NuWro Monte Carlo event generator

NuFact11, Geneve, August 3

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Outline

NuWro - motivation

- The project started $\sim$ 2005 at the Wrocław University.
- Encouragment from Danka Kiełczewska (Warsaw).
- Aim: investigation of nuclear effects and its impact on observables.
- The only neutrino MC event generator done by theorists
- Main authors:
  - Cezary Juszczak - basic scheme, flux, detector interface
  - Jarosław Nowak (now at the Minnesota University) - hadronization model
  - Tomasz Golan - improvements in the intranuclear cascade model
  - JTS

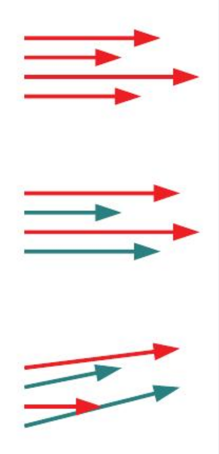
General remarks

- the code written in C++.
- NuWro shares many common features with better known codes: NEUT, GENIE, NUANCE, FLUKA
- the code is very effective: only $\sim 13'$ needed to produce 100 kiloevents for the T2K beam in the ND280 detector !

Beam

Three options:

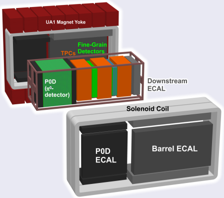
- one flavour neutrinos, fixed direction, an arbitrary energy distribution
- a mixture of flavours, each one with its own energy distribution
- neutrinos retrieved from data files (arbitrary flavours, directions, energies)



Target

Three options

- a single isotope model (including also a single nucleon mode)
- a mixture of isotopes (composition defined by relative weights)
- detector's geometry given as a root Geometry object.
  - geometry is read from a file containing the detector's definition
  - region of interest can be limited to a box by specifying its center and halfsize vectors.



Interactions - basic assumptions

Description of neutrino interactions in MCs is based on several (not obvious) assumptions:

- Impulse Approximation - a nucleus is composed from quasi-free nucleons
  - interaction is a two-step process: primary vertex followed by Final State Interactions
  - in MCs FSI effects do not affect final lepton, it is a unitary transformation in the space of final hadron states.
- FSI effects are modeled (at best) within an intranuclear cascade model
  - between interactions particles move in the classical way
  - typically free hadron-hadron cross sections are used.

Basic assumption: Impulse Approximation

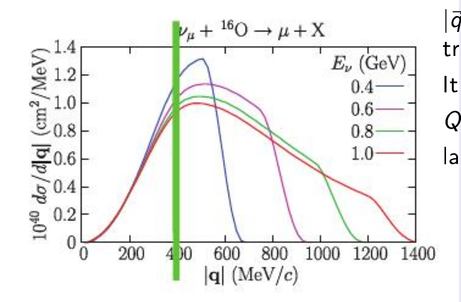
- nucleus is composed from individual quasi-free nucleons. How well is this assumption justified?...
- de Broglie wave length of a virtual vector bosons should be at least $\frac{1}{|\vec{q}|} \sim 1$ fermi.
- experience from electron scattering: the momentum transfer should be $\geq 300 - 500$ MeV/c.

Electron- neutrino- nucleus scattering

- in electron scattering experiments E is known and by selecting scattering angle one can control the value of the momentum transfer
- in neutrino experiments energy is smeared and the above is impossible.

Impulse Approximation

In neutrino inclusive experimental data there is always a large contribution from low momentum transfers. Below: results obtained within IA.



$|\vec{q}| > \omega$ (momentum and energy transfers), $Q^2 = \vec{q}^2 - \omega^2$.

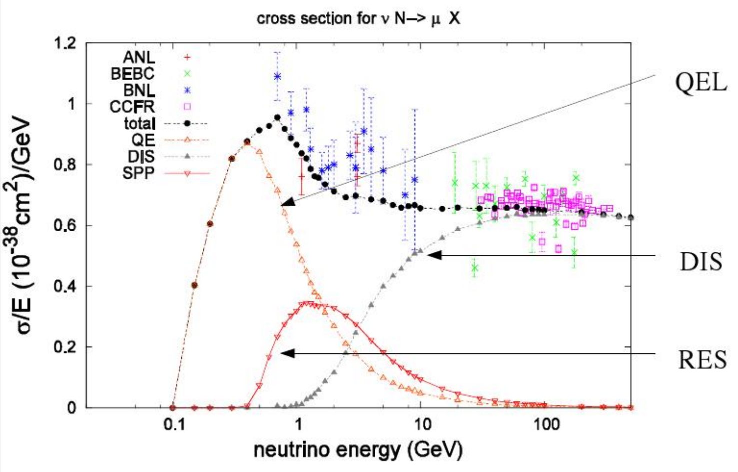
It follows that the region $Q^2 <\sim 0.2$ GeV^2 is a subject of large uncertainty.

