NEUTRINO CROSS SECTIONS

Sam Zeller
Fermilab

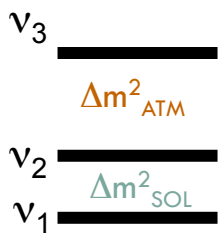
Final State Nucleons for Neutrino-Nucleus Interactions Workshop at JLAB

May 14, 2015

- this is a topic that has gotten a lot more interesting over the past several years
- perspective from a neutrino experimentalists point of view

Future of Neutrino Physics

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



  - what are the masses of the neutrinos?
  - are neutrinos their own anti-particles?

  β and $\beta\beta$ decay

  - is our picture correct?
  - what is the ν mass ordering?
  - do neutrinos violate CP?
  - are there more than 3 neutrinos?

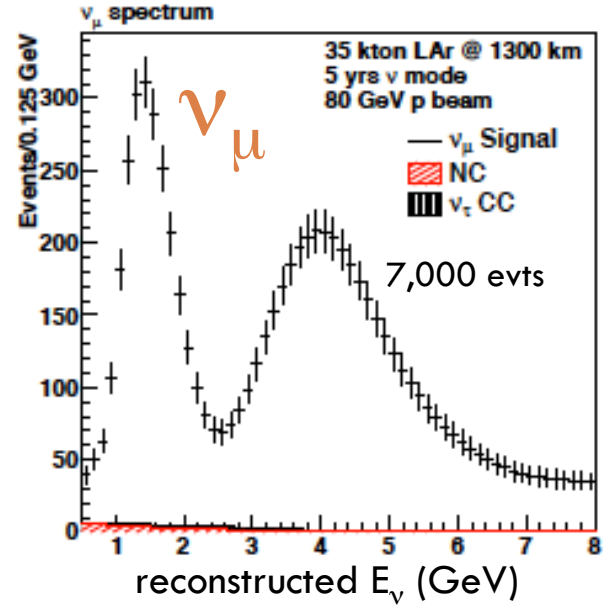
  enabled now that we know θ_{13} is non-zero

  neutrino oscillation experiments ← will focus on

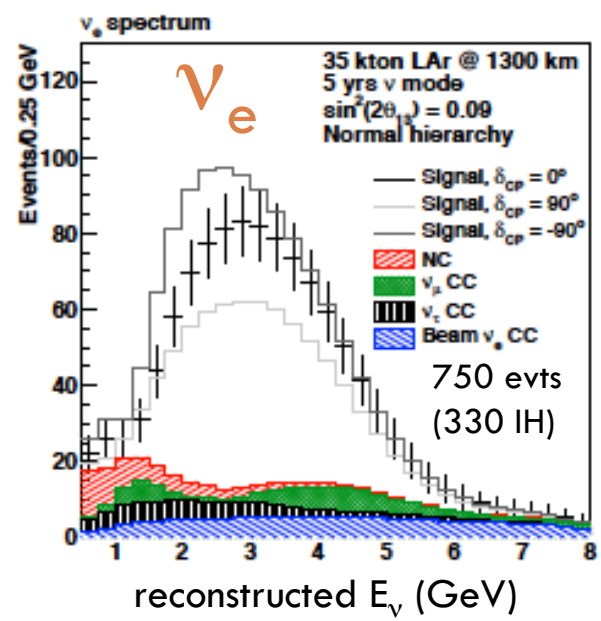
- a correct interpretation of the outcome of ν oscillation experiments requires precise understanding of ν and $\overline{\nu}$ interaction cross sections in a rather challenging energy regime

What We Care About

- studying $\nu_\mu \rightarrow \nu_e$ (appearance) and $\nu_\mu \rightarrow \cancel{\nu}_\mu$ (disappearance) for both neutrinos and antineutrinos
- **measuring E_ν**
- probing a range of ν energies
  (WBB, important to disentangle MH and CP violating effects)
- modeling ν interactions from **100's of MeV to few-GeV**
  (depends on the neutrino baseline, whether on or off axis)
- processes that are essentially the same as what is measured in e^- scattering …

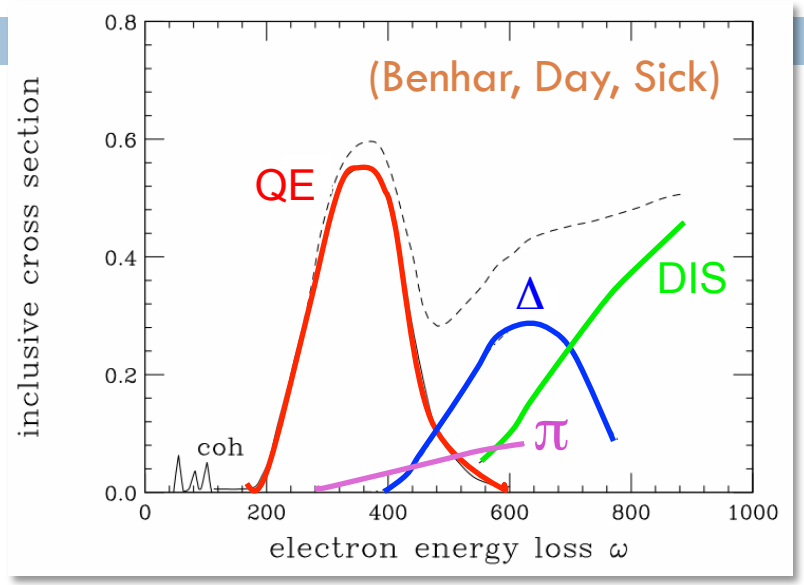


- projections for DUNE -

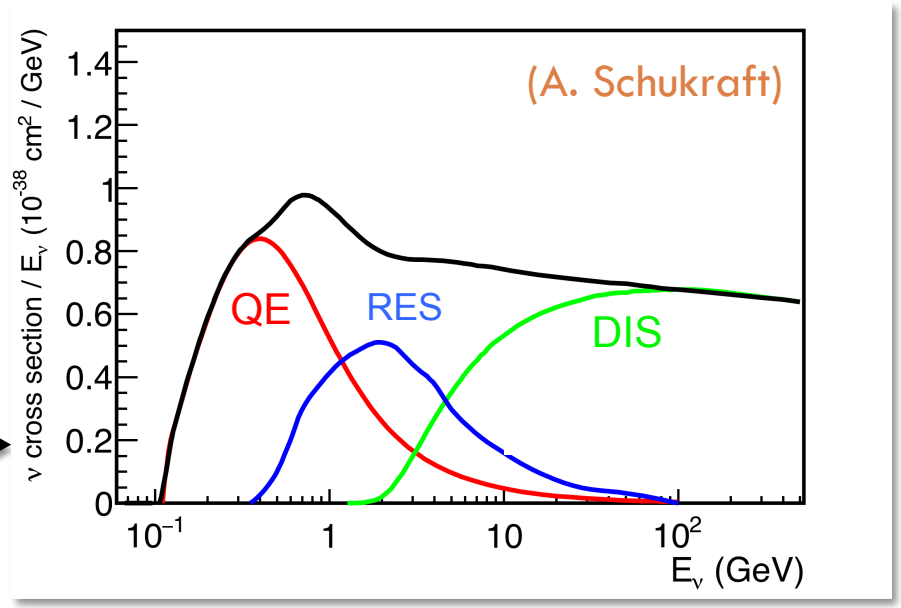


Electrons vs. Neutrinos

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

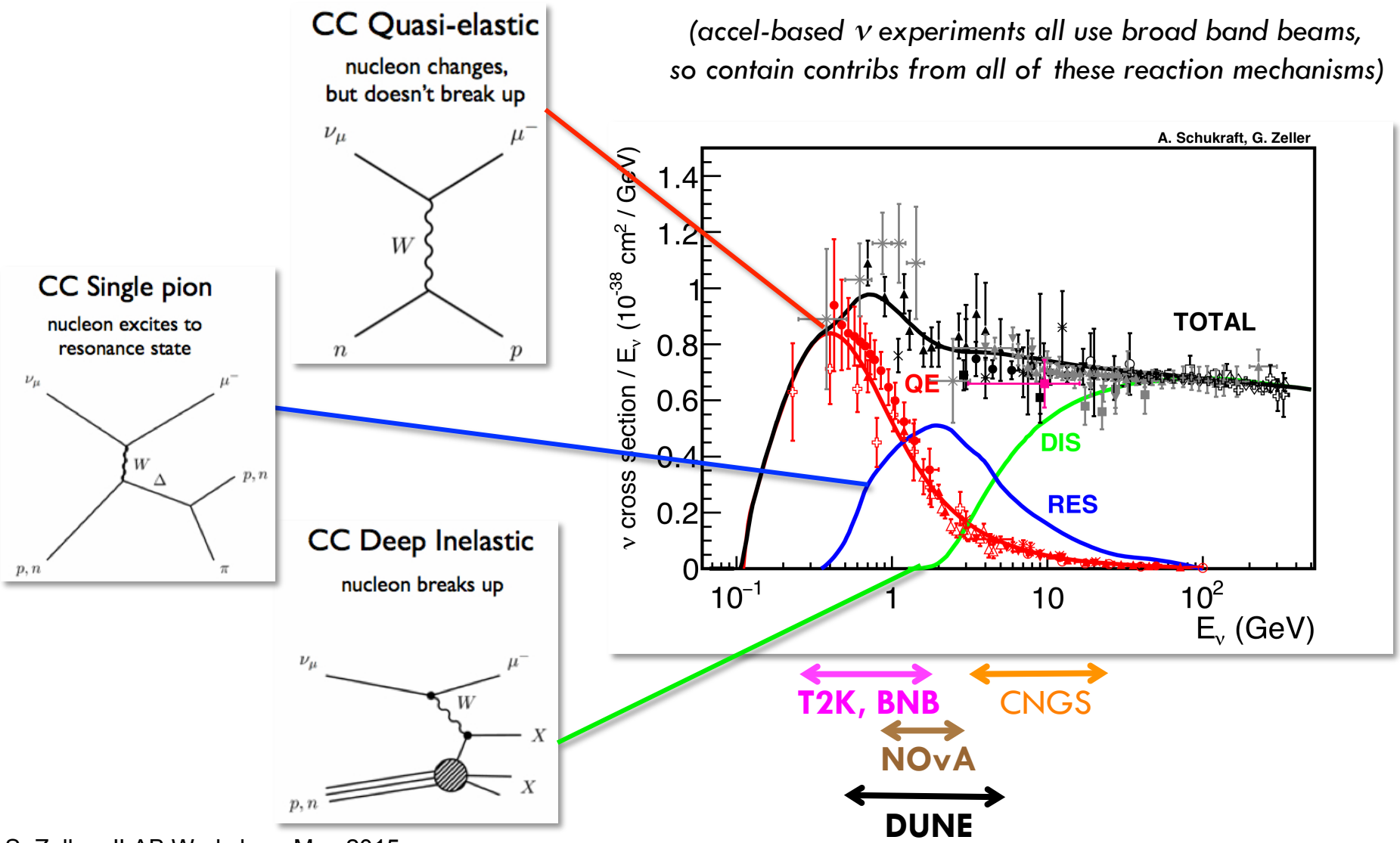


- **neutrino scattering:**
  - beam energy is <u>not</u> known
  - not monochromatic (spectrum of E_ν)
  - added axial-vector contribution
  - think in terms of E_ν →
    (infer E_ν from E_{lep}, θ_{lep} or $E_{lep}+E_{had}$)



