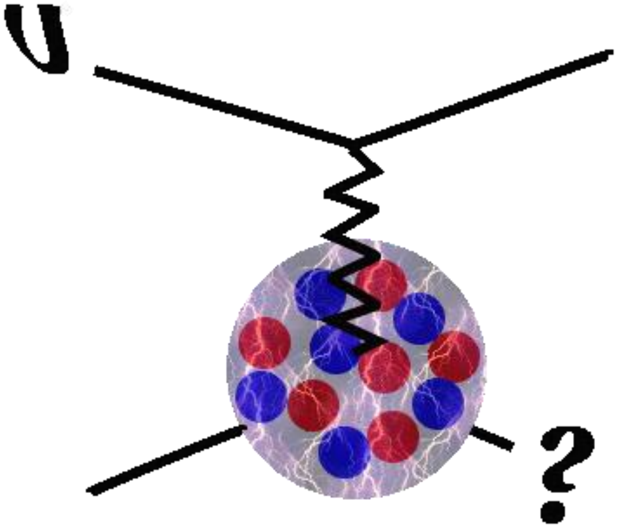
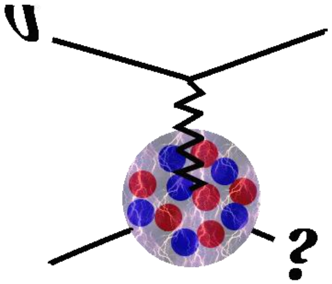
Neutrino Interactions: The Experimental Landscape



Kevin McFarland
University of Rochester

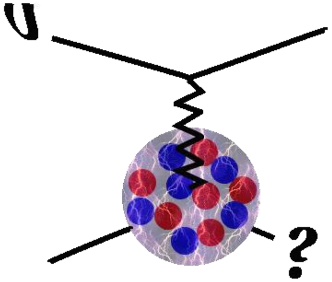
Neutrino Factories 2010, TIFR
21 October 2010

Outline



- Some (Historical?) Perspective
- Goals of Neutrino Interaction Experiments
  - Support oscillation measurements
  - Fundamental weak and strong force physics
- Highlights and Puzzles from Current Results
- New Experiments
- Outlook

Neutrinos and Weak Interactions

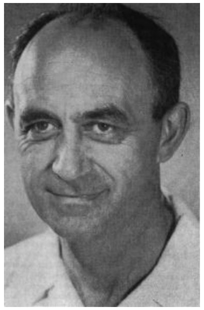


- Pauli's proposal of the Neutrino as a signature of the weak force… "Dear Radioactive Ladies and Gentlemen"
- Realized in Fermi's Theory of Weak Interactions, Z. Physik, 88, 161 (1934)

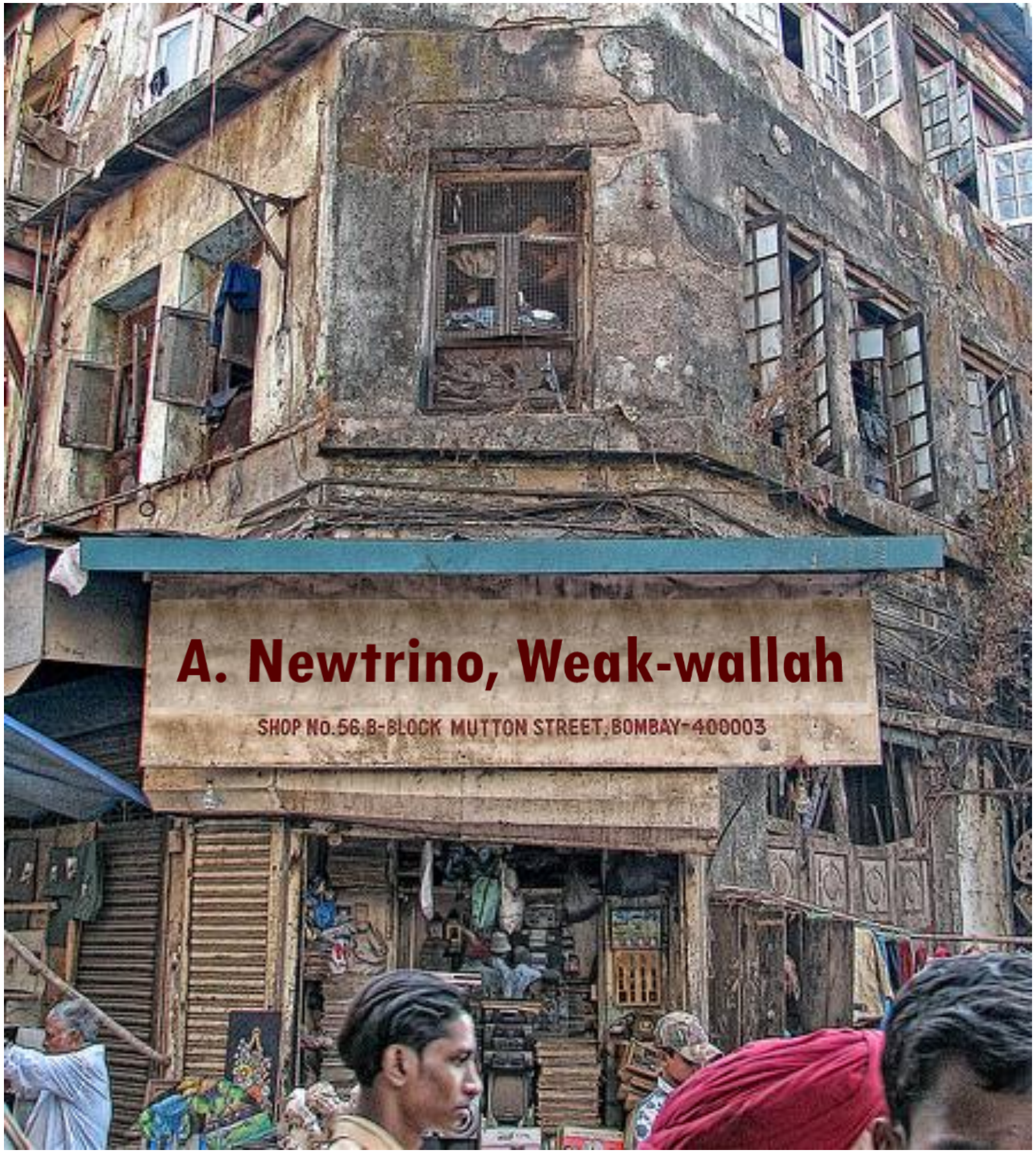
$$H_W = \frac{G_F}{\sqrt{2}} J^{\mu} J_{\mu}$$

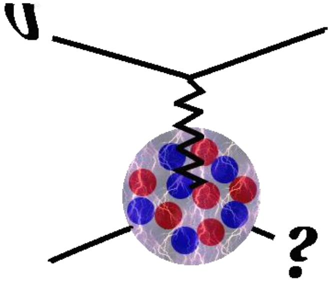
  - Predicted a rate for the neutrino discovery reaction of Reines and Cowan,

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



- Discovery of the neutrino with roughly the correct interaction rate, $\sigma \sim 5\times10^{-44}\text{cm}^2$, was a key validation of this picture of the weak force

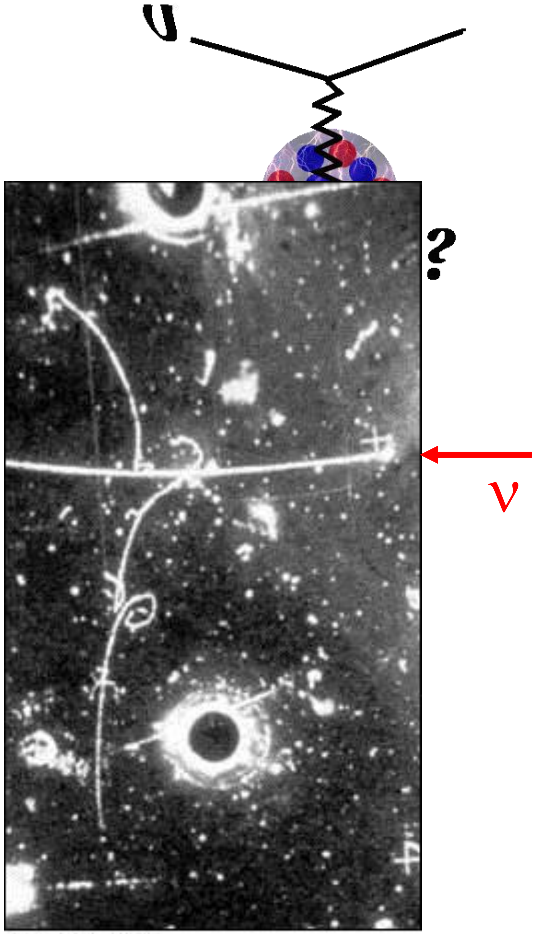

A. Newtrino, Weak-wallah
SHOP No.56.B-BLOCK MUTTON STREET.BOMBAY-400003


ν
?

Another Neutrino Interaction Discovery

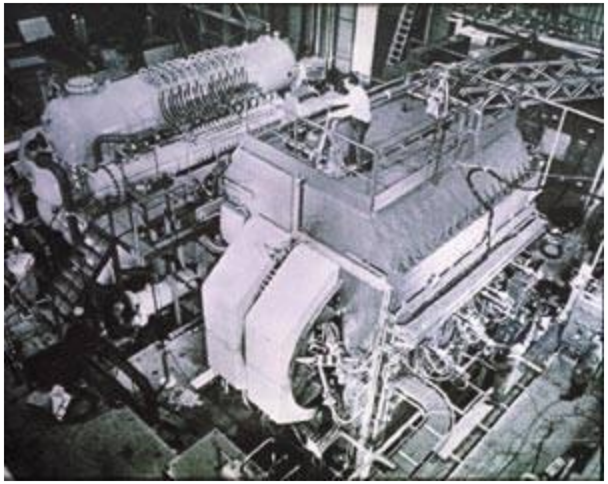
- The Weinberg-Salam theory called neutrinos into service again
- Search for neutral current
  - ☐ arguably the most famous neutrino interaction ever observed is shown at right

$$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$$

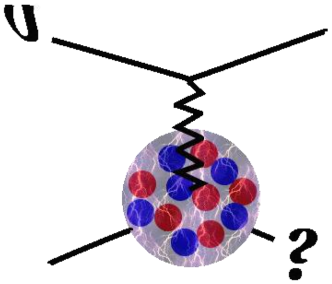


AEROMETRIC photo

Gargamelle, event from neutral weak force

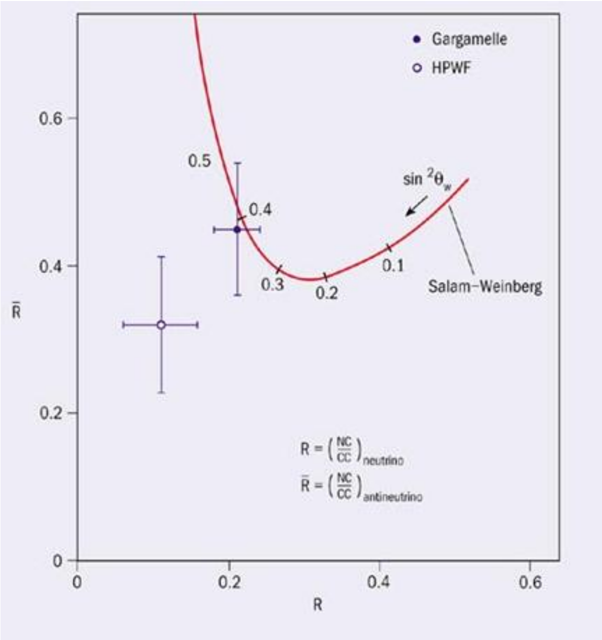


The Messy Reality



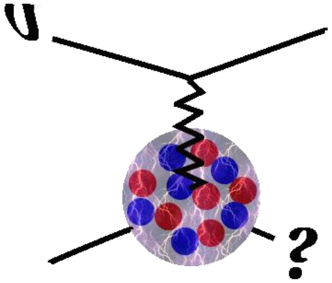
- The “discovery signal” for the neutral current was really neutrino scattering from nuclei
  - usually quoted as a ratio of muon-less interactions to events containing muons

$$R^{\nu} = \frac{\sigma(\nu_{\mu} N \rightarrow \nu_{\mu} X)}{\sigma(\nu_{\mu} N \rightarrow \mu^{-} X)}$$

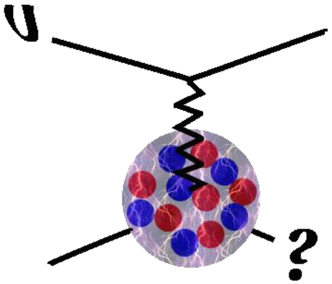


- This discovery was held back a crucial year or two by not understanding neutrino interactions
  - backgrounds from neutrons induced by neutrino interactions outside the detector
  - not understanding probability of fragmentation to high E hadrons which then “punched through” to fake muons

Cross-Sections: Medicine for Neutrino Physicists



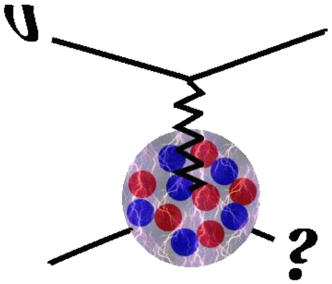
- Sometimes it tastes awful.
- We know it’s good for us, but that doesn’t mean we like it.
- Oh, and by the way, whether we like it or not, we force feed it to our children.
  - ☐ *Most oscillation experiments have more students writing a thesis exploring neutrino interactions than doing fits to data for oscillations!*
- So it’s time for our daily dose



GOALS

1. Oscillation Experiment Signals and Backgrounds
2. Strong and Weak Interaction Physics

Neutrino Interactions are Simple

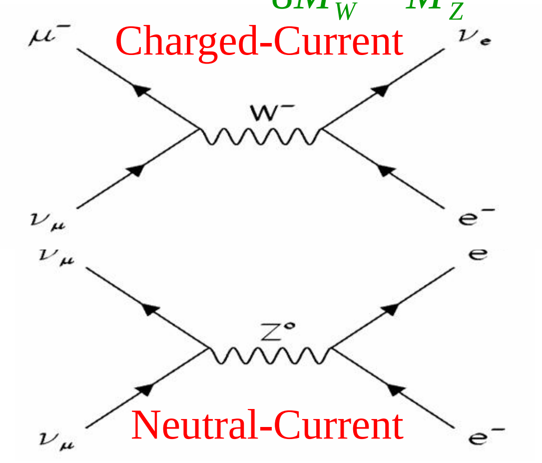


- Neutrino interactions are predicted
  - ☐ EWK SM: SU(2) ⊗ U(1) gauge theory unifying weak/EM

    ⇒ weak NC follows from EM, Weak CC
  - ☐ Measured physical parameters related to mixing parameter for the couplings, $g' = g\tan\theta_W$

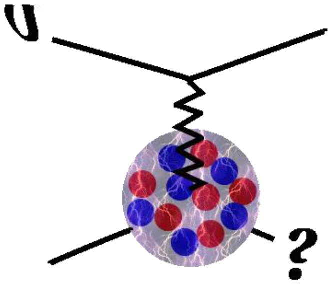
$$e = g\sin\theta_W,\ G_F = \frac{g^2\sqrt{2}}{8M_W^2},\ \frac{M_W}{M_Z} = \cos\theta_W$$

Z Couplings	g_L	g_R
$\nu_e,\ \nu_\mu,\ \nu_\tau$	$1/2$	0
$e,\ \mu,\ \tau$	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
$u,\ c,\ t$	$1/2 - 2/3\ \sin^2\theta_W$	$-\ 2/3\ \sin^2\theta_W$
$d,\ s,\ b$	$-1/2 + 1/3\ \sin^2\theta_W$	$1/3\ \sin^2\theta_W$

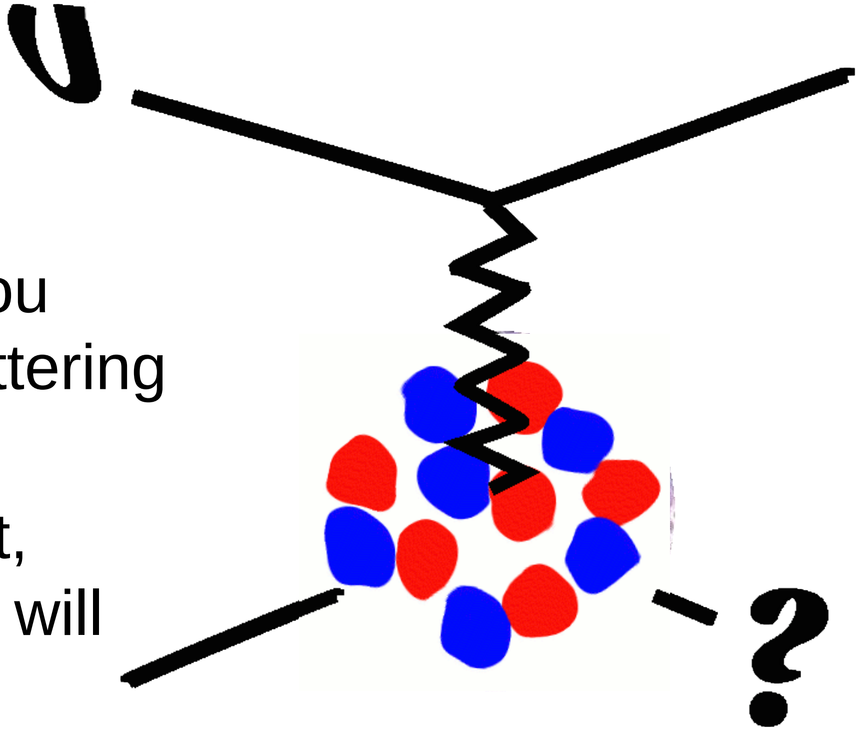


- ☐ Right-handed neutrino has ***NO*** interactions!

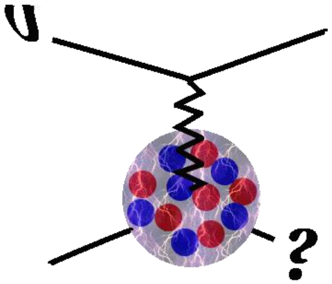
Neutrino Interactions are Hard



- If the target (nucleon) has structure, there are form factors
  - including un(der)-known axial form factors and form factors from final state lepton mass
- And if you know those, then you face the complication of rescattering in nuclear medium
- And if you can understand that, then the nuclear medium itself will modify your target nucleons
- In short, it’s a mess.

