MINERνA

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21 November 2005
Toronto Seminar

A Drama in Three Acts…

I. Neutrino Oscillations *(a lengthy exposition…)*
   - current status of knowledge
   - future goals

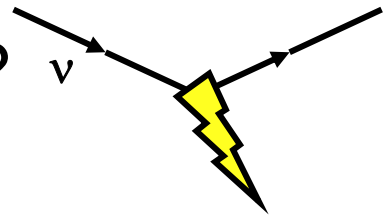
II. Neutrino Interactions *(detailed plot development)*
   - implications for future oscillation studies

III. MINERvA *(denouement and happy[?] ending)*
   - the experimental design
   - expected results
   - status

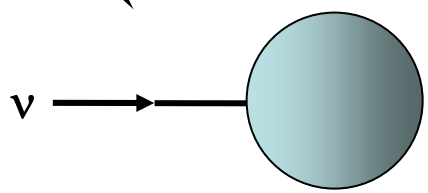
Neutrinos: The Broadest Goals

- Understand mixing of neutrinos
  - a non-mixing? CP violation?
- Understand neutrino mass
  - absolute scale and hierarchy

- Understand ν interactions
  - new physics? new properties?



- Use neutrinos as probes
  - nucleon, earth, sun, supernovae



Summary of Neutrino Mass Eigenstates

- The building blocks of what we know
  - #νs with weak couplings:
    - W^+: 3 observed (DONUT)
    - Z^0: exactly 3 (LEP, SLD)
- Neutrino Flavor Oscillations:
  - Solar neutrino oscillation: …, SNO, KAMLAND
  - Atmospheric neutrinos: …, Super-K, K2K
  - Puzzles and null results: LSND, CHOOZ
    - LSND “puzzle” is requirement of more neutrinos
    - CHOOZ/Palo Verde suggest one small mixing

Qualitative Questions

- The questions facing us now are fundamental, and not simply a matter of "measuring oscillations better"
- Examples:
  - Are there more than three neutrinos?
  - What is the hierarchy of masses?
  - Can neutrinos contribute significantly to the mass of the universe?
  - Is there CP violation in neutrino mixings?

Of The Broadest Goals…

- Understand mixing of neutrinos
  - a non-mixing? CP violation?
- Understand neutrino mass
  - absolute scale and hierarchy

- Understand ν interactions
  - new physics? new properties?

- Use neutrinos as probes
  - nucleon, earth, etc.

What We Hope to Learn From Neutrino Oscillations

- Near future
  - validation of three generation picture
    - confirm or disprove LSND oscillations
    - precision tests of “atmospheric” mixing at accelerators
- Farther Future
  - neutrino mass hierarchy, CP violation?
    - Precision at reactors
    - sub → multi MegaWatt sources
    - 10 → 100 → 1000 kTon detectors

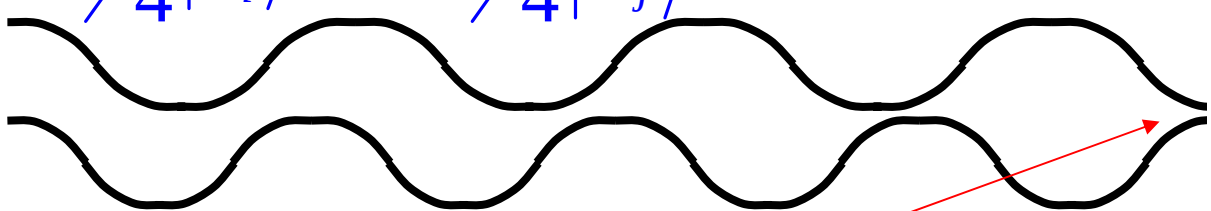
Minimal Oscillation Formalism

- If neutrino mass eigenstates: ν_1, ν_2, ν_3, etc.
- … are not flavor eigenstates: ν_e, ν_μ, ν_τ
- … then one has, e.g.,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

take only two generations for now!

$$|\nu_\alpha\rangle = \cos \pi/4 \, |\nu_i\rangle + \sin \pi/4 \, |\nu_j\rangle$$



different masses alter time evolution

time →

$$|\nu_\beta\rangle = -\sin \pi/4 \, |\nu_i\rangle + \cos \pi/4 \, |\nu_j\rangle$$

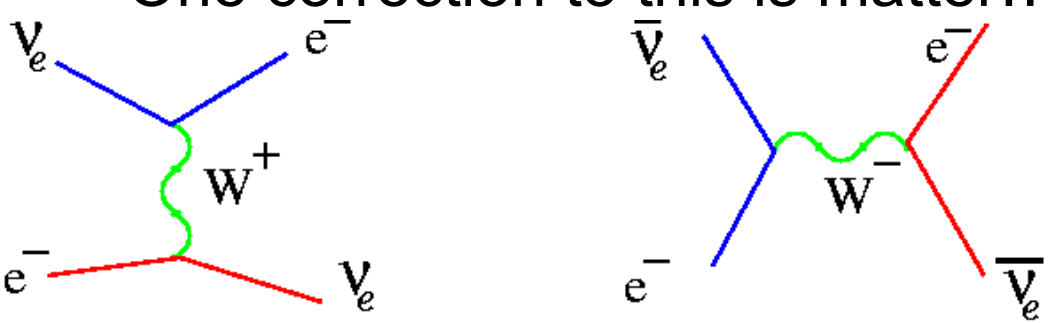
Oscillation Formalism (cont'd)

- So, still for two generations…

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

appropriate units give the usual numerical factor **1.27 GeV/km-eV²**

- Oscillations require mass differences
- Oscillation parameters are mass-squared differences, δm^2, and mixing angles, θ.
- One correction to this is matter… changes θ, L dep.



Coherent Elastic Scattering: ν_e $\bar{\nu}_e$ only!

Wolfenstein, PRD (1978)

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

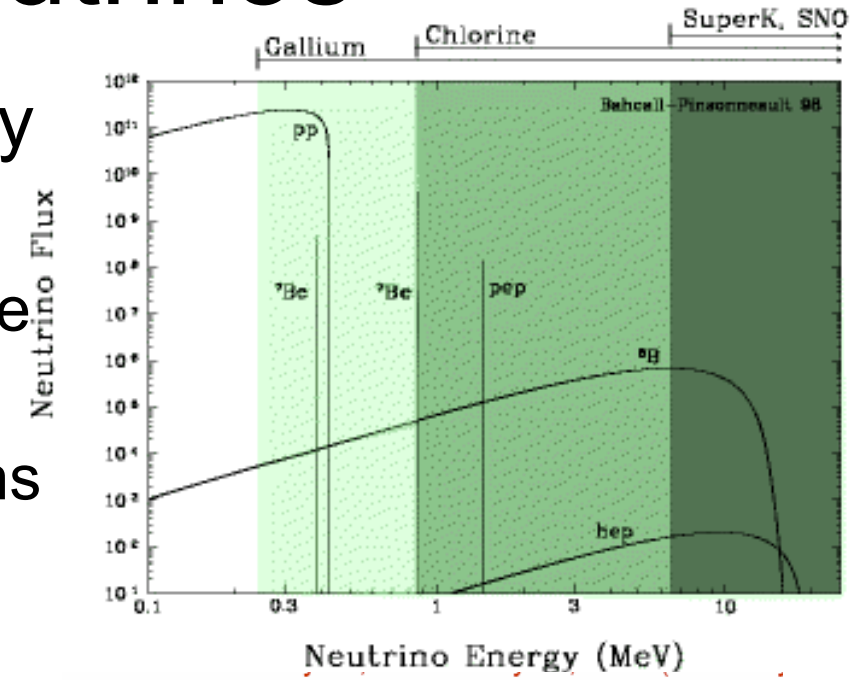
$$L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

$$x = \frac{2\sqrt{2} G_F n_e E_\upsilon}{\Delta m^2}$$

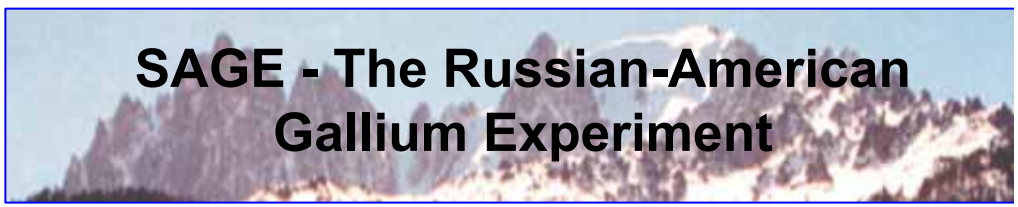
$n =$ e⁻ density

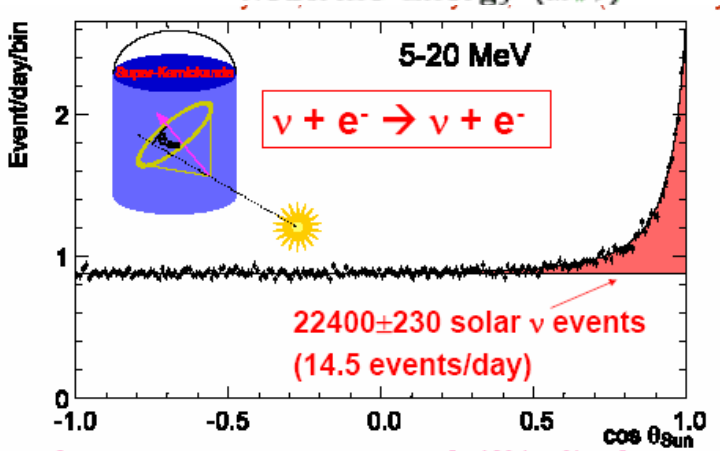
Solar Neutrinos

- There is a glorious history of solar neutrino physics
  - original goals: demonstrate fusion in the sun
  - first evidence of oscillations



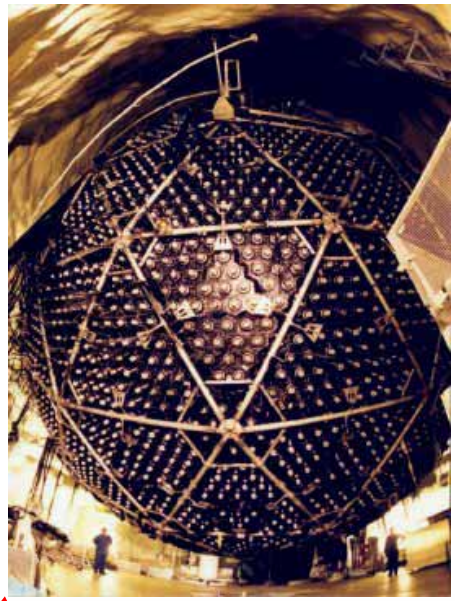
GALLEX
INTERNATIONAL SOLAR NEUTRINO RESEARCH COLLABORATION

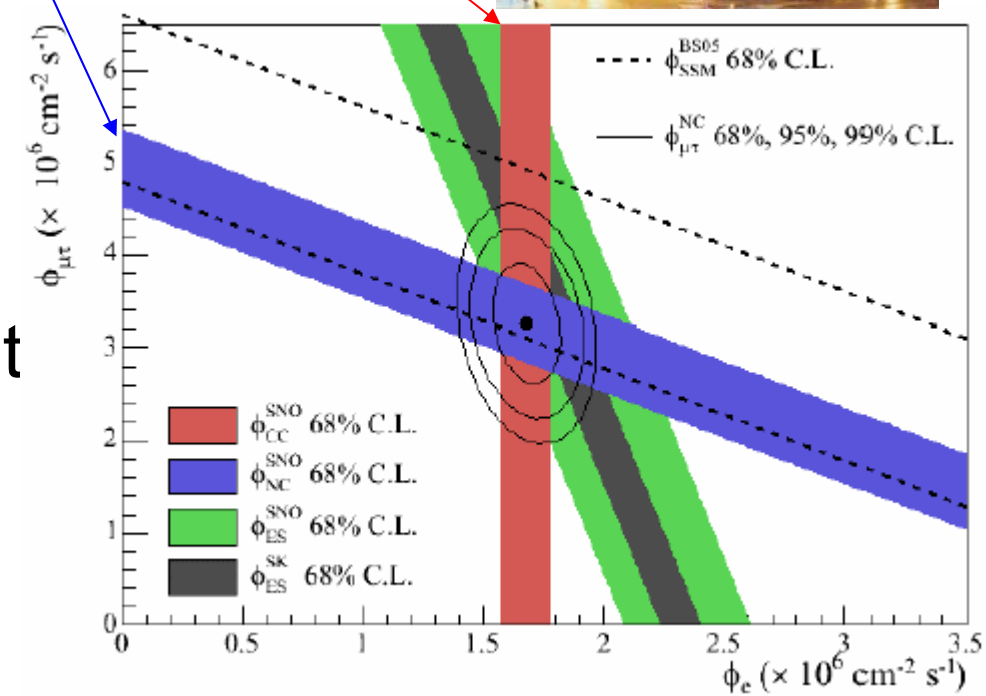




Culmination: SNO

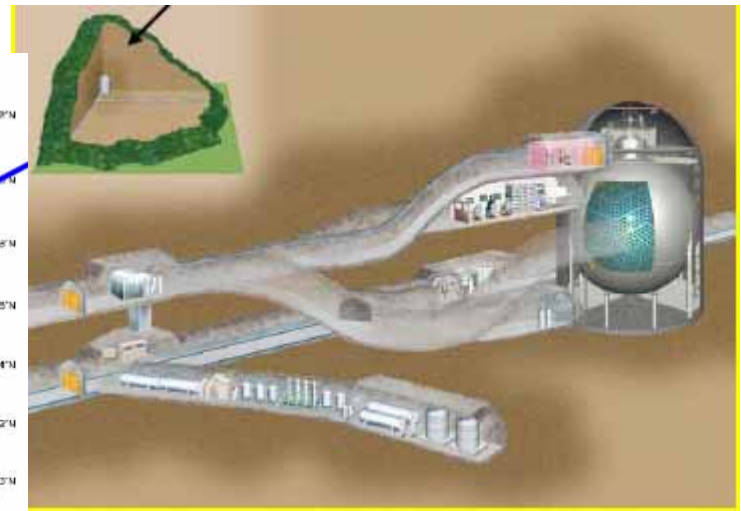
- D_2O target uniquely observes:
  - charged-current $\nu_e d \rightarrow ppe^-$
  - neutral-current $\nu_X d \rightarrow \nu_X pn$
- The former is only observed for ν_e (lepton mass)
- The latter for all types
- Solar flux is consistent with models
  - but not all ν_e at earth

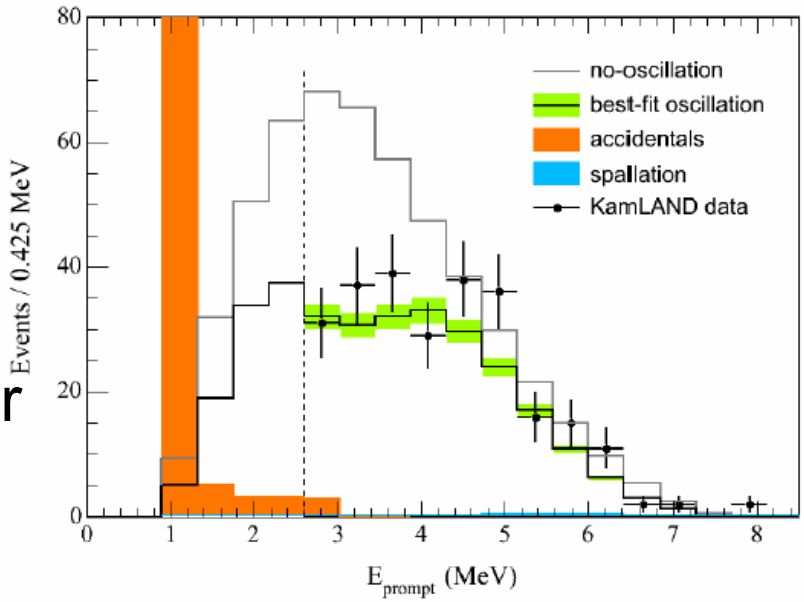




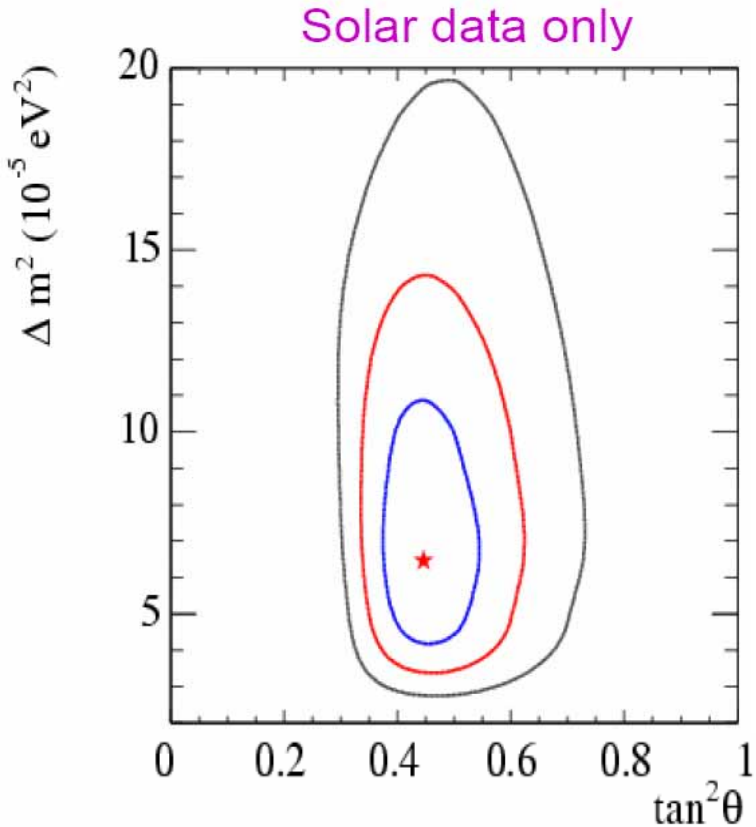
KAMLAND

- Sources are Japanese reactors
  - *150-200 km* for most of flux. *Rate uncertainty ~6%*
- 1 kTon scint. detector in old Kamiokande cavern
  - overwhelming confirmation that neutrinos change flavor in the sun *via* matter effects

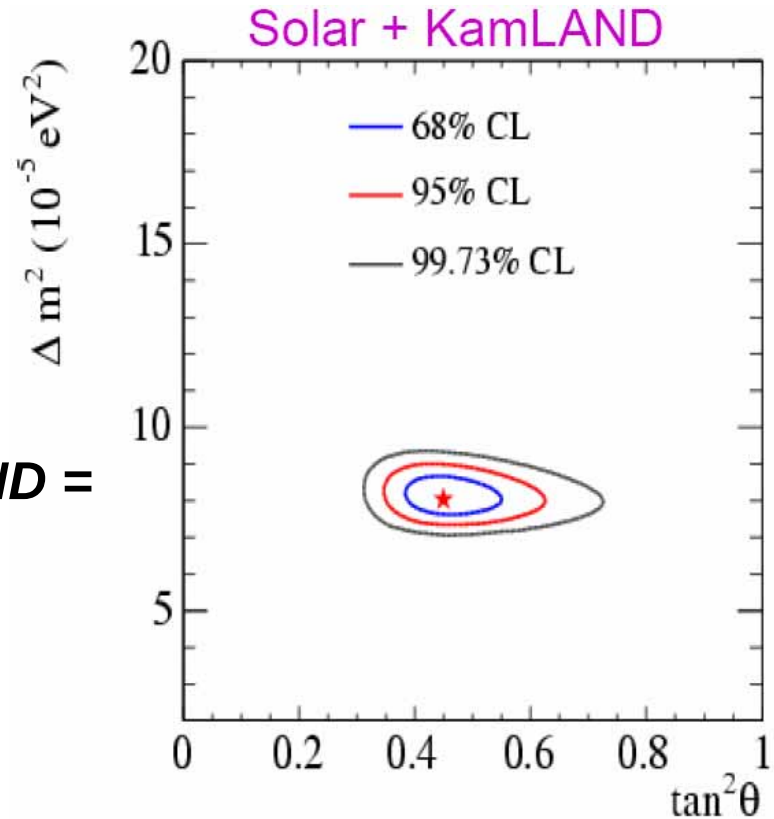




Solar Observations vs. KAMLAND

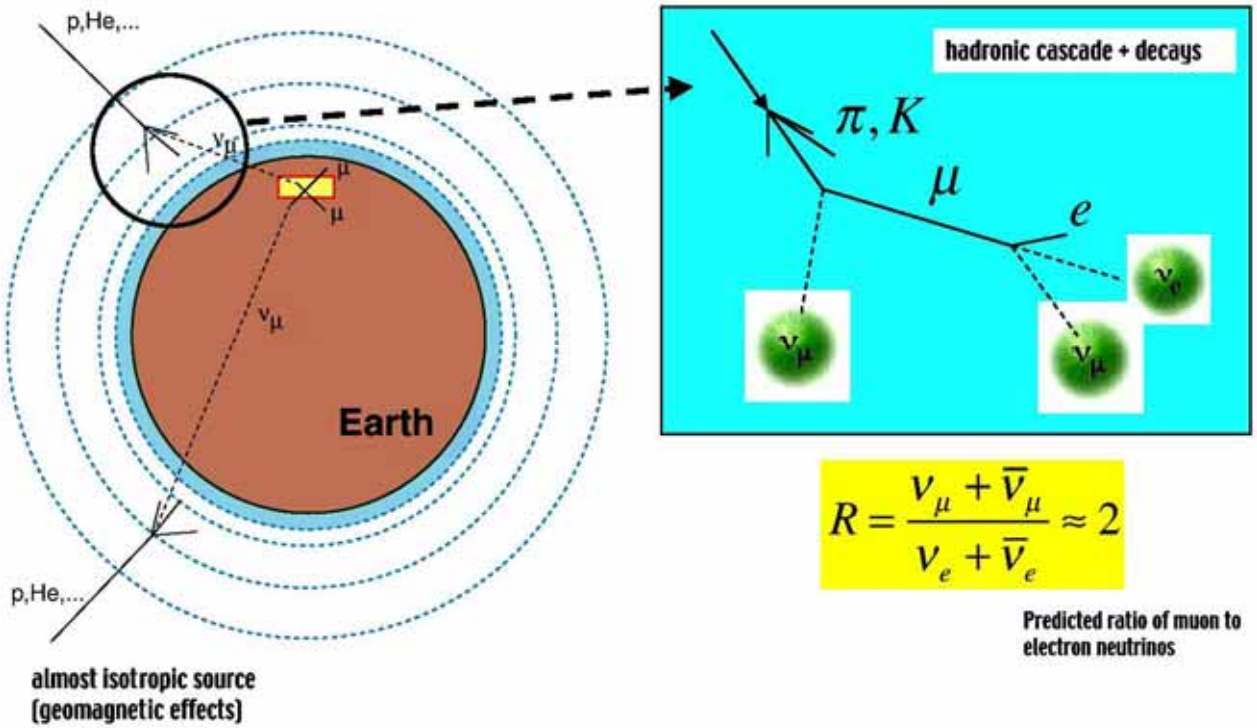


+ KAMLAND =



- Solar neutrino observations are best measurement of the mixing angle
- KAMLAND does better on δm^2_{12}

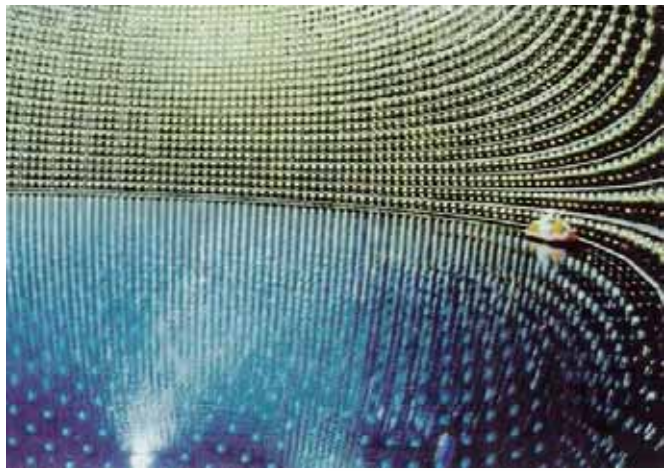
Atmospheric Neutrinos

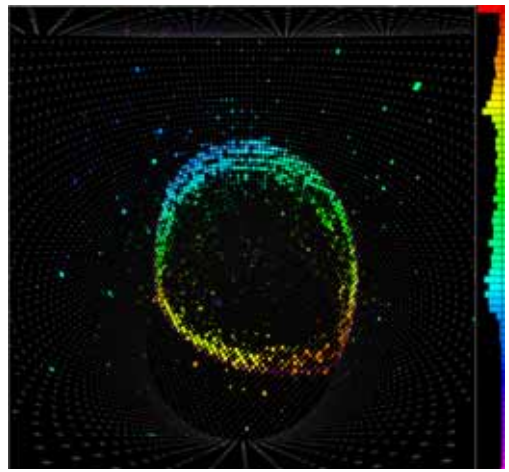


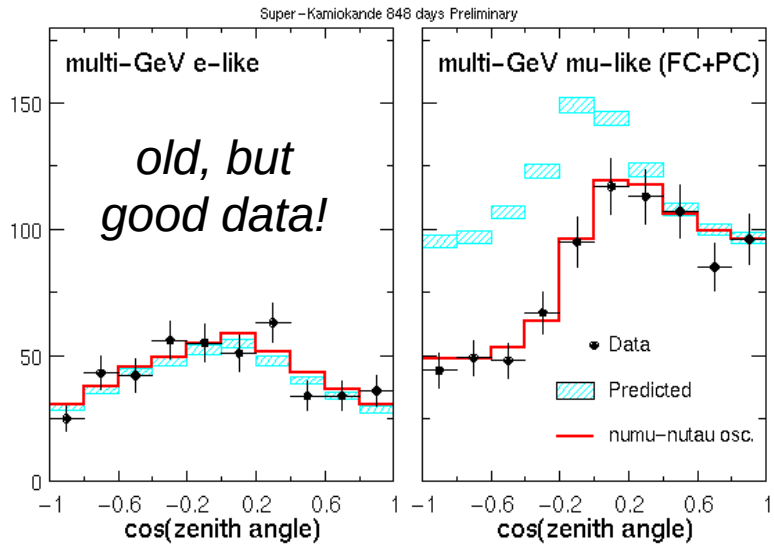
- Neutrino energy: few 100 MeV – few GeV
- Flavor ratio robustly predicted
- Distance in flight: ~20km (down) to 12700 km (up)

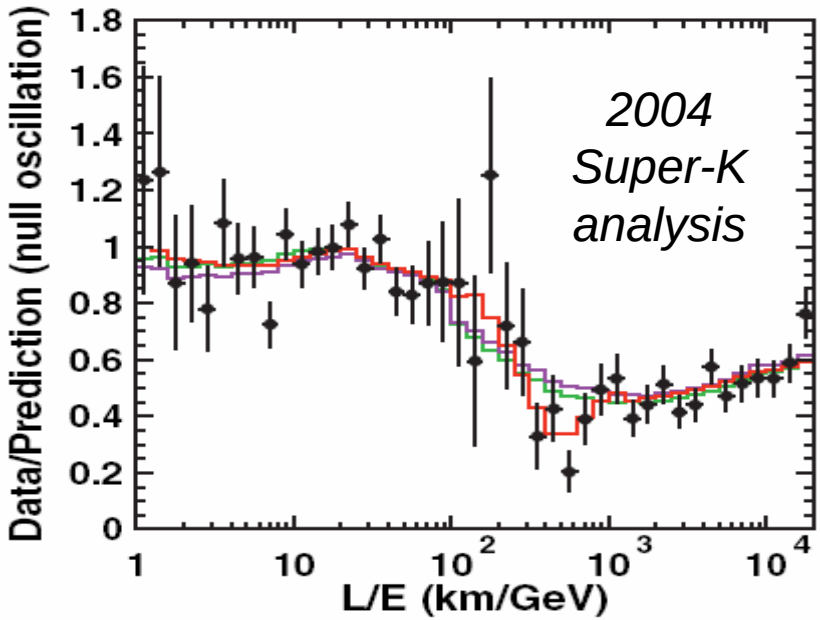
Super-Kamiokande

- Super-K detector has excellent e/μ separation







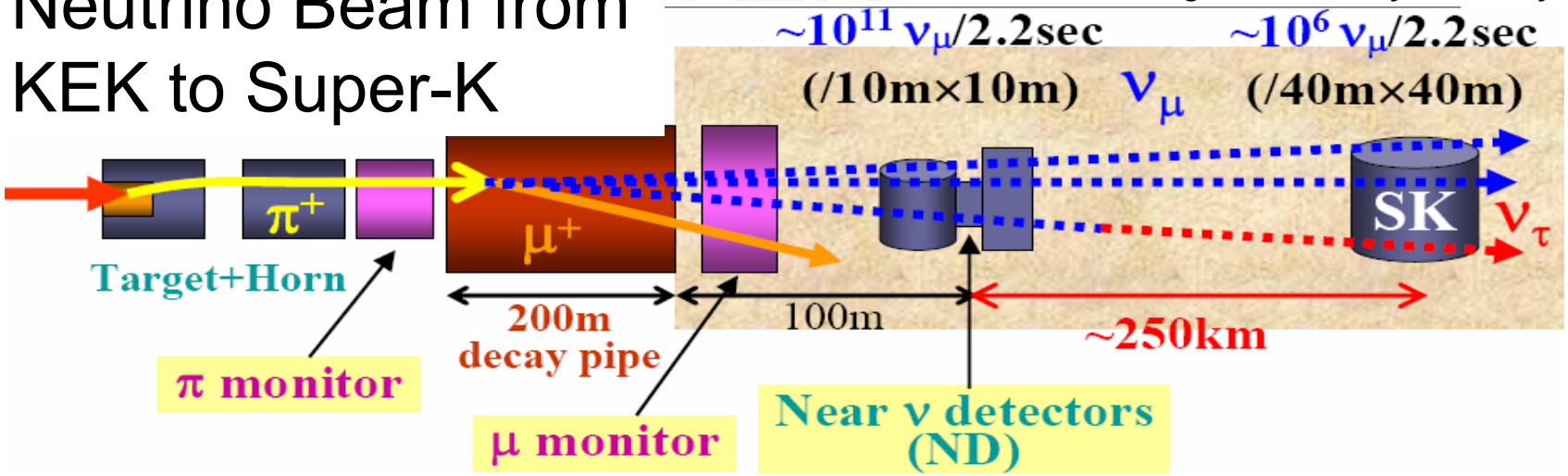


- Up / down difference!

