NEUTRINO-NUCLEUS CROSS SECTIONS

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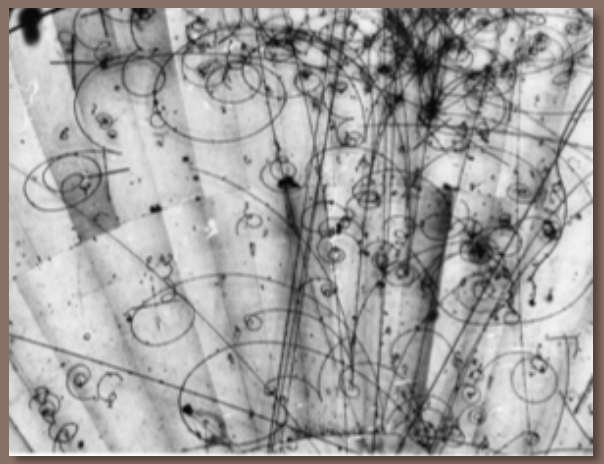
Fermilab

APS

May 2, 2011



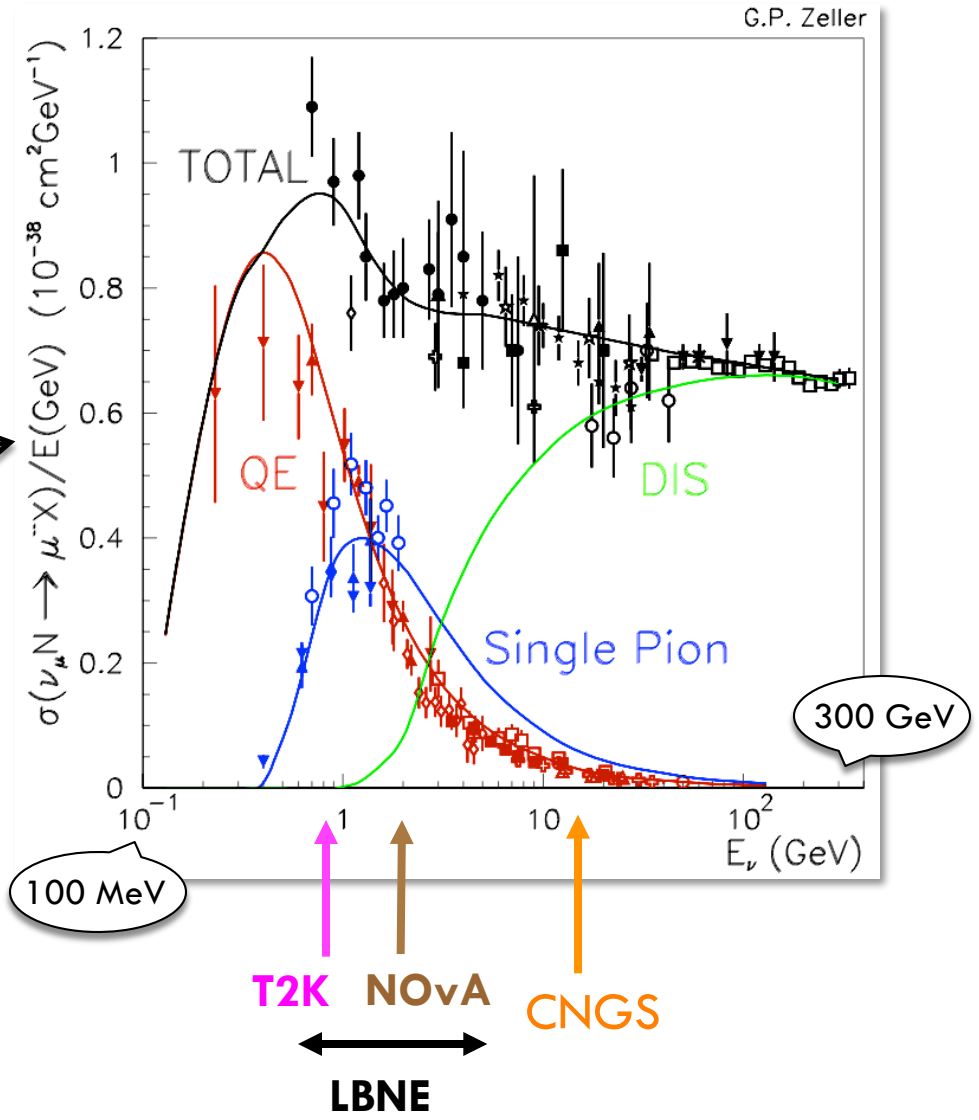
- this topic has become quite interesting lately
- revisiting this type of ν scattering physics again for 1st time in decades
- new data is challenging our thinking … & turning up a few surprises

Neutrino Cross Sections

- pursuit of ν oscillations has unfortunately forced us to do physics at energies ~ GeV

  - *where our exp'l knowledge of ν interactions is limited*

- future ν oscillation experiments will be addressing some very important questions (θ_{13}, MH, $\not{CP}$) and will operate in this complex E_ν region (100's MeV to few-GeV)



Neutrino Cross Sections

quasi-elastic

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

pion production

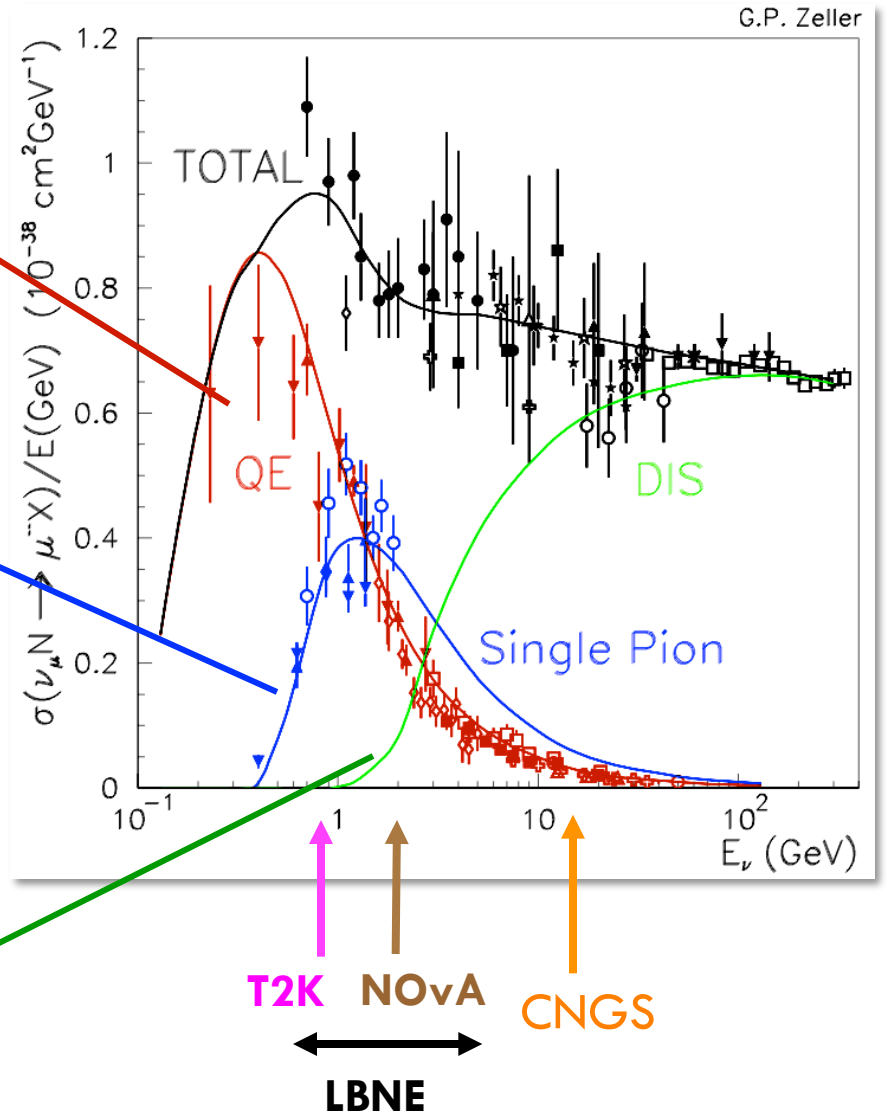
$\nu_\mu N \rightarrow \Delta$

$\hookrightarrow N'\pi$

deep inelastic scattering

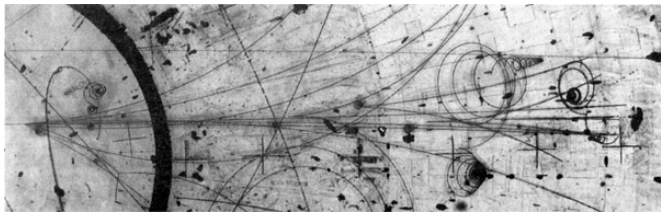
$\nu_\mu N \rightarrow \mu^- X$

need to extrapolate into low energy region

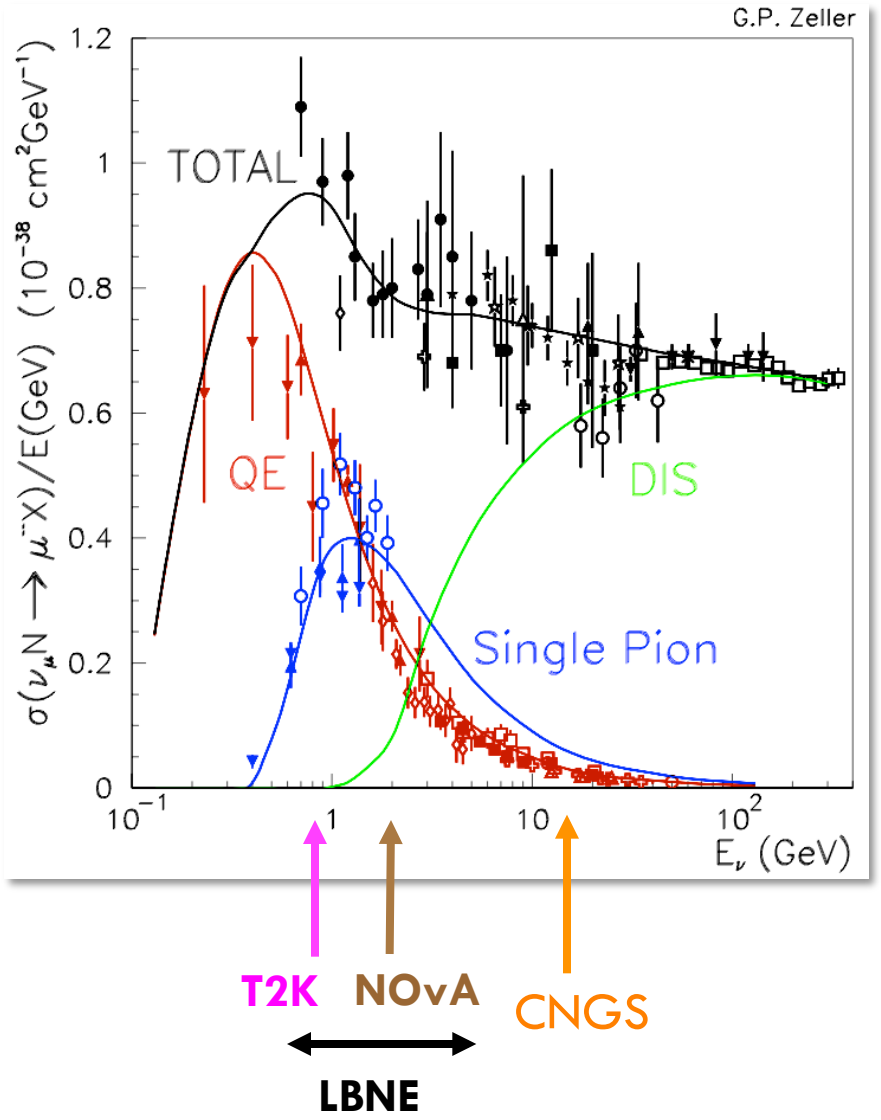


Neutrino Cross Sections

- data that constrains this region is over 30 years old
  - low statistics (100's of events)
  - mostly D_2, H_2 bubble chambers



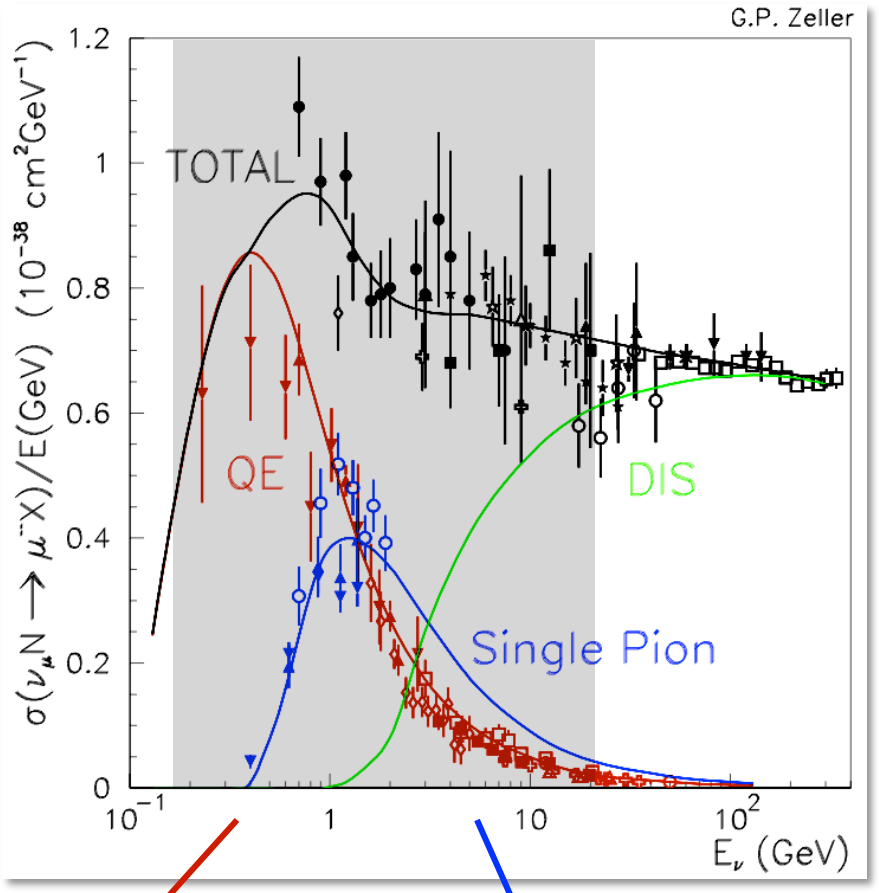
- crucial difference: ν osc exps use heavy nuclei
- nuclear effects are important
- has necessitated a dedicated campaign of new measurements



Neutrino Cross Sections

- new experiments making improved σ_ν measurements covering a broad E range

- <u>advantages of new data</u>:
  - nuclear targets (osc exps)
  - higher statistics
  - intense, well-known ν beams
  - studying ν and $\overline{\nu}$'s
    (will be important for ~~CP~~)



K2K, MiniBooNE,
MicroBooNE, SciBooNE, T2K

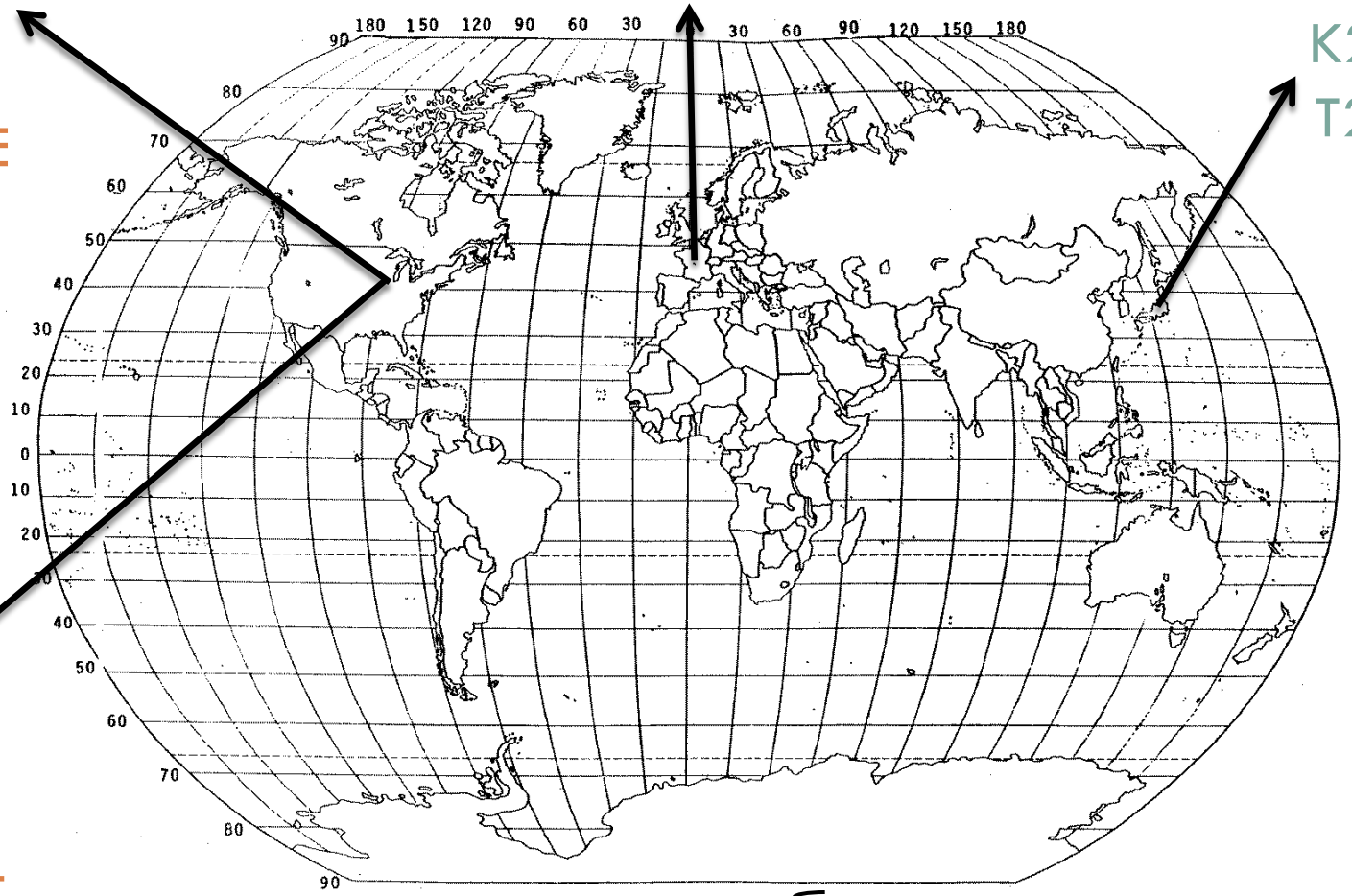
ArgoNeuT, MINOS,
MINERvA, NOMAD, NOvA

Modern σ_ν Experiments

MiniBooNE
SciBooNE
MicroBooNE

NOMAD

K2K
T2K

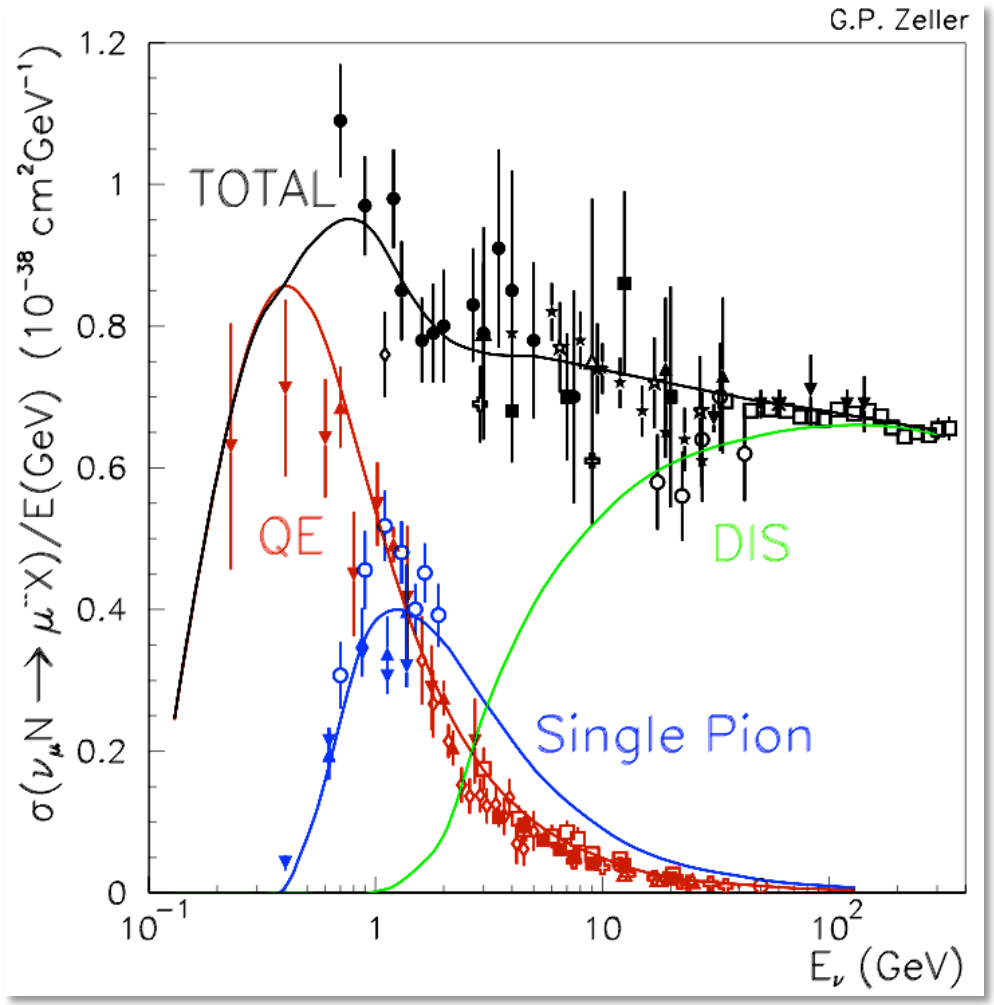


MINOS
NOvA
MINERvA
ArgoNeuT

accelerator-based program
* ν oscillation experiments
* experiments dedicated to σ_ν

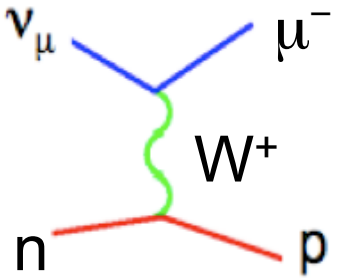
Neutrino Interactions

- let's start on the left and work our way up in energy …
  - QE
  - NC and CC π^0
  - CC π^+
  - CC inclusive
- use this plot as our guide as we survey the landscape
- what new information have we learned 30+ years later?



