Low Energy Neutrino-Nucleus Interactions

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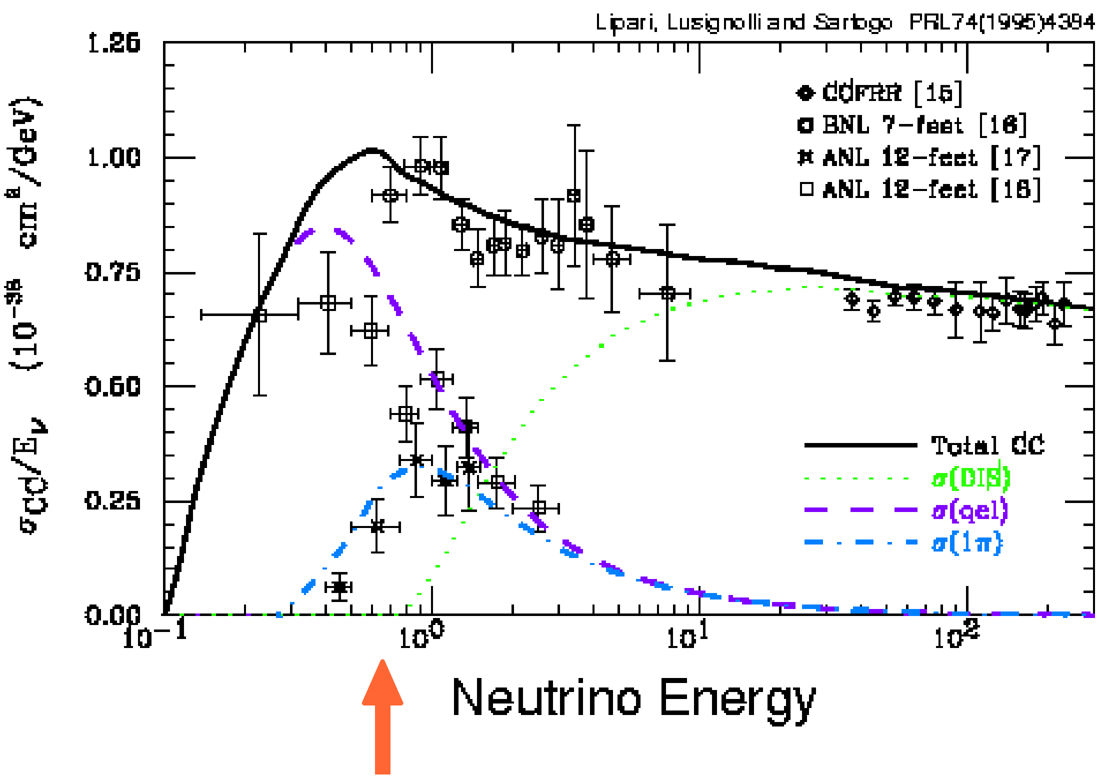
Outline

1. Neutrino-Nucleus Interactions in Oscillation experiments.
2. Nuclear effects
3. Fitting the axial mass.
4. Recent Progress in Calculation (NuInt01/02)
   - Elastic Form Factors
   - Spectral Function = Beyond Fermi Gas
   - Nuclear PDF
   - Deep Inelastic Scattering
5. Conclusions

Reminder: Cross Sections~ 1 GeV

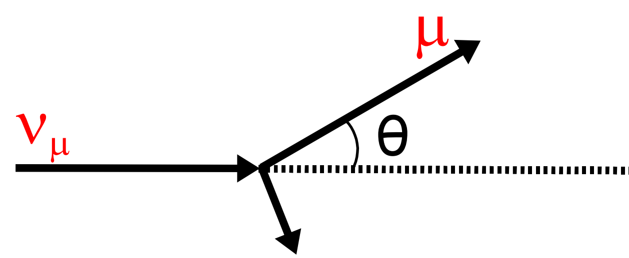


Energy of JHF/K2K
oscillation supression

A Concrete example:
E_ν Reconstruction (assuming QE)

In a Quasi-Elastic reaction, even if only the muon is visible we can reconstruct the neutrino energy.

If the interaction is non Quasi-Elastic then the reconstructed energy will be incorrect.



