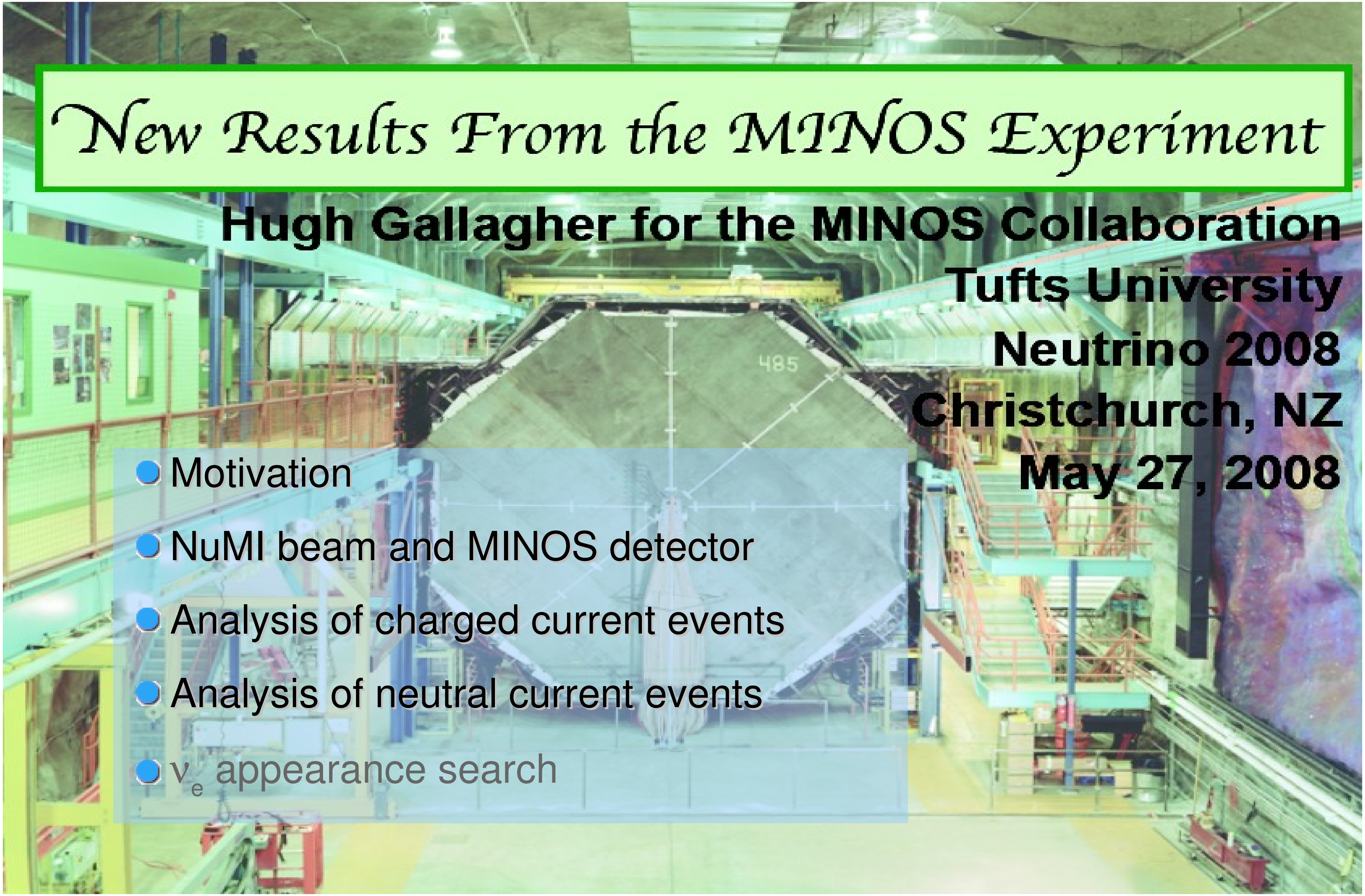
Summary of atmospheric and long baseline neutrinos at Neutrino 08 in Christchurch, NZ

MINOS, Super Kamiokande, MiniBooNE, OPERA



New Results From the MINOS Experiment

Hugh Gallagher for the MINOS Collaboration

Tufts University

Neutrino 2008

Christchurch, NZ

May 27, 2008

- Motivation
- NuMI beam and MINOS detector
- Analysis of charged current events
- Analysis of neutral current events
- ν_e appearance search

Outline

1) Introduction

2) The MINOS Experiment and NuMI Facility

3 times more POT

3) Analysis of Charged Current Events
   - Precision measurements of Δm^2, $\sin^2(2\theta)$
   - Oscillations vs. alternative hypotheses

NEW

4) Analysis of Neutral Current Events
   - Do ν_μ oscillate to sterile neutrinos?

5) ν_e Appearance

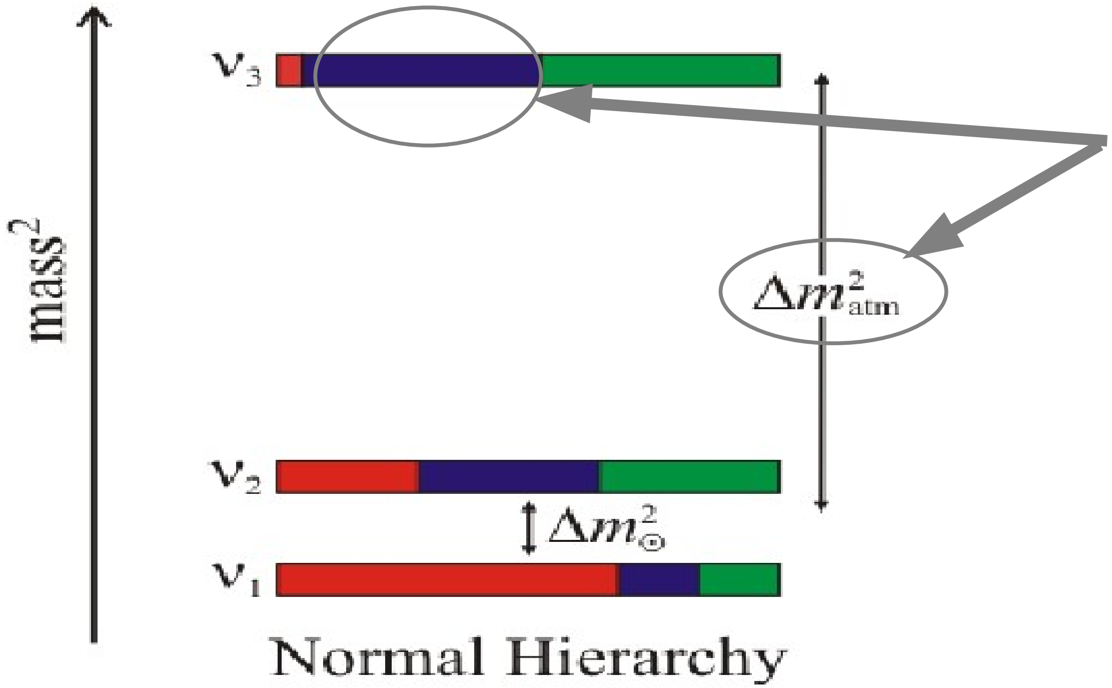
6) Conclusion

Published:
Phys.Rev.Lett.97,191801,2006
Phys.Rev.D77:072002,2008
1.27 x 10^{20} POT

This Analysis:
3.36 x 10^{20} POT

The Goals of MINOS

H. Gallagher
Tufts University
Neutrino 2008
May 27, 2008



Make precision measurements of the oscillation parameters Δm^2 and $\sin^2(2\theta)$.

Search for subdominant oscillations at Δm^2_{atm}.

Confirm oscillations vs. exotic explanations (decay, decoherence).

Mixing to sterile neutrinos?

Use the magnetized detectors to make CPT tests.

Far Detector-only studies of atmospheric neutrinos and cosmic rays.

Near detector-only measurements of neutrino interaction physics. 7

One mass scale dominance: $\Delta m^2_{atm} >> \Delta m^2_{\odot}$

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{atm})\sin^2\left(\frac{1.27\Delta m^2_{atm}L}{E}\right)$$

The MINOS Experiment

H. Gallaghe
Tufts University
Neutrino 2008
May 27, 2008

MINOS (Main Injector Neutrino Oscillation Search) – a long baseline neutrino oscillation experiment:

Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.

A "Near Detector" at Fermilab to measure the beam composition and energy spectrum.

A "Far Detector" deep underground in the Soudan Mine, Minnesota, to search for evidence of oscillations.

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Neutrinos at the Main Injector (NuMI)

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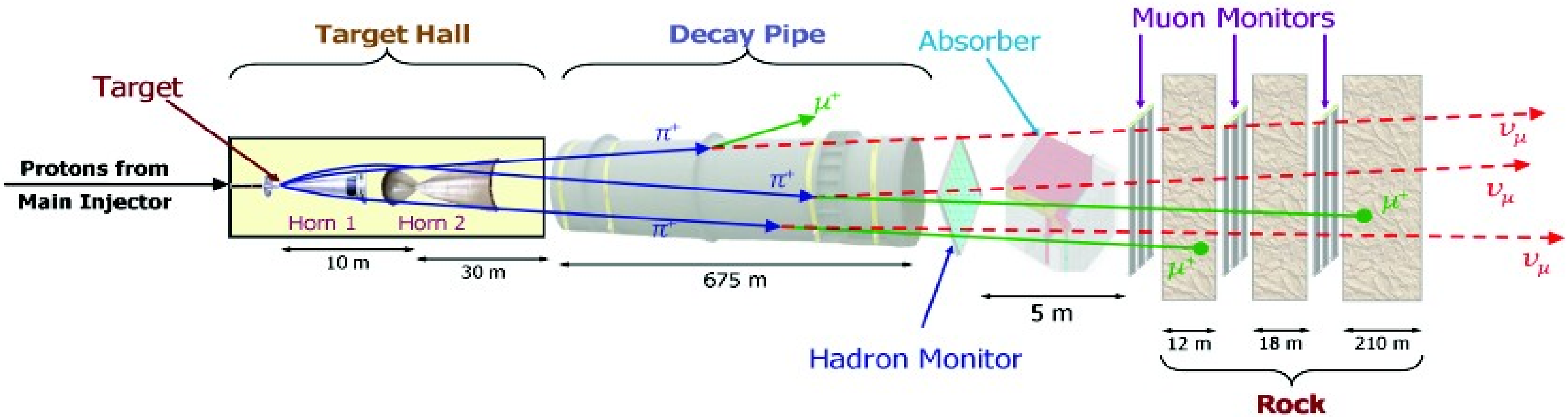
Neutrino 2008
May 27, 2008



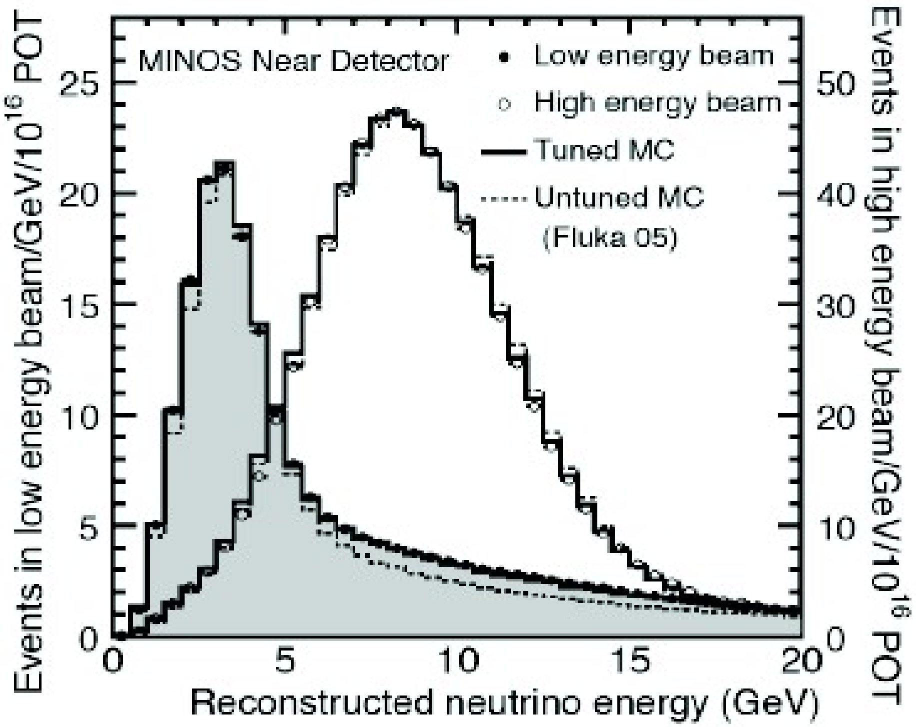
Beam energy spectrum can be tuned by varying the relative positions of target and horns.

In the LE configuration, interactions are:

$$92.9\%\ \nu_\mu,\ 5.8\%\ \bar{\nu}_\mu,\ 1.3\%\ \nu_e + \bar{\nu}_e$$

Performance (Week of 5/12):

- 10μs spill of 120 GeV protons every 2.2s
- Intensity: 3.0×10^{13} POT/spill
- 0.275 MW beam power
- 10^{18} POT /day



NuMI Beam Performance

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Neutrino 2008
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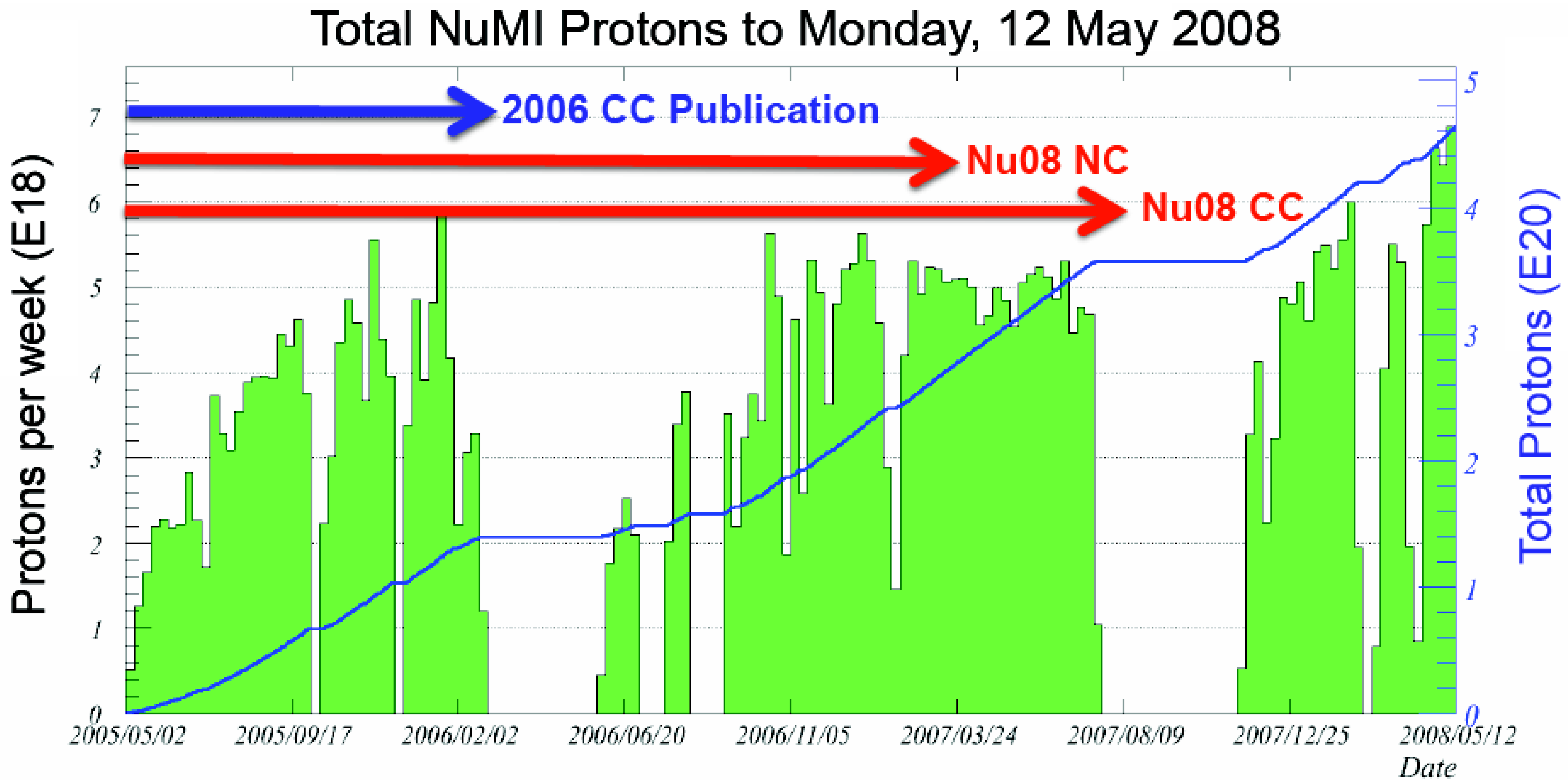


(2006 publication)
RUN I - 1.27×10^{20} POT

RUN IIa
1.23×10^{20} POT

RUN III
1.1×10^{20} POT

Other running
HE beam: 0.15×10^{20} POT

RUN IIb
0.71×10^{20} POT

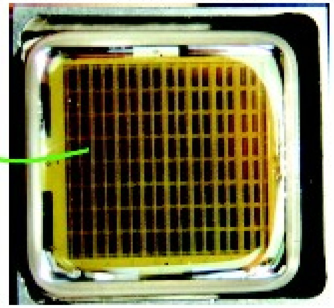
The MINOS Detectors

H. Gallag
Tufts Universit
Neutrino 200
May 27, 2008

Functionally equivalent detectors:

- 2.54 cm thick magnetized steel plates
- 4.1 x 1 cm co-extruded scintillator strips (MINOS developed technology)
- optical fiber readout to multi-anode PMTs

Hamamatsu M-64



- 5.4 kton
- 8 x 8 x 30 m
- 484 steel/scintillator planes
- M16 PMT, x8 multiplexing
- VA electronics

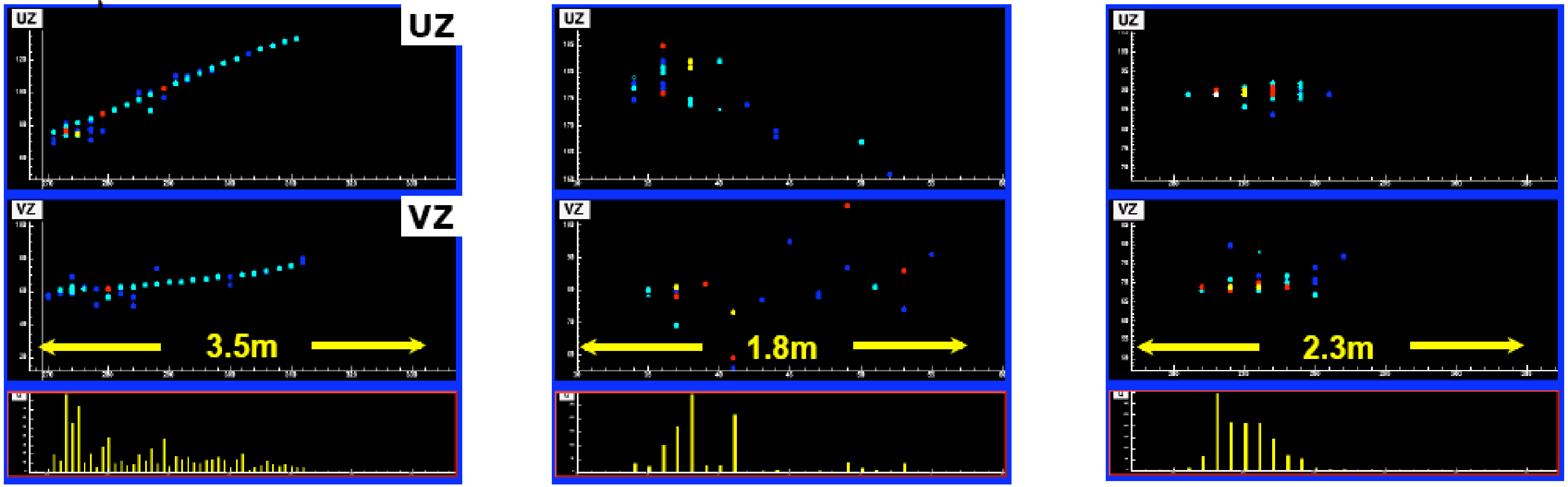
- 1 kton
- 3.8 x 4.8 x 15 m
- 282 steel, 153 scintillator planes
- M64 PMT
- Fast QIE electronics

Event Topologies

H. Gallagher
Tufts University
Neutrino 2008
May 27, 2008

Monte Carlo

ν_μ CC Event | NC Event | ν_e CC Event



- long μ track+ hadronic activity at vertex
- short event, often diffuse
- short, with typical EM shower profile

$$E_\nu = E_{shower} + P_\mu$$

$55\%/\sqrt{E}$ 6% range, 10% curvature

Charged Current Analysis

Precision measurement of Δm^2 and $\sin^2(2\theta)$

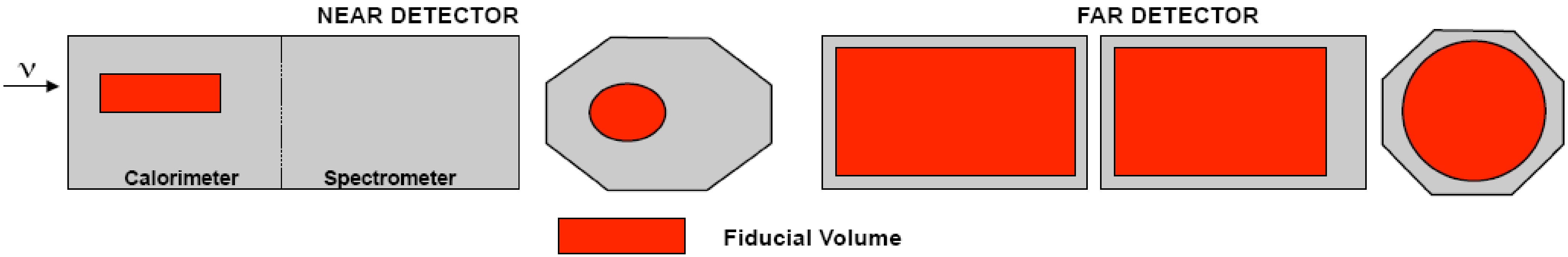
Testing the oscillation hypothesis

CC Event Selection

ν_μ CC-like events are selected in the following way:

Event must contain at least one good reconstructed track

The reconstructed track vertex should be within the fiducial volume of the detector:



Coil hole cut

The fitted track should have negative charge (selects ν_μ)

Cut on kNN-based Particle ID parameter which is used to separate CC and NC events.

