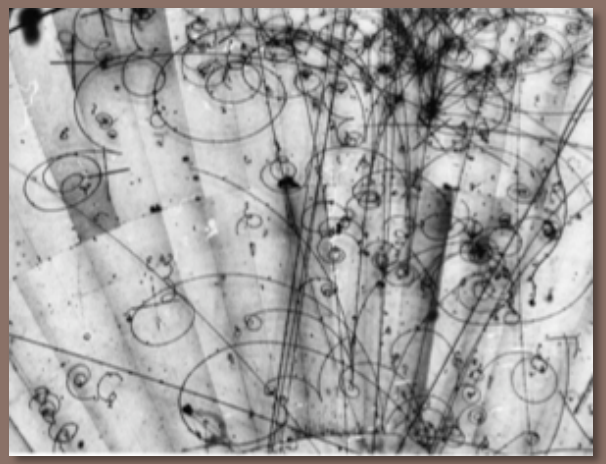
NEUTRINO CROSS SECTIONS

Sam Zeller
Fermilab

PANIC 2011

July 26, 2011

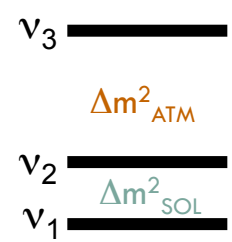


- this topic has become quite interesting lately
- revisiting ν scattering physics again for 1st time in decades
- new data is revealing some surprises

Neutrino Physics

- looking forward, there are some big ?'s we will be trying to answer …

  - what are the masses of neutrinos?
  - are neutrinos their own anti-particles?
  - is θ_{23} maximal? is θ_{13} non-zero?
  - what is their mass ordering?
  - is CP violated in the ν sector?



- extensive international effort aimed at addressing these ?'s will place even greater demands on our knowledge of underlying ν interactions

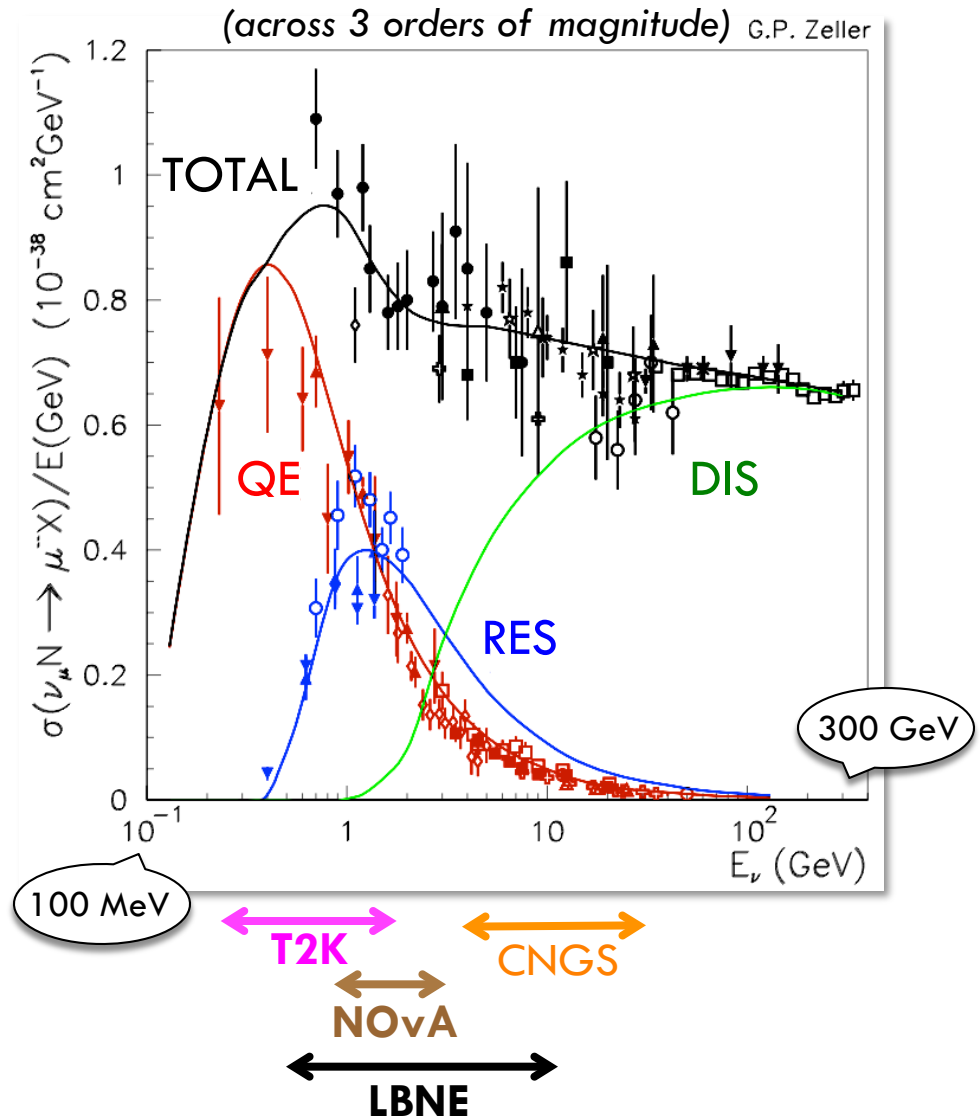
  (this knowledge will quickly become inadequate as aim for next level in precision & search for smaller and smaller effects)

Neutrino Cross Sections

- pursuit of ν oscillations has unfortunately forced us into a rather complex region of ν interaction physics
  (100's MeV to few-GeV)

- lots of rich physics here; is where are also building our future ν oscillation experiments

(broad band beams contain contributions from multiple reaction mechanisms)



Why Is this Complicated?

quasi-elastic

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

resonance production

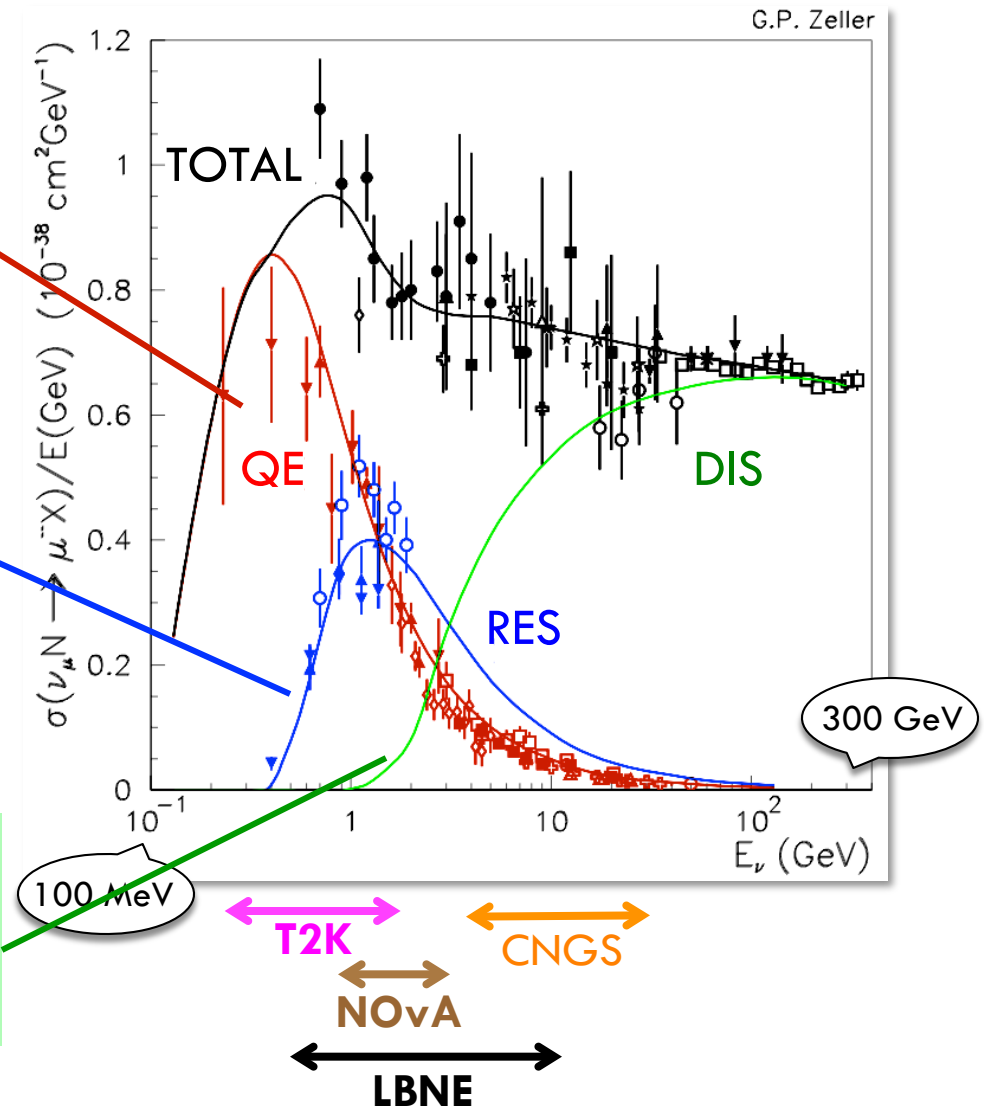
$\nu_\mu N \rightarrow \Delta$

$\hookrightarrow N'\pi$

deep inelastic scattering

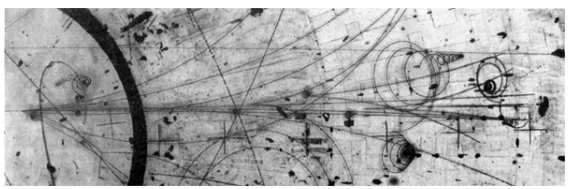
$\nu_\mu N \rightarrow \mu^- X$

need to extrapolate into low energy region

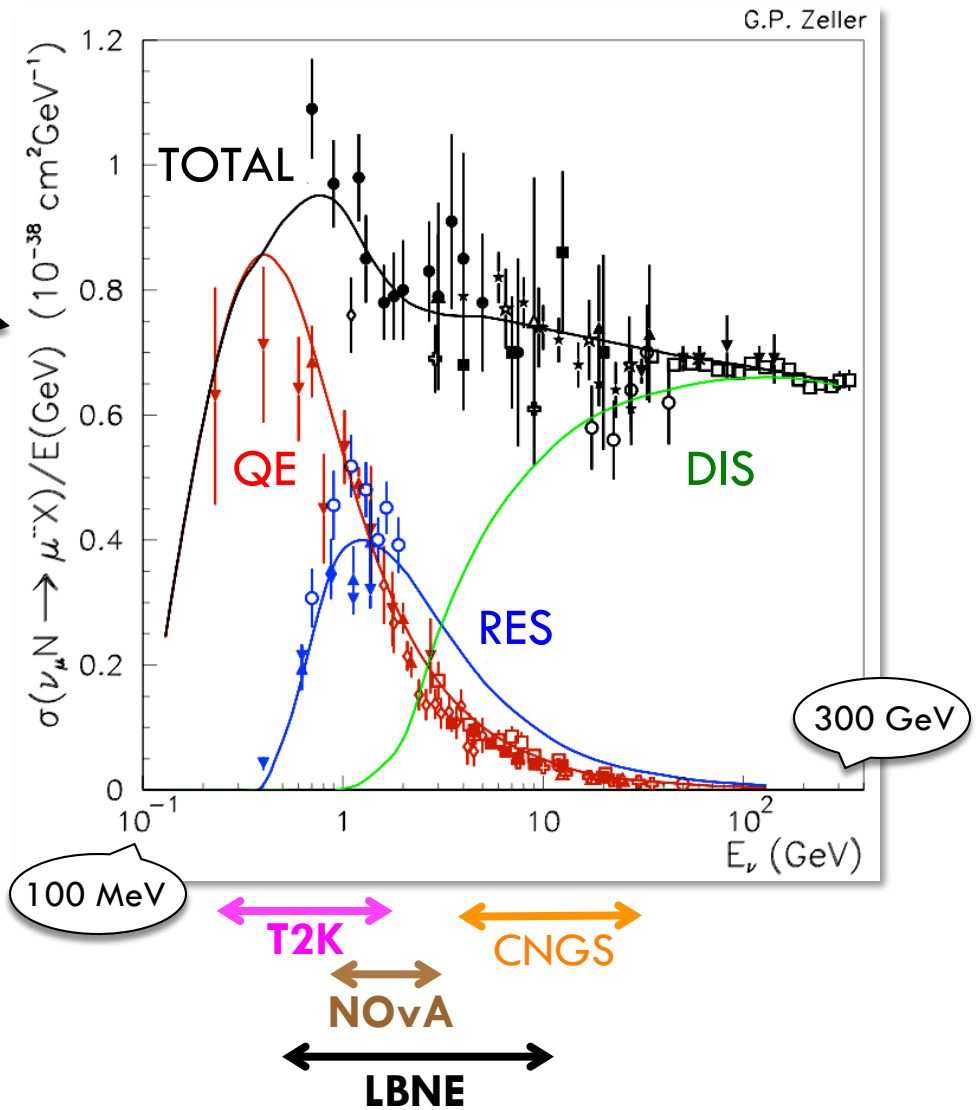


Historical Measurements

- region where exp'l knowledge of σ_ν has been limited
- most of info in this region comes from data that is >30 yrs old
  - *low statistics*
  - *mostly D_2, H_2 bubble chambers*



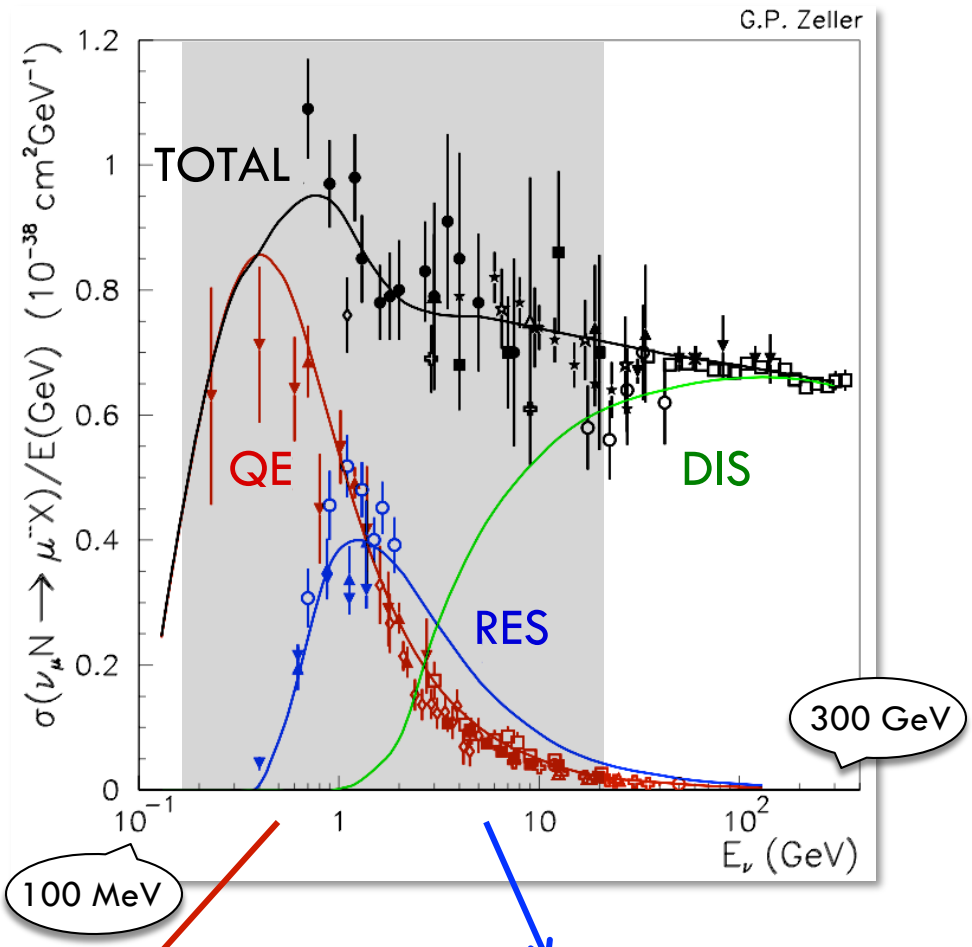
- one crucial difference: modern experiments use heavier nuclei
- has necessitated a dedicated campaign of new measurements



Modern Measurements

- 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 $\not{CP}$)*

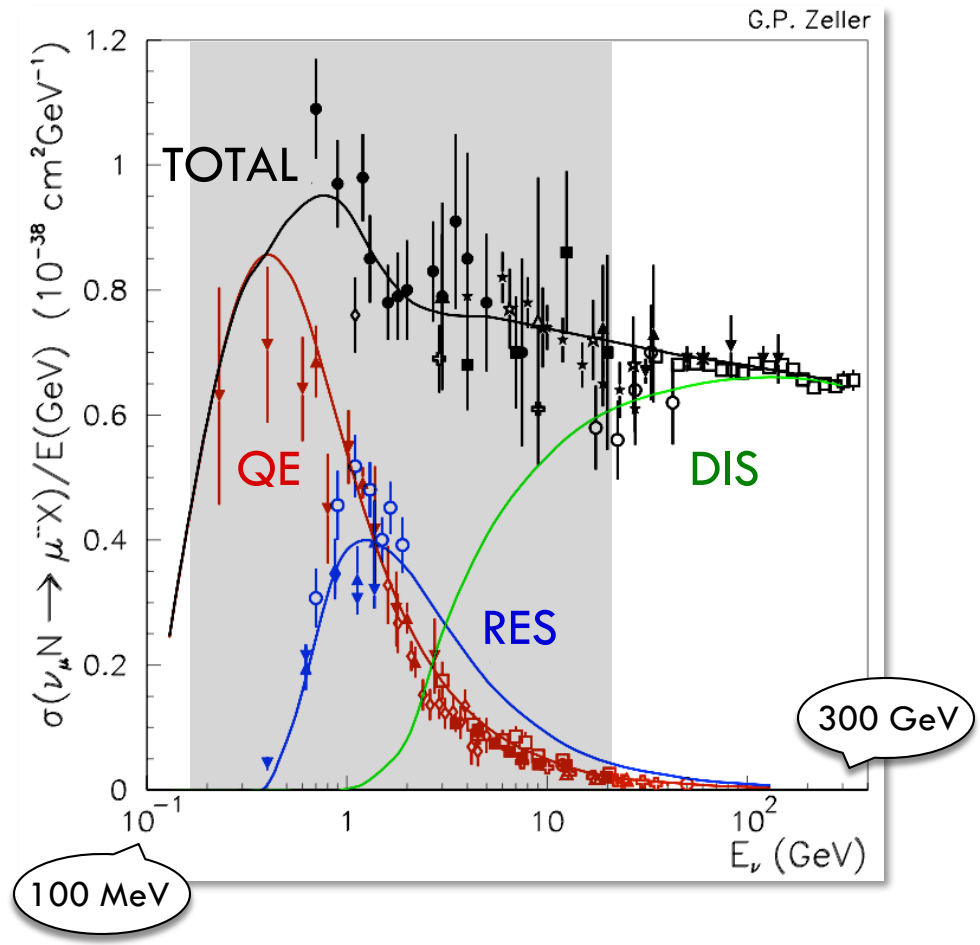


K2K ND, MicroBooNE, MiniBooNE, SciBooNE, T2K ND

ArgoNeuT, ICARUS, MINERνA, MINOS, NOMAD, NOvA ND

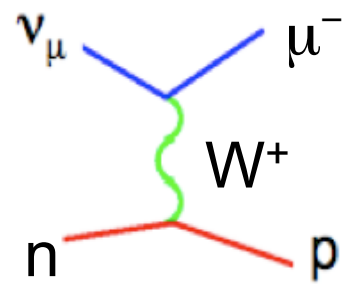
Neutrino Interactions

- let's start on the left and work our way up in energy …
  - QE
  - π production
  - CC inclusive
- use this plot as our guide as we survey the landscape
- what have we learned in exploring this region again 30+ years later? … along the way, will also point out next steps …



Quasi-Elastic Scattering

Why important?