$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos(\Theta_\mu)}$$

m_N = Neutron mass

E_μ = Muon energy

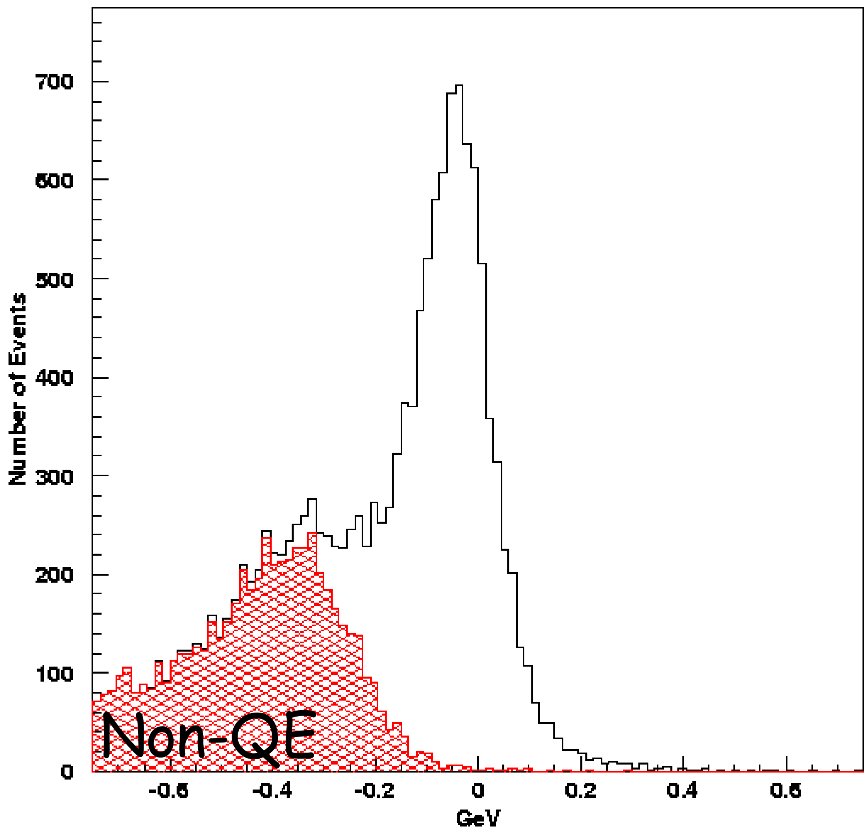
m_μ = Muon mass

p_μ = Muon momentum

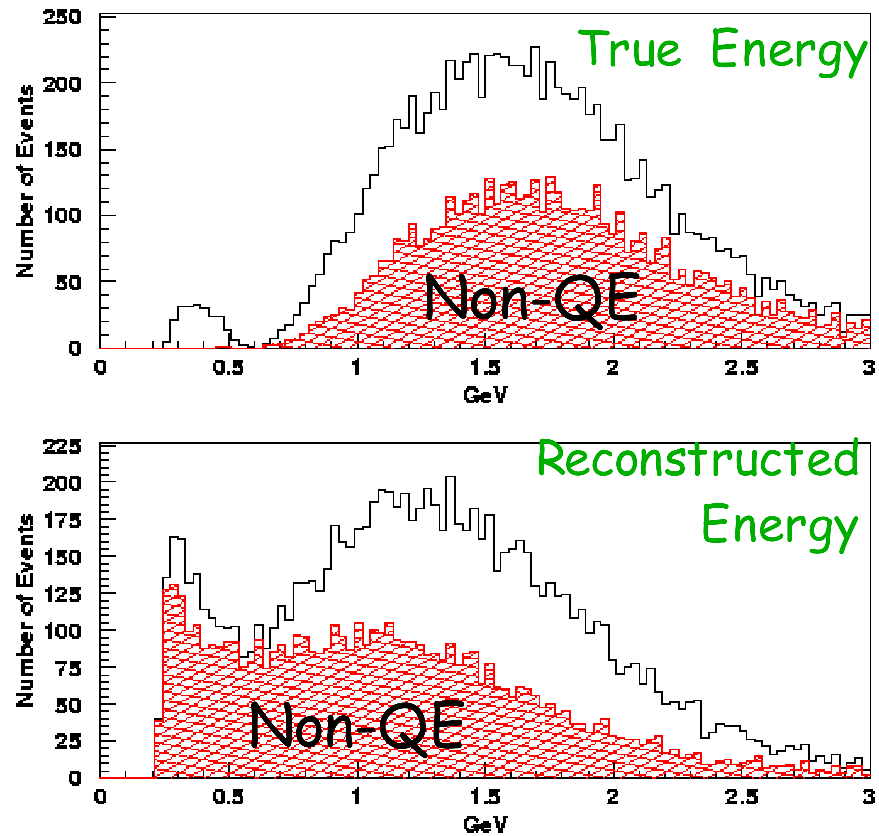
Θ_μ = Muon angle wrt beam

Non-QE interactions and E_ν Reconstruction

Example: K2K Flux MC



True - Reconstructed Energy

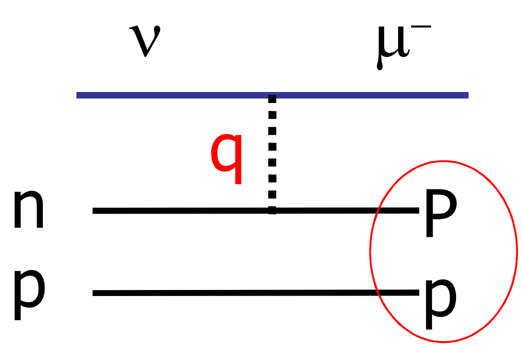


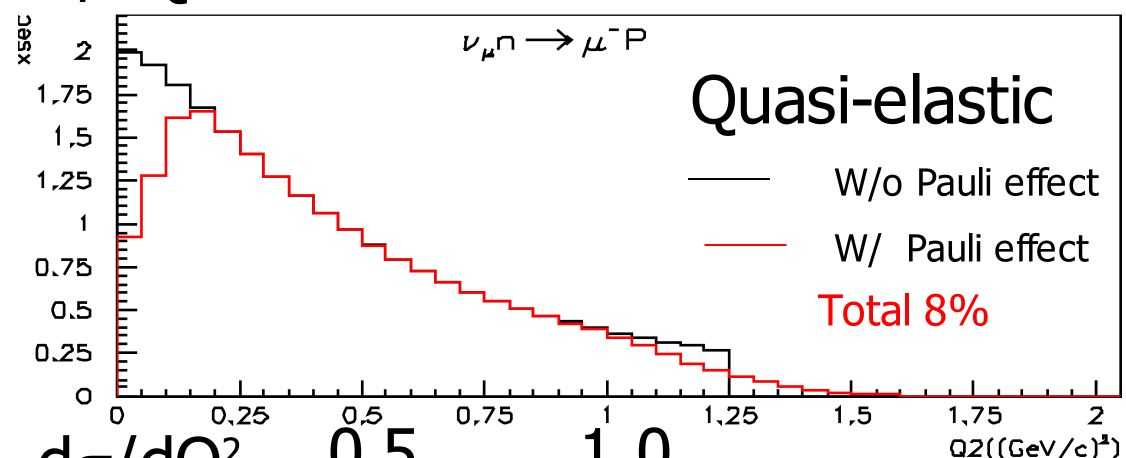
Non-QE reconstructs at low-energy in the oscillation dip!

Pauli Exclusion Effect

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

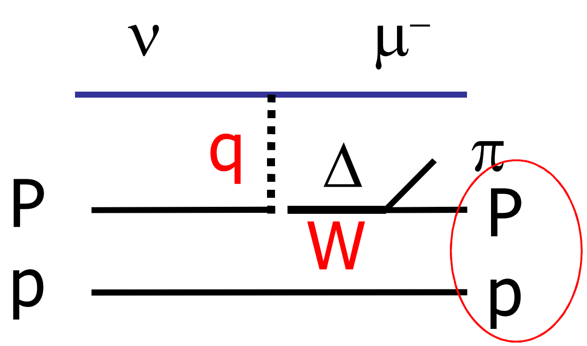
E_ν=1.3 GeV k_F=220 MeV/c

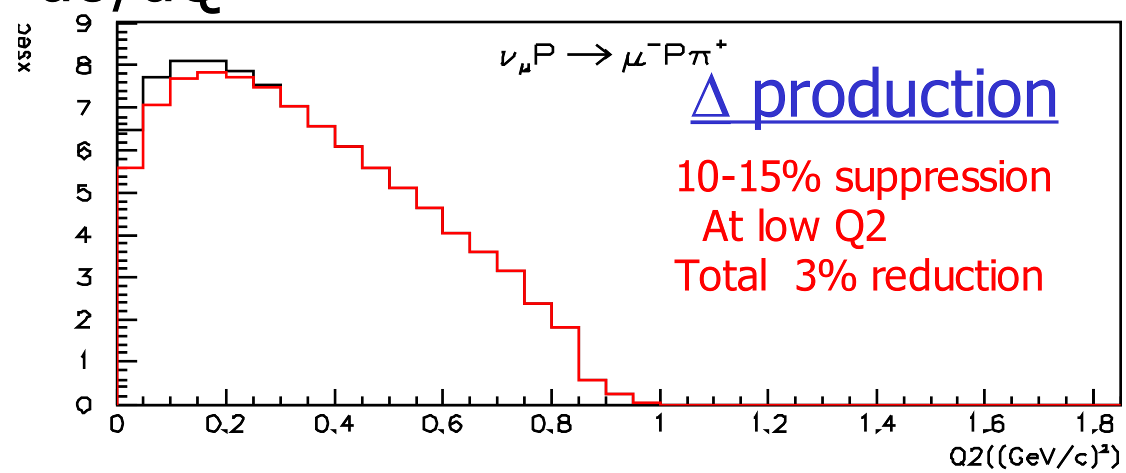




If P <k_F , suppressed.

dσ/dQ² 0.5 1.0

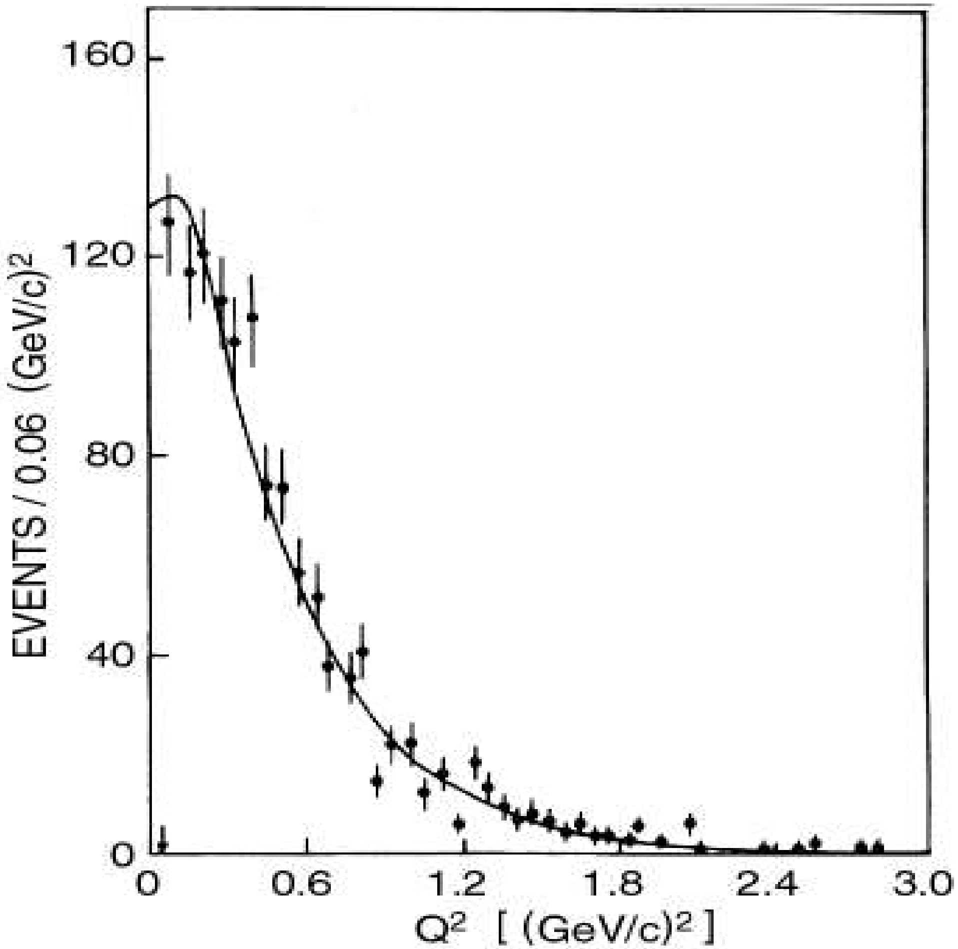




$d\sigma/dQ^2$ (quasi-elastic scattering)

