Co nowego w modelowaniu oddziaływań neutrin w zakresie energii kilku GeV?

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(współpraca: C. Juszczak, T. Golan, S. Lee [JINR Dubna])

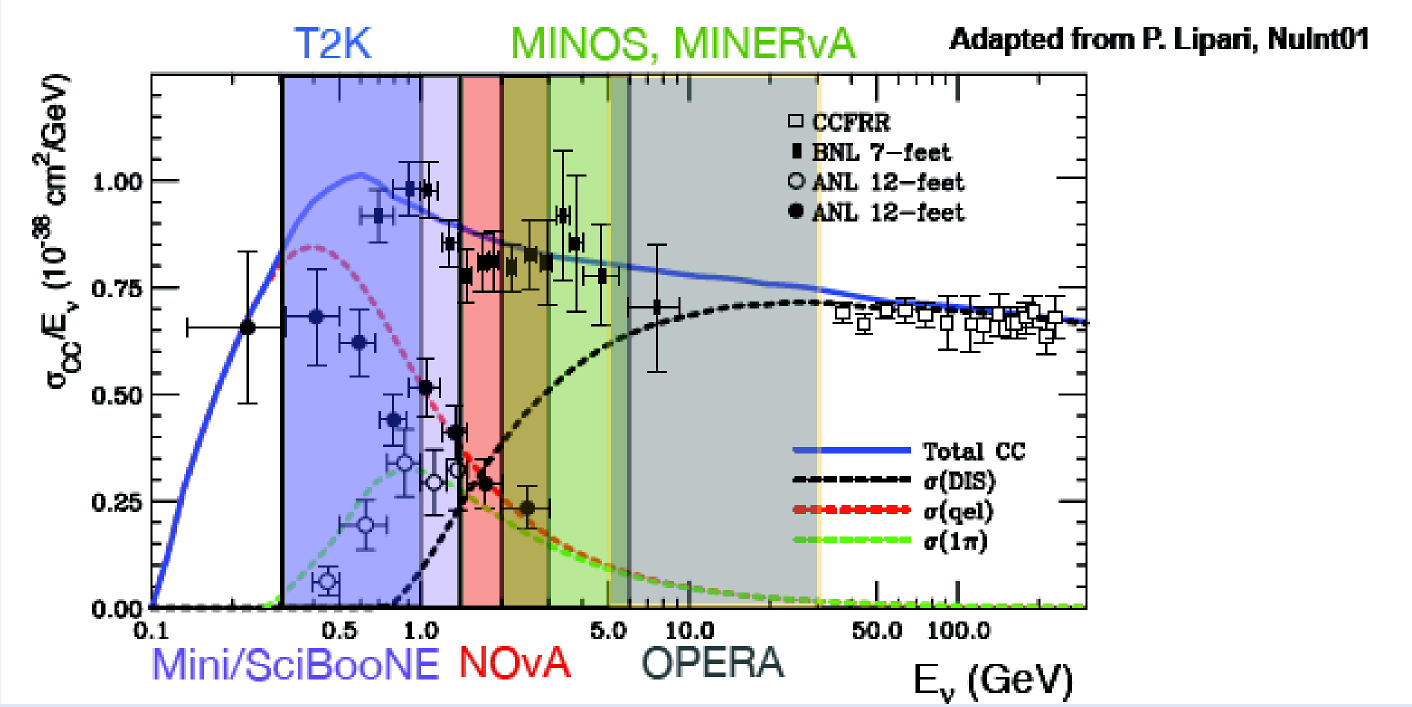
Plan

- motywacja
- zagadka quasi-elastycznej masy aksjalnej
- koherentna produkcja pionów
- produkcja Pi0 przez prąd neutralny
- inne pomiary
- generatory MC, znaczenie funkcji spektralnej
- wnioski

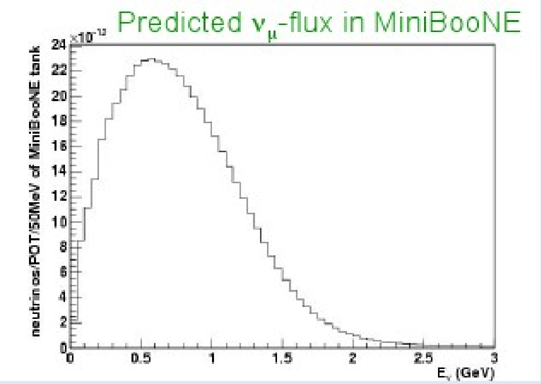
Motivation

1 GeV is the typical energy region of all long

baseline neutrino oscillation experiments.



(from Hiroshi Tanaka)



Motivation

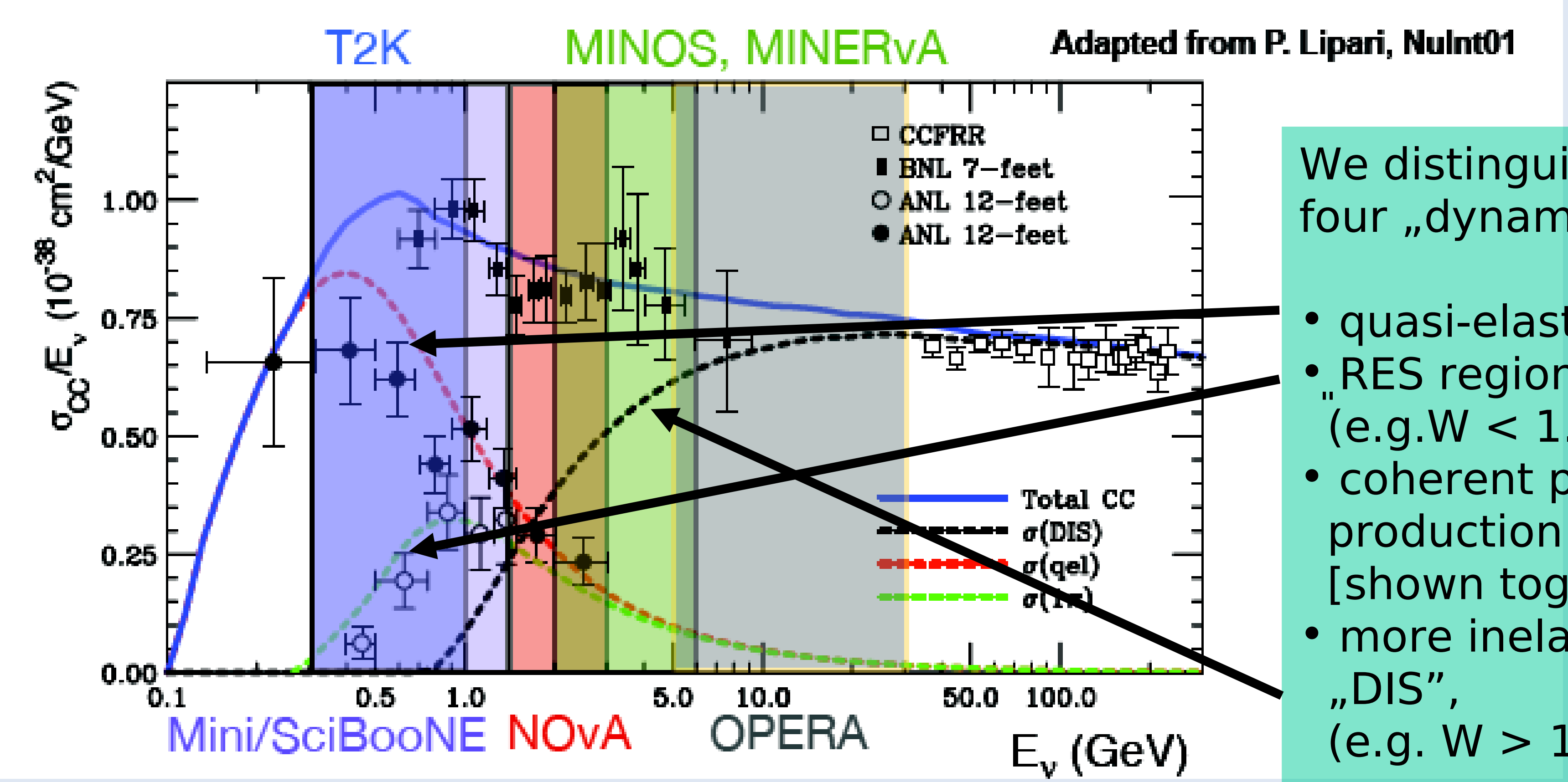
Why do we need cross sections?

- We do not know neutrino energy, we only see final states.
- Oscillations are energy dependent !
- In order to investigate oscillations we must reconstruct neutrino energy or to investigate observed distribution of muons – in both cases we should understand cross sections.

In particular nuclear effects are important for targets like: carbon, oxygen, argon, iron.

Motivation

On the theoretical side, several dynamical mechanisms must be considered together.



We distinguish four „dynamics":

- quasi-elastic
- „RES region", (e.g. W < 1.6 GeV)
- coherent pion production [shown together]
- more inelastic „DIS", (e.g. W > 1.6 GeV)

Quasi-elastic axial mass puzzle

How do we define „quasi-elastic” reaction?

The name refers to the free target CC processes:

$$\nu + n \to l^- + p$$

$$\bar{\nu} + p \to l^+ + n$$

But typically, the reaction occurs on nucleus targets:

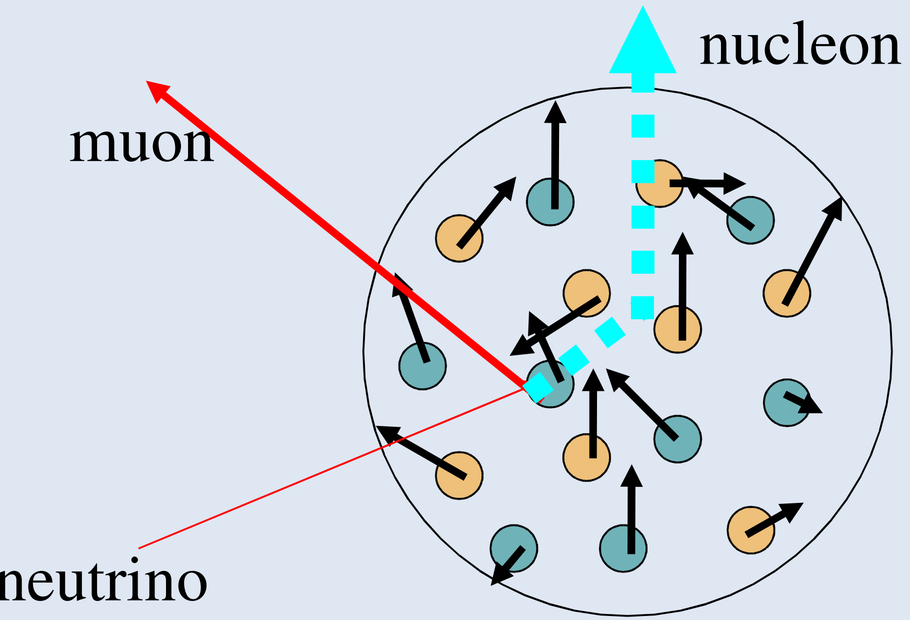
$$\nu + {}^{A}_{Z}X \to l^- + p + {}^{A-1}_{Z}X$$

Quasi-elastic axial mass puzzle

We assume *factorization*, every interaction is a two-step process:

• a *primary interaction* on a quasi-free nucleon

• *final state interactions* affecting only hadrons, here viewed as a unitary transformation in the space of final hadronic states



We define „quasi-elastic" events as coming from the quasi-elastic primary interaction.

But keep in mind that experimentalists observe only final states!

Quasi-elastic axial mass puzzle

$$\nu + n \rightarrow l^- + p$$

$$\bar{\nu} + p \rightarrow l^+ + n$$

$$\Gamma_\mu = \gamma_\mu F_1(Q^2) + i\sigma_{\mu\nu} q^\nu \frac{F_2(Q^2)}{2M} + \gamma_\mu \gamma_5 F_A(Q^2) + \gamma_5 q_\mu \frac{F_P(Q^2)}{M}$$

F1 and F2 are determined by isospin symmetry, electromagnetic data is used

For the axial part the PCAC hypothesis is used to fix Fp

$$F_P(Q^2) = \frac{2M^2 F_A(Q^2)}{m_\pi^2 + Q^2}$$

We still need FA: the dipole form is assumed

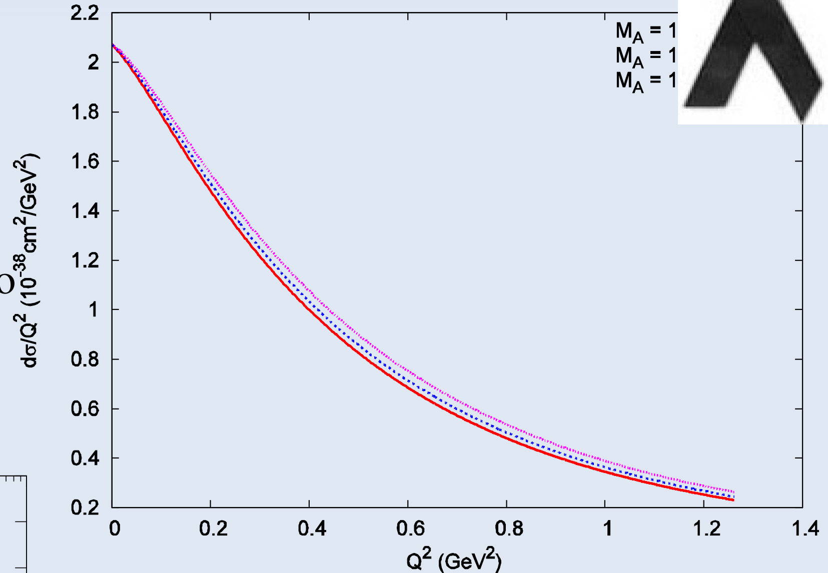
$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

g_A = 1.26 from the beta decay,
M_A a free parameter (the only one!)

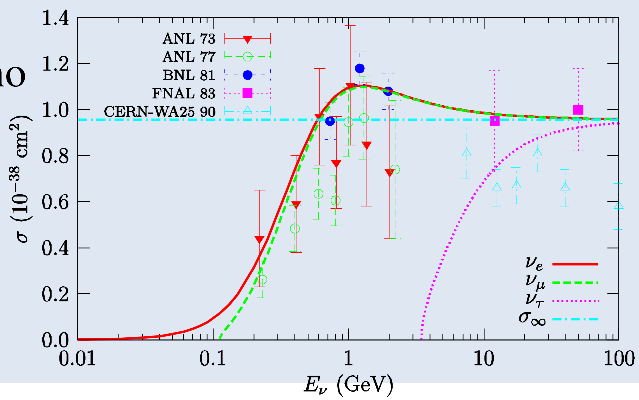
Quasi-elastic axial mass puzzle

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

Axial mass determines **the shape** of differential cross section in Q2 and also **the total cross section**.