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

(single knock-out nucleon)

- **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

- <u>examples:</u>

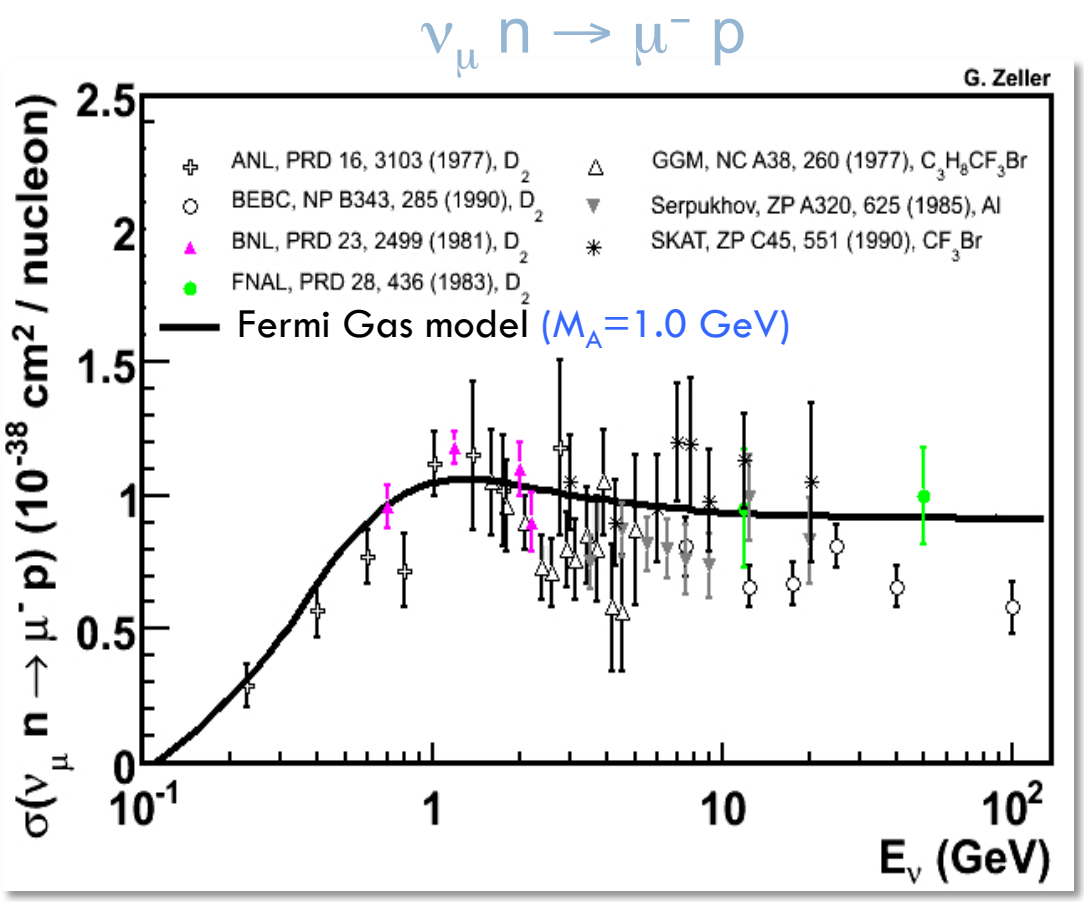
signal events

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

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

Historical Context

- conventional wisdom is that QE σ is well-known
  - *it's a simple 2-body process*
- can consistently describe all the experimental data
  - *most is on D_2*
  - *assume scattering takes place on individual nucleons*
  - *Fermi Gas model*
  - *M_A=1.0 GeV*
- this description has been quite successful
  - *can predict size & shape of σ*

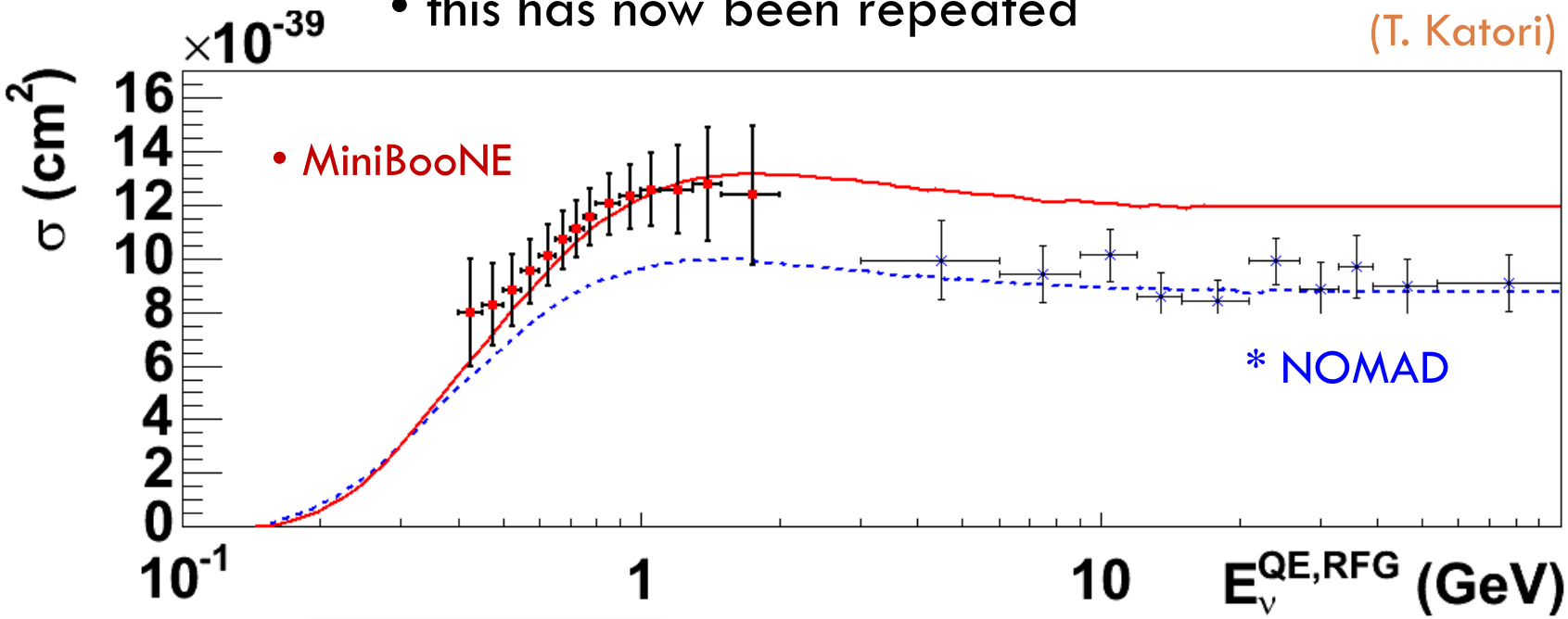


with these ingredients, it looked straightforward to describe ν QE scattering on nuclei

QE Cross Section on Carbon

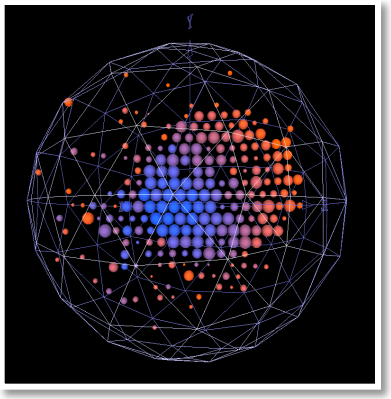
- this has now been repeated

(T. Katori)



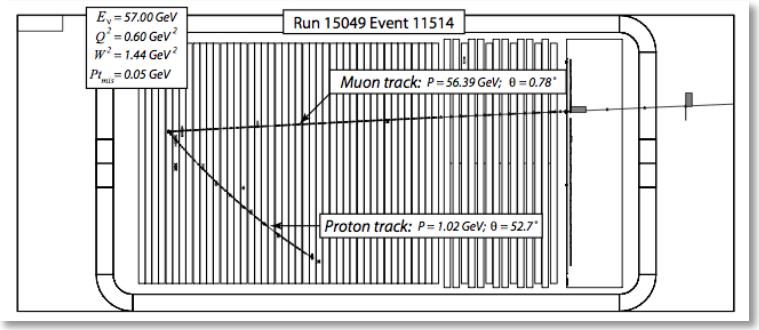
MiniBooNE 2002-present:

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

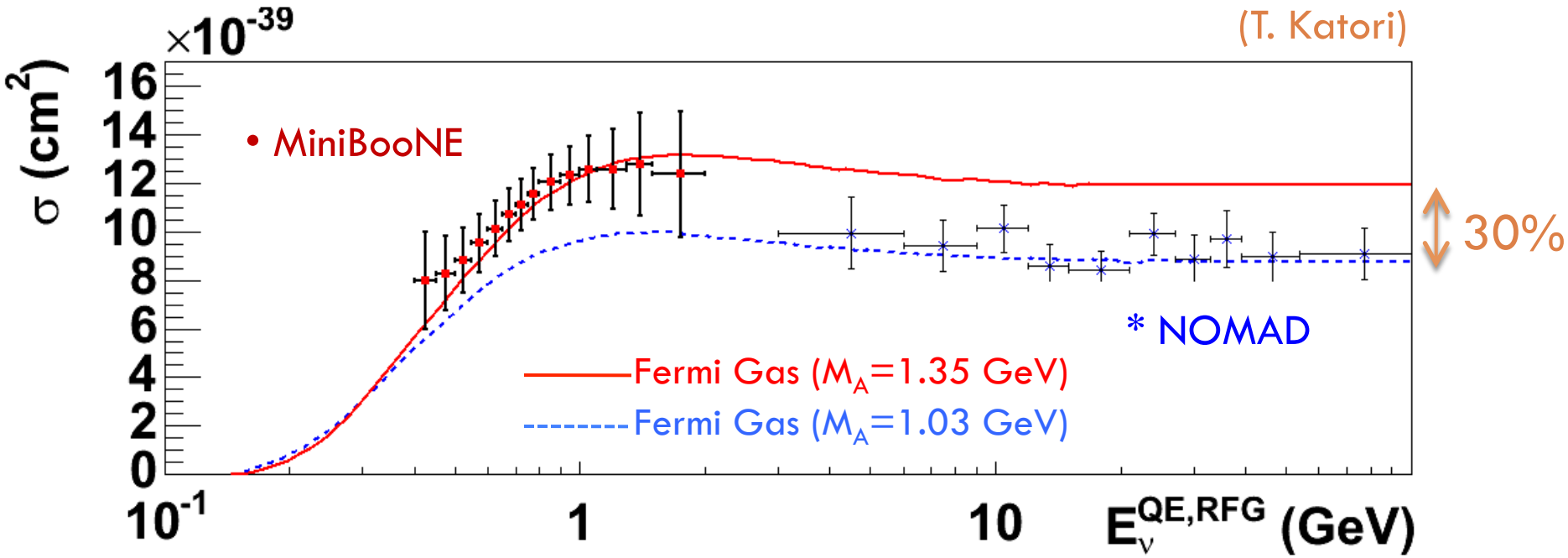


NOMAD 1995-1998:

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

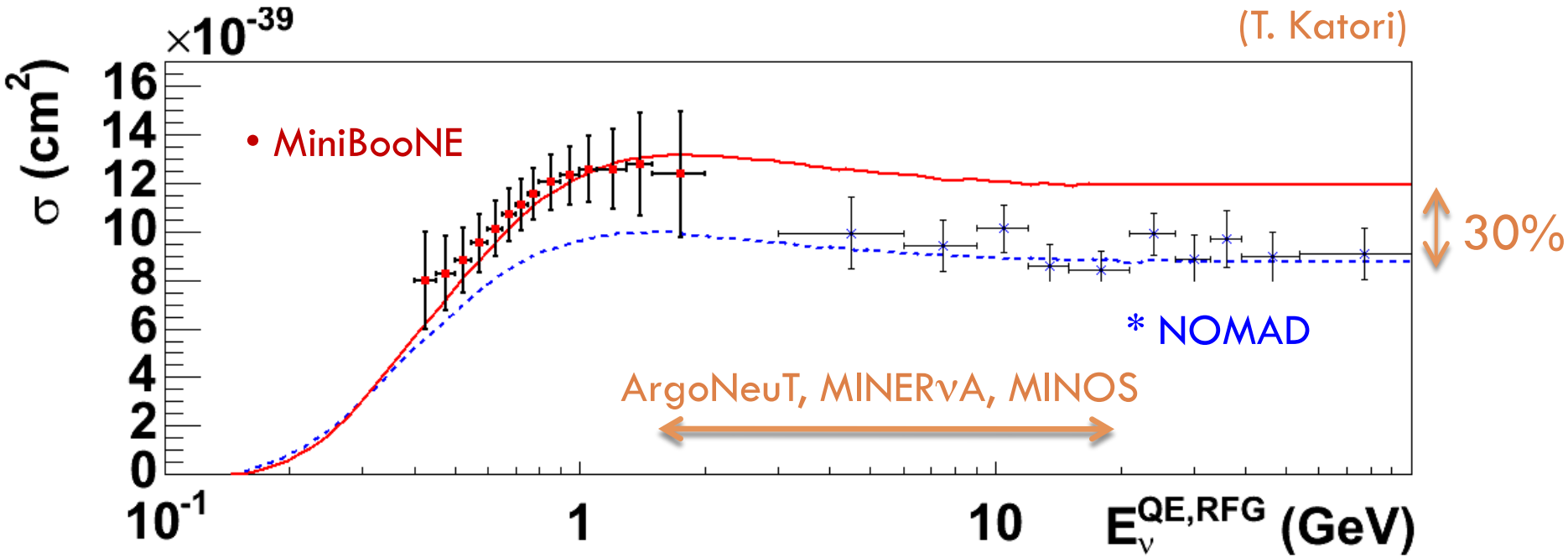


QE Cross Section on Carbon



- MiniBooNE data is well above "standard" QE prediction
  (increasing M_A can reproduce σ)
- NOMAD data consistent with "standard" QE prediction
  (with M_A=1.03 GeV)

QE Cross Section on Carbon



- results of low & high E experiments appear to be inconsistent; cannot be described with a single prediction *(we'll come back to this)*
- good news: new data will be weighing in on this soon
  (will show some preliminary QE results from MINERνA)

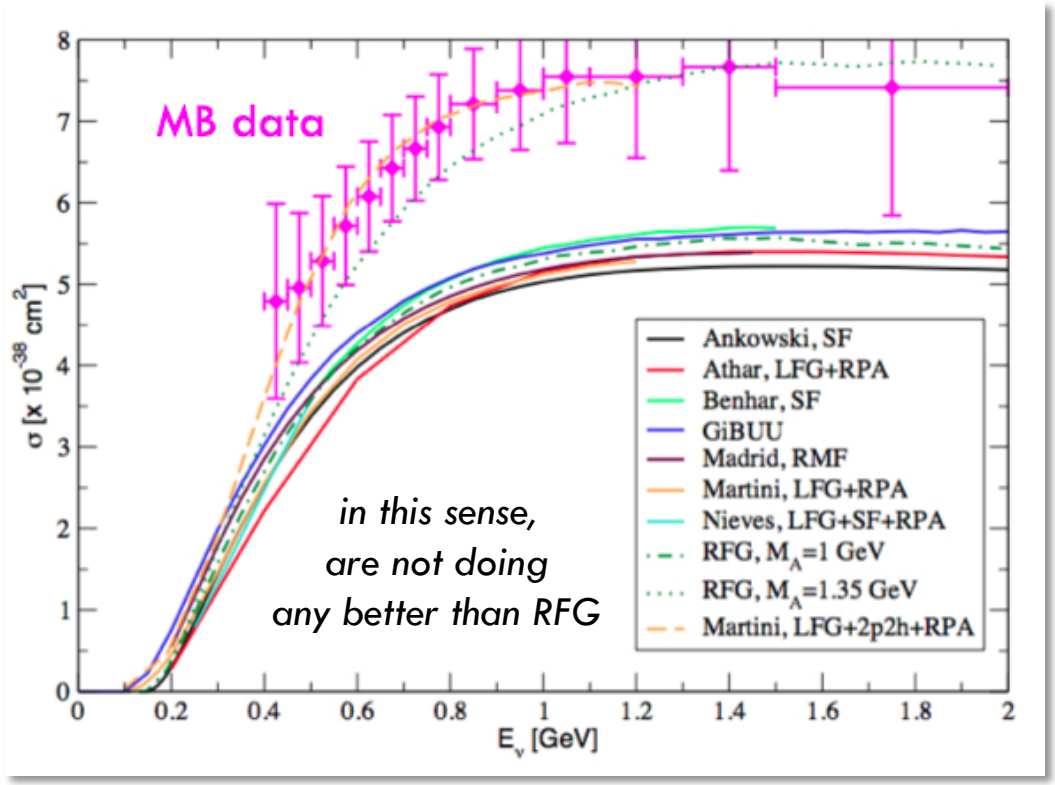
QE Cross Section at Low Energy

- MiniBooNE data has provided the 1st measurement of ν QE scattering on a nuclear target heavier than D_2 at low E_ν (E_ν<2 GeV)

  - *naturally, these results have garnered a lot of attention lately, largely because they were unexpected*
    (effects first seen in K2K ND)

- more sophisticated models also underpredict the low E σ
  (fall short by 30-40%!)