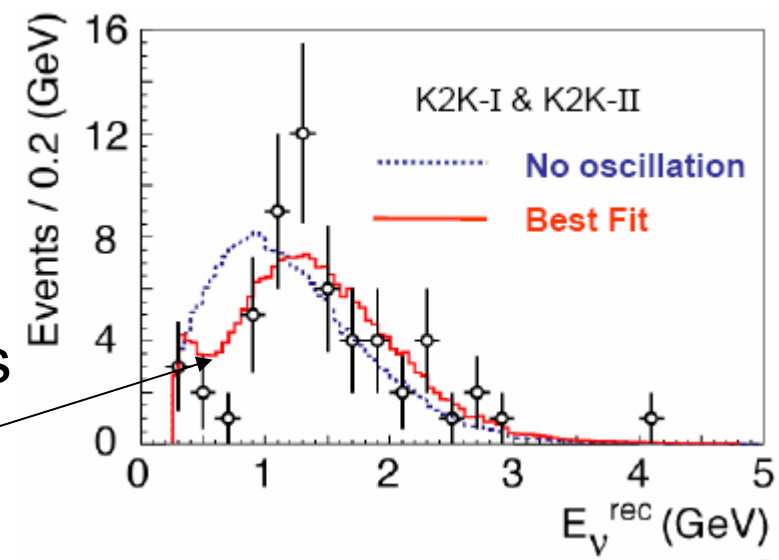
K2K

Neutrino Beam from KEK to Super-K

figures courtesy T. Nakaya

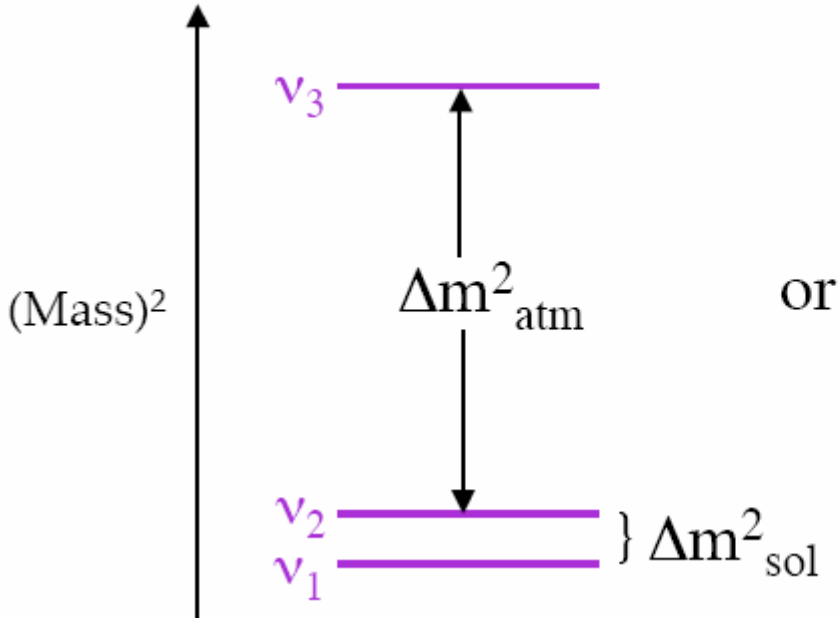


- Experiment has completed data-taking
  - confirms atmospheric neutrino oscillation parameters with controlled beam
  - constraint on δm^2_{23} (limited statistics)

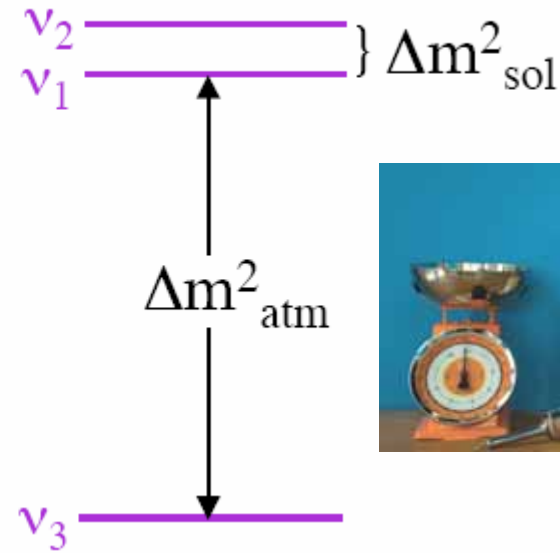


Enough For Three Generations

figures courtesy B. Kayser



or



$\delta m_{sol}^2 \rightarrow \delta m_{12}^2 \approx 8\times10^{-5} eV^2$ $\delta m_{atm}^2 \rightarrow \delta m_{23}^2 \approx 2.5\times10^{-3} eV^2$

- Oscillations have told us the splittings in m^2, but nothing about the hierarchy
- *The electron neutrino potential (matter effects) can resolve this in oscillations, however.*

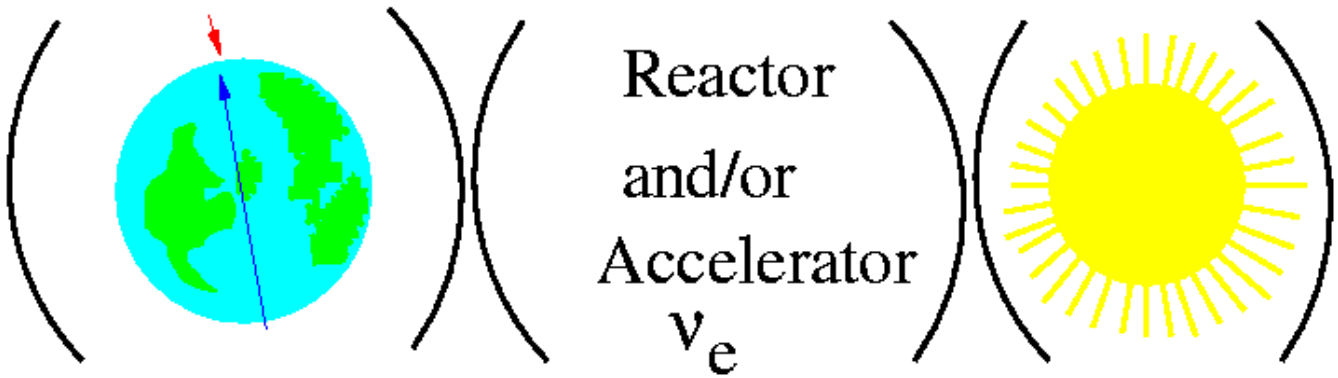
Three Generation Mixing

slide courtesy D. Harris

Lesson Learned from CKM: 3 mixing angles and a phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

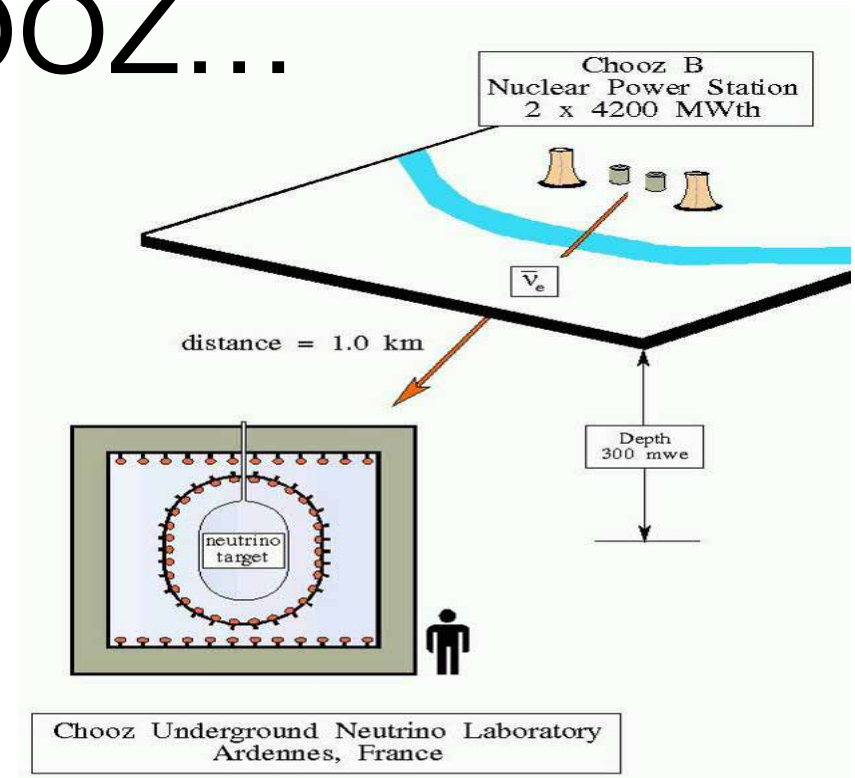
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

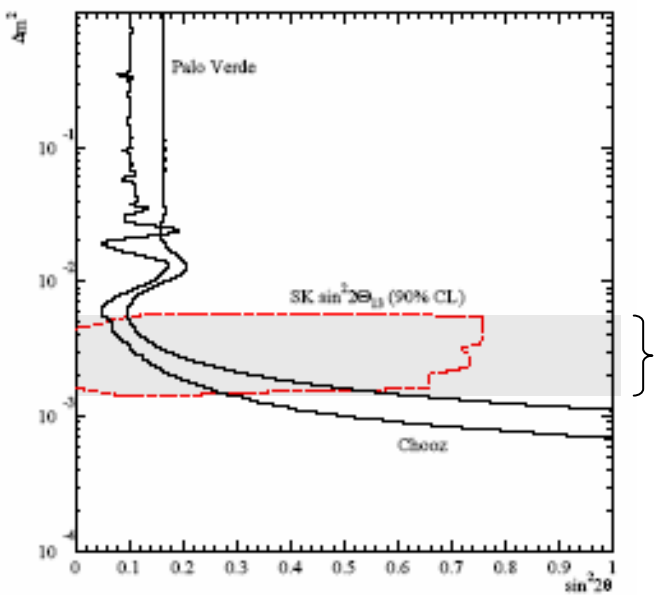
U= 

- Note the new mixing in middle, and the phase, δ

But CHOOZ…

- Like KAMLAND, CHOOZ and Palo Verde expt's looked at anti-ν_e from a reactor
  - compare expected to observed rate, σ~4%



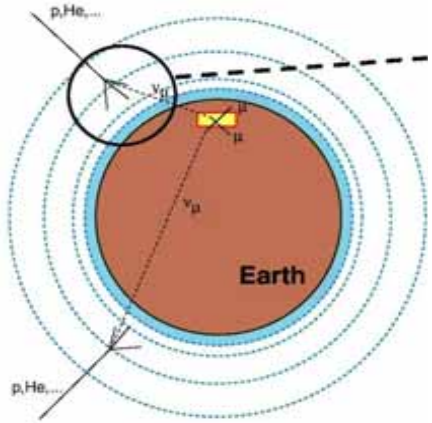


- If electron neutrinos don't disappear, they don't transform to muon neutrinos
  - limits ν_μ->ν_e flavor transitions at and therefore $|U_{e3}|$ is "small"

Optimism has been Rewarded

"We live in the best of all possible worlds"

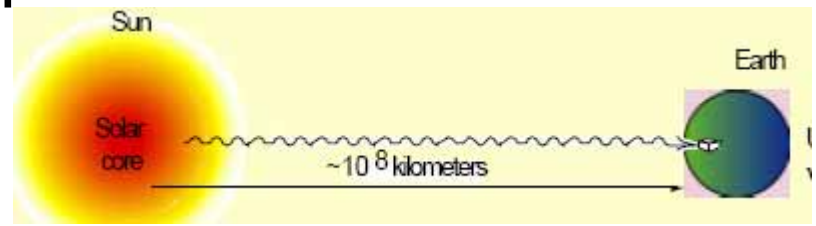
– Alvaro deRujula, Neutrino 2000



- By which he meant…
  had not

  $$E_{atm\ \nu}/R_{earth} < \delta m_{atm}^2 < E_{atm\ \nu}/h_{atm}$$

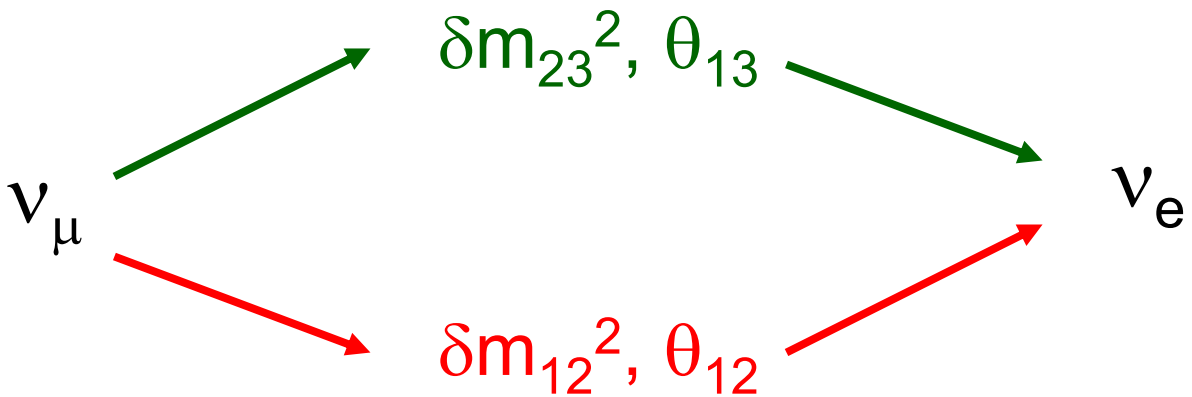
  and had not solar density profile
  and δm_{sol}^2 been
  well-matched…



- *We might not be discussing ν oscillations!*

Are Two Paths Open to Us?

- If "CHOOZ" mixing, θ_{13}, is small, but not too small, there is an interesting possibility



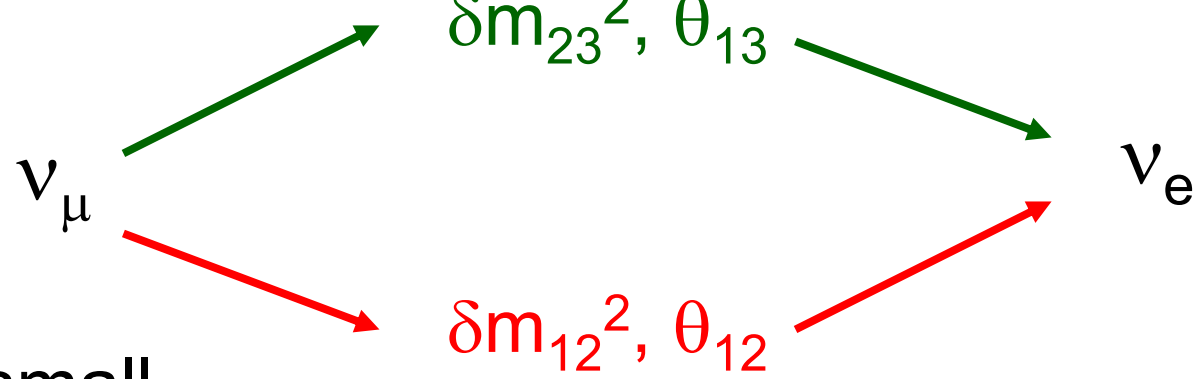
- At atmospheric L/E,

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

SMALL LARGE LARGE SMALL

Implication of two paths

- Two amplitudes

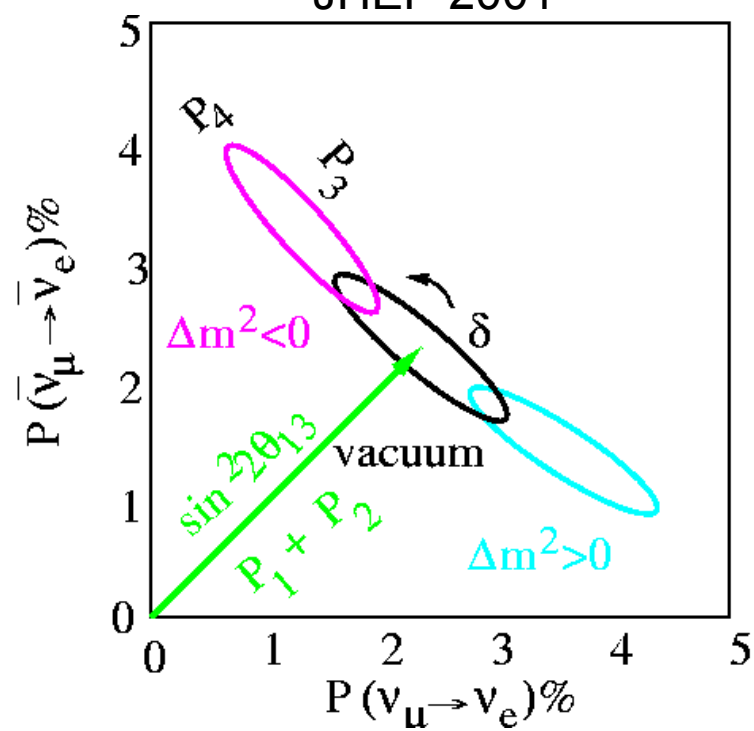


- If both small,
  but not too small,
  both can contribute ~ equally
- Relative phase, δ, between them can lead to CP violation (neutrinos and anti-neutrinos differ) in oscillations!

Leptons Have Rediscovered the Wonders of Three Generations!

- CP violation and matter effects lead to a complicated mix…
- CP violation gives ellipse but matter effects shift the ellipse in a long-baseline accelerator experiment…

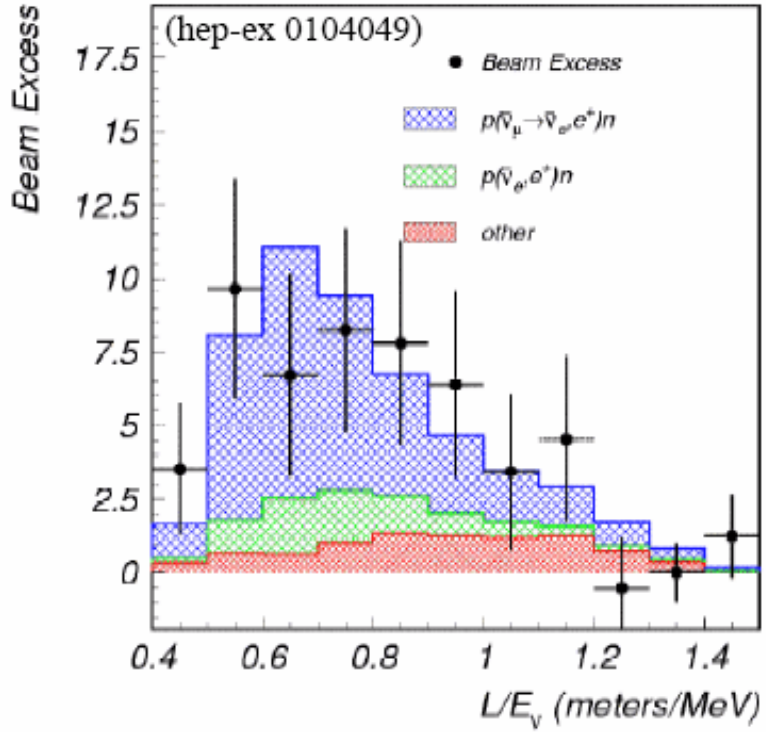
Minakata & Nunokawa
JHEP 2001

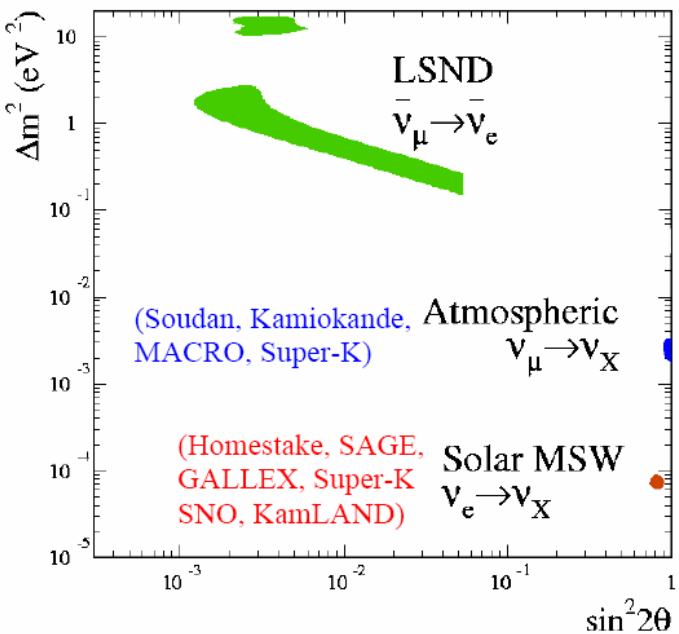


But LSND…

figures courtesy S. Brice

- LSND anti-ν_e excess
  - 87.9±22.4±6.0 events
  - statistically overwhelming; however…





LSND $\delta m^2 \sim 0.1\text{-}1.0\ eV^2$

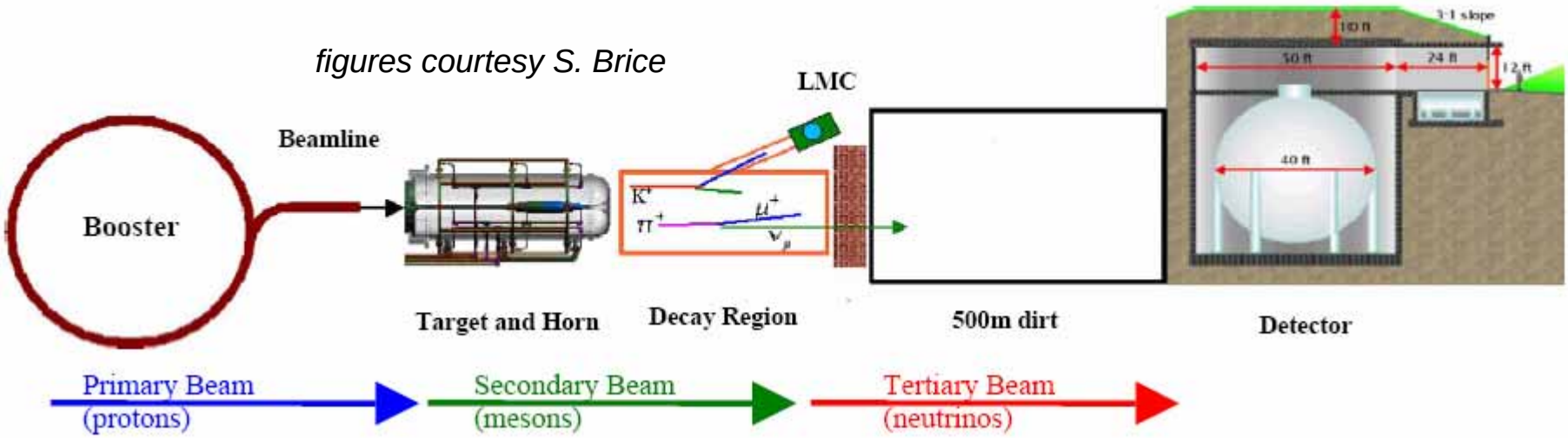
Atmos. $\delta m^2 \approx 2.5\times10^{-3}\ eV^2$