Three Different Models

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



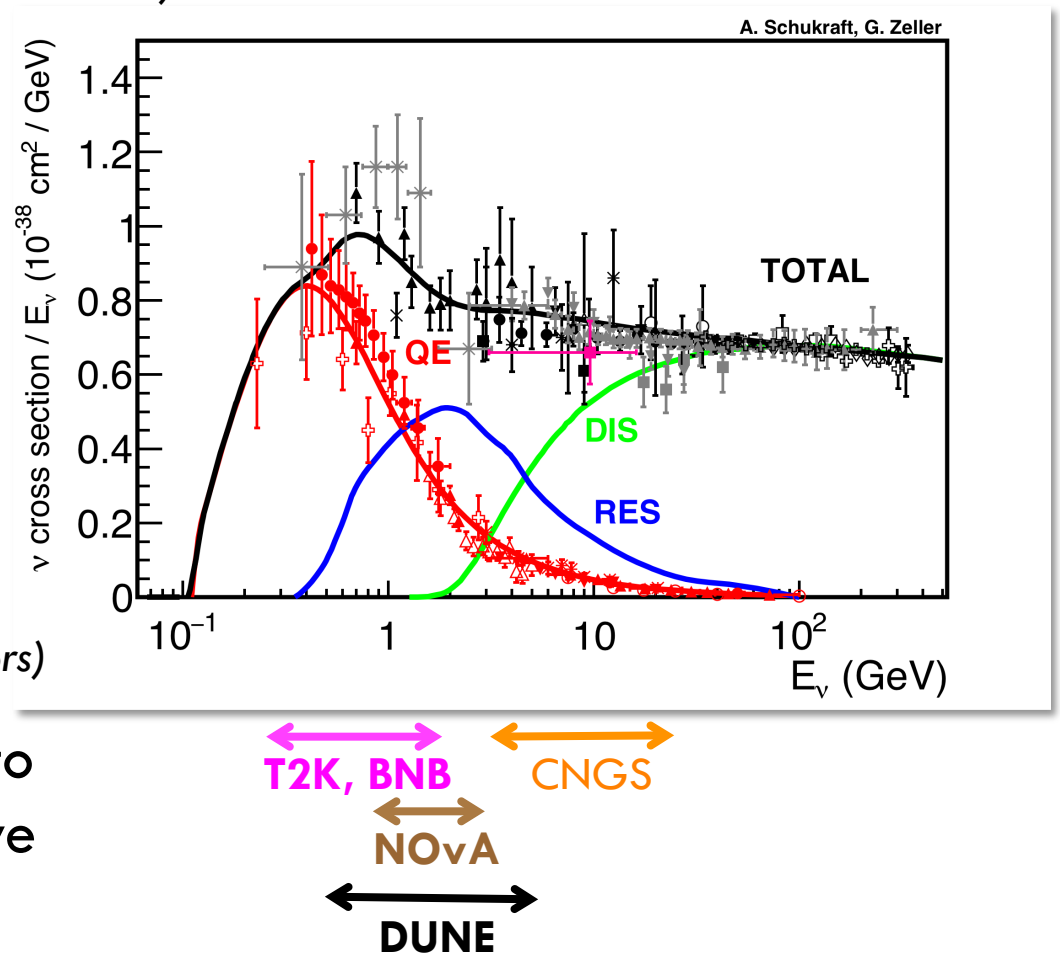
Some of the Challenges

- ν beams are not mono-energetic → *multiple processes contributing at a given E_ν*
  (broad flux of neutrinos illuminating the detector)

- σ_ν's are not particularly well-constrained in the region we care about

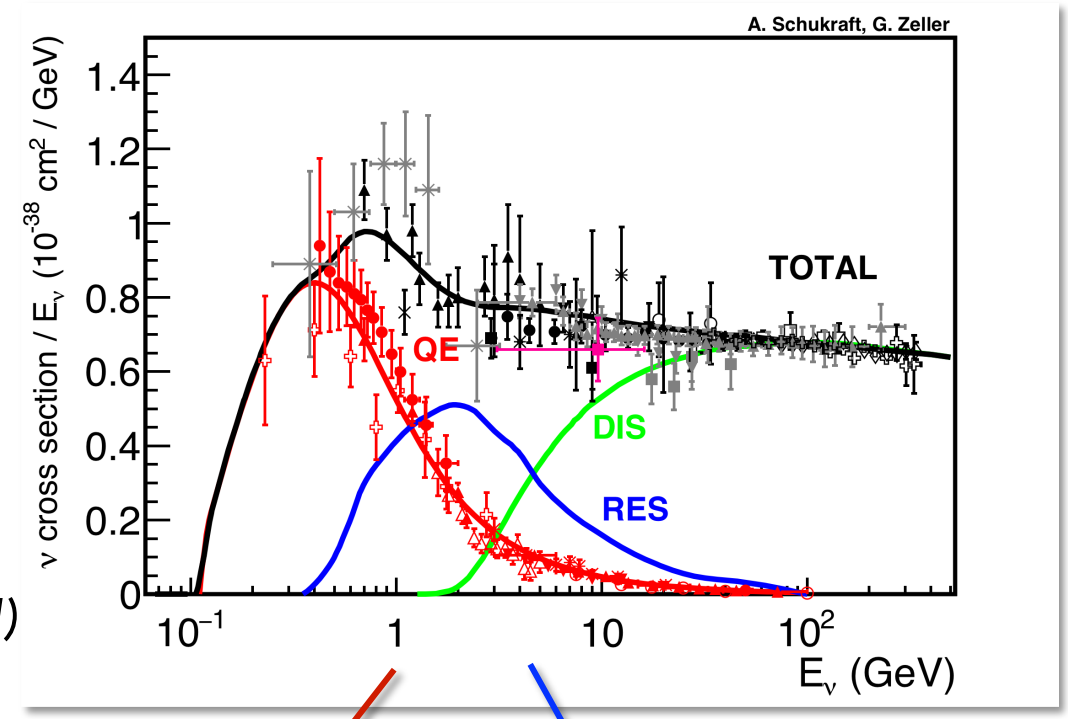
- ν experiments use nuclear targets; **nuclear effects** significantly alter σ_ν's, f.s. particle topology/kinematics
  (all of this phyx has to go into generators)

- at the end of the day, have to infer E_ν from what we observe



Some of the Good News

- there are a lot of new and improved theoretical calculations of ν-nucleus scattering
- and there are new exp'l measurements being made of ν cross sections
- advantages of new data:
  - *higher statistics*
  - *more well-known ν beams*
    (need to know Φ_ν to measure σ_ν!)
  - *variety of nuclear targets*
  - *also studying antineutrinos*
    (important for future $\not{C}\not{P}$ searches)

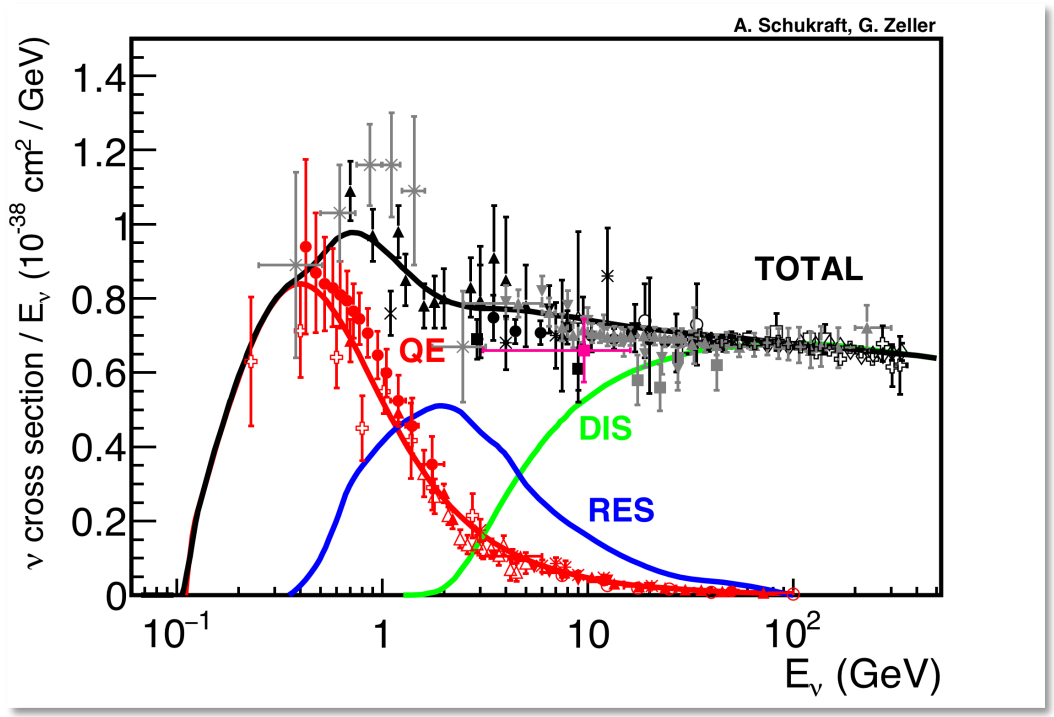


MiniBooNE, T2K, MicroBooNE

ArgoNeuT, MINERνA, ICARUS, MINOS, NOMAD, NOνA

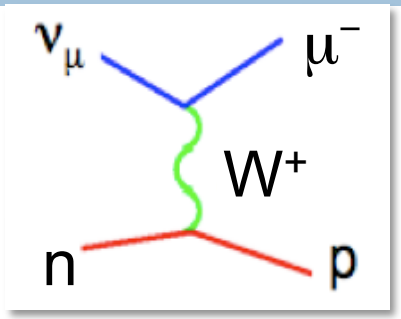
Neutrino Interactions

- next, let's talk about some specific neutrino interactions and why they are important
- we will start on the left and work our way up in energy



- what are some of the issues we face now ~30 years later?

ν Quasi-Elastic Scattering



Why important?

