ISSUES and PROSPECTS

IN NEUTRINO NUCLEUS SCATTERING

by

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at

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PN12 / Nov. 2004

COLLABORATIONS:

i) Ingo Schienbein, J-Y. Yu, EAP
Pion Rescattering in Nuclei • hep-ph 04 08 148
with M. Sakuda • Phy. Rev. 69 (2004) 014013

ii) Olga Lalakulich, EAP • In preparation
(in preparation)

INTODUCTION

Close relation between neutrino and electron reactions

For NEUTRINOS :

- Oscillations parameters
- CP-Violation on leptonic sector
- Majorana - Dirac Particles

INTERESTED on interactions with

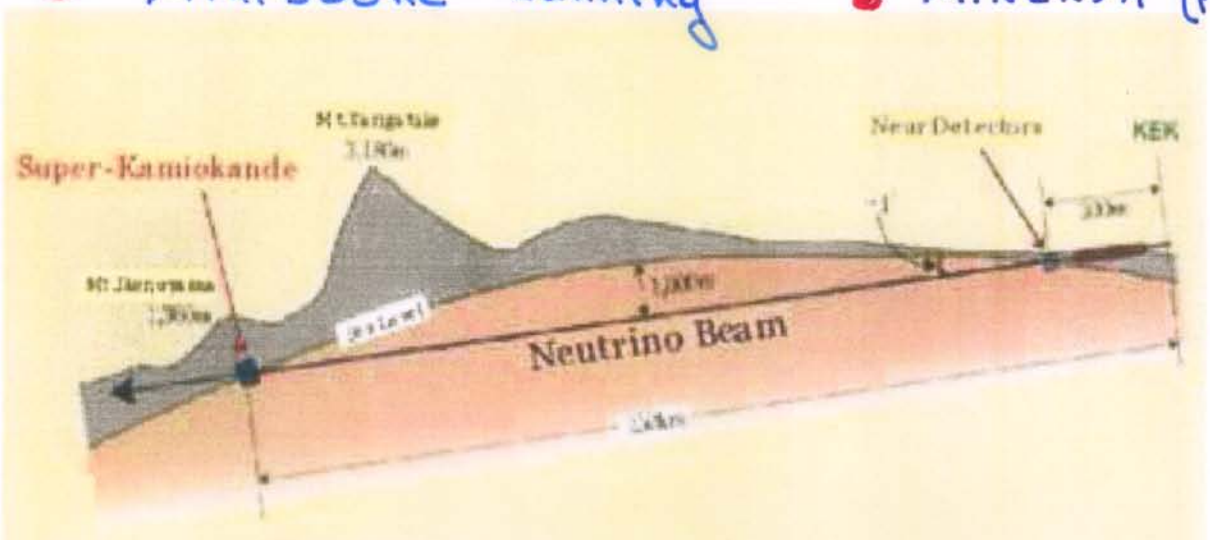
NUCLEONS and NUCLEI - SEPARATELY

Undestanding nuclei is not a luxury but a necessity since targets are nuclei : C_{12}, O_{16}, ..., Fe, ...

CONTENTS

Long baseline experiments

- T2K (Tokai to Kamioka) $\langle E_\nu \rangle \sim 0.7$ GeV (planned)
- K2K (KEK to Kamioka) $\langle E_\nu \rangle \sim 1$ GeV (operating)
- MINOS (Fermilab to Soudan) $\langle E_\nu \rangle \sim 3$ GeV
- CNGS (CERN to GranSasso) $\langle E_\nu \rangle \sim 17$ GeV (under construction)
- Miniboone Running
- MINERVA (proposed)



neutrino.kek.jp/news/

2004.06.10/index-e.html

Precision Measurements of neutrino Interactions. This could be done, perhaps, in terrestrial experiments with accelerator neutrino beams.

- ν_μ - Disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{1.27\,\Delta m^2_{23} L}{E_\nu}\right) + \dots$$

- ν_e - Appearance

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\,\Delta m^2_{23} L}{E_\nu}\right)$$

Several reasons demand precise knowledge of neutrino hadron cross section in the few GeV region.

Leptogenesis requires

$$Y_B = \frac{n_B}{n_s} = (\underline{\underline{\text{Sph.}}}) \cdot D \cdot \varepsilon$$

D: Dilution Factor ; $(\underline{\underline{\text{Sph}}}) \approx \frac{1}{3}$

ε: CP Violation in Lepton Sector

In models $\tilde{m}_D = m_D U_R$

and $$\varepsilon \propto \mathrm{Im}\left[(\tilde{m}_D^+ \tilde{m}_D)^2_{1j} \right] \frac{1}{[\tilde{m}_D^+ \tilde{m}_D]_{11}} \cdot$$

$$\sqrt{x} \left\{ \frac{1}{1 - \left(\frac{M_j}{M_1}\right)^2} + 1 - (1+x) \ln\left(\frac{1+x}{x}\right) \right\}$$

with $x = \frac{M_j}{M_1}$ (Vertex Fukugita-Yanagita) {Self-energy) Flanz, EAP, Sarkar}

IMPORTATNT TO ESTABLISH

CP-Violation in Leptonic Sector

$$A_{CP} = \frac{P - \bar{P}}{P + \bar{P}} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$\sim \frac{\Delta m^2_{12} L}{E} \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \sin\delta$$

Near/far detector cancellations of xsec errors

K2K SK

Number: N_1 Events $N_2 = a \cdot N_1 \cdot \text{Ratio}(2/1)$

Flux

Function of Flux, X-sec, eff.
cancels for identical detectors

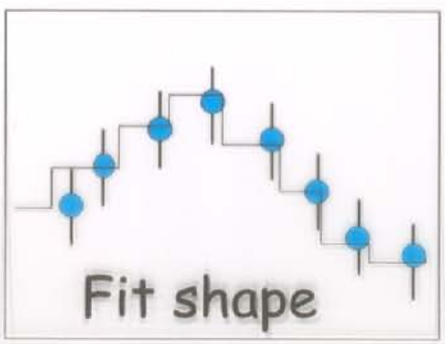
$\nu + n \to \mu^- p$
$\nu + N \to \mu^- \Delta$

Detector 1

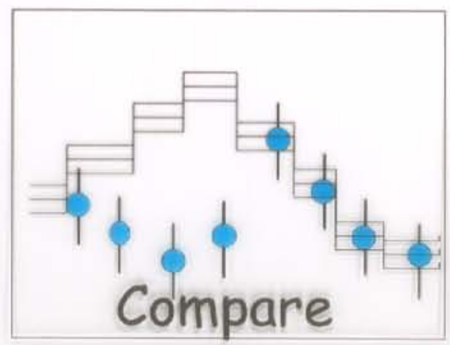
Detector 2

Shape:

E A P.
D. P. Roy
J. Y. Yu



E_μ



E_μ

Fitting errors correspond to an uncertainty on prediction.

