The impact of neutrino scattering data for oscillation measurements

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William & Mary

13th International Workshop on
Neutrino Factories, Superbeams & Beta Beams

University of Geneva/CERN
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Outline

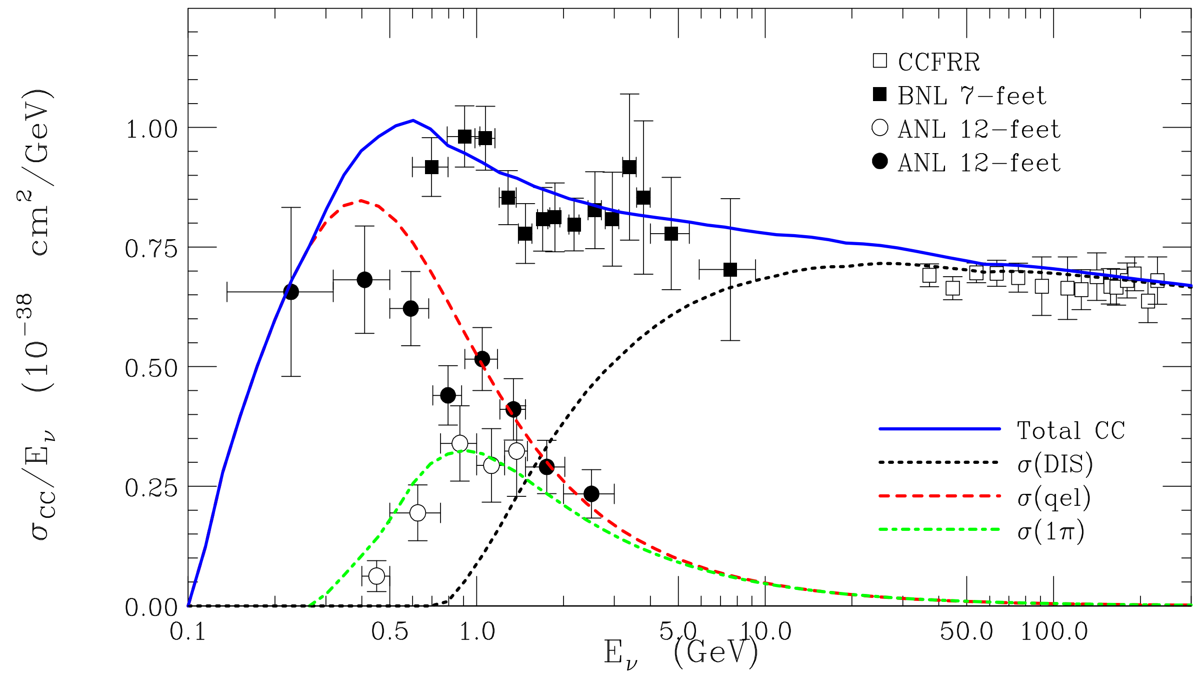
- A bit of history …
- A few examples
  - muon neutrino disappearance
  - antineutrino disappearance
  - neutrino electron appearance
  - The QE saga as a lesson
- Looking forward
  - Precision disappearance and appearance
  - The roles/needs for the players of the future

An obvious things to start with …

- Total cross section -> event totals -> sensitivity
- Oscillations depend on L/E
  - Improved oscillations measurements require better modeling of "E" based on final state
  - FSI/nuclear effects
    - What you see E_{vis} doesn't add up to "*ν*"
  - Angles modified, particles absorbed
    - Can't always trust kinematic reconstruction
- Backgrounds are need to be modeled with their own cross sections
  - More aggressive signal selection & background suppression can imply more systematics unless one knows the background accurately
- Need to know rates and properties of below-threshold particles
  - Background contributor, resolution killer & systematic bias

We were "here" just after proof of oscillations …

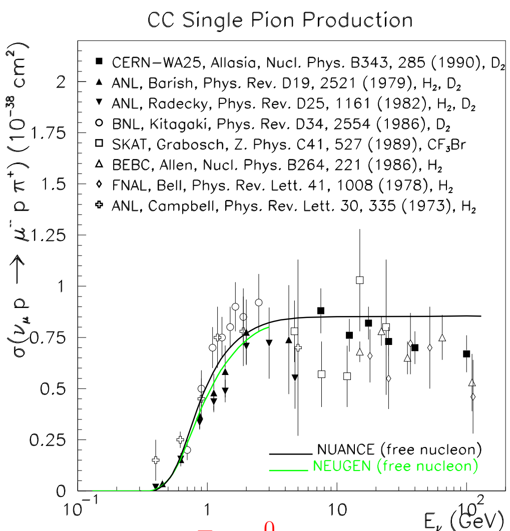
- NUINT01: Lipari, arXiv hep-ph/0207172



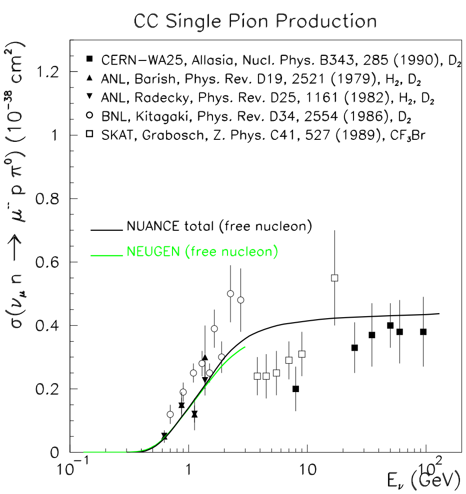
- The first of a long set of productive workshops bringing together the neutrino and electron scattering communities, theory and experiment
  - Recall that Jlab was in its 6th year of beam
  - Their early results were starting to pour in – it was a very exciting time for the hadronic physics community

From S. Zeller's nufact03 neutrino data summary

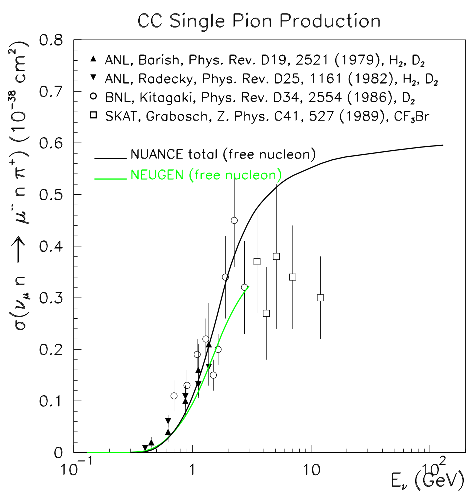
$\nu_\mu p \rightarrow \mu^- p \pi^+$

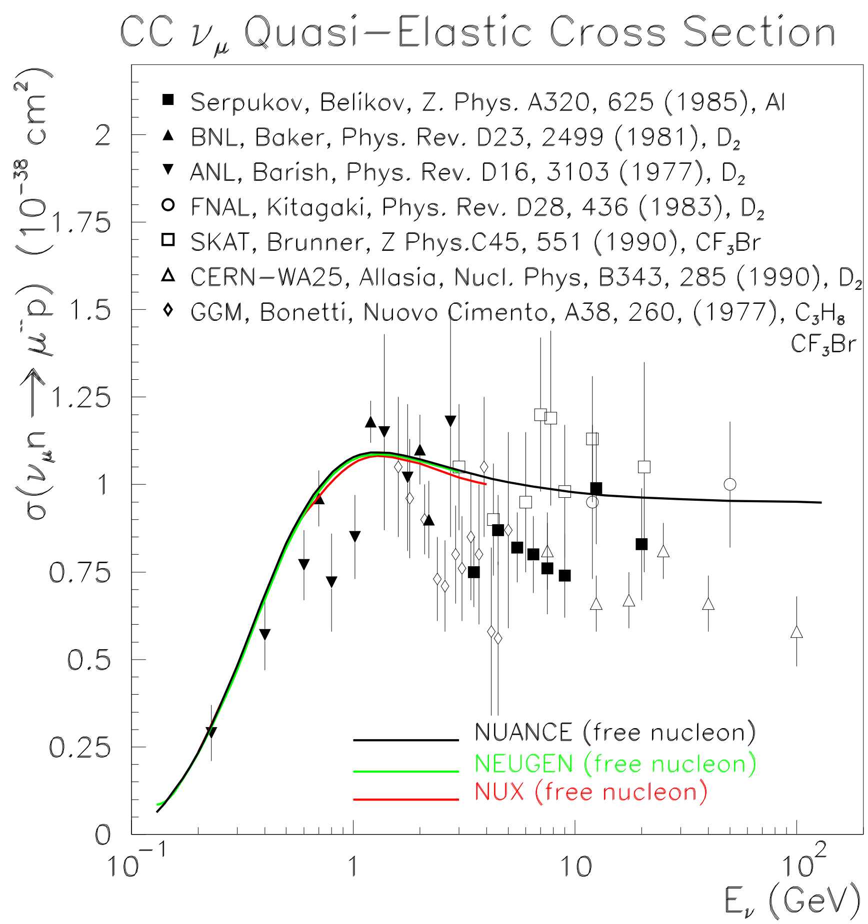


$\nu_\mu n \rightarrow \mu^- p \pi^0$

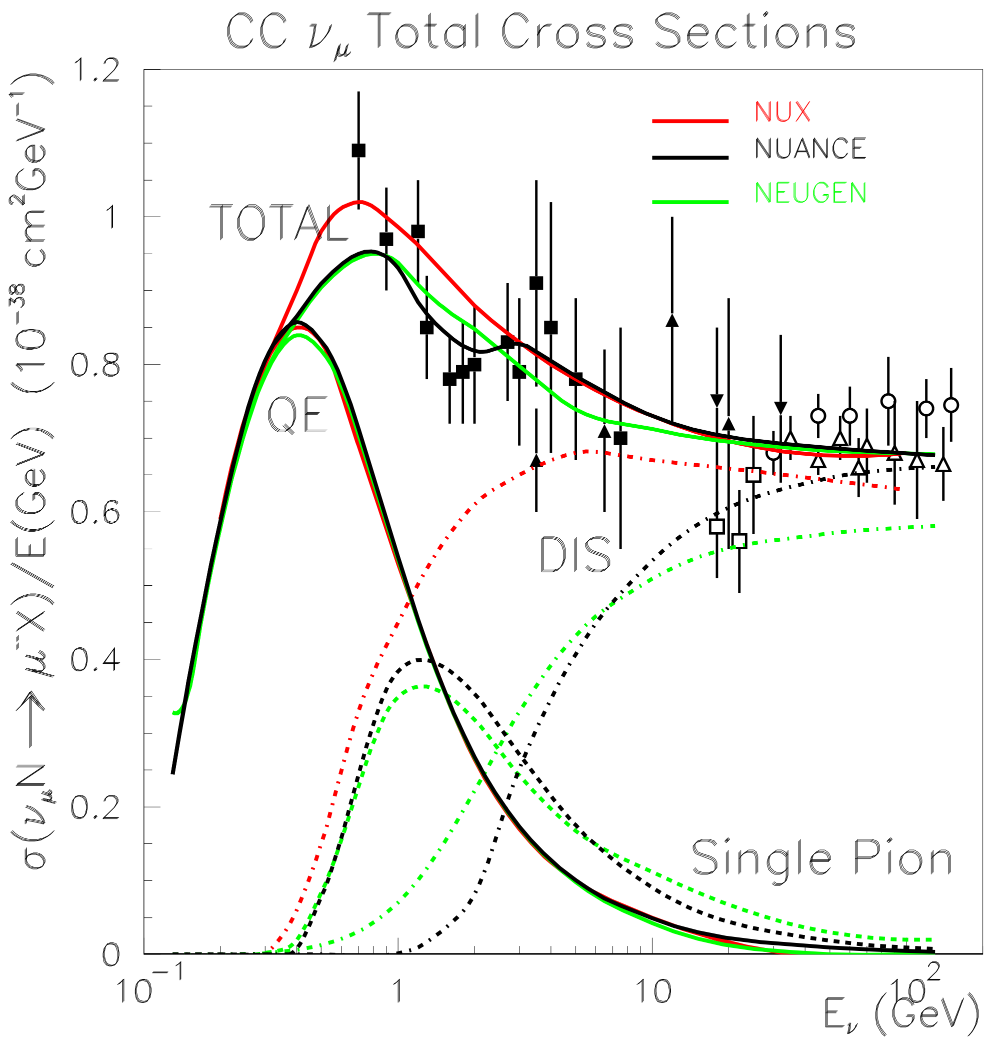


$\nu_\mu n \rightarrow \mu^- n \pi^+$





From S. Zeller's nufact03 neutrino data summary



- Program of systematic comparisons of the generators
- Note the correlation Between the different generators
- Spread of generators is not a good error estimate

