Conventional Neutrino Beams
Lecture II

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Neutrino Physics Summer School

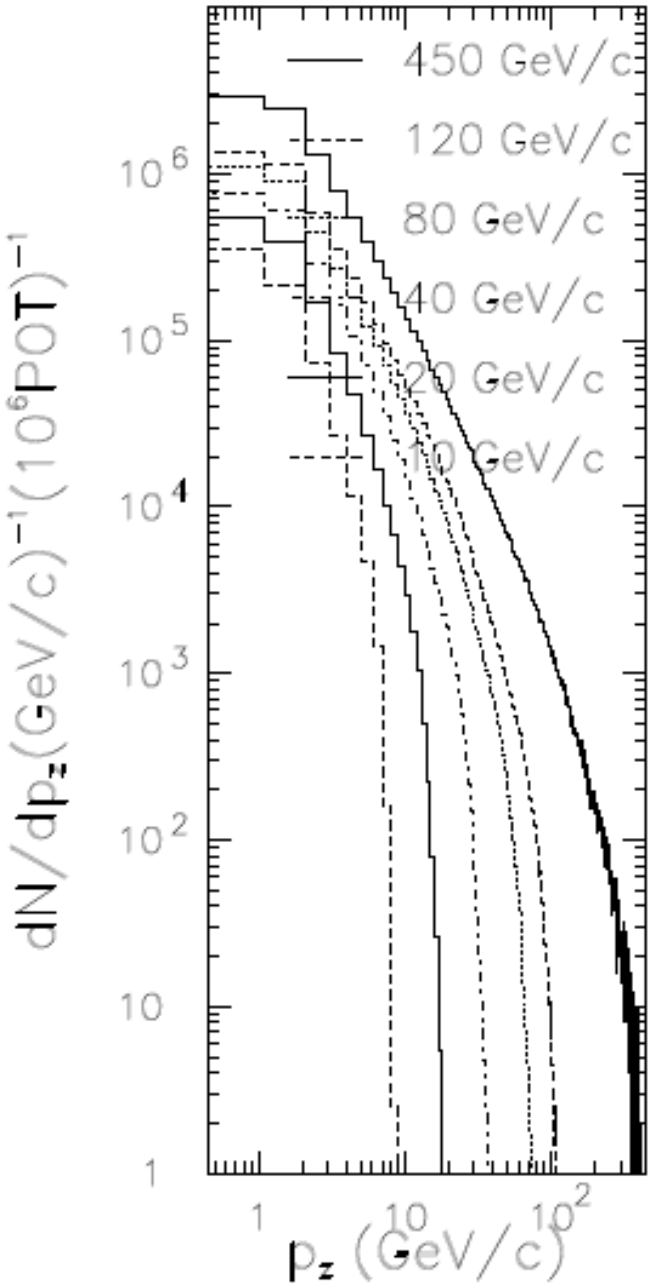
Fermilab

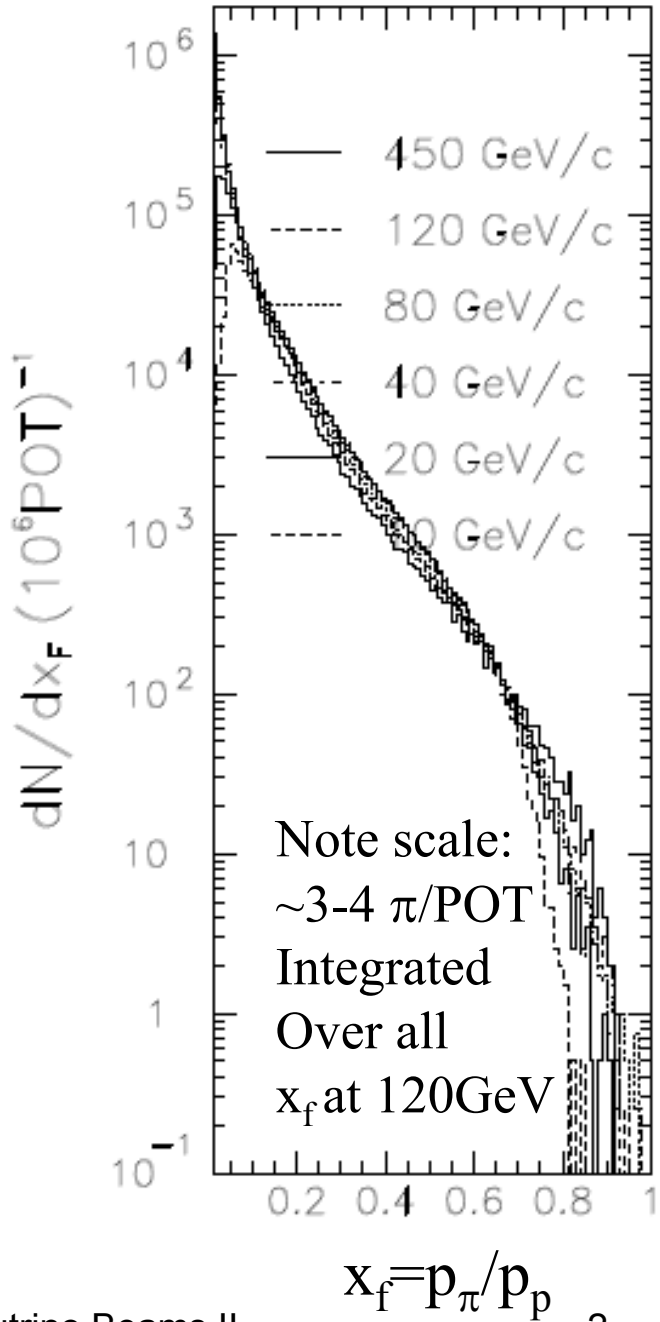
July 12, 2007

Question from July 11 Lecture

- How many pions do you make for a given incoming proton at some energy?

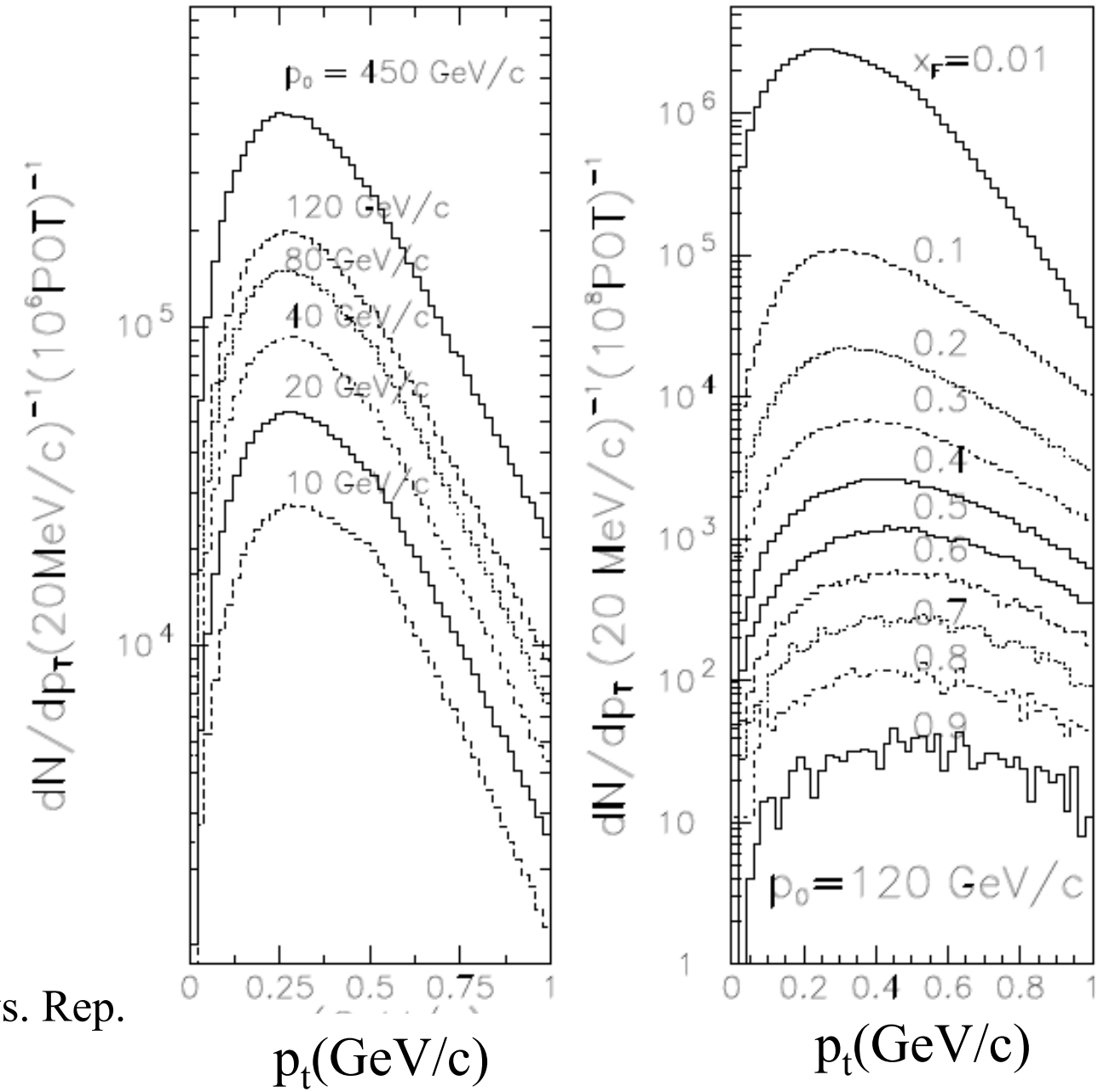
Ref: S.Kopp, Phys. Rep. 439: 101-159, 2007





Question from July 11

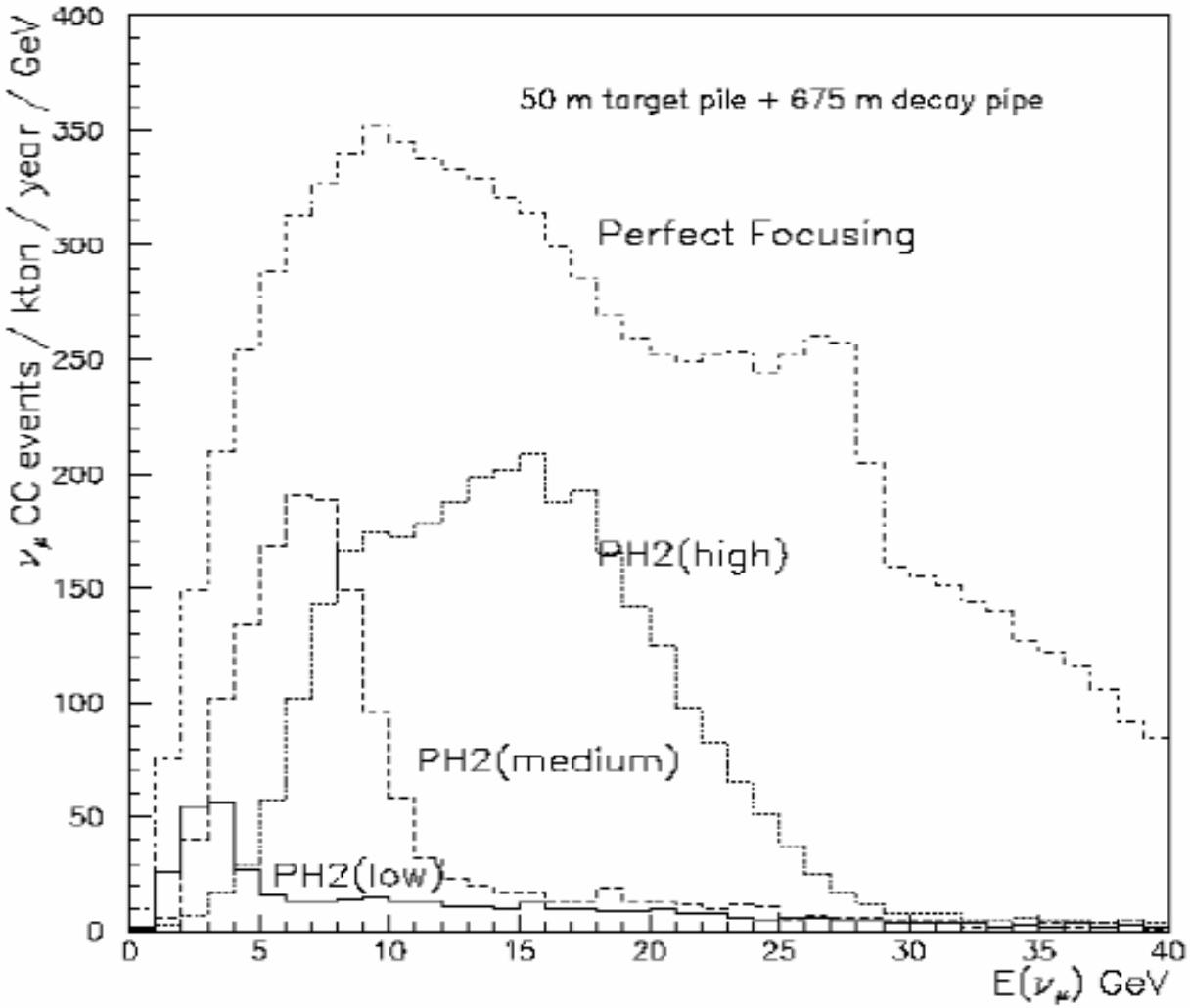
- How many pions do you make for a given incoming proton at some energy?
- I lied yesterday: p_t is more like 280MeV, not 200MeV



Reference: S.Kopp, Phys. Rep. 439:101-159, 2007

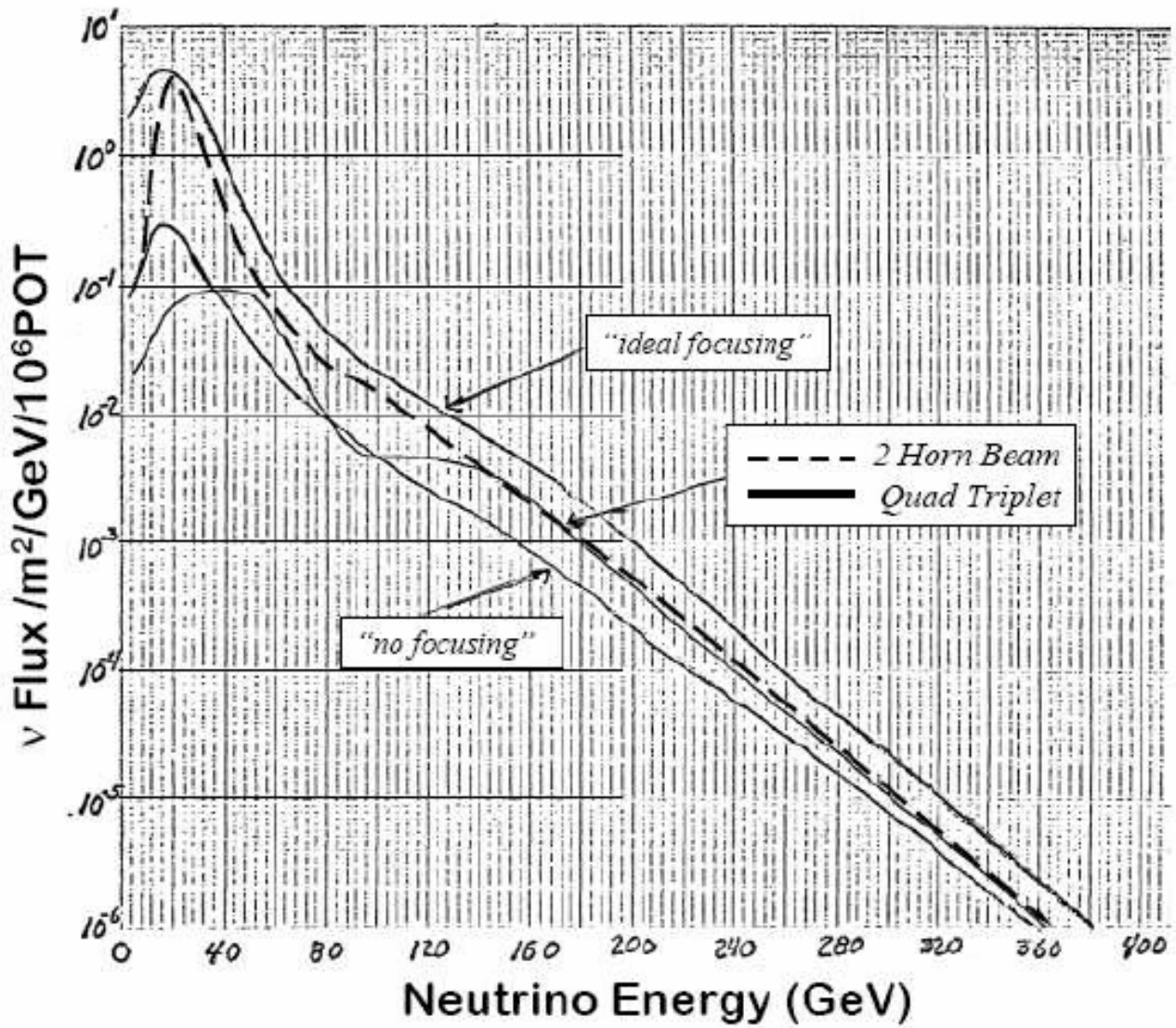
Question from July 11

- How efficient is this horn focusing?
- Reference: NuMI Technical Design Report
- 3 different beams are from 3 different target/horn positions
- Note famous "GEANT Bump" from problem in hadron production model