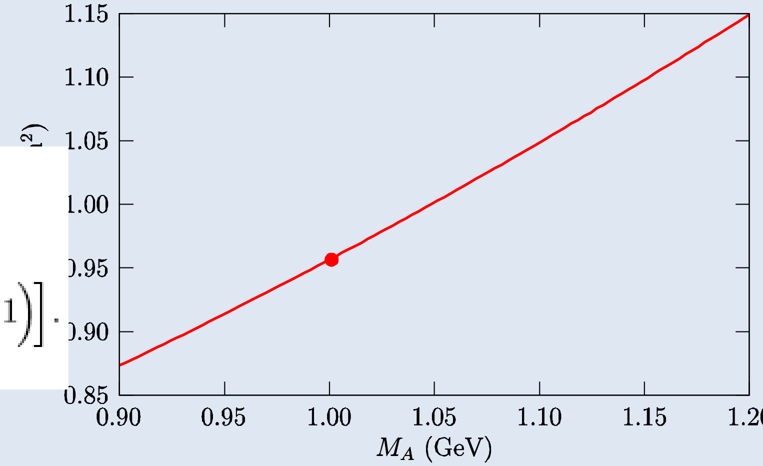
The limiting value of the cross section at large neutrino energy under assumption of dipole vector form factors:



$$\sigma_\infty = \frac{G_F^2 \cos^2\theta_C}{6\pi}\Big[M_V^2 + g_A^2 M_A^2 + \frac{2\xi(\xi+2)M_V^4}{(4M^2 - M_V^2)^2}(M^2 - M_V^2) + \frac{3\xi(\xi+2)M_V^8}{(4M^2-M_V^2)^3}\left(\frac{4M^2}{4M^2-M_V^2}\ln\frac{4M^2}{M_V^2} - 1\right)\Big].$$

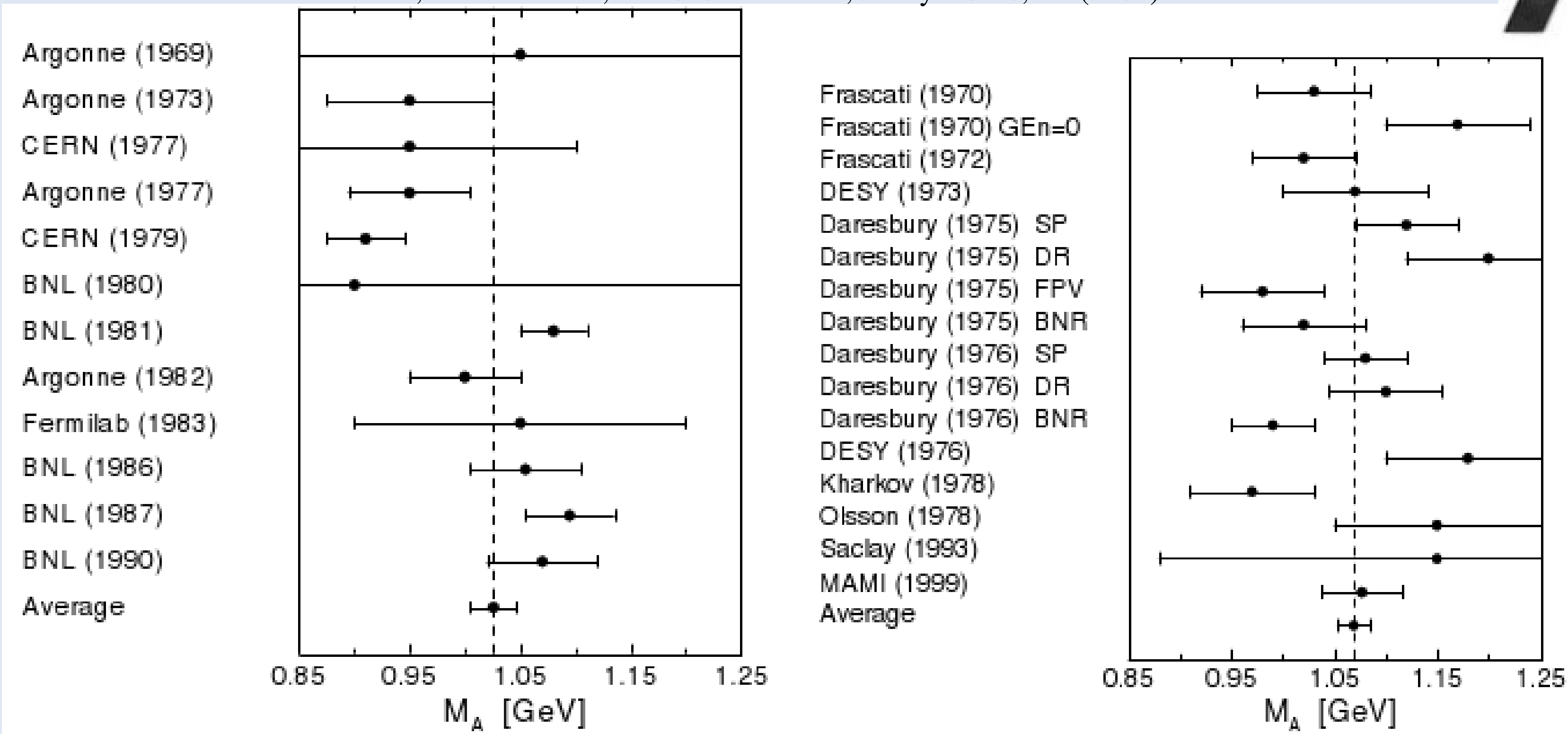
(A. Ankowski, Acta Phys. Pol. B37 (2005) 377)

1e-38cm2



Quasi-elastic axial mass puzzle

V. Bernard, L. Elouadrhiri, and U.G. Meissner, J. Phys. G 28, R1 (2002)



Neutrino experiments:
MA=1.026±0.021

Charged pion electroproduction (via PCAC!):
MA=1.069± 0.016 GeV
but ... there are corrections to be calculated within chiral perturbation theory.

Quasi-elastic axial mass puzzle

Most recent neutrino data:

TABLE 1. Modern determinations of M_A determined from shape fits to neutrino QE data assuming the FG model. Note: the K2K and MiniBooNE data were collected at lower neutrino energies than the MINOS and NOMAD samples.

experiment	M_A (GeV)	target	fit range
K2K	1.20 ± 0.12 [4]	^{16}O	$Q^2 > 0.2$ GeV^2
K2K	1.14 ± 0.11 [5]	^{12}C	$Q^2 > 0.2$ GeV^2
MiniBooNE (2009)	1.27 ± 0.14 [6]	^{12}C	$Q^2 > 0.25$ GeV^2
MiniBooNE (2009)	1.35 ± 0.17, $\kappa = 1.007 \pm 0.007$ [6]	^{12}C	$Q^2 > 0$ GeV^2
MINOS	1.26 ± 0.17 [7]	^{56}Fe	$Q^2 > 0.3$ GeV^2
MINOS	1.19 ± 0.17, p_F scale= 1.28 [7]	^{56}Fe	$Q^2 > 0$ GeV^2
NOMAD	1.07 ± 0.07 [8, 9]	^{12}C	$Q^2 > 0$ GeV^2

SciBooNE → „consistent with MA=1.21" (within Neut MC)

If the value of axial mass in increased from 1.03 to 1.23, the expected number of QE events is raised by ~20% !

Quasi-elastic axial mass puzzle

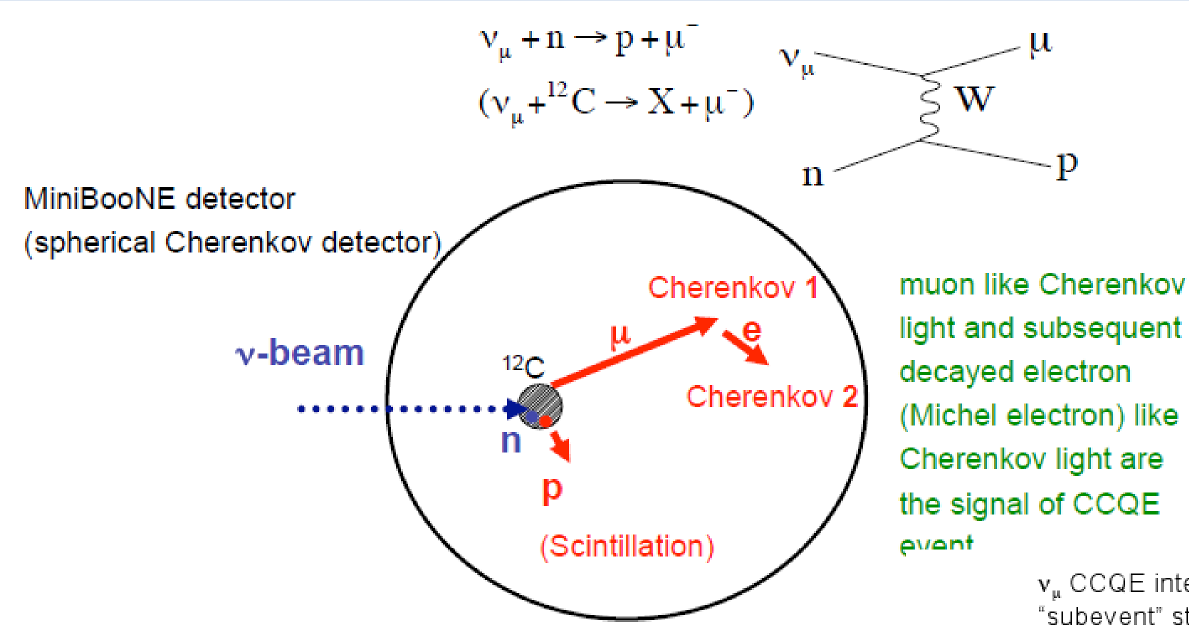
Possible explanations:

- statistical fluctuations (after all the discrepancy is on the 2σ level)

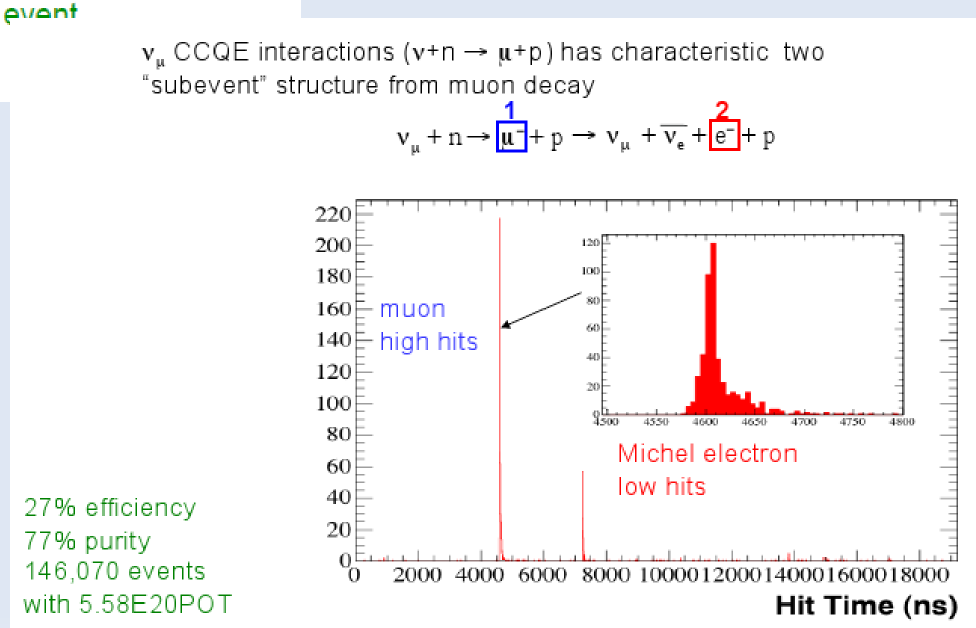
- MiniBooNE overestimates the beam (the claim is that it is know with uncertainty of 10.7%; but all the cross sections reported by MB are very large – see later)

- something goes wrong in the data analysis...

Quasi-elastic axial mass puzzle



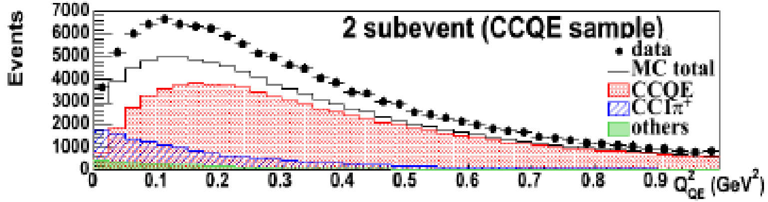
MiniBooNE collaboration tried to made the analysis independent on the models implemented in the Monte Carlo generator (Nuance).



(from Teppei Katori)

Quasi-elastic axial mass puzzle

The background is dominated with CC1π without pion (CCQE-like). We need a background prediction with an absolute scale.



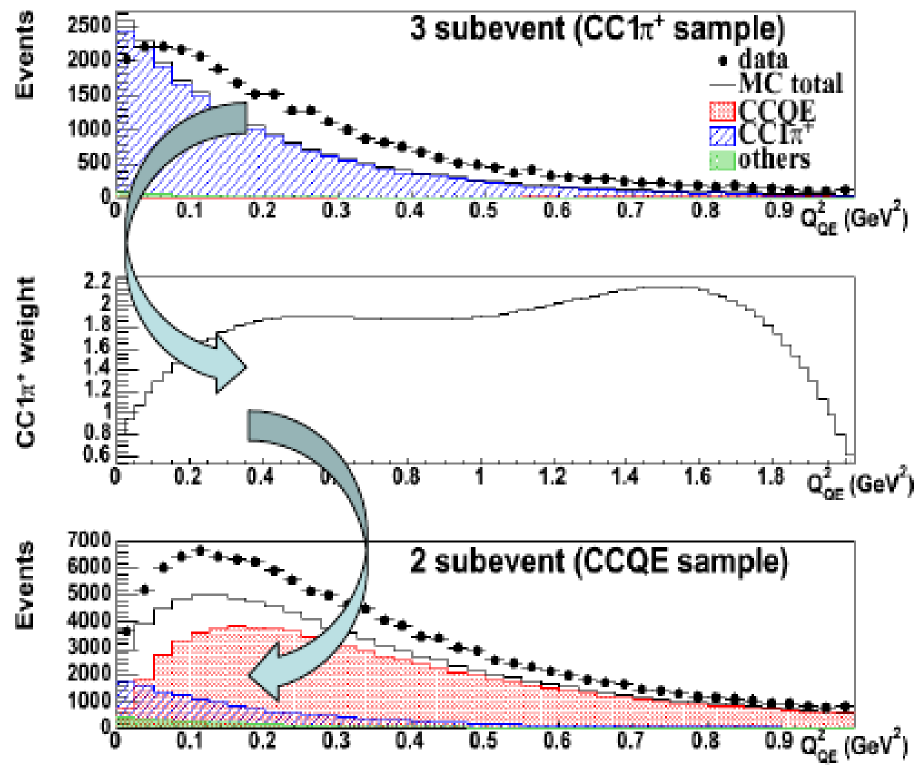
(from Teppei Katori)

Solution

Use data-MC Q^2 ratio in CC1π sample to correct all CC1π events in MC.

Then, this "new" MC is used to predicts CC1π background in CCQE sample

This correction gives both CC1π background normalization and shape in CCQE sample



Background subtraction is essentially MC independent !

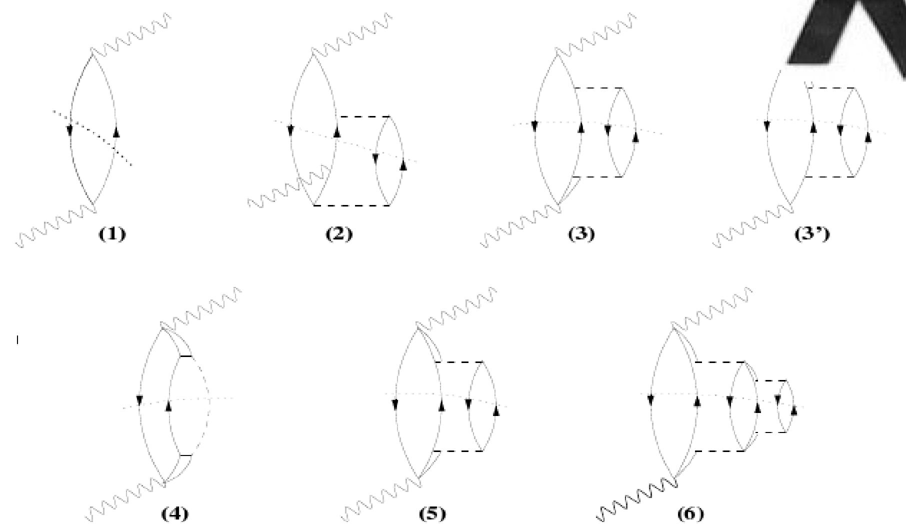
Quasi-elastic axial mass puzzle

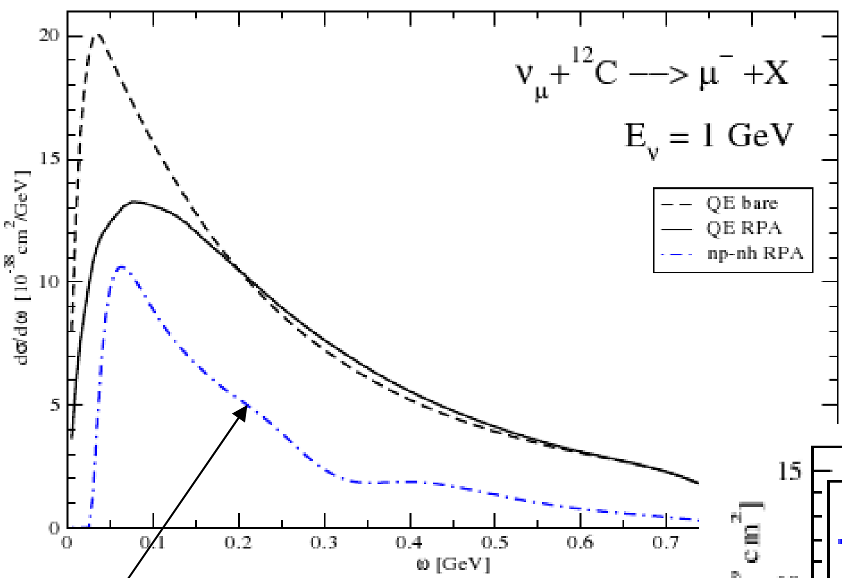
Possible explanations:

- statistical fluctuations (after all the discrepancy is on the 2σ level)
- MiniBooNE overestimates the beam (the claim is that it is know with uncertainty of 10.7%; but all the cross sections reported by MB are very large)
- something is wrong in the data analysis...
- large 2p-2h contribution ?!

