NEUTRINO-NUCLEUS MEASUREMENTS

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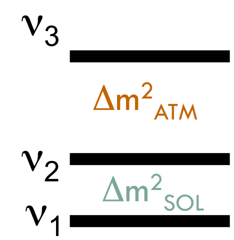
Hadrons in the Nuclear Medium Workshop at ECT*, Trento

May 15, 2012

- this is a topic that has gotten a lot more interesting over the past year
- will focus on results from the MiniBooNE experiment
  (… from an experimentalists point of view)

Neutrino Physics

- there are some big questions we will be trying to answer; forthcoming experiments will largely be focused on:



  - measuring the neutrino masses
  - determining whether or not neutrinos are their own anti-particles
  - measuring ν oscillation parameters more-precisely
  - determining the ν mass ordering
  - discovering whether ν's violate CP

  (mass ordering and CP: enabled now that we know θ_{13} is non-zero)

  (last three: long-baseline neutrino oscillation experiments)

- correct interpretation of the outcome of ν oscillation experiments requires a precise understanding of ν and $\bar{\nu}$ interaction cross sections

Long-Baseline ν Oscillation Experiments

- in order to be sensitive to the MH and ~~CP~~, experiments will be looking for the conversion of ν_μ to ν_e (and $\overline{\nu}_\mu$ to $\overline{\nu}_e$) over large distances:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

distance between source and detector (known)

incoming neutrino energy (unknown; need to infer)

- ***neutrino energy is a crucial quantity***

- we typically fit distributions as a function of E_ν (or L/E_ν) to extract information on neutrino oscillations (important to keep in mind)

In Practice, this is Complex

- in reality, the ν oscillation formula looks like this:

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

$$T_1 = \sin^2 \theta_{23} \frac{\sin^2[(1-x_\nu)\Delta]}{(1-x_\nu)^2} \ ,$$

$$T_2 = \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x_\nu \Delta)}{x_\nu} \frac{\sin[(1-x_\nu)\Delta]}{(1-x_\nu)} \ ,$$

$$T_3 = \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x_\nu \Delta)}{x_\nu} \frac{\sin[(1-x_\nu)\Delta]}{(1-x_\nu)} \ ,$$

$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x_\nu \Delta)}{x_\nu^2} \ .$$

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30 \qquad x_\nu \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

θ_{13} is the "gate-keeper"

CP violating phase, δ

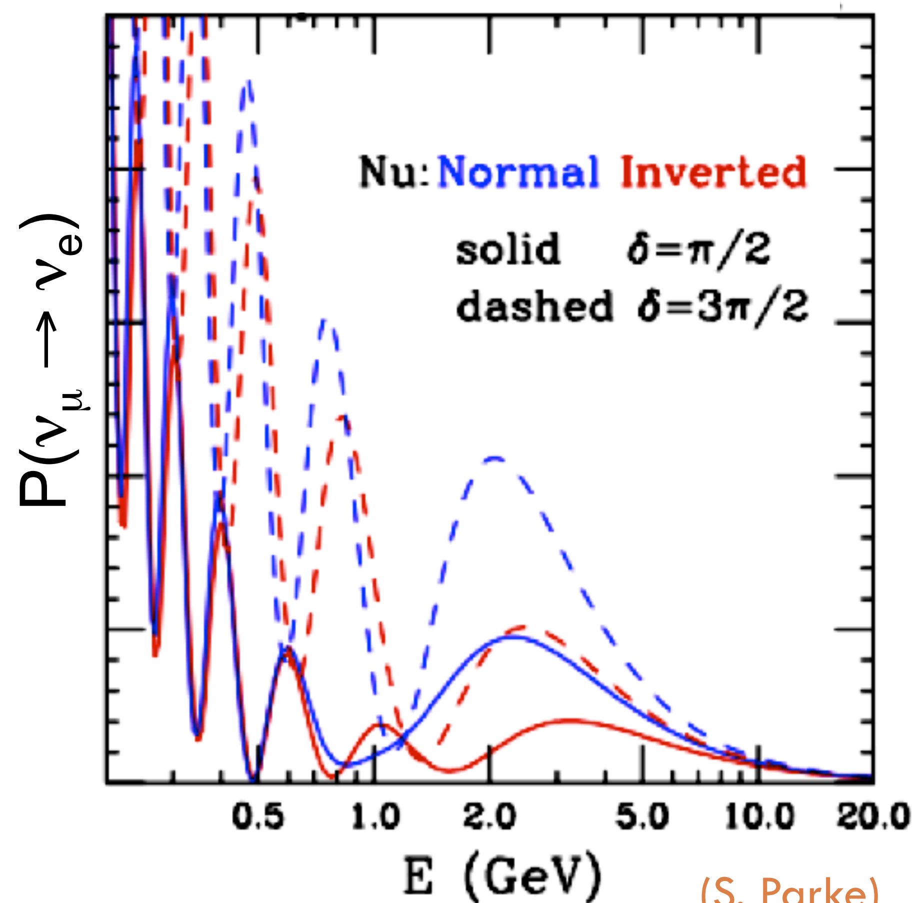
matter effects

neutrino mass ordering

Where We are Headed

- measure the neutrino energy spectrum to disentangle MH and CP violating effects
- to get at this physics, need to probe a range of ν energies
- means that we are studying ν interactions from 100's MeV to few-GeV (depends on baseline)
- processes that we care about are the same as what we study in e^- scattering …

appearance of ν_e over a distance of 1300km

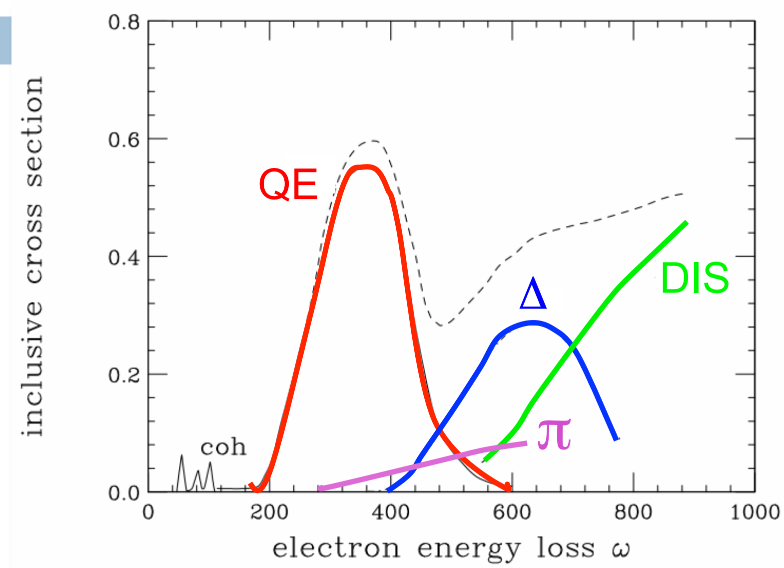


(S. Parke)

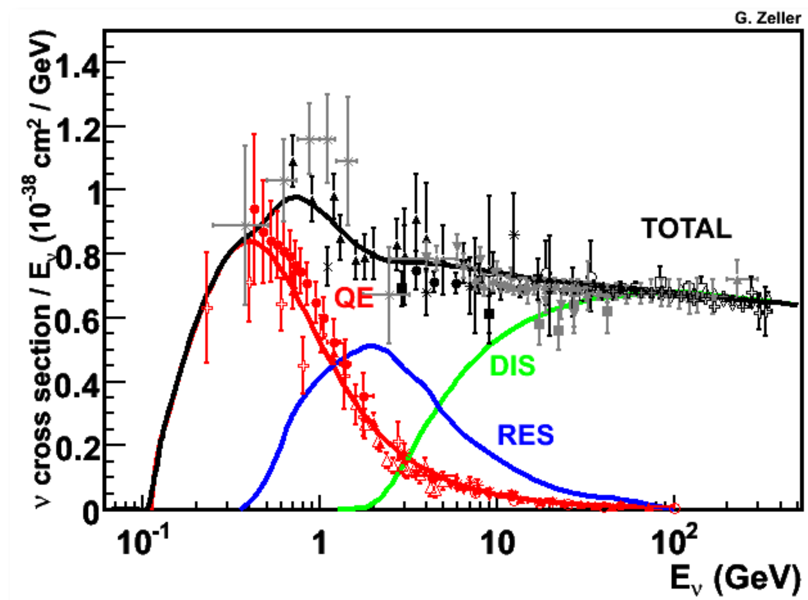
Electrons vs. Neutrinos

(O. Benhar)

- **electron scattering:**
  - beam energy is known
  - monochromatic (fixed E_e,θ_e)
  - think in terms of ω →



- **neutrino scattering:**
  - beam energy is not known
  - not monochromatic (spectrum of E_ν)
  - plus axial current contribution
  - think in terms of E_ν →
    (infer E_ν from E_{lep},θ_{lep} or $E_{lep}+E_{had}$)



Some of the Challenges

- ν beams not mono-energetic

  (broad flux of neutrinos illuminating the detector)

- multiple contributions

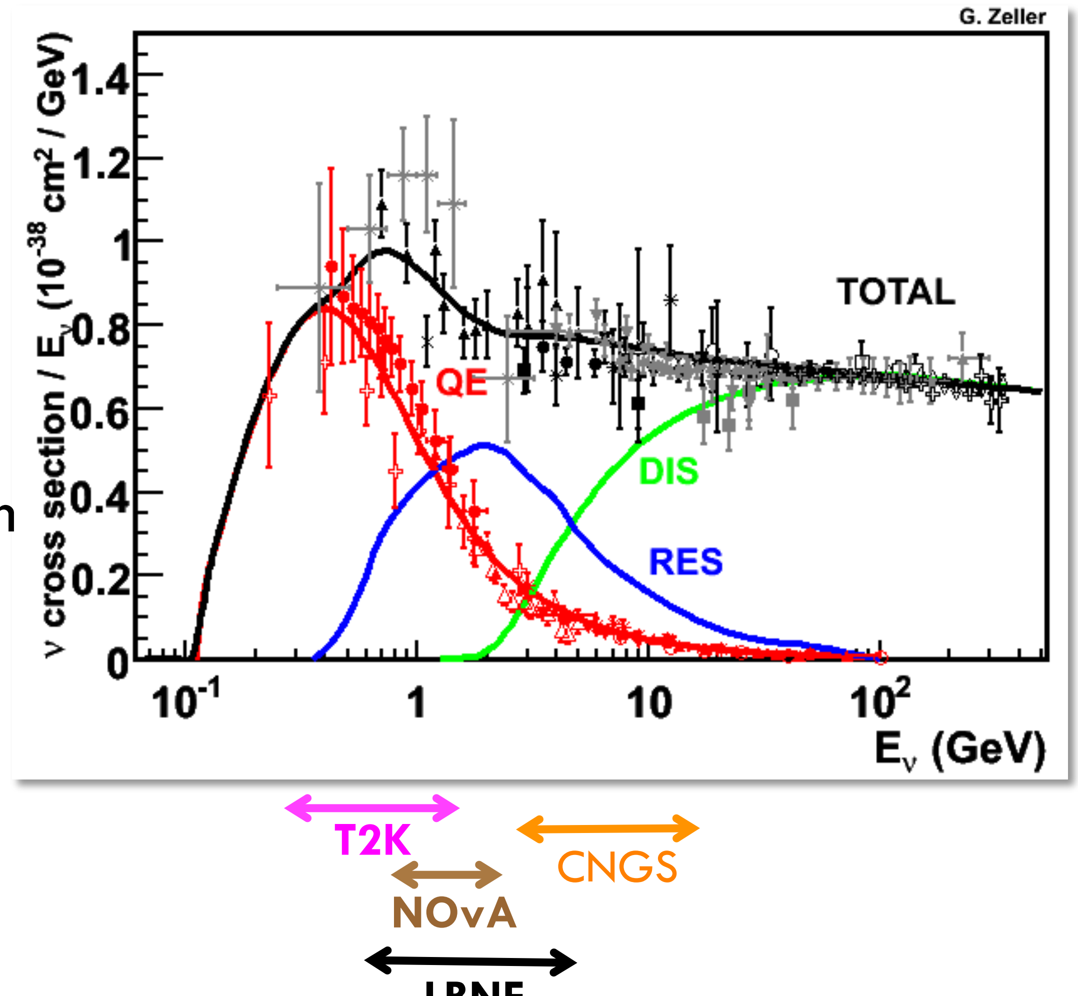
- σ_ν's are not particularly well-constrained in this region

  (most of the existing ν data is low statistics, collected on H_2, D_2 targets)

- experiments nowadays use nuclear targets

  (nuclear effects alter what we see)

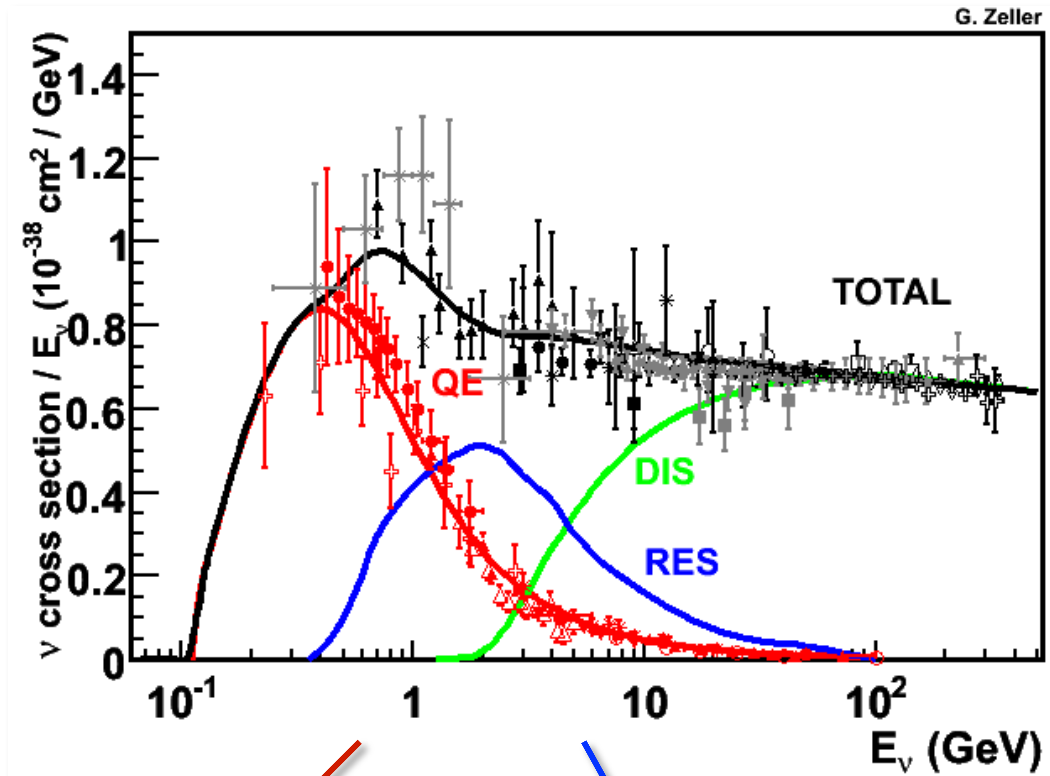
(accel-based ν experiments all use broad band beams, so contain contribs from all of these reaction mechanisms)



Modern Experiments

- modern experiments are making improved σ_ν measurements

- <u>advantages of new data</u>:
  - *higher statistics*
  - *intense, well-known ν beams*
  - *nuclear targets (crucial!)*
  - *also studying antineutrinos (important for CP studies)*



K2K, **MiniBooNE**, MicroBooNE, SciBooNE, T2K

ArgoNeuT, ICARUS, MINERνA, MINOS, NOMAD, NOνA

MiniBooNE Experiment

- MiniBooNE designed and built to study neutrino oscillations ($\nu_\mu \rightarrow \nu_e$ at large Δm^2 to address LSND)

- have been running for ~10 yrs now
  have multiple ν oscillation publications

- over a million neutrino & antineutrino interactions!
  (world's largest data set in this E range; we quickly realized there were some useful measurements to be made here)

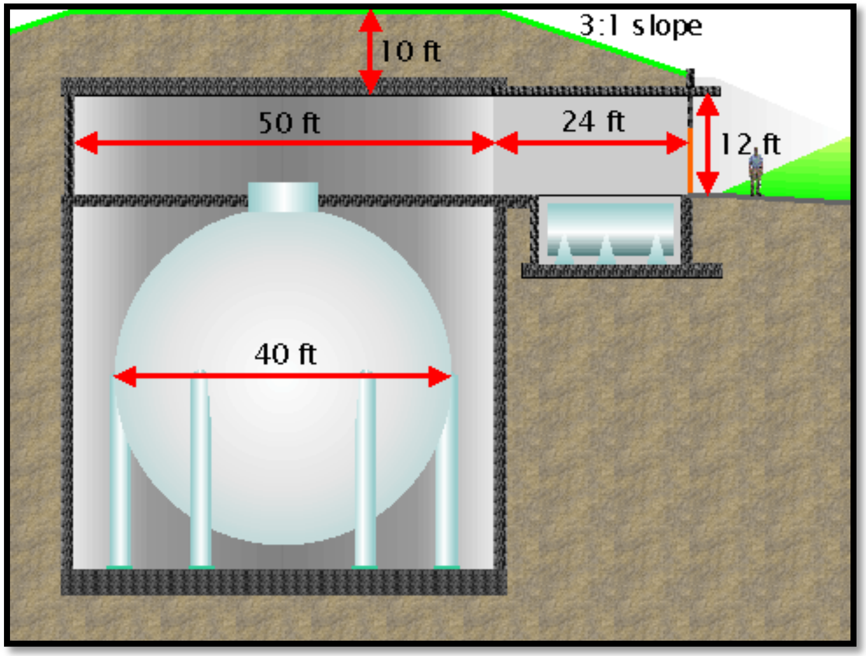
~74 physicists, 18 institutions

- σ_ν are a big part of our program

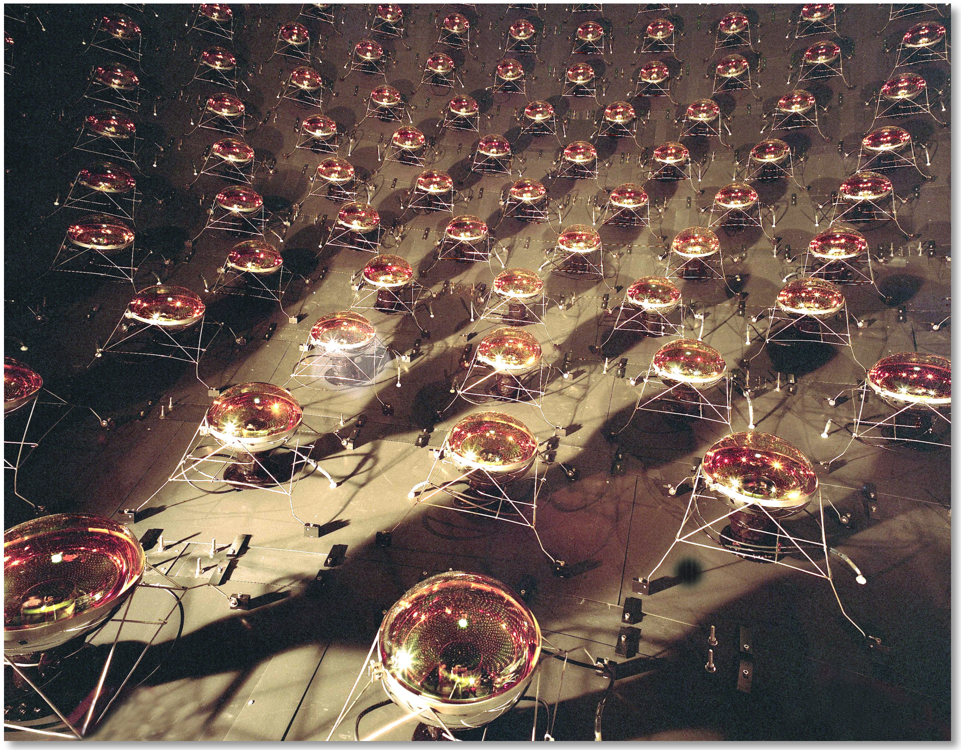
- have since measured σ's for ~90% of ν events in MiniBooNE
  (high statistics, high quality data … will summarize some of our findings)