An example use of scattering data and model/generators

MINOS neutrino disappearance analysis …

(c.f. J. Hartnell's talk)

AGKY model of recoil system (2008)

- A hadronization model for few-GeV neutrino interactions
  - T. Yang, C. Andreopoulos, H. Gallagher, K. Hofmann, P. Kehayias, Eur. Phys. J. C (2009) 63, 1
    - Into GENIE
- Tuned on an extensive mining of bubble chamber data
- Developed to try to model the initial differences seen in MINOS ND NC events

An example of a plot used in their validation

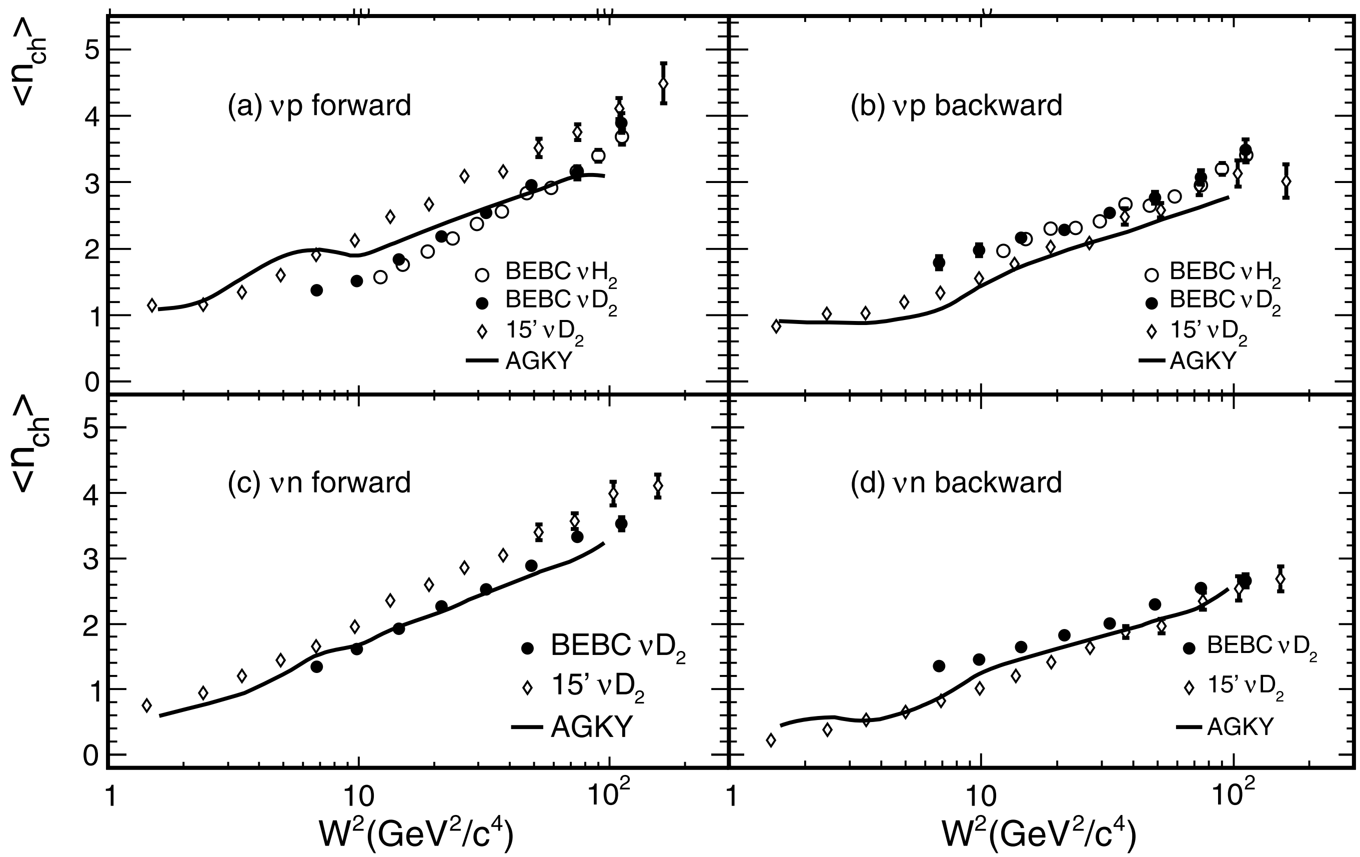
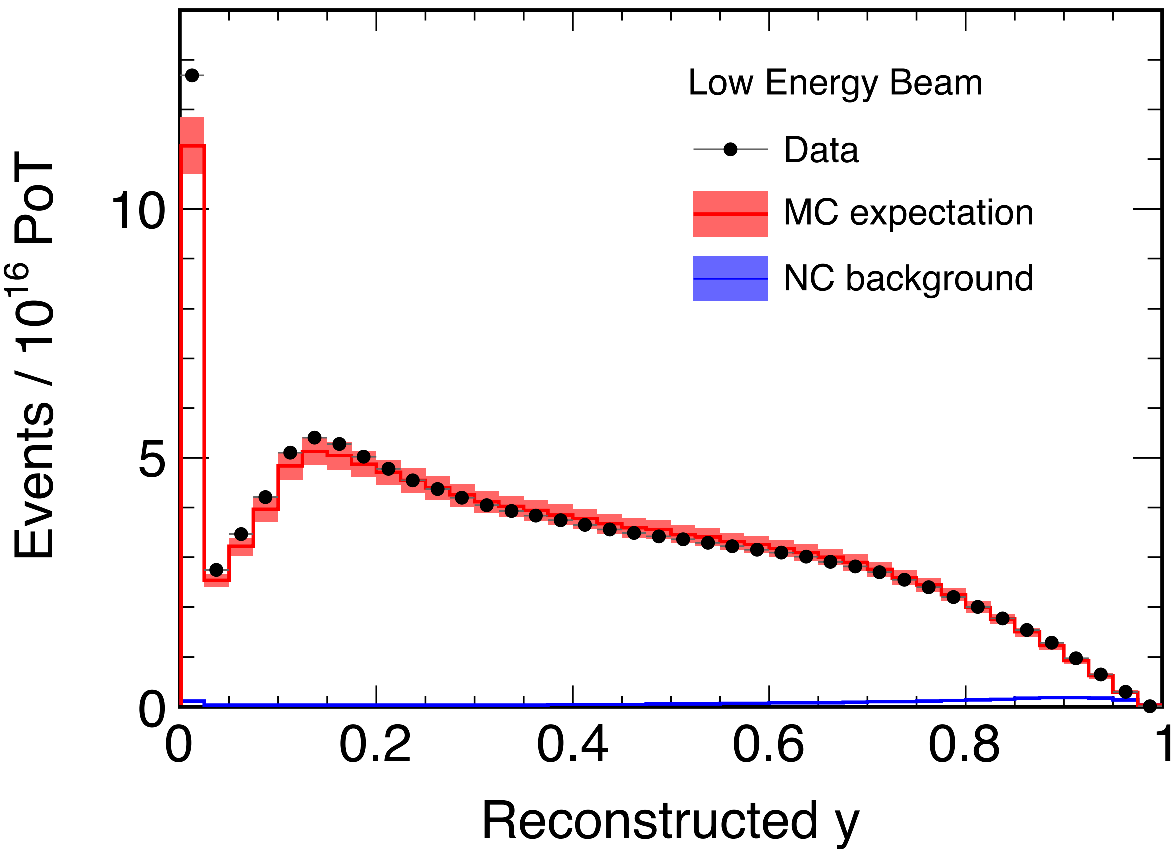
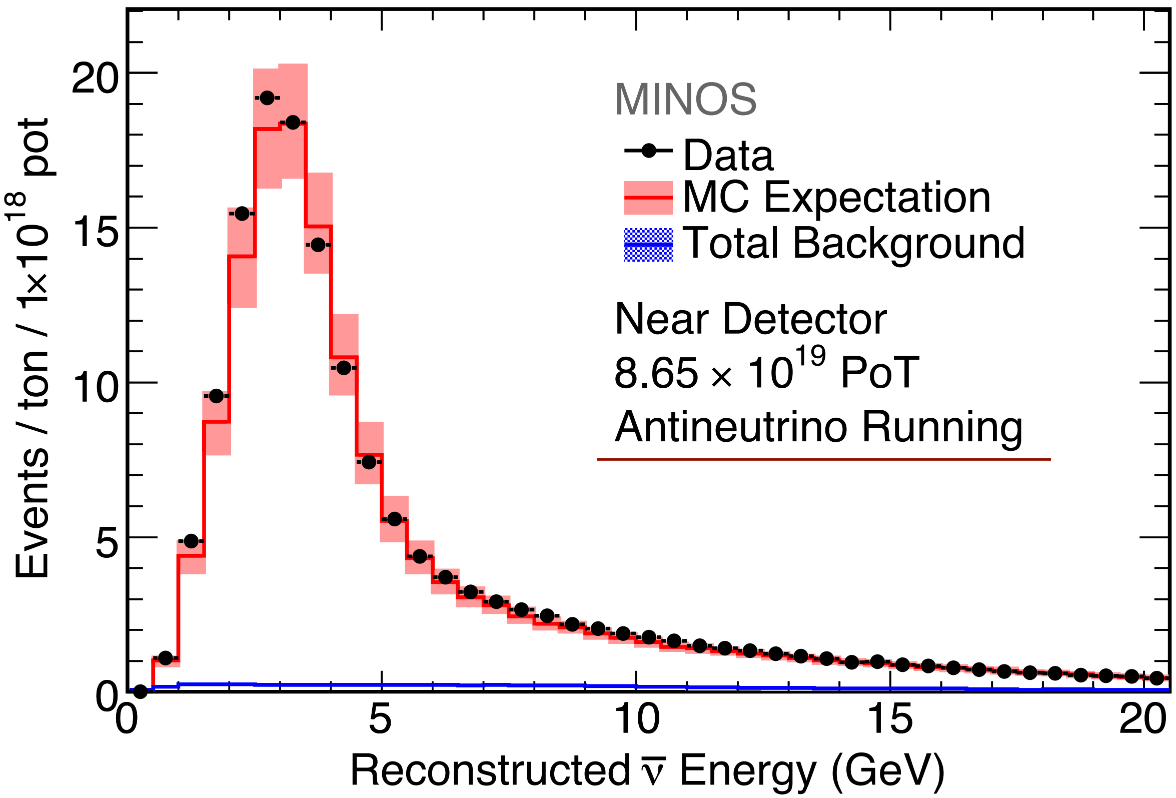


Fig. 7 Average charged-hadron multiplicity in the forward and backward hemispheres as functions of W^2: (**a**) νp, forward, (**b**) νp, backward (**c**) νn, forward, (**d**) νn, backward. Data points are taken from [7, 25, 26]

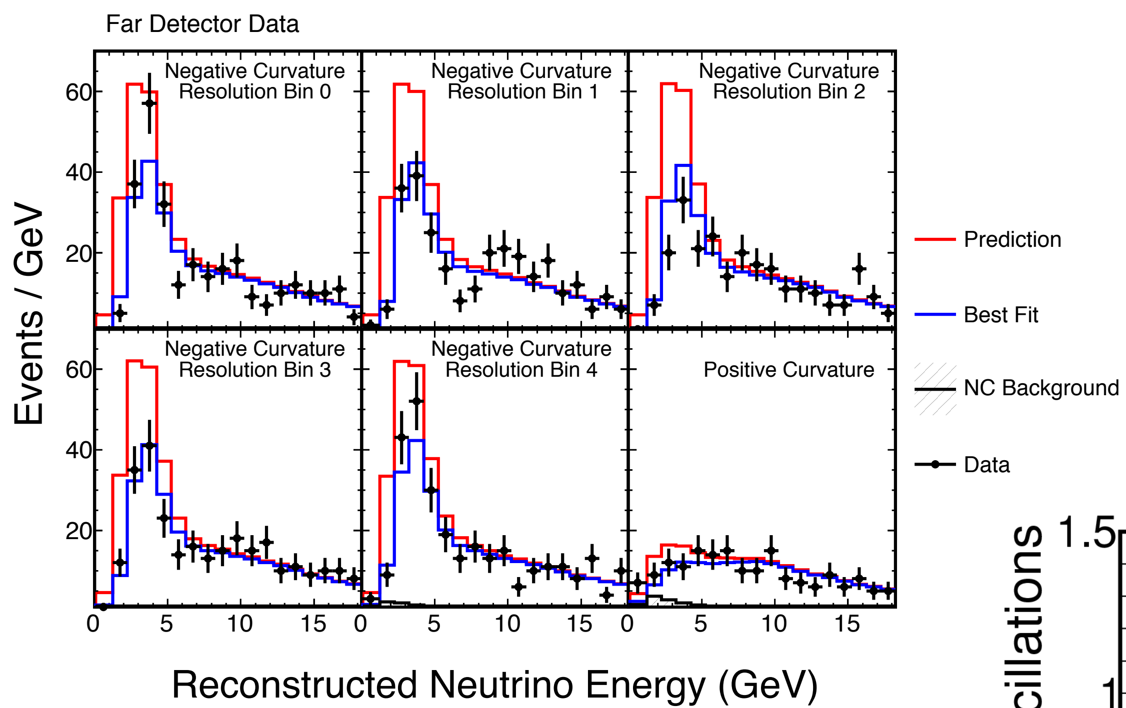
Example distribution (FHC, CC selected, Near Detector)