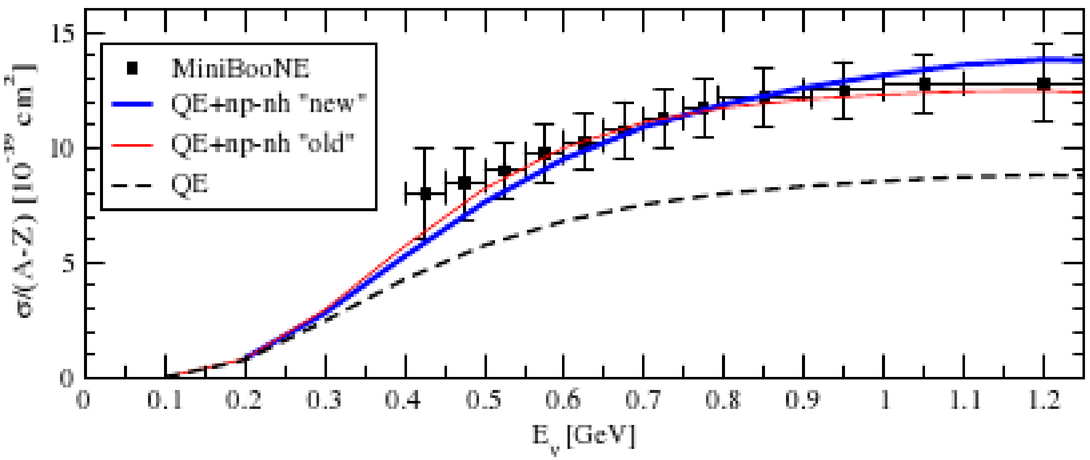
Quasi-elastic axial mass puzzle

Martini-Marteau model
(many body RPA computations)





(M.Martini, M.Ericson, G.Chanfray, J. Marteau, arXiv: 0910.2622 [nucl-th])



new contribution claimed
to be disregarded in „standard”
computations

Quasi-elastic axial mass puzzle

Martini-Marteau model
(many body RPA computations)

Test: antineutrinos!
The effect is expected to be smaller.

$$R_\tau = \sum_n \langle n| \sum_{j=1}^{A} \tau(j) e^{i\,\boldsymbol{q}\cdot\boldsymbol{x}_j} |0\rangle \times \langle n| \sum_{k=1}^{A} \tau(k) e^{i\,\boldsymbol{q}\cdot\boldsymbol{x}_k} |0\rangle^* \, \delta(\omega - E_n + E_0).$$

$$\tau_j^{\pm}, \quad (\boldsymbol{\sigma}_j . \widehat{q})\, \tau_j^{\pm}, \quad (\boldsymbol{\sigma}_j \times \widehat{q})^i\, \tau_j^{\pm},$$

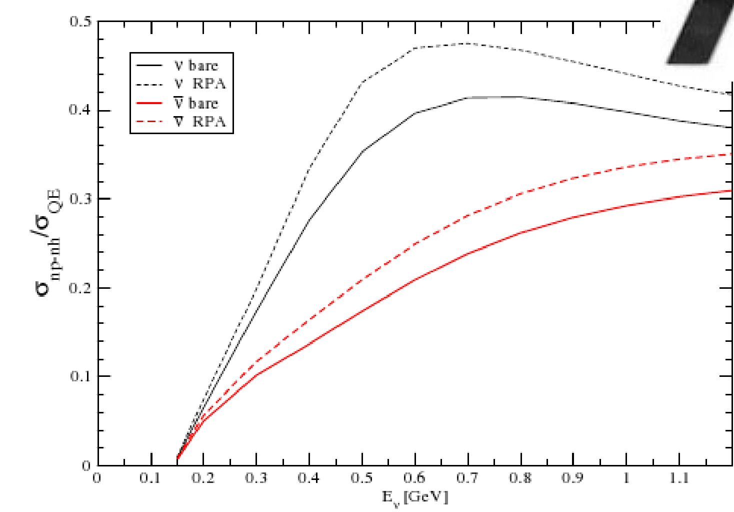


FIG. 6: Ratio of multinucleon component of "quasielastic" cross section on ^{12}C to the single nucleon one for ν_μ and $\bar{\nu}_\mu$ as a function of neutrino energy.

(M.Martini, M.Ericson, G.Chanfray, J. Marteau, arXiv: 1002.4538 [hep-ph])

	ν			$\bar{\nu}$		
	[redacted]	np-nh	QE+np-n[redacted]	[redacted]	np-nh	QE+np-nh
ba[redacted]	[redacted]	2.77	[redacted]	[redacted]	[redacted].52	[redacted]
RPA	6.40	2.73	[redacted]	1.60	0.47	[redacted]

TABLE I: MiniBooNE flux-integrated CC ν_μ-^{12}C and $\bar{\nu}_\mu$-^{12}C total cross sections per neutron and per proton respectively in unit of 10^{-39} cm^2. The experimental CCQE ν_μ-^{12}C value measured by MiniBooNE is 9.429×10^{-39} cm^2 with a total normalization error of 10.7 % [10].

Quasi-elastic axial mass puzzle

MiniBooNE provided double differential cross section data which is very useful in more detail discussions

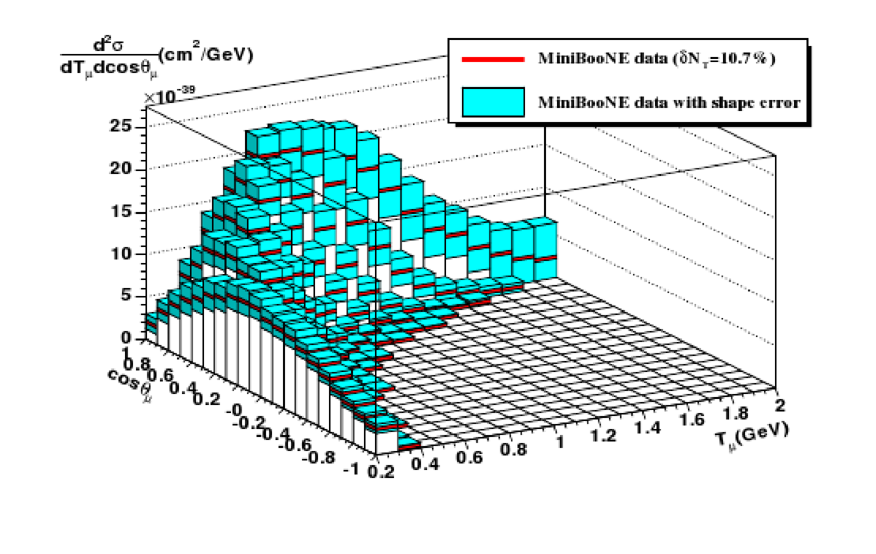
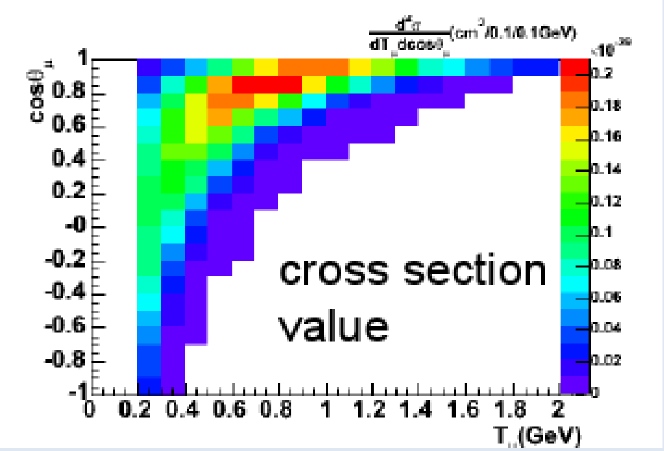


FIG. 13: (Color online). Flux-integrated double differential cross section per target neutron for the ν_μ CCQE process. The dark bars indicate the measured values and the surrounding lighter bands show the shape error. The overall normalization (scale) error is 10.7%. Numerical values are provided in Table VI in the Appendix.

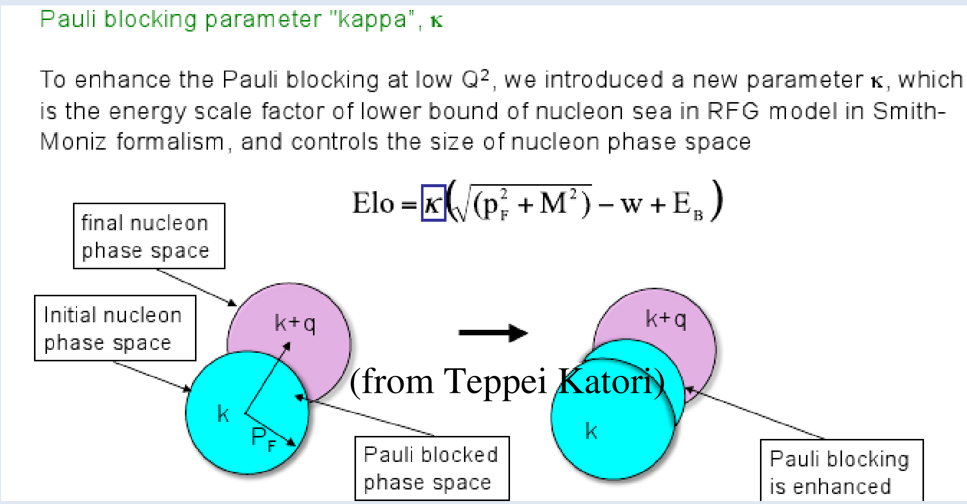
arXiv: 1002.2680 [hep-ex], to be published in Phys. Rev.



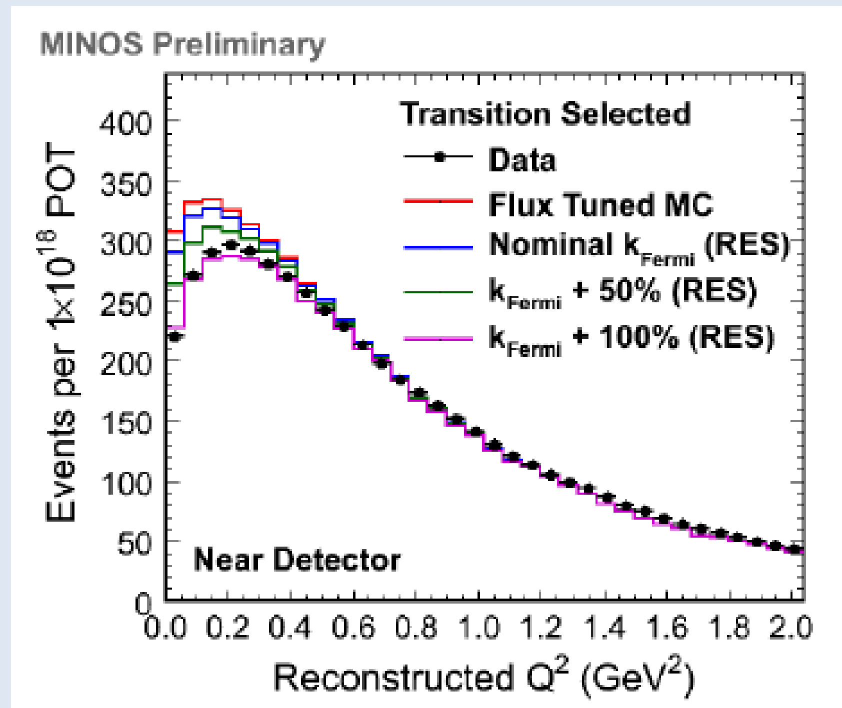
It is important to confront with Martini's double differential cross section !

Quasi-elastic low Q2 problem

MiniBooNE and Minos introduced *ad hoc* parameters to correct for low Q2 behavior.



(from Teppei Katori)



How well do we understand the flux?

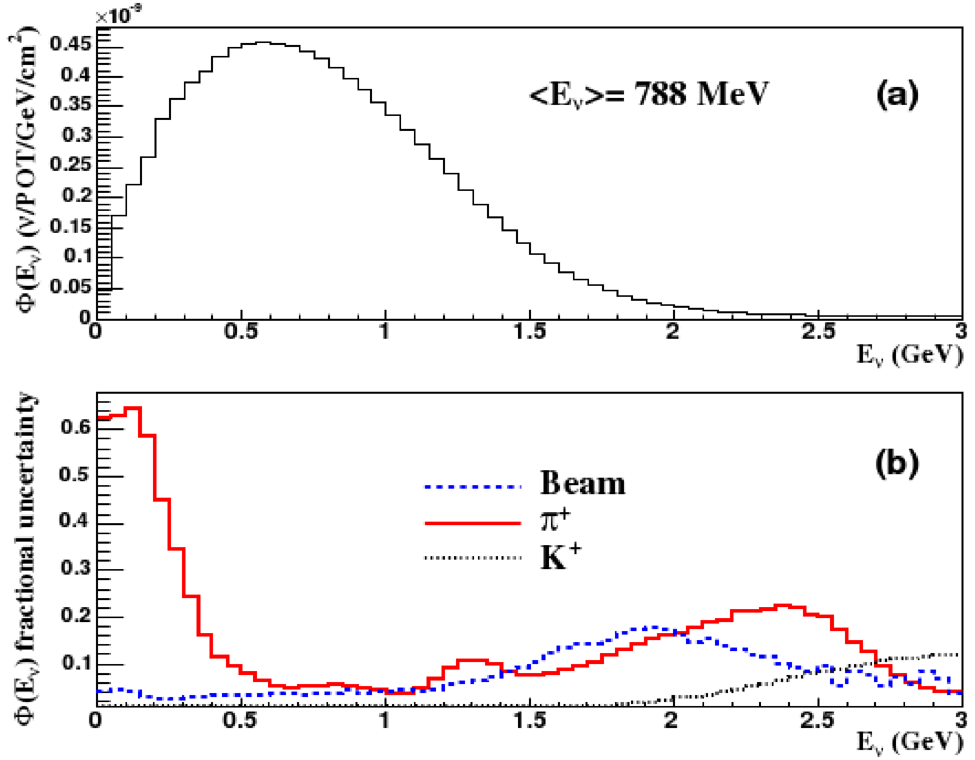


FIG. 2: (color online) Predicted ν_μ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is 5.16×10^{-10} ν_μ/POT/cm^2 ($0 < E_\nu < 3$ GeV) with a mean energy of 788 MeV. Numerical values corresponding to the top plot are provided in Table V in the Appendix.

Coherent pion production

Reaction is (nucleus X remains in the ground state):

$$\nu + {}^{A}_{Z}X \rightarrow l^{-} + \pi^{+} + {}^{A}_{Z}X$$

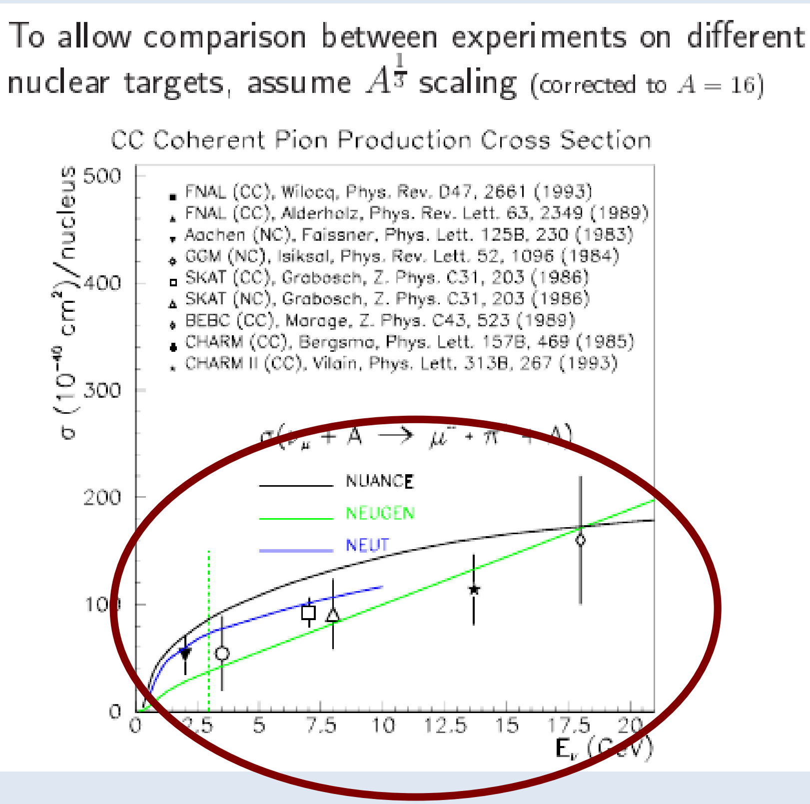
$$\nu + {}^{A}_{Z}X \rightarrow \nu + \pi^{0} + {}^{A}_{Z}X$$

This is a small fraction of the overall single pion production cross section, but there has been recently a lot of experimental and theoretical activity.

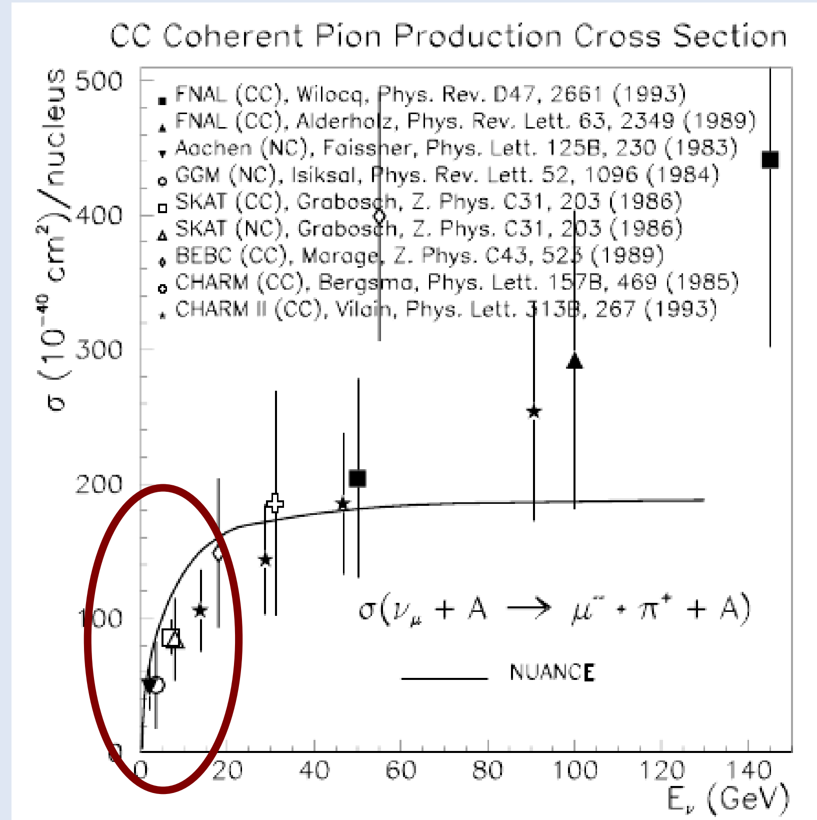
(dominant mechanism for pion production is via resonance excitation)

Coherent pion production

Well established at higher neutrino energies:



(from Sam Zeller, NuInt02)



$$\sigma_{NC}(\mathrm{coh}) = 1/2\, \sigma_{CC}(\mathrm{coh})$$

$$\sigma^{\nu}(\mathrm{coh}) = \sigma^{\overline{\nu}}(\mathrm{coh})$$

All the data are put together !