MiniBooNE Detector

Aguilar-Arevalo *et al.*, NIM **A599**, 28 (2009)



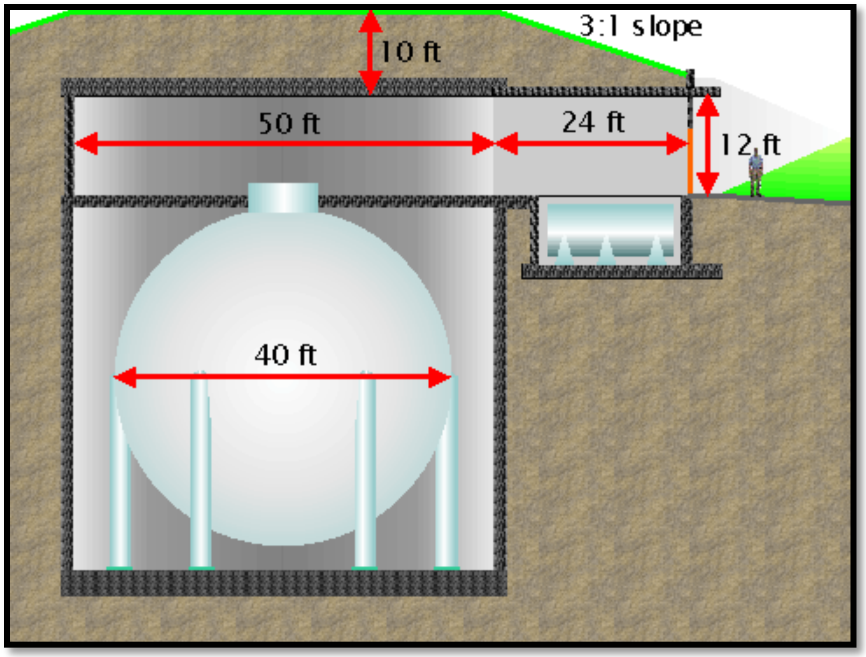
(inside view of MiniBooNE tank)

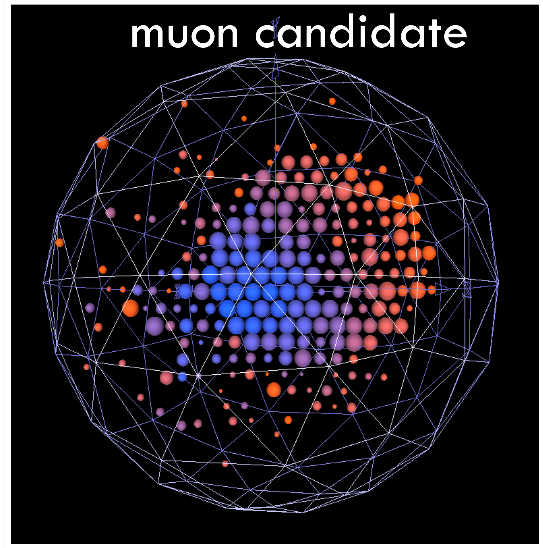


- 800 tons of mineral oil
- ν interactions on CH_2
- Čerenkov detector → ring imaging for event reconstruction and PID

MiniBooNE Detector

Aguilar-Arevalo *et al.*, NIM **A599**, 28 (2009)



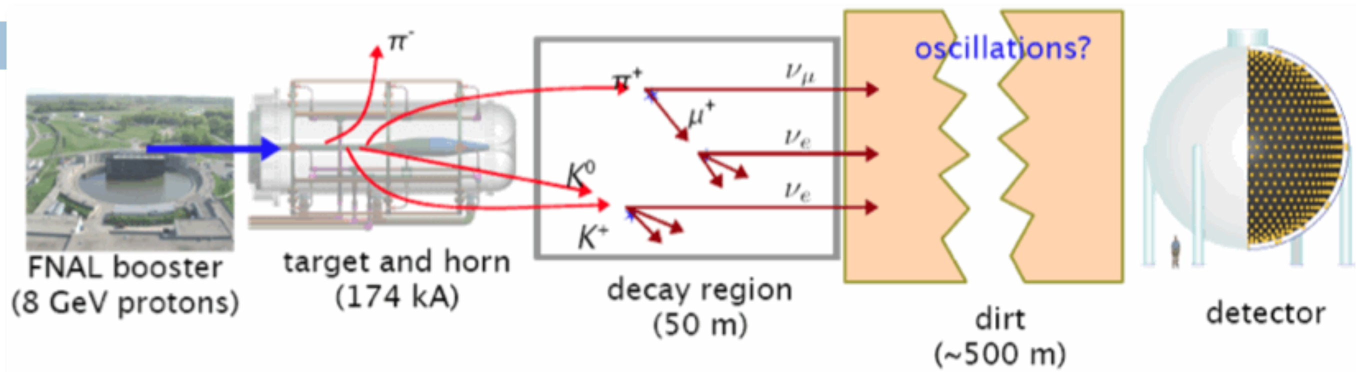


based on Č ring topology, can differentiate different particle types

- 4π coverage
- scintillation light (enables NC elastic)
- use particle decays for event ID ($\mu \rightarrow e$, $\pi^+ \rightarrow \mu \rightarrow e$ decays)

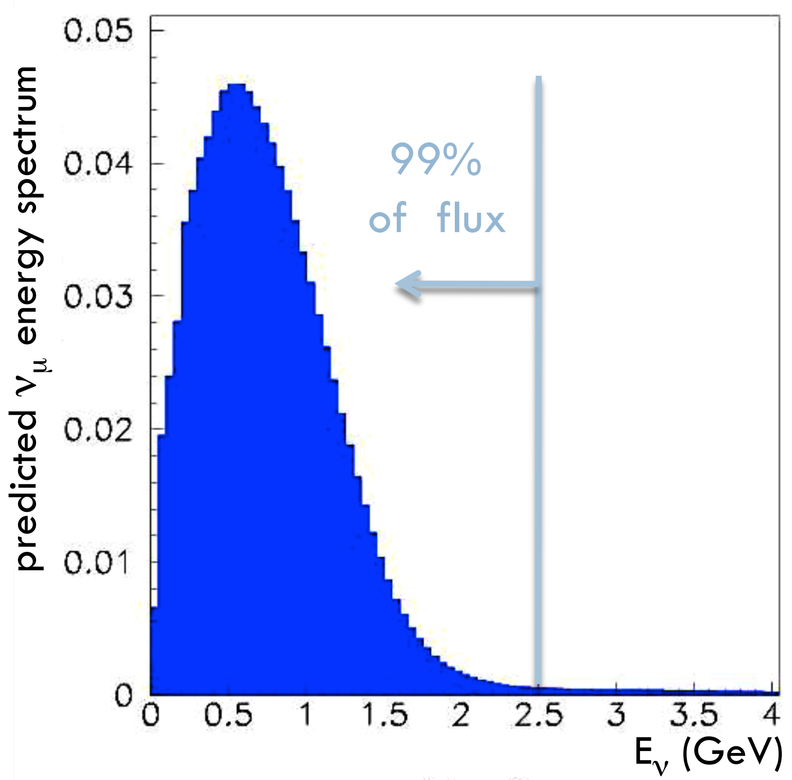
- 800 tons of mineral oil
- ν interactions on CH_2
- Čerenkov detector → ring imaging for event reconstruction and PID

Neutrino Beam



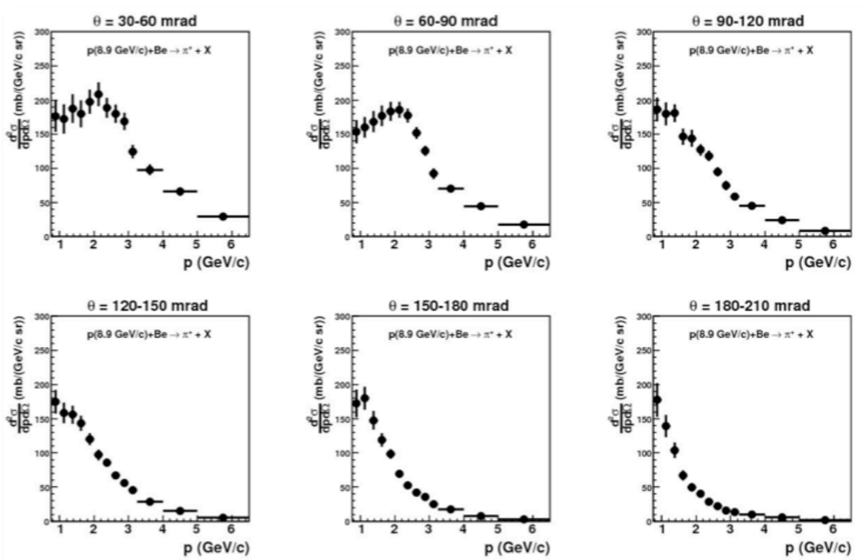
flux of neutrinos seen by the detector:
(for contained events, 98% from π decays in beam)

- both ν and $\bar{\nu}$ modes
- $<E_\nu> = 0.8$ GeV
- perfect for studying QE and Δ production regions



Flux Prediction

- need to know your ν flux to make ν cross section measurements
  (spent 5+ years on this on MiniBooNE)



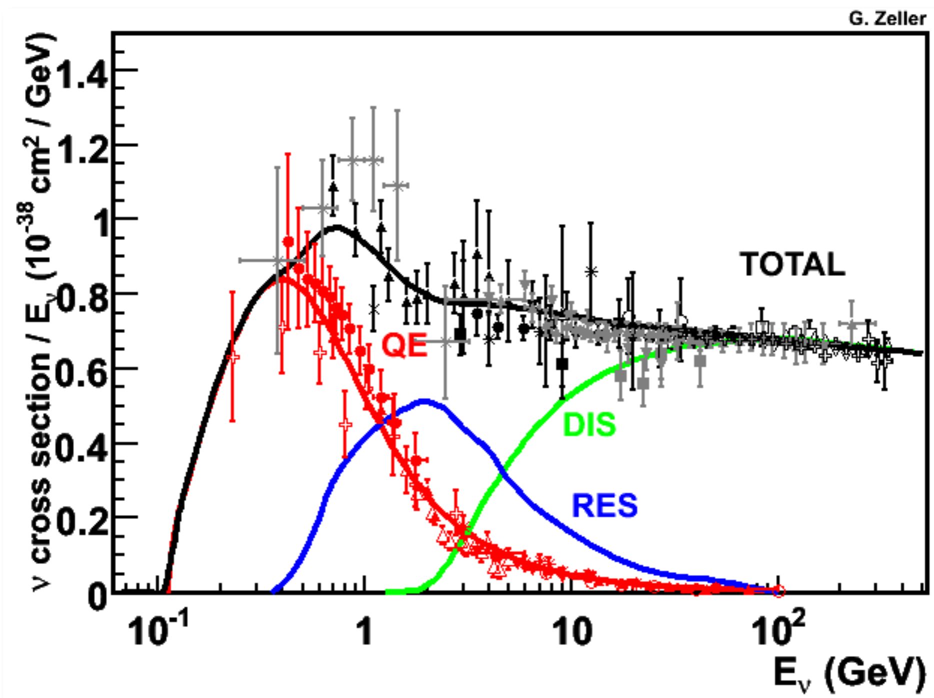
(D. Schmitz, Columbia, Ph.D. thesis)

- made dedicated hadro-production meas at CERN specifically for MB
  M. Catanesi *et al.*, Eur. Phys. J. **C52**, 29 (2007)
  - same beam energy
  - exact replica target
- also analyzed data from BNL E910
- comprehensive ν flux paper
  Aguilar-Arevalo *et al.*, PRD **79**, 072002 (2009)

- there was no tuning of the ν flux based on MiniBooNE ν data
- flux known to ~11% at the peak (larger errors at lower and higher E_ν)

Neutrino Interactions

- now want to start talking about some specific interaction measurements
- let's start on the left and work our way up in energy …



- what have we learned in exploring this region again 30+ years later?

Neutrino Quasi-Elastic Scattering

Why important?

- **important for ν oscillation experiments**

  - typically gives largest contribution to signal samples in many osc exps

signal events

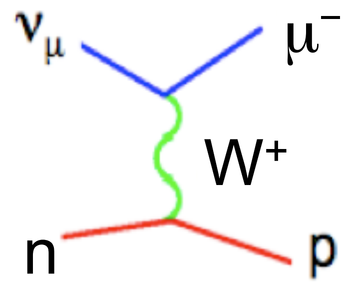
examples:

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

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

- biggest piece of the σ at ~1 GeV

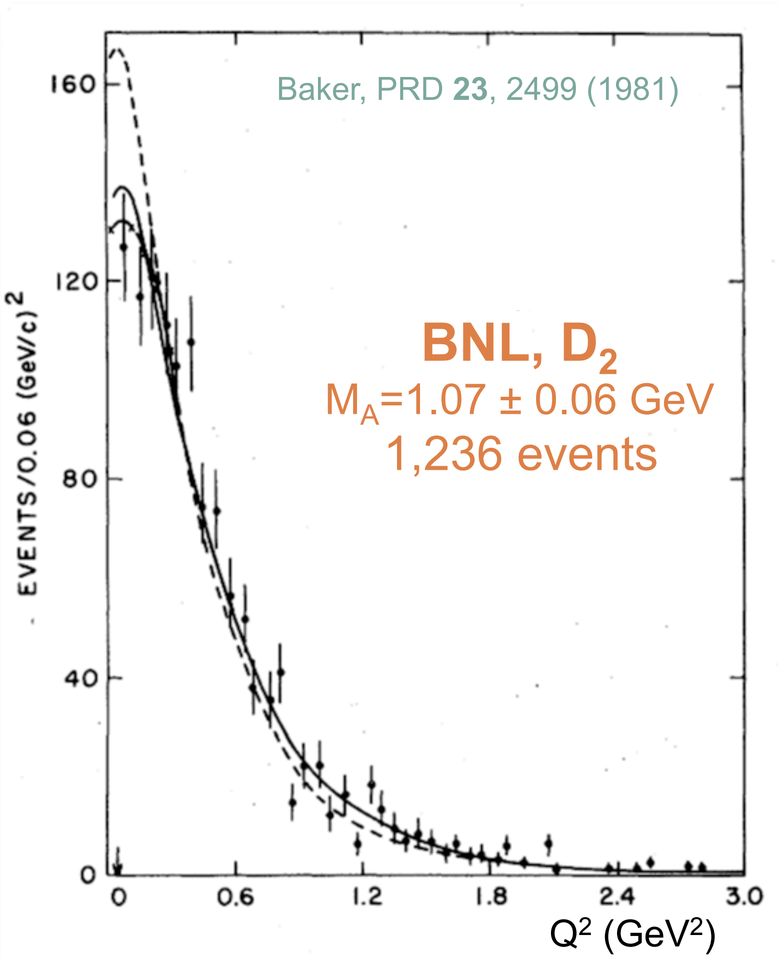
  (lepton kinematics are used to infer E_ν)

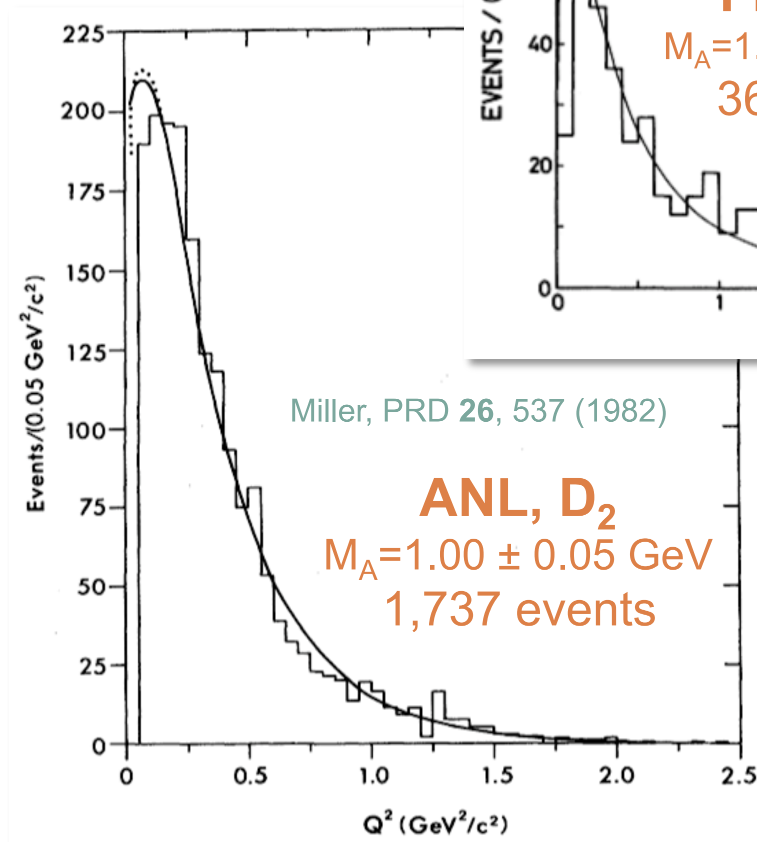


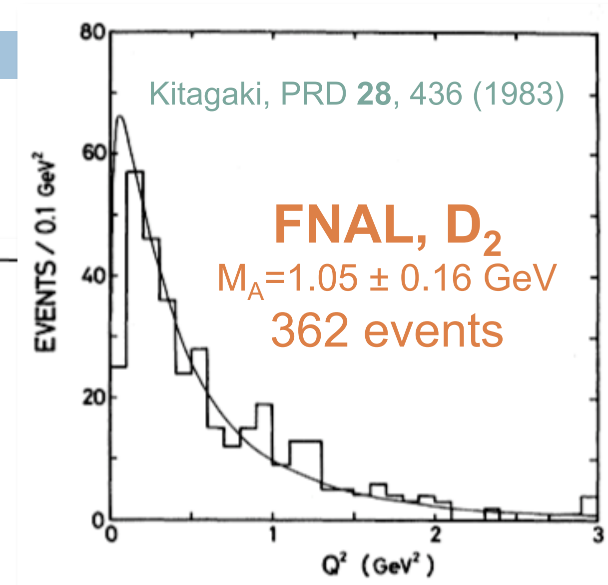
(typically thought of as a process with a single knock-out nucleon)

