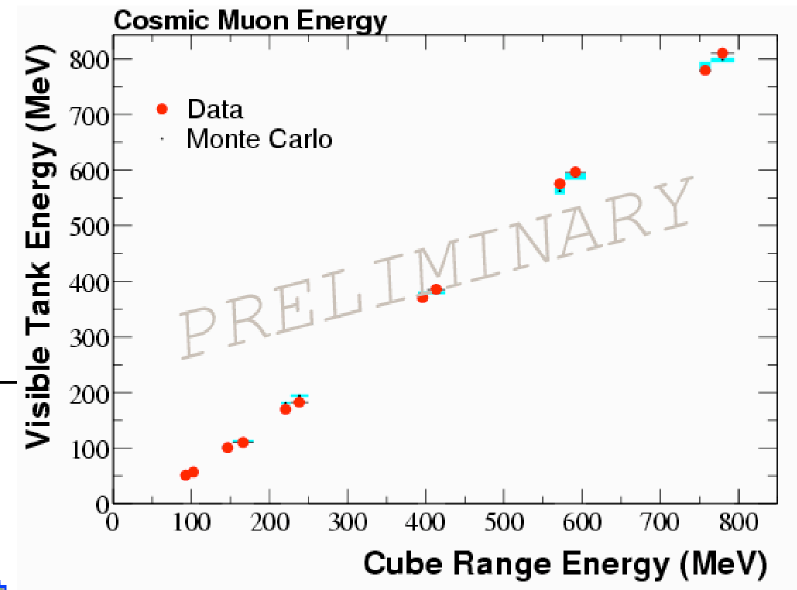
Oscillation Search: **Analysis Strategy**

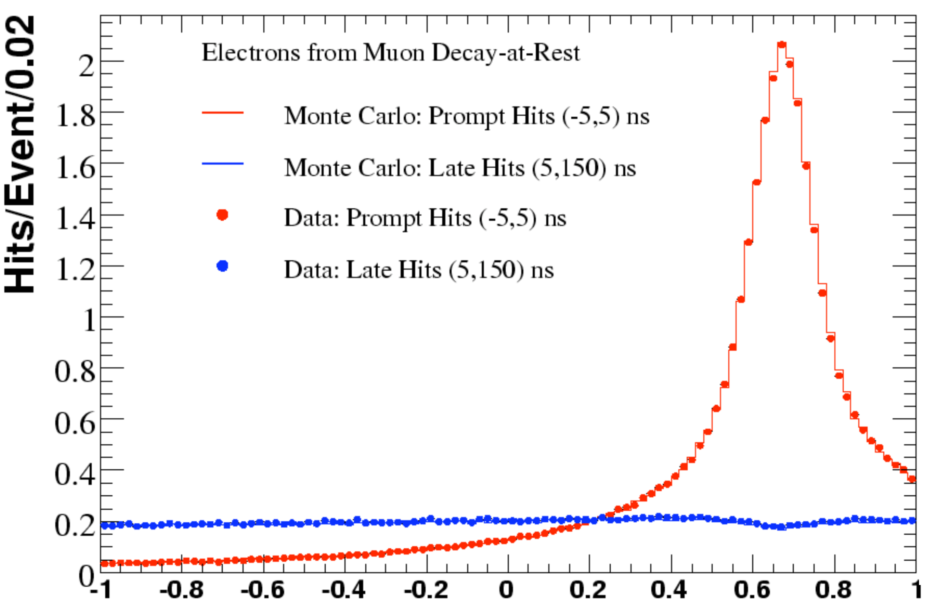


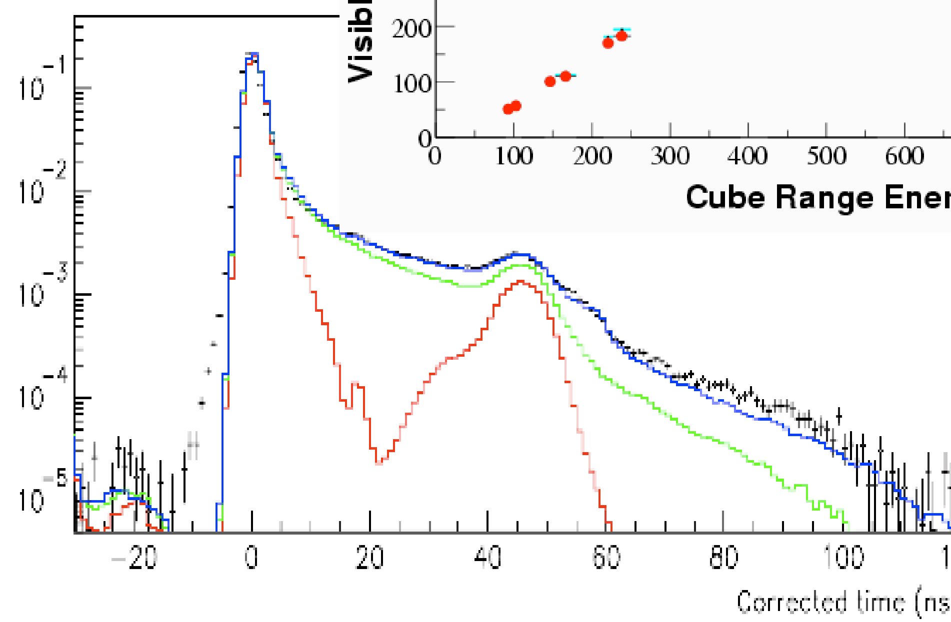
in-situ data is incorporated wherever possible...

0. MC tuning with calibration data

- energy scale
- energy extrapolation
- PMT response
- optical model of light propagation in the detector







Oscillation Search: **Analysis Strategy**

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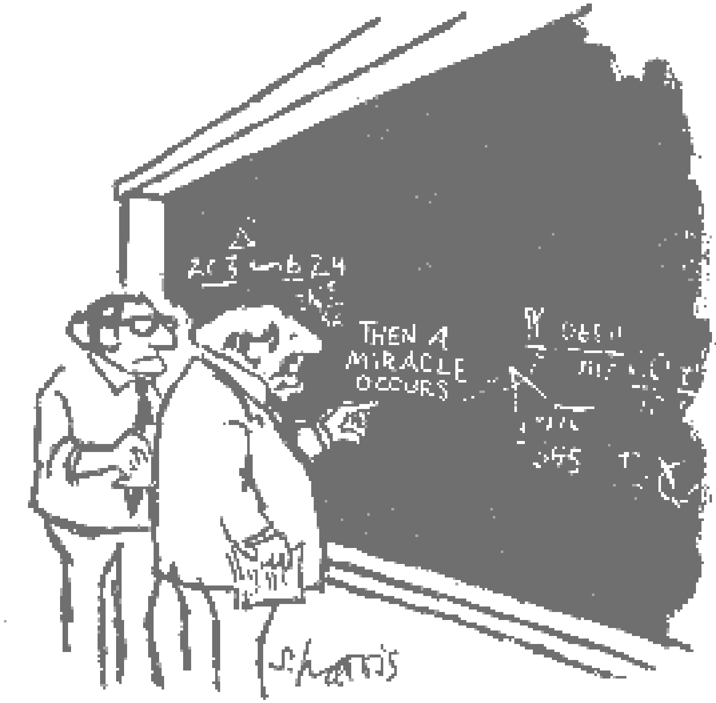


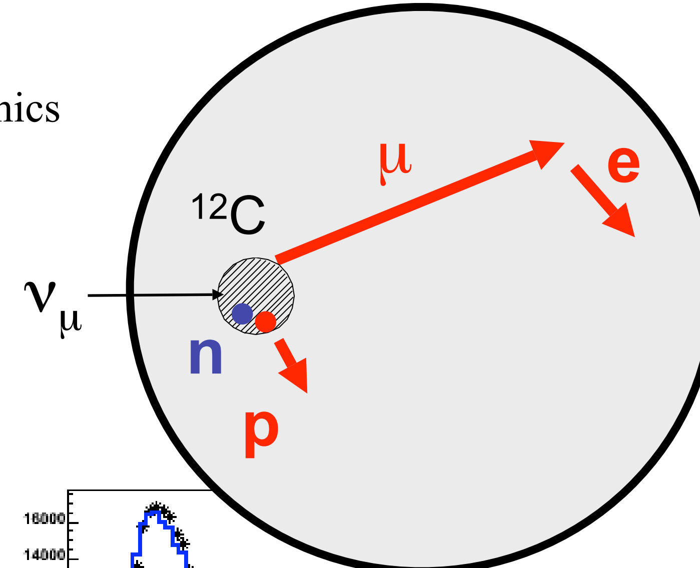
"I think you should be more explicit here in step two."