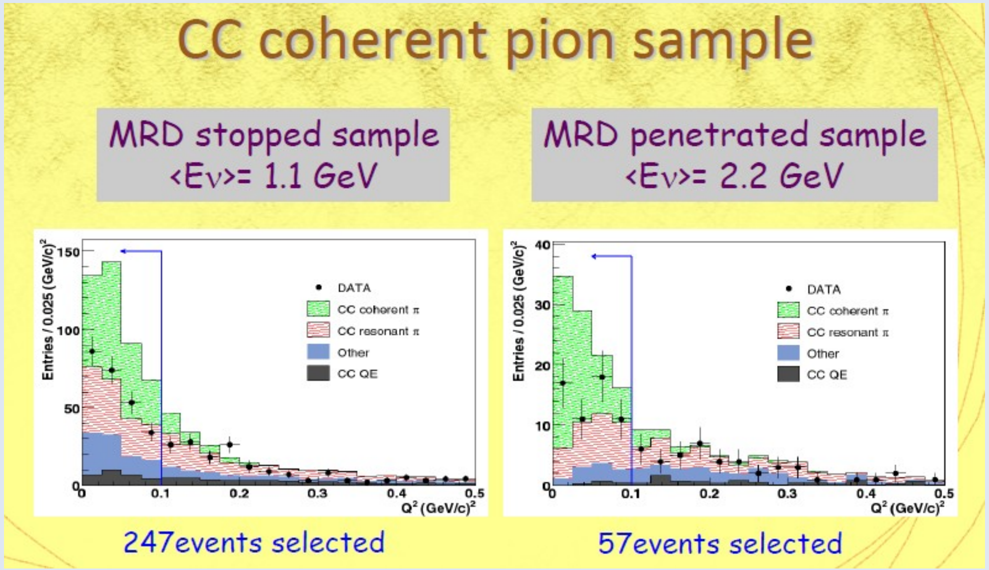
Coherent pion production

Experimentally the situation with low(~ 1 GeV) energy coherent pion production is little puzzling:

- for NC reaction K2K and MiniBooNE reported a nonzero coherent contribution to the cross section
- for CC reaction K2K and SciBooNE reported no coherent signal

After imposing suitable cuts:

- QE rejection
- RES rejection (forward going pions are kept)



(from K. Hiraide)

Coherent pion production

SciBooNE's conclusions:

MRD stopped sample
<Eν>= 1.1 GeV

$$\sigma(\text{CC coherent } \pi)/\sigma(\text{CC}) = (0.16 \pm 0.17(stat)^{+0.30}_{-0.27}(sys)) \times 10^{-2}$$

MRD penetrated sample
<Eν>= 2.2 GeV

$$\sigma(\text{CC coherent } \pi)/\sigma(\text{CC}) = (0.68 \pm 0.32(stat)^{+0.39}_{-0.25}(sys)) \times 10^{-2}$$

No evidence of CC coherent pion production is found

90% CL upper limit (Bayesian)

σ(CC coherent π)/σ(CC) $< 0.67\times10^{-2}$ for <Eν>=1.1 GeV

$< 1.36\times10^{-2}$ <Eν>=2.2 GeV

K. Hiraide et al, PRD78,112004 (2008)

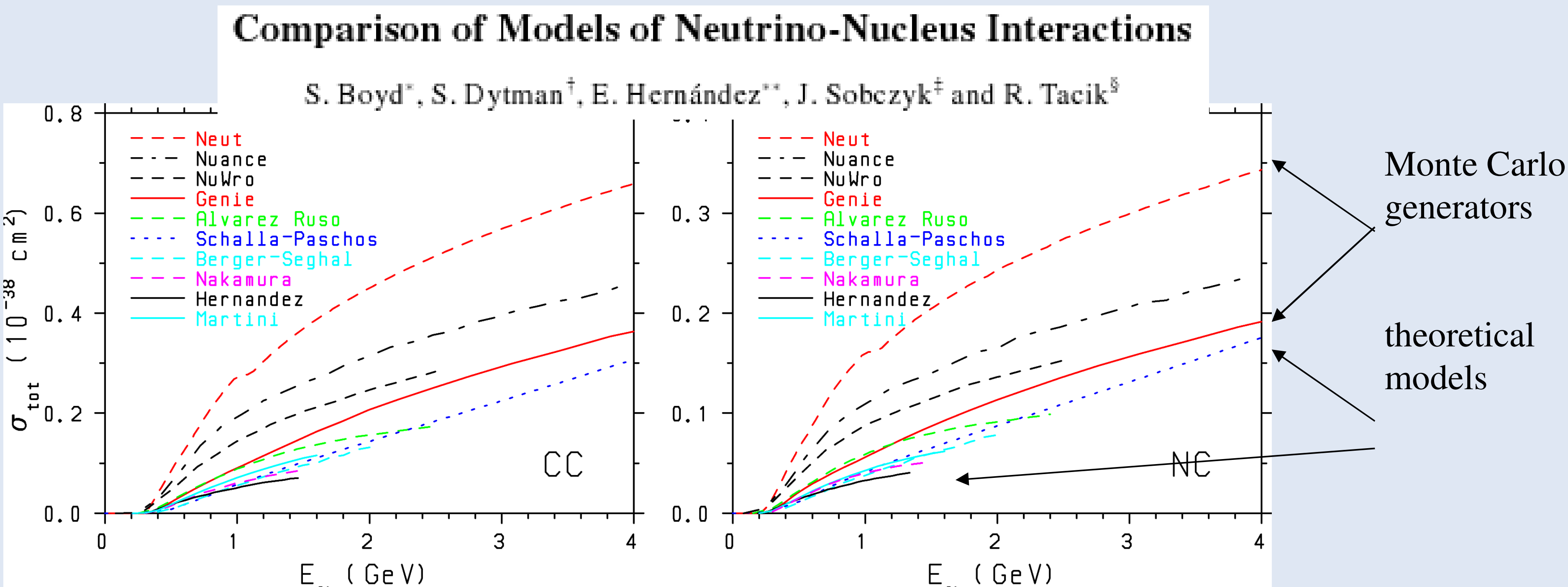
(from K. Hiraide)

The COH signal refers to what is expected from MC...

Coherent pion production

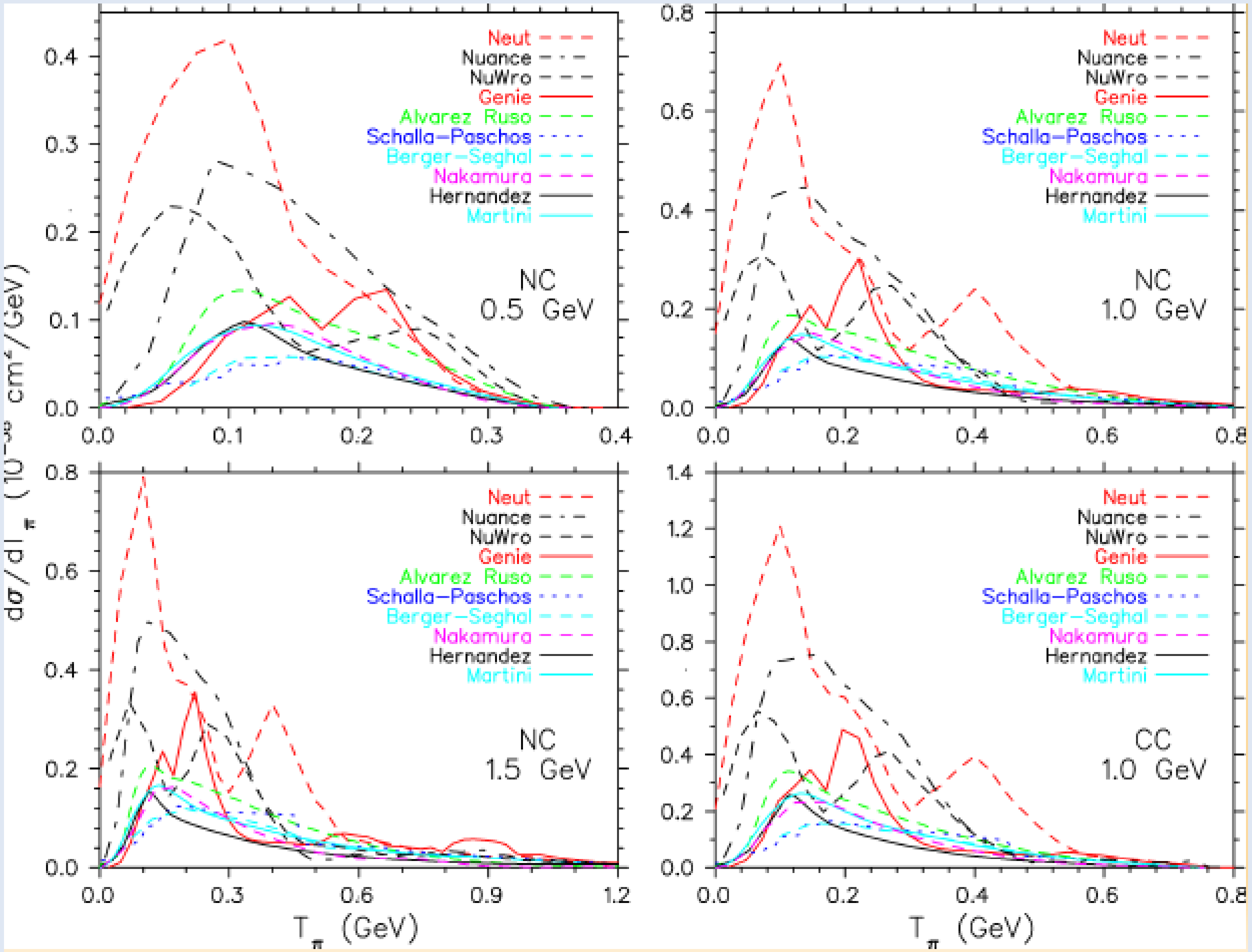
Current MC describe coherent pion production using the Rein-Sehgal model. They (we!) all claim to use the same model...

The few plots below come from the comparison project done for the last year NuInt09.



Jan T. Sobczyk, Warszawa, 15 kwietnia 2010

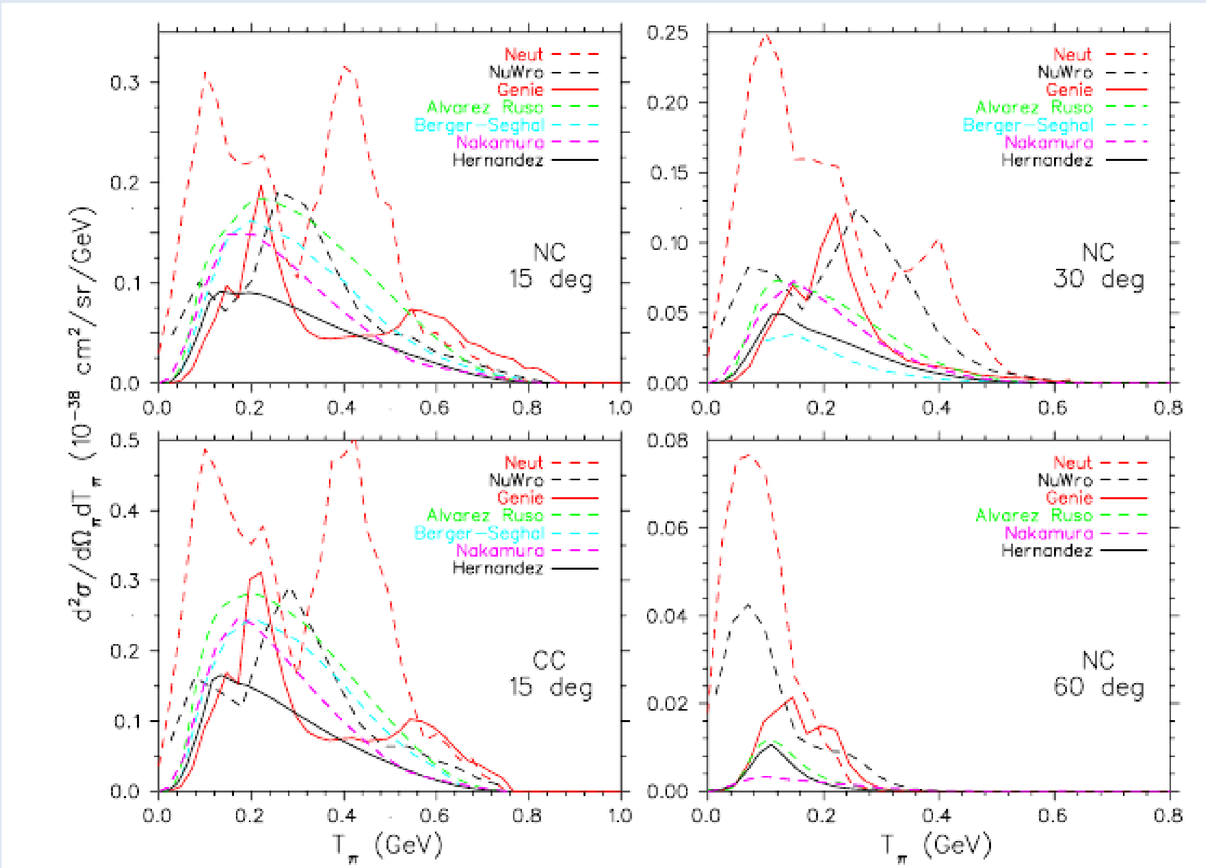
Coherent pion production



Predictions for distributions of pions kinetic energy.

Monte Carlo's produce a lot of structure not seen in modern theoretical computations!

Coherent pion production



Double differential cross sections at fixed pion production angle.

Neutrino energy is always 1 GeV.

Coherent pion production

There are three main theoretical approaches:

- PCAC relates neutrino coherent process to elastic pion-nucleus scattering
- microscopic computations with Δ resonance
- Martini-Marteau model, RPA many body computations
 to cover both quasi-elastic and Δ excitation.

Coherent pion production

Rein&Sehgal founded their model on the Adler's PCAC based theorem relating

$\nu + |\alpha> \rightarrow l^- + |\beta>$ and $\pi + |\alpha> \rightarrow |\beta>$

$$q_\mu q^\mu \rightarrow 0 \Longrightarrow |M(\nu + |\alpha> \rightarrow l^- + |\beta>)|^2 =$$

$$= 16 G^2 \cos^2\theta_c f_\pi^2 \frac{E_\nu E_l}{(E_\nu - E_l)^2} |M(\pi + |\alpha> \rightarrow |\beta>)|^2$$

It is enough to choose: $|\alpha> = {}^A_Z X \quad \wedge \quad |\beta> = \pi + {}^A_Z X$

and coherent pion production becomes related to elastic pion-nucleus scattering!

Further improvements and clarifications:

- a form-factor to extrapolate to nonzero Q2
- lepton mass corrections (Berger & Sehgal)
- kinematics
- precise pion-nucleus elastic scattering data

NC1Pi0

Motivation: dangerous background in the electron neutrino appearance measurement in SK. Needs good theoretical control.

There are 4 **different** (but not *completely* independent) measurements:

Beams: K2K, MiniBooNE neutrinos, MiniBooNE antineutrinos

Targets: $H_2O,\ CH_2,\ C_8H_8 \left(\textit{different ratios of carbon to hydrogen} \right)$

Events: NC1Pi0 with FSI, NCPi0 with some (?) cuts (SciBooNE)

Cross section: normalized (MiniBooNE),
ratio NC1Pi0/CC (K2K, SciBooNE).

