Status of Neutrino Cross Sections

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Fermilab

U Pittsburgh Workshop

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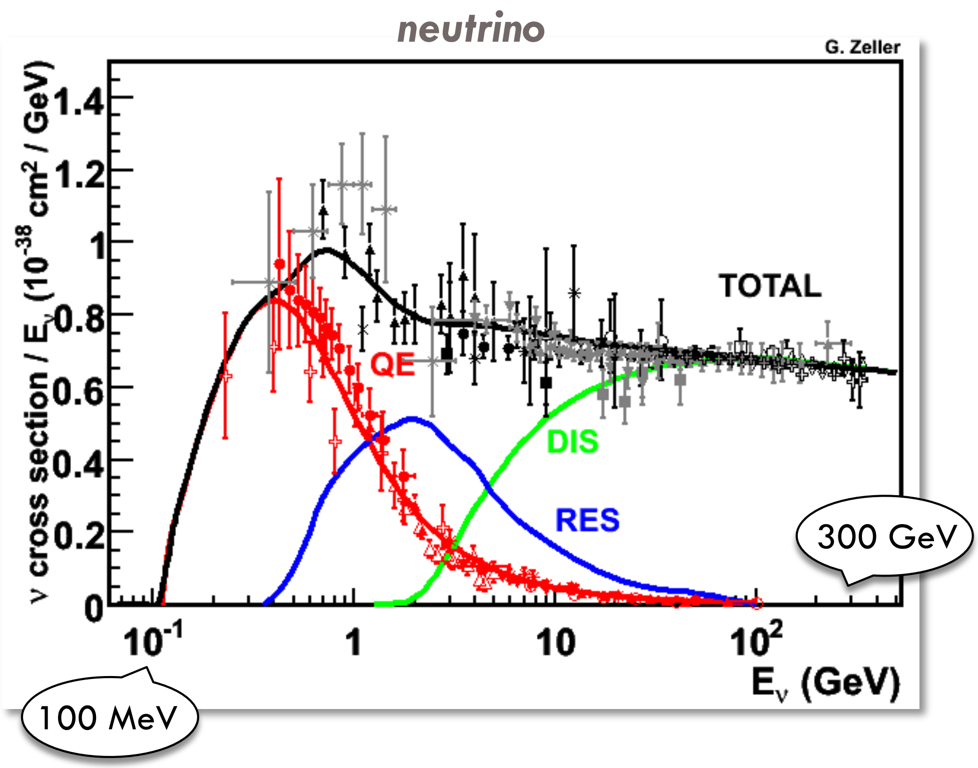
- what we know and don't know
- will point out well-known neutrino processes that can be used for flux determinations in neutrino experiments

"standard candles"

Neutrino Cross Sections

CC ν-nucleon cross sections:



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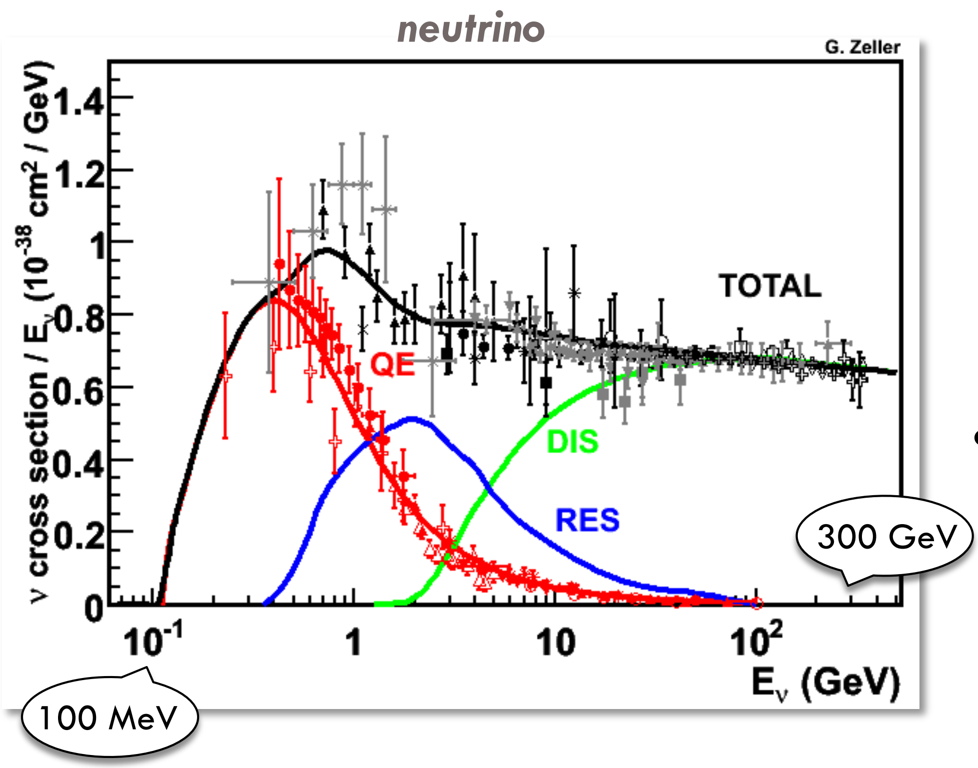


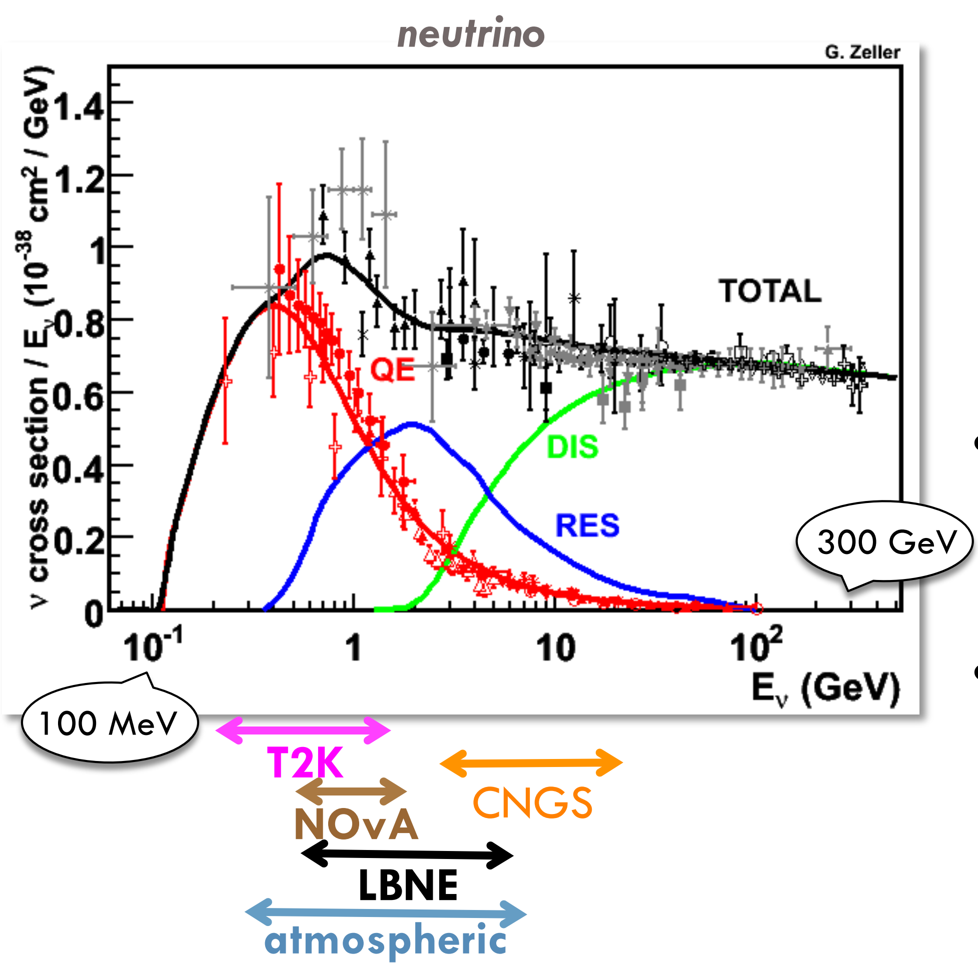
- cross sections typically well known <u>at very low energies</u>
  - * *IBD (10's MeV)* < *reactor ν's* / *solar ν's*

  and <u>at very high energies</u>
  - * *DIS (100's GeV)*

- but not so well-known in the middle (100's MeV – 10's GeV)

Neutrino Cross Sections

CC *ν-nucleon cross sections:*

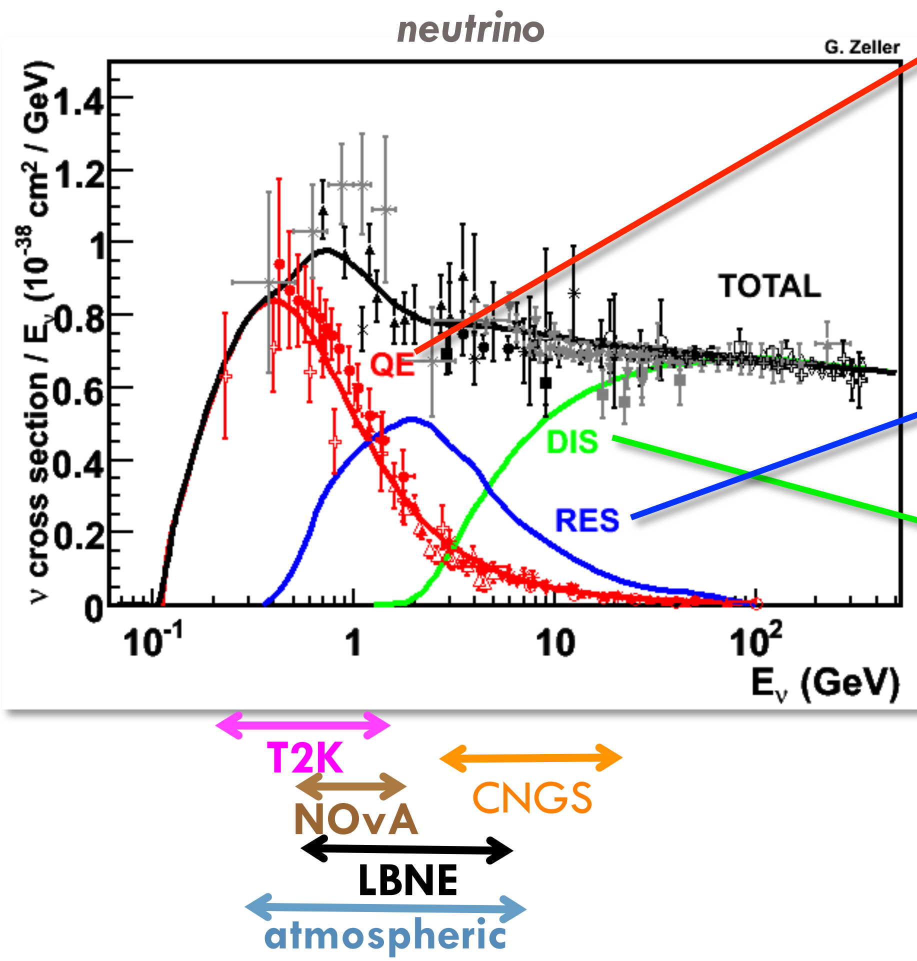


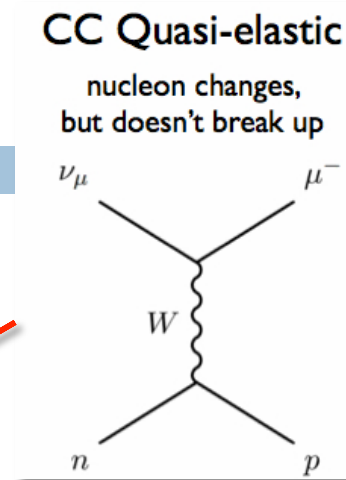
- cross sections typically well known <u>at very low energies</u>
  - * *IBD (10's MeV)* < *reactor ν's* / *solar ν's*

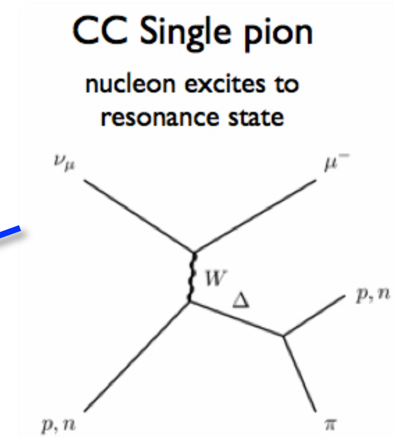
  and <u>at very high energies</u>
  - * *DIS (100's GeV)*
- but not so well-known in the middle (100's MeV – 10's GeV)
- this intermediate E region is important because this is where we're conducting our ν oscillation experiments (MH, C̸P)

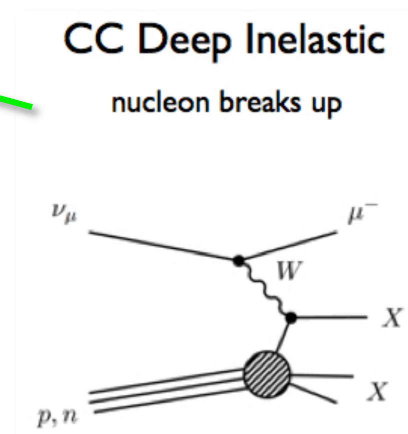
Complicated Region

(event samples contain contributions from multiple reaction mechanisms)







