# *Neutrino News from Fermilab*


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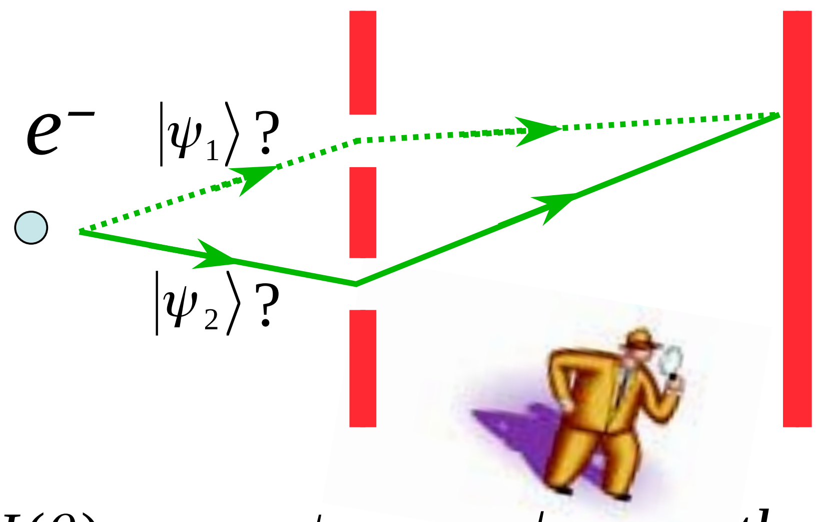
SMU Physics Department Seminar

22 October 2007

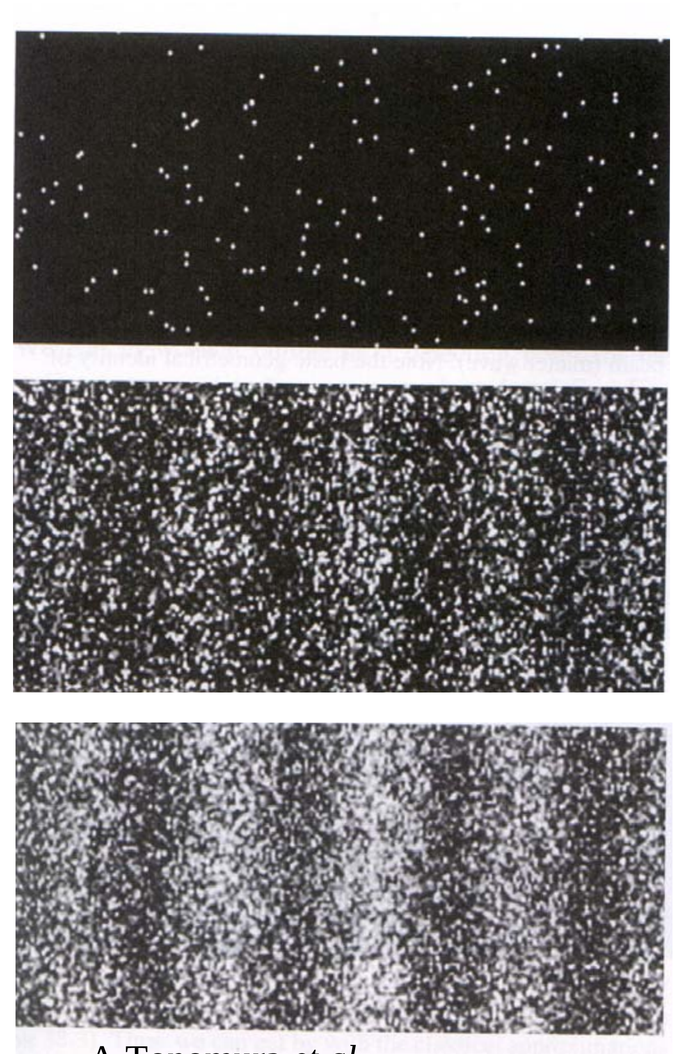
# Quantum Mechanics
*and*
# Double Slit Experiments

- Particles exhibit wave interference
- Indeterminacy (pattern lost if measure which slit)
- One particle *vs* ensemble
- Interpretation: probability waves

$$|\psi_{TOT}\rangle = |\psi_1\rangle + |\psi_2\rangle$$




$$\frac{I(\theta)}{I_0} = \cos^2(\frac{\phi}{2}) \qquad \frac{\phi}{2\pi} = \frac{path}{\lambda} = \frac{d\sin\theta}{\lambda}$$



A Tonomura *et al.*,
*Am. J. of Phys.* **57** 117-120 (1989)

# What We Observe "at the Screen": Lepton Number

- Why must the muon decay weakly?
  - Long lifetime result of heavy *W*
  - Lifetime $\tau \sim 2\mu s$

$$\mu^- \rightarrow e^- \quad \overline{\nu}_e \quad \nu_\mu$$

| | | | | |
|---|---|---|---|---|
| $L_\mu$ | +1 | 0 | 0 | +1 |
| $L_e$ | 0 | +1 | -1 | 0 |

- More favorable decay

$$\mu^- \rightarrow e^- \quad \gamma$$

| | | | |
|---|---|---|---|
| $L_\mu$ | +1 | 0 | 0 |
| $L_e$ | 0 | +1 | 0 |

  - Electromagnetic interaction
  - Should have lifetime $\sim 10^{-18}$ sec
  - Observed rate $< 1.2 \times 10^{-11}$ of all $\mu$ decays

(M.L. Brooks *et al*, *Phys. Rev. Lett.* ***83****, 1521 (1999)*)

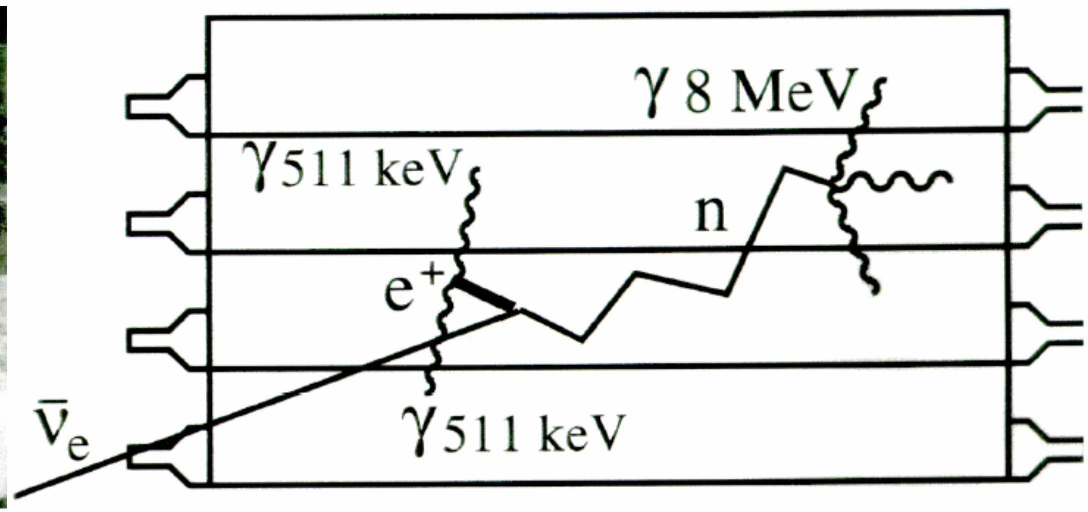
Lepton Number!

# ν's Have Lepton Number

- Nuclear β decay has *e*, reactors produce $\nu_e$
- Reines & Cowen exp't to observe free $\bar{\nu}_e$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

*Reines & Cowan, Science* ***124****, 103 (1956), Phys. Rev.* ***113****, 273 (1959)*




- Contrast to "failed" experiment by R. Davis

$$\bar{\nu}_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

*R. Davis, Phys. Rev.* ***97****, 766 (1955)*

***NOT OBSERVED***

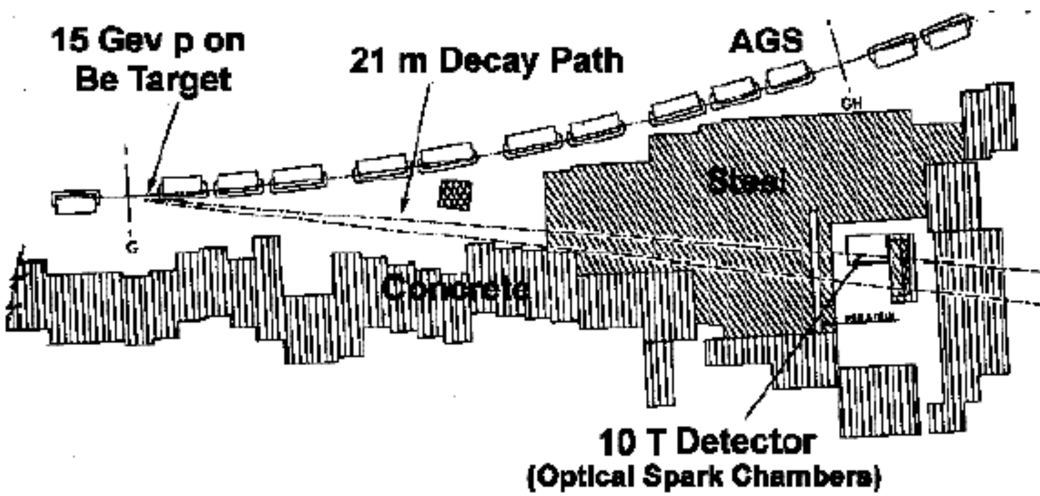
# ν's Have Lepton Number (*cont'd*)

- In 1957, Brookhaven AGS and CERN PS first accelerators intense enough to make ν beam

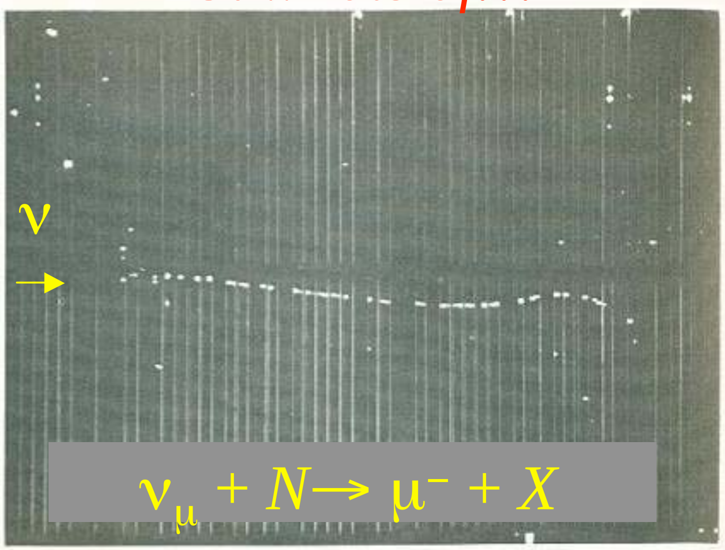
  $p + Be \rightarrow \pi^+ + X, \quad \pi^+ \rightarrow \mu^+ \nu$

- 1962: Lederman, Steinberger, Schwartz propose experiment to see

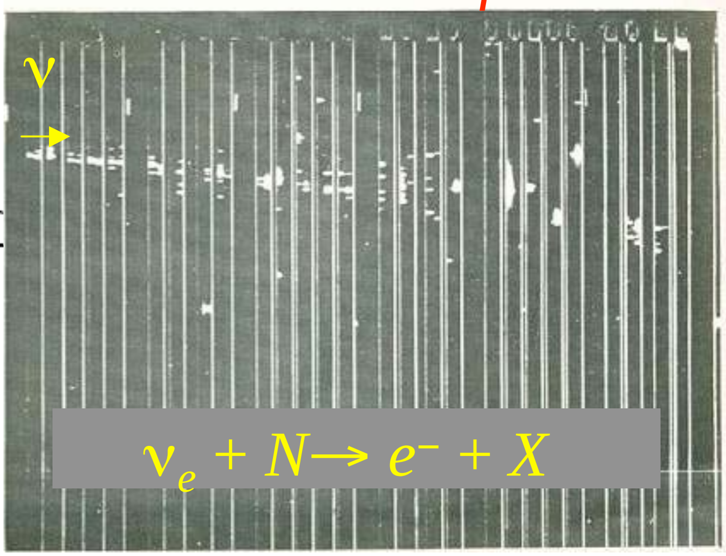
  $\nu_\mu + N \rightarrow \mu^- + X$ (*Phys.Rev.Lett.* **9**, 36 (1962))



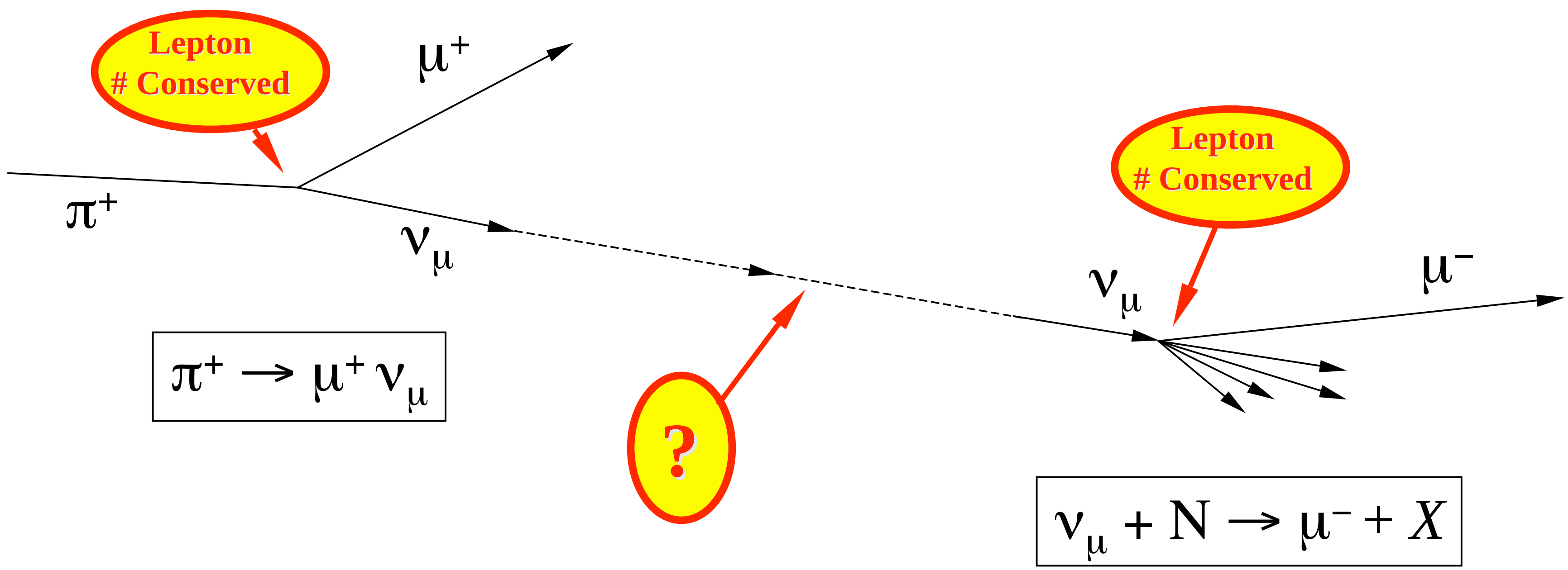

*Saw lots of…*




*Saw none of…*



# Weak Interactions Conserve Lepton Number



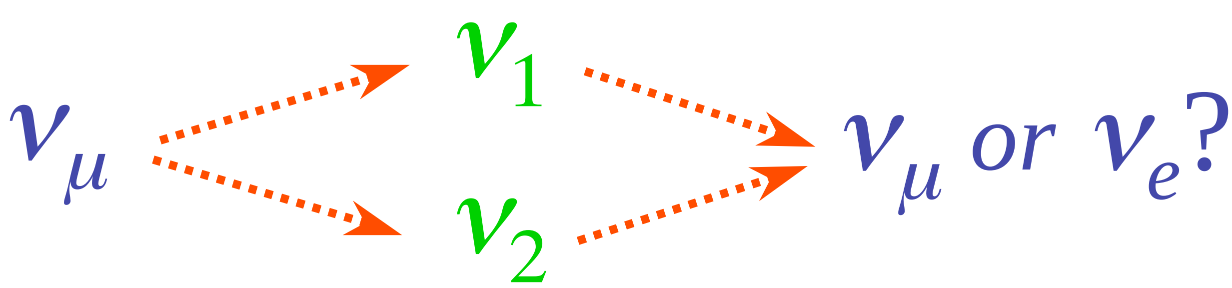

- Many exp't confirmations of Lepton number conservation ($\mu$, $\tau$ decays, *etc*)
- Neutrino interactions conserve lepton number too.
- But what happens to the neutrino in between creation/annihilation, while in flight?

# Neutrino Double Slit Experiment

- We create and observe $|\nu_\mu\rangle$ & $|\nu_e\rangle$ via weak interaction
- But suppose ν's have mass ≠ 0. Can label them by

  $|\nu_1\rangle$ -- the heavier mass state with $m = m_1$.

  $|\nu_2\rangle$ -- the lighter mass state with $m = m_2$.
- We do not know in which mass state the neutrino propagates (it's an unknown 'slit') – must assume both ⇒ interference!




- Suppose at $t$=0 have a state $|\psi(0)\rangle = |\nu_\mu\rangle$. Later…?

$$\text{Probability}\{\nu_\mu \rightarrow \nu_e\}(t) \propto \sin^2[1.27\Delta m^2 L/E_\nu]$$

*NB:* $\sin^2(x)$ *because now talking about fraction of beam that disappears!*

To see the effect, must have $E_\nu/L \sim \Delta m^2$

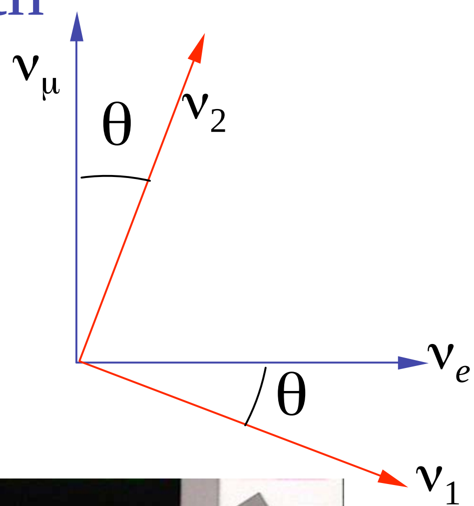
# A Mixture of ν States

- How can a quantum state produced at $t=t_1$ appear as a different quantum state at $t=t_2$?

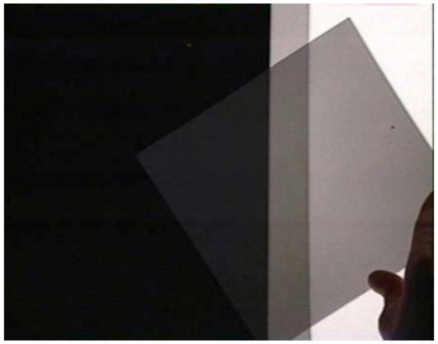
- Mass eigenstates need not coincide with weak eigenstates (two indep. bases)

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$



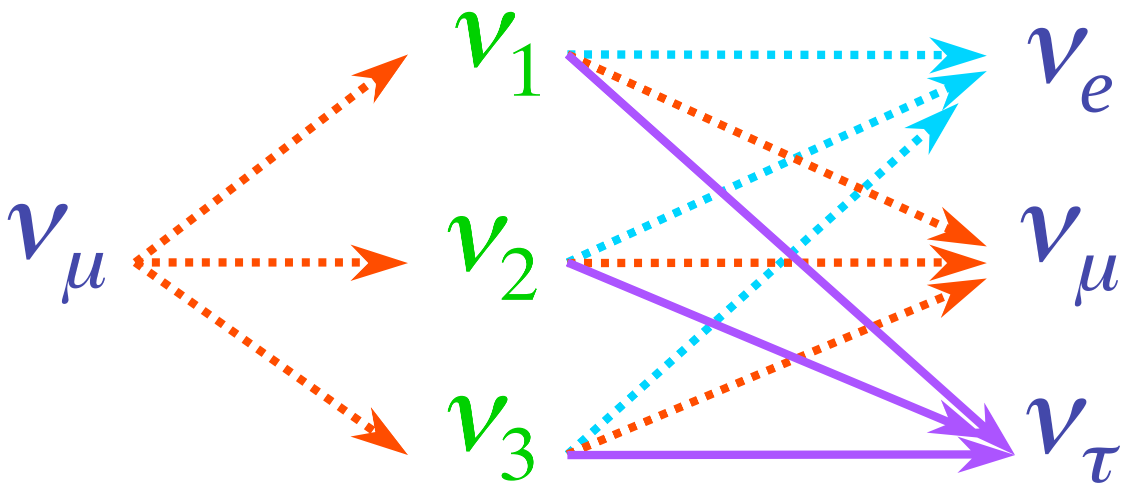

- Reminiscent of crossed polarizers.



# Neutrinos have 3 slits

- The $\nu_\tau$ discovered $\Rightarrow$ $\geq$3 lepton flavors must exist
  (K. Kodama *et al.*, *Phys. Lett.* **B504** *218 (2001)*]

- Measurements of $Z^0$ boson resonance $\Rightarrow$ only 2.983±0.009 lepton flavors participate in weak interaction
  [S. Eidelman et al., *Phys. Lett.* **B592**, 1 (2004) ]



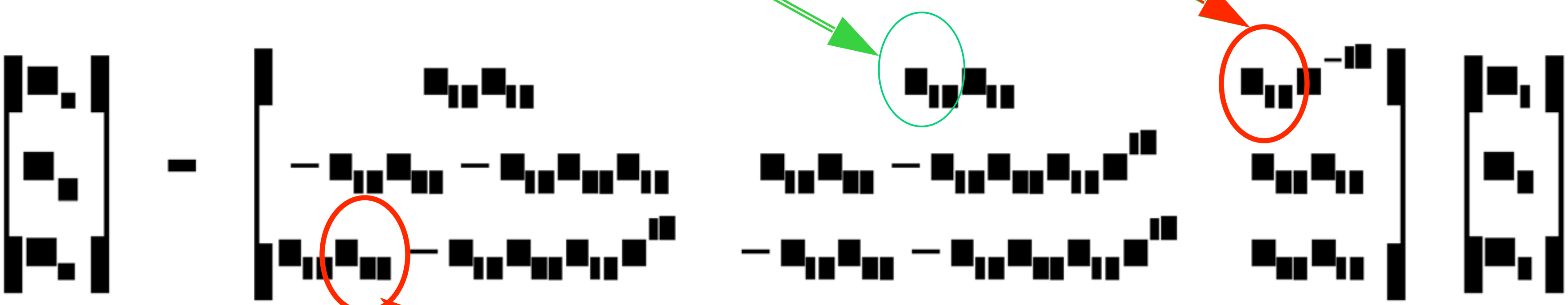

- With 3 ν families we expect
  - 3 mixing probabilities between flavor $i \rightarrow j$
  - 2 distinct mass splittings

# ν Mixing Orthodoxy

- If you believe in flavor mixing, there must be a 3×3 unitary transformation to mass states:

Is this ***non-zero???***
Large enough to measure ~~CP~~ in $\nu_\mu \rightarrow \nu_e$

$\sin\theta_{solar} < 0.62$
*(Smirnov, hep/0309299)*



$c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$

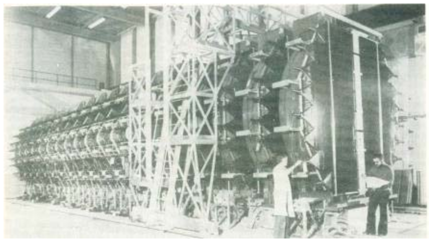
Is the mixing angle truly ***maximal???***

- In the quarks, mixing matrix has phase δ≠0 responsible for ~~CP~~.

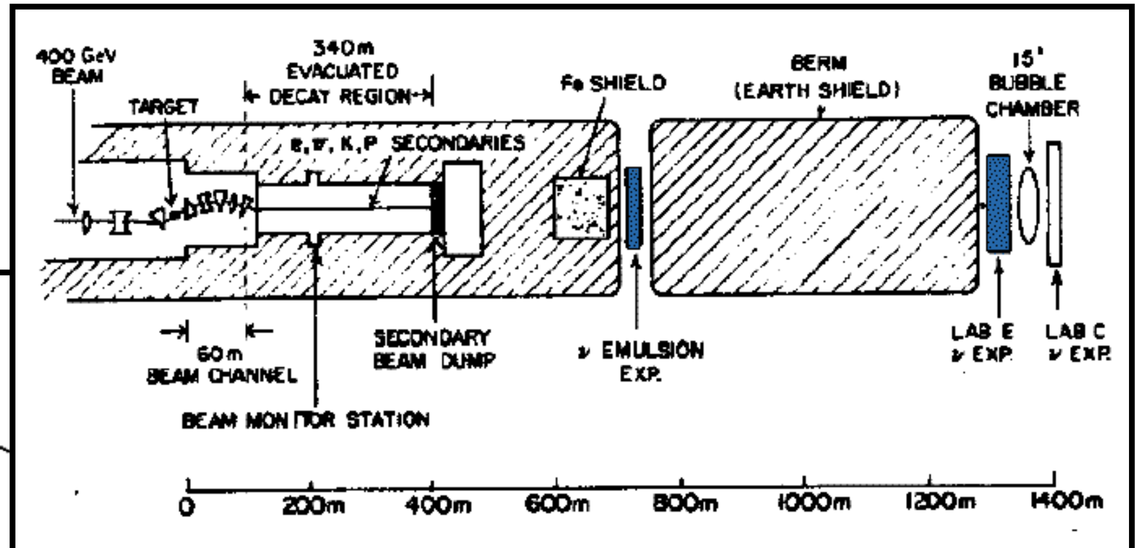
**But hopefully this picture is wrong or incomplete!**

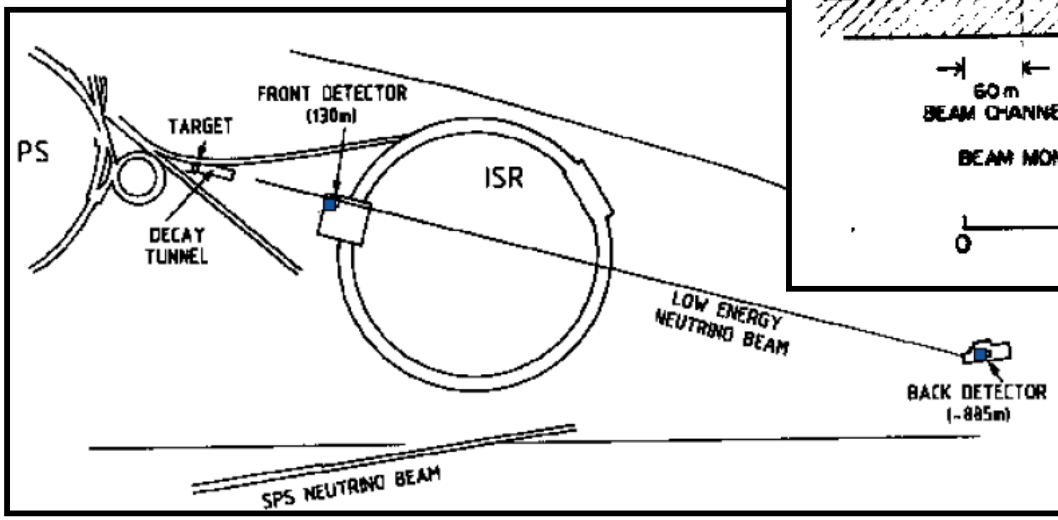
**(Peggy Lee: *"Is that all there is?"*)**

# Two Detector ν Experiments

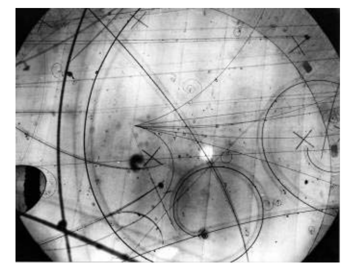


FNAL CCFR experiment, 1982-83



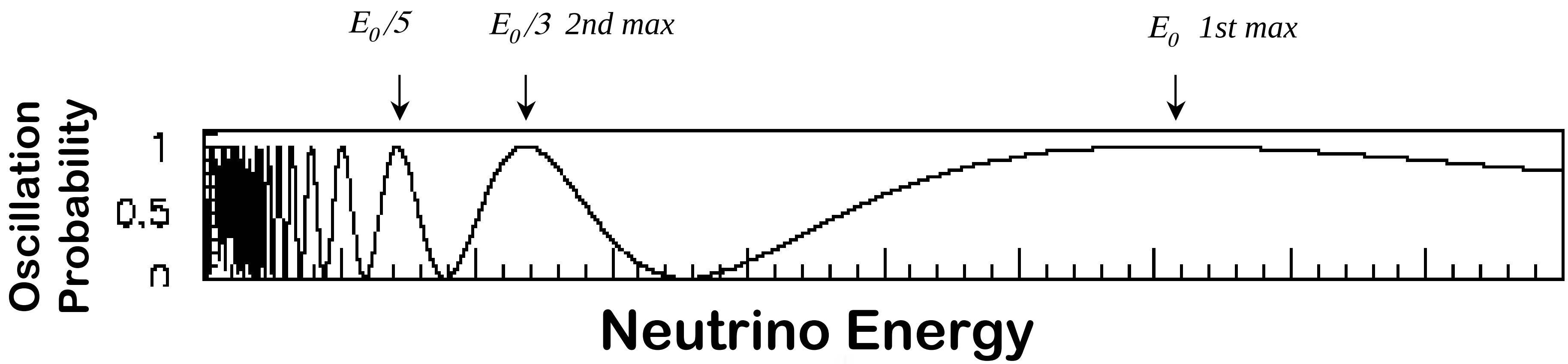




CERN CHARM/CDHS experiments, 1982-83



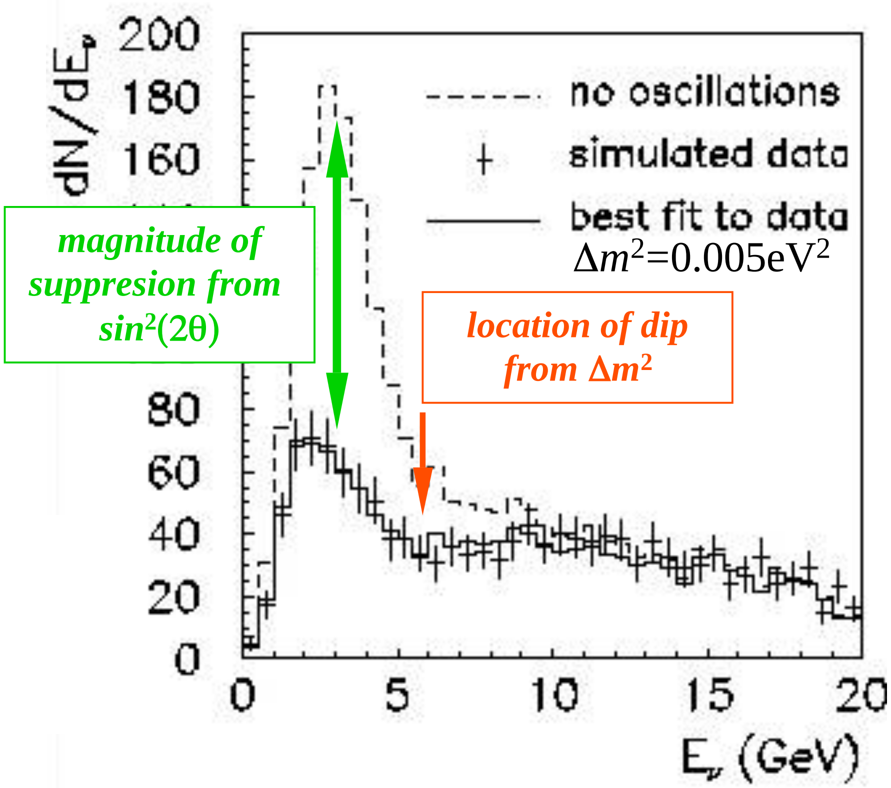
- Near detector predicts ν energy spectrum and rate at far detector (asssuming an absence of oscillations)
- Greatly reduces systematic uncertainties due to calculating beam flux.