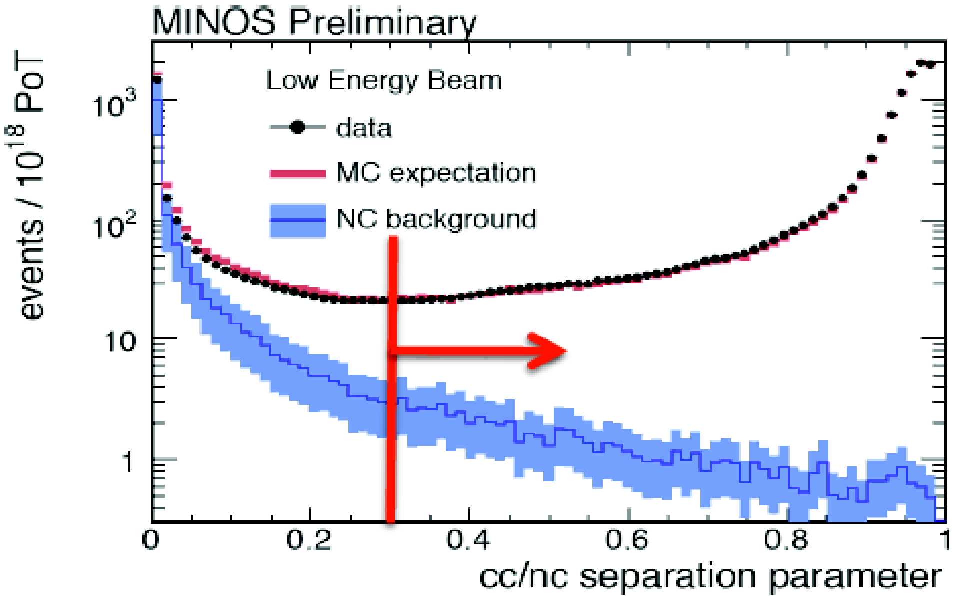
CC Event Selection

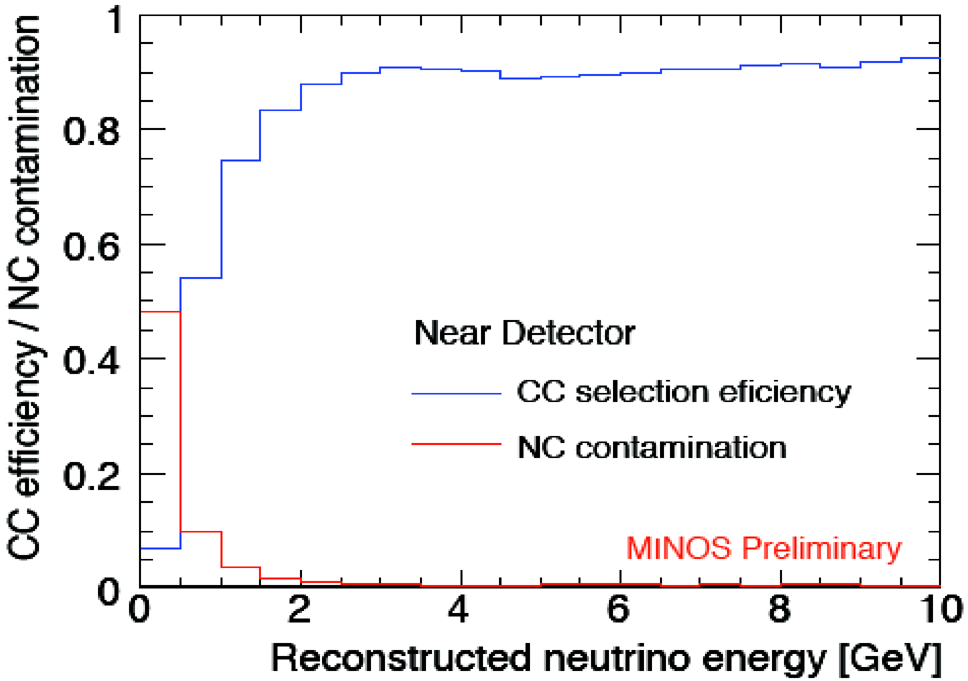
CC / NC Event classification is performed with a new k-nearest neighbor (kNN) based algorithm with four inputs:

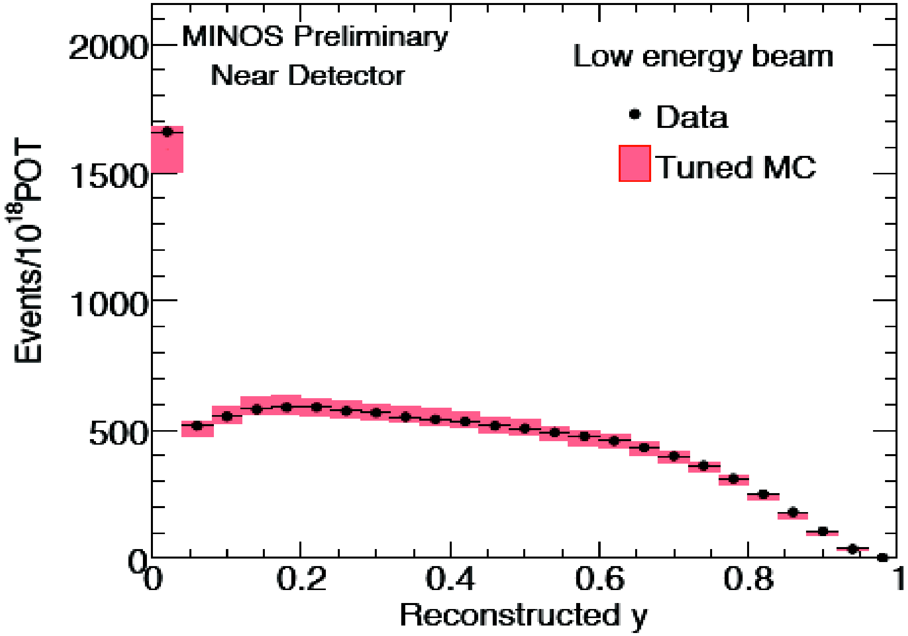
1. Track length (planes)

For hits on the track:

2. Mean pulse height
3. Fluctuation in pulse height
4. Transverse track profile







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Far Detector Data Quality - LE

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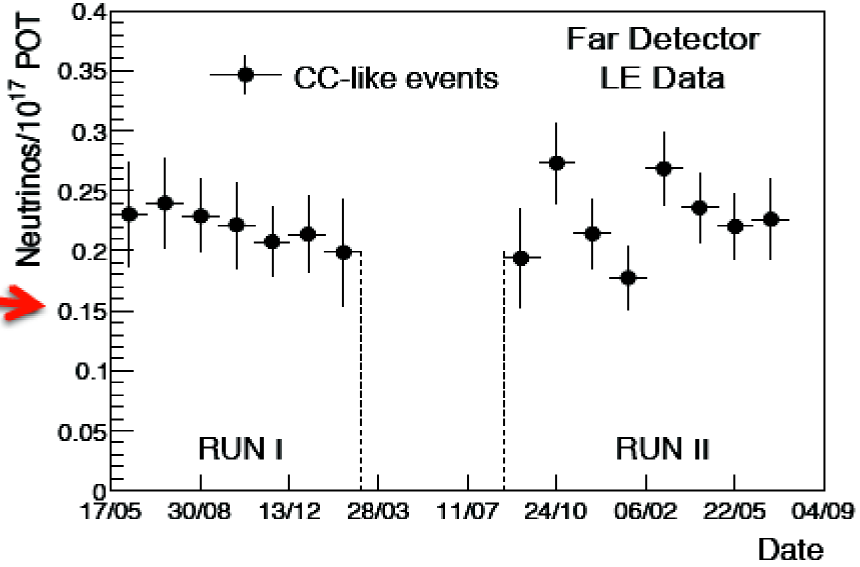
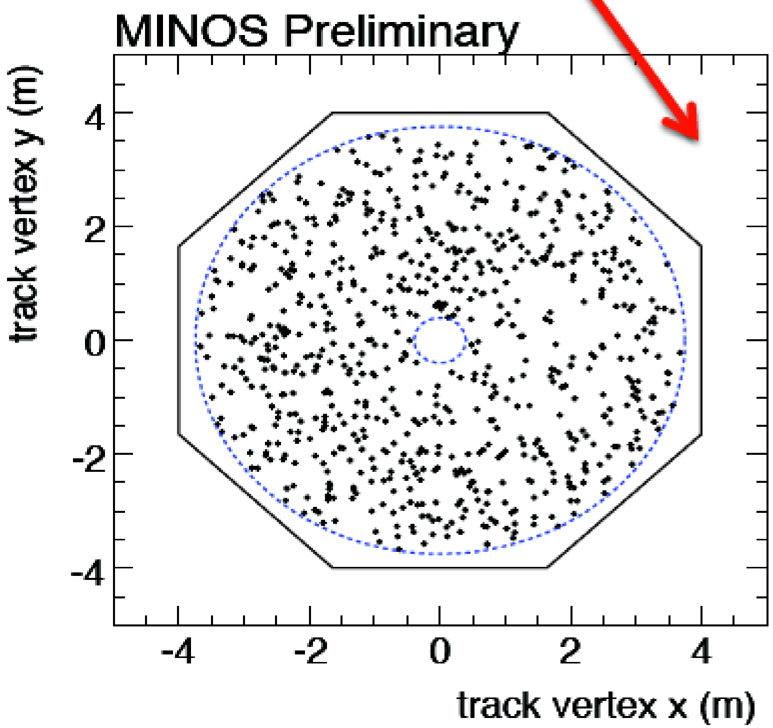
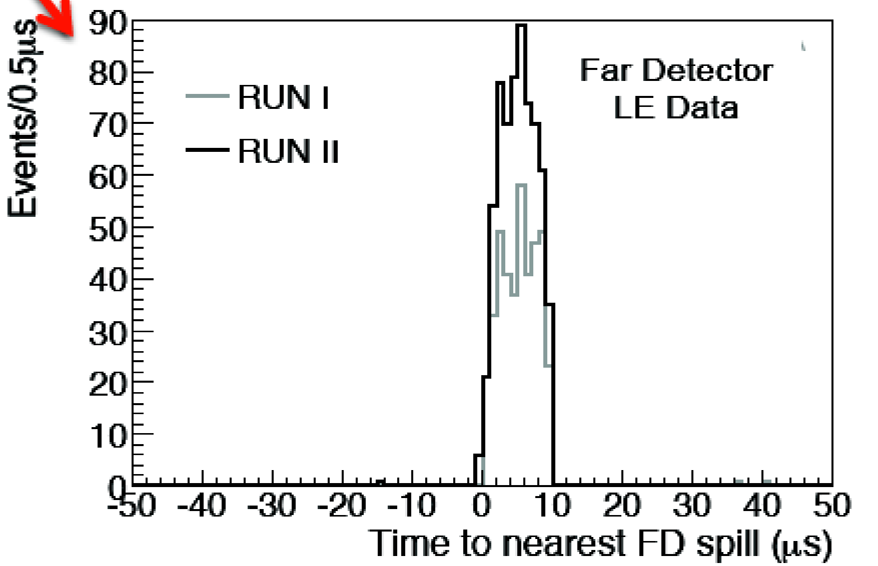
Neutrino 200...
May 27, 2008

848 events observed in the FD
1065±60 (syst) expected without oscillations

Data are well described by MC:
- Events/POT over this exposure
- Event time
- Spatial vertex distributions



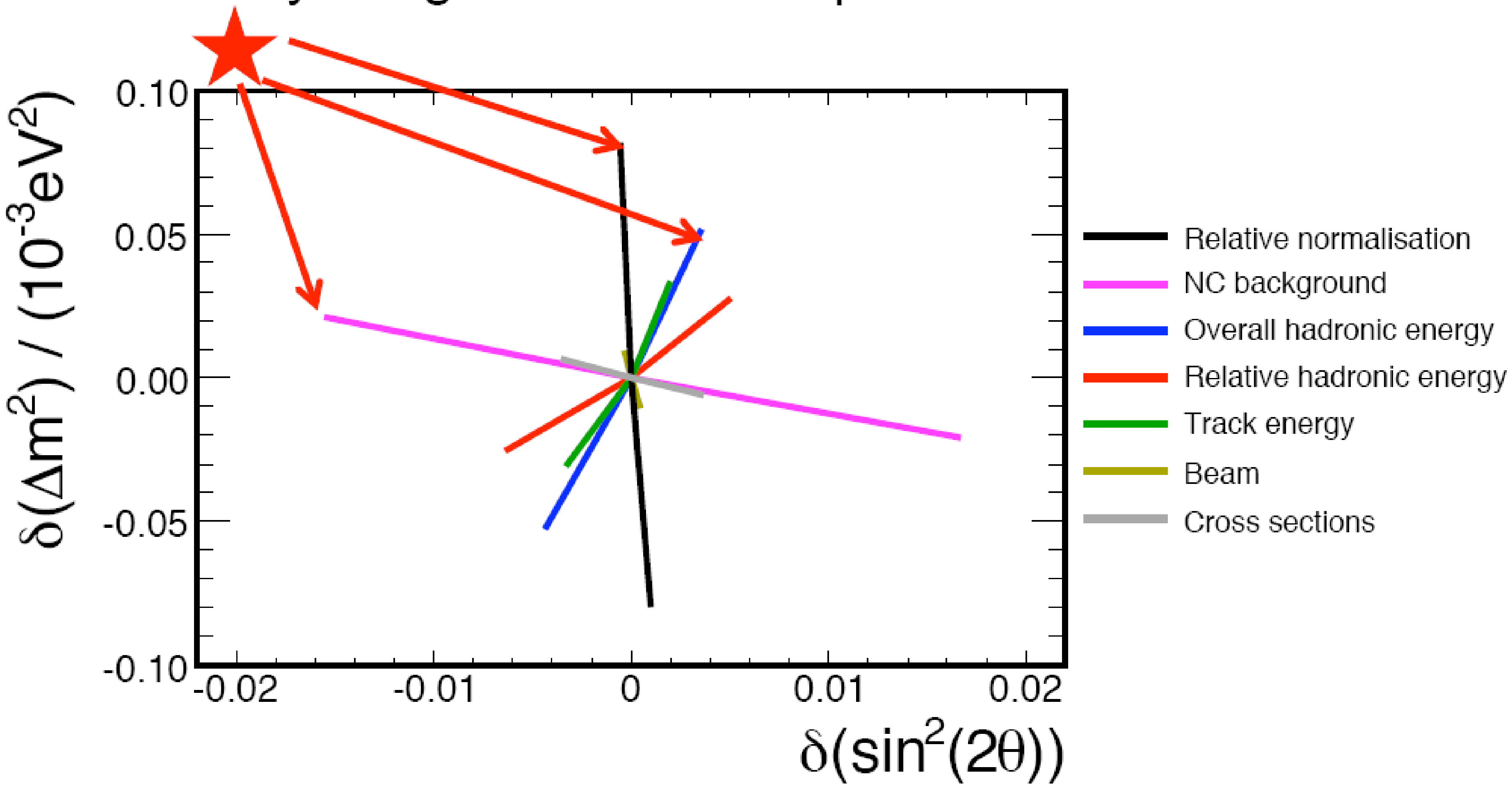




Systematic Uncertainties

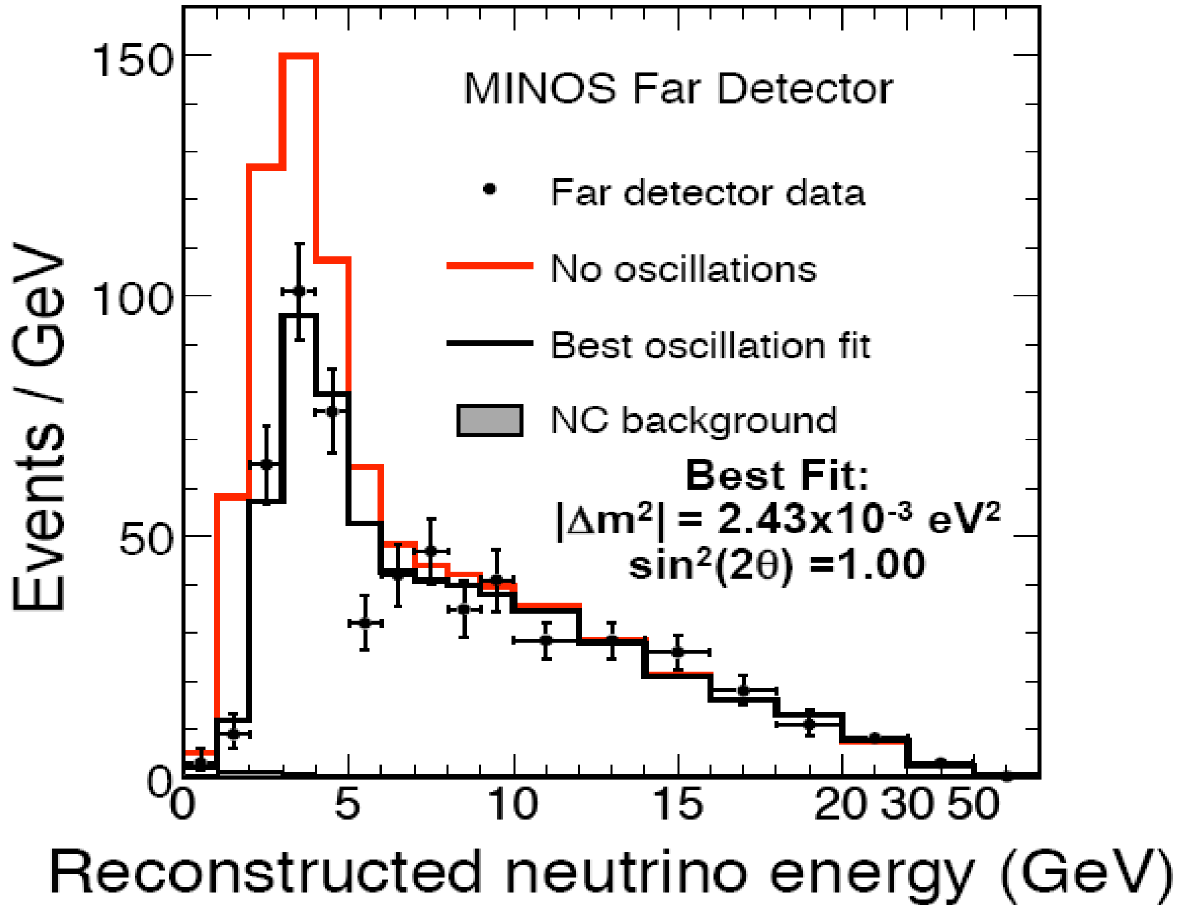
H. Gallagher
Tufts University
Neutrino 2008
May 27, 2008

The impact of different sources of systematic uncertainty were evaluated by fitting modified MC in place of the data:



★ *The three largest will be included as nuisance parameters in the oscillation fit.*

Energy Spectrum



Fit the energy distribution to the oscillation hypothesis:

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Including the three largest sources of systematic uncertainty as nuisance parameters:

- Absolute hadronic energy scale: 10.3%
- Normalization: 4%
- NC contamination: 50%

$$\chi^2 = \sum_{nbins}(2(e_i - o_i) + 2\, o_i \ln(o_i/e_i)) + \sum_{nsys}\frac{\Delta s_j^2}{\sigma_{s_j}^2}$$

$\chi^2/\text{ndof} = 90/97$

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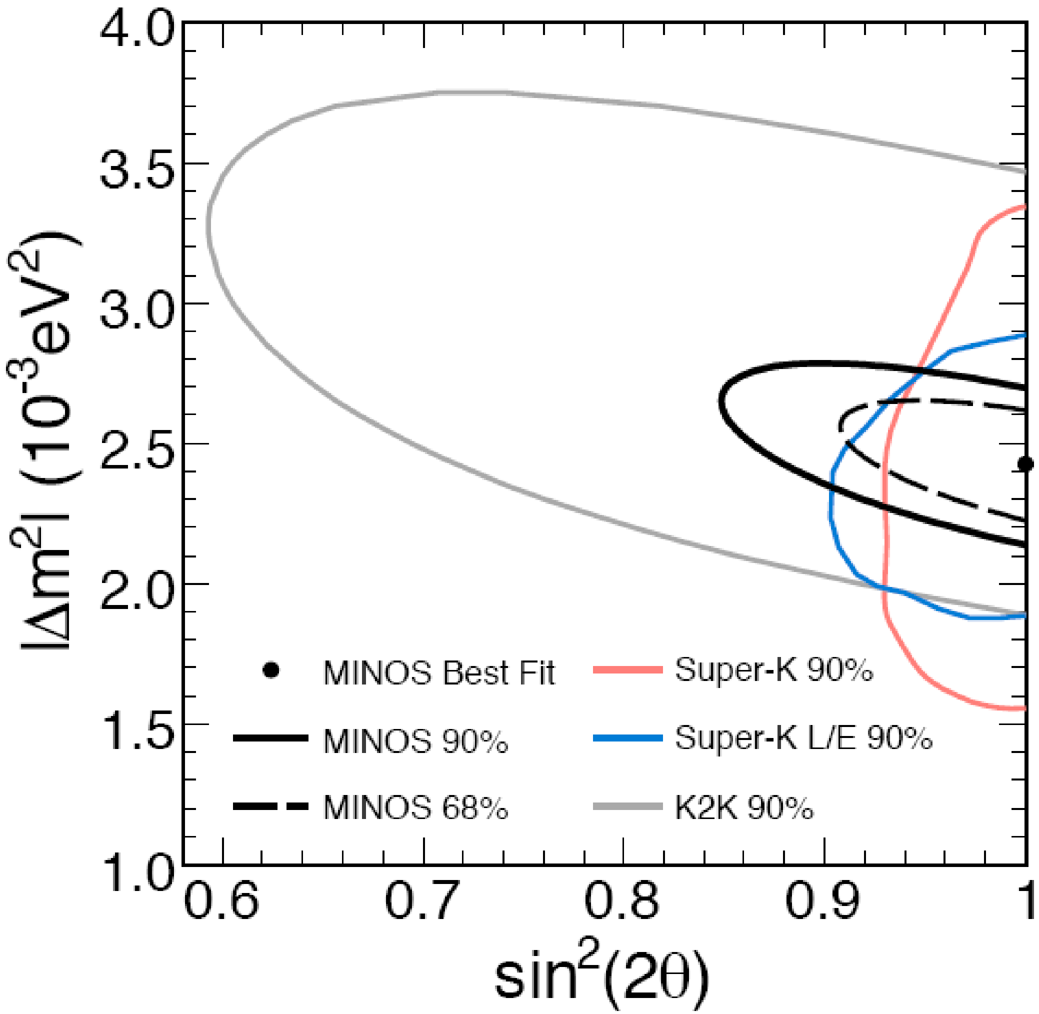
Allowed Region



$|\Delta m^2|$ =(2.43±0.13) x 10^{-3} eV^2
(68% C.L.)

$\sin^2(2\theta)$ > 0.90
(90% C.L.)

χ^2/ndof = 90/97

Fit is constrained to the physical region.

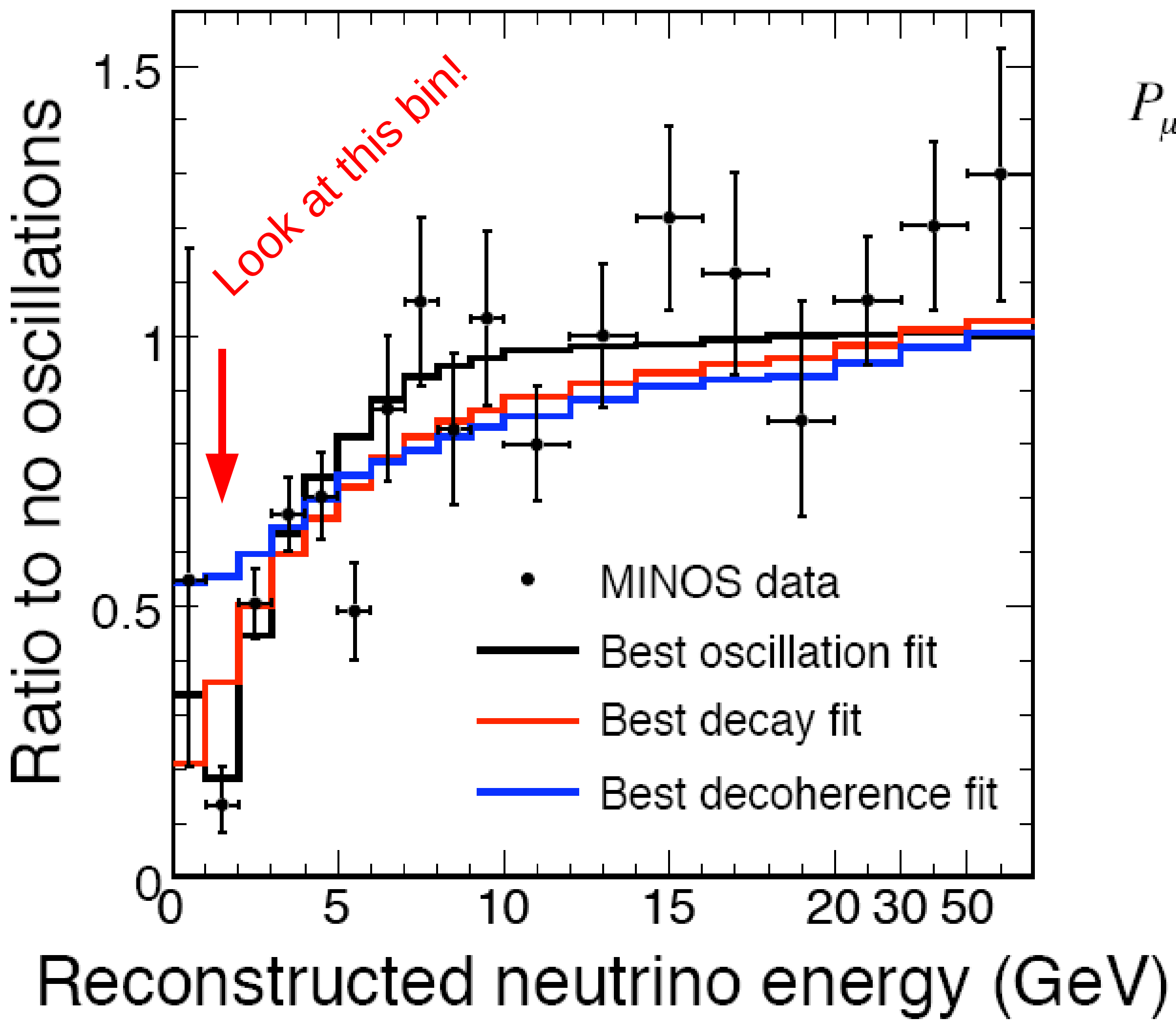
Unconstrained:

$|\Delta m|^2$ = 2.33 x 10^{-3} eV^2

$\sin^2(2\theta)$=1.07

$\Delta\chi^2$=-0.6

Alternative Hypotheses



Decay:

$$P_{\mu\mu} = (\sin^2\theta + \cos^2\theta \ \exp(-\alpha L/2E))^2$$

V. Barger *et al.*, PRL82:2640(1999)

χ^2/ndof = 104/97

$\Delta\chi^2 = 14$

disfavored at 3.7σ

Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006 (2003)

χ^2/ndof = 123/97

$\Delta\chi^2 = 33$

disfavored at 5.7σ

Neutral Current Analysis

Searching for evidence of oscillations to sterile neutrinos.

Motivation

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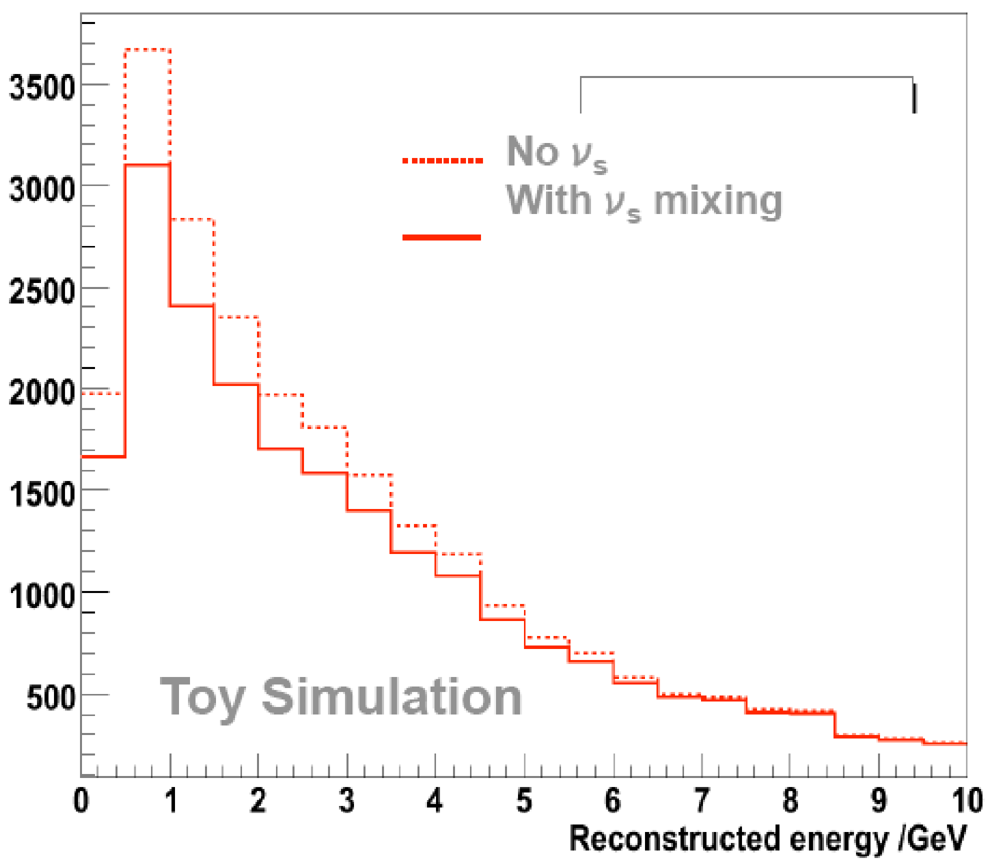
Tufts University
Neutrino 2008
May 27, 2008

In the standard 3-flavor picture neutrinos are oscillating between ν_e, ν_μ, ν_τ.