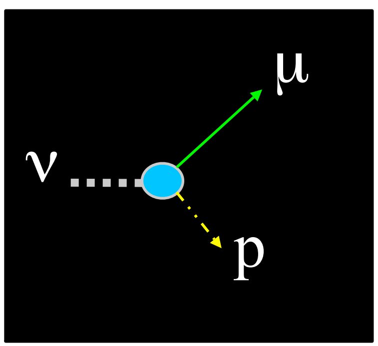
Incorporating ν_μ Data: ν_μ CCQE Event Selection

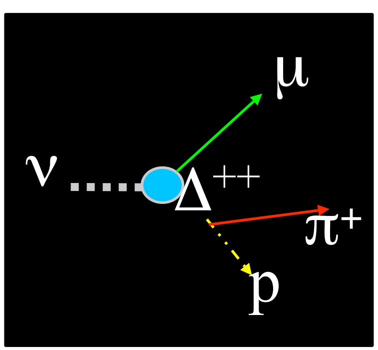
To find ν_μ CCQE final state:

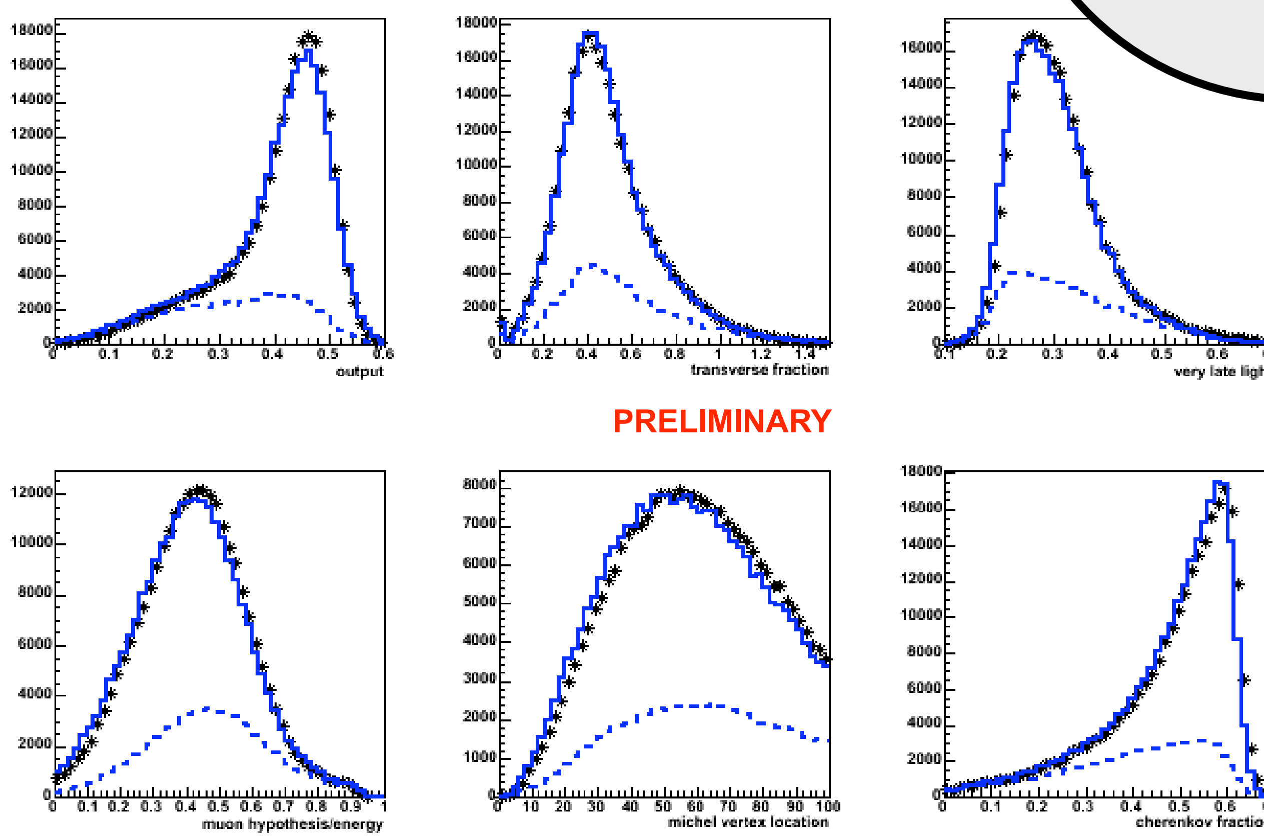
1. apply simple cuts on event time and number of hit PMTs to eliminate cosmics
2. tag muons by requiring 2 sub-events in time, with distance between < 1*m*
3. employ Fisher discriminant to get rid of CC1π background
   - "single muon final state hypothesis" for inputs (proton ~invisible)