- **important for ν oscillation experiments**
  - typically gives largest contribution to the signal samples in many osc exps
    (largest contribution to the σ_ν at ~ 1 GeV)

    examples:

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

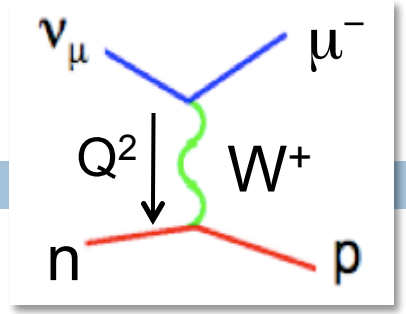
    $\nu_\mu \rightarrow \cancel{\nu}_\mu$ (ν_μ disappearance)

  - two-body reaction, so in principle, can determine E_ν solely from lepton kinematics

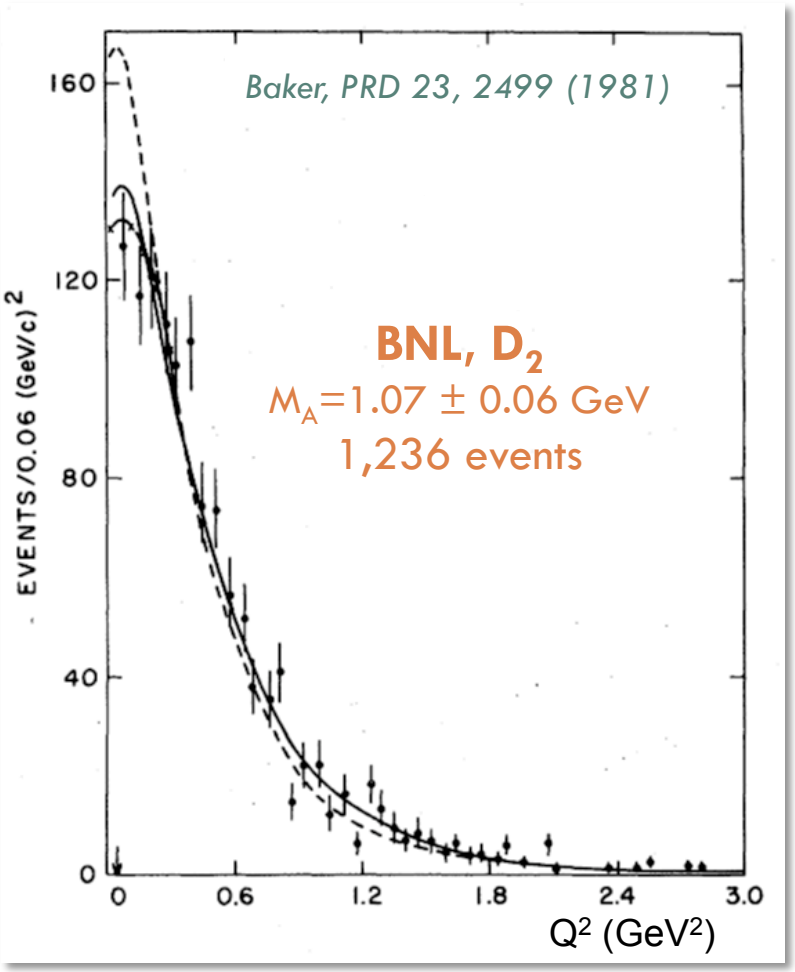
for free nucleon scattering, produces a single lepton & a single nucleon, but nuclear effects complicate this picture: this is not the final state should always expect to observe on a nuclear target!

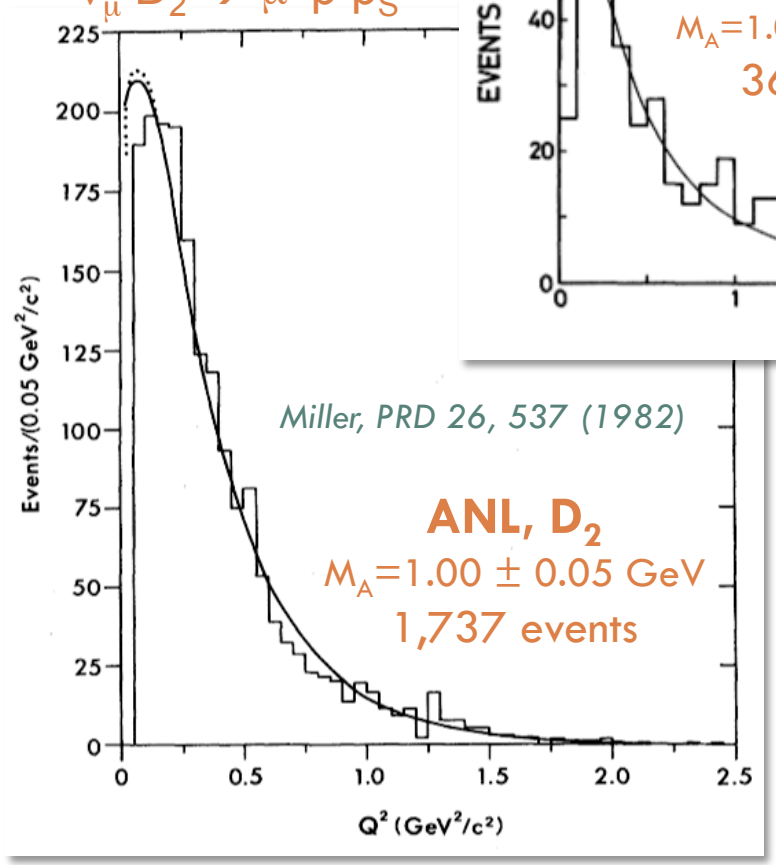
(heavily studied in 1970's and 80's, one of the 1st ν interactions measured)

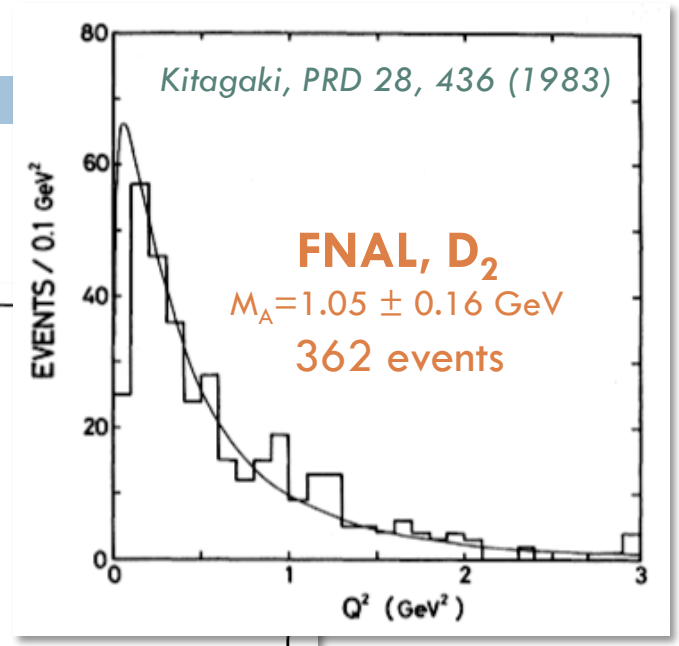
Historical Data



ν_μ D_2 → μ^- p p_S







goal: to look for NCs, so measured the axial FF in the CC channel

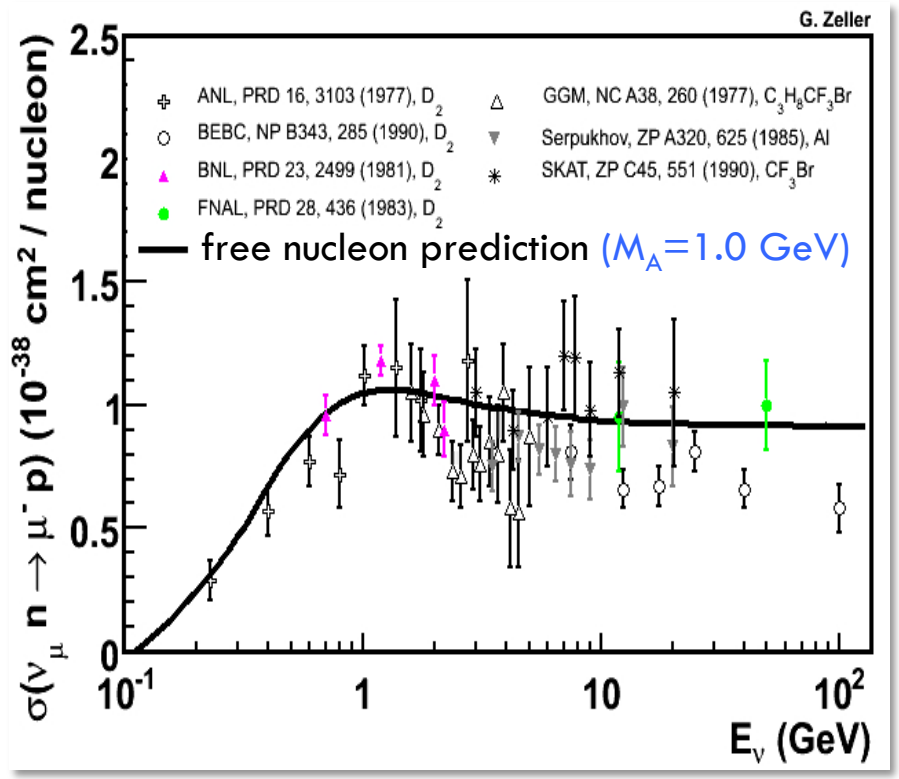
- *we would not look at ν QE again for another 20+ years until ν oscillations put us back here*

Neutrino QE Cross Section

- conventional wisdom had always been that this σ_{QE} is well-known
  - *it's a simple 2-body process*
  - *predictions relied on impulse approx: ν interacts with one nucleon at time*
- e^- scattering give us vector piece and ν's tell us axial-vector piece
- this description had been quite successful …
  - *at least in describing the bulk of the historical ν data (D_2)*
  - *can predict size & shape of σ*

→ see talk by Van Orden

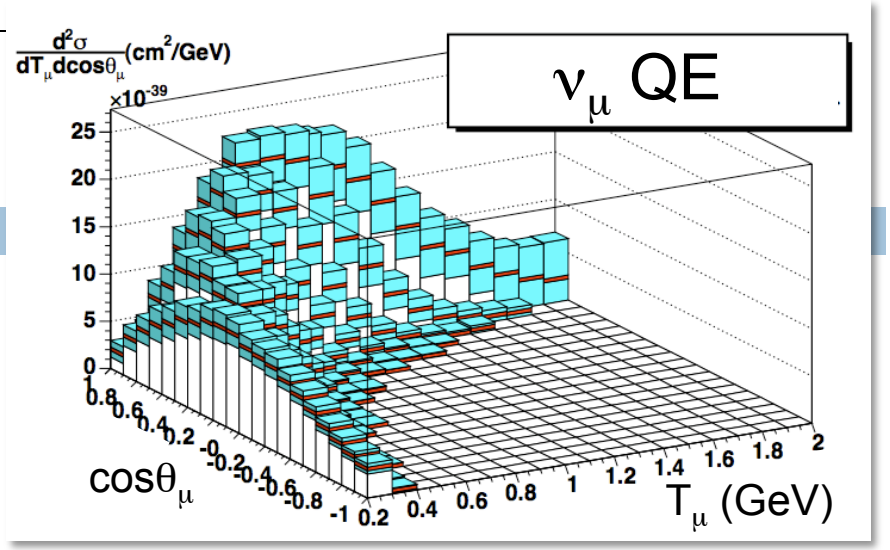
these same exps also measured $\sigma(E_\nu)$



with these ingredients, it looked straightforward to extend this to describe ν QE scattering <u>on nuclei</u> (at least we thought)