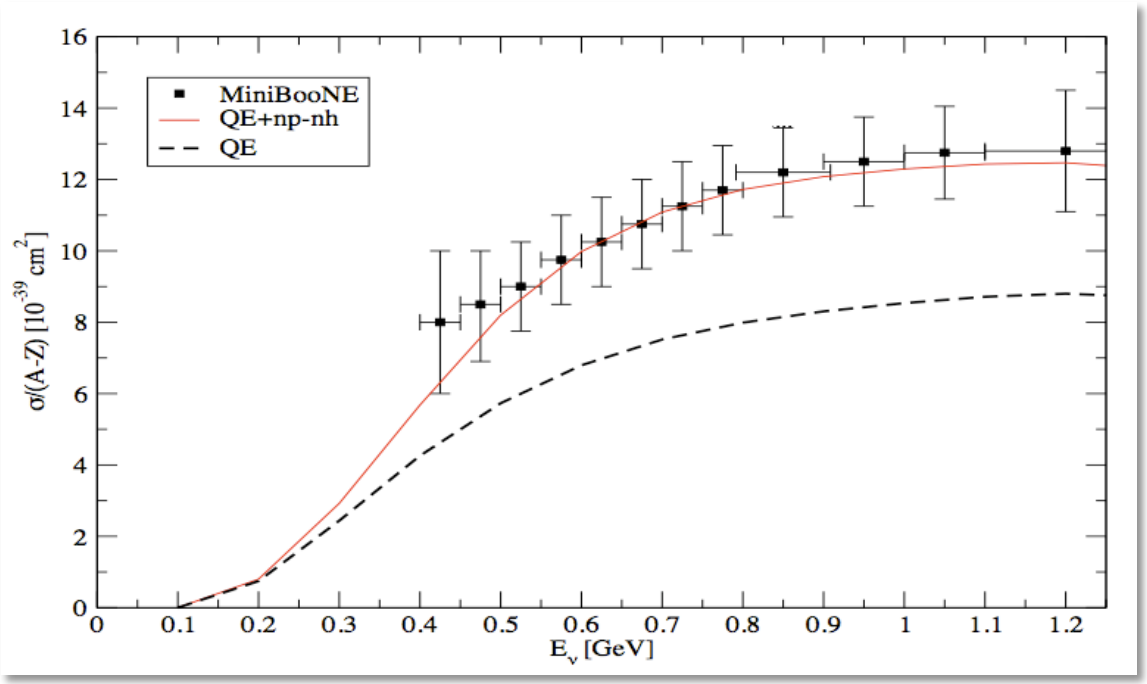
- remedy has been to increase M_A in these predictions



(L. Alvarez-Ruso, NuFact11)

Nuclear Effects to the Rescue?

- another possible explanation has recently emerged
- while traditional nuclear effects <u>decrease</u> the σ, there are processes that can <u>increase</u> the total yield …



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

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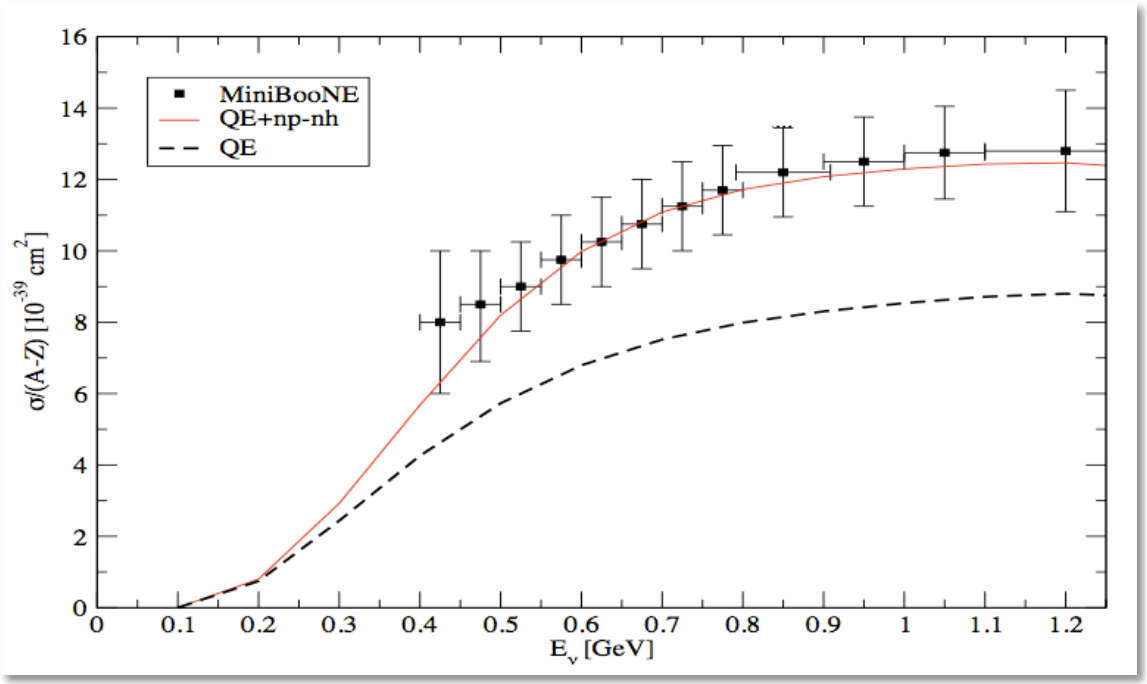

Martini *et al.*, PRC **80**, 065001 (2009)

- extra contributions coming from <u>nucleon correlations</u> in the nucleus

  (all prior calculations assume nucleons are independent particles)

- can predict MiniBooNE data without having to increase M_A *(here, M_A=1.0 GeV)*

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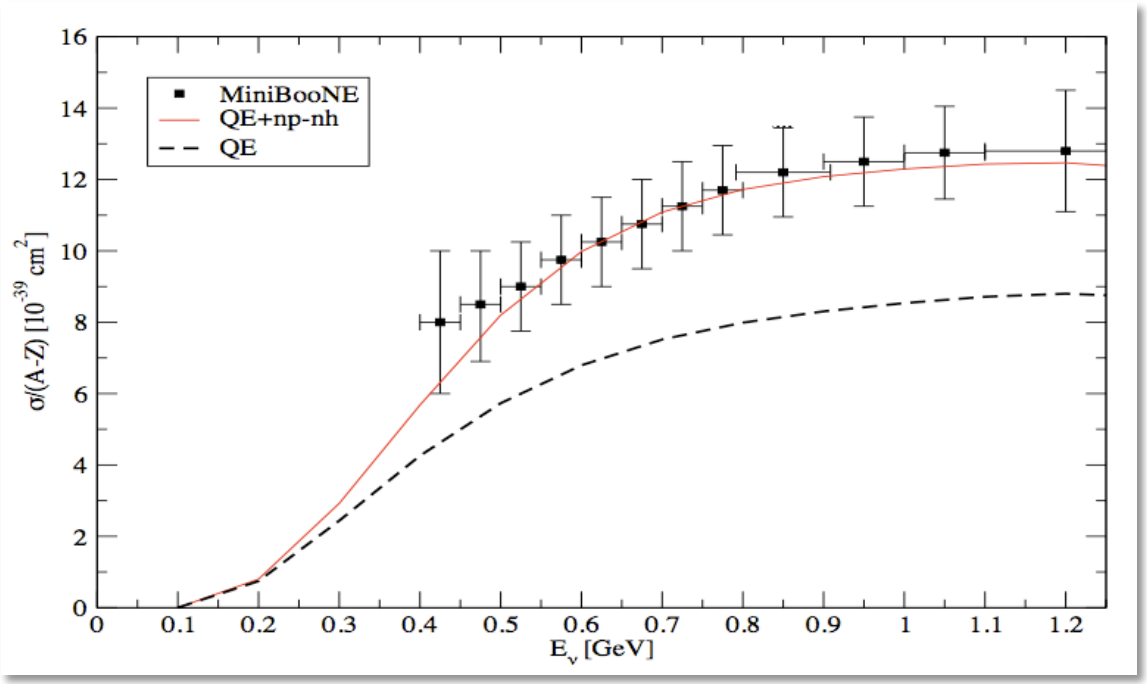

Martini *et al.*, PRC **80**, 065001 (2009)

- idea is not new
  - Dekker *et al.*, PLB **266**, 249 (1991)
  - Singh, Oset, NP **A542**, 587 (1992)
  - Gil *et al.*, NP **A627**, 543 (1997)
  - J. Marteau, NPPS **112**, 203 (2002)
  - Nieves *et al.*, PRC **70**, 055503 (2004)

calculation first came out in 2001 before MB started taking data

Nuclear Effects to the Rescue?

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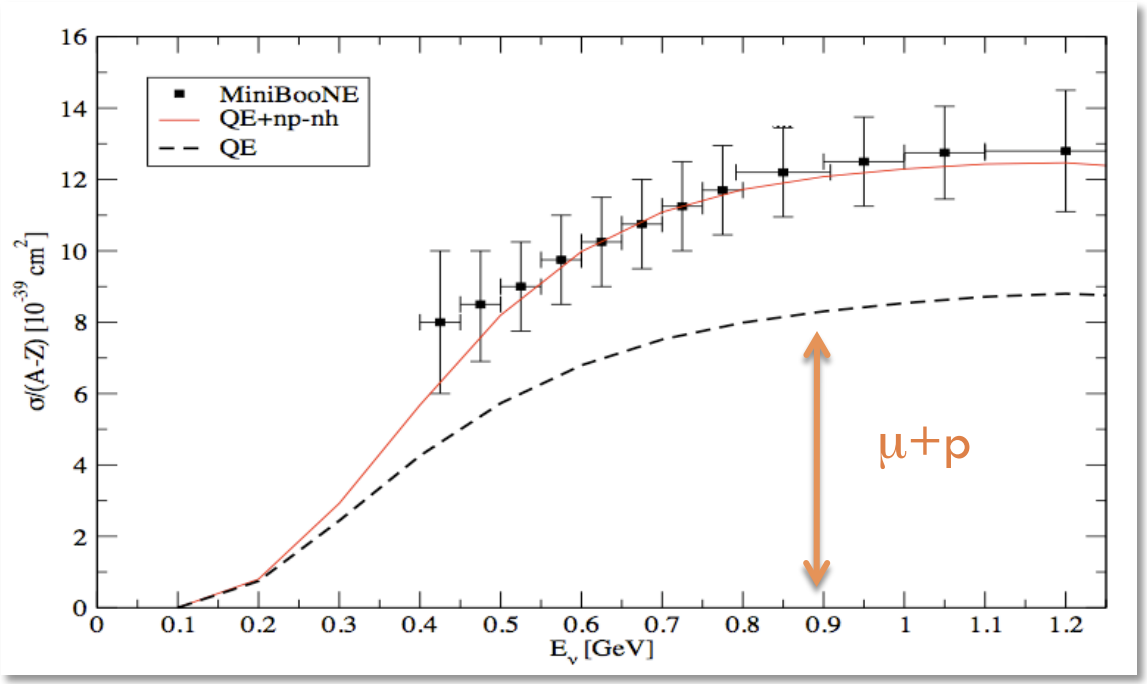

"standard" QE prediction we saw earlier

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

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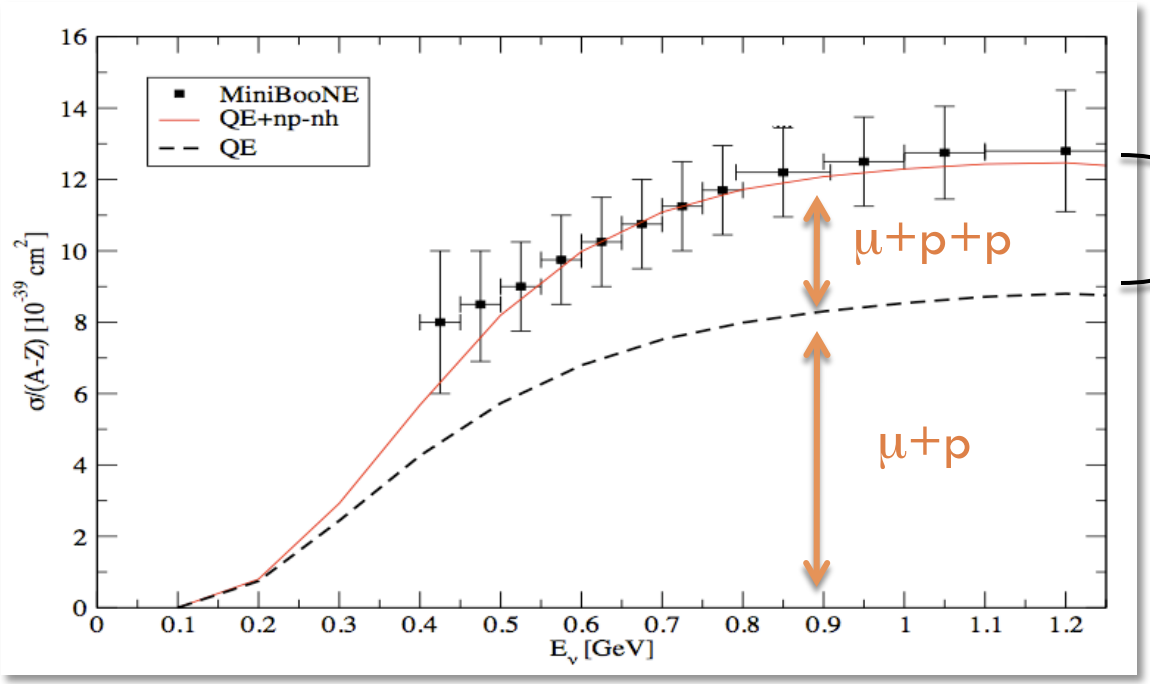

add'l nuclear processes contribute ~40% more σ at these ν energies and produce a multi-nucleon final state (μ+p+p)

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

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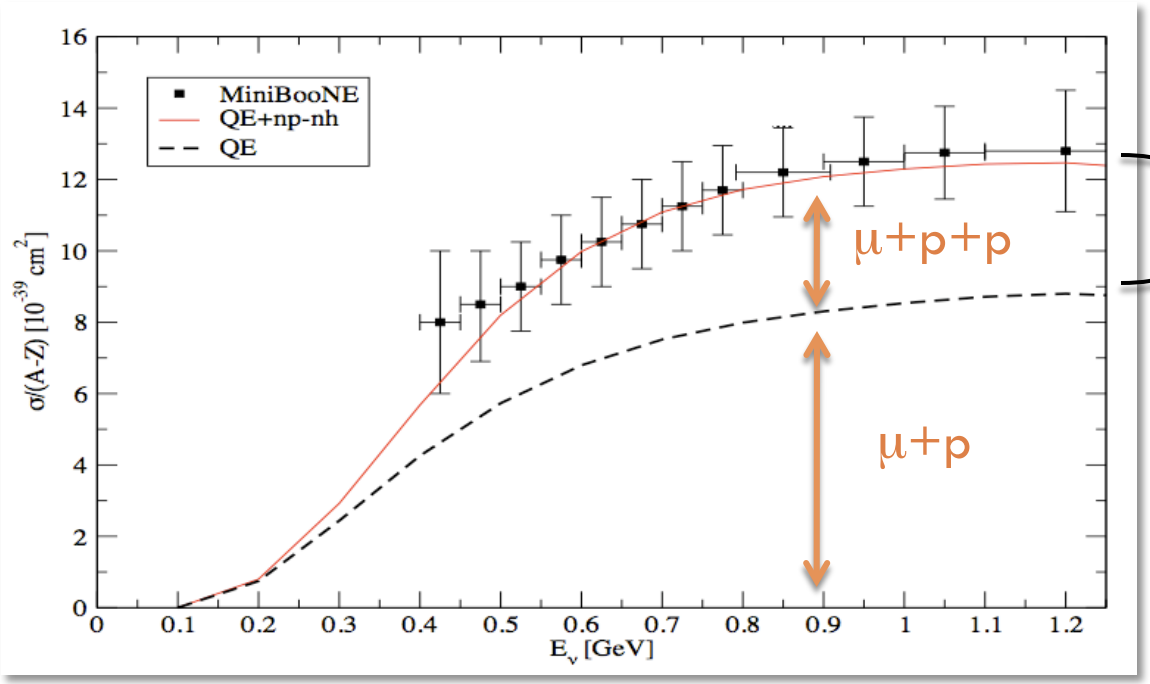

Martini *et al.*, PRC **80**, 065001 (2009)

add'l nuclear processes contribute ~40% more σ at these energies and 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?

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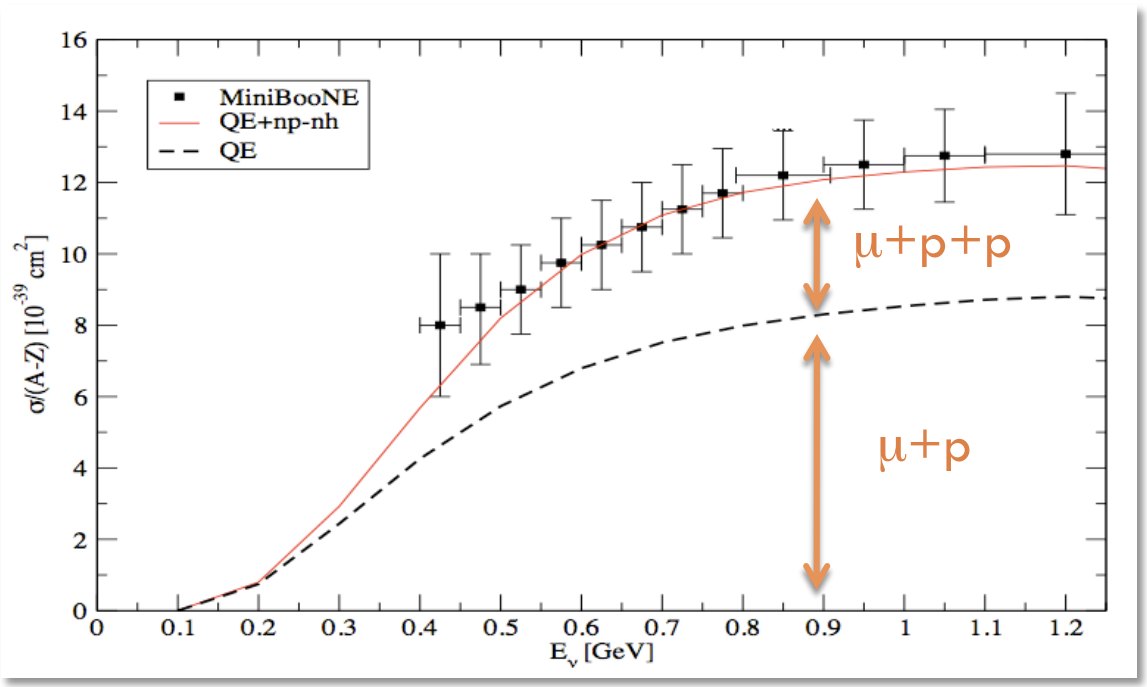


Martini *et al.*, PRC **80**, 065001 (2009)

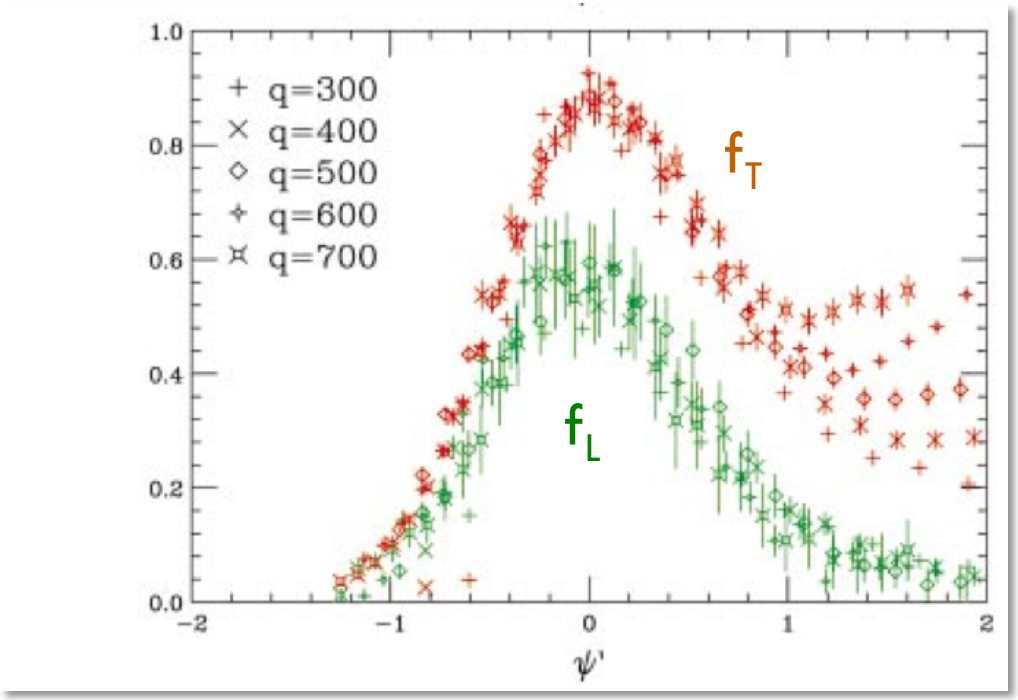
- could this explain the difference between MiniBooNE & NOMAD?

jury is still out on this

need to be clear what we mean by "QE" when scattering off nuclear targets!