# Interpretation of Oscillation Results



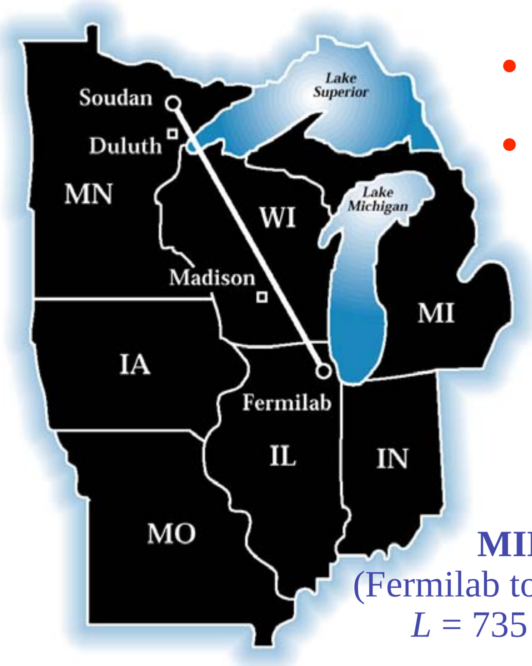

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E_\nu}\right)$$

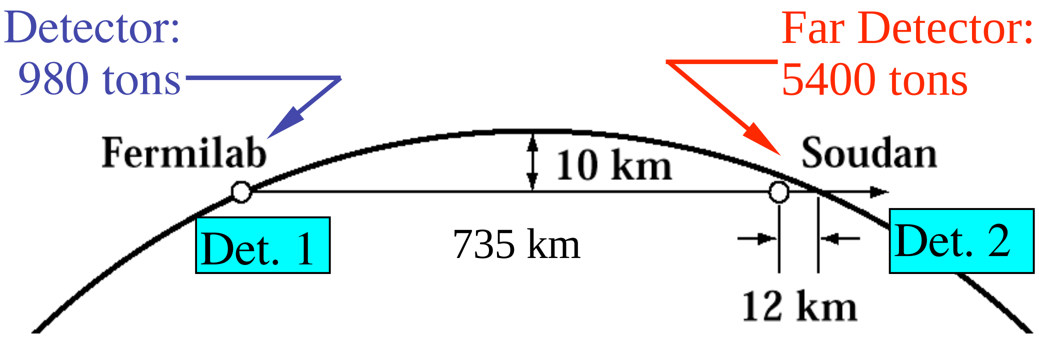
- Oscillations into unknown flavor causes dip in obvserved spectrum.



# Long Baseline ν Oscillation Exp's

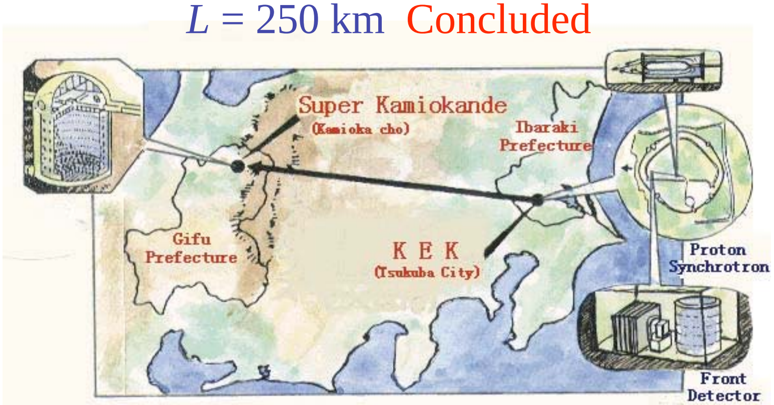
- Reproduce atmospheric ν effect using accelerator beam
- *L* ~ 100's kilometers to match oscillation frequency



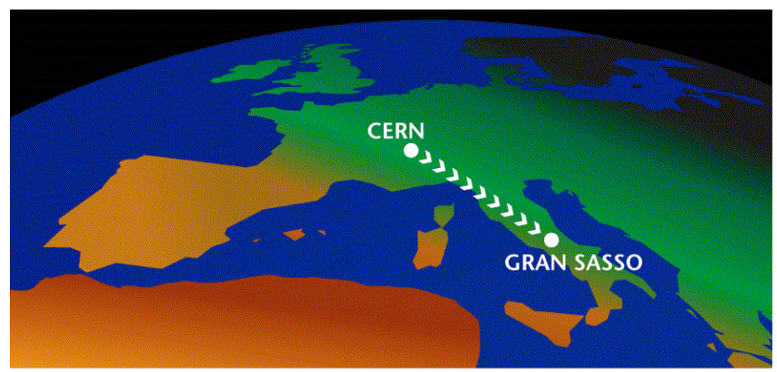




**MINOS**
(Fermilab to Minnesota)
*L* = 735 km 2005

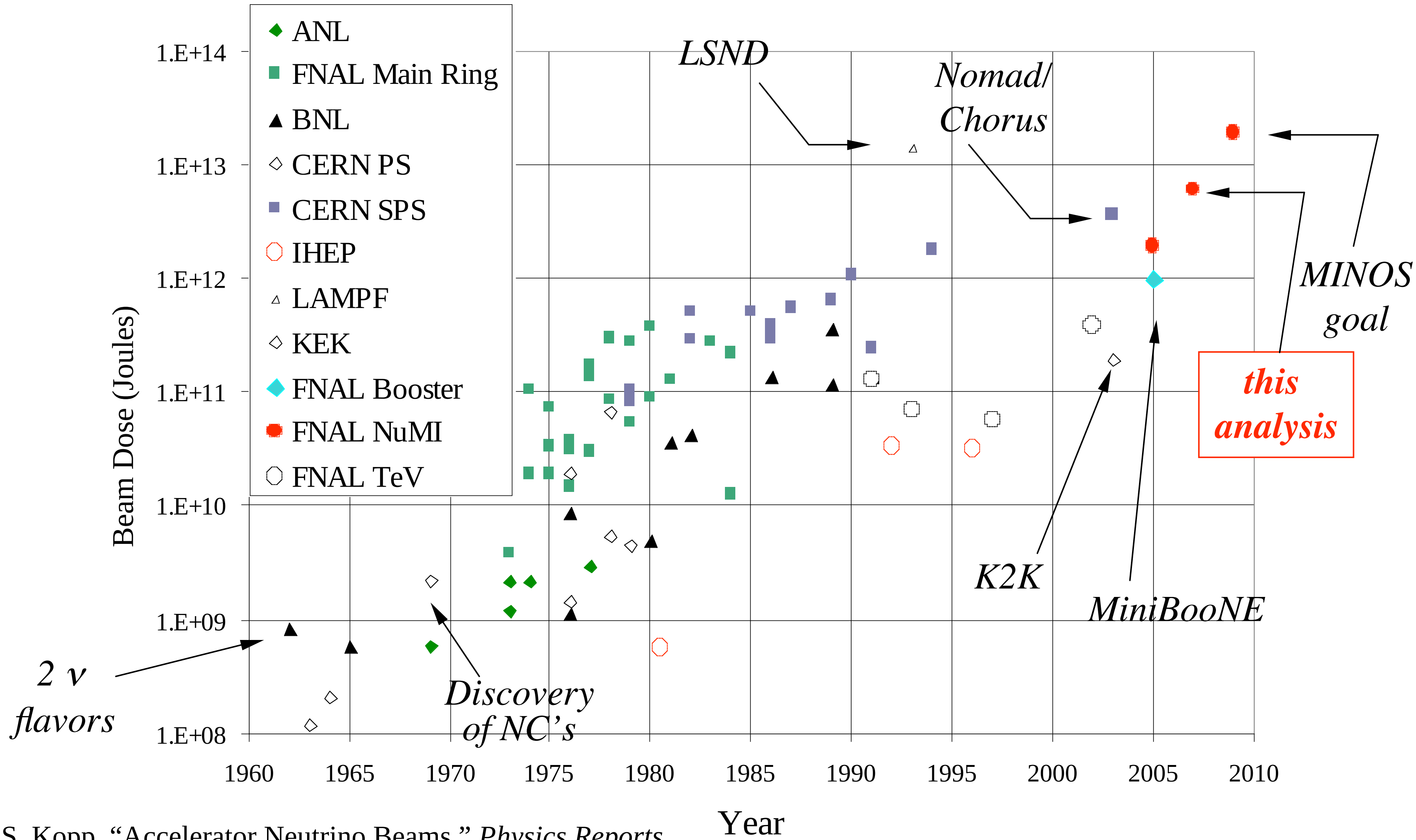
**K2K** (KEK to SuperK)
*L* = 250 km Concluded




**CNGS** (Cern to Gran Sasso, Italy)
*L* = 750 km tested 2006, run 2008

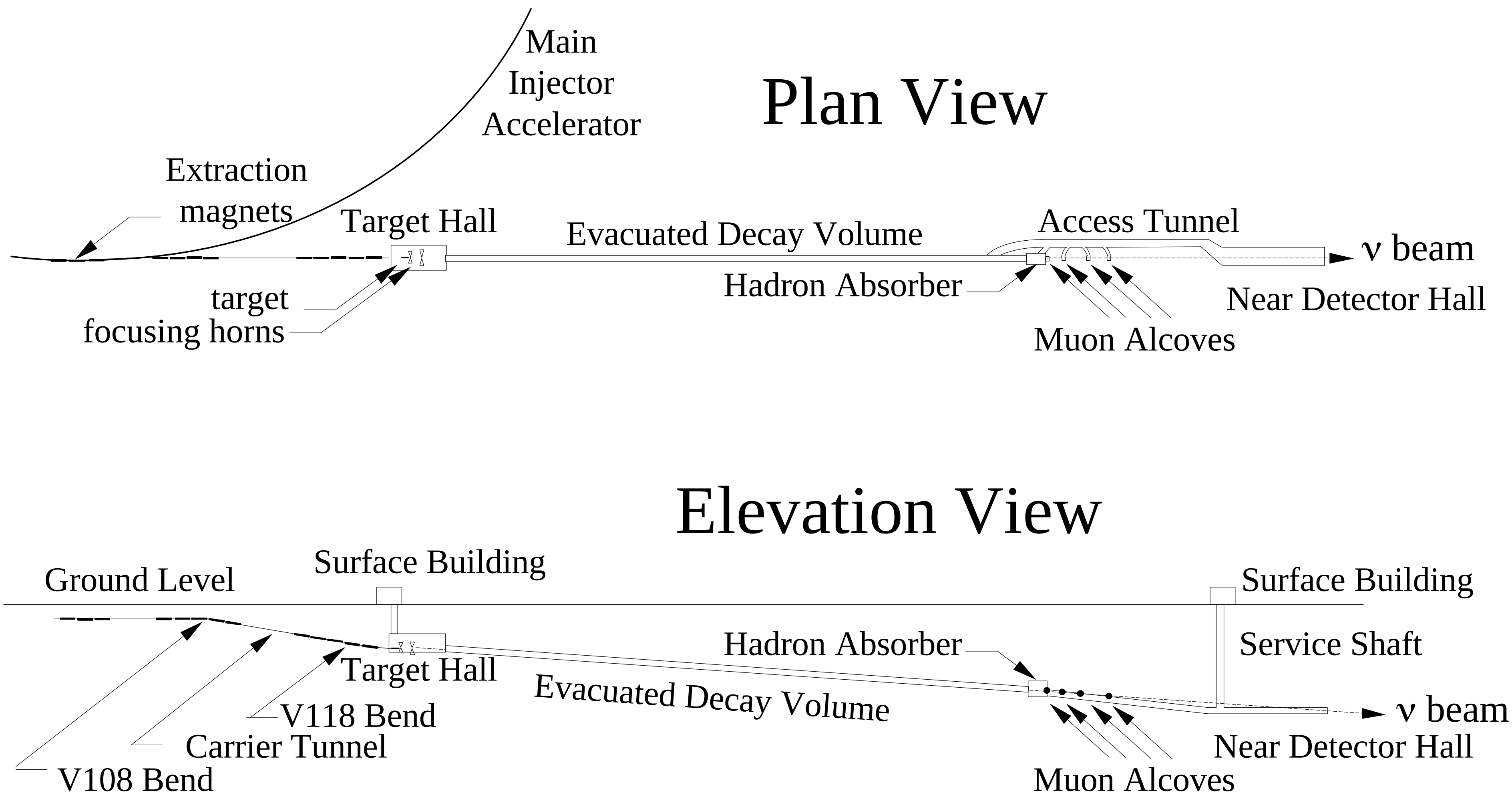


# The Challenge of Long Baselines…



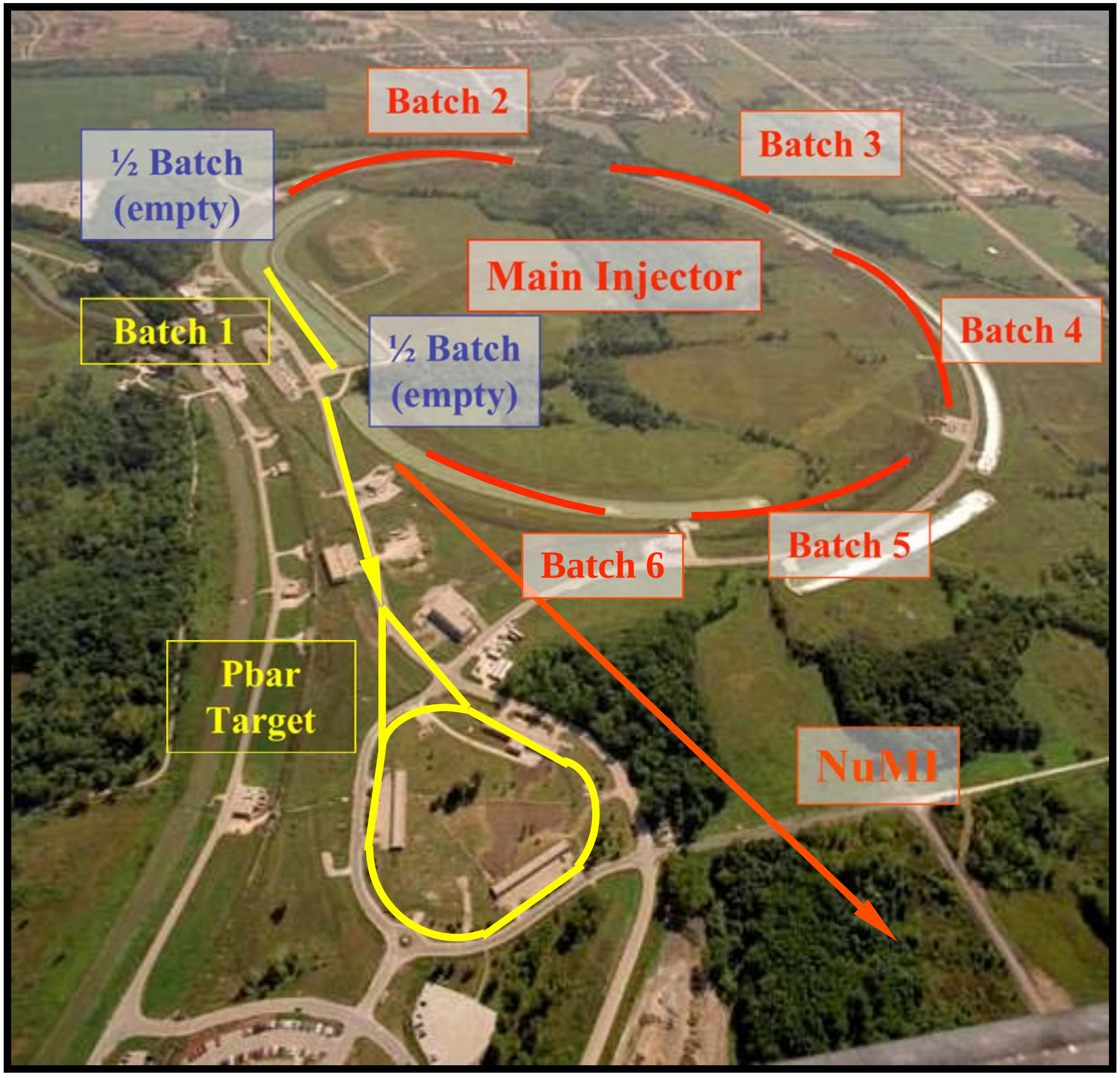

S. Kopp, "Accelerator Neutrino Beams," *Physics Reports* **439**, 101 (2007), arXiv:hep-ex/0*609129*

# The NuMI Beam



# Neutrinos at the Main Injector

- MI ramp time ~1.5sec
- MI is fed 1.56μs batches from 8 GeV Booster
- Simultaneous acceleration & dual extraction of protons for
  - Production of $\overline{p}$ (Tevatron collider)
  - Production of neutrinos (NuMI)
- NuMI designed for
  - 8.67 μs single turn extraction
  - $4\times10^{13}$ppp @ 120 GeV
- Antiproton Production:
  - Requires bunch rotation (Δt~1.5nsec)
  - Merges two Booster batches into one batch ("slip-stacking")



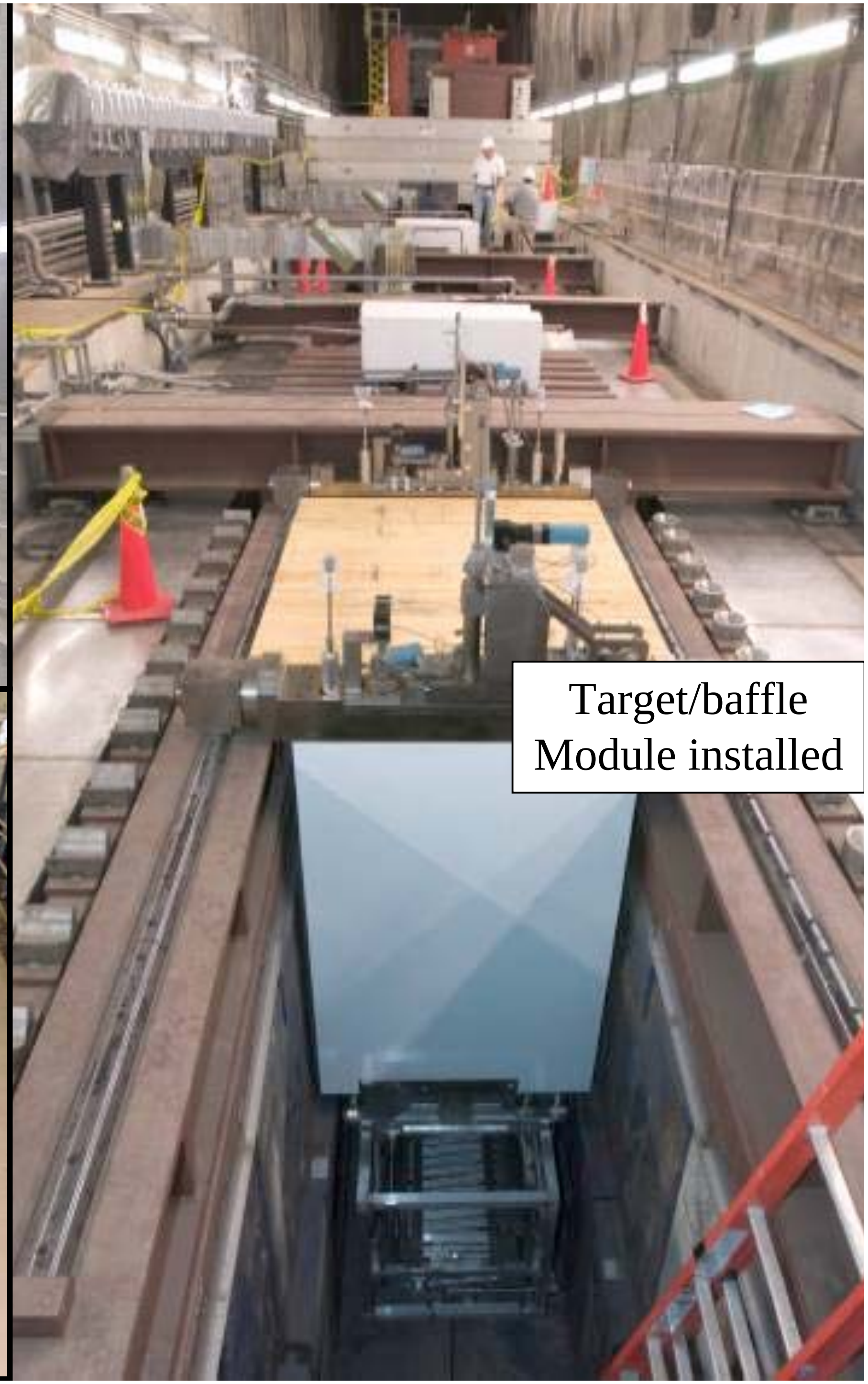
# NuMI Proton Beam Line



# Target Hall

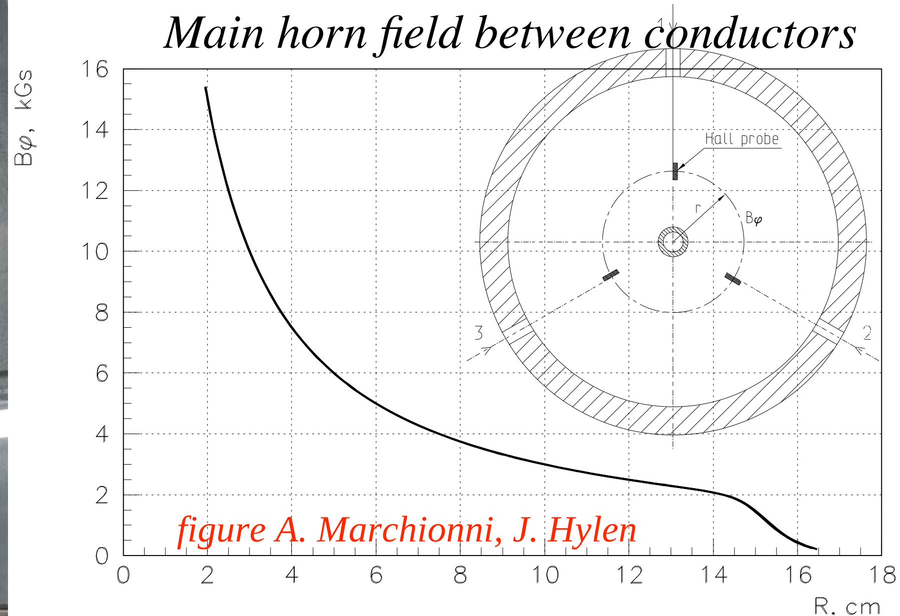

Target Hall
after
Contractor
completion
Decay pipe


Target Hall shielding installation


Target/baffle
Module installed

# Focusing Horns

Horn 2 suspended from shielding module being lowered into shielding pit




Hall probe moving along horn axis

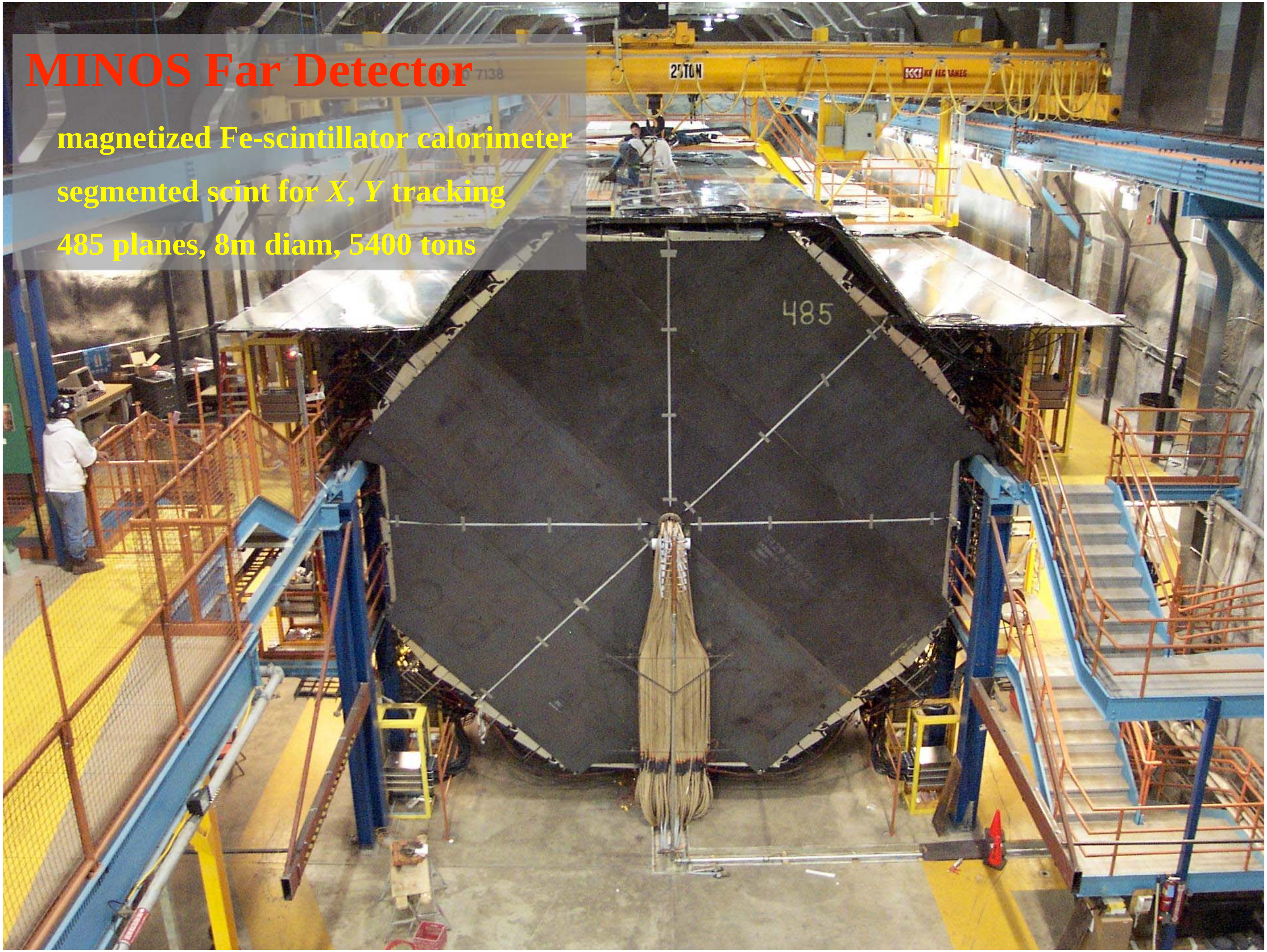
# MINOS Near Detector

# MINOS Far Detector

magnetized Fe-scintillator calorimeter

segmented scint for *X, Y* tracking

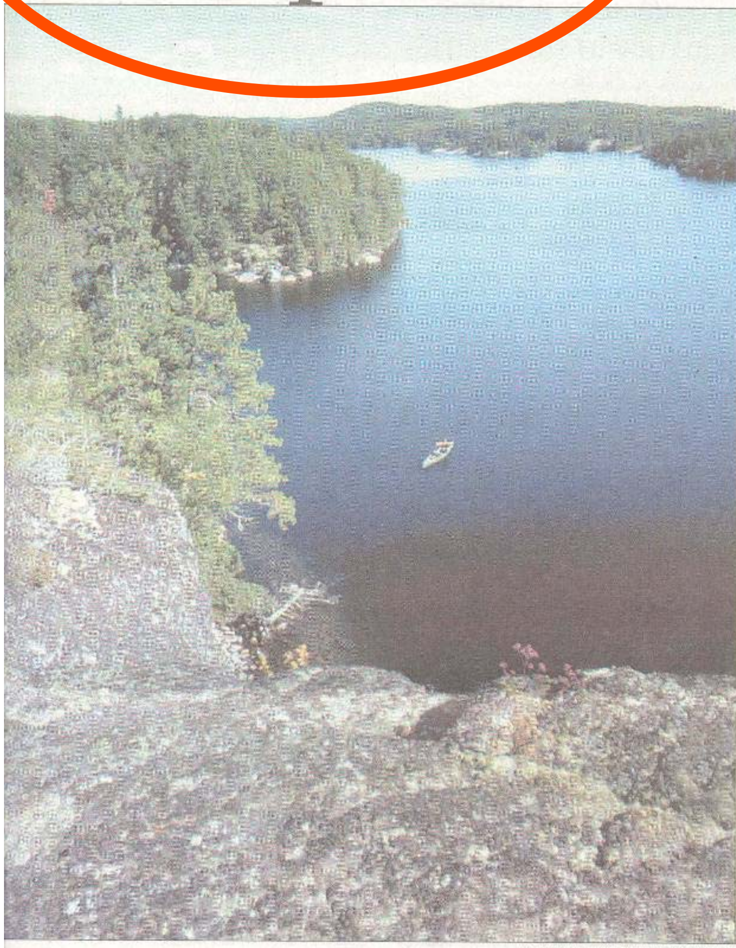
485 planes, 8m diam, 5400 tons



# *Raison d'Être* for a Northern Minnesota Experiment!

# Bound to impress

## Canoes glide through Minnesota's vast unspoiled trove of lakes and wilderness



ELY, MINN. CHAMBER OF COMMERCE PHOTOS

You can canoe all day without seeing another person in the Boundary Waters Canoe Area Wilderness, which has more than 1,500 miles of water trails. The area is the largest wilderness preserve east of the Rocky Mountains.

By Beth Gauper
SAINT PAUL PIONEER PRESS

Along Minnesota's northern border with Canada, more than 200,000 people a year find an increasingly rare commodity — absolute wilderness.

The million-acre Boundary Waters Canoe Area Wilderness is barely changed since voyageurs used its chain of lakes and rivers to push deep into the continent's interior. Today, the foot trails over which they carried canoes and 180-pound packs are used by vacationers, who wind their way from lake to lake in search of the perfect combination of woods, water and solitude.