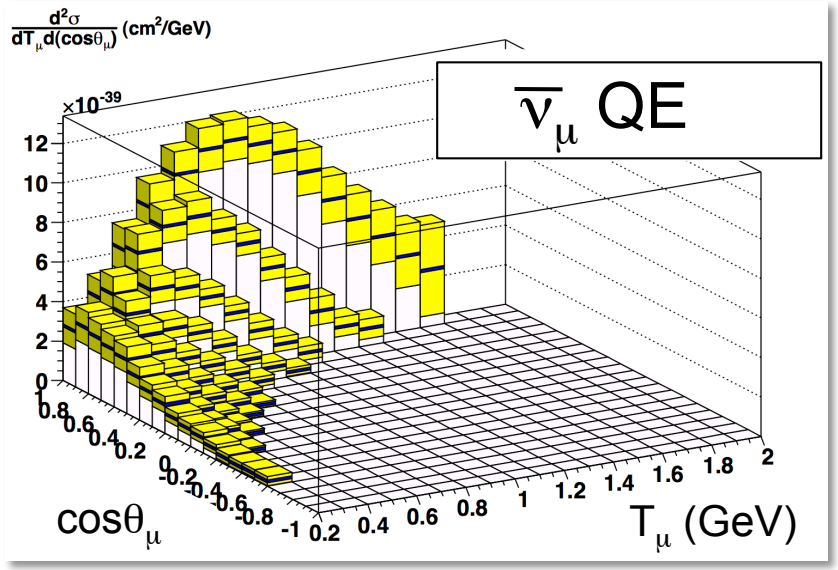
MiniBooNE

- reported differential cross sections for ν_μ and $\overline{\nu}_\mu$ QE scattering on ^{12}C
  (may not seem fancy but it is fancy for ν physics; this had never been done before; not enough stats)



- x10 larger sample than what had been available *(146k ν_μ, 71k $\overline{\nu}_\mu$)*
- results are less model-dependent; provide a lot more info than $\sigma(E_\nu)$
- <u>observe:</u> ~45% larger cross section than impulse-approximation based calculations ($\langle E_\nu^{MB}\rangle$~0.8 GeV); larger discrepancy for larger θ_μ
  (important to have large angular acceptance)

$\nu_\mu\, ^{12}C \rightarrow \mu + 0\pi$ + any # nucleons
(π absorption contribution is subtracted out & reported separately)

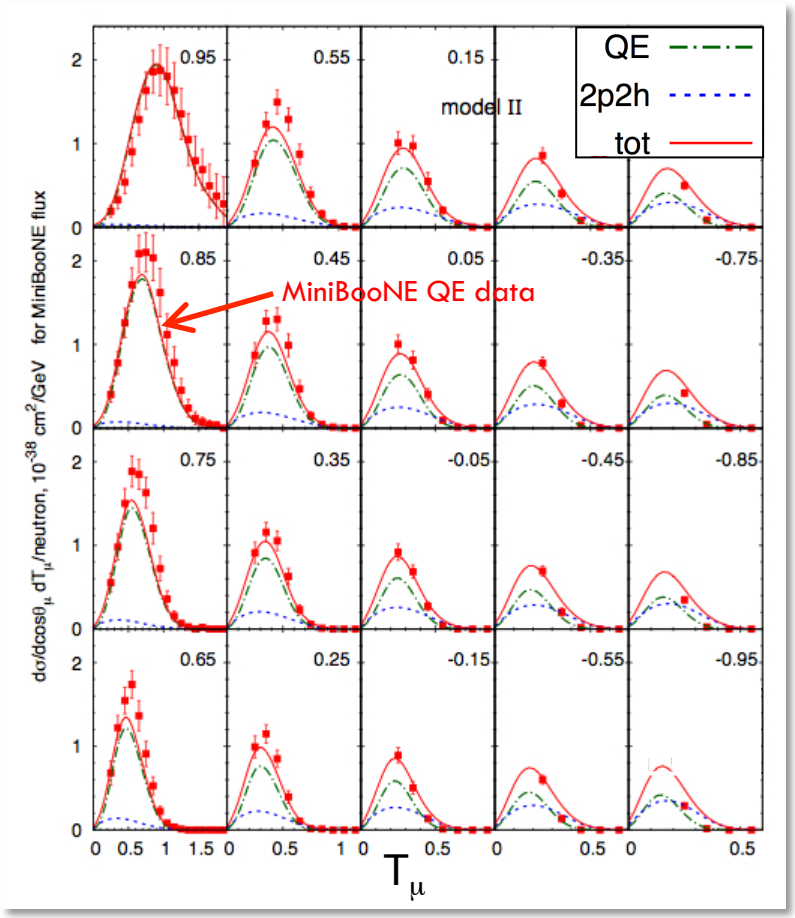


Aguilar-Arevalo et al., PRD 81, 092005 (2010)
Aguilar-Arevalo et al., PRD 88, 032001 (2013)

Nuclear Effects Are Important

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

(could really put our thinking to the test)



one example: Lalakulich, Gallmeister, Mosel PRC 86, 014614 (2012)

- nucleon-correlations and 2-body currents play a role!

none of this physics was in ν event generators

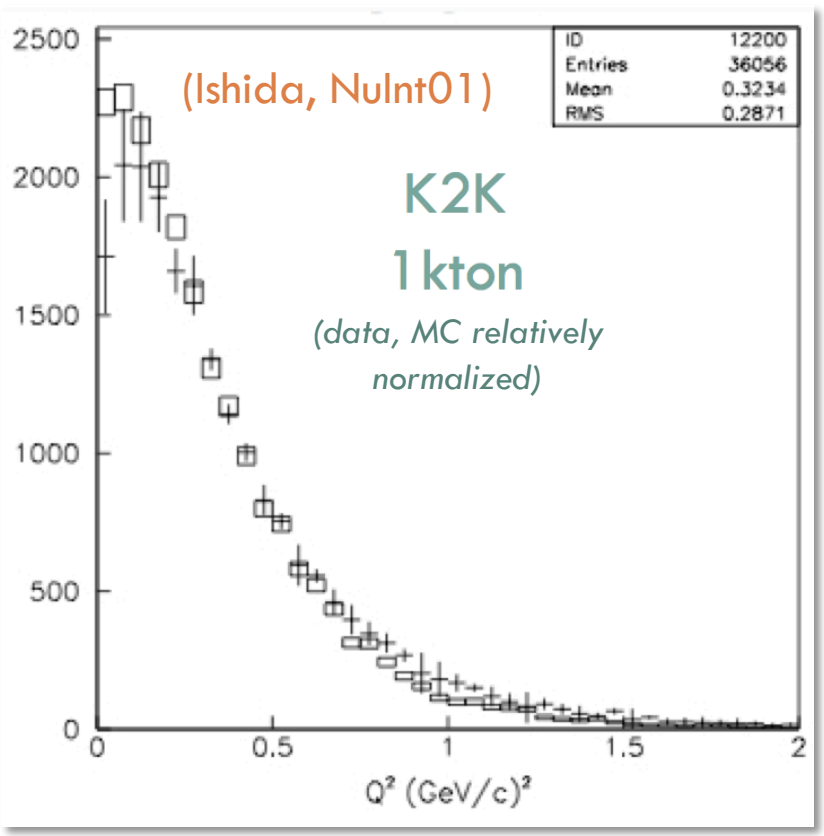
(would not have seen this large an effect in D_2 so this would have been missed in early ν experiments)

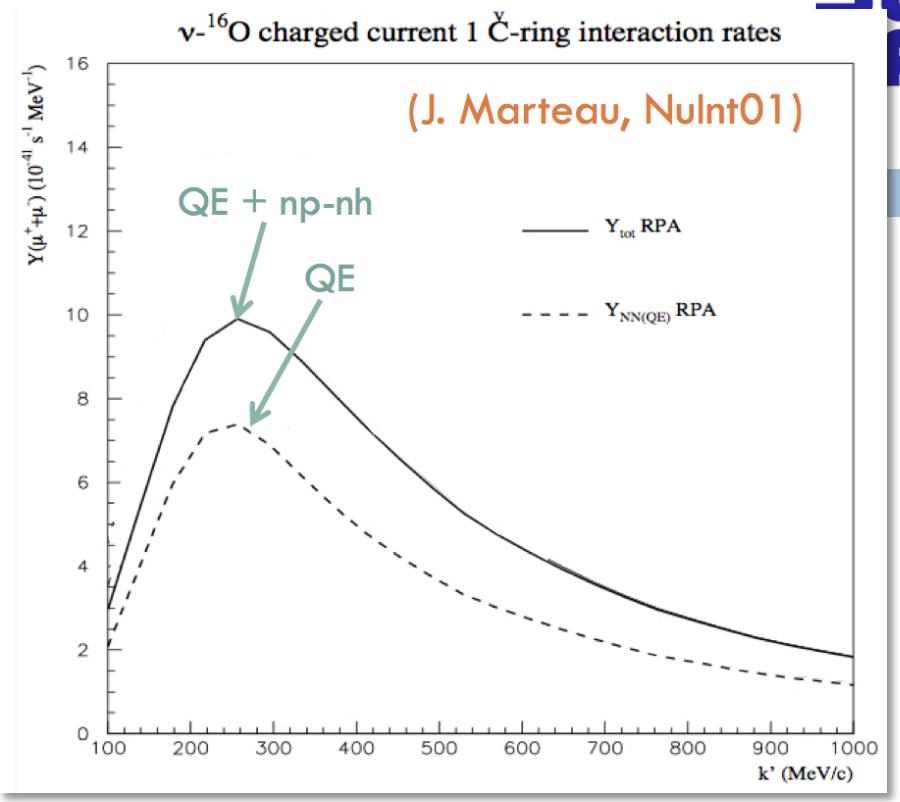
- important to have this phyx modeled
  - *impacts # signal, bkg events*
  - *final state particles you observe*
  - *ultimately, what you infer for E_ν*

- also want to examine the hadronic side of the interaction and probe this physics at different E_ν, A

This is Not New

- discrepancies like this were first seen in the K2K ν_μ near detector





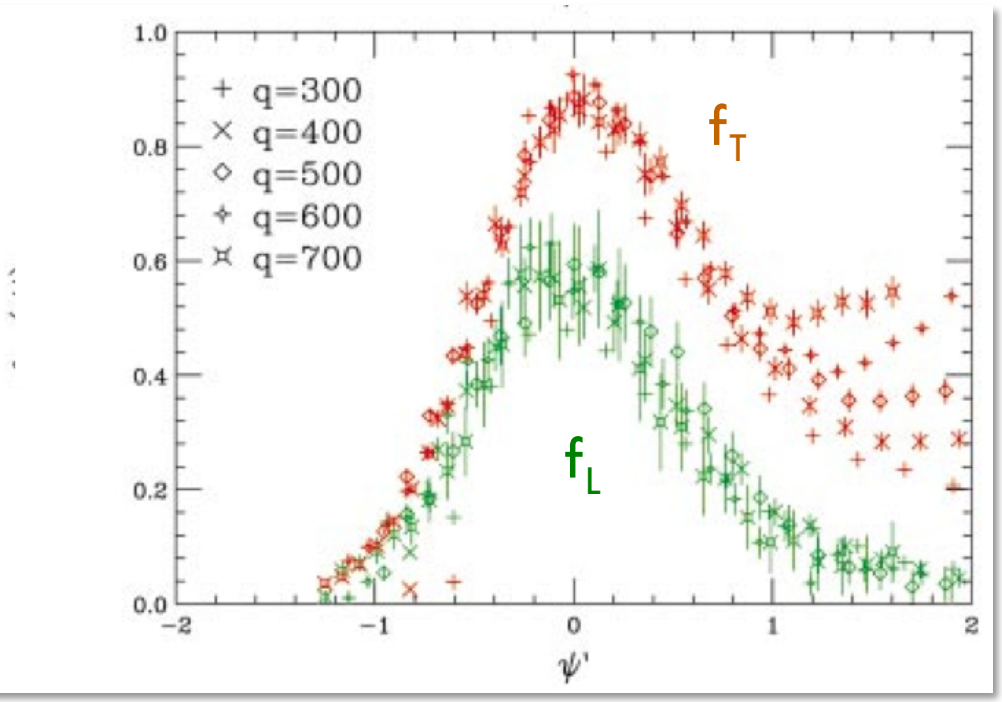
- and theorists warned about the potential effects of np-nh on ν's

