Long Baseline Neutrino Experiments

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Part 2

Brief CV

Professor of Experimental Particle Physics at the University of Cambridge

Research Interests/History

- ★ Cosmic-ray/Astroparticle Physics (Soudan 2)
- ★ Electroweak Physics at LEP (OPAL)
  - Z lineshape and leptonic couplings
  - W mass and couplings
- ★ Neutrino physics (MINOS)
  - atmospheric neutrinos
  - ν_e appearance

time

★ Calorimetry at future colliders

Synopsis

Lecture 1

➊ Introduction
➋ Neutrino Beams
➌ Predicting the Beam Energy Spectrum
➍ The MINOS Experiment

Lecture 2

➎ Measuring the Beam Spectrum in MINOS
➏ $\nu_\mu \rightarrow \nu_\tau$ Disappearance in MINOS
➐ $\nu_\mu \rightarrow \nu_e$ Appearance in MINOS
➑ $\nu_\mu \rightarrow \nu_e$ Appearance in T2K
➒ Prospects/Conclusions

(➐–➑: Hot topic)

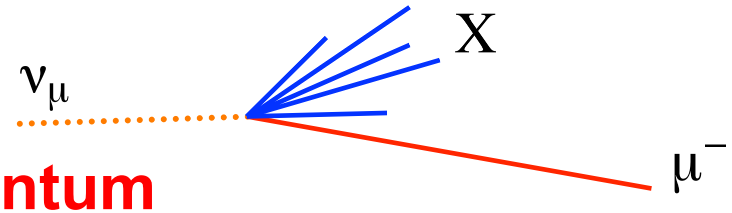
★ Topics chosen to illustrate the main techniques/issues
★ Not intended as a global review – far too little time
★ Use MINOS as the main example

Recap

★ Discuss generation of neutrino beams

★ Started discussion of **MINOS** on-axis experiment
- wide-band beam – need to measure neutrino energy on an event-by-event basis

★ Can measure energy for charged current interactions



- muon momentum
- hadron shower energy

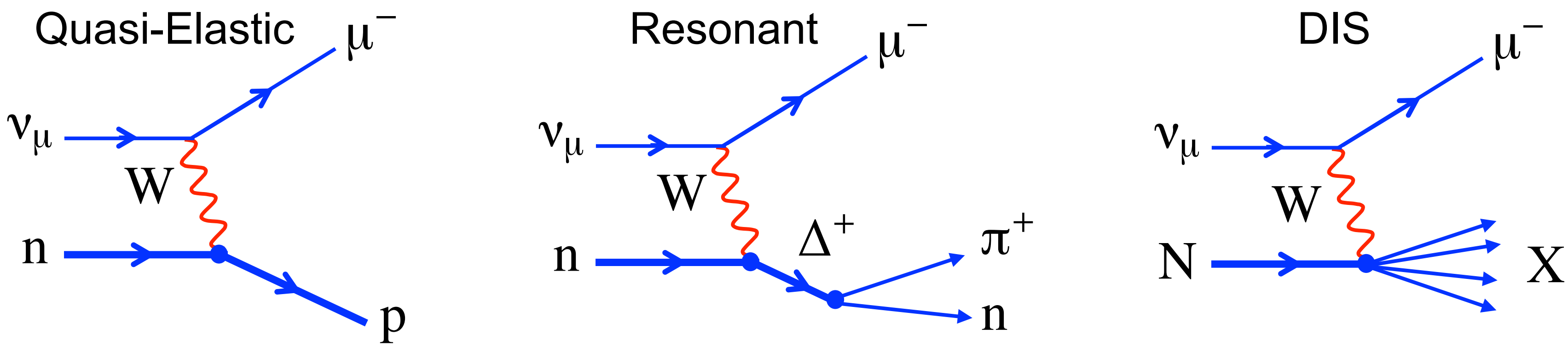
Towards Physics:

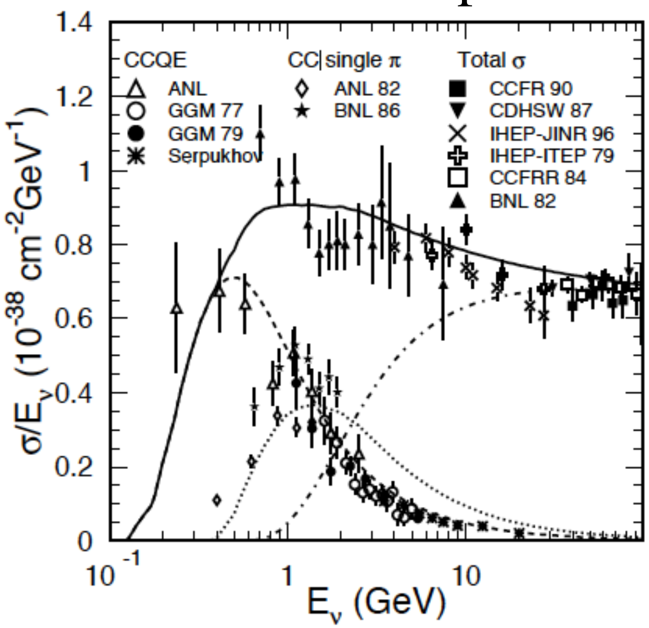
★ First step: identify CC interactions

★ Understand beam

★ Then discuss main techniques for precision neutrino physics

CC Event Types

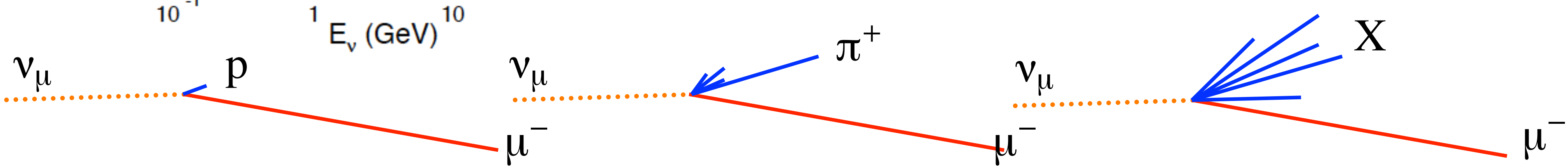




- ★ < 1.5 GeV : QE dominates
- ★ > 5 GeV : DIS dominates
- ★ in between - mixture of QE/RES/DIS

MINOS beam 1-5 GeV + high energy tail

⇨ **All processes are relevant**

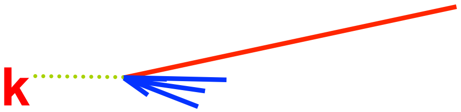


★ **All very different, but tagged by the muon**

Event selection cuts : Near and Far

★ $\nu_\mu \mathrm{CC}$: Require

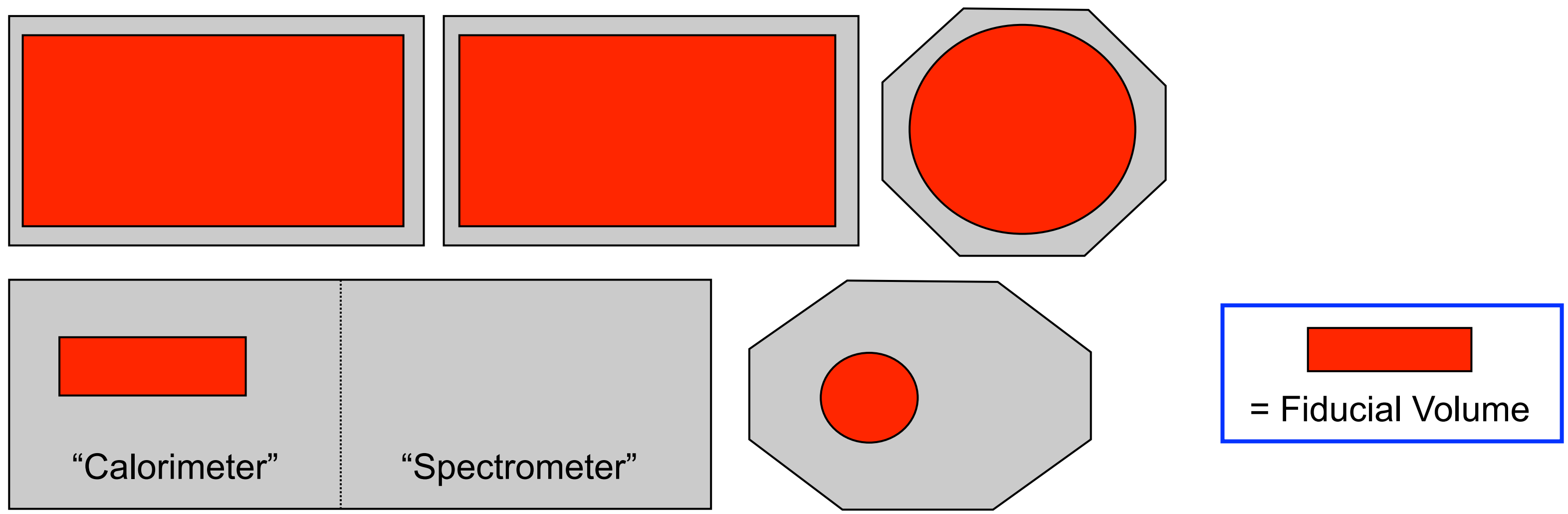
- The event must have a **good reconstructed track**



- The reconstructed track vertex must lie in the detector fiducial volume
  (avoid edges and less well understood regions of detector)

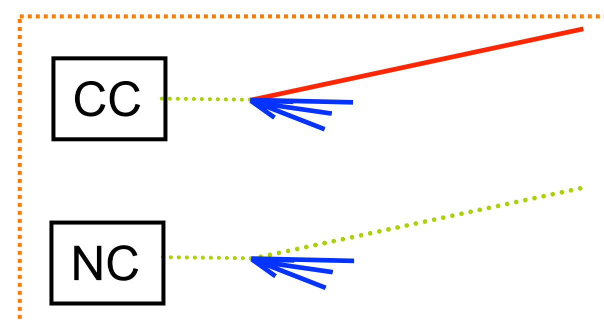
FAR DETECTOR

NEAR DETECTOR



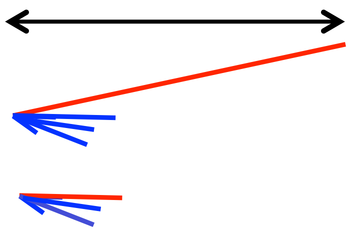
★ Use a multivariate technique: **4 reconstructed quantities**

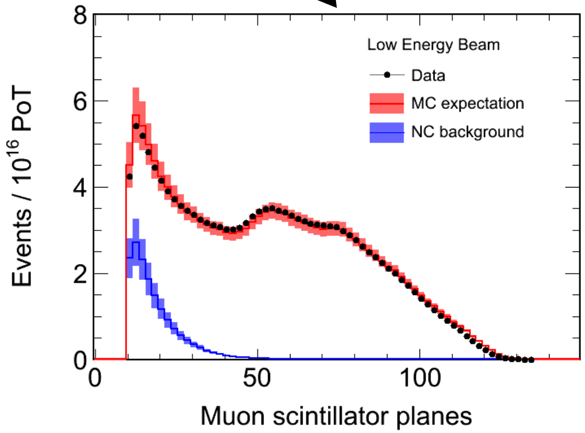
- Number of muon planes
- Mean energy per strip
- Transverse profile
- Signal fluctuation parameter on track



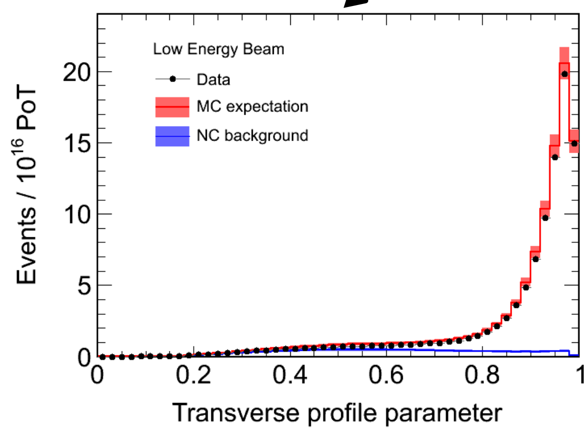
Identifying CC Events

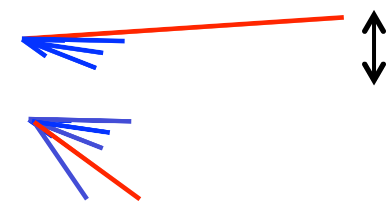
Number of Track planes

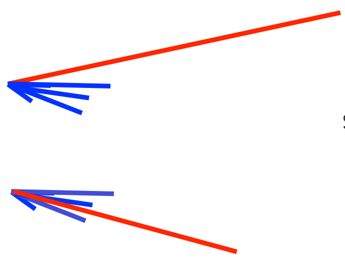


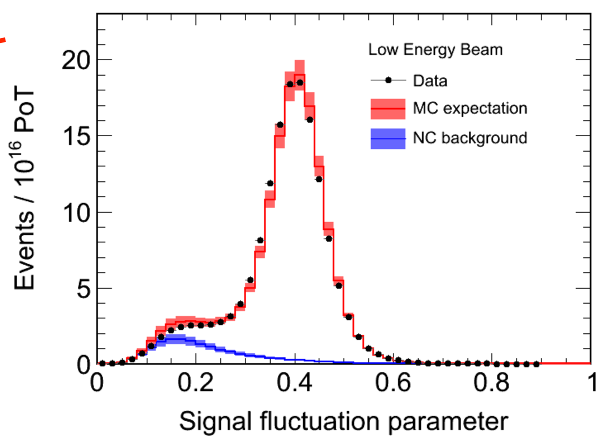


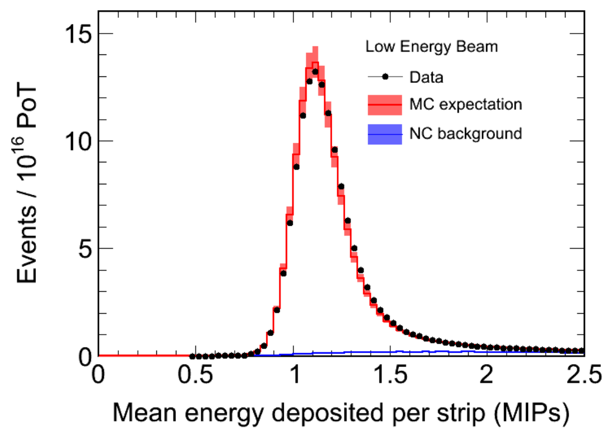
Transverse Profile











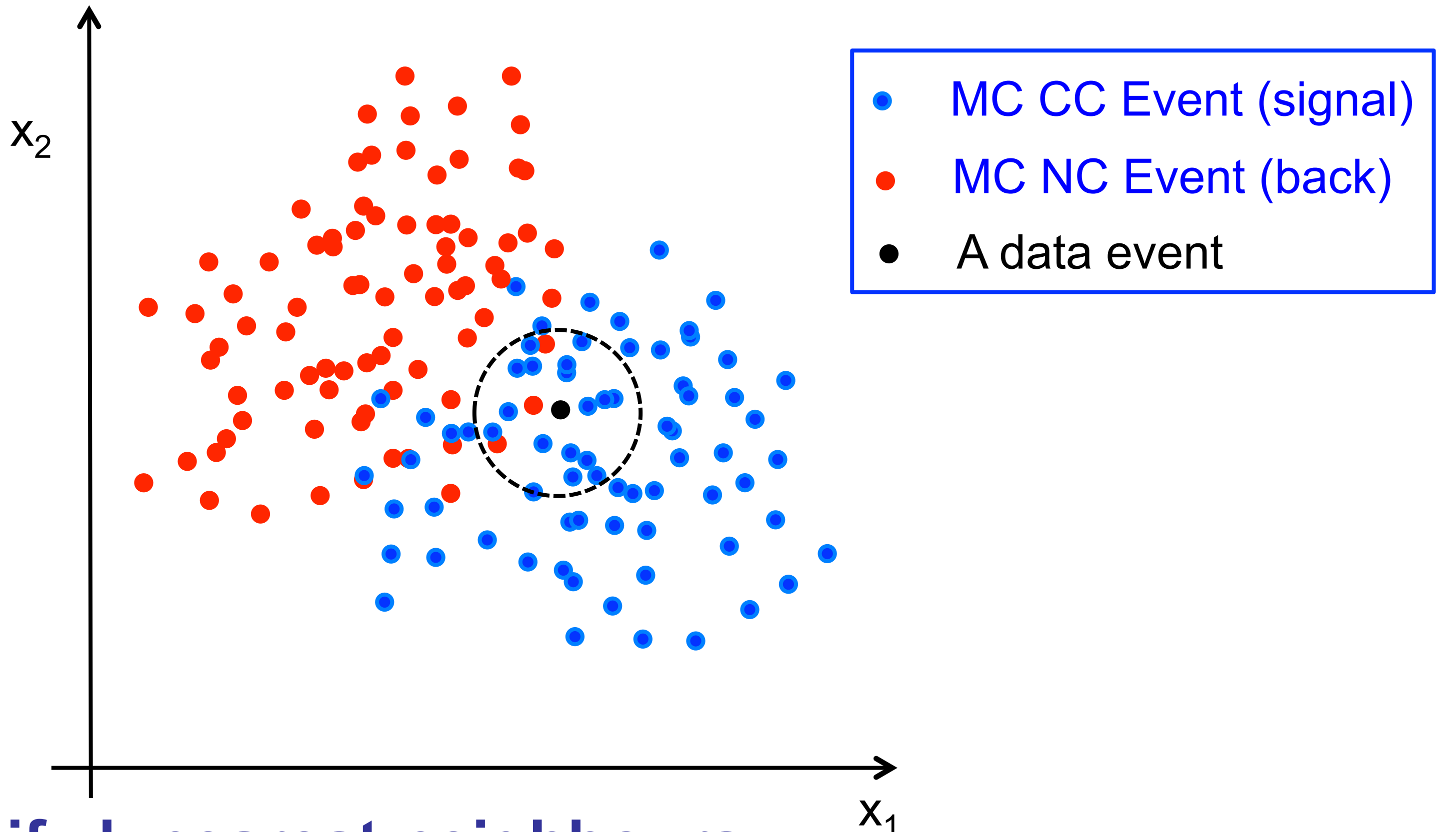
Blobiness along track

Mean hit energy

kNN Selection

★ For each data event compare it to MC in multivariate space

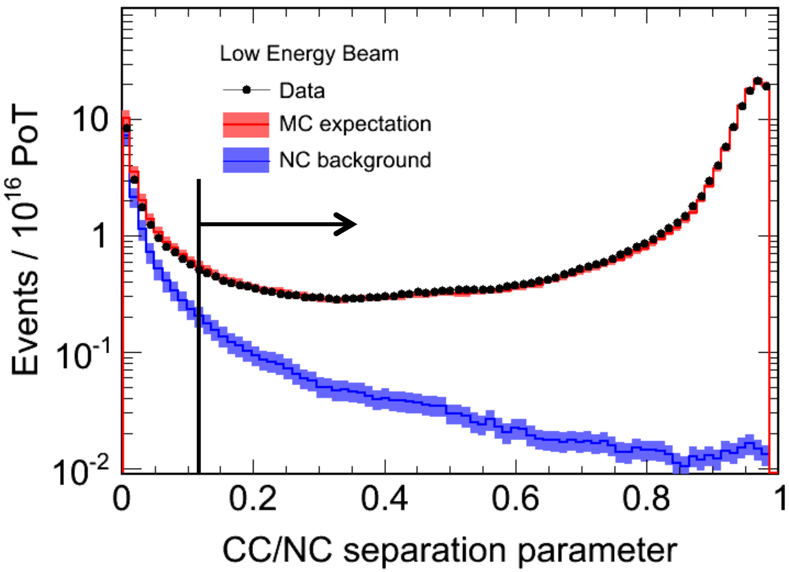
$\{x_1, x_2, x_3, x_4\}$



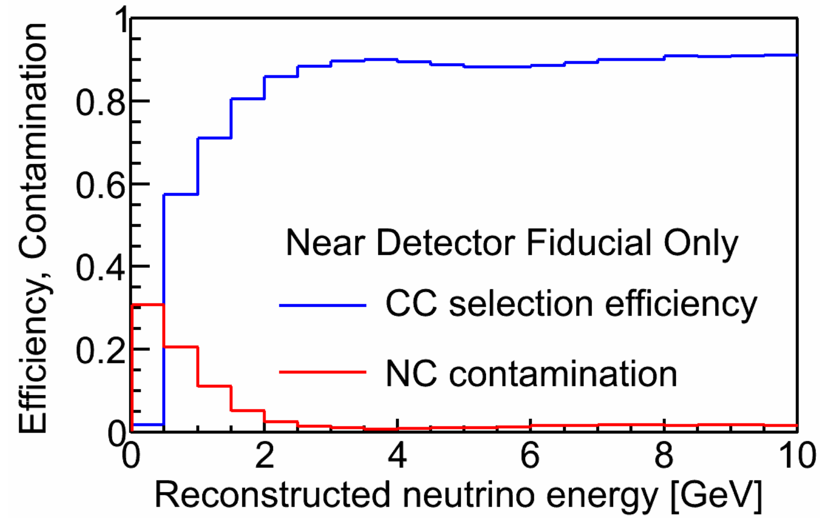
★ Identify k nearest neighbours

★ Cut variable is fraction which are signal

Near Detector Data



★ **Good agreement between data/MC**
★ **Clear separation between CC and NC**



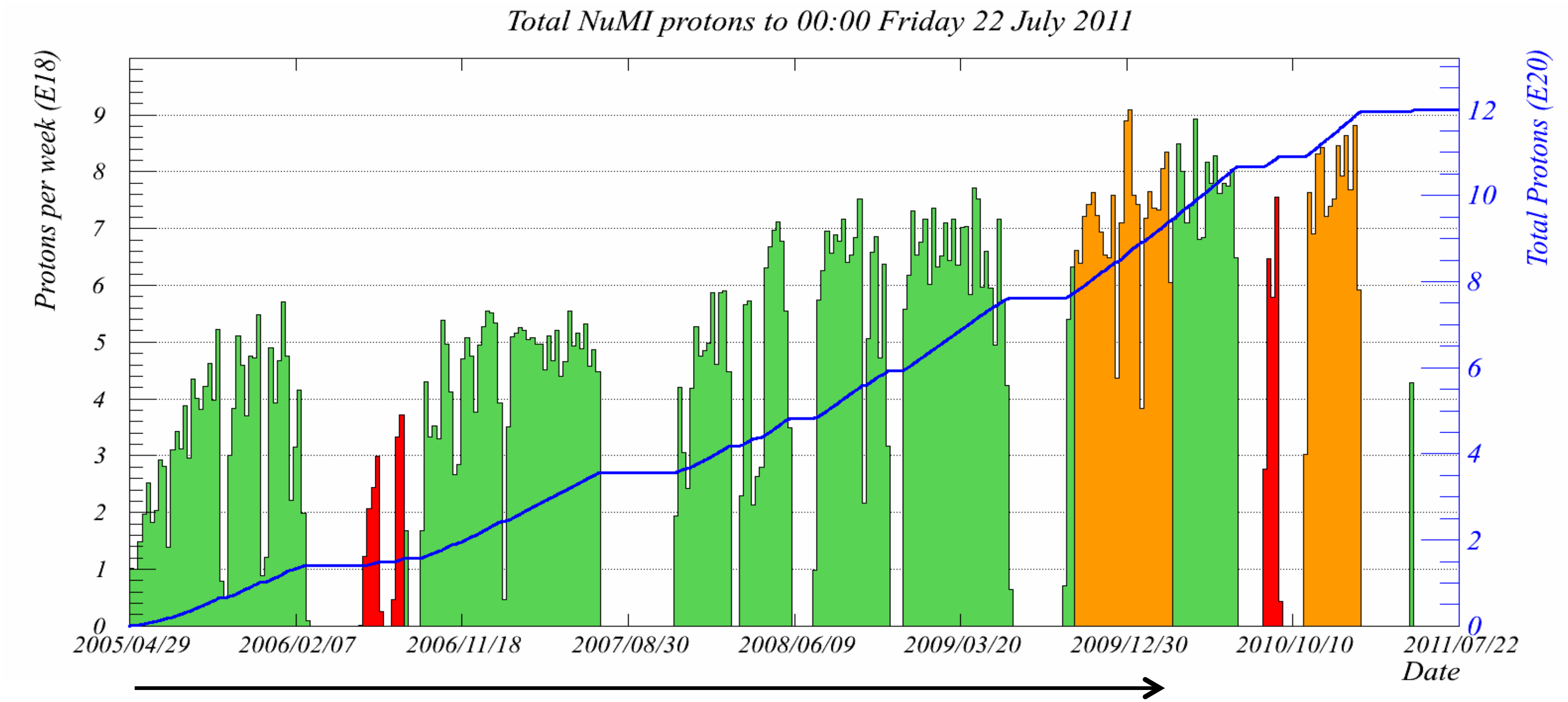
★ **High Efficiency: 88.7 %**
★ **High Purity: 98.3 %**

