Dynamical Model of Electroweak Production of Nucleon Resonances

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Collaborators :

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- General Introduction
- Theoretical framework
- Results in the Δ region
  - Photo- and Electro-production reactions
  - Neutrino-induced reactions
  - Duality and Parity-violating asymmetry
- Concluding Remarks

Objective

Develop reaction models for extracting the nucleon resonance (N^*) from data of electroweak meson production reactions at Few GeV

$\rightarrow$

Test predictions from

- QCD-based hadron models (at the present time)
- Lattice QCD calculations (in the near future)

$\rightarrow$

Understand hadron structure within QCD in the non-perturbative region

Electroweak reactions in the N^* region:

- dominanted by non-perturbative dynamics

- most tractable theoretical methods :

  Models in terms of hadronic degrees of freedom with

  interactions constrainted by symmetries of Standard Model

Current Approaches

- On-shell models

  (tree-diagram models, K-matrix models, dispersion-relations)

- Dynamical models

  Account for off-shell effects which determine the meson-baryon scattering wavefunction in the short range region where we want to map up the structure of N^*

Why we need dynamical model

General picture : structure of N^*, Δ resonances

$$|N^* > \quad = |N^*_0 > \quad + |N^*_0, \pi > + |N^*_0, \pi\pi > + ...$$

'quark core' $+$ meson cloud and/or scattering state

- Structure: $N^*_0 \leftarrow$ hadron model or quenched Lattice QCD.
- Reaction : $N^*_0 \pi .. \leftarrow$ Meson-Baryon reaction theory(Dynamical model)

Dynamical Model : separate reaction dynamics, extract N^* parameters from the data

This talk:

- The SL model (Sato and Lee) in the Δ region :
  - 1995 - 2001 (J^{μ}_{em}): (γ, π) and $(e, e'\pi)$
  - 2002 - 2003 (J^{μ}_{cc}): (ν_{μ}, μ, π)
  - 2004 - 2005 (J^{μ}_{nc}): $(\nu, \nu'\pi)$, Duality, parity violating asymmetry

Hadronic Models

Starting point : Symmetry properties of Standard Model

Quark currents can be classified by 'strong' isospins:

$$
\begin{aligned}
J^{\mu}_{em} &= V^{\mu}_{3} + V^{\mu}_{isoscalar} \\
J^{\mu}_{cc} &= -\sqrt{2} cos\theta_c [(V^{\mu}_{1} + iV^{\mu}_{2}) - (A^{\mu}_{1} + iA^{\mu}_{2})] \\
J^{\mu}_{nc} &= (1 - 2sin^2\theta_W) J^{\mu}_{em} - V^{\mu}_{isoscalar} - A^{\mu}_{isoscalar}
\end{aligned}
$$

with Vector (V) and Axial-Vector (A) isospin currents

$$
\begin{aligned}
V^{\mu}{}_{i} &= \bar{q}\ [\gamma^{\mu} \frac{\tau_i}{2}]\ q\ ; \quad A^{\mu}{}_{i} = \bar{q}\ [\gamma^{\mu}\gamma_5 \frac{\tau_i}{2}]\ q \\
V^{\mu}_{isoscalar} &= \bar{q}\ [\frac{1}{6}\gamma^{\mu} I]\ q\ ; \quad A^{\mu}_{isoscalar} = \bar{q}\ [\frac{1}{6}\gamma^{\mu}\gamma_5 I]\ q
\end{aligned}
$$

$\rightarrow$

The SL model :

write $\vec{V}^{\mu}$ and $\vec{A}^{\mu}$ isospin currents in terms of

hadronic degrees of freedom : N, Δ, π, ρ, ω

Electroweak currents in SL model :

$$\vec{V}^{\mu} \cdot \vec{v}_{\mu} = \bar{N}[\gamma^{\mu}\vec{v}_{\mu} - \frac{\kappa^{V}}{2m_N}\sigma^{\mu\nu}\partial_{\nu}\vec{v}_{\mu}] \cdot \frac{\vec{\tau}}{2}N + \frac{g_A}{2F}\bar{N}\gamma^{\mu}\gamma_5[\vec{v}_{\mu} \cdot \vec{\tau}]N \times \vec{\pi}$$
$$+[\vec{\pi} \times \partial^{\mu}\vec{\pi}] \cdot \vec{v}_{\mu} + \frac{-g_{\omega\pi V}}{m_{\pi}}\epsilon_{\alpha\mu\nu\delta}[\partial^{\alpha}\vec{v}^{\mu}] \cdot \vec{\pi}[\partial^{\nu}\omega]$$
$$-i\bar{\Delta}_{\mu}\vec{T} \cdot \vec{v}_{\nu}\Gamma_{V}^{\mu\nu}N\,,$$
$$\vec{A}^{\mu} \cdot \vec{v}_{\mu} = g_A\bar{N}\gamma^{\mu}\gamma_5\frac{\vec{\tau}}{2} \cdot \vec{v}_{\mu}N - F\partial^{\mu}\vec{\pi} \cdot \vec{v}_{\mu} - f_{\rho\pi A}(\vec{\rho}^{\mu} \times \vec{\pi}) \cdot \vec{v}_{\mu} + -i\bar{\Delta}_{\mu}\vec{T} \cdot \vec{v}_{\nu}\Gamma_{A}^{\mu\nu}$$

$\vec{v}_{\mu}$: an arbitary isovector function, Approach of SL Model :

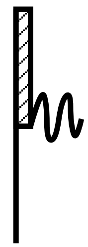
- Start from effective Lagrangians with
  - chiral symmetry (consistent with non-perturbative QCD)
  - Electroweak currents with symmetries of Standard Model
- Apply unitary transformation to derive a Model Hamiltonian

$$H = H_0 + \Gamma_{\Delta \leftrightarrow \pi N} + \Gamma_{\Delta \leftrightarrow \gamma N} + \sum_{\alpha,\beta} V_{\alpha,\beta}$$

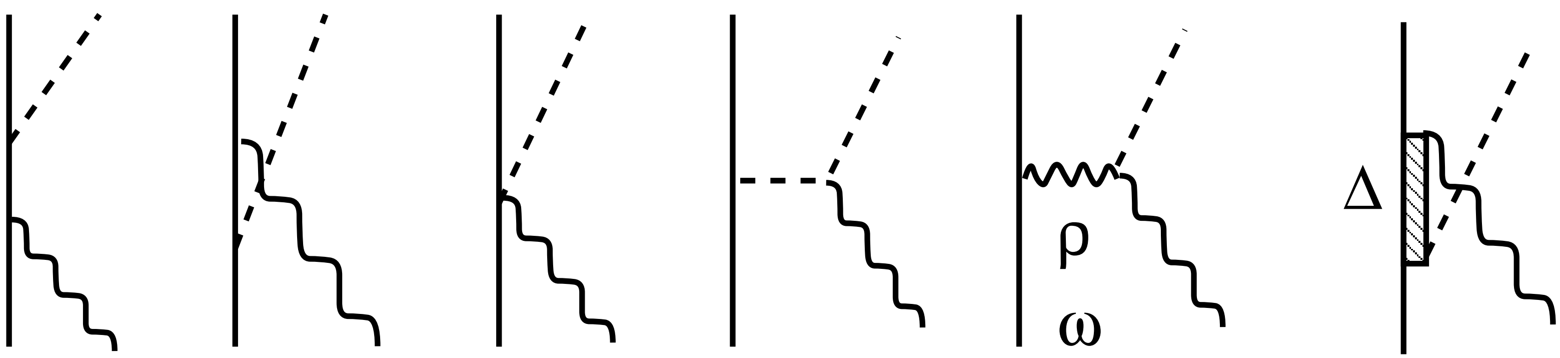
$\alpha, \beta = \pi N, \gamma N$

- $\Gamma_{\Delta \leftrightarrow \pi N}$, $\Gamma_{\Delta \leftrightarrow \gamma N}$: identified with constituent quark model
- $V_{\alpha,\beta}$: from effective lagrangians

Excitation of quark core :



Non-resonant mechanisms :