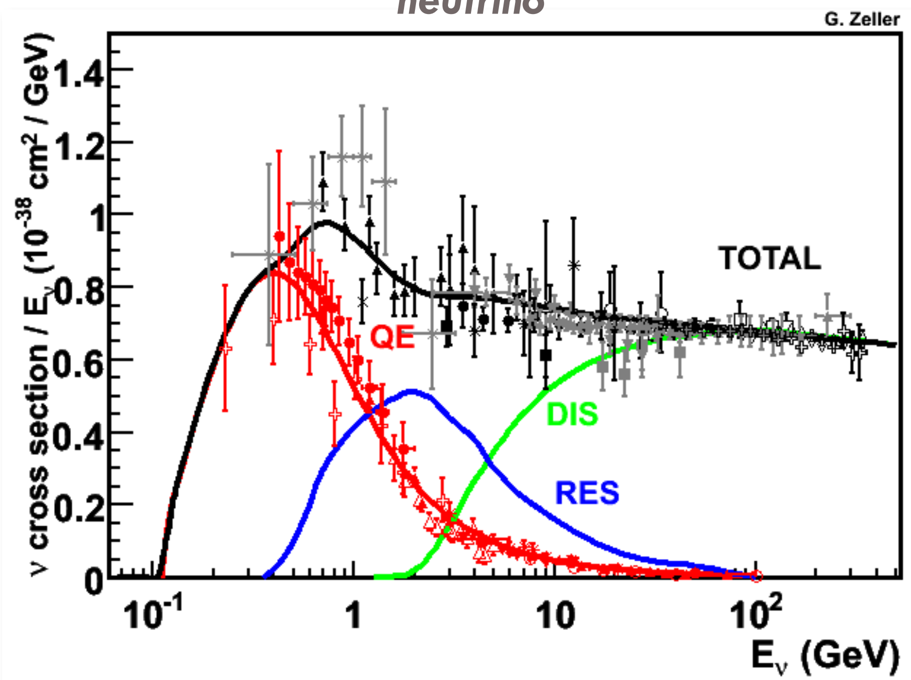


Current Knowledge

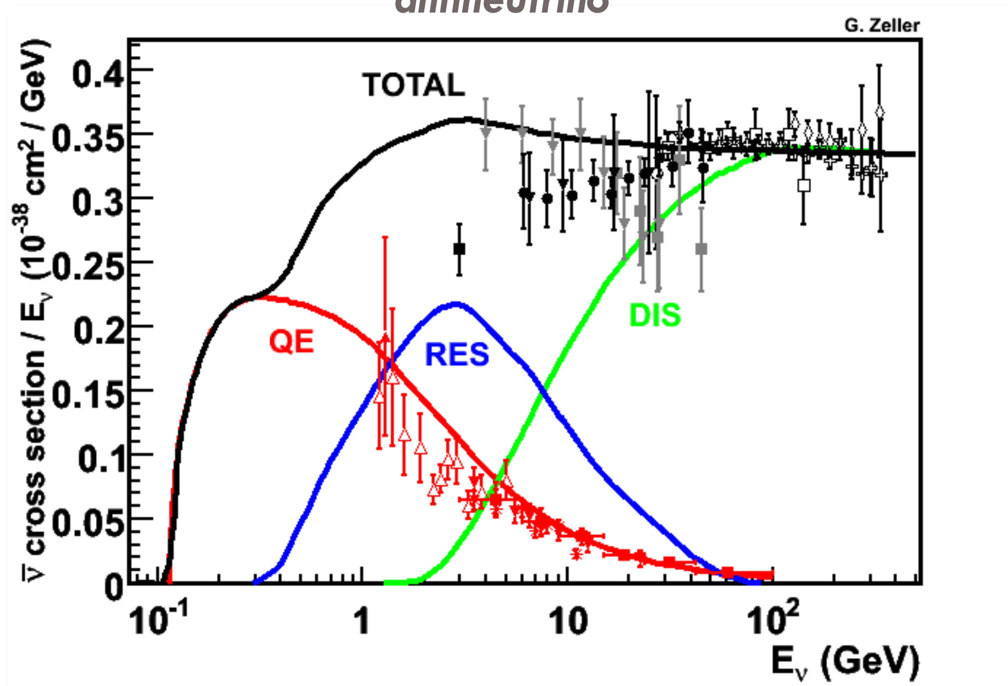
- σ_ν's are not particularly well-constrained in this intermediate E region

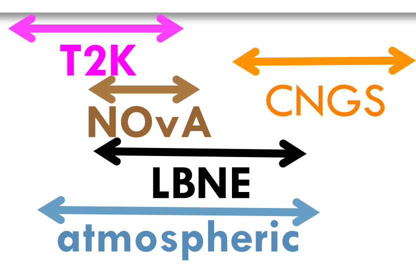
  (situation is embarassingly worse for NC and for $\overline{\nu}$)

neutrino



antineutrino



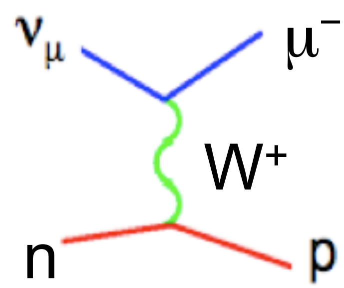


… the situation has been improving

(with the availability of new higher statistics data)

Neutrino QE Scattering

Why important?



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

- **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)

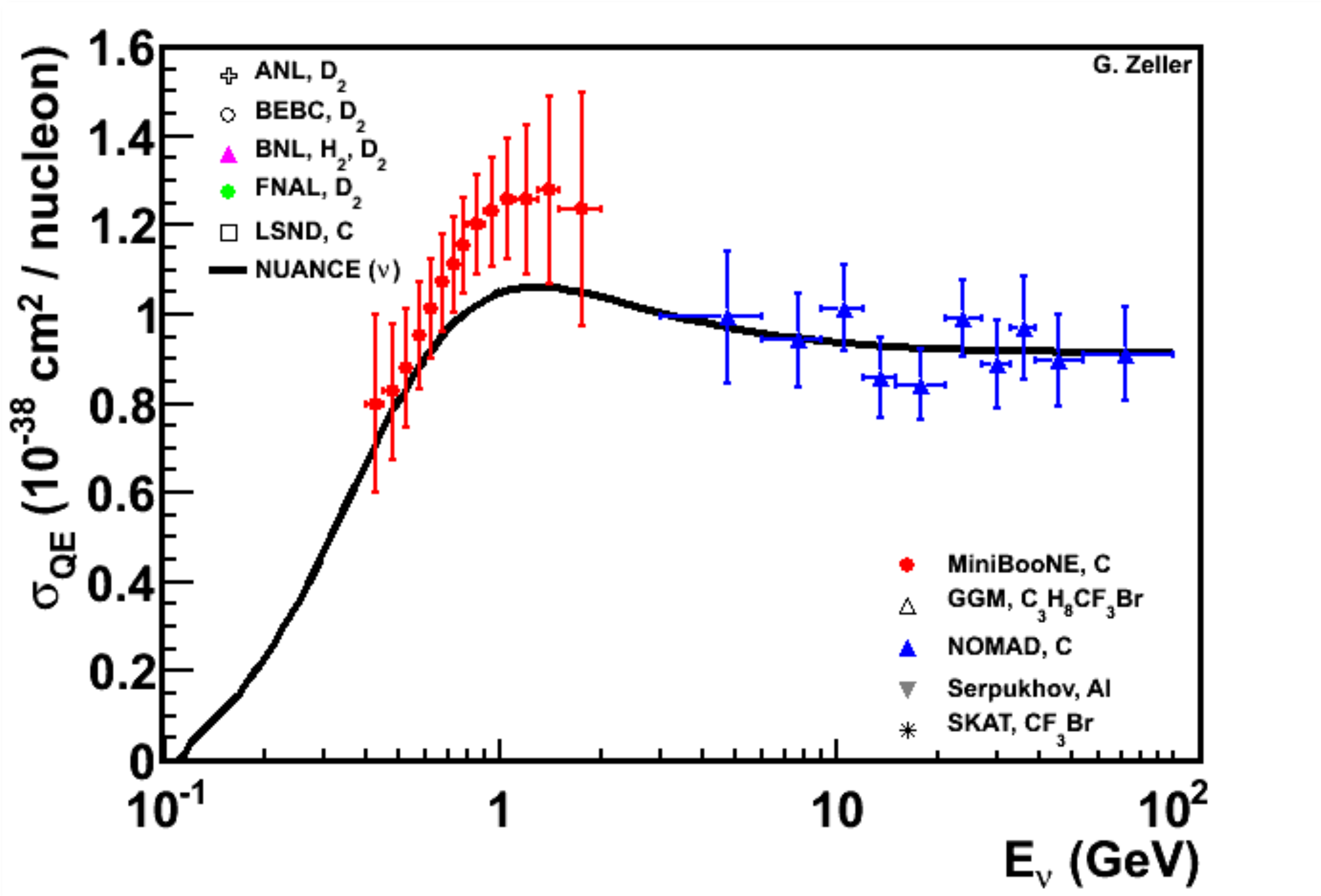
$\nu_\mu \rightarrow \nu_x$ (ν_μ disappearance)

- biggest piece of the σ at ~1 GeV

(lepton kinematics are used to infer E_ν)

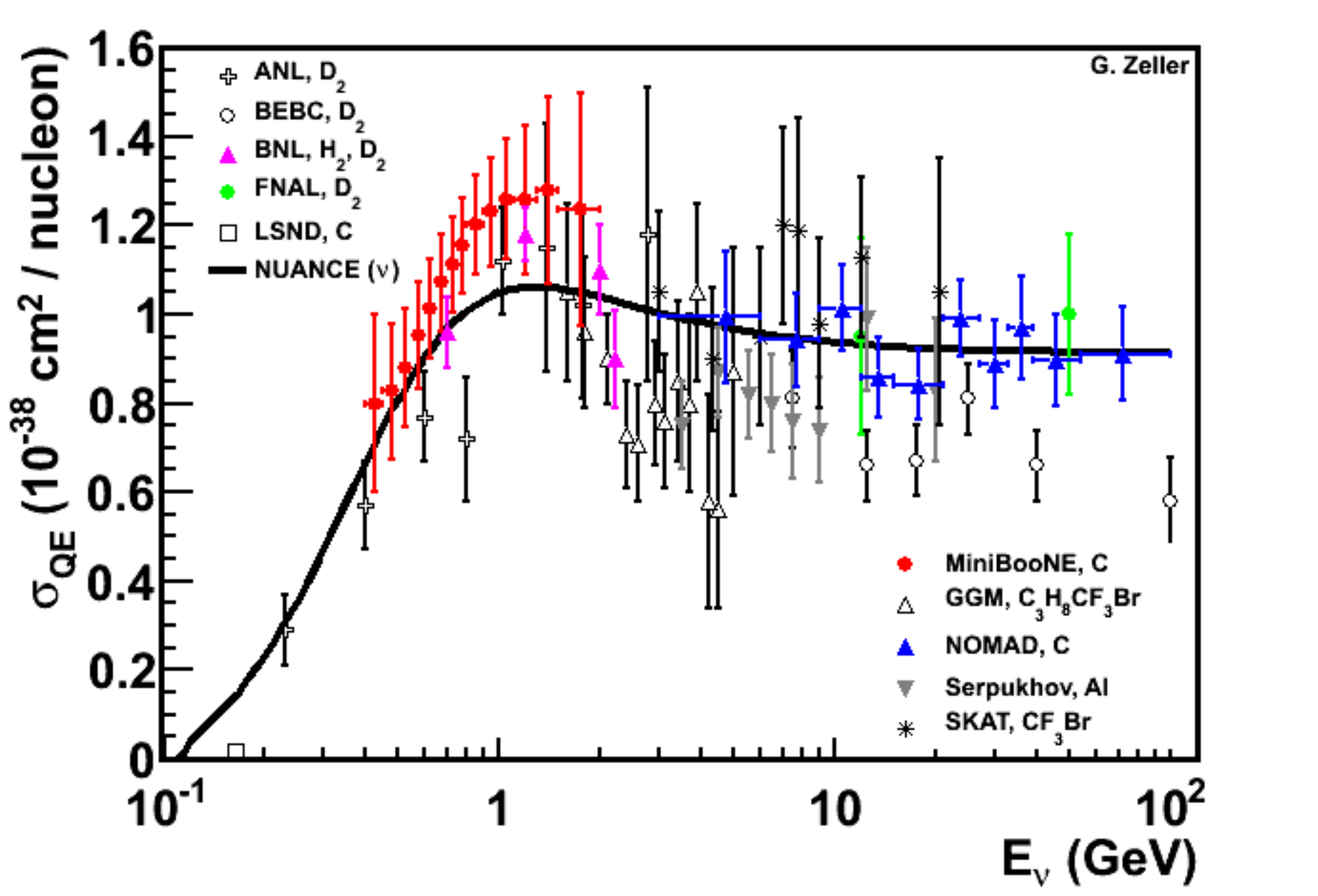
(heavily studied in 1970's and 80's, one of the 1st ν interactions measured)

Neutrino QE Scattering



(see Laura's talk!)

Neutrino QE Scattering

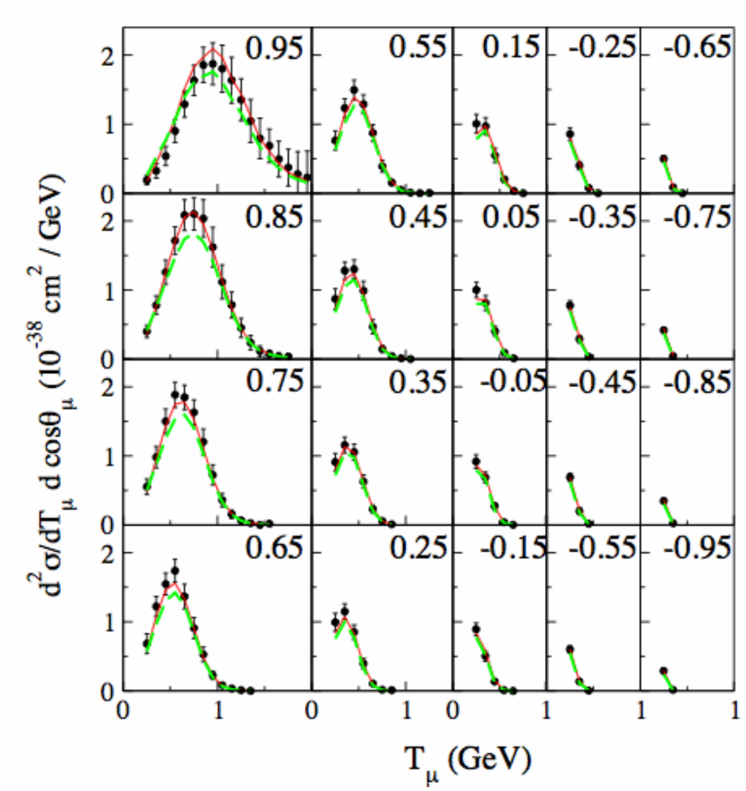


* *be careful (re: QE selection and use of E_ν)!*

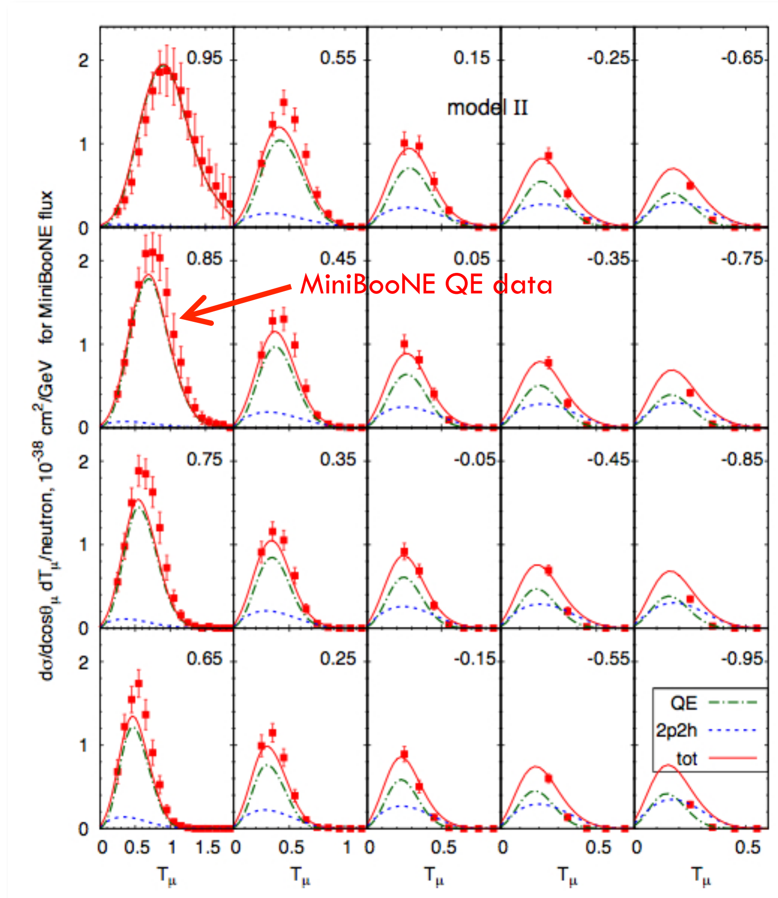
(see Laura's talk!)