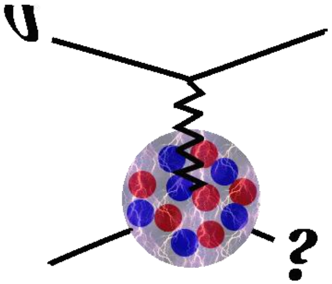


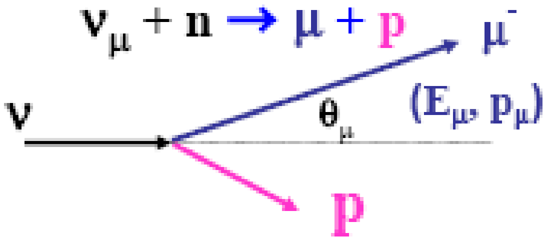
How do cross-sections affect oscillation analysis?



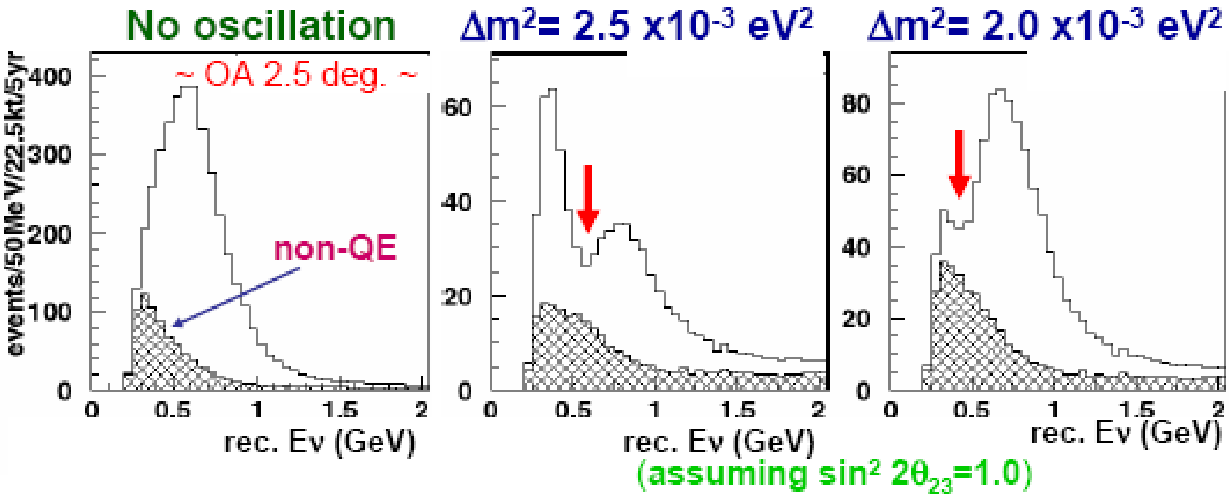
- ν_μ disappearance at conventional beams
  - Backgrounds at signal “dip”
  - Neutrino energy measurement from final state
- ν_e appearance at conventional beams
  - Backgrounds from neutral currents (π^0s) and others
  - Small signal with restrictive identification, so signal identification also depends on final state details
- ν_μ appearance at future beams
  - ν_μ cross-sections at very low energies for beta beams
  - backgrounds from hadrons to μ at neutrino factories
- ν_τ appearance at neutrino factories
  - details of charm production (backgrounds), τ mass suppression

Backgrounds to ν_μ disappearance in NBB



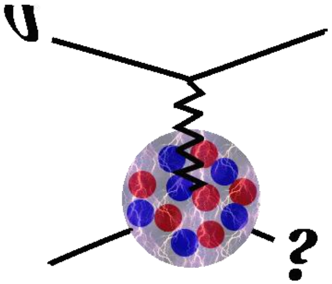


- Backgrounds for ν_μ disappearance
  - ☐ at Super-K reconstruct these events by muon angle and momentum (proton below Cerenkov threshold in H_2O)
  - ☐ other final states with more particles below threshold ("non-QE") will disrupt this reconstruction
- T2K must know these events at few % level to do disappearance analysis to measure Δm^2_{23}, θ_{23}

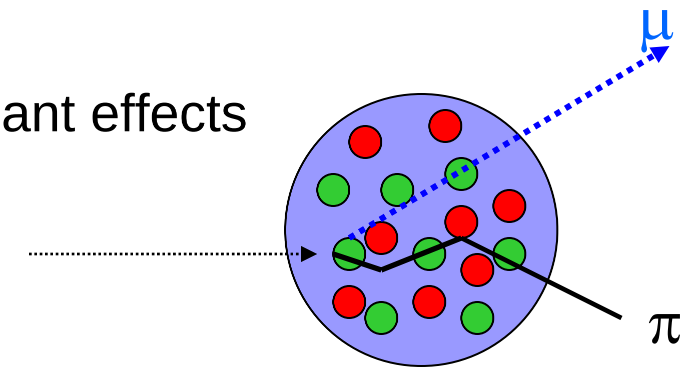


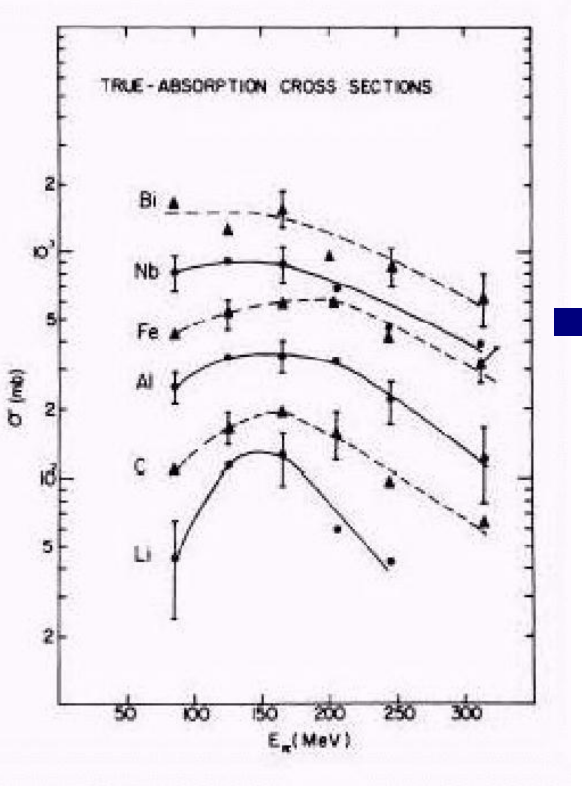
(fig. courtesy Y. Hayato)

ν_μ Neutrino Energy for Δm^2 in WBB



- Even if reaction is correctly categorized, visible energy is NOT ν energy
  - π absorption, re-scattering are significant effects

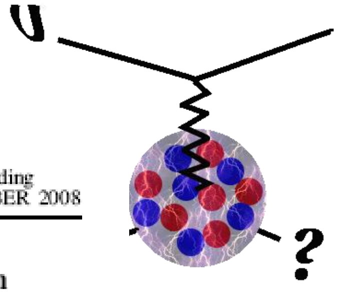


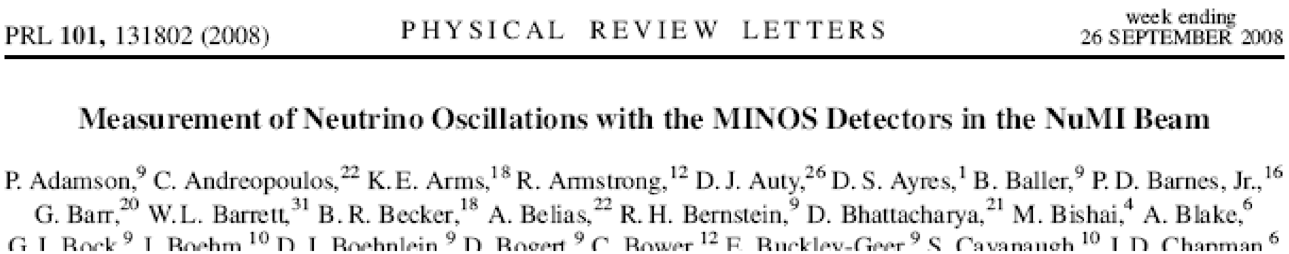


D. Ashery et al, PRC **23**,1993

- To correctly understand this effect, need
  - Knowledge of the probability of seeing different final states in the detector
  - And that knowledge *on the nuclei* that comprise your neutrino detector

Not a hypothetical worry




PRL **101,** 131802 (2008) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2008

Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam

P. Adamson,[9] C. Andreopoulos,[22] K.E. Arms,[18] R. Armstrong,[12] D. J. Auty,[26] D. S. Ayres,[1] B. Baller,[9] P. D. Barnes, Jr.,[16] G. Barr,[20] W.L. Barrett,[31] B. R. Becker,[18] A. Belias,[22] R. H. Bernstein,[9] D. Bhattacharya,[21] M. Bishai,[4] A. Blake,[6] G. J. Bock,[9] J. Boehm,[10] D. J. Boehnlein,[9] D. Bogert,[9] C. Bower,[12] E. Buckley-Geer,[9] S. Cavanaugh,[10] J. D. Chapman,[6]

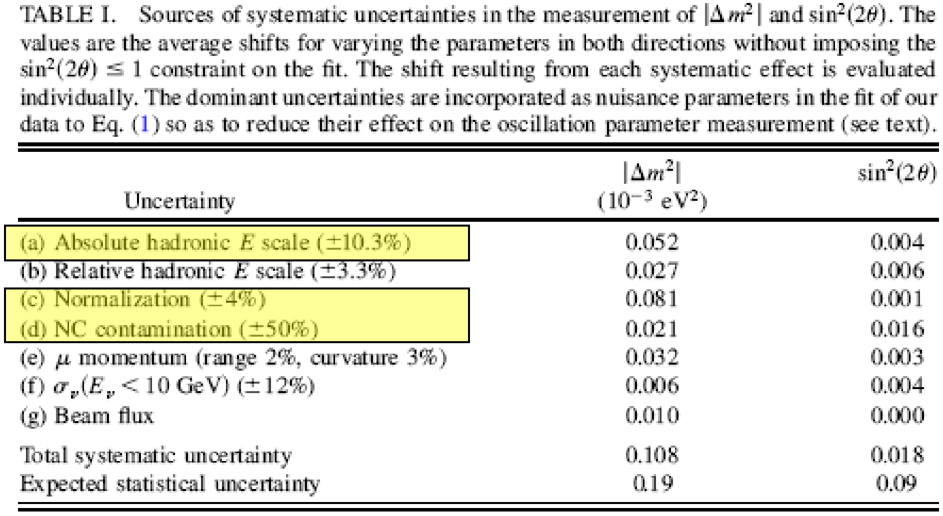
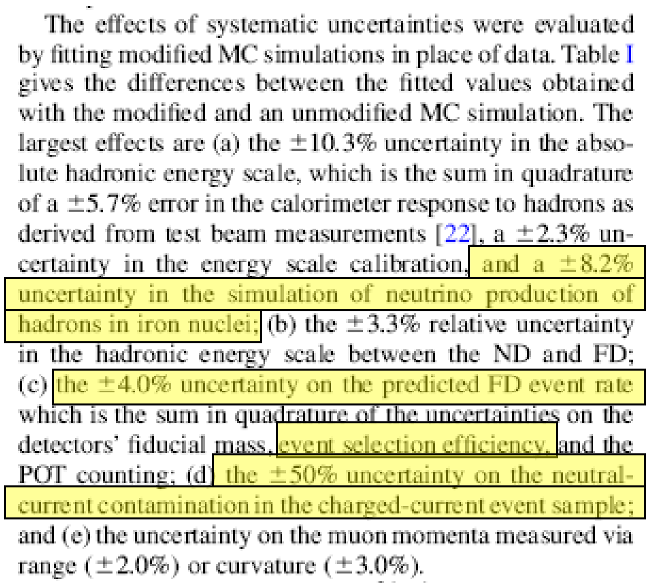


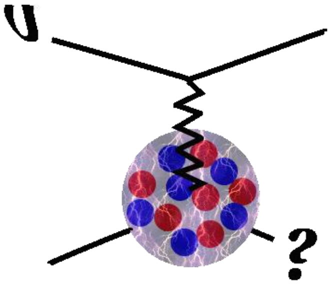
TABLE I. Sources of systematic uncertainties in the measurement of $|\Delta m^2|$ and $\sin^2(2\theta)$. The values are the average shifts for varying the parameters in both directions without imposing the $\sin^2(2\theta) \leq 1$ constraint on the fit. The shift resulting from each systematic effect is evaluated individually. The dominant uncertainties are incorporated as nuisance parameters in the fit of our data to Eq. (1) so as to reduce their effect on the oscillation parameter measurement (see text).

Uncertainty	$\lvert\Delta m^2\rvert$ (10^{-3} eV^2)	$\sin^2(2\theta)$
(a) Absolute hadronic E scale (±10.3%)	0.052	0.004
(b) Relative hadronic E scale (±3.3%)	0.027	0.006
(c) Normalization (±4%)	0.081	0.001
(d) NC contamination (±50%)	0.021	0.016
(e) μ momentum (range 2%, curvature 3%)	0.032	0.003
(f) $\sigma_\nu(E_\nu < 10$ GeV) (±12%)	0.006	0.004
(g) Beam flux	0.010	0.000
Total systematic uncertainty	0.108	0.018
Expected statistical uncertainty	0.19	0.09

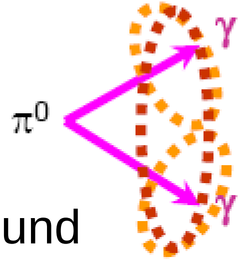

The effects of systematic uncertainties were evaluated by fitting modified MC simulations in place of data. Table I gives the differences between the fitted values obtained with the modified and an unmodified MC simulation. The largest effects are (a) the ±10.3% uncertainty in the absolute hadronic energy scale, which is the sum in quadrature of a ±5.7% error in the calorimeter response to hadrons as derived from test beam measurements [22], a ±2.3% uncertainty in the energy scale calibration, and a ±8.2% uncertainty in the simulation of neutrino production of hadrons in iron nuclei; (b) the ±3.3% relative uncertainty in the hadronic energy scale between the ND and FD; (c) the ±4.0% uncertainty on the predicted FD event rate which is the sum in quadrature of the uncertainties on the detectors' fiducial mass, event selection efficiency, and the POT counting; (d) the ±50% uncertainty on the neutral-current contamination in the charged-current event sample; and (e) the uncertainty on the muon momenta measured via range (±2.0%) or curvature (±3.0%).

Largest systematic errors dominated by understanding of which final states are present, and how they affect energy measurement and event selection

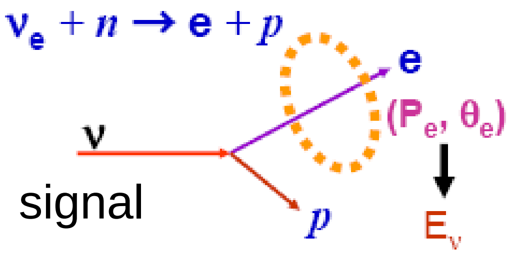
Backgrounds to ν_e appearance off-axis



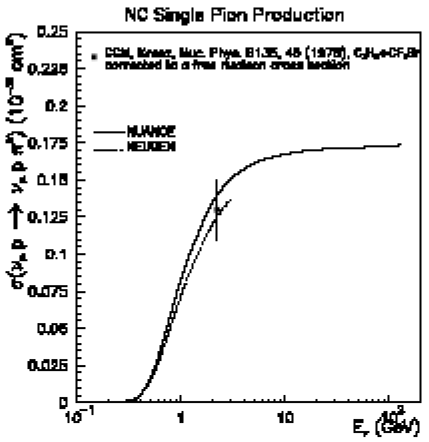
- ν_e appearance
  - different problem: signal rate is very low so even rare backgrounds contribute!



π^0 background from E_ν>peak



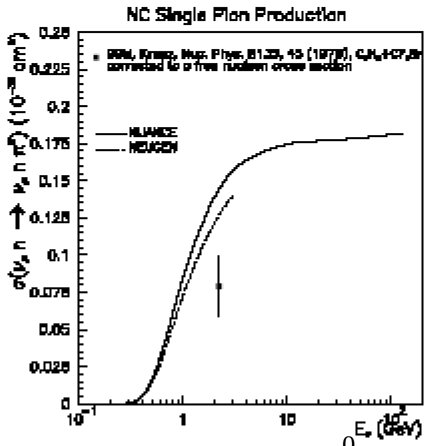
signal



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

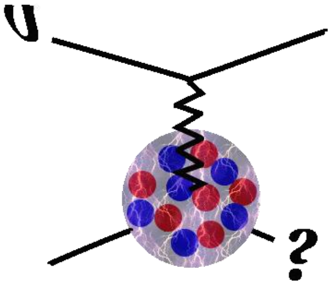
the world's data on this background before dedicated cross-section experiments

(compiled by G. Zeller, hep-ex/0312061)



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

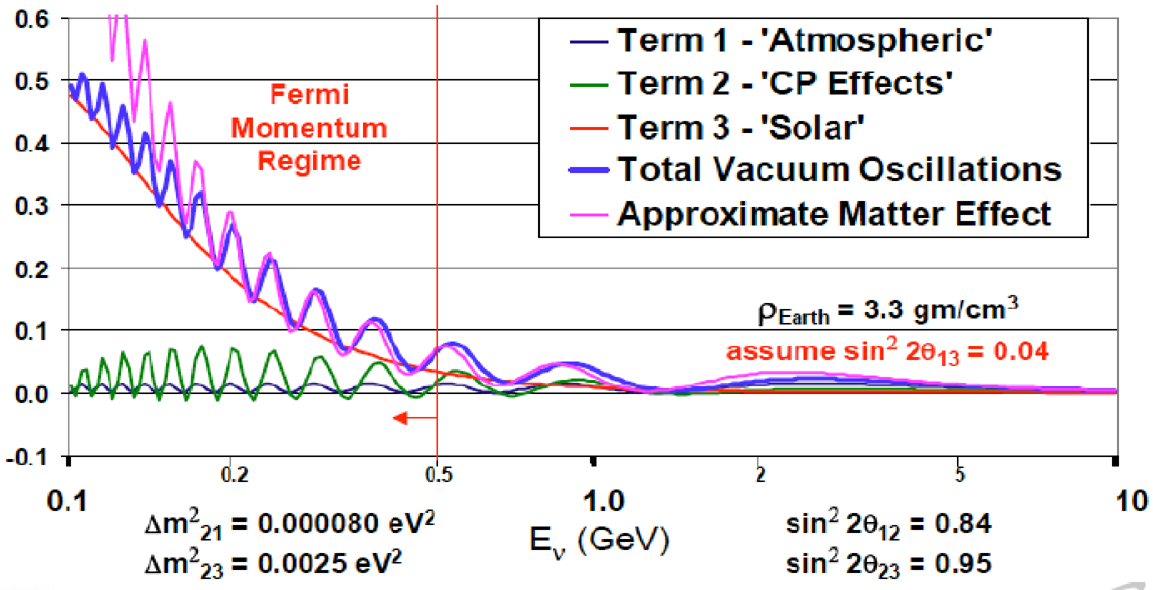
Super(beam)! Oscillations?