(pre-dates the $d^2\sigma/dT_\mu d\theta_\mu$ results from MiniBooNE)

- Delorme, Ericson, PLB 156, 263 (1985)
- Dekker *et al.*, PLB 266, 249 (1991)
- Singh, Oset, NP A542, 587 (1992)
- Gil, Nieves, Oset, NP A627, 543 (1997)
- Marteau, EPJA 5, 183 (1999); NIM A451, 76 (2000)
- Nieves, Amaro, Valverde, PRC 70, 055503 (2004)
- Martini, Ericson, Chanfray, Marteau, PRC 80, 065501 (2009)

Electron-Nucleus Scattering

- while this was new to ν scattering, we have known about the role of correlations & 2-body currents for over 2 decades from e-nucleus data



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

- large enhancement in **transverse** cross section both in QE peak and "dip region"
  (→ more than single nucleon physics is involved!)

- after the MiniBooNE results, we realized that these effects also play a significant role in ν scattering

- it just took us a while to realize that we may be seeing the same thing in our ν data

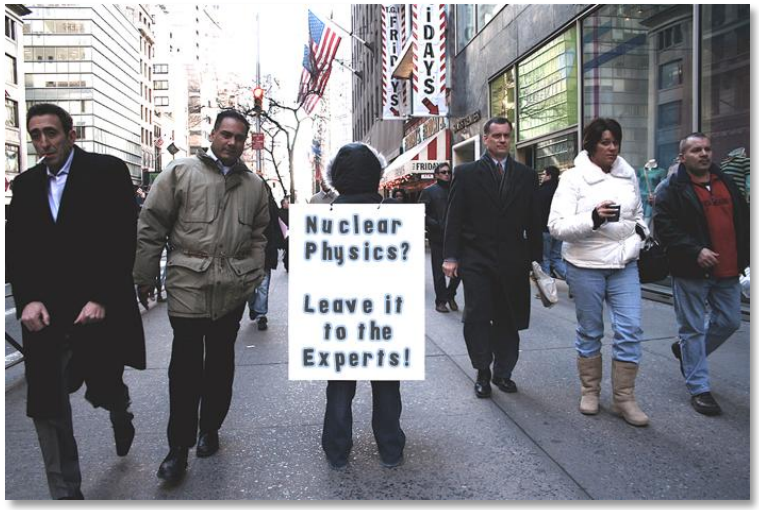
Has Sparked A Lot of Attention

- O. Benhar *et al.*, arXiv:1502.00887, arXiv:1501.06448, IJMP E23, 1430005 (2014); arXiv:1312.1210; arXiv:1310.3869; , arXiv:1012.2032; 1103.0987; 1110.1835
- M. Cheoun *et al.*, J. Phys. G42, 045102 (2015); PLB 723, 464 (2013)
- V. Pandey *et al.*, arXiv:1501.04018; arXiv:1412.4624; PRC 89, 024601 (2014)
- K.S. Kim *et al.*, PRC 91, 014606 (2015); PRC 90, 017601 (2014)
- A. Meucci *et al.*, arXiv:1501.03213; PRD 89, 117301 (2014); PRD 89, 057302 (2014); PRD 88, 013006 (2013); arXiv:1304.2166; PRD 85, 093002 (2012), PRC 83 064614 (2011); PRD 84 113003 (2011)
- M. Ericson *et al.*, PRC 91, 035501 (2015)
- G.D. Megias *et al.*, PRD 91, 073004 (2015); PLB 725, 170 (2013)
- J. Nieves *et al.*, arXiv:1411.7821; aeXiv:1304.1032; PLB 721, 90 (2013); arXiv:1204.5404; 1106.5374; 1110.1200; PRC 83, 045501 (2011)
- B. Li, arXiv:1411.6029
- M.B. Barbaro *et al.*, arXiv:1411.5981; arXiv:1303.6508; arXiv:1110.4739
- C. Giusti *et al.*, arXiv:1409.5653; arXiv:1309.4267; arXiv:1110.4005
- R. Gonzalez-Jimenez *et al.*, PRC 90, 035501 (2014); PRC 88, 025502 (2013)
- I. Ruiz Simo *et al.*, PRD 90, 053010 (2014); PRD 90 033012 (2014)
- M. Martini *et al.*, PRC 90, 025501 (2014); PRC 87, 065501 (2013); PRD 85, 093012 (2012); 1110.0221; PRC 81, 045502 (2010); JPCS 408, 012041 (2013)
- M.V. Ivanov *et al.*, PRC 89, 014607 (2014); PLB 727, 265 (2013)
- P. Coloma et al., PRD 89, 073015 (2014)
- A.V. Butkevich et al., PRD 89, 053014 (2014); arXiv:1204.3160; PRC 85, 065501 (2012)
- J.T Sobczyk *et al.*, PRC 87, 065503 (2013); PRC 86, 015504 (2012); 1109.1081; PRC 86, 015504 (2012)
- J.A. Caballero *et al.*, JPCS 366, 012006 (2012)
- J.E. Amaro *et al.*, PRL 108, 152501 (2012)
- O. Lalakulich *et al.*, PRC 86, 014614 (2012)
- U. Mosel, arXiv:1204.2269, 1111.1732; AIP Conf. Proc. 1441, 465 (2012)
- A. Bodek *et al.*, arXiv:1106.0340
- L. Alvarez-Ruso, arXiv:1012.3871; AIP Conf. Proc. 1382, 161 (2011)
- Martinez *et al.*, PLB 697, 477 (2011)

(disclaimer: this is not a complete list)

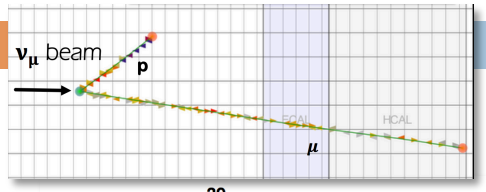
- >100 theoretical papers in the last 5 years on the topic of ν-nucleus QE scattering alone

this work is critical to the ν experimental program

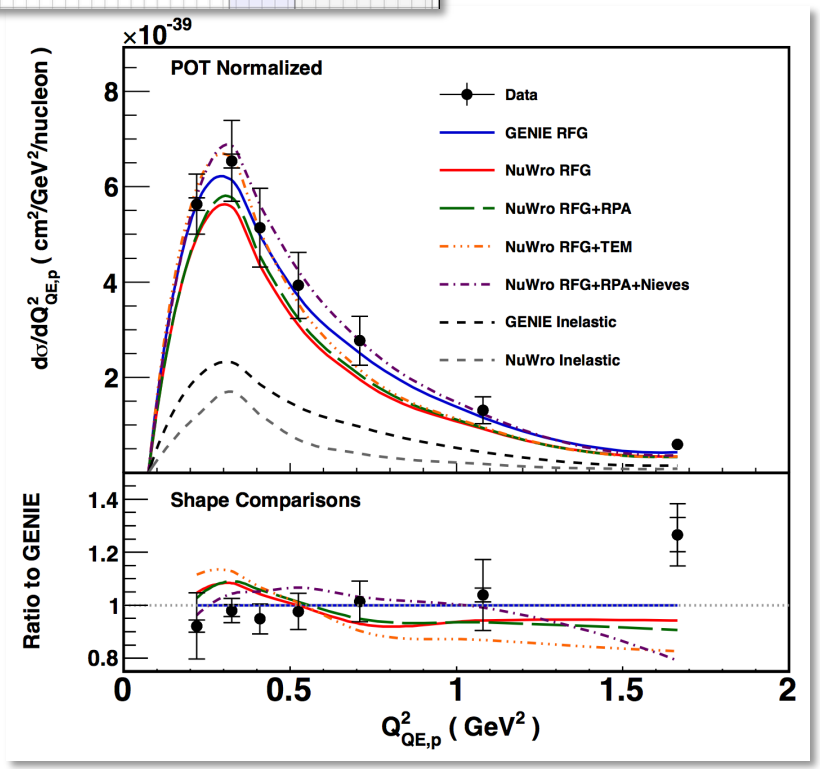


→ see talks by Benhar, Carlson, Lovato, Moreno, Martini, Mosel ("state of the art")

Examining the Hadronic Side



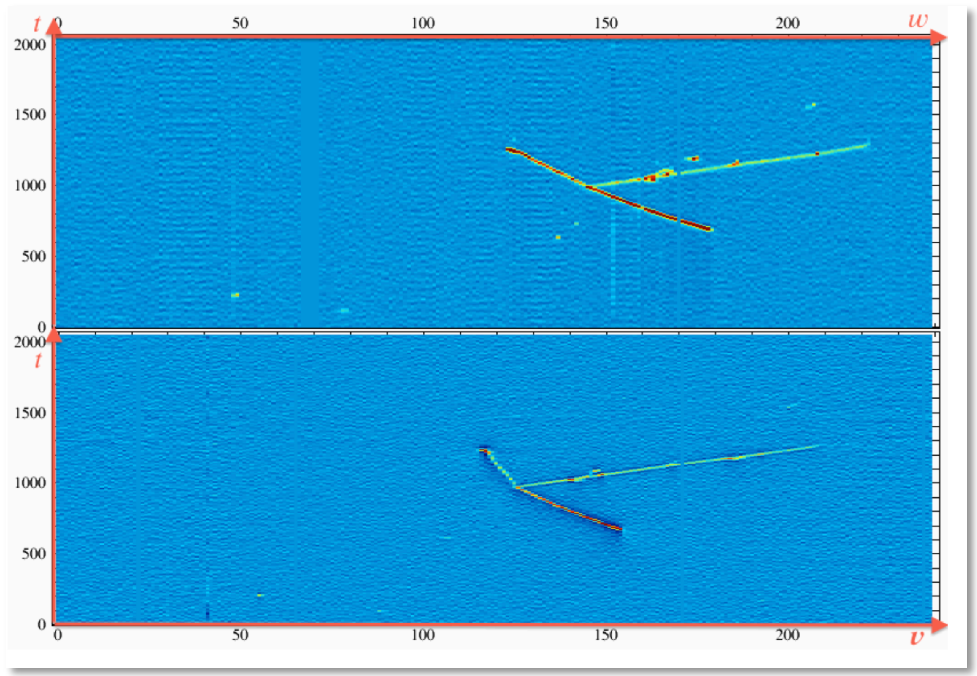
MINERvA:



T. Walton et al., PRD 91, 071301 (2015)

- analysis with an identified proton
  → see talk by Dytman

ArgoNeuT:



Acciarri et al., PRD 90, 012008 (2014)

- observation of energetic back-to-back protons
  → see talk by Palamara

What Does This All Mean?