C. Walter

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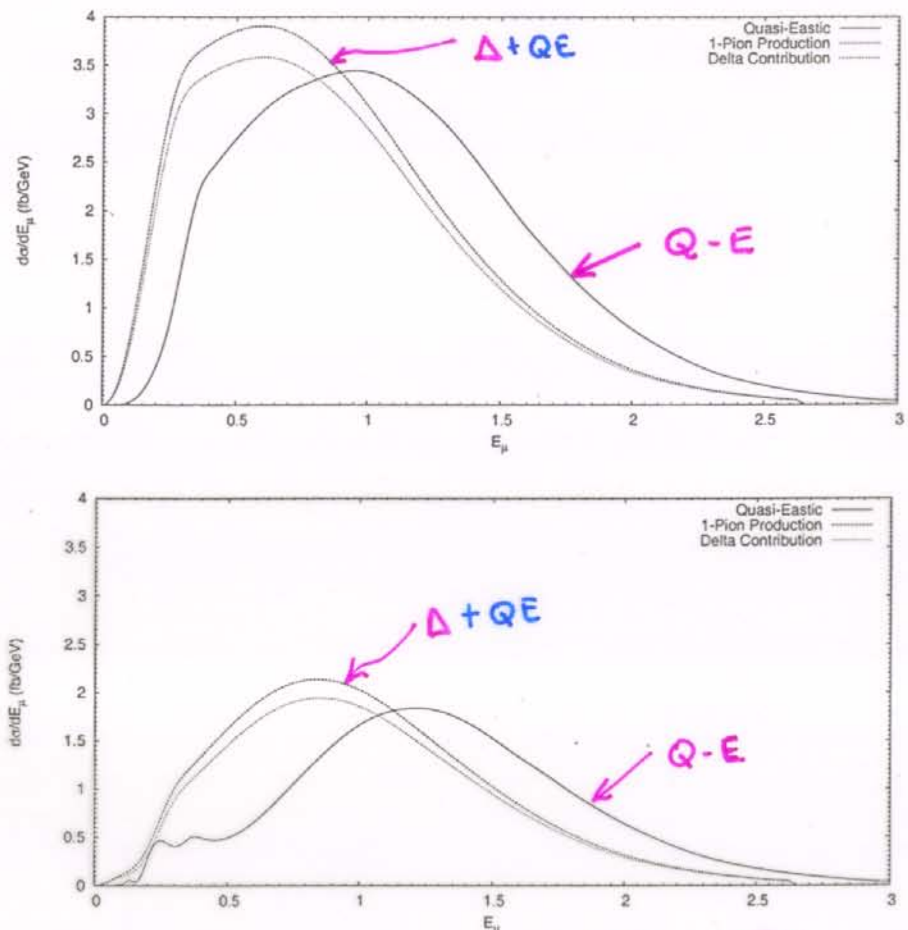
QE : $\nu + n \rightarrow \mu^- + p$

form factors for the vector and axial currents. The vector form factor is a modified dipole, while the axial one is a dipole [10]. For the P_{11} and S_{11} resonances we use the form factors from [11].



E.P., D.P. Roy, I. Schiebein and J. Yu Phys. Lett B 574 (2003) 239

Figure 2: Exact predictions of the muon energy spectra for the (a) Nearby and (b) SK detectors of the K2K experiment. The Quasi-Elastic and the 1-Pion production cross-sections are shown along with the Δ contribution to the latter.

KAMLAND

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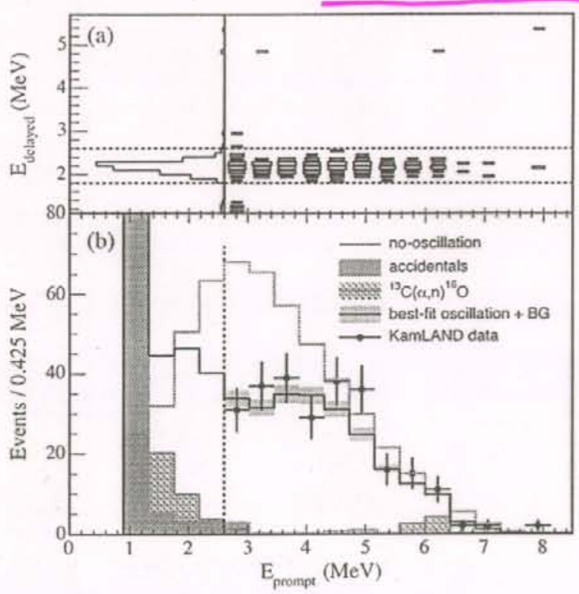

FIG. 2: (a) The correlation between the prompt and delayed event energies after cuts. The three events with $E_{\rm delayed} \sim 5\,\rm MeV$ are consistent with neutron capture on carbon. (b) Prompt event energy spectrum of $\overline{\nu}_e$ candidate events with associated background spectra.

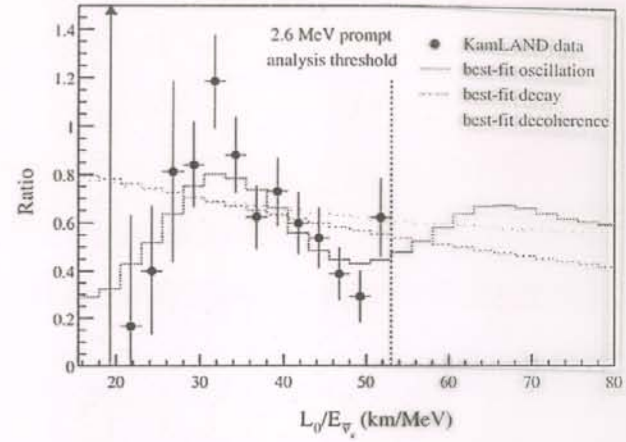

FIG. 3: Ratio of the observed $\overline{\nu}_e$ spectrum to the expectation for no-oscillation versus L_0/E. The curves show the expectation for the best-fit oscillation, best-fit decay and best-fit decoherence models taking into account the individual time-dependent flux variations of all reactors and detector effects. The data points and models are plotted with L_0=180 km, as if all anti-neutrinos detected in KamLAND were due to a single reactor at this distance.

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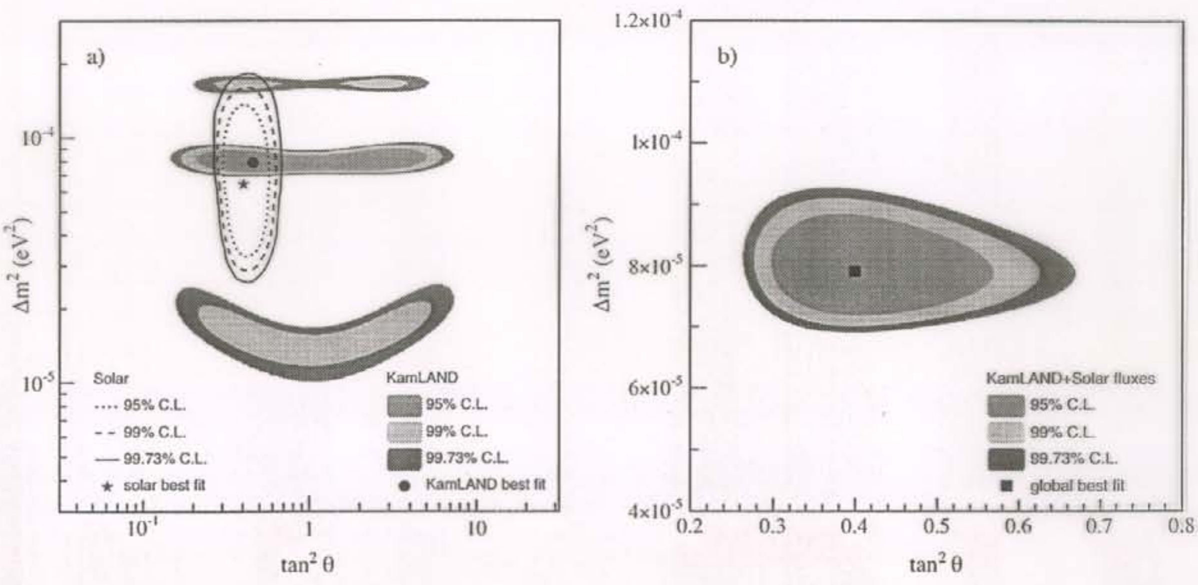
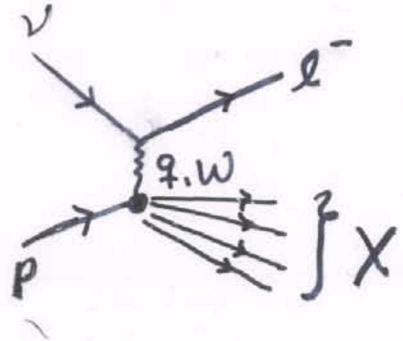


FIG. 4: (a) Neutrino oscillation parameter allowed region from KamLAND anti-neutrino data (shaded regions) and solar neutrino experiments (lines) [12]. (b) Result of a combined two-neutrino oscillation analysis of KamLAND and the observed solar neutrino fluxes under the assumption of CPT invariance. The fit gives $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\rm eV^2$ and $\tan^2\theta = 0.40^{+0.10}_{-0.07}$ including the allowed 1-sigma parameter range.

