Dynamical Resonance Production Model

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Focus on

Results from Dynamical Model of Electroweak Production of Nucleon Resonances

Collaborators :

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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' $\quad + \quad$ 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 :

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

$\vec{v}_{\mu}$: an arbitary isovector function,

Approach of SL Model :

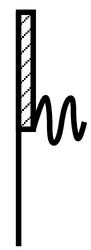
- Start from effective Lagrangians with
  - chiral symmetry (consistent with non-perturbative QCD)
  - Electroweak currents with symmetries of Standard Model
- Apply unitary transformation to derive a Model Hamiltonian

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

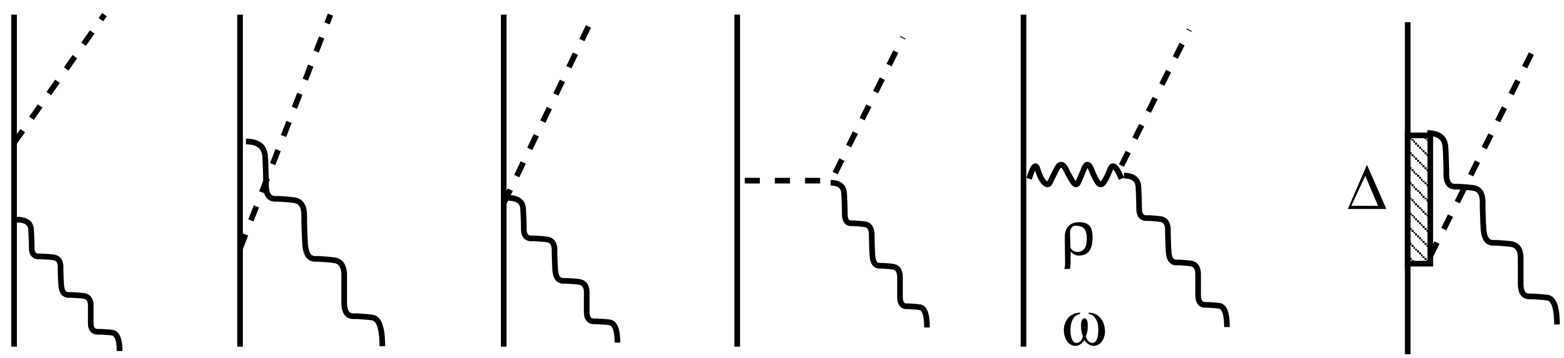
$\alpha, \beta = \pi N, \gamma N$

- $\Gamma_{\Delta \leftrightarrow \pi N}$, $\Gamma_{\Delta \leftrightarrow \gamma N}$: 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