ALMOST BACKGROUND FREE

Can now measure beam spectrum

❺ Measuring the beam spectrum

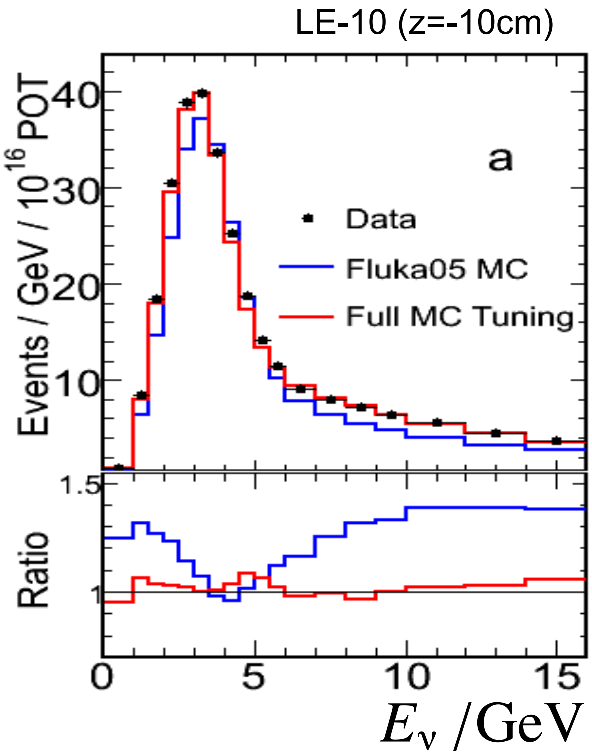
- ★ Total of 1.2E20 protons on target:
  - Neutrinos (Low Energy beam)
  - Neutrinos (High Energy beam)
  - Anti-neutrinos (Low Energy beam)
- ★ Gaps due to NuMI shutdowns and target failures



- ★ Most recent disappearance analysis based on 7.2E20 neutrino data

Measured ND Energy Spectrum

- ★ Measured Near Detector (ND) energy spectrum does not agree with MC
- ★ No surprise – large hadron production and cross section uncertainties



Early Data

- But is the discrepancy due to flux or cross section?

Measured ND Energy Spectrum

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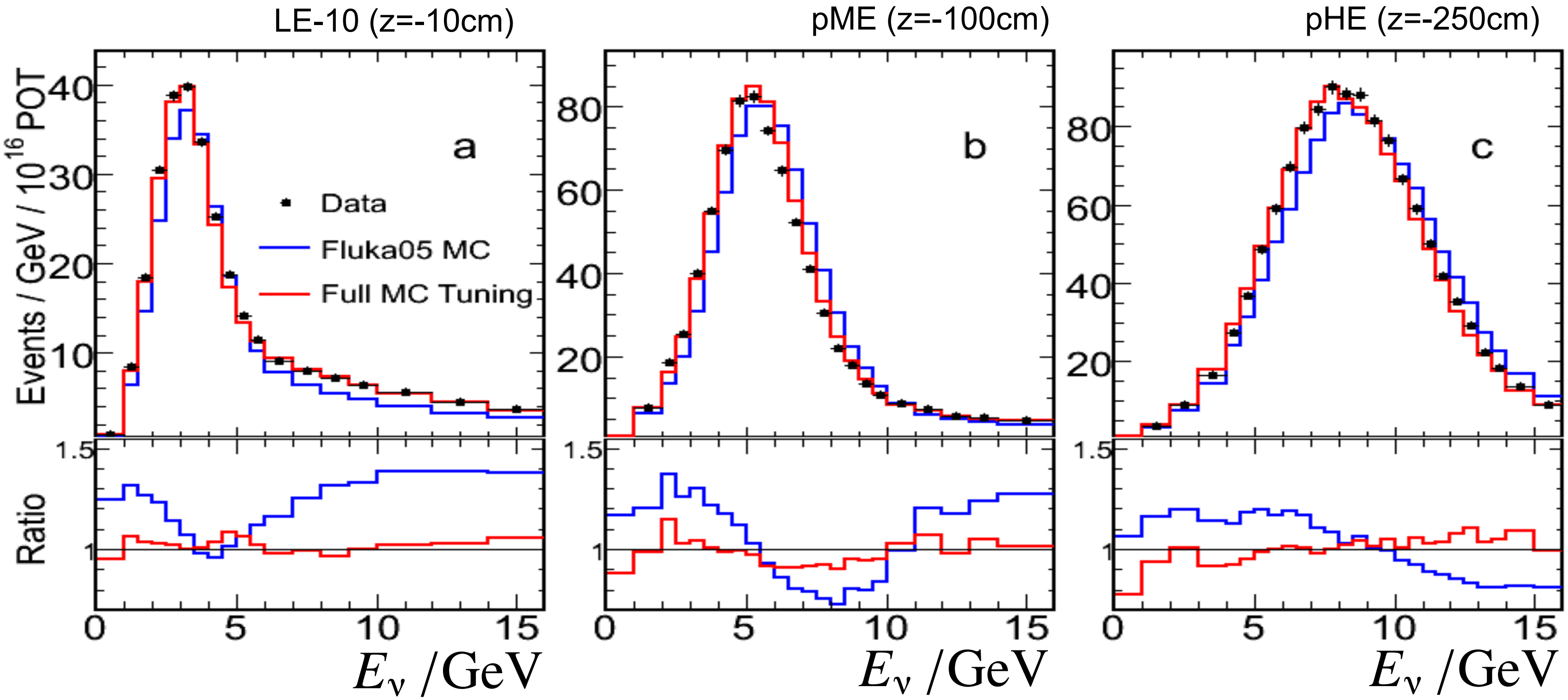
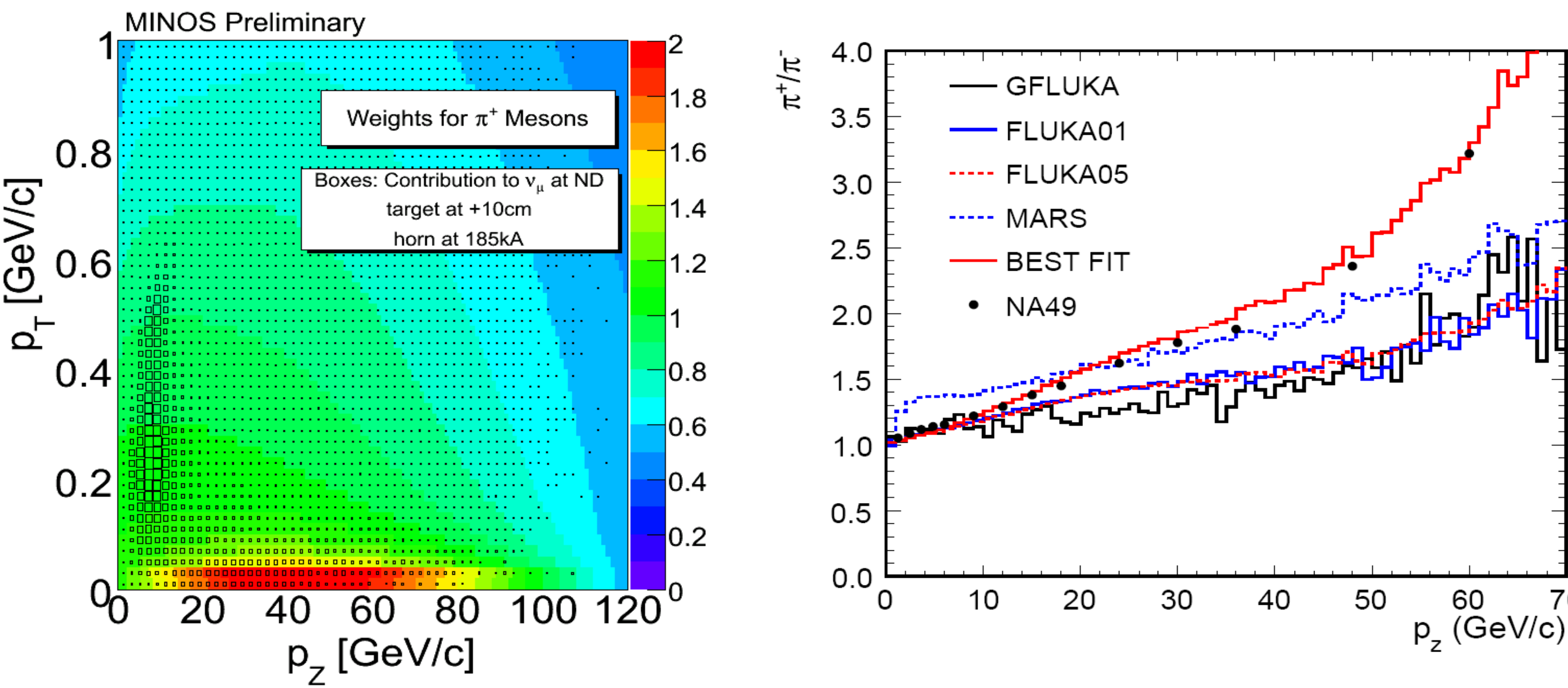


Early Data

- But is the discrepancy due to flux or cross section?
- Power of having data at different beam configurations !
- Discrepancy changes with beam setting
- Suggestive due to flux modeling rather than cross-section model

Hadron Production Tuning

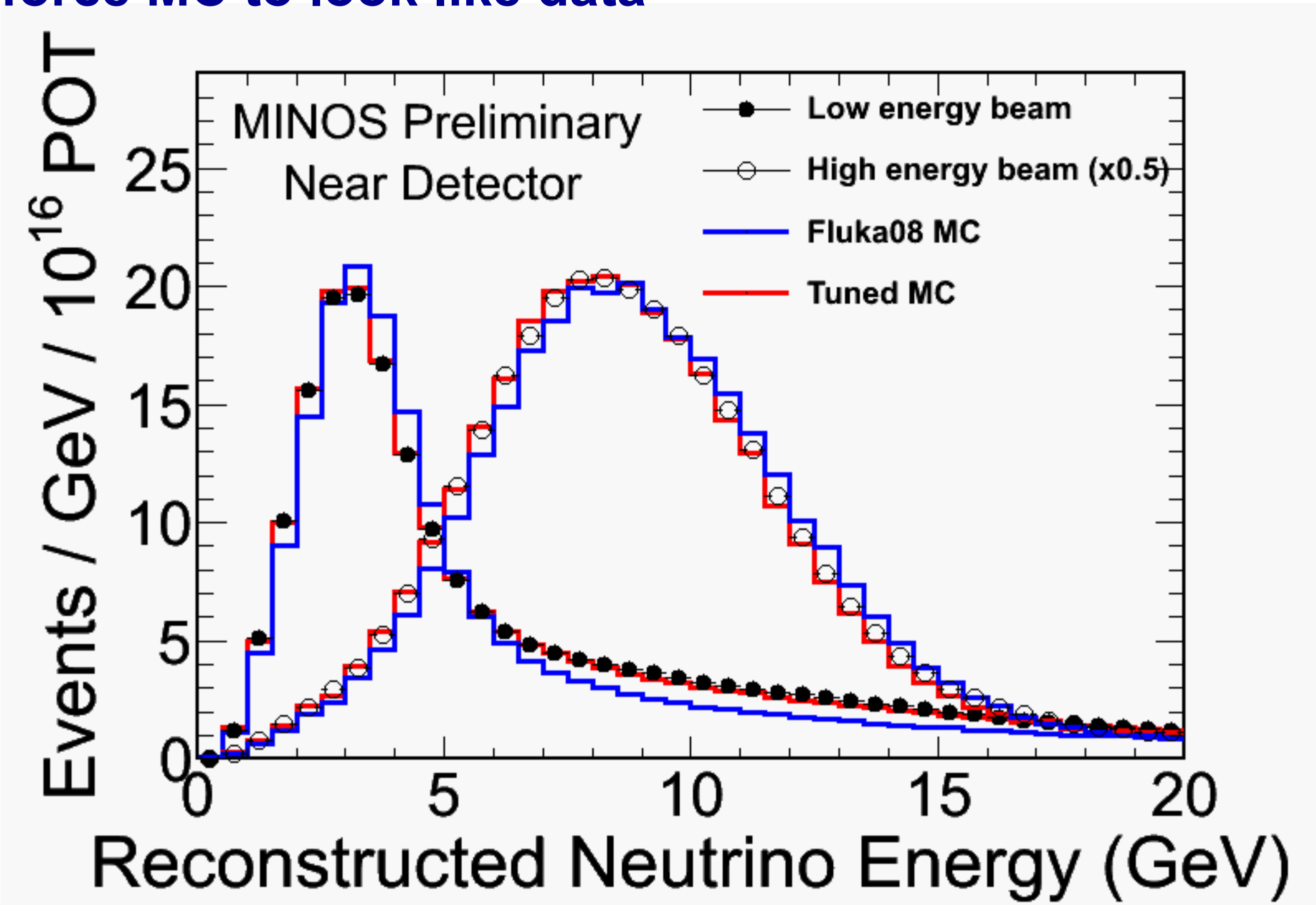
- Reweight MC at hadron production level to fit BD data using a smooth function of x_F and p_T
- Cross check against recent experimental measurements, e.g. NA49



- Effectively force MC to look like data

It works !

- Effectively force MC to look like data



(There are still residual uncertainties in neutrino flux and neutrino cross section)

But also have MEASURED Reconstructed Spectrum in Near Detector

❻ Disappearance Analysis

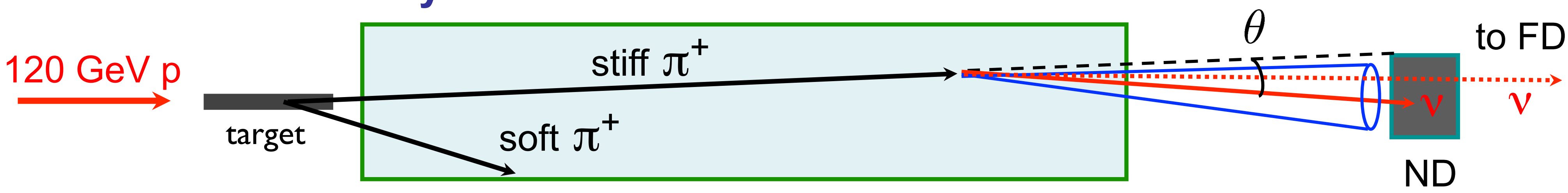
★ Even in the absence of oscillations **the NEAR and FAR detector neutrino spectra are different !**

<u>**Easy to understand…**</u>

★ Consider a pion decaying in the decay pipe

★ Neutrino can intersect the ND for a relatively wide range of decay angles

★ For far detector only decays in a very small range of angles will cross the FD 735 km away



★ At small angles, neutrino energy depends on decay angle relative to pion

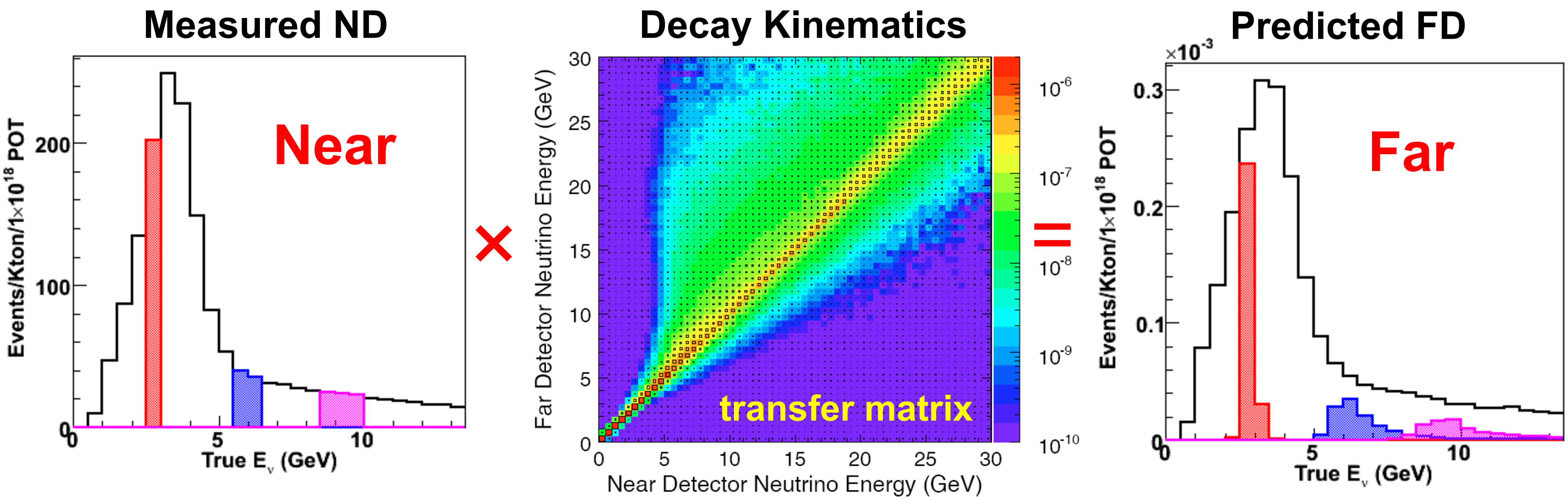
$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

★ Decays with neutrinos pointing towards the FD tend to have smaller θ and hence have slightly higher energy

