Overview of Neutrino Physics: II
Oscillations - Phenomenology and Experiment
HUGS 2004

Introduction to Concepts and Vocabulary

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Evidence that ν have a (small) mass!

- There is a deficit of ν_e coming from the sun - Recent SNO results are the strongest evidence yet that ν_e leave the sun however, ν_e , ν_μ and ν_τ arrive at the earth: **OSCILLATION OF NEUTRINOS**
  - Clear evidence that the MAJORITY of ν_e OSCILLATE to ν_μ / ν_τ
  - Null hypothesis (no oscillation) ruled out at 5.3 σ level
  - Total measured ν flux agrees well with Standard Solar Model
- There are missing ν_μ coming from cosmic ray interactions in the upper atmosphere, again verified by many experiments - SuperKamiokande:
  - $R_{data/MC} = 0.65 \pm 0.02 \pm 0.05$
  - Zenith Angle Distribution - $\nu_\mu(up) / \nu_\mu(down) = 0.54 \pm 0.04$
  - Evidence for ν_τ **OSCILLATION OF NEUTRINOS**
- The LSND experiment has found evidence - yet to be verified - for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

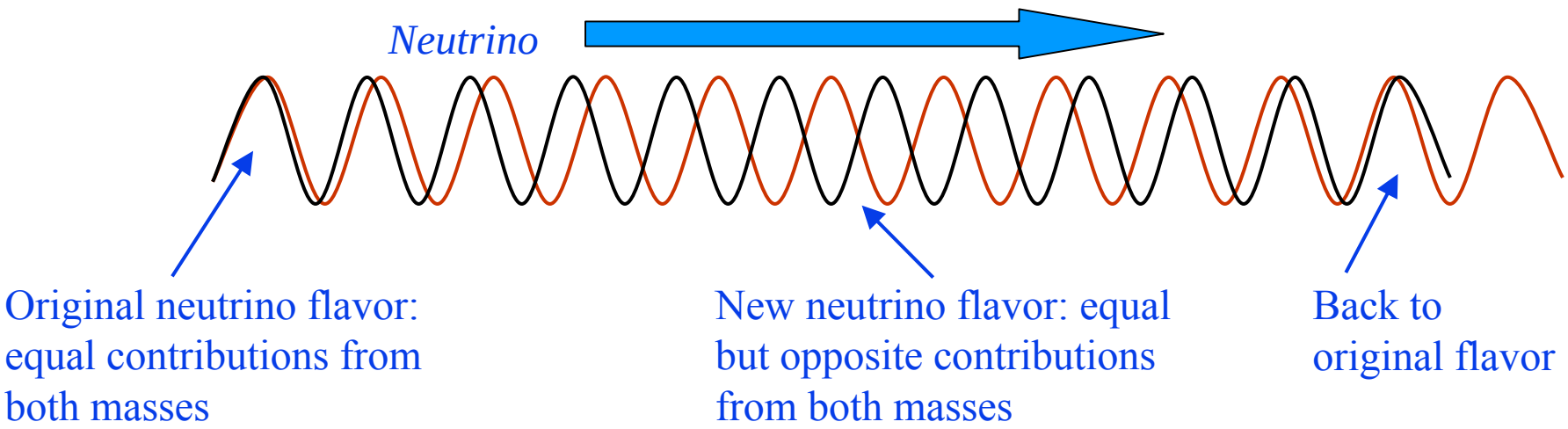
What is going on here? Why are neutrinos changing flavor from creation to detection?

- Let's postulate that neutrinos can have several masses at once!
  - Quantum mechanics allows particles to be in several "states" simultaneously… *superposition principle*
  - If states of definite mass aren't states of definite flavor…
    - » Define ν_1, ν_2, ν_3 – neutrino mass states
    - » ν_e, ν_μ, ν_τ – neutrino flavor states
  - Mixing of masses in each flavor:

$$\nu_e = V_{e1}\nu_1 + V_{e2}\nu_2 + V_{e3}\nu_3$$
$$\nu_\mu = V_{\mu 1}\nu_1 + V_{\mu 2}\nu_2 + V_{\mu 3}\nu_3$$
$$\nu_\tau = V_{\tau 1}\nu_1 + V_{\tau 2}\nu_2 + V_{\tau 3}\nu_3$$

Neutrino Flavor Oscillations

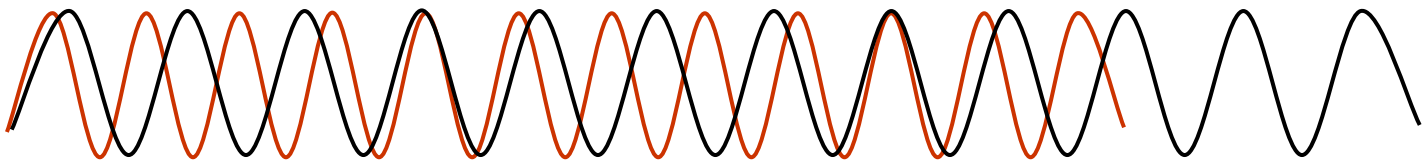
- Different masses in each neutrino flavor allow flavors to change among each other
- *How?*
  - Quantum mechanics – particles have wavelike nature…
  - Oscillation frequency depends on the energy (and therefore the mass) of the particle



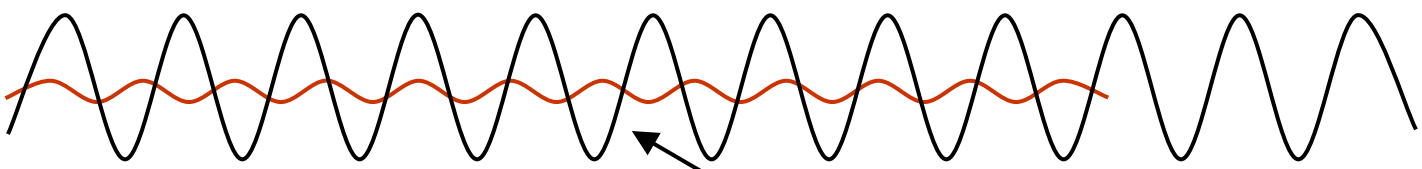
Oscillation Probability

Probability of seeing a neutrino flavor change, at a given energy and distance, depends on:

Mass difference: the bigger the mass difference, the faster the flavor oscillation



Mixing: how different the original neutrino is from a single mass



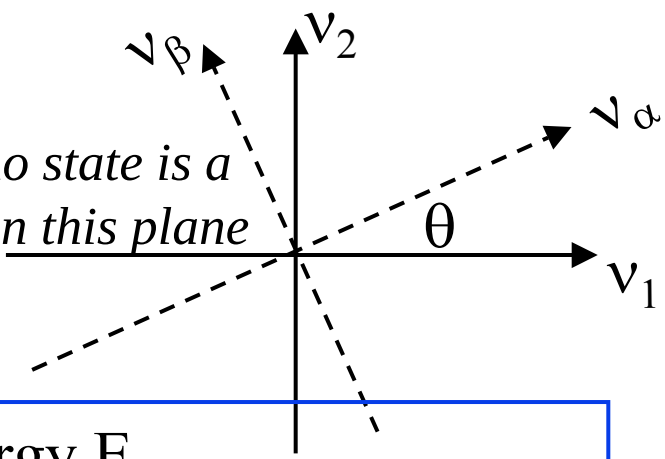
Wave peaks are different, but the overall effect on flavor is small

Simple 2 Flavor Mixing

- Imagine only two neutrino flavors mix

$$\nu_\alpha = \cos(\theta)\nu_1 - \sin(\theta)\nu_2$$
$$\nu_\beta = \sin(\theta)\nu_1 + \cos(\theta)\nu_2$$

Neutrino state is a vector in this plane



Oscillation probability of neutrino with energy E (GeV) traveling a distance L (km), $m_2^2 - m_1^2 \equiv \Delta m^2$ in eV^2

$$P(\nu_a \rightarrow \nu_b) = \sin^2(2\theta)\sin(1.27\Delta m^2 L/E)$$

Larger $\Delta m^2 \Rightarrow$ Faster oscillation
(*no mass $\Rightarrow$ no $\Delta m^2 \Rightarrow$ no oscillation*)

Larger $\sin^2(2\theta) \Rightarrow$ Larger mixing $\Rightarrow$ Larger oscillation probability

Tell me again, what are Neutrino Oscillations ?