Almost a Question from July 11

- How efficient is horn focusing compared to other focusing?
- 500GeV proton-fed beam shown

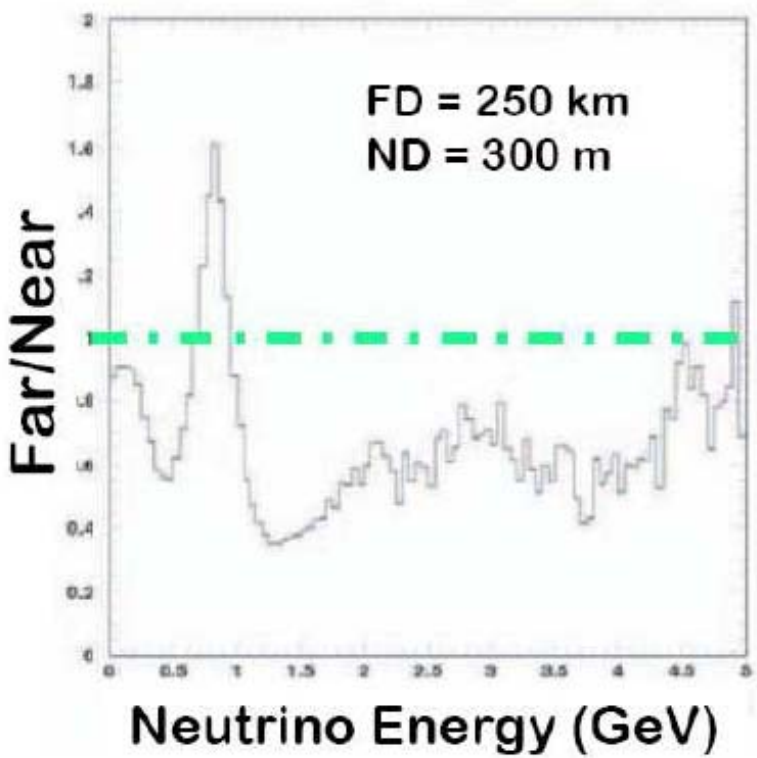


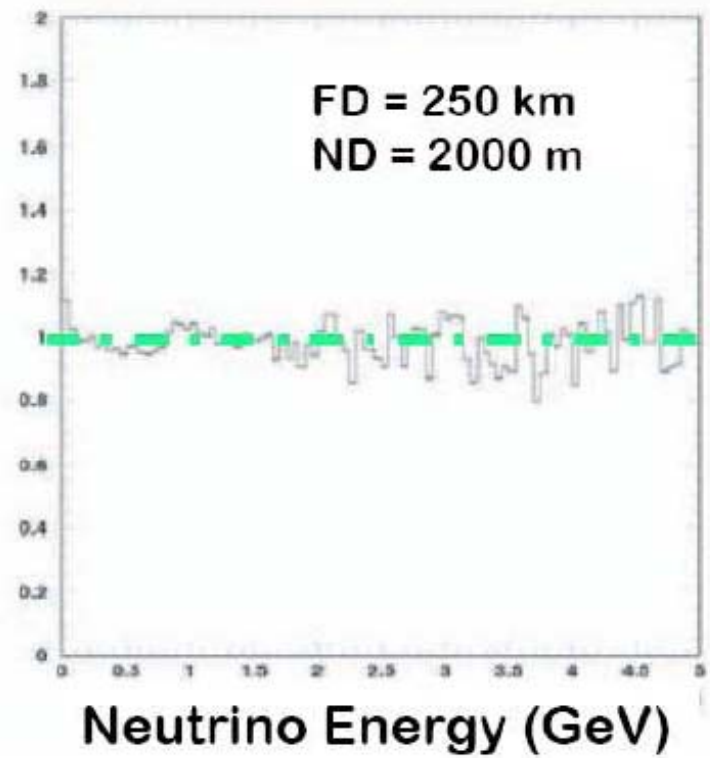
Reference: S.Kopp, Phys. Rep. 439:101-159, 2007

Question from July 11

- Are the near and far detector fluxes identical? (Example: T2K experiment)
- Remember: θ depends A LOT on whether or not you've focused the pions that made those neutrinos

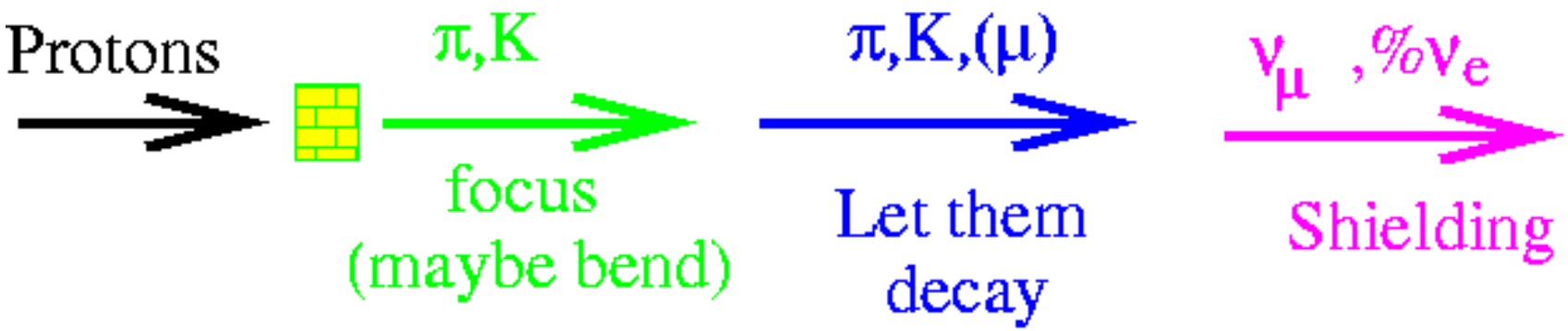
$$\Phi_\nu = BR\frac{1}{4\pi L^2}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$





Question from July 11

- How many particles are we talking about here?



Protons	π,K	μ	ν at Near Det
~10^{13} per pulse	Few π per 120 GeV protons	Depends on decay length: ~1 per π	20 interactions/ 2x 10^{13}

Getting from Event Rates to ν Flux

$$N = \phi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M$$

$$\phi_{\nu_\mu} = \frac{N(events)}{\sigma_{\nu_x}(cm^2 / nucleon)\varepsilon_x M(kton)} \times \frac{kton}{10^9 g} \times \frac{g}{6.02x10^{23} nucleons}$$

$$\phi_{\nu_\mu} = \frac{20}{6x10^{-38} cm^2 x6x10^{32}}$$

$$\phi_{\nu_\mu} = 0.6x10^6 \frac{\nu}{cm^2}$$

Or at 1km away, $2x10^{13}$ protons make about $2x10^{10}$ neutrinos (2mx2m)

In the words of Ken Peach

"When I was on an experiment to determine ε'/ε, once we were close to getting the result out, I realized something:

All the theorists asked 'what value did you measure?' and

All the experimentalists asked 'what uncertainty on the measurement did you end up getting?' "

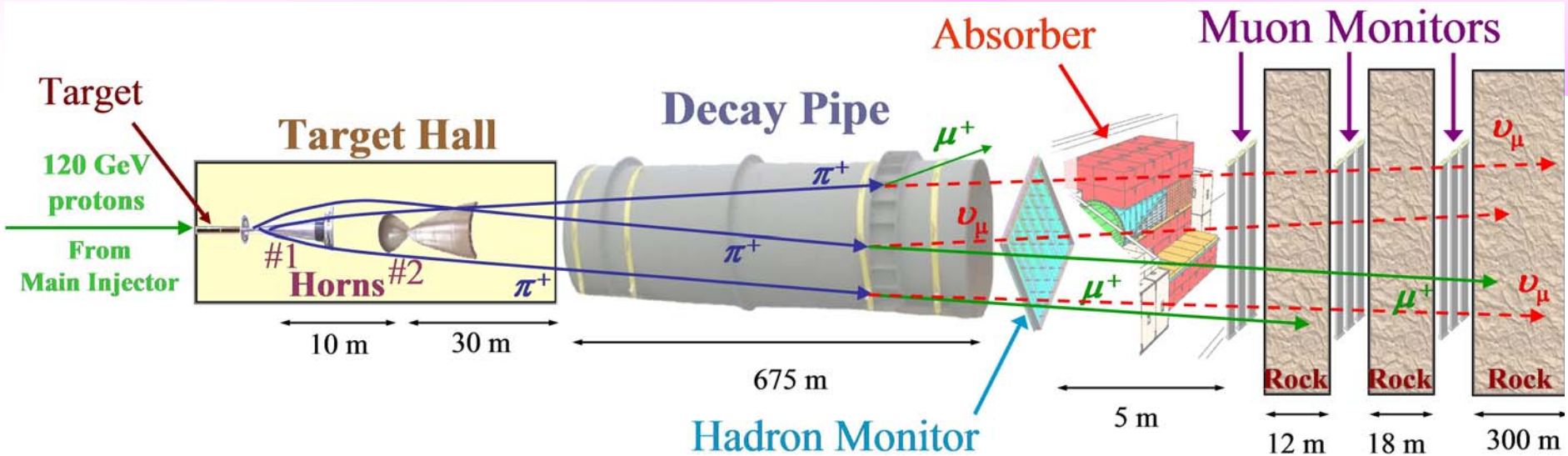
This talk will try to speak to both theorists and experimentalists…

but remember who wrote the talk…

Goals of Long Baseline Oscillation Measurements

- Measurements of "atmospheric neutrino oscillation parameters": ν_μ disappearance as a function of neutrino energy
- Searches for CP violation and understanding the neutrino mass hierarchy: ν_e appearance
- Verify Oscillation Framework: ν_τ appearance
- Search for Sterile Neutrinos: Neutral Current disappearance, looking for three distinct Δm^2

Conventional Neutrino Beam Summary



Major Components:

- Proton Beam
- Production Target
- Focusing System
- Decay Region
- Shielding
- Monitoring

Ways to Understand ν Flux:

Hadron Production

Proton Beam measurements

Pion Measurements

Muon Measurements

at angles vs momentum

at 0° versus shielding

Systematic Uncertainties

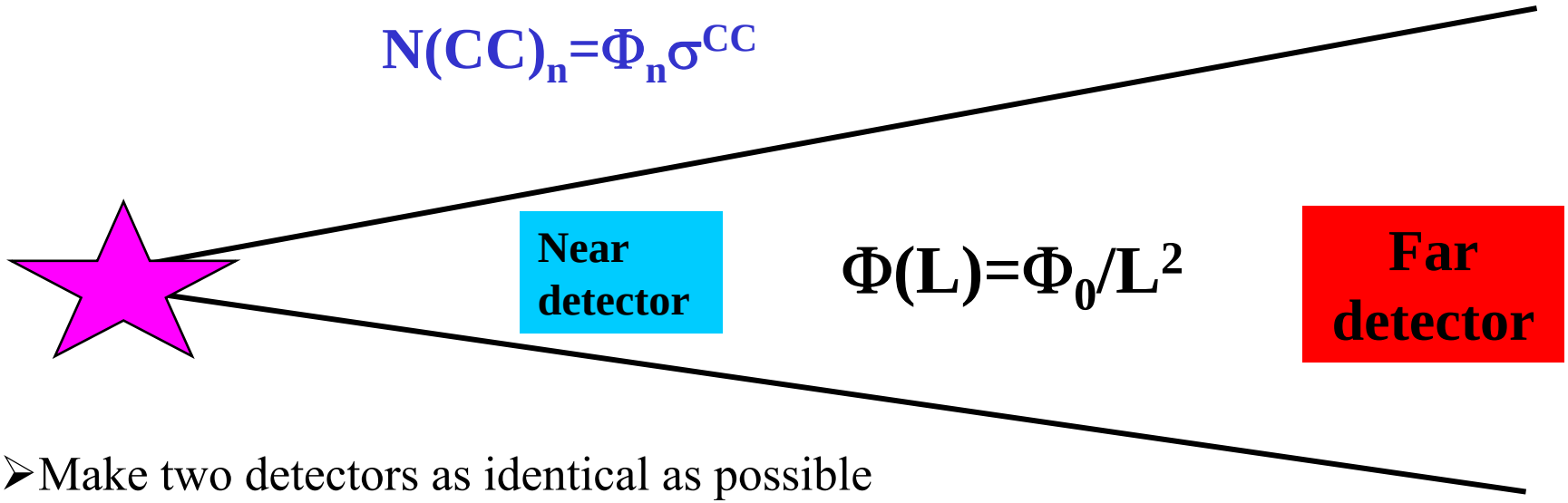
- Neutrino Flux
  - Hadron Production
    - π/K ratio
    - x and p_t spectrum of produced Pions/Kaons
  - Beamline Geometry
    - Focusing uncertainties
    - Alignment Uncertainties
- Neutrino Interactions: Background and Signal!
  - Quasi-elastic Uncertainties
  - Resonance (low W) Uncertainties
  - DIS (high W)
  - Nuclear Effects
- Event Selection
- Event Energy Resolution
  - Important especially for measurements versus neutrino energy
  - Narrow Band beams: energy resolution is key to background rejection

Problem: uncertainties all affect the near and far detector both, you can't always separate one from the other

Two detector experiment (in theory)

$N(NC)_n = \Phi_n \sigma^{NC}$

$N(CC)_n = \Phi_n \sigma^{CC}$



- Make two detectors as identical as possible
  - same scintillator, water, steel etc.
- Measure ν spectrum in the near detector
- Predict the ν spectrum in the far detector
- Cross section uncertainties should cancel…
- Detector efficiency uncertainties should cancel…
- Simple, right?

$N(NC)_f = \Phi_f \sigma^{NC}$

$N(CC)_f = \Phi_f \sigma^{CC}$

Two Detector Experiment (in practice)

- Near Detector sees a line source of neutrinos, far detector sees a point source
  - Think: where do ν_μ's in beam decay compared to ν_e's?
- Near Detector will have different event rate
  - Beam-induced rates differ by 10^4 to 10^5
  - Cosmic ray rates differ due to different shielding and detector size
- Near Detector Design is different
  - Different electronics, PMT's, active area coverage…
- $\nu_\mu \rightarrow \nu_\tau$ may be large: ν_τ CC suppression large
  - ν_μ CC energy distribution is very different

Near Detector Design

- Far detector must be massive: the more instrumented it is, the more $/kton…
- Tradeoff between segmentation and far detector mass
- Near Detector Design options:
  - "Identical" to far detector
    - Argue that detector efficiencies and cross sections are the "same", you just need independent flux measurements
  - Much more segmented and fine-grained
    - Try to measure fluxes and cross sections as best you can, make far detector prediction
- Ideally, you would do both…

K2K near neutrino detectors (K2K-II)

SciBar detector

Full active scintillator tracker

CH target (9.38t fid. vol.)