(heavily studied in 1970's and 80's, one of the 1st ν interactions measured)

Historical Data







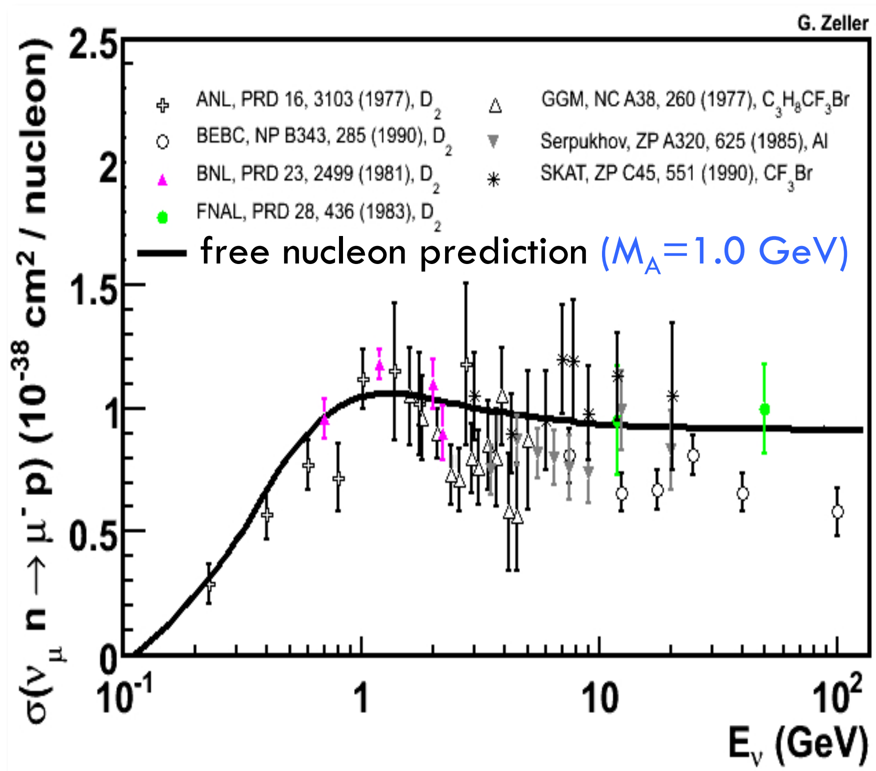
goal: make more accurate predictions for NC, so measured the axial FF in CC scattering

- focus of many early bubble chamber exps (D_2) ⟶ M_A~1.0 GeV

QE Cross Section

- conventional wisdom has always been that this σ **is well-known**
  - *it's a simple 2-body process*
  - *predictions rely on impulse approx: ν interacts with one nucleon at time*
- e^- scattering tells us vector piece
- ν fits tell us axial piece
- this description has been quite successful
  - *at least in describing bulk of historical data (D_2)*
  - *can predict size, shape of σ* M_A*=1.0 GeV*

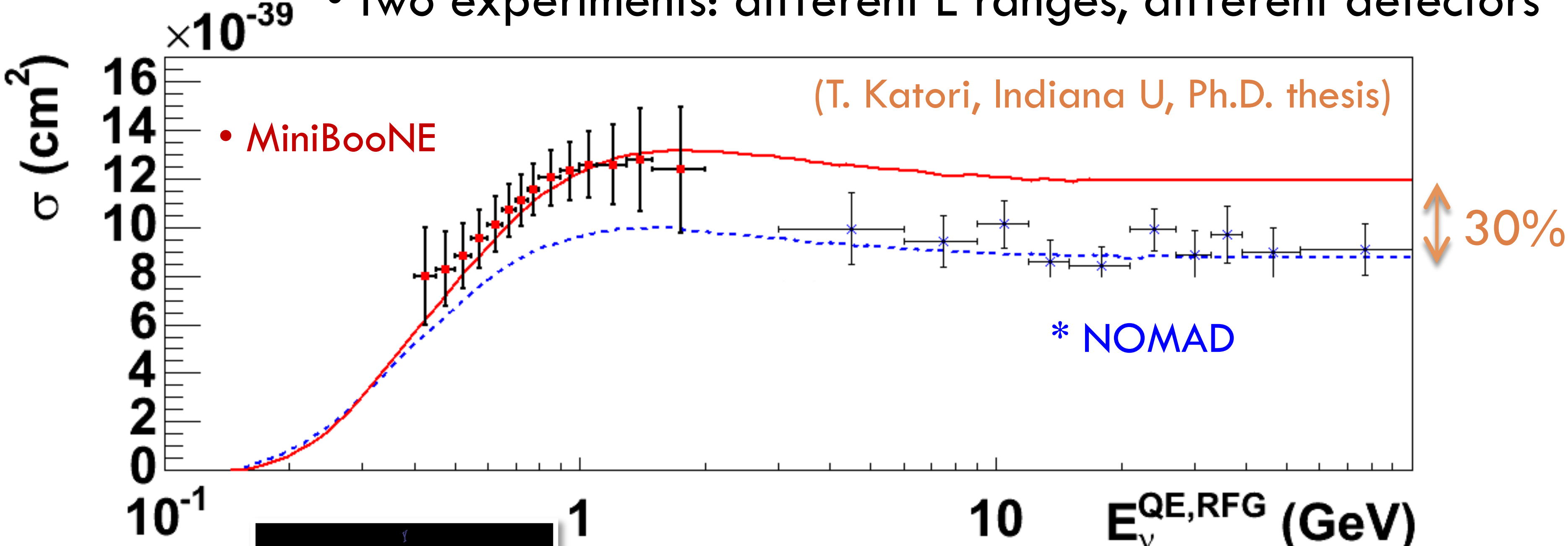
these same exps also measured σ(E_ν)



with these ingredients, it looked straightforward to extend this to describe ν QE scattering *<u>on nuclei</u>*

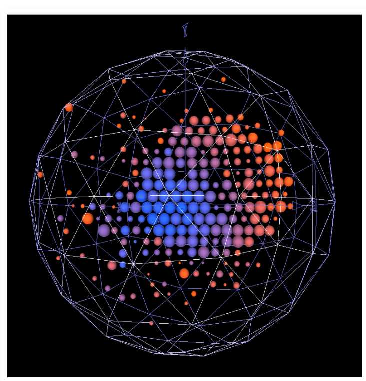
Repeated 30yrs Later on Carbon

- two experiments: different E ranges, different detectors



MiniBooNE
2002-2012

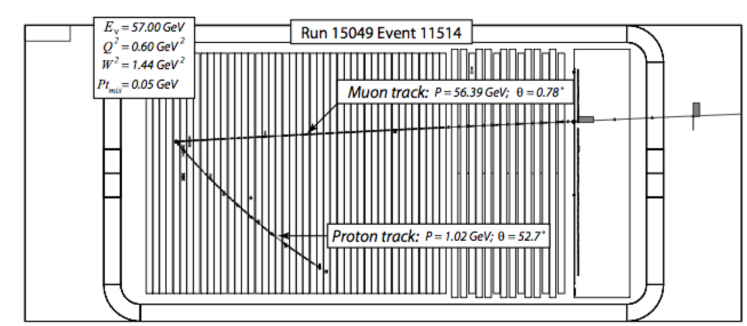
detects μ
& not knock-out nucleon(s)



PRD **81**, 092005 (2010)

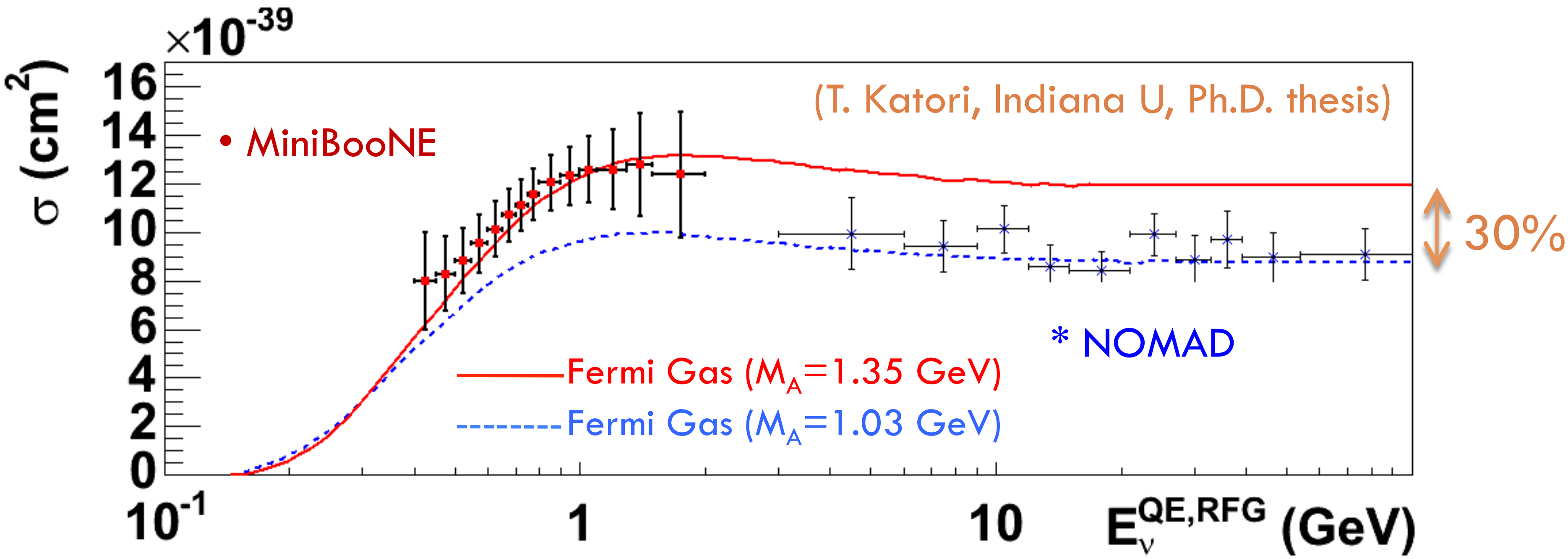
NOMAD
1995-1998

sees both μ and proton



EPJ **C63**, 355 (2009)

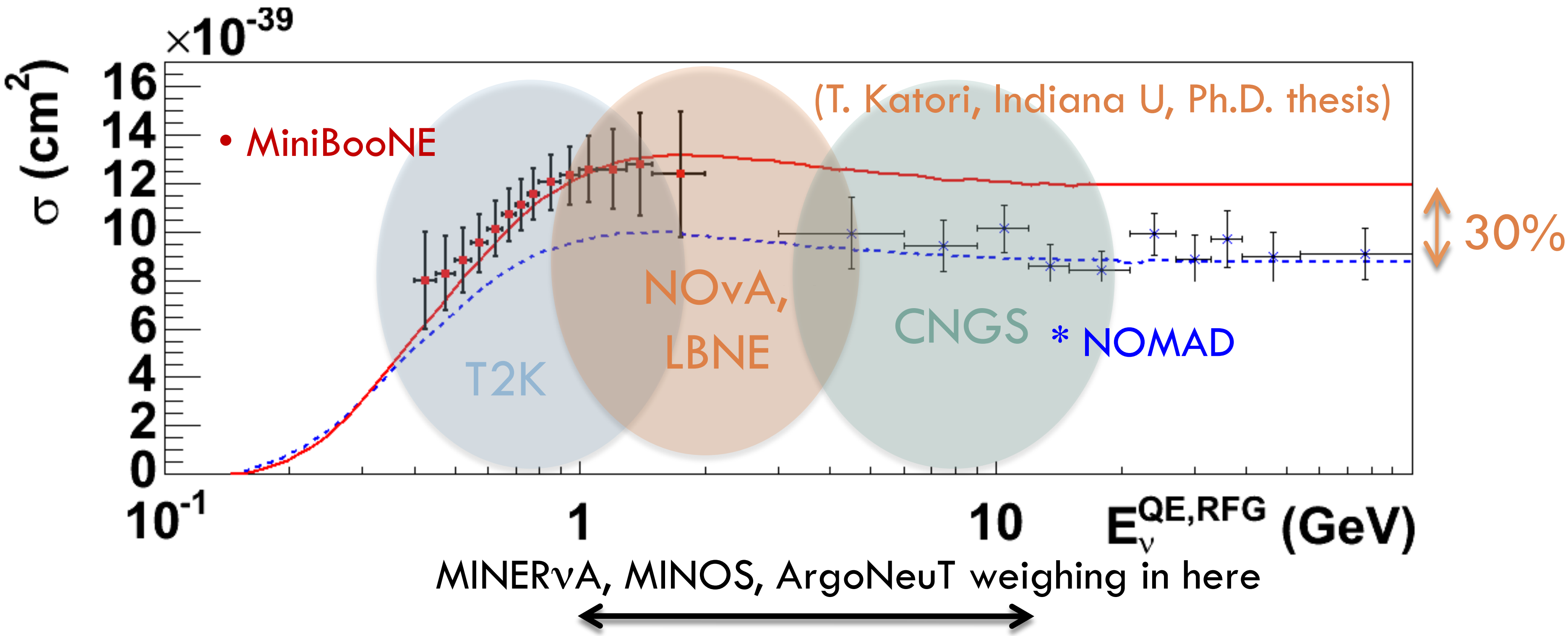
QE Cross Section on Carbon



- MiniBooNE data is well above "standard" QE prediction
  (increasing M_A can reproduce σ)
- NOMAD data consistent with "standard" QE prediction
  (with M_A=1.0 GeV)

cannot consistently describe the data with a single prediction

QE Cross Section on Carbon



- the difference is not many σ, but can leave one in a quandary if want to predict how many QE signal events you should see in your ν osc exp
- this is the situation we've been in for some time now

QE Cross Section at Low Energy

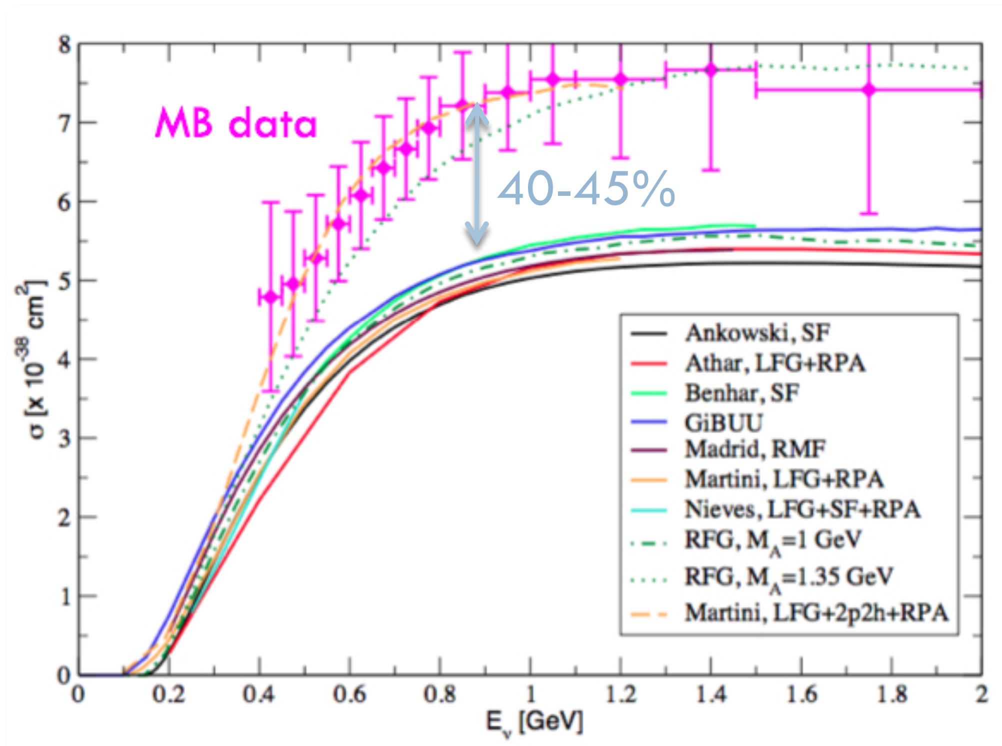
- MiniBooNE data is the 1st time have measured the ν QE σ on a nuclear target at these low energies (< 2 GeV)

  - *naturally, these results garnered a lot of attention, largely because they were unexpected*
    (increased QE rates also seen in K2K, MINOS, SciBooNE)

- σ's are appreciably higher than any conventional approach

  (discrepancy is not 30%, but really 40-45%)

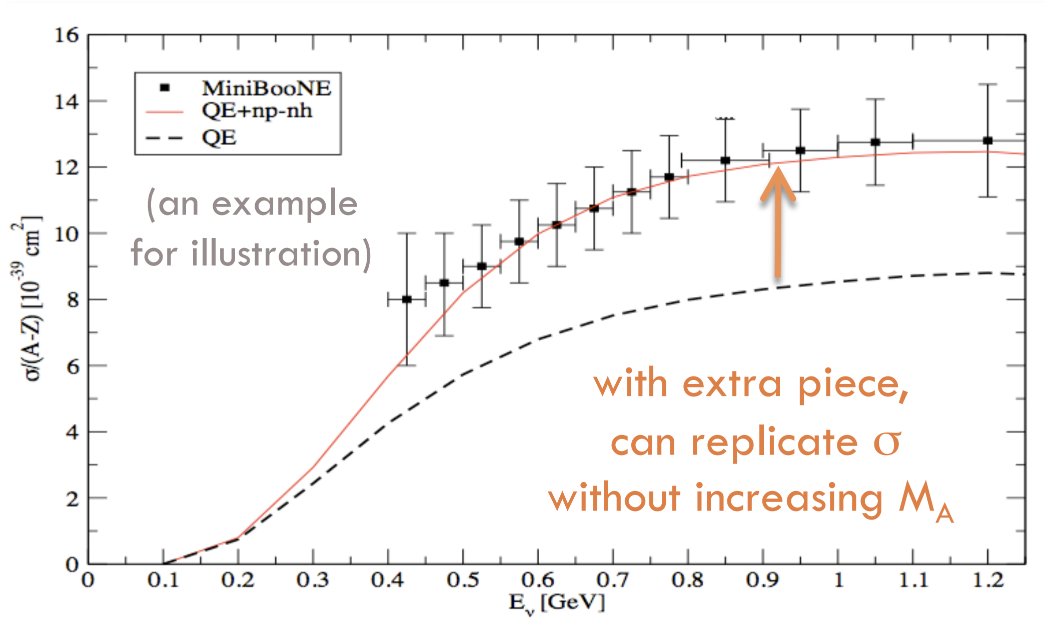
- community has been trying to reconcile these results



(L. Alvarez-Ruso, NuFact11)

Nuclear Effects to the Rescue?