BNL Deuterium BC

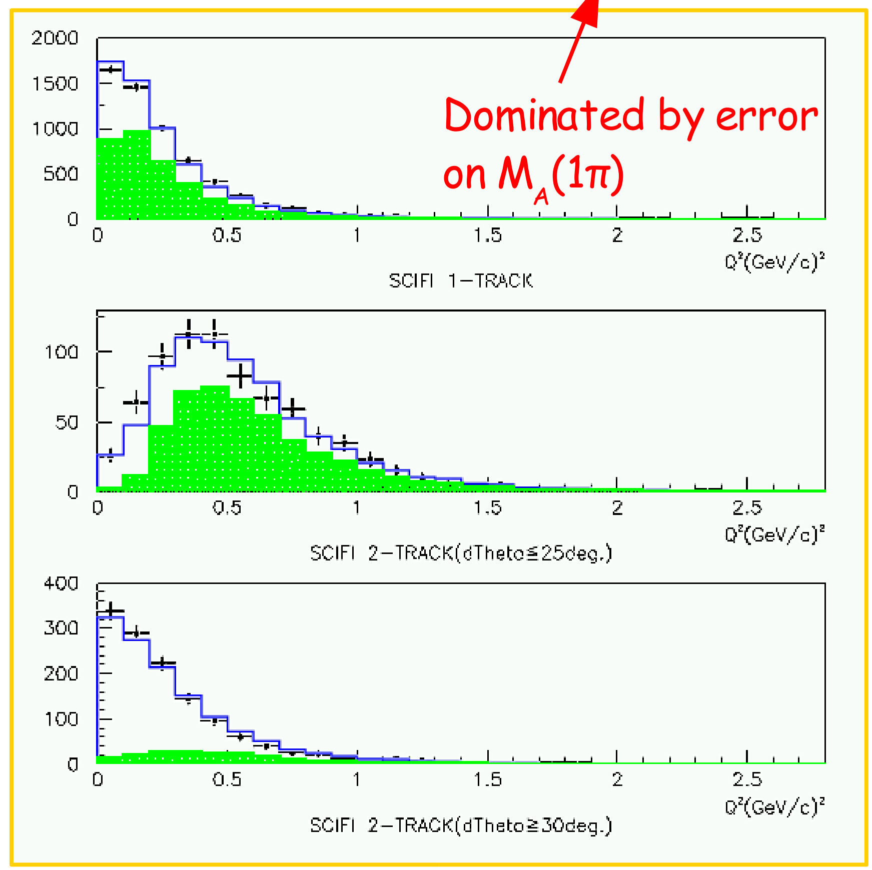
M_A=1.07±0.05



Ishida(K2K)@nuint02 Sensitivity to MA

M_A ~ 1.1

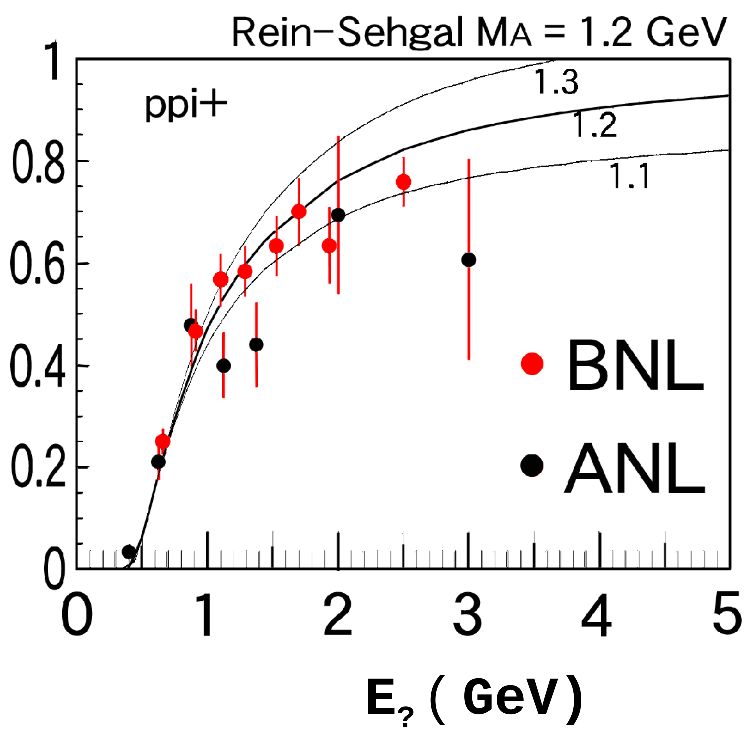
Errors ~ ± .05(stat) ± .15(Sys) GeV/c²



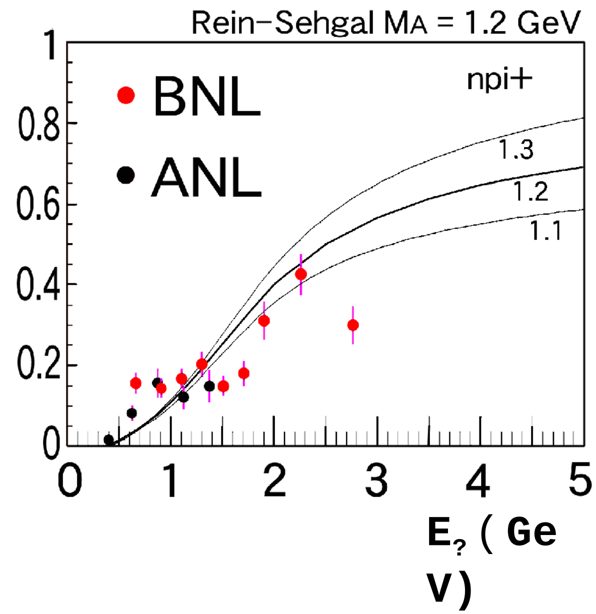
Flux independent ratio σ(single π)/σ(QE):

The BNL data still exists and can be reanalyzed: Furuno@nuint02

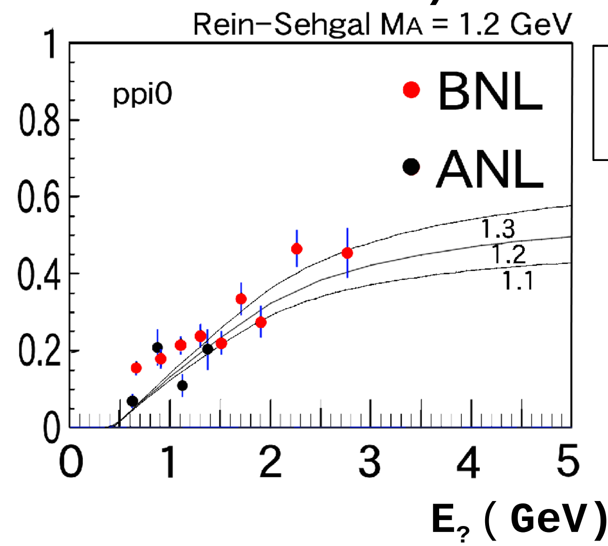
$\mu^- p \pi^+$



$\mu^- n \pi^+$



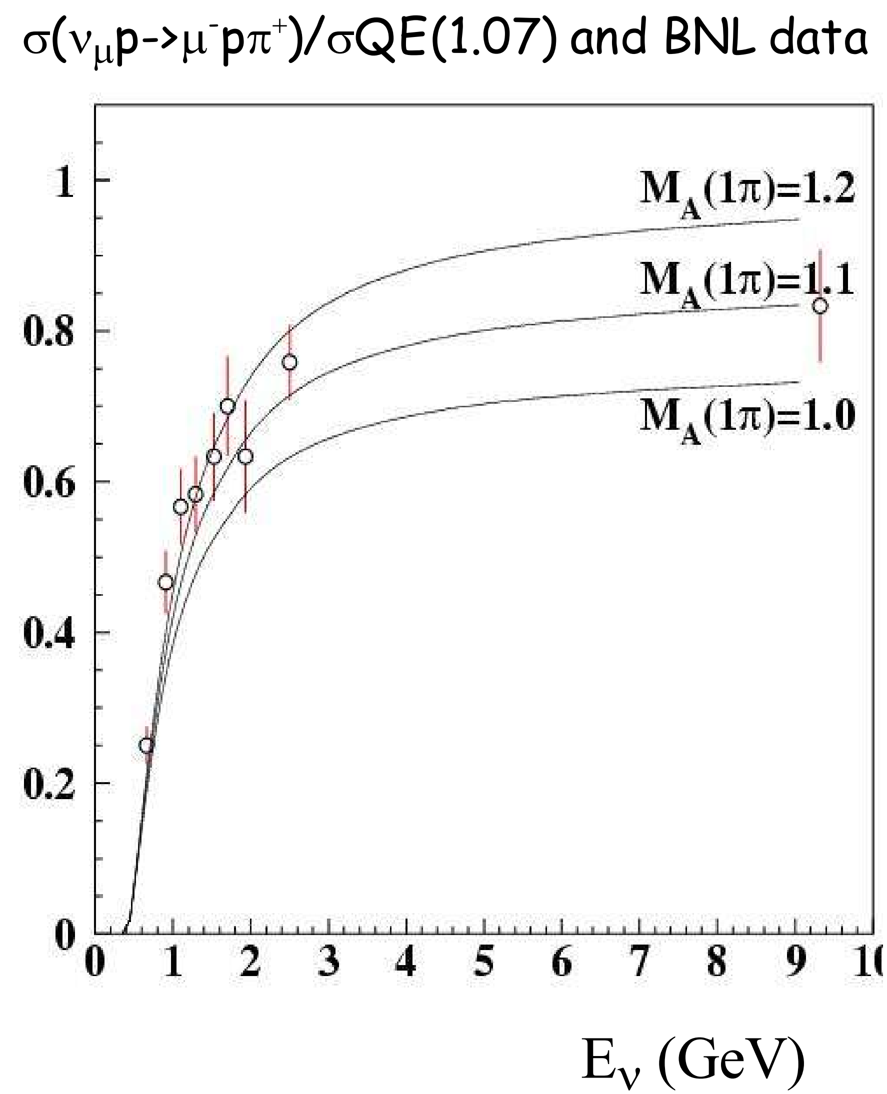
$\mu^- p \pi^0$



BNL Data: T. Kitagaki et al. PRD34 (86)
ANL Data: Radecky et al, PRD25,1161,'82
S.J.Barish et al,PRD16,3103,'77

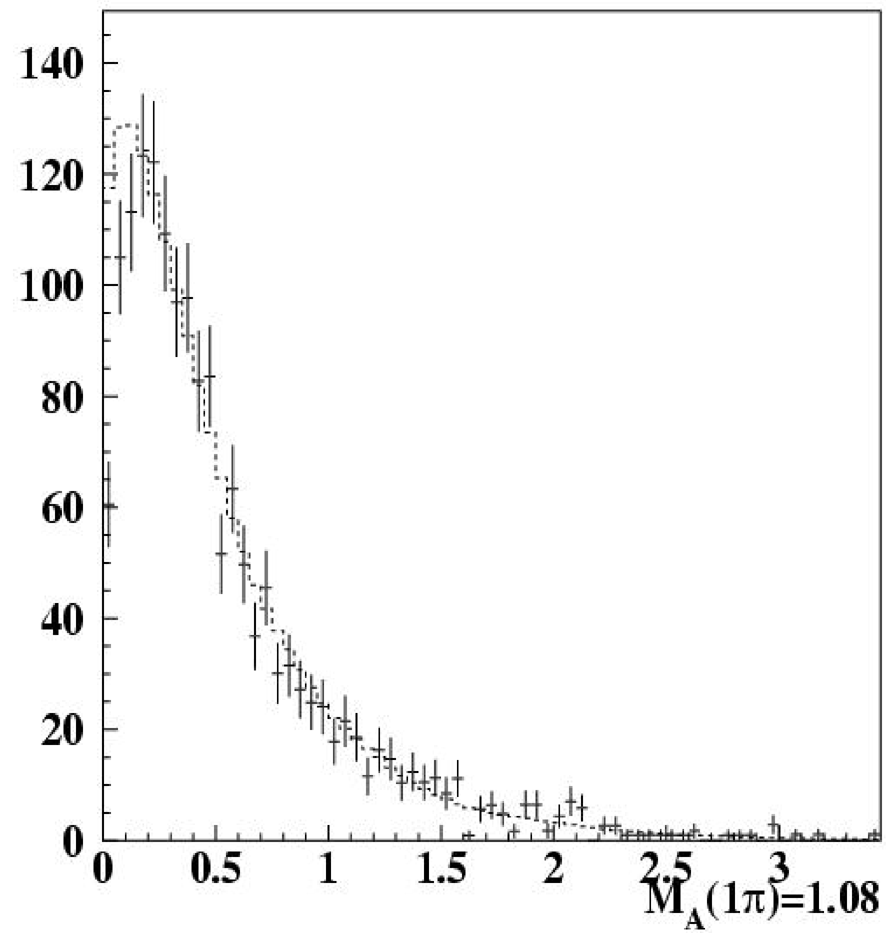
$M_A(1\pi)$ fit using $\sigma_{1\pi}/\sigma_{QE}$ ratio