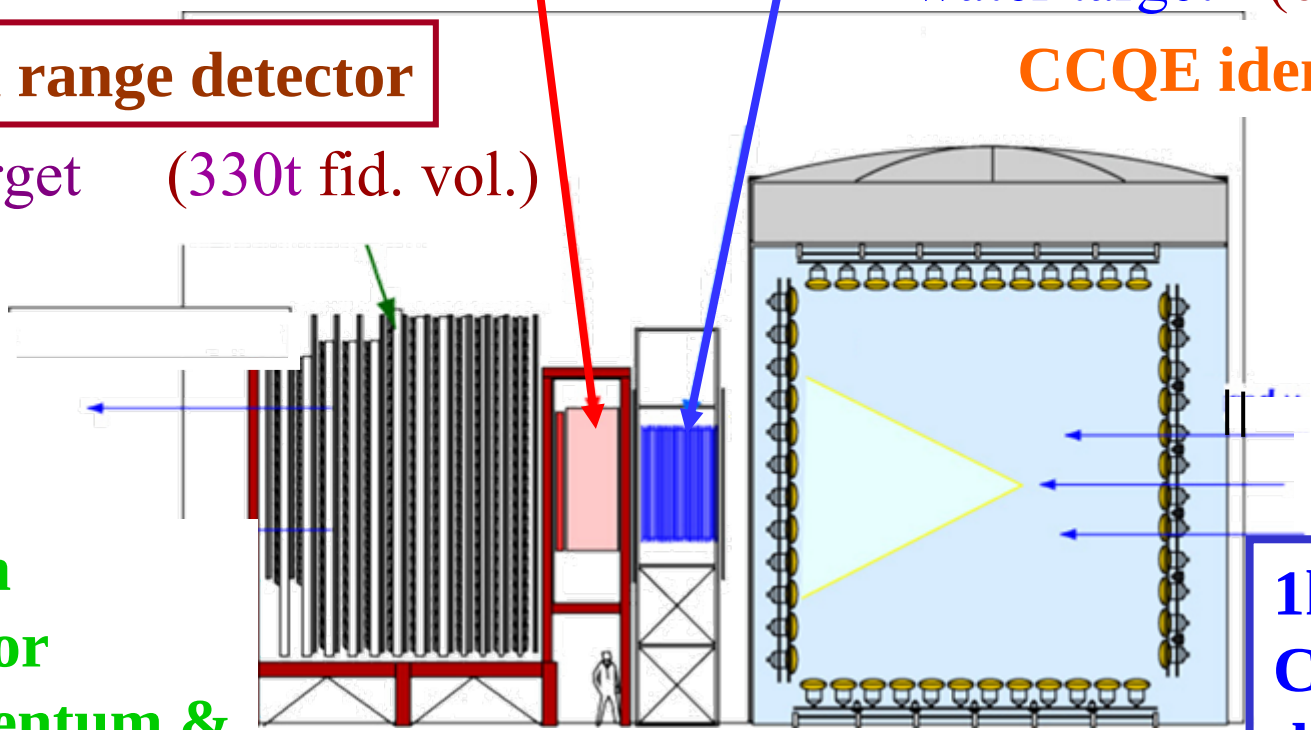
Scintillating fiber tracker

water target (6t fid. vol.)

CCQE identification

Muon range detector

Iron target (330t fid. vol.)



ν beam

1kt water Cherenkov detector

νbeam monitor (momentum & direction.)

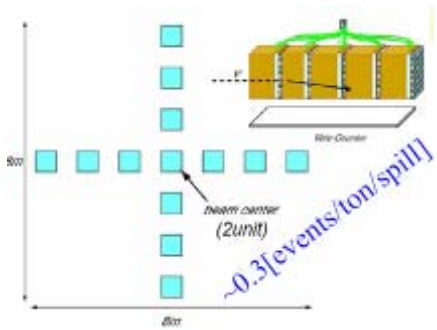
water target (25t fiducial volume)

T2K Near Detector Suite

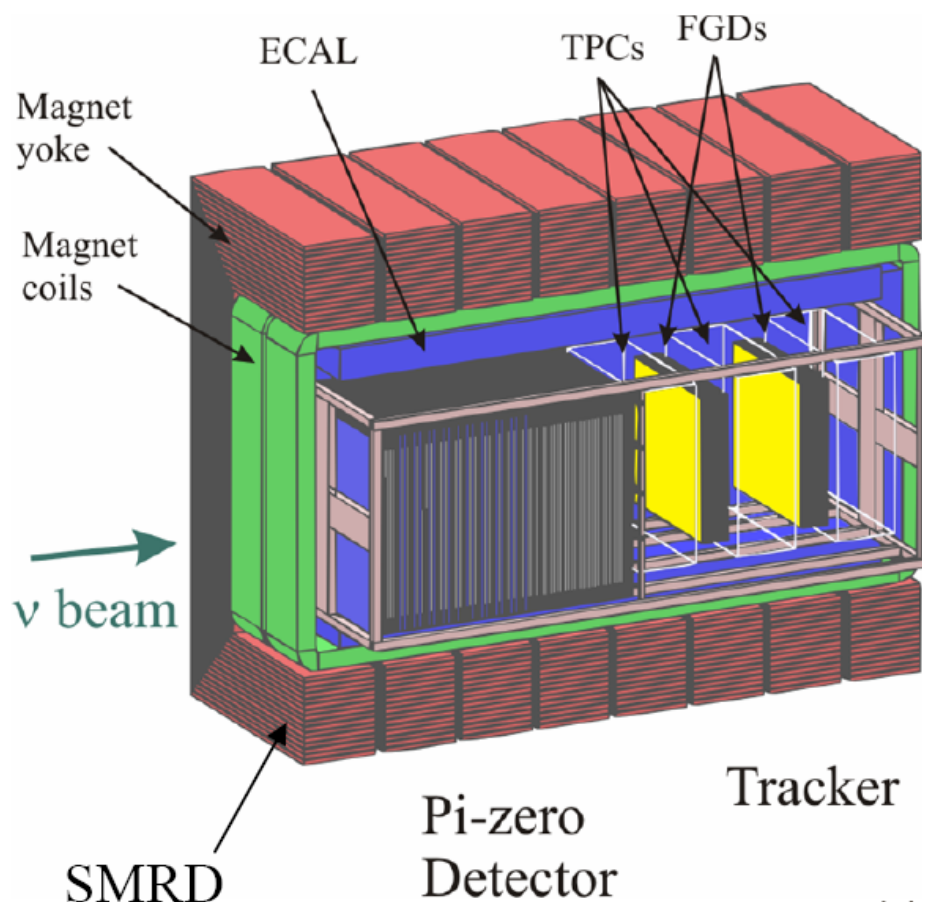
- What's interesting here is how it differs from the K2K Near Detector suite: no Cerenkov detector

Nakadaira, ν2006

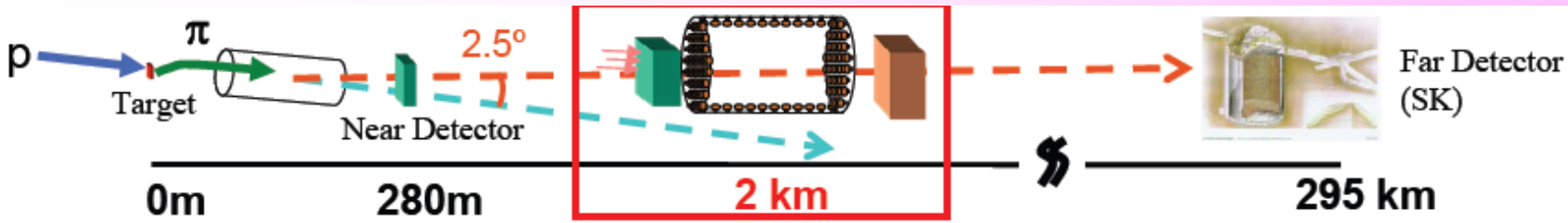
- On-axis detector
  - Measure ν-beam profile
    → ν-beam direction at 1mrad precision.
  - iron - scintillator stacks × 14 units



- Off-axis detector: In Magnet (*B=0.2T*)
  - Measure ν-flux in SK direction : $\Phi_\nu^{ND}(E_\nu)$.
    - Measure ν_μ, $\bar{\nu}_\mu$ and $\nu_e+\bar{\nu}_e$ fluxes separately.
    - Neutrino Energy ← CC-QE kinematics.
  - Cross sections of ν interactions
    - CC-1π/CC-QE … BG for E_ν reconstruction
    - NC-π^0 production … BG for ν_e detection



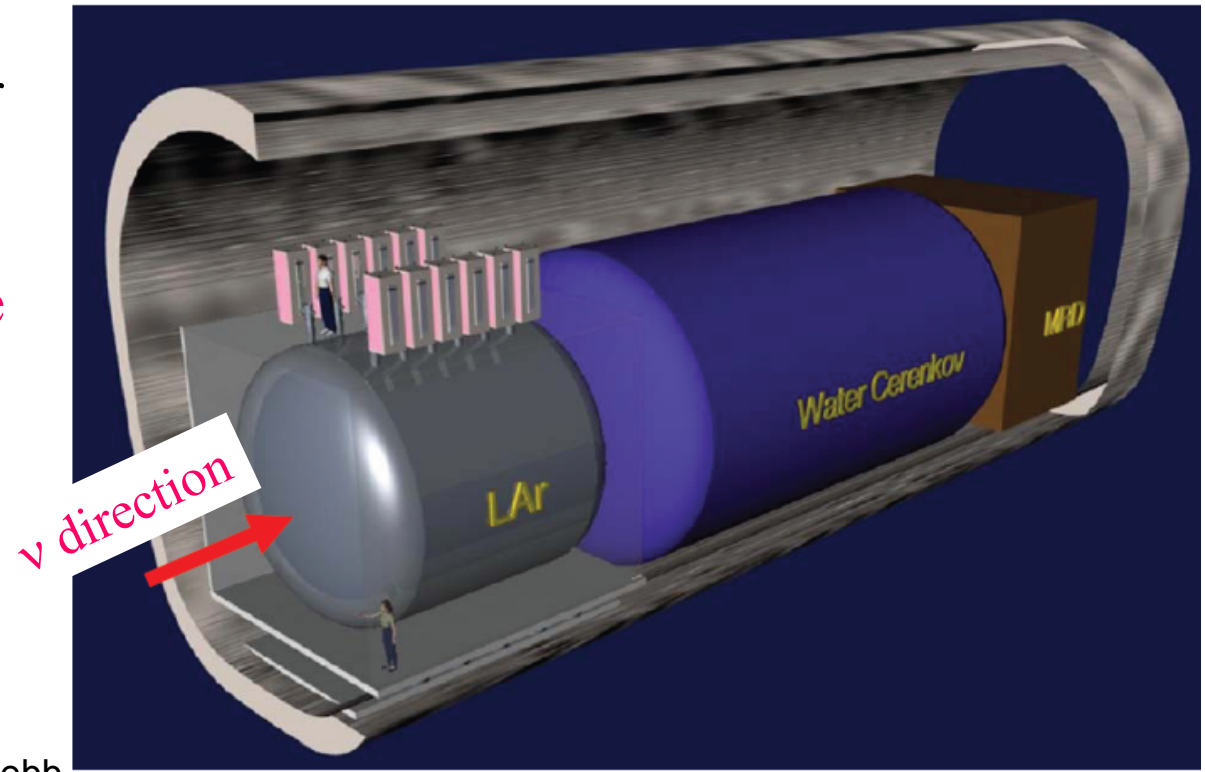
T2HK Near Detector Addition: 2km



Detectors located 2km from target sees point source of neutrinos, like Far Detector

Question:
what about $\nu_\mu \rightarrow \nu_\tau$ at the 2km detector?

2km detectors:
Liquid Argon
Water Cerenkov
Muon Range Detector



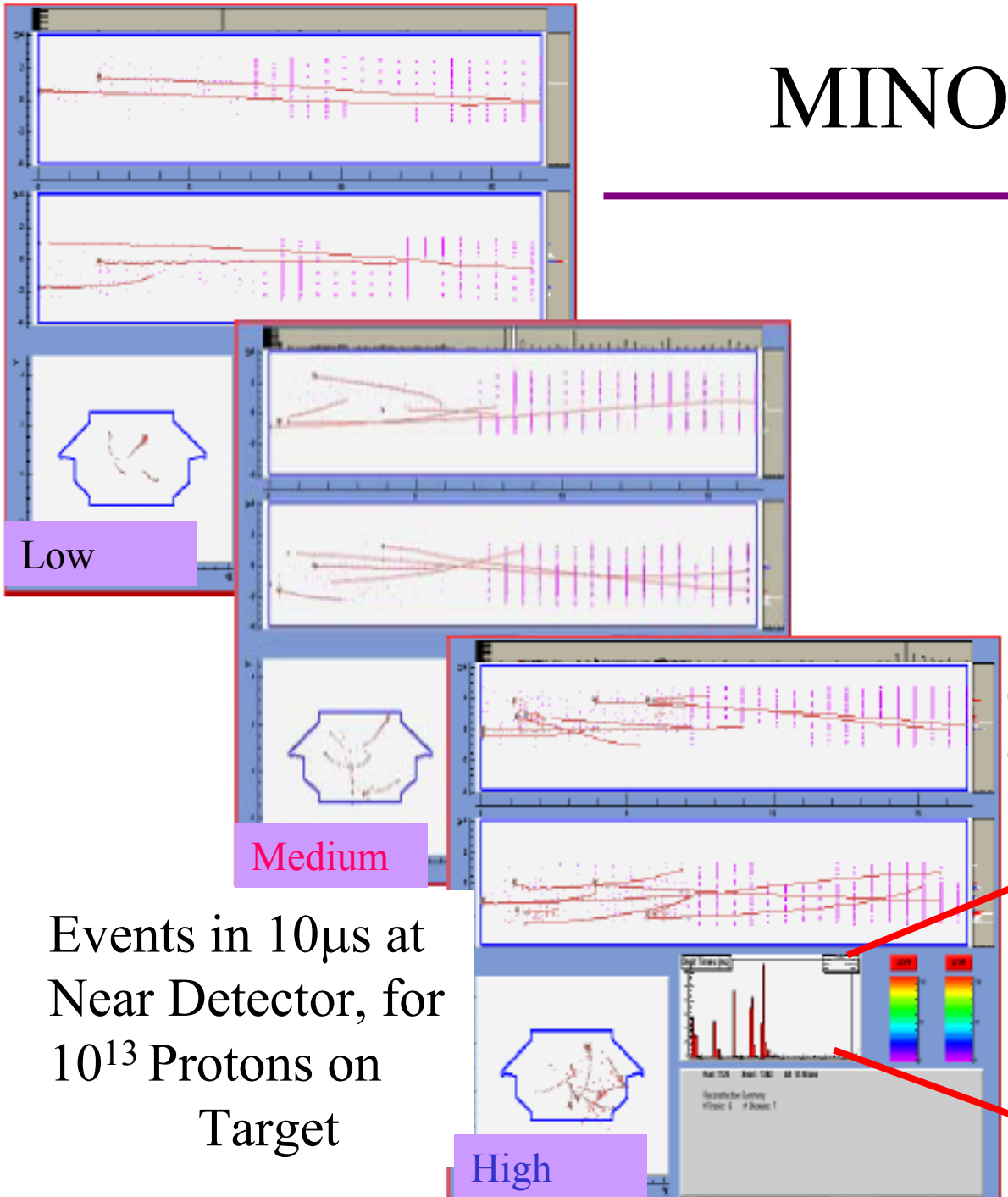
MINOS Near Detector (*cf* Far)

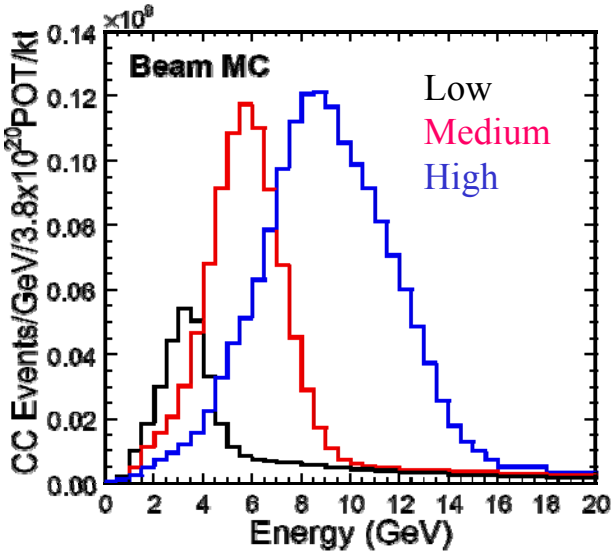
- 1040m from target (735km)
- 103m underground (705m)
- 980 ton mass (5400 ton mass)
- 3.8m x 4.8m x 16m (8m octagon)
- 282 steel + 153 scintillator planes (484 planes)
- Two distinct sections:

  Front: Calorimeter
  - Every plane instrumented

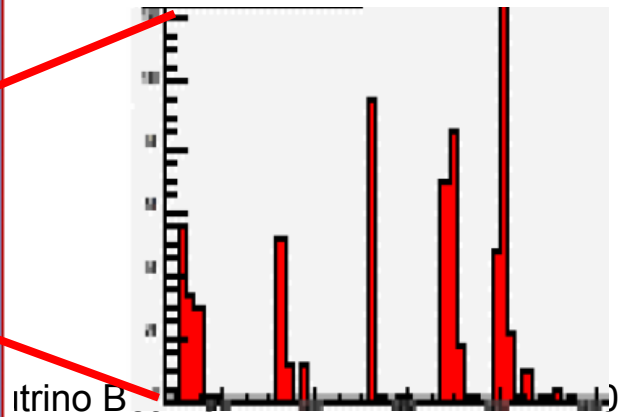
  Back: Spectrometer
  - One in five planes instrumented
- Fast QIE electronics
  - Continuous (19ns) sampling in spill

MINOS Near Rates





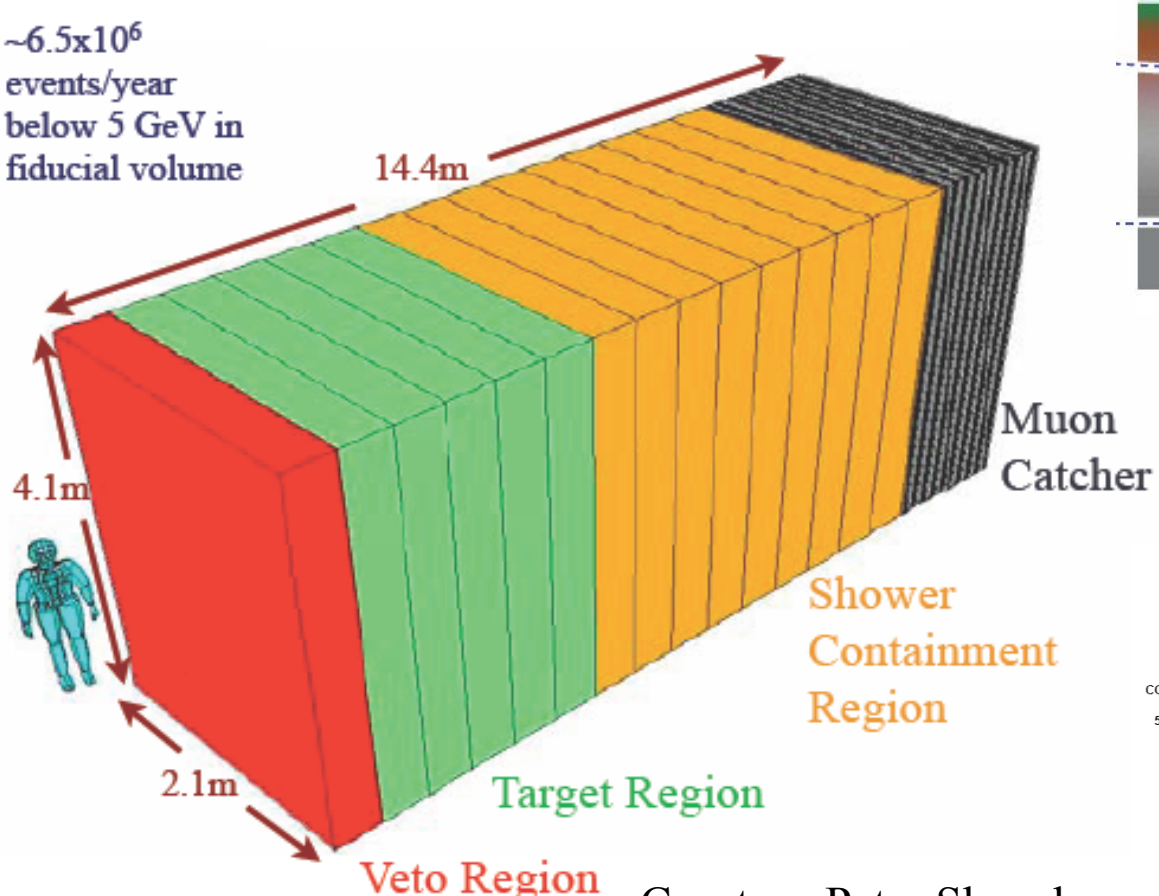
Signal Time (nsec)

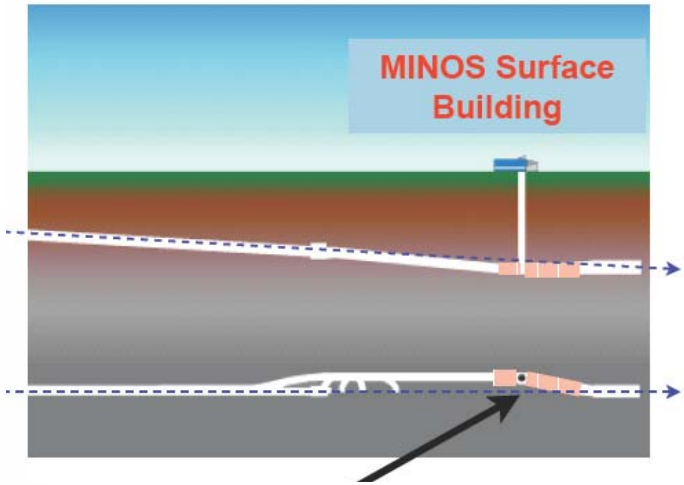


Events in 10μs at Near Detector, for 10^{13} Protons on Target

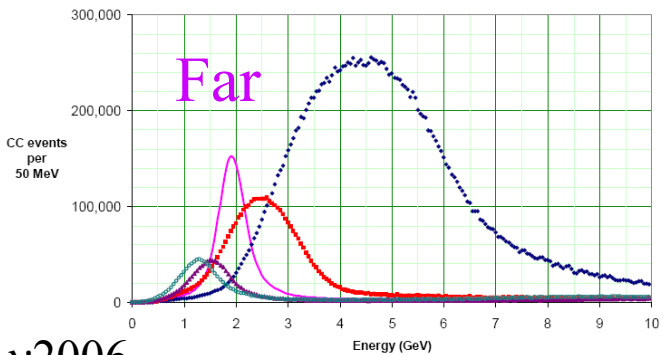
NOvA Near Detector

- Same segmentation and structure as far detector, but
  - sees line source
  - Needs very tight fiducial cuts
- Designed to operate at several different angles





Can operate between 4-21 mrad Off axis (Far Detector is 14mrad)



Courtesy Peter Shanahan, v2006

Near Detector Summary

Exp't	Detector	Near Detector Strategy
K2K	Water Cerenkov	Several, one "identical"
MINOS	Steel Scintillator	"Identical", but faster electronics
OPERA	Emulsion-Lead	No Near Detector
T2K	Water Cerenkov	2 at 280m for flux (coarse) and cross sections (fine-grained), 1 at 2km that is "identical+"
NOvA	Segmented Scintillator	1 that is "identical" but moves, plus fine-grained MINERvA in almost same beam

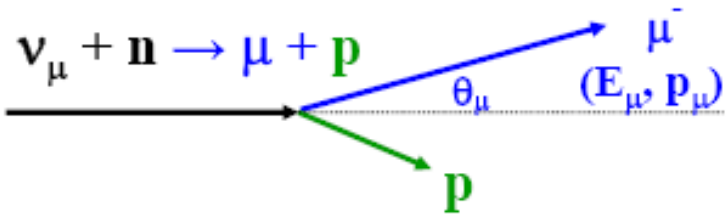
Remainder of Talk

- ν_μ disappearance
  - K2K Near Detector Analysis and Result
  - MINOS Near Detector Analysis and Result
- ν_e Appearance
  - K2K Result
  - MINOS, NOvA, T2K, OPERA Sensitivity and Background Comparison
- What will we need to take advantage of more statistics?
  - Hadron Production Experiments
  - Dedicated Cross Section Measurements
- Reward for working hard: combining NOvA and T2K
  - Mass Hierarchy

Reminder from Nakaya's Lecture I

K2K Neutrino Energy E_ν Reconstruction

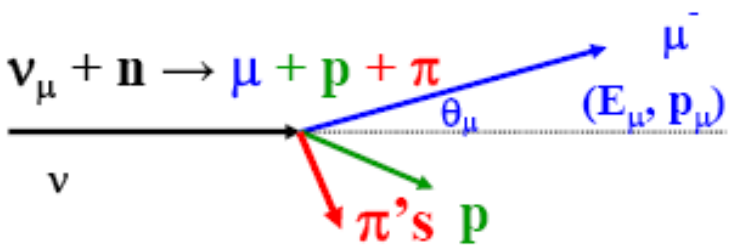
CC quasi elastic (QE)

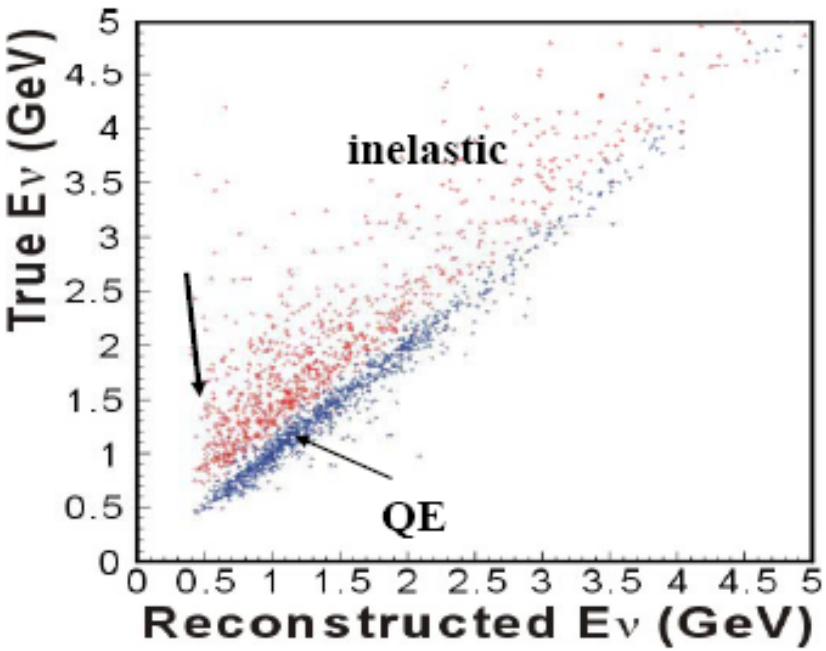


$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

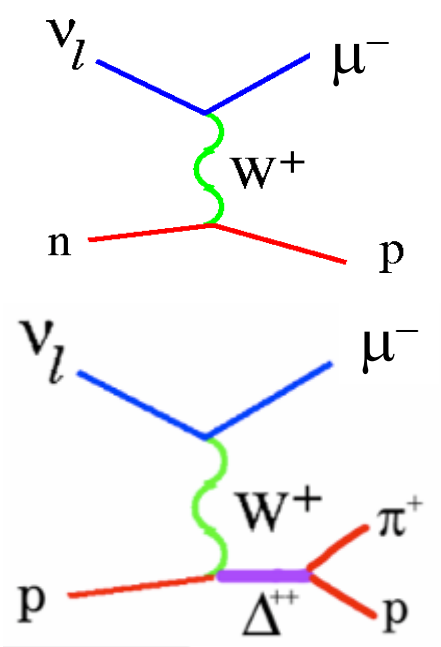
$$\text{Rate}(E\nu,\text{Near}) \rightarrow \underline{\phi(E\nu,\text{Near})}$$
$$\uparrow$$
$$\sigma(\text{QE}),\ \sigma(\text{nonQE})$$