In the giant resonance region FG (and neither SF) based models cannot be considered as reliable. CRPA or RPA techniques should be used instead.

Interaction modes

- four dynamic channels: quasielastic (QEL), resonance (RES), more inelastic (DIS), coherent pion production (COH)
- each one in charge or neutral current modes
- each mode can be separately switched on and off
- an interaction is followed by FSI (also can be switched off)

Contributions to νN CC cross section

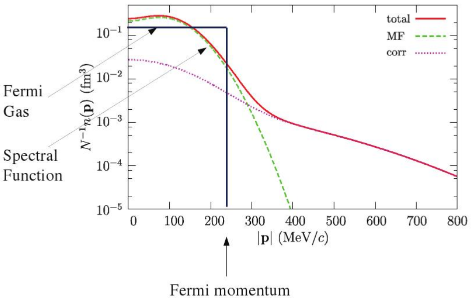


Predictions for QEL, RES and DIS obtained from NuWro.

Primary interaction

In each (but the coherent) case a particular nucleon is selected with nuclear matter density used as the probability density.
Its momentum is chosen:

- from a ball with the radius set to Fermi momentum
- as a draw from the Spectral Function.

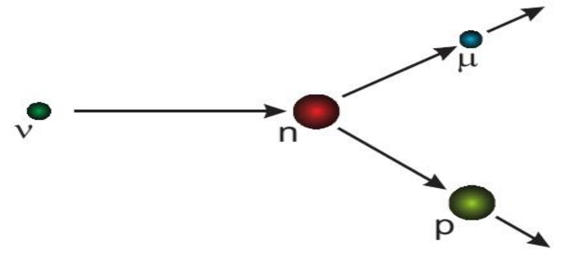


Usually interactons are modelled in the CMS frame (of the nucleon and neutrino pair). Particles in the final state are boosted back to the LAB frame.

Quasielastic reaction on free nucleon target

$$\nu_l + n \to l^- + p,$$

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



Quasielastic interaction

The standard Llewellyn Smith formula with several options for the vector form factors (dipole, BBA03, BBBA05, Alberico, Graczyk et al).

Choices for kinematics:

- global or local Fermi Gas
- Spectral Function (Carbon, Oxygen, Iron, Calcium and Argon)
  - for Carbon, Oxygen and Iron tables obtained from Omar Benhar (**THANKS!**)
  - for Calcium and Argon the approximate model
    [A.M. Ankowski, JTS, Phys. Rev. C77 044311 (2008)]
- momentum dependent nuclear potential (Brieva, DellaFiore)
  [C. Juszczak, J.A. Nowak, and JTS, Eur. J. Phys. C39 (2005) 195]

De Forest prescription for off-shell matrix elements in the SF model.

Resonance (Δ) production

- defined by $W < 1.6$ GeV
- only Δ treated explicitly
- **no** Rein-Sehgal model
  - quark-hadron duality,
  - heavier resonances not seen in reactions on nuclear targets
  - our hadronization model works well for low W
- non-resonant background is approximated as a fraction of the DIS contribution
- smooth (linear) transition to pure DIS for $W \in (1.3, 1.6)$ GeV

Δ production

Vector current:

$$\langle \Delta^{++}(p')|\, \mathcal{J}^V_\mu \,|N(p)\rangle = \sqrt{3}\bar{\Psi}_\lambda(p')$$

$$\times \left[g^\lambda_{\ \mu} \left(\frac{C_3^V}{M}\gamma_\nu + \frac{C_4^V}{M^2}p'_{\ \nu} + \frac{C_5^V}{M^2}p_\nu \right) q^\nu \right.$$

$$\left. -q^\lambda \left(\frac{C_3^V}{M}\gamma_\mu + \frac{C_4^V}{M^2}p'_\mu + \frac{C_5^V}{M^2}p_\mu \right) \right] \gamma_5 u(p),$$

M - nucleon mass, $\Psi_\mu(p')$ - Rarita-Schwinger field for Δ, $u(p)$ - Dirac spinor for N, $q^\mu = p'^\mu - p^\mu$.