- For $M_A(1\pi)$:
  - Fit value of 1.15 +.08-.06
  - X^2=9.88 d.o.f=9 (X^2/d.o.f=1.10)
  - Error on M_A(QE) included in fit
  - consistent with the K2K M_A value of 1.2



$M_A(1\pi)$ fit using $d\sigma_{1\pi}/dQ^2$ shape

- For $M_A(1\pi)$:
  - Same data, different format
  - Fit for $Q^2 > 0.2$ only
  - Fit value of 1.08 +/-.07 (stat.)
  - X^2 = 63.1 d.o.f=65 (X^2/d.o.f=.971)



$d\sigma(\nu\mu\pi\rightarrow\mu{-}p\pi+)/dQ^2$ vs Q^2 data and calculation

3. Recent Progress in Calculation (NuInt01/02)

- Elastic Form Factors
- Spectral Function = Beyond Fermi Gas
- Deep Inelastic Scattering
- Nuclear PDFs

Neutrino Interactions

From EM Scattering:

$G_{EP}(Q^2=0) = 1$ $G_{EN}(Q^2=0) = 0$

$G_{MP}(Q^2=0) = 2.79$ $G_{MN}(Q^2=0) = -1.91$

$$G_E^P(Q^2) = \frac{G_M^p(Q^2)}{2.79} = \frac{G_M^n(Q^2)}{-1.91} = G^{dipole}(Q^2) = \left(1 + \frac{Q^2}{0.71\,(GeV/c)^2}\right)^{-2}$$

Charged Current

$$J_\alpha^{1+i2} = V_\alpha^{1+i2} - A_\alpha^{1+i2}$$

$$< p(p')|J_\alpha^{CC}|n(p) > = < p(p')|V_\alpha^{1+i2} - A_\alpha^{1+i2}|n(p) >$$

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

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

$$F_A(Q^2) = \frac{F_A(0)}{(1+Q^2/M_A^2)^2} \quad ,with \quad F_A(0) = -1.2617 \pm 0.0035$$

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

Quasi-Elastic Cross Section

$$\frac{d\sigma_{QE}}{dQ^2} = \frac{M^2 G^2 \cos(\theta_c)}{8\pi E_\nu^2}\left[A(Q^2) - B(Q^2)(s-u) + C(Q^2)(s-u)^2\right]$$

- $A=4(m^2/4M^2+\tau)[(1+\tau)|F_A|^2-(1-\tau)|F^V{}_1|^2+\tau(1-\tau)|\xi F^V{}_2|^2+4\tau\xi \mathrm{Re}F^{V*}{}_1F^V{}_2]-m^2/4M^2(|F^V{}_1+\xi F^V{}_2|^2+|F_A+2F_p|^2-4(1+\tau)F_p{}^2)]$
- $B=-4\tau \mathrm{Re}F_A{}^*(F^V{}_1+\xi F^V{}_2)$
- $C=4(|F_A|^2+|F^V{}_1|^2+\tau|\xi F^V{}_2|^2)$

Where $(s-u)=4ME_\nu-Q^2-M_\mu$, $\tau = Q^2/4M^2$, $\xi = u_p - u_n$,

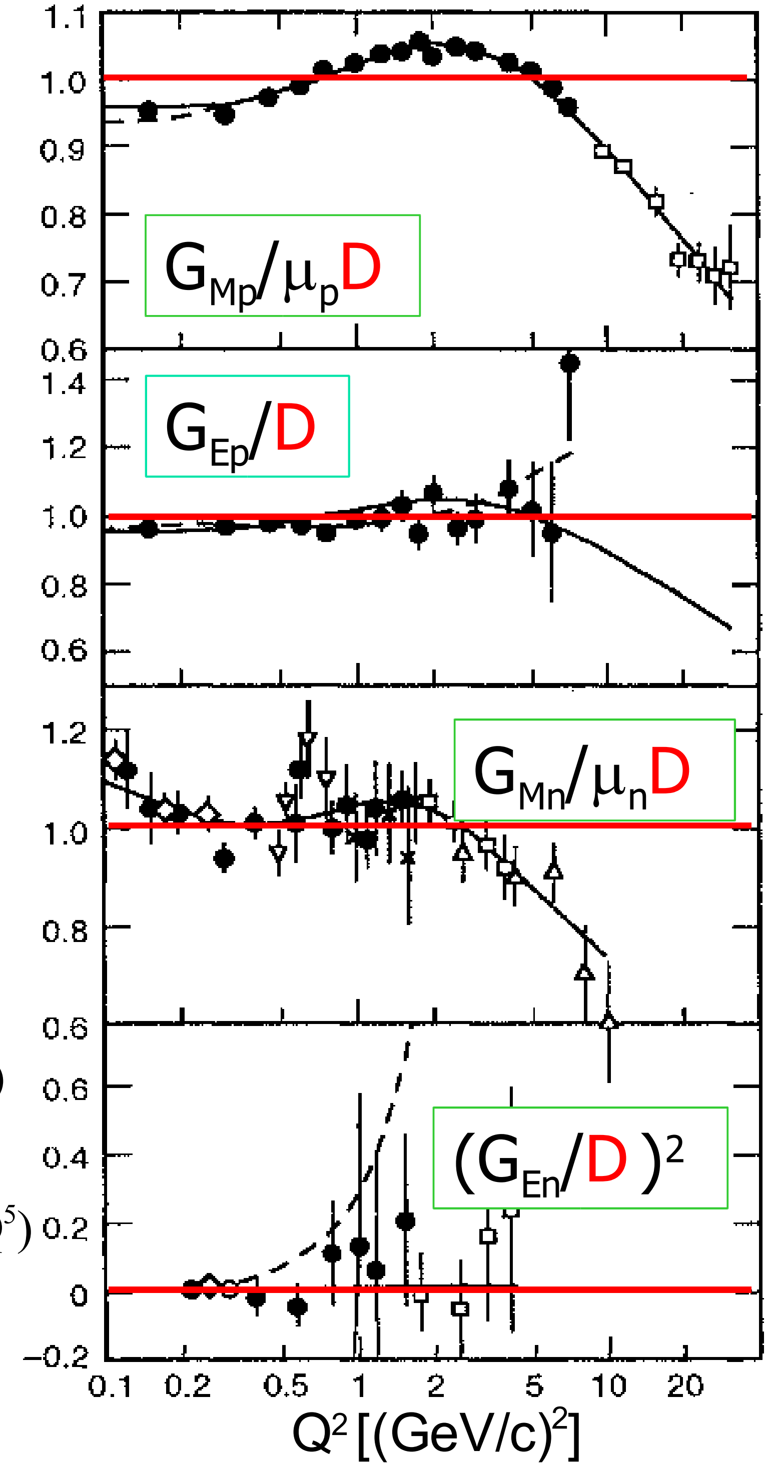
F_p is the pseudo scalar form factor, and F_A is the axial vector form factor.

- The vector form factors:
  - $F^V{}_1 = (G_{Ep} - G_{En} - \tau(G_{Mp}-G_{Mn}))/(1+\tau)$
  - $\xi F^V{}_2 = (G_{Mp} - G_{Mn} - G_{Ep} + G_{En})/(1+\tau)$

Nucleon Vector Form Factors

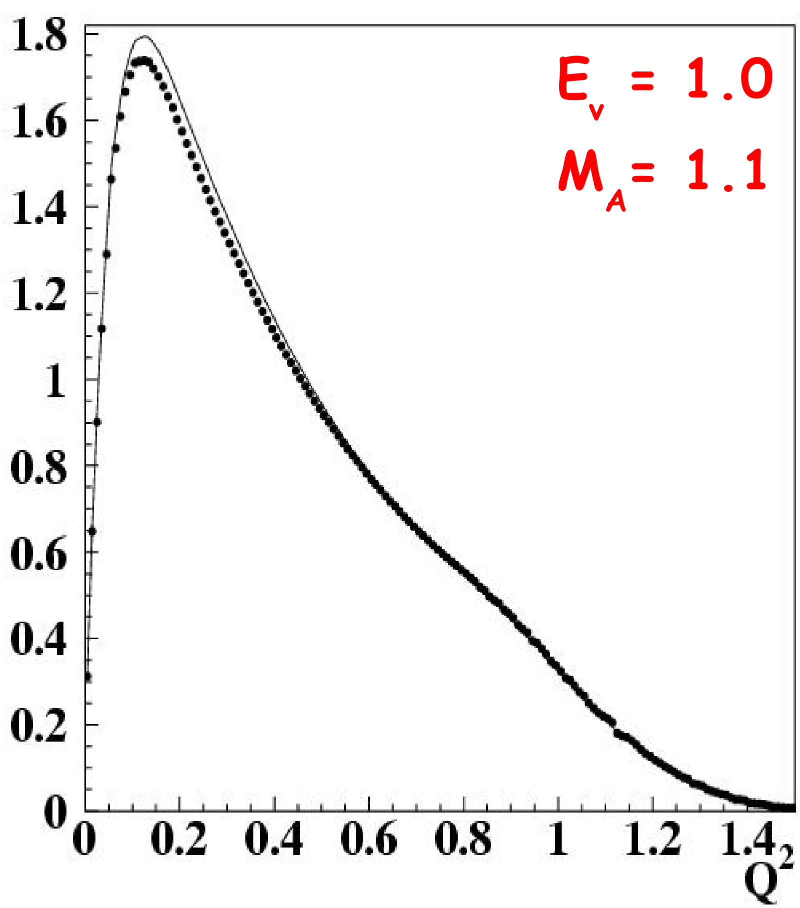
- The simple dipole fit is only good to ~10-20%
- New SLAC/JLAB e-p/e-D data shows that vector form factors must be updated
- New parameters from P.E. Bosted, "Empirical fit to nucleon electromagnetic form factors, Phys Rev C, V 51, 409, '95
  (Also E.J.Brash et al,PRC65,051001,2002)