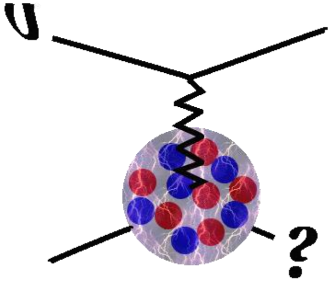
- A wideband beam with a single detector to untangle matter effects and CP violation is a particularly challenging case
  - Multiple maxima requires different L/E_ν, in this case realized by different E_ν, and need precision measurements for both neutrinos and anti-neutrinos
  - Worse, all of this is done with neutrino interactions at E_ν ~1 GeV, near the threshold between elastic and inelastic νN scattering

FNAL-DUSEL

$$P(\nu_\mu \rightarrow \nu_e)$$

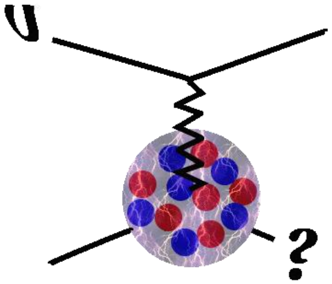


Strong Interaction Physics

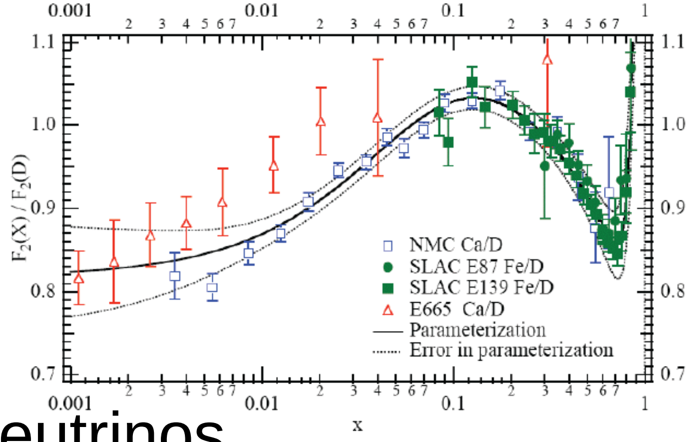


- The development of QCD in the 70's required high energy processes to test predictions
  - Needed tests of perturbative calculations. Low energy QCD was left behind in a mass of uncalculable structure functions and form factors
- With the underlying theory established, the challenge is now to explain complicated systems
  - Heavy ion colliders, low energy continuous beam electron scattering all share these goals
  - *Neutrino experiments offer a new window into nuclei*

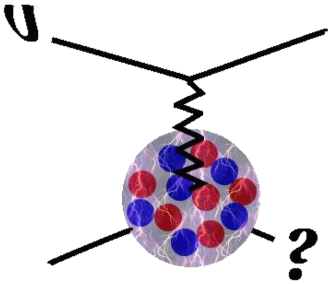
Examples of Strong Interaction Topics



- We understand how nuclei affect DIS scattering in charged leptons
  - ☐ Because there is lots of data!
  - ☐ That knowledge is absent in neutrinos

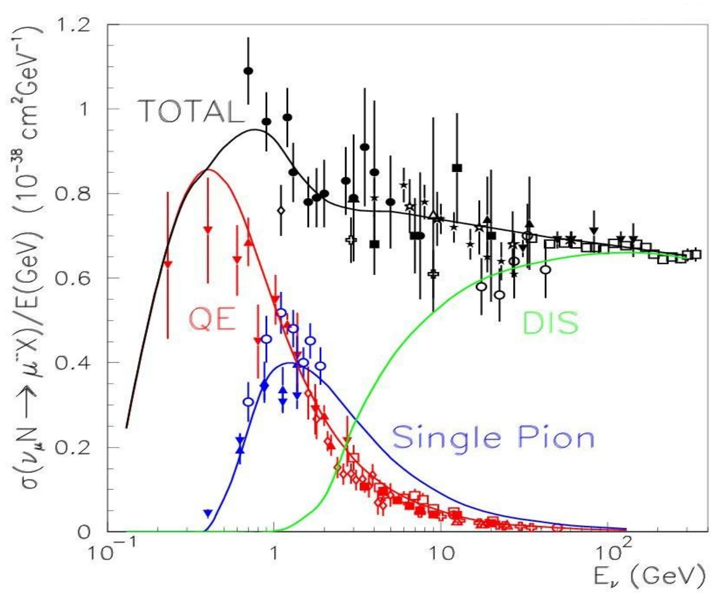


- How do nuclei distort elastic form factors?
- What does the transition between resonance and deep inelastic scattering look like?
  - ☐ Does quark-hadron duality hold as it does in charged-lepton scattering? (Assumption of Bodek-Yang model)

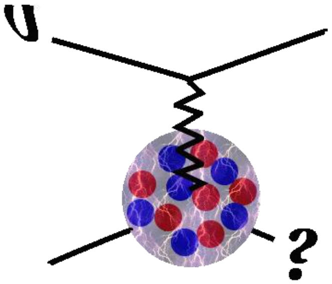


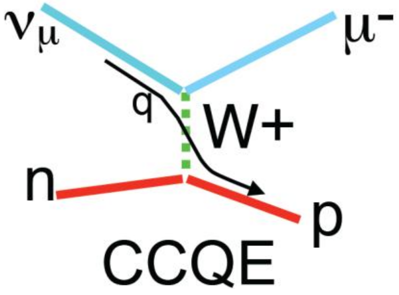
HIGHLIGHTS AND PUZZLES IN CURRENT DATA

1. Quasi-elastic scattering
2. Single pion production
3. Inclusive Cross-Sections



Quasi-Elastic Scattering (CCQE)

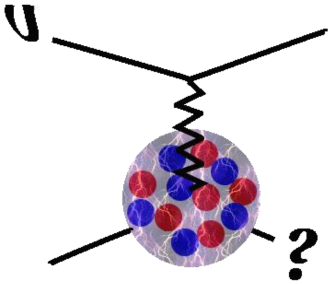




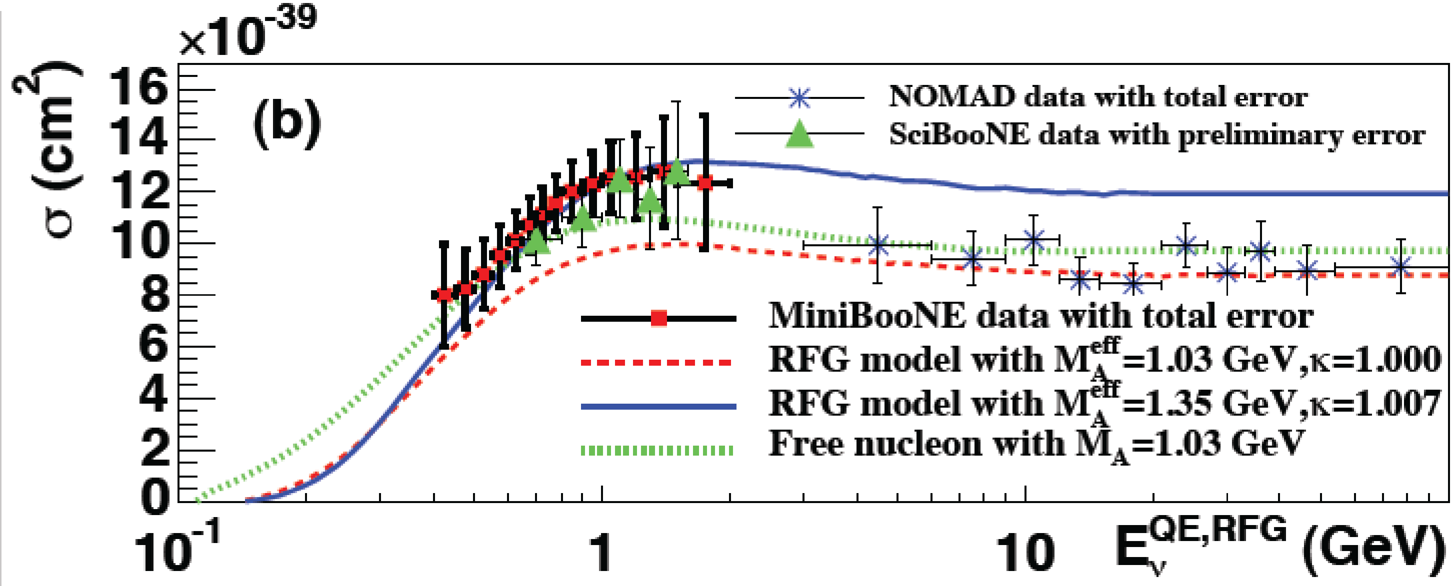
- Dominant reaction for low energy experiments
  - T2K, K2K, Mini-BooNE
- Experimentally useful because of energy reconstruction from muon kinematics
  - But backgrounds from other sources move events from high to low E_ν. Nasty for off-axis experiments
- “Theoretically robust”
  - But only on free nucleons and axial form factor is poorly known

$$F(Q^2) \cong \frac{F_A(0)}{\left(1 - {Q^2}/{M_A{}^2}\right)^2}$$

Overview of Recent CCQE Data



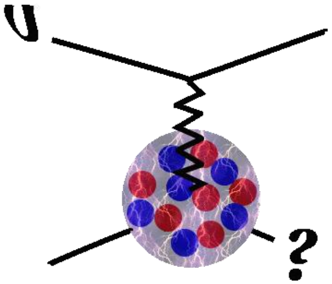
- Current data cannot be fit by a single prediction for low energy data (BooNEs) and high energy data (NOMAD)
    - In dipole form-factor picture, different "M_A"
    - Free nucleon "correct" M_A is probably ~1 GeV from other data



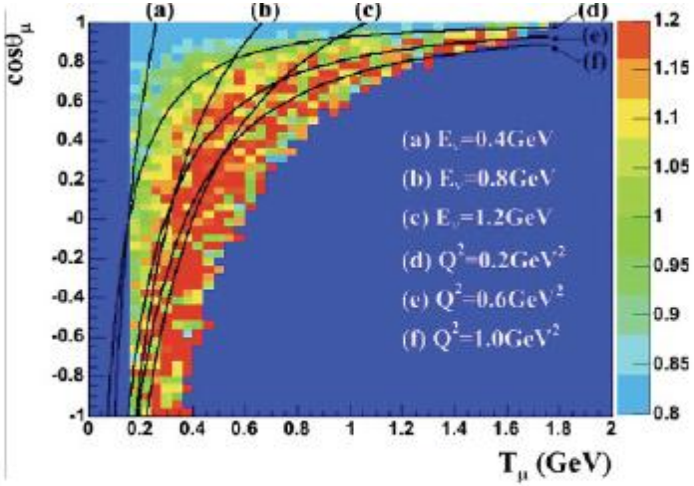
Plot courtesy of T. Katori

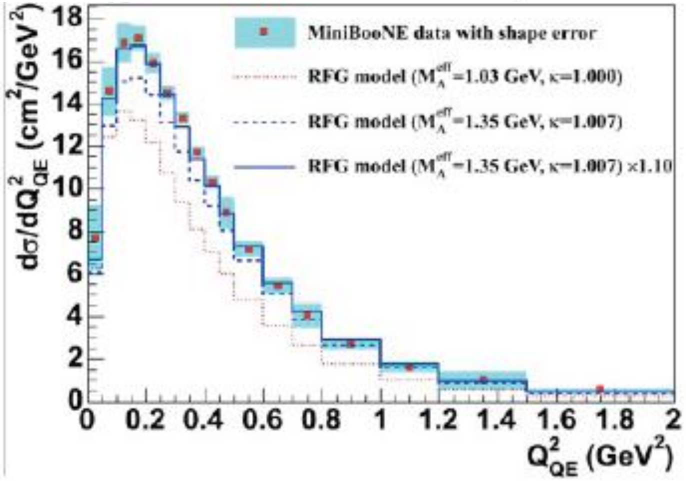
See Stancu's WG2 talk

MiniBooNE (*Phys. Rev.* ***D81*** *092005, 2010)*

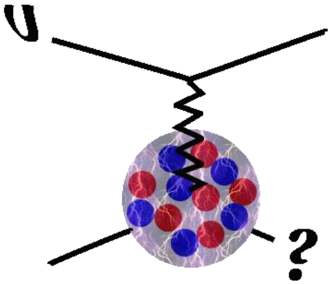


- Oil Cerenkov detector, views only muon
- Fit to observables, muon energy & angle, confirm discrepancy with low "M_A" is a Q^2 distortion
- Good consistency between total cross-section and this Q^2 shape



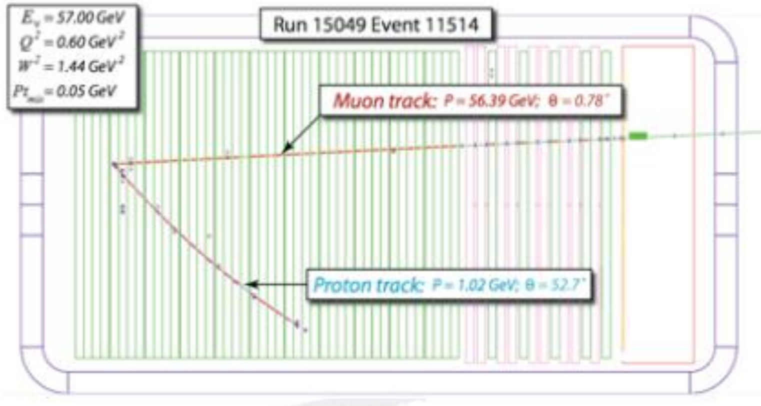


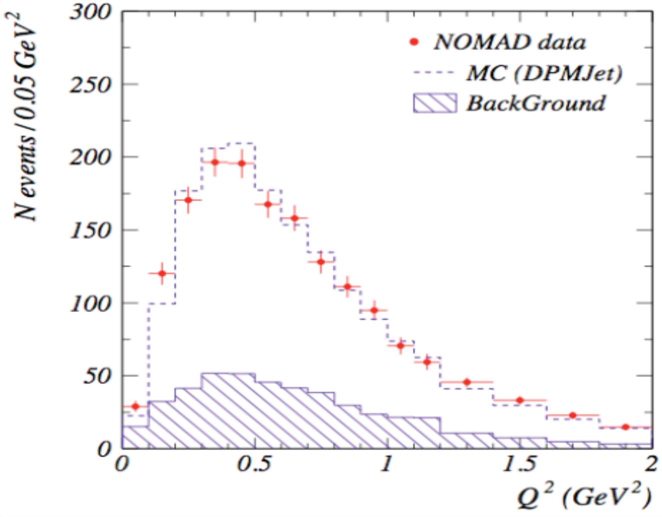
NOMAD *(Eur.Phys.J.C63:355-381,2009)*



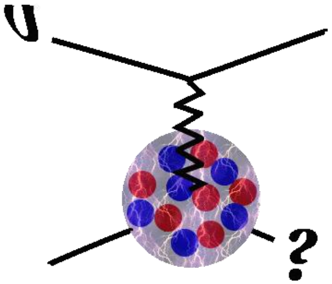
- Like MiniBooNE, target is mostly carbon (drift chamber walls)
- Reconstruct both recoiling proton and muon
- Total cross-section is used to infer M_A, but Q^2 shape is also consistent
- *Two experiments, same target, but different energies and reconstruction…*

  … incompatible results?