- Difference between:
  - flavor states; ν_l interacts with matter it yields a charged lepton of flavor l and
  - Mass states; ν_l need not be a mass eigenstate but rather a superposition of mass eigenstates, at least 3 mass eigenstates and perhaps more.

$$|\nu_l\rangle = \sum_m U_{lm} |\nu_m\rangle$$

- The U_{lm} are known as the leptonic mixing matrix U.
- If ν_l is a superposition of several mass states with differing masses which cause them to propagate differently, we have neutrino oscillations.
- The amplitude for the transformation ν_l --> $\nu_{l'}$ is:

$$A(\nu_l \rightarrow \nu_{l'}) = \sum A(\nu_l \text{ is } \nu_m) A(\nu_m \text{ propagates}) A(\nu_m \text{ is } \nu_{l'})$$

$$A(\nu_m \text{ propagates}) = \exp\left(-i \frac{M_m^2}{2} \frac{L}{E}\right)$$

Neutrino Oscillation: continued

- As an example, if there are only two flavors involved in the oscillations then the U matrix takes on the following form and the probability (square of the amplitude) can be expressed as:

$$U = \begin{pmatrix} \cos\theta & e^{i\delta}\sin\theta \\ -e^{-i\delta}\sin\theta & \cos\theta \end{pmatrix} \text{ and}$$

$$P(\nu_1 \rightarrow \nu_{1'}) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right]$$

$$\text{with } \Delta m^2 \equiv M_2^2 - M_1^2$$

- Naturally, life is more complicated with 3 flavors, but the principle is the same and
  we get the bonus of CP violations as in the quark sector $P(\nu_\mu \text{ --> } \nu_e) \neq P(\nu_\mu \text{ --> } \nu_e)$.

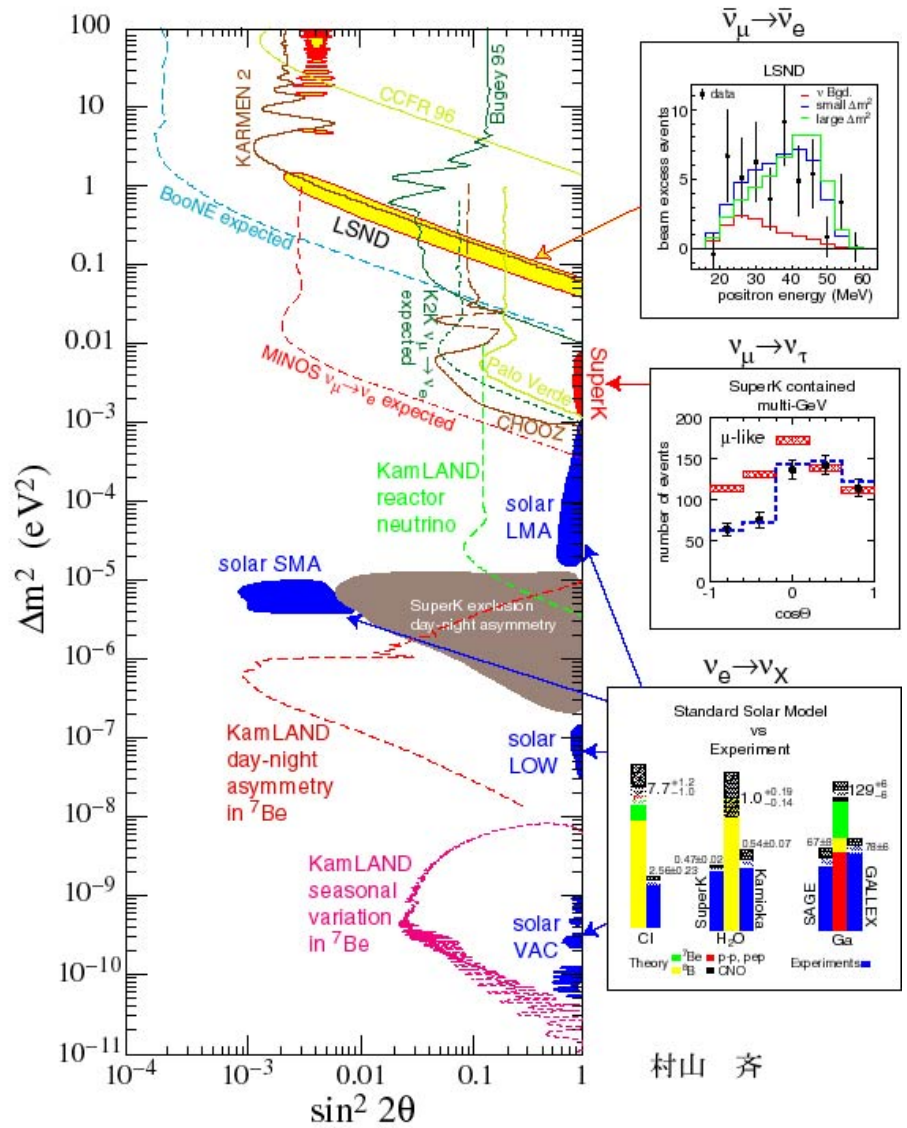
- The components of U now involve θ_{13} , θ_{23} ,θ_{12} and δ and the probabilities involve Δm_{13} , Δm_{23} and Δm_{12} . Standard Theorists Scenario: $\Delta m^2_{23} >> \Delta m^2_{12}$

Sum of many experiments…

Lot of effort since ‘60s

Finally convincing evidence for “neutrino oscillation”

Neutrinos appear to have tiny but finite mass

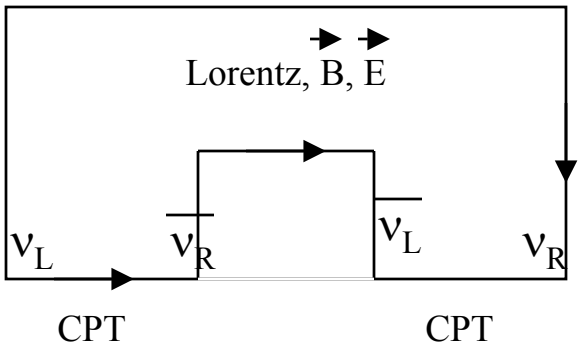


Extended Standard Model

- Massive Neutrinos $\Rightarrow$ Minimal SM incomplete
- How exactly do we extend it?
- Abandon either
  - "Minimality": introduce new unobserved light degrees of freedom (right-handed neutrinos)
  - Lepton number: abandon distinction between neutrinos and anti-neutrinos and hence matter and anti-matter
- Dirac or Majorana neutrino
- Without knowing which, we don't know how to extend the Standard Model

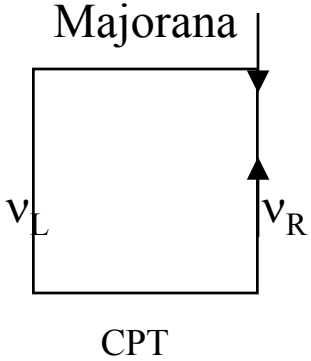
Majorana vs Dirac Neutrinos

Dirac



Assume we have massive ν_L via CPT we then have a $\overline{\nu_R}$
For massive ν_L , v < c implies via Lorentz we have ν_R
This ν_R may or may not be the same as $\overline{\nu_R}$
If NOT the same then ν_R has its own CPT mirror $\overline{\nu_L}$
There are FOUR states with the same mass called a Dirac neutrino ν^D . It has distinct particle-antiparticle states
And may have magnetic and even electric dipole moment.
For a Dirac neutrino ν_L can be converted to opposite helicity both by Lorentz transformation and an external $\vec{B}$ or $\vec{E}$

Majorana



If, on the other hand, the ν_R obtained by the Lorentz transformation is the SAME particle as the CPT image of the original ν_L , there are only two states with a common mass. This is a Majorana neutrino ν^M . Magnetic and electric dipole moments vanish

DIRAC vs Majorana - Summary

- Dirac Neutrinos
  - Neutrino and Antineutrino are distinct particles (like their charged lepton partners)
  - Lepton number conserved
    - Neutrino $\rightarrow \mu^-$
    - Antineutrino $\rightarrow \mu^+$
  - Dirac Mass Term
    - Need to have a right-handed neutrino ***(Not in the Standard Model)***
    - Mass term like e, μ, τ

$$-m_D\left(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L\right)$$

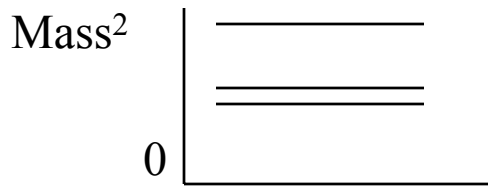
- Majorana Neutrinos
  - Neutrinos and Antineutrinos are the same particle (This can only happen since neutrinos have no charge!)