Form Factor	Old	New
G_{En}	0	$-1.25\,\mu_n D\,\tau/(1+18.3\,\tau)$
G_{Ep}	D	$1/(1+.14Q+3.01Q^2+.02Q^3+1.20Q^4+.32Q^5)$
G_{Mn}	$\mu_n D$	$\mu_n/(1-1.74Q+9.29Q^2-7.63Q^3+4.63Q^4)$
G_{Mp}	$\mu_p D$	$\mu_p/(1+.14Q+3.01Q^2+.02Q^3+1.20Q^4+.32Q^5)$
F_p	0	$2M^2F_A(Q^2)/(m_\pi^2+Q^2)$

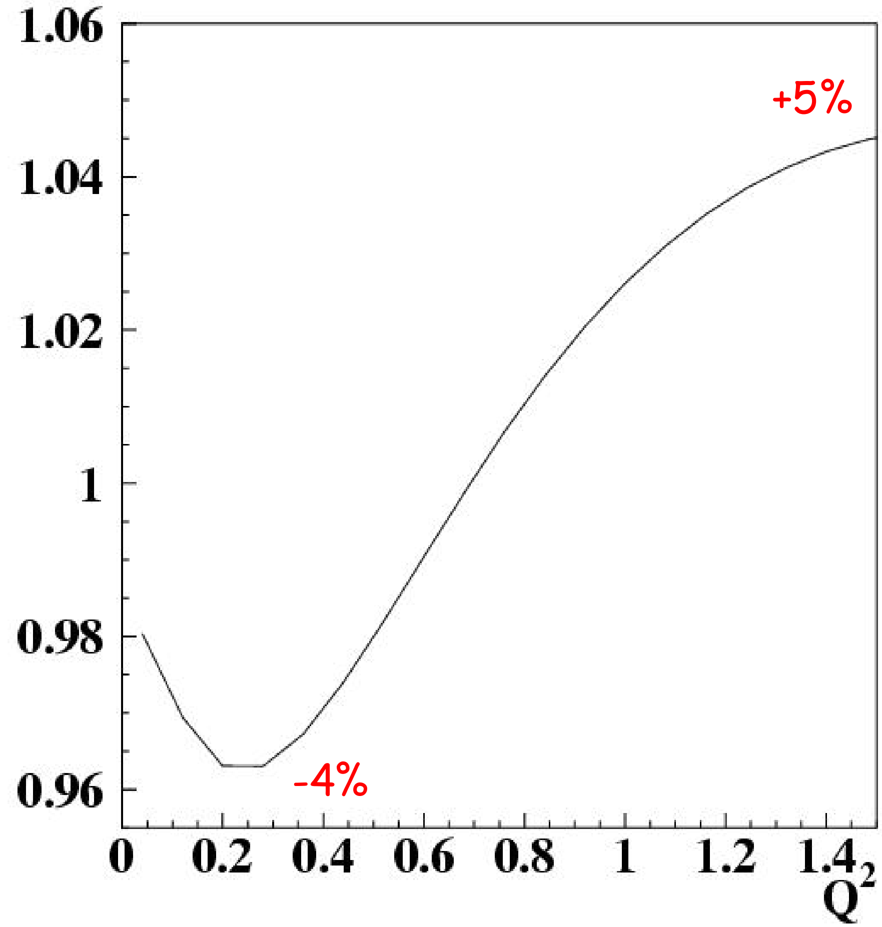


$d\sigma/dQ^2$ vs. Q^2 with new Vector Form Factors G_{Mn},G_{Mp},G_{Ep} ,G_{EN}

Old code (line) vs new code (dot)



Ratio of new cross section to old cross section.

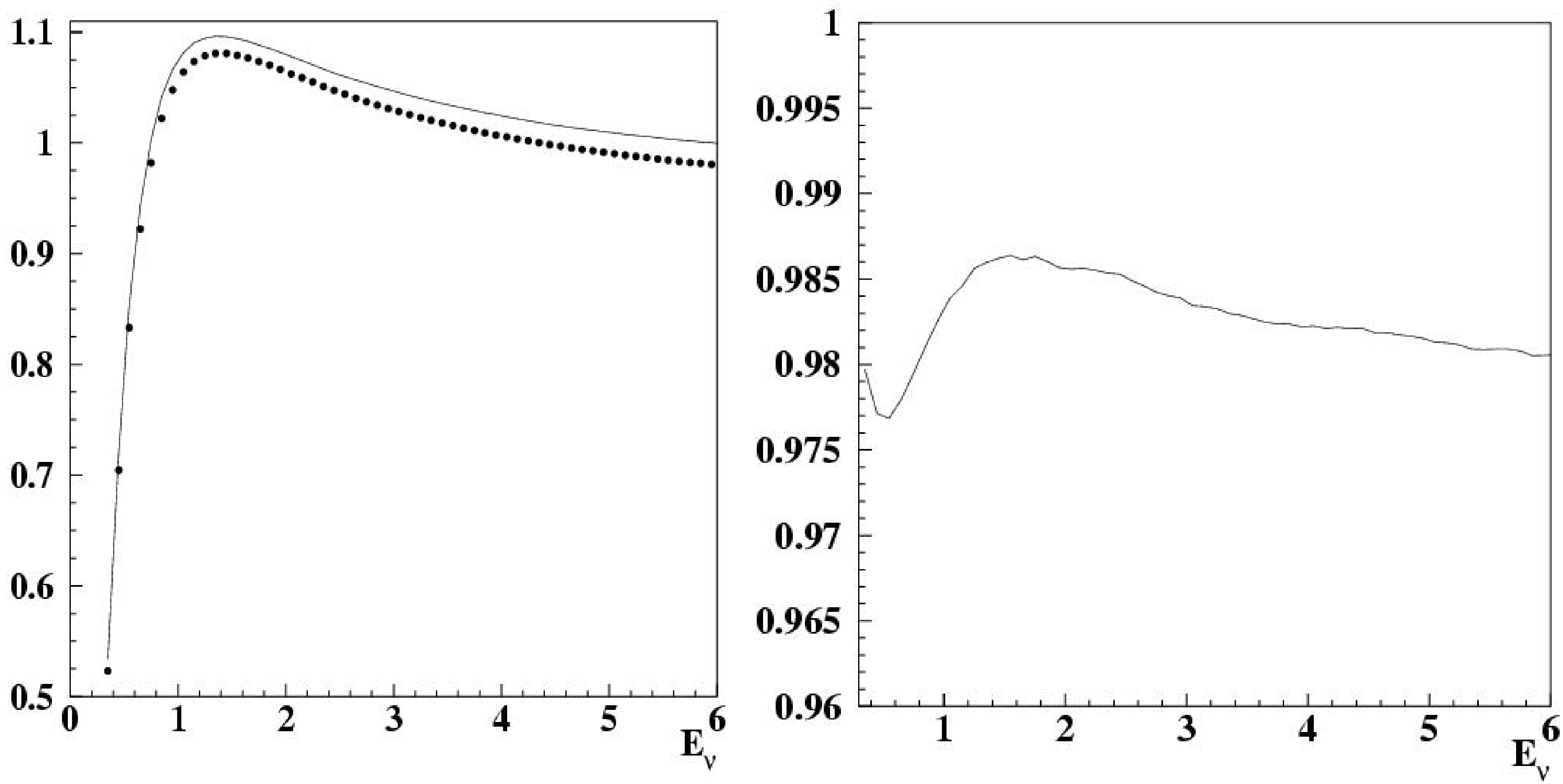


- New cross section is smaller at low Q^2, and larger at higher Q^2
- ~5% overall difference in $d\sigma_{QE}/dQ^2$
- F_p is a < 1 % difference, G_{En} is ~2% difference, both largest at low Q^2
- Changes M_A fit value by .05

