BACK FROM THE DEAD

Steve Boyd

WARWICK

A Drama in Three Acts

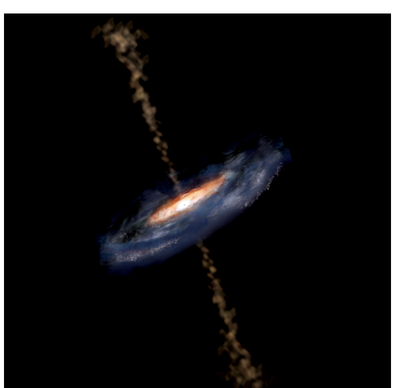
I. Neutrino Oscillations *(exposition…)*
   - current status of knowledge
   - future goals

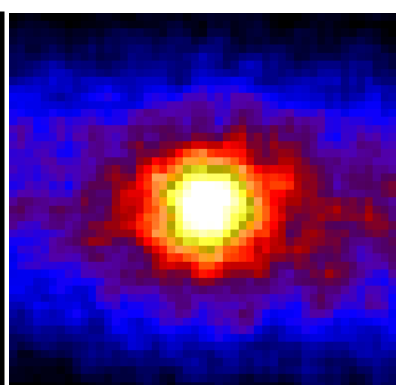
II. Neutrino Interactions *(plot development)*
   - implications for future oscillation studies

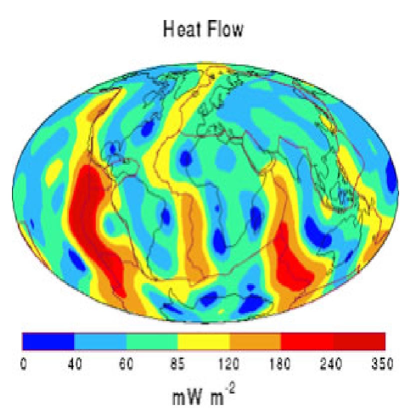
III. Future Scattering Experiments *(denouement)*
   - SciBoone
   - MINERνA

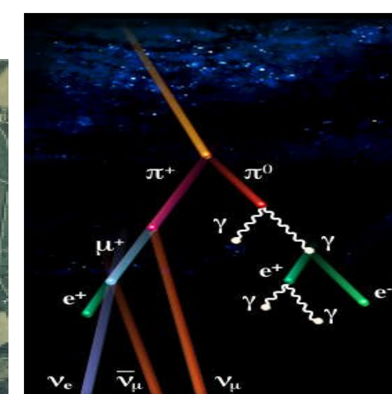
Neutrinos

- Spin ½ neutral partners to the charged leptons
- 50 meV < mass < 3 eV
- Flavours mix, and oscillate during propagation
- Only interact (hence only generated or detected) through the weak interaction
    - $\sigma \sim 10^{-4}$ fb @ 1 MeV
- Come with energies ranging from 3 meV up to 10^{16} eV







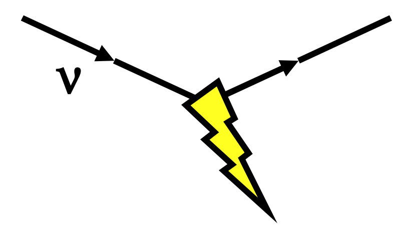


Neutrino Physics – Goals

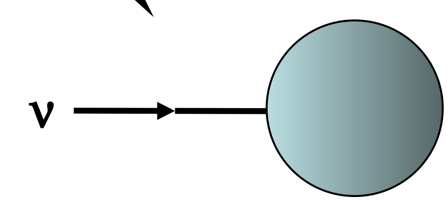
- Understand mixing of neutrinos
  - a non-mixing? CP violation?

- Understand neutrino mass
  - absolute scale and hierarchy

- Understand ν interactions
  - new physics? new properties?



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



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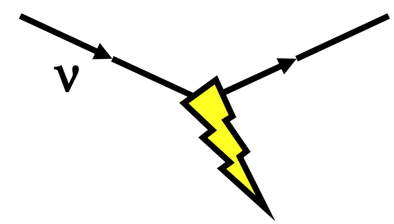

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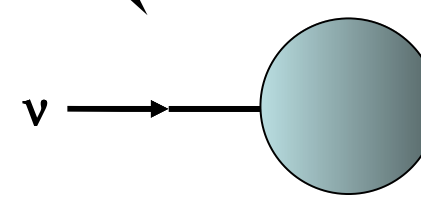
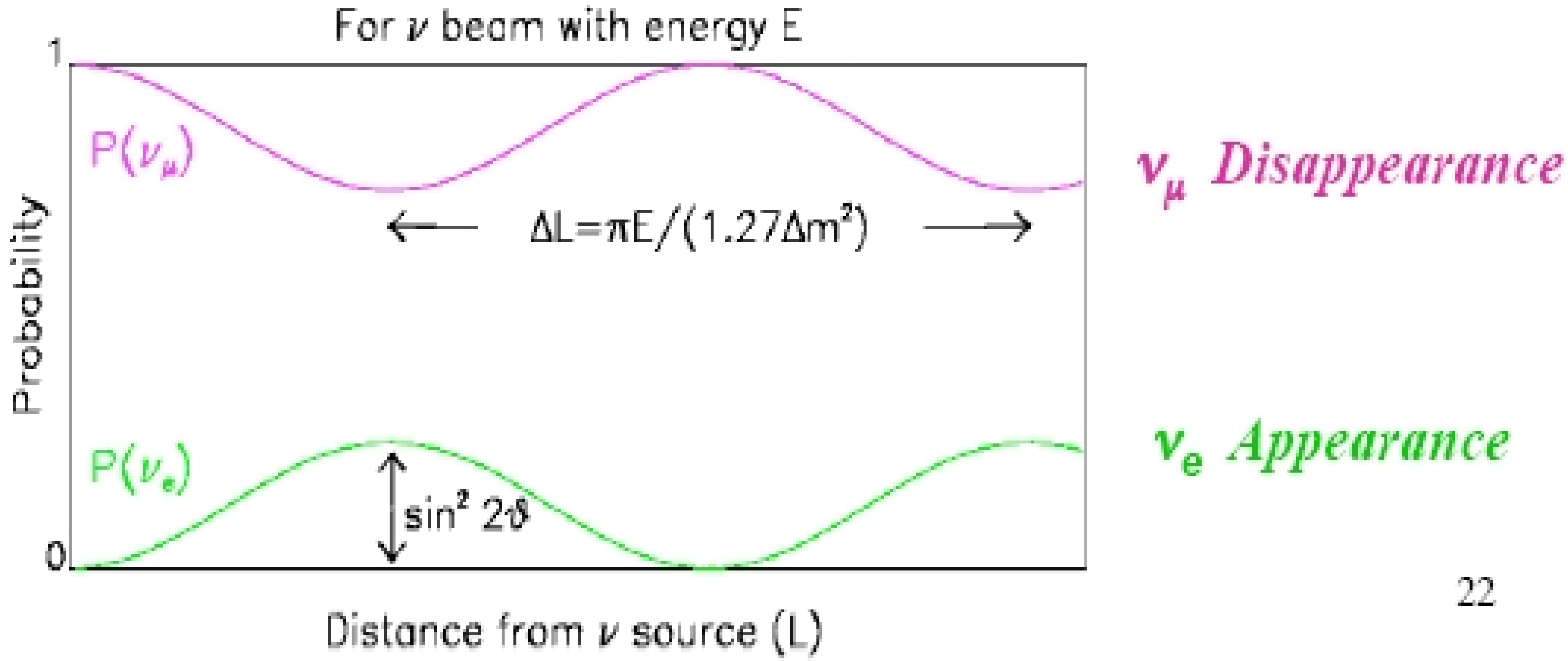


ν Oscillations

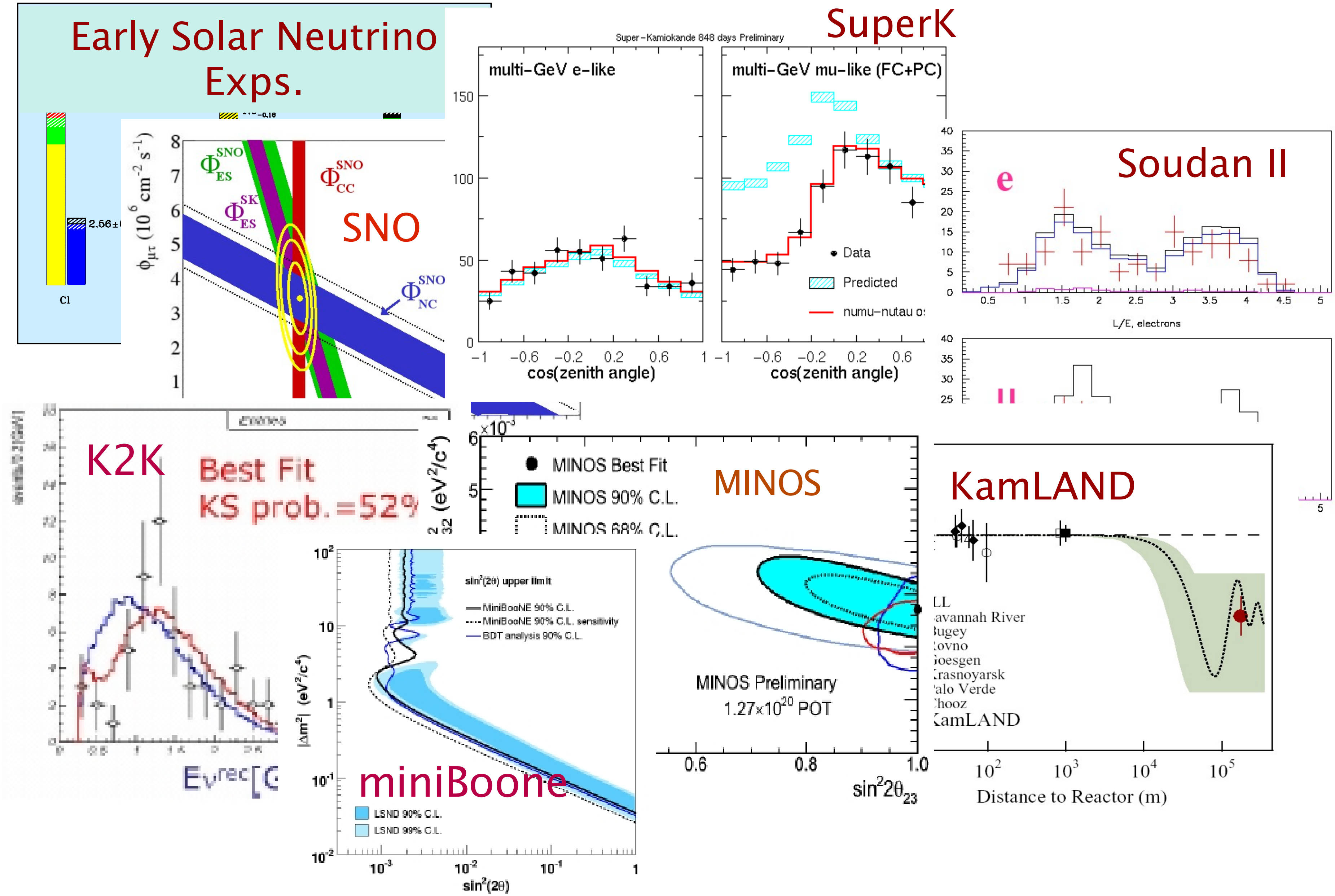
A QM effect whereby neutrino mass states are non-diagonal linear combinations of neutrino weak states.

Or to put it another way, an effect whereby neutrinos of one flavour can oscillate to other flavours in flight.



This can only happen if neutrinos have mass

ν Oscillations



ν oscillations for pedestrians

If neutrinos have mass then

$$l \in e, \mu, \tau \quad |\nu_l> = \sum_i U_{li} |\nu_i> \quad i \in 1,2,3$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Leftrightarrow U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}; \; s_{ij} = \sin\theta_{ij}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2(1.27 \Delta m_{ij}^2 \frac{L}{E})$$

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Three angles

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$$c_{ij} = \cos\theta_{ij} ; s_{ij} = \sin\theta_{ij}$$

Two independent mass splittings – each with a sign

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \sin^2(1.27 \Delta m_{ij}^2 \frac{L}{E})$$

ν oscillations for pedestrians

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A CP violating term

$$c_{ij} = \cos\theta_{ij};\ s_{ij} = \sin\theta_{ij}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2(1.27 \Delta m_{ij}^2 \frac{L}{E})$$

What do we know?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Leftrightarrow U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

$$\theta_{12} = 32.5^{\circ} \pm 2.4^{\circ}$$

$$\Delta m_{12}^2 = +7.1 \times 10^{-5} eV^2$$

$$\nu_e \rightarrow \nu_\mu$$

Solar

$$\theta_{23} = 45^{\circ} \pm 10^{\circ}$$

$$\Delta m_{23}^2 = \left| 2.1 \times 10^{-3} \right| eV^2$$

$$\nu_\mu \rightarrow \nu_\tau$$

Atmospheric

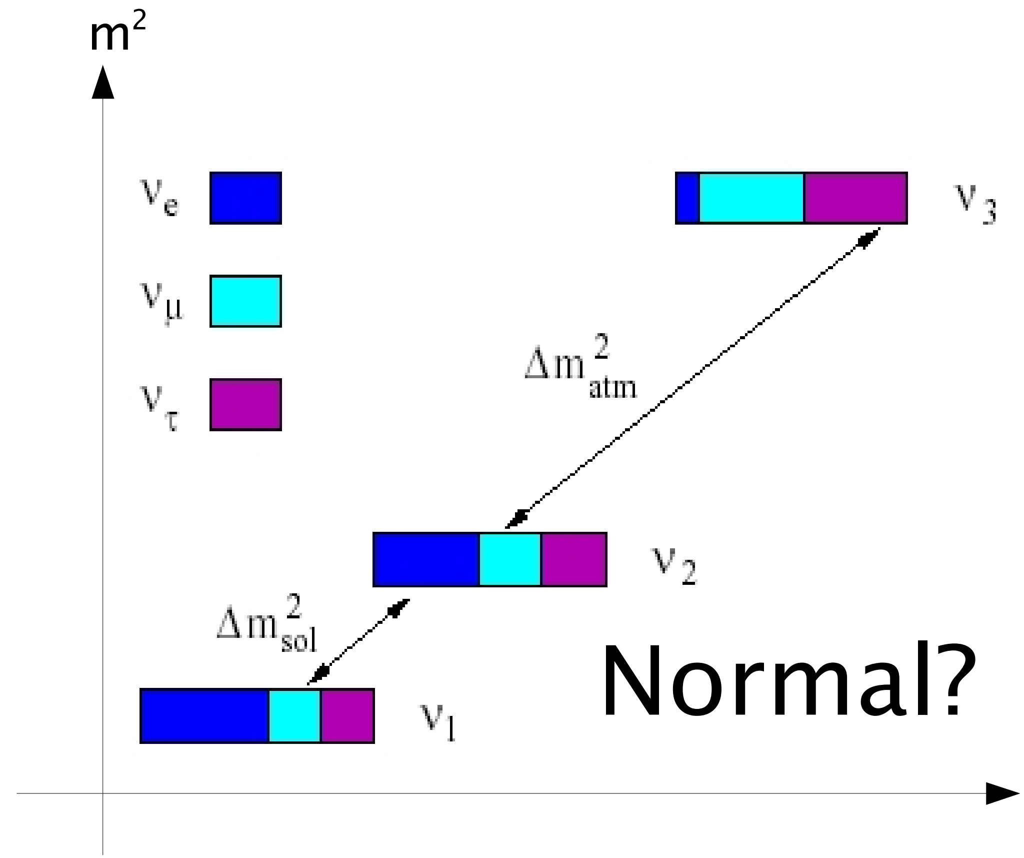
$$\theta_{13} < 10^{\circ}$$

$$0 < \delta_{CP} < 2\pi$$

Reactor

What we still have to do...

- Better measurements of known parameters
- Is $\theta_{23} = 45^o$?
- Value of θ_{13}?
- Value of δ_{CP}?
- Mass heirarchy?
- Absolute mass scale
- Dirac vs Majorana



$$U_{MNSP} = \begin{pmatrix} 0.8 & 0.5 & \epsilon \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \Leftrightarrow U_{CKM} = \begin{pmatrix} 0.975 & 0.222 & 0.004 \\ 0.221 & 0.97 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

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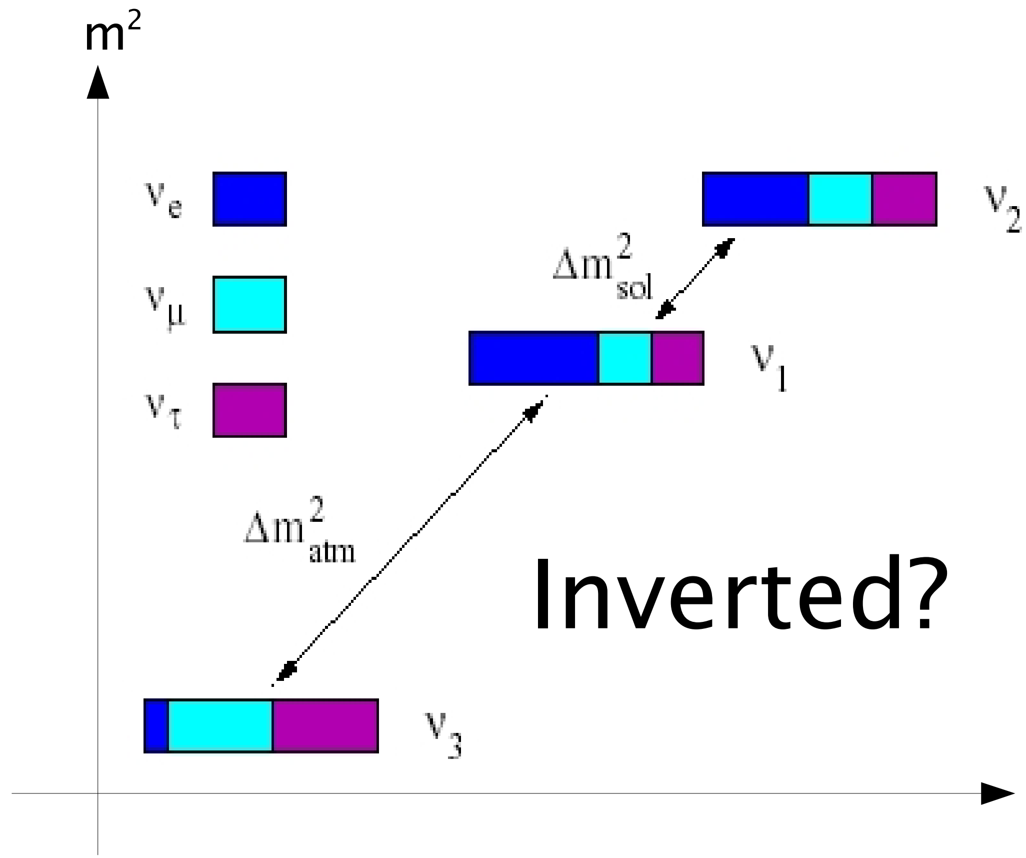

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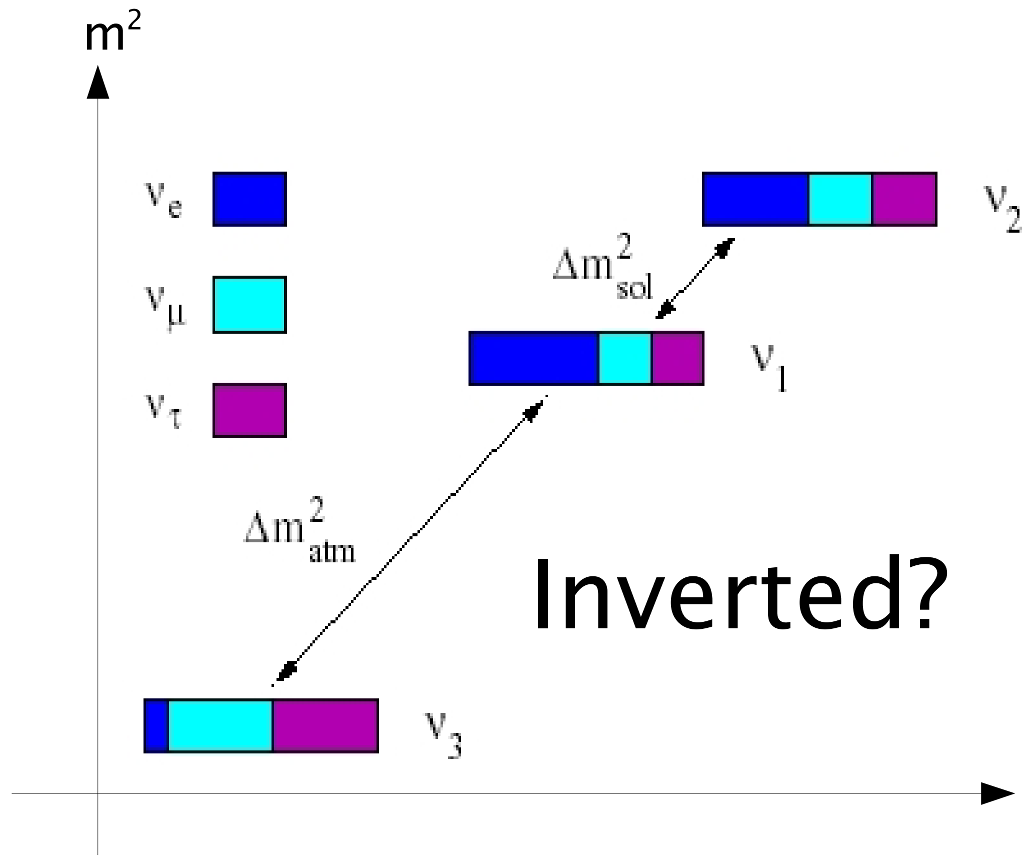

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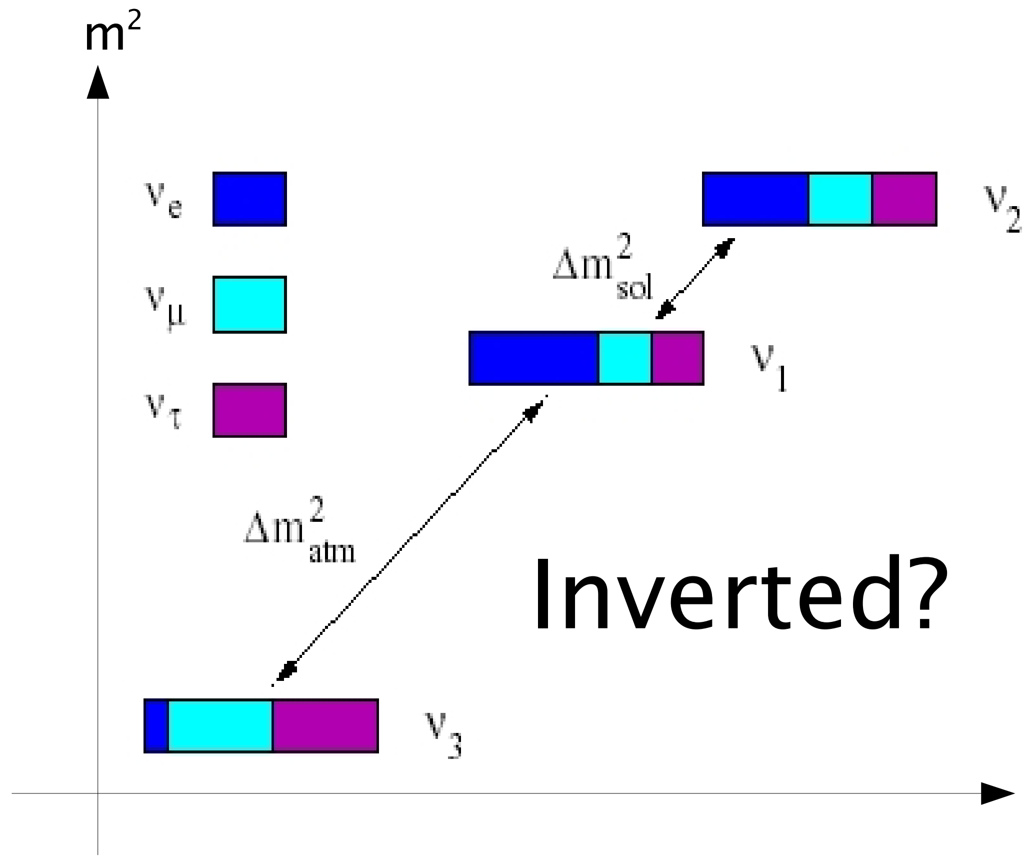