- Apply Reaction Theory based on Hamiltonian

$\gamma N \rightarrow \pi N$ amplitude

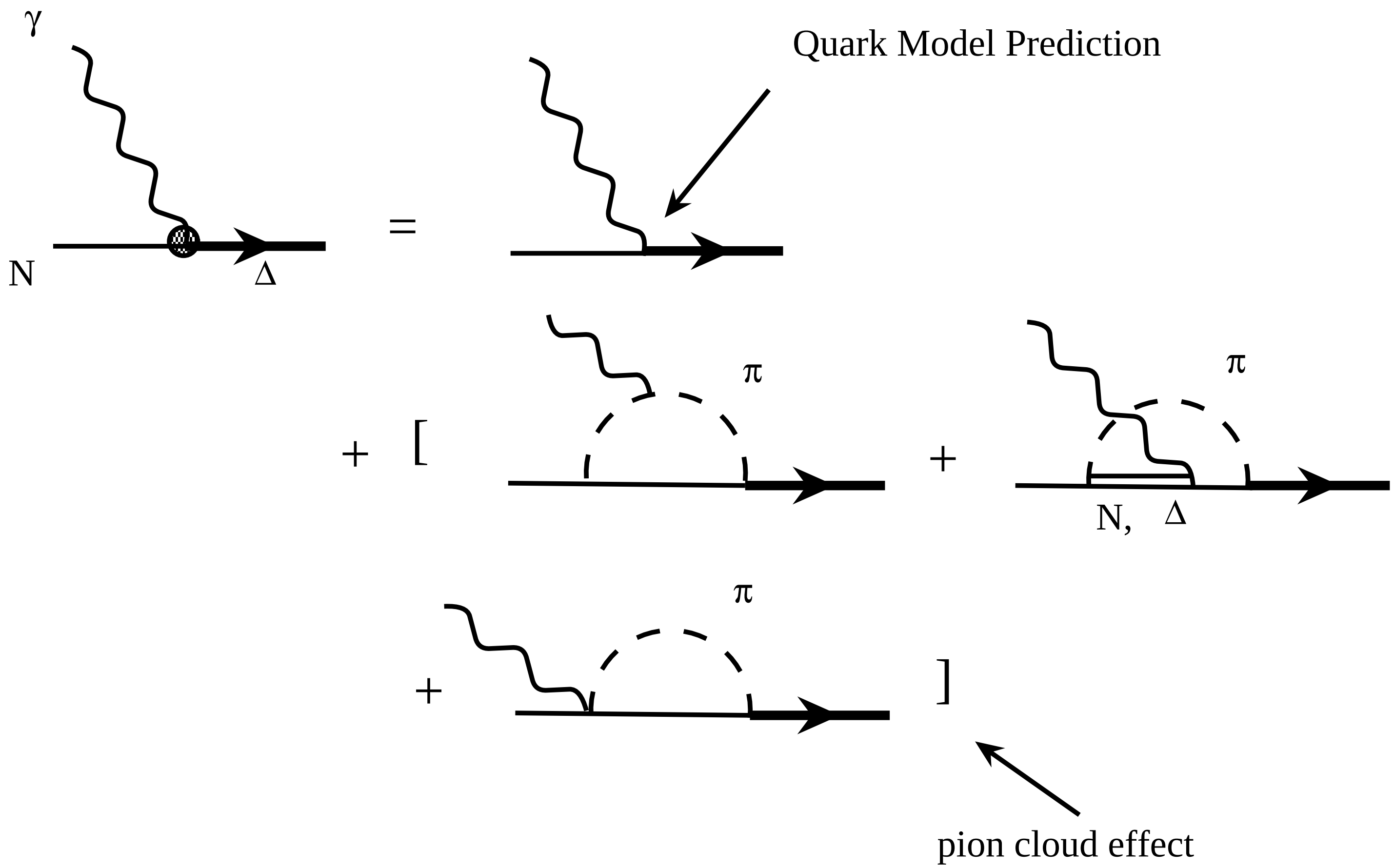
$$T_{\gamma\pi}(E) = t_{\gamma\pi}(E) + \frac{\bar{\Gamma}_{\Delta\rightarrow\pi N}\bar{\Gamma}_{\gamma N\rightarrow\Delta}}{E - m_\Delta^0 - \Sigma_\Delta(E)}.$$

- $t_{\gamma\pi}$: non-resonant amplitude (e.g. from $V_{\gamma N,\pi N}$)
- Dressed $\gamma N \rightarrow \Delta$ vertex

$$\bar{\Gamma}_{\gamma N\rightarrow\Delta} \quad = \quad \Gamma_{\gamma N\rightarrow\Delta} + \bar{\Gamma}_{\pi N\rightarrow\Delta} G_{\pi N}(E) v_{\gamma\pi}$$

  - $\Gamma_{\gamma N\rightarrow\Delta}$: identified with constituent quark model predictions

$$\bar{\Gamma}_{\gamma N \to \Delta} \quad = \quad \Gamma_{\gamma N \to \Delta} + \bar{\Gamma}_{\pi N \to \Delta} G_{\pi N}(E) v_{\gamma \pi}$$



Main interests :

Vector (V) and Axial (A) form factors of $N \rightarrow \Delta$ transitions.

$$
\begin{aligned}
F_{em} &= V_3 + V_{isoscalar} \\
F_{cc} &= -\sqrt{2}cos\theta_c[(V_1 + iV_2) - (A_1 + iA_2)] \\
F_{nc} &= (1 - 2sin^2\theta_W)F_{em} - V_{isoscalar} - A_{isoscalar}
\end{aligned}
$$

$\rightarrow$

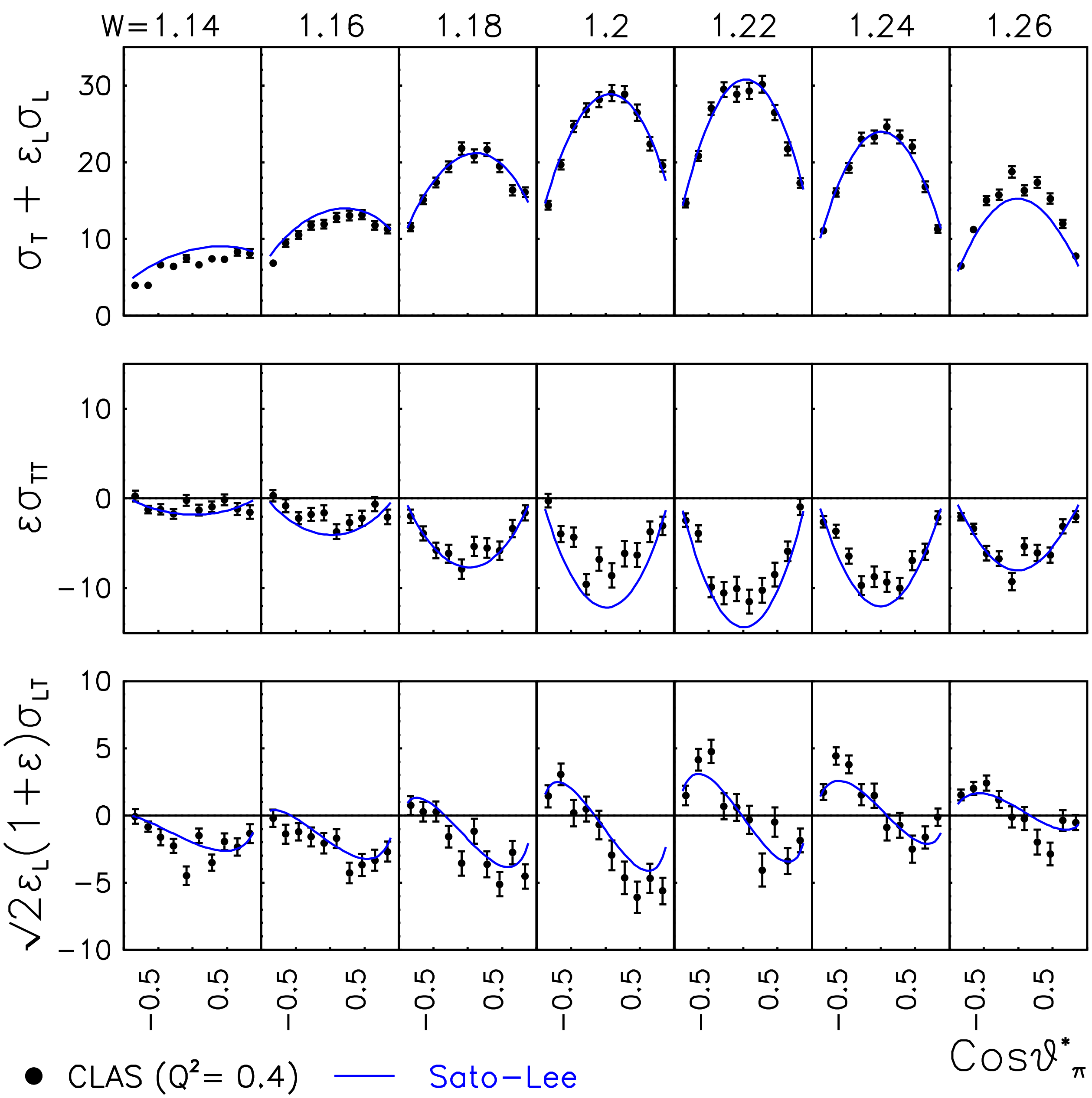
Procedures :

- $N(e, e'\pi)N \rightarrow \vec{V}$, $V_{isoscalar}$
- $N(e, e'\pi)N$ + $N(\nu, \mu\pi)N \rightarrow \vec{A}$
- Parity-violating asymmetry of inclusive $N(e, e') \rightarrow A_{isoscalar}$