σ_{QE} vs. E_ν with new Vector Form Factors $G_{Mn}, G_{Mp}, G_{Ep}, G_{EN}$

Old (line) vs new (dot) QE cross section

Ratio of new/old QE cross section



M_A=1.1 for both plots

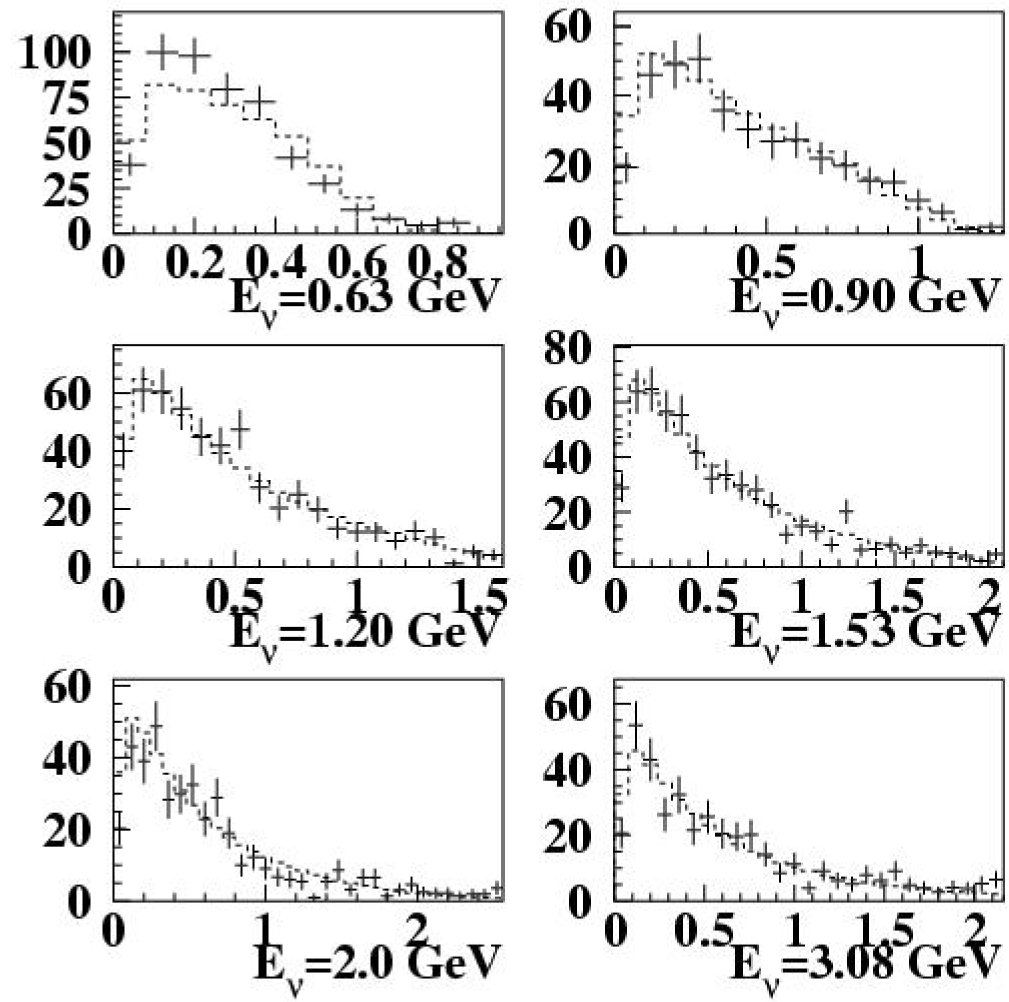
~2% overall difference for σ_{QE}

Will cause M_A fit value to change by 2%

New $d\sigma_{QE}/dQ^2$ shape fit for M_A(QE)

For M_A(QE):

- fit at different energies to BNL Q^2 distribution; only $Q^2 > 0.2$
- Old code best fit: M_A(QE) = 1.05 ± .06, consistent with BNL result of 1.07 ± .05
- New code best fit: M_A(QE)=1.0 ± .05
- shift of .05 in M_A(QE) expected from ~5% change in model.



Fit to BNL Q^2(QE) distributions

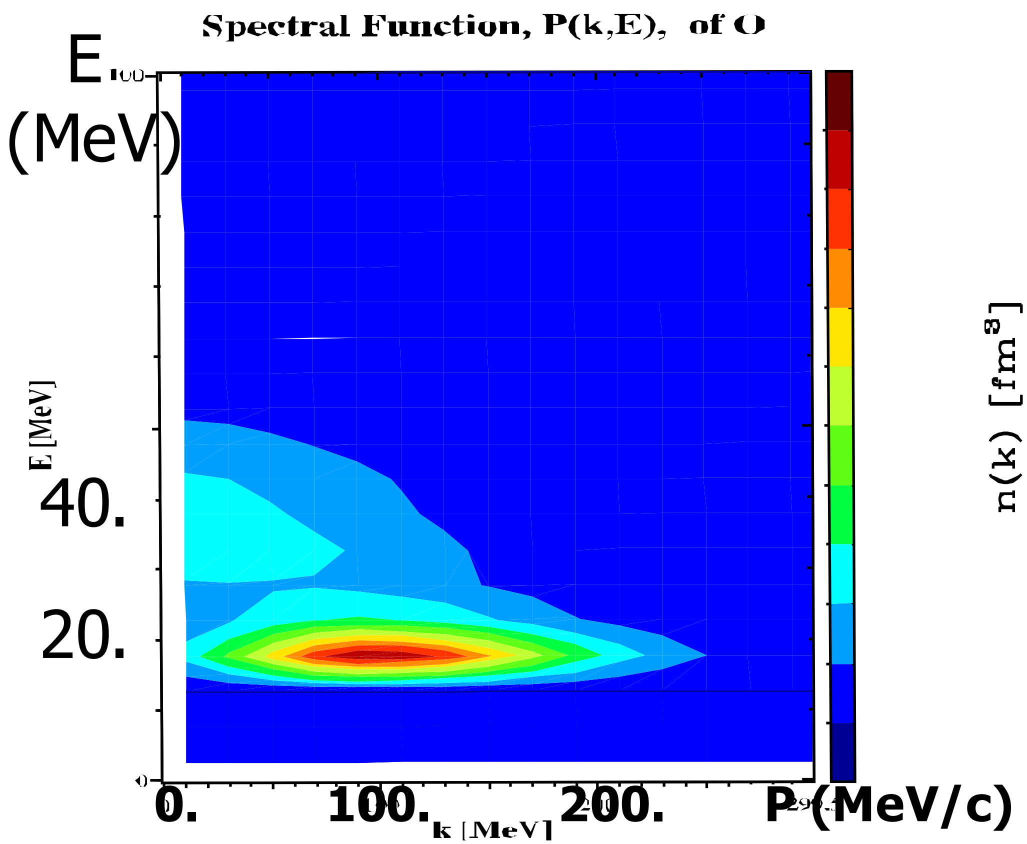
Models beyond the Fermi-gas model

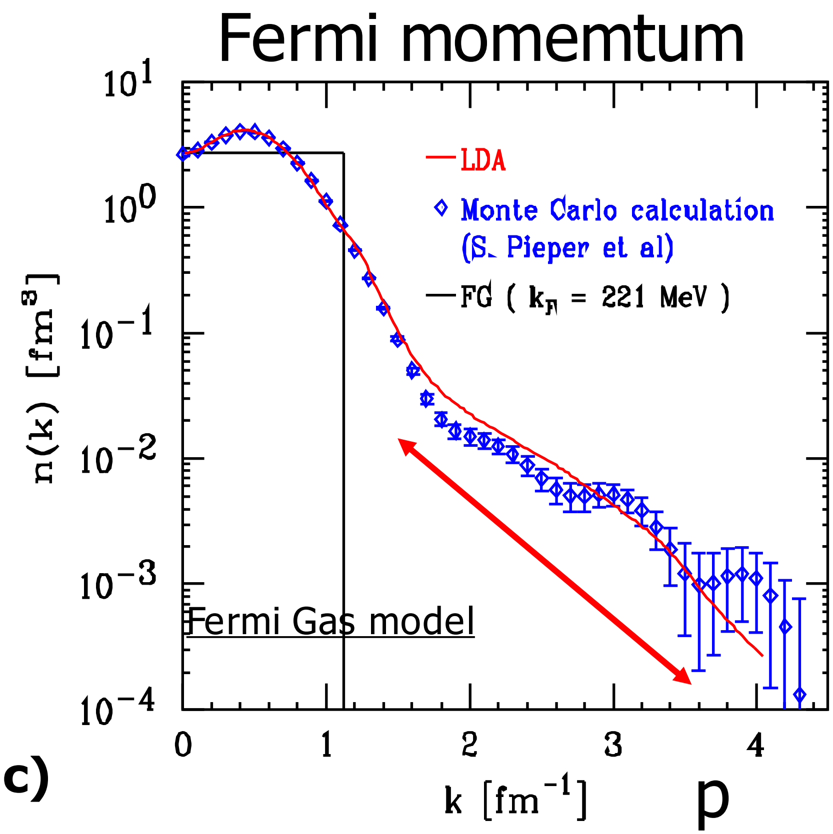
Spectral Function Calculation or Local Density Approximation

(Pandharipande@nuint01, Benhar, Nakamura, Gallagher@nuint02)

Spectral Functions P(**p**,E) for various nuclei, eg.^{16}O, are estimated by Benhar et al. using e-N data.

P(p,E) : Probability that the target nucleon has momentum p and binding energy E.

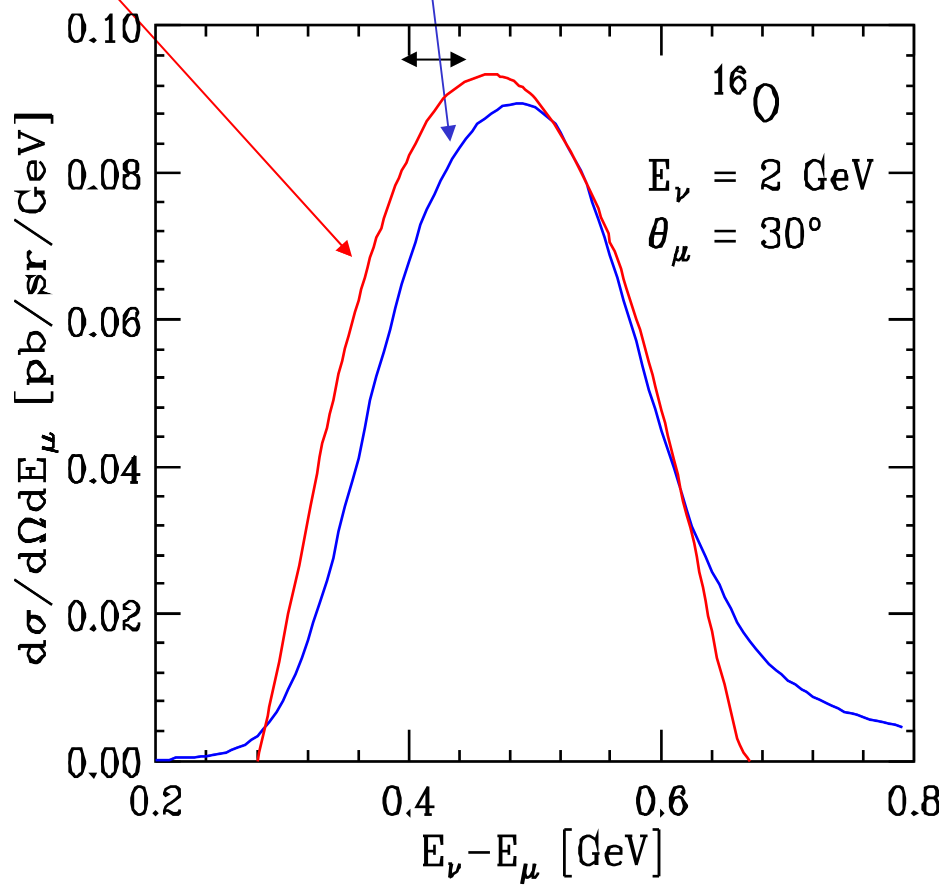




Lepton energy in quasi-elastic ν-N interaction

-Comparison of **Fermi Gas** model and **Spectral Function** Calculation-

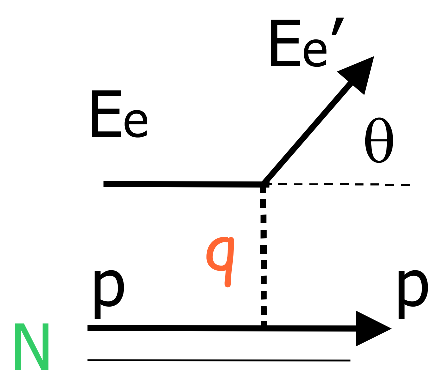
- Spectral function gives high energy tail.
- Shift at a level of 10 MeV may exist.
- $\langle \varepsilon_B \rangle$=25 MeV (Fermi-Gas)
- $\langle E \rangle_{LDA}$=40 MeV