Solar $\delta m^2 \approx 8.0\times10^{-5}\ eV^2$

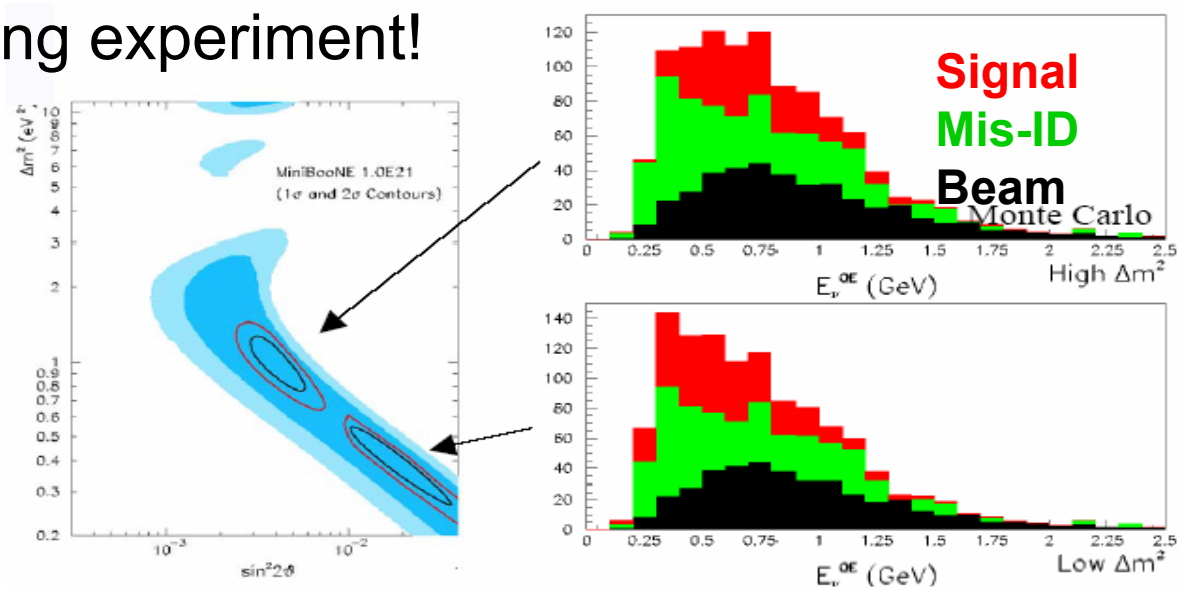
cannot be accommodated with only three neutrinos

MiniBooNE

figures courtesy S. Brice



- A very challenging experiment!
- Have >0.5E21 protons on tape
- First ν_e appearance results in early 2006



Next Steps
(Brazenly Assuming Three Neutrinos)

- MINOS and CNGS
- Reactors
- T2K and NOvA

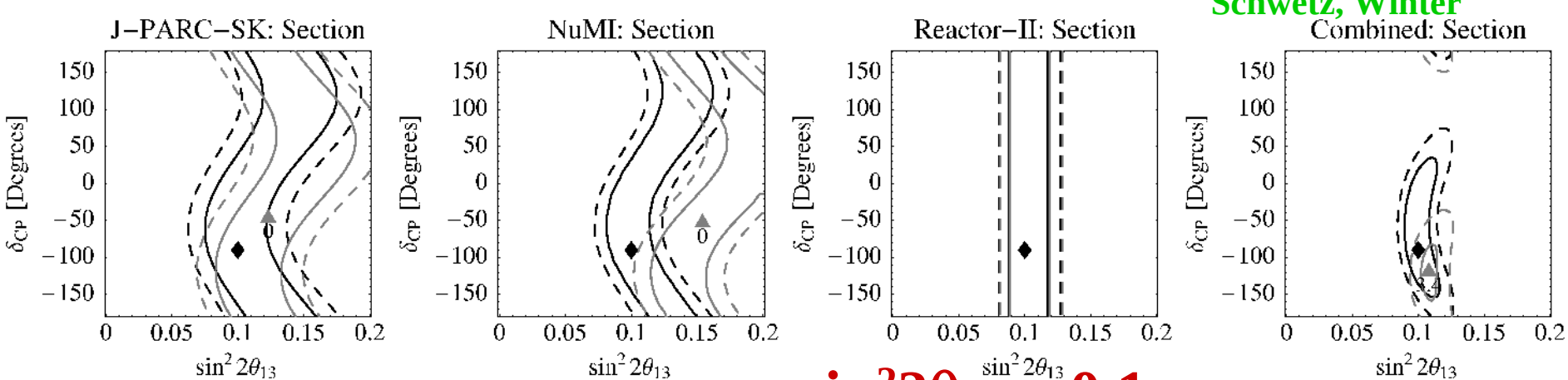
graphical wit
courtesy A. deRujula

- Mating Megatons and Superbeams
- Beta (ν_e) beams and
  neutrino factories ($\mu \rightarrow \nu_e$ and ν_μ)

Isn't all of this overkill?

- Disentangling the physics from the measurements is complicated
- Different measurements have different sensitivity to matter effects, CP violation
  - Matter effects amplified for long L, large E_ν
  - CP violation cannot be seen in disappearance (reactor) measurement $\nu_e \rightarrow \nu_e$

Huber, Lindner, Rolinec, Schwetz, Winter



<u>assumes</u> $\sin^2 2\theta_{13} = 0.1$

NuMI-Based Long Baseline Experiments

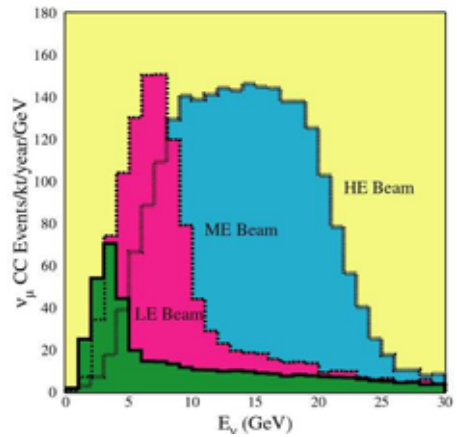
- 0.25 MWatt → 0.4 MWatt proton source
- Two generations:
  - MINOS (running)
  - NOvA (future) 15mrad Off Axis

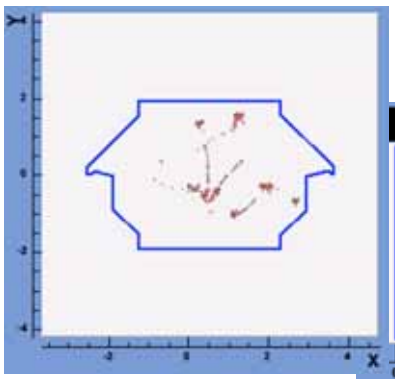
MINOS

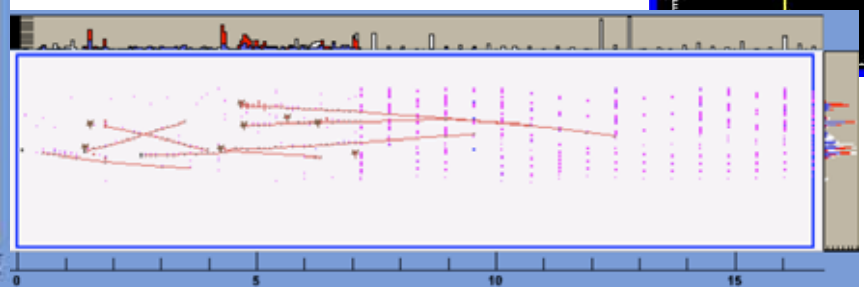
Goal: precise ν_μ disappearance measurement

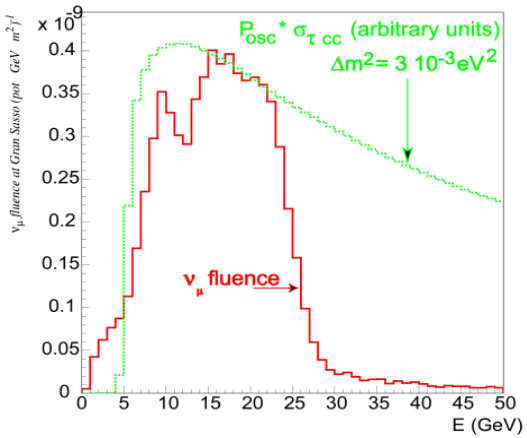
Gives δm^2_{23}

735km baseline
5.4kton Far Det.
1 kton Near Det.
Running since early 2005





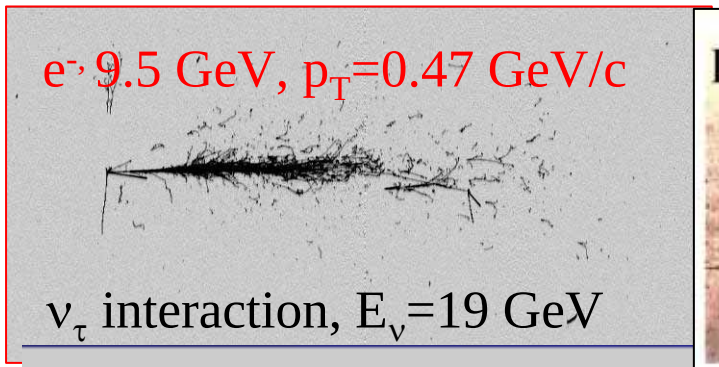


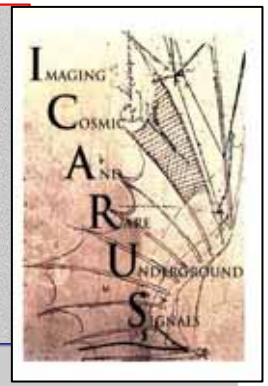


CNGS

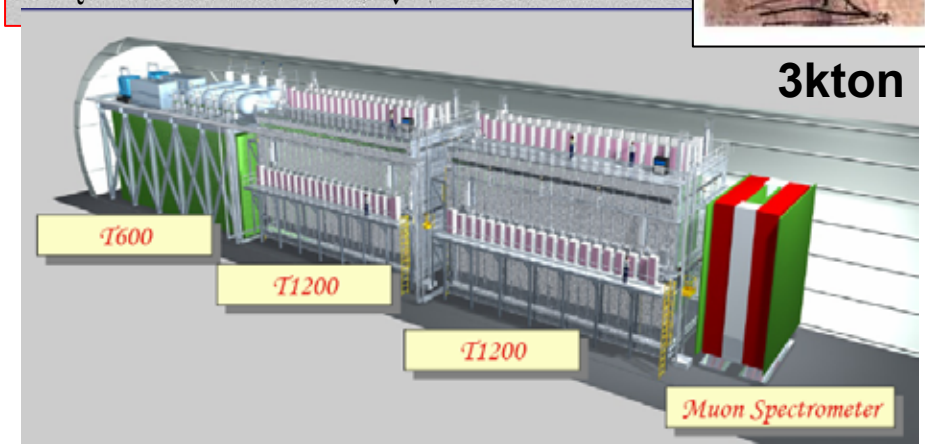
Goal: ν_τ appearance

- 0.15 MWatt source
- high energy ν_μ beam
- 732 km baseline
- handfuls of events/yr



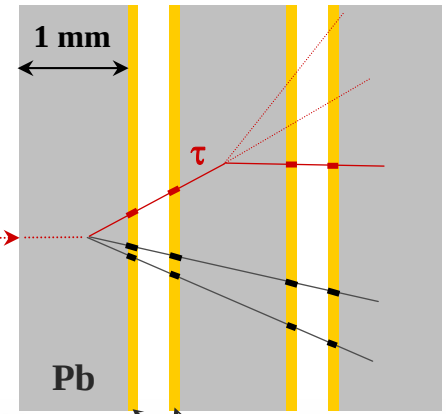


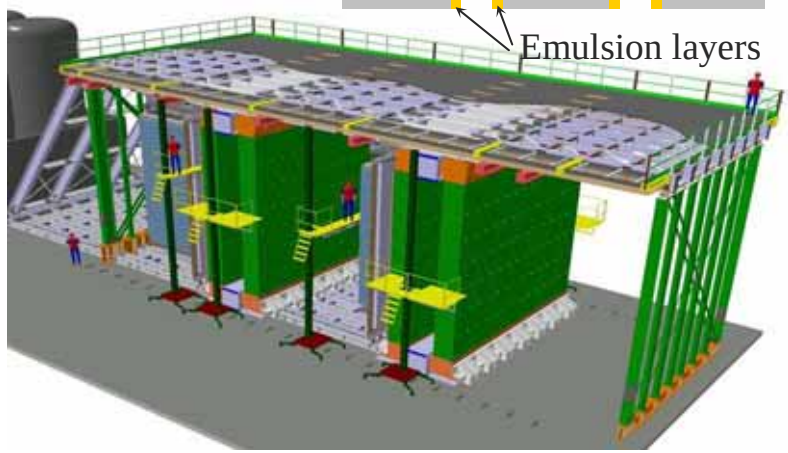
3kton



fiugres courtesy A. Bueno

1.8kTon

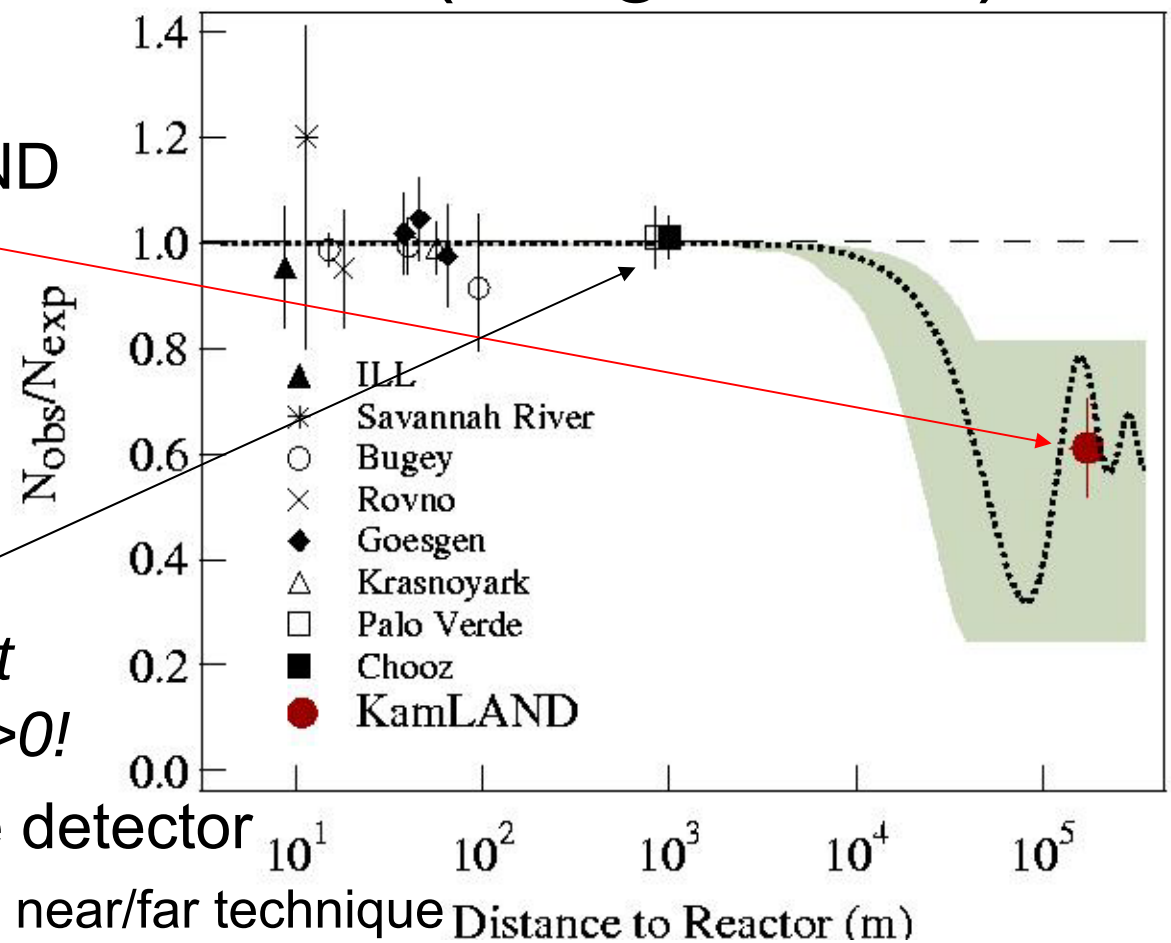




figures courtesy D. Autiero

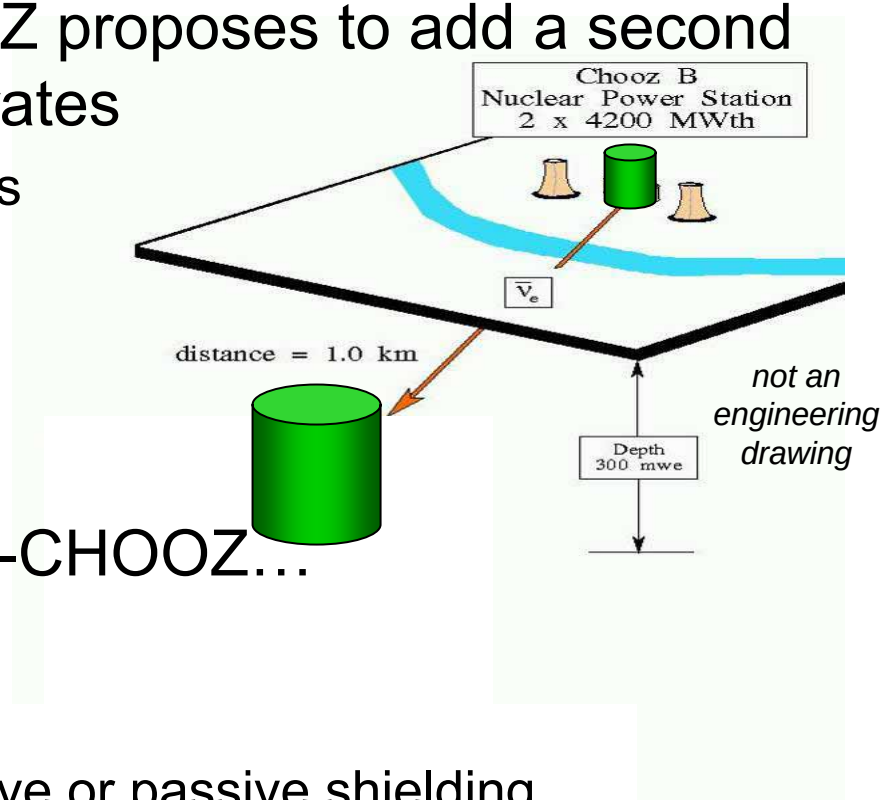
Back to Reactors (a digression)

- Recall that KAMLAND saw anti-ν_e disappearance at solar L/E
- Not seen disapp. at atmospheric L/E
  - *reactors still most sensitive to $|U_{e3}|>0$!*
- CHOOZ used single detector
  - could improve with a near/far technique
- KAMLAND has improved knowledge of how to reject backgrounds (remember, their reactors are ~200 km away!)



How Reactors? (more digression)

- To get from ~4% uncertainties to ~1% uncertainties, need a near detector to monitor neutrino flux
- For example, Double-CHOOZ proposes to add a second near detector and compare rates
  - new detectors with 10 ton mass
  - total error budget on rate ~2%
  - low statistics 10t limit spectral distortion, 1 km baseline likely shorter than optimum



- Optimization beyond Double-CHOOZ…
  - ~100 ton detector mass
  - optimize baseline for δm^2_{23}
  - background reduction with active or passive shielding

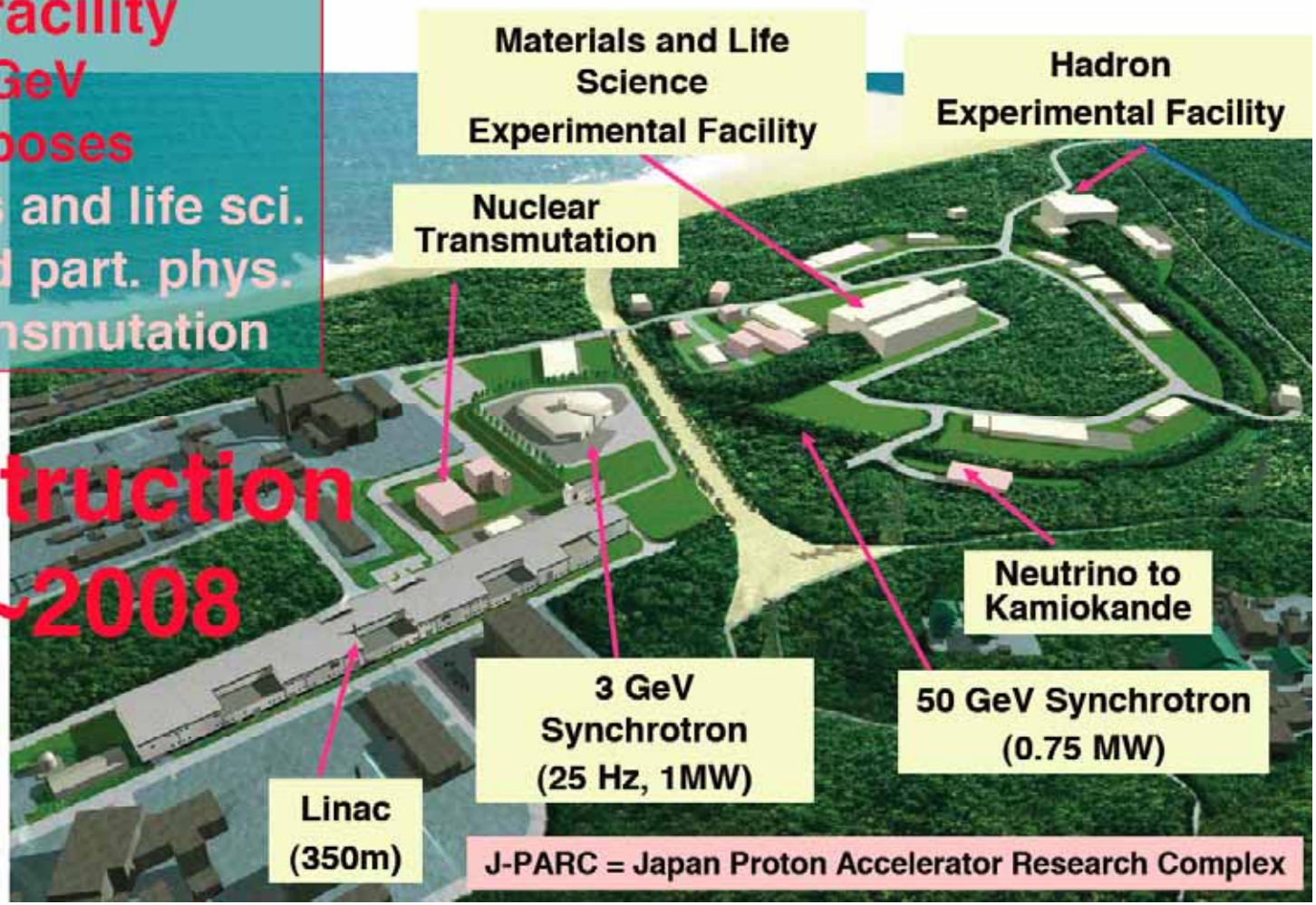
Megawatt Class Beams

- J-PARC
  - initially 0.7 MWatts → 4 MWatts
- FNAL Main Injector
  - current goal 0.25 MWatts → 0.4 MWatts → 0.6 MWatts post-Tevatron
  - future proton driver upgrades?
- Others?

J-PARC Facility

Unique facility
3GeV+50GeV
Multi-purposes
- Materials and life sci.
- Nucl. and part. phys.
- Nucl. transmutation

Construction
2001~2008



A Digression: Off-axis

- First Suggested by Brookhaven (BNL 889)
- Take advantage of Lorentz Boost and 2-body kinematics
- Concentrate ν_μ flux at one energy
- Backgrounds lower:
  - NC or other feed-down from high→low energy
  - ν_e (3-body decays)

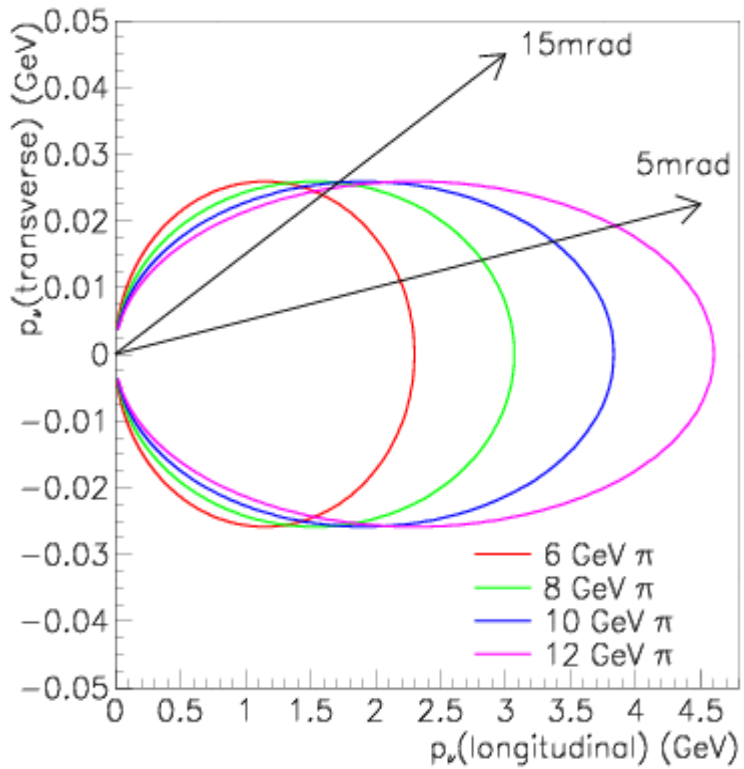
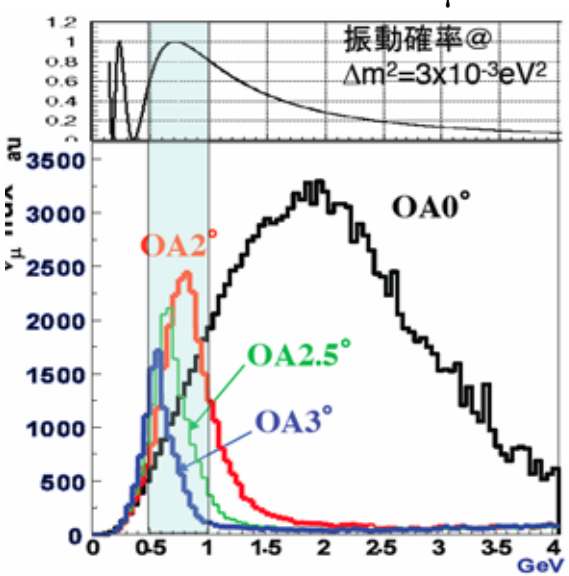
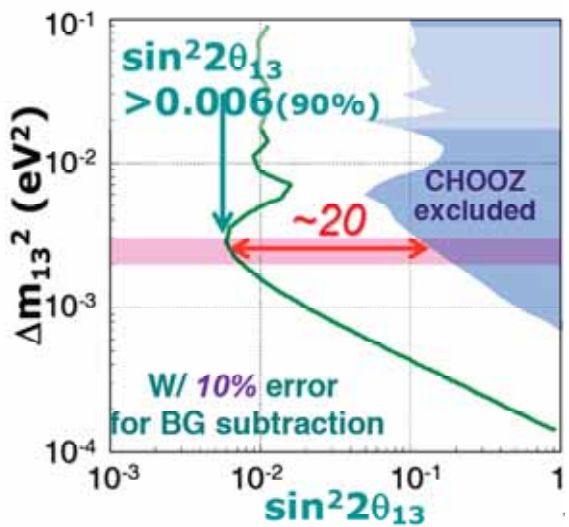


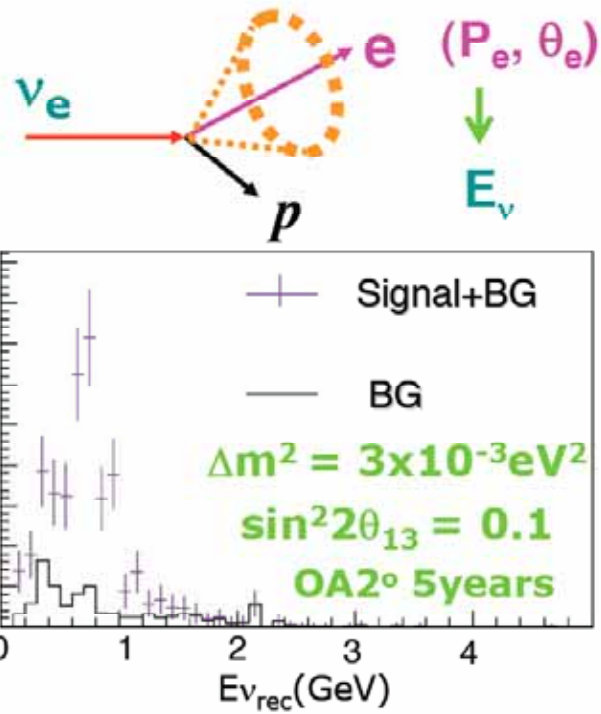
figure courtesy D. Harris

T2K

- Tunable off-axis beam from J-PARC to Super-K detector
  - beam and ν_μ backgrounds are kept below 1% for ν_e signal
  - ~2200 ν_μ events/yr (w/o osc.)