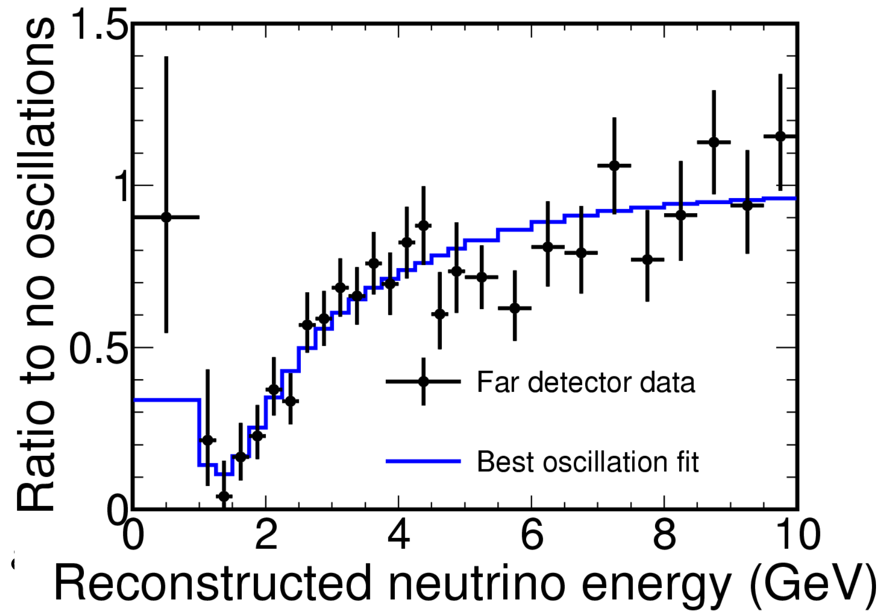


Example (RHC – antineutrino-tune) distribution after beam tuning



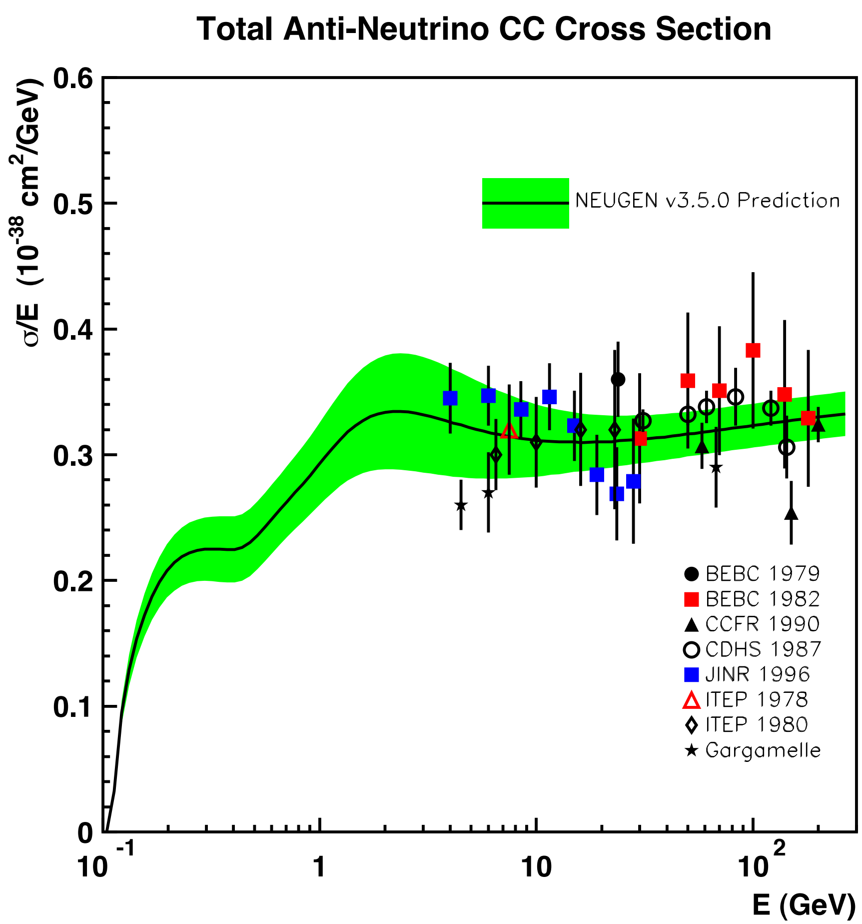
MINOS FD data by resolution bin

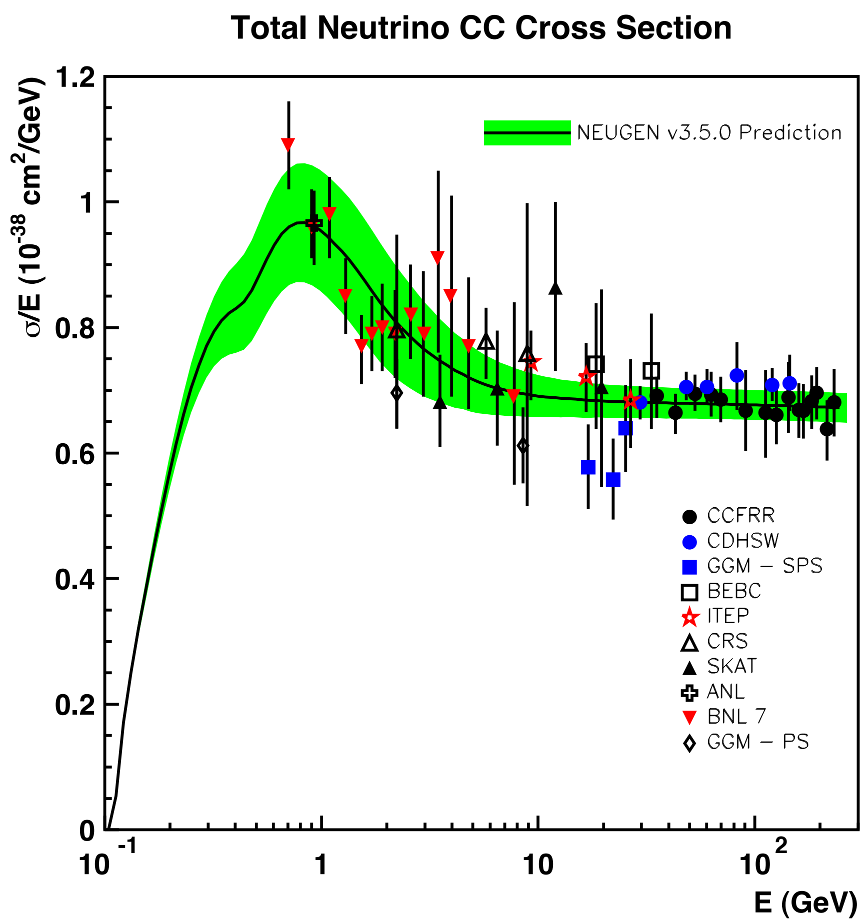




Genie/NEUGEN moving to more complete error estimates

for the MINOS 2008 disappearance analysis
(See Gallagher 45th Karpacz School, ’09)

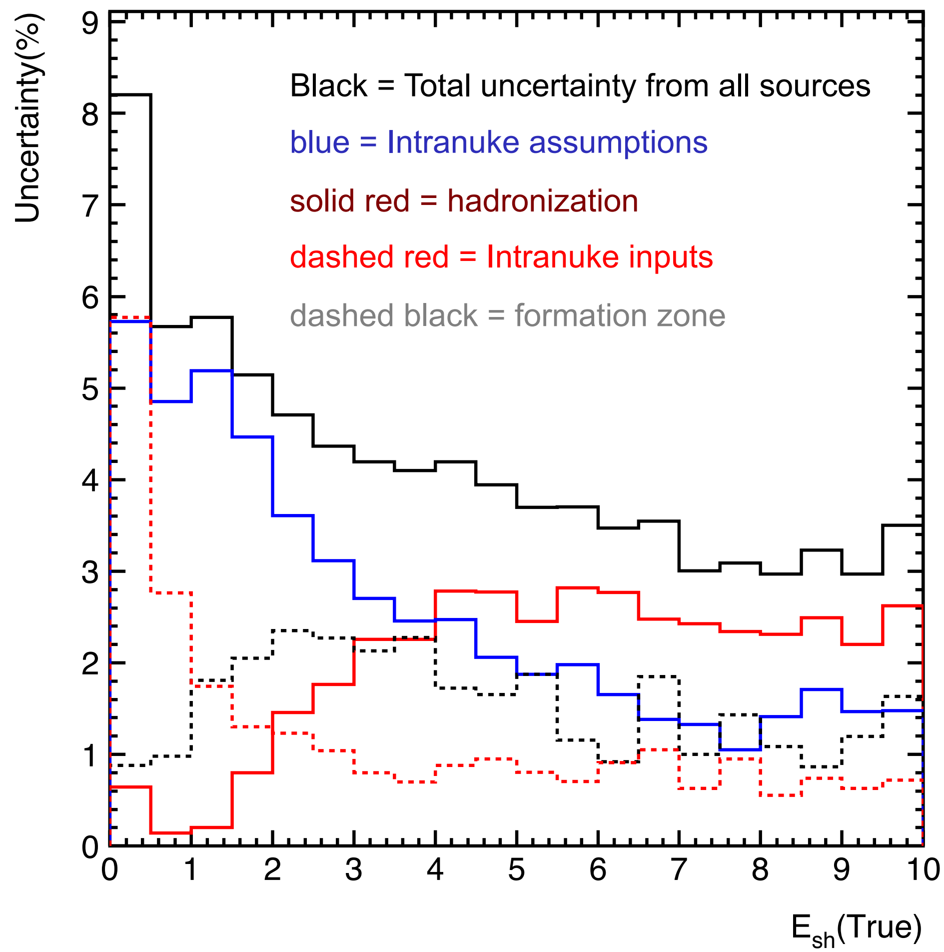




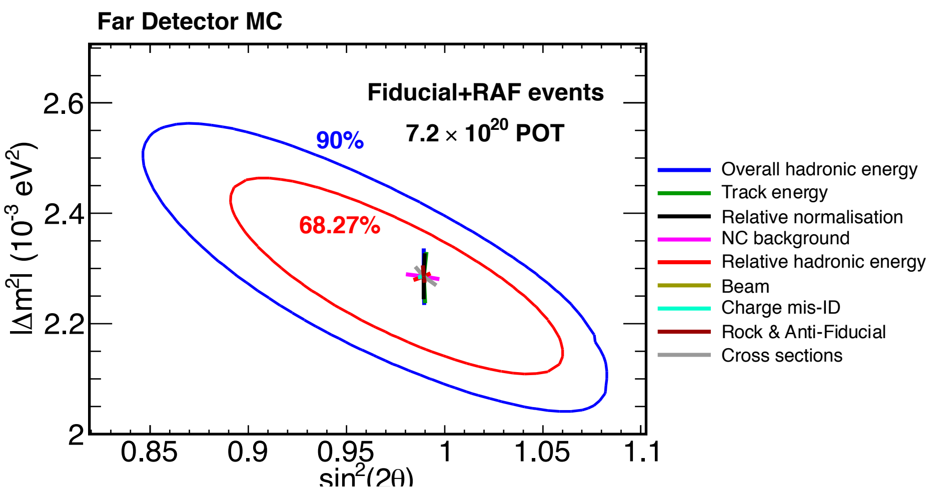
Dytman, Gallagher & Kordosky (arXiv:0806.2119)