★ **However**, difference is just kinematics, i.e. **well understood !**

The Beam Transfer Matrix

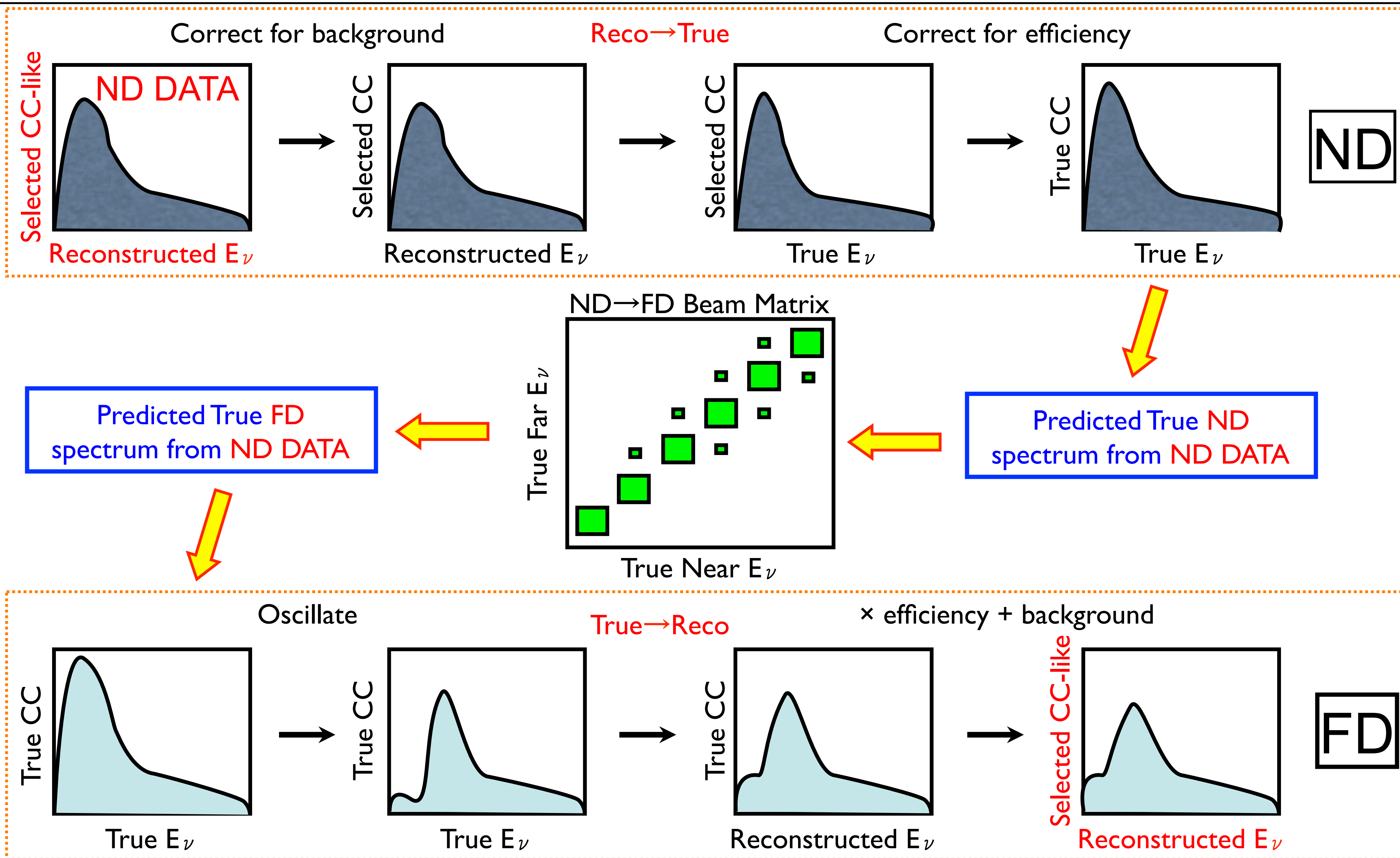
★ **Attempt to directly use ND spectrum to predict FD spectrum**



<u>Beam Transfer Matrix:</u>

- **Encapsulates knowledge of 2-body pion decay and geometry**
- **Beam matrix determined from MC but does not depend strongly on details - kinematics & geometry dominate**
- **MC tuning only enters as a second order effect in determining matrix**
  - almost identical FD predictions for tuned and untuned MC

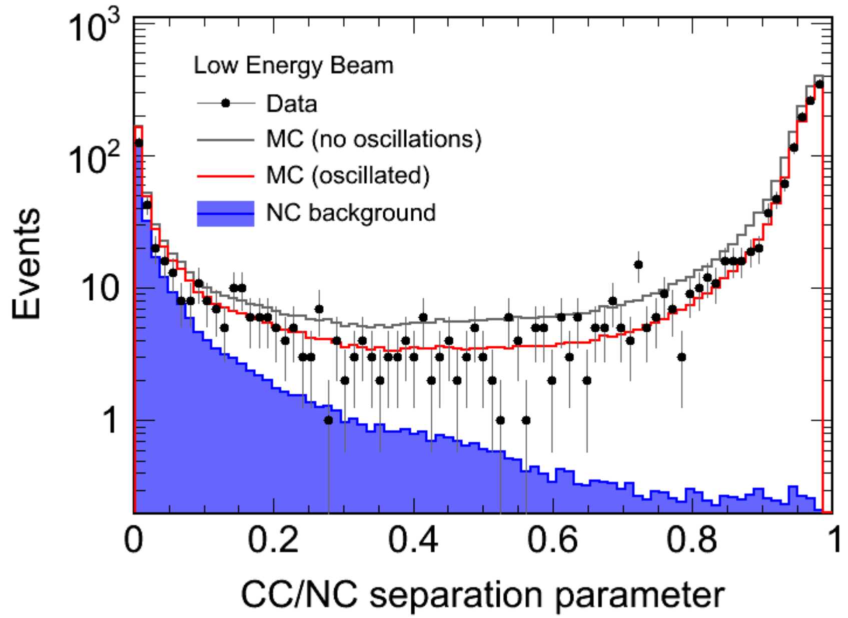
Details of matrix Near → Far beam extrapolation



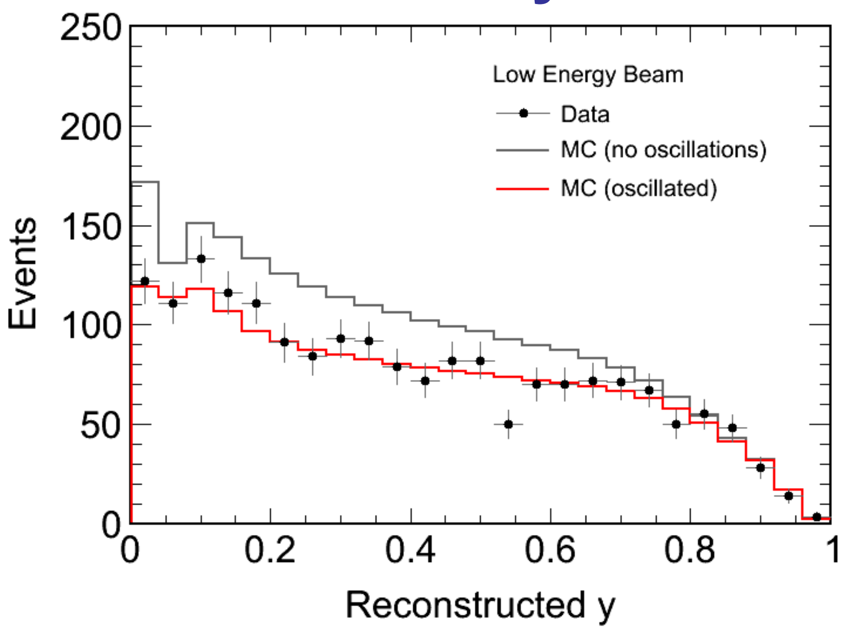
Far detector data

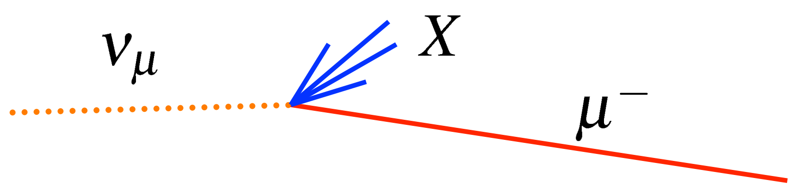
★ **Reconstructed event distributions in FD very well modelled**

- **CC/NC separation parameter**



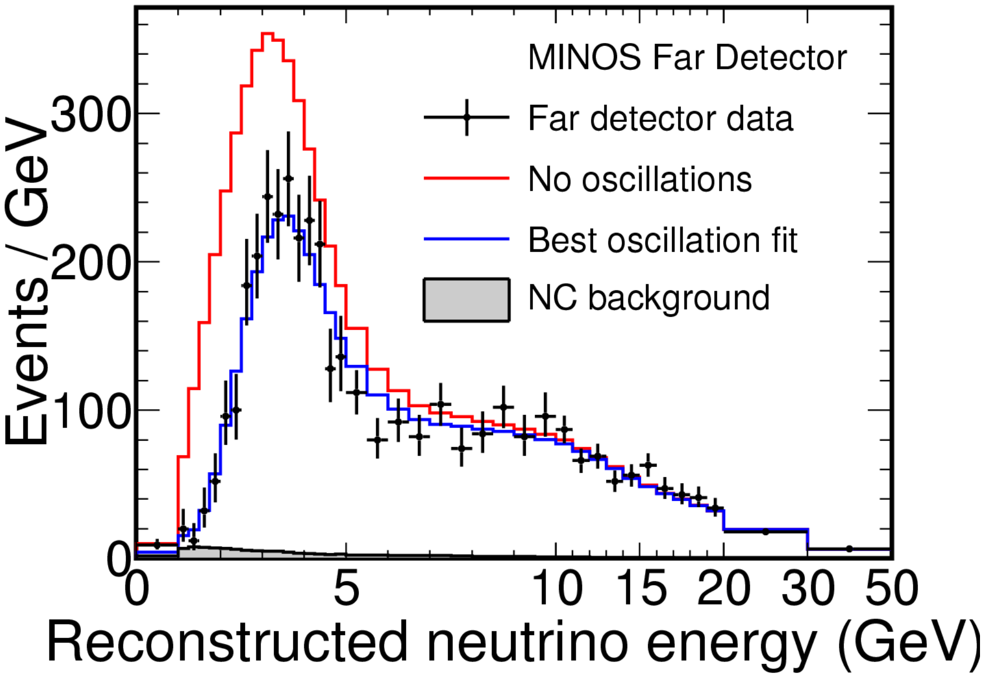
- **Reconstructed y distribution**



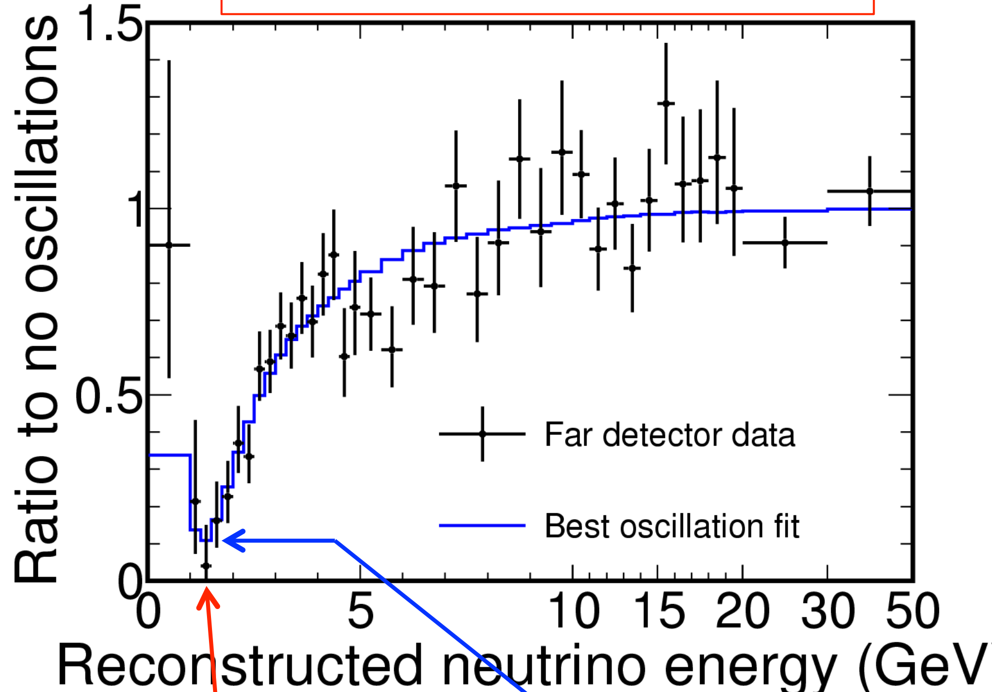


$$y = \frac{E_{\text{Shower}}}{E_{\text{Track}} + E_{\text{Shower}}}$$

Far Detector Energy Spectrum



Ratio: Data/No oscillations



Position of min. ➡ Δm^2

Depth of minimum ➡ $\sin^2 2\theta$

- ★ **Expected: 2451 without oscillations**
  includes ~1 CR μ, 8.1 rock μ, 41 NC, 3 ν_τ
- ★ **Observed events: 1986**
- ★ **Clear Oscillation signal**

➡ **Fit to get oscillation parameters**

Oscillation Fit/Systematic Uncertainties

- Oscillation parameters extracted from likelihood fit to reconstructed energy distribution

$$\chi^2(\Delta m^2, \sin^2 2\theta, \alpha_j, \ldots) = \sum_{i=1}^{nbins} \underbrace{2(e_i - o_i) + 2o_i \ln(o_i/e_i)}_{\text{statistical error}} + \underbrace{\sum_{j=1}^{nsyst} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j^2}}}_{\text{systematic errors}}$$

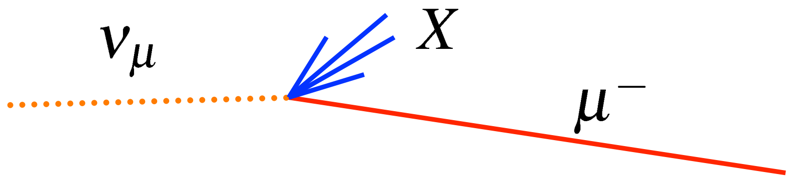
- Relatively few important systematic uncertainties

Uncertainty	Δm^2 (10^{-3} eV^2)	$\sin^2 2\theta$
Absolute shower energy scale (10%)	0.049	0.001
Muon mom. Scale (2-3%)	0.030	0.001
NC contamination (20%)	0.008	0.008
All other systematics	0.039	<0.005
Total systematic (quad. sum)	0.07	0.01
Statistical uncertainty	0.13	0.06

★ Only significant uncertainties come from absolute energy scales
 - determines position in energy of oscillation dip

Energy Scale

★ **The absolute energy scale can only be determined from data !**

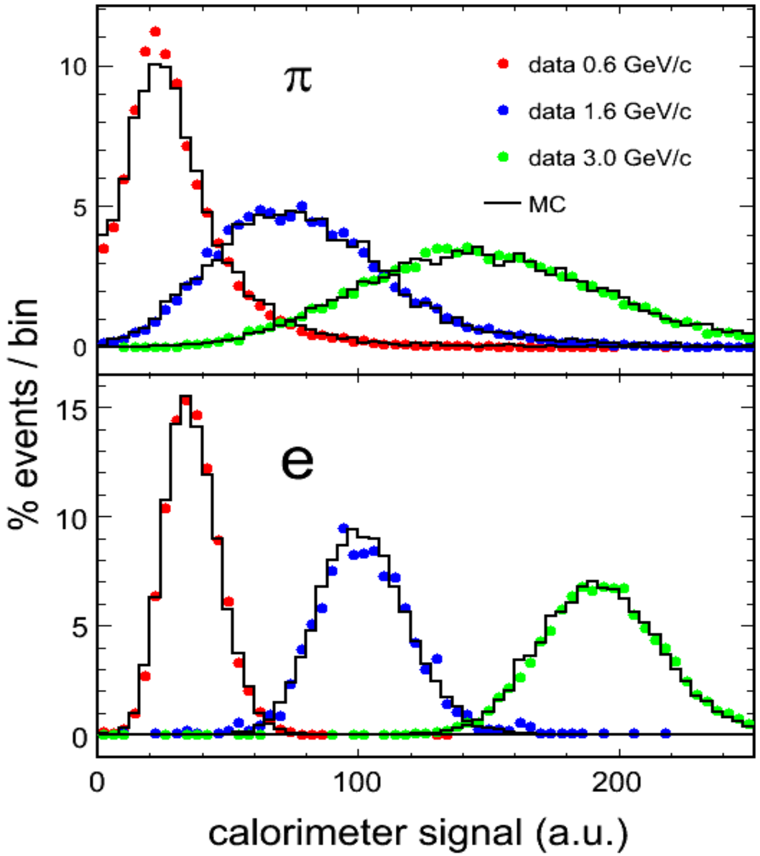


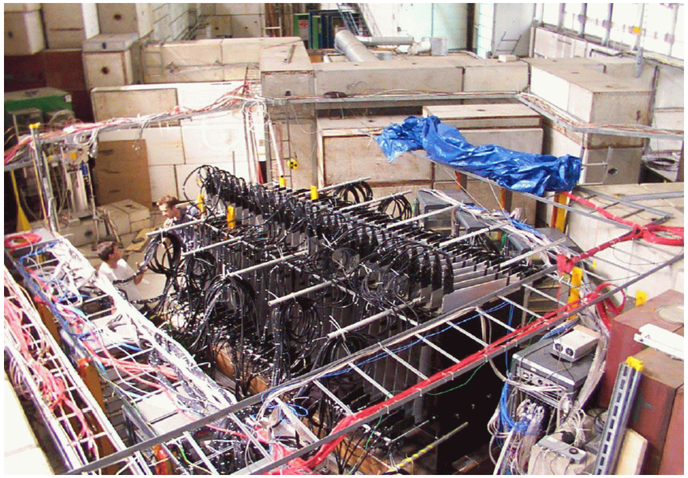
★ **In particular hadronic energy scale is problematic**
- **simulation of underlying event**
- **simulation of detector response to low energy hadrons**
- **simulation of low energy neutron transport**
- **….**

The absolute energy scale has to be established from test beam

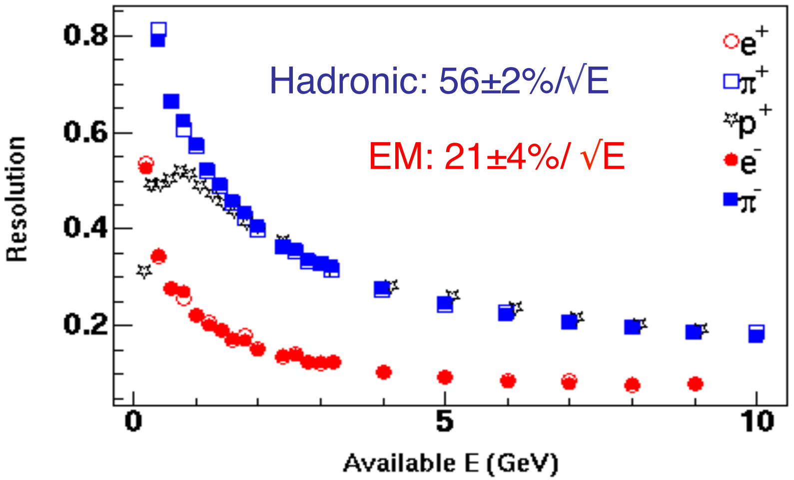
Test beam Calibration Detector

- ★ **60-plane 'mini-MINOS' exposed in CERN test-beam (2001-2003)**
- ★ **Energy uncertainties: 3% relative and 1.9% (ND) & 3.5% (FD) absolute**



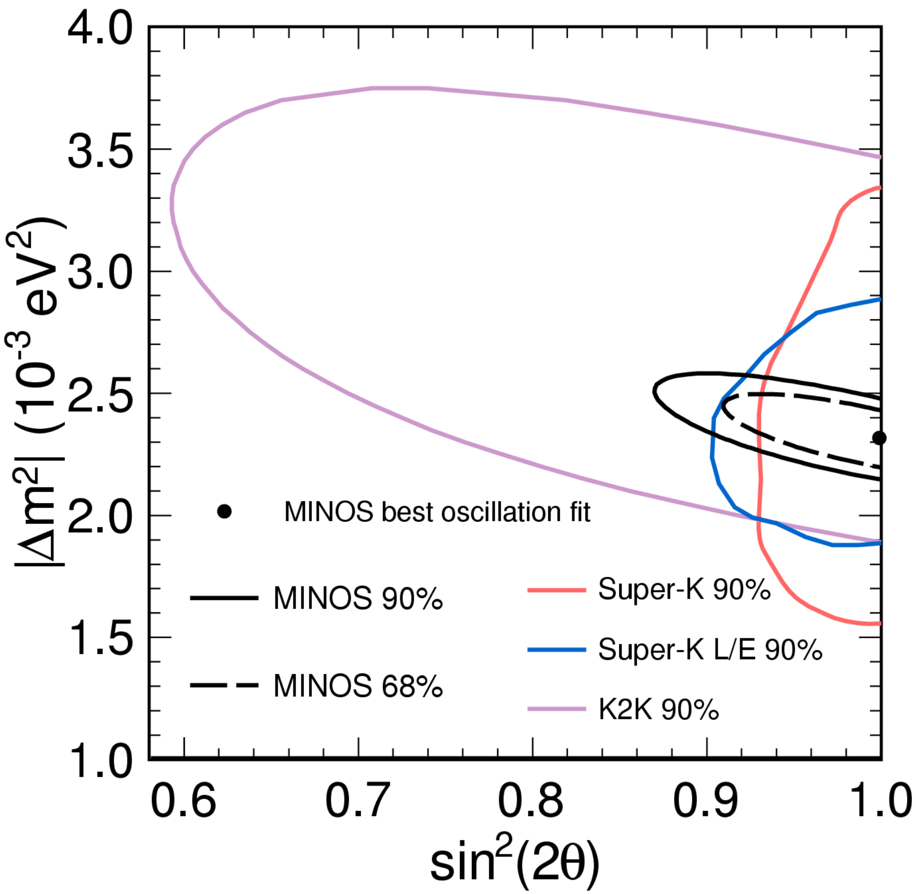


- ★ **Also determine energy resolution**



Final Oscillation Fit

★ **Fit to two flavour approximation** $P(\nu_i \to \nu_j) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$



$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$

★ **4 % measurement**

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

★ **Consistent with maximal mixing**

★ **Excellent fit probability: 41%**

MINOS Physics : Alternative Scenarios

- ★ MINOS is the first **high statistics** long-baseline experiment
- ★ Can study shape of oscillation curve in detail
- ★ In particular, compare standard oscillation hypothesis to other scenarios, **e.g**

Neutrino Decay

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

$$P(\nu_\mu \to \nu_\mu) = (\sin^2\theta + \cos^2\theta e^{-\frac{\alpha L}{2E}})^2$$