$\Delta m^2_{21} = 7.9^{+0.6}_{-0.1} \times 10^{-5}\, eV^2$

with 0.2 % uncertainty in theory

Neutrino nucleon reactions



a) Deep inelastic scattering

$CC: \nu N \rightarrow \ell^- X$

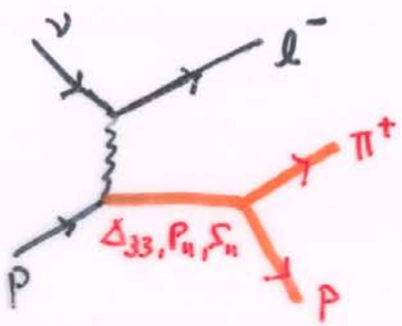
$NC: \nu N \rightarrow \nu X$

N: Nucleon

ℓ: μ, τ lepton

X: the system of the outgoing hadrons

Nuclear Effects at $0.4 < x$ play a role



P_{11} (1440)

S_{11} (1535)

b) Resonance production ($\Delta_{33}, P_{11}, S_{11}$)

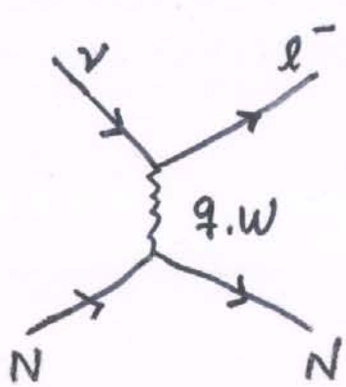
$CC: \nu p \rightarrow \ell^- p \pi^+$

$\nu n \rightarrow \ell^- n \pi^+$

$\nu n \rightarrow \ell^- p \pi^0$

$NC: \nu p \rightarrow \nu p \pi^0, \; \nu p \rightarrow \nu n \pi^+$

$\nu n \rightarrow \nu n \pi^0, \; \nu n \rightarrow \nu p \pi^-$



c) Quasi-elastic scattering

$CC: \nu N \rightarrow \ell^- N$

$NC: \nu N \rightarrow \nu N$

COHERENT SCATTERING IN NUCLEI

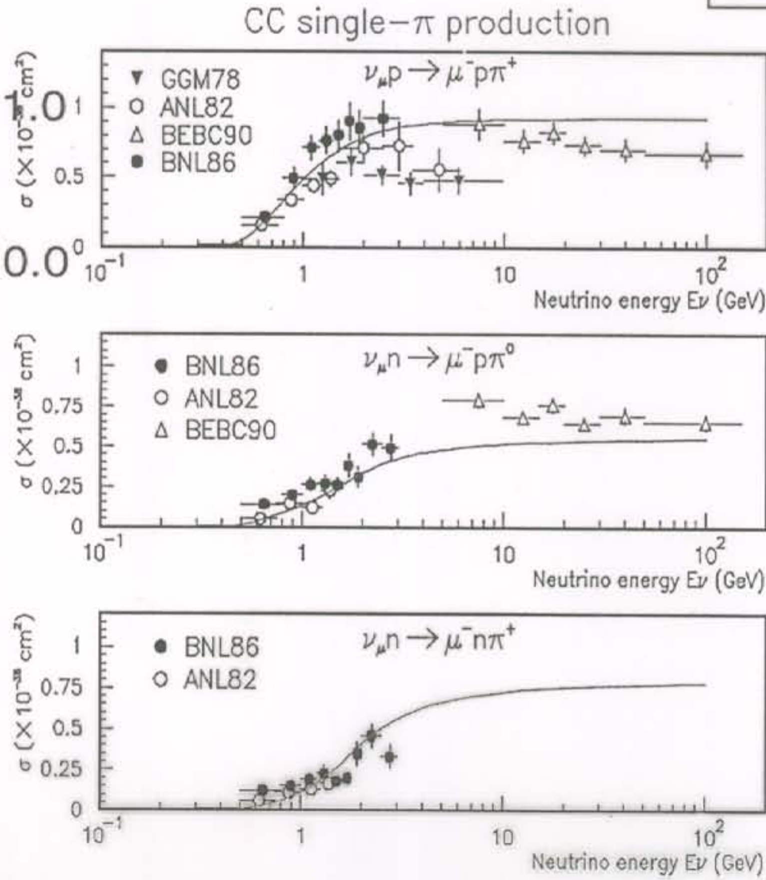
(DIFFRACTIVE)

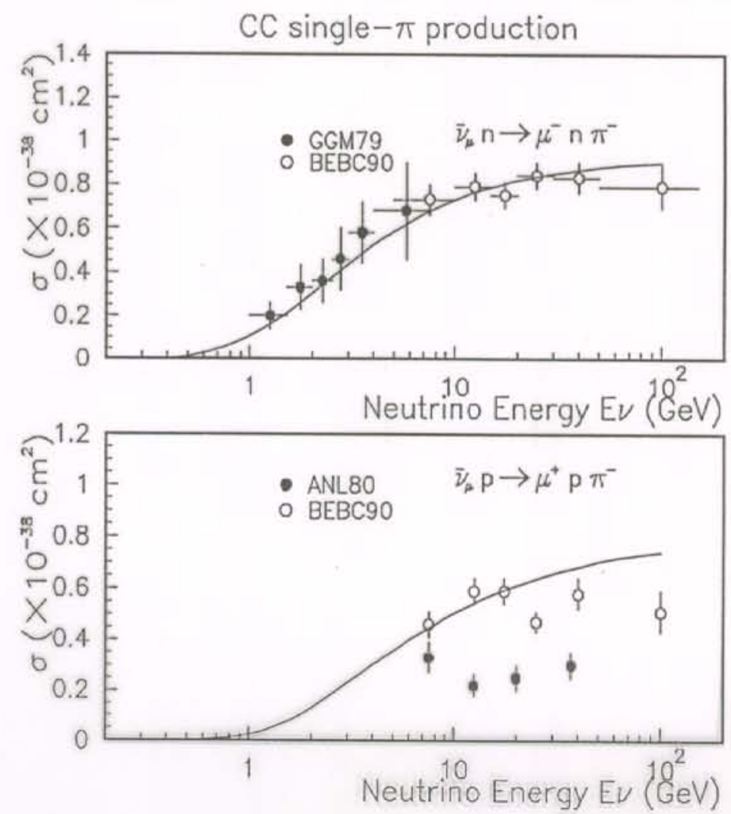
Single Pion Production Cross Section

Prediction = Rein-Sehgal M_A=1.2 GeV/c^2

1x10^{-38}
(cm^2)