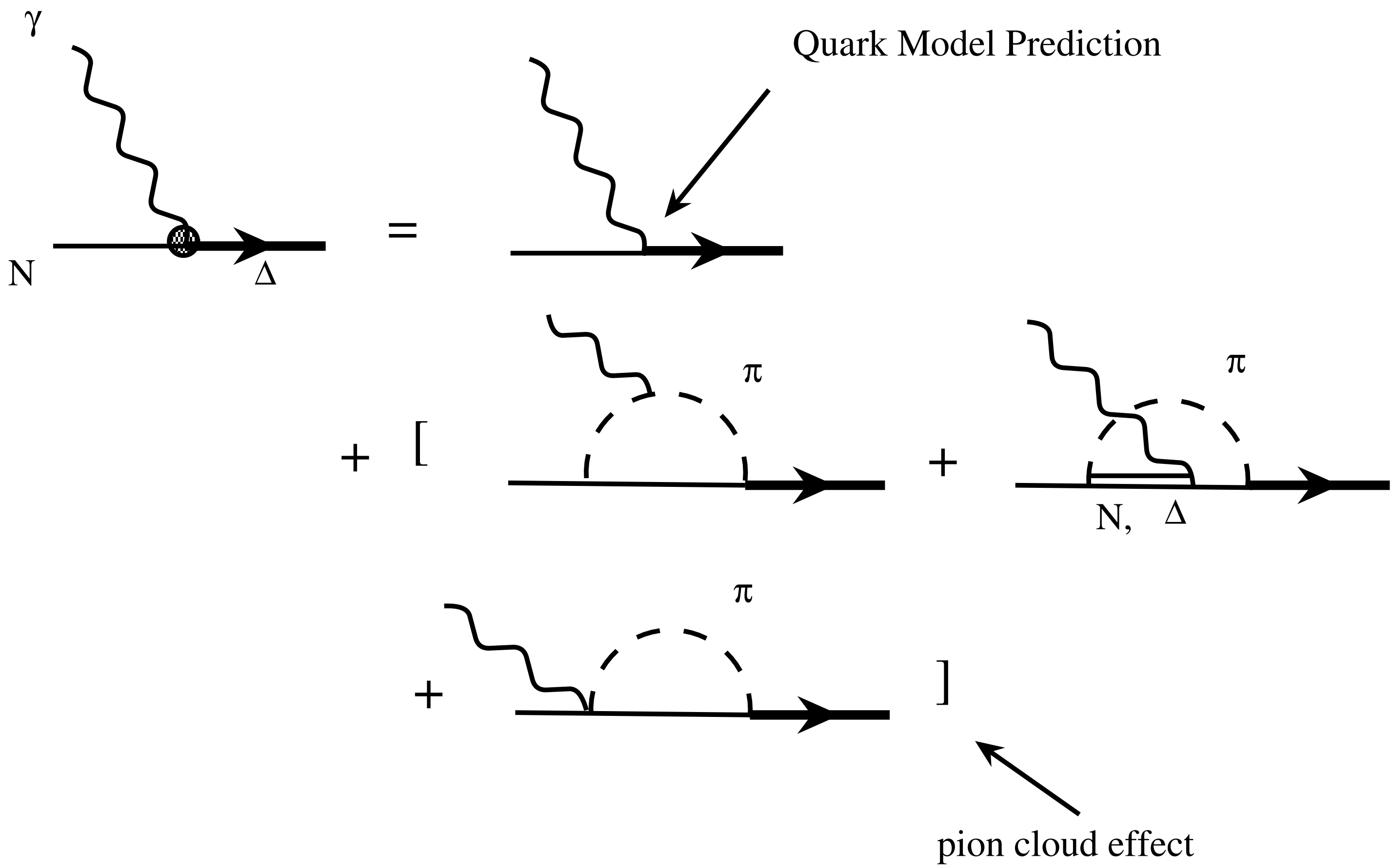
$$T_{\gamma\pi}(E) = t_{\gamma\pi}(E) + \frac{\bar{\Gamma}_{\Delta\rightarrow\pi N}\bar{\Gamma}_{\gamma N\rightarrow\Delta}}{E - m_{\Delta}^{0} - \Sigma_{\Delta}(E)}.$$

- $t_{\gamma\pi}$: 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 $N \to \Delta$ transitions.

