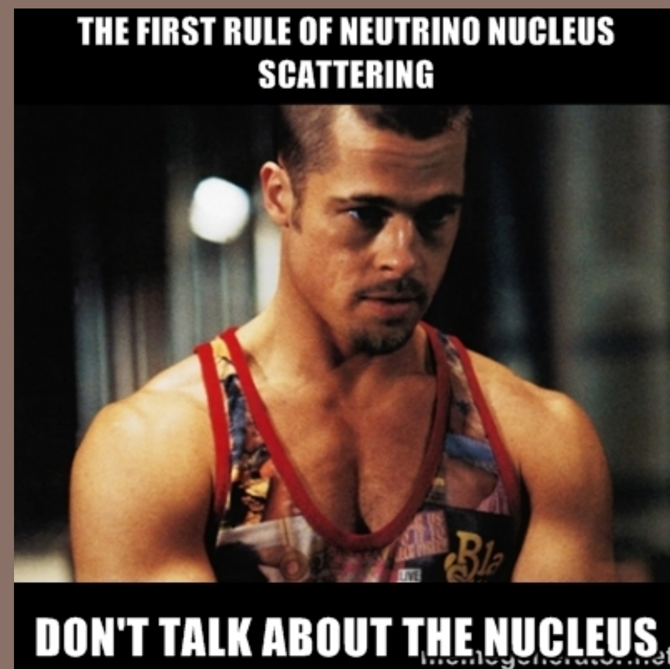
NEUTRINO-NUCLEUS INTERACTIONS
(A REPORT FROM THE INT WORKSHOP)

Sam Zeller
Fermilab

IF seminar

February 13, 2014



(K. McFarland, ICFA workshop)

- collection of thoughts from a recent workshop we had at INT
  disclaimer: this will be from an experimentalists point of view

(also, apologies for some of the things I have left out)

The Workshop

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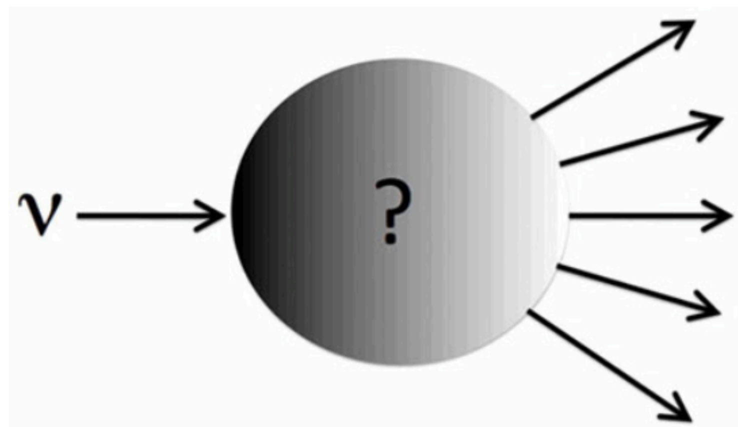
Agenda

Suggested materials for QE discussion

INT Workshop INT-13-54W

Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments

December 3-13, 2013



The recent establishment of non-zero and relatively large θ_{13} has paved the way for the next generation of long-baseline neutrino oscillation experiments to probe CP violation in the lepton sector, a critical ingredient in understanding the persistent question of how the Universe evolved from its birth to its current matter-dominated state. To enable a discovery of CP violation, such neutrino experiments will also need to determine the neutrino mass-hierarchy and provide more precise measurements of the neutrino mixing parameters. Combined, this inquiry will lead to a full understanding of lepton mixing which could provide clues to new physics that may govern the mixing pattern or reveal new phenomenon that cannot be accommodated by the standard three-neutrino model.

http://www.int.washington.edu/PROGRAMS/13-54w/

Introduction

- workshop at INT in Seattle
  - *>60 theorists & experimentalists (ν, e^-, π) in one room for 2 weeks*
  - ***very lively** discussions, made some important progress*

- three main topics:

  (1) quasi-elastic scattering
  (2) inelastic interactions (resonance production, DIS)
  (3) photon production

- talk will be less technical than the worksohop & aimed at 2 audiences
  - *those on neutrino experiments: you should know this history & what's going on*
  - *those not on neutrino experiments: you should know the ?'s to ask*

Electron Scattering

- most of what we know about lepton-nucleus interactions comes from electron scattering experiments

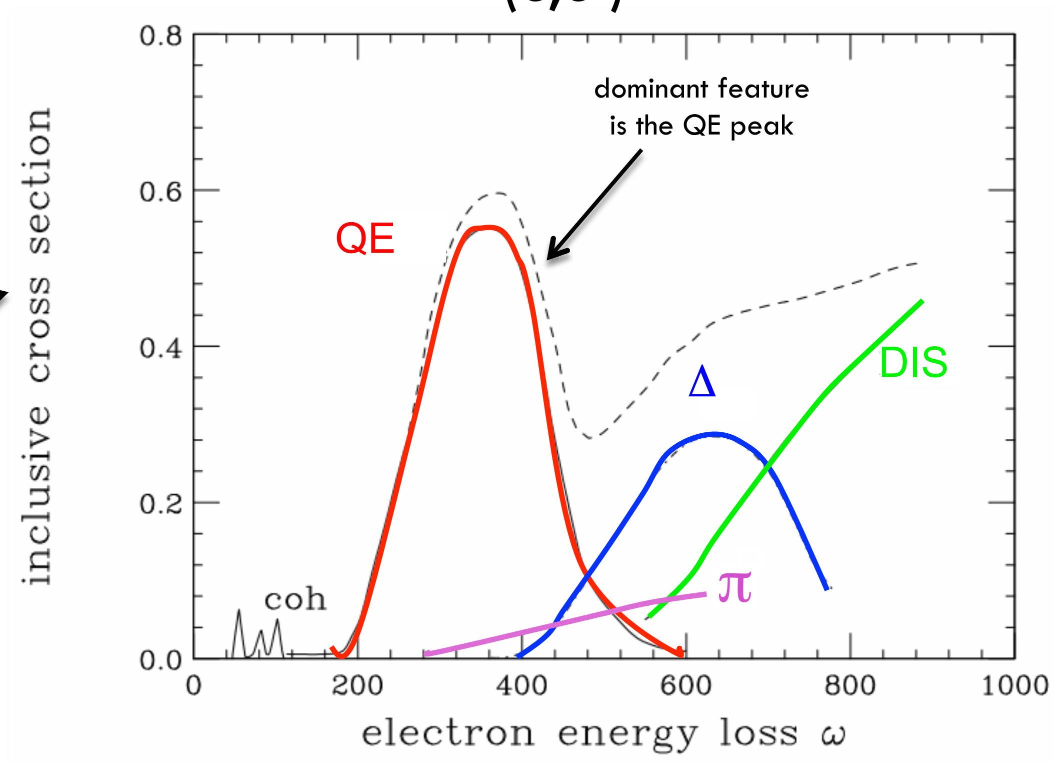
  - *there are some important differences between e^- and ν scattering*

  - *beam energy is known, monochromatic*

  - *energy & momentum transferred to the nucleus can be precisely measured*

  - *typically think in terms of ω $(E_{lep}^{in}-E_{lep}^{out} = \omega = \nu = E_{had})$*

(e,e')



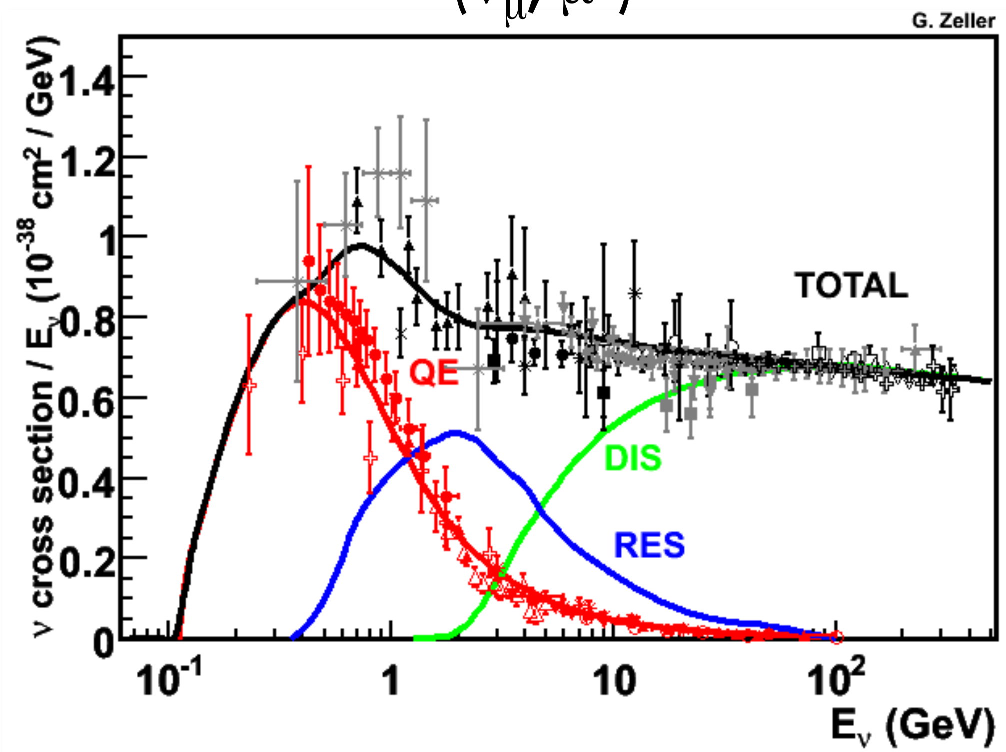
Benhar, Day, Sick, Rev. Mod. Phys. 80, 189 (2008)

Neutrino Scattering

- contrast this with ν scattering (where have preserved the color scheme)

  - *beam energy is not known, and is not monochromatic (spectrum of incoming E_ν)*
  - *have poorer kinematic specification*
  - *tend to think in terms of E_ν*
  - *have to infer E_ν from observed final state particles ($=E_{lep}+E_{had}$ or $E_\nu^{QE}=f(E_{lep},\theta_{lep})$)*
  - *plus, addition of an axial-vector contribution*

(ν_μ, μ^-)

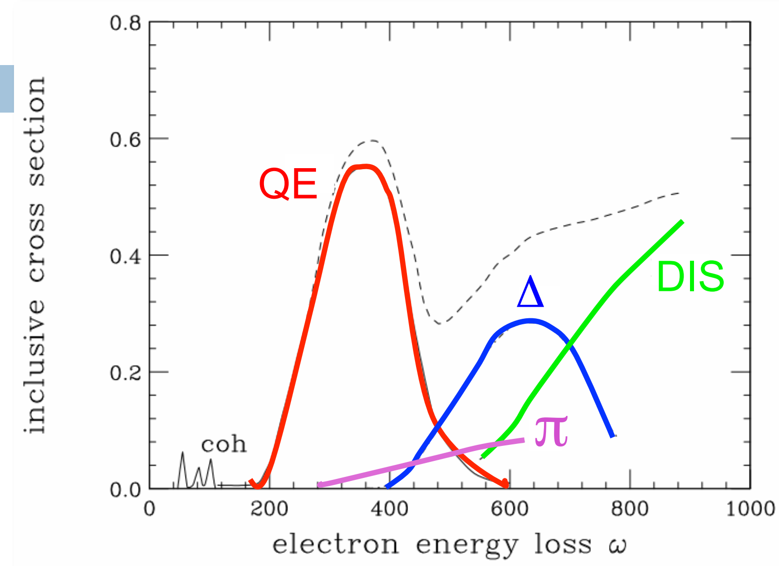


Formaggio, Zeller, Rev. Mod. Phys. 84, 1307 (2012)

QE Scattering

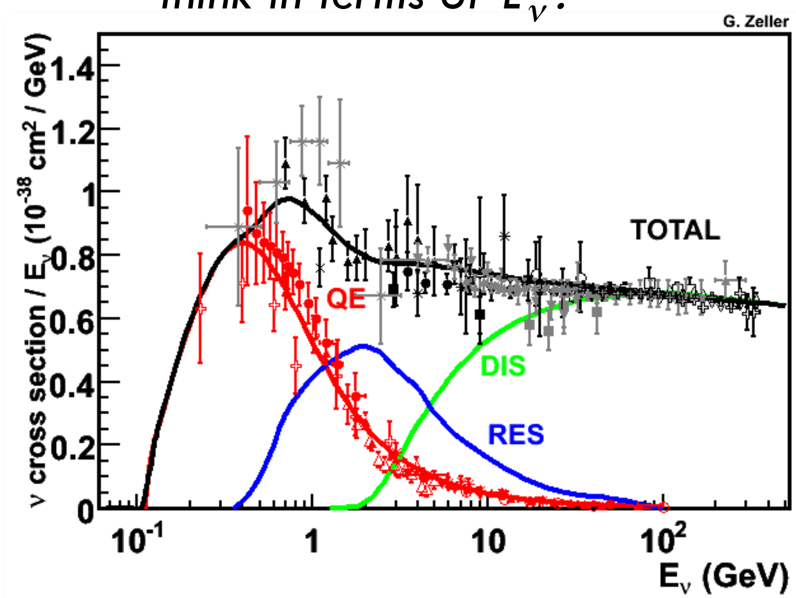
- **electron scattering**

think in terms of ω :



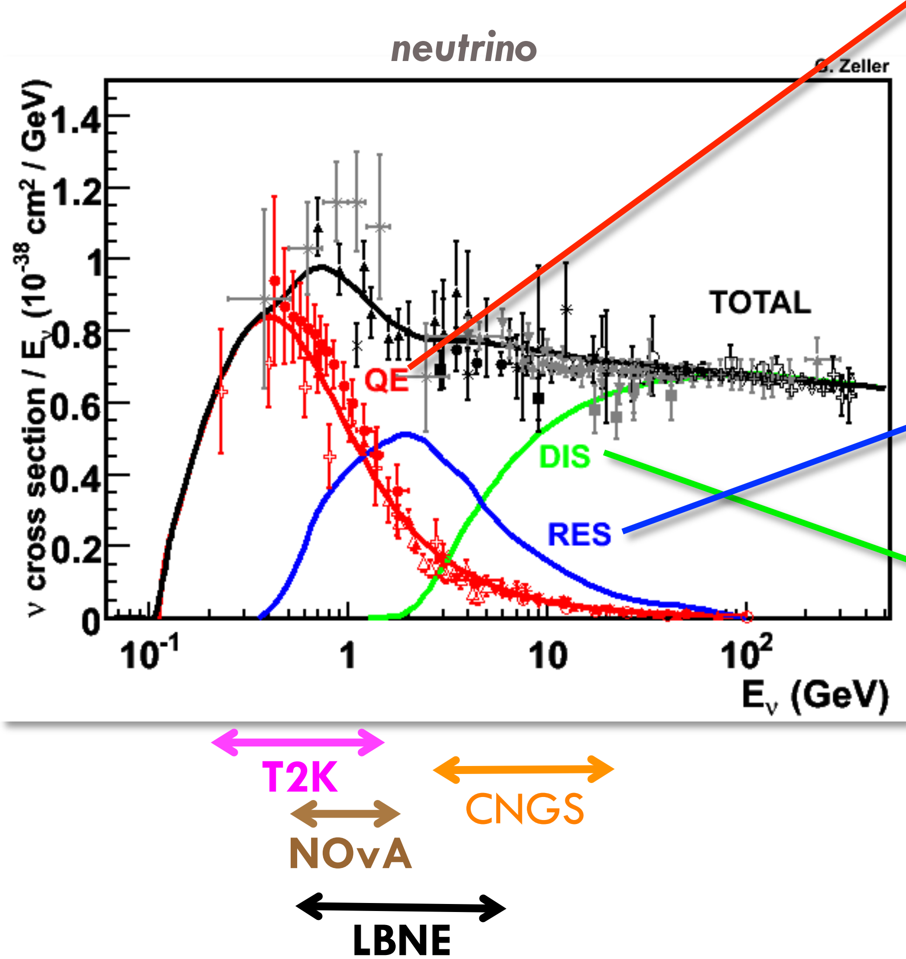
- **neutrino scattering**

think in terms of E_ν :



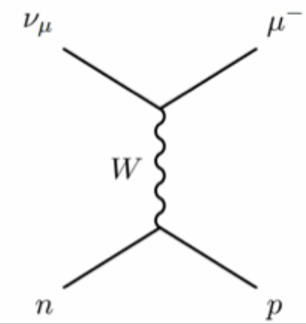
Complicated Region

(event samples contain contributions from multiple reaction mechanisms)



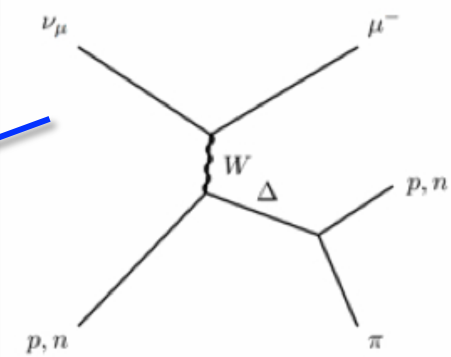
CC Quasi-elastic

nucleon changes, but doesn't break up



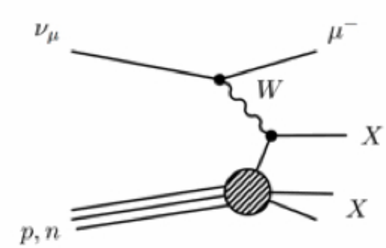
CC Single pion

nucleon excites to resonance state



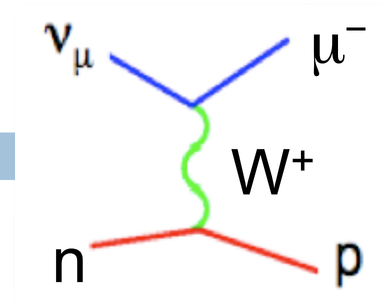
CC Deep Inelastic

nucleon breaks up



let's start with QE …

Neutrino QE Scattering



Why Do We Care?

- **important for ν oscillation experiments**
  - biggest piece of the cross section at energies $E_\nu \lesssim 1$ GeV, so typically gives the largest contribution to signal samples in many osc exps
  - can infer E_ν solely from the out-going lepton (E_{lep}, θ_{lep})
  - once thought of as the simplest neutrino process to calculate

(in all of our MCs, assume scattering takes place on individual nucleons; traditionally thought of as a process with a single knock-out nucleon)

the description becomes more complicated when this process occurs within a nucleus, as we'll see

Neutrino QE Measurements

Table 1 Attributes of experiments that have measured neutrino quasi-elastic scattering processes or that will complete such studies in the near future[a,b]

Experiment	$<E_\nu>$	Target	Detector(s)	Years	Reference(s)
ANL	0.5 GeV	Fe, D_2	Spark chamber, bubble chamber	1969–1982	2, 13, 14
BEBC	54 GeV	D_2	Bubble chamber	1990	15
BNL	1.6 GeV	D_2, H_2	Bubble chamber	1980–1981	16
FNAL	27 GeV	D_2, Ne-H_2	Bubble chamber	1982–1984	17
GGM	2.2 GeV	C_3H_8, CF_3Br	Bubble chamber	1964–1979	18
Serpukhov	3–30 GeV	Al	Spark chamber	1985	19
SKAT	9 GeV	CF_3Br	Bubble chamber	1988–1992	20
ArgoNeuT	3.3 GeV	Ar	Liquid argon time-projection chamber	2009–2010	21
K2K	1.3 GeV	CH_2, H_2O	Tracking detectors: solid scintillator strips plus scintillating fiber tracker	2003–2004	22
MicroBooNE	0.8 GeV	Ar	Liquid argon time-projection chamber	2013–	23
MINERνA	3.3 GeV	C, Fe, Pb	Tracking detector (solid scintillator strips) plus electromagnetic and hadronic calorimetery	2009–present	24
MiniBooNE	0.8 GeV	CH_2	Cherenkov detector	2002–present	25, 26
MINOS	3.3 GeV	Fe	Tracking calorimeter: iron plates plus solid scintillator strips	2004–present	27
NOMAD	26 GeV	C	Drift chambers	1995–1998	7
NOνA ND	2 GeV	CH_2	Tracking detector: liquid scintillator cells	2010–present	28
SciBooNE	0.8 GeV	CH	Tracking detector (solid scintillator strips) plus electromagnetic calorimeter	2007–2008	29
T2K ND	2.1 GeV	C, H_2O	Tracking detectors: solid scintillator plus time-projection chambers plus electromagnetic calorimeters	2010–present	30

Gallagher, Garvey, Zeller, Ann. Rev. Nucl. Part. Sci, 61, 355 (2011)

historical measurements ↑

↓ modern measurements

employ a wide range of detector technologies, detection techniques, and nuclear targets (exploring these diffs was a main goal of the workshop at INT)

Deuterium

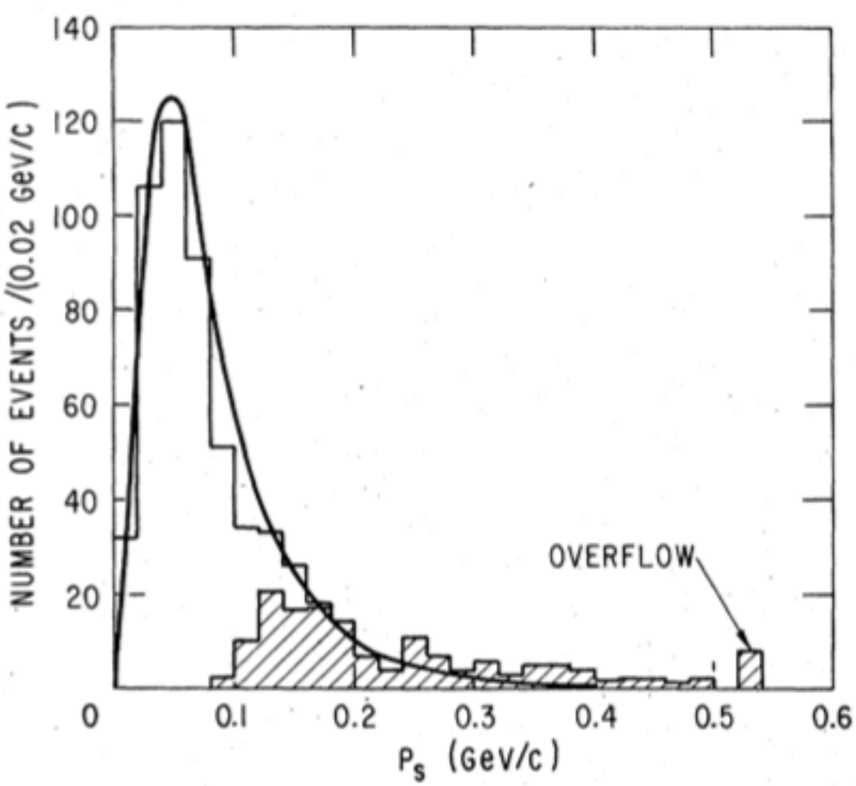


FIG. 19. Spectator momentum distributions for events fitting $\nu d \to \mu^- p p_s$. The shaded area represents the events with a visible spectator. The curve is the Hulthén wave function normalized to the total number of events.