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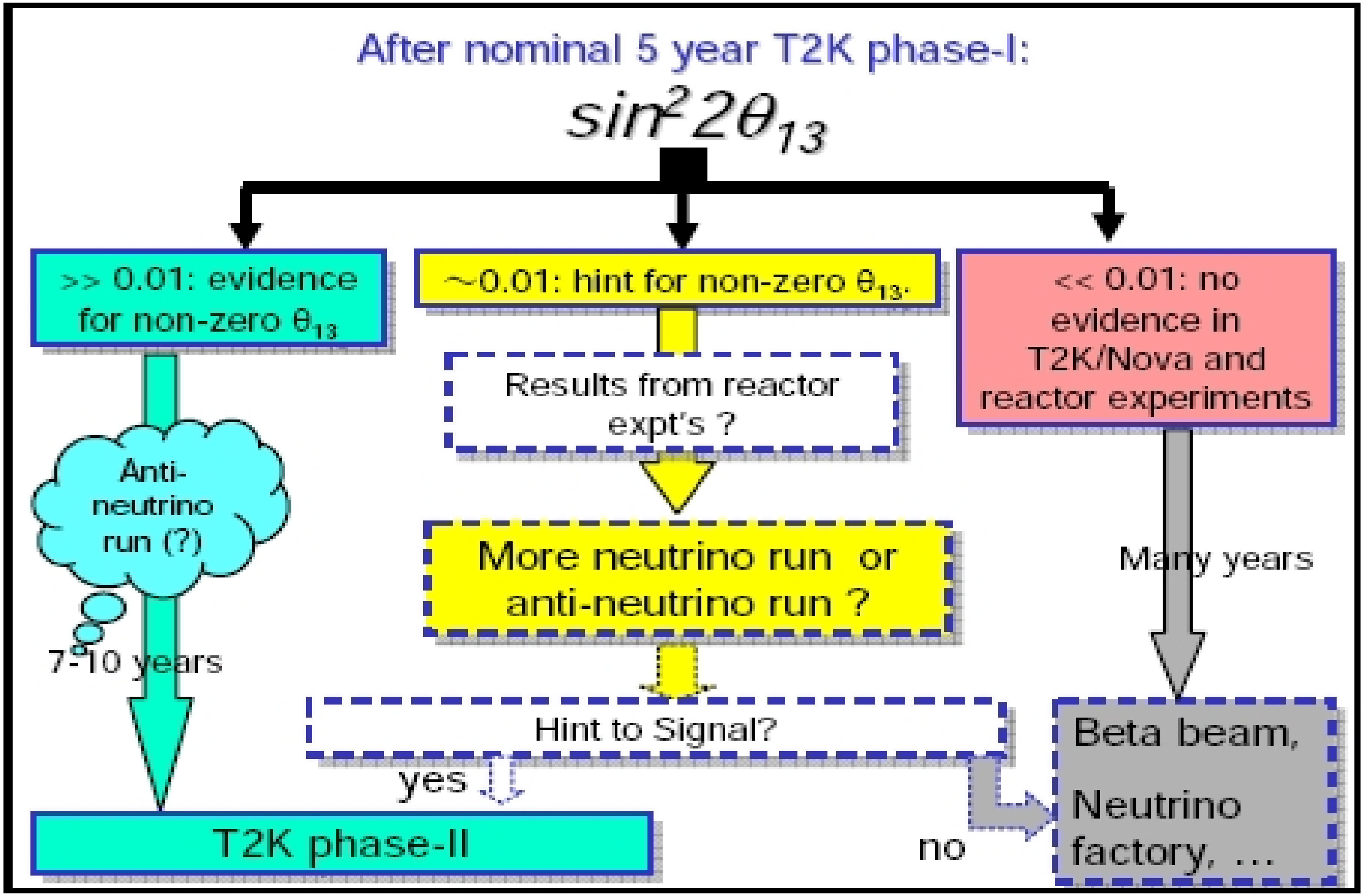
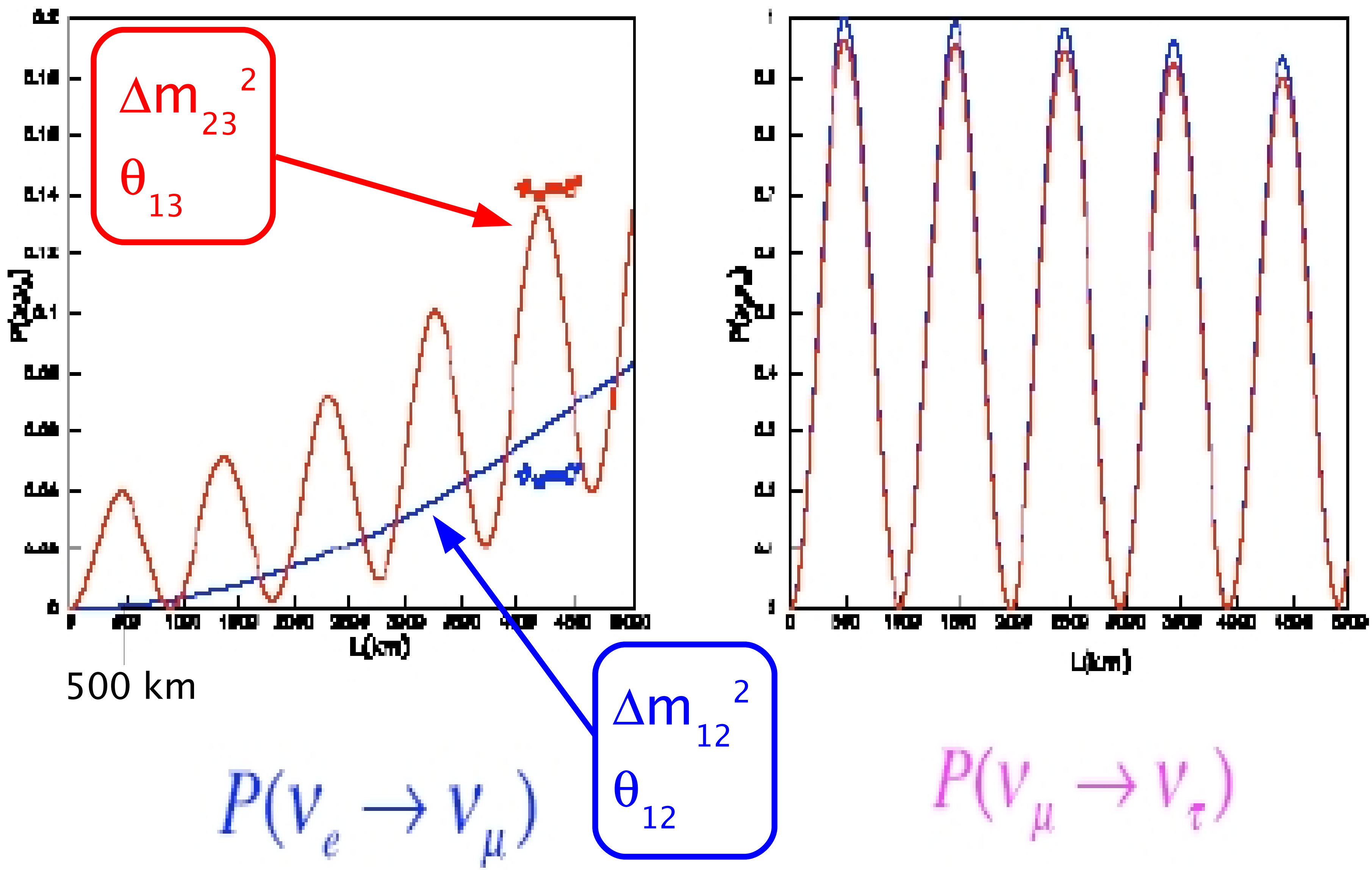
The Master Plan



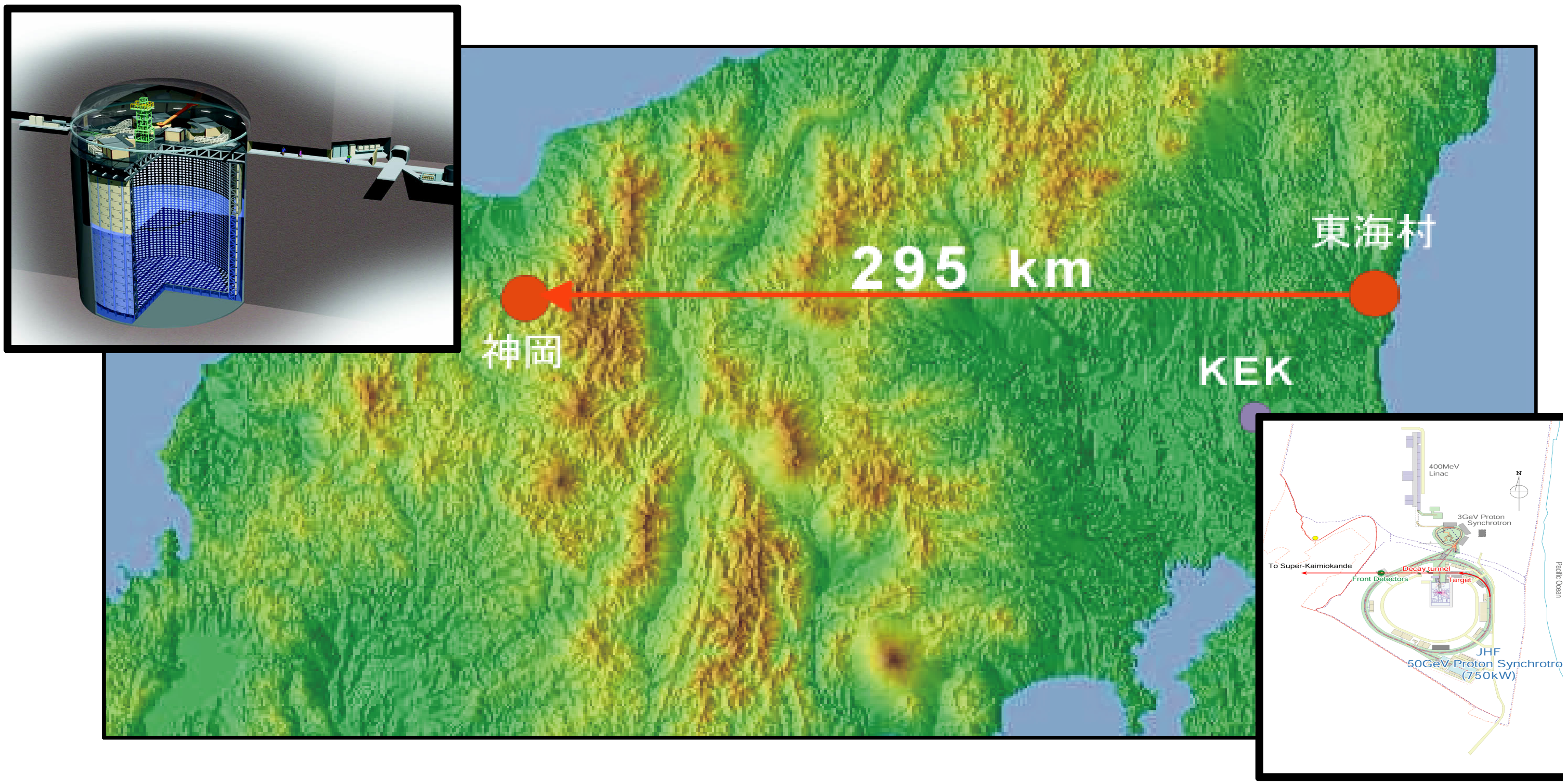
θ_{13} determines the next 15-30 years or so of the field

How to get to θ_{13}?

For 1 GeV beam

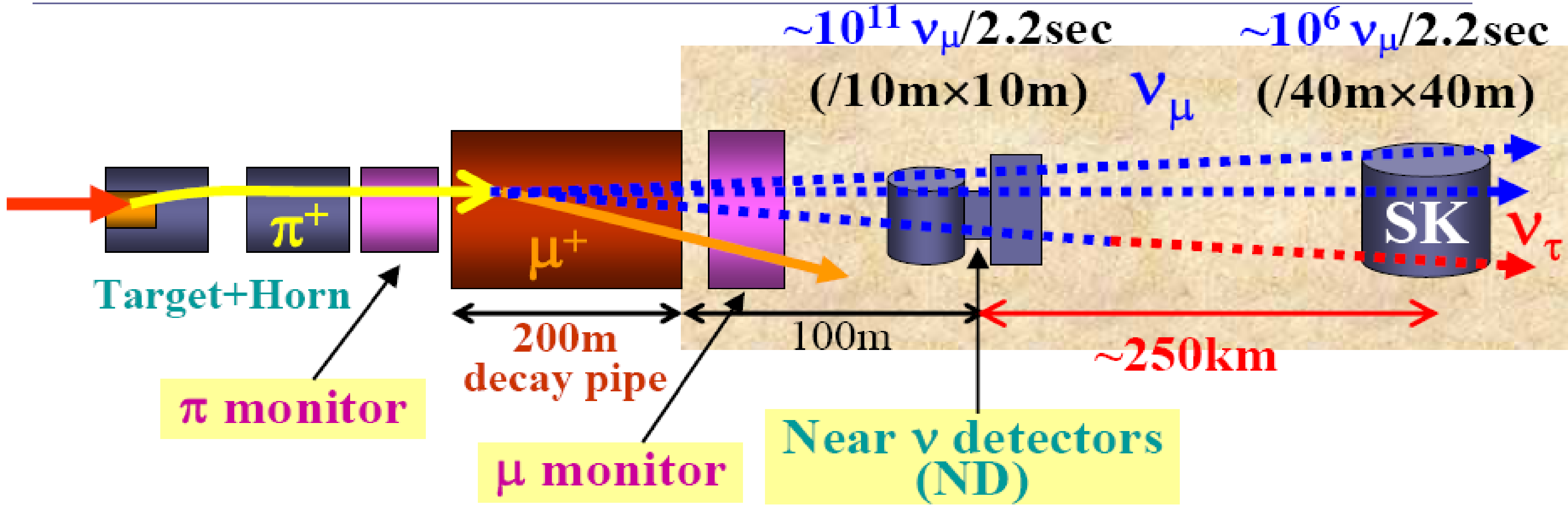


One component – Long Baseline Experiments



$P(\nu_\mu - \nu_e)$ at new off-axis Superbeam

An appearance experiment



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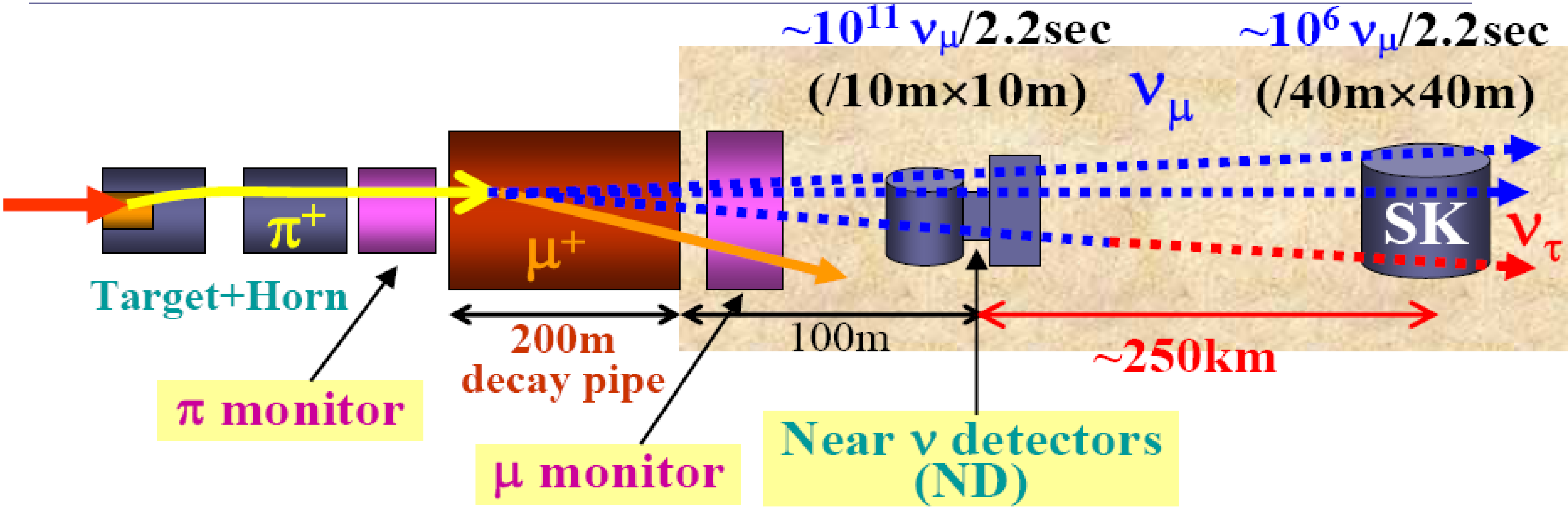
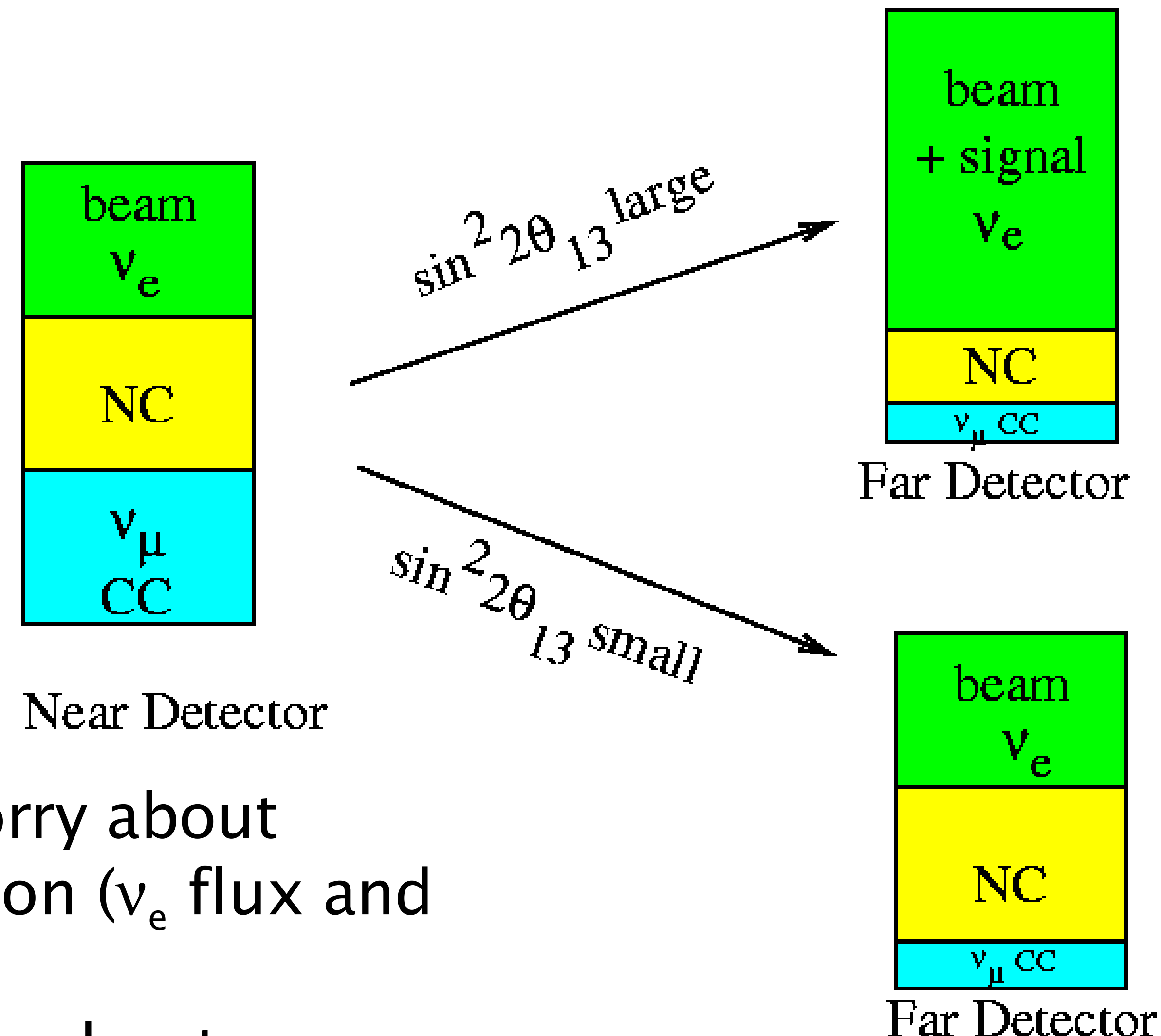


$$\frac{N_\nu^{Far}}{N_\nu^{Near}} = \frac{\Phi_\nu^{SK}\sigma\, M_F\epsilon_F}{\Phi_\nu^{N}\sigma\, M_N\epsilon_N} \sim P_{osc}\frac{R_{FN}\Phi_\nu^{N}\sigma\, M_F\epsilon_F}{\Phi_\nu^{N}\sigma\, M_N\epsilon_N}$$

Uncertainties in σ cancel, right?

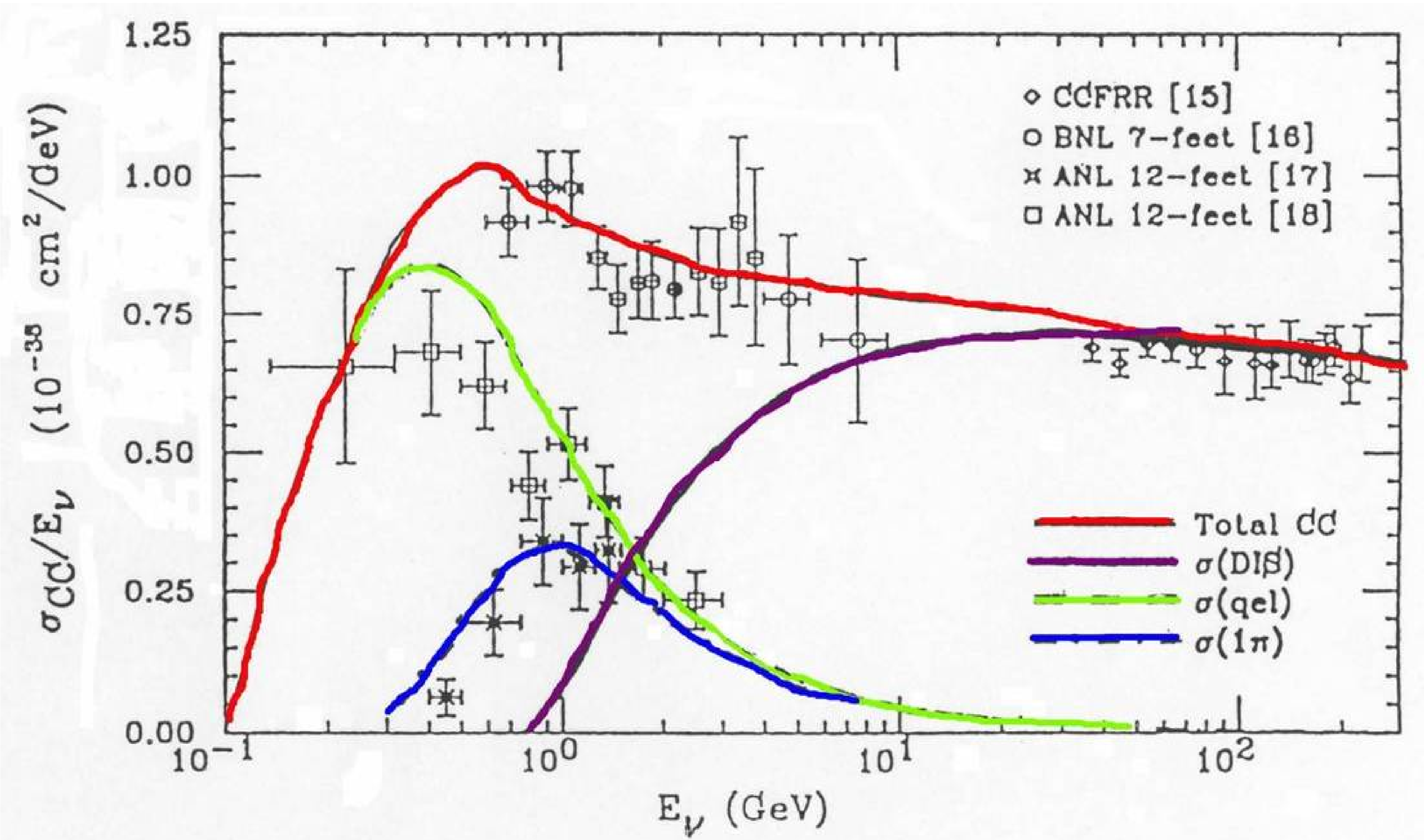
Um....no, actually

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

Neutrino Cross Sections



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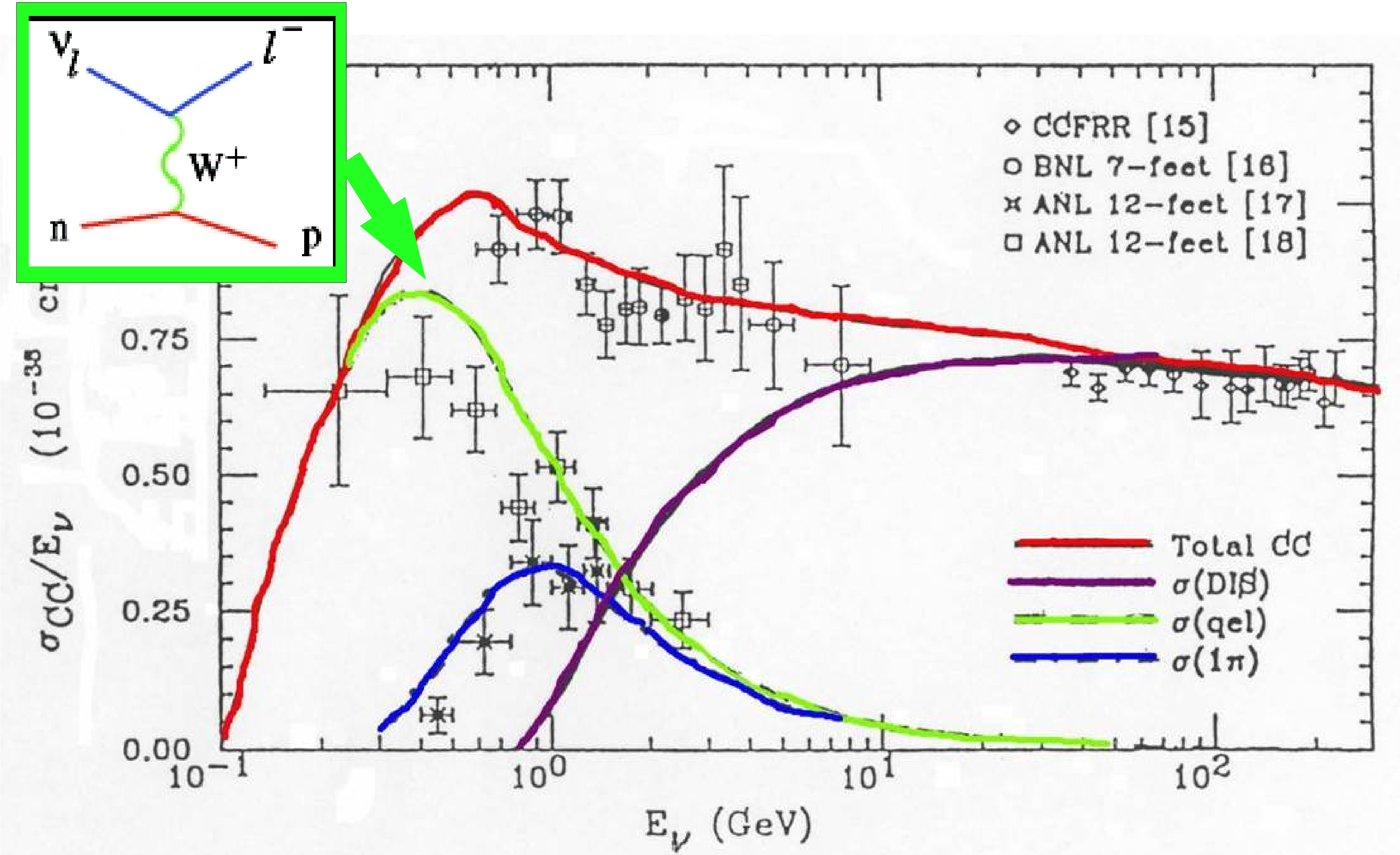

