Importance of the low Q^2 region in the neutrino-nucleus scattering experiments

Makoto Sakuda (Okayama Univ)

5 May, 2006 @ JLAB Neutrino Workshop

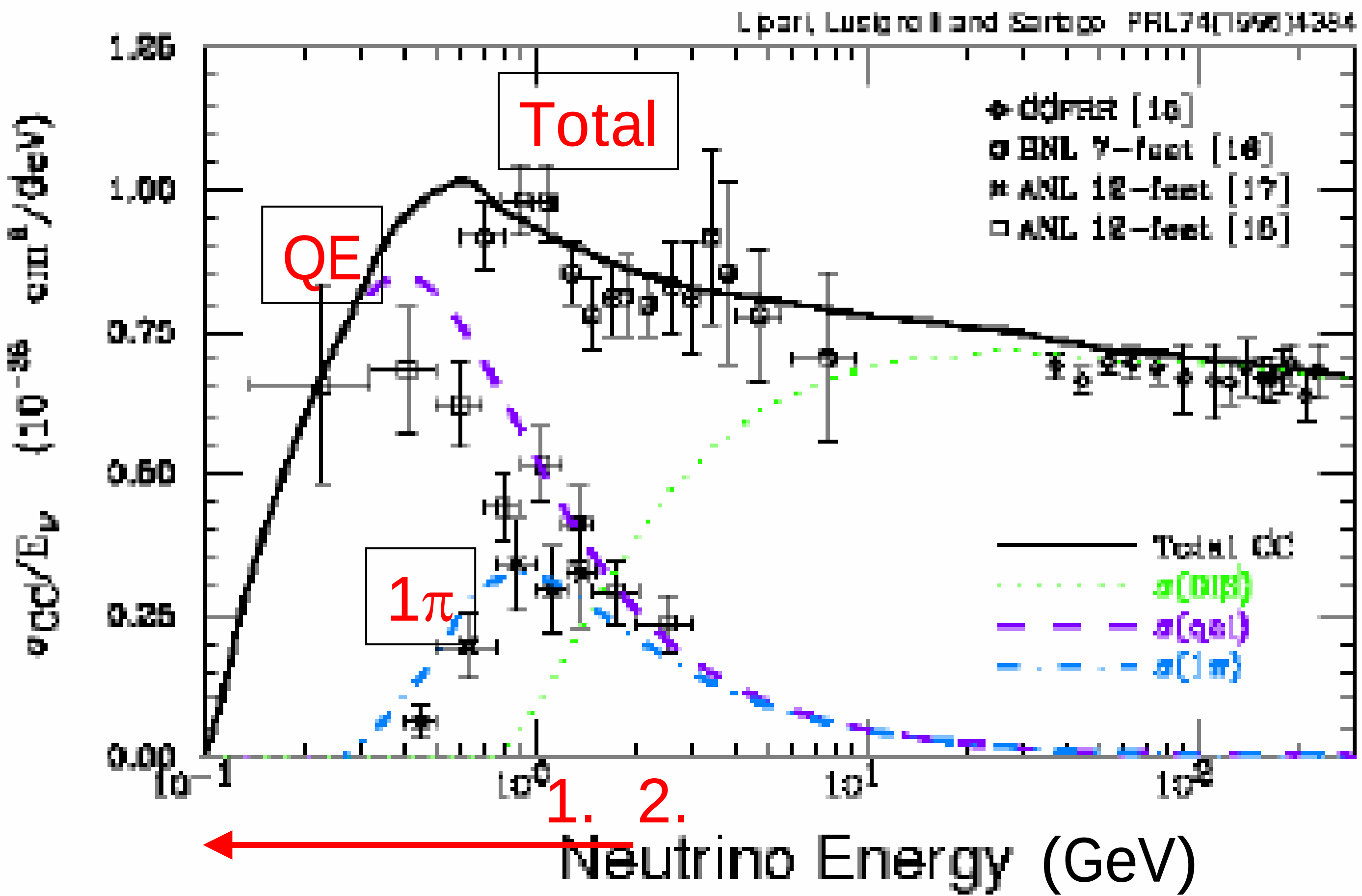
-Overview on Quasi-elastic interaction and Resonance In the 100MeV to a few GeV Region-

Outline

1. Why we like to understand low Q^2 region and how we study neutrino-nucleus interactions at NuInt Workshops
2. Some Results from NuInt04/05
3. Next step
4. Summary

Neutrino Cross Section (by Lipari ‘90)

- For Eν< 2 GeV, Quasi-Elastic interaction and Single pion production (Δ production) dominate the cross section.



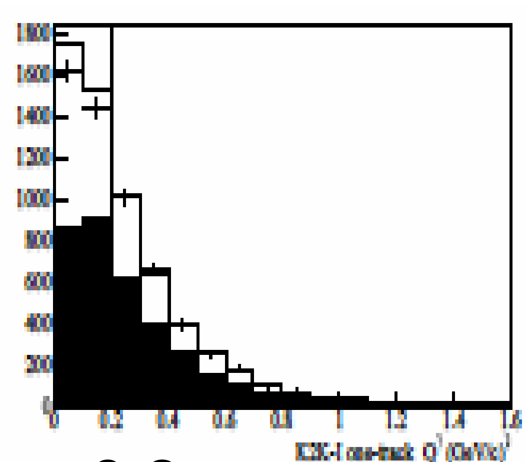
1. Why low Q^2 is important? →Cross section is large.

-Typical Q^2 distributions in K2K and MiniBOONE-

K2K– hep-ex/0603034
M_A=1.20+-0.12 (GeV)^2

MiniBOONE QE sample
-- Neutrino2004

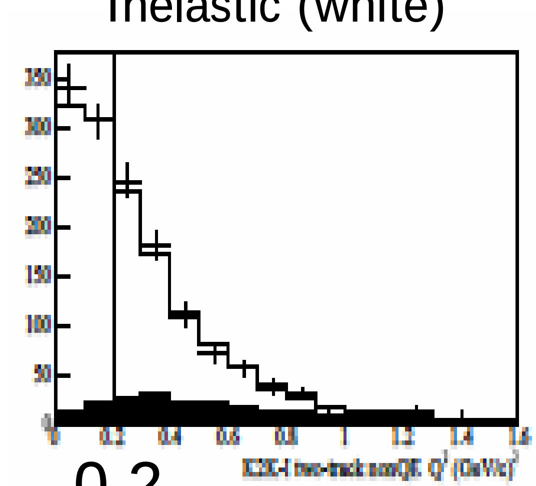
QE (black)



0.2

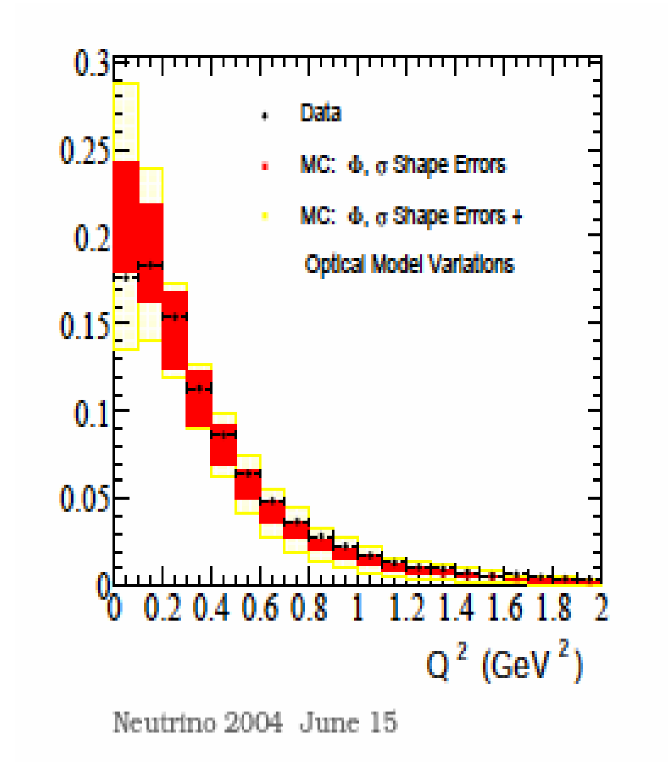
Q^2 (GeV/c)^2

Inelastic (white)



0.2

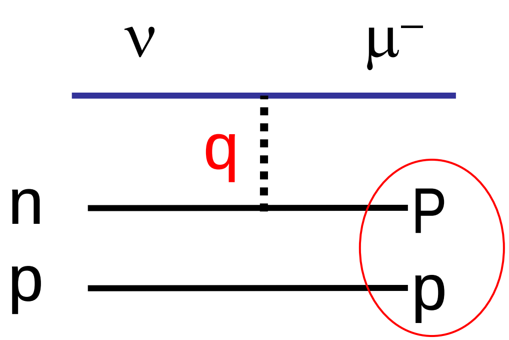
Q^2 (GeV/c)^2



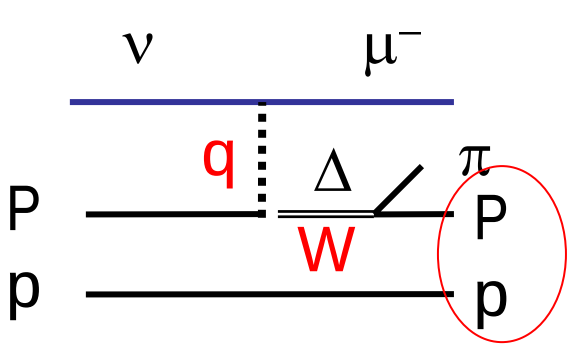
Quasi-elastic and Resonanc cross sections (Fermi Gas Model) in the GeV region and the nuclear effect

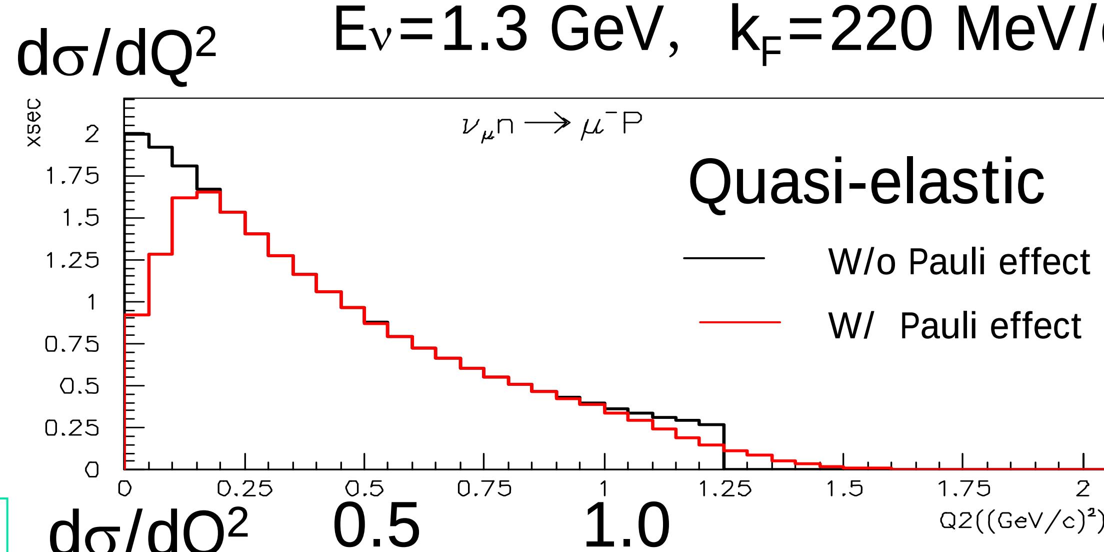
Nuclear effects are large in the low Q^2 region, where the cross section is large.