     result: 91% CCQE purity, ~100k events







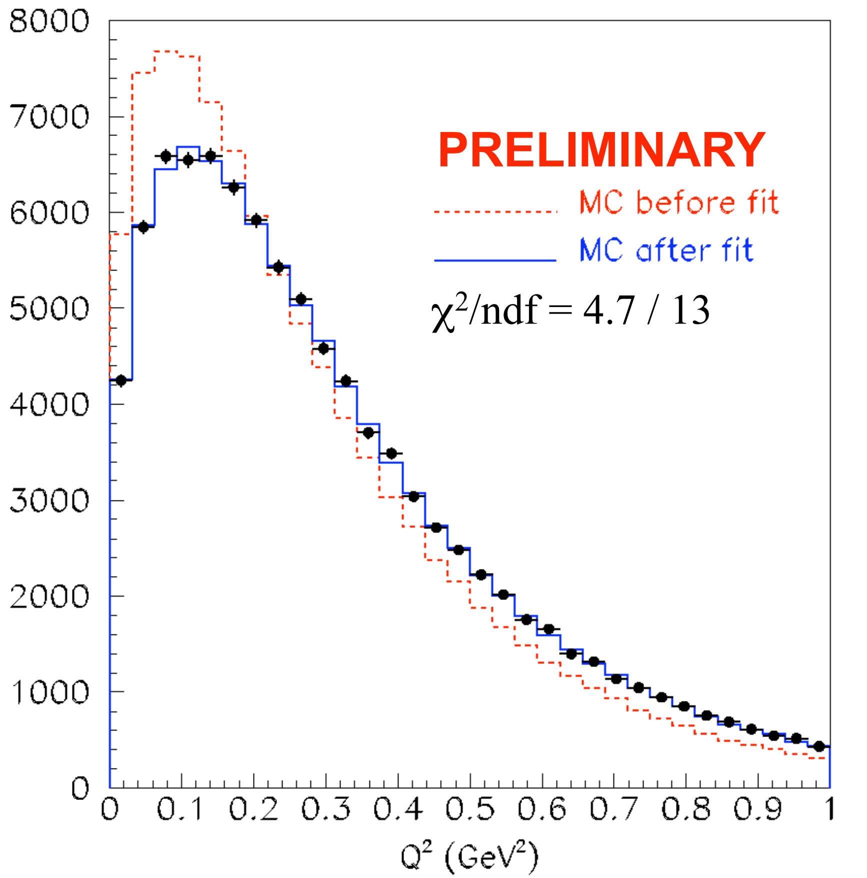


- Data
- ---- MC total
- \- - - MC bgnd

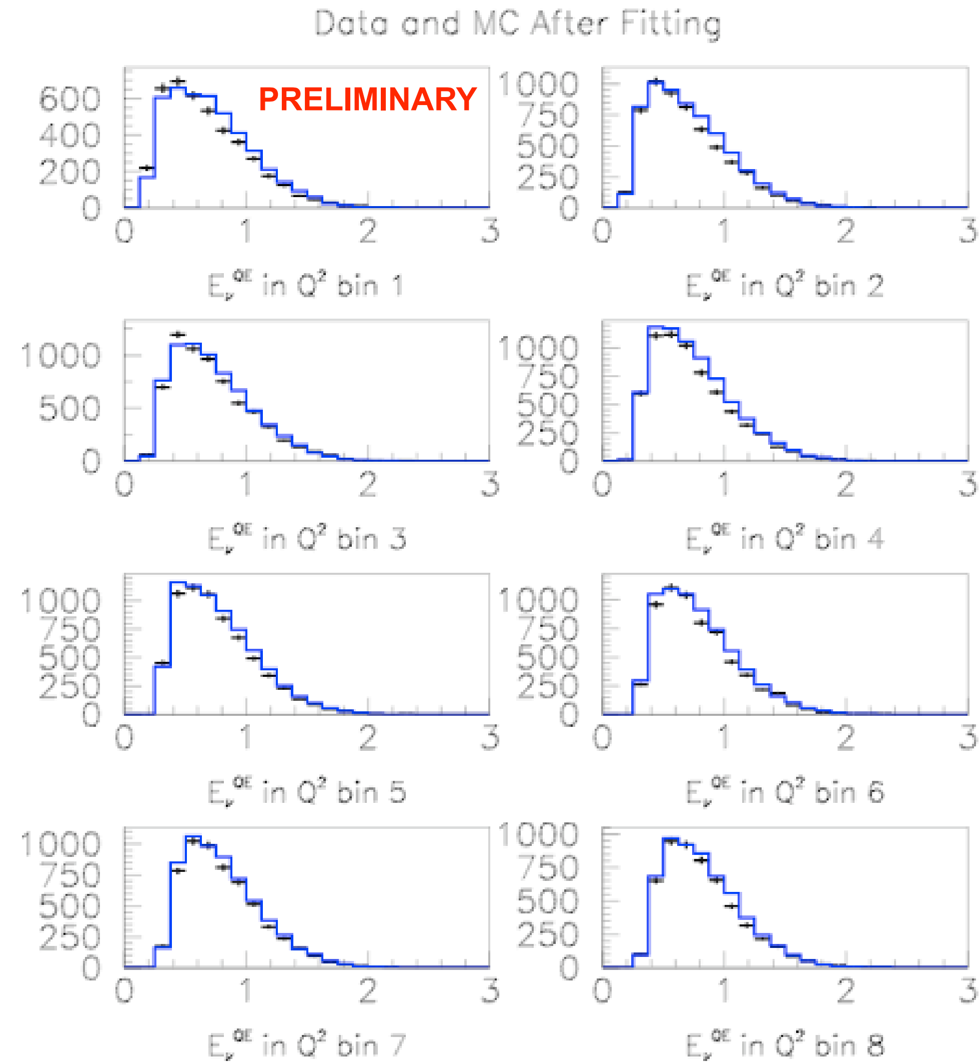
unit-area normalization

Incorporating ν_μ Data: CCQE Cross Section

The ν_μ CCQE data Q^2 distribution is fit to tune empirical parameters of the nuclear model (^{12}C target)

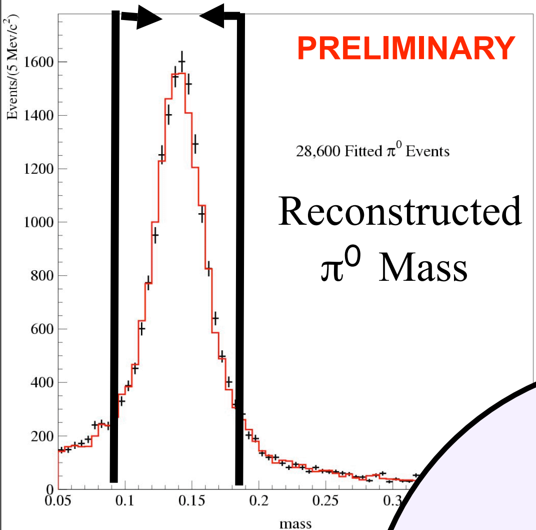


this results in good data-MC agreement for variables **not** used in tuning



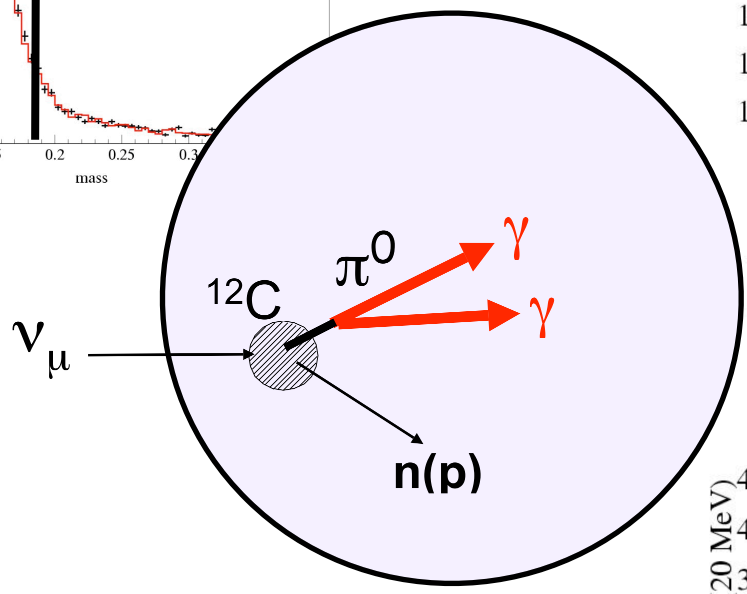
the tuned model is used for both ν_μ and ν_e CCQE, the only difference between these is lepton mass

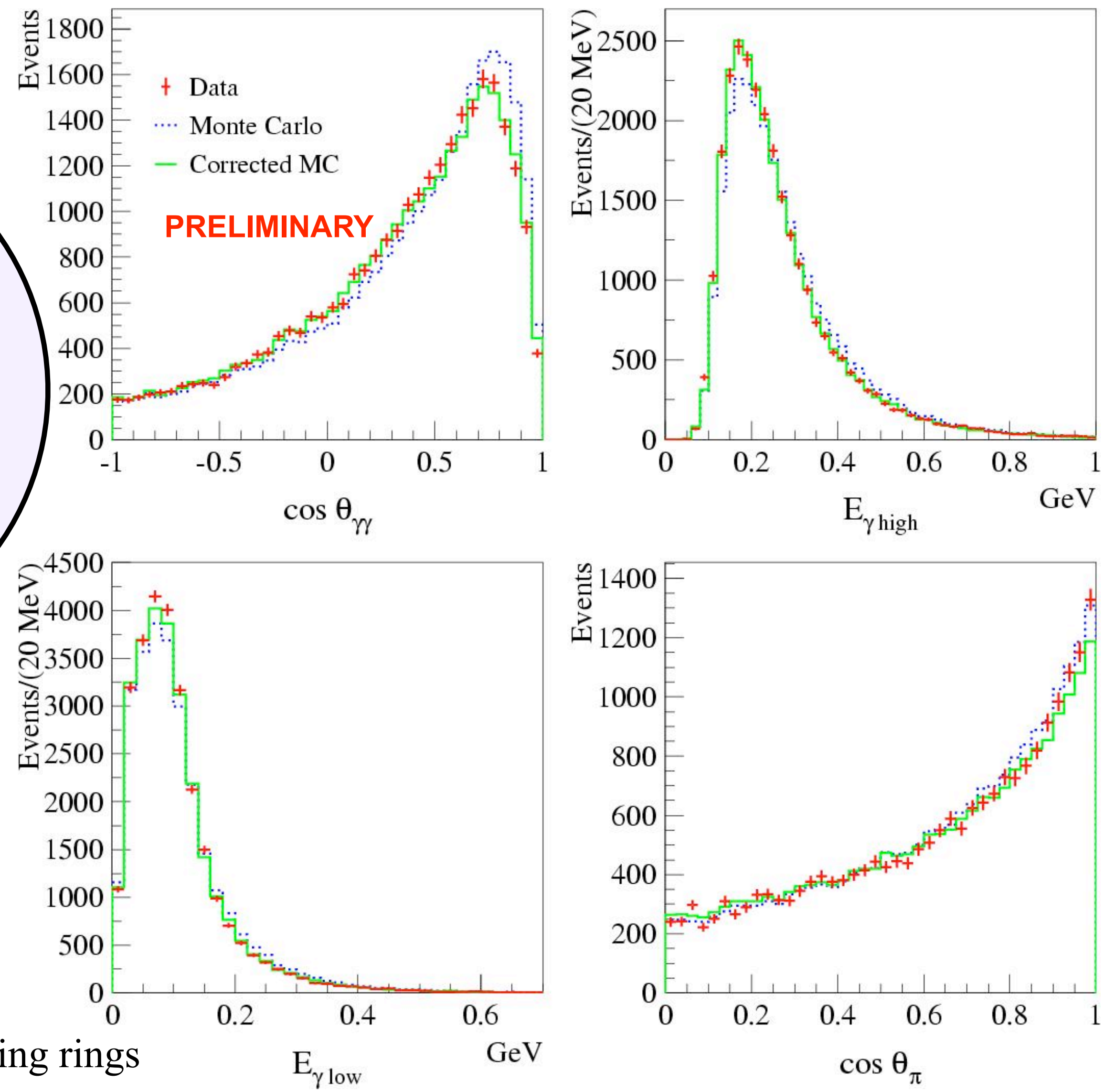
Incorporating ν_μ Data: π^0 Mis-ID Background



clean π^0 events are used to tune the MC rate vs. π^0 momentum

this results in good data-MC agreement for variables **not** used in tuning





π^0 events can reconstruct outside of the invariant mass peak when:

1. asymmetric decays fake 1 ring
2. 1 of the 2 photons exits the detector
3. high momentum π^o decays produce overlapping rings

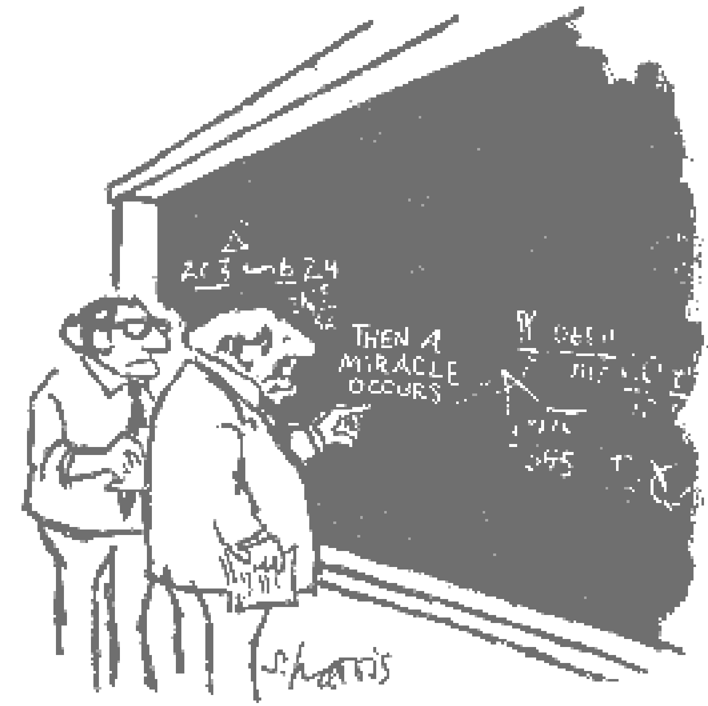
Oscillation Search: Analysis Strategy

in-situ data is incorporated wherever possible...

0. MC tuning with calibration data
   - energy scale
   - PMT response
   - optical model of light propagation in the detector

1. MC fine-tuning with neutrino data
   - neutrino cross section nuclear model parameters
   - π^0 rate constraint

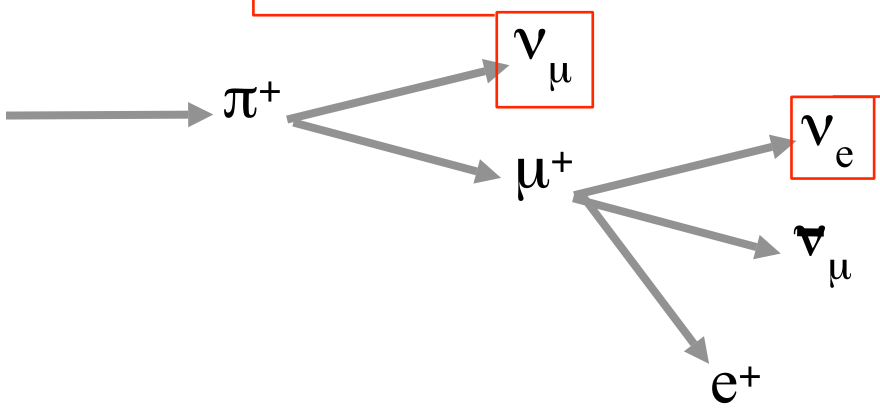
2. constraining systematic errors with neutrino data
   - combined oscillation fit to high-statistics ν_μ CCQE data set *and* ν_e oscillation data set
      - example: ν_e from μ decay background

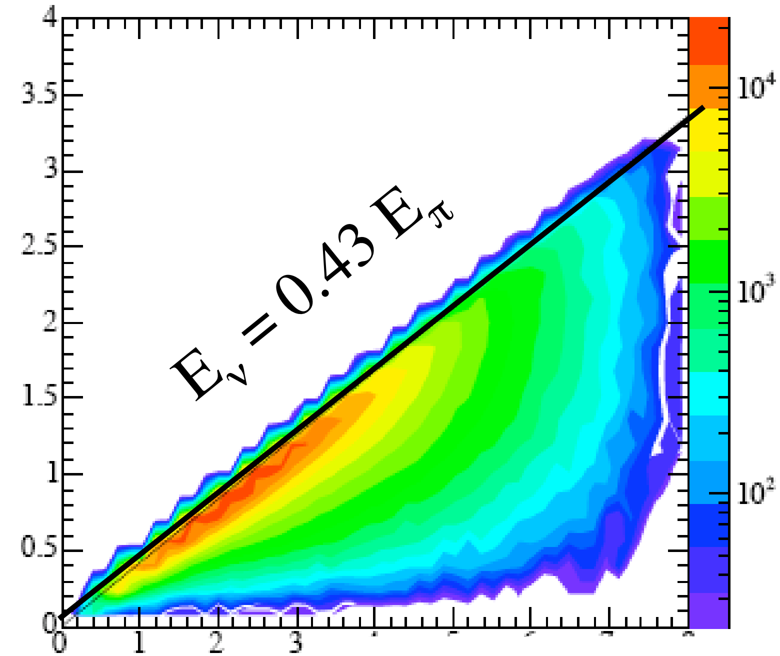


"I think you should be more explicit here in step two."

Incorporating ν_μ Data: μ^+-Decay ν_e Background

ν_μ CCQE events can infer the π^+ spectrum, which constrains μ^+-decay ν_e & π^+-decay ν_μ flux predictions





this works well because the ν_μ energy is highly correlated with the parent π^+ energy

how to implement μ^+-decay ν_e background constraint:

1. simulation based on external data predicts a central value and some range of possible $\nu_\mu(\pi)$ fluxes

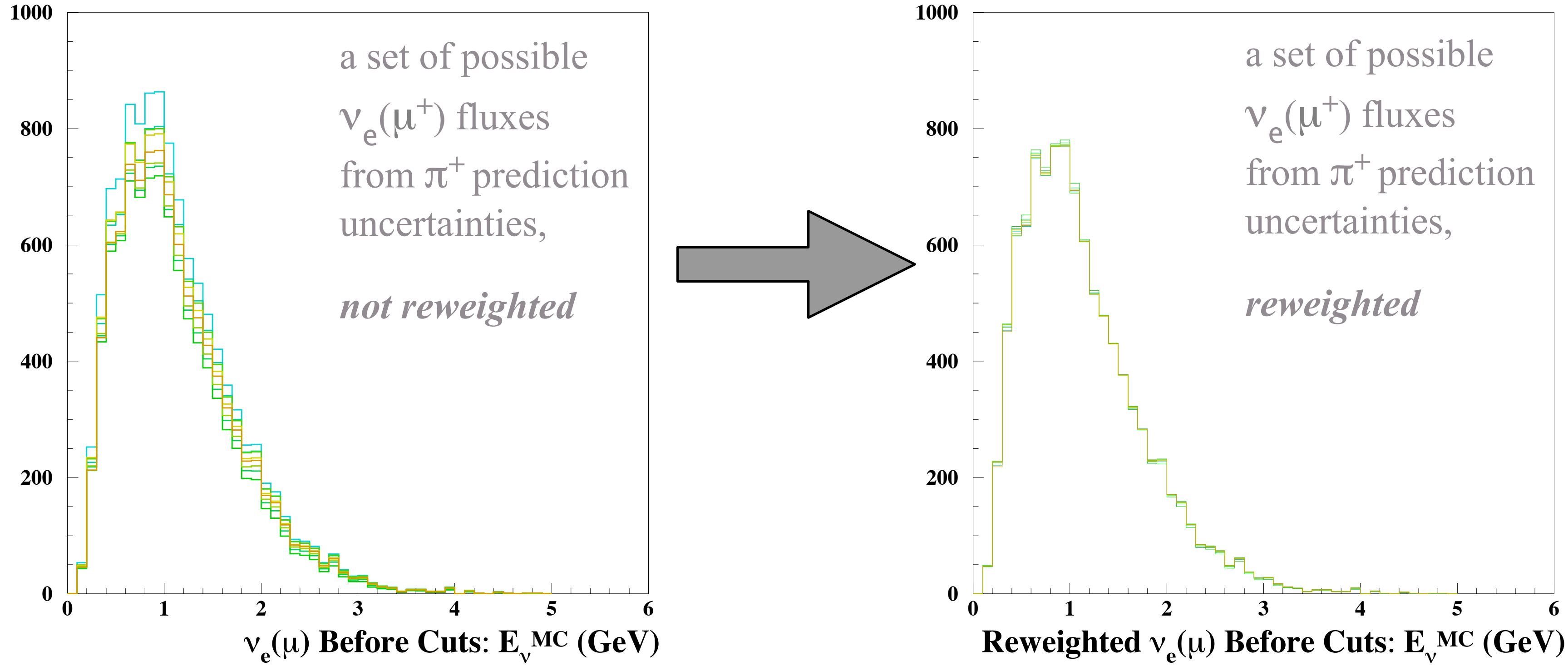
2. make Data/MC ratio vs. E_ν^{QE} for the ν_μCCQE data set,

