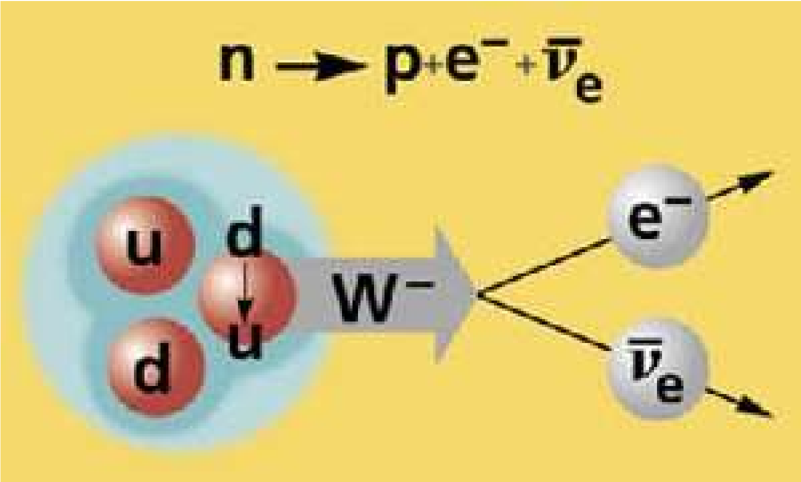
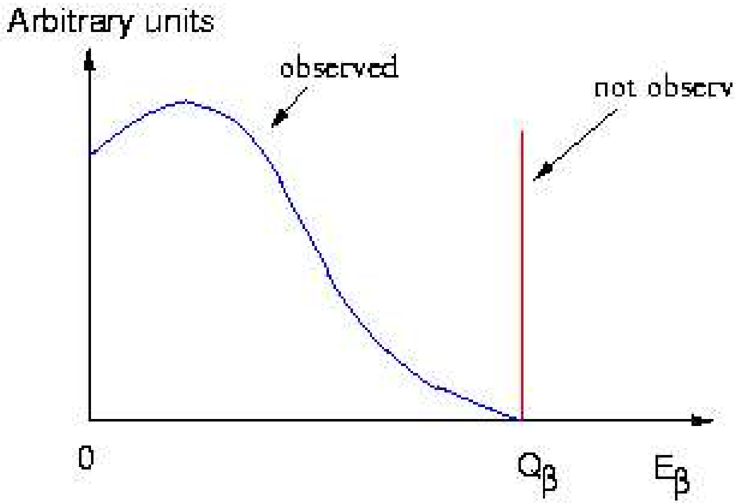
B. T. Fleming
SLAC Summer Institute
August 9th, 2007

MiniBooNE First Oscillation Results

The beginnings of the neutrino: Desperate Remedies



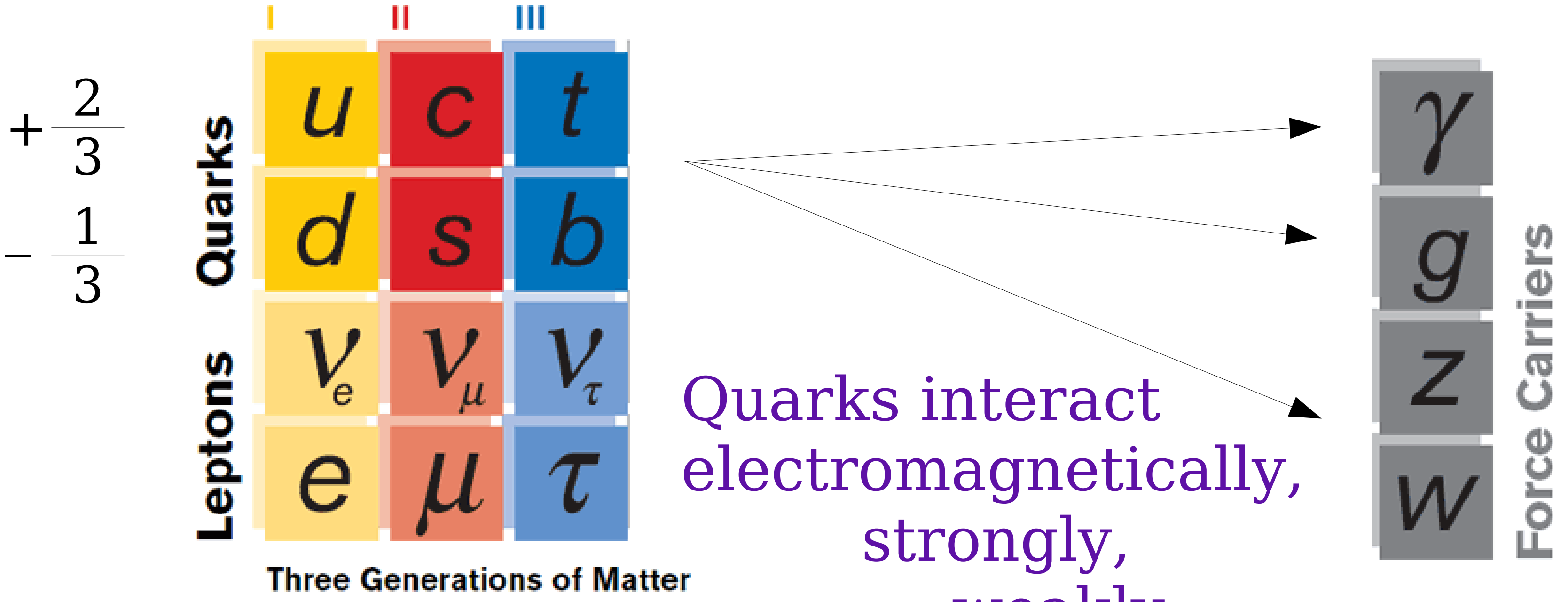


Bohr was ready
to abandon
Conservation of Energy
to explain this missing
energy phenomena until Pauli
proposed this
"desperate remedy":
the neutrino

1930: Pauli
“...I have predicted
something which
shall never be detected
experimentally!”

1956: Electron neutrino
detected
2007: Continually growing
field of neutrino physics!

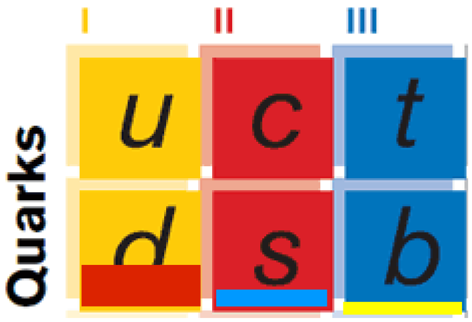
Neutrinos in the Standard Model



Quarks interact
electromagnetically,
strongly,
weakly

Quark masses range from ~1 MeV to 170 GeV

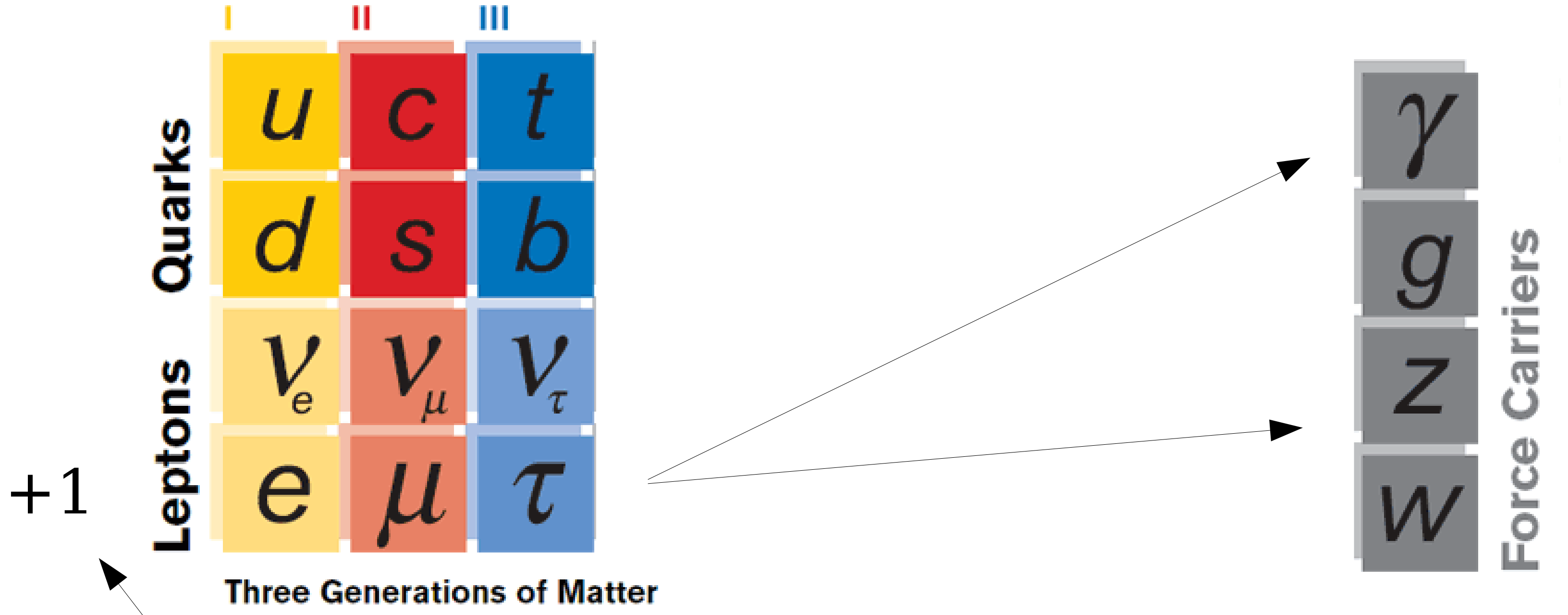
Quarks mix between their flavors



The CKM Matrix

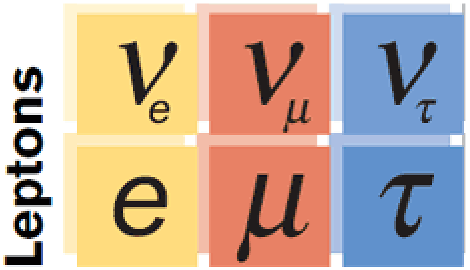
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Neutrinos in the Standard Model



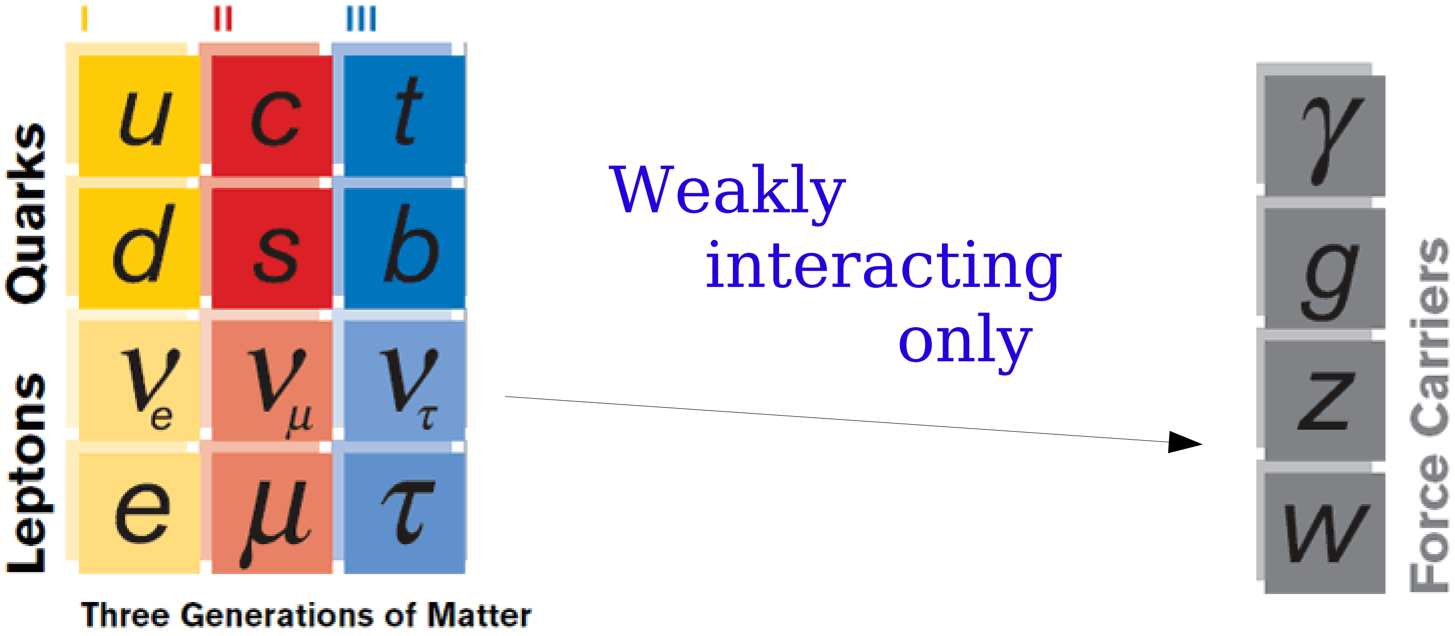
Charged leptons interact electromagnetically and weakly

Charged leptons range in mass from 0.5 MeV to 1.7 GeV



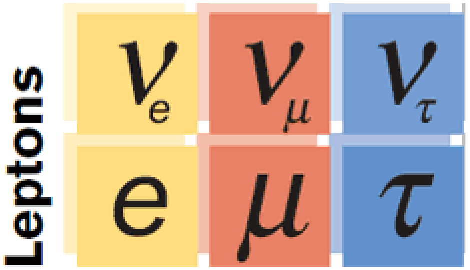
paired in doublets with neutrinos

Neutrinos in the Standard Model



Weakly
interacting
only

By comparison, we know relatively
little about the neutrinos....

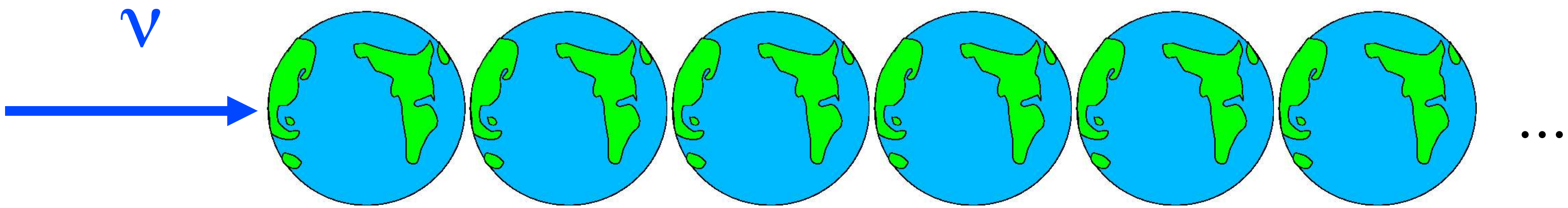


paired in doublets
with electrons
no charge
until recently....no mass?

Why have we known so little?

→ Took 26 years from Pauli just to see the neutrino

the weak force is weak!
neutrinos interact
100,000,000,000
times less often than quarks



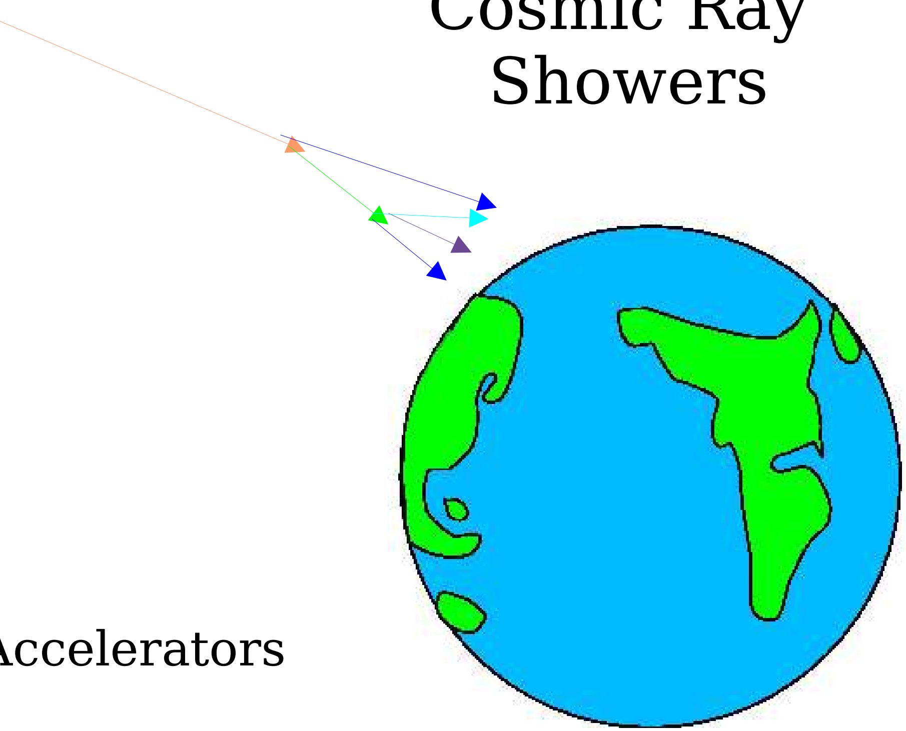
A neutrino has a good chance of traveling through
200 earths before interacting at all!

Fortunately, there are many sources of neutrinos from all over the universe!

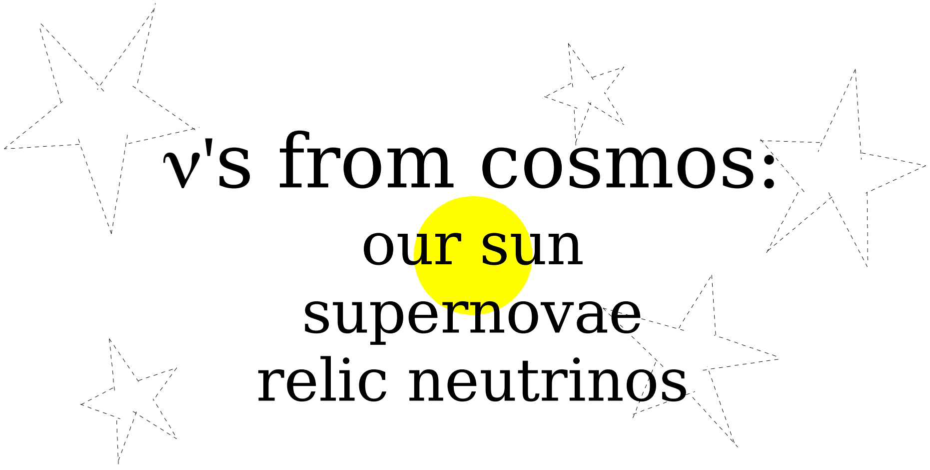
Unfortunately, they are so small, they don't make up much of the universe

created in particle decay:

Cosmic Ray Showers



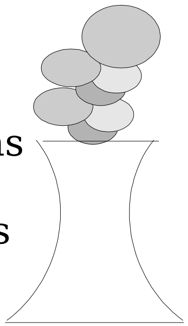
Neutrino Beams made from Particle Accelerators



ν's from cosmos:

our sun
supernovae
relic neutrinos

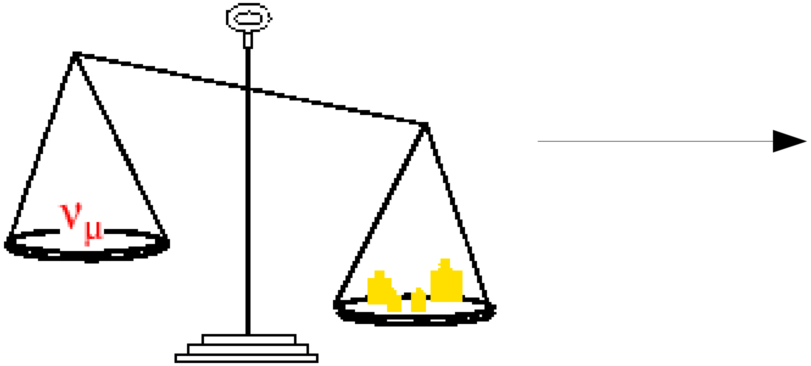
Neutrino Beams
made
from Reactors



Neutrino Mass:

Mass is a fundamental property of particles

Took many years to demonstrate neutrinos have mass
So small -> Can't measure mass in the usual way...



decay kinematics

What other behavior is associated with mass?
A quantum mechanical effect called
Neutrino Oscillations

$\nu_\mu \longrightarrow \nu_e$

Neutrino Oscillations indication of mass:

If we postulate:

- Neutrinos have (different) masses
- The Weak Eigenstate is a mixture of Mass Eigenstates:

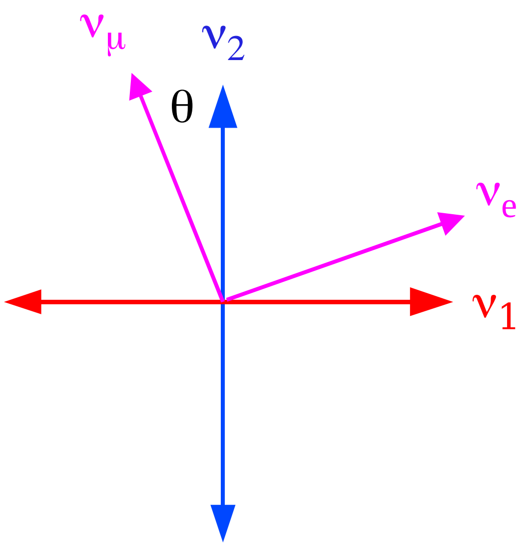
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

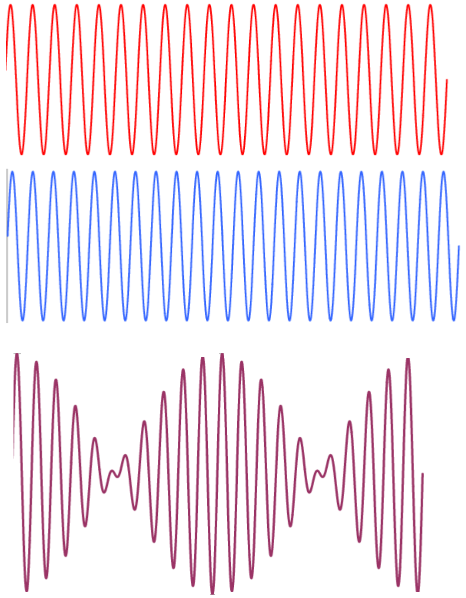
Then a pure ν_μ beam at $t = 0$,
may evolve a ν_e component with time!