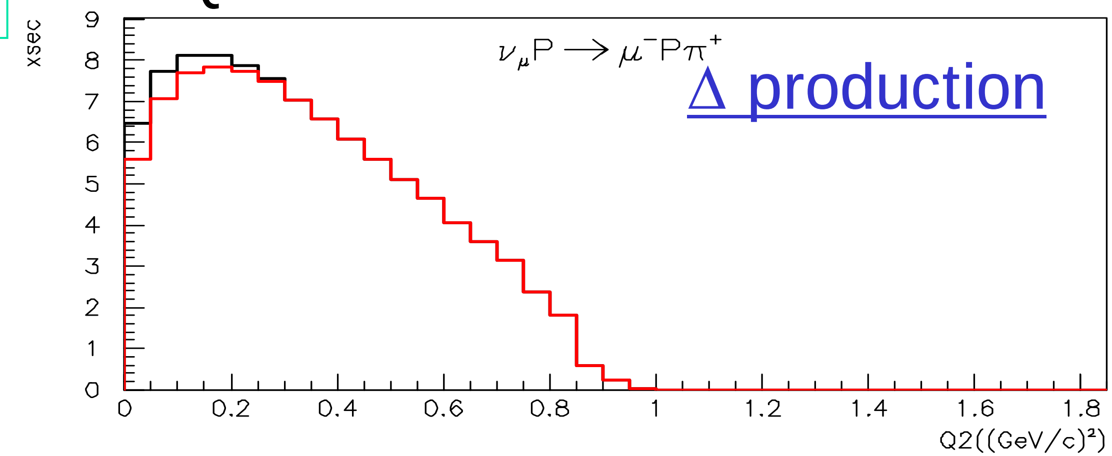
$E_\nu = 1.3$ GeV, $k_F = 220$ MeV/c



If $P < k_F$, suppressed.







Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region

(1) NuInt01

(KEK, Dec.13-16, 2001)

Nucl.Phys.B(Proc.Suppl.)112, 2002

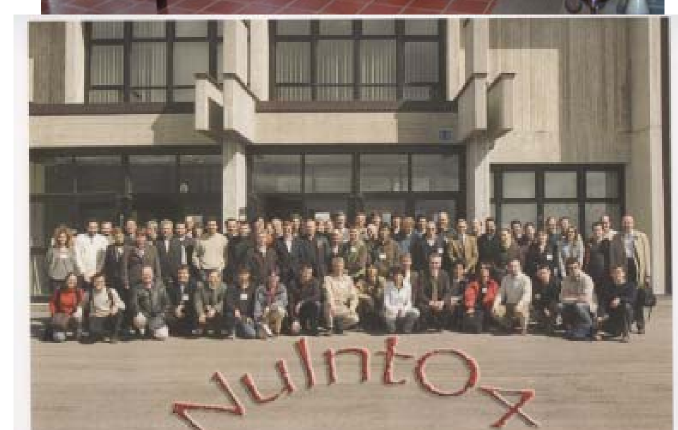
(2) NuInt02

(UC Irvine, Dec.12-15, 2002)

(3) NuInt04

(Gran Sasso, March 17-21, 2004)

Nucl.Phys.B(Proc.Suppl.)139, 2005



NuInt05 (Okayama, Sep.26-29, 2005)

http://fphy.hep.okayama-u.ac.jp/NuInt05/

Purpose of NuInt Workshop

- Theoretically,

  We would like to establish a canonical calculation and to quantify the accuracy.

- Experimentally,

  We like to measure the electron- and neutrino-nucleus cross sections with better accuracy.

Electron-Nucleus and Neutrino-Nucleus quasi-elastic interactions

- Electromagnetic current (J_a^{em}) and weak hadronic charged current ($J_a^{CC}=V_a^{1+i2}-A_a^{1+i2}$) is written in terms of form factors**:**

$$< N(p')|J_\alpha^{em}|N(p) >= \bar{u}(p')\left[\gamma_\alpha F_1^N(Q^2) + \frac{i}{2M}\sigma_{\alpha\beta} q^\beta F_2^N(Q^2)\right]u(p),$$

$$< p(p')|V_\alpha^{1+i2}|n(p) >= \bar{u}(p')\left[\gamma_\alpha F_1^V(Q^2) + \frac{i}{2M}\sigma_{\alpha\beta} q^\beta F_2^V(Q^2)\right]u(p),$$

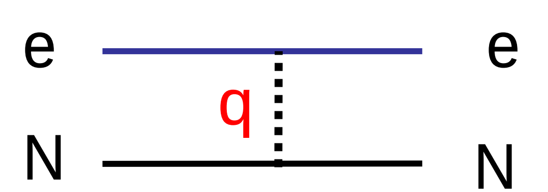
$$< p(p')|A_\alpha^{1+i2}|n(p) >= \bar{u}(p')\left[\gamma_\alpha \gamma_5 F_A(Q^2) + q_\alpha F_p(Q^2)\right]u(p),$$

$$G_E^N(Q^2) = F_1^N(Q^2) - \tau F_2^N(Q^2)$$

$$G_M^N(Q^2) = F_1^N(Q^2) + F_2^N(Q^2) \qquad with \quad \tau = \frac{Q^2}{4M^2}$$

$$G_{E,M}^{V(}(Q^2) = \frac{1}{2}\left[G_{E,M}^p(Q^2) - G_{E,M}^n(Q^2)\right]$$

$$F_1^V(Q^2) = \frac{G_E^V(Q^2) + \tau G_M^V(Q^2)}{1+\tau} \quad and \quad F_2^V(Q^2) = \frac{G_M^V(Q^2) - G_E^V(Q^2)}{1+\tau}$$



Δ production and N→Δ transition form factors

$$<\Delta(p')|J^{\alpha}|N(p)> = <\Delta(p')|V^{\alpha}|N(p)> - <\Delta(p')|A^{\alpha}|N(p)>$$

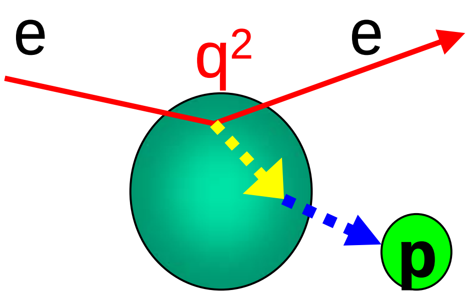
$$<\Delta(p')|V^{\alpha}|N(p)>$$

$$=\overline{\Psi}_{\mu}(p')\left[\frac{C_3^V(Q^2)}{M}(g^{\mu\alpha}\not{q}-q^{\mu}\gamma^{\alpha})+\frac{C_4^V(Q^2)}{M^2}(g^{\mu\alpha}q\cdot p'-q^{\mu}p'^{\alpha})+\frac{C_5^V(Q^2)}{M^2}(g^{\mu\alpha}q\cdot p-q^{\mu}p^{\alpha})+C_6^V(Q^2)q^{\mu}q^{\alpha}\right]\gamma_5\Psi(p)$$

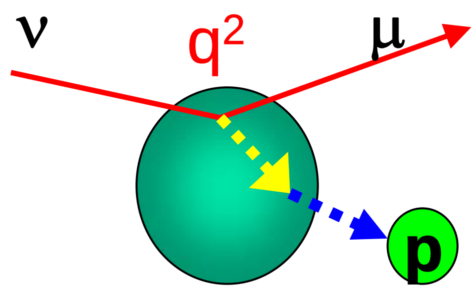
$$<\Delta(p')|A^{\alpha}|N(p)>$$

$$=\overline{\Psi}_{\mu}(p')\left[\frac{C_3^A(Q^2)}{M}(g^{\mu\alpha}\not{q}-q^{\mu}\gamma^{\alpha})+\frac{C_4^A(Q^2)}{M^2}(g^{\mu\alpha}q\cdot p'-q^{\mu}p'^{\alpha})+C_5^A(Q^2)g^{\mu\alpha}+\frac{C_6^A(Q^2)}{M^2}q^{\mu}q^{\alpha}\right]\gamma_5\Psi(p)$$

Electron-Nucleus and Neutrino-Nucleus Interactions



Electro-magnetic interaction



Weak interaction

We test our neutrino models using electron data which are measured with better accuracy.

Contributed papers to NuInt04/05

- Quasi-elastic
  - Nieves, Co' (RPA), Benhar, Nakamura (LDA), Barbaro (SuperScaling)
- Resonance
  - Sato, Lalakulich, Paschos, Barbaro
- Final state interaction
  - Rohe, Barbieri, Benhar, Ransome
- New nucleon form factors
  - Jones, Budd, Bradford
- Spectral function, Correlations
  - Benhar, Giusti, Rohe

2. Results from NuInt

-Quantitative comparison of calculation and data-

- Quasi-Elastic is understood to 10% for E=700MeV-2000MeV (and $Q^2>0.2\ (GeV/c)^2$)
  - Reference=Relativistic Fermi-Gas model (Smith-Moniz)
  - Spectral Function S(p,E): validated by JLAB E97-001
  - Final state interaction: validated by JLAB E97-001
- 1π (Δ) production →Lee,Lalakulich
  - Understood to 20-30%?
- Dip region

  QE, 1π and Dip region are related to each other.
- New data H,D,C(e,e’) at Low Q^2 are coming soon.

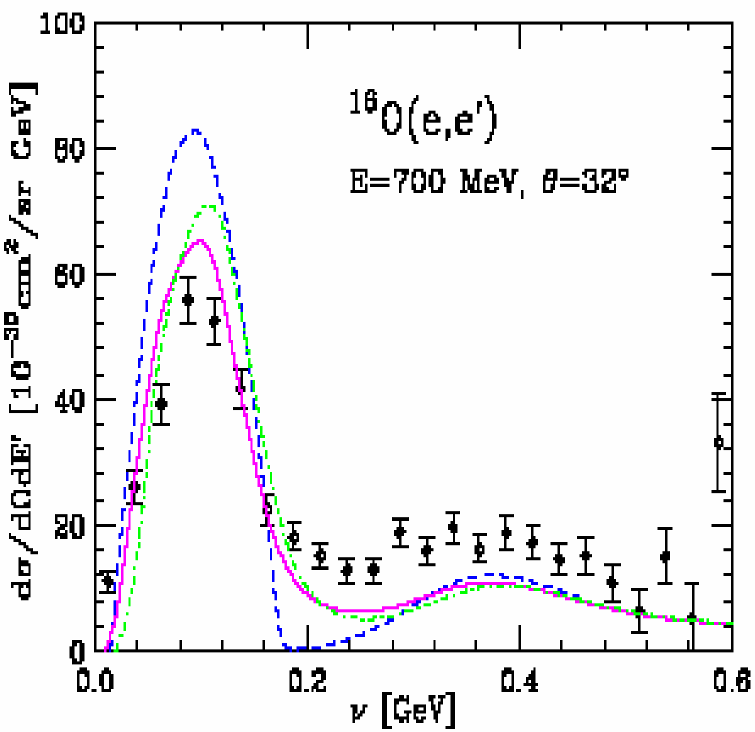
●Quasi-elastic Interaction from 700 to 2000MeV.