3. reweight each possible MC flux by the ratio from (2) including the ν_μ, the parent π^+, the sister μ^+, and the niece ν_e

Incorporating ν_μ Data: μ^+-Decay ν_e Background

Impact of reweighting the simulation using "fake data" (MC):

$\nu_e(\mu^+)$:

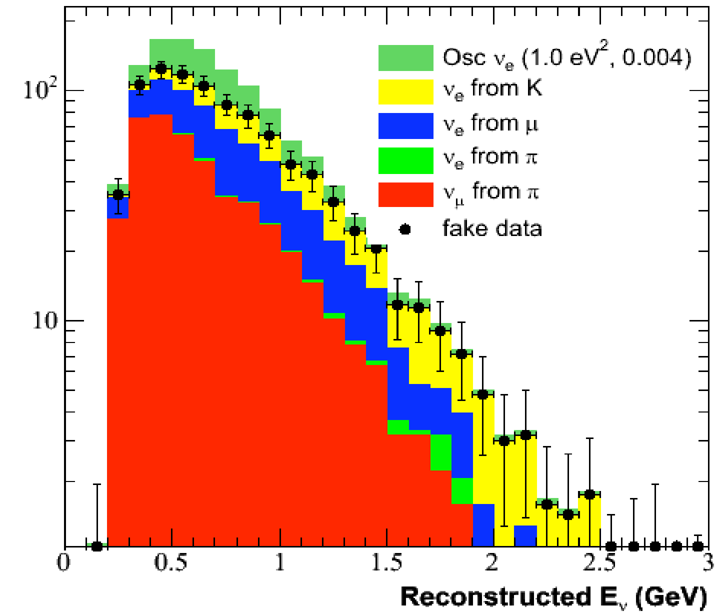


this reduction in the spread of possible fluxes translates directly into a reduction in the μ^+-decay ν_e background uncertainty

Incorporating ν_μ Data: Combined Fit Example

Fit the E_ν^{QE} distributions of ν_e and ν_μ events for oscillations, together

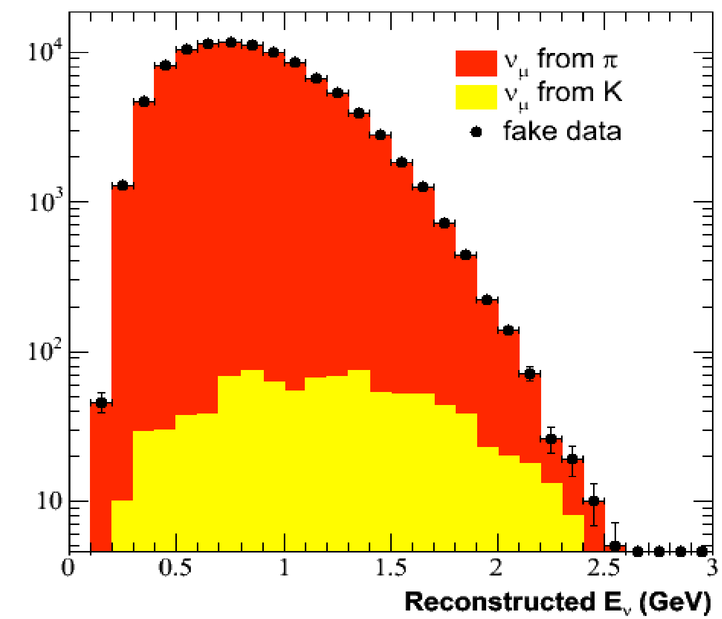
Raster scan in Δm^2 ,and and $sin^2 2\theta_{\mu e}$ ($sin^2 2\theta_{\mu x}$ == 0), calculate χ^2 value over ν_e **and** ν_μ bins



$$\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} (m_i - t_i)\ \mathcal{M}_{ij}^{-1}\ (m_j - t_j)$$

For this example, systematic error matrix $\boldsymbol{M_{ij}}$ includes predicted π^+ flux uncertainties only, for ν_e **and** ν_μ bins

$$\boldsymbol{M_{ij}} = \begin{pmatrix} \nu_\mu & \nu_\mu \nu_e \\ \nu_e \nu_\mu & \nu_e \end{pmatrix}$$



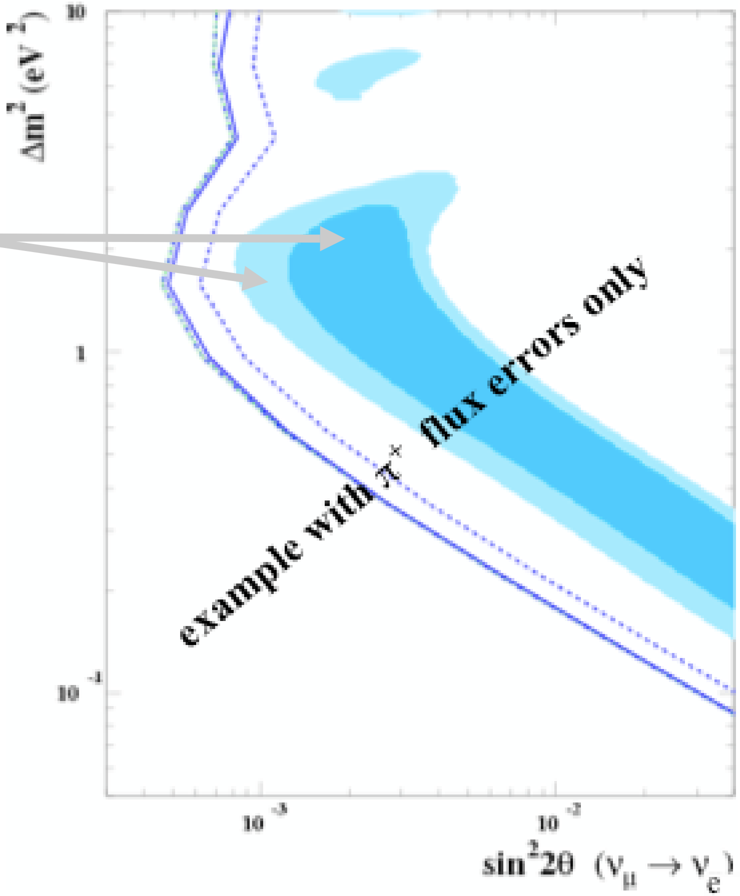
For this example, m_i = "fake data" = MC with no oscillation signal

combined fit constrains uncertainties common to ν_e and ν_μ

Incorporating ν_μ Data: Combined Fit Example

Example fit result for π^+ flux errors

90, 99% confidence level allowed regions from LSND



To calculate an oscillation sensitivity curve:

1. assume no signal in the data, therefore best-fit point is always at $sin^2 2\theta_{\mu e} = 0$ for all Δm^2 values (such that $m_i \cong t_i$)

2. calculate χ^2 for all (Δm^2, $sin^2 2\theta_{\mu e}$),

$$\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} (m_i - t_i)\, \mathcal{M}_{ij}^{-1}\, (m_j - t_j)$$