The Probability for Oscillations...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

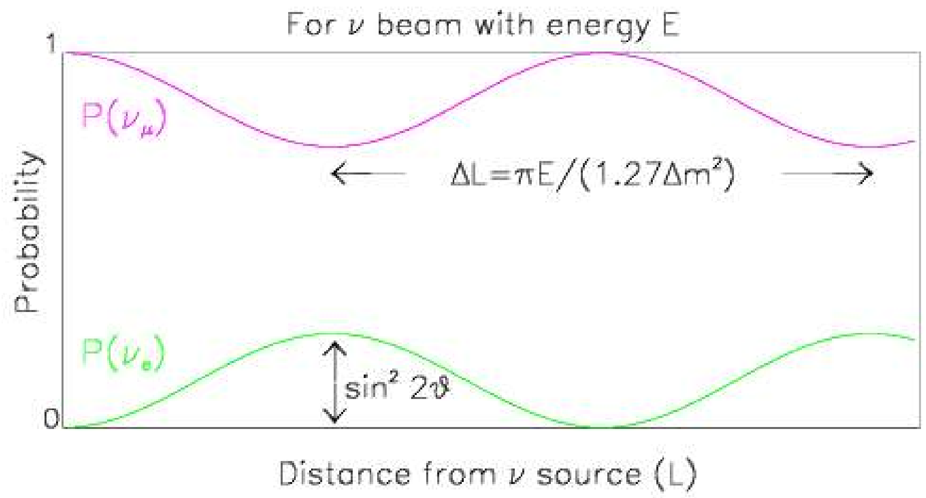
in 2 neutrino dimensions:





straighforward to extend to the 3 neutrino world...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

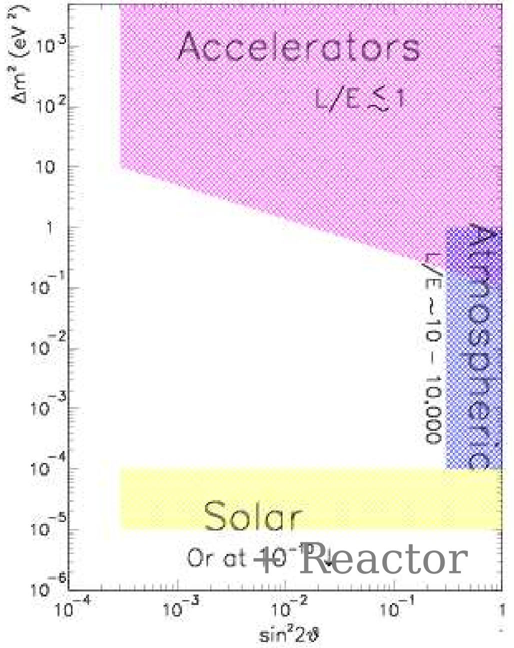


ν_μ disappearance

ν_e appearance

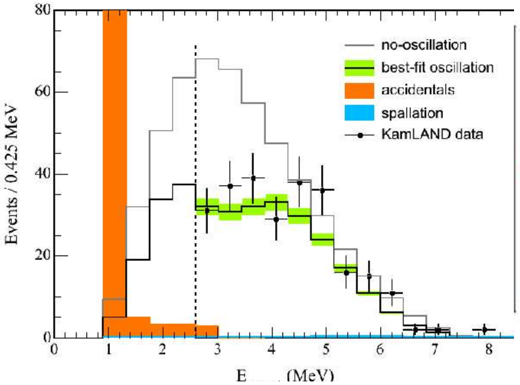
Oscillation Probability depends on:

- Two fundamental parameters
  - Δm^2
  - $\sin^2 2\theta$
- Two experimental parameters
  - L: distance from source to detector
  - E: Neutrino energy



Probe different oscillation parameters by changing L and E

Oscillation Landscape

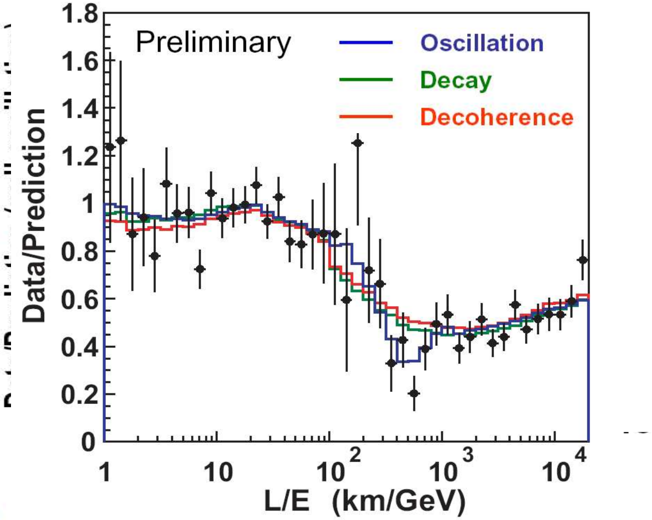


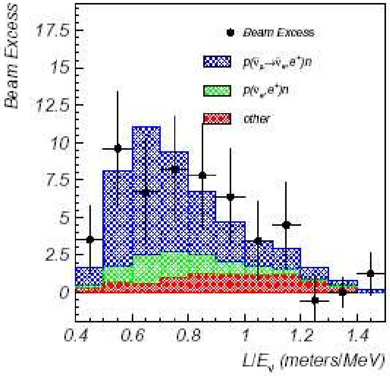
Solar Neutrino Oscillations

- Deficit of ν_e observed from Sun
  Cl (Homestake), H_2O ((Super-)K), Ga (GALLEX, SAGE)
- Confirmation at SNO and KamLAND (reactor $\overline{\nu}_e$)

Atmospheric Neutrino Oscillations

- Zenith angle-dependent deficit of ν_μ:
  Kamioka, Super-Kamiokande, Soudan, MACRO
- Confirmed by accelerator exp K2K; MINOS





LSND Neutrino Oscillations

- Excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam produced from μ^+ decay-at-rest
- Unconfirmed by other experiments, but not excluded

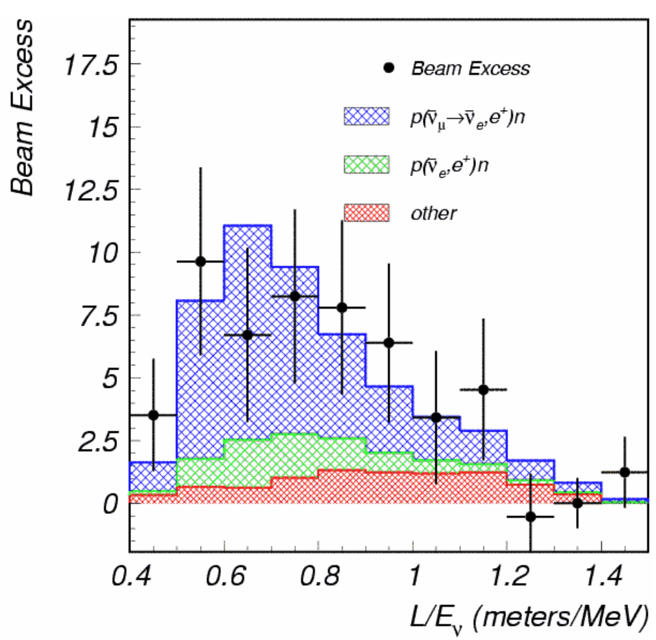
LSND anomaly:

an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam,

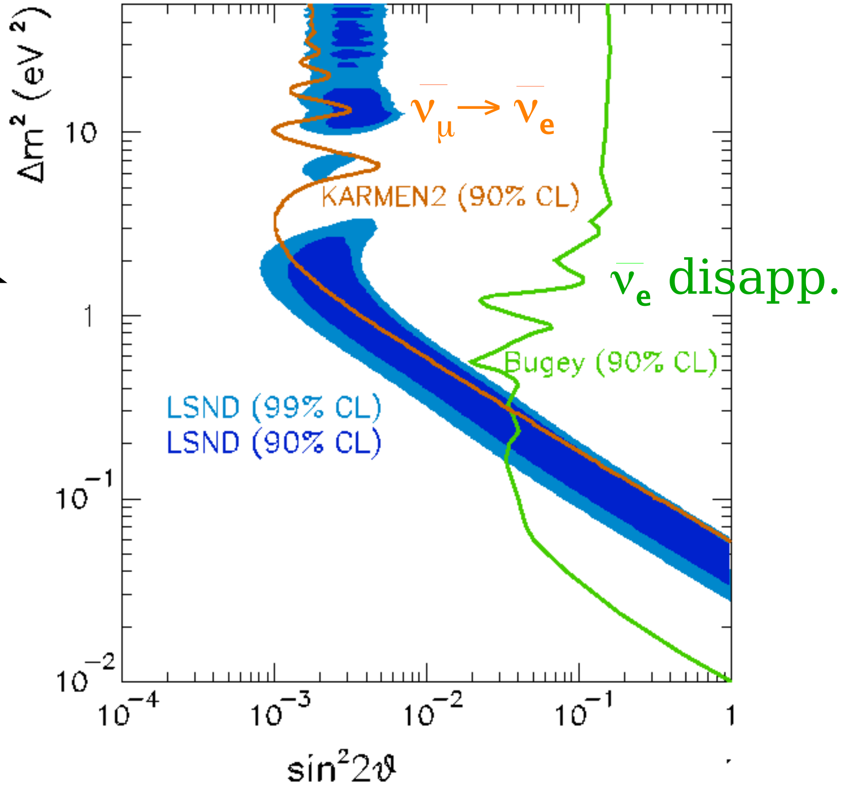
87.9 ± 22.4 ± 6.0 (3.8σ)

which can be interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:

LSND Collab, PRD 64, 112007

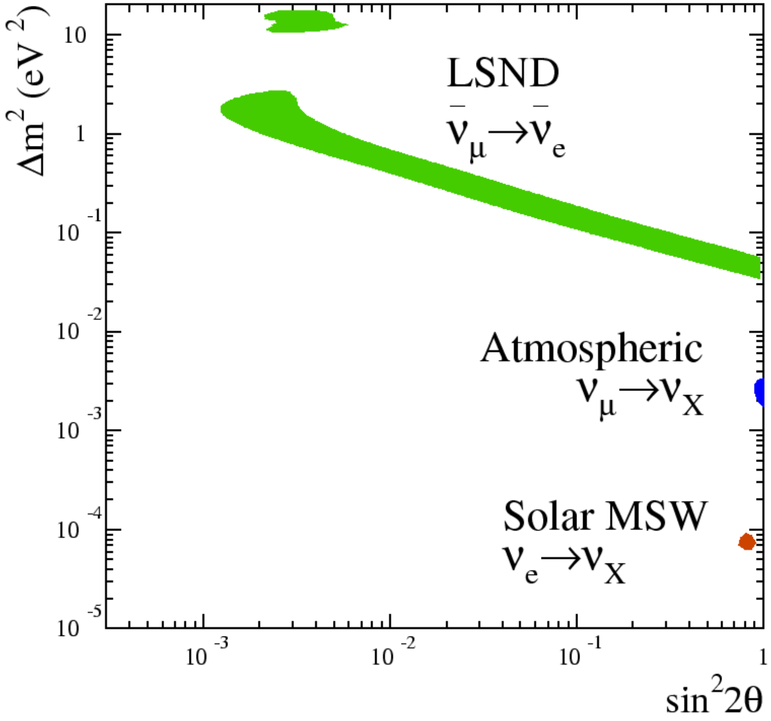


Points -- LSND data
Signal (blue)
Backgrounds (red, green)

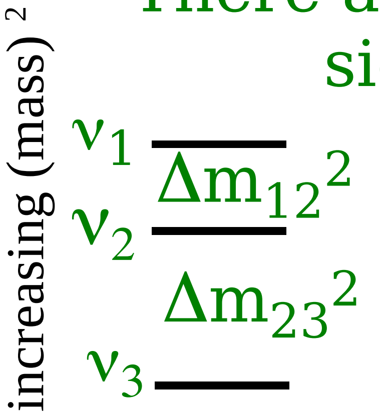


In a simple 3 neutrino picture:

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$



There are too many signals!



$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$

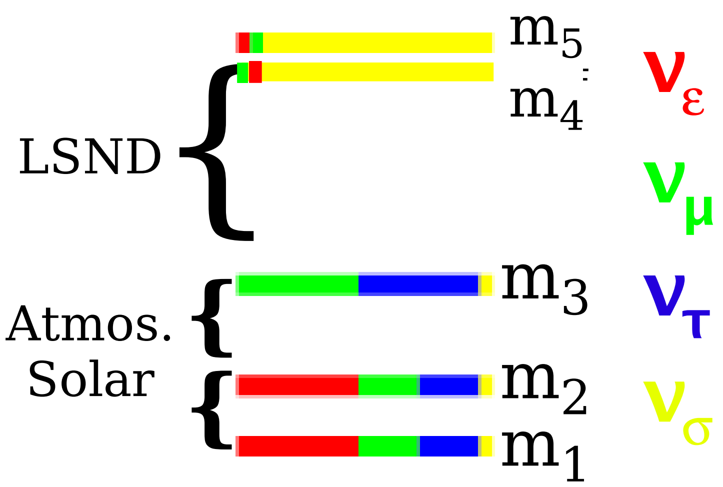
The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics

1) LSND is wrong?

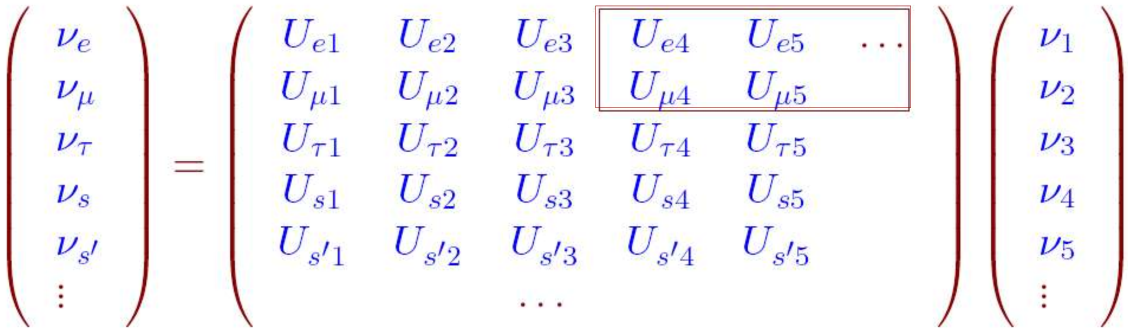
Too many signals...

2) There are sterile neutrinos
-possible....as crazy an idea as Pauli's *"desperate remedy"*

3+1 and 3+2 models



Then these are the main mixing matrix elements



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

4) Something else unexpected?
   a) Background that has not been predicted
   b) Other new physics: neutrinos in the bulk,
      neutrino decay....

MiniBooNE: address the LSND anomoly

→ look for ν_e appearance in a ν_μ beam at Fermilab

The MiniBooNE Collaboration

A. A. Aguilar-Arevalo, A. O. Bazarko, S. J. Brice, B. C. Brown, L. Bugel, J. Cao, L. Coney, J. M. Conrad, D. C. Cox, A. Curioni, Z. Djurcic, D. A. Finley, B. T. Fleming, R. Ford, F. G. Garcia, G. T. Garvey, J. A. Green, C. Green, T. L. Hart, E. Hawker, R. Imlay, R. A. Johnson, P. Kasper, T. Katori, T. Kobilarcik, I. Kourbanis, S. Koutsoliotas, J. M. Link, Y. Liu, Y. Liu, W. C. Louis, K. B. M. Mahn, W. Marsh, P. S. Martin, G. McGregor, W. Metcalf, P. D. Meyers, F. Mills, G. B. Mills, J. Monroe, C. D. Moore, R. H. Nelson, P. Nienaber, S. Ouedraogo, R. B. Patterson, D. Perevalov, C. C. Polly, E. Prebys, J. L. Raaf, H. Ray, B. P. Roe, A. D. Russell, V. Sandberg, R. Schirato, D. Schmitz, M. H. Shaevitz, F. C. Shoemaker, D. Smith, M. Sorel, P. Spentzouris, I. Stancu, R. J. Stefanski, M. Sung, H. A. Tanaka, R. Tayloe, M. Tzanov, M. O. Wascko, R. Van de Water, D. H. White, M. J. Wilking, H. J. Yang, G. P. Zeller, E. D. Zimmerman

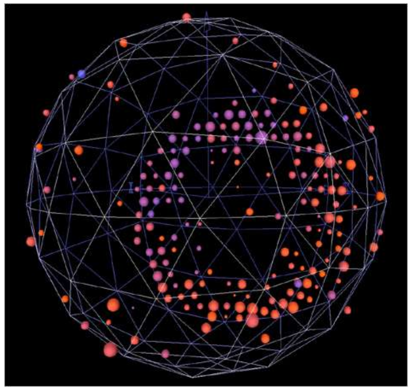
University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
Fermi National Accelerator Laboratory
Indiana University

Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary’s University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

The New York Times

April 12, 2007

How Did the Universe Survive the Big Bang? In This Experiment, Clues Remain Elusive



Pauli Predicts the Neutrino

Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrinos

Davis discovers the solar deficit

2 distinct flavors identified

Kamioka II confirms solar deficit

LEP shows 3 active flavors

SAGE and Gallex see the solar deficit

Kamioka II and IMB see atmospheric neutrino anomaly

Kamioka II and IMB see supernova neutrinos

Nobel prize for discovery of distinct flavors!

LSND sees possible indication of oscillation signal

Nobel Prize for $\overline{\nu}$ discovery!

Super K sees evidence of atmospheric neutrino oscillations

Super K confirms solar deficit and "images" sun

SNO shows solar oscillation to active flavor

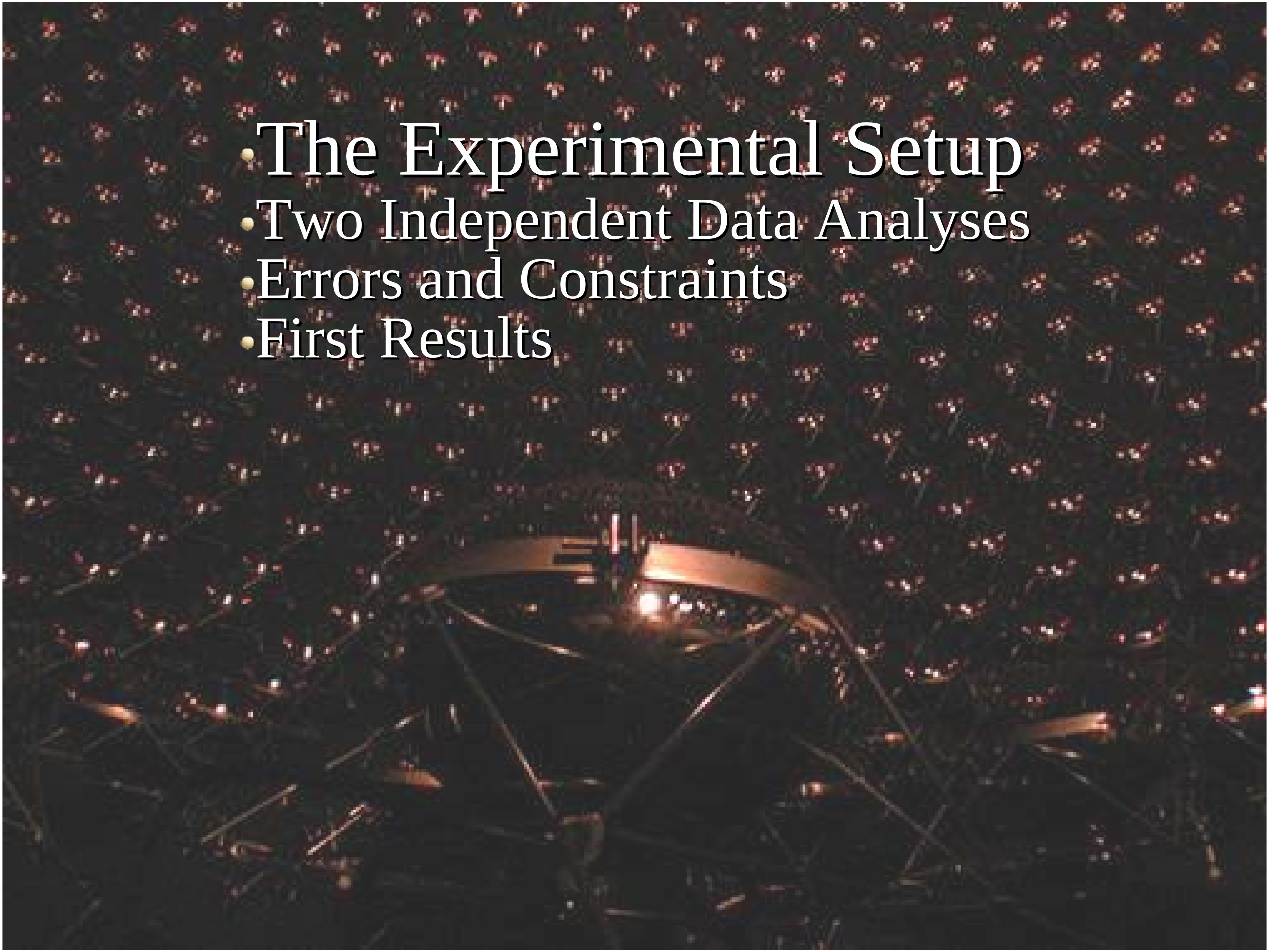
Nobel Prize for neutrino astroparticle physics!