-Comparison of FG, SP, SP+FSI validated by electron scattering data

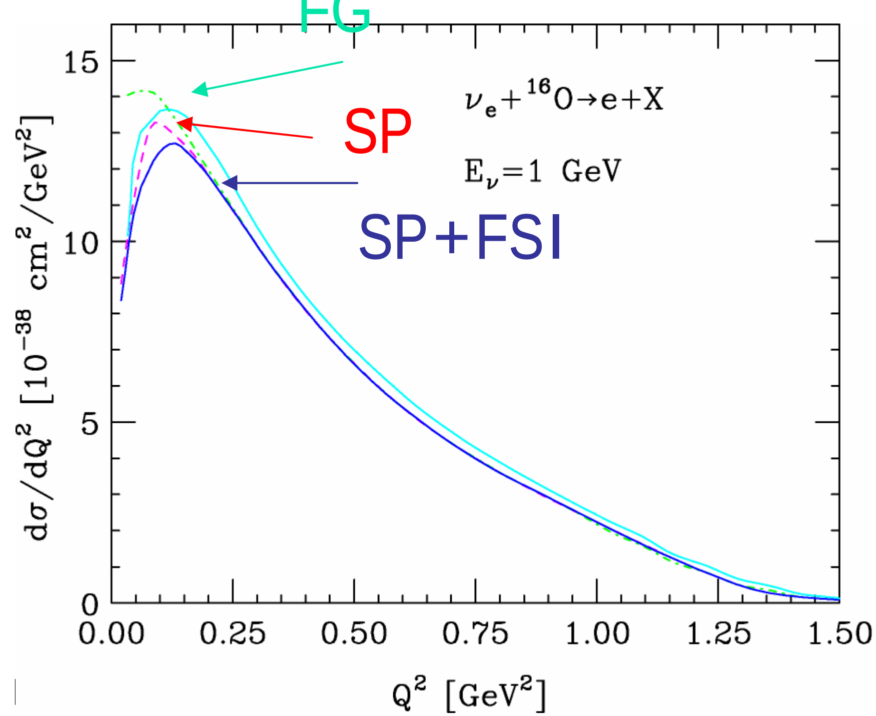
Nakamura et al.,NPB(Proc)139,' 05.
Benhar et al, PRD72,053005,2005

- New form factors are used.

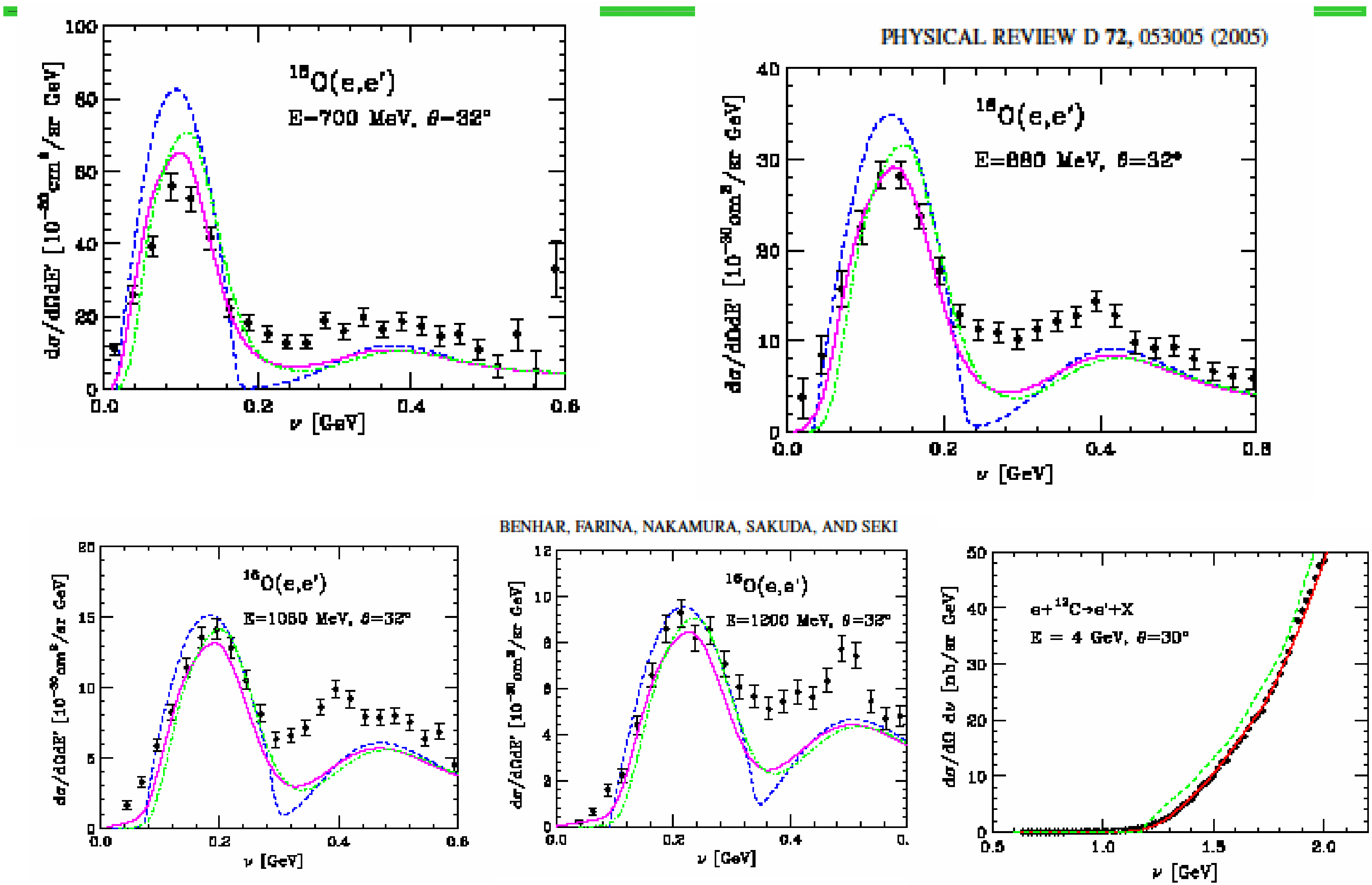
O(e,e')



O(ν,e)



C(e,e’) at Ee=700-1200 MeV

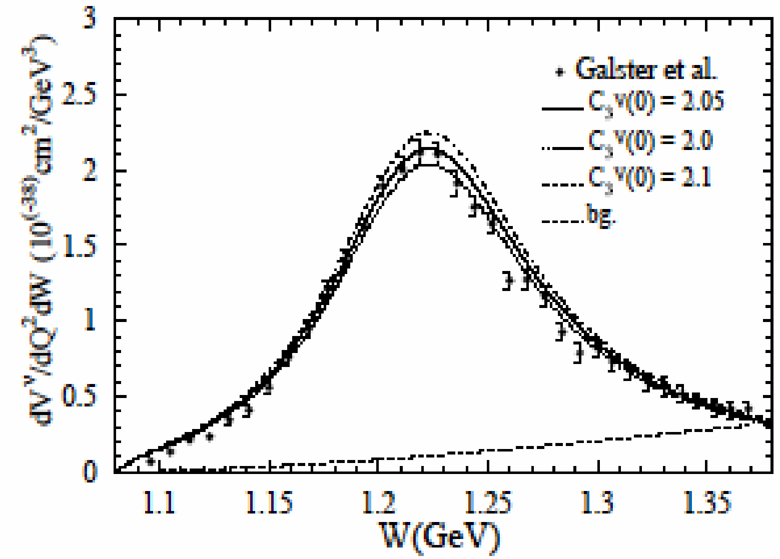


● Improved Δ production model

Paschos et al, PRD69('04)
Sato-Lee, PRC67('03)

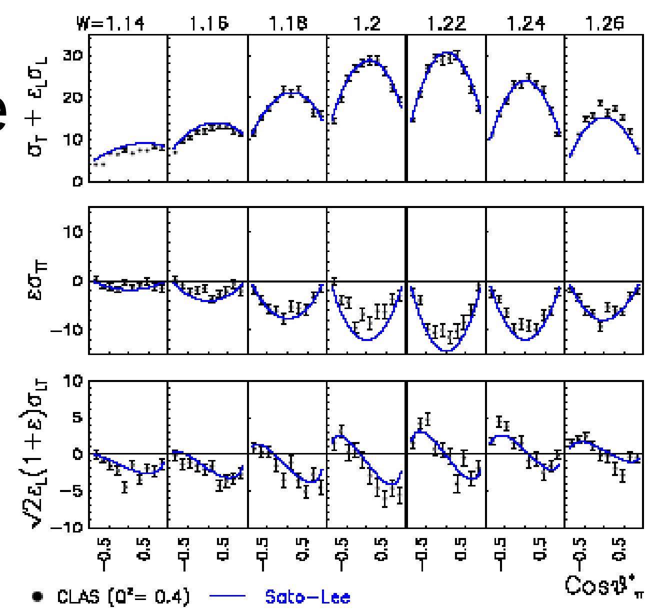
- Pauli effect $G(W,Q^2,k_F)$
- New N-Δ form factor
- 3-4 resonances
- Pion absorption
- e-p data look good.

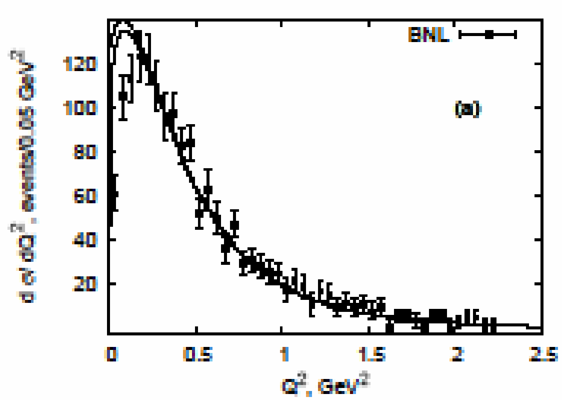
Paschos



$e + p \rightarrow e' + \pi^0 + p$ (Unpol)

Sato-Lee

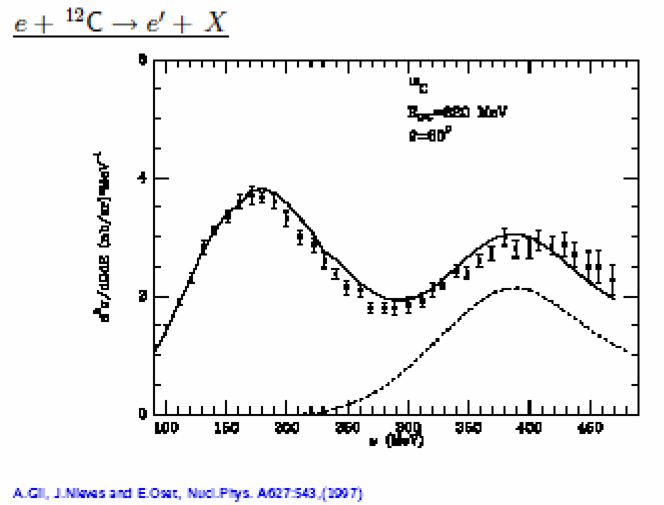




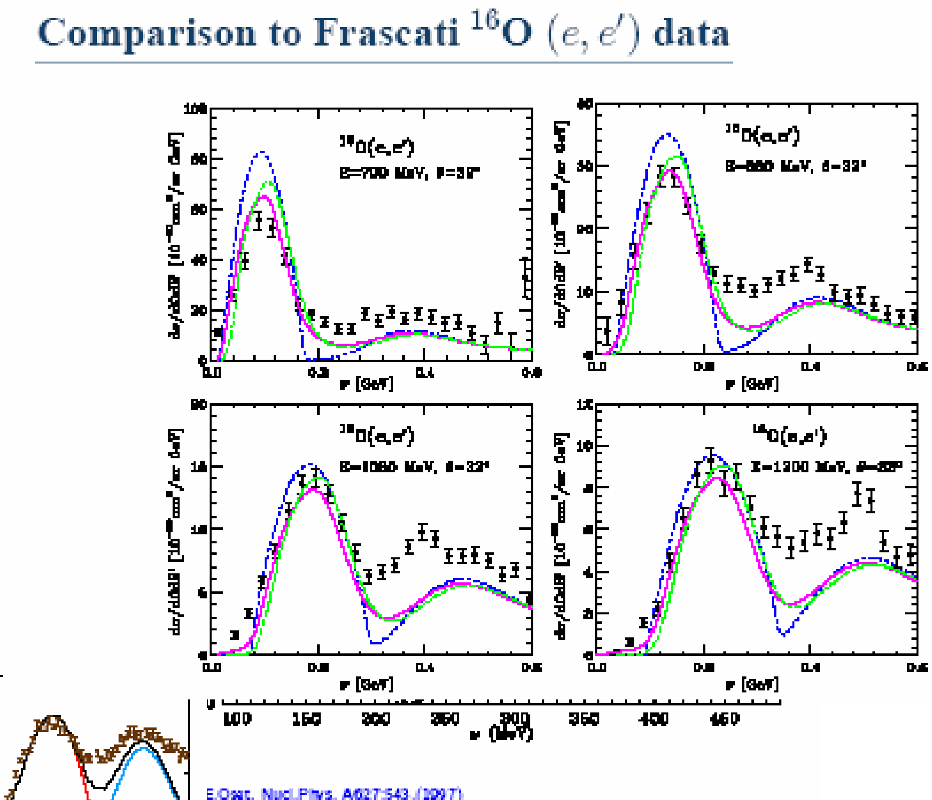
BNL(1990): deuterium

Δ production –Some differences in e-C (Nucleus). Dip region must be understood.