1.0
0.0





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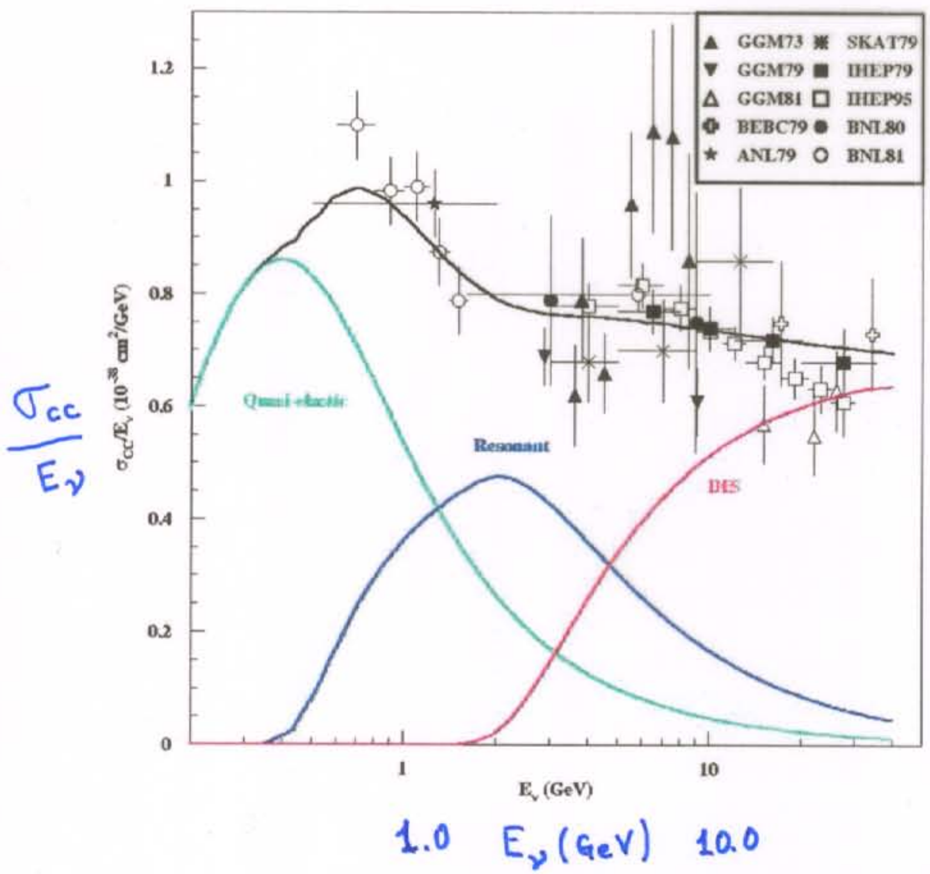
The total cross section



$\sigma_{tot} = \sigma_{\rm QE} + \sigma_{\rm RES} + \sigma_{\rm DIS}$

1) quasi-elastic (QE)

$\nu_\mu n \to \mu^- p$

2) one-pion-production $\equiv$

resonance production (RES)

$\nu_\mu N \to \mu^- R \to \mu^- N'\pi$

3) deep inelastic scattering (DIS)

$\nu_\mu N \to \mu^- X$

How many form factors do we need for N-R vertex

Form factors for $P_{33}(1232)$ $(J^P = \frac{3}{2}^+)$ C.H. Llewellyn Smith, Phys. Rep. 3 (1972) 261

$$\langle\Delta|V^\nu|N\rangle = \bar{\psi}_\lambda^{(R)} \left[\frac{C_3^V}{m_N}(\not{q} g^{\lambda\nu} - q^\lambda\gamma^\nu) + \frac{C_4^V}{m_N^2}(q\cdot p g^{\lambda\nu} - q^\lambda p^\nu) + \frac{C_5^V}{m_N^2}(q\cdot p' g^{\lambda\nu} - q^\lambda p'^\nu) + C_6^V g^{\lambda\nu}\right]\gamma_5 u_{(N)}$$

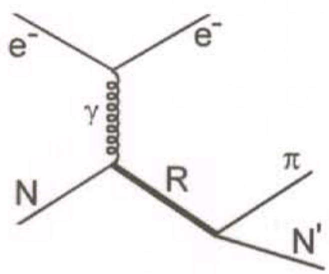
Working hypothesis:

$$\langle\Delta|A^\nu|N\rangle = \bar{\psi}_\lambda \left[\frac{C_3^A}{m_N}(\not{q} g^{\lambda\nu} - q^\lambda\gamma^\nu) + \frac{C_4^A}{m_N^2}(q\cdot p g^{\lambda\nu} - q^\lambda p^\nu) + C_5^A g^{\lambda\nu} + \frac{C_6^A}{m_N^2} q^\lambda q^\nu\right] u_{(N)}$$

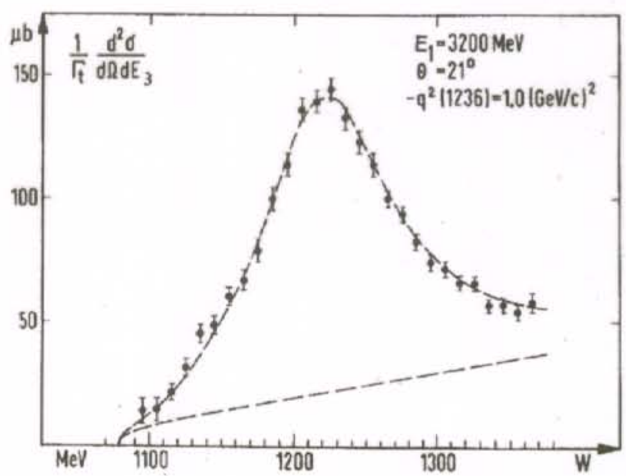
Can any of them be theoretically fi xed?

CVC $\Longrightarrow C_6^V = 0$, PCAC $\Longrightarrow C_5^A = 1.2$, $C_6^A = m_N^2 \frac{C_5^A}{m_\pi^2 - Q^2}$

Vector form factors



reveal theirselves in electro- (and neutrino-) production



Magnetic multipole dominance lead to

$$C_3^V(0) = 2.05, \quad C_4^V(0) = -\frac{m_N}{W} C_3^V, \quad C_5^V = 0$$

S. Galster et. al, Phys. Rev. D 5 (1972) 519, the curve is the phenomenological fi t by the authors

$$\frac{d\sigma^{em,\, I=1}}{dQ^2 dW} = \frac{8}{3}\frac{\pi^2}{G_F^2}\frac{\alpha^2}{Q^4}\frac{dV^\nu}{dQ^2 dW} \begin{cases} \frac{2}{3} : p\pi^0 \\ \frac{1}{3} : n\pi^+ \\ \frac{1}{3} : p\pi^- \\ \frac{2}{3} : n\pi^0 \end{cases}$$

Ratios are not satisfied : Background, Isospin ½

As Q^2 increases, the form factors fall down steeper than dipole (that is the case for the nucleon) representing the larger size of the resonance states because of the mesonic cloud, surrounding them.

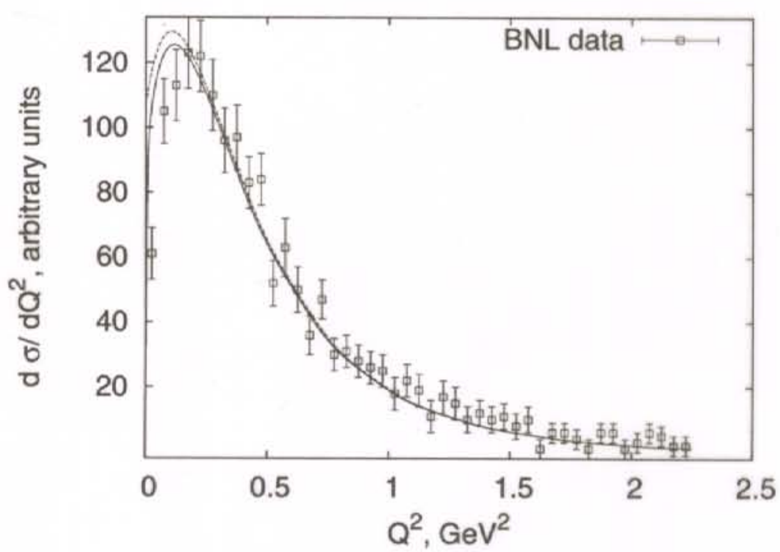
$$C^V(Q^2) = \frac{C^V(0)}{\left(1+\frac{Q^2}{{M_V}^2}\right)^2} \cdot \frac{1}{1+\frac{Q^2}{4{M_V}^2}} \quad \text{vector mass } M_V = 0.84\ \text{GeV}.$$

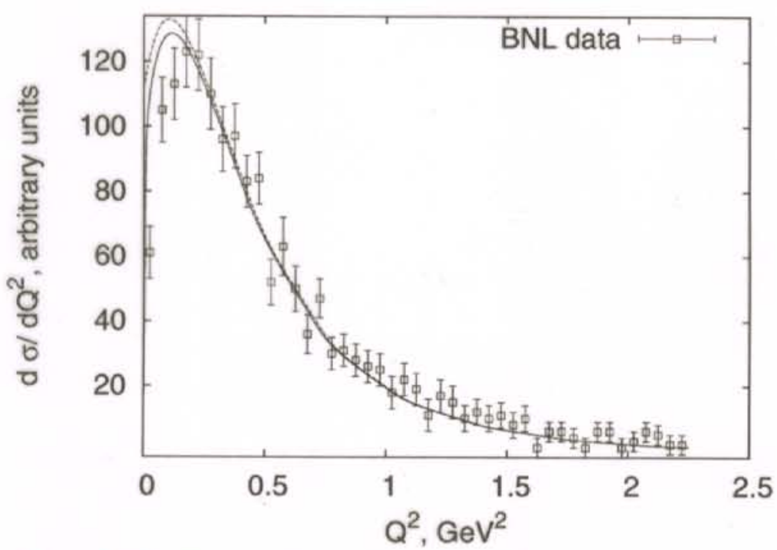
New data form Jefferson Laboratory: the contribution of the electric multipole $E2 \sim -2.5\%$, of scalar multipole $Q2 \sim -5\%$ – faster Q^2-dep. than M_{1+}

K. Joo et al. (CLAS) PRL 88 (2002) 122001

V. Burket EPJ Status of N^* Program at JeffLab

BNL data on the $d\sigma/dQ^2$.