Oscillations into ν_s affect number of observed NC interactions as ν_s do not interact in the detector.

Look for NC disappearance at the Far Detector::

- Sterile neutrino mixing would deplete NC energy spectrum



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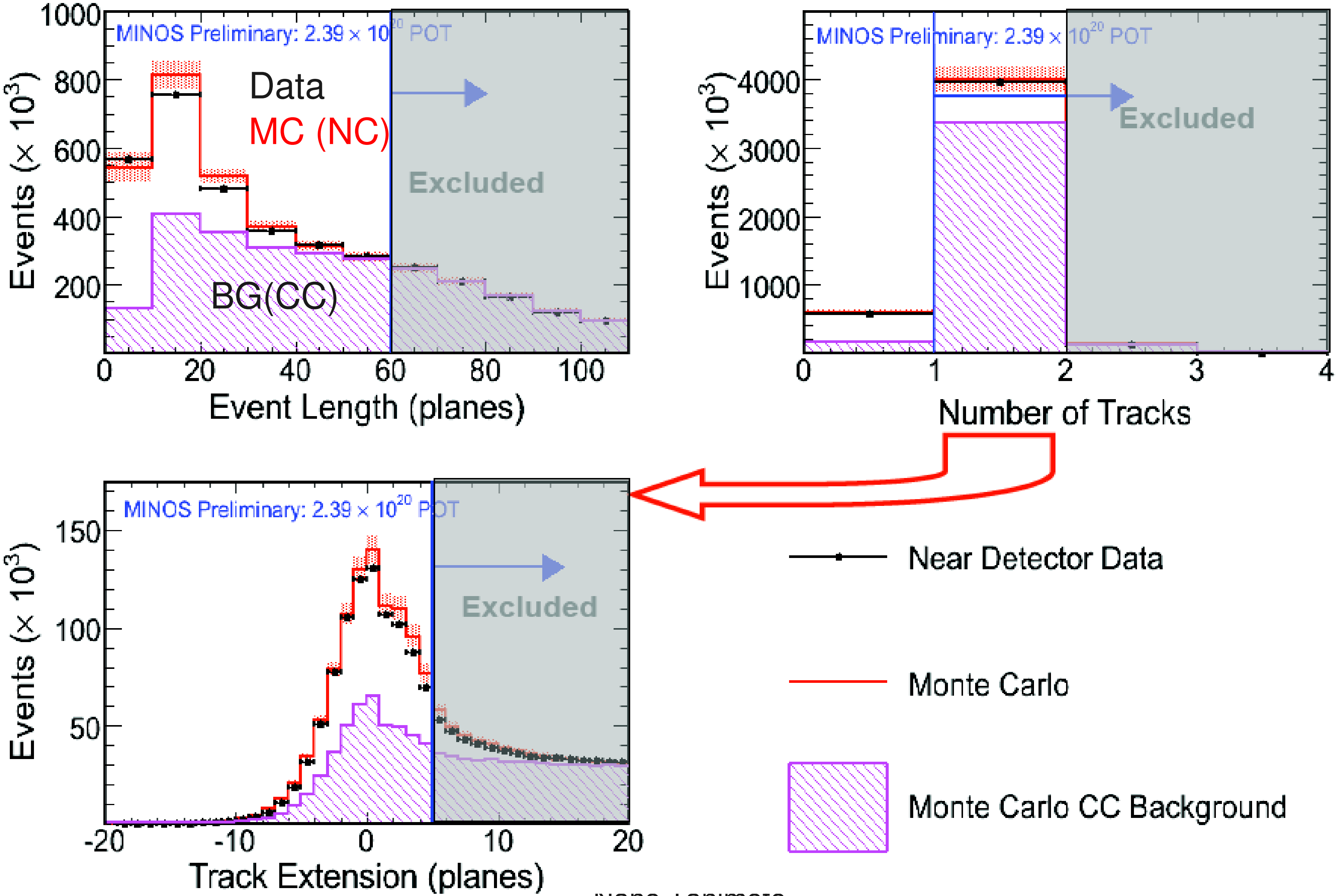
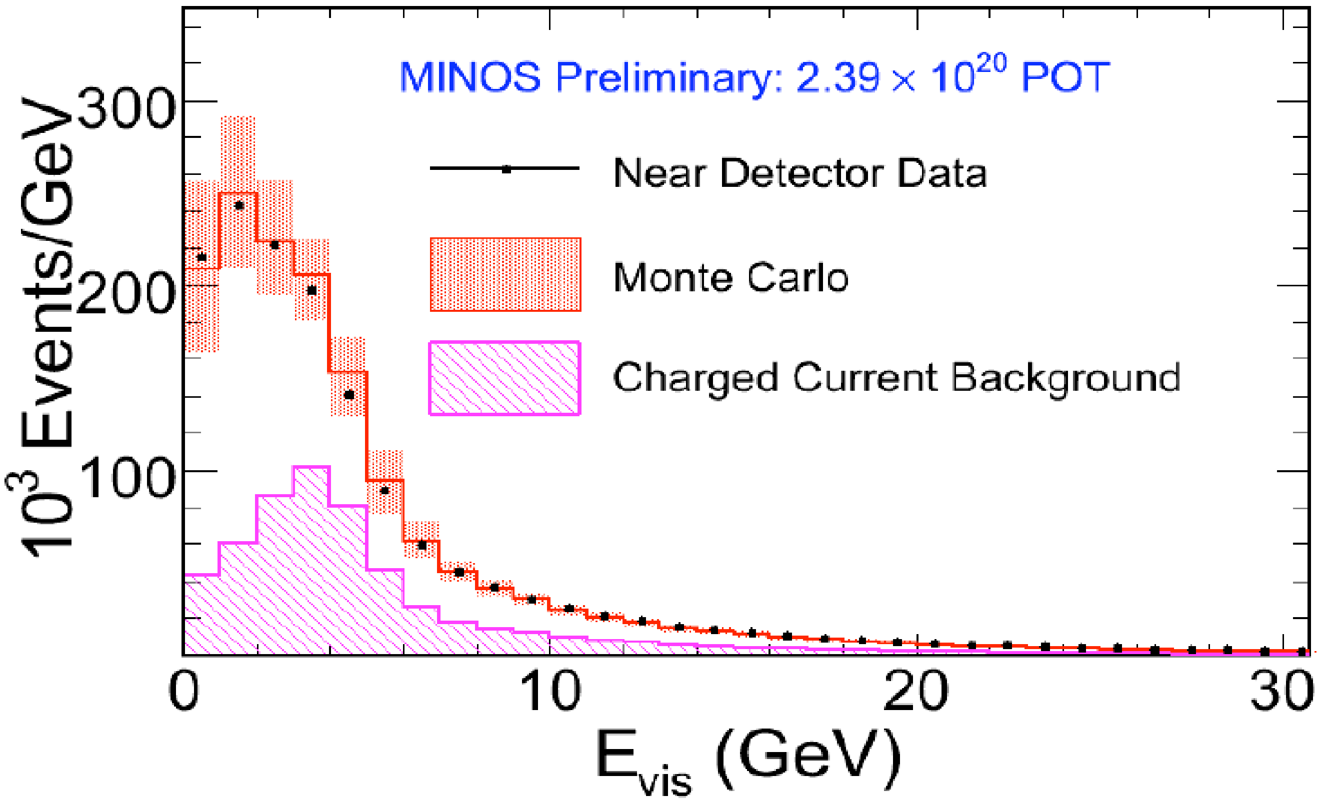
Near Detector NC Selection



NC Energy Spectrum

H. Gallagher
Tufts University
Neutrino 2008
May 27, 2008

NC selected Data and MC energy spectra for Near Detector



NC events are selected with 90% efficiency and 60% purity

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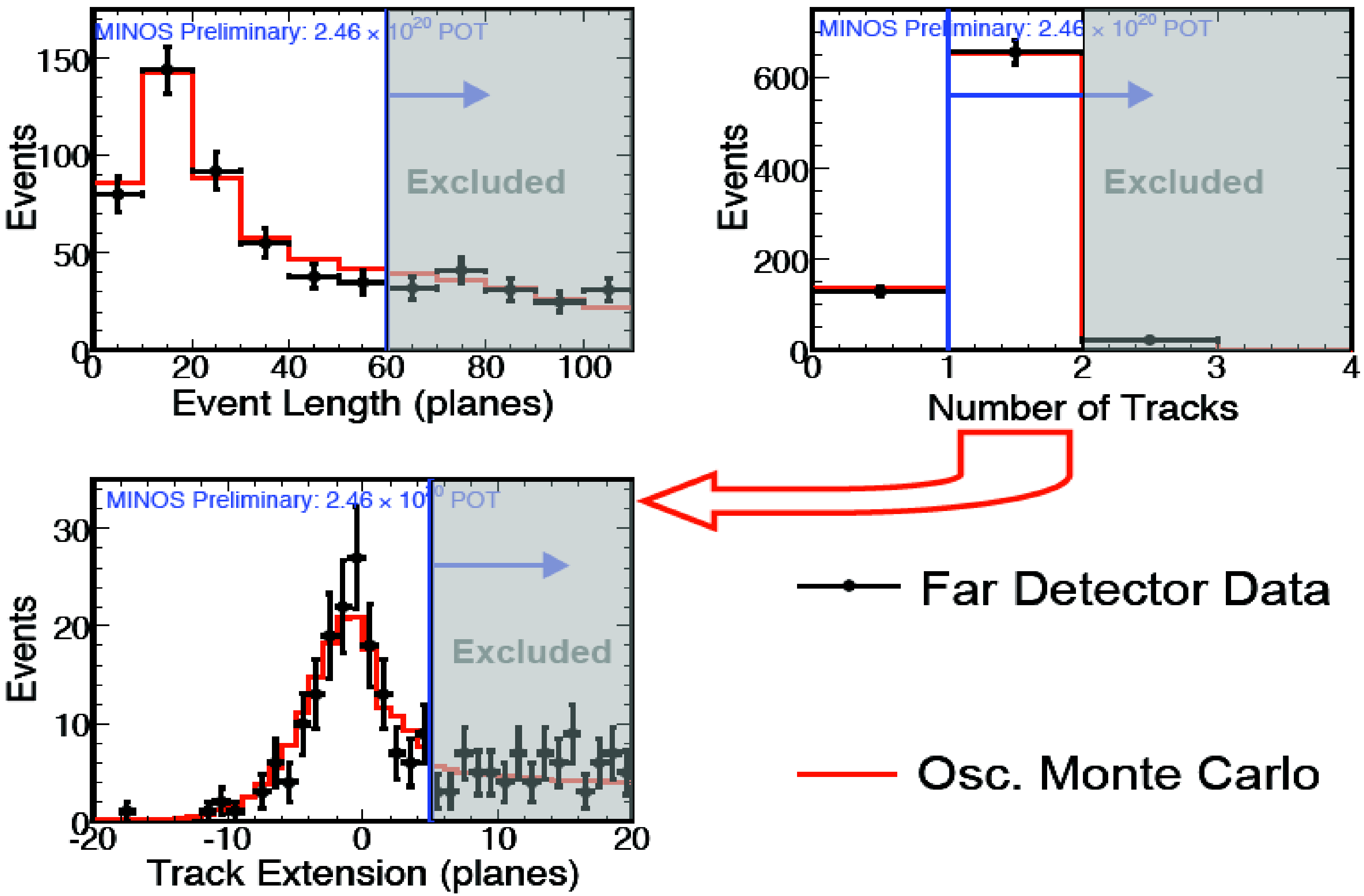
→Demonstrated NC events can be reconstructed with ND.
Do the same thing with FD.

Far Detector NC Selection

The FD selection uses the same variables as the ND selection, with identical cut values

MC oscillated with 2007 MINOS CC best fit: $\Delta m^2 = 2.38 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2(2\theta)=1$



3 Flavor Analysis

Compare the NC energy spectrum with the expectation of standard 3-flavor oscillation physics.

Pick the oscillation parameter values

- $\sin^2 2\Theta_{23} = 1$
- Δm^2_{32} = 2.38×10^{-3} eV^2
- Δm^2_{21} = 7.59×10^{-5} eV^2, $\Theta_{12} = 0.61$ from KamLAND+SNO
- Θ_{13} = 0 or 0.21 (normal MH, $\delta = 3\pi/2$) from CHOOZ Limit
- Note that CC ν_e are classified as NC by the analysis

Make comparison in terms of number of events in different energy ranges

- 0-3 GeV
- 0-5 GeV
- All events (0-120 GeV)

Result is #σ (dis-)agreement

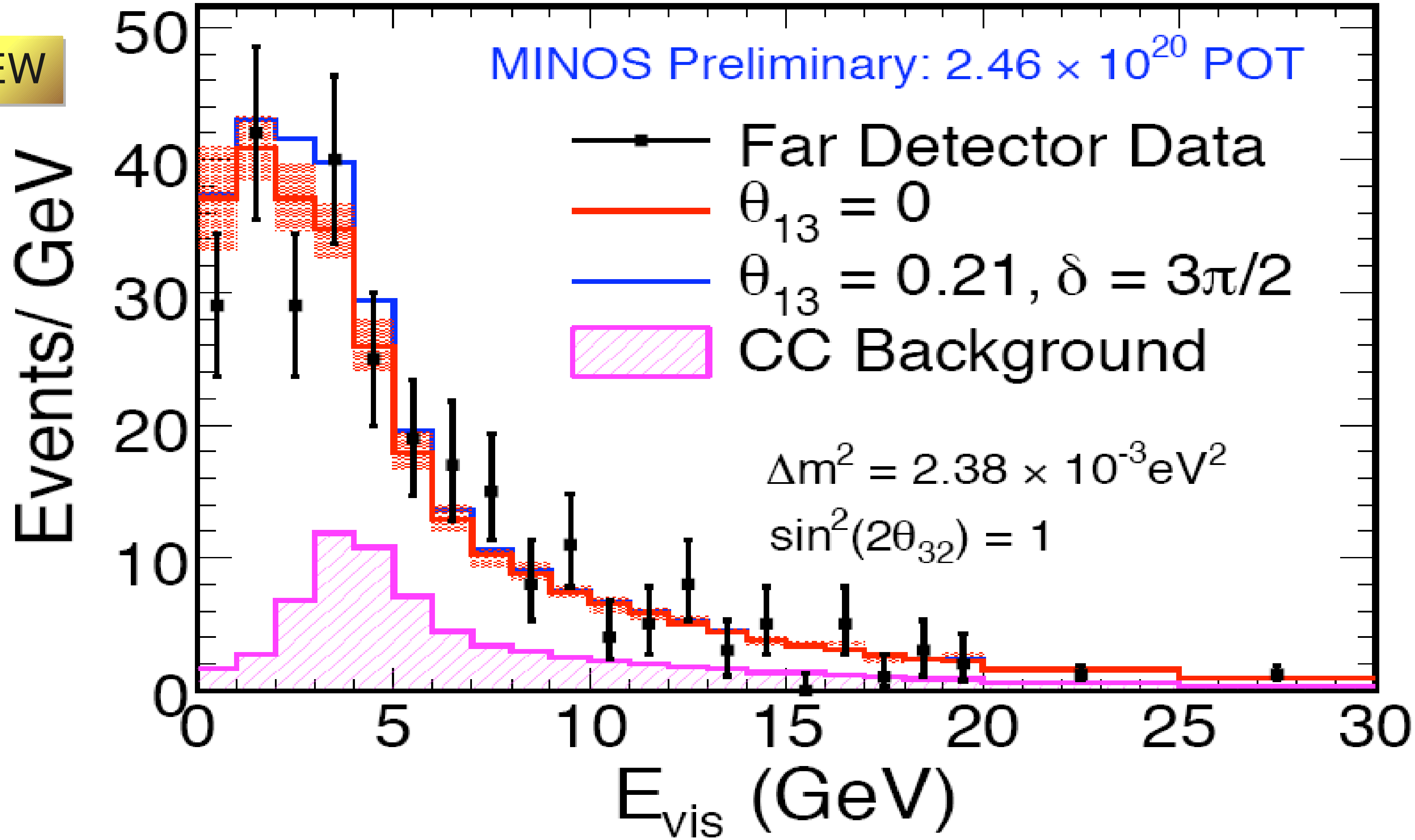
Energy Distribution

H. Gallagher
Tufts University

Far Detector reconstructed energy spectra for NC-like events.

Oscillation parameters are fixed. MC predictions with $\Theta_{13}=0$ and Θ_{13} at the CHOOZ limit are shown.

NEW



Results and Significance

Comparisons between observed Data and MC Prediction (for θ_{13}=0)

NEW

Energy Range (GeV)	Data	MC	Significance (σ)
0-3	100	115.16 ± 7.67	1.15
0-5	165	175.92 ± 10.42	0.65
0-120	291	292.63 ± 15.02	0.10

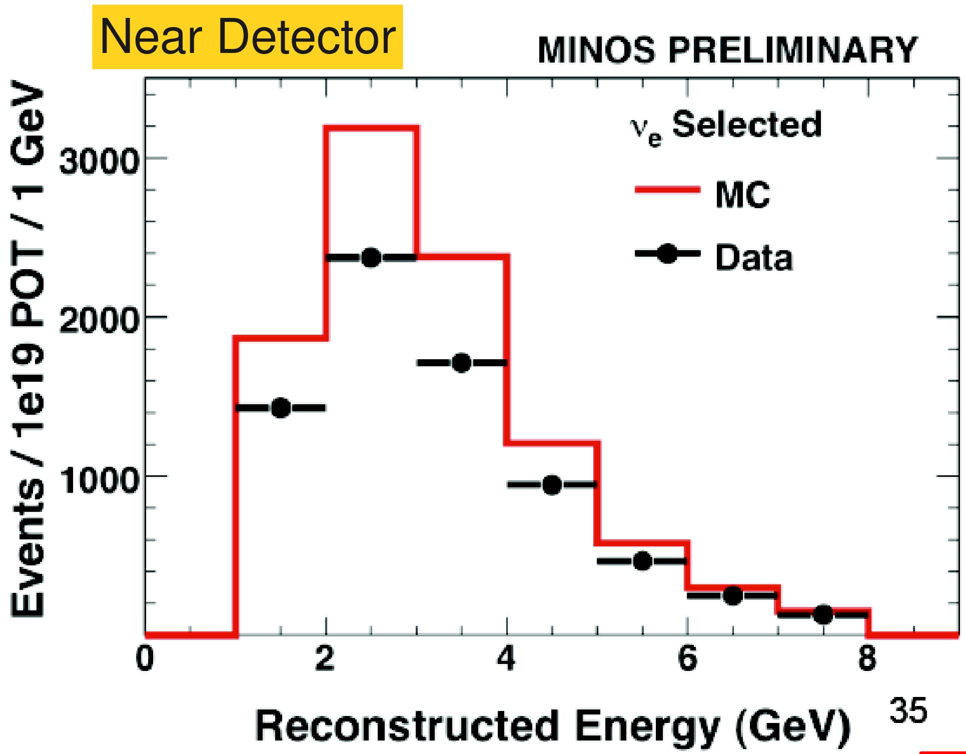
The data-MC difference is slightly larger for θ_{13} at the Chooz limit.

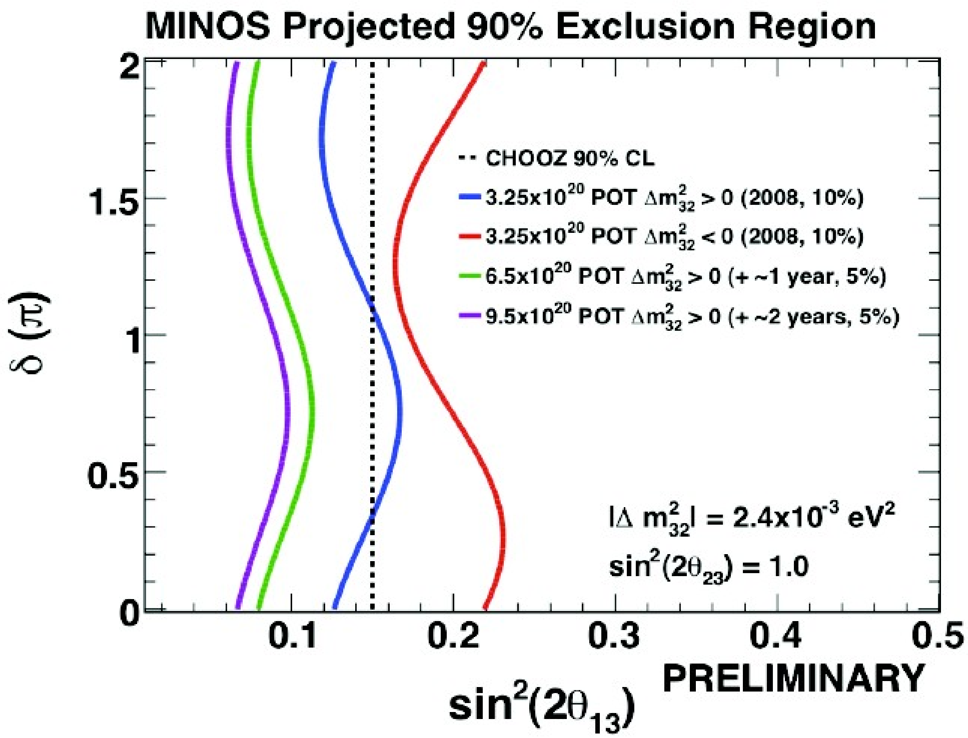
For E_{vis}< 3 GeV the fraction of neutral current events that disappear is less than 35% at 90% CL.

For E_{vis}< 120 GeV the fraction of neutral current events that disappear is less than 17% at 90% CL.

Search for ν_e appearance in a beam that is 98.7% ν_μ.
Select ν_e CC in the near and far detector with a neural network.
ND measures a mix of beam ν_e, NC and ν_μ CC events.

Solution: use two independent data driven methods to estimate NC and CC ν_μ backgrounds





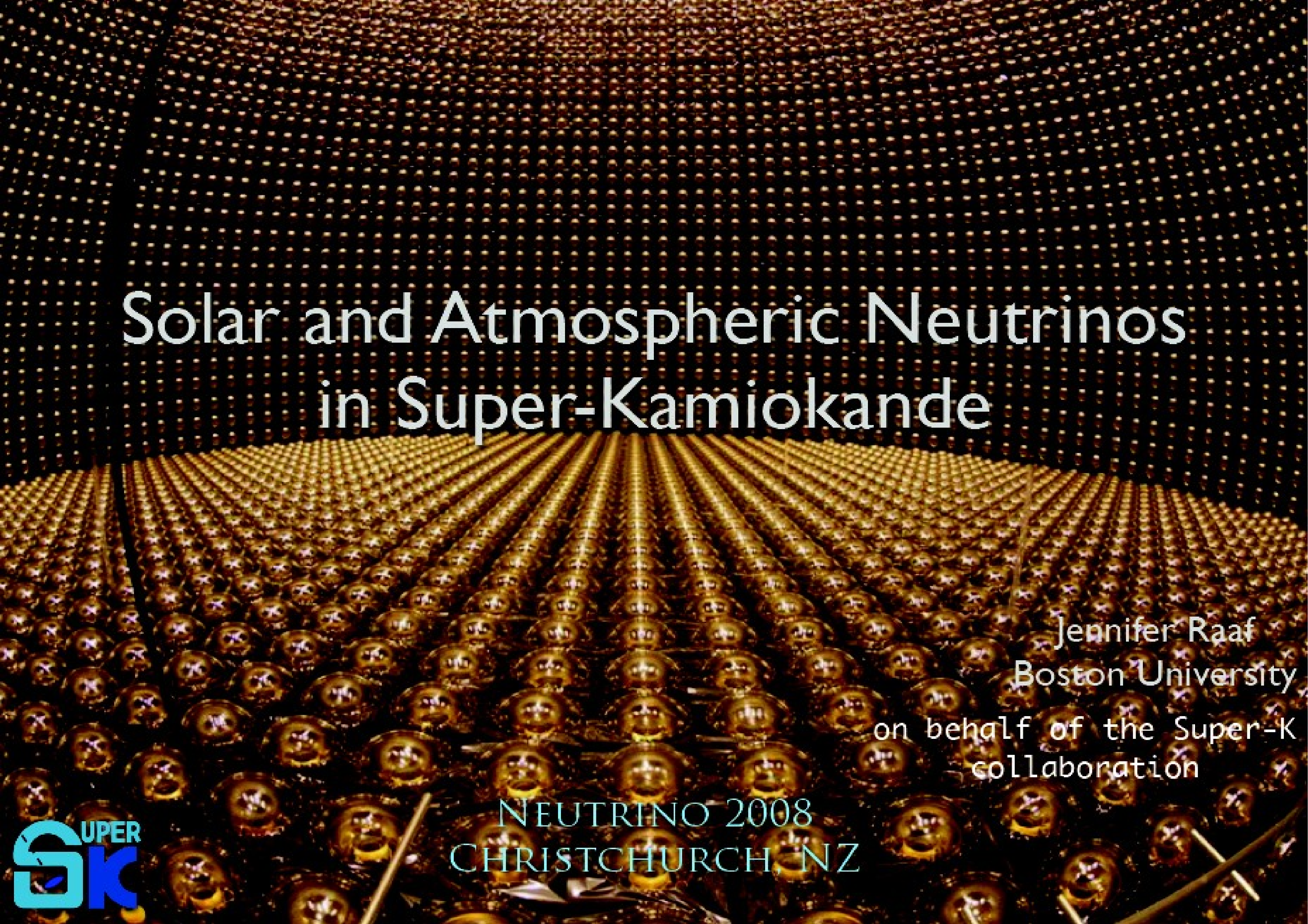
At CHOOZ limit expect 12 ν_e signal events and 42 BG events with 3.25×10^{20} protons

Conclusion & Future

- New measurement of the atmospheric neutrino oscillation parameters for 3.36×10^{20} POT:

$$|\Delta m|^2 = (2.43 \pm 0.13) \times 10^{-3}\ eV^2\ (68\%\ C.L.)$$
$$\sin^2(2\theta) > 0.90\ (90\%\ C.L.)$$

- From an analysis of CC events, decay and decoherence are disfavored at 3.7 and 5.7σ, respectively.
- From an analysis of NC events in the FD for an exposure of 2.46×10^{20} POT, the fraction of NC events that disappear is less than 0.17 at 90%C.L.
- First results on ν_e appearance are expected later this year and have sensitivity below the Chooz limit. Other ND-only results expected later this year also.