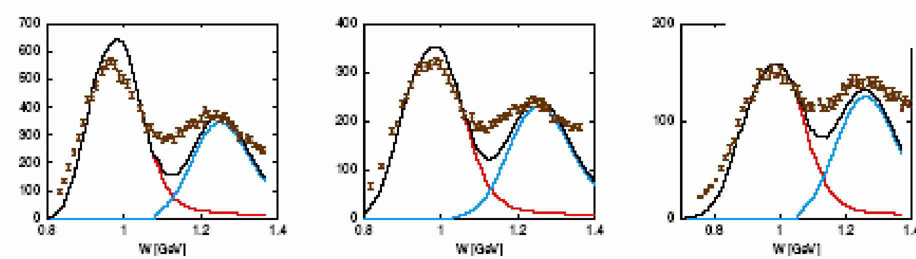
Nieves et al.,PRC70(‘04)



Benhar et al,PRD72(‘05)



Sato-Lee $e + {}^{12}C$

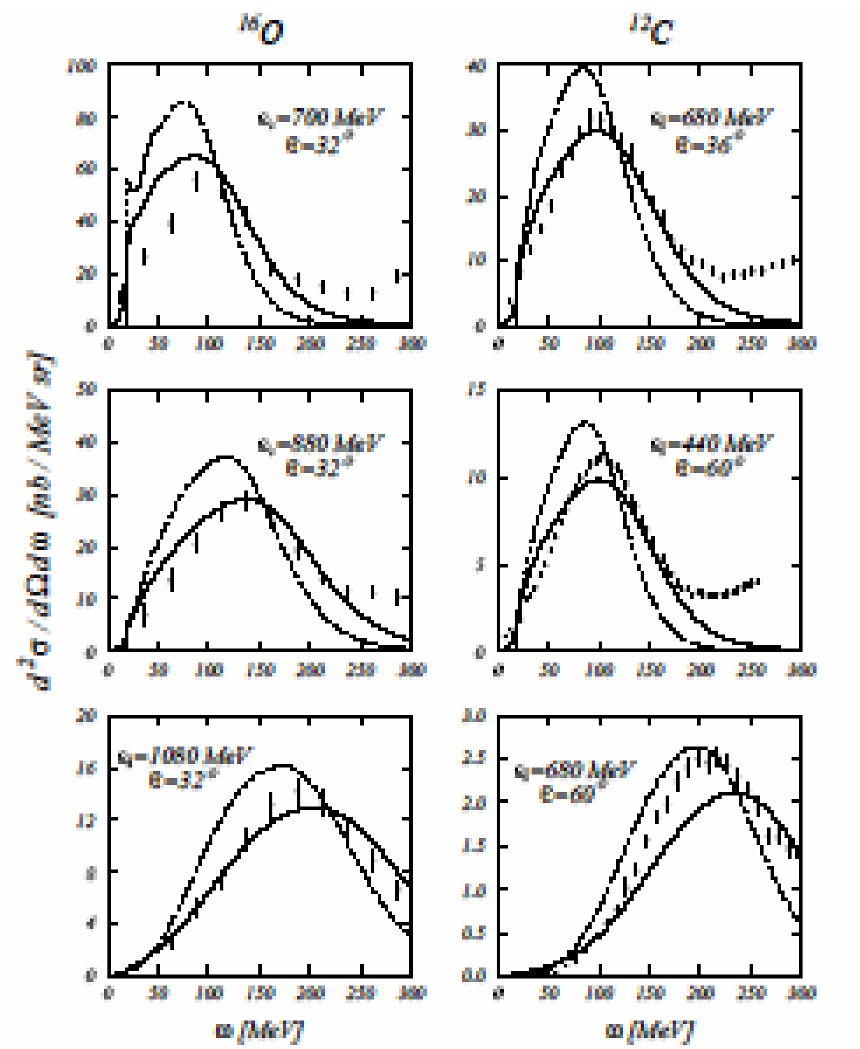


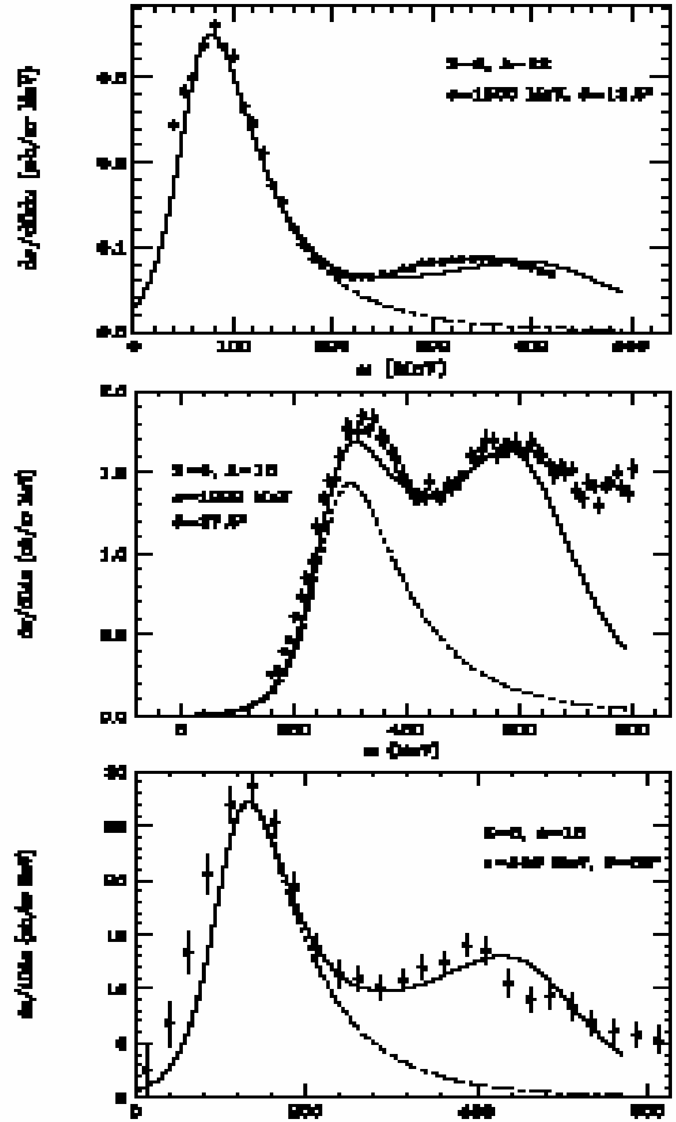
$E_e = 0.96GeV$ $E_e = 1.1GeV$ $E_e = 1.3GeV$

$\theta = 37.5^o$

- spectral function $P(k, E)$ (O. Benhar et al.)

Co’ (RPA)
Barbaro(Superscaling)





Superscaling prediction on dσ/dk$_\mu$ at θ=45° of C(ν,μ) at 1 GeV (Barbaro@NuInt05)

- Red:FG
- Solid:Δ+QE

- Now, all models agree with the size of the difference between FG model and data (models).

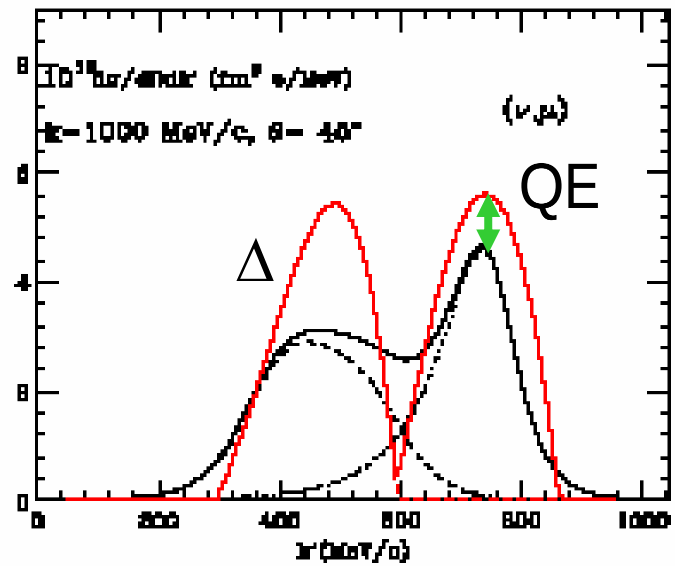


Figure 2. Charge-changing neutrino cross section for for 1 GeV neutrinos on ^{12}C and neutrino-muon scattering angles of 45 degrees. The cross section is plotted versus the final-state muon momentum k'. Solid line: superscaling prediction; heavier line (red on line): RFG. The separate QE and Δ contribution are shown (dotted lines). (Ref. [6])

3. Next step

- It is important that the calculation of the cross section is tested in all angles and energies.

  QE+Δ+Dip should be understood.

  "Typical" figures are not good enough. One can fit one figure, but fails in another.

- E<700MeV is also important for MiniBOONE, SciBOONE, T2K,MINOS,ATMν,SNν etc.