The cross section for the running width $\Gamma \sim p^3_{(\pi)}$ (left figure) and $\Gamma \sim p^1_{(\pi)}$ (right figure). The full lines are for the case $m_\mu = 0.105\ \mathrm{GeV}$, the dashed lines are for the approximation $m_\mu = 0$.

Isospin-1/2 resonances, spin-1/2

$P_{11}(1440)$ ($J^P = \frac{1}{2}^+$)

$$\langle P_{11}|V^\nu|N\rangle = \bar{u}^{(P_{11})}\left[g_1^V\gamma^\nu + \frac{i}{M_P+m_N}g_2^V\sigma^{\nu\lambda}q_\lambda + g_3^V q^\nu\right]\gamma_5 u_{(N)}$$
$$\langle P_{11}|A^\nu|N\rangle = \bar{u}^{(P_{11})}\left[g_1^A\gamma^\nu + \frac{i}{M_P+m_N}g_2^A\sigma^{\nu\lambda}q_\lambda + g_3^A q^\nu\right] u_{(N)}$$

CVC: $g_1^V = g_3^V = 0$

CP invariance: $g_2^A = 0$

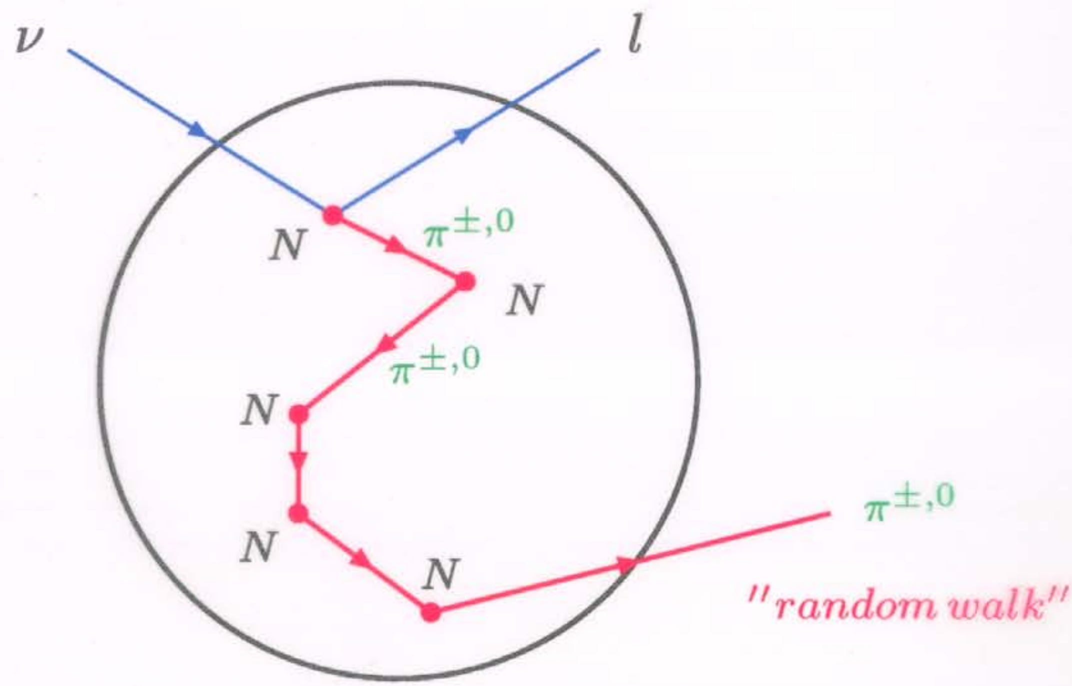
PCAC: $g_3^A = g_1^A \frac{\not{q}}{Q^2}$, $g_1^A = \frac{g_{\pi NR} f_\pi}{M_R + m_N}$

$S_{11}(1535)$ ($J^P = \frac{1}{2}^-$) (the similar formular)

Result: for spin-1/2 resonances one has 1 vector and 1 axial (theoretically fi xed from PCAC) form factors for each resonance

Factorization

- Reactions $e + T \to e' + T' + \pi^{+,0,-}$
  $$\nu + T \to l + T' + \pi^{\pm,0}$$
  - T: nuclear target (${}_8O^{16}$, ${}_{18}Ar^{40}$, ${}_{26}Fe^{56}$)
  - T': final nuclear state
- Two step process



Step 1.

1. single pion production in νN scattering
   $\to$ Pauli Principle, Fermi motion
2. multiple scattering of pions
   $\to$ Charge exchange, absorption, Pauli Principle

- step 2 is described by the charge exchange matrix M
  - only depends on properties of the target
    $\to$ charge density profile $\rho(r)$
- basic assumption: two steps independent $\to$ predictive power

The charge exchange matrix M

- Differential cross sections for leptonic pion production on free nucleon targets → cross sections on nuclear targets:

$$\underbrace{\begin{pmatrix} \frac{d\sigma({}_Z T^A;\pi^+)}{dQ^2 dW} \\ \frac{d\sigma({}_Z T^A;\pi^0)}{dQ^2 dW} \\ \frac{d\sigma({}_Z T^A;\pi^-)}{dQ^2 dW} \end{pmatrix}}_{\text{nuclear target}} = M \underbrace{\begin{pmatrix} \frac{d\sigma(N_T;\pi^+)}{dQ^2 dW} \\ \frac{d\sigma(N_T;\pi^0)}{dQ^2 dW} \\ \frac{d\sigma(N_T;\pi^-)}{dQ^2 dW} \end{pmatrix}}_{\text{free nucleon}}$$

where

$$\frac{d\sigma(N_T;\pm 0)}{dQ^2 dW} = Z\frac{d\sigma(p;\pm 0)}{dQ^2 dW} + (A-Z)\frac{d\sigma(n;\pm 0)}{dQ^2 dW}$$

- charge exchange matrix M for isoscalar targets
($M = M^T, \sum_j M_{ij} = A_p, M_{+0} = M_{-0} \to$ 3 param. A_p, d, c)

$$M = A_p \begin{pmatrix} 1-c-d & d & c \\ d & 1-2d & d \\ c & d & 1-c-d \end{pmatrix}$$

structure dictated by charge-symmetry

- Factorization assumption (two step process) → predicitve power

⇒ • $M(T; Q^2, W)$ (i.e. A_p, d, c) to be measured experimentally
neutrino-prod., electro-prod. → Test of Factorization

⇒ • ... to be predicted theoretically → for example ANP model [1]

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[1] Adler, Nussinov, Paschos, Phys. Rev. **D9**, 2125 (1974)

$A_p(Q^2, W) = f_1(1, W)\, g(Q^2, W)$

In the general case

$$\frac{\sum_{k=0,\pm} \frac{d\sigma({}^{z}T_A, \pi^k)}{dQ^2\, dW}}{\sum_{j=0,+,-} \frac{d\sigma(N_T, \pi^j)}{dQ^2\, dW}} =: A_p(Q^2; W)$$

IN MODEL CALCULATION

$$A_p = 1 - \frac{1}{2} \bar{L}\, \rho_0\, \sigma_{abs}(W)$$

$\bar{L}$ is the density profile $= 1.9R$

For ${}^{8}O_{16}$

$$R = 1.83\ \text{fm}\,, \quad \rho_0 = 0.14\ \text{fm}^{-3}$$

STEP 2: Solve PROPAGATION of Δ's, π^{k}'s, ...