Solar and Atmospheric Neutrinos in Super-Kamiokande

Jennifer Raaf
Boston University

on behalf of the Super-K collaboration

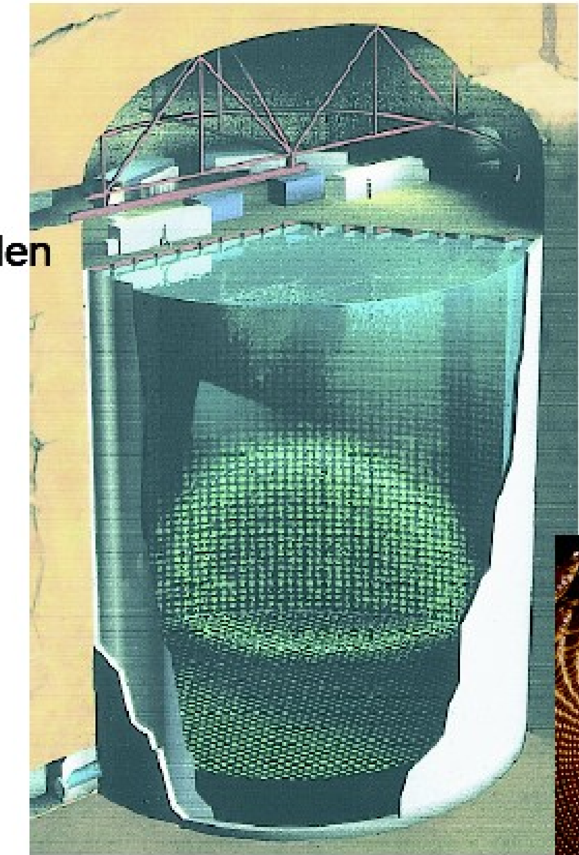
Neutrino 2008
Christchurch, NZ

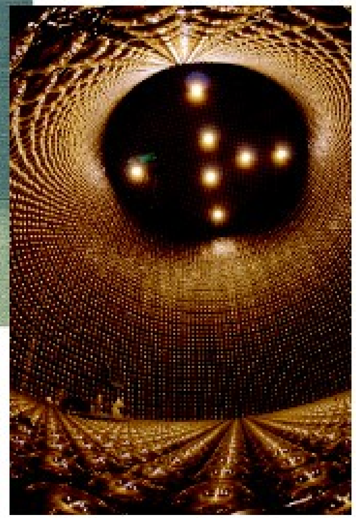
Super-Kamiokande

Kamioka-Mozumi zinc mine
1 km (2700 meters-water-equiv.) rock overburden

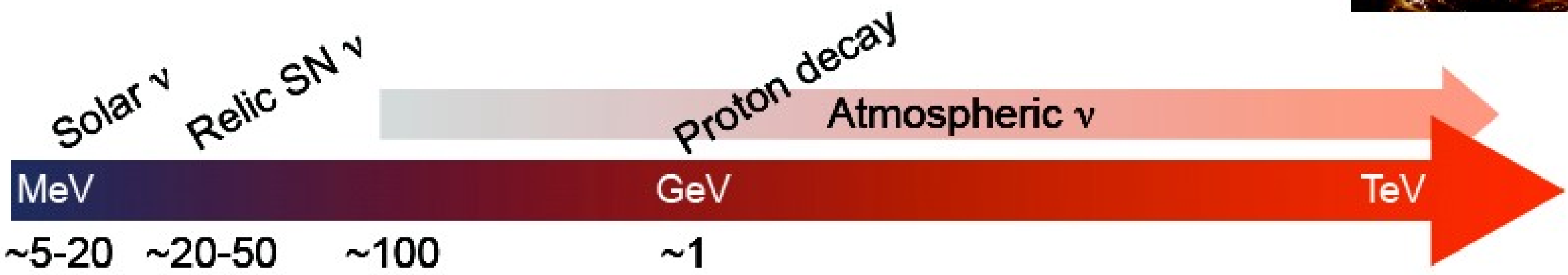
Water Čerenkov detector
    50 ktons (22.5 ktons fiducial)

Instrumented with
    50-cm PMTs in Inner Detector (ID)
    20-cm PMTs in Outer Detector (OD)

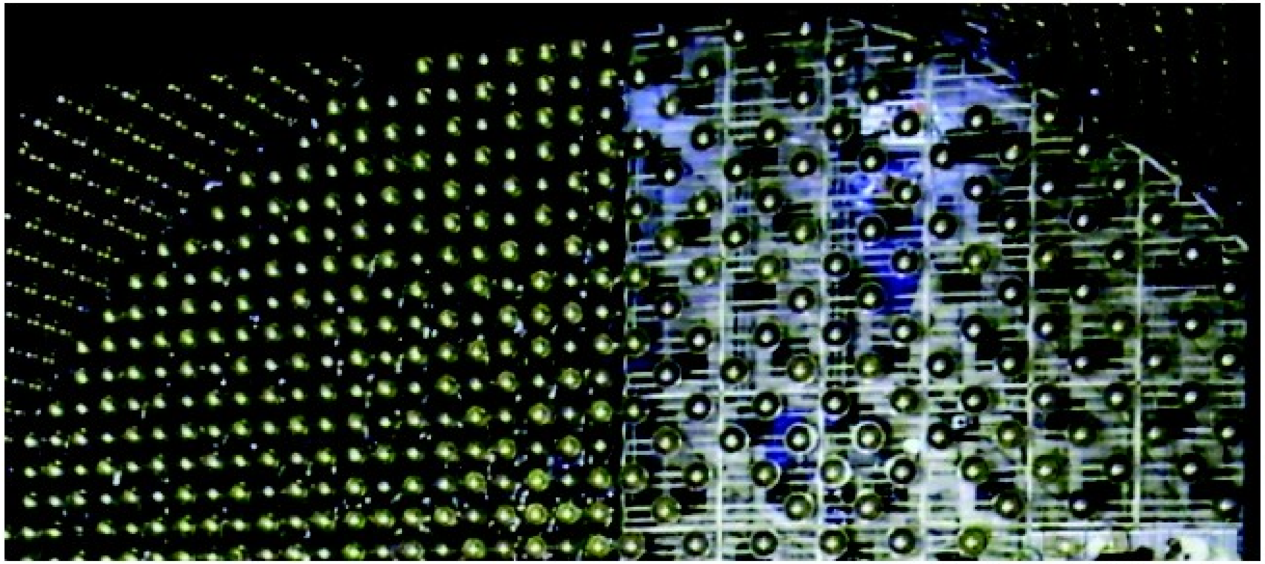




Goals of Super-K
- Solar neutrinos
- Supernova neutrinos (+ relic SN)
- Atmospheric neutrinos ← This talk
- Proton decay



Timeline



During SK-III construction

1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009

SK-I (1996-2001)
11,146 ID PMTs
(40% coverage)
1,885 OD PMTs

accident

SK-II (2003-2005)
5182 ID PMTs
(19% coverage)
Acrylic shields added

SK-III (2006-2008)
11,129 ID PMTs (40% cov.)
OD segmentation
(top/barrel/bottom)

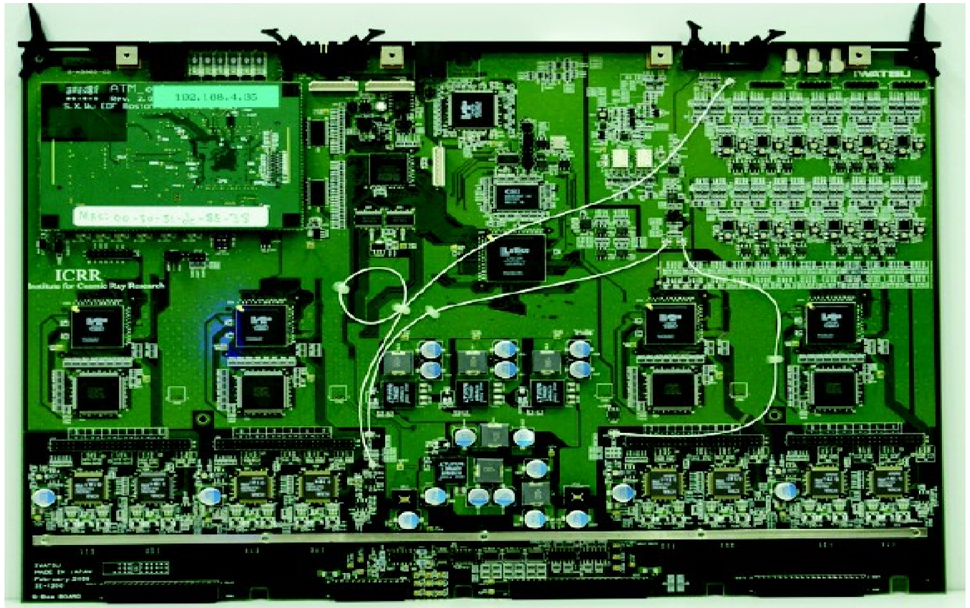
Coming soon:
SK-IV (2008- ...)
Replace DAQ electronics

In this talk :

- Coming update : SK-IV
- SK-III status
- Analysis updates : SK-I and SK-II

SK-IV : DAQ Upgrade

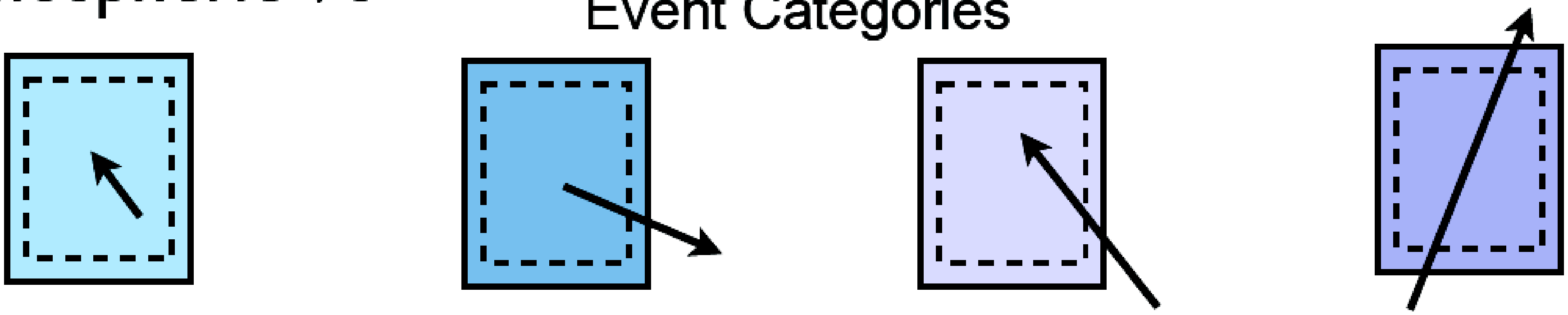
- Simplified detector operations
  - Unified readout scheme for ID and OD
- Increased reliability/performance
  - Improve multiple energy resolution
    - Wider dynamic range
  - Improve multiple-hit capability
    - Efficient ID of m-decay electrons
- Ethernet-based readout



  - Increased bandwidth and reduced dead time
- New DAQ readout system
  - No hardware trigger : instead record all hits and apply software triggers
- SK-IV installation begins Aug 2008 : to be completed mid Sep.
  - 6 months commissioning period before T2K beam

Atmospheric ν's

Event Categories

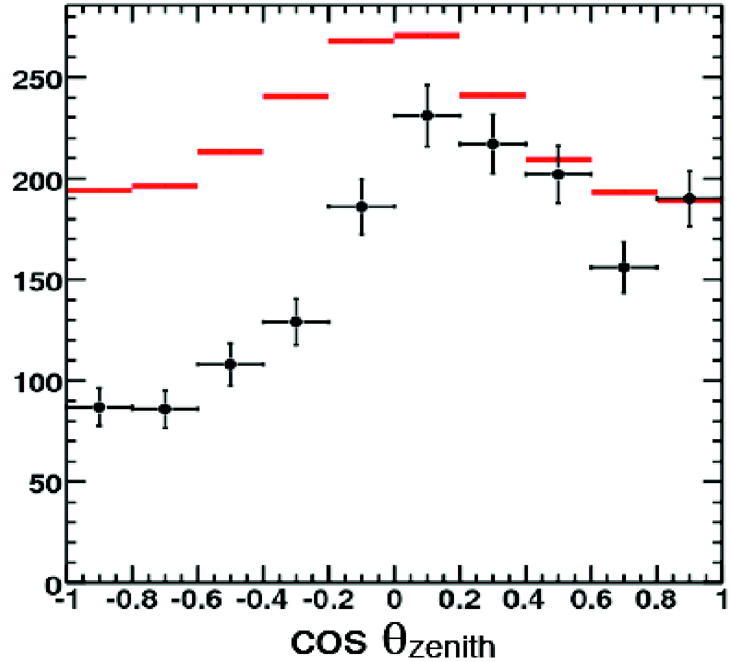


SK-III run period: July 29, 2006 - present

Event Category	**Event Rate (events/day)**		
	SK-I	SK-II	SK-III (Preliminary)
Fully Contained (FC)	8.18 ± 0.07	8.22 ± 0.10	8.31 ± 0.22
Partially Contained (PC)	0.61 ± 0.02	0.54 ± 0.03	0.57 ± 0.06
Upward-stopping μ (Upstop)	0.25 ± 0.01	0.28 ± 0.02	0.24 ± 0.03
Upward-thrugoing μ (Upthru)	1.12 ± 0.03	1.07 ± 0.04	1.11 ± 0.06

Event rates consistent across all phases of SK

Oscillation Analyses



Zenith angle 2-flavor analysis (fine-binned)

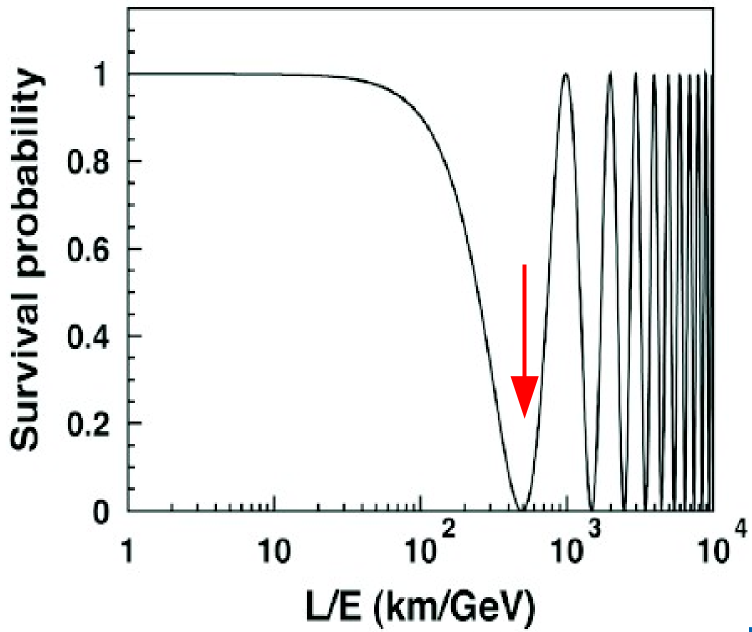
Use many subsamples of data
Look for zenith angle distortion

Data binned according to:

event type + momentum + zenith angle } 400 bins for SK-I, 350 bins for SK-II

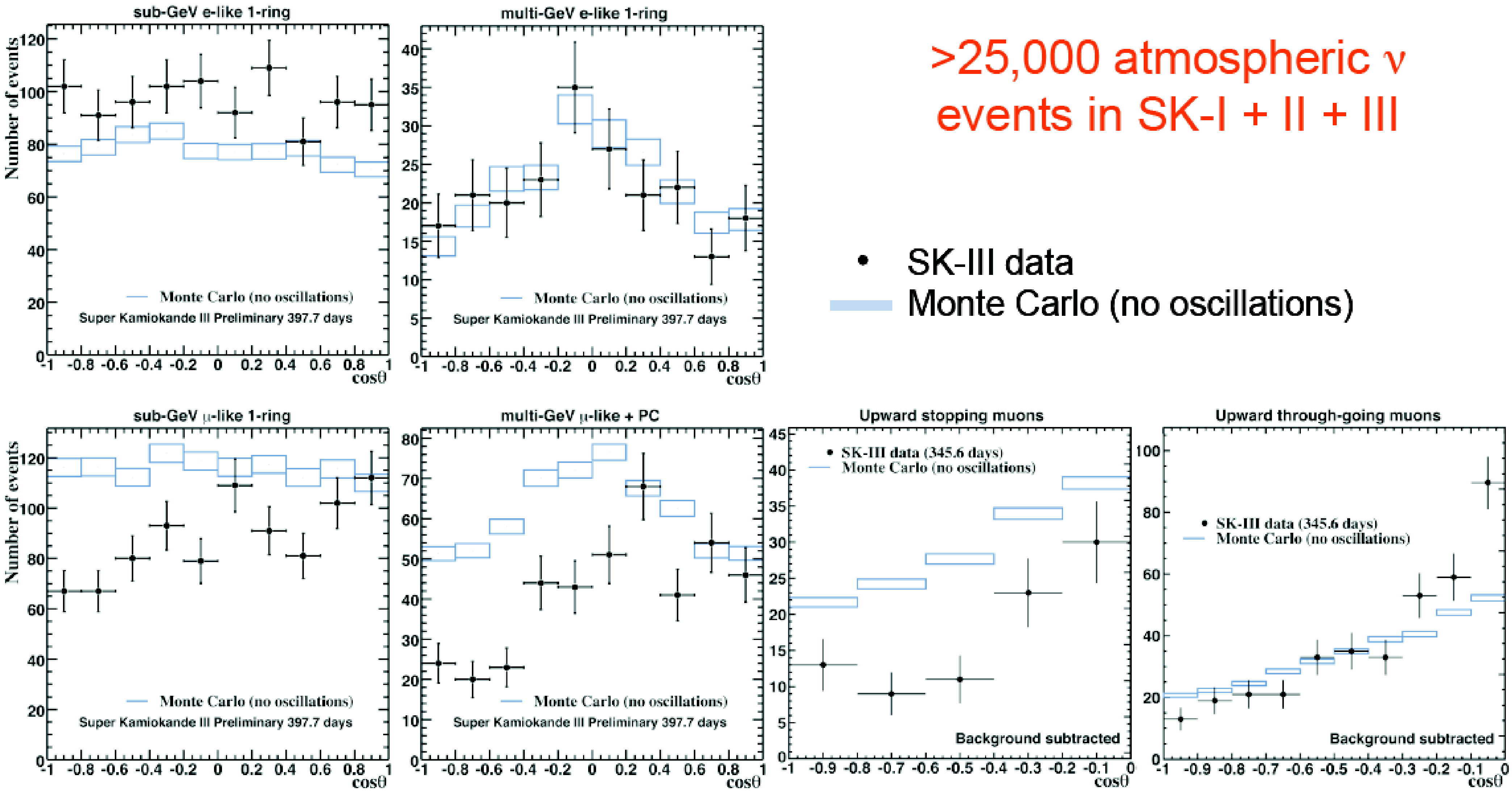
χ^2 fit in bins of zenith angle with systematic error pull terms

L/E analysis



Use much more selective subsample of data
Require good L/E resolution
Look for first oscillation dip

SK-III Atmospheric ν Zenith Distributions



>25,000 atmospheric ν events in SK-I + II + III

- SK-III data
- Monte Carlo (no oscillations)

No oscillation analysis yet, but zenith angle distortion clearly visible

Updated : changes and improvements

Super-K Simulation/Reconstruction Updates

Re-analysis of SK-I and SK-II data due to many changes/improvements:

Simulation

atmospheric neutrino flux model: Honda06

neutrino interaction model (neut)

QE: M_A = 1.2 GeV

1π (resonant): M_A = 1.2 GeV

Add $\Delta \rightarrow N\gamma$

Add lepton mass effects in CC1π

1π (coherent): Rein & Sehgal with lepton mass correction

DIS: GRV98 PDF with Bodek-Yang correction

detector simulation

more detailed model of light reflections and scattering

better OD tuning

Changed to agree with K2K measurement.
Effect: Increase number of events

Effect: Small change in lepton momentum distributions

Effect: Suppression in forward direction of lepton scattering angle

Effect: Reduction in number of multiple-π events

Effect: Better data/MC agreement for various quantities

Reconstruction

improved ring counting

Effect: Reduced systematic errors

Other

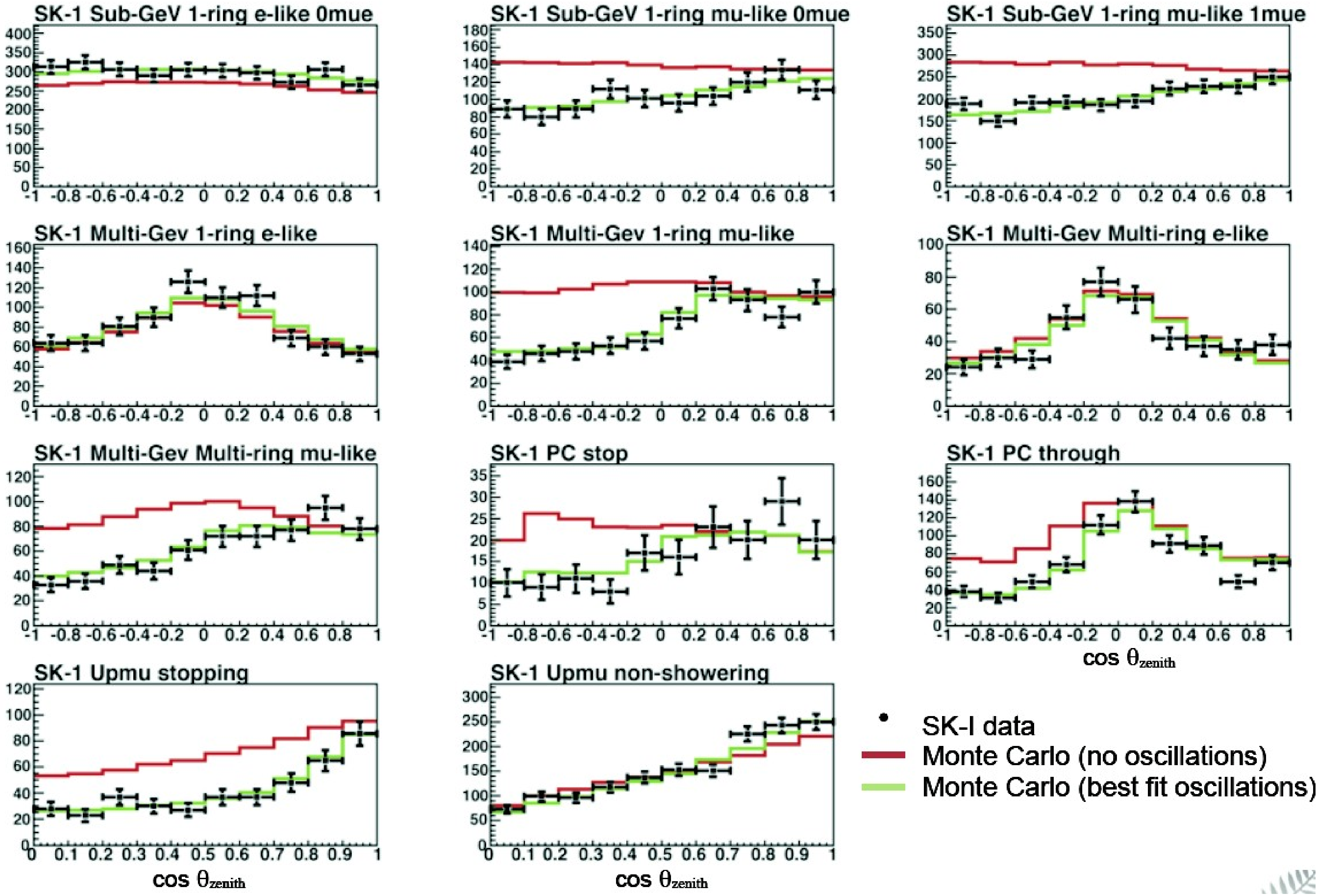
higher MC statistics

re-evaluate and add systematic uncertainties

Increase from 100 yrs to 500 yrs

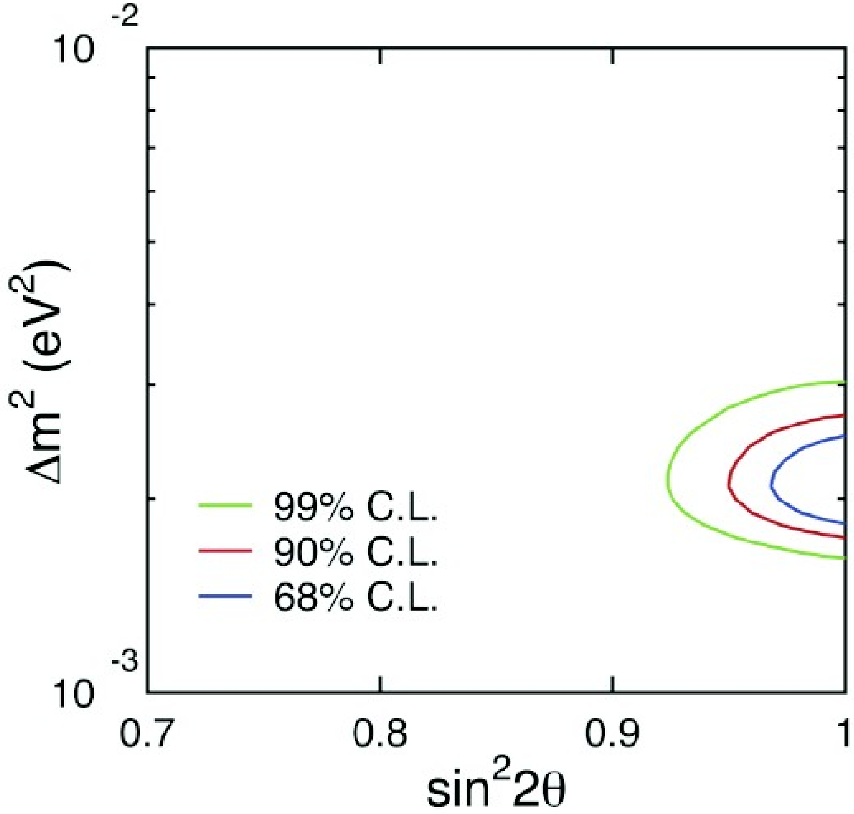
Updated

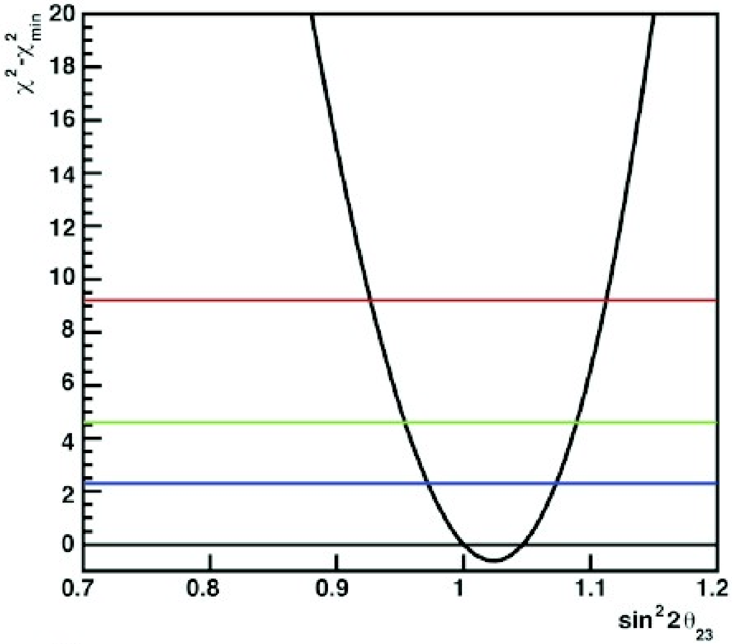
Zenith Angle Analysis: SK-I + SK-II

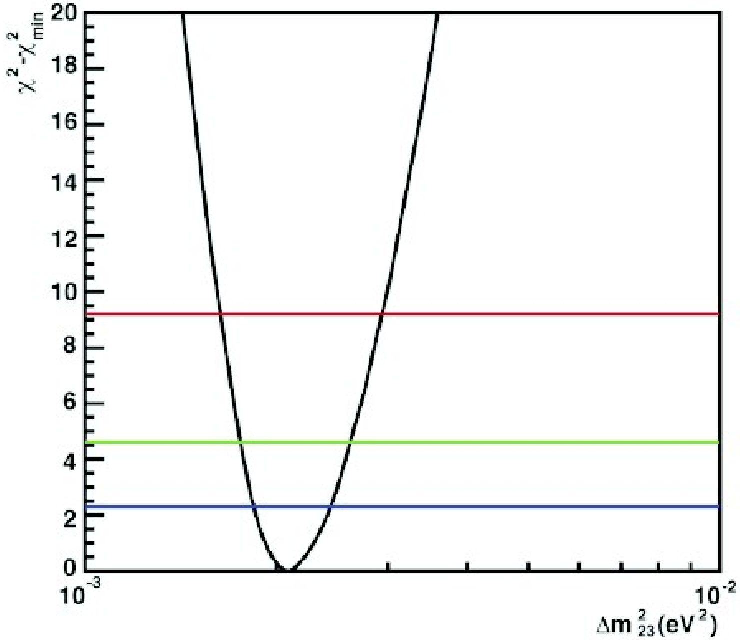


Updated

Zenith Angle Analysis: SK-I + SK-II







Best fit:

$\Delta m^2 = 2.1 \times 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.02$

$\chi^2 = 830.1 / 745$ d.o.f.