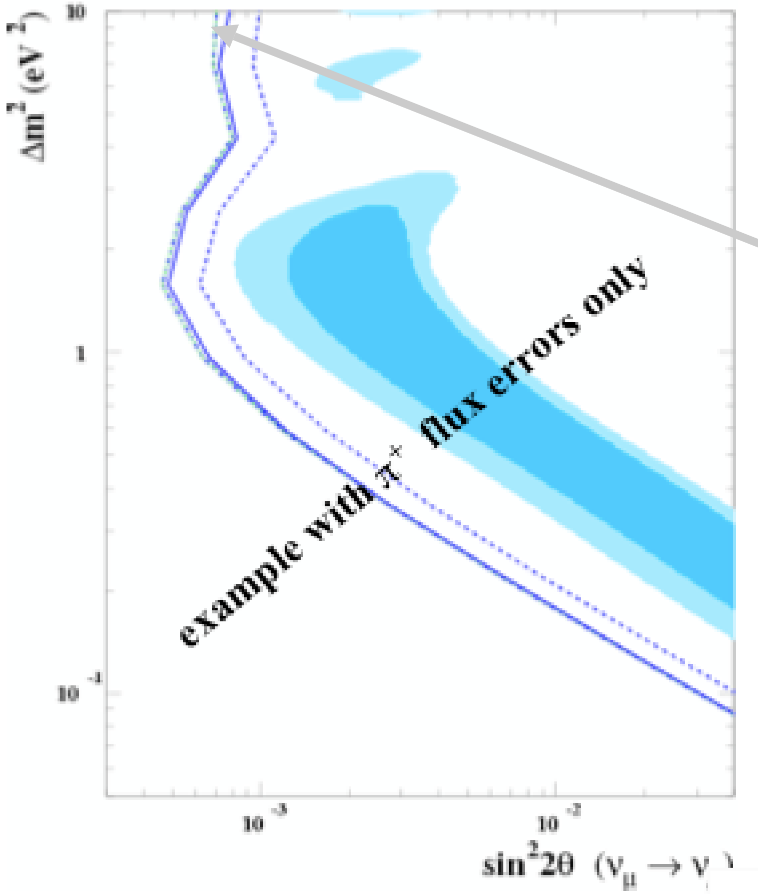
3. find $sin^2 2\theta_{\mu e}$ where $\Delta\chi^2 = \chi^2 - \chi_{min}^2 = 1$ for each Δm^2, systematic errors come in via $\Delta\chi^2$

these sensitivities are only examples to illustrate what the combined fit does

Incorporating ν_μ Data: **Combined Fit Example**

Example fit result for π^+ flux errors

90, 99% confidence level allowed regions from LSND



MiniBooNE 90% confidence level sensitivity limit with:

statistical errors only

these sensitivities are only examples to illustrate what the combined fit does

Incorporating ν_μ Data: **Combined Fit Example**

Example fit result for π^+ flux errors

90, 99%
confidence
level
allowed
regions
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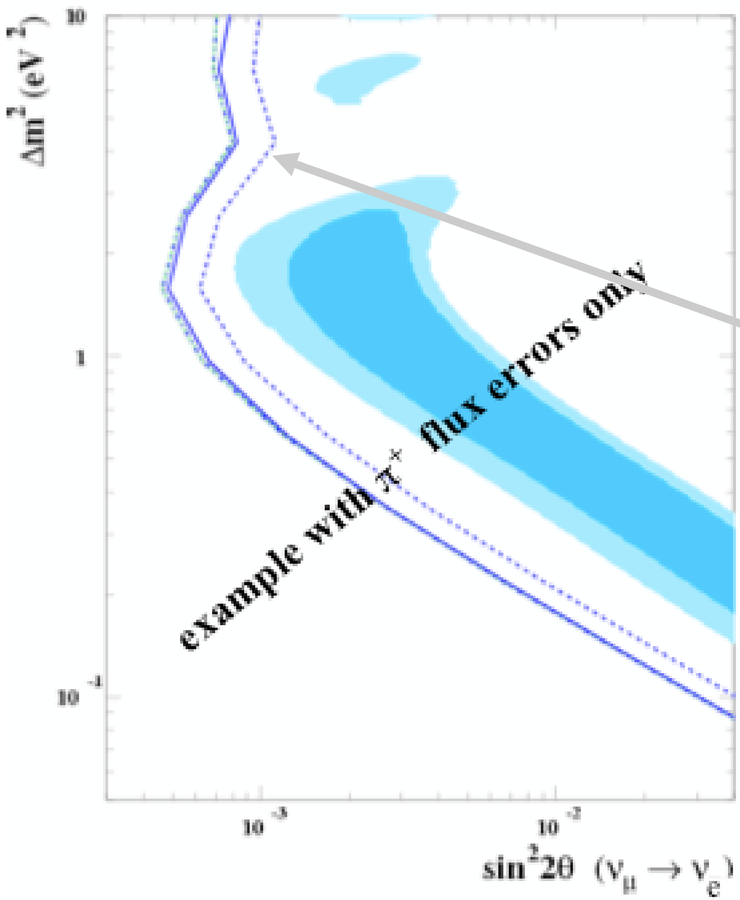


MiniBooNE
90% confidence
level sensitivity
limit with:

statistical errors only

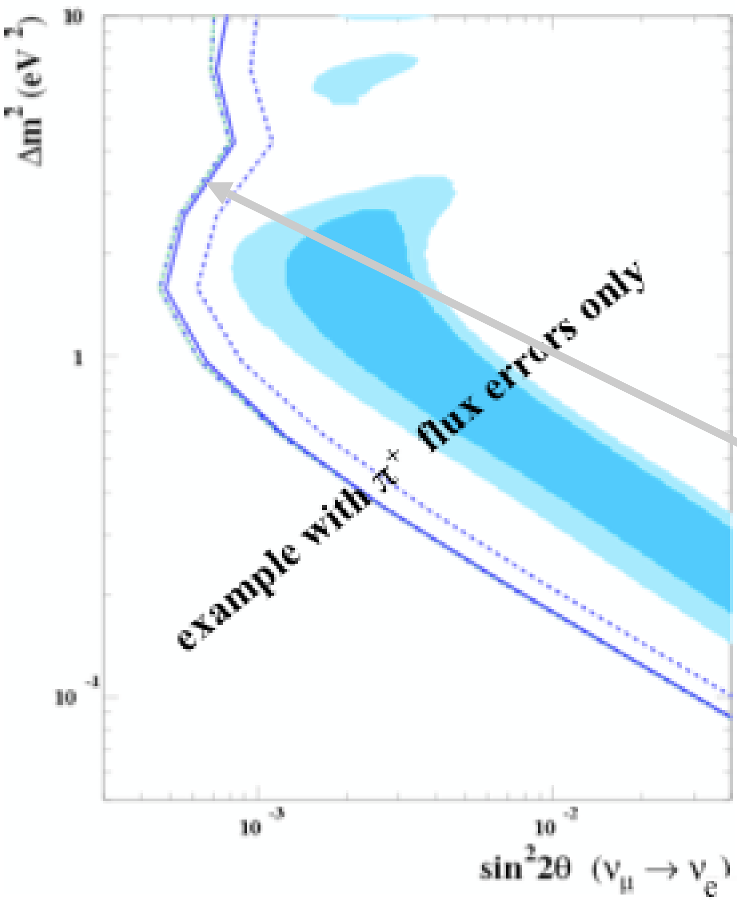
π^+ flux errors from prediction, ν_e fit only

these sensitivities are only examples to illustrate what the combined fit does

Incorporating ν_μ Data: Combined Fit Example

Example fit result for π^+ flux errors

90, 99% confidence level allowed regions from LSND



MiniBooNE 90% confidence level sensitivity limit with:

statistical errors only

π^+ flux errors from prediction, ν_e fit only

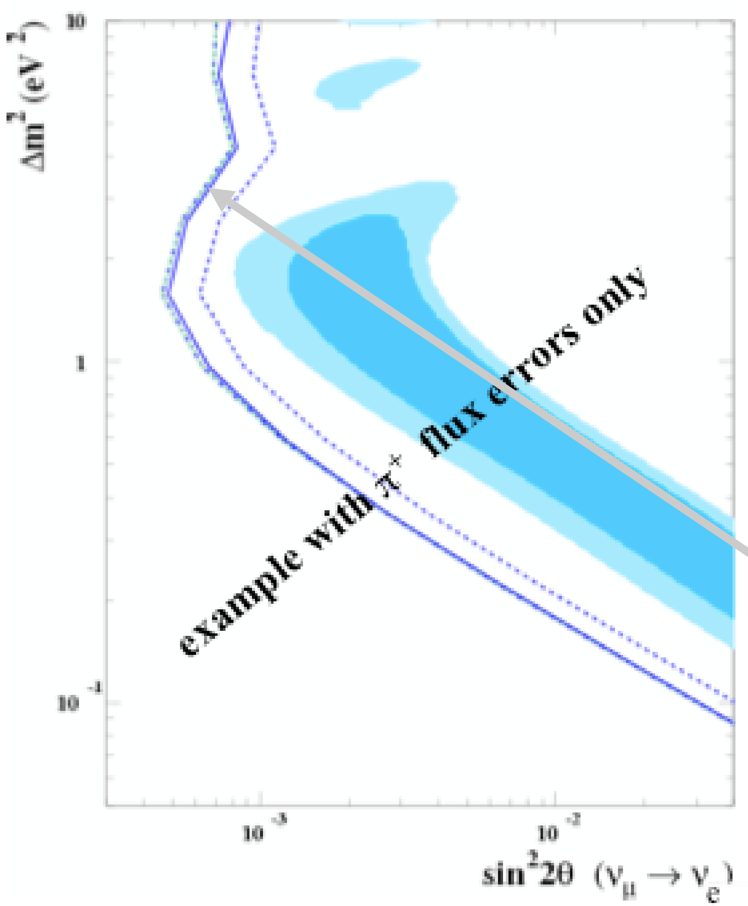
π^+ flux errors from reweighted prediction, ν_e fit only

these sensitivities are only examples to illustrate what the combined fit does

Incorporating ν_μ Data: Combined Fit Example

Example fit result for π^+ flux errors

90, 99% confidence level allowed regions from LSND



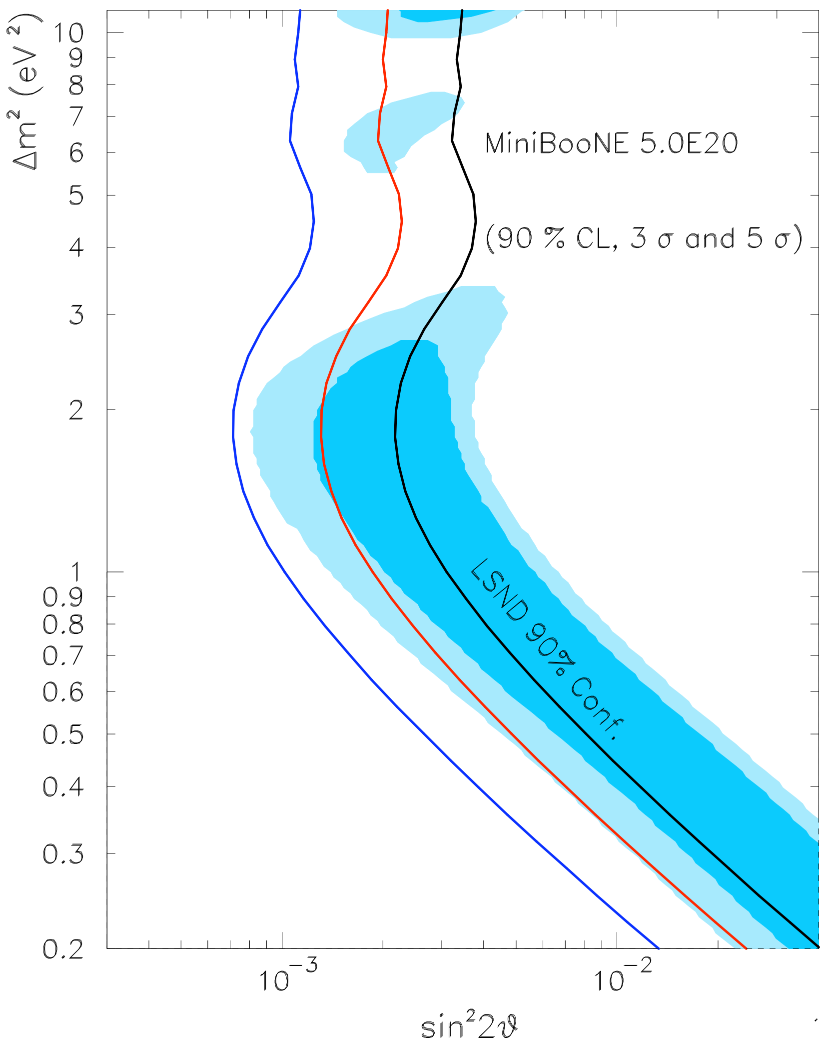
MiniBooNE 90% confidence level sensitivity limit with:

- statistical errors only
- π^+ flux errors from prediction, ν_e fit only
- π^+ flux errors from reweighted prediction, ν_e fit only
- π^+ flux errors from prediction, combined ν_e and ν_μ fit

these sensitivities are only examples to illustrate what the combined fit does

Oscillation Search: Summary and Outlook

Of course, there are many other sources of systematic error as well...



Summary of systematic error sources:

1. neutrino flux predictions
   - π^+, π^-, K^+, K^-, K^0, n, and p total and differential cross sections
   - secondary interactions
   - focusing horn current
   - target + horn system alignment

2. neutrino interaction cross section predictions
   - nuclear model
   - rates and kinematics for relevant exclusive processes
   - resonance width and branching fractions

3. detector modelling
   - optical model of light propagation in oil
   - PMT charge and time response
   - electronics response
   - neutrino interactions in dirt surrounding detector hall

MiniBooNE expected sensitivity covers LSND 90% C.L. allowed region at ~3σ

Oscillation Search: **Summary and Outlook**

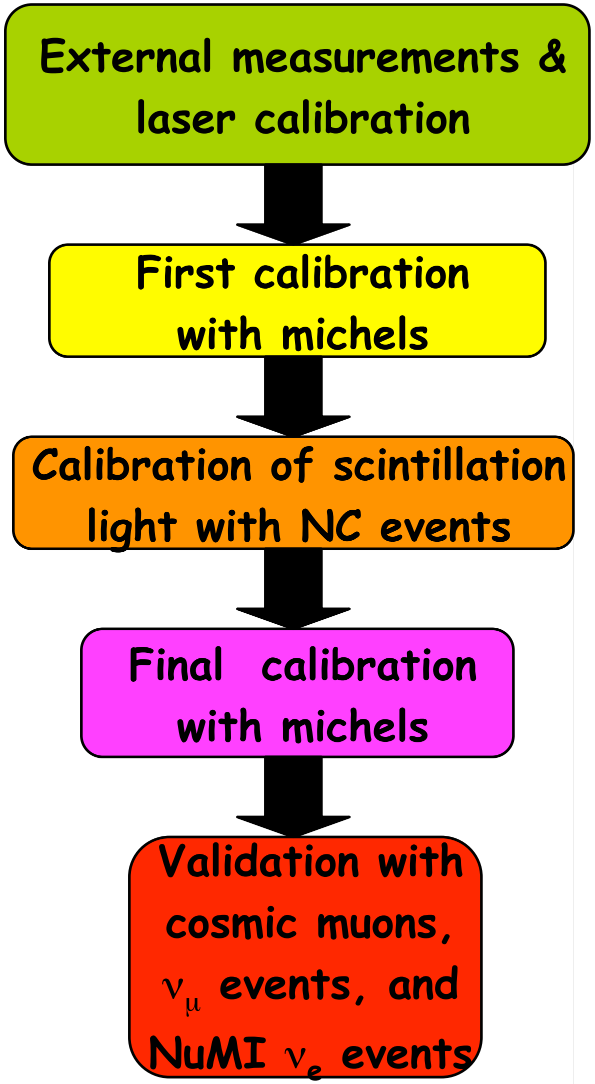
Incorporating the ν_μ data set provides a valuable constraint for the ν_e appearance oscillation search.

- uncertainty on ν_e from μ decay is highly constrained
- combined fit naturally incorporates ν_μ data constraint for all sources of systematic error
- can constrain and cross-check ~*all* of the ν_e and ν_μ backgrounds with in-situ data

MiniBooNE
is close to the finish line,
oscillation results soon!