This methods has similarities between particle-hole (Oset, Salcedo, Strottman Mosel et al.. Marteau) and stochastic propagation

IS THERE RELATION ?

$$A_p(Q^2, W) = g(Q^2, W) \cdot f(\lambda = 1, W)$$

$g(Q^2, W)$ is the Pauli suppression factor

$f(\lambda = 1, W)$ is the transport function

for equal populations of π^+, π^0, π^-

$$M({}^{8}O_{16}) = A_p \begin{pmatrix} 0.79 & 0.16 & 0.05 \\ 0.16 & 0.68 & 0.16 \\ 0.05 & 0.16 & 0.79 \end{pmatrix}$$

and

$$A_p = 0.77$$

Matrix and parameters defined for $W \left\{ \begin{array}{l} \text{invariant} \\ \text{mass} \end{array} \right.$ over the Δ resonance region

STEP 1 : Extract parameters from electroprod. or neutrino-production

S

Random Walk Problem

PROBABILITY OF GOING FROM x TO y

and interact. at y: $\boxed{e^{+\kappa(x-y)}\,\kappa\,dy}$

with $\kappa(y) = \rho(y)\,\sigma_{tot}$

$$\begin{pmatrix} \sigma_t(\pi^+) \\ \sigma_t(\pi^0) \\ \sigma_t(\pi^-) \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \sigma_{abs} + \begin{pmatrix} 5/9 & 1/9 & 0 \\ 1/9 & 4/9 & 1/9 \\ 0 & 1/9 & 5/9 \end{pmatrix} \cdot \frac{3}{2}\,\sigma_{\pi^+p}$$

Transmission is a matrix problem on the population $\begin{pmatrix} N_{\pi^+} \\ N_{\pi^0} \\ N_{\pi^-} \end{pmatrix}$

Find Eigenvalues and Eigenfunctions

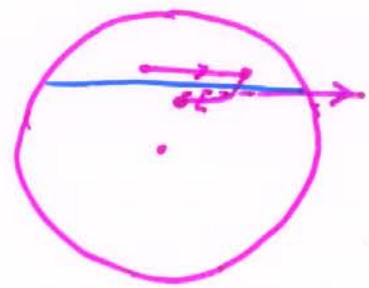
$$q_1 = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \qquad \lambda_1 = 1$$

$$q_2 = \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \qquad \lambda_2 = \frac{5}{6}$$

$$q_3 = \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix} \qquad \lambda_3 = \frac{1}{2}$$

Each eigenfunction has its own transport probability $f(\lambda, W)$ — given by solution of random walk solution (analytic or numerical)

Picture of Model



Two results from Neutrino Reactions

$$R^{\nu} = \frac{\sigma(\nu + T \to \nu + T' + \pi^0)}{\sigma(\nu + T \to \mu^- + T'' + \pi^0)} \quad \text{Decreases}$$

For $(R^{\nu})_{\substack{\text{theory} \\ \text{without corr.}}} = 0.44 \xrightarrow[\text{with corr.}]{} 0.22 \qquad (R^{\nu})_{exp} = 0.17 \pm 0.06$

CC: $\left(\frac{\pi^+ + \pi^-}{\pi^0}\right)_{\text{Theory}} = 4.5$ reduced to 2.5 by corrections

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TABLE V. Cross sections for electroproduction of pions. The errors contain a systematic and normalization erro of 3%. $E_1 = 3200$ MeV, $\theta = 21°$, $q^2(1236) = -1.0$ (GeV/c)^2, $\epsilon(1236) = 0.89$.

			$\frac{1}{\Gamma_t}\frac{d^2\sigma}{d\Omega_e dE_3}$ (μb)		
E_3 (MeV)	K (MeV)	W (MeV)	$e+p \to e+\begin{cases}p+\pi^0\\ n+\pi^+\end{cases}$	$e+p\to e+p+\pi^0$	$e+p\to e+n+\pi^+$
2470	171	1096	15.2 ± 3	1.5 ± 1.5	13.7 ± 6
2460	183	1106	16.3 ± 3	5.4 ± 5	10.9 ± 6
2450	195	1116	22.2 ± 3	13.0 ± 5	9.2 ± 6
2440	208	1127	32.7 ± 3	15.3 ± 5	17.4 ± 6
2430	220	1137	45.5 ± 3	19.1 ± 5	26.4 ± 6
2420	232	1147	49.0 ± 3	27.5 ± 5	21.5 ± 6
2410	246	1157	60.1 ± 4	29.8 ± 5	30.3 ± 6
2400	257	1167	67.7 ± 4	35.2 ± 5	32.5 ± 6
2390	269	1177	79.4 ± 4	42.9 ± 5	36.5 ± 6
2380	281	1186	100.4 ± 4	53.9 ± 6	46.5 ± 7
2370	293	1196	114.4 ± 4	63.9 ± 6	50.5 ± 7
2360	306	1206	136.5 ± 5	80.7 ± 6	55.8 ± 8
2350	318	1215	140.0 ± 5	81.5 ± 6	58.5 ± 8
2340	331	1225	144.7 ± 5	86.4 ± 7	58.3 ± 9
2330	343	1234	133.0 ± 5	$\boxed{90.2\pm7}$	$\boxed{42.8\pm9}$
2320	355	1243	123.7 ± 5	70.0 ± 7	53.7 ± 9
2310	367	1252	114.4 ± 4	76.5 ± 6	37.9 ± 7
2300	380	1262	101.5 ± 4	57.0 ± 6	44.5 ± 7
2290	392	1271	94.5 ± 4	57.0 ± 6	37.5 ± 7
2280	404	1280	82.9 ± 3	47.4 ± 5	35.5 ± 6
2270	417	1289	74.7 ± 3	44.7 ± 5	30.0 ± 6
2260	429	1298	72.3 ± 3	44.7 ± 5	27.6 ± 6
2250	440	1306	66.5 ± 3	37.1 ± 5	29.4 ± 6
2240	453	1315	66.5 ± 3	39.3 ± 5	27.2 ± 6
2230	465	1324	57.2 ± 3	36.0 ± 5	21.2 ± 6
2220	478	1333	57.2 ± 3	38.2 ± 5	19.0 ± 6
2210	490	1341	53.7 ± 3	30.6 ± 5	23.1 ± 6
2200	502	1350	58.3 ± 3	45.9 ± 5	12.4 ± 6

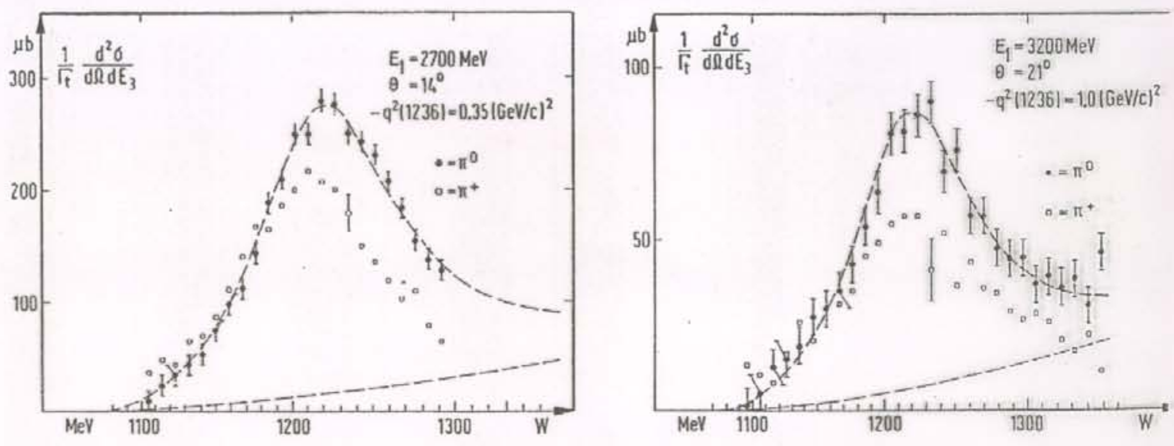


FIG. 5. Same as Fig. 4, except the $p\pi^0$ and $n\pi^+$ channels are separated.