    $\Rightarrow$ Only difference is "handedness"
    - Neutrinos are left-handed ν $\rightarrow \mu^-$
    - Antineutrinos are right-handed ν $\rightarrow \mu^+$
  - Lepton number not conserved
    - Neutrino $\Leftrightarrow$ Antineutrino with spin flip
  - Majorana Mass Term
    - New type of mass

$$-\frac{1}{2}m_M^L\left(\overline{\overline{\nu_L}(\nu_L)^c} + \overline{(\nu_L)^c}(\nu_L)\right) - \frac{1}{2}m_M^R\left(\overline{\overline{\nu_R}(\nu_R)^c} + \overline{(\nu_R)^c}(\nu_R)\right)$$

What are the MAIN open questions?

- How many neutrinos are there and what kind (D or M) are they?
- What are the exact mass splittings between the eigenstates
- What is the zero offset of the pattern?



- What are the elements of U (mixing angles, CP phases, **is θ_{13} non-zero?)**
- Do neutrinos violate CP?
- Do neutrinos violate CPT!?
- What is the origin of ν flavor physics?
- Neutrinos as probes of extra dimensions, Neutrino dipole moments, Neutrinos as probes of astrophysics and cosmology?

How do we answer these questions?

- CURRENT GENERATION: long and medium baseline terrestrial ν oscillation experiments designed to:
  - Confirm SuperK results with accelerator ν's (K2K & MINOS)
  - Demonstrate oscillatory behavior of ν_μ's (MINOS)
  - Make precise measurement of some oscillation parameters (MINOS)
  - Demonstrate explicitly $\nu_\mu \rightarrow \nu_\tau$ oscillation mode by detecting ν_τ's (OPERA, ICARUS)
  - Improve limits on $\nu_\mu \rightarrow \nu_e$ subdominant oscillation mode, or detect it (MINOS, ICARUS)
  - Resolve the LSND puzzle (MiniBooNE)
  - Confirm indications of LMA solution (SNO, Borexino, KamLAND)

- **Many issues in neutrino physics will then still remain unresolved.**

NEXT GENERATION experiments will try to address them.

The Fermilab Plan to Address These Questions

- Facility: The NuMI Beam
- The MINOS Experiment: **This Generation** - being built
- NuMI Off-axis ν Oscillation Experiment:

  Next Generation - Proposal Submitted
- **MINERνA: High-statistics NuMI $\nu/\bar{\nu}$ Scattering Experiment**: Important for reducing systematics of ALL neutrino oscillation experiments!

NuMI Facility / MINOS Experiment at Fermilab

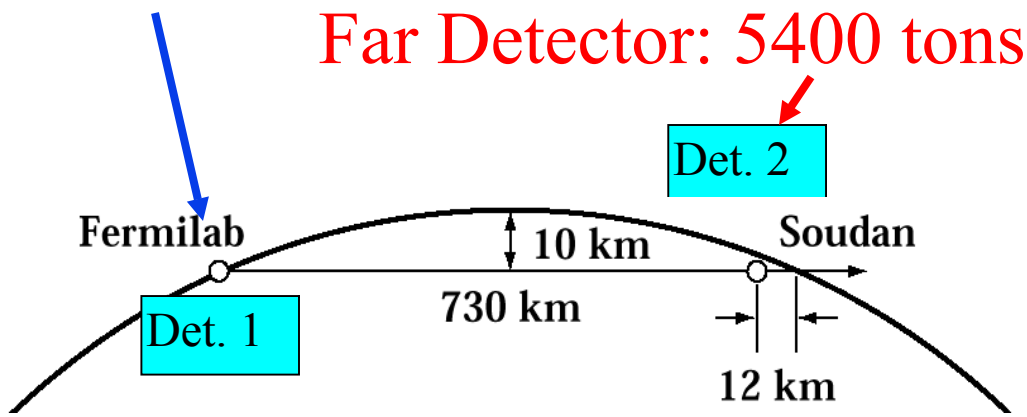
NuMI: Neutrinos at Main Injector

120 GeV protons
1.9 second cycle time
Single turn extraction (10μs)

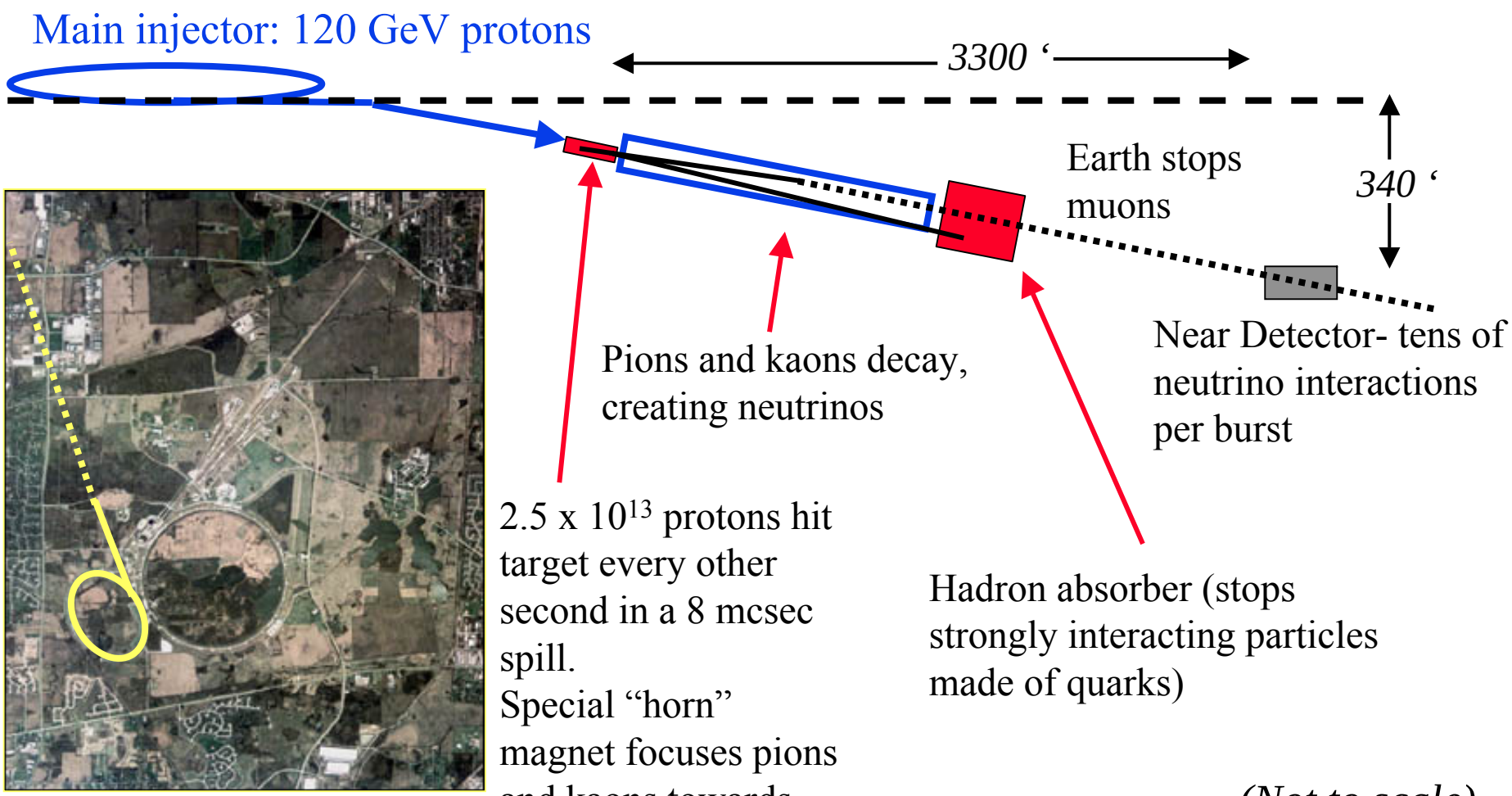
- Precision measurements of:
  - Energy distribution of oscillations
  - Measurement of oscillation parameters
  - Participation of neutrino flavors
- Direct measurement of ν vs ν oscillation
  - Magnetized far detector: atm. ν's.
  - Likely eventual measurement with beam