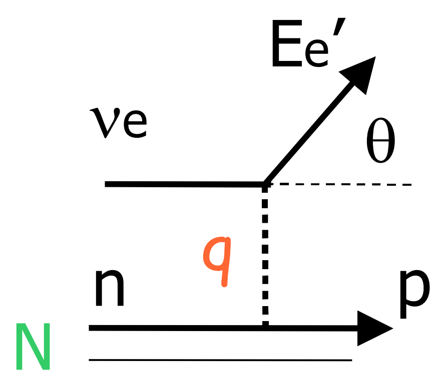


Benhar,Gallagher,Nakamura@nuint02

Using e-N scattering data to validate models

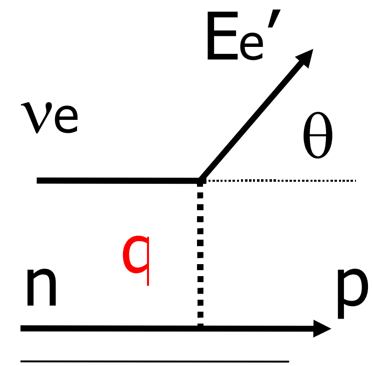
- There is a lot of e-scattering data available.
- By choosing a fixed energy and scattering angle we are probing a fixed Q transfer. This is sensitive to both the binding energy(V_b) and fermi-momentum (K_f).
- We can compare this to our neutrino MC generated at fixed Q.





Test of neutrino models using (e,e’) Data (•).

The energy transfer (ω=Ee-Ee’) at the fixed scattering angle .



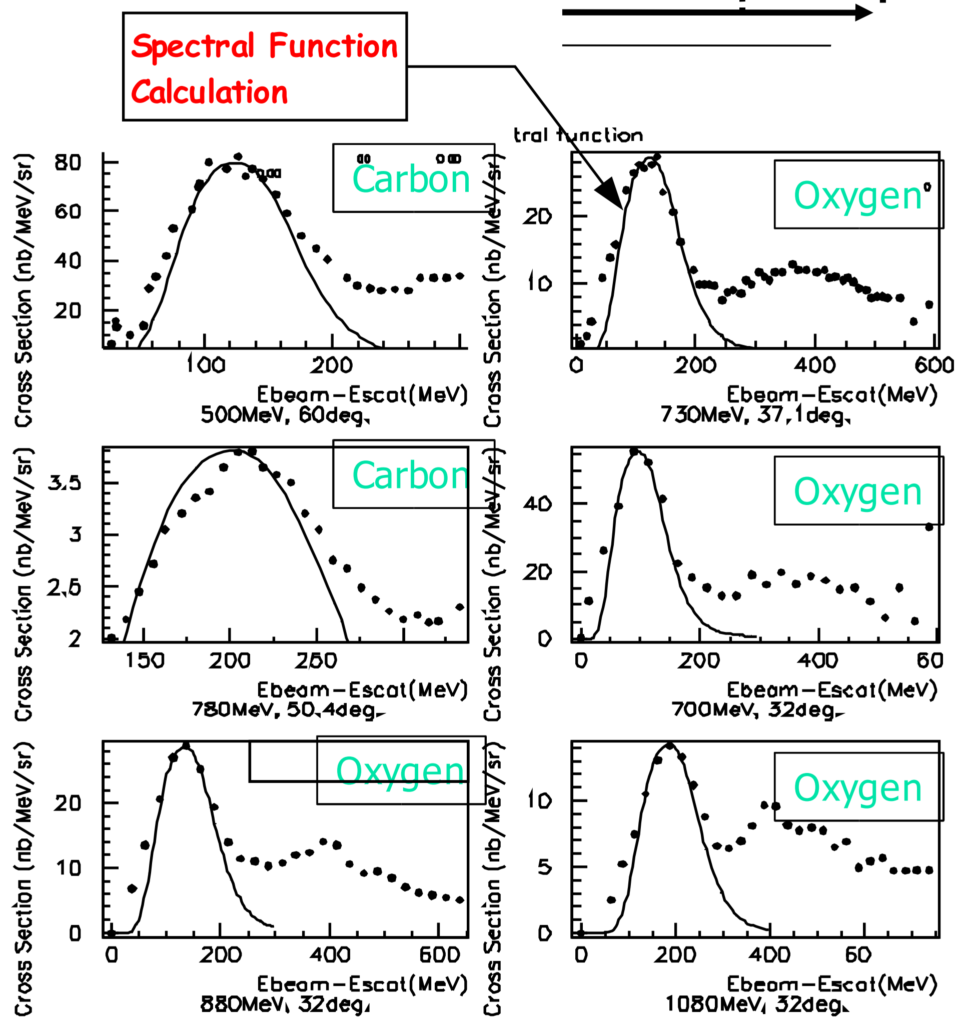
Spectral function calculation agrees with data.

Thus, the lepton energy kinematics c an be checked within a few MeV.

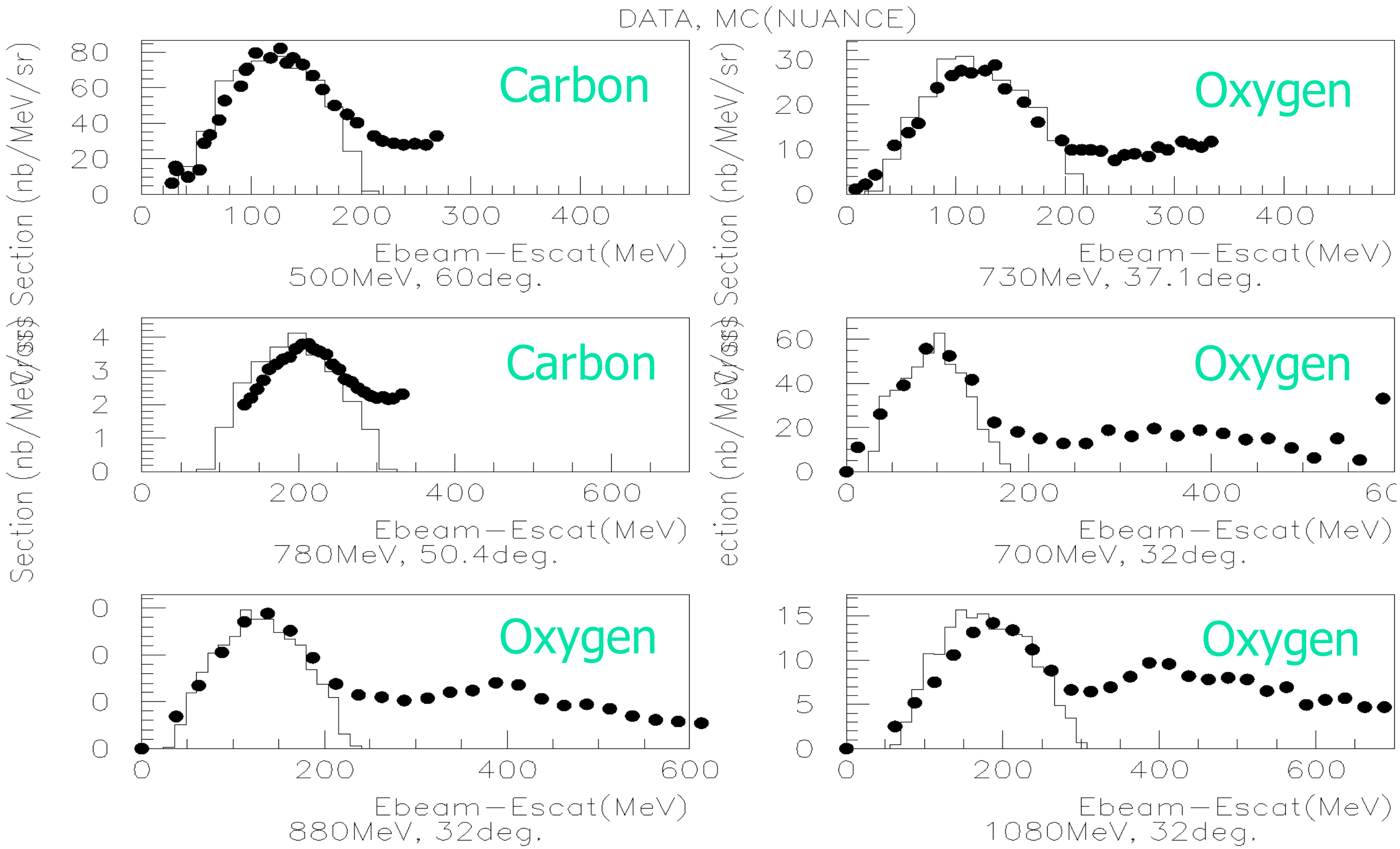
For example, accuracy of <10 MeV is needed in Eν reconstruction in the fu ture while the present accuracy is ab out 20-40 MeV due to the energy cal ibration and nuclear effects.