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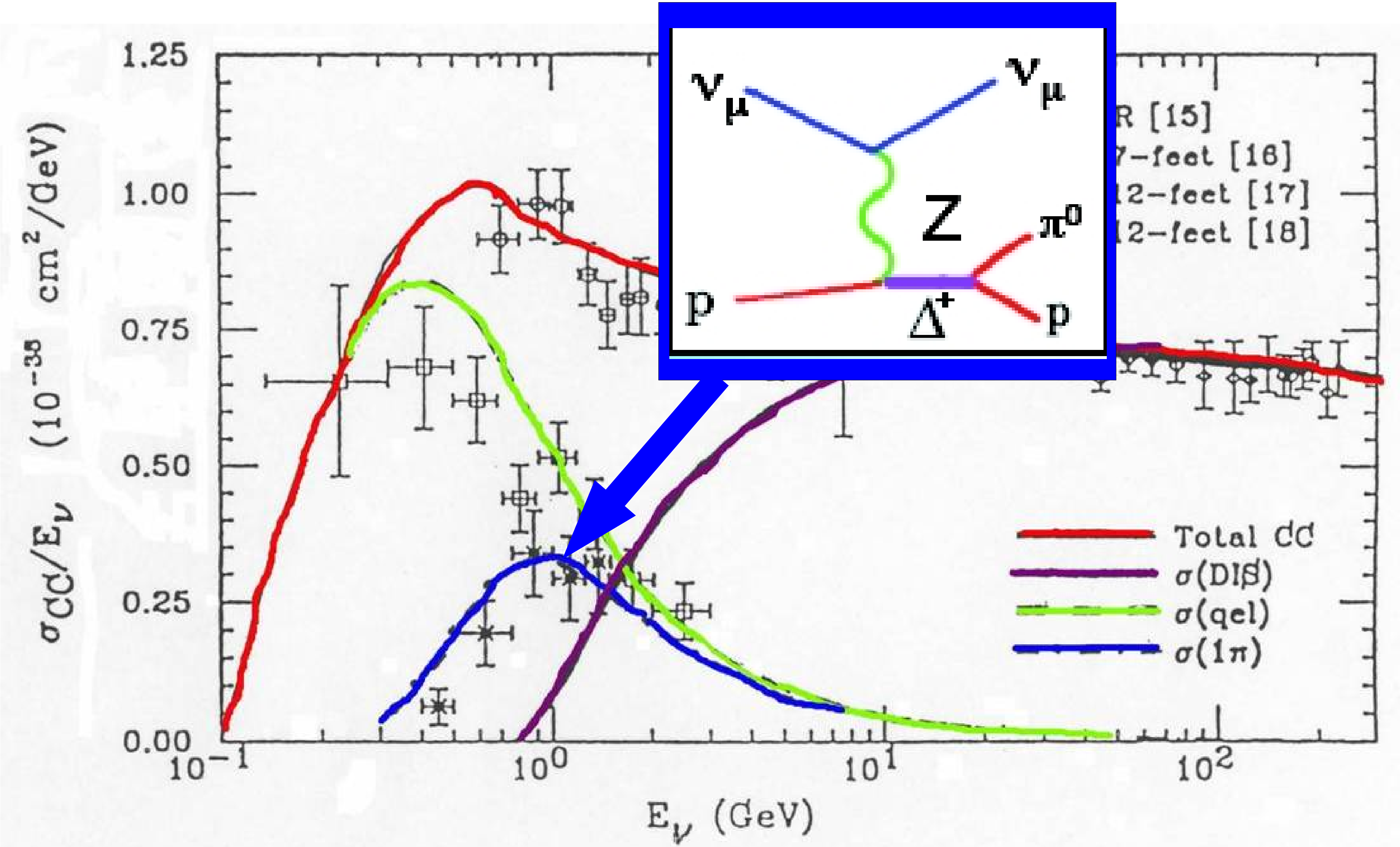

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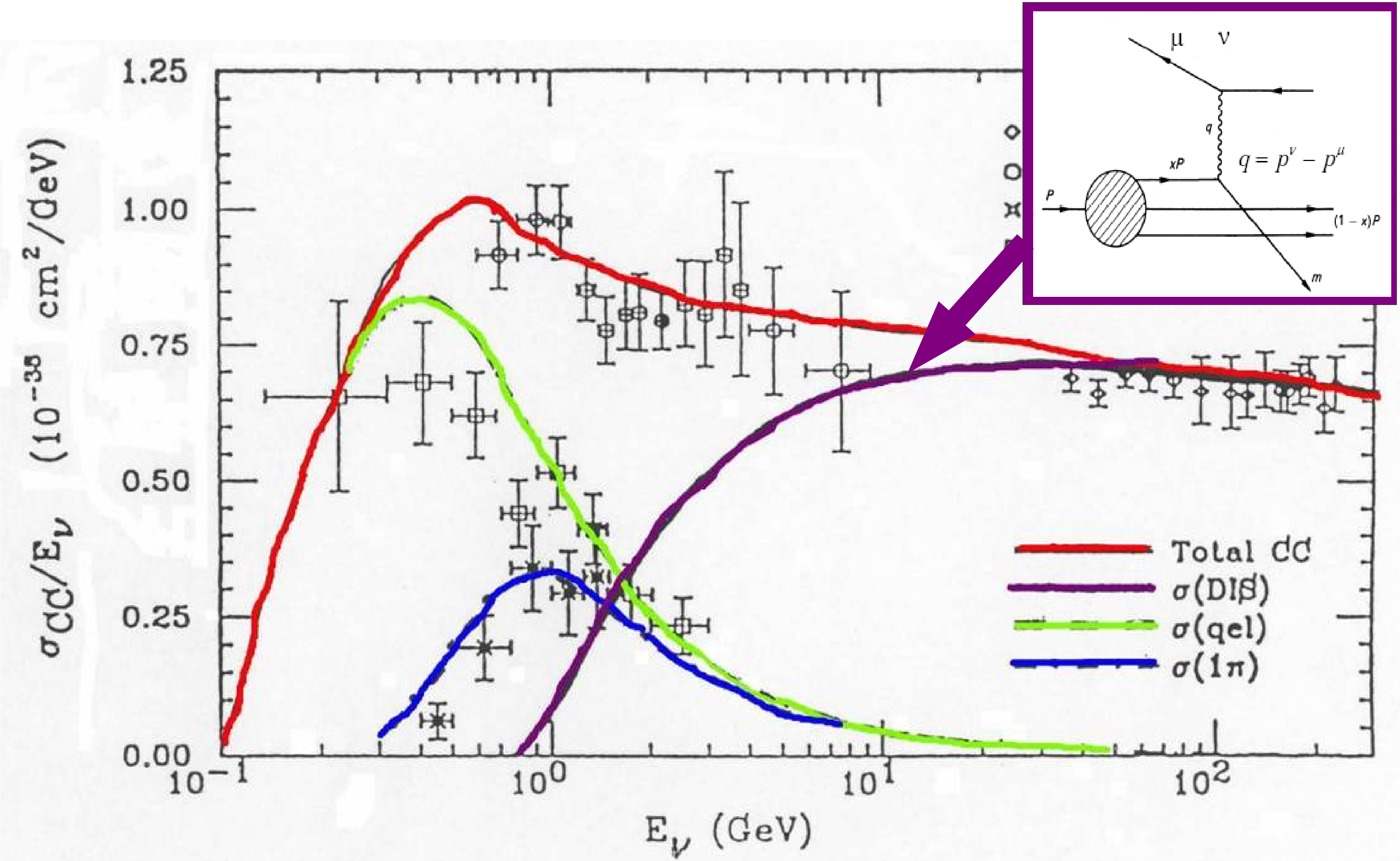

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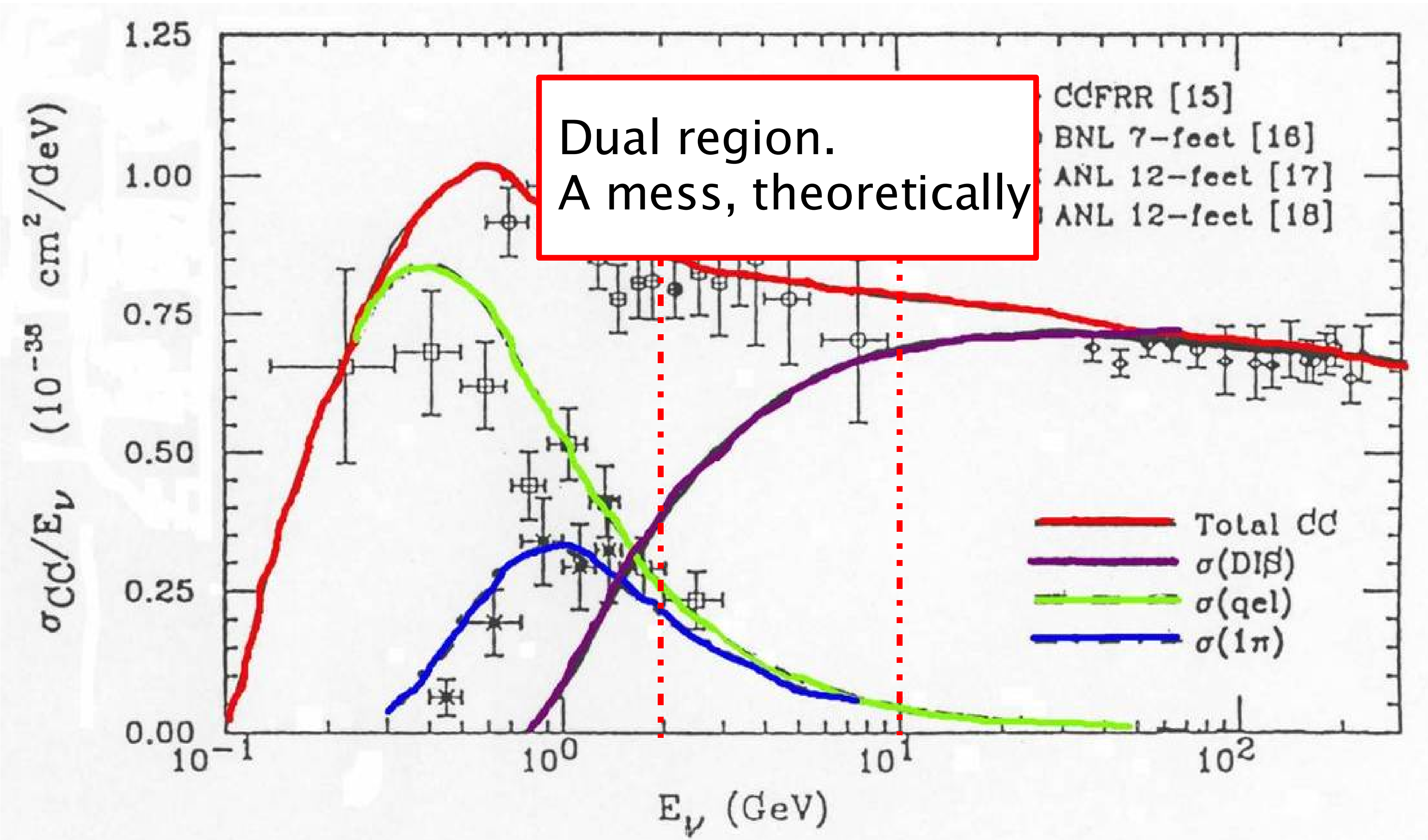

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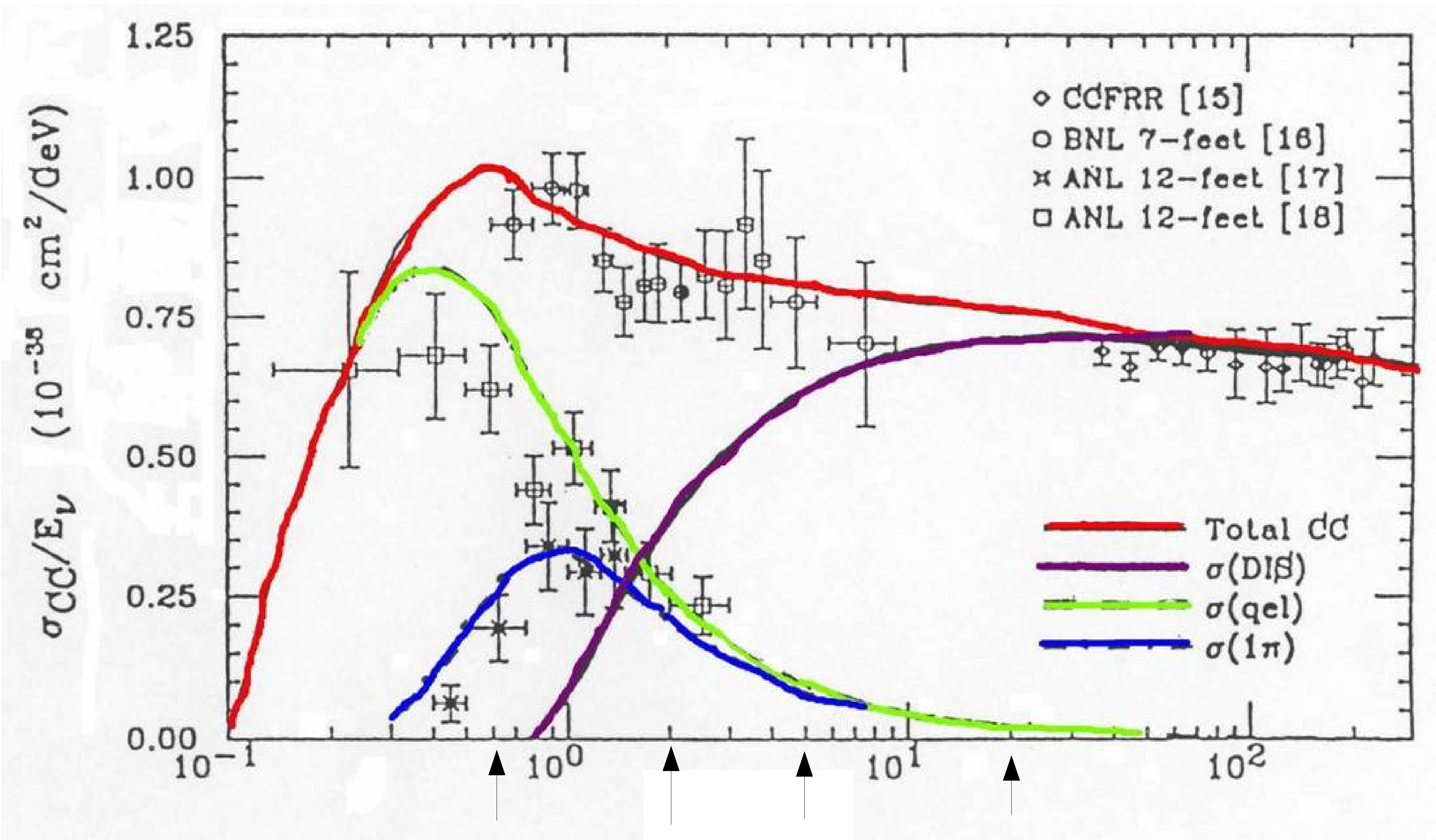
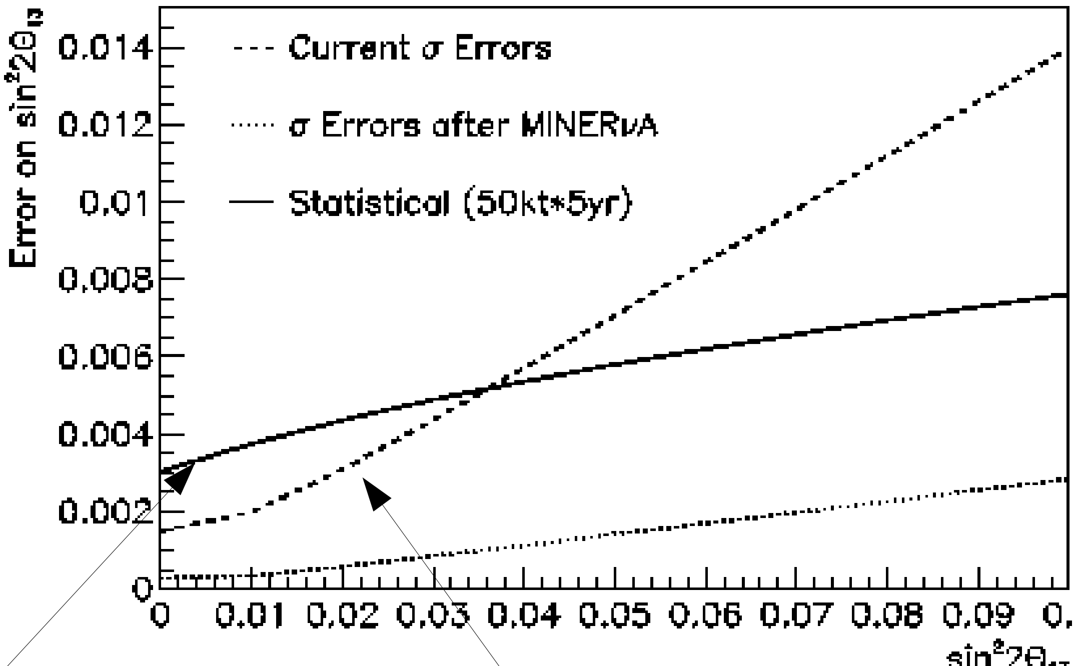


T2K NOνA MINOS OPERA

The Effect of Ignorance

Toy MC Analysis of ν_e appearance experiment assuming θ_{13} just below current limit

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%

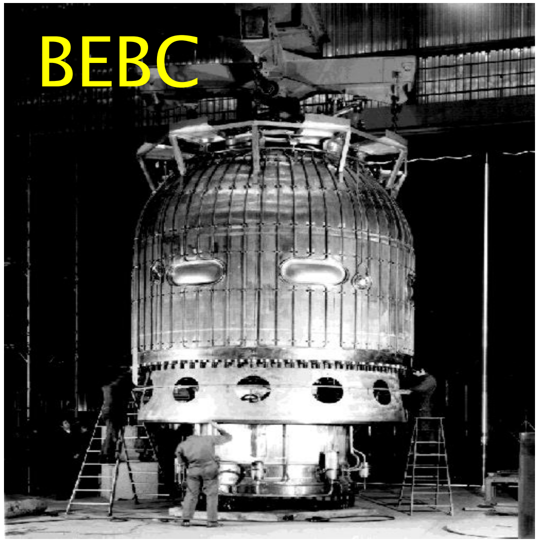


Statistical Errors

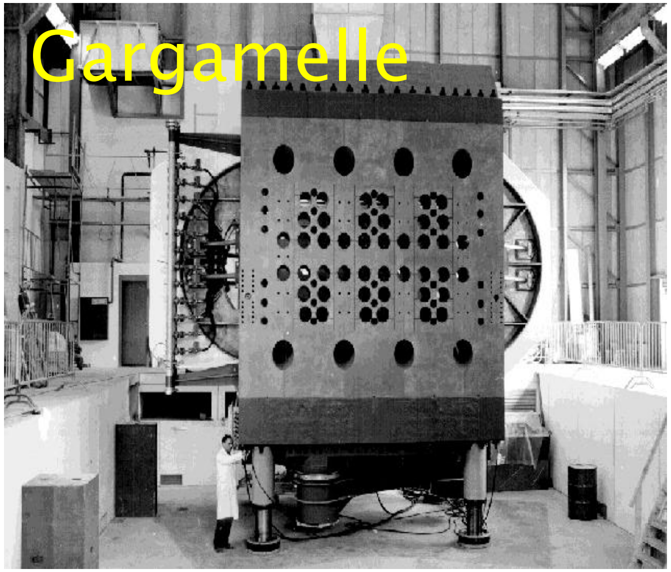
Systematic Error from Cross sections

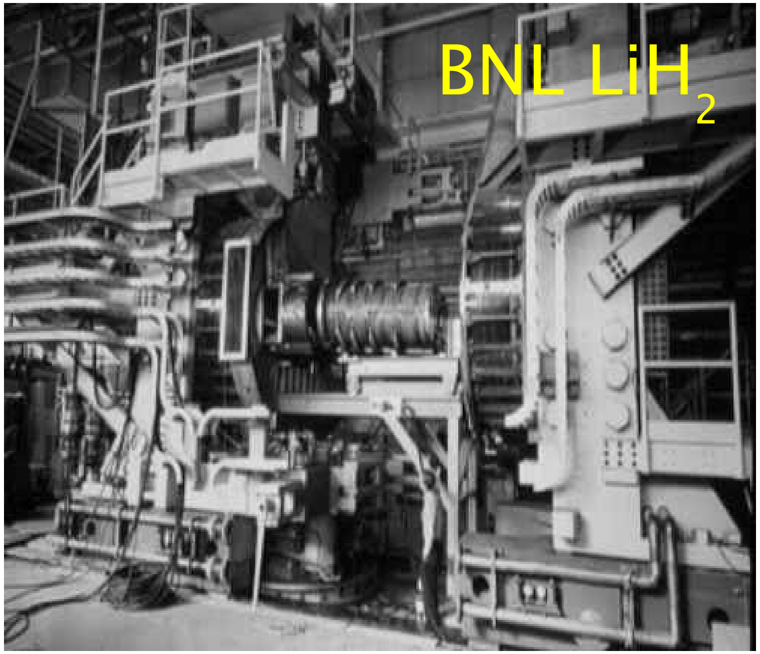
Come on – 20%, 50,%, 100%? The cross sections can't be *that* poorly understood, can they?

What is in the sims now?

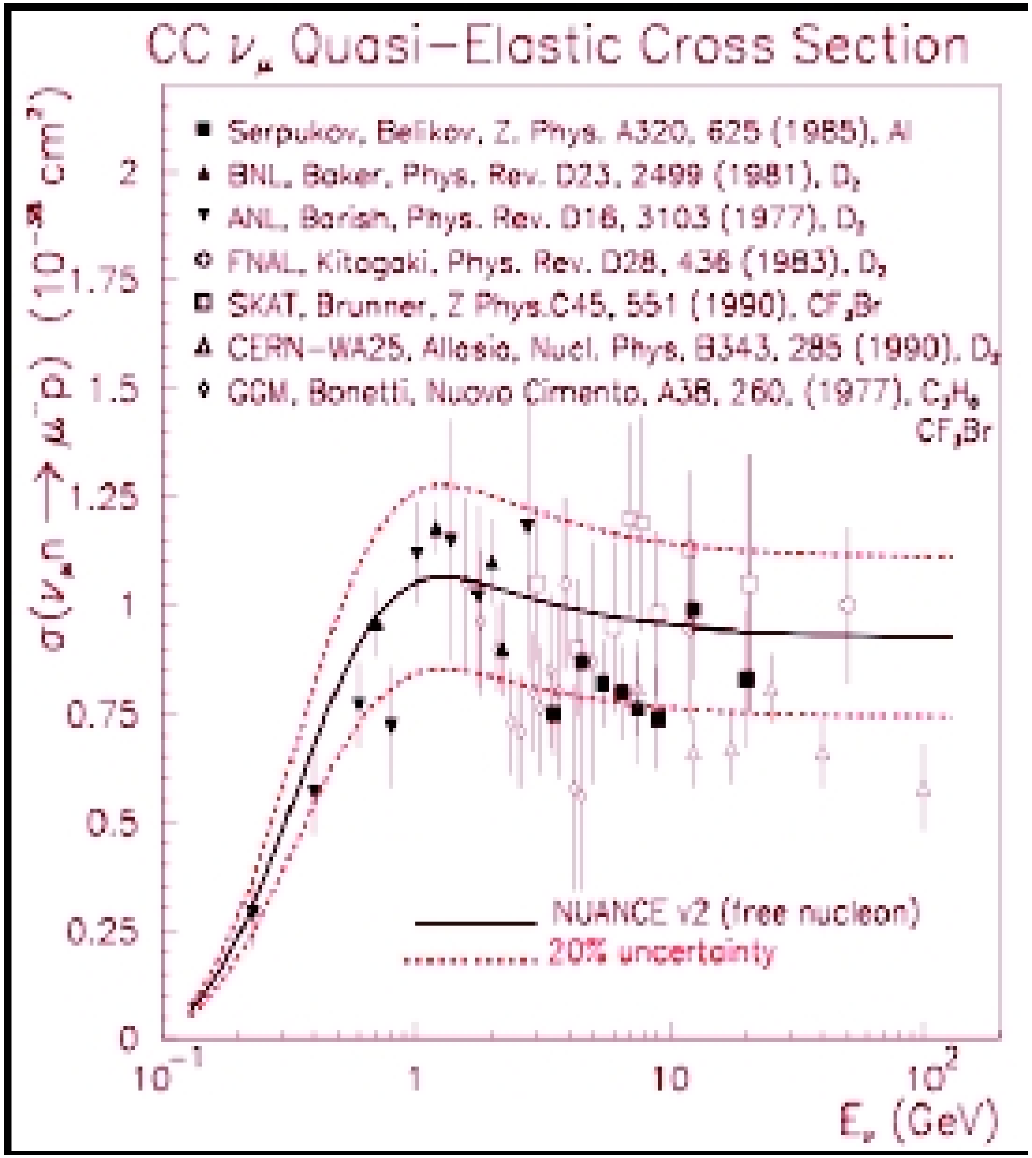


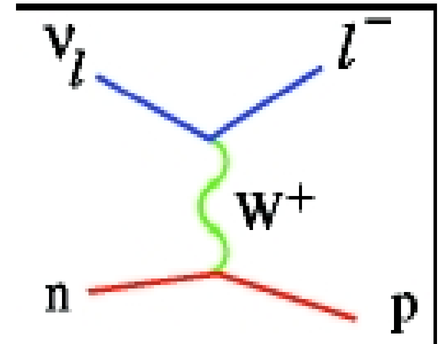
- Most present knowledge comes from the old bubble chamber data (FNAL, CERN, ANL, BNL, Serpukhov)
- Low neutrino fluxes, low statistics
- Data sometimes conflicting
- Very important in constraining MC





CC Quasielastics

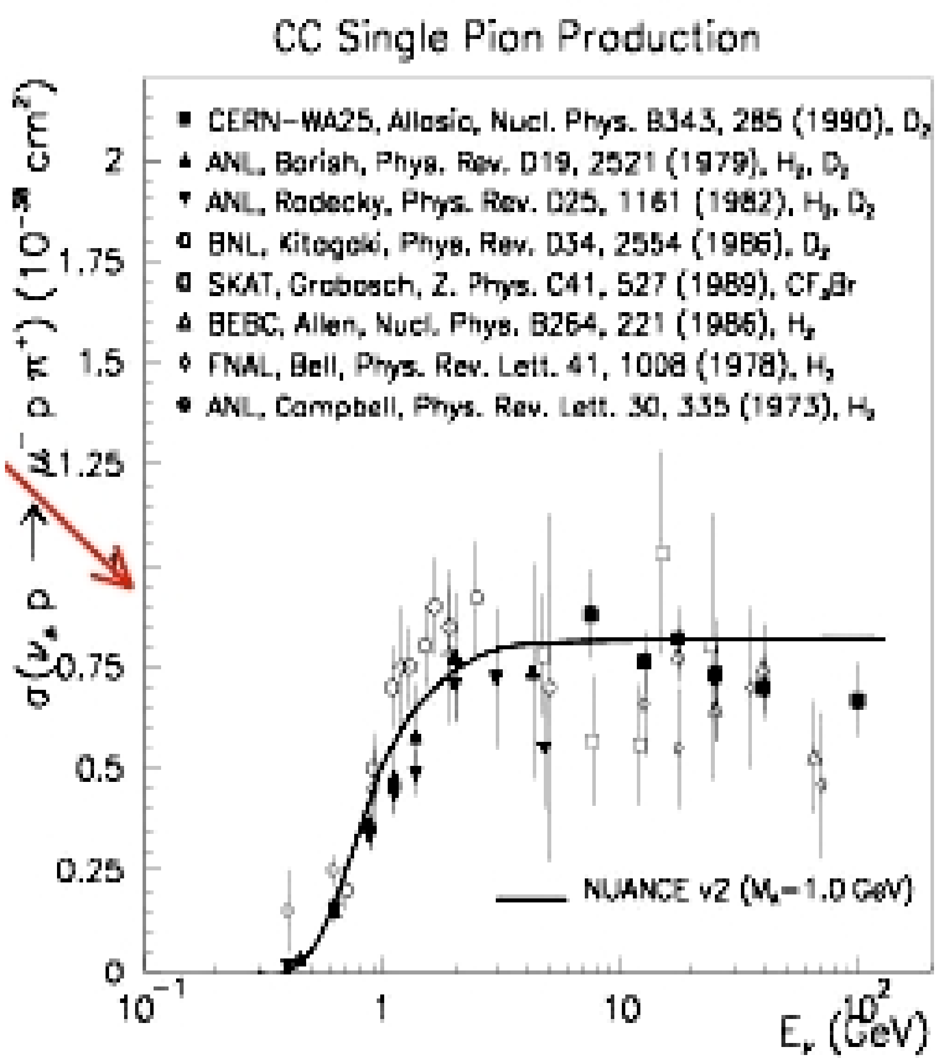




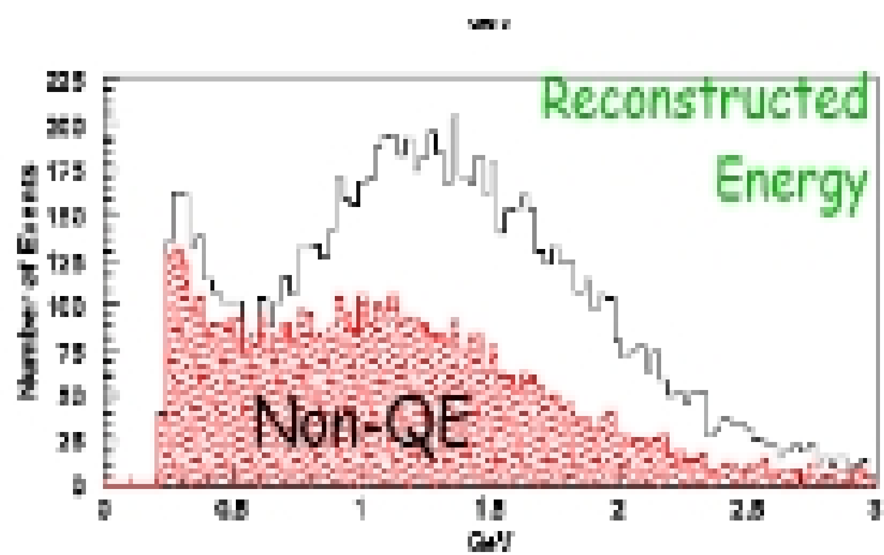
- 2 body interaction allows neutrino energy reconstruction