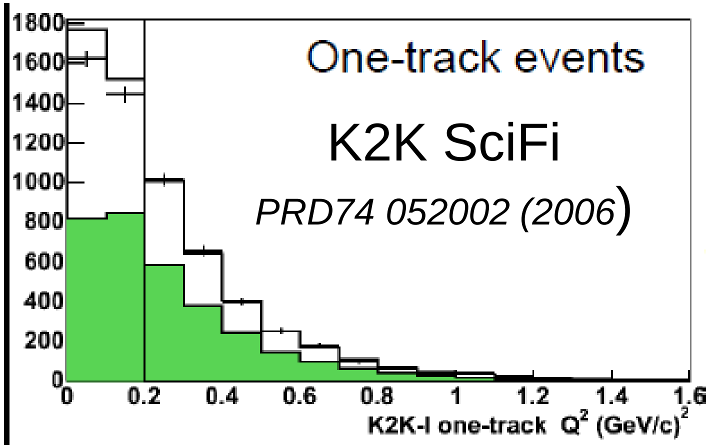




Role of Backgrounds to CCQE



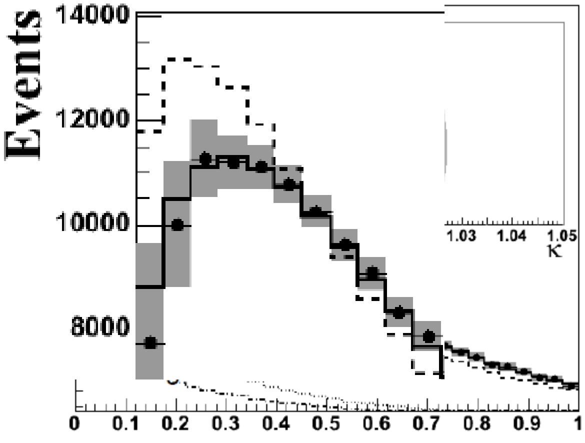
- K2K famously observed a “low Q^2 deficit” in its analysis
- MiniBooNE originally had a significant discrepancy at low Q^2 as well
  - ☐ Original approach was to put in a large enhancement to Pauli suppression to “fix” low Q2
  - ☐ Was resolved by using single pion background seen in data



One-track events

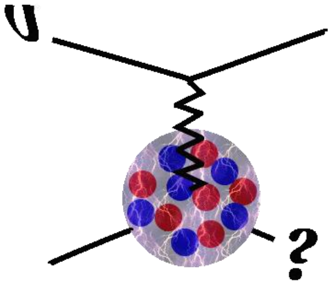
K2K SciFi

PRD74 052002 (2006))



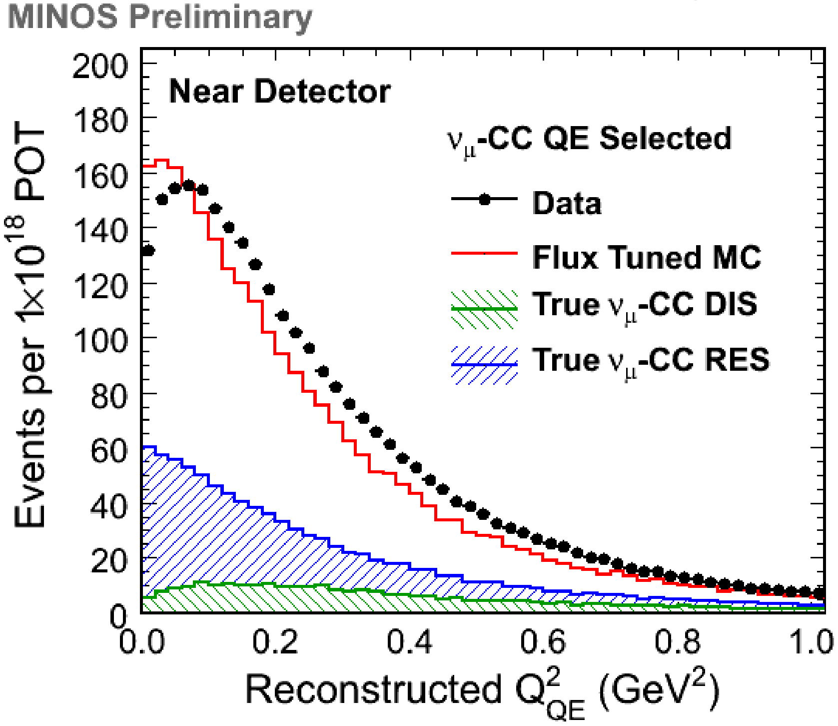
PRL100 032301 (2008)

MINOS CCQE



- Different target, iron, and different reconstruction technique
  - Select events with little visible hadronic energy in MINOS target calorimeter
- See significant discrepancy at low Q^2 and a excess at high Q^2 relative to M_A~1 GeV
- MINOS did a Mini-BooNE style analysis with extra Pauli suppression and floating M_A

AIP Conf.Proc.1189:133-138,2009

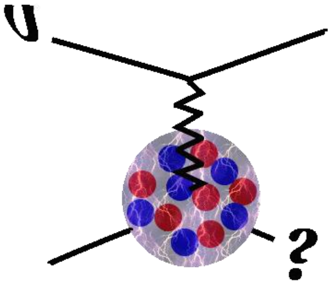


MINOS Preliminary

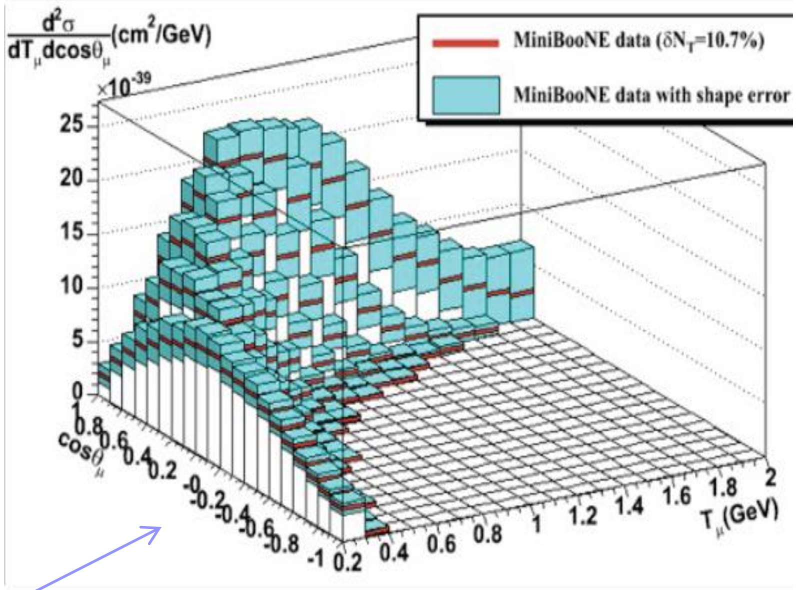
$M_A^{QE} = 1.19\,^{+0.09}_{-0.10}$ (fit) $^{+0.12}_{-0.14}$ (syst) GeV

$k^{Fermi} \rightarrow 1.28 \times k^{Fermi}$

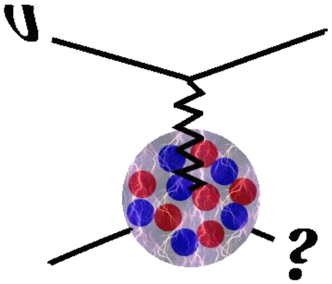
Next Steps Forward



- With more sophisticated analyses and models, we need a new paradigm
- Experimental measurements and calculations are moving to final states, rather than process-specific measurements and extracted parameters
  - MiniBooNE CCQE a good example
- These results can support development new to understand underlying physics and support oscillation experiments

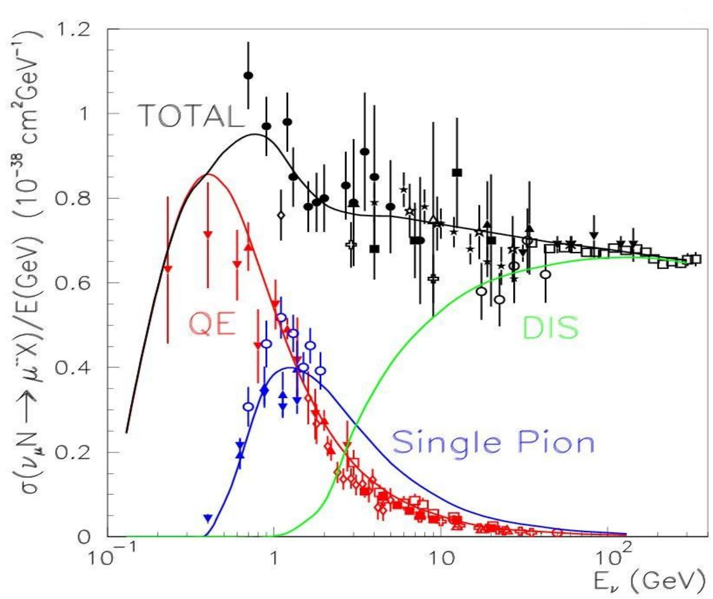


(*Phys. Rev.* ***D81*** *092005, 2010)*

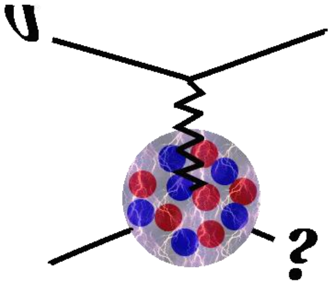


HIGHLIGHTS AND PUZZLES IN CURRENT DATA

1. Quasi-elastic scattering
2. Single pion production
3. Inclusive Cross-Sections



Resonant Pion Production



- Recall that these are major backgrounds to ν_μ disappearance and ν_e appearance exp'ts

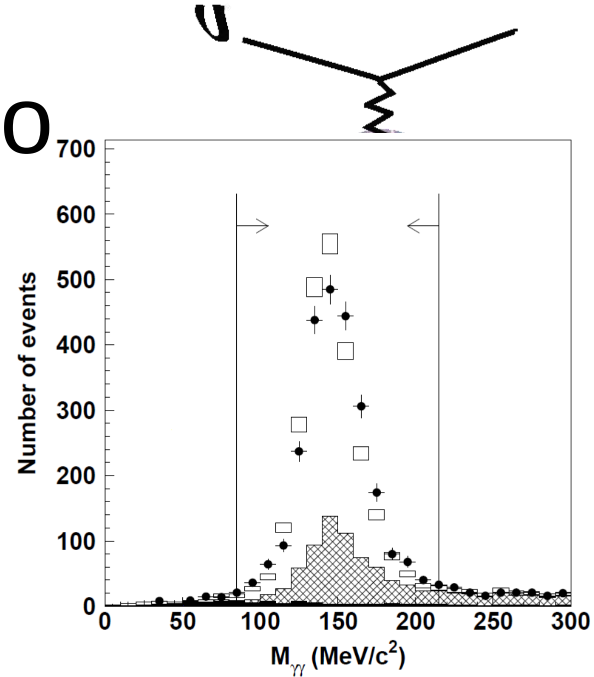
See Tanaka's WG2 talk

Experiments	$\langle E_\nu \rangle$ GeV	Main goal	Detector	ν target	ν MC	Cross section results
K2K	1.3	θ_{23}, Δm_{23}	Fine Grained, Water Cher	CH, H_2O	NEUT	Pub: $NC\pi^0$, $CC\pi^+$ Prelim: $CC\pi^0$
MiniBooNE	0.7	$\nu_\mu \rightarrow \nu_e$	Oil Cher	CH_2	NUANCE	Pub: $NC\pi^0$ Prelim: $CC\pi^+$, $CC\pi^0$
SciBooNE	0.7	σ_ν	Fine Grained	CH	NEUT, NUANCE	Pub: $NC\pi^0$ Prelim: $CC\pi^0$

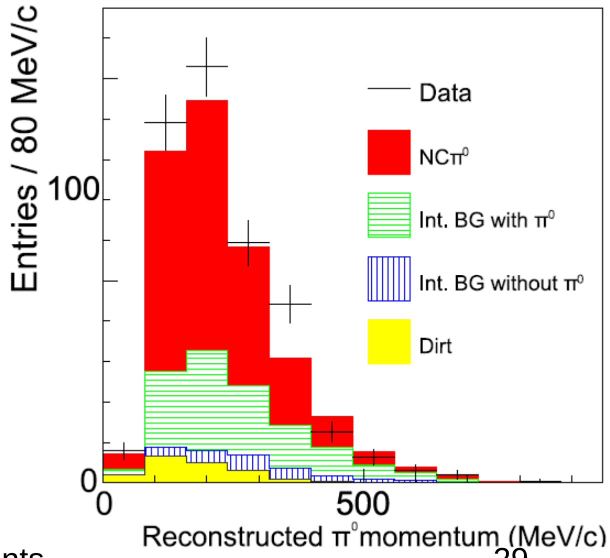
Compilation by Martin Tzanov

ν_μ NC π^0 Cross Section Ratio

- K2K made first measurement of this with a goal of verifying their background prediction
  - Require two rings in 1kTon near det.
  - $\sigma^{NC\pi^0}/\sigma^{CC}$= 0.064±0.001(stat.)±0.007(sys.)
  - MC prediction is 0.065.
- SciBooNE made a similar measurement in spirit, but completely different reconstruction
  - 2 γ tracked in SciBar and contained in external EM calorimeter
- $\sigma^{NC\pi^0}/\sigma^{CC}$= (7.7 ± 0.5(stat.) ± 0.5(sys.)) × 10^{-2}
  - MC prediction $6.8\mathrm{x}10^{-2}$

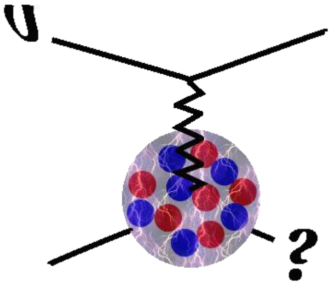


Phys.Lett. B619 (2005) 255

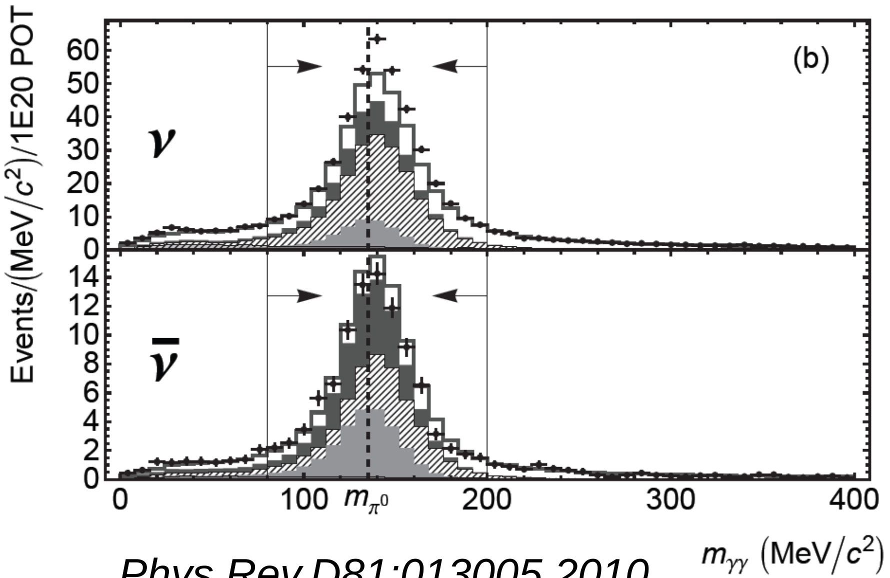


Phys. Rev. D 81, 033004 (2009)

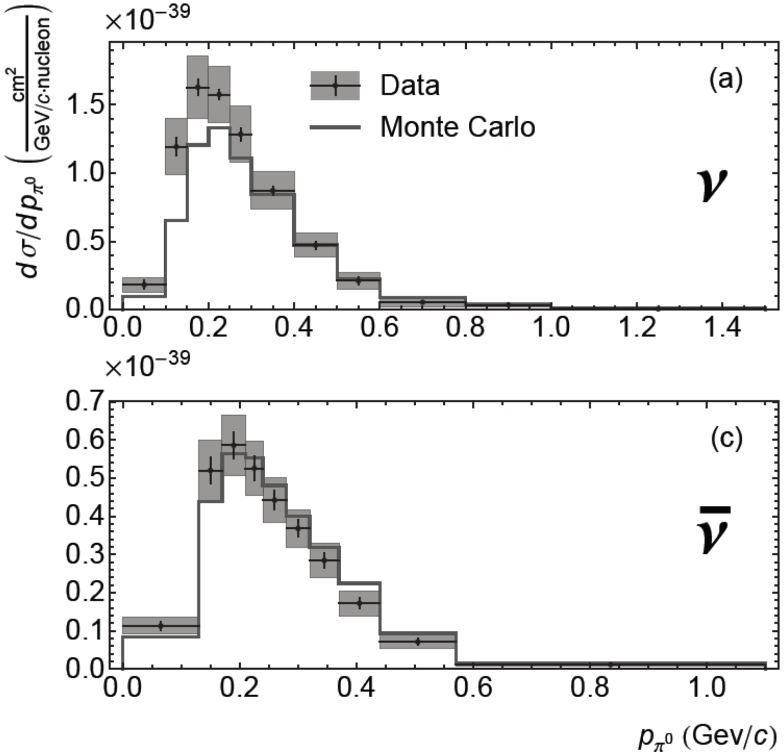
Beyond Ratios: Input to Models instead of Specific Analyses



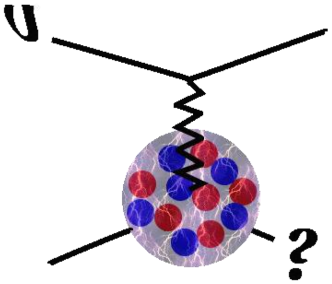
- MiniBooNE differential cross-section analysis
  - Reconstruction by two Cerenkov rings, excellent mass resolution as with K2K 1kTon analysis
  - 21K events!
- dσ/dp$_\pi$ for ν and anti-ν



Phys.Rev.D81:013005,2010



Coherent Pion Production

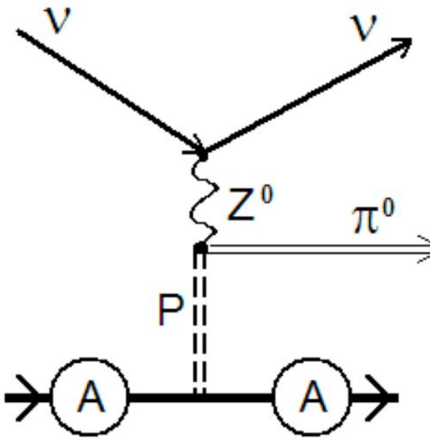


- If the last five years of neutrino interaction workshops have taught us nothing else, the experimentalists now know how to get theorists to fight
  - ☐ But of course it would be wrong to do so…

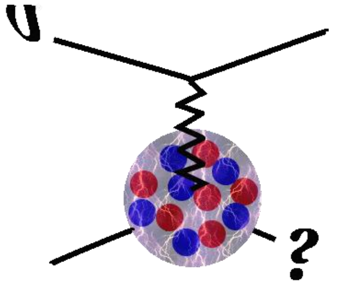
$$\nu_\mu + A \rightarrow l^- + \pi^+ + A$$

$$\nu_\mu + A \rightarrow \nu_\mu + \pi^0 + A$$

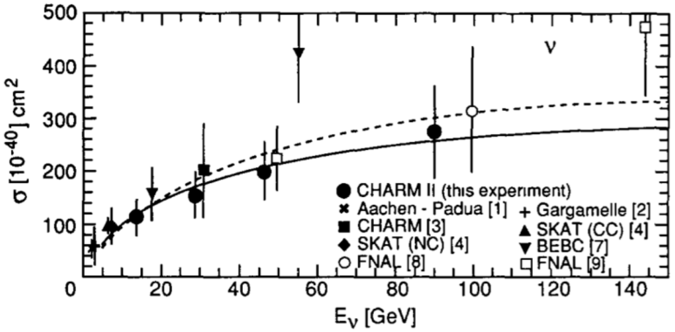
- Interacts coherently with the whole nucleus
  - ☐ No break up.
  - ☐ Small momentum transfer.
  - ☐ Very forward pion
  - ☐ No other particles in the final state.