δ=0, no matter effects

figures courtesy T. Kobayashi

NuMI-Based Long Baseline Experiments

- 0.25 MWatt → 0.4 MWatt proton source
- Two generations:
  - MINOS (running)
  - NOvA (future) 15mrad Off Axis

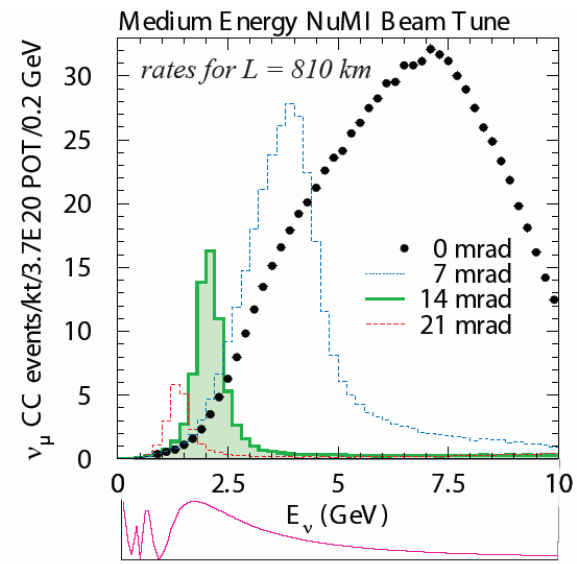
NOνA

- Use Existing NuMI beamline
- Build new 30kTon Scintillator Detector
- 820km baseline--compromise between reach in θ_{13} and matter effects

Goal:

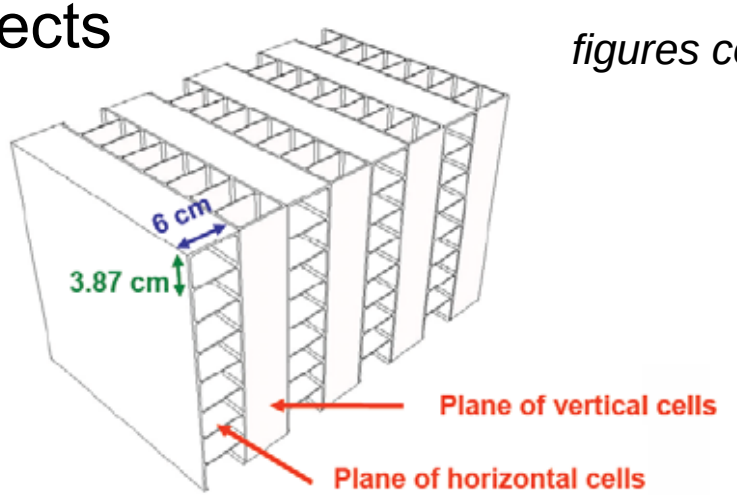
ν_e appearance In ν_μ beam

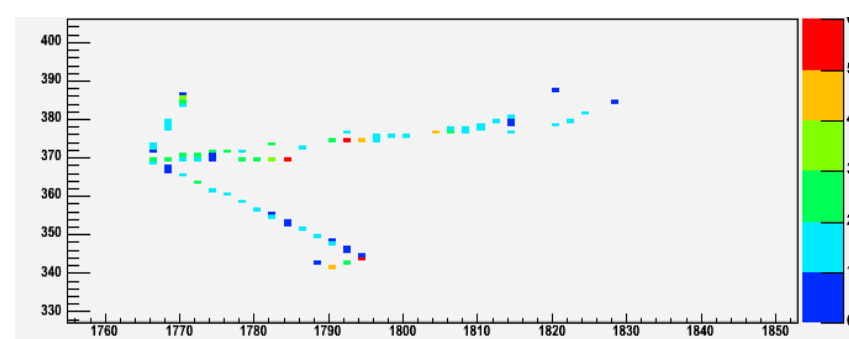
figure courtesy M. Messier



Assuming $\Delta m^2=2.5\times10^{-3}eV^2$

figures courtesy J. Cooper





$\nu_e + A \rightarrow p\ \pi^+\ \pi^-\ e^-$

Future Steps after T2K, NOvA

- Beam upgrades (2x – 5x)
- Megaton detectors (10x – 20x)

- ***BUT***, it's hard to make such steps without encountering significant
  TECHNICAL DIFFICULTIES
  - hereafter "T.D."

TD: More Beam Power, Cap'n Example: Fermilab Proton Driver

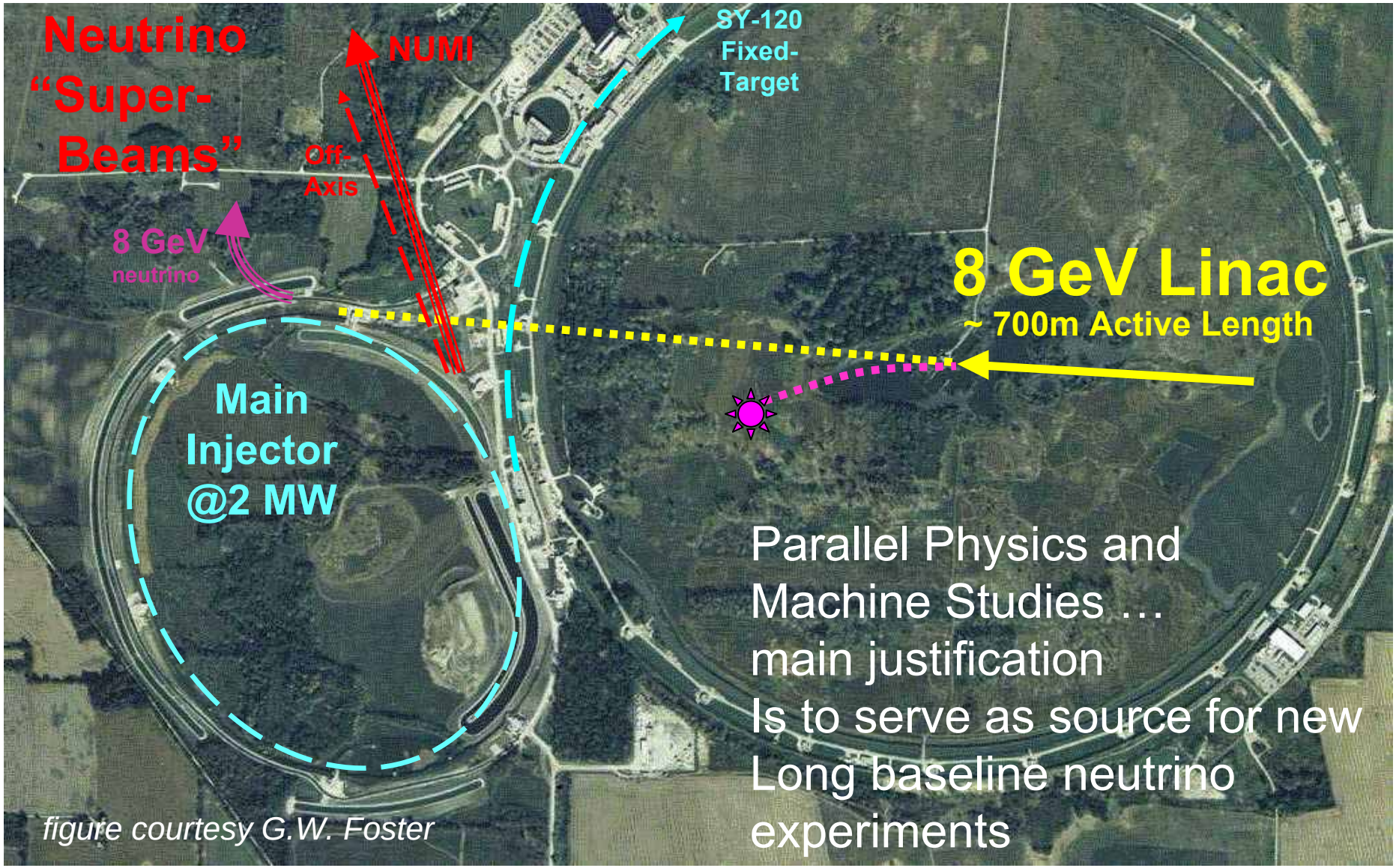


figure courtesy G.W. Foster

TDs: Beamlines

pictures courtesy D. Harris

- Handling Many MWatts of proton power and turning it into neutrinos is not trivial!

NuMI tunnel boring machine. 3.5yr civil construction

NuMI downstream absorber. Note elaborate cooling. "Cost more than NuTeV beamline…" – R. Bernstein

NuMI Horn 2. Note conductors and alignment fixtures

NuMI Target shielding. More mass than far detector!

TDs: Detector Volume

- Scaling detector volume is not so trivial

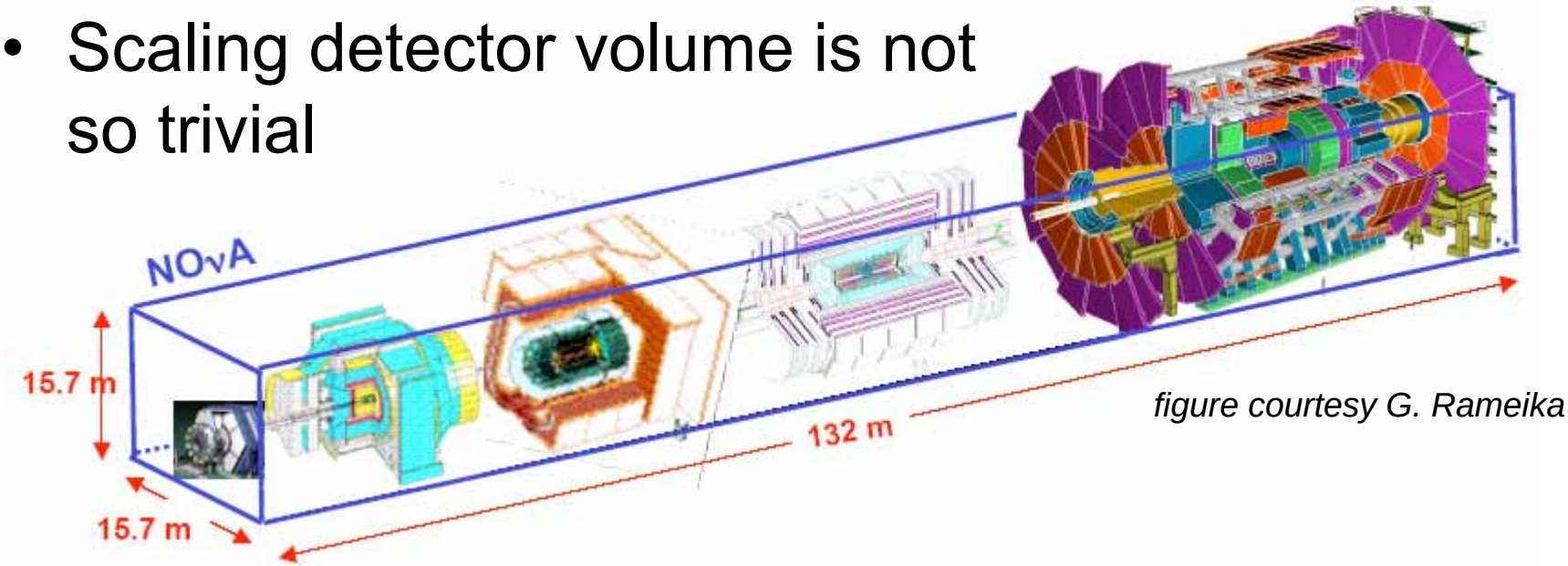
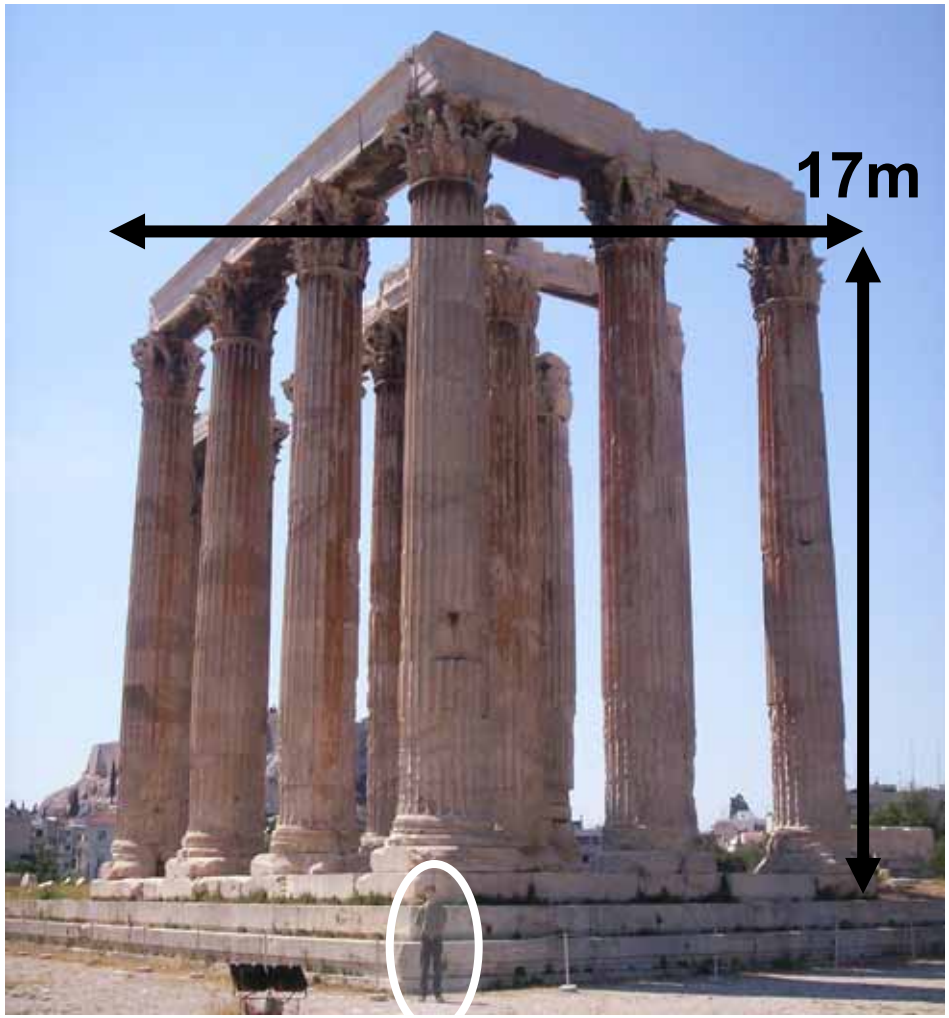


figure courtesy G. Rameika

- At 30kt NOvA is about the same mass as BaBar, CDF, Dzero, CMS and ATLAS combined…
  - want monolithic, manufacturabile structures
  - seek scaling as surface rather than volume if possible

For Perspective…

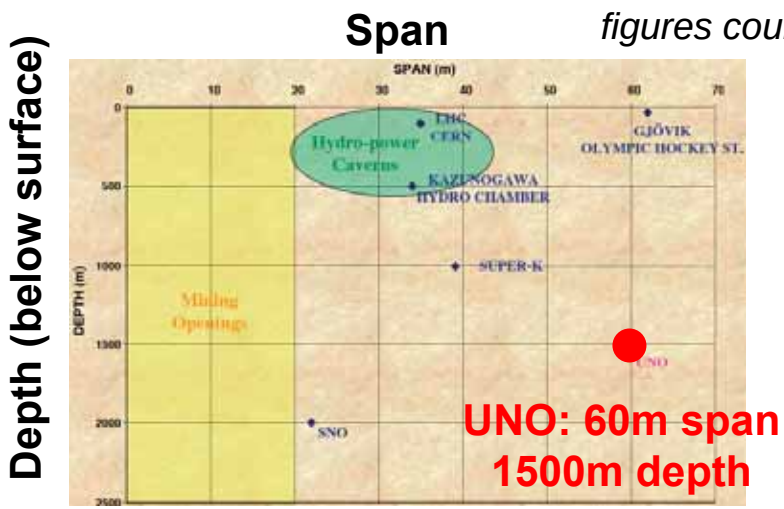


your speaker

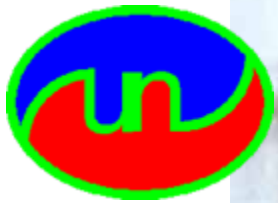
- Consider the Temple of the Olympian Zeus in Athens
- 17m tall, just like NOvA!
  - a bit over ½ the length
- It took 700 years to complete
  - delayed for lack of funding for a few hundred years
- Fortunately construction technology has improved
  - has the funding situation?

TDs: Detector Volume (cont'd)

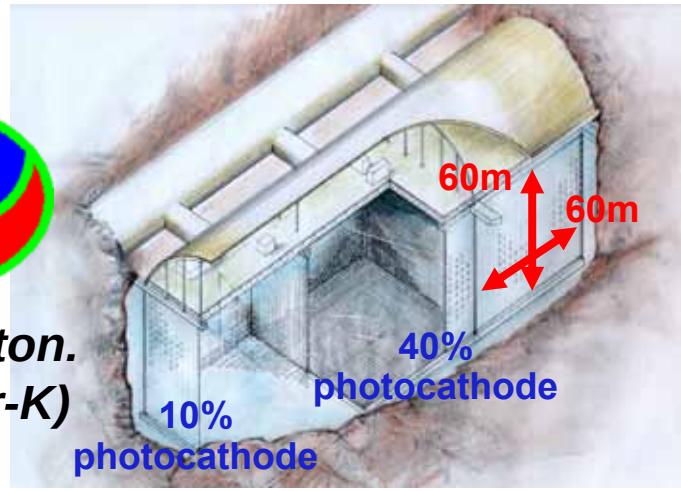
- For megatons, housing a detector is difficult!



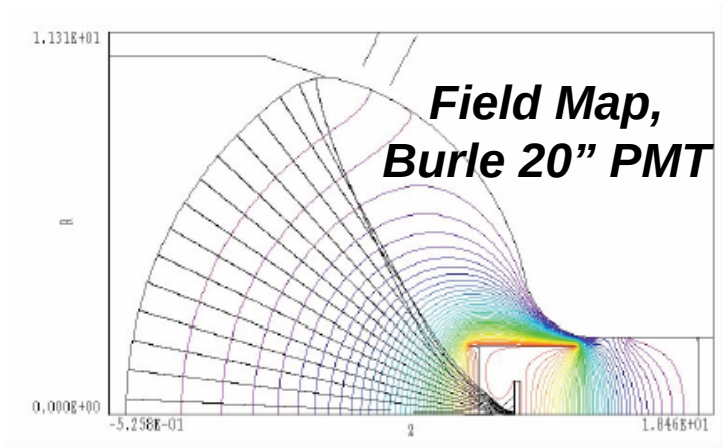
figures courtesy C.-K. Jung



UNO. ~1Mton. (20x Super-K)



- Sensor R&D: focus on reducing cost
  - in case of UNO, large photocathode PMTs
  - goal: automated production, 1.5k$/unit

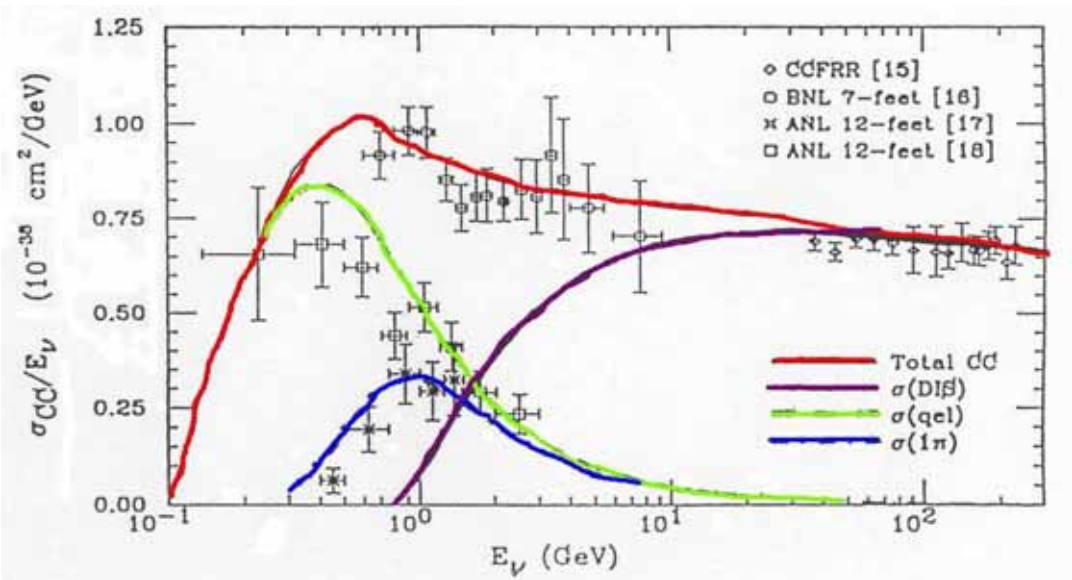


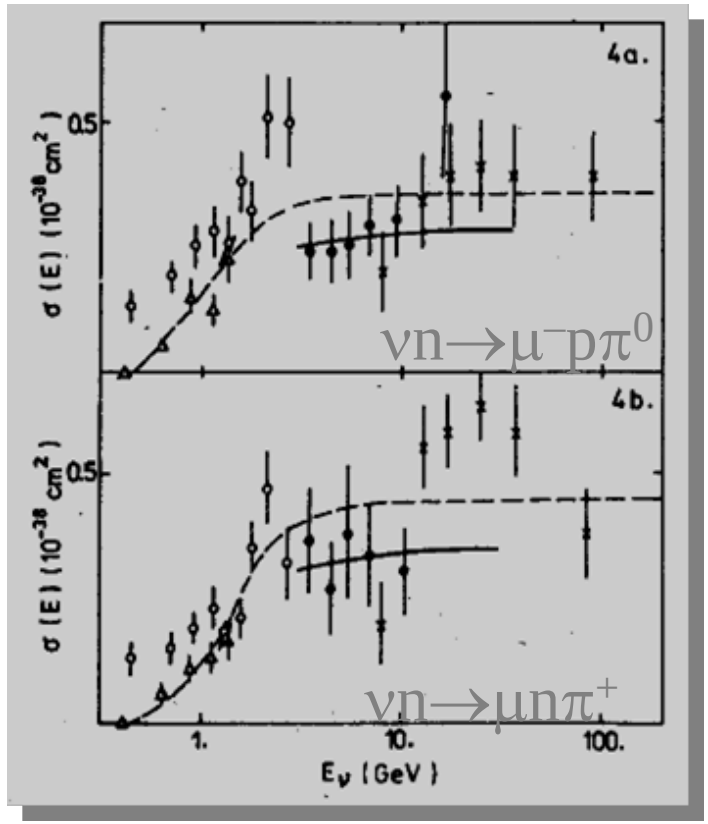
My Favorite TD: Neutrino Interactions

(this is a talk about neutrino interactions…)

- At 1-few GeV neutrino energy (of interest for osc. expt's)
  - Experimental errors on total cross-sections are large
    - almost no data on A-dependence
  - Understanding of backgrounds needs *differential* cross-sections on target
  - Theoretically, this region is a mess... transition from elastic to DIS

figures courtesy D. Casper, G. Zeller

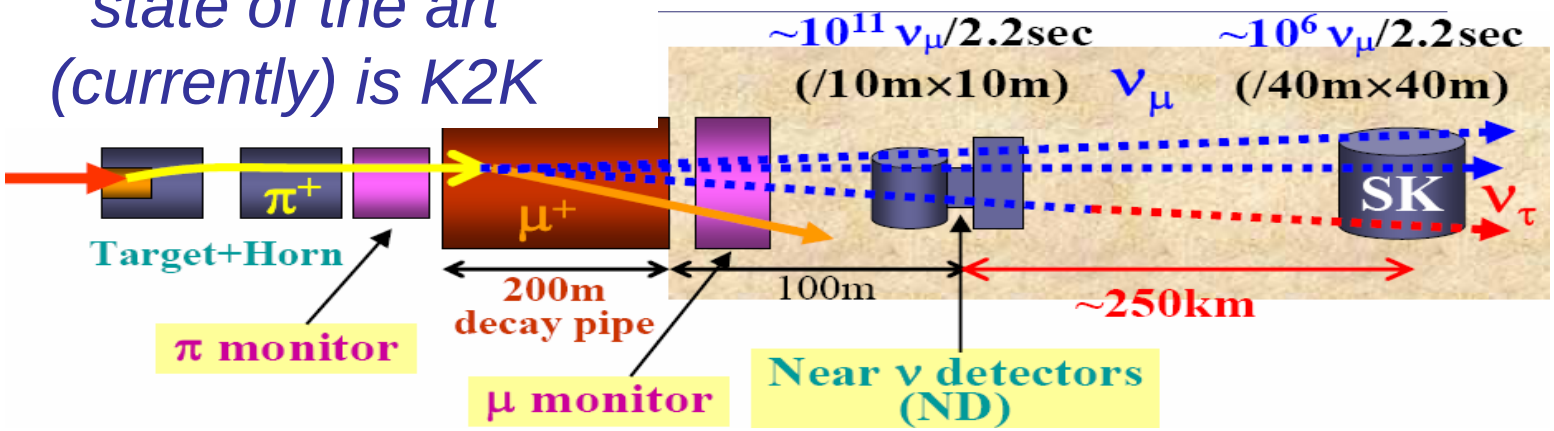




But isn't this simple?