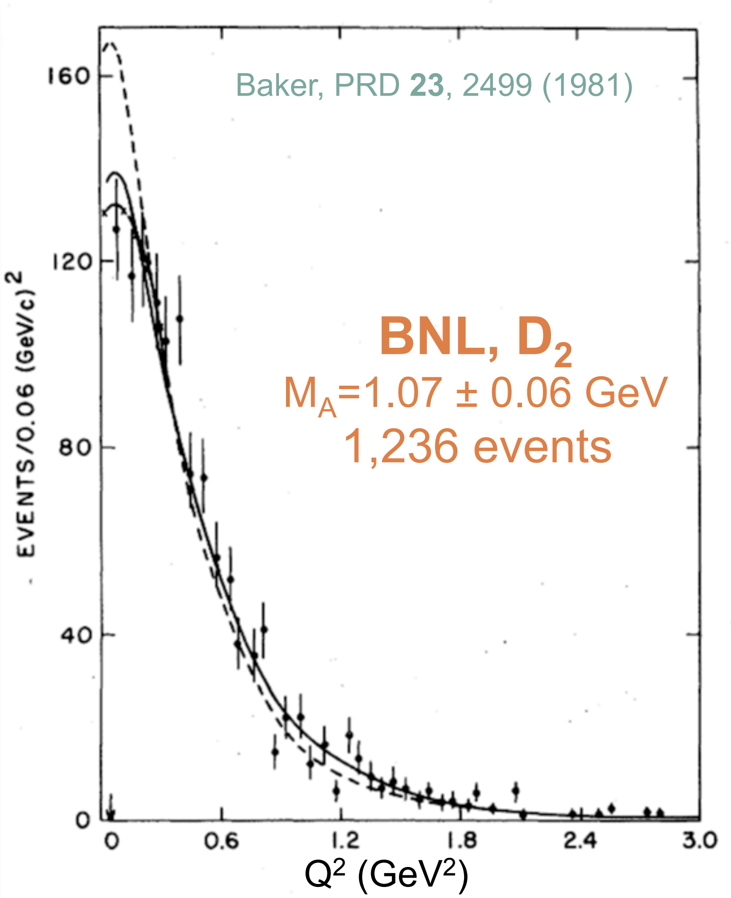
ANL, S.J. Barish et al., PRD 16, 3103, 1977

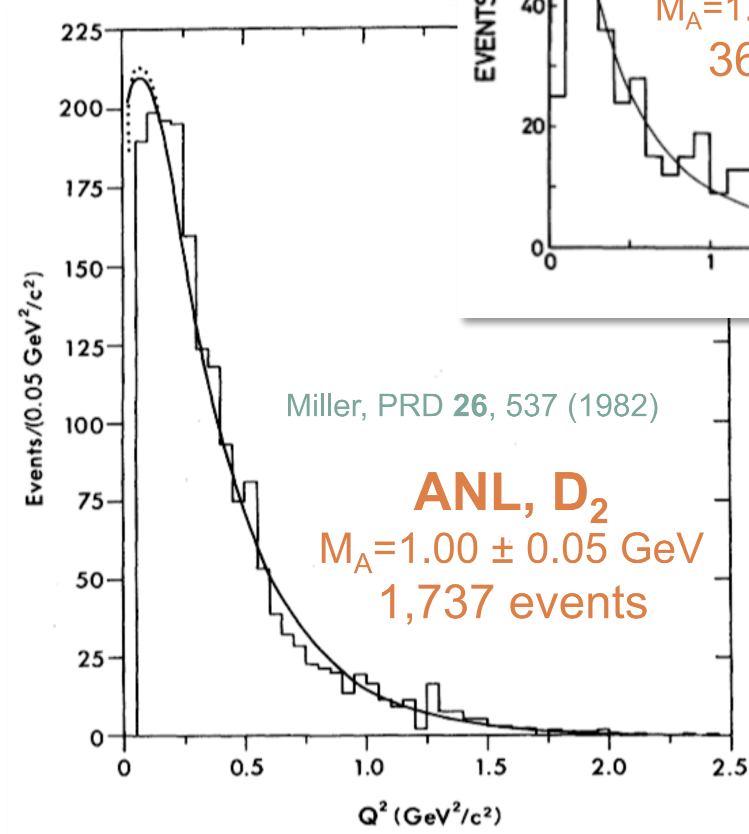
- many of these early ν exps used bubble chambers filled with D_2 *(less influenced by nuclear effects)*
- advantage is that can observe:

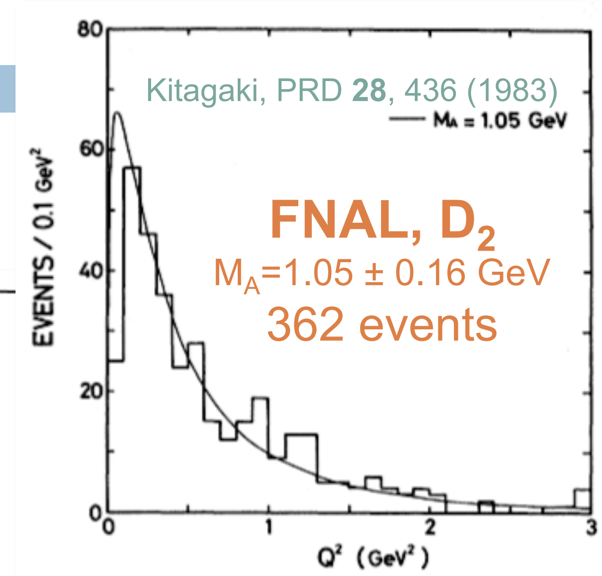
$$\nu_\mu \, n \rightarrow \mu^- \, p \, p_S$$

- advantages:
  - *event selection is more robust & can enforce QE kinematics*
  - *impressive 97-99% QE purities*
- disadvantages:
  - *ν flux not known as well as one might have liked*
  - *low statistics*

Historical Data







recognized as an important ingredient in the analysis of NCs so carefully scrutinized CC equivalent

- primary aim was to measure the axial-vector form factor (M_A~ 1.0 GeV)

ν_μ QE Measurements

Gallagher, Garvey, Zeller, Ann. Rev. Nucl. Part. Sci, 61, 355 (2011)

Table 2 **Summary of analysis techniques employed in the experimental study of neutrino quasi-elastic (QE) scattering**

Experiment	Selection	Number of events	QE purity	Flux (reference)	M_A	$F_A(Q^2)$	$\sigma(E_\nu)$	$\frac{d\sigma}{dQ^2}$	$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$
ANL	Two- and three-track	1,737	98%	Hadro (14)	√		√	√	
BEBC	Three-track	552	99%	ν_μ CC (15)	√		√	√	
BNL	ν: three-track $\bar{\nu}$: one-track	ν: 1,138 $\bar{\nu}$: 13	ν: 97% $\bar{\nu}$: 76%	ν_μ QE (49)	√		√		
FNAL	ν: two- and three-track $\bar{\nu}$: one-track	ν: 362 $\bar{\nu}$: 405	ν: 97% $\bar{\nu}$: 85%	ν_μ QE (50)	√		√		
GGM	ν: two-track $\bar{\nu}$: one-track	ν: 337 $\bar{\nu}$: 837	ν: 97% $\bar{\nu}$: 90%	Hadro (51)	√	√	√	√	
Serpukhov	One-track	ν: 757 $\bar{\nu}$: 389	ν: 51% $\bar{\nu}$: 54%	Hadro, ν_μ CC (19)	√	√	√		
SKAT	ν: two-track $\bar{\nu}$: one-track	ν: 540 $\bar{\nu}$: 159		ν_μ CC (20)	√		√	√	
K2K	One- and two-track	5,568	62%	Hadro, ν_μ CC (52)	√				
MiniBooNE	One-track	146,070	77%	Hadro (53)	√		√	√	√
SciBooNE (preliminary)	One- and two-track	16,501	67%	Hadro (53)			√		
MINOS (preliminary)	One-track	345,000	61%	ν_μ CC (27)	√				
NOMAD	ν: one- and two-track $\bar{\nu}$: one-track	ν: 14,021 $\bar{\nu}$: 2,237	ν: 42%/74% $\bar{\nu}$: 37%	Hadro, DIS, IMD (7)	√		√		

historically, the main focus

+ new MINERvA QE results!

<u>some observations:</u>

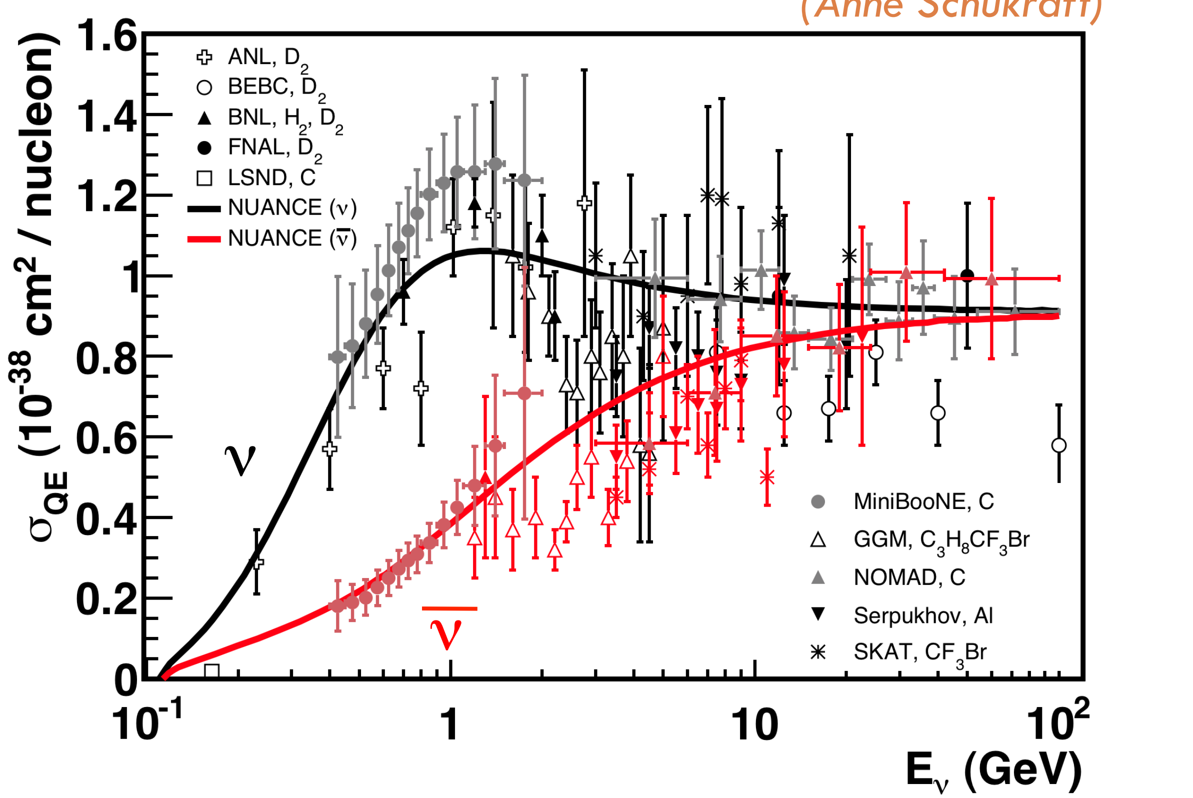
- QE event selection varies experiment to experiment (ex. some require a proton some do not)

- more recently, much larger event samples have become available but purities are typically due to use of heavier nuclear targets

ν_μ QE as a Function of E_ν

- reporting $\sigma(E_\nu)$ has the advantage that can compare measurements from different experiments

(Anne Schukraft)



(Review of Particle Properties, to appear in 2014 edition)

- *but now, we recognize that $\sigma(E_\nu)$, M_A are model-dependent quantities especially when scattering off nuclear targets; strong preference is instead for reporting diff'l σ's in terms of μ,p kinematics!*

and are we all really measuring same thing?

Modern QE Measurements

- there are multiple modern experimental measurements of neutrino QE scattering, all use targets heavier than D_2

    - *much higher statistics*
    - *more well-known incoming neutrino flux predictions*
    - *but the use of* ***nuclear targets*** *brings additional complications*

- at INT, we reviewed what each experiment measures and defines as QE scattering (ArgoNeuT, MiniBooNE, MINERvA, MINOS, NOMAD, NOvA, SciBooNE, T2K)

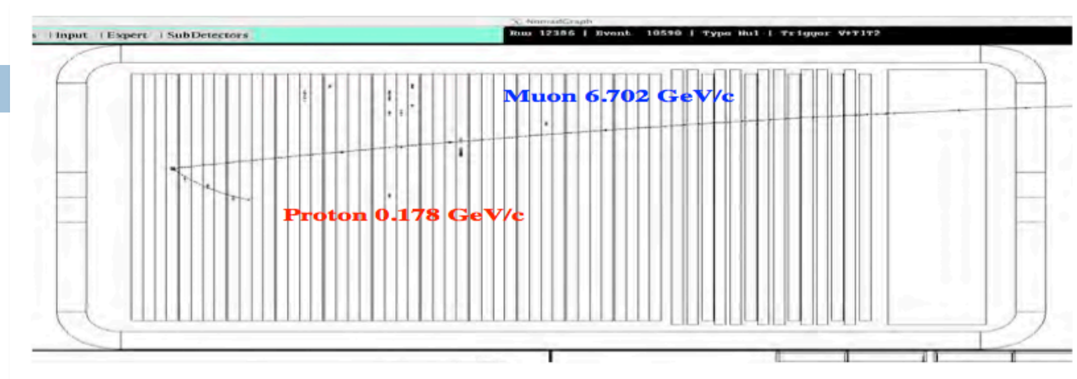
what is ν quasi-elastic scattering?

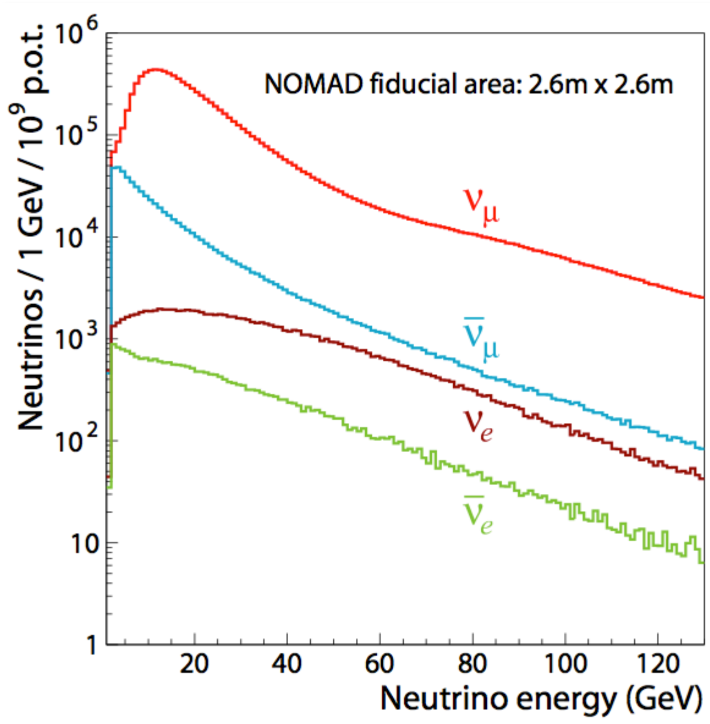
(when you are scattering off a nucleus)

- important to keep in mind: what each exp calls QE is not necessarily the same thing *(is somewhat subjective)* & nuclear effects are important!

NOMAD QE

low density magnetic spectrometer





- "more traditional" QE analysis
- for ν QE, measure both 1 and 2 track samples on carbon, extract $\sigma(E_\nu)$, M_A

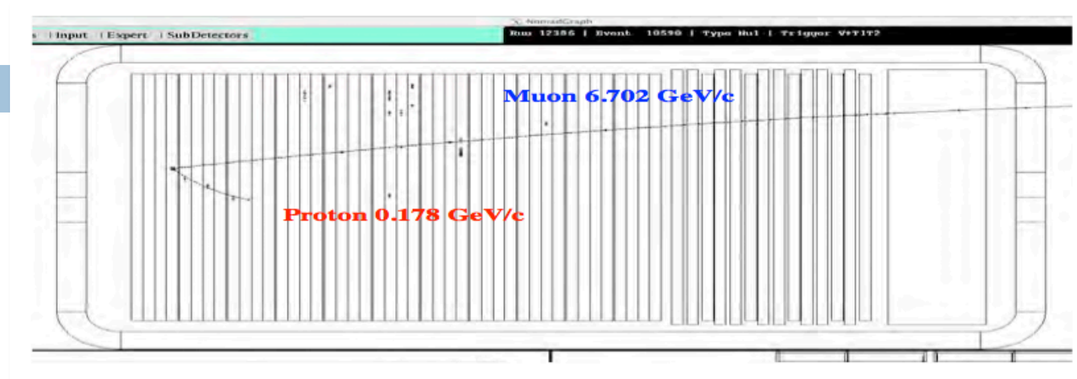
$\Longrightarrow$ *Selected 10358 QE candidates in data with $\varepsilon_{QE} = 21\%$ and purity of 50%.*

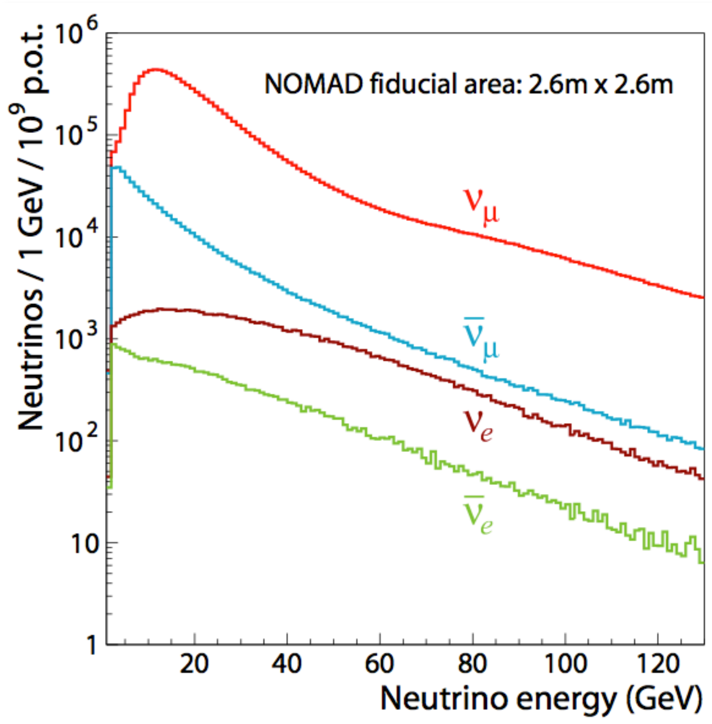
- $<E_\nu>$=24 GeV, both ν, $\bar{\nu}$
- flux verification with IMD and low ν DIS events

- this data is important, it's the only high energy data we have right now *(note: will soon have MINERvA ME data)*

NOMAD QE

low density magnetic spectrometer





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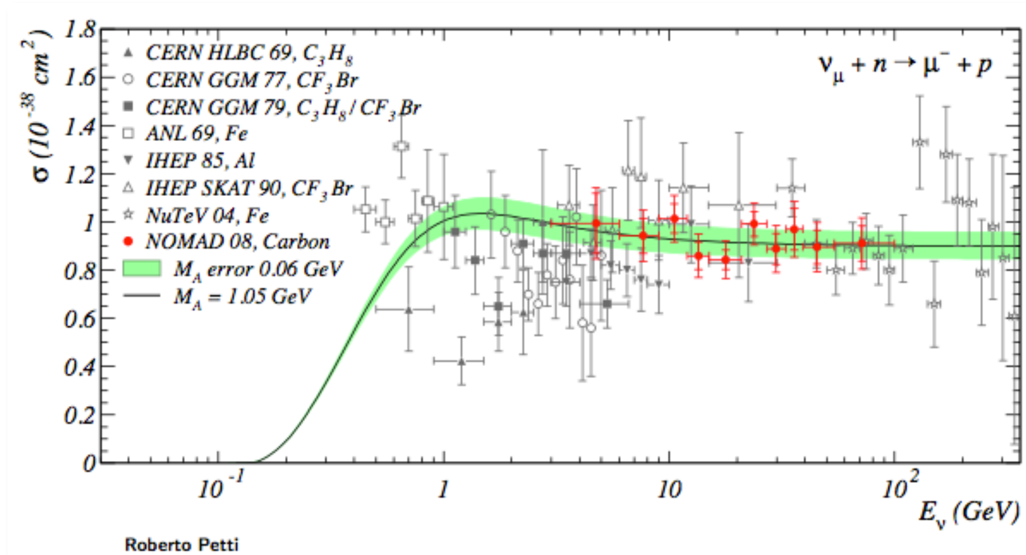

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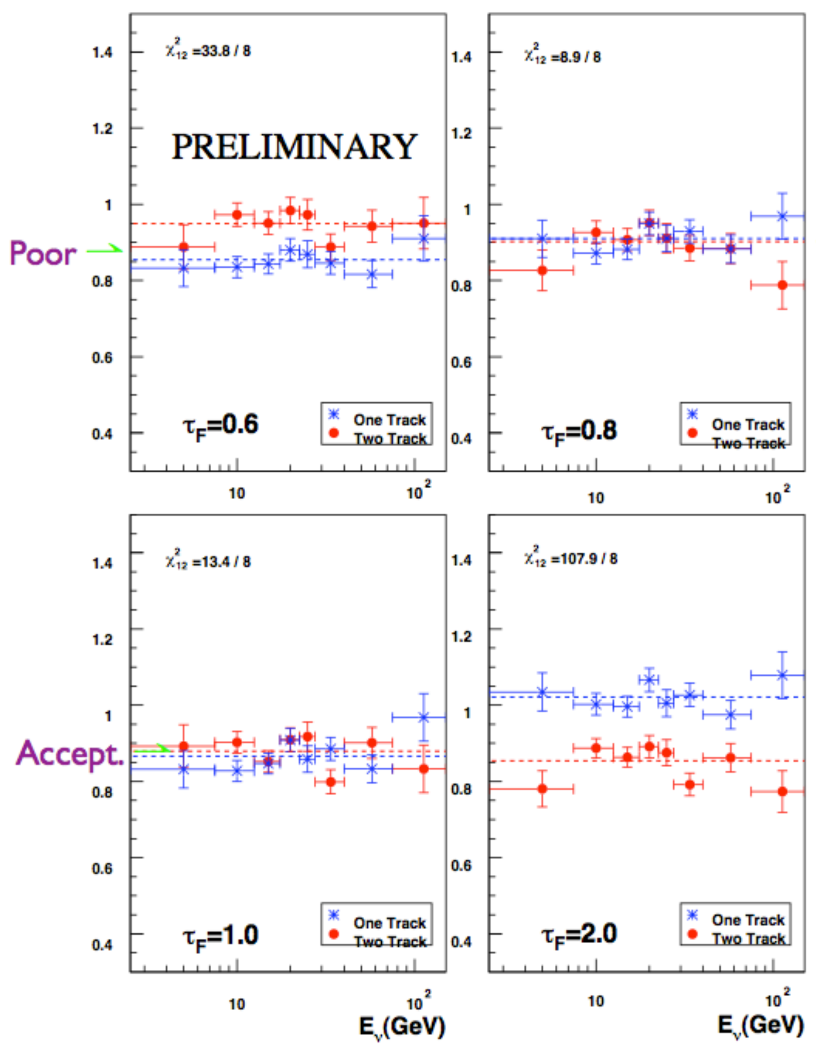
NOMAD QE



(R. Petti)

← Good

Comparison between 2-trk and 1-trk cross-sections gives model-independent constraint on FSI

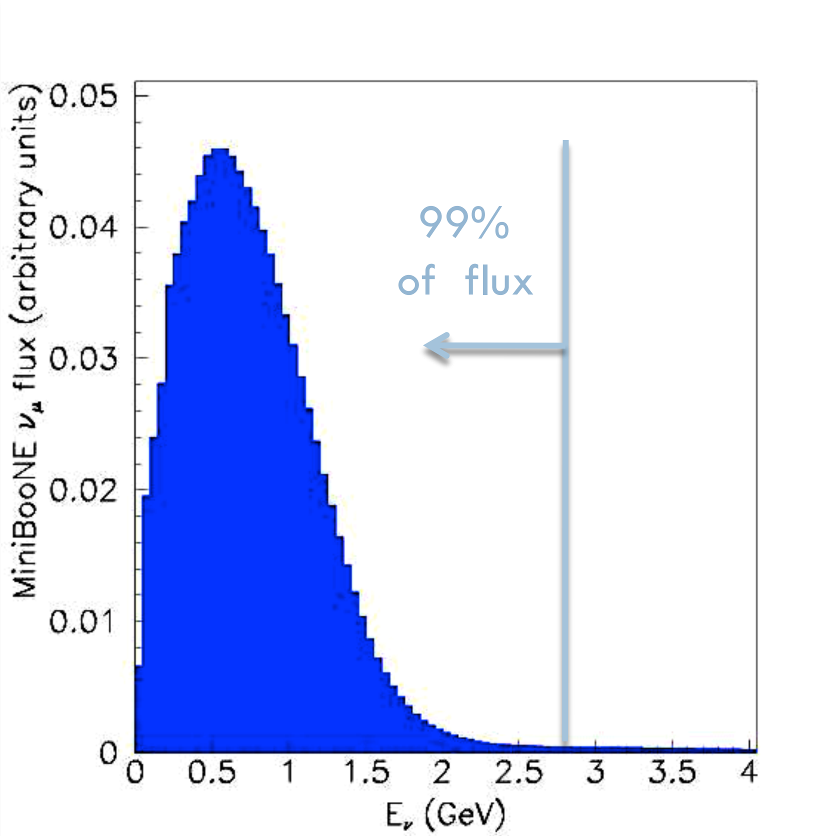
← V.Poor!

select the FSI parameters that yield 1track = 2track

- a lot of discussion at INT about this assumed 2 vs. 1-track equivalence

- **INT homework:** repeat this exercise with nucleon correlations included in the simulation to make sure the results don't change and report $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$

MiniBooNE QE



- much lower energy ν flux
- Cerenkov detector

  ring imaging for event reconstruction & PID

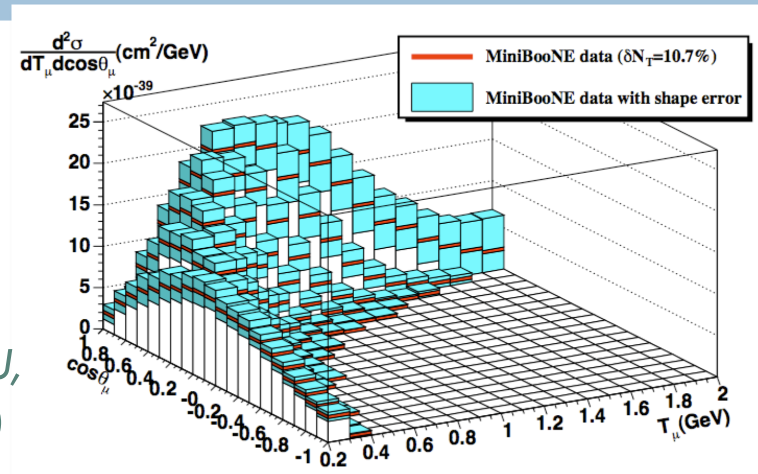
- **spherically symmetric detector**
  - *4π coverage leads to full μ angular coverage*
- use **particle decays** for event ID (QE requirement = μ + 1 Michel e^-)
  - *no p or π detection thresholds, just require particles to decay → this lessens some of the model-dependence; no requirement that event contains a proton*
- with this, QEs in MB are defined as **ν_μ CC with 0 π's, any # nucleons**
  - *more like inclusive (e,e')*
- dominant background from CC π^+ events with π^+ absorbed: constrain with data & subtract-off but report

MiniBooNE QE

- because of high statistics, can measure
  (146,070 ν events, 26% ε_{QE}, purity of 77%, CH_2)
  double diff'l σ's for the first time
  $$d^2\sigma/dT_\mu d\theta_\mu$$
- historically, we never had enough statistics to do this

ν

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



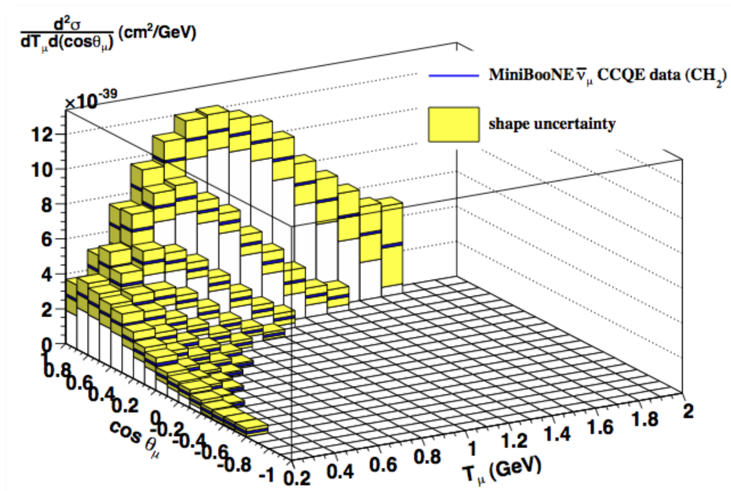
Aguilar-Arevalo et al., PRD 81, 092005 (2010)

- MB has led the field in producing state-of-the-art σ_ν results; T_μ, θ_μ are directly measured & less model dependent than $\sigma(E_\nu)$ or M_A

but unlike the NOMAD results, they don't agree with our "standard" QE predictions

$\bar{\nu}$

(J. Grange, U Florida, Ph.D. thesis)



Aguilar-Arevalo et al., PRD 88, 032001 (2013)

