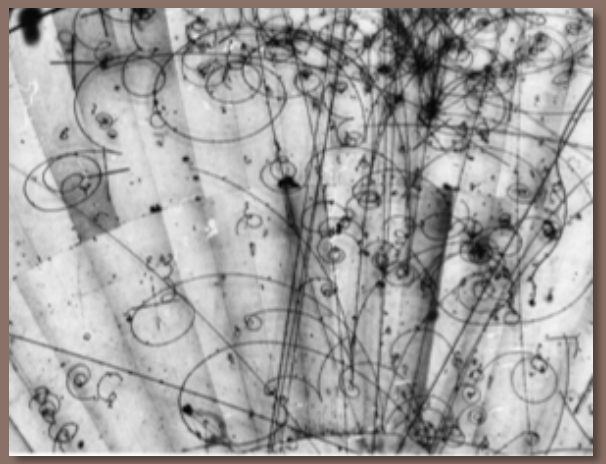
NEUTRINO CROSS SECTIONS

Sam Zeller
Fermilab

SBL Workshop
May 13, 2011



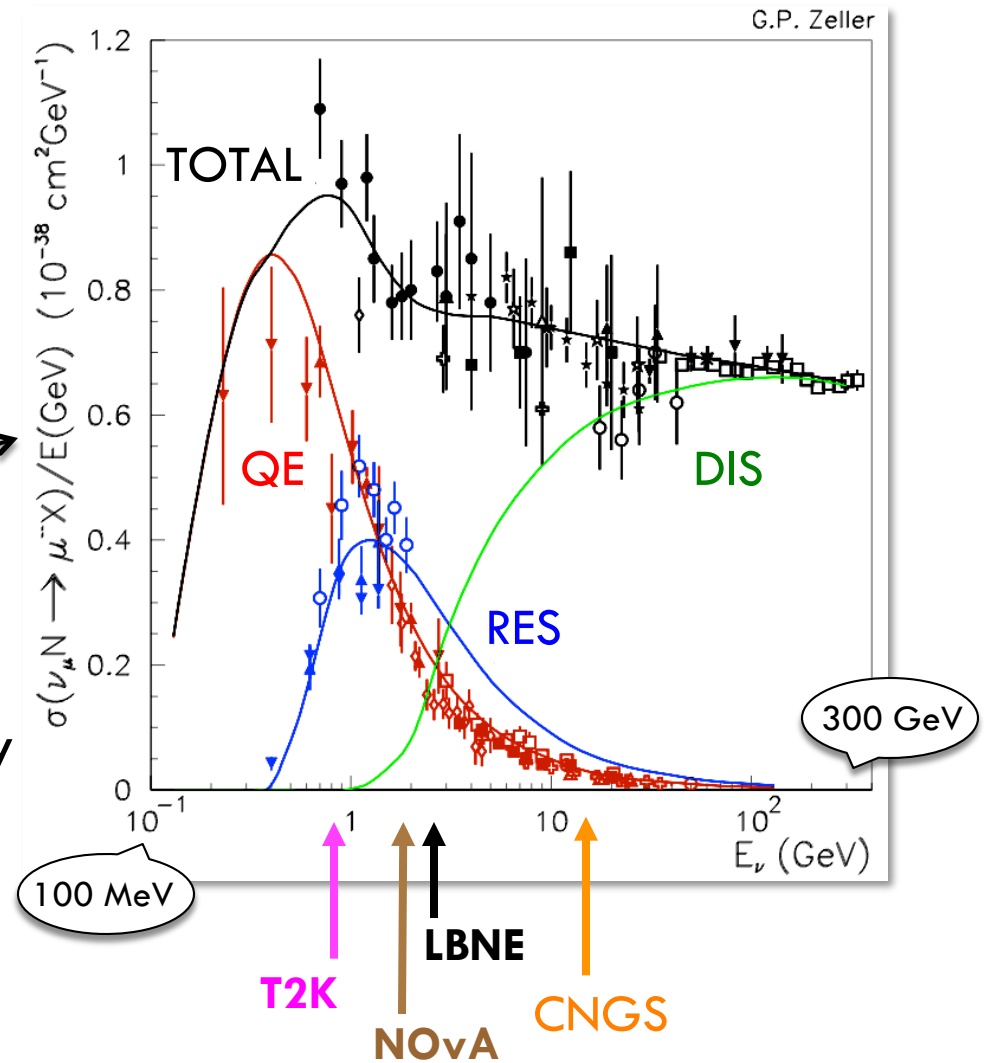
- this topic has become quite interesting lately
- revisiting ν scattering physics again for 1st time in decades
- new data is turning up a few surprises

Neutrino Cross Sections

- pursuit of ν oscillations has unfortunately forced us into a rather complex region of ν interaction physics

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

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



Neutrino Cross Sections

quasi-elastic

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

resonance production

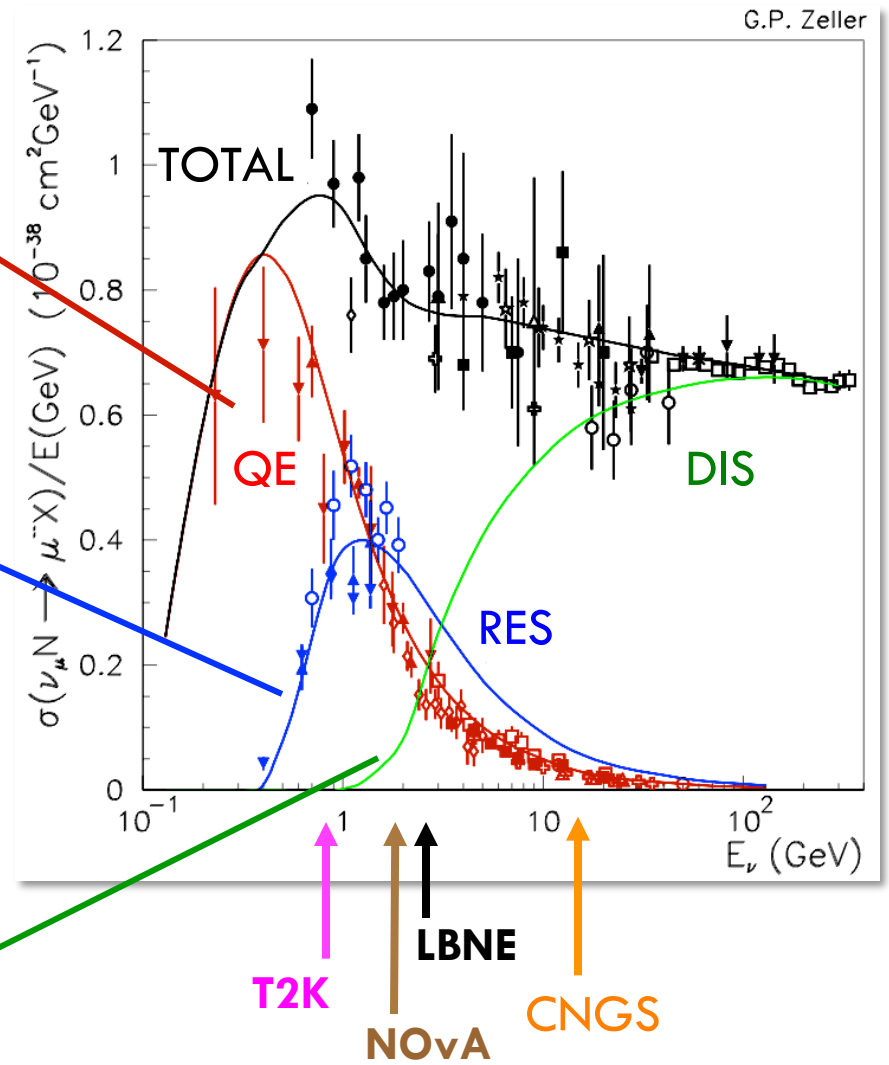
$\nu_\mu N \rightarrow \Delta$

$\hookrightarrow N'\pi$

deep inelastic scattering

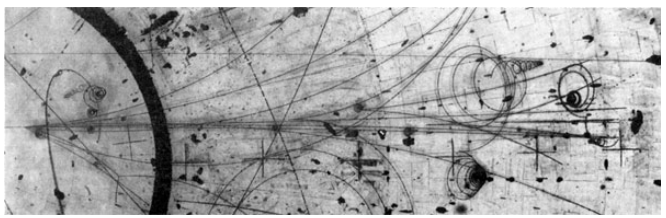
$\nu_\mu N \rightarrow \mu^- X$

need to extrapolate into low energy region

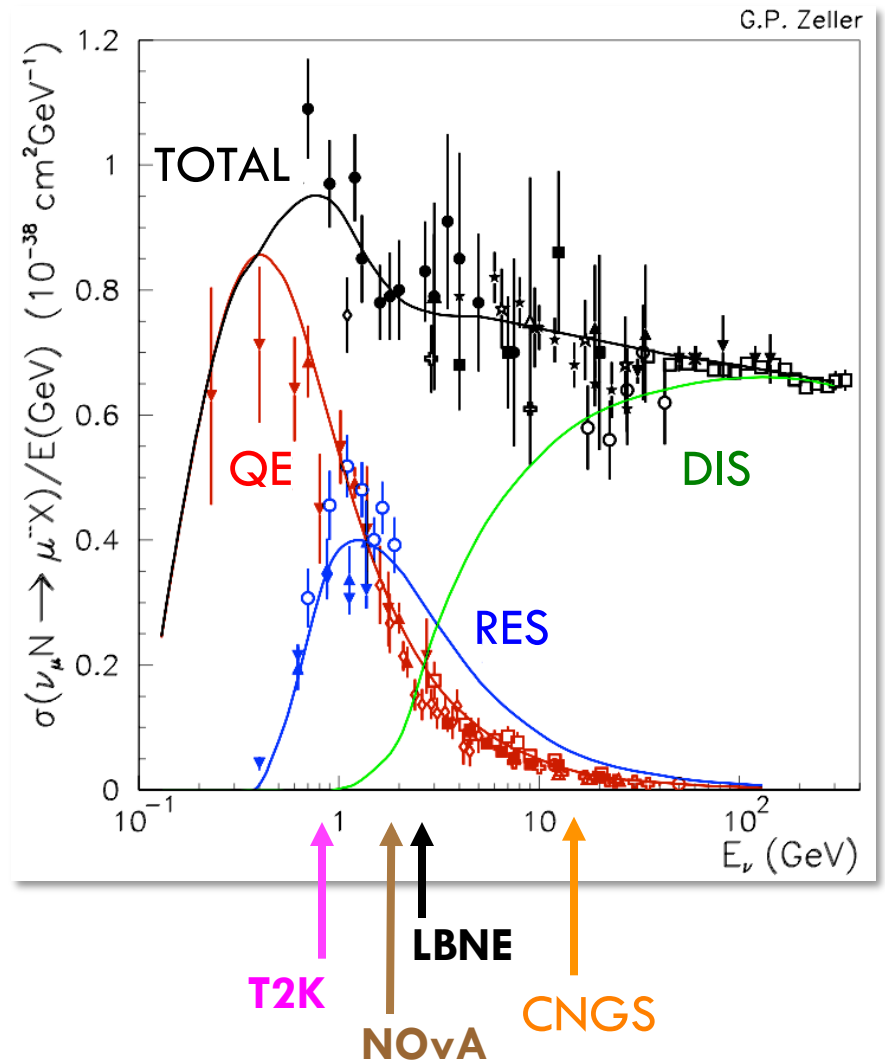


Neutrino Cross Sections

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



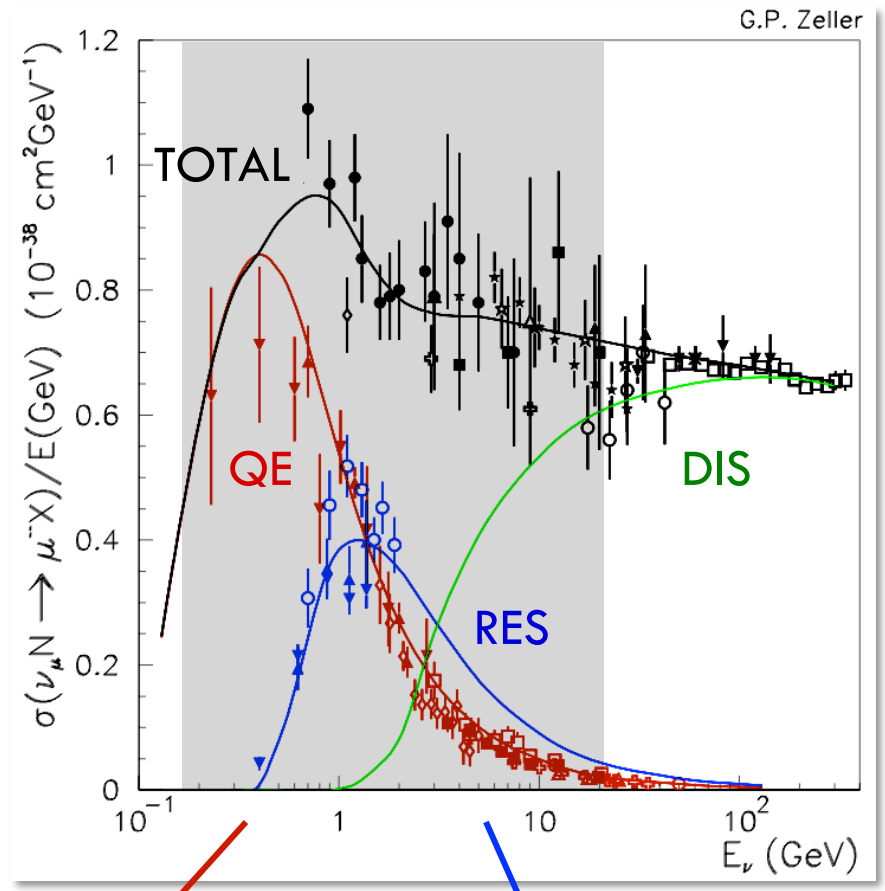
- crucial difference: ν osc exps use heavy nuclei
- nuclear effects are important
- has necessitated a dedicated campaign of new measurements



Neutrino Cross Sections

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

- <u>advantages of new data</u>:
  - nuclear targets (crucial!)
  - higher statistics
  - intense, well-known ν beams
  - studying ν and $\overline{\nu}$'s (will be important for $\not{CP}$)



K2K, MicroBooNE, MiniBooNE, SciBooNE, T2K

ArgoNeuT, ICARUS, MINERνA, MINOS, NOMAD, NOvA

Modern σ_ν Experiments

BNB:

MiniBooNE

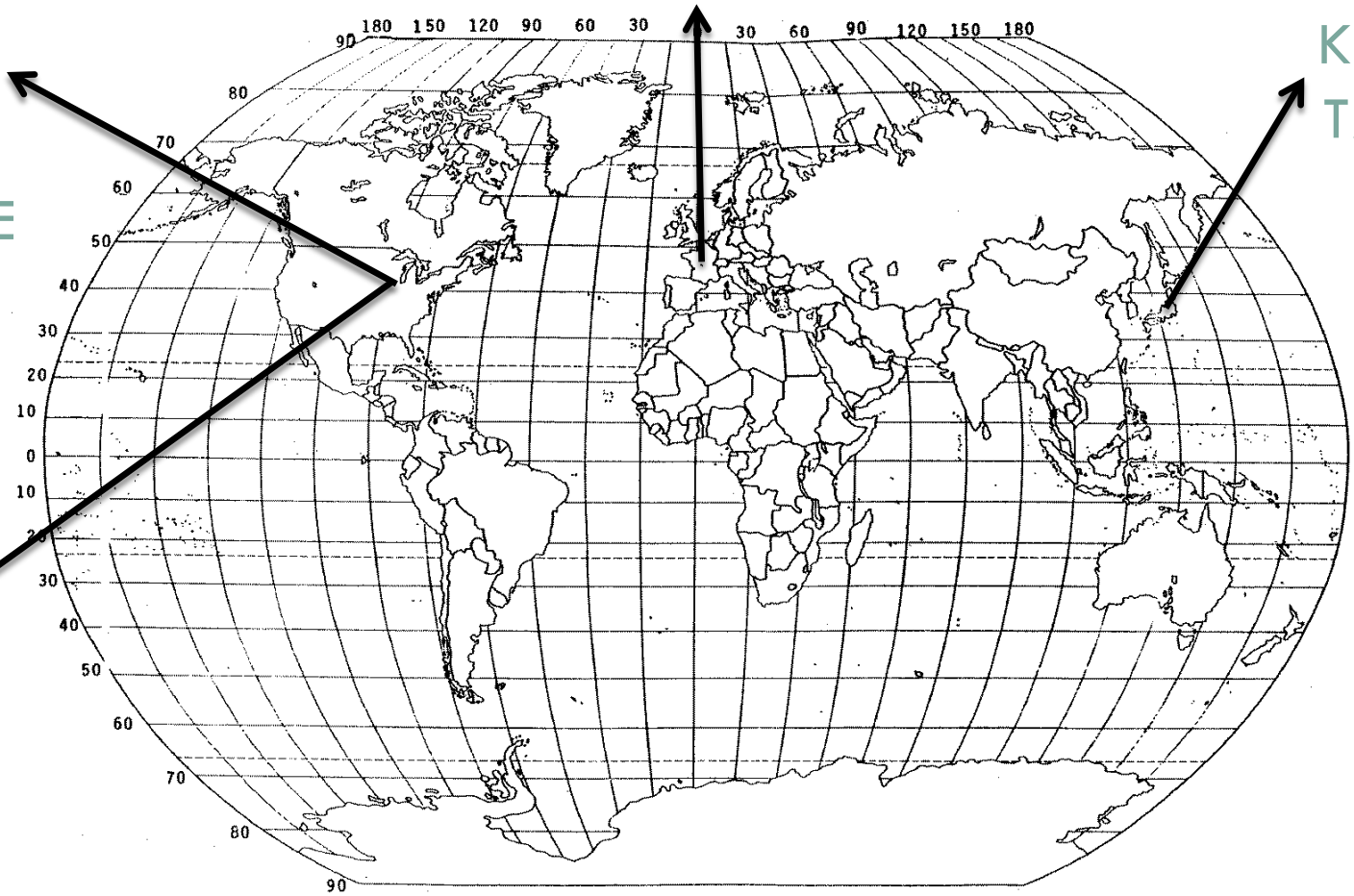
SciBooNE

MicroBooNE

NOMAD, ICARUS

K2K

T2K



NuMI:

MINOS

NOvA

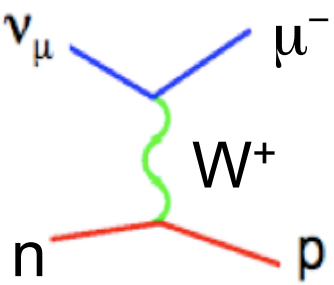
MINERνA

ArgoNeuT

accelerator-based program includes both ν oscillation exps and exps devoted to ν interaction measurements

1st Topic: Quasi-Elastic Scattering

Why important?