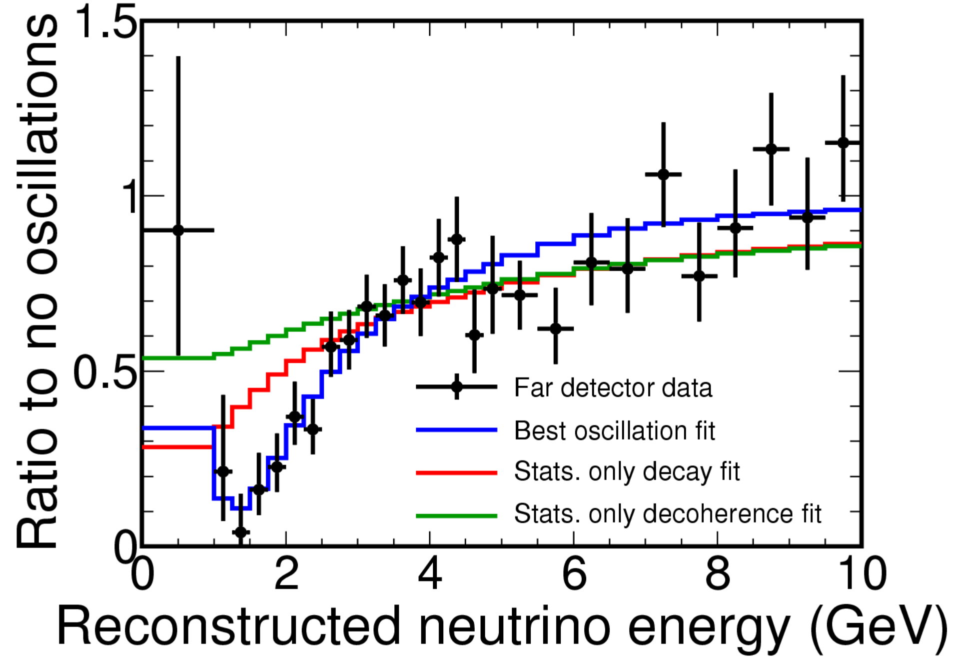
Disfavoured at 7 σ level

Neutrino Quantum Decoherence

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

$$P(\nu_\mu \to \nu_\mu) = 1 - \frac{\sin^2 2\theta}{2}(1 - e^{\frac{\mu^2 L}{2E}})$$

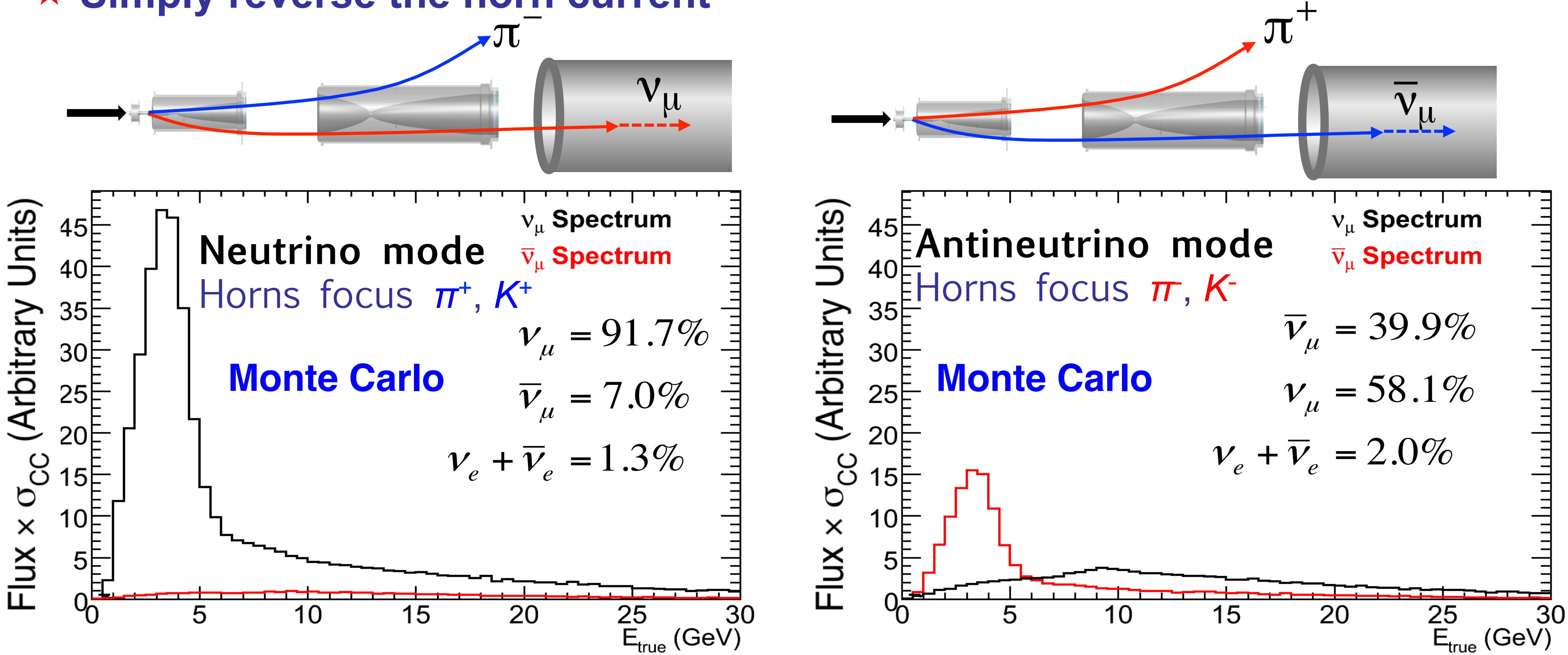
Disfavoured at 9 σ level



OSCILLATIONS IT IS !

Anti-neutrino oscillations

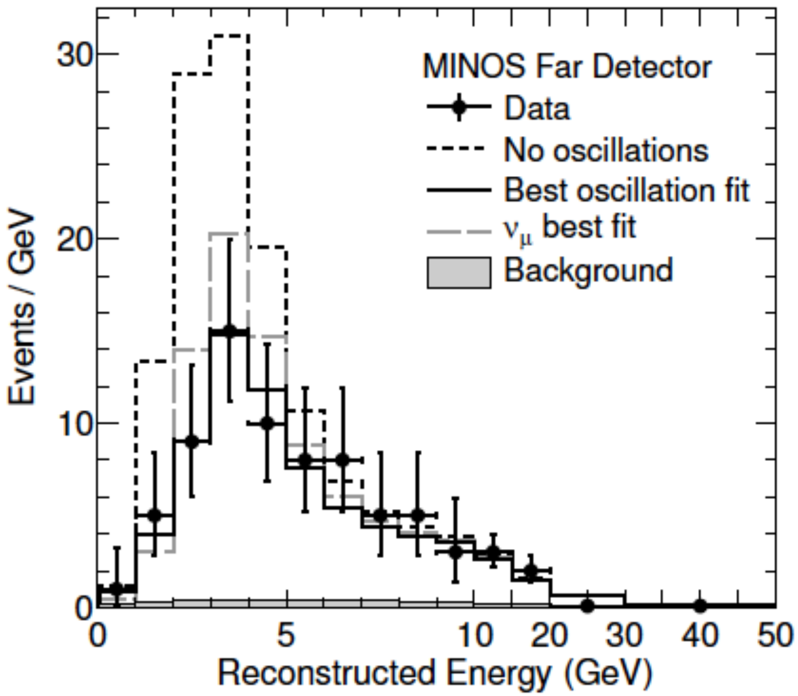
- ★ MINOS can also study the oscillations of anti-neutrinos
- ★ Unless CPT is violated, should see the same parameters as for neutrino
- ★ Simply reverse the horn current

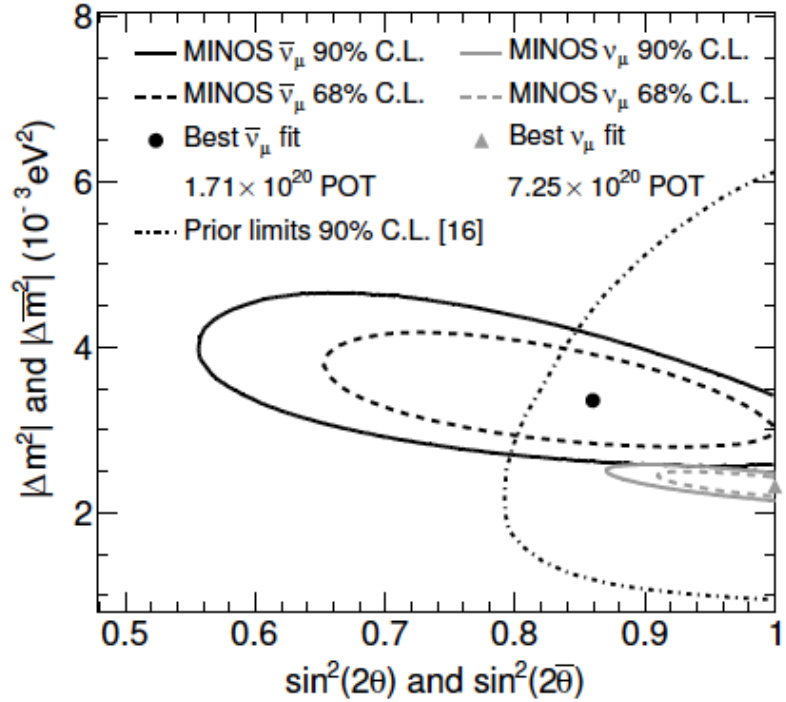


- ★ More "wrong-sign" background due to: $\sigma(\nu_\mu N) \sim 2\sigma(\bar{\nu}_\mu N)$
  - + leading particle charge asymmetry (proton beam)

Results

- ★ Current results based on only 1.7E20 of data (factor 5 lower than neutrinos)
  + Reduced flux x cross-section, lower sensitivity, but …
- ★ 97 events observed (no oscillation expectation of 155)





$$|\Delta\overline{m}^2| = 3.36^{+0.46}_{-0.41}\times10^{-3}\,\text{eV}^2$$ c.f. $$|\Delta m^2| = 2.32^{+0.12}_{-0.08}\times10^{-3}\,\text{eV}^2$$

⇨ **Equivalent to a 2.1 standard deviation difference**

- ★ Updated results (larger data sample) very soon…

Searching for $\nu_\mu \rightarrow \nu_e$ Oscillations in a wide-band beam

❼ Search for $\nu_\mu \to \nu_e$ Oscillations

★ **Neglecting CP violation and matter effects**

$$P(\nu_\mu \to \nu_e) \approx -4U_{e1}U_{\mu 1}U_{e2}U_{\mu 2}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) + 4U_{e3}^2 U_{\mu 3}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

★ **For long baseline experiments, only the "32" mass scale is relevant**

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

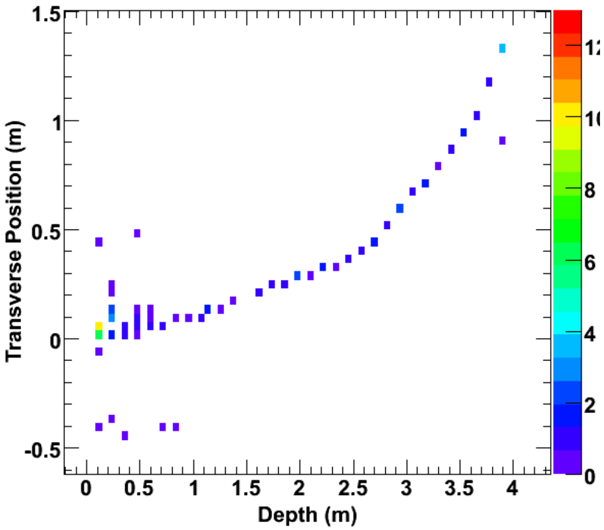
★ **From the CHOOZ reactor experiments, know θ_{13} is small**

$$\sin^2 2\theta_{13} < 0.16$$

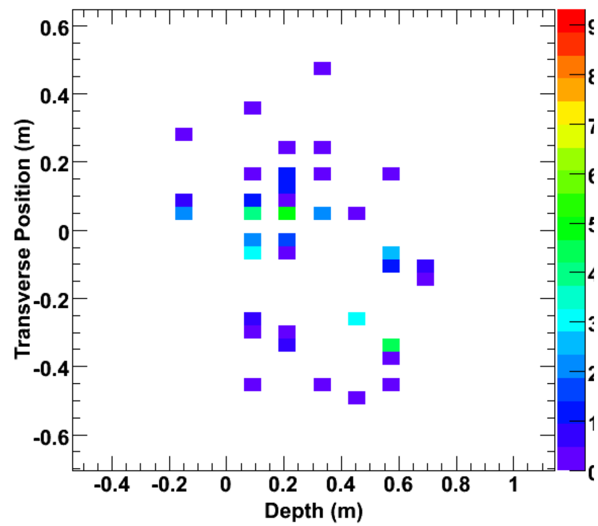
Looking for a small signal

Looking for ν_e appearance in MINOS

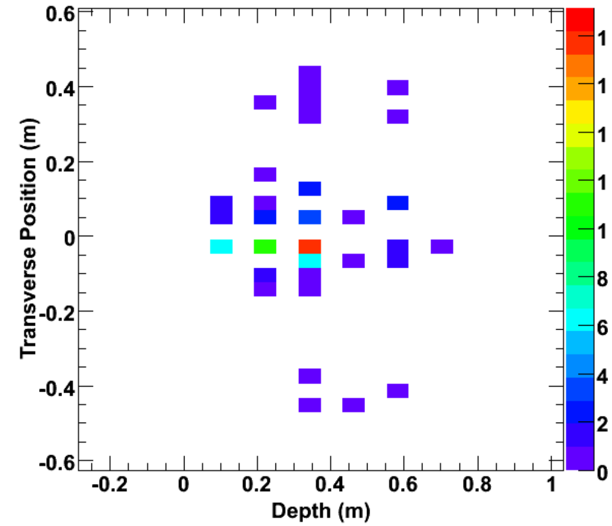
★ The signature for ν_e CC in MINOS is not very clean



ν_μ CC



ν_μ NC



ν_e CC

★ The main issue is distinguishing the signal from the NC background

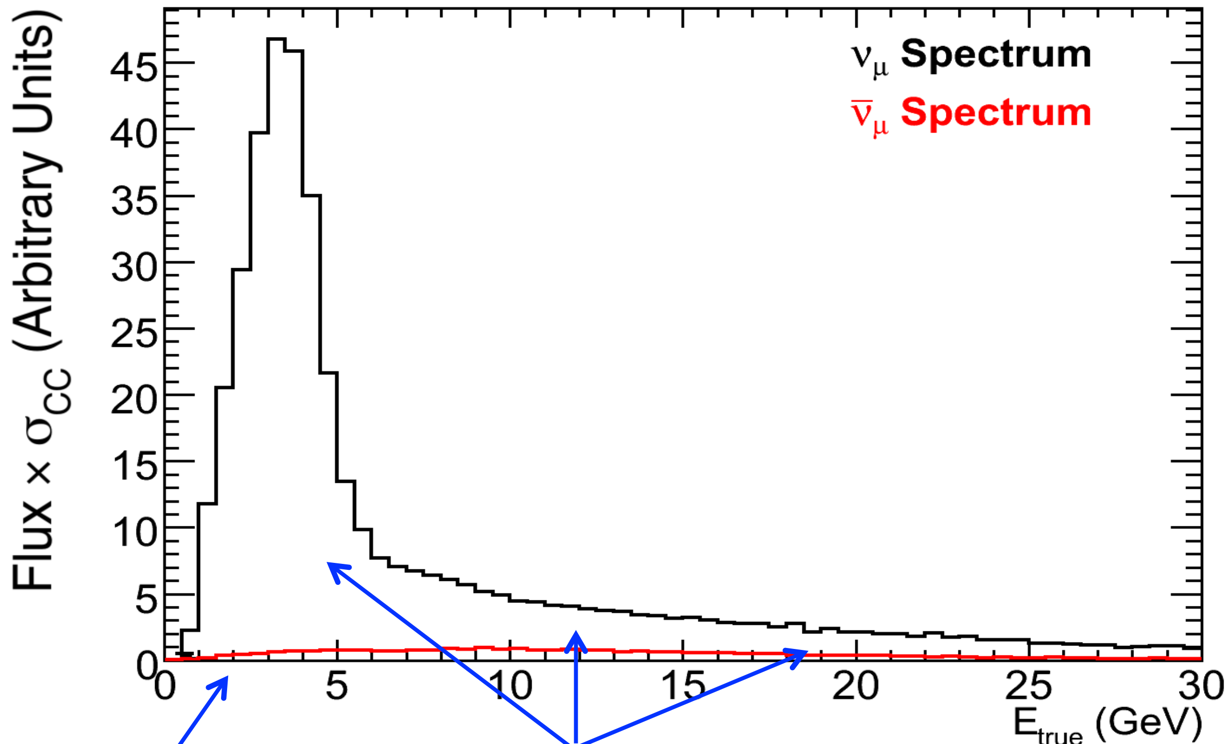
★ NC events can fake ν_e if significant EM fraction in hadronic shower, e.g. from $\pi^0 \rightarrow \gamma\gamma$

★ MINOS detector is far from ideal….

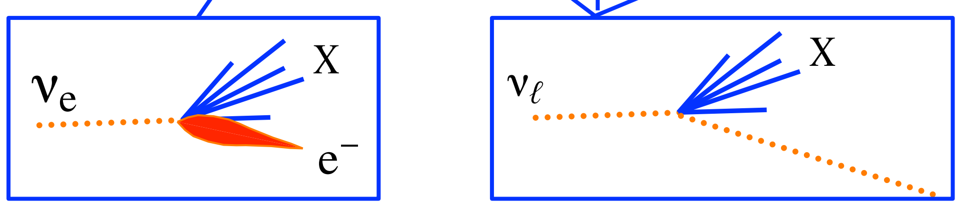
EM Showers in MINOS	Detector Parameters
Radiation length in steel: 1.76 cm	Steel thickness: 2.54 cm
Molière radius: 3.7 cm	Strip width: 4.1 cm

+ Wide band beam

★ **MINOS wide band beam does not help…**



$E_{vis} = E_\nu$



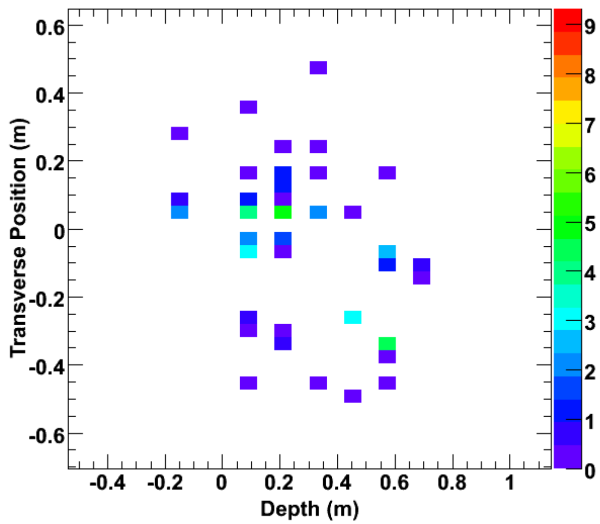
$E_{vis} = yE_\nu < E_\nu$

★ **Signal below peak of spectrum**

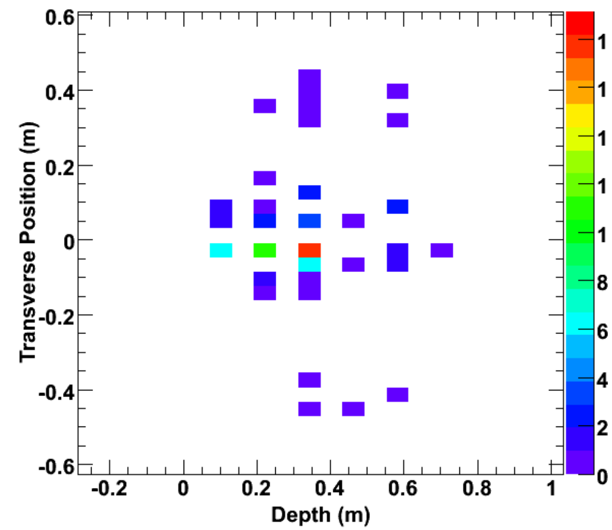
★ **all NC events with neutrino energy > 2 GeV can form background**

Event Identification

★ Need to separate NC background from "similar looking" signal



ν_μ NC



ν_e CC

★ Traditionally would reconstruct set of variables
  - Energy, Number of hits, Shower profile, …

★ Use ANN multivariate discriminator

★ BUT here the number of hits is not large
  - potentially smaller than number of variables

★ Came up with a new approach (Cambridge/CalTech)

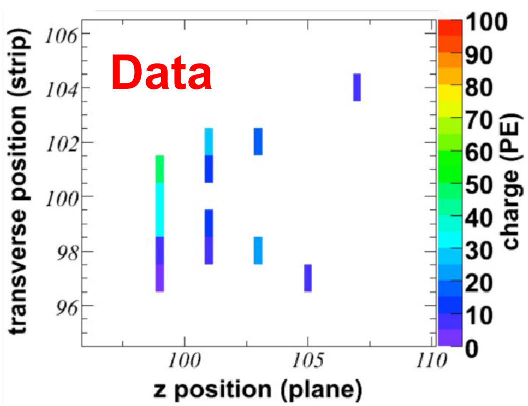
★ Use hit patterns directly - no loss of information !