Electron QE Scattering

- supporting evidence from electron QE scattering
  (J. Carlson, G. Garvey)



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

- **longitudinal** part of σ_{QE} can be described in terms of scattering off independent nucleons
- in contrast, a significant increase observed in **transverse** component
  (can be explained by SRC and 2-body currents)
- has been known for over a decade, seemingly forgotten
- implies that there should also be a corresponding transverse enhancement in ν QE scattering!

New Approach

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

- Nieves *et al.*, arXiv:1106.5374 [hep-ph]
- Bodek *et al.*, arXiv:1106.0340 [hep-ph]
- Amaro, *et al.*, arXiv:1104.5446 [nucl-th]
- Antonov, *et al.*, arXiv:1104.0125
- Benhar, *et al.*, arXiv:1103.0987 [nucl-th]
- Meucci, *et al.*, Phys. Rev. **C83**, 064614 (2011)
- Ankowski, *et al.*, Phys. Rev. **C83**, 054616 (2011)
- Nieves, *et al.*, Phys. Rev. **C83**, 045501 (2011)
- Amaro, *et al.*, arXiv:1012.4265 [hep-ex]
- Alvarez-Ruso, arXiv:1012.3871[nucl-th]
- Benhar, arXiv:1012.2032 [nucl-th]
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- Amaro, *et al.*, Phys. Lett **B696**, 151 (2011)
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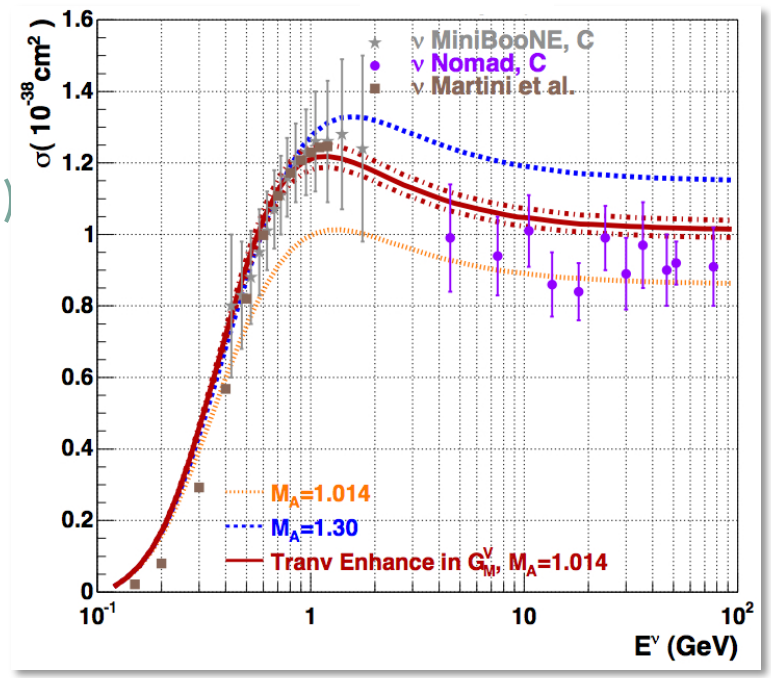
(work to incorporate increased transverse response from e^- A. Bodek, parallel 2E)

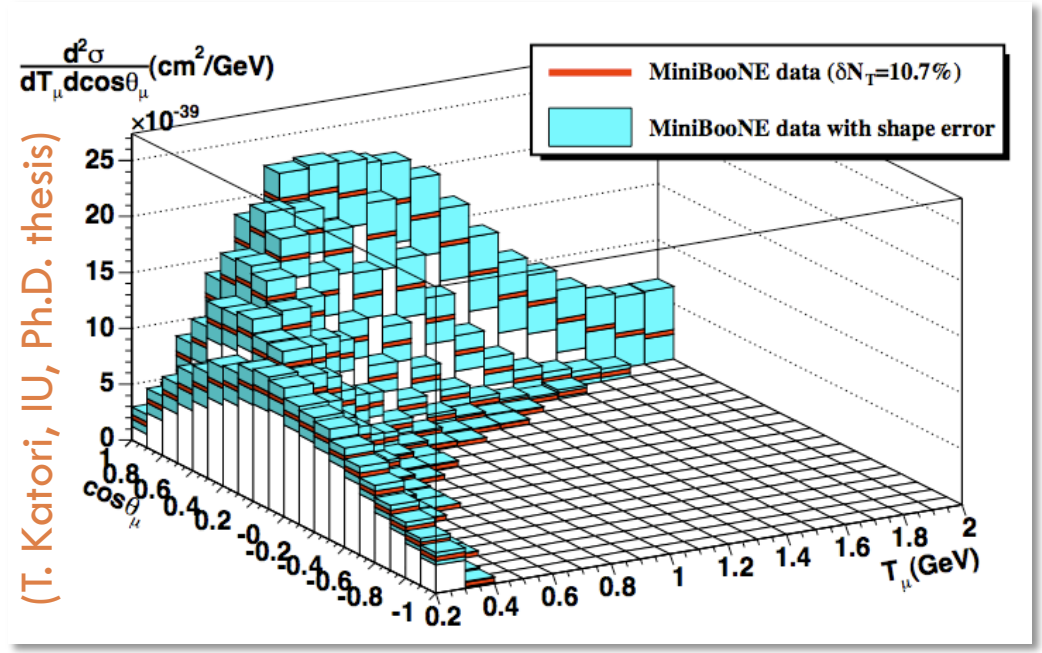


Moving Forward

- 146,000 ν_μ "QE" events
  (currently world's largest sample)
- 1st double differential σ's (from MiniBooNE)

  $d^2\sigma/dT_\mu d\theta_\mu$
- historically, never had enough statistics to do this

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

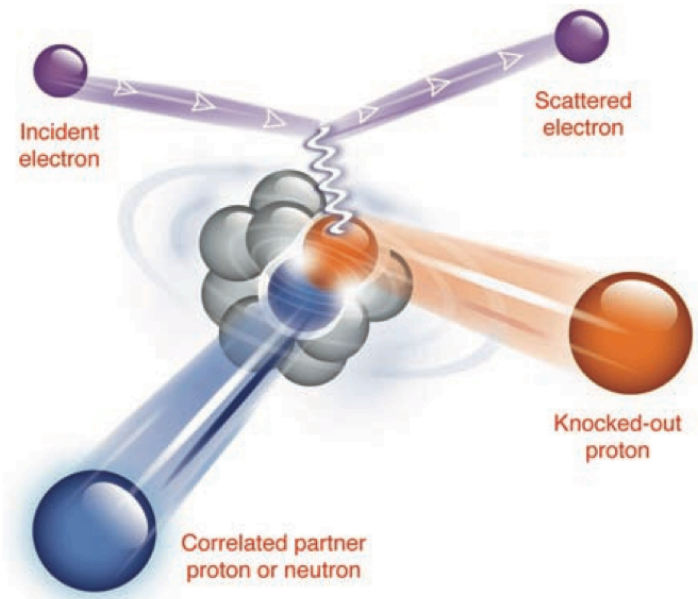


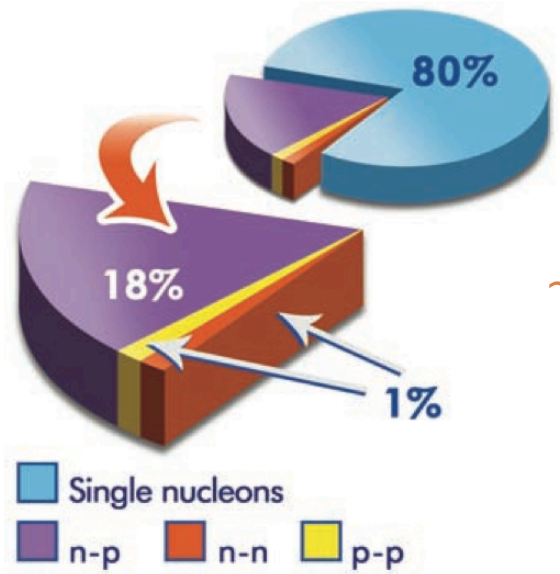
- provides much richer info than $\sigma(E_\nu)$ & less model-dependent
- posing a formidable challenge for new nuclear model calcs
  (need more data like this … not only μ but also measurements of p kinematics!)

wish list

Direct Evidence

- e^- scattering experiments have already provided evidence for SRC
  *big splash in Science magazine: R. Subedi et al., Science **320**, 1476 (2008)*

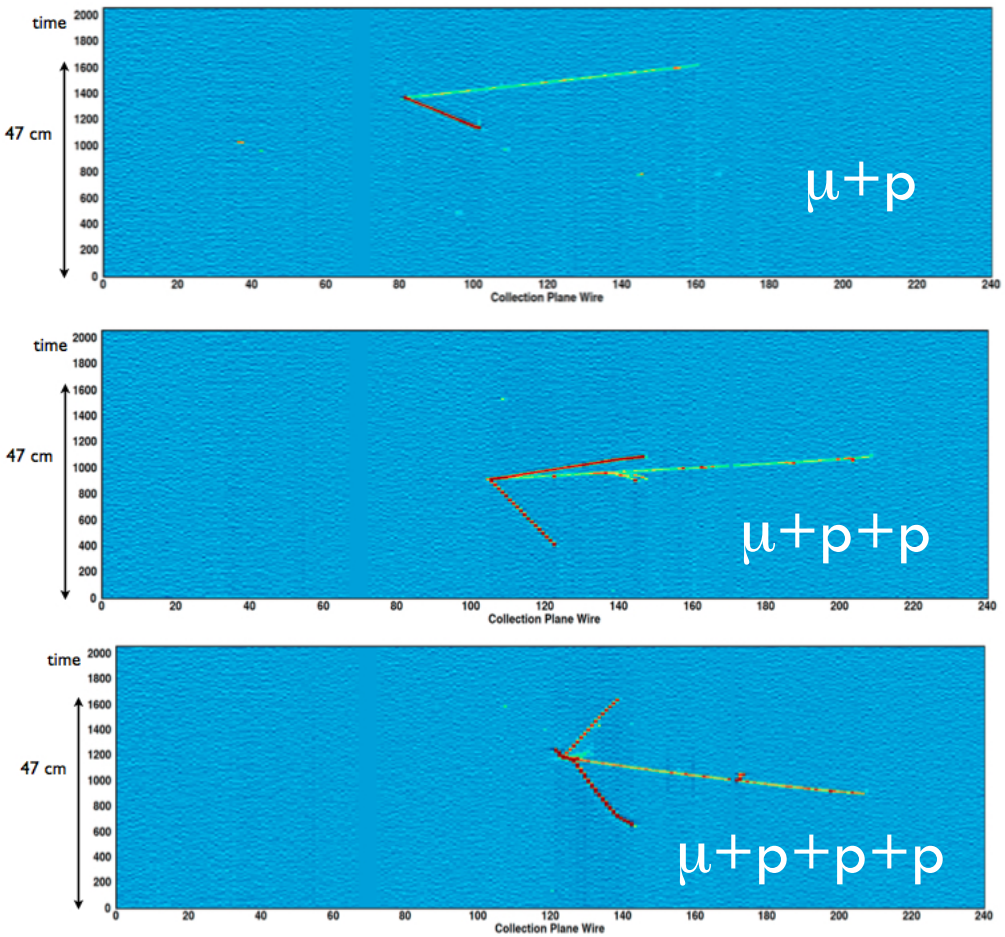




~20% of nucleons in carbon are in a correlated state

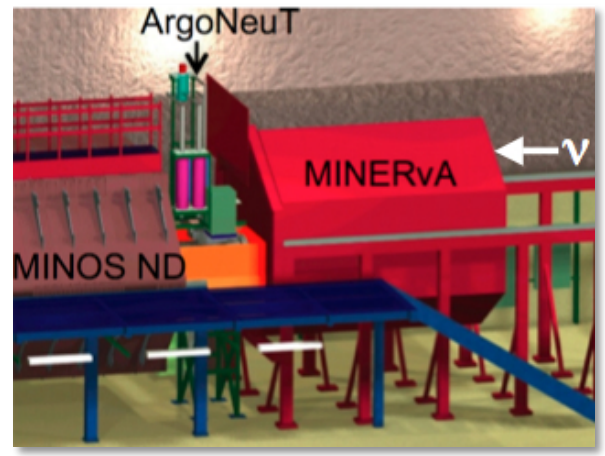
- direct measurement of multi-nucleon final states in a ν detector with low thresholds could play an important role in quantifying scattering from such correlated nucleon states (NOMAD, Veltri *et al.*, NP **B609**, 255 (2001))

QE Scattering in a Liquid Argon TPC



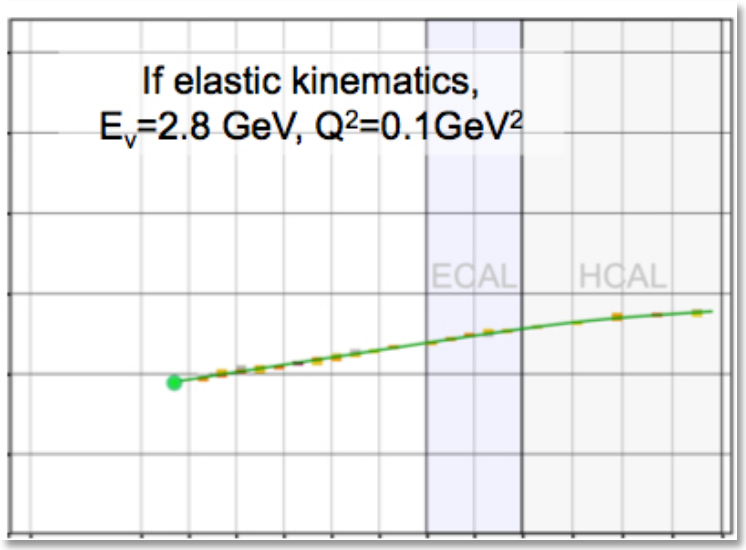
J. Spitz, arXiv:1009.2515 [hep-ex]

- **ArgoNeut** = 175L LAr TPC in NuMI beam (2009-2010)



- ν interactions in exquisite detail
  (ex., can detect protons down to 50 MeV)
- plus data from **ICARUS, μBooNE**
- need to disentangle SRC from FSI

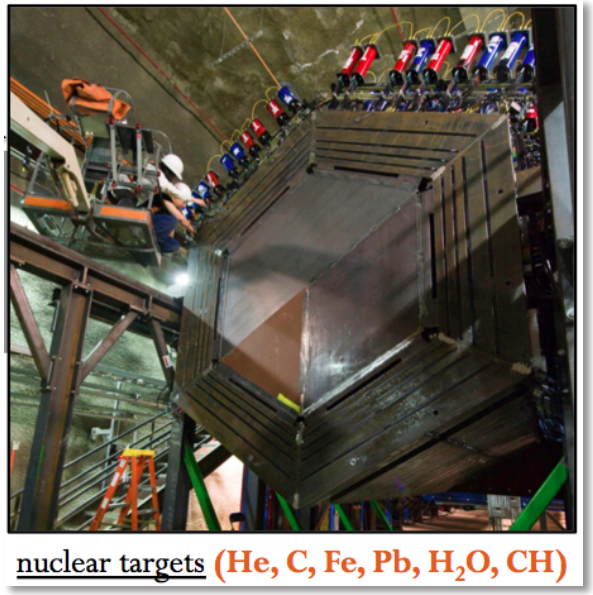
$\bar{\nu}$ QE at MINERνA!



