Progress in modelling neutrino interactions in 1 GeV energy region

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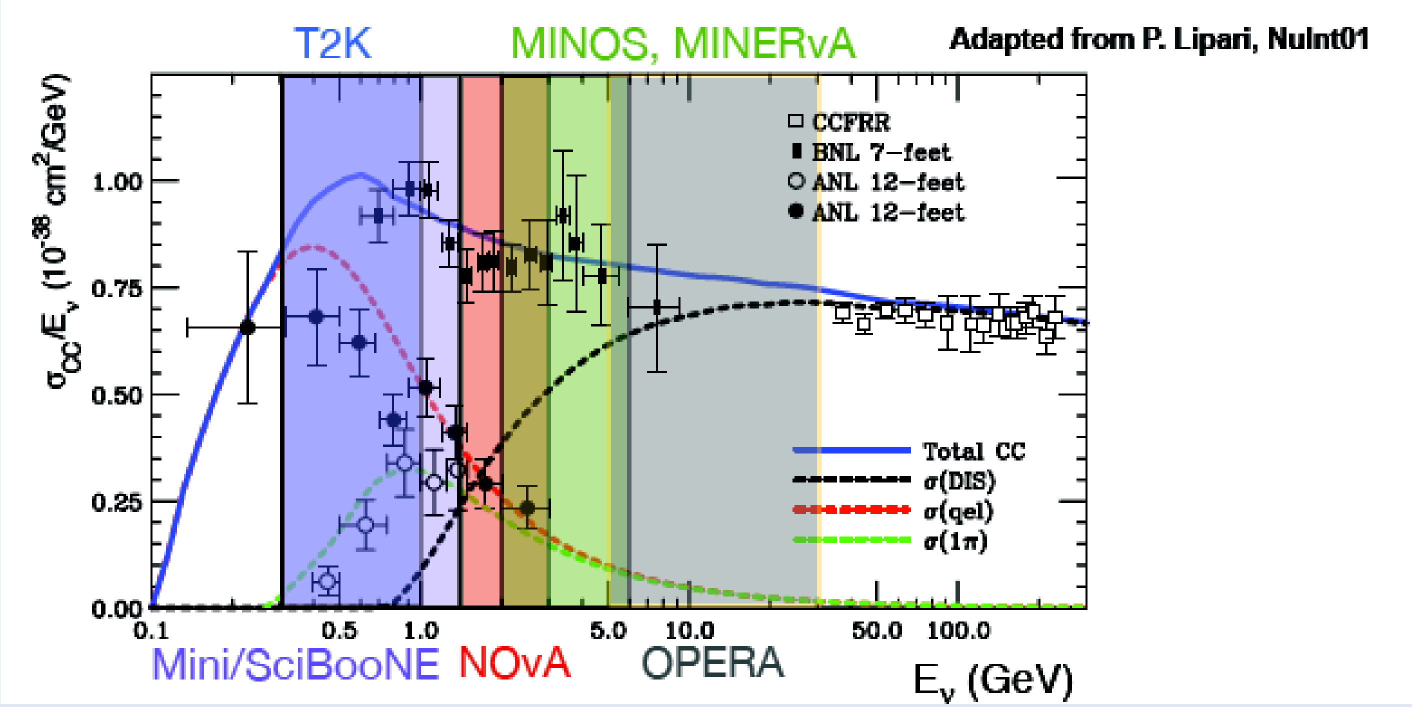
Outline

- motivation
- quasi-elastic axial mass puzzle
- coherent pion production
- other measurements
- Monte Carlo generators
- conclusions
- [NC1Pi0 production --only back-up slides]

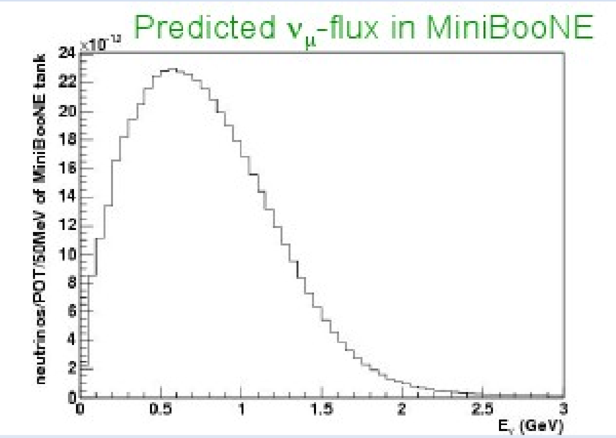
Motivation

1 GeV is the typical energy region of all long baseline neutrino oscillation experiments.



(from Hiroshi Tanaka)

Motivation



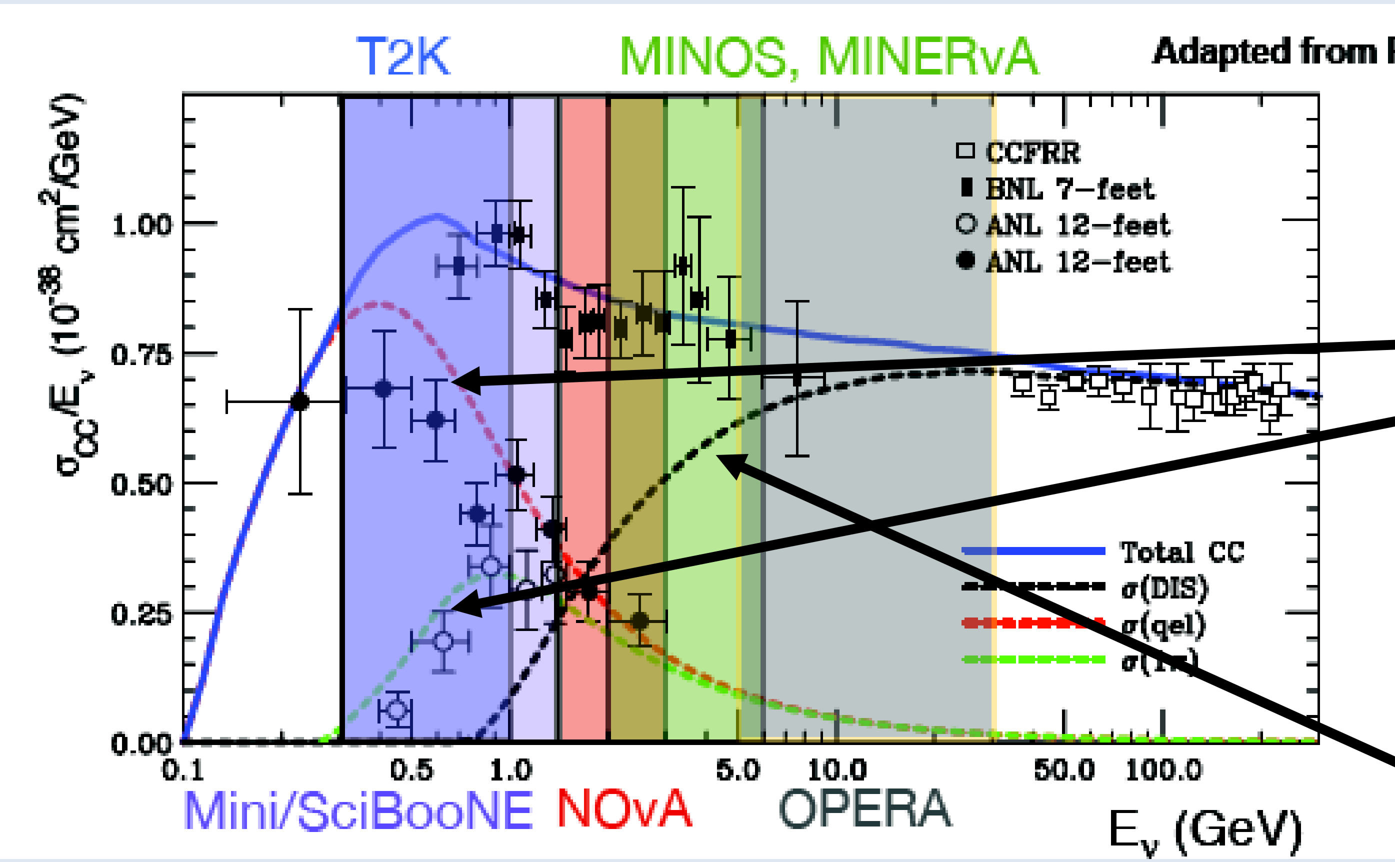
Why do we need cross sections?

- 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:

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

But typically, the reaction occurs on nucleus target:

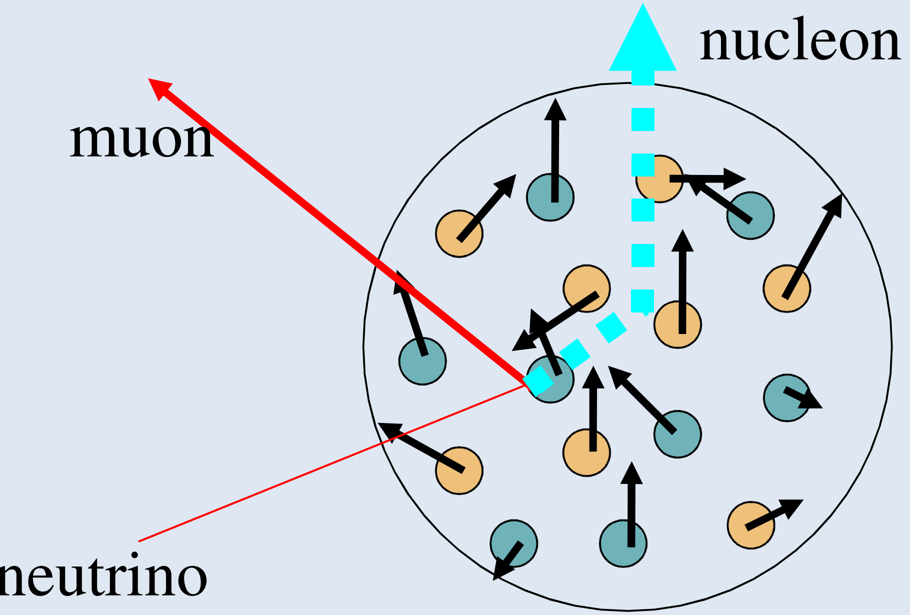
$$\nu + {}^{A}_{Z}X \rightarrow l^- + p + {}^{A-1}_{Z}X$$

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

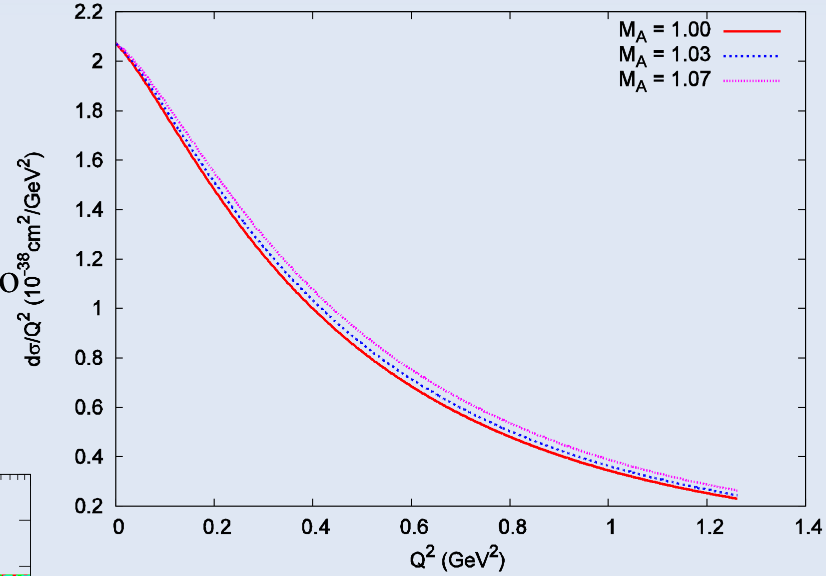
$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

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

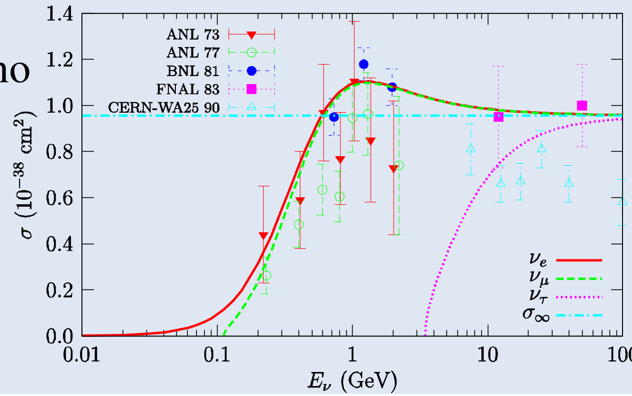
Quasi-elastic axial mass puzzle

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

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



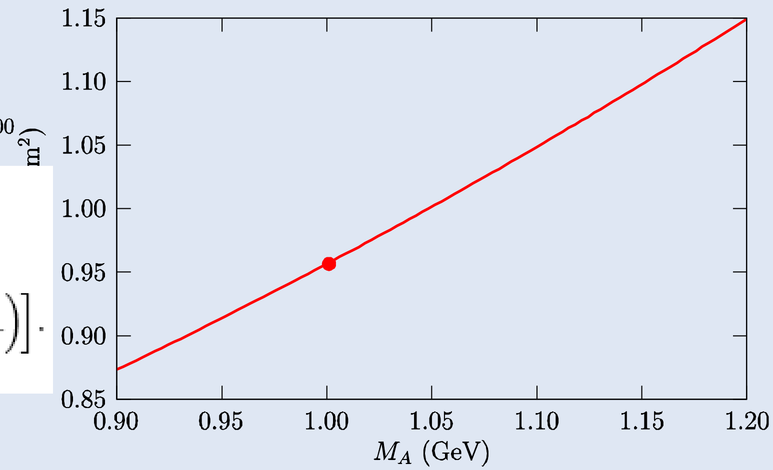
The limiting value of the cross section at large neutrino energy under assumption of dipole vector form factors:



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

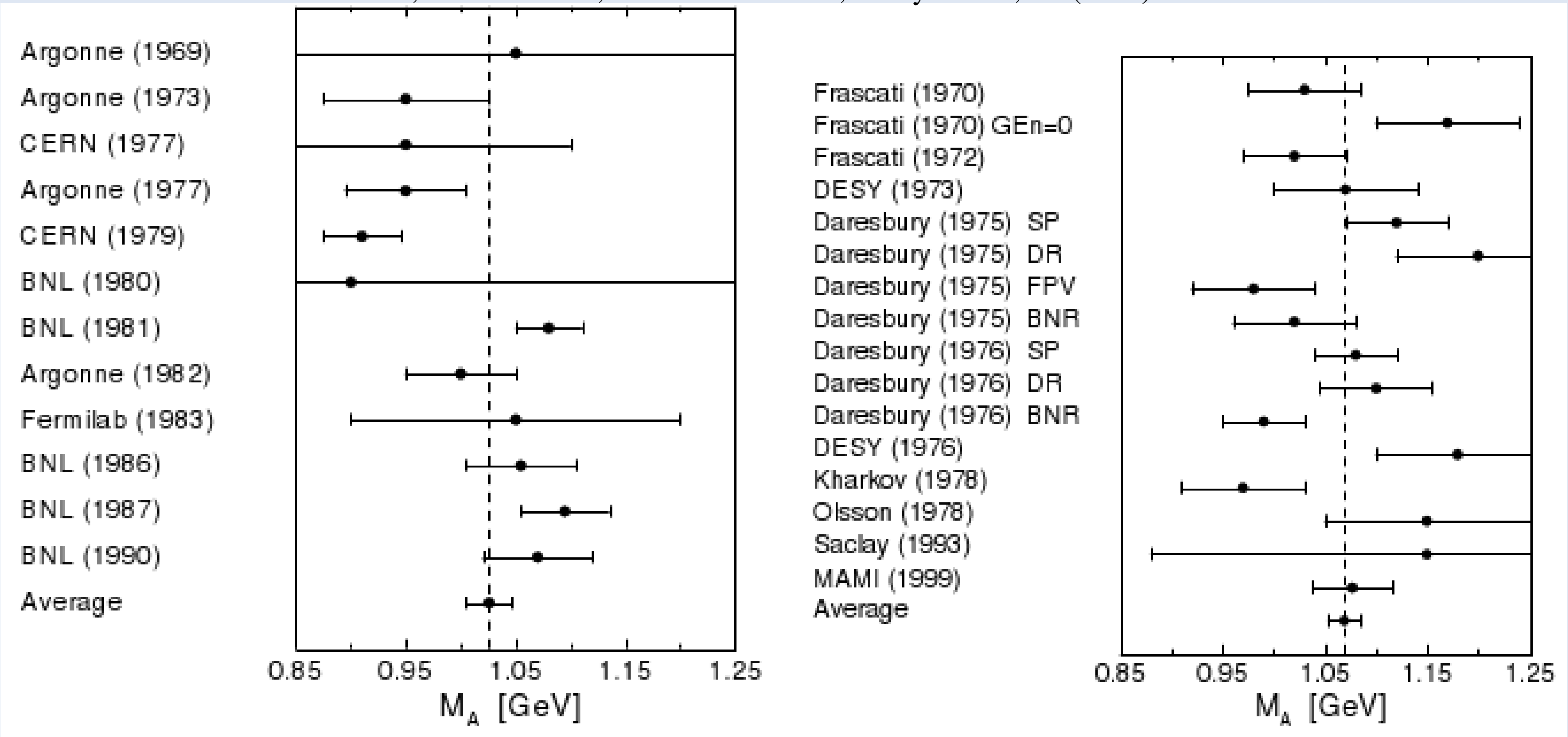
(A. Ankowski, Acta Phys. Pol. B37 (2005) 377)

10e-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

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

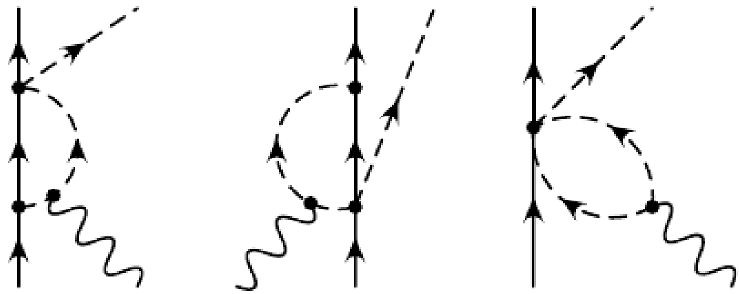


Figure 7. One-loop diagrams that lead to the axial radius correction. Crossed partners are not shown. The solid, dashed and wiggly lines denote nucleons, pions and photons, in that order.

$$G_A\left(Q^2\right)=g_A\left(1-\frac{1}{6}\langle r_A^2\rangle Q^2+O\left(Q^4\right)\right)$$

$$\langle r_A^2\rangle=-\frac{6}{g_A}\left(\frac{dG_A\left(Q^2\right)}{Q^2}\right)_{Q^2=0}=\frac{12}{M_A^2}$$

$$\langle \tilde{r}_A^2\rangle=\langle r_A^2\rangle+\frac{3}{64\,F_\pi^2}\left(1-\frac{12}{\pi^2}\right)$$

The agreement seems to be very good...

$$\Delta\langle r_A^2\rangle\equiv\langle \tilde{r}_A^2\rangle-\langle r_A^2\rangle=-0.0456\,fm^2$$

$$\Delta M_A=0.055\,GeV$$

Quasi-elastic axial mass puzzle

Most recent neutrino data:

TABLE I. 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)

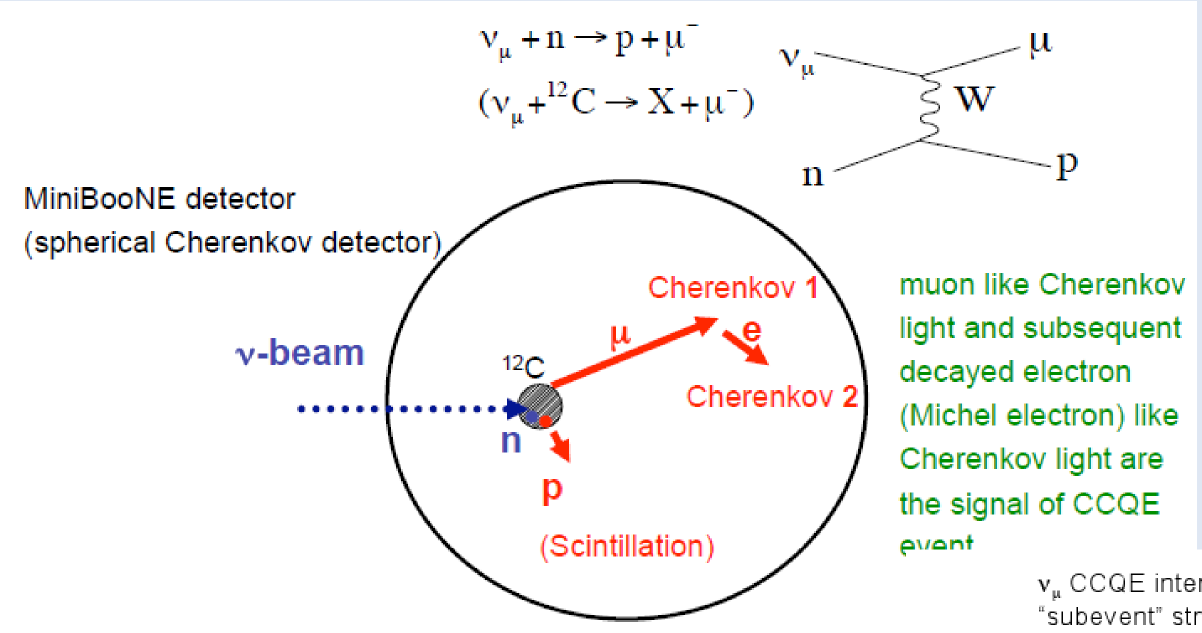
If axial mass in increased from 1.03 to 1.23, the number of QE events is increased by ~20% !

Quasi-elastic axial mass puzzle

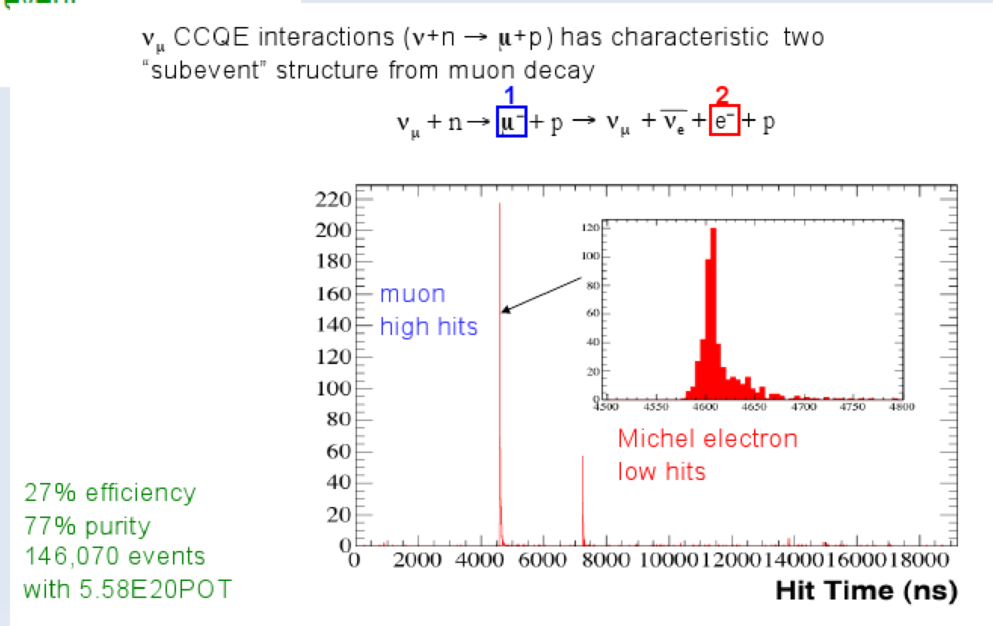
Possible explanations:

- 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 is wrong in the data analysis...

Quasi-elastic axial mass puzzle



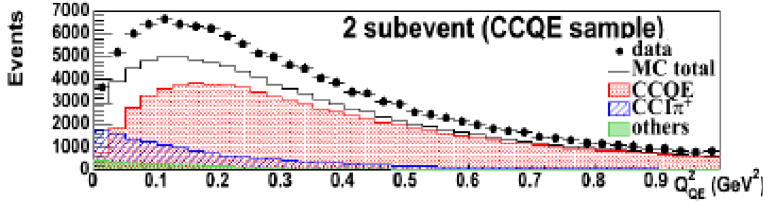
MiniBooNE collaboration tried to made the analysis independent on the models implemented in the Monte Carlo generator (Nuance).



(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.



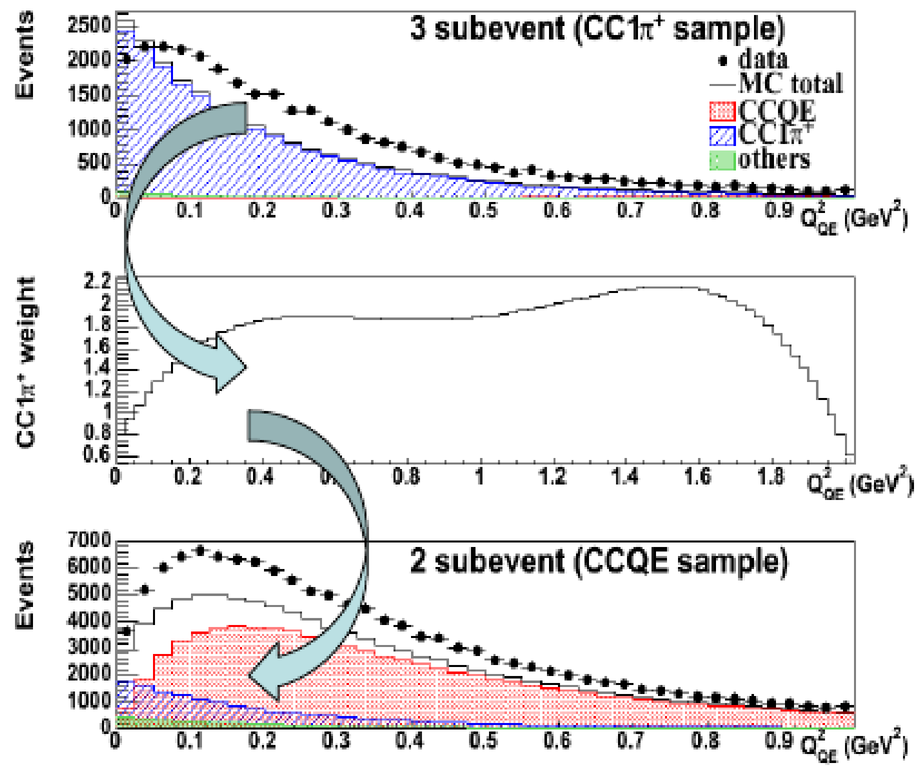
(from Teppei Katori)

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 MC independent !