MiniBooNE QE

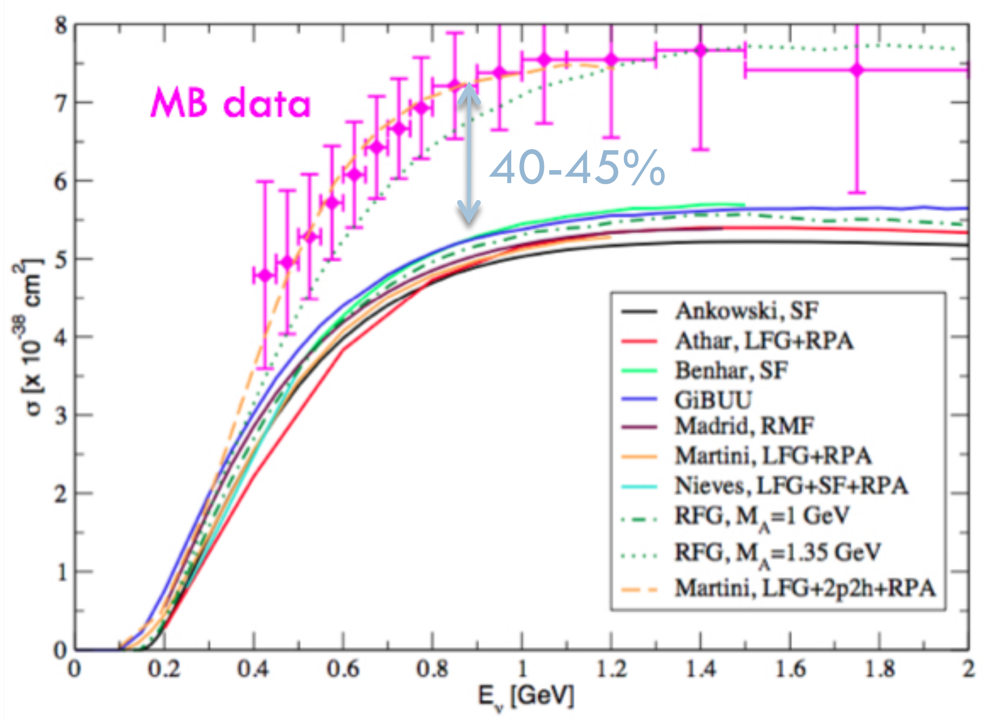
- MiniBooNE data is the 1st time have measured the ν QE σ on a nuclear target at these low energies (< 2 GeV)

- with this more inclusive definition of QE, observe a substantially larger σ than the predictions we have all been using for decades; effect is larger for larger μ scattering angles (larger Q^2)

  - *naturally, these results have garnered a lot of attention, because they were unexpected*

  (these sorts of effects first seen in K2K ND, NuInt01)

(L. Alvarez-Ruso, NuFact11)



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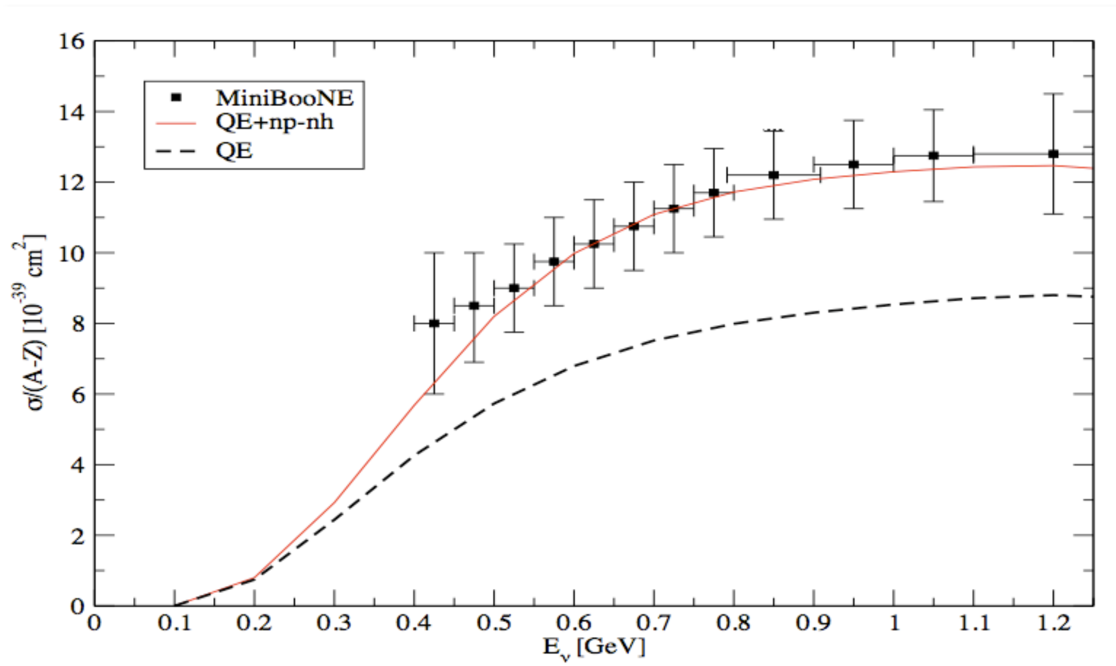
(these sorts of effects first seen in K2K ND, NuInt01)

- community has been working to better understand/model what's going on

Nuclear Effects to the Rescue

- traditionally, nuclear effects decrease σ, but there is new appreciation that there are are processes that can increase the total yield …



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

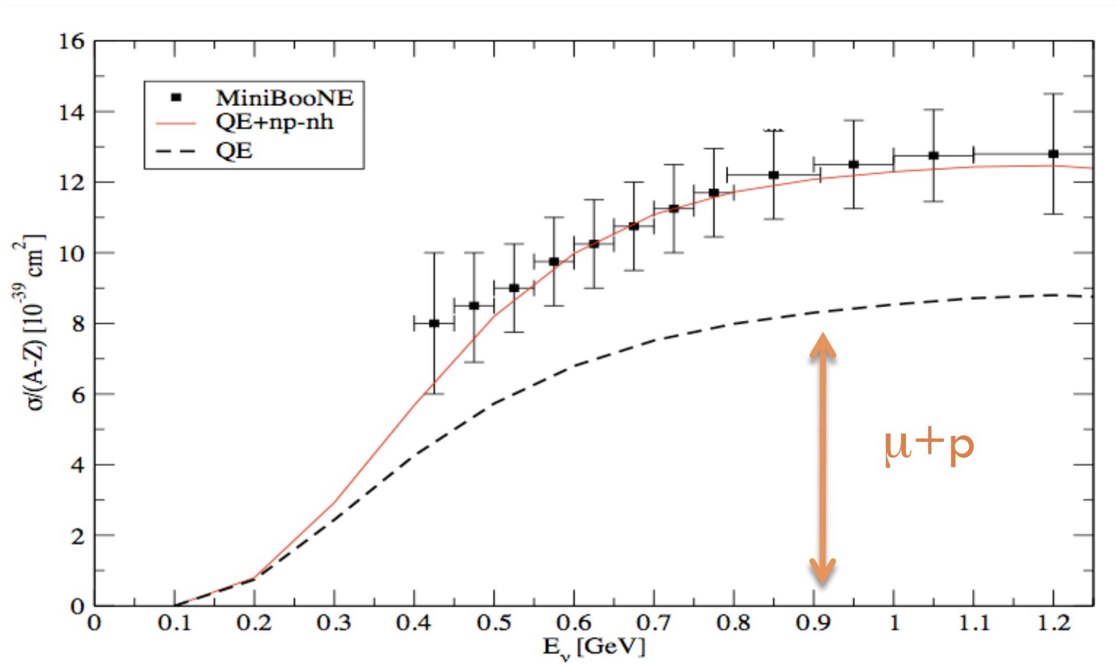
- extra contributions coming from nucleon correlations in the nucleus

  (all prior calculations assume nucleons are independent particles)

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

Nuclear Effects to the Rescue

- traditionally, nuclear effects <u>decrease</u> σ, but there is new appreciation that there are are processes that can <u>increase</u> the total yield …



- "standard" QE prediction we saw earlier (μ+p)

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

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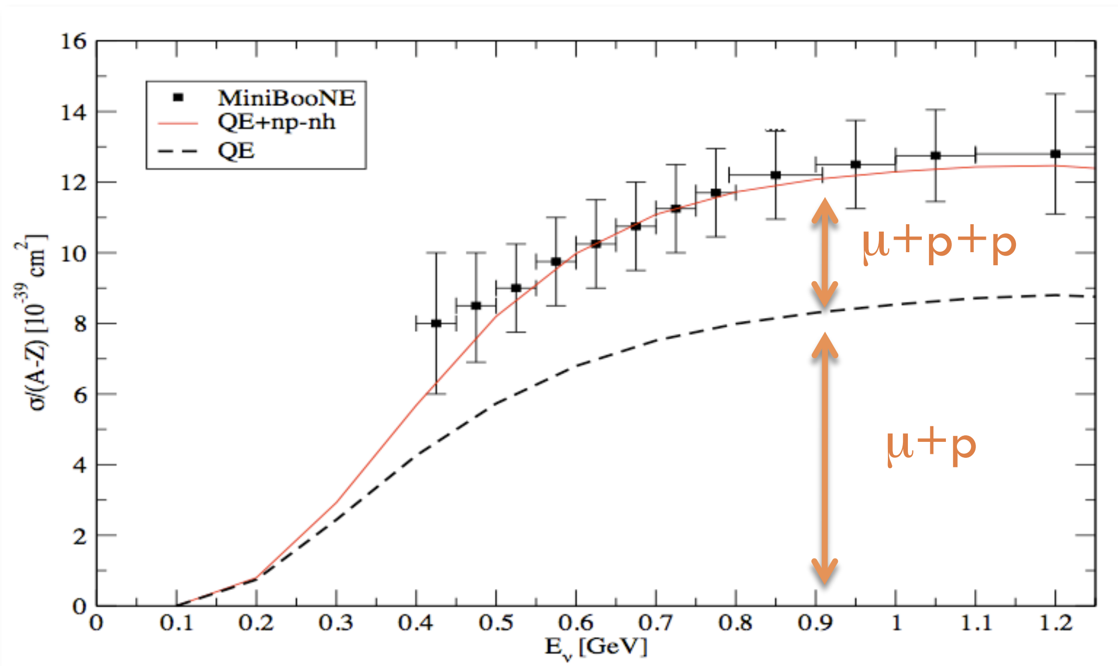

Martini *et al.*, PRC **80**, 065001 (2009)

- add'l nuclear processes contribute ~40% more σ at these ν energies and produce a multi-nucleon final state (μ+p+p)
  - seen in (e,e'pp)
- together account for MB

Nuclear Effects to the Rescue

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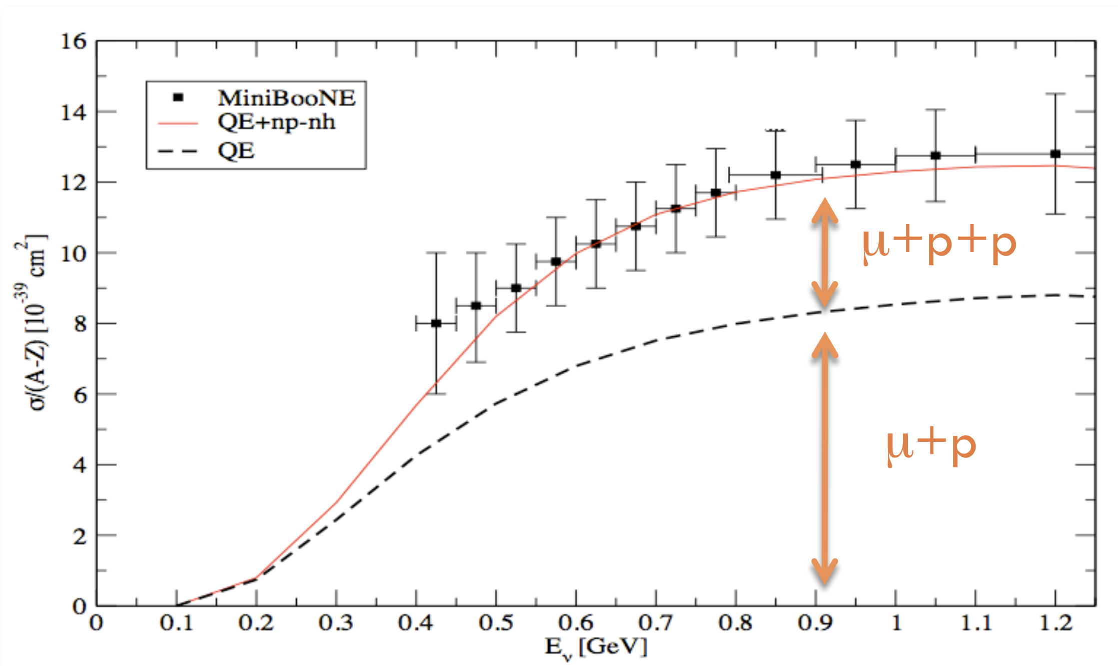

Martini *et al.*, PRC **80**, 065001 (2009)

- could this explain the difference between MiniBooNE & NOMAD?

jury is still out on this

- QE selection?
- angular coverage?
- neutrino energy?

Nuclear Effects to the Rescue

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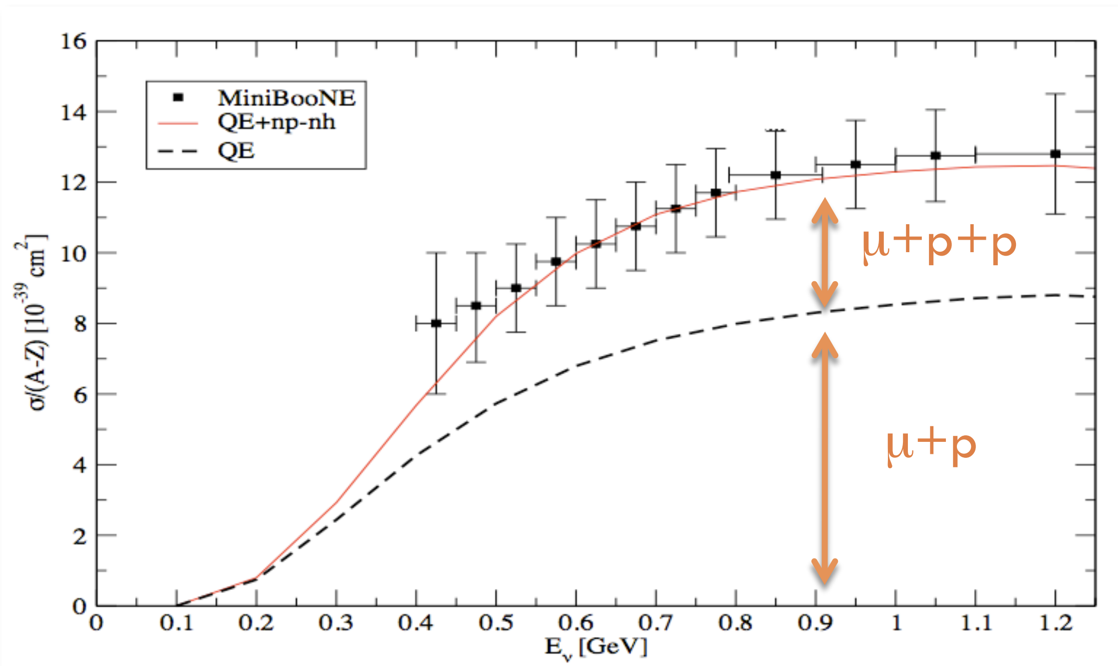


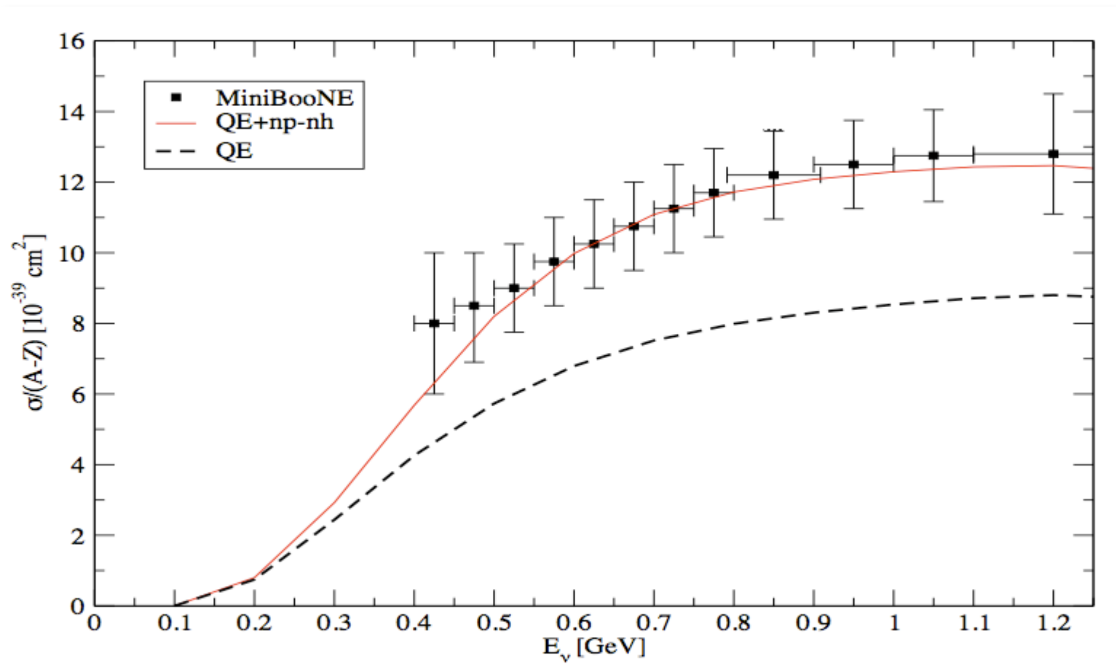
Martini *et al.*, PRC **80**, 065001 (2009)

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

there are nuclear effects that can lead to increased event rates & more complex final states

Nuclear Effects to the Rescue

- traditionally, nuclear effects decrease σ, but there is new appreciation that there are are processes that can increase the total yield …



Martini *et al.*, PRC **80**, 065001 (2009) ← *calculation first came out in 2001 before MB started taking data*

- 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)

Back in 2001

- prediction from >10 yrs ago
- warned that could see 20% more 1-ring events in Super-K

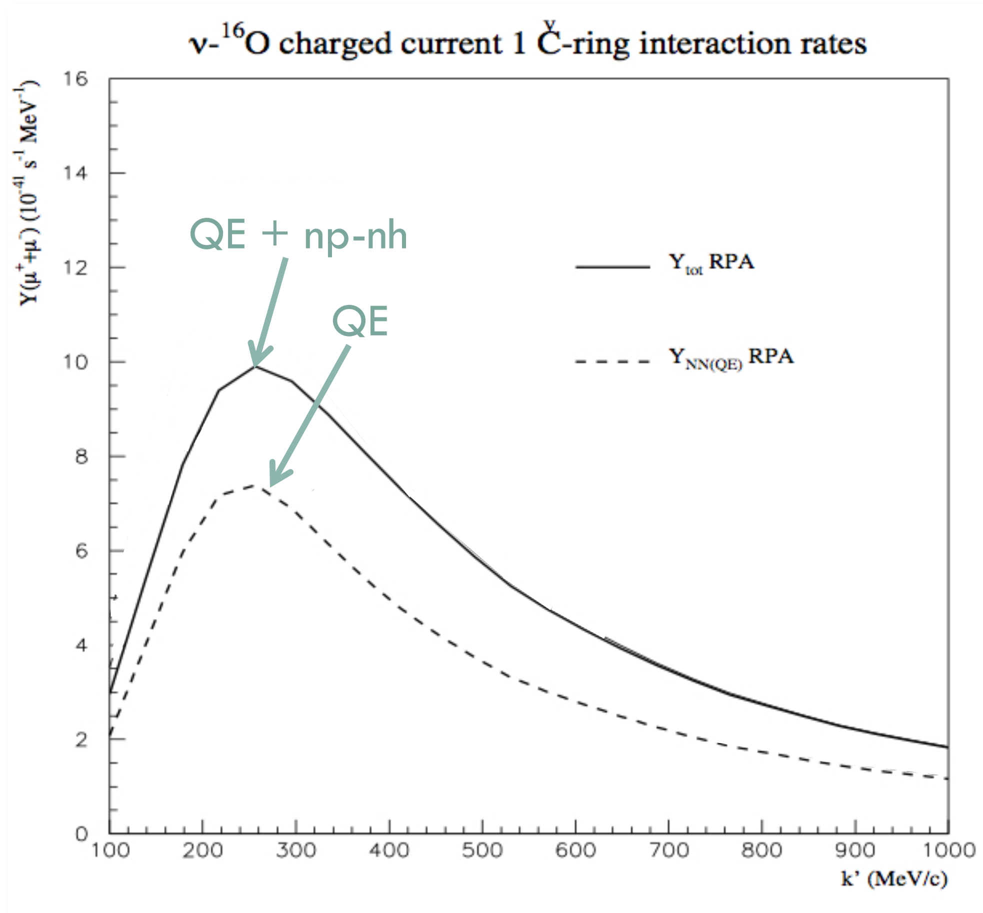
$= QE_{\text{free nucleon}} + \text{np-nh}$

$= (\mu+p) + (\mu+p+p)$

$= QE_{\text{nucleus}}$

we see an enhancement 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.

(NuInt workshop 2001)

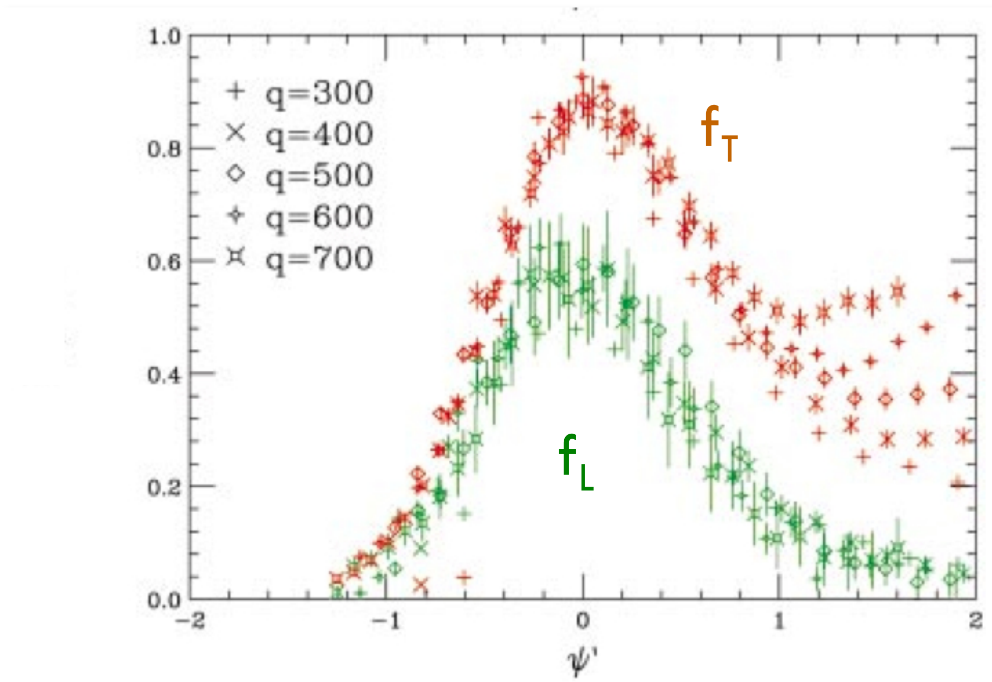


J. Marteau, Eur. Phys. J. **A5**, 183 (1999)

We Should Have Expected This

- also, have known about this physics for more than 2 decades from e-A scattering

- there are important connections between e^- & ν scattering (G. Garvey)



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

- **longitudinal** part of σ_{QE} can be described in terms of scattering off independent nucleons ← easier to interpret

- in contrast, there is a large enhancement in **transverse** part in both QE peak and dip region ***(preferentially effected by nucleon correlations, MEC)*** ← contains more info

  - MB results suggest these effects also play a significant role for ν's

We Should Have Expected This

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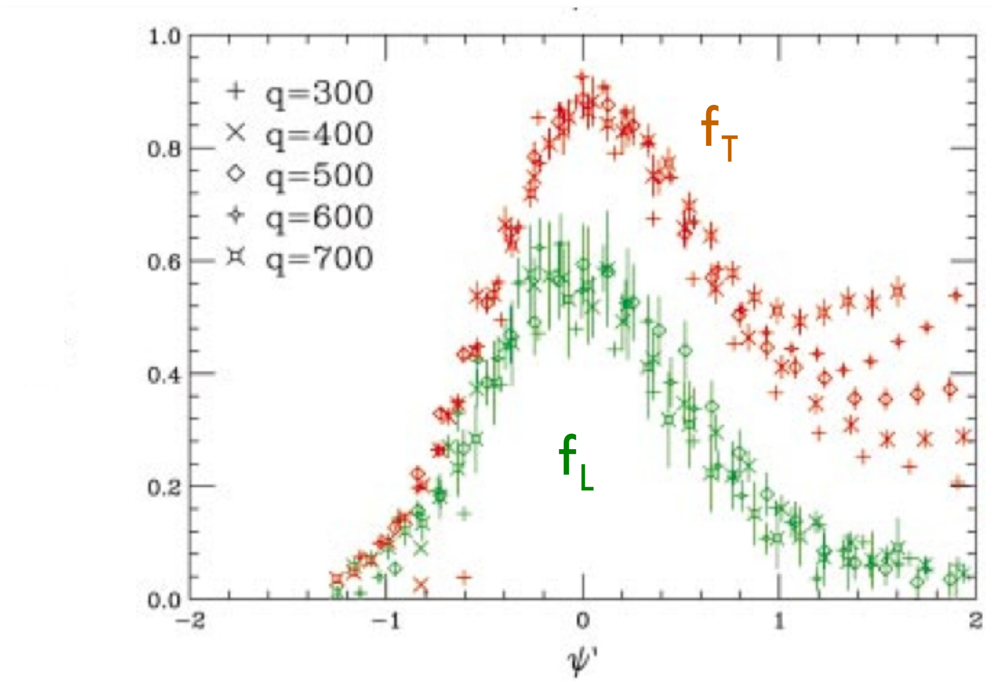