Past and Recent Measurements



- Observed at high energy, although with large errors and a narrow range of nuclei
- Recent low energy measurements:



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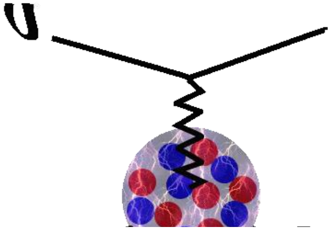
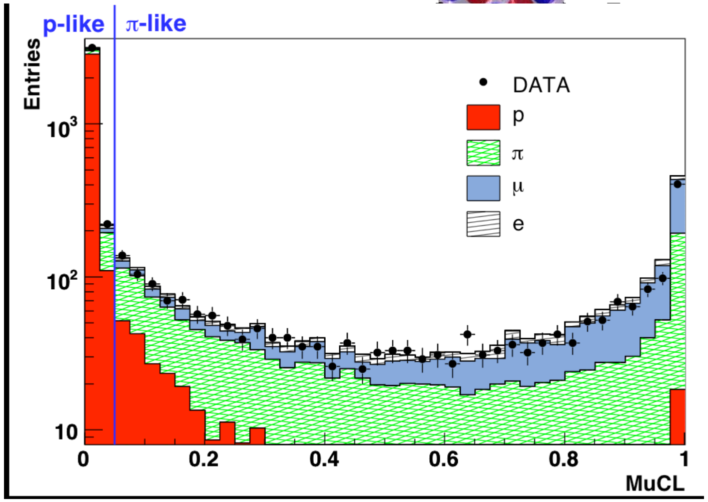
MiniBooNE	0.7	$\nu_\mu \to \nu_e$	Oil Cher	CH_2	NUANCE	Pub: NCπ^0
SciBooNE	0.7	σ_ν	Fine Grained	CH	NEUT, NUANCE	Pub: NCπ^0, CCπ^+
NOMAD	24.8	$\nu_\mu \to \nu_\tau$	Drift Chambers	C		Pub: NCπ^0

Thanks again, Martin!

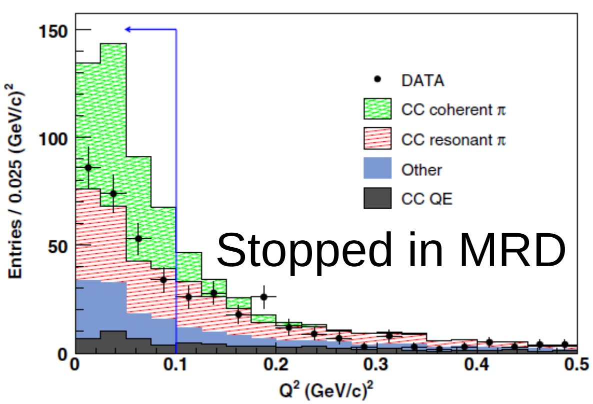
Coherent Charged Pions



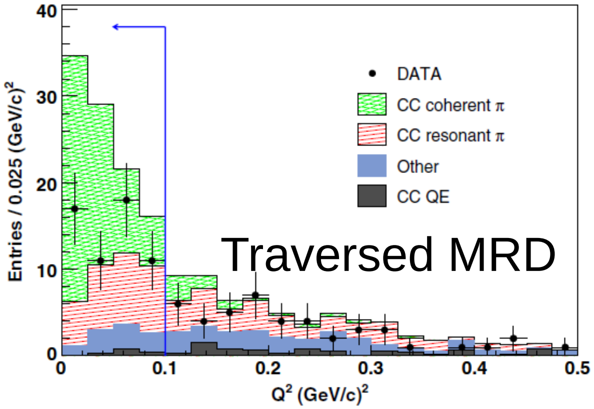
- SciBooNE analysis isolates two track events, with positive muon and pion (not proton!) tags
    - Require low vertex activity, forward π, inconsistent with QE kinematics
- Look at low Q^2 events
    - Rein-Seghal model for Monte Carlo
- Do not see expected signal seen in MC
- Energies of two samples are ~1 and ~2 GeV, respectively



Phys. Rev. D78:112004 (2008)

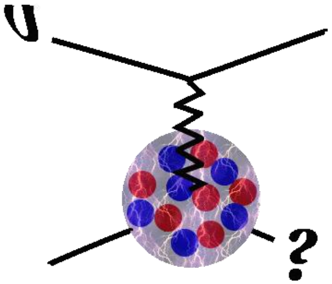


Stopped in MRD

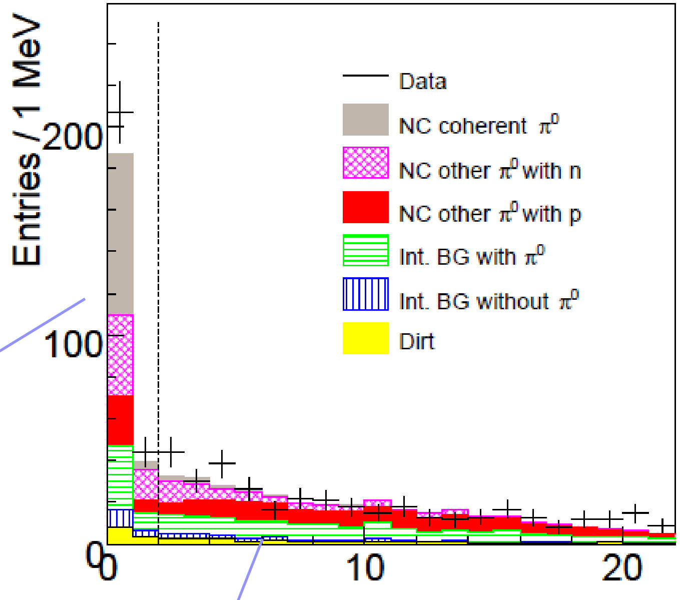


Traversed MRD

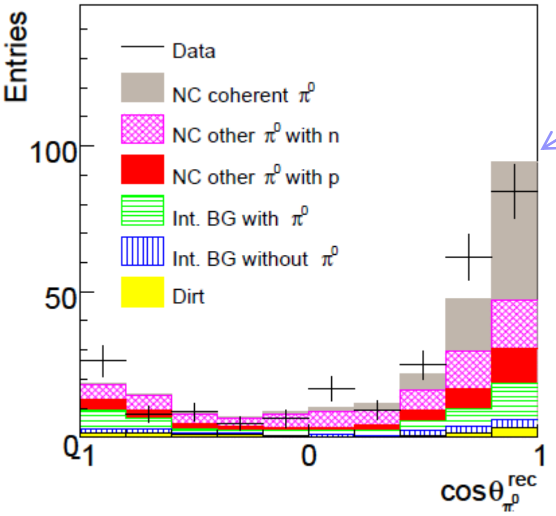
Coherent Neutral Pions

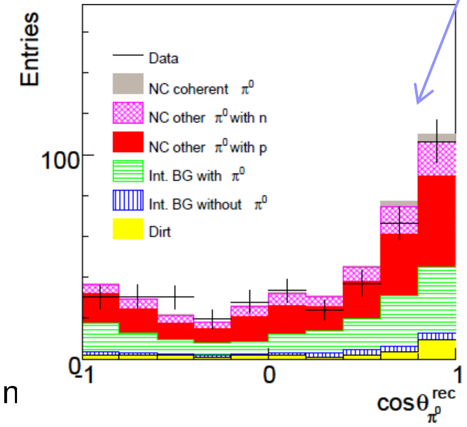


- By contract, this analysis also from SciBooNE finds the expected signal in low energy experiments
  - Require clear π^0 and no other activity near vertex
  - Low activity also shows forward peaking

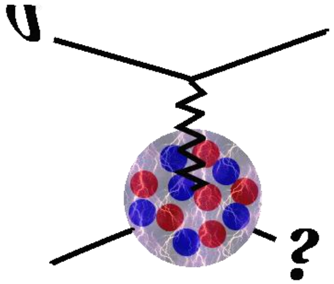


Vertex Activity (MeV)



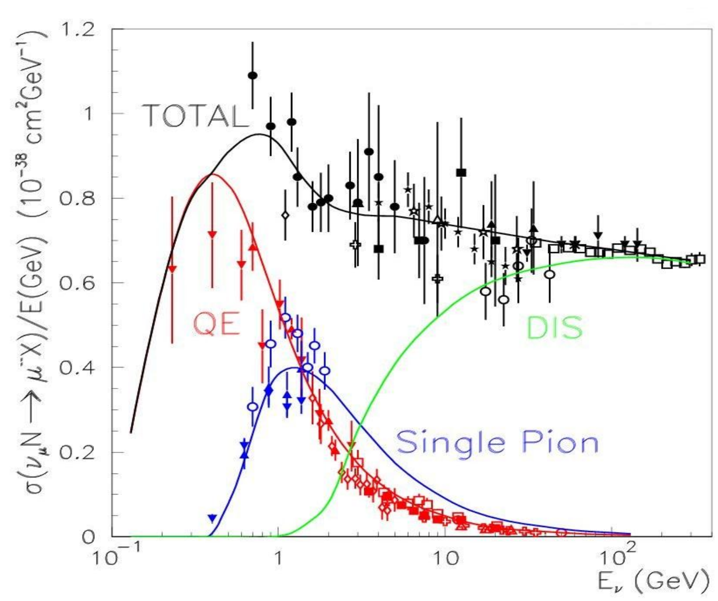


See talk by Tanaka

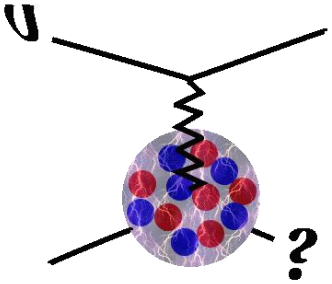


HIGHLIGHTS AND PUZZLES IN CURRENT DATA

1. Quasi-elastic scattering
2. Single pion production
3. Inclusive Cross-Sections



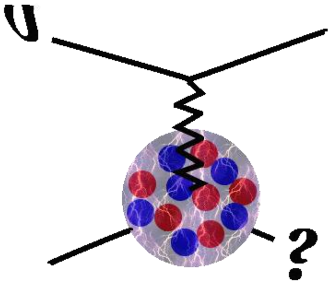
Inclusive Interactions



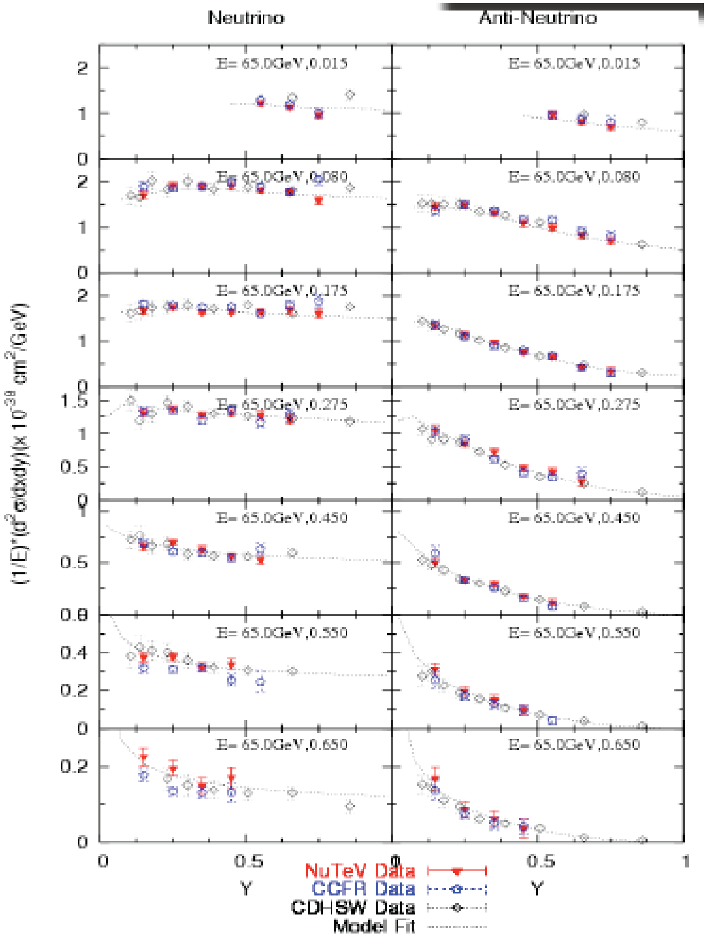
- Much of the data we have is at high energies
  - Common wideband technique is “low recoil” method which uses the observation that $\lim_{\nu \to 0} \frac{d\sigma}{d\nu}$ is independent of E_ν
  - Cross-section normalized from narrow band expt’s which counted secondary particles to measure flux
- Typical goal is to extract structure functions from dependence in x, Q^2 and E_ν.
- Most recently, NuTeV, CHORUS, NOMAD, MINOS

NuTeV CC Differential Cross-Sections

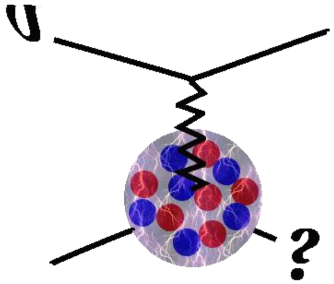
Phys.Rev.D74:012008,2006

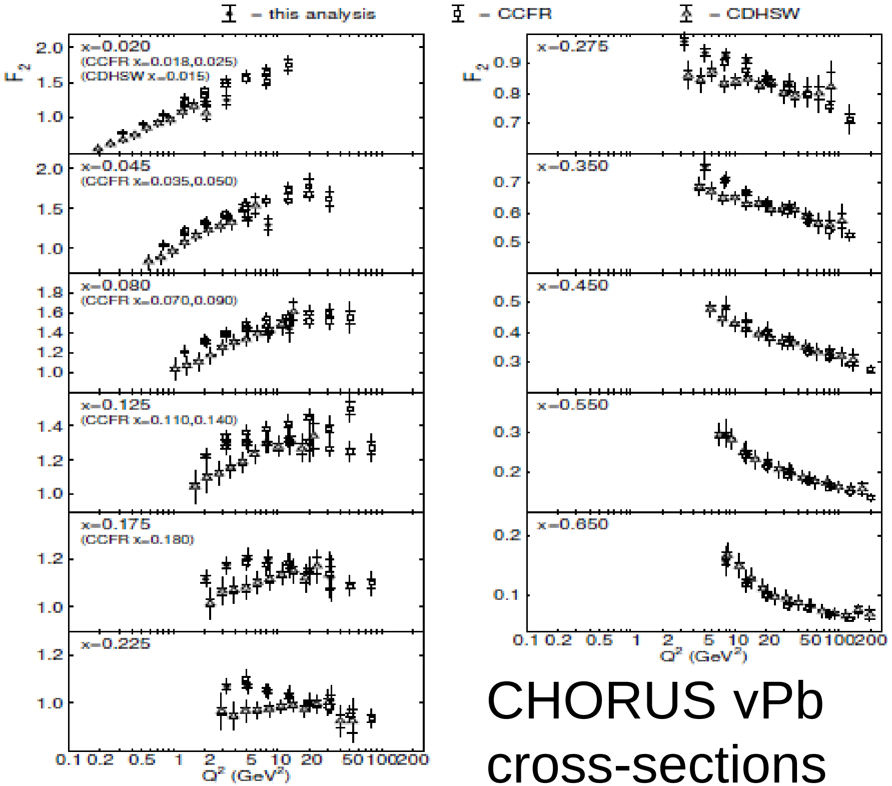


- NuTeV has a very large data sample on iron
  - High energies, precision calibration from testbeam
- Uses:
  - pQCD fits for Λ_{QCD}
  - Extract structure functions for comparisons with other experiments