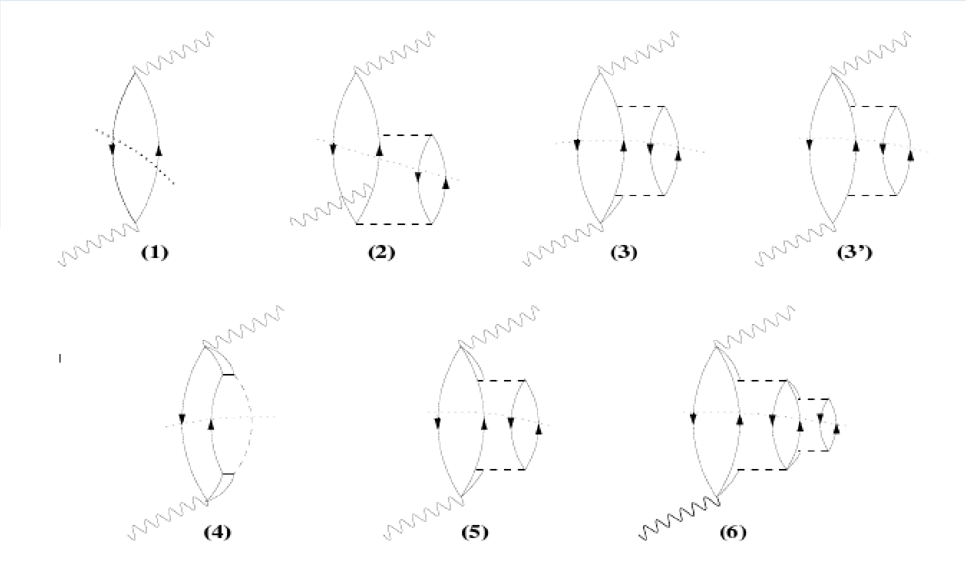
Quasi-elastic axial mass puzzle

Possible explanations:

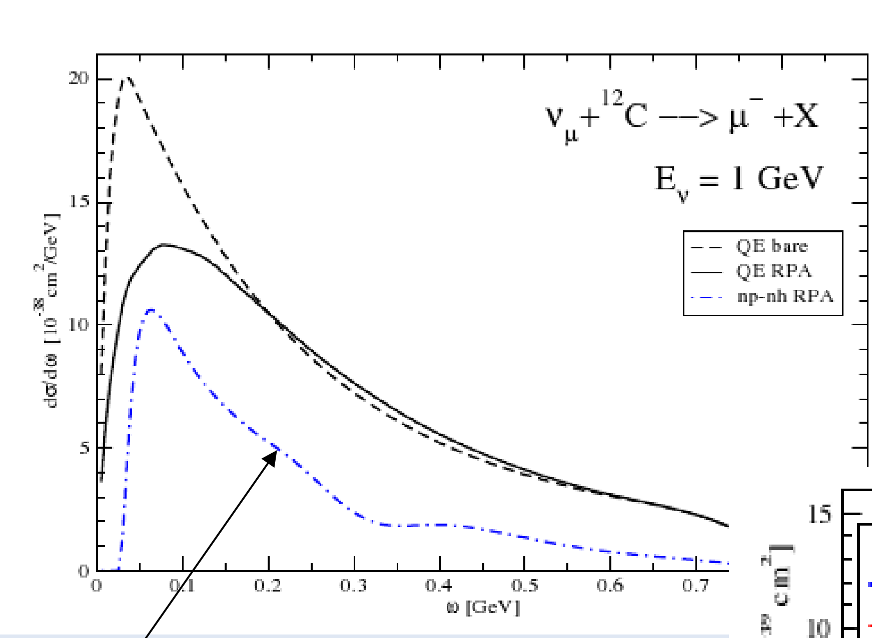
- statistical fluctuations (after all the discrepancy is on the 2σ level)
- MiniBooNE overestimates the beam (the claim is that it is know with uncertainty of 10.7%; but all the cross sections reported by MB are very large)
- something is wrong in the data analysis...
- large 2p-2h contribution ?!

Quasi-elastic axial mass puzzle

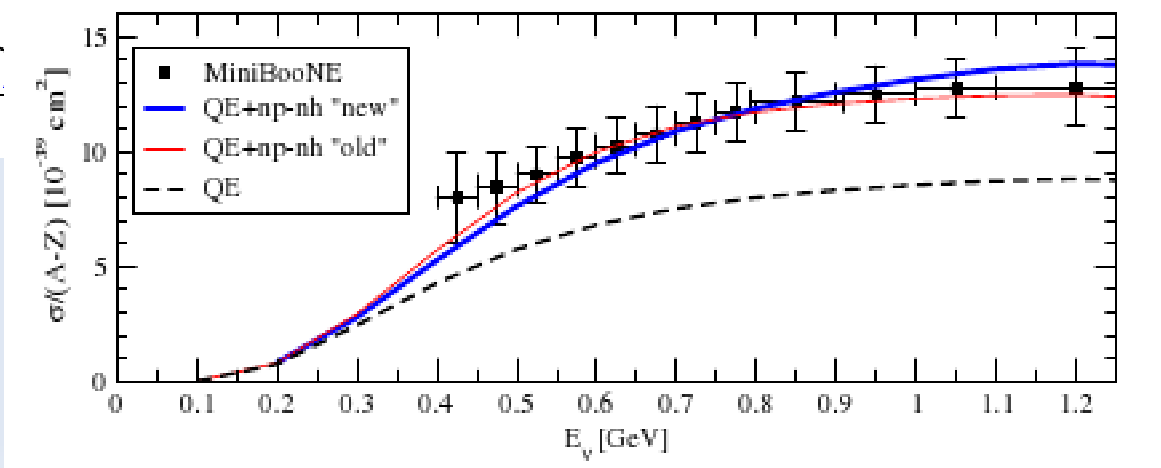
Martini-Marteau model
(many body RPA computations)



(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!

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

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

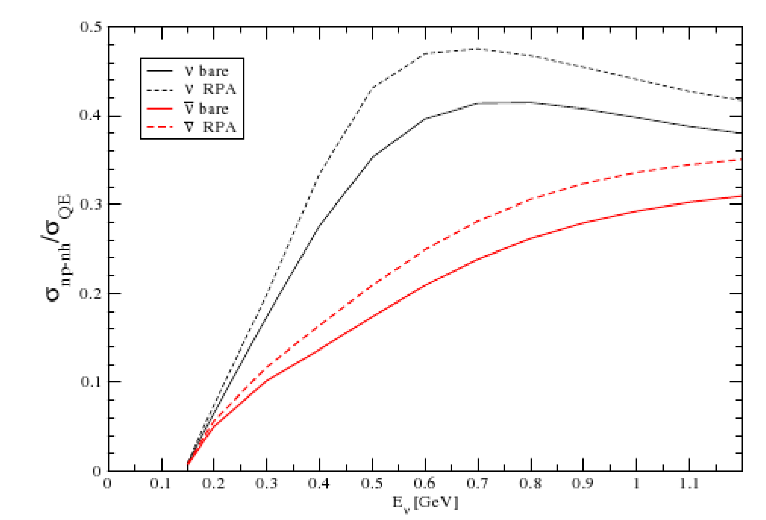


FIG. 6: Ratio of multinucleon component of "quasielastic" cross section on ^{12}C to the single nucleon one for ν_μ and $\bar{\nu}_\mu$ as a function of neutrino energy.

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

	ν			$\bar{\nu}$		
	QE	np-nh	QE+np-nh	QE	np-nh	QE+np-nh
bare	7.46	2.77	10.23	2.09	0.52	2.61
RPA	6.40	2.73	9.13	1.60	0.47	2.07

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 will be very useful in more detail discussion.

(among authors Jarek Nowak!)

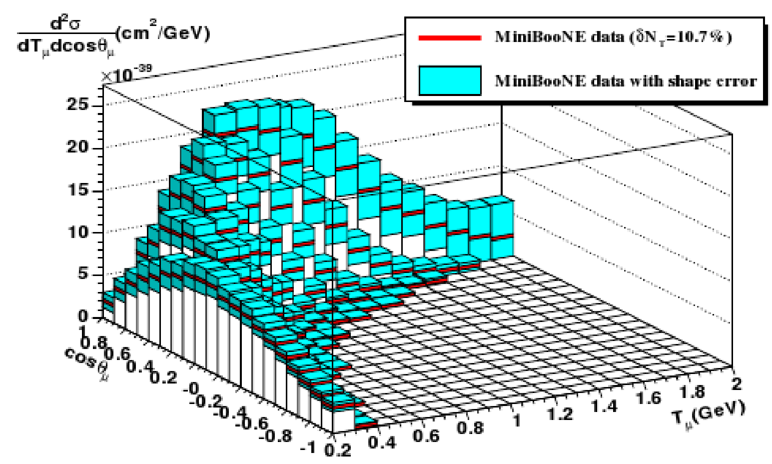
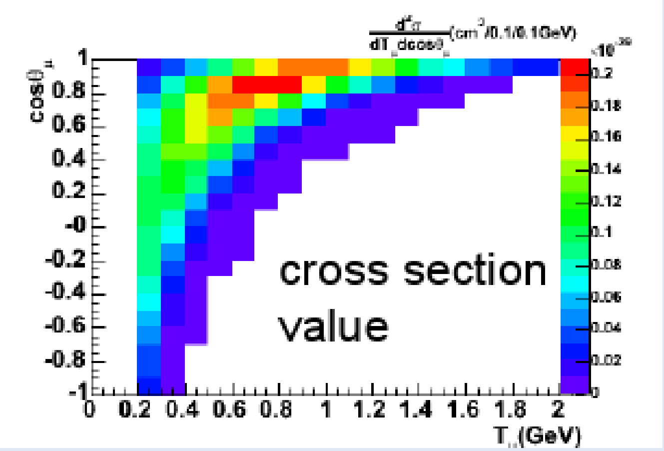


FIG. 13: (Color online). Flux-integrated double differential cross section per target neutron for the ν_μ CCQE process. The dark bars indicate the measured values and the surrounding lighter bands show the shape error. The overall normalization (scale) error is 10.7%. Numerical values are provided in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

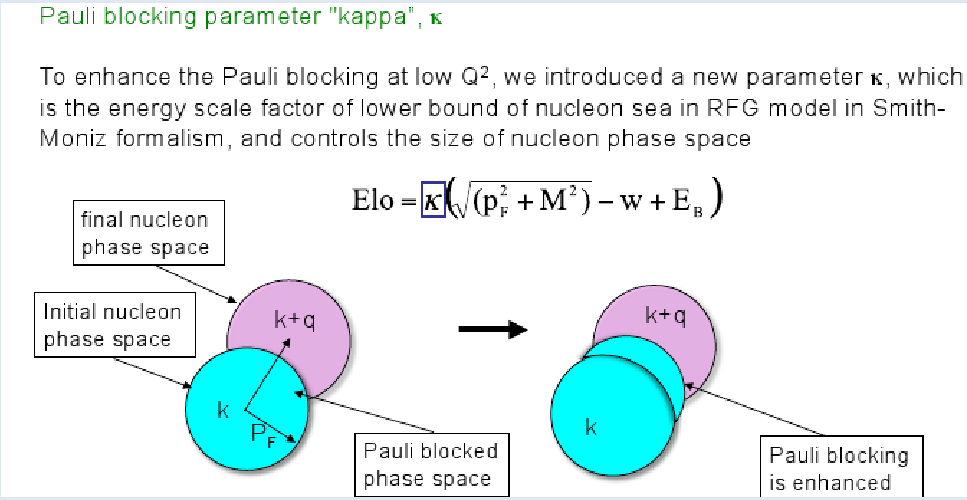
arXiv: 1002.2680 [hep-ex]



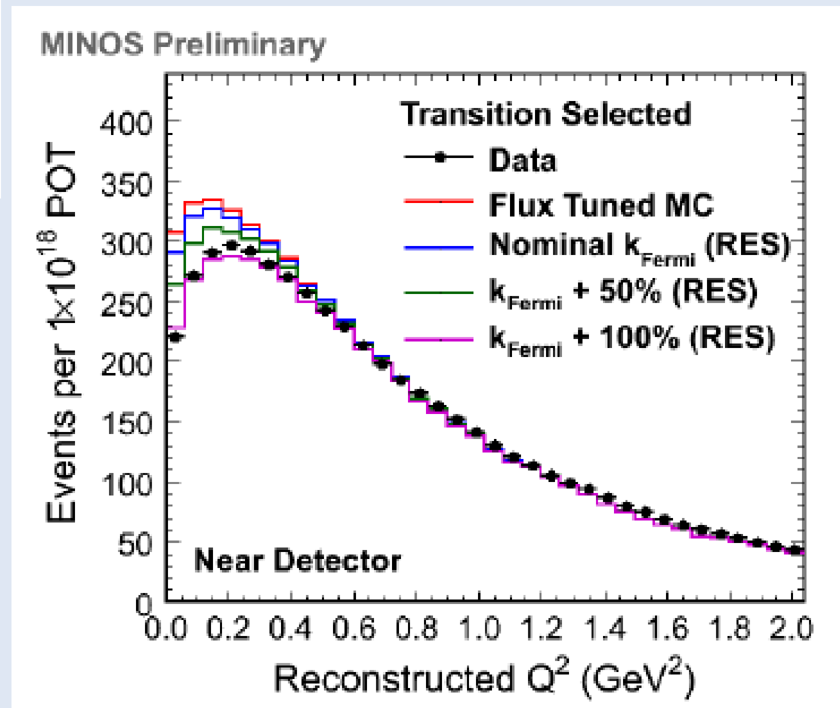
It is important to compare with Martini's double differential cross section !