Near Detector: 980 tons

Far Detector: 5400 tons

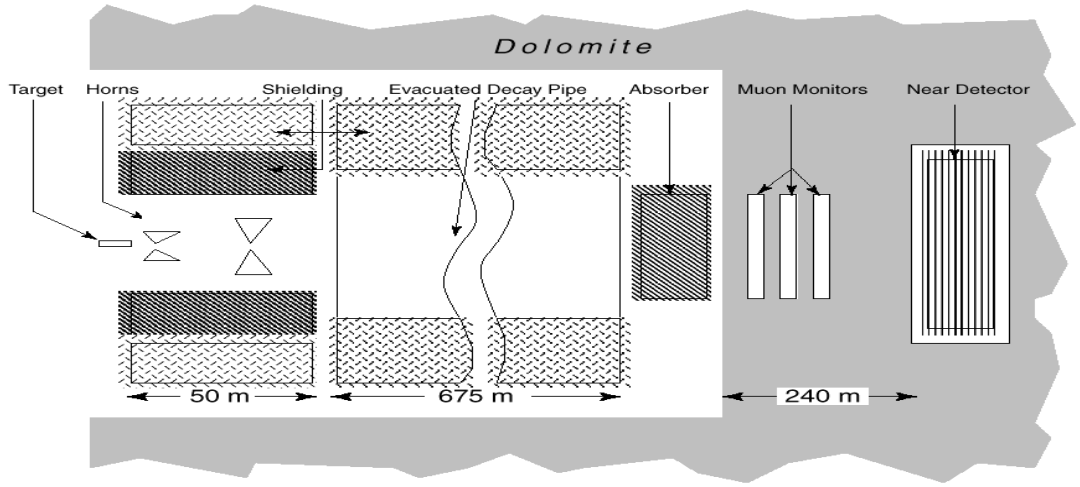


The NUMI Neutrino Beam

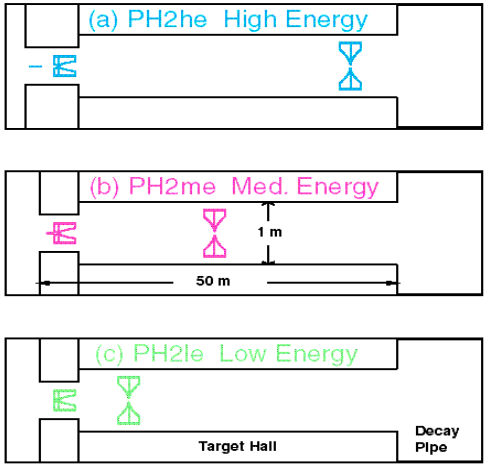


(Not to scale)

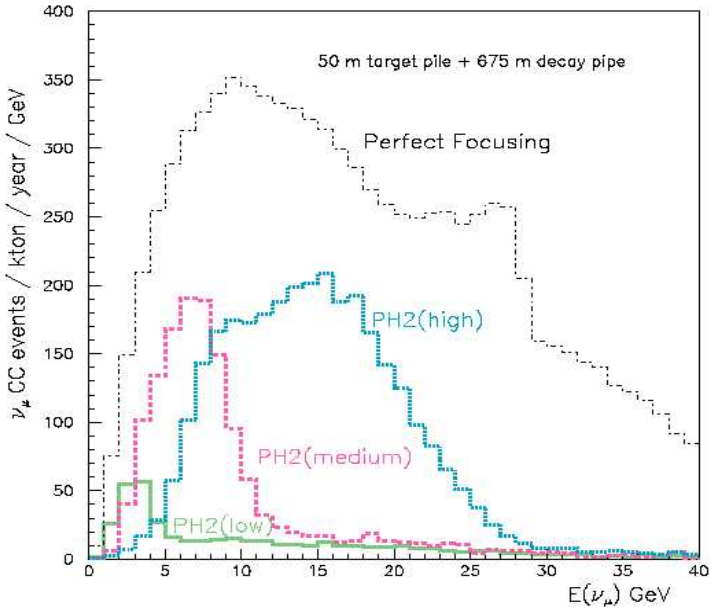
NuMI Neutrino Beam Configurations



- Horn 1 position fixed - move target and horn 2 to change mean energy of beam.
- Three "nominal" configurations: low-, medium-, high energy.
- In addition, "pseudo-me" and "pseudo-he" beams. Horns left in le configuration and only target moved.
- MINOS will run with a **combination of configurations.** It will be heavily weighted toward lower energy **but also involve pme- and phe-beam running.**