- a possible explanation has recently emerged …
- while traditional nuclear effects <u>decrease</u> the σ_ν, there are processes that can <u>increase</u> the total yield *(has been well-known in e^- scattering)*



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

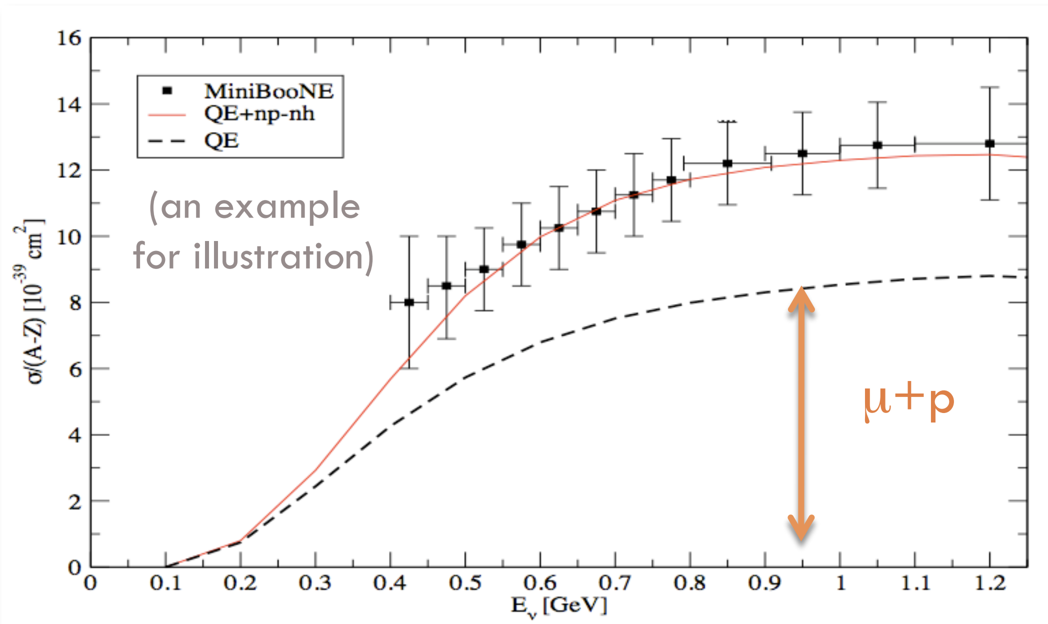
- there are add'l nuclear dynamics present

  (i.e., effects not included in the independent particle approaches we have been using for decades)

- enhancement caused by the interaction of incoming ν with more than 1 nucleon in the target nucleus

Nuclear Effects to the Rescue?

- idea is that there are <u>two contributions</u> present when we talk about ν QE scattering off of a nuclear target:



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

← "true QE" prediction we saw earlier (μ+p)

(single-nucleon knock-out; same as you would get for free nucleon scattering)

Nuclear Effects to the Rescue?

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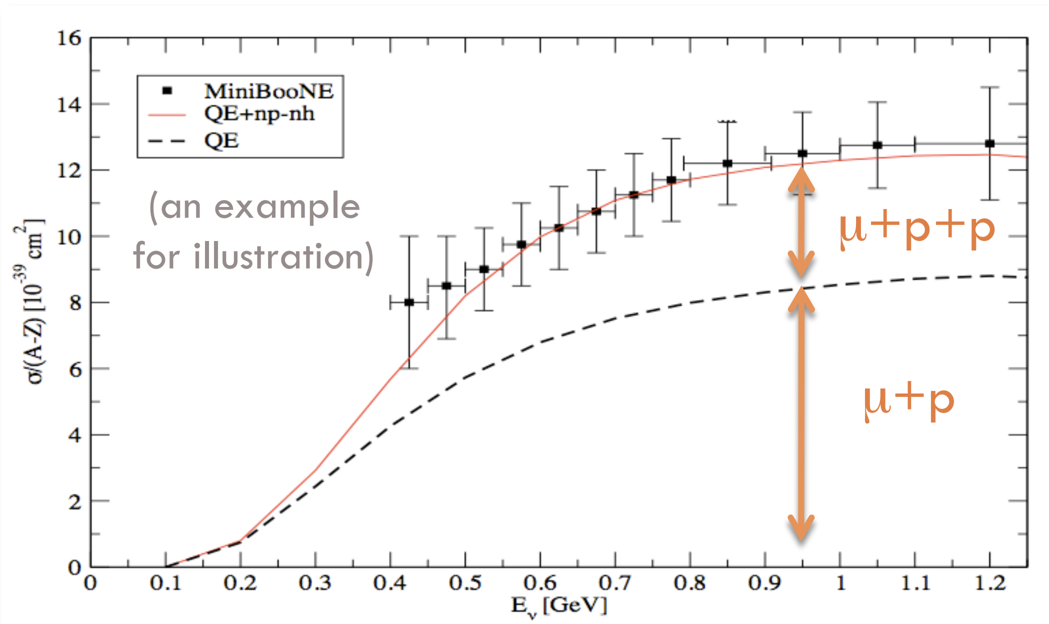


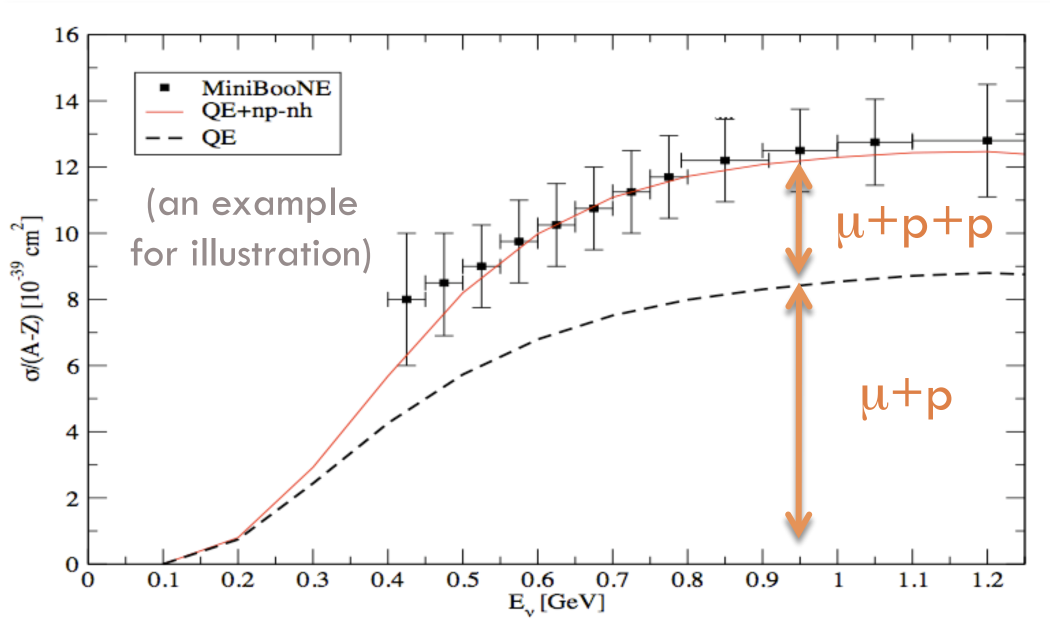
Martini *et al.*, PRC **80**, 065001 (2009)

ν scattering off of a correlated nucleon state contributes more σ at these energies and produces a multi-nucleon final state (μ+p+p)

(would not have seen this large an effect in D_2 so this would have been missed in early ν experiments)

Nuclear Effects to the Rescue?

- idea is that there are <u>two contributions</u> present when we talk about ν QE scattering off of a nuclear target:



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

it has been suggested that 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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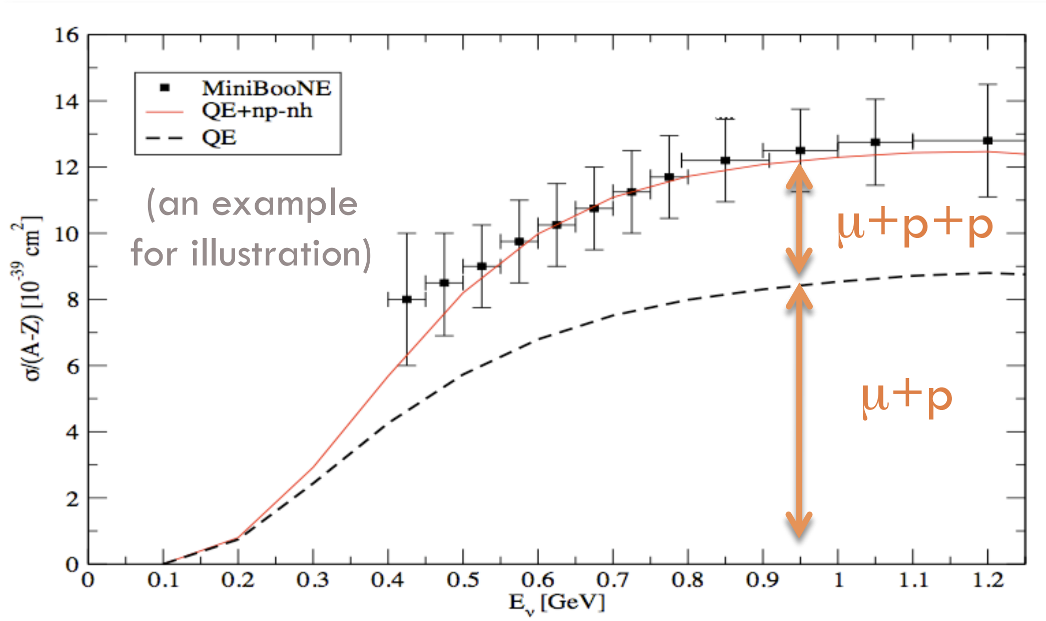


Martini *et al.*, PRC **80**, 065001 (2009)

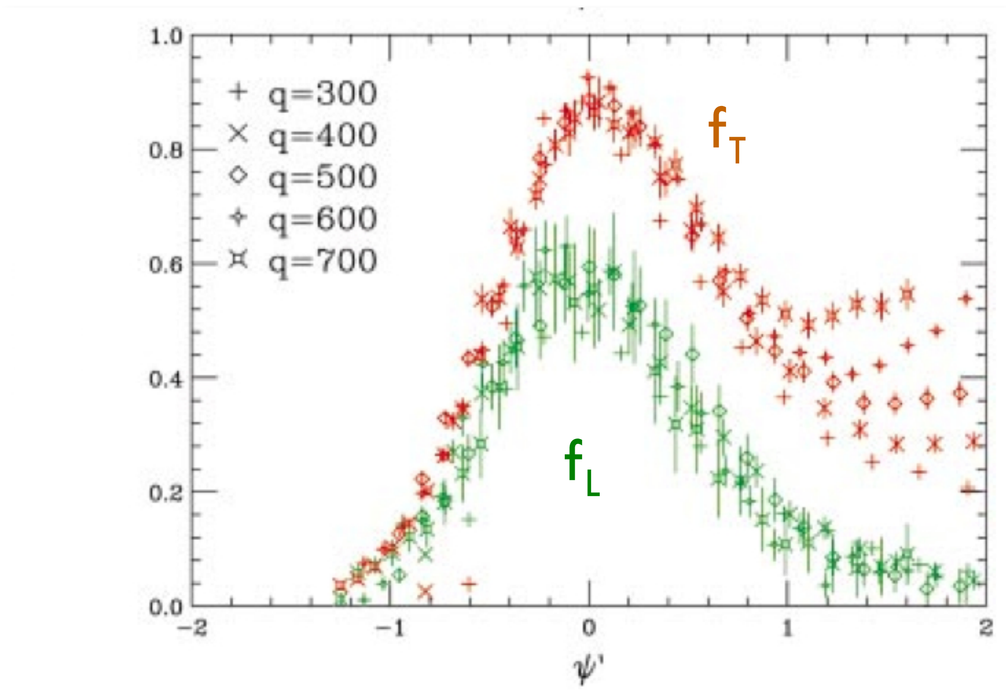
- could this explain the difference between MiniBooNE & NOMAD?

jury is still out on this

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

Electron Scattering

- while this is new to ν scattering, have known for over 2 decades from e-nucleus scattering that more complicated processes can take place



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

- **longitudinal** part of σ_{QE} can be described in terms of scattering off independent nucleons
- in contrast, there is a large enhancement in **transverse** part in both QE peak and dip region
  (can be explained by SRC and 2-body currents)
- likely also play a role in neutrinos!

- took us awhile to realize that we may be seeing the same thing in ν scattering

Has Been a Focus in the Past Year

- 50+ theoretical papers on the topic of QE ν-nucleus scattering

- Butkevich, arXiv:1204.3160
- Lalakulich *et al.*, arXiv:1203.2935
- Mosel, arXiv:1204.2269, 1111.1732
- Barbaro *et al.*, arXiv:1110.4739
- Giusti *et al.*, arXiv:1110.4005
- Meloni *et al.*, arXiv:1203.3335, 1110.1004
- Martini *et al.*, arXiv:1202.4745, 1110.0221, 1110.5895, Phys. Rev **C81**, 045502 (2010)
- Paz, arXiv:1109.5708
- Sobczyk, arXiv:1201.3673, 1109.1081, 1201.3673
- Nieves *et al.*, arXiv:1204.5404, 1106.5374, 1110.1200, Phys. Rev. **C83**, 045501 (2011)
- Bodek *et al.*, arXiv:1106.0340
- Amaro, *et al.*, arXiv:1112.2123, 1104.5446, 1012.4265, Phys. Lett **B696**, 151 (2011)
- Antonov, *et al.*, arXiv:1104.0125
- Benhar, *et al.*, arXiv:1012.2032, 1103.0987, 1110.1835
- Meucci *et al.*, arXiv:1202.4312, Phys. Rev. **C83**, 064614 (2011)
- Ankowski *et al.*, Phys. Rev. **C83**, 054616 (2011)
- Alvarez-Ruso, arXiv:1012.3871
- Martinez *et al.*, Phys. Lett **B697**, 477 (2011)

(disclaimer: this is not a complete list!)

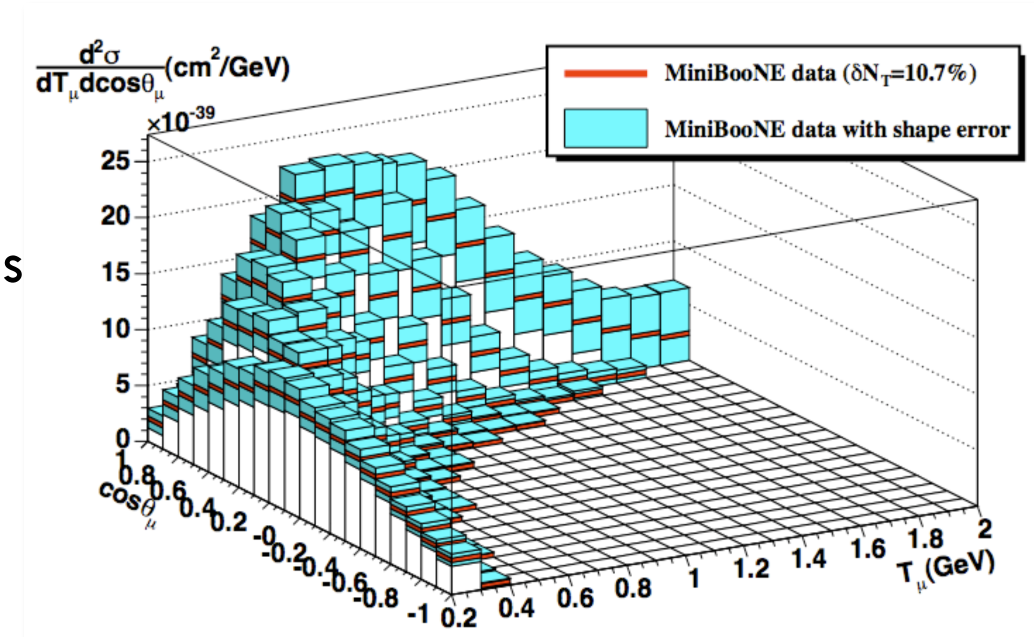
- need to do more than describe behavior of σ as a function of E_ν

(model-dependent)

Moving Forward

- preference is for differential distributions
  (may not seem fancy but is fancy for ν physics)

(T. Katori, Indiana U, Ph.D. thesis)



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

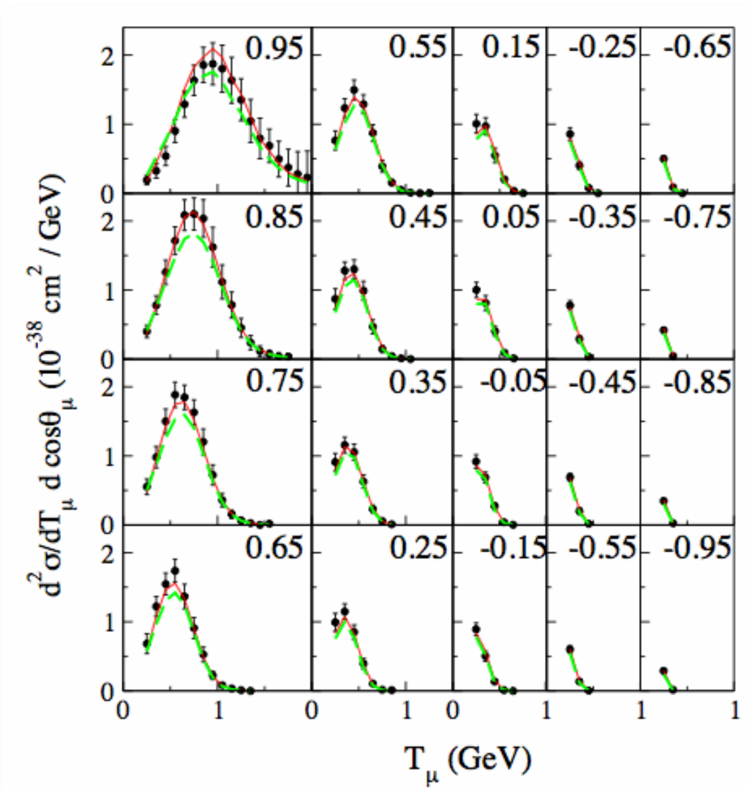
- because of high statistics
  (MB data sample is 146,000 events)
  can measure double diff'l σ's for the first time! (like E_e, θ_e)
  $d^2\sigma/dT_\mu d\theta_\mu$