Quasi-elastic low Q2 problem

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



(from Teppei Katori)

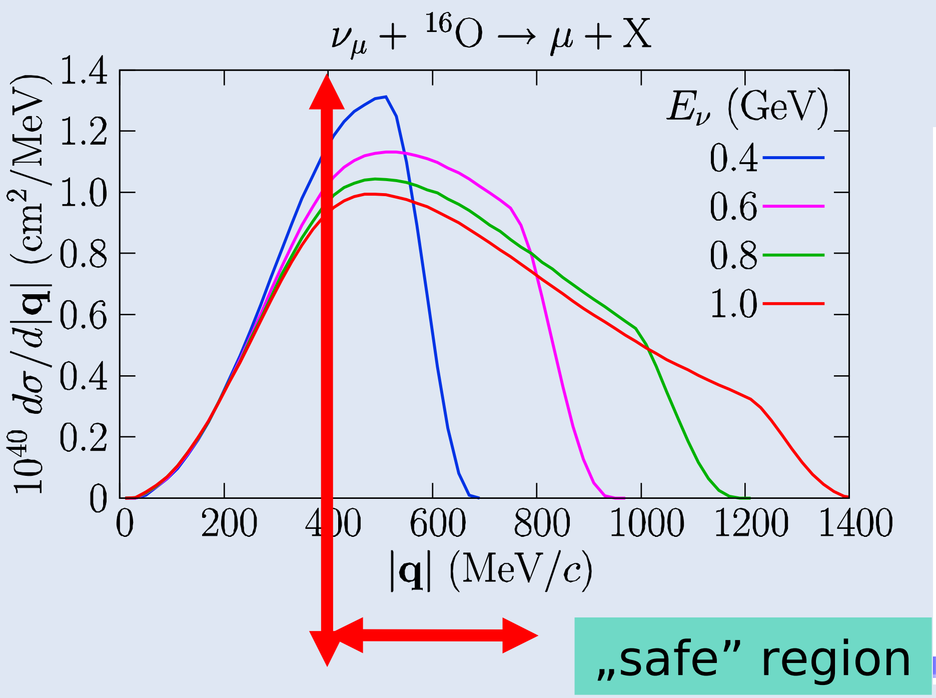


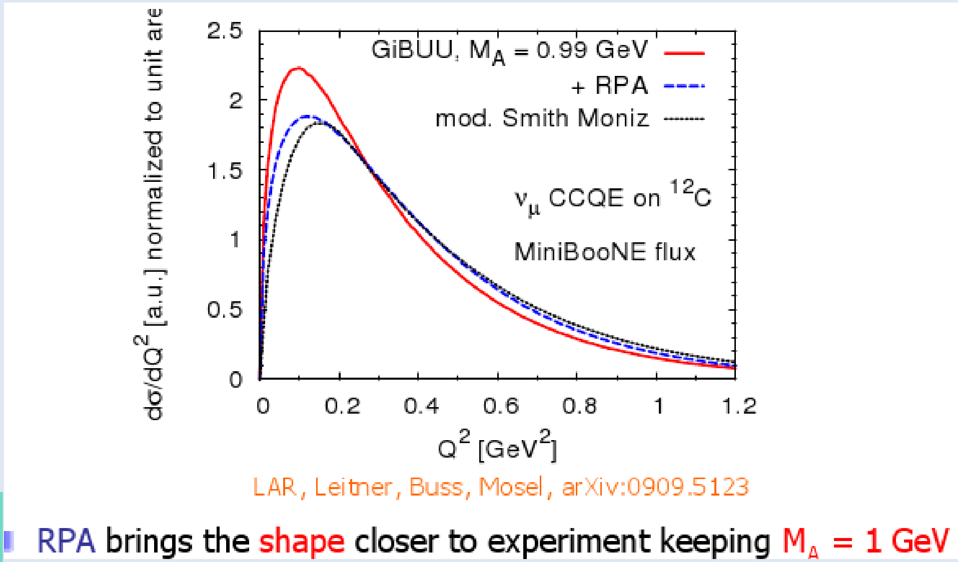
Quasi-elastic low Q2 problem

. At low Q2 collective effects become important.

For momentum transfer q, the spacial resolution is ∼ 1/q.

At q ≥ 300-400 MeV individual nucleons „are seen”.





(from Luis Alvarez-Ruso)

How well do we understand flux?

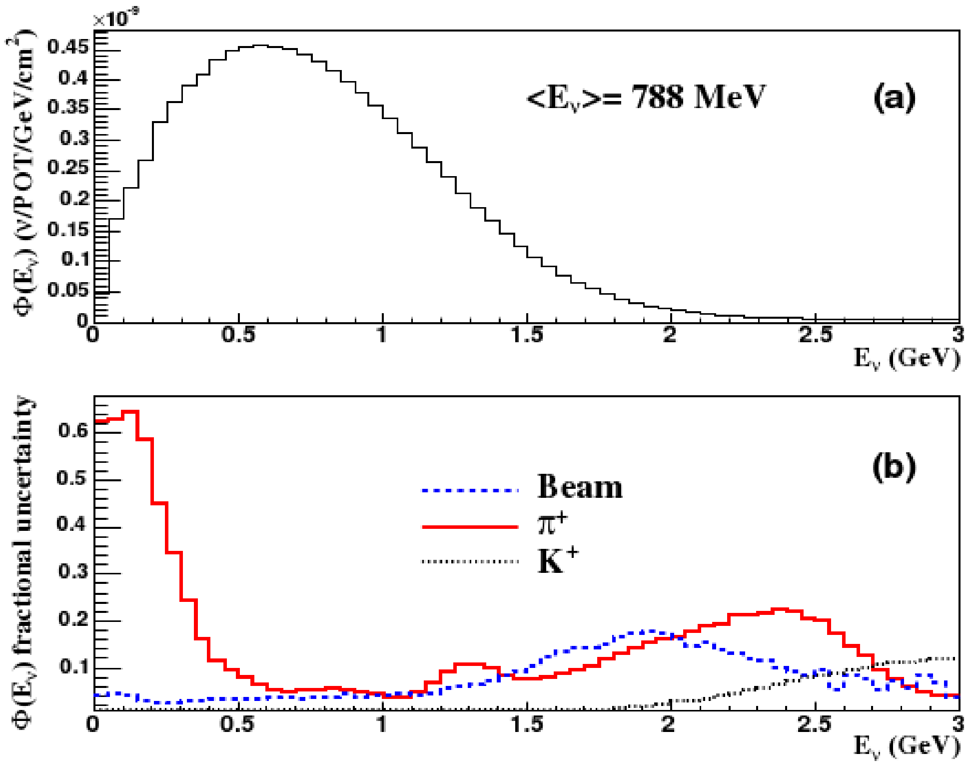


FIG. 2: (color online) Predicted ν_μ flux at the MiniBooNE detector (a) along with the fractional uncertainties grouped into various contributions (b). The integrated flux is 5.16×10^{-10} $\nu_\mu/\text{POT}/\text{cm}^2$ ($0 < E_\nu < 3$ GeV) with a mean energy of 788 MeV. Numerical values corresponding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

Coherent pion production

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

$$\nu + X \rightarrow \nu + \pi^0 + X$$

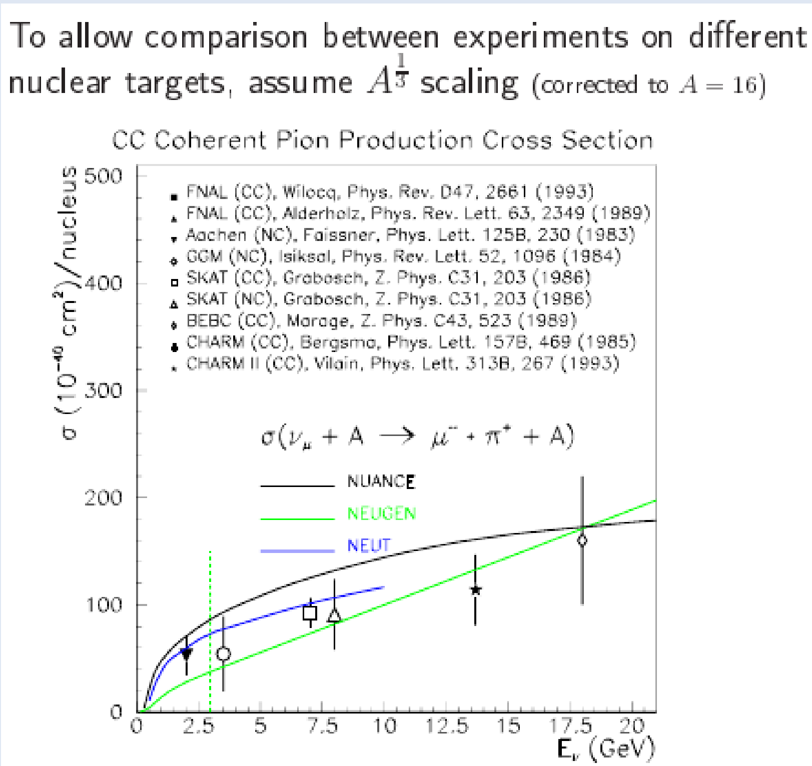
$$\nu + X \rightarrow l^- + \pi^+ + X$$

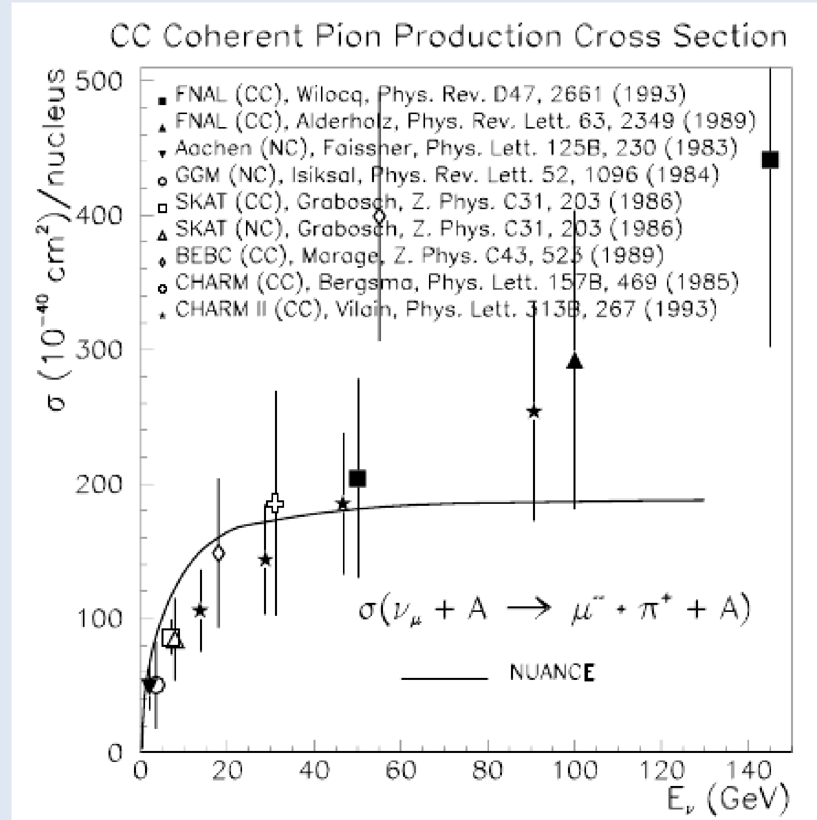
This is a small fraction of the overall single pion production cross section, but there has been recently a lot of experimental and theoretical activity.

(dominant mechanism for pion production is via resonance excitation)

Coherent pion production

Well established at higher neutrino energies:





(from Sam Zeller, NuInt02)

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

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

NC and CC data are put together !

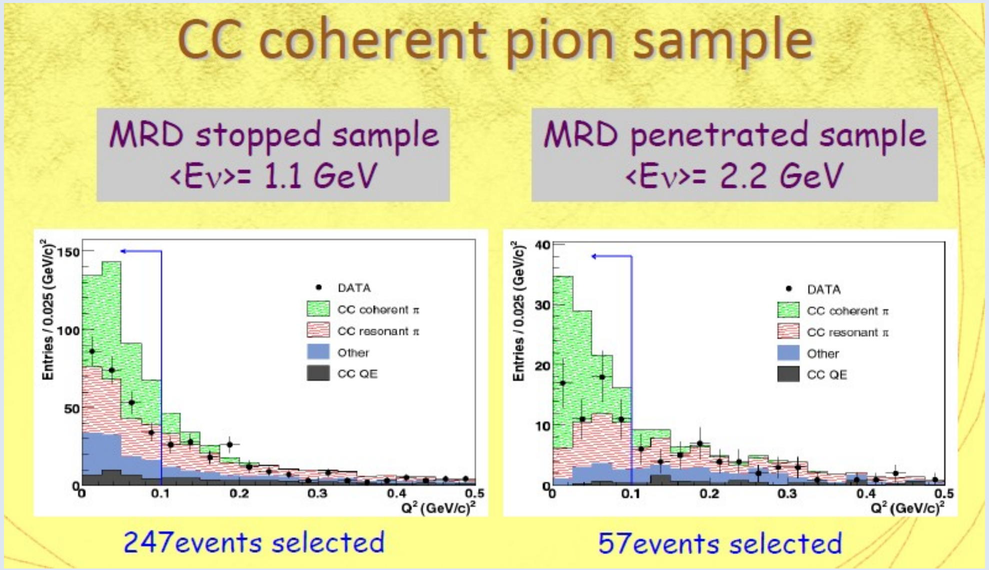
Coherent pion production

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)

$\sigma(\text{CC coherent }\pi)/\sigma(\text{CC}) < 0.67\times10^{-2}$ for ⟨Eν⟩=1.1 GeV

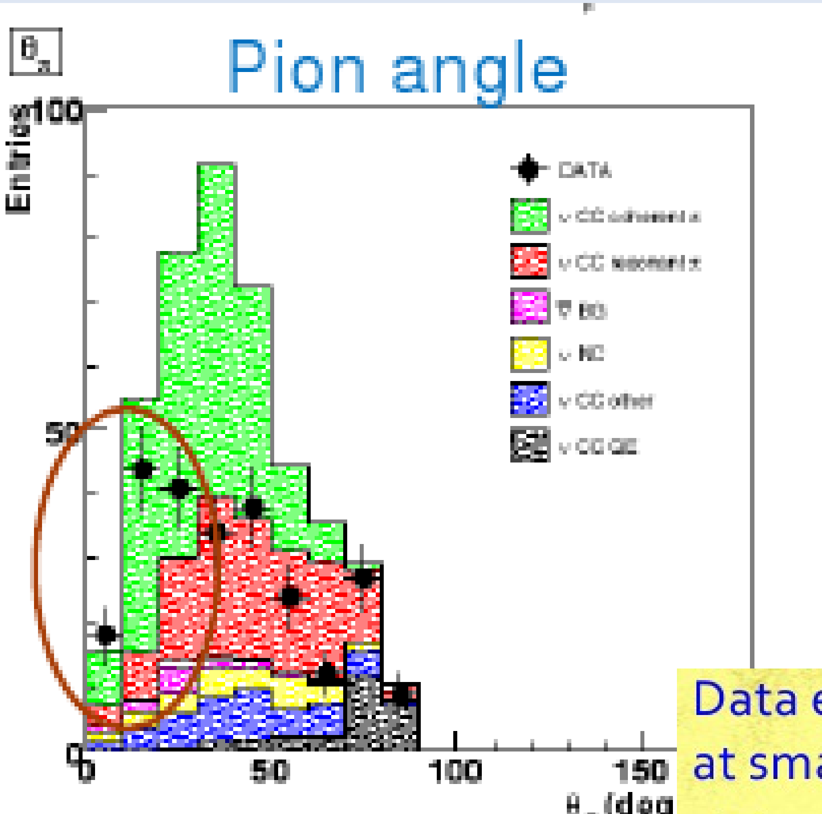
$< 1.36\times10^{-2}$ ⟨Eν⟩=2.2 GeV

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

(from K. Hiraide)

but...