- Neutrino oscillation experiments (nearly) all have near detectors!

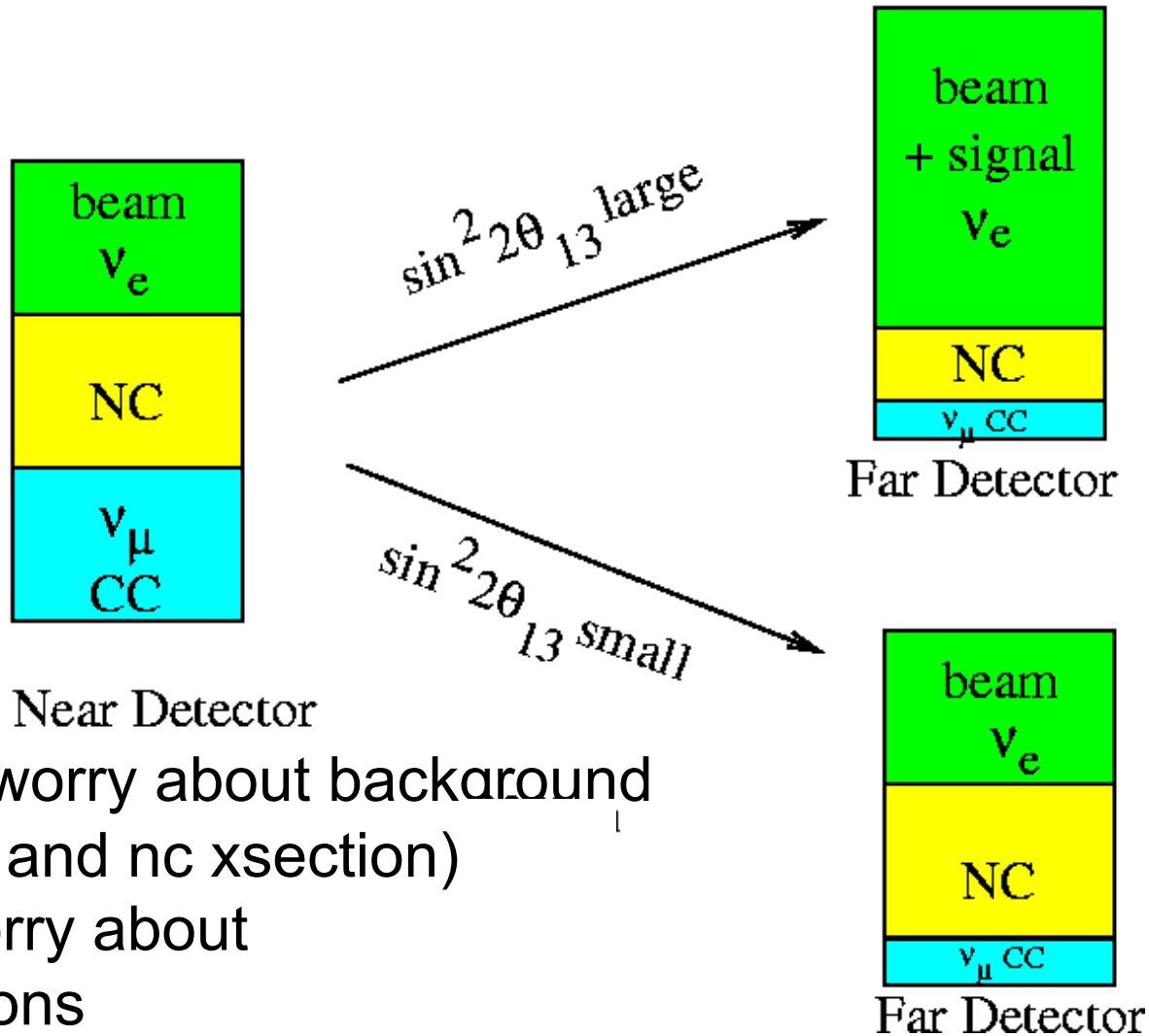
state of the art (currently) is K2K



- Shouldn't cross-section uncertainties cancel between near and far detectors?

Toy ν_e Appearance Analysis

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

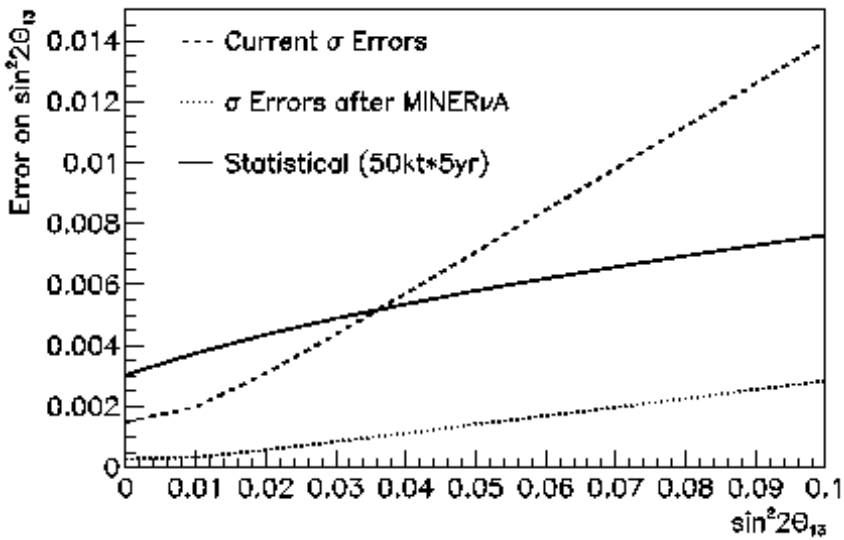


If signal is small, worry about background prediction (ν_e flux and nc xsection)
If signal is big, worry about signal cross sections

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%



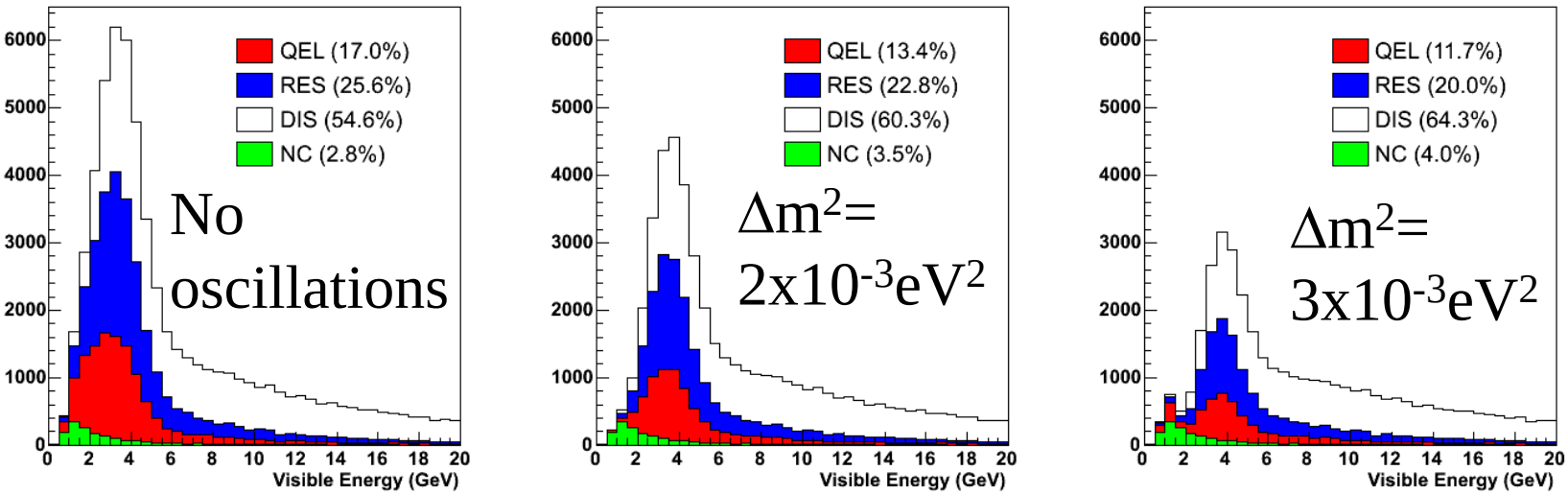
For large $\sin^2 2\theta_{13}$, statistical=8%
For small $\sin^2 2\theta_{13}$, statistical=16%

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

ν_μ Disappearance: MINOS

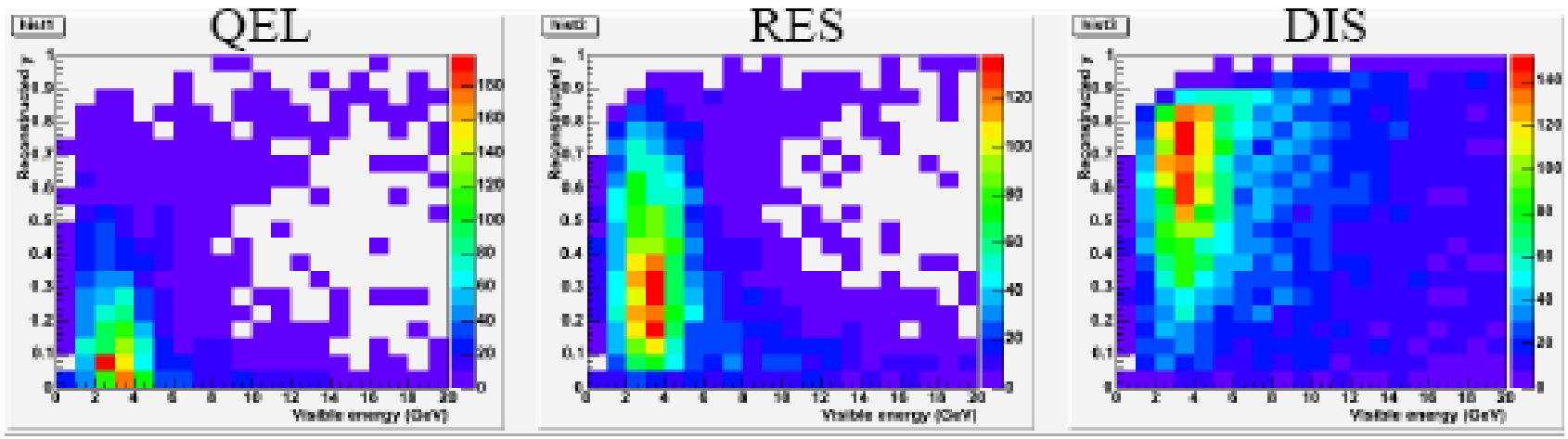
Figure courtesy D. Petyt

CC-like Visible Energy Distributions split by interaction type:

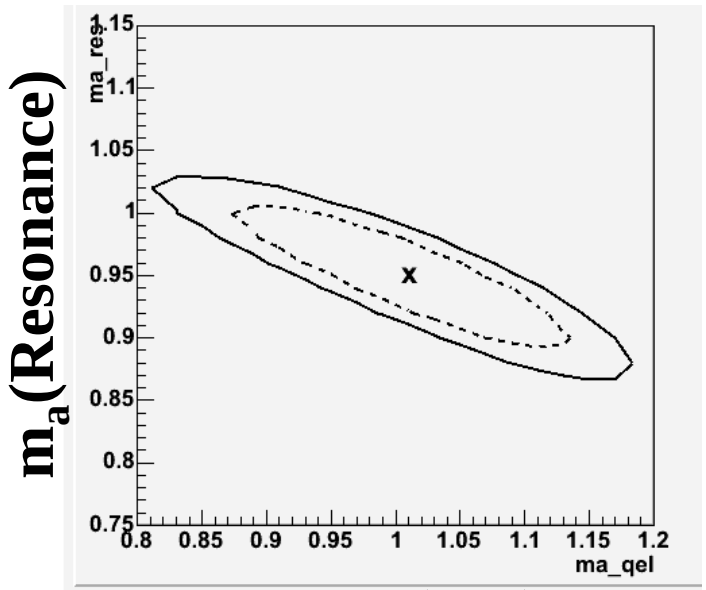


Near Detector has one neutrino energy scale, far detector will have a different scale because of oscillations…need to take cross section uncertainties into effect

ν_μ Disappearance: MINOS, II



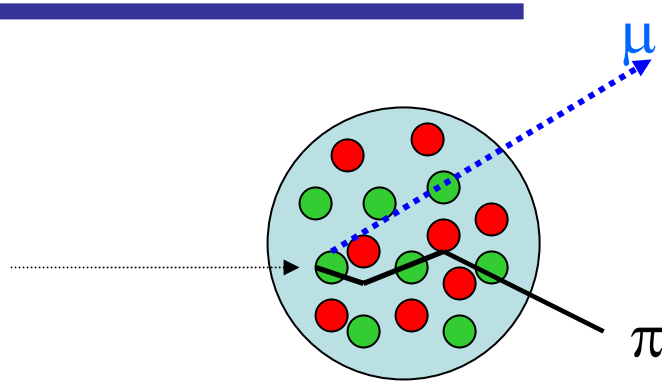
- Fit near detector spectra versus "visible y distribution" to separate different components
- Need to consider all systematic uncertainties simultaneously for total syst. error analysis



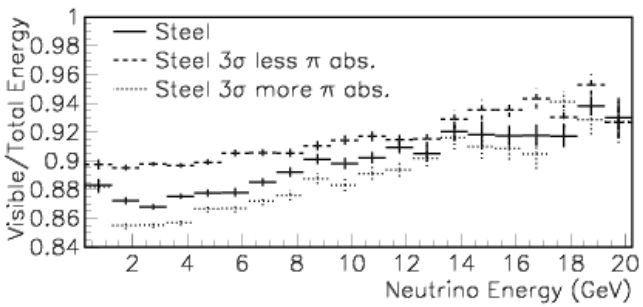
Figures courtesy D.Petyt

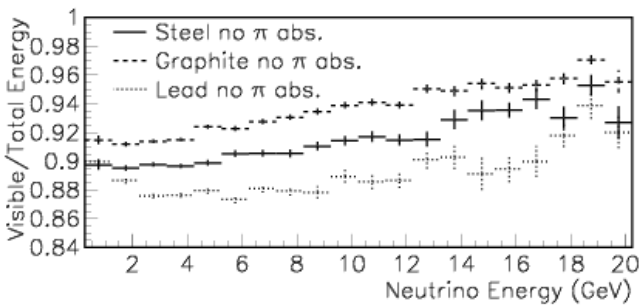
Nuclear effects at MINOS

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

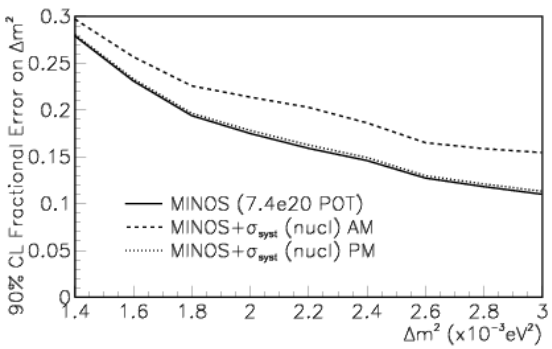


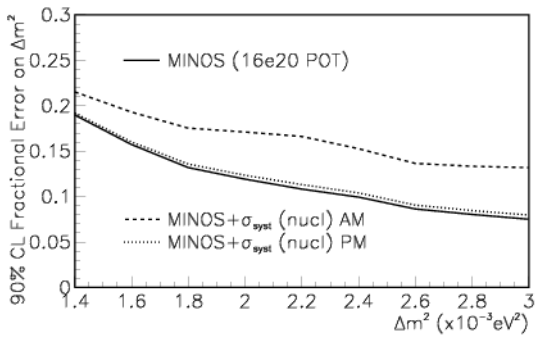
Toy MC analysis:





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





Enter MINERνA…

Essence of MINERvA

- MINER*v*A is a compact, fully active neutrino detector designed to study neutrino-nucleus interactions in detail at high statistics
- The detector will be placed in the NuMI beam line upstream of the MINOS Near Detector

- MINERvA's role in the worldwide program:
  - Combination of detector site, intensity and beam energy range of NuMI is unique
  - Detector with several different nuclear targets allows 1st study of neutrino nuclear effects
  - Crucial input to current and future oscillation measurements

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\# MINERvA Executive Committee

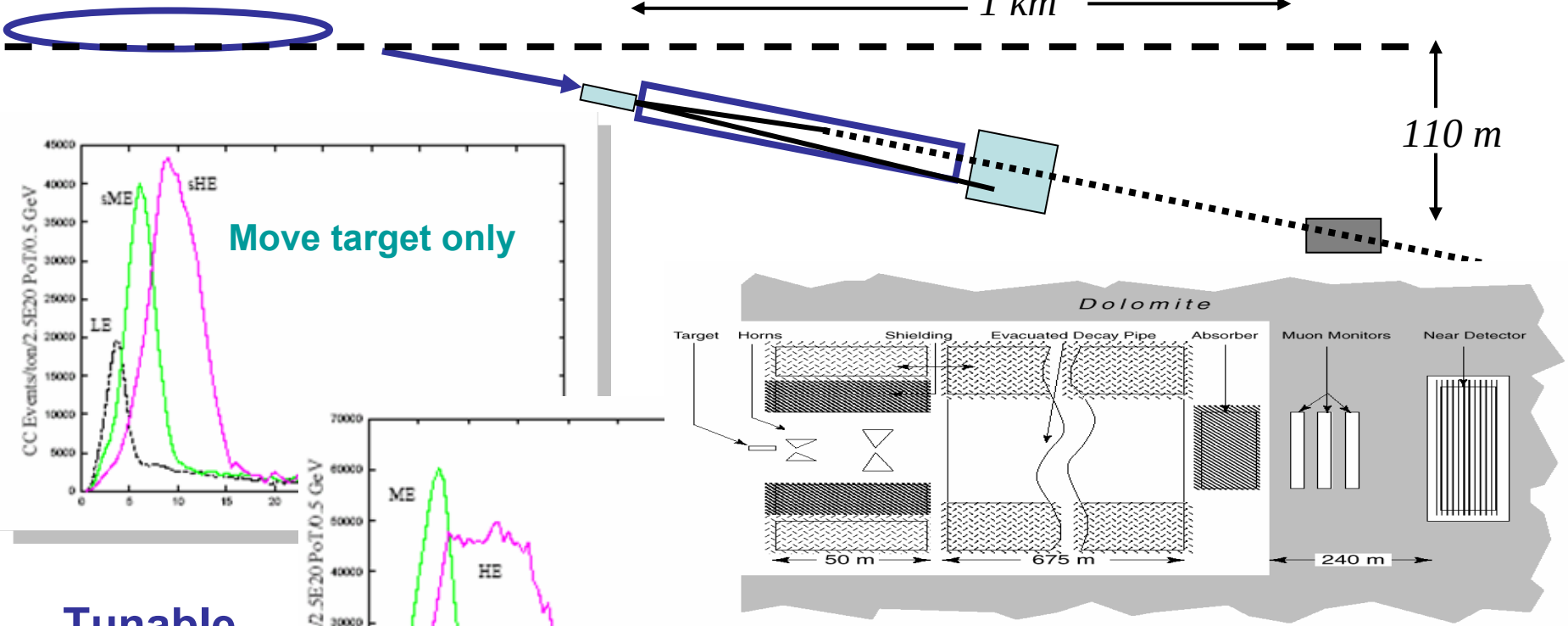
A collaboration of Particle, Nuclear, and Theoretical physicists

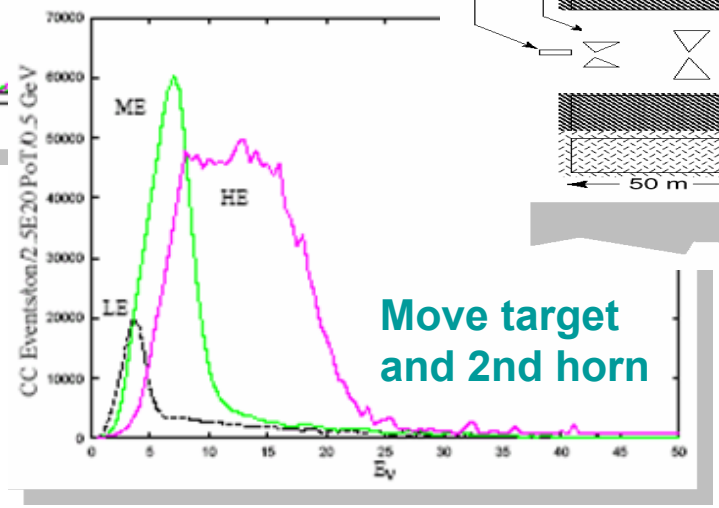
NuMI Beamline

- FNAL has recently commissioned NuMI beamline for MINOS long-baseline experiment
- Why is NuMI an ideal home for a neutrino cross-section experiment?
  - Variable energy, well-understood neutrino flux

The NuMI Neutrino Beam

Main injector: 120 GeV protons

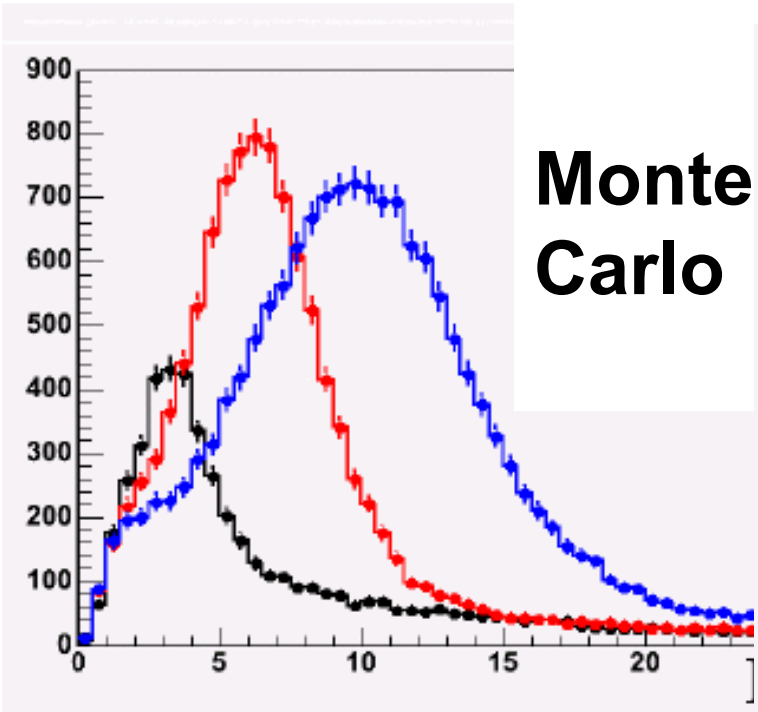




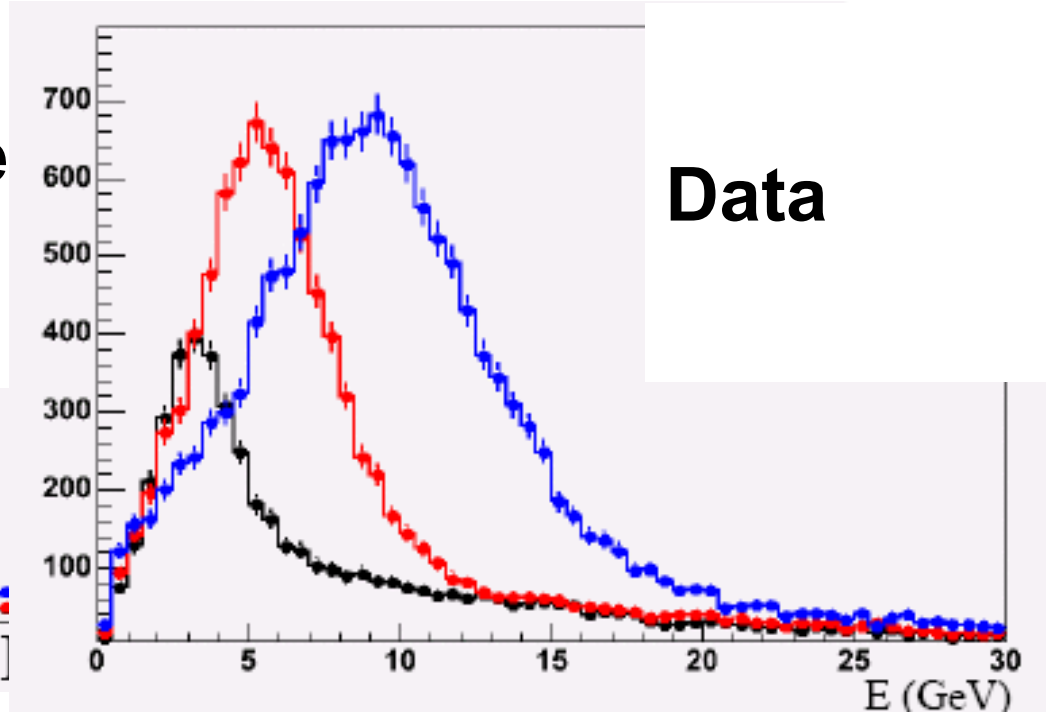
Tunable beam energy

With E-907(MIPP) at Fermilab (measure production from NuMI target) expect to know neutrino flux to ± 4%.