- historically, never had enough statistics to do this

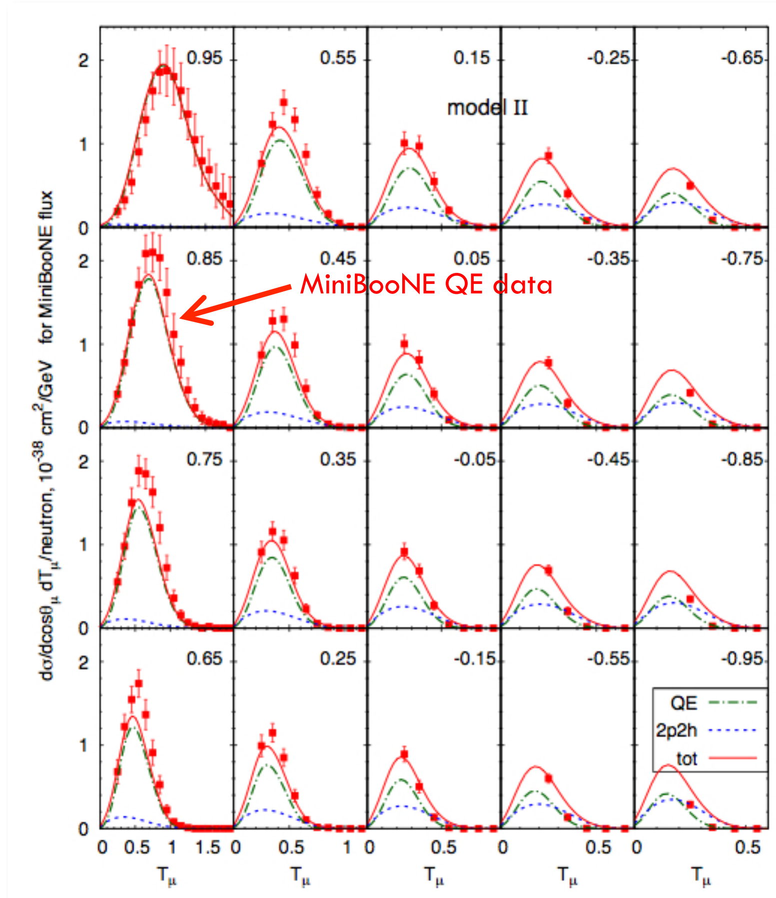
- much less model-dependent (both T_μ, θ_μ are directly measured quantities) and provides much richer information than $\sigma(E_\nu)$

Some Examples: 2D Comparisons

- this is the 1st time we've had this sort of information available



Nieves, Simo, Vacas, PL **B707**, 72 (2012)



Lalakulich, Gallmeister, Mosel arXiv:1203.2935

- we need measurements at other E_ν, A and the outgoing proton(s)!

What Does This All Mean?

- 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 in our simulations is a big deal

- good news: expect larger event yields

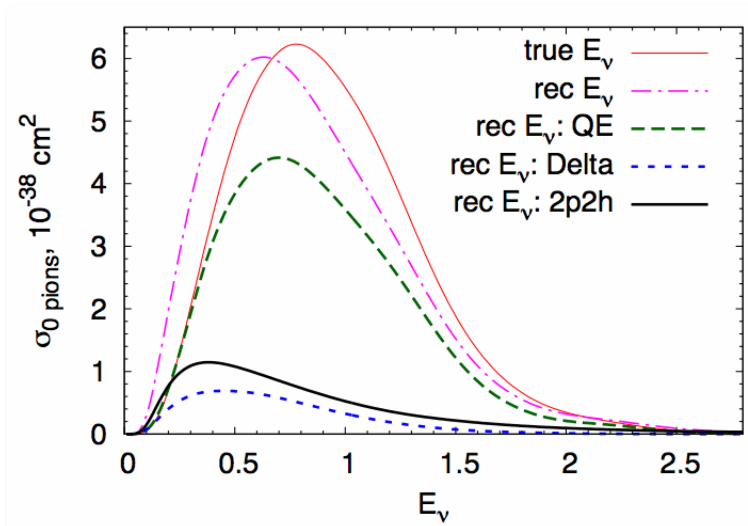
- bad news: need to understand the underlying physics

(1) impacts E_ν determination

ex: Mosel/Lalakulich 1204.2269, Martini *et al.* 1202.4745, Lalakulich *et al.* 1203.2935, Leitner/Mosel PRC81, 064614 (2010)

(2) effects will be different for ν vs. $\bar{\nu}$

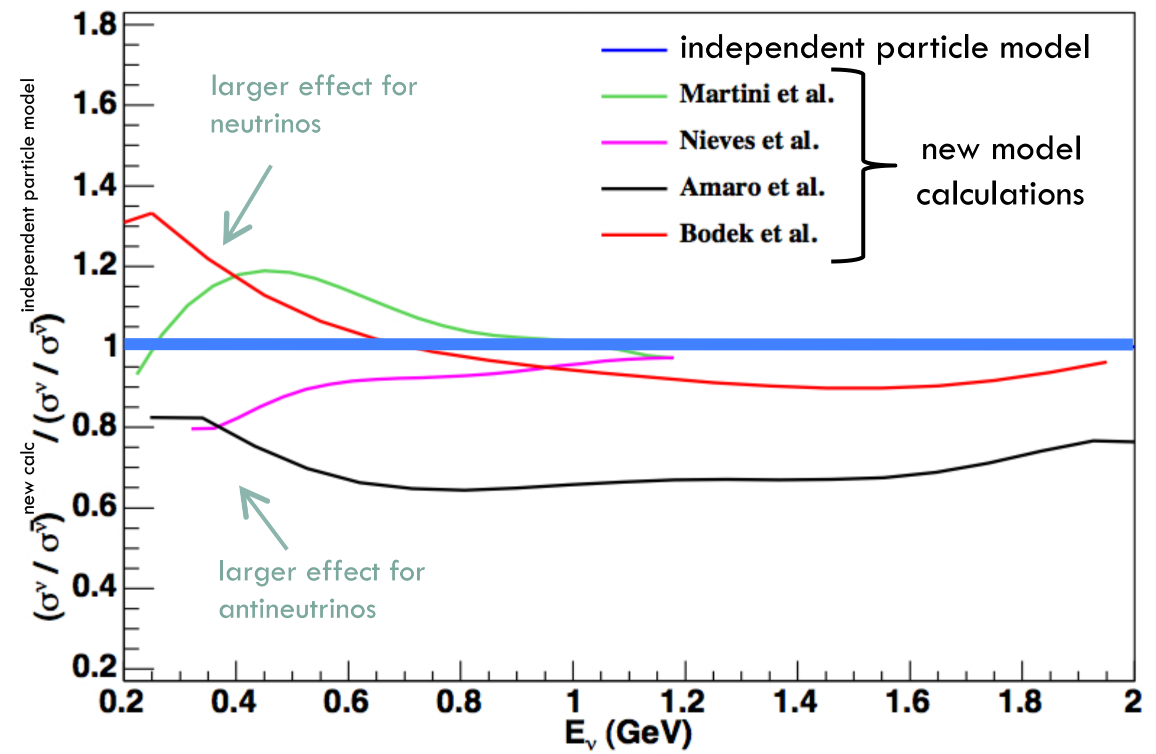
(at worse, could produce a spurious ȻP effect)



Lalakulich, Gallmeister, Mosel,1203.2935

Neutrino/Antineutrino Ratio

(J. Grange)

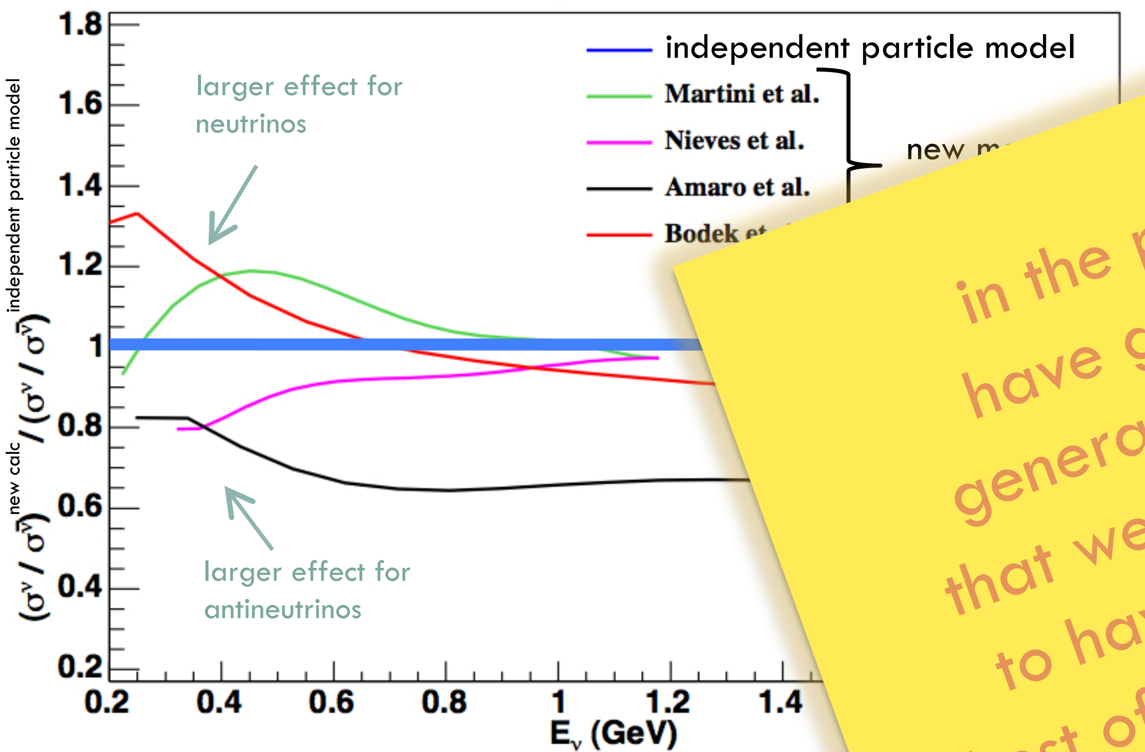


we are currently working on a $\nu/\bar{\nu}$ σ *ratio measurement in MiniBooNE (J. Grange)*

- models give different predictions for $\nu/\bar{\nu}$
- the situation is unclear and will need to get resolved …
- large θ_{13} means $\nu/\bar{\nu}$ CP asymmetry we're trying to detect is small so will need a detailed understanding of these $\nu,\bar{\nu}$ differences!

Neutrino/Antineutrino Ratio

(J. Grange)



• mo... erent ... $\bar{\nu}$ ... ar ... ned ... ng of these ... differences!

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

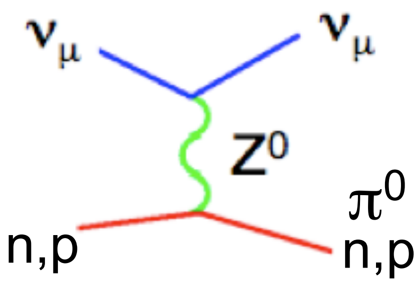
... story will continue to evolve

we are currently working on a $\nu/\bar{\nu}$ σ ratio measurement in MiniBooNE (J. Gra...

Pion Production

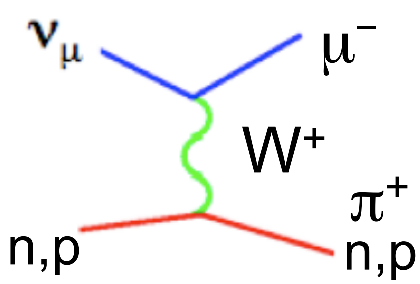
- NC π^0 production

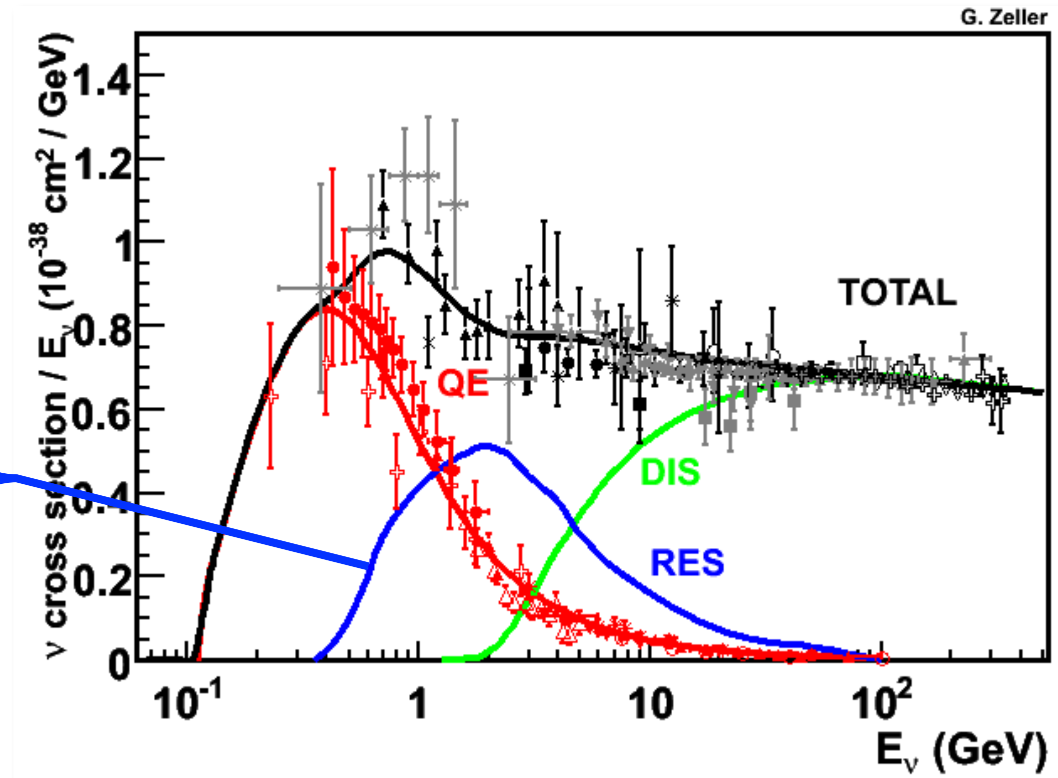
(background for ν_e appearance)



- CC π^+, π^0 production

(a complication for ν_μ disappearance)





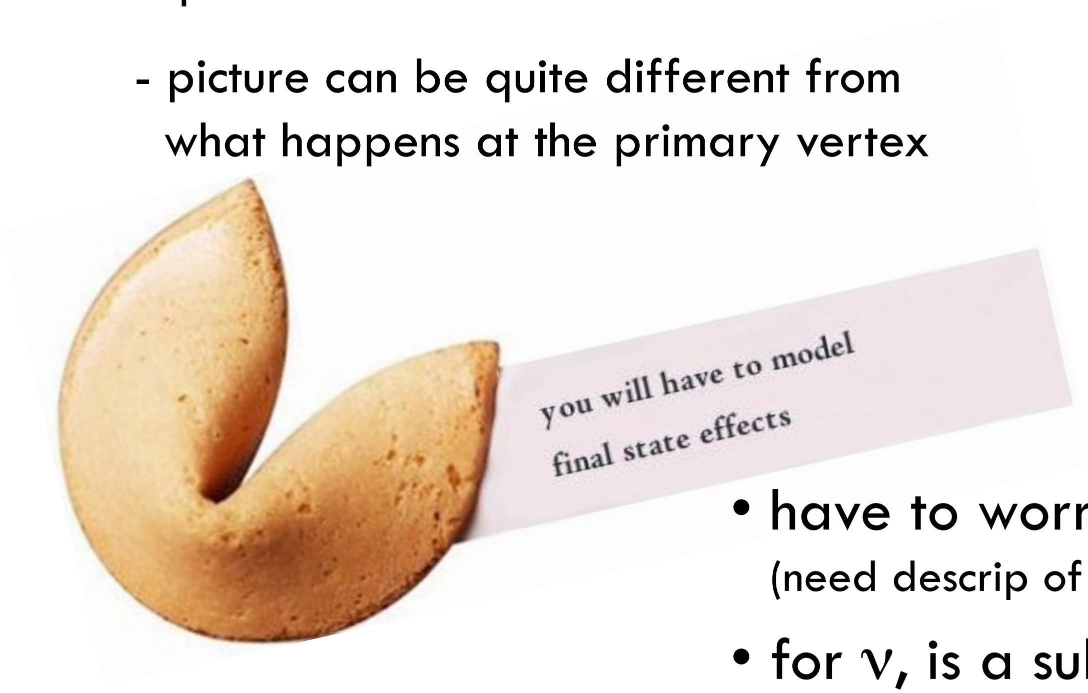
- π production also has important connections to ν osc measurements

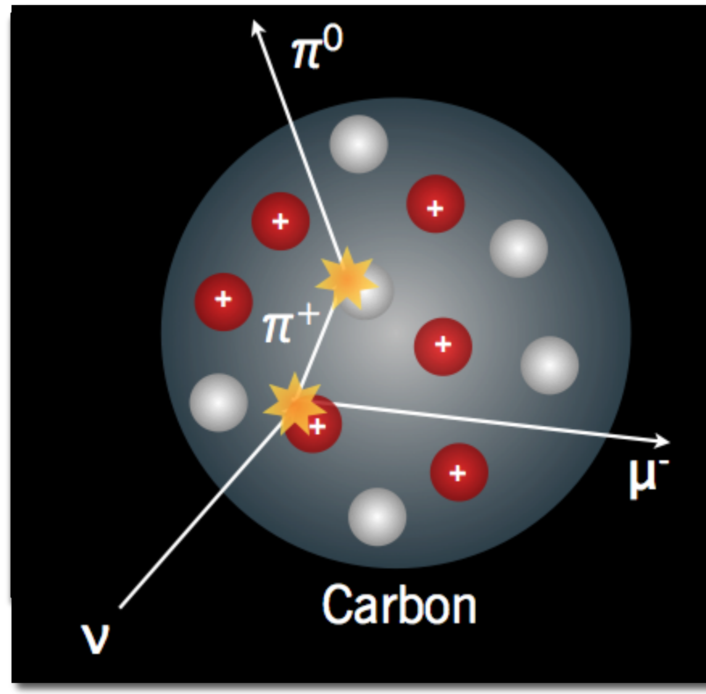
Final State Effects Can Change the Picture