- $Q^2<0.2\ (\mathrm{GeV/c})^2$

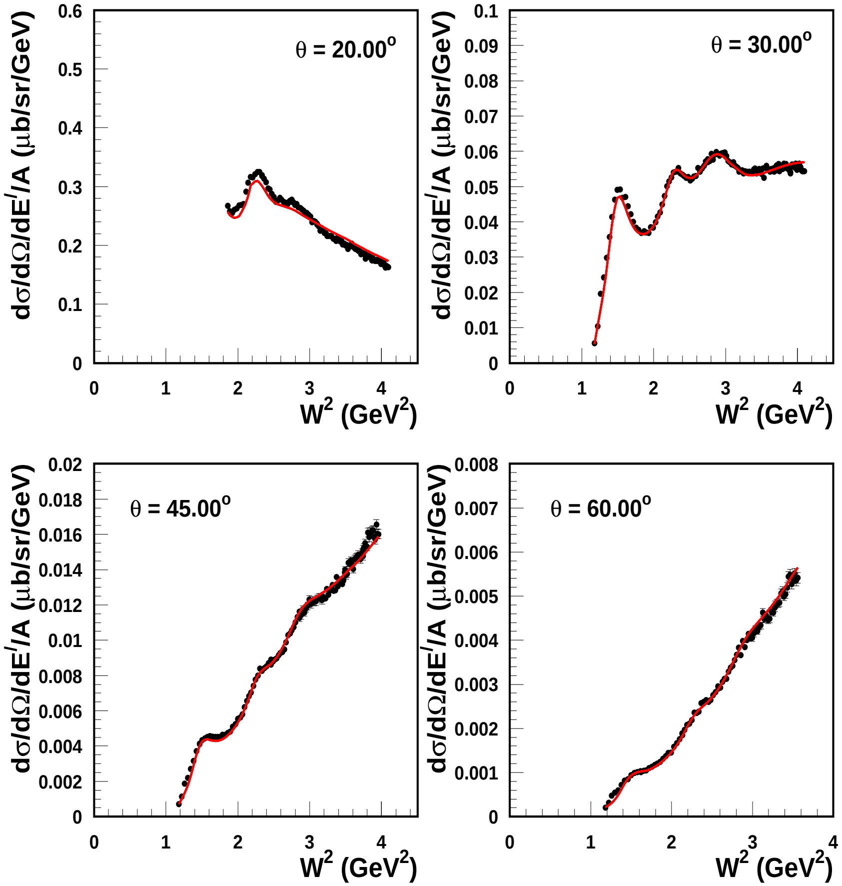
  E04-001 measured H,D,C(e,e') at 1.2 GeV for low Q^2 region. This will give the direct measurement of the nuclear effect (inc. Pauli Blocking):

  $[d\sigma(C,D)/dQ^2]/\ [d\sigma(H)/dQ^2]$ (QE&Δ) for $Q^2=0.04\text{-}0.4\ (\mathrm{GeV/c})^2$.

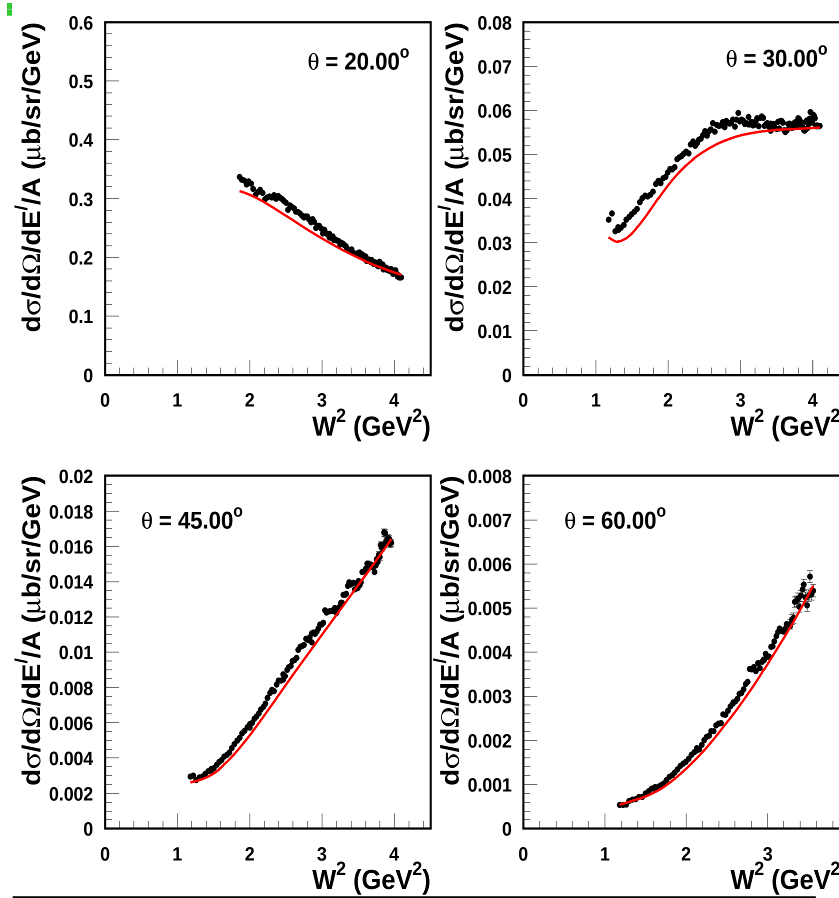
Preliminary Cross Section Results (JUPITER)

Tvaskis/Bradford@NuInt05

E_{Beam} = 2.3 GeV, Target = D



E_{Beam} = 2.3 GeV, Target = C



----- Input models for RCs, etc.

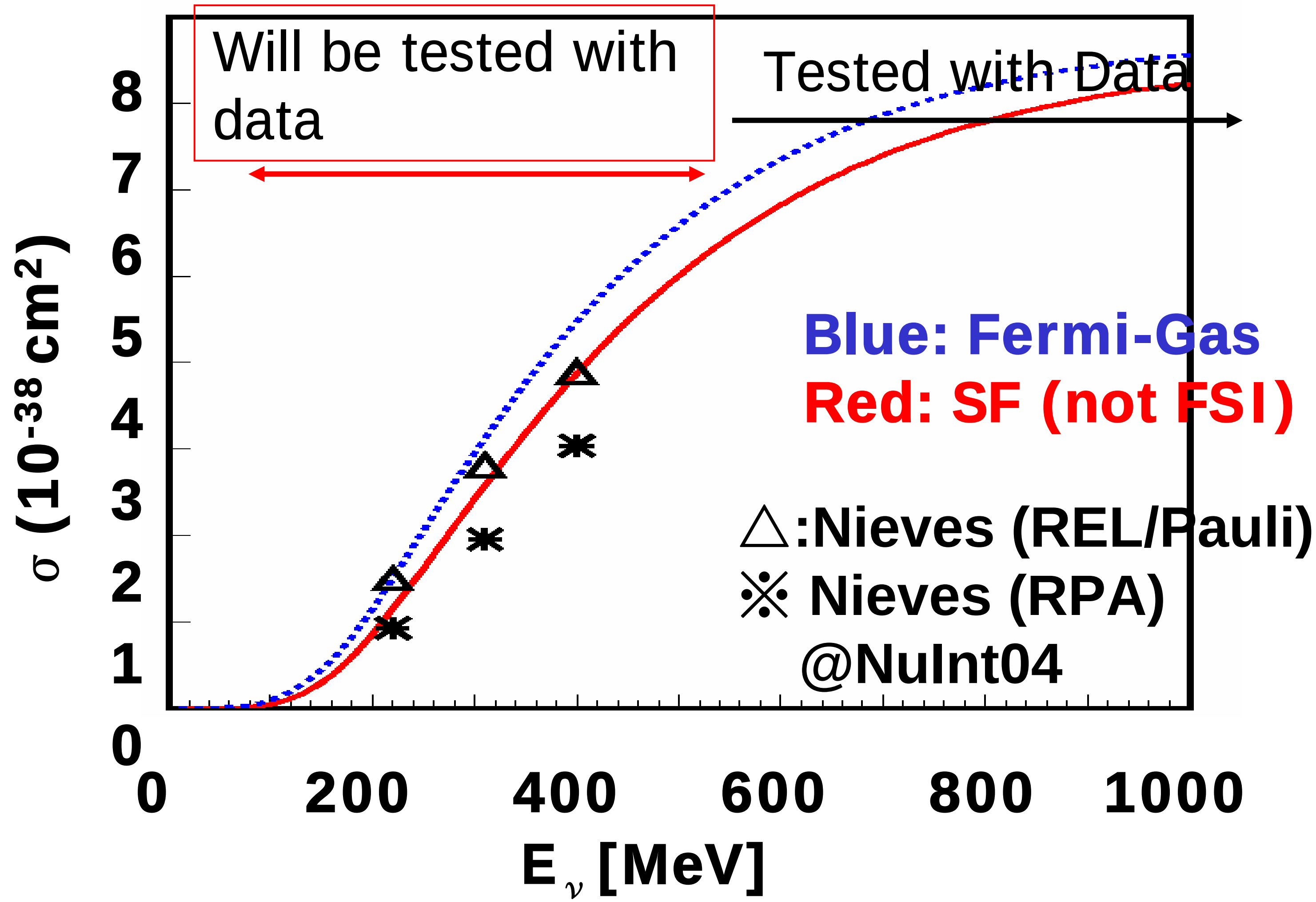
- Error bars are statistical only.
- Only inelastic data shown. Elastic under way.

Deuterium: Fits to previous JLab & SLAC resonance region data.

Heavy targets: fits to DIS data (F_2 & R) + y-scaling QE model.

@JLAE

Quasi-elastic cross section O(ν_e,e) in 100－500MeV Region



J.Mougey et.al.,PRL41,1978

C(e,e’) at Ee=240-520MeV.

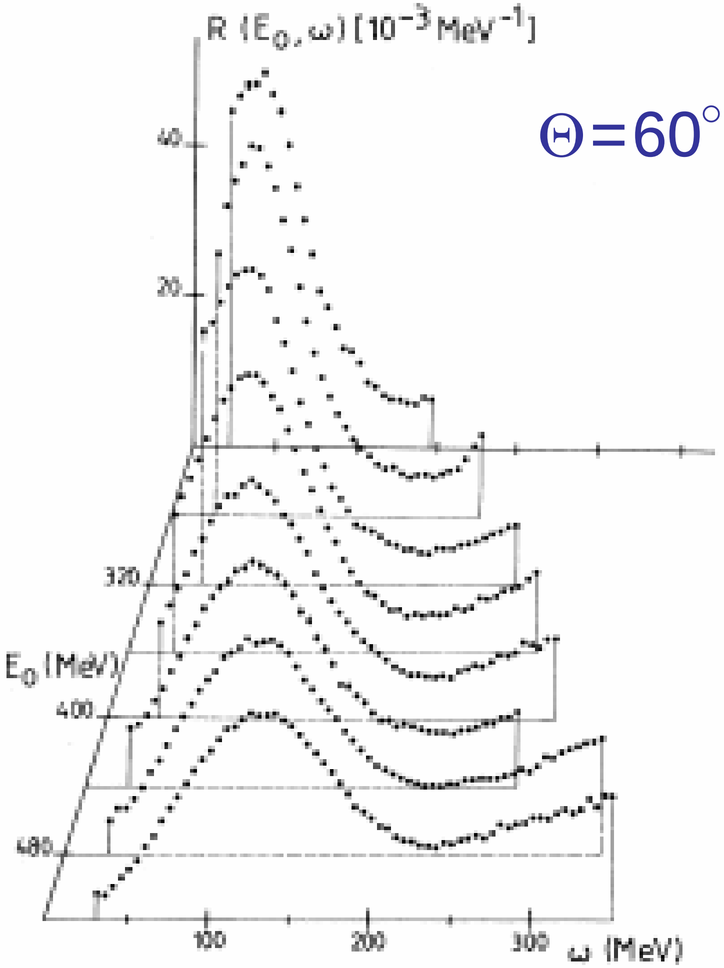


FIG. 1. Inelastic response function for [12]C at 60° and electron incident energies between 240 MeV (topmost curve) and 520 MeV in steps of 40 MeV. Where not shown, the error bar is smaller than the dot.