As they paddle along the glassy waters of more than 1,000 lakes, they may see moose, lynx, otters and beaver, who have rebounded from near-extinction at the hands of trappers. In the evening, at nearly 2,200 campsites, they listen for the trill of loons and the howl of wolves, whose numbers also have rebounded.

To people who consider the Midwest flyover land, the BWCA Wilderness puts Minnesota on the map. National Geographic Traveler listed it as one of 50 Places of a Lifetime/The World's Greatest Destinations, along with the Grand Canyon and Big Sur. In the book "1,000 Places to See Before You Die," it's the only Minnesota entry.

Whenever I travel outside the Midwest, people I meet always scan their brains for whatever they know about Minnesota, then ask, "Have you been to the Boundary Waters?"

Last August, I finally took a week and went. And I was surprised. The

See **CANOE**, back page

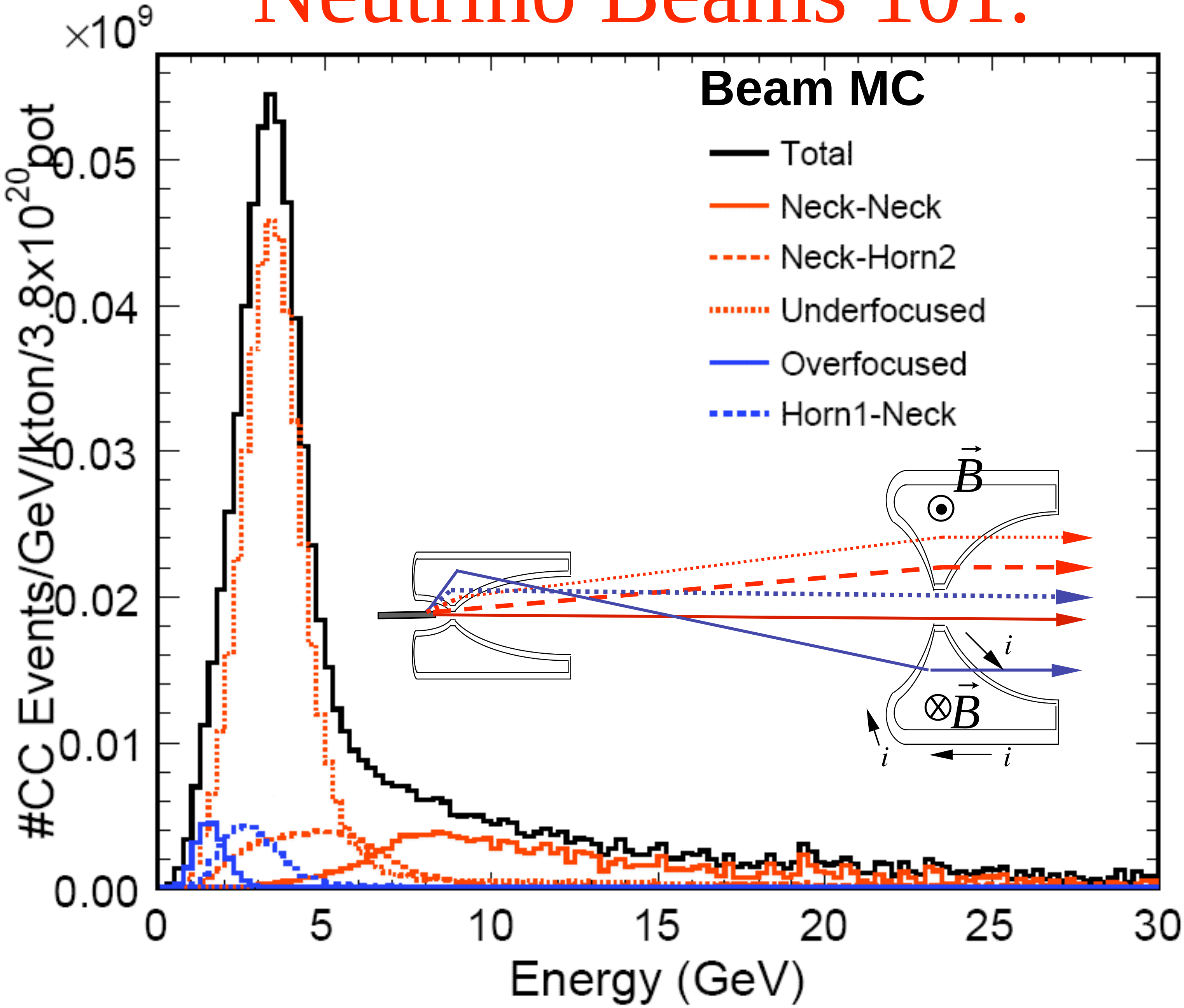
## Rangers, outfitters help you dip your toe in the waters

The easiest way for a beginner to go to the Boundary Waters is with a group or a friend who has good gear to share — lightweight tent, stove and water filter, in addition to the lightweight sleeping bag. Therma-

To people who consider the Midwest flyover land, the BWCA Wilderness puts Minnesota on the map. National Geographic Traveler listed it as one of 50 Places of a Lifetime/The World's Greatest Destinations, along with the Grand Canyon and Big Sur. In the book "1,000 Places to See Before You Die," it's the only Minnesota entry.

**Austin *American-Statesman* Newspaper, Sunday, April 18, 2004**

# Neutrino Beams 101:



# Consequence: Flux Uncertainty

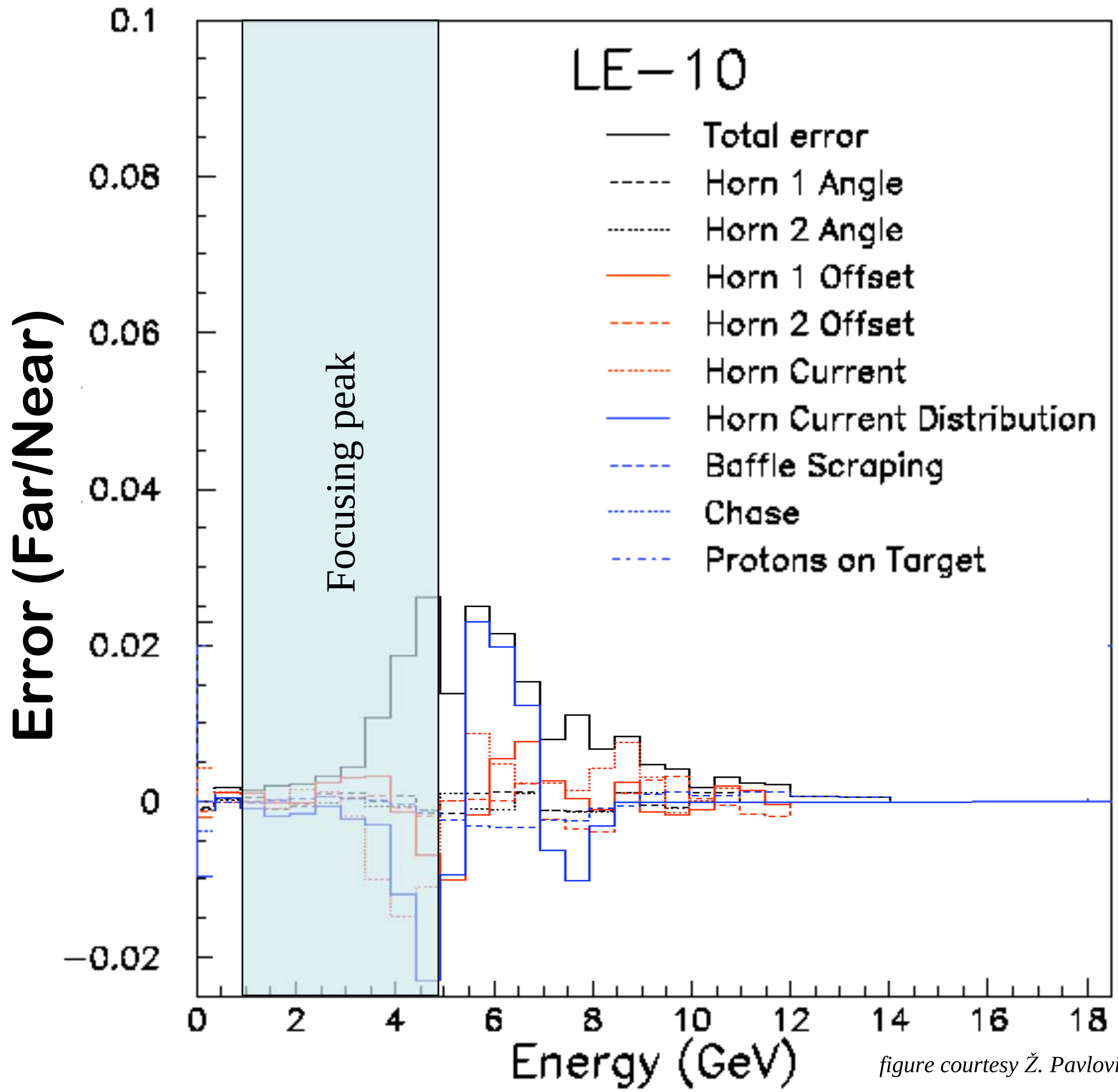
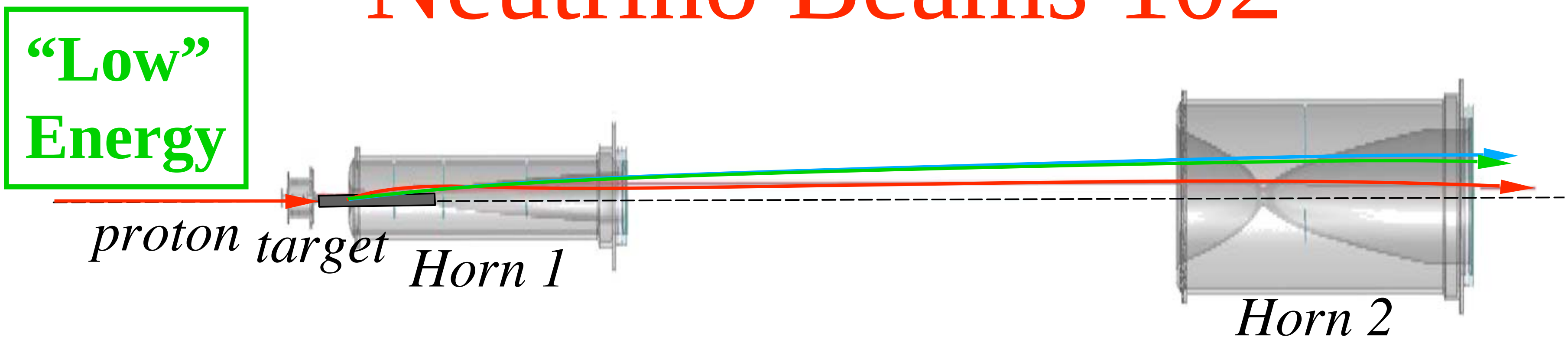



*figure courtesy Ž. Pavlović*

# Neutrino Beams 102




**Pions with**
**$p_T$=300 MeV/*c* and**
***p*=5 GeV/*c***
***p*=10 GeV/*c***
***p*=20 GeV/*c***

*Vary ν beam energy by sliding the target in/out of the 1st horn*

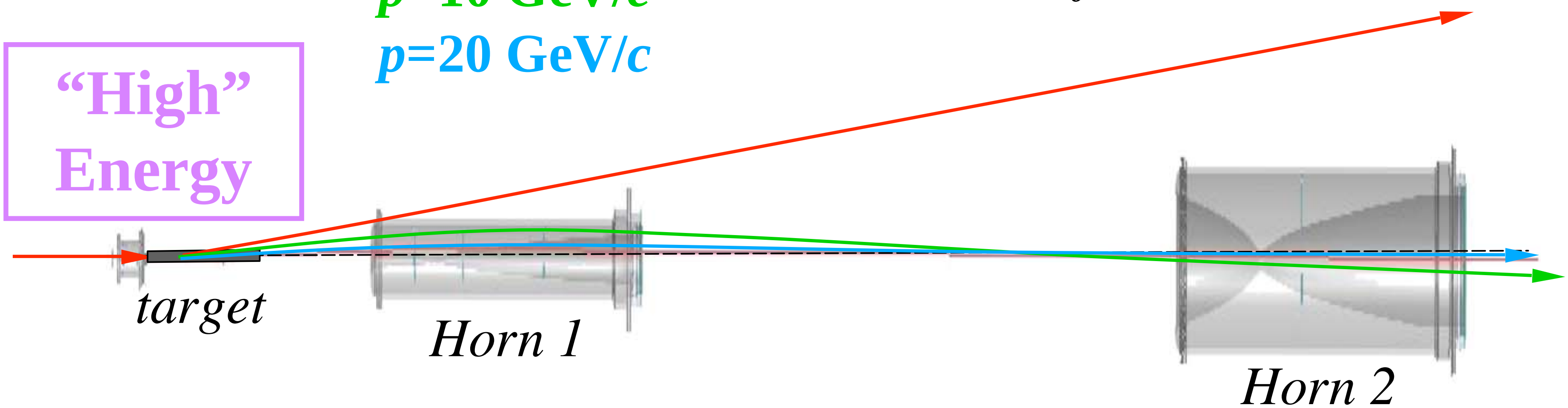
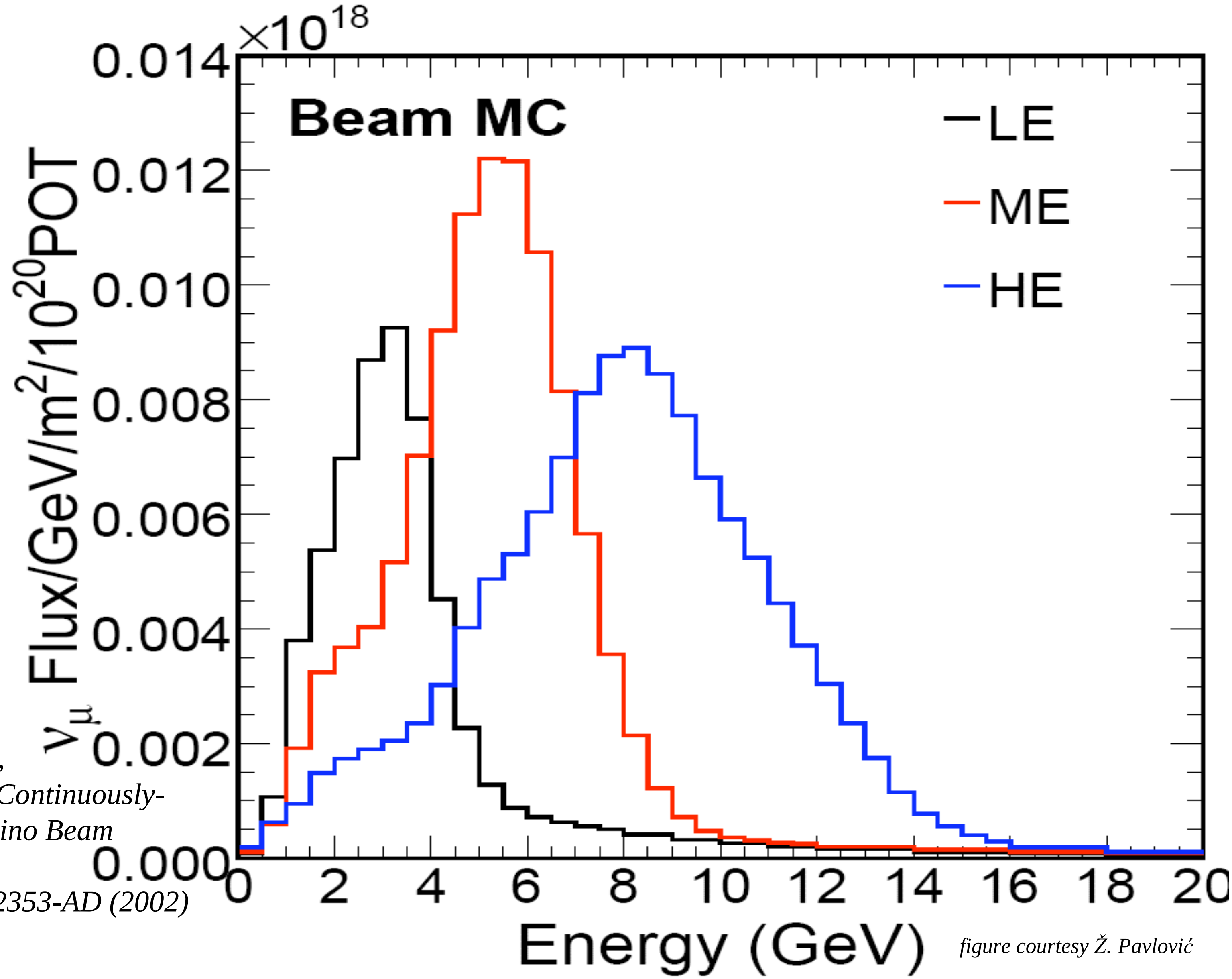



*figure courtesy Ž. Pavlović*

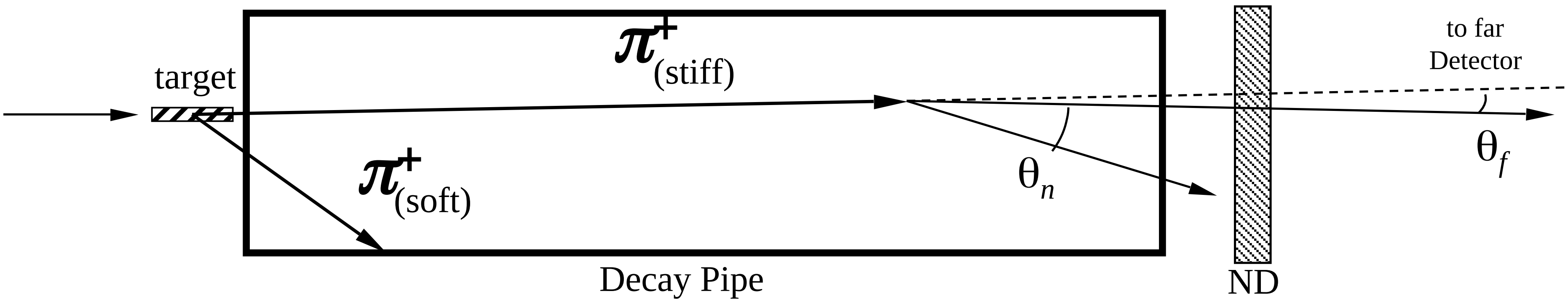
# Opportunity:  Flexible Beam Energy




*M. Kostin et al, "Proposal for Continuously-Variable Neutrino Beam Energy," Fermilab-TM-2353-AD (2002)*

*figure courtesy Ž. Pavlović*

# Neutrino Beams 103:




- ND and FD spectra similar, but not identical

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

$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$

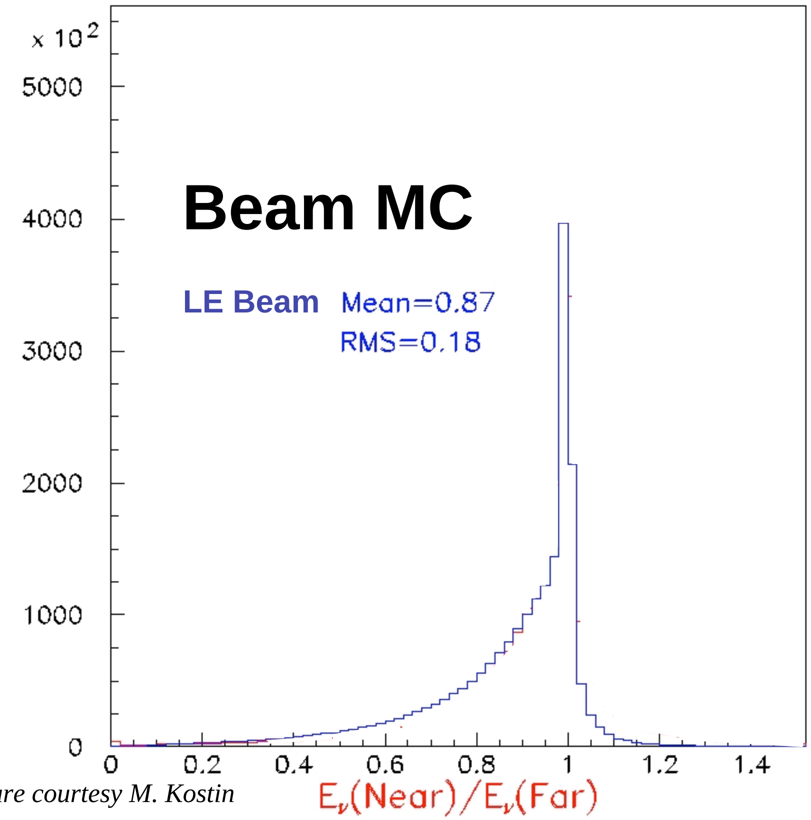
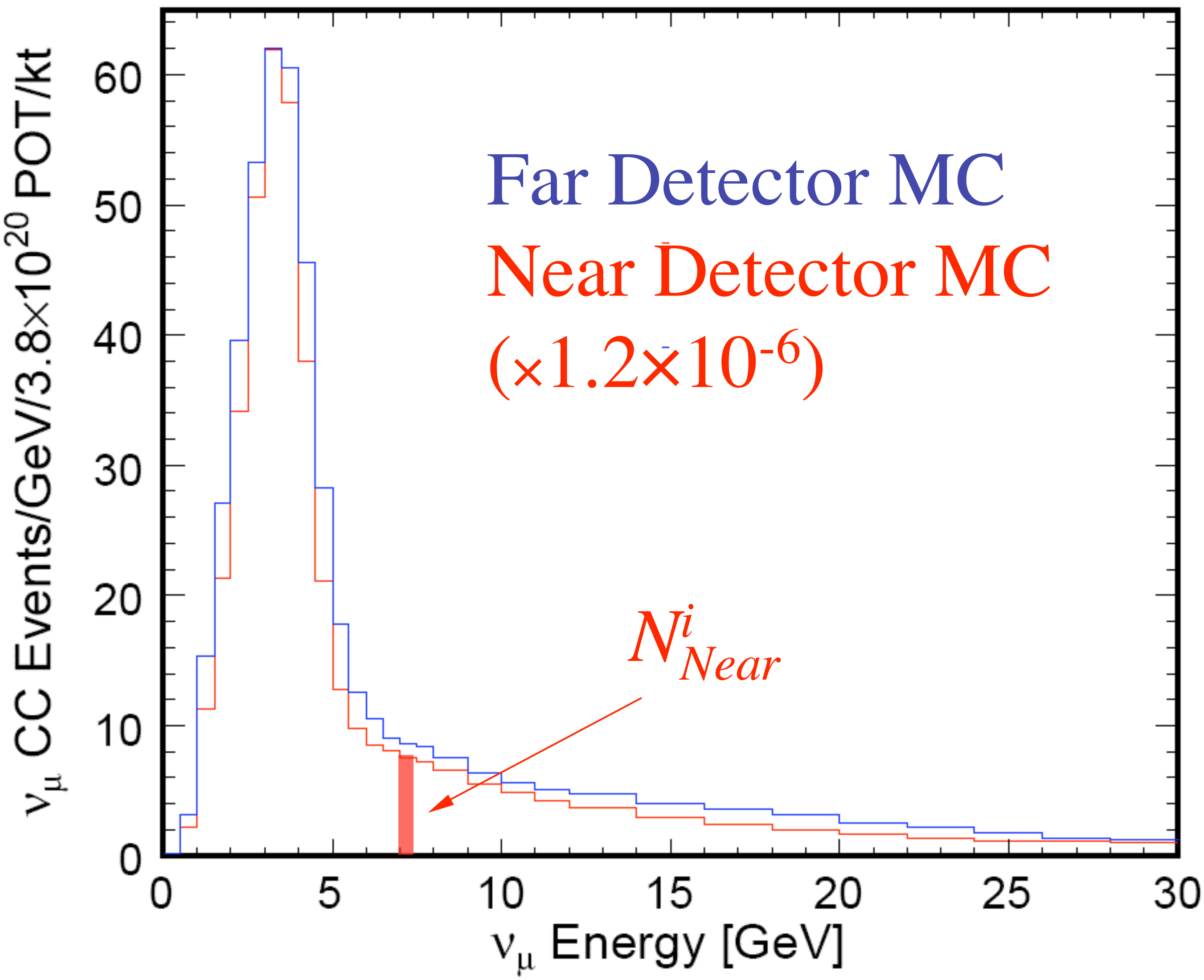



*figure courtesy M. Kostin*

# Consequence: Extrapolating to the FD




- ND and FD spectra are similar, but *not* identical
- If they were identical, (NuMI approximating a point source) could say

$$N^i_{Far} = \Re_{FN} N^i_{Near}$$

where

$$\Re_{FN} = (Z_{near}/Z_{far})^2$$

# Extrapolating to the FD (*cont'd*)

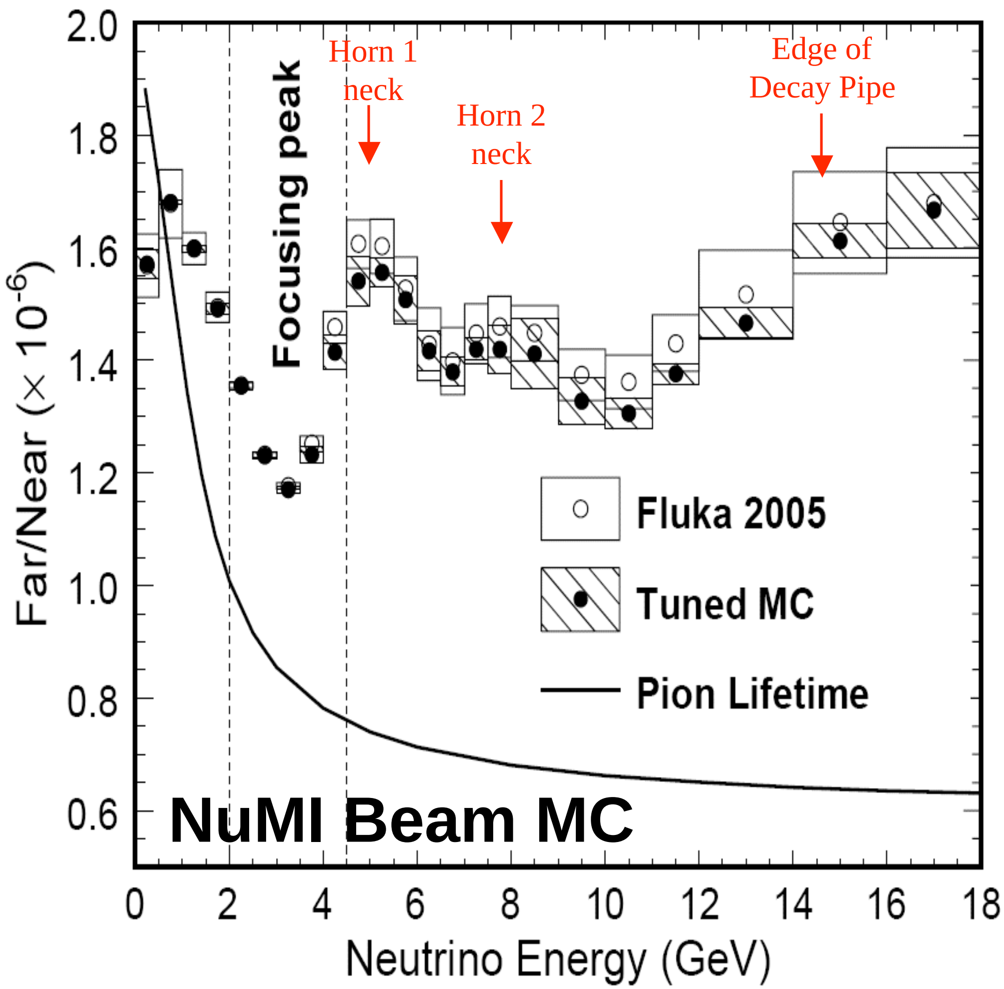
- The ND sees the NuMI beam as an extended line source of neutrinos, while FD sees a point source,

*solid angle* — *weighted by π lifetime*

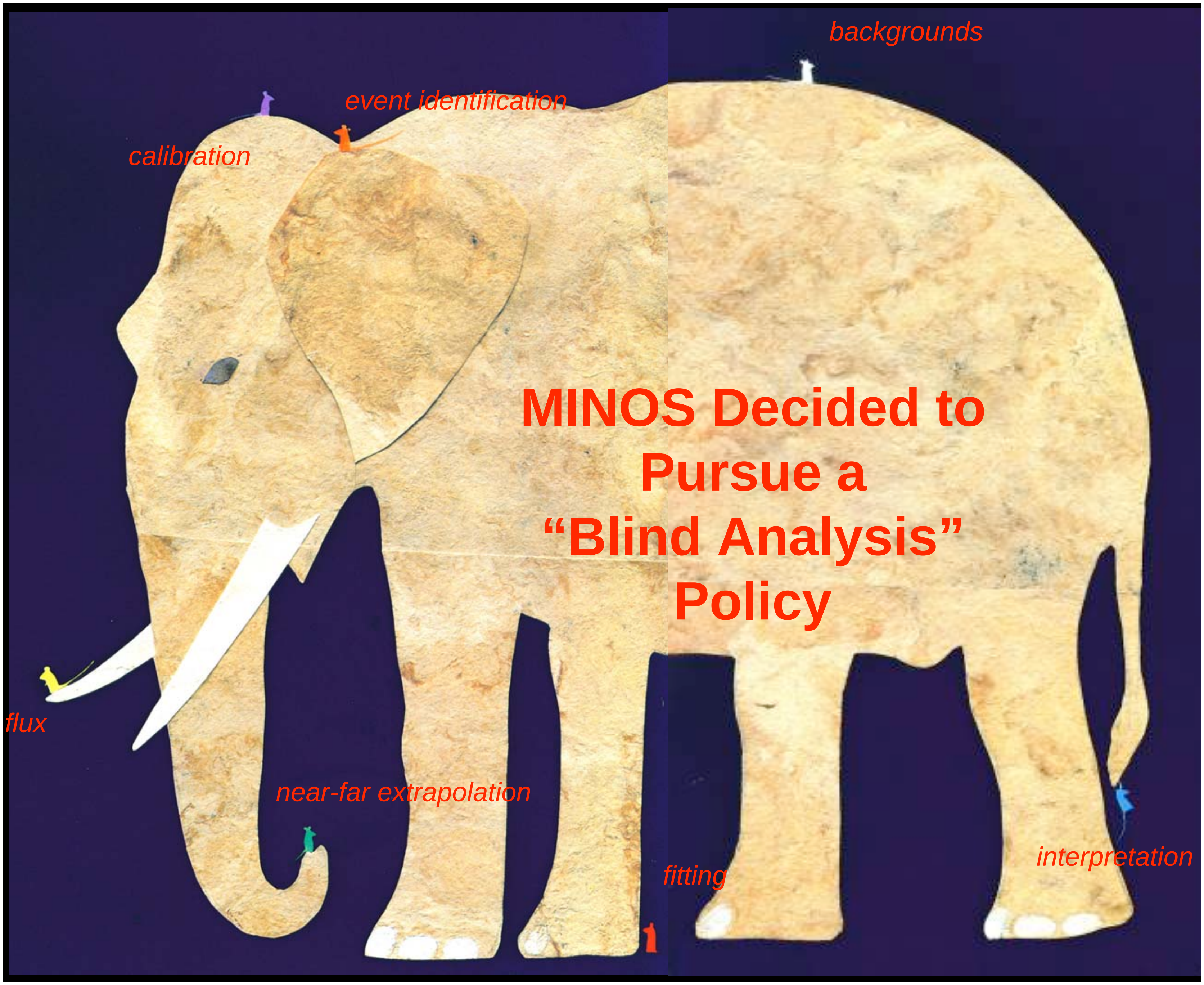
$$\Re_{FN} = \frac{\int_{48m}^{720m} \frac{1}{(Z_{FD}-z)^2} e^{-0.43 m_\pi z / E_\nu c\tau} dz}{\int_{48m}^{720m} \frac{1}{(Z_{ND}-z)^2} e^{-0.43 m_\pi z / E_\nu c\tau} dz}$$

where $E_\nu \approx 0.43\, E_\pi$.