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

$\longrightarrow$

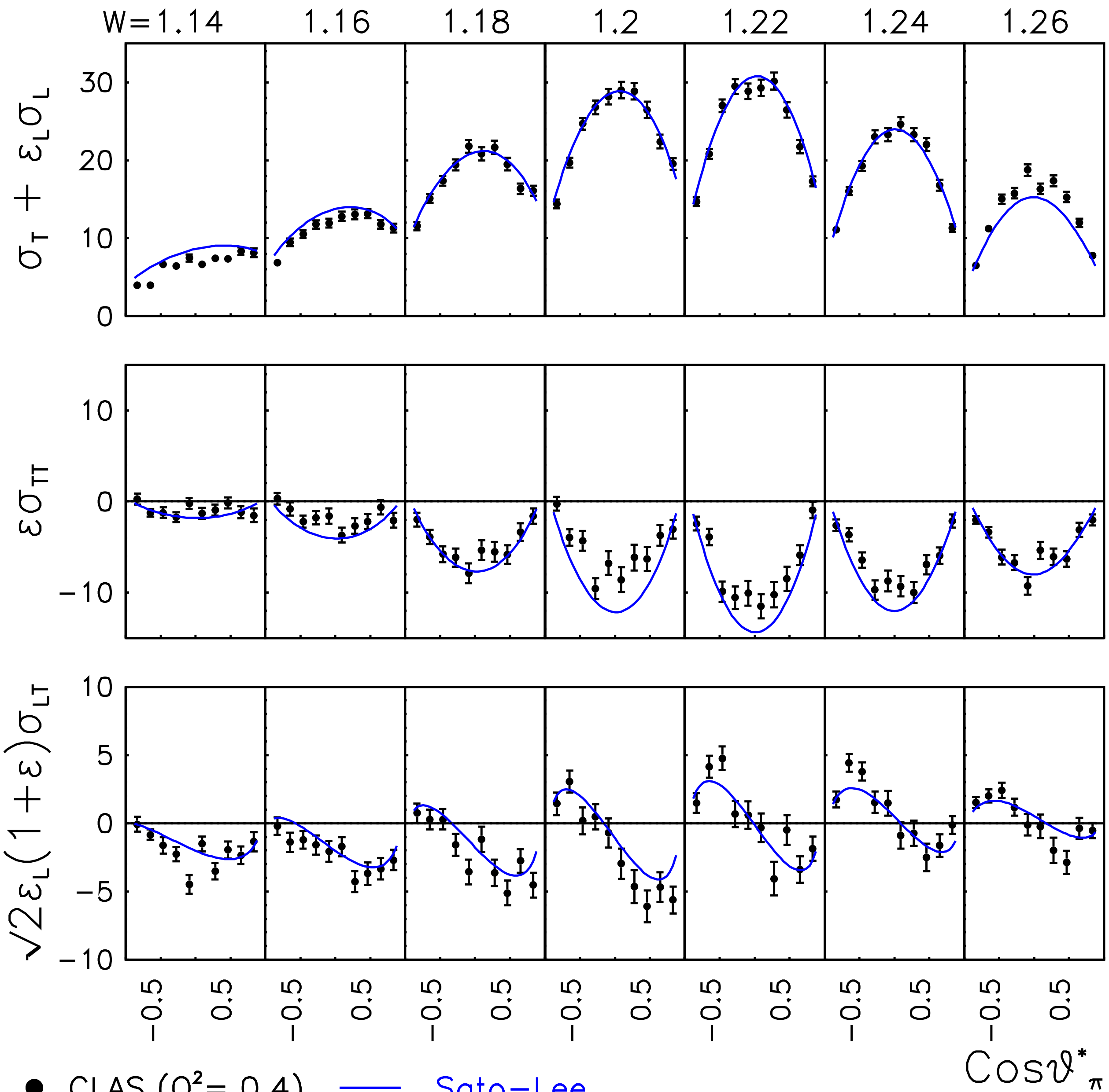
Procedures :