- **important for ν oscillation experiments**
  - typically gives largest contribution to signal samples in many osc exps
    (flavor ID, also E_ν from μ kinematics)
  - one of the most basic ν interactions

- <u>examples:</u>

signal events

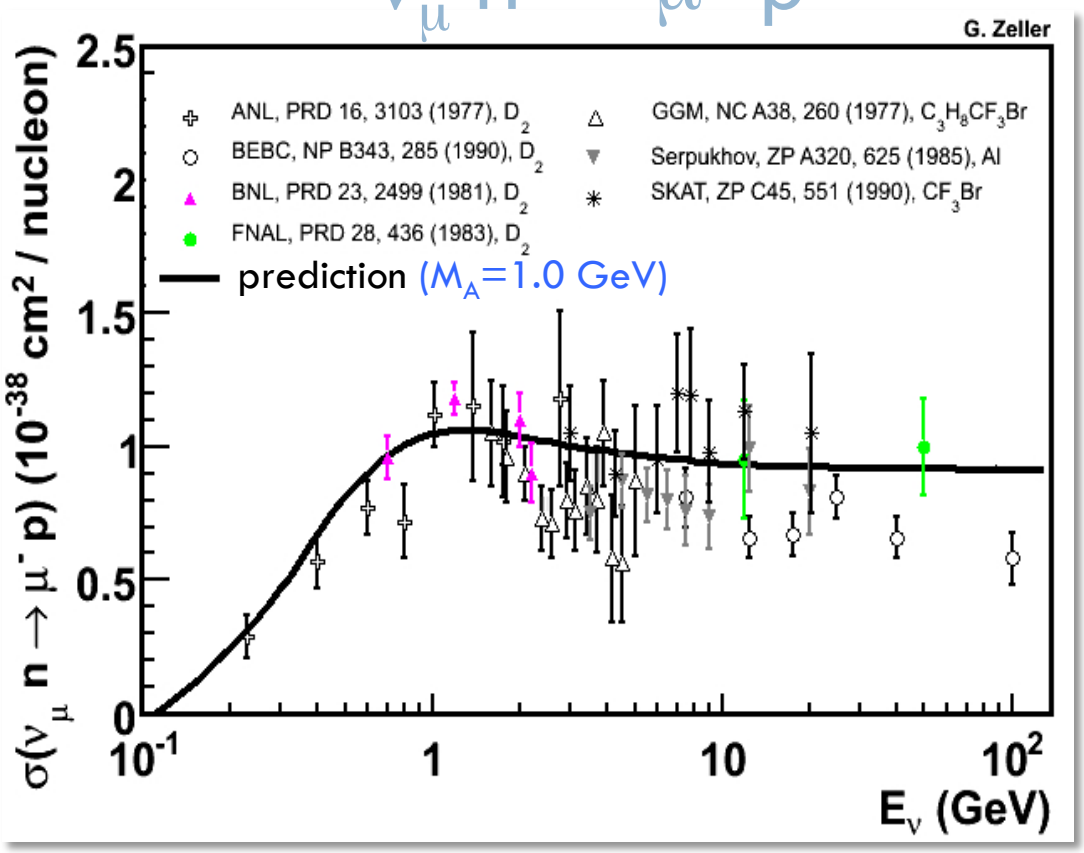
$\nu_\mu \rightarrow \nu_e$ (ν_e appearance)

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

What Do We Know?

- <u>conventional wisdom:</u>
  - QE σ is well-known
  - can consistently describe all the experimental data
    - *most is on D_2*
    - Fermi Gas model
    - M_A=1.0 GeV
- QE considered the "standard candle"
  - it's simple … clean
  - know size & shape of σ

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

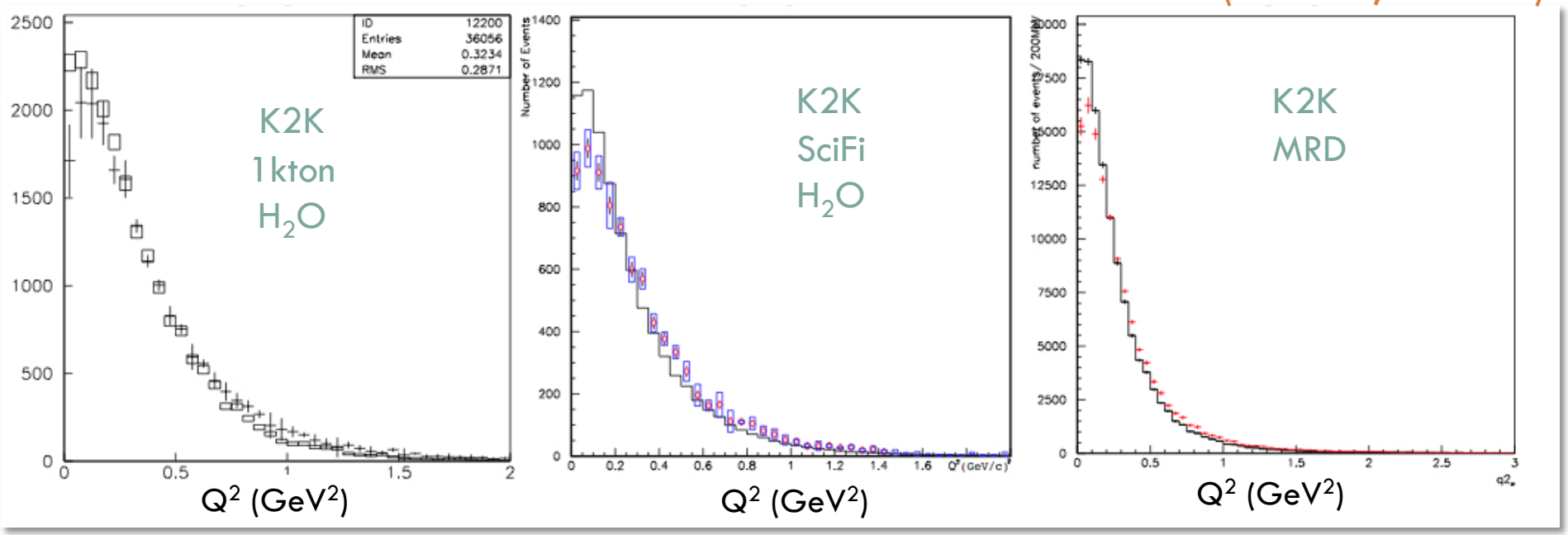


if we can't predict this, then we have problems!

First, Some History

- kinematic discrepancies 1st noted in K2K (looking at Q^2 = momentum transfer)

(T. Ishida, NuInt01)

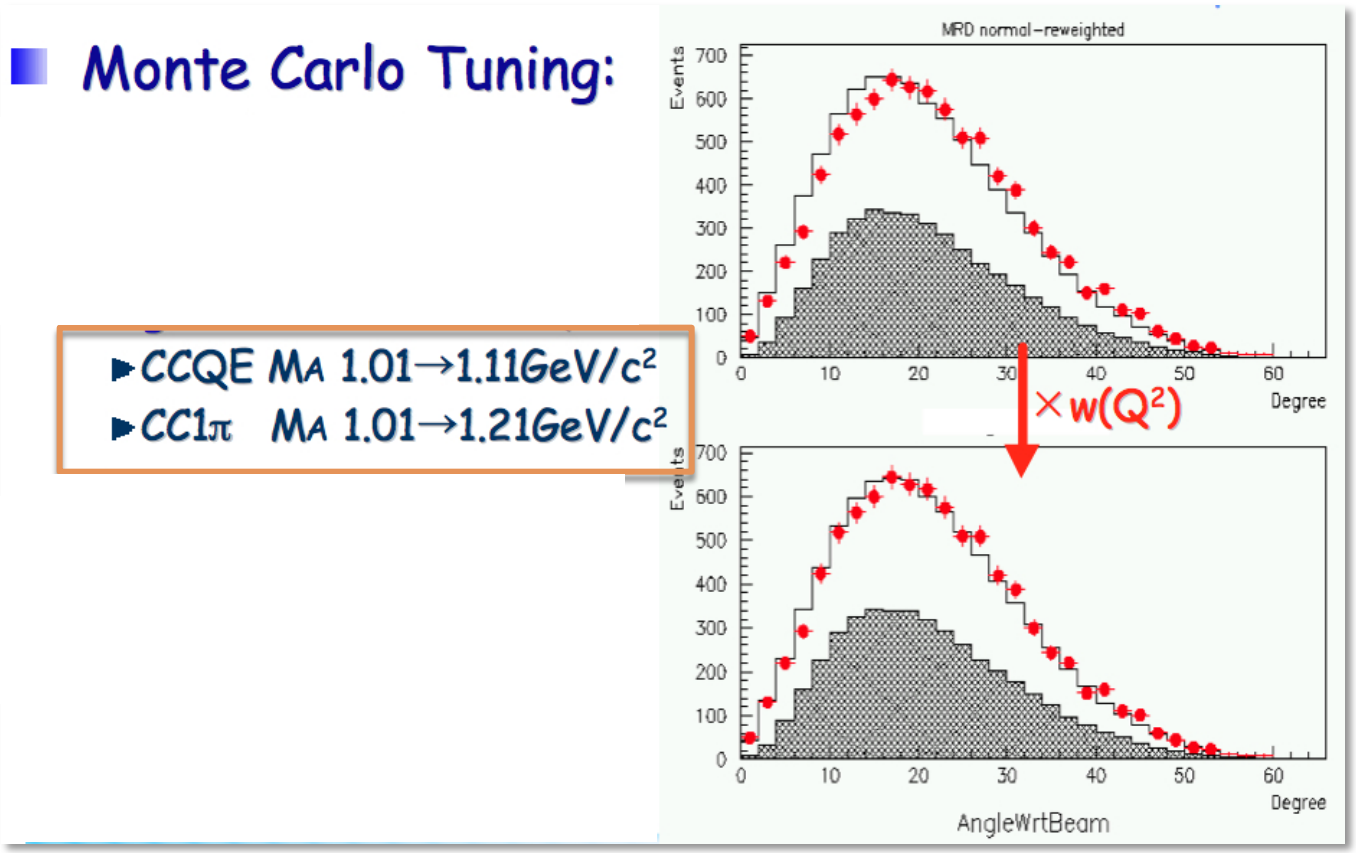


In all of these plots, we can admit a tendency that the data distribution looks *harder* than that of MC. Especially in the low-q^2 region, the disagreement seems to be significant.

- these are relatively normalized comparisons; but an excess of events was also observed

Adjusting M_A

- recognized early on by K2K that kinematic agreement could be improved by increasing M_A (world average from D_2 data: M_A = 1.0 GeV)



(T. Ishida, NuInt02)

M_A Fits

Experiment	Target	Cut in Q^2 [GeV^2]	$M_A[GeV]$
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

- many experiments measure M_A as was common practice
  (shape fits to observed Q^2 distributions)

most favor $M_A \sim 1.2$-1.3 GeV
"axial mass anomaly"

exception

Juszczak *et al.*, PR **C82**, 045502 (2010)

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Juszczak *et al.*, PR **C82**, 045502 (2010)

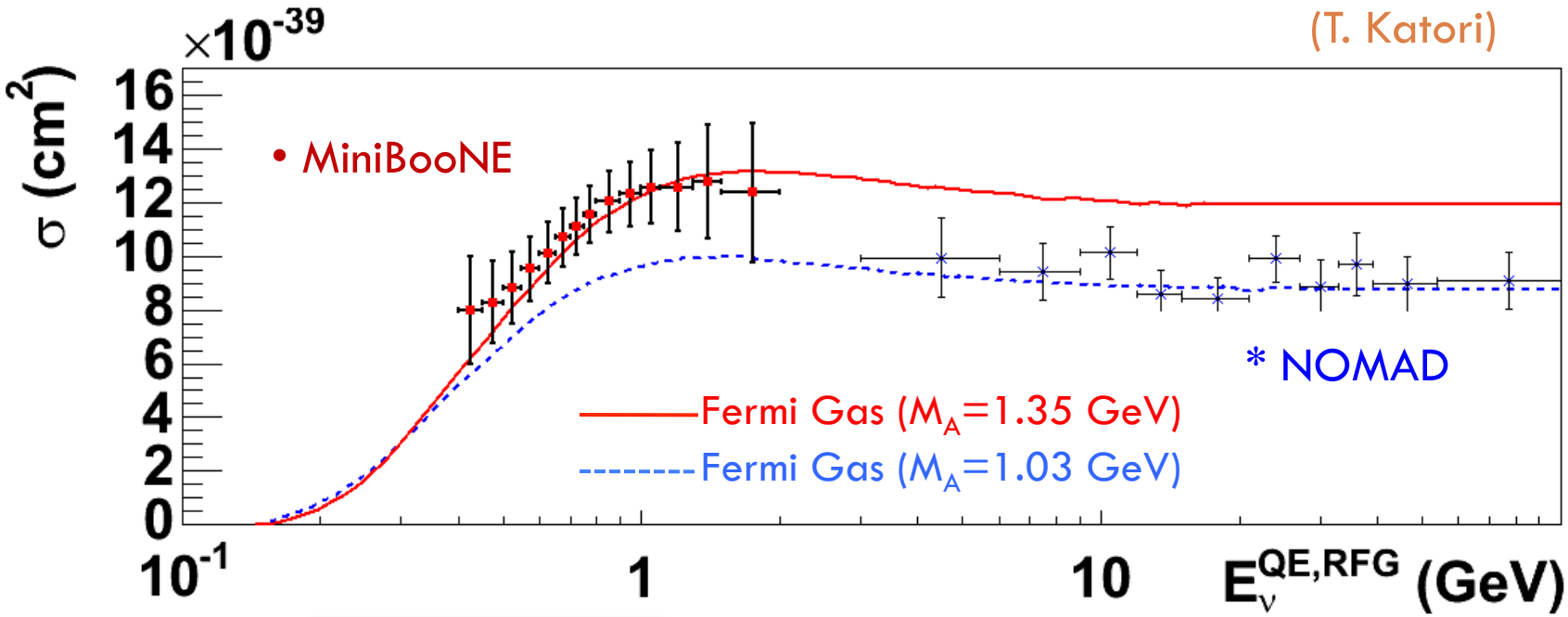
- many experiment e M_A as was co

(sh ons)

to make progress
we need
to go beyond
comparing
M_A values

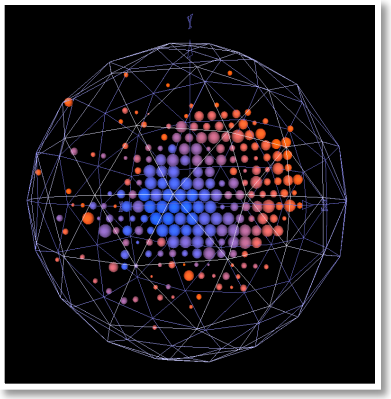
QE Cross Section on ^{12}C

(T. Katori)



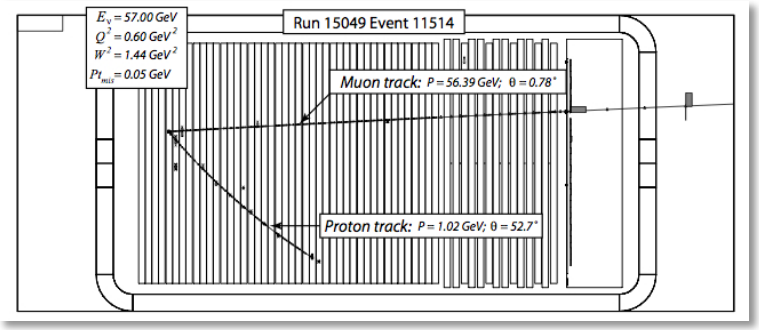
MiniBooNE 2002-present:

PRD **81,** 092005 (2010)



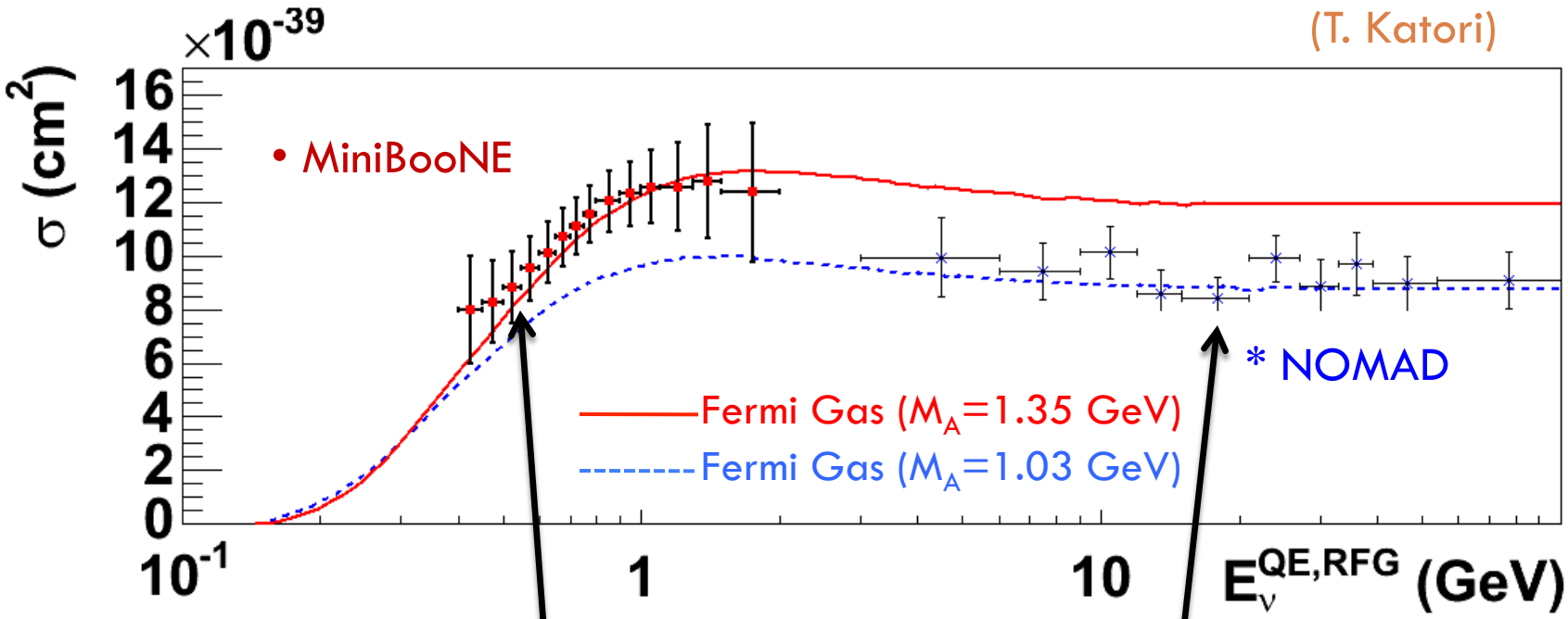
NOMAD 1995-1998:

EPJ **C63,** 355 (2009)



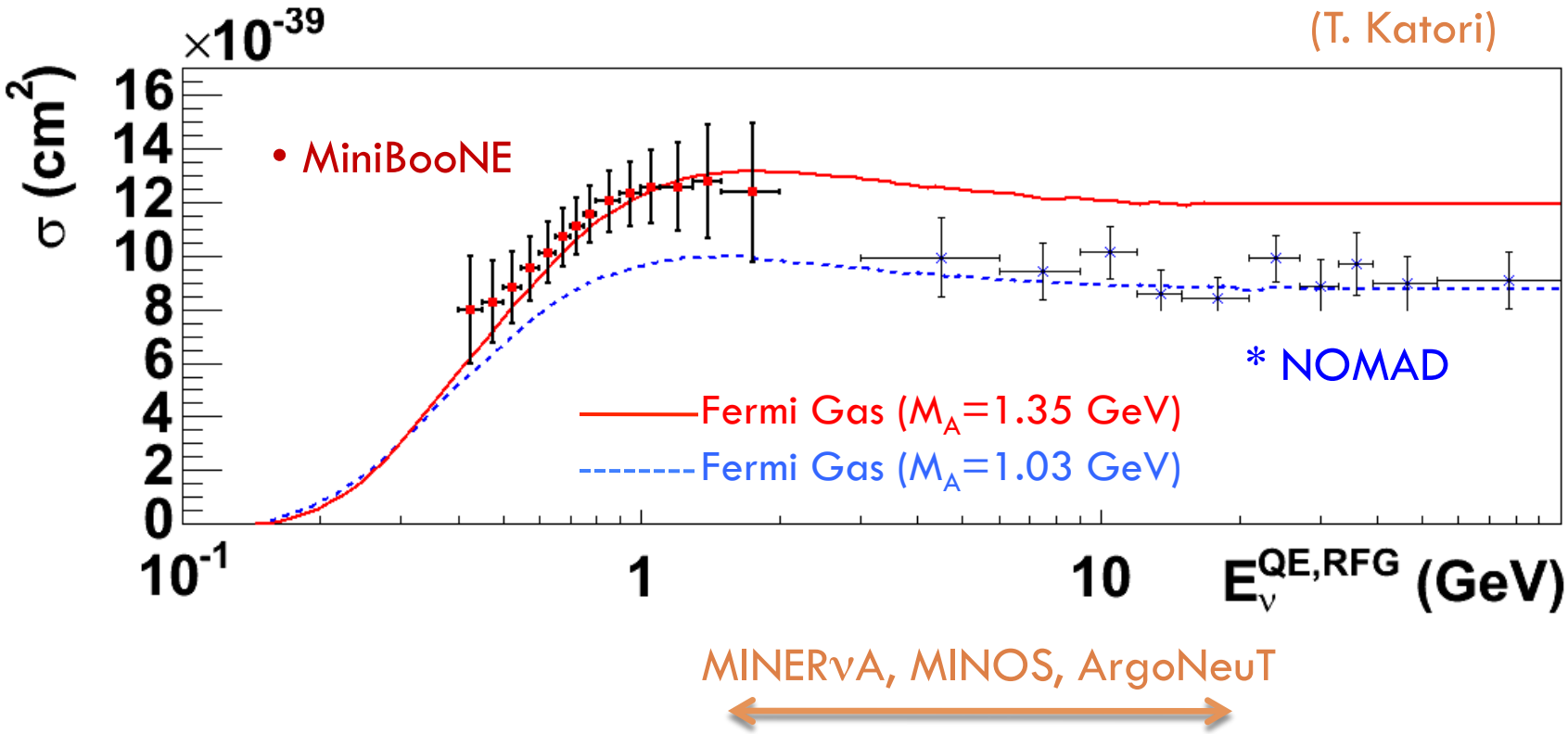
QE Cross Section on ^{12}C

(T. Katori)



- MiniBooNE data ~30% higher than standard QE prediction
  (even exceeds free nucleon σ, for E_ν>0.7)
- NOMAD data consistent with standard QE prediction
  (with M_A=1.03 GeV)

QE Cross Section on ^{12}C



- <u>current situation</u>:

  unable to describe modern QE data on carbon with a single prediction

Larger Cross Section?

- MiniBooNE results have received a lot of attention lately (largely because they were unexpected)

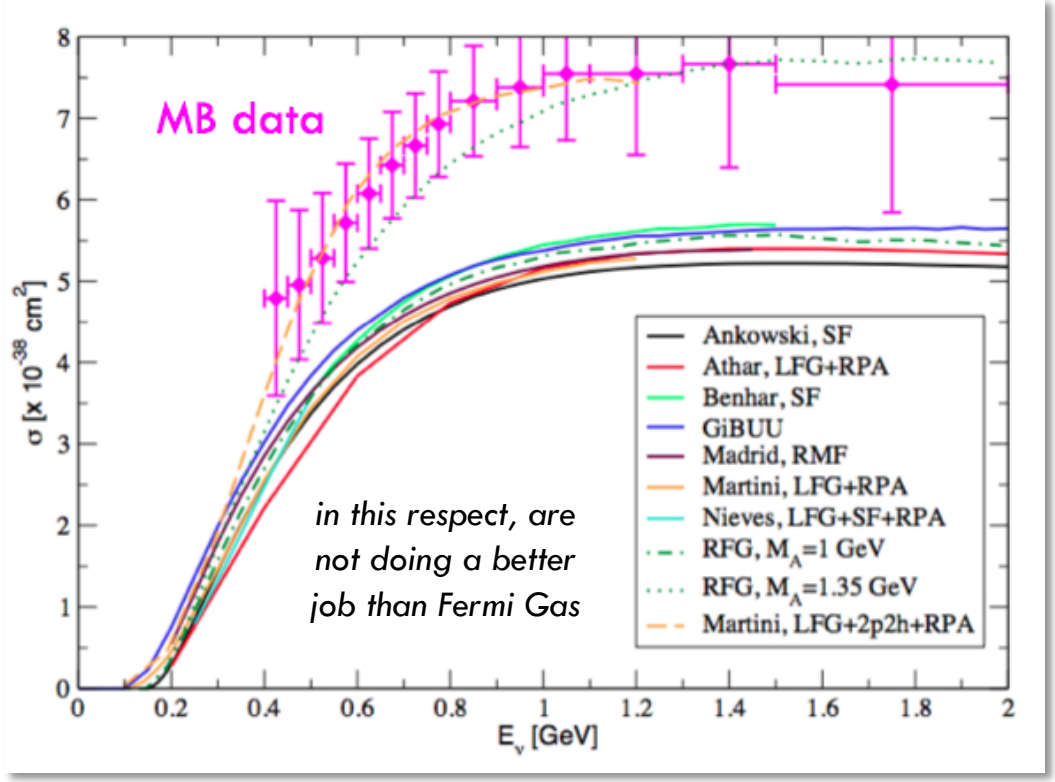
- modern nuclear models (M_A=1.0 GeV) also underpredict the measured σ

  fall short by 40-50%!

- remedy has been to:

  - increase M_A

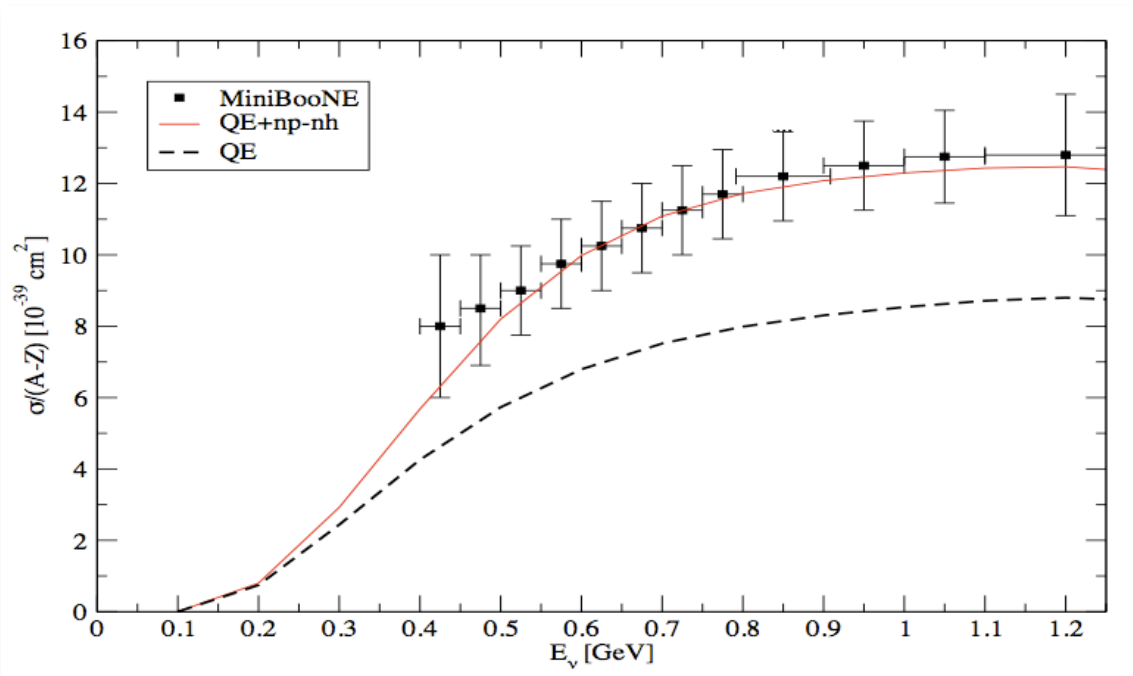
but more recently, has led to an important debate concerning the role played by nuclear dynamic effects beyond these indep. particle approaches



(L. Alvarez-Ruso, NuFact11)

Nuclear Effects to the Rescue?

- *possible explanation*: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)



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

- large enhancement from short range correlations (SRC) and 2-body currents
- can predict MiniBooNE data without having to increase M_A (here, M_A=1.0 GeV)

Nuclear Effects to the Rescue?

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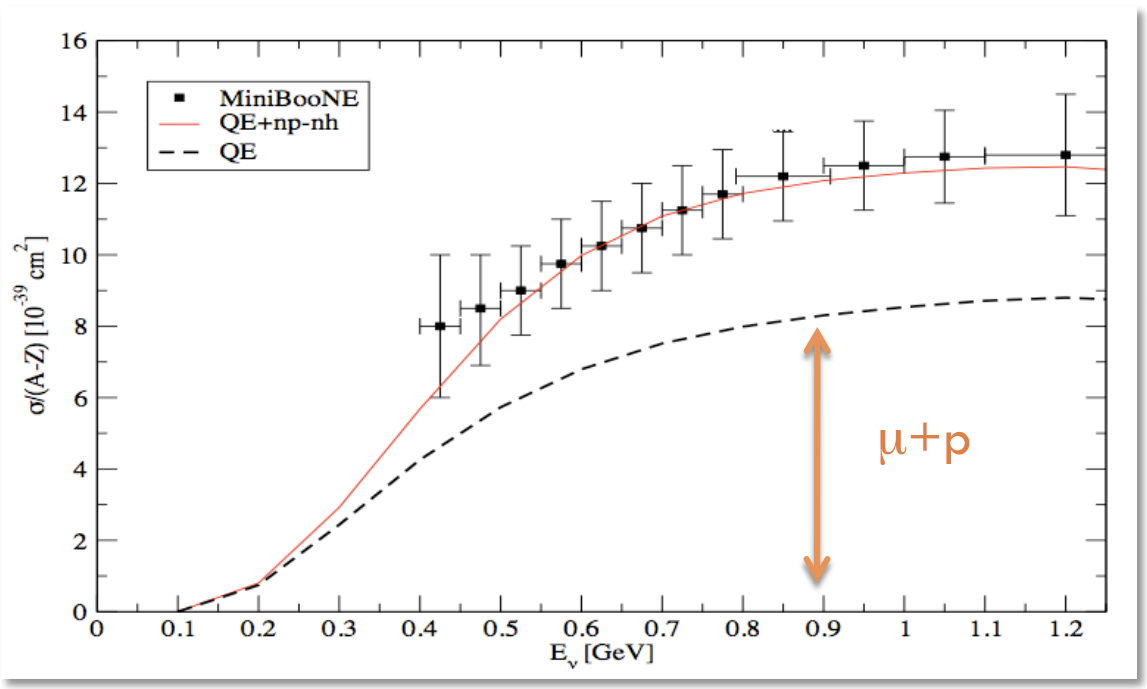

standard QE prediction saw earlier

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

Nuclear Effects to the Rescue?

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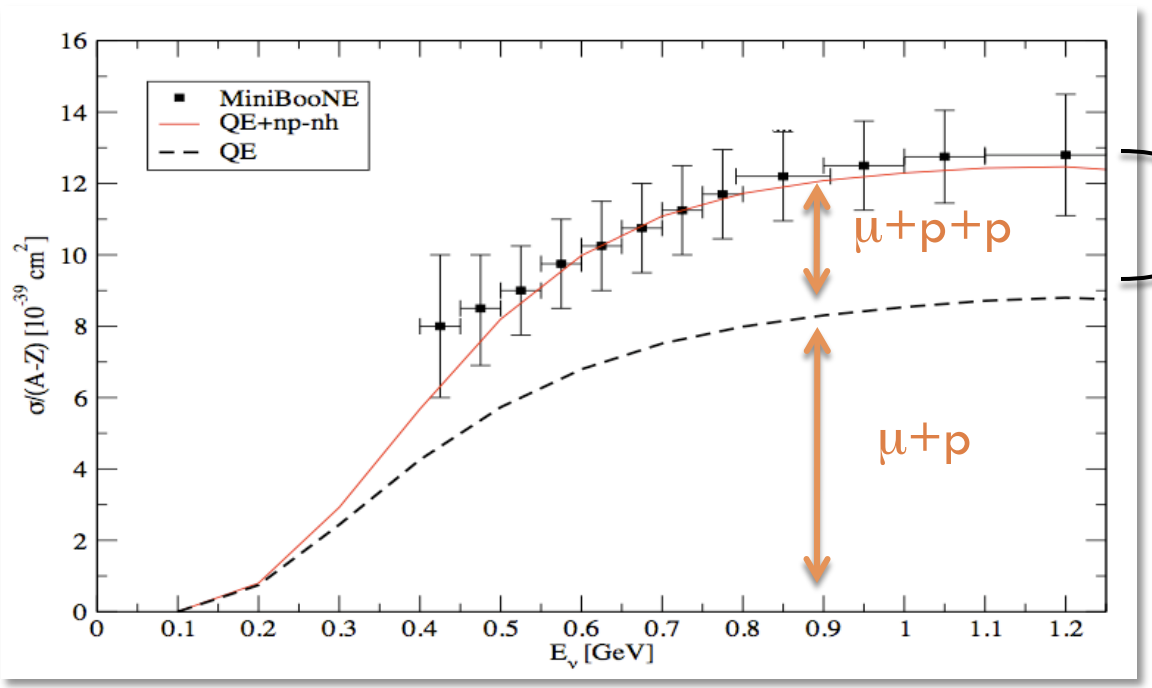


Martini *et al.*, PRC **80**, 065001 (2009)

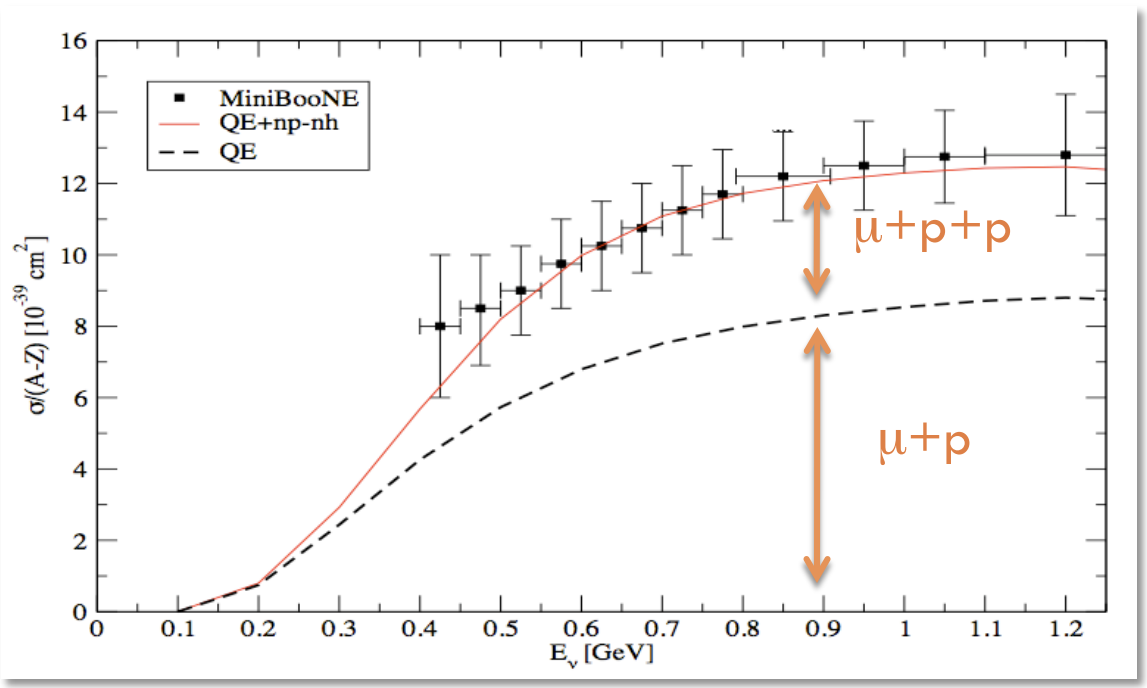
add'l nuclear effects contribute ~40% more σ & produce a multi-nucleon final state (μ+p+p)

- together account for MB

these two final states are indistinguishable in MB and in Cerenkov detectors in general

Nuclear Effects to the Rescue?

- *possible explanation*: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)



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

- could this explain the difference between MiniBooNE & NOMAD?