- 15-20% uncertainty
- Less well-known in threshold region
- Low E data mostly on D_2

CC 1π production

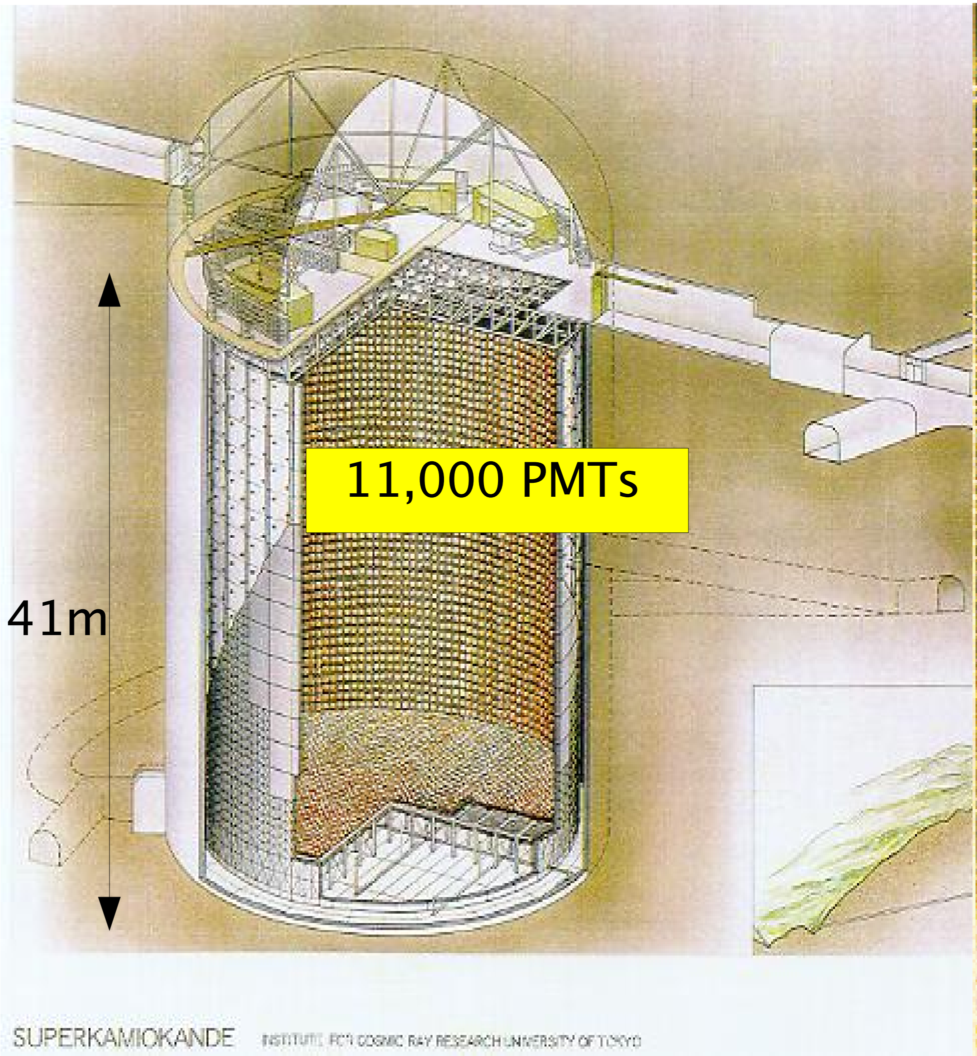


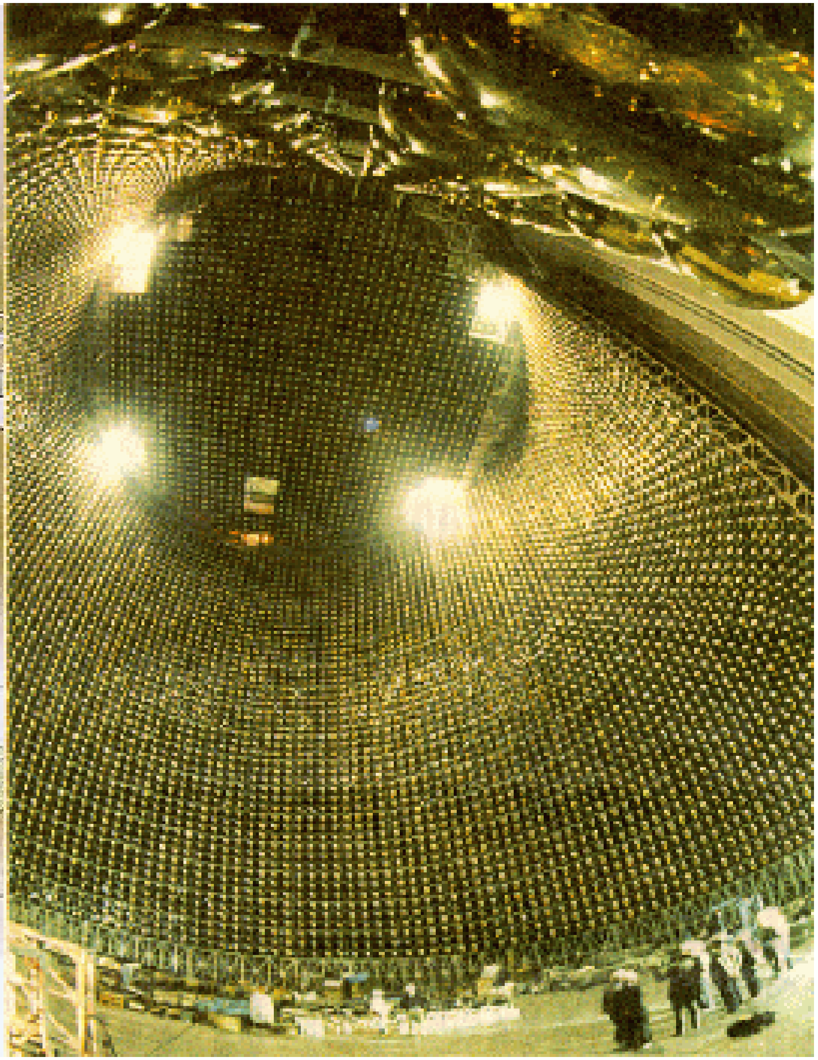
$$\nu_\mu p \rightarrow \mu^- \pi^+ p(\Delta^{++})$$
$$\nu_\mu n \rightarrow \mu^- n \pi^+$$



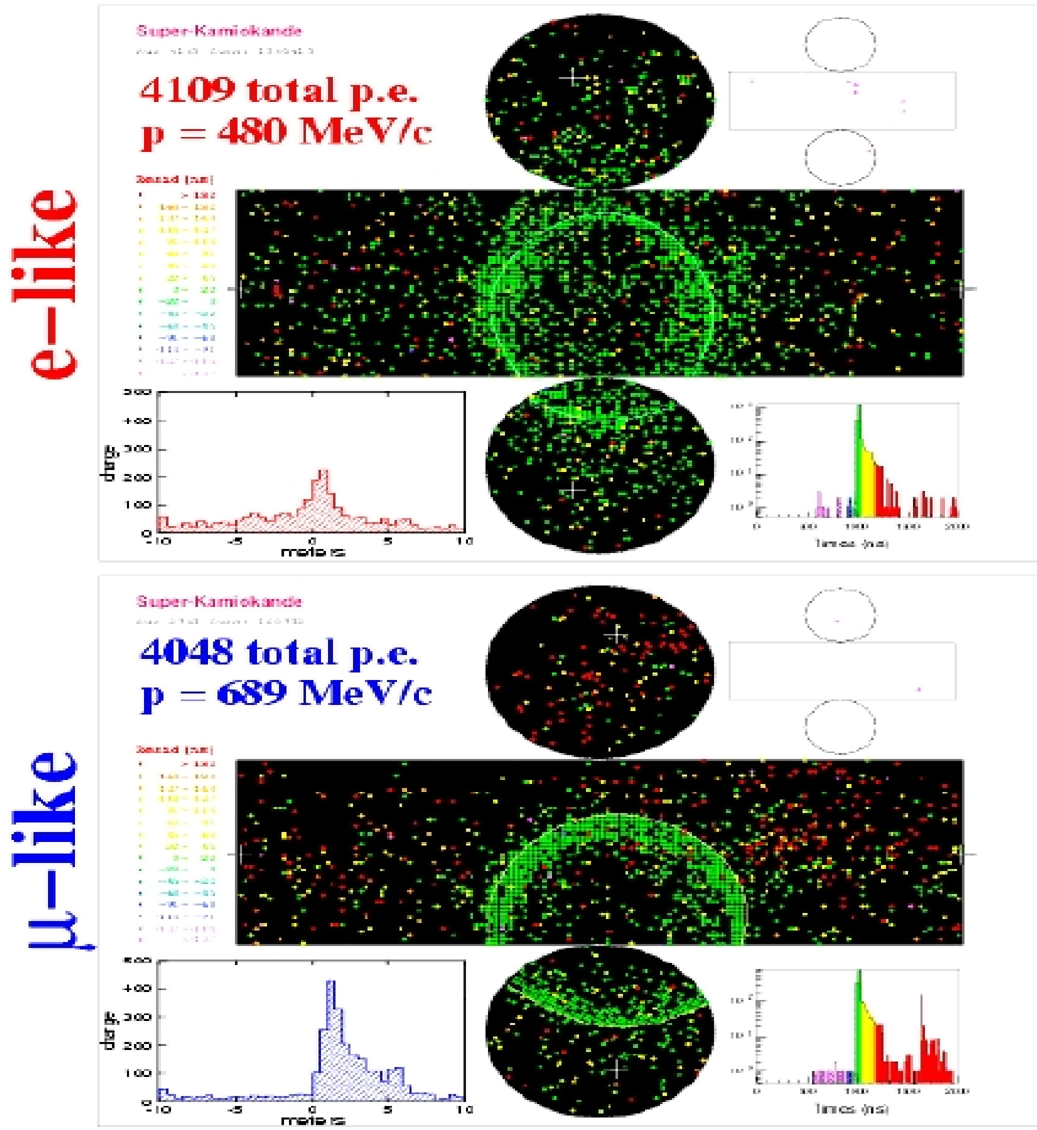
Background to QE signal

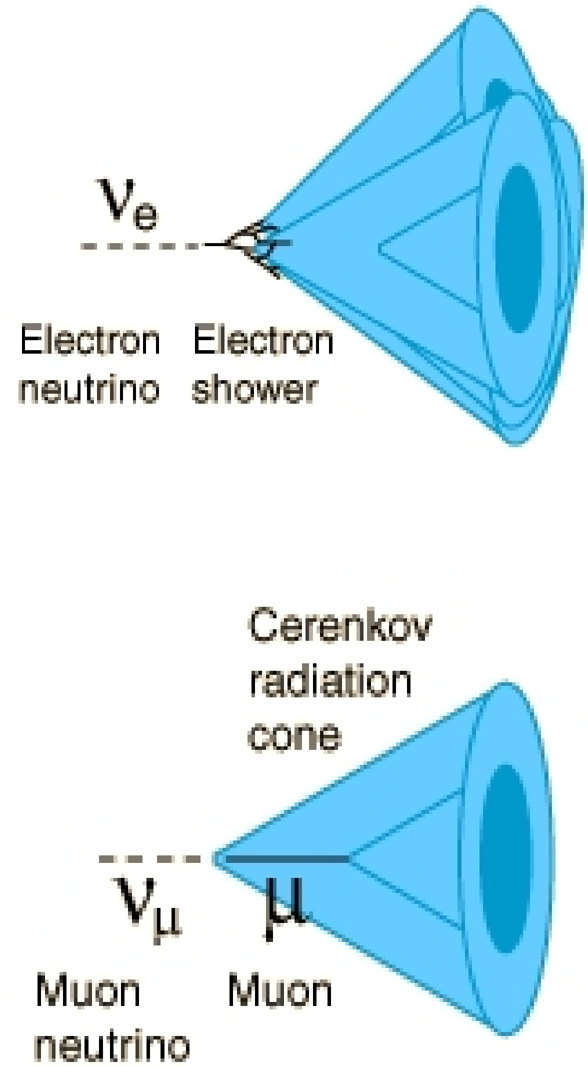
ν_e appearance in T2K





Detection Principle

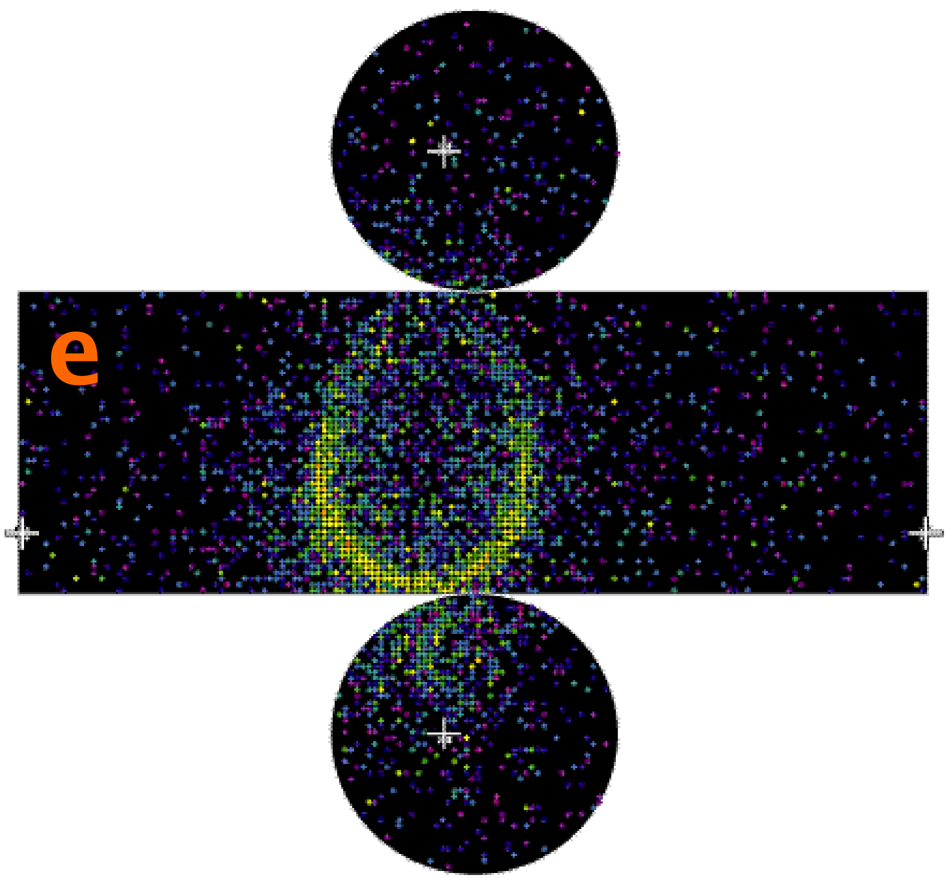


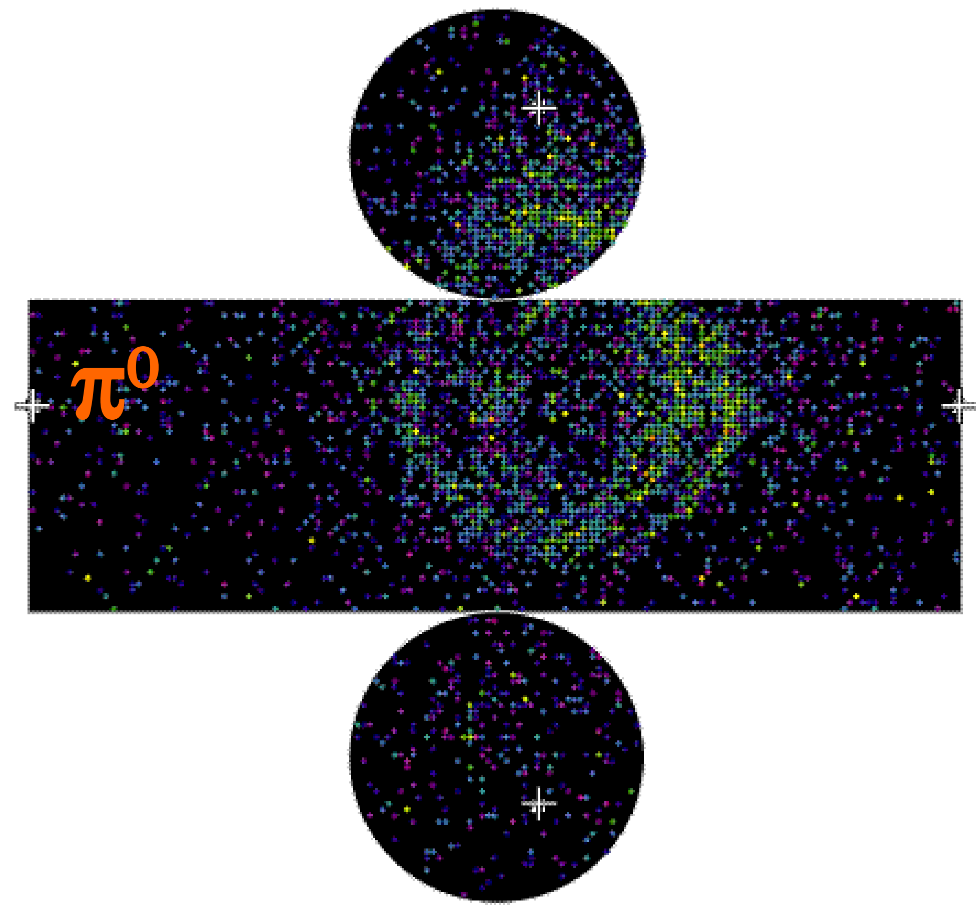


NC 1 π^0 Production

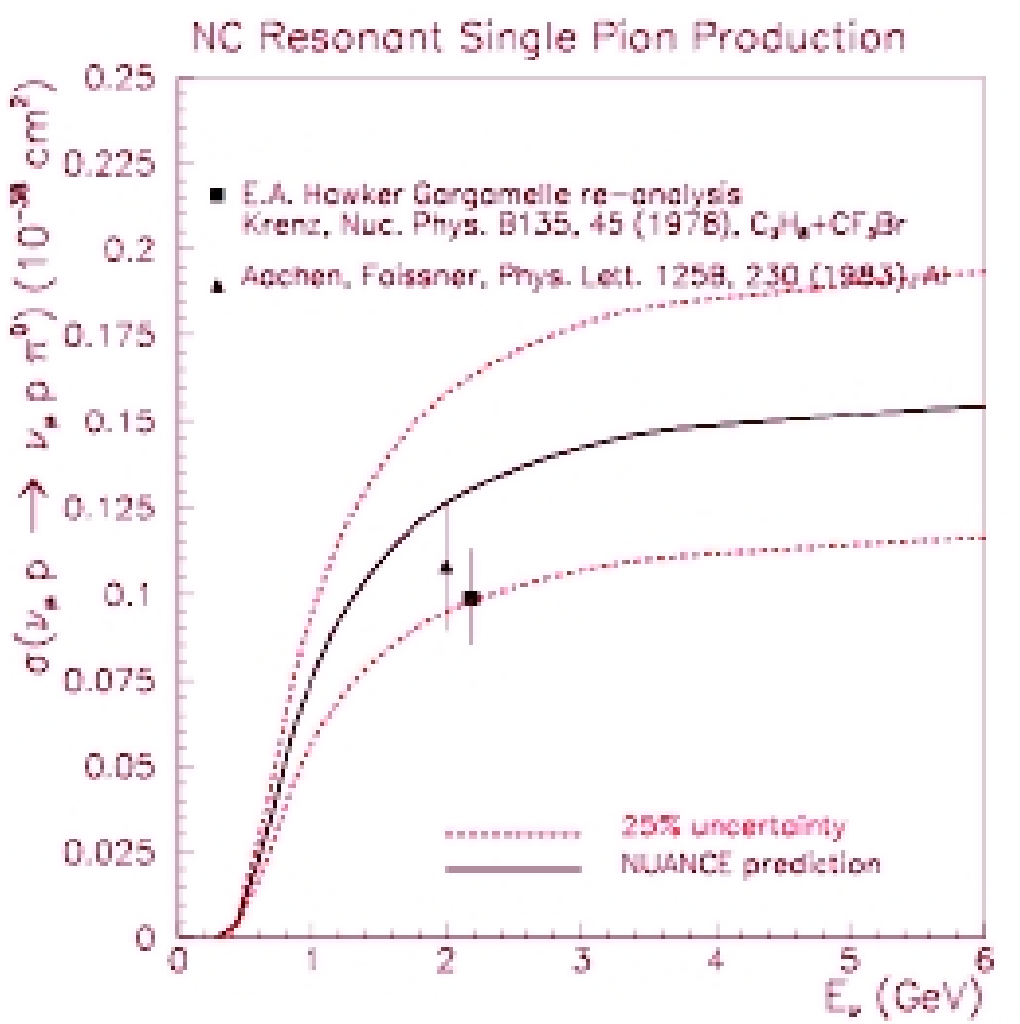
$$\nu N \rightarrow \nu \Delta \rightarrow \nu N \pi^0$$

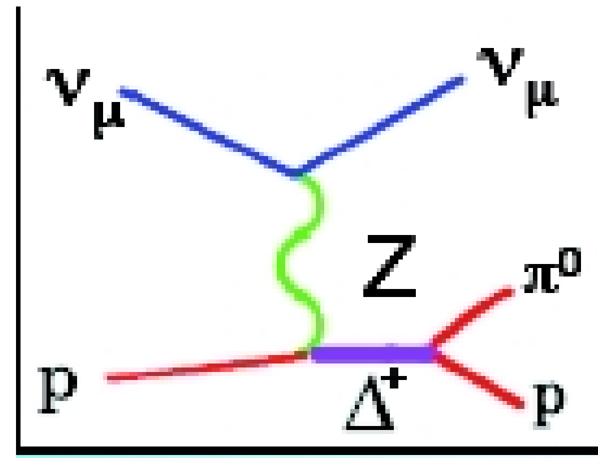
Major background to ν_e appearance search in T2K