- a new appreciation for nuclear effects in this region as well

"final state interactions (FSI)"

- before they leave the nucleus, pions & nucleons can re-interact
- picture can be quite different from what happens at the primary vertex



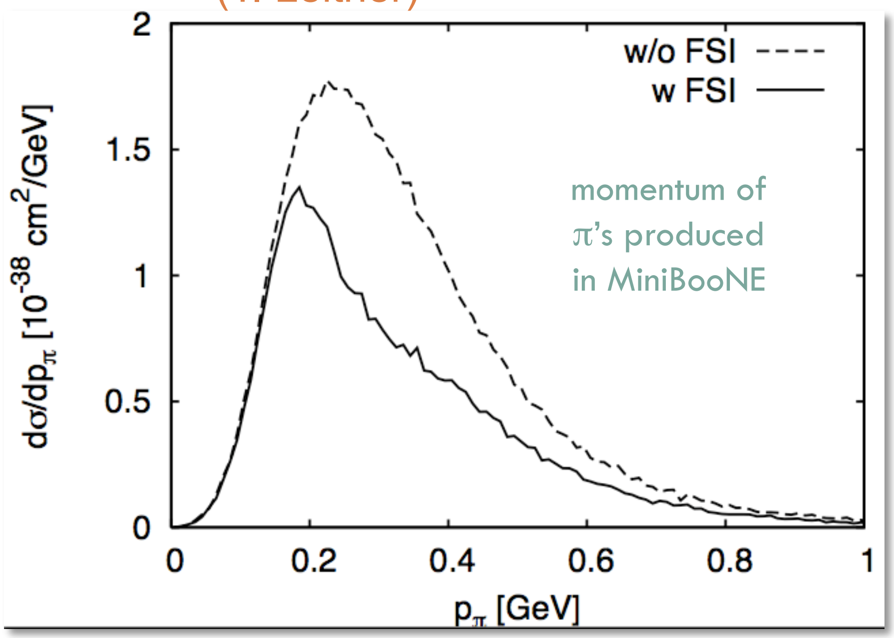


- have to worry about these effects
  (need descrip of initial ν-nucleus σ + produced f.s. particles)
- for ν, is a subject that needs more attention
  (U. Mosel,1108.1692 [nucl-th])

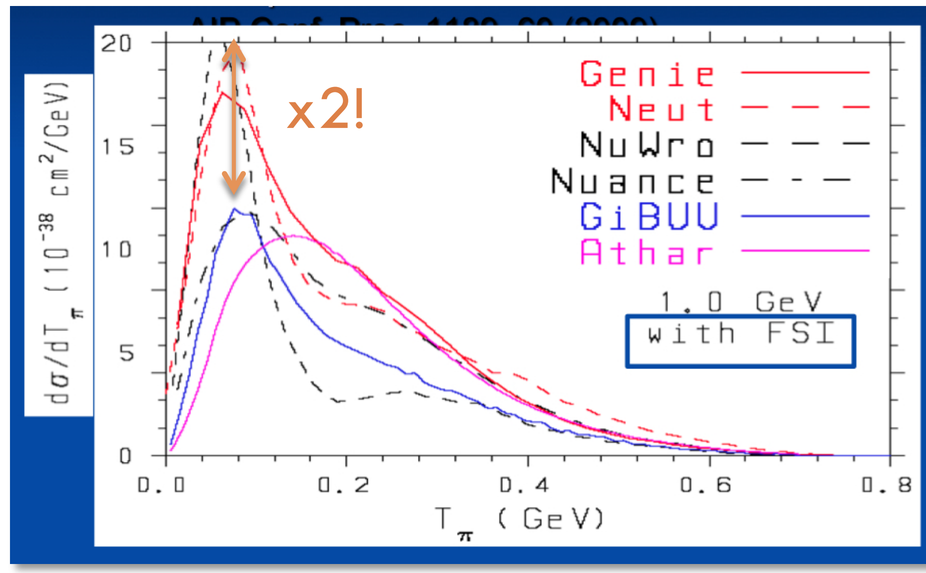
Final State Effects are Important

- <u>the distortions are large</u> (>20%)
- <u>and the predictions of their effects can vary</u>

(T. Leitner)



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



- leave a big imprint on what you see in your ν detector
- area where ν generators differ the most
- need π kinematic measurements!

  (has never been carefully studied in ν scattering)

Pion Production in MiniBooNE

- trying to forge a new path here also
- extensive program to measure final state particle kinematics

(measure "observable" single π σ
π in final state regardless of
what was produced in initial state)

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

"standard" cross section → $\sigma(E_\nu)$

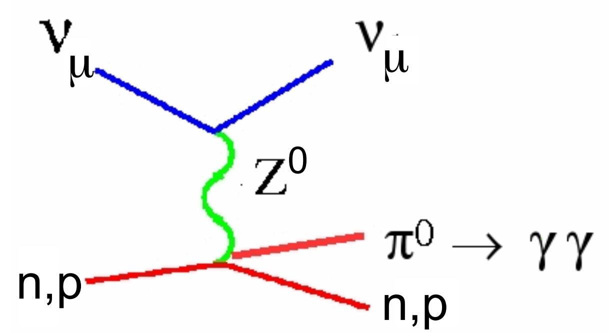
the rest is new!

measurement	NC π^0	CC π^0	CC π^+
$\sigma(E_\nu)$	X	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

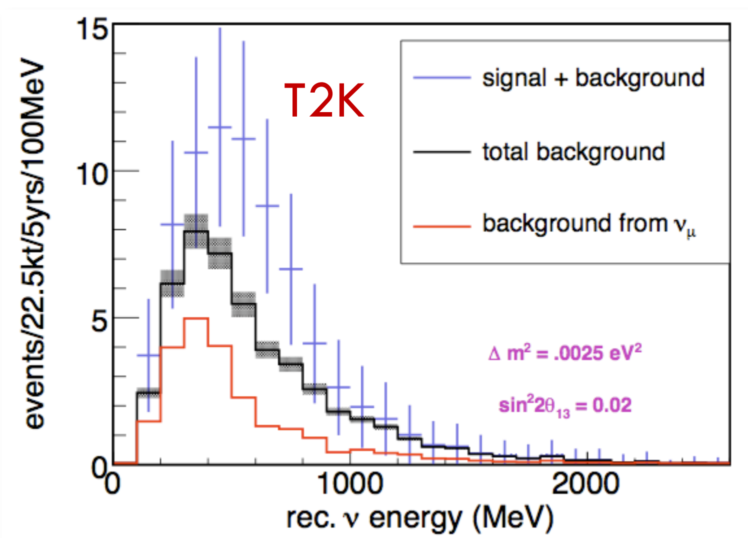
- 3 channels, 14 diff'l σ's
- data has immediate implications for ν osc measurements (including MB)

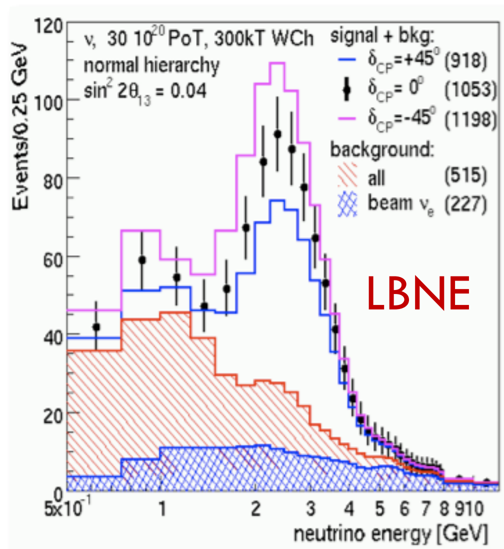
NC π^0 Production

Why important?



- **important for neutrino oscillation experiments**
  - very important background for experiments looking for $\nu_\mu \rightarrow \nu_e$ (θ_{13}, MH, ~~CP~~) final state can mimic a ν_e interaction if $\pi^0 \rightarrow \gamma$ ~~γ~~



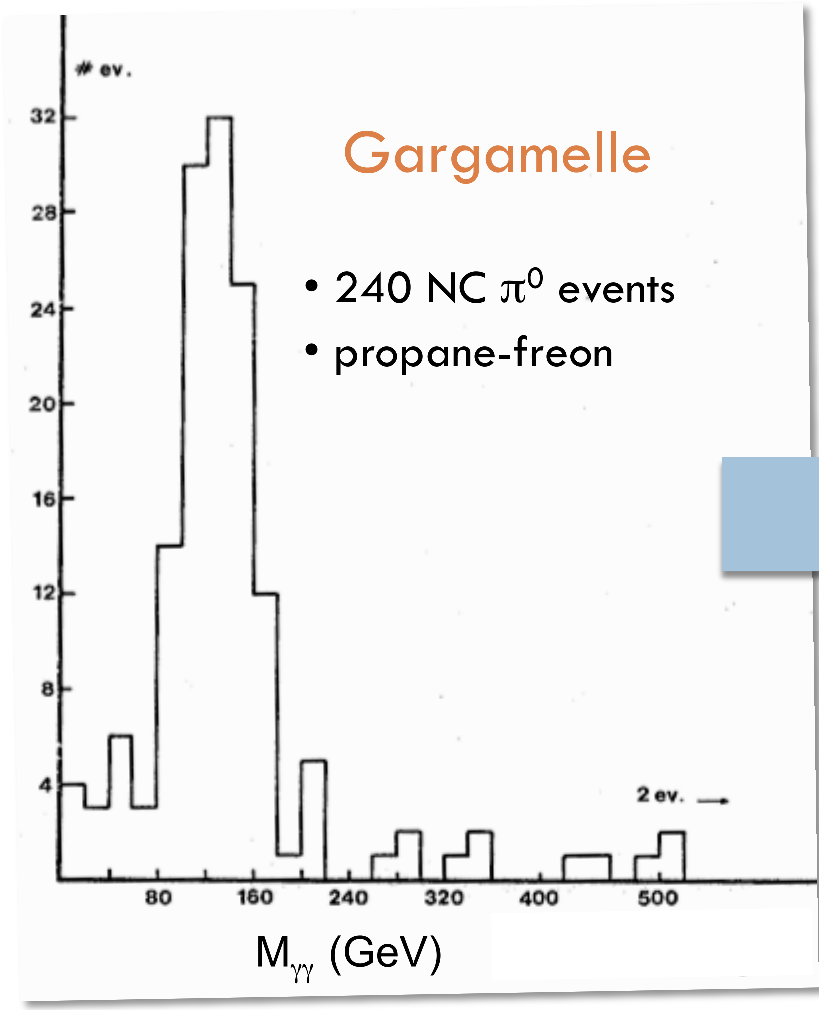


NC π^0 can be a sizable background

also $\Delta \rightarrow N\gamma$

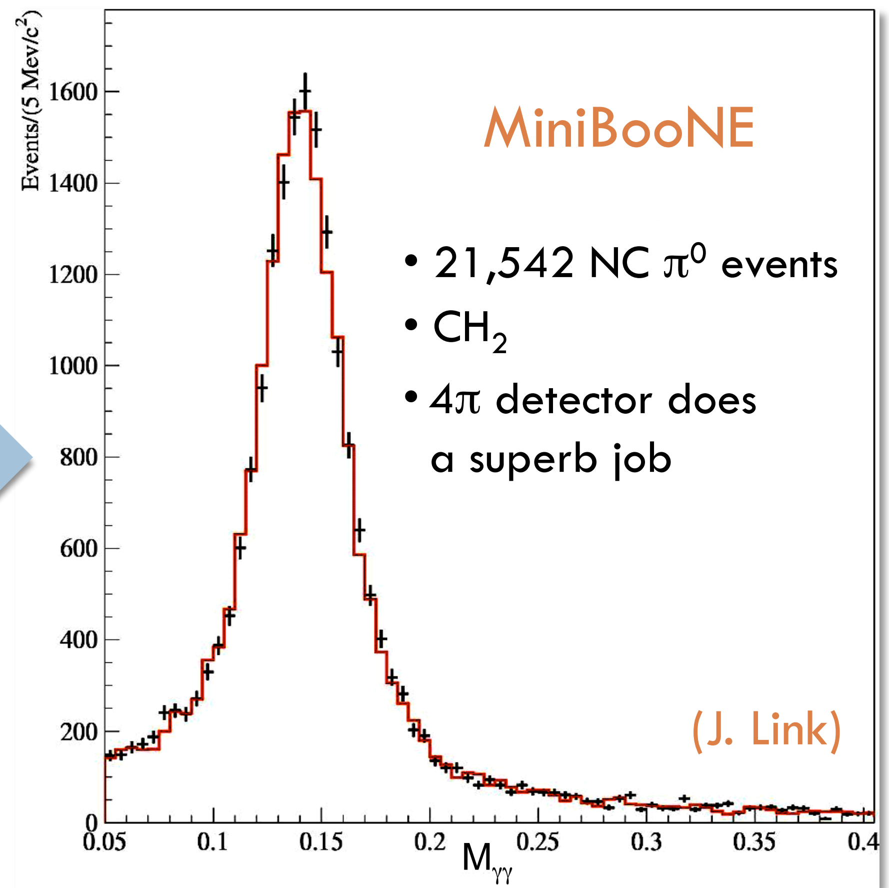
goal: 5-10% level or better

NC π^0 Production ($\pi^0 \rightarrow \gamma\,\gamma$)



Krenz *et al.*, Nucl. Phys. **B135**, 45 (1978)

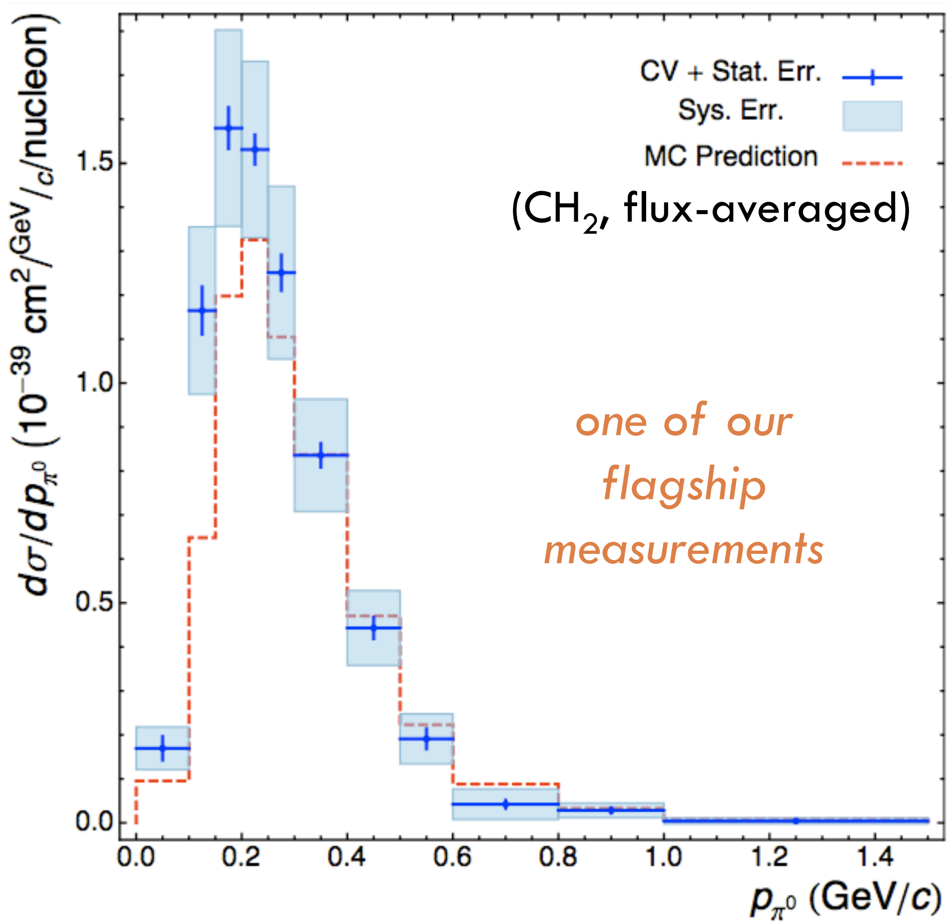
• coming back to this 30 years later …



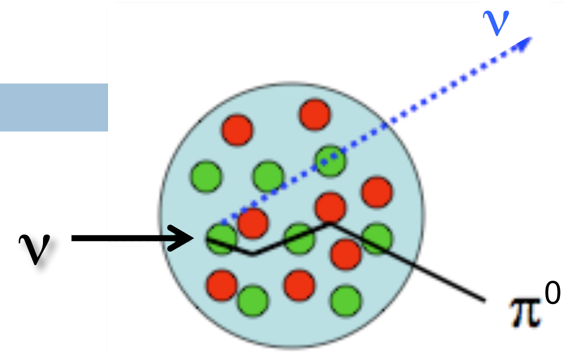
1st time we've had a high statistics measurement of this process in ν scattering

NC π^0 at MiniBooNE

- different philosophy than historical measurements



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



- total σ for a NC ν interaction to produce a π^0 exiting the target nucleus, "observed σ"

  (this is what we care about)

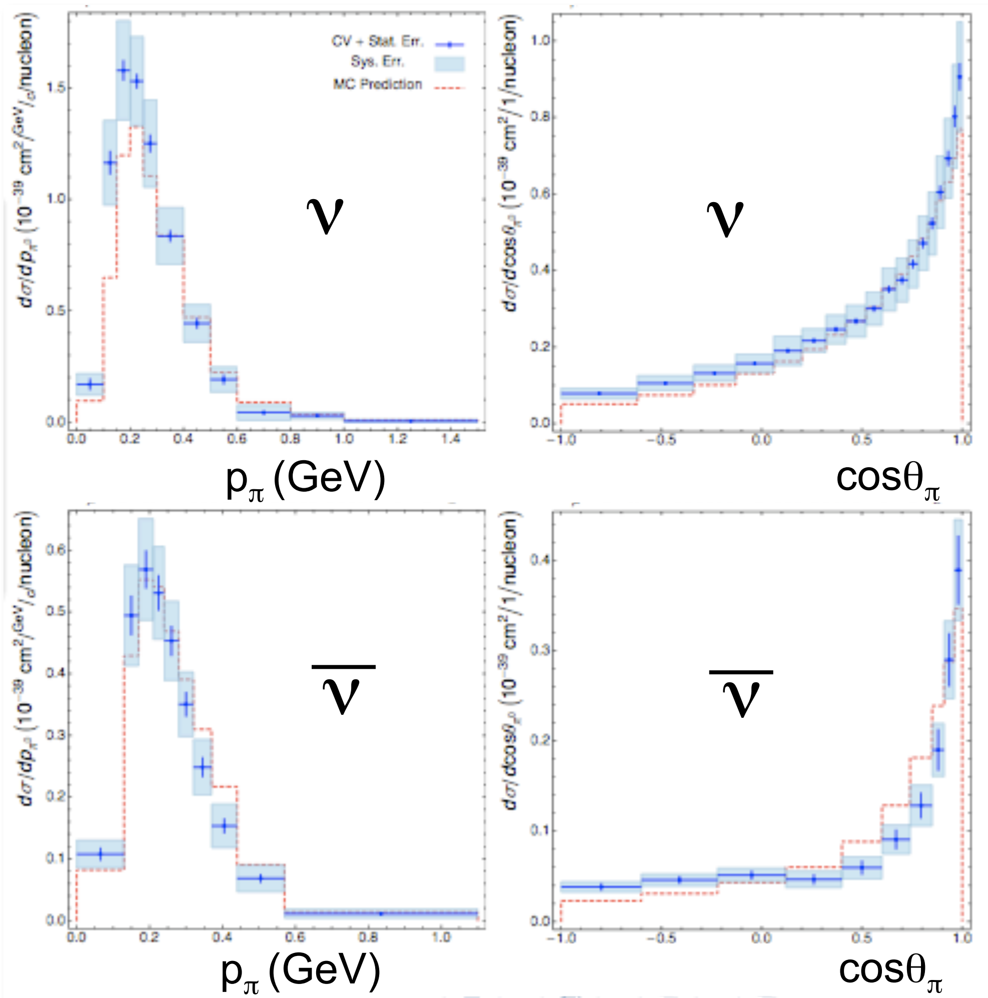
- measures initial ν interaction σ, nuclear effects, & FSI effects