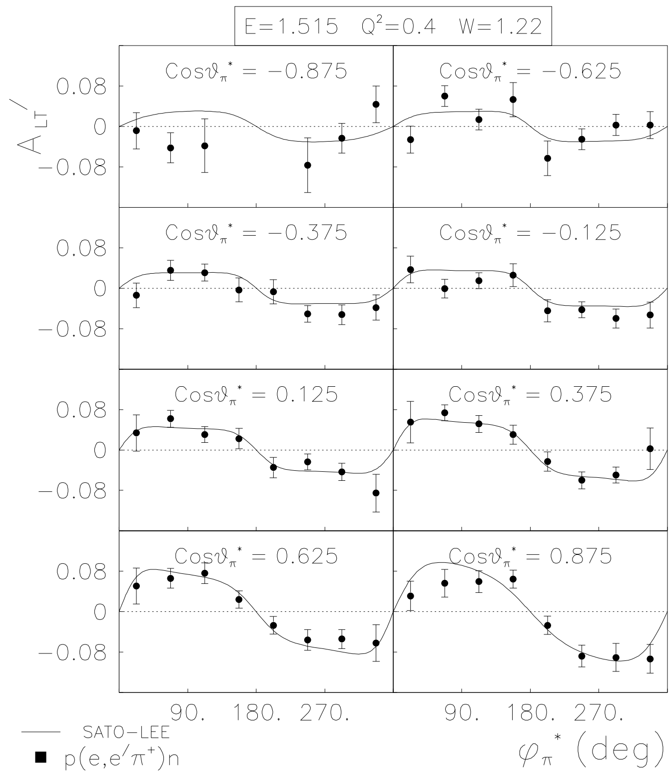
Results from SL model

- extensive data of (γ,π), $(e,e'\pi)$ and $(\nu_\mu,\mu^-\pi)$ can be described
- electromanetic and axial N-Δ form factors have been determined

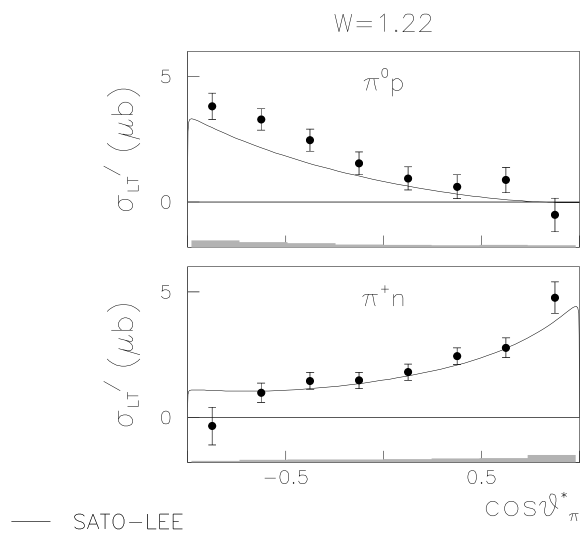
unpolarized $p(e, e'\pi^0)p$ data from JLAB (2001)



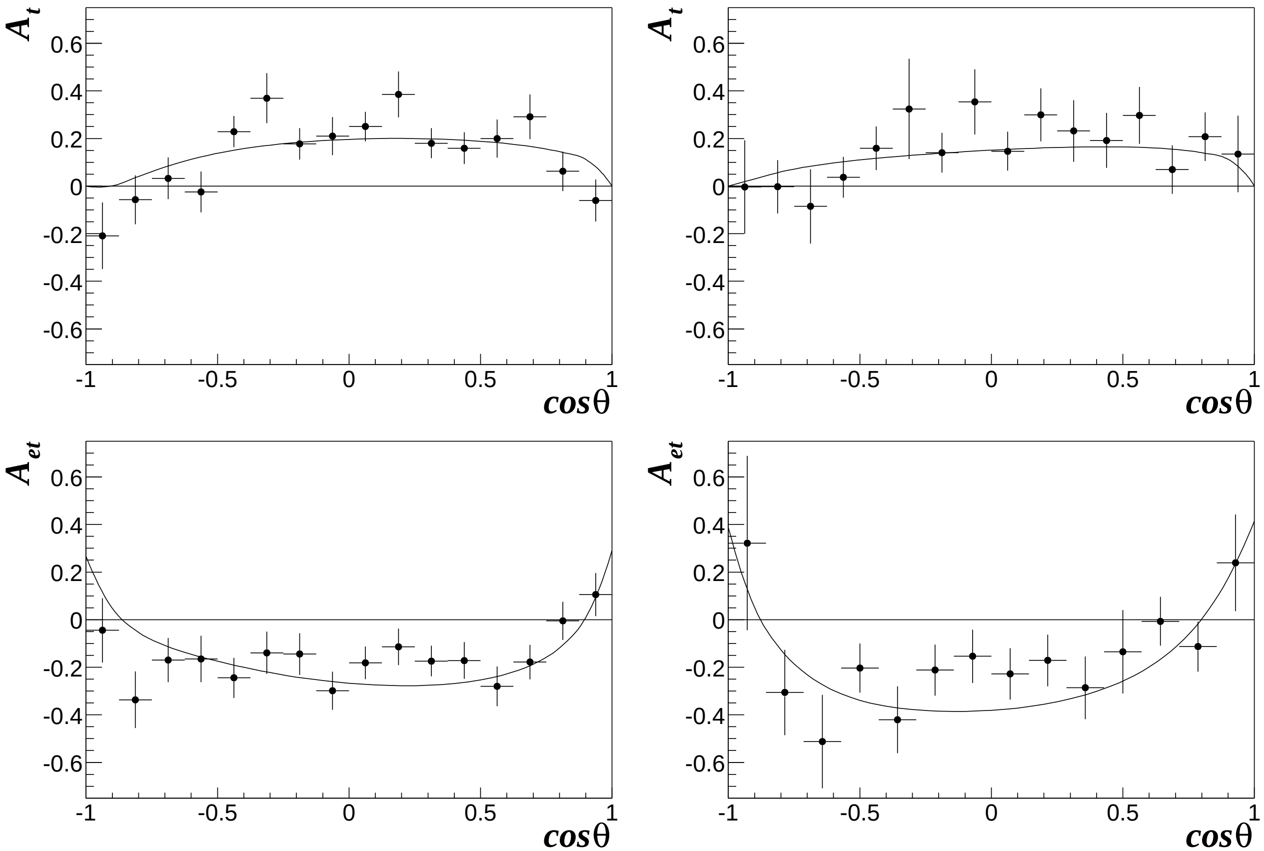
$A_{LT'}$ from $p(\vec{e}, e'\pi)$ data of JLab (2004)



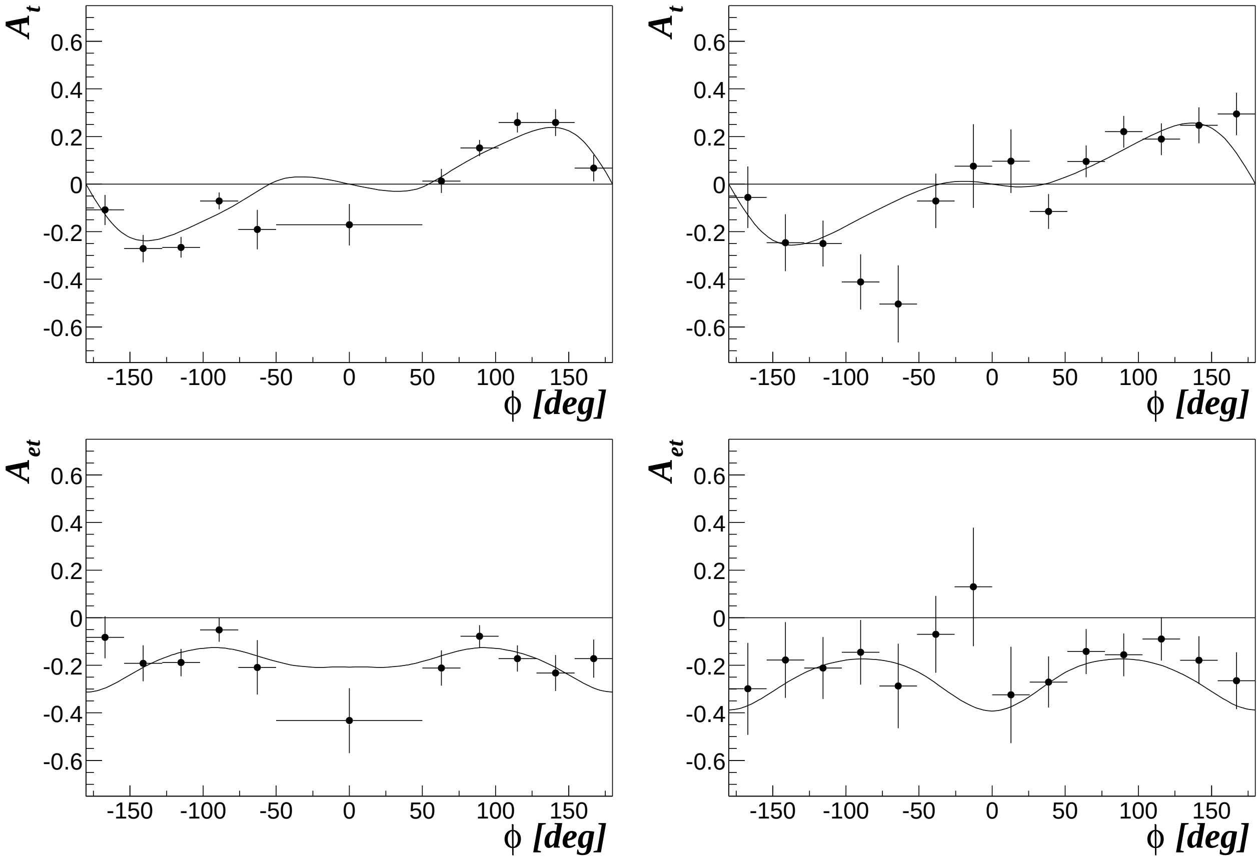
σ'_{LT} from $p(\vec{e}, e'\pi)$ data of JLab (2004)