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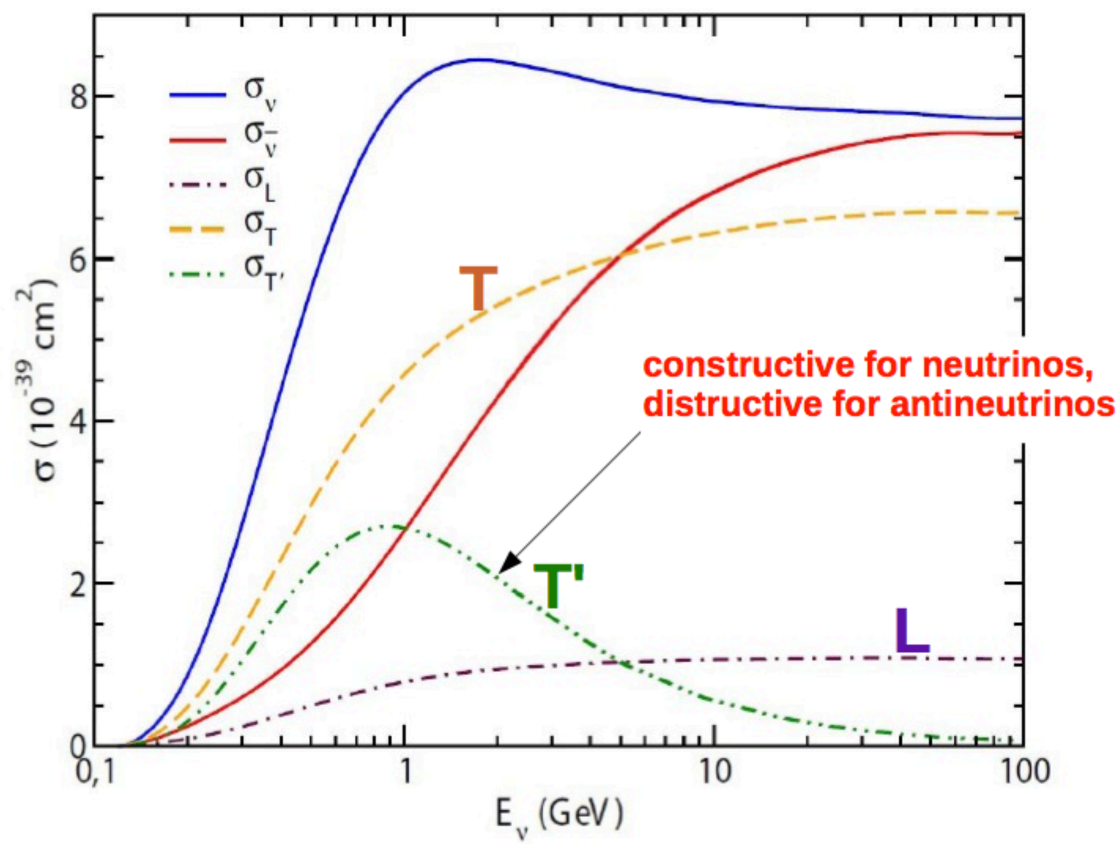
- "it is really ν scattering that brought this out of the bag" – G. Garvey

Contributions to ν Scattering

(M. Barbaro)

- this physics is important to capture because neutrino's are mostly transverse

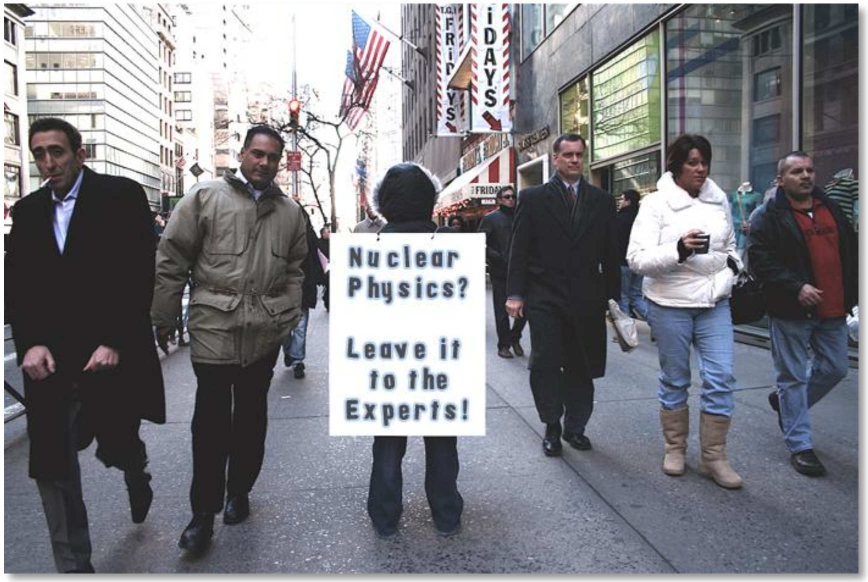


G.D.Megias, J.E.Amaro, MBB, J.A.Caballero, T.W.Donnelly, Phys.Lett. B725 (2013) 170-174

Theory

- ~100 theoretical papers on the topic of QE ν-nucleus scattering since the MiniBooNE results first came out …

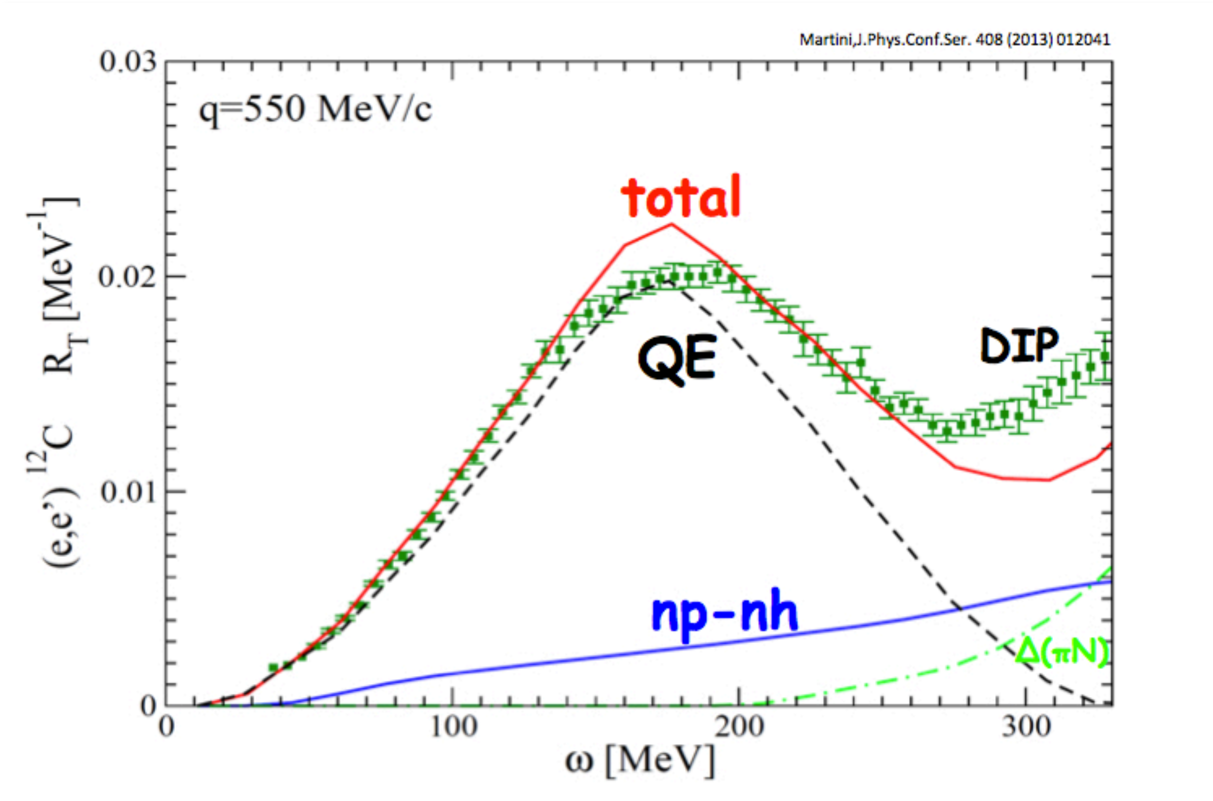
  - Butkevich, arXiv:1204.3160
  - Lalakulich *et al.*, arXiv:1203.2935
  - Mosel, arXiv:1204.2269, 1111.1732
  - Barbaro *et al.*, arXiv:1110.4739
  - Giusti *et al.*, arXiv:1110.4005
  - Meloni *et al.*, arXiv:1203.3335, 1110.1004
  - Martini *et al.*, arXiv:1202.4745, 1110.0221, 1110.5895, Phys. Rev **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 and needs to be updated!)

First Requirement

1. Any model that does not succeed for electron scattering is very unlikely to be valid for neutrino reactions. (B. Donnelly)



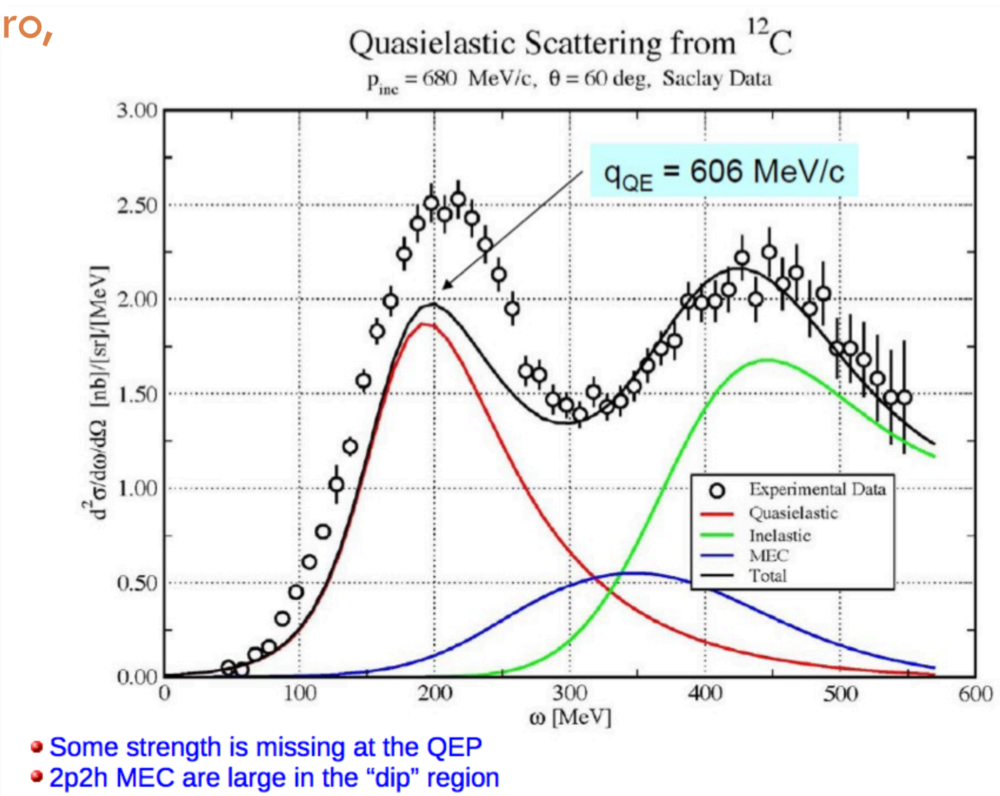
- calculations must reproduce e-nucleus data (both L and T)

(M. Martini)

First Requirement

(M. Barbaro, tests of SuSA model)

"good to be low"; they know that they have more effects to put in

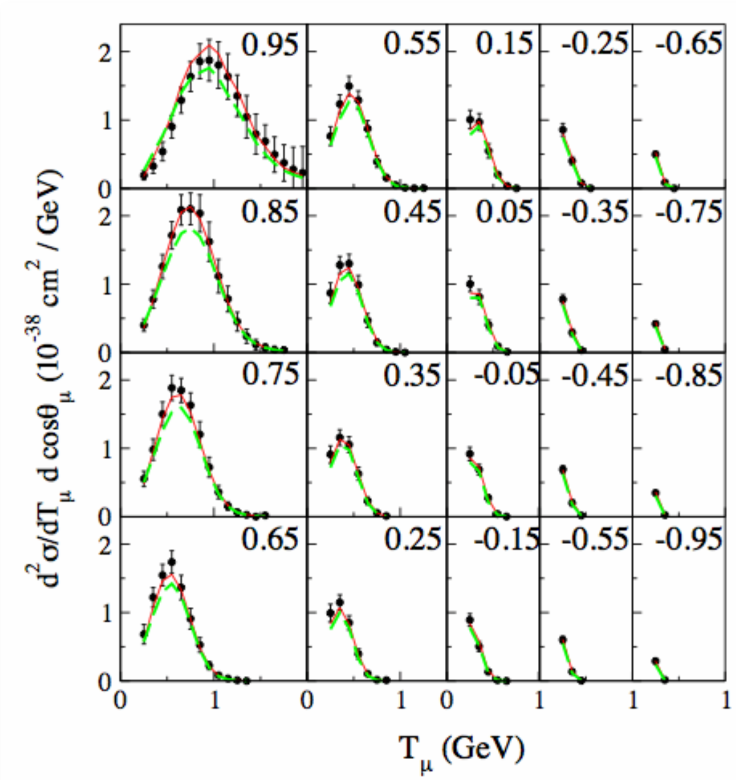


- *warning*: "electron physicists have become masters of enhancing or suppressing effects (2p2h, MEC, FSI) by preferentially selecting certain kinematics, so be careful to look at the kinematics"

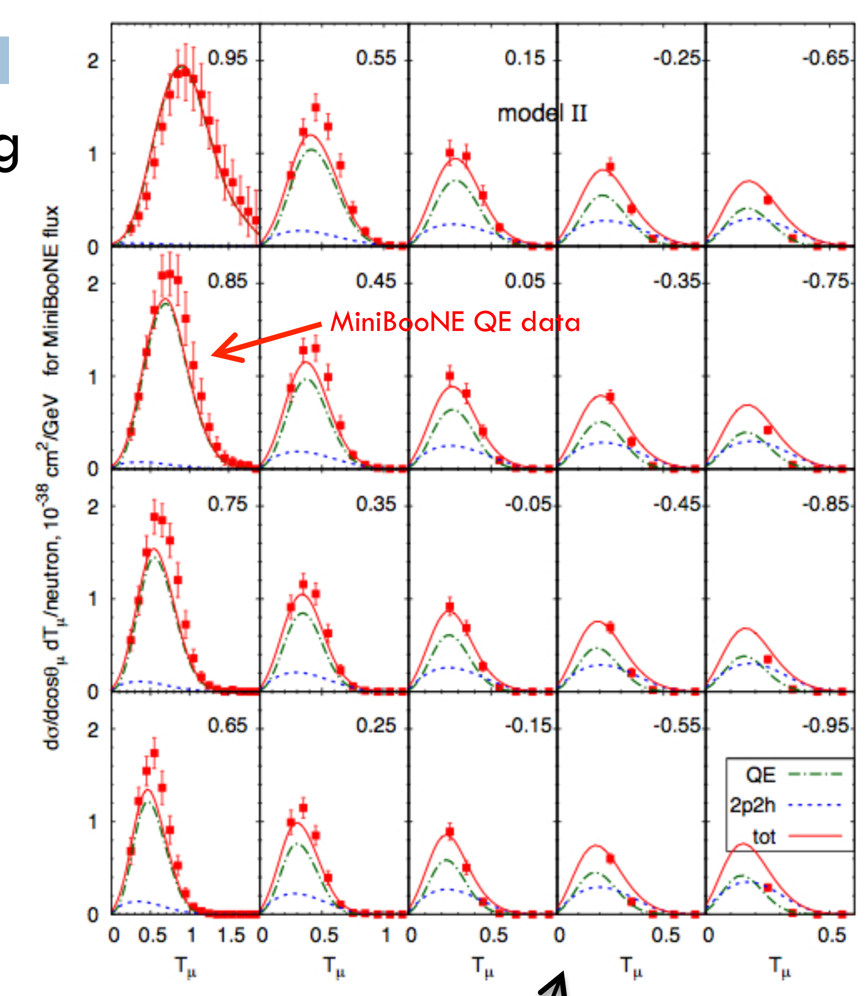
homework from INT: the community should agree on a core set of e^- data and kinematics that must be reproduced (at a minimum)

Second Requirement

- 2D data from MiniBooNE providing a rigorous test, this is the 1st time we've had such info available



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

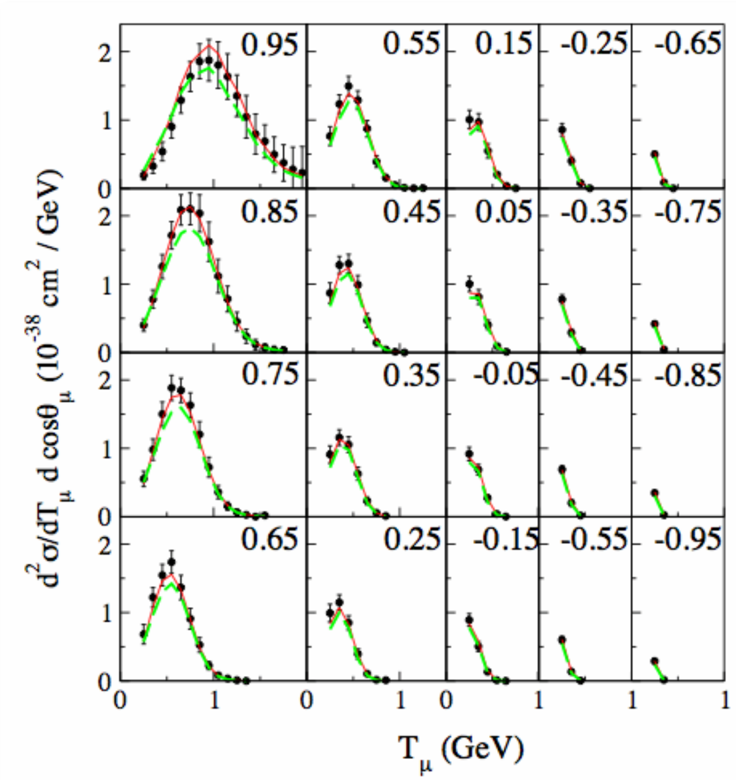


Lalakulich, Gallmeister, Mosel arXiv:1203.2935

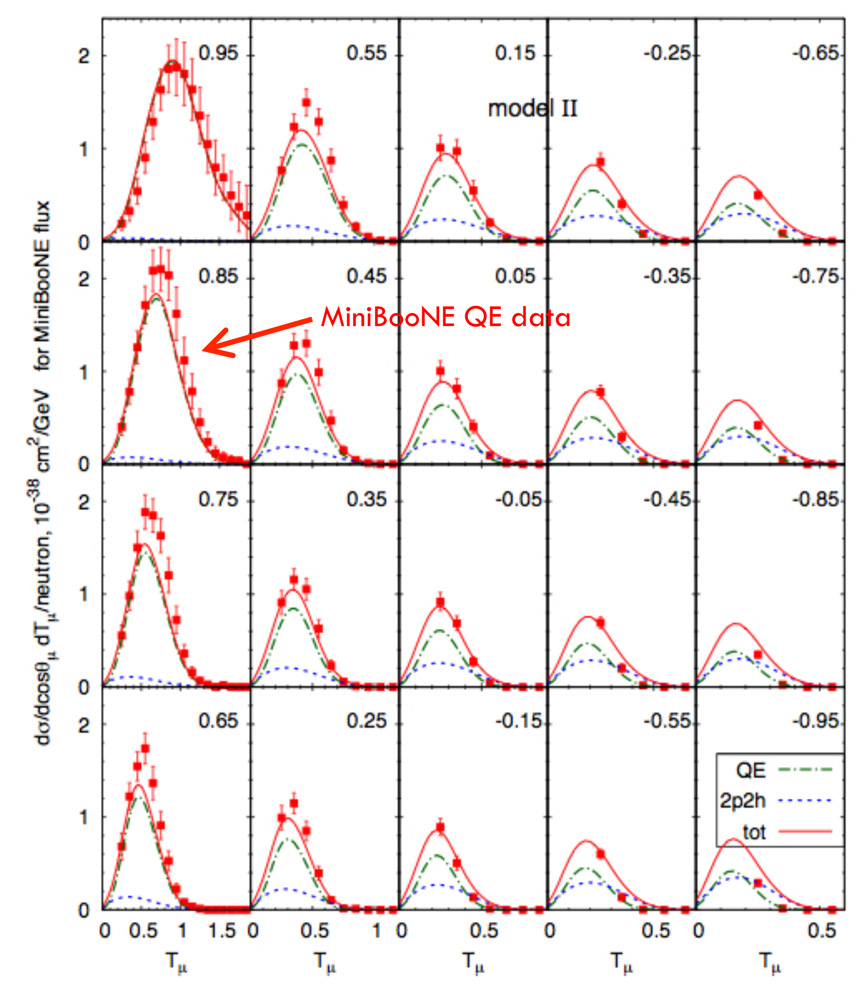
- fractional contrib from nucleon pair correlations is largest at large θ_μ

Second Requirement

- there is a lot we still need to learn about these correlated pairs



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



Lalakulich, Gallmeister, Mosel arXiv:1203.2935

- needed: diff'l σ measurements like this at other E_ν, A + for outgoing proton(s)

What About Hadrons?

We absolutely need calculations for final state hadrons … even if it makes you really uncomfortable!

- Electron scattering measurements don't need them, but we do.
- We'd rather that the theorists make their best guess, however bad, since otherwise we'll use our own best guess. (And you don't want that.) (S. Oser)

(currently, none of the state-of-the art theory calculations provide information on the final state nucleons in QE interactions)

Why Do We Want This?

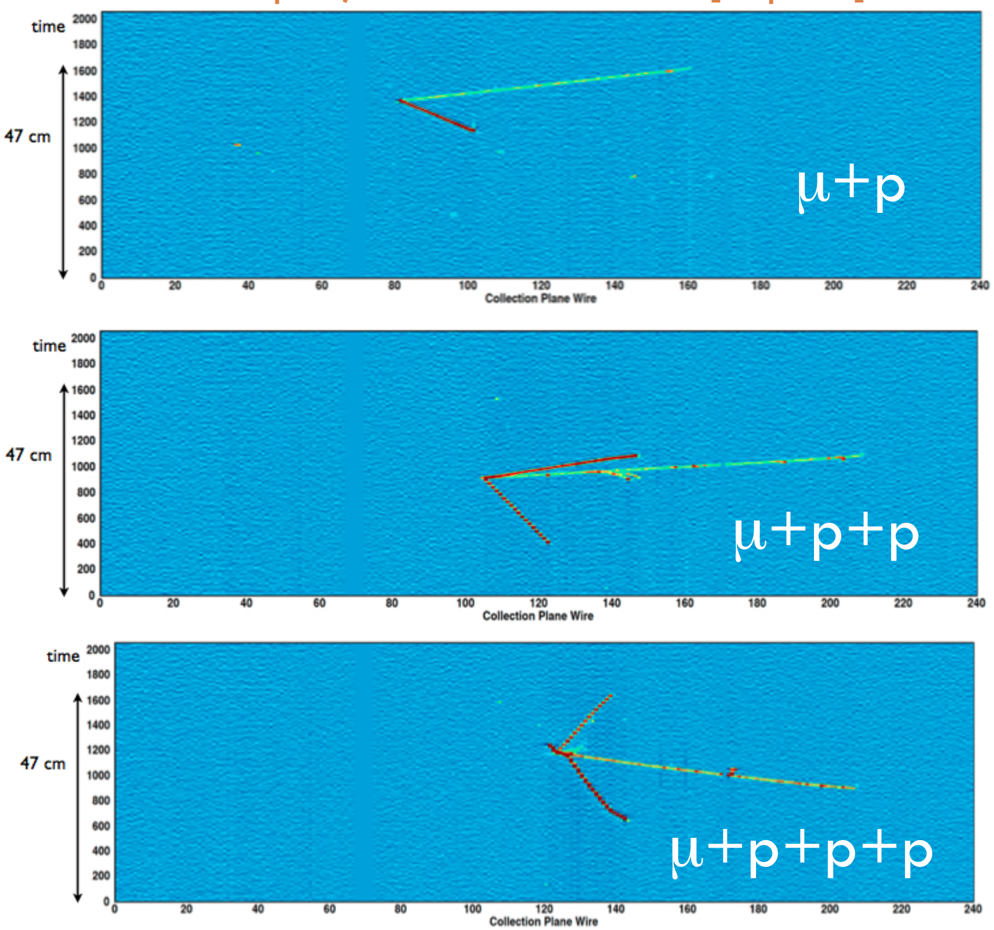
- we would like to use the entire final state ($E_\mu+E_{hadrons}$) to get a better E_ν estimate for our oscillation experiments and not just rely on the outgoing lepton $E_\nu^{QE}=f(T_\mu,\theta_\mu)$; especially true for LBNE

- as experimentalists, "we don't like hadrons either" (H. Gallagher) they are a lot harder to simulate than leptons
  - we would like to do experiments without them, but they are unavoidable

- unfortunately, predicting nucleon emission in such QE interactions is incredibly challenging: nuclear theorists cringe whenever we ask for this and our ν event generators vary widely on what they predict

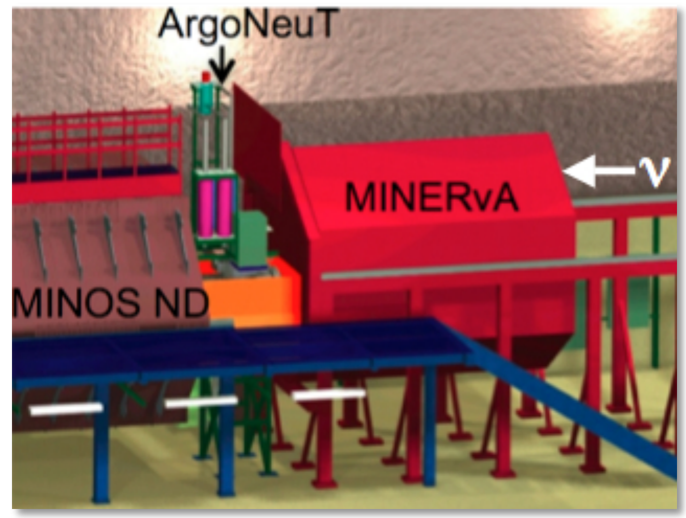
What's In the Final State?

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



just like MB is asking what are the kinematics of μ's coming out of QE ints, ArgoNeuT is asking how many protons come out?