Quasi-Elastic Scattering

Why important?



- **important for ν oscillation experiments**
  - typically gives largest contribution to signal samples in many osc exps (atm+accel)
  - one of the most basic ν interactions

- examples:

signal events

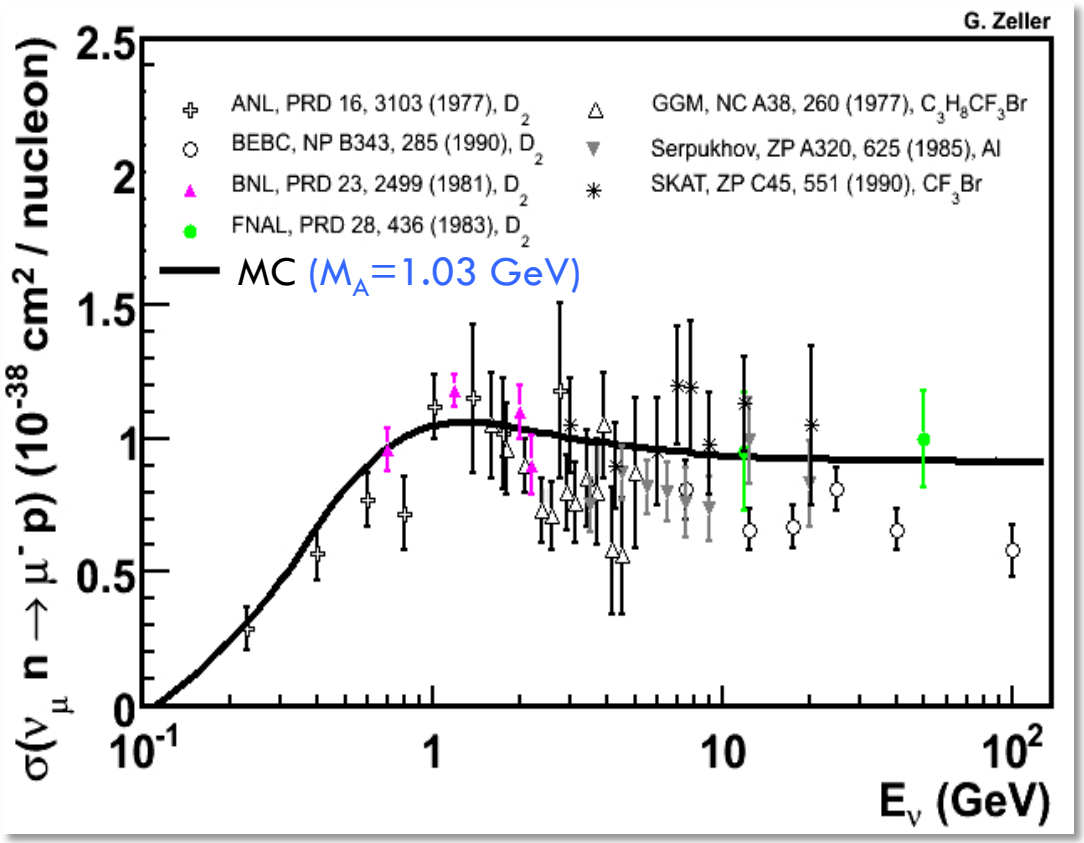
$\nu_\mu \rightarrow \nu_e$ (ν_e appearance)

$\nu_\mu \rightarrow \nu_X$ (ν_μ disappearance)

QE Cross Section

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

- common wisdom has been: QE σ is well-known & we can consistently describe all the experimental data
  - *most is on D_2*
- QE considered the "golden channel"
  - it's simple … clean
  - know size & shape of σ

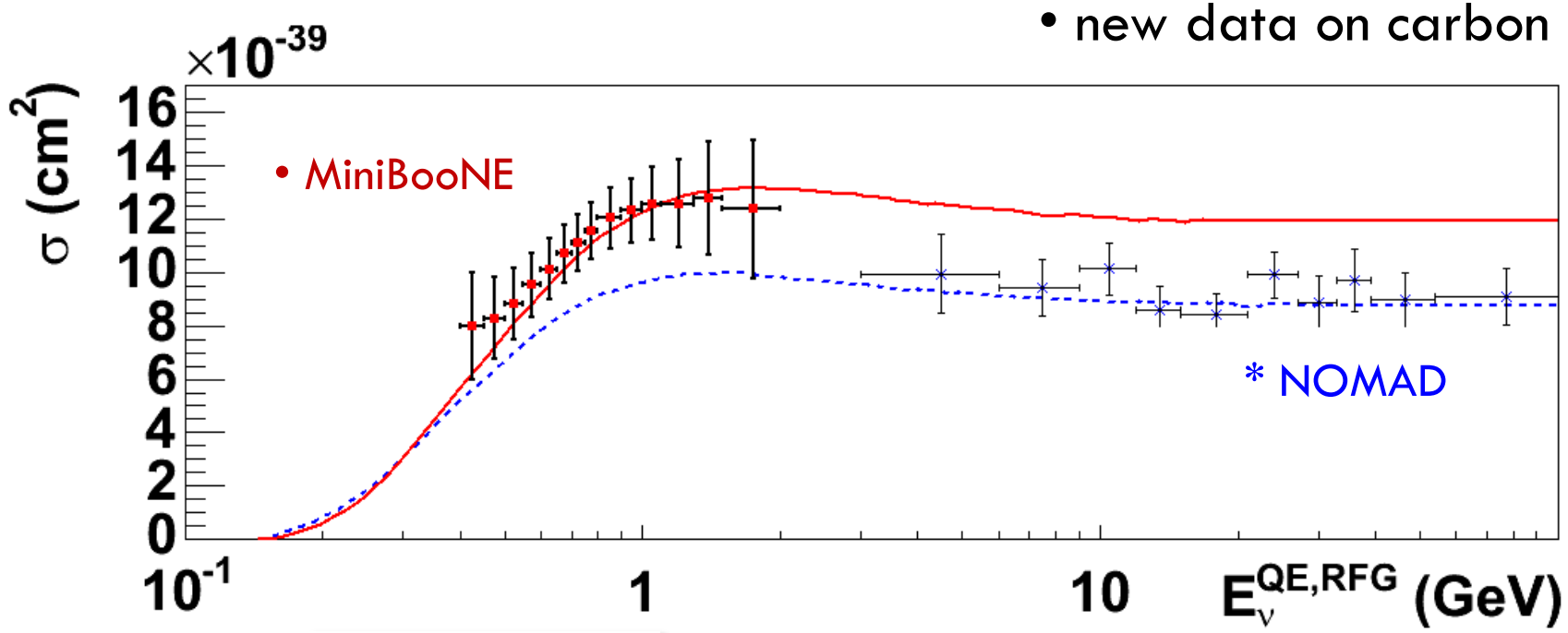


if we can't predict this, then we have problems!

QE Cross Section

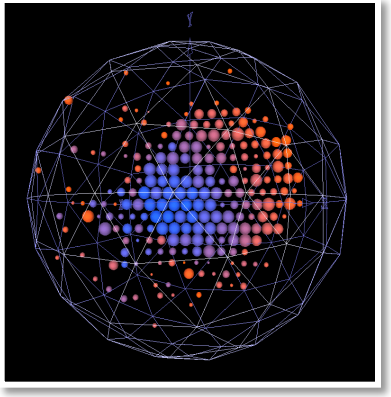
$\nu_\mu n \rightarrow \mu^- p$

• new data on carbon



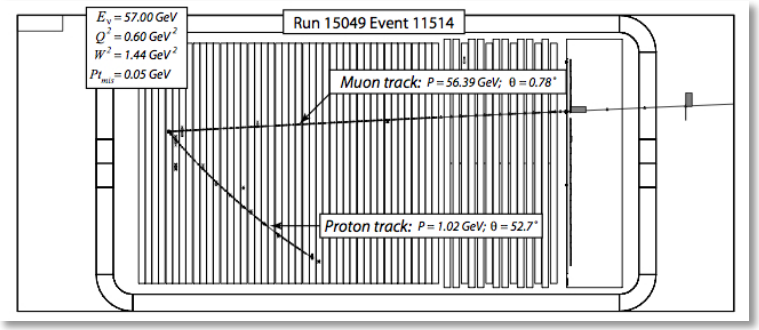
MiniBooNE 2002-present:

Aguilar-Arevalo *et al.*, PRD **81**, 092005 (2010)



NOMAD 1995-1998:

Lyubushkin *et al.*, EPJ **C63**, 355 (2009)



QE Cross Section

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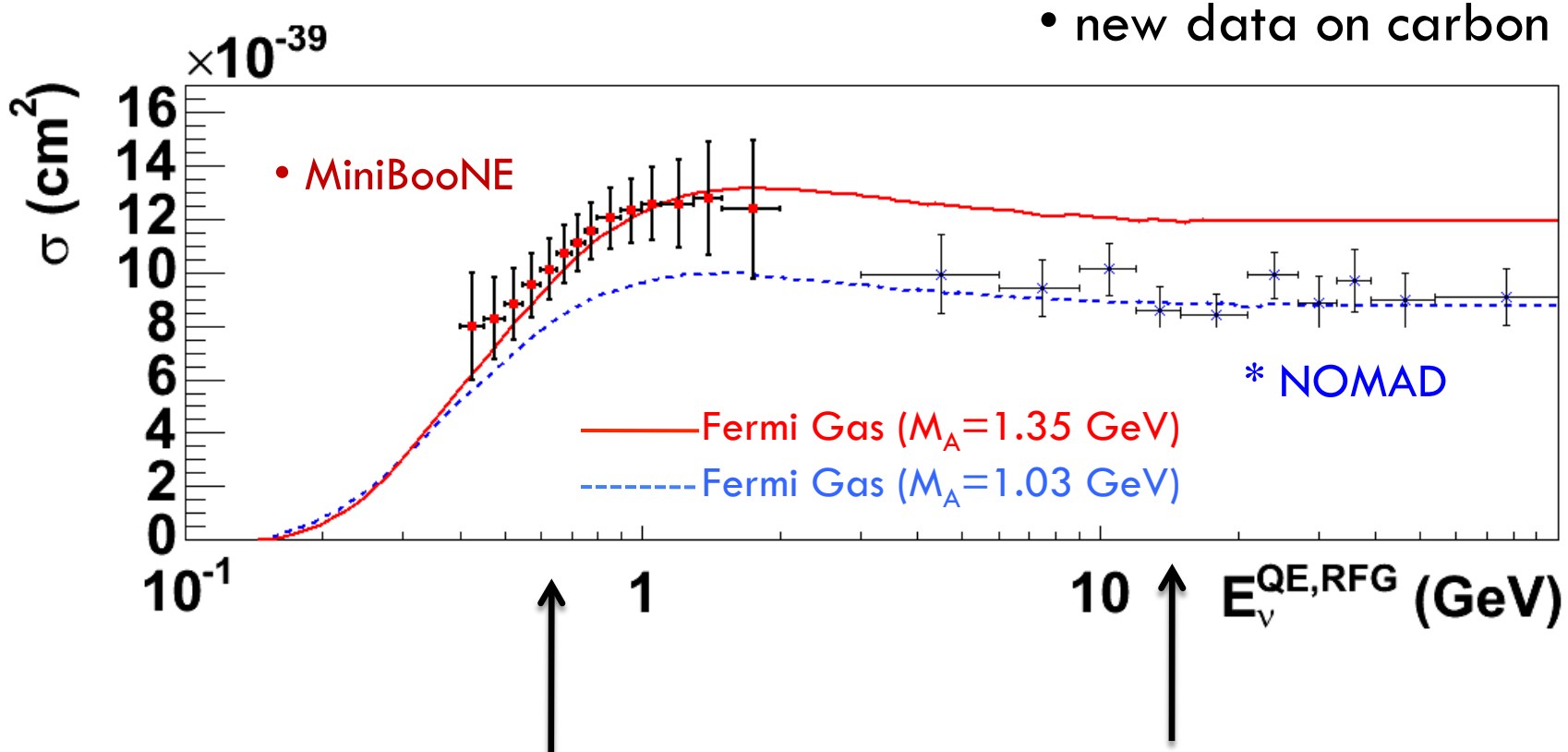


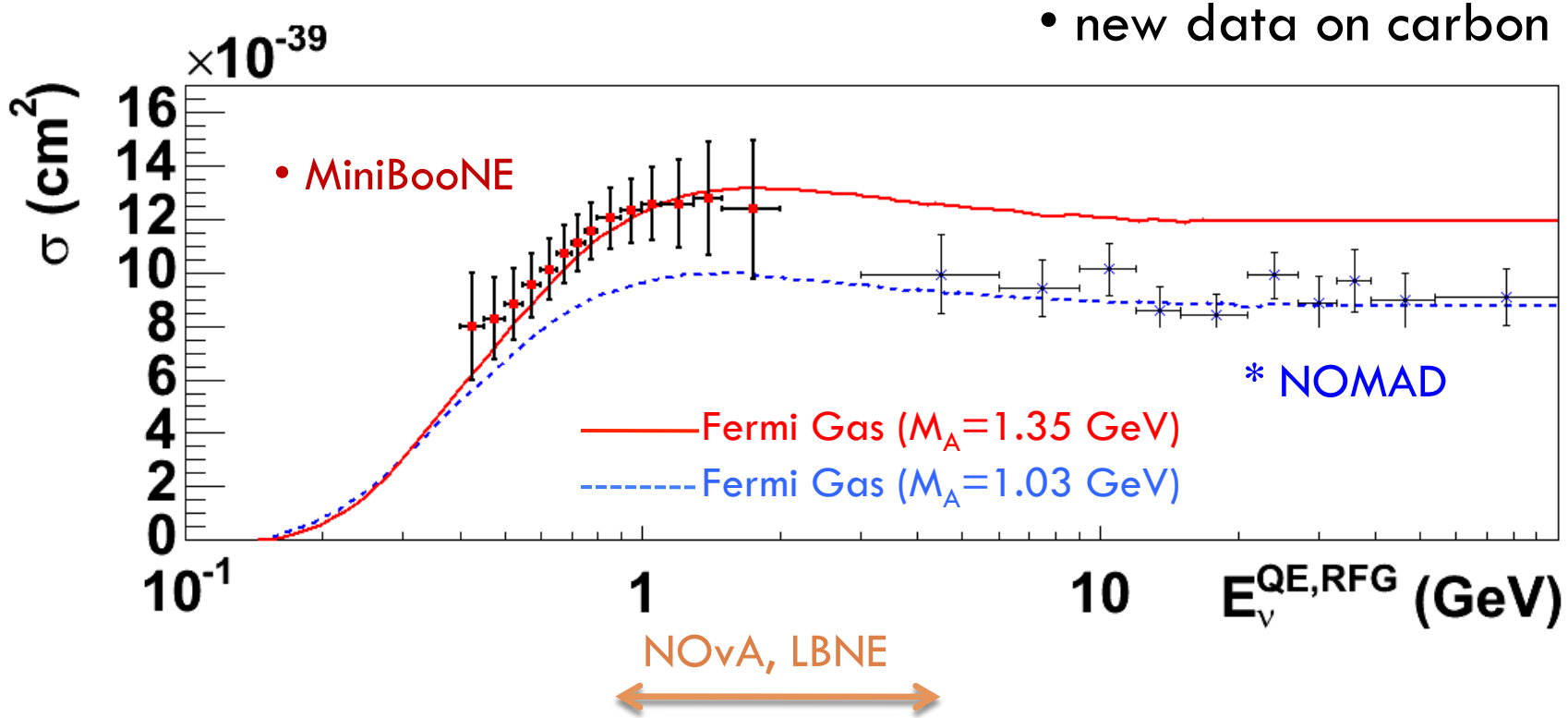
• MiniBooNE data ~30% higher than "standard" QE prediction

• NOMAD data consistent with "standard" QE prediction (with M_A=1.03 GeV)

QE Cross Section

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

• new data on carbon



• modern QE data (^{12}C) cannot be described by a single prediction

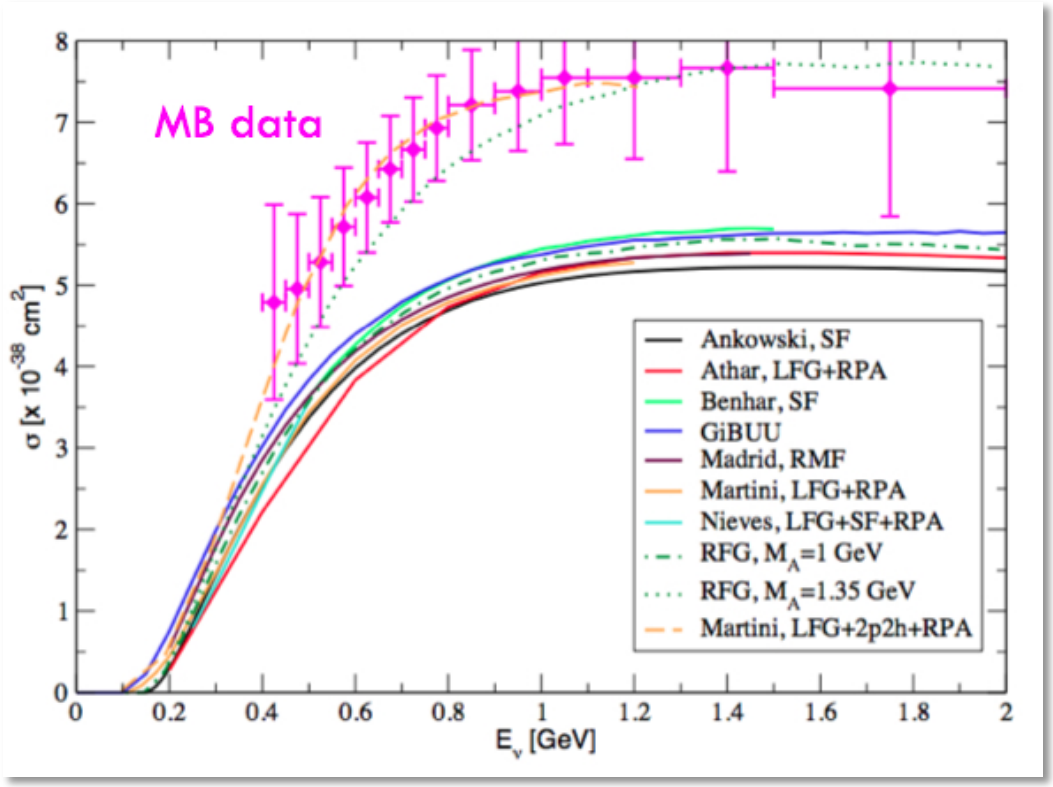
leaves one in an immediate quandary if want to predict how many QE events you should expect to see in your detector → huge effect

Larger Cross Section?