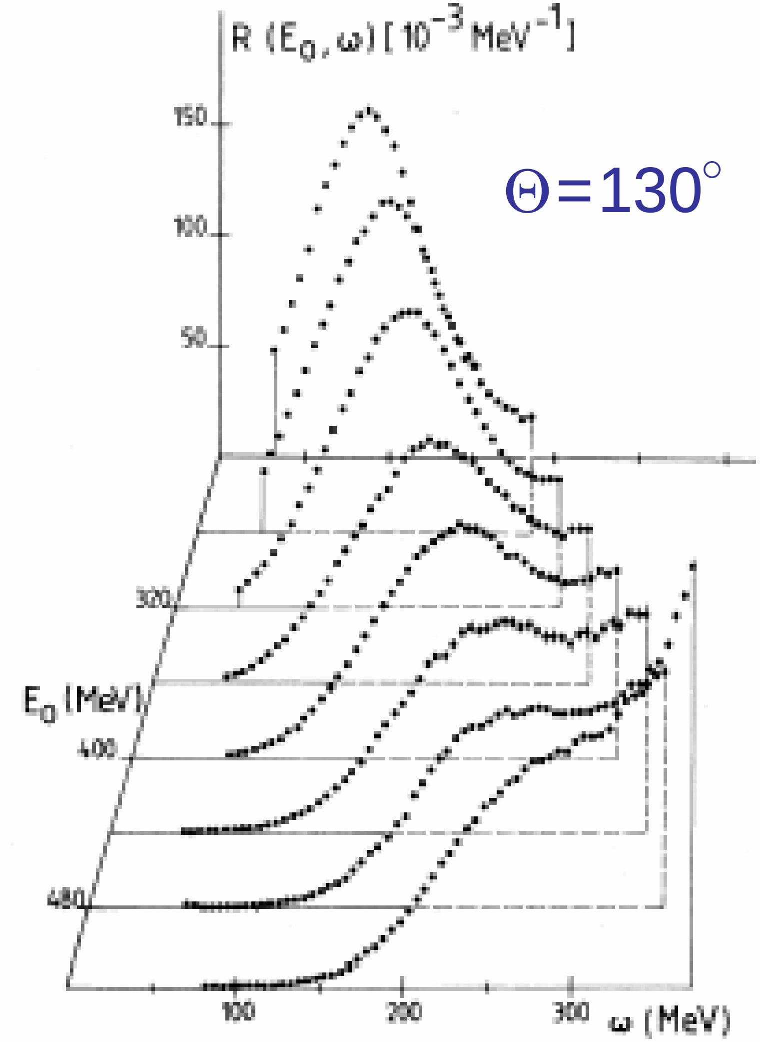


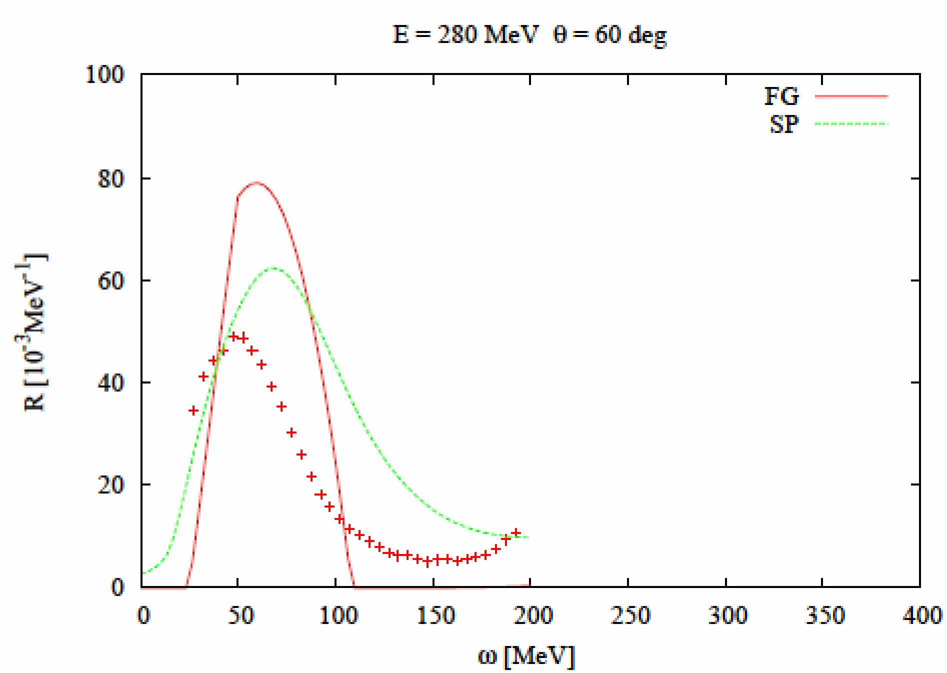
FIG. 2. Inelastic response function for [12]C, as in Fig. 1 but for 130°.

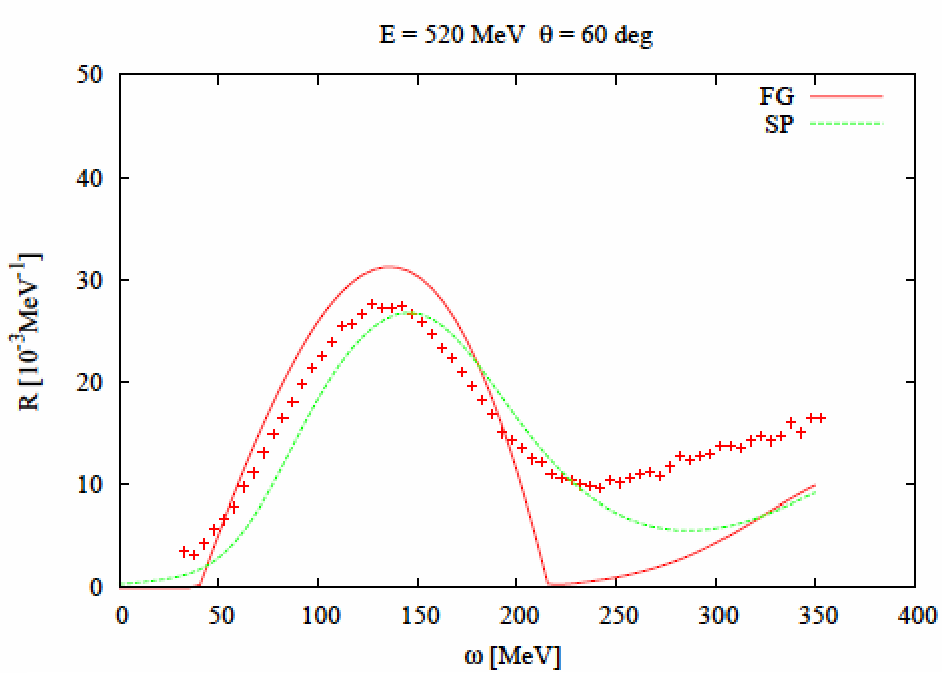
Preliminary look ("Typical" ones)

-Nakamura(Waseda)

Bad ← Ok.

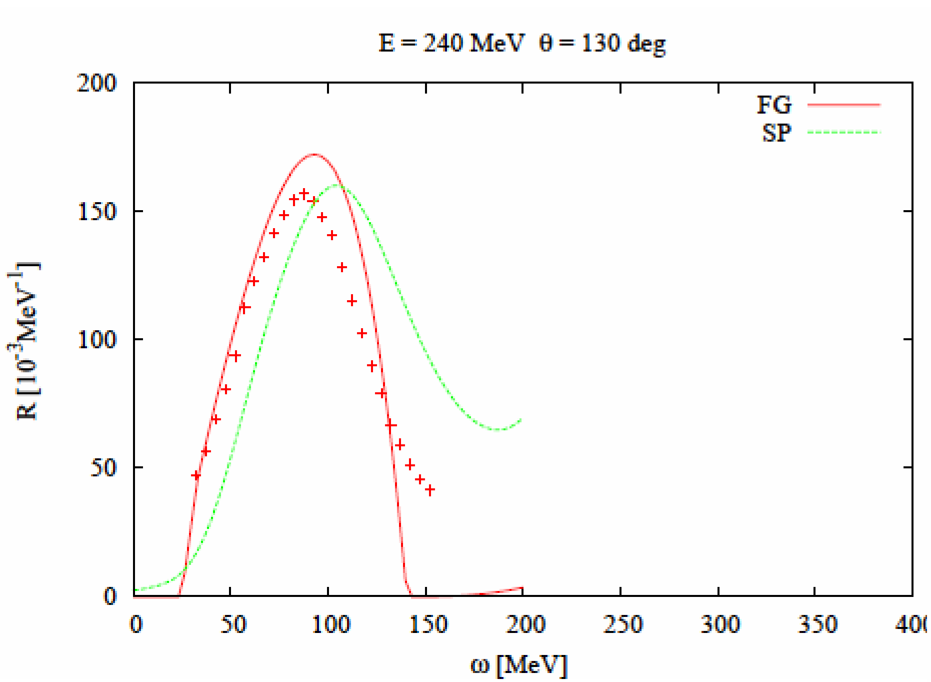
Q^2=0.06 (GeV/c)^2 ← Q^2=0.20 (GeV/c)^2

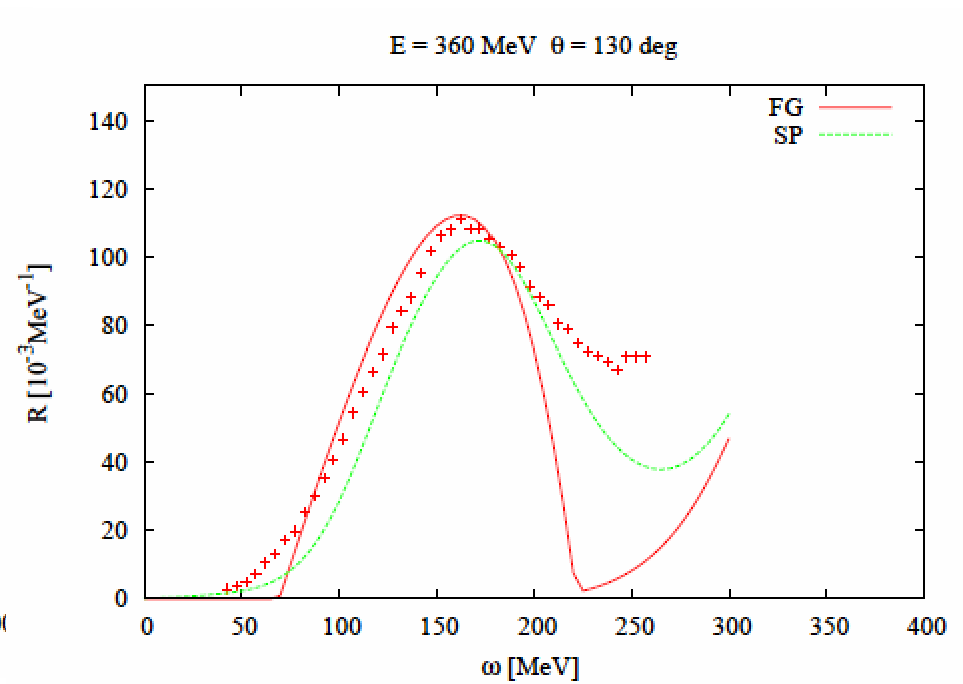




Not so good   Okay?