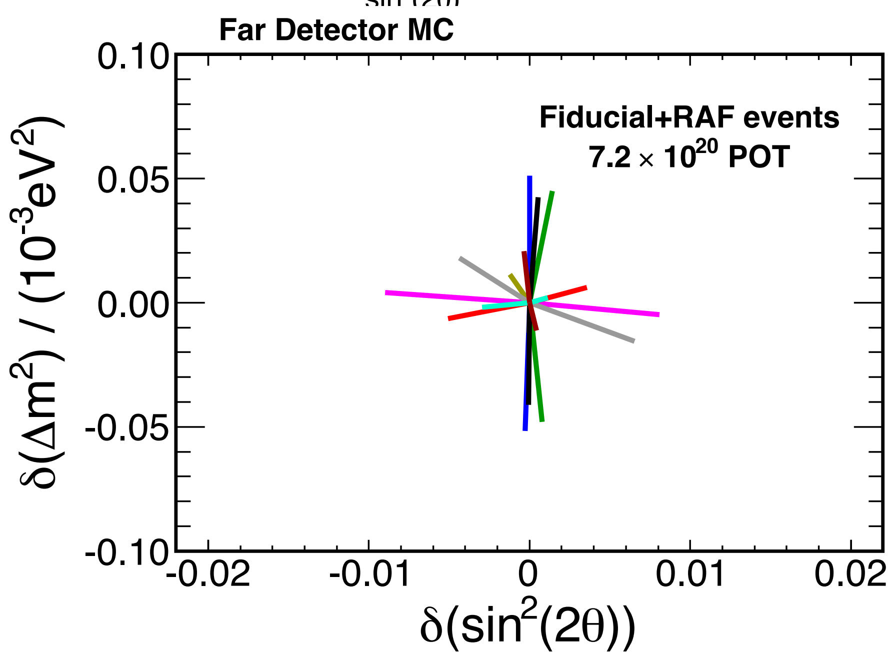
- Systematic error estimate on the visible (calorimetric) shower energy for the MINOS for disappearance analysis

branching ratios	
parameter	1σ uncertainty (%)
π charge-exchange	50
π elastic	10
π inelastic	40
π absorption	30
π secondary π production	20
N absorption	20
N secondary π production	20
N elastic	30
cross-sections	
parameter	1σ uncertainty (%)
π total cross-section	10
N total cross-section	15



Systematics on the MINOS CC result





Includes component due to syst comparing gcalor pion modeling to test beam results – secondary interactions

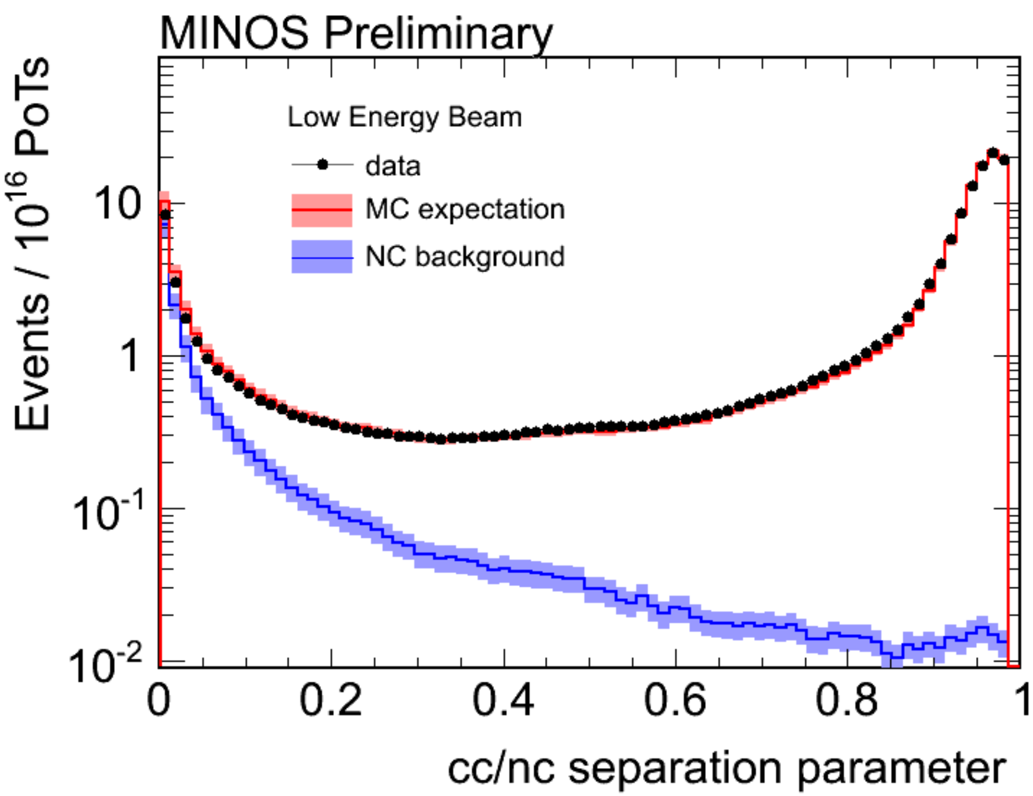
Shift	Amount	7.2×10^{20}POT Fiducial $\delta(\Delta m^2)$	$\delta(\sin^2(2\theta_{23}))$
Shower Energy	1σ	0.049	0.001
Rel. Shower Energy	$1.9\%/1.1\%$	0.008	0.004
Norm.	1.6%	0.030	0.001
NC Bknd.	20%	0.008	0.008
μ Momentum	$2\%/3\%$	0.038	0.001
σ_ν (sum in quadrature)	1σ	0.007	0.004
Beam	1σ	0.009	0.000
$\overline{\nu}_\mu$ wrong-sign	30%	0.003	0.002
RAF only	1σ	-	-
Total		0.071	0.010

Piano/Harpsicord program

- It is not just neutrino cross sections
- They are exposing a small detector to pions at TRIUMF to help better model secondary interactions of muons in T2K data [WG #2 Ikeda, yesterday]
  - MINOS had their test beam run too
- This sort of measurement of hadron scattering data needed for better precision results in any neutrino cross section measurement and E recontruction

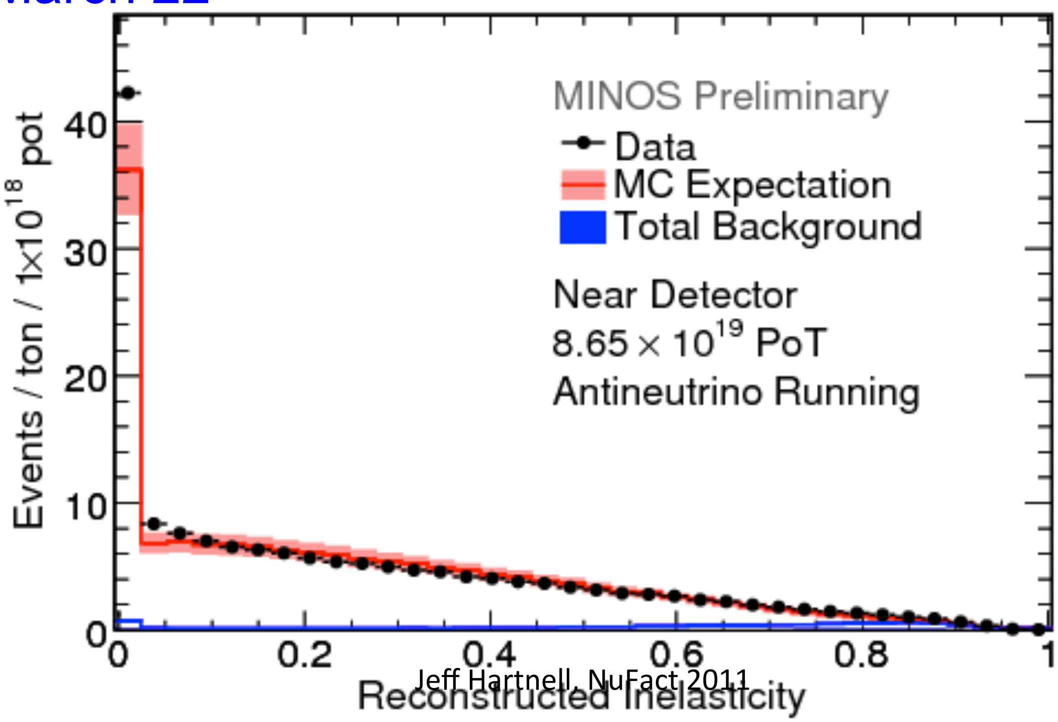
Muon/pion ID in MINOS

- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile

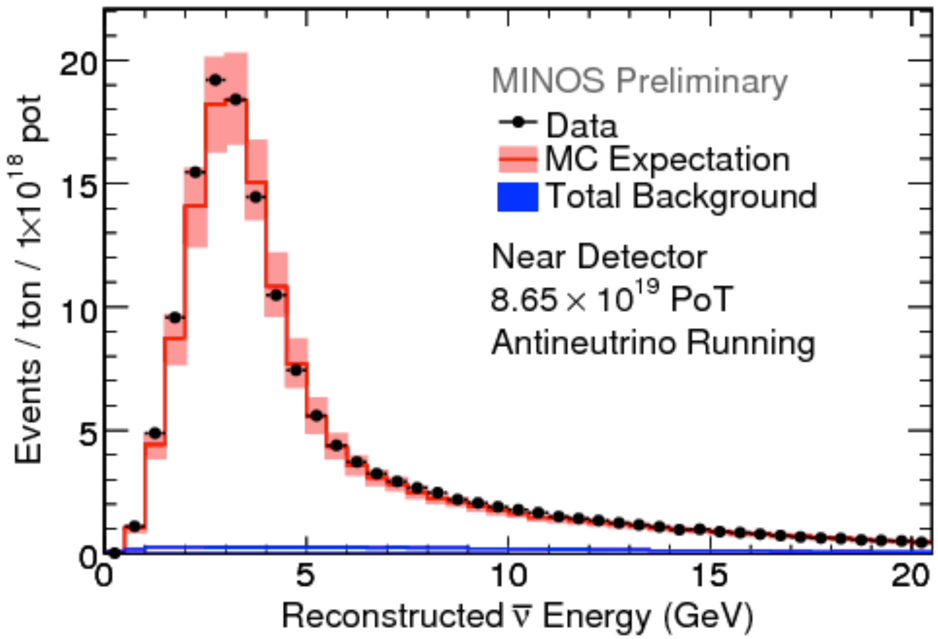


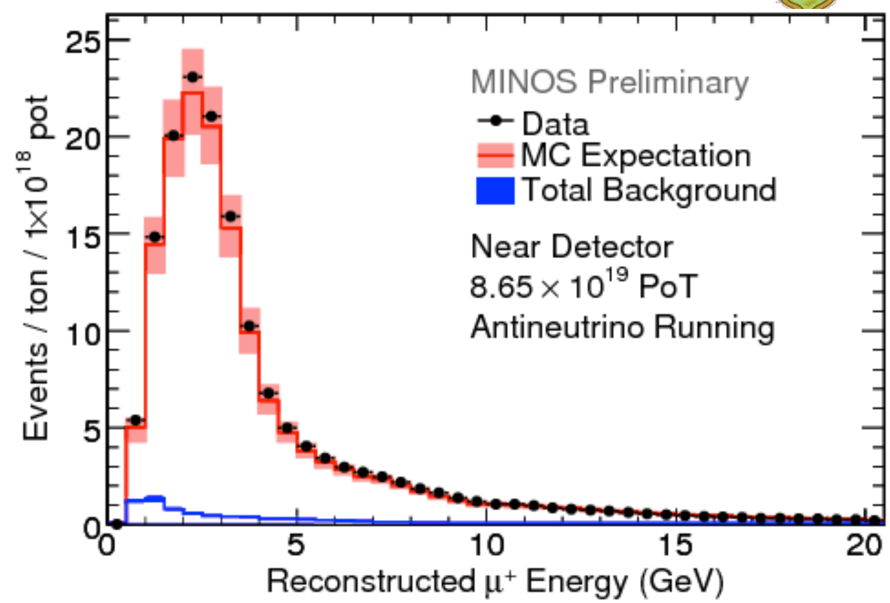
The Anti-neutrino Analysis

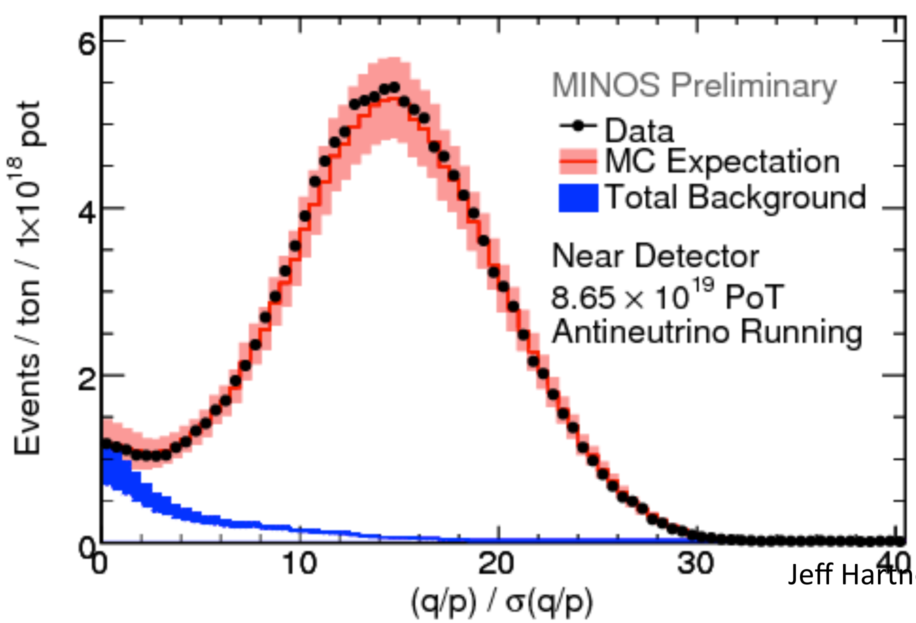
- Essentially the neutrino analysis of 2008
  - No resolution binning, shower estimator, new selector
  - Only stopped taking antineutrino data on March 22nd
- What's different with antineutrinos?
  - Lower statistics ~1/12th events
  - Larger wrong-sign component
  - Interactions are less hadronic