NuMI: MINOS ND Events



Monte Carlo



Data

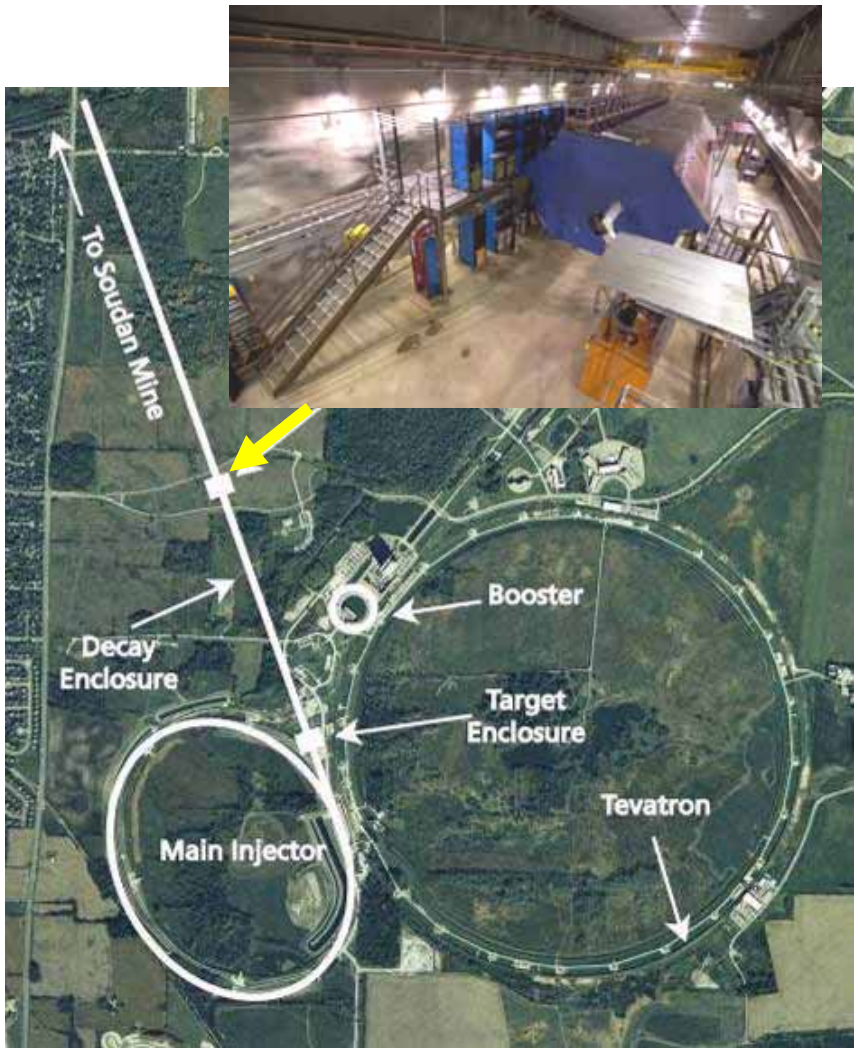
Low Energy
Target back 1m
Target back 2.5m

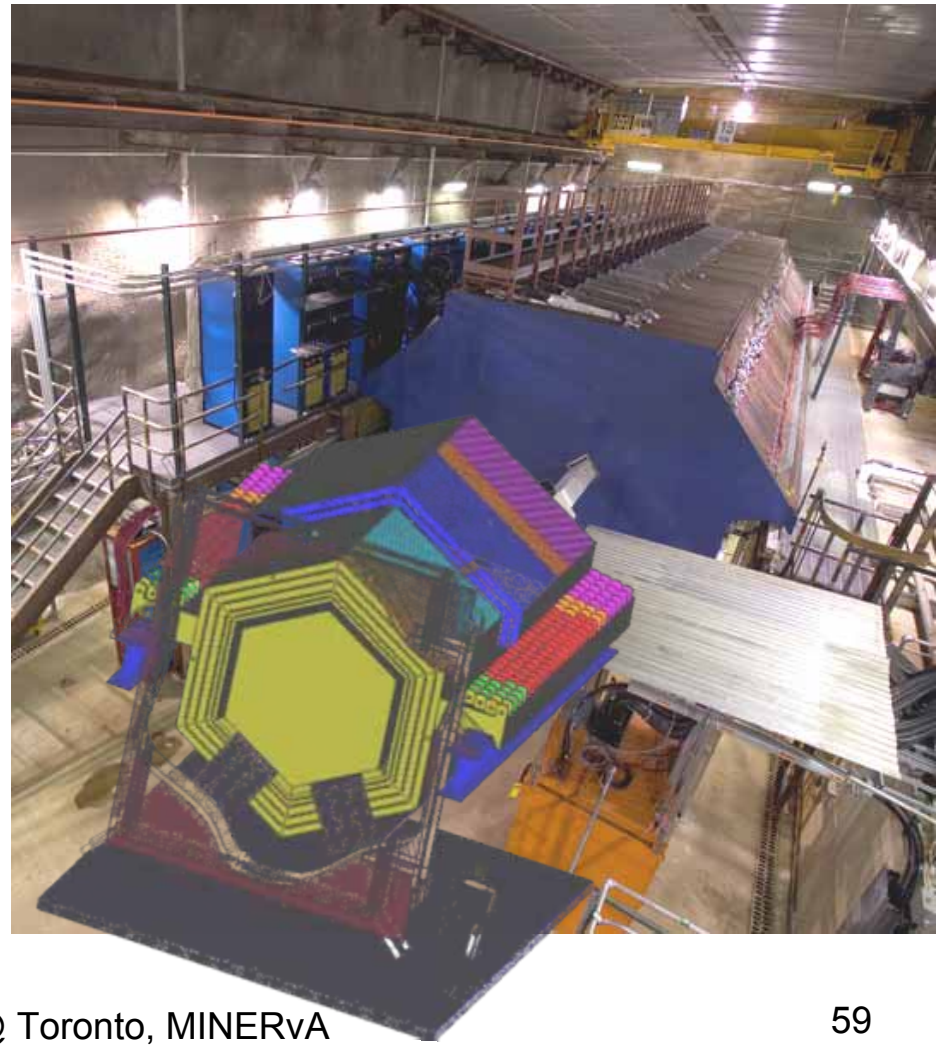
Plots from N.Saoulidou, Fermilab Users Meeting

NuMI Beamline

- FNAL has recently commissioned NuMI beamline for MINOS long-baseline experiment
- Why is NuMI an ideal home for a neutrino cross-section experiment?
  - Variable energy, well-understood neutrino flux
  - Spacious on-axis near hall
    - also possible off-axis sites

NuMI Near Hall

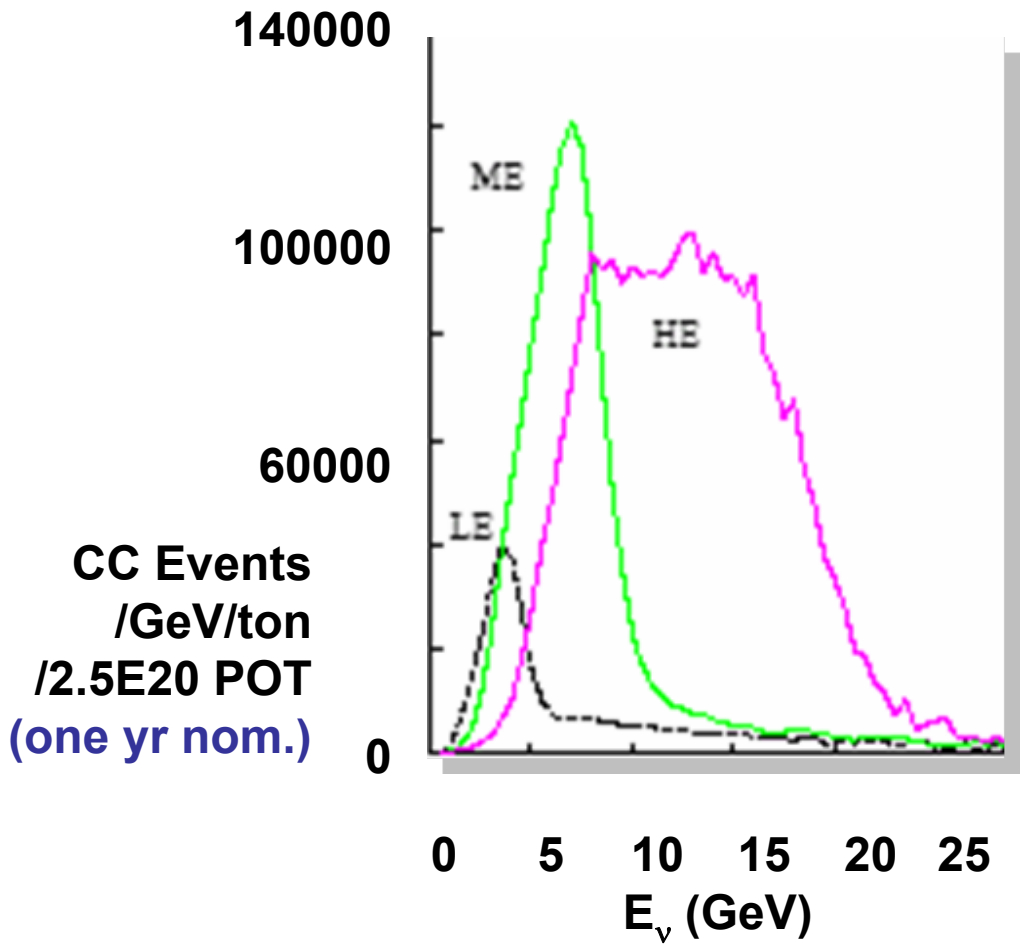


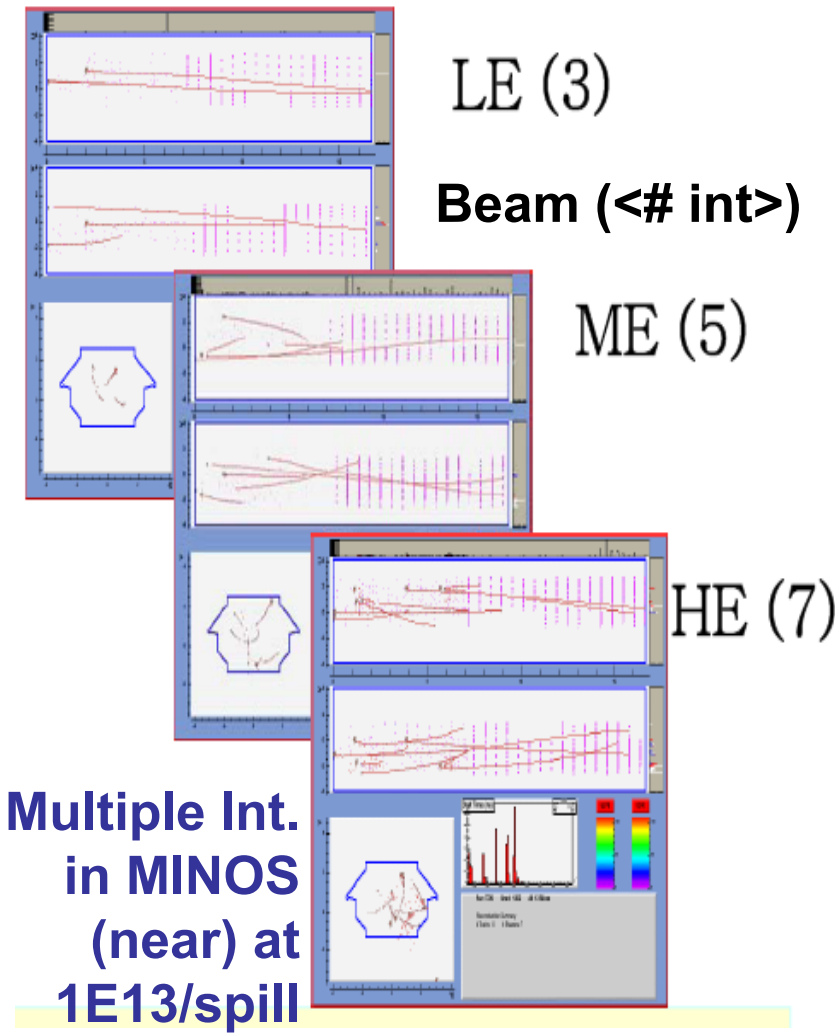


NuMI Beamline

- FNAL has recently commissioned NuMI beamline for MINOS long-baseline experiment
- Why is NuMI an ideal home for a neutrino cross-section experiment?
  - Variable energy, well-understood neutrino flux
  - Spacious on-axis near hall
    - also possible off-axis sites
  - High intensity
    - statistics for low mass detector, capable of reconstructing exclusive final states

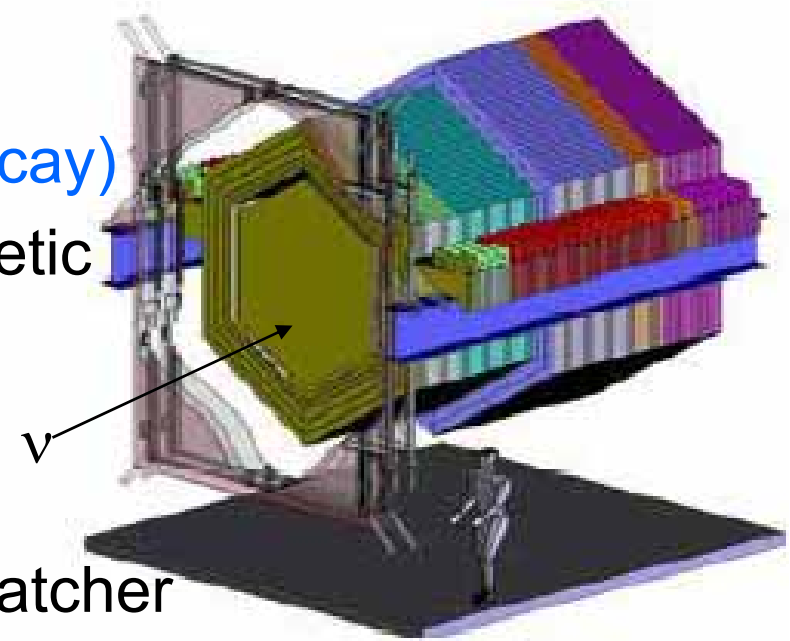
NuMI Beam Intensity (Near)



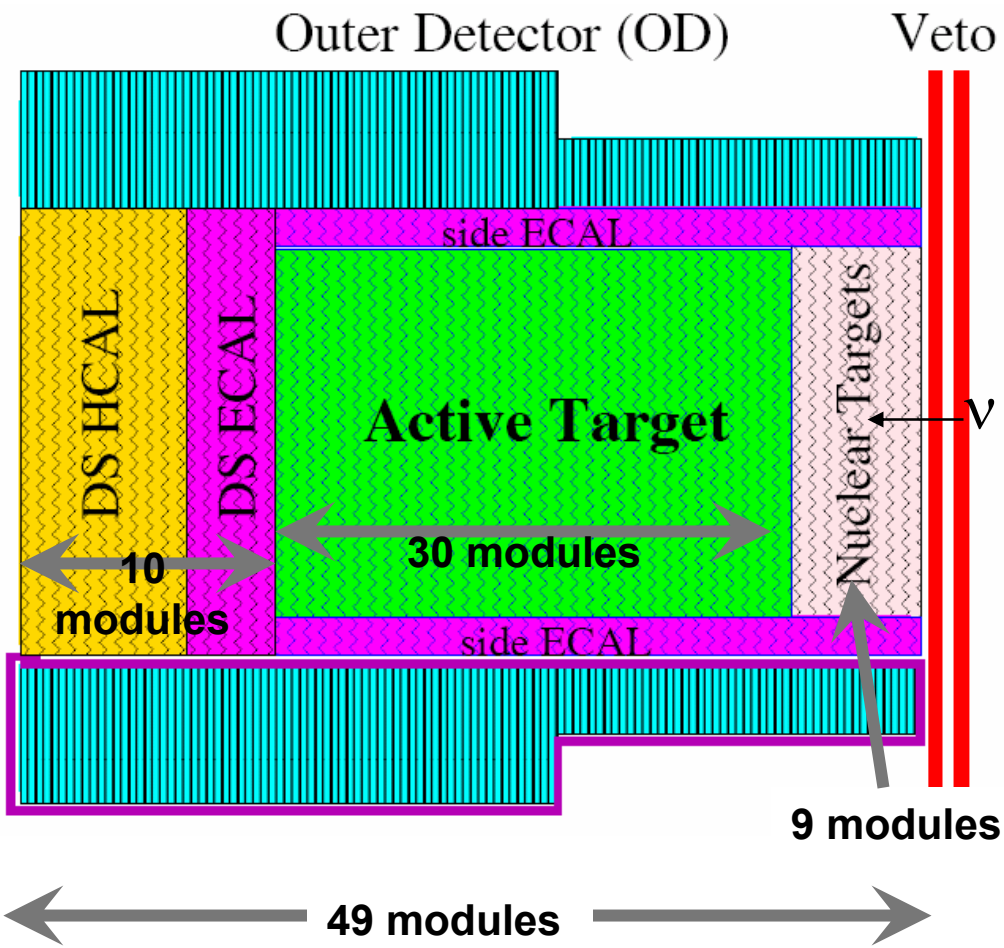


Basic Detector

- MINER*v*A proposes to build a low-risk detector with simple, well-understood technology
- Active core is segmented solid scintillator
  - Tracking (including low momentum recoil protons)
  - Particle identification
  - <3 ns (RMS) per hit timing (track direction, stopped $K^{\pm}$ decay)
- Core surrounded by electromagnetic and hadronic calorimeters
  - Photon (π^0) & hadron energy measurement
- MINOS Near Detector as muon catcher



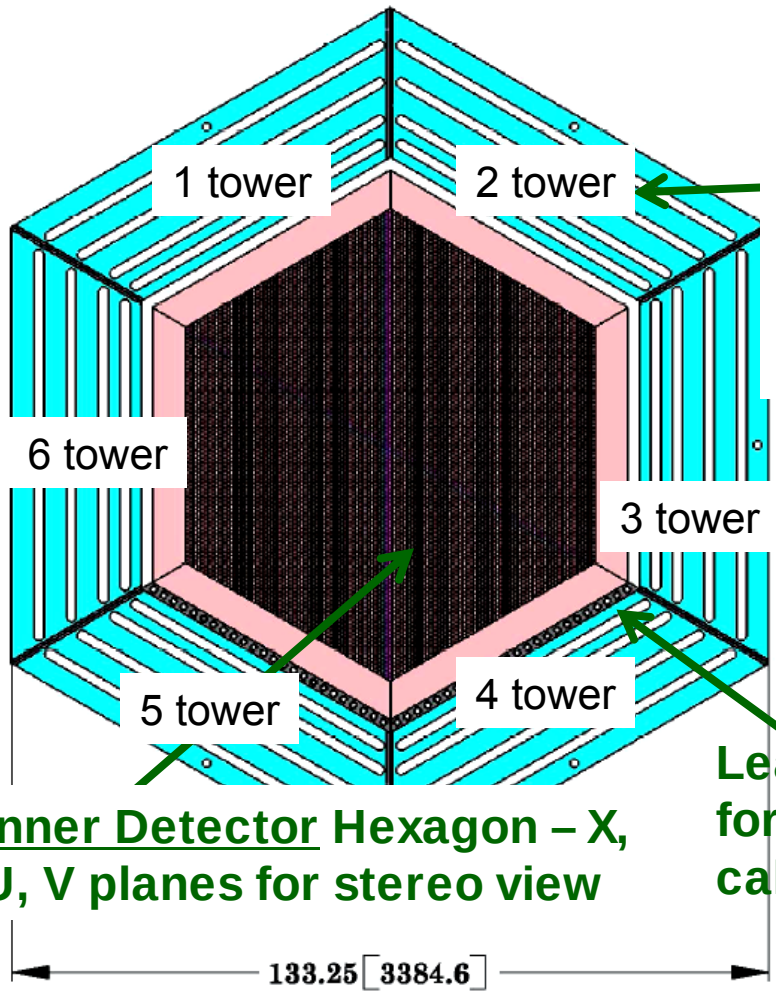
Basic Detector Geometry



	Modules	Frames	Scintillator Planes
Nuclear Targets	9	18	27
Active Target	30	60	120
DS ECAL	5	10	20
DS HCAL	5	20	20
Totals	49	108	187

- Downstream Calorimeter: 10 modules, 2% active
- 2 thin lead “rings” for side ECAL
- Absorbers, if part of DS calorimetry

MINERvA Detector Planes



Outer Detector (OD) Layers of iron/scintillator for hadron calorimetry: 6 Towers

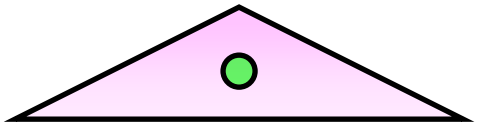
Inner Detector Hexagon – X, U, V planes for stereo view

Lead Sheets for EM calorimetry

- **31,000 channels**
  - 80% in inner hexagon
  - 20% in Outer detector
- **503 M-64 PMTs** (64 channels)
- **1 wave length shifting fiber per scintillator**, which transitions to a clear fiber and then to the PMT
- **128 pieces of scintillator per Inner Detector plane**
- **4 or 6 pieces of scintillator per Outer Detector tower, 6 OD detector towers per plane**

MINERvA Optics

Scintillator



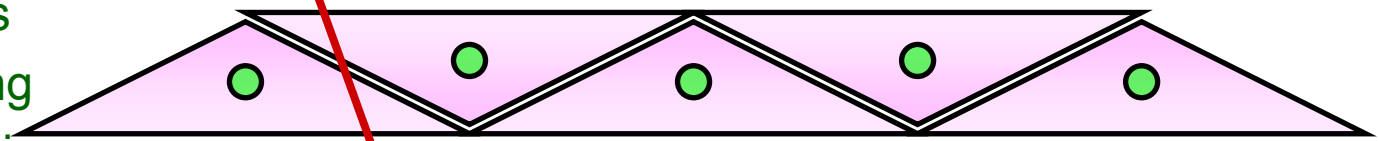
1.7 × 3.3 cm^2 strips

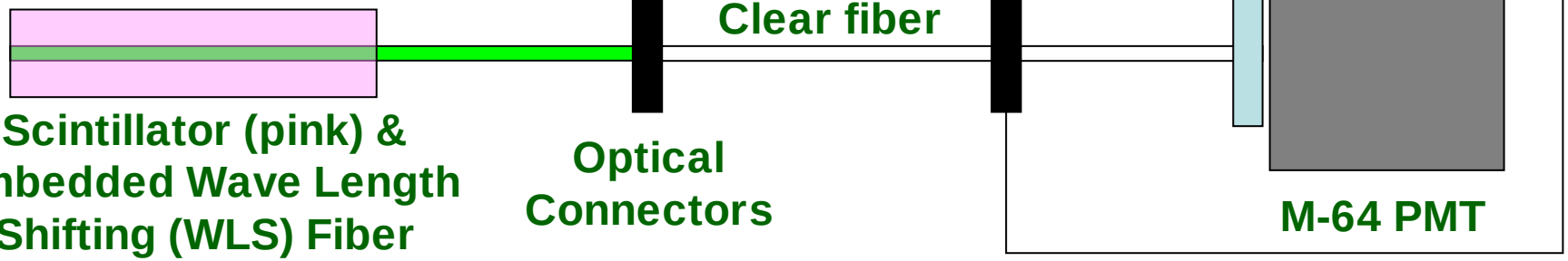
Wave Length Shifting (WLS) fiber readout in center hole

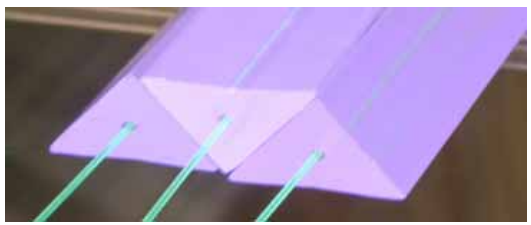
Particle

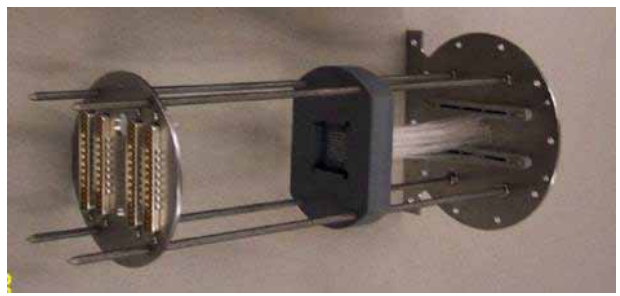
For the Inner Detector, scintillator is assembled into 128 strip scintillator planes

Position determined by charge sharing



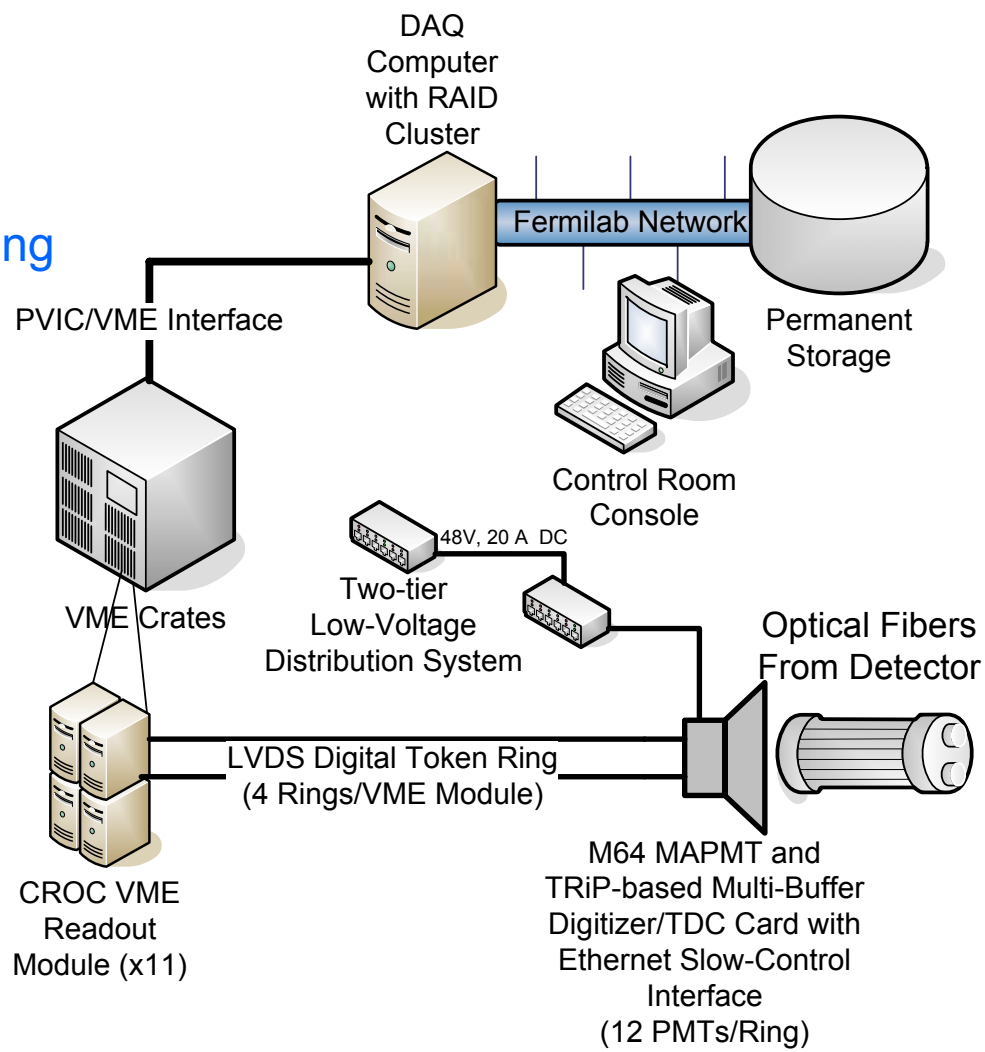






MINERvA Electronics

- **Front End Boards**
  - One board per PMT
  - High Voltage (700-800V)
  - Digitization via TriP Chips, taking advantage of D0 design work
  - Timing
- **CROC Boards and DAQ**
  - One board per 48 PMT's
  - Front-end/computer interface
  - Distribute trigger and synchronization
  - 3 VME crates & one DAQ computer
- **Power and rack protection**
  - Uses 48V power
  - 7kW needed