- have not corrected any of these effects out of the data

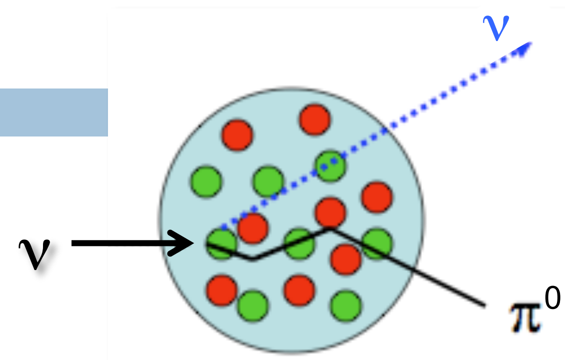
  (this is something new)

NC π^0 at MiniBooNE

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



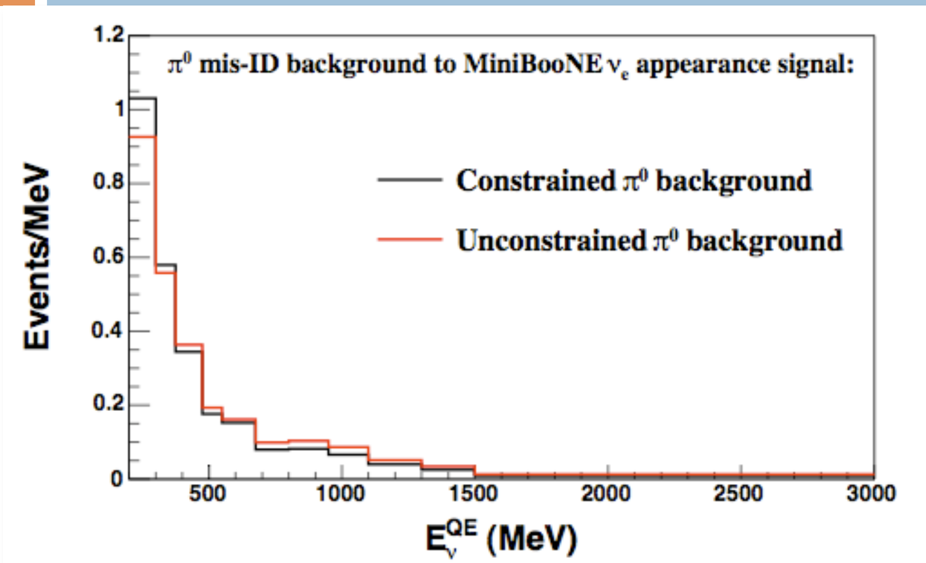
(CH_2, flux-averaged)

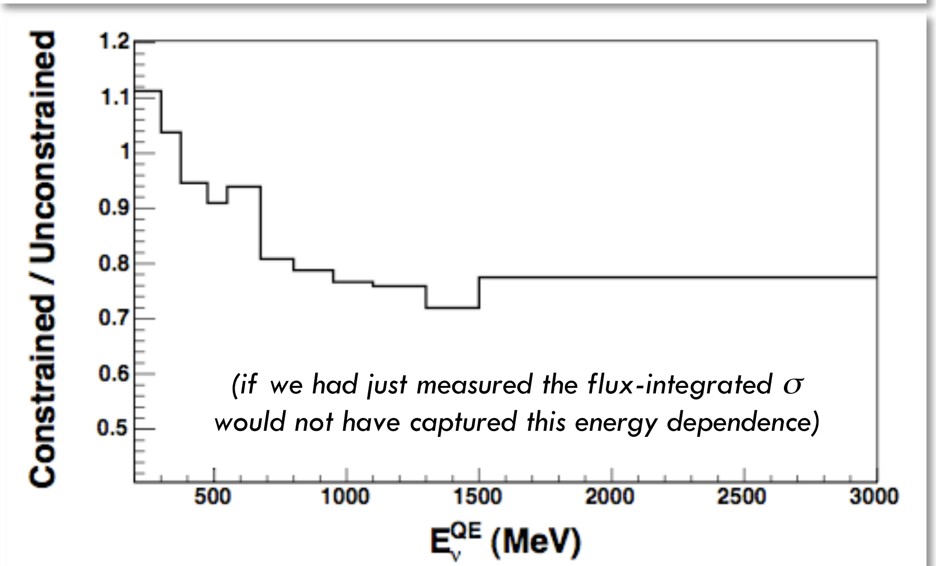


- this is the 1st time differential σ's have been provided for such neutrino interactions
- this kinematic information was crucial for $\nu_\mu \rightarrow \nu_e$ search in MiniBooNE (E_ν dependence of bkgs)

(C. Anderson, Yale, Ph.D. thesis)

NC π^0 Constraints



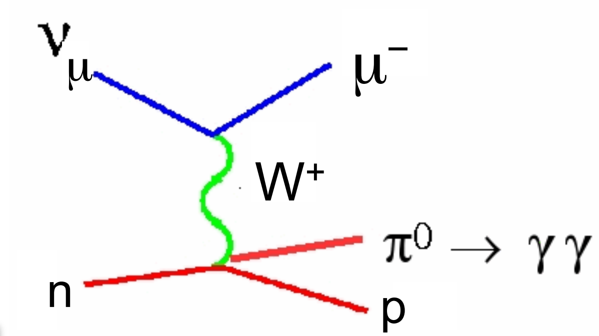


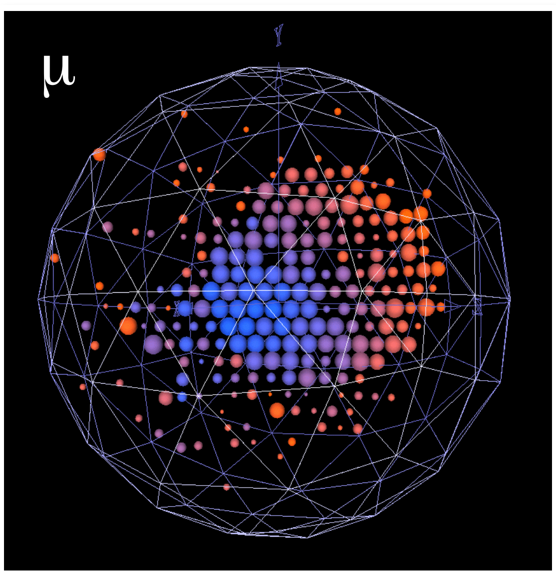
(G. Karagiorgi, MIT)

- need measurements on other targets and at other energies
  - MINERνA
  - ArgoNeuT
  - ICARUS
  - MicroBooNE
- important for understanding:
  - initial ν-nucleus interaction
  - π transport (abs, cex)
  - role of axial-vector contrib
  - effect of 2p2h on 1π prod

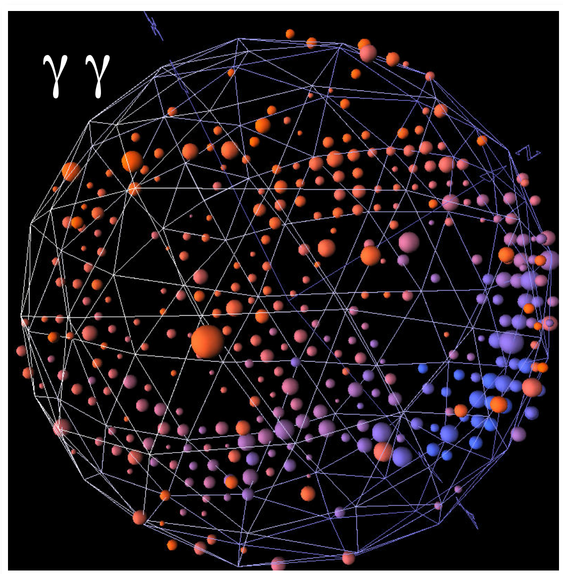
CC π^0 at MiniBooNE

- as a cross-check, also studied the CC equivalent of this process
- main difference is that get μ in addition to π^0
- these events have 3 Čerenkov rings, so developed a custom 3-ring fitter (B. Nelson, UC Boulder, Ph.D. thesis)





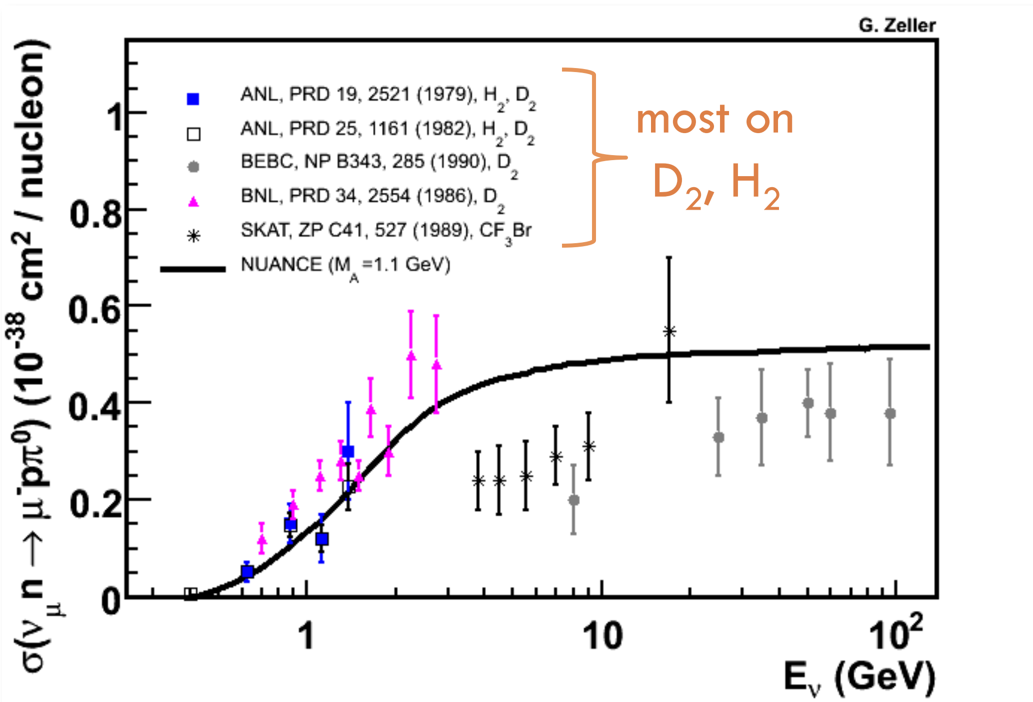
+

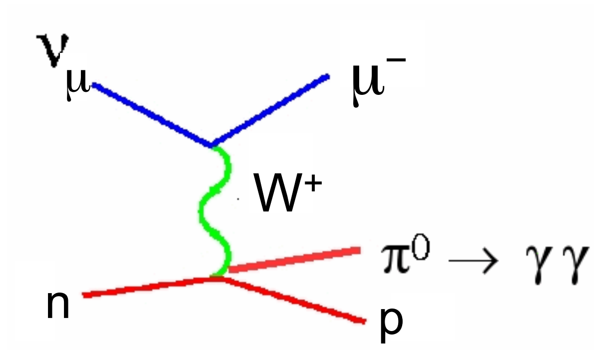


- most complex final state that we attempt to reconstruct in MB
- 5,800 events
  (3 times all previous ν data sets combined)

Historic CC π^0 Measurements

- this is what we've known on this reaction
  … this is our starting point





- again, most of the historical focus was on measuring $\sigma(E_\nu)$
- models tended to underpredict the cross section at low E_ν
- x2 difference between some of the measurements

CC π^0 at MiniBooNE

Aguilar-Arevalo, PRD **83**, 052009 (2011)

Measurement of ν_μ-induced charged-current neutral pion production cross sections on mineral oil at $E_\nu \in 0.5 - 2.0$ GeV

A. A. Aguilar-Arevalo,[14] C. E. Anderson,[19] A. O. Bazarko,[16] S. J. Brice,[8] B. C. Brown,[8] L. Bugel,[13] J. Cao,[15] L. Coney,[6] J. M. Conrad,[13] D. C. Cox,[10] A. Curioni,[19] R. Dharmapalan,[1] Z. Djurcic,[2] D. A. Finley,[8] B. T. Fleming,[19] R. Ford,[8] F. G. Garcia,[8] G. T. Garvey,[11] J. Grange,[9] C. Green,[8,11] J. A. Green,[10,11] T. L. Hart,[5] E. Hawker,[4,11] R. Imlay,[12] R. A. Johnson,[4] G. Karagiorgi,[13] P. Kasper,[8] T. Katori,[10,13] T. Kobilarcik,[8] I. Kourbanis,[8] S. Koutsoliotas,[3] E. M. Laird,[16] S. K. Linden,[19] J. M. Link,[18] Y. Liu,[15] Y. Liu,[1] W. C. Louis,[11] K. B. M. Mahn,[6] W. Marsh,[8] C. Mauger,[11] V. T. McGary,[13] G. McGregor,[11] W. Metcalf,[12] P. D. Meyers,[16] F. Mills,[8] G. B. Mills,[11] J. Monroe,[6] C. D. Moore,[8] J. Mousseau,[9] R. H. Nelson,[5,*] P. Nienaber,[17] J. A. Nowak,[12] B. Osmanov,[9] S. Ouedraogo,[12] R. B. Patterson,[16] Z. Pavlovic,[11] D. Perevalov,[1,8] C. C. Polly,[8] E. Prebys,[8] J. L. Raaf,[4] H. Ray,[9] B. P. Roe,[15] A. D. Russell,[8] V. Sandberg,[11] R. Schirato,[11] D. Schmitz,[8] M. H. Shaevitz,[6] F. C. Shoemaker,[16,†] D. Smith,[7] M. Soderberg,[19] M. Sorel,[6,‡] P. Spentzouris,[8] J. Spitz,[19] I. Stancu,[1] R. J. Stefanski,[8] M. Sung,[12] H. A. Tanaka,[16] R. Tayloe,[10] M. Tzanov,[5] R. G. Van de Water,[11] M. O. Wascko,[12,§] D. H. White,[11] M. J. Wilking,[5] H. J. Yang,[15] G. P. Zeller,[8] and E. D. Zimmerman[5]

(MiniBooNE Collaboration)

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[3] *Bucknell University; Lewisburg, PA 17837*
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[6] *Columbia University; New York, NY 10027*
[7] *Embry-Riddle Aeronautical University; Prescott, AZ 86301*
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[9] *University of Florida; Gainesville, FL 32611*
[10] *Indiana University; Bloomington, IN 47405*
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[13] *Massachusetts Institute of Technology; Cambridge, MA 02139*
[14] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, D.F. 04510, México*
[15] *University of Michigan; Ann Arbor, MI 48109*
[16] *Princeton University; Princeton, NJ 08544*
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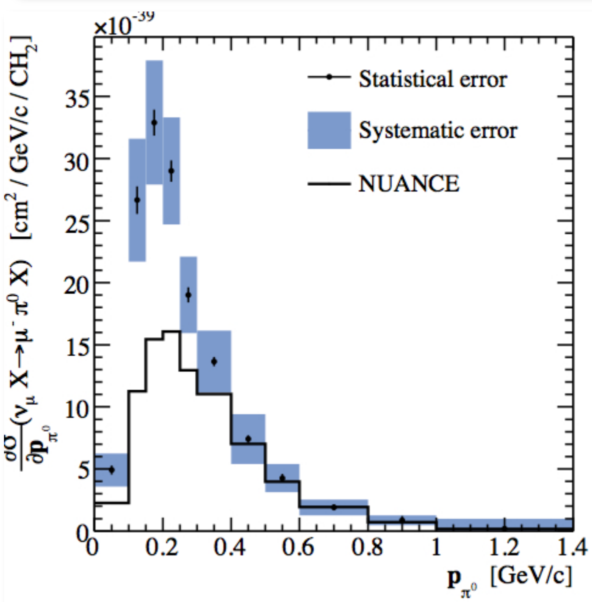
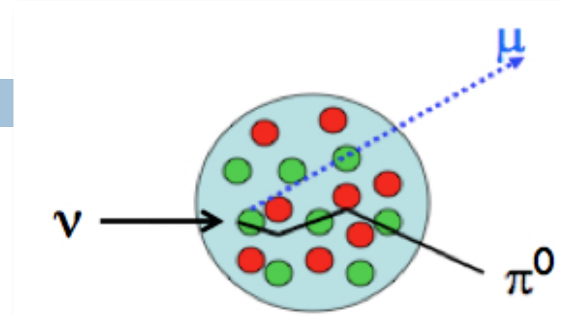
[19] *Yale University; New Haven, CT 06520*

(Dated: December 28, 2010)

Using a custom 3 Čerenkov-ring fitter, we report cross sections for ν_μ-induced charged-current single π^0 production on mineral oil (CH_2) from a sample of 5810 candidate events with 57% signal purity over an energy range of 0.5 – 2.0 GeV. This includes measurements of the absolute total cross section as a function of neutrino energy, and flux-averaged differential cross sections measured in terms of Q^2, μ^- kinematics, and π^0 kinematics. The sample yields a flux-averaged total cross section of $(9.2 \pm 0.3_{stat.} \pm 1.5_{syst.}) \times 10^{-39}$ cm^2/CH_2 at mean neutrino energy of 0.965 GeV.