Near Detector Data





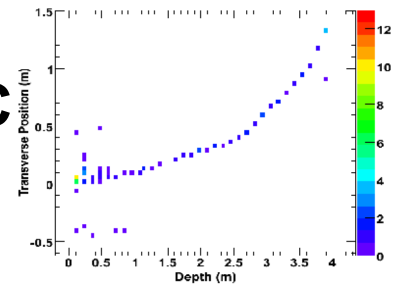


- Data/MC agreement comparable to neutrino running

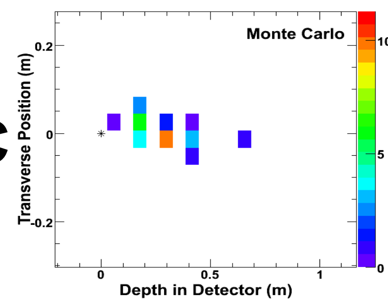
Electron appearance in MINOS

- Electrons leave a compact core of high pulse height hits
- Contamination
  - NC: can be mistaken for EM shower (e.g. if here is a π^0 in the recoil or unlucky collection of unassociated depositions)
  - ν_μ CC: Hard to eliminate if track is small/embedded
  - ν_e CC: the 1.3% beam ν_e CC events

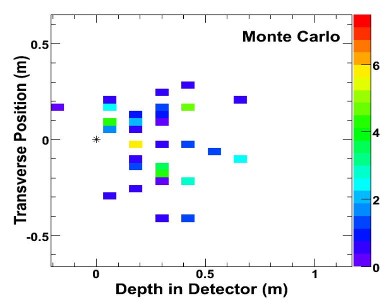
ν_μ CC



ν_e CC

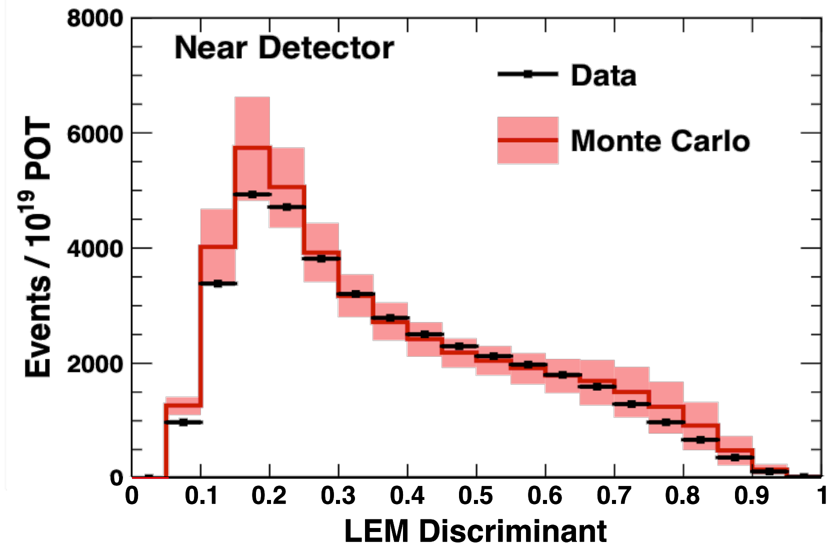


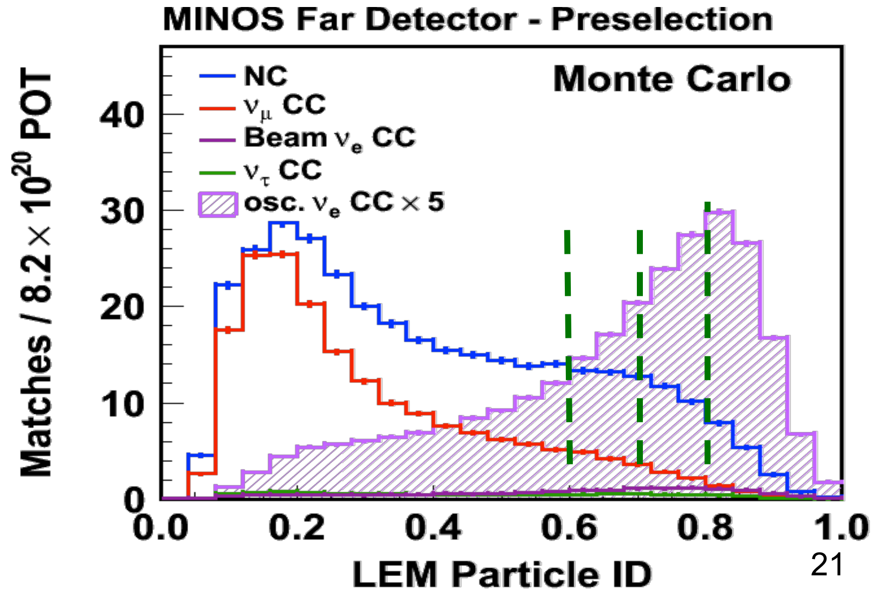
NC



MINOS 2011
nue discriminant variable

- The electron identification variable
- MC based on tuned flux and GENIE
- LHS: NC-like
- RHS: electron-enhanced
- Some residual issues after hard cuts to removed background





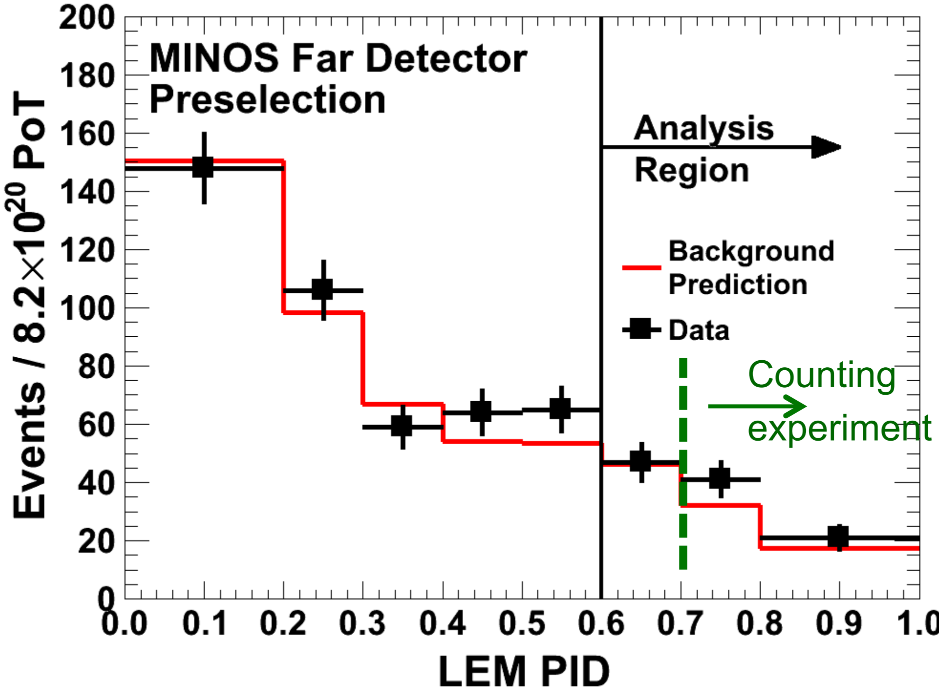
Systematics

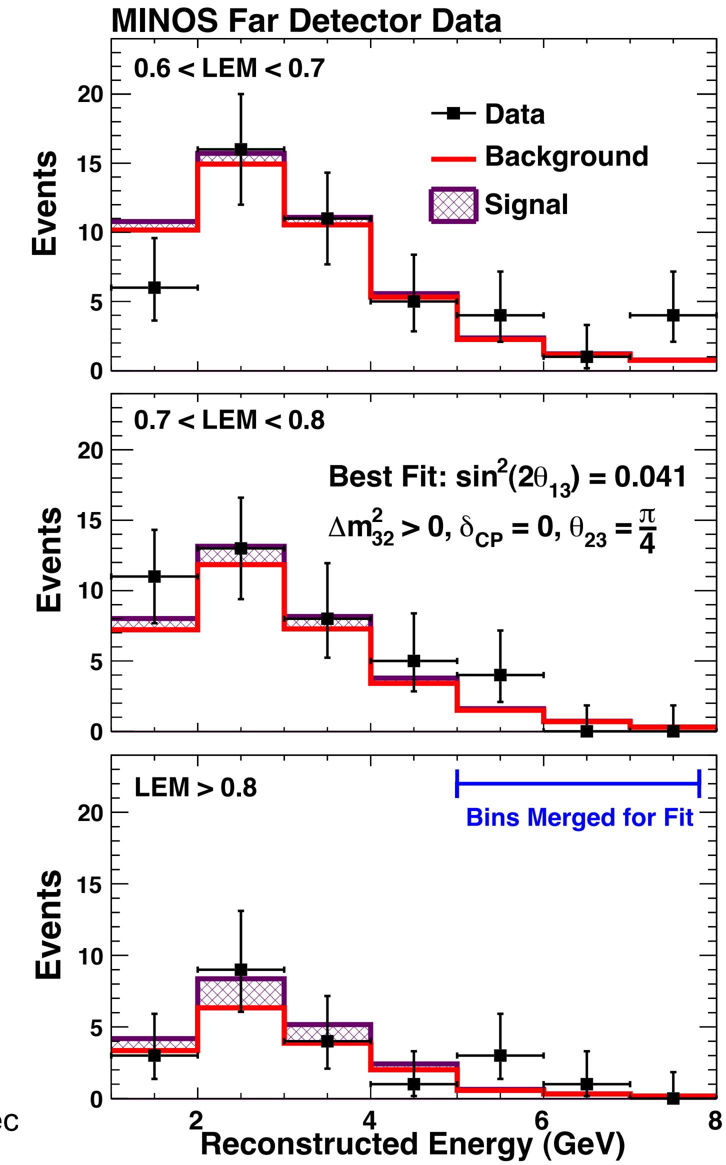
Uncertainty source	Uncertainty on background events
Event energy scale	4.0%
ν_τ background	2.1%
Relative FD/ND rate	1.9%
Hadronic shower model	1.1%
All others	2.0%
Total	5.4%

FD data
and best fit for each LEM PID bin

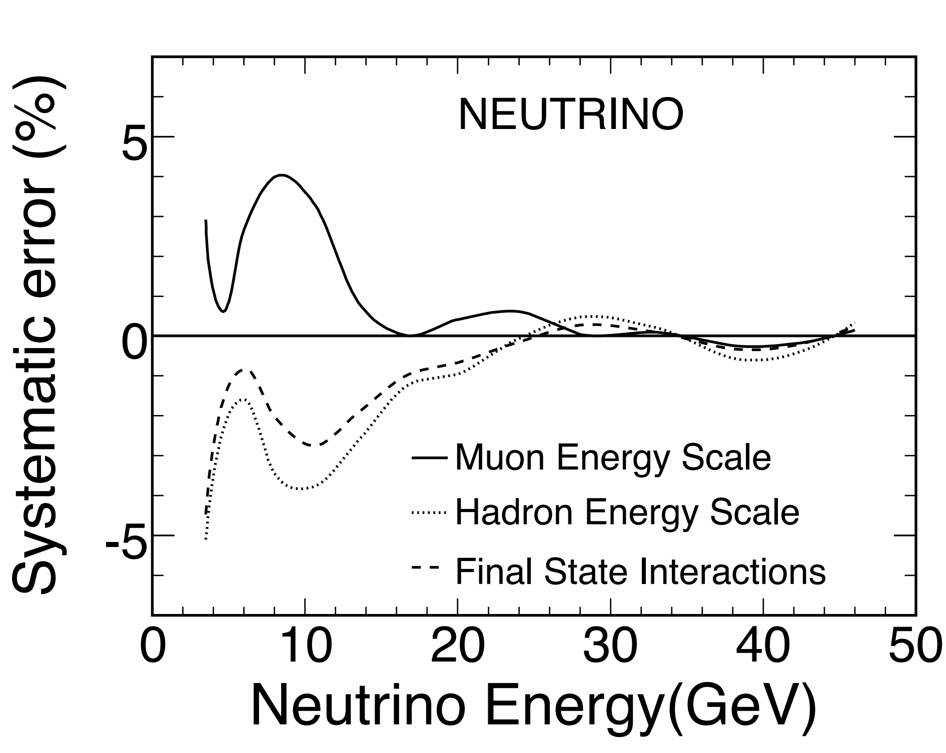
Counting experiment results
(LEM PID > 0.7)