NOMAD: μ & μ + p

MiniBooNE: μ + no π's + any # p's

jury is still out on this

need to be clear what we mean by "QE"

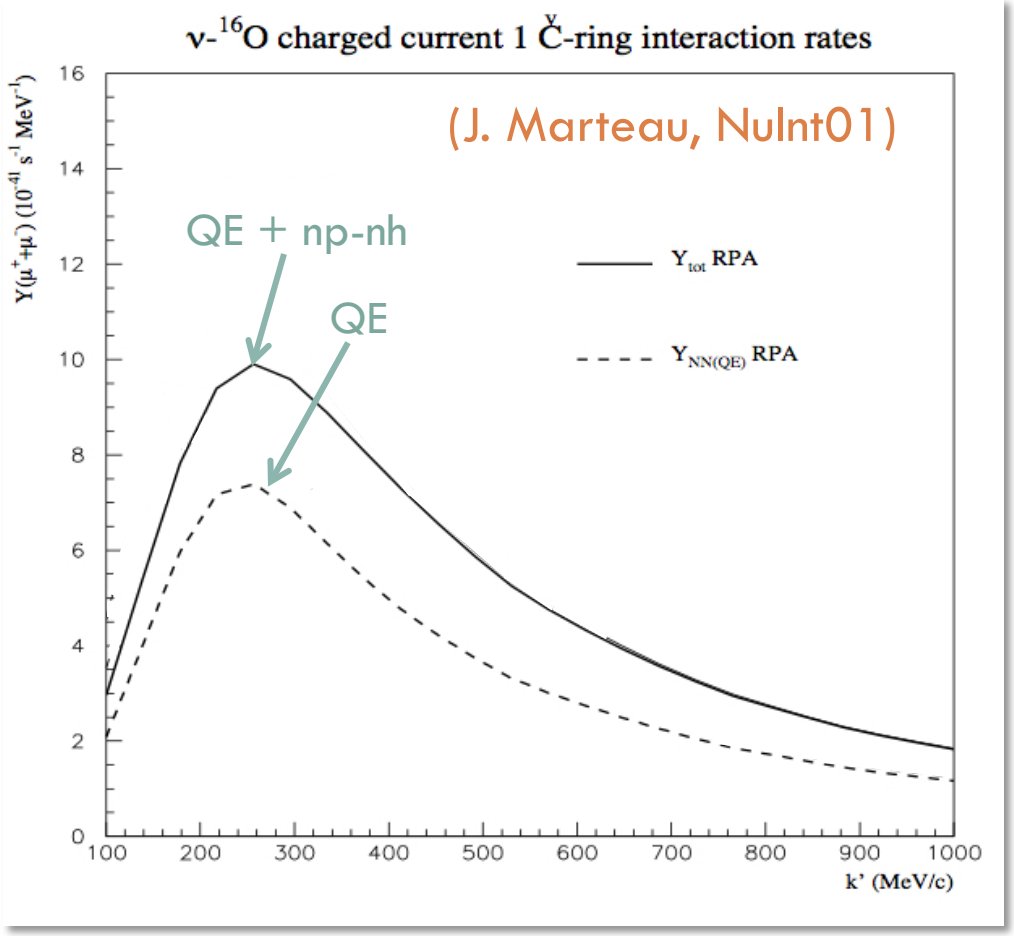
Idea is Not New

- work originally motivated by 1-ring events in Super-K

  = QE + np-nh

  = (μ+p) + (μ+p+p) = "QE"

we see an enhacement of the total yield with respect to the free quasi-elastic around 20 %. This result points out the importance of a good evaluation of such neutrino induced *np-nh* excitations.



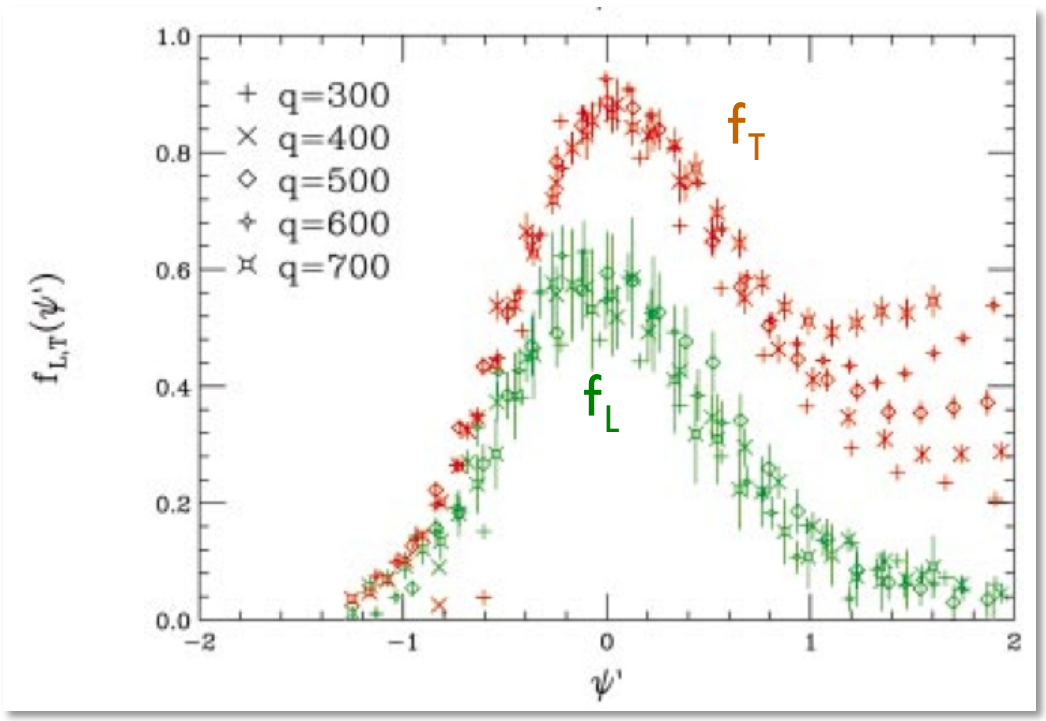
- also:
  - Dekker *et al.*, PLB **266**, 249 (1991)
  - Singh, Oset, NP **A542**, 587 (1992)
  - Gil, Nieves, Oset, NP **A627**, 543 (1997)
  - Nieves, Amaro, Valverde, PRC **70**, 055503 (2004)

prediction, not post-diction

Electron QE Scattering

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

(J. Carlson's talk, this workshop)



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

- seemingly forgotten
- ν QE calculations assume IA and $f_L = f_T$
- credit goes to Gerry Garvey for re-discovering these results

New Theoretical Work

- calculation of additional nuclear dynamics (nucleon correlations & 2-body currents) in the treatment of ν QE scattering has been a recent focus:

  - Amaro, Barbaro, Caballero, Donnelly, Udias, arXiv:1104.5446
  - Antonov, Ivanov, Caballero, Barbaro, Udias, Guerra, Donnelly, arXiv:1104.0125
  - Benhar, Veneziano, arXiv:1103.0987
  - Meucci, Caballero, Giusti, Udias, arXiv:1103.0636
  - Ankowski, Benhar, arXiv:1102.3532
  - Nieves, Ruiz Simo, Vicente Vacas, PR **C83**, 045501 (2011)
  - Amaro, Barbaro, Caballero, Donnelly, arXiv:1012.4265
  - Alvarez-Ruso, arXiv:1012.3871
  - Benhar, arXiv:1012.2032
  - Fernandez-Martinez, Meloni, PL **B697**, 477 (2011)
  - Amaro, Barbaro, Caballero, Donnelly, Williamson, PL **B696**, 151 (2011)
  - Amaro, Maieron, Barbaro, Caballero, Donnelly, PR **C82**, 046601 (2010)
  - Martini, Ericson, Chanfray, Marteau, PR **C81**, 045502 (2010)

QE at MiniBooNE

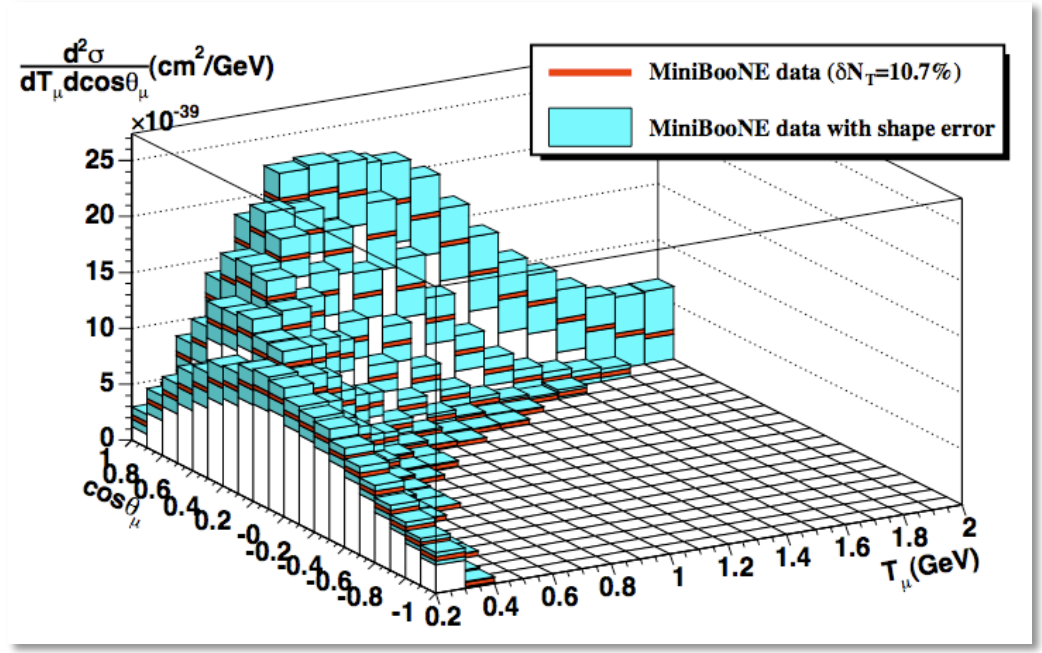
Aguilar-Arevalo *et al.*, PRD **81**, 092005 (2010)

- 1st double differential σ's

  $d^2\sigma/dT_\mu d\theta_\mu$

- 146,000 ν_μ "QE" events
  (currently world's largest sample)

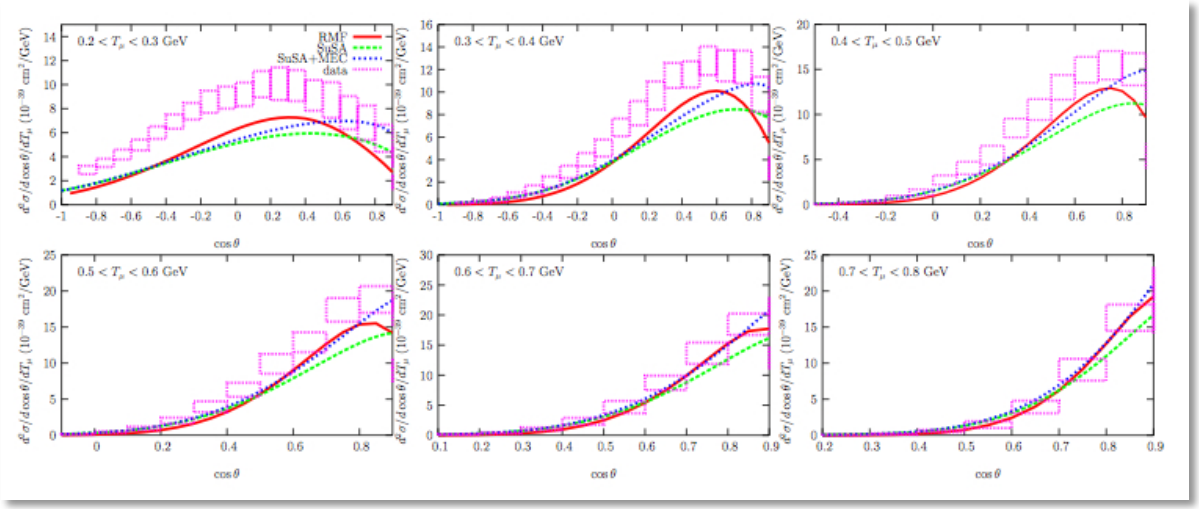
- historically, never had enough statistics to do this



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

- provides most complete info on ν QE scattering to date
- posing a formidable challenge for new nuclear model calculations

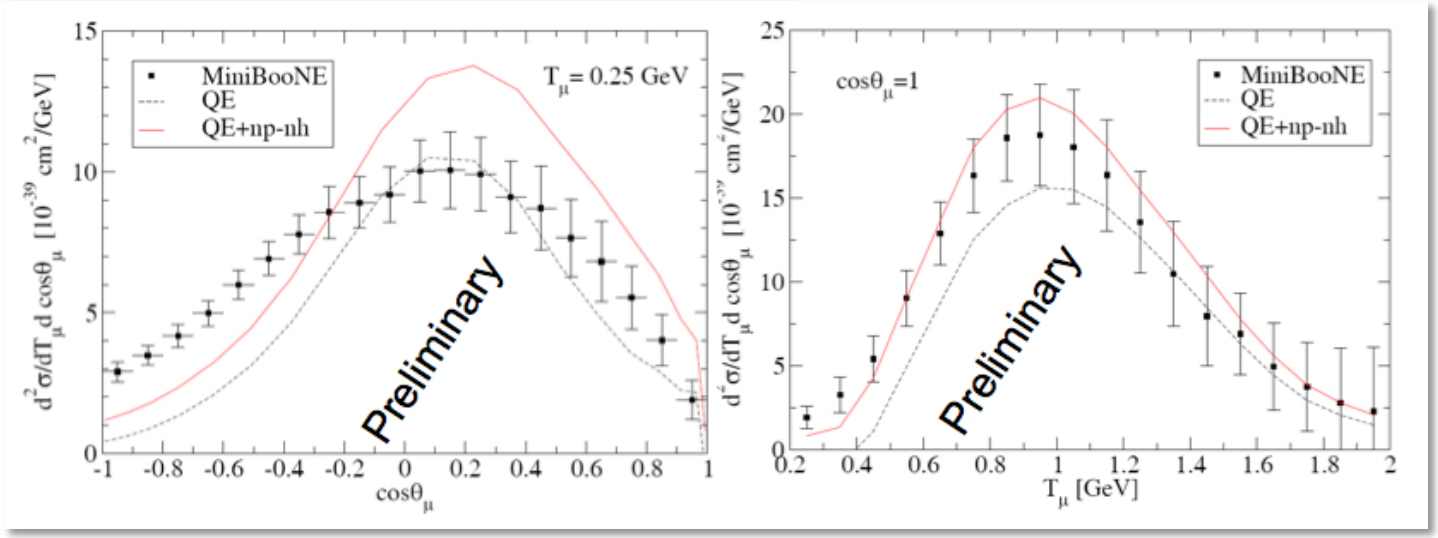
Comparisons to MB Double Diff'l σ



Amaro *et al.*, arXiv:1104.5446 [nucl-th]

- underestimate the data at large scattering angles particularly for small T_μ

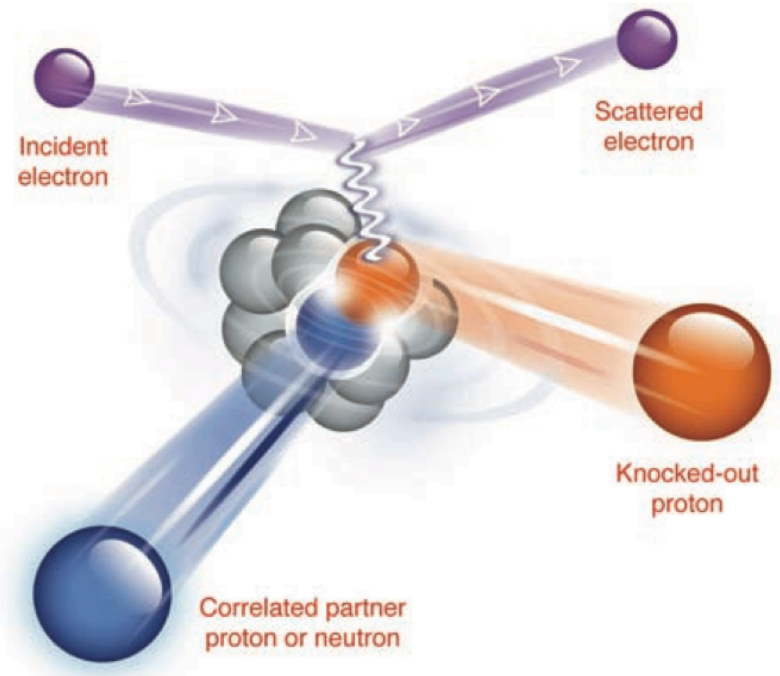
Martini, FNAL PPD ν dept. presentation, 09/30/10

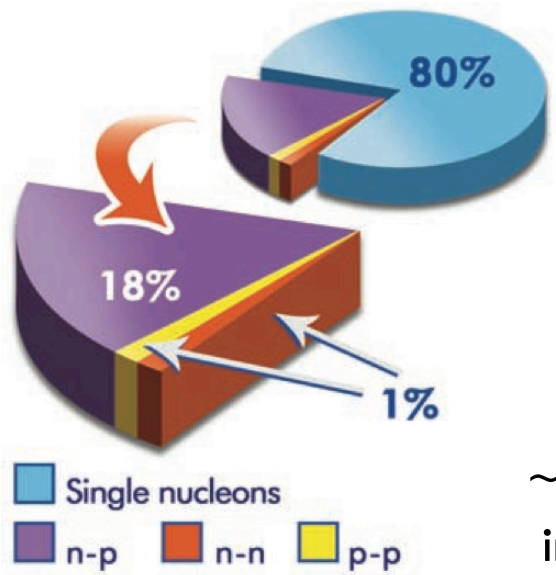


- need more measurements of muon (and proton) kinematics!