KamLAND confirms solar oscillations

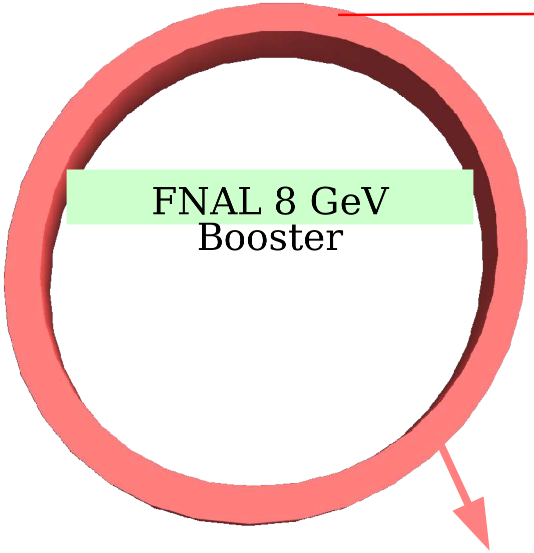
K2K confirms atmospheric oscillations

1930 1955 1980 2005 2007

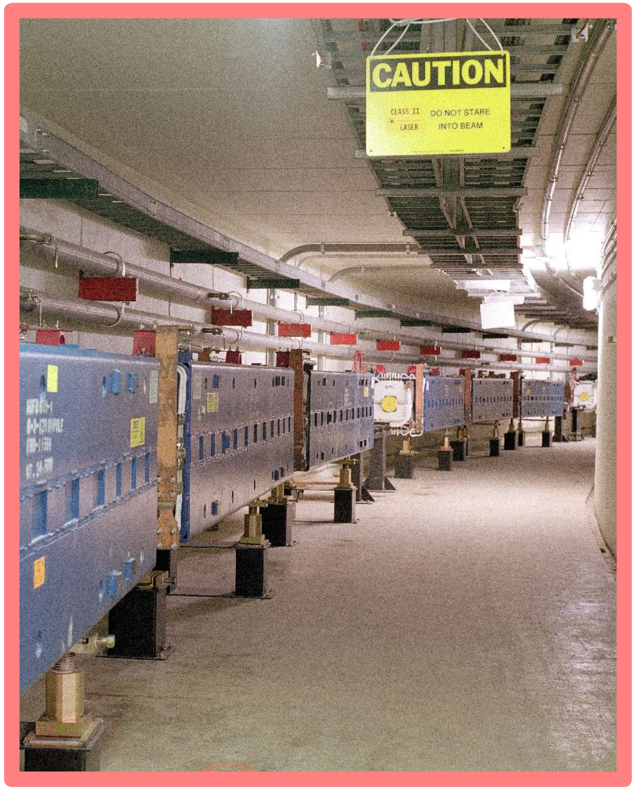
MiniBooNE's first results!

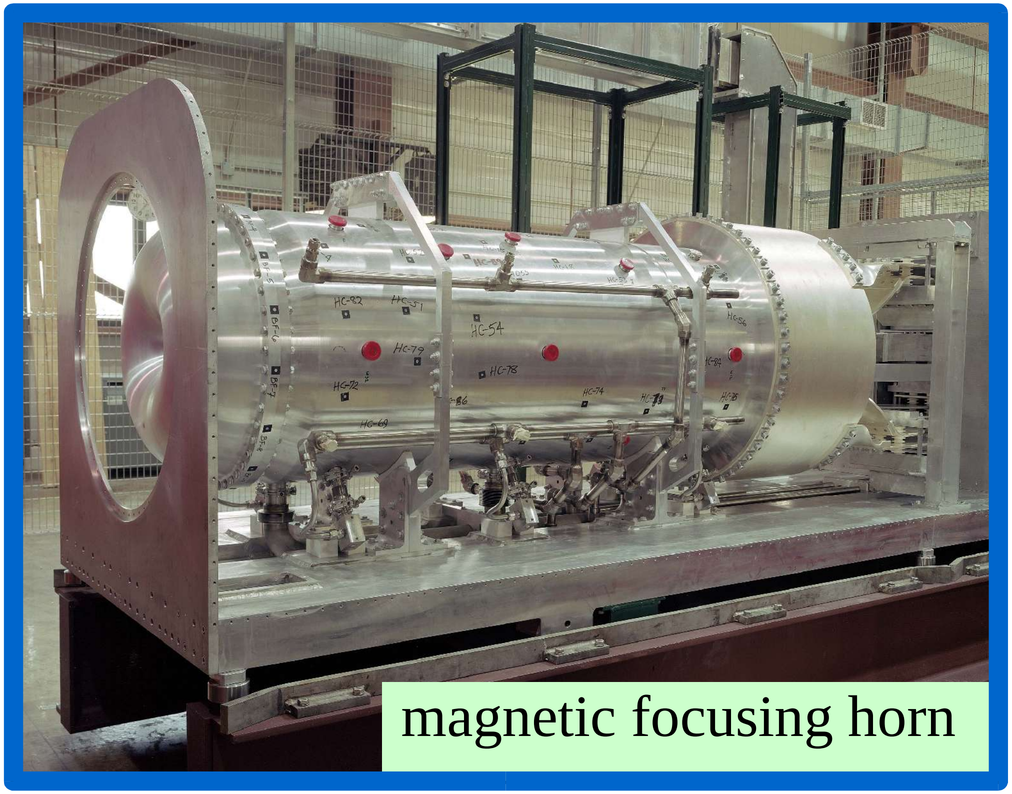


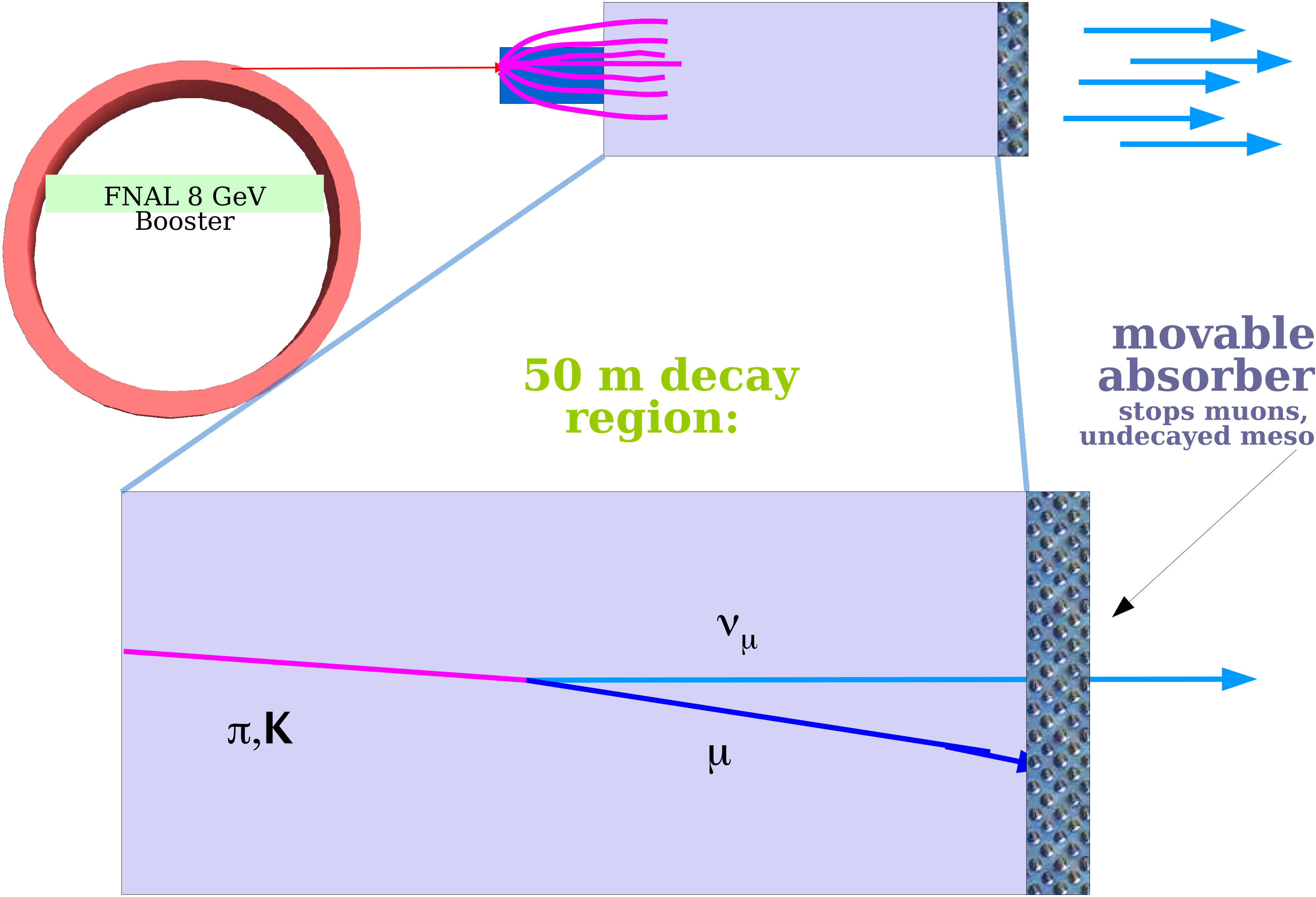
- The Experimental Setup
- Two Independent Data Analyses
- Errors and Constraints
- First Results

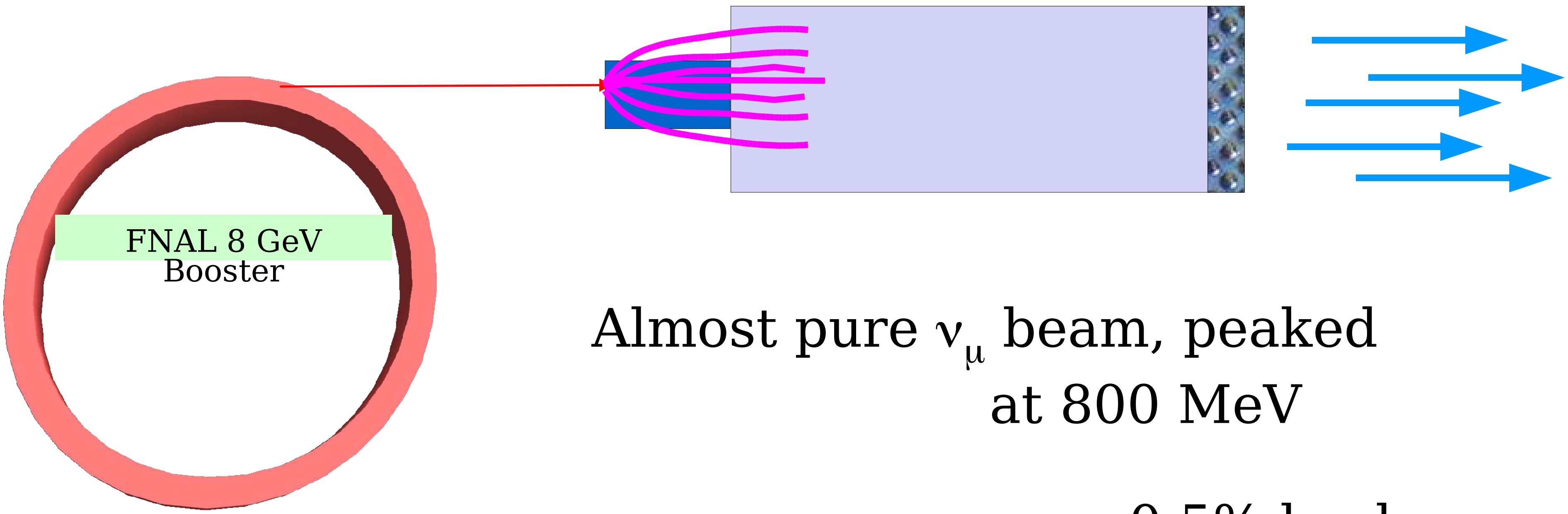


8 GeV protons on Beryllium Target
in a magnetically focusing horn



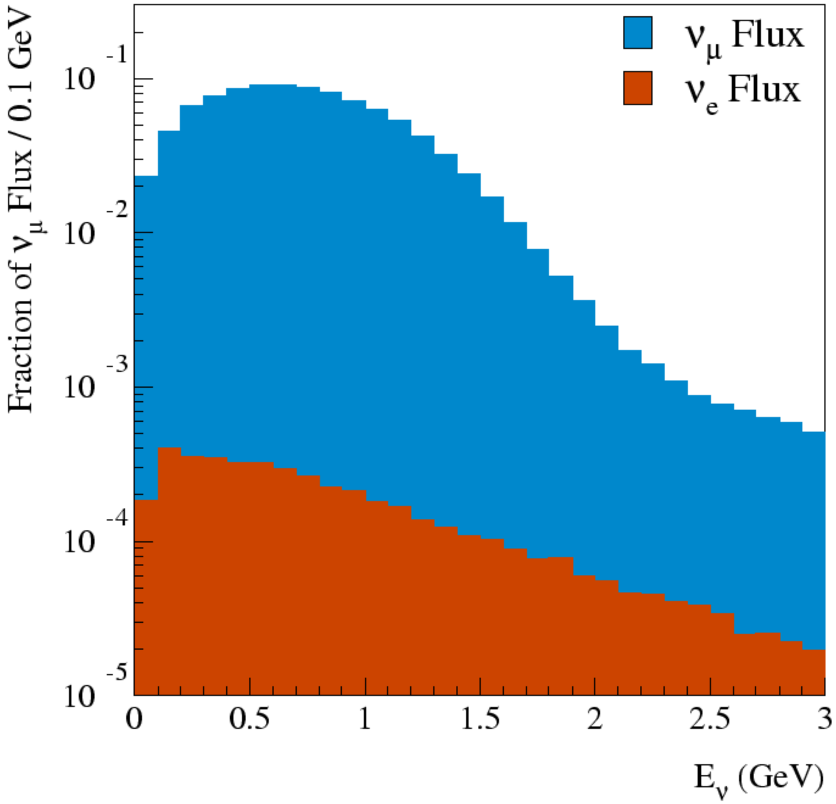



FNAL 8 GeV Booster
50 m decay region:
movable absorber:
stops muons, undecayed mesons
ν_μ
π,**K**
μ



Almost pure ν_μ beam, peaked at 800 MeV

~0.5% background “intrinsic” ν_es



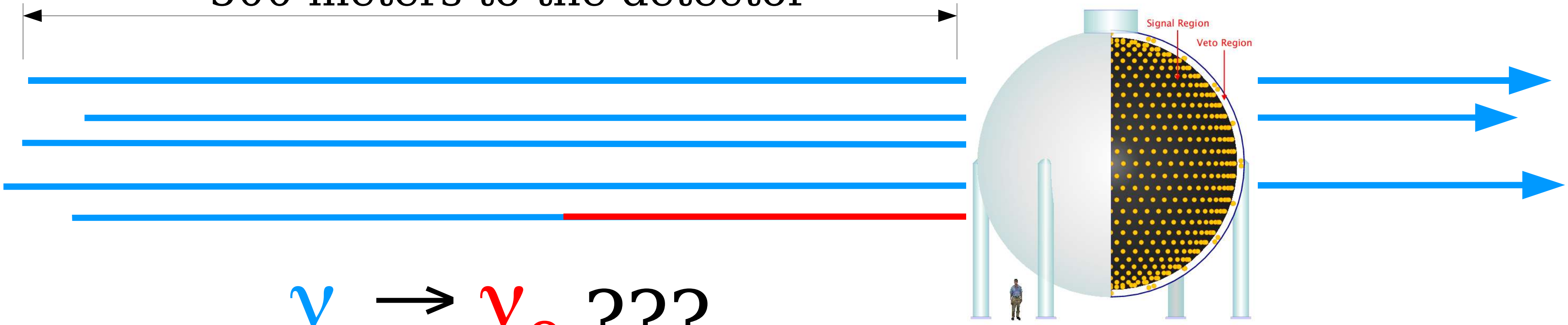
ν_e intrinsics:

$\pi^+ \to \nu_\mu \mu$

$e^+ \nu_e \nu_\mu$

$k^+ \to \pi^\circ \nu_e e^+$

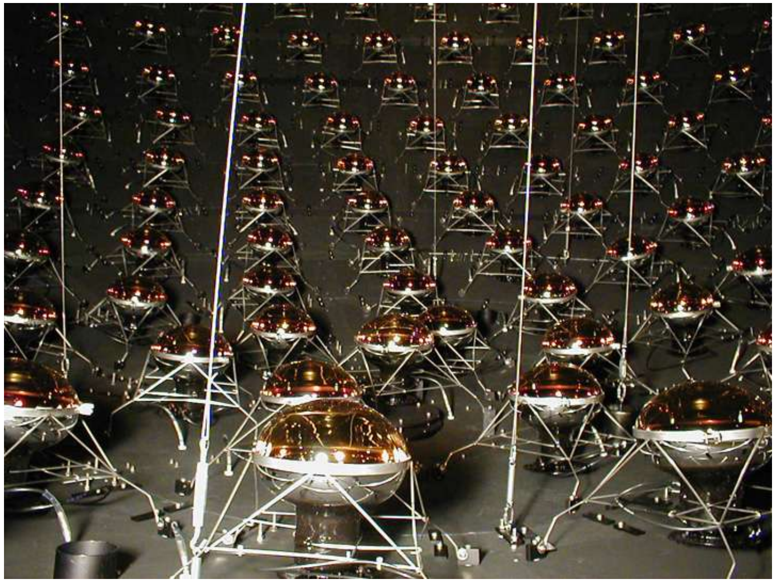
$k_L \to \pi^- \nu_e e^+$



~500 meters to the detector

$\nu_\mu \rightarrow \nu_e$???

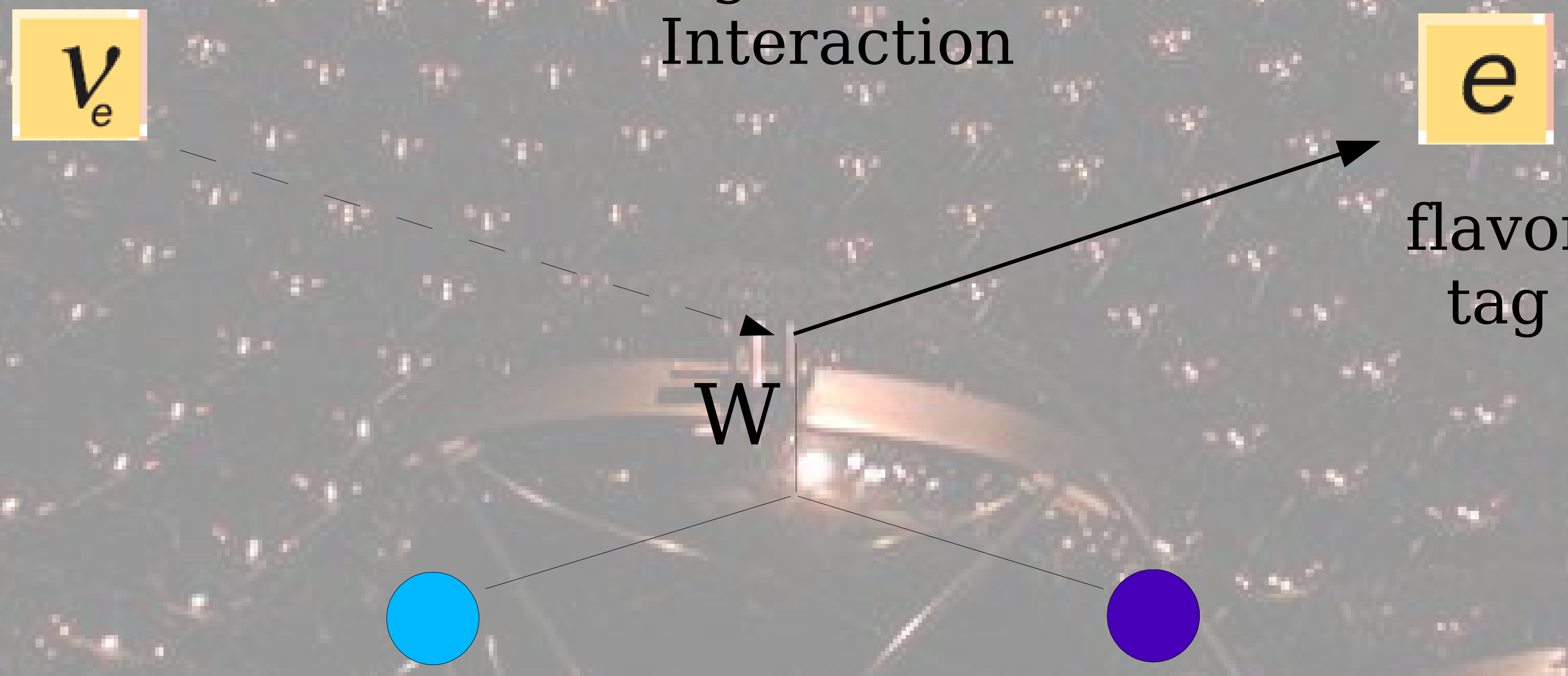
MiniBooNE
Detector



- 12m in diameter sphere
- 800 tons of
  ultra pure mineral oil
- sphere-within-a-sphere
- light tight signal region
  1280 PMTs
- veto region
  240 PMTs

See them interact by seeing remnants of the interaction....