Neutrino QE Scattering

- first time we've had enough stats to measure double diff'l dists



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



Lalakulich, Gallmeister, Mosel arXiv:1203.2935

- example: QE data from MiniBooNE
  Phys. Rev. D81, 092005 (2010)

Neutrino QE Scattering

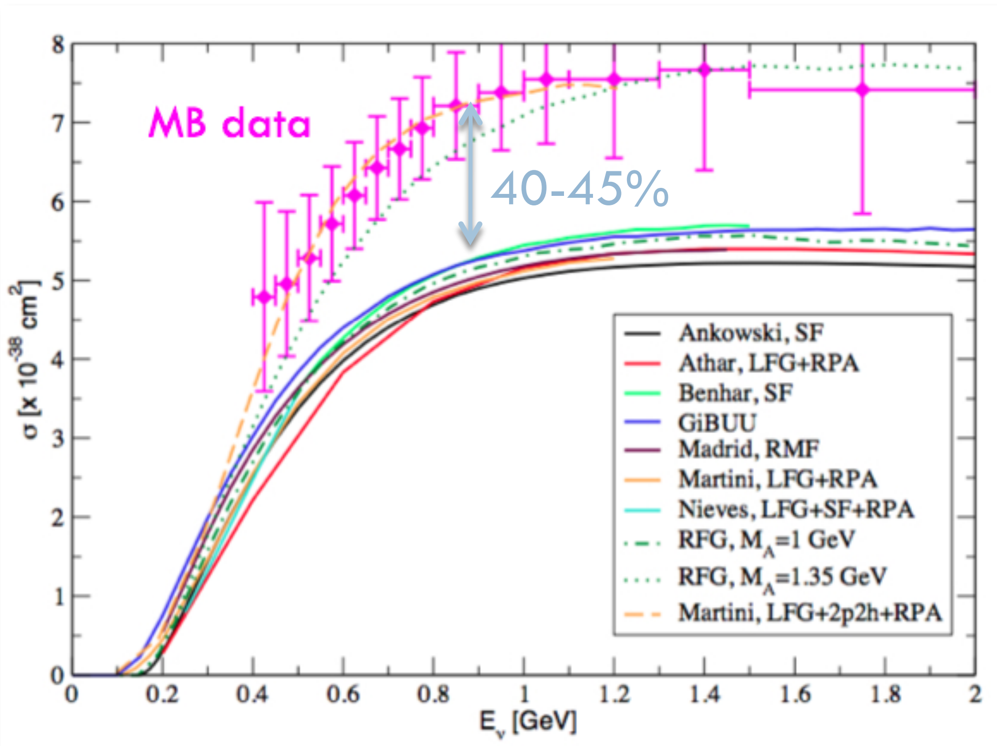
- QE scattering is a great example of how we shouldn't assume that ν cross sections are well in hand (even "simple" ones)

MiniBooNE data is the 1st time have measured the ν QE σ on a nuclear target below 2 GeV

- σ's are appreciably larger than conventional approaches

  (also K2K, MINOS, SciBooNE)

- there are other nuclear effects in play (MEC, np-nh)? idea is not new: *theory papers in 1990's + also seen in e-nucleus QE scattering*



(L. Alvarez-Ruso, NuFact11)

Theory Side

- this is something that needs to get sorted out and people are working hard on this …

  - Lalakulich, Mosel, arXiv:1208.3678
  - Bodek *et al.*, arXiv:1207.1247
  - Ankowski, PRC 86, 024616 (2012)
  - 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, PRC 81, 045502 (2010)
  - Paz, arXiv:1109.5708
  - Sobczyk, arXiv:1201.3673, 1109.1081, 1201.3673
  - Nieves *et al.*, PRD 85, 113008 (2012), 1106.5374, 1110.1200, PRC 83, 045501 (2011)
  - Bodek *et al.*, arXiv:1106.0340
  - Amaro, *et al.*, arXiv:1112.2123, 1104.5446, 1012.4265, PL 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, PRC 83, 064614 (2011)
  - Ankowski *et al.*, Phys. Rev. C83, 054616 (2011)
  - Alvarez-Ruso, arXiv:1012.3871
  - Martinez *et al.*, Phys. Lett B697, 477 (2011) + …

- over 50 theory papers on the topic of ν QE in the past year!

Implications

- neutrino-nucleus QE scattering is <u>not</u> a "standard candle"
  - *could be missing a sizable contrib to σ in our simulations* (~40% at 1 GeV)
  - *additional measurements are crucial to fully understand & model the underlying physics (MINERνA, LAr TPCs)*

- <u>why you should care</u>:

(1) impacts E_ν determination

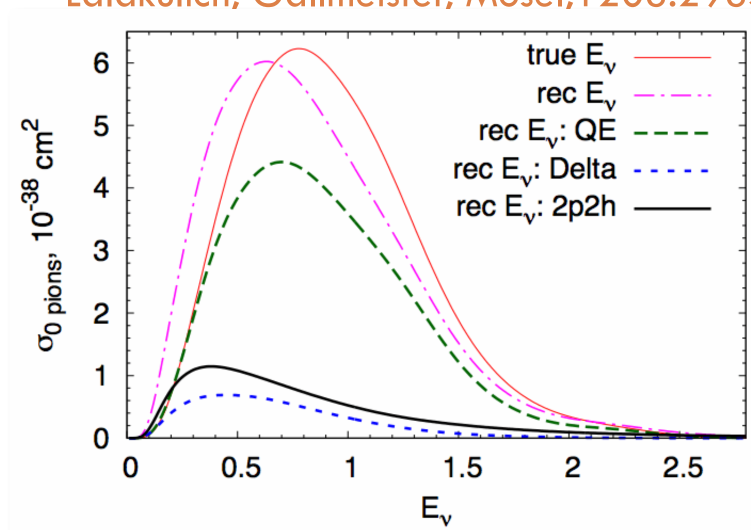
ex: Mosel/Lalakulich 1204.2269, Martini *et al.* 1202.4745, Lalakulich *et al.* 1203.2935, Leitner/Mosel PRC81, 064614 (2010)

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

(at worse, could produce a spurious ~~CP~~ effect)

has direct implications on neutrino oscillation experiments

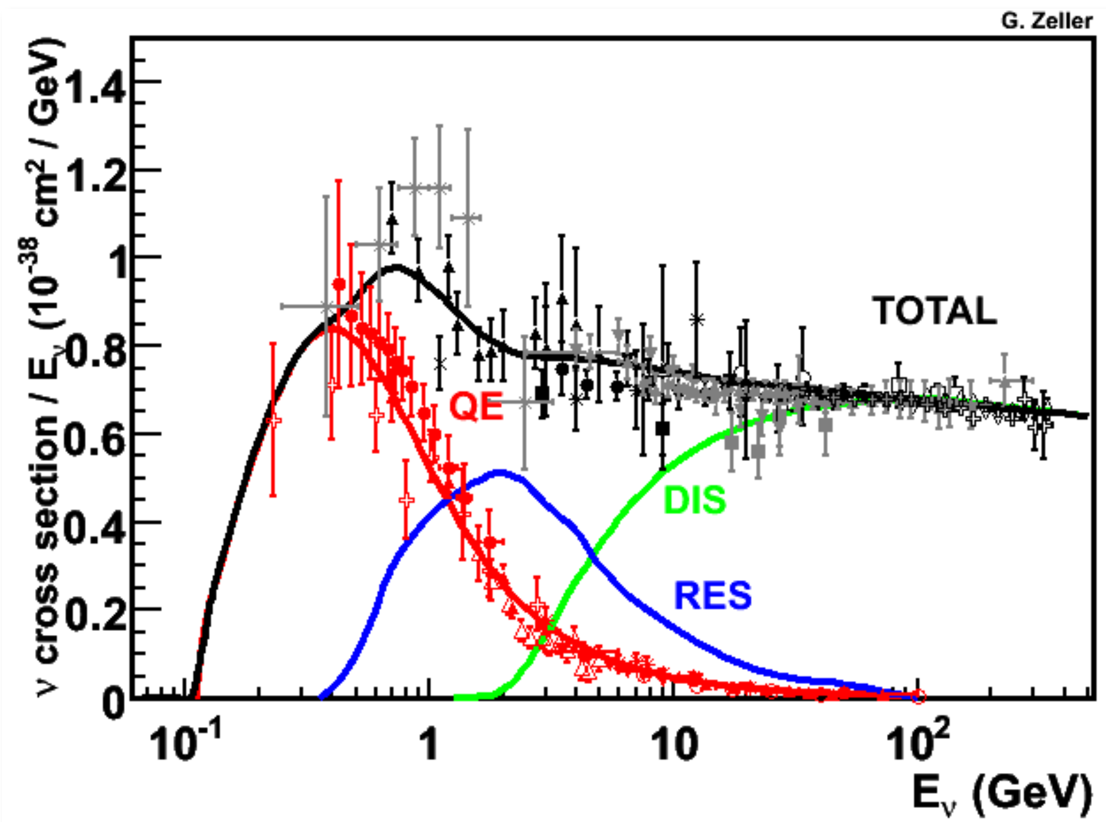
Lalakulich, Gallmeister, Mosel,1203.2935



(see Jorge and Debbie's talks)

Single Pion Production

- as move up in energy, resonance production starts to dominate
  – this is a large source of pion production in neutrino interactions



example:

$\nu_\mu\, p \rightarrow \mu^- \Delta^{++}$

$\quad\quad\quad\quad \hookrightarrow p\, \pi^+$

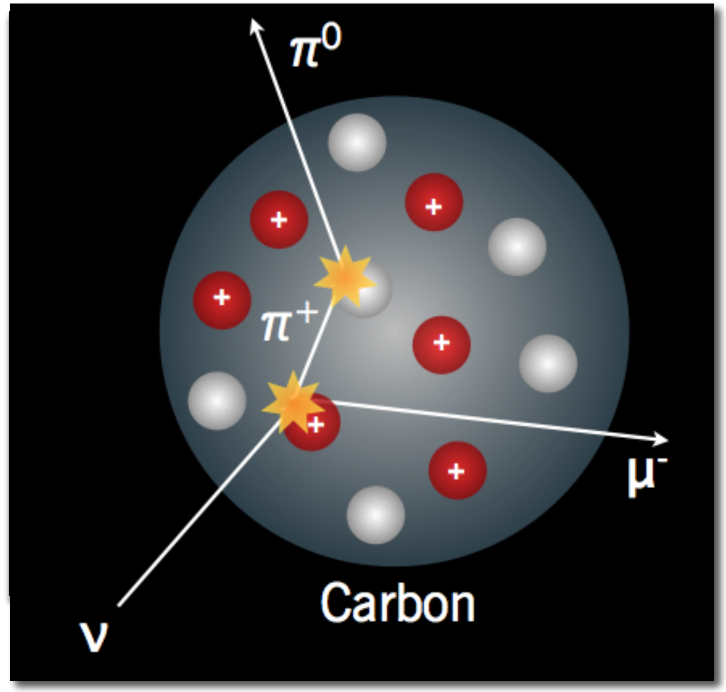
(such baryonic resonances can also decay to multi-π, other mesons, and even γ's)

- 1π production is the one that has been most-well measured

Single Pion Production

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

- FSI change f.s. particle composition and kinematics *(these can be large effects!)*

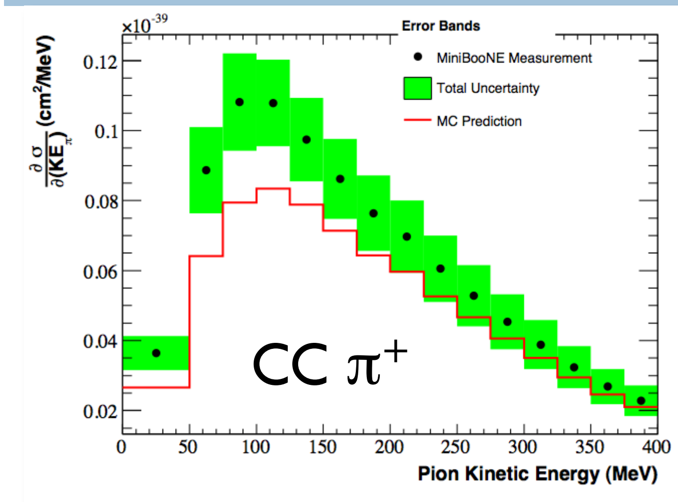


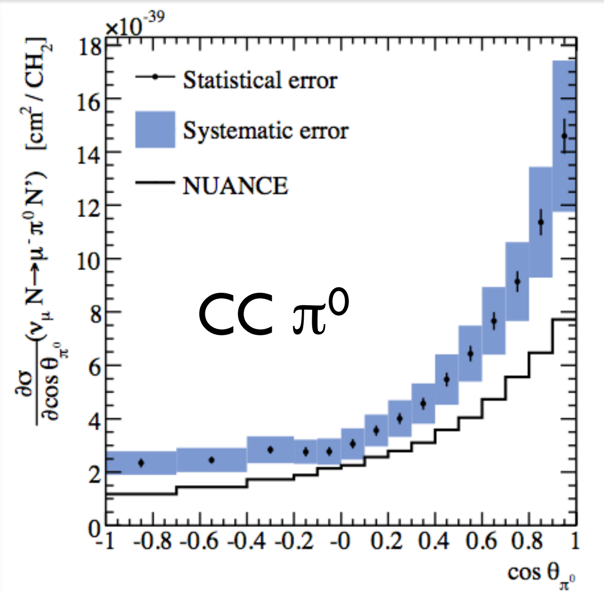
(ex. pion charge exchange)