Δ production

Axial current:

$$\left\langle \Delta^{++}(p') \right| \mathcal{J}^A_\mu \left| N(p) \right\rangle = \sqrt{3}\bar{\Psi}_\lambda(p')$$

$$\times \left[g^\lambda{}_\mu \left(\gamma_\nu \frac{C_3^A}{M} + \frac{C_4^A}{M^2} p'{}_\nu \right) q^\nu - q^\lambda \left(\frac{C_3^A}{M} \gamma_\mu + \frac{C_4^A}{M^2} p'{}_\mu \right) \right.$$

$$\left. + g^\lambda{}_\mu C_5^A + \frac{q^\lambda q_\mu}{M^2} C_6^A \right] u(p).$$

There are altogether 7 form-factors.

Vector FF

We use CVC and the experimental fits proposed by Olga Lalakulich et al

$$C_3^V(Q^2) = 2.13 \left(1 + \frac{Q^2}{4M_V^2}\right)^{-1} G_D(Q^2),$$

$$C_4^V(Q^2) = -1.51 \left(1 + \frac{Q^2}{4M_V^2}\right)^{-1} G_D(Q^2),$$

$$C_5^V(Q^2) = 0.48 \left(1 + \frac{Q^2}{0.776M_V^2}\right)^{-1} G_D(Q^2),$$

where $G_D(Q^2) = \left(1 + \frac{Q^2}{M_V^2}\right)^{-2}$, $M_V = 0.84$ GeV.

Axial FF

[K.M. Graczyk, D. Kiełczewska, P. Przewłocki, and JTS, Phys. Rev. D80 (2009) 093001]

- typically one sets $C_3^A(Q^2) = 0$;
- the Adler model suggests $C_4^A(Q^2) = -C_5^A(Q^2)/4$,
- the PCAC hypothesis implies $C_6^A(Q^2) = \frac{M^2}{m_\pi^2+Q^2} C_5^A(Q^2)$, m_π is the pion mass;
- $C_5^A(0)$ from the off-diagonal Goldberger-Treiman relation: $C_5^A(0) = \frac{g_{\pi N\Delta} f_\pi}{\sqrt{6}M} = 1.15 \pm 0.01$,
- one of two analyzed functional forms is:

$$C_5^A(Q^2) = \frac{C_5^A(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2},$$

We fit either only M_A or both M_A and $C_5^A(0)$.

Fitting procedure

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{\sigma_{th}^{diff}(Q_i^2) - p\sigma_{ex}^{diff}(Q_i^2)}{p\Delta\sigma_i} \right)^2 + \left(\frac{p-1}{\Delta p} \right)^2,$$

p accounts for the overall normalization.

Both ANL and BNL data are used in the simultaneous fit.

Deuterium nuclear corrections are included:

$$R(Q^2) = \frac{\left(d\sigma(\nu d \to \mu^- n \Delta^{++})/dQ^2\right)_{deuteron}}{\left(d\sigma(\nu p \to \mu^- \Delta^{++})/dQ^2\right)_{free\ target}}$$

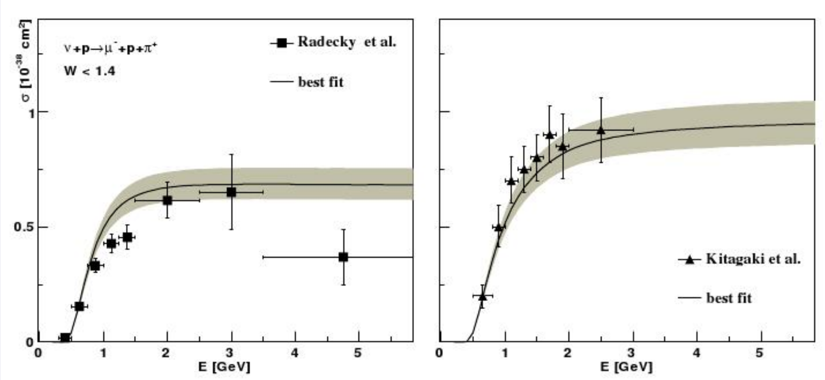
[L. Alvarez-Ruso, S. K. Singh and M. J. Vicente Vacas, Phys. Rev. C 59 (1999) 3386.
S.K. Singh, S. Ahmad, and Sajjad Athar, talk at NuInt02]

Results

	M_A (GeV)	$C_5^A(0)$	p_{ANL}	p_{BNL}	χ^2/NDF	GoF
dipole, only M_A, free target	0.95 ± 0.04		1.15 ± 0.06	0.98 ± 0.03	25.5/28	0.60
dipole, only M_A, deuteron	0.94 ± 0.04		1.04 ± 0.06	0.97 ± 0.03	24.5/28	0.65
dipole, M_A and $C_5^A(0)$, free target	0.95 ± 0.04	1.14 ± 0.08	1.15 ± 0.11	0.98 ± 0.03	25.5/27	0.54
dipole, M_A and $C_5^A(0)$, deuteron	0.94 ± 0.03	1.19 ± 0.08	1.08 ± 0.10	0.98 ± 0.03	24.3/27	0.60

Nuclear effects change $C_5^A(0)$ by 5%. Renormalization factors p_{ANL} and p_{BNL} are quite different: ANL and BNL data become compatible.