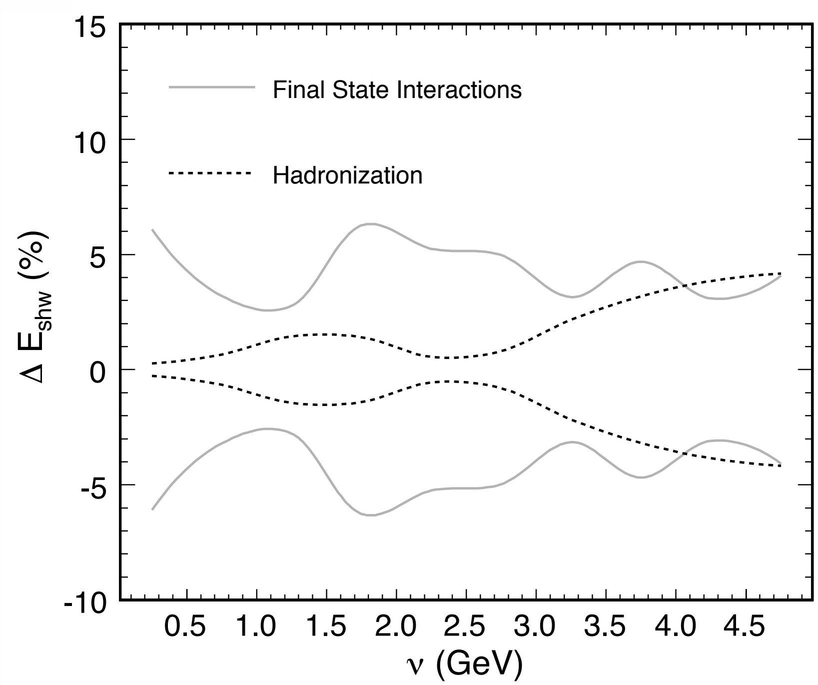
Observe	62 events
Background	50 ± 7 (stat.) ± 3 (syst.)



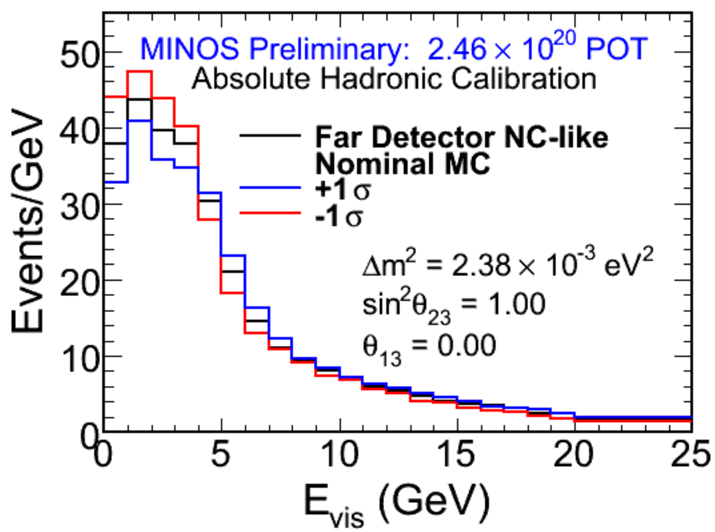


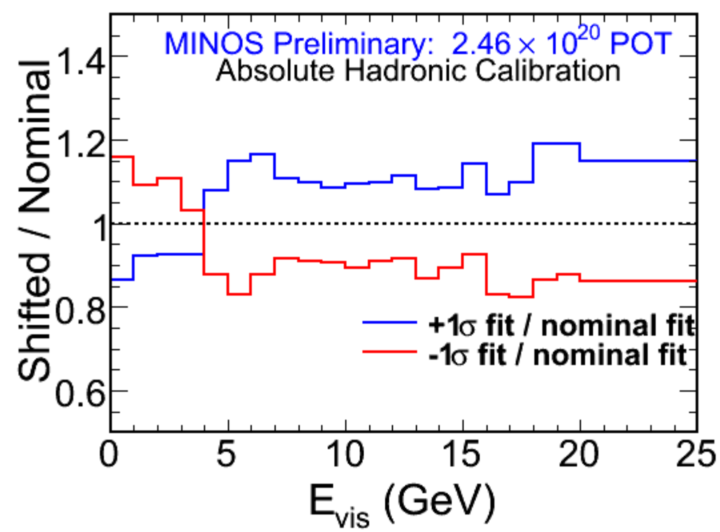
Some systematics from MINOS cross section measurements





A example of NC-like systematic in MINOS



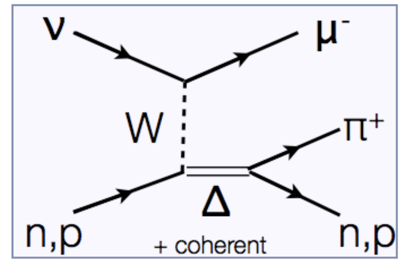


A step lower in energy -> MiniBooNE

Charged-Current π^+

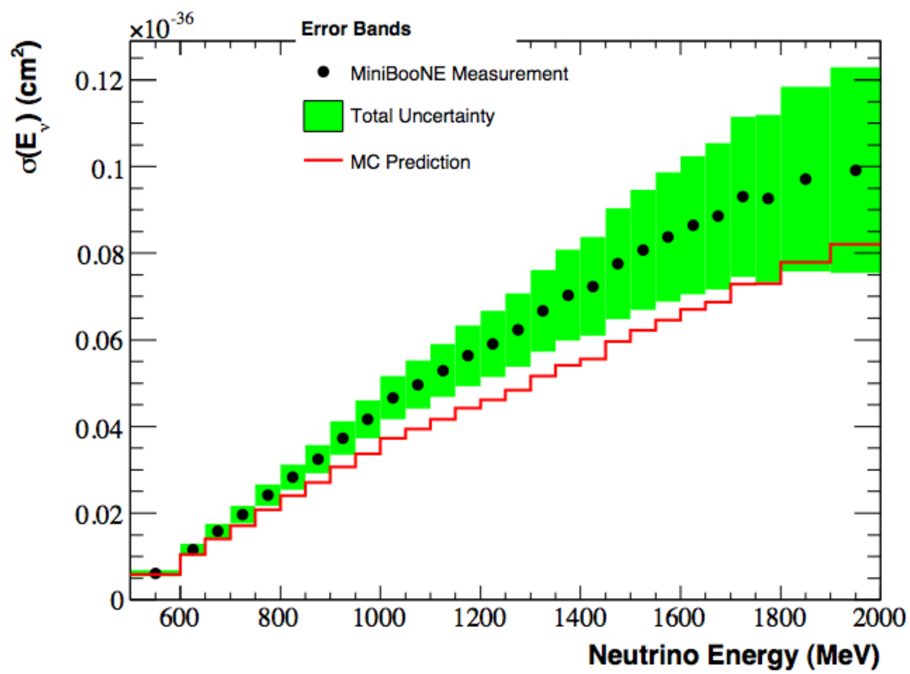
Phys. Rev. D83, 052007 (2011)

- Crucial channel for ν_μ disappearance measurements
  - can bias CCQE signal if π^+ lost



- First tracking of charged pions in a Cherenkov detector!

- Measured quantities:
  - $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$, $d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\mu d\theta_\mu$, $d^2\sigma/dT_\pi d\theta_\pi$ (many firsts)



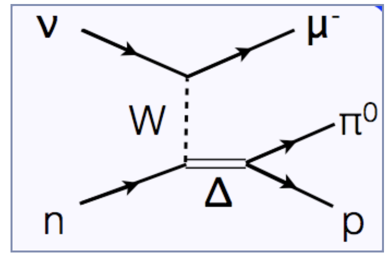
Ph.D. thesis, M. Wilking, University of Colorado

Phys. Rev. **D83**, 052009 (2011)

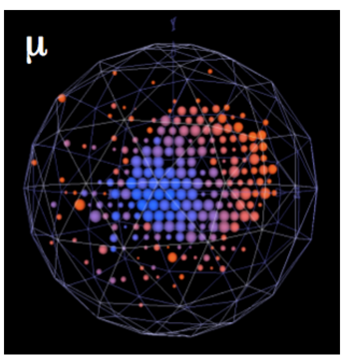
WG #2: Louis

Charged-Current π^0

Phys. Rev. D83, 052009 (2011)



- Custom 3 Cherenkov-ring fitter developed to reconstruct both μ, π^0
  - Resonant-only process
  - Measured quantities:
    - $\sigma(E_\nu)$, $d\sigma/dQ^2$, $d\sigma/dT_\mu$, $d\sigma/dp_\pi$, $d\sigma/d\theta_\mu$, $d\sigma/d\theta_\pi$ (many firsts)



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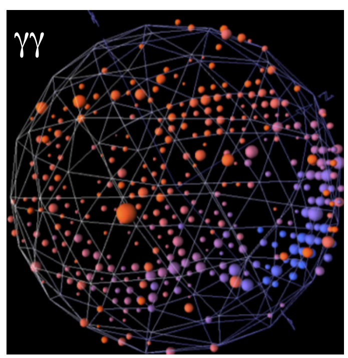
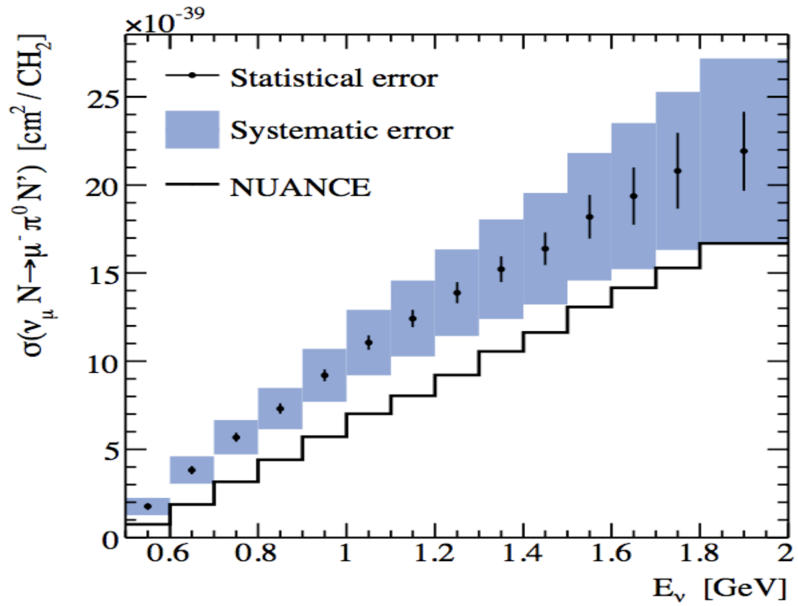