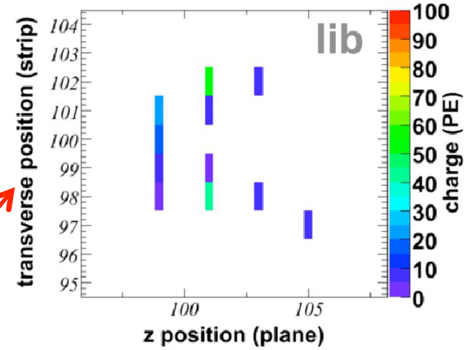
Library Event Matching

- ★ Build large library of about 50,000,000 MC events
  - 20M ν_e and 30M NC
- ★ For each data compare pattern of hits to entire library
- ★ Form quality of match likelihood for events ***i*** and ***j***

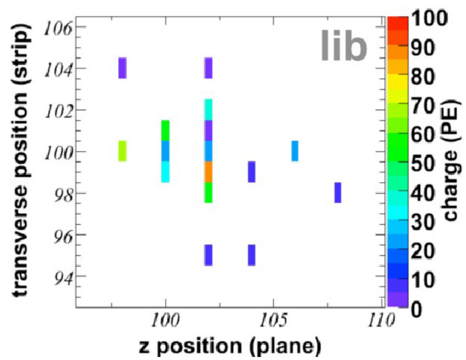
$$-\ln \prod_{\text{hits}} \int_0^{\lambda} P(n_i,\lambda)P(n_j,\lambda)\mathrm{d}\lambda$$

Where $P(n,\lambda)$ is Poisson probability of seeing n photoelectrons in a strip, when λ are expected





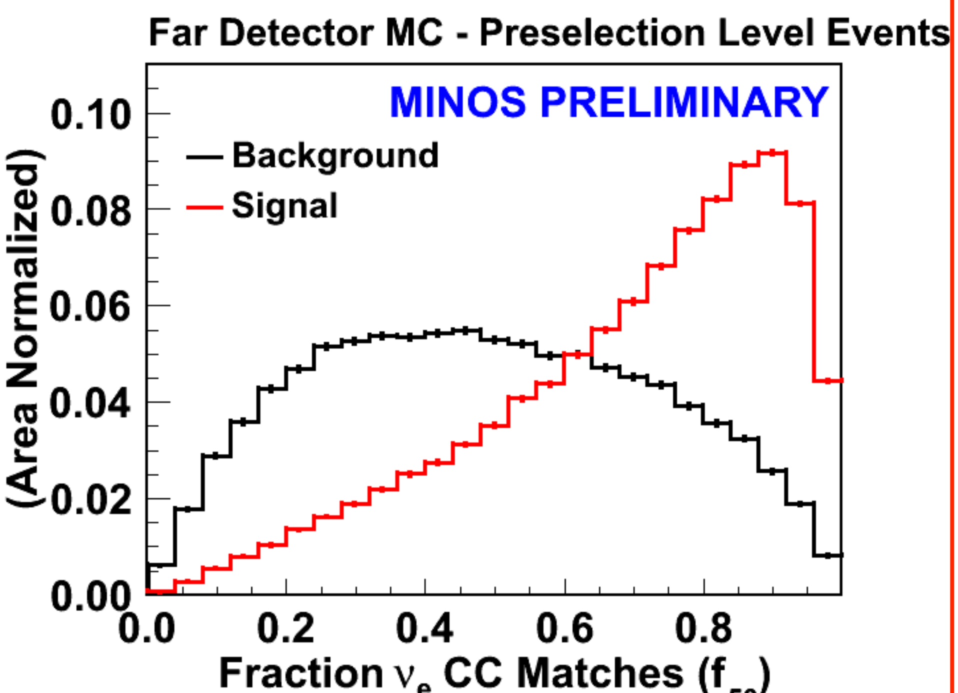
Good match

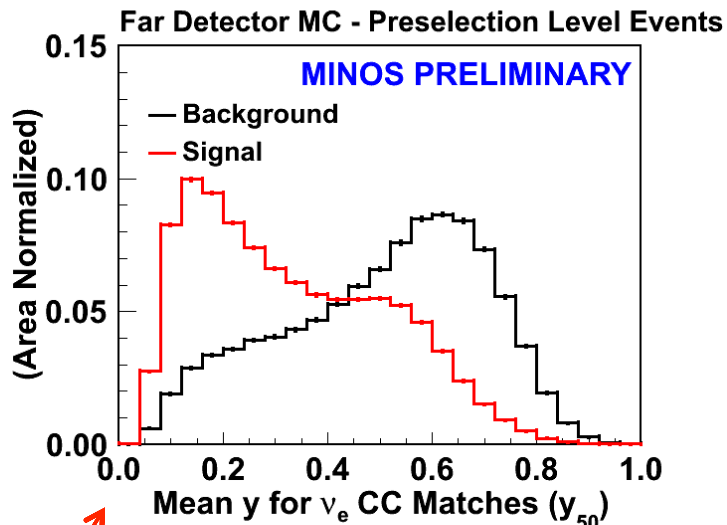


Bad match

… repeat 50M times
… identify 50 best matches

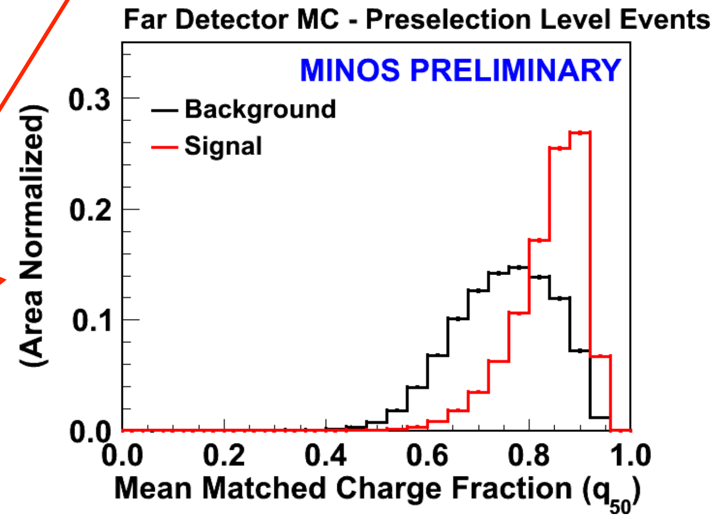
★ Fraction of best matches which are MC ν_e provides a powerful discriminant





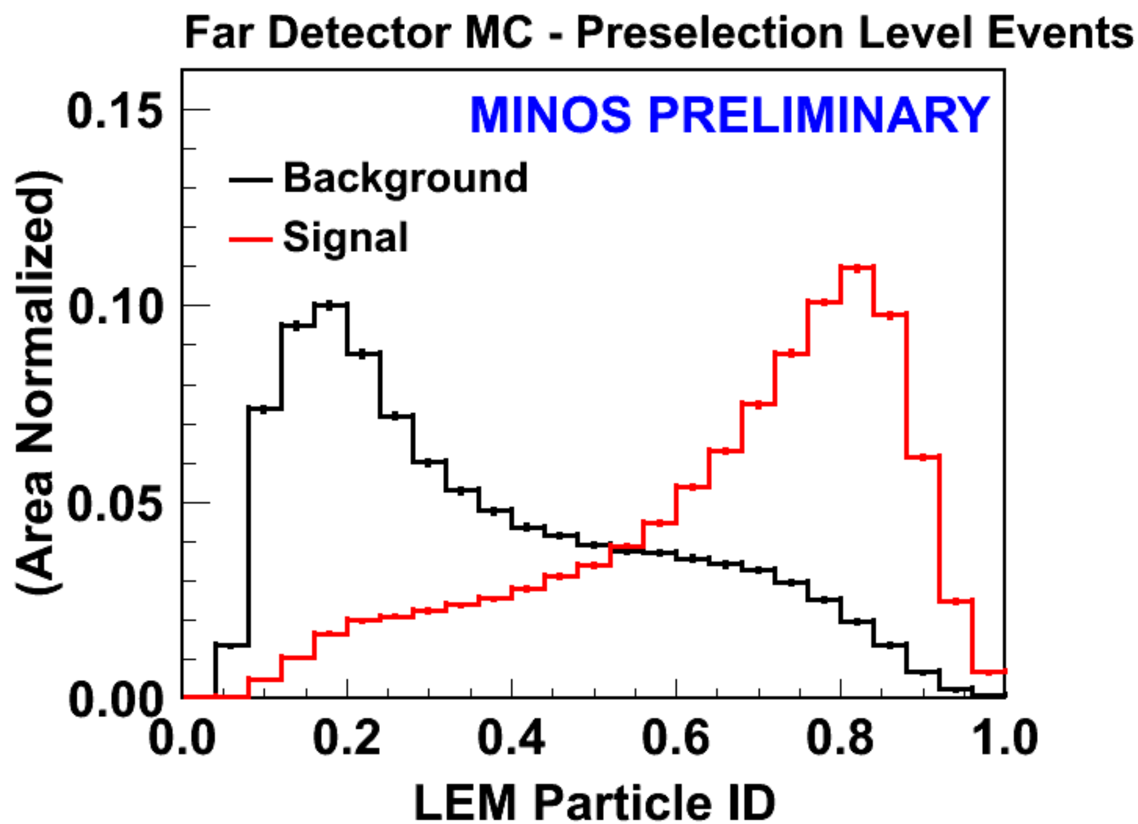
★ also "mean y of best matches"

★ fraction of charge matched



LEM Discriminant

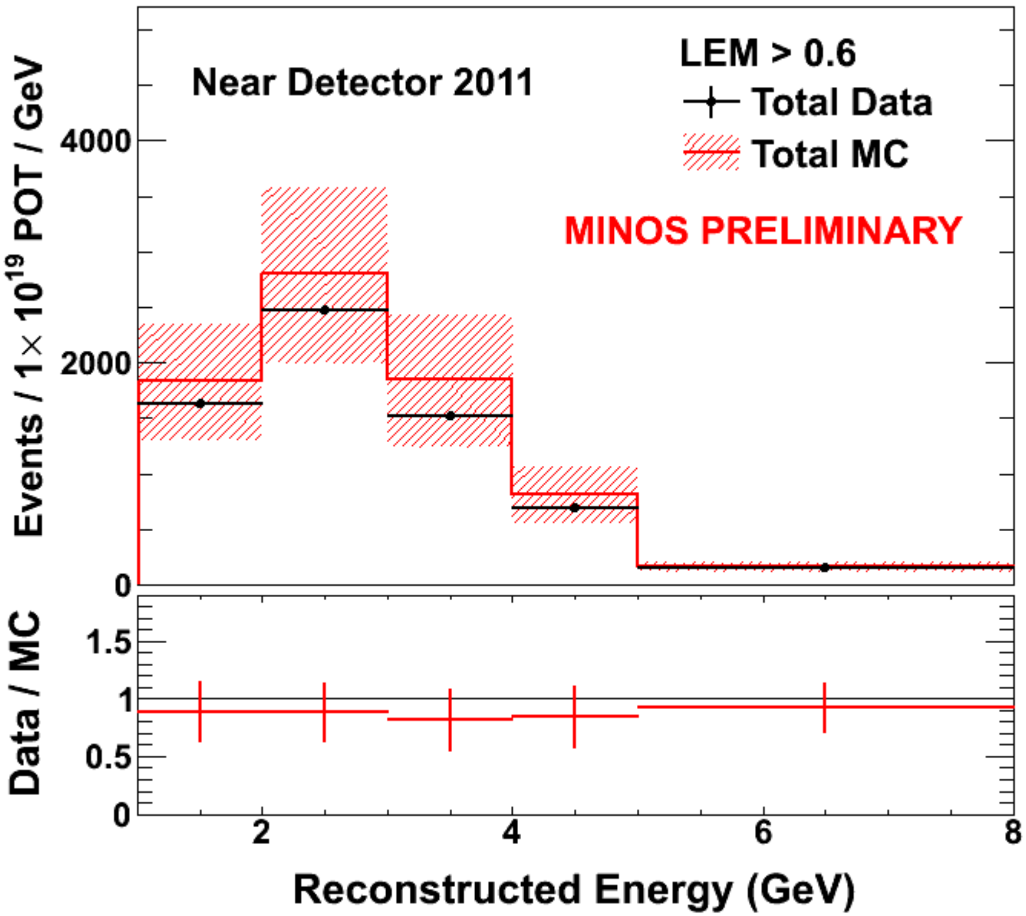
★ Combine 3 LEM output variables using an ANN



★ 40 % signal efficiency
★ 98 % background rejection

★ Good – but in a wide-band beam the background is high…

★ So still looking for a very small signal above a large background
- need an accurate prediction of FD background
- use ND data - analysis would be impossible without it !

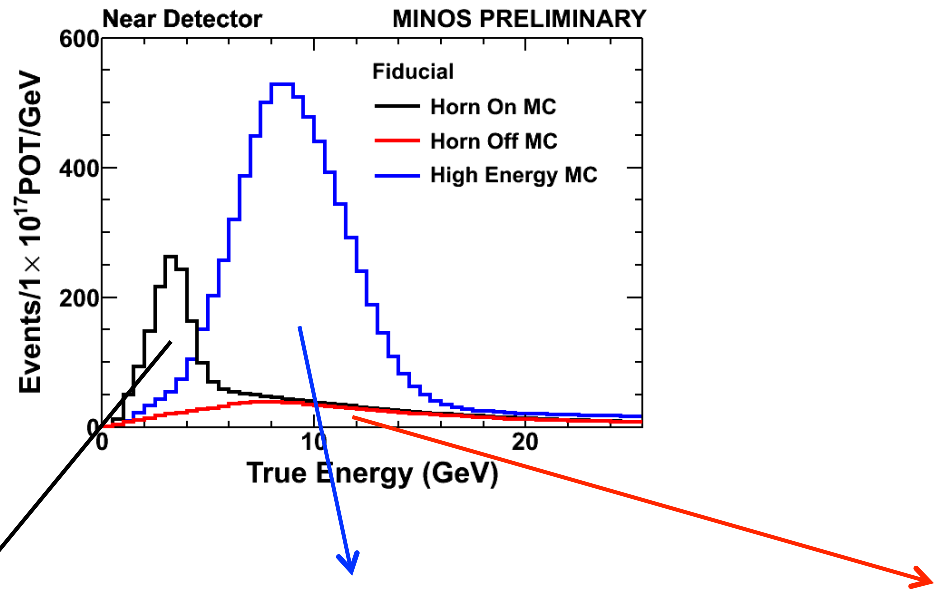


★ Large uncertainty on raw MC prediction
- mainly hadronisation
- also nuclear effects

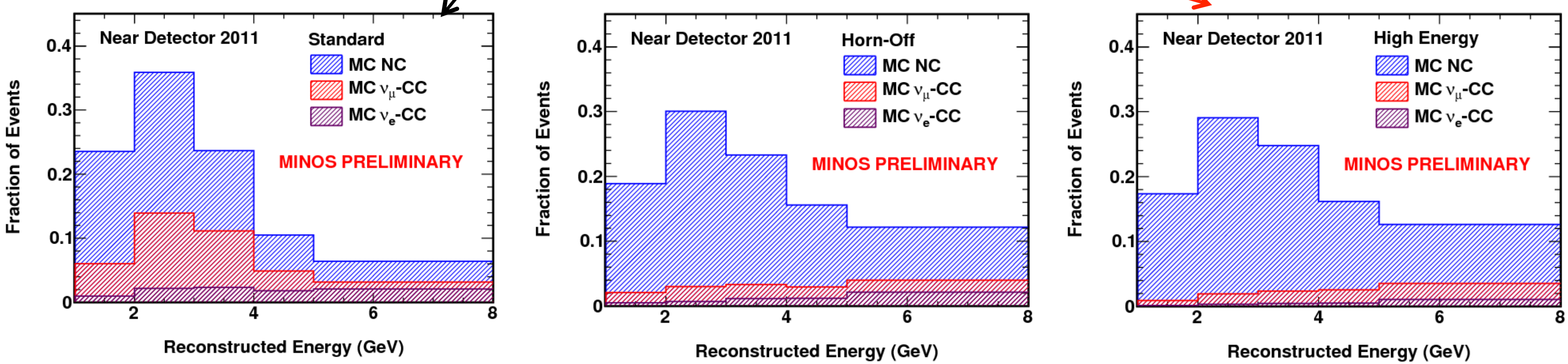
★ Need to correct to data
- then extrapolate to FD
- also need to know what fraction of the background is NC vs CC ν_μ

Different Beam Conditions

★ Different beam configurations have different levels of NC/CC and beam ν_e components which allows each to be extracted separately

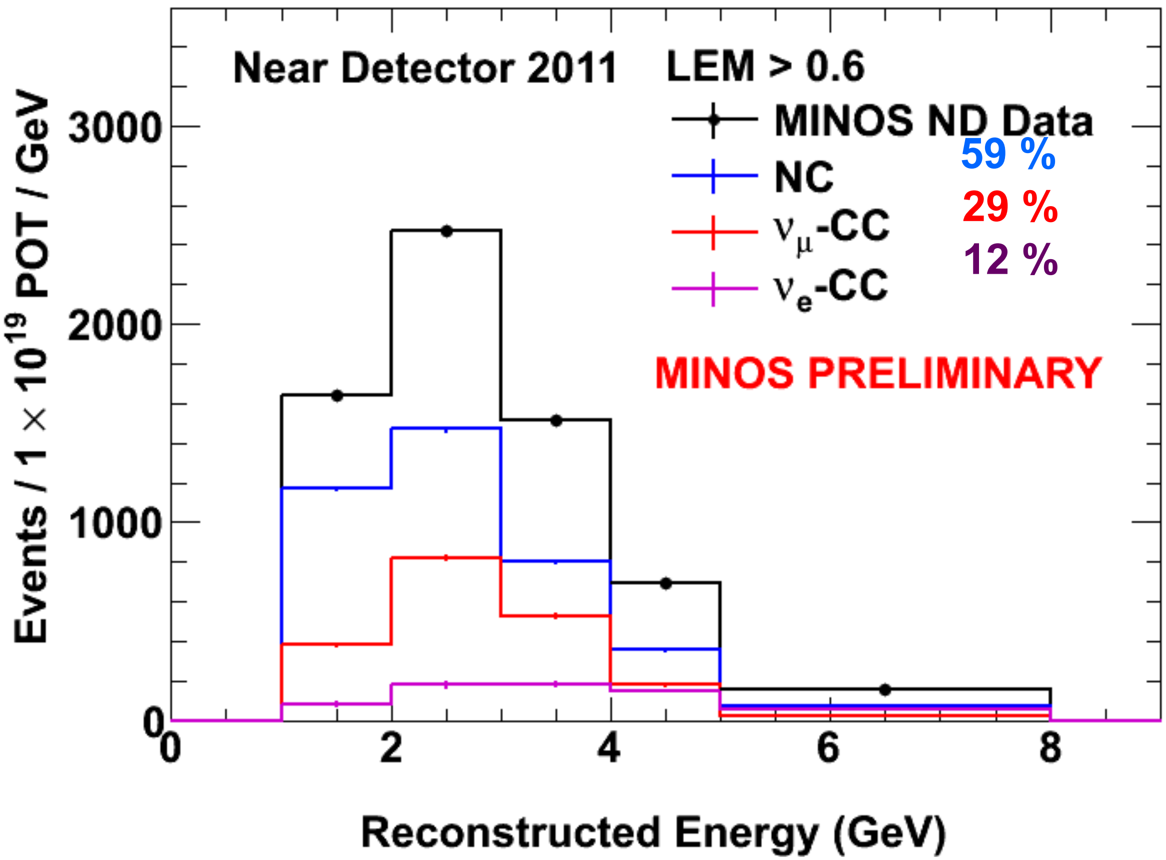


★ LEM selected…



ND Spectrum

★ Data driven decomposition of the ND selected energy distribution

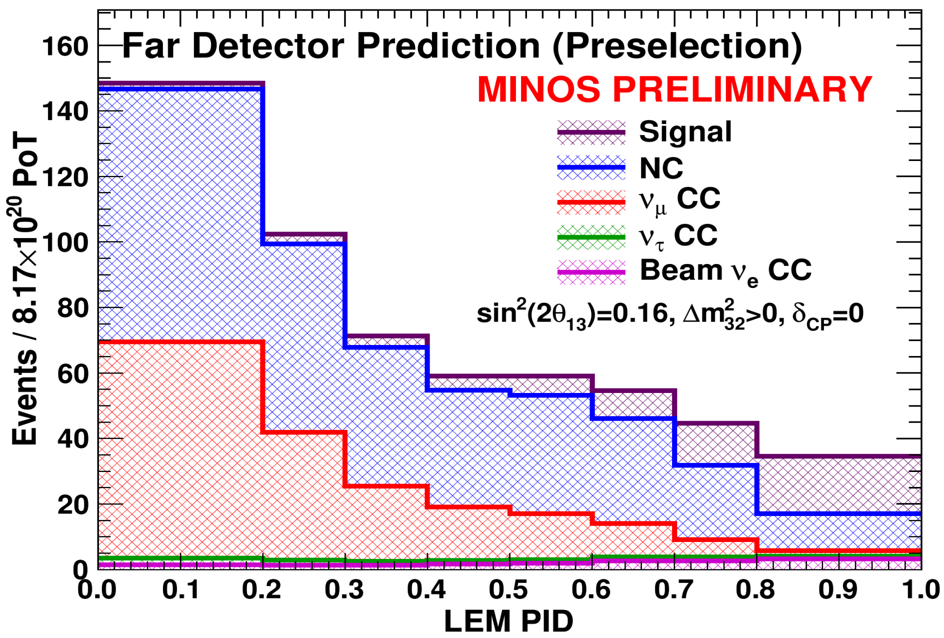


★ Can now extrapolate to FD

- CC Oscillated
- NC Unoscillated

Hard work, but…

★ FD prediction as function of PID



Component	Predicted
NC	34
ν_μ CC	7
Beam ν_e CC	6
ν_τ CC	2
TOTAL	49
ν_e at θ_{13} = 0.2	30

S/N<0.6

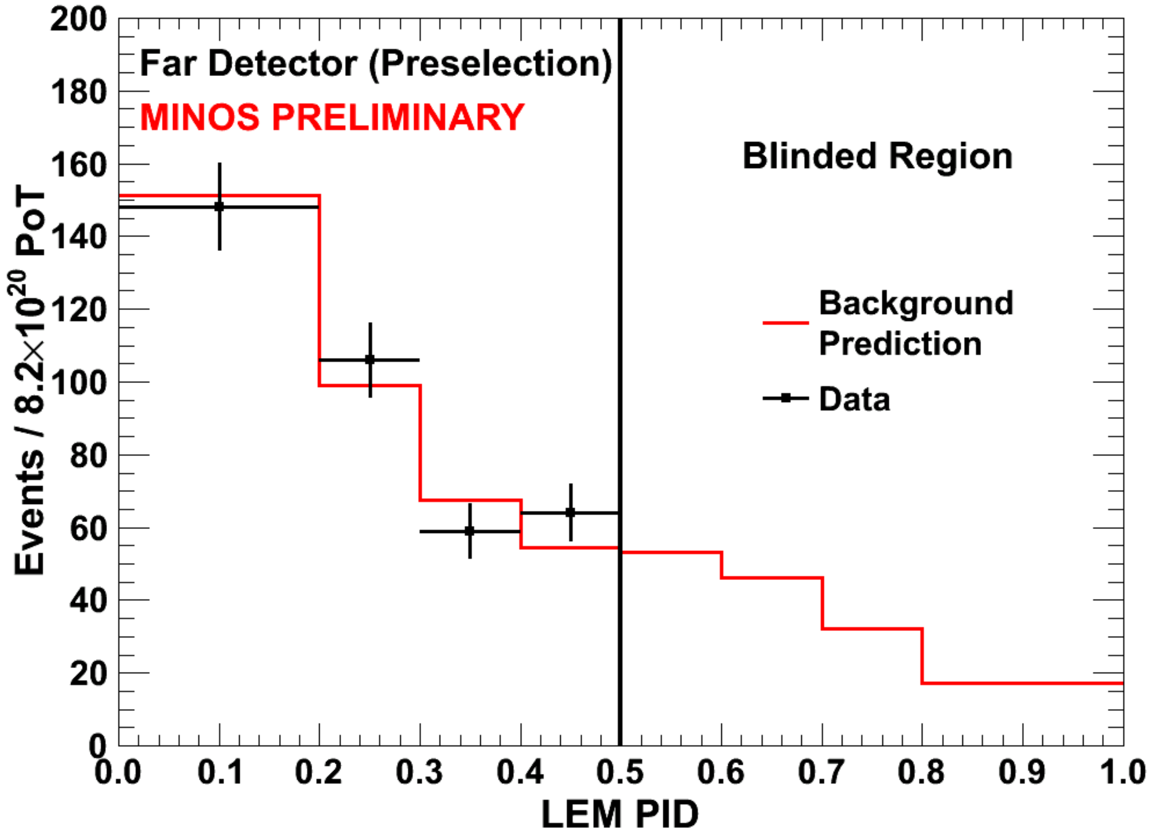
★ Background uncertainty ~6 %

★ All down to having (almost) identical near detector which is used to directly determine the background !