Updated

L/E Analysis: SK-I + SK-II

Datasets	
SK-I FC/PC μ-like:	1489 days
SK-II FC/PC μ-like:	799 days

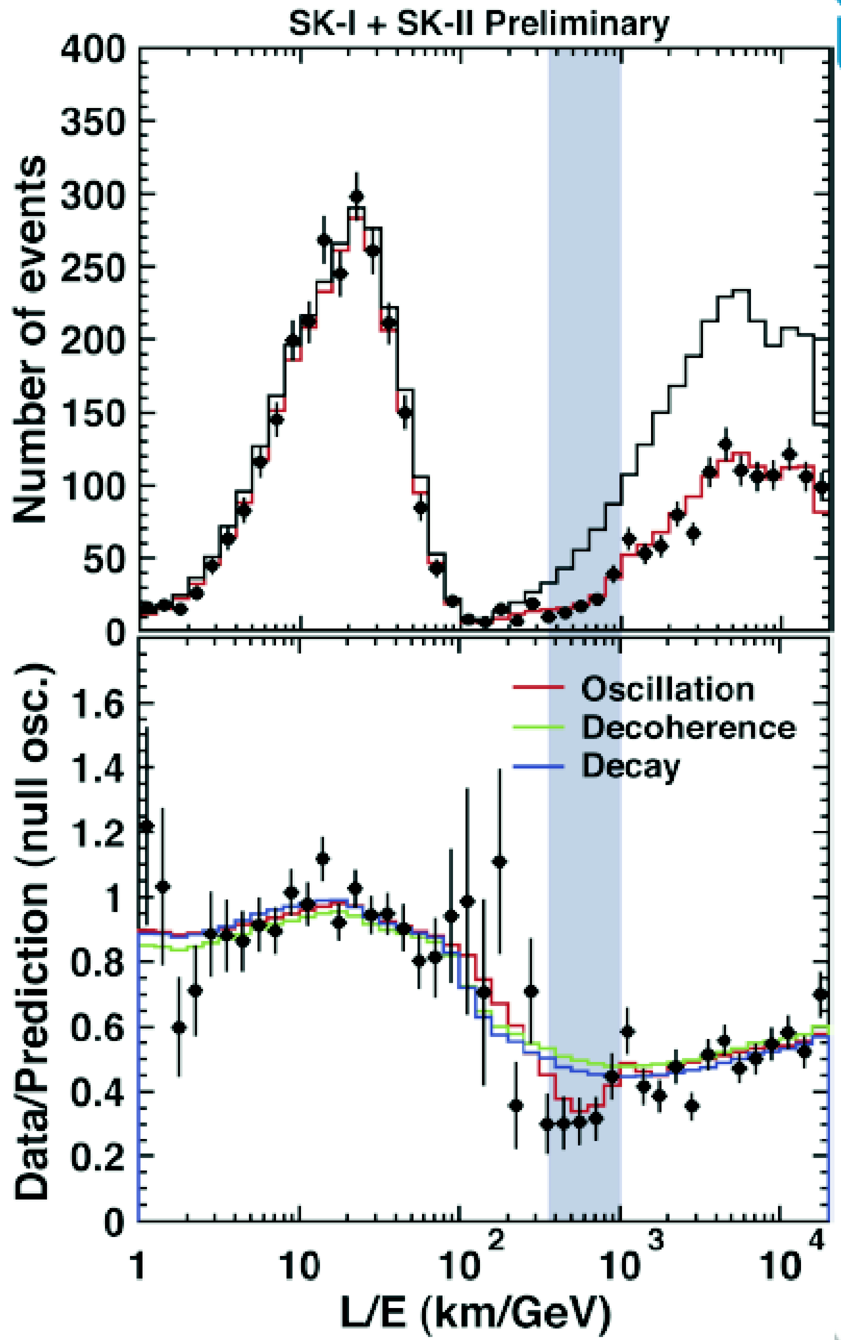
Use only event categories with good L/E resolution:

Partially-contained muons
Fully-contained muons

χ^2 fit to 43 bins of $\log_{10}(L/E)$ with 29 systematic error terms

Compare against:

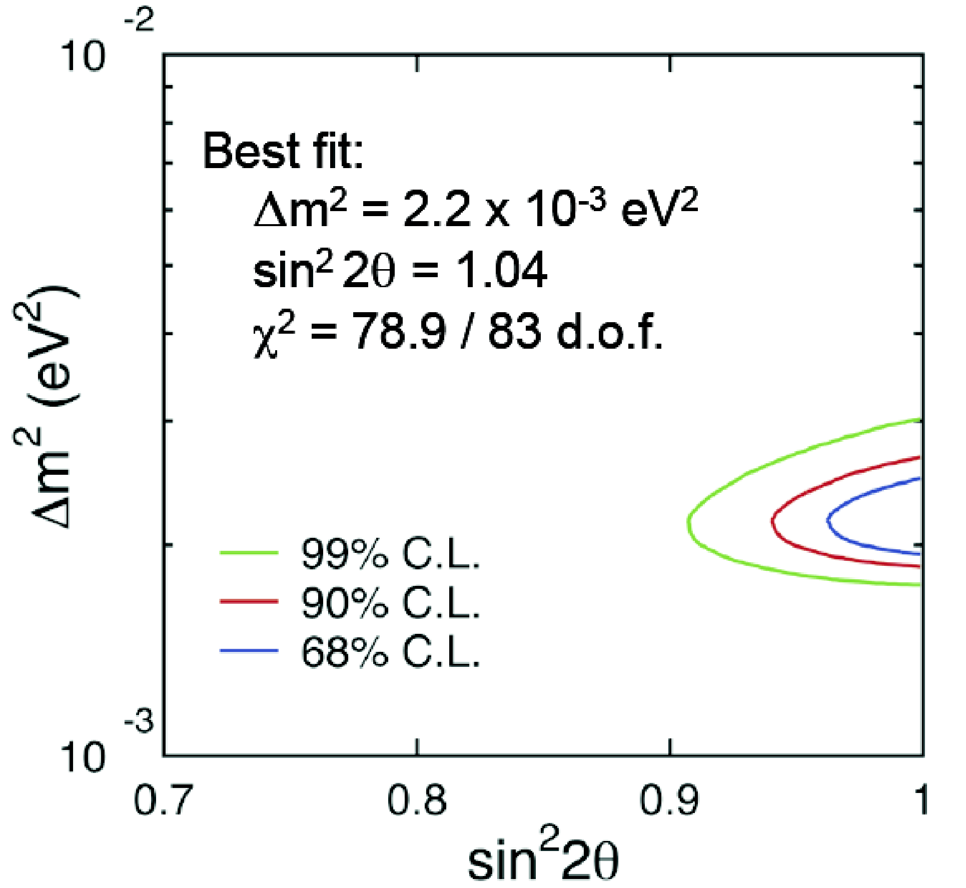
	MINOS
Neutrino decoherence (5.0σ)	5.7σ
Neutrino decay (4.1σ)	3.7σ



Grossman and Worah: hep-ph/9807511
Lisi *et al.*: PRL85 (2000) 1166
Barger *et al.*: PRD54 (1996) 1, PLB462 (1999) 462

Updated

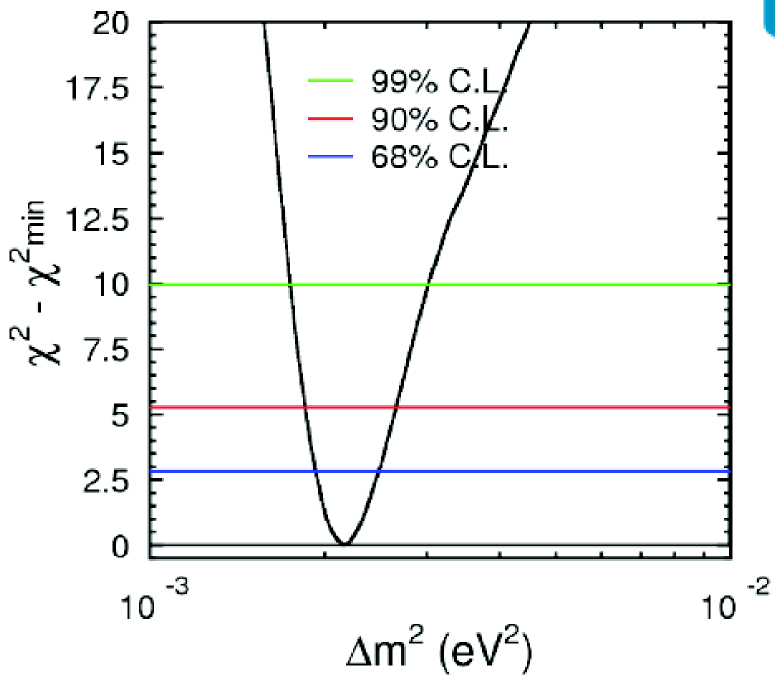
L/E Analysis: SK-I + SK-II

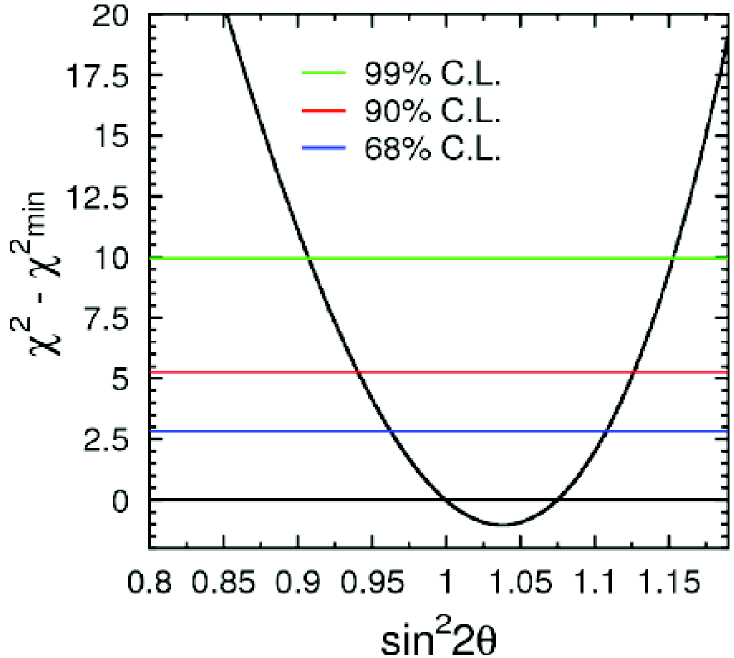


90% C.L. allowed region

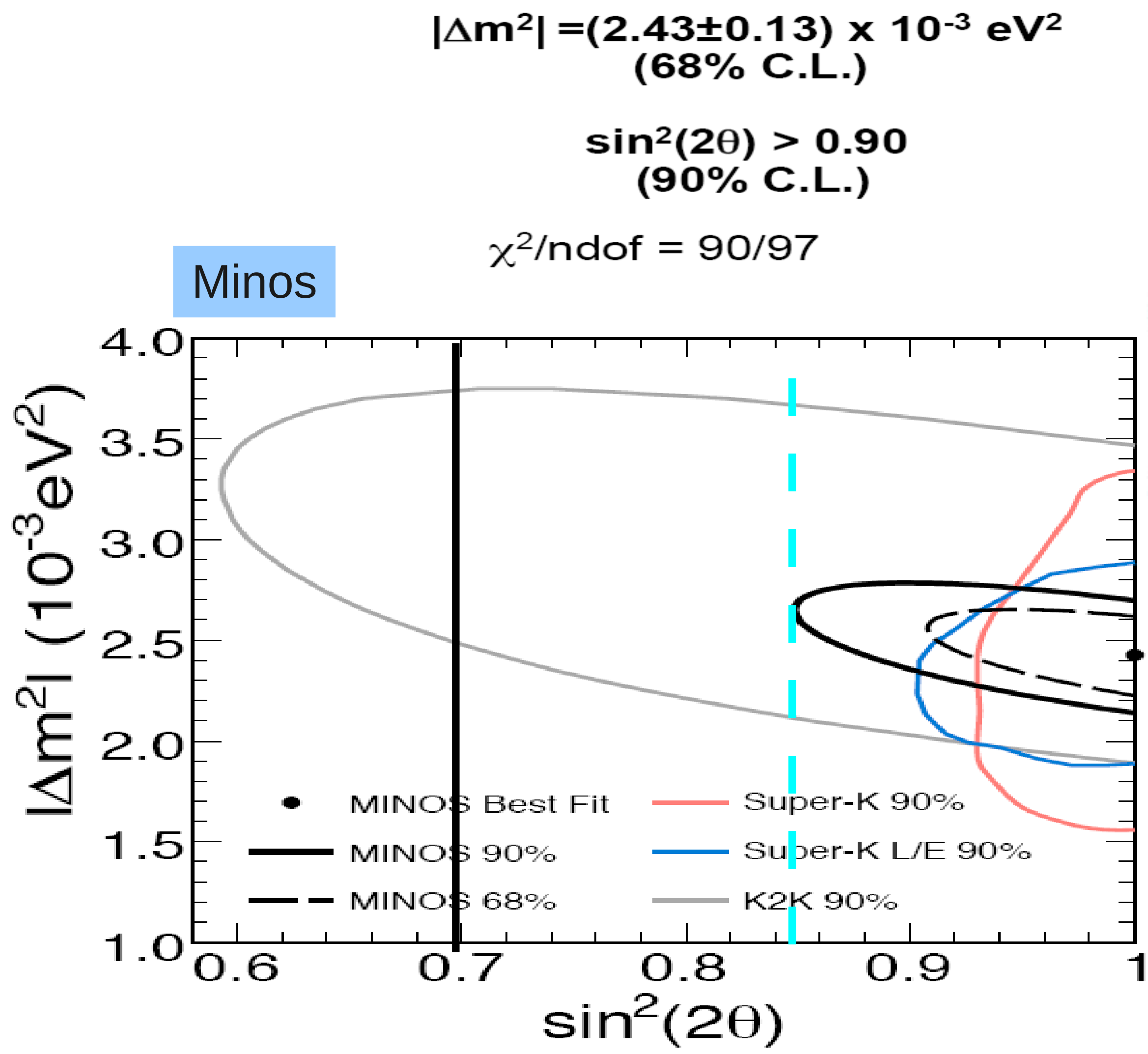
$\sin^2 2\theta > 0.94$

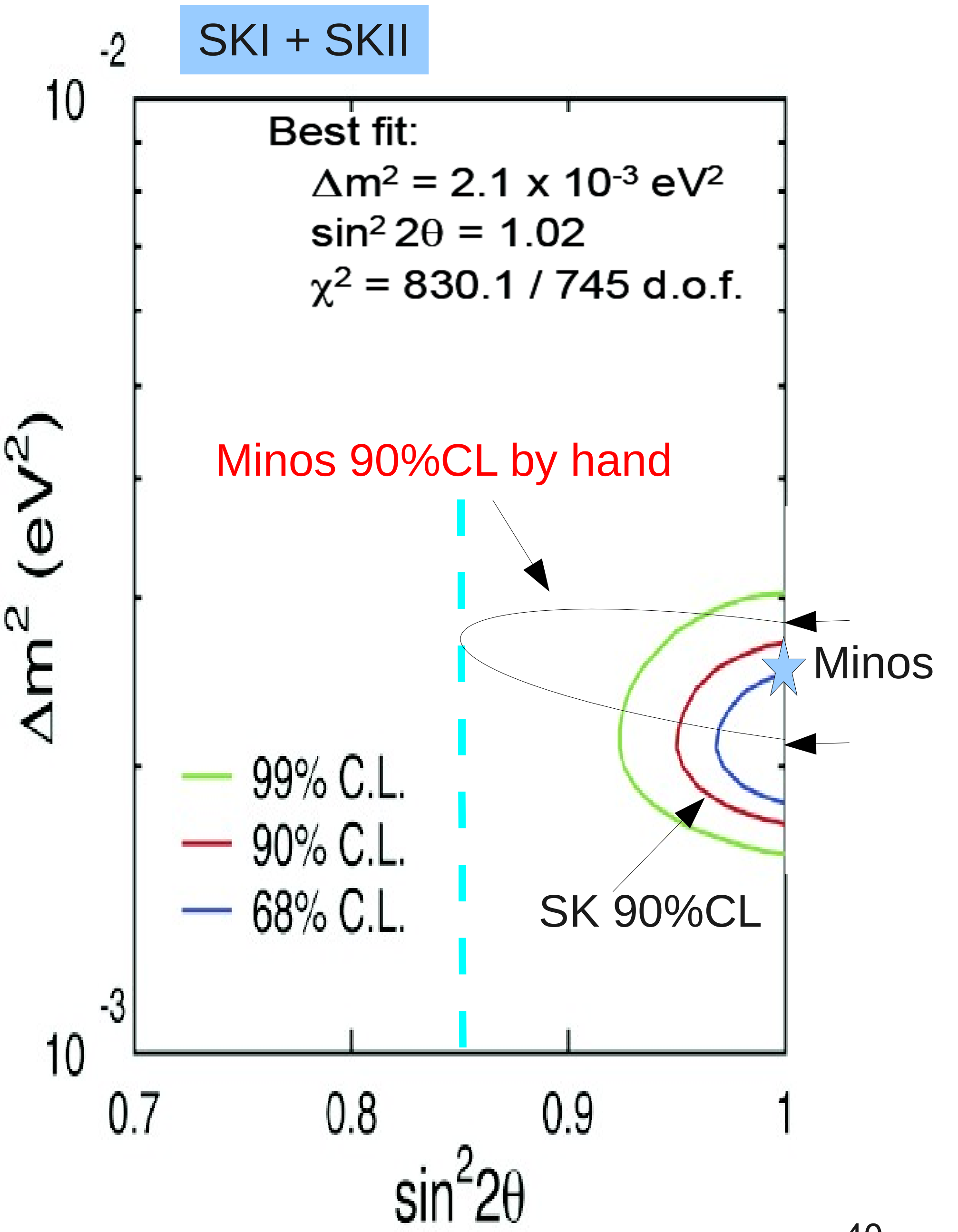
$1.85 \times 10^{-3} < \Delta m^2 < 2.65 \times 10^{-3}$ eV^2





Comparison between SK and Minos





Conclusion and Future

SK-I + II + III

12 years dataset for atmospheric & solar neutrinos

SK-IV

detector improvements by upgraded electronics

By Neutrino2010... $\rightarrow$T2K beam on Apr 2009

~40,000 solar ν

~30,000 atmospheric ν

Search for sub-dominant, exotic, and non-oscillation physics

Study "Standard Model" oscillation physics

- help constrain solar parameters
- precisely measure atmospheric parameters
  best constraint on mixing angle
- try to observe every predicted effect

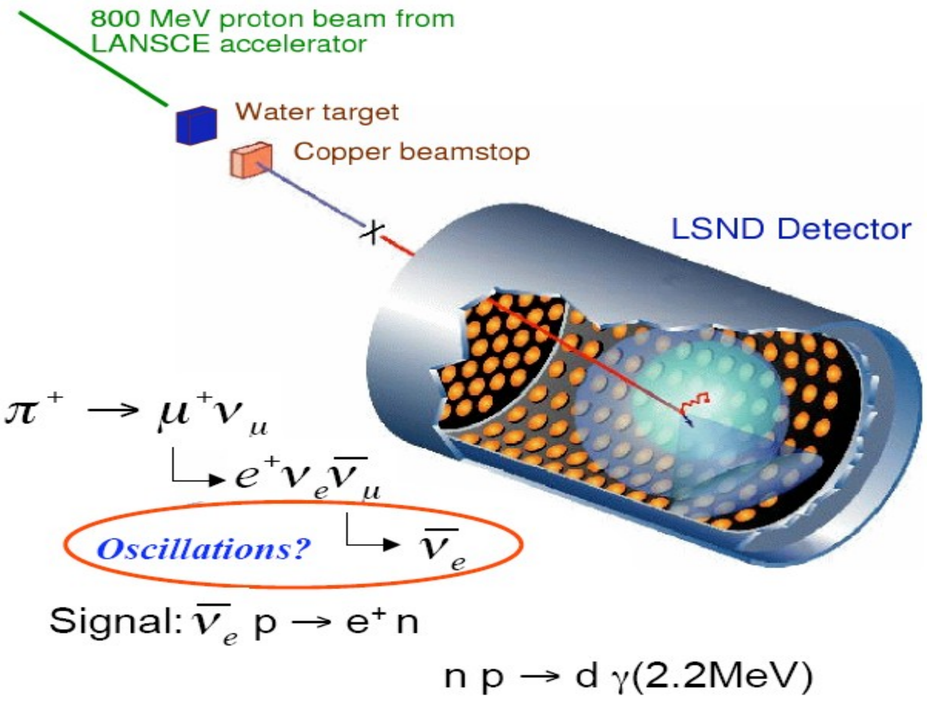
MiniBooNE Oscillation searches

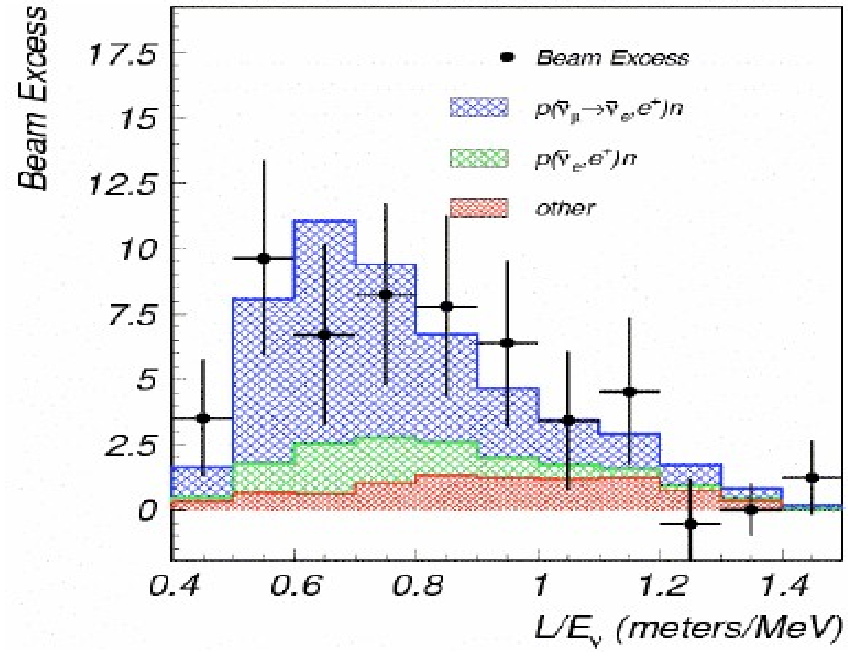
- Motivation
  - After LSND
- Detector
- Oscillation analysis
  - Global data analysis
- Low Energy ν_e candidate excess
- Events from NuMI beamline
- Anti-neutrino appearance at MiniBooNE

The MiniBooNE Strategy

Test the LSND indication of anti-electron neutrino oscillations

Oscillation status after LSND





With an oscillation probability of $(0.264 \pm 0.067 \pm 0.045)\%$.