NC1Pi0

K2K: Nakayama et al, PLB619 (2005) 255

Definition:
1Pi0 &&
no other
pions

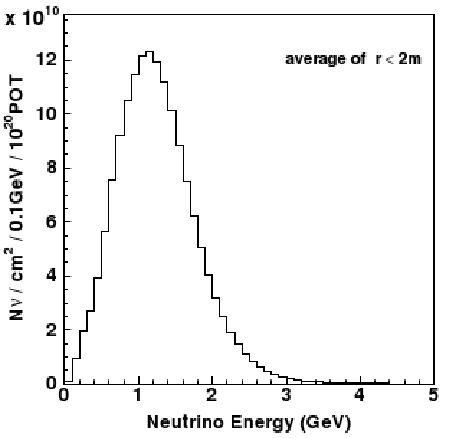
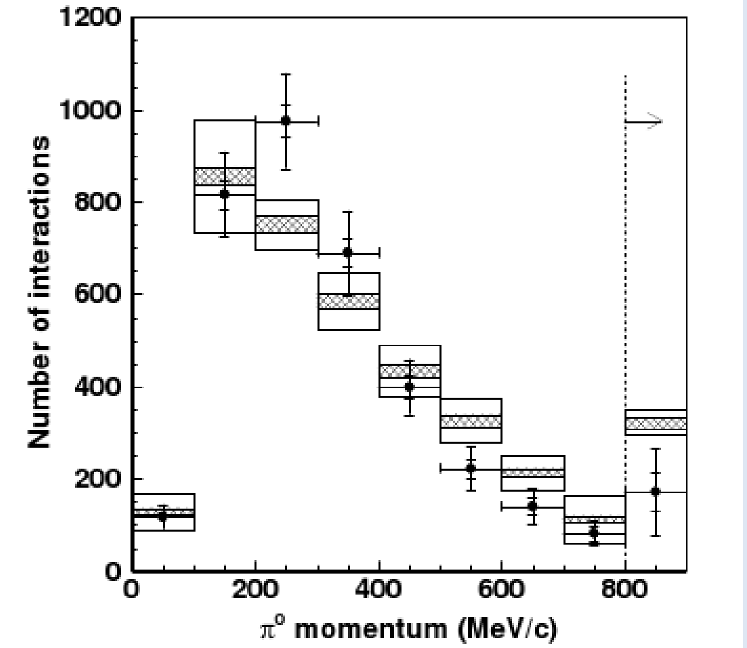


FIG. 1: The energy spectrum of the K2K neutrino beam at 300 m downstream from the target in the near site with a 10^{20} protons on target exposure predicted by a neutrino beam simulation. The spectrum is averaged within 2 m from the beam center.



By taking the ratio, the relative cross section for NC1π^0 interactions to the total ν_μCC cross section is measured to be $0.064 \pm 0.001\,(stat.) \pm 0.007\,(sys.)$.

Target: H_2O

NC1Pi0

MiniBooNE (and SciBooNE) beams:

Neutrino mode

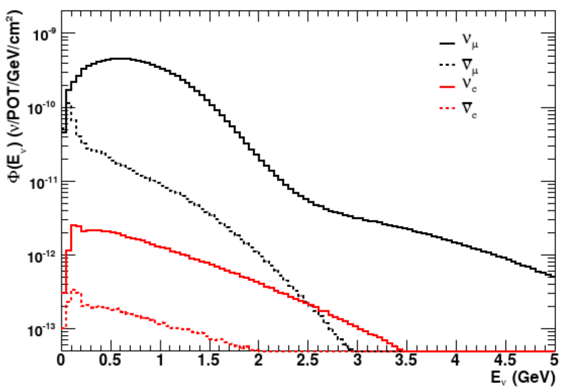


FIG. 27: Total predicted flux at the MiniBooNE detector by neutrino species with horn in neutrino mode.

Antineutrino mode

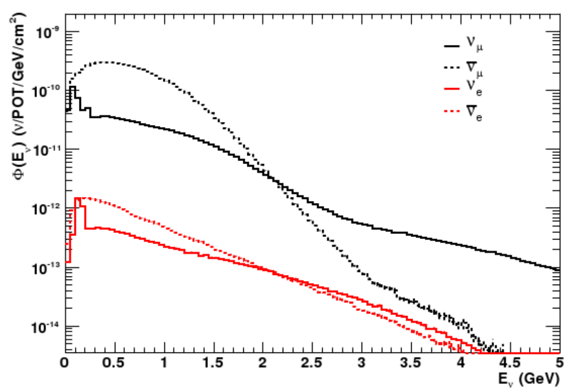


FIG. 28: Total predicted flux at the MiniBooNE detector by neutrino species with horn in anti-neutrino mode.

NC1Pi0

MiniBooNE:
Phys. Rev. D81 (2010) 013005

scattering. We define signal NC $1\pi^0$ events to be NC interactions wherein only one π^0 and no additional meson exits the target nucleus (no requirement on the number or identity of outgoing nucleons is made). This definition is consistent with that used at K2K[22]. It is specifically

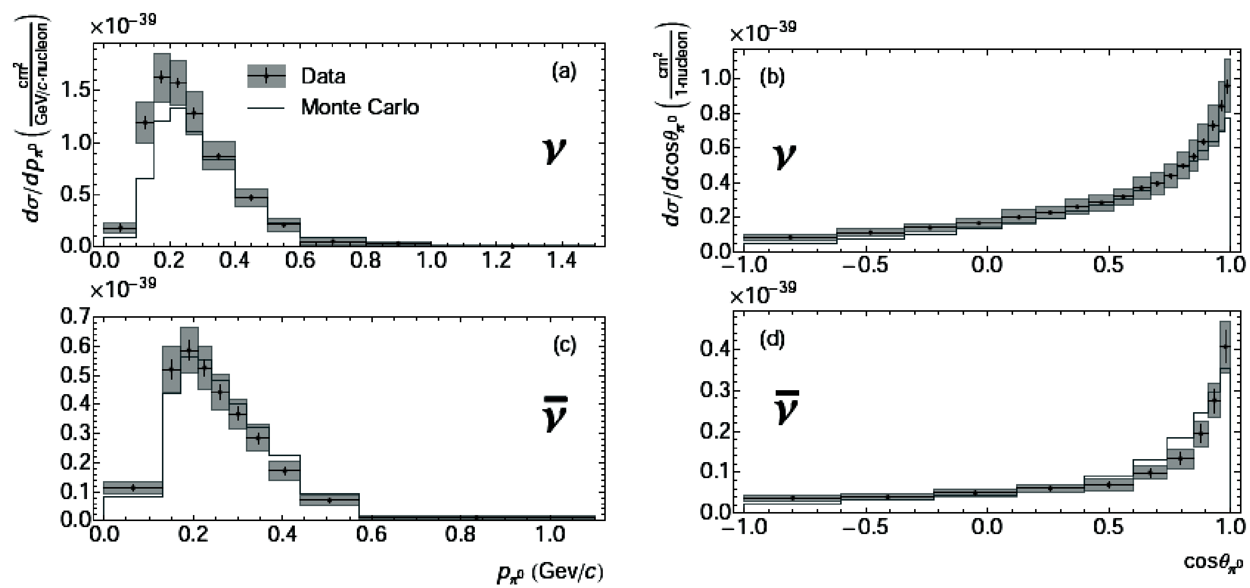


FIG. 7: Flux-averaged absolute differential cross sections for NC $1\pi^0$ production on CH_2 including the effects of FSI. Data are shown as black dots with statistical error bars and systematic error boxes. The dark-gray line is the Monte Carlo prediction[26] using R-S models of single pion production[2, 5] modified as described in the text. (a) $\frac{d\sigma}{dp_{\pi^0}}$ for ν_μ-induced production. (b) $\frac{d\sigma}{d\cos\theta_{\pi^0}}$ for ν_μ-induced production. (c) $\frac{d\sigma}{dp_{\pi^0}}$ for $\bar{\nu}_\mu$-induced production. (d) $\frac{d\sigma}{d\cos\theta_{\pi^0}}$ for $\bar{\nu}_\mu$-induced production. The numerical values for the cross sections appear in Appendix C and are also available at the MiniBooNE website[36].

target: CH_2

NC1Pi0

SciBooNE:

Phys. Rev. D81 (2010) 033004

neutrino beam on a polystyrene target (C_8H_8). We obtain $(7.7 \pm 0.5(\text{stat.}) \pm 0.5(\text{sys.})) \times 10^{-2}$ as the ratio of the neutral current neutral pion production to total charged current cross section; the

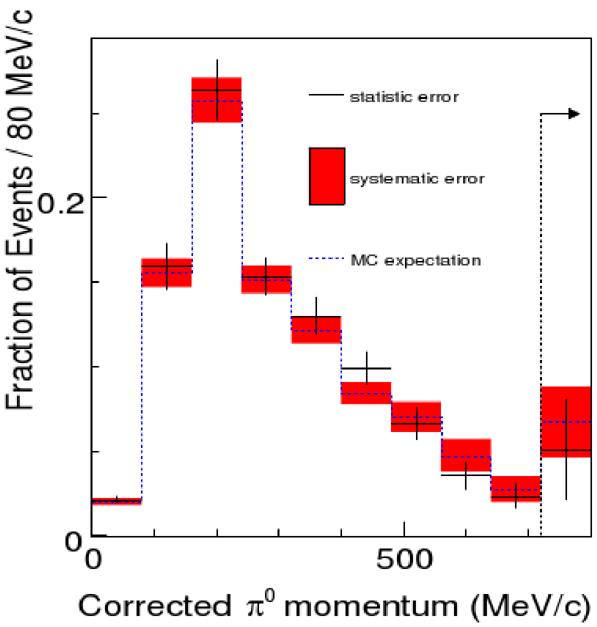


FIG. 21: The π^0 momentum distribution after all corrections described in the text, with statistical (error bars) and systematic (red boxes) uncertainties. The dashed line shows the Monte Carlo expectation based on the Rein and Sehgal model.

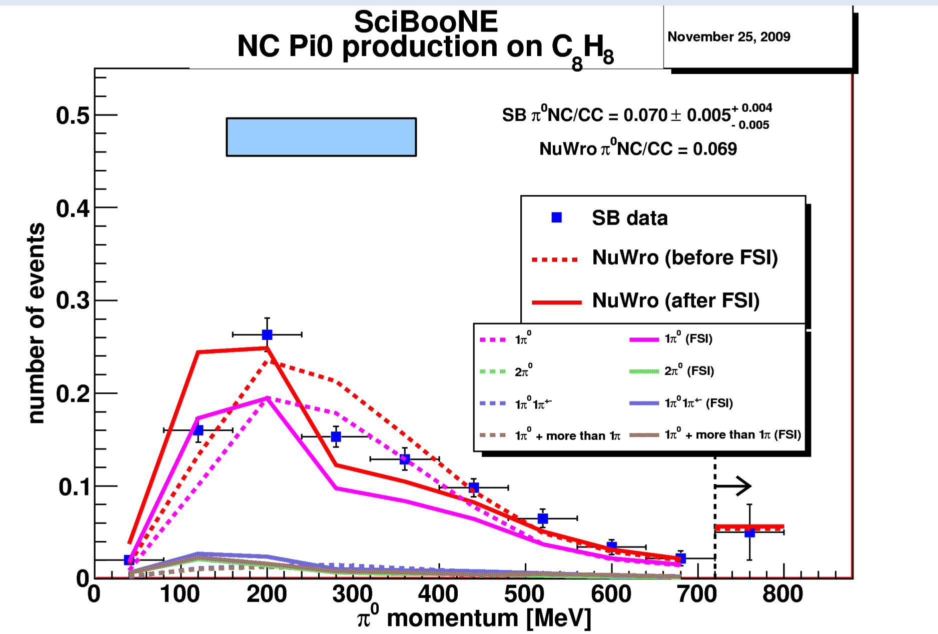
We define an NCπ^0 interaction as an NC neutrino interaction in which at least one π^0 is emitted in the final state from the target nucleus, $\nu_\mu C \to \nu_\mu \pi^0 X$ where X represents the nuclear remnant and any combination of nucleons and mesons. According to our MC simulation,

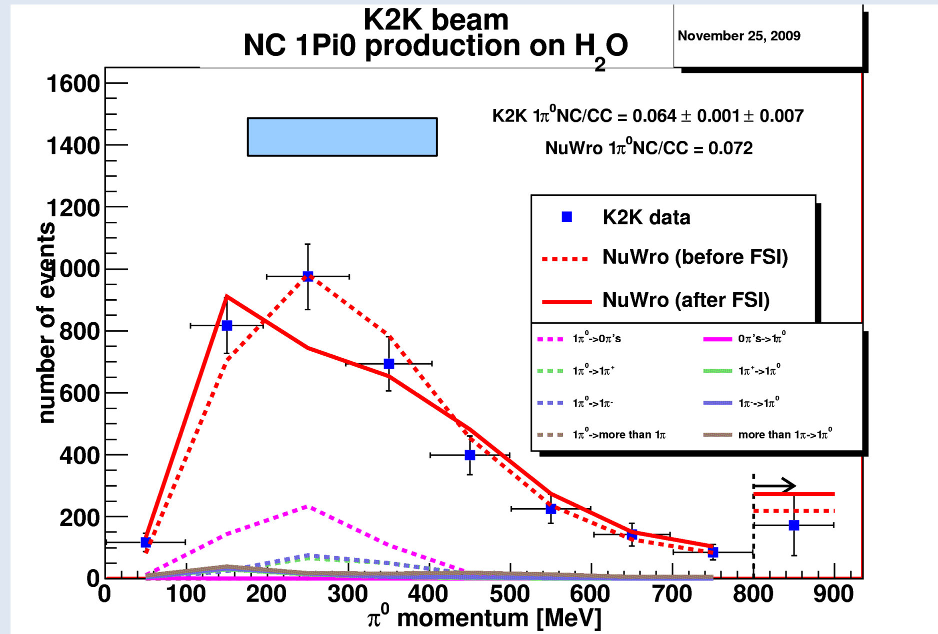
target: C_8H_8

NC 1 Pi0 production

The data presents a challenge to Monte Carlo generators of events.
FSI effects like pion absorption and „formation zone" are important.

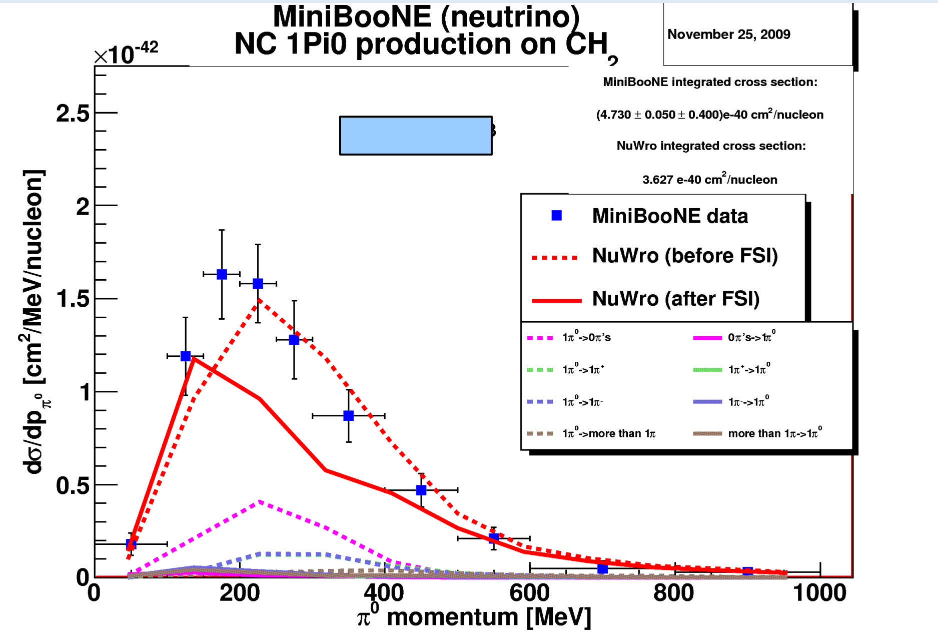
I show predictions from NuWro MC generator of events.