Results



The fit was done in the Δ^{++} channel in which a non-resonant background is very small. However, the background contributes significantly to other channels.

RES - more details

$$\frac{d\sigma^{SPP}}{dW} = \frac{d\sigma^{\Delta}}{dW}(1-\alpha(W)) + \frac{d\sigma^{DIS}}{dW}F^{SPP}(W)\alpha(W),$$

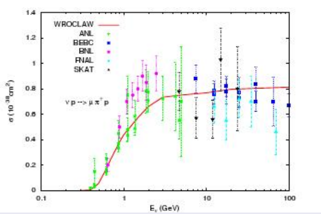
$$F^{SPP} \equiv \frac{\frac{d\sigma^{DIS,1\pi}}{dW}}{\frac{d\sigma^{DIS}}{dW}}, \qquad \alpha_0 \ \text{ is a free parameter}$$

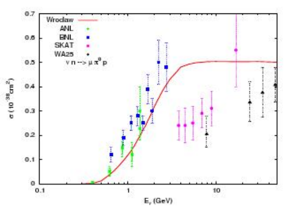
$$\alpha(W) = \Theta(W - W_{max}) + \Theta(W_{min} - W)\frac{W - W_{thr}}{W_{min} - W_{thr}}\alpha_0$$

$$+\Theta(W_{max} - W)\Theta(W - W_{min})\frac{W - W_{min} + \alpha_0(W_{max} - W)}{W_{max} - W_{min}}.$$

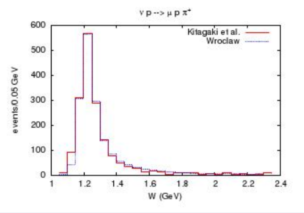
RES - performance

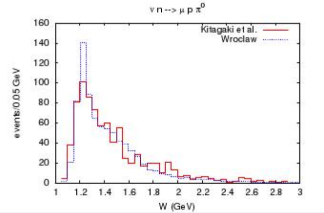
$\nu_\mu p \to \mu^- p \pi^+$ $\nu_\mu n \to \mu^- p \pi^0$





A cut $W < 2$ GeV was imposed. For the distribution of events in W we compare with the BNL data (Kitagaki et al):