- effects what you observe experimentally
  (can only detect what exits the target nucleus)

One Example: CC π Production

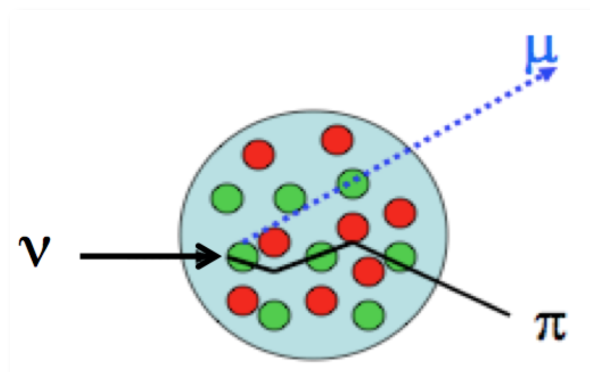
Aguilar-Arevalo, PRD **83**, 052007 and 052009 (2011)





- cross section for CC ν interactions producing a single π exiting nucleus
  (measures initial interaction x nuclear effects x FSI)

- recent π production measurements on nuclear targets also from K2K, SciBooNE, and NOMAD



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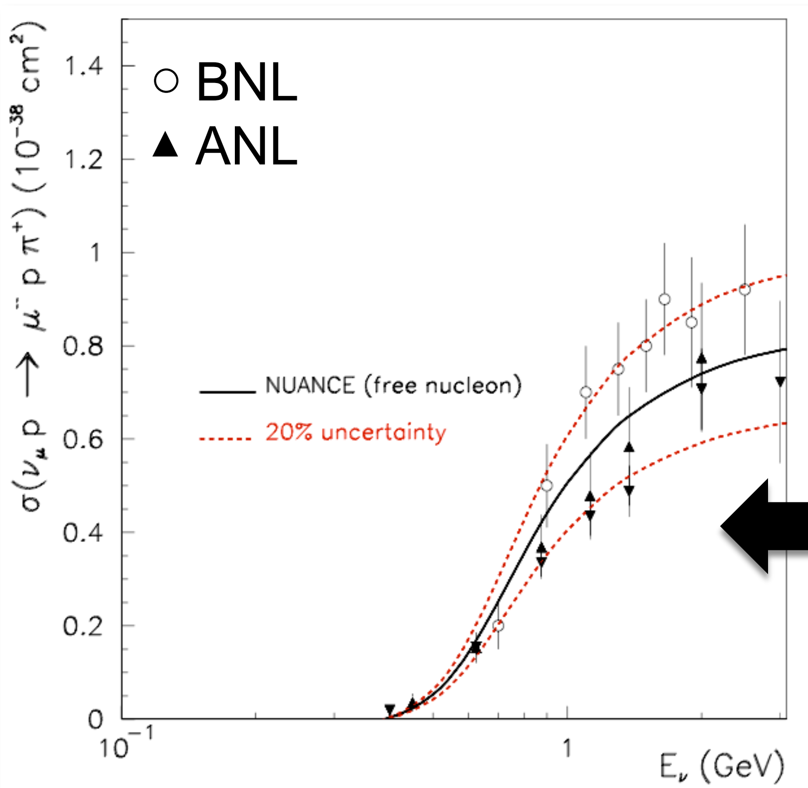


- cross section for CC ν interactions producing a single π exiting nucleus *(measures initial interaction x nuclear effects x FSI)*

- recent π production measurements on nuclear targets also from K2K, SciBooNE, and NOMAD

- best meas of <u>initial</u> interaction σ come from ANL, BNL (D_2); even these differ by ~20% from each other

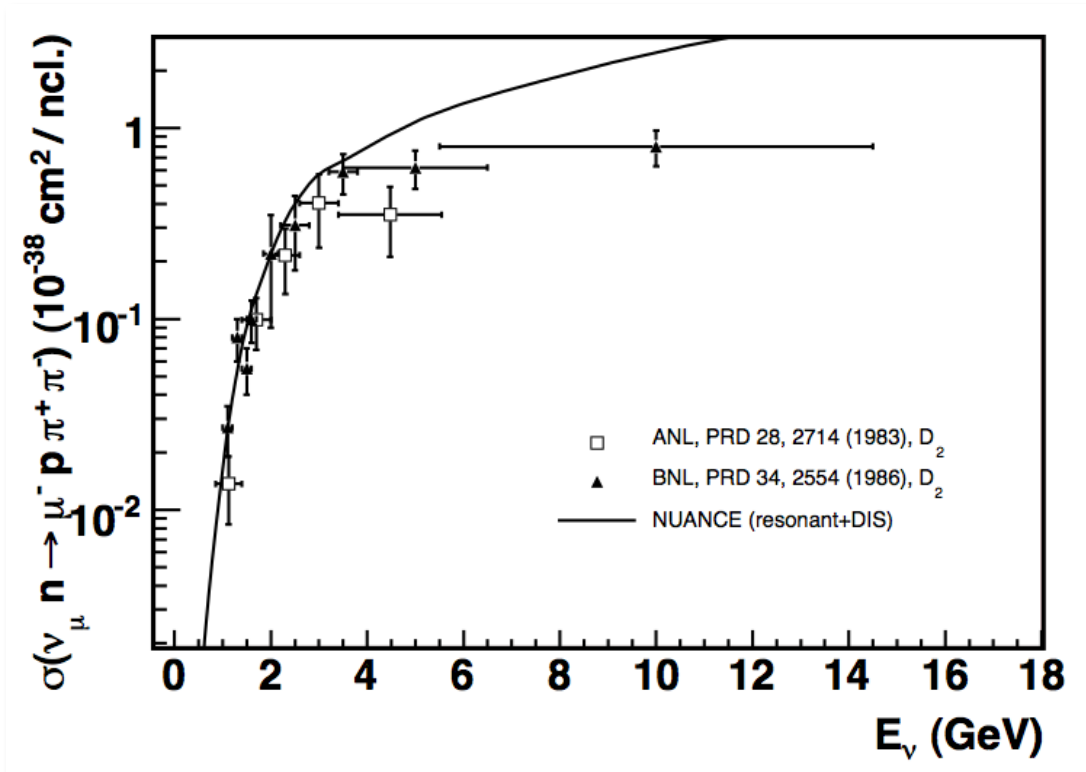
- ν-induced single π production is <u>not</u> a "standard candle" either

Multi-Pion Production

- only existing measurements of multi-π production come from D_2-based bubble chamber measurements *(contain contributions from both RES & DIS)*

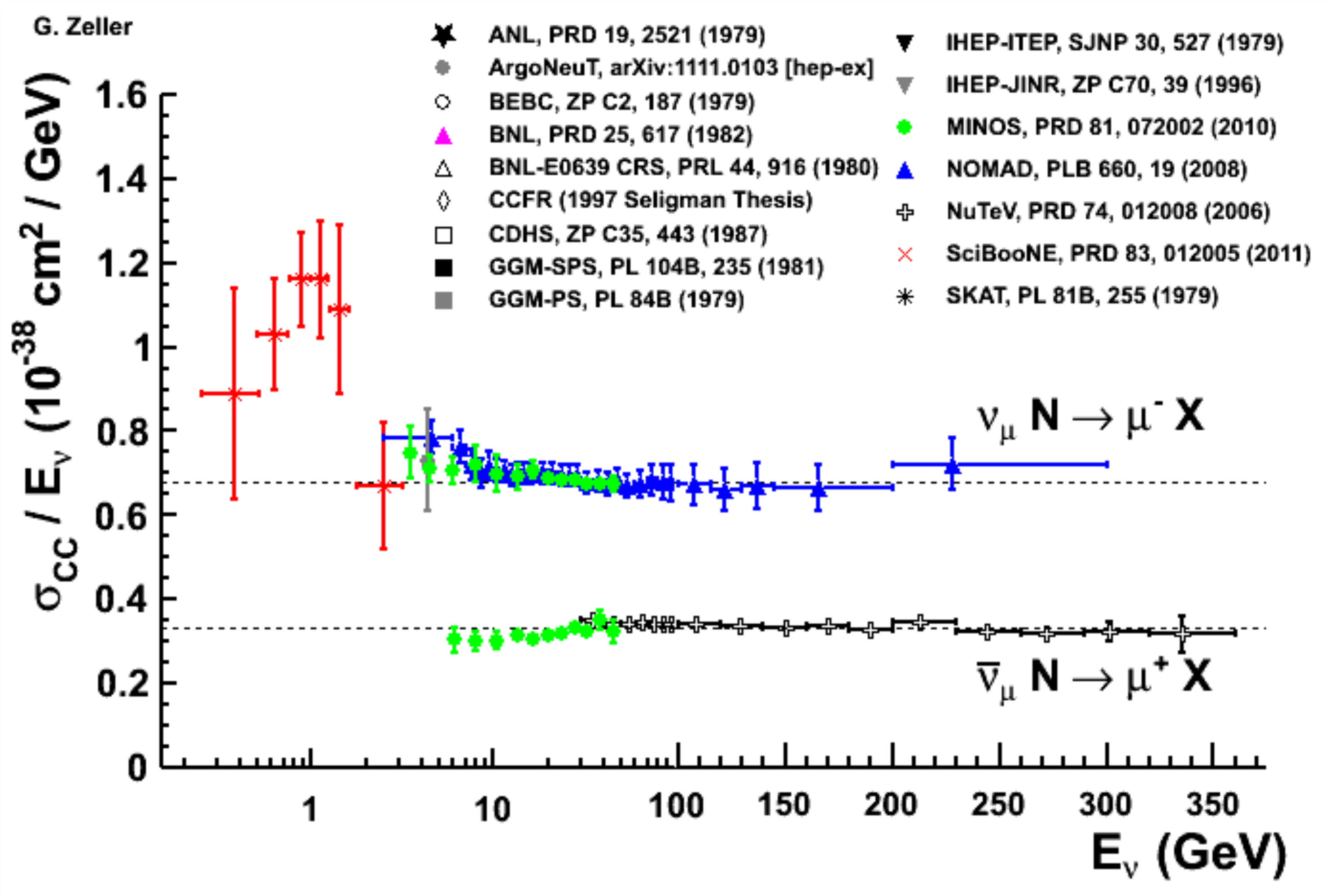
- we're in for a bit of trouble here - multi-π production is one of the largest contributing processes in LBNE (MINERνA can help!)

- multi-π production is <u>not</u> a "standard candle"

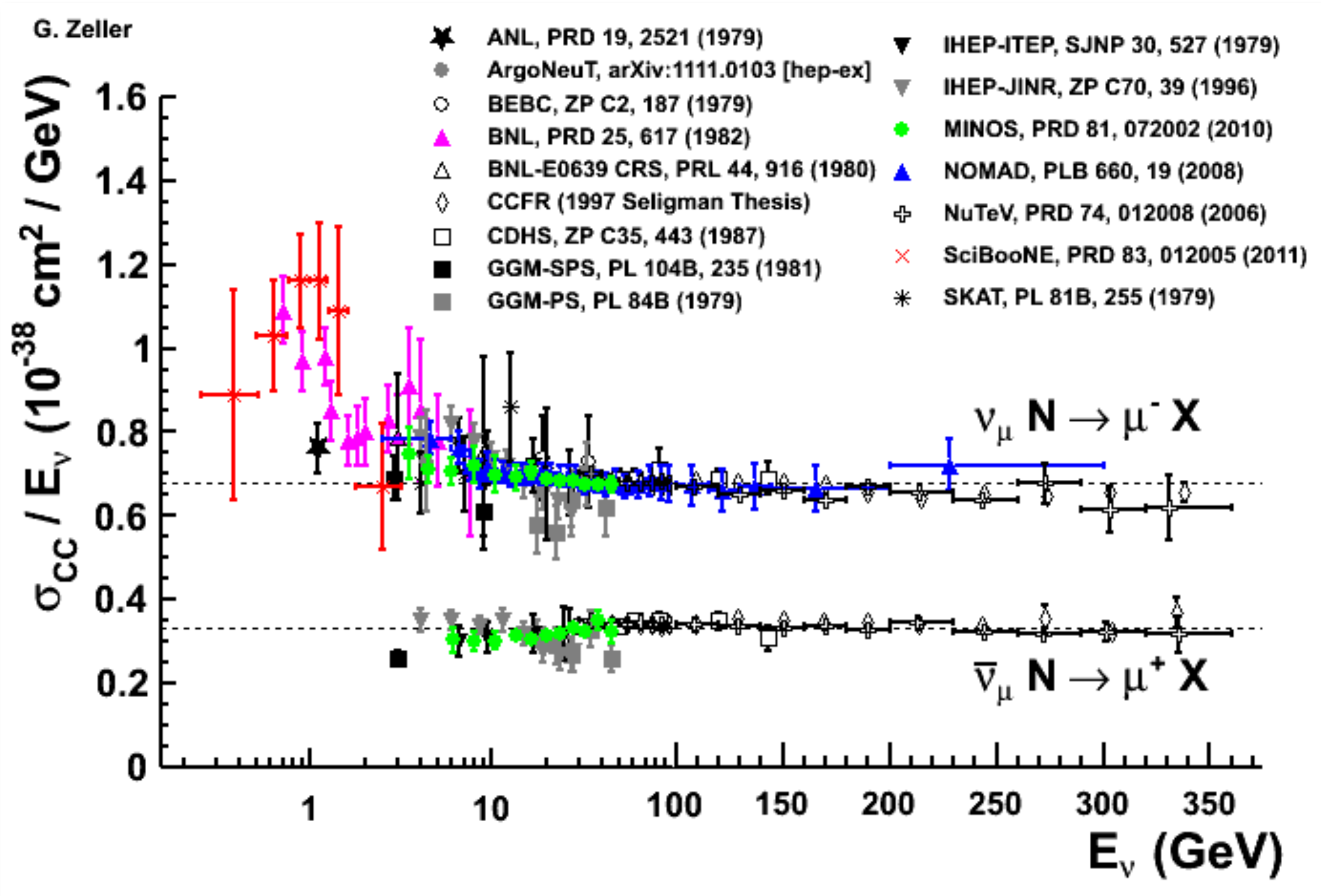


Rev. Mod. Phys. 84, 1307 (2012)