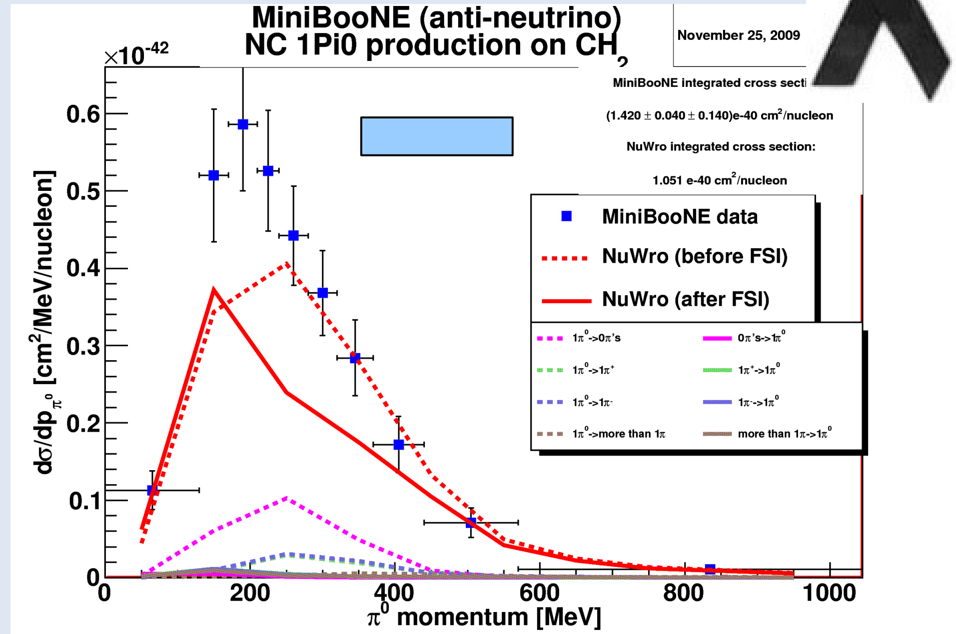


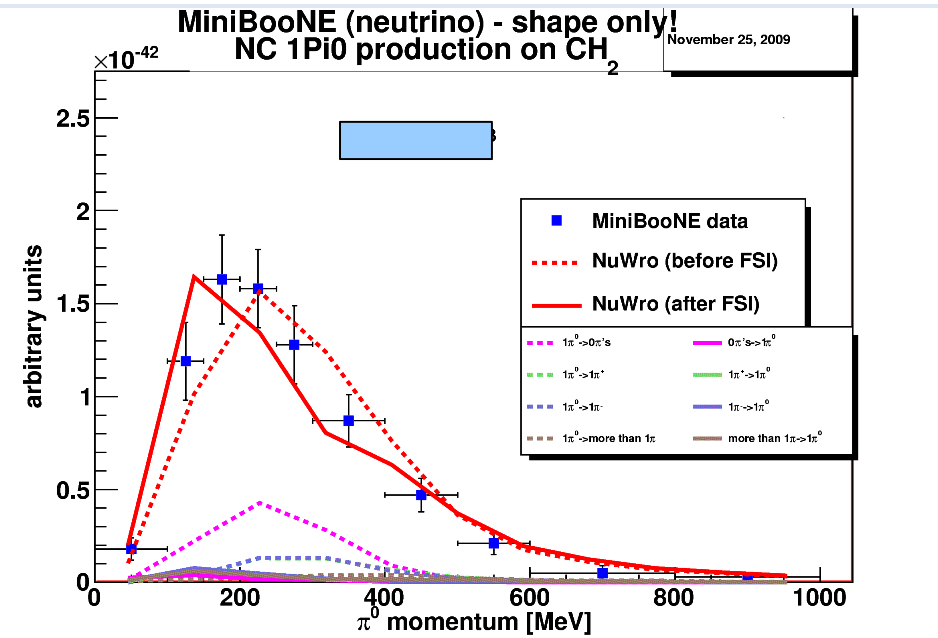


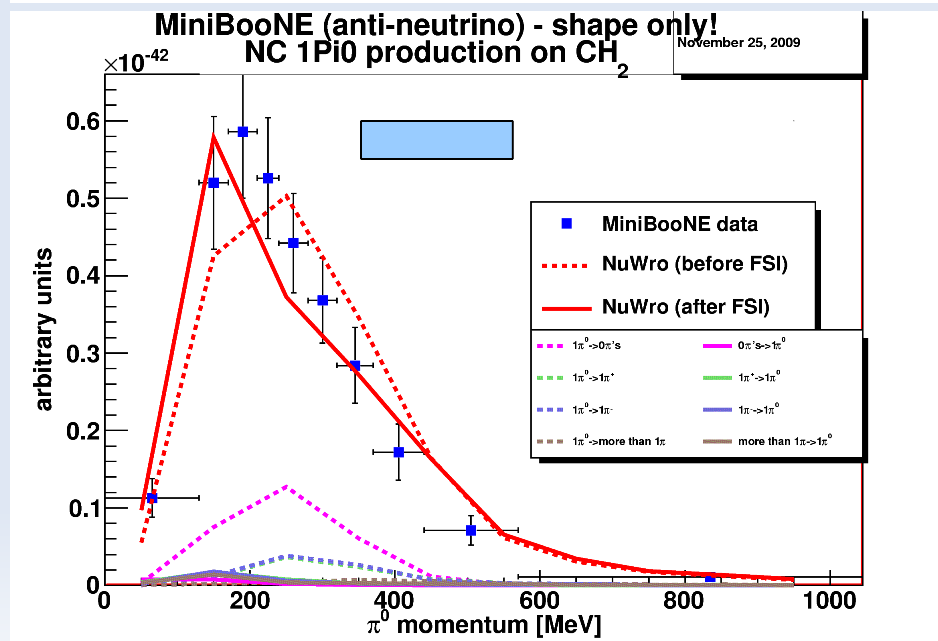
Jan T. Sobczyk, Warszawa, 15 kwietnia 2010

NC 1 Pi0 production



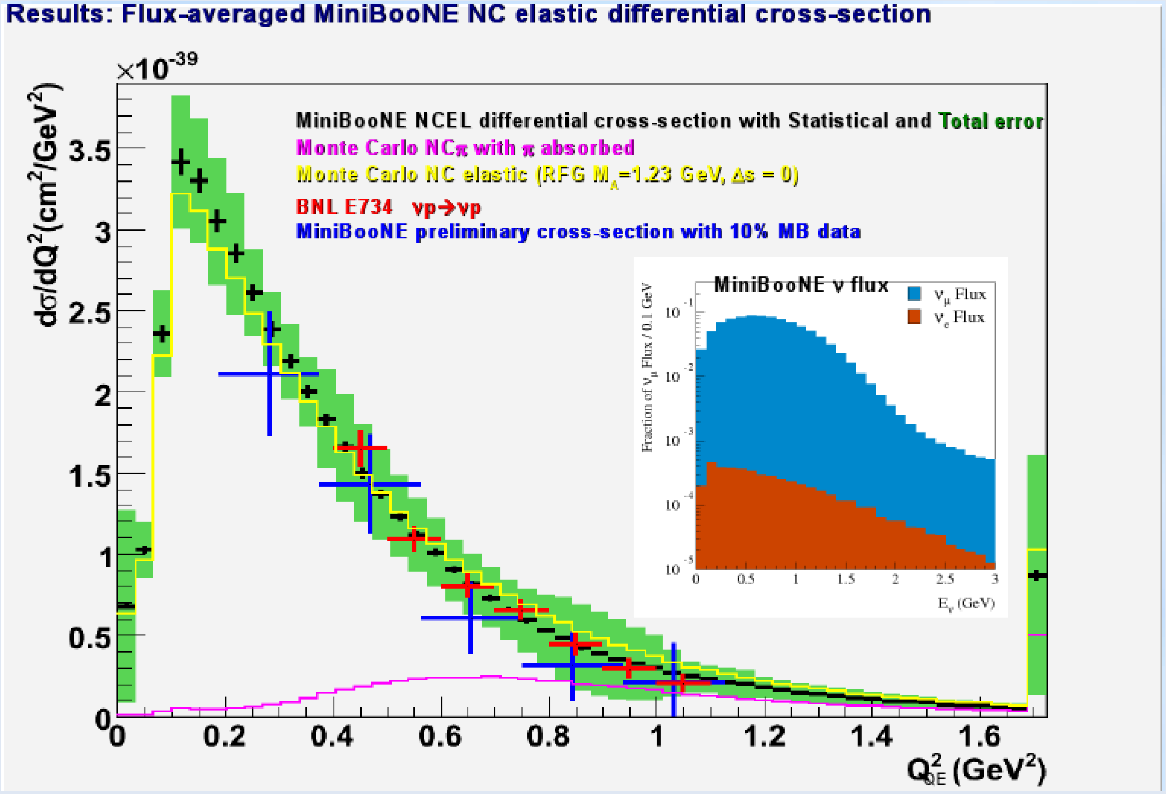






Other measurements

Neutral current elastic cross section

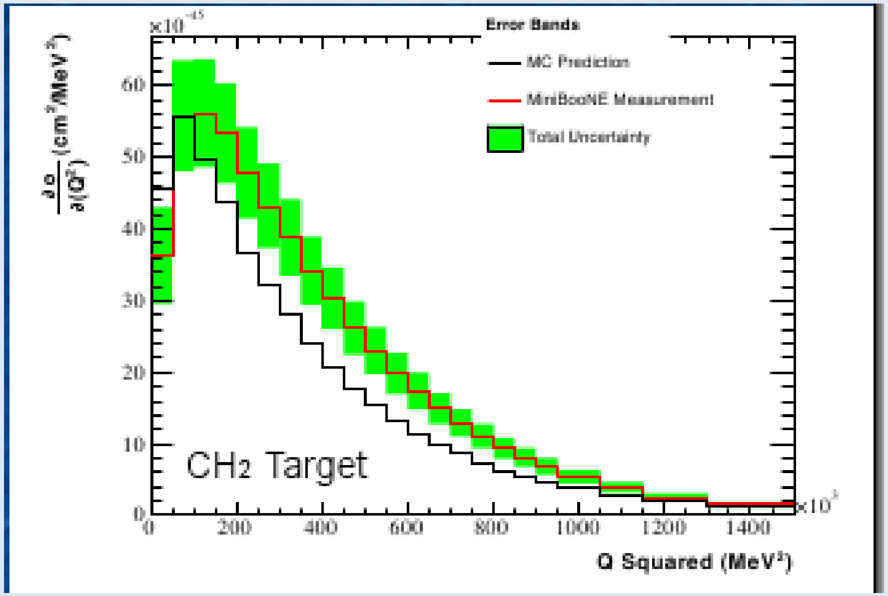


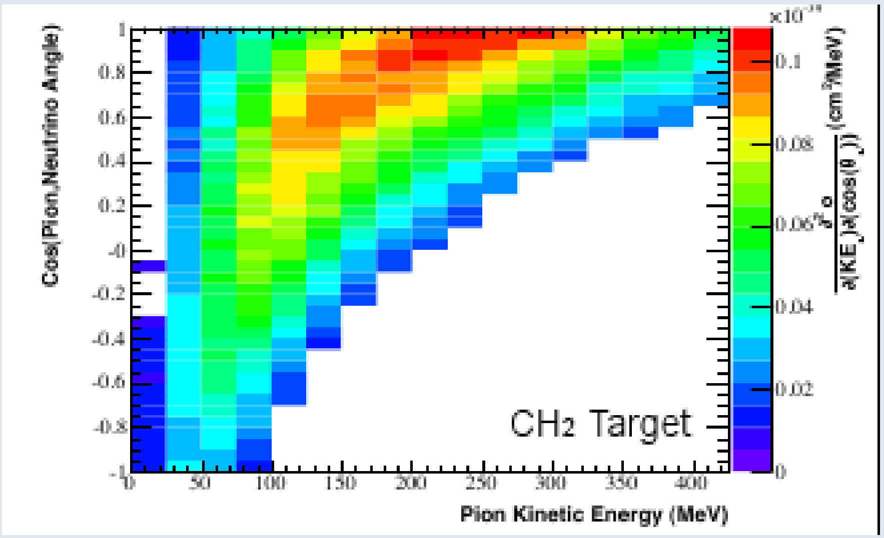
MiniBooNE measures both Cerenkov and scintillation light !

(from D. Perevalov)

Other measurements

Charge current Pi+ production (MiniBooNE)





(from M. Wilking)

Note that the measured cross section is much larger then MC predictions !

Other measurements

Ratio CC1Pi+/CCQE (MiniBooNE)

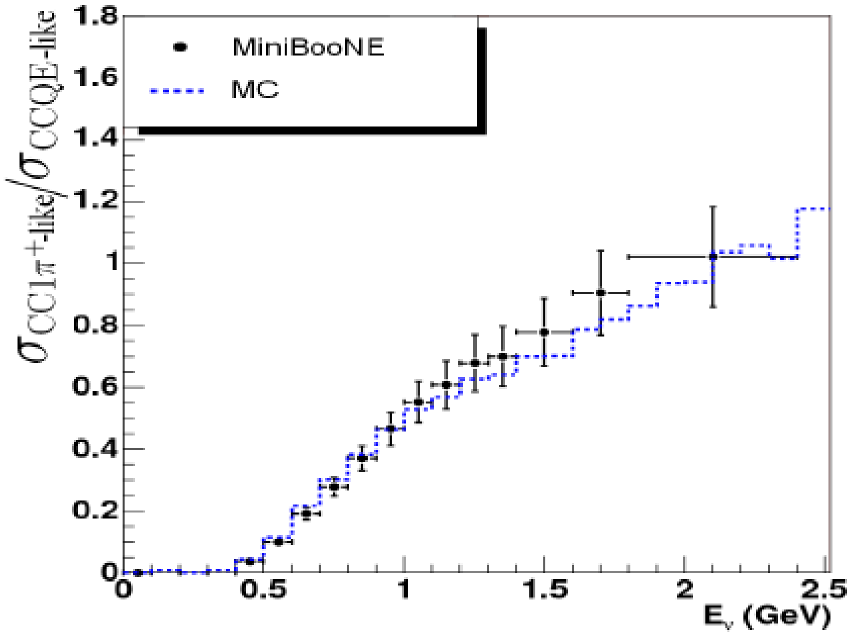


FIG. 1: Observed CC1π^+-like/CCQE-like cross section ratio on CH_2, including both statistical and systematic uncertainties, compared with the MC prediction [6]. The data have not been corrected for hadronic re-interactions.

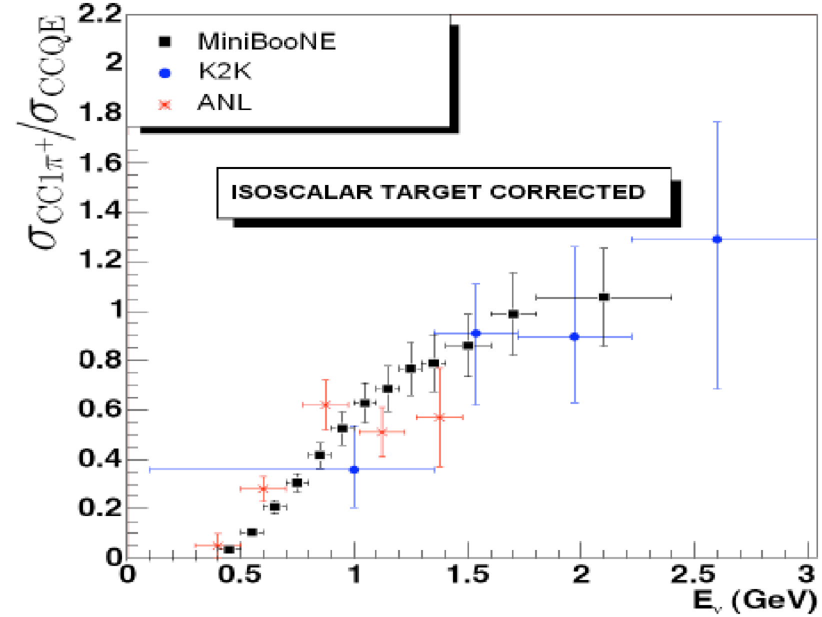


FIG. 2: FSI-corrected CC1π^+ to CCQE cross section ratio on CH_2 compared with results from ANL (D_2) [1] and K2K (C_8H_8) [3]. The data have been corrected for final state interactions and re-scaled for an isoscalar target.

The results are very useful and widely used in comparisons because they are free from normalization controversy.

Monte Carlo generators

The market of MCs:

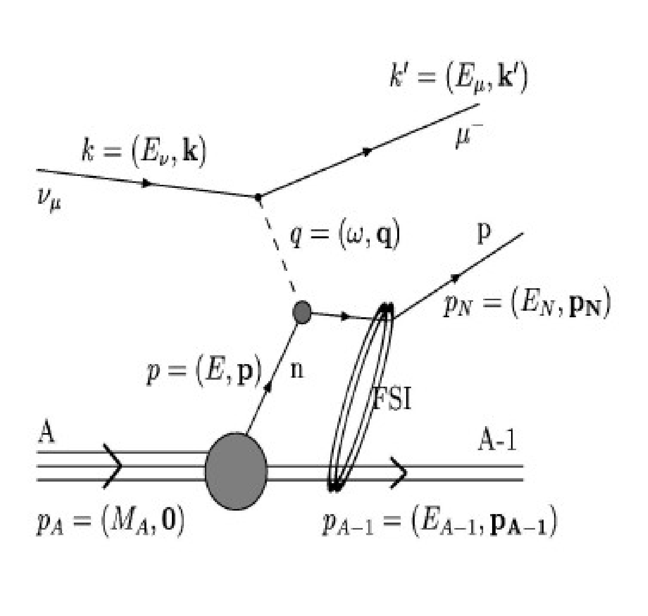
Neut (K2K, SciBooNE, T2K)
Nuance (SK, Minos, MiniBooNE)
GENIE/Neugen (Minos, Minerva, T2K, Nova)
FLUKA (ICARUS)

Tools developed by theorists:

GiBUU
NuWro

It takes years to construct a MC and to test it.