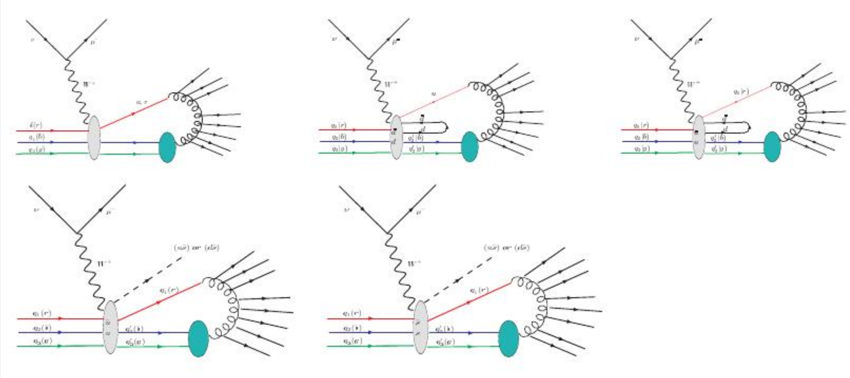


DIS

DIS stands for *more inelastic channels*

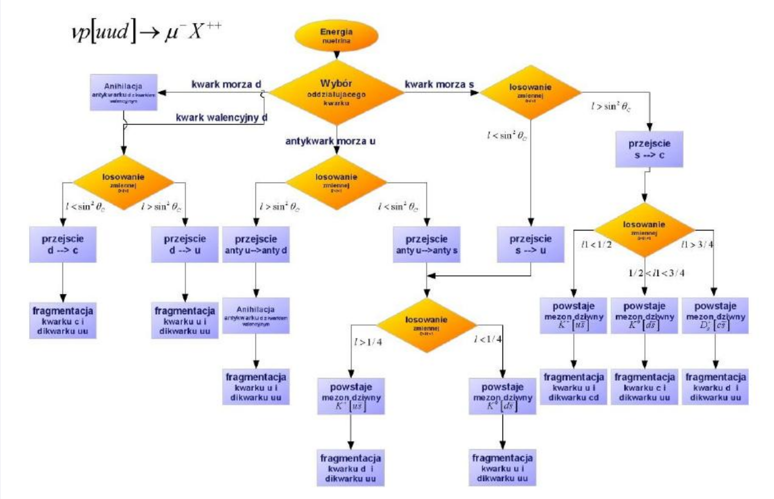
- defined as $W > 1.6$ GeV
- total cross section taken from the Bodek-Yang approach
- hadronization done by a custom-made model
  - inspired by F. Sartogo PhD thesis (supervised by Paolo Lipari)
  - contributions from individual quarks
  - PYTHIA6 fragmentation routines are used
  - some parameters were fine tuned:
    - PARJ(32) = 0.1 GeV (default value: 1.0 GeV)
    - PARJ(33) = 0.5 GeV (0.8 GeV)
    - PARJ(34) = 1.0 GeV (1.5 GeV)
    - PARJ(36) = 1.0 GeV (2.0 GeV)
    - MSTJ(17) = 3 (2)

DIS - contribution from scattering on individual partons



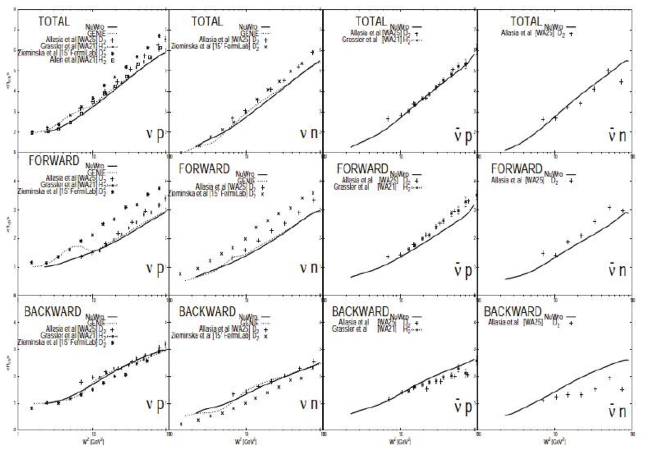
A νN CC interaction can happen on quarks $d, s, \bar{u}$.

DIS - details of particular scenarios



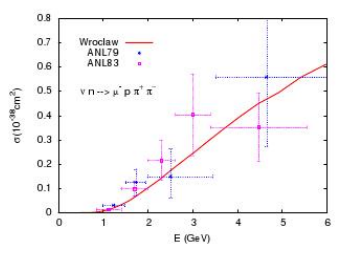
DIS - NuWro performance 1

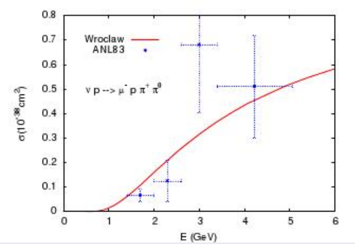
Charged hadron multiplicities in neutrino reactions: total, forward and backward hemispheres.

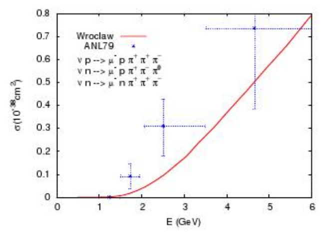


DIS - NuWro performance 2

Another interesting test: multpion production.
From top right in the clockwise direction:
1) $\nu_\mu n \to \mu^- p \pi^+ \pi^-$
2) $\nu_\mu p \to \mu^- p \pi^+ \pi^0$
3) Sum of 3π production channels







Final State Interactions effects

Particles present in the interaction point are subject to reinteractions.