- Better than this need a MC to evaluate $\Re_{FN}$.
  - ❖ Angular correlations in decay
  - ❖ Pi's that interact before decaying

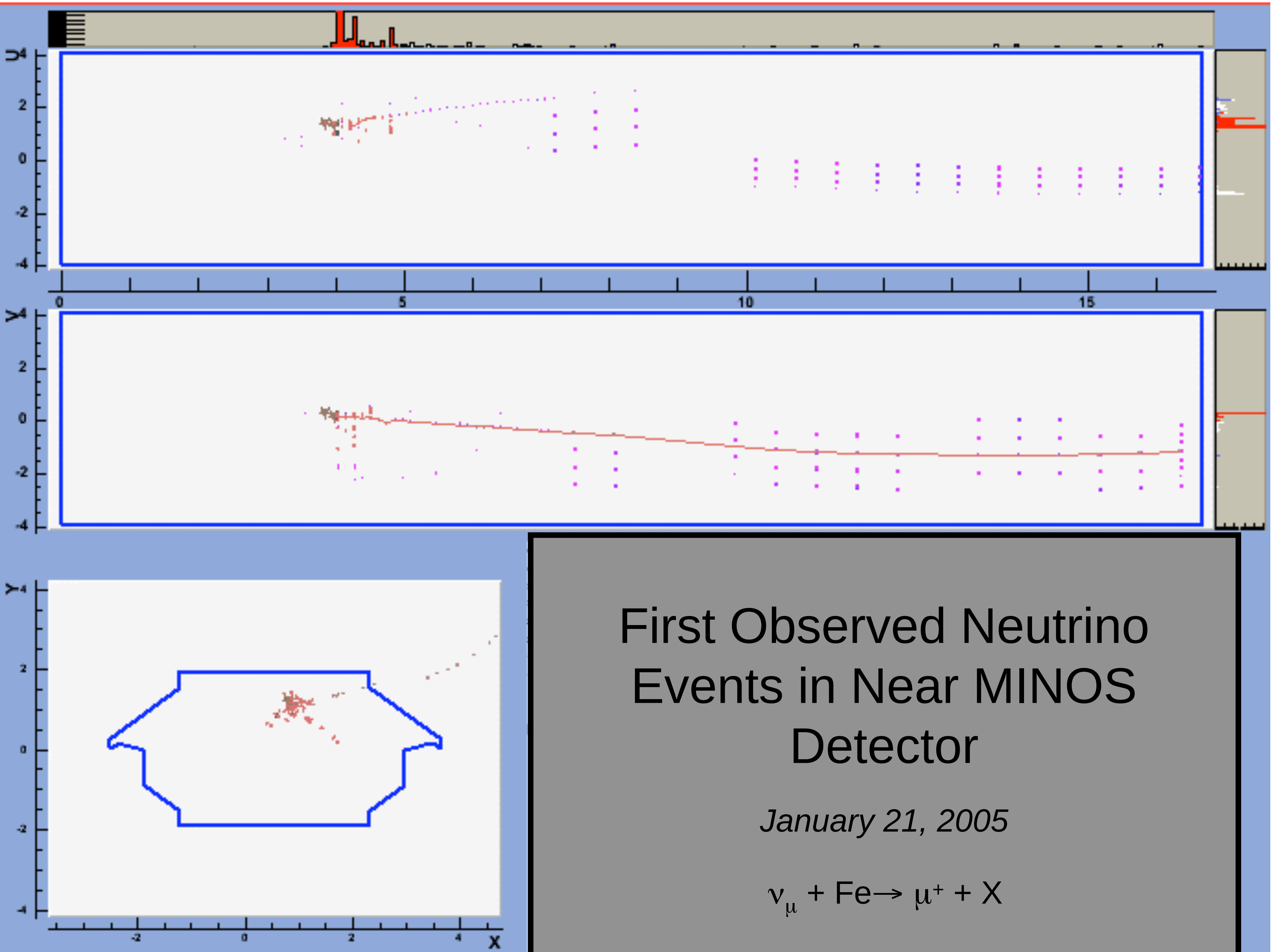


# MINOS Decided to Pursue a "Blind Analysis" Policy



# Step 1:  Look at ND Data

- Hope no gross disagreements with beam MC
- See if neutrino identification is OK



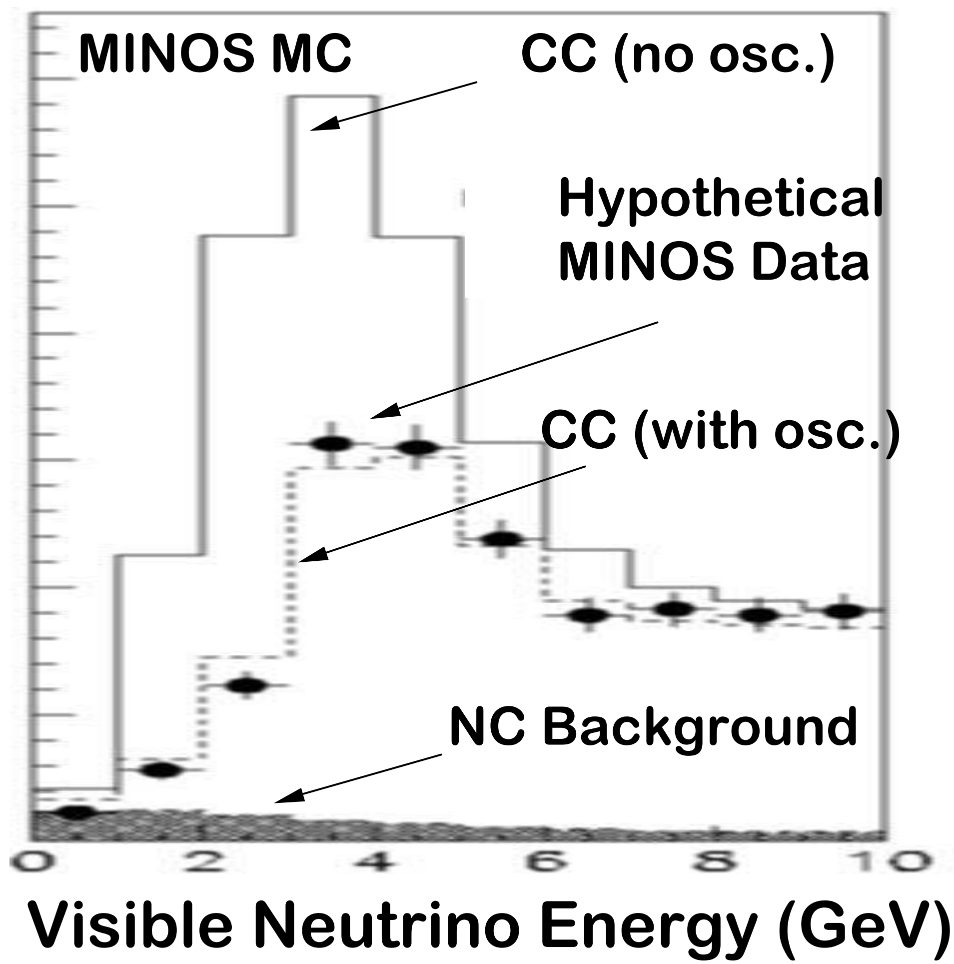

# First Observed Neutrino Events in Near MINOS Detector

*January 21, 2005*

$\nu_\mu + Fe \rightarrow \mu^+ + X$

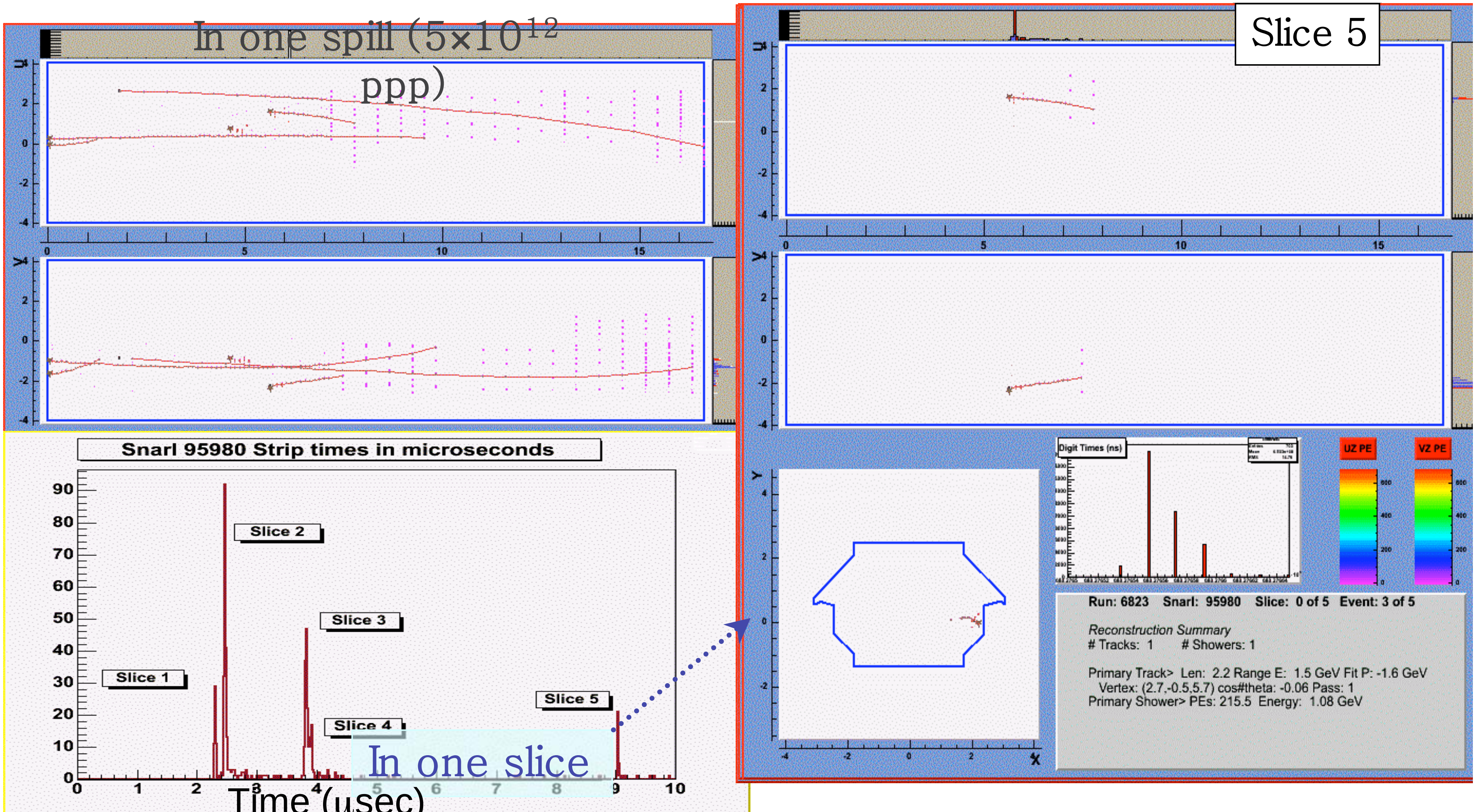
# Neutral Current $\nu_\mu$ Backgrounds

- Analysis requires an energy spectrum measurement.
- In $\nu_\mu$+Fe→$\mu^+$ + $X$ interaction, reconstruct $E_\nu = p_\mu + E_X$,
- Can't see full neutrino energy in NC $\nu_\mu$+Fe→$\nu_\mu$ + $X$ interactions.

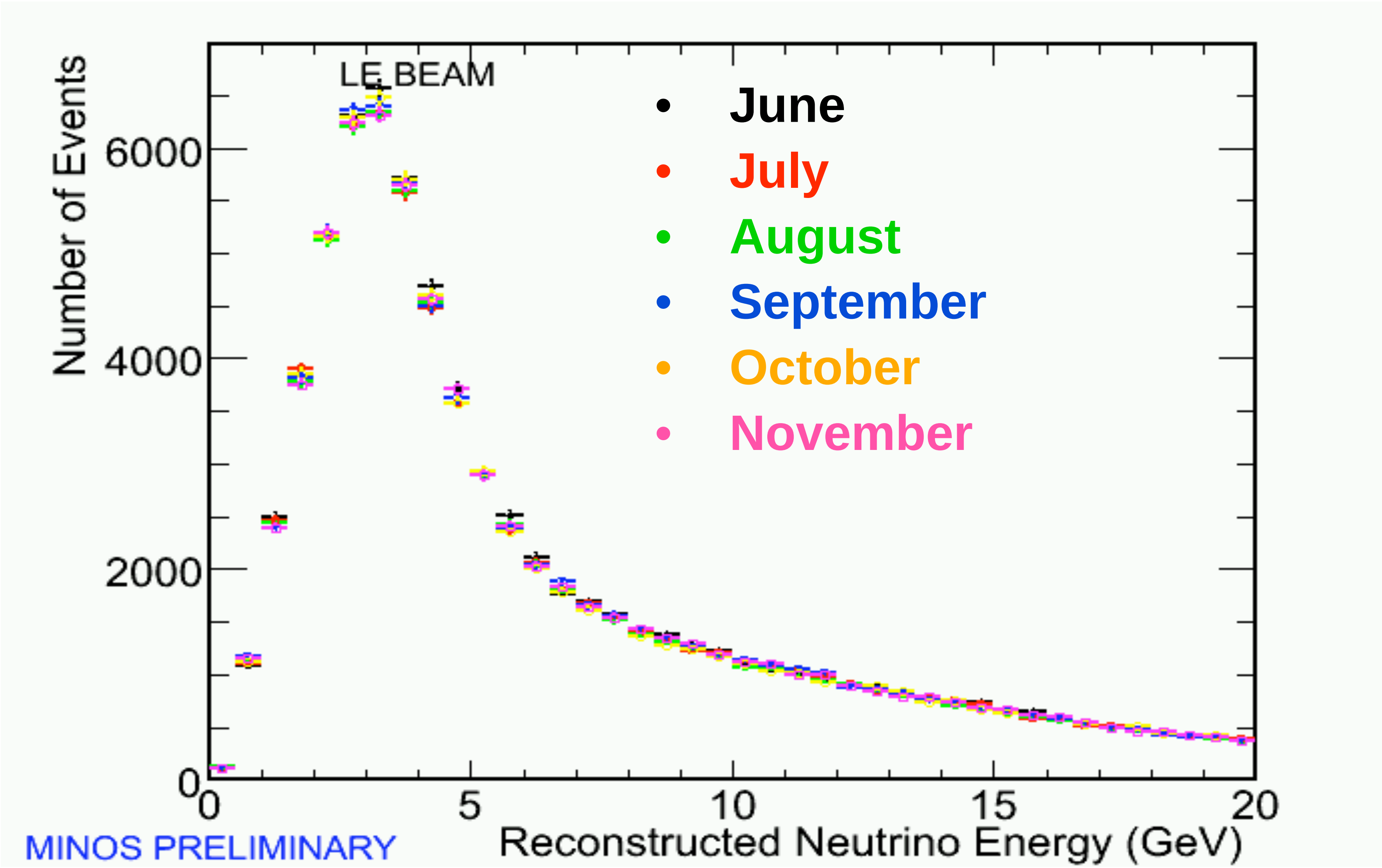


# Coping with High Intensity

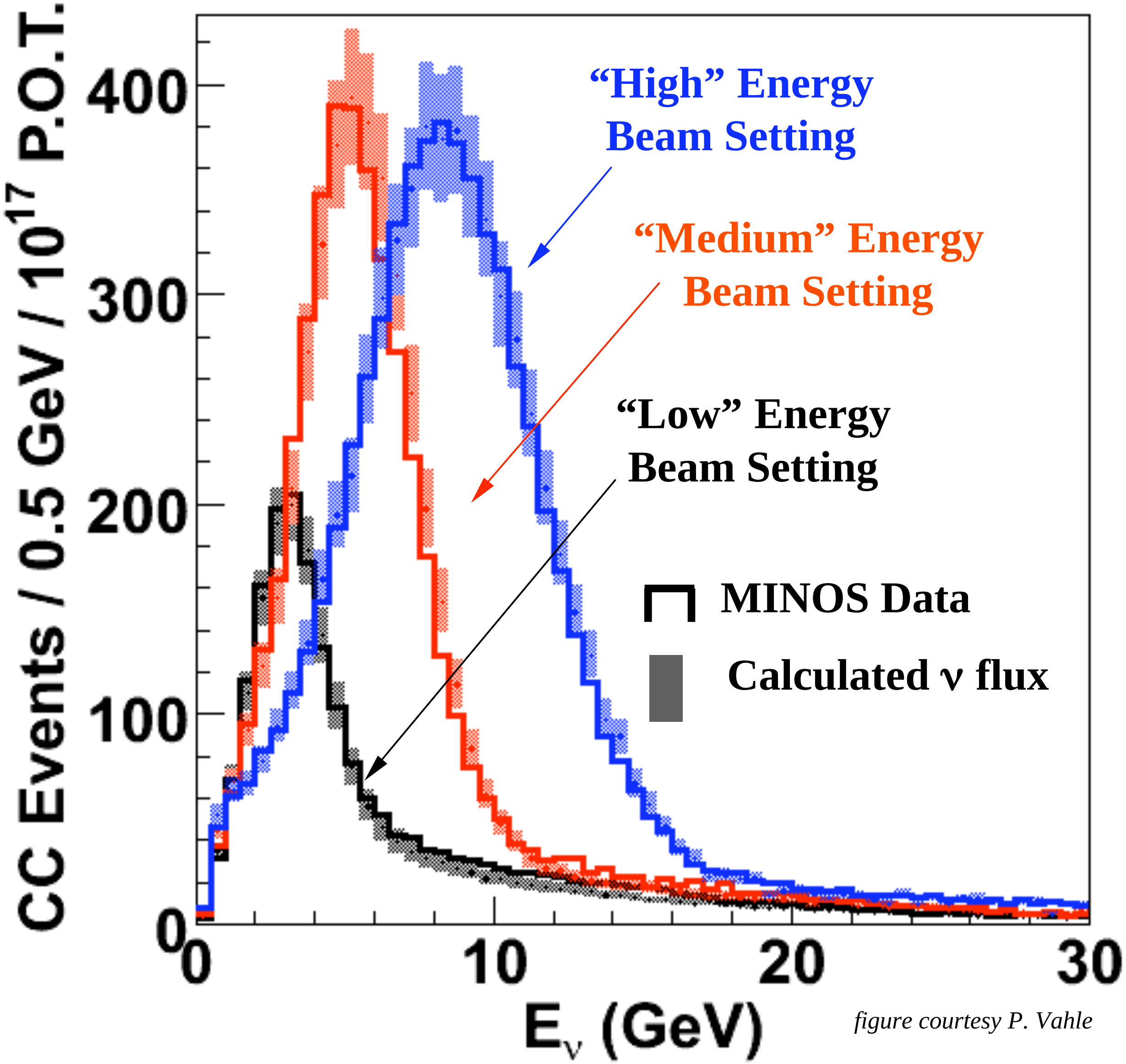
- 10-20 events/spill in the ND (*cf* $10^{-4}$/spill in the FD!)



# Beam is Stable



# ND Compared to Beam MC




- These plots show the beam spectrum as “dead reckoned” by Fluka2005 + our tracking MC through the beam line.
- Errors bars from the beam systematics (dominated by $\pi/K$ production in the target).
- Some real apparent contradictions? MC is low in the LE beam, but high in the ME beam.

# ND Spectra After Tuning

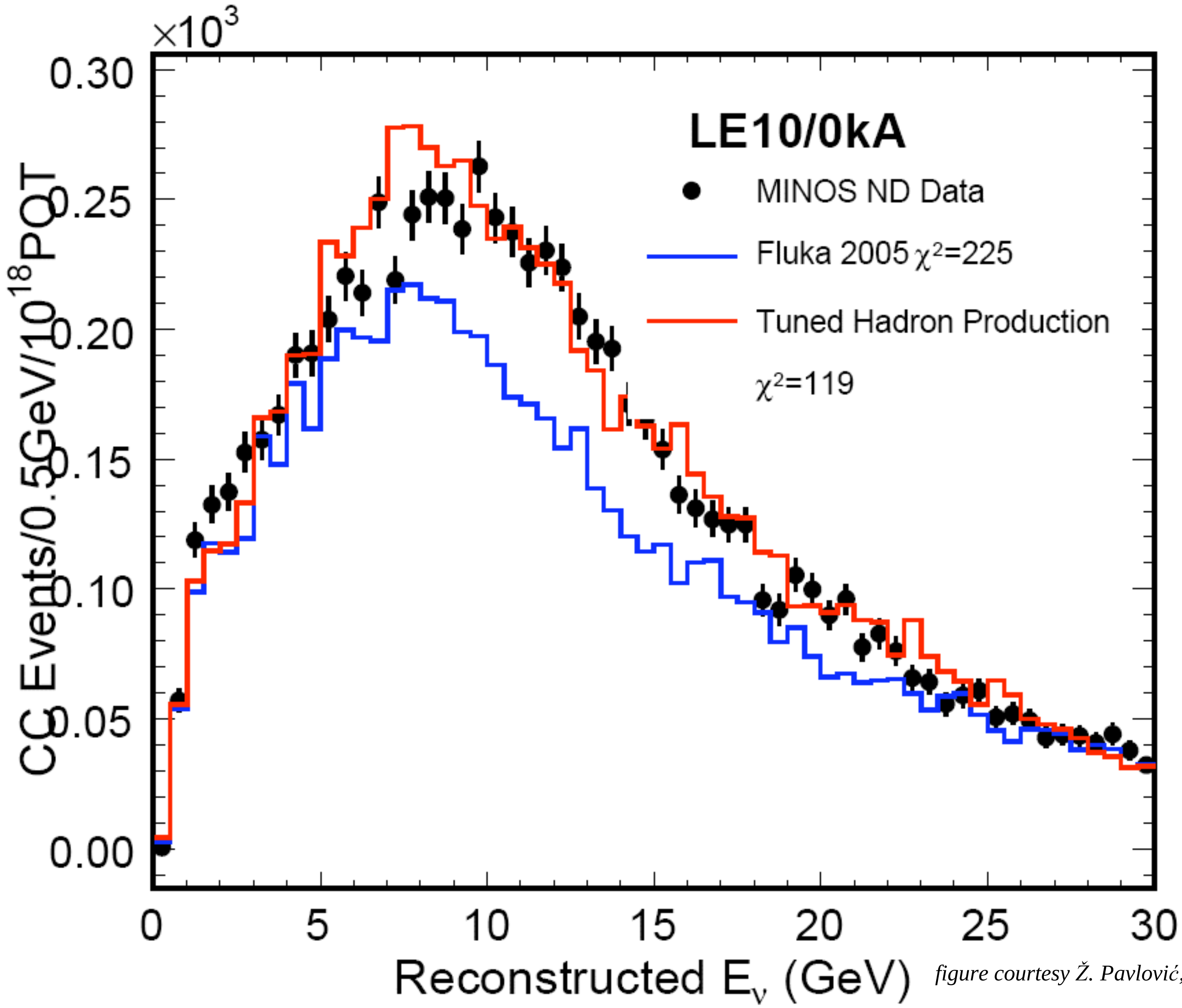



*figure courtesy Ž. Pavlović, P. Vahle*

# Step 2: Decide How to Extrapolate ND → FD

- FD Spectrum = (F/N ratio) × ND Spectrum

$$N^{i}_{E_\nu,FD} = \Re^{i}_{FN} \times N^{i}_{E_\nu,ND}$$

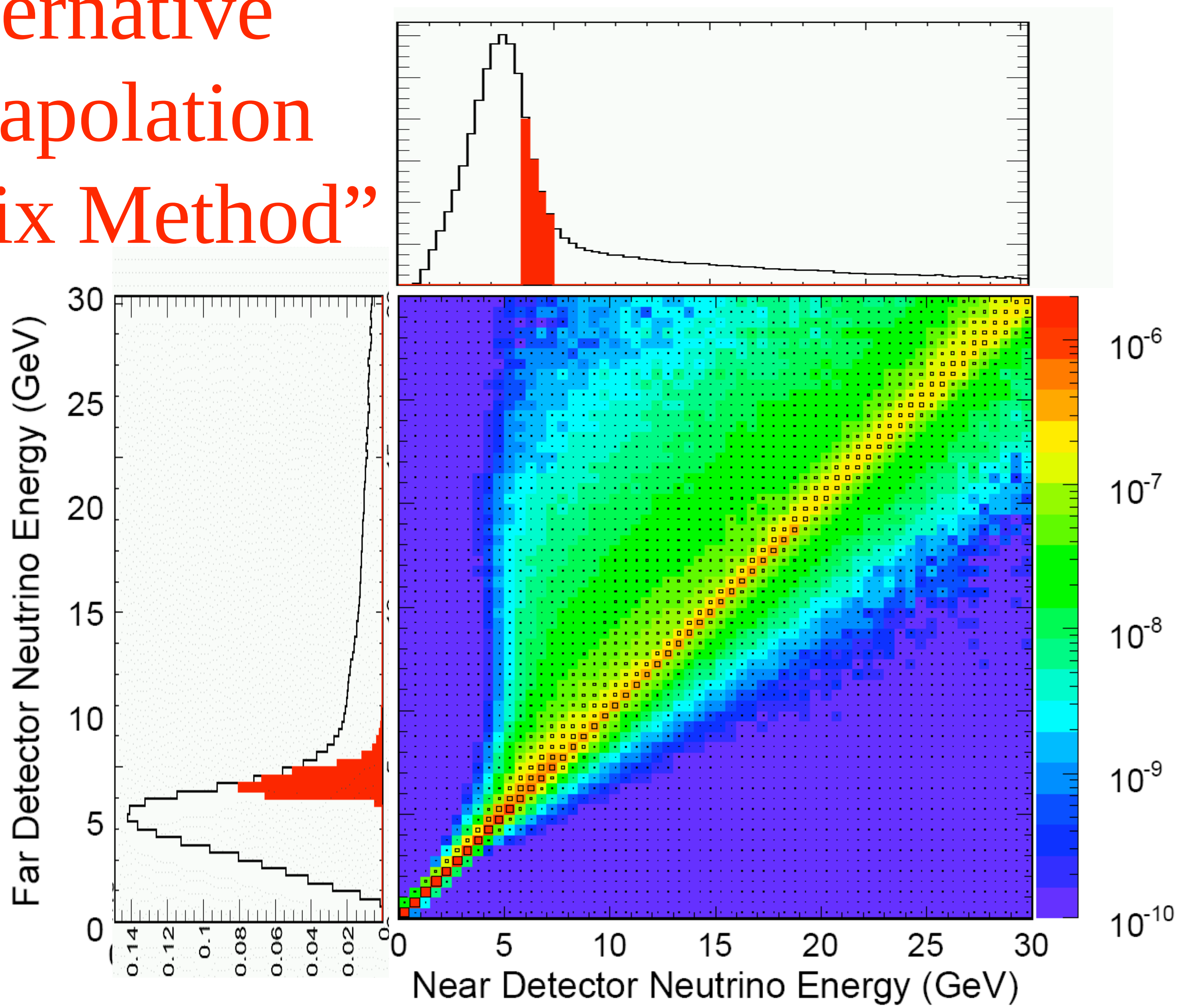
$N_{E_\nu}$ = Number of events at given energy of neutrino in ND or FD

$i$ = particular energy bin

- Tests on “mock data” to ensure no biases, understand systematics

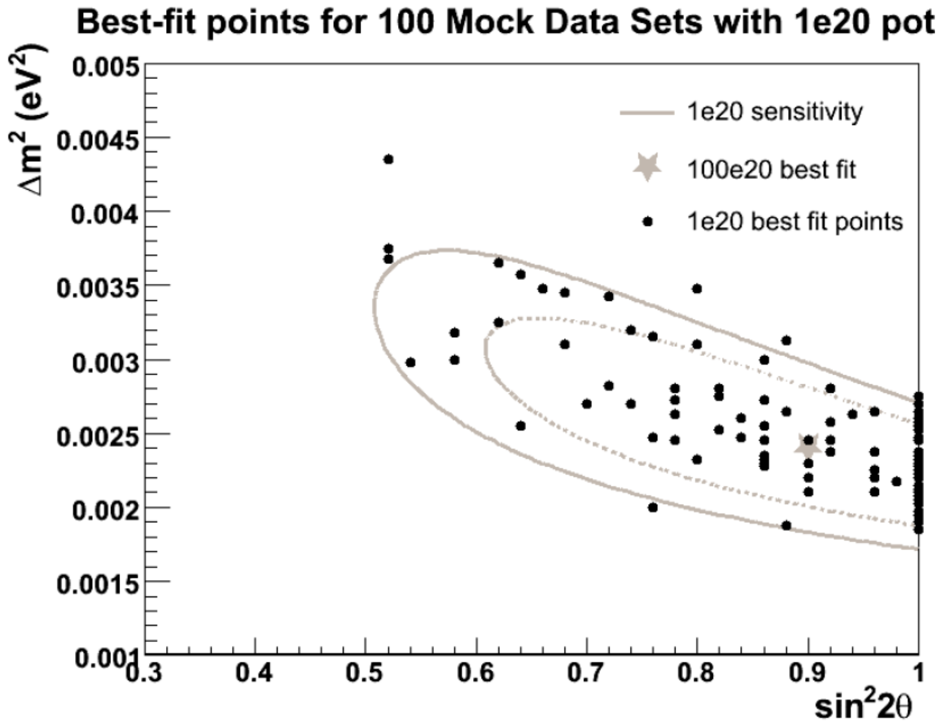
# Alternative Extrapolation "Matrix Method"