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

- will pursue a broad range of σ_ν's with multiple beam E's and nuclear targets
  (much of focus up to now has been on O, C)
- starting data-taking with full detector in Mar 2010

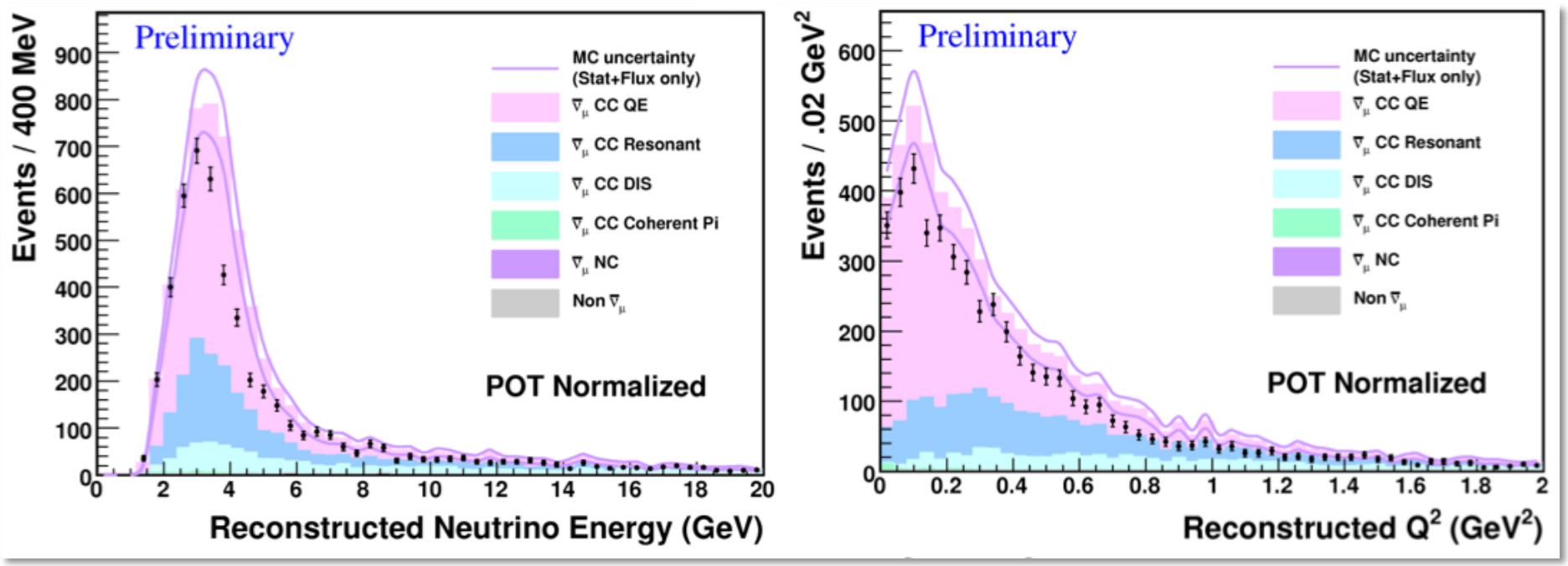
(R. Ransome, parallel 2E)



- starting with $\bar{\nu}$ QE analysis; for a tracking detector has some advantages: unlike ν case:
  - *less sensitive to details of the event selection (n in f.s.)*
  - *less ambiguity as to whether or not selection includes extra effects of nucleon-nucleon correlations (produces an n+n in f.s.)*

$\overline{\nu}$ QE at MINERνA

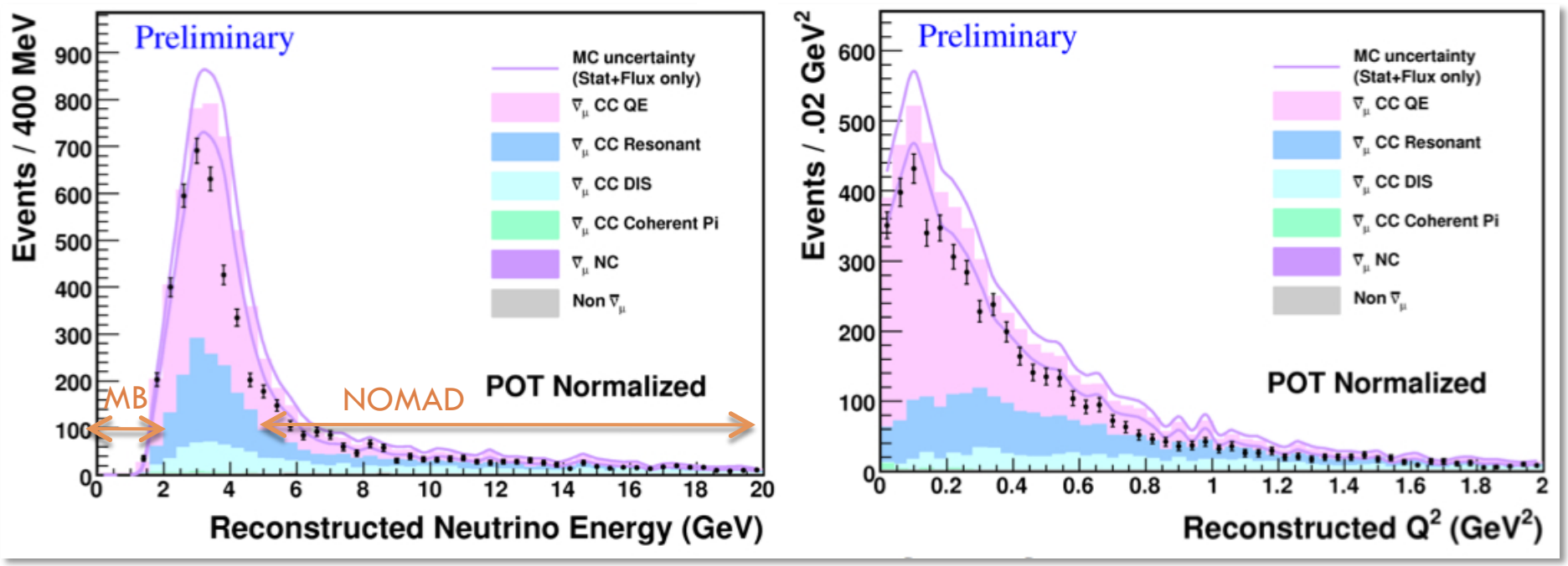
(K, McFarland, NuInt11)



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

$\overline{\nu}$ QE at MINERνA

(K, McFarland, NuInt11)

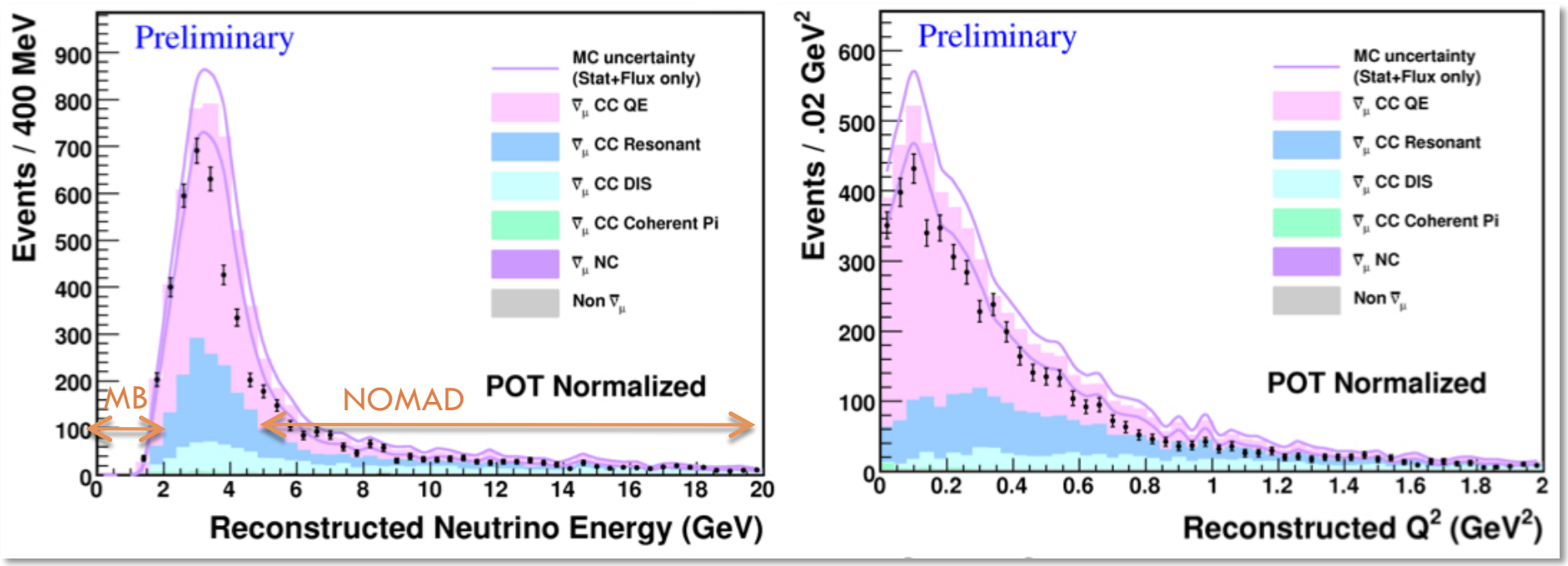


- $\overline{\nu}_\mu$ QE interactions in CH across a large energy range

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

$\overline{\nu}$ QE at MINERνA

(K, McFarland, NuInt11)



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

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

- observe an event **deficit;** not fully understood

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

determining ν flux using special run data, add'l stats, ν QE, different selections

This is Important

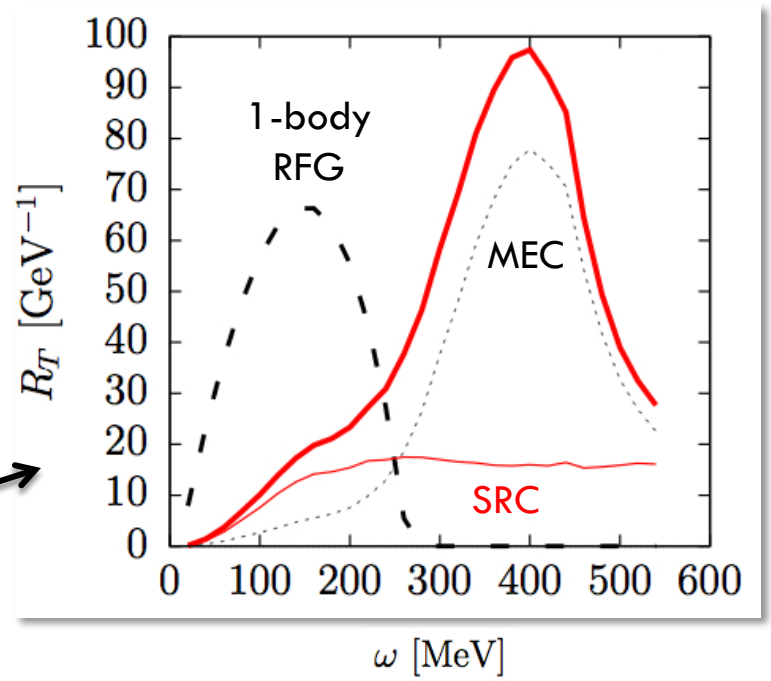
- something as simple as QE scattering is not so simple
  - nuclear effects can significantly increase the cross section
  - idea that could be missing ~40% of σ is a big deal!

- good news: expect larger event yields
- bad news: need to understand/simulate the underlying physics

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

  (at worse, could produce a spurious $\not{C}\not{P}$ effect)

- can impact E_ν reconstruction



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

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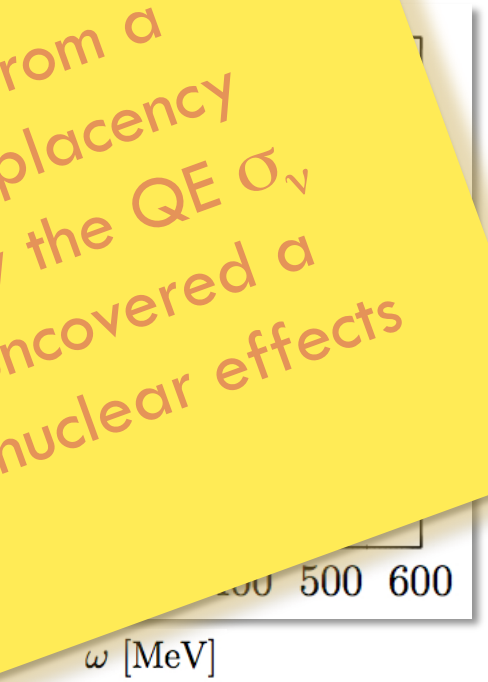
- effects will be different for ν vs.
  (at worse, could produce a spurious ∅P effect)
- can impact E_ν reconstruction

in the past year, have gone from a general complacency that we know the QE σ_ν to having uncovered a host of rich nuclear effects

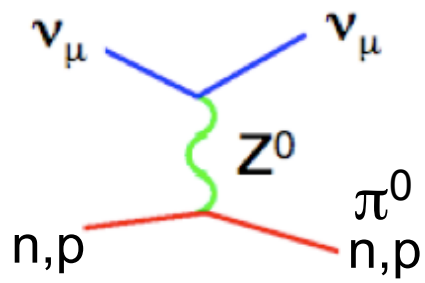


al., PRC **82**, 044601 (2010)

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

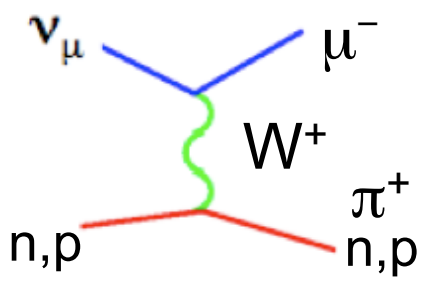
- NC π^0 production

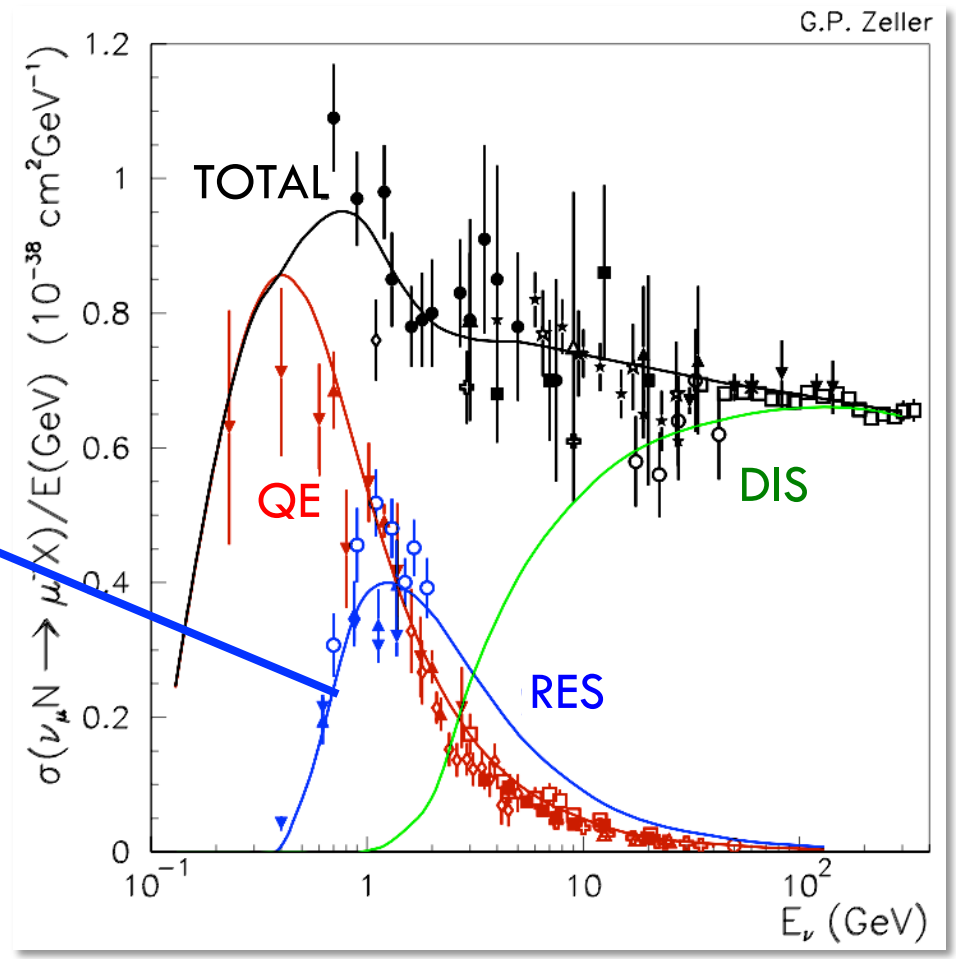
  (background for ν_e appearance)



- CC π^+, π^0 production

  (background for ν_μ disappearance)





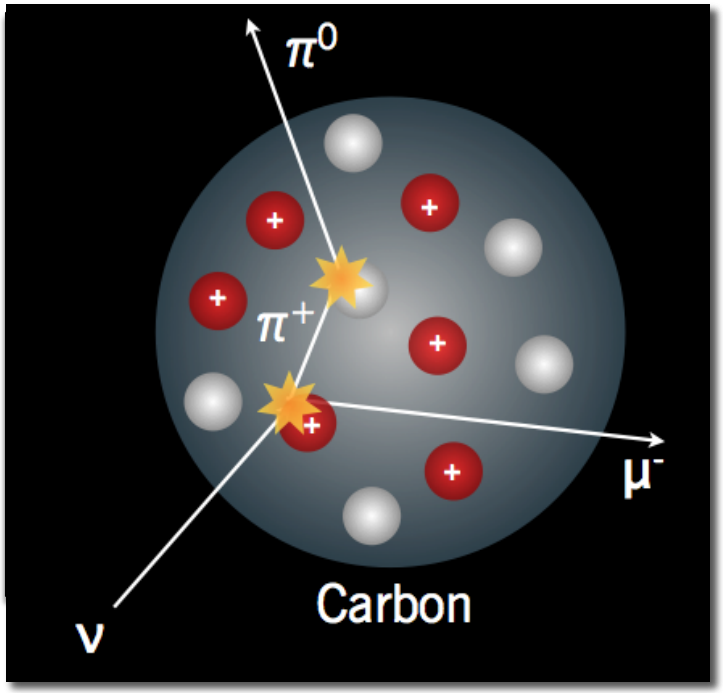
- important for different reasons → backgrounds

Final State Effects

- new appreciation for nuclear effects in this region as well

"final state interactions (FSI)"

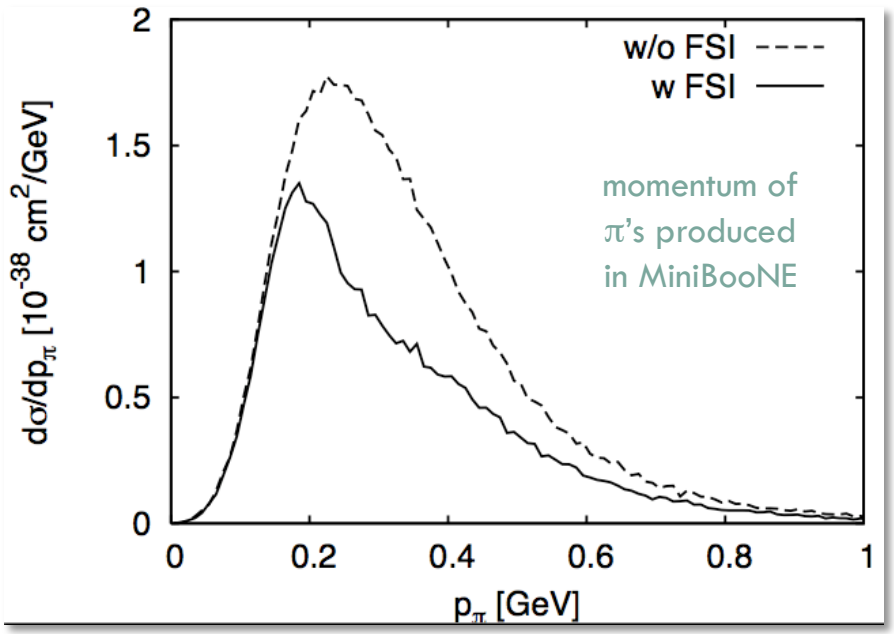
- once a hadron is produced, is has to make it out of the target nucleus
- nucleon rescattering
- π absorption & charge exchange



- have to worry about these effects
- for ν, is a subject that needs more attention *(U. Mosel, parallel 5F, Thursday)*