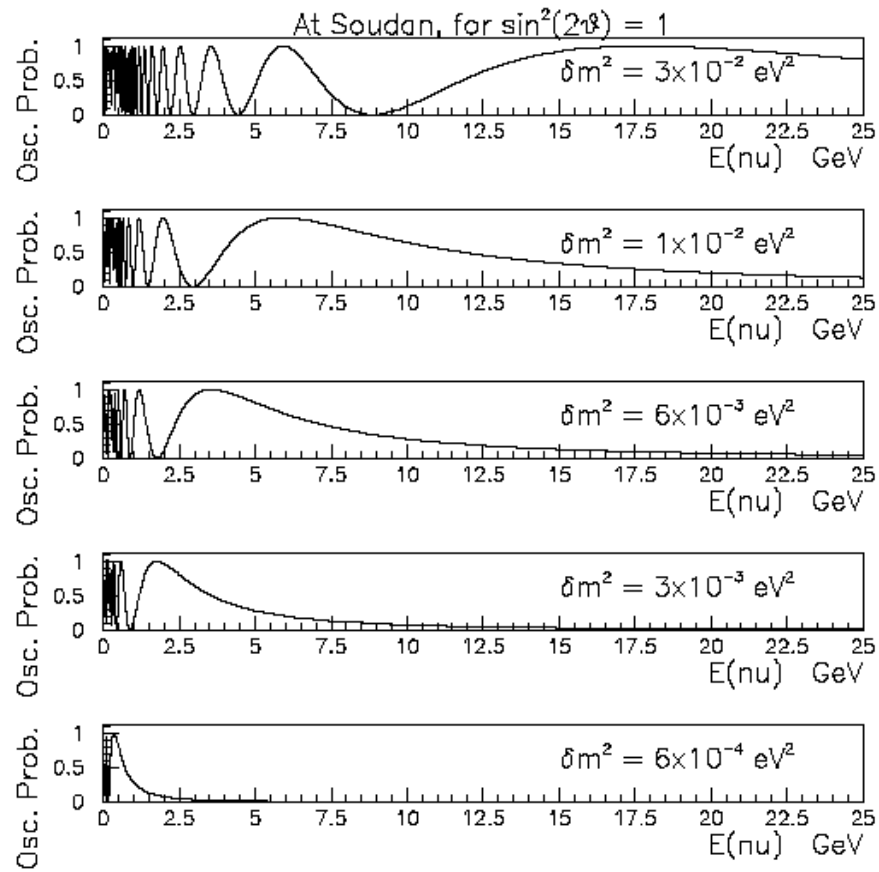
NuMI Far Neu



ν_μ CC Events/kt/year

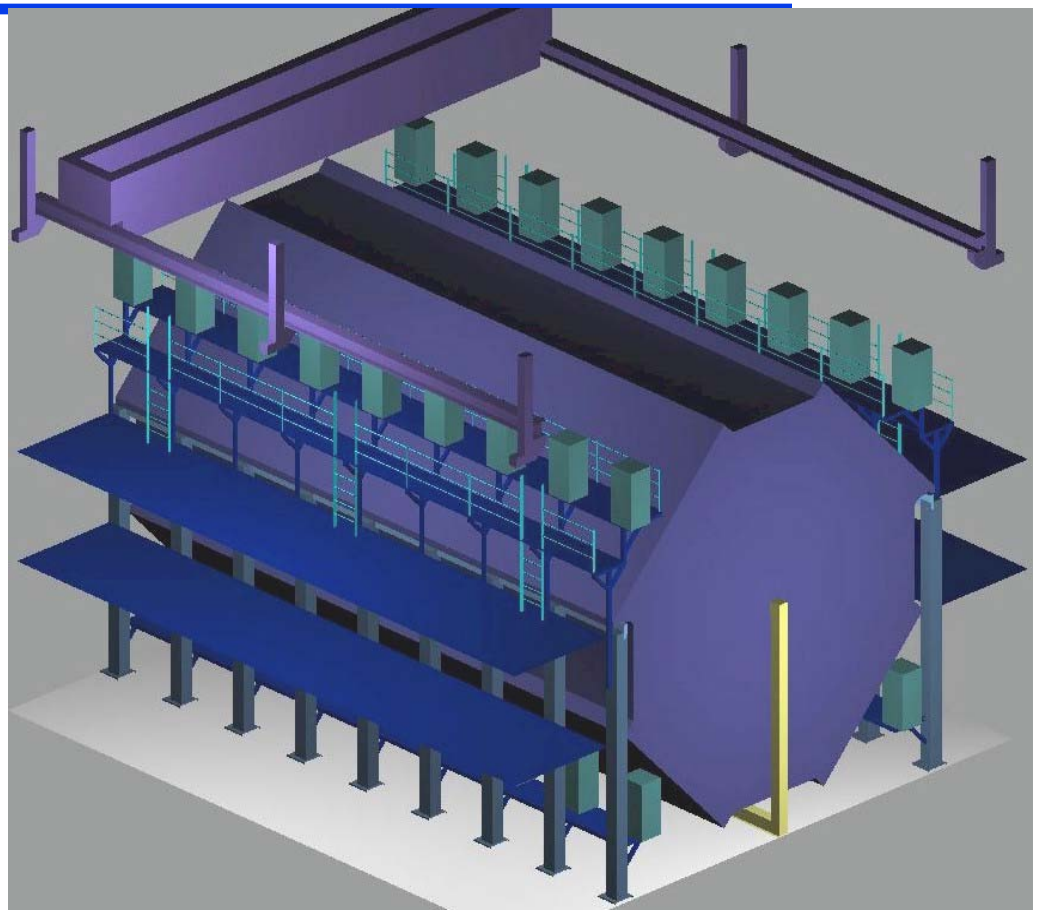
Low	Medium	High
250	815	1815

2.5×10^{20} protons on target/year



The MINOS Far Detector

- 8m octagonal steel & scintillator tracking calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 2 sections, 15m each
  - 5.4 kton total mass
  - 55%/√E for hadrons
  - 23%/√E for electrons
- Magnetized Iron (B~1.5T)
- 484 planes of scintillator
  - 26,000 m^2

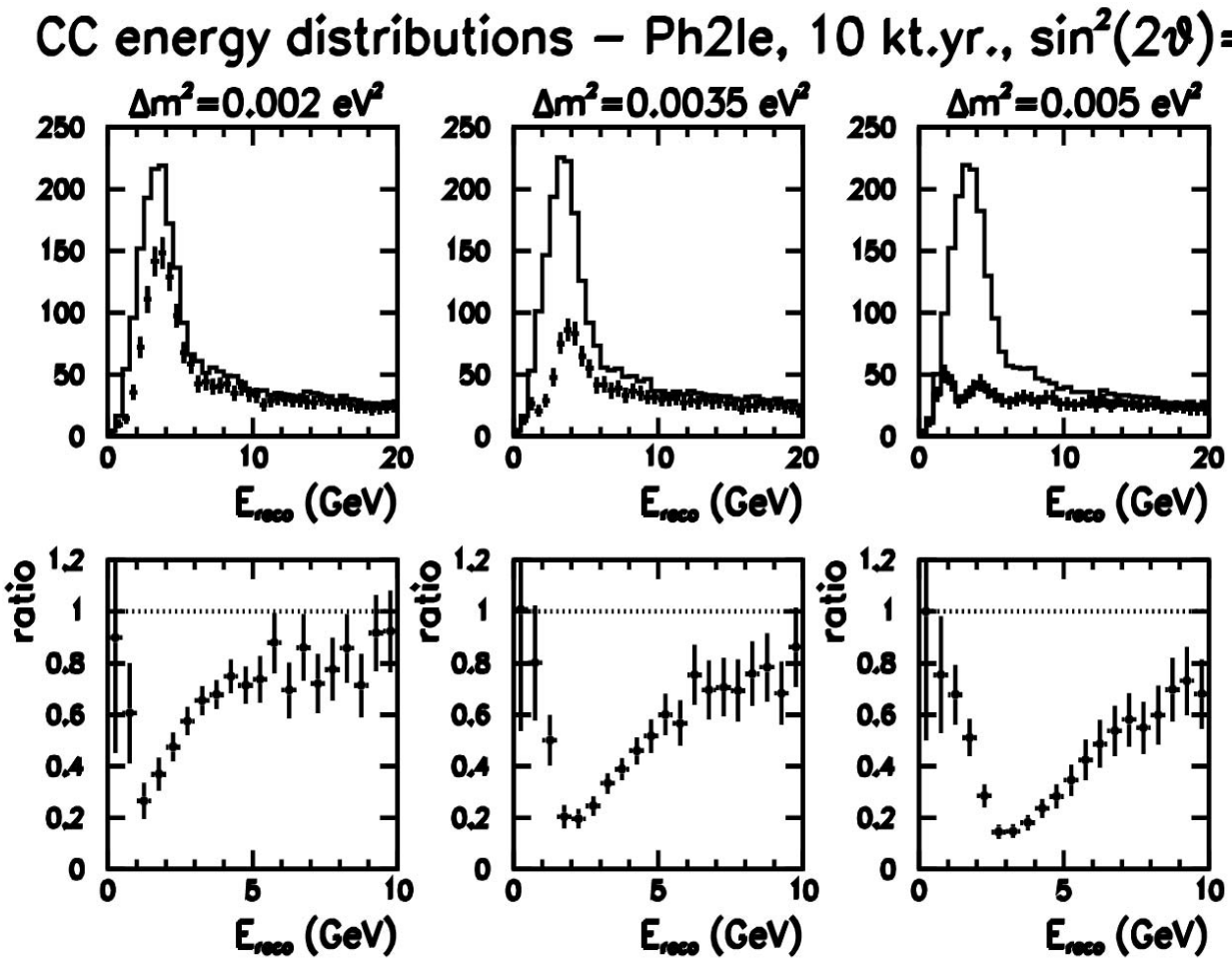


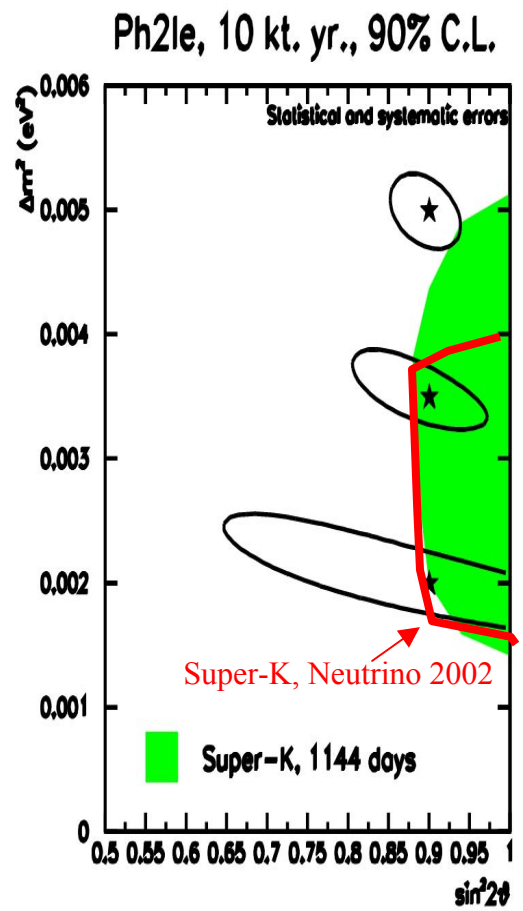
Both Supermodules of the Far Detector taking data of atmospheric neutrino interactions.