Quasi-Elastic Scattering: Charged Current Interaction

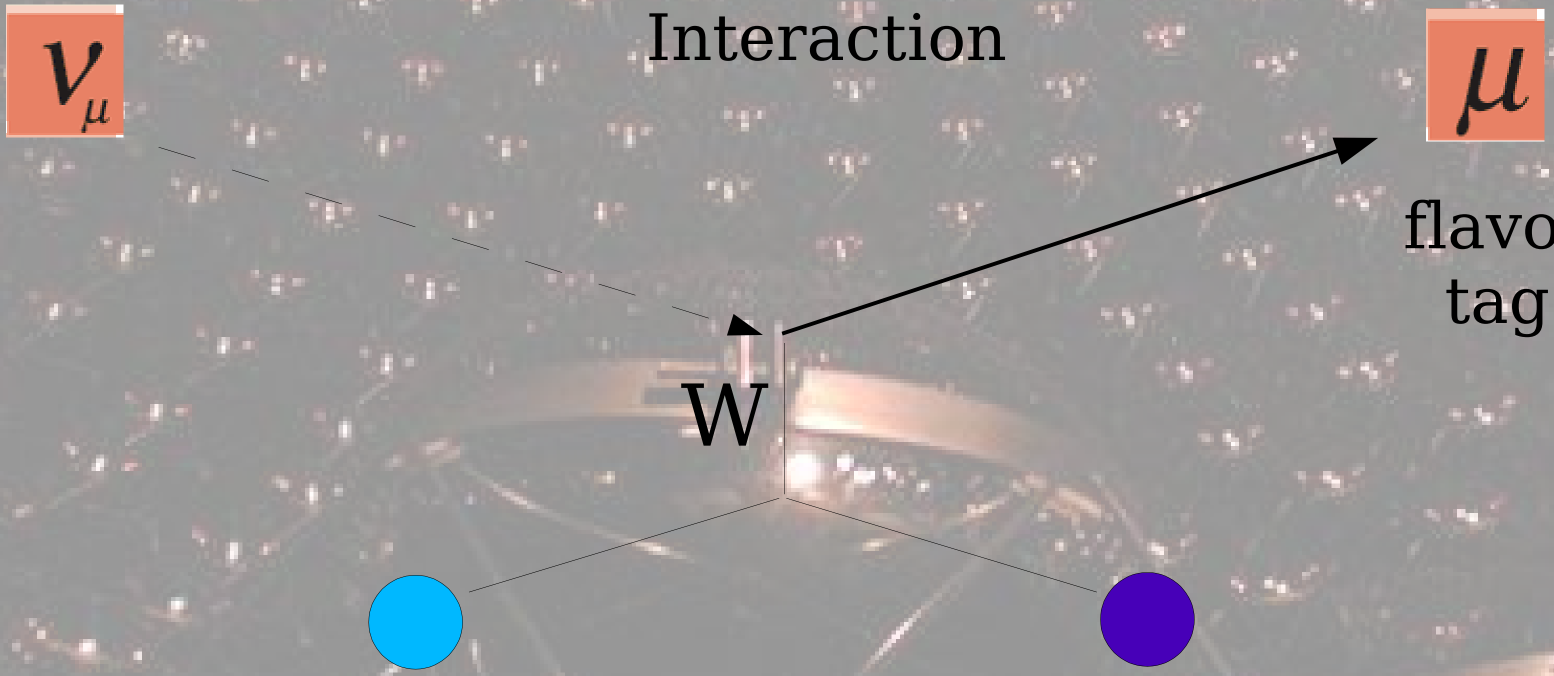


flavor tag

see the recoil nucleon

See them interact by seeing remnants of the interaction....

Quasi-Elastic Scattering: Charged Current Interaction

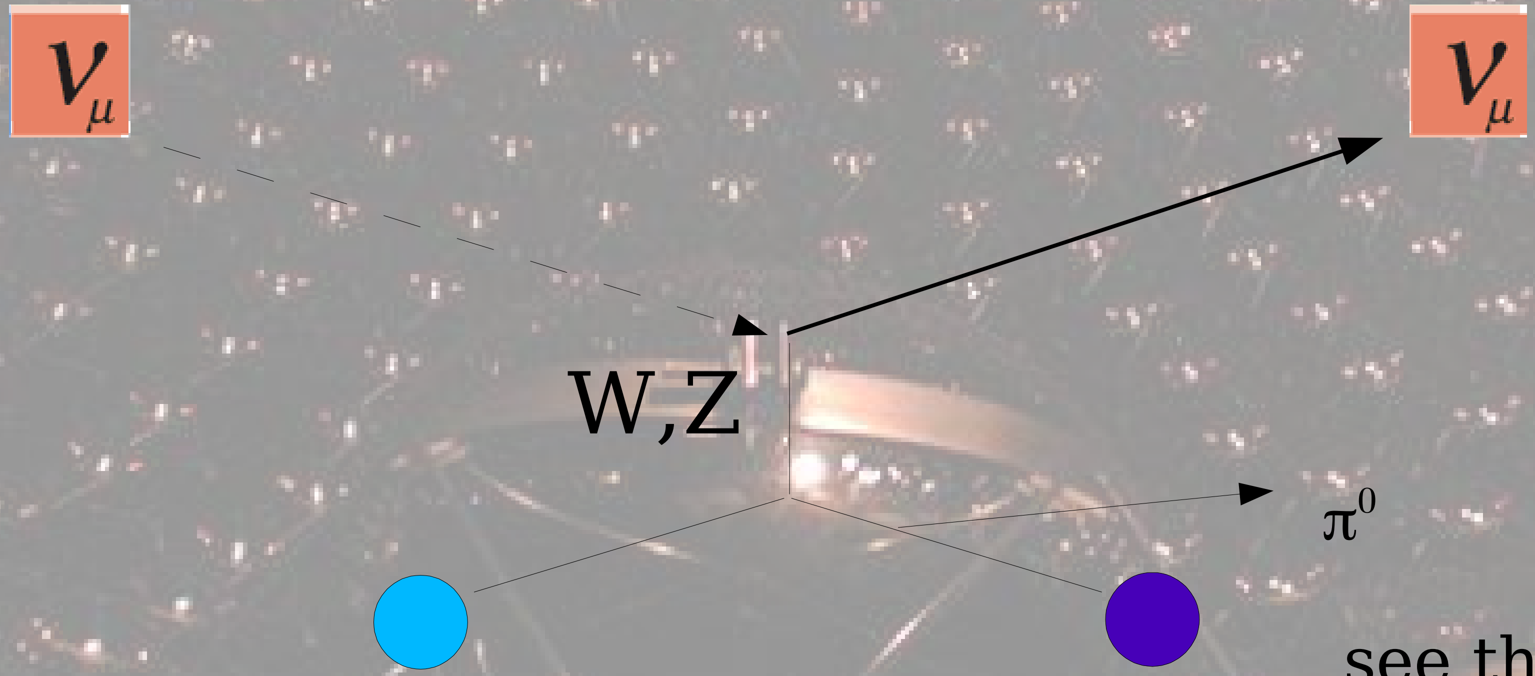


flavor tag

see the recoil nucleon

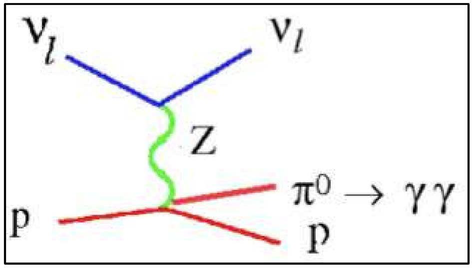
See them interact by seeing remnants of the interaction....

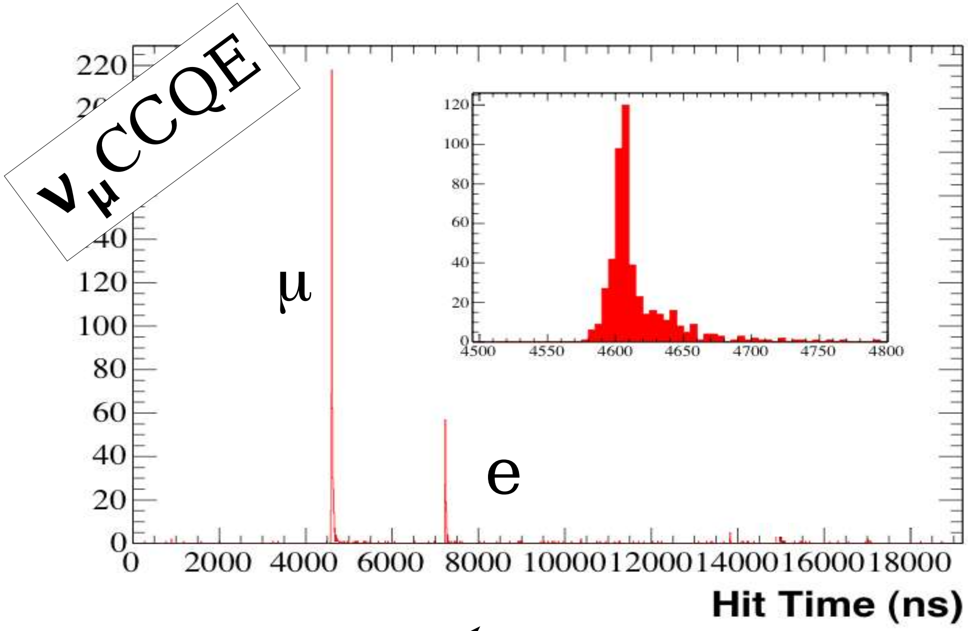
Single Pion Production to Deep Inelastic Scattering

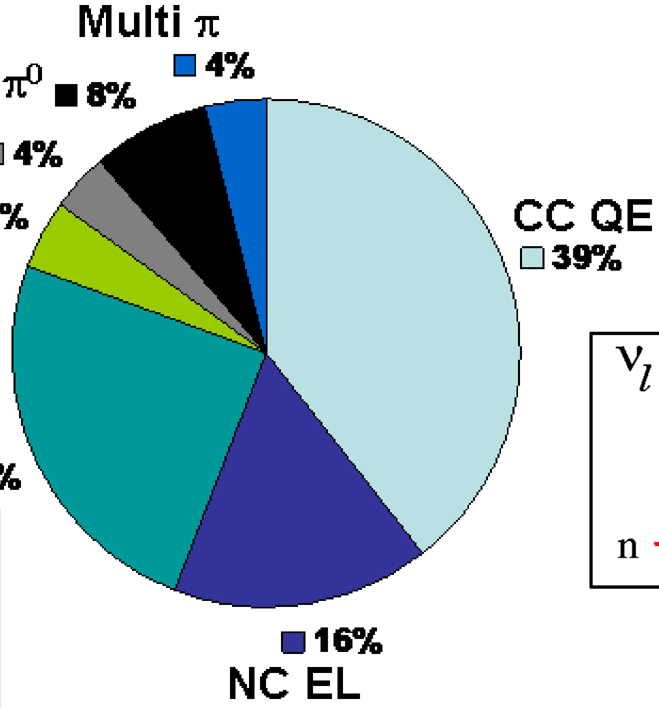


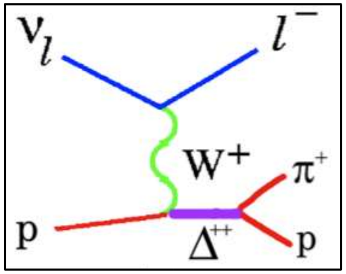
see the
outgoing
particles

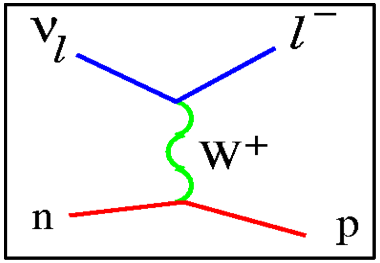
Neutrino interactions in MiniBooNE...











Event signature: First cluster of hits (first subevent) is the muon. Followed by smaller cluster of hits: decay electron

signal channel

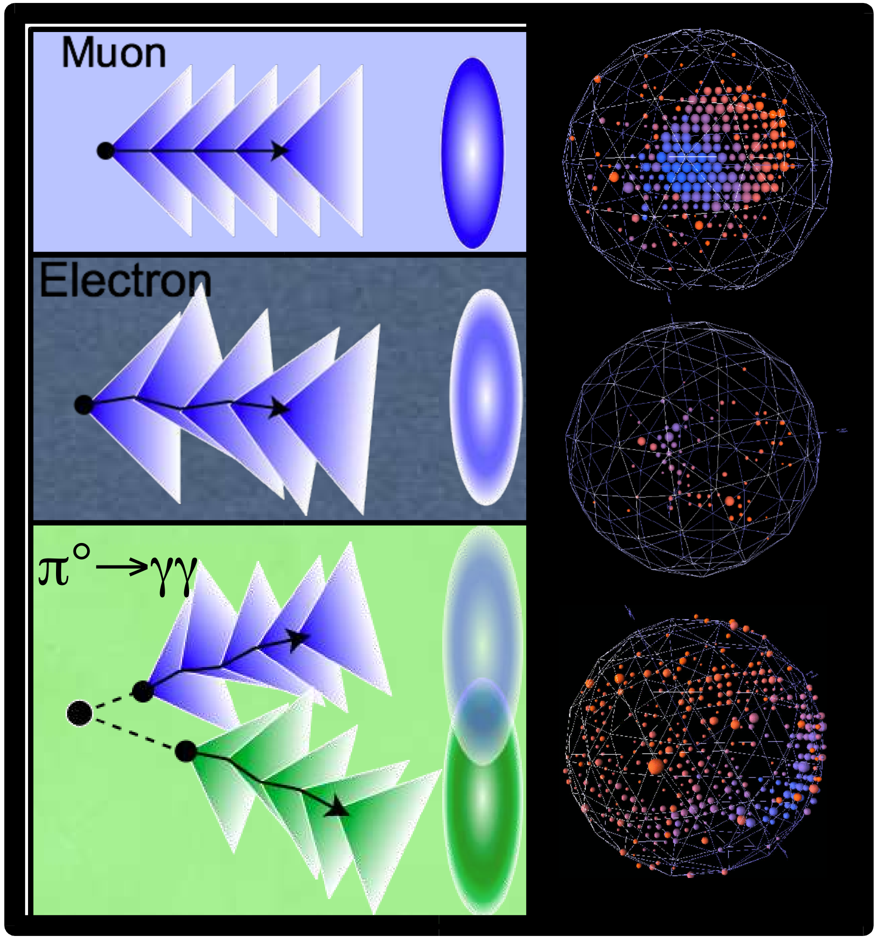
Predicted event rates before cuts (NUANCE Monte Carlo)

D. Casper, NPS, 112 (2002) 161

Muons:
Produced in most CC events.

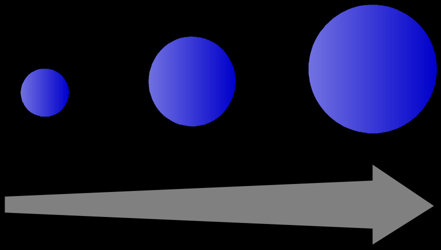
Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.

π^0s:
Can form a background if one photon is weak or exits tank.

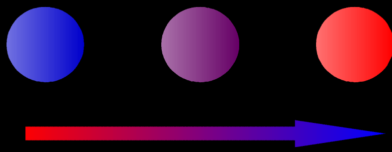


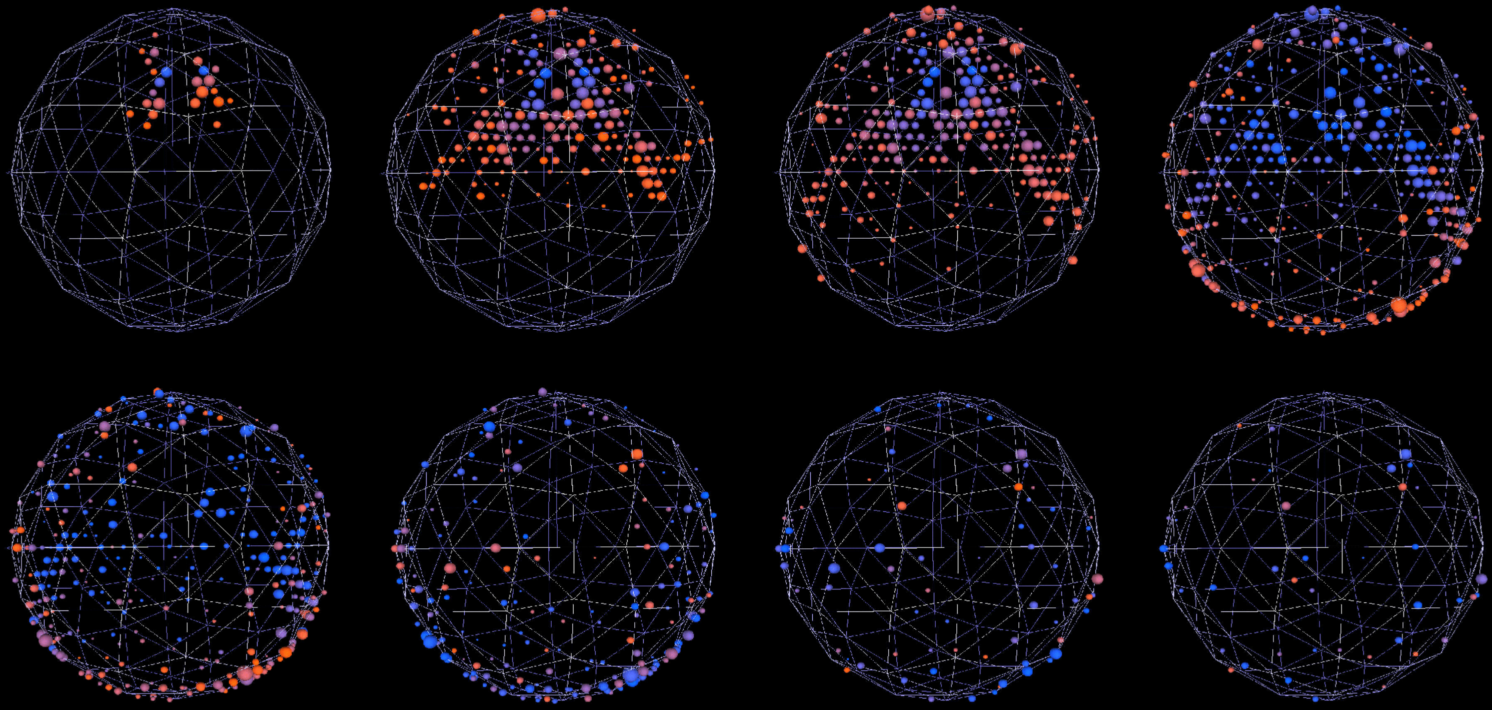
Example of Cerenkov Rings: A stopping cosmic ray

Charge (Size)



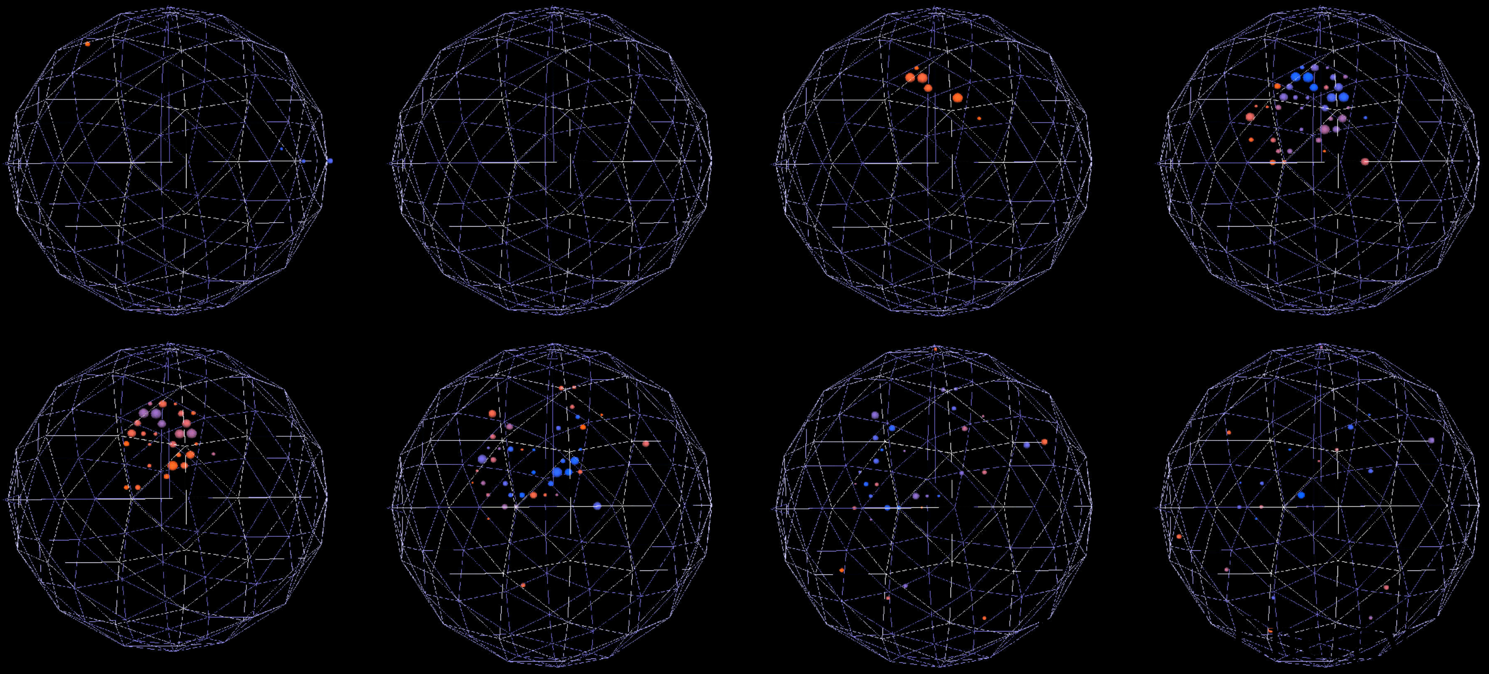
Time (Color)





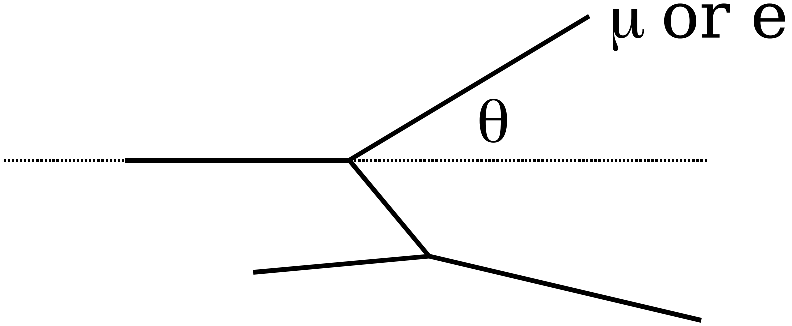
First the muon enters the tank and stops...