Ph.D. thesis, R. Nelson, University of Colorado

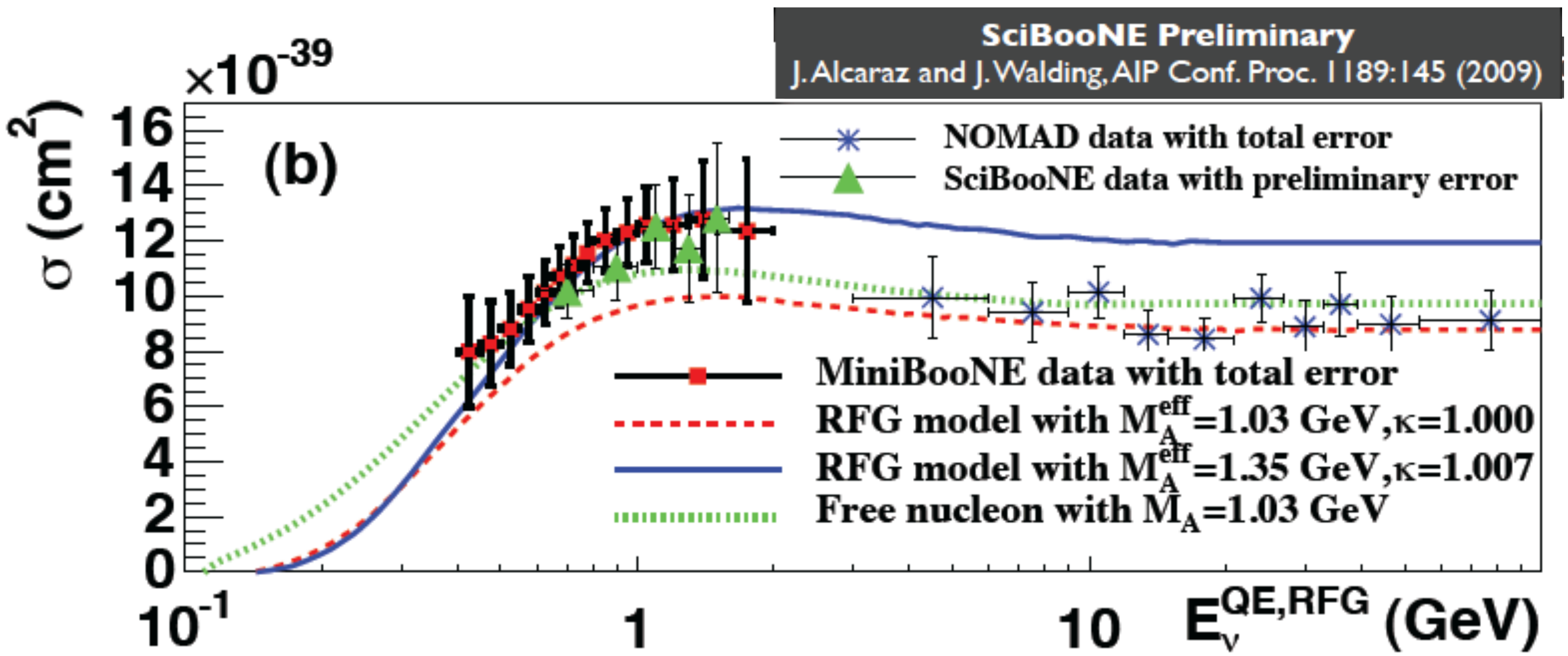
Phys. Rev. D. **83**, 052009 (2011)

Examples of recent data: SciBooNE

- ν CC coh-π: Phys.Rev.D78, 112004 (2008)
  - No evidence of CC coh-π
- ν NC-π^0: Phys.Rev.D81, 033004 (2010)
  - Cross section and π^0 kinematics, MC agree with data
- ν NC coh-π^0: Phys.Rev.D81, 111102 (2011)
  - Clear evidence of coh-π, R-S model agrees with data
- ν̄ CC coh-π: preliminary results
  - Cross section ratio ~2σ away from zero
  - Data hint that non-zero CC coh-π events in very forward region (than R-S model)
- ν CC-π^0: preliminary results
  - Absolute cross section, working on syst. uncertainties
- K^+ production measurement at the BNB: Phys. Rev. D84, 012009
- CC inclusive production measurement: Phys. Rev. D83, 012005

ν_μ CCQE Scattering

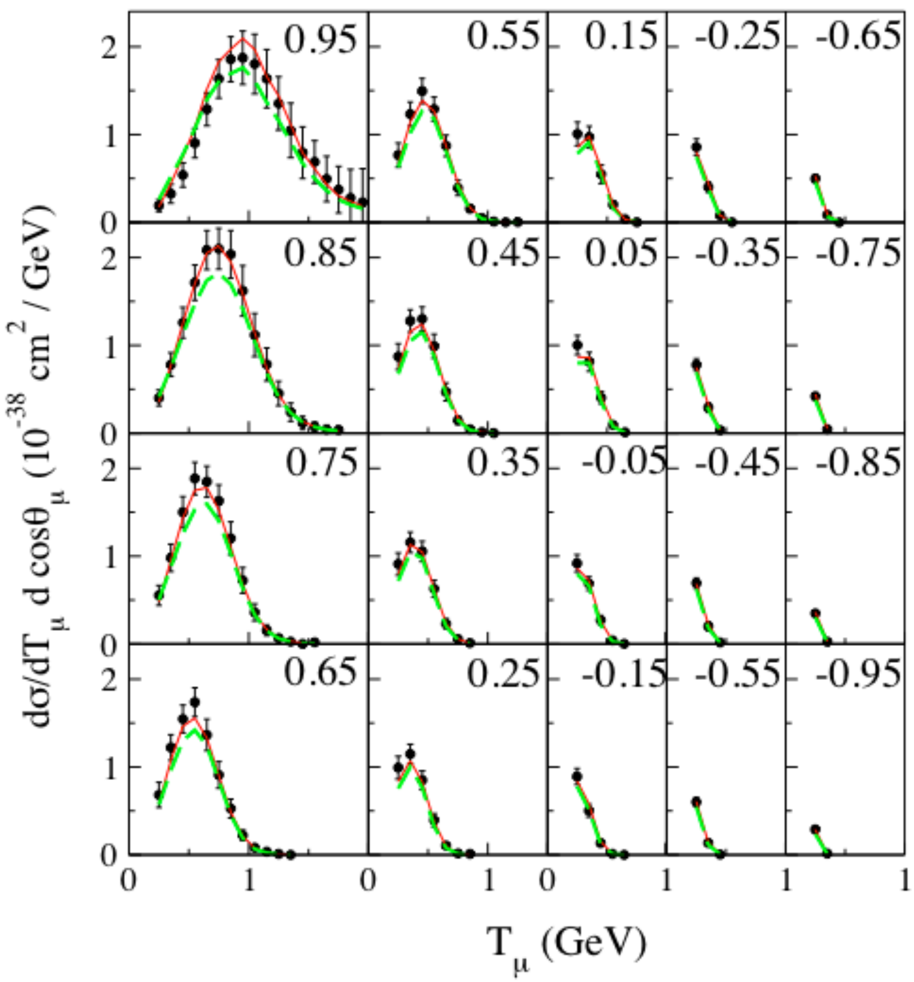
MB: A.A. Aguilar-Arevalo, Phys. Rev. D81, 092005 (2010).



New data and modeling being brought to address this problem

Can’t put it all on one plot any more

Comparisons to MB Double Diff'l σ



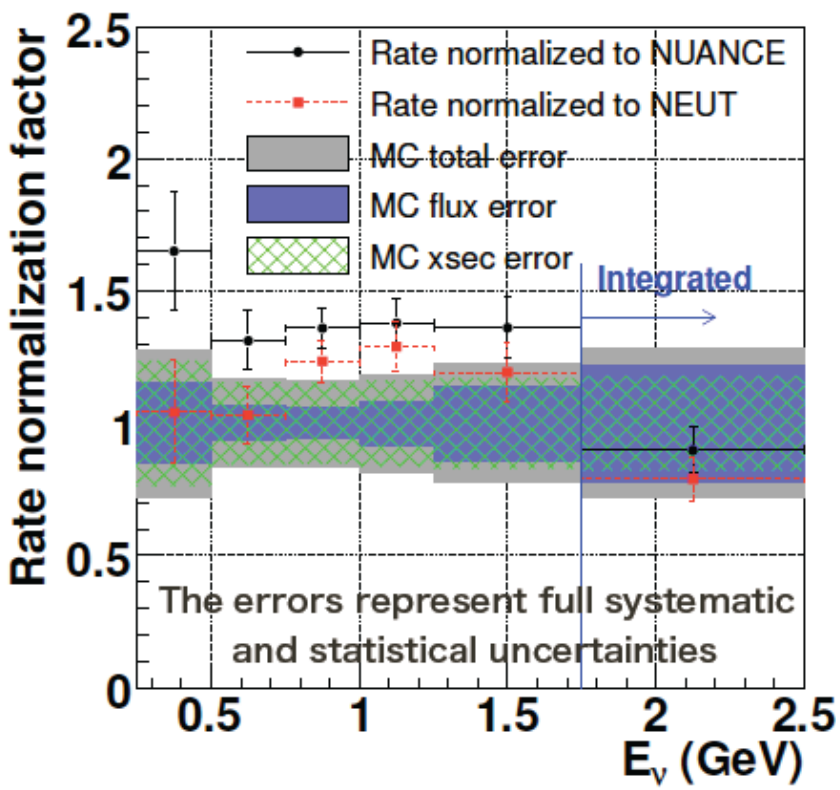
Nieves, Simo, & Vacas,
arXiv:1106.5374

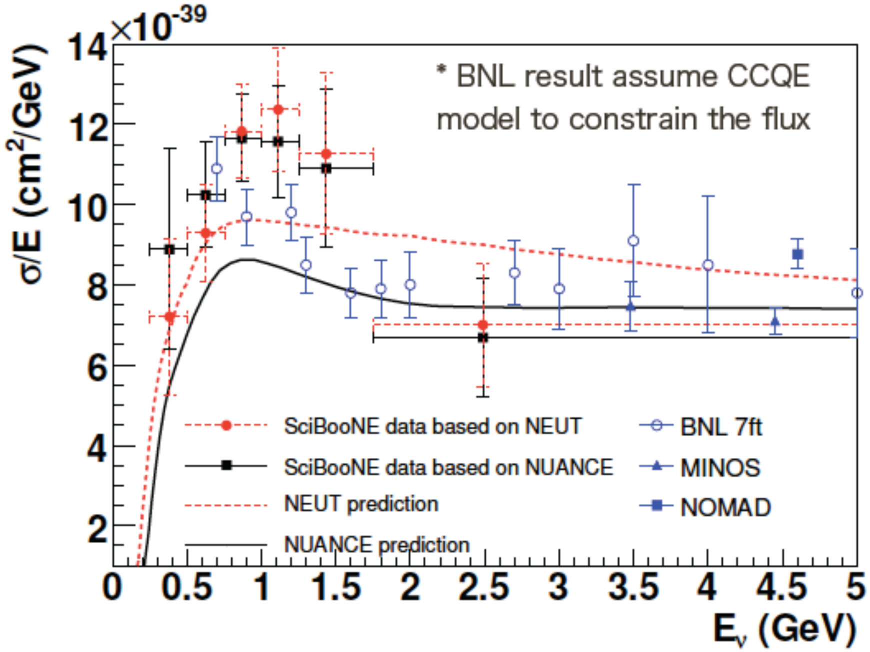
2p, 2h effects

Accounts for long range
nuclear correlations &
Multi-nucleon scattering
with M_A = 1.049 GeV

Implications for resolution
in QE energy reconstruction with muon

Examples of recent data: SciBooNE





SciBooNE Coll., PRD 83:012005 (2011)

A step even lower in energy

beta beam & 2nd maximum in super beam

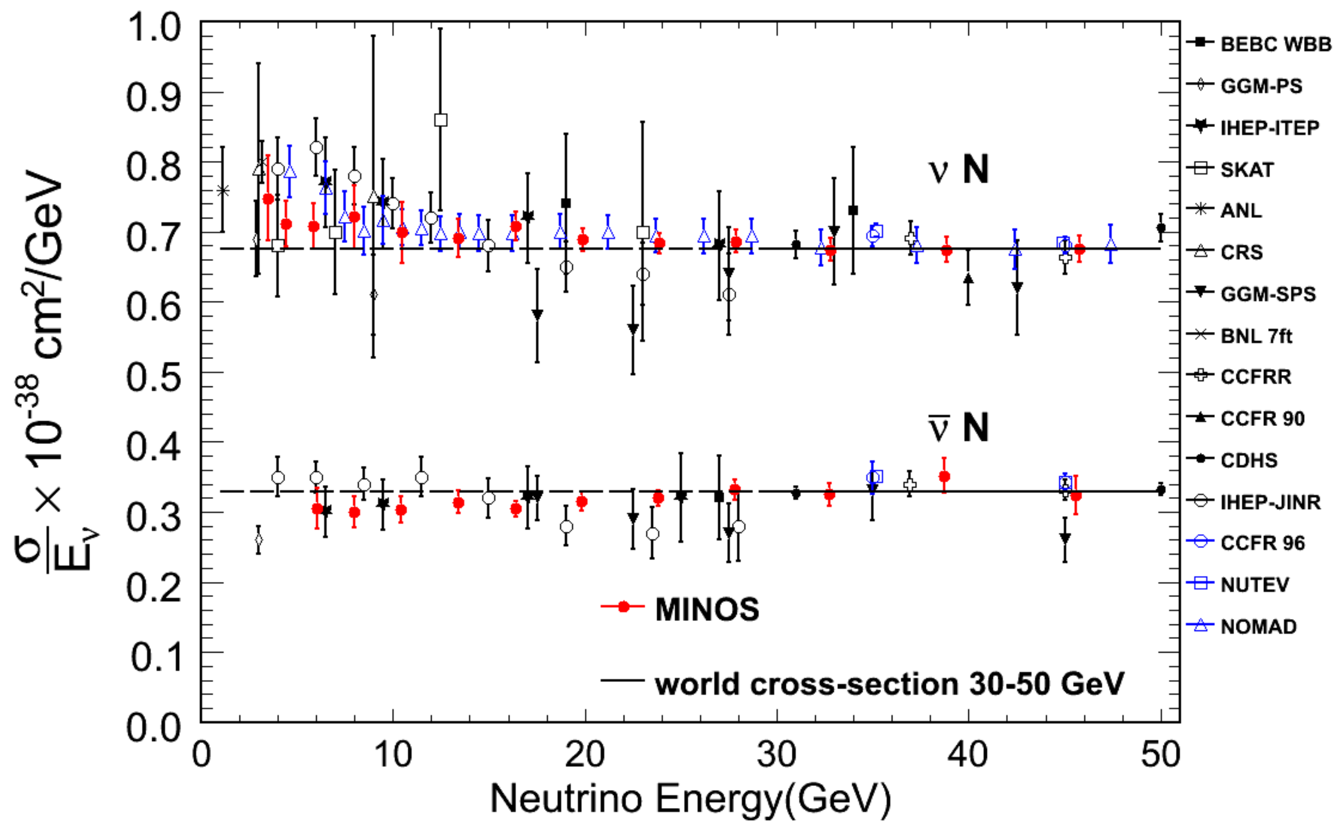
Saw here that “2p, 2h processes” significantly change overall cross sections