CC inelastic





Constraining Cross Section Model in K2K Near Detector



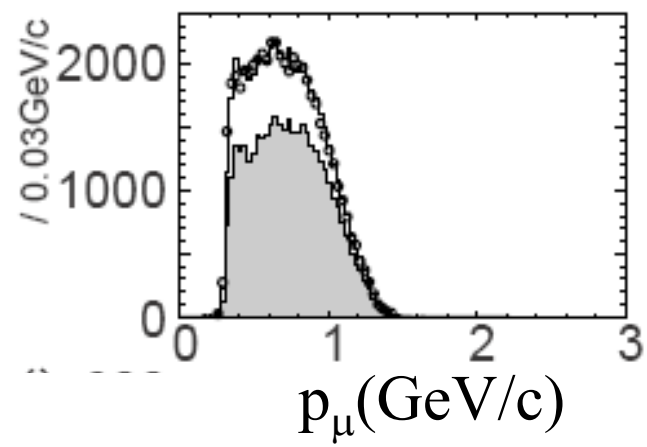
QE

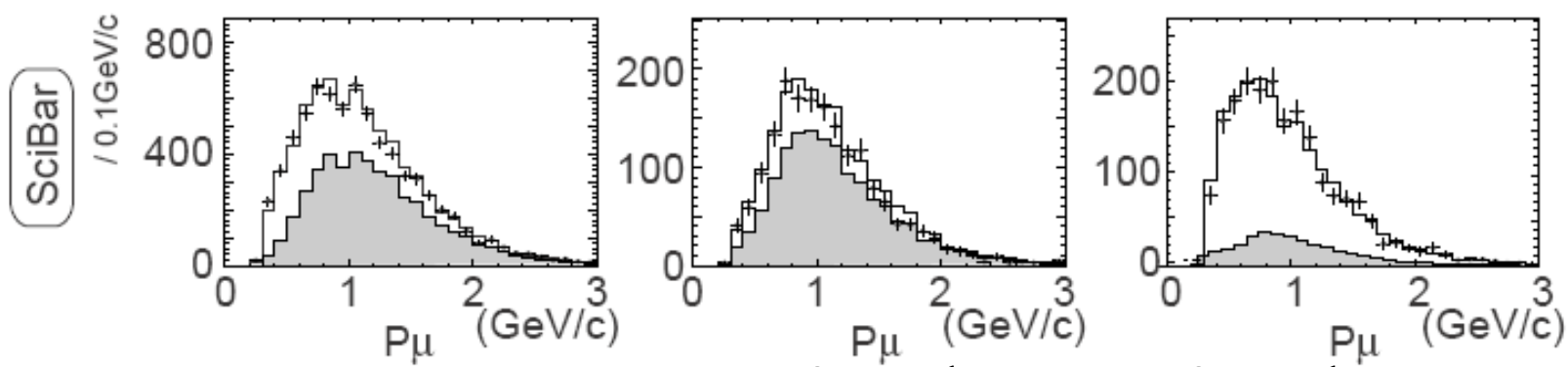
non-QE

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

You can derive this…

1-ring events at 1kT





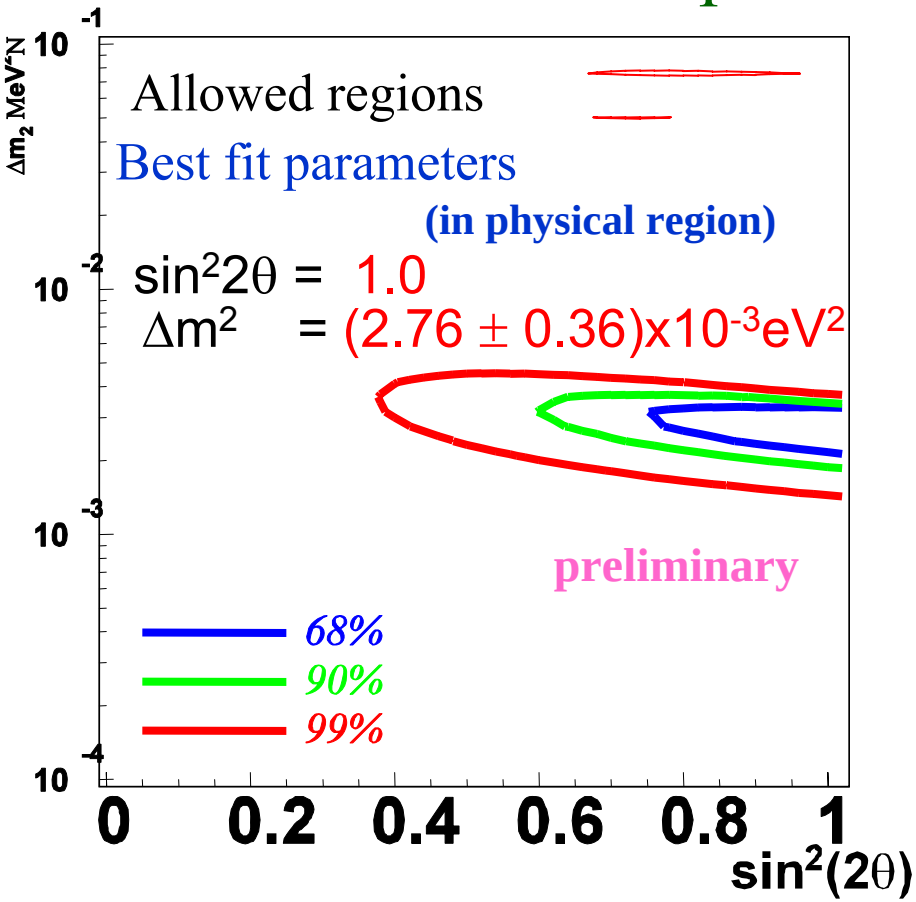
hep-ex/0606032

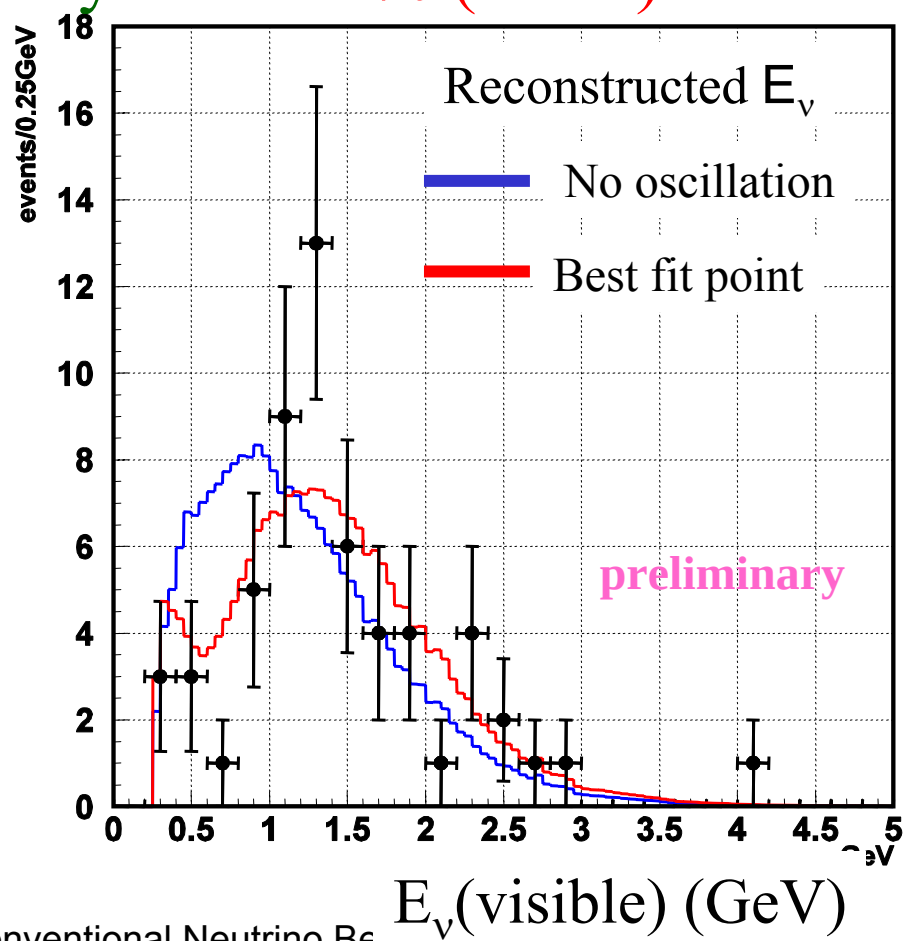
1 track 2 track 2 track non-qe

Measurement of $\nu_\mu \rightarrow \nu_\mu$ survival in K2K

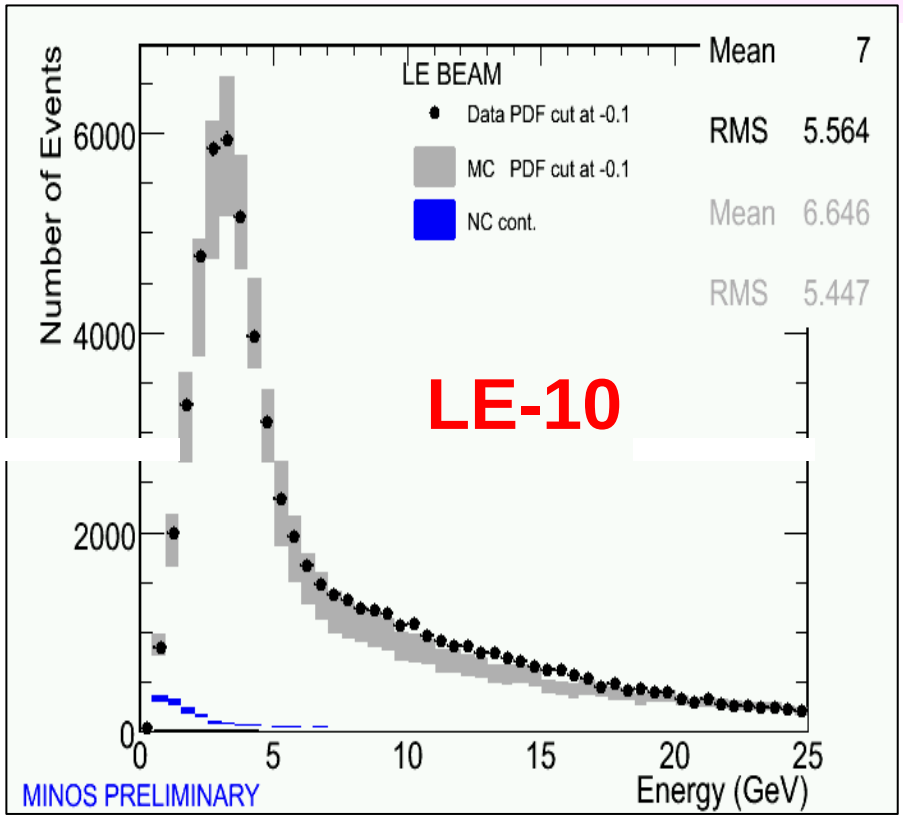
Use both **Number of events** + **Spectrum shape**

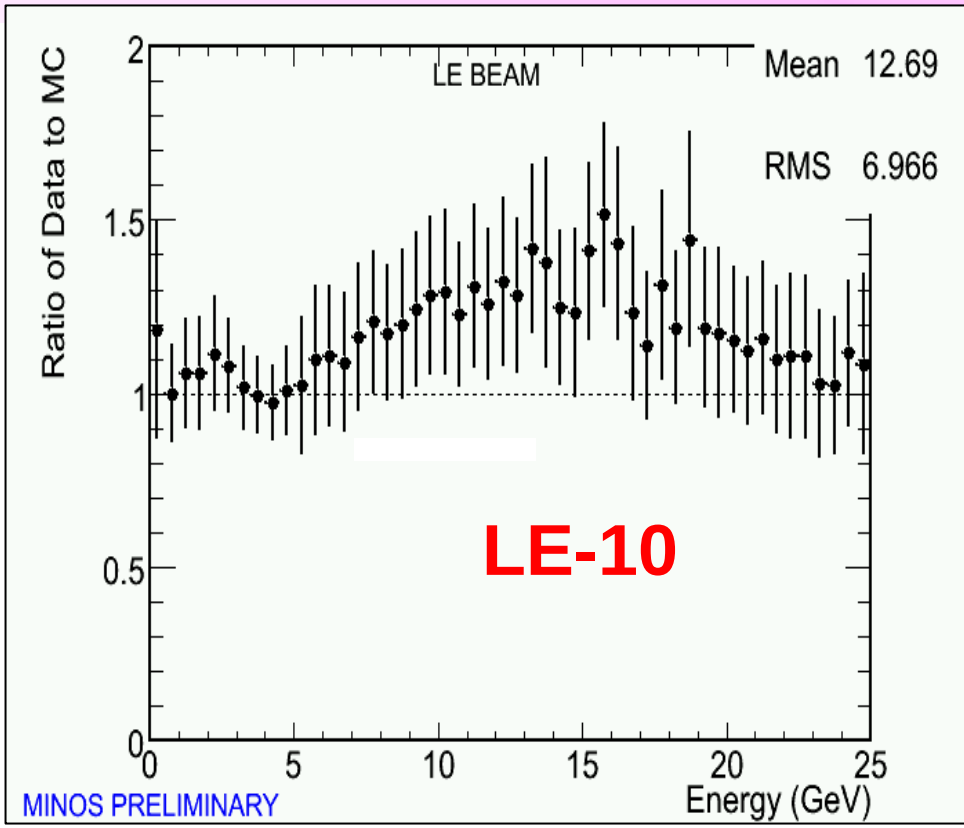
Null oscillation probability is 0.003% (4.19s)





Measurement of $\nu_\mu \rightarrow \nu_\mu$ survival in MINOS





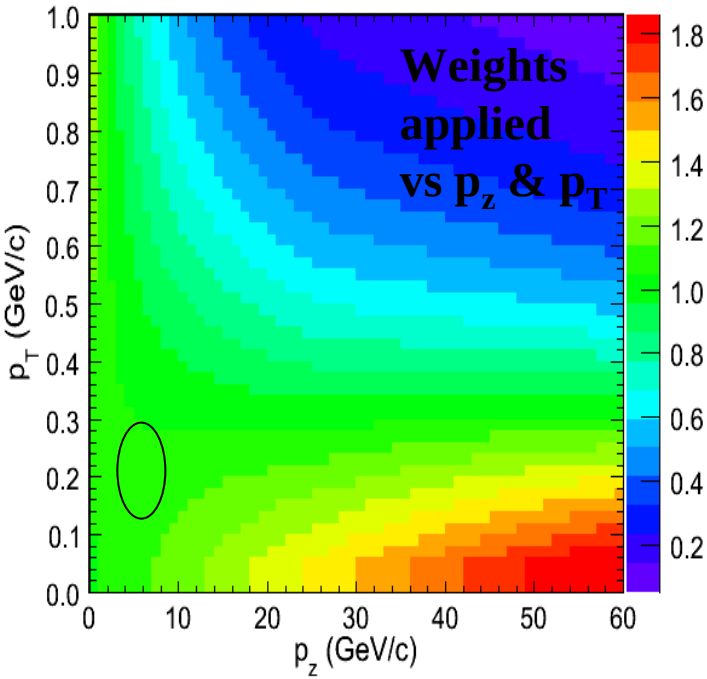
See 10%-40% data-MC differences in near detector:
how to extrapolate to Far?

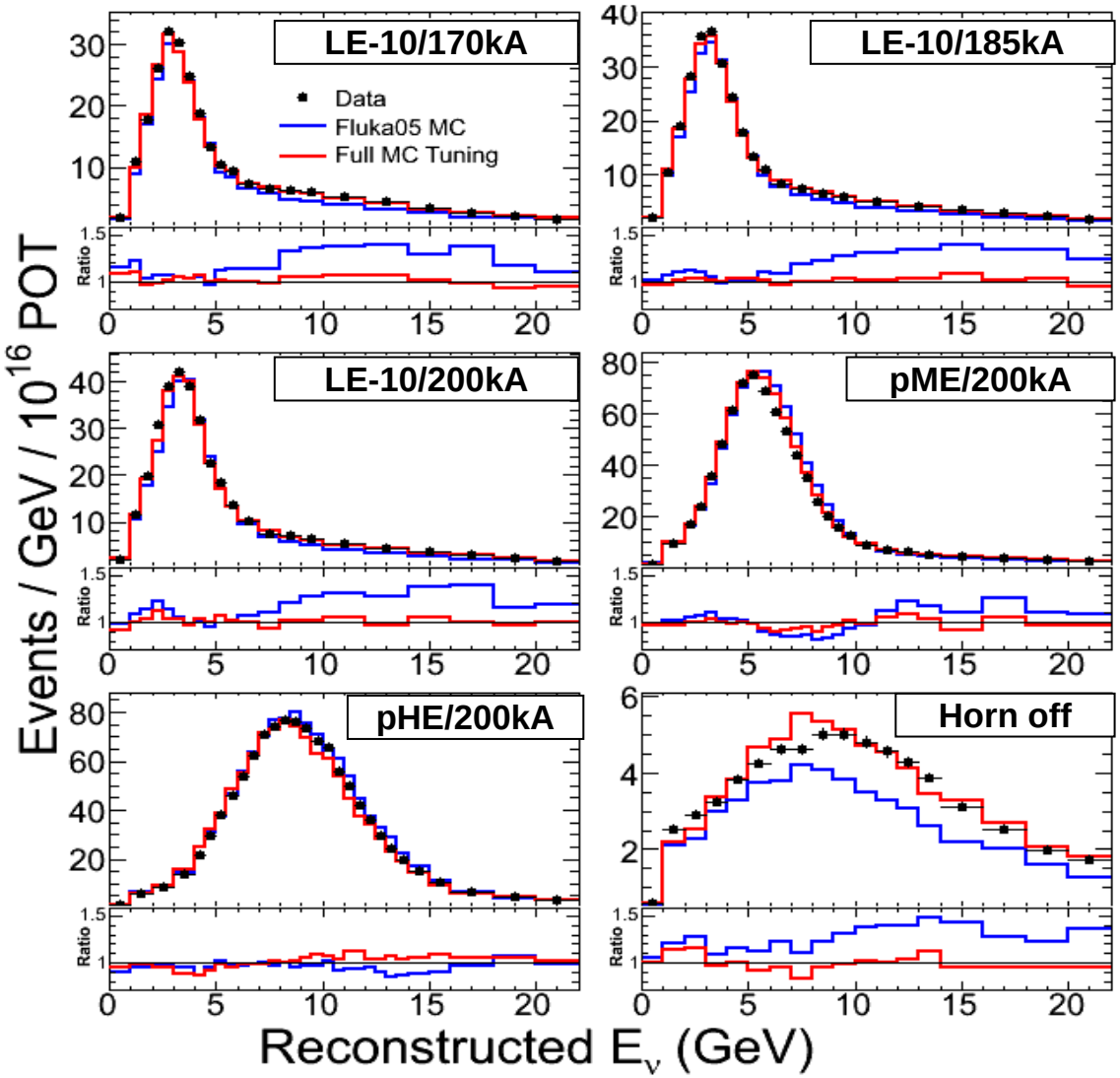
Error envelopes include uncertainties in cross-sections, beam and detector

Near Detector Tuning at MINOS

- By taking data at several horn currents and target positions, MINOS isolated the problem to Hadron Production Model

◯ = pions focused by horns





MINOS ν_μ Systematic Errors

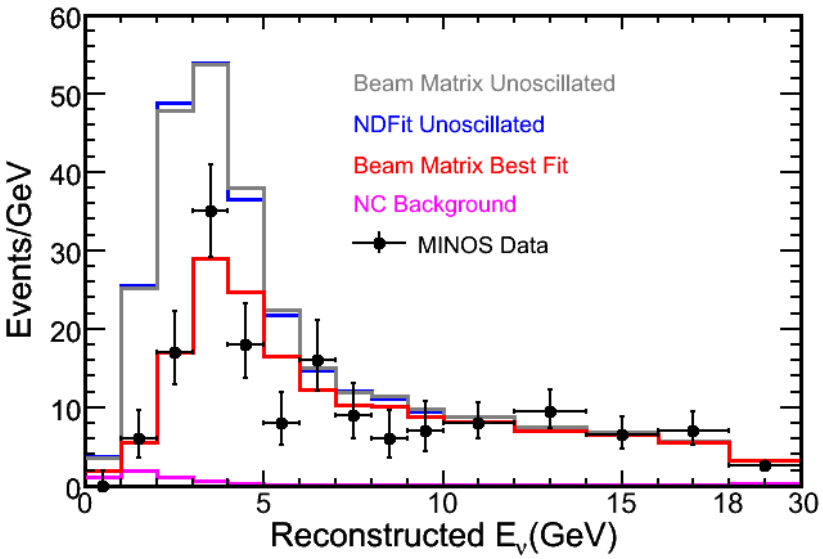
- Systematic shifts in the fitted parameters are computed using MC "fake data" samples for $\Delta m^2=2.7\times10^{-3}$ eV^2 and $\sin^2 2\theta=1.0$
- The uncertainties considered and shifts obtained:

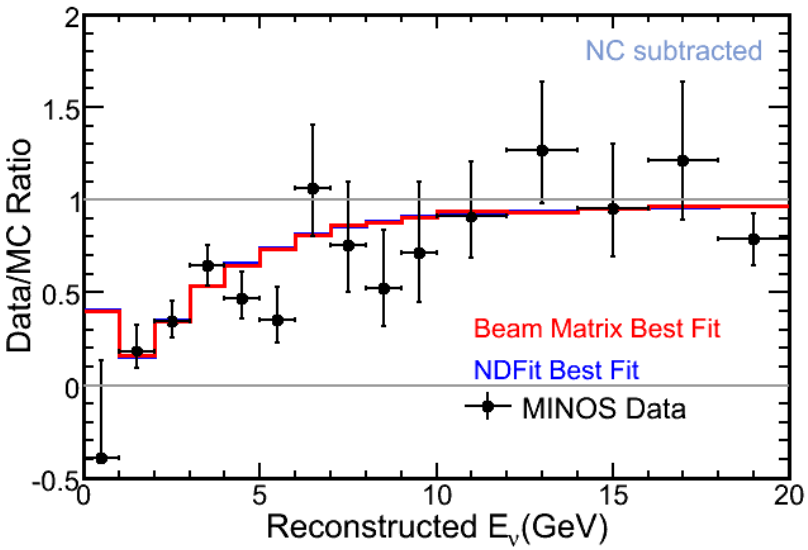
Preliminary Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2 2\theta$
Near/Far normalization ±4%	**0.050**	**0.005**
Absolute hadronic energy scale ±11%	**0.060**	**0.048**
NC contamination ±50%	**0.090**	**0.050**
All other systematic uncertainties	**0.044**	**0.011**
Total systematic (summed in quadrature)	**0.13**	**0.07**
Statistical error (data)	**0.36**	**0.12**

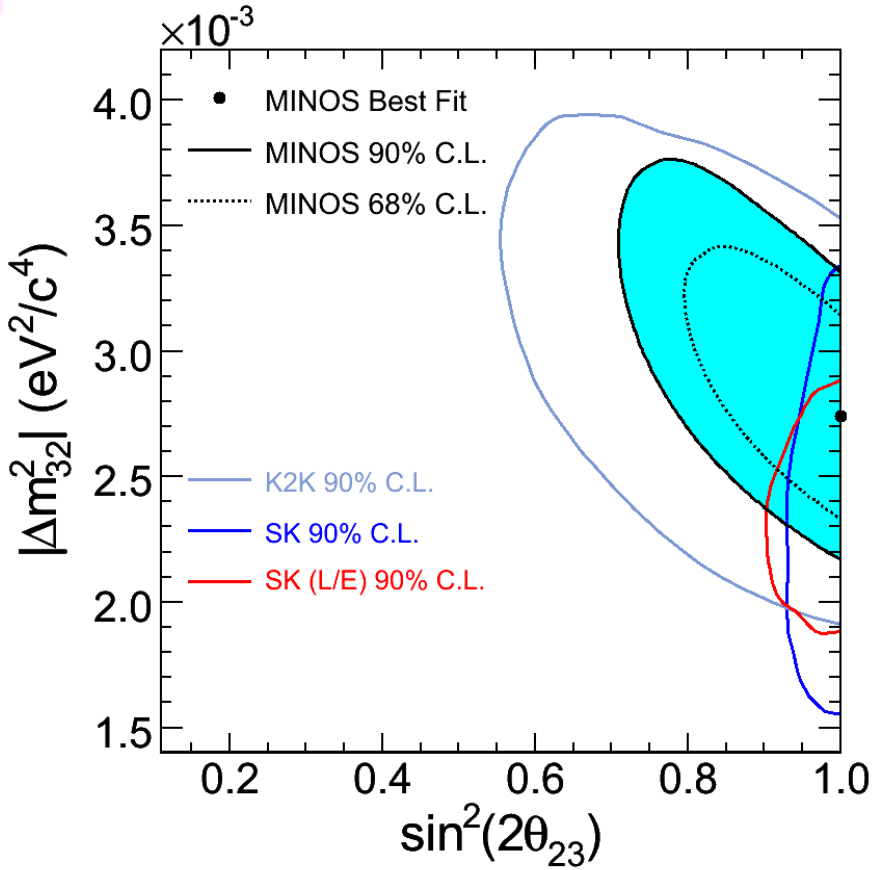
- Magnitude of systematic error is ~40% of statistical error for Δm^2
- Several systematic uncertainties are data driven → improve with more data and study

Chris Smith, FNAL Seminar

MINOS ν_μ Survival Results







$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst}) \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\text{stat} + \text{syst})$$

$$\text{Normalization} = 0.98$$

Challenges to ν_e Appearance

Problem: looking for a ν_e in a beam of ν_μ's

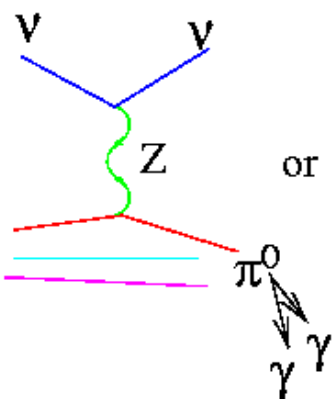
- Intrinsic beam ν_e
  - K decays

$$K \rightarrow \pi e \nu_e$$

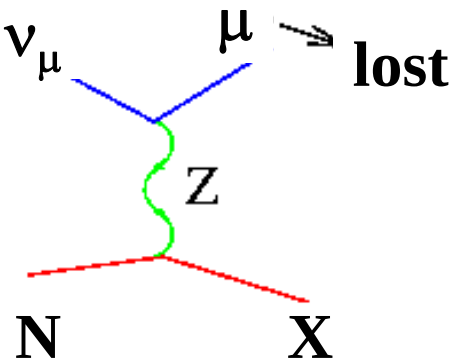
  - μ decays

$$\pi \rightarrow \mu \rightarrow e \nu_e \nu_\mu$$

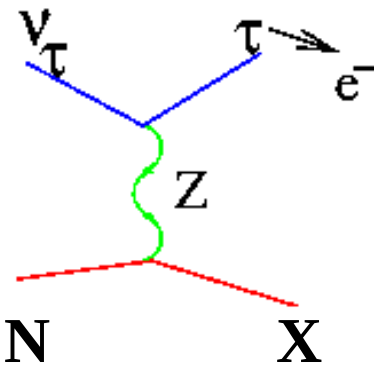
- Neutral Current events



- ν_μ charged current events



- ν_τ charged current events



Probabilities

$$N_{far} = \phi_{\nu_\mu} \sigma_{\nu_x} P(\nu_\mu \rightarrow \nu_x) \varepsilon_x M_{far} + B_{far}$$

ϕ=flux, σ= cross section ε=efficiency M=mass

$$P(\nu_\mu \rightarrow \nu_x) = \frac{N_{far} - B_{far}}{\phi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M_{far}}$$

B_{far}= Backgrounds at far detector, from any flux

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i}(P) \sigma_{\nu_i} \varepsilon_{ix} M_{far}$$

Probabilities, continued

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + \frac{N_{far} - B_{far}}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)^2}[\delta(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x)]^2$$

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + (N_{far} - B_{far})\left(\left[\frac{\delta\phi_{\nu_\mu}}{\phi_{\nu_\mu}}\right]^2 + \left(\frac{\delta\sigma_{\nu_x}}{\sigma_{\nu_x}}\right)^2 + \left(\frac{\delta\varepsilon_{\nu_x}}{\varepsilon_{\nu_x}}\right)^2\right)$$

2 Regimes:

$$N_{far} >> B_{far}$$

$$N_{far} \approx B_{far}$$

Problem:

Don't always know *a priori* which regime you are in

---depends on Δm^2,

---depends on $\sin^2 2\theta_{13}$

Near Detector Strategy

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i\ far}(P)\sigma_{\nu_i}\varepsilon_{ix}M_{far}$$

Backgrounds come from several sources

$$N_{near} = \sum_{i=\mu,e} \phi_{\nu_i\ near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}$$

Build near detector with same ε

$$B_{far} = N_{near}\frac{\sum_{i=\mu,e} \phi_{\nu_i\ far}(P)\sigma_{\nu_i}\varepsilon_{ix}M_{far}}{\sum_{i=\mu,e} \phi_{\nu_i\ near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}}$$

Simulations better at predicting ratios absolute levels

$$B_{far} = \sum_{i=\mu,e} N_{near,i}\frac{\phi_{\nu_i\ far}}{\phi_{\nu_i\ near}}\frac{\sigma_{\nu_i}}{\sigma_{\nu_i}}\frac{\varepsilon_{ix}}{\varepsilon_{ix}}\frac{M_{far}}{M_{near}}$$

Near Detector Strategy (cont'd)

$$B_{far} = \int dE_\nu \sum_{i=\mu,e} N_{near,i}(E_\nu)\left(\frac{\phi_{\nu_i\ far}}{\phi_{\nu_i\ near}}\right)(E_\nu)\left(\frac{\sigma_{\nu_i}}{\sigma_{\nu_i}}\right)(E_\nu)\left(\frac{\varepsilon_{ix}}{\varepsilon_{ix}}\right)(E_\nu)\frac{M_{far}}{M_{near}}$$

- But ratios don't cancel everything
- Underlying problem: fluxes are different
  - Near detector: line source, far detector: point source
  - But even if that is solved, still ν_μCC oscillations
- All of these terms are functions of energy
  - Uncertainties in energy dependence of cross sections translate into far detector uncertainties…

Search for $\nu_\mu \rightarrow \nu_e$ oscillation in K2K

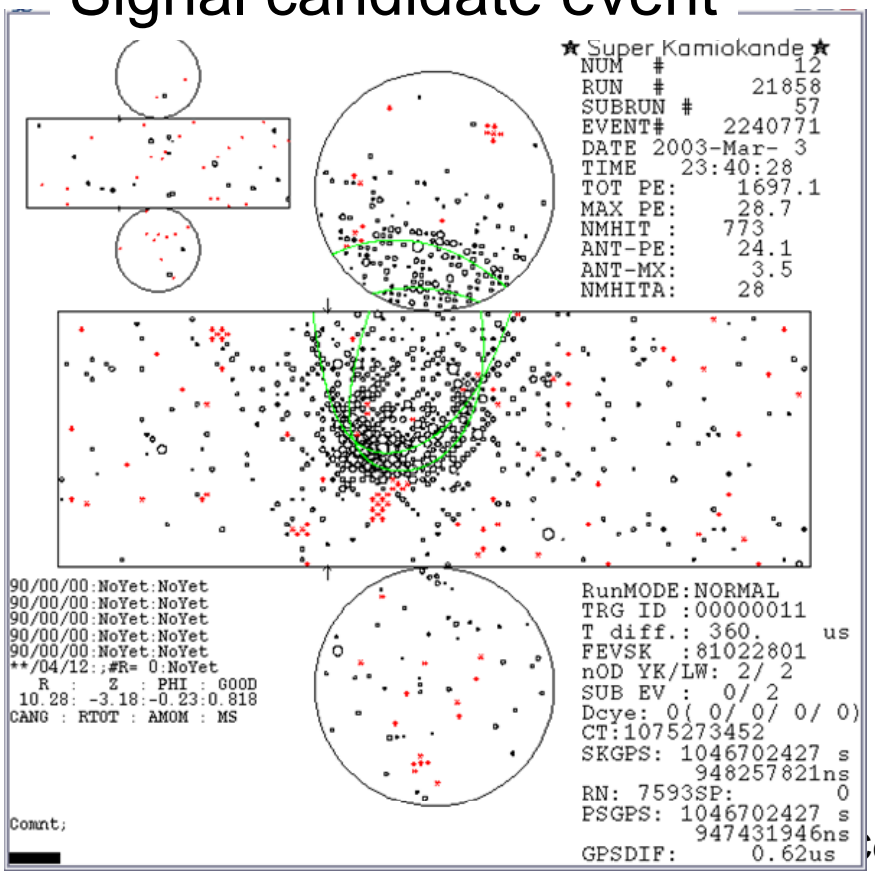
As a result,

# of expected BG 1.63 events

(1.25 from ν_μ & 0.38 from beam ν_e)

# of observed events 1 event

Signal candidate event



RUN: 21858

EVENT: 2240771

$E_{\gamma 1}$: 266.7MeV

$E_{\gamma 2}$: 170.8MeV

$q_{\gamma\gamma}$: 22.5 deg.

$M_{\gamma\gamma}$: 83.1MeV/c^2

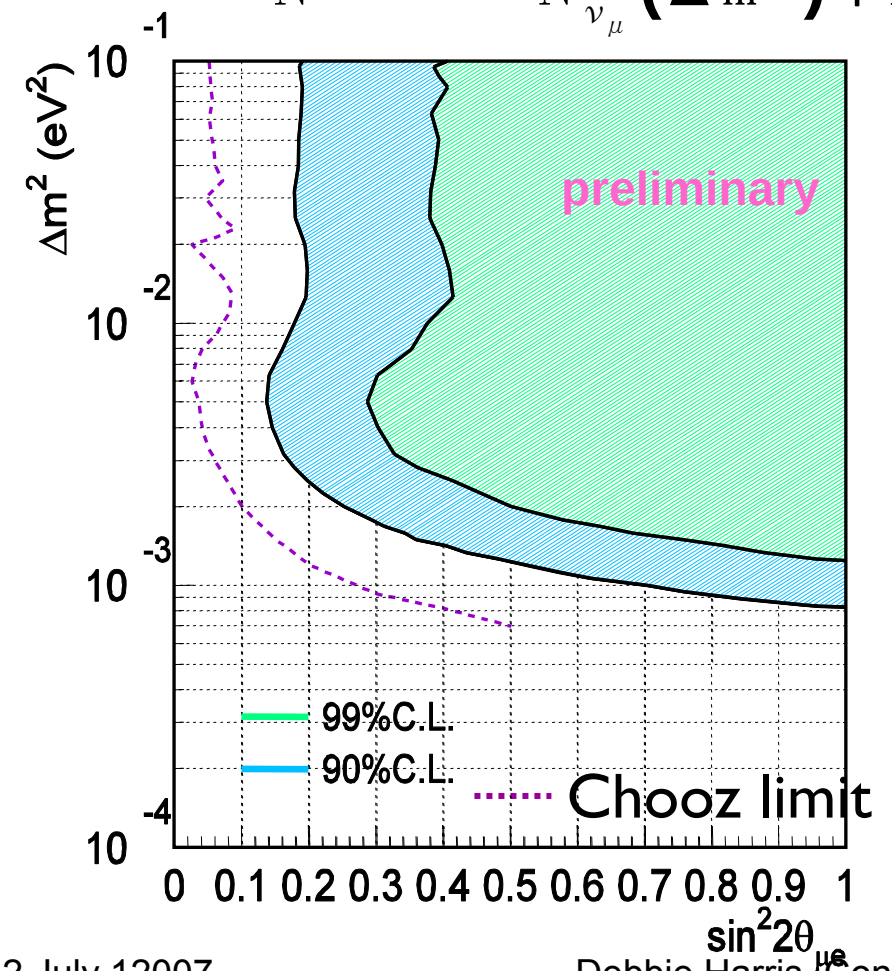
Though, this event looks like multi-ring…

Slide courtesy Y. Hayato

Search for $\nu_\mu \rightarrow \nu_e$ oscillation in K2K

Expected # of electron candidates (N_{SK})

$$N^{SK} = N^{BG}_{\nu_\mu}(\Delta m^2) + N^{BG}_{BEAM\,\nu_e} + N^{SIG}_{OSC\,\nu_e}(\sin^2 2\theta, \Delta m^2)$$



Expected BG: 1.63
Observed: 1

upper limit on **$\sin^2 2\theta_{\mu e}$**

(90% CL)

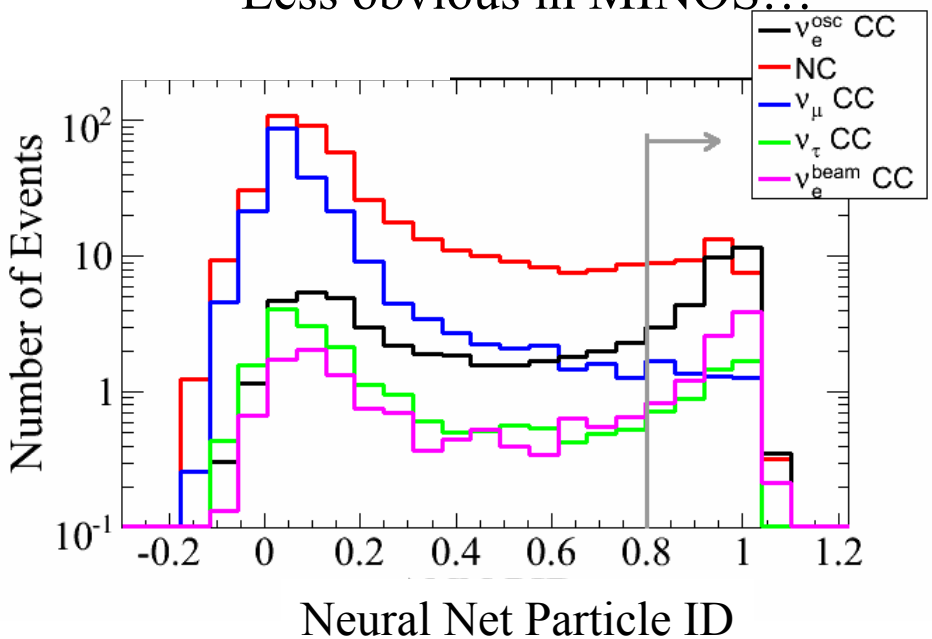
$0.18@\Delta m^2=2.8\times10^{-3}eV^2$

($0.25@\Delta m^2=2.0\times10^{-3}eV^2$
$0.16@\Delta m^2=3.0\times10^{-3}eV^2$)