Final State Effects

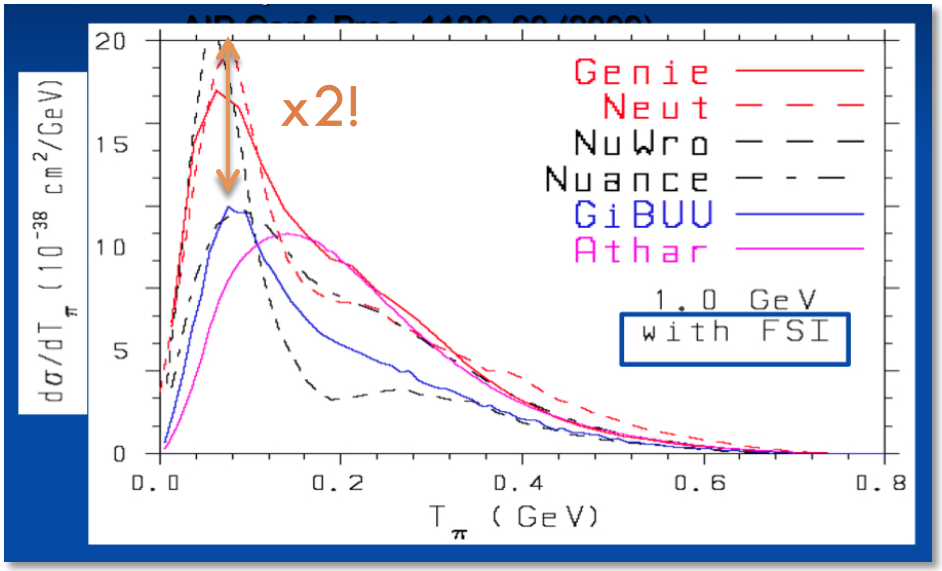
- distortions are large
- important for predicting π^0 bkgs in ν_e searches



(T. Leitner)

- and predictions of their effects can vary

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



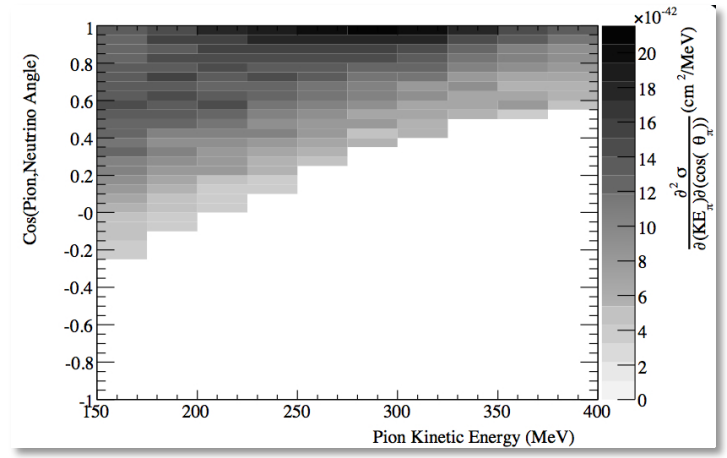
- new FSI model work
  - *GENIE (S. Dytman), GiBUU (U. Mosel), NEUT (P. dePerio)*
- understanding π kinems is important
  - *has never been carefully studied in ν scattering*

Pion Production in MiniBooNE

- extensive program to measure kinematics
  (report what is directly observed to reduce model dep)

(E. Zimmerman, parallel 1E)

- Phys. Rev. **D81**, 013005 (2010)
- Phys. Rev. **D83**, 052009 (2011)
- Phys. Rev. **D83**, 052007 (2011)



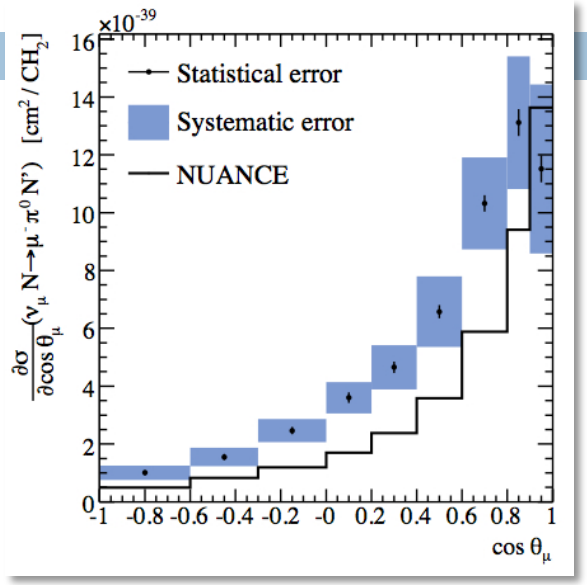
having this type of info is new!

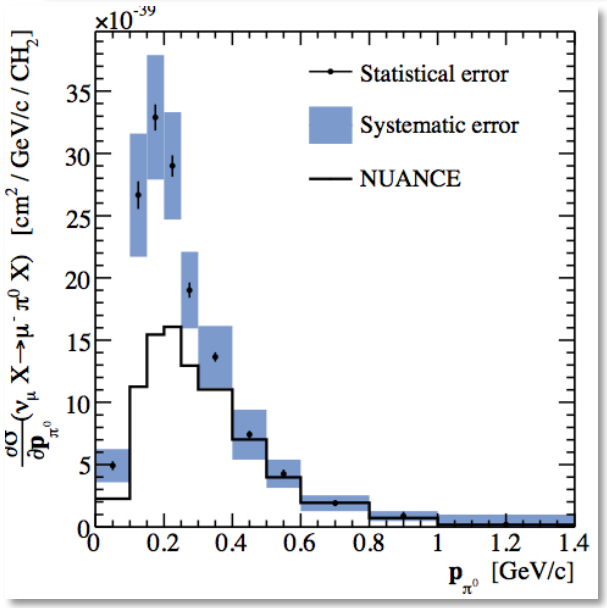
measurement	NC π^0	CC π^0	CC π^+
$\sigma(E_\nu)$		X	X
$d\sigma/dQ^2$		X	X
$d\sigma/dp_\pi$	X	X	X
$d\sigma/d\cos\theta_\pi$	X	X	X
$d\sigma/dT_\mu$		X	X
$d\sigma/d\cos\theta_\mu$		X	X
$d^2\sigma/dT_\mu d\cos\theta_\mu$			X
$d^2\sigma/dT\pi d\cos\theta_\pi$			X

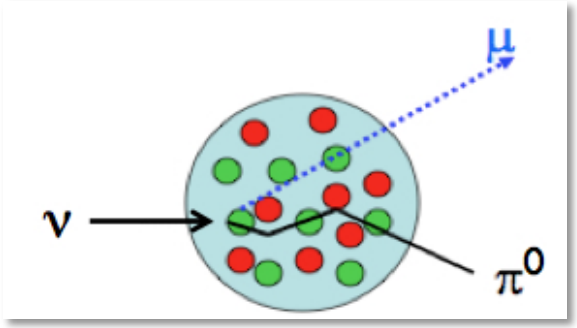
- 16 different measurements!
- all of this data available online

http://www-boone.fnal.gov/for_physicists/data_release/

Example: CC π^0







- 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

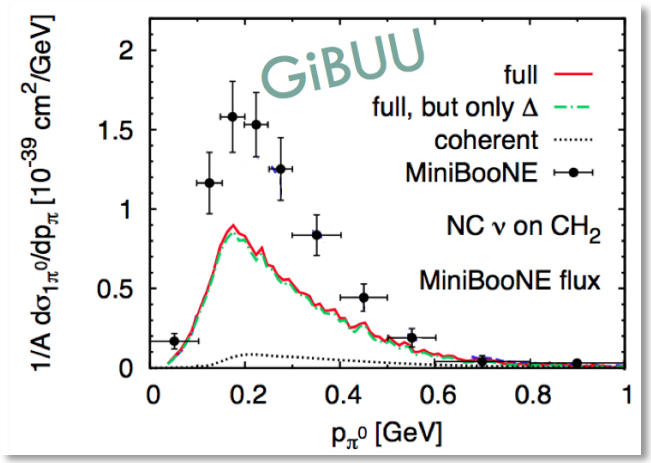
- most comprehensive study of CC π^0 to date

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

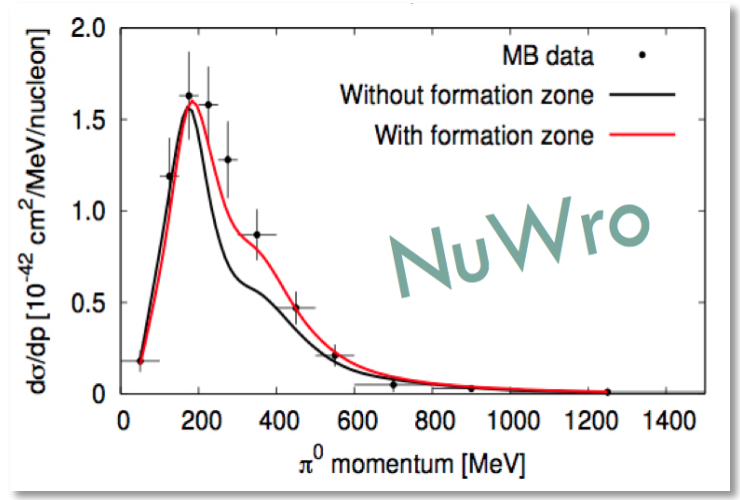
FSI Models

- data in heavy use by model builders

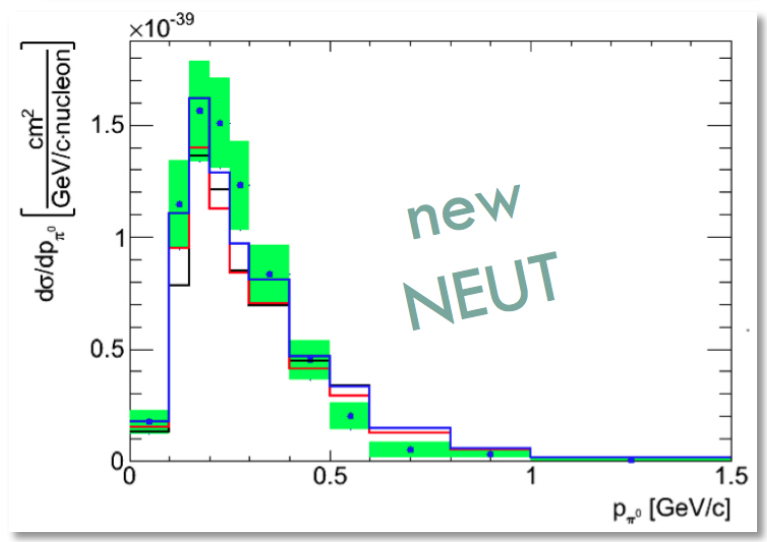
(U. Mosel) arXiv:1106.1344 [hep-ph]



(T. Golan)



(P. dePerio)



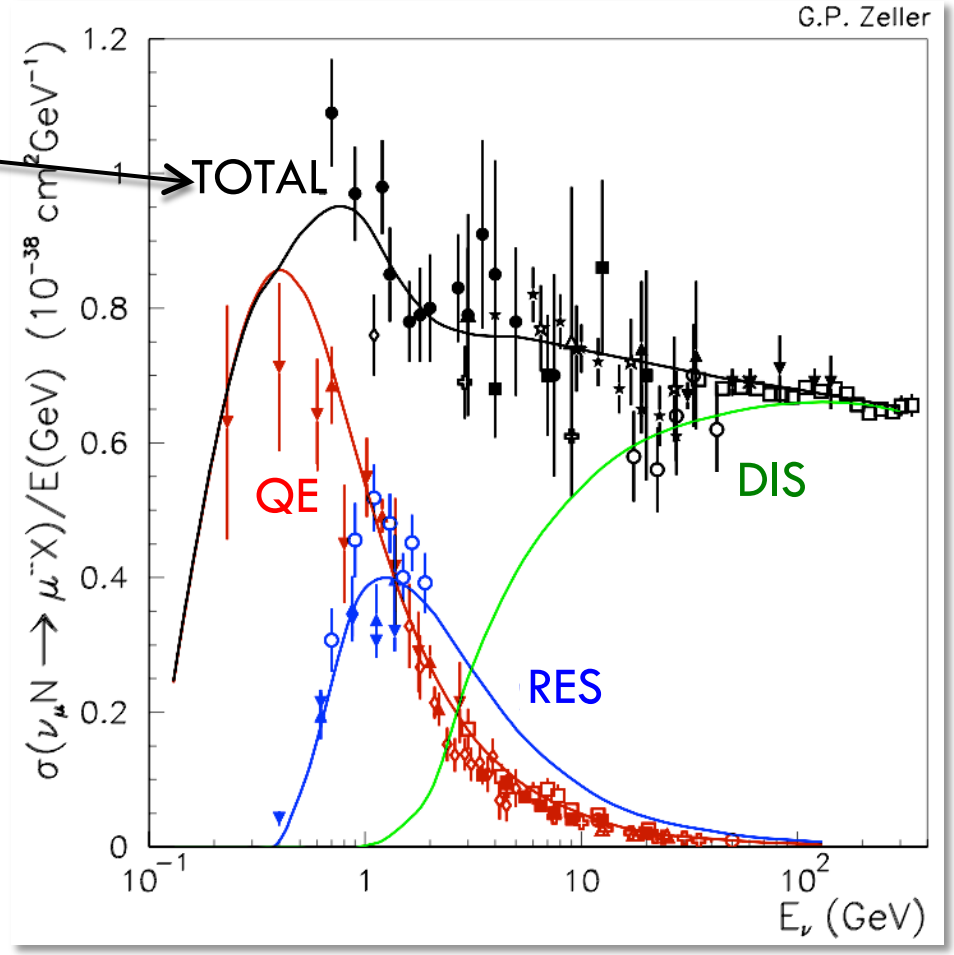
- need measurements on other targets
- and at higher energies
  - ArgoNeuT, ICARUS, μBooNE
  - MINERνA

wish list

- could use help from nuclear physicists!

Putting this All Together

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

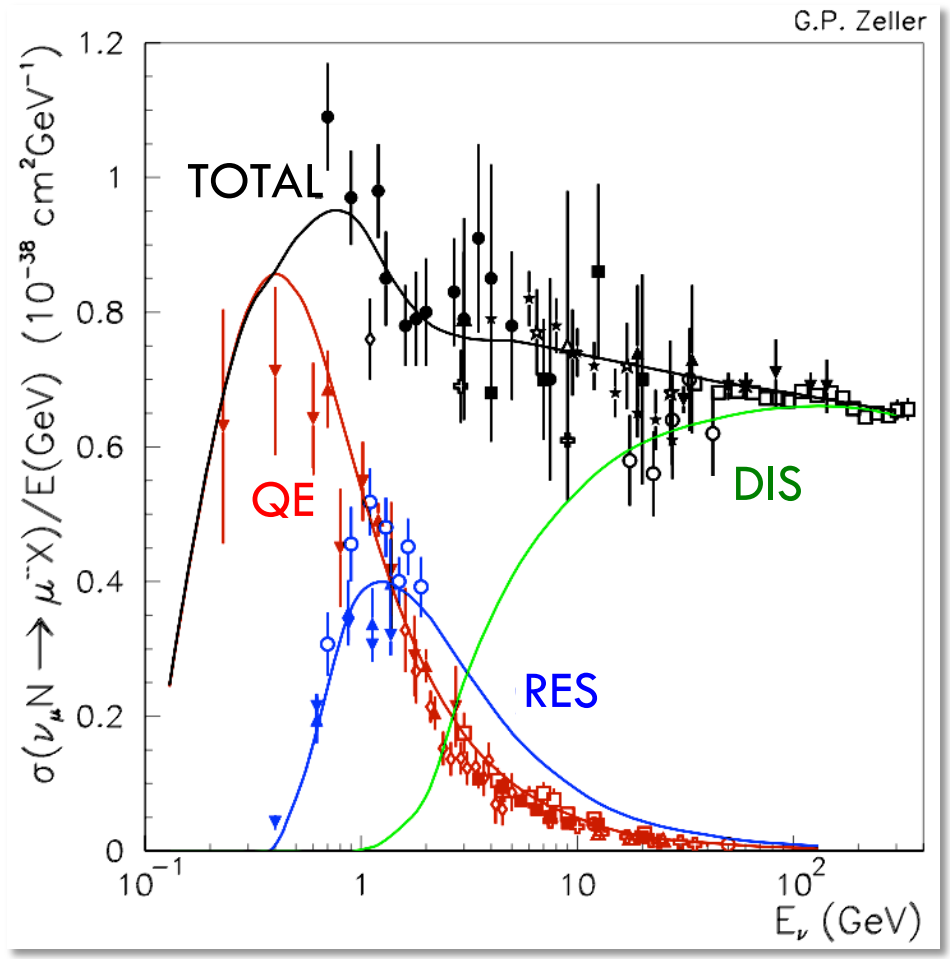


CC Inclusive Cross Section

- advantage is that measures everything all at once:

+ QE
+ nucleon-nucleon correlations
+ π production
+ π absorption
+ DIS …

- can do so with very high purity samples (events with a μ)