A_{et} and A_t of from $\vec{p}(\vec{e}, e'\pi)$ data of JLab (2003)



A_{et} and A_t from $\vec{p}(\vec{e}, e'\pi)$ data of JLab (2003)



Findings of SL model :

The determined bare N-Δ form factors are:

$$G_\alpha(Q^2) = G_\alpha(0)(1 + aQ^2)exp(bQ^2)G_D(Q^2)$$

with

a = 0.154 (GeV/c)$^{-2}$, b = 0.166 (GeV/c)$^{-2}$

$G_D(Q^2) = 1./(1 + Q^2/0.71)^2$

$G_M(0) = 2.42$

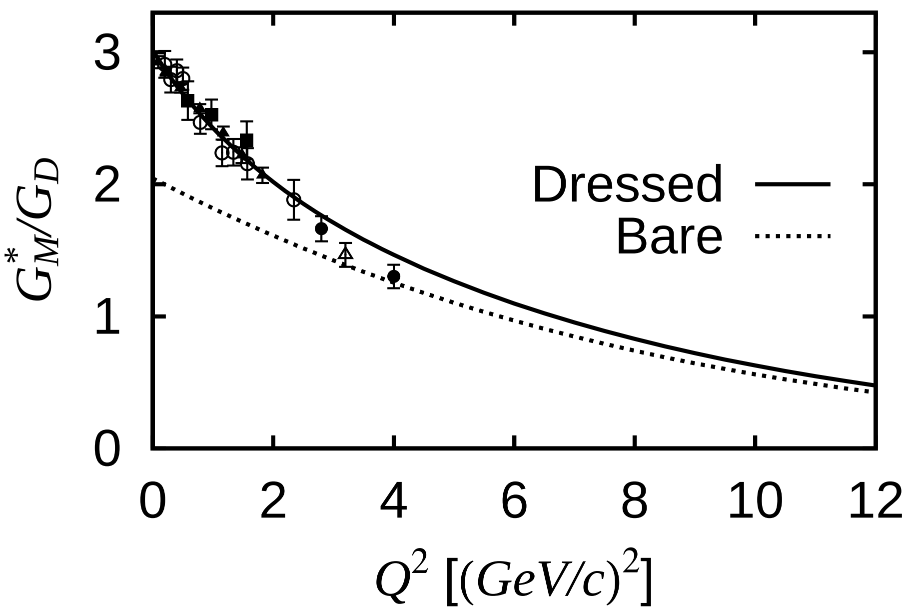
$G_E(0) = 0.0315$

$G_C(0) = -0.30$

Note:

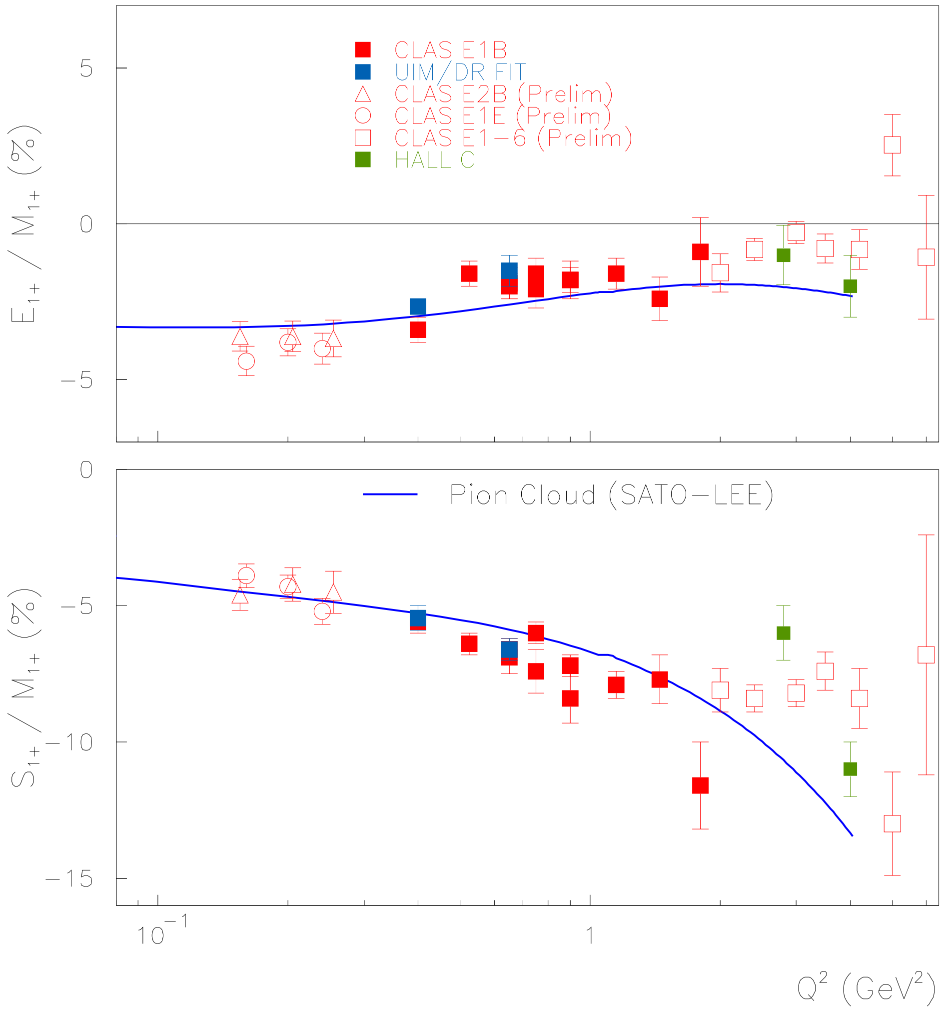
strengths at $Q^2 = 0$ are consistent with constituent quark model

Determined M1 form factor of $\gamma N \to \Delta$



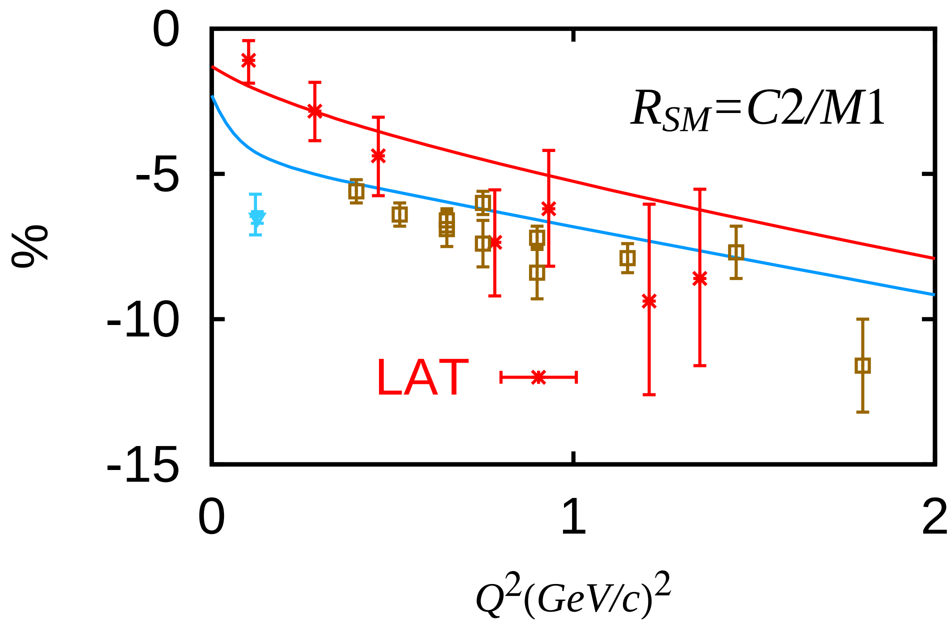
- Pion cloud has 40% effect at low Q^2 and becomes weaker at high Q^2
- $G^*_M(Q^2)$ drops faster than proton form factor $G_D(Q^2)$