- neutrino QE scattering is not so simple when scattering off nuclei
  - nuclear effects can significantly <u>increase</u> the interaction cross section at certain energies and for certain kinematics
  - idea that could be missing ~45% of σ_ν in our simulations is a big deal

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

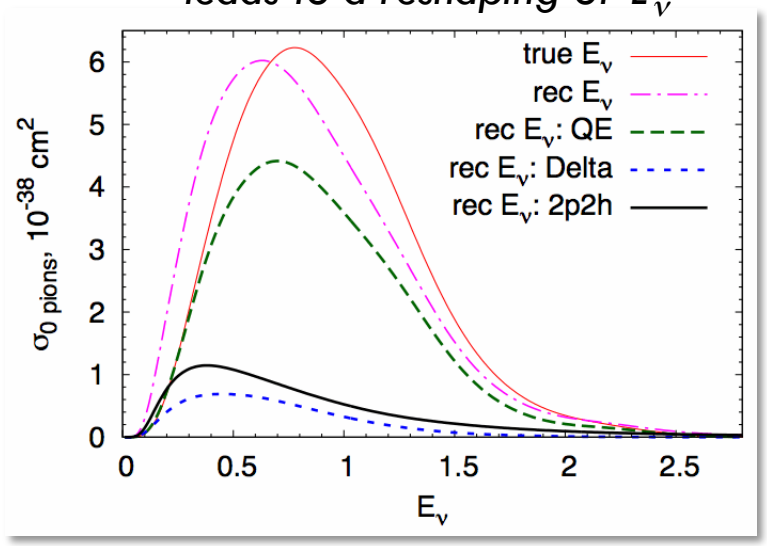
(1) impacts E_ν determination

ex: Ankowski et al., PRD 91, 033005 (2015); Nieves et al., 1310.7091, PRD 85, 113008 (2012); Mosel et al., 1204.2269; Martini et al. PRD 85, 093012 (2012); PRD 87, 013009 (2013); Lalakulich et al. PRC 86, 054606 (2012); Leitner/Mosel PRC 81, 064614 (2010)

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

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

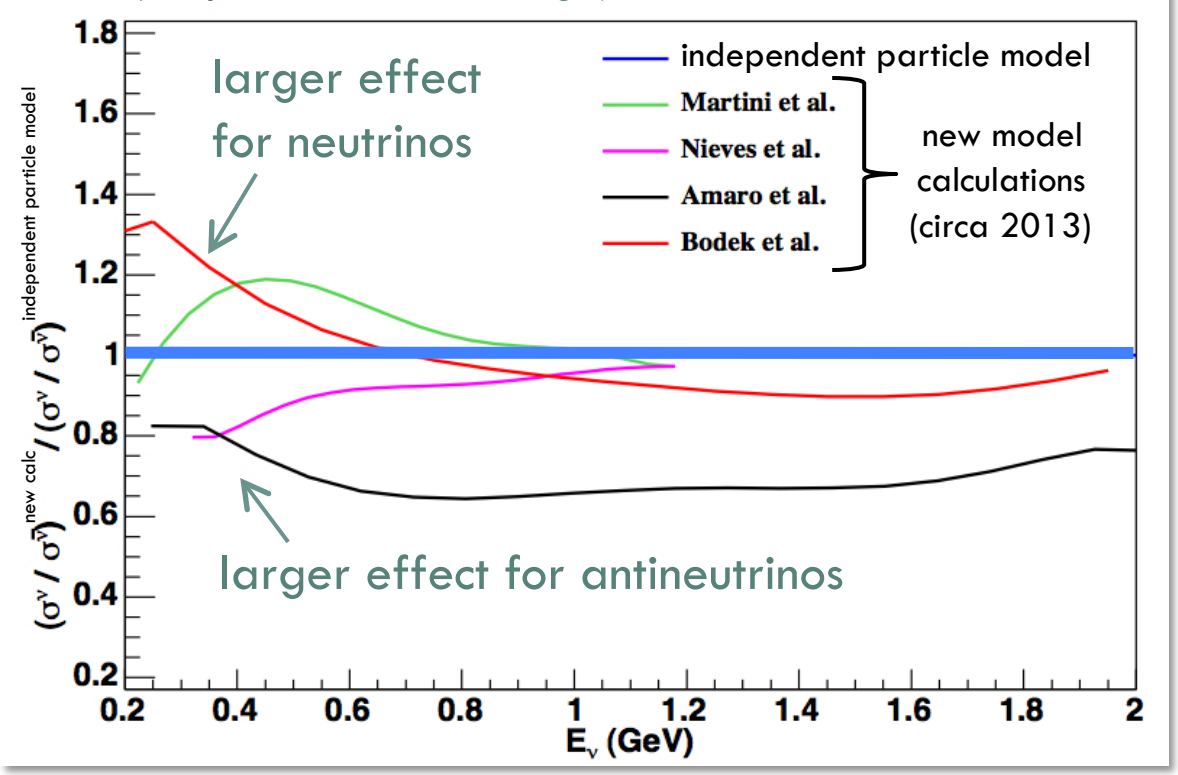
leads to a reshaping of E_ν



Lalakulich, Gallmeister, Mosel, 1203.2935

Neutrino/Antineutrino Ratio

(snapshot from J. Grange)



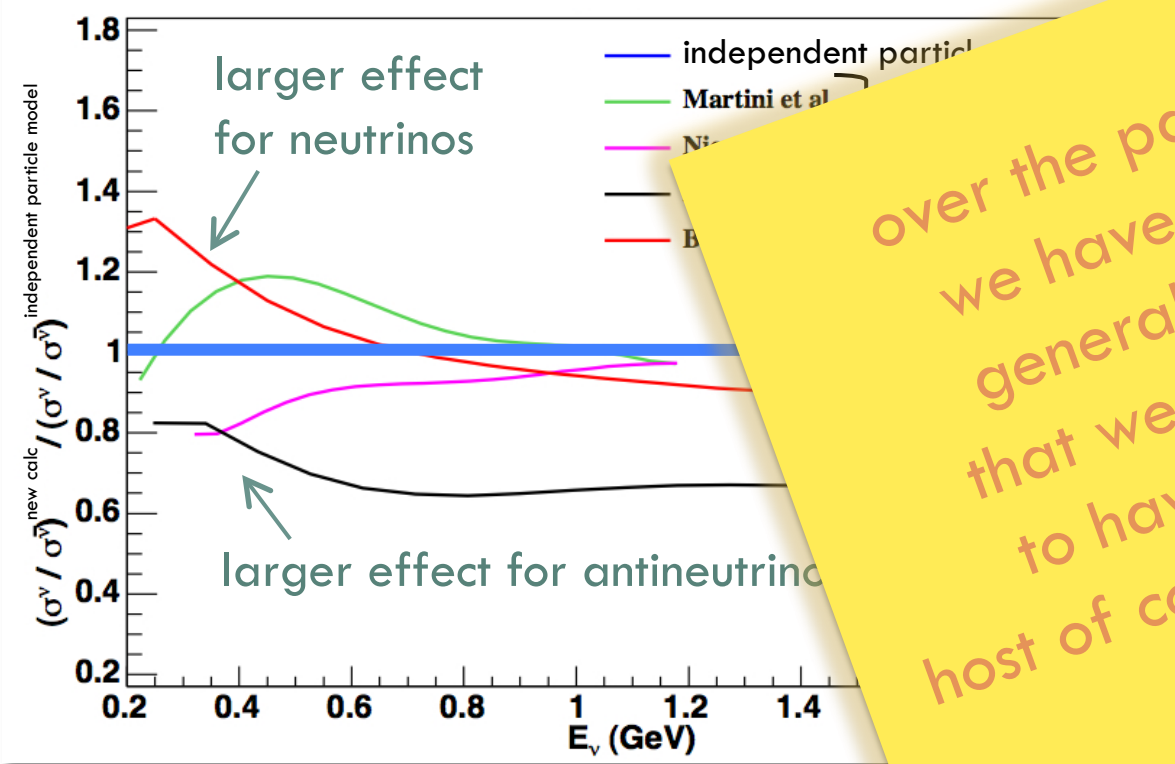
- models give different predictions for $\nu/\bar{\nu}$
  - *in large part, this has to do with the treatment of axial-vector contribution*

  (Martini, INT workshop 2013)
- this situation will need to get resolved
- large θ_{13} means the CP asymmetry we will be trying to detect is small so will need a detailed understanding of these $\nu,\bar{\nu}$ differences!

→ see talk by Mahn

Neutrino/Antineutrino Ratio

(snapshot from J. Grange)



over the past few years, we have gone from a general complacency that we know the QE σ_ν to having uncovered a host of complex nuclear effects

... story to be continued

ent

be

detect is small

will need a detailed understanding of these $\nu,\bar{\nu}$ differences!

two good reviews:

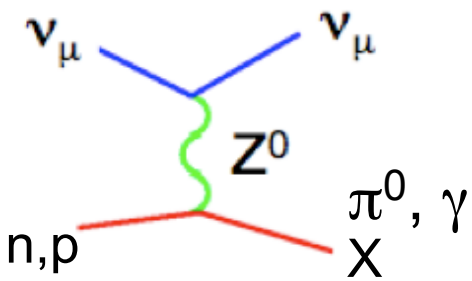
(1) G.T. Garvey et al., arXiv:1412.4294

(2) L. Alvarez-Ruso et al., arXiv:1403.2673

Resonance Region

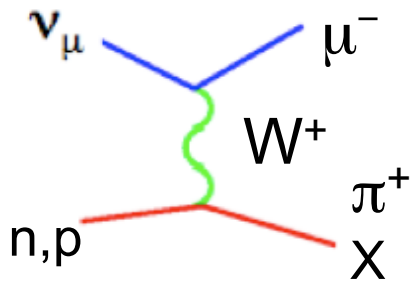
- NC π^0, γ production

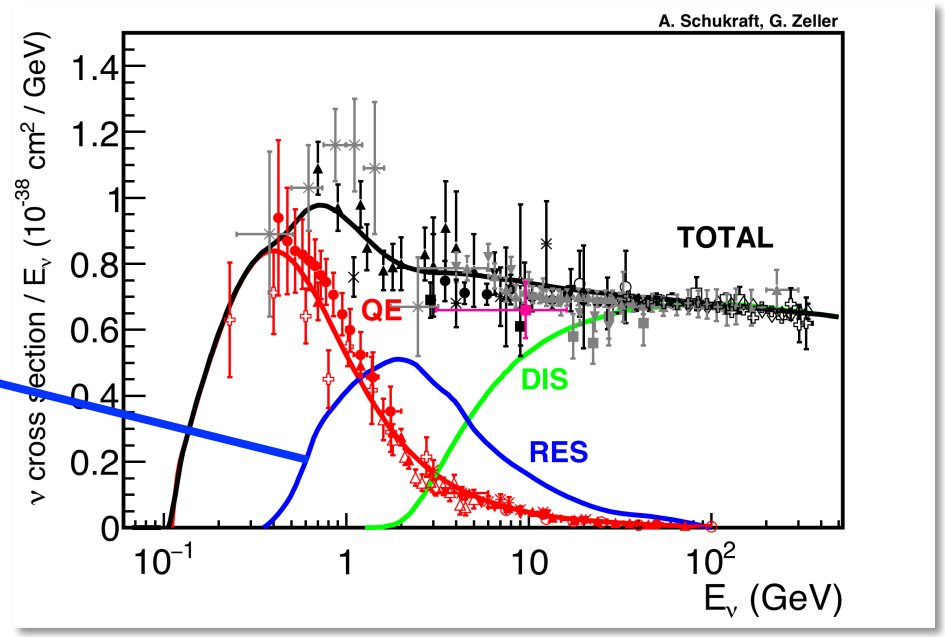
  (background for $\nu_\mu \rightarrow \nu_e$ appearance)