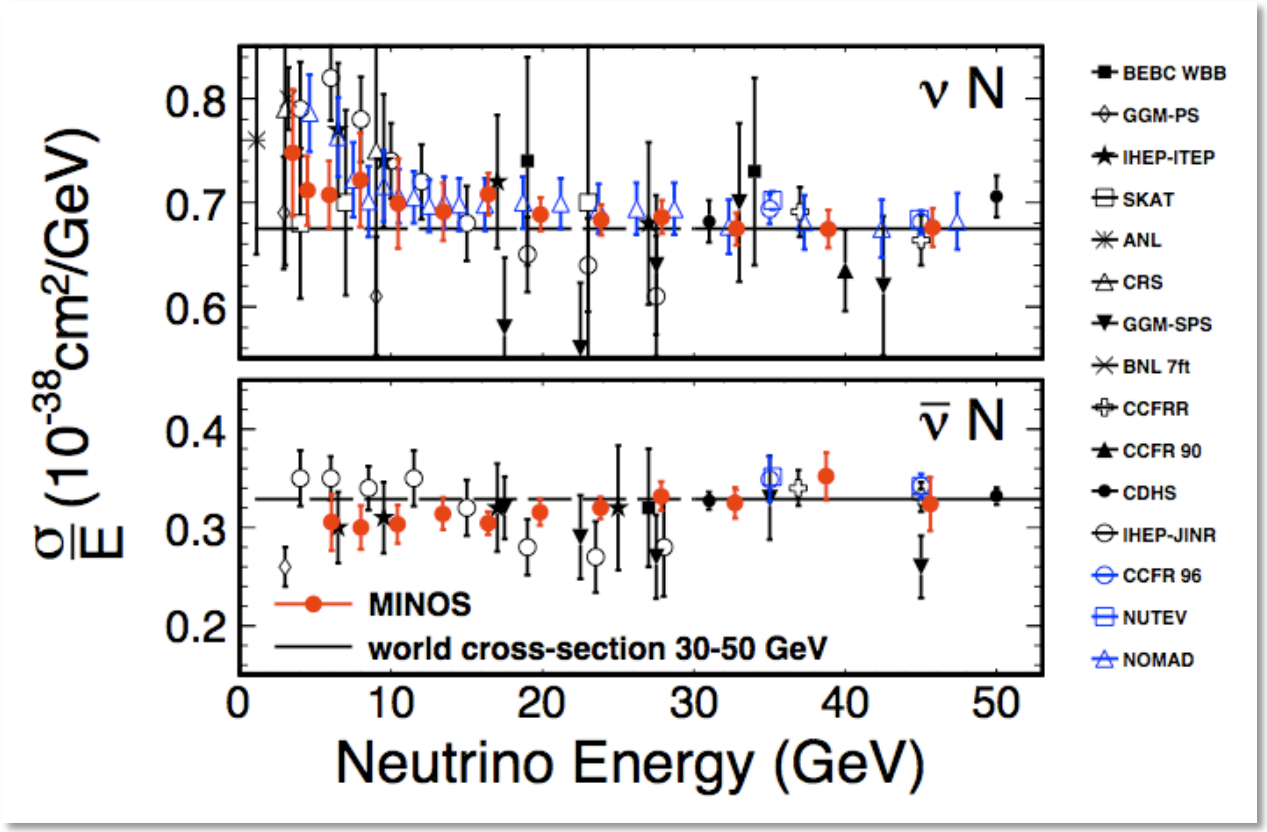


clear need for improved measurements $E_\nu \lesssim 50$ GeV

CC Inclusive Cross Section

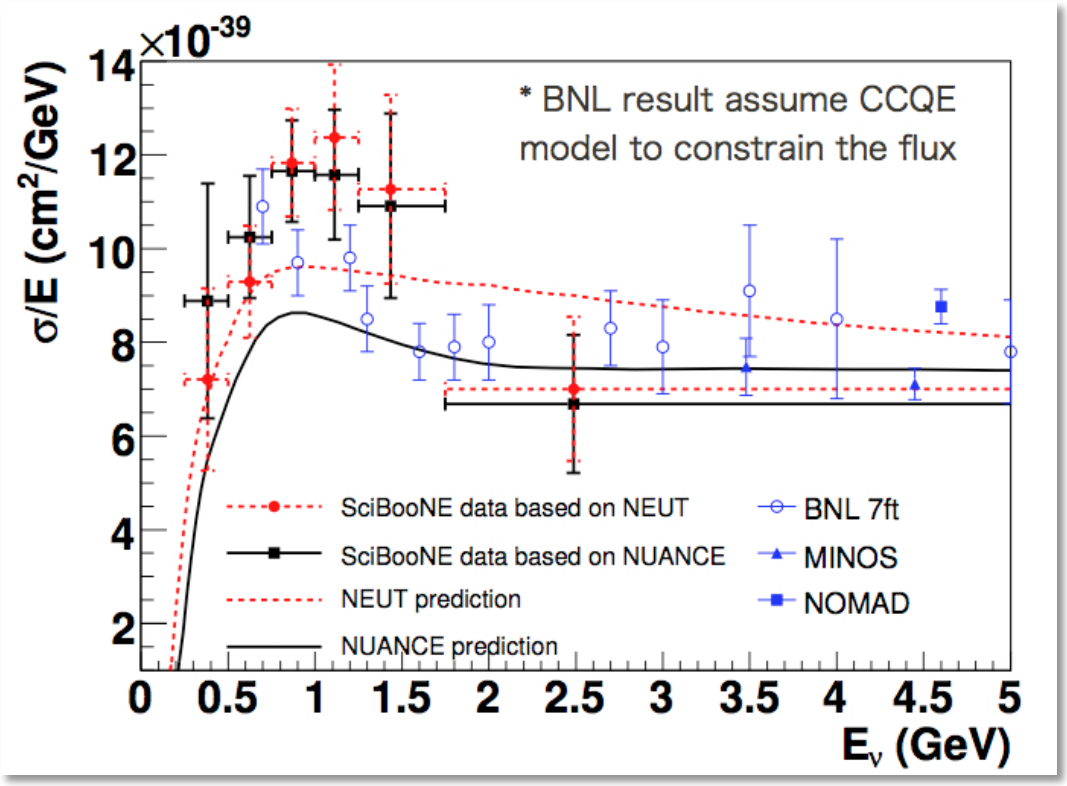
$\nu_\mu N \rightarrow \mu^- X$

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



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

CC Inclusive at SciBooNE



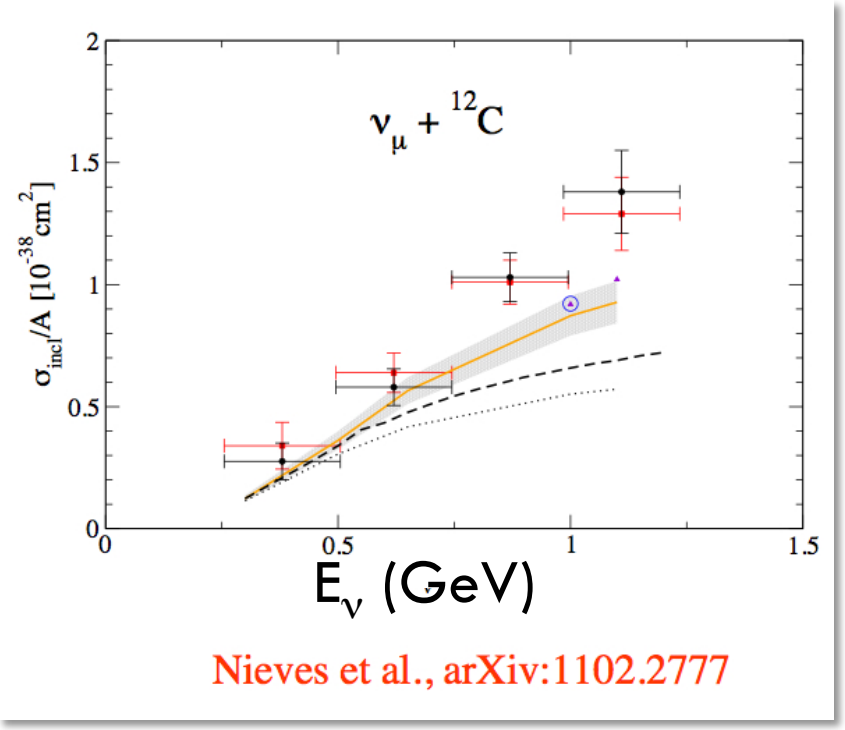
Nakajima, *et al.*, PRD **83**, 012005 (2011)

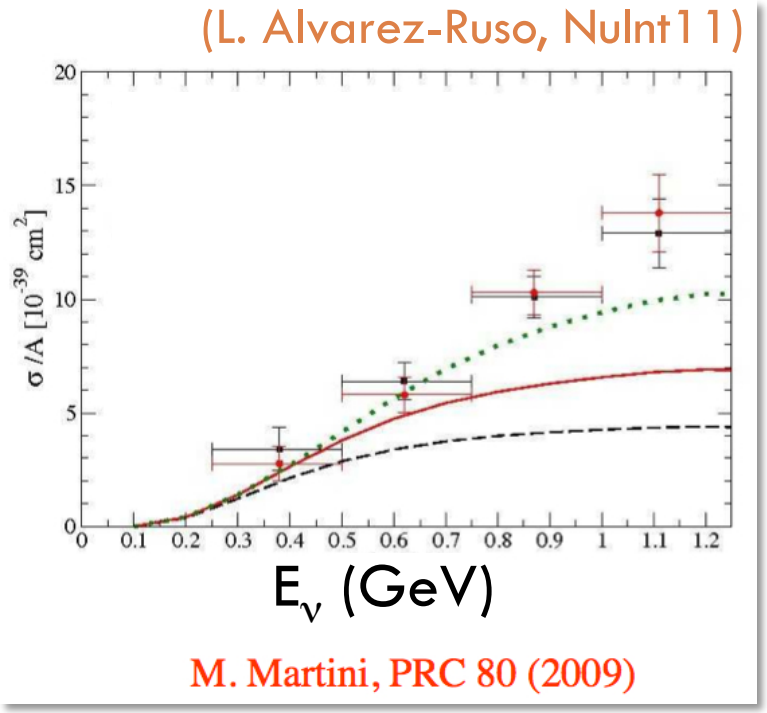
$\nu_\mu N \rightarrow \mu^- X$

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

SciBooNE Results in Use

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





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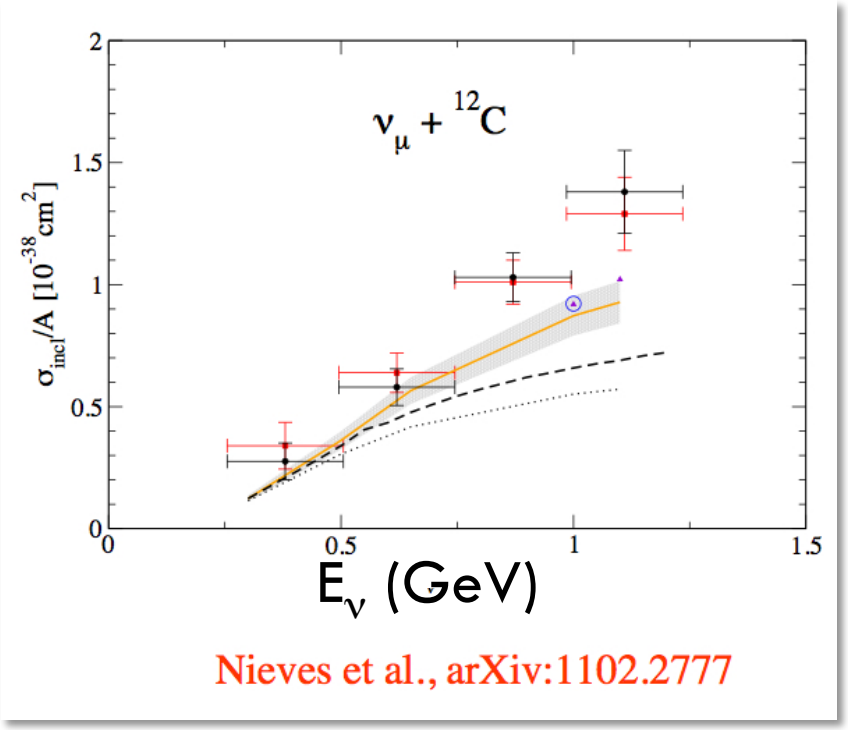

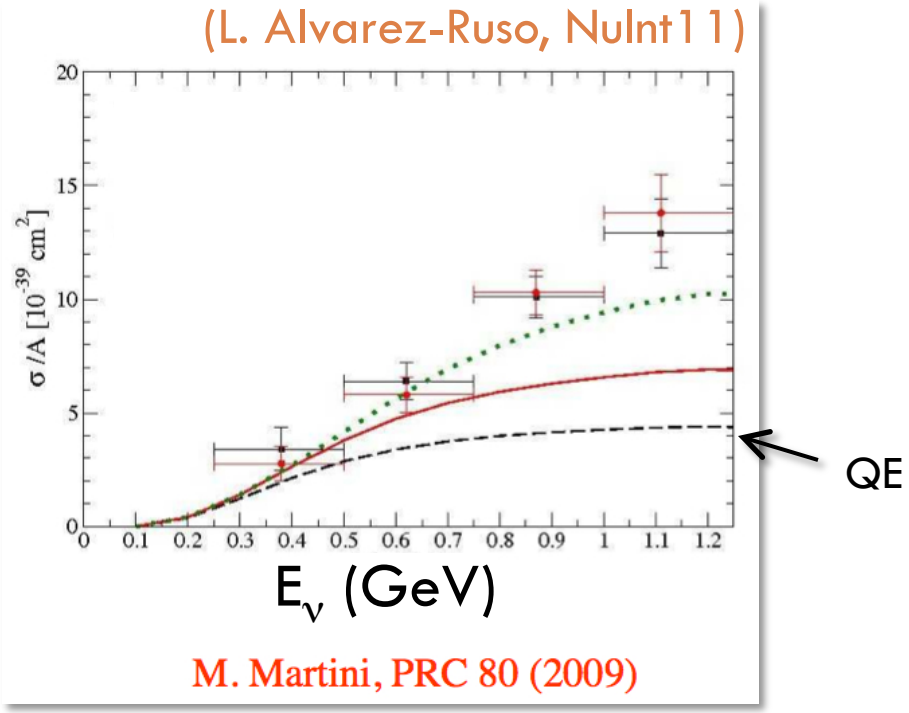

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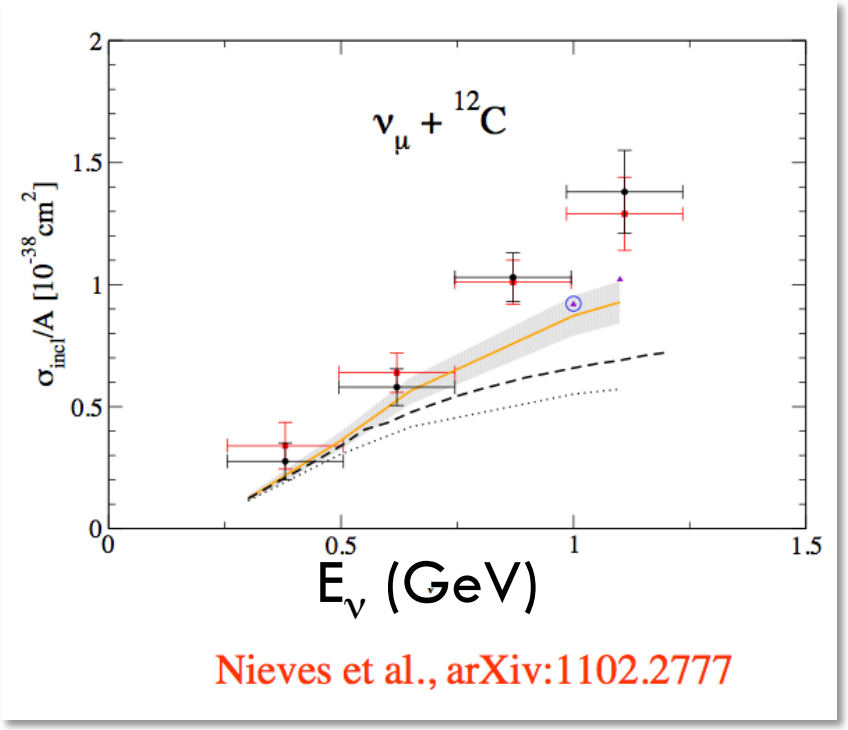

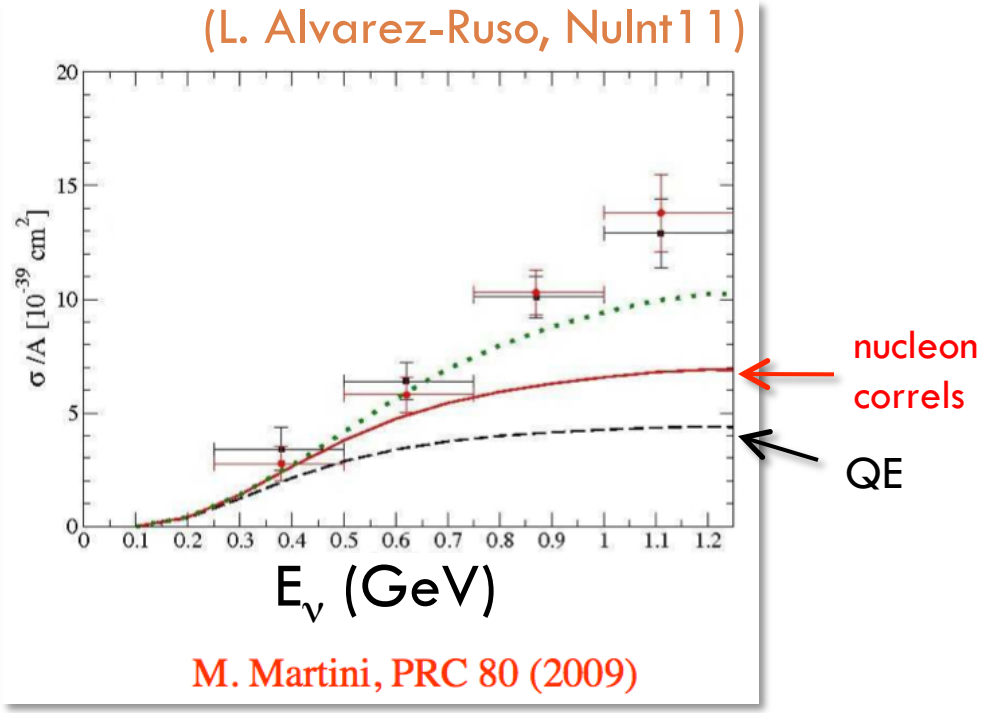

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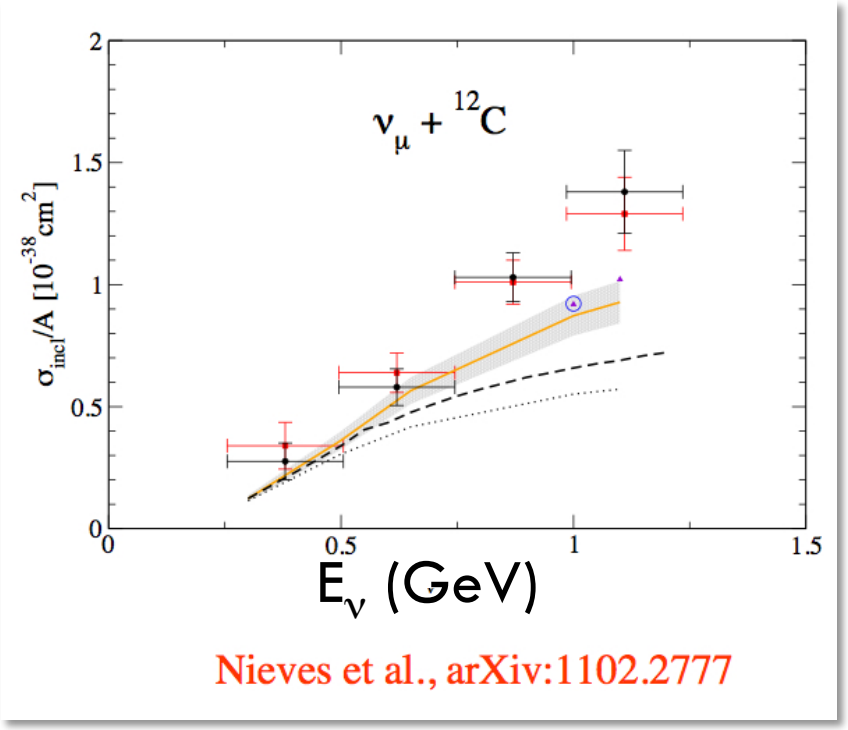