Later a the Michel electron is observed



Michel electrons provide muon tags and calibration

CCQE
(Charged Current Quasi-Elastic)

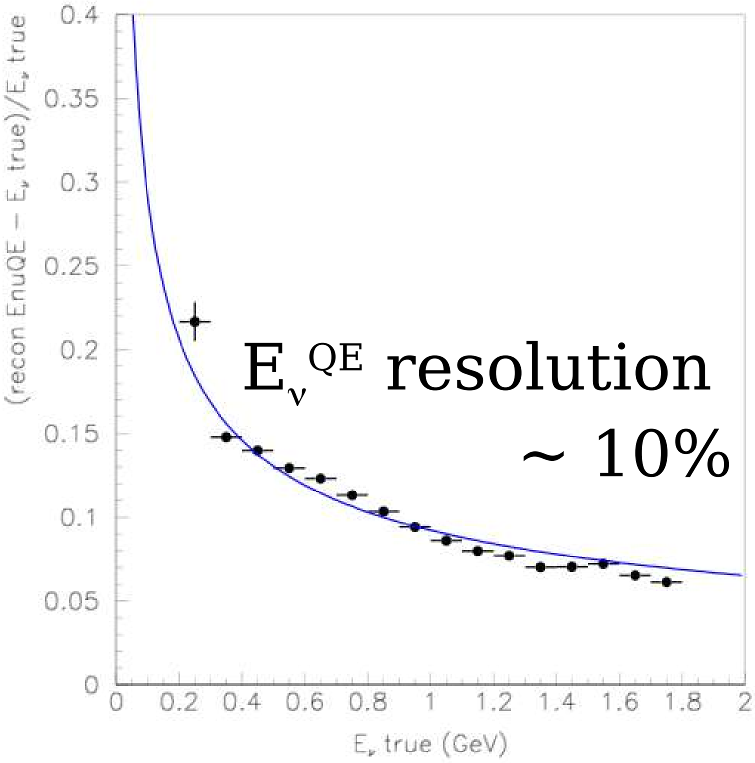


39% of total

- Events are "clean" (few particles)
- Energy of the neutrino can be reconstructed

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}\cos\theta_\ell}$$

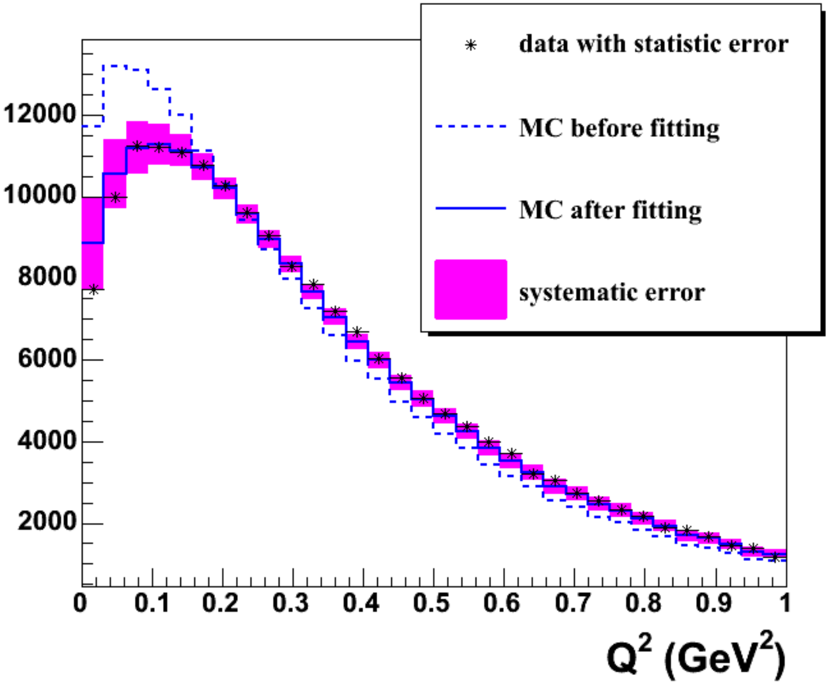
Reconstructed from:
Scattering angle
Visible energy ($E_{visible}$)



E_ν^{QE} resolution
~ 10%

An oscillation signal is
an excess of ν_e events as a function of E_ν^{QE}

NUANCE Parameters:



From Q^2 fits to MB ν_μ CCQE data:

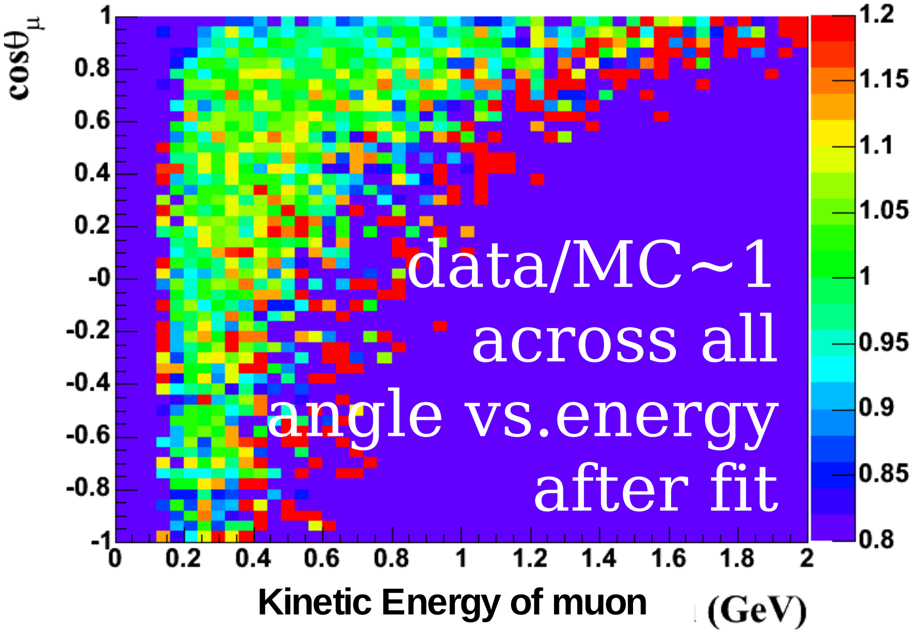
M_A^{eff} -- effective axial mass

E_{lo}^{SF} -- Pauli Blocking parameter

From electron scattering data:

E_b -- binding energy

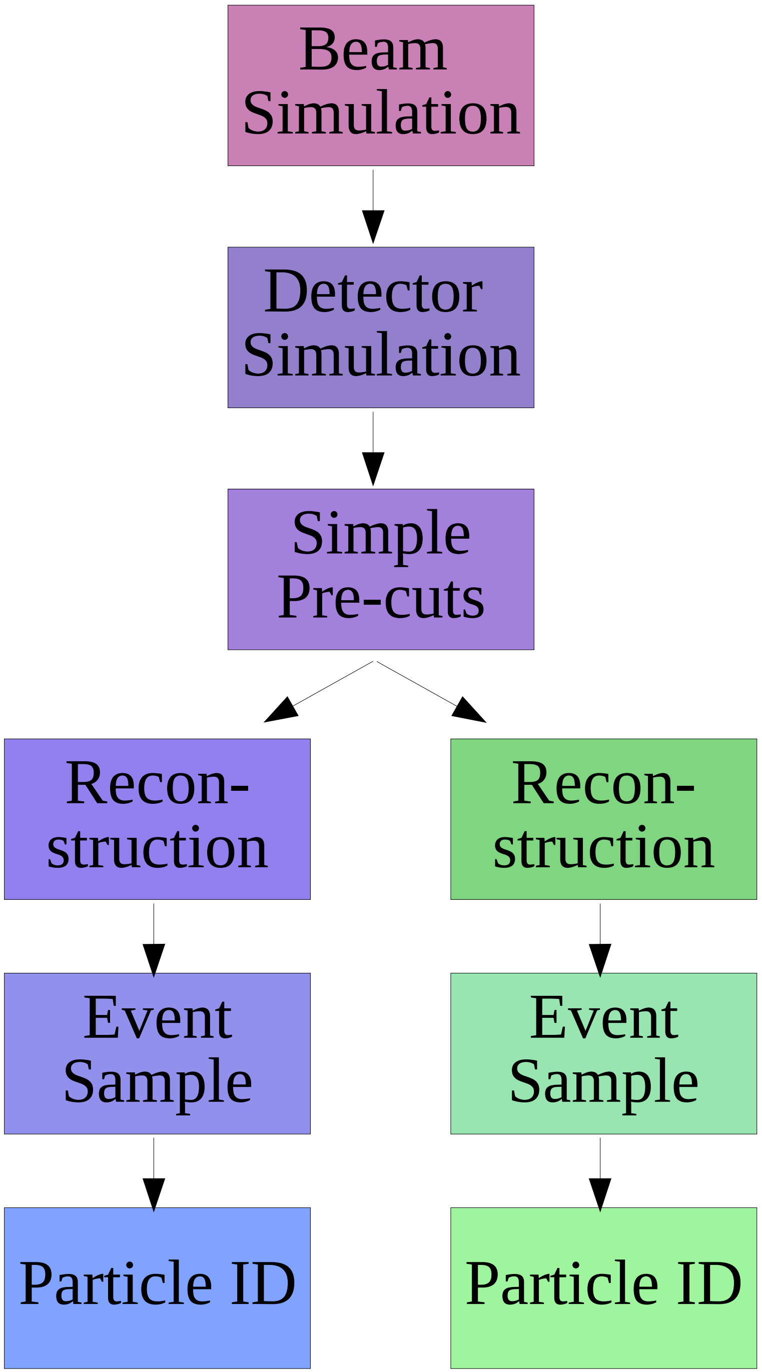
p_f -- Fermi momentum



data/MC~1 across all angle vs.energy after fit

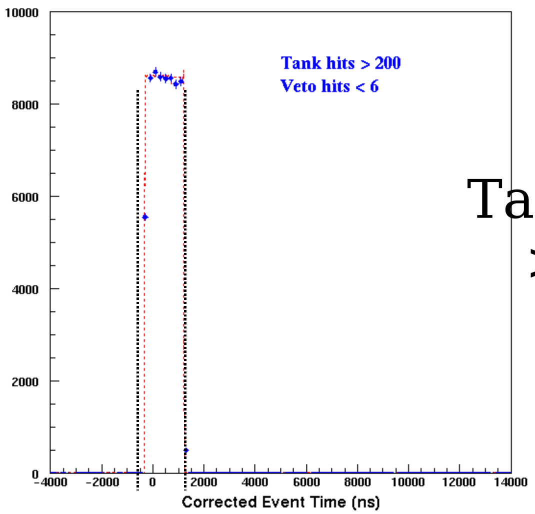
Model describes CCQE ν_μ data well

- The Experimental Setup
- Two Independent Data Analyses
    - Track Based Analysis
    - Boosted Decision Trees
- Errors and Constraints
- First Results



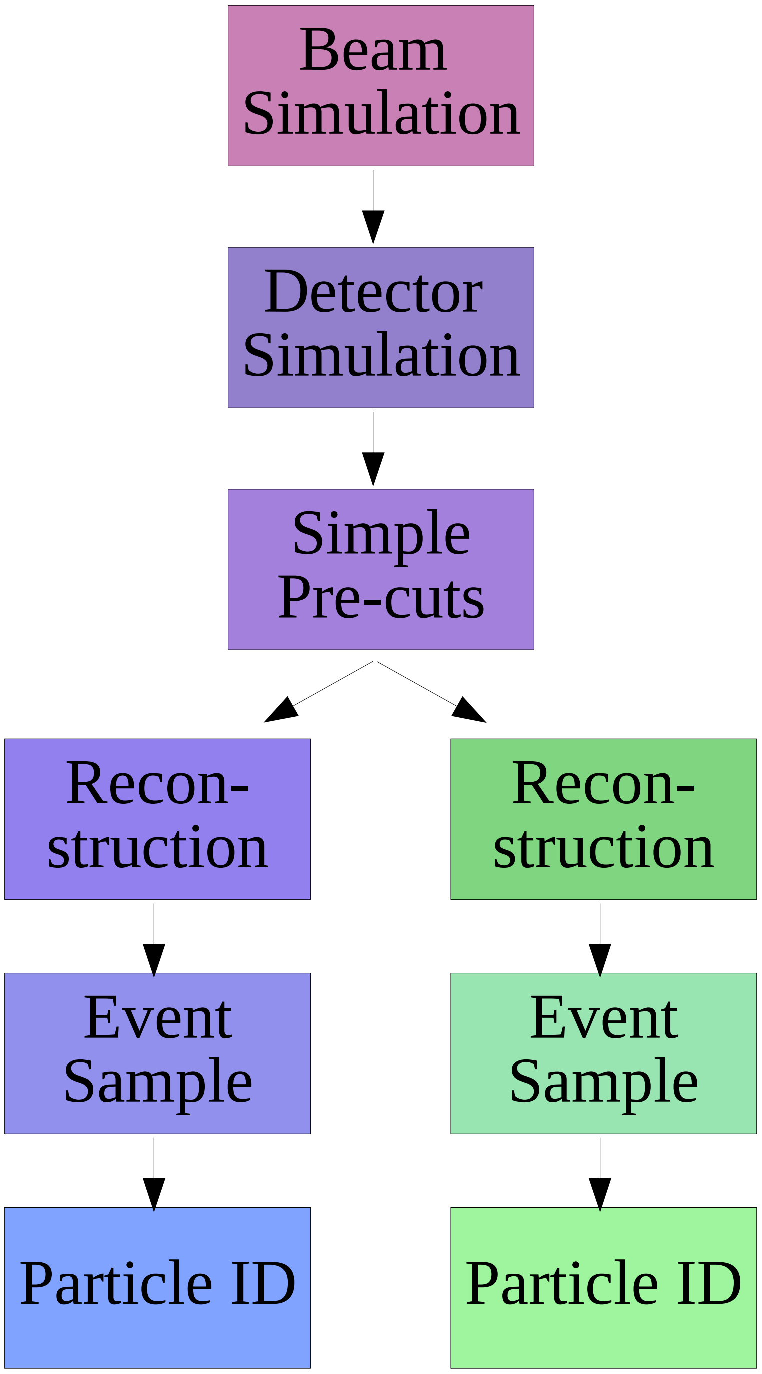
Share

- GEANT 4 beam Monte Carlo
- NUANCE v3 event generator
- GEANT3 detector Monte Carlo
- Simple pre-cuts



Tank Hits > 200

removes low energy Michel electrons
(+ 1 subevent and R<500 cm)



Beam Simulation

Detector Simulation

Simple Pre-cuts

Recon-struction

Event Sample

Particle ID

Recon-struction

Event Sample

Particle ID

Both were blind analyses:

data

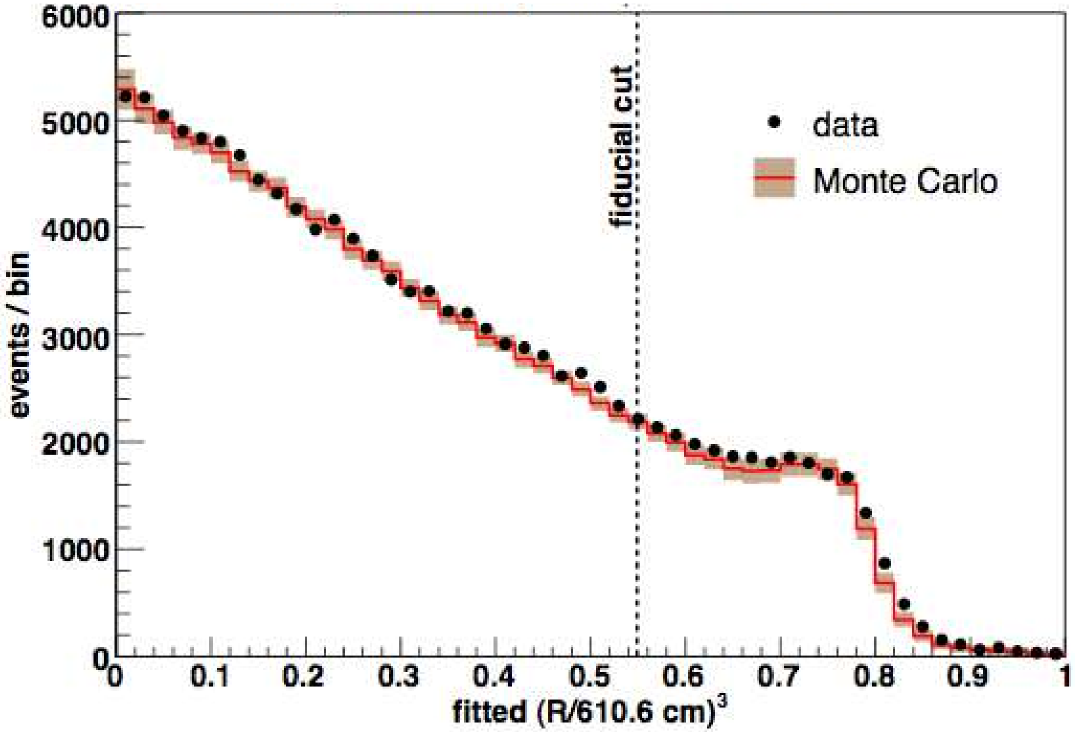
Filter: electron-like events were hidden from analysis

non-electron like (~99% of events) available for analysis

As well, for all events, low level information was available

Each event is characterized by 7 reconstructed variables:
vertex (x,y,z), time, energy, and
direction (θ, φ)→(U_x, U_y, U_z).

Resolutions: vertex: 22 cm
direction: 2.8°
energy: 11%

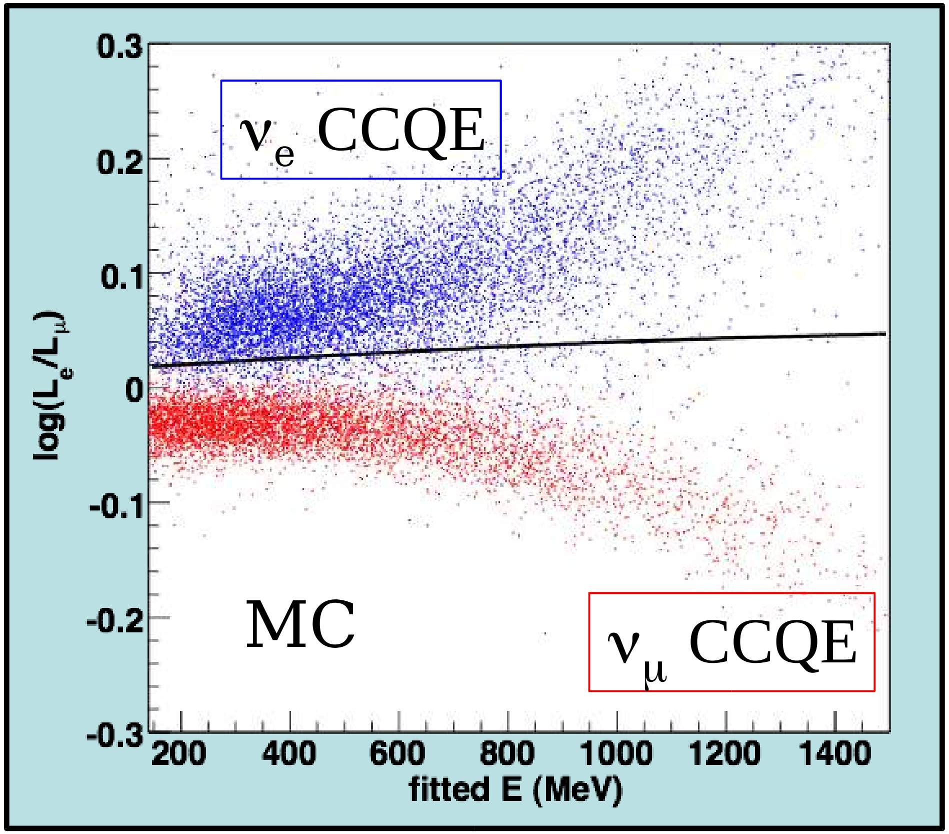


ν_μ CCQE events

2 subevents
Veto Hits<6
Tank Hits>200

Each event is reconstructed under several different reconstruction hypotheses electron like (L_e), Muon-like (L_μ), π° like, (L_{π°)

$\log(L_e/L_\mu)>0$ favors electron-like hypothesis



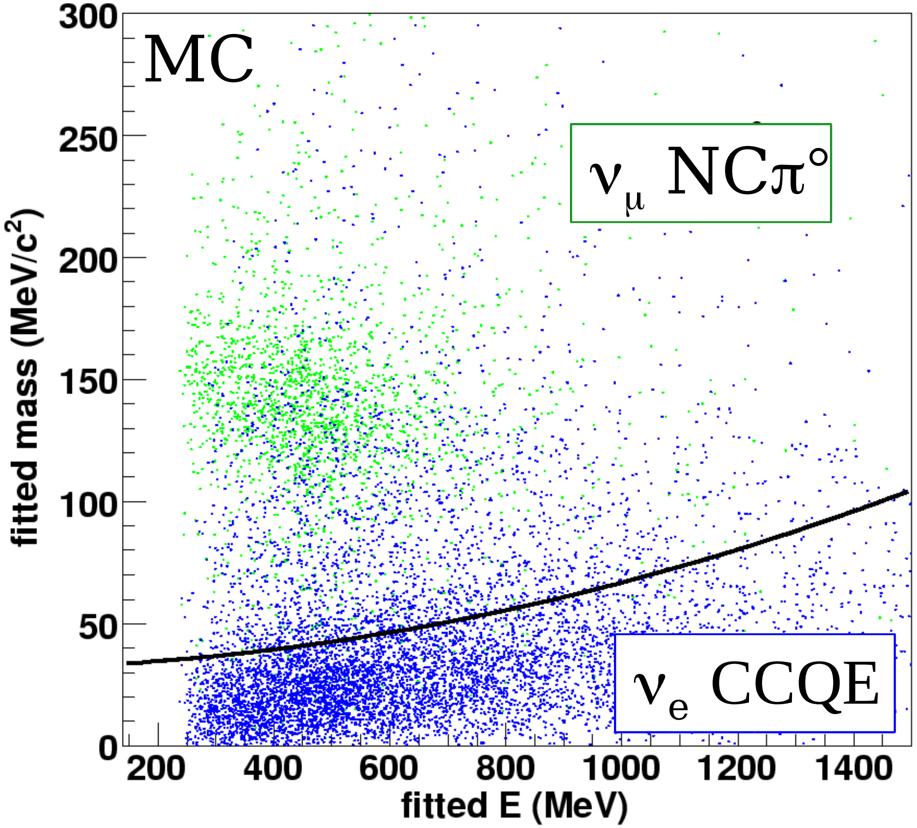
Separation is clean at high energies where muon-like events are long.

Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

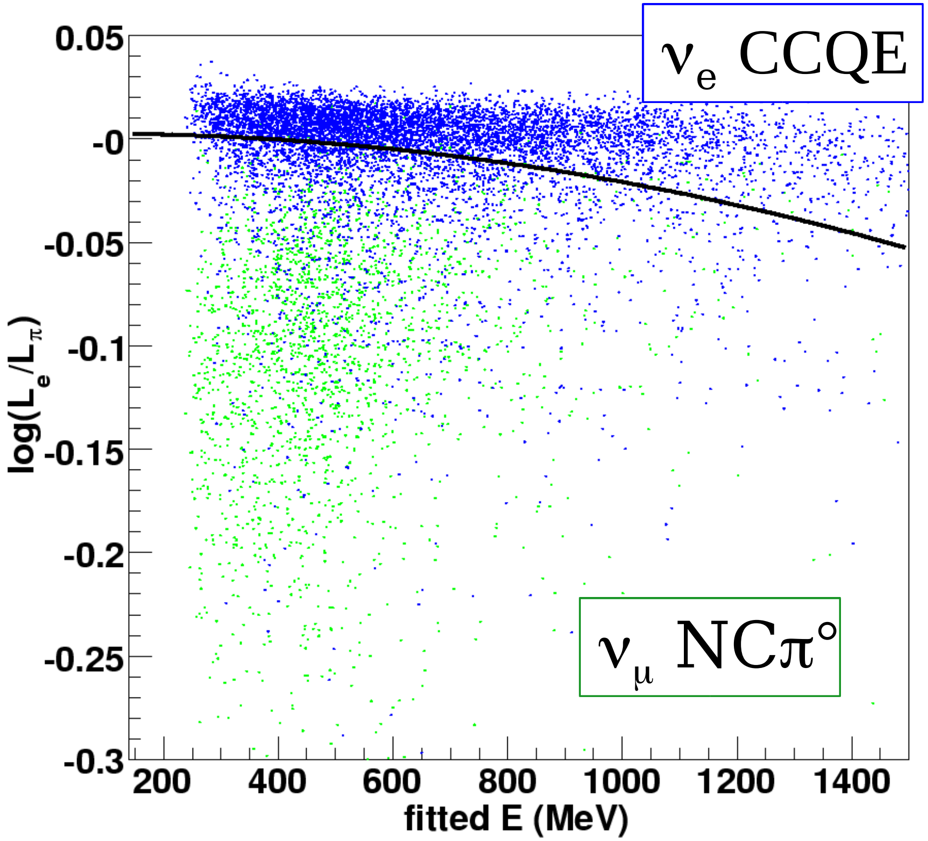
Photon conversions are electron-like.
These are not cut here

Rejecting “π^0-like” events

Using a mass cut



Using $\log(L_e/L_{\pi^\circ})$



Cuts were chosen to maximize $\nu_\mu \rightarrow \nu_e$ sensitivity

Testing e-π^0 separation using <u>data</u>

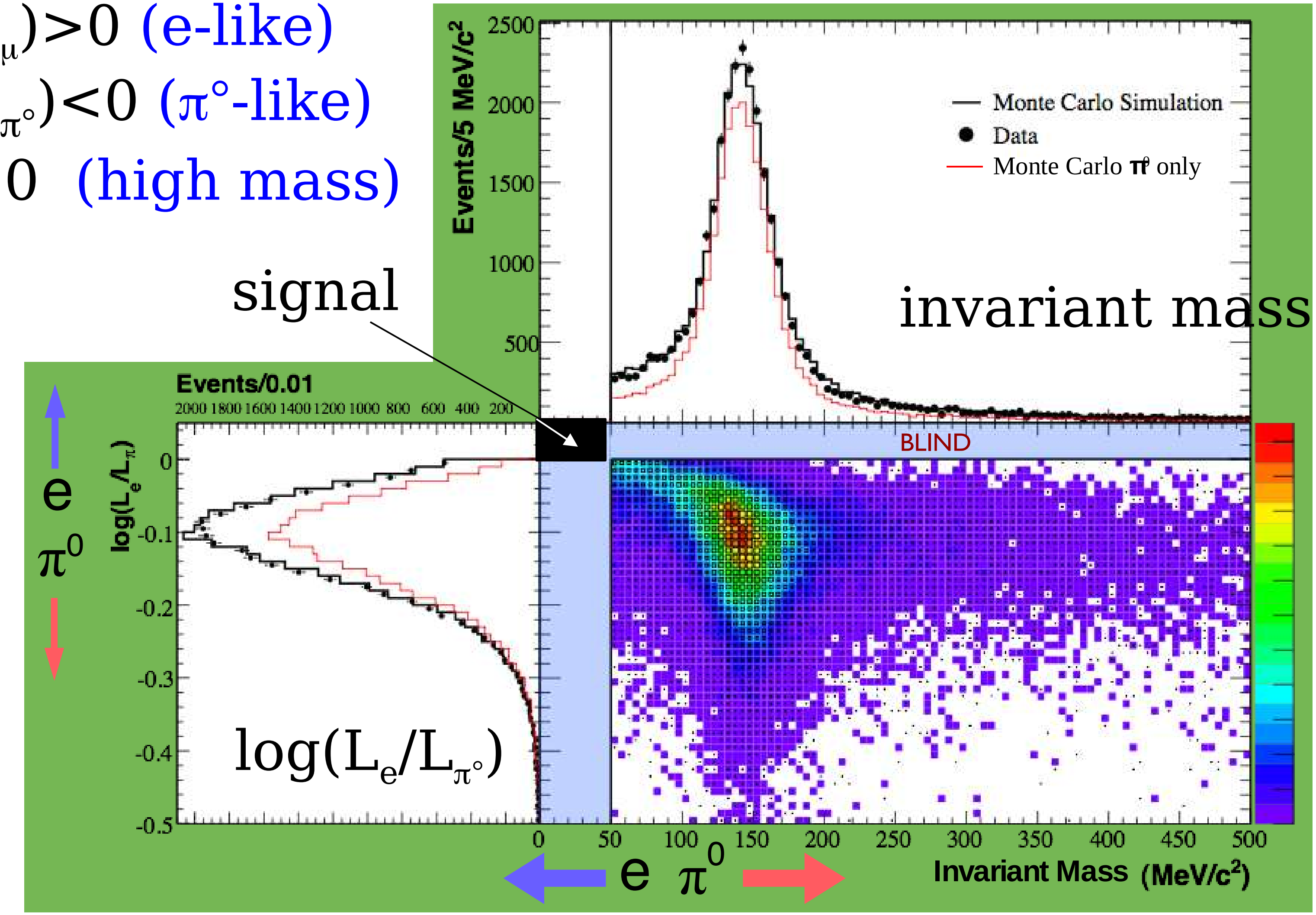
1 subevent

$\log(L_e/L_\mu)>0$ (e-like)

$\log(L_e/L_{\pi^\circ})<0$ (π°-like)

mass>50 (high mass)

signal



invariant mass

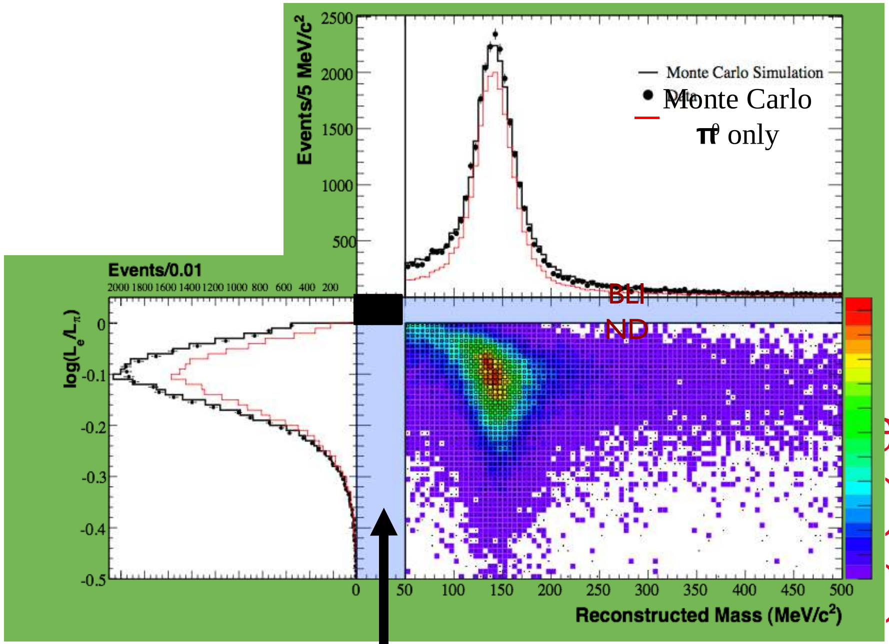
$\log(L_e/L_{\pi^\circ})$

1 subevent

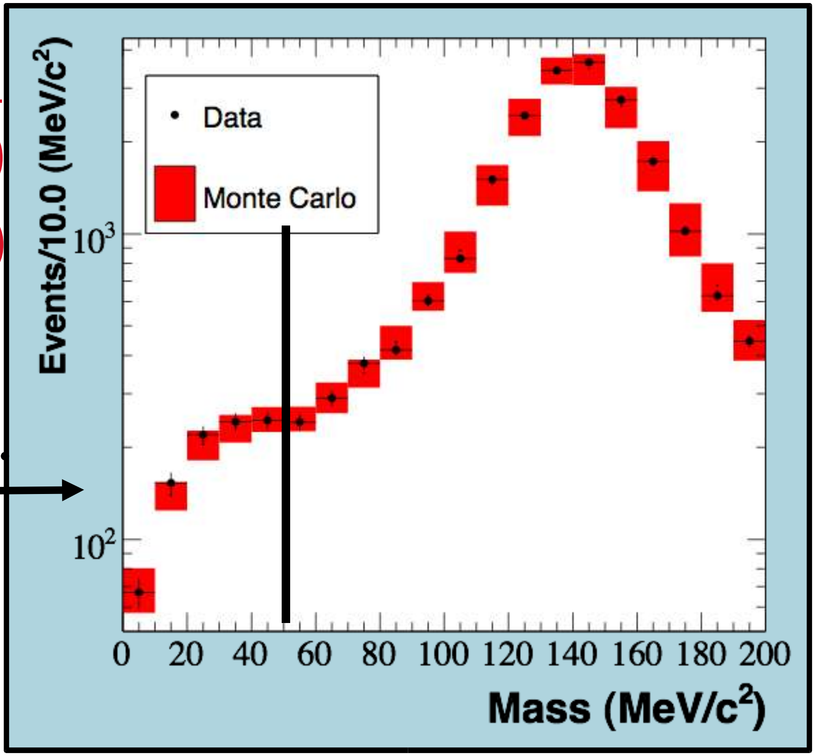
$\log(L_e/L_\mu)>0$ (e-like)

$\log(L_e/L_{\pi^\circ})<0$ (π°-like)

mass<200 (high mass)



Next: look here….



χ^2 Prob for mass<50 MeV

(“most signal-like”): 69%

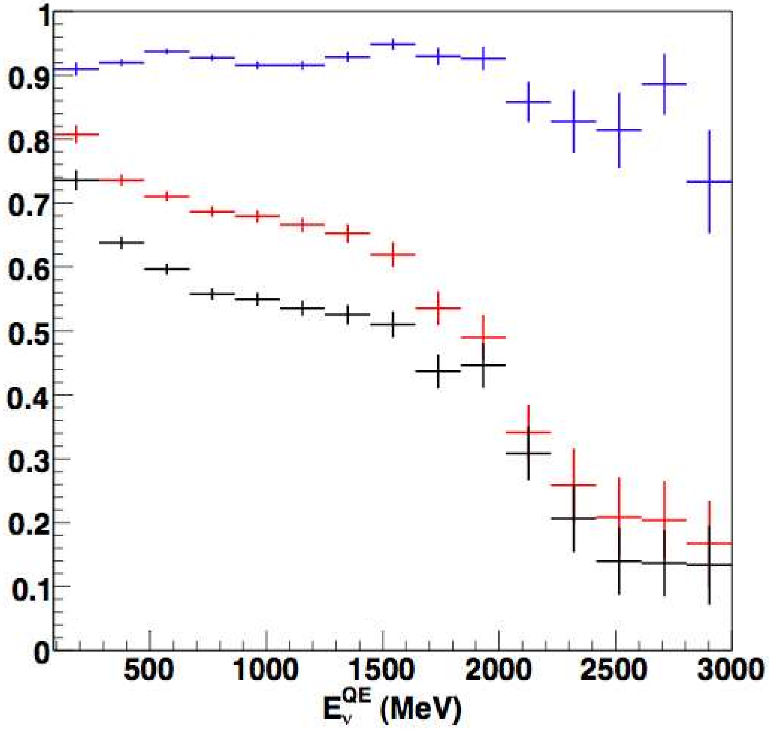
Summary of TB cuts

Efficiency:

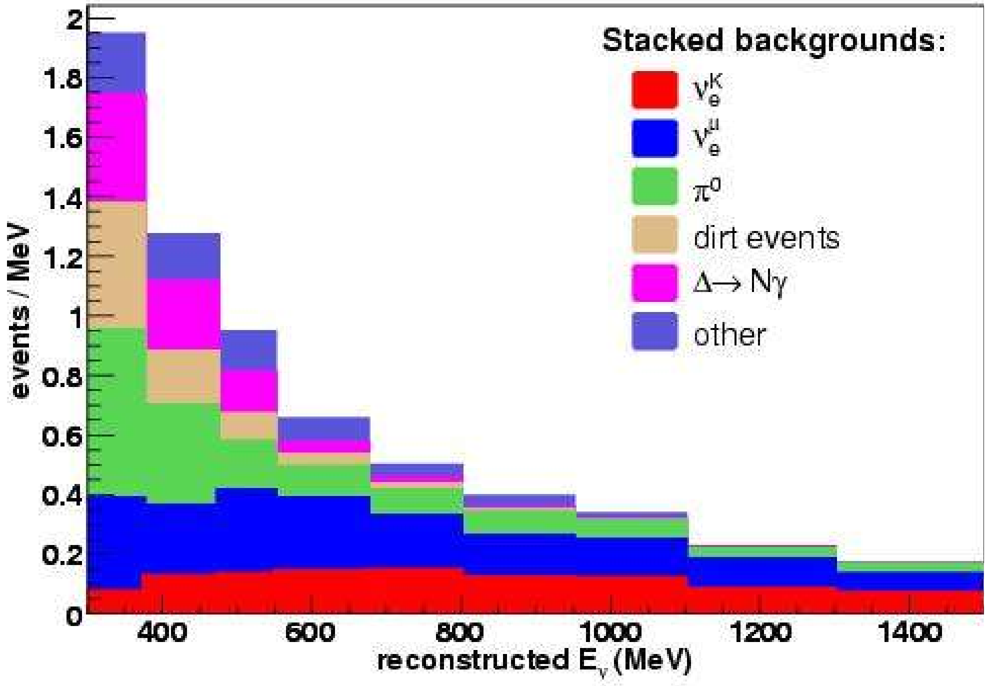
Log(L_e/L_μ)

Log(L_e/L_{π°)

invariant mass



Backgrounds after cuts

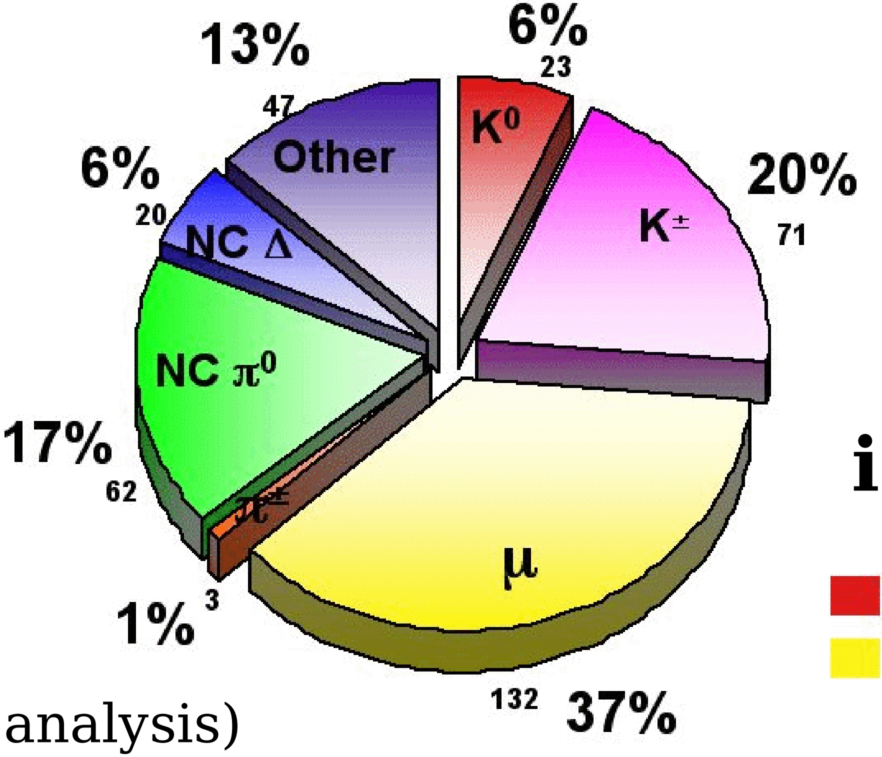


- The Experimental Setup
- Two Independent Data Analyses
- Errors and Constraints
- First Results

We have two categories of backgrounds:

ν_μ mis-id

🟪
🟦
🟩



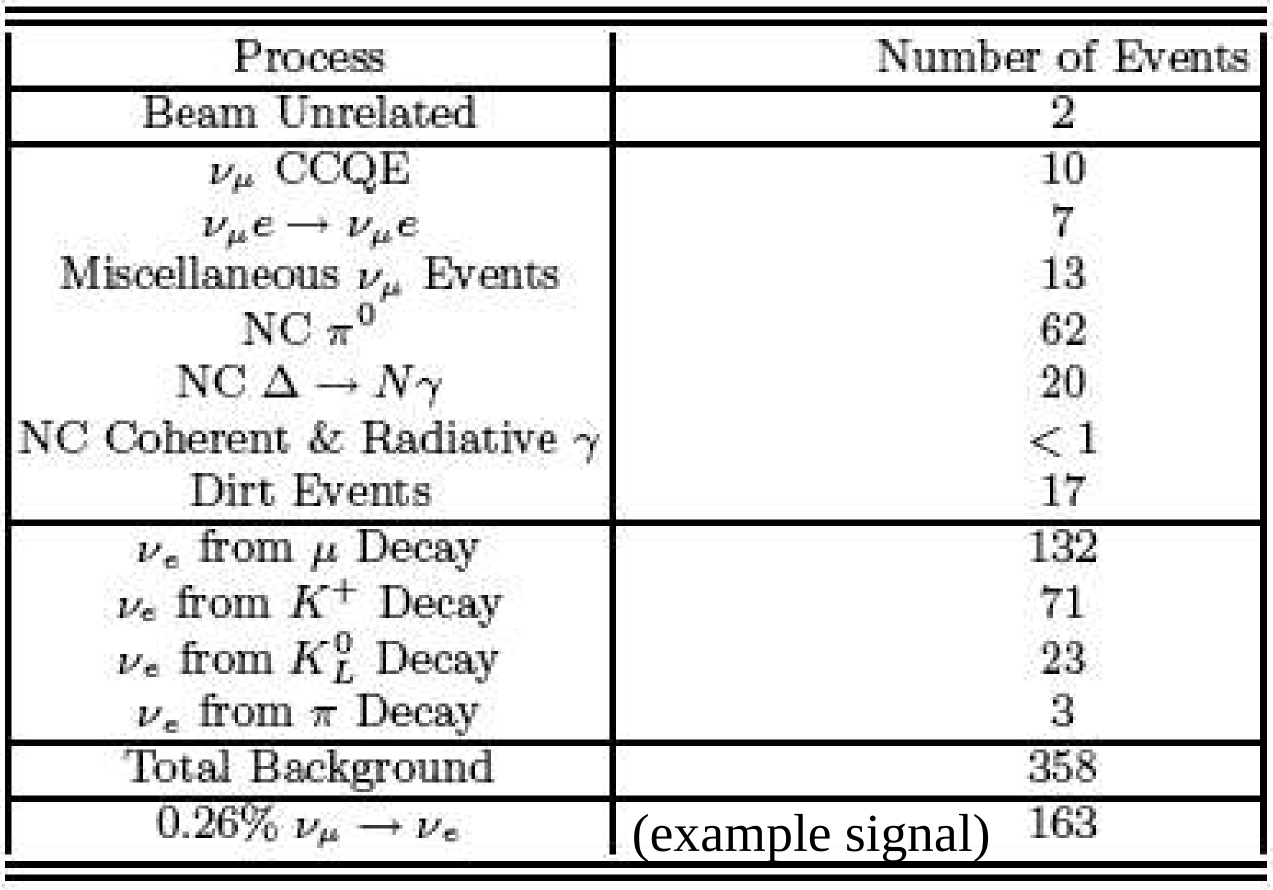
intrinsic ν_e

🟥 🟪
🟨 🟧

(TB analysis)

Predictions of the backgrounds are among the nine sources of significant error in the analysis

Summary of predicted backgrounds for the final MiniBooNE result (TB Analysis):



Process	Number of Events
Beam Unrelated	2
ν_μ CCQE	10
$\nu_\mu e \rightarrow \nu_\mu e$	7
Miscellaneous ν_μ Events	13
NC π^0	62
NC $\Delta \rightarrow N\gamma$	20
NC Coherent & Radiative γ	< 1
Dirt Events	17
ν_e from μ Decay	132
ν_e from K^+ Decay	71
ν_e from K^0_L Decay	23
ν_e from π Decay	3
Total Background	358
0.26% $\nu_\mu \rightarrow \nu_e$	(example signal) 163

Handling uncertainties in the analyses:

What we begin with...