Total CC Inclusive ($\nu_\mu N$)



Total CC Inclusive (ν_μN)



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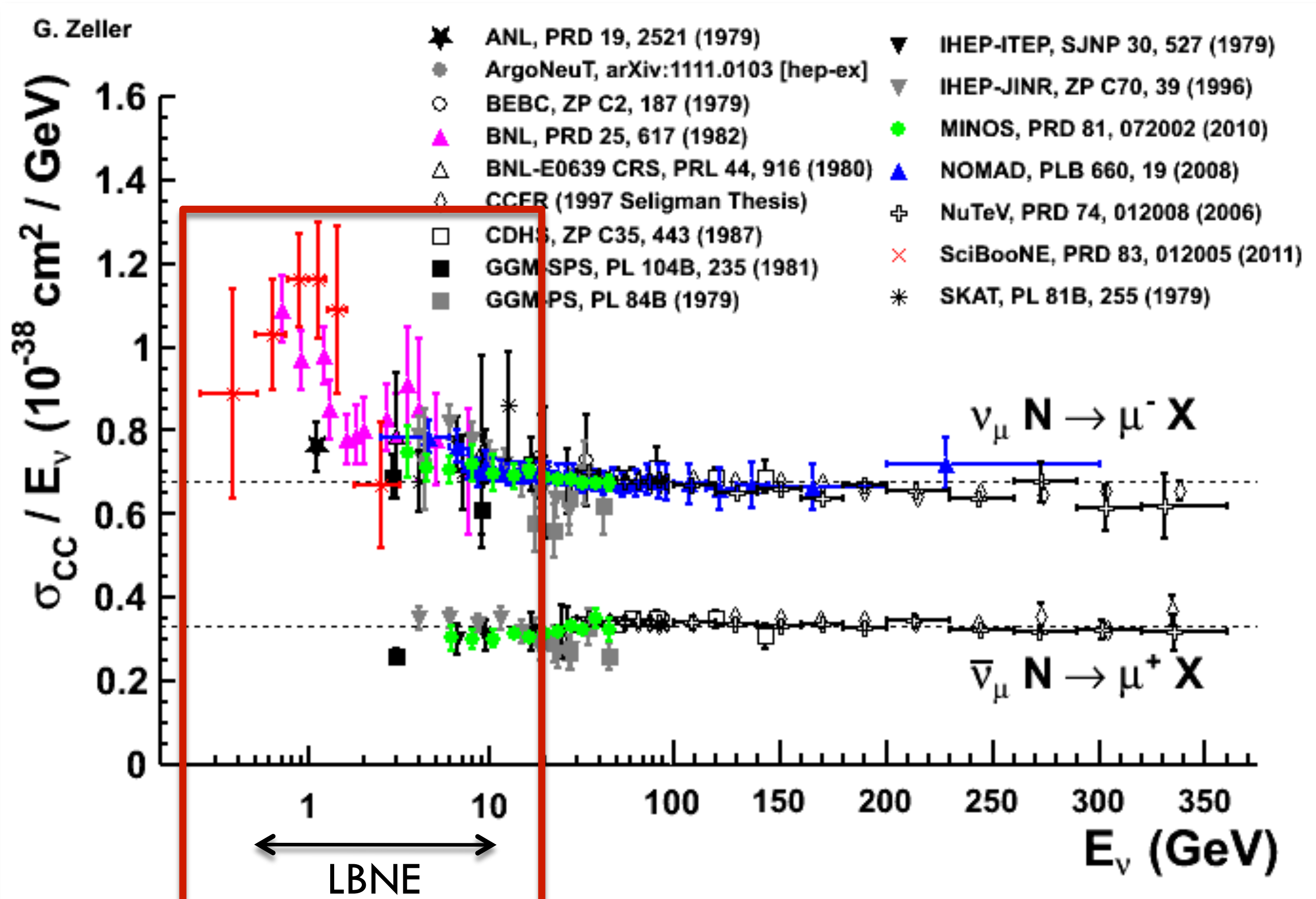

- used to help set Φ_ν predictions in exps like BEBC, SKAT, Serpukhov, and K2K, MINOS, NOMAD

this is the region we care about for accel-based oscillation experiments

ν_e Cross Sections

- ν_e cross section measurements are much harder to come by especially at GeV energies *(in accelerator sources, we intentionally reduce # of ν_e's in our beams)*
- existing ν_e, $\bar{\nu}_e$ cross section measurements are limited to decay-at-rest, radiological, and reactor sources … all at very low energies

Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	^{2}H(ν_e, e^-)pp	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara *et al.*, 1990)
^{12}C	^{12}C$(\nu_e, e^-)^{12}$N$_{g.s.}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	10.5 ± 1.0(stat) ± 1.0(sys)	9.2 [EPT] (Fukugita *et al.*, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C$(\nu_e, e^-)^{12}$N*	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4-5.6 [CRPA] (Kolbe *et al.*, 1999b)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and S, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
^{56}Fe	^{56}Fe$(\nu_e, e^-)^{56}$Co	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	^{71}Ga$(\nu_e, e^-)^{71}$Ge	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	^{127}I$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

$<$ 50 MeV

$\sim$ 700 keV

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

- need a higher energy, well-known ν_e source: νSTORM!

What We Know and Don't Know

- spent a lot of time talking about things we don't know very well:
  - nuclear effects in ν QE scattering
  - final state effects in resonant π production
  - ν_e cross sections, etc.

- this intermediate E range (~0.1-10 GeV) remains a challenge

  (new data telling us that things are more complex than we may have thought)
  - not a lot of processes we can anchor to with well-known (few-%) σ's

- <u>so what do we know</u>?
  - look back in history at some of the "standard candles" ν experiments used to determine their ν fluxes

Using ν Events to Determine ν Fluxes

- neutrino experiments measure the product of flux x cross section:

$$N_\nu = \Phi_\nu \times \sigma_\nu \times \varepsilon$$

- so if can identify an event sample with a <u>well-known cross section</u>, can in principle, measure your ν flux to some high degree of precision:

$$\Phi_\nu = \frac{N_\nu}{\sigma_\nu \times \varepsilon}$$

- historically, there are a lot of examples of this, at least in the cases where can find out how the experiment determined their ν flux

(this information is often hard to find)

Summary of Φ_ν Methods in QE Experiments

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)	√	—	√	—	—

Abbreviations: CC, charged-current; DIS, deep-inelastic scattering; hadro, hadro-production; IMD, inverse muon decay.

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

Summary of Φ_ν Methods in QE Experiments

- **QE** *lower energy beams*
  (BNL, FNAL)
- **hadro-production**
  (ANL, GGM, MB, SB)

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higher energy beams

- **total CC**
  (BEBC, Serpukhov, SKAT, K2K, MINOS, NOMAD)
- **IMD**
  (NOMAD)

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Abbreviations: CC, charged-current; DIS, deep-inelastic scattering; hadro, hadro-production; IMD, inverse muon decay.

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

First Neutrino Experiments

- early experiments (1970's, 1980's) had more faith in their neutrino cross section predictions than their flux estimates

  - ν_μ QE scattering considered a "standard candle"

- QE was a common sample used to determine the flux normalization in many of the first neutrino experiments

"the absolute normalization of the flux can be calculated from the theoretical expressions if one knows M_A"
(FNAL 15-ft bubble chamber)

- BTW, this led to some unfortunate circularity in a few experiments

  - same data used to determine the ν flux and later the σ_{QE}
  - **this is something we need to be careful about today too!**

Gargamelle

- one of the earliest examples I could find …

- 236 ν_μ QE events on <u>freon</u>
- $M_A = 1.0 \pm 0.35$ GeV (Q^2 fit)

"Fig. 6 shows the energy distribution of the neutrino flux up to 4 GeV derived from the elastic event rate and cross section computed for M_A=1.0 GeV. Except at low energy, it is consistent with the flux calculated by Van der Meer on the basis of measured pion and kaon production spectra."

(M. Block *et al.*, PL 12, 281, 1964)

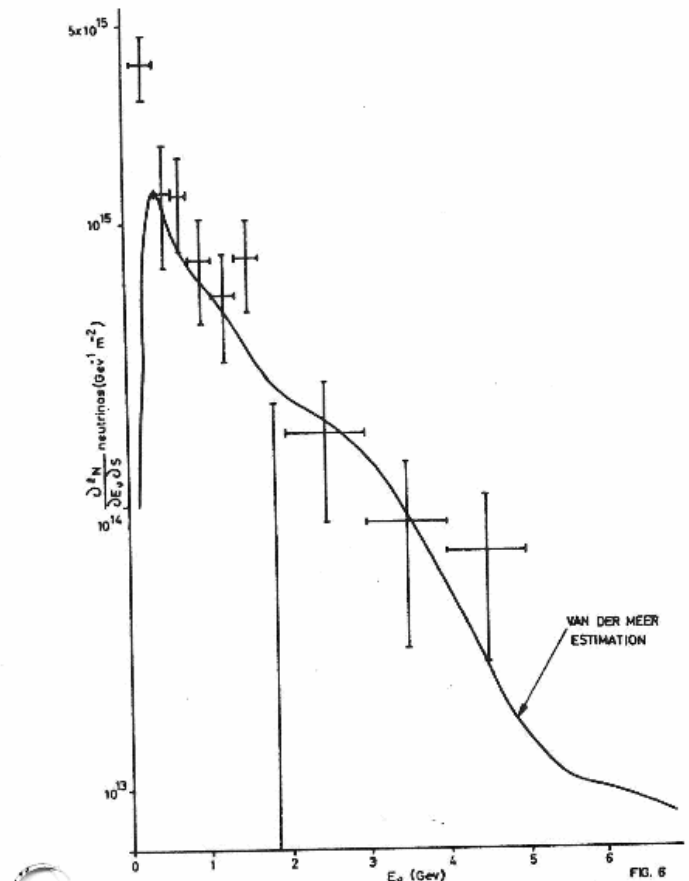


Fig. 6. Neutrino flux calculated from event rate and cross section, compared with predicted flux.

Deuterium

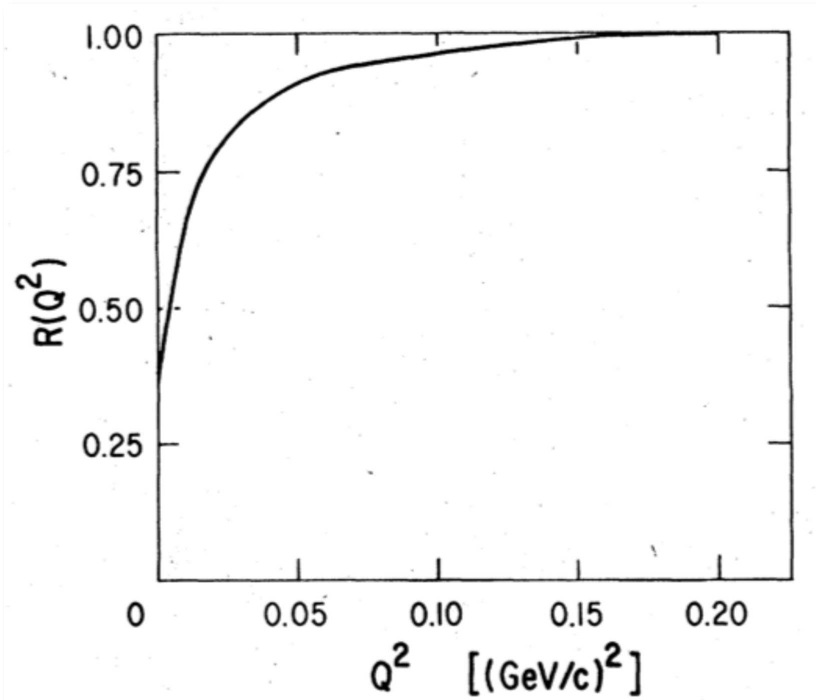
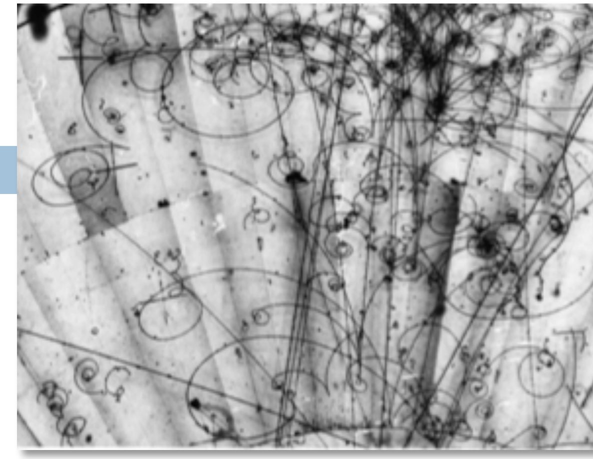


FIG. 21. Correction factor $R(Q^2)$ defined as $R(Q^2) = \sigma(\nu d \to \mu^- p p_s)/\sigma(\nu n \to \mu^- p)$.