Coherent pion production



(from K. Hiraide)

Data excess with respect to no CC coherent pion MC at small pion angle

If this is due to CC coherent pion events, data suggest that pion tends to go in smaller angle than the Rein-Sehgal prediction

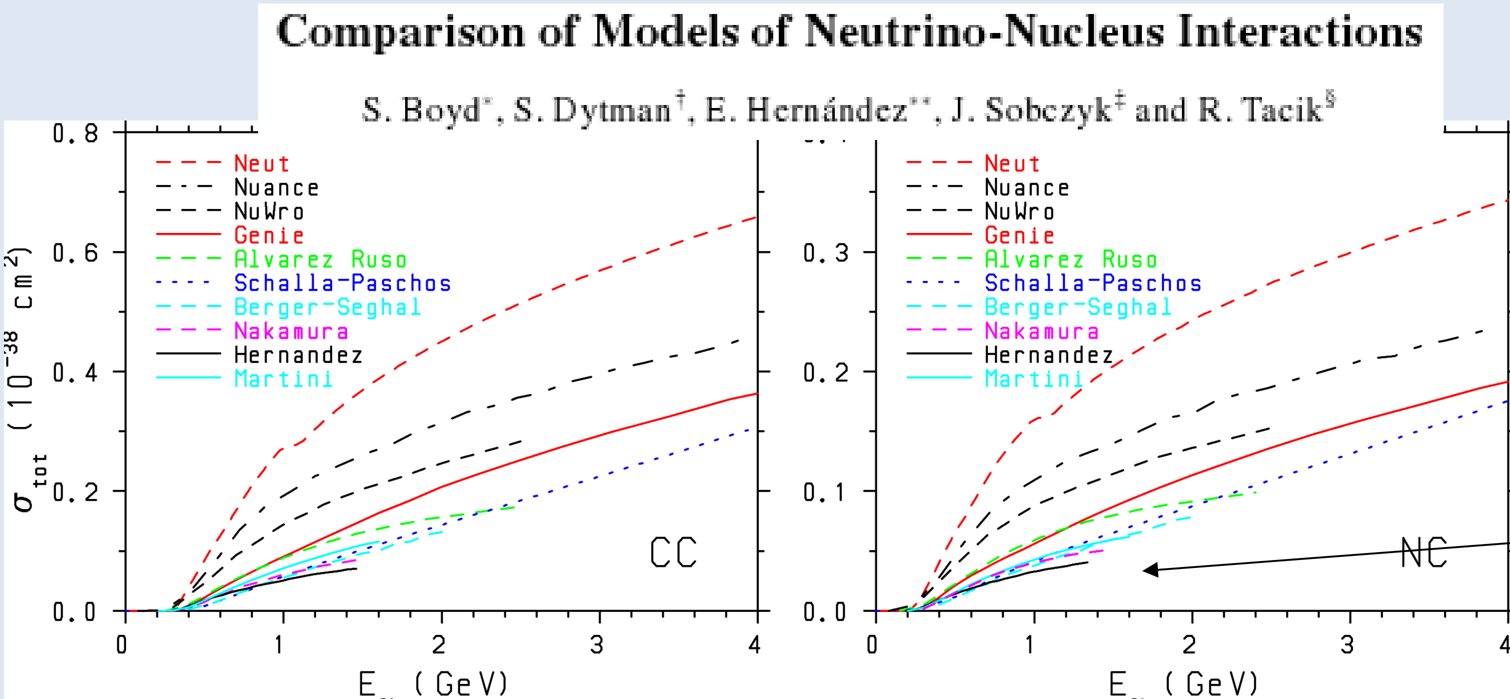
How precise is COH signal's template given by MC ?

Coherent pion production

Experimental analysis is based on comparison with predictions from Monte Carlo generators of events.

Current MC describe coherent pion production using the Rein-Sehgal model.

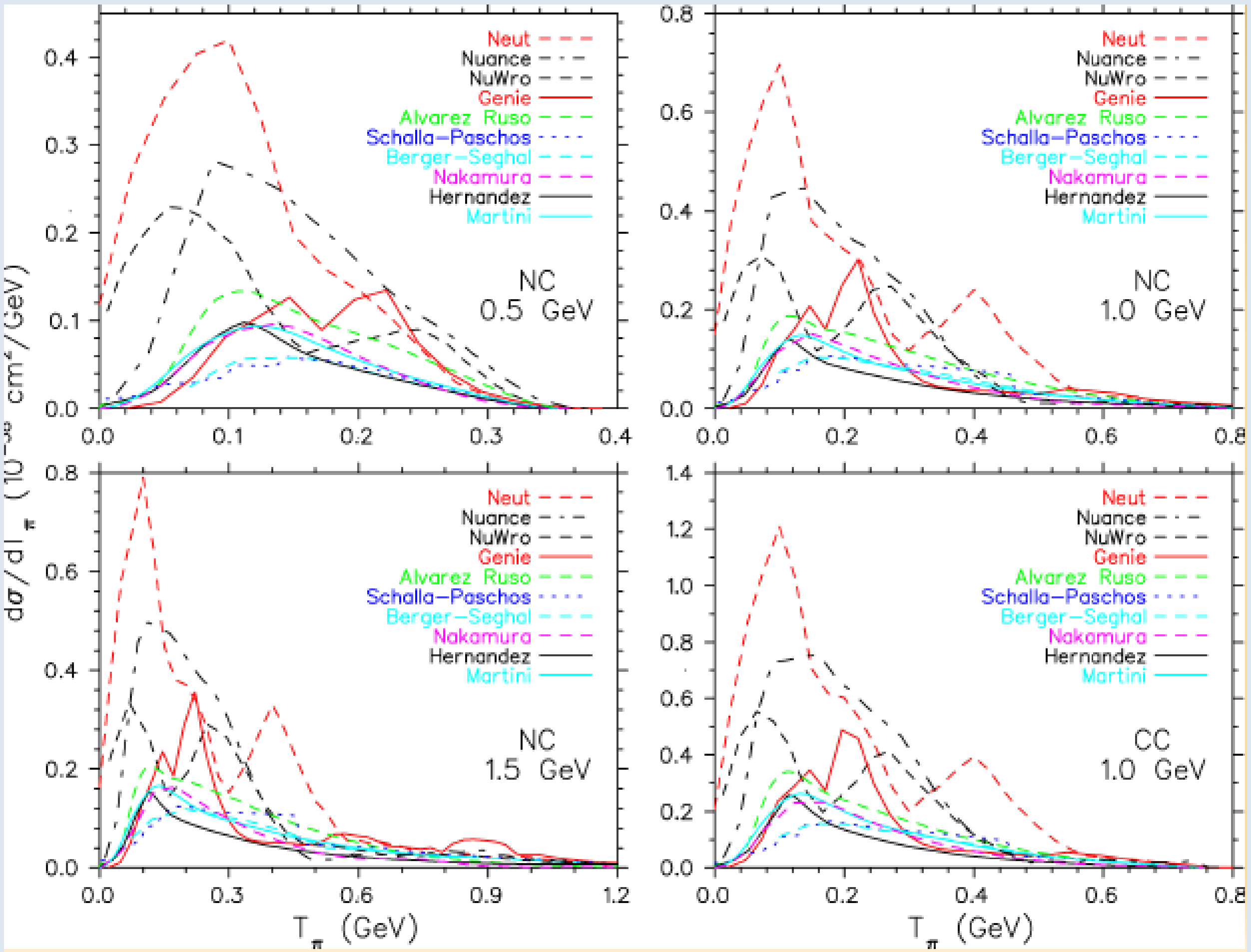
The plots below come from the comparison project done for the last year NuInt09.



Monte Carlo generators

theoretical models

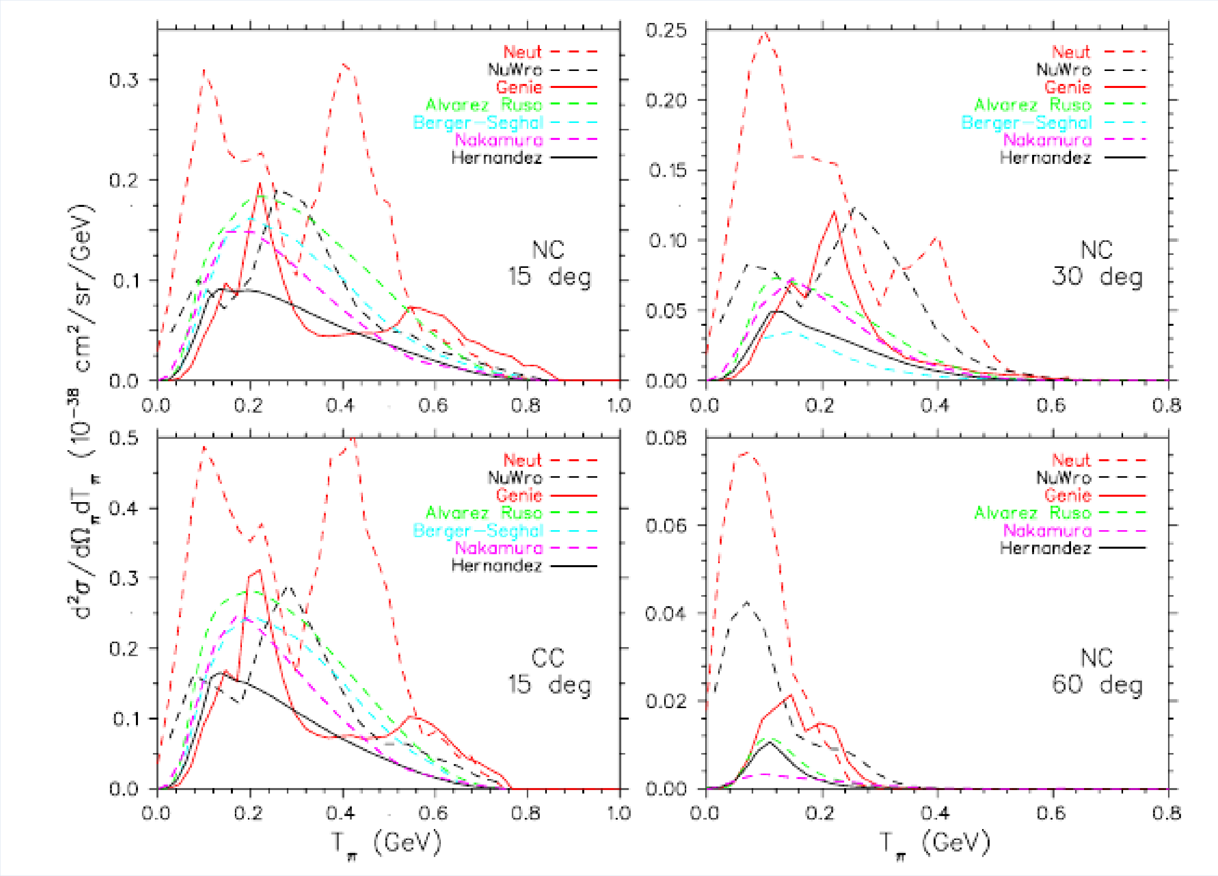
Coherent pion production



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 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 $\pi+\alpha\rightarrow\beta$

$$For \quad q_\mu q^\mu \rightarrow 0 \quad |M(\nu+\alpha\rightarrow l+\beta)|^2 = 16\, G^2 \cos^2(\theta_C)\, f_\pi^2 \frac{E_\nu E_l}{(E_\nu - E_l)^2} |M(\pi+\alpha\rightarrow\beta)|^2$$