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

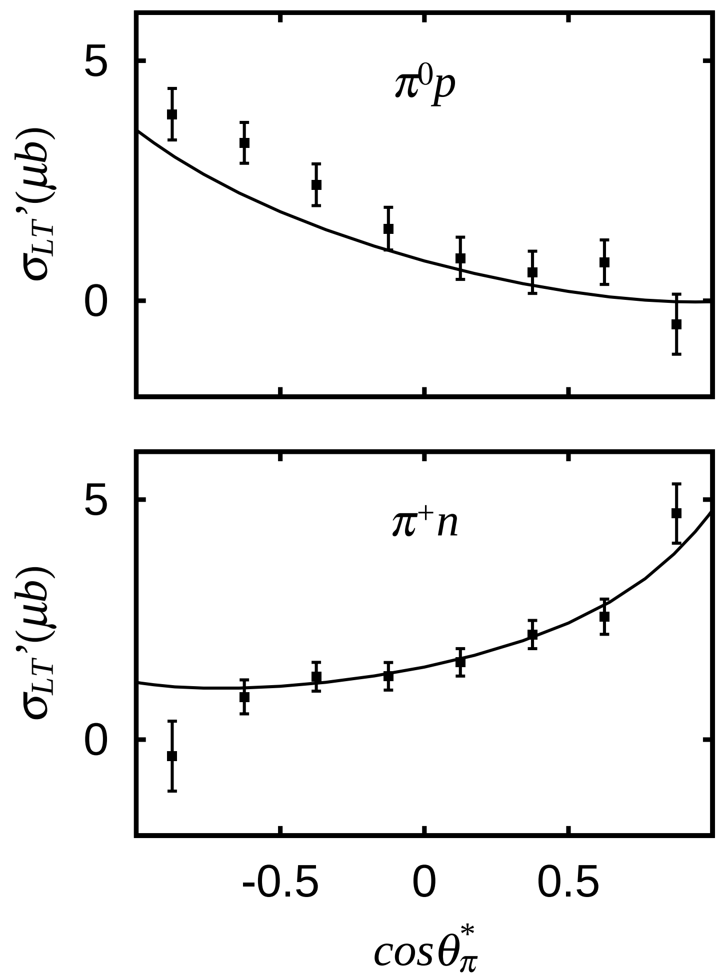
Results from SL model

- 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

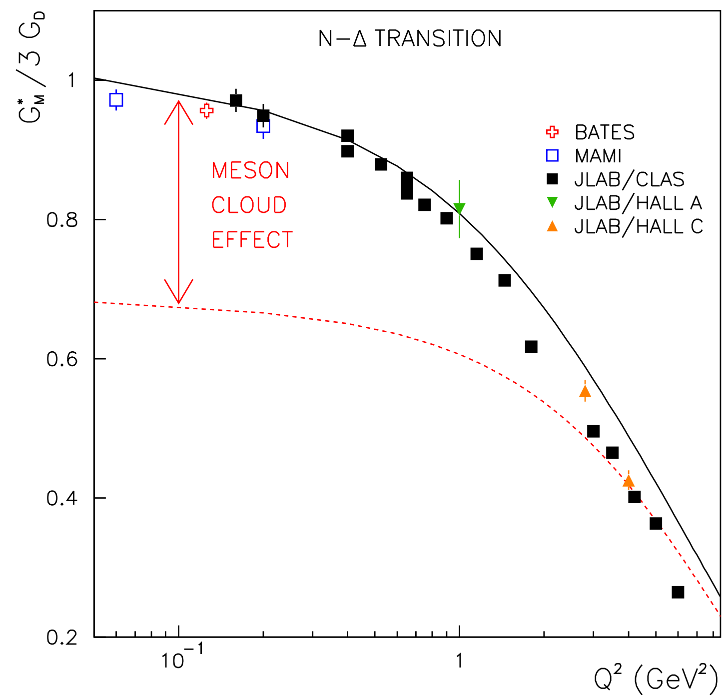
unpolarized $p(e, e'\pi^0)p$ data from JLAB (2001)