E2/M1 and C2/M1 Ratios



Note: CLAS data at low Q^2 are preliminary (from C. Smith, May 2005)

Comparision with Lattice QCD calculation



SL-Model(2001) : Dressed, bare

Red data : Lattice QCD (C. Alexandrou et al. hep-lat/0409122)

Extension of the SL model for Weak Charged and Neutral Currents

$\rightarrow$

- Extract $N - \Delta$ axial form factors from :
  - $N(\nu, \mu\pi)$ reactions
  - Parity-violating asymmetry of inclusive $N(e, e')$

- Explore quark-hadron duality in inclusive $N(\nu, \mu)$ and $N(\nu, \nu')$

Procedures :

$$j_\mu^{em} \quad = \quad V_\mu^3 + V_\mu^{IS}$$

- Vctor currents V_μ : determined in $(e, e'\pi)$ studies

$\rightarrow$

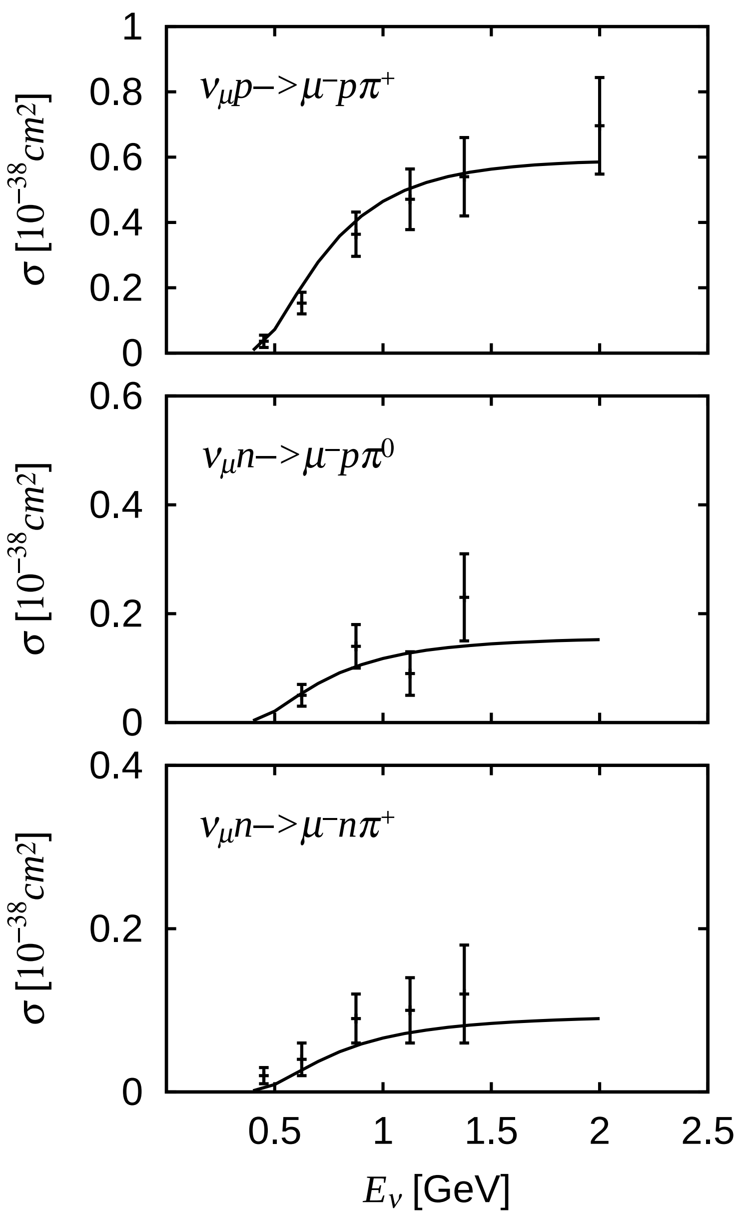
$$\begin{aligned} \text{CC} \;\; j_\mu^{CC} \quad &= \quad V_\mu^{1+i2} - A_\mu^{1+i2} \\ \text{NC} \;\; j_\mu^{NC} \quad &= \quad (1 - 2\sin^2\theta_W) j_\mu^{em} - V_\mu^{IS} - A_\mu^3 \end{aligned}$$