It is enough to choose: $\alpha\equiv X \ \wedge\ \beta\equiv\pi+X$

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

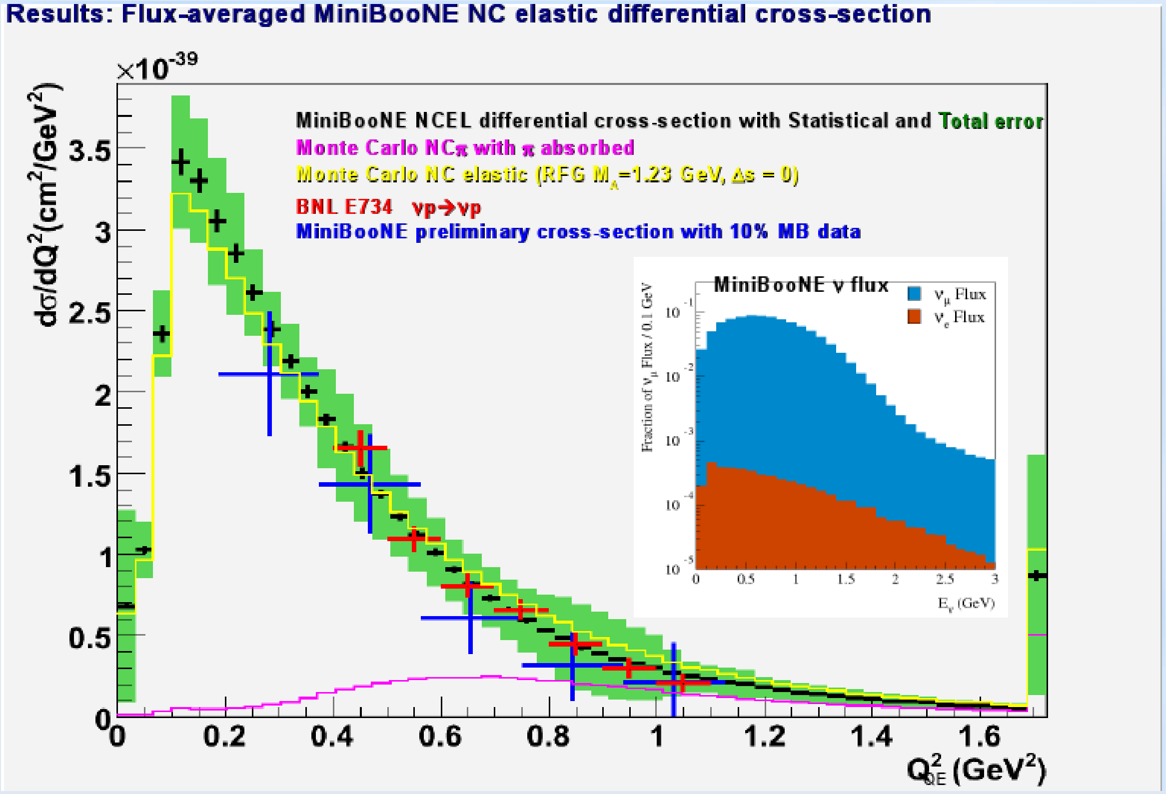
Coherent pion production

Microscopic computations:

- one starts from a theoretical description of the nuclear structure and sums the pion production amplitude coherently over all target nucleus state
- „local approximation” is adopted: the pion production amplitude is factorized into a part containing the pion production amplitude and one containing the nuclear size information
- predictions are very sensitive to the value of C5A(0) (axial nucleon-Δ transition form-factor); PCAC arguments suggest C5A(0)=1.2, but there is a lot of recent discussion on that issue with suggestions that the value can be as small as ~0.85.

Other measurements

Neutral current elastic cross section

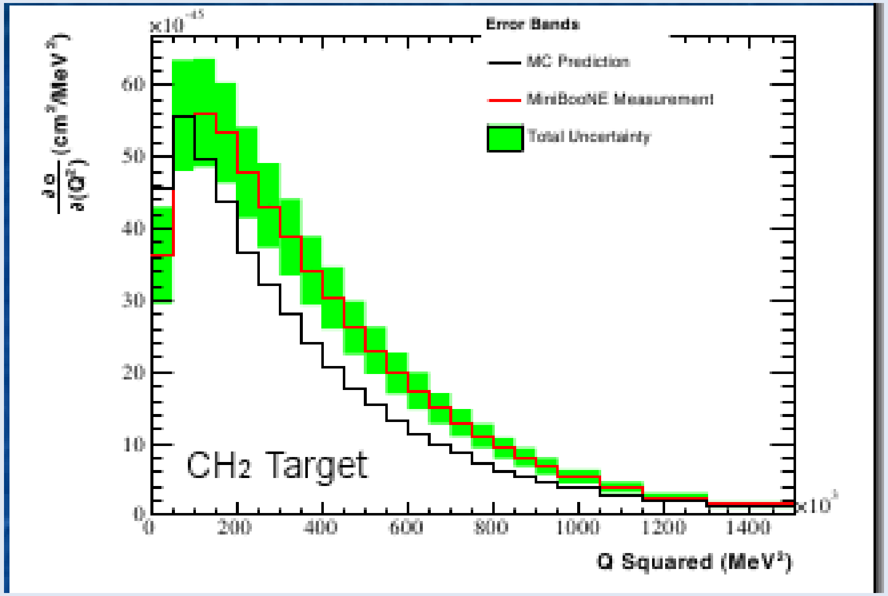


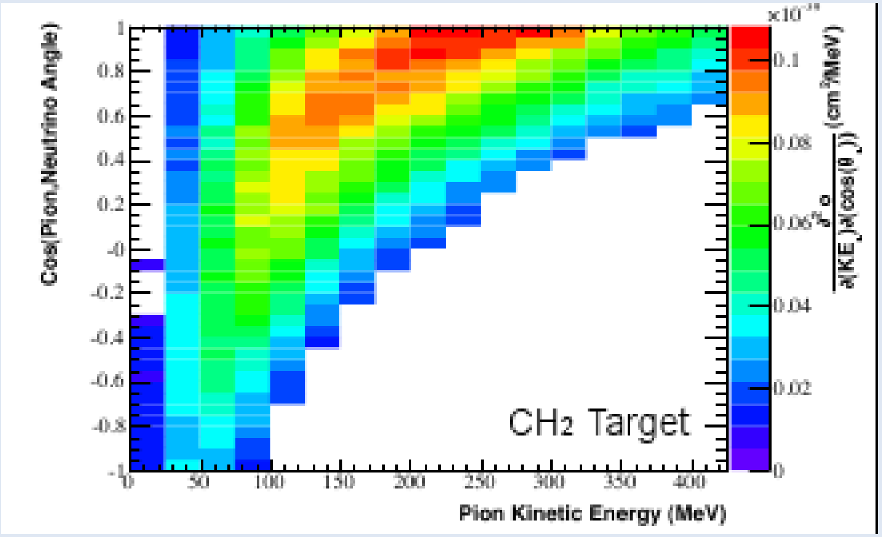
MiniBooNE measures both Cerenkov and scintillation light !

(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)

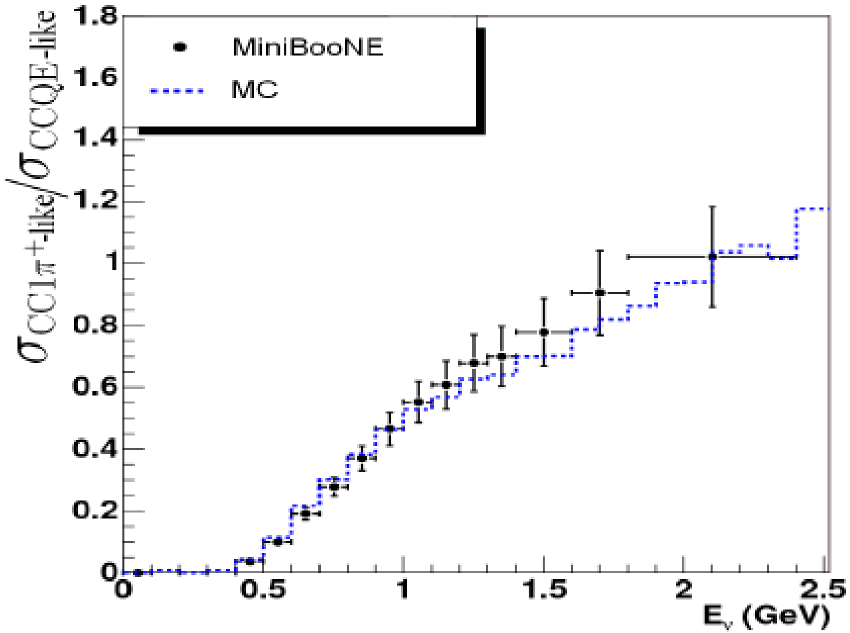


FIG. 1: Observed CC1π^+-like/CCQE-like cross section ratio on CH_2, including both statistical and systematic uncertainties, compared with the MC prediction [6]. The data have not been corrected for hadronic re-interactions.

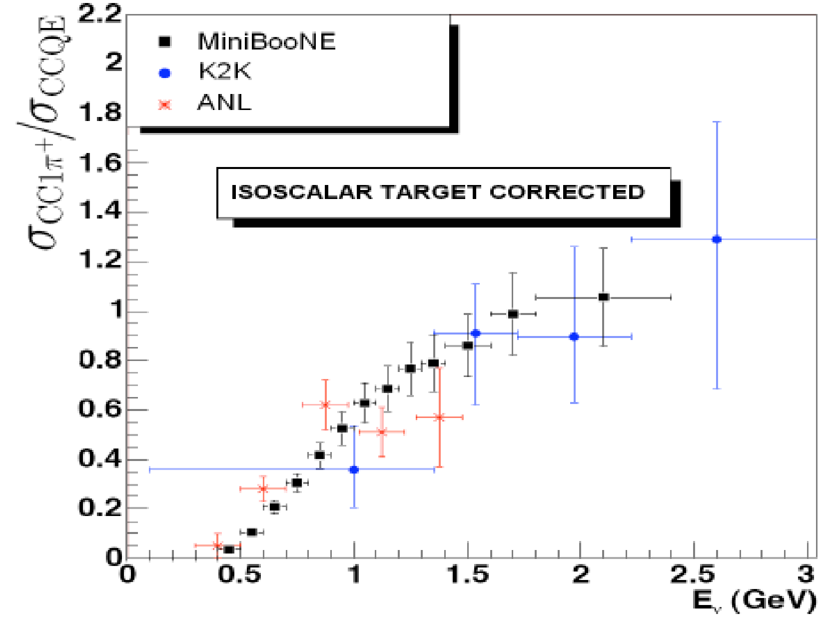


FIG. 2: FSI-corrected CC1π^+ to CCQE cross section ratio on CH_2 compared with results from ANL (D_2) [1] and K2K (C_8H_8) [3]. The data have been corrected for final state interactions and re-scaled for an isoscalar target.

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

Monte Carlo generators

- Production of neutrinos (how to constrain flux uncertainty?)
- **interactions**
- detector's performance.

All the degrees of freedom must be understood!

MC codes provide a bridge between theory and experiment:

- MCs contain description of our knowledge
- unexpected events can be a sign of „new” physics (example: excess of low energy electron neutrino events in MiniBooNE)

[this is an ideal situation: in reality MCs contain many simplifications...]

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.

Monte Carlo generators

Non-trivial differences come from:

RES => how many resonances? interference? non-resonant background? RES/DIS boundary? π angular distribution?

DIS => hadronization model?

COH => implementation of Rein-Sehgal model? modifications?

Most important differences come from:

Nuclear effects => Fermi gas? spectral function? off-shell effects? Δ in medium effects? final state interactions? absorption? formation zone?

There are also „trivial" differences coming from unknown parameters.

Monte Carlo generators

Until recently all the MC rely on the Fermi gas (FG) model

- very simple in implementation
- useful as a first approximation, but...

- we know from electron scattering that FG fails to reproduce exactly inclusive electron data in the quasi-elastic (electron community language!) region !

How to improve MC performance? Focus on QE reaction.

Monte Carlo generators

What do we need?

- we would like to have correct description of the integrated inclusive cross section
- it would be nice to have also reliable treatment of low Q2 behavior in the kinematical region of giant resonances.

How to proceed?

Strategy: review appoaches giving rise to good agreement with electron scattering data and select one which can be impelemented in MC.

Monte Carlo generators

An overview of approaches is presented in:

Comparison of Models of Neutrino-Nucleus Interactions

S. Boyd*, S. Dytman†, E. Hernández**, J. Sobczyk‡ and R. Tacik§

In order to deal with the fact that nucleon before and after interaction are bound one introduces self-energy which enters the (here non-relativistic) propagator:

$$G(\vec{p},E)=\int dE'\left(\frac{P_h(\vec{p},E')}{E-E'-i\eta}-\frac{P_p(\vec{p},E')}{E'-E-i\eta}\right)$$

$$P_h(\vec{p},E)=\frac{1}{\pi}\frac{\Im\,\Sigma(\vec{p},E)}{\left(E-\varepsilon(\vec{p})-\Re\,\Sigma(\vec{p},E)\right)^2+\left(\Im\,\Sigma(\vec{p},E)\right)^2}$$

Monte Carlo generators

- **Omar Benhar (Rome**) calculates the hole SF including short range correlation contribution. The particle SF (FSI effects) is evaluated in the eikonal approximation.

- **Ulrich Mosel (Giessen)** includes only real part of self-energy for the hole part while the density dependent potential are applied for the particle part.

- **Jan Ryckebusch (Ghent)** describes the struck nucleon within Walecka many body σ-ωmodel. Glauber theory is used for FSI.

- **Jose Udias (Madrid)** also uses Walcka mean field theory but the final nucleon is a solution of the Dirac equation with the same potential.

- **Juan Nieves (Valencia**) does RPA computations.

- **Carlotta Giusti (Pavia**) Green function approach

All the approaches claim to be succesfull in dealing with electron data.