MINOS Physics Goals by 2007

- Demonstrate Oscillation Behavior
  - Precise measurement of CC energy distribution between near and far detector (2-4% sys. uncertainty in E_ν per 2 GeV bin).
  - "Standard" or non-standard oscillations?
    - » Can we see clear "oscillatory" behavior from the first osc. max?
    - » Are there features in the energy spectrum not well described by a standard oscillation?
- Precise Measurement of Oscillation Parameters
- Precise Determination of Flavor Participation
  - Number of CC ν_μ events far/near ~2%: Probability for $\nu_\mu - \nu_x$ oscillation.
  - Number of CC ν_e events far/near: Sensitive to $\nu_\mu - \nu_e$ oscillation to $\approx$ 2%.
  - Number of NC events far/near: probability for $\nu_\mu - \nu_{sterile}$ oscillation to $\approx$ 5%.
  - ν_μ's which disappear but don't appear as ν_e or disappear to $\nu_{sterile}$ must be ν_τ!
- Direct Measurement of Atmospheric ν vs $\bar{\nu}$.

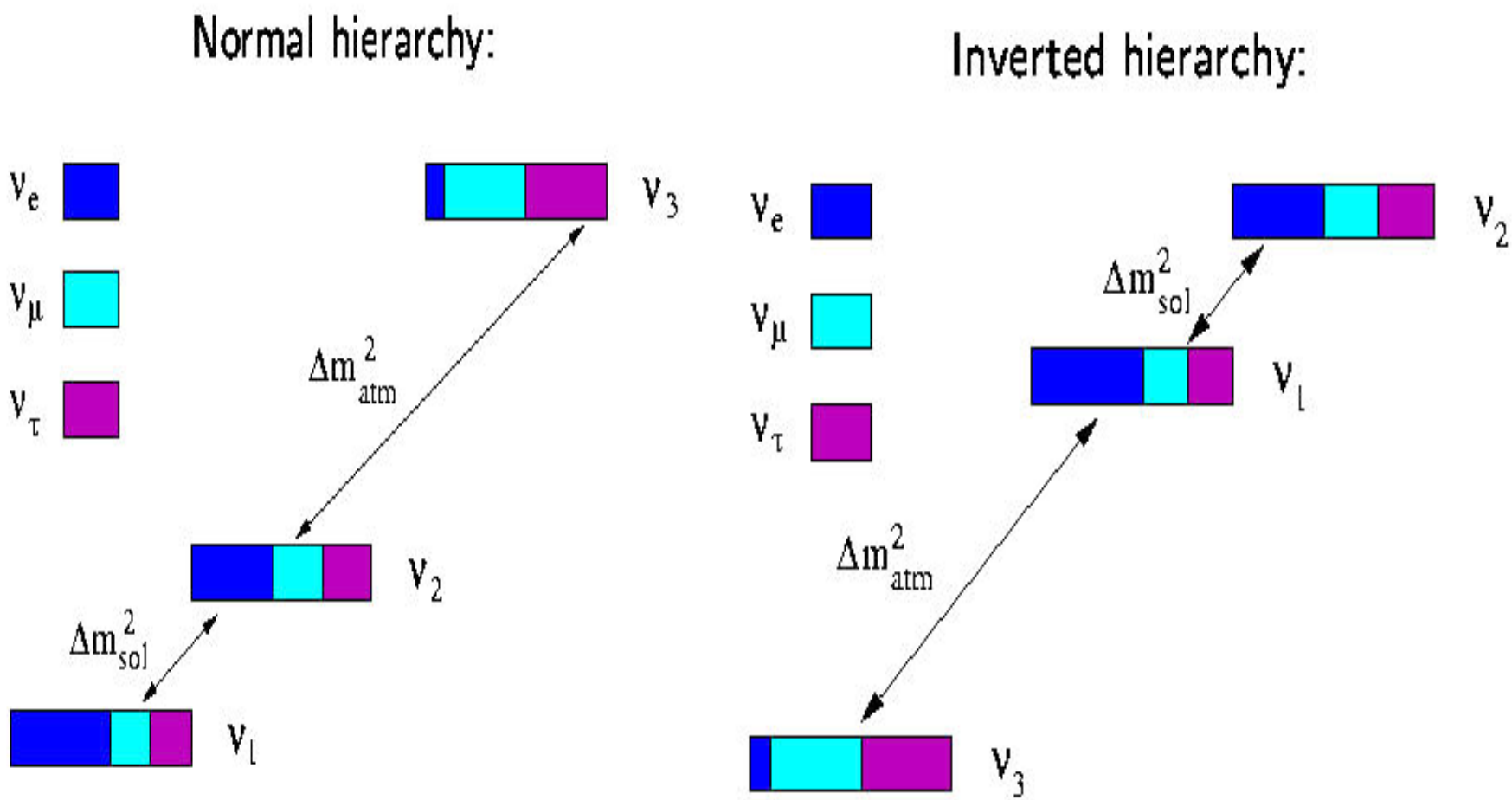
Measurement of Oscillations in MINOS





Note: MINOS beam results are presented for 2 years of running!

Sum of our knowledge today - Mass Hierarchy Possibilities



Next Generation: MINOS Off-axis Experiment

- The physics issues to be investigated are clearly delineated
- The dominant oscillation parameters are known reasonably well
- One wants to maximize flux at the desired energy (near oscillation maximum)
- One wants to minimize flux at other energies
- One wants to have narrow energy spectrum: minimize backgrounds

Measurement of θ_{13}

Determination of mass hierarchy (sign of Δm_{23} squared)

Search for CP violation in neutrino sector

Measurement of CP violation parameters

(Testing CPT with high precision)

Θ_{13} , CP-Violation, Mass Hierarchy and the $\nu_\mu \Rightarrow \nu_e$ Transition.

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2}G_F n_e;$$

$$B_\pm = \left|A \pm \Delta_{13}\right|;$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

A. Cervera et al., Nuclear Physics B 579 (2000) 17 – 55,

expansion to second order in $\theta_{13}, \frac{\Delta_{12}}{\Delta_{23}}, \frac{\Delta_{12}}{A}, \Delta_{12}L$

Collaboration Formed

Proposal
To build an Off-Axis Detector
To study $\nu_\mu \Rightarrow \nu_e$ oscillations
With the NuMI Neutrino Beam

36 Institutions including

Submit to the Fermilab PAC
This Month

MINERνA

A High-Statistics Neutrino Scattering Experiment
Using an On-Axis, Fine-grained Detector
in the NuMI Beam

Understanding Low-energy Neutrino - Nucleus Interactions

RECENTLY APPROVED BY THE FERMILAB PAC

Both HEP and NP collaborators

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Tufts University, Medford, Massachusetts

J. Nelson
William and Mary College, Williamsburg, Virginia

Red = HEP, Blue = NP, Green = Theorist

MINERνA will have the statistics to cover a wide variety of important ν physics topics

ν_μ Event Rates per fiducial ton		
Process	CC	NC
Quasi-elastic	103 K	42 K
Resonance	196 K	70 K
Transition	210 K	65 K
DIS	420 K	125 K
Coherent	8.4 K	4.2 K
TOTAL	**940 K**	**305 K**