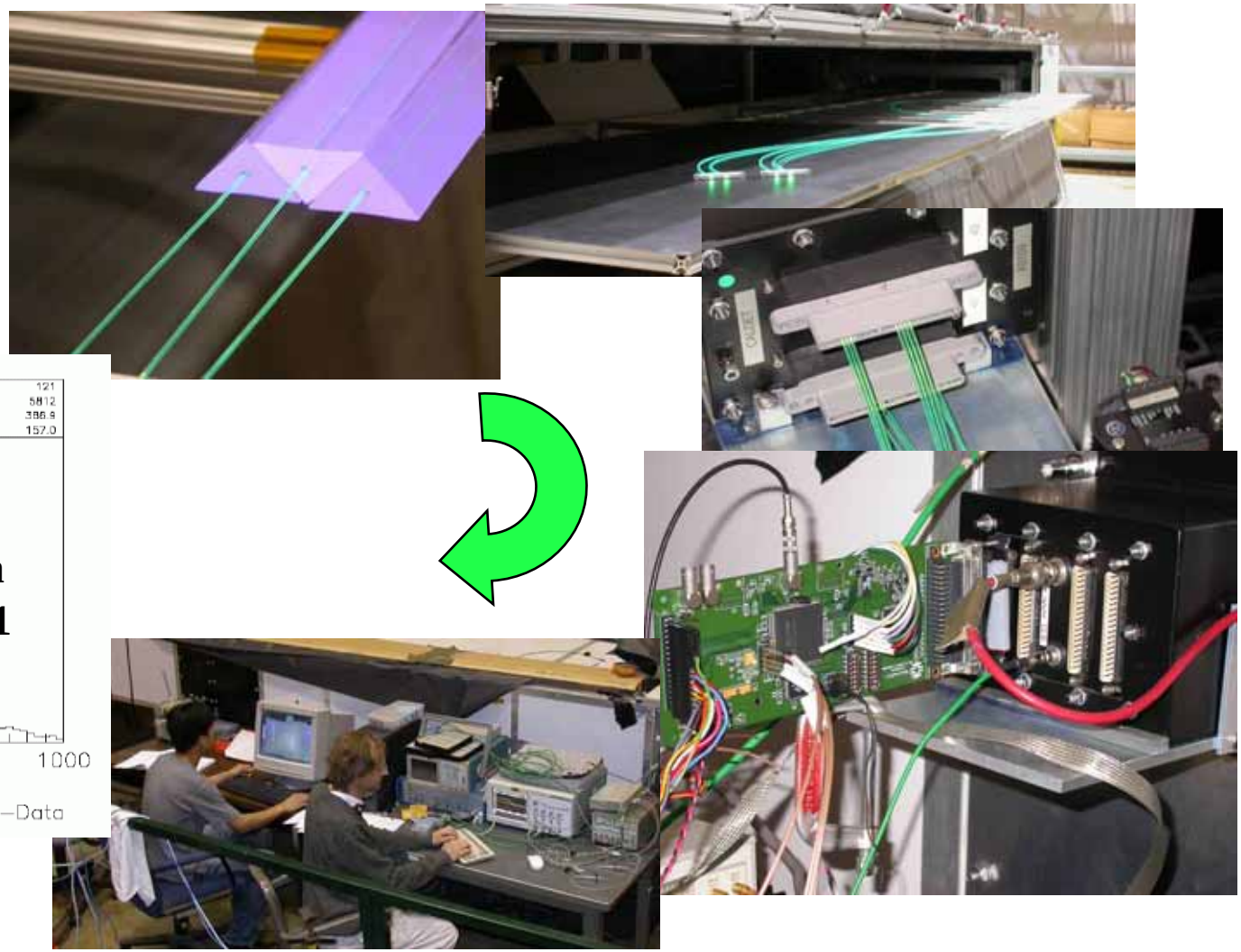
MINERvA Subsystem Costs

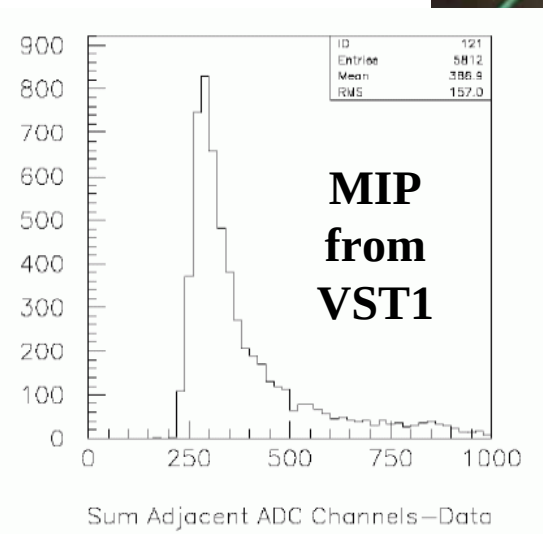
Obligation Profile Summaries (Base + Contingency + Indirect AY M$), excludes already expends FY05 funds, 0.8M$

	FY2006 through FY2008		
WBS	**Prototypes**	**Construction**	**TOTAL**
1 Scintillator Extrusion	0.3 M$	0.3 M$	0.5 M$
2 WLS Fibers	0.1 M$	0.7 M$	0.8 M$
3 Scintillator Plane Assembly	0.5 M$	1.1 M$	1.6 M$
4 Clear Fiber Cables	0.2 M$	0.9 M$	1.1 M$
5 PMT Boxes	0.2 M$	0.6 M$	0.8 M$
6 PMT Procurement and Testing	0.3 M$	1.3 M$	1.6 M$
7 Electronics and DAQ	0.9 M$	0.5 M$	1.4 M$
8 Frame, Absorbers and Stand	0.1 M$	0.7 M$	0.9 M$
9 Module Assembly & Inst.	0.3 M$	0.3 M$	0.6 M$
10 Project Management	0.6 M$	0.4 M$	1.0 M$
Total	**3.6 M$**	**6.7 M$**	**10.2 M$**

Vertical Slice Test (VST1)

VST1 array, electronics and DAQ

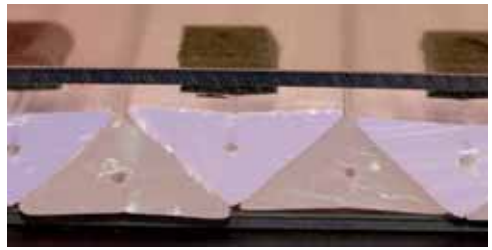


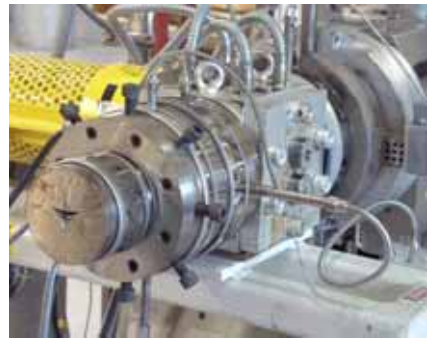


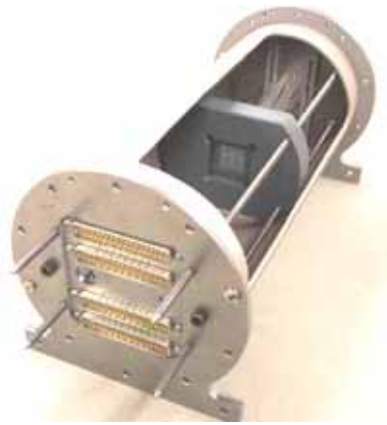
8 PE/MIP per doublet

MINERvA Prototyping

- Refining scint. extrusion
- First “trapezoid” of OD steel
- Prototype PMT box
- Prototype clear fiber cables in progress
- 2nd Prototype front-end and prototype readout electronics

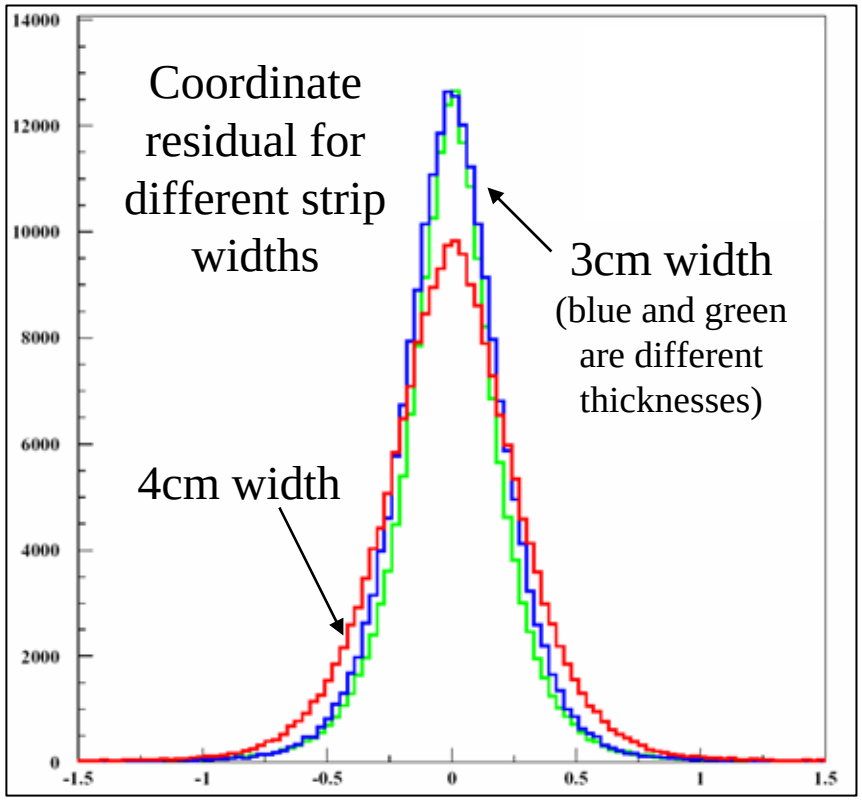




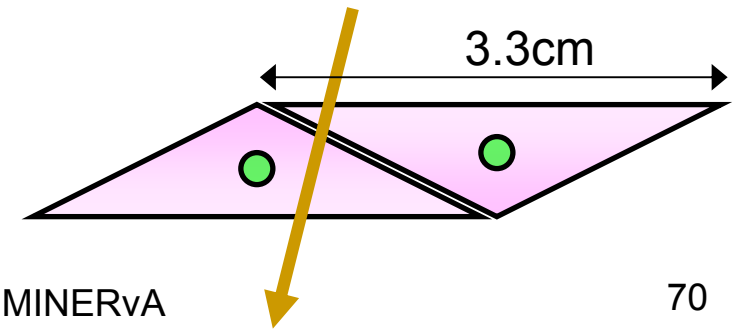


- Winter-Summer 2006: Construct and Characterize Full-plane prototypes

Hit Resolution in Active Target

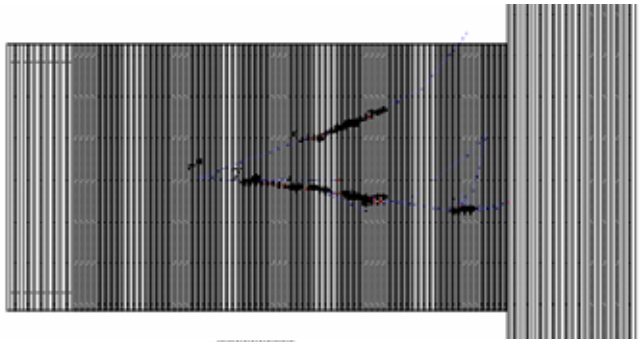


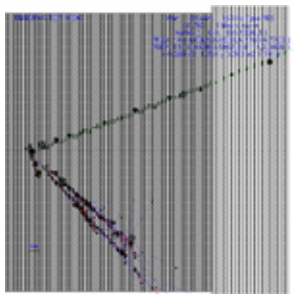
- Triangular extrusion
  - σ~3 mm in transverse direction from light sharing
  - More effective than rectangles (resolution/segmentation)
  - Key resolution parameters:
    - transverse segmentation and light yield
    - longitudinal segmentation for z vertex determination



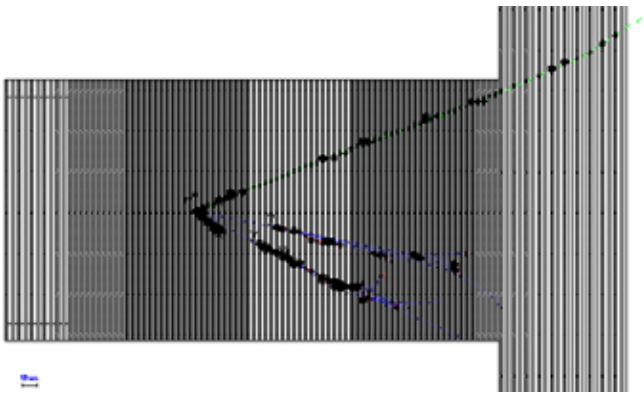
- technique pioneered by D0 upgrade pre-shower detector

π^0 Reconstruction

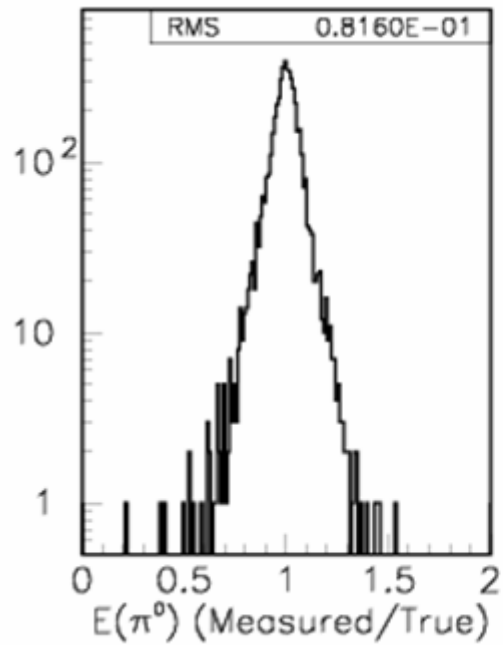


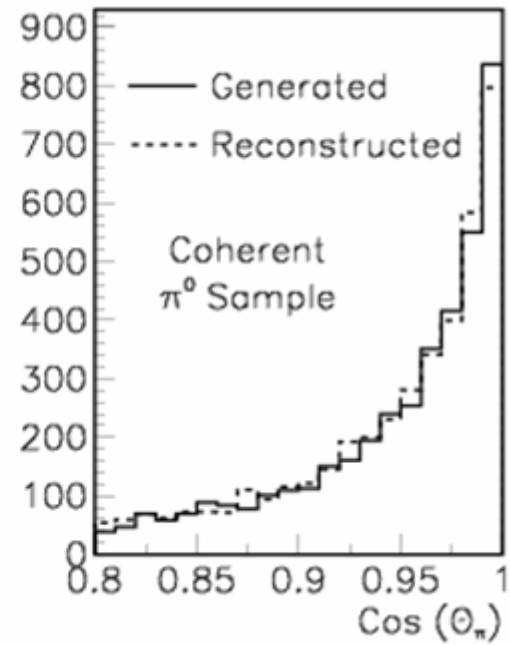


Resonance events with π^0



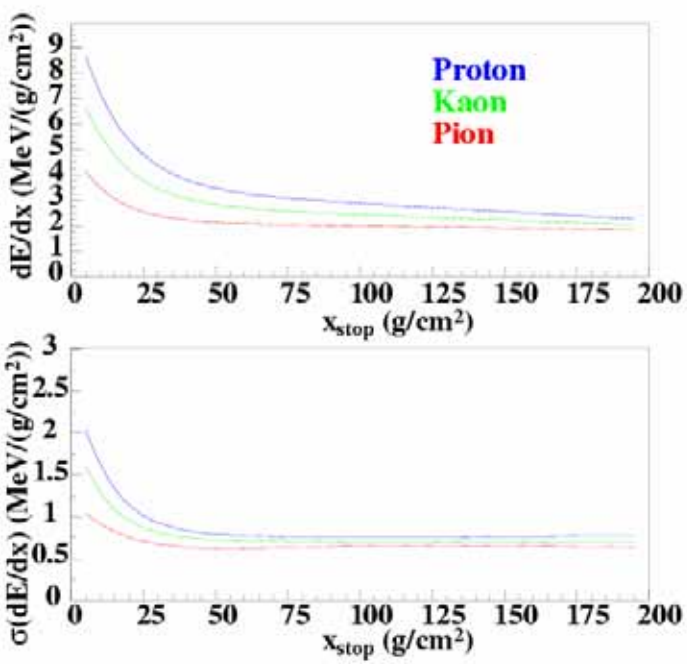
- π^0's cleanly identified
- π^0 energy res.: $6\%/\sqrt{E}$ (GeV)
- For coherent, π^0 angular resolution < physics width



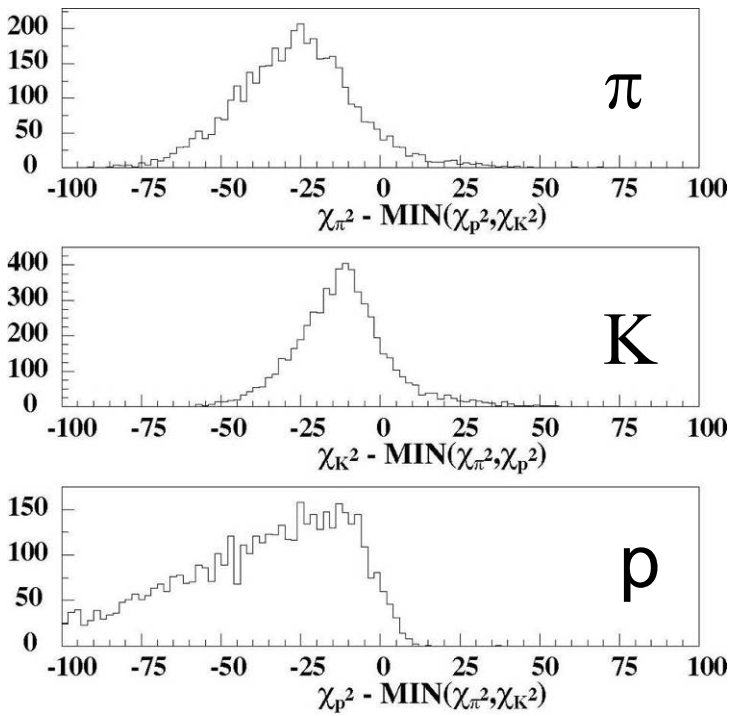


Particle Identification

- Particle ID by dE/dx in strips and endpoint activity



Chi2 differences between right and best wrong hypothesis



- Many dE/dx samples for good discrimination

R = 1.5 m - p: μ =.45 GeV/c, π = .51, K = .86, P = 1.2
R = .75 m - p: μ =.29 GeV/c, π = .32, K = .62, P = .93

Illustration: $\nu_\mu n \rightarrow \mu^- p$

- Reminder: proton tracks from quasi-elastic events are typically short. Want sensitivity to p_p~ 300 - 500 MeV
- "Thickness" of track proportional to dE/dx in figure below
- proton and muon tracks are clearly resolved
- precise determination of vertex and measurement of Q^2 from tracking

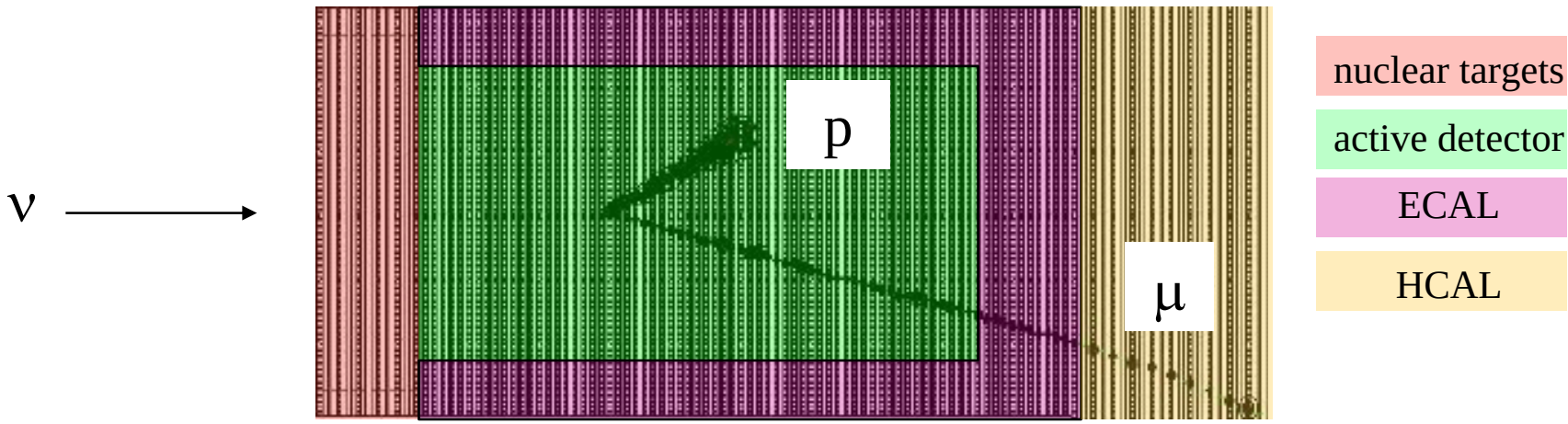
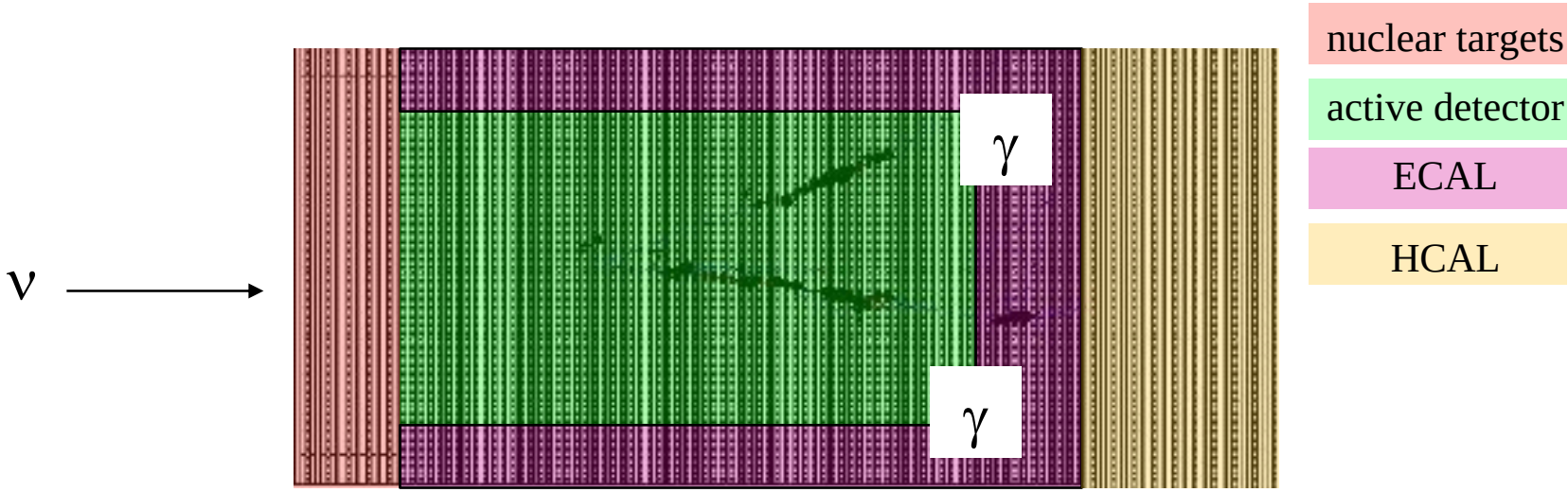


Illustration: $\nu_\mu p \rightarrow \nu_\mu \pi^0 p$



- two photons clearly resolved (tracked). can find vertex.
- some photons shower in ID, some in side ECAL (Pb absorber) region

Expected Physics Results

(a sample, see hep-ex/405002)

Event Rates

Fiducial Volume:
3 tons CH, ≈ 0.6 t C, ≈ 1 t Fe and ≈ 1 t Pb
Expected CC event samples:

8.6 M ν events in CH
1.4 M ν events in C
2.9 M ν events in Fe
2.9 M ν events in Pb

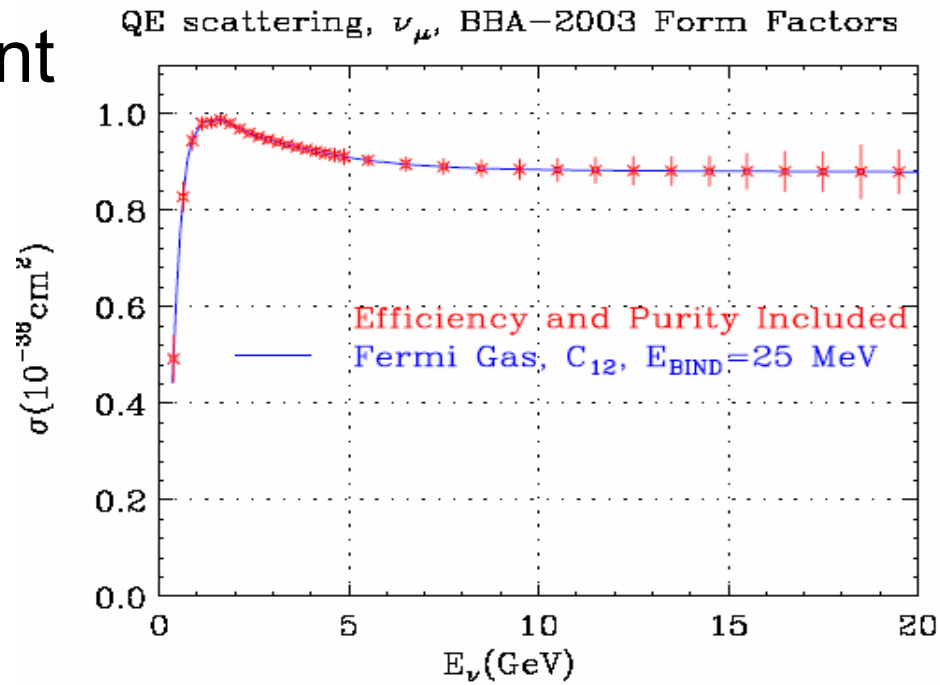
Assumes 16.0×10^{20} in LE, ME, and sHE NuMI beam configurations over 4 years

Main CC Physics Topics (Statistics in CH)

• Quasi-elastic	0.8 M events
• Resonance Production	1.6 M total
• Transition: Resonance to DIS	2 M events
• DIS, Structure Funcs. and high-x PDFs	4.1 M DIS events
• Coherent Pion Production	85 K CC / 37 K NC
• Strange and Charm Particle Production	> 230 K fully reconstructed