(S.J. Barish et al., PRD 16, 11, 1977)

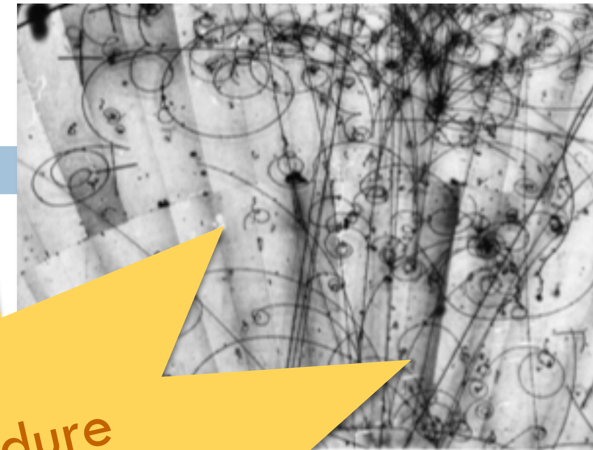


- ν_μ QE scattering on D_2 was process of choice for the flux determination in many early ν experiments:

$$\nu_\mu\, d \to \mu^-\, p\, p_S$$

- nuclear effects are small and calculable (Singh, NP B36, 419, 1972)
- vector form factors from e^-
- get M_A from Q^2 shape fit to ν QE
  (*"independent of absolute flux normalization"*)

Deuterium



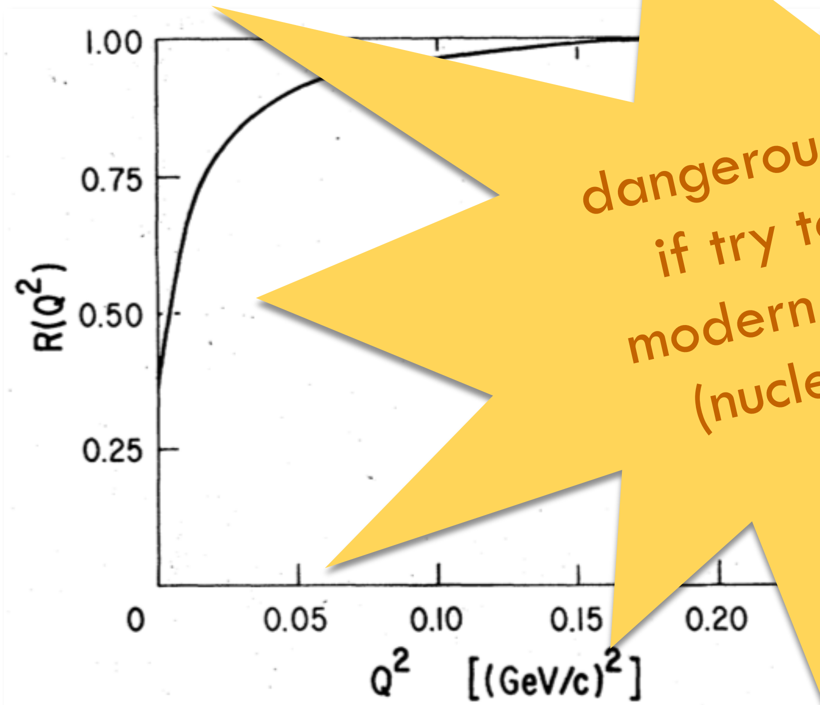


FIG. 21. Correction factor $R(Q^2)$ defined as $R(Q^2) = \sigma(\nu d \to \mu^- p p_s)/\sigma(\nu n \to \mu^- p)$.

(S.J. Barish et al., PRD 16, 11, 1977)

dangerous procedure if try to apply in modern experiments (nuclear targets)

... on D_2 was process ... flux determination ... ν experiments:

ν_μ d → ... p p_S

- nucle... effects are small and calculable (Singh, NP B36, 419, 1972)
- vector form factors from e^-
- get M_A from Q^2 shape fit to ν QE ("*independent of absolute flux normalization*")

FNAL

VOLUME 49, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1982

Neutrino Flux and Total Charged-Current Cross Sections in High-Energy Neutrino-Deuterium Interactions

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa, A. Yamaguc
T. Hayashino, Y. Ohtani, and H. Hayano
Tohoku University, Sendai 980, Japan

To obtain the total cross section from the number of events, the neutrino flux has to be measured on an absolute scale. In this analysis, we determine the neutrino flux using 362 quasielastic events identified in our data[10] and the cross section for reaction (2) derived from the $V-A$ theory.

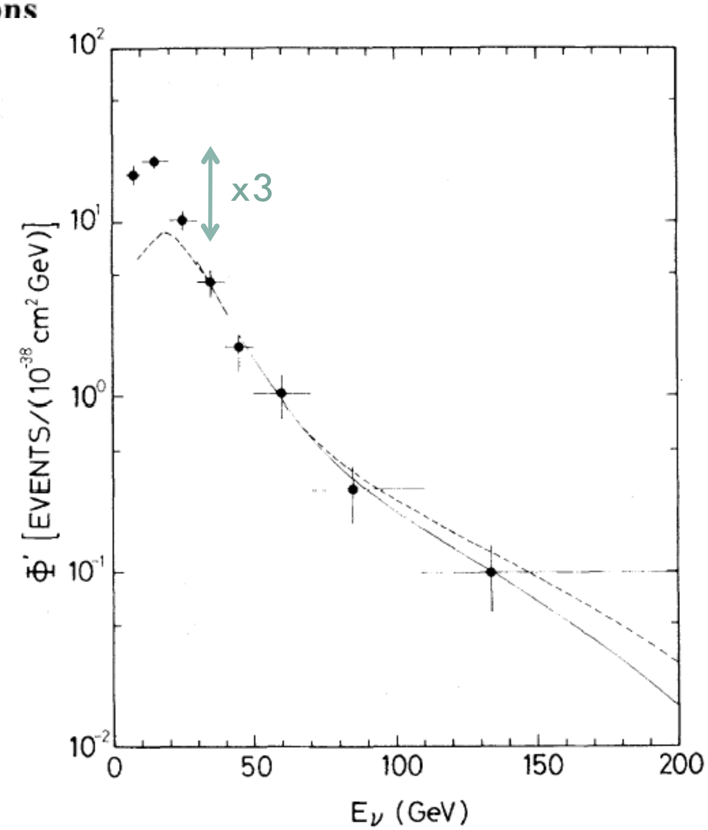


FIG. 2. Neutrino flux distribution obtained from the quasielastic events and the predicted cross section with M_A = 1.05 GeV. The solid curve is obtained from the best fit to the flux data for E_ν > 30 GeV. The dashed curve is taken from the Monte Carlo simulation of the flux.

measured ν flux = (6.15 ± 0.36) x 10^{14} ν/m^2

(10-200 GeV) prediction = 3.62 x10^{14} ν/m^2

x 1.7 difference

FNAL

PHYSICAL REVIEW D VOLUME 28, NUMBER 3 1 AUGUST 1983

High-energy quasielastic $\nu_\mu n \to \mu^- p$ scattering in deuterium

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa,
A. Yamaguchi, K. Tamai, T. Hayashino, Y. Otani, H. Hayano, and H. Sagawa
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R. A. Burnstein, J. Hanlon, and H. A. Rubin
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C. Y. Chang, S. Kunori, G. A. Snow, D. Son,* P. H. Steinberg, and D. Zieminska†
University of Maryland, College Park, Maryland 20742

R. Engelmann, T. Kafka, and S. Sommars‡
State University of New York at Stony Brook, Stony Brook, New York 11974

C. C. Chang,§ W. A. Mann, A. Napier, and J. Schneps
Tufts University, Medford, Massachusetts 02155
(Received 13 December 1982)

We have studied the quasielastic reaction $\nu_\mu n \to \mu^- p$ in an exposure of the Fermilab deuterium-filled 15-foot bubble chamber to a high-energy wide-band neutrino beam. From an analysis of the Q^2 distribution based on the standard $V-A$ theory, the axial-vector mass in a dipole parametrization of the axial-vector form factor is determined to be $M_A = 1.05^{+0.12}_{-0.16}$ GeV, consistent with the values previously reported from low-energy experiments.

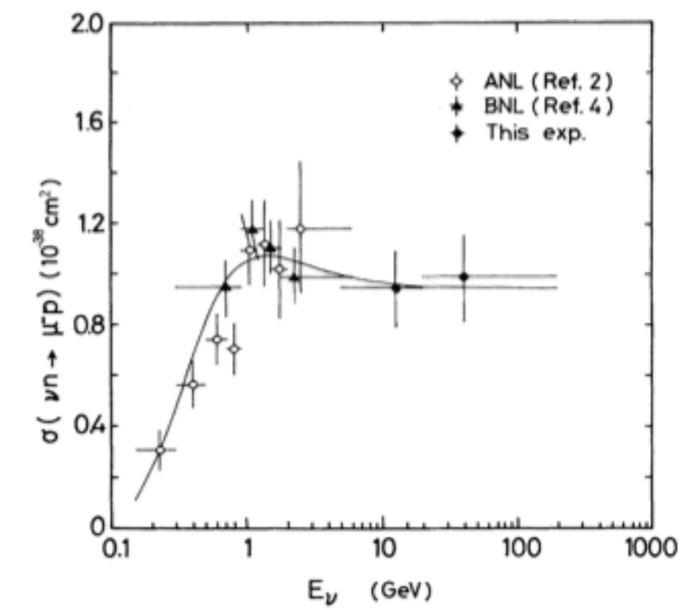

FIG. 10. Quasielastic cross section $\sigma(\nu_\mu n \to \mu^- p)$ as a function of E_ν. The data points from this experiment and Ref. 4 are calculated from Eq. (7) using the M_A values in Table I. The curve is derived from Eq. (7) with $M_A = 1.05$ GeV.

- flux used to publish an absolute ν_μ QE cross section *(a bit of circularity here)*

BNL

PHYSICAL REVIEW D VOLUME 34, NUMBER 1 1 JULY 1986

Determination of the neutrino fluxes in the Brookhaven wide-band beams

L. A. Ahrens, S. H. Aronson, P. L. Connolly,* B. G. Gibbard, M. J. Murtagh, S. J. Murtagh,† S. Terada, and D. H. White
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

- measured their ν_e, $\bar{\nu}_\mu$, and ν_μ flux using samples of QE events on D_2

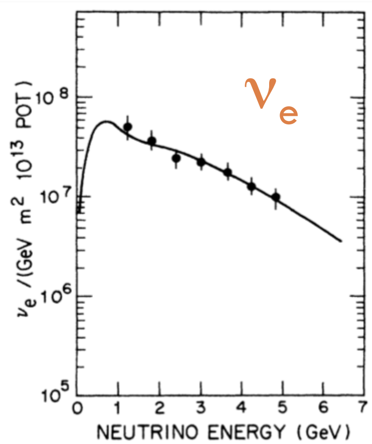

FIG. 10. The measured flux $\phi(E(\nu_e))$ together with the calculated result of Fig. 14. The data have been adjusted by a factor of 1.1 consistent with the scale uncertainties in the data and Monte Carlo calculations.

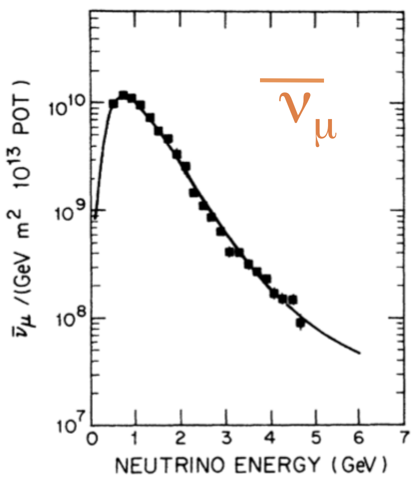

FIG. 9. The measured flux $\phi(E(\bar{\nu}_\mu))$ together with the calculated result of Fig. 13. The data have been adjusted by a factor of 1.3 consistent with the scale uncertainties in the data and Monte Carlo calculations.

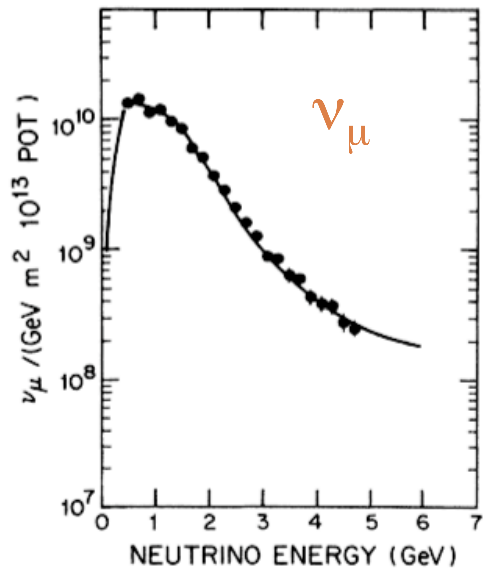

FIG. 8. The measured flux $\phi(E(\nu_\mu))$ together with the calculated result of Fig. 12. The data have been adjusted by a factor of 1.1 consistent with the scale uncertainties in the data and Monte Carlo calculations. POT stands for protons incident on target.

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PHYSICAL REVIEW D VOLUME 34, NUMBER 1 1 JULY 1986

Determination of the neutrino fluxes in the Brookhaven wide-band beams

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Physics Department, Brookhaven National Laboratory, Upton, New York 11973

- measured their ν_e, $\overline{\nu}_\mu$, and ν_μ flux using samples of QE events on D_2

The beam calculations described here were based on the Grote, Hagedorn, and Ranft (GHR) (Ref. 11) parametrization; that of Sanford and Wang was used for comparison. An estimate was made of pion production by reinteracting protons guided by the shape of the observed ν_μ spectrum and the observed angular distribution of muons from quasielastic events. The procedure is described[12] in the Appendix.

↘

atively untouched. To modify the production spectrum to fit the neutrino data we multiplied the four p_π columns (1, 2, 3, 4 GeV/c) by four parameters which alter the neutrino flux spectrum only below 1.2 GeV. The fit parameters are relatively small (1.18, 1.79, 1.24, 1.21 in increasing order of p_π) and the modification is consistent with the effect expected from secondary interactions. We have calculated $\phi(E(\overline{\nu}_\mu))$, $\phi(E(\nu_e))$, and $\phi(E(\overline{\nu}_e))$ using the same

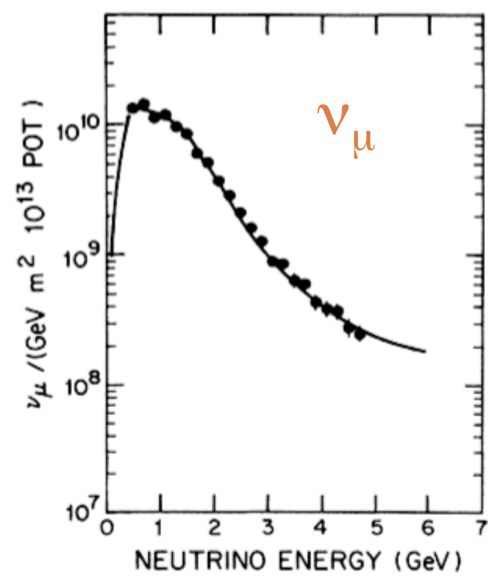

FIG. 8. The measured flux $\phi(E(\nu_\mu))$ together with the calculated result of Fig. 12. The data have been adjusted by a factor of 1.1 consistent with the scale uncertainties in the data and Monte Carlo calculations. POT stands for protons incident on target.