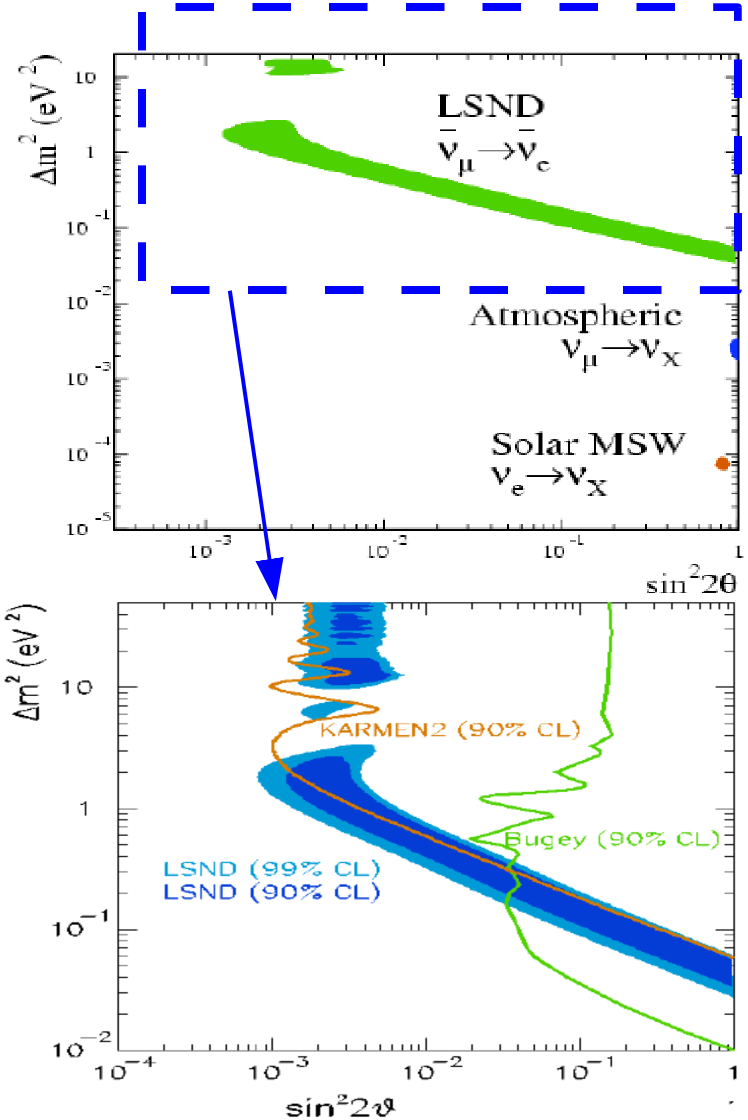
3.8 σ significance for excess.

Slide from Zelimir Djurcic's talk at PPC 2008

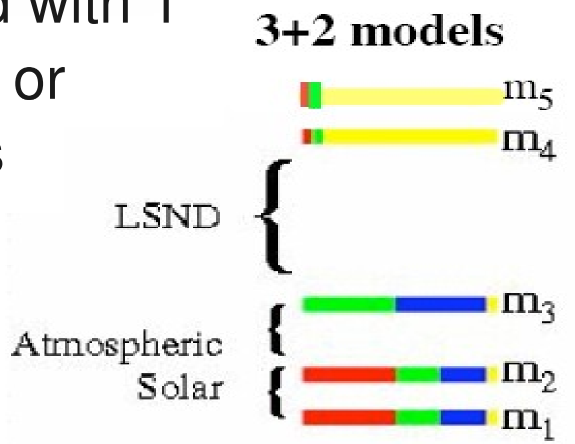
The MiniBooNE Strategy

Test the LSND indication of anti-electron neutrino oscillations

Oscillation status after LSND



- This signal looks very different from other experiments.
  - Much higher Δm^2=0.1~10 eV^2
  - Much smaller mixing angle
  - Only 1 experiment
- Needed more than 3 ν's
  - Models developed with 1 or more sterile ν's or other new physics models

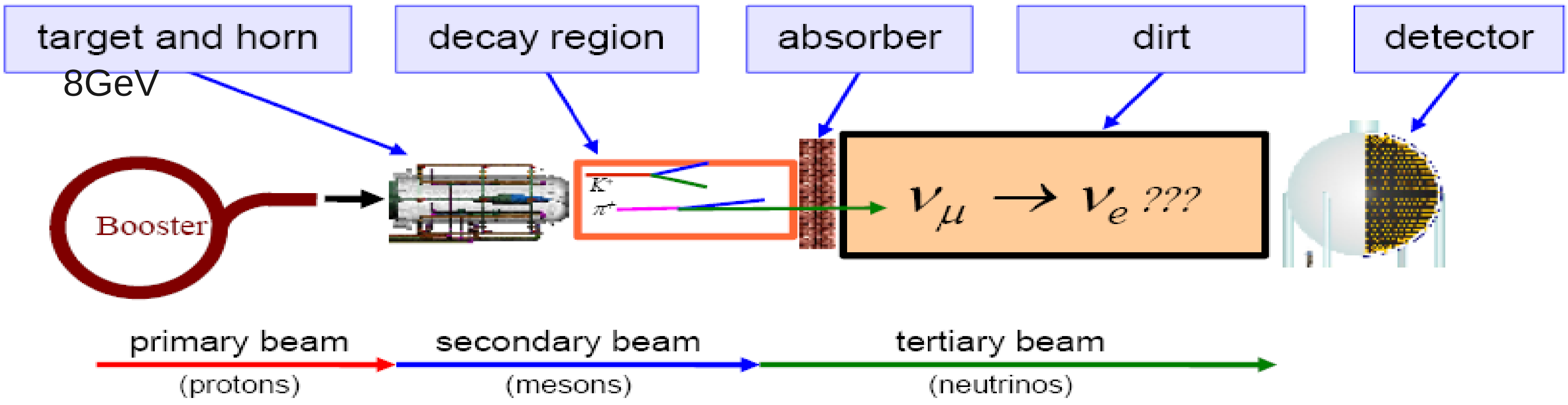


The MiniBooNE Strategy

Test the LSND indication of anti-electron neutrino oscillations
Keep L/E same, change beam, energy, and systematic errors

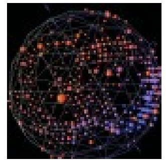
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 \, L/E)$$

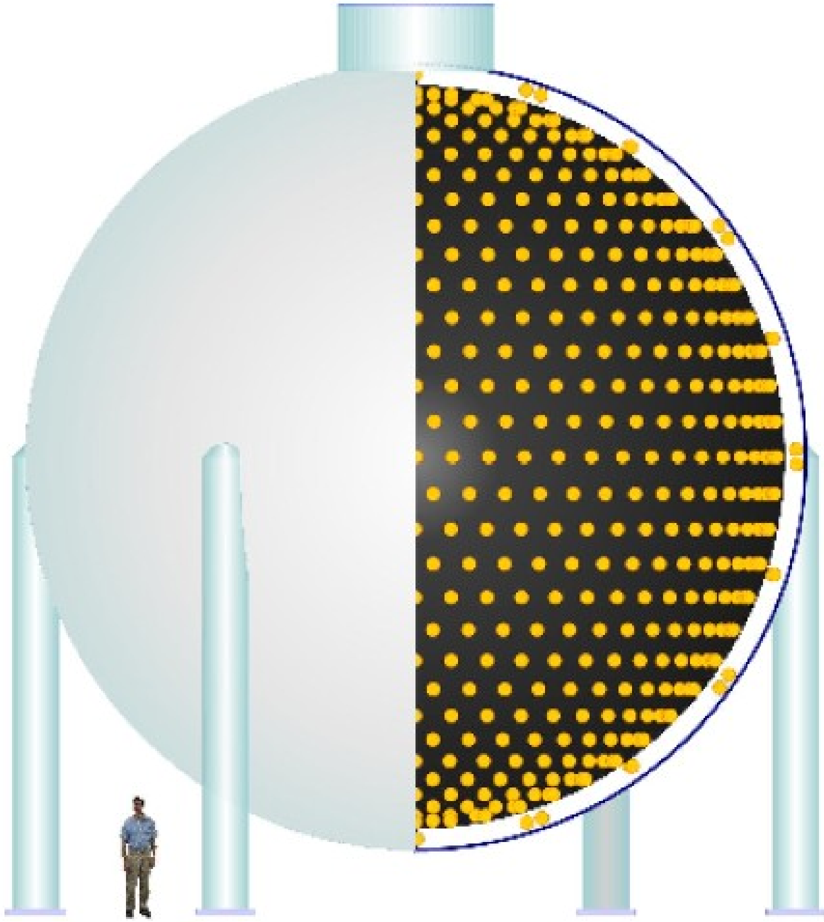
neutrino energy (E):		baseline (L):	
MiniBooNE:	~500 MeV	MiniBooNE:	~500 m
LSND:	~30 MeV	LSND:	~30 m



Event rates: $\nu_\mu = 98.1\%, \;\; \nu_e = 0.6\%, \;\; \bar{\nu}_\mu = 1.2\%, \;\; \bar{\nu}_e = 0.03\%$

The MiniBooNE Detector





541 meters downstream of target

3 meter overburden of dirt

12 meter diameter sphere

Filled with 800 t of pure mineral oil

(CH_2--density 0.86, n=1.47)

Fiducial volume: 450 t

1280 inner 8” phototubes-10% coverage,

240 veto phototubes

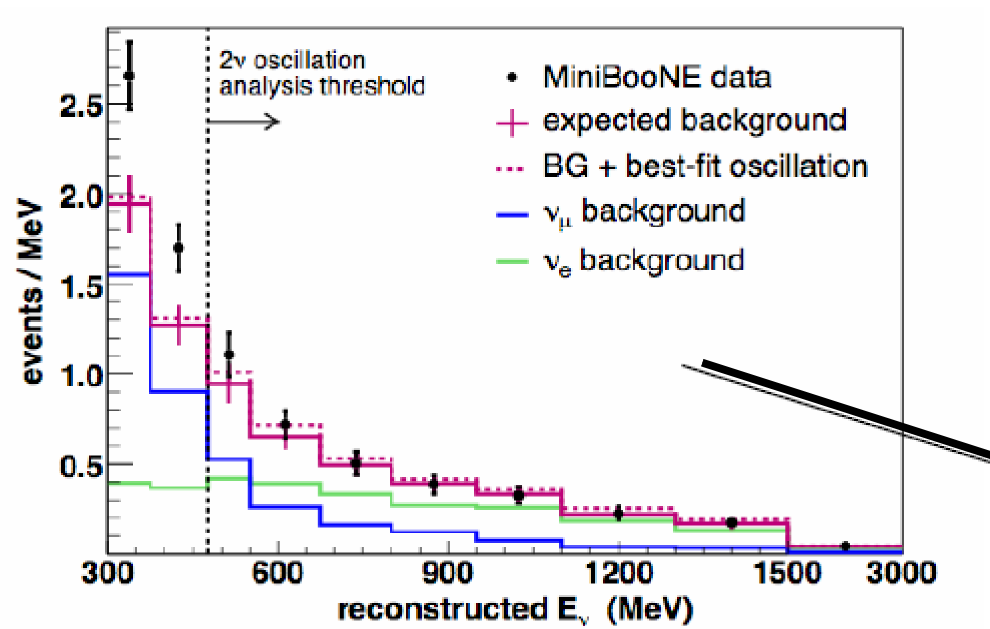
(Less than 2% channels failed during run)

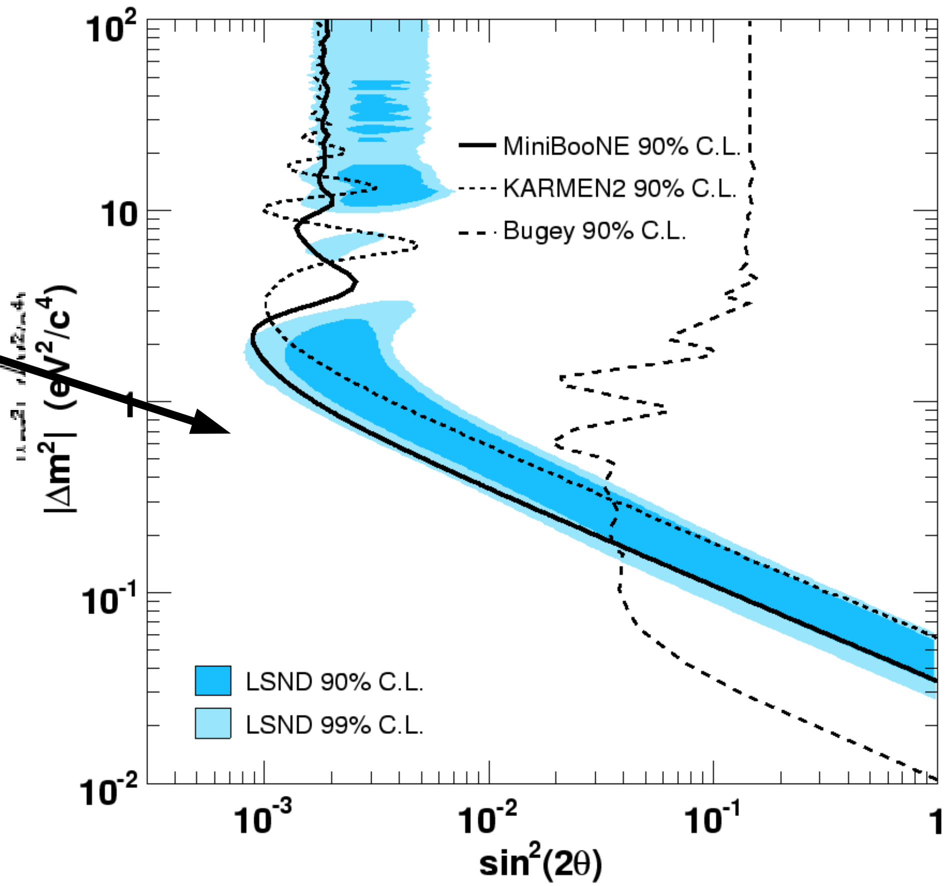
Oscillation Analysis Results: April 2007

Phys. Rev. Lett. 98, 231801 (2007)

track-based analysis:

Counting Experiment: $475<E_\nu<1250$ MeV
data: 380 events
expectation: 358 ±19 (stat) ± 35 (sys)
significance: 0.55 σ





No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region

Neutrino 2008

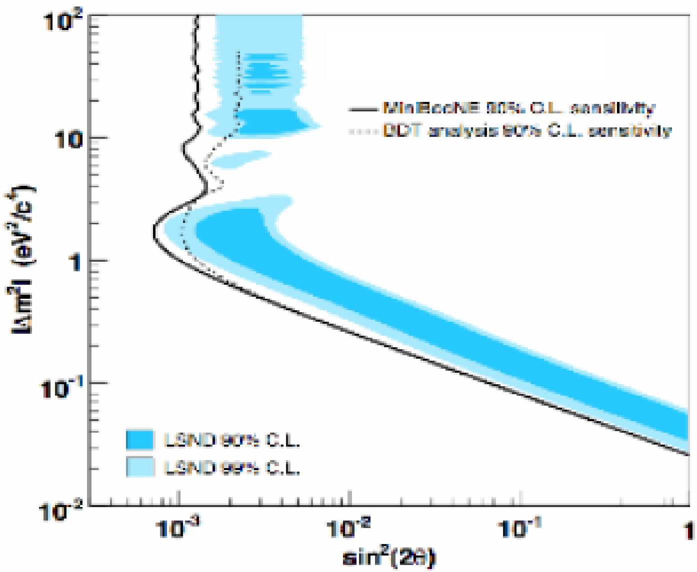
Oscillation Analysis Strategy

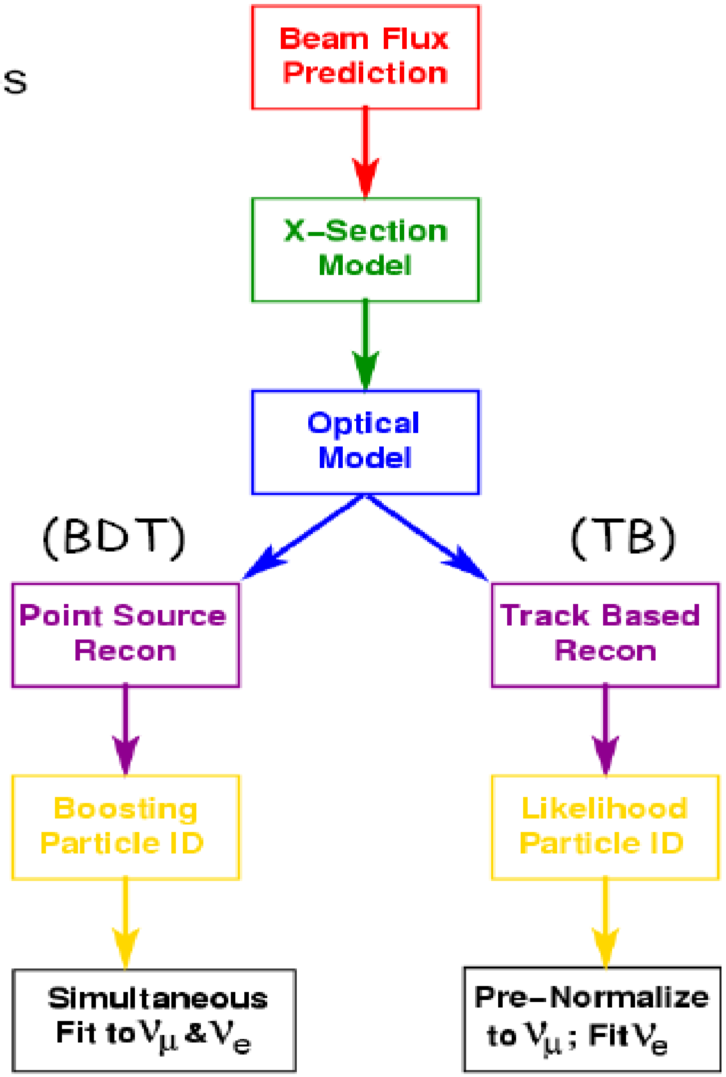
Two algorithms were used:

- "track-based likelihood" (TBL)
  Uses direct reconstruction of particle types and likelihood ratios for particle-ID

- "boosted decision trees" (BDT)
  Set of low-level variables combined with BDT algorithm -> PID "score"

- In the end, the TB analysis had slightly better sensitivity, so was used for primary results.





Combining ν_eBDT + ν_eTBL Samples

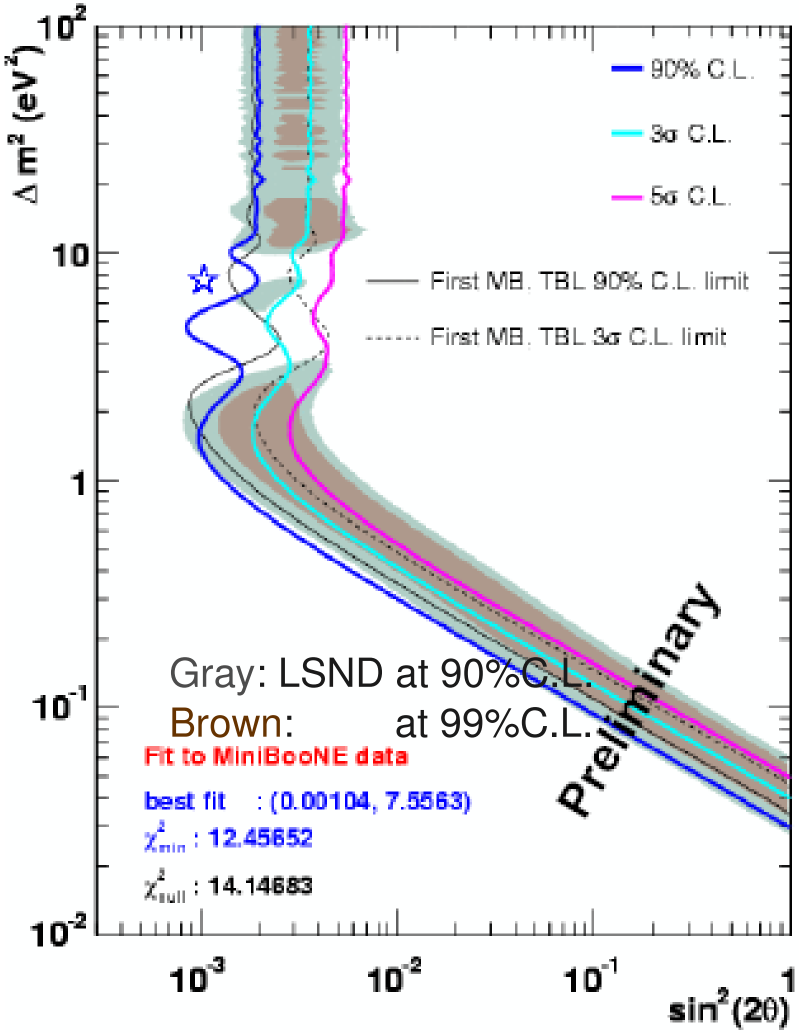
paper at draft stage

The combination of the two ν_e samples gives an increase in coverage in the region $\Delta m^2 < 1\ eV^2$.

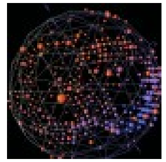
Differences in the details are due to the specific fluctuations in the data samples and the interplay with correlations among them.

The combination yields a consistent result.

Limits from fits to open data



10%-30% improvement in 90% C.L. limit below ~$1eV^2$.



Global data analysis

- Combine results from several experiments : LSND, KARMEN2, MiniBooNE, Bugey
  - Compatibility
    - How probably is it that all experimental results come from the same underlying 2-ν oscillation hypothesis?
    - $\Delta\chi^2 = \Delta\chi^2_{exp1} + \Delta\chi^2_{exp2} + \Delta\chi^2_{exp3} + \dots$
    - Robust search
  - Allowed regions
    - Indicate where oscillation parameters would lie, at a given CL, assuming all experiments results can arise in a framework of 2-ν osc.
    - The compatibility is the metric for the validity of this assumption.

arXiv:0805.1764 [hep-ex], submitted to Phys. Rev. D

Method : M.Maltoni, T. Schwetz, Phys. Rev. D 68, 033020(2003).

New

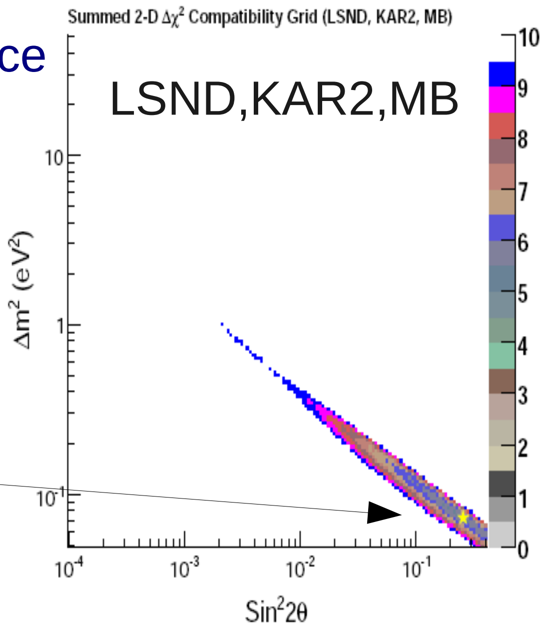
Global Fits to Experiments

LSND	KARMEN2	MB	Bugey	Max. Compat %	Δm^2	$Sin^2 2\theta$
X	X	X		25.36	0.072	0.256
X	X	X	X	3.94	0.242	0.023
X		X		16.00	0.072	0.256
X		X	X	2.14	0.253	0.023
	X	X		73.44	0.052	0.147
	X	X	X	27.37	0.221	0.012

- Combination of ν_e appearance searches (non-reactor)

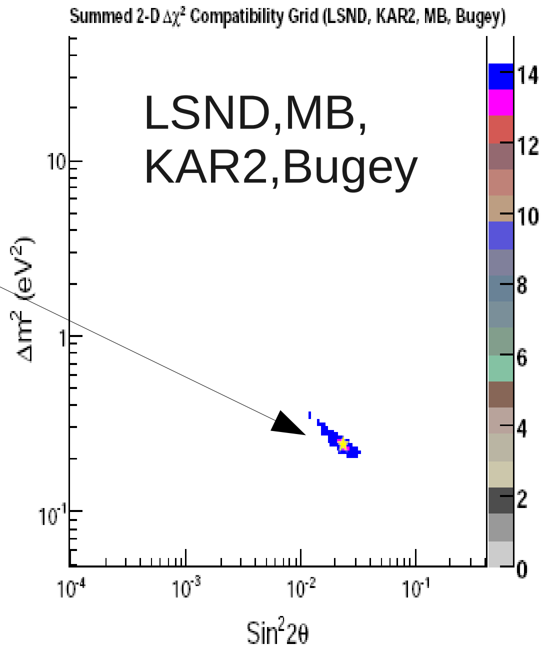
25.36% compatible with having come from 2-ν osc

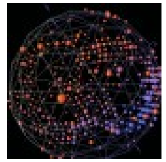
Best fit point is excluded area by Bugey.