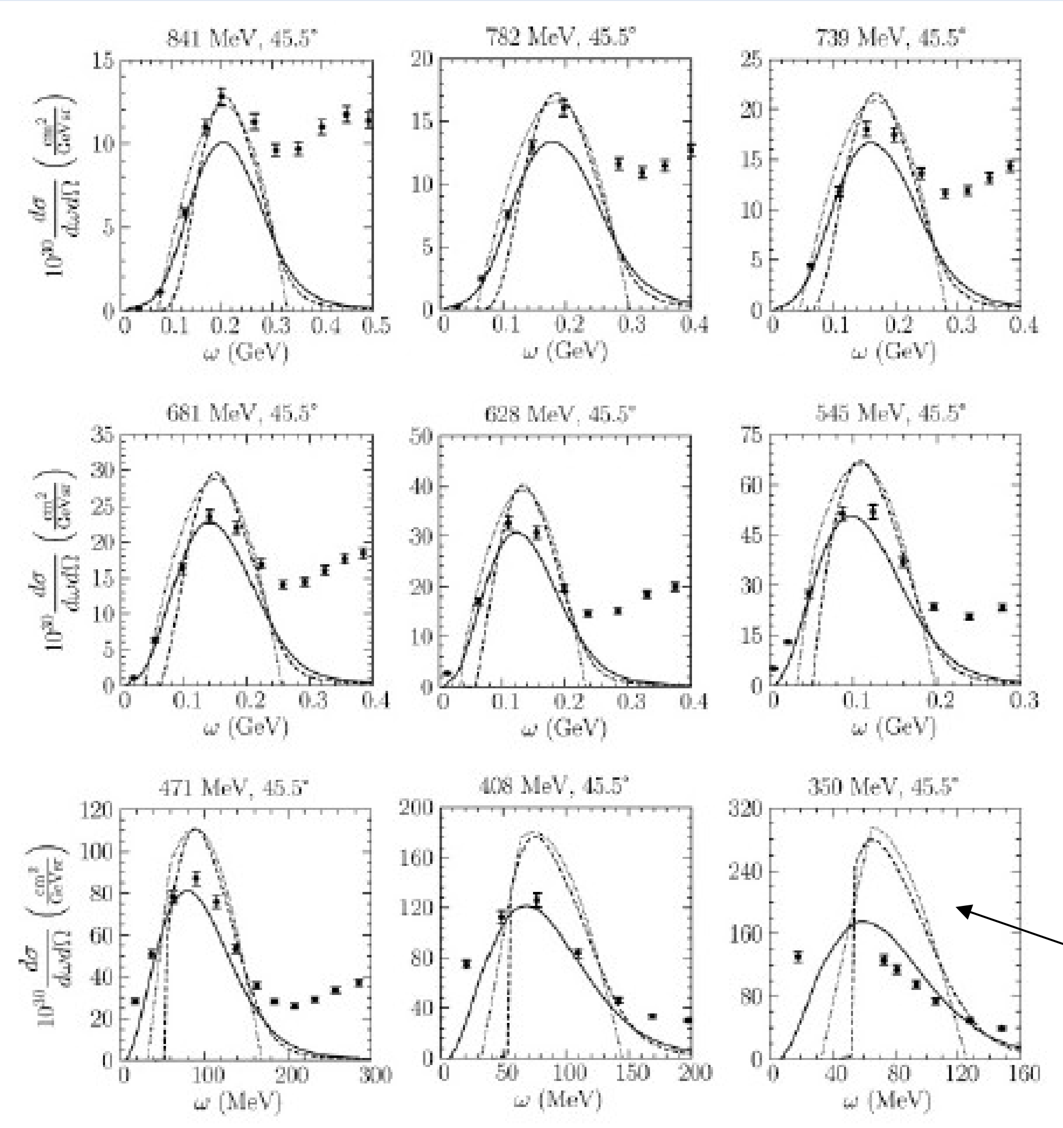
Monte Carlo generators

For Monte Carlo implementation the Omar Benhar's approach seems to be the simplest one:

- the hole's spectral function is the joint probability distribution to find a nucleon with given momentum leaving nucleus with a given excitation energy

- the particle's spectral function can be either taken as a free one (Plane Wave Impulse Approximation) or approximated by a model leading to the simple folding formula.

Monte Carlo generators



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.

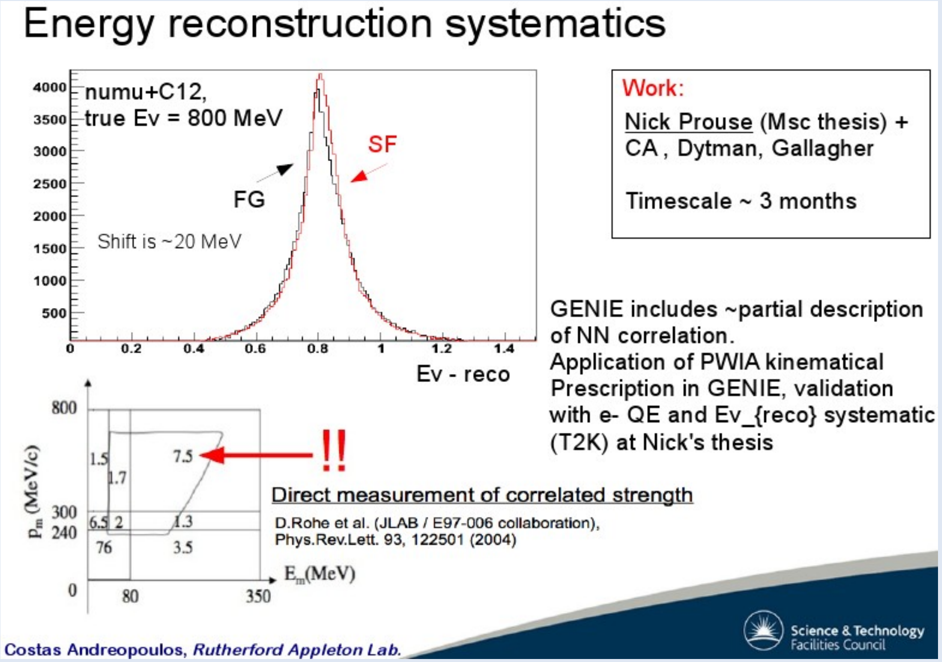
Data is for the inclusive cross section!

momentum transfer at the peak is 250 MeV !

Monte Carlo generators

Implementation of the spectral function:

- intermediate step: „effective spectral function” .
  (Ankowski, JTS, Phys. Rev. C74 (2006) 054016)
- genuine spectral function in NuWro (author: Cezary Juszczak)

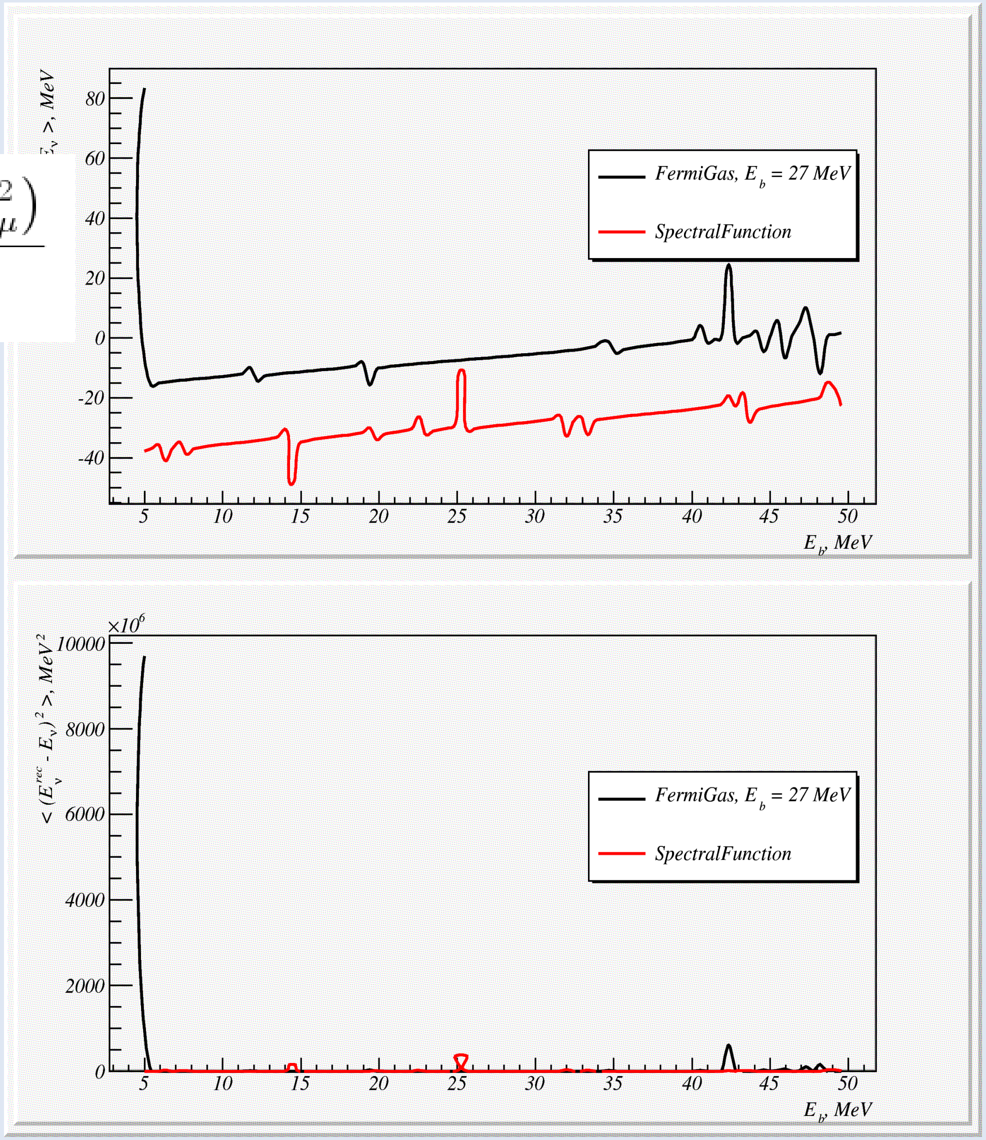


GENIE plans
(from Costas Andreopoulos talk
on October 30, 2009)

Spectral function in action

$$E_{rec} = \frac{\varepsilon_f (M - \epsilon_b) + \frac{1}{2}\left(\epsilon_b^2 - 2M\epsilon_b + m_\mu^2\right)}{(M - \epsilon_b) - \varepsilon_f + k_f \cos\Theta}$$

„Binding energy" is a free parameter here

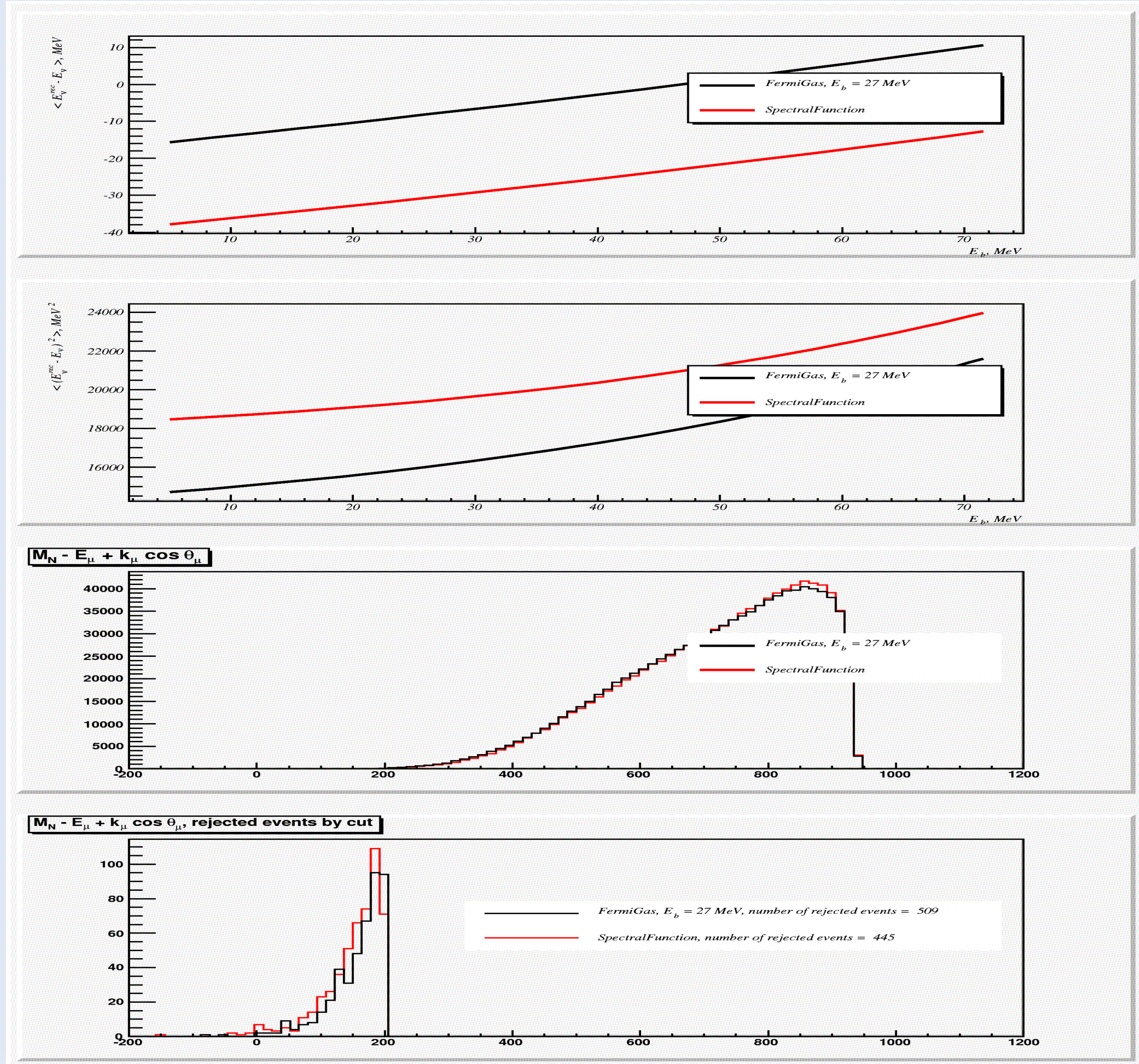


Plots done by Slava Lee

Spectral function in action

Explanation:
denominator
can be very small

Plots done by
Slava Lee



Conclusions

- neutrino interactions in 1 GeV region is an area of intensive activity
- low Q2 for quasi-elastic reaction requires more sophisticated nuclear models
- how important is 2p-2h contribution?... further cross-checks are necessary
- analysis of coherent pion production requires upgraded Monte Carlo generators
- does MiniBooNE understand the flux normalization?...
- finally in MC Fermi gas model was replaced by Benhar's spectral function approach
- **new data is necessary for further progress.**
- [nice agreement between NC1Pi0 data (with all FSI) and MC]