CC Quasi-Elastic

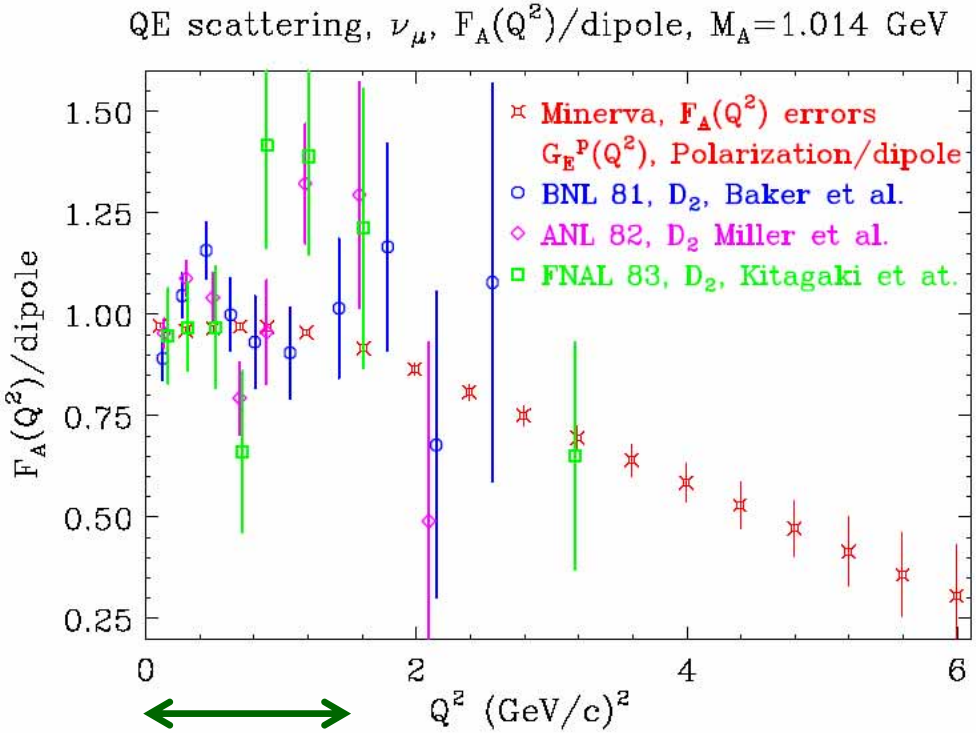
- Quasi-elastic ($\nu n \rightarrow \mu^- p$)
  - high efficiency and purity
    - 77% and 74%, respectively
  - Precise measurement of $\sigma(E_\nu)$ and $d\sigma/dQ^2$
    - absolute normalization from beam flux
  - Nuclear effects
    - C, Fe and Pb targets



CC QE: Form Factors

- Vector form factors measured with electrons
- G_E/G_M ratio varies with Q^2 - a surprise from JLab
- Axial form factor poorly known
- Medium effects for F_A measurement unknown
  - Will check with C, Fe, & Pb targets

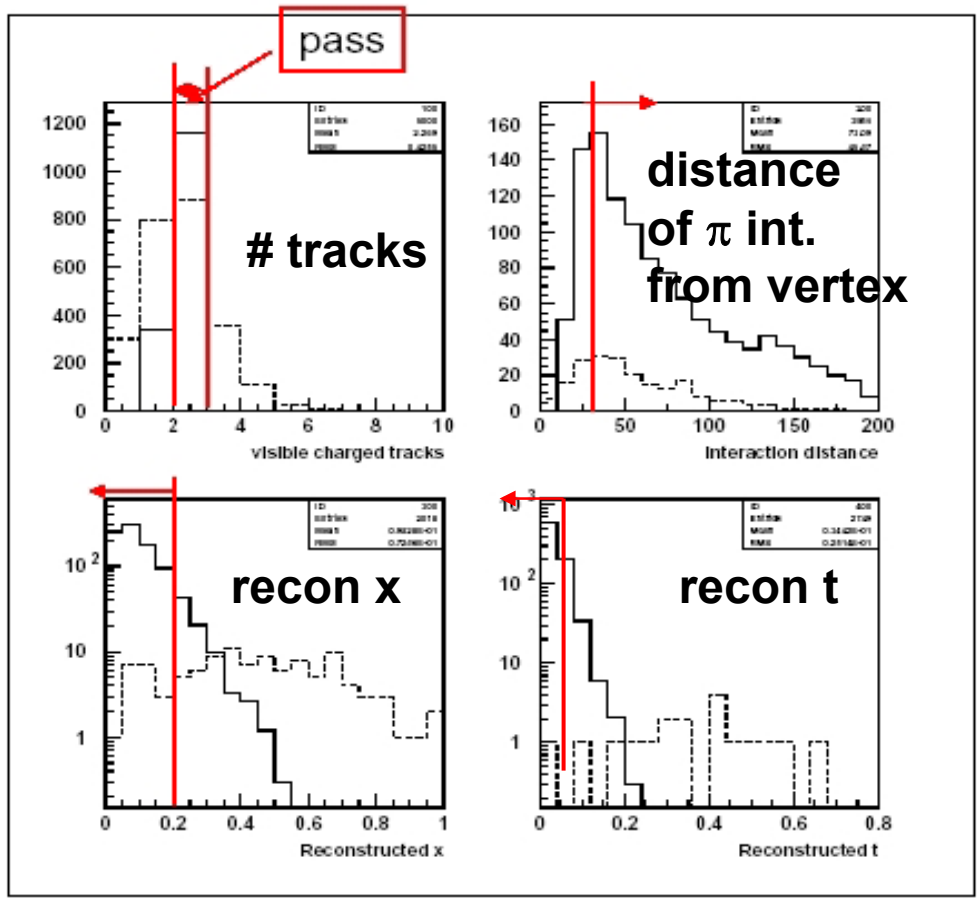
Projected MINER*ν*A Measurement of Axial FF



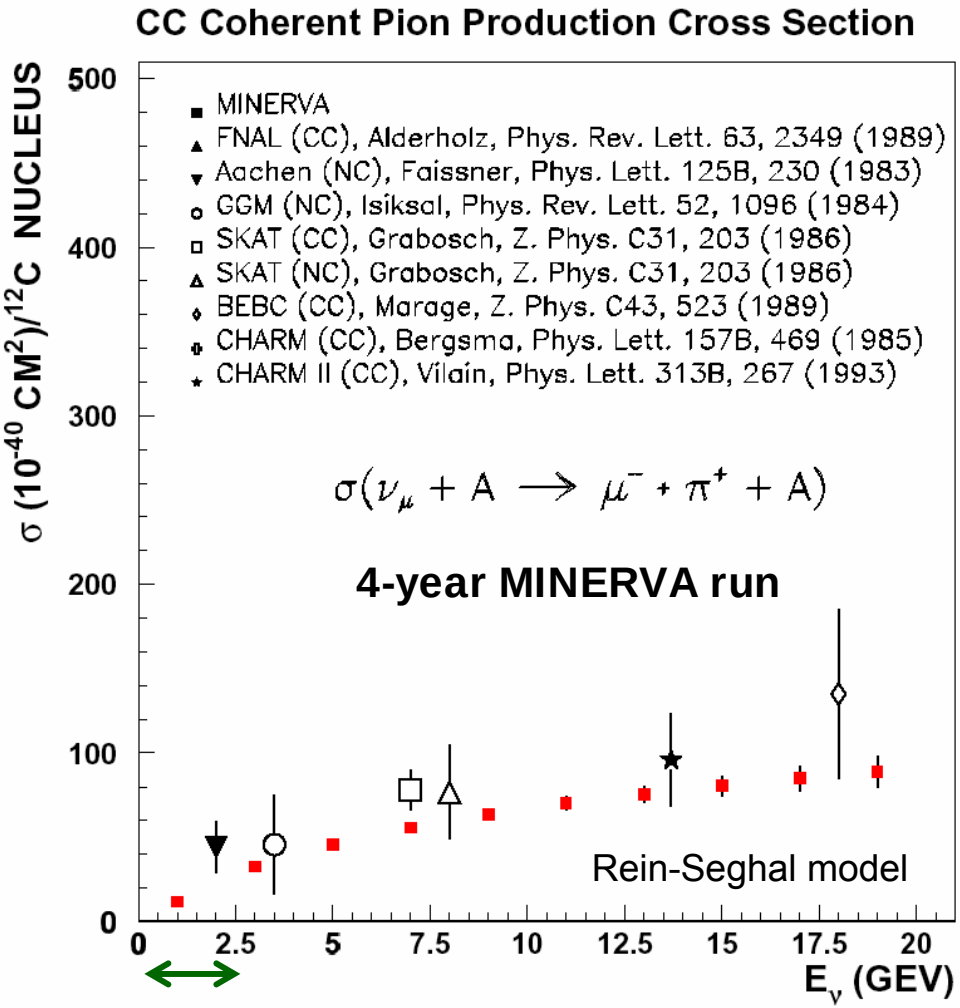
Range of MiniBooNE & K2K measurements

Coherent Pion Production

- Precision measurement of σ(E) for CC channel
  - Reconstruct 20k CC / 10k NC (Rein-Seghal model)
  - In NC channel, can measure rate for different beams to check σ(E)
- Measure A-dependence
- Good control of coherent vs. resonance, esp. at high E
  - CC selection criteria reduces signal by factor of three
  - but reduces background by factor of 1000

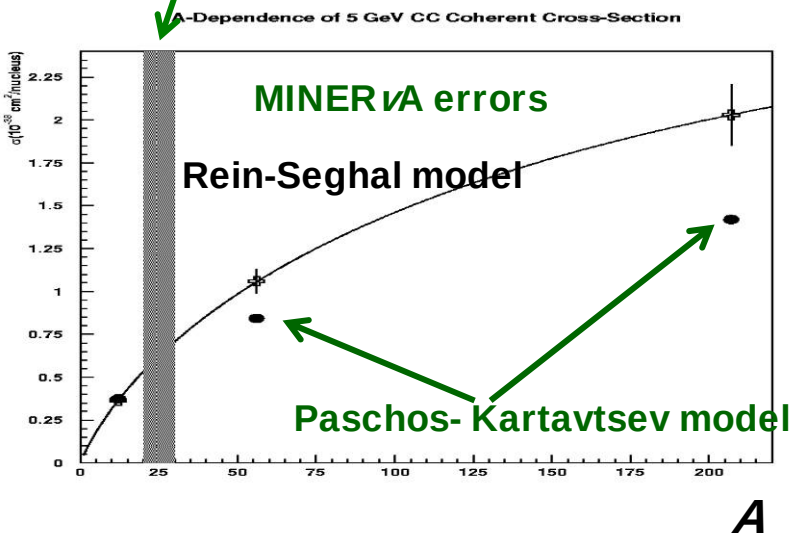


Coherent Pions (cont'd)



MiniBooNe & K2K measurements

A-range of current measurements before K2K !



MINERνA's nuclear targets allow the first measurement of the *A*-dependence of σ_{coh} across a wide *A* range

MINERvA Status

- FNAL is solidly committed to MINERvA
  - construction $$ in Oct. 2006 – Sept. 2008
    - prototyping, “factory” setup now – Sept. 2006
  - FNAL budget is tight
    (US has war, floods, but no pestilence *yet*)
  - however, MINERvA has a high profile as only major accelerator experiment to start at lab before NOvA

- *We are on track for first physics quality data at the end of 2008*

Conclusions

- Neutrino oscillations has a bright future with "superbeam" experiments: T2K, NOvA
  - but experiments need new information on cross-sections, or may be limited by systematics
- MINERvA is poised to measure these cross-sections over a wide range of energies
  - NuMI beamline:
    - tunable 1 – 20 GeV, precisely known neutrino flux
  - The MINERvA detector is optimized to study both inclusive reactions and exclusive final states
- We are building it now!

A Few More Expected Physics Results

(a sample, see hep-ex/405002)

Strange and Charm Production

- MINERvA will focus on exclusive channel strange particle production
  - small sub-sample of fully reconstructed events .
- **Important for background calculations of nucleon decay experiments**
- Measurements of inclusive charm production near threshold to probe charm-quark effective mass
  - siimilar to NOMAD

Existing Strange Particle Production

Gargamelle-PS - **15** Λ events. FNAL - ≈ 100 events
ZGS -30 events BNL - 8 events
Larger NOMAD **inclusive** sample expected

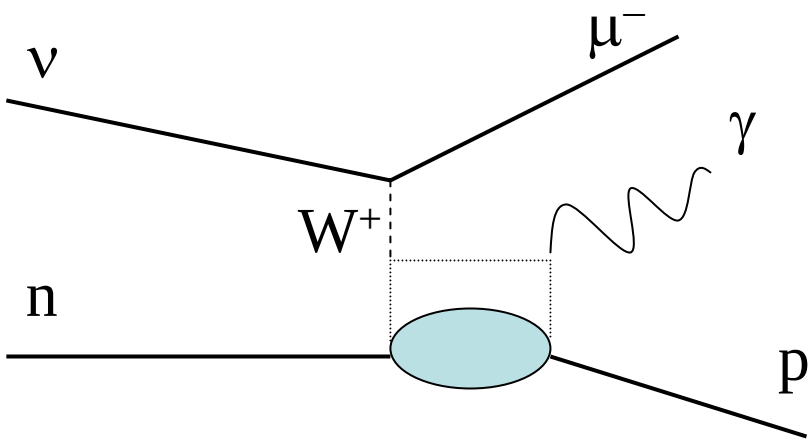
MINERνA Exclusive States

100x earlier samples

3 tons and 4 years

$\Delta S = 0$	
$\mu^- K^+ \Lambda^0$	10.5 K
$\mu^- \pi^0 K^+ \Lambda^0$	9.5 K
$\mu^- \pi^+ K^0 \Lambda^0$	6.5 K
$\mu^- K^- K^+ p$	5.0 K
$\mu^- K^0 K^+ \pi^0 p$	1.5 K
$\Delta S = 1$	
$\mu^- K^+ p$	16.0 K
$\mu^- K^0 p$	2.5 K
$\mu^- \pi^+ K^{0n}$	2.0 K
$\Delta S = 0$ - Neutral Current	
$\nu K^+ \Lambda^0$	3.5 K
$\nu K^0 \Lambda^0$	1.0 K
$\nu K^0 \Lambda^0$	3.0 K

GPDFs: Weak Deeply Virtual Compton Scattering



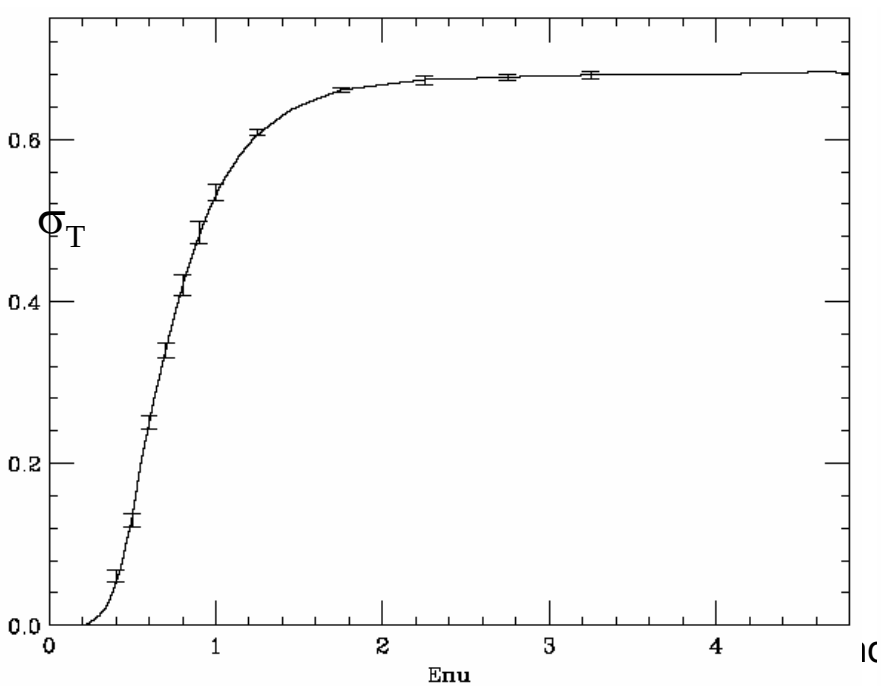
W> 2 GeV, t small, E_γ large - Exclusive reaction

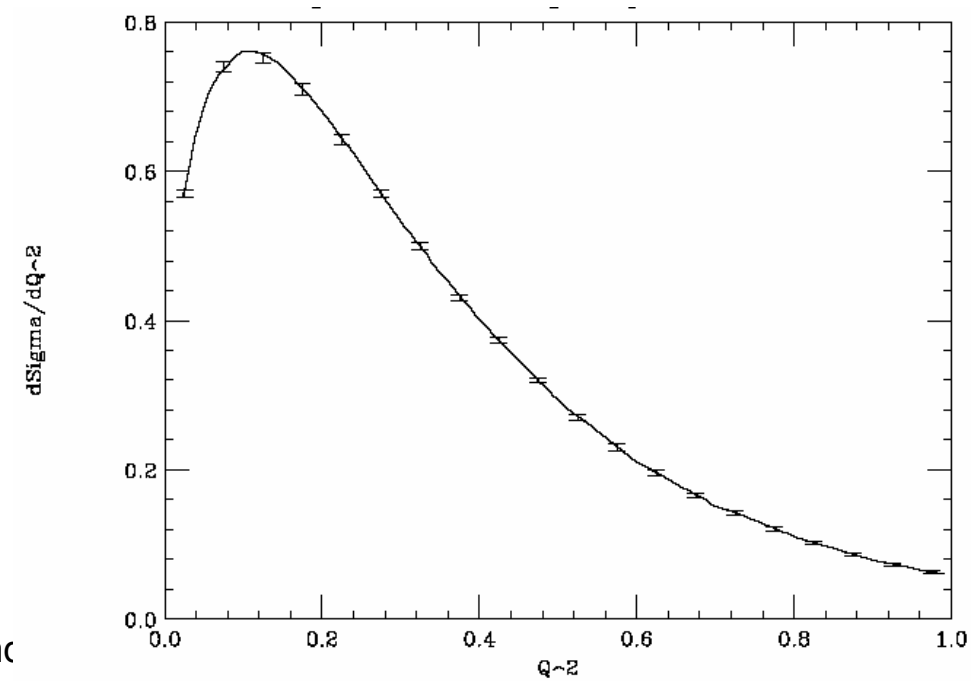
- First measurement of GPDs with neutrinos
- Weak DVCS would allow flavor separation of GPDs
- According to calculation by A. Psaker (ODU), MINERνA would accumulate 10,000 weak DVCS events in a 4-year run

Resonance Production - Δ

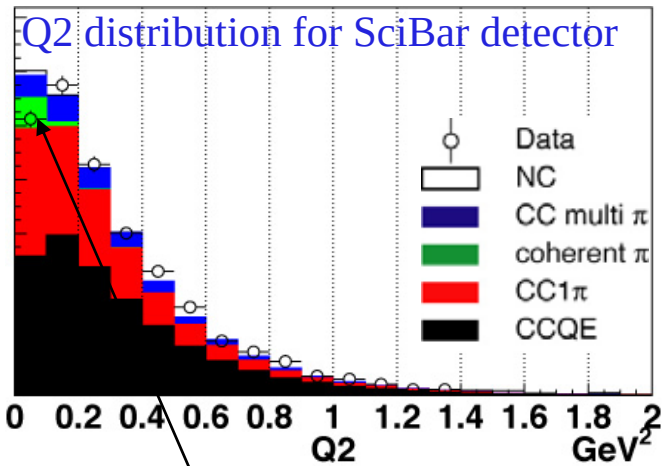
- Resonance Production (e.g. $\nu + N \rightarrow \nu / \mu^- + \Delta$, **1600 K total, 1200K 1π)**
  - Precision measurement of σ and dσ/dQ for individual channels
  - Detailed comparison with dynamic models, comparison of electro- & photo production, the resonance-DIS transition region -- duality
  - Study of nuclear effects and their A-dependence e.g. 1 π <–– > 2 π <––> 3 π final states

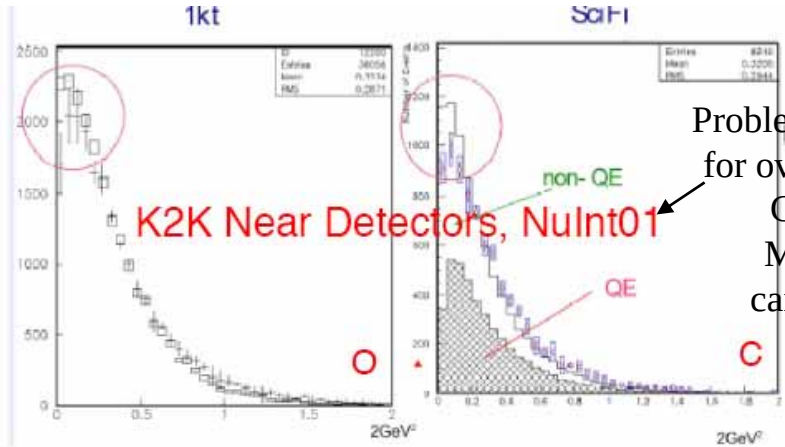
Total Cross-section and $d\sigma/dQ^2$ for the Δ^{++} **- Errors are statistical only**





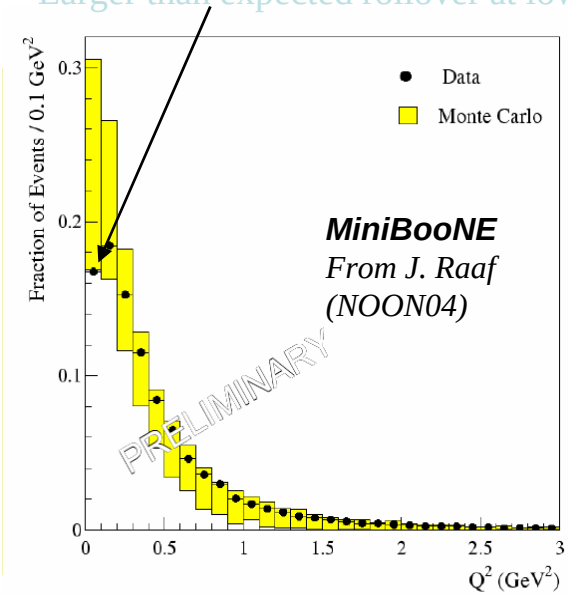
Nuclear Effects





Problem has existed for over four years. Coherent? MINERvA can separate.

Larger than expected rollover at low Q^2



All "known" nuclear effects taken into account:
Pauli suppression, Fermi Motion, Final State Interactions

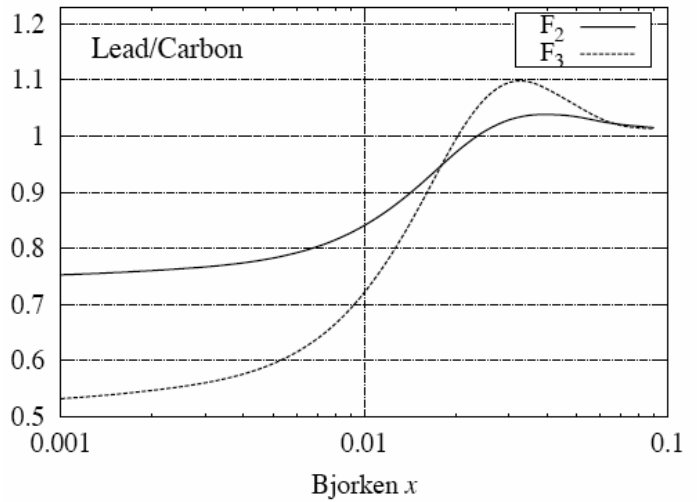
They have **not included** low-ν shadowing that is only allowed with axial-vector (Boris Kopeliovich at NuInt04)

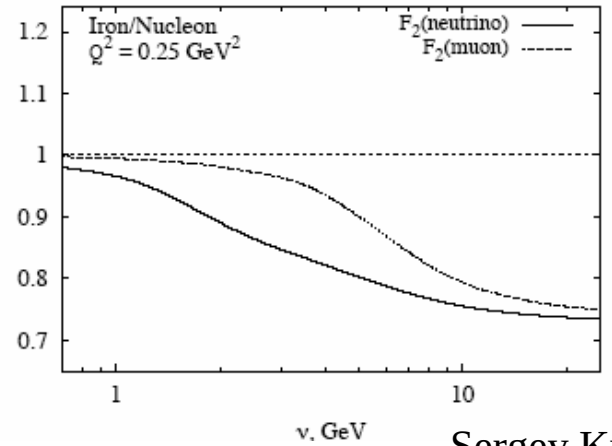
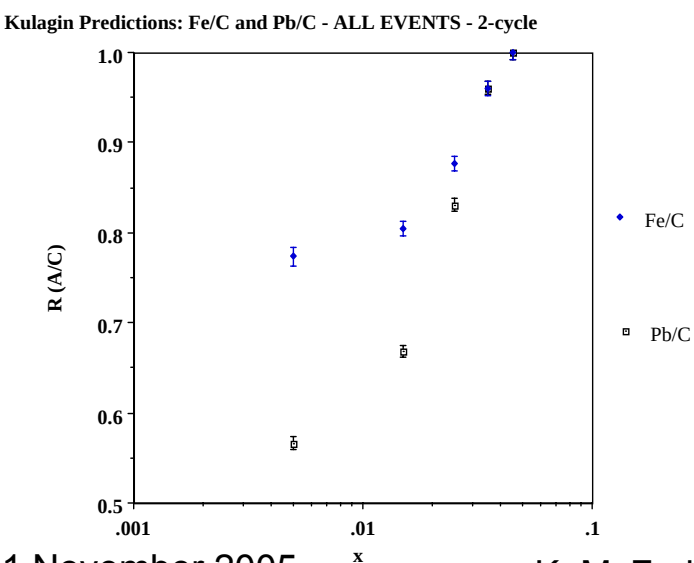
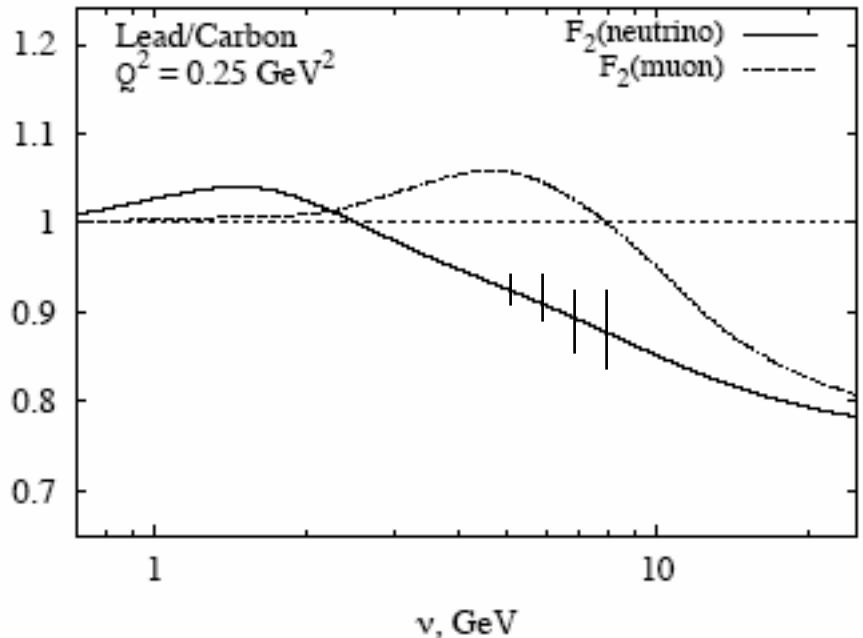
$L_c = 2\nu / (m_\pi^2 + Q^2) \geq R_A$ **(not m_A^2)**

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**

Difference between ν–A and μ–A nuclear effects in DIS





Sergey Kulagin