NC 1 π^0 Resonance

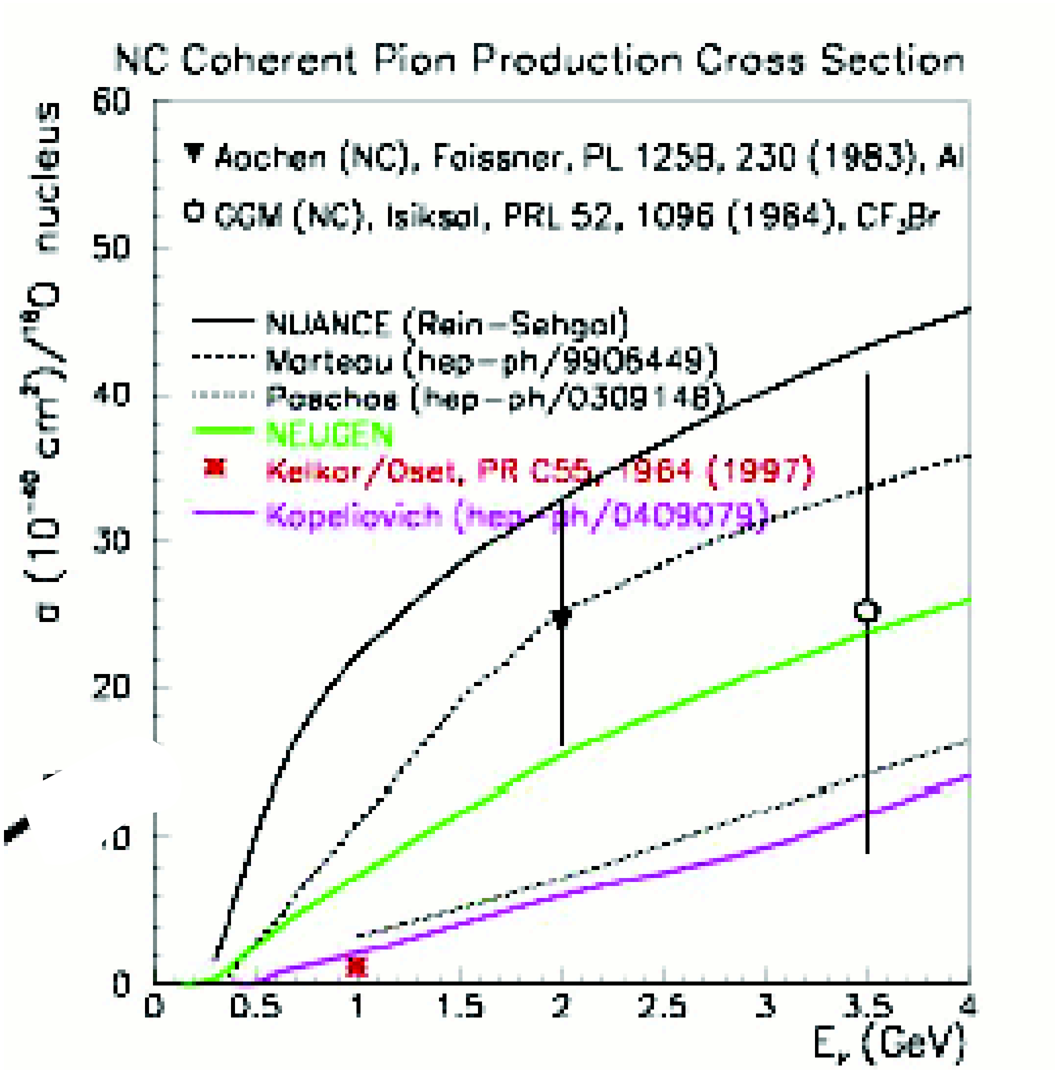


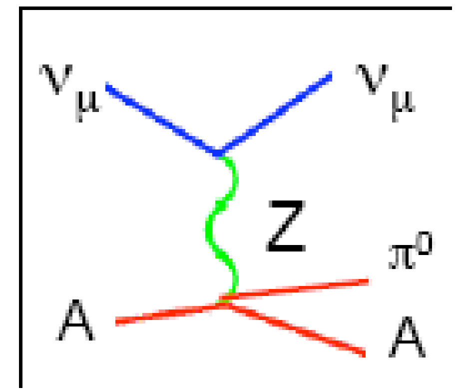


2 Measurements at 2 GeV

Total world data < 500 events

NC 1 π^0 Coherent





Coherent production off nucleus, keeping nucleus intact

Forward emitted π

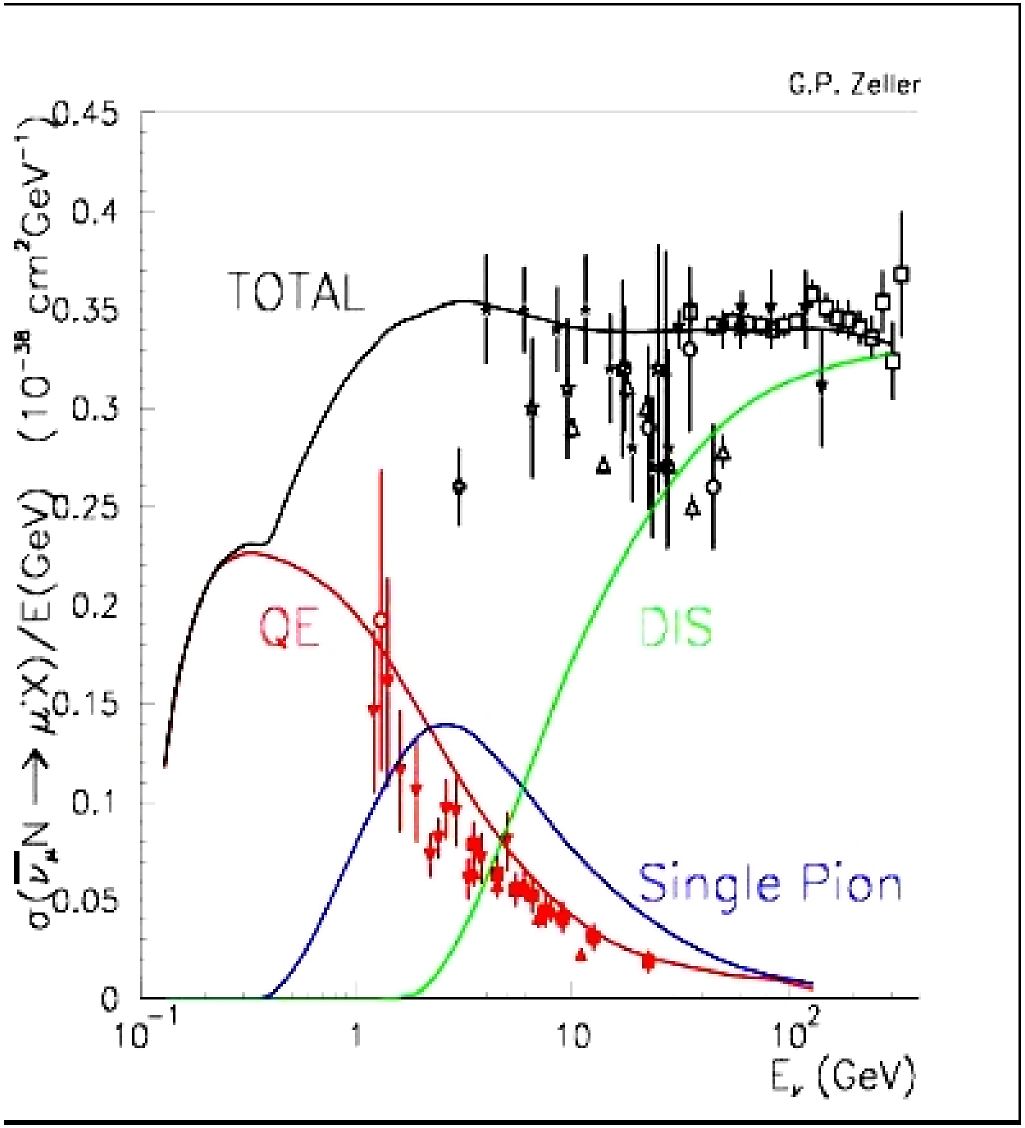
low Q^2

~ 20% of resonant rate

but look at the errors....

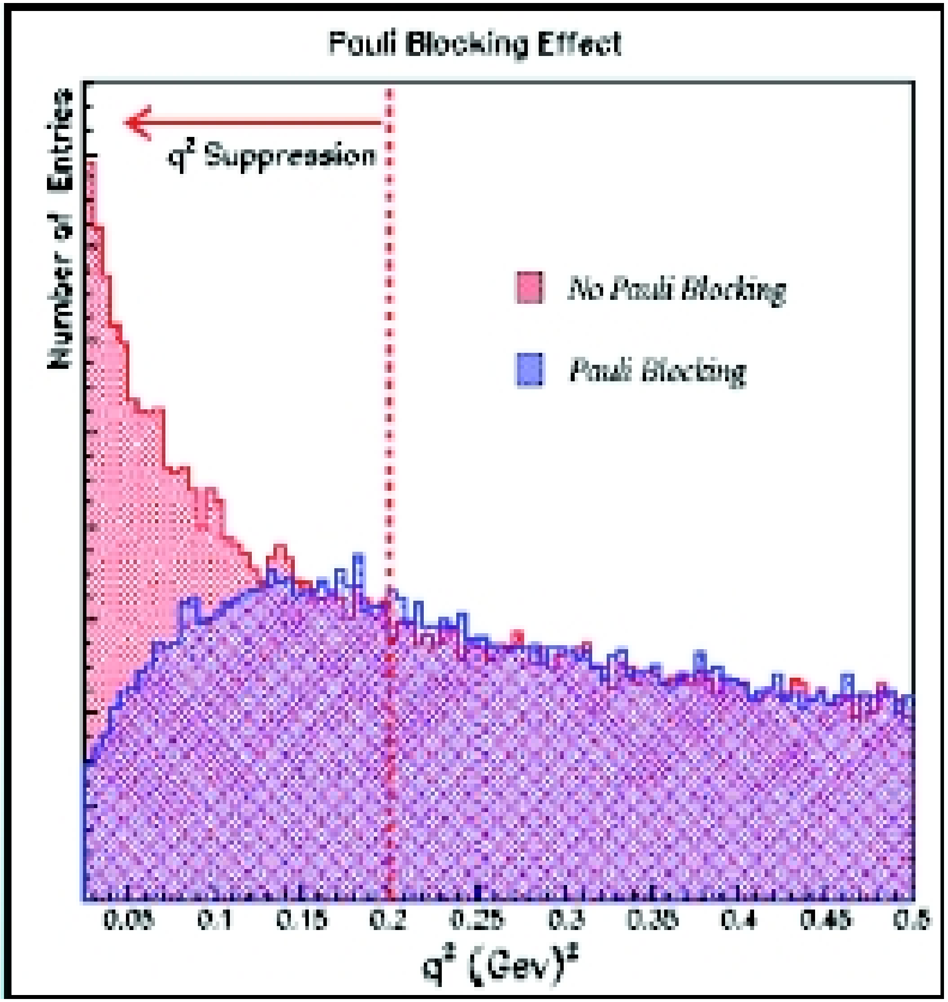
Can it get any worse?

World Data for Antineutrinos



Nuclear Effects

Neutrinos typically interact with a bound nucleon



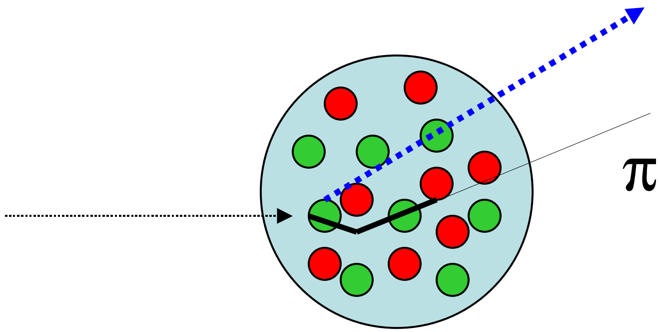
Simplest and most common model is basic Fermi gas

- Fermi momentum model
- Pauli blocking

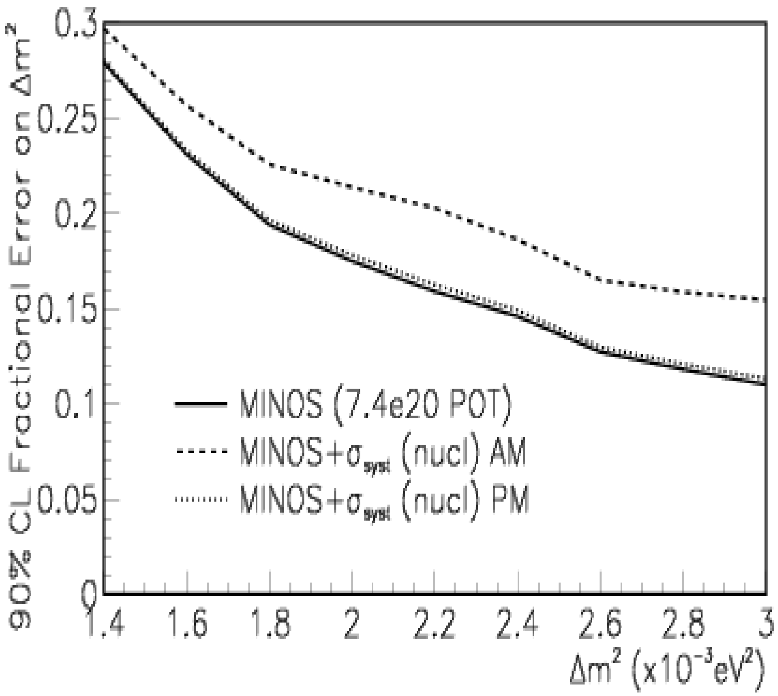
Modifies the scattering angle and momentum spectra of outgoing final state.

Nuclear effects largest at low E_ν, low Q^2

Nuclear Effects

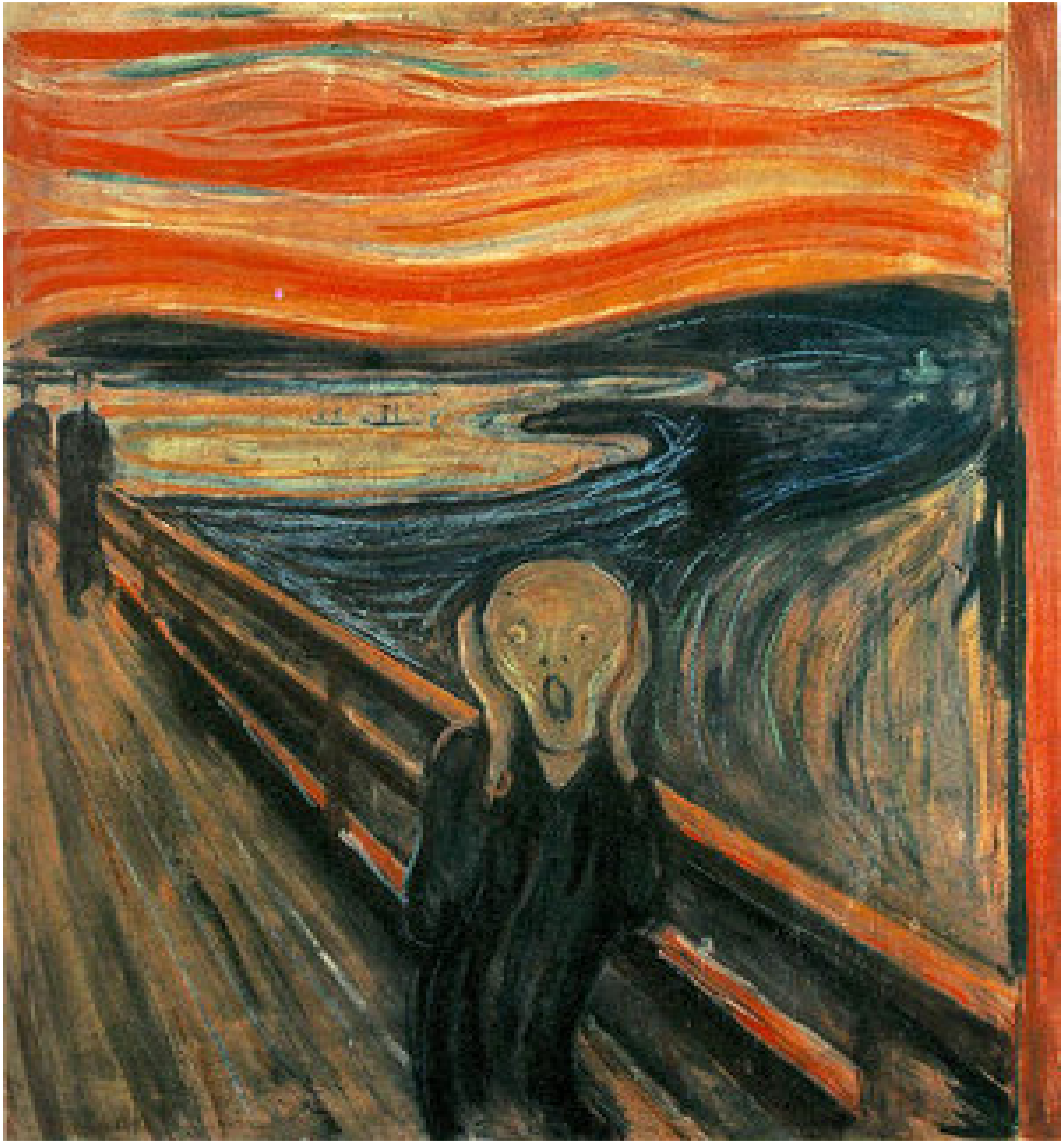


Fermi surface modelling
Pion absorption/rescattering
Final state mass effects
Nucleon rescattering



Nuclear effects studied in charged lepton scattering.

But, there are signs in the data that nuclear effects for neutrinos are different than for charged lepton interactions.



Good Grief! Something must be done!

APS Joint Study on Neutrino Physics – 2006

- NEW HIGH-PRECISION CROSS-SECTION EXPERIMENTS SHOULD BE UNDERTAKEN.

cancel some of the uncertainty in cross sections, the better and more precise solution is to actually measure the cross sections better than currently known once and for all! We encourage that the experiments necessary for this be carried out.

SciBooNE

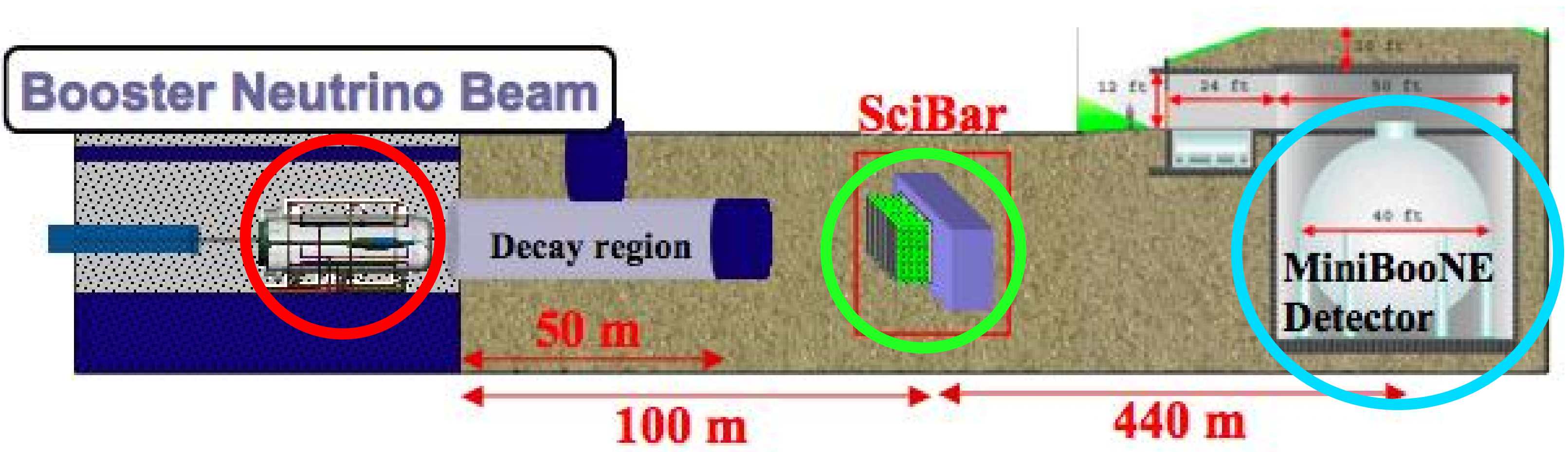
Universitat Autonoma de Barcelona
University of Cincinnati
University of Colorado
Columbia University
Fermi National Accelerator Laboratory
High Energy Accelerator Research Organization (KEK)
Imperial College London*
Indiana University
Institute for Cosmic Ray Research
Kyoto University*
Los Alamos National Laboratory
Louisiana State University
Purdue University Calumet
Università degli Studi di Roma and INFN-Roma
Saint Mary's University of Minnesota
Tokyo Institute of Technology
Universidad de Valencia

<u>Spokespeople</u>:

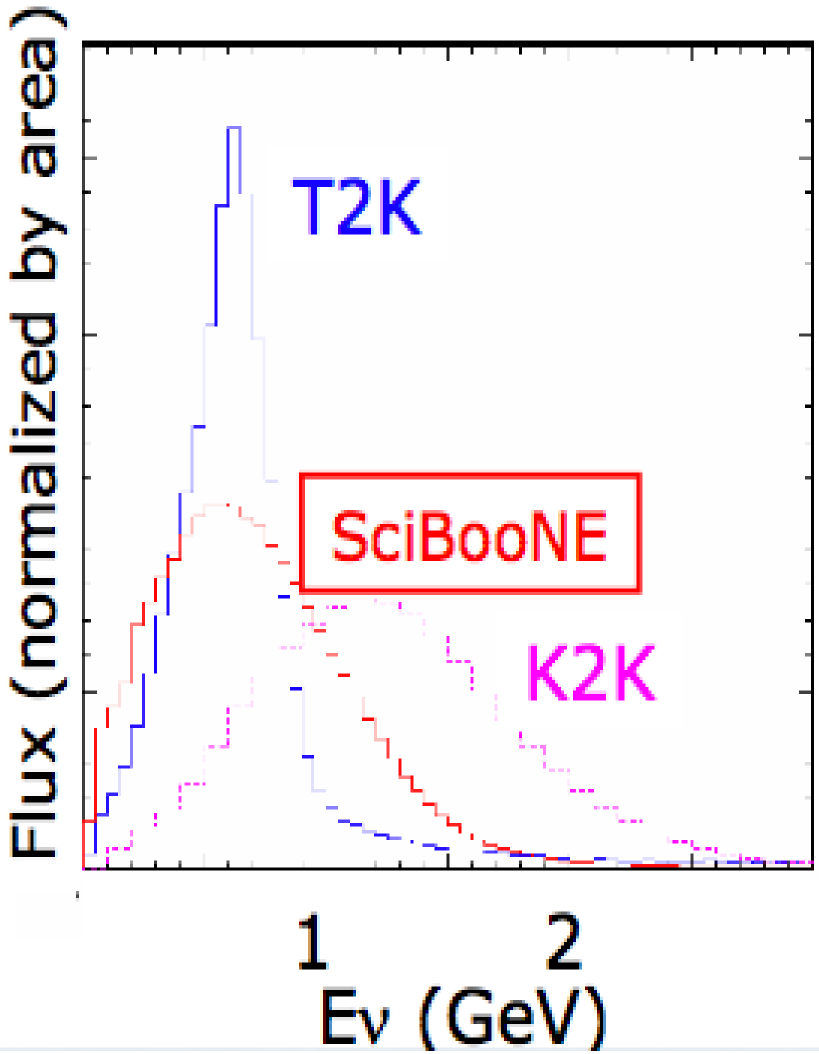
T. Nakaya, Kyoto University

M.O. Wascko, Imperial College

SciBooNE


Booster Neutrino Beam
Decay region
SciBar
MiniBooNE Detector
50 m
100 m
440 m

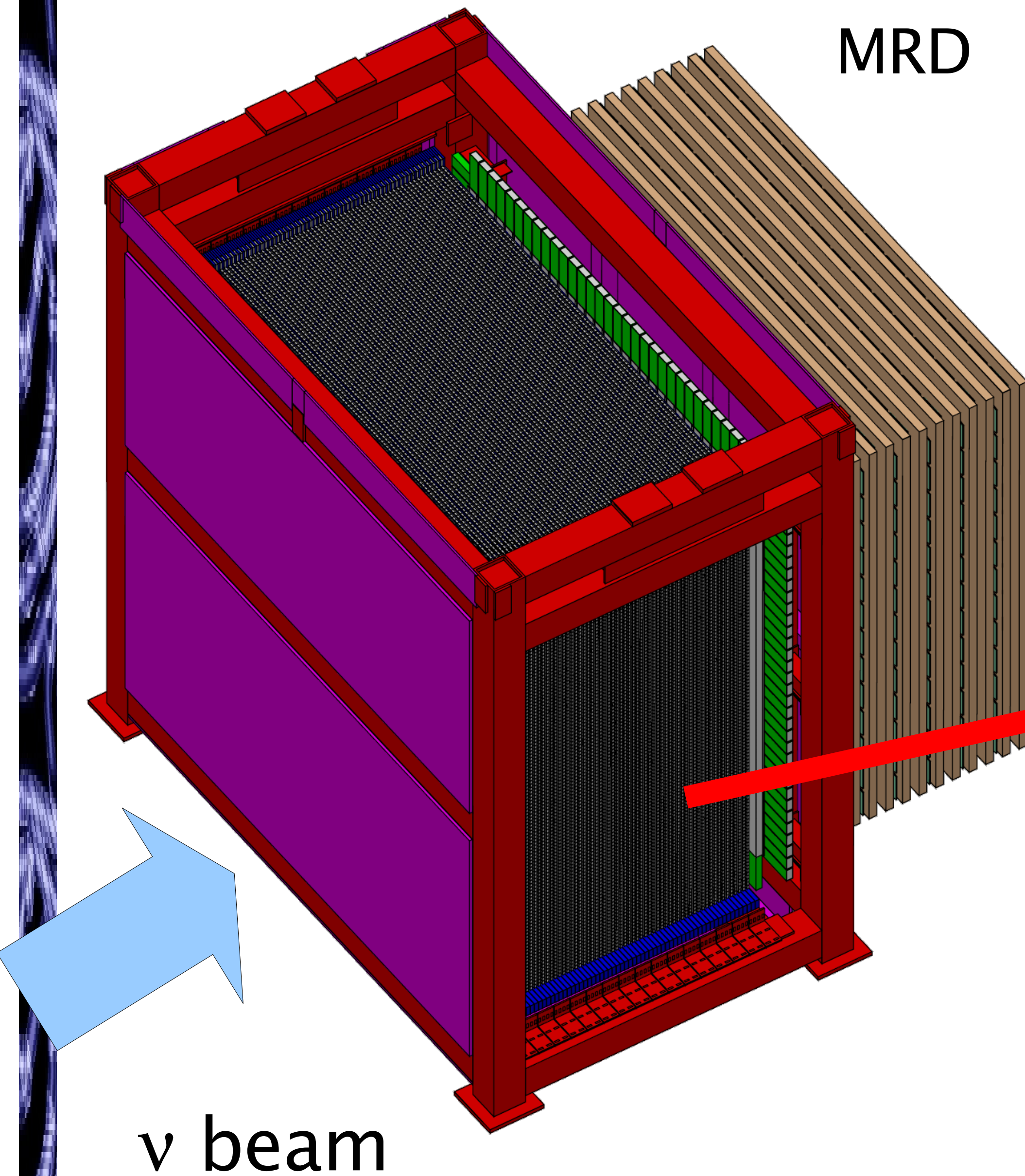
Physics Motivation

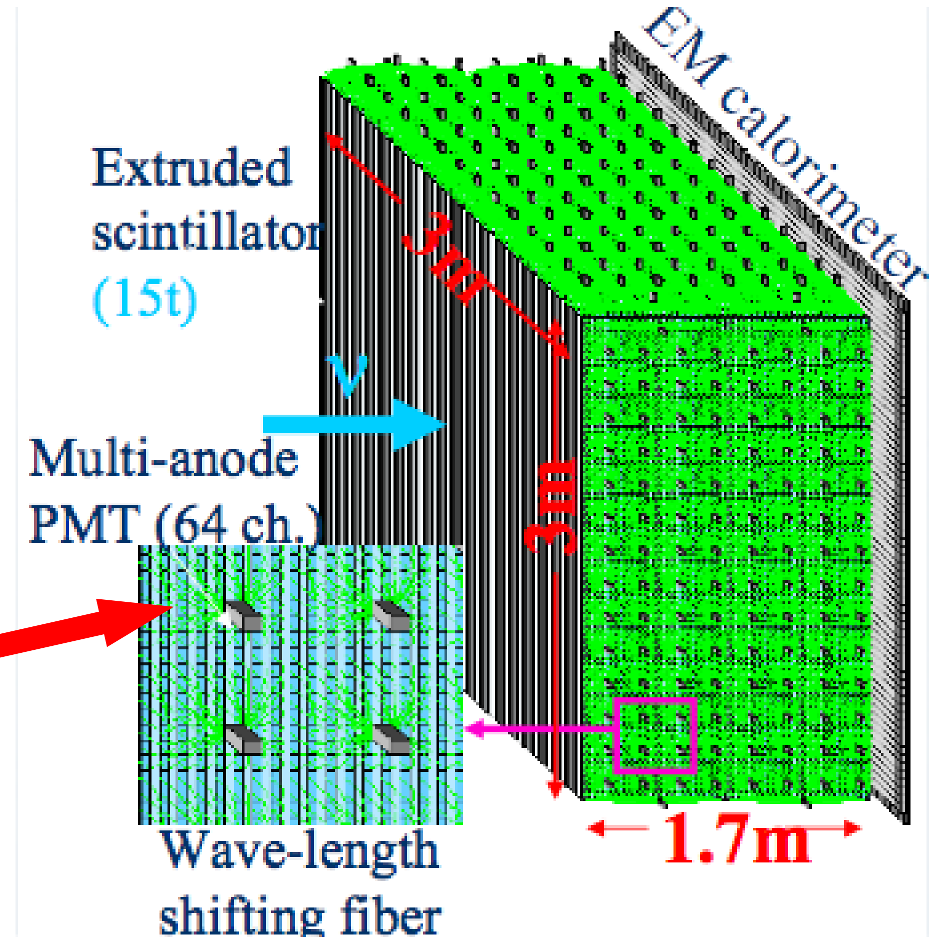


CHANNEL	ν	Anti-ν
CCQE	39k	7.5k
$CC1\pi^+$	24k	2k
$NC1\pi^0$	9k	1.3k
NC Coherent	0.8k	0.3k