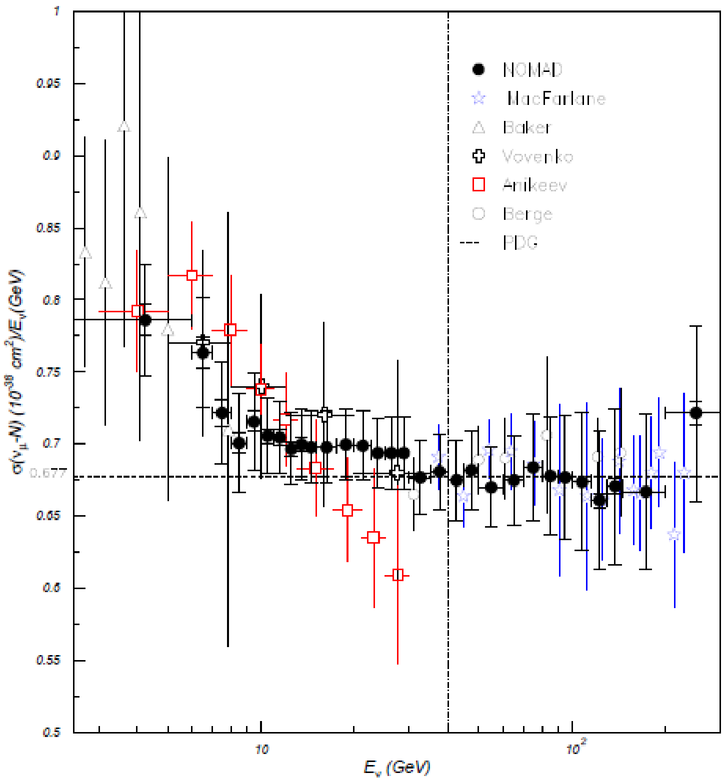
CHORUS and NOMAD





CHORUS νPb cross-sections

Phys.Lett..632(2006) 65

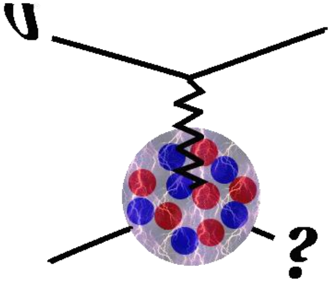


NOMAD νC CC total cross-sections

Phys.Lett.B660:19-25,2008

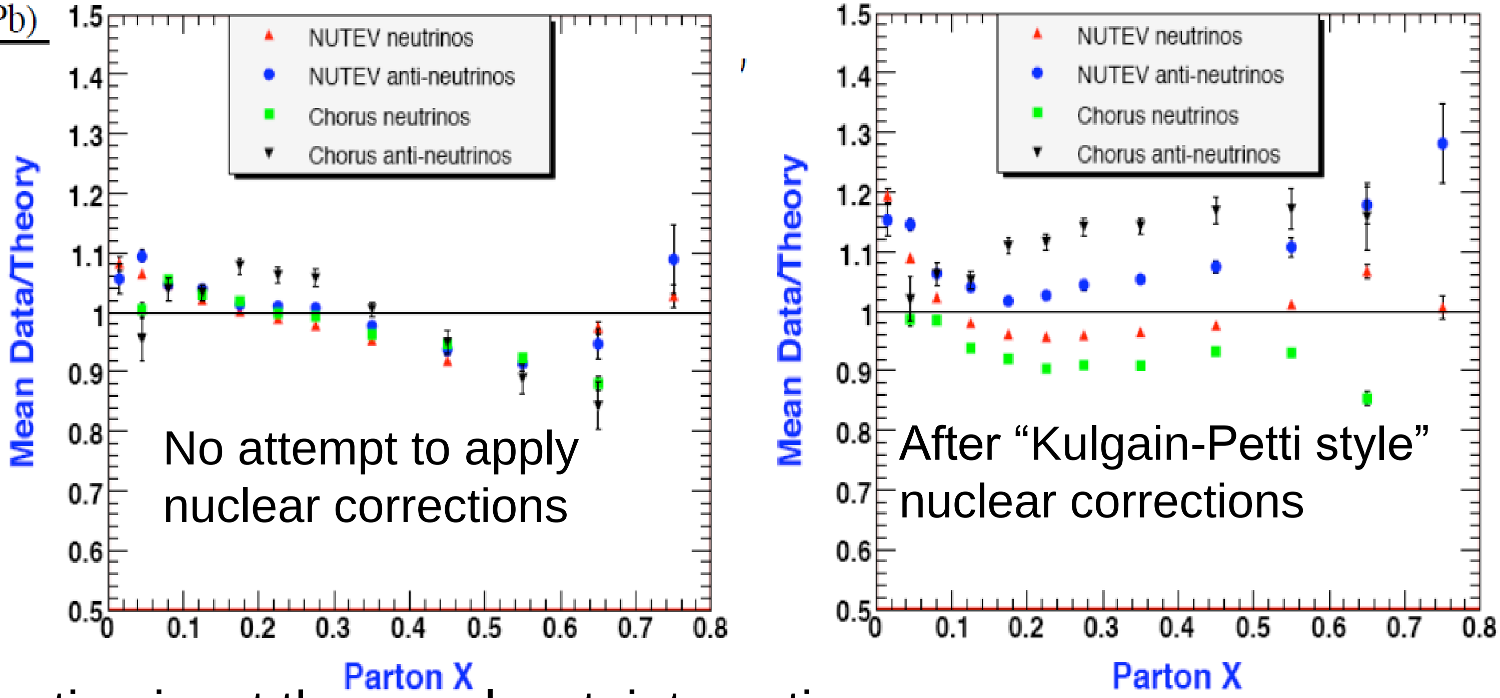
See Mishra talk

Nuclear Corrections and High-x PDFs



CTEQ global fit compared to neutrinos

$$\frac{\sigma(\nu\text{Fe or }\nu\text{Pb})}{\sigma(\nu\text{"}D_2\text{"})}$$



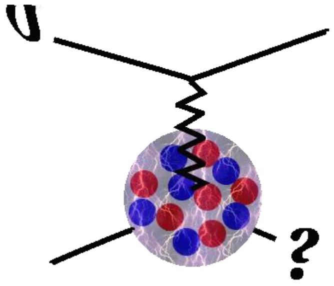
No attempt to apply nuclear corrections

After “Kulgain-Petti style” nuclear corrections

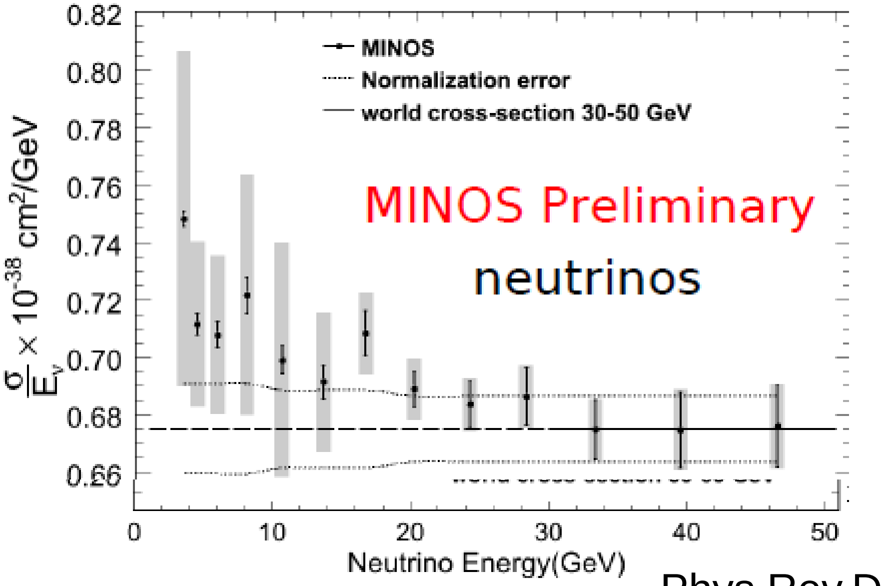
Figures courtesy J. Morfín

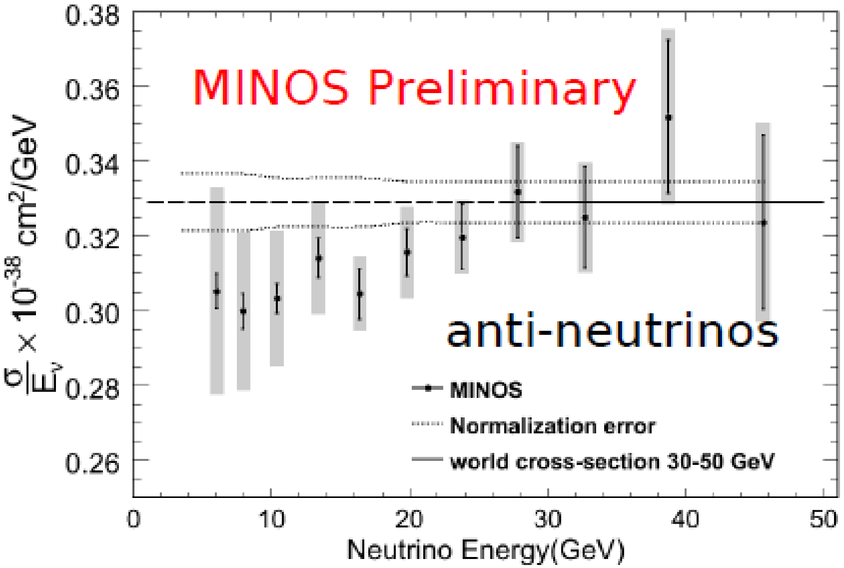
- Situation is, at the very least, interesting
- Suggests that much more data is needed before a reliable model of nuclear corrections is on the horizon

MINOS Total Cross-Section



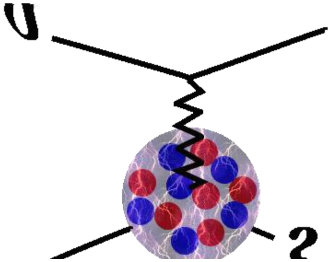
- Attempt to bravely extend low recoil technique to very low energies
  - “Low recoil” sample is visible hadronic energy below 1 GeV, so a fair fraction of the cross-section at the lowest energy (3 GeV)

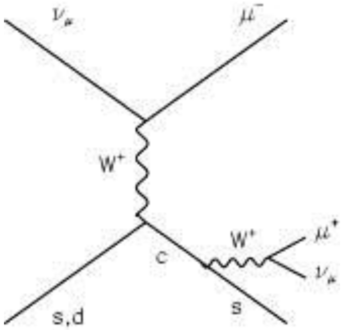




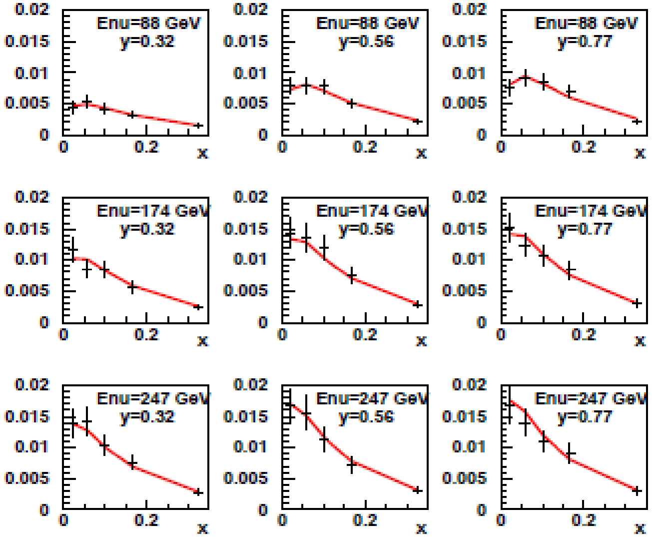
Phys.Rev.D81:072002,2010

Charm Production Cross-Sections





- Charm production of particular interest
  - ☐ Experimentally accessible dimuon signature
  - ☐ Clean probe of strange sea of nucleon

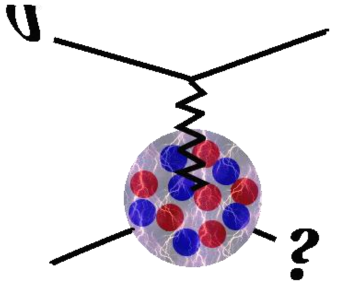


NuTeV dimuon cross-sections
Phys.Rev.Lett.99:192001,2007

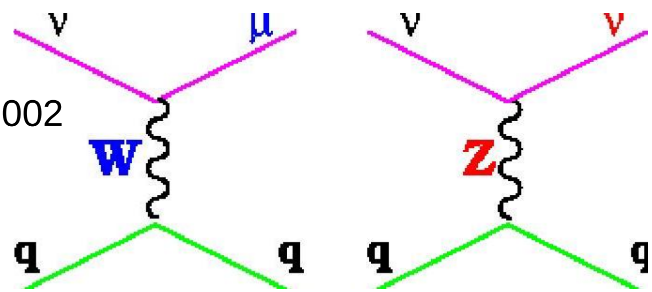
- Addition of data from NOMAD and other charm production exp’ts now giving global fits to strange sea
  - ☐ Test of differences between strange and anti-strange quarks!

Alekhin, Kulagin and Petti, arXiv:0910.3762,
and Phys.Lett.B675:433-440,2009

And of course, “The Gift that Keeps on Giving”

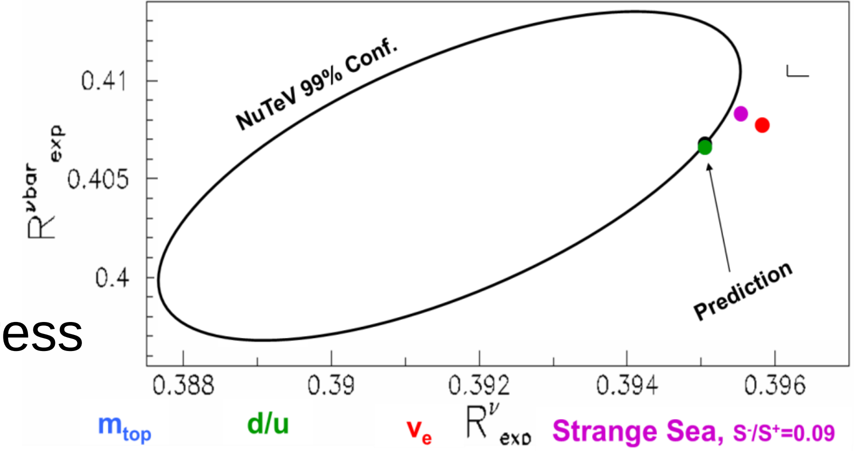


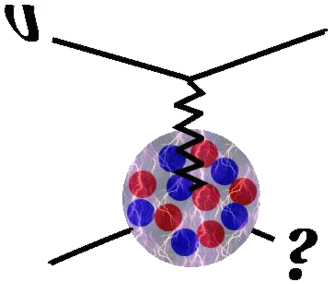
- NuTeV “weak mixing angle” measurement Phys.Rev.Lett.88:091802,2002
  - ☐ Really neutral-to-charged current cross-sections in neutrino and anti-neutrino beams
  - ☐ NuTeV got the “wrong” answer
- Complications of the target quarks inside a nucleus leave room to interpret the result
  - ☐ Isospin violation in PDFs, asymmetric strange sea
  - ☐ “Last word” from NuTeV in progress



Paschos - Wolfenstein Relation

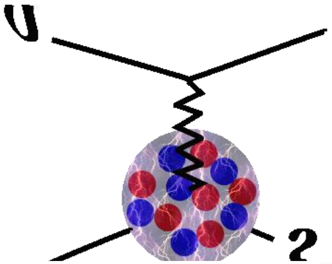
$$R^{-}=\frac{\sigma_{NC}^{\nu}-\sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu}-\sigma_{CC}^{\bar{\nu}}}=\rho^{2}\left(\tfrac{1}{2}-\sin^{2}\theta_{W}\right)$$





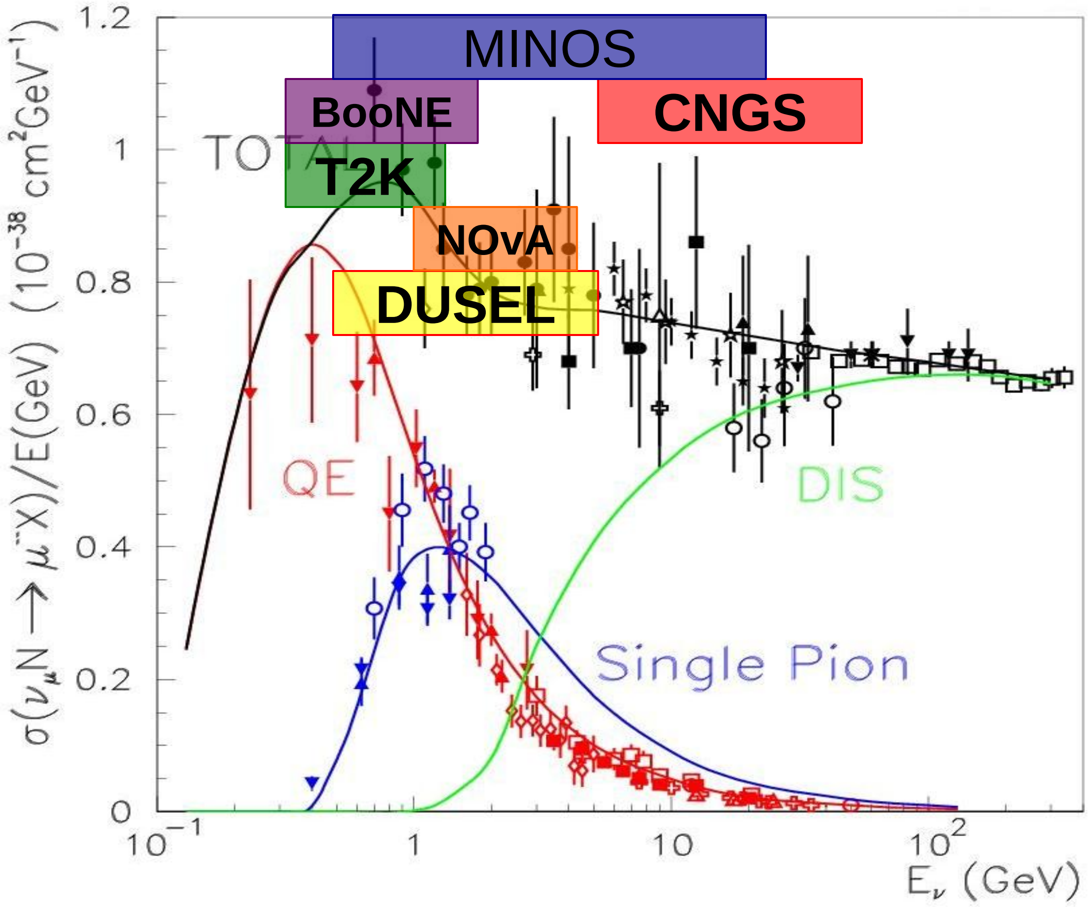
NEW EXPERIMENTS

What are Energies and Targets of Oscillation Experiments?