- Non-resonant axial current A_μ : derived from effective Lagrangians

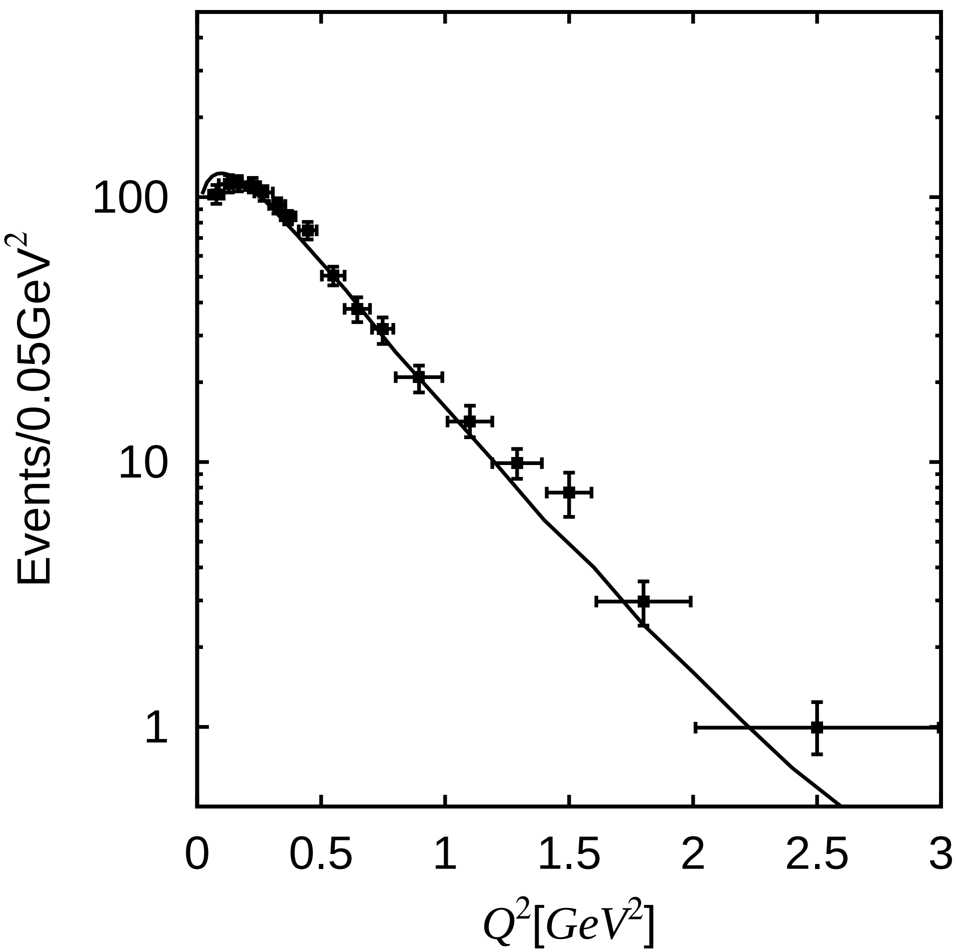
$\rightarrow$

Extract $G^A_{N,\Delta}(Q^2)$ from $N(\nu, \mu\pi)$ data at few GeV

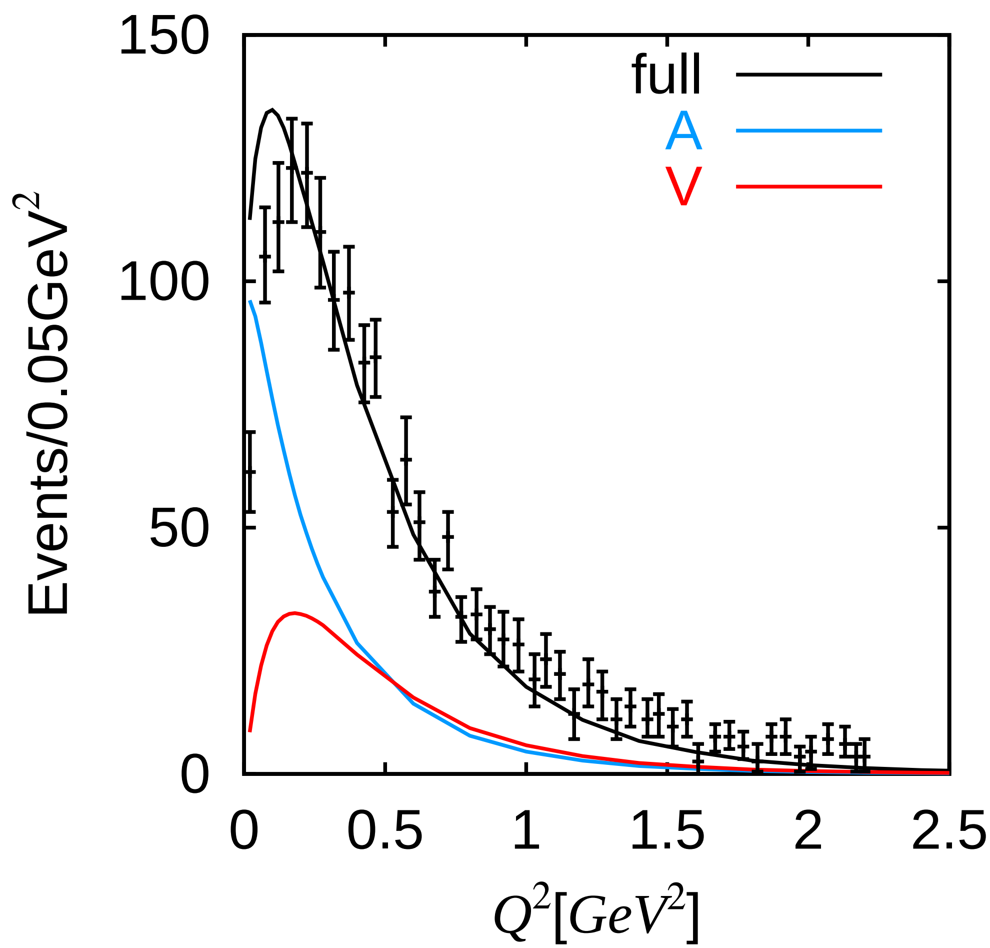
Total cross sections of $p(\nu_\mu, \mu^- \pi)$ results from SL model



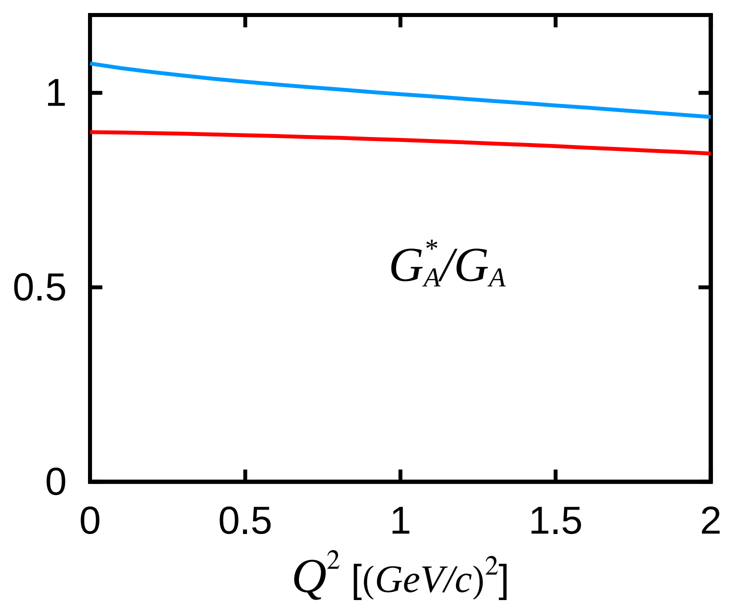
$d\sigma/dQ^2$ of $p(\nu_\mu, \mu^-\pi^+)$



$d\sigma/dQ^2$ of $p(\nu_\mu, \mu^-\pi^+)$



Determined axial N-Δ form factor G_A^*



Dotted curves : no pion cloud effect

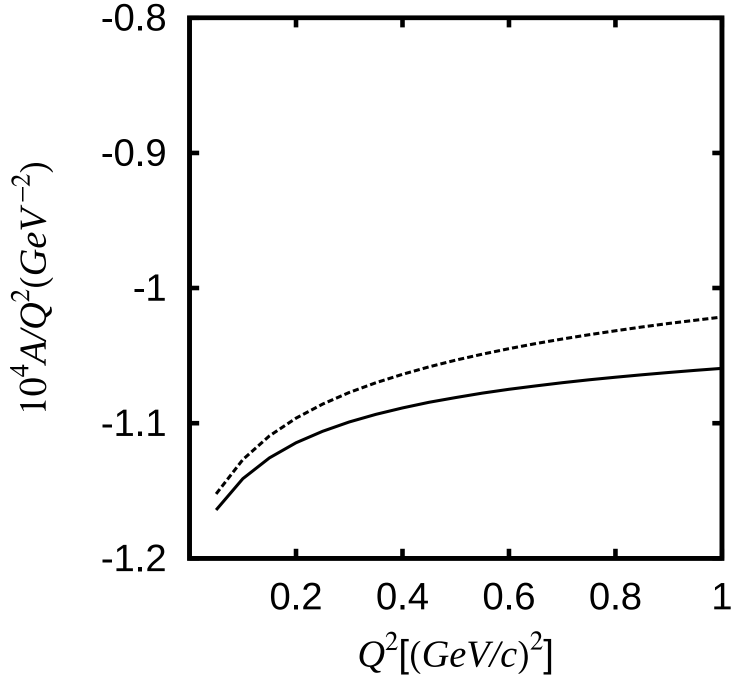
Role of neutral currents

- Consider Parity-violating asymmetry (A)of $e + p \to e' + X$

$$
\begin{aligned}
A &= \frac{d\sigma(h_e = +1) - d\sigma(h_e = -1)}{d\sigma(h_e = +1) + d\sigma(h_e = -1)} \\
&= -\frac{Q^2 G_F}{\sqrt{2}(4\pi\alpha)}[2 - 4\sin^2\theta_W + \Delta_V + \Delta_A]
\end{aligned}
$$

$$
\begin{aligned}
\Delta_V &: \quad determined(SL - model) \\
\Delta_A &\propto \sin^2\frac{\theta}{2}(1 - 4\sin^2\theta_W)W_3(em - nc)
\end{aligned}
$$

$W_3(em - nc) \leftarrow$ isoscalar axial form factor $A_{isoscalar}$



$E_e = 1$ GeV, $\theta = 110^o$, $W = 1.232$ GeV

Experimental tests by the data from G_0 experiment ??

- Invistigate quark-hadron duality in neutrino-induced reactions

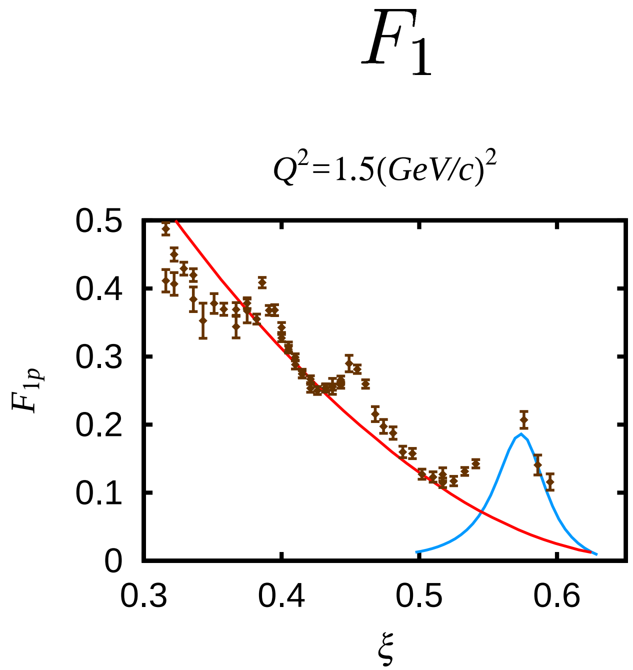
What is Duality ?

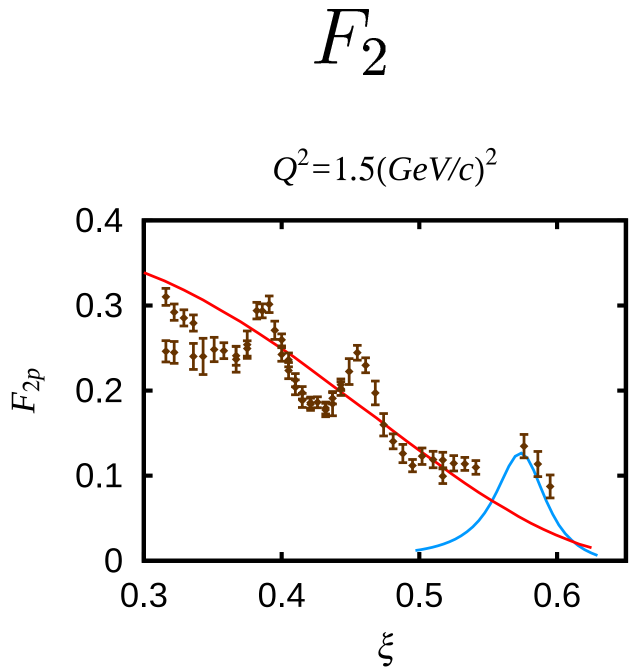
An average of the inclusive electron scattering observables in the resonance region should be close to the predictions from using the parton distribution functions determined in Deeply Inelastic Scattering (DIS) .