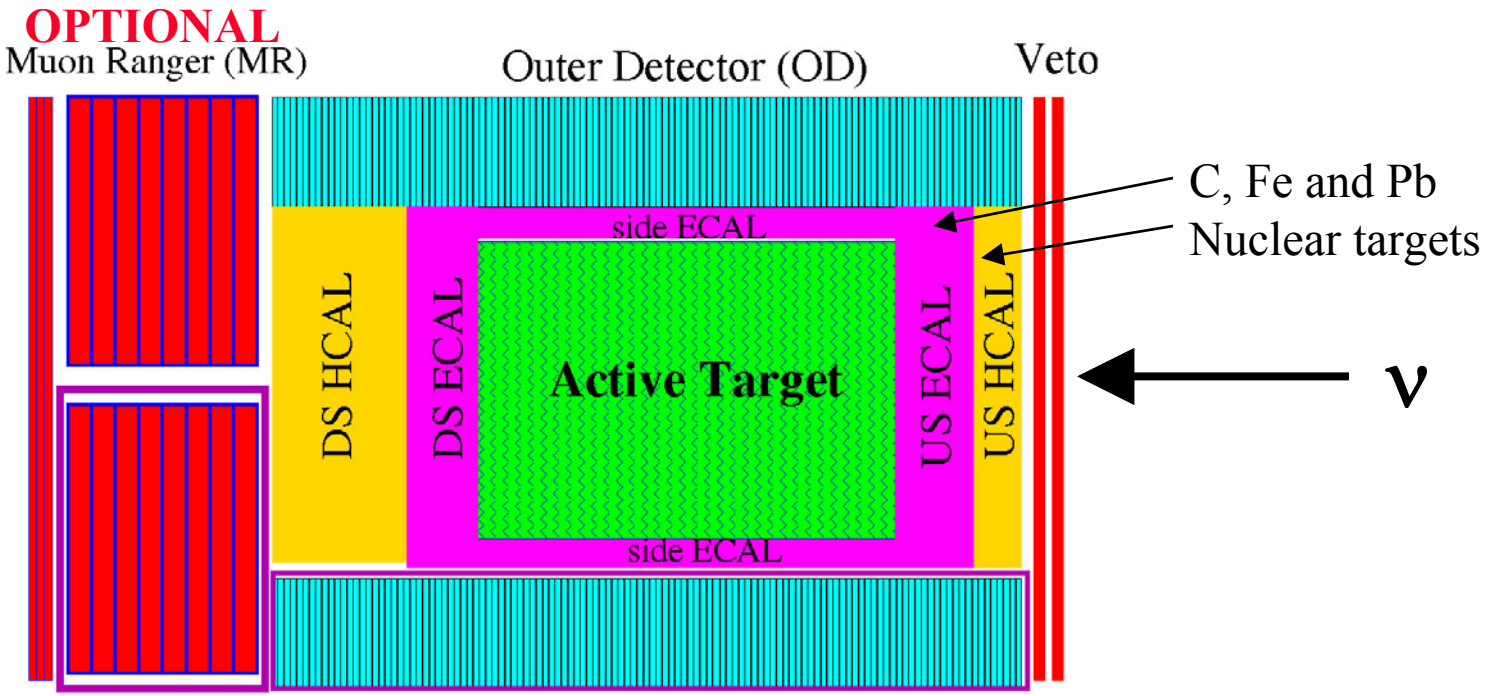
Typical Fiducial Volume =
3-5 tons CH, 0.6 ton C, ≈ 1 ton Fe and ≈ 1 ton Pb

3 - 4.5 M events in CH
0.5 M events in C
1 M events in Fe
1 M events in Pb

Main Physics Topics with Expected Produced Statistics

- Quasi-elastic - $\nu + n \rightarrow \mu^- + p$ - 300 K events off 3 tons CH
- Resonance Production - e.g. $\nu + N \rightarrow \nu / \mu^- + \Delta$ 600 K total, 450K 1π
- Coherent Pion Production - $\nu + A \rightarrow \nu / \mu^- + A + \pi$, 25 K CC / 12.5 K NC
- Nuclear Effects - C: 0.6M events, Fe: 1M and Pb: 1 M
- σ_T and Structure Functions - 2.8 M total /1.2 M DIS events
- Strange and Charm Particle Production - (> 60 K **fully** reconstructed events)
- Generalized Parton Distributions - (few K events?)

The MINERνA Detector: SMALL and Compact

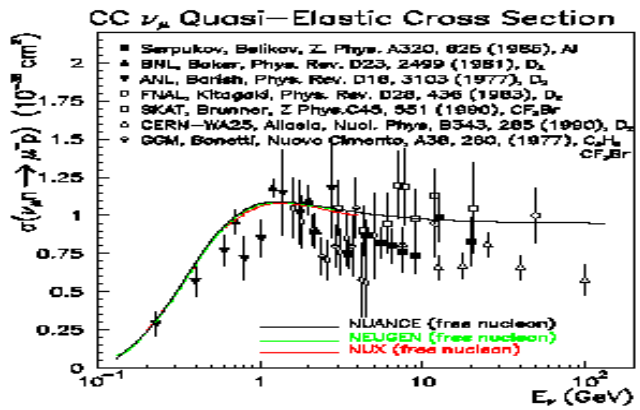


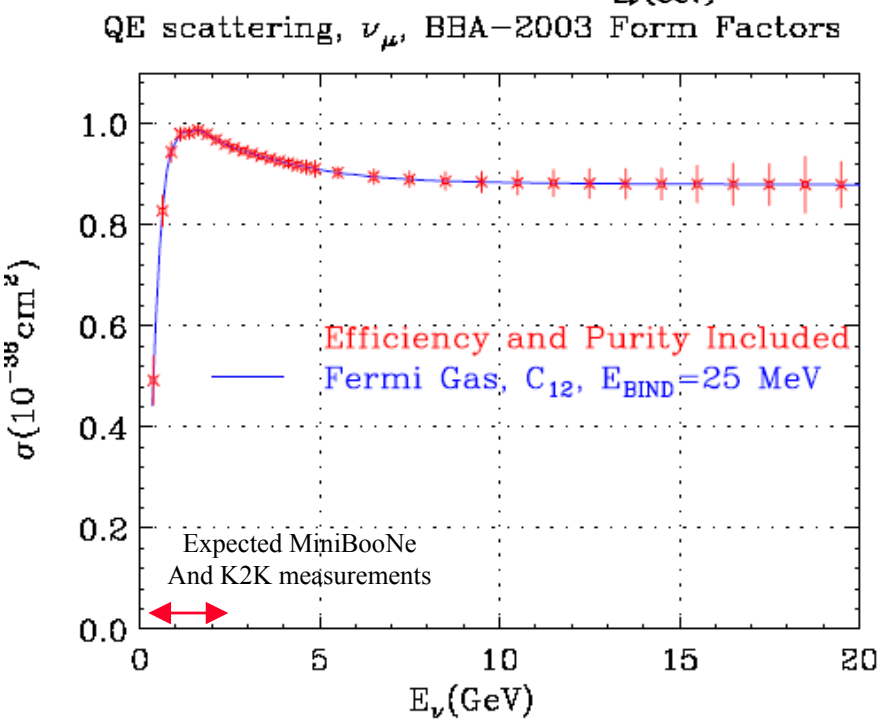
- Active target (6t total, 3 - 5 t fiducial)
- Surrounded by calorimeters
  - upstream calorimeters are Pb, Fe targets (~1t each)
  - magnetized side and downstream tracker/calorimeter

MINERνA Physics Results:

Quasi-elastic Scattering - H. Budd, A. Bodek & K. McFarland

MINERνA: 300 K events off CH and over 100 K off of Fe and Pb



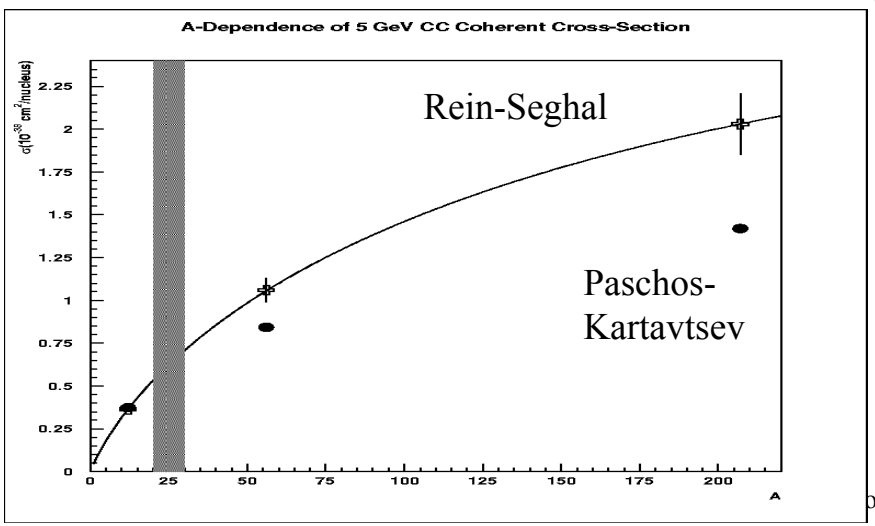


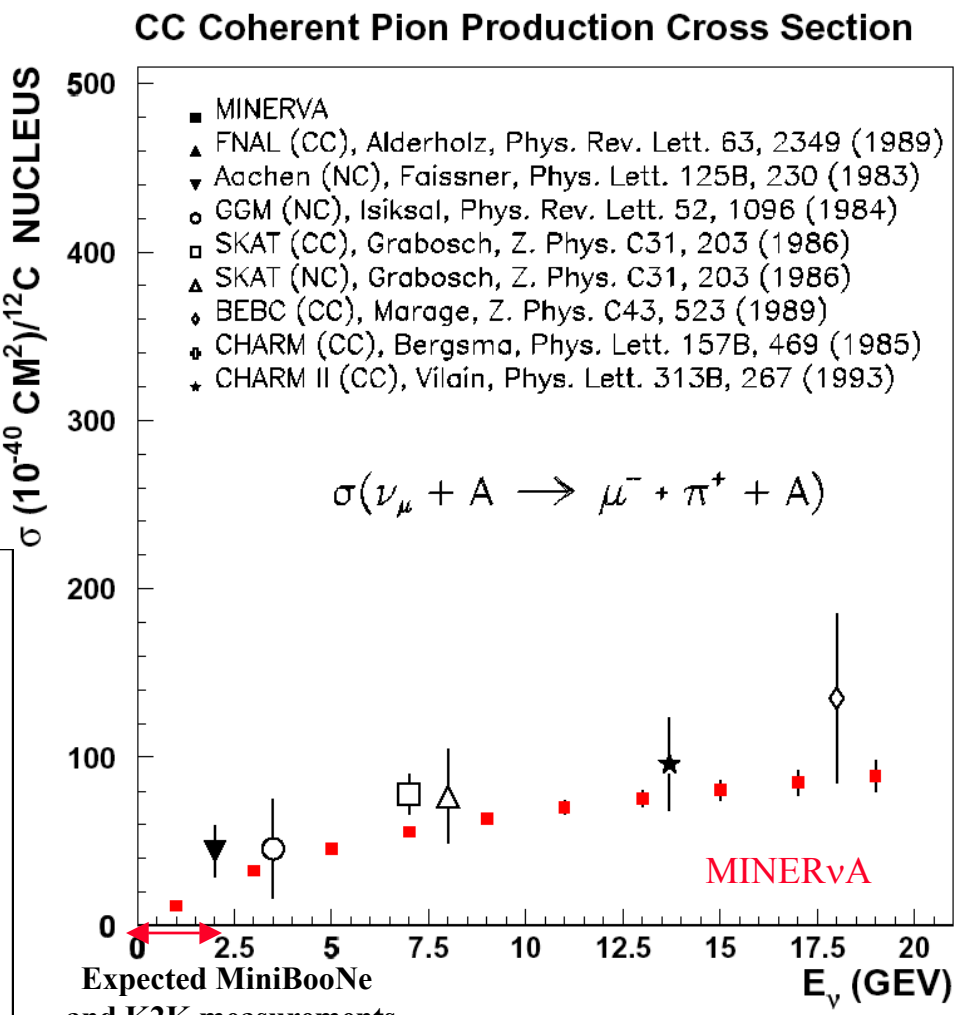
- Theory: Reliable expression of cross-section in terms of nucleon vector and axial-vector form factors (F_A). F_A very poorly known, particularly at high Q^2.
- Cross-section important for understanding low-energy neutrino oscillation results and Needed for all low energy neutrino monte carlos used in neutrino oscillation analyses.
- Constrained kinematics help measure final state interactions.

Coherent Pion Production - H. Gallagher

MINERνA: 25 K CC / 12.5 K NC events off C - 8.3 K CC/ 4.2 K NC off Fe and Pb

- Characterized by a small energy transfer to the nucleus, forward going π. NC (π^0 production) significant background for ν_μ --> .ν_e oscillation search
- Data has not been precise enough to discriminate between several very different models.
- Expect roughly (30-40)% detection efficiency with MINERνA.
- Can also study A-dependence with MINERνA

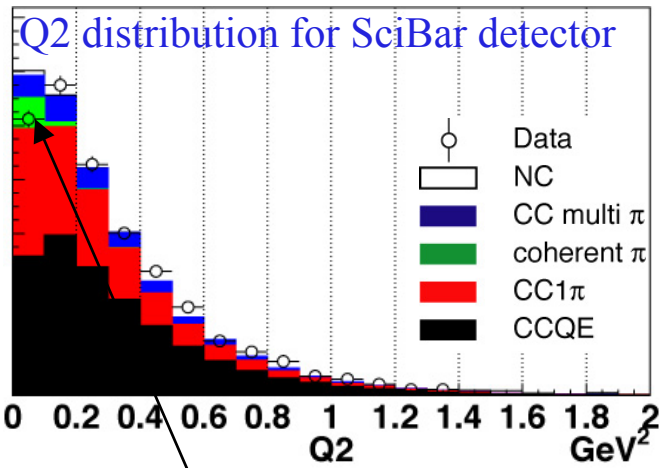




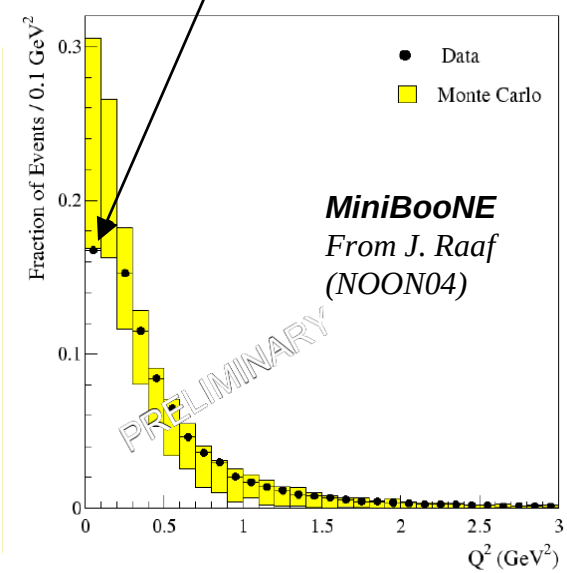
Expected MiniBooNe and K2K measurements

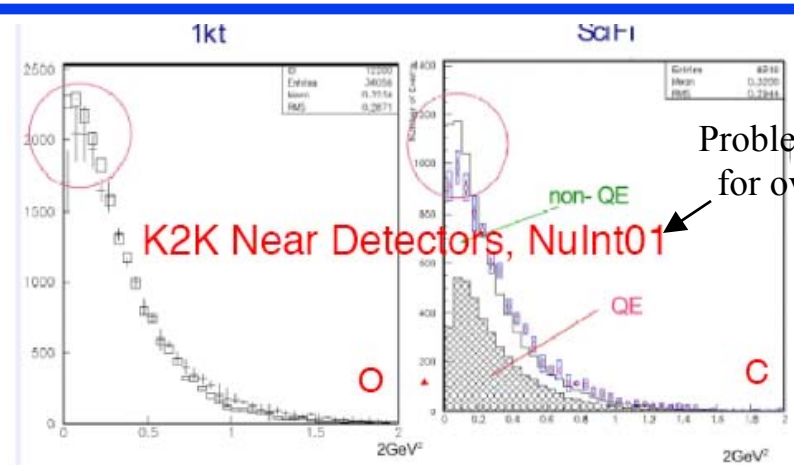
Nuclear Effects - S. Boyd, JGM, R. Ransome

MINERνA: 2.8 M events off CH, 600 K off C and 1 M events off of Fe and Pb



Larger than expected rollover at low Q^2





Problem has existed for over two years

All "known" nuclear effects taken into account:
Pauli suppression, Fermi Motion, Final State Interactions
They have **not included** low-ν shadowing that is only allowed with axial-vector (Boris Kopeliovich at NuInt04)

$L_c = 2\nu / (m_\pi^2 + Q^2) \geq R_A$ **(not m_A^2)**

L_c 100 times shorter with m_π allowing low ν-low Q^2 shadowing

ONLY MEASURABLE VIA NEUTRINO - NUCLEUS INTERACTIONS! **MINERνA WILL MEASURE THIS ACROSS A WIDE ν AND Q^2 RANGE WITH C : Fe : Pb**

Conclusions

- Neutrinos are a unique kind of particle
  - Very weakly interacting – originally detected indirectly
  - Very, very light
- Neutrinos a great probe of the nature of matter
  - No Electromagnetic interactions – great for studying weak forces
  - Unique abilities to probe structure of proton and neutron
  - What makes them so light?
  - What can mixing and oscillations tell us about particle flavor? – W*hat is flavor*???
- Exciting time in neutrino physics!