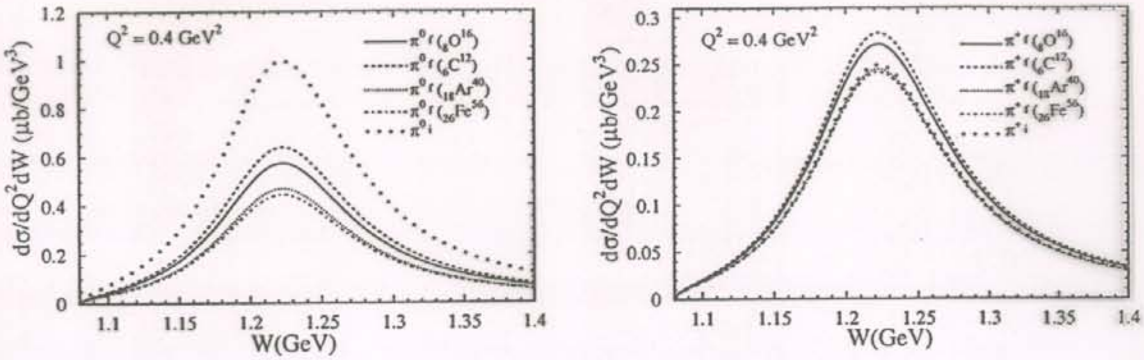


Figure 2: Double differential cross sections per nucleon for single-pion electroproduction for different target materials. W-spectra for π^0 and π^+ production are shown for $Q^2 = 0.4$ GeV^2 using an electron energy $E_e = 2.7$ GeV. The pion rescattering corrections have been calculated in the double-averaging approximation (2.6) using the ANP matrices in (2.7) and App. A. For comparison, the free nucleon cross section (2.3) is shown.

GENERAL RULE: In a lepton nuleus interaction the pions which have the same charge as the current are reduce by 30-40%, and for the pions with different charge there is a slight increase.

(2)

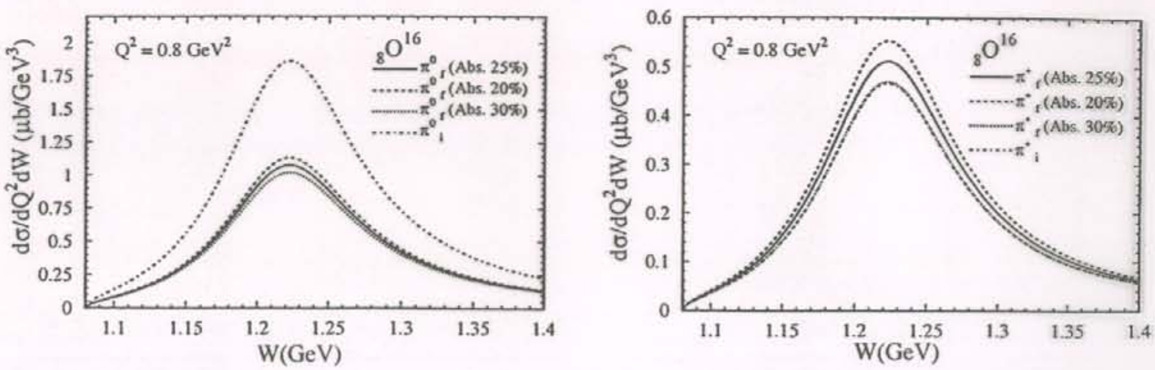
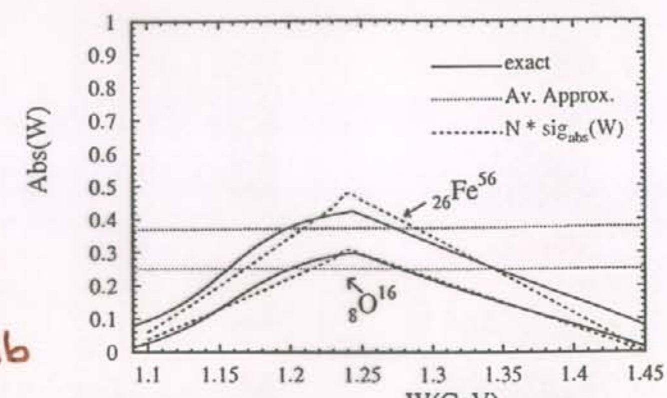
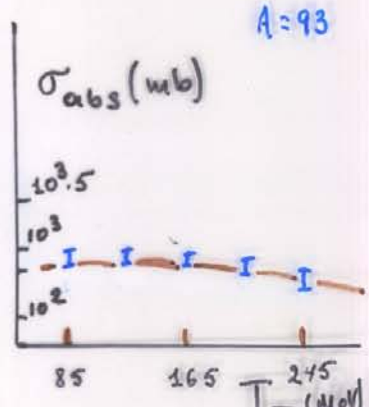


Figure 3: Double differential cross sections per nucleon for single-pion electroproduction for oxygen with 20% (dashed line), 25% (solid line) and 30% (dotted line) pion absorption. Furthermore, $Q^2 = 0.8\ \mathrm{GeV}^2$ and $E_e = 2.7\ \mathrm{GeV}$.

(1)

From E.A.P., I. Schiebein, Yu (in preparation)





σ_{abs} = 10 to 20 mb

Oset et al. PL B 165 (85) 13.

Mosel U. et al.

Figure 4: The fraction of absorbed pions, $\mathrm{Abs(Q^2, W)}$, in dependence of W for oxygen and iron targets for $Q^2 = 0.3\ \mathrm{GeV}^2$. Also shown is the cross section $\sigma_{\mathrm{abs}}(W)$ (model B) multiplied by free normalization factors (dashed lines). The dotted lines are the result for $\mathrm{Abs(Q^2, W)}$ in the averaging approximation.

$\sigma_{abs} = 24 \cdot A^{0.8}$ (mb)

COHERENT SCATTERING

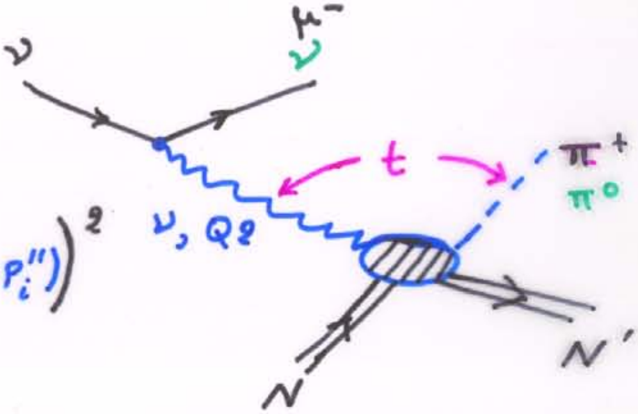
(Diffractive)

Rein + Sehgal

Many neutrino experiments have observed a peak at $|t| < 0.05\ \mathrm{GeV}^2$.
It is produced by exchange of light mesons plus coherence.

$$t = (q - p_\pi)^2$$

$$\approx \Big(\sum_{\pi, \mu} p_i^\perp\Big)^2 - \Big(\sum_i (E_i - p_i^{\parallel})\Big)^2$$



Reaction

DOES THIS REACTION TAKE PLACE IN ELECTROPRODUCTION ?