BNL

PHYSICAL REVIEW D VOLUME 3[...]BER 1 1 JULY 1986

Determination of t[...]eutrino flu[...] Br[...] wide-band beams

L. A. Ahrens, S. H. Arc[...] M[...]rtagh,†

Depa[...] [...]73

“if all of the low energy σ_ν’s are measured wrt the QE σ, then how is the QE σ measured?”

- measured th[...] of QE events on D_2

The bea[...] the Gro[...] rametrization; th[...] comparison. An est[...] by reinteracting [...] served ν_μ spect[...] the d[...]istr[...] of muons f[...] quasielastic [...]s. [...]rocedure described[12] in the Appendix.

atively untouched. To modify the production spe[...] to fit the neutrino data we multiplied the four p_π [...]nns (1, 2, 3, 4 GeV/c) by four parameters which alter th[...]eu- trino flux spectrum only below 1.2 GeV. The fit pa[...]me- ters are relatively small (1.18, 1.79, 1.24, 1.21 in increasing order of p_π) and the modification is consistent with the effect expected from secondary interactions. We have cal- culated $\phi(E(\bar{\nu}_\mu))$, $\phi(E(\nu_e))$, and $\phi(E(\bar{\nu}_e))$ using the same

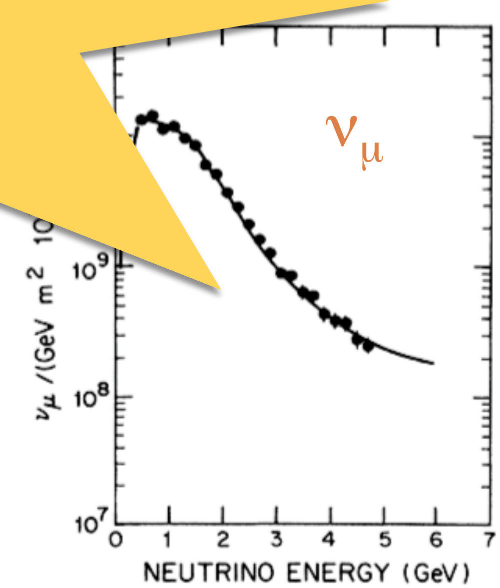

FIG. 8. The measured flux $\phi(E(\nu_\mu))$ together with the calcu- lated result of Fig. 12. The data have been adjusted by a factor of 1.1 consistent with the scale uncertainties in the data and Monte Carlo calculations. POT stands for protons incident on target.

ANL

PHYSICAL REVIEW D VOLUME 16, NUMBER 11 1 DECEMBER 1977

Study of neutrino interactions in hydrogen and deuterium: Description of the experiment and study of the reaction $\nu + d \rightarrow \mu^- + p + p_s$†

S. J. Barish,* J. Campbell,‡ G. Charlton,§ Y. Cho, M. Derrick, R. Engelmann,‖ L. G. Hyman, D. Jankowski, A. Mann,¶ B. Musgrave, P. Schreiner, P. F. Schultz, R. Singer, M. Szczekowski,** T. Wangler, and H. Yuta††
Argonne National Laboratory, Argonne, Illinois 60439

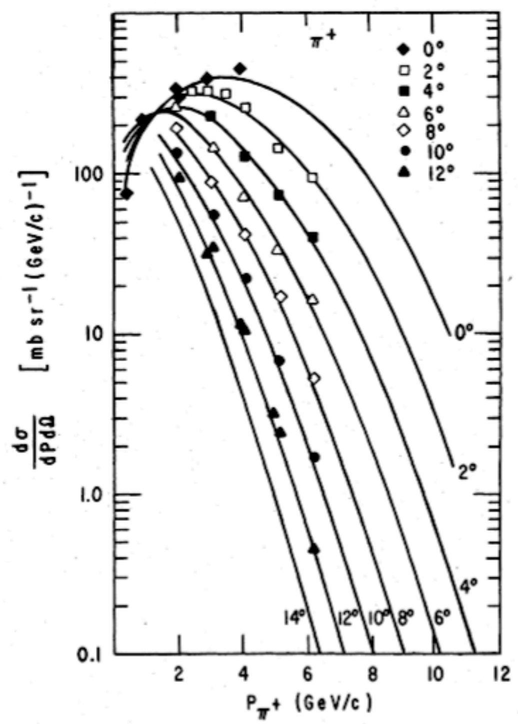

FIG. 4. Cross sections for π^+ production from p-Be collisions at 12.4 GeV/c.

- this is one case where the situation is clear
- neutrino QE cross sections are measured using a flux calculated from π production data alone (and not ν QE)

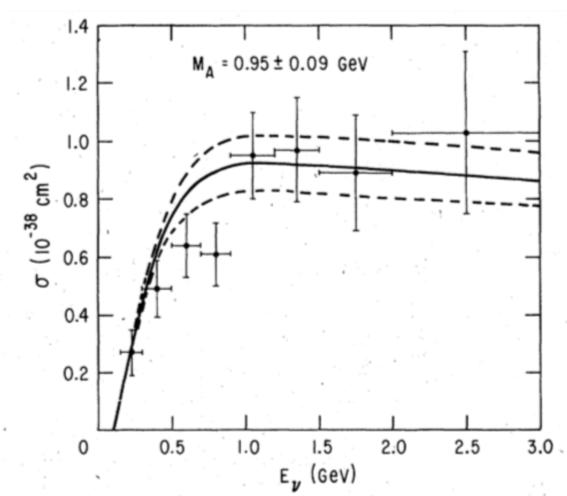

FIG. 22. Total cross section $\nu n \rightarrow \mu^- p$ as a function of neutrino energy. The highest-energy data point extends from 2.0 to 6.0 GeV.

ANL

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Argonne National Laboratory, Argonne, Illinois 60439

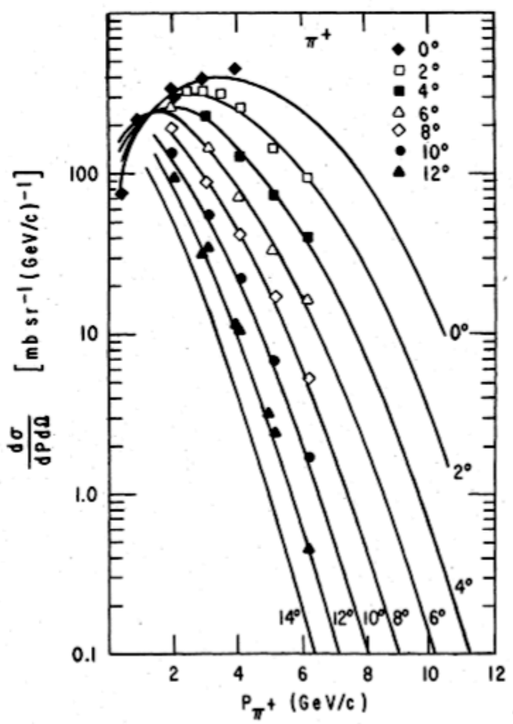

FIG. 4. Cross sections for π^+ production from p-Be collisions at 12.4 GeV/c.

VII. CHECK OF NEUTRINO FLUX FROM THE QUASIELASTIC SCATTERING EVENTS

The cross sections, shown in Fig. 22, are calculated using the flux measured from our pion production cross sections. If we assume a value for M_A, then we can, in turn, use the total cross-section data to measure the neutrino flux. Since M_A can be measured from the shape of the Q^2 distribution only, this provides a useful independent measurement of the flux. The M_A value we use is $M_A = 0.95$ GeV, our flux-independent result as given in Table IV, which is also consistent with values obtained by other neutrino experiments listed in Table V.

- in appendix, QE events used as a check
- again, D_2

ANL

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Study of neutrino interactions in hydrogen and deuterium: Description of the experiment and study of the reaction $\nu + d \rightarrow \mu^- + p + p_s$†

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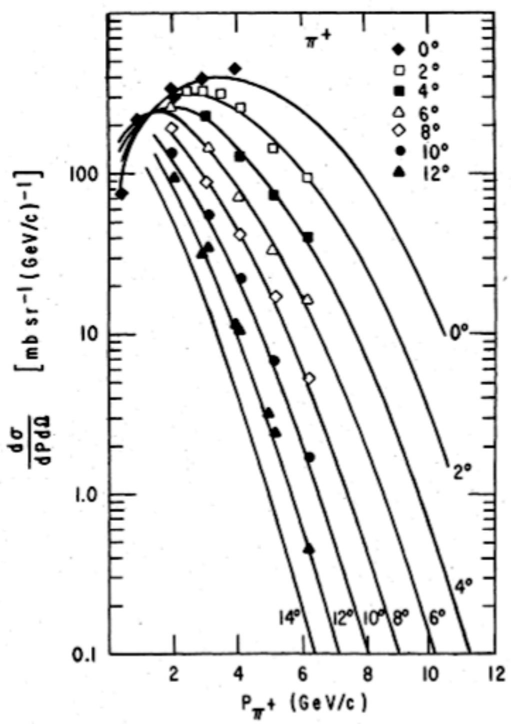

FIG. 4. Cross sections for π^+ production from p-Be collisions at 12.4 GeV/c.

TABLE IV. Results of axial-form-factor fits.

Likelihood function	M_A^{Dipole} (GeV)	M_A^{Monopole} (GeV)
Rate	$0.75^{+0.13}_{-0.11}$	$0.45^{+0.11}_{-0.07}$
Shape	1.010 ± 0.09	0.56 ± 0.08
Rate and shape	0.95 ± 0.09	0.52 ± 0.08
Flux independent	0.95 ± 0.09	0.53 ± 0.08

Table V. Our event numbers then give a flux that is 21% lower than that measured from our pion yields.[40]

(BTW: modern fit are about 25% lower than Cho fits)

ANL

PHYSICAL REVIEW D VOLUME 16, NUMBER 11 1 DECEMBER 1977

Study of neutrino interactions in hydrogen and deuterium: Description of the experiment and study of the reaction $\nu + d \rightarrow \mu^- + p + p_s$†

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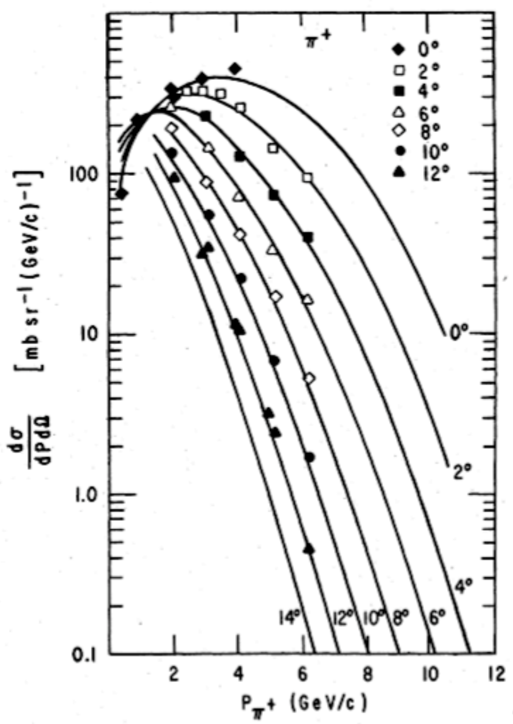


FIG. 4. Cross sections for π^+ production from p–Be collisions at 12.4 GeV/c.

A second technique which is completely independent of the form factors is to extrapolate the differential cross section to $Q^2=0$, where the cross section is given by

$$\left.\frac{d\sigma}{dQ^2}\right|_{Q^2=0} = \frac{G^2\cos^2\theta}{2\pi}\left[F_V(0)^2 + F_A(0)^2\right]$$

$$= 1.98\times 10^{-38}\ \mathrm{cm^2/GeV^2}.$$

Extrapolating the data of Fig. 23 to $Q^2=0$ also gives a flux that is 22% lower than shown in Fig. 8 in agreement with the previous method.

we'll come back to this idea later

(BTW: modern fit are about 25% lower than Cho fits)

Standard Candles

- a lot of past experiments used QE scattering on D_2, so what are the "standard candle" ν interactions for modern IF experiments wishing to get a better handle on their flux?

  (i.e., what are the σ_ν that are well-known in this E region, to a few %)?

- typically <u>not</u> ν-nucleus scattering

  - not even QE, despite any temptations you might have from previous experimental techniques (unless H_2 or D_2)!

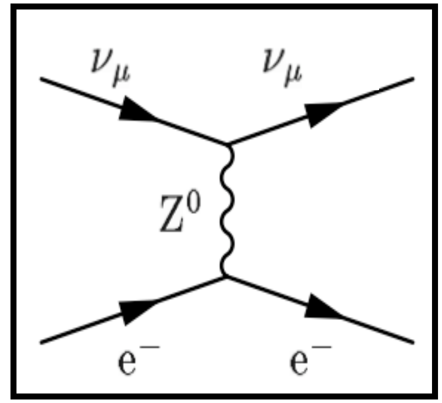
- what are some standard candle reactions in this E region?

  - neutrino-electron scattering ($\nu_\mu e^- \rightarrow \mu^- \nu_e$)
  - DIS (low ν method)

  - ν-deuterium QE scattering (in limit $Q^2 \rightarrow 0$)
  - certain nuclear transitions ($\nu_\mu {}^{12}C \rightarrow \mu^- {}^{12}N_{g.s.}$)

Neutrino-electron scattering

- purely-leptonic process, so σ calculation is very straightforward (no strongly interacting particles involved!)



$$\sigma = \frac{2G_F^2 m_e}{\pi}\left[\left(g_L^2 + \frac{g_R^2}{3}\right)E_\nu - g_L g_R \frac{m_e}{2}\right] \qquad g_L = \sin^2\theta_W \underset{\mu,\tau}{\overset{e}{\pm}} \frac{1}{2} \qquad g_R = \sin^2\theta_W$$

some facts:

- σ is ~ linear with E_ν (generic feature of point-like scattering)
- σ is small: $\sigma \sim (E_{CM})^2 = 2M_{target}E_\nu$
- directional: $E_e\,\theta_e^{\,2} < 2m_e$

~4 orders of magnitude less likely than scattering off nucleons at 1 GeV

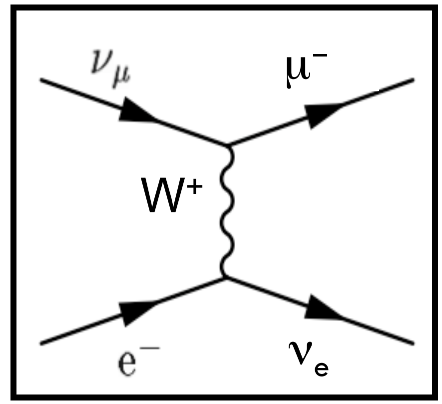
- challenge is to get enough statistics
- and need good electron reconstruction

(see Jaewon's talk)

Inverse Muon Decay and DIS

- more commonly, experiments have used the CC version of this ν-electron scattering process, **IMD**

$$\nu_\mu \, e^- \rightarrow \mu^- \, \nu_e$$
$$\bar{\nu}_e \, e^- \rightarrow \mu^- \, \bar{\nu}_\mu$$



- however, this can't help you with $\bar{\nu}_\mu$ fluxes
- often combined with using **DIS** events (low ν method)
- both IMD and DIS require having higher energy events (see Arie's talk)
  - used for the Φ_ν determination in ν experiments like NOMAD
    - IMD: 496 ± 33 events (7% flux constraint)
    - DIS (1.6% & 5.9% check in ν & $\bar{\nu}$)
- what about lower energy experiments? what can they use?