- In the relevant kinematical region one can adopt semi-classical picture and consider all the QM effects as contained in *effective* hadron-nucleon cross section (including pion absorption probability) and formation zone/coherent length
- models of this kind are quite succesfull

  [L.L. Salcedo, E. Oset, M.J. Vicente-Vacas, and C. Garcia-Recio, Nucl. Phys. A484 (1988) 557]

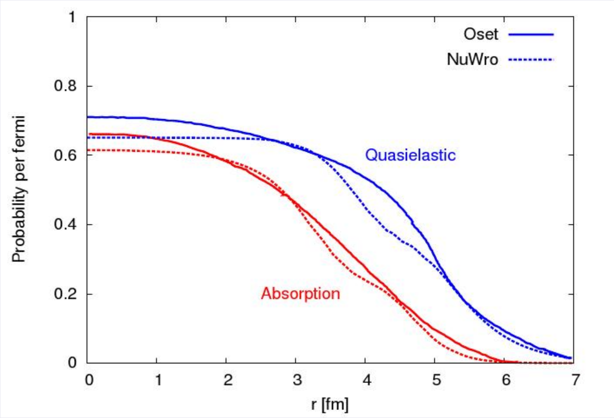
  [S.G. Mashnik and A.J. Sierk, LANL Report LA-UR-98-5999 (1998)]
- in this picture (adopted by all MCs!) FSI effects do not change the inclusive cross section acting merely as a unitary transformation in the space of final hadronic states.

NuWro FSI model

A standard approach:

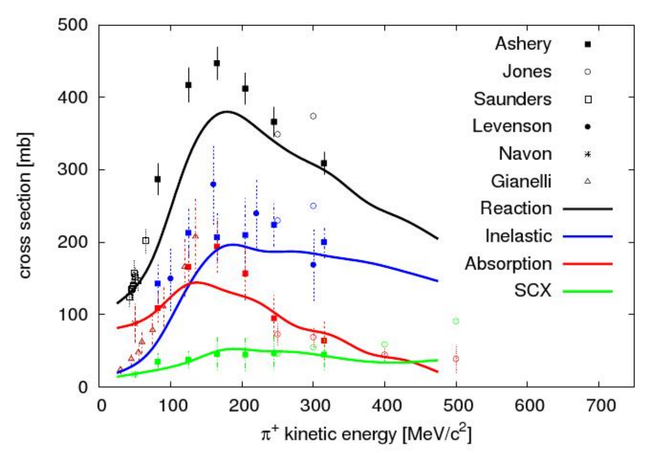
- an idea goes back to old Metropolis papers
- π cross sections in the Δ region taken from Oset et al approach (like NEUT)
- πN pion production directly from the data
- free NN cross sections
- Pauli blocking in LDA approach
- a lot of work on the formation zone effects (no clear conclusion yet)

Comparison with the original Oset paper



Probabilities (per 1 fm) of microscopic quasielastic and absorption reactions in ^{56} Fe for π^+ of energy $T_\pi = 165$ MeV. The agreement is satisfactory.

π^+ ^{12}C cross section



π^+ ^{12}C cross section

Formation zone

Intuition: hadrons travel some distance before they can reinteract.

- original idea: Landau & Pomeranchuk
- in the context of QCD: color transparency
- quantum diffusion motivated model:
  G. R. Farrar, H. Liu, L. L. Frankfurt, and M. I. Strikman, Phys. Rev. Lett. 61 (1988) 686; W. Cosyn, PhD thesis.

$$L = \left(1 - \frac{x}{Q^2}\right)\frac{p}{\mu},$$

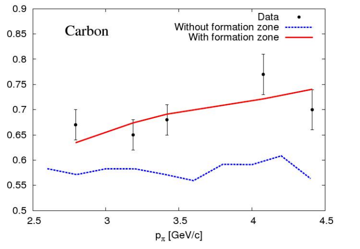
$x = 0.5$ GeV^2 (pions) and 0.9 GeV^2 (nucleons),

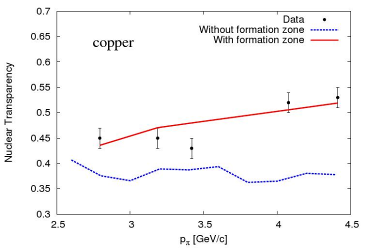
p - momentum,

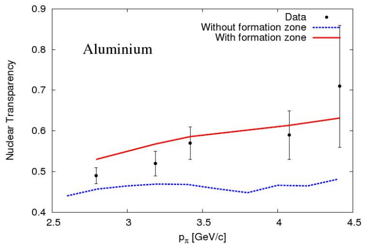
$\mu = 0.6$ GeV^2 (a fit to the pion transparency data, see below).

Pion transparency

The data from B. Clasie et al, Phys. Rev. Lett. **99** (2007) 242502.