- CC π production

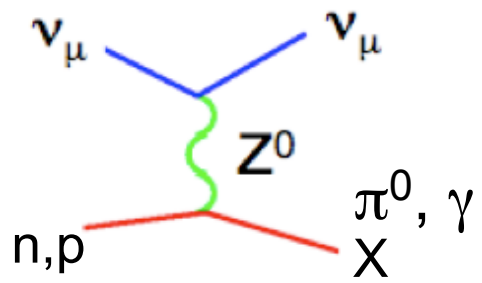
  (a complication for $\nu_\mu \rightarrow \nu_\mu$ disappearance)





Resonance Region

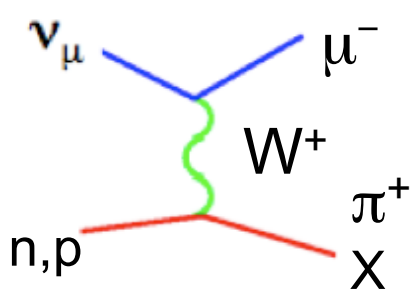
- NC π^0, γ production
  (background for $\nu_\mu \rightarrow \nu_e$ appearance)



why do we care?

a NC interaction of a ν_μ producing a π^0 or γ can mimic a ν_e signal

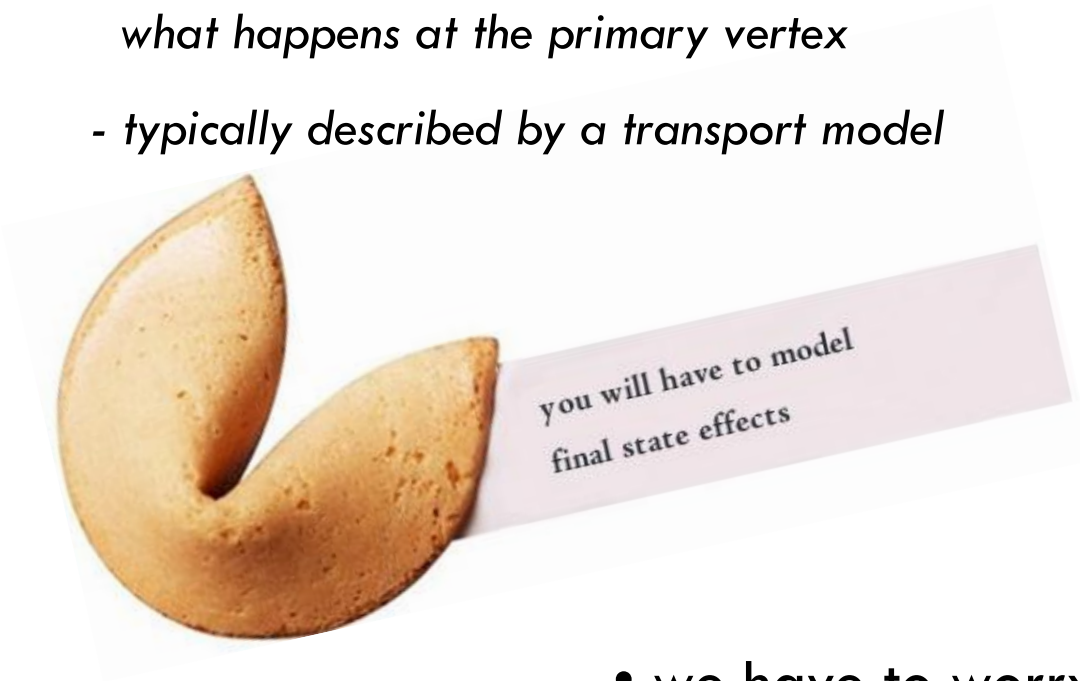
- CC π production
  (a complication for $\nu_\mu \rightarrow \nu_\mu$ disappearance)

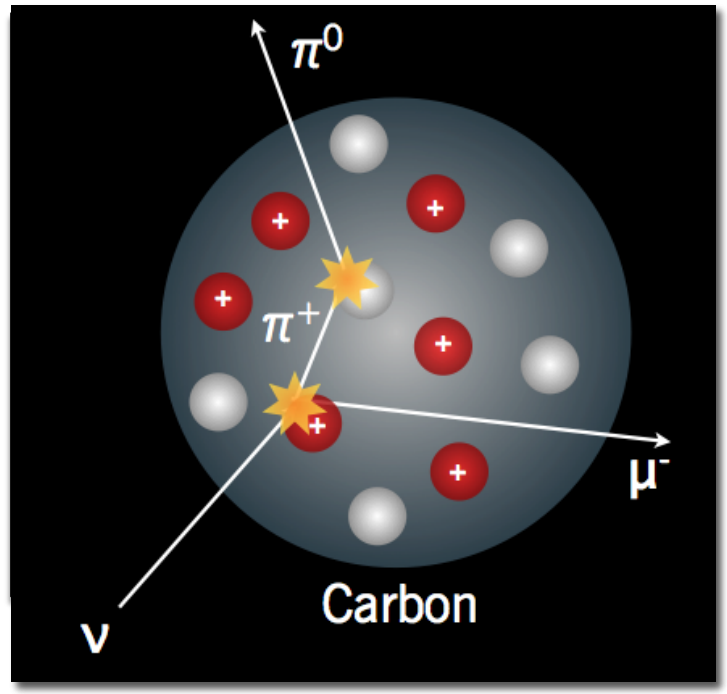


if a π is absorbed in the nucleus this can directly impact the estimation of E_ν (that energy is lost)

Again, Nuclear Effects Are Important

- before they leave the nucleus, pions and nucleons can rescatter …
  - *picture can be quite different from what happens at the primary vertex*
  - *typically described by a transport model*





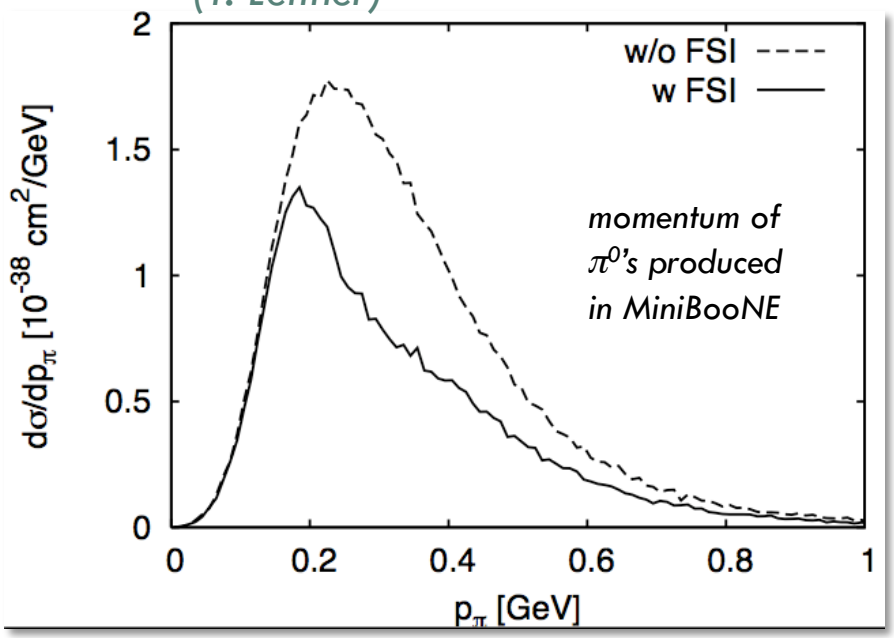
→ see talks by Ankowski, Huber

- we have to worry about these effects
  (need to model initial ν interaction & f.s. particle propagation)
- is a subject that needs more attention for ν's
  Mosel, arXiv:1108.1692

Pion Rescattering Effects

- the distortions are large

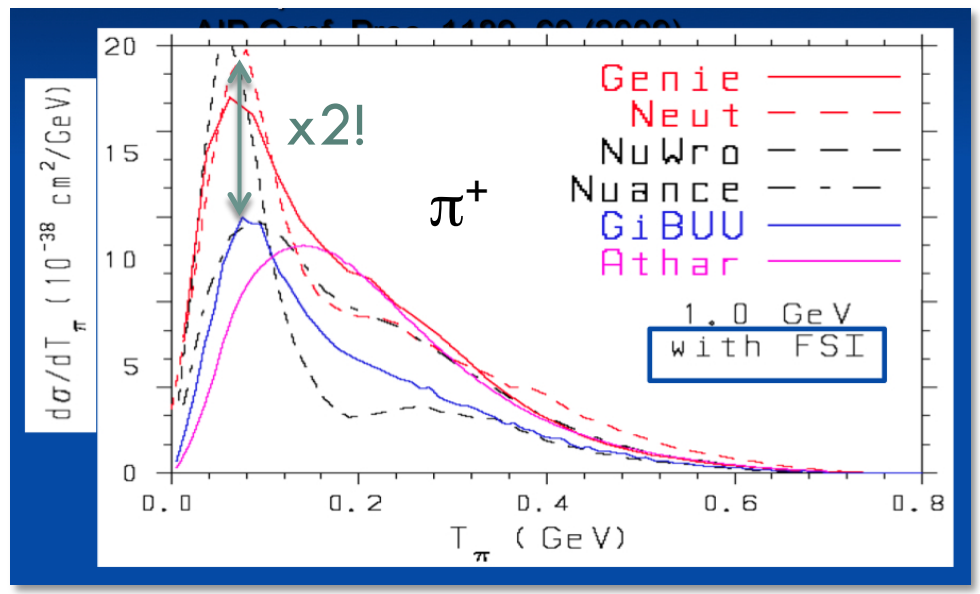
(T. Leitner)



- leave a big imprint on what you see in your ν detector

- and the predictions of their effects can vary

(Tacik 2009, http://regie2.phys.uregina.ca/neutrino/)