- have measured a variety of kinematics for this process:

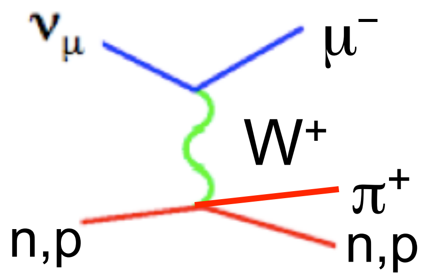
  $\sigma(E_\nu)$, $d\sigma/dQ^2$

  $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$
  $d\sigma/dp_\pi$, $d\sigma/d\theta_\pi$ } reduced model-dependence

- most comprehensive study of CC π^0 to date (B. Nelson, UC Boulder, Ph.D. thesis)
  - excess of data/model also present in this channel too
  - similar effects seen by K2K (higher E_ν)

    C. Mariani *et al.*, Phys. Rev. D83, 054023 (2011)

CC π^+ at MiniBooNE



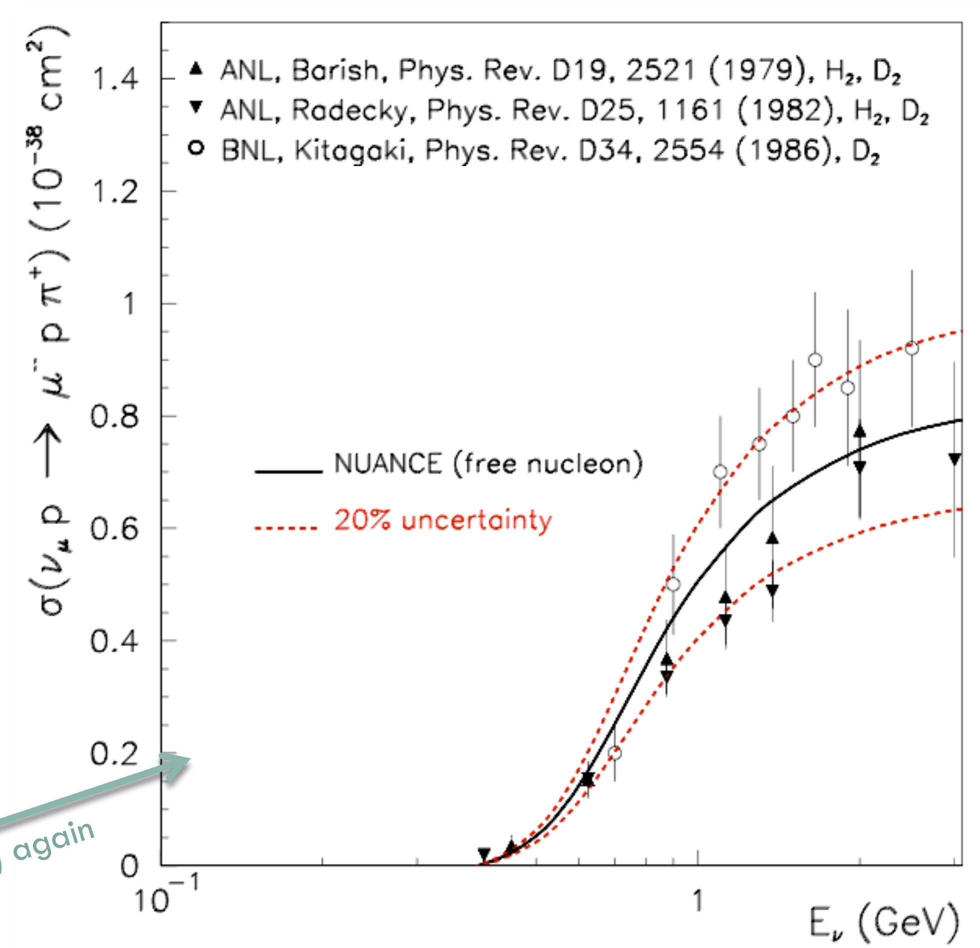
- important background for disappearance experiments

$$\nu_\mu \rightarrow \not\nu_\mu$$

- if π absorbed, impacts E_ν determination
- introduces a systematic on Δm^2_{23}, θ_{23}

- long-standing discrepancy between ANL & BNL (D_2)

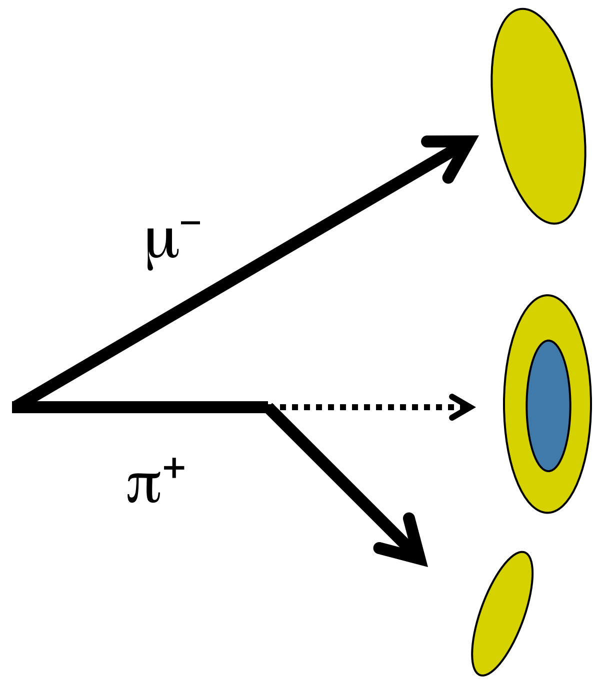
$\sigma(E_\nu)$ again



(didn't want to live with this for MB disappearance search)

CC π^+ at MiniBooNE

- but π^+ reconstruction in a Č detector, μ/π^+ separation are challenging (had never been done before)



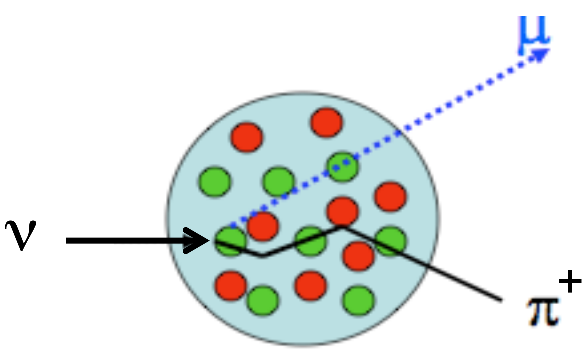
- π's frequently interact hadronically, losing energy & changing direction sharply
- kinked track produces two rings → kinked track fitter
- plus detect e^- from μ, π^+ decays

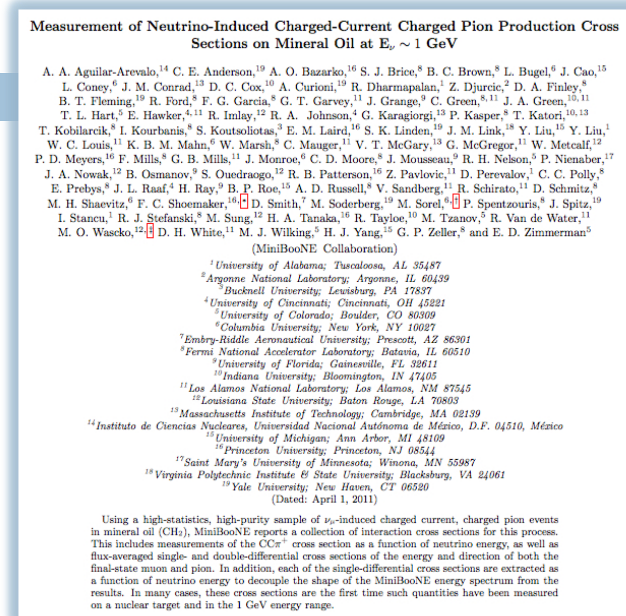
- algorithm separately reconstructs muon & charged pion
  (M. Wilking, UC Boulder, Ph.D. thesis)
- really pushing Č capabilities (but get correct identification 88% of the time)

CC π^+ at MiniBooNE

- highest purity sample (90% CC π^+)

Aguilar-Arevalo *et al.*, PRD **83**, 052007 (2011)





Measurement of Neutrino-Induced Charged-Current Charged Pion Production Cross Sections on Mineral Oil at $E_\nu \sim 1$ GeV

A. A. Aguilar-Arevalo,[14] C. E. Anderson,[19] A. O. Bazarko,[16] S. J. Brice,[8] B. C. Brown,[8] L. Bugel,[6] J. Cao,[15] L. Coney,[6] J. M. Conrad,[13] D. C. Cox,[10] A. Curioni,[19] R. Dharmapalan,[1] Z. Djurcic,[2] D. A. Finley,[8] B. T. Fleming,[19] R. Ford,[8] F. G. Garcia,[8] G. T. Garvey,[11] J. Grange,[9] C. Green,[8,11] J. A. Green,[10,11] T. L. Hart,[5] E. Hawker,[4,11] R. Imlay,[12] R. A. Johnson,[4] G. Karagiorgi,[13] P. Kasper,[8] T. Katori,[10,13] T. Kobilarcik,[8] I. Kourbanis,[8] S. Koutsoliotas,[3] E. M. Laird,[16] S. K. Linden,[19] J. M. Link,[18] Y. Liu,[15] Y. Liu,[1] W. C. Louis,[11] K. B. M. Mahn,[6] W. Marsh,[8] C. Mauger,[11] V. T. McGary,[13] G. McGregor,[11] W. Metcalf,[12] P. D. Meyers,[16] F. Mills,[8] G. B. Mills,[11] J. Monroe,[6] C. D. Moore,[8] J. Mousseau,[9] R. H. Nelson,[5] P. Nienaber,[17] J. A. Nowak,[12] B. Osmanov,[9] S. Ouedraogo,[12] R. B. Patterson,[16] Z. Pavlovic,[11] D. Perevalov,[1] C. C. Polly,[8] E. Prebys,[8] J. L. Raaf,[4] H. Ray,[9] B. P. Roe,[15] A. D. Russell,[8] V. Sandberg,[11] R. Schirato,[11] D. Schmitz,[8] M. H. Shaevitz,[6] F. C. Shoemaker,[16,*] D. Smith,[7] M. Soderberg,[19] M. Sorel,[6,†] P. Spentzouris,[8] J. Spitz,[19] I. Stancu,[1] R. J. Stefanski,[8] M. Sung,[12] H. A. Tanaka,[16] R. Tayloe,[10] M. Tzanov,[5] R. Van de Water,[11] M. O. Wascko,[12,‡] D. H. White,[11] M. J. Wilking,[5] H. J. Yang,[15] G. P. Zeller,[8] and E. D. Zimmerman[5]

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[12] *Louisiana State University; Baton Rouge, LA 70803*
[13] *Massachusetts Institute of Technology; Cambridge, MA 02139*
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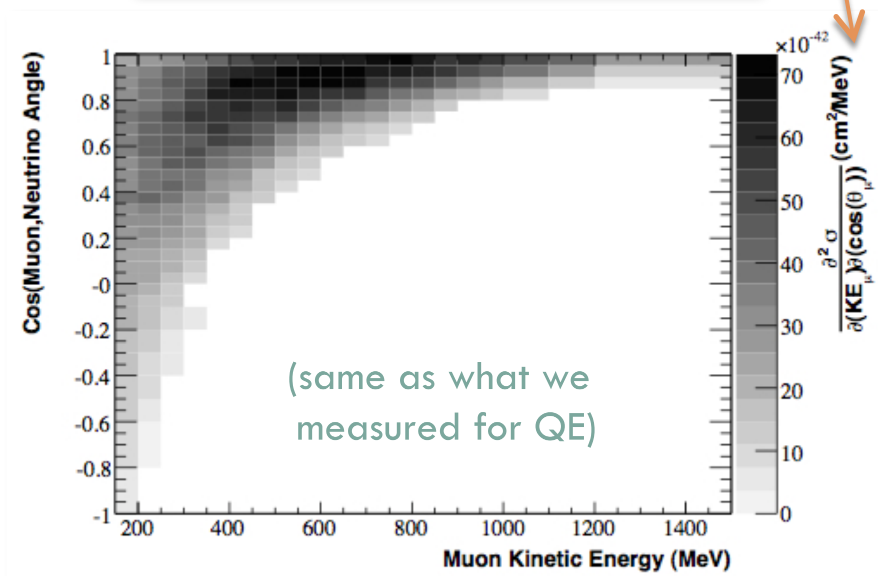
(Dated: April 1, 2011)

Using a high-statistics, high-purity sample of ν_μ-induced charged current, charged pion events in mineral oil (CH_2), MiniBooNE reports a collection of interaction cross sections for this process. This includes measurements of the $CC\pi^+$ cross section as a function of neutrino energy, as well as flux-averaged single- and double-differential cross sections of the energy and direction of both the final-state muon and pion. In addition, each of the single-differential cross sections are extracted as a function of neutrino energy to decouple the shape of the MiniBooNE energy spectrum from the results. In many cases, these cross sections are the first time such quantities have been measured on a nuclear target and in the 1 GeV energy range.

- again, measuring what comes out of nucleus = "observed σ" & complete final state kinematics

σ units



(same as what we measured for QE)

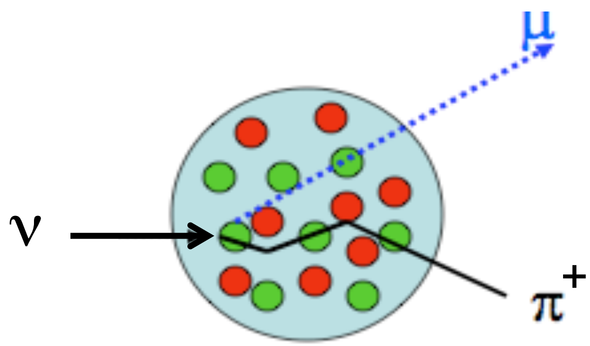
$\sigma(E_\nu)$, $d\sigma/dQ^2$, $d^2\sigma/dT_\mu d\theta_\mu$,
$d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$,
$d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\pi d\theta_\pi$

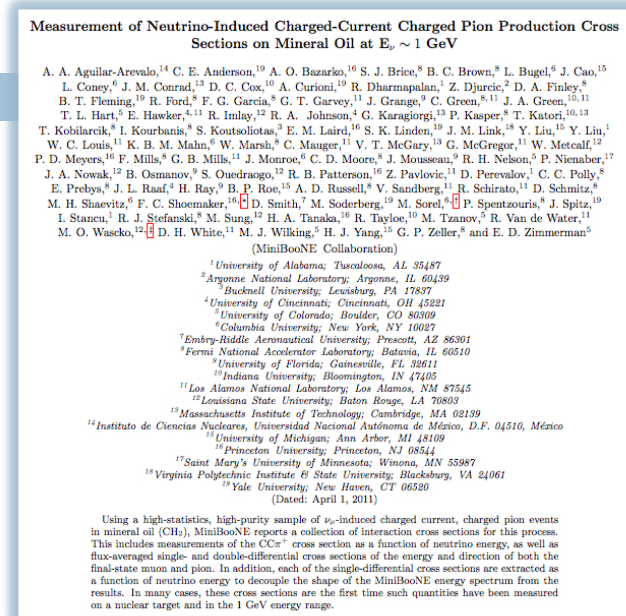
8 dists (many firsts!)

CC π^+ at MiniBooNE

- highest purity sample (90% CC π^+)

Aguilar-Arevalo *et al.*, PRD **83**, 052007 (2011)





Measurement of Neutrino-Induced Charged-Current Charged Pion Production Cross Sections on Mineral Oil at $E_\nu \sim 1$ GeV

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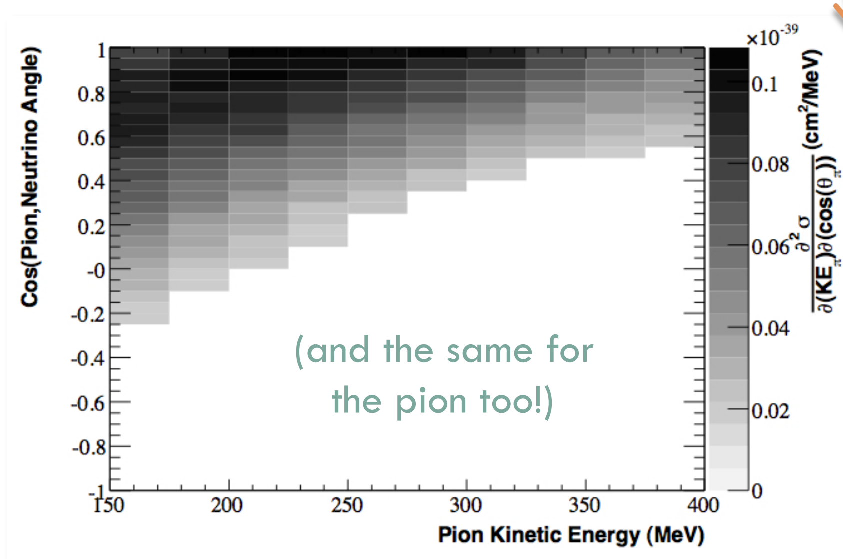
(Dated: April 1, 2011)

Using a high-statistics, high-purity sample of ν_μ-induced charged current, charged pion events in mineral oil (CH_2), MiniBooNE reports a collection of interaction cross sections for this process. This includes measurements of the $CC\pi^+$ cross section as a function of neutrino energy, as well as flux-averaged single- and double-differential cross sections of the energy and direction of both the final-state muon and pion. In addition, each of the single-differential cross sections are extracted as a function of neutrino energy to decouple the shape of the MiniBooNE energy spectrum from the results. In many cases, these cross sections are the first time such quantities have been measured on a nuclear target and in the 1 GeV energy range.

σ units

- again, measuring what comes out of nucleus = "observed σ" & complete final state kinematics



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

8 dists (many firsts!)

Future Prospects for MiniBooNE

- MiniBooNE has provided a new wealth of ν-nucleus scattering data over past 2 years

- in this process, we have thought about how to provide the most useful information possible

- <u>coming soon:</u>

  - *CC inclusive diff'l cross sections (M. Tzanov)*
  - *$\bar{\nu}$ QE diff'l cross sections (J. Grange)*
  - *$\bar{\nu}$ NC elastic diff'l cross sections (R. Dharmapalan)*
  - *μ+p QE analysis (A. Wickremasinghe)*

Conclusions

- in the past couple years, there has been renewed appreciation for the complexities surrounding ν-nucleus scattering in the few-GeV region
- this has been a very active area of investigation in MiniBooNE
  (9 publications, 5 channels, 24 differential σ distributions)
  - *went through some of the highlights*
  - *probing nuclear effects with new precision*
  - *challenging assumptions about the size and source of nuclear effects at these energies*

- still have a lot to learn from e^-, γ scattering
- look forward to additional ν data
  (MINERνA, T2K & NOνA, ArgoNeuT, ICARUS, MicroBooNE)
- crucial to have this physics under control for future ν oscillation investigations (MH, $\not{CP}$)