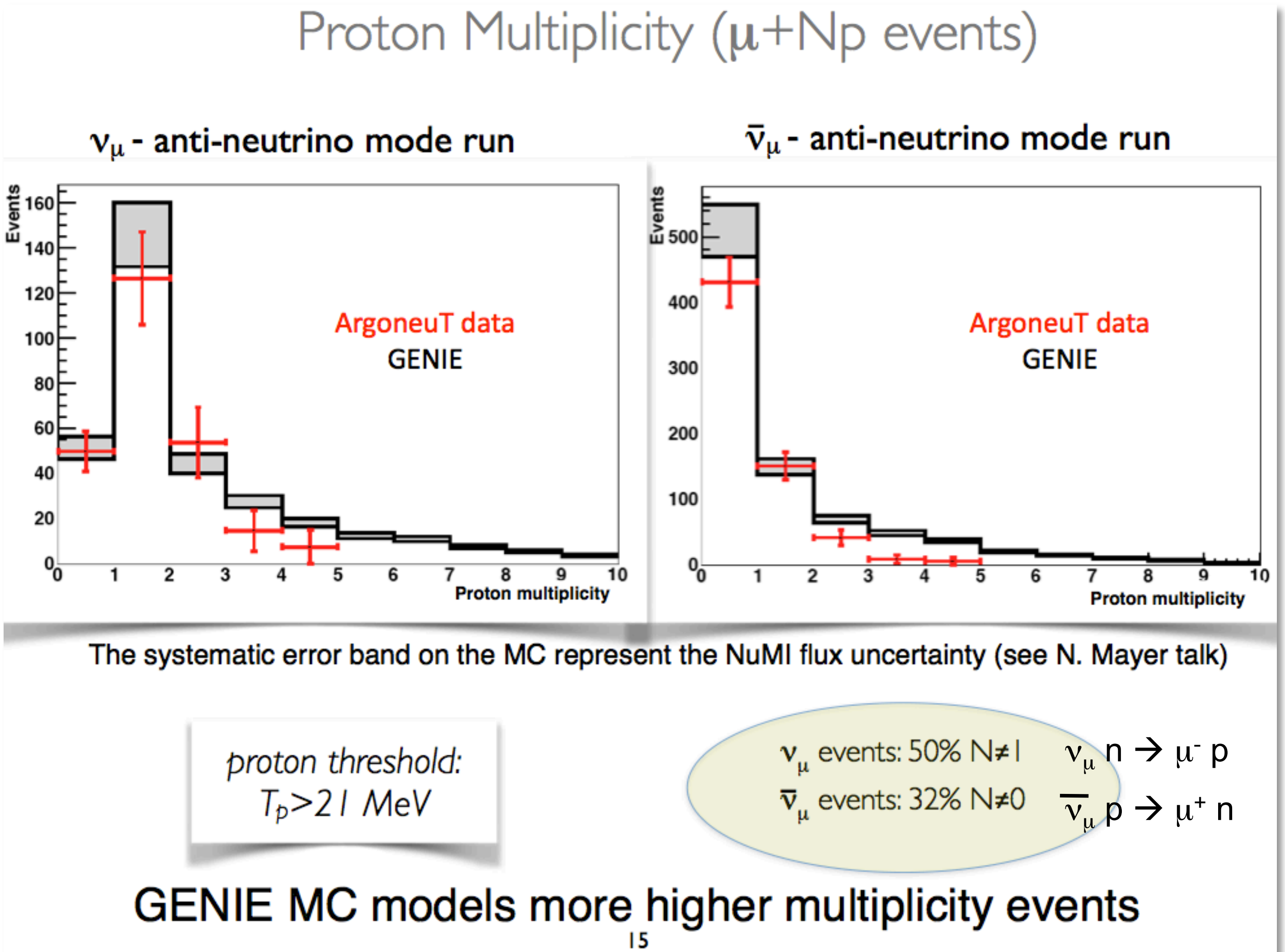
- liquid argon TPCs have excellent final state particle resolution



- ArgoNeuT is providing the first measurements of proton multiplicities in ν (and $\overline{\nu}$) interactions

(O. Palamara)

ArgoNeuT QE



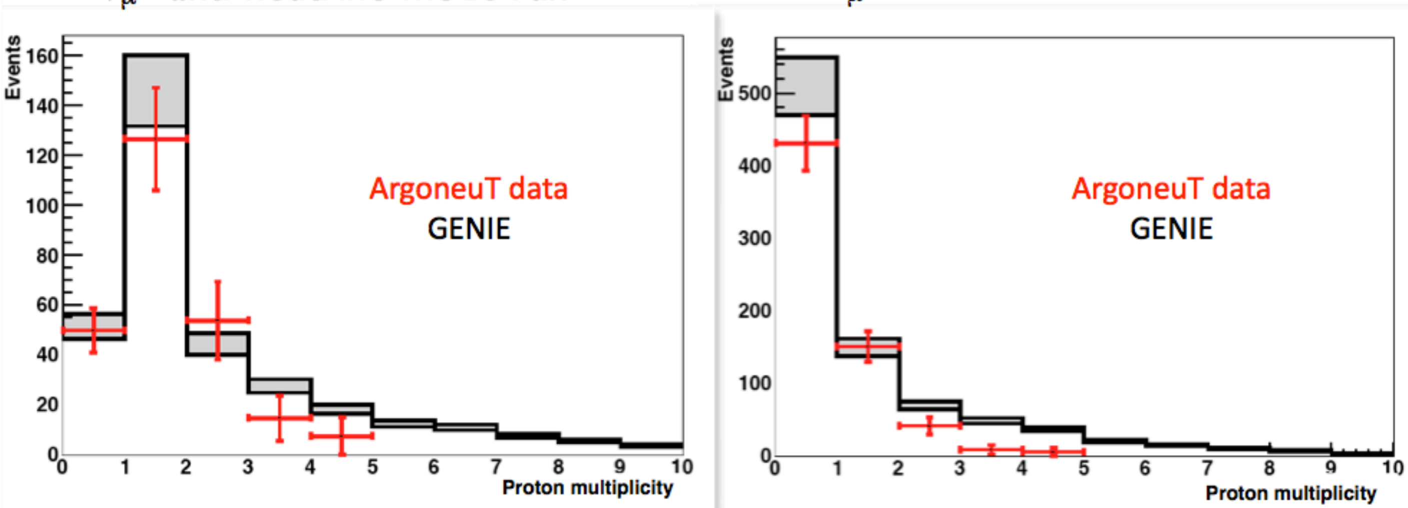
- of course, it is extremely challenging to separate initial state nucleon correlations from final state effects

(O. Palamara)

ArgoNeuT QE

Proton Multiplicity (μ+Np events)

ν_μ - anti-neutrino mode run | $\bar{\nu}_\mu$ - anti-neutrino mode run



The systematic error band on the MC represent the NuMI flux uncertainty (see N. Mayer talk)

proton threshold:
T_p>21 MeV

ν_μ events: 50% N≠1 ν_μ n → μ^- p

$\bar{\nu}_\mu$ events: 32% N≠0 $\bar{\nu}_\mu$ p → μ^+ n

GENIE MC models more higher multiplicity events

15

- **homework:** are there regions we can isolate 2p2h, MEC from FSI?

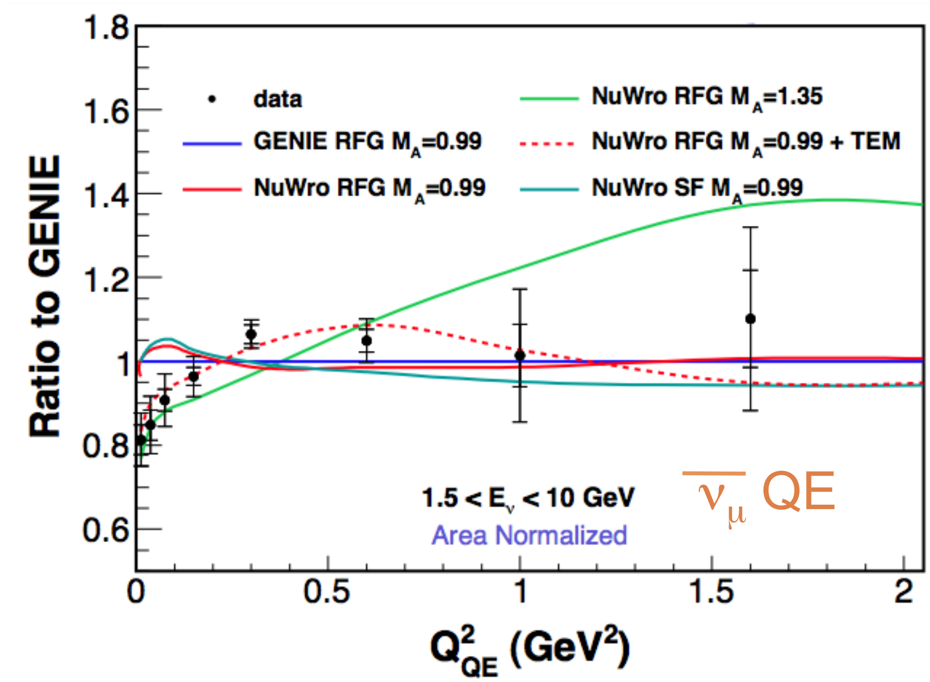
- **homework:** also mine CLAS and BONUS data

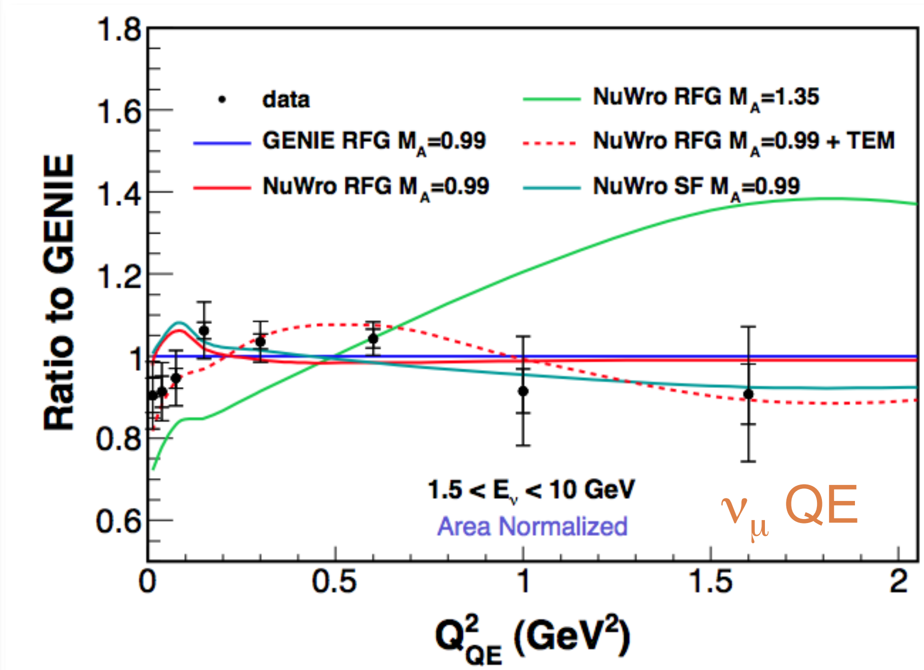
(O. Palamara)

MINERvA QE

(G. Perdue)

• **homework:** need calculations extended to higher energies (>2 GeV)

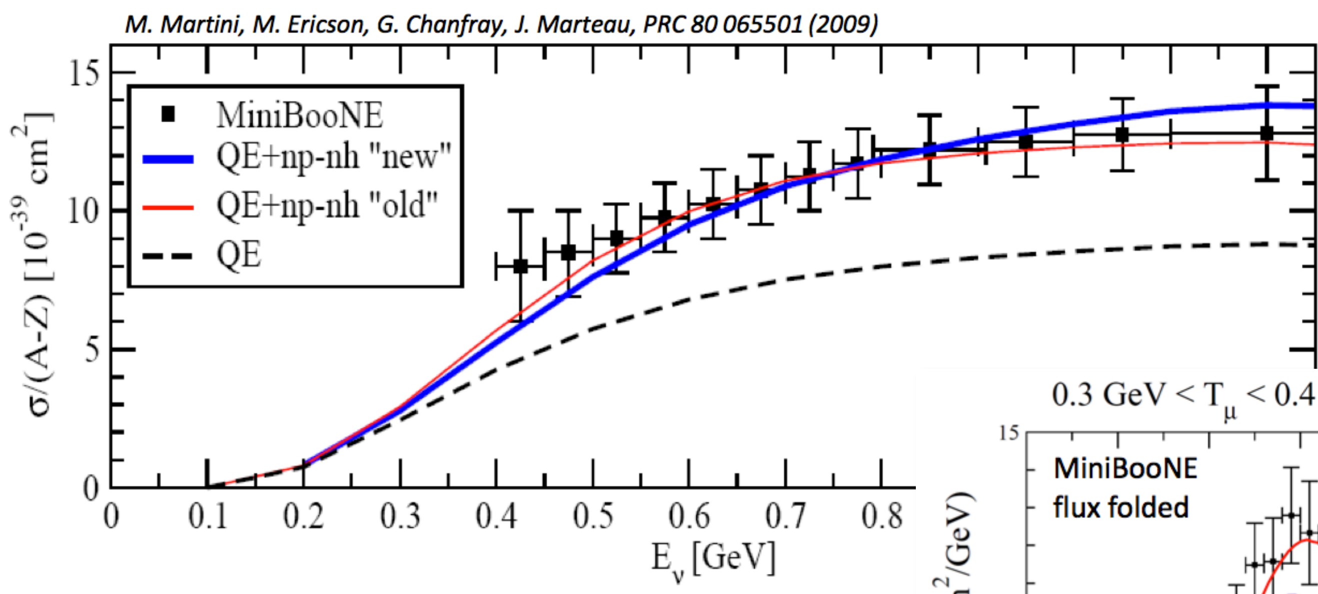




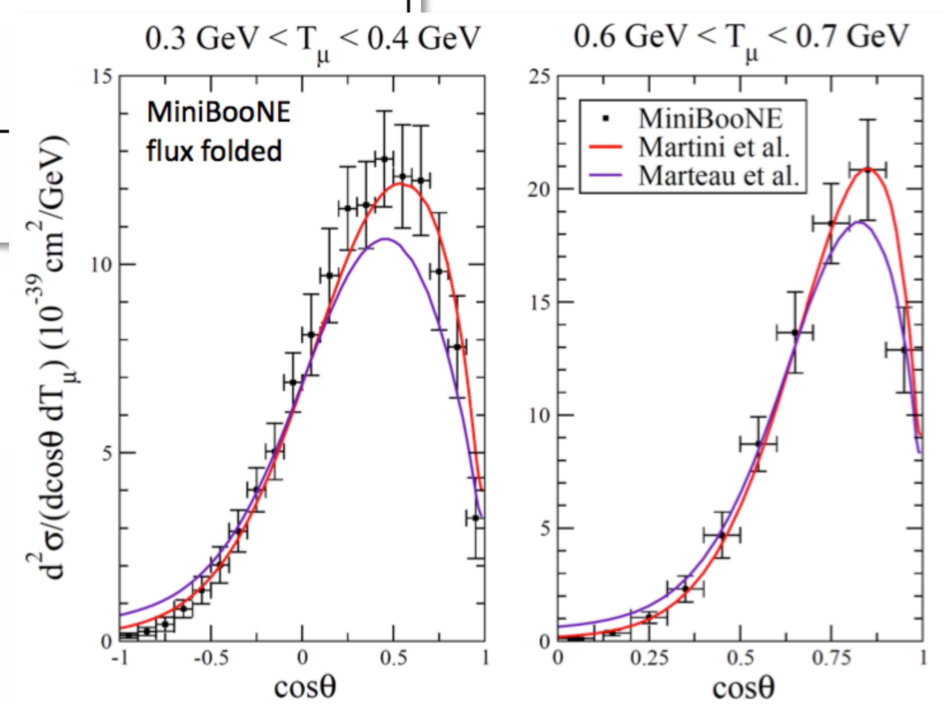
• next for MINERvA: will measure $d^2\sigma/dT_\mu d\theta_\mu$ and $d^2\sigma/dT_p d\theta_p$

(the latter would also be interesting to measure for both ν and $\bar{\nu}$ as the mechanism for producing the proton is very different in each)

Importance of Differential σ Data



(M. Martini)



These two approaches give results
- very similar for the total cross section
- very different for the differential cross sections

- if you have some new data and want to help this issue, measuring $\sigma(E_\nu)$ or M_A is not so helpful

We Will Need to Be Careful

neutrino QE scattering selections in modern ν experiments:

ArgoNeuT	1 muon, no pions, any # nucleons
MiniBooNE	1 muon + 1 Michel e^- (implies no pions, any # nucleons)
MINOS	1 muon + E_{had}<225 MeV
MINERvA	1 muon, recoil consistent with QE, # tracks not used
NOMAD	1 track (μ) and 2 track (μ+p)
NOvA NDOS	1 track (μ), multivariate ID
SciBooNE	1 track (μ) and 2 track (μ+p)
T2K	1 muon, no charged pion

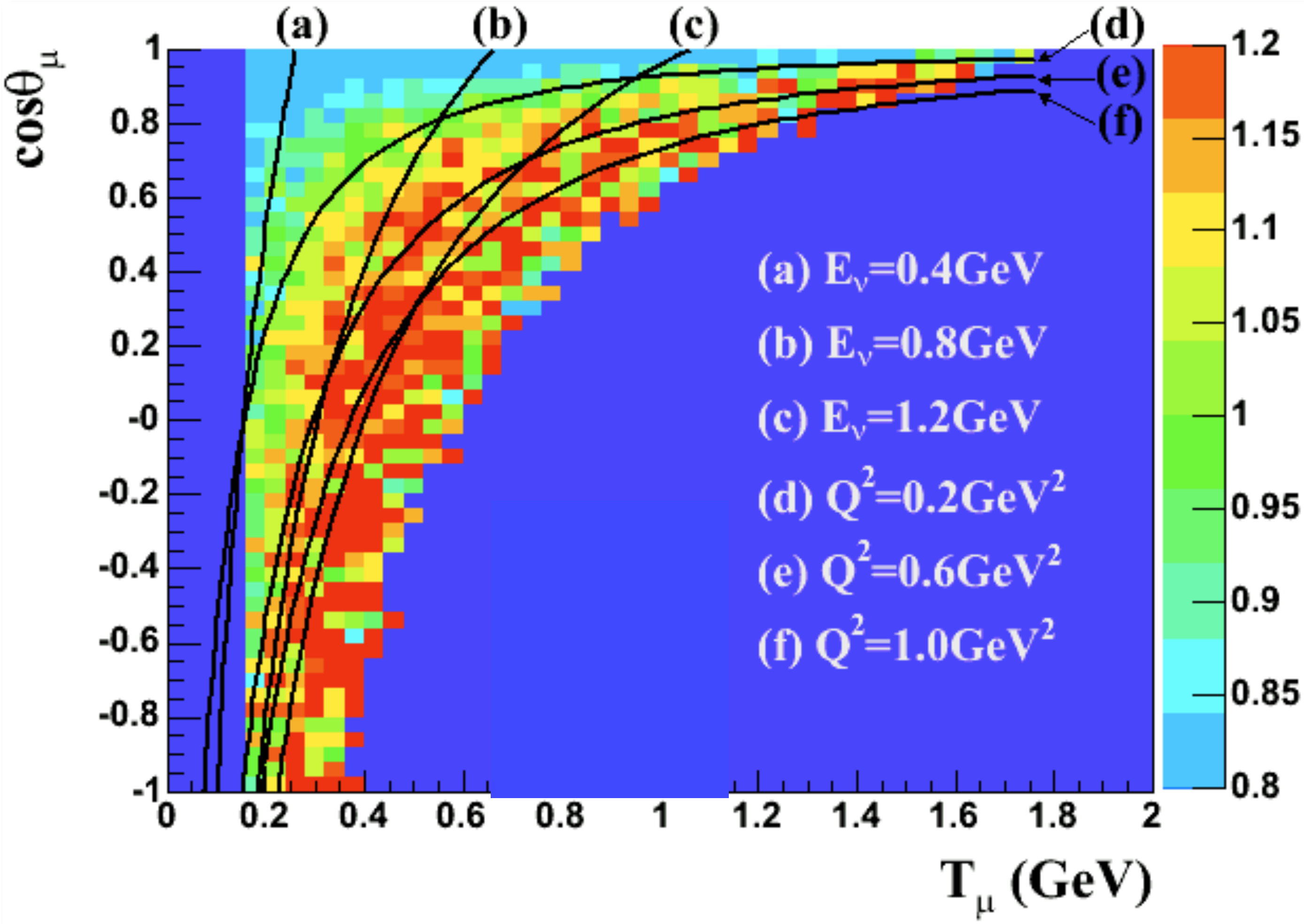
- *some require a proton, some do not*
  some are more inclusive, others are not
- *we now have this record all in one place*
  (see INT experimental tables)

what is ν QE scattering?

when you are scattering off a nucleus
it's not just $\nu_\mu\, n \rightarrow \mu^-\, p$

QE Kinematics

- *MiniBooNE QE data shape comparison to RFG with M_A=1.0 GeV*



(T. Katori)

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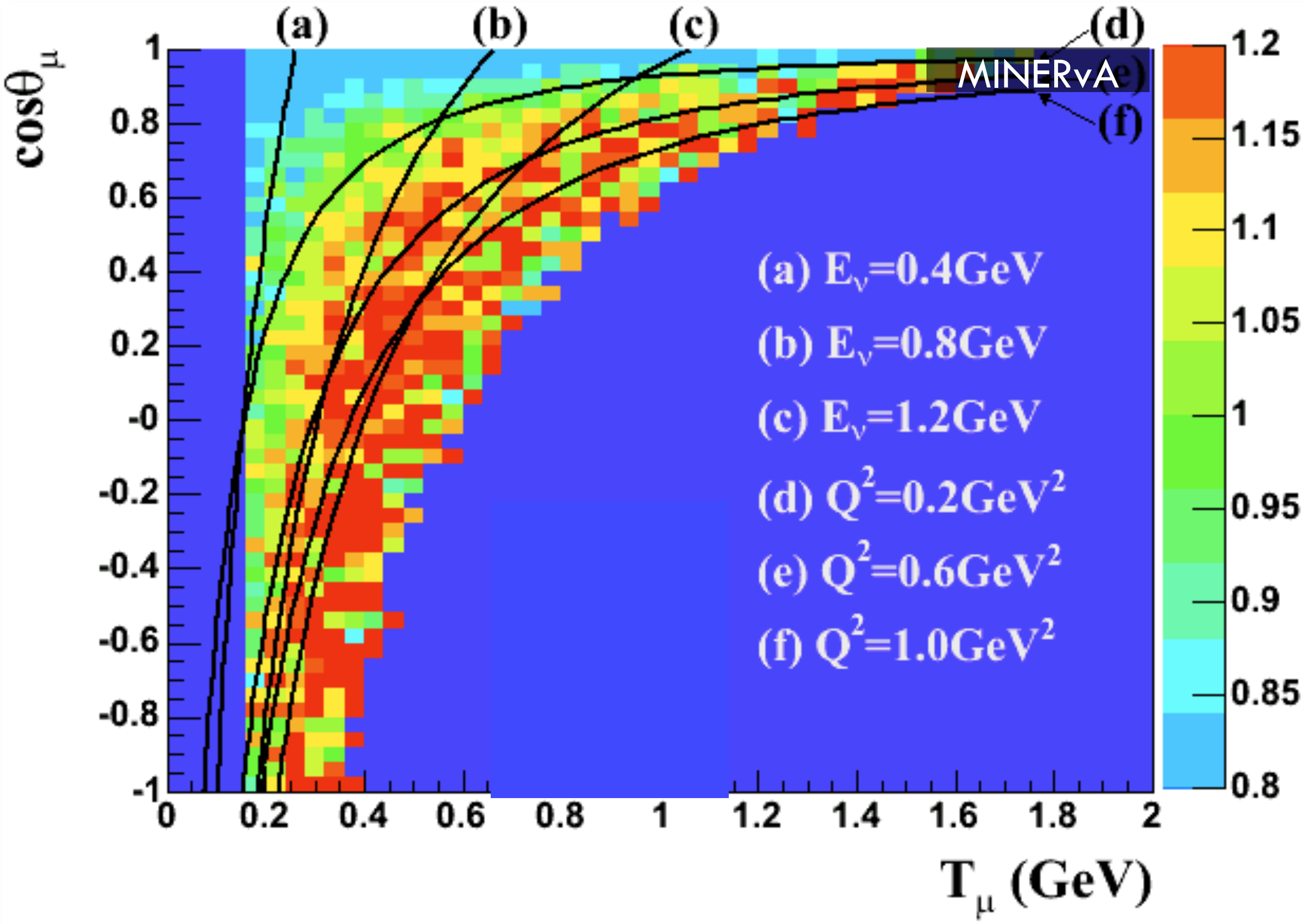

- *experiments cover different kinematics*

(T. Katori)