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

- MiniBooNE results have received a lot of attention lately (largely because they were unexpected)
- modern nuclear models with standard inputs (M_A=1.0 GeV) all unable to reproduce MiniBooNE results

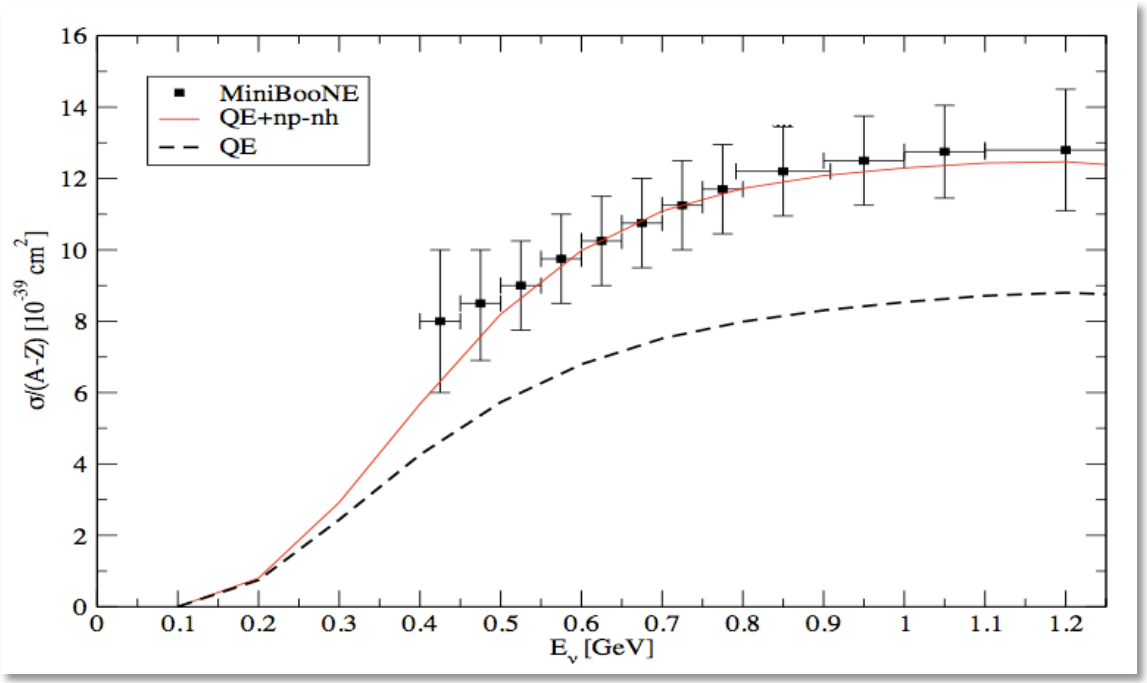
(fall short by 30-40%!)



(L. Alvarez-Ruso, NuFact11)

Nuclear Effects to the Rescue?

- *possible explanation*: there are extra contributions coming from multi-nucleon correlations in the nucleus

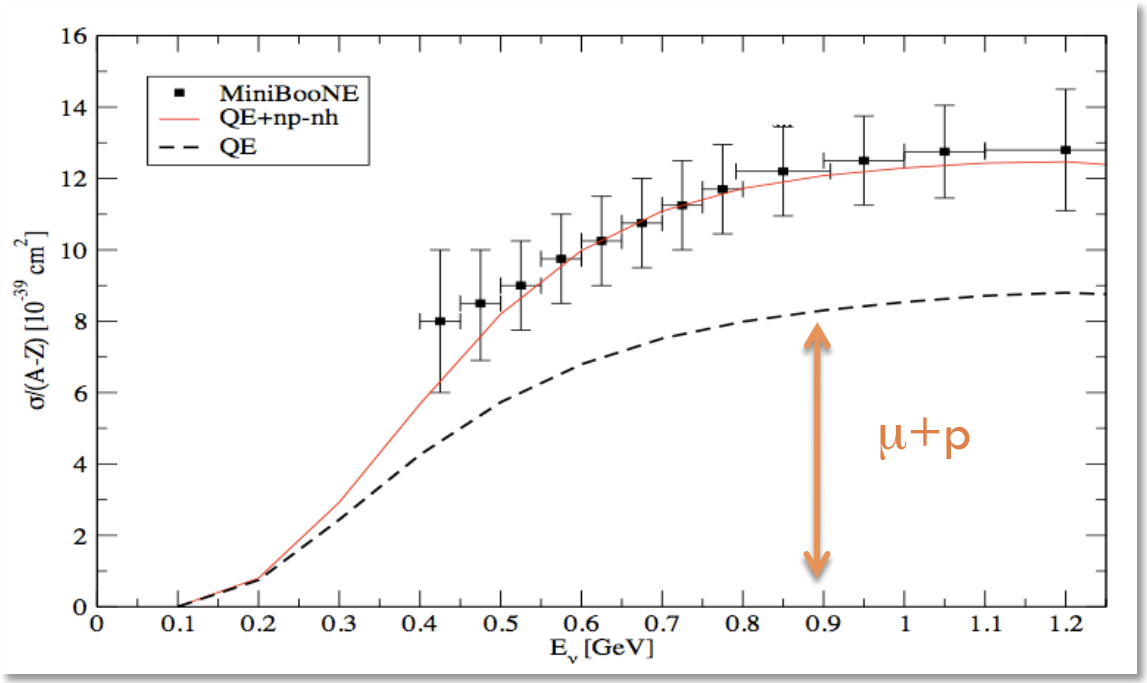


Martini *et al.*, PRC **80**, 065001 (2009)

- large enhancement from short range correlations (SRC) and 2-body currents
- predictions can explain MiniBooNE σ_{QE} without increasing M_A (here, M_A=1.03 GeV)

Nuclear Effects to the Rescue?

- *possible explanation*: there are extra contributions coming from multi-nucleon correlations in the nucleus



← standard QE prediction saw earlier

Martini *et al.*, PRC **80**, 065001 (2009)

Nuclear Effects to the Rescue?

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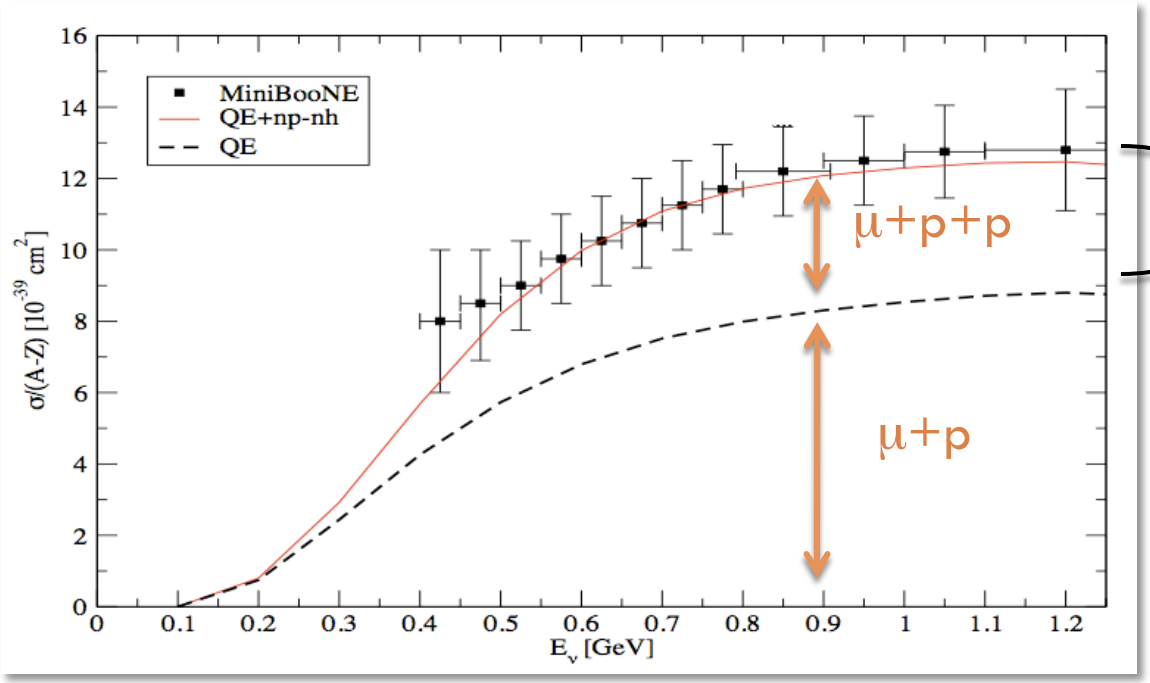


Martini *et al.*, PRC **80**, 065001 (2009)

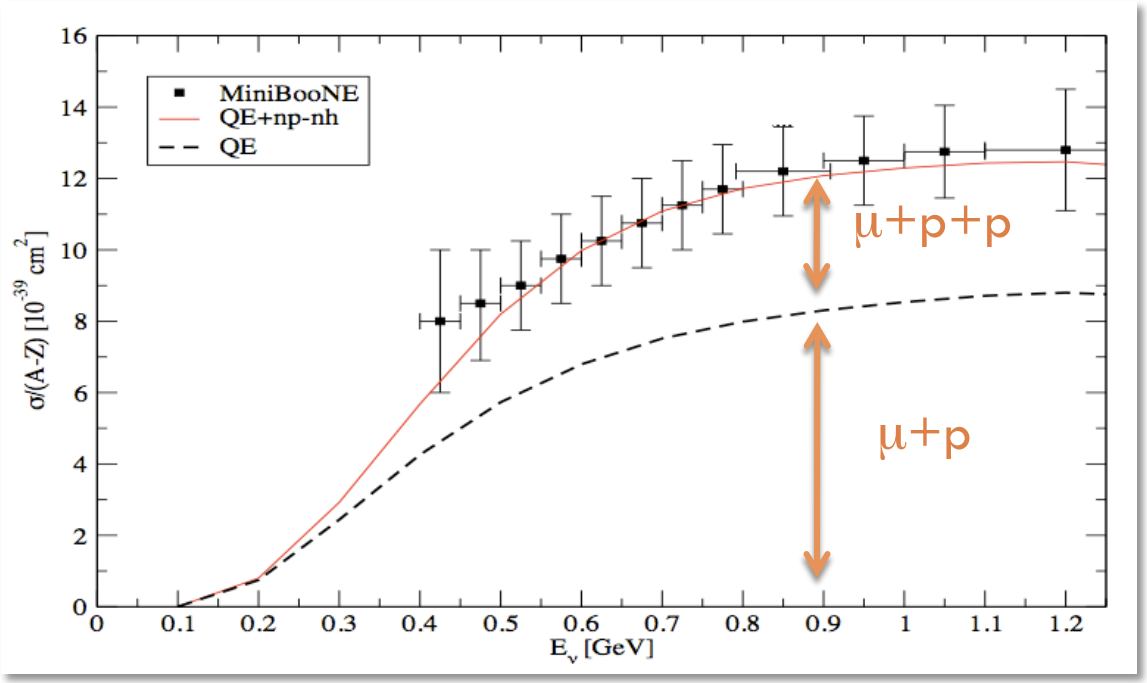
add'l nuclear effects contribute ~40% more σ & produce a multi-nucleon final state (μ+p+p)

- together account for MB

two final states can be indistinguishable

Nuclear Effects to the Rescue?

- *possible explanation*: there are extra contributions coming from multi-nucleon correlations in the nucleus



Martini *et al.*, PRC **80**, 065001 (2009)

- could this also explain the difference between MiniBooNE & NOMAD?

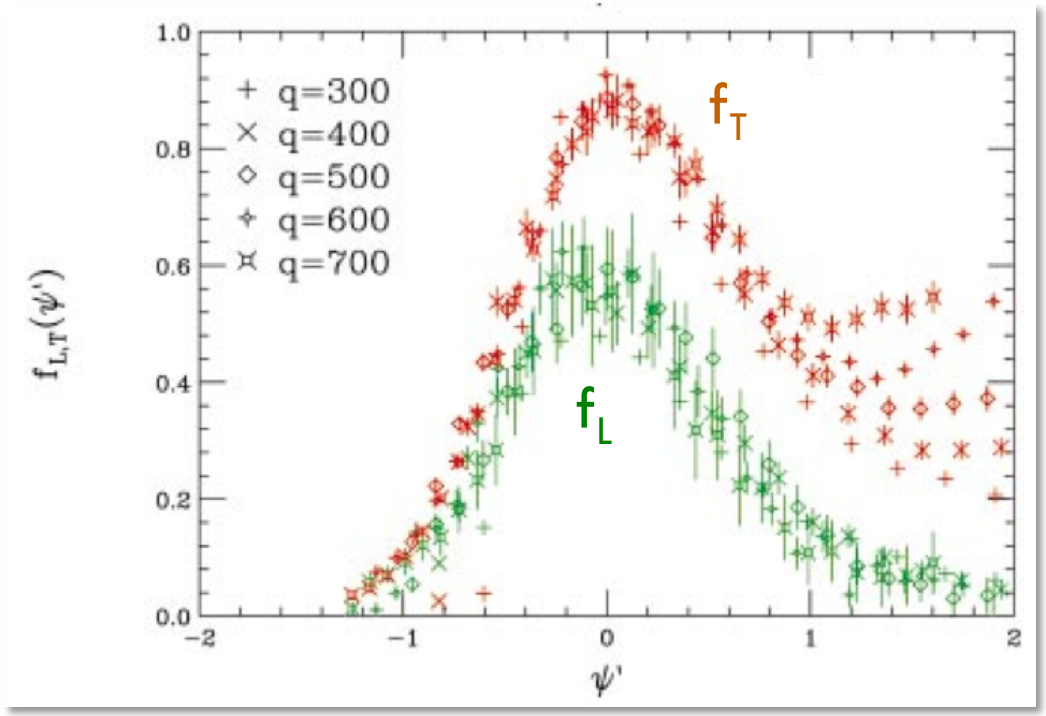
NOMAD: μ + p

MiniBooNE: μ + no π's + any # p's

jury is still out on this

Electron QE Scattering

- large increase observed in **transverse** component of cross section; successfully explained by SRC and 2-body currents



Carlson *et al.*, PRC **65**, 024002 (2002)

- had been seemingly forgotten
- perhaps it is not so unexpected that the ν QE σ on carbon is larger than predicted?
- observations in e^- and ν scattering are related?

new!

ν QE Scattering

- *new revelation*: something as simple as QE scattering is not so simple
  - nuclear effects can significantly increase the cross section
  - idea that could be missing ~40% of σ is a big deal!

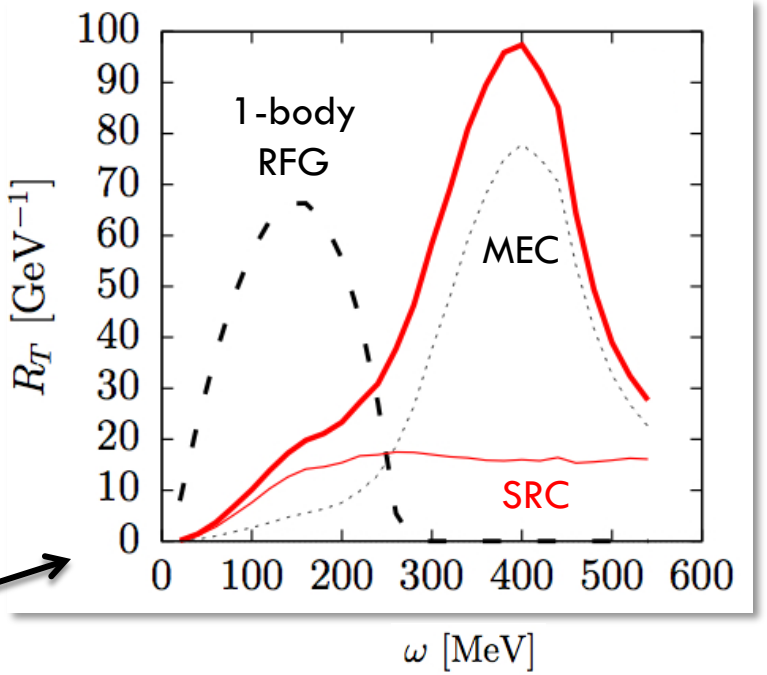
- need new nuclear dynamics to describe ν QE scattering
- no such model currently exists

(will be a challenge; needs attention!)