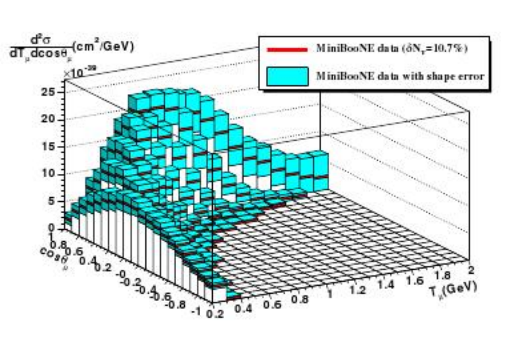






Application: MiniBooNE double differential cross section data

The data is available in the form of double differential cross section in muon kinetic energy and production angle:



A.A. Aguilar-Arevalo et al.,[MiniBooNE collaboration] Phys. Rev. D81, 092005 (2010)

The best fit value is $M_A^{eff} = 1.35 \pm 0.17$ GeV, $\kappa = 1.007 \pm 0.012$.

Similar values of M_A^{eff} were obtained both for shape only and for normalized cross section analysis.

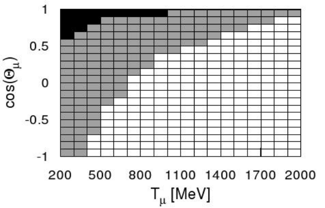
J-S-Ż

[C. Juszczak, JTS, J. Żmuda, Phys. Rev C82 045502 (2010)]

- Spectral Function and Fermi Gas model
- fitting both M_A and the overall normalization (fully correlated) uncertainty λ
- fitting to the 2D differential cross section

Low momentum transfer cut

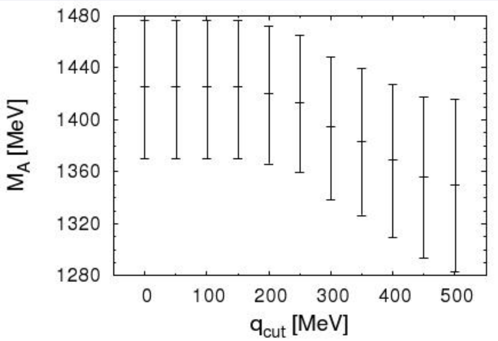
Bins with large (over 50%) contribution from the momentum transfer below q_{cut} (in black) are excluded from the analysis:



- $q_{cut} = 400$ MeV/c
- the excluded region contains almost all the bins for which Butkevich reported disagreement with the data!

J-S-Ż; low momentum transfer cut

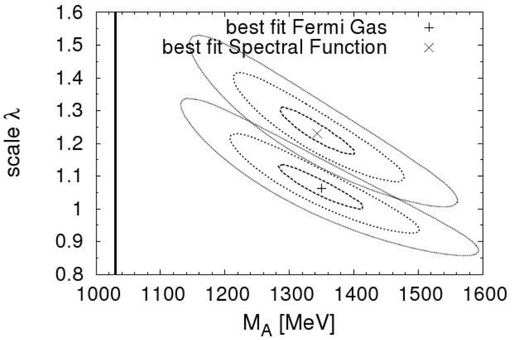
An impact on the best fit value of M_A:



For still larger q_{cut} statistical fluctuations appear (one looses more and more information).

The best fit value of M_A becomes smaller but the effect is not strong enough.

J-S-Ż; final results



$q_{cut} = 500$ MeV/c. 1-, 3- and 5σ regions are shown above.

- fits for M_A are very similar for FG and SF
- difference in cross section values for FG and SF is compensated by λ
- $M_A = 1.03$ GeV is excluded on the beyond 5σ level

The problem seems to be solved, see: J. Nieves, I. Ruiz Simo, and M.J. Vicente Vacas, *The nucleon axial mass and the MiniBooNE Quasielastic Neutrino-Nucleus Scattering problem*, arXiv:1106.5374.

Plans for the future

- documentation
  - update of the on-line version http://nuwro.ift.uni.wroc.pl/
  - the basic description (C. Juszczak, *Running NuWro*, Acta Phys. Polon. B**40** (2009) 2507) will be extended
- an implementation of multinucleon ejection mechanism (M. Martini or J. Nieves approaches)
- further studies of FSI effects
- better description of the non-resonant background
- last but not least: **use NuWro in the T2K ND280 data analysis** (in collaboration with the Warsaw group)

Thank you!