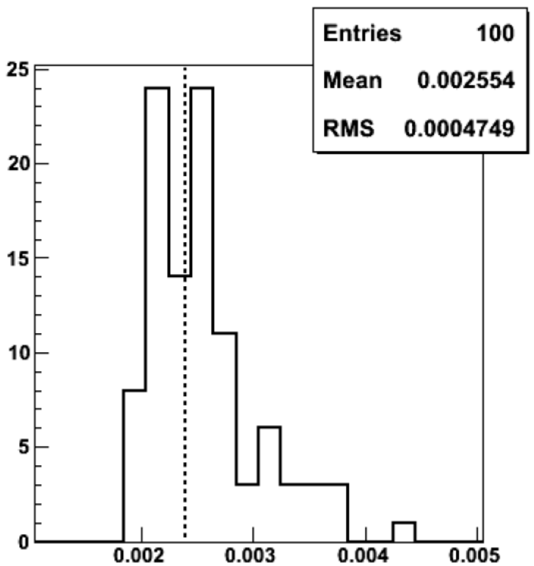
*A. Para & M. Szleper, arXiv:hep-ex/0110032*



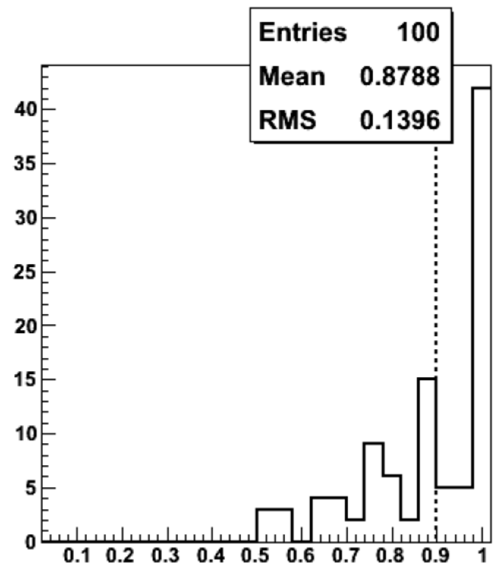
# Checks of the Fitting

- MC "Mock data sets"
  - ❖ 100 experiments
  - ❖ each $10^{20}$ POT exposure
- Studies of
  - ❖ biases
  - ❖ statistical precision



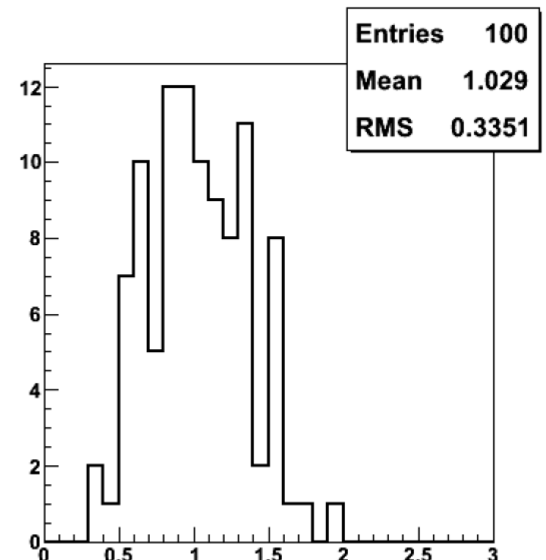




Best Fit $\Delta m^2$ ($eV^2$)




Best Fit $\sin^2(2\theta)$

*figures courtesy D. Petyt*




Best Fit $\chi^2$

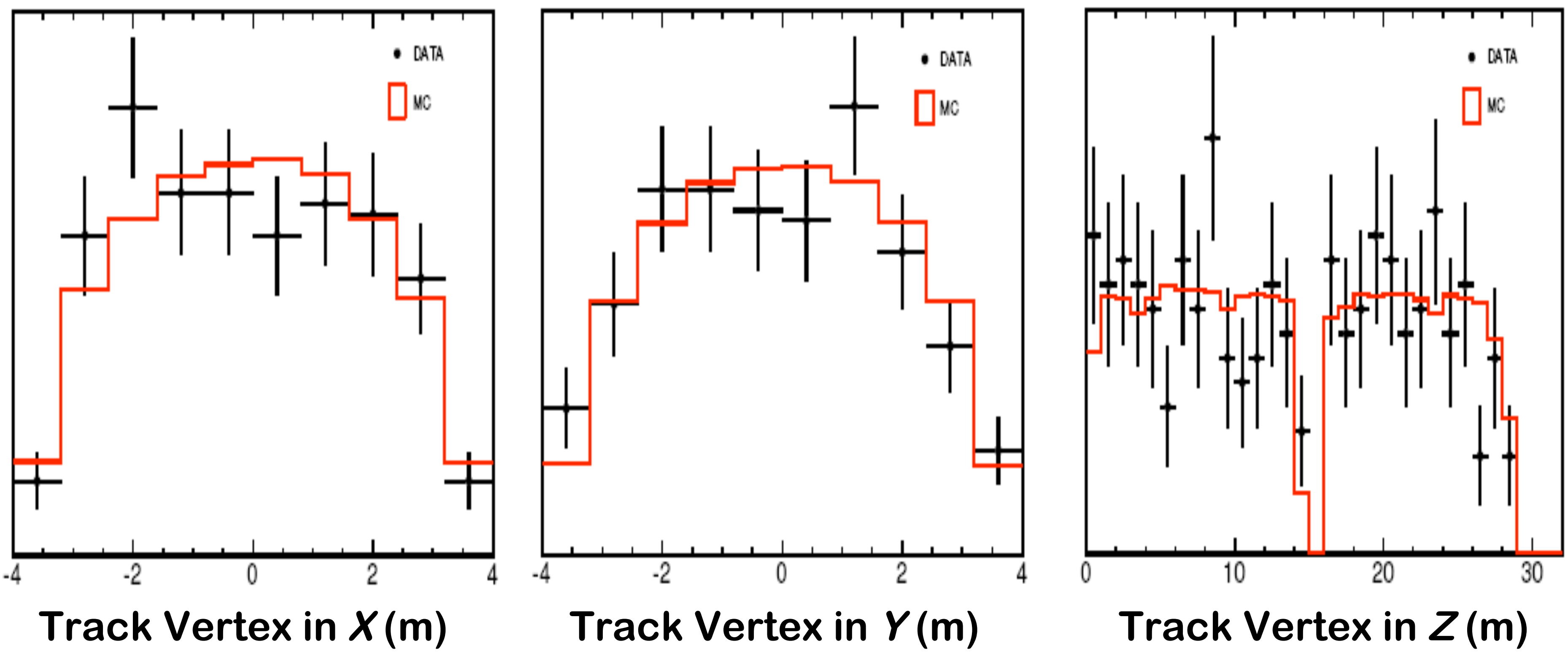
# Systematic Uncertainties

| Uncertainty | Shift in $\Delta m^2$ ($10^{-3}$ eV$^2$) | Shift in $\sin^2(2\theta)$ |
|---|---|---|
| Near/Far norm. (livetime, fid vol) ±4% | 0.065 | $<0.005$ |
| Absolute hadronic energy scale ±10% | 0.075 | $<0.005$ |
| NC contamination ±50% | 0.010 | 0.008 |
| All other systematic uncertainties | 0.041 | $<0.005$ |
| Total systematic (summed in quadrature) | 0.11 | 0.008 |
| Statistical error (data) | 0.17 | 0.080 |

# Step 3: Peek *at the* Far Detector Data ( “Box is still closed”)

- In 2006 analysis, question was “Do $\nu$’s disappear?”
  - ❖unknown “blinding function” to hide most of the data
  - ❖Collaborators given free access to “open” data set
  - ❖Only got to see full data set once “box was open”
- In 2007 analysis, want unbiased $\Delta m^2$, $\sin^2(2\theta)$ measurement
  - ❖Access to all the data, but complete blinding of all rates
  - ❖Did not look at energy spectrum, so couldn’t bias $\Delta m^2$

# Checks on the FD Data




- These are all CC neutrino events
- Rates blinded – we don't know the normalization
- MC has been scaled to agree with data

# Calibration

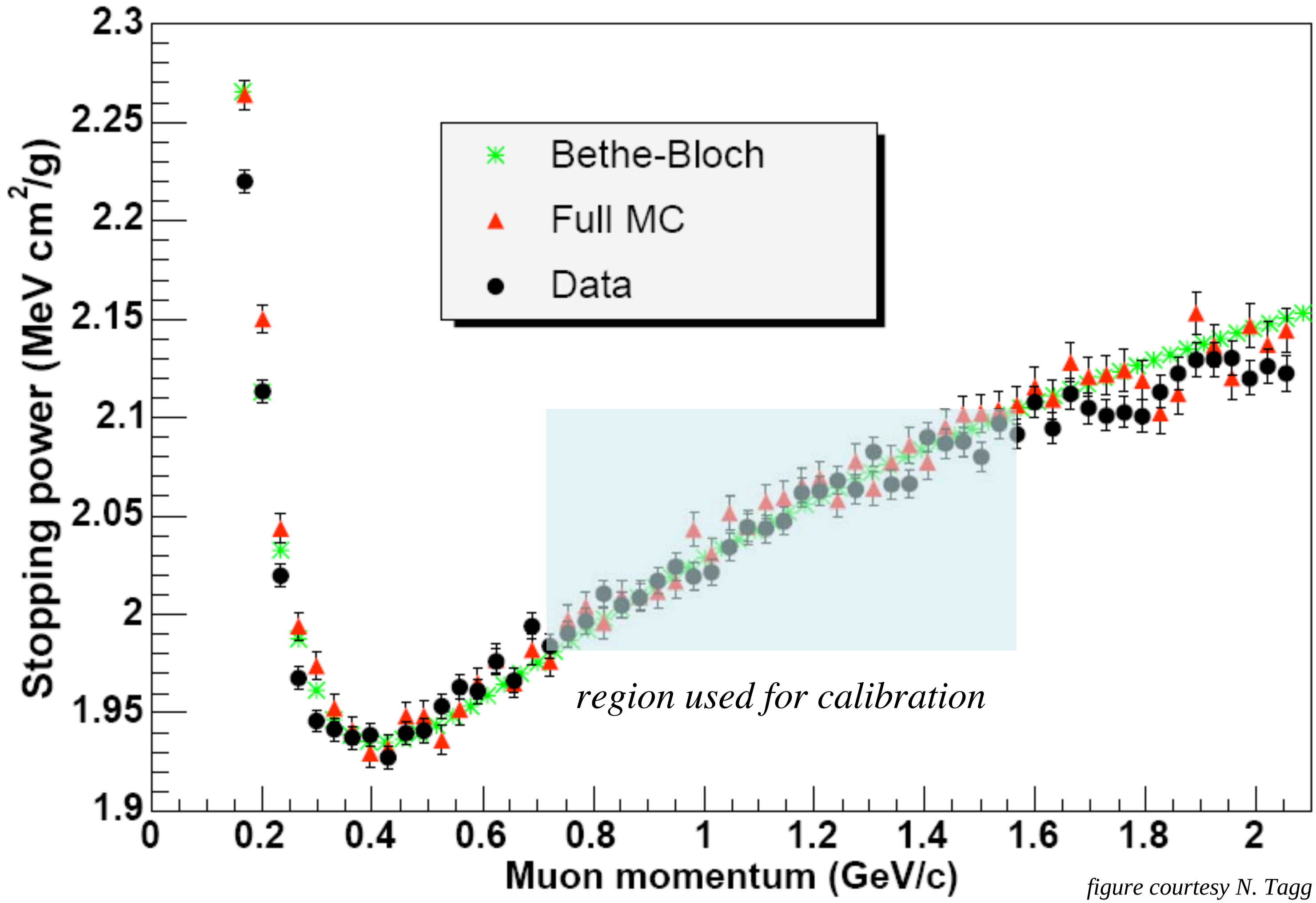
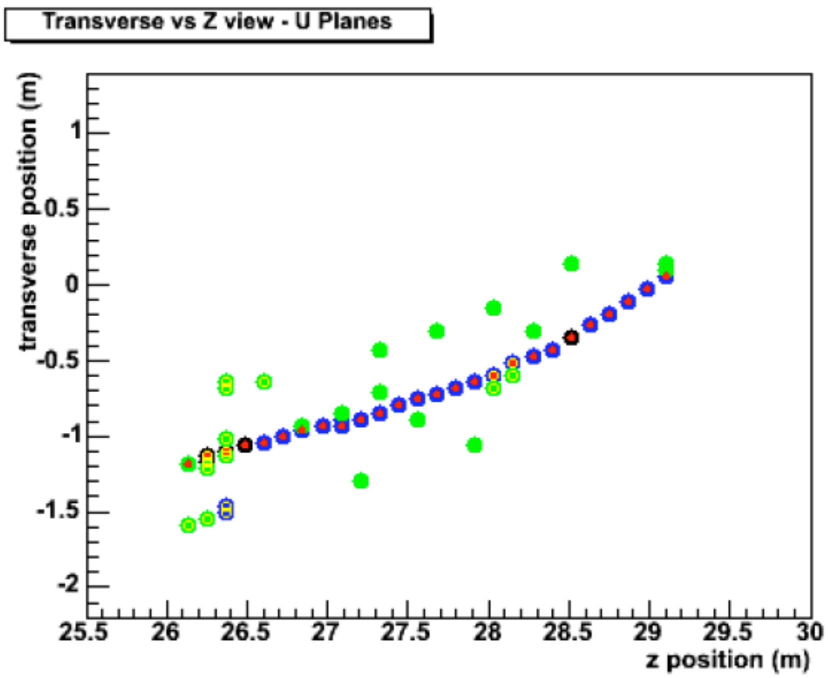
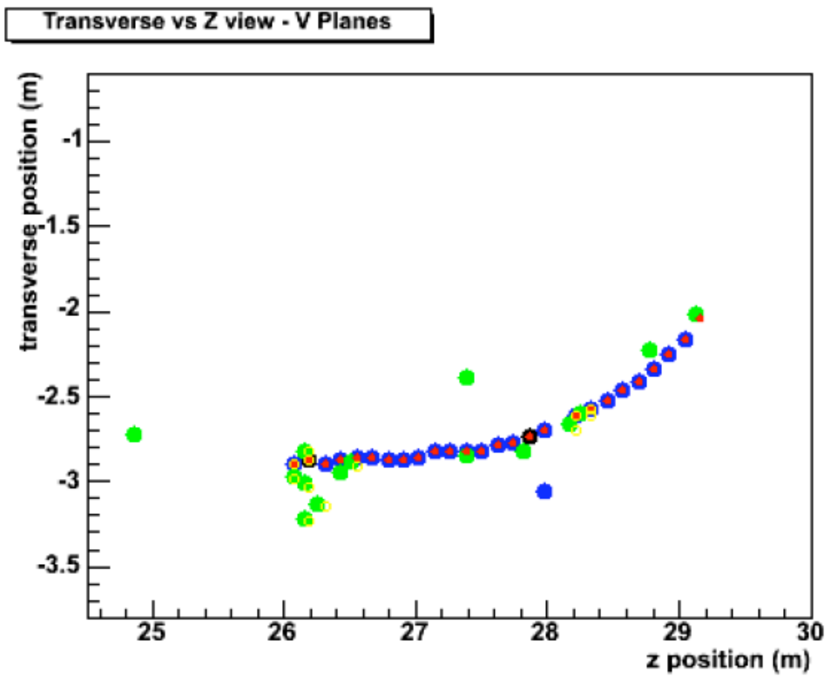



*figure courtesy N. Tagg*

- Calibratrions based on stopping cosmic ray μ's.
- Study ionization for 20-plane window upstream of stopping μ location.

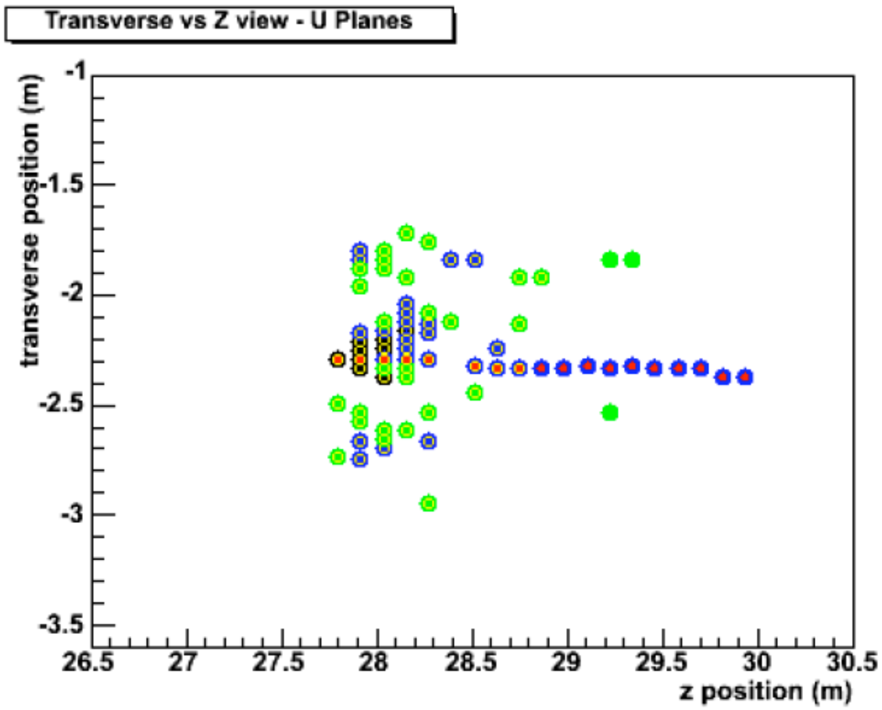
# Example Events (I)

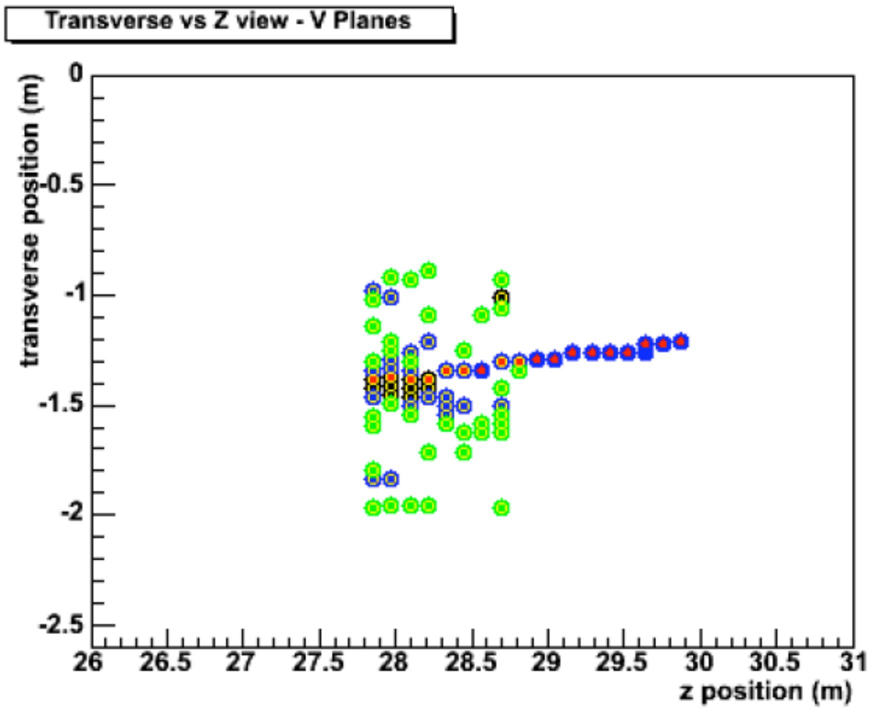



- These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
- $E_\nu$ = 3.0 GeV
- $y = E_{had}/E_\nu$=0.3

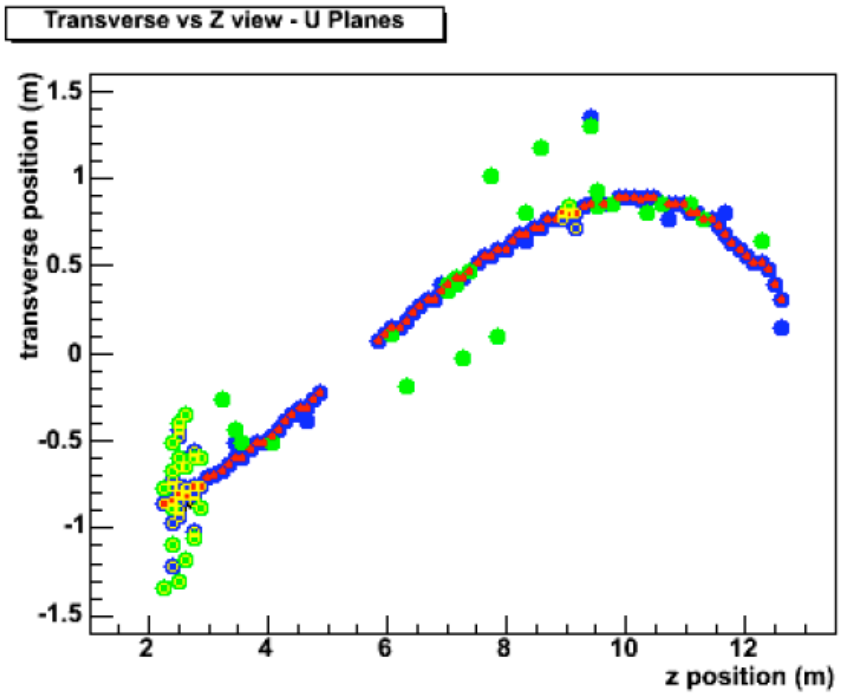
# Example Events (II)

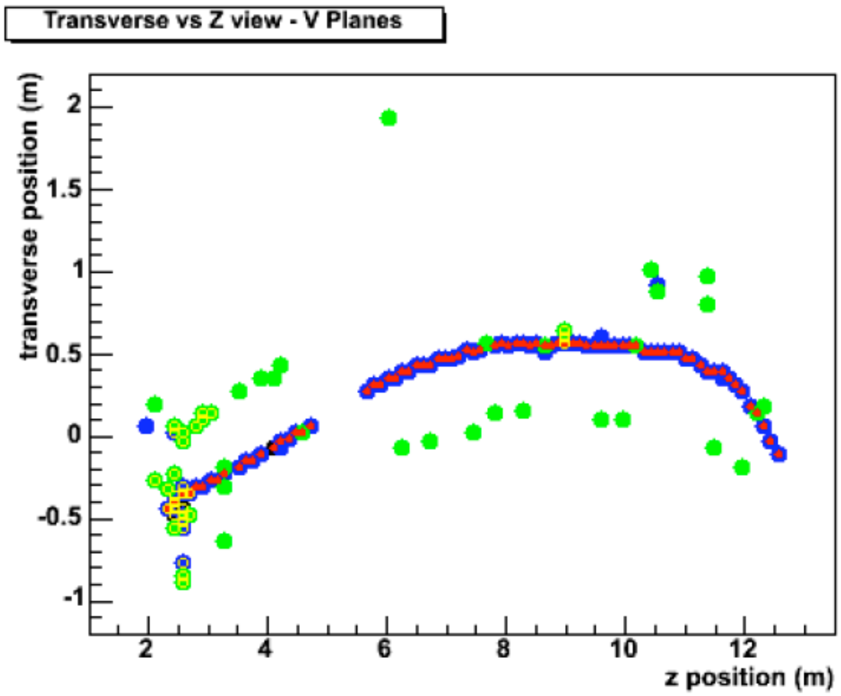



- These events taken from the "open" data sample in the FD (which we are permitted to look at in detail).
- $E_\nu$ = 24.4 GeV
- $y = E_{had}/E_\nu$=0.4

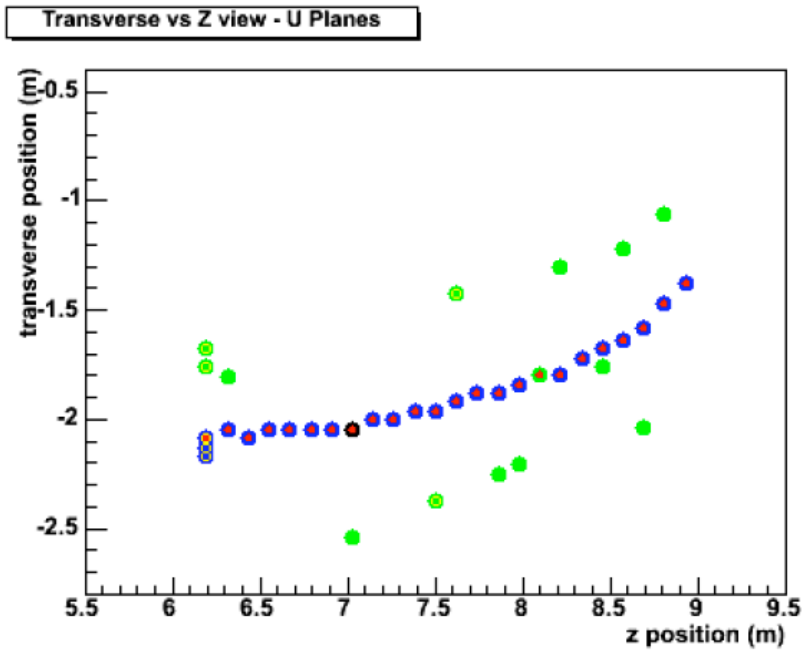
# Example Events (III)

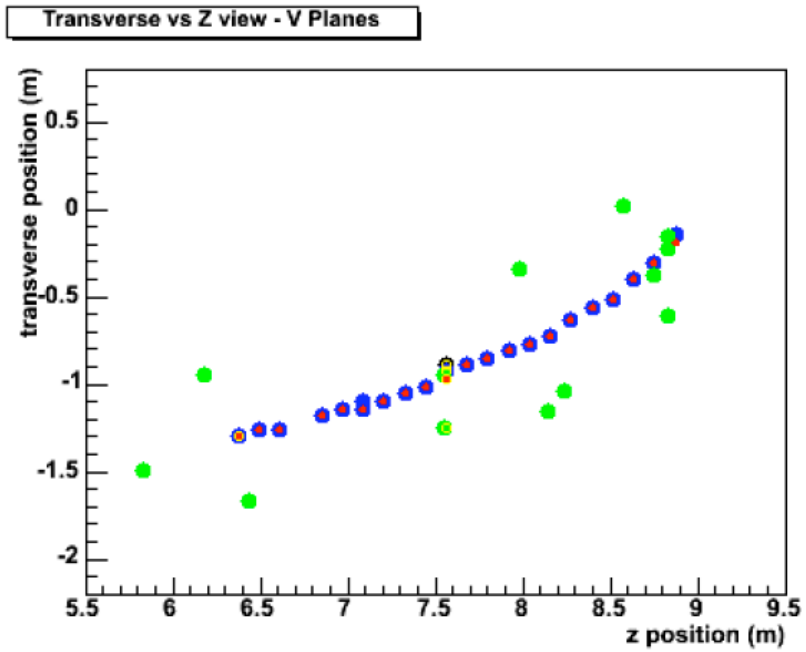



- These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
- $E_\nu$ = 10.0 GeV
- $y = E_{had}/E_\nu$=0.3

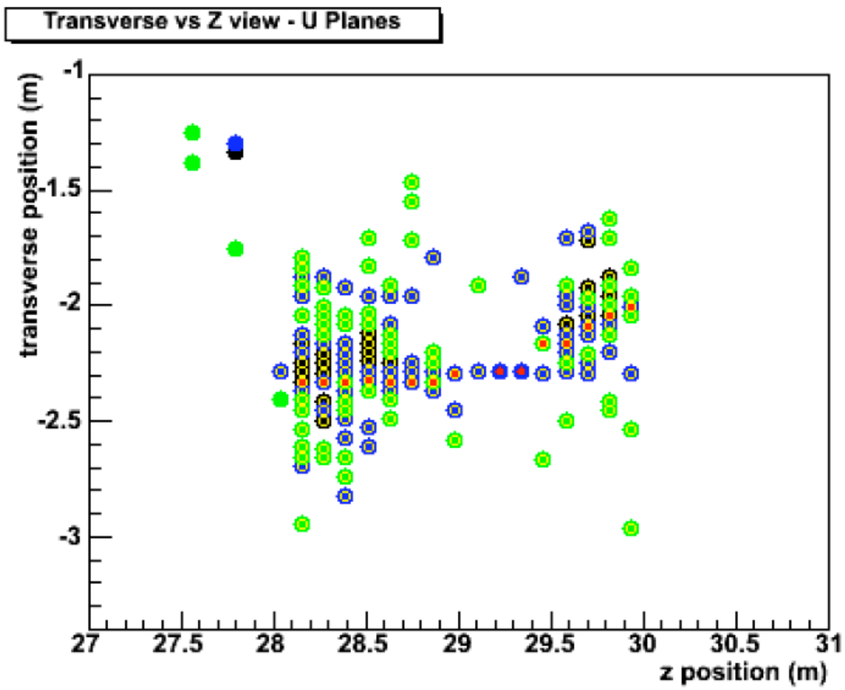
# Example Events (IV)

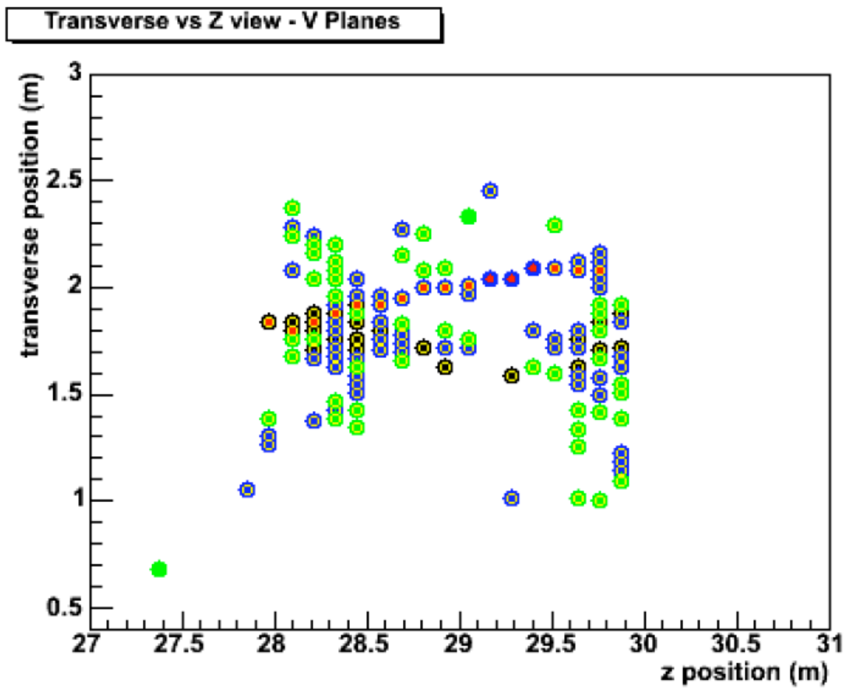



- These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
- $E_\nu$ = 2.1 GeV
- $y = E_{had}/E_\nu$=0.1 (‘quasi-elastic’?)