- effects will be different for ν vs. $\overline{\nu}$

(could produce a spurious CP violating effect)

- can impact E_ν reconstruction

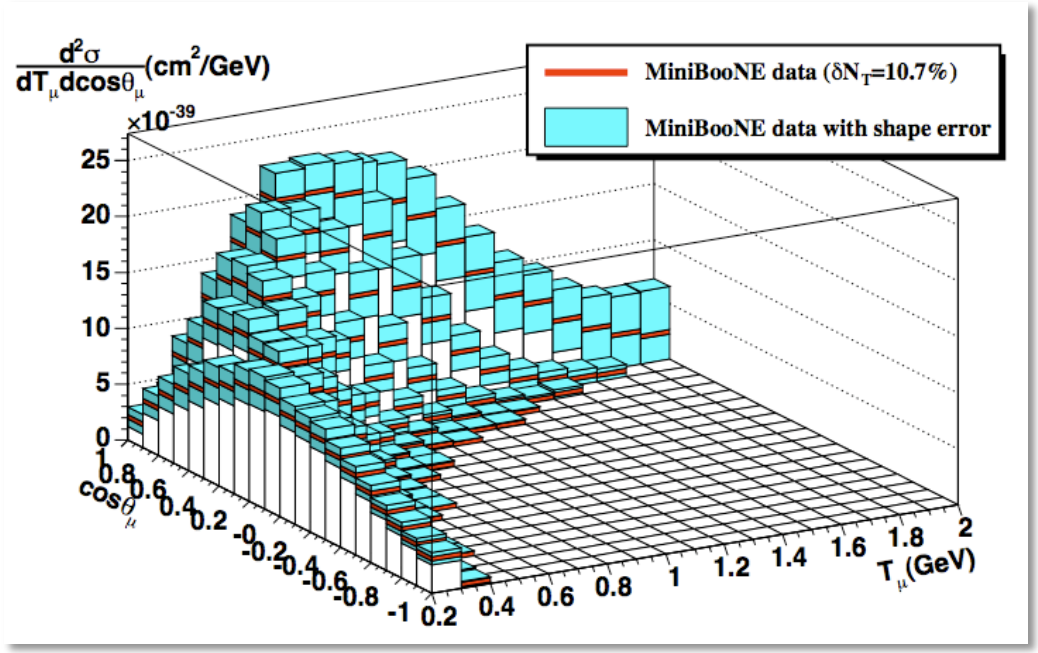


Amaro *et al.*, PRC **82**, 044601 (2010)

QE at MiniBooNE

Aguilar-Arevalo *et al.*, PRD **81**, 092005 (2010)

- 1st double differential σ's
- 146,000 ν_μ "QE" events
  (currently world's largest sample)
- historically, never had enough statistics to do this

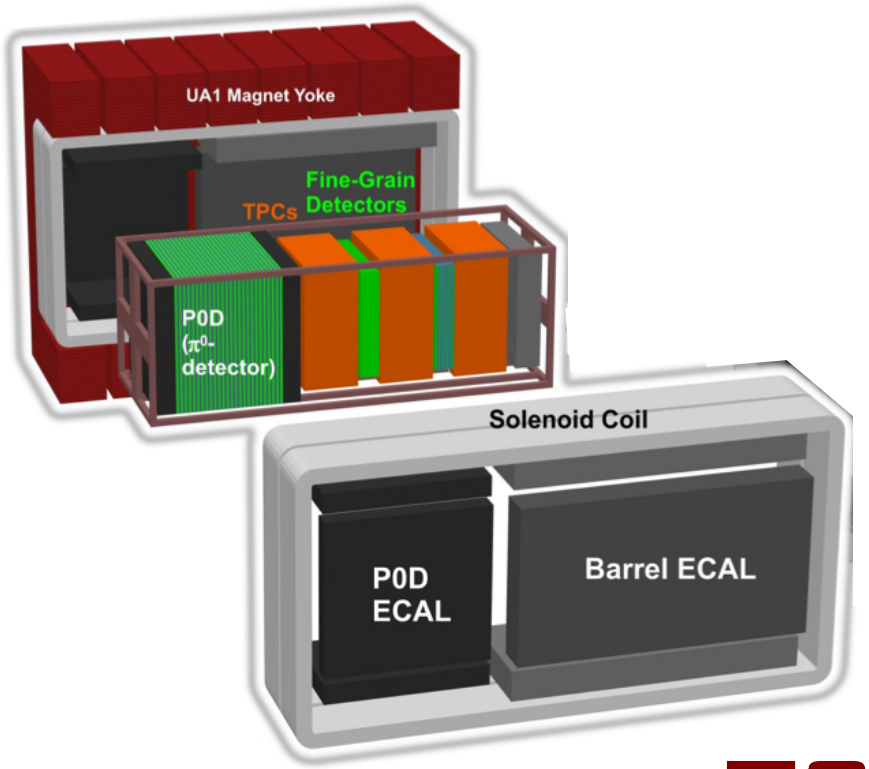


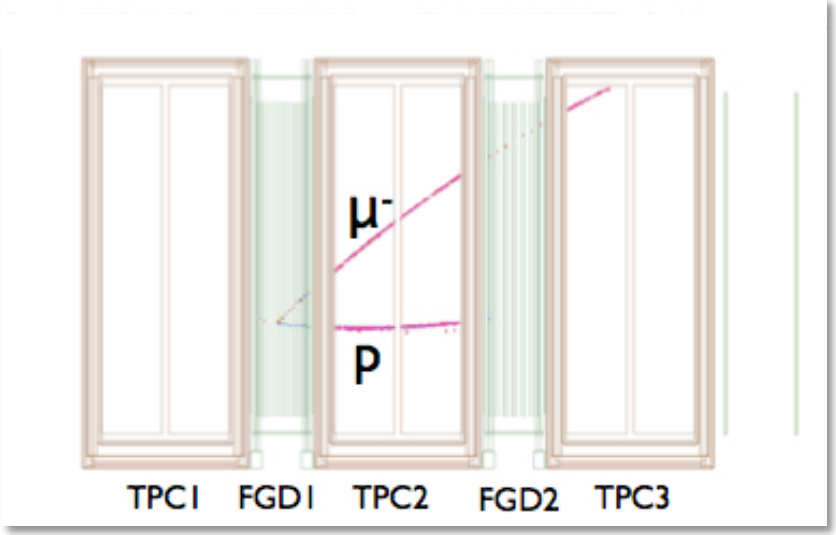
(T. Katori, IU, Ph.D. thesis)

- provides most complete info on ν QE scattering to date ($d^2\sigma/dT_\mu d\theta_\mu$)
- posing a formidable challenge for new nuclear model calculations

QE at T2K

- ND280 off-axis detector began ν data-taking in March 2010

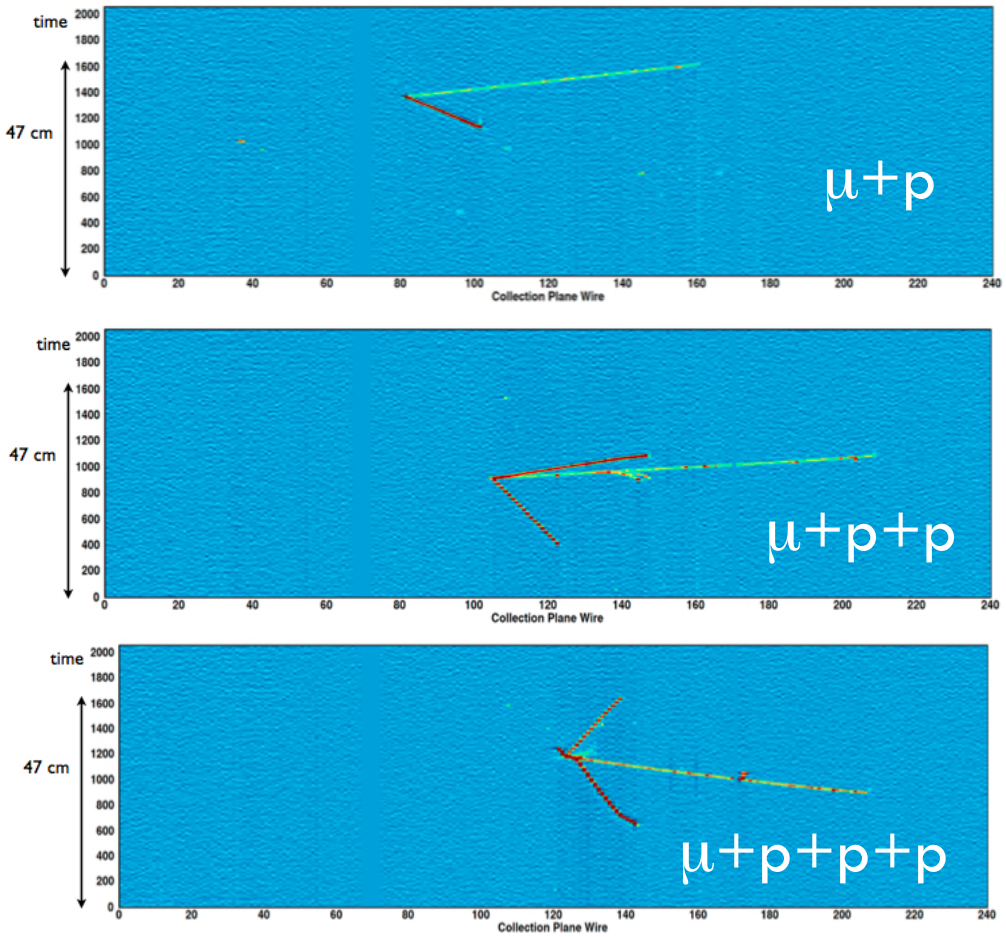




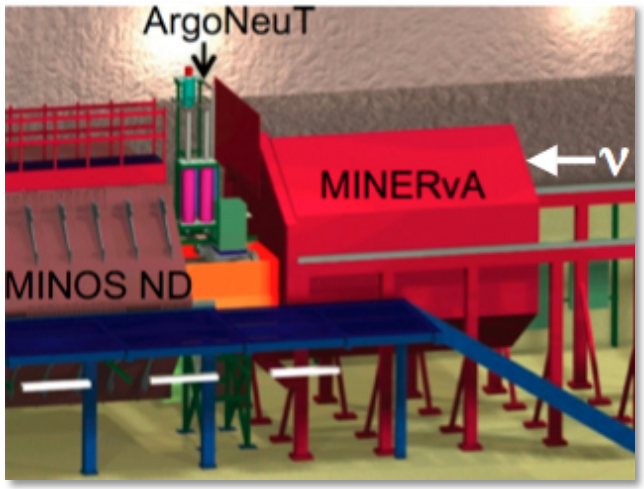
(L. Monfregola, NuInt11)

- QE analysis also underway in T2K ND280
  - thinking carefully about analysis strategy here
  - measurements on ^{12}C, ^{16}O similar energy range as MB

QE in ArgoNeuT

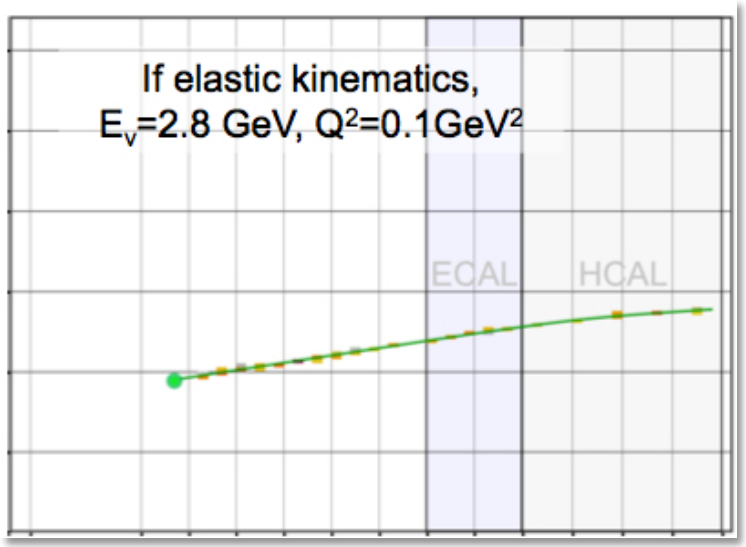


J. Spitz, arXiv:1009.2515 [hep-ex]



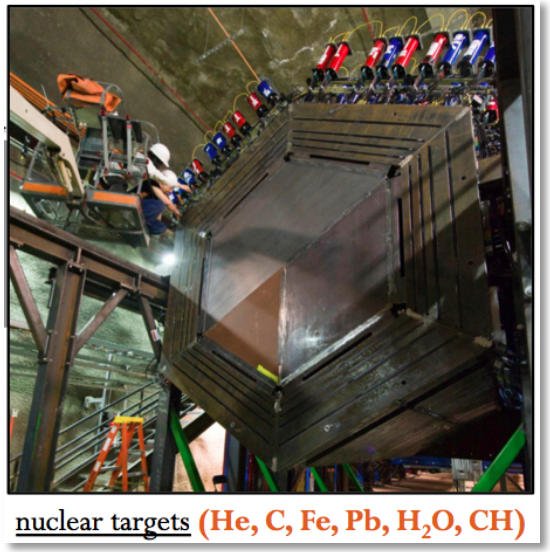
- 175L LAr TPC that took data in NuMI beamline (2009-2010)
- ν interactions in exquisite detail (ex., can detect protons down to 50 MeV)
- ν interactions in ^{40}Ar
- + MicroBooNE coming soon!

QE in MINERνA!



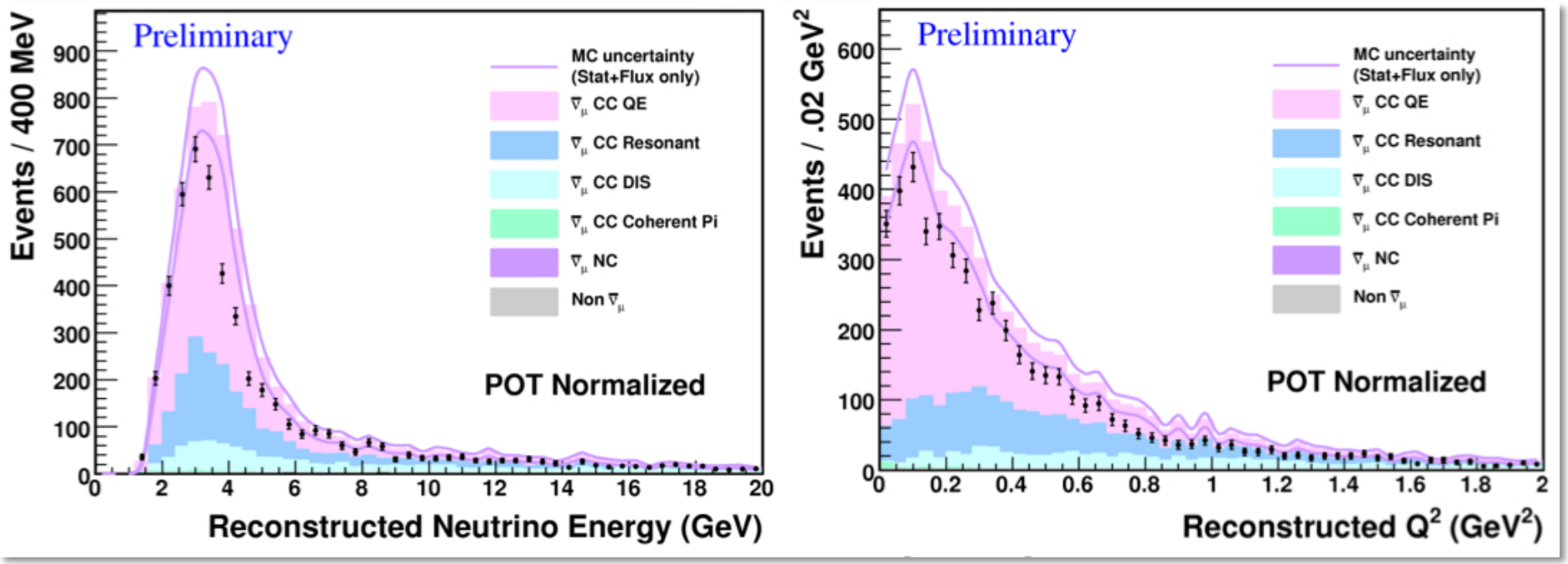
$\overline{\nu}_\mu p \rightarrow \mu^+ n$

- will pursue a broad range of σ_ν multiple beam E's and nuclear targets
- starting data-taking in March 2010



- starting with antineutrino QE (LE beam)
  - less sensitive to modeling of final state nucleon (unlike ν case)
  - less ambiguity as to whether or not selection includes extra effects of nucleon-nucleon correlations (unlike ν case)

$\overline{\nu}$ QE at MINERνA



- $\overline{\nu}_\mu$ QE interactions in CH across large energy range

  (note: MiniBooNE ν_μ QE measurement is below 2 GeV)

(K. McFarland, NuInt11)

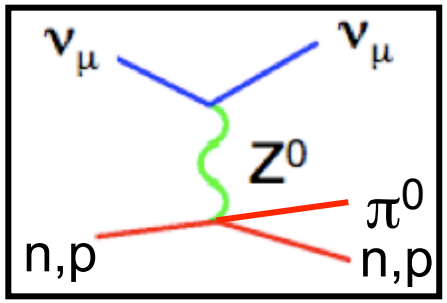
- observe an event **deficit;** has some E_ν-dependence

  (relative to "standard" MC, untuned NuMI flux, GENIE, M_A=0.99 GeV)

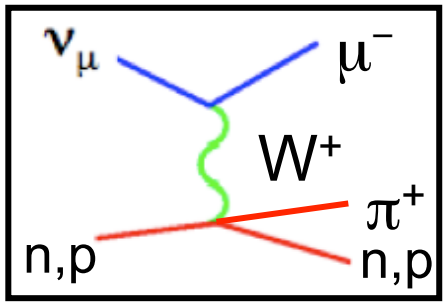
for more: see Jesse Chvojka's talk in R7

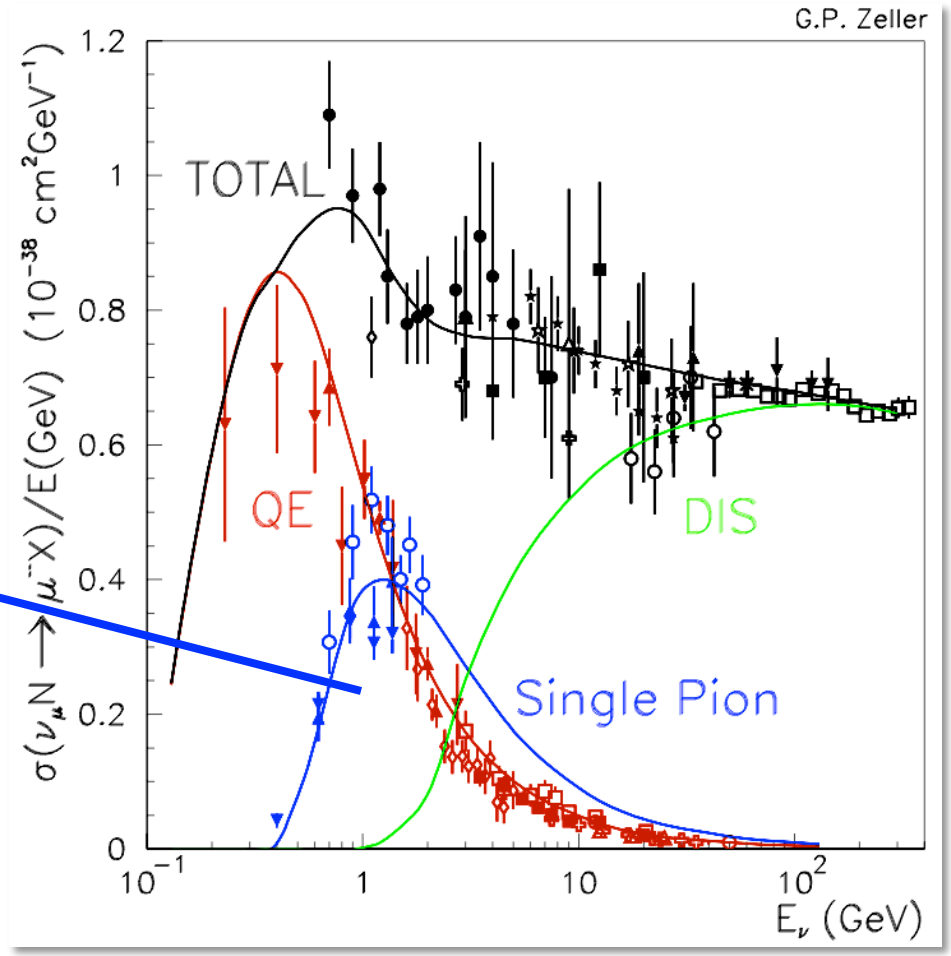
Resonance Production (Δ,N*$\rightarrow$Nπ)

- π^0 production



- π^+ production

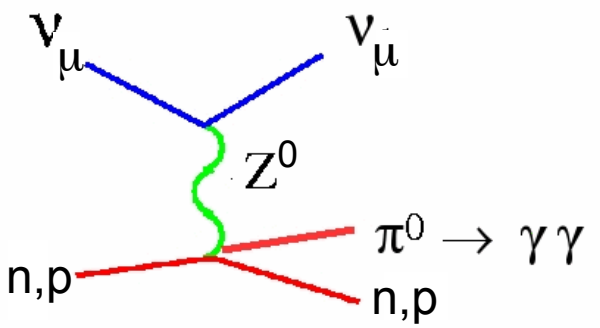




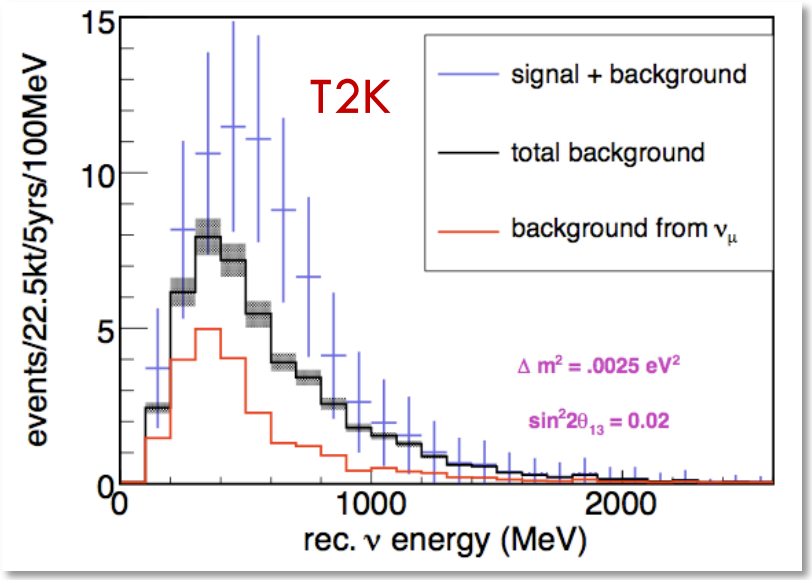
- important for different reasons → backgrounds

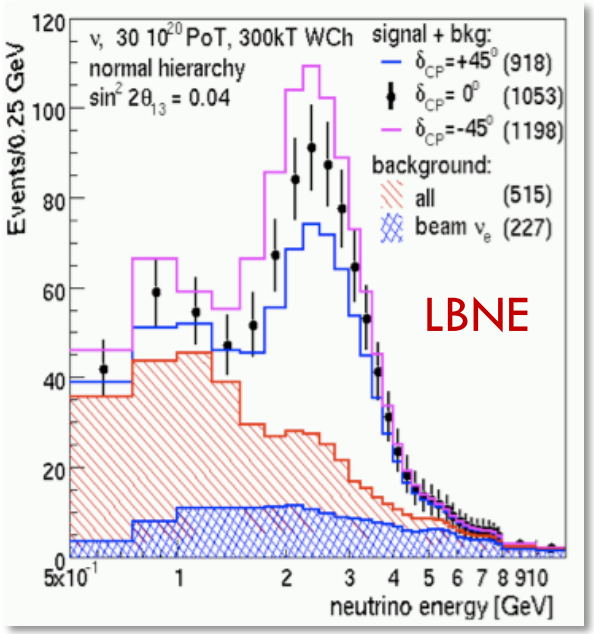
NC π^0 Production

Why important?