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

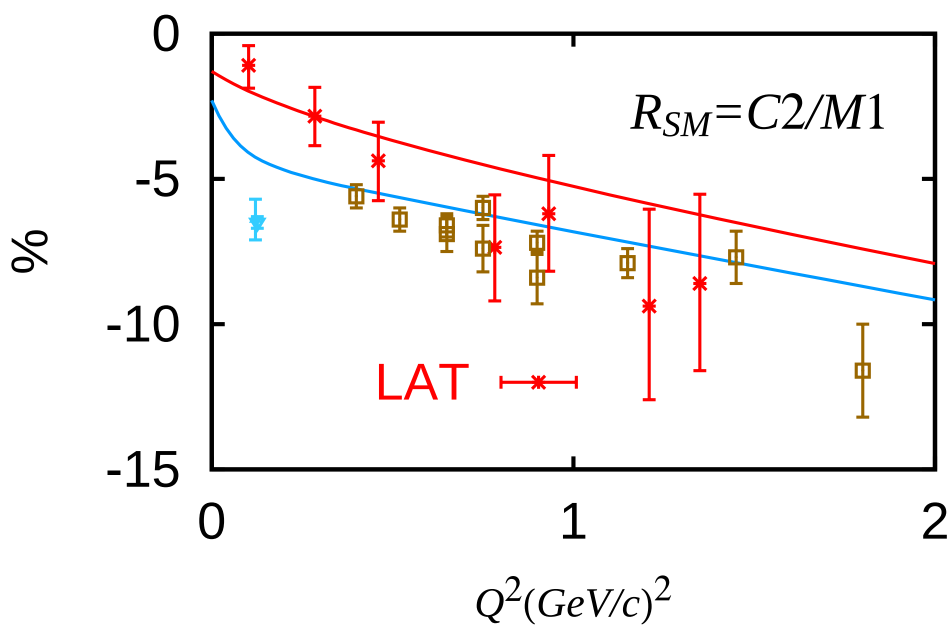


Determined M1 form factor of $\gamma N \to \Delta$



- 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 $G_D(Q^2)$
- strengths at $Q^2 = 0$ are consistent with constituent quark model

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

$\longrightarrow$

- 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

$\longrightarrow$

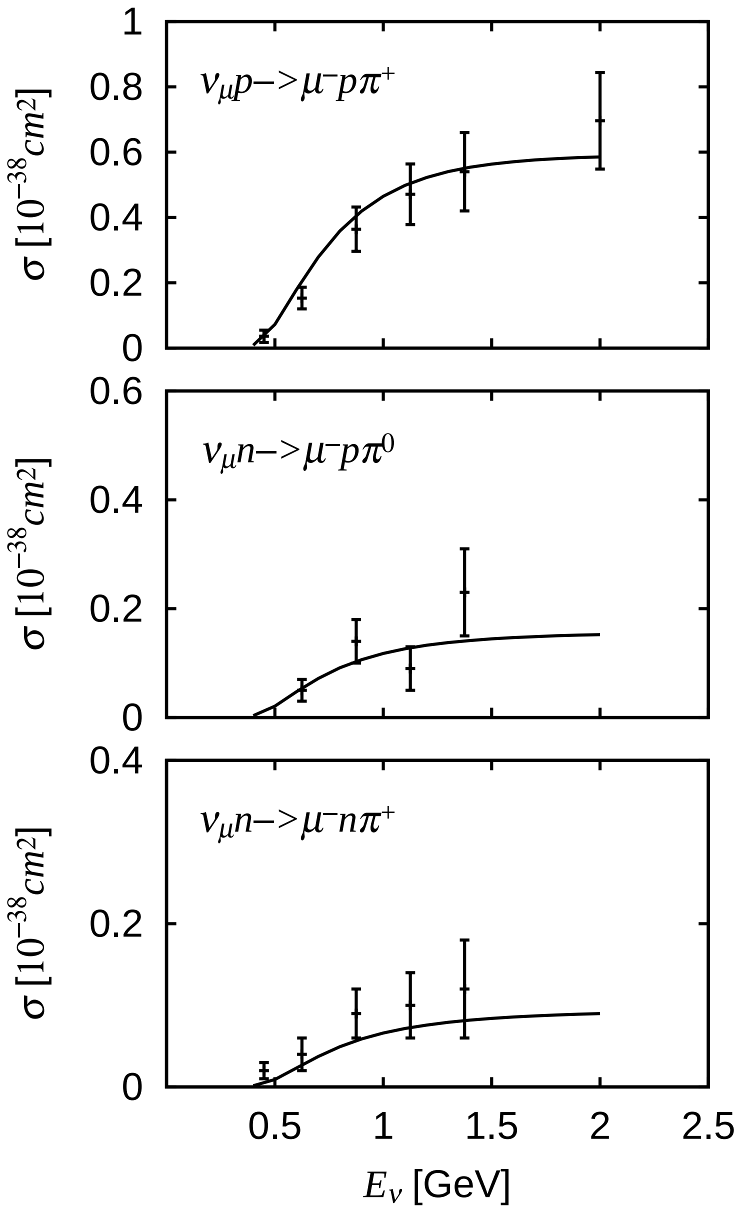
$$\begin{aligned} \text{CC} \;\; j_\mu^{CC} &= V_\mu^{1+i2} - A_\mu^{1+i2} \\ \text{NC} \;\; j_\mu^{NC} &= (1 - 2\sin^2\theta_W) j_\mu^{em} - V_\mu^{IS} - A_\mu^3 \end{aligned}$$