Q^2=0.13 (GeV/c)^2 ← Q^2=0.21 (GeV/c)^2





Summary

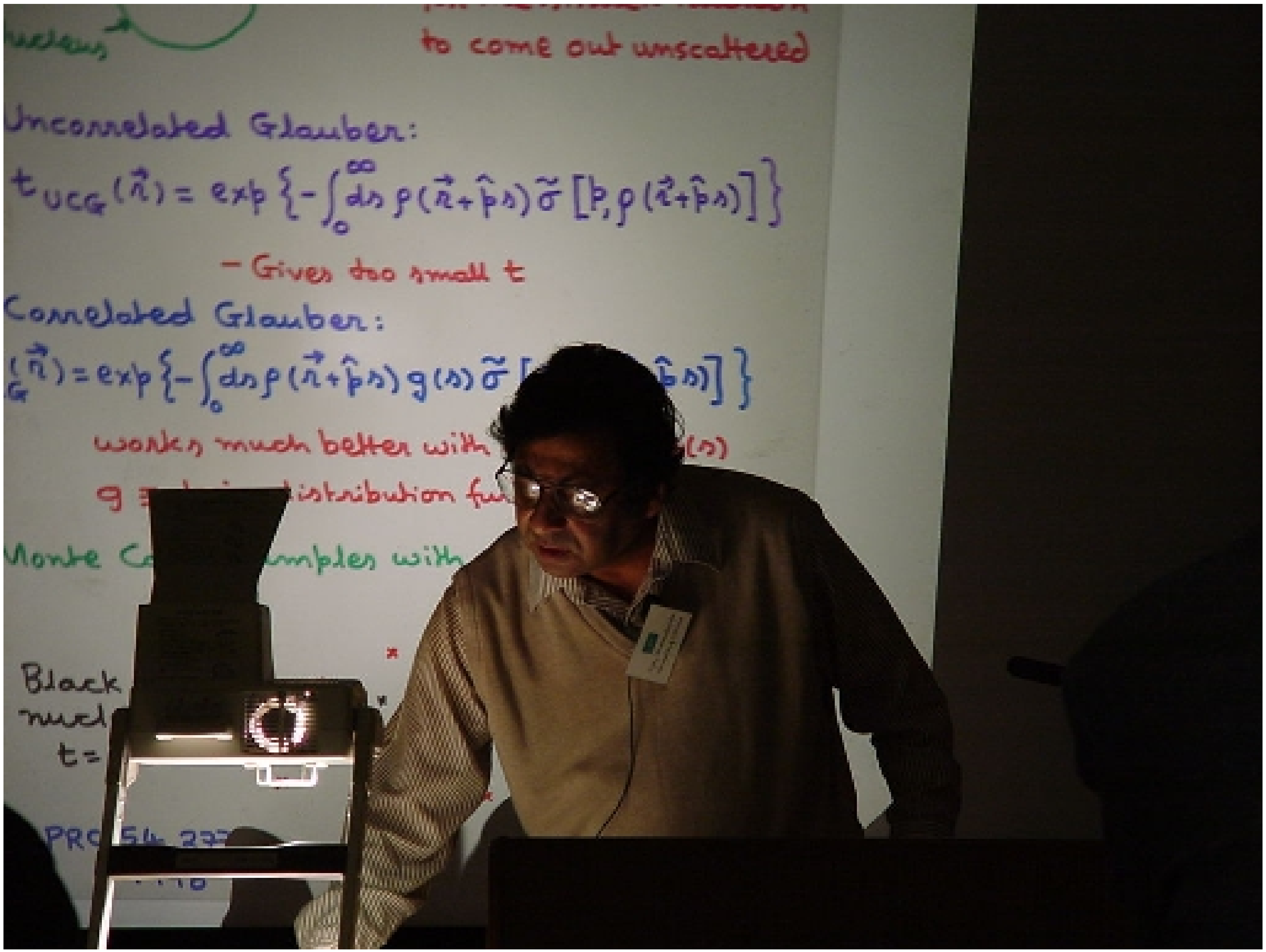
- Quantitative understanding of neutrino-nucleus quasi-elastic interaction and 1π production is progressing.
  - QE is in good shape, 10% accurate, for E>700MeV (Q^2>0.2 GeV^2)
    - New nucleon form factors, Spectral function, Final state interaction
  - 1π production is a bit more complicated, known to 20-30%.
    - Δ
    - non-resonant production, 2nd resonance
    - Pion absorption
  - Dip region
    - This is related to QE and 1π production.
    - Δ-hole, 2p-2h etc

- Quantitative comparison continues..

Summay (continued)

- Existing and new electron beam data are very valuable to the precise determination of neutrino-nucleus interactions, including low Q^2 region.
  - 1-5% accuracy on the vector-current interaction and the nuclear effect may be possible. JLAB E04-001 (JUPITER), E02-109, E97-001, Mougey et al.
- We extend our energy region down to 20-500MeV region, where MiniBOONE,T2K,MINOS,SuperNova neutrinos and Sub-GeV atmospheric neutrinos are relevant.
- JLAB has the wealth of data and knowledge on the nuclear physics. Everyone will welcome the commitment of JLAB to neutrino physics.

Jorge and I would like to pay a tribute to the memory of Vijay Pandharihande who lectured us the Nuclear Physics at NuInt01.



December, 2001
@NuInt01, KEK

Quote From the APS Neutrino Study "Neutrino Matrix" 2004

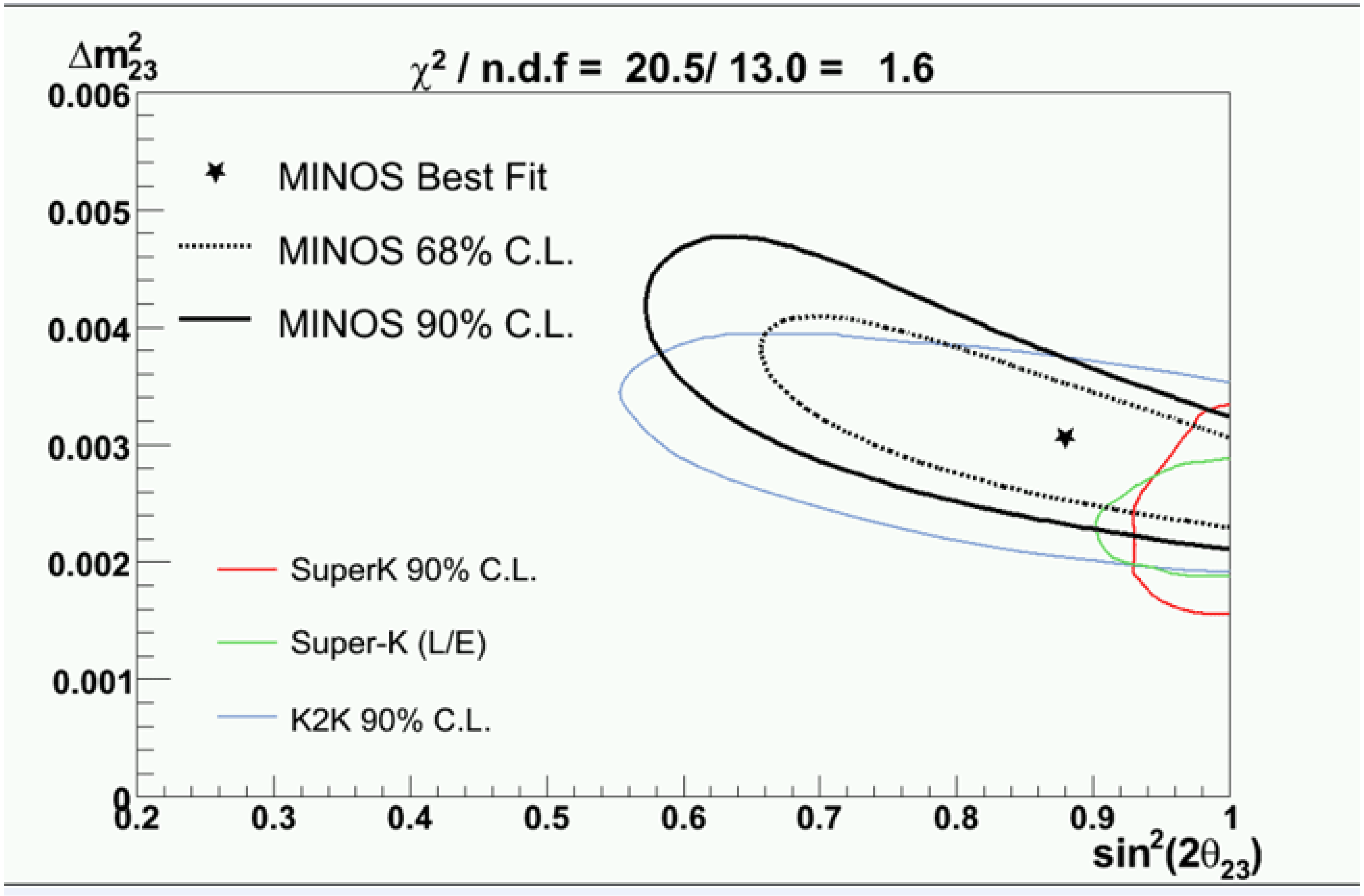
Section 4 Recommendations

"The precise determination of neutrino cross sections is an essential ingredient in the interpretation of neutrino experiments...

Interpretation of atmospheric and long-baseline accelerator-based neutrino experiments, understanding the role of neutrinos in Supernova explosions, and predicting the abundances of the elements produced in those explosions all require knowledge of neutrino cross sections. New facilities, such as the Spallation Neutron Source and existing neutrino beams can be used to meet this essential need."

I would like to add, "Electron beam experiments are equally important."

ν_μ-ν_τ oscillations established by SK and K2K at 90%CL (2004), And now by MINOS (2006)