- **important for neutrino oscillation experiments**
  - dominant background for experiments looking for $\nu_\mu \rightarrow \nu_e$



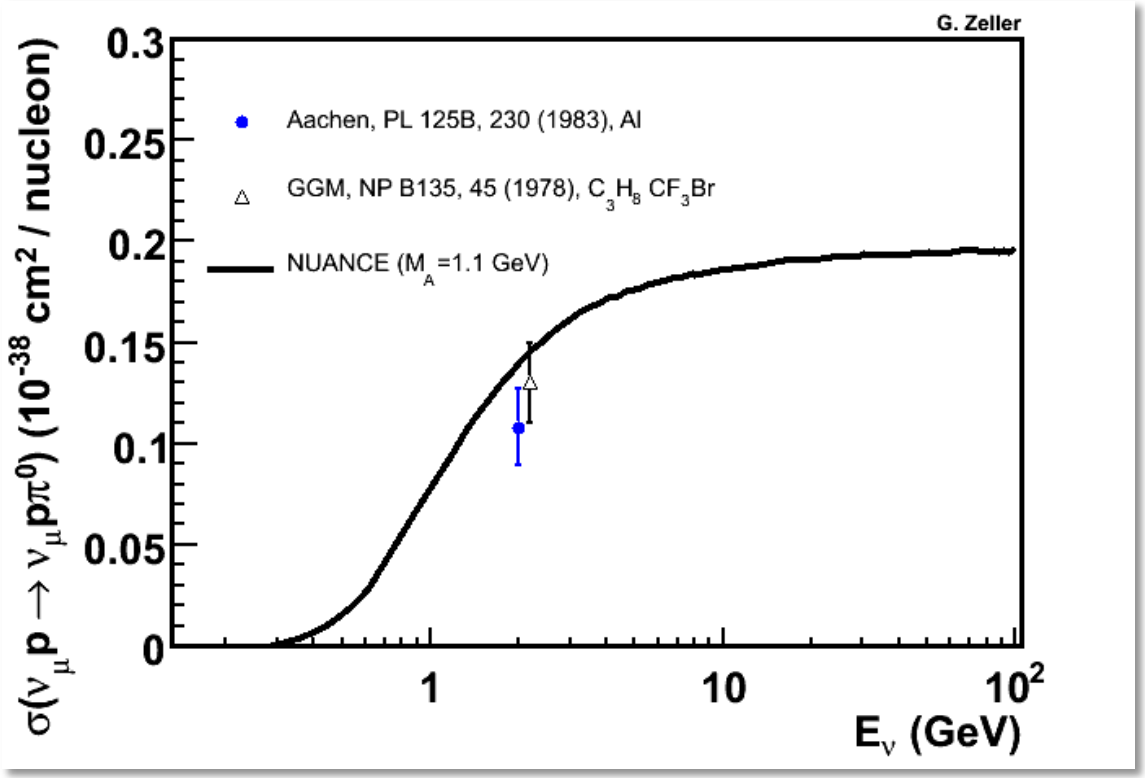


ν_e signals are small so need to worry about this

Historically …

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

- only two pre-existing NC π^0 measurements (1978, 1983)
- both at ~2 GeV
- based on <500 events combined



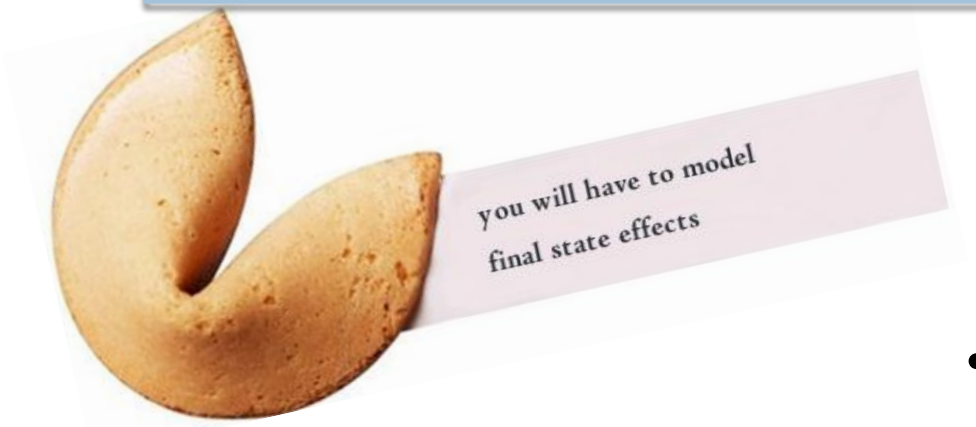
Final State Effects

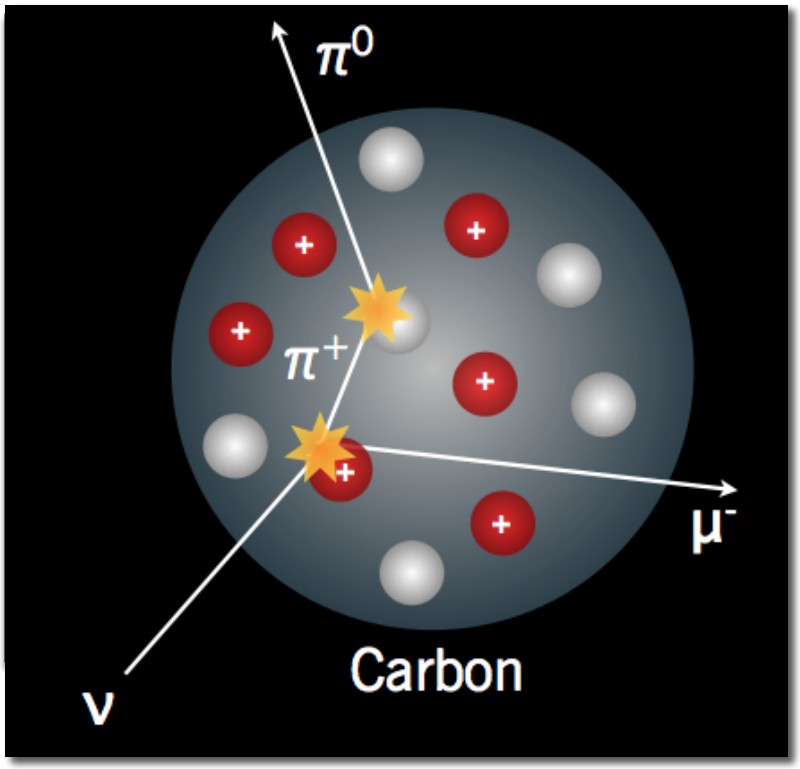
- new appreciation for nuclear effects in this region as well

  (nuclear effects can affect the final state; immediately complicate things)

"final state interactions (FSI)"

- once produced, hadrons have to make it out of the target nucleus
- π absorption dominates; but π can also charge exchange ($\pi^+ n \longrightarrow \pi^0 p$)





- have to worry about these effects

  (they are not small)

Final State Effects

- new appreciation for nuclear effects in this region as well

(nuclear effects can affect the final state; immediately complicate things)

(T. Leitner)

"final state interactions (FSI)"

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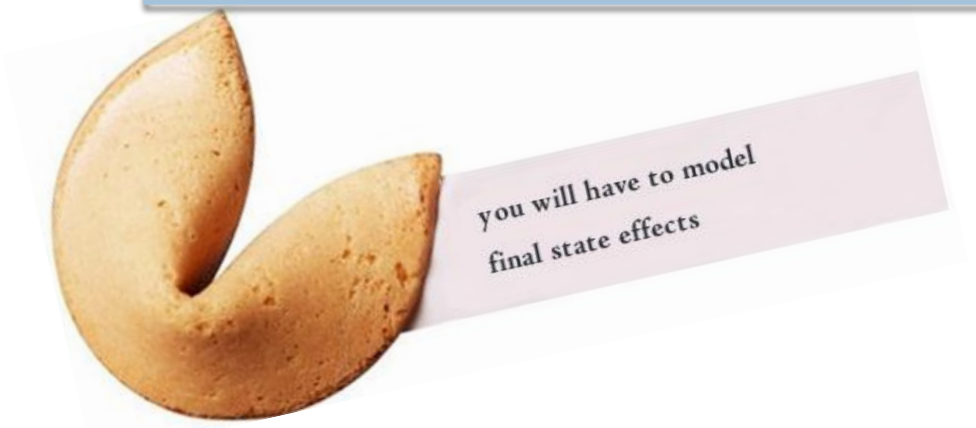
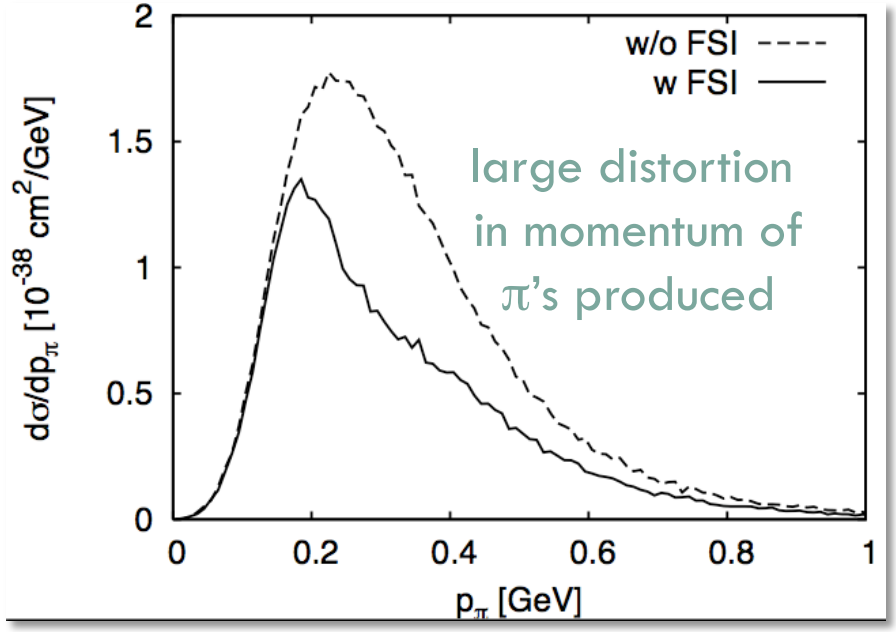
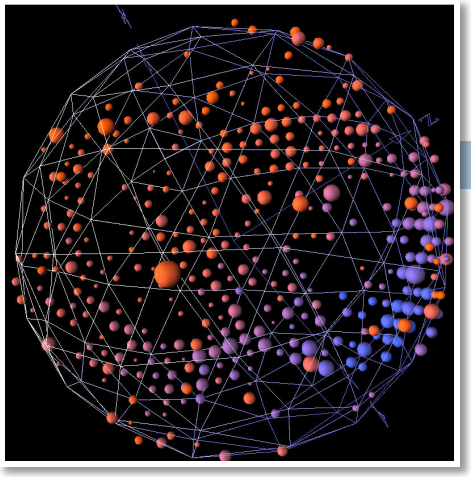




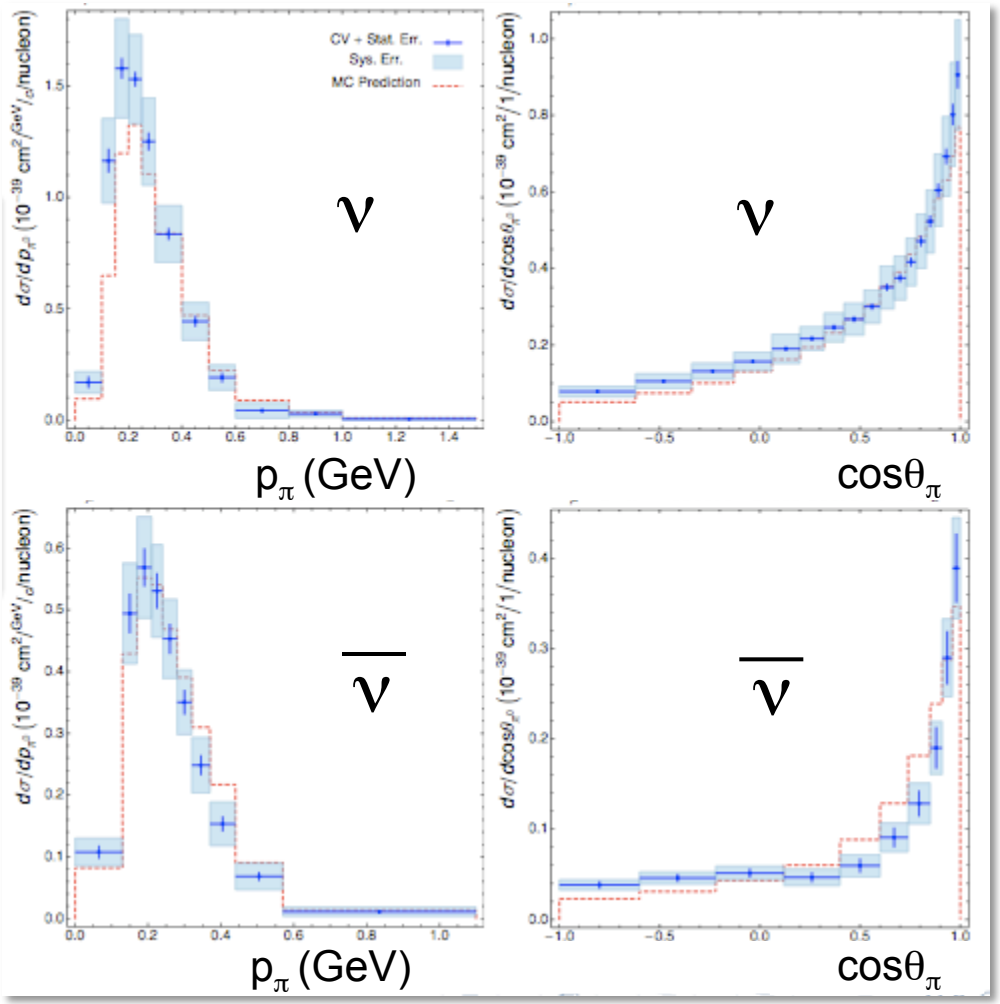
understanding π kinematics is important!

(has never been carefully studied)

NC π^0 at MiniBooNE



Aguilar-Arevalo *et al.*, PRD **81**, 013005 (2010)



(CH_2, flux-averaged)

- 1st diff'l cross sections (on CH_2)
- 21,275 ν_μ NC π^0
  2,789 $\overline{\nu}_\mu$ NC π^0

C. Anderson, Yale, Ph.D. thesis

this data was crucial for MB $\nu_\mu \rightarrow \nu_e$ oscillation search

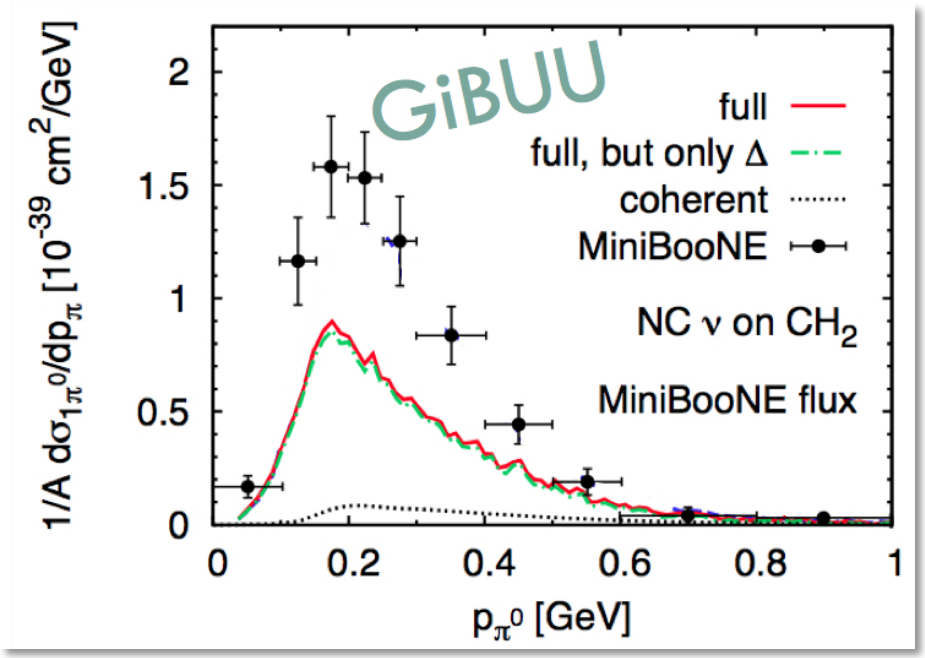
- data has been provided in a way that others can use

(and available on the web)

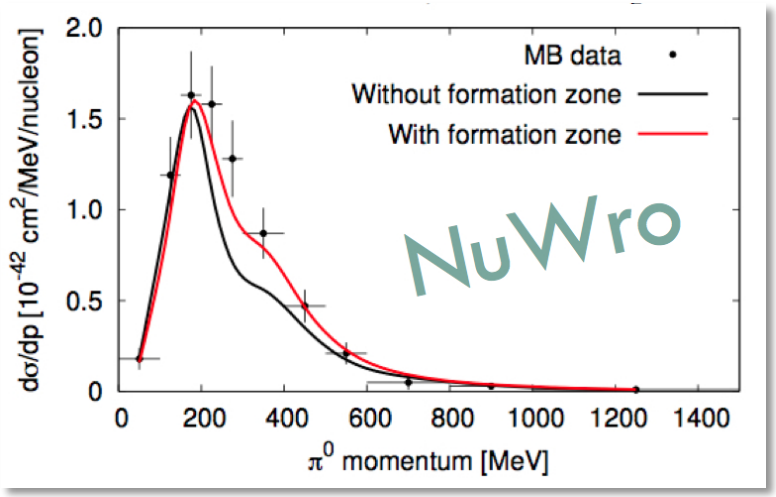
FSI Models

- data in heavy use by model builders

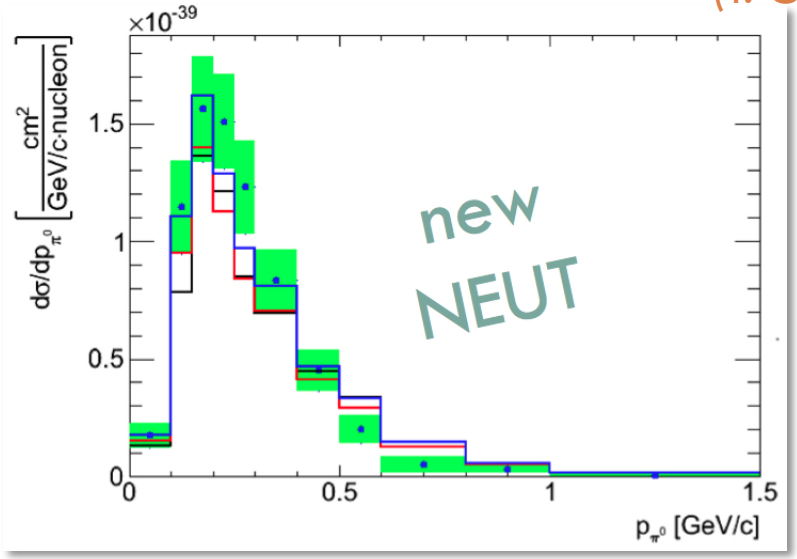
  (shown at the NuInt11 conference last month)