Big Splash

- it would be nice to observe SRC's in ν scattering
- electron scattering experiments have already provided such evidence

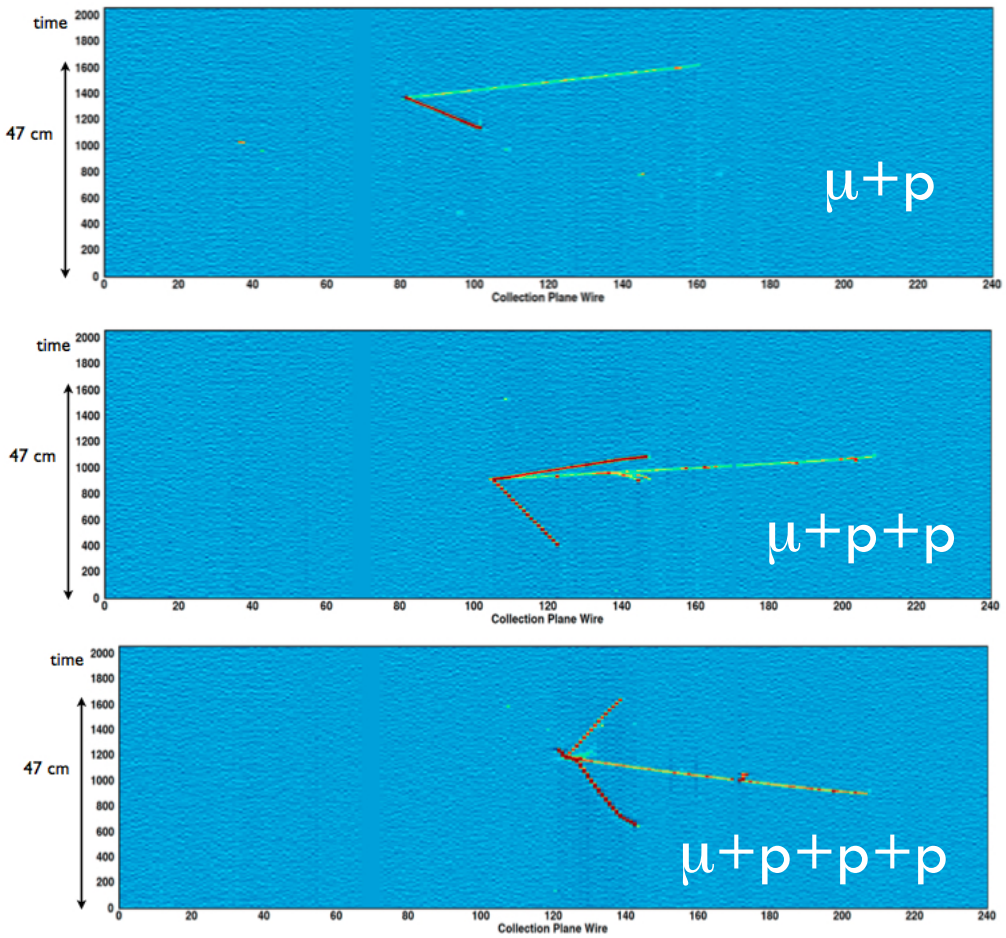




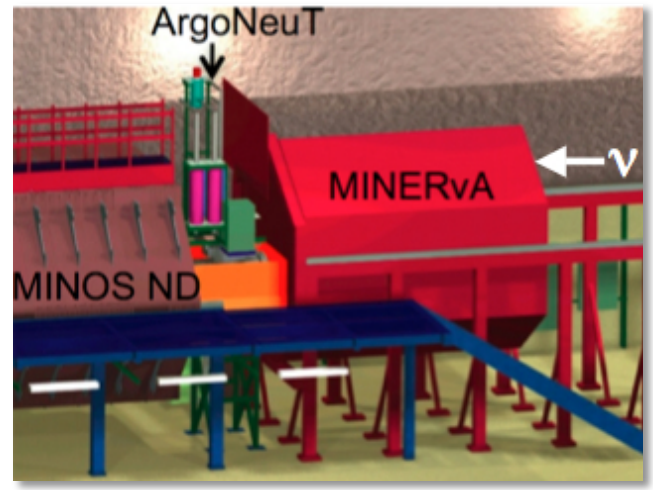
~20% of nucleons in carbon are in a correlated state

R. Subedi *et al*., Science 320, 1476 (2008)

QE in ArgoNeuT



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

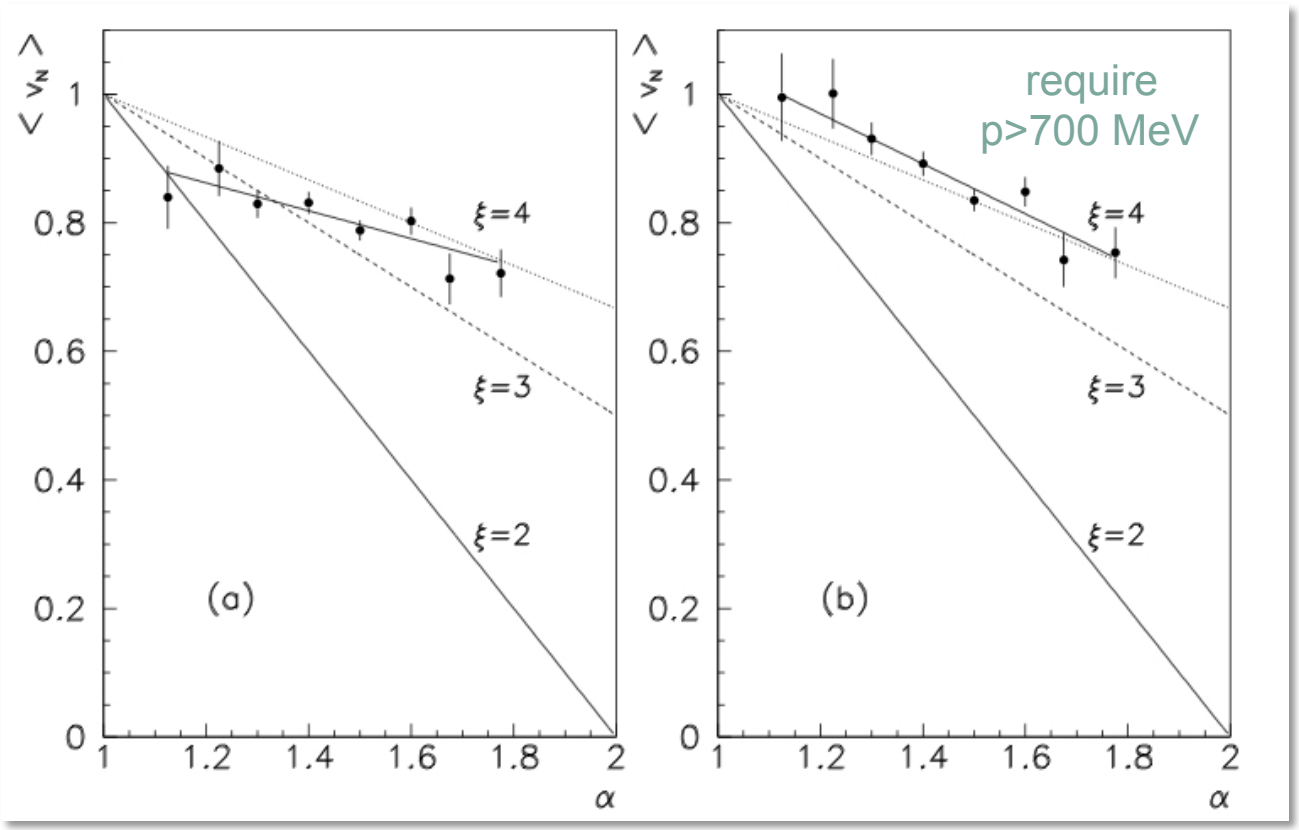


- 175L LAr TPC that took data in NuMI beamline (2009-2010)
- ν interactions in ^{40}Ar
- need to isolate SRC from standard final state effects (proton re-interactions and π absorption)

Looking for These Effects in ν's

NOMAD studied backward protons emitted in ν_μ CC events (940k)

- attempts to disentangle SRC vs. proton FSI



$$\alpha = (E-p_L)/M|_{Bp}$$

$$\langle\nu_N\rangle = \frac{\langle\nu\rangle_{Bp}}{\langle\nu\rangle_{\text{no Bp}}}$$

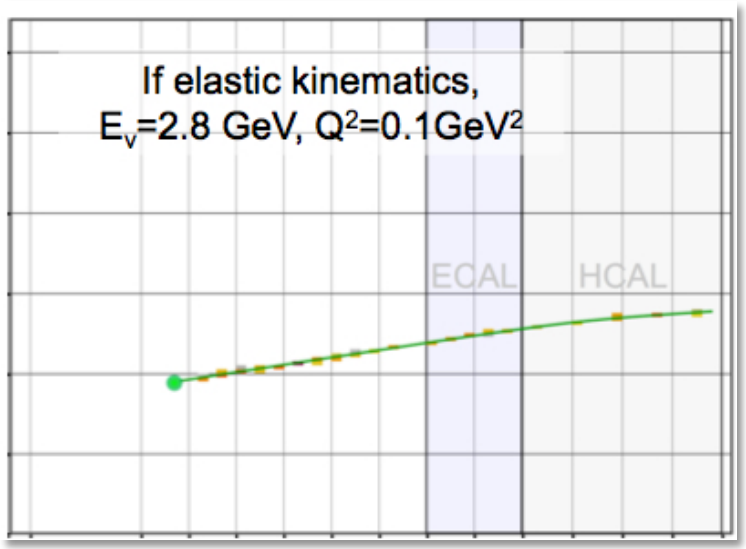
- slope → SRC
- need to revisit

(R. Tayloe's talk, this workshop)

Veltri *et al.*, Nucl. Phys. **B609**, 255 (2001)

$\bar{\nu}$ QE at MINERνA!

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



(K. McFarland, NuInt11)

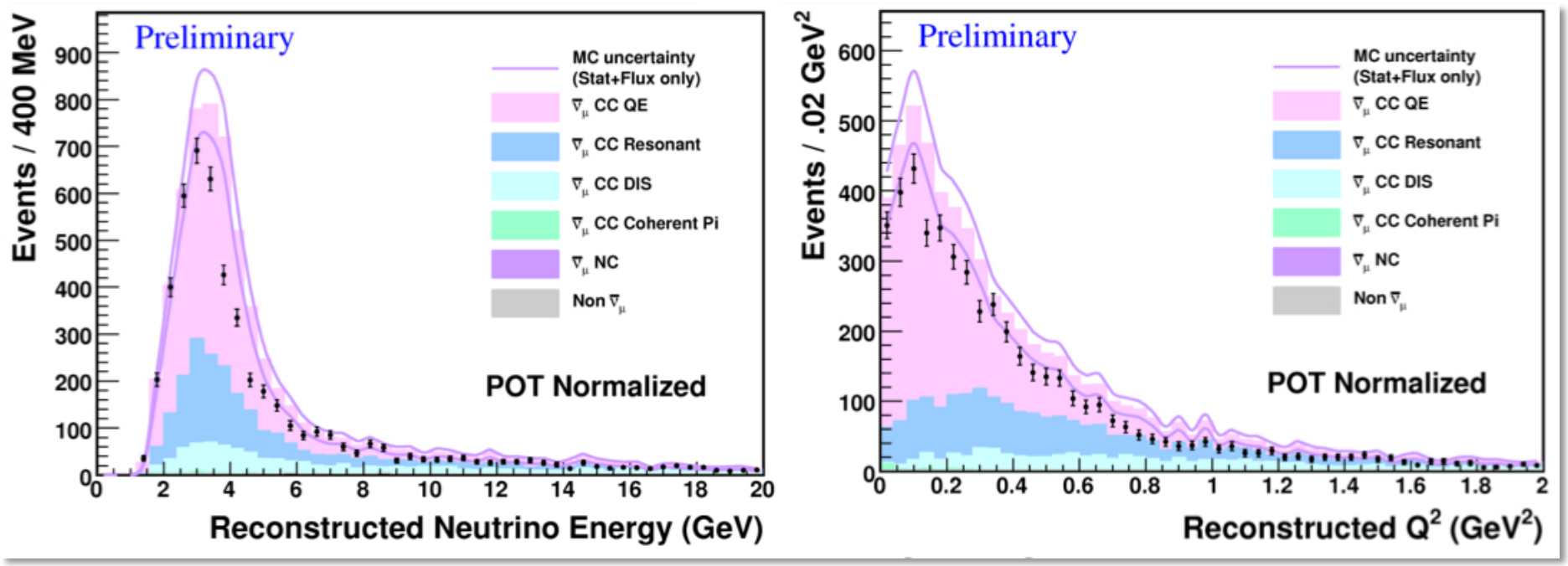
- start with antineutrino case
- less sensitive to rescattering and nucleon threshold effects that plague ν mode QE studies
- less ambiguity as to whether selection includes np-nh or not

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

$$\bar{\nu}_\mu p \longrightarrow \mu^+ n\ n$$

- will pursue several QE reconstruction/selection approaches
- this analysis: 1 μ^+ track + no recoil = more like MB QE selection

$\bar{\nu}$ QE at MINERνA



- $\bar{\nu}_\mu$ QE interactions in CH

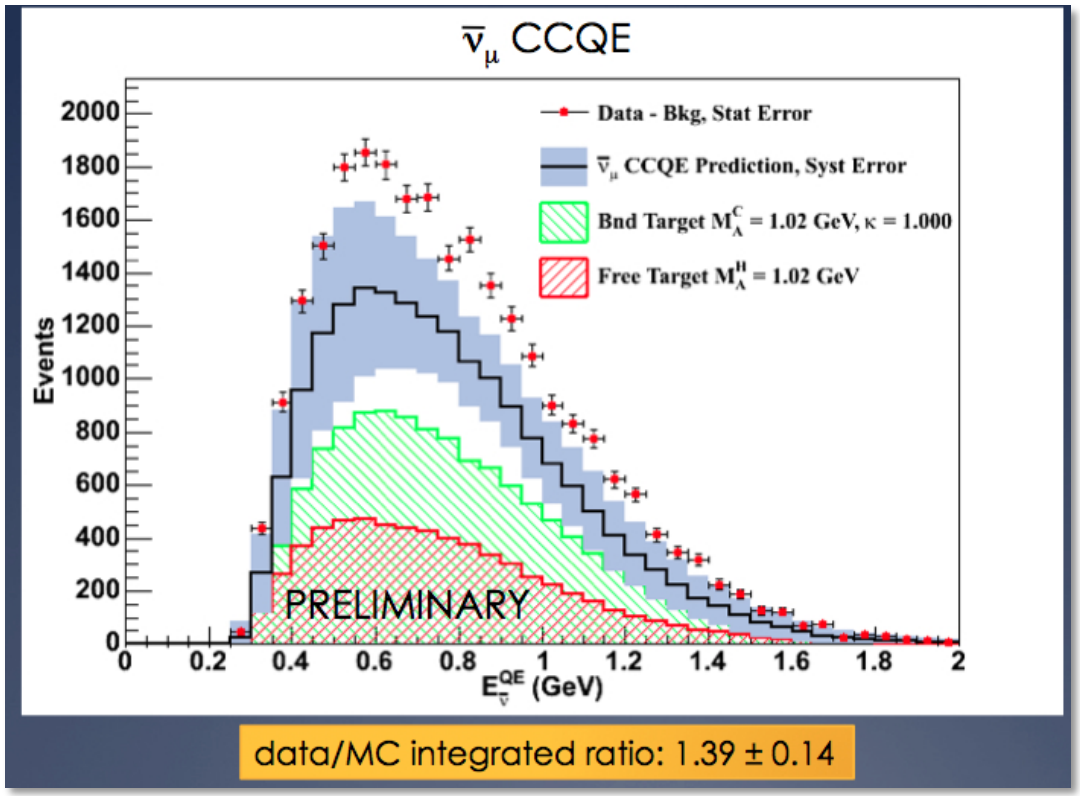
  (note: MiniBooNE ν_μ QE: 0.4-2 GeV, NOMAD: 4.5-60 GeV)

- observe an event **deficit;** flat in Q^2, not flat in E_ν

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

(B. Osmanov's talk, this workshop)

$\overline{\nu}$ QE at MiniBooNE



(J. Grange, NuInt11)

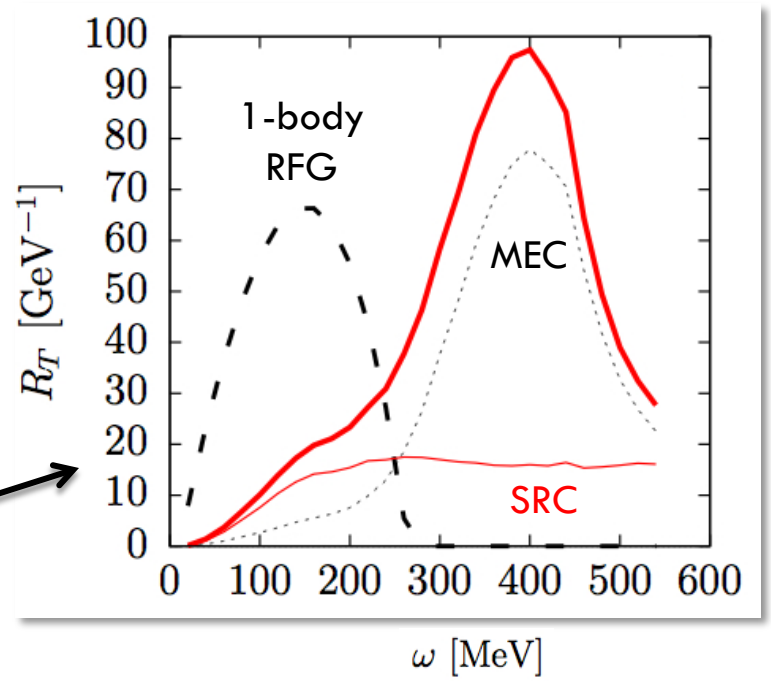
- $\overline{\nu}$ QE scattering on CH_2
- enhancement also seen in MB $\overline{\nu}$ data; larger than ν but consistent within present normalization uncertainties
- σ analysis in progress (goal: $d^2\sigma/dT_\mu d\theta_\mu$)

ν "QE" Scattering

- something as simple as QE scattering is not so simple
  - nuclear effects can significantly <u>increase</u> the cross section
  - idea that could be missing ~40% of σ is a big deal!