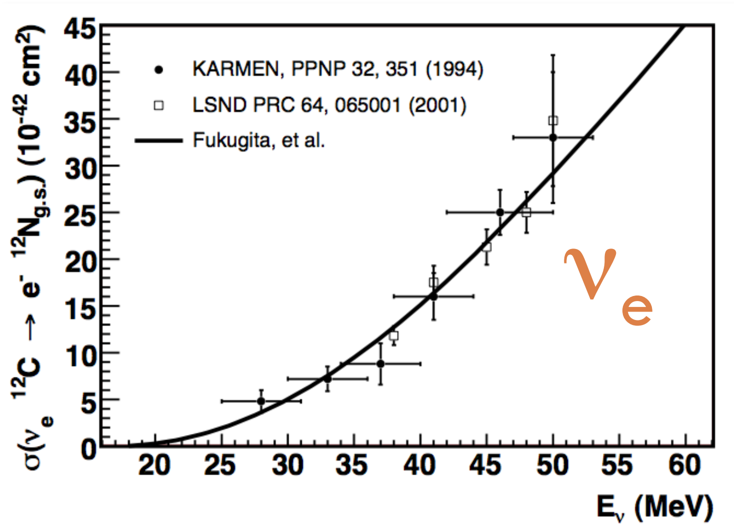
Carbon

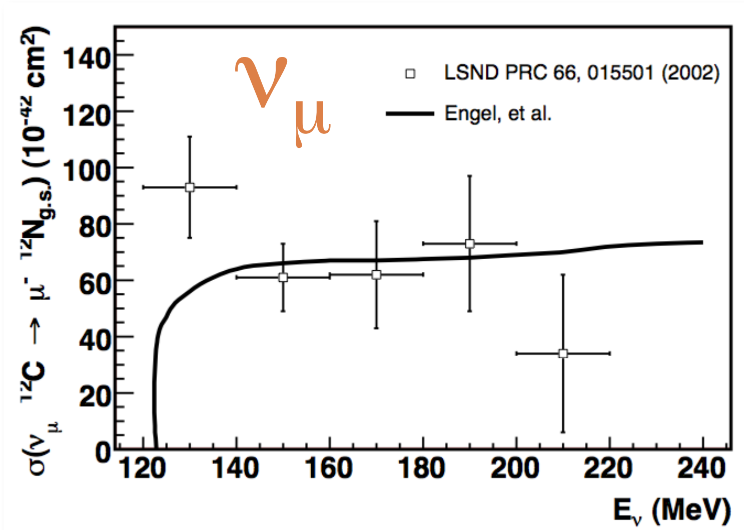
- there are certain nuclear transitions that have well-known cross sections

$$\nu_\mu \, {}^{12}C \rightarrow \mu^- \, {}^{12}N_{g.s.}$$
$$\downarrow$$
$$ {}^{12}C_{g.s} + e^+ + \nu_e$$

β decay of $^{12}N_{g.s.}$:
$\tau = 15.9$ ms
max KE of $e^+ = 16.3$ MeV

- σ well-known (~5%) but increasingly small (4% of σ_{QE} at 250 MeV, 0.5% at 400 MeV)
- signature: low E μ^- followed by delayed e^+ from β decay of $^{12}N_{g.s.}$





Deuterium

- neutrino QE scattering on D_2 ($Q_2 \rightarrow 0$)

(re: G. Garvey and R. VandeWater, explored for LBNE near detector)

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

$$\frac{d\sigma}{dQ^2}\left|Q^2=0\right| = \frac{G^2\cos^2\theta_c}{2\pi}[F_1^2(0)+G_A^2(0)]$$

$$= \frac{G^2\cos^2\theta_c}{2\pi}[1+1.267^2] = 2.08x10^{-38}\,cm^2GeV^{-2}$$ (< 1% uncertainty)

(first mention of this in ANL paper, 1977)

- at Q^2=0, the cross section is determined by neutron β decay; use a light target to minimize nuclear effects

  - event topology: see a μ + very little vertex activity

- idea is that could use low Q^2 events at different E's and positions to measure energy and radial dependence of flux

Conclusions

- σ_ν's in the E range relevant to present & future ν oscillation exps (~0.1-10 GeV) are not nearly as well known as their low and high energy counterparts

  - *multiple processes that contribute in this transition region & associated nuclear physics make this region complicated*

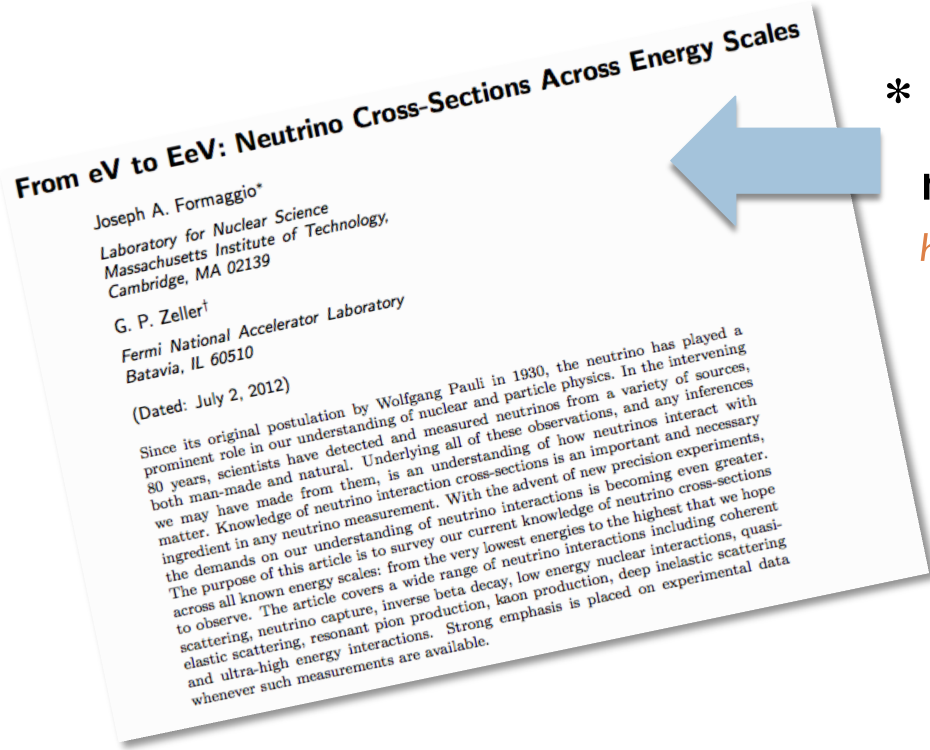
- modern data is turning up some surprises

  - *ν-nucleus QE scattering is not a standard candle!*

- there are a few interactions with well-known cross sections at these E's
  (ν+e^- scattering, DIS, ν-D_2 scattering as $Q^2 \rightarrow 0$, and $^{12}C \rightarrow {}^{12}N_{g.s.}$)

- beyond that, we need better σ_ν determinations from experiments with solid flux predictions
  (ArgoNeuT, μB, MINERνA, MB, NOMAD, NOνA, SB, T2K … νSTORM)

Additional Reading



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

Joseph A. Formaggio*
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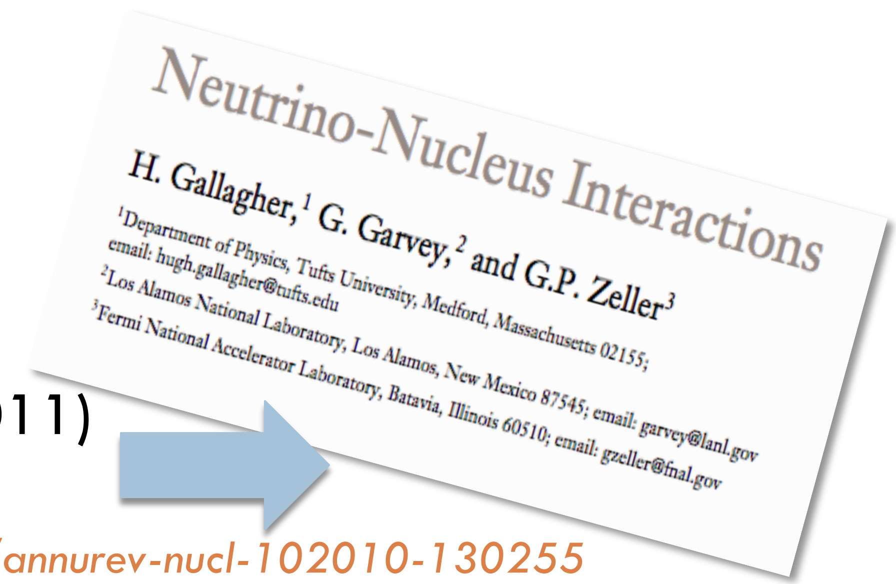
Massachusetts Institute of Technology,
Cambridge, MA 02139

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

(Dated: July 2, 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.

* Rev. Mod. Phys. 84, 1307 (2012)
  review of all neutrino cross sections
  http://rmp.aps.org/abstract/RMP/v84/i3/p1307_1



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

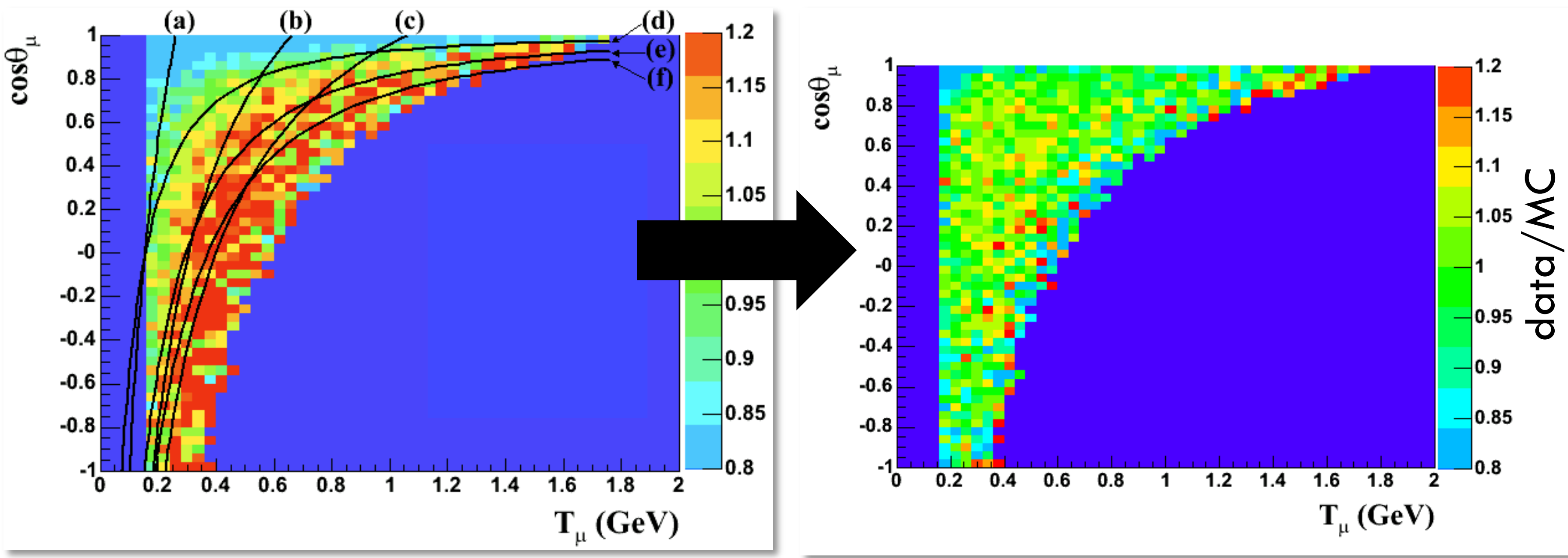
* Ann. Rev. Nucl. Part. Sci. 61, 355 (2011)
  discussion of quasi-elastic scattering
  http://www.annualreviews.org/doi/abs/10.1146/annurev-nucl-102010-130255

Backups

In Two Dimensions

- data/MC disagreement in MiniBooNE ν_μ QE sample follows lines of constant Q^2 not E_ν … cross section not a flux problem

M_A=1.0 GeV in RFG: after increase M_A :



(both relatively normalized)

Antineutrino Fluxes

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Study of low-energy antineutrino interactions on protons

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The determination of the antineutrino flux and energy is crucial for the calculation of an absolute cross section. The first step was the measurement of the neutrino spectrum in a previous experiment.[13] This experiment utilized the quasi-elastic reaction $\nu n \to \mu^- p$ observed in the same bubble chamber filled with deuterium. From a theoretical model the cross section for quasielastic events was calculated. The observed number of such reactions can then be directly related to the neutrino flux.

We now calculate the antineutrino spectrum by scaling this experimentally deduced neutrino spectrum with the ratio of antineutrino to neutrino spectrum as obtained from a Monte Carlo.[13] This ratio is not sensitive to the spectral shape introduced into the Monte Carlo. We find that the antineutrino flux, integrated over energy, is 2.4×10^5 antineutrinos/cm^2 pulse for 5×10^{12} protons on target per pulse (5×10^{12} protons/pulse is a typical proton flux in our experiment); the antineutrino flux-energy (product of antineutrino flux and antineutrino energy) is 3.4×10^5 antineutrinos GeV/cm^2 pulse. The errors in these calculations are estimated to be ~12%. These errors include uncertainties due to assumptions in the Monte Carlo program and statistical errors in the experimentally determined neutrino flux. We estimate that approximately 10% of the charged-current interactions in this experiment come from neutrino contamination.