Results

- ★ Blind analysis
- ★ In background-like region, LEM < 0.5
  - observe: 377 events
  - expect: 372 events (θ_{13}=0)

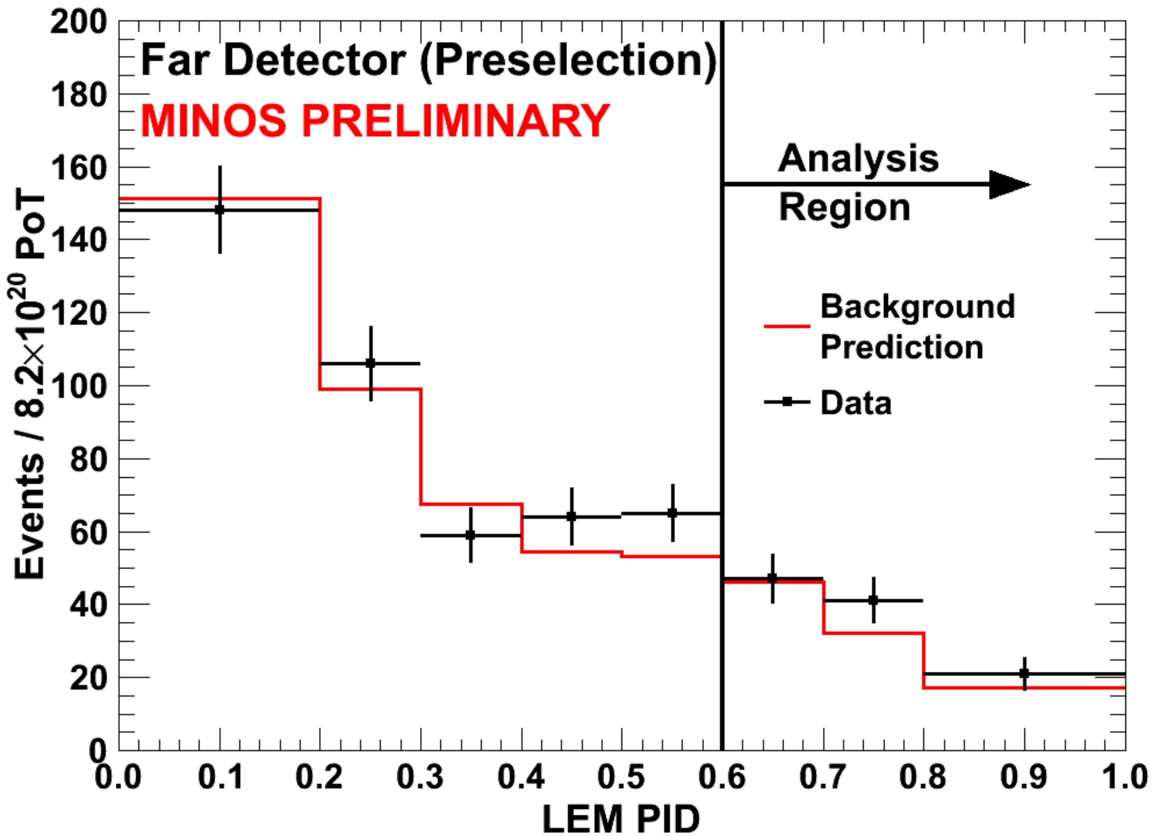
} Tests complete analysis chain



Results

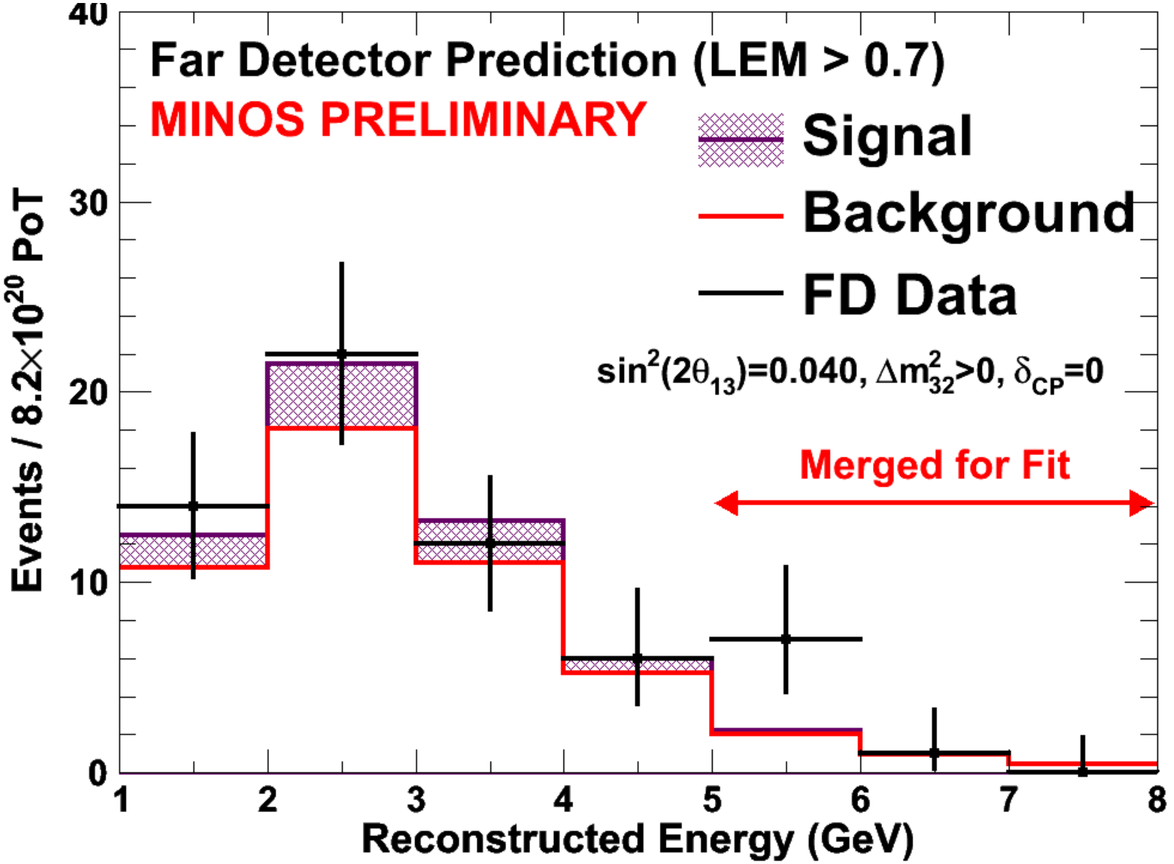
★ In signal-like region, LEM > 0.6
- observe: 62 events
- expect: 49.5+- 2.8 (θ_{13}=0)

1.65 σ excess in high PID region



Fit

- Fit energy distribution in 3 PID bins observe: 377 events
  - 0.6<LEM<0.7,   0.7<LEM<0.8,   LEM>0.8
- Figure shows signal enhanced region, LEM>0.7
  - for best fit $\sin^2 2\theta_{13} = 0.04$



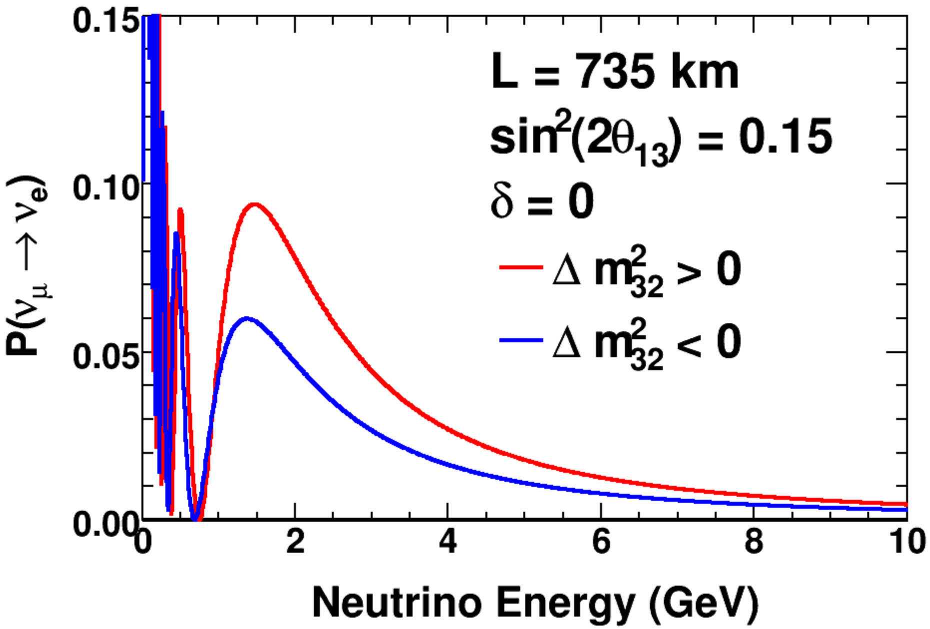
Interpretation

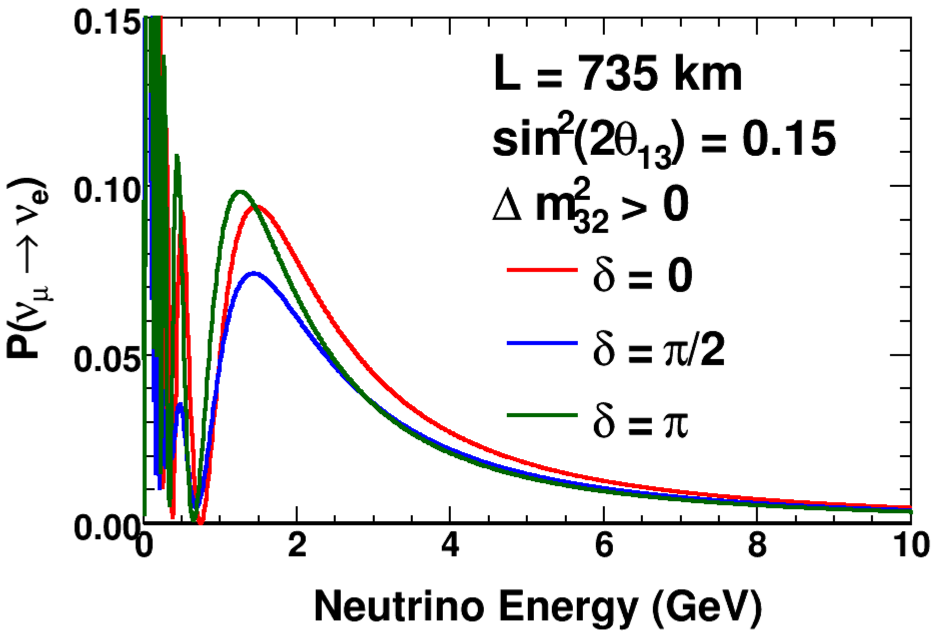
★ **Simple two-flavour formula**

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

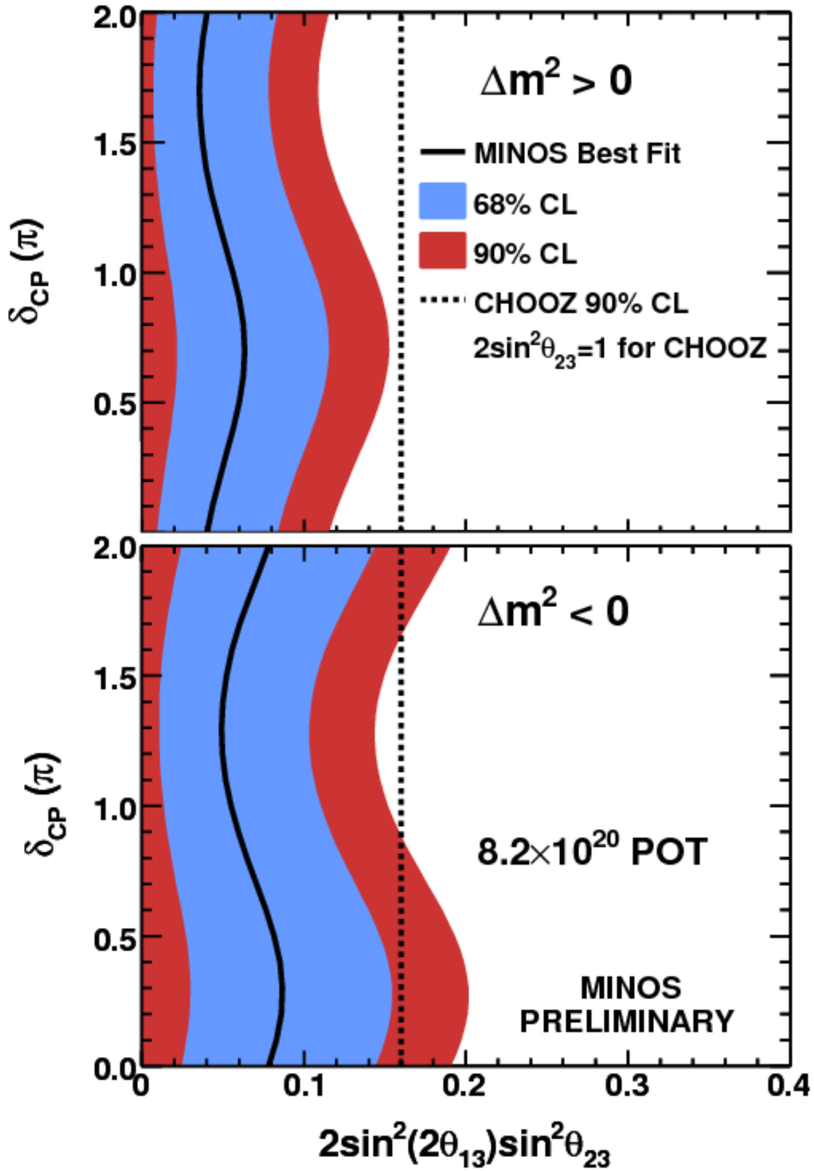
is only approximate.

★ **Including matter effects and CP violation get small dependence on mass hierarchy and CP phase**





MINOS Results (Summer 2011)



★ Assuming $\delta = 0\,,\ \theta_{23} = \pi/4$

- **Exclude zero at 89 % C.L.**

★ For normal (inverted) hierachy

$$\sin^2 2\theta_{13} = 0.04\,(0.08) \text{ best fit}$$
$$\sin^2 2\theta_{13} < 0.12\,(0.19) \text{ 90 \% C.L.}$$

★ Hints of non-zero value of θ_{13}

Comments:

★ Interesting result…

★ but, very hard work

- Detector not optimized for ν_e
  - granularity too coarse
- Beam not optimized for ν_e
  - Wide band beam, NC backgrounds are high!

MINOS Summary

- MINOS is a <u>very simple</u> experiment
  - Made a number of important measurements/limits
    - $|\Delta m^2_{32}|$
    - $|\Delta \overline{m}^2_{32}|$
    - θ_{13}
- Power comes from two functionally identical detectors
  - Most systematics just cancel
- Optimised for disappearance measurement
  - Most systematics just cancel
- Not optimised for electron appearance
  - detector too little granularity
  - wide-band beam leads to large NC background

The next generation…

T2K

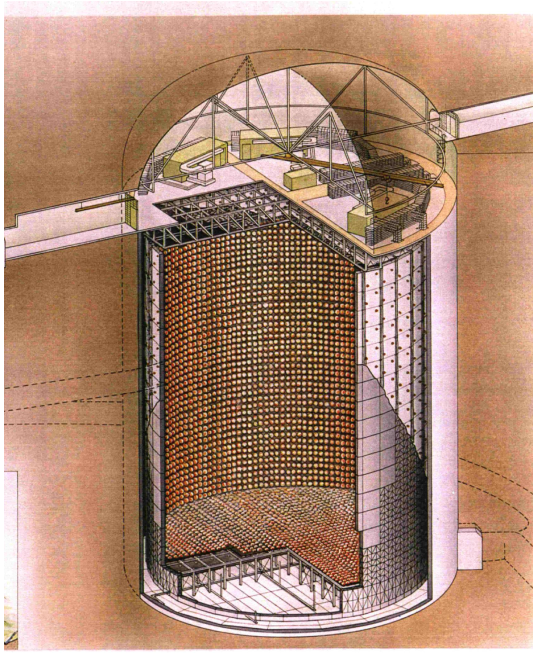
T2K Motivation

★ Super-Kamiokande water Cherekov detector is the largest neutrino detector in existence

★ Well understood detection of electrons and muons

★ Much lower thresholds than MINOS,

★ T2K = SK + JPARC neutrino beam:
L= 295 km



Neutrino Beam

★ Optimised for subdominant oscillations $\nu_\mu \rightarrow \nu_e$

★ Maximise S/N ratio – i.e. minimize backgrounds

⇨ Off-axis narrow-band beam tuned to oscillations at

$$|\Delta m^2| \sim 2 \times 10^{-3}\,\mathrm{eV}^2$$

T2K Beam

★ Aim for maximum flux at oscillation maximum of **600 MeV**

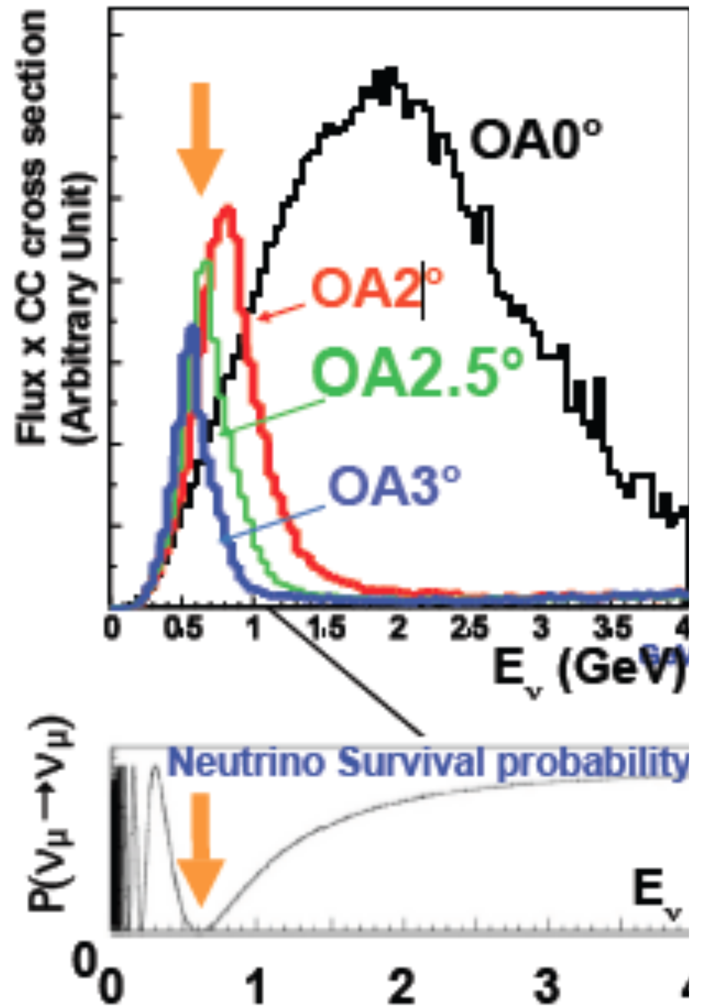
recall $$E_\nu \approx \frac{0.03}{\theta}$$