Slide courtesy Y. Hayato

Search for $\nu_\mu \rightarrow \nu_e$ oscillation in MINOS

- How to discriminate between electrons and $\pi^\pm\mu^\pm$?
  - Longitudinal, transverse event shape…
- How to discriminate between electrons and π^0?
  - Less obvious in MINOS…



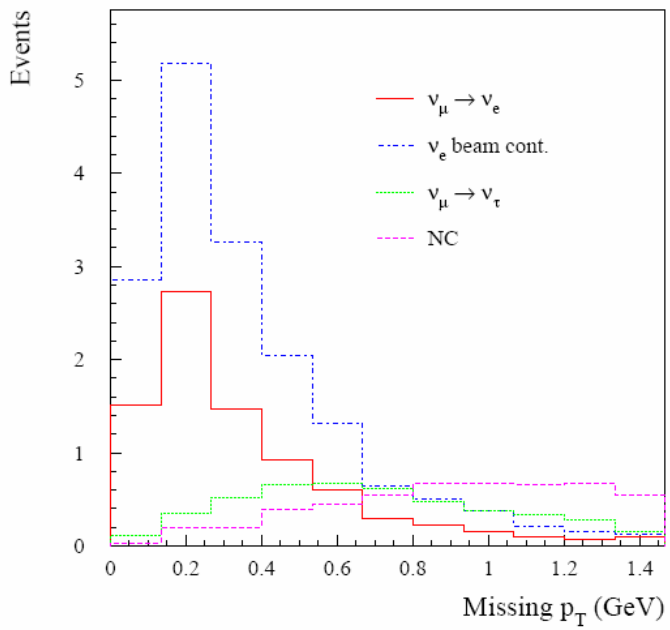
ν_μ CC	NC	ν_e^{beam}	ν_τ CC	Total	ν_e^{osc}
5.6	39.0	8.7	4.7	58.0	29.1

Neural Net MC example

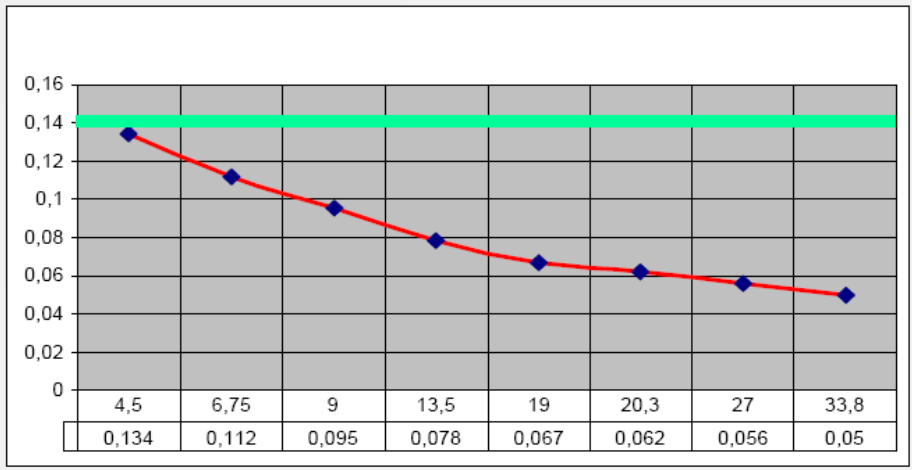
- Oscillation parameters:
  $\sin^2(2\theta_{13}) = 0.1$
  $|\Delta m_{32}|^2 = 2.7\times10^{-3}\text{eV}^2$
  $\sin^2(2\theta_{23}) = 1$
- POT = $16\text{x}10^{20}$ ($\times12$ what has already collected)

Today's signal is tomorrow's background…

- OPERA: main goal is to see ν_τ CC events through $\tau \rightarrow e$ decay channel, so should be sensitive to



Combined fit of E_e, E_{vis}, $(pt)_{miss}$



OPERA $\sin^2 2\theta_{13}$ vs pot's

$\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV^2 $\Theta_{23} = 45°$

$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2

$\sin^2 2\theta_{13}$	ν_eCC signal	$\tau \rightarrow e$	ν_μCC $\rightarrow \nu_\mu$NC	ν_μNC	ν_eCC beam
0.095	9.3	4.5	1.0	5.2	18

5 years, 4.5×10^{19}POT/year

Sensitivity versus Time

- People writing proposals much prefer to be in the situation where you have <1 event background.
- Then sensitivity $\propto$ time
- Note: ν_e searches are already at 1 or more background events:
  - K2K: 1.6 background events per 10^{20}
  - MINOS: 3.6 background events per 10^{20} POT
  - OPERA: 13 background events per 10^{20} POT
- Need to improve
  - Intrinsic χ in the beam: use Off-axis trick
    - ν_μ peaked in energy. Electron neutrinos over a broad spectrum.
  - ν_e CC/ NC event separation: use lower energy, or better detector, or off axis beam (since NC events reconstruct with energy lower than the peak)
  - Statistics: more detector mass or proton power or both
- Next Generation ν_e searches:
  - T2K: 23 background events in 5-year run
  - NOvA: 19 background events in 6-year run

How well do new designs do?

	ν_μ CC	NC	Beam ν_e	ν_τ CC	Total Back-ground	Signal	S/√(S+B)
K2K	0	1.3	0.4	0	1.7	**~1**	**0.6**
MINOS	5.6	39	8.7	4.7	58	**29.1**	**3.1**
OPERA	1	5.2	18	4.5	28.7	**10**	**1.6**
T2K	1	9	13	0	23	**103**	**9.2**
NOvA*	0.5	7	11	0	18.5	**148**	**11.5**

Assume $\sin^2\theta_{13}=0.1$, $\delta=0$, *normal hierarchy, but not all same Δm^2

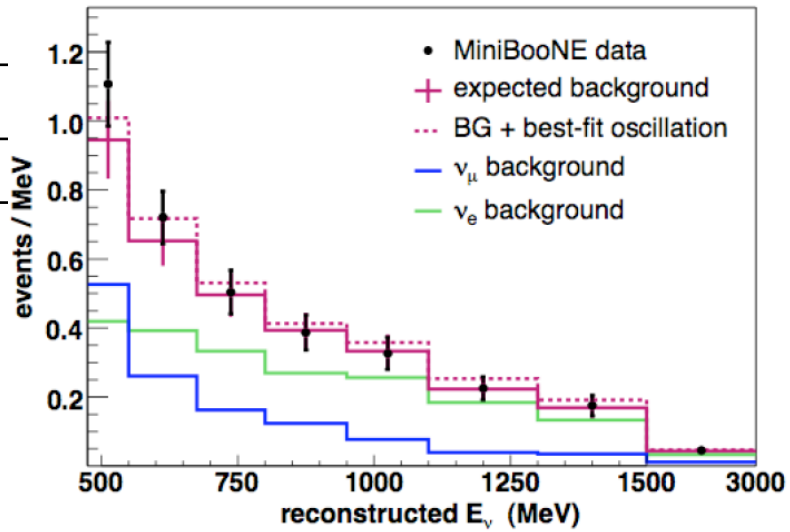
References: K2K PRL(96)2006, MINOS: Smith, FNAL Seminar

OPERA: JPhysG(29) 2003, T2K: Nakadaira ν2006, NOvA:Shanahan,ν2006

How does MiniBooNE compare?

	ν_μ CC	NC	Beam ν_e	ν_τ CC	Total Bk-grnd	Sgnl	S/ √(S+B)
Mini-BooNE	**23**	**89**	**229**	**0**	**358**	**163**	**7.1**
K2K	0	1.3	0.4	0	1.7	**~1**	**0.6**
MINOS	5.6	39	8.7	4.7	58	**29.1**	**3.1**
OPERA	1	5.2	18	4.5	28.7	**10**	**1.6**
T2K	1	9	13	0	23	**103**	**9.2**
NOvA*	0.5	7	11	0	18.5	**148**	**11.5**

Total Background above 475MeV:
358 events
Total signal for 0.26% probability:
163 events



MiniBooNE Signal assumes mixing angle is **factor of ~20 lower** than the that of the other experiments
Reference: FNAL Seminar, April 2007

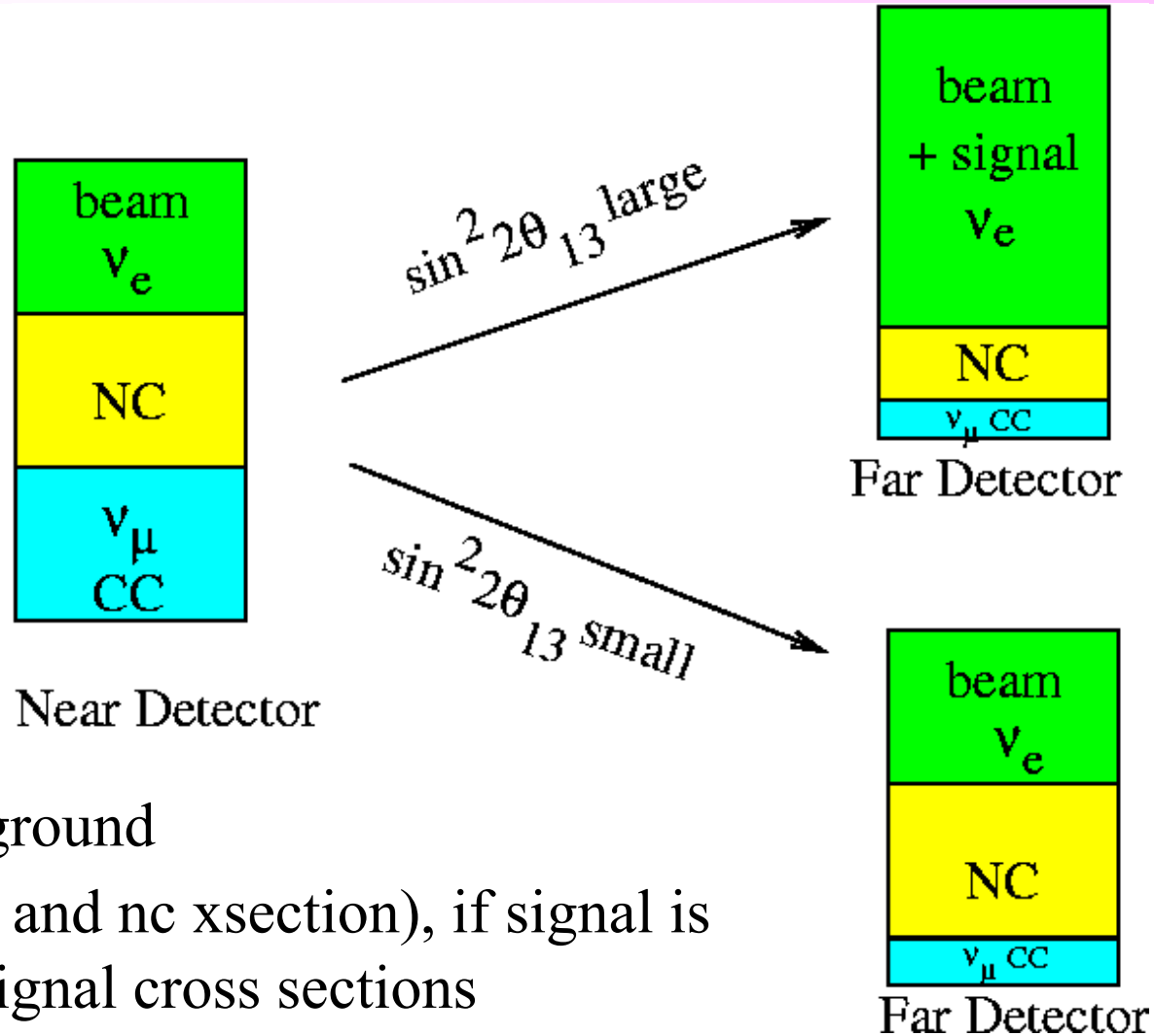
See also Richard Van De Water's Lecture II

Now that we have reduced backgrounds and increased mass…

- Remember, just because your simulation says it is true, that doesn't mean the simulation is right
- Need to measure neutrino interactions better
  - What really comes flying out of the nucleus when it is hit by a neutrino?
- Need to measure hadron production better
  - What really comes flying out of the target when it is hit by protons?

ν_e Appearance Analysis

Summary:
Event Samples are different
Near to far, so
Uncertainties
In cross sections
Won't cancel



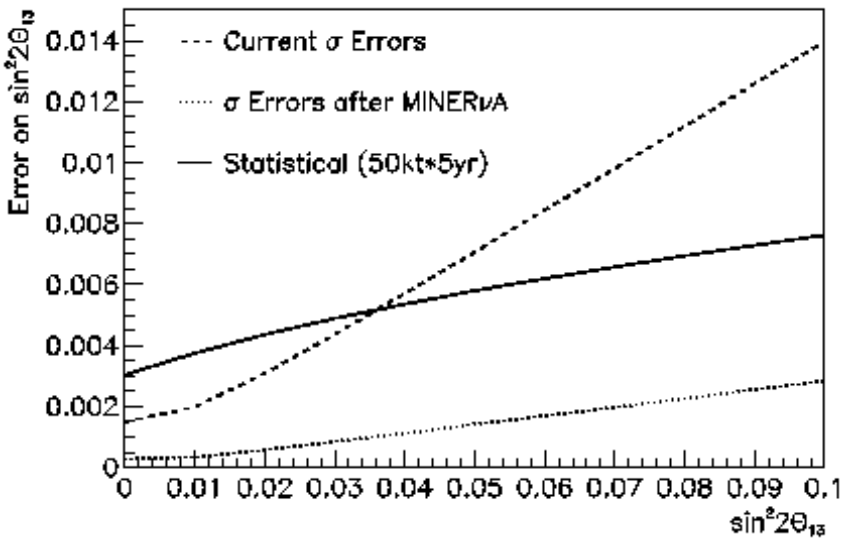
If signal is small,
Worry about background

Prediction (ν_e flux and nc xsection), if signal is Big, worry about signal cross sections

How much do cross section errors cancel near to far?