QE Kinematics

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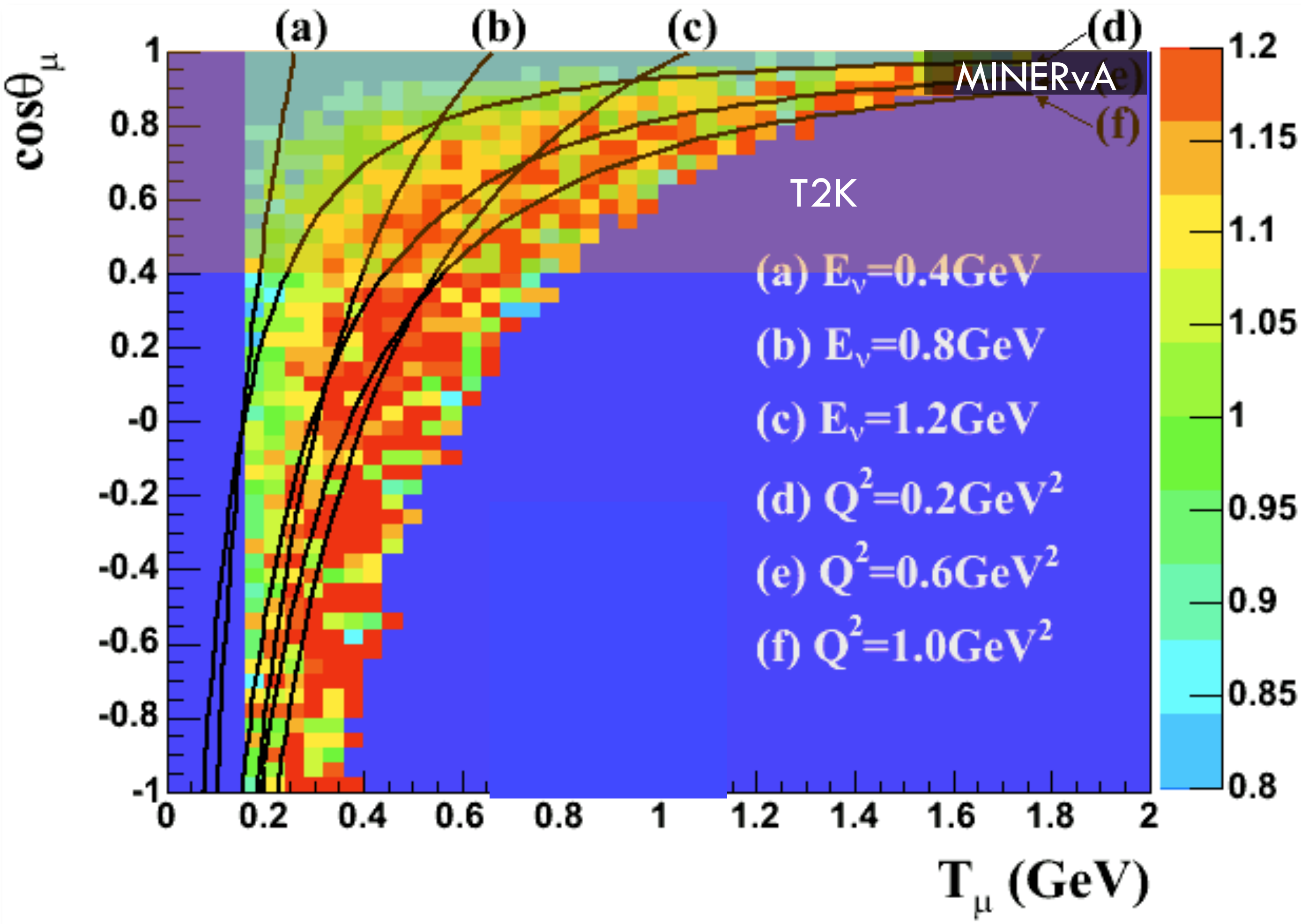

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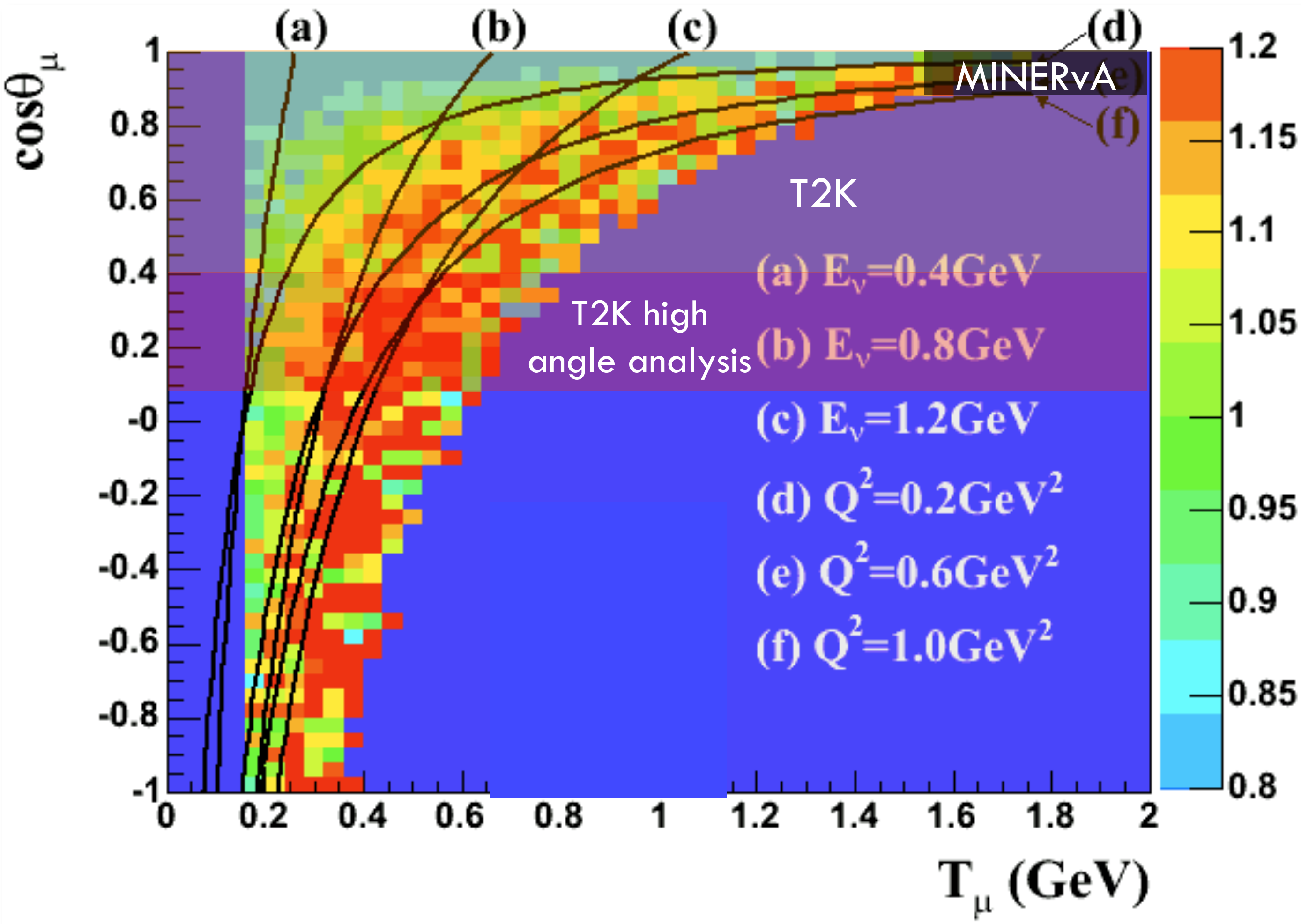

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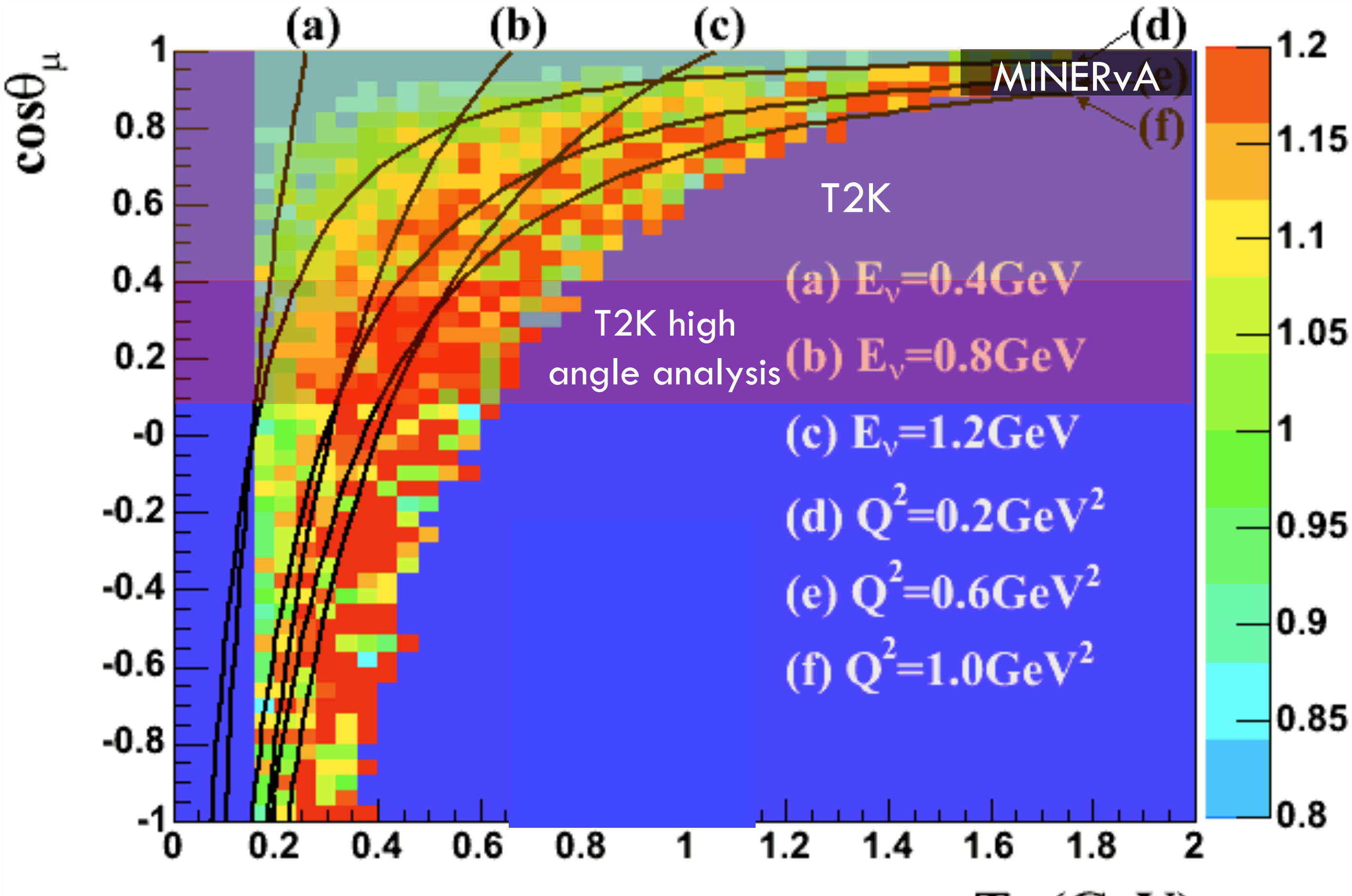


+ new NOMAD analysis with increased μ kinematic range

- *experiments cover different kinematics*

- **homework:** need wider muon angular acceptance to get into region where MB sees largest effects

(T. Katori)

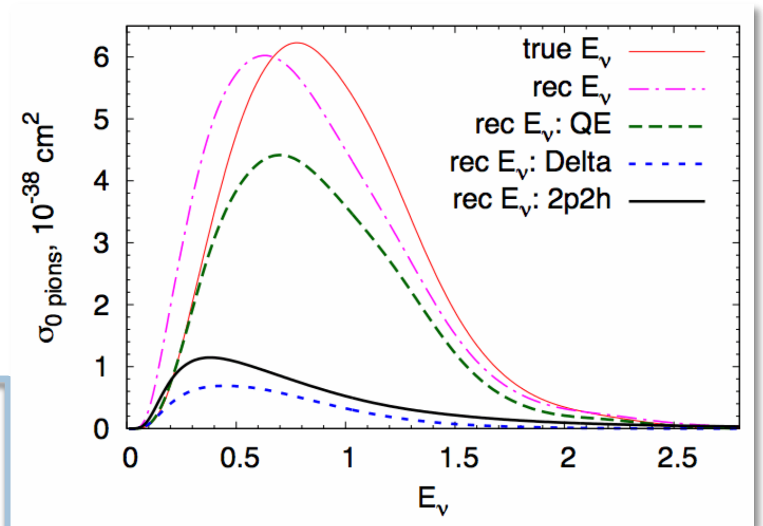
What Have We Learned?

- something as simple as **QE scattering** is not so simple
  - nuclear effects can significantly increase the QE cross section
    (this was certainly not part of our thinking prior to the MB measurements)
  - idea that could be missing ~40% of σ at low E_ν in our simulations is a big deal

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

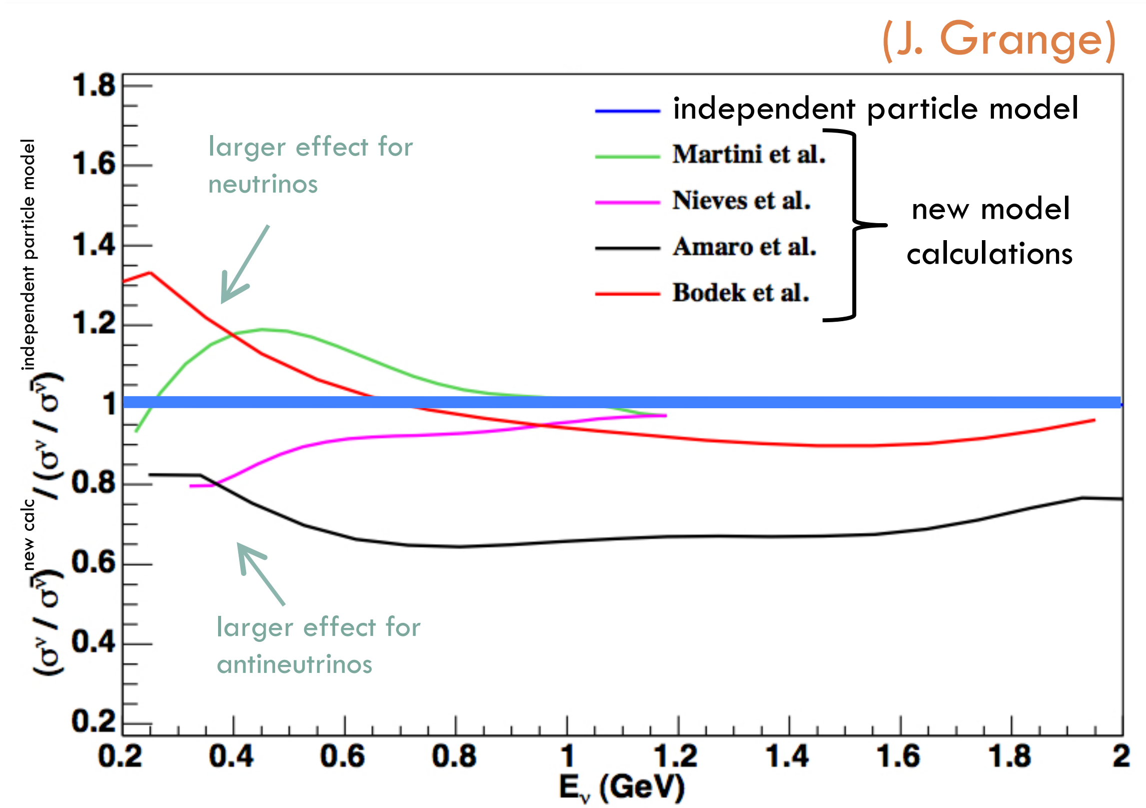
(1) impacts E_ν determination *(*T2K study!)*

(2) effects can be different for ν vs. $\bar{\nu}$
(at worse, could produce a spurious CP effect)



one example: Lalakulich, Gallmeister, Mosel, arXiv: 1203.2935

Neutrino/Antineutrino Ratio



- models give different predictions for $\nu/\bar{\nu}$
- the situation will need to get resolve
- 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!

- **homework from INT:** there are differences for ν & $\bar{\nu}$, but has anyone quantified what the expected 2p2h differences are for ν_μ & ν_e?

Model Comparisons

(M. Martini)

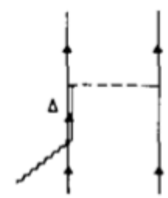
- we finally got a better understanding of why this is at INT
- 5 groups doing these calculations

Analogies and differences of 2p-2h

M. Martini, M. Ericson, G. Chanfray, J. Marteau

[Genuine CCQE (1p-1h): LRFG+RPA]

Axial and Vector NN corr. Δ-MEC NΔ interf.



J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas et al.

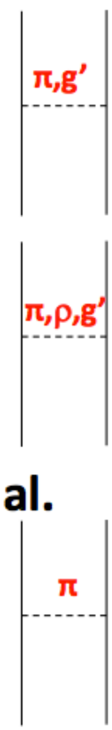
[Genuine CCQE (1p-1h): LRFG+SF+RPA]

Axial and Vector NN corr. MEC N-MEC interf.

J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly et al.

[Genuine CCQE (1p-1h): Superscaling]

Only Vector MEC



+ Carlson et al. (Green's function), **+ Bodek** (TEM)

Model Comparisons

(M. Martini)

2p-2h contributions in the different approaches

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial k'} = \frac{G_F^2\cos^2\theta_c\,(\boldsymbol{k}')^2}{2\,\pi^2}\cos^2\frac{\theta}{2}\Big[G_E^2\,(\frac{q_\mu^2}{\boldsymbol{q}^2})^2 R_\tau^{NN}$$
$$+\; G_A^2\frac{(M_\Delta - M_N)^2}{2\,\boldsymbol{q}^2} R_{\sigma\tau(L)}$$
$$+\; \left(G_M^2\frac{\omega^2}{\boldsymbol{q}^2} + G_A^2\right)\left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\tan^2\frac{\theta}{2}\right) R_{\sigma\tau(T)}$$
$$\pm\; 2\,G_A G_M\frac{k+k'}{M_N}\tan^2\frac{\theta}{2} R_{\sigma\tau(T)}\Big]$$

M. Martini, M. Ericson, G. Chanfray, J. Marteau — Contribution to all terms in G_M and G_A

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas et al. — to all the terms

J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly et al. — only to the G_M^2 term

Relative role of 2p-2h for neutrinos and antineutrinos is different

- there are differences in whether these effects are applied to the axial vector contribution

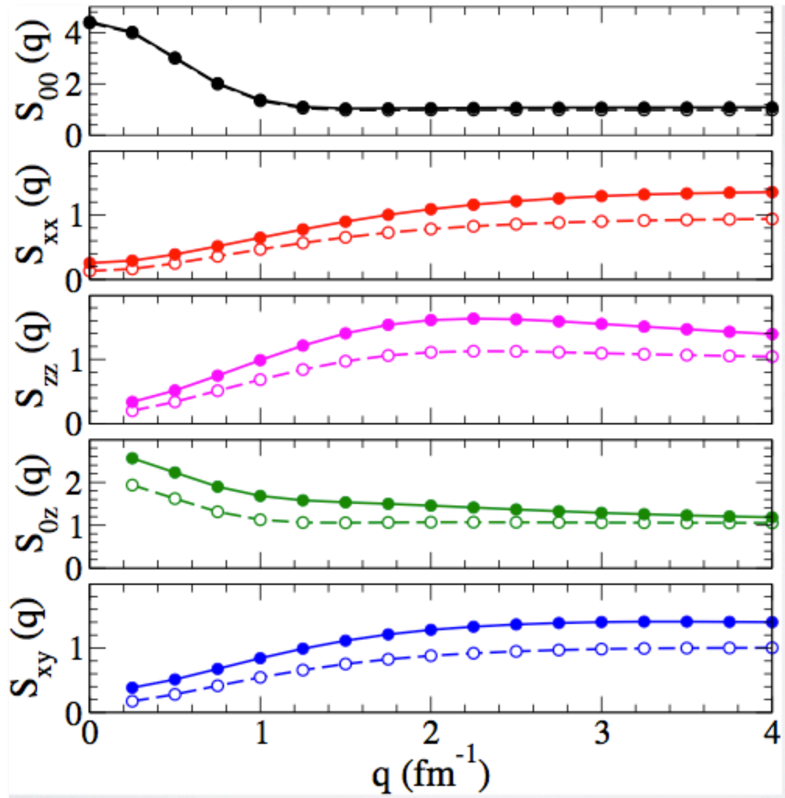
- need $\overline{\nu}/\nu$ ratio data

- Martini, Carlson, and Nieves include axial vector enhancement of varying sizes
- Bodek and SuSA include only vector enhancement (SuSA: "stay tuned")

Path Forward

be careful mixing & matching models

(J. Carlson)



questions:

- axial current
- 1p1h, 2p2h, MEC, Δ
- interference between 1 and 2 body currents
- double counting (SF, 2p2h)
- relativistic effects

- at least this way, can compare our generators to models that are state-of-the-art to see what we are missing

  (gets us further down the road)

- **homework from INT**: each theorist should provide their predictions for the 5 response functions in q,ω for their model

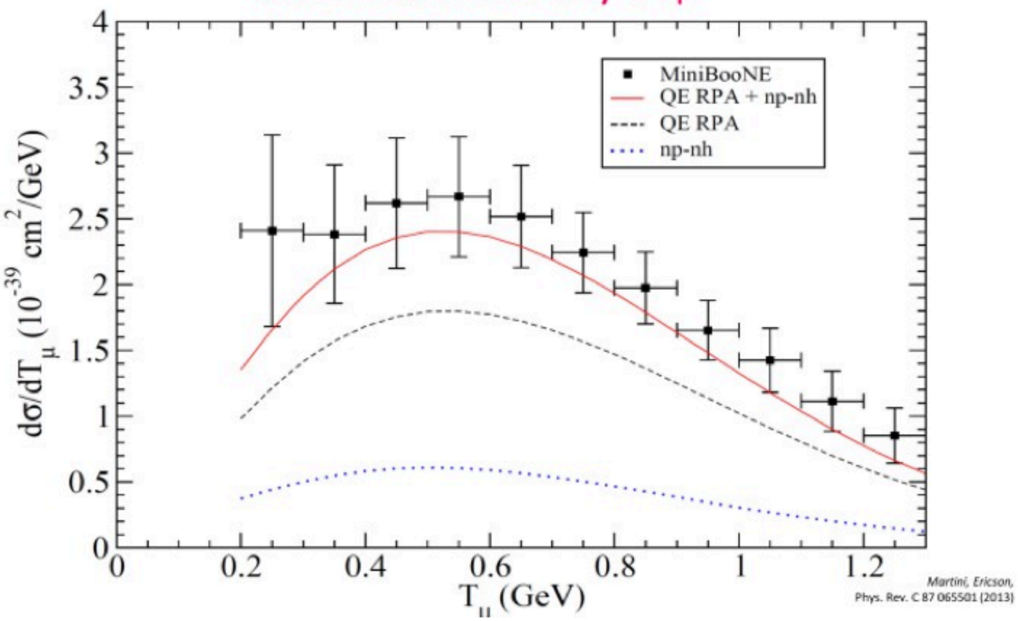
Uncertainties

- "in some ways, we care more about the uncertainties on the model than the model itself"
  - Hugh Gallagher

Something is missing

What we are given (and are grateful for):

Antineutrino $d\sigma/dT_\mu$



(S. Oser)

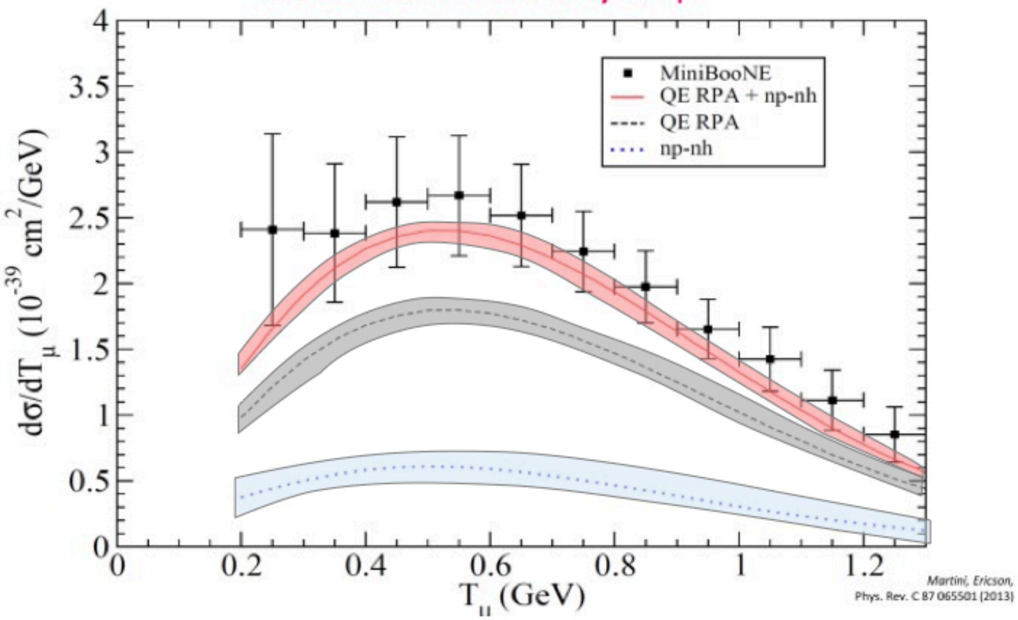
Uncertainties

- "in some ways, we care more about the uncertainties on the model than the model itself"
  - Hugh Gallagher

We need uncertainties, or at least wiggle room

What we wish we had:

Antineutrino dσ/dTμ



(S. Oser)

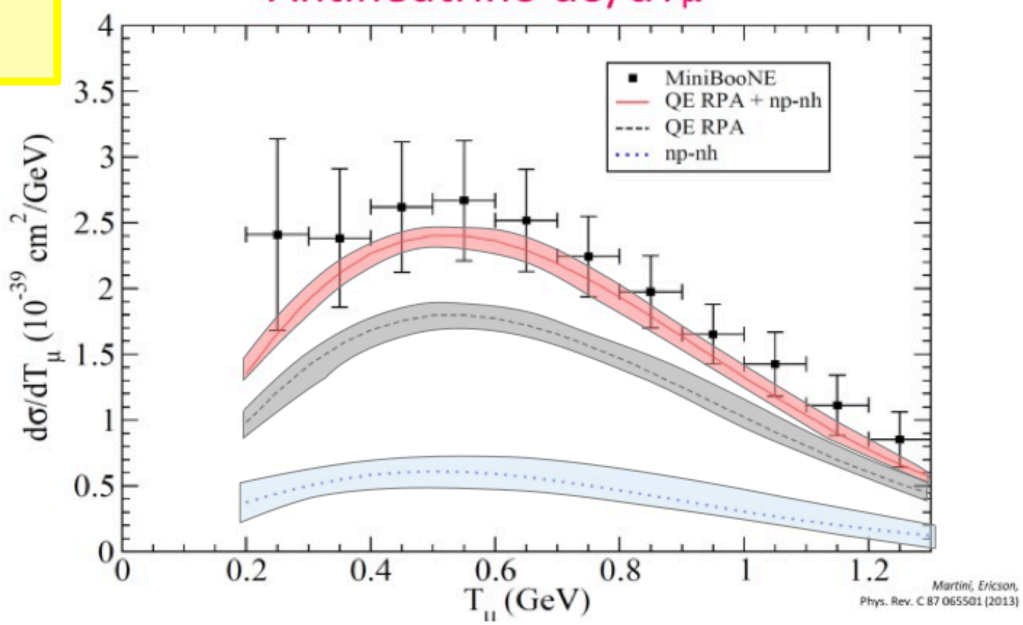
Uncertainties

homework from INT: please report uncertainties with your nuclear model!