★ For JPARC beam the optimum is

$$\theta = 2.5^\circ$$

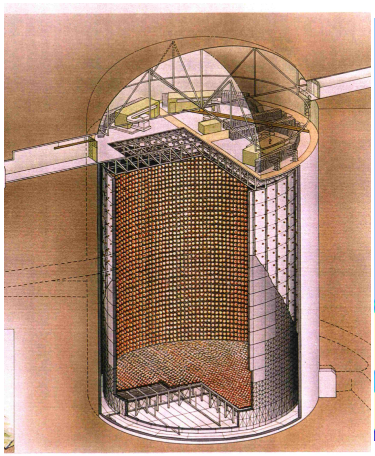
★ Far lower overall **flux x σ**

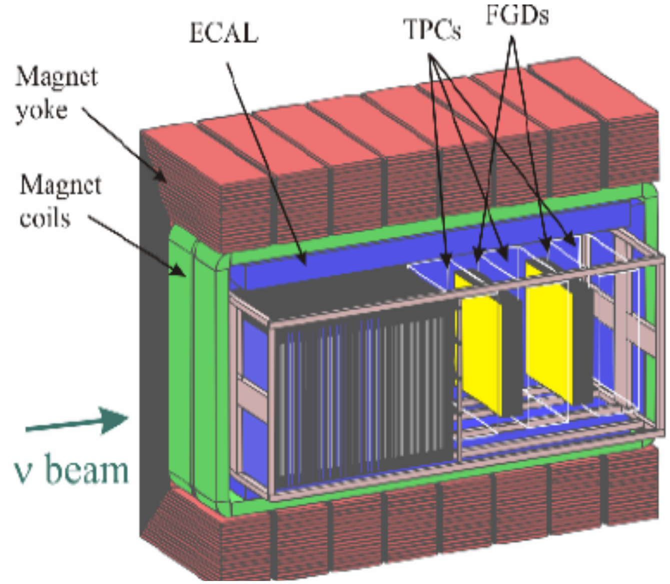
- But higher where it matters
- Much lower HE tail
  - ⇨ less NC background



T2K

- Tokai to Kamioka





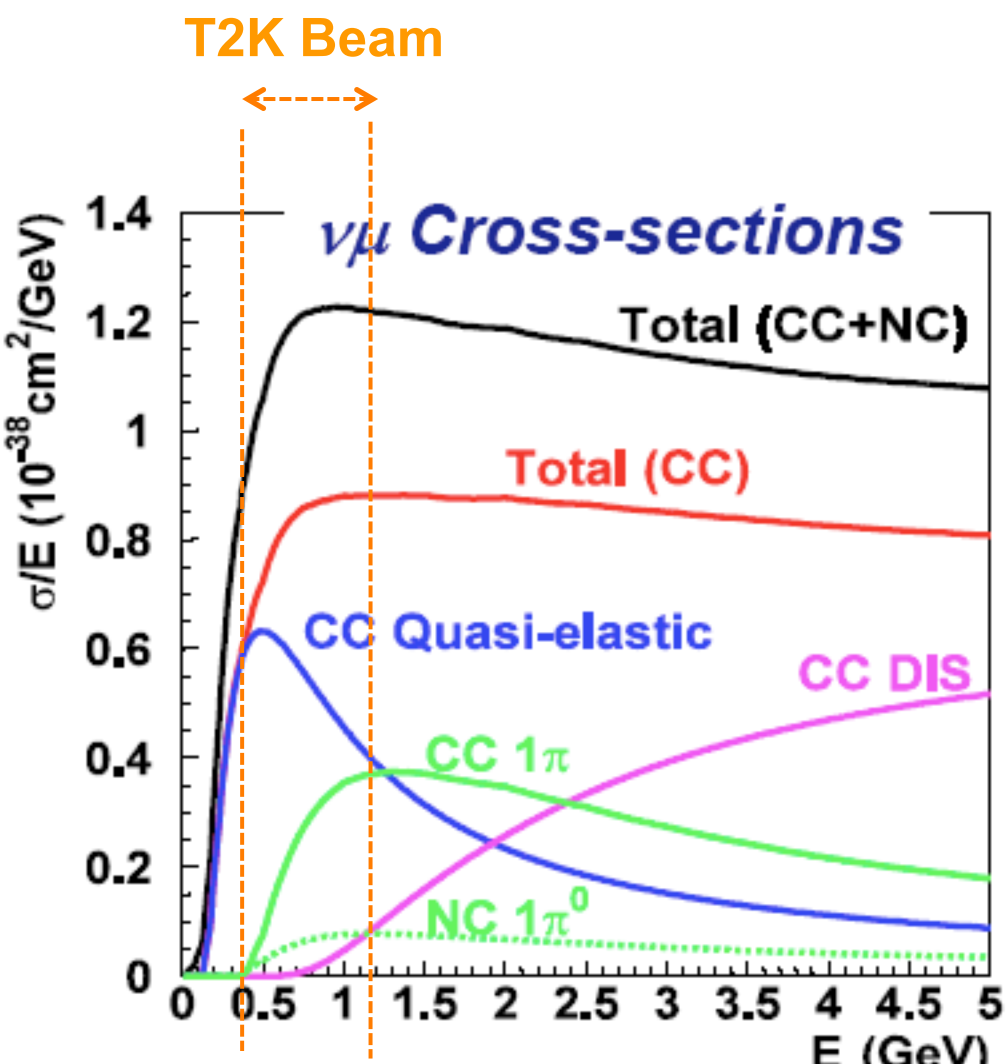
Far detector:
- Super-Kamiokande
- at 295 km
- 2.5 degrees off-axis

"Beam Profiler"
- at 280 m
- on-axis
- Fe/Sci Tracker
- Measure beam

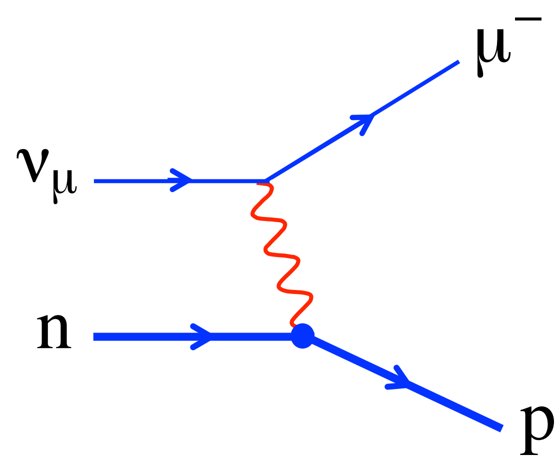
- First beam operations ~April 2009
- First physics beam run ~2010
- First results summer 2011

Near detector:
- at 280 m
- off-axis
- Very different to FD
- Calorimeters + Trackers + TPC
- Inside UA1 magnet
- P0D : Scintillator fibre to measure NC π^0 content

Neutrino Cross Sections at T2K



★ Dominated by CC Quasi-Elastic interactions



★ QE cross section relatively well known +- 7 %

★ Narrow-band beam: most NC background from peak

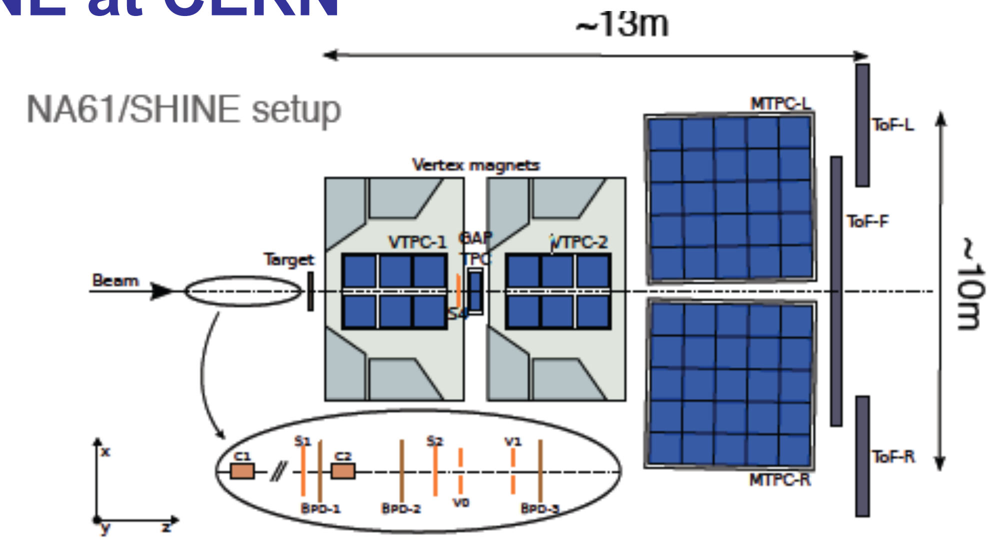
- Single π^0 NC cross-section is small !

Predicting the FD Spectrum

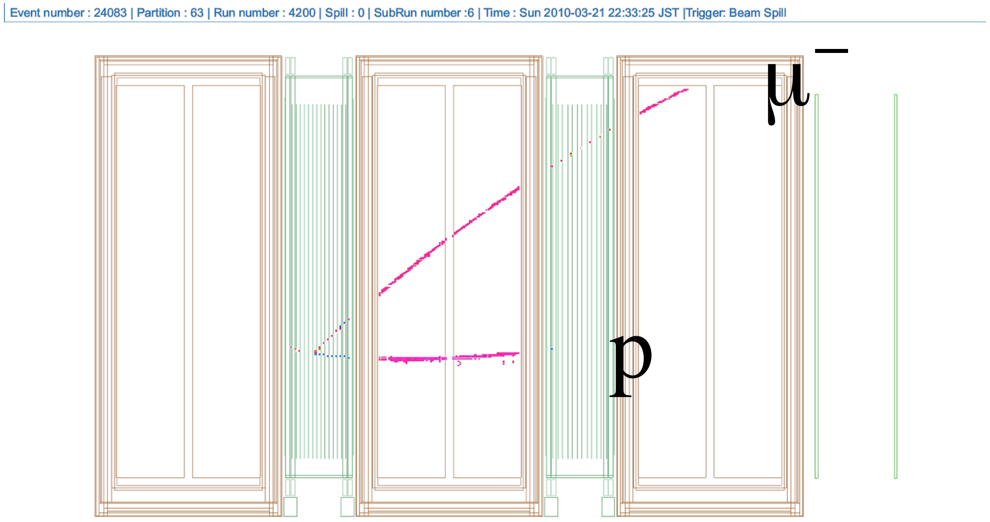
- ★ Scale FD MC predictions to ratio of selected QE CC ν_μ events in Data and MC

$$N_{FD}^{exp} = N_{FD}^{MC} \times \frac{R_{ND}^{\mu,DATA}}{R_{ND}^{\mu,MC}}$$

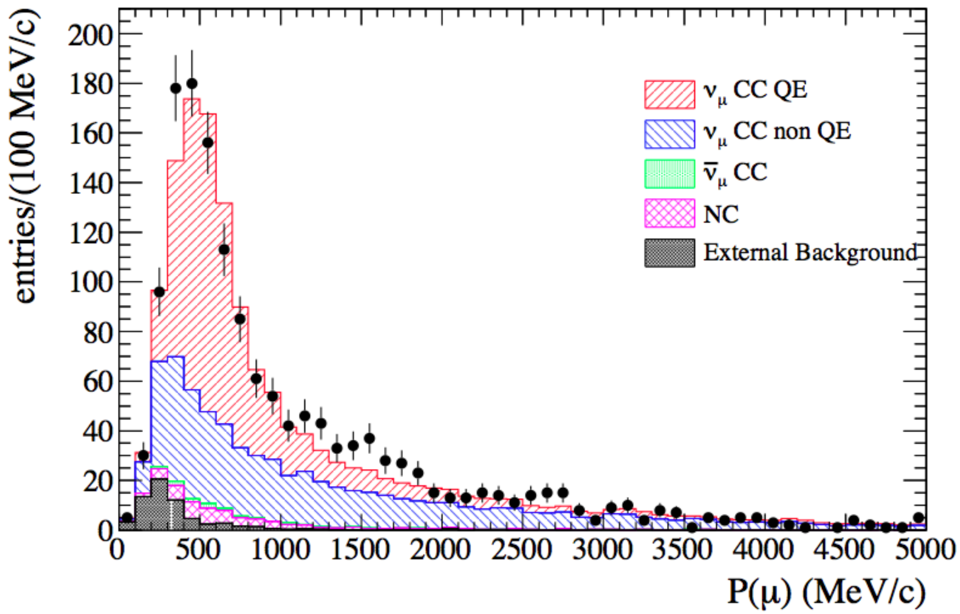
- ★ Scale FD MC predictions to ratio of selected QE CC events in Data and MC
- ★ Flux predictions based on hadron production data, NA61/SHINE at CERN



Check predictions in ND



- ★ Select CCQE events in ND
- ★ Clean signal – can see both muon and proton



- ★ Data is consistent with prediction from hadron production

$$\frac{R_{ND}^{\mu,\mathrm{DATA}}}{R_{ND}^{\mu,\mathrm{MC}}} = 1.036 \pm 0.028\,(\mathrm{stat.})^{+0.044}_{-0.037}\,(\mathrm{det.\ syst.}) \pm 0.038\,(\mathrm{phys.\ syst.})$$

Extrapolating to FD

- In T2K, the near and far detectors are very different
- Significant uncertainties in predicting FD expectations, requires a careful estimation

$$N_{FD}^{exp} = R_{ND}^{\mu,\mathrm{DATA}} \times \frac{N_{FD}^{MC}}{R_{ND}^{\mu,\mathrm{MC}}}$$

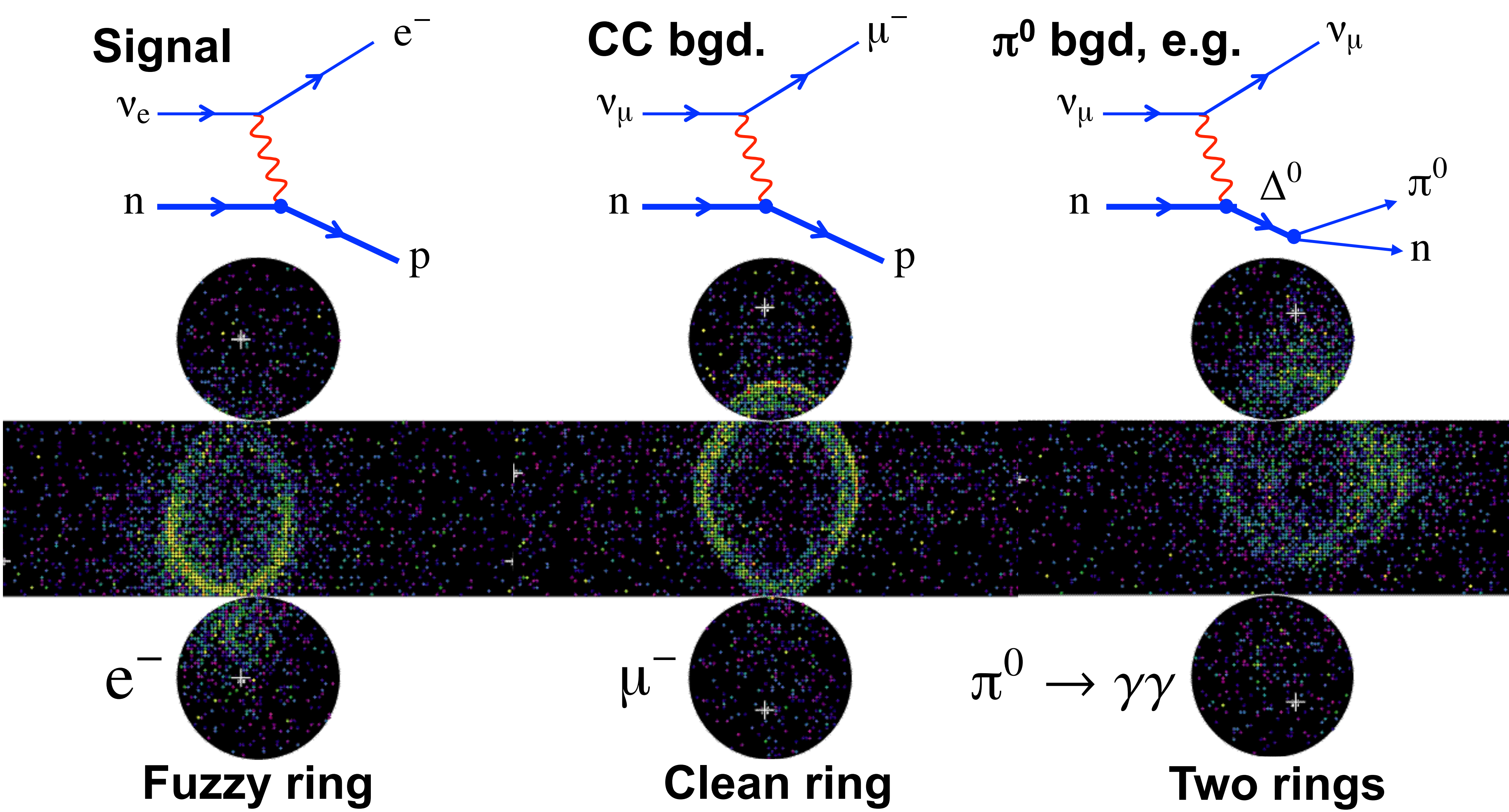
Error Source	Sys.
Beam Flux	±8.5 %
Cross sections	±14.0 %
Near Detector	±5.4 %
Far Detector	±14.7 %
ND Statistics	±2.7 %
Total	±23 %

Background	Events
Beam ν_e	0.8
NC	0.6
ν_e from Δm^2_{12} term	0.1
Total	1.5

- Systematic error is relatively large … but backgrounds are low

$$N_{FD}^{exp} = 1.5 \pm 0.3 \quad \text{for} \quad (\sin^2 2\theta_{13} = 0)$$

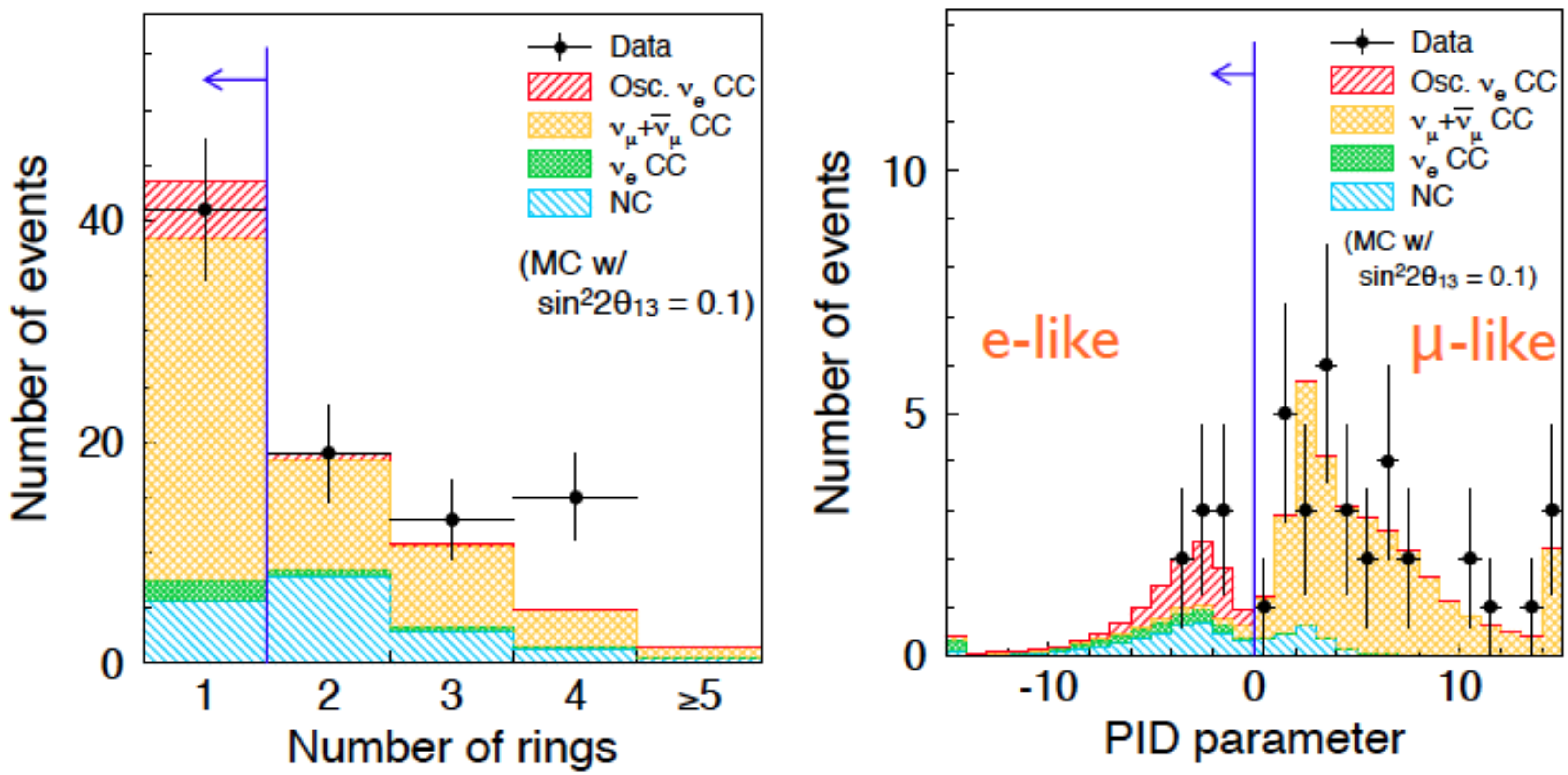
Far Detector Events



★ **Good background rejection – well understood detector**

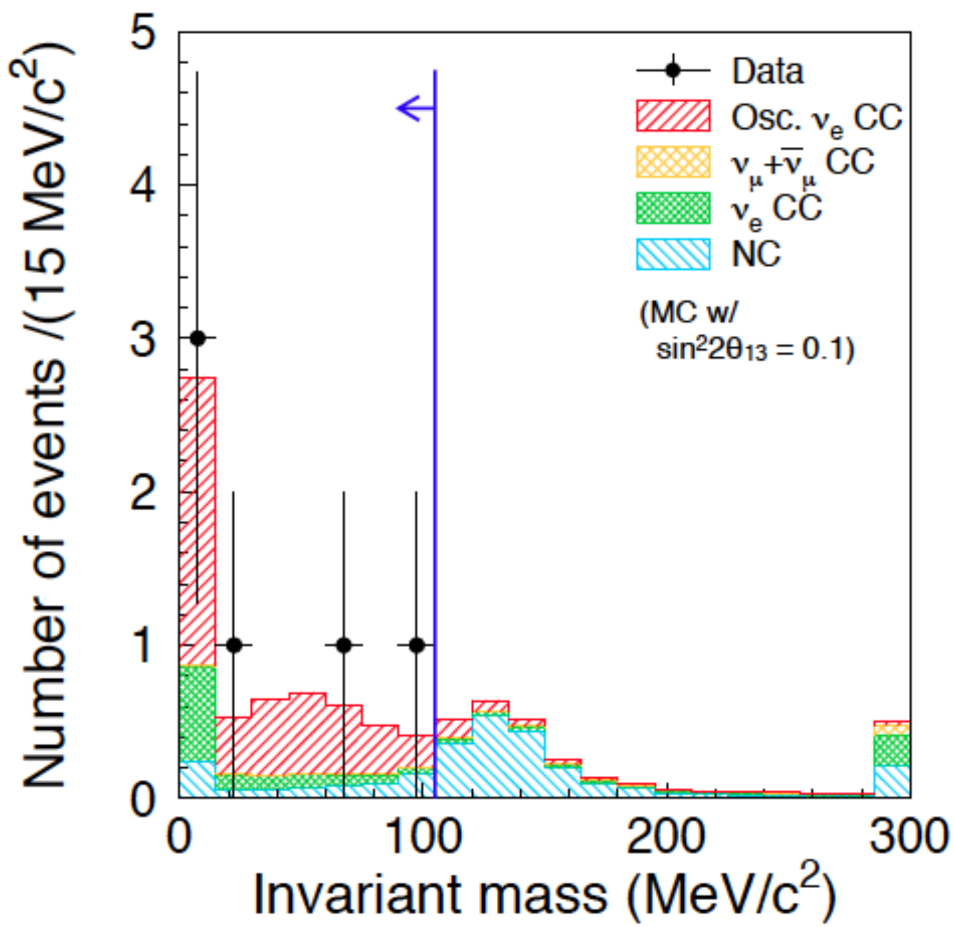
Far Detector Event Selection

★ **Require single ring e-like events**



★ **Loose cut on visible energy + no decay electrons**

- ★ **Reconstruct event using best two ring hypothesis**
- ★ **Require invariant mass to be less than** $m(\pi^0)$