Inclusive (e,e')Cross Sections ($x = Q^2/(2\omega M_N)$)

$$\frac{d\sigma^{(e,e')}}{d\Omega dE'} = \sigma_{Mott}[\frac{1}{\omega}F_2(x,Q^2) + 2\frac{1}{M_N}F_1(x,Q^2)tan^2\frac{\theta}{2}]$$

Duality in $p(e,e')$





Data : Y. Liang et al, JLab, 2004

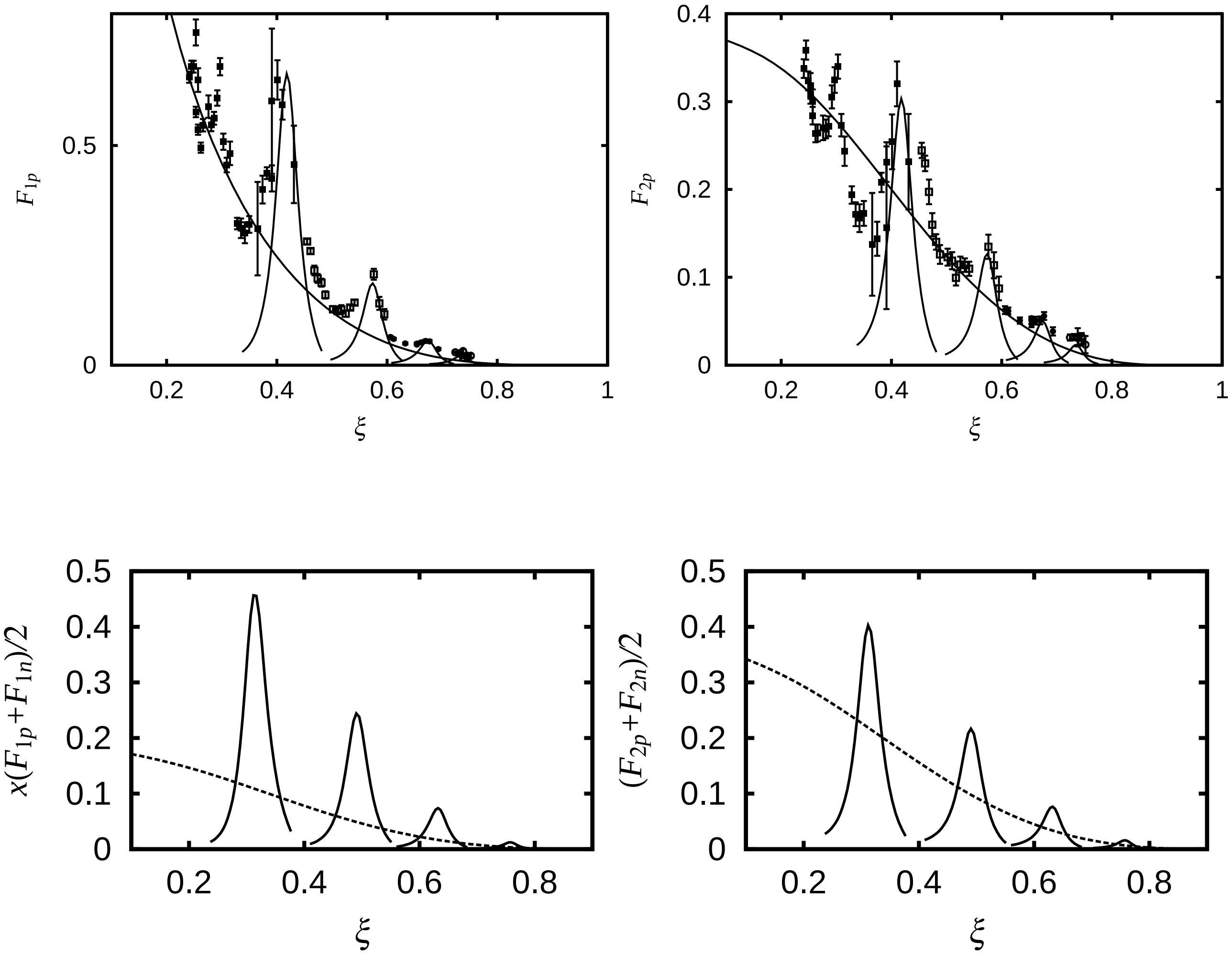
$\rightarrow$

How about Duality for the neutron target and (ν, e) and (ν, ν') ?