For a given source
of uncertainty,

Errors on a wide range
of parameters
in the underlying model

... what we need

For a given source
of uncertainty,

Errors in bins of
E_ν^{QE}
and information on
the correlations
between bins

Use “Multisims” To convert from errors on parameters to errors in E_ν^{QE} bins:

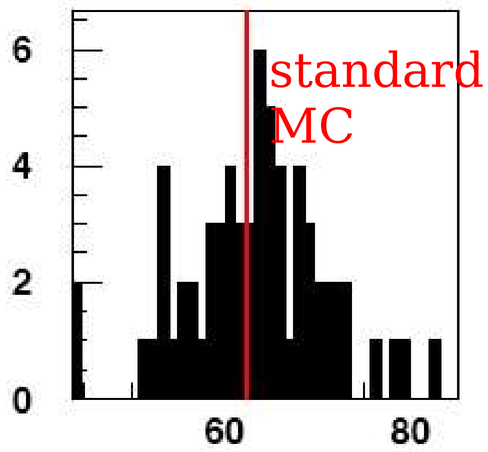
For each error source,

“Multisim” experiments are generated within the allowed variations by reweighting the standard Monte Carlo.

In the case of the OM, hit-level simulations are used.

70 multisims
for the Optical Model

number of
multisims



Number of events passing cuts
in bin 500<E_ν^{QE}<600 MeV

From differences between central value and each Multisim, Form correlated Error Matrices

Error bars on plots are the diagonals of the error matrix, but the fully correlated matrix goes into oscillation fit

- The Experimental Setup
- Two Independent Data Analyses
- Errors and Constraints
- First Results

The Box Opening

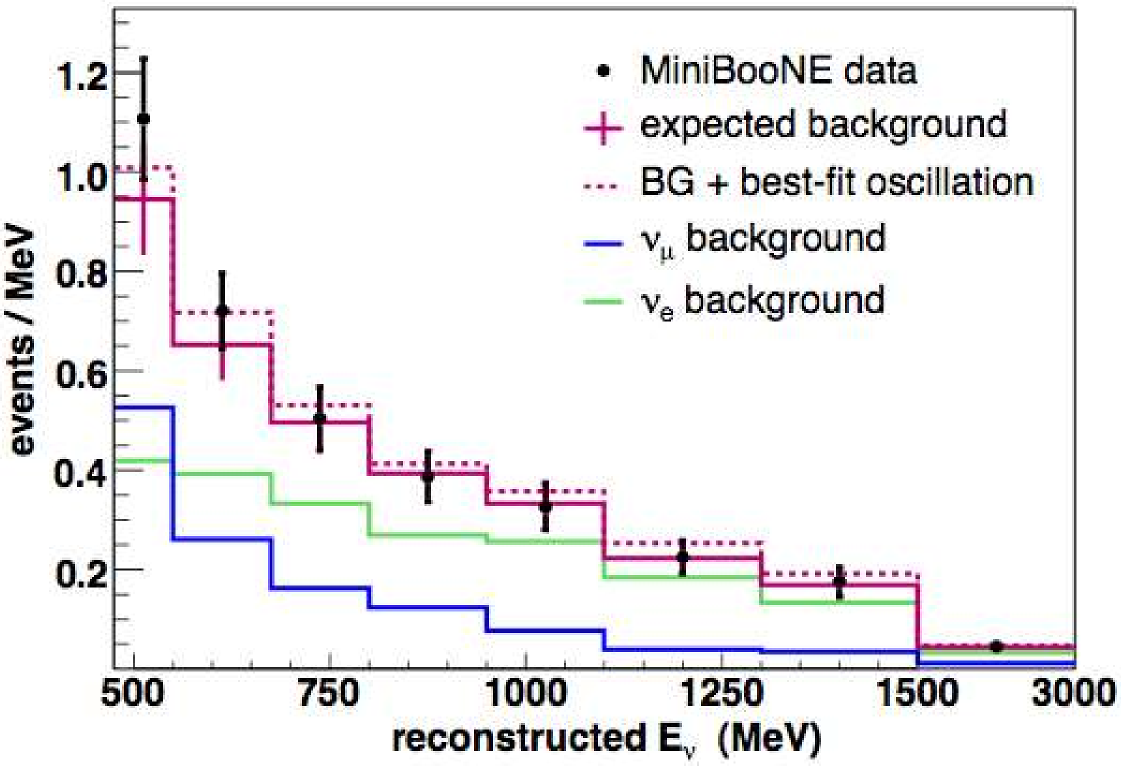
The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:

Counting Experiment: $475 < E_\nu^{QE} < 1250$ MeV

data: 380 events
expectation: 358 ±19 (stat) ± 35 (sys) events

significance:
0.55 σ

TB energy dependent fit results:

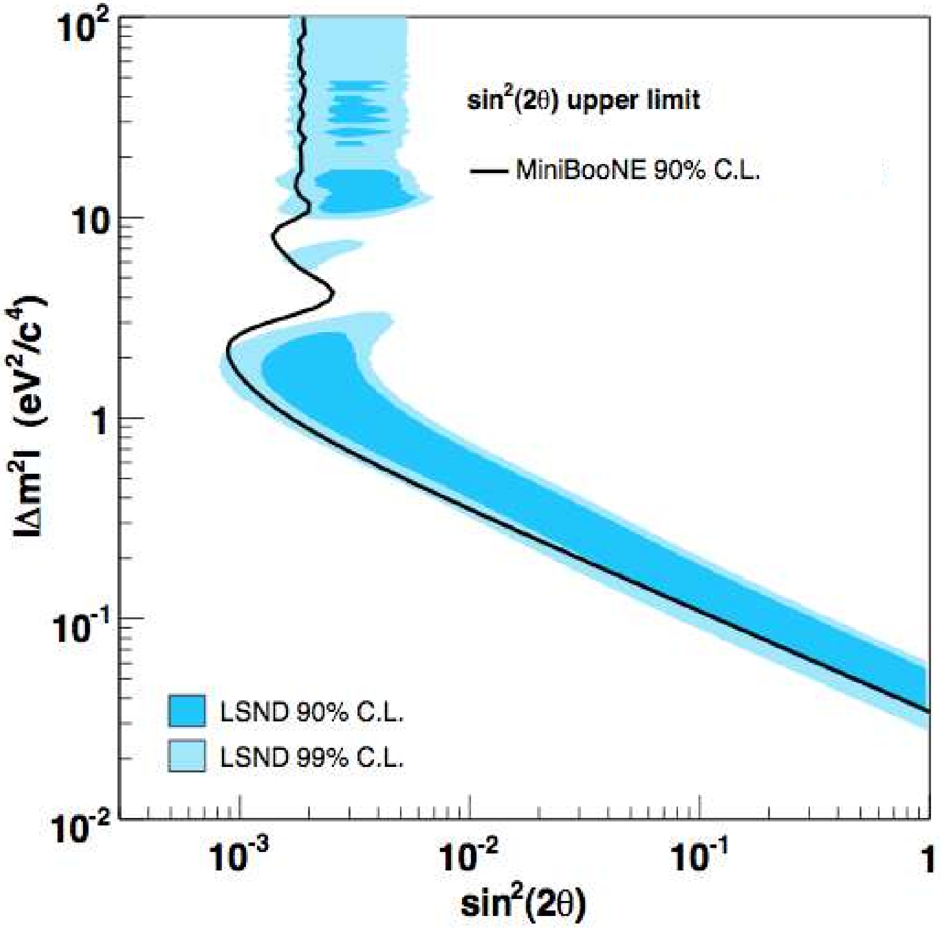


Error bars are diagnonals of error matrix.

Fit errors for >475 MeV:
Normalization 9.6%
Energy scale: 2.3%

Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ \mathrm{eV}^2)$

This places a limit on on oscillations for ν_μ to ν_e appearance only oscillations



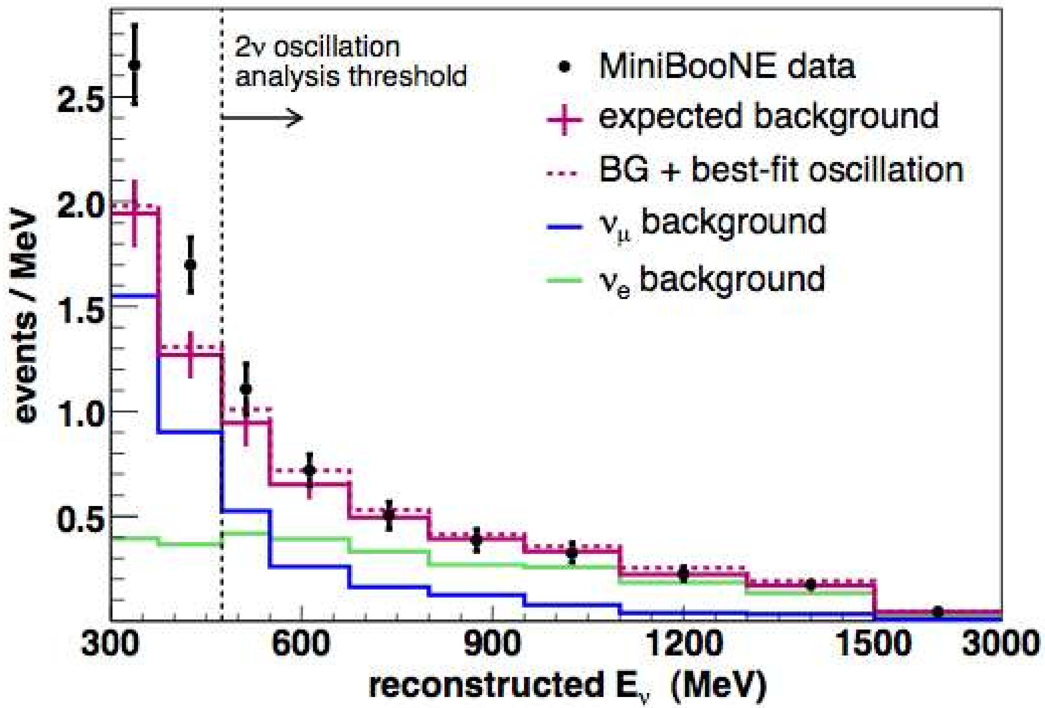
Incompatible with
the LSND experiment
at 98% CL.

Energy fit: $475 < E_\nu^{QE} < 3000$ MeV

Boosted decision tree analysis is consistent (both as counting experiment and in energy fit) with this

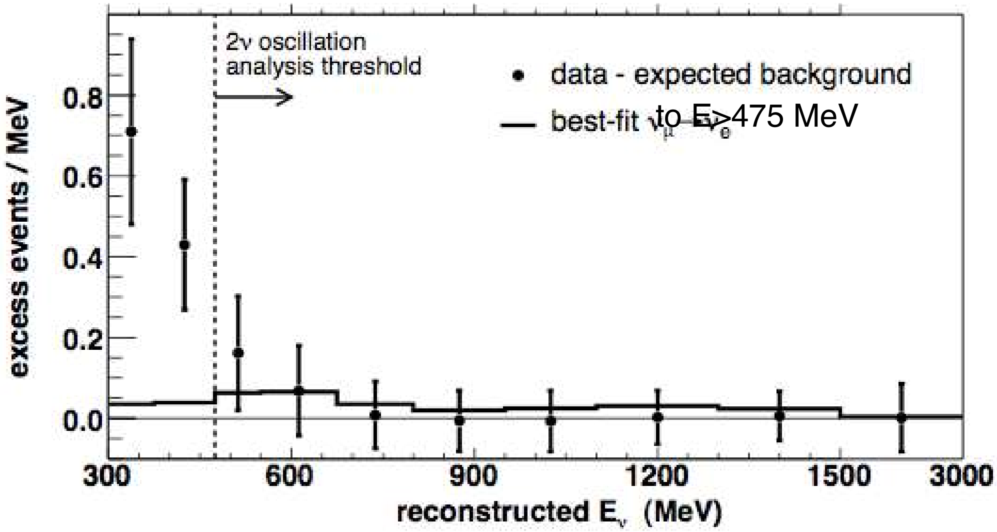
Across a broader range of energies:

$300 < E_\nu^{QE} < 3000$ MeV



96 ± 17 ± 20 events above background, for $300 < E_\nu^{QE} < 475$ MeV

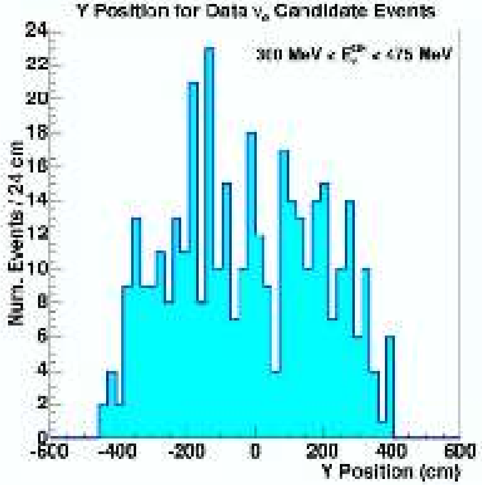
Background-subtracted:



MiniBooNE investigating low energy events: Need to understand these in any case:

- new physics
- background which must be understood for next class of experiments

What we already know about these events.....

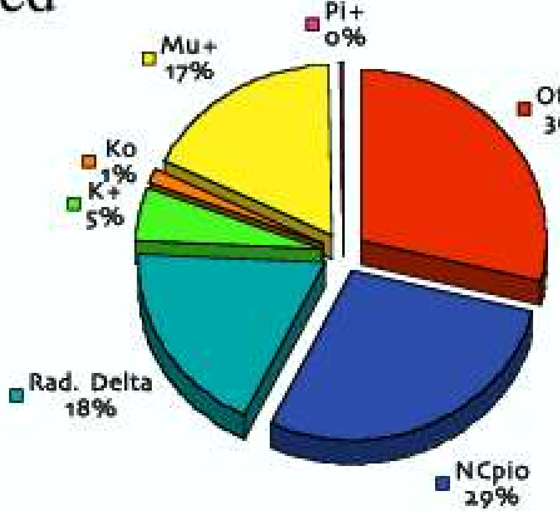


- They are spread throughout the run,
- They show no bias in event timing
- They show no bias in spatial distribution
  (they are not from outside)
- The backgrounds in this region are large,
  but they are well constrained

intrinsic ν_e 🟩 🟧 🟨 🟪
ν_μ mis-id 🟦 🟦 🟥

Likelihood Analysis

300 MeV to 475 MeV



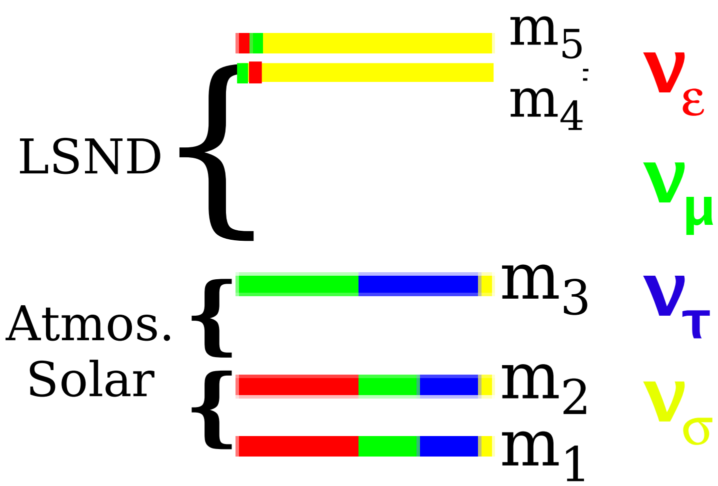
(outside)

1) LSND is wrong?

LSND is not standard muon neutrino to electron neutrino appearance

2) There are sterile neutrinos

3+1 and 3+2 models



Then these are the main mixing matrix elements

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

4) Something else unexpected?
- a) Background that has not been predicted
- b) Other new physics: neutrinos in the bulk,
  neutrino decay….

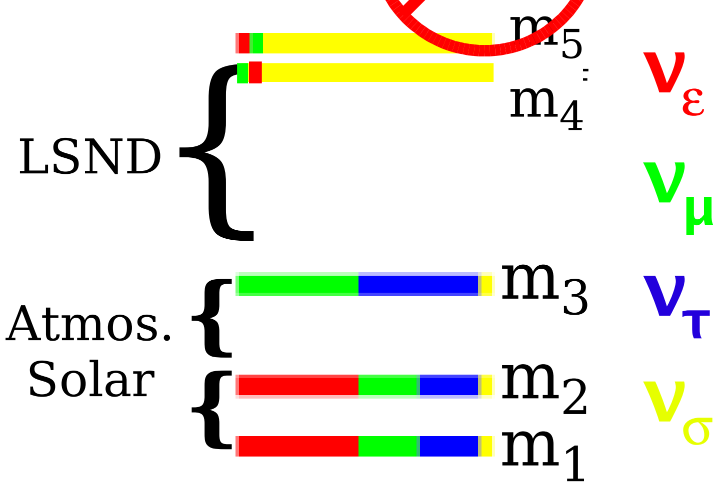
1) LSND is wrong?

3+1 models are ruled out but 3+2 and 3+3 fit MiniBooNE + LSND well
...tension with SBL disappearance expts.
...tension for some configurations with cosmological constraints

2) There are sterile neutrinos

~~3+1~~ and 3+2 models

Then these are the main mixing matrix elements



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\\ \nu_{s'}\\ \vdots\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\\ \nu_5\\ \vdots\end{pmatrix}$$

4) Something else unexpected?
   a) Background that has not been predicted
   b) Other new physics: neutrinos in the bulk,
      neutrino decay....

Are sterile neutrinos an asset for astrophysics?

The R-process needs a large neutron imbalance

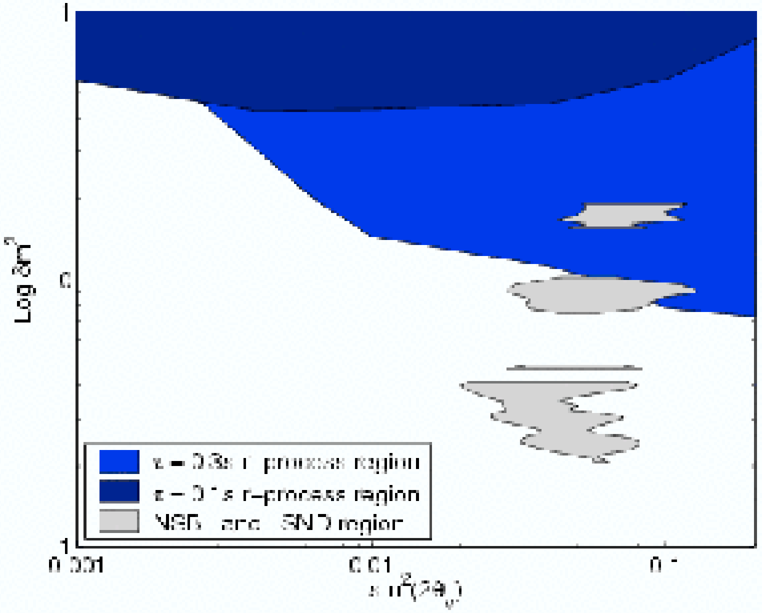
How do you create a very large neutron-imbalance?
First create an anti-electron neutrino rich environment.

$$\bar{\nu}_e + p \rightleftharpoons e^+ + n, \; \nu_e + n \rightleftharpoons e^- + p$$

... which works if the conditions are right (high electron density, right oscillation parameters) to produce a $\nu_e \rightarrow \nu_s$ "resonance"

Allowed ranges for oscillation to enable sufficient U production

Beun, Surman, McLaughlin & Hix, preliminary



Are they a problem for cosmology?

Cosmology constrains neutrino mass to ~1-2 eV

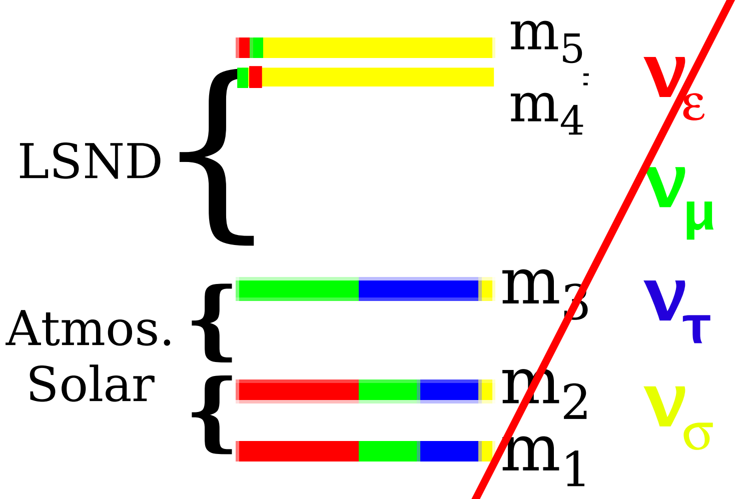
Depending on the sterile neutrino mass ordering, neutrino mass ~2-10 eV. So some constraints are there.