Neutrino Data Resource by M.Whalley@NuInt04

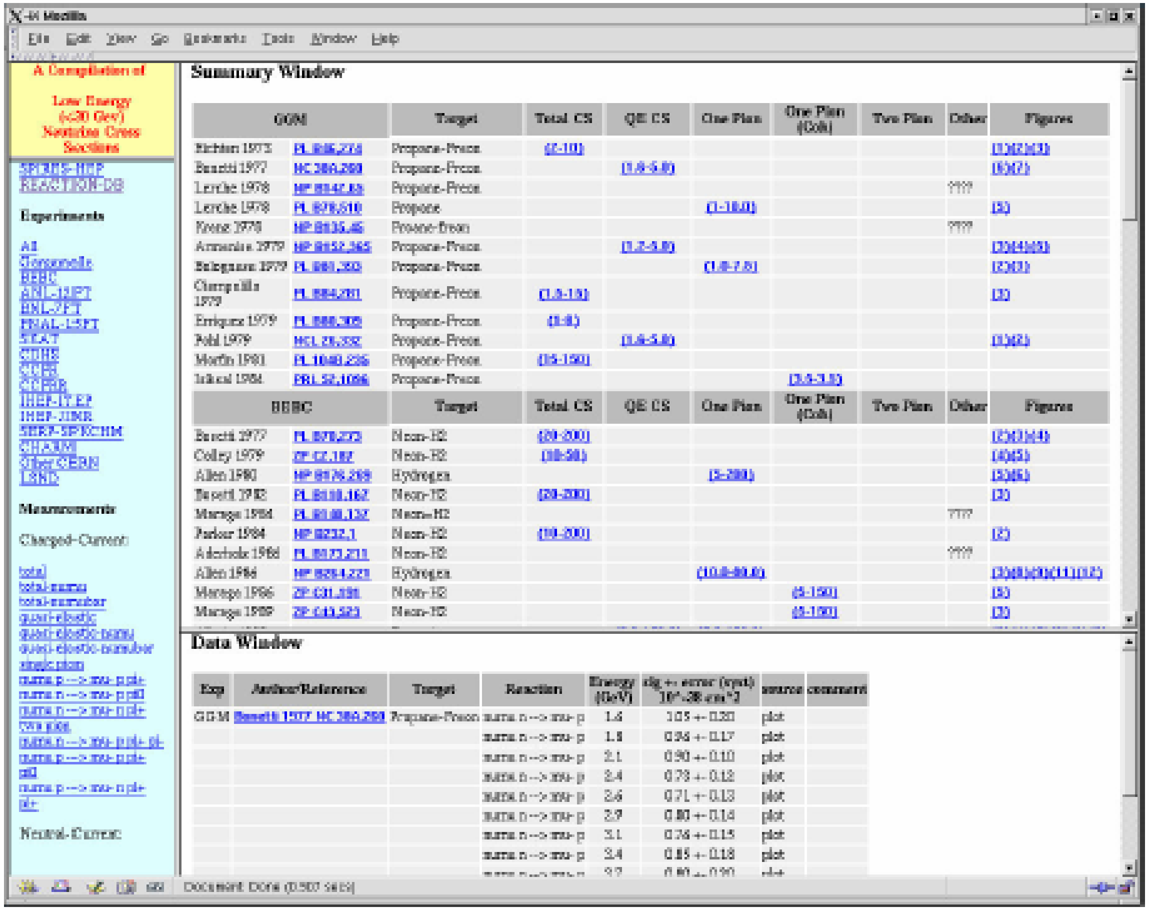


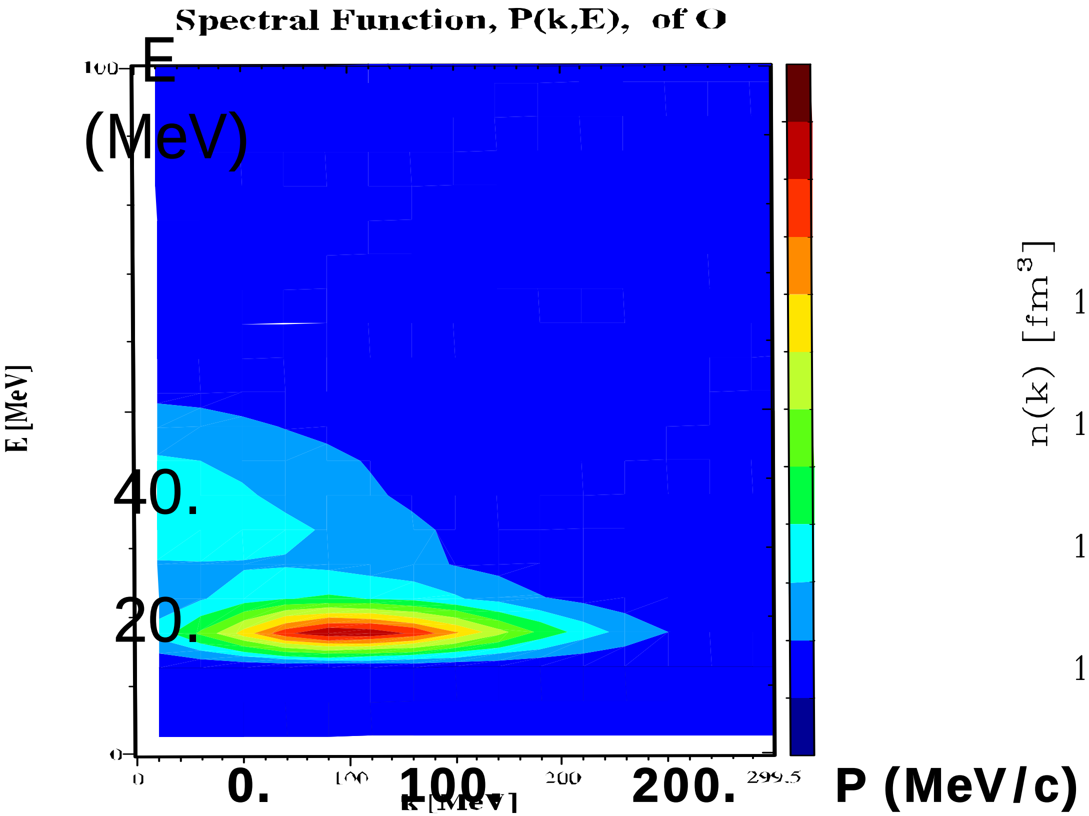
Figure 1. The main home web page of the Neutrino Data Resource (http://durpdg.dur.ac.uk/hepdata/online/neutrino/)

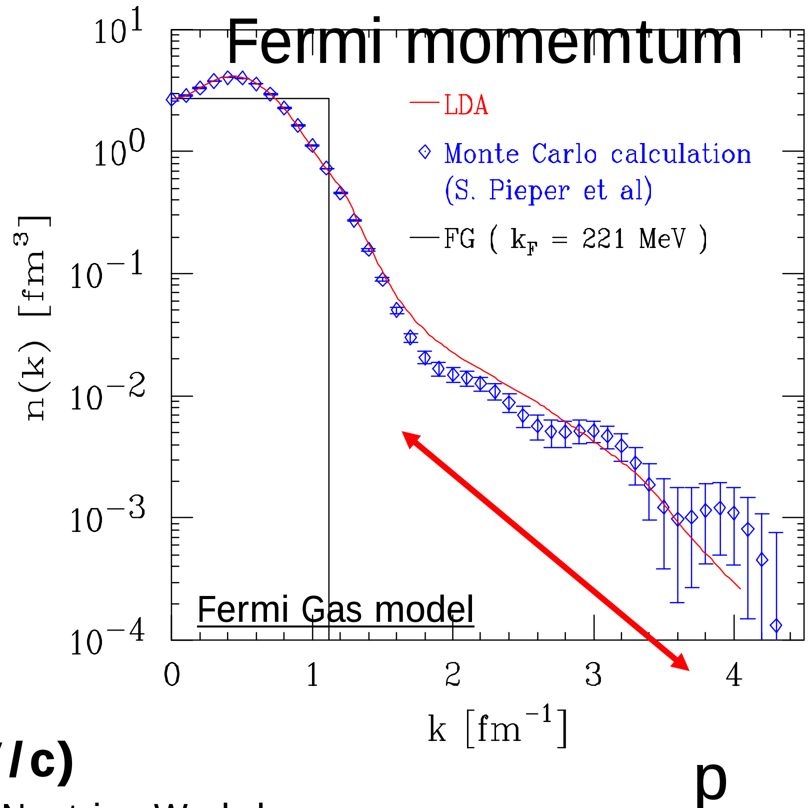
	Quasi-elastic	Δ
Nieves・Oset	All diagram	All diagram
Sato,Lee et al		Checked with Data
Paschos,Lalakulich et al.		Checked with Data Nuclear effect (Absorption effect, Pauli effect)
Benhar et al.	Checked with Data Spectral function FSI	Using Bodek-Ritchie and Paschos

Uniform Fermi-Gas and Spectral Function for Various Nuclei

- Spectral Functions P(**p**,E) for various nuclei, eg.^{16}O, ^{12}C, are measured at JLAB and estimated by Benhar.

  P(p,E) : Probability of removing a nucleon of momentum p from ground state leaving the residual nucleus with excitation energy E.

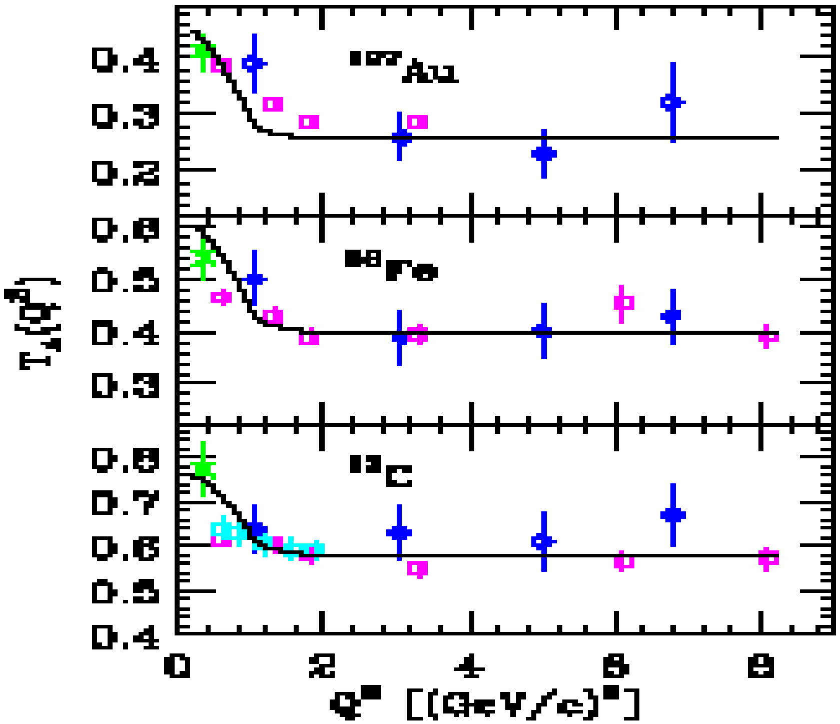




Validation of FSI effect:
Calculated transparency compared to data

Transparency= Probability that a nucleon can escape from the nucleus without being subject to any interaction.
i.e. T=1.0 = Completely transparent=No interaction

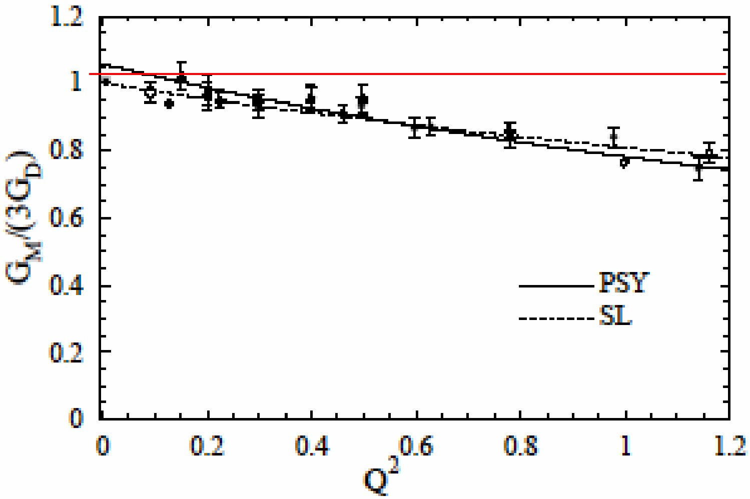
Benhar,Nakamura,Seki,MS, PRD72,053005,2005



3.3) NΔ Form factor and Single Pion Production

- Size of Δ is larger

=Q^2 distribution steepe



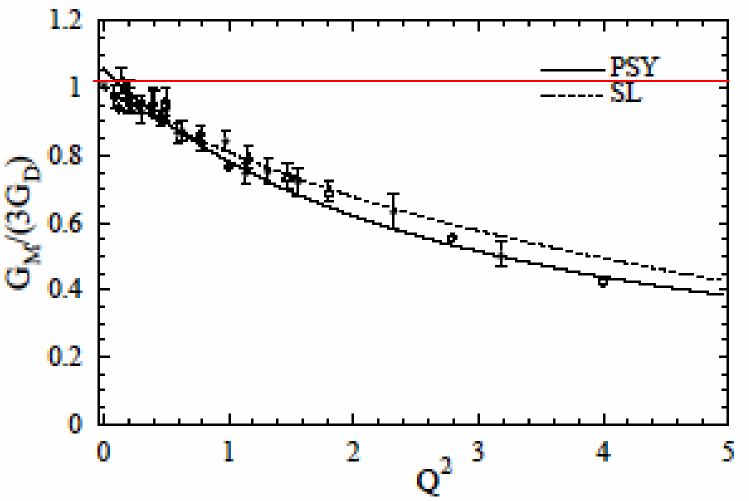


FIG. 1: The magnetic $N-\Delta$ transition form factor G_M^* in dependence of Q^2 [16]. The solid and dotted lines denote our form factor eq. (5) and the Sato-Lee(SL) form factor [17], respectively.