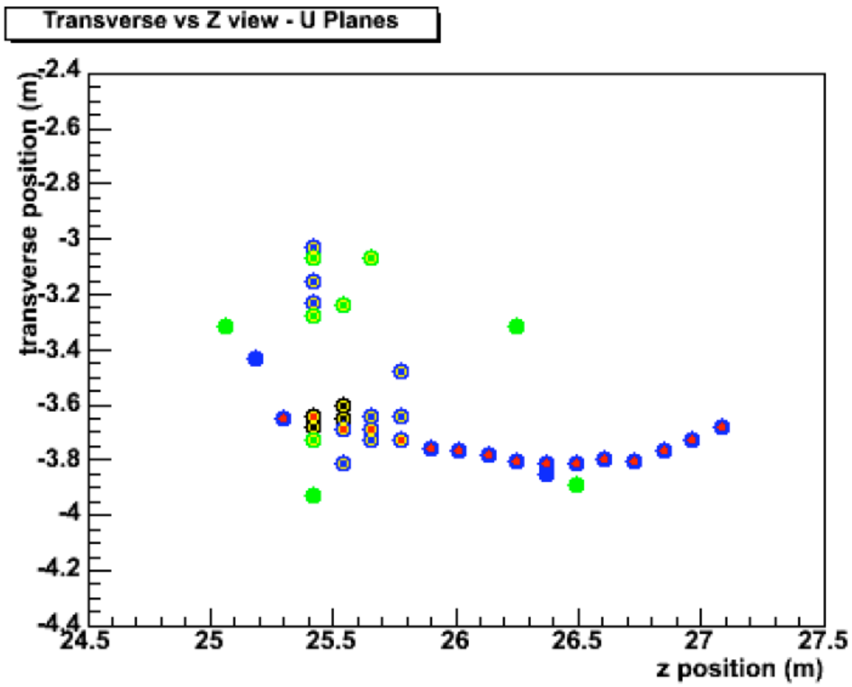
# Example Events (V)

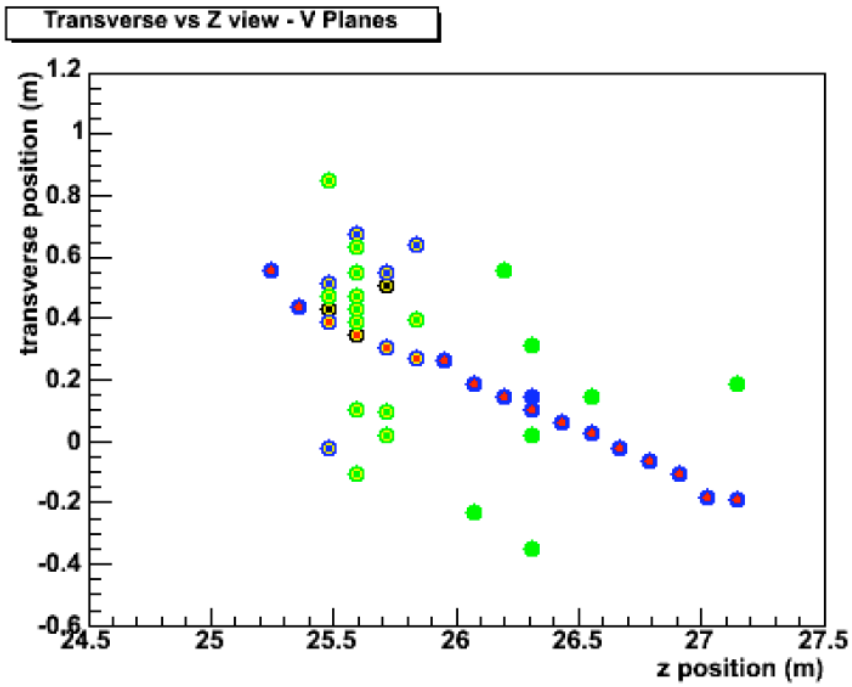



- These events taken from the "open" data sample in the FD (which we are permitted to look at in detail).
- $E_\nu$ = 18.7 GeV
- $y = E_{had}/E_\nu$=0.9

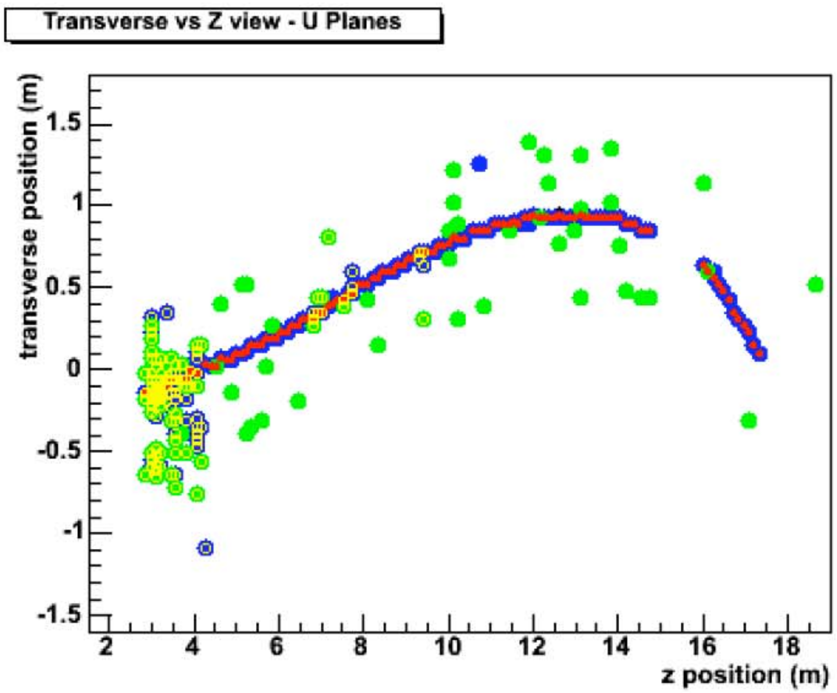
# Example Events (VI)

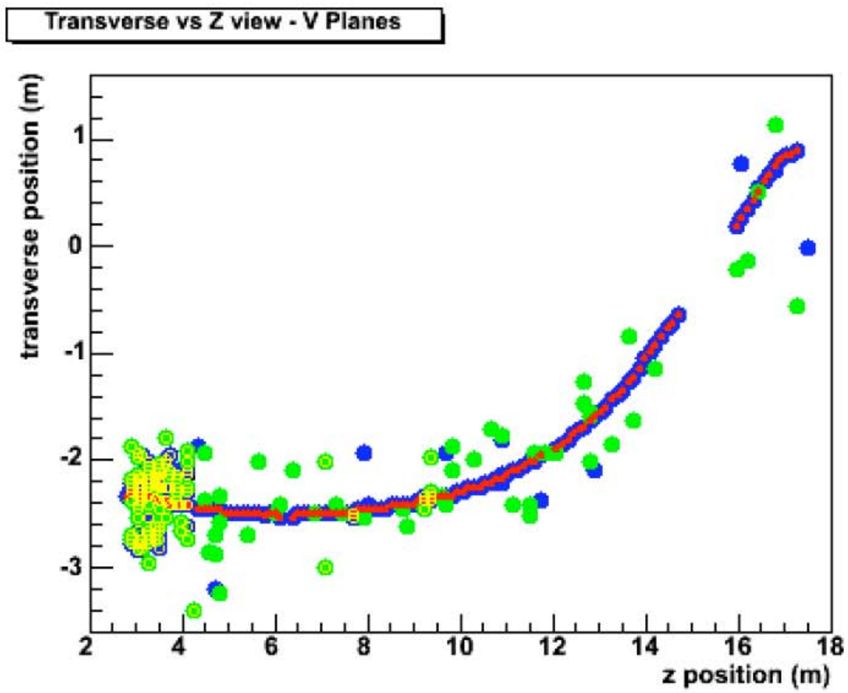



- These events taken from the "open" data sample in the FD (which we are permitted to look at in detail).
- $E_\nu$ = 3.3 GeV
- $y = E_{had}/E_\nu$=0.6

# Example Events (VII)



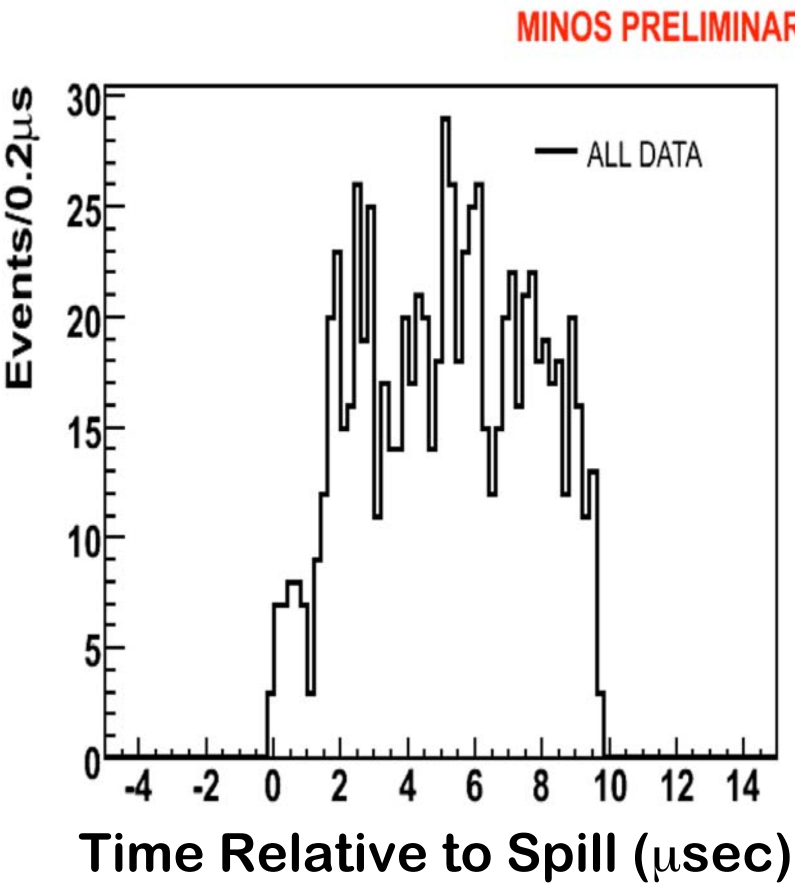



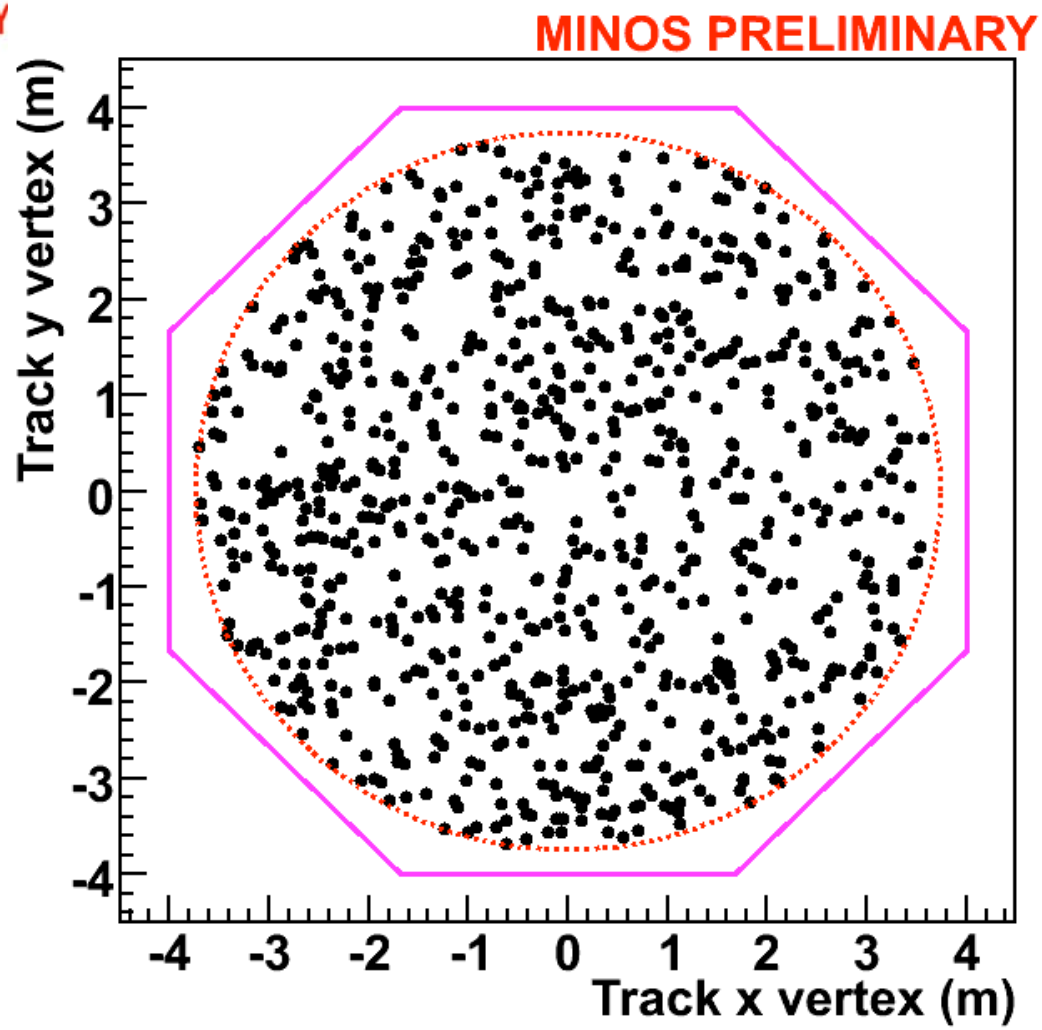

- These events taken from the "open" data sample in the FD (which we are permitted to look at in detail).
- $E_\nu$ = 25 GeV
- $y = E_{had}/E_\nu$=0.6

# Step 4:  Look at All Events

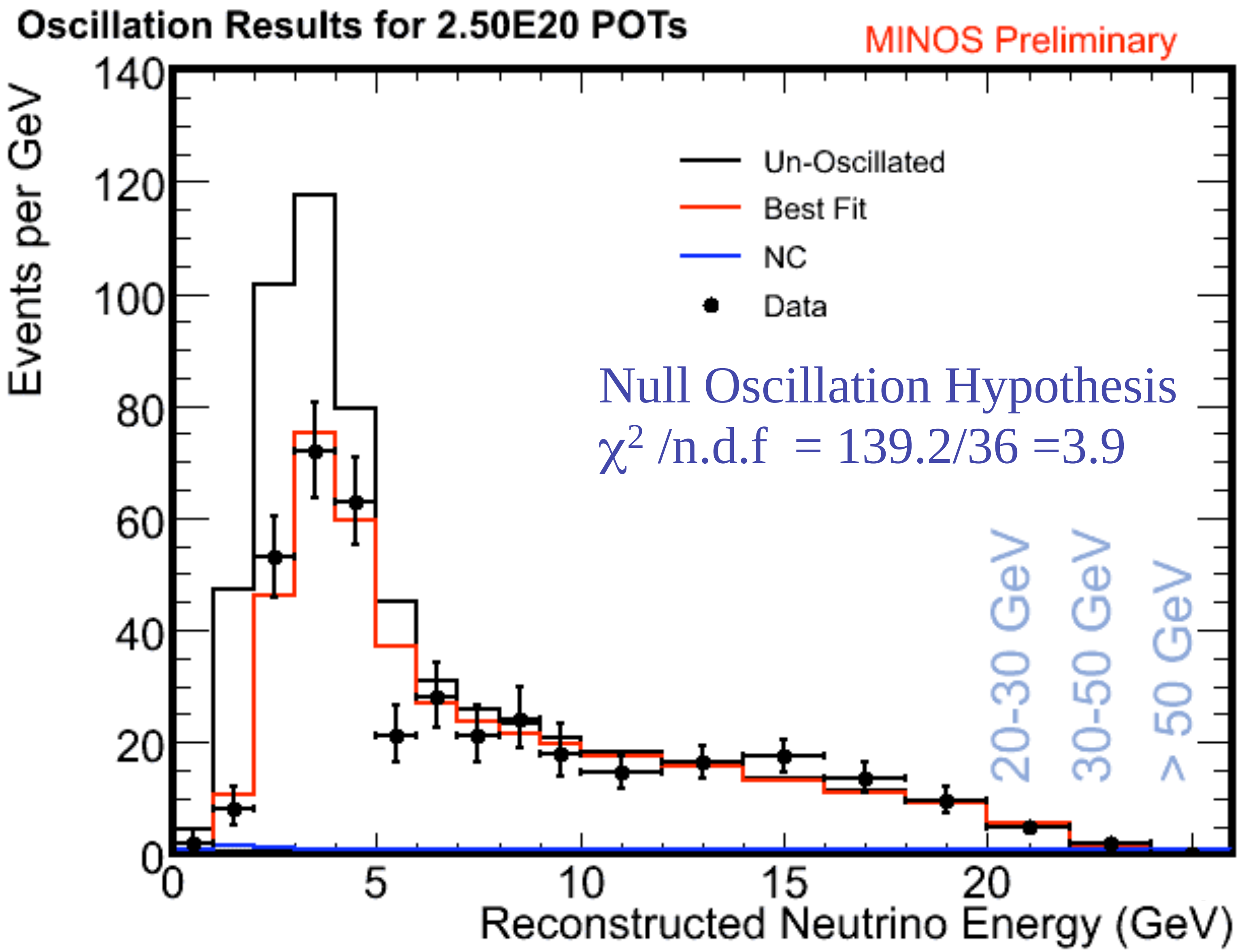
“Open the Box”

# FD Events are "In time" and Uniform

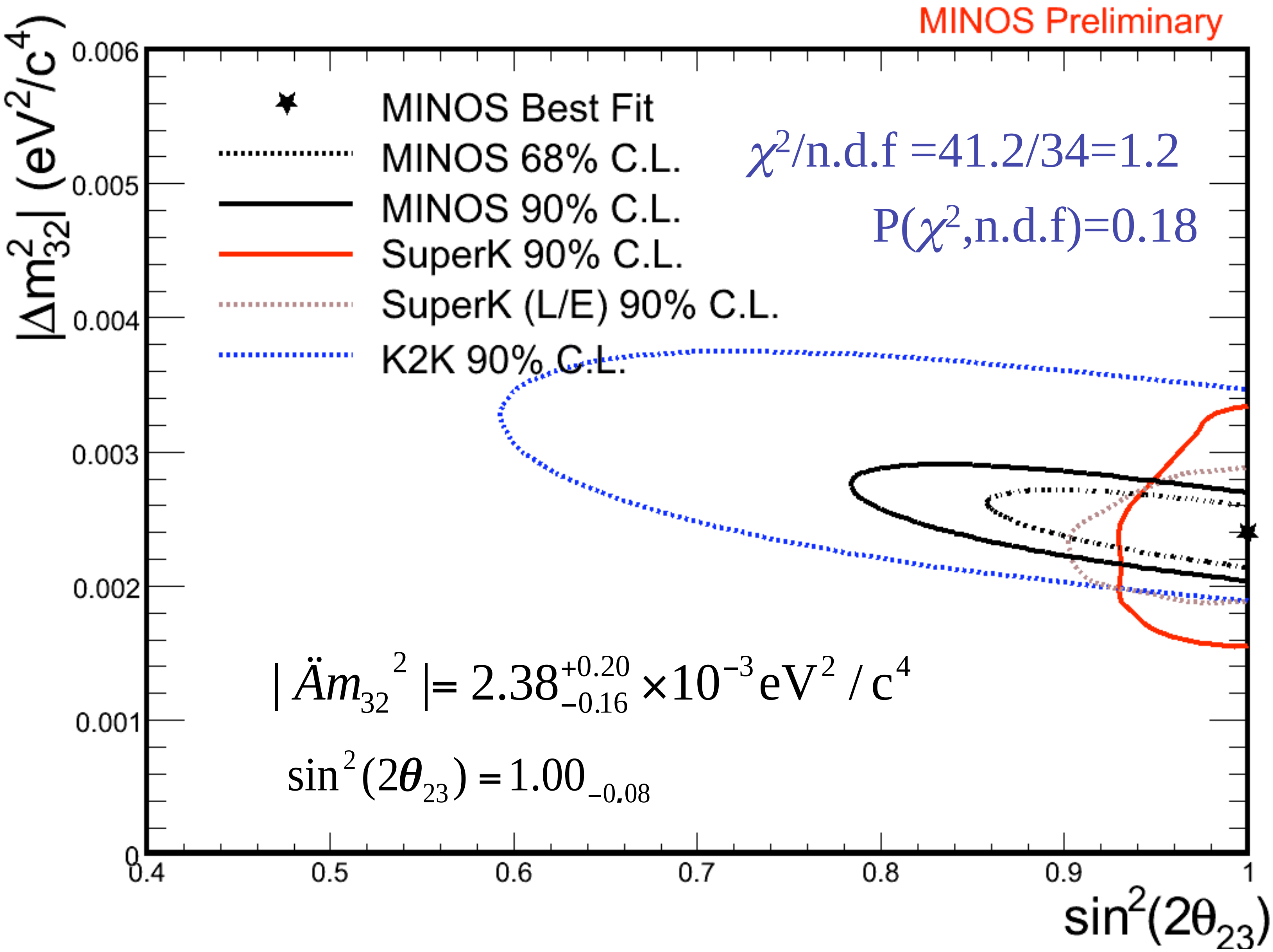


# Neutrino Energy Spectrum



# Oscillation Hypothesis Fit



# “Accident & Substance: Two possible explanations for the bulk of reality”

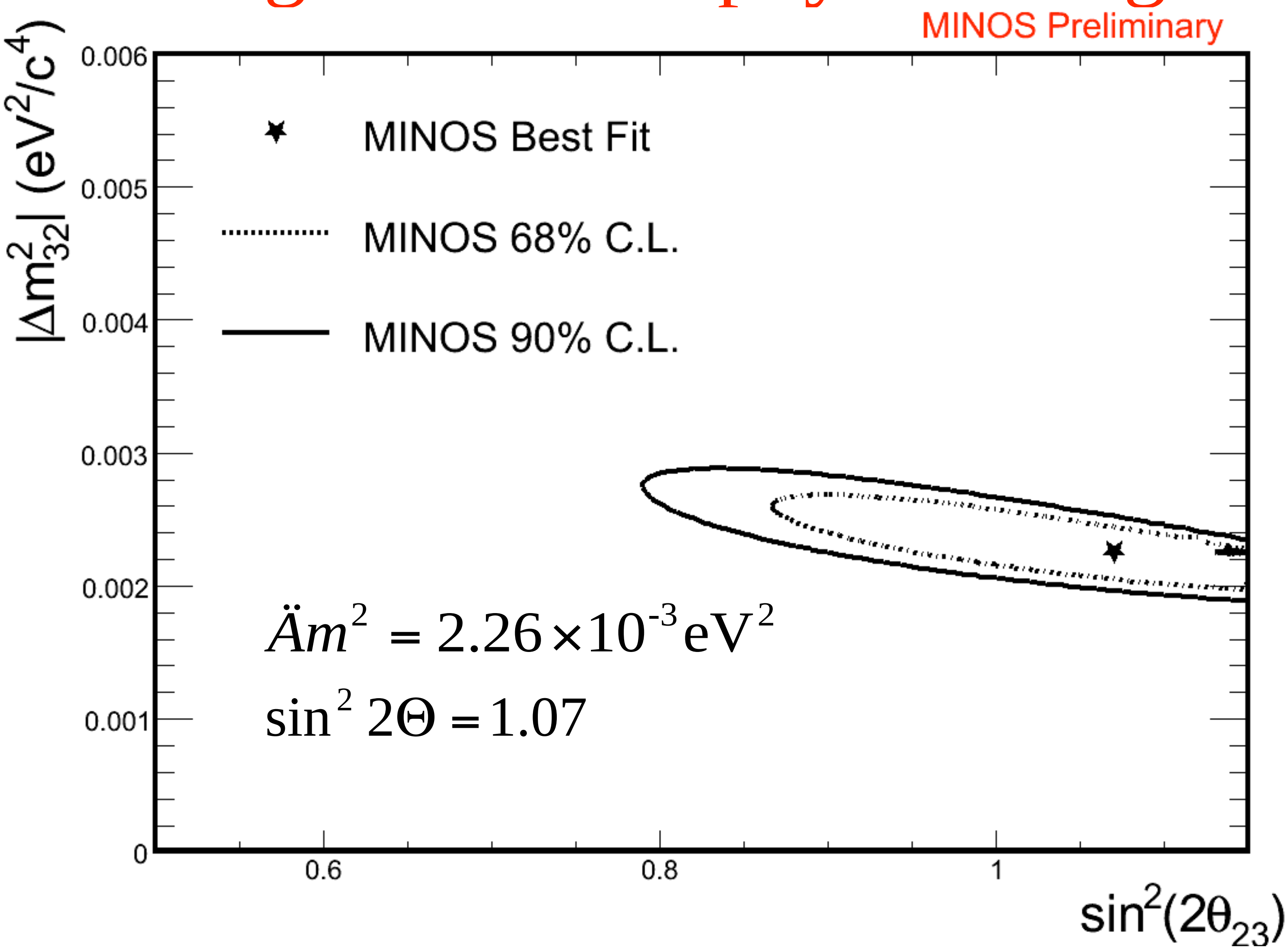
*April 6, 2006 Inside article:*


*“One possible explanation for dark matter is a group of subatomic particles called neutrinos. … Last week, researchers working on the MINOS experiment at Fermilab, near Chicago, confirmed these results. …”*

*“The researchers created a beam of muon neutrinos … The neutrinos then travelled 750km (450 miles) through the Earth to a detector in a former iron mine in Soudan, Minnesota.”*

*“By comparing how many muon neutrinos arrived there with the number generated, Fermilab's researchers were able to confirm that a significant number of muon neutrinos had disappeared—that is, they had changed flavour. Thus the neutrino does, indeed, have mass and a more accurate number can be put on it.”*

# Fitting into the Unphysical Region

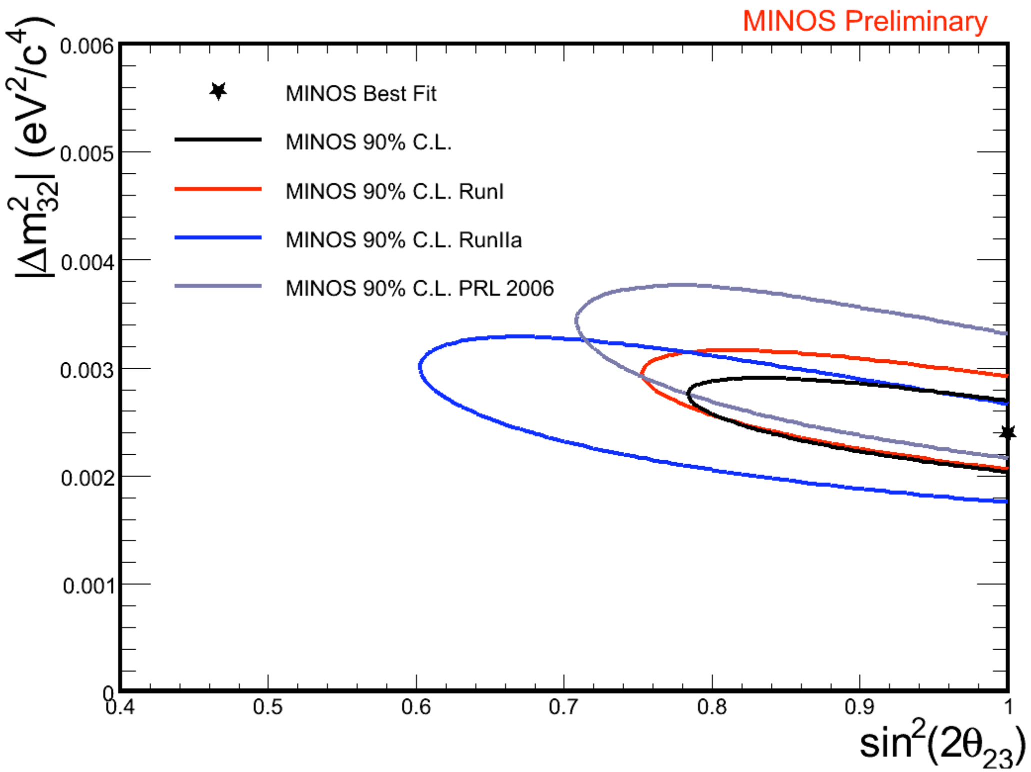


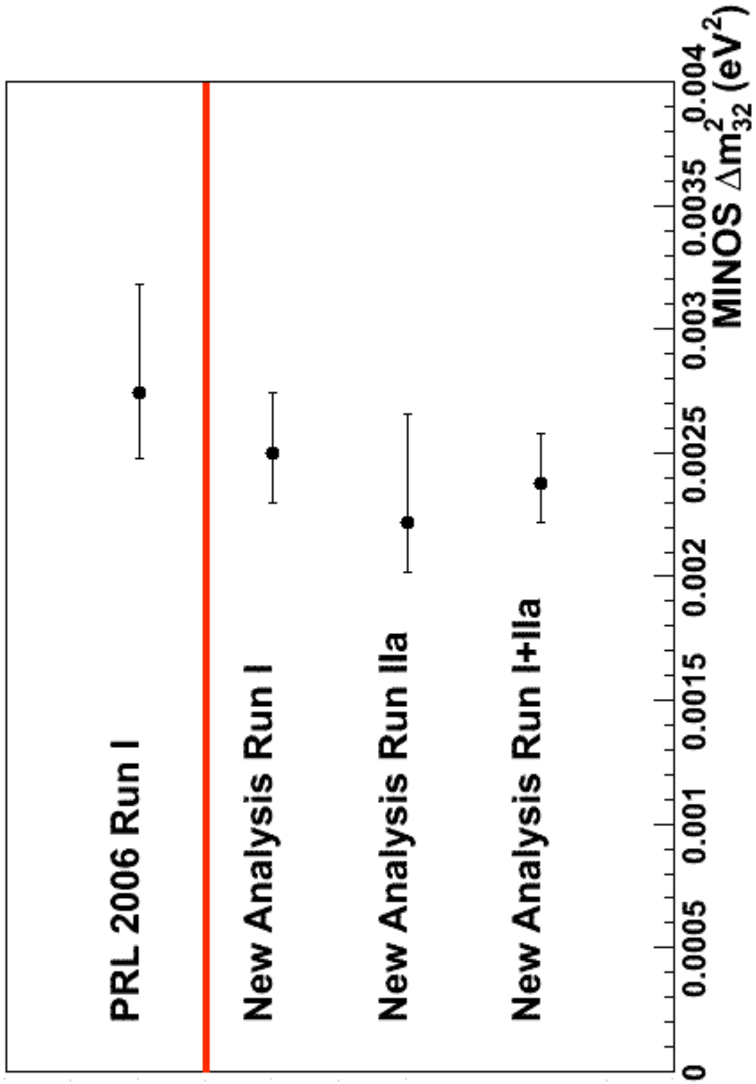

$$\Delta m^2 = 2.26 \times 10^{-3} eV^2$$

$$\sin^2 2\Theta = 1.07$$

# Compare 1.3 & 2.5 $\times 10^{20}$POT Datasets

- Reconstruction and selection method
  - Changes number of events
  - ~2σ change in $\Delta m^2$
- Shower modeling
  - $\Delta m^2$ systematic decrease $0.06\times10^{-3}$eV$^2$
- New data set fluctuates down