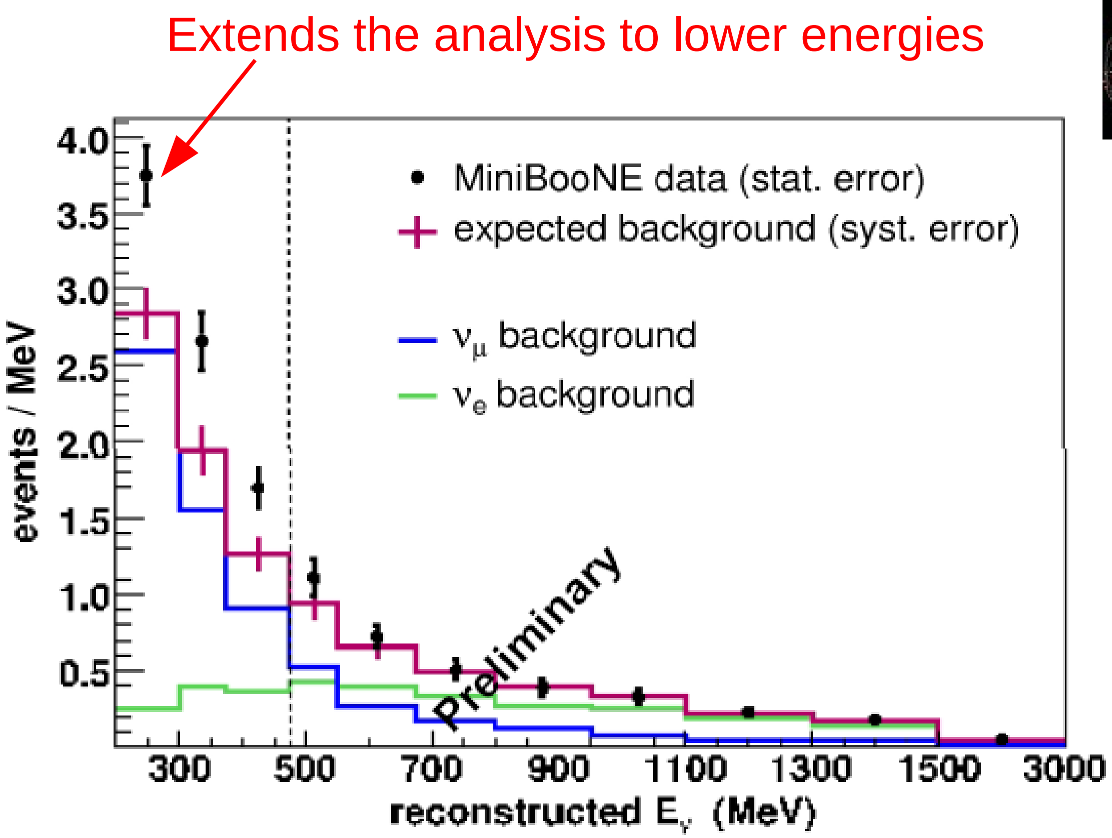
- Combination of all

There is no more than 3.94% compatible (chance) with having resulted from 2-ν osc.





Low Energy ν_e Candidate Excess



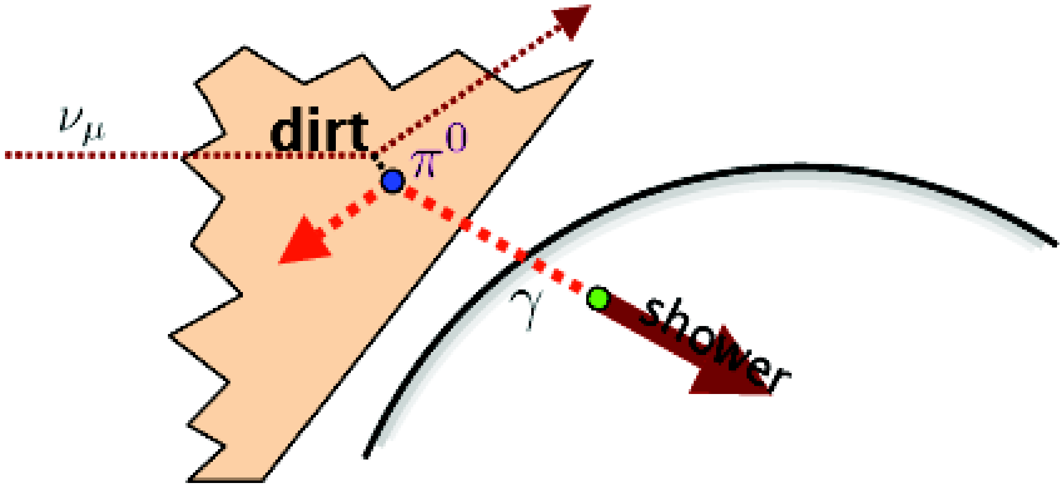
- No significant excess at higher E, where ν_e bkgd dominates.

- Largest backgrounds at lower E are ν_μ-induced, in particular:
  - NC π^0
  - NC $\Delta \rightarrow N\gamma$
  - Dirt

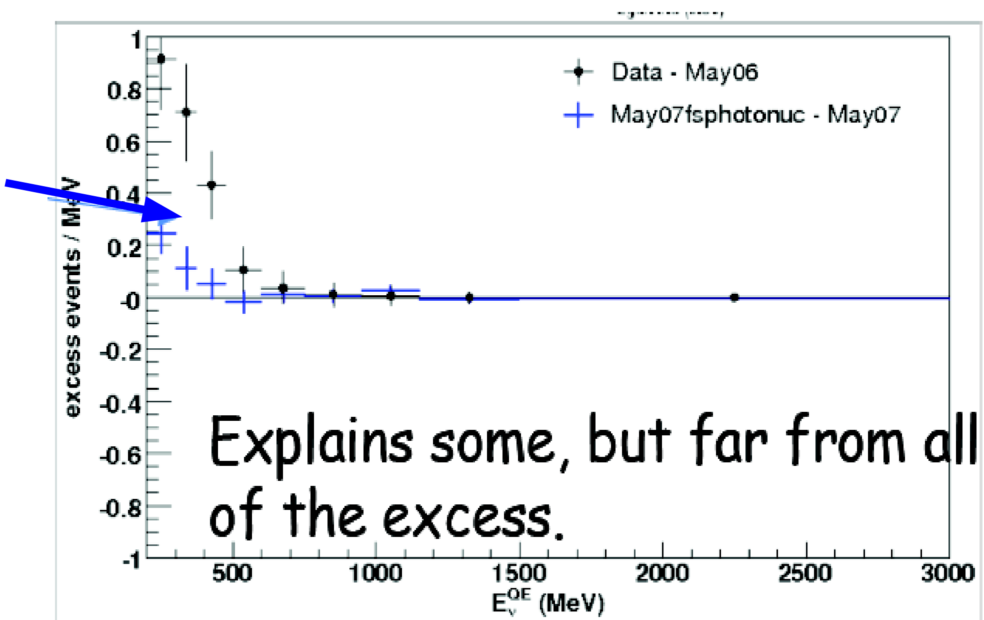
	reconstructed neutrino energy bin (MeV)		
	200-300	300-475	475-1250
Data	375±19	369±19	380±19
total background	284±25	274±21	358±35
ν_e intrinsic	26	67	229
ν_μ induced	258	207	129
Data-MC	91± 31	95 ± 28	22 ±40

Updates to low Energy ν_e cut

- Removing BG from neutrino interactions in the dirt outside the tank

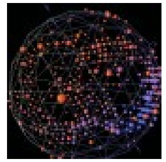


- Adding this cut and photonuclear absorption of π^0 production into MC



Clearly, more evidence is needed to quantify/verify the excess...

Conclusion and Future



- No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region
- Global fits with other experiments
- Update of low E ν_e candidates

MiniBooNE Present and Future

- Taken ~6.6 x 10^{20} POT in neutrino mode
  - Making suite of cross-section measurements
  - Searching for various neutrino oscillations
  - Publications coming out
- Taken ~2.5 x 10^{20} POT in anti-neutrino mode
  - Making suite of cross-section measurements
  - Searching for anti-neutrino disappearance
- In Nov 2007 request granted for extra running for an anti-nue appearance search
  - LSND result was an indication of anti-nue appearance
  - Extra ~2.5 x 10^{20} POT (making grand total of ~5 x 10^{20} POT)
  - Should take FY2008 and FY2009 running

Setting the scene for ν_τ appearance at CNGS

OPERA

G. Rosa
Sapienza University and INFN, Rome

on behalf of
The OPERA Collaboration
(13 Countries, 35 Institutions,~ 200 members)

Contents:

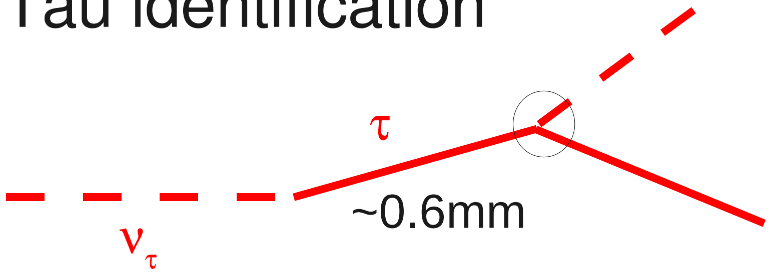
- Motivation, Design
- Detector overview
- At work with CNGS (& cosmics)
- Location and study of neutrino events
  (the 2007 *appetizer* run)
- About to start the full action
  (the scheduled 2008 *physics* run, and beyond)

Belgium
IIHE(ULB-VUB) Brussels
Bulgaria
Sofia
Croatia
IFB Zagreb
France
LAPP Annecy, IPNL Lyon,
IRES Strasbourg
Germany
Hamburg, Münster, Rostock
Israel
Technion Haifa
Italy
Bari, Bologna, LNF Frascati,
L'Aquila, LNGS, Naples Federico II,
Padova, Rome Sapienza, Salerno
Japan
Aichi, Nagoya, Kobe,
Toho, Utsunomiya
Korea
Gyeongsang Jinju
Russia
INR Moscow, LPI Moscow,
ITEP Moscow, SINPMSU Moscow,
JINR Dubna, Obninsk
Switzerland
Bern, Neuchâtel, ETHZ Zurich
Tunisia
UPHNE Tunis
Turkey
METU Ankara

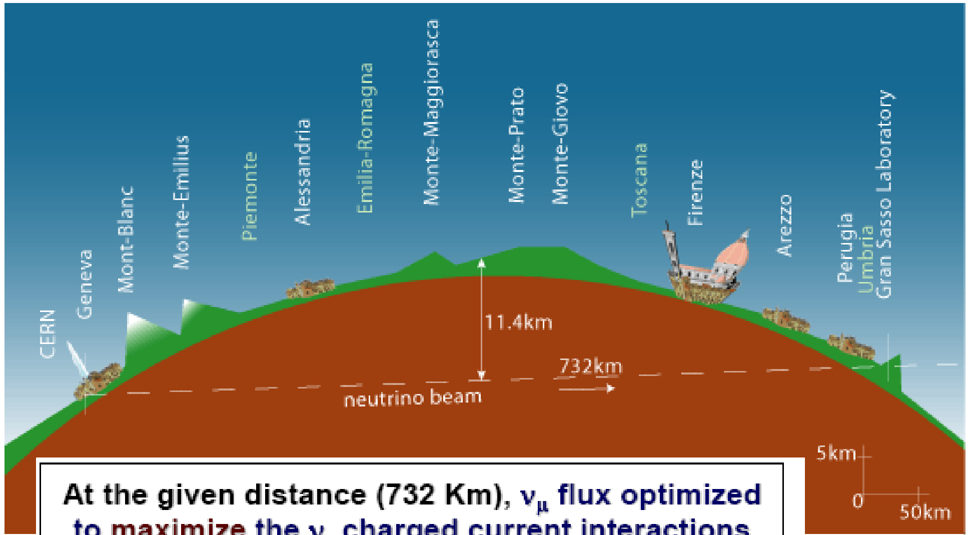
Neutrino 2008
Christchurch May 27th 2008

Oscillation Project with Emulsion tRacking Apparatus

- Motivation
  - Provide a direct evidence of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation look for ν_τ appearance in a pure ν_μ beam
- Tau identification



$\tau^- \to$:	$\mu^-\ \nu_\tau\ \nu_\mu$	(17.4%)	Kink
	$e^-\ \nu_\tau\ \nu_e$	(17.8%)	
	$h^-\ \nu_\tau\ n\pi^0$	(49.5%)	
	$\pi^+\pi^-\pi^-\ \nu_\tau\ n\pi^0$	(14.5%)	Multiprong



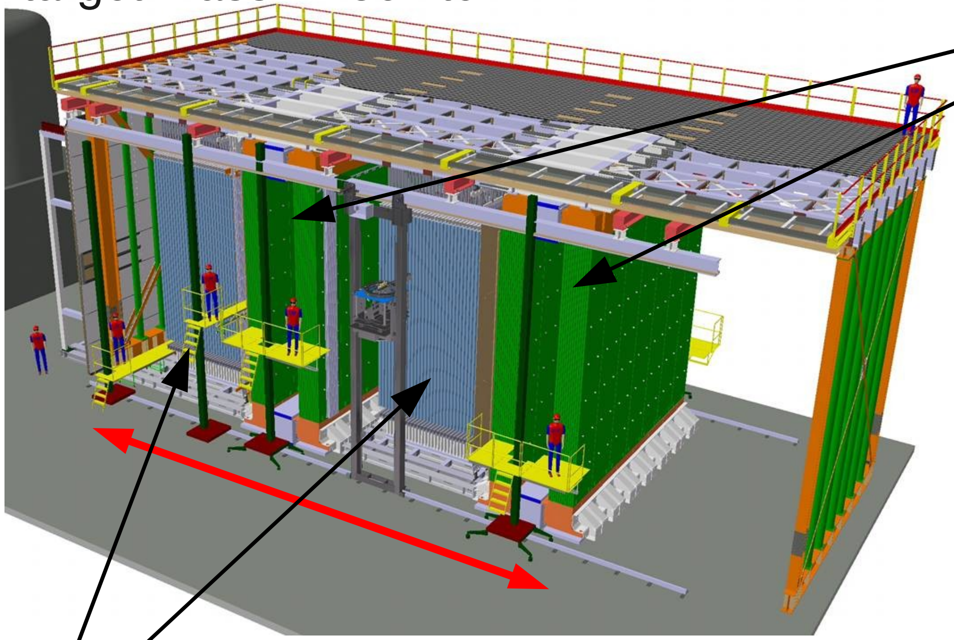
At the given distance (732 Km), ν_μ flux optimized to maximize the ν_τ charged current interactions
<L/E> = 43 Km/GeV

$\langle E\nu_\mu \rangle$	17 GeV
$(\nu_e+\bar{\nu}_e)/\nu_\mu$	0.87%
$\bar{\nu}_\mu$ / ν_μ	2.1%
ν_τ prompt	negligible

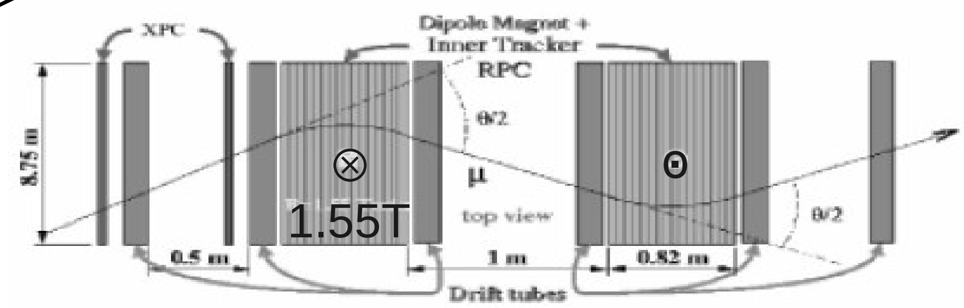
- Need Large target mass, high spacial resolution, lepton ID
  - $c\tau$~0.6mm

OPERA detector overall

Total target mass : 1.35 kton



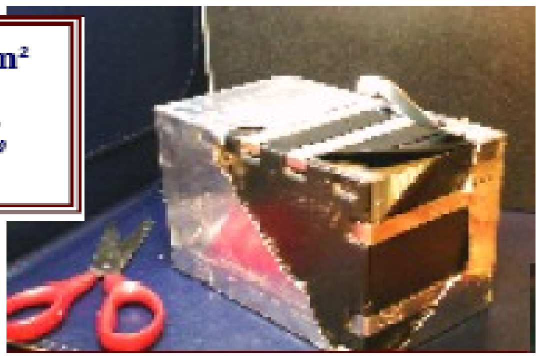
- μ ID : magnetic spectrometer



- Data taking
  - DAQ at Gran Sasso
  - Emulsion scanning at EU & Japan

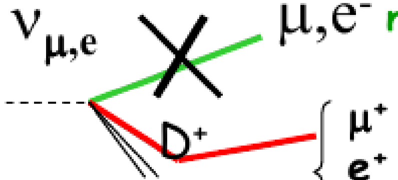
- ν_τ target and tracker : target tracker
  - Emulsion Cloud Chamber bricks & scintillator strips

12.5x10.2 cm²
8 cm thick
8.4 kg, 10 X_0
(94% Pb)



- A ECC brick has
  - 57 Emulsion films
  - 56 Pb sheets(1mm thick)
- ~154,000 ECC bricks in total

τ search : Backgrounds

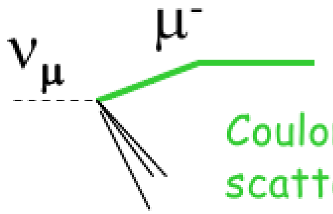


Primary lepton not identified

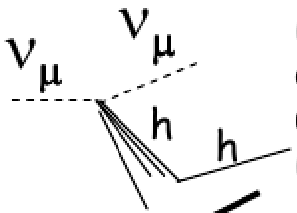
Same decay topology as τ

Charm production in CC, common to the 3 channels

Good muon identification is fundamental



Coulombian large angle scattering of muons in Lead : Bck. to $\tau \to \mu$



Hadronic interactions in Pb: Bck. to $\tau \to h$ or to $\tau \to \mu$ (if hadron mis-identified as muon)

Expected number of background events after 5 years running with nominal beam:

	$\tau \to e$	$\tau \to \mu$	$\tau \to h$	$\tau \to 3h$	Total
Charm background	.173	.008	.134	.181	.496
Large angle μ scattering		.096			.096
Hadronic background		.077	.095	.	.172
Total per channel	.173	.181	.229	.181	.764

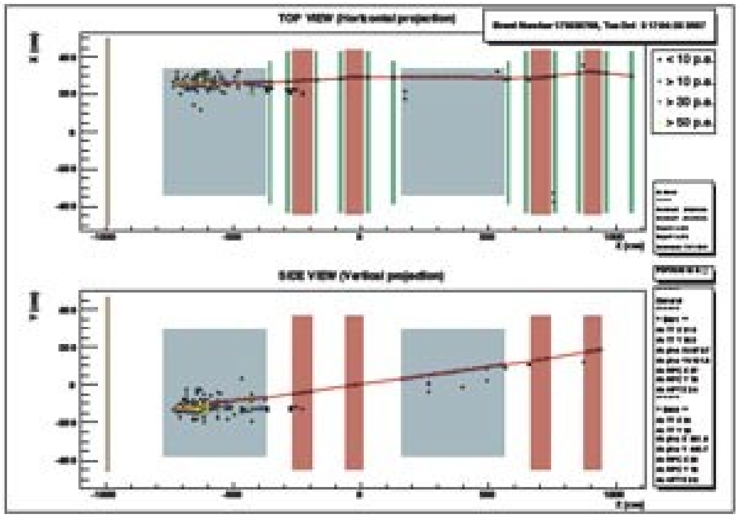
First beam induced event

Neutrino events in OPERA

- 2007 “appetizer” run : very short
  - 36 out of 38 events with good CS tagging
  - Wall finding, brick finding : OK
  - TT to CS position accuracy : ~ 3 cm

Bricks at the start of the run (5/10/07)	Bricks at the end of the run (29/10/07)	Integrated p.o.t	In-target events (bricks + scintillators + walls → extra 10% contribution)
57040	64060	8.24×10^{17}	38 (31,5 expected)

- First event recorded in the OPERA target : Oct 2, 2007



Future : sensitivity to ν_τ search

About to start the full action
(2008 schedule and beyond)
Sensitivity to ν_τ search

CNGS in 2008

After restart, setting-up etc:

june 16th to nov. 11th :
130 effective days
@ $4x10^{13}$ pot/cycle

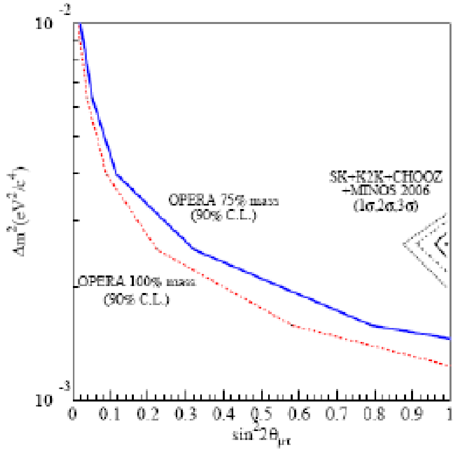
$2.4 \div 2.6x10^{19}$ pot

~ 2500 interactions
in OPERA target

~ *1.2* ν_τ candidates expected!

First ν_τ event expected in 1-2 yr

- **5 years CNGS data taking ($4.5\ 10^{19}$ pot/year)**
- **1.35 ktons target mass**



τ^- decay channels	Signal ÷ Δm^2 (Full mixing)		Background
	2.5×10^{-3} (eV^2)	3.0×10^{-3} (eV^2)	
$\tau^- \to \mu^-$	2.9	4.2	0.17
$\tau^- \to e^-$	3.5	5.0	0.17
$\tau^- \to h^-$	3.1	4.4	0.24
$\tau^- \to 3h$	0.9	1.3	0.17
ALL	10.4	15.0	0.76

Conclusion and Future

- Detector is about to fully installed
- First beam related event has been observed last October
- First ν_τ event is expected to be observed in 1-2 yr

Grand Conclusion

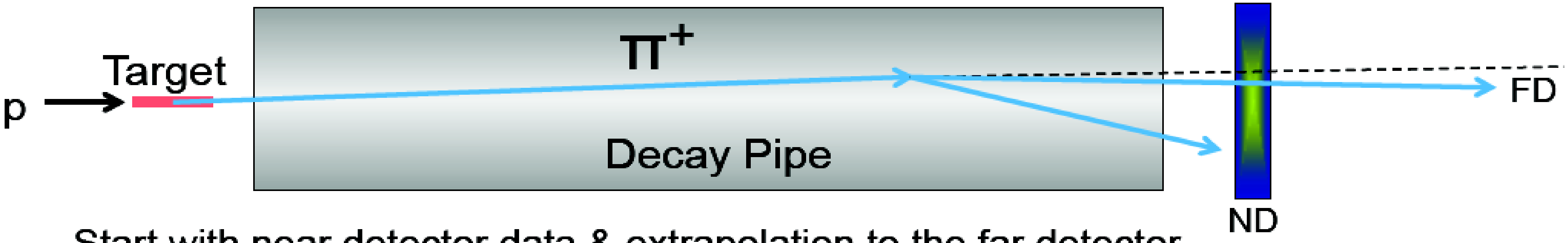
Upside down Moon

- MINOS
  - CC : atmospheric ν osc, decay and decoherence are disfavored
  - NC : haven't seen significant disappearance
- SK
  - SKI+II analysis, SKIII result is coming soon, SKIV upgrade is on going
- MiniBooNE
  - ν_e appearance search --- combined analysis & low E
- OPERA
  - Detector is almost fully installed. Will see first ν_τ in 1-2 yr.