More data than the current global dataset on anti-neutrinos

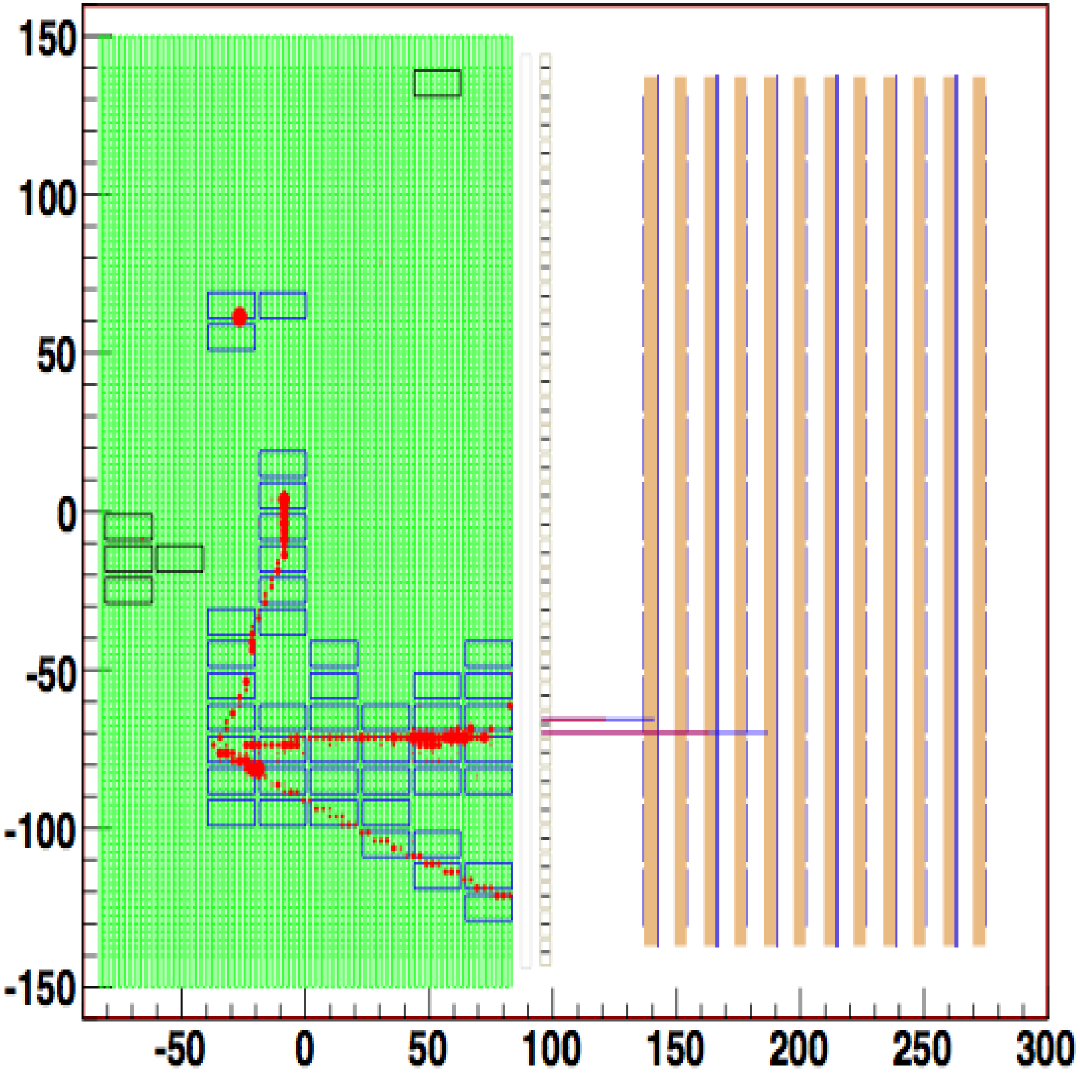
Detector Technology



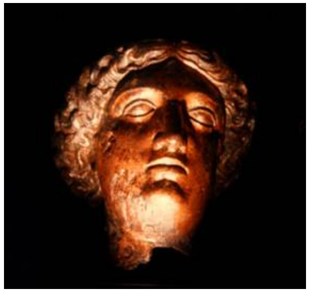


Scintillator–WLS fibre technology

Schedule



- SciBooNE already running!
- 2 years from formation of collaboration to first data!



MINERνA

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James Madison University

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Universidad Nacional de Ingenieria. Lima, Peru

J.K. Nelson#, R.M. Schneider, D.S. Damiani
The College of William and Mary

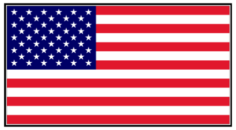
* Co-Spokespersons
\# MINERvA Executive Committee

A collaboration of ~80 Particle, Nuclear, and Theoretical physicists from 23 Institutions



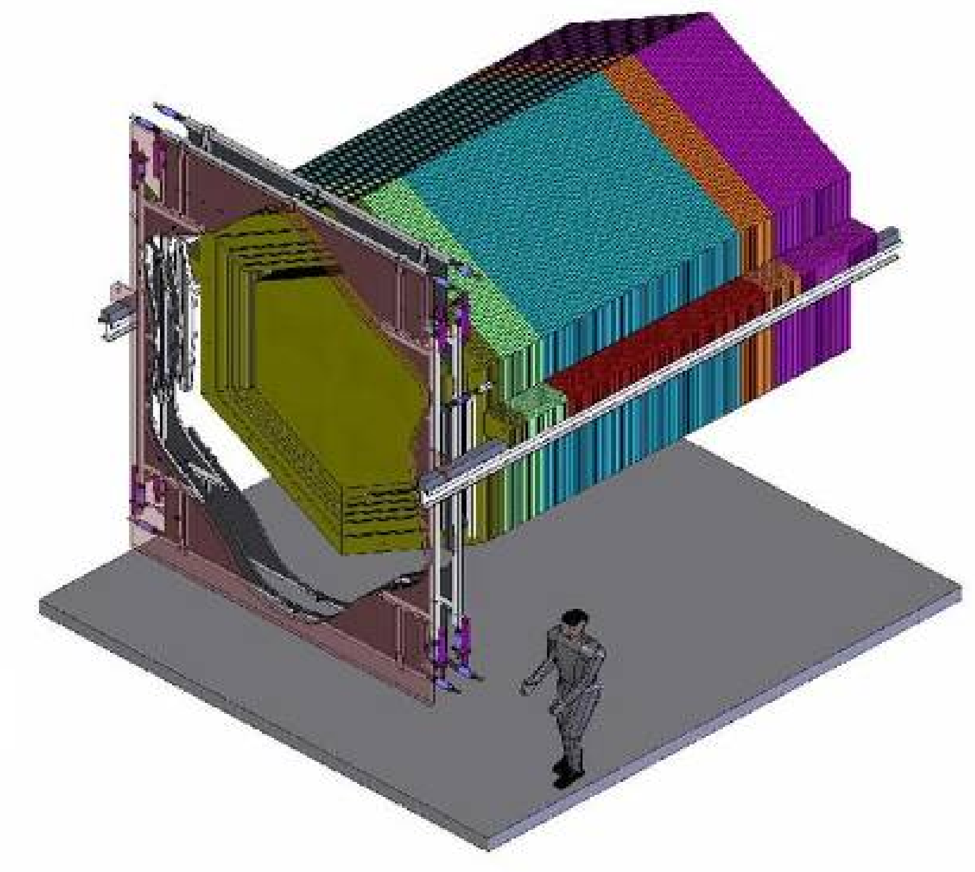






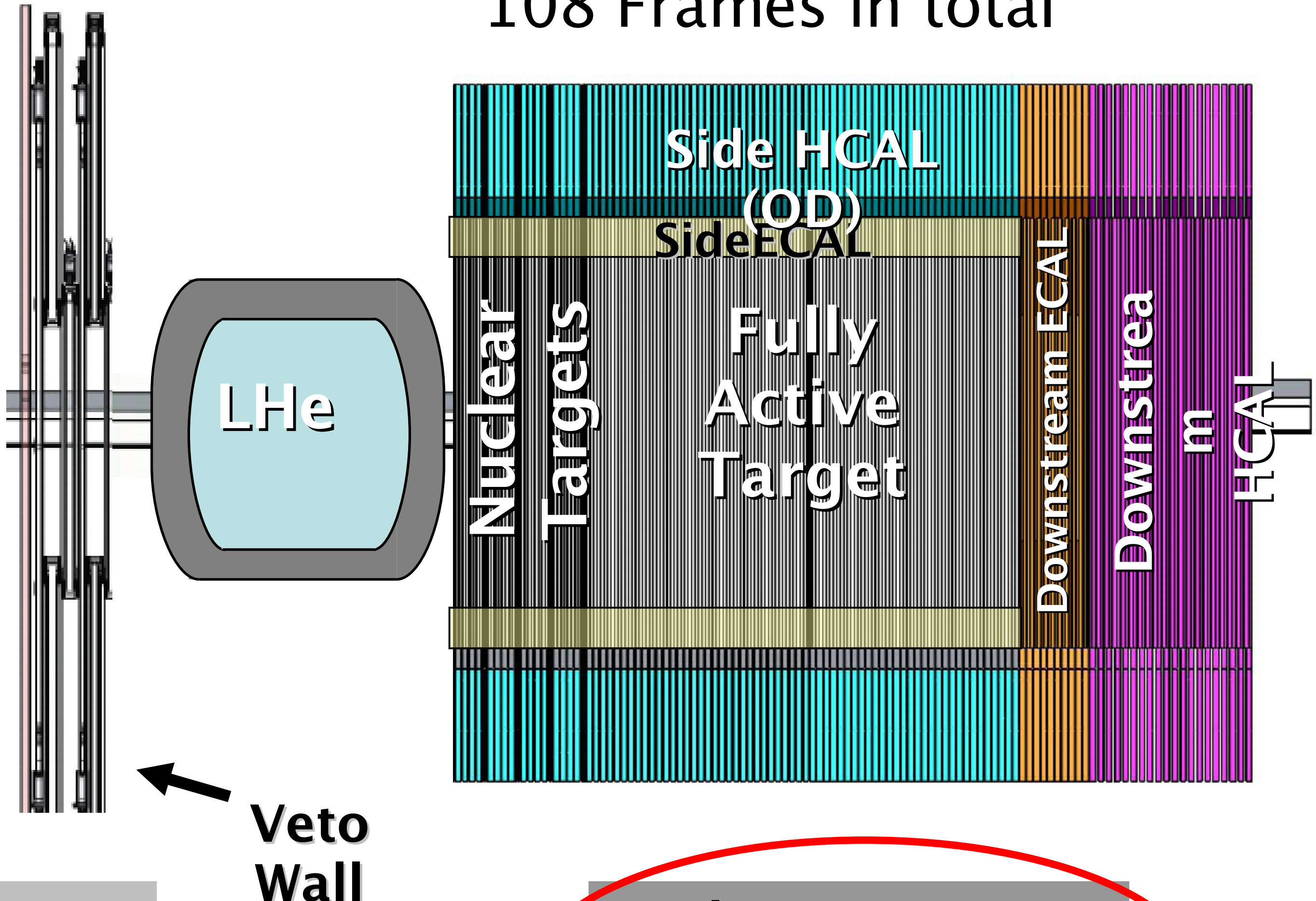
Detector design

- Active core is segmented solid scintillator
  - Tracking (including low momentum recoil protons)
  - Particle identification by energy deposition (dE/dx)
  - 3 ns (RMS) per hit timing (track direction, identify stopped $K^{\pm}$)
- Core surrounded by electromagnetic and hadronic calorimeters
  - Photon (π^0) & hadron energy measurement
- Upstream region has simultaneous C, Fe, Pb, He targets to study nuclear effects
- MINOS Near Detector as muon catcher



Detector Design 2

108 Frames in total



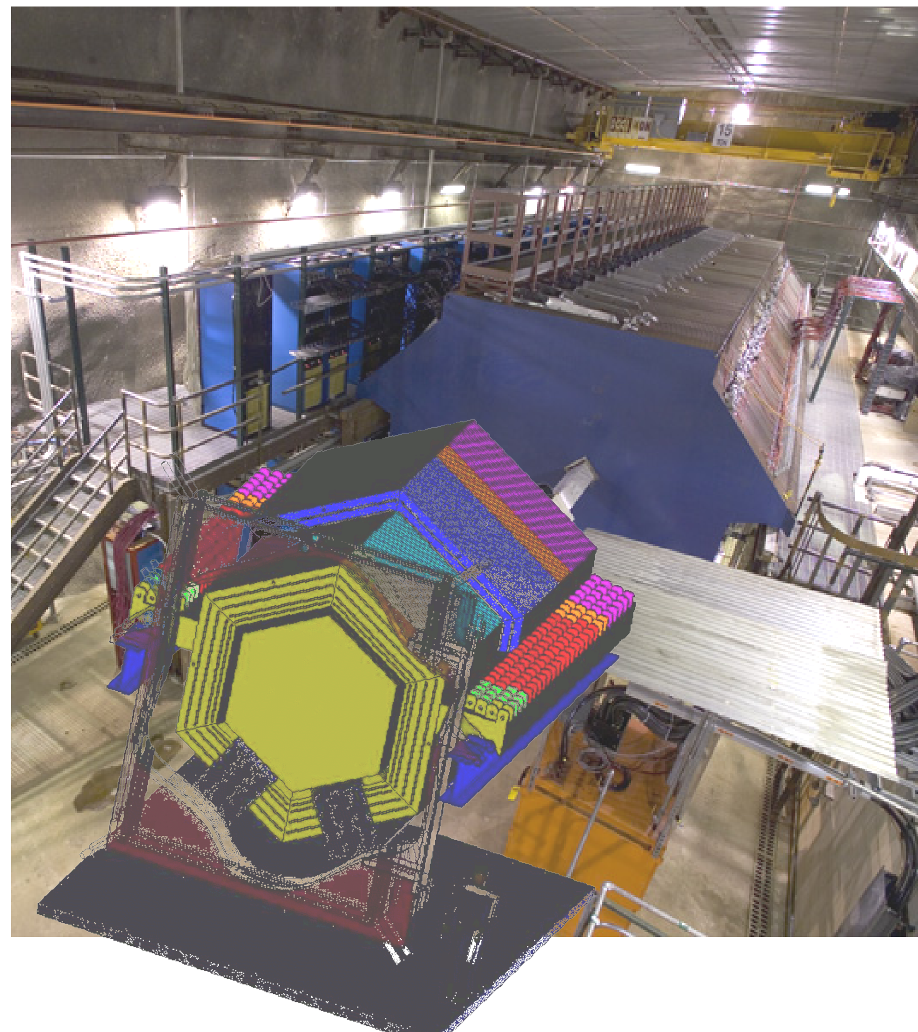
Fully Active Target: 8.3 tons

Nuclear Targets: 6.2 tons (40% scint.)

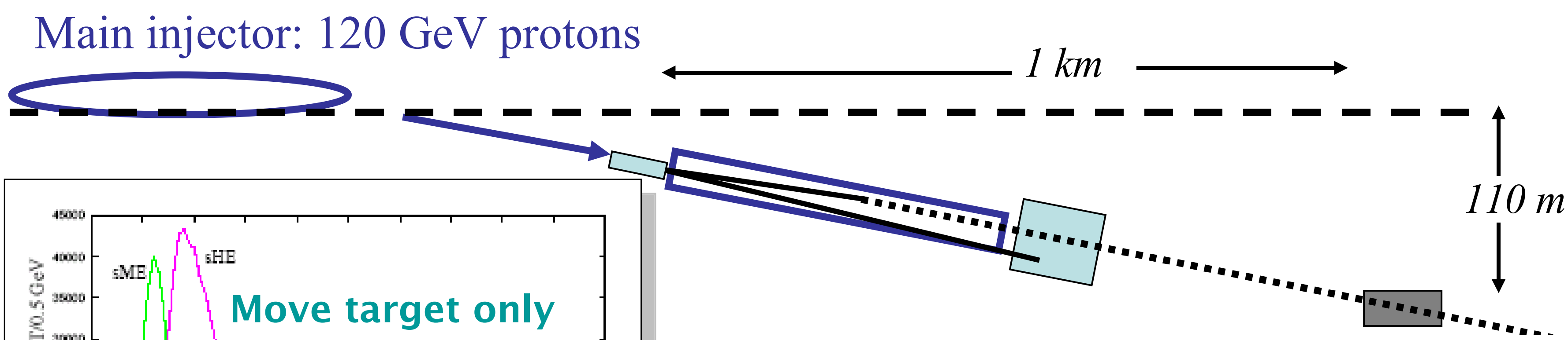
Lead, Steel, Graphite

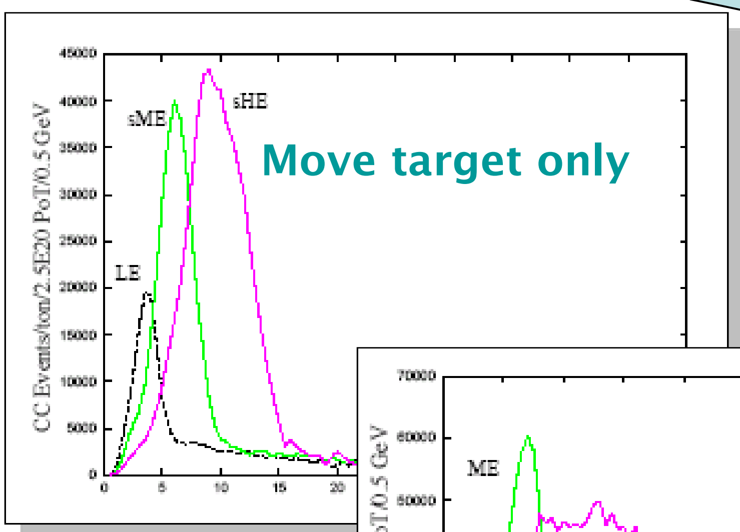
Position

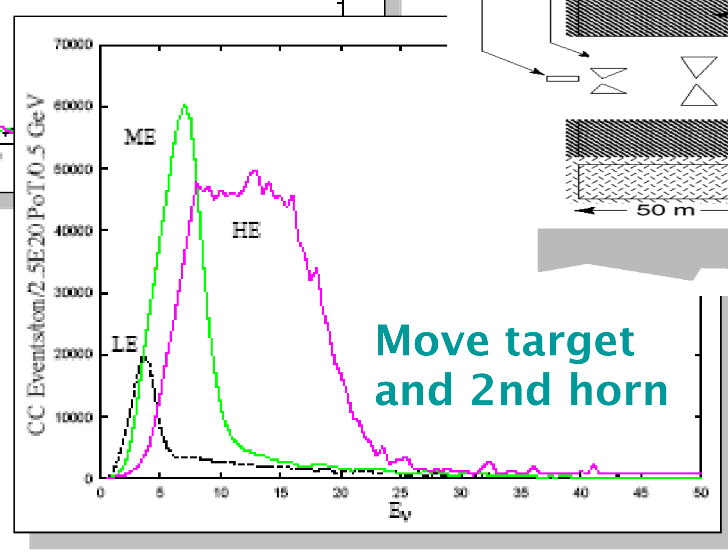
Installed in front of the MINOS Near Detector at FNAL

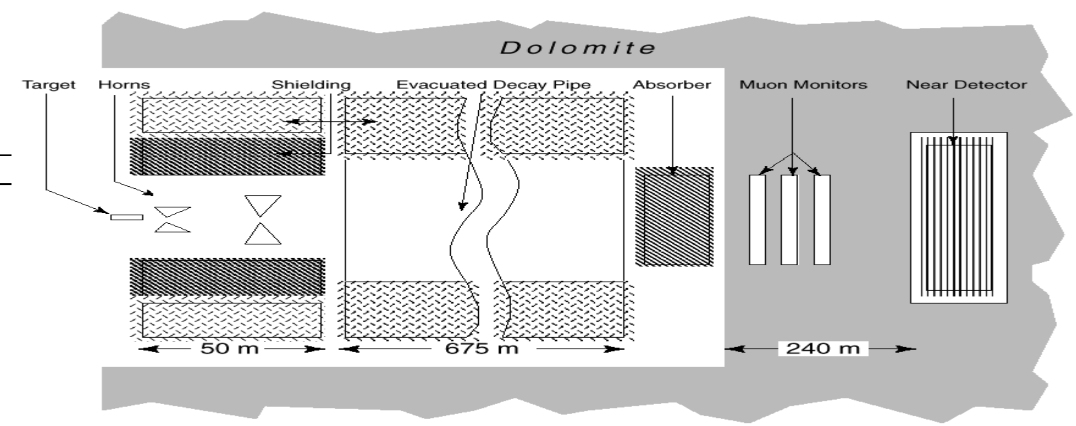


NuMI Neutrino Beam







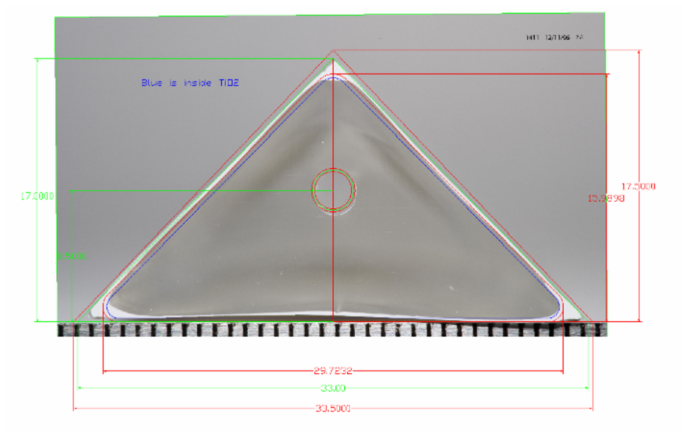


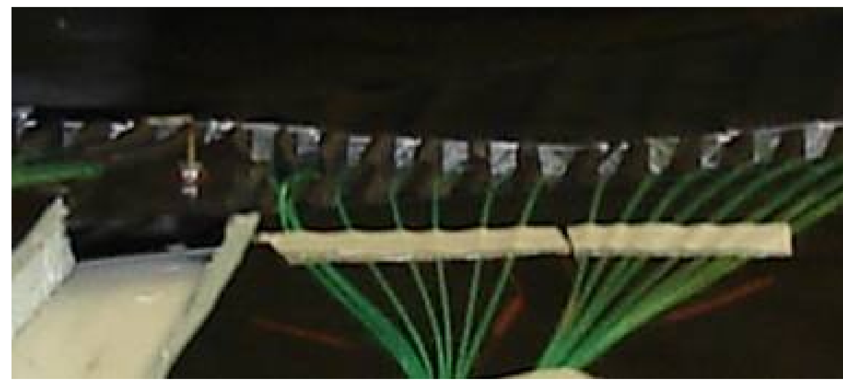
Tunable beam energy

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

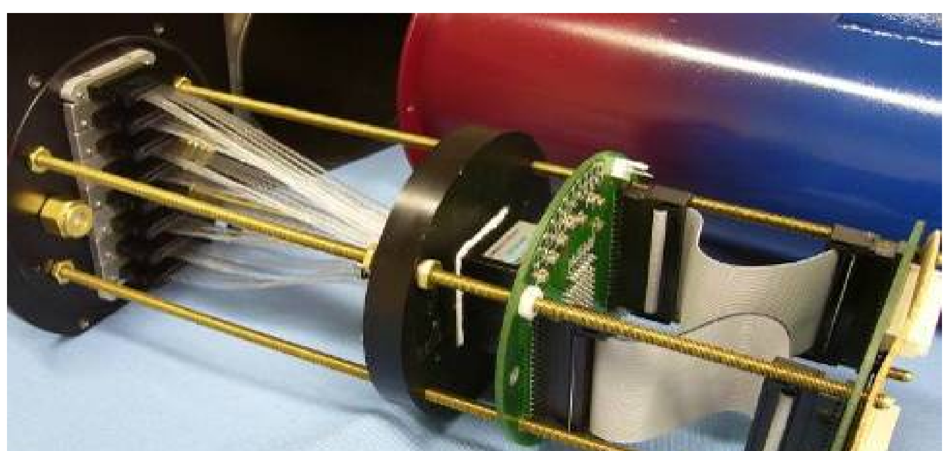
Detection Technology

- Blue emitting extruded triangular scintillator bars
- Wavelength shifting fibre glued into central hole



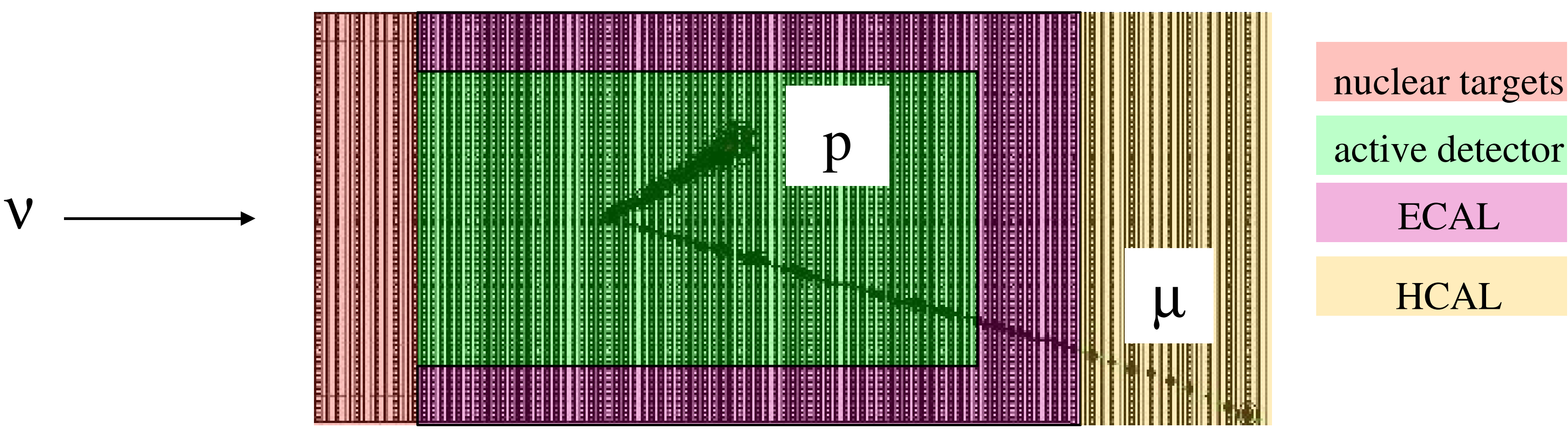


- Clear fiber in light tight cables takes light to PMT



Why this technology?