WG #1 Meloni

Moving up in energy: NF & MINOS+

In general the situation is better as DIS becomes dominant …

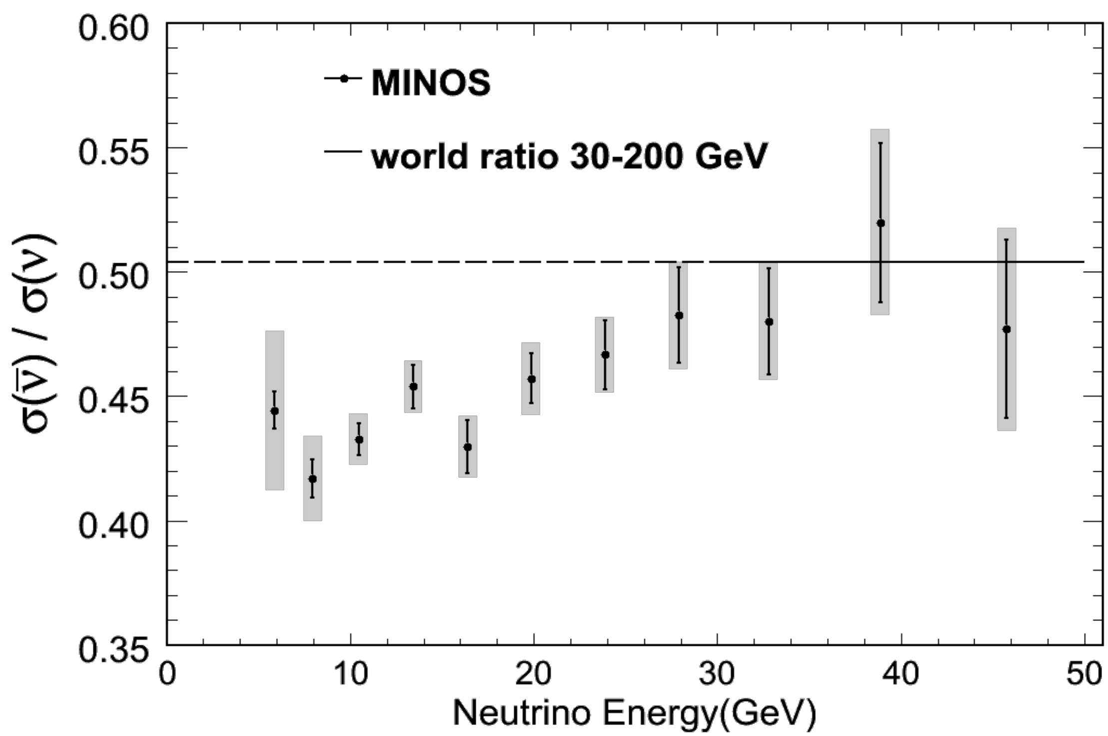
Improved total cross section data (MINOS ND)



Ratio of cross sections

Could well need to know these better depending in

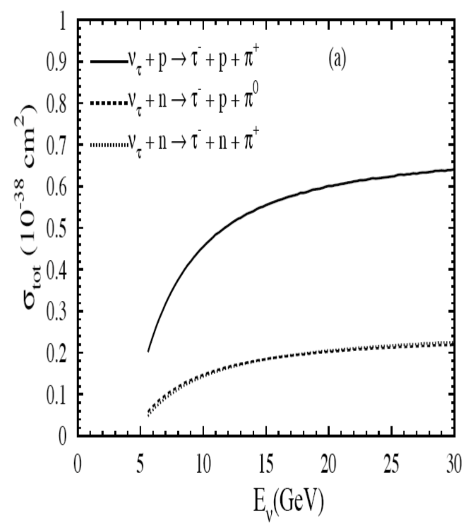
nature and the machine we decide to build for CP / CPT tests



Tau appearance …
World's from DONUT & OPERA

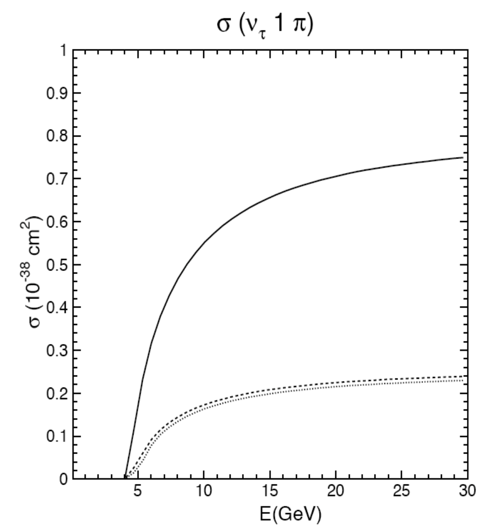
- Examples in SK & present in MINOS
- In low energy super-beam experiments they are not so significant
- In neutrino factory or higher energy atmospheric neutrinos they become significant

Take difference between two models as additional systematic:



Paschos and Yu,

Phys.Rev.D65:033002,2002



GENIE 2.4.0

Moving onward

Current landscape (<≈GeV)

- SciBooNE and MiniBooNE mature and transforming our knowledge of neutrinos interaction physics near 1 GeV
  - Strong interplay with neutrino experiments, theory & electron scattering data critical
- T2K ND-280 getting into the game (WG #2 Mccauley)
- MicroBooNE coming in a couple years

- Critical regime for precisions oscillations physics and sterile neutrino searches

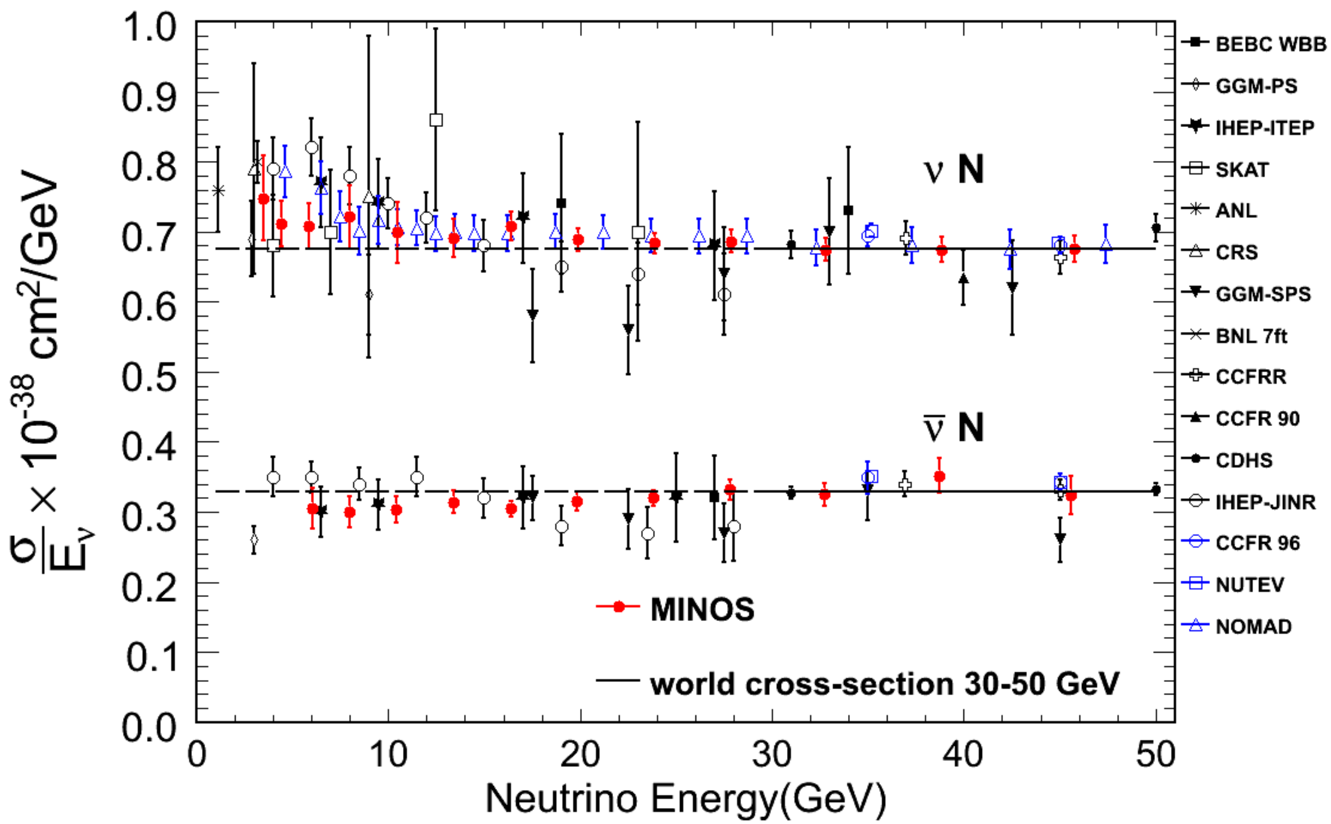
Current landscape (<<GeV)

- Needed for super beam experiments looking for 2nd peak
- Needed for LE beta beam
- Not currently in the world's program ???
  - MicroBooNE might help ???
  - Address low energy excess in MiniBooNe
- Note to self: FS radiative corrections for e's not in current generators
  - Will be needed for precision work

>1 GeV

- MINERvA is collecting data
  - Running in NuMI low energy for next year
  - Running in NuMI medium energy during the NOvA
  - Good prospects, initial physics distributions
- Proposal for a LD/LH target for precision studies in low-density nuclei
  - Recall He nucleus is dense

Why so good at high energies? Narrow band beams



LE NBB scattering experiments …

- T2K ND280 exists and collecting data
- NOvA is considering an off-axis fine-grain ND
  - SciNOvA Working Group within NOvA
    - Costing and optimizing detector Scibar-like detector in front of NOvA ND & muon stack
- Off-axis gives a 1+ GeV NBB
  - Allows detailed studies for NOvA particle ID development
  - NBB measurement centered above the T2K oscillation dip
    - Study feed down into T2K oscillation minimum

Use these event generators …

- Scattering and oscillation experiments use the generators to make exclusive final states that can be propagated through a detector simulation
  - We need fully detailed descriptions or at least prescriptions to get there ourselves
- For interactions between theorists and experimenters we generally work with specific distributions
- Goal
  - The scattering experiments need to hear from theorists what distributions and conditions will give them the best ability to tune/test their models
  - Of course, we have to tell them what we can actually do
  - This has been on going

Moving forward ...

- Need precision neutrino scattering data in the energy regime of the experiment and on the correct targets
  - To squeeze the best sensitivity from an experiment need to have good modeling of the physics in the near detector
    - More than just feel-good physics
  - This means that theory needs to be melded with event generator design to make sure that predictions can be turned into detailed event kinematics
  - Look forward to seeing the details of the T2K systematics analysis
- Ingredients for precision & discovery
  - Precise flux determination by beam component by multiple methods, e.g.
    - Hadron production (dedicated session in WG2)
    - Muon flux measurement
    - Low-ν/w method
    - A chance for common goals addressed collaboratively
  - Absolute shower energy scale
    - High quality test beams
    - Tests of secondary scattering (general & specific to experiment)
    - Measurements of nuclear effects / FSI
    - Seems like a good chance for common goals addressed collaboratively
  - Tight collaboration with experimenters in the electron scattering community
  - Theory & experiment talking the same language
    - Making sure to our data measures the same thing the theorist computed