$$\Delta m^2 \sim \frac{E_\nu (GeV)}{L(km)}$$

MS @nuint01,Walter Wood@nuint 02



Nuance vs. e-scattering data



- Nuance uses a Smith-Moniz relativistic Fermi-Gas Model
- The paramaters can be tuned to make the peak/width agree

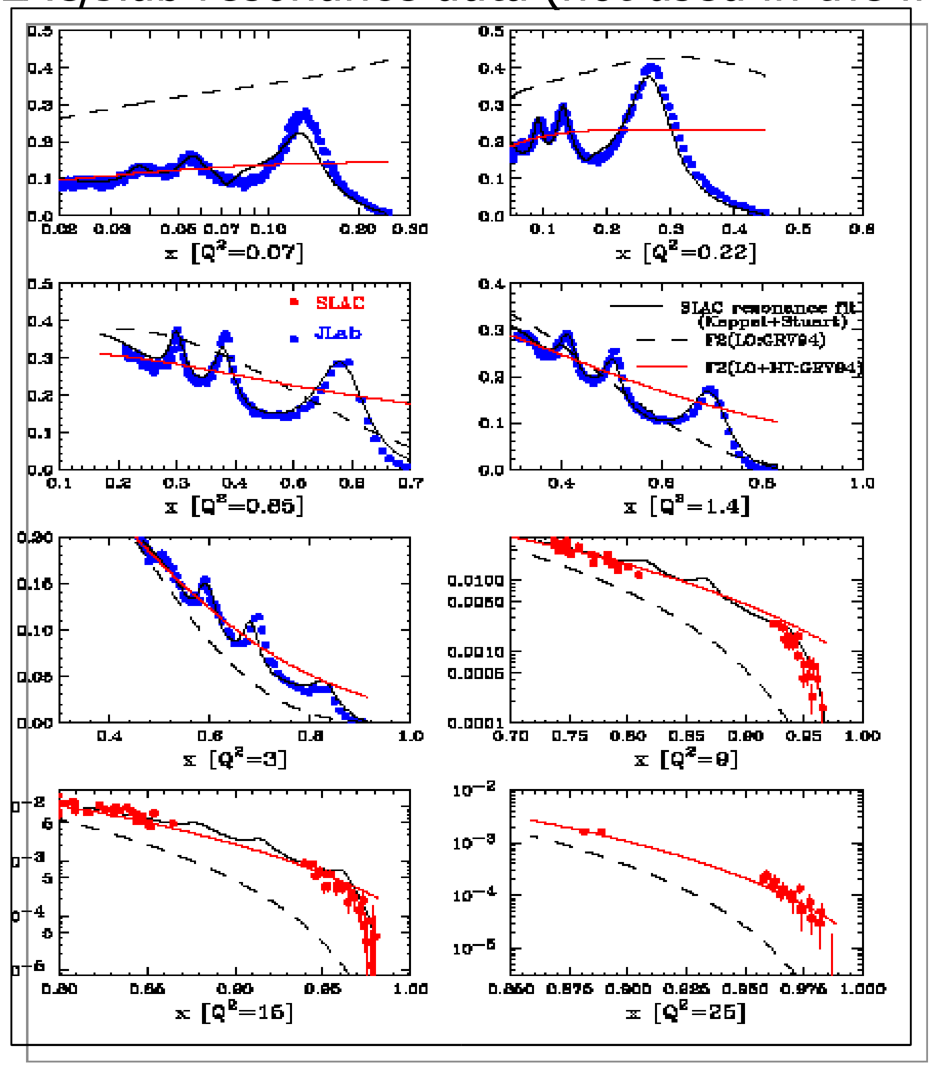
DIS (Bodek-Yang at NuInt01/02)

$$F_2(x) = \sum_i e_i^2 \left(xq(x) + x\overline{q_i(x)} \right)$$

$$F_2(x) = \frac{Q^2}{Q^2 + 0.188} F_2(x_w)$$

$$\text{where } x_w = x(Q^2 + 0.624)/(Q^2 + 1.735x).$$

SLAC/Jlab resonance data (not used in the fit)



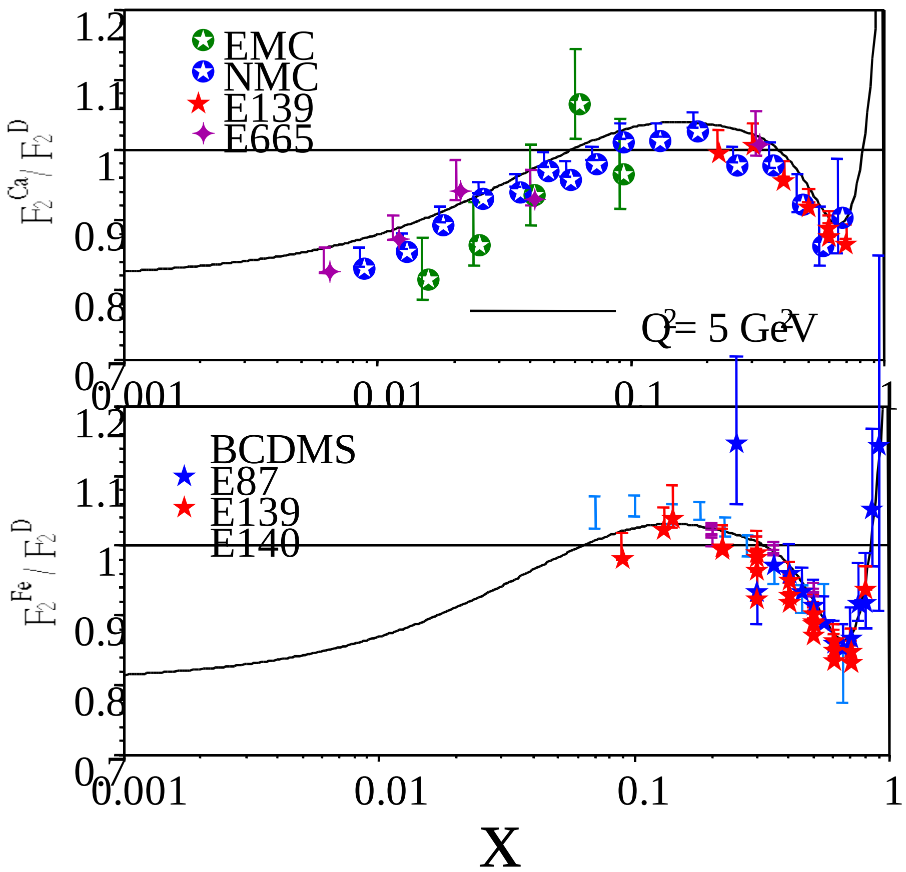
Dashed: GRV94

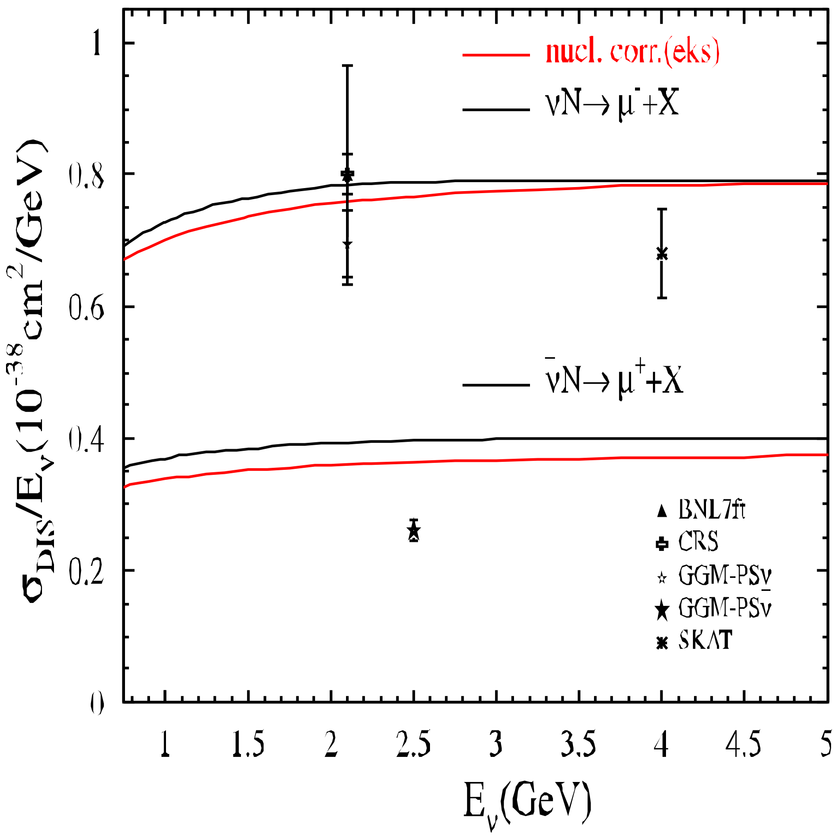
Red:Bodek-Yang

This correction is significant at low Q2 region.

NB. Three resonances are evident.

Nuclear PDF and its effect on the DIS cross section





Kimano @ NuInt02

Paschos @ NuInt01

Summary

- The accuracy of Neutrino-Nucleus (ν-N) interactions at $E\nu$=0.1-10 GeV is still poor, about 10-20% in cross section measurements and distributions.
- We will combine both e-N data and ν-N data to understand ν-N interactions better. Re-analysis of old data (BNL,ANL) using current formalism is still valuable.
- Old nucleon form factors are now being updated. It has +-5% effect on Q^2 distribution and 2-3% on the cross section.
- Spectral function calculation which improves the old Fermi-gas model calculation is extensively studied.
- Transition between DIS and resonance region is complex. Bodek's calculation is the first trial.
- K2K near detectors (1kton/SciFi) : producing new data.
  BooNE : soon. K2K upgraded detector (SciBar) will be complete this summer. MINOS near detector and ICARUS will come into operation in 2005/2006.
- All these studies will become a step toward precision neutrino experiments.