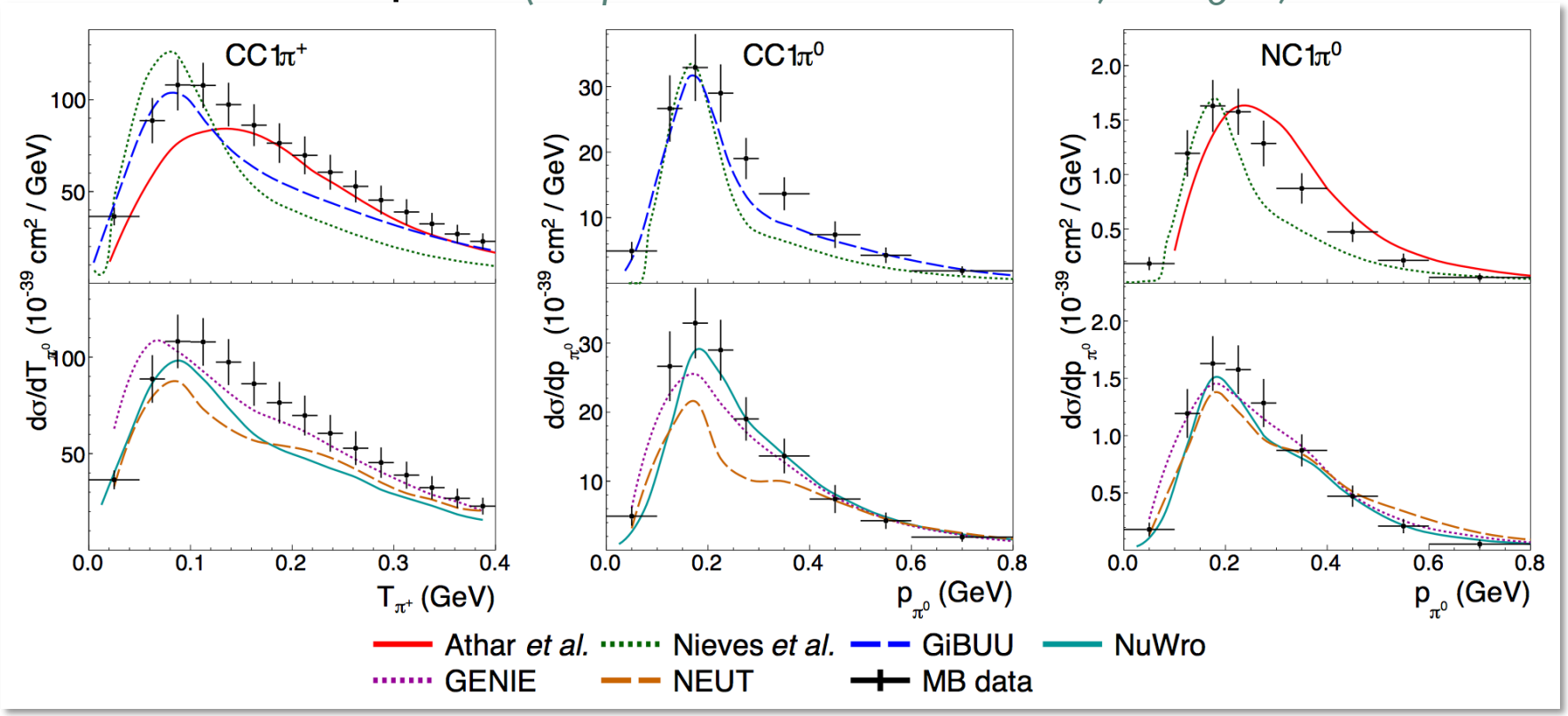


- area where models differ the most
- need π kinematic measurements!

(had never been carefully studied in ν scattering)

ν-Induced Pion Production

- some recent examples: *(comparisons to MiniBooNE π data, Rodrigues, arXiv:1402.4709)*



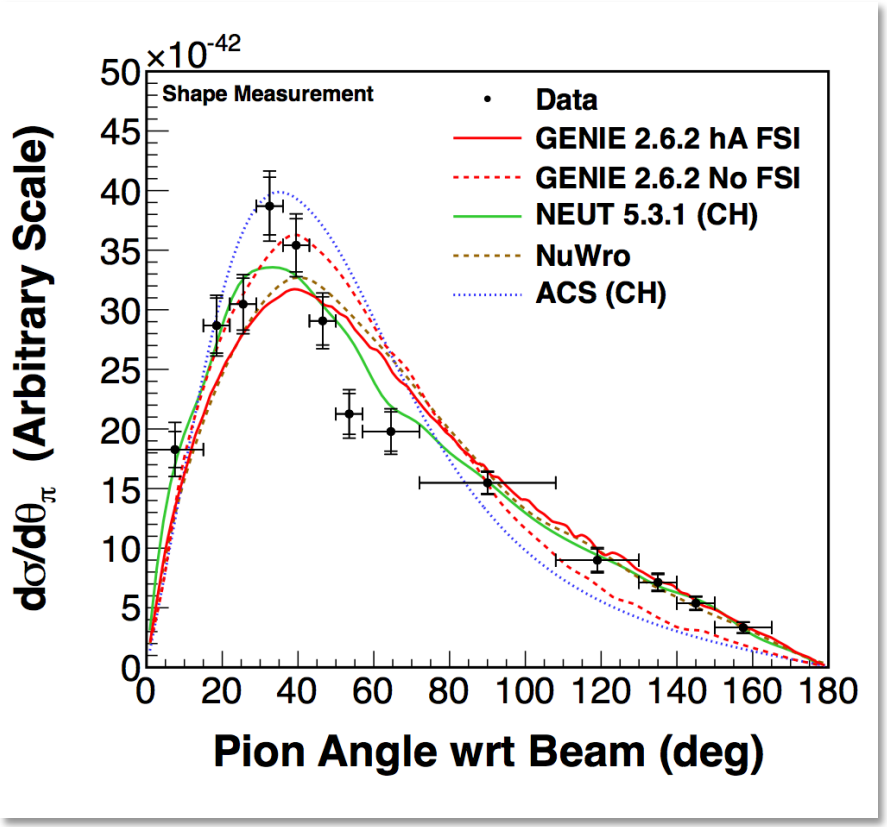
- *would be interesting to also compare to double diff'l σ's that are available*
- *to be fair, need to start including uncertainties on the predictions too!*

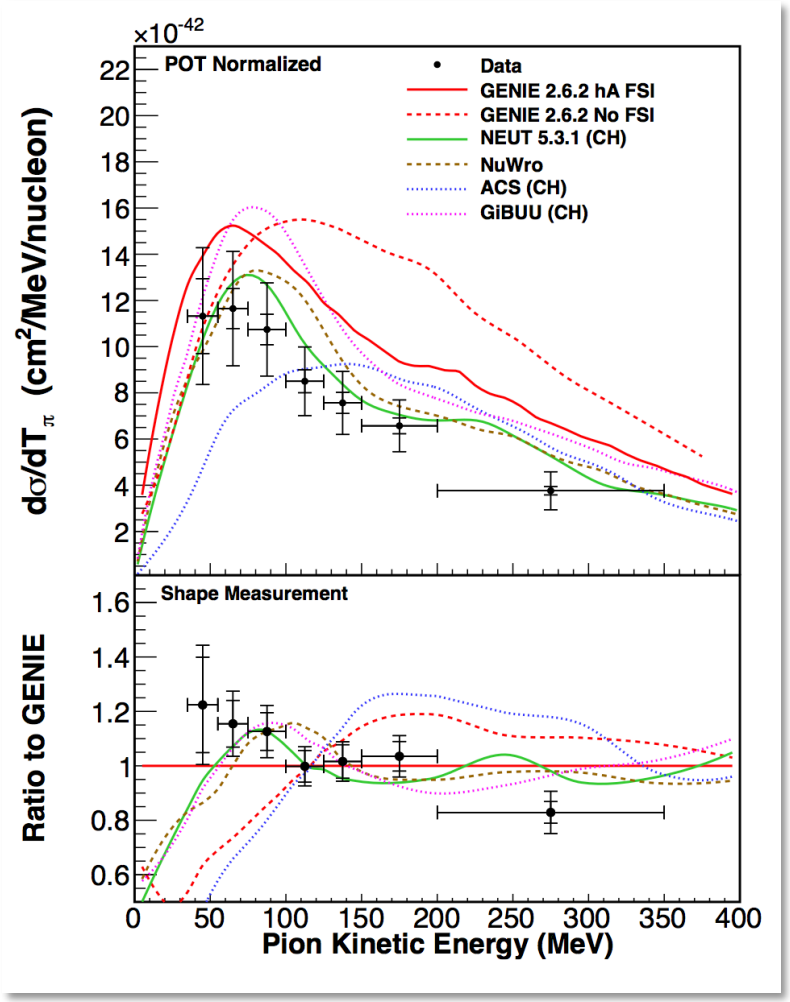
  (e.g. uncertainties in π absorption, π rescattering, charge exchange, initial interaction σ, etc. are not small)

ν-Induced Pion Production

- another more recent example:

(comparisons to MINERvA CC π^+ data, Eberly et al., arXiv:1406.6415)





→ see talk by Dytman

What Do We Need?

- we know we need to move away from the IA-based calculations that are present in the ν event generators in common use

- moving forward, the ν community needs a model(s) that:

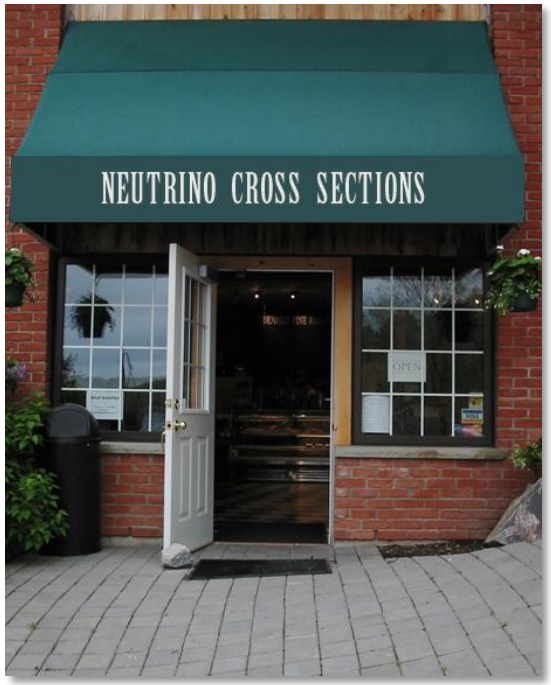
  - *connects to e-nucleus scattering & other relevant data*
  - *predicts detailed final states & kinematics (not just the lepton) & includes the effects of hadron re-scattering in the target nucleus*
    - *this is ultimately how we estimate our signals/bkgs and how we determine E_ν in our oscillation experiments*
  - *is predictive across a range of nuclei (C,O → Ar) and energies (E_ν = 100's of MeV to a few GeV) for both neutrino and antineutrinos*

- we are going to need add'l exp'l data to get us there

→ see talk by Tanaka

Conclusions

- there is new appreciation for the significant role that nuclear effects play in ν-nucleus scattering *(100's MeV- few GeV)*
- it is vital to have this physics under control for our future ν physics endeavors *(ν oscillations + also SN ν detection and $0\nu\beta\beta$ decay)*
- we have more to learn from e^-, γ scattering
- can look forward to new ν scattering data that is coming in now or that is on the horizon *(MINERνA, T2K, NOνA, ArgoNeuT, ICARUS, MicroBooNE)*



- there is a growing body of new theoretical calculations addressing our increasing needs *(however, incorporation into generators is not always trivial)*
- this is all crucial for the success of the ν program moving forward