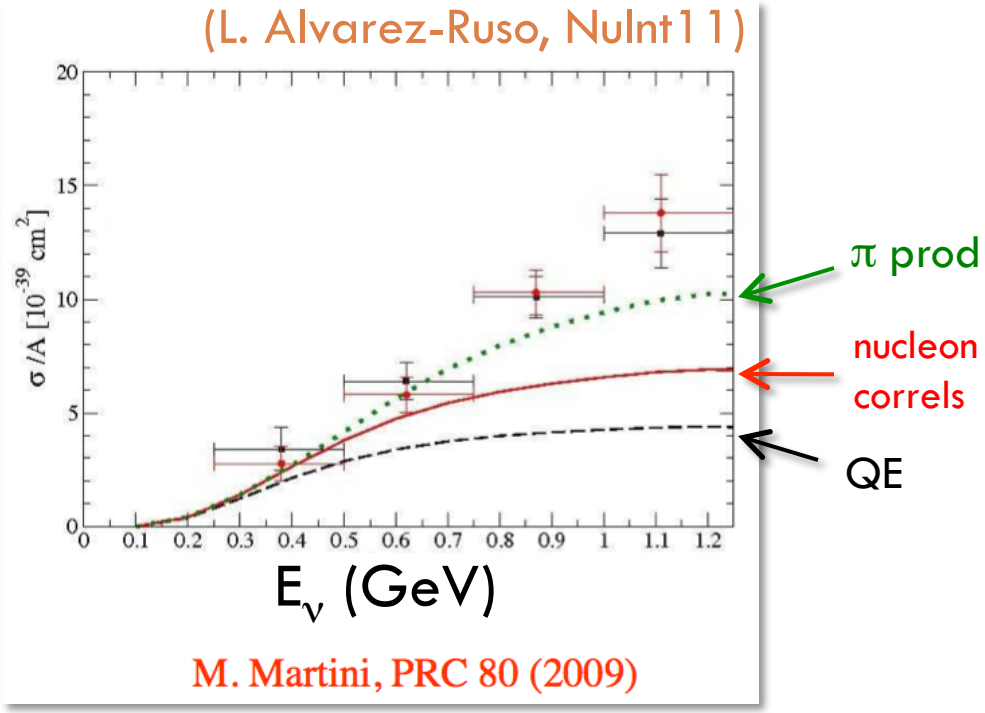

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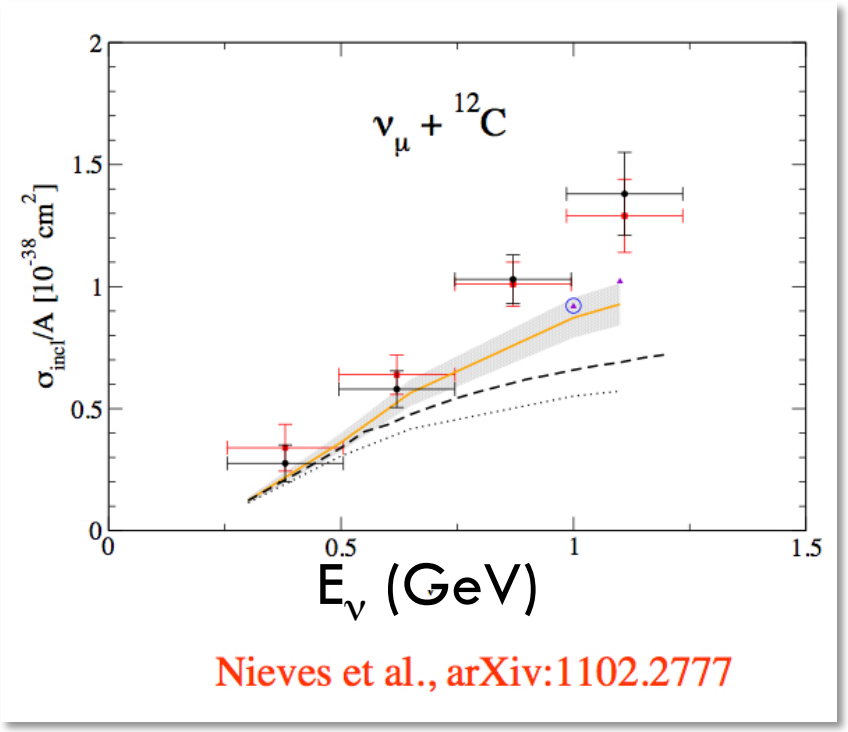
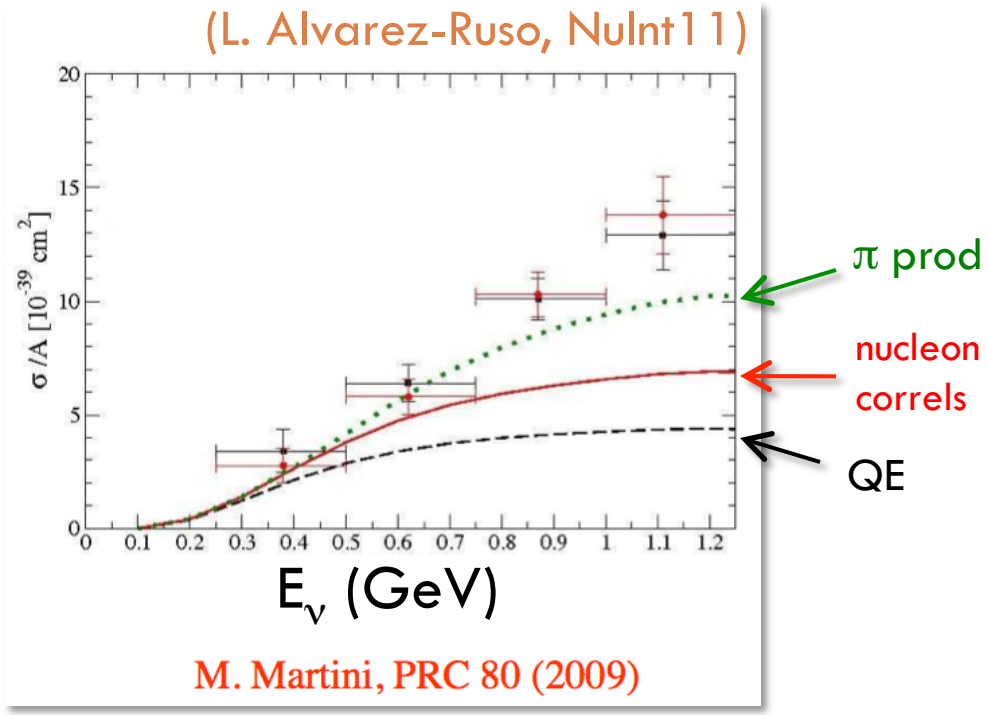


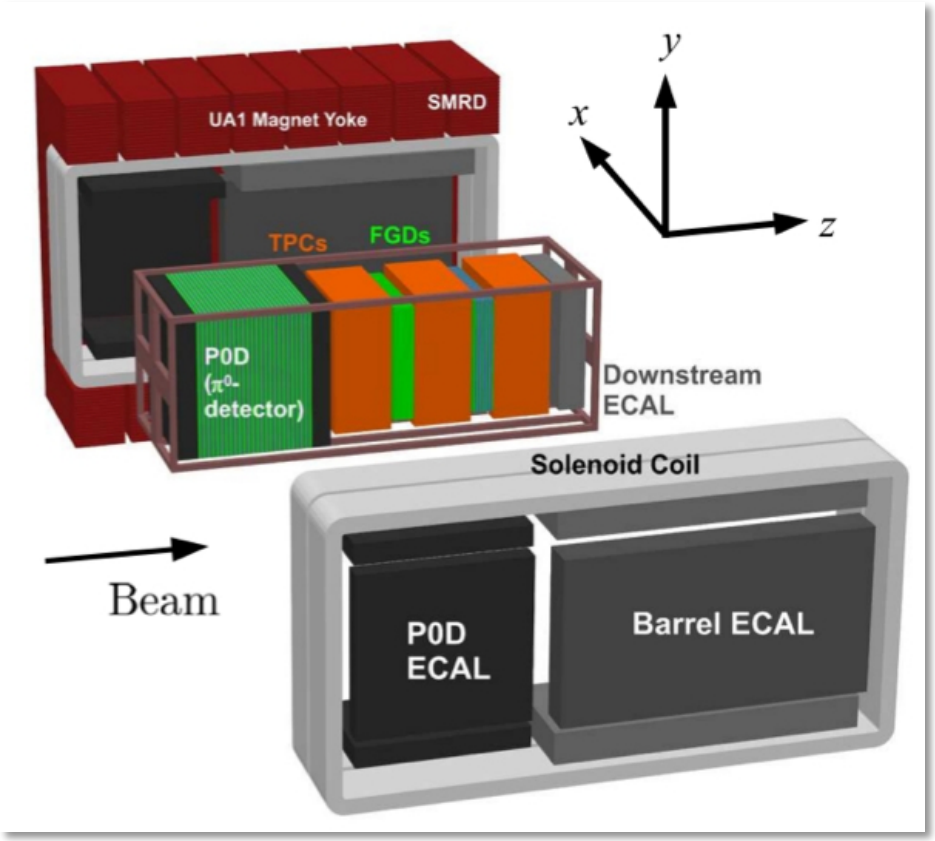


wish list

- comparisons need to be extended out to higher energies
- need kinematic measurements, e.g. $d^2\sigma/dT_\mu d\theta_\mu$ (ala QE)
- need measurements on different nuclei (FSI vs. nucleon correls)

CC Inclusive at T2K

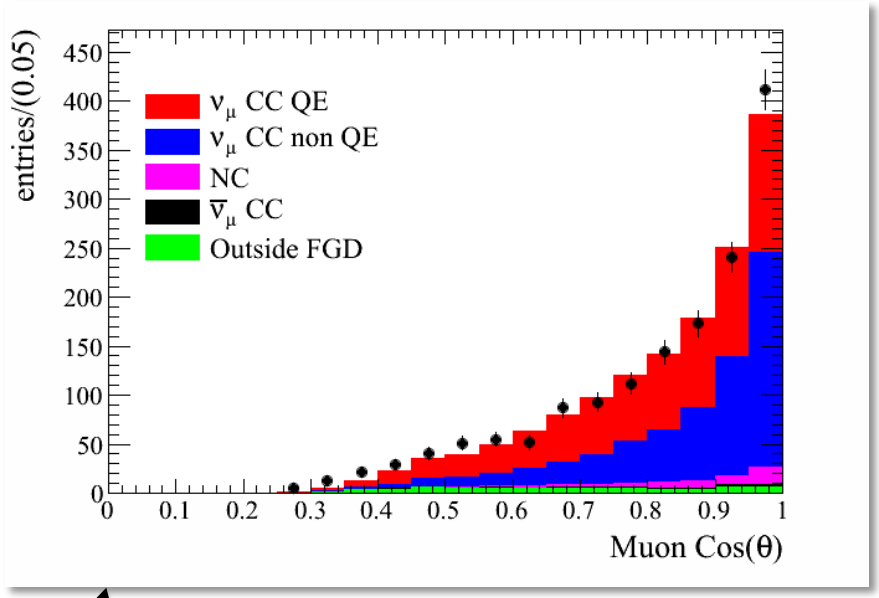
- ND280 off-axis detector began ν data-taking in March 2010
  (highlights importance of ND measurements which can weigh-in on these issues!)

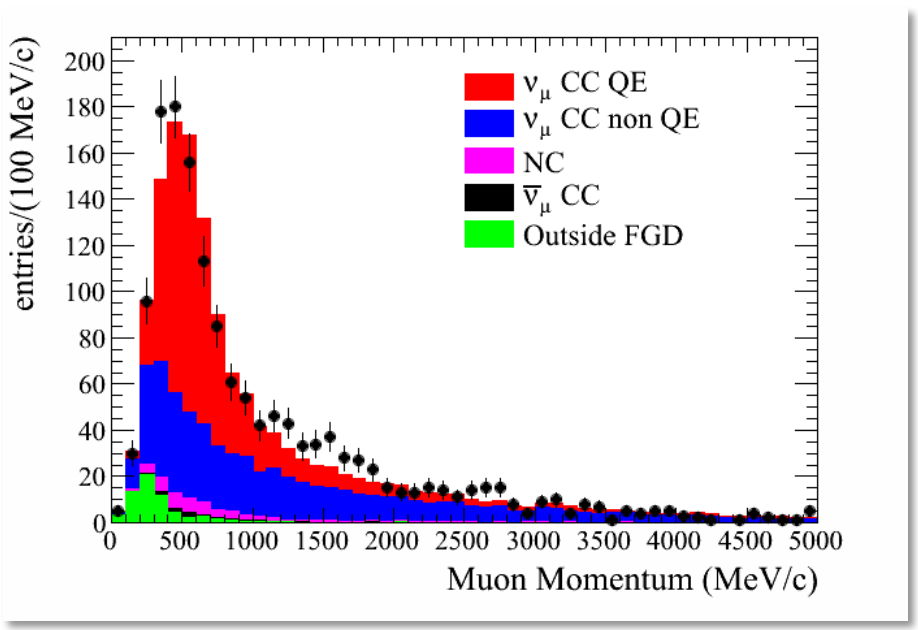


- low energy beam
  (very similar E_ν range to SB, MB)
- measurements on both C, O
- magnetized, fine-grained tracking detectors

CC Inclusive at T2K

- the first neutrino data from T2K ND has recently come out!





- ingredients for $d^2\sigma/dT_\mu d\theta_\mu$
- good agreement with NEUT
  (tuned to prior ν data from K2K, SB)

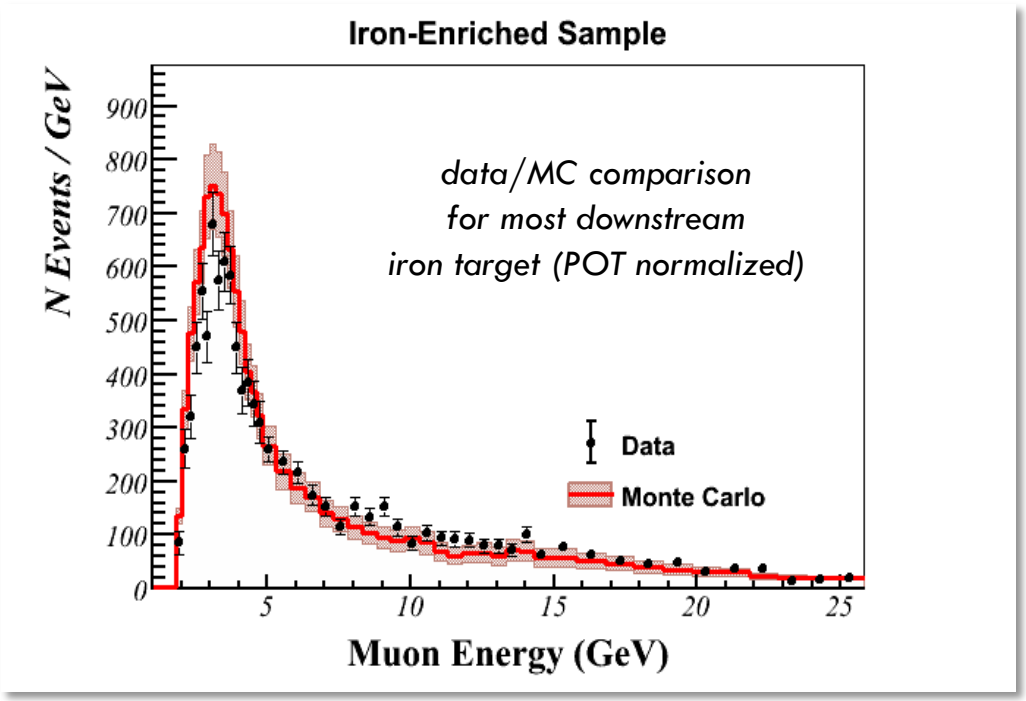
(B. Berger, parallel 2E)

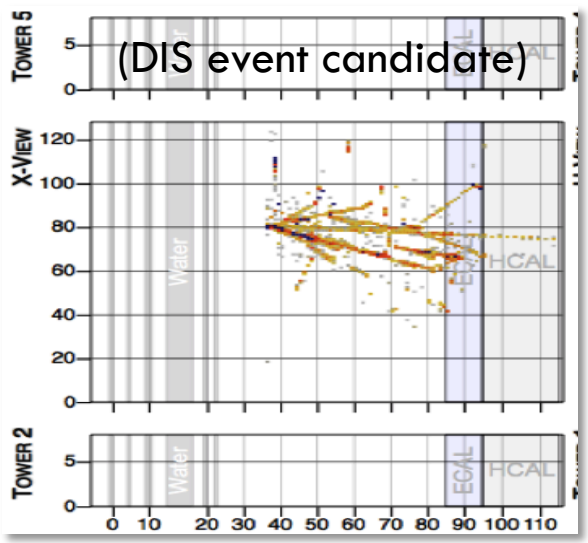
CC Inclusive at MINERνA

- one of 1st goals is to measure CC inclusive σ ratios for various nuclei across very large energy range *(will be a real power house!)*

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

MINERνA 1st glimpse!



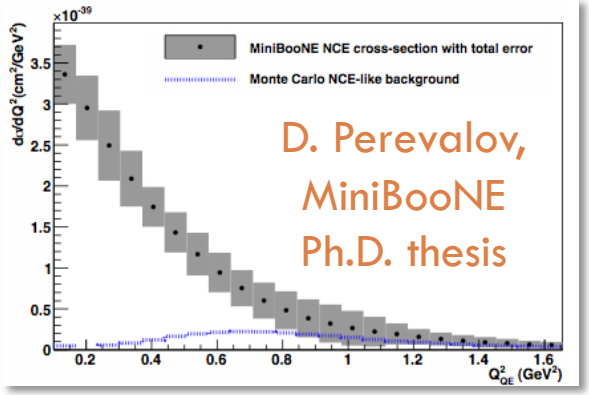


really nice data, plus … much more to come!

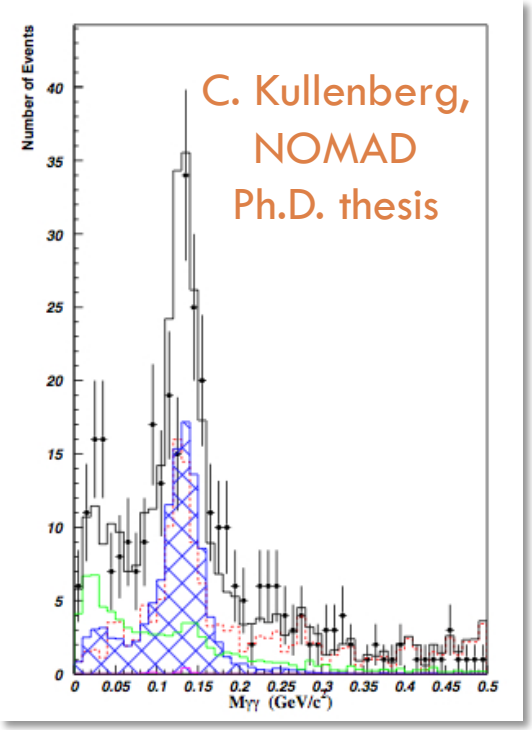
(R. Ransome, parallel 2E)

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. Cherdack, 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

- there has been a surge of new results on a variety of different ν interaction channels from multiple exps in an important E region *(few-GeV)*
  (K2K ND, MiniBooNE, MINOS ND, NOMAD, SciBooNE)

- what was supposed to be boiler-plate physics has turned out to be far from that

  - *nuclear effects are important!*

* need continued help from theory community to better understand impact of these effects

* need add'l experimental measurements to provide both confirmation and clarity
(ArgoNeuT, ICARUS, MicroBooNE, MINERνA, NOvA & T2K NDs)

- $d\sigma/dx_{obs}$ in favor of $\sigma(E_\nu)$
- antineutrinos too!