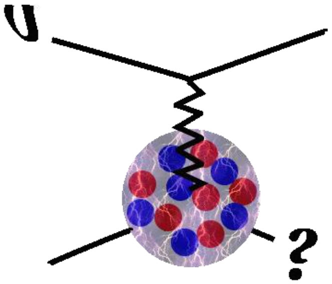
- Target Materials:
  - MINOS = Fe
  - BooNE = CH
  - CNGS = Pb, Ar
  - T2K = H_2O
  - NOvA = CH
  - DUSEL = H_2O, Ar

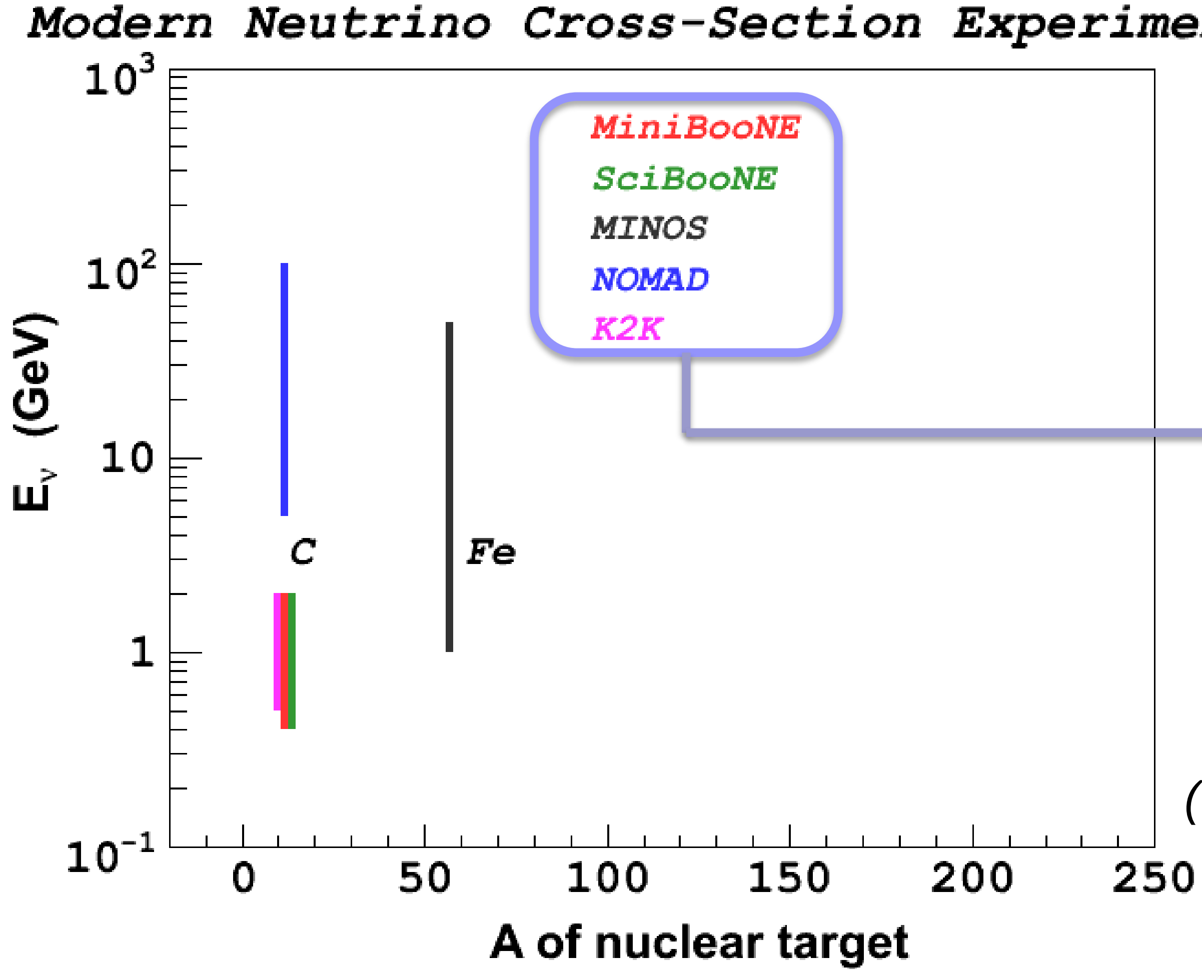
(Compilation from D. Schmitz)



charged-current cross-sections (G. Zeller)

Energies and Targets of Cross-Section Measurements

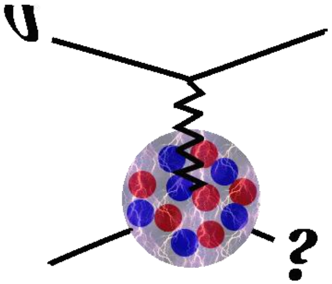


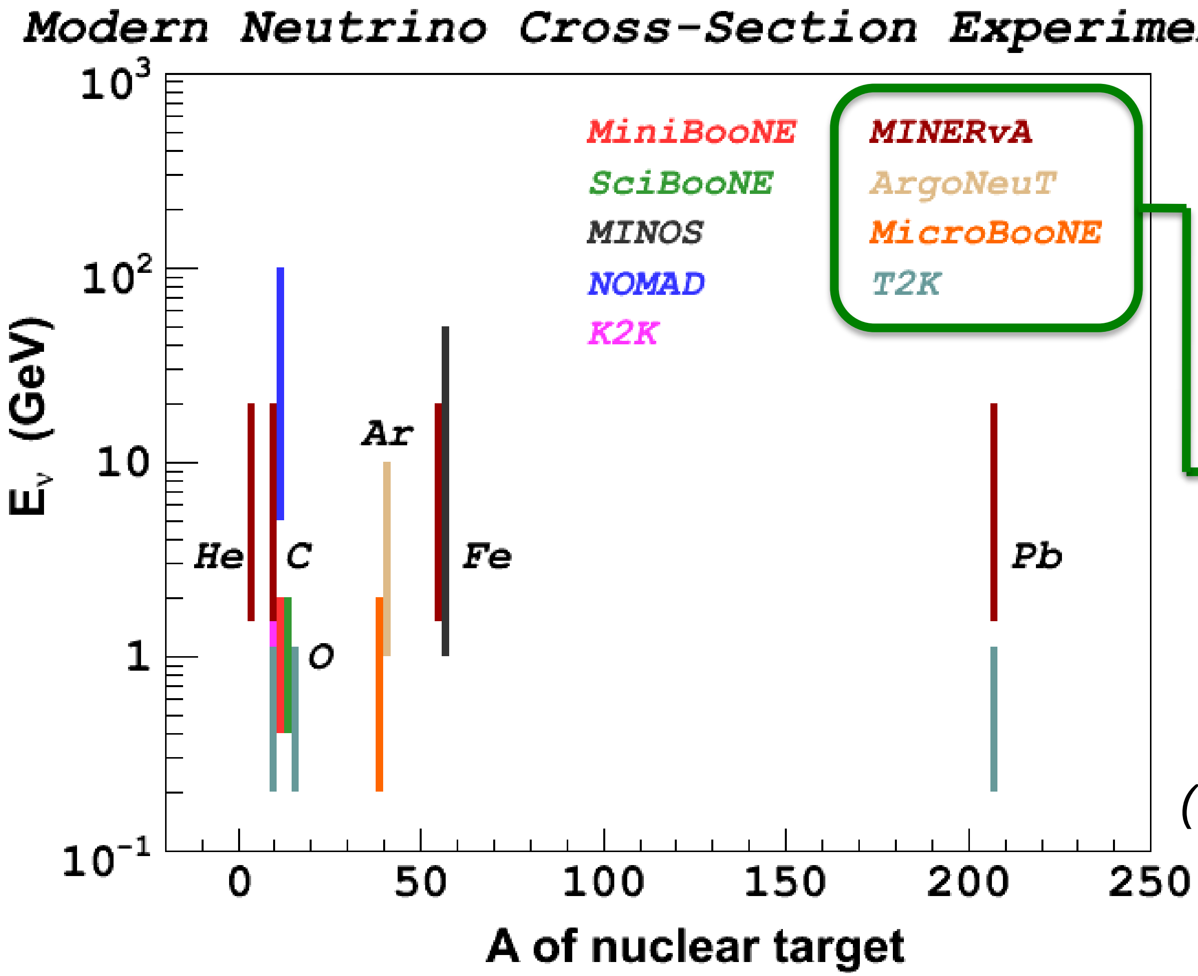


recent results and/or currently analyzing and publishing new cross-section data

(Compilation from D. Schmitz)

Energies and Targets of Cross-Section Measurements

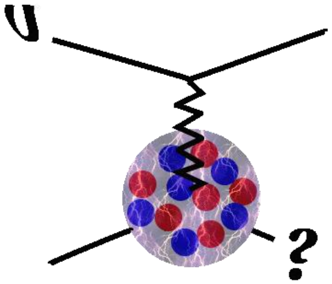




near future cross-section experiments

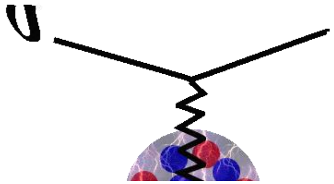
(Compilation from D. Schmitz)

What are these experiments?

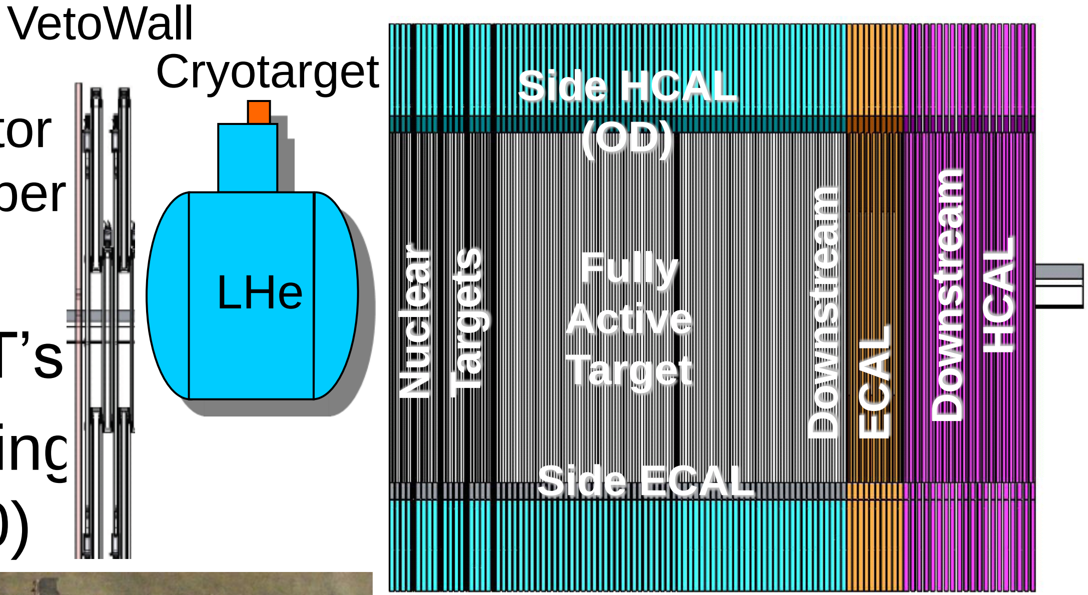


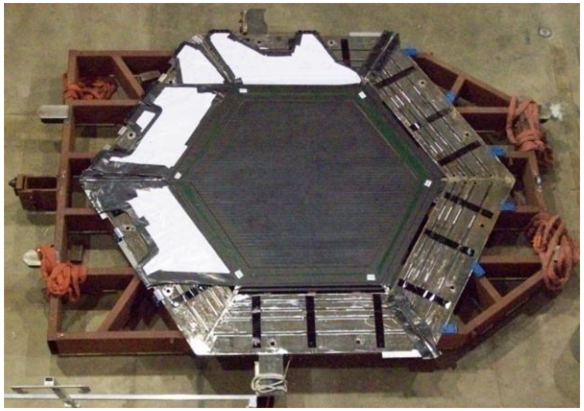
- MINERνA: in NuMI at Fermilab
  - ☐ Fine-grained scintillator detector
  - ☐ Nuclear targets of He, C, H_2O, Fe, Pb
- T2K 280m Near Detector at J-PARC
  - ☐ Fine-grained scintillator, water, and TPC's in a magnetic field
- NOνA near detector: to run in 2013
  - ☐ Liquid scintillator in off-axis beam, running above ground before 2013
- MicroBooNE: to run in/after 2013
  - ☐ Liquid Argon TPC in FNAL Booster Beam
  - ☐ Some data from ArgoNeuT test in NuMI

MINERνA Detector

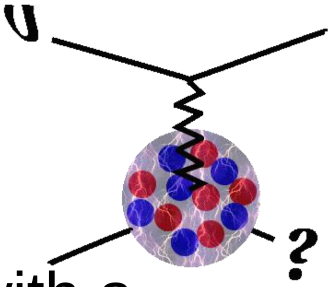


- 120 modules
  - Finely segmented scintillator planes read out by WLS fiber
  - Side calorimetry
- Signals to 64-anode PMT's
- Front End Electronics using Trip-t chips (thanks to D0)
- Side and downstream EM and hadron calorimetry
- MINOS Detector gives muon momentum and charge

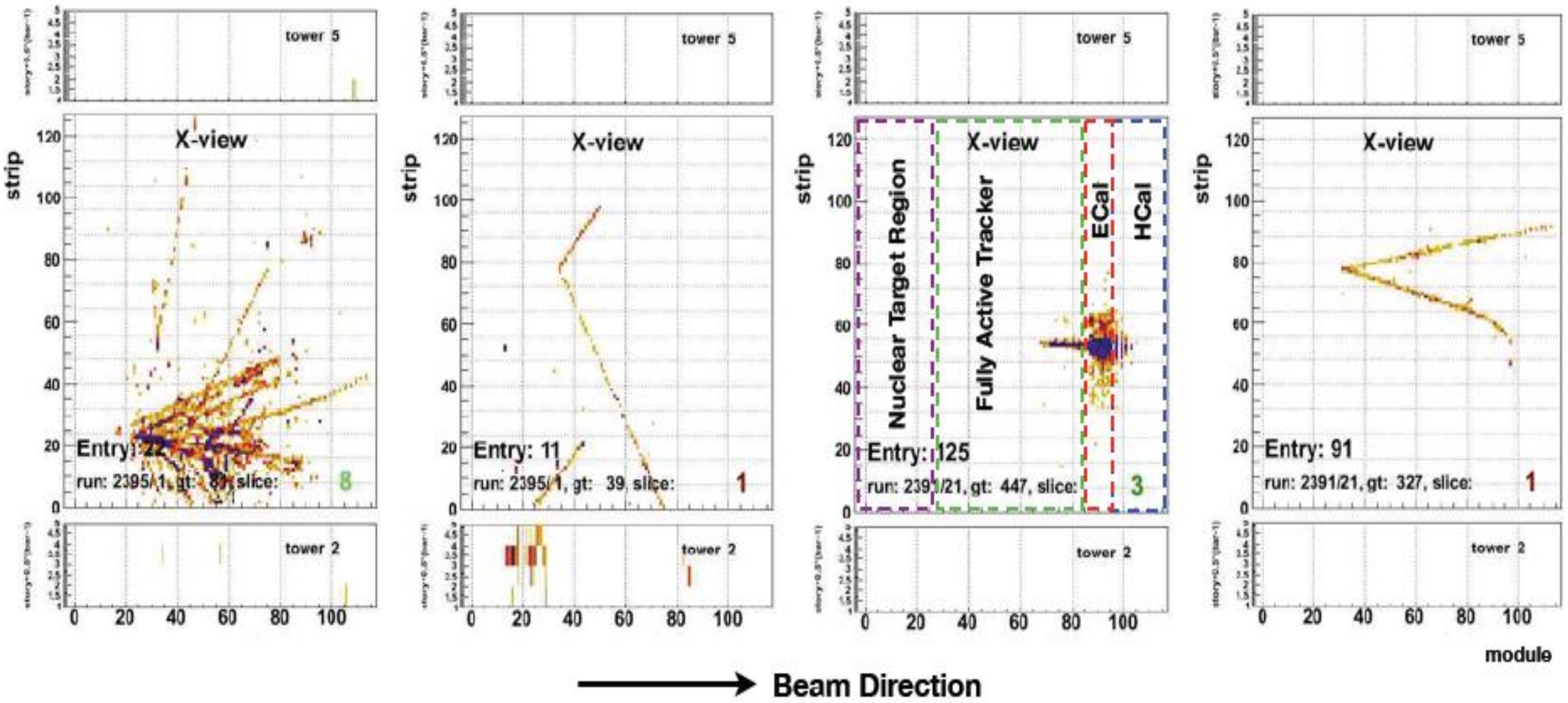




MINERvA Sees

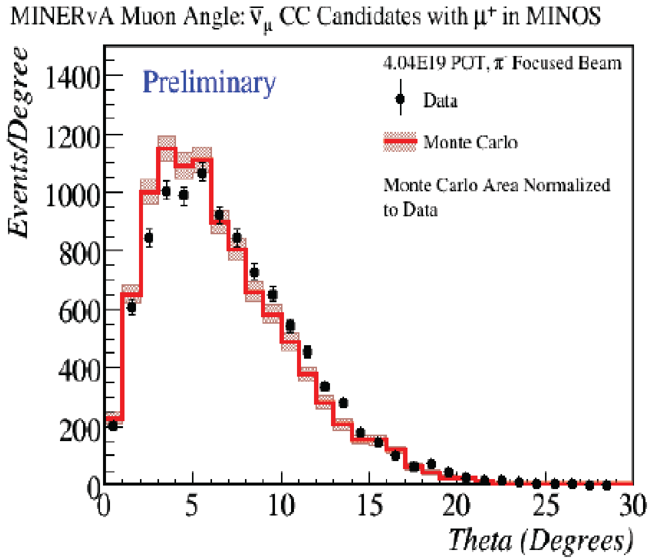


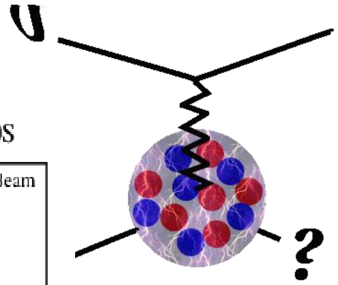
- Integrated about 1E20 POT in anti-neutrinos with a partial detector and in neutrinos with a full detector
  - A gallery of neutrino events: range of energies and interactions



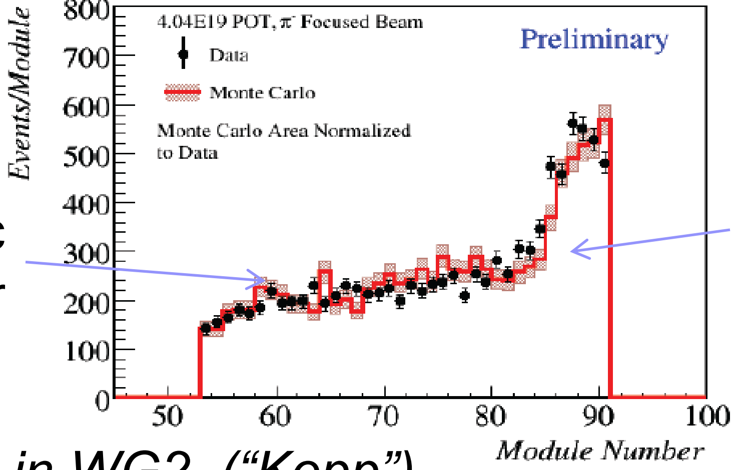
First MINERvA Distributions

- MC generator is GENIE v2.6.0 with a full GEANT4 detector simulation.
- 4.04e19 POT in anti-ν mode
- Inclusive anti-ν CC
  - Note the cut-off in momentum - this is not our full kinematic range!