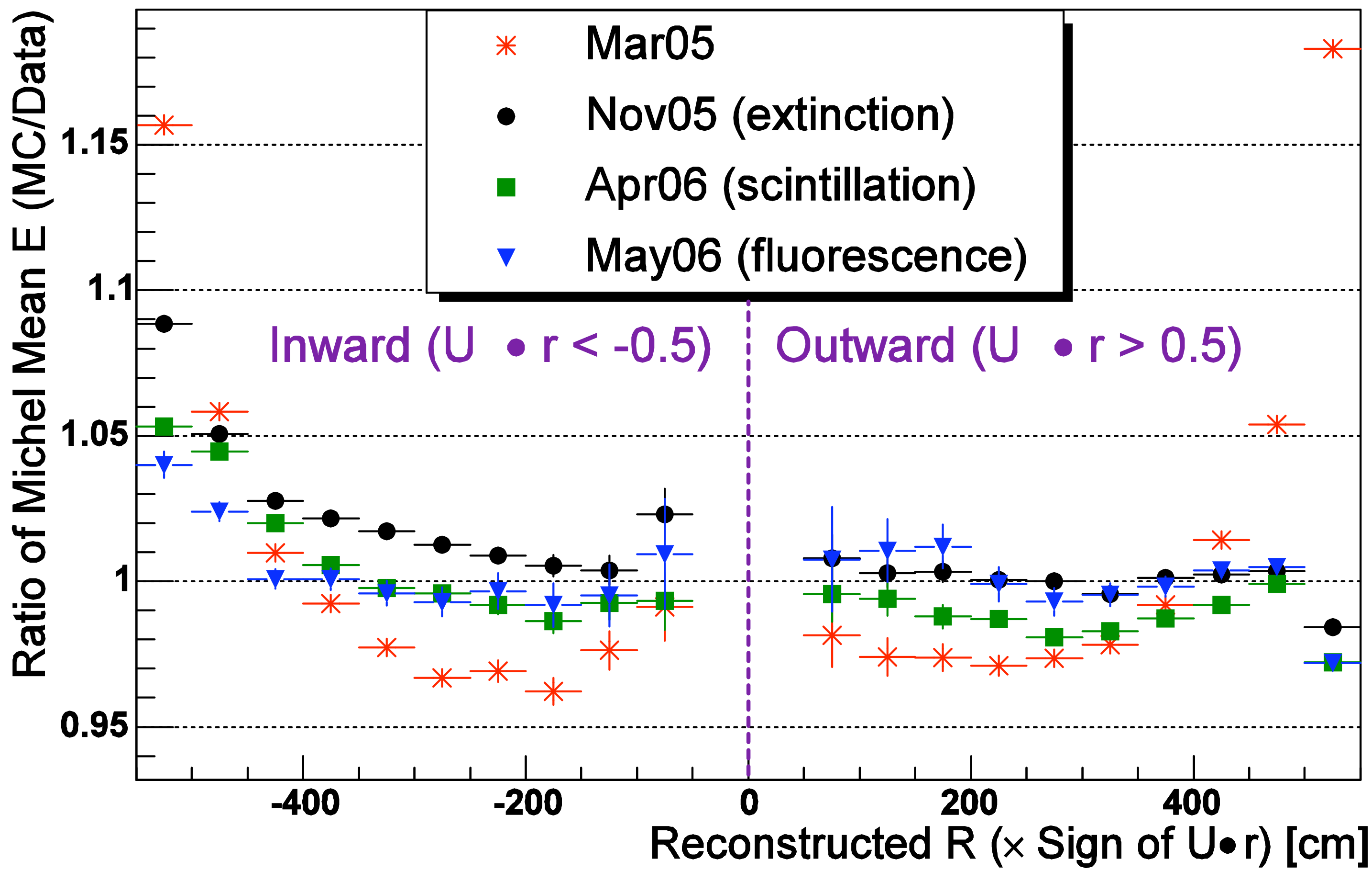
Other Slides

MiniBooNE Overview: Optical Model Tuning



The optical model describes light propagation in the detector:

- Cherenkov and scintillation emission
- scattering, flourescence, and extinction
- PMT detection efficiency

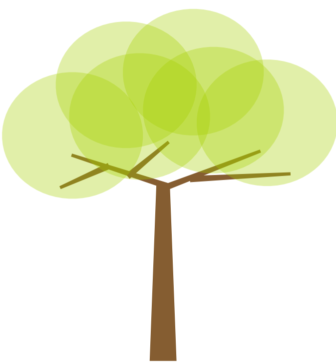


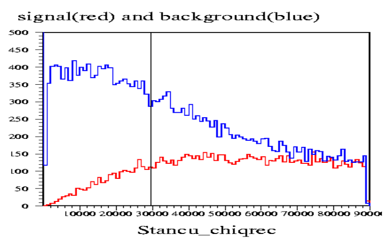
This is hard: need wavelength, angular, and time dependence + normalization for each process!

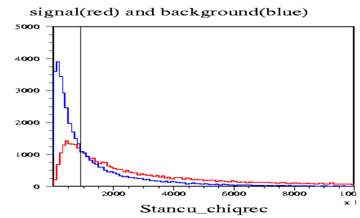
MiniBooNE Overview: **Boosting**

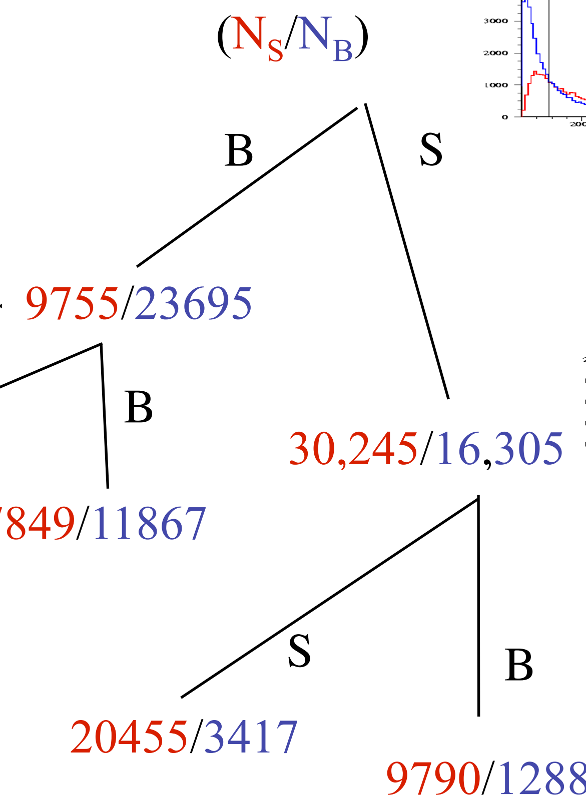
“A procedure that combines many weak classifiers to form a powerful committee”

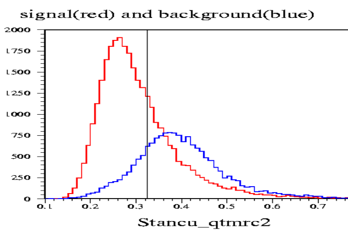
a decision tree that is forced to try harder on mis-classified events







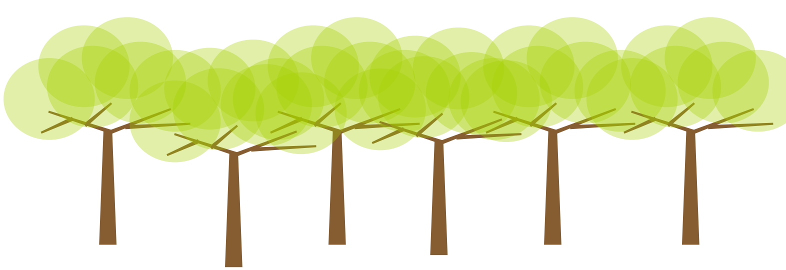




This tree is not unique!
A set of decision trees can be developed

Each data event is then sent through the full set of trees.
For each tree, the data event is assigned
+1 if it is identified as signal,
-1 if it is identified as background.

The total for all trees is then combined.
The resulting “score” for the event
can be thought of as a probability that it is signal.



H. Yang, B. Roe, J. Zhu, “Studies of Boosted Decision Trees for MiniBooNE Particle Identification”, Nucl.Instrum.Meth.A555; 370-385 (2005)
B. Roe et. al. “Boosted Decision Trees as an Alternative to Artificial Neural Networks for Particle Identification” Nucl.Instrum.Meth.A543; 577-584 (2005)