1. Observation of peak
2. E_ν - Dependence
3. A - Dep., : $A^2, A^{2/3}, \ldots$?
4.

$$\frac{d\sigma_{NS}}{d\Omega}(E^*_\gamma, \Theta^*_\pi) = \frac{1}{2}\frac{q^*}{k^*}\left|\mathcal{F}_2(E^*_\gamma, \Theta^*_\pi)\right|^2 \sin^2(\Theta^*_\pi), \quad (2)$$

B. Krusche et al. (Mainz)

Coherent π^0 photoproduction from Atomic Nuclei

PL 526B (2002) 287

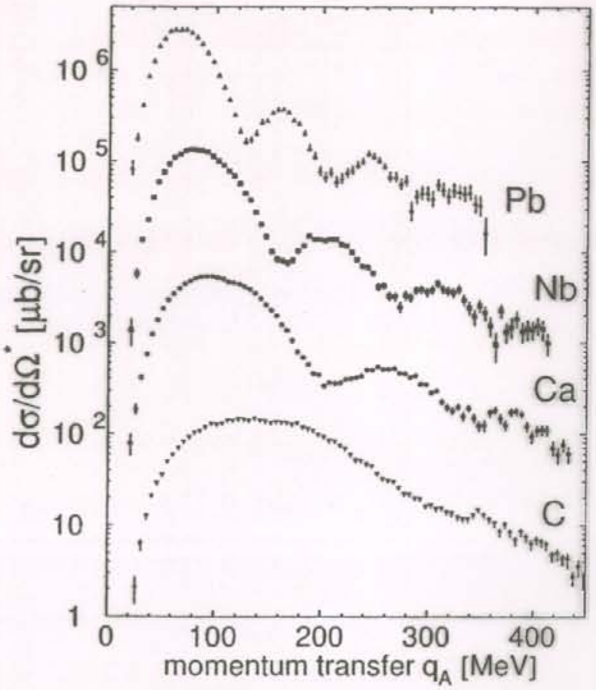
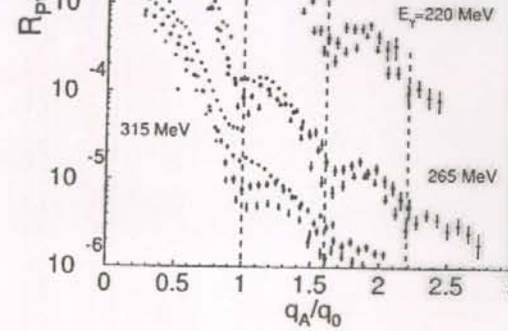


Fig. 2. Differential cross sections for $A(\gamma,\pi^0)A$ averaged over incident photon energies from 200–290 MeV as function of the momentum transfer. The scale corresponds to the carbon data, the

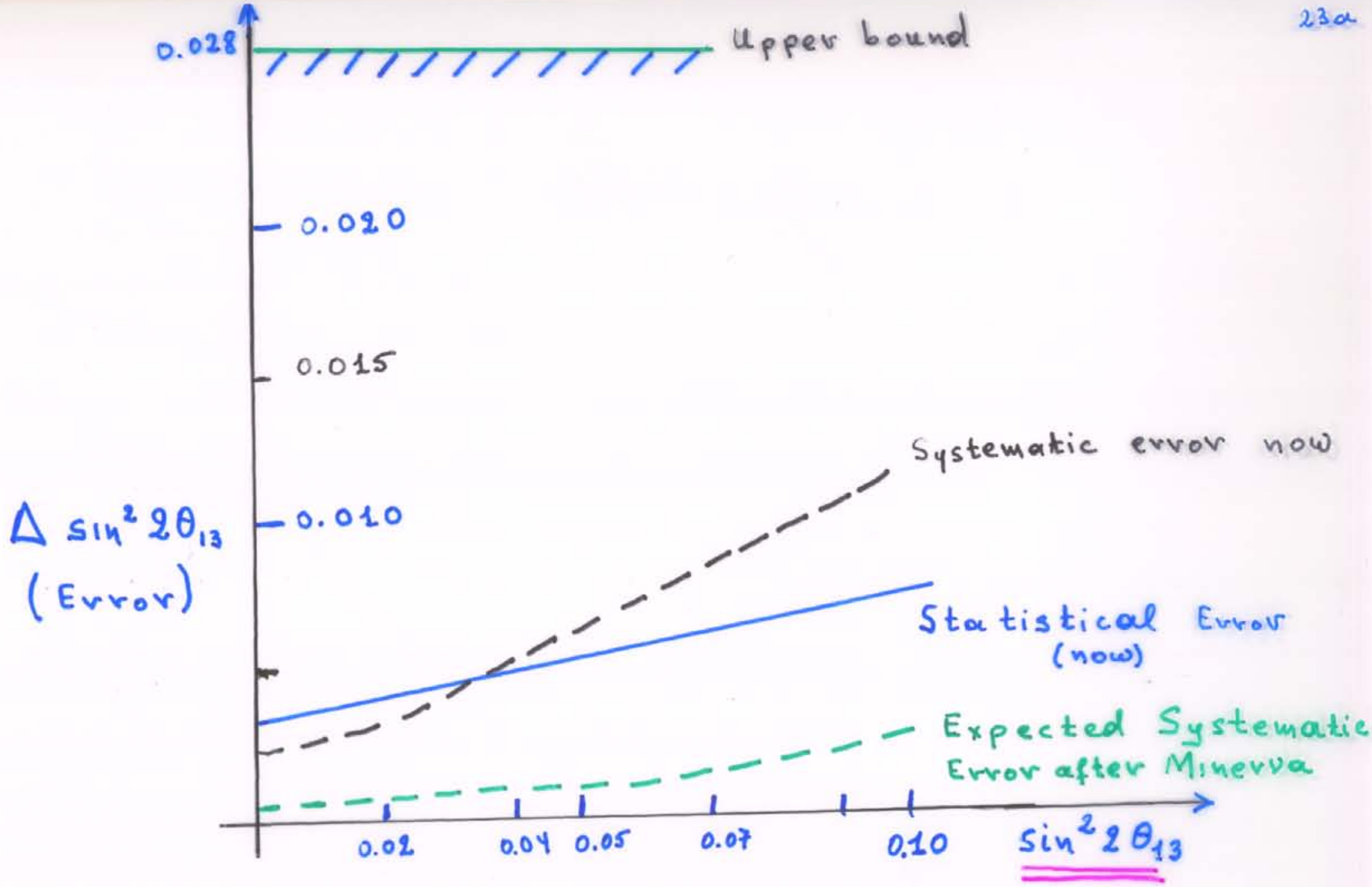
$$R_{\mathrm{PWIA}} = \left(\frac{d\sigma_{\exp}}{d\Omega}\right) \Big/ \left[\frac{s}{m_N^2} A^2 \left(\frac{d\sigma_{NS}}{d\Omega}\right)\right]$$
$$= F^2(q_A)\left(\frac{d\sigma_{\exp}}{d\Omega}\right) \Big/ \left(\frac{d\sigma_{\mathrm{PWIA}}}{d\Omega}\right) \quad (3)$$



q_0 - position of 1st minimum

For 220 MeV A^2-dep.

Fig. 3. Ratio R_{PWIA} (see Eq. (3)) as function of q_A/q_0 where q_0 is the momentum transfer at the first minimum of the form factor. The scale corresponds to the 220 MeV data, the 265, 315 MeV data are scaled down by factors 10, 100.



IMPORTANCE (IMPACT) OF BETTER ACCURACY

SUMMARY

1. Structure of Form Factors for Δ at 5% level

2. Form factors for higher resonances

3. Nuclear corrections: Ratios $\pi^+ : \pi^0 : \pi^-$, $\sigma_{abs}(W)$, ...

4. Connections to other approaches:
   - Nuclear correlations (particle-hole)
   - QCD (Color transparency) ??? Marteau)
   - particle-hole excitations $\Leftrightarrow$ $\sigma_{abs}(W)$

5. GROWTH OF INCOHERENT BACKGROUND TO BECOME DIS.

6. COHERENT SCATTERING (Diffractive Scatt.)

7. Estimates of theoretical uncertainties for θ_{13}, $\sin\delta$, ...