$\rightarrow$

Apply the SL Model to explore local duality in Δ region

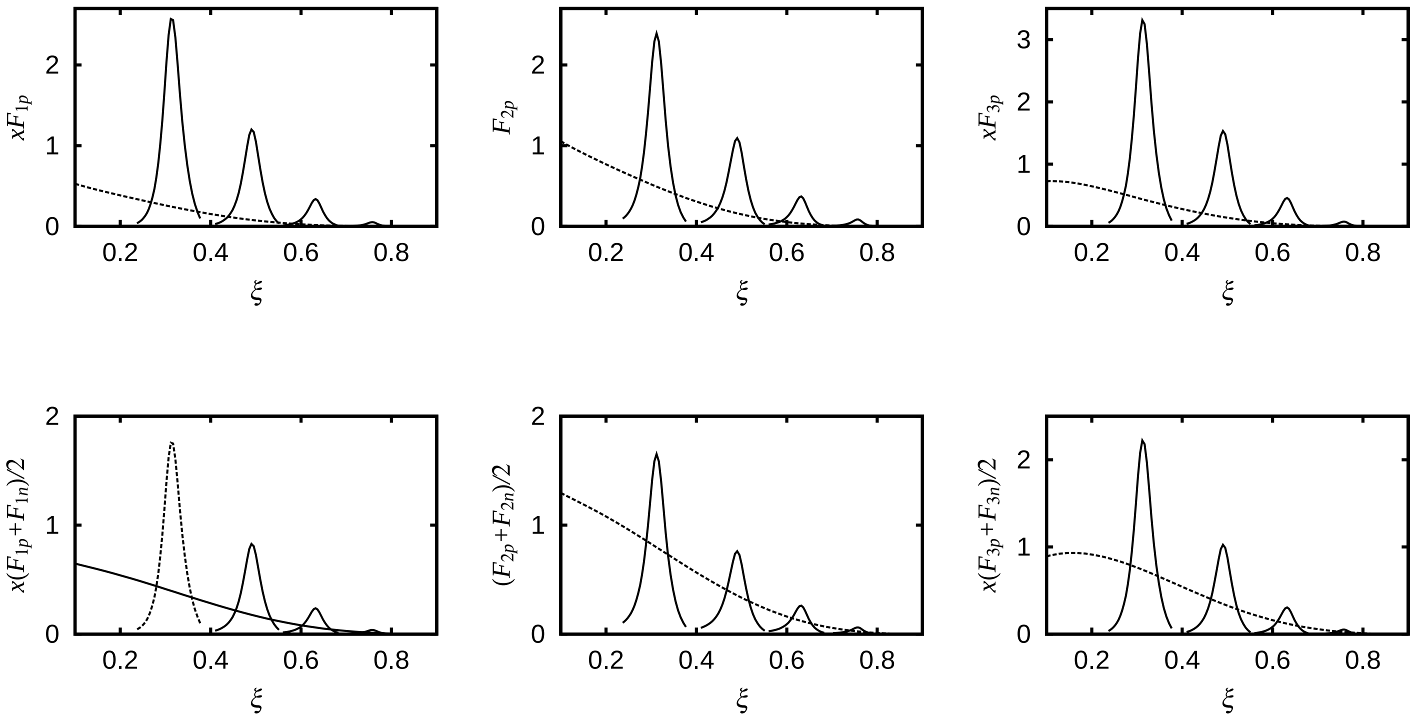
$$N(e, e')$$



Upper : proton taget

Lower : neutron target

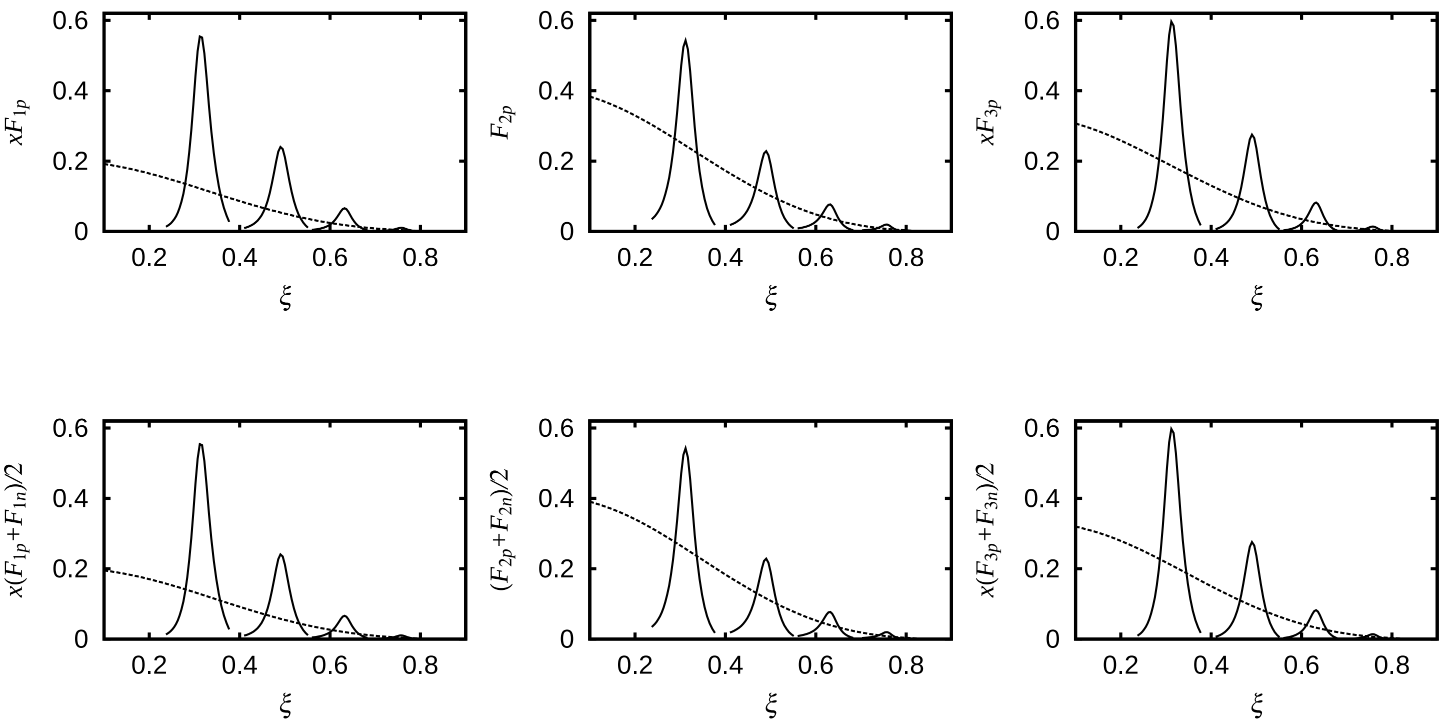
Predictions for $N(\nu, \mu)$



Upper : proton taget

Lower : neutron target

Predictions for $N(\nu, \nu')$

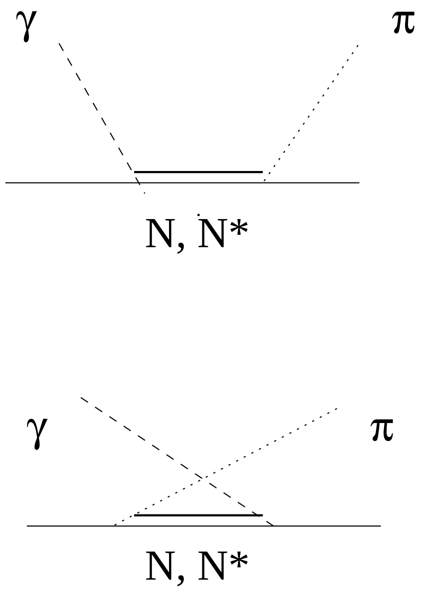


Upper : proton taget

Lower : neutron target

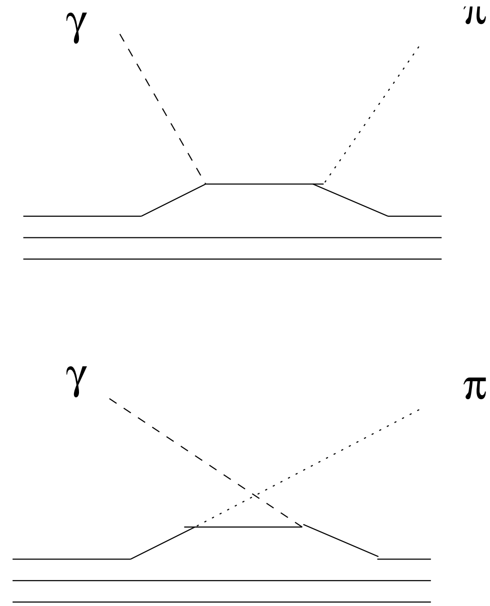
$\rightarrow$

- Duality is confirmed for the unpolarized structure functions of all electroweak processes
- De Rujula, Georgi, and Politzer : Parton model prediction is the twist-2 (handbag) mechanism of the Operator Product Expansion of QCD



Hadronic Model

(W < 2 GeV)



Quark−Gluon Model

(2 GeV < W)

→

How to relate them within a unified model ??

Concluding Remarks

- Very extensive data of electroweak reactions in the Δ region can be described by hadronic model

- The electroweak N-Δ form factors up to $Q^2 \sim 4$ (GeV/c)^2 have been determined

  $\rightarrow$

  Theoretical challenges :

  - Which QCD-based model can explain these form factors ?
  - Can they be explained by Lattice QCD ?

- We have predicted that the Quark-Hadron Duality also exists in the neutrino-induced weak processes

  $\rightarrow$

  Future experimental confirmations will be interesting !!

- Duality suggests the possibility of constructing a unified model which can account for the transition from hadronic picture to quark-gluon picture

  A challenge in the future !

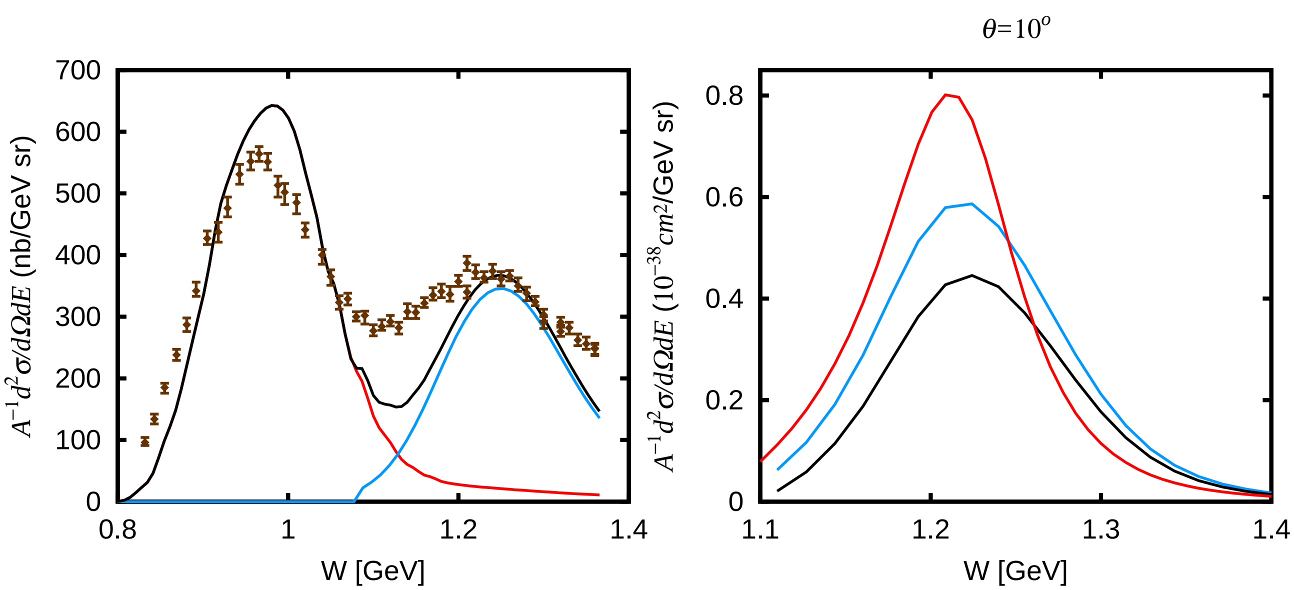
- Current efforts
  - Extend the model to describe production of higher mass N^* in a dynamical coupled-channel approach

    Main focus of Excited Baryon Analysis Center (EBAC)

    (With A. Matsuyama, T. Sato, M. Paris, B. Julia-Diaz)

  - Apply the model to predict neutrino-nucleus reaction

    (with B. Szczerbinska, K. Kubodera, and T. Sato)



$e +^{12} C \to e + X$ $\qquad$ $\nu +^{12} C \to e + X$