We need uncertainties, or at least wiggle room

What we wish we had:

Antineutrino dσ/dTμ

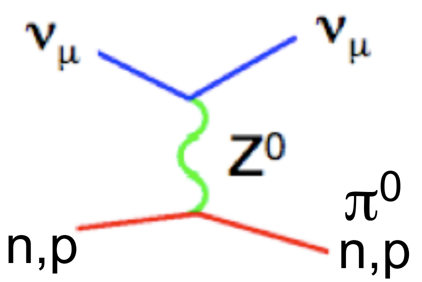


(S. Oser)

We Also Care About Pions

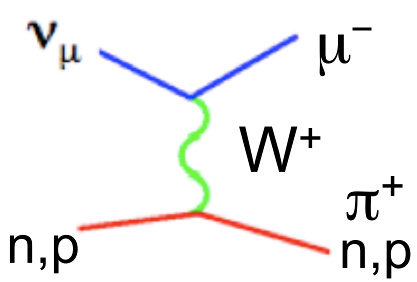
- NC π^0 production

  (background for ν_e appearance)

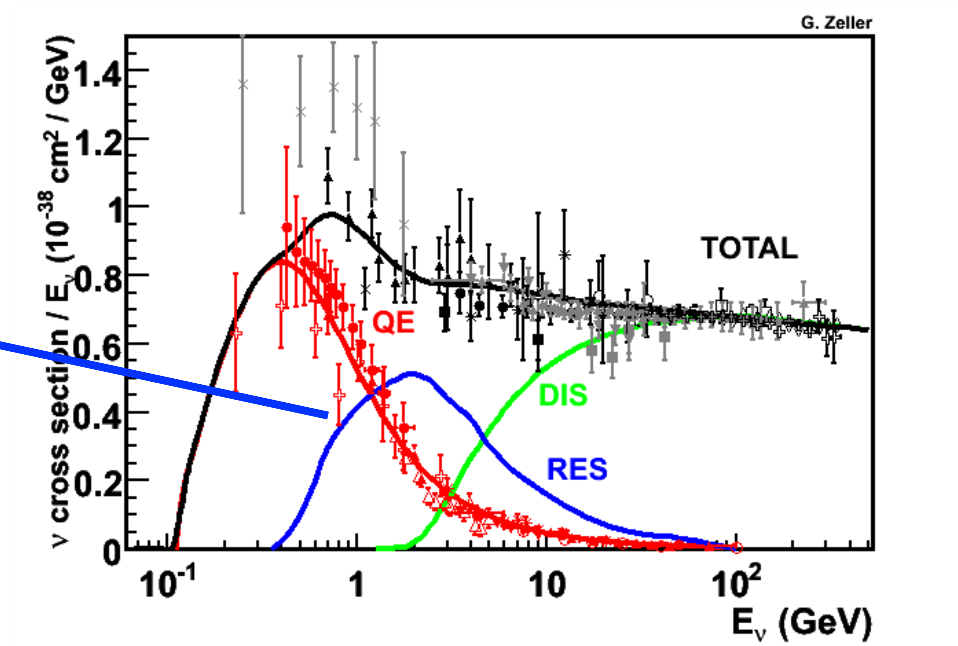


- CC π^+, π^0 production

  (a complication for ν_μ disappearance)



- QE = "no apparent π" *(did you see a π or didn't you?)*
- π production also has important connections to ν osc measurements

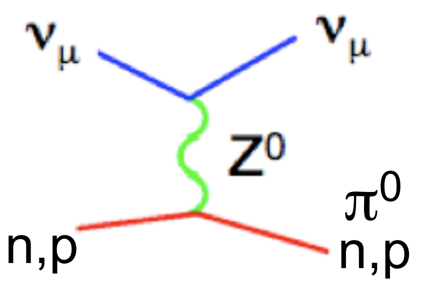


- in ν scattering, it's all mixed together, because are sampling an E_ν spectrum

We Also Care About Pions

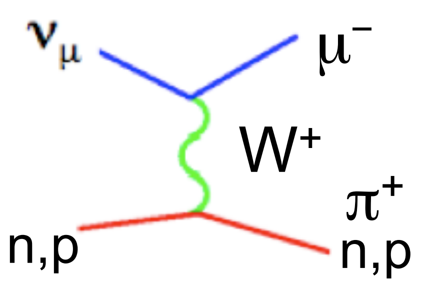
- NC π^0 production

  (background for ν_e appearance)

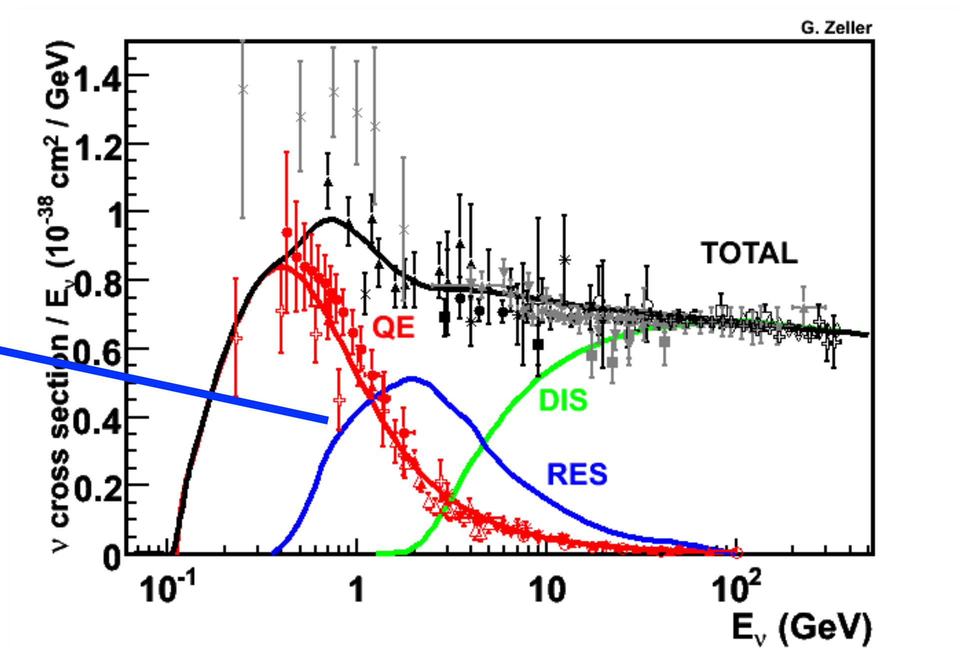


- CC π^+, π^0 production

  (a complication for ν_μ disappearance)



- QE = "no apparent π" *(did you see a π or didn't you?)*
- π production also has important connections to ν osc measurements



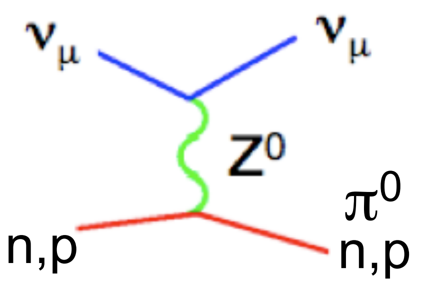
- CC inclusive data is very important!!

  (ArgoNeuT, MINOS, NOMAD, SciBooNE, T2K)

We Also Care About Pions

- NC π^0 production

  (background for ν_e appearance)



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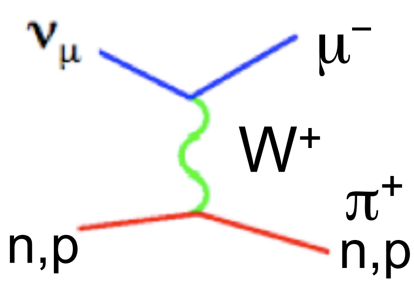

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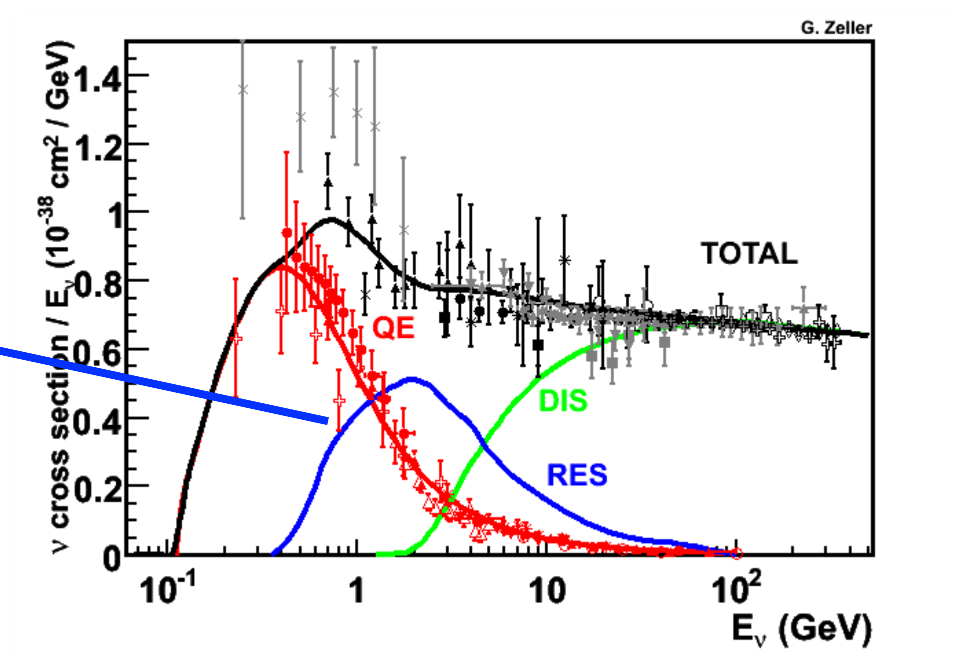


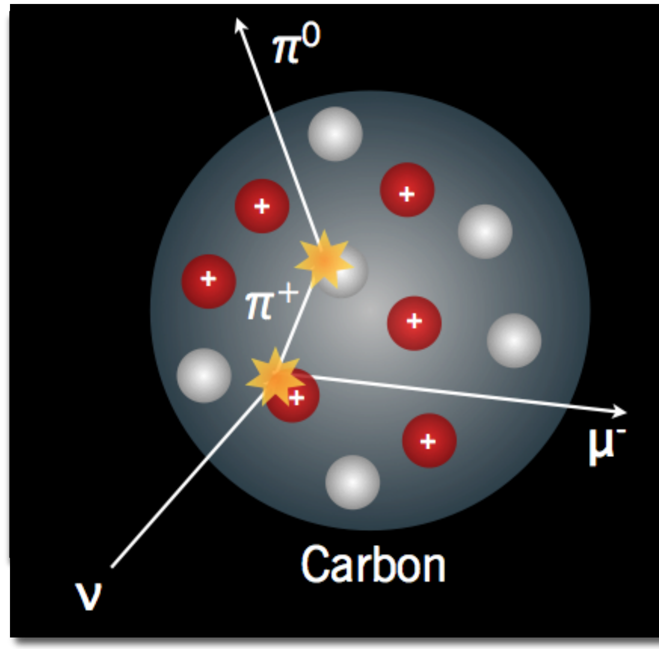
(J. Morfin and C. Mauger lead the inelastic discussions at INT)

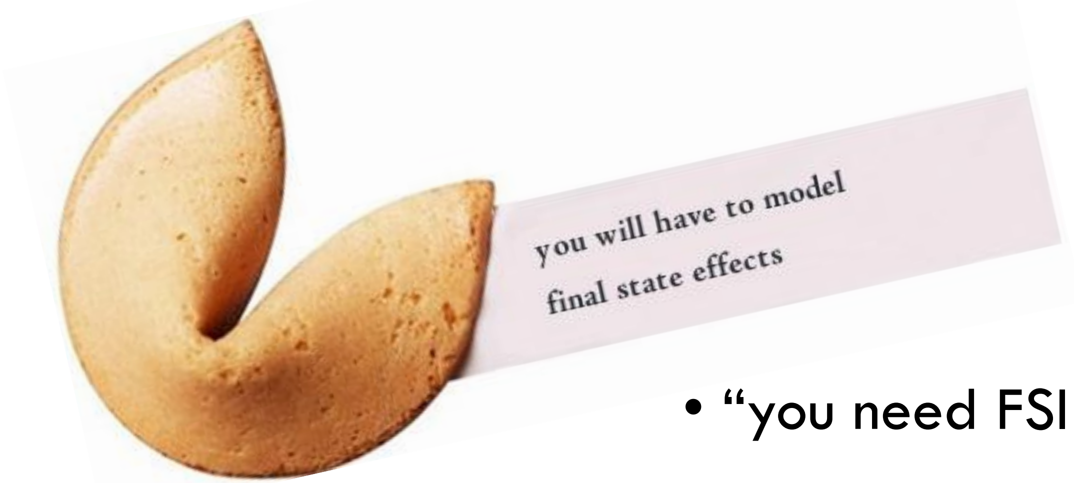
Final State Effects Change the Picture

- there is an increasing appreciation for nuclear effects here as well

"final state interactions (FSI)"

- once a hadron is produced, is has to make it out of the target nucleus
- nucleons can rescatter
- π's can charge exchange, get absorbed

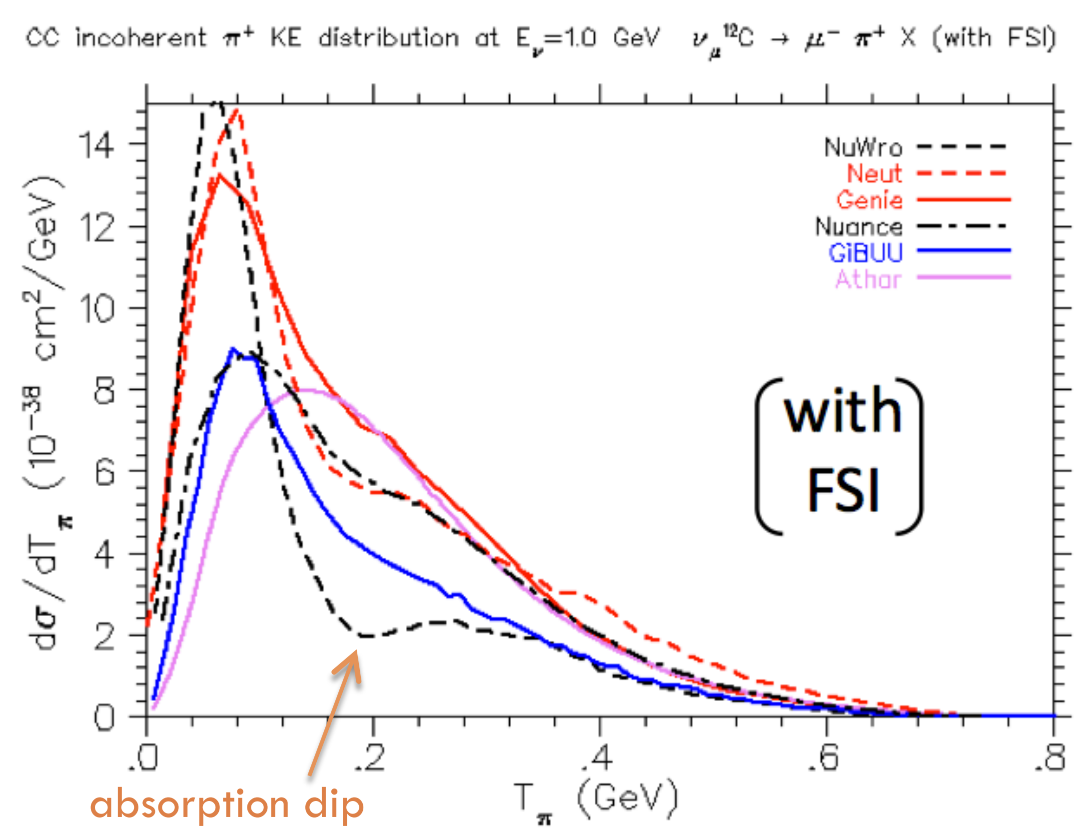




- "you need FSI just like your car needs wheels"

Transport Model Comparison

- FSI is an area where neutrino event generators can differ a lot …



R. Tacik NuInt comparisons, http://regie2.phys.uregina.ca/neutrino/piprod.html

- one example: spectrum of charged pions coming out of carbon for a 1 GeV CC ν_μ interaction
- we have new data to test this! (wait 2 slides)

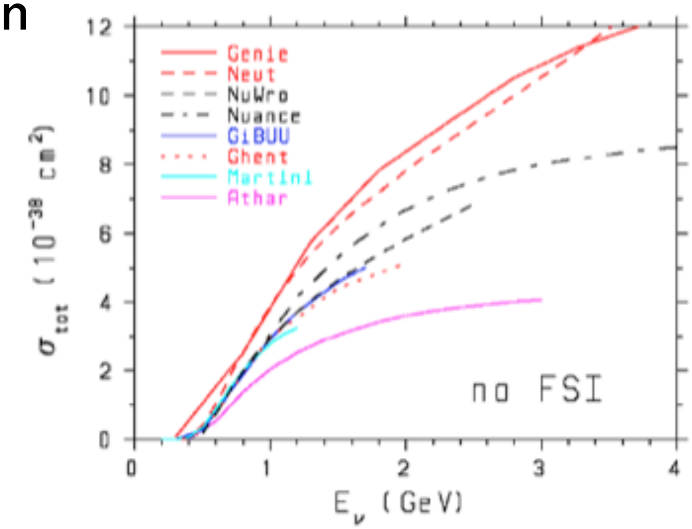
Free Nucleon CC π^+ Cross Section

H. Gallagher

(Don't) Blame it on the Nucleus

S. Dytman et al., NuINT 09

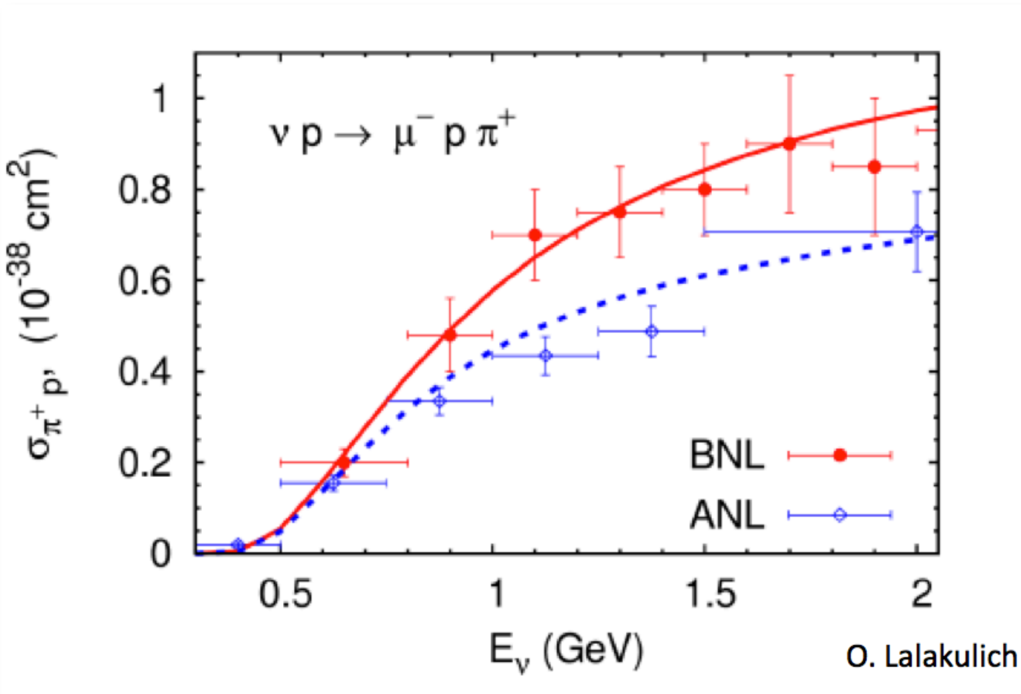
- recognition that "we need to get our stories straight"



- remember, in your ν experiment, you are unavoidably measuring a combination of the:
  - free nucleon σ
  - nuclear effects
  - final state interactions

FIGURE 5. Total CC single π^+ production cross section on ^{12}C. All calculations use the CC pion production vertex. All include nonresonant processes except NUANCE. No coherent events are included.

Part of This is Due to …



- a longstanding ~25% discrepancy between ANL and BNL 1π measurements on D_2
- at INT, there were multiple pleas for new high statistics H_2 or D_2 measurements

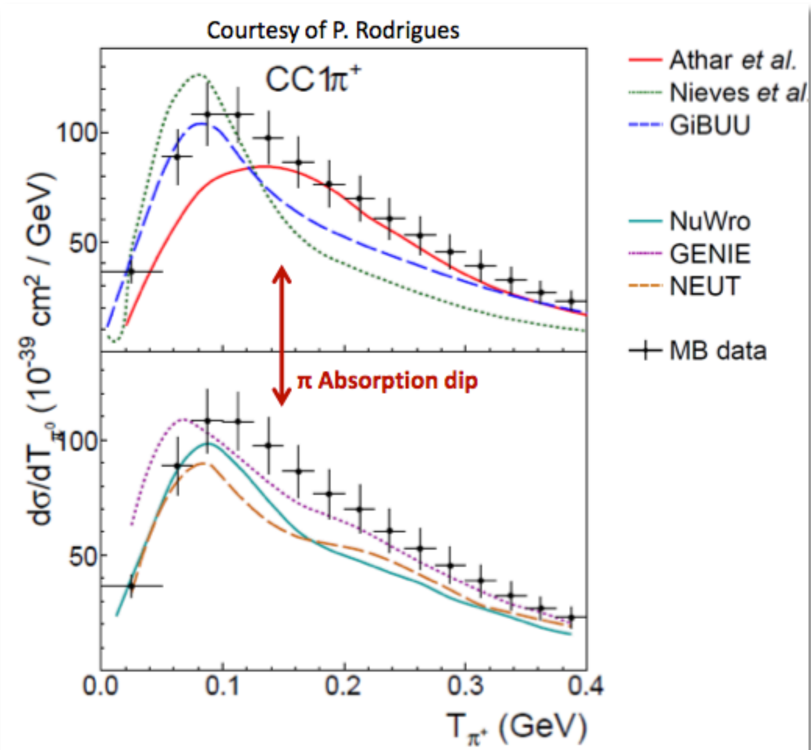
- **homework from INT:** call for a re-analysis of D_2 data from BNL and ANL to see if this discrepancy can be resolved (e.g., fluxes)

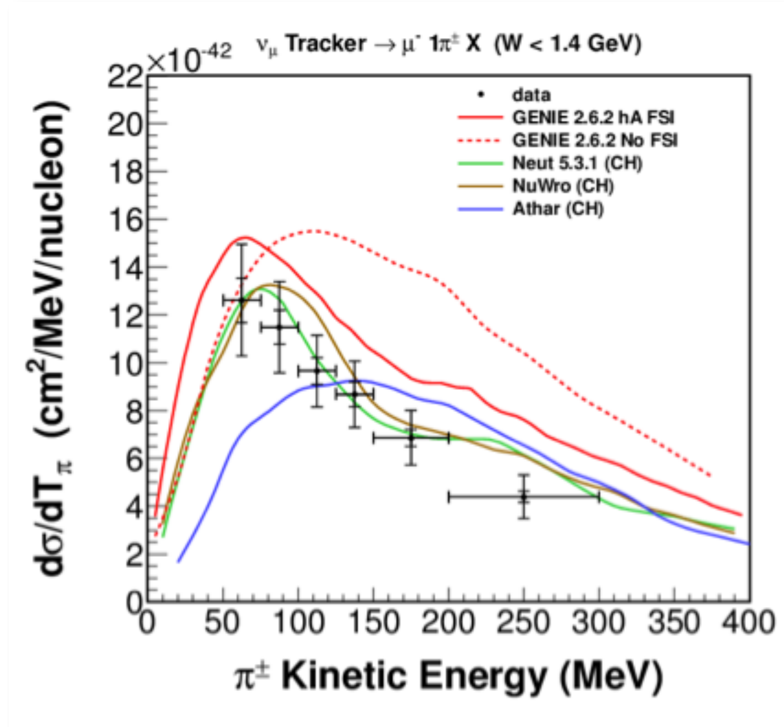
CC π^+ Production on Carbon

M. Wilking, MiniBooNE
PRD 83, 052007 (2011)

(flux-averaged distributions)

B. Eberly, MINERvA
W&C, Feb 2014

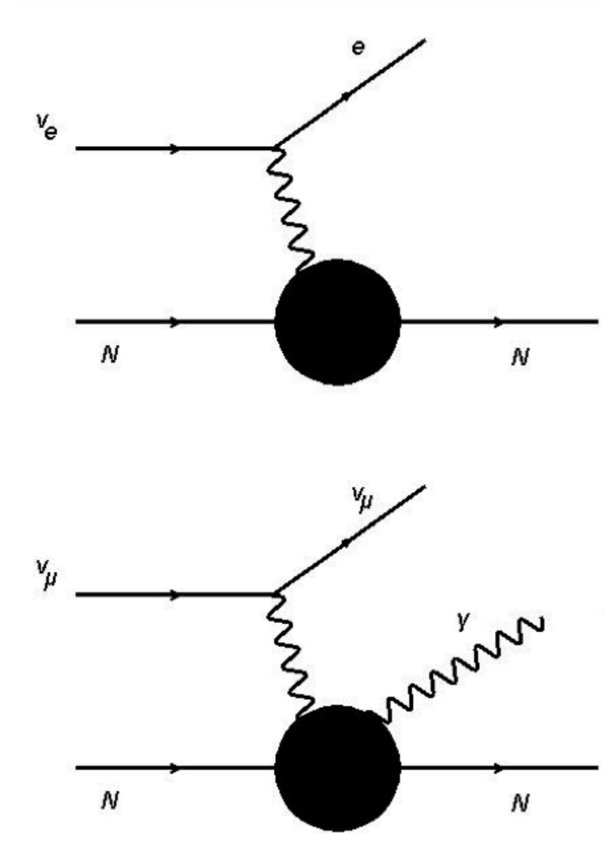


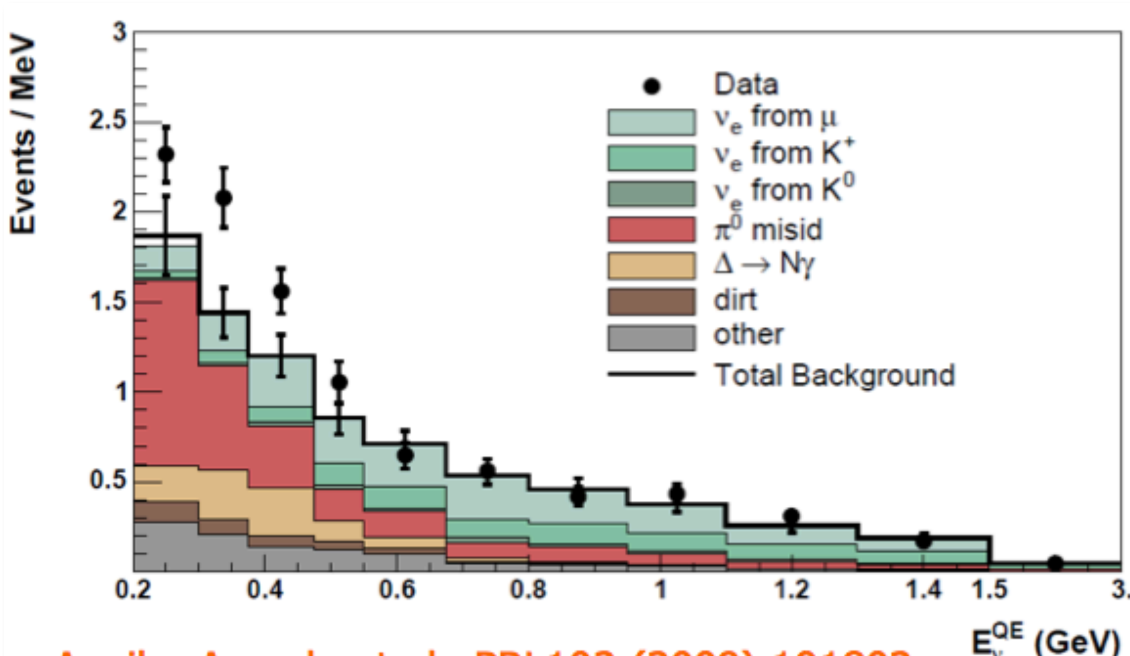


homework: do the MiniBooNE and MINERvA π^+ data agree? to what extent are they measuring the same thing?