Back-up slides:

Spectral Function in action

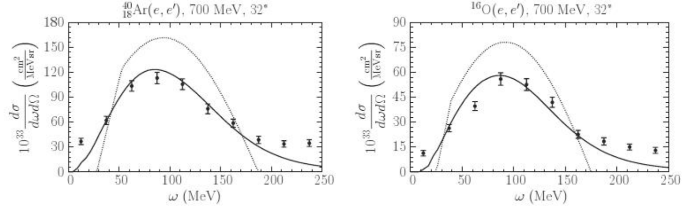


FIG. 7. (Left panel) Comparison of the cross section of GSF (solid line) and the FG model (dotted line) with experimental points for Ar(e,e') at beam energy 700 MeV and scattering angle 32° [7]. (Right panel) Same but for oxygen. Note that in both cases the similar accuracy is obtained. The value of momentum transfer at the peaks is 371 MeV.

[from: A.M. Ankowski, JTS, Phys. Rev. C 77 044311 (2008)]

Typically, SF based computations reproduce better QE peak. But...

- we compared to inclusive data which include Δ excitation and other dynamics in the DIP region (see later)
- SF computations include effects going beyond the PWIA (Plane Wave Impulse Approximation).

Cross section formula C.H. LLewellyn-Smith, Phys. Rep. 3, 261 (1972)

$$\frac{d\sigma_{\nu,\bar{\nu}}}{dQ^2} = \frac{G^2\cos^2\theta_C M^2}{8\pi E^2}\times$$

$$\times\left(A(Q^2) \pm B(Q^2)\frac{s-u}{M^2} + C(Q^2)\left(\frac{s-u}{M^2}\right)^2\right).$$

$s-u = 4ME - m^2$

$$C(Q^2) = \frac{1}{4}\left(F_A^2 + F_V^2 + \frac{Q^2}{4M^2}F_M^2\right),$$

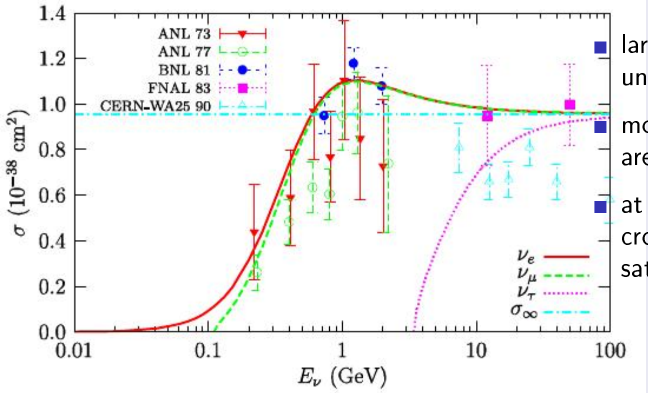
$$B(Q^2) = \frac{Q^2}{M^2}F_A(F_V + F_M),$$

$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\Bigg[(4+\frac{Q^2}{M^2})F_A^2 - (4-\frac{Q^2}{M^2})F_V^2$$

$$+\frac{Q^2}{M^2}(1-\frac{Q^2}{4M^2})F_M^2 + 4\frac{Q^2}{M^2}F_V F_M$$

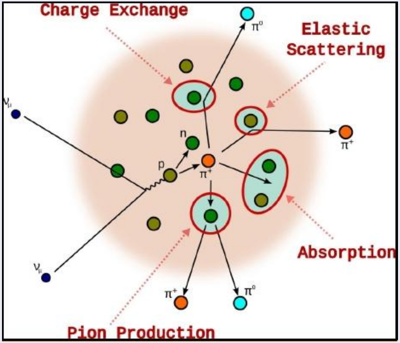
$$-\frac{m^2}{M^2}\left((F_V+F_M)^2+(F_A+2F_P)^2-(4+\frac{Q^2}{M^2})F_P^2\right)\Bigg]$$

Total CCQE cross section



- large experimental uncertainty
- most recent data are not included
- at large energy cross section saturates

FSI effects

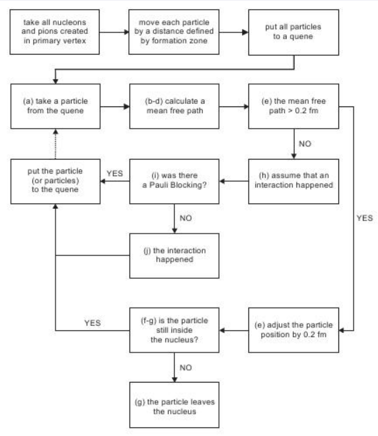


Experimentalists distinguish:

- QE-like events (no pions in the final state)
- 1π -like events (a single pion in the final state)
- etc

Pions produced in the primary interaction are subject to: absorption, charge exchange reactions, inelastic reactions (if they only have enough kinetic energy).

FSI - scheme



- hadrons move in steps of 0.2 fm
- nucleons are in the potential
  $V = E_{fermi}(r) + 8$ MeV