- need new nuclear dynamics to describe ν QE scattering
- must extend out to higher E_ν

- effects will be different for ν vs. $\bar{\nu}$
  (could produce a spurious CP violating effect)
- can impact E_ν reconstruction



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

ν "QE" Scattering

- something as simple as QE scattering is not so simple
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  - idea that could be missing ~40%
- need new nuclear dynamics
  ν QE scattering
- must extend out to higher E_ν

- effects will be different for ν vs.
  (could produce a spurious CP violating effect
- can impact E_ν reconstruction

pretty remarkable that have gone from a general complacency that we know the QE σ_ν to having uncovered a host of rich nuclear effects

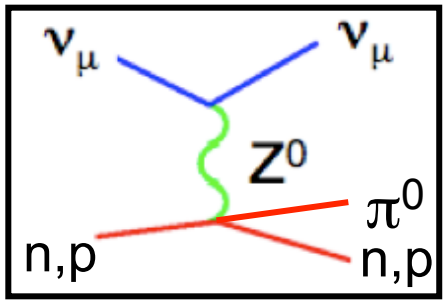
500 600

ω [MeV]

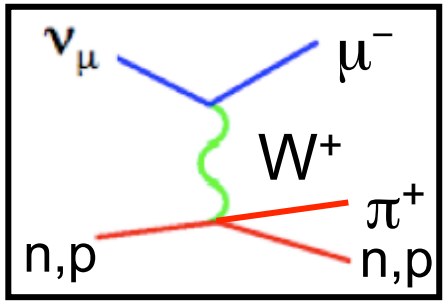
et al., PRC **82**, 044601 (2010)

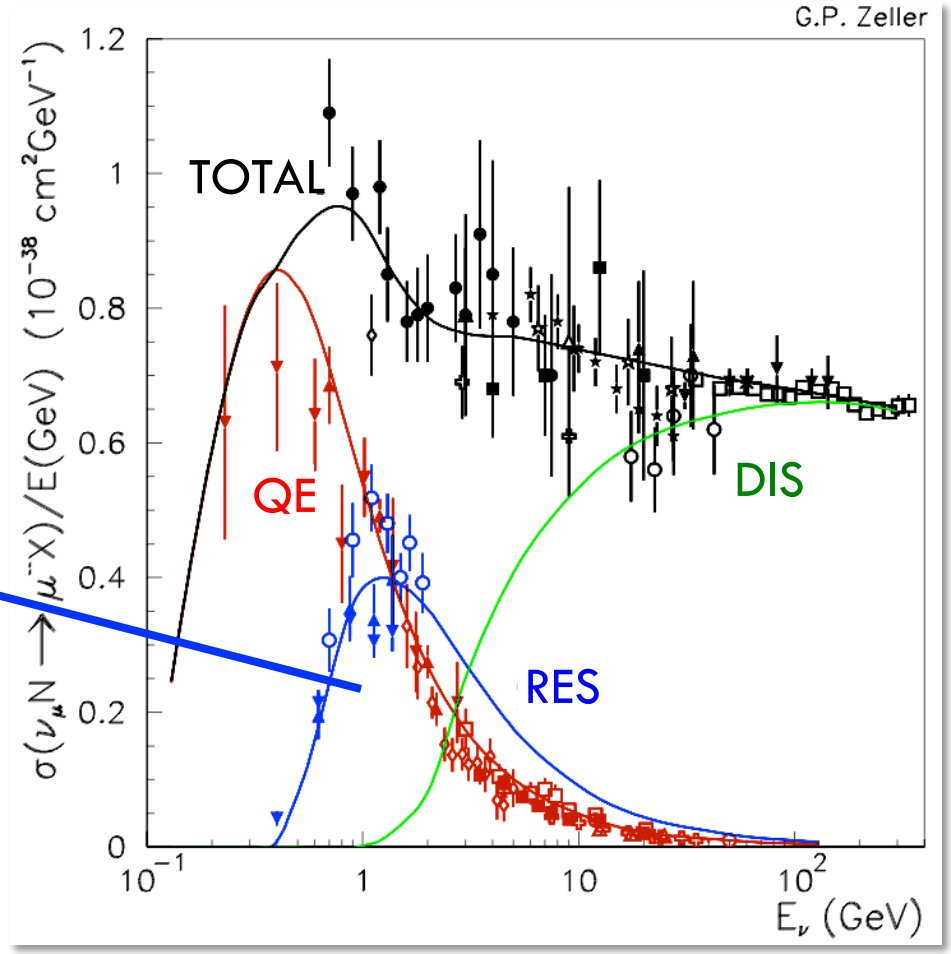
Pion Production ($\Delta, N^* \rightarrow N\ \pi$)

- π^0 production



- π^+ production





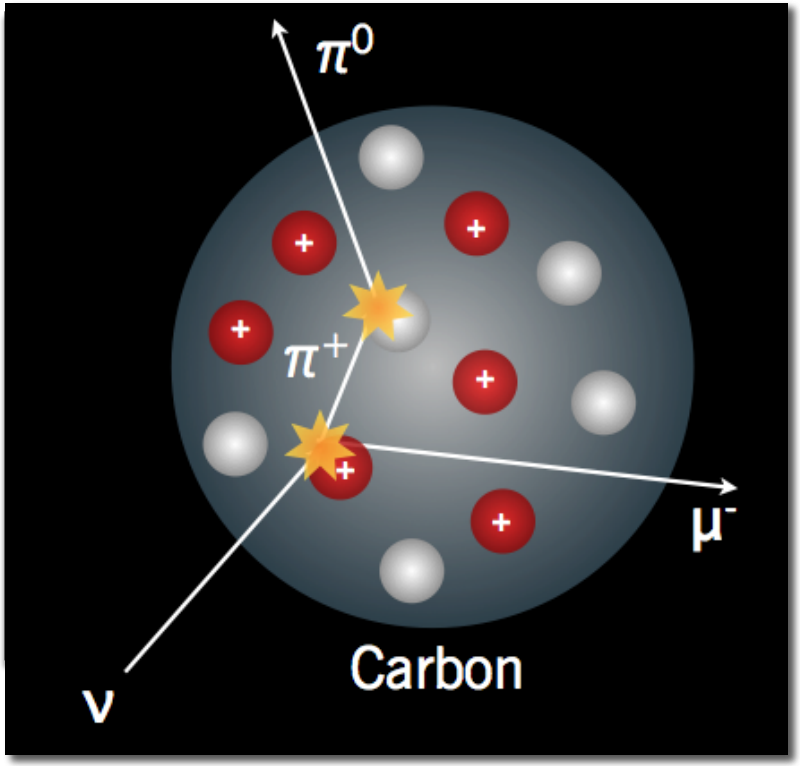
- important for different reasons → backgrounds

Final State Effects

- new appreciation for nuclear effects in this region as well

"final state interactions (FSI)"

- once produced, hadrons have to make it out of the target nucleus
- nucleon rescattering
- π absorption & charge exchange



- have to worry about these effects

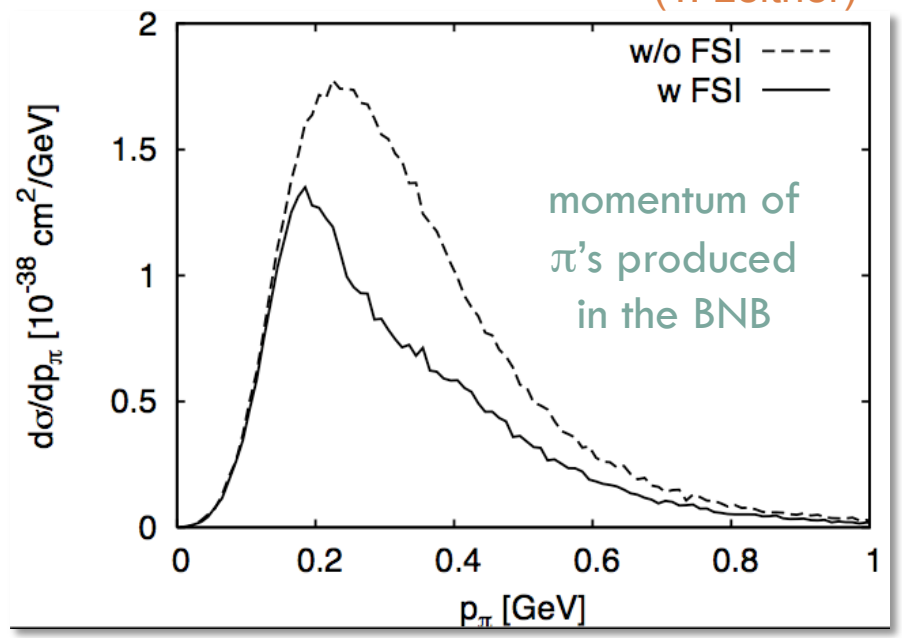
Final State Effects

- new appreciation for nuclear effects in this region as well

"final state interactions (FSI)"

- once produced, hadrons have to make it out of the target nucleus
- nucleon rescattering
- π absorption & charge exchange

(T. Leitner)



distortions are large &
predictions of their effects vary …

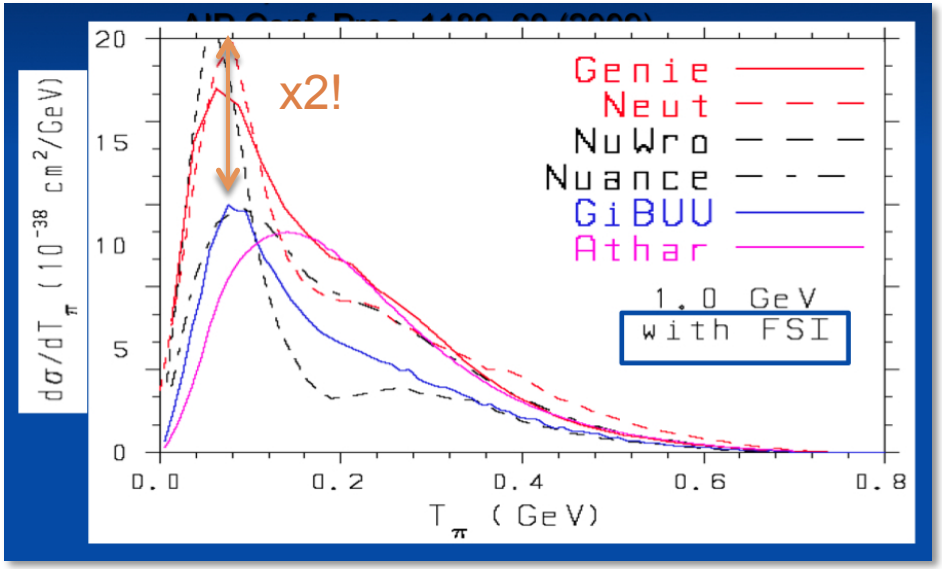
Final State Effects

- new appreciation for nuclear effects in this region as well

"final state interactions (FSI)"

- once produced, hadrons have to make it out of the target nucleus
- nucleon rescattering
- π absorption & charge exchange

http://regie2.phys.uregina.ca/neutrino/



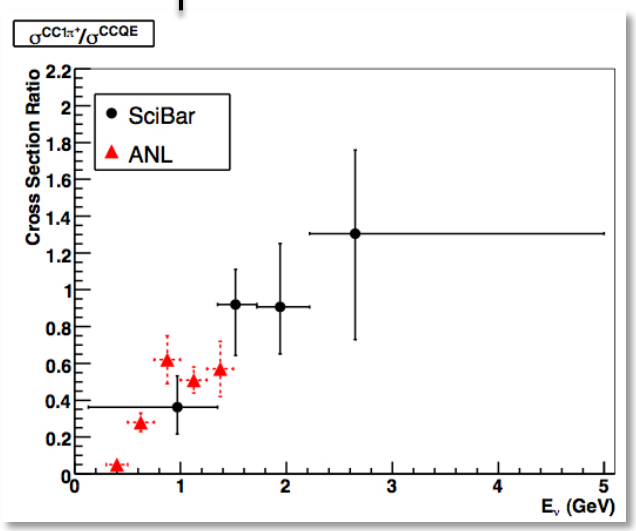
understanding π kinems is important!

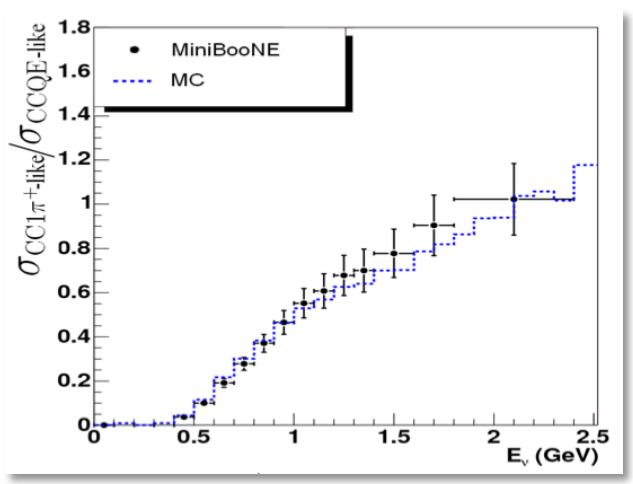
(has never been carefully studied in ν scattering)

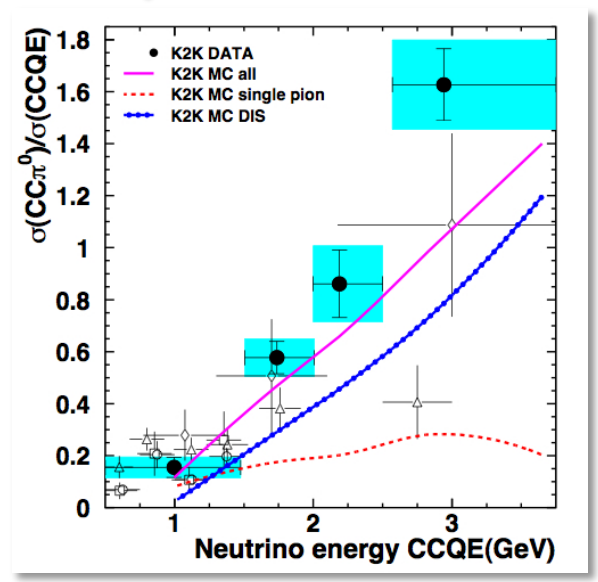
Single Pion Measurements

- there have been recent measurements of $\sigma(E_\nu)$ & σ ratios for these processes from a number of modern neutrino experiments:

  - **K2K** NC π^0/CC ratio: PL **B619**, 255 (2005)
  - **K2K** CC π^0 $\sigma(E_\nu)$: PRD **83**, 054023 (2011)
  - **K2K** CC π^+/QE ratio: PRD **78**, 032003 (2008)
  - **MiniBooNE** CC π^+/QE ratio: PRL **103**, 081801 (2009)
  - **SciBooNE** NC π^0/CC ratio: PRD **81**, 033004 (2010)







Measurement Strategy

- rethinking after appreciation for FSI and consultation with theorists
  (measure final state kinematics in detail; report what we observe)

- NC π^0: $1\pi^0$ Phys. Rev. **D81**, 013005 (2010)
- CC π^0: $\mu + 1\pi^0$ Phys. Rev. **D83**, 052009 (2011)
- CC π^+: $\mu + 1\pi^+$ Phys. Rev. **D83**, 052007 (2011)

MiniBooNE results

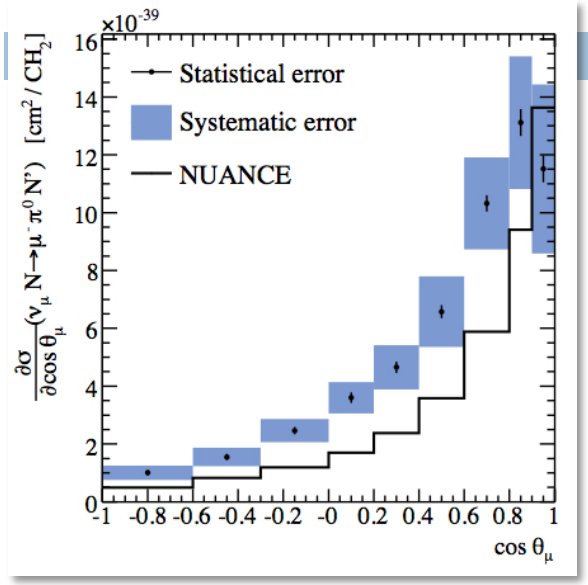
(R. Nelson, NuInt11)

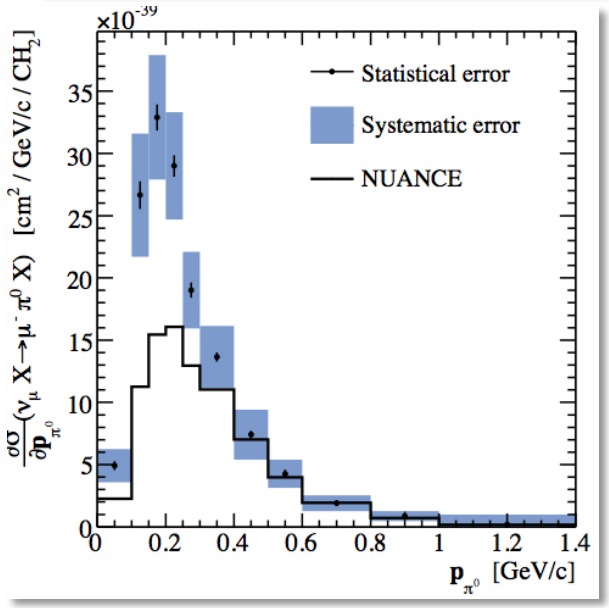
- A total of 16 measurements!
- ✱ = presented as a function of neutrino energy.
- Least model dependent results!

Measurement\Mode	NCπ^0	CCπ^0	CCπ^+
$\sigma(E_\nu)$		✓	✓
$d\sigma/dQ^2$		✓	✓✱
$d\sigma/dp_\pi$	✓	✓	✓✱
$d\sigma/d\cos\theta_\pi$	✓	✓	✓✱
$d\sigma/dT_\mu$	2	✓	✓✱
$d\sigma/d\cos\theta_\mu$		✓	✓✱
$d^2\sigma/dT_\mu d\cos\theta_\mu$		6	✓
$d^2\sigma/dT_\pi d\cos\theta_\pi$			✓
			8

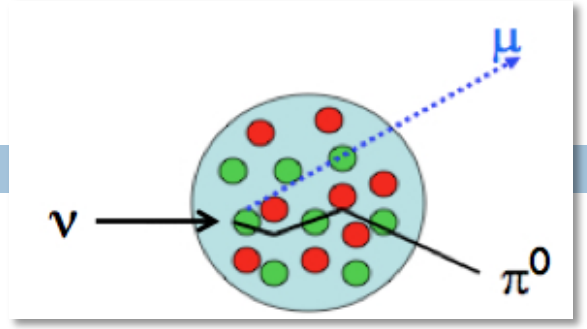
all data available on the MB webpage!