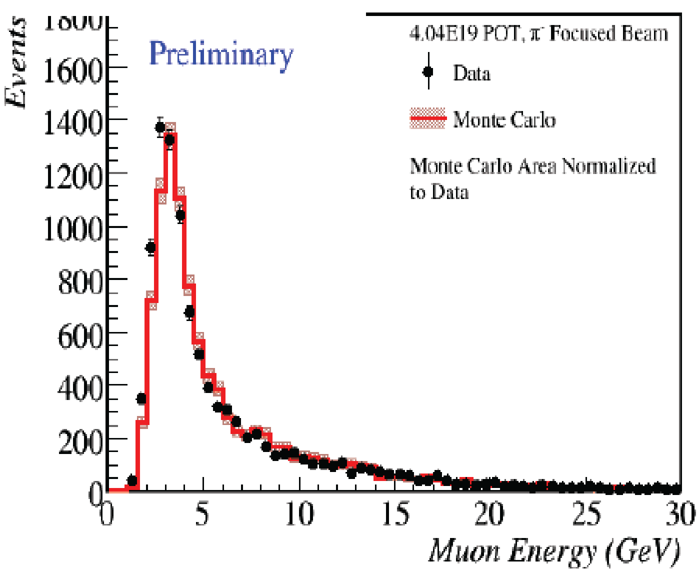


Current absolute flux uncertainty on the (untuned anti-ν) MC is ~30-40% (error not shown.)

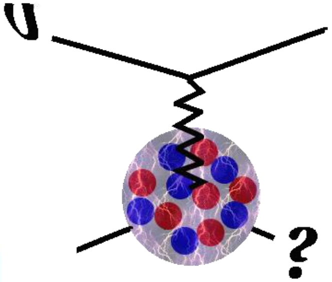


Plastic tracker

ECAL



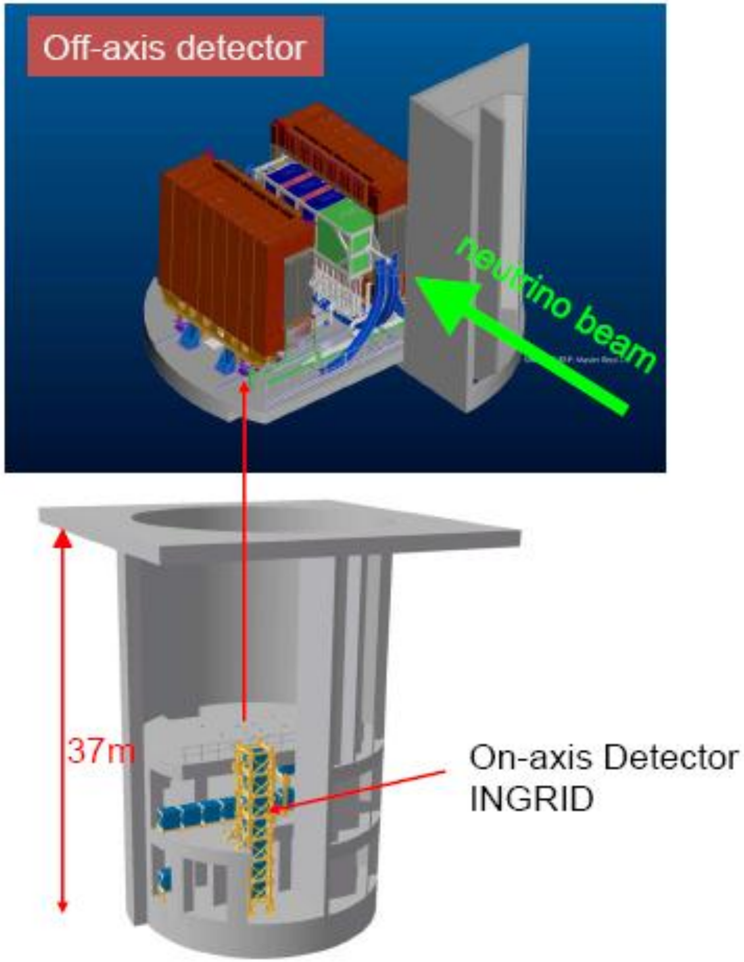
See talk in WG2 ("Kopp")



T2K Near Detectors

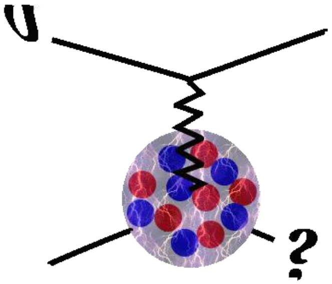
T2K Near Detector Suite

- Understand the neutrino beam before oscillations occur
- On – Axis Detector
  - Monitor beam direction
  - Monitor beam intensity
- Off – Axis Detector
  - Beam flux
  - Beam ν_e contamination
  - Cross sections



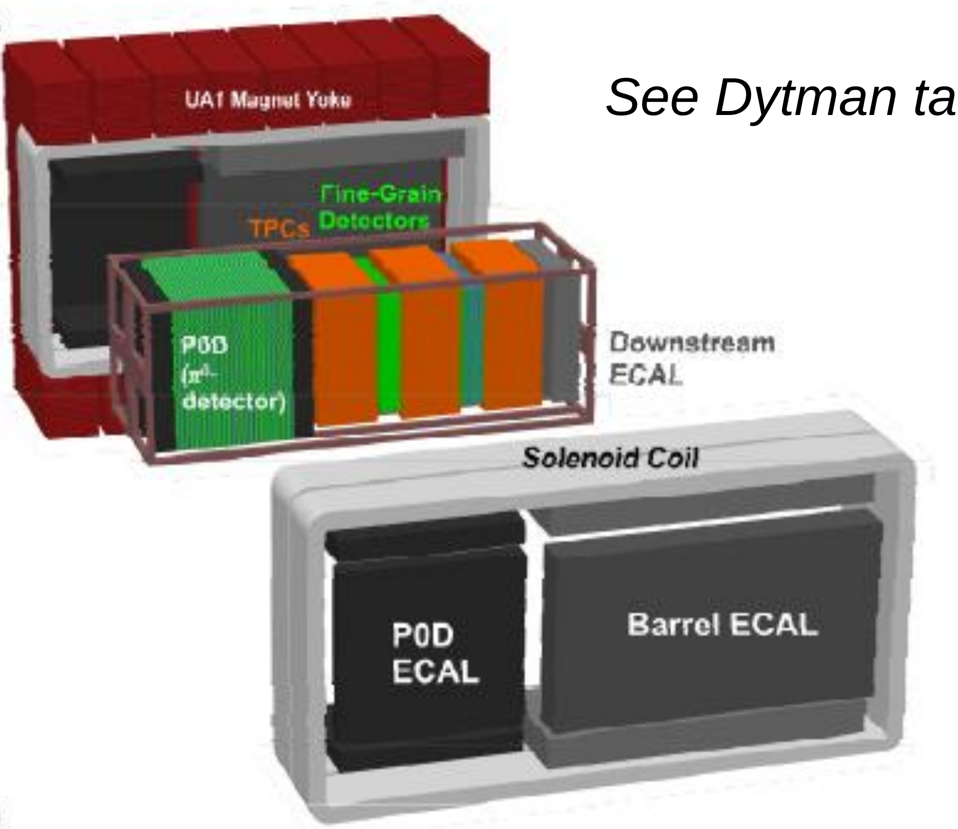
slide courtesy of R. Terri

Off-Axis Detector



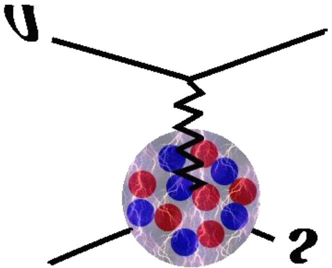
- UA1 Magnet 0.2T field
- Includes a water target in P0D and Tracker
  - Understand interactions at SK
- Tracker Region
  - Fine Grained Detectors (FGDs) & TPCs
  - Particle Tracking
- P0D
  - Measure NC π^0 rate
- ECAL
  - Surrounds tracker and P0D
  - Capture EM energy
- SMRD
  - Muon ranging instrumentation in the magnet yoke

See Dytman talk



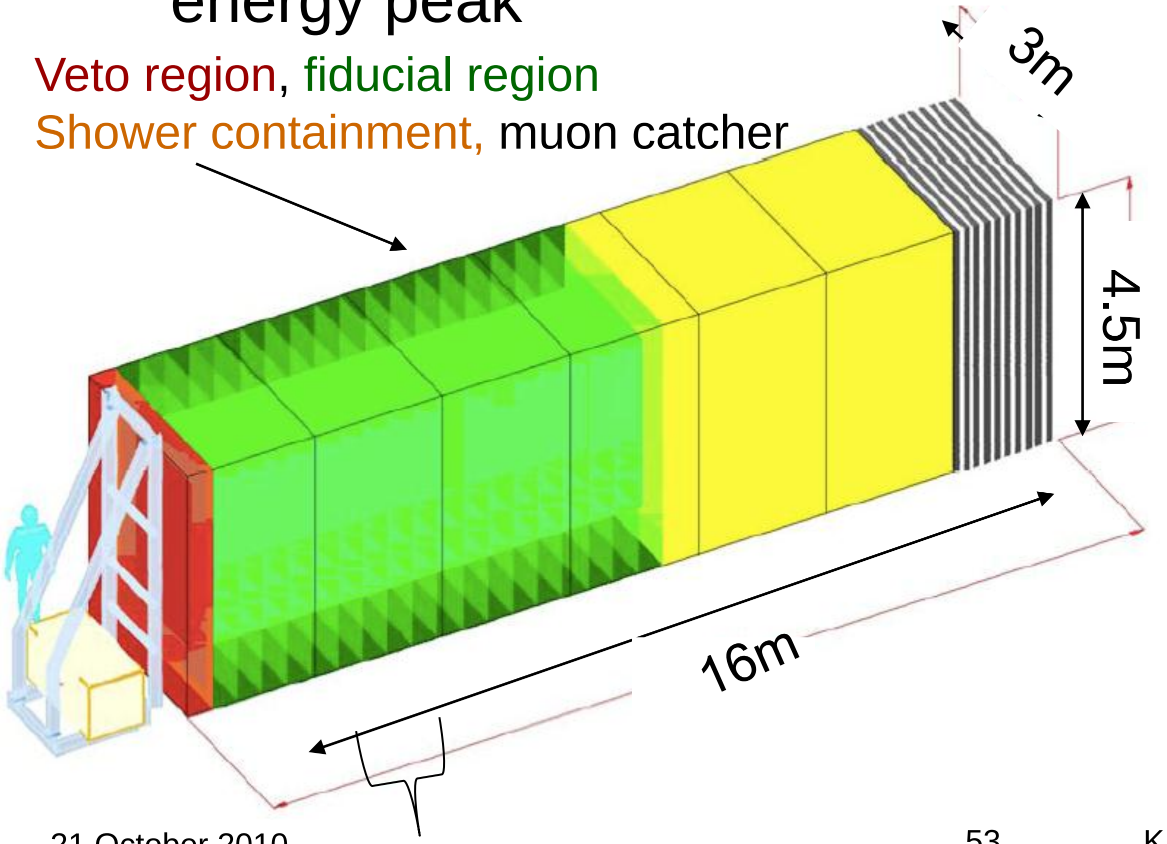
slide courtesy of R. Terri

NOvA Near Detector



- Scintillator extrusion cross section of 3.87cm x 6cm , but with added muon range stack to see 2 GeV energy peak

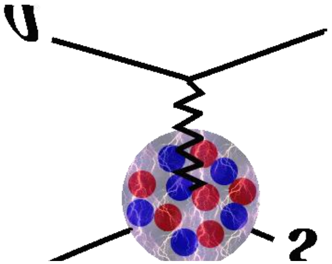
Veto region, fiducial region
Shower containment, muon catcher



•Range stack: 1.7 meters long, steel interspersed with 10 active planes of liquid scintillator

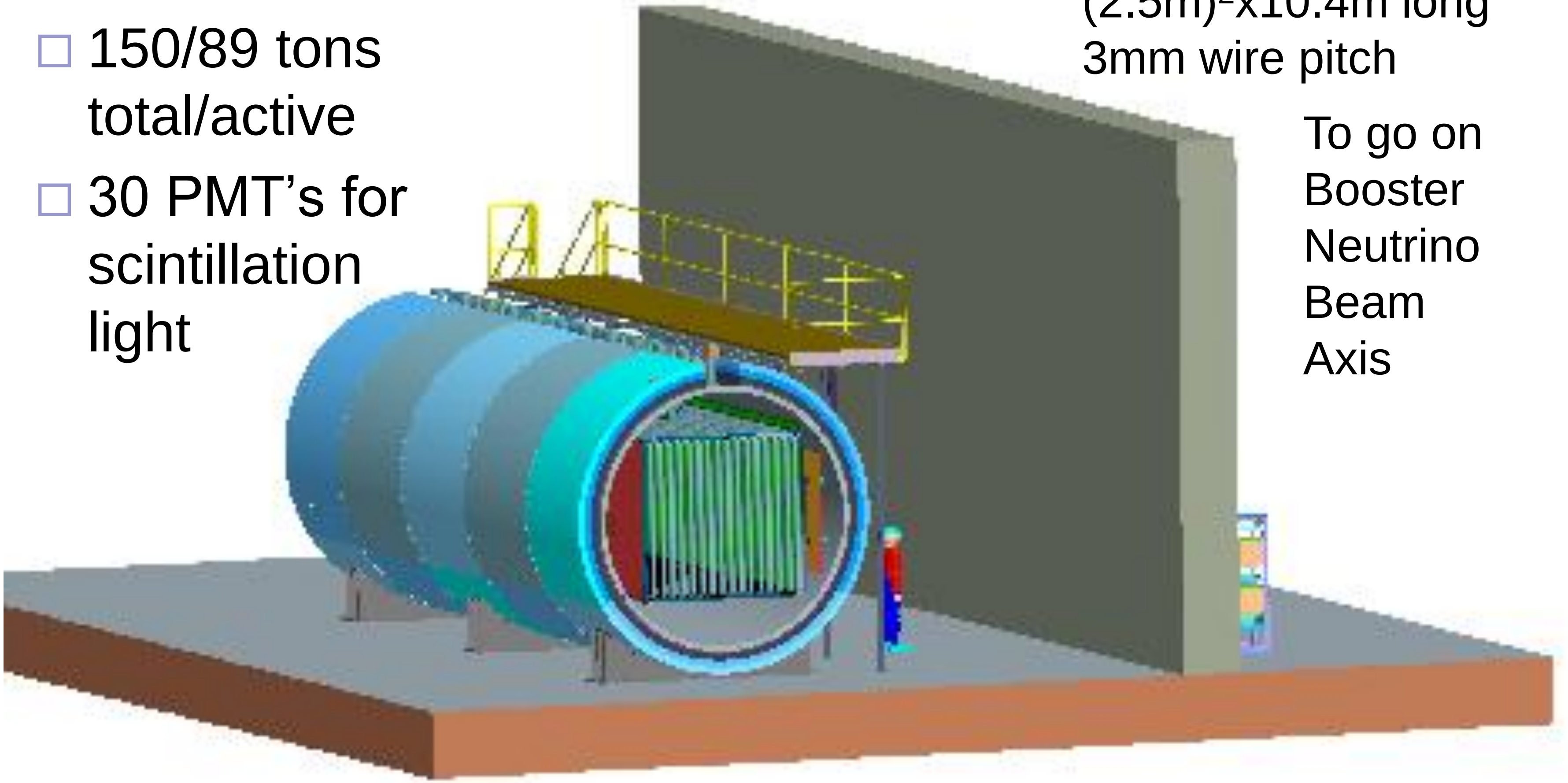
•First located on the surface, then moved to final underground location

MicroBooNE



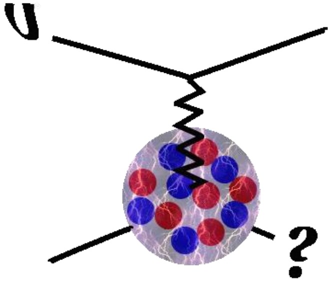
- Liquid Argon TPC
  - 150/89 tons total/active
  - 30 PMT’s for scintillation light

TPC:
(2.5m)^{2}x10.4m long
3mm wire pitch



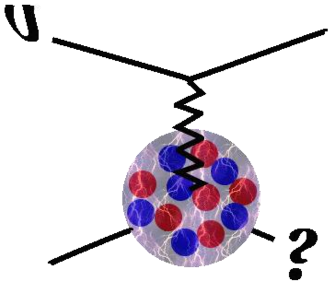
To go on Booster Neutrino Beam Axis

Future Experiments at a Neutrino Factory



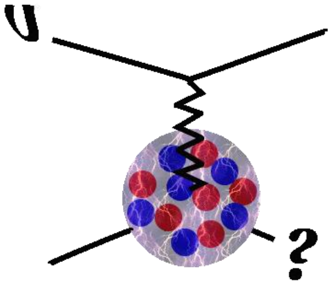
- Early on in the consideration of neutrino factories, this generated a lot of excitement
  - Concepts for experiments tried to leverage flux in high energy beams
  - Precision weak interaction physics through νe→ νe
  - Separated flavor structure functions through neutrino and anti-neutrino scattering on H_2 and D_2 targets
- Expect proposals for these experiments, or sensible versions thereof, to match parameters of whatever we eventually build

D. Harris, KSM, AIP Conf.Proc.435:376-383,1998;
AIP Conf.Proc.435:505-510,1998,
R. Ball, D. Harris, KSM, hep-ph/0009223
M. Mangano et al. CERN-TH-2001-131, 2001
I.I. Bigi et al, Phys.Rept.371:151-230,2002.



CONCLUSIONS

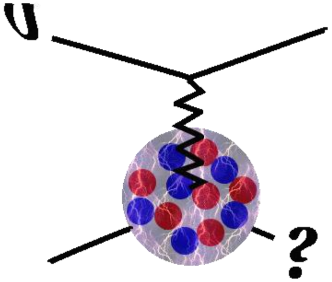
What is Left to Say?



> *"I'm not going to discuss neutrino interactions in my summary" – R.G.H. Robertson, Neutrino 2010*

- Neutrino interactions, despite the mixed press, is a vibrant and evolving field
- Near future experiments have the capability to meet a number of our scientific goals, to resolve a number of interesting puzzles, and to provide critical input to oscillation experiments
- In the far future, a program in interactions would likely play a similar role at a neutrino factory
  - When life and governments offer us such wonderful opportunities, we should and will make the most of them!

Acknowledgments



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