Final Energy Distribution

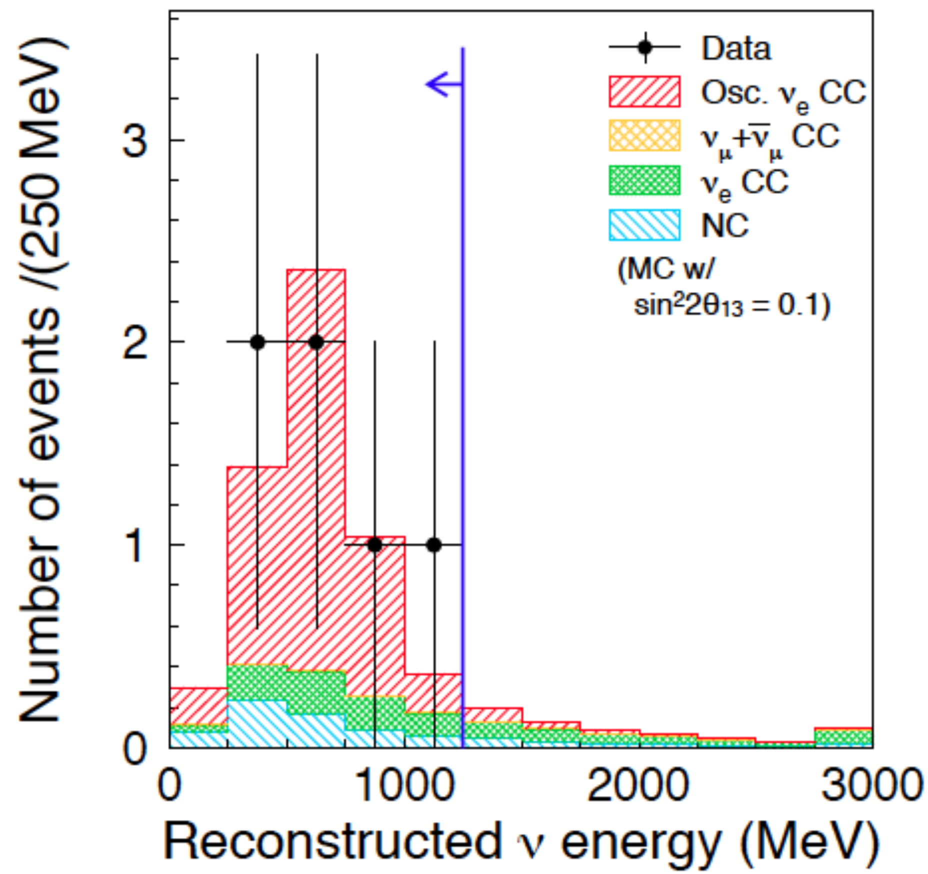
- In SK proton is below Cherenkov threshold
- Neutrino energy obtained assuming QE decay kinematics, $W^2 = m_p^2$ use energy and angle wrt beam

$$E_{\rm reco} = \frac{m_n E_e - m_e^2/2 - (m_n^2 - m_p^2)/2}{m_n - E_e + p_e \cos\theta_e}$$

Observe: 6 events
Expect: 1.5±0.3

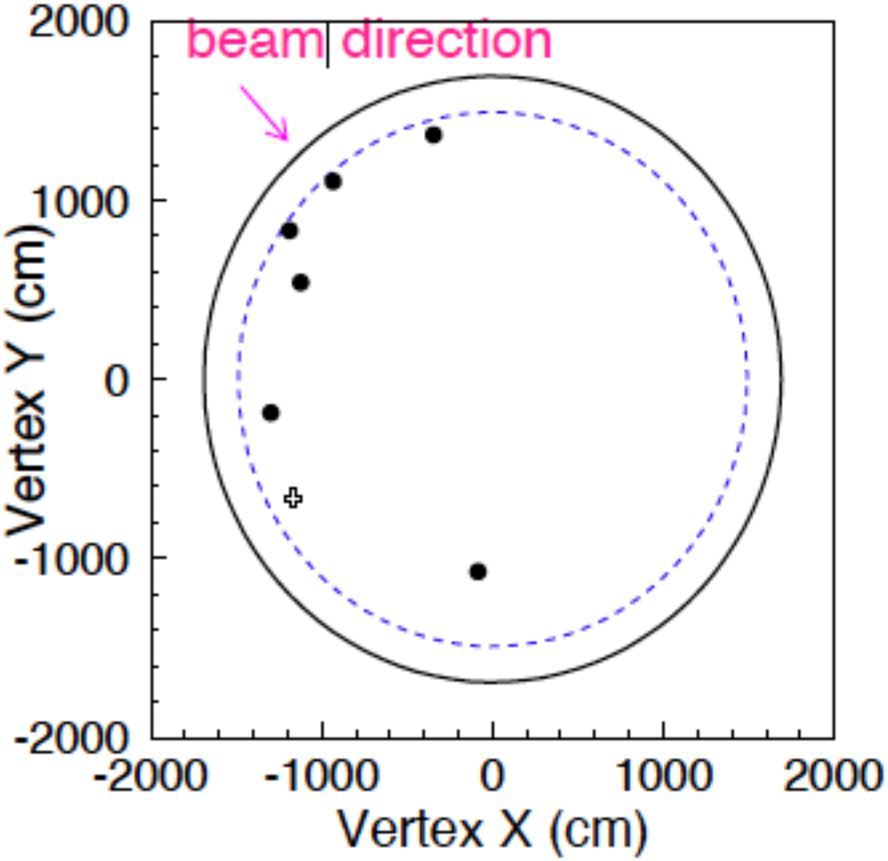
⇓

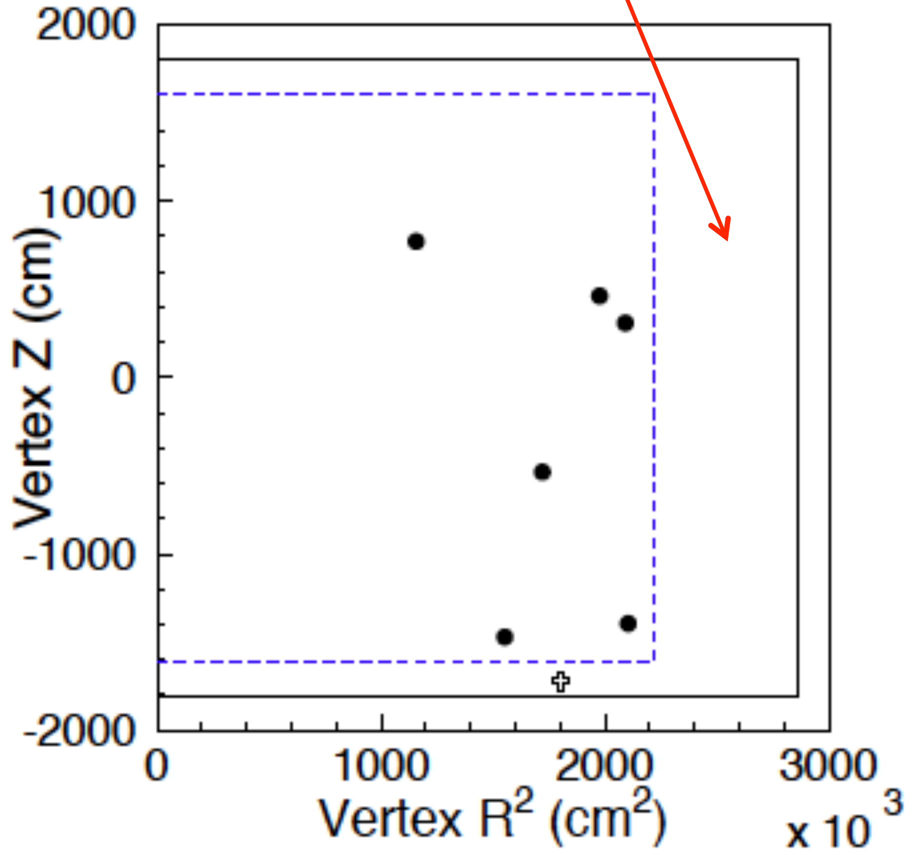
Prob: 0.007
Sig.: 2.5σ



The only "oddity"

- ★ Events clustered close to edge of detector
- ★ But no events selected outside fiducial region
- ★ Many checks – no indications of problem

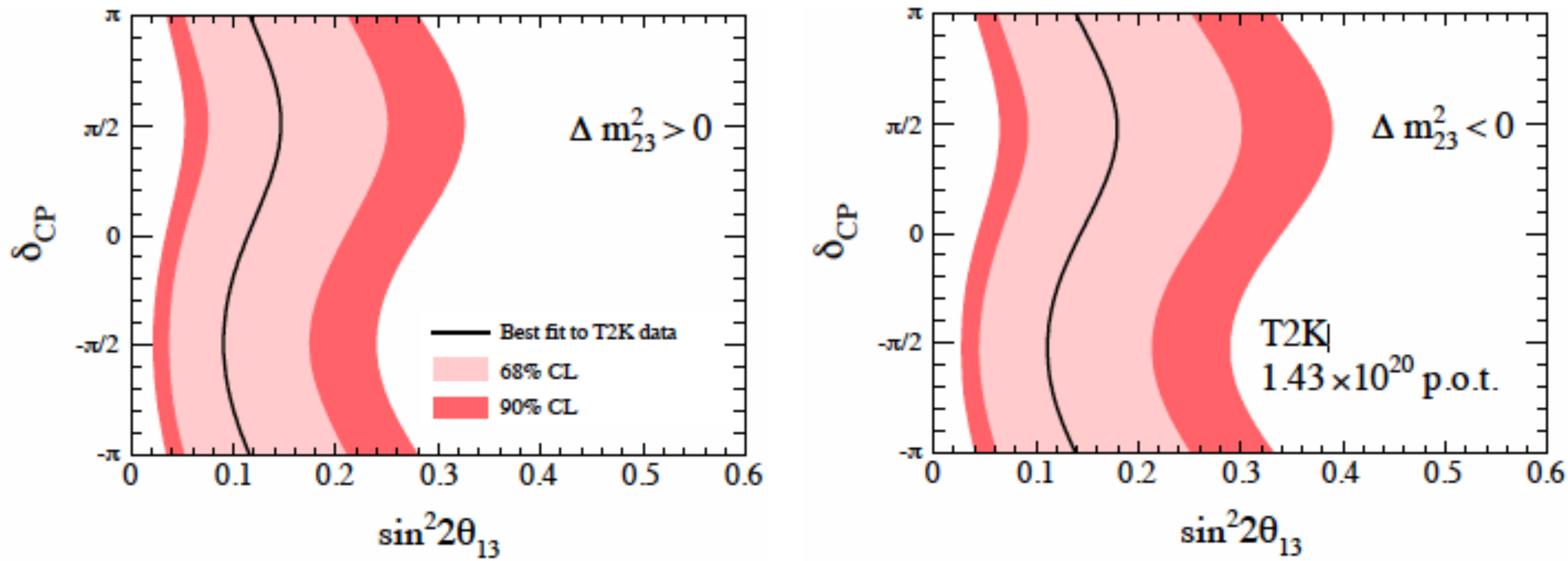




Limits

(assuming $\Delta m^2_{23} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$)

Normal Hierarchy **Inverted Hierarchy**



at $\delta = 0$

	Normal Hierarchy		Inverted Hierarchy
	$0.03 < \sin^2 2\theta_{13} < 0.28$	**90% C.L**	$0.04 < \sin^2 2\theta_{13} < 0.34$
	$\sin^2 2\theta_{13} = 0.11$	**best fit**	$\sin^2 2\theta_{13} = 0.14$

MINOS vs T2K

★ Interesting to compare analyses

	MINOS	T2K
Data/PoT	8.2E20	1.4E20
Efficiency	40 %	60 %
Background rej.	98 %	99 %
Background sys.	6 %	23 %
Expected back	49.5 ± 2.8	1.5 ± 0.3
Sig ($\sin^2 2\theta_{13}=0.1$)	19	5.5
S/N	0.38	3.7
Expected significance	2.5 σ	2.4 σ

My compilation made early this morning

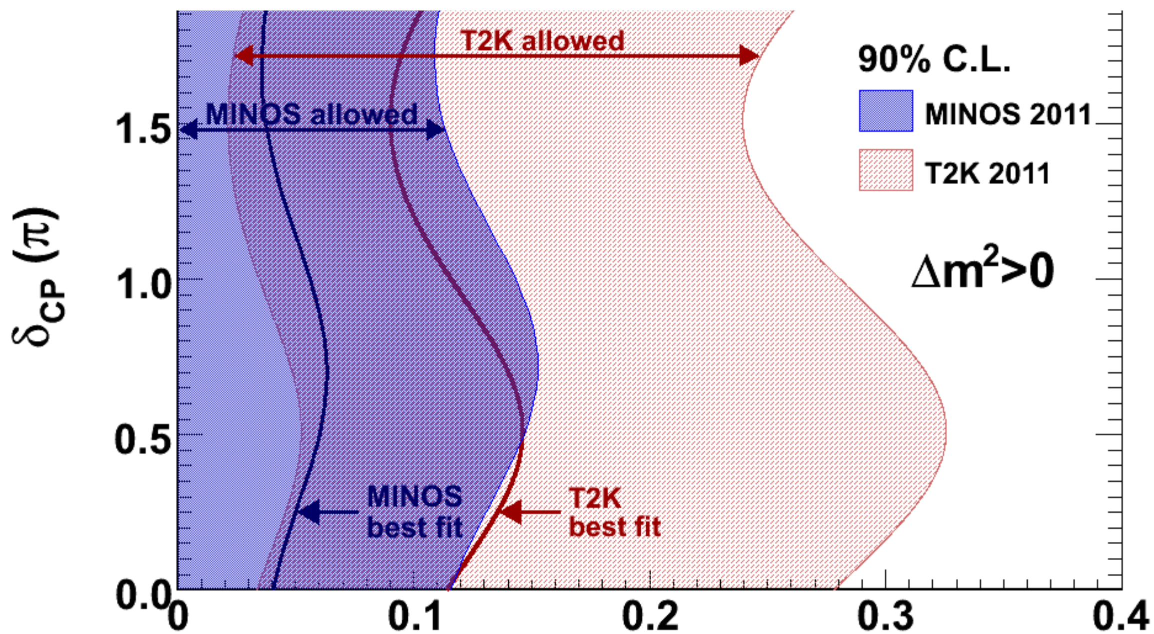
★ T2K background very much lower : off-axis

★ MINOS systematics are much lower: same ND and FD

★ Similar sensitivity (although T2K has much less data)

MINOS and T2K consistency

★ Simple overlay of MINOS and T2K contours (normal hierarchy)

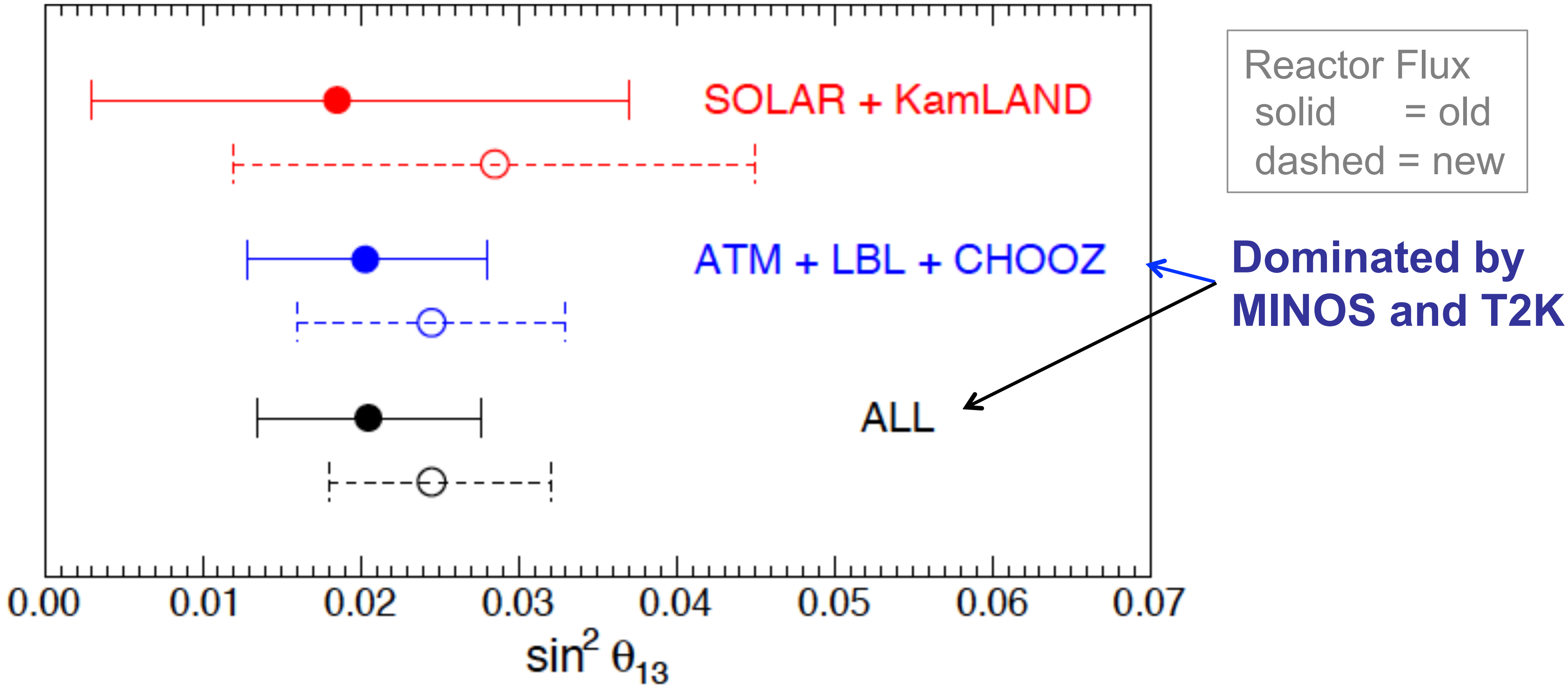


★ Some tension, but not inconsistent

★ By "eye" combined best fit value ~0.08

Global analysis

Fogli, et al., arXiv:1106.6028



- ★ **Global: 3 standard deviation evidence for non-zero θ_{13}**
- ★ **Best fit $\sin^2 2\theta_{13} \sim 0.08$**
- ★ **Indications of large value ! But early days…**
- ★ **If true, good news for future of field… CP… mass hierarchy…**

❾ Conclusions

In these lectures discussed:

- ★ Neutrino beams in general
  - on-axis and off-axis
- ★ General principles of Long Baseline experiments
  - examples: MINOS & T2K
- ★ Three example analysis in some detail
  - ν_μ disappearance
  - $\nu_\mu \rightarrow \nu_e$ in a wide band beam
  - $\nu_\mu \rightarrow \nu_e$ in a narrow band beam
- ★ Possible first observation of $\theta_{13} \neq 0$
- ★ Many topics not covered, CNGS, NOνA, Mini-boone, …
  - sorry just not sufficient time
- ★ Hopefully, have given a reasonable overview of main ideas

Very exciting future: T2K, NOnA, LBNE, T2K upgrade, …

Thank you