The end

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: $H_2O,\ CH_2,\ C_8H_8$ (*different ratios of carbon to hydrogen*)

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

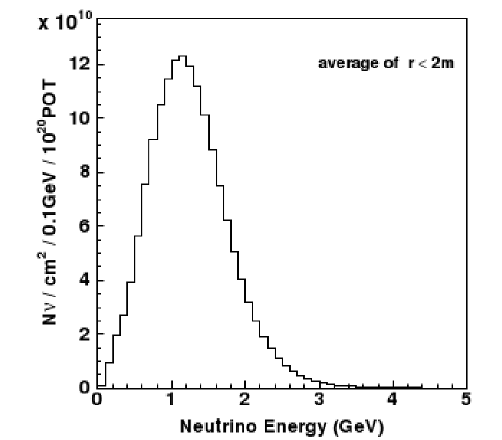
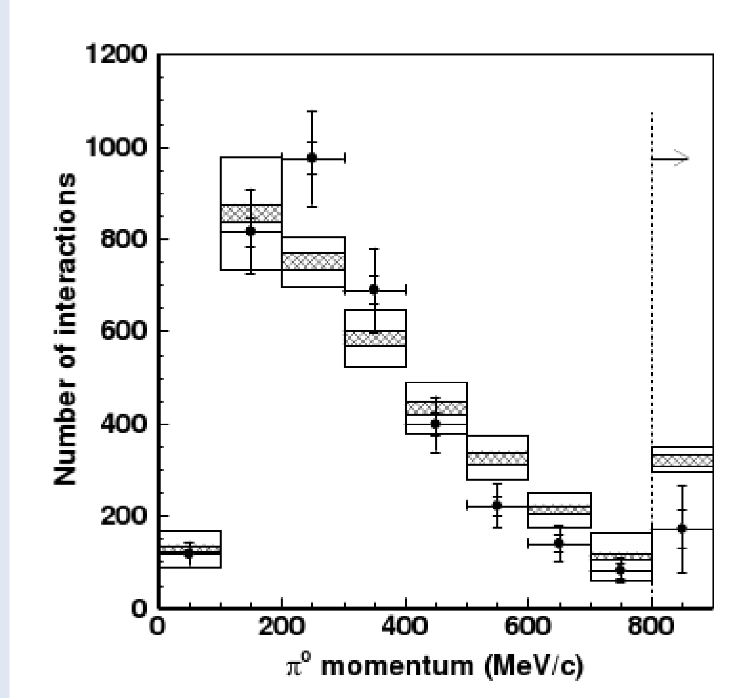


FIG. 1: The energy spectrum of the K2K neutrino beam at 300 m downstream from the target in the near site with a 10^{20} protons on target exposure predicted by a neutrino beam simulation. The spectrum is averaged within 2 m from the beam center.



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

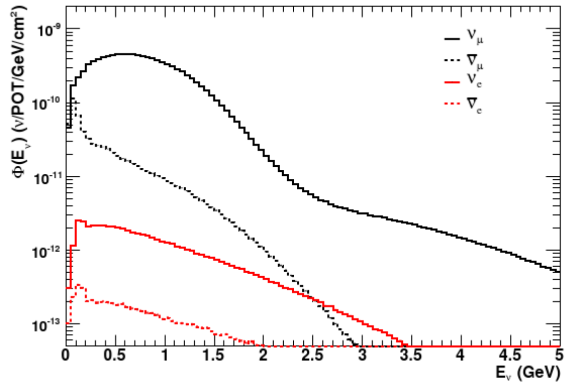


FIG. 27: Total predicted flux at the MiniBooNE detector by neutrino species with horn in neutrino mode.

Antineutrino mode

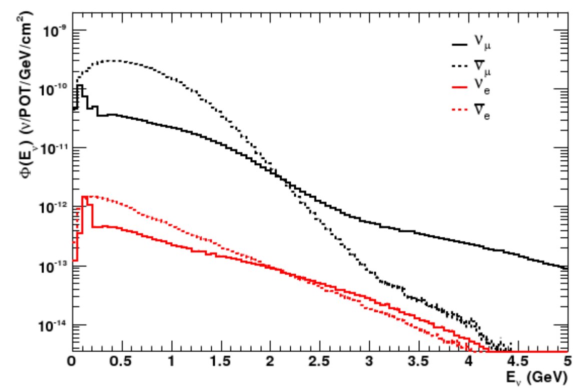


FIG. 28: Total predicted flux at the MiniBooNE detector by neutrino species with horn in anti-neutrino mode.

NC1Pi0

MiniBooNE:
arXiv:0911.2063[hep-ex]

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

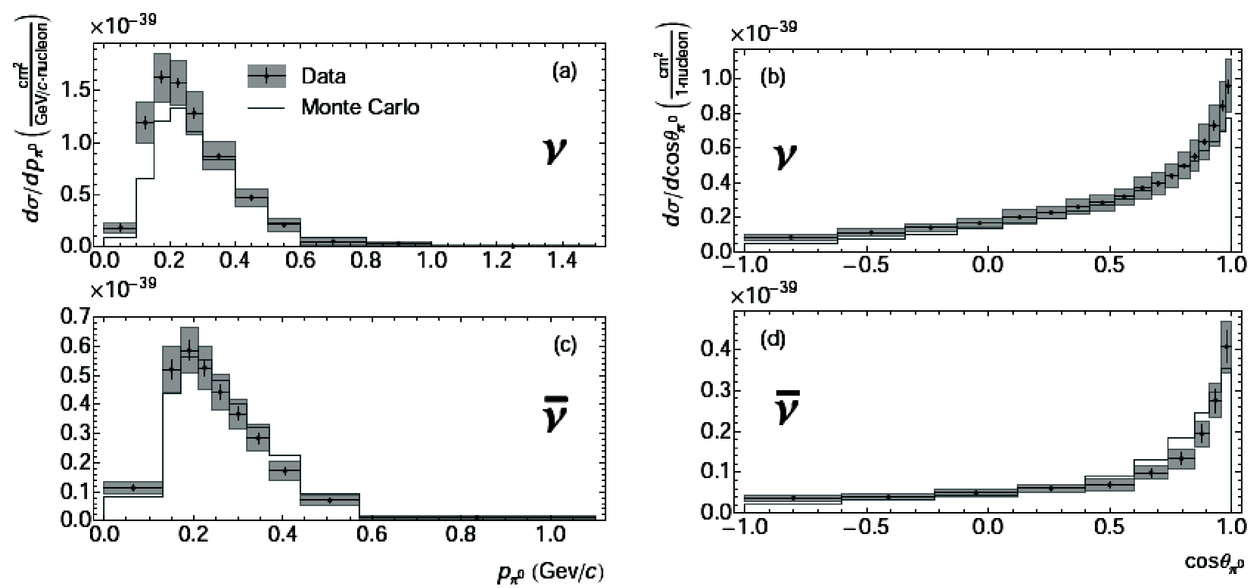


FIG. 7: Flux-averaged absolute differential cross sections for NC $1\pi^0$ production on CH_2 including the effects of FSI. Data are shown as black dots with statistical error bars and systematic error boxes. The dark-gray line is the Monte Carlo prediction[26] using R-S models of single pion production[2, 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

NC1

SciBooNE:
arXiv:0910.5768[hep-ex]

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, $\nu_\mu C \rightarrow \nu_\mu \pi^0 X$ where X represents the nuclear remnant and any combination of nucleons and mesons. According to our MC simulation,

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

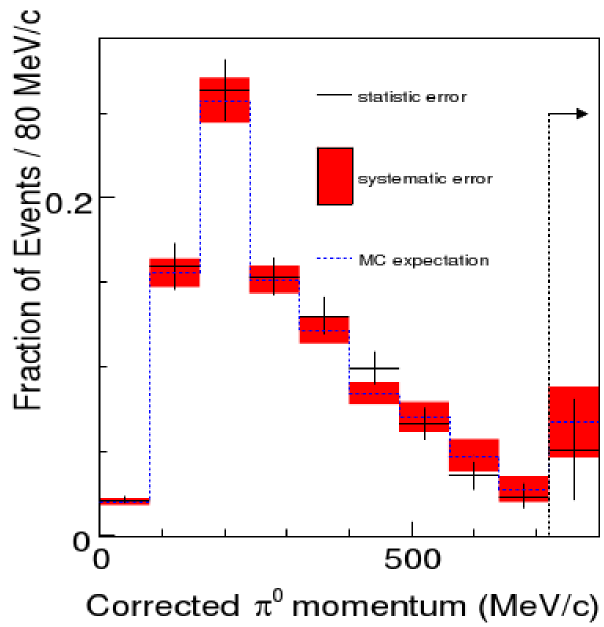


FIG. 21: The π^0 momentum distribution after all corrections described in the text, with statistical (error bars) and systematic (red boxes) uncertainties. The dashed line shows the Monte Carlo expectation based on the Rein and Sehgal model.

target: C_8H_8

NC1Pi0

SciBooNE (cont)

The definition of the measured events is little unclear:

IV.A --->

nucleons and mesons. According to our MC simulation, 96% of NCπ^0 events passing our selection cuts have a single π^0 (85 % from a single π^0 without any other mesons and 11 % from a single π^0 with charged mesons) and 4 % have two π^0s. Any π^0 emitted from the initial target nu-

IV.D.8 --->

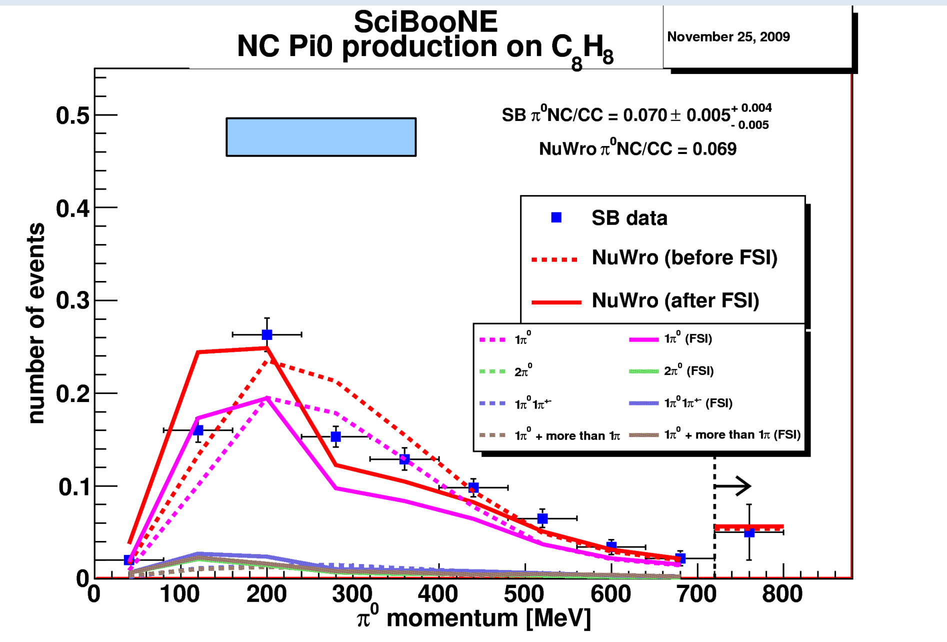
inelastic scattering). According to our MC simulation, 96% of selected NCπ^0 events have one π^0 (91 % from a single π^0 without any other mesons and 5 % from a single π^0 with charged mesons) and 4% have two π^0s. The

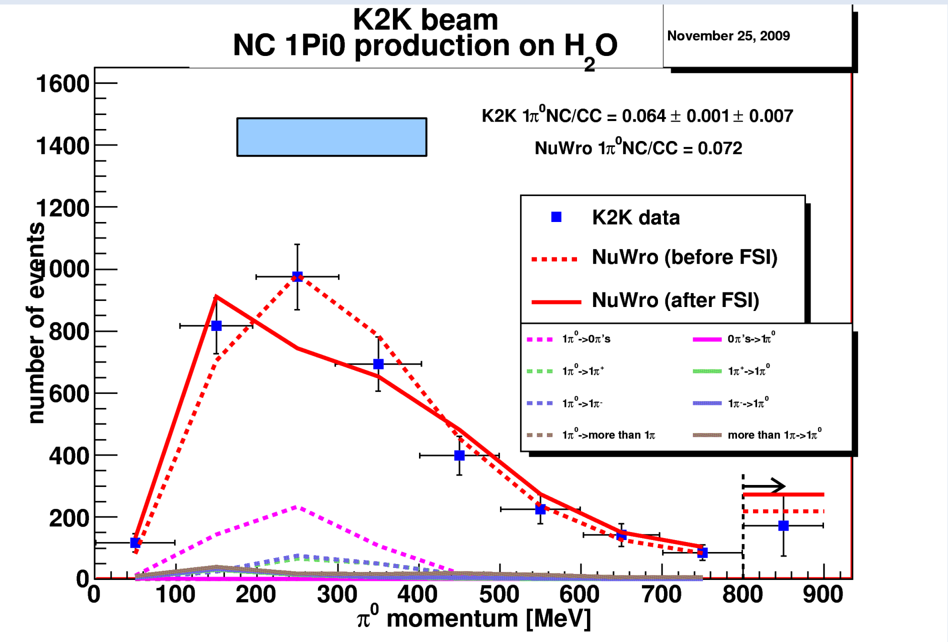
It means that some cuts are imposed: how they are defined?...

NC 1 Pi0 production

The data presents a challange 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.





NC 1 Pi0 production