Supplements

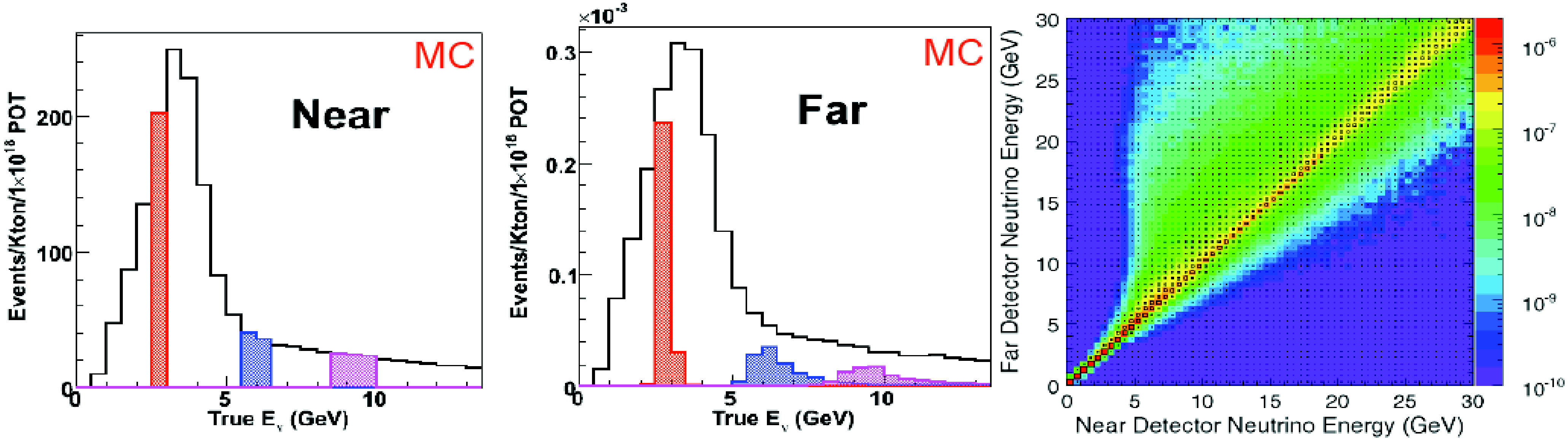
Near to Far Extrapolation

H. Gallag
Tufts Universit
Neutrino 200
May 27, 2008



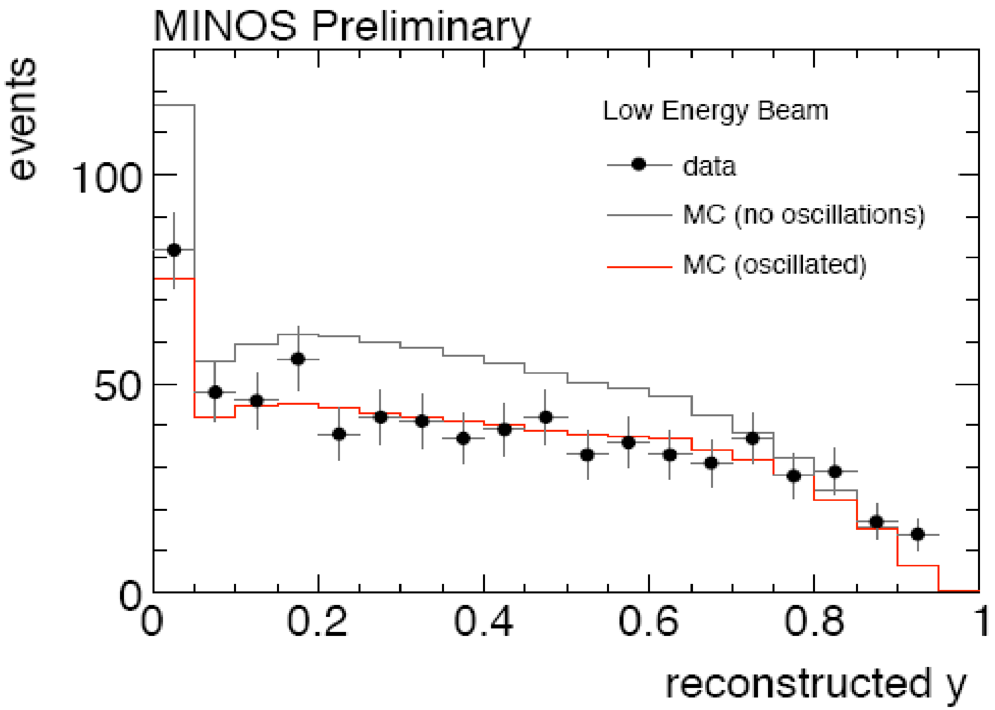
Start with near detector data & extrapolation to the far detector

- Use Monte Carlo to provide corrections due to energy smearing and acceptance
- Encode pion decay kinematics & the geometry of the beamline into a matrix used to transform the ND spectrum into the FD energy spectrum



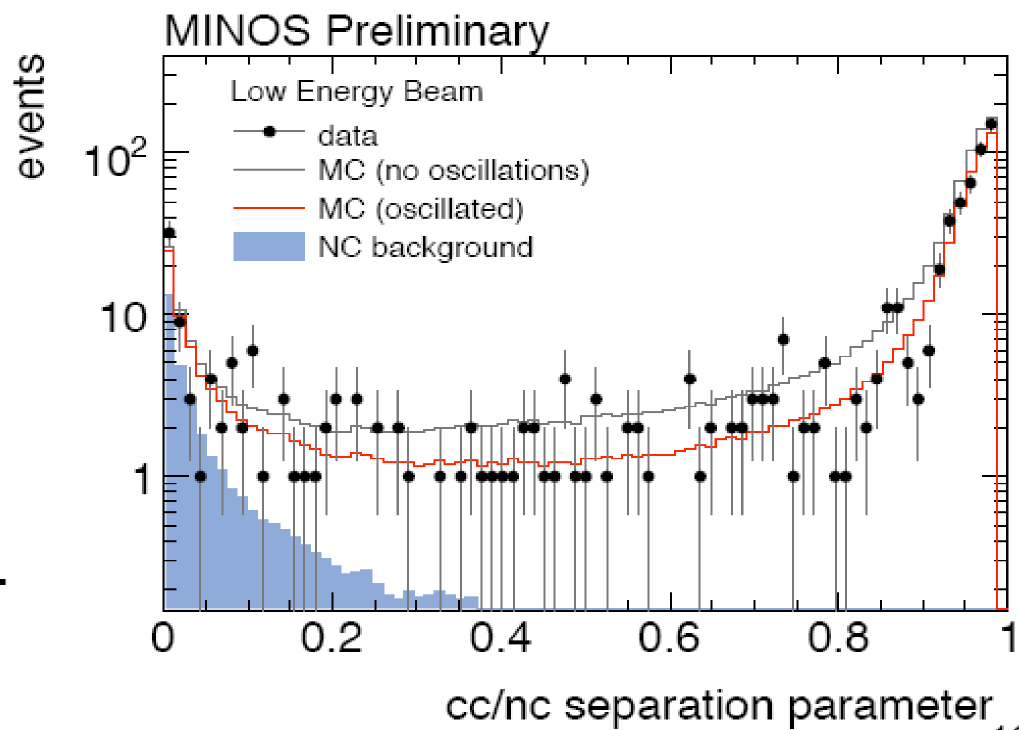
Far Detector Distributions - LE

H. Gal
Tufts Unive
Neutrino 2
May 27, 2008



Good agreement is also seen in reconstructed quantities.

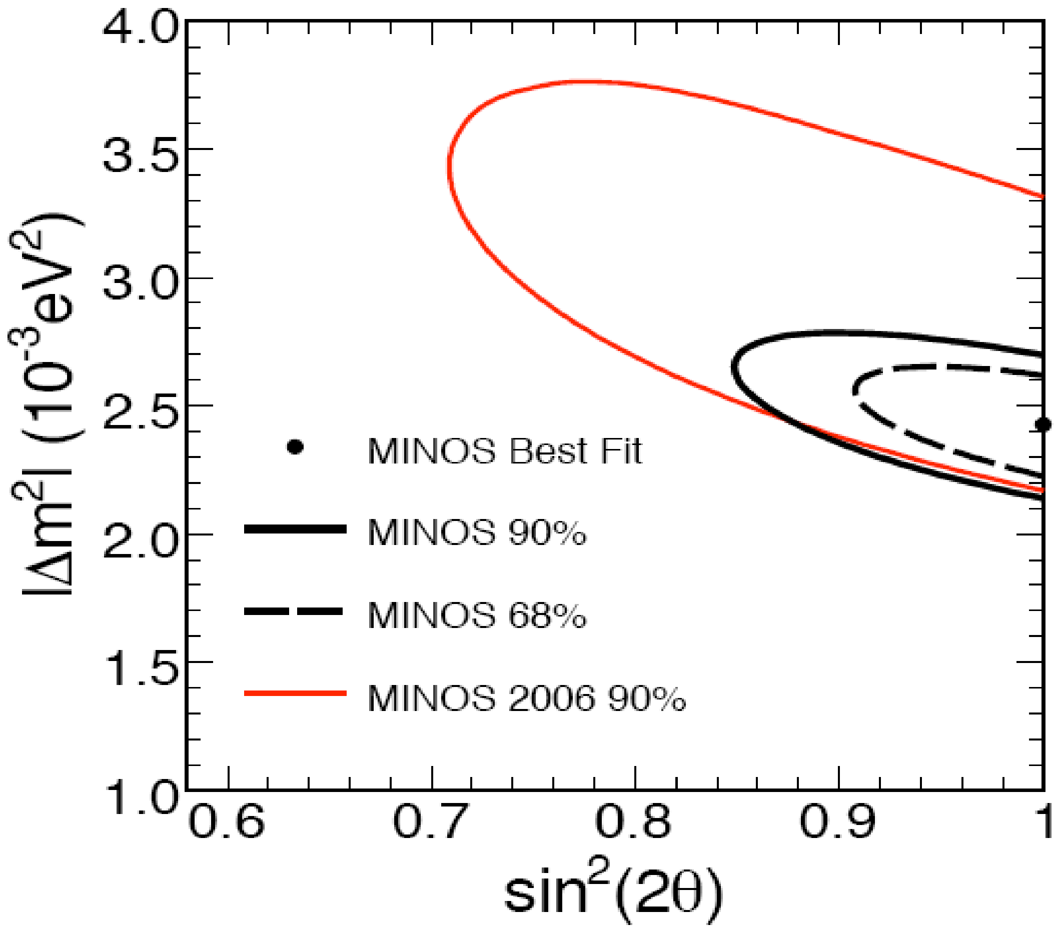
- Numbers of tracks/showers
- Track energies
- Shower energies
- Kinematic distributions



Oscillation fit data:

Run I LE data: 1.27×10^{20} POT
Run II LE data: 1.94×10^{20} POT
Run II HE data: 0.15×10^{20} POT

Comparison with 2006 Result



Run I: $|\Delta m^2|=(2.57^{+0.19}_{-0.20})\ x10^{-3}\ eV^2,\ \sin^2(2\theta)=1.0$ ← Improved:

Run II: $|\Delta m^2|=(2.32^{+0.15}_{-0.16})\ x10^{-3}\ eV^2,\ \sin^2(2\theta)=1.0$

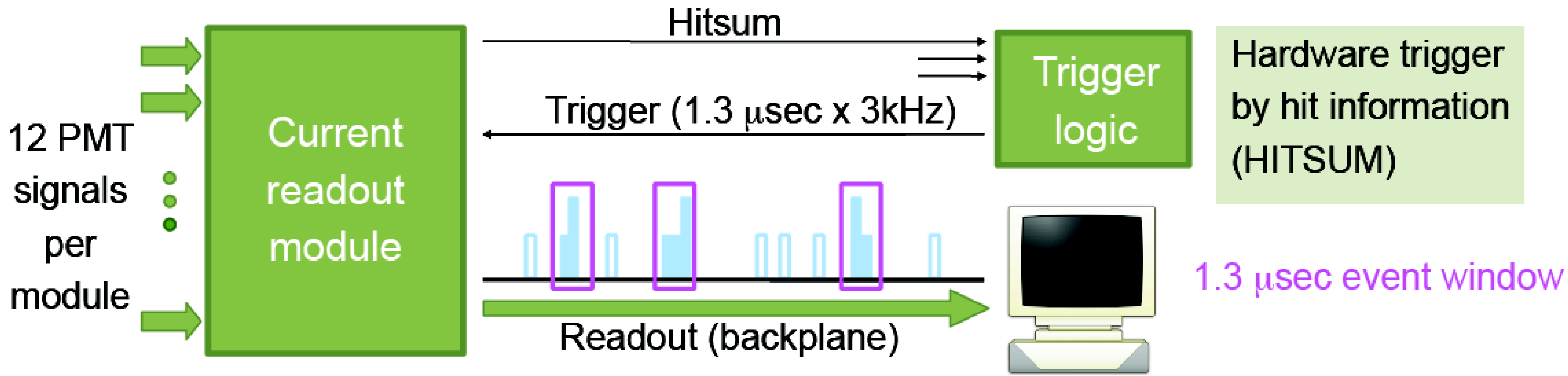
- Reconstruction
- Monte Carlo
- Analysis

NC Systematic Errors

- **Normalization**: ±4%
  - POT counting, Near/Far reconstruction efficiency, fiducial mass
- **Relative Hadronic Calibration:** ±3%
  - Inter-Detector calibration uncertainty
- **Absolute Hadronic Calibration:** ±11%
  - Hadronic Shower Energy Scale(±6%), Intranuclear rescattering(±10%)
- **Muon energy scale:** ±2%
  - Uncertainty in dE/dX in MC
- **CC Contamination of NC-like sample:** ±15%
- **NC contamination of CC-like sample:** ±25%
- **Cross-section uncertainties:**
  - m_A (qe) and m_A (res): ±15%
  - KNO scaling: ±33%
- **Poorly reconstructed events:** ±10%
- **Near Detector NC Selection:** ±8% in 0-1 GeV bin
- **Far Detector NC Selection:** ±4% if E < 1 GeV, <1.6% if E > 1 GeV
- **Beam uncertainty:** 1σ error band around beam fit results

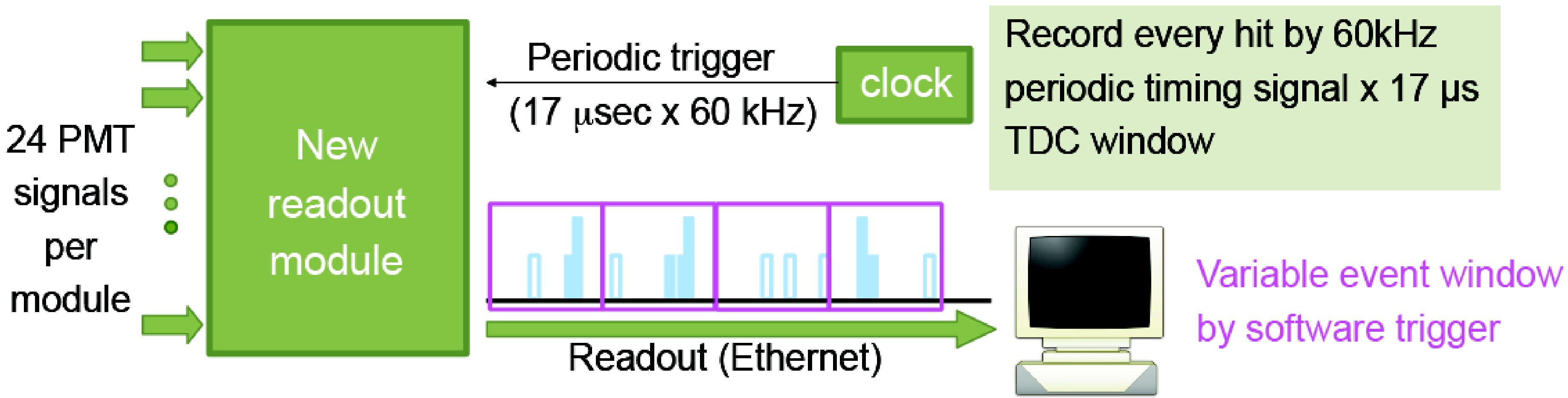
New DAQ readout scheme

SK-I,II,III DAQ scheme:

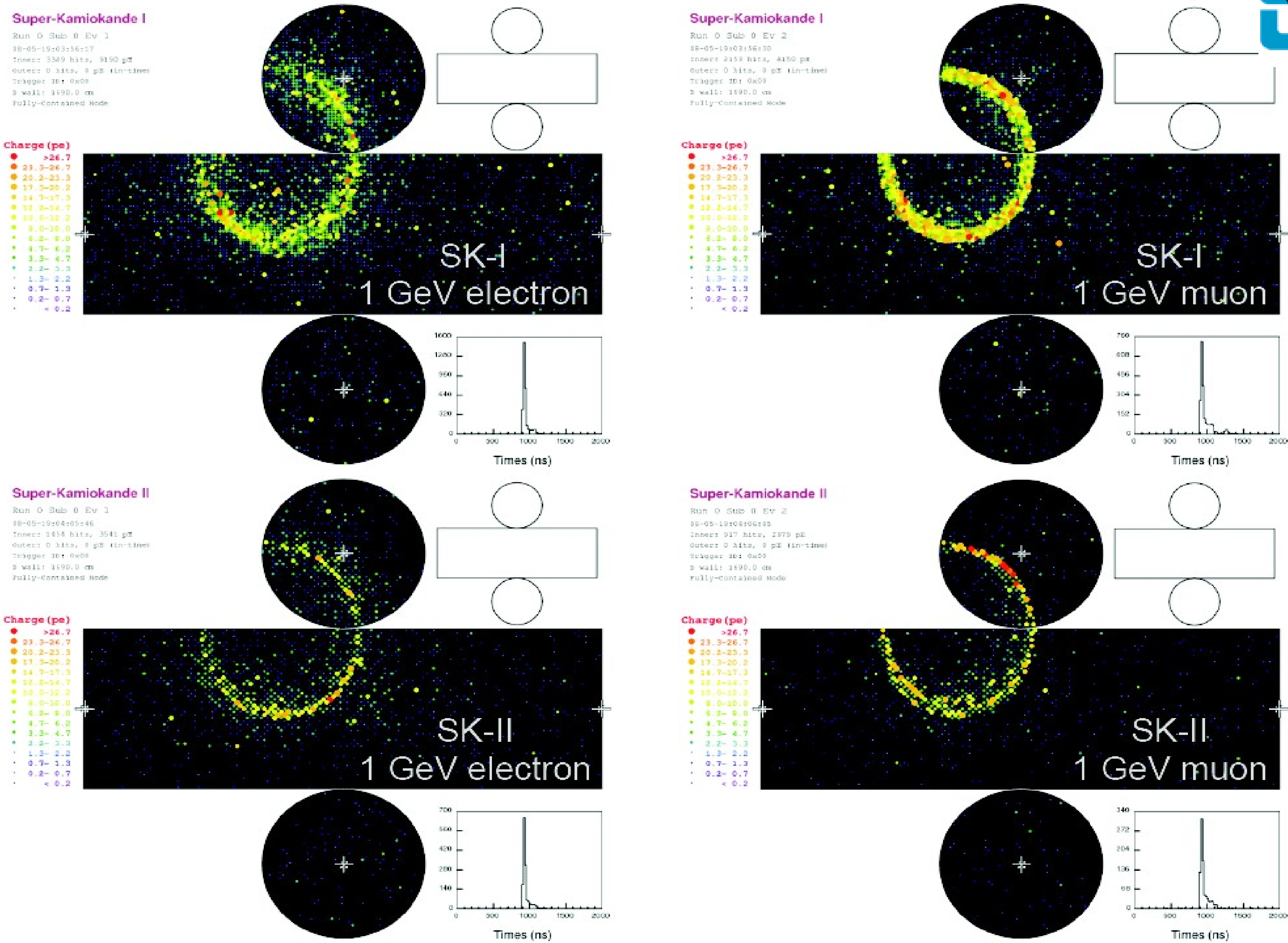


SK-IV DAQ scheme:

No hardware trigger. Instead record all hits and apply software triggers.



Atmospheric ν's at Super-K (simulated events)



Atmospheric ν Analyses

Exotic Scenarios

Model	Exclusion level or limit
$\nu_\mu \rightarrow \nu_s$ oscillation	SK-I+II: 7.3σ
Admixture (2+2 hierarchy)	SK-I+II: 23% allowed
Decay I ($\sin^4\theta + \cos^4\theta\, e^{-\alpha L/E}$)	SK-I+II: 17σ
Decay II ($(\sin^2\theta + \cos^2\theta\, e^{-\alpha L/2E})^2$)	SK-I+II: 3.9σ
Decay Limit (GeV^2)	SK-I+II: 6.5×10^{-23}
Decoherence ($(1+e^{-\beta L/E})/2$)	SK-I+II: 4.2σ
Decoherence Limit (GeV)	SK-I+II: 6.0×10^{-24}
LIV Limit	SK-I+II: 1.2×10^{-24}
CPTV Limit (GeV)	SK-I+II: 0.9×10^{-23}
MaVaNs (various models)	SK-I: 3.5-3.8σ
Non-Standard Interactions	See poster by G. Mitsuka

Neutrinos frequently set stringent limits, although not usually testing exactly the same parameters.

e.g., cosmic ray spectrum LIV < 10^{-15}, NMR LIV < 10^{-22}
K^0K^0bar CPTV < 10^{-18}

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Zenith Angle Analysis (2-flavor)

Datasets	
SK-I FC/PC:	1489 days
SK-I Upmu:	1646 days
SK-II FC/PC:	799 days
SK-II Upmu:	828 days

Data binned according to:

event type
+
momentum
+
zenith angle

} 400 bins for SK-I
350 bins for SK-II

χ^2 fit in bins of zenith angle with systematic error pull terms:

$$\chi^2 = \sum_{i=1}^{N_{bins}} 2 \left(N_i^{exp} - N_i^{obs} + N_i^{obs} \ln \frac{N_i^{obs}}{N_i^{exp}} \right) + \sum_{j=1}^{N_{sys}} \left(\frac{\varepsilon_j}{\sigma_j^{sys}} \right)^2$$

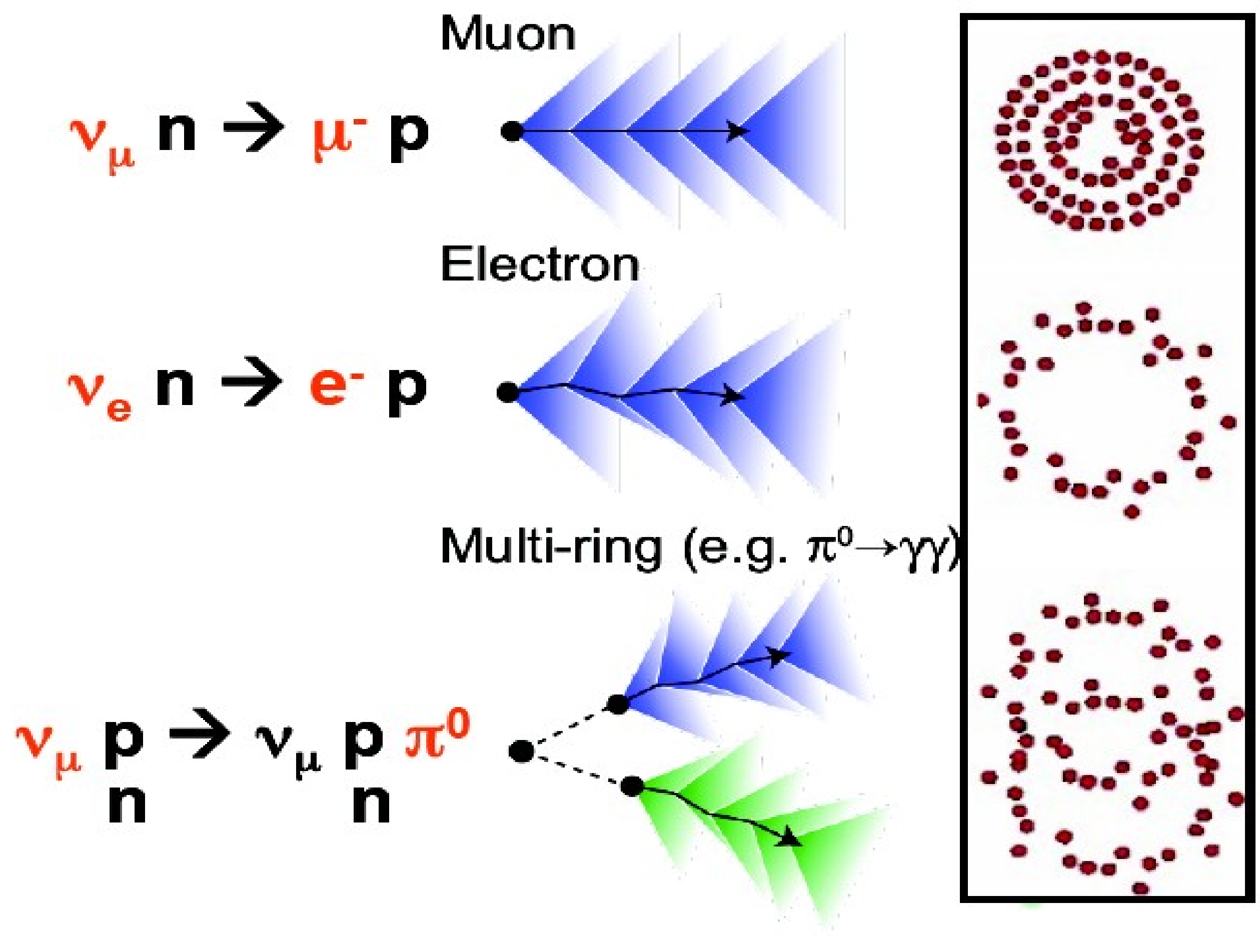
where $$N_i^{exp} = N_i^0 \cdot P(\nu_\alpha \to \nu_\beta) \left(1 + \sum_{j=1}^{N_{sys}} f_j^i \varepsilon_j \right)$$

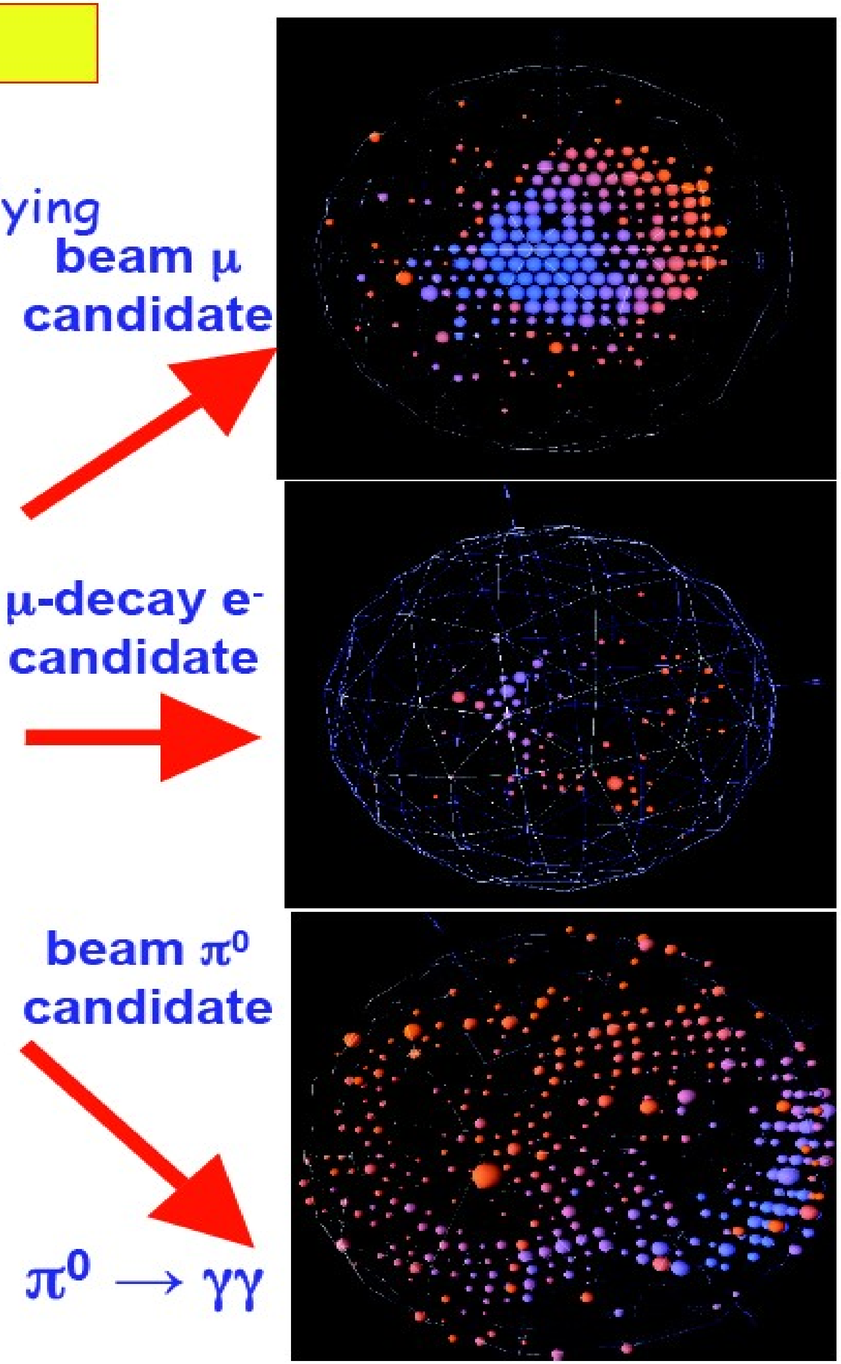
90 systematic error terms to account for uncertainties in:

- Neutrino flux
- Cross sections
- Event reconstruction
- Data reduction

Particle Identification

Čerenkov rings provide primary means of identifying products of ν interactions in the detector





Slide from Zelimir Djurcic's talk at PPC 2008