Example: CC π^0





B. Nelon, Ph.D. thesis, PRD **83**, 052009 (2011)



- <u>measures</u>:

(initial interaction) * (FSI) * (nuclear effects)

initial interaction → verified with low stats decades ago (D_2)

FSI → (−) π^0 absorption; (+) $\pi^{+/-} \rightarrow \pi^0$; n,p $\rightarrow \pi^0$

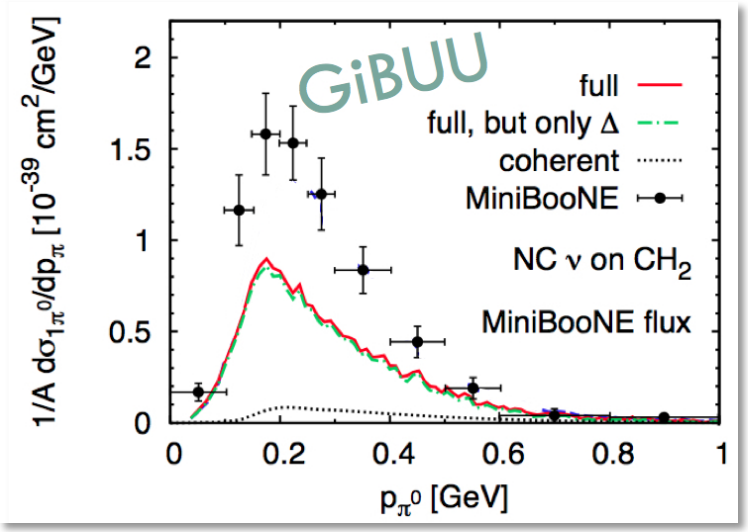
nuclear effects → np-nh ?

- to make progress, should strive to report interaction cross sections in this way
  - f.s. particle kinematics, not just $\sigma(E_\nu)$
  - don't correct out FSI (keep as model-indep as possible)

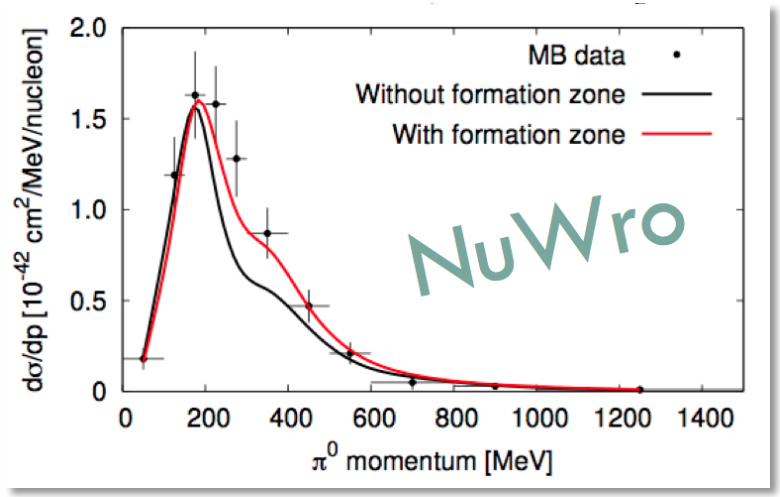
FSI Models

- data in heavy use by model builders
  (examples shown at NuInt11 last month)

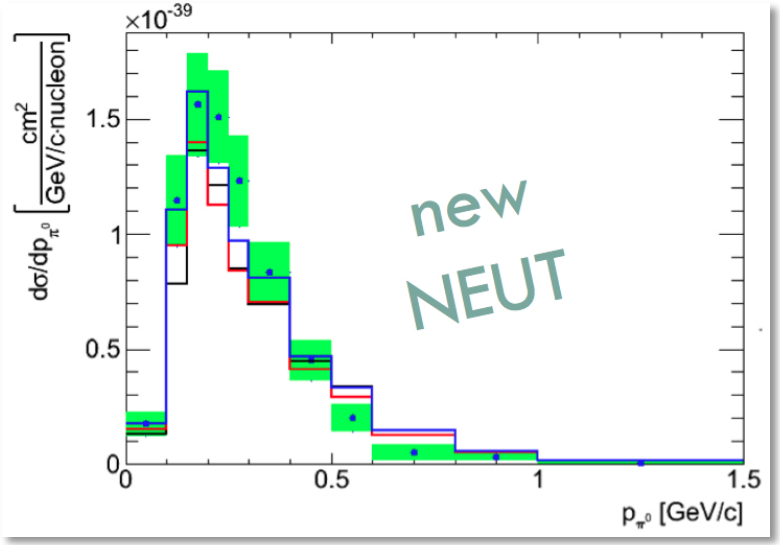
(U. Mosel)



(T. Golan)



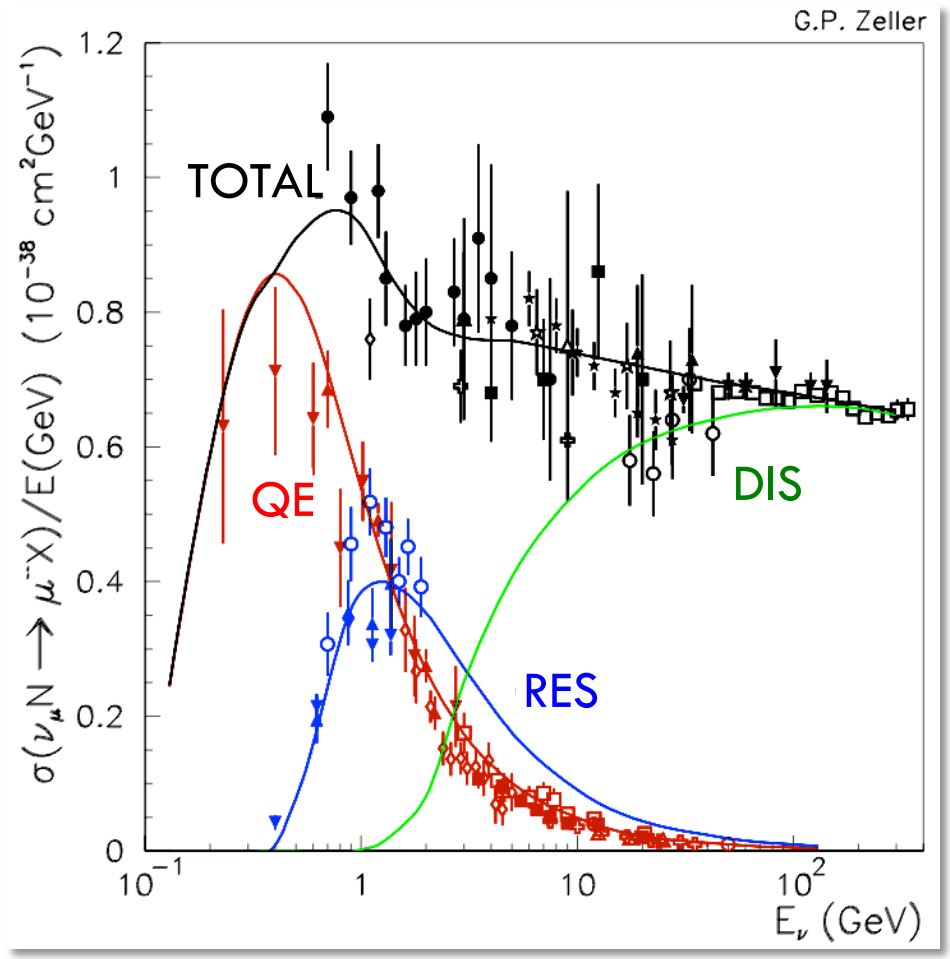
(P. dePerio)



- need measurements on other targets
- and at higher energies (multi-π)
  - LAr: ArgoNeuT, MicroBooNE, ICARUS
  - MINERνA!

CC Inclusive Cross Section

- new appreciation for the role that inclusive measurements can play especially as we try to sift through these complex nuclear effects

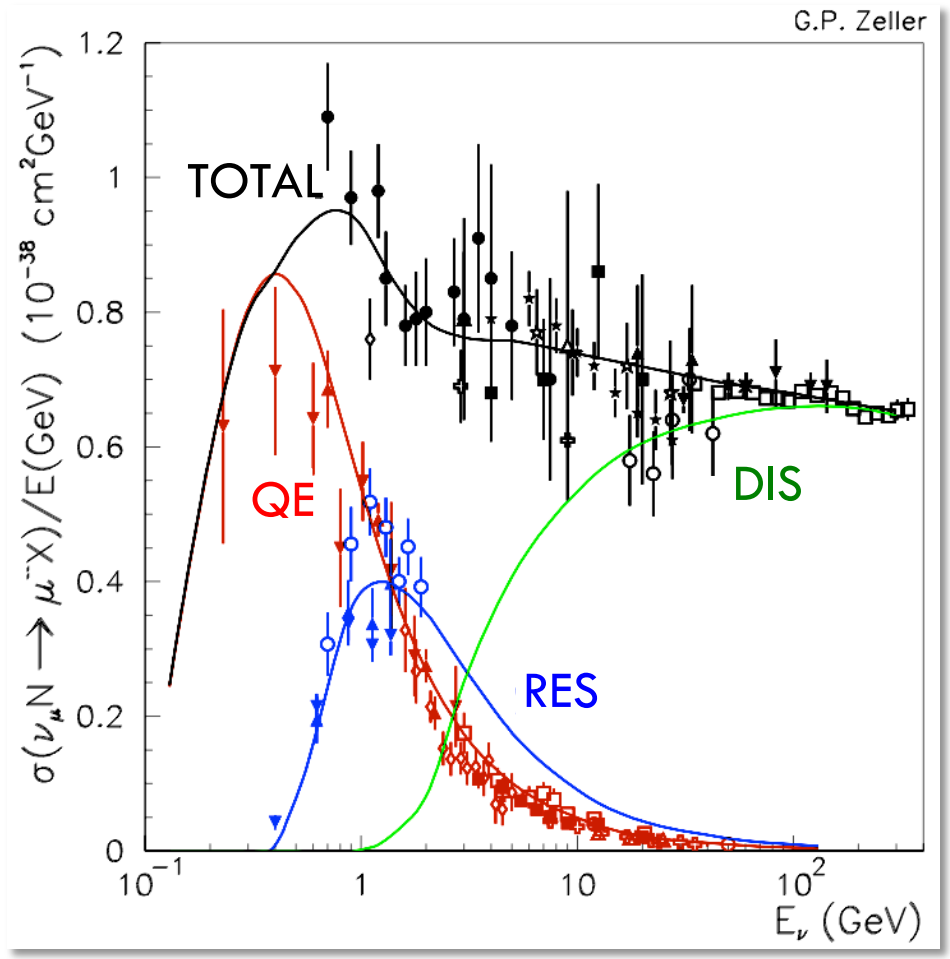


CC Inclusive Cross Section

- measures everything at once:

+ QE
+ np-nh
+ Δ, N* $\rightarrow$ 1π, multi-π
+ Δ, N* $\rightarrow$ $\cancel{\pi}$
+ DIS …

- high purity samples (events with a μ)

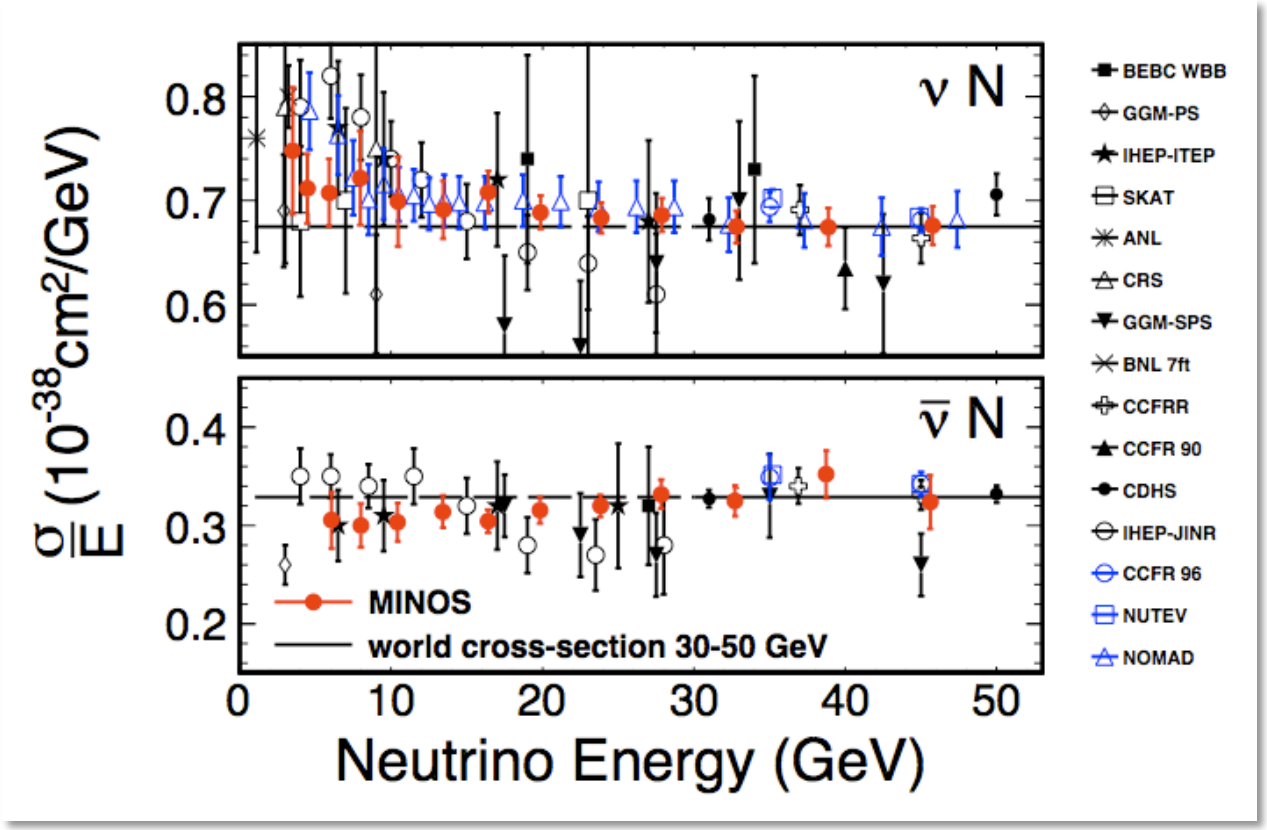


clear need for improved measurements $E_\nu \lesssim 50$ GeV

CC Inclusive Cross Section

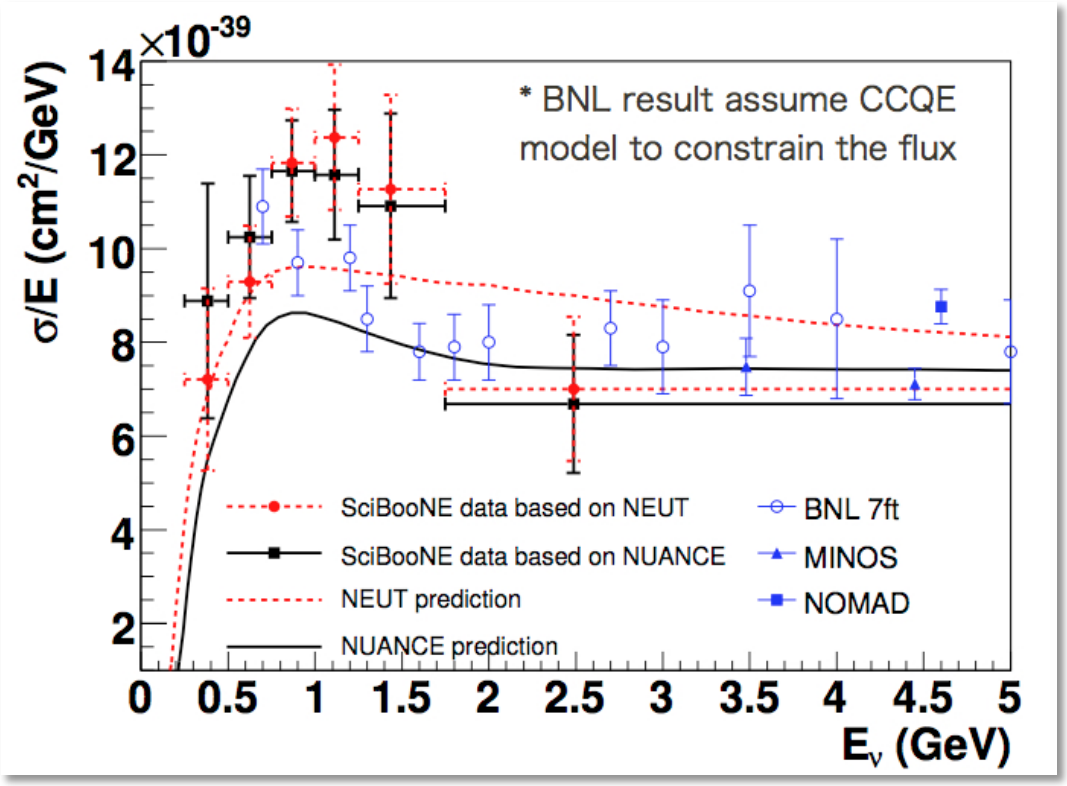
$\nu_\mu N \rightarrow \mu^- X$

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



- **NOMAD:** (ν ^{12}C), 4.5<E_ν<230 GeV, PLB **660** 19 (2008)
- **MINOS:** ($\nu,\bar{\nu}$ ^{56}Fe), 3.5<E_ν<45 GeV, PRD **81**, 072002 (2010)

CC Inclusive at SciBooNE



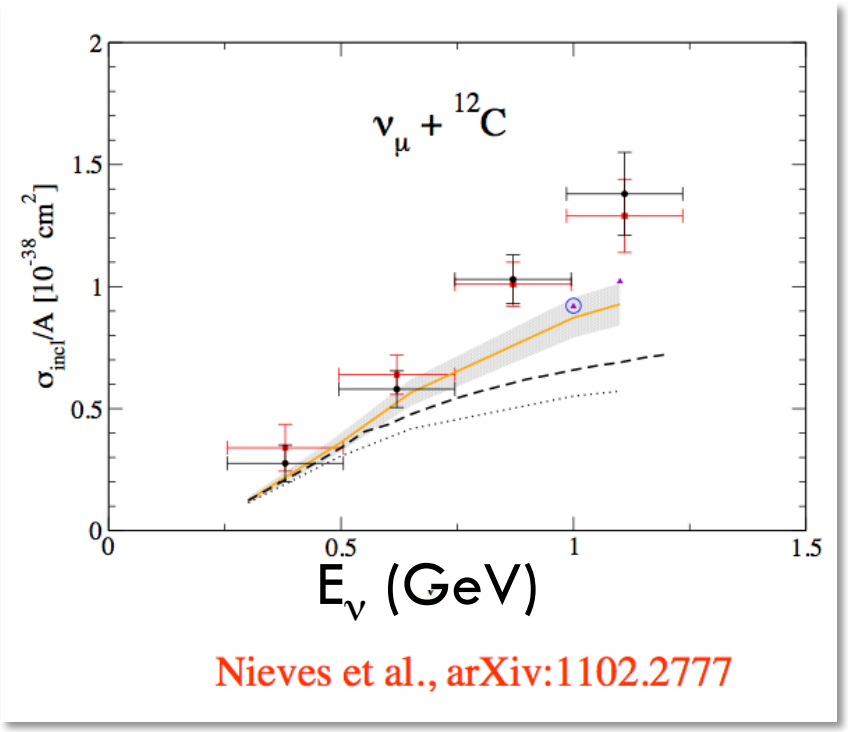
Nakajima, *et al.*, PRD **83**, 012005 (2011)