1) LSND is wrong?

- *New physics? Possible*
- *Background? Well constrained but we're still looking!*
- *MiniBooNE, SciBooNE and follow-on experiments will look*

2) There are sterile neutrinos

3+1 and 3+2 models



Then these are the main mixing matrix elements

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

4) Something else unexpected?
   a) Background that has not been predicted
   b) Other new physics: neutrinos in the bulk, neutrino decay....

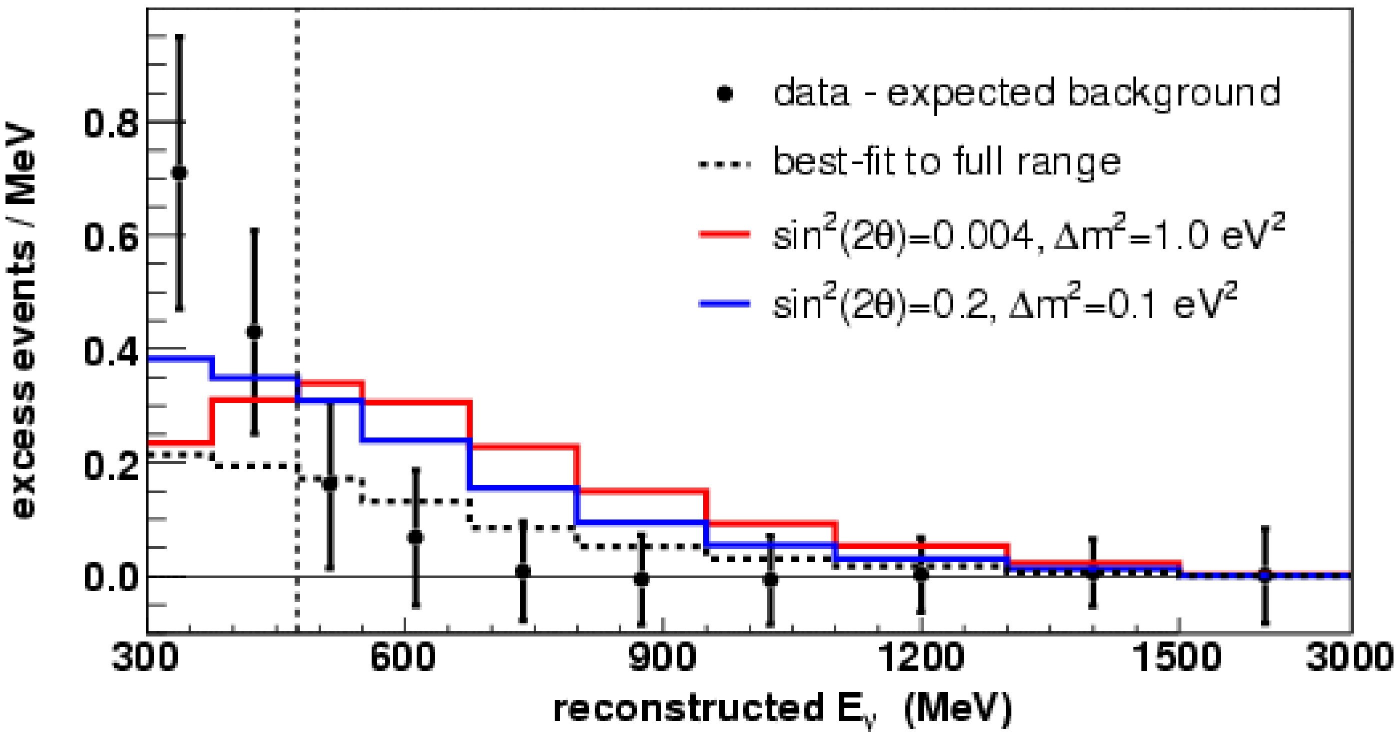
MiniBooNE rules out a two neutrino interpretation of LSND

Discrepancy at low energy is under study

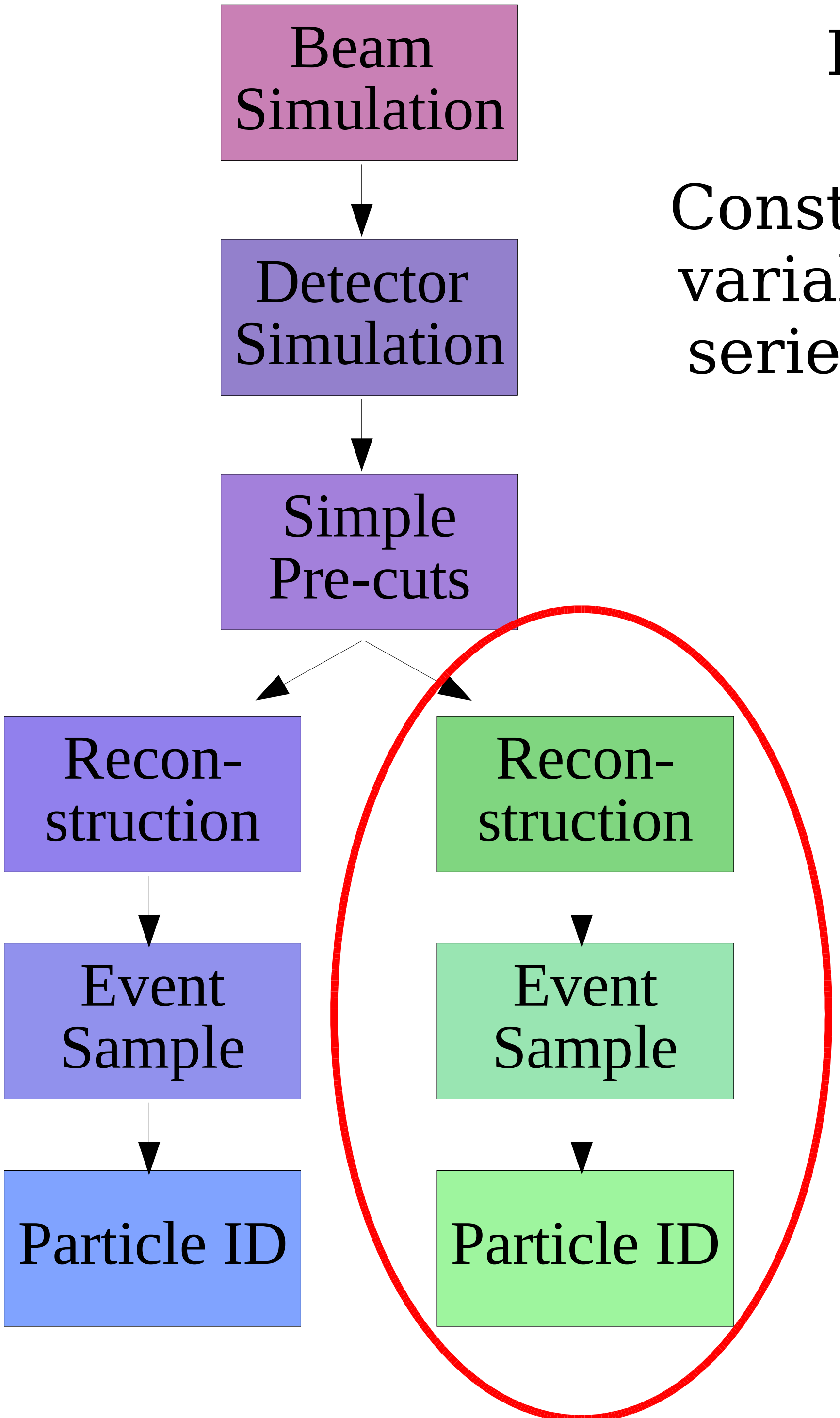
Fit to the > 300 MeV range:

Best Fit (dashed): (sin²2θ, Δm²) = (1.0, 0.03 eV²)

χ^2 Probability: 18%



Boosted Decision Trees

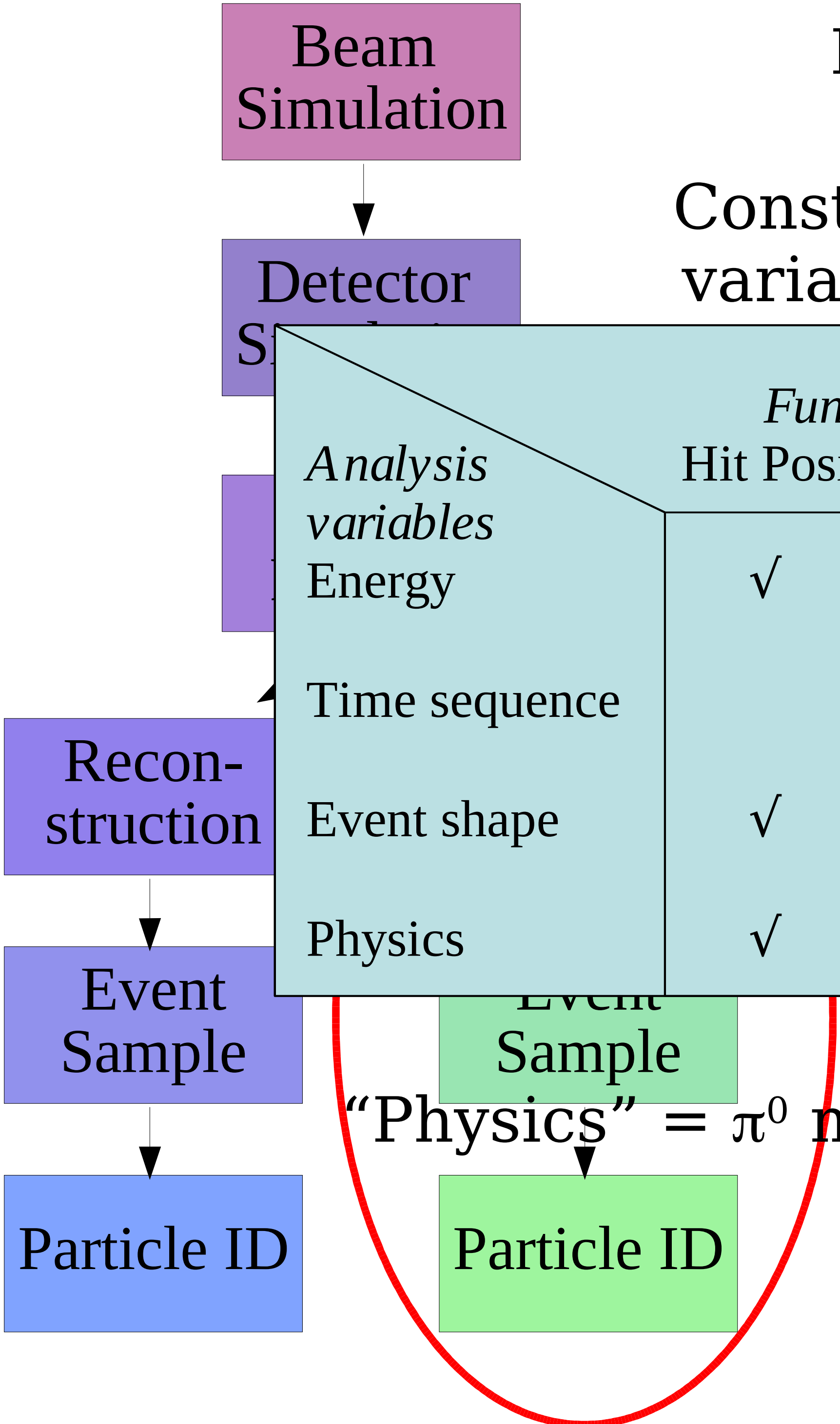


Construct a set of low-level analysis variables which are used to make a series of cuts to classify the events.

Convert “Fundamental Variables” into “Analysis Variables” then develop trees to score events as signal or background

This is an independent cross check of the Track Based Analysis

Boosted Decision Trees



Construct a set of low-level analysis variables which are used to make a

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Analysis variables	*Fundamental information* Hit Position	Charge	Hit Timing
Energy	√	√	
Time sequence		√	√
Event shape	√	√	√
Physics	√	√	√

“Physics” = π^0 mass, E_ν^{QE}, etc

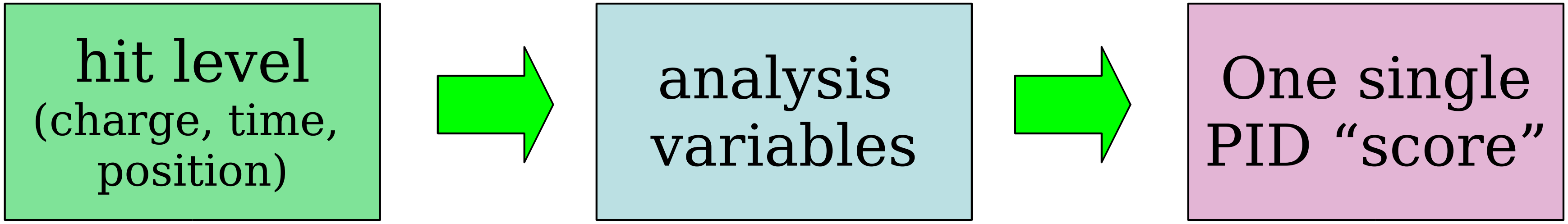
This is an independent cross check of the Track Based Analysis

Reduce Analysis Variables to a Single PID Variable

Boosted Decision Trees

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

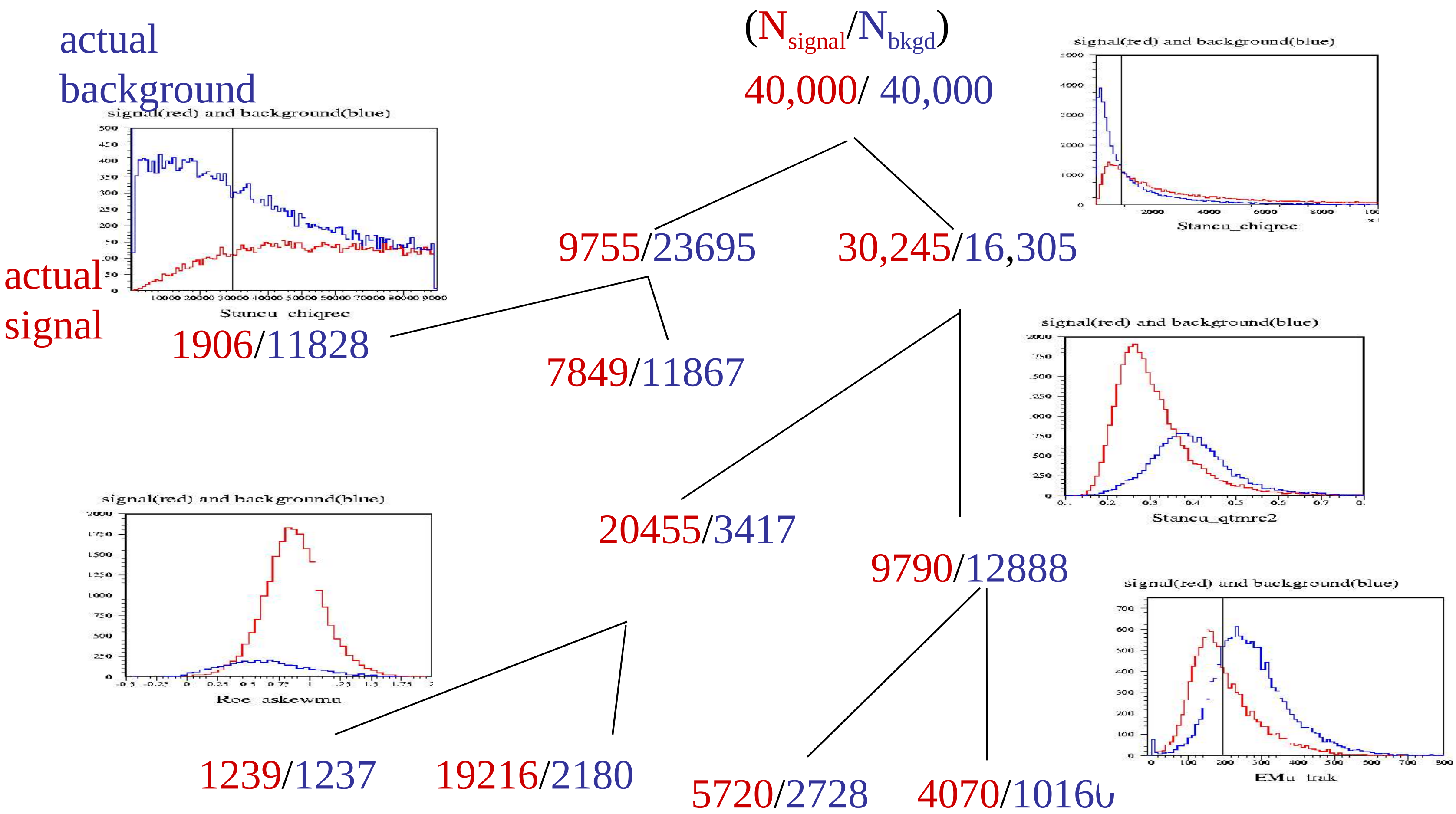
Byron P. Roe, et al.,
NIM A543 (2005) 577.


hit level
(charge, time, position)

analysis variables

One single PID “score”

Boosting uses Decision Trees
(sequential series of cuts)



(N_{signal}/N_{bkgd})

40,000/ 40,000

9755/23695 30,245/16,305

1906/11828 7849/11867

20455/3417 9790/12888

1239/1237 19216/2180 5720/2728 4070/1016

Continue decision tree until each “leaf”
is either very pure or statistically small.

Combine output of many trees → Boosting

Boosted Decions Trees

A set of deceision trees is created using Monte Carlo

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.

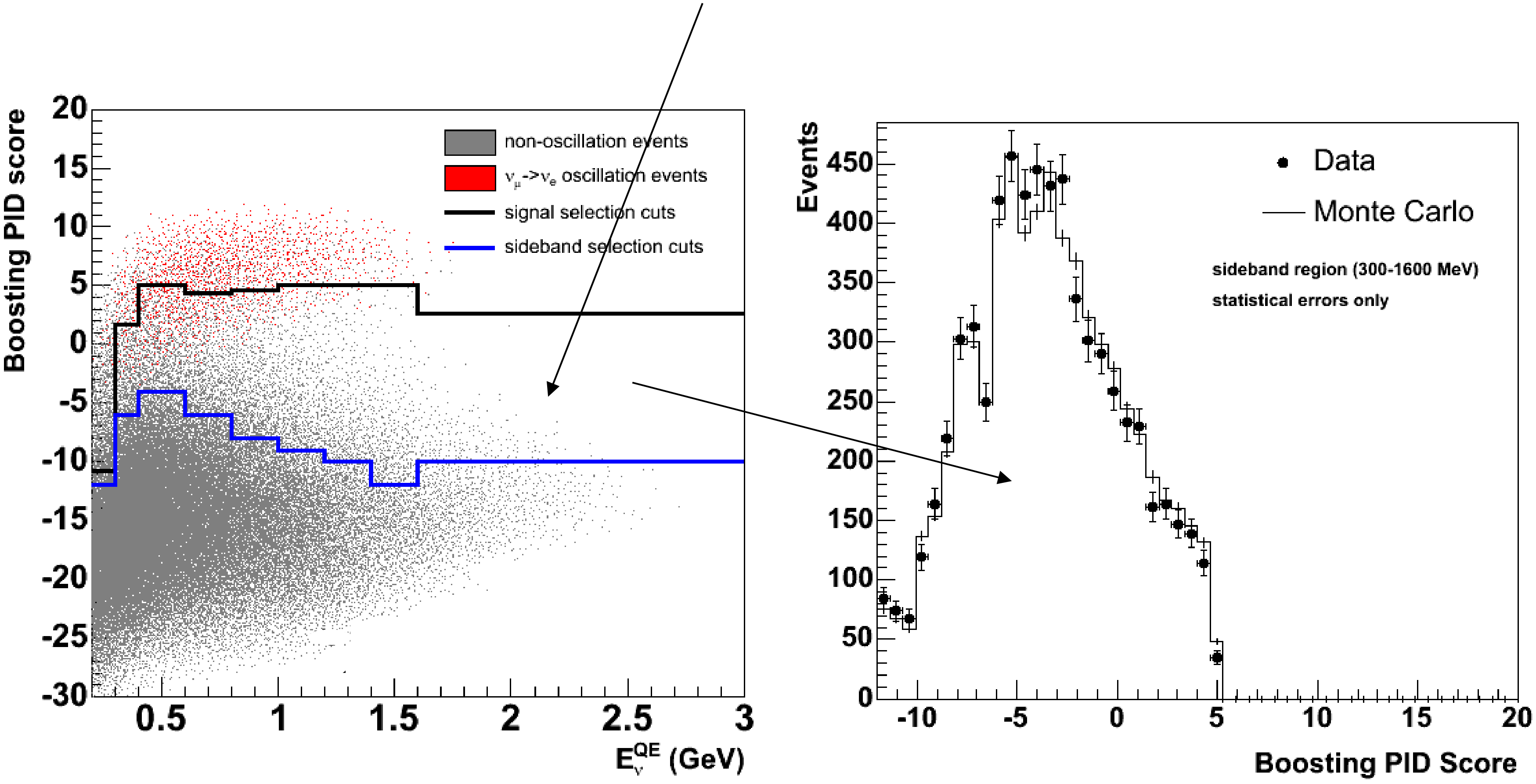
The resulting "score" for the event
can be thought of as a probability that it is signal.

Background-
like


negative positive

signal-like

BDT cuts on PID score as a function of energy.
We can define a “sideband” just outside of the signal region



MiniBooNE data constrains uncertainties!

Source of Uncertainty On ν_e background	TB/BDT error in %	Checked or Constrained by MB data	Further 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 and beam models	2.8 / 1.3	√	
ν-cross section	12.3 / 10.5	√	√
NC π^0 yield	1.8 / 1.5	√	
External ints. (“Dirt”)	0.8 / 3.4	√	
Optical model	6.1 / 10.5	√	√
DAQ electronics model	7.5 / 10.8	√	

Different analyses are sensitive to different uncertainties