- Nature of neutrino physics requires massive target
- Need to detect short tracks → active target
- Tried and tested
- dE/dx in scintillator can be used for particle ID
- Reasonable hit resolution (3 mm) using charge weighted position from triangle doublets.



$$\text{CCQE}: \quad \nu_\mu n \rightarrow \mu^- p$$

Event Rates

Fiducial Mass : 3 ton CH, 0.6 ton C, 1 ton Fe, 1 ton Pb

Total Event rate

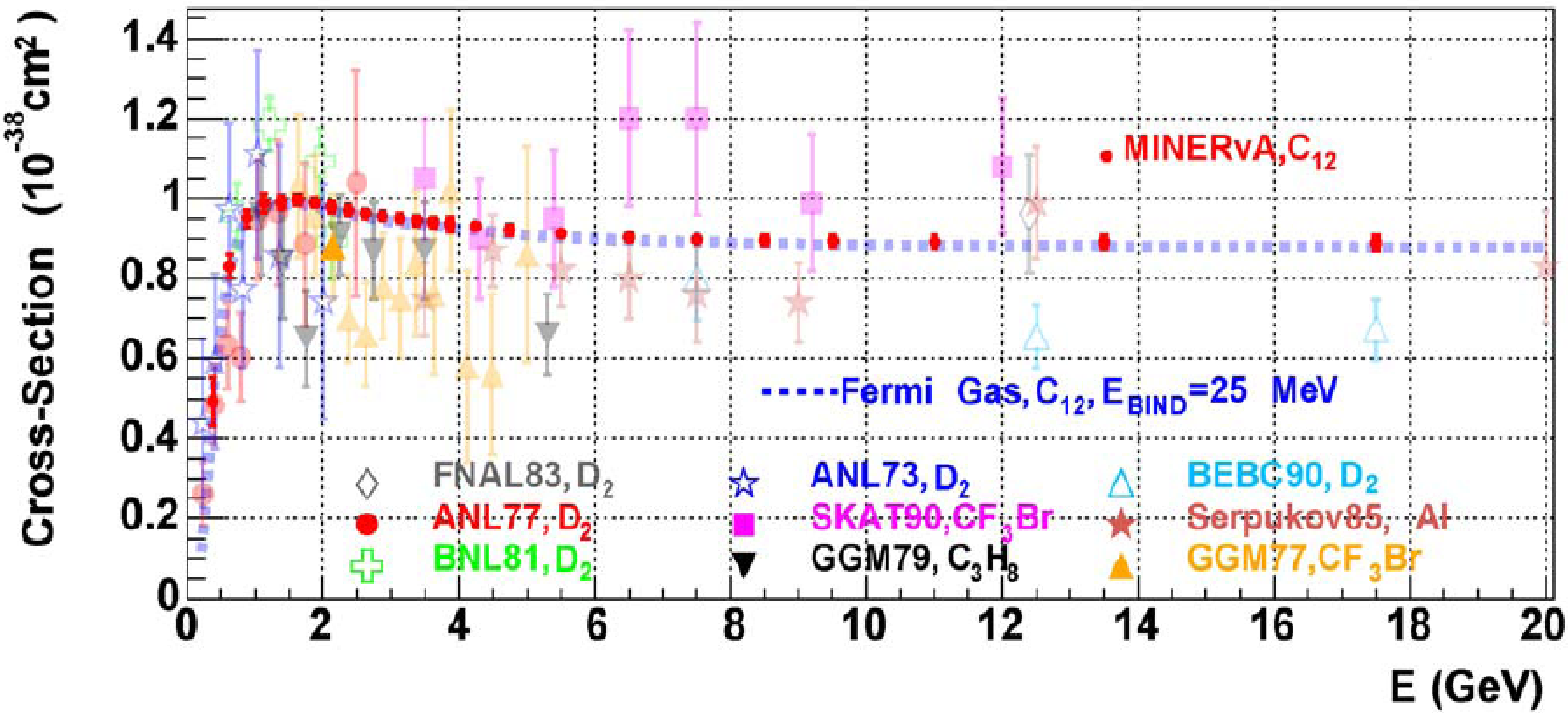
Target	CC ν Rate
CH	8.6 M
C	1.4 M
Fe	2.9 M
Ph	2.9 M

Physics Event rate in CH

Process	Rate
QE	0.8 M
1 pion	1.6 M
Transition	2.0 M
DIS	4 M

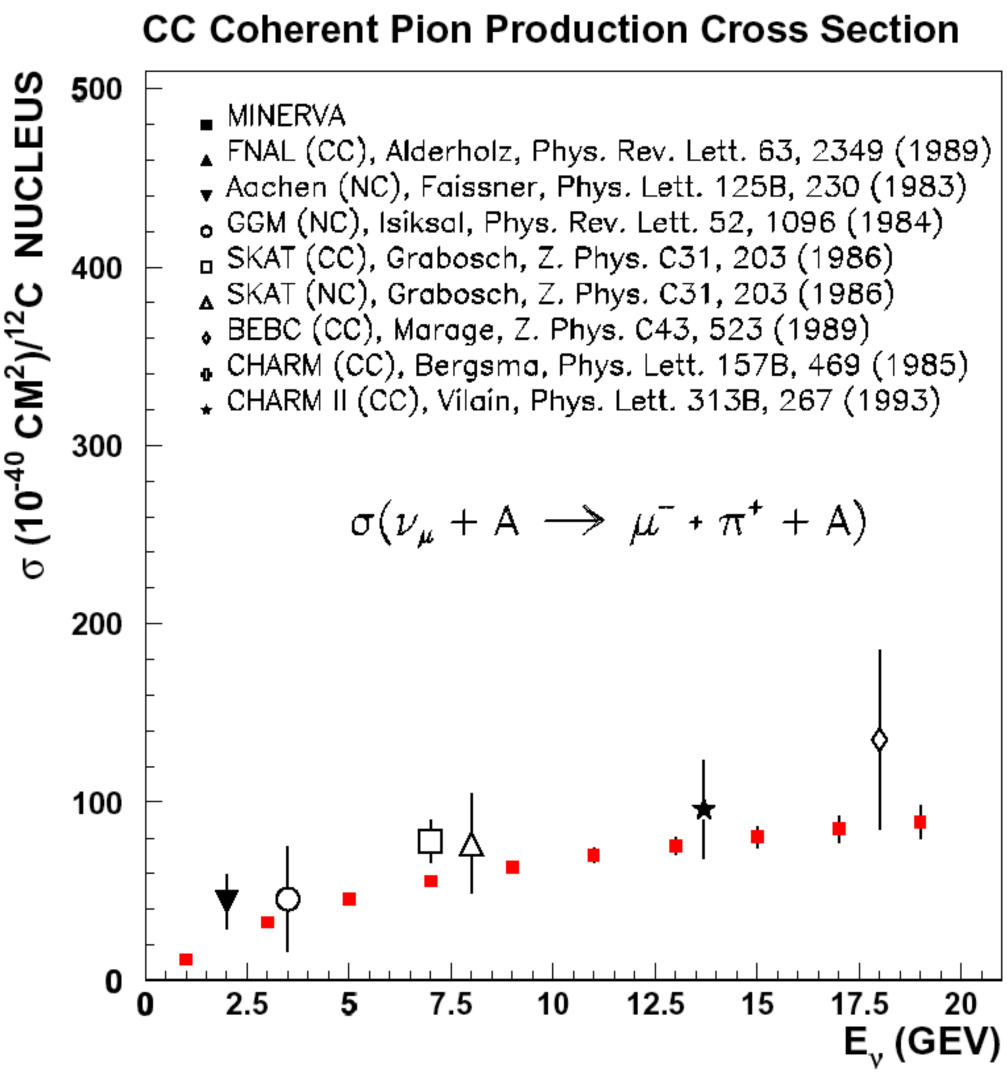
* For one beam scenario

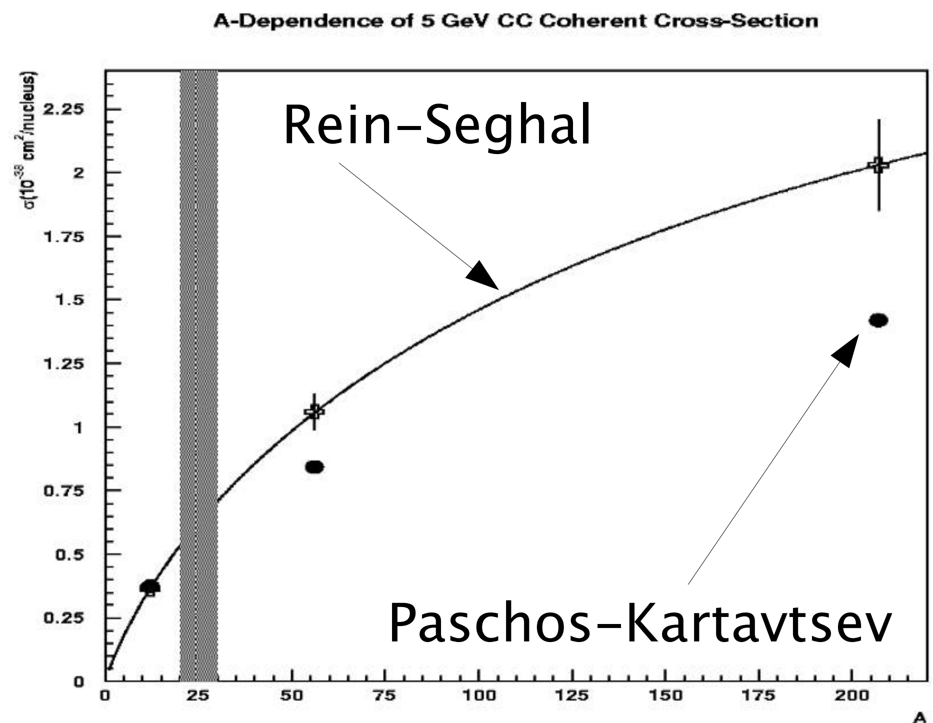
CCQE Cross section



High efficiency and purity (~ 77% and ~ 74% resp.)
Nuclear Effects can be studied in nuclear targets
Deviation from dipole form factors can be studied

Coherent pion cross section



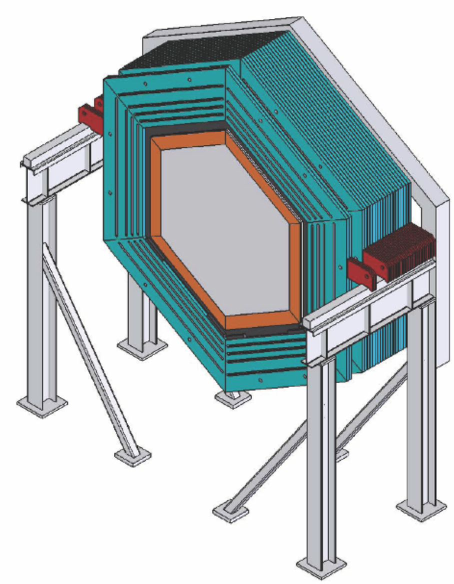


First measurement of σ_{coh} over a wide range of A

Statistical errors only

MINERνA Schedule

- 2008:
  - Build and test 20-frame prototype above ground
  - Start building full detector (108 frames)
  - Build Test beam detector, run in the fall
- 2009:
  - Finish building full detector
  - Install as early as possible
  - End of 2009: take data with MINOS
- 2010:
  - Low Energy Neutrino Data taking
- 2011 and beyond:
  - Medium Energy Neutrino data with NOvA(????)



Theoretical work

QE

- J.A. Caballero *et al.*, nucl-th/0705.1429 (2007)
- K.S. Kim, L.E. Wright, nucl-th/0705.0049 (2007)
- E. Hernandez *et al.*, PL **B647**, 452 (2007)
- C. Giusti *et al.*, nucl-th/0607037 (2006)
- P. Lava *et al.*, PRC 73, 064605 (2006)
- K.S. Kuzmin *et al.*, Acta Phys. Polon. B37, 2337 (2006)
- M.C. Martinez *et al.*, PRC 73, 024607 (2006)
- N. Jachowicz *et al.*, NP. Proc. Suppl. **155**, 260 (2006)
- M. Valverde *et al.*, PL **B642**, 218 (2006), PL **B638**, 325 (2006)
- A. Butkevich, S. Kulagin, nucl-th/0705.1051 (2007)
- M. Martini *et al.*, Phys. Rev. C75, 034604 (2007)
- J.E. Amaro *et al.*, PRC 75, 034613 (2007)
- O. Benhar *et al.*, nucl-ex/0603029 (2006)
- R. Bradford *et al.*, hep-ex/0602017 (2006)
- J. Nieves *et al.*, Phys. Rev. C73, 025504 (2006)
- A. Meucci *et al.*, Acta Phys. Polon, **B27**, 2279 (2006)
- G. Co, ActaPhys.Polon.B37, 2235 (2006)

single π production

- H. Nakamura *et al.*, hep-ph/0705.3884 (2007)
- E.A. Paschos *et al.*, hep-ph/0704.1991 (2007)
- M. Sajjad *et al.*, NP **A782**, 179 (2007), PRD 75, 093003 (2007)
- O. Lalakulich, E.A. Paschos *et al.*, Nucl. Proc. Suppl. 159, 133 (2006), PRD 74,014009 (2006)
- S. Ahmad *et al.*, PRD **74**, 073008 (2006)
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- O. Buss *et al.*, PRC **74**, 044610 (2006), Eur. Phys. J. **A29**, 189 (2006)
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- E.A. Paschos, A. Kartavtsev, Nucl. Proc. Suppl. **159**, 203 (2006), PRD **74**, 054007 (2006)
- S.K. Singh *et al.*, PRL **96**, 241802 (2006)
- D. Rein, L.M. Sehgal, hep-ph/0606185 (2006)
- B.Z. Kopeliovich, Nucl. Phys. Proc. Suppl. **139**, 219 (2006)

DIS

- S. Kulagin, R. Petti, hep-ph/0703033 (2007)
- O. Lalakulich *et al.*, PRC **75**, 015202 (2007)
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- K.S. Kuzmin *et al.*, Phys. Atom. Nucl. **69**, 1857 (2006)
- L. Leitner *et al.*, PRC 73, 065502 (2006), PRC **74**, 065502 (2006), Int.J.Mod.Phys. **A22**, 416 (2007)

a lot of theoretical activity!

G. Zeller

Conclusion

	NOW	FUTURE
CCQE	15-20%	5%
NC π0	25-40%	<10%
CC π+	25-40%	5%
CC π0	25-40%	5%
Coherent π	100%	5-10%
Inclusive	>10%	5-10%

Conclusion

	NOW	FUTURE
CCQE	15-20%	5%
NC π0	25-40%	<10%
CC π+	25-40%	5%
CC π0	25-40%	
Coherent π	100%	
Inclusive	>10%	

Now with added nuclear effects!

There are known knowns.

There are things we know we know.

We also know there are known unknowns.

That is to say,

We know there are some things we do not know.

But there are also unknown unknowns.

The ones we don't know we don't know.

D. Rumsfeld, American Poet

QE Cross section

QE cross section can be written in terms of nucleon FF

$$<N'|J_\mu|N> = \bar{u}(N')\ [\gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5 \gamma_\mu F_A(q^2)]\ u(N)$$

Form factors describe the nuclear structure.

$F_V(q^2)$ is the vector form factor. It's related to the electric charge distribution of the nucleon and is measured well in electron scattering.

$$F_V(q^2) \sim \frac{1}{1 + \frac{Q^2}{M_V^2}}$$

Historically represented by the dipole form

But known not to be

QE Cross section

QE cross section can be written in terms of nucleon FF

$$<N'|J_\mu|N> = \bar{u}(N')\ [\gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5 \gamma_\mu F_A(q^2)]\ u(N)$$

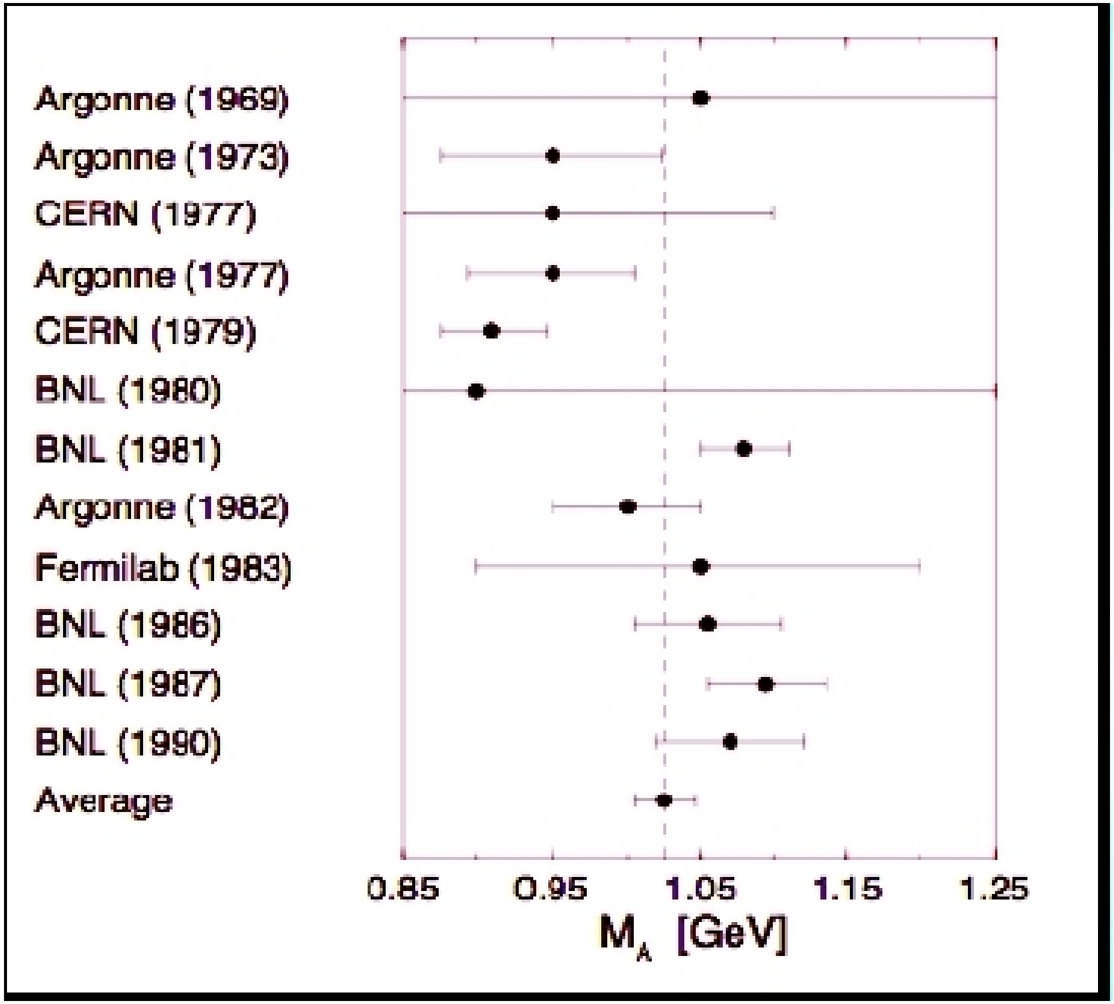
Form factors describe the nuclear structure.

$F_A(q^2)$ is the axial-vector form factor. It's related to the helicity structure of the nucleon and not known well at all. It can only be measured in neutrino interactions.

$$F_A(q^2) \sim \frac{g_A}{1 + \frac{Q^2}{M_A^2}}$$

Function of a single parameter called the "axial mass" (M_A)

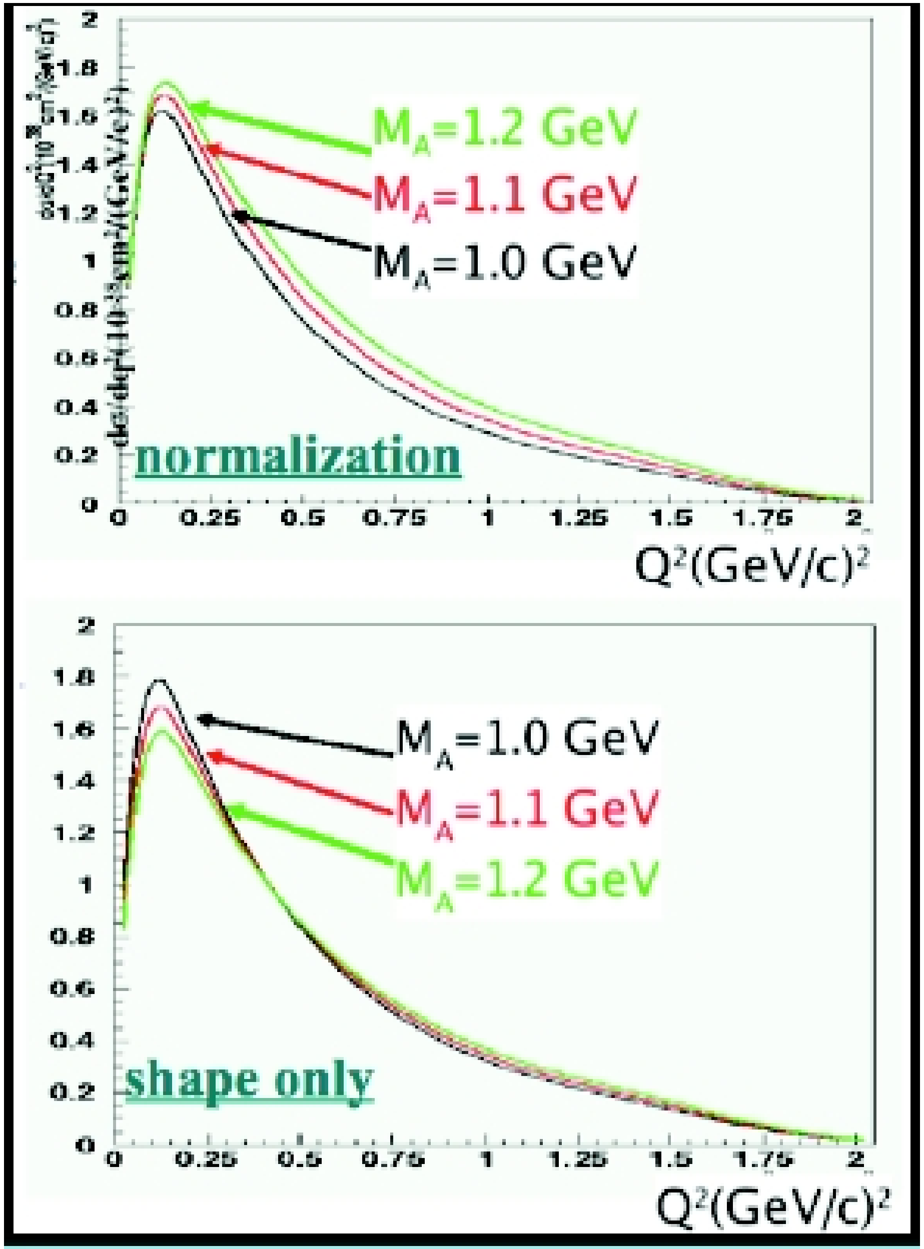
Measurement of M_A



- Parameter must be measured
- Simulation use average derived using a deuterium target
- Is this right when using an iron target?

World Average : $M_A = 1.03 \pm 0.02$

Measurement of M_A



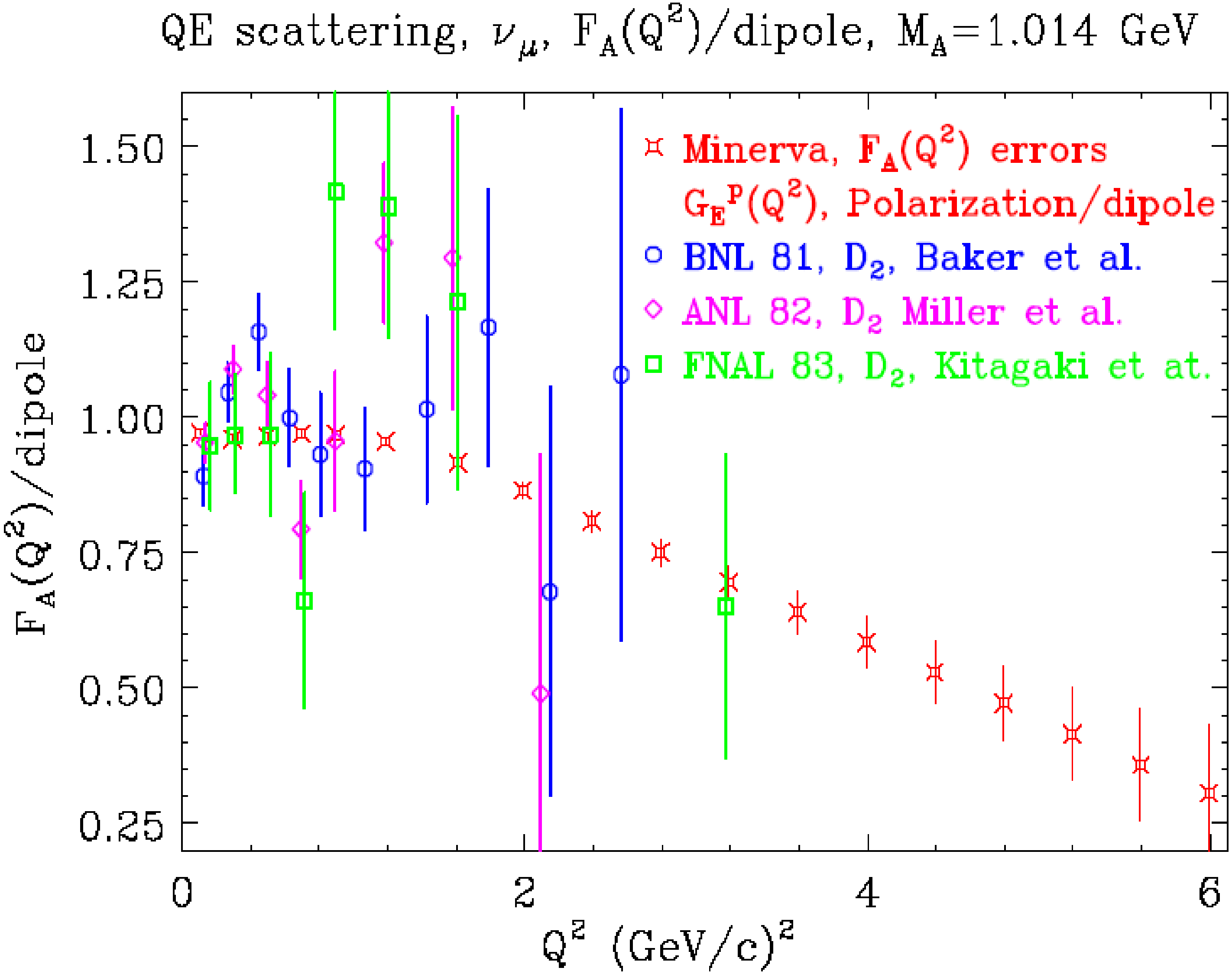
M_A changes total cross section

($M_A \uparrow \sigma \uparrow$)