(U. Mosel)



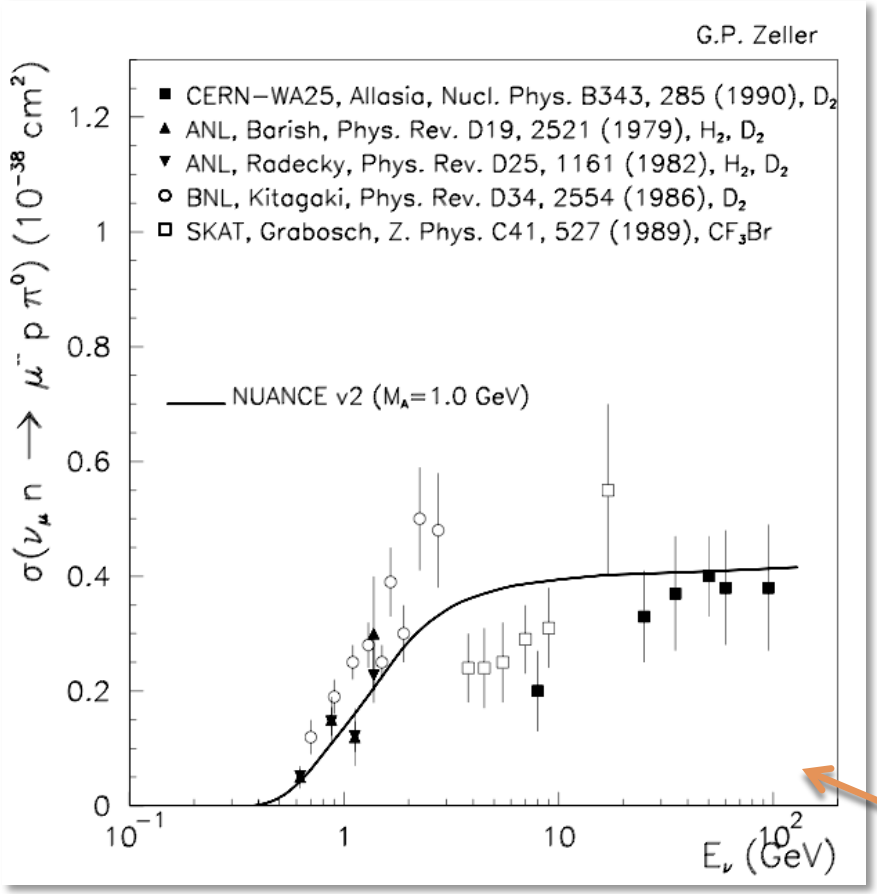
(T. Golan)

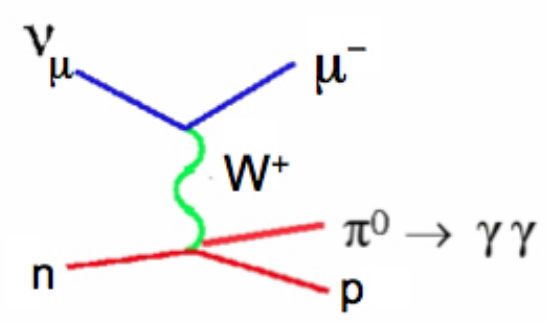


(P. dePerio)

CC π^0

- new studies of π^0 production in CC interactions too!





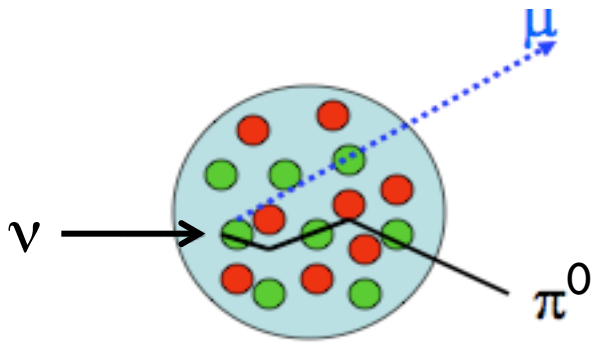
$\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0$

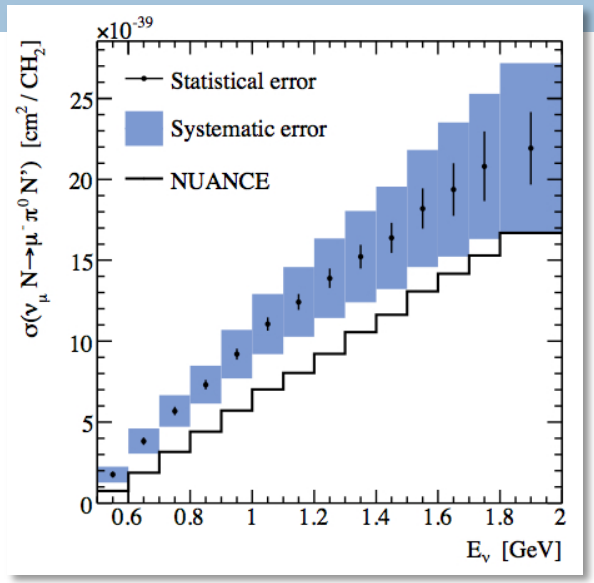
- CC so can reconstruct full kinematics (ex., E_ν) and provide some added input for NC π^0

this is what we've known
(room for improvement here too)

CC π^0 at MiniBooNE

- 5,810 CC π^0 events; paper last month:
  Aguilar-Arevalo *et al.*, PRD **83**, 052009 (2011)

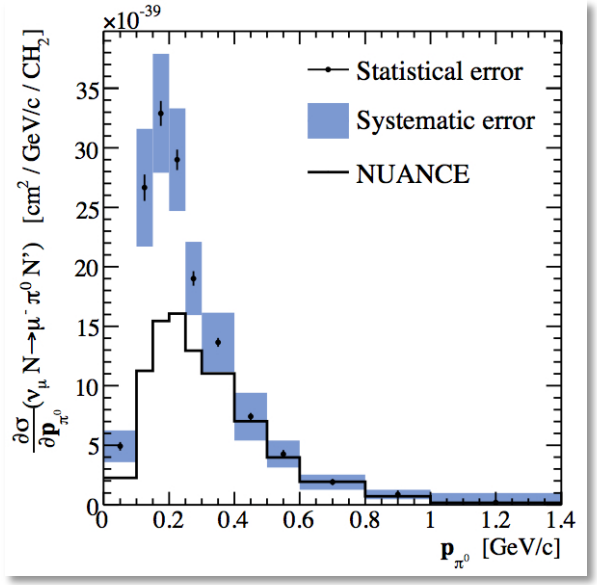




B. Nelson, UC Boulder, Ph.D. thesis

- 1st ever differential cross sections for this process on a nuclear target (CH_2)

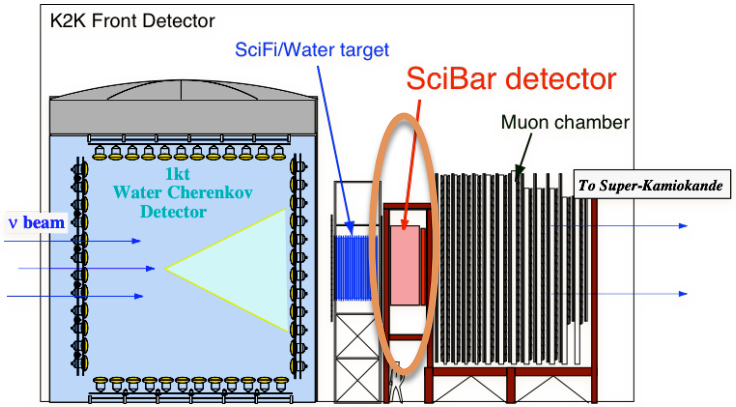
$\sigma(E_\nu)$, $d\sigma/dQ^2$
$d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$
$d\sigma/dp_\pi$, $d\sigma/d\theta_\pi$
} 6 dists



- most comprehensive study of CC π^0 to date

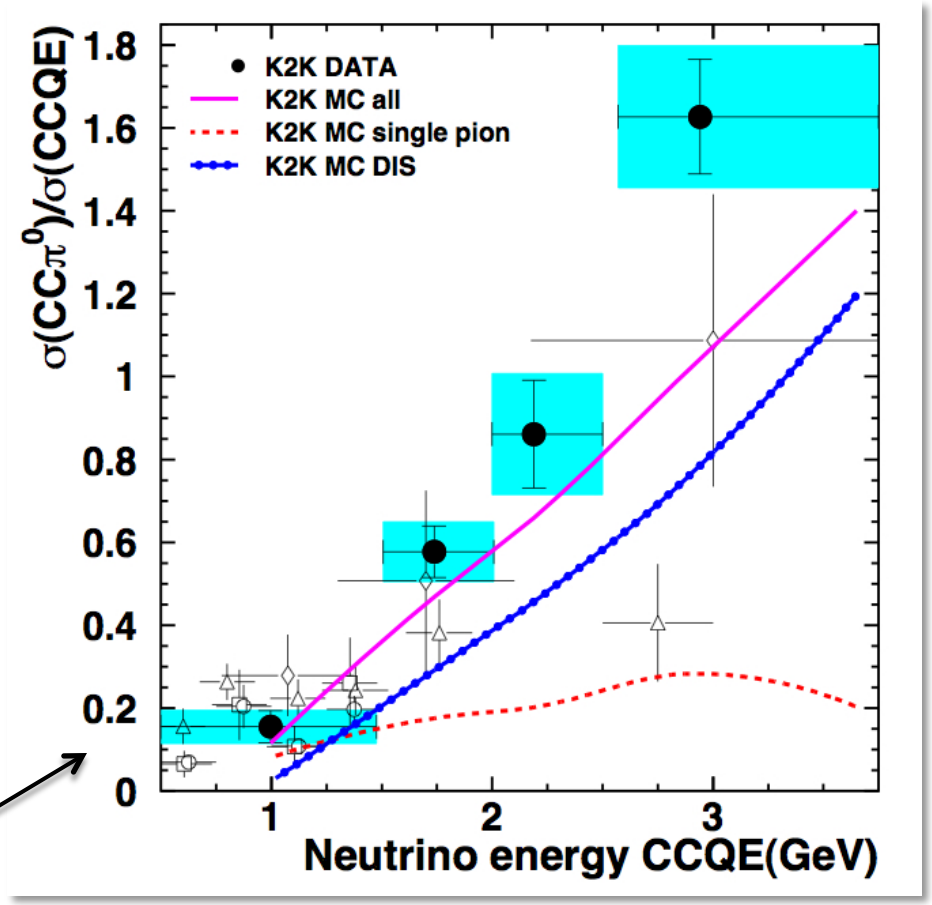
CC π^0 at K2K

- K2K ND took data 2003-2004



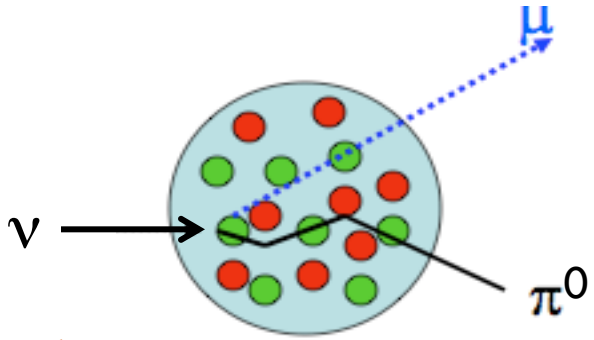
- 479 CC π^0 events on CH
- recently published CC π^0/QE ratio as a fcn of E_ν

Mariani *et al.*, PRD **83**, 054023 (2011)



CC π^0 at SciBooNE

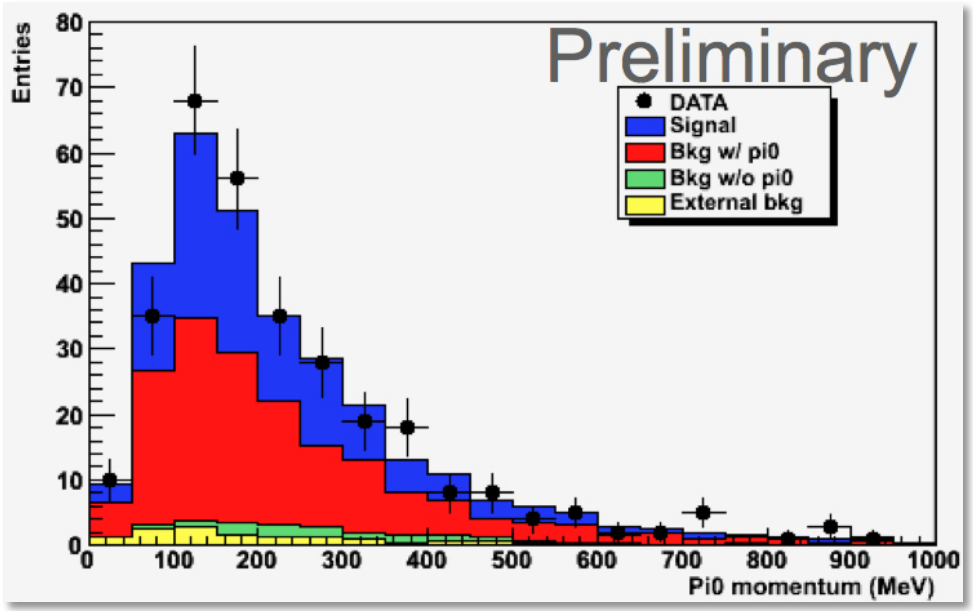
- using this same K2K detector
  but in Fermilab 8 GeV beam (2007-2008)



- 231 CC π^0 events on CH
- released a preliminary
  absolute σ last month:

$\sigma(CC\ \pi^0) = 5.6 \pm 1.9$ (stat)
$\times 10^{-40}$ cm^2/nucleon
at $\langle E_\nu \rangle$ *893 MeV*

(H. Tanaka, Nunt11)



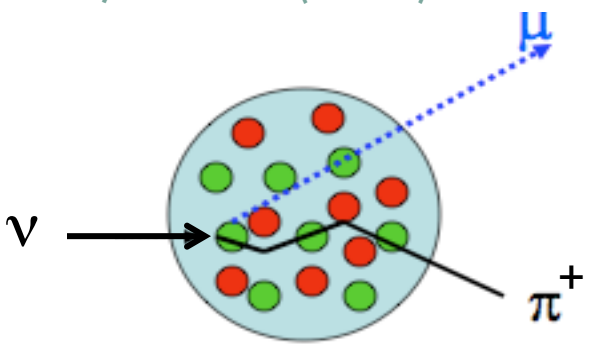
- also, CC π^0 analysis underway using T2K ND (J8: Dan Ruterbories)

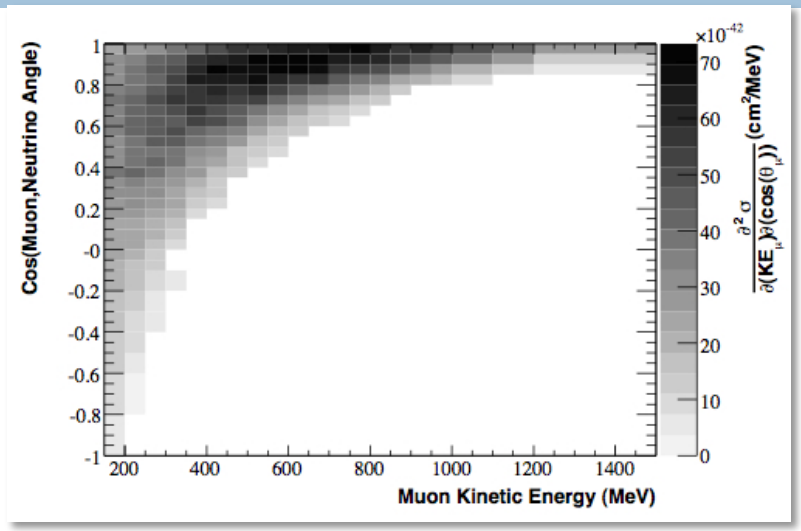
CC π^+ at MiniBooNE

- important bkg for disapp exps

$$\nu_\mu \rightarrow \not{\nu}_\mu$$

- 48,322 CC π^+ events (CH_2)
  PRD **83**, 052007 (2011)



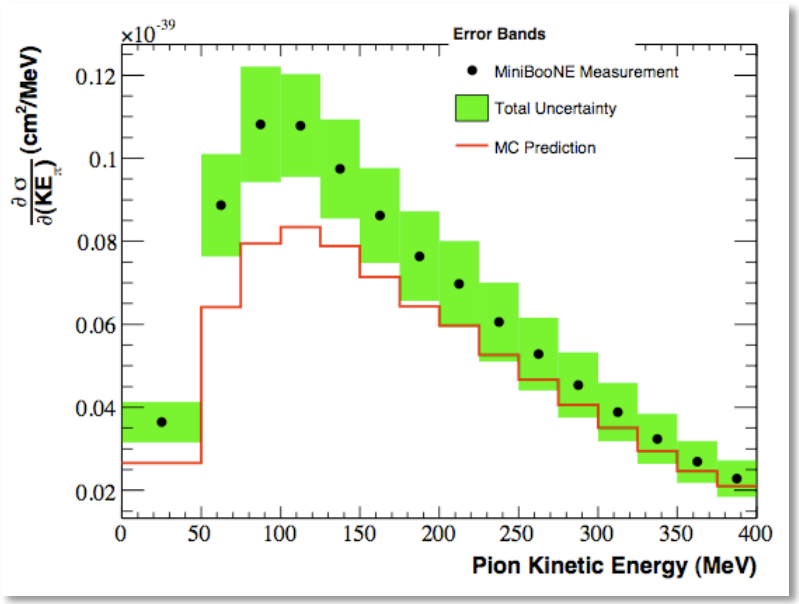


M. Wilking, UC Boulder, Ph.D. thesis

- MiniBooNE leading the pack

$\sigma(E_\nu)$, $d\sigma/dQ^2$, $d^2\sigma/dT_\mu d\theta_\mu$,
$d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$,
$d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\pi d\theta_\pi$

} 8 dists (many 1st's)



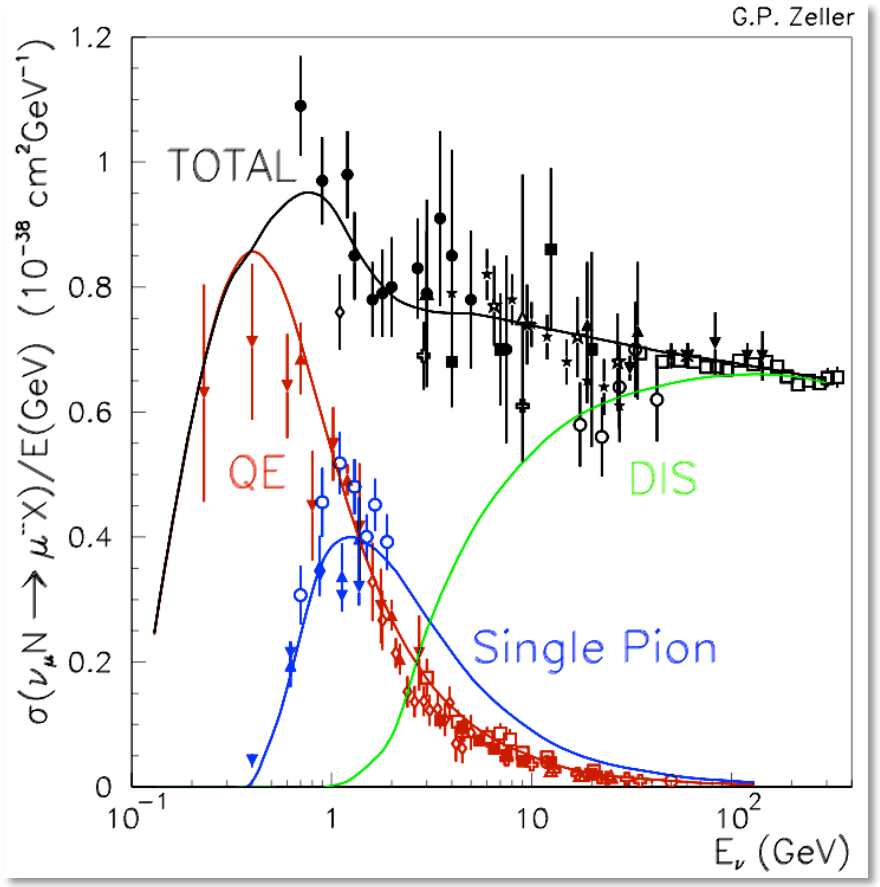
- information we have not had access to

Total CC Inclusive Cross Section

- measures everything at once:

+ QE
+ np-nh
+ Δ, N* $\rightarrow$ $\not{\pi}$
+ Δ, N* $\rightarrow$ 1π, multi-π
+ DIS …

- high purity samples (σ for events with a μ)

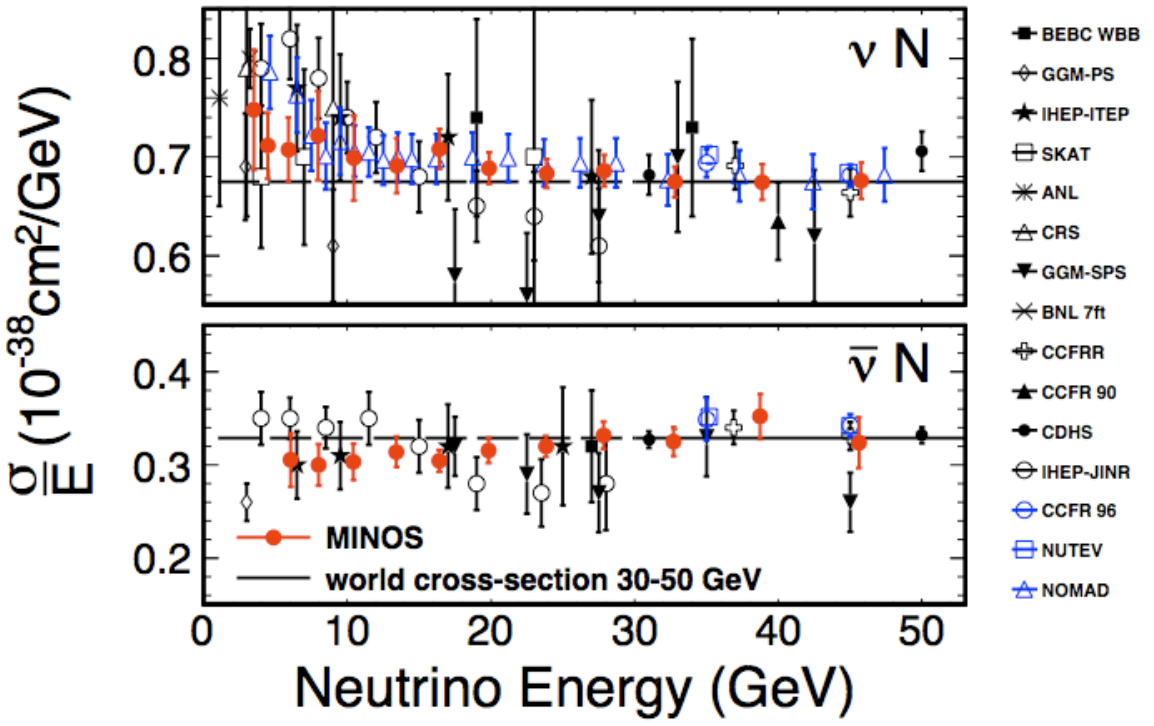


clear need for improved measurements $E_\nu \lesssim 50$ GeV

Total CC Cross Section

$\nu_\mu N \rightarrow \mu^- X$

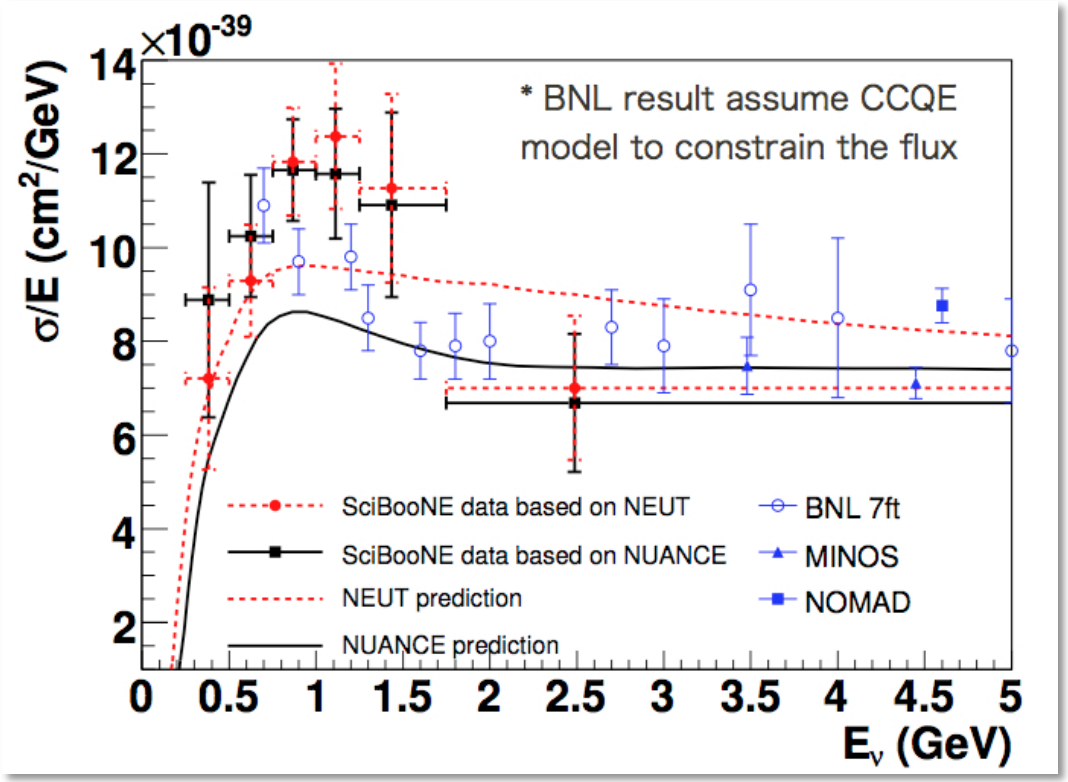
- new data in the past couple years
- have greatly increased precision in this energy region



- **NOMAD:** (ν ^{12}C), 2.5<E_ν<230 GeV, PLB **660** 19 (2008)
- **MINOS:** (ν,$\overline{\nu}$ ^{56}Fe), 3<E_ν<50 GeV, PRD **81**, 072002 (2010)

Total CC at SciBooNE

(Y. Nakajima, NuInt11)



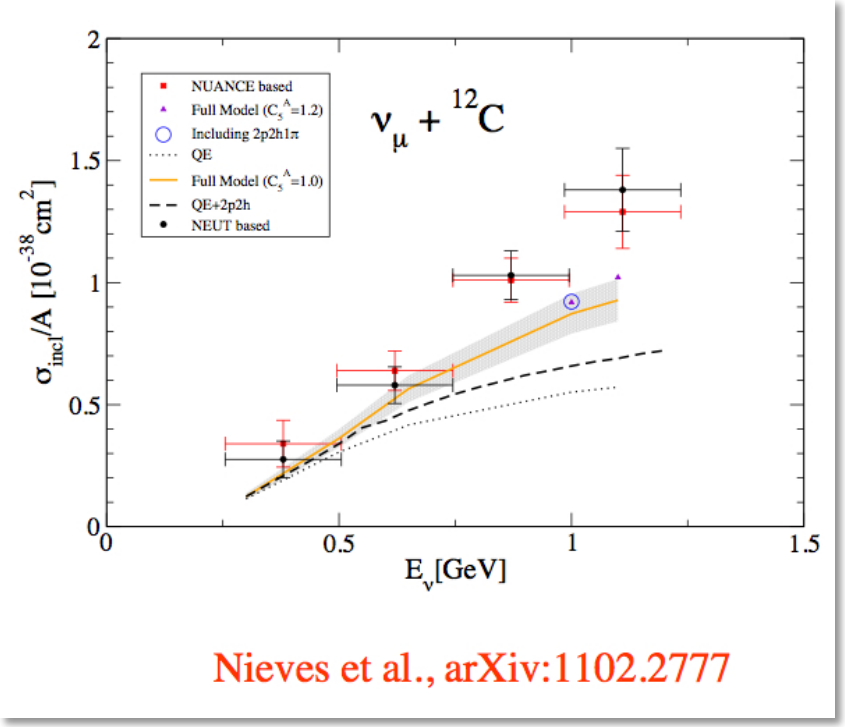
$\nu_\mu N \rightarrow \mu^- X$

- SciBooNE has now provided the 1st measurement of the CC inclusive σ on a nuclear target (^{12}C) below 3 GeV

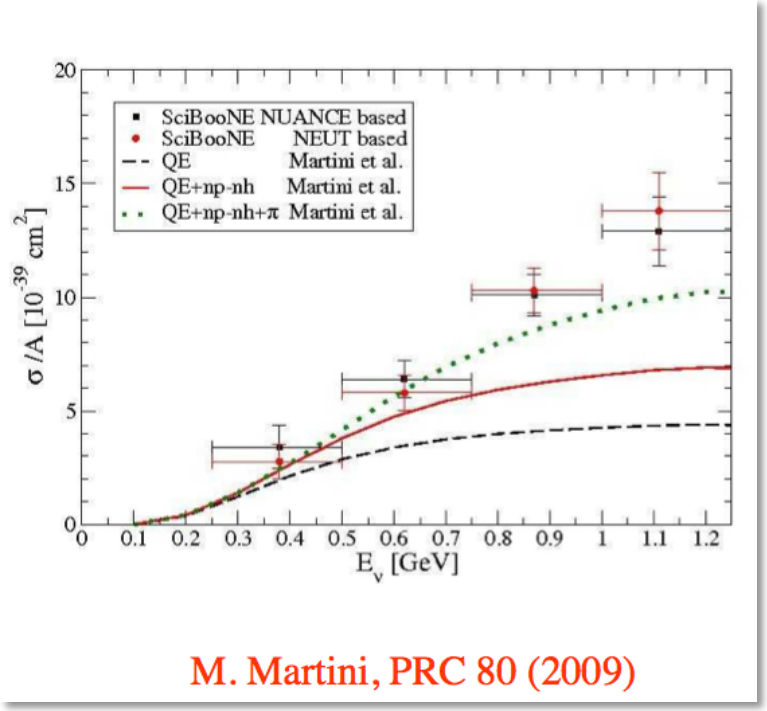
Nakajima, *et al.*, PRD **83**, 012005 (2011)

SciBooNE Results in Use

- this is a needed starting point for model comparisons



Nieves et al., arXiv:1102.2777



M. Martini, PRC 80 (2009)

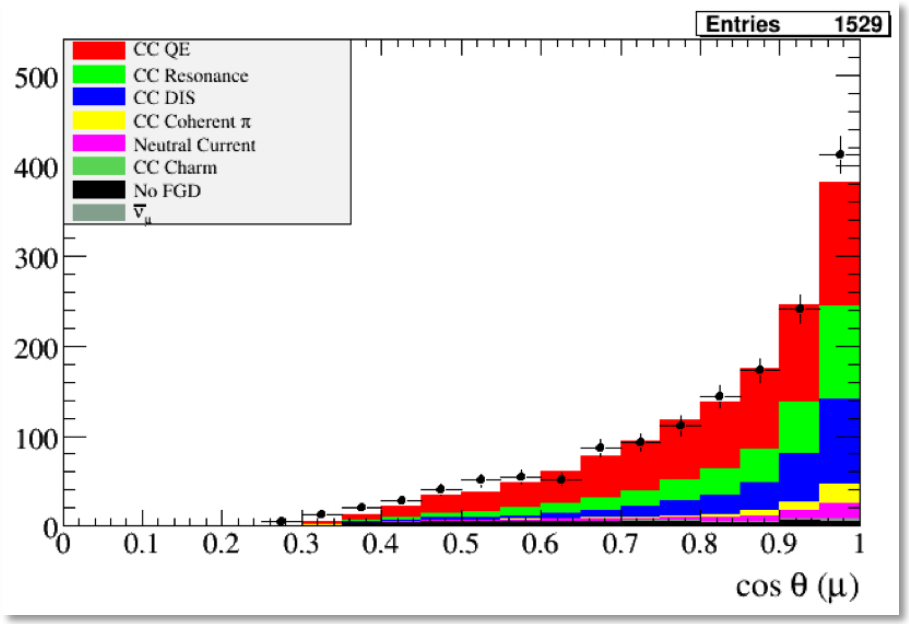
(L. Alvarez-Ruso, NuInt11)

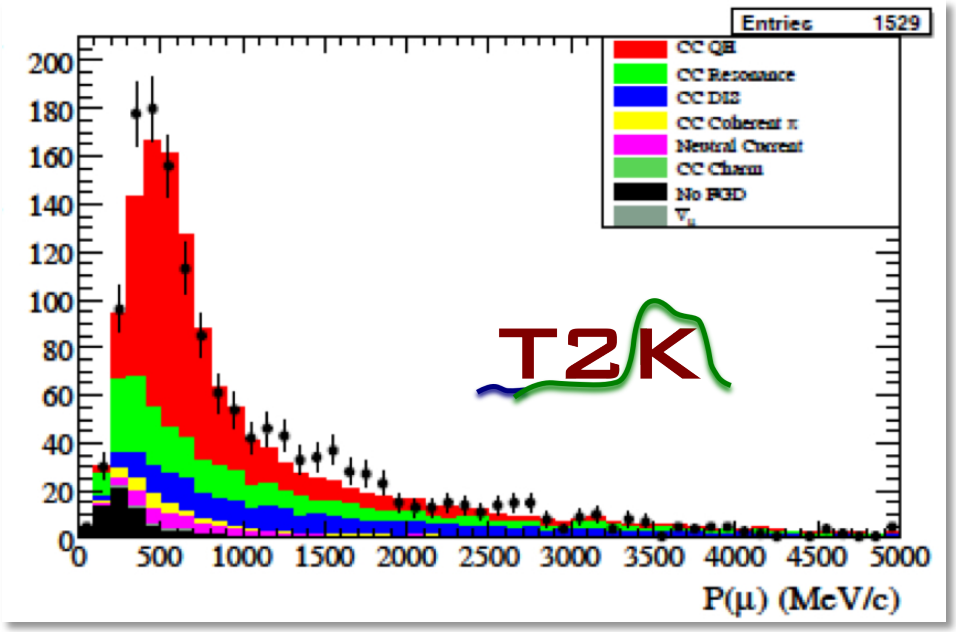
- next, really need $d^2\sigma/dT_\mu d\theta_\mu$!
- and A dependence!

Total CC at T2K

- very similar E_ν range to SciBooNE
- T2K plans to measure $d^2\sigma/dT_\mu d\theta_\mu$
- ingredients for such a measurement:

(J. Imber, J8 session)



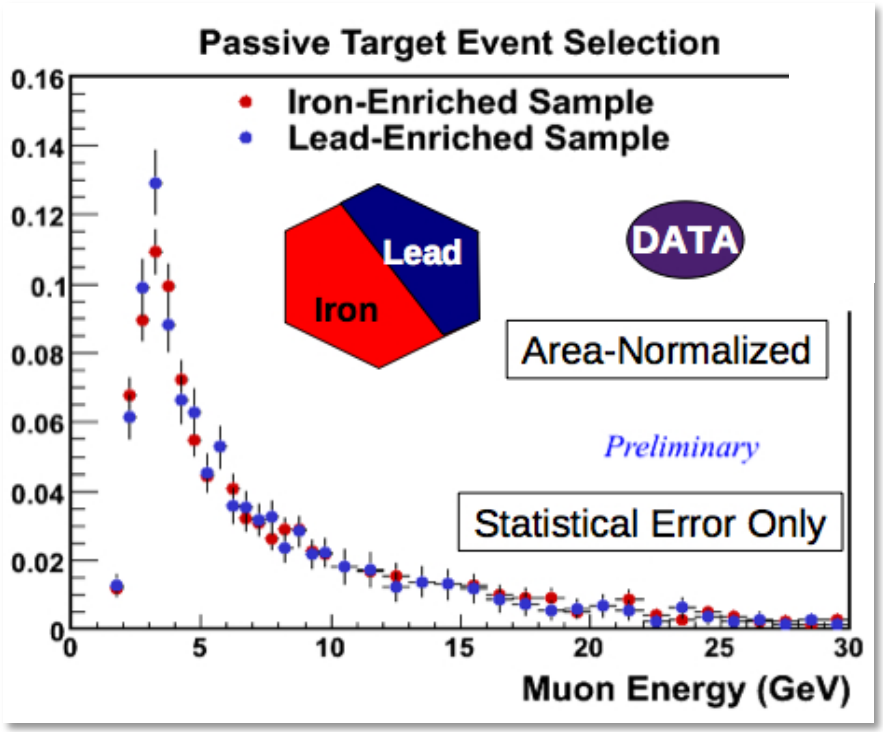


- 1st data from ND280 detector released last month!

Total CC at MINERνA

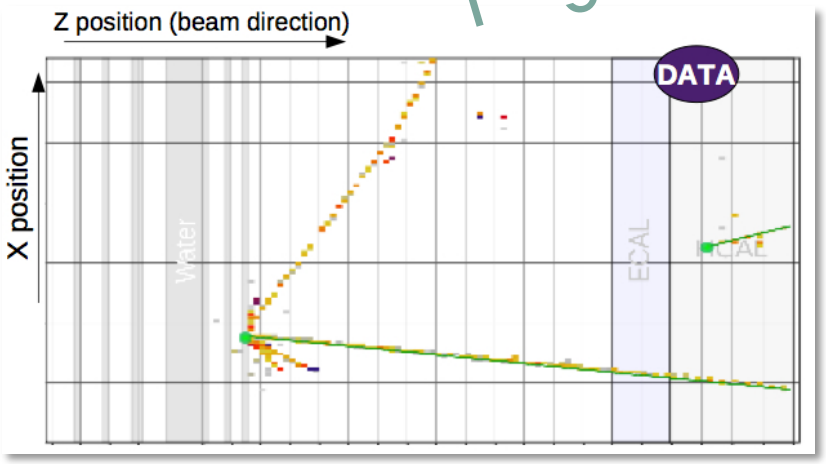
- MINERνA will measure ratios of ν and $\overline{\nu}$ CC events on plastic, Pb, Fe across very large energy range *(will be a real power house!)*

  - *LE mode alone*: 409k events in plastic, 68k Pb, 65k Fe



(B. Tice, NuInt11)

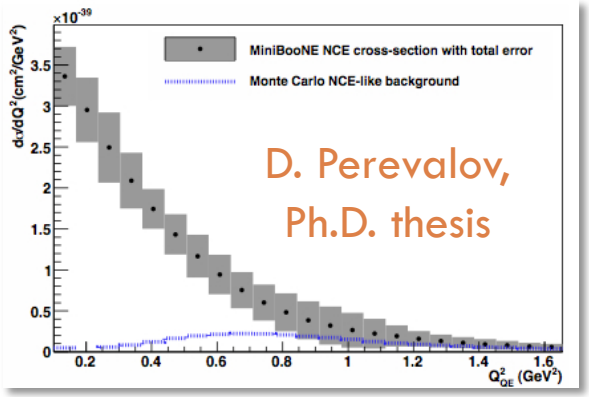
MINERνA 1st glimpse!