Single Photon Production

- just like $\Delta \rightarrow N\pi$, can also have $\Delta \rightarrow N\gamma$
- this is an important background for ν_e appearance experiments





Aguilar-Arevalo et al., PRL102 (2009) 101802

(R. Tayloe lead these discussions at INT)

Single Photon Production

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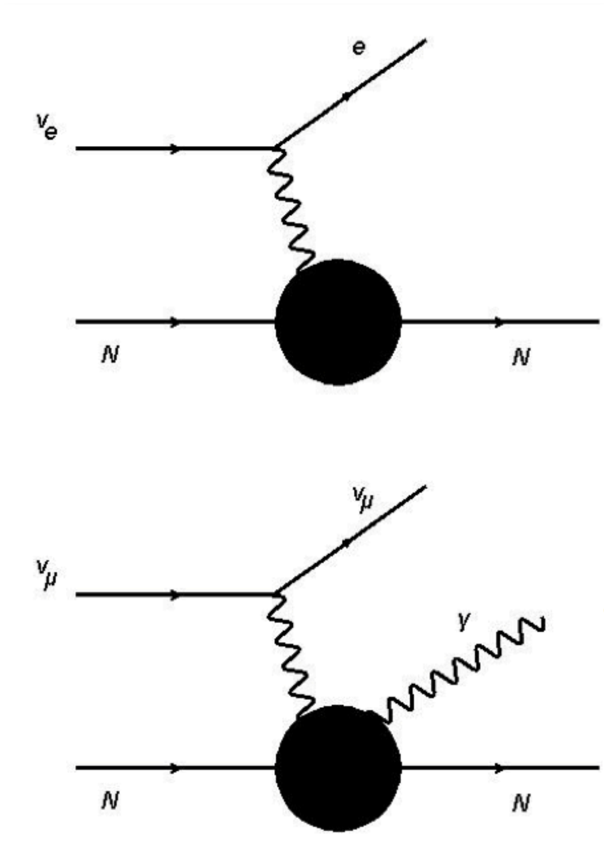
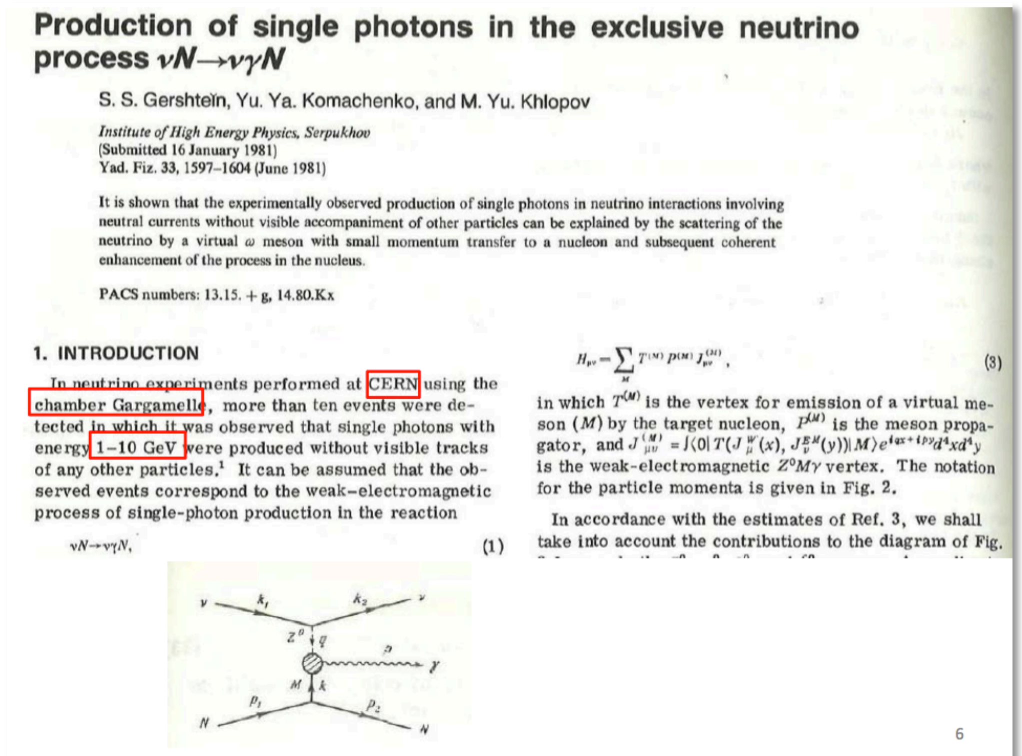


- again, this is not a new idea …



Production of single photons in the exclusive neutrino process $\nu N \rightarrow \nu\gamma N$

S. S. Gershteĭn, Yu. Ya. Komachenko, and M. Yu. Khlopov

Institute of High Energy Physics, Serpukhov
(Submitted 16 January 1981)
Yad. Fiz. 33, 1597–1604 (June 1981)

It is shown that the experimentally observed production of single photons in neutrino interactions involving neutral currents without visible accompaniment of other particles can be explained by the scattering of the neutrino by a virtual ω meson with small momentum transfer to a nucleon and subsequent coherent enhancement of the process in the nucleus.

PACS numbers: 13.15. + g, 14.80.Kx

1. INTRODUCTION

In neutrino experiments performed at CERN using the chamber Gargamelle, more than ten events were detected in which it was observed that single photons with energy 1–10 GeV were produced without visible tracks of any other particles.[1] It can be assumed that the observed events correspond to the weak–electromagnetic process of single-photon production in the reaction

$$\nu N \rightarrow \nu\gamma N, \quad (1)$$

$$H_{\mu\nu} = \sum_M T^{(M)} P^{(M)} J_{\mu\nu}^{(M)}, \quad (3)$$

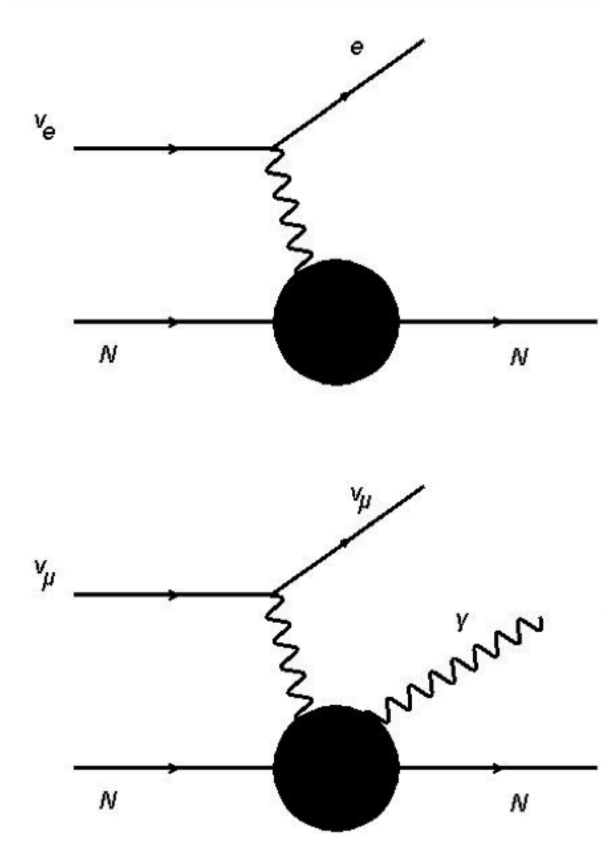
in which $T^{(M)}$ is the vertex for emission of a virtual meson (M) by the target nucleon, $P^{(M)}$ is the meson propagator, and $J_{\mu\nu}^{(M)} = \int \langle 0| T(J_\mu^W(x), J_\nu^{EM}(y))|M\rangle e^{iqx+ipy} d^4x d^4y$ is the weak-electromagnetic $Z^0 M\gamma$ vertex. The notation for the particle momenta is given in Fig. 2.

In accordance with the estimates of Ref. 3, we shall take into account the contributions to the diagram of Fig.

6

Single Photon Production

- just like $\Delta \rightarrow N\pi$, can also have $\Delta \rightarrow N\gamma$
- this is an important background for ν_e appearance experiments



- several groups have since revisited this physics with brand new calculations of ν-induced single photon production
  - *Hill, Hill, Harvey,*
  - *Jenkins, Goldman*
  - *Zhang, Serot*
  - *Wang et al.*

(L. Alvarez-Ruso)

- theorists are working together and comparing results – this is very valuable (difficult for experimentalists to do) and was a good outcome of the workshop

Single Photon Production

- model calculations are in good agreement with each other (~0.1-1 GeV)

- miraculously, predictions are also in good agreement with MiniBooNE estimate
  - $\Delta \rightarrow N\gamma$ dominates

total prediction compared to MB estimate:

ν

E_{QE}(GeV)	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.25]
coh	1.5 (2.9)	6.0 (9.2)	2.1 (8.0)
inc	12.0 (14.1)	25.5 (31.1)	12.6 (23.2)
H	4.1 (4.4)	10.6 (11.6)	4.6 (6.3)
Total	17.6 (21.4)	42.1 (51.9)	19.3 (37.5)
MiniBN	19.5	47.3	19.4
Excess	42.6 ± 25.3	82.2 ± 23.3	21.5 ± 34.9

$\bar{\nu}$

E_{QE}(GeV)	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.25]
coh	1.0 (2.2)	3.1 (5.5)	0.87 (5.4)
inc	4.5 (5.3)	10.0 (12.2)	4.0 (10.2)
H	1.3 (1.6)	3.6 (4.3)	1.1 (2.4)
Total	6.8 (9.1)	16.7 (22.0)	6.0 (18.0)
MiniBN	8.8	16.9	6.8
Excess	34.6 ± 13.6	23.5 ± 13.4	20.2 ± 22.8

(X. Zhang)

- an output from INT will be a summary of where this stands, next step is getting this into the other event generators (μB, NOvA, T2K)

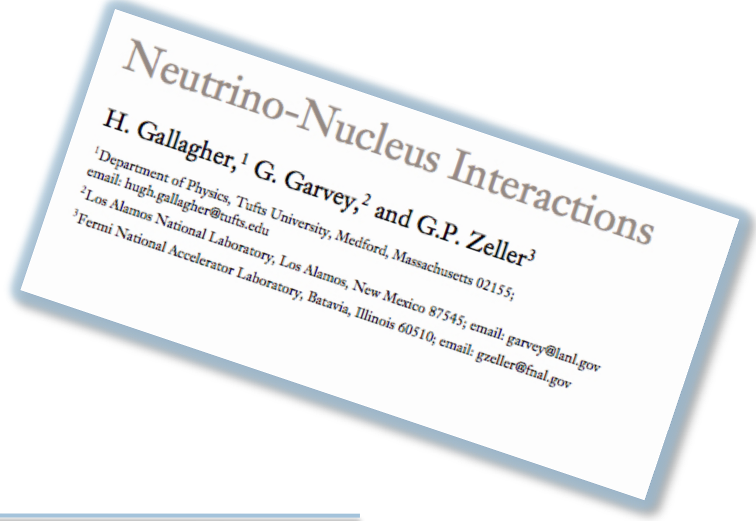
Conclusions

- ν-nucleus interactions are a key component of our ν oscillation program
  - *QE, inelastic, γ production*
  - *this physics is complex and it's important to get right*
- we made some very important headway at INT this past December
  - *be careful what you call QE (be mindful of the selection & th kinematics)*
  - *there are large nuclear effects that impact our QE samples (2p2h, MEC)*
  - *your nuclear model must fit the right e^- scattering data to capture this physics (L,T)*
  - *however, don't always blame things on nuclear effects (especially true for π prod)*
  - *we have some homework to do*

- next steps:
  - *written summary*
  - *forum*
  - *NuSTEC (J. Morfin)*
- meetings coming up: **GENIE** developers meeting at Fermilab in March, **NuInt** workshop in London in May, **NuSTEC σ_ν summer school** in 2014

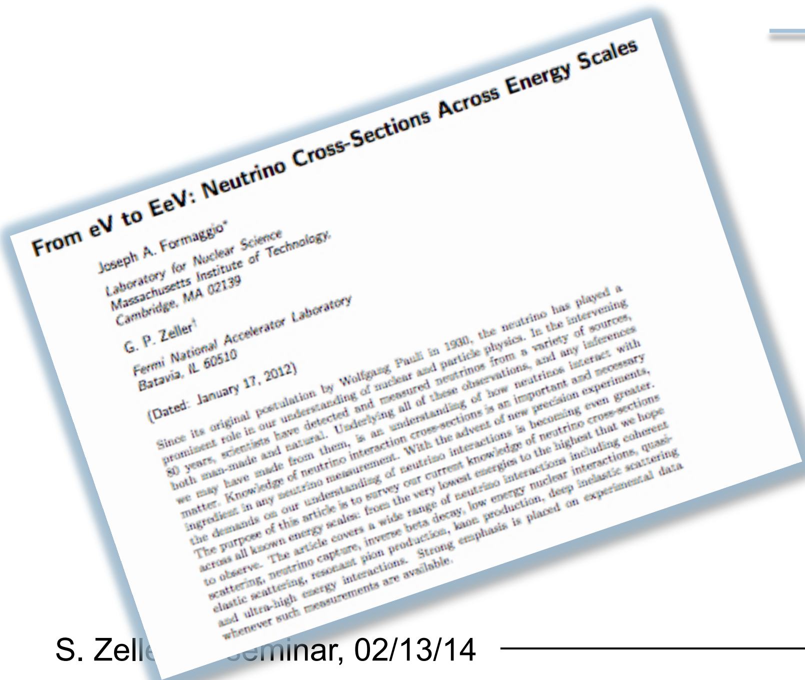
Further Reading

"Neutrino-Nucleus Interactions",
focus is on ν and e^- QE scattering
Ann. Rev. Nucl. Part. Sci. 61, 355 (2011)



Neutrino-Nucleus Interactions

H. Gallagher,[1] G. Garvey,[2] and G.P. Zeller[3]
[1]Department of Physics, Tufts University, Medford, Massachusetts 02155; email: hugh.gallagher@tufts.edu
[2]Los Alamos National Laboratory, Los Alamos, New Mexico 87545; email: garvey@lanl.gov
[3]Fermi National Accelerator Laboratory, Batavia, Illinois 60510; email: gzeller@fnal.gov



From eV to EeV: Neutrino Cross-Sections Across Energy Scales

Joseph A. Formaggio*
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139

G. P. Zeller†
Fermi National Accelerator Laboratory
Batavia, IL 60510

(Dated: January 17, 2012)

Since its original postulation by Wolfgang Pauli in 1930, the neutrino has played a prominent role in our understanding of nuclear and particle physics. In the intervening 80 years, scientists have detected and measured neutrinos from a variety of sources, both man-made and natural. Underlying all of these observations, and any inferences we may have made from them, is an understanding of how neutrinos interact with matter. Knowledge of neutrino interaction cross-sections is an important and necessary ingredient in any neutrino measurement. With the advent of new precision experiments, the demands on our understanding of neutrino interactions is becoming even greater. The purpose of this article is to survey our current knowledge of neutrino cross-sections across all known energy scales: from the very lowest energies to the highest that we hope to observe. The article covers a wide range of neutrino interactions including coherent scattering, neutrino capture, inverse beta decay, low energy nuclear interactions, quasi-elastic scattering, resonant pion production, kaon production, deep inelastic scattering and ultra-high energy interactions. Strong emphasis is placed on experimental data whenever such measurements are available.

"From eV to EeV: Neutrino Cross Sections Across Energy Scales",
covers σ_ν from the lowest to highest E_ν's
Rev. Mod. Phys. 84, 1307 (2012)

Backup

Response Functions

Neutrino Scattering:

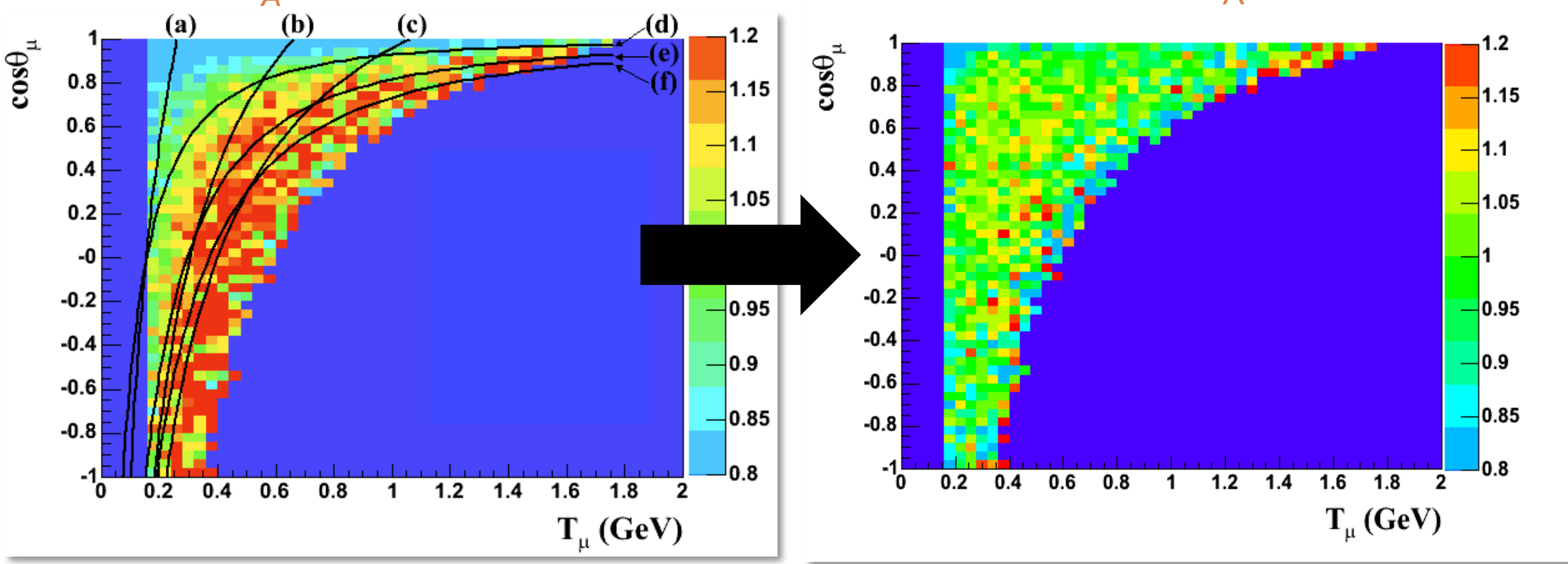
$$\left(\frac{d\sigma}{d\epsilon' d\Omega}\right)_{\nu/\bar{\nu}} = \frac{G_F^2}{2\pi^2} k'\epsilon' \cos^2\frac{\theta}{2}\left[R_{00} + \frac{\omega^2}{q^2} R_{zz} - \frac{\omega}{q} R_{0z} + \left(\tan^2\frac{\theta}{2} + \frac{Q^2}{2\,q^2}\right) R_{xx} \mp \tan\frac{\theta}{2}\sqrt{\tan^2\frac{\theta}{2} + \frac{Q^2}{q^2}}\, R_{xy}\right]$$

$$\begin{aligned}
R_{00}(q,\omega) &= \overline{\sum_i}\sum_f \delta(\omega + m_A - E_f)\, |\langle f|\, j^0(\mathbf{q},\omega)\, |i\rangle|^2 , \\
R_{zz}(q,\omega) &= \overline{\sum_i}\sum_f \delta(\omega + m_A - E_f)\, |\langle f|\, j^z(\mathbf{q},\omega)\, |i\rangle|^2 , \\
R_{0z}(q,\omega) &= \overline{\sum_i}\sum_f \delta(\omega + m_A - E_f)\Big[\langle f|\, j^0(\mathbf{q},\omega)\, |i\rangle \\
&\quad \times \langle f|\, j^z(\mathbf{q},\omega)\, |i\rangle^* + \text{c.c.}\Big] , \\
R_{xx}(q,\omega) &= \overline{\sum_i}\sum_f \delta(\omega + m_A - E_f)\Big[\, |\langle f|\, j^x(\mathbf{q},\omega)\, |i\rangle|^2 \\
&\quad + |\langle f|\, j^y(\mathbf{q},\omega)\, |i\rangle|^2 \Big] , \\
R_{xy}(q,\omega) &= \overline{\sum_i}\sum_f \delta(\omega + m_A - E_f)\Big[\langle f|\, j^x(\mathbf{q},\omega)\, |i\rangle \\
&\quad \times \langle f|\, j^y(\mathbf{q},\omega)\, |i\rangle^* - \text{c.c.}\Big] ,
\end{aligned}$$

MiniBooNE Shape Comparison

- large data/MC discrepancies exist and they are Q^2-dependent
- circa 2007: MiniBooNE originally "fixed" this in our simulations by increasing M_A (which worked pretty well!)

M_A=1.0 GeV in RFG: after increase M_A = 1.35 GeV:



(a), (b), (c) = lines of constant E_ν, (d), (e), (f) = lines of constant Q^2

Path Forward

IV. A message for MC generators:

- improvements in treatment of nuclear effects (NN correlations) should be done
- spectral function should probably become a default option
- before more rigorous computations are done, existing treatments of two body contribution should be applied
  - comparison to MiniBooNE ν_μ and $\bar{\nu}_\mu$ data is a necessary consistency check
- it will be very difficult to get everything that is required in the completely satisfactory way
  - rigorous computations are non-relativistic
  - experimentalists need to know results for oxygen, argon, ...
  - MCs need predictions for final state nucleons

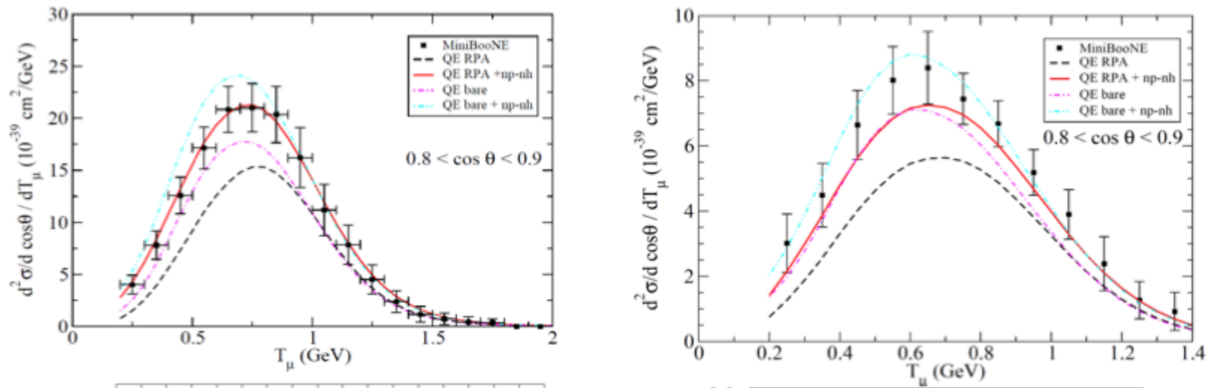
(J. Sobczyk)

Model Comparisons

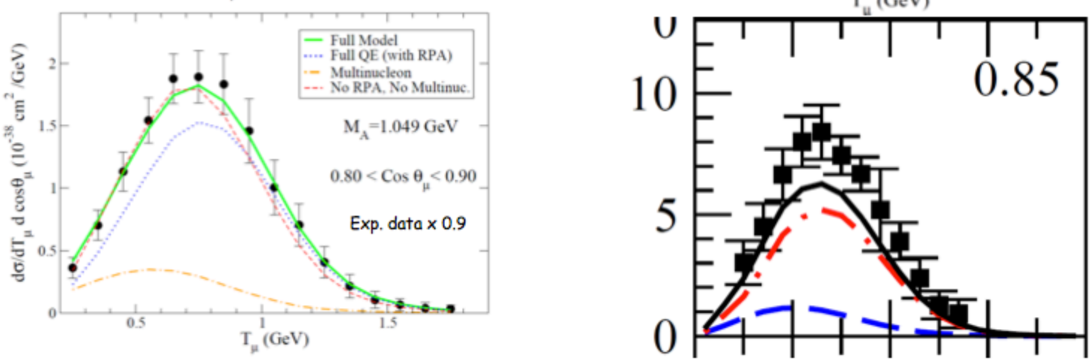
(M. Martini)

ν $\bar{\nu}$

Martini et al.



Nieves et al.



black: QE RPA+2p2h

red: QE RPA

Amaro et al.