# Our Long-term Goal:

*Oscillated/unoscillated ratio of number of $\nu_\mu$ CC events in far detector vs $E_{observed}$*

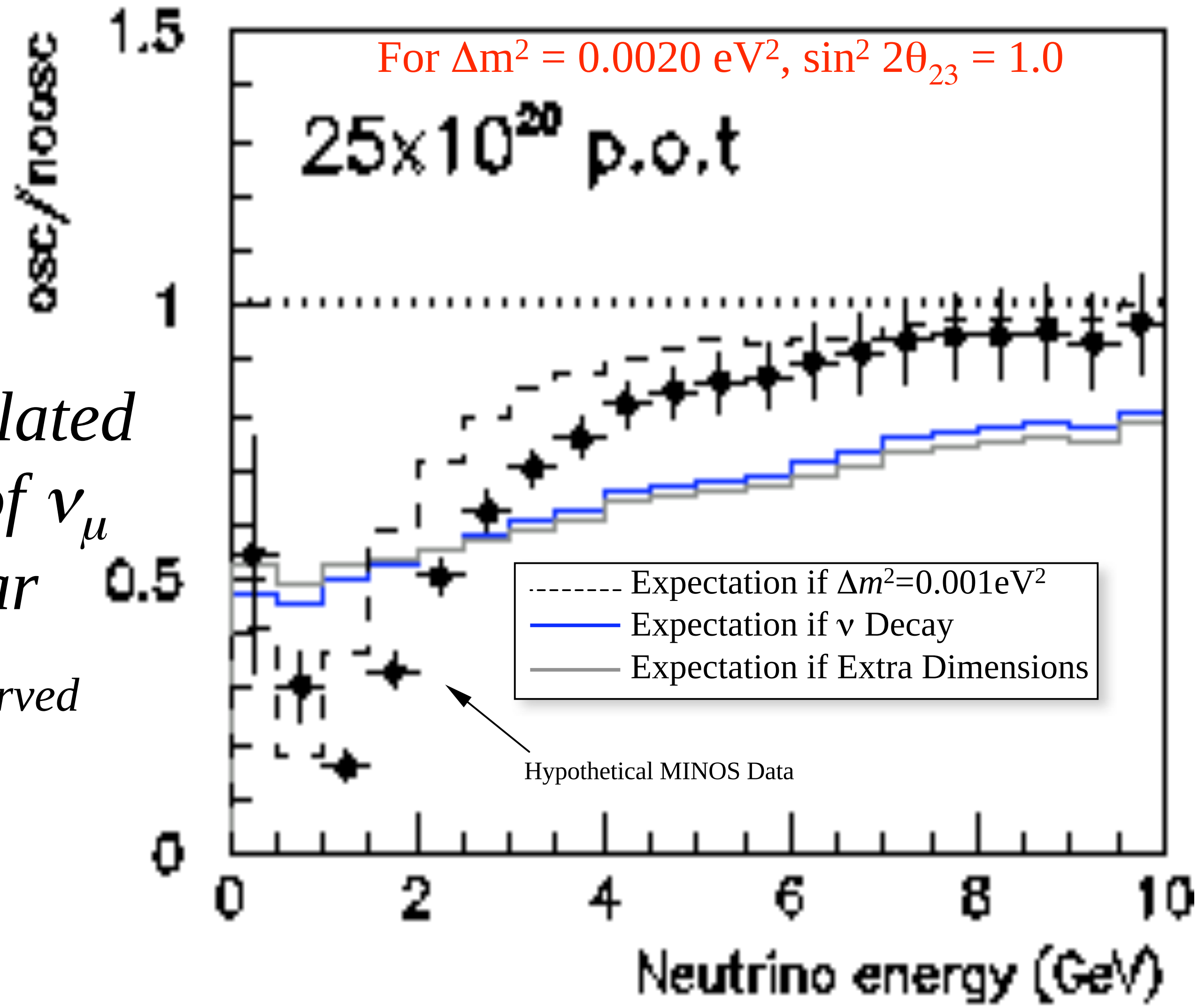
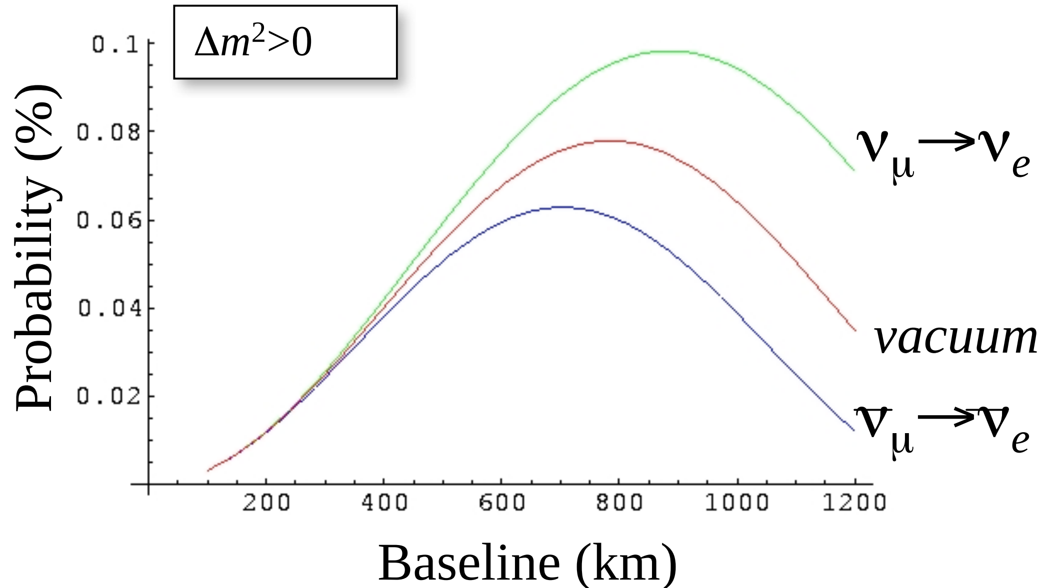
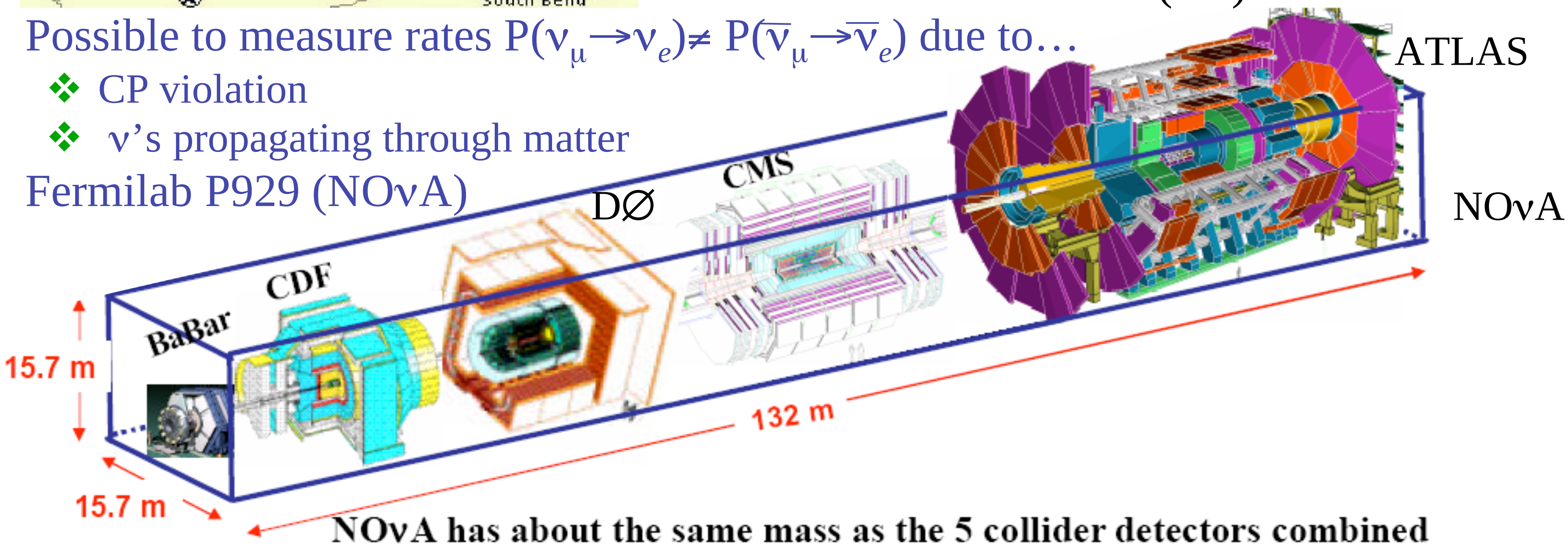



*figure courtesy D. Petyt*

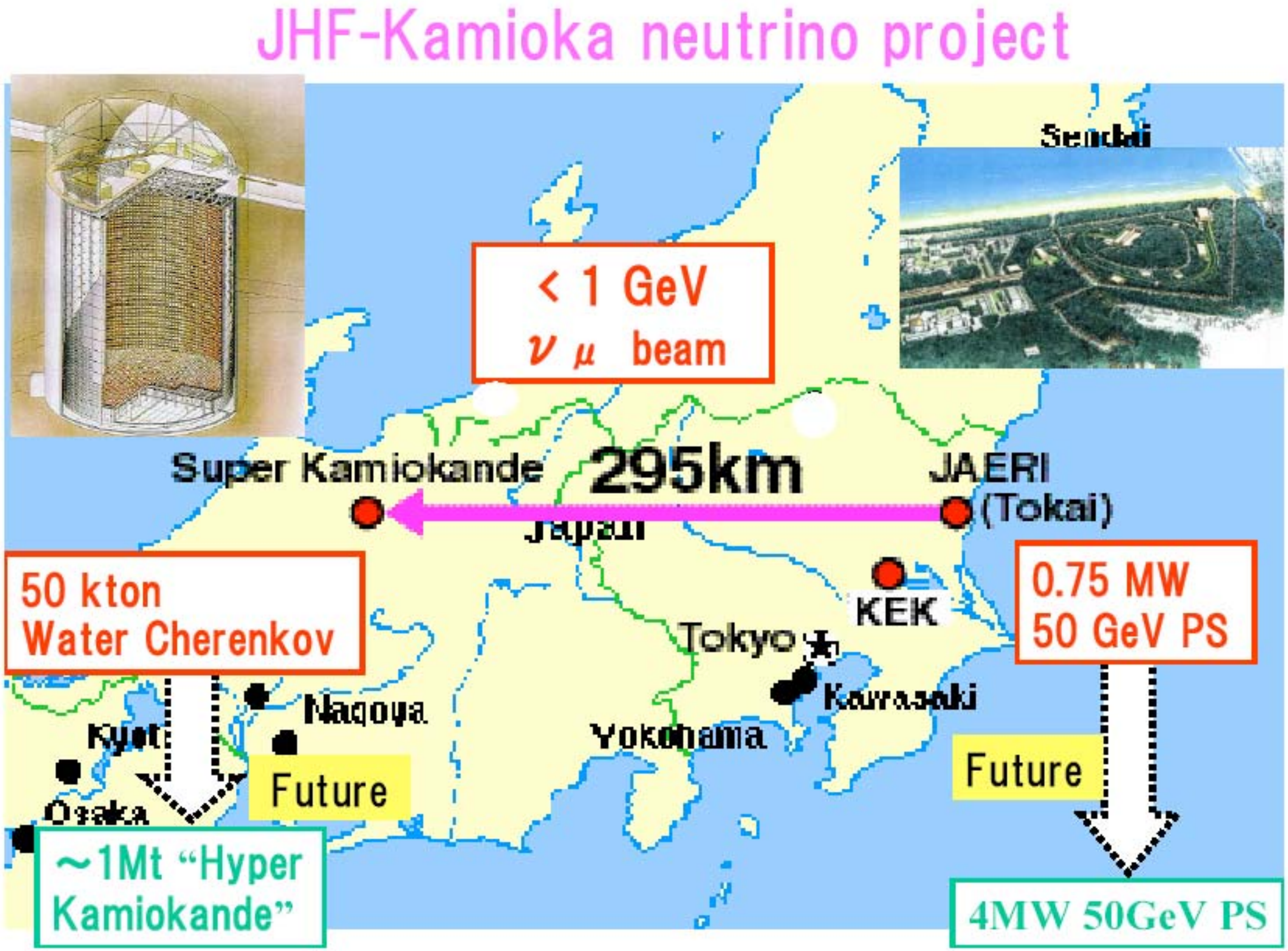
# Off-Axis Beam from NuMI

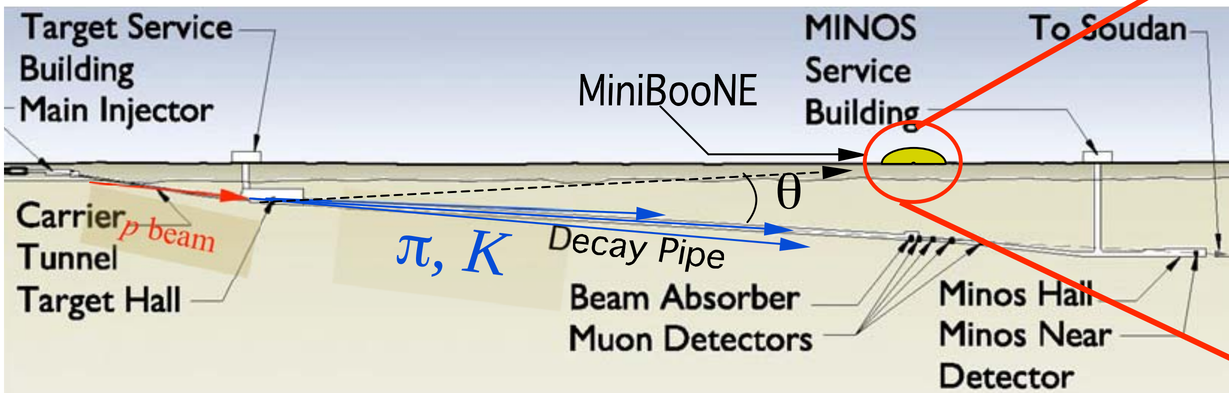

- Possible to measure rates $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ due to…
  - ❖ CP violation
  - ❖ ν's propagating through matter
- Fermilab P929 (NOνA)

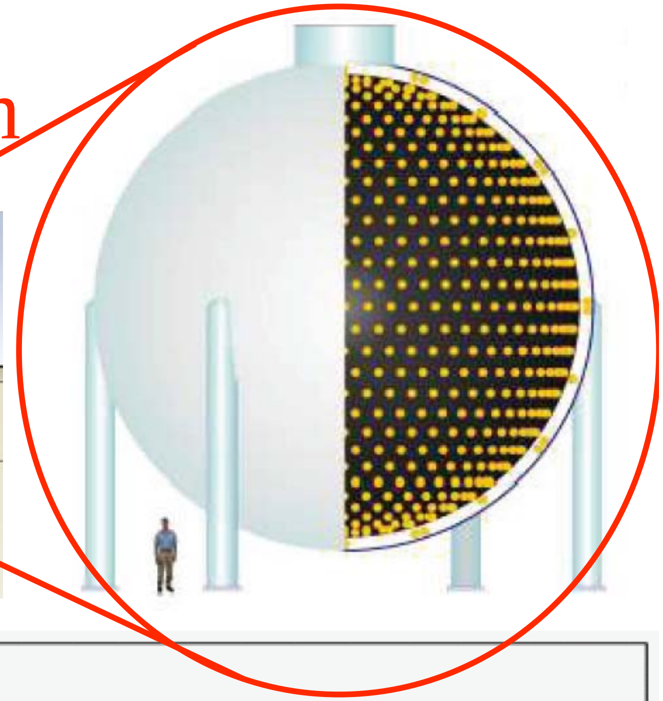


# Competition in Japan



# 1st Demonstration of Off-Axis Beam



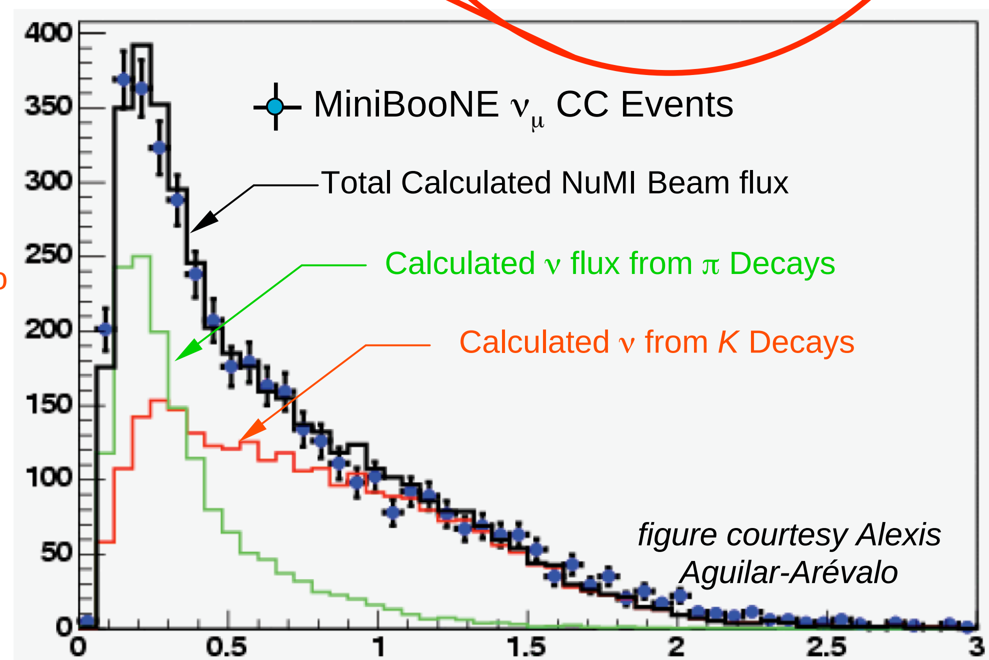
- NuMI ν's sprayed in all directions.

- $K \to \mu\nu$ and $\pi \to \mu\nu$ decays lead to lower $E_\nu$ at large decay angle

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

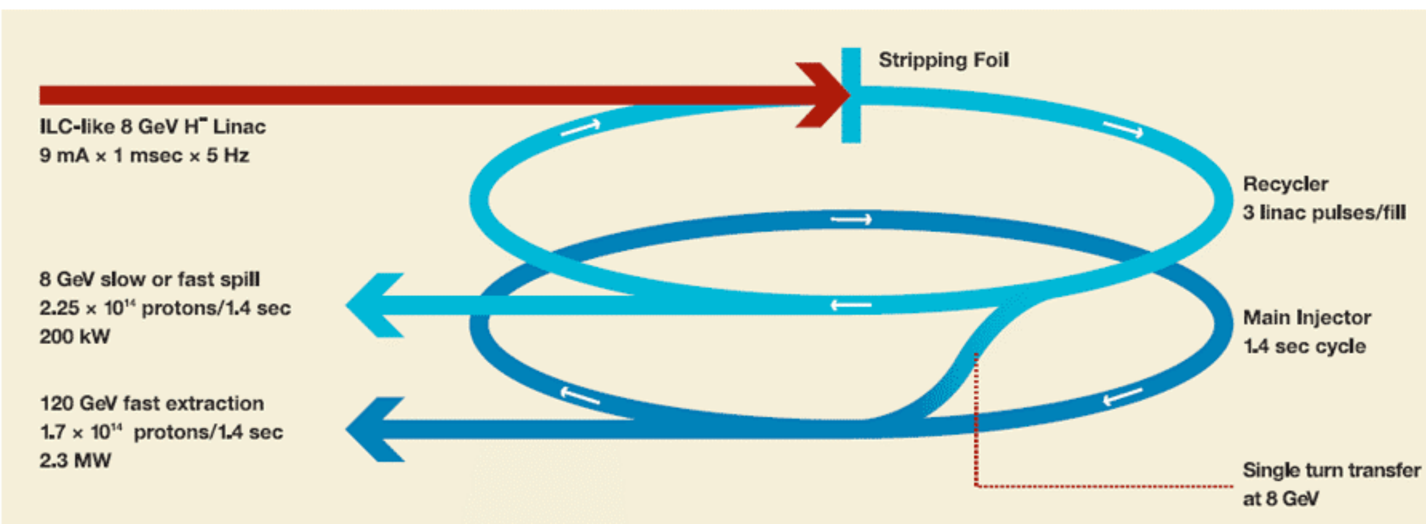
~110mrad to MiniBooNE

- Opportunity to double-check our beam flux calculations using 'mature' neutrino detector



# The Fermilab Neutrino Program

- Many ideas are now being discussed/proposed/built
  - MINOS – Precision oscillation parameters
  - NOvA – first observation of $\nu_\mu \rightarrow \nu_e$, matter effects?
  - MINErVA – precision scattering cross sections
  - MicroBooNE – Liquid Argon TPC R&D
  - NuSOnG – weak mixing angle
  - FNAL-DUSEL – CP Violation in neutrinos?
- Project X accelerator would enable diverse program




***Workshop on Physics Opportunities with the Project X Accelerator***

***Fermilab, Nov 16-17, 2007***

*The path forward is crystal clear …*

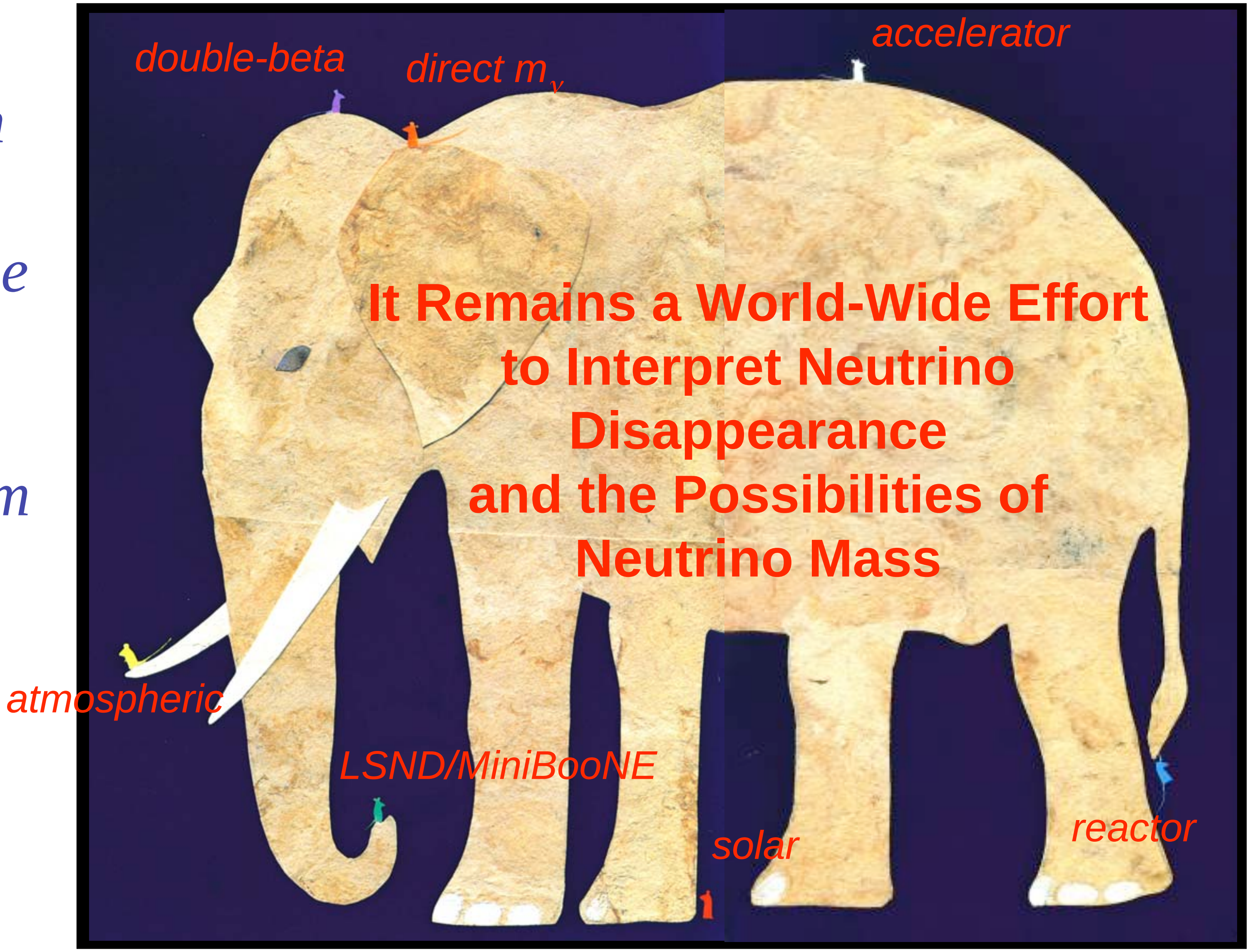
SMU student Yurii Maravin, Summer 1994

Prof. Thomas Coan, Fall 1993

*…but very fragile indeed.*

# The Blind Leading the Blind?

*"Knowing in part may make a fine tale, but wisdom comes from seeing the whole."*

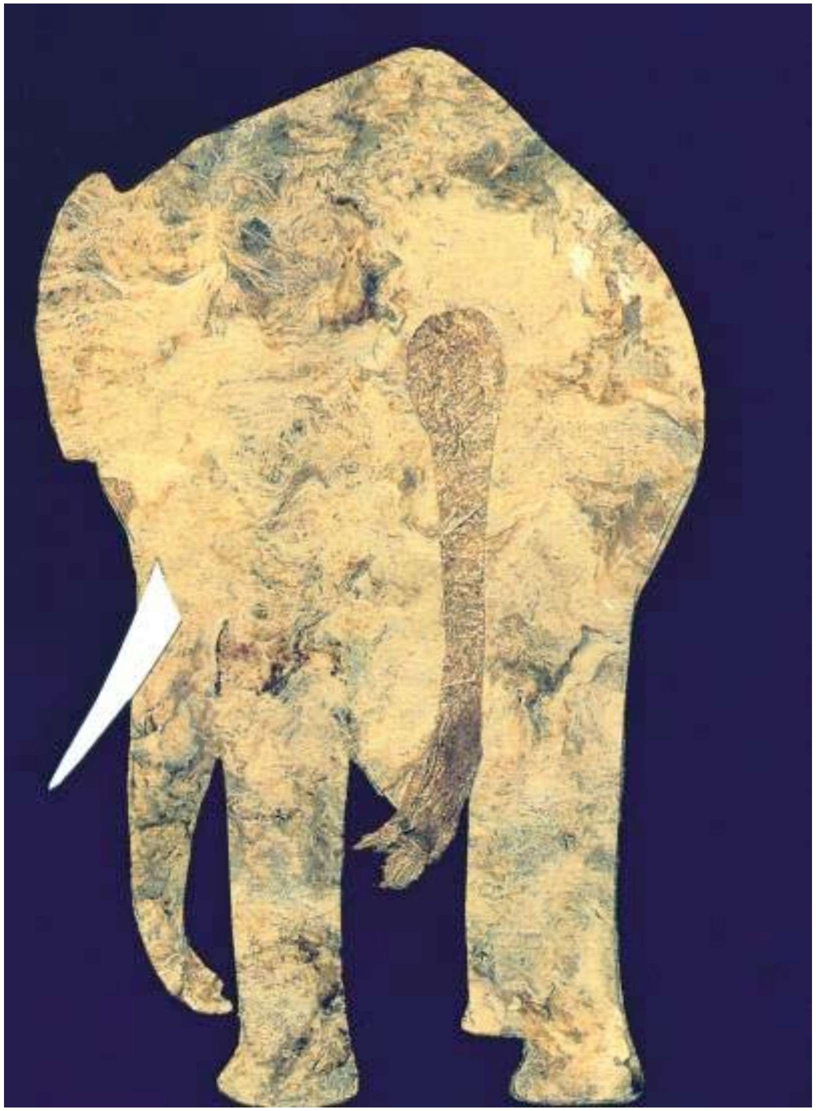


# Conclusions

- MINOS rapidly progressing
  - Construction complete after 6 years
  - $3.5\times10^{20}$ POT delivered
  - First result confirms ν's disappear
  - Under oscillation hypothesis,

$$\Delta m^2_{23} = (2.38^{+0.20}_{-0.16})\times10^{-3} eV^2$$
$$\sin^2(2\theta_{23}) = 1.00_{-0.08}$$

- Rich program of physics ahead
  - Results on oscillations *vs* other new physics
  - Search for rare osc. phenomena, like $\nu_\mu\rightarrow\nu_e$, $\nu_\mu\rightarrow\nu_s$
  - Is $\nu_\mu\rightarrow\nu_\tau$ mixing maximal?
  - Future experiments: CP violation

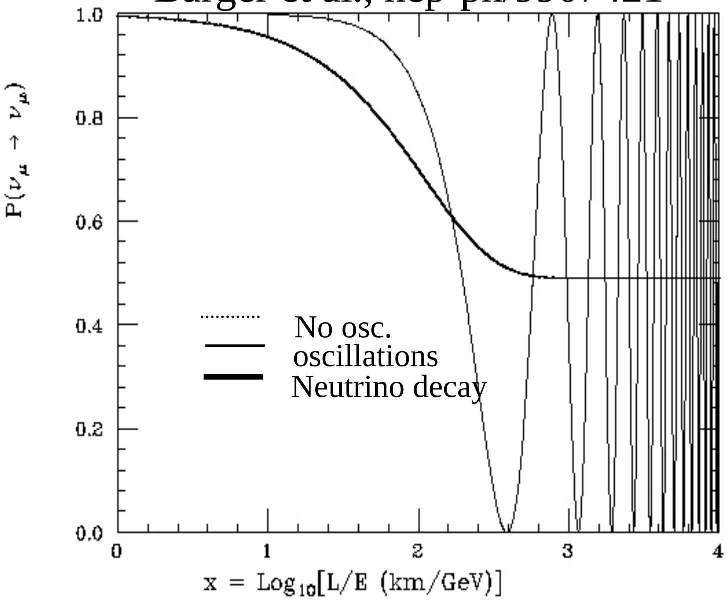


# Backup Slides

# Alternatives for $\nu_\mu$ Disappearance

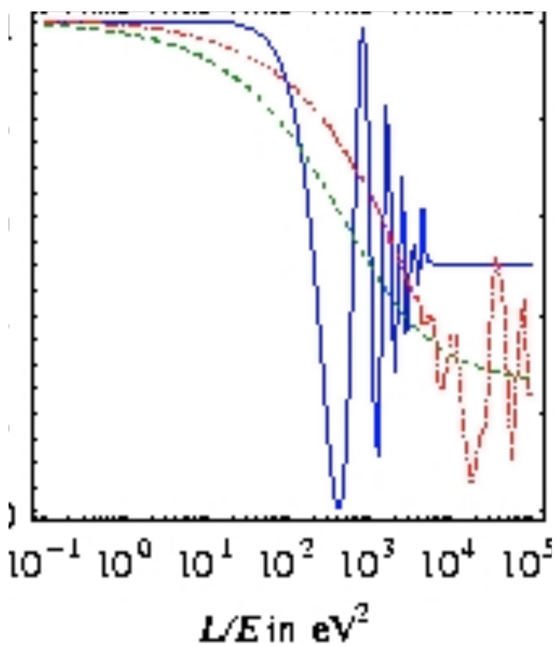
"Neutrinos actually decay to lighter states"