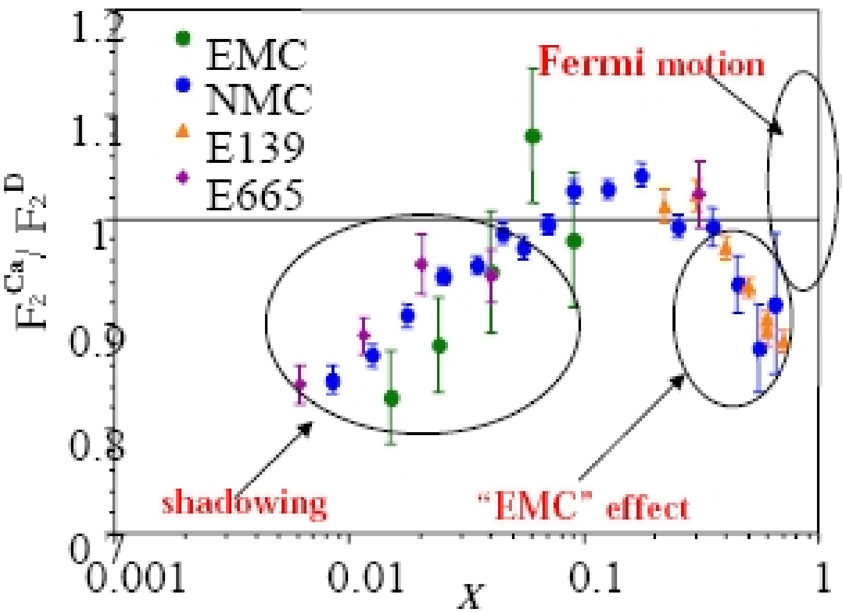
M_A changes Q^2 dependence

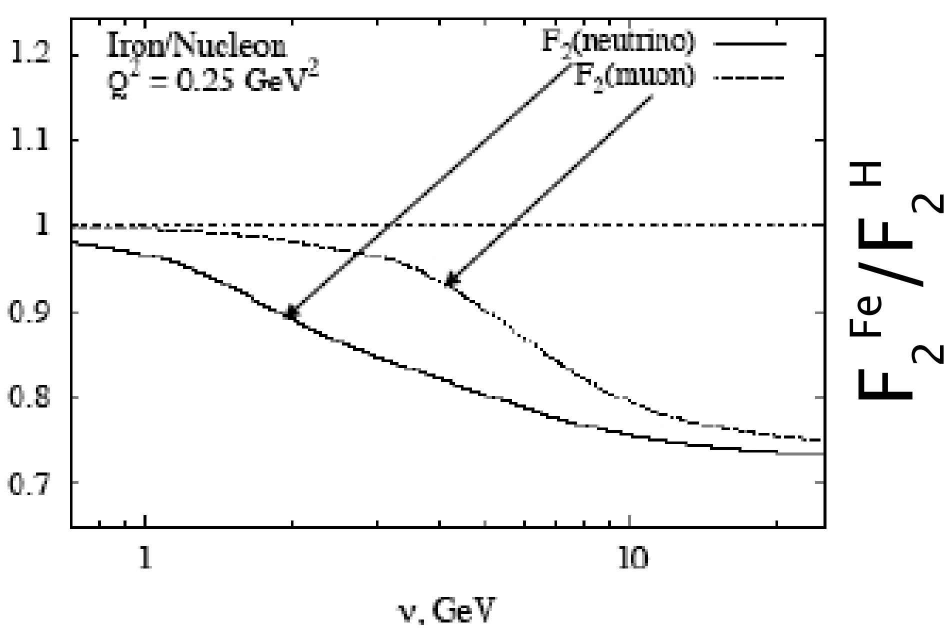
($M_A \uparrow$ harder Q^2)

Form factor shape (MINERνA)



Nuclear Effects

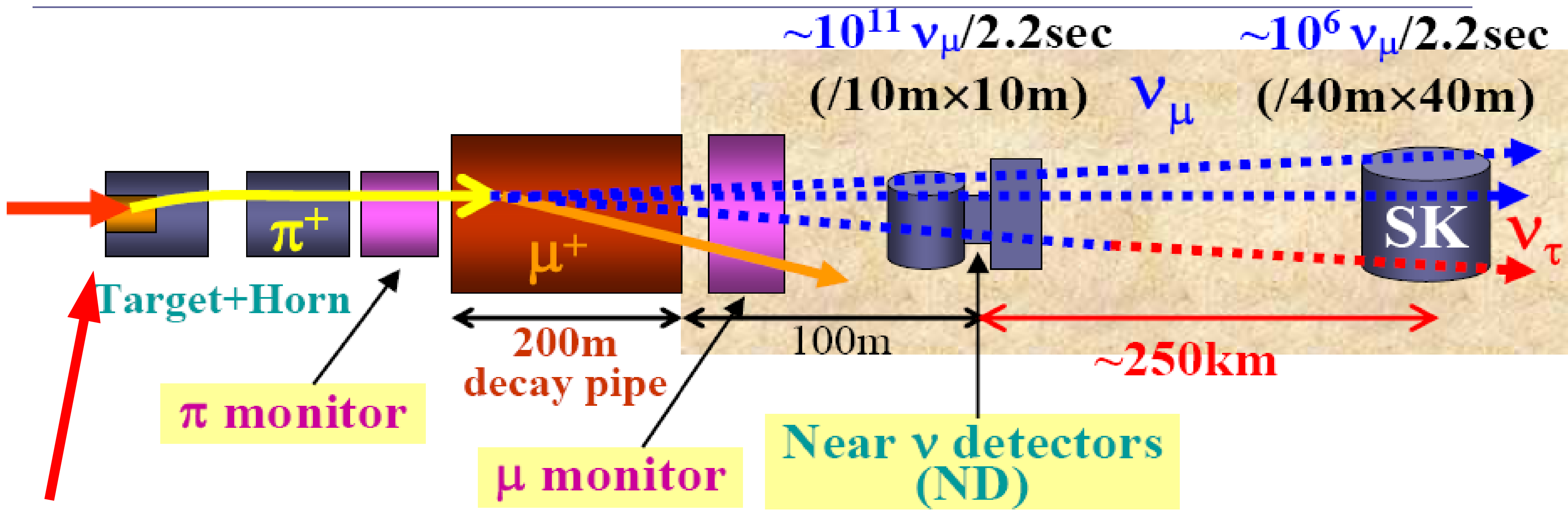


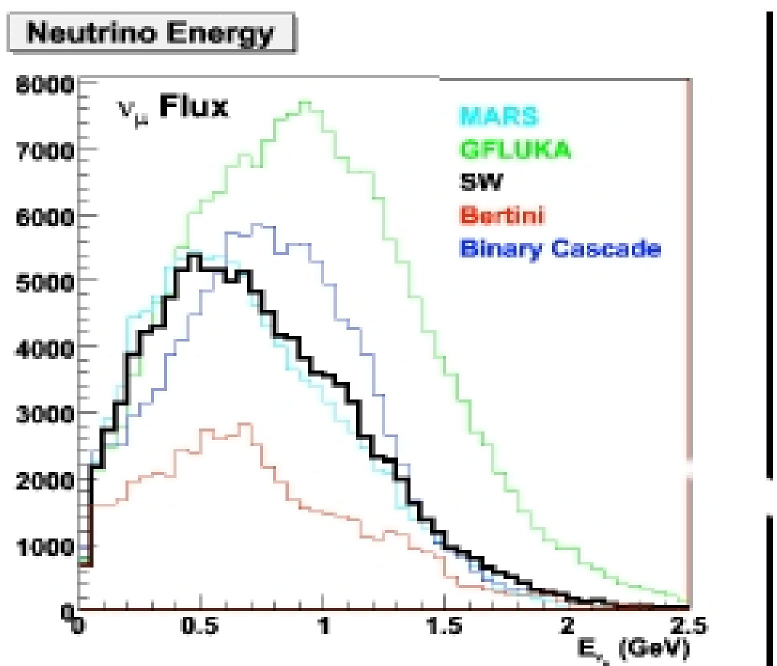


Nuclear effects change as a function of A

- Presence of axial current affects shadowing
- NUTeV sees smaller nuclear effects at high-x than charged lepton scattering
- Different nuclear effects for valence and sea (F_2, xF_3)

An appearance experiment



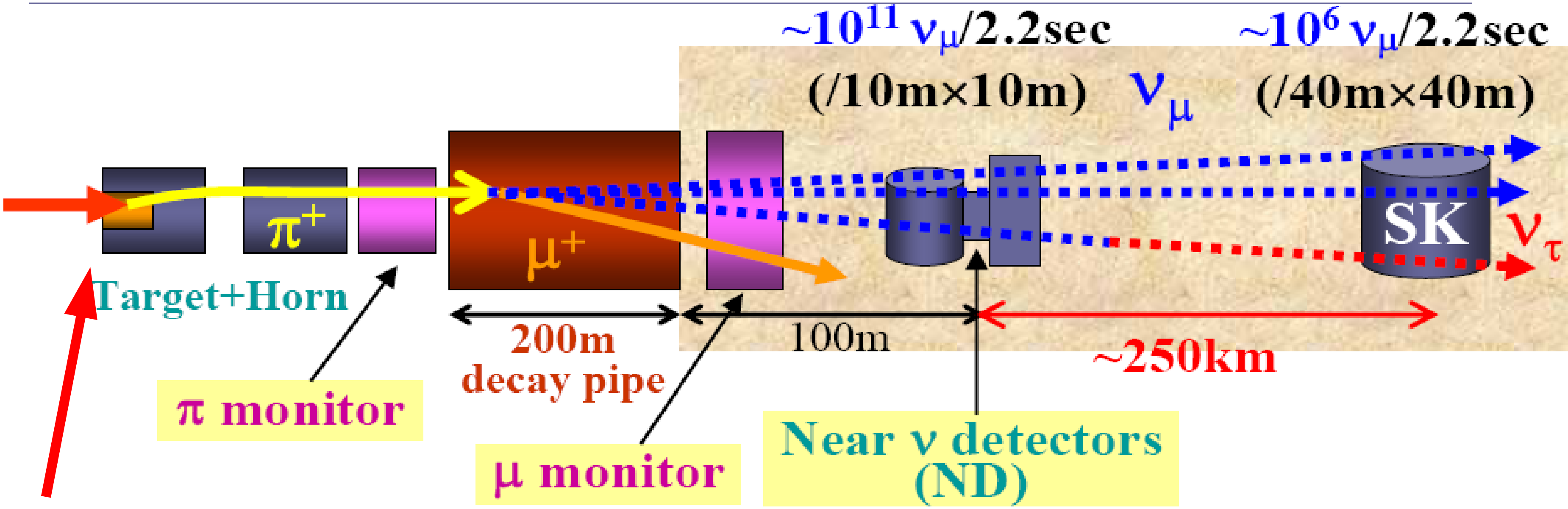


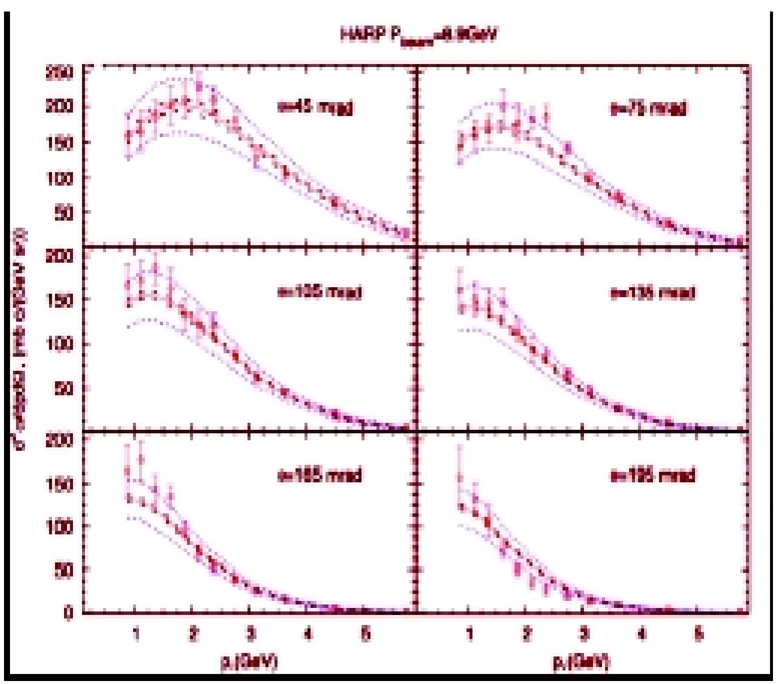
How well we know σ depends on how well we know the neutrino flux

$$N_\nu \propto \sigma_\nu \epsilon_\nu \Phi_\nu$$

Prediction of 8 GeV p off Be

An appearance experiment





HARP, MIPP, NA49, E910, SPY now providing data on meson production from p on heavy targets

☞Absolute flux error of 5%

Ambiguities

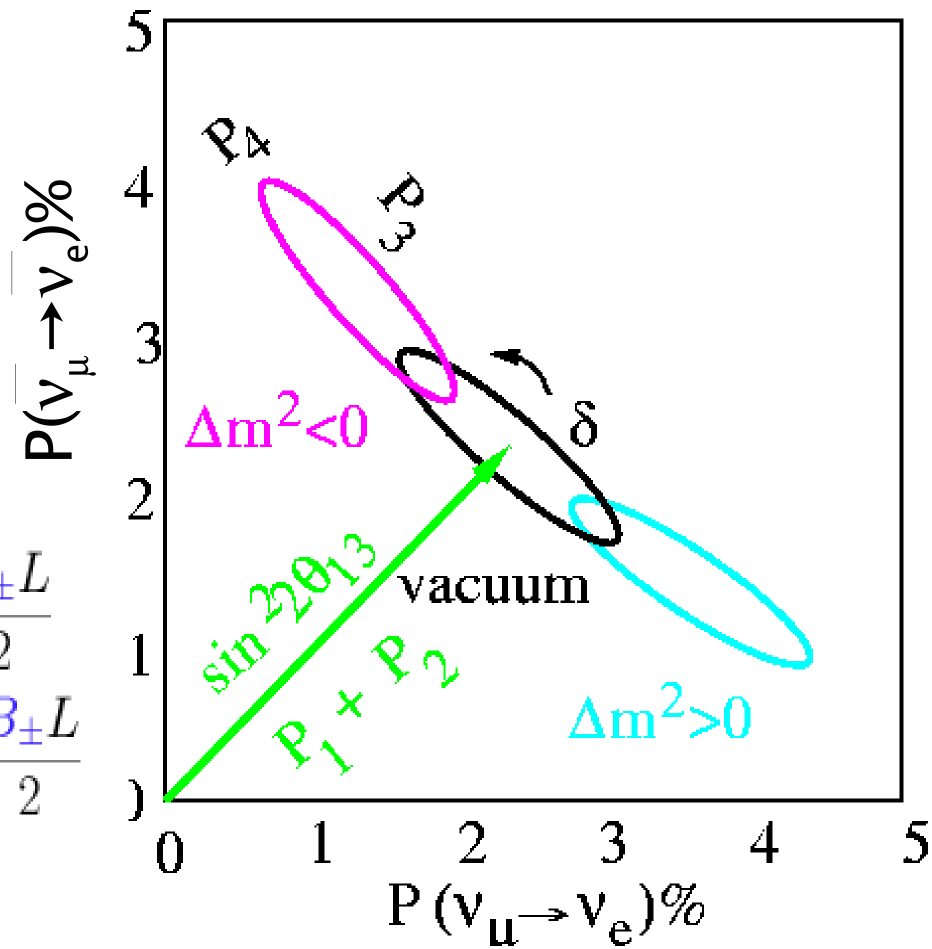
$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

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

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

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

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



- For any one energy and baseline, you don't get the whole story…
- Need two energies, or two baselines, and at least one baseline needs to be long enough to see matter effects
- Need high precision measurements of *EVERYTHING*

Ambiguities

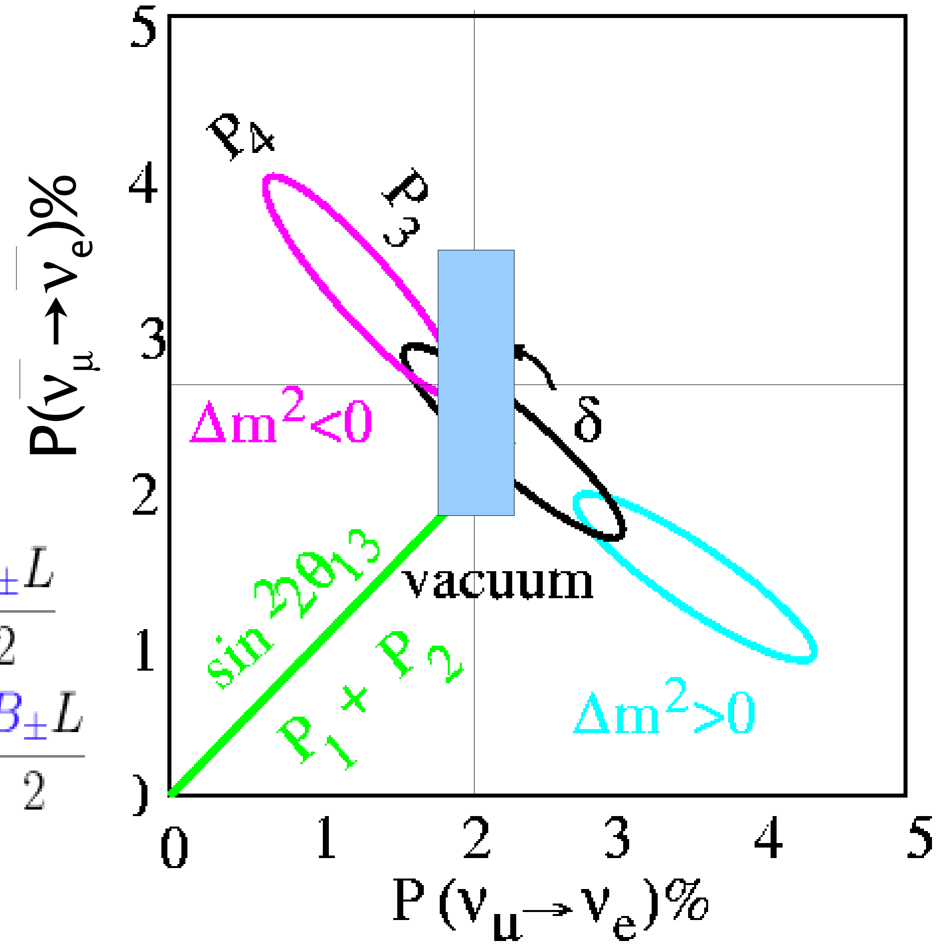
$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

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

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

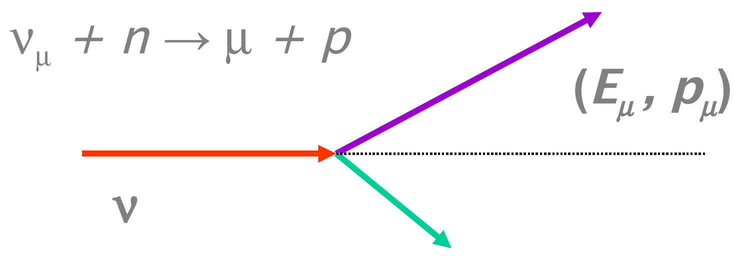
$$P_3 = J \cos\delta \left(\frac{\Delta_{12}}{A}\right) \left(\frac{\Delta_{13}}{B_\pm}\right) \cos\frac{\Delta_{13} L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

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

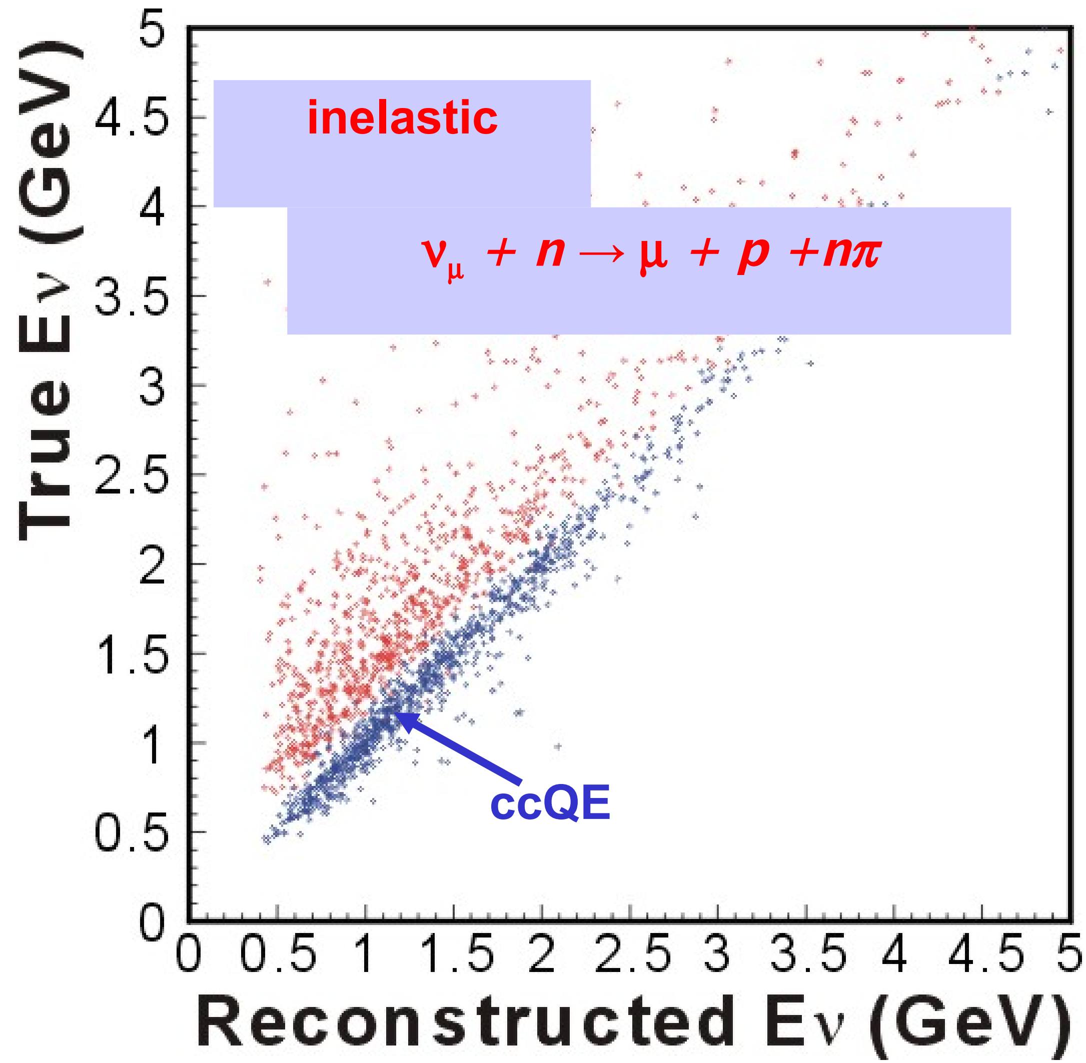


- For any one energy and baseline, you don't get the whole story…
- Need two energies, or two baselines, and at least one baseline needs to be long enough to see matter effects
- Need high precision measurements of *EVERYTHING*

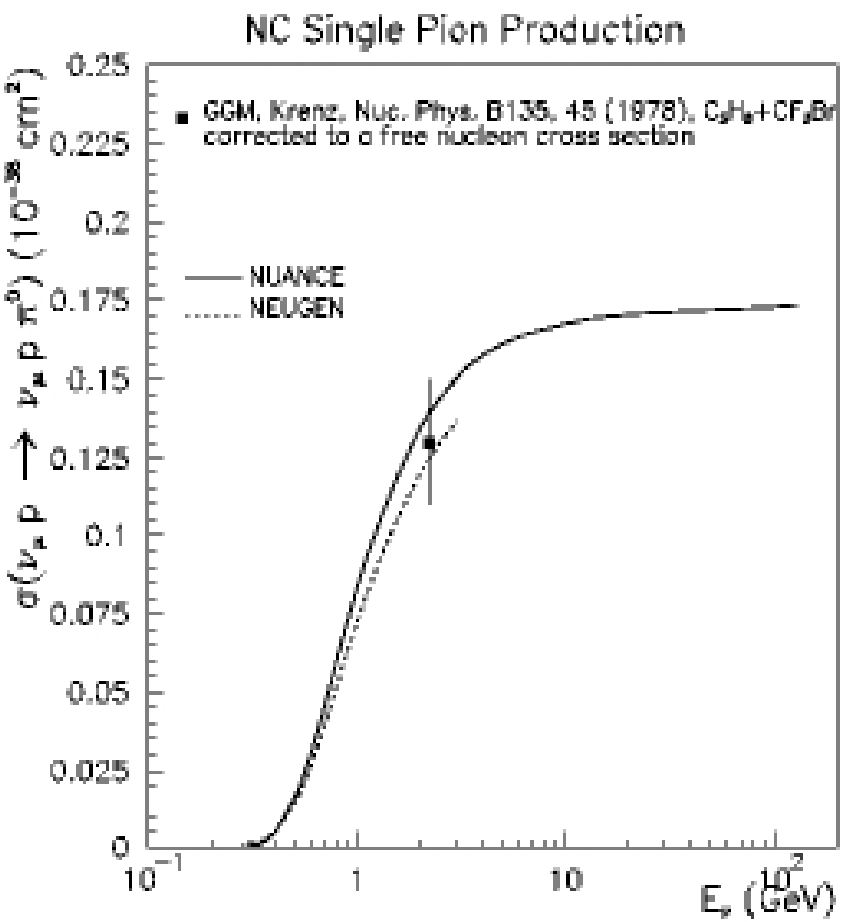
CC QE



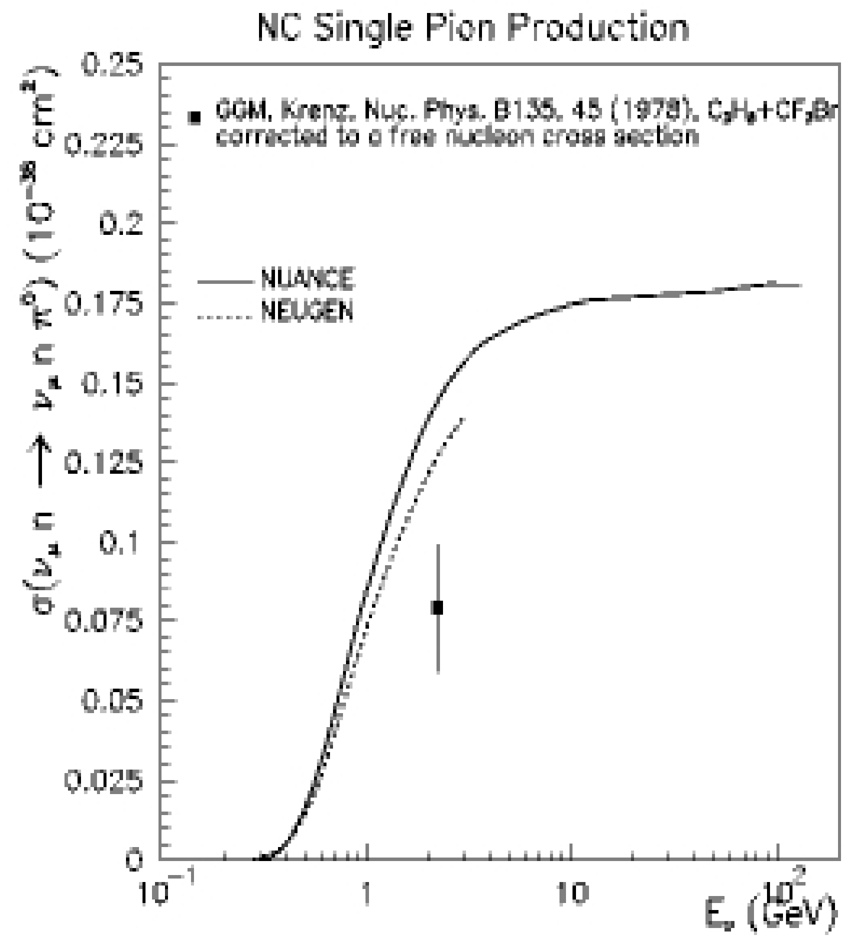
$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta}$$



Yes. Yes, it can.



$$\nu_\mu p \to \nu_\mu p \pi^0$$



$$\nu_\mu n \to \nu_\mu n \pi^0$$