Impulse approximation



(from Ch. Maieron, XX Max Born Symposium)

- neutrino interacts with an individual (bound) nucleons
- followed by „final state interactions" (FSI);

understood as:

a) only redistribution of the cross-section into exclusive final states (MCs)
b) a modification of the inclusive cross section

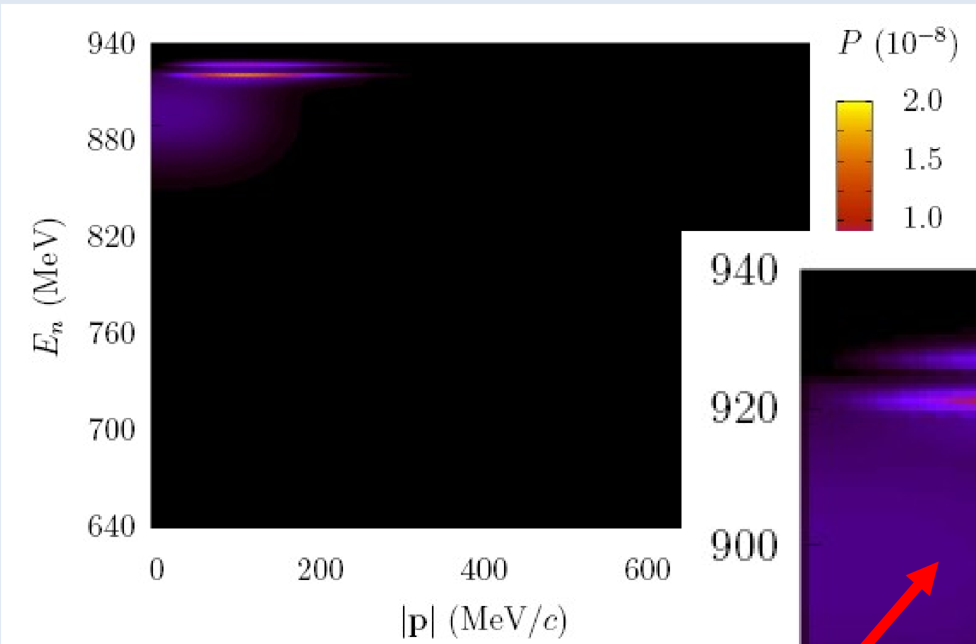
The simplest realization:
Fermi gas model with 2 free parameters:
Fermi momentum and binding energy.

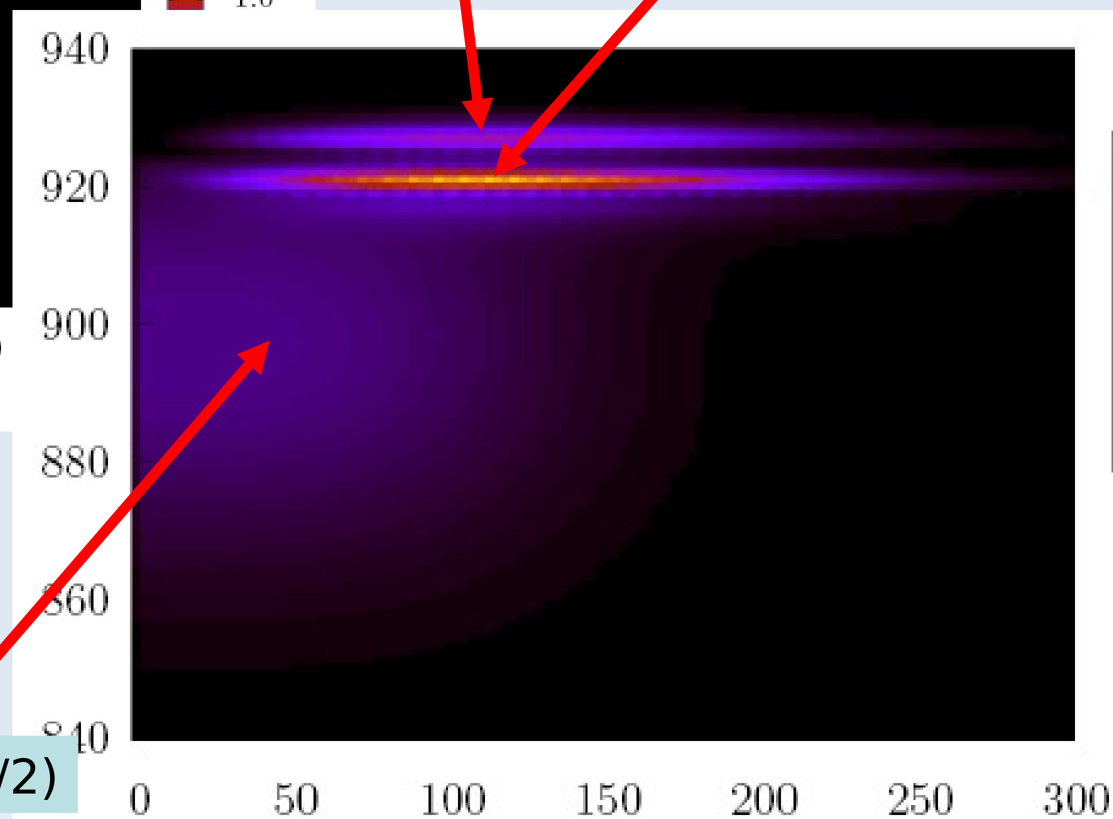
More realistic model: **spectral function**

Spectral function

	$1s_{1/2}$	$1p_{3/2}$	$1p_{1/2}$
E	45	18.44	12.11

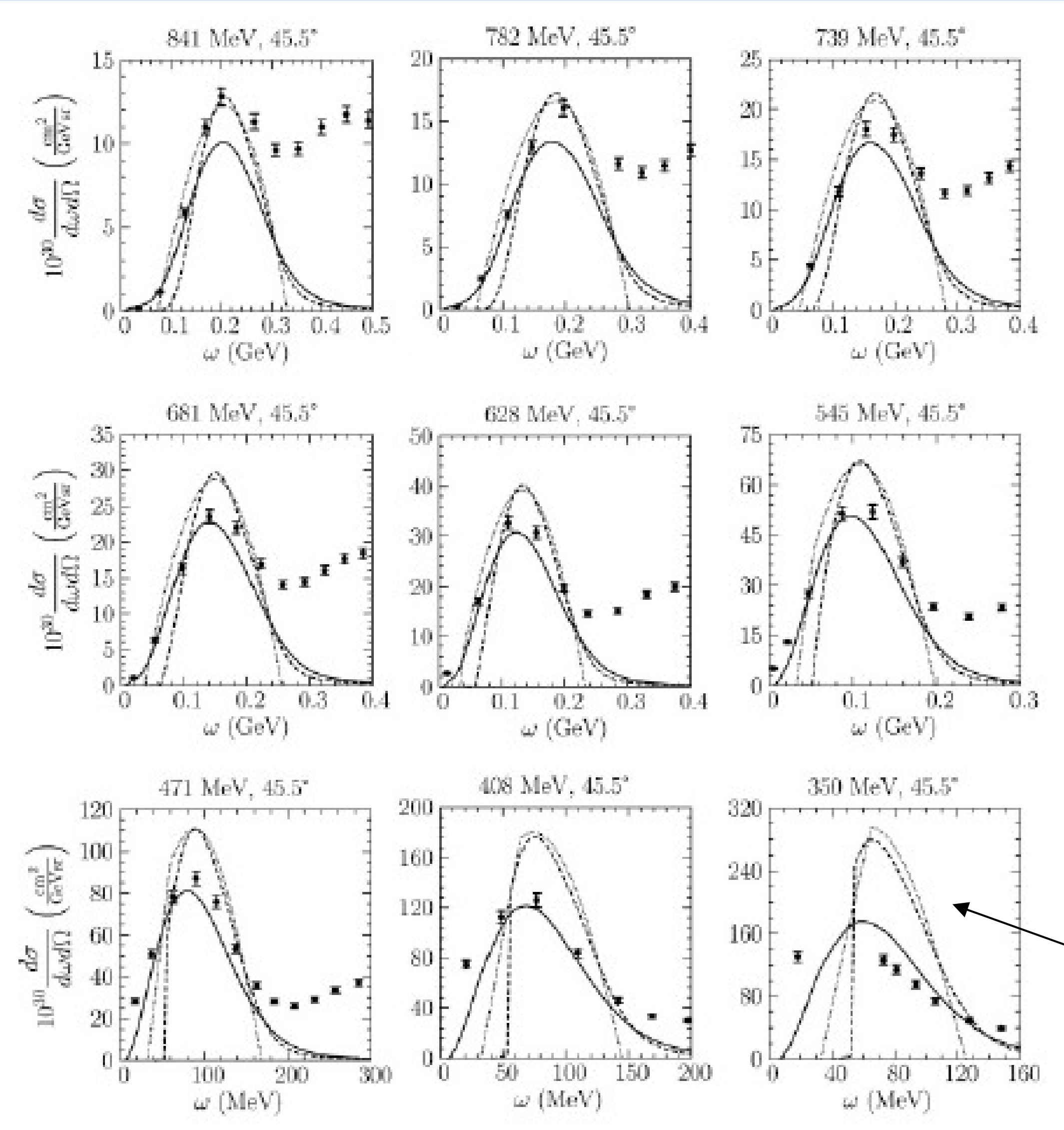
ectral function for oxygen





Spectral function approach is parameter free.
But FSI/Pauli blocking effects should be added.

Spectral function



Calcium (Ca40) target:

solid line → the hole spectral function from the paper Ankowski, JTS, PRD77 (2008) 044311 (with FSI effects included)
dashed line → Butkevich, Mikheyev model
dotted line → Fermi gas model

Note that theoretical model do not include Δ excitation dynamics.

Data is for the inclusive cross section!

momentum transfer at the peak is 250 MeV !

Implementation

It was done by Cezary Juszczak based on Artur Ankowski code (verified to produce identical results).

References

- A. Ankowski, J. Sobczyk, Argon Spectral Function and Neutrino Interactions, Phys. Rev. C74, 054316-1-10 (2006)
- A.M. Ankowski, J.T. Sobczyk Construction of spectral functions for medium-mass nuclei, Phys. Rev. C 77, 044311, 2008.

(we follow closely Omar Benhar approach)

Energy reconstruction

The standard energy reconstruction formula:

$$E_{rec} = \frac{E'(M-B) + \frac{1}{2}\left(B^2 - 2MB + m^2\right)}{M - B - E' + k'\cos\theta}$$

E' and k' are muon energy and momentum, M and m are nucleon and muoon masses, B is the binding energy; θ is the angle between incident neutrino's and muon's momenta.

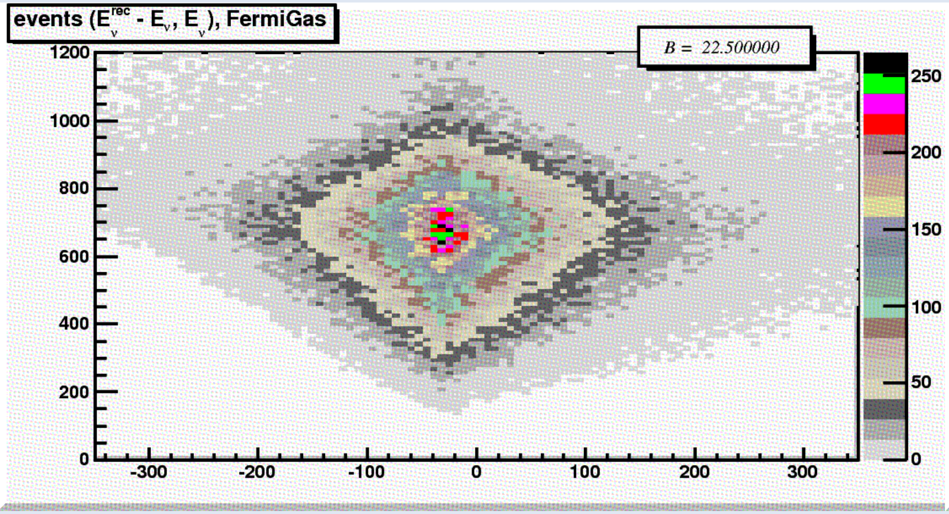
uses only info about final muon and assumes the target nucleon to be at rest. Binding energy is used as in the Fermi gas model energy balance.

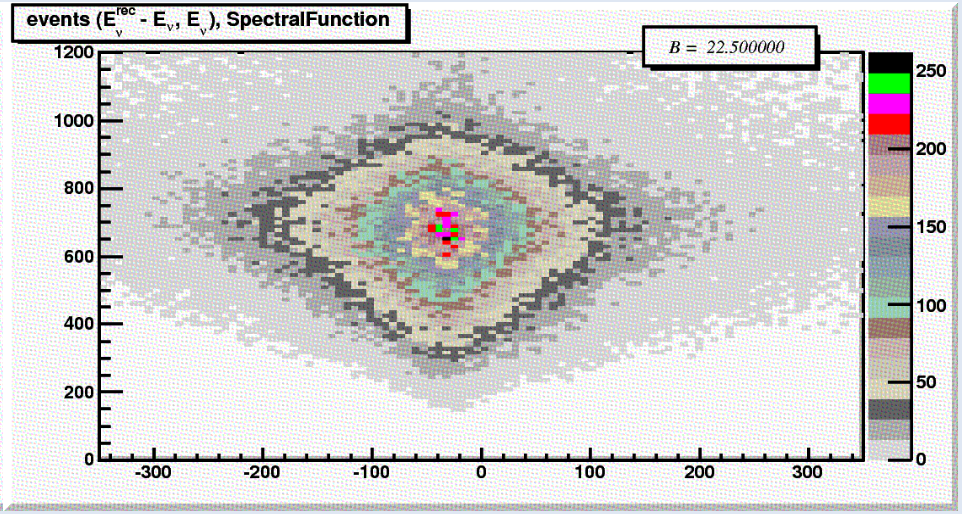
The estimation of the quality of the reconstruction formula should take into account proper description of the Fermi motion and this is what SF is designed to do correctly.

Energy reconstruction

How much Erec differ form Etrue? We can estimate it using MC bas on the FG model. How much this evaluation differ from the results from MC based on the SF?

Two samples of CCQE events were produced by NuWro using the same T2K beam: one with FG model and the second one with the SF model.



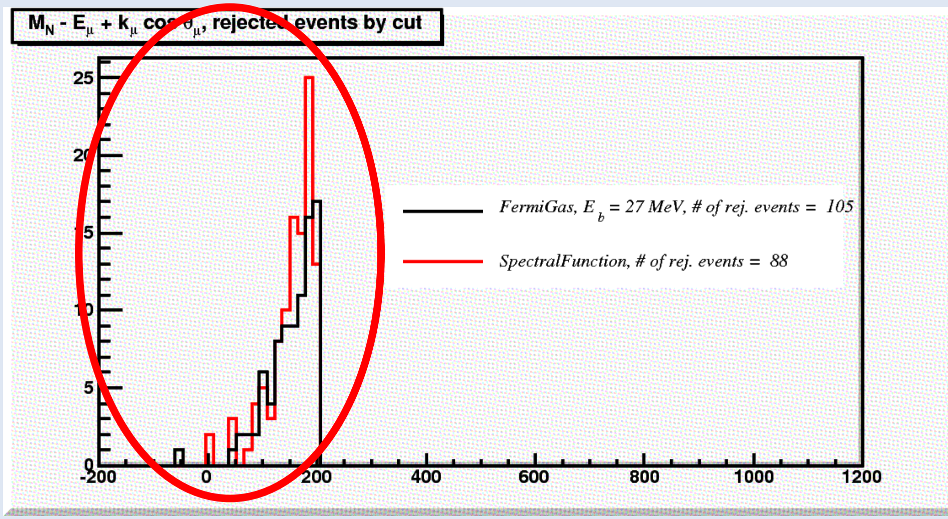


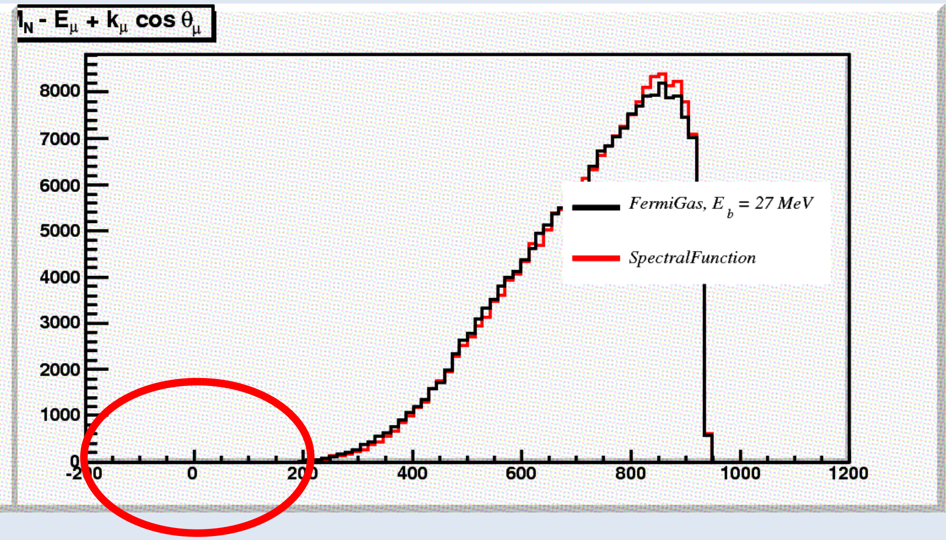
Energy reconstruction

Warning: the denominator in the formula:

$$E_{rec} = \frac{E'(M-B) + \frac{1}{2}\left(B^2 - 2MB + m^2\right)}{M - B - E' + k'\cos\theta}$$

can be very small:



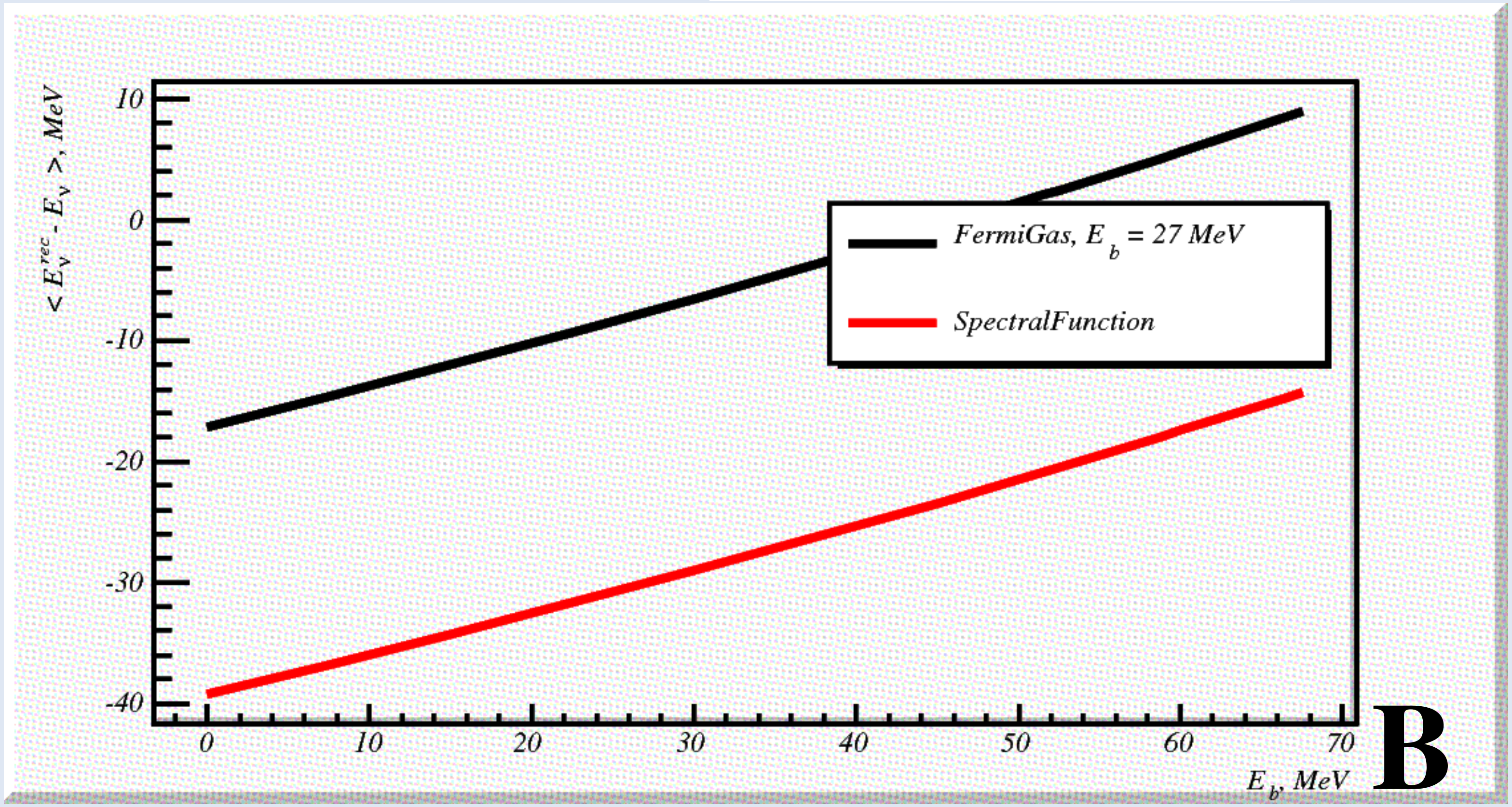


We introduce the cut: $M - B - E' + k'\cos\theta > 200\ MeV$

Energy reconstruction

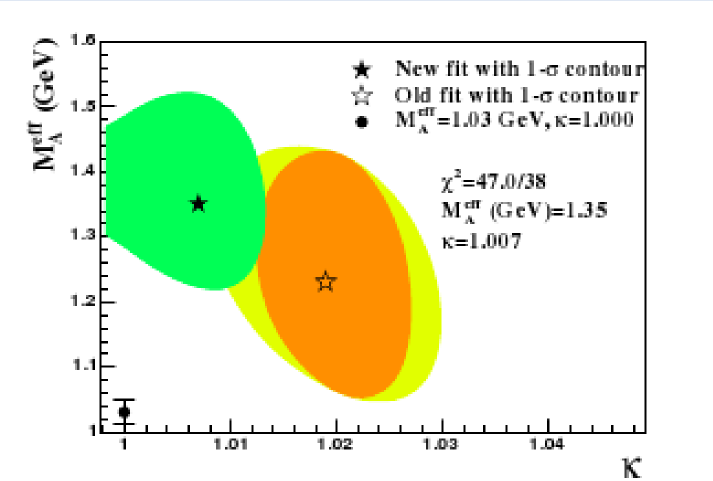
How does it work?

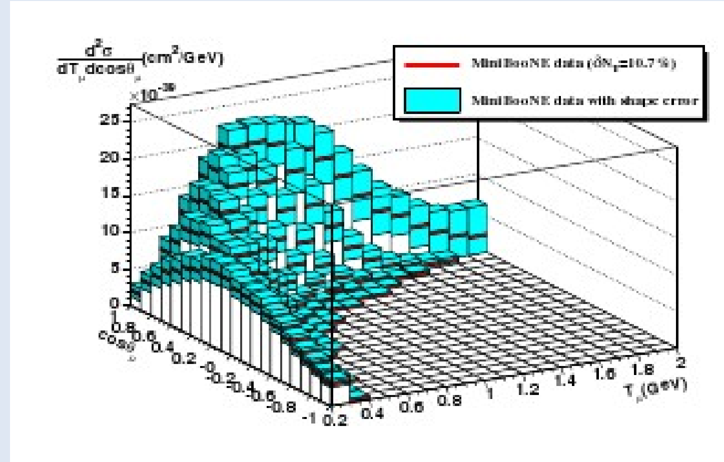
$$E_{rec} = \frac{E'(M-B) + \frac{1}{2}\left(B^2 - 2MB + m^2\right)}{M - B - E' + k'\cos\theta}$$



There is a B dependent bias. For SF it is larger by ~22 MeV (the actual energy is on average **larger** then the reconstructed one).

CCQE MiniBooNE data





$\cos\theta_\mu$ \ T_μ (GeV)	0.2,0.3	0.3,0.4	0.4,0.5	0.5,0.6	0.6,0.7	0.7,0.8	0.8,0.9	0.9,1.0	1.0,1.1	1.1,1.2	1.2,1.3	1.3,1.4	1.4,1.5	1.5,1.6	1.6,1.7	1.7,1.8	1.8,1.9	1.9,2.0
+0.9,+1.0	190.0	326.5	539.2	901.8	1288	1633	1857	1874	1803	1636	1354	1047	794.0	687.9	494.3	372.5	278.3	227.4
+0.8,+0.9	401.9	780.6	1258	1714	2084	2100	2035	1620	1118	783.6	451.9	239.4	116.4	73.07	41.67	36.55	—	—
+0.7,+0.8	553.6	981.1	1501	1884	1847	1629	1203	723.8	359.8	156.2	66.90	26.87	1.527	19.50	—	—	—	—
+0.6,+0.7	681.9	1222	1546	1738	1365	909.6	526.7	222.8	81.65	35.61	11.36	0.131	—	—	—	—	—	—
+0.5,+0.6	765.6	1233	1495	1289	872.2	392.3	157.5	49.23	9.241	1.229	4.162	—	—	—	—	—	—	—
+0.4,+0.5	871.9	1279	1301	989.9	469.1	147.4	45.02	12.44	1.012	—	—	—	—	—	—	—	—	—
+0.3,+0.4	910.2	1157	1054	628.8	231.0	57.95	10.69	—	—	—	—	—	—	—	—	—	—	—
+0.2,+0.3	992.3	1148	850.0	394.4	105.0	16.96	10.93	—	—	—	—	—	—	—	—	—	—	—
+0.1,+0.2	1007	970.2	547.9	201.5	36.51	0.844	—	—	—	—	—	—	—	—	—	—	—	—
0.0,+0.1	1003	813.1	404.9	92.93	11.63	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.1, 0.0	919.3	686.6	272.3	40.63	2.176	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.2,-0.1	891.8	503.3	134.7	10.92	0.071	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.3,-0.2	857.5	401.6	79.10	1.947	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.4,-0.3	778.1	292.1	33.69	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.5,-0.4	692.3	202.2	17.42	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.6,-0.5	600.2	135.2	3.624	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.7,-0.6	497.6	85.80	0.164	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.8,-0.7	418.3	44.84	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.9,-0.8	348.7	25.82	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-1.0,-0.9	289.2	15.18	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

TABLE VI: The MiniBooNE ν_μ CCQE flux-integrated double differential cross section in units of 10^{-41} cm^2/GeV in 0.1 GeV bins of T_μ (columns) and 0.1 bins of $\cos\theta_\mu$ (rows).

CCQE MiniBooNE data

Using NuWro we make 2-dimensional fits:
axial mass, overall normalization.

$$\chi^2(\lambda, M_A) = \sum_{j=1}^{bins} \frac{\left(\frac{d^2\sigma_j^{MB}}{d\cos\theta dT_k} - \lambda \cdot \frac{d^2\sigma_j^{NuWro}(M_A)}{d\cos\theta dT_k} \right)^2}{\left(\delta \frac{d^2\sigma_j^{MB}}{d\cos\theta dT_k}\right)^2} + \frac{\left(1-\lambda^{-1}\right)^2}{(\delta\lambda^{MB})^2}$$

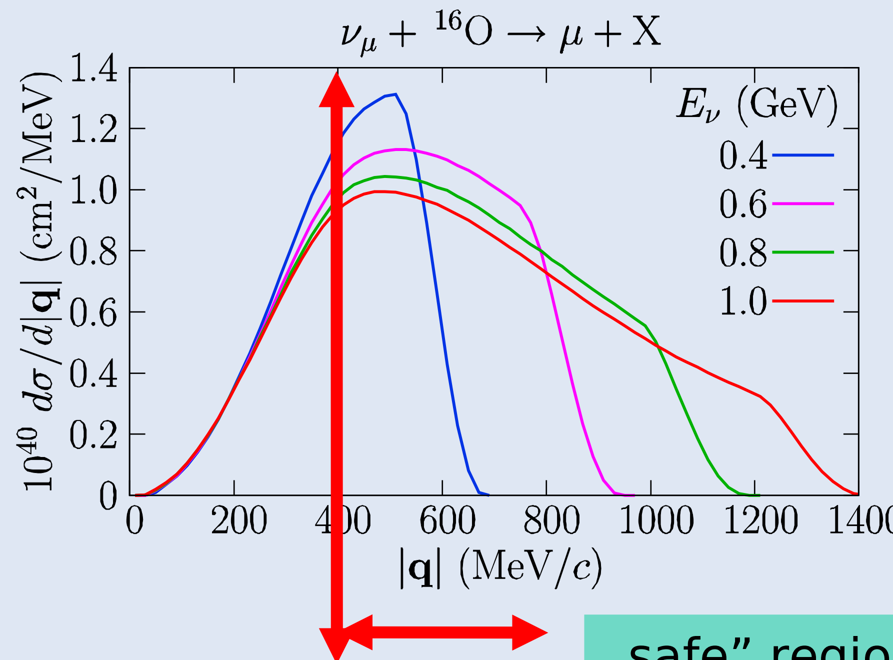
MiniBooNE data are given in the paper $\delta\lambda^{MB} = 10.7\%$

Validity of impulse approximation

General conclusion from electron scattering data: the impulse approximation is reliable only for momentum transfers down to~350-400 MeV.

Message for the neutrino physics:

The contribution from q < 400MeV region is always large, even for higher neutrino energies.



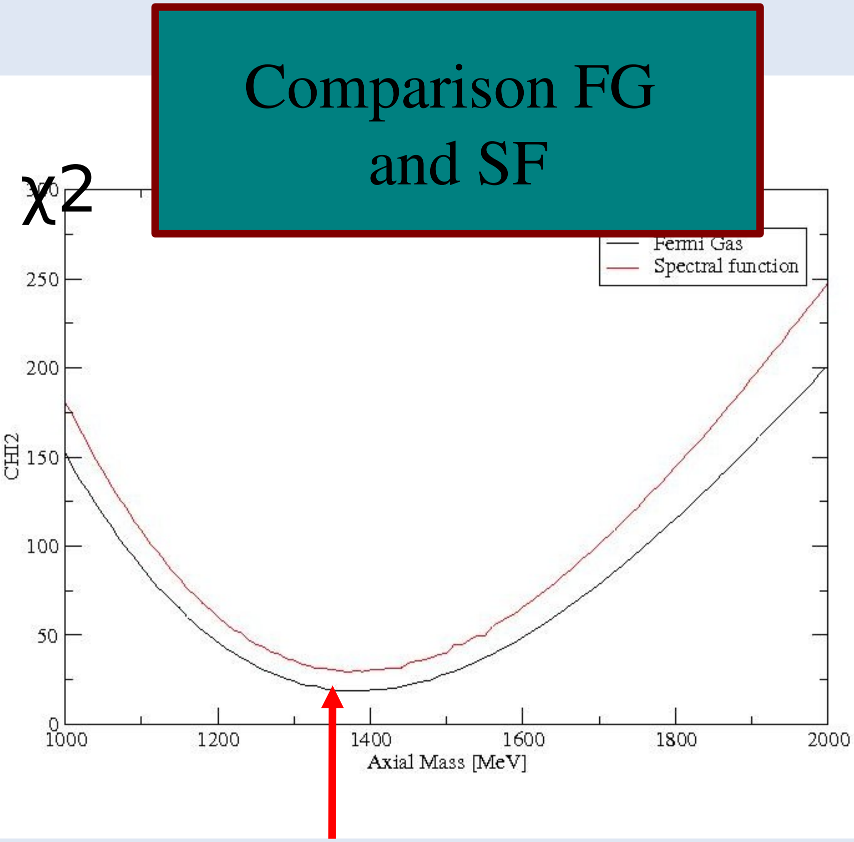
„safe" region

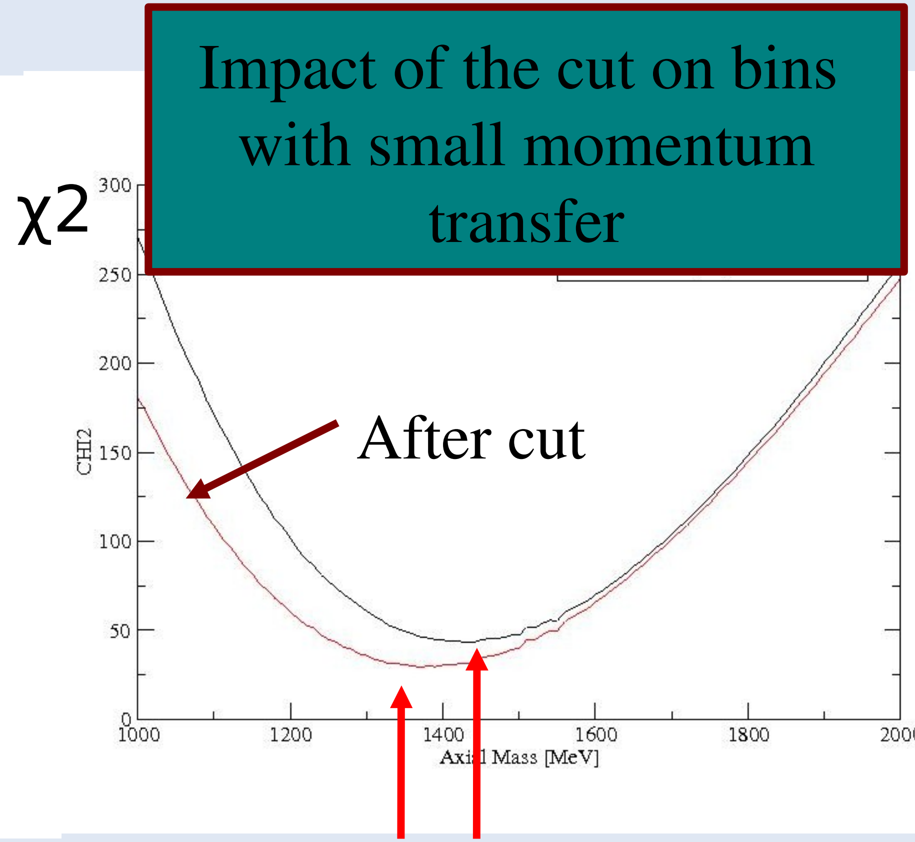
CCQE MiniBooNE data

We make two fits:

- we use all the bins
- we eliminate bins with large (>50%) low momentum transfer contribution

CCQE MiniBooNE data





Very recent and preliminary results!

Wnioski

- oddziaływania neutrin o energiach rzędu 1 GeV to dziedzina dużej aktywności
- obszar małych wartości q (również Q2) wymaga bardziej wyrafinowanych modeli fizyki jądrowej
- ważne pytanie: jak istotny jest wkład 2p-2h? konieczne kolejne testy
- analiza koherentnej produkcji pionów wymaga ulepszeń w kodach Monte Carlo
- jest sporo nowych ciekawych wyników (np. NC 1Pi0) umożliwiających weryfikację opisu efektów jądrowych
- póki co funkcja spektralna nie wnosi wiele nowego, co nie oznacza, że nie powinno się używać jej zamiast gazu Fermiego
- d**alszy postęp wymaga nowych danych (Minerva!)**

Dziękuję
za
uwagę!