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

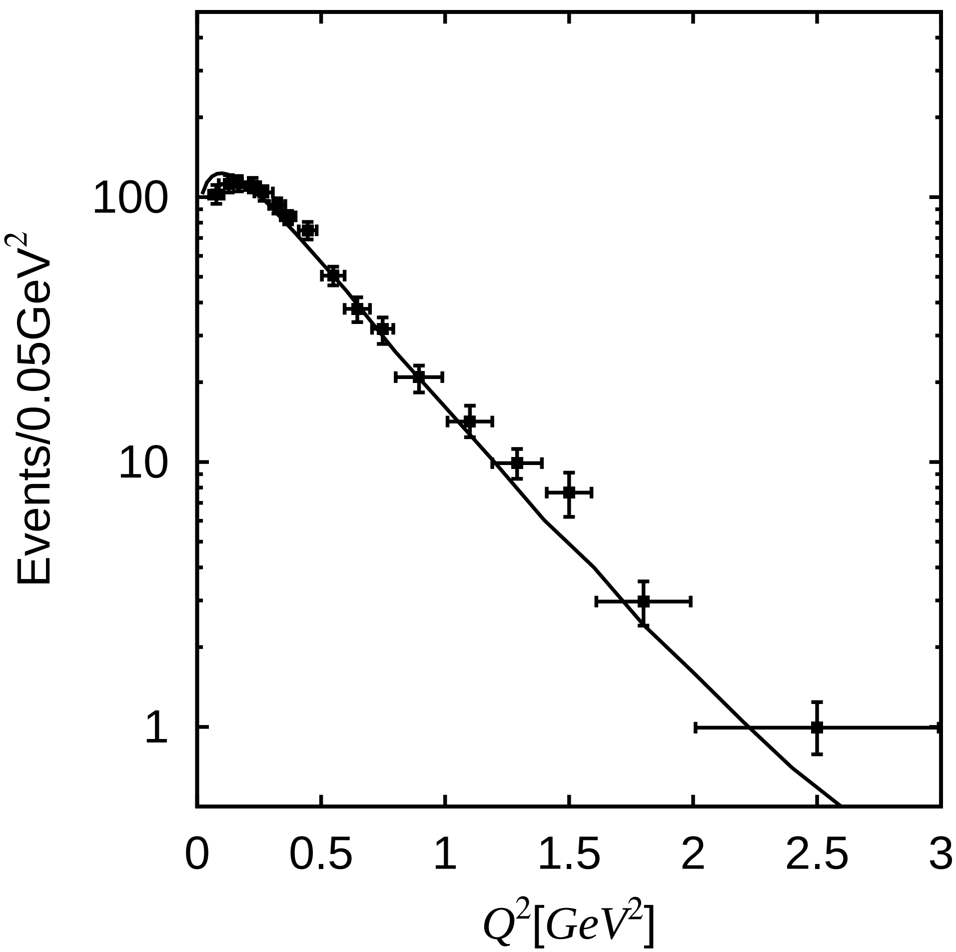
$\longrightarrow$

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 $p(\nu_\mu, \mu^- \pi^+)$



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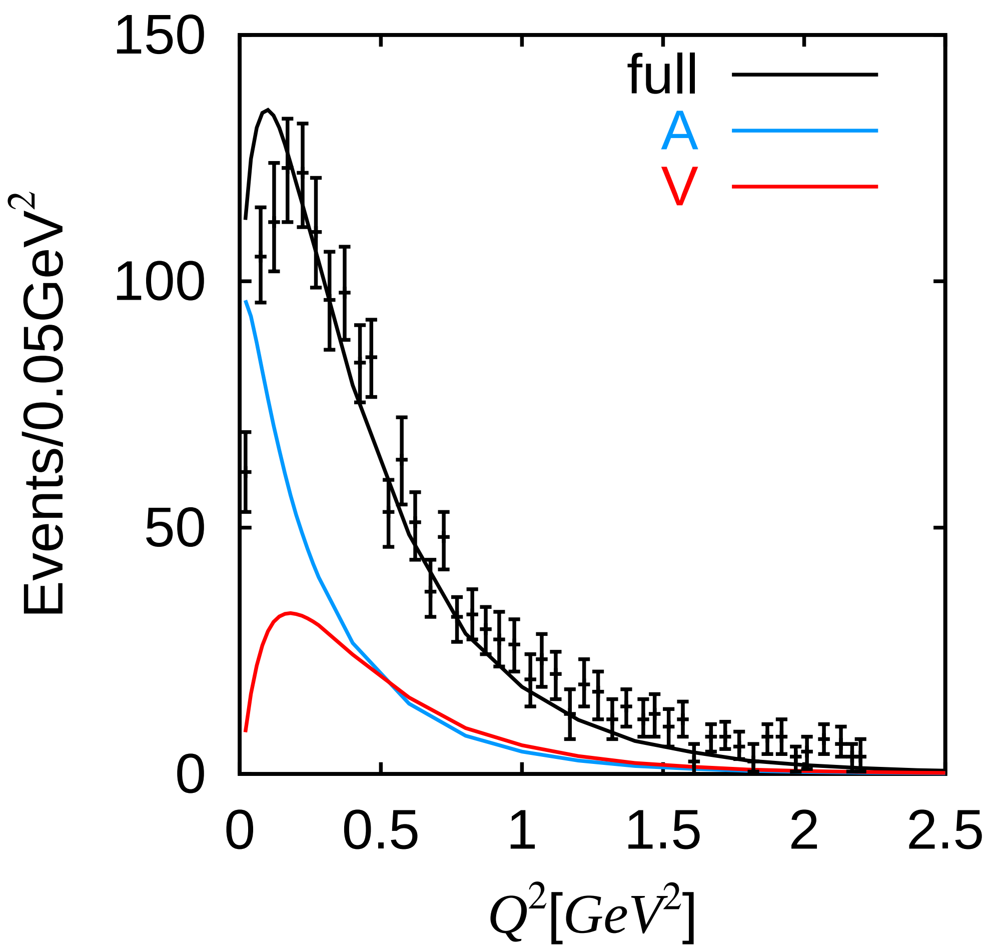
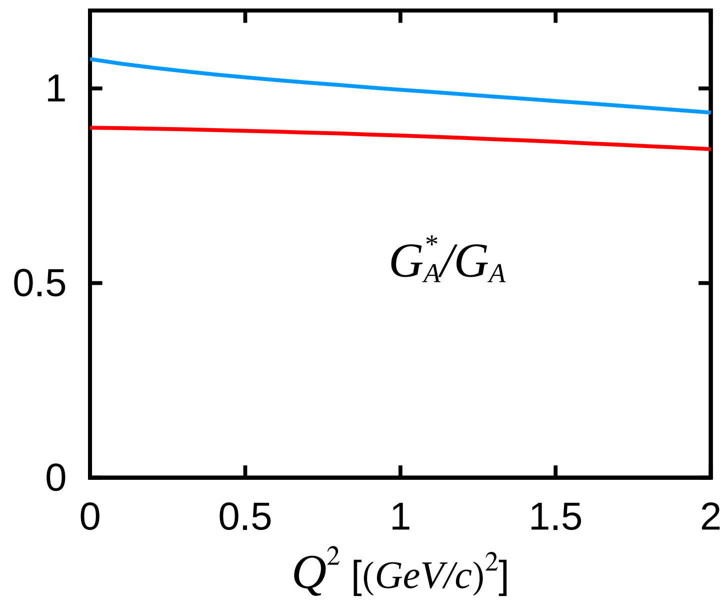