Barger et al., hep-ph/9907421



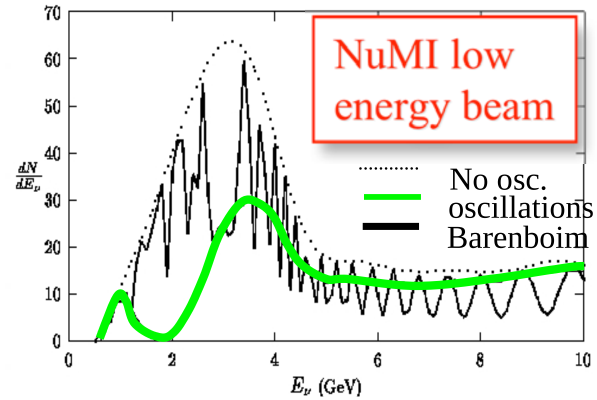

"Neutrinos propagating in Extra Dimensions"

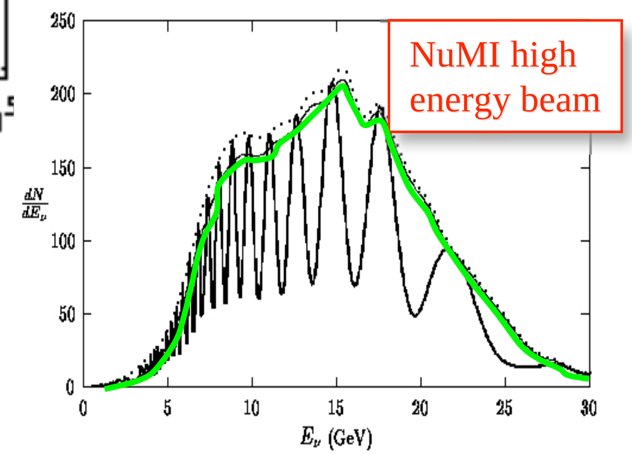
Barbieri et al., hep-ph/9907421




"SuperK effect is combination of $\Delta m^2$(solar) and $\Delta m^2$(LSND)"

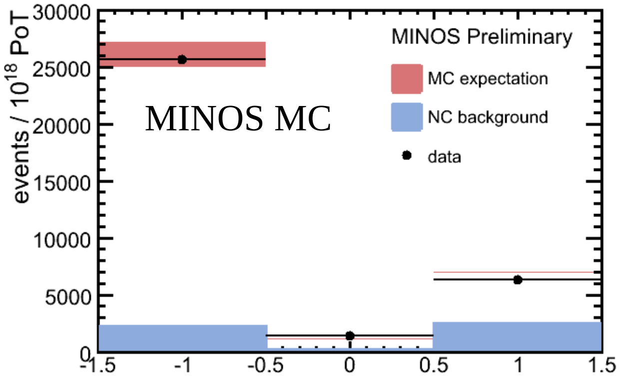
Barenboim et al., hep-ph/0009247



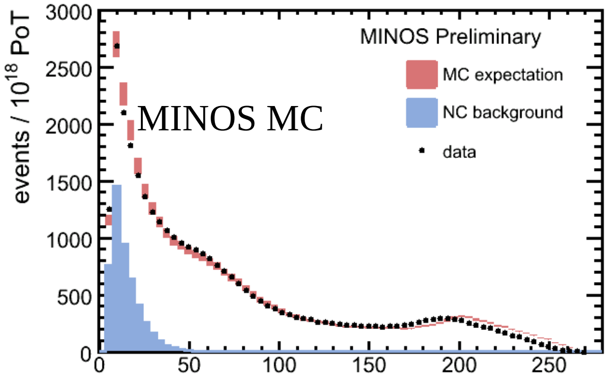




- Most think $\nu_\mu \to \nu_\tau$ looks like a good explanation of the atmospheric $\nu$ depletion, but one must be open to other possibilities given
  - The 3 $\Delta m^2$ problem
  - Naturalness, attraction of a $\nu_{sterile}$ GUT's
  - Due skepticism of jumping to conclusions in hard experiments

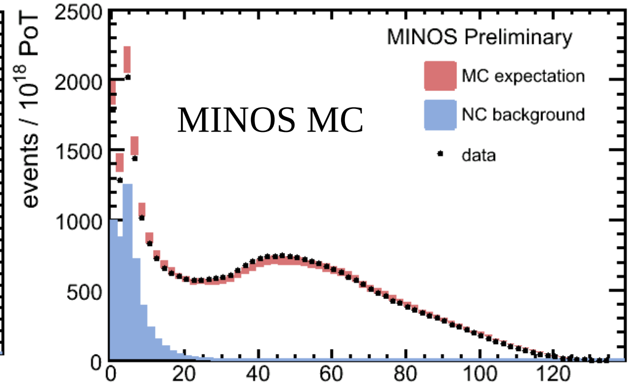
# Charged Current $\nu_\mu$ Selection



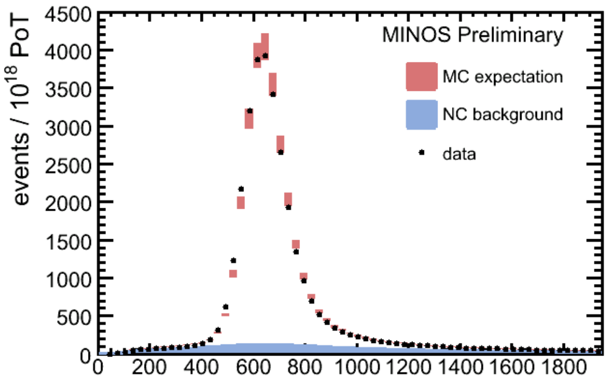

**Track Charge**



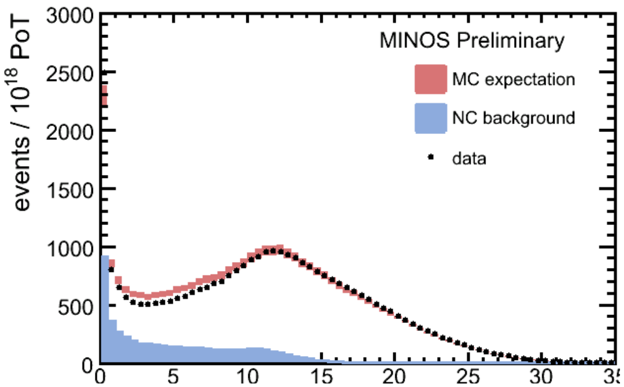

**Track length (planes)**



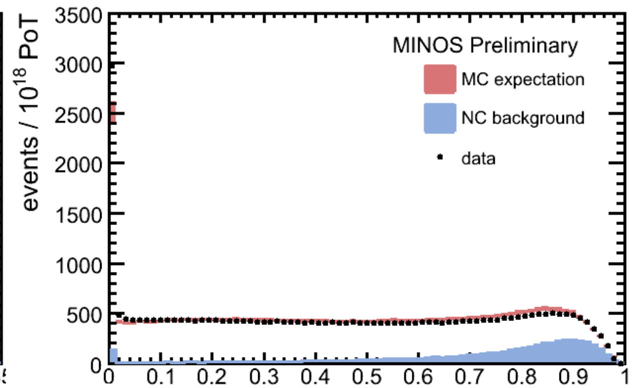

**Track length beyond Showe**




**Track Pulse Height / Plane**



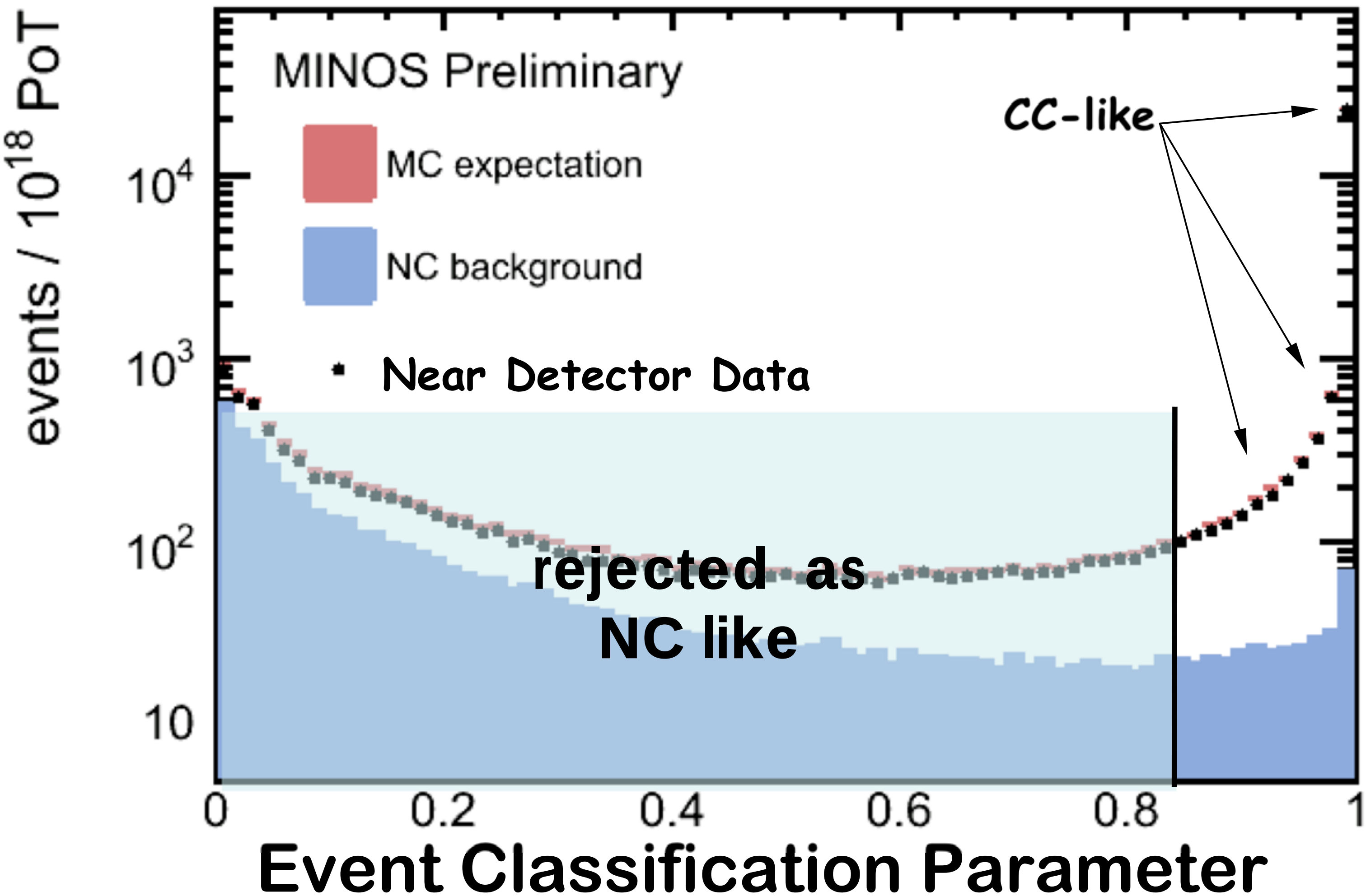

**Track Curvature/Resolution**




**$Y = 1 - p_\mu/E_\nu$**

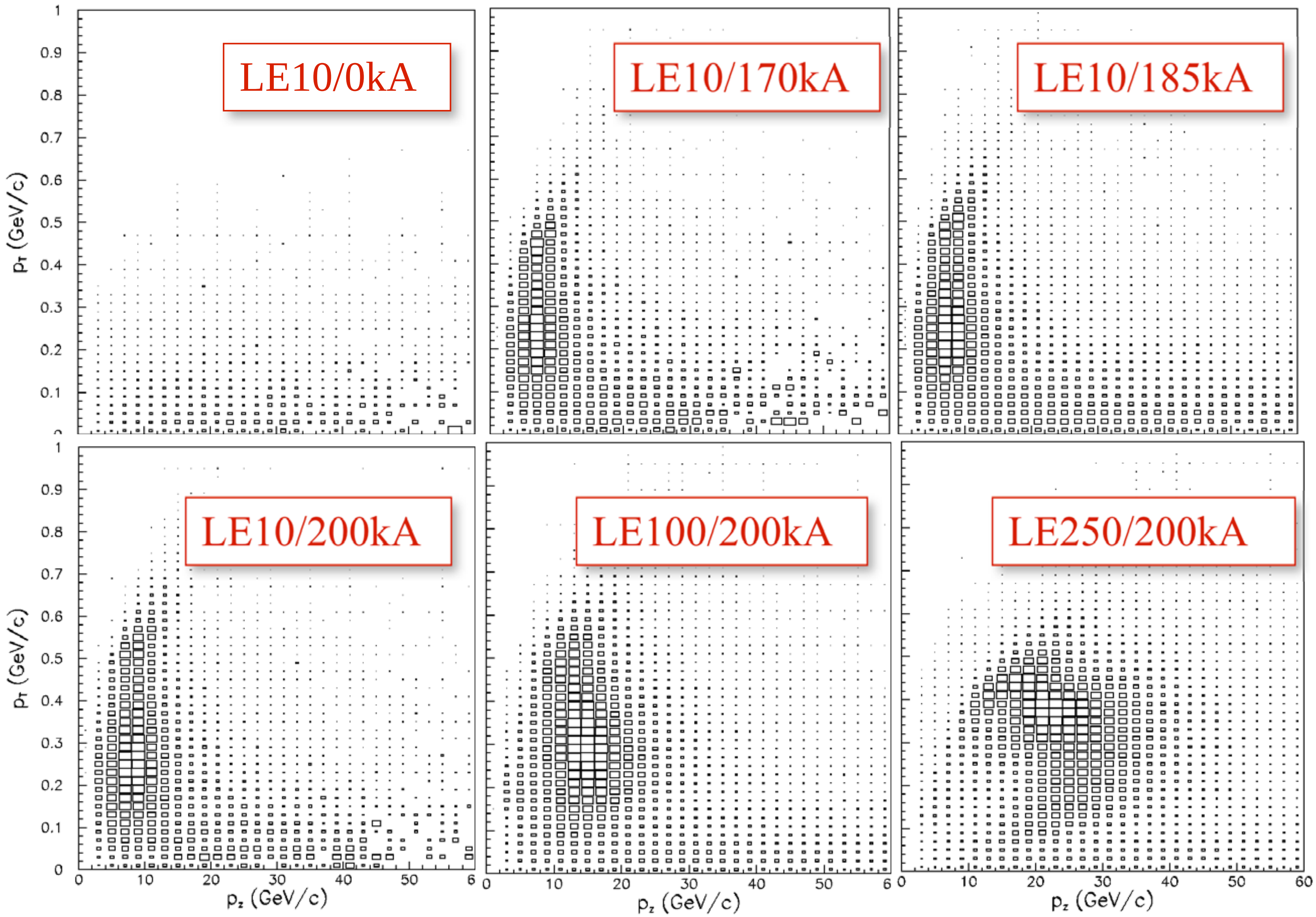
- Charged current events distinguished by
  - muon track
  - long event length
- Probability distribution function to reduce $\nu_\mu$-NC bckgd to $\nu_\mu$-CC sample.

# Charged Current $\nu_\mu$ Selection (*cont'd*)




- In LE beam, expect 89% efficiency, 98% CC purity

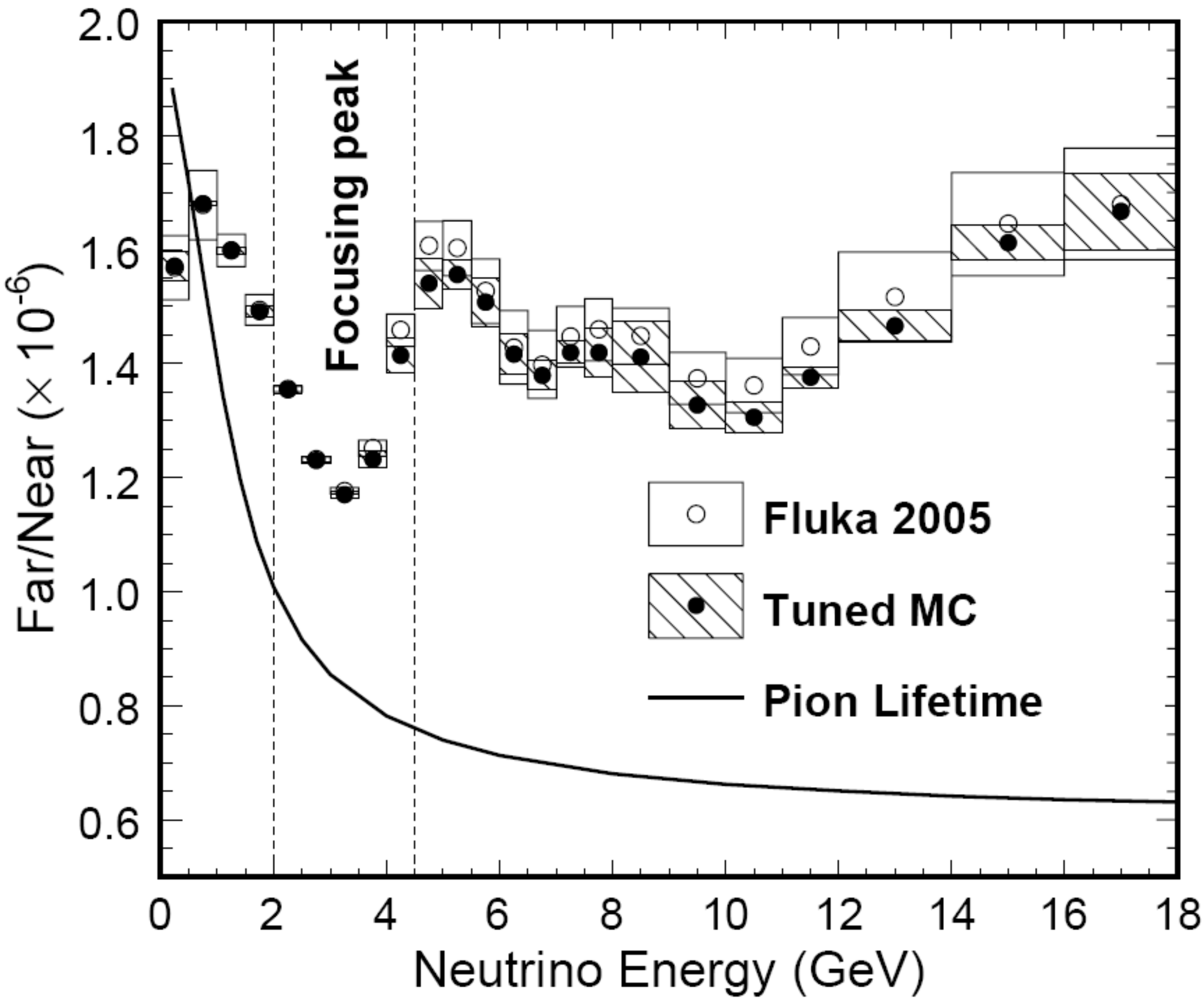
# “Tuning” the Beam Spectra in ($x_F$, $p_T$)




Vary the horn current

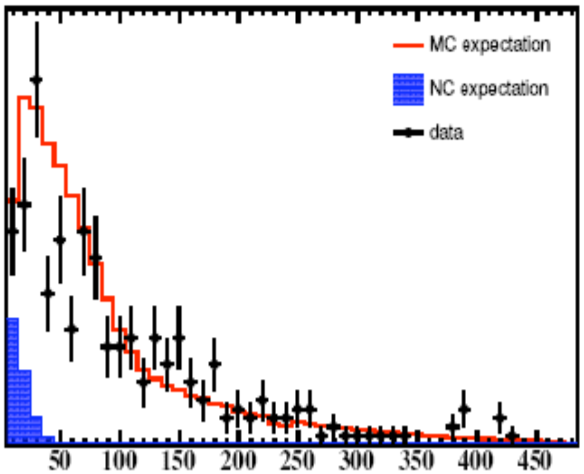
Vary the target's location

# F/N Ratio After Tuning

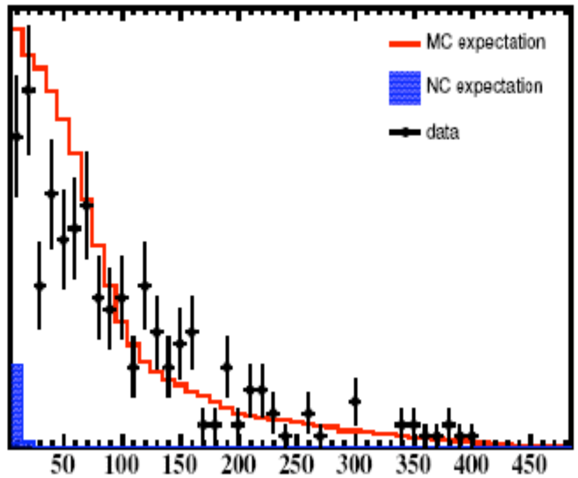



- Several tunings of the ($x_F$, $p_T$) spectra were attempted.
- All can accommodate the ND neutrino spectra.
- All yield similar tuned F/N ratio (within 2%)

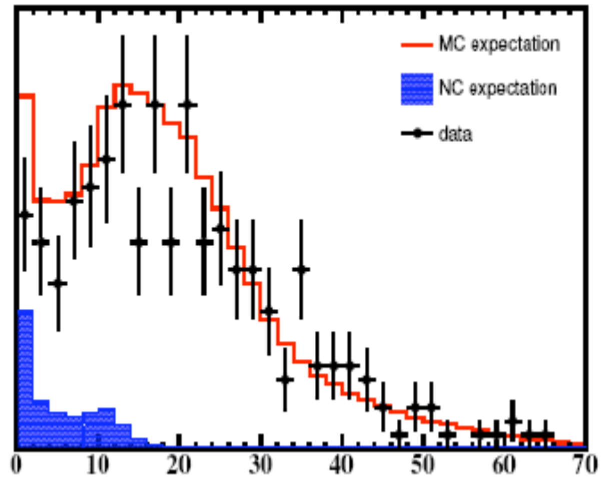
# Charged Current $\nu_\mu$ Selection Variables



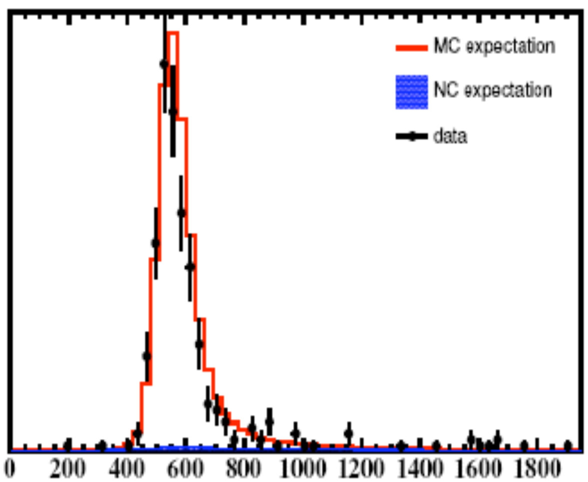

Track length (planes)



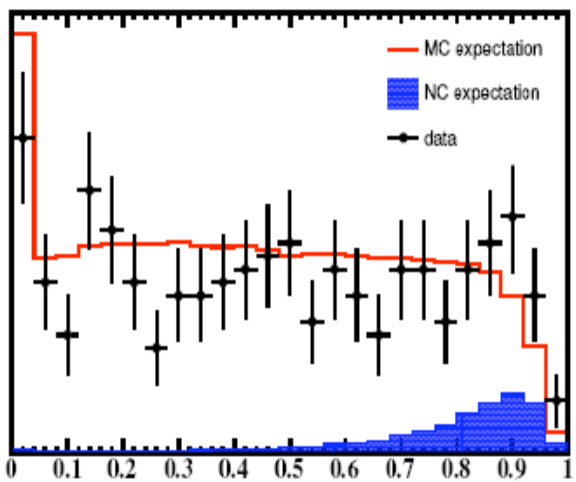

Track length beyond Shower



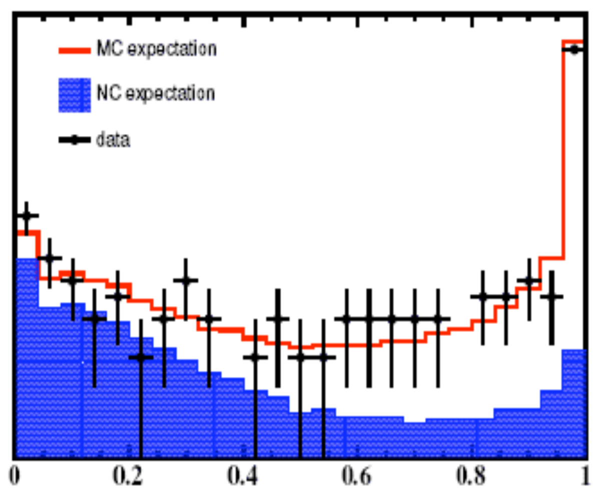

Curvature/Resolution




Track Pulse Height / Plane

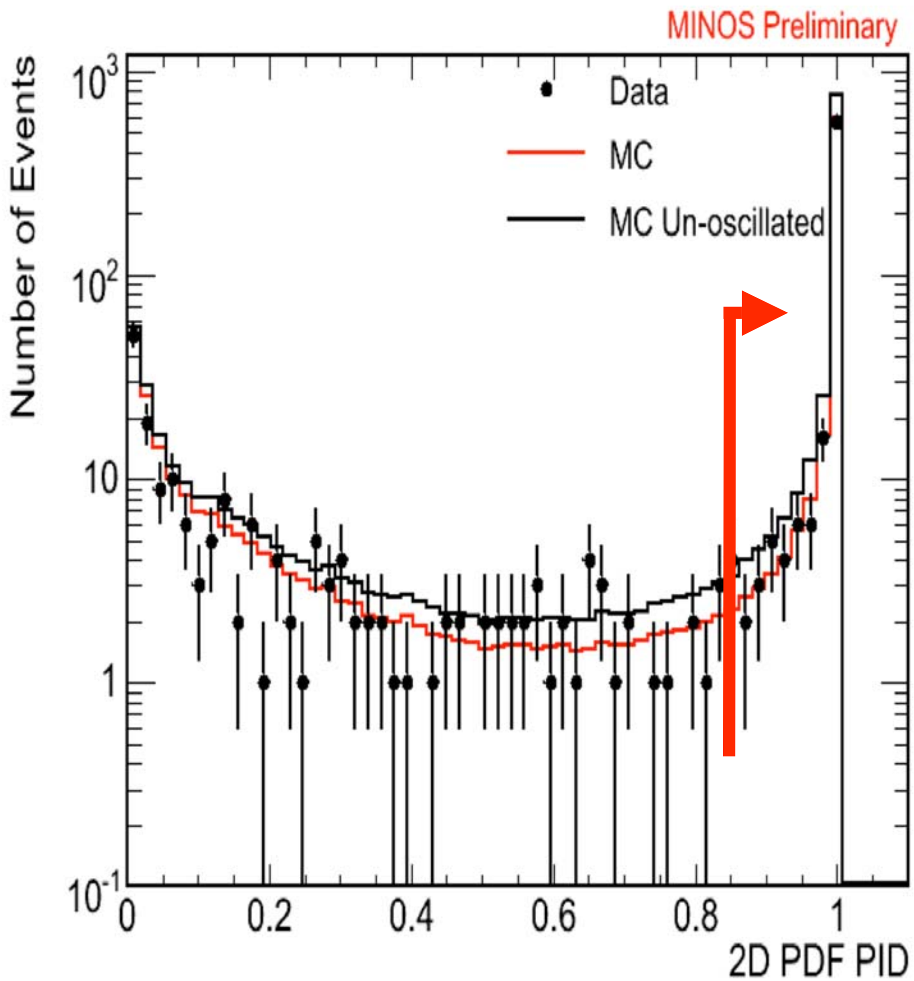


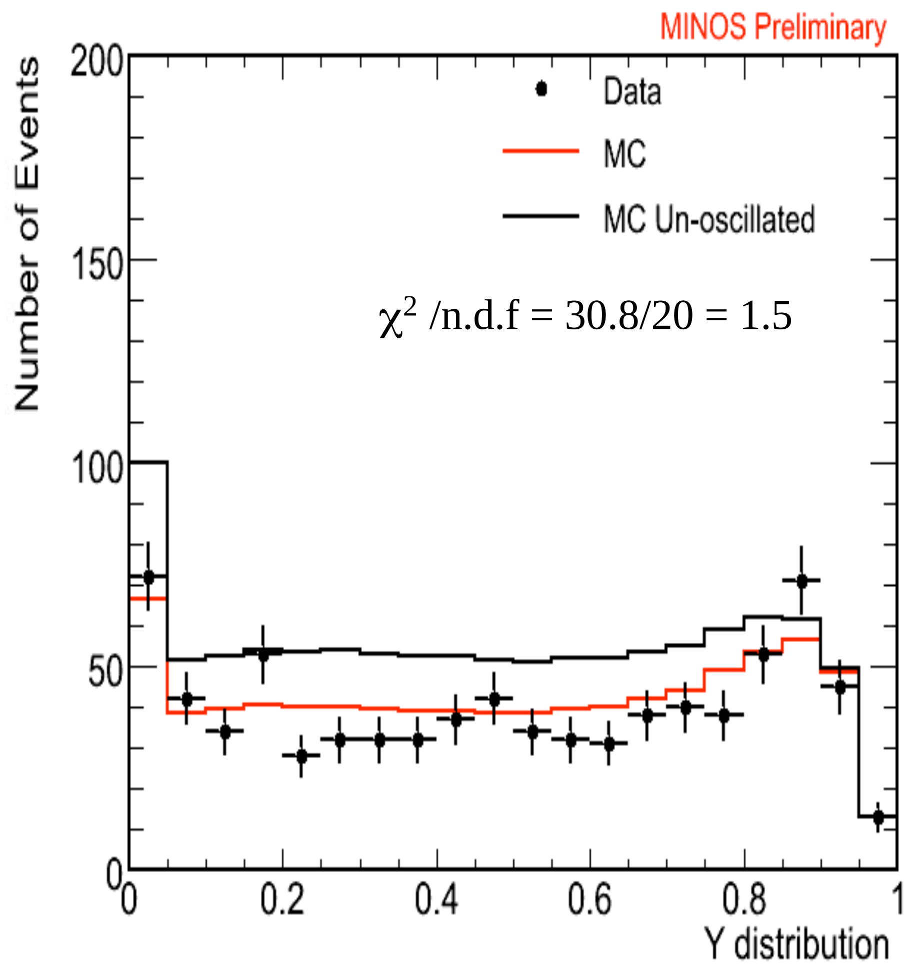

$Y = 1 - p_\mu / E_\nu$




Classification Parameter

# Comparison with Unblinded MC




**No Osc.**

**Osc. ($\Delta m^2$=0.0024 eV$^2$)**

**MINOS Data**