- **Toy analysis**: start with old NOvA detector simulation, which had same ν_e/NC ratio, mostly QE & RES signal events accepted, more ν_μCC/NC accpeted
- Near detector backgrounds have ~3 times higher $\nu_\mu$cc!
- Assume if identical ND, can only measure 1 background number: hard to distinguish between different sources

Process	Events	QE	RES	COH	DIS
$\delta\sigma/\sigma$		20%	40%	100%	20%
Signal ν_e $\sin^2 2\theta_{13}=0.1$	175	55%	35%	n/i	10%
NC	15.4	0	50%	20%	30%
ν_μCC	3.6	0	65%	n/i	35%
Beam ν_e	19.1	50%	40%	n/i	10%

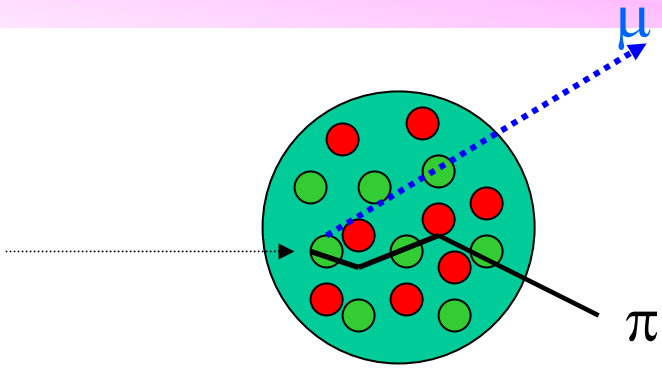


For large $\sin^2 2\theta_{13}$, statistical=8%
For small $\sin^2 2\theta_{13}$, statistical=16%

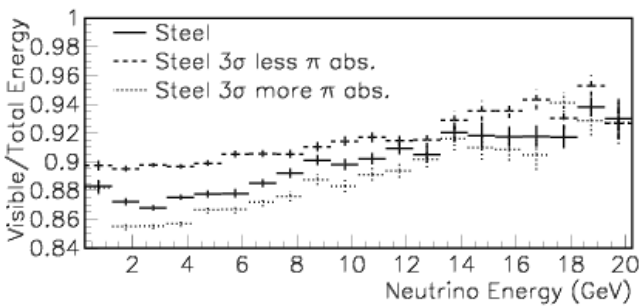
Assume post-MINERνA, σ's known at:
ΔQE = 5%, ΔRES = 5, 10% (CC, NC)
ΔDIS = 5%, ΔCOH_{Fe} = 20%

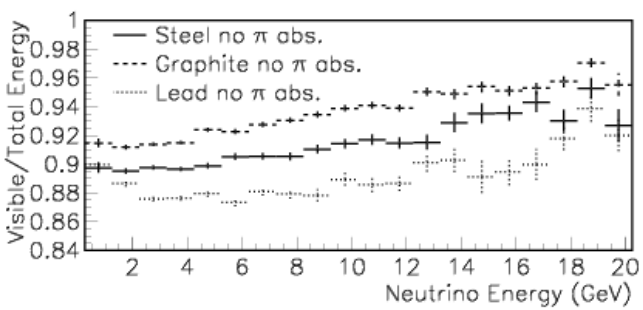
Nuclear effects at MINOS

- Visible Energy in Calorimeter is NOT ν energy!
  - π absorption, rescattering
  - final state rest mass

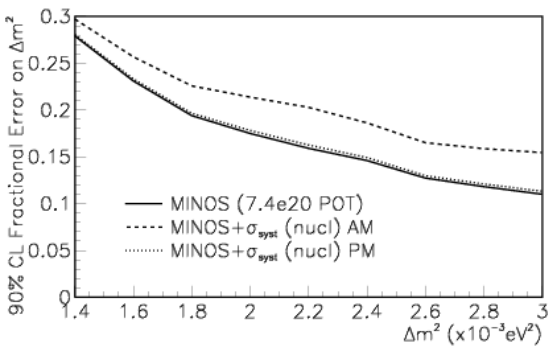


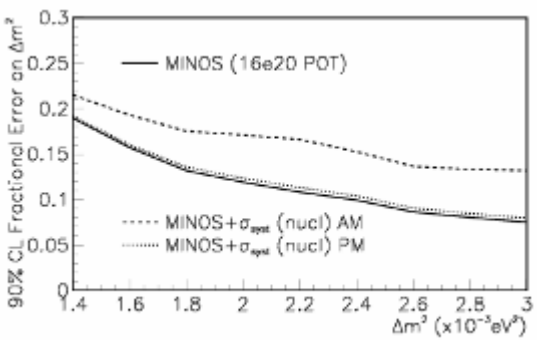
Toy MC analysis:



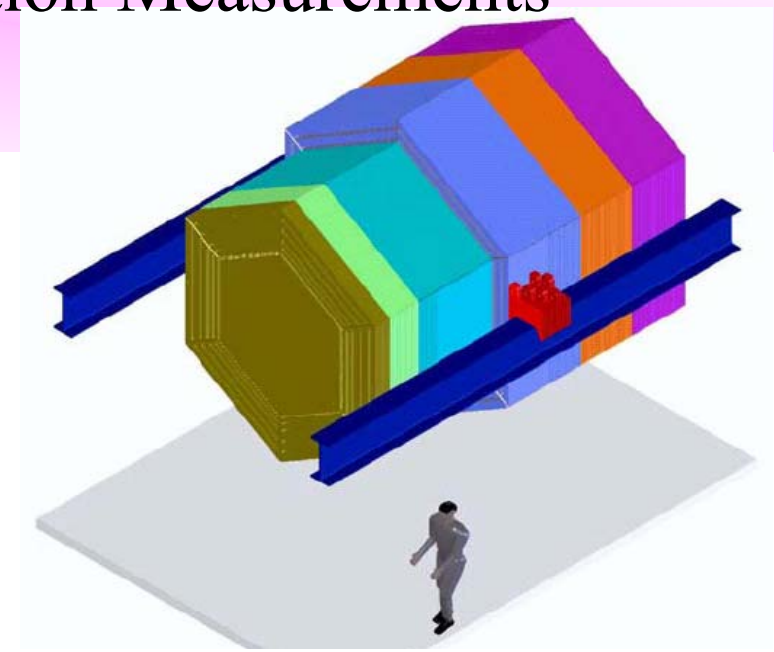


Nuclear Effects Studied in Charged Lepton Scattering, from Deuterium to Lead, at High energies, but nuclear corrections may be different between e/μ and ν scattering

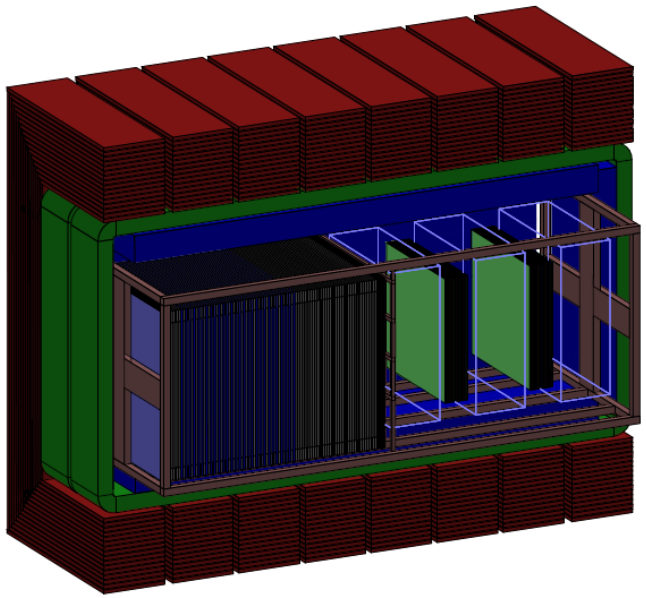




Dedicated Neutrino Interaction Measurements



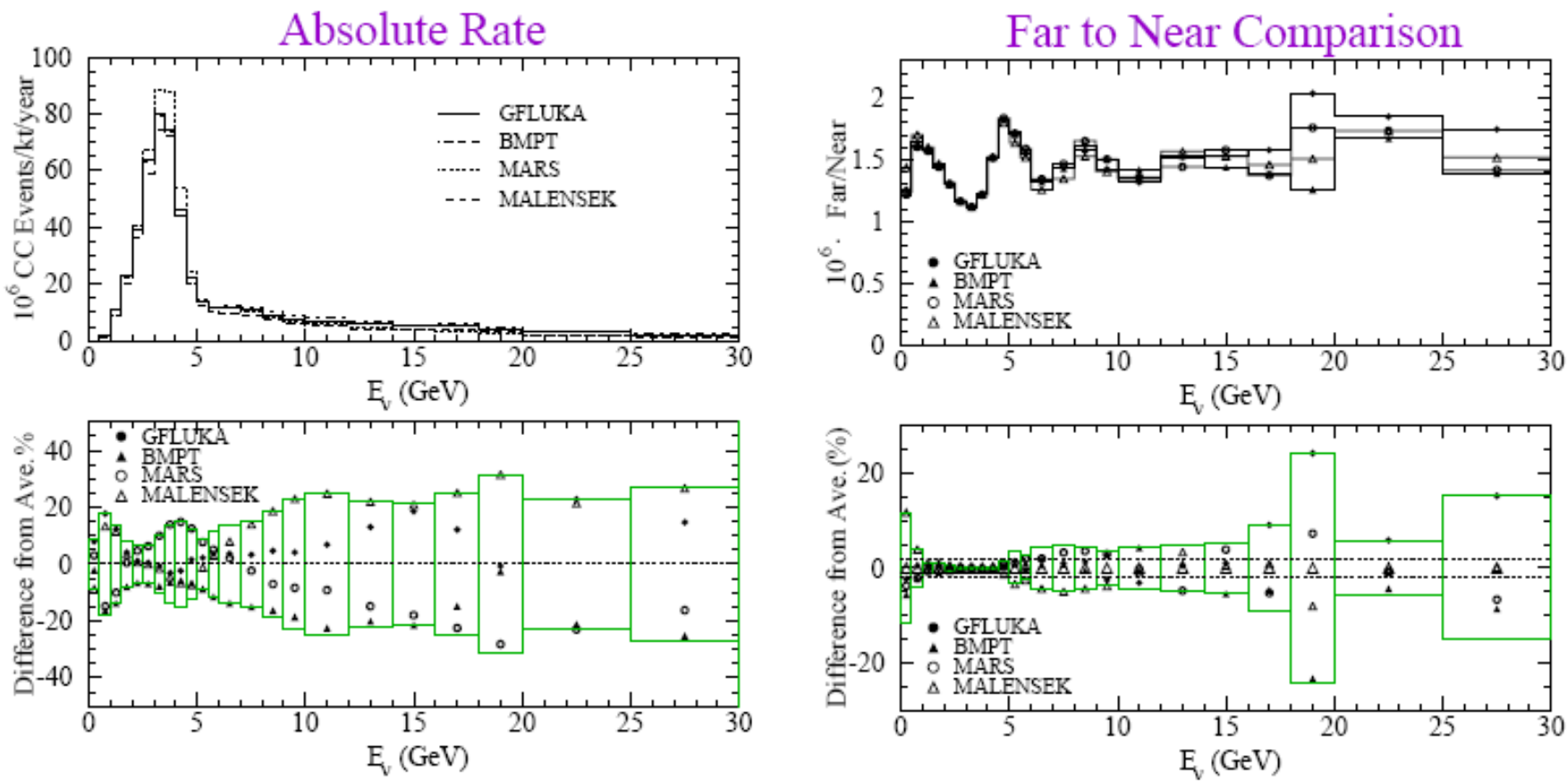
- MINERvA: exclusive final state measurements, 3 nuclear targets, to run in NuMI beamline in time for MINOS and NOvA (and T2K's) data



- T2K 280m Off axis detector: inclusive π^0 measurements and some exclusive states, water target
- SciBooNE: use SciBAR in MiniBooNE beam to look at anti-ν's NOW!

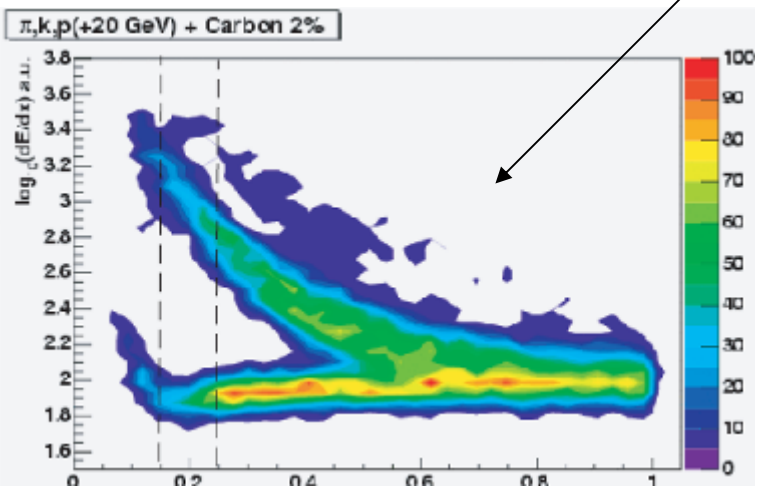
Need Dedicated Hadron Production Experiments!

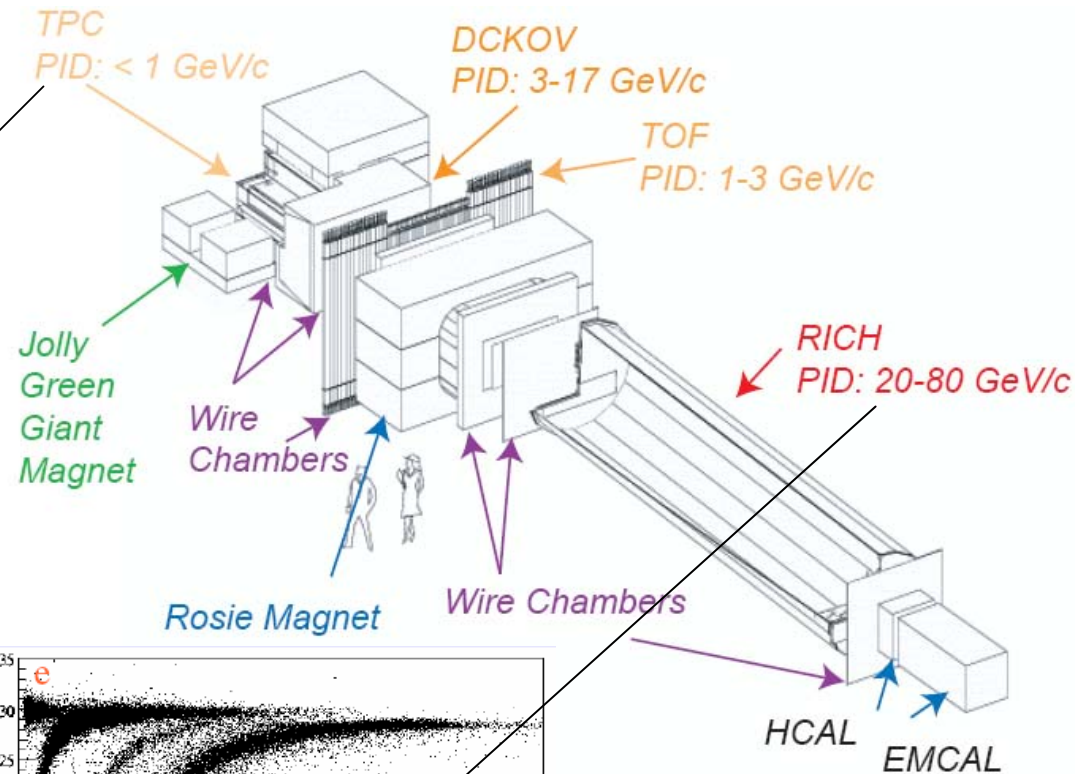
Example: NuMI: Absolute rates known only to 20% in high energy tail, Far/near ratio known better, but still only at 5% ratio without MIPP

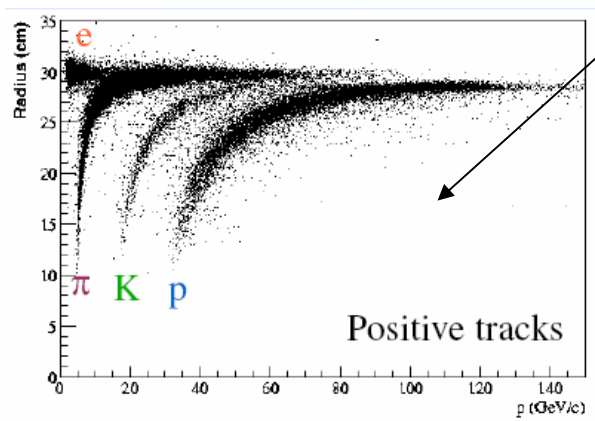


Hadron Production Experiment
Case Study: MIPP

FNAL expt E907,
ran with NuMI Target for MINOS
Will run with thin targets as well







HARP is CERN H.P. experiment that looked at K2K and MiniBooNE targets

Figures courtesy M.Messier

What should you take away from this course?

	Experimentalist	Theorist
Beams	Conventional Neutrino Beams are a critical and challenging problem. Need targets, horns, decay regions and lots of Design work!	Beams aren't flavor eigenstates, and contamination depends on which detectors your friends use.
Systematics	Don't believe it's true just because the Monte Carlo says so. Don't be caught by surprise… the other measurements you need (cross-sections, hadron production, test beam) may take years.	You can't do % or better measurements without spending all your time worrying about systematics.

Last Words…

	Experimentalist	Theorist
ν_e appearance	Find a may to make experimental efforts compliment each other.	Help the experimentalists do this, but only in a way that is realistic!!!
ν_μ disappearance	Don't ignore the difficulty of this measurement if it is important!	Tell experimentalists again how critical it is to know if θ_{23} is 45°
ν_τ appearance	Everything comes to those who can wait.	Don't assume you know the answer. And what if the answer is not what you expected?