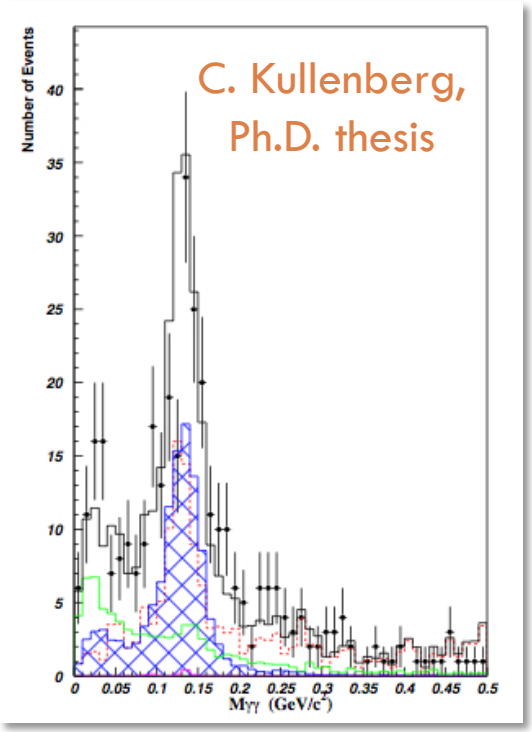
(DIS event reconstructed in iron)

Didn't Have Time To Discuss …

- NC elastic scattering (ν_μ N $\rightarrow$ ν_μ N)
  - MiniBooNE, PRD **82**, 092005 (2010)

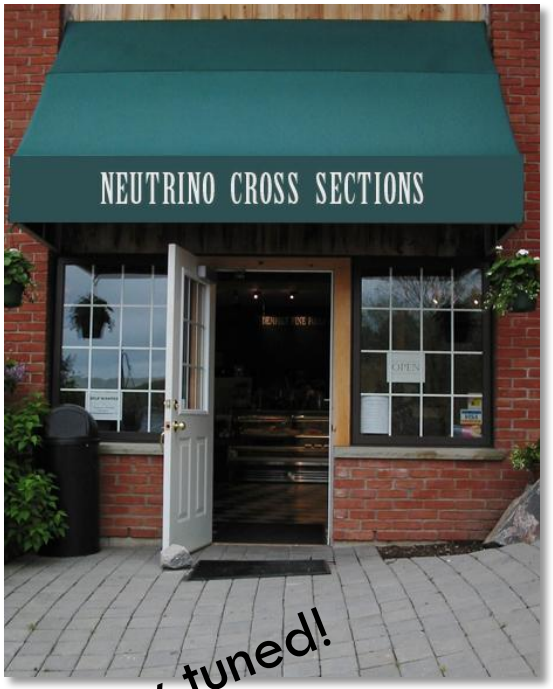


- NC coherent π^0 production (ν_μ A $\rightarrow$ ν_μ A π^0)
  - MiniBooNE, PLB **664**, 41 (2008)
  - NOMAD, PLB **682**, 177 (2009)
  - SciBooNE, PRD **81**, 033004 (2010), 11102 (2010)
  - MINOS, D. Cherdak, NuInt11 workshop
- CC coherent π^+ production (ν_μ A $\rightarrow$ μ^- A π^+)
  - K2K, PRL **95**, 252301 (2005)
  - SciBooNE, PRD **78**, 112004 (2008)
  - SciBooNE $\overline{\nu}$, H. Tanaka, NuInt11 workshop



Conclusions

- a lot of new results on a variety of different ν interaction channels from multiple experiments in this important energy region (few-GeV)
- new data uncovering added complexities in QE & resonance regions
  - *nuclear effects are important*
  - *also need antineutrino measurements*
- modern experiments have the capability to resolve a number of these interesting puzzles & provide critical input to future ν osc exps
  - K2K, MiniBooNE, NOMAD, SciBooNE
  - ArgoNeuT, MicroBooNE, MINERνA
    also, MINOS, NOvA, & T2K near detectors



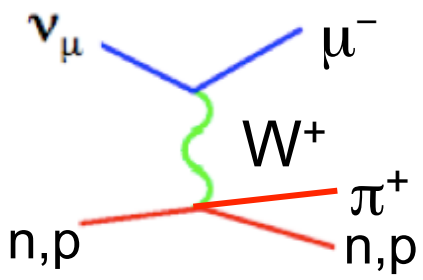
Advertisement

Session R7: Neutrinos (this afternoon, 1:30-3:30pm)

- "Measuring nuclear effects with MINERνA" (G.A. Fiorentini)
- "Study of Λ^0 Polarization at Low Energies" (M.C. Zarazua)
- "Weak π and γ Production from Nuclei" (X. Zhang)
- "MINERνA Test Beam Studies" (J. Felix)
- "ν QE Scattering in MINERνA" (J. Chvojka)
- "Early ν Data in the NOvA Near Detector on Surface" (M. Betancourt)

Backups

CC π^+ Production

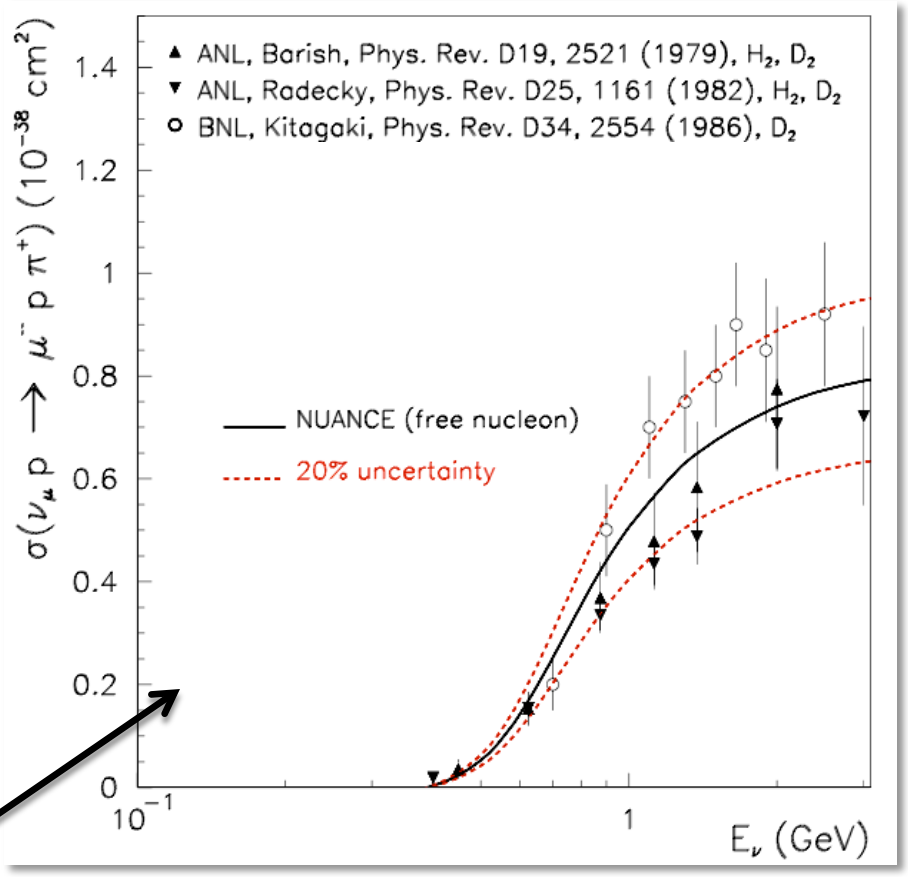


- important to measure this process on nuclear targets for ν_μ and $\overline{\nu}_\mu$ disappearance experiments

  (directly impacts Δm^2_{23}, θ_{23})

  $\nu_\mu \rightarrow \not{\nu}_\mu$

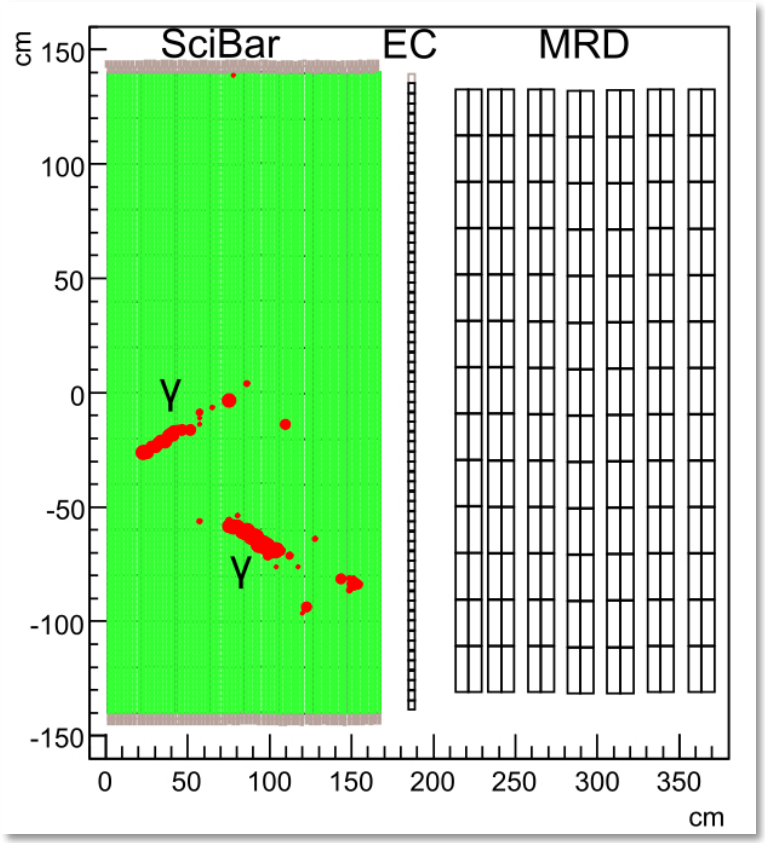
- example of what we've known at the lowest ν energies



- more recently, CC π^+/QE:

  * *K2K*: PRD **78**, 032003 (2008)
  * *MiniBooNE*: PRL **103**, 081801 (2009)

NC π^0 at SciBooNE



Kurimoto *et al.*, PRD **81**, 033004 (2010)

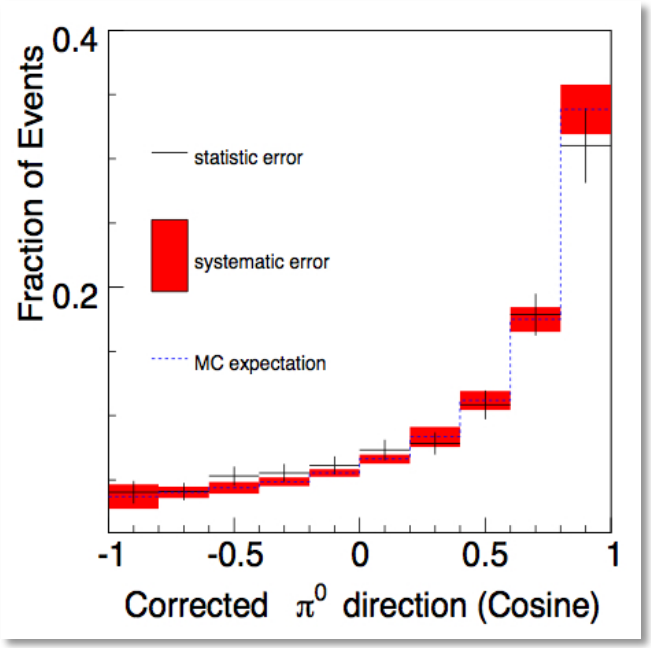
$$\frac{\sigma(\text{NC } \pi^0)}{\sigma(\text{CC})} = (7.7 \pm 0.7)\ \text{x}10^{-2}$$

at 1.1 GeV, CH

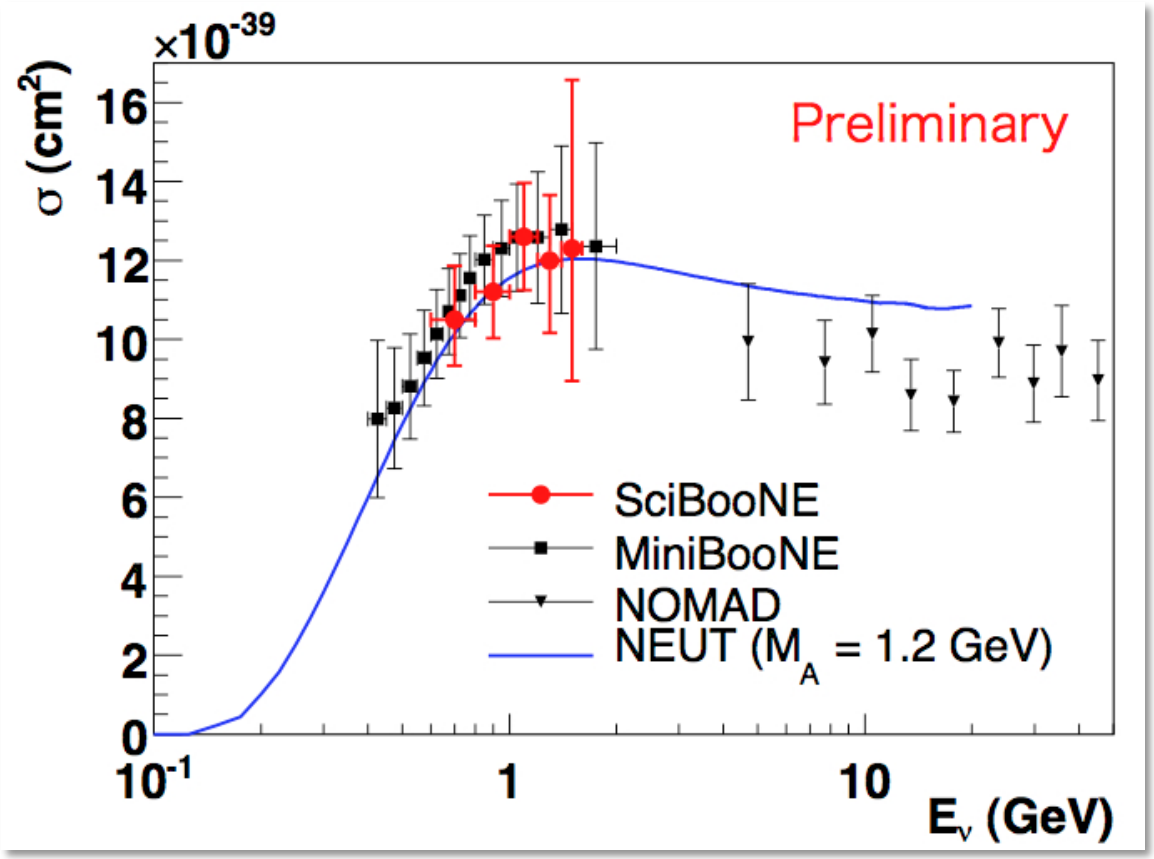
- consistent with earlier K2K measurement

  Nakayama *et al.*, PL **B619**, 255 (2005)

- again, providing an important check of π^0 kinematics →



Challenging to Reconcile all QE Data



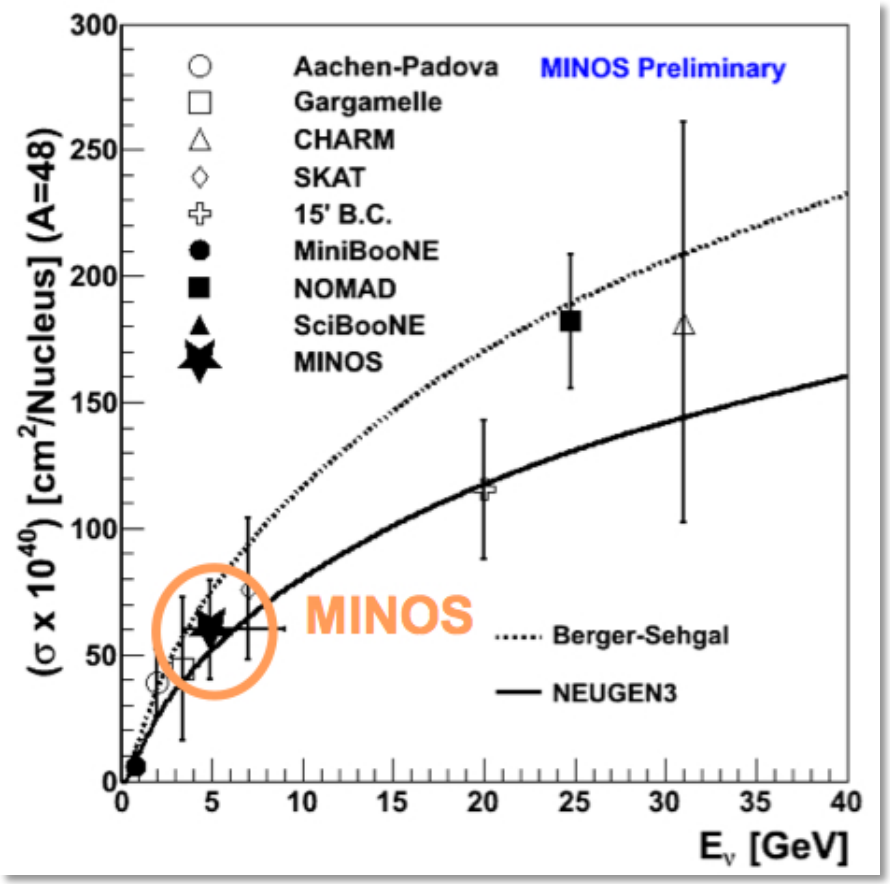
(Y. Nakajima, NuInt11)

- **MiniBooNE**
  = μ+ no π + any # n,p
  = QE + np-nh

- **NOMAD**
  = 1-track μ
  2-track μ+p
  = QE + ?

- **SciBooNE** (data in 2007-2008)
  = 1-track μ
  2-track μ+p
  = QE + ?

MINOS NC Coherent π^0



(D. Cherdak, NuInt11)

- new data point in between existing low (K2K, MB, SB) & high (NOMAD) energy data
- 1st measurement of NC coh π^0 for A>30 and 1st on iron
- also working on $\overline{\nu}$ analysis

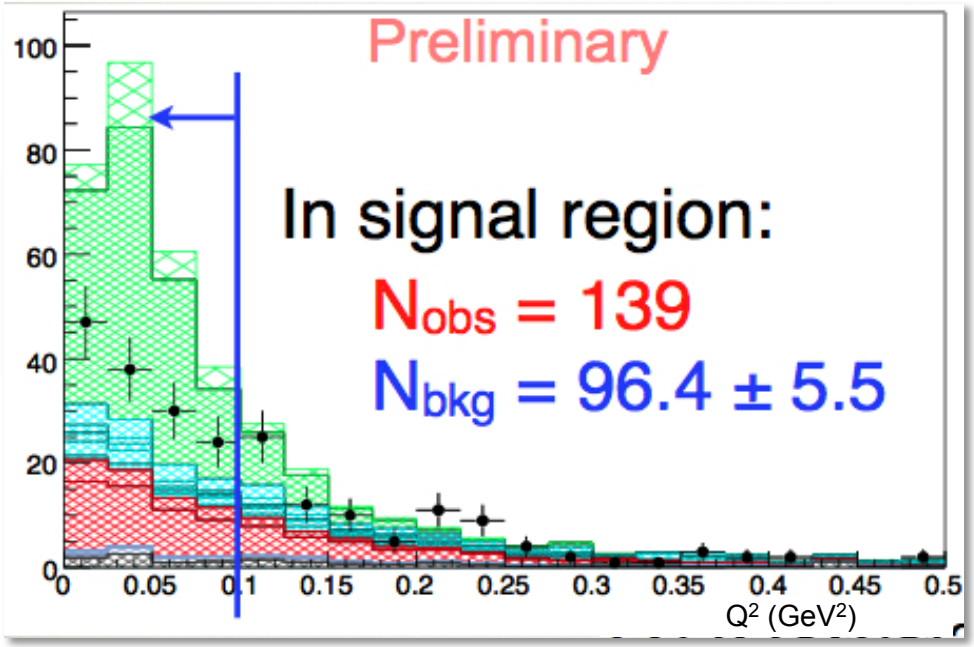
SciBooNE $\overline{\nu}$ Coherent CC π^-

- 1st modern measurement of coherent π production using antineutrinos!

(H. Tanaka, NuInt11)

$$\frac{\sigma(\bar{\nu}\ \text{CC coh-}\pi) + r\cdot\sigma(\nu\ \text{CC coh-}\pi)}{\sigma(\bar{\nu}\ \text{CC}) + r\cdot\sigma(\nu\ \text{CC})} = (\ 1.13 \pm 0.34(\text{stat})\ ^{+0.31}_{-0.36}(\text{sys})\ ) \times 10^{-2}$$

Preliminary



- ~2σ evidence for CC coherent π production in very forward scattering region (low Q^2)