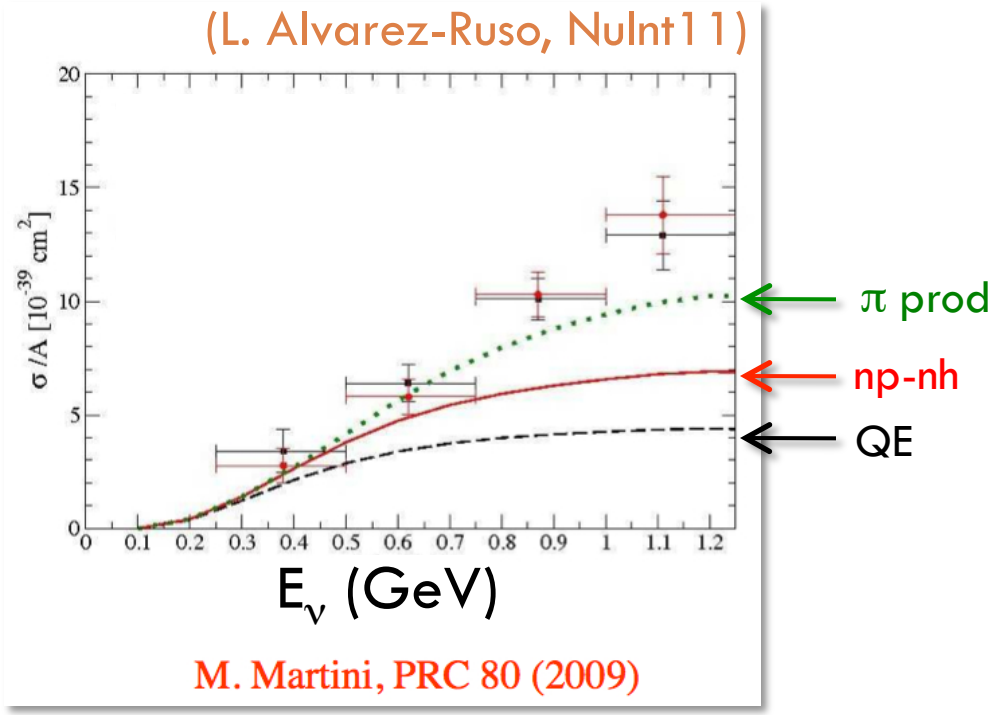
$\nu_\mu N \rightarrow \mu^- X$

- more recently, SciBooNE published 1st measurement of CC inclusive σ on a nuclear target at low energy
- carbon, E_ν<3 GeV

SciBooNE Results in Use

- these data are a very useful starting point for model comparisons

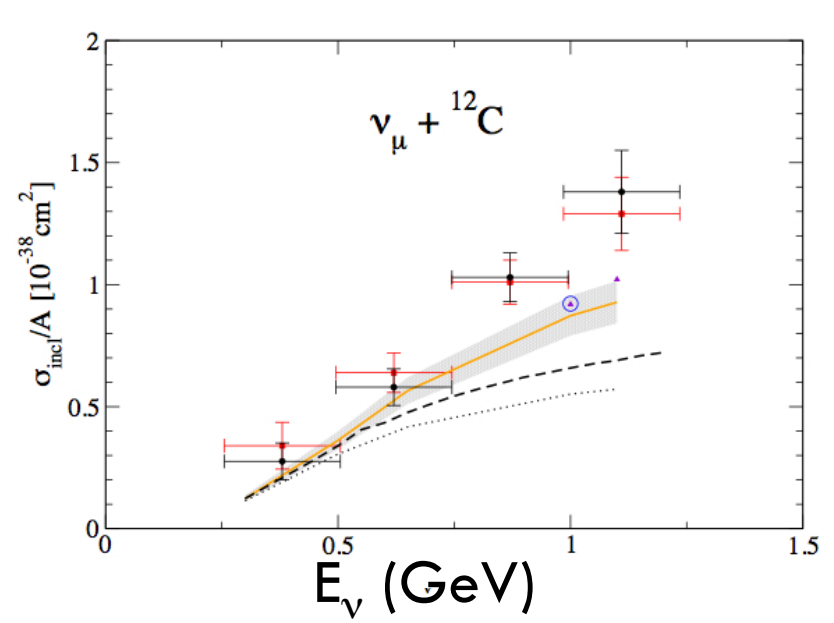




- these type of comparisons need to be expanded out to higher energies

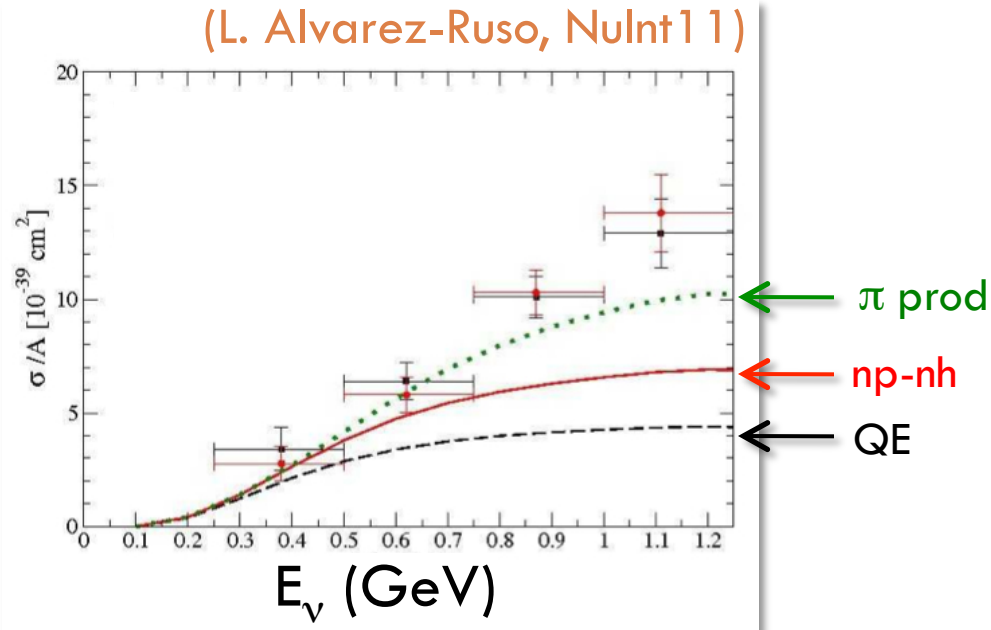
SciBooNE Results in Use

- these data are a very useful starting point for model comparisons



Nieves et al., arXiv:1102.2777

(L. Alvarez-Ruso, NuInt11)



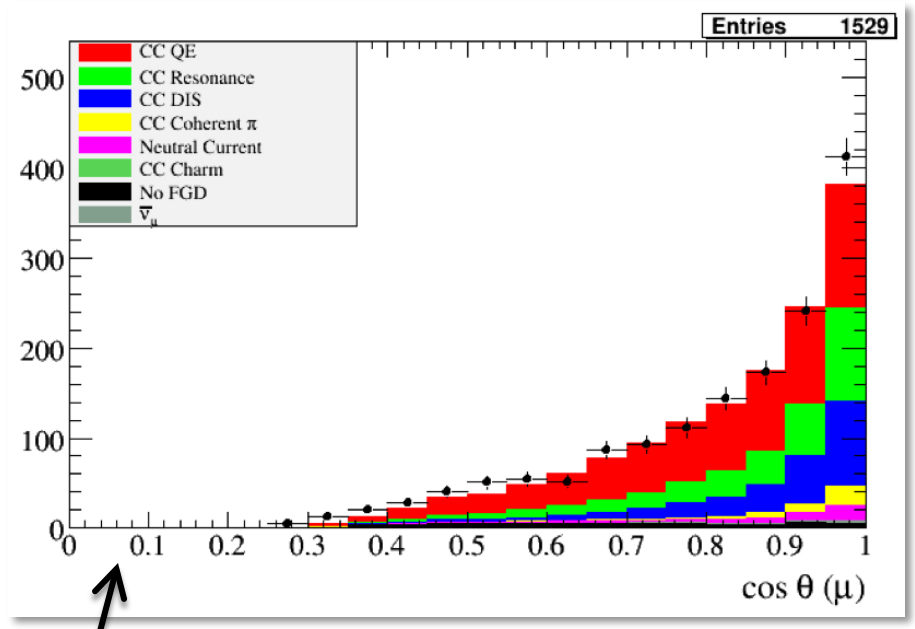
M. Martini, PRC 80 (2009)

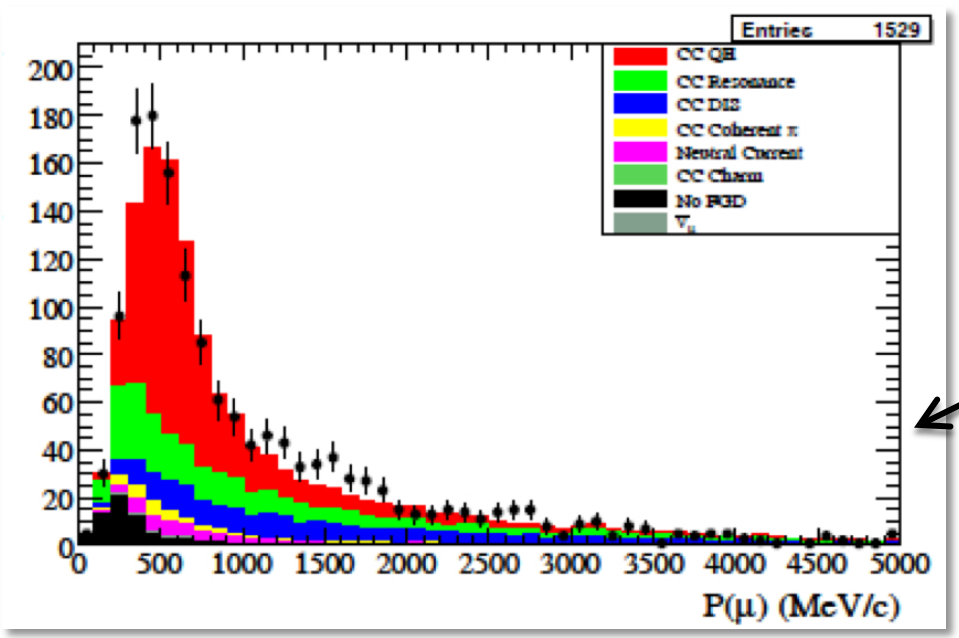
- also, being able to replicate $\sigma(E_\nu)$ is not a sufficient test
  - need $d^2\sigma/dT_\mu d\theta_\mu$ (ala QE; don't exist for CC)
  - and A dependence (different for FSI vs. np-nh)

CC Inclusive at T2K

- 1st data from T2K ND
- very similar E_ν range to SciBooNE, also carbon-based target

(H. Tanaka's talk, this workshop)



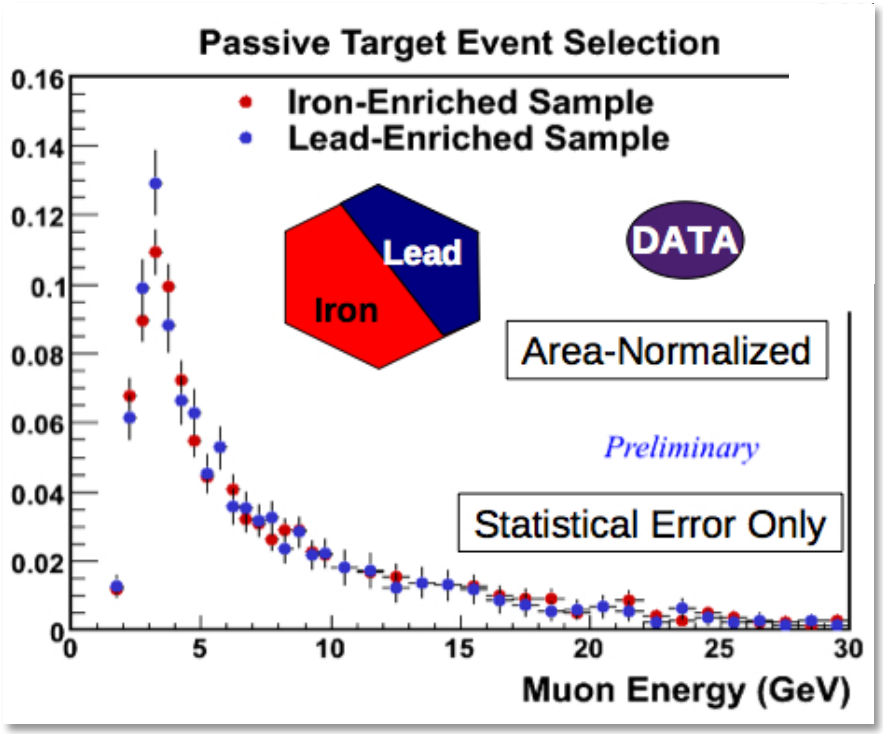


- ingredients for $d^2\sigma/dT_\mu d\theta_\mu$
- also possibility for such a measurement in ArgoNeuT

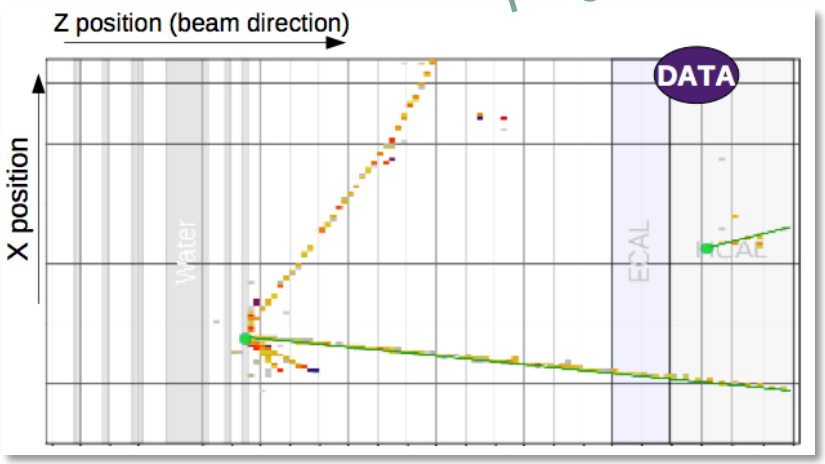
(M. Soderberg's talk, this workshop)

CC Inclusive 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



MINERνA 1st glimpse!

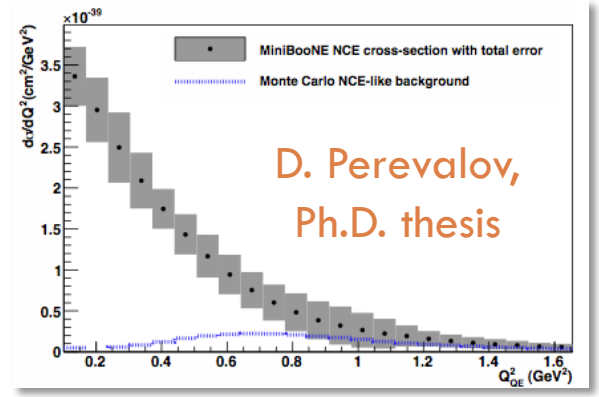


(DIS event reconstructed in iron)

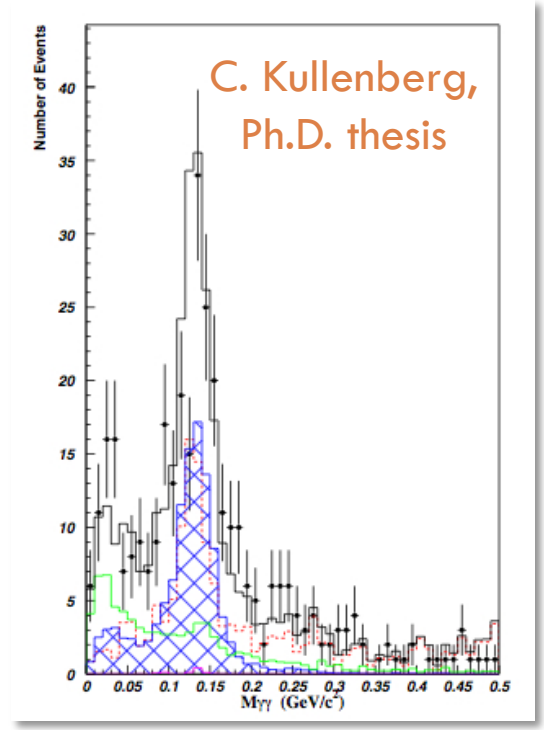
(B. Osmanov's talk, this workshop)

Didn't Have Time To Discuss …

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



- NC coherent π^0 production (ν_μ A $\rightarrow \nu_\mu$ 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 $\rightarrow \mu^-$ A π^+)
  - K2K, PRL **95**, 252301 (2005)
  - SciBooNE, PRD **78**, 112004 (2008)
  - SciBooNE $\bar{\nu}$, H. Tanaka, NuInt11 workshop



Conclusions

- new results on a variety of different ν interaction channels (few-GeV)
- new data uncovering added complexities in QE & resonance regions

- the more we probe this region, the more we seem to uncover … a lot we need to sort out

  - *nuclear effects are important!*
  - *need revised nuclear model calculations*
  - *need additional experimental input, especially $\bar{\nu}$ measurements!*

- SBL ν interaction physics is far more interesting than we thought!

Conclusions (con't)

- in the coming years, a host of experiments will have the capability to explore these interesting puzzles
  - K2K, MiniBooNE, MINOS, NOMAD, SciBooNE
  - **MINERνA** … ArgoNeuT, MicroBooNE, ICARUS
  - near detectors: NOvA, T2K
- **looking beyond this …**
  - repeat H_2, D_2 measurements w/ modern ν beams (L. Zhu, Saturday)
  - SciNoVA (R. Tayloe, Saturday)
  - LBNE ND (S. Mishra, Saturday)
  - cyclotron ν beams (J. Conrad, Saturday)
  - what can we learn using a 3 GeV beam?