Determined axial N-Δ form factor G_A^*



Dotted curves : no pion cloud effect

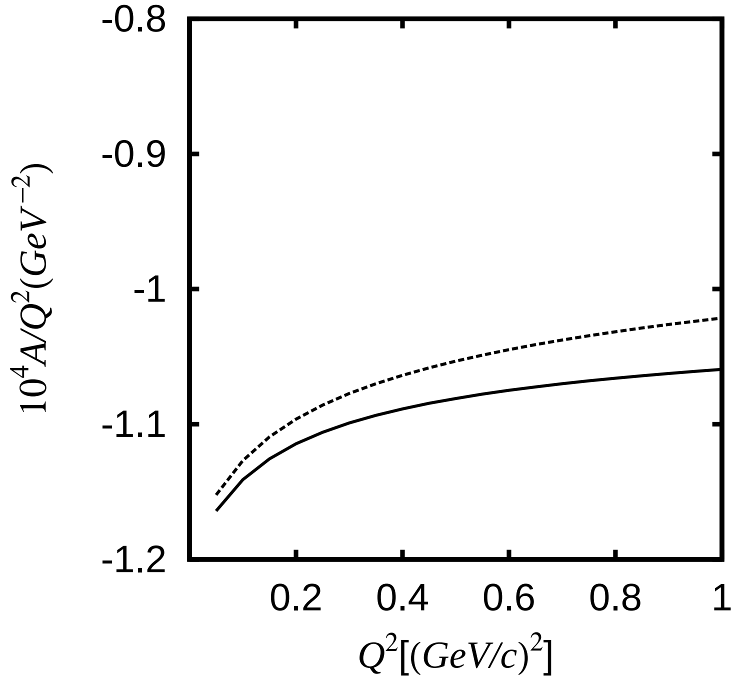
Role of neutral currents

- 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 ?

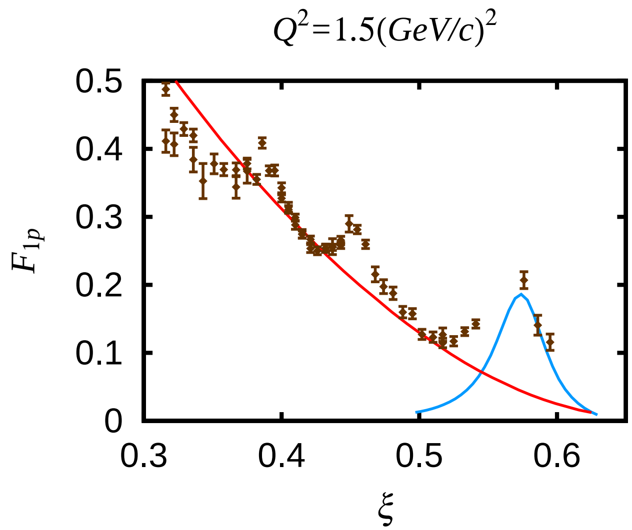
An average of the inclusive electron scattering observables in the resonance region should be close to the predictions from using the parton distribution functions determined in Deeply Inelastic Scattering (DIS) .

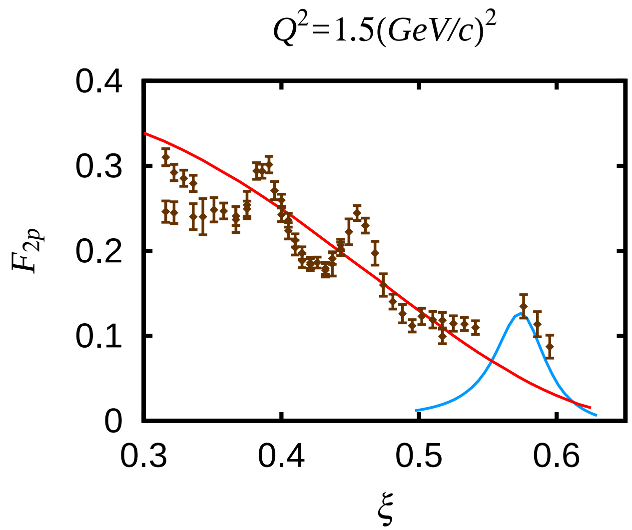
Inclusive (e, e')Cross Sections ($x = Q^2/(2\omega M_N)$)

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

Duality in $p(e, e')$

F_1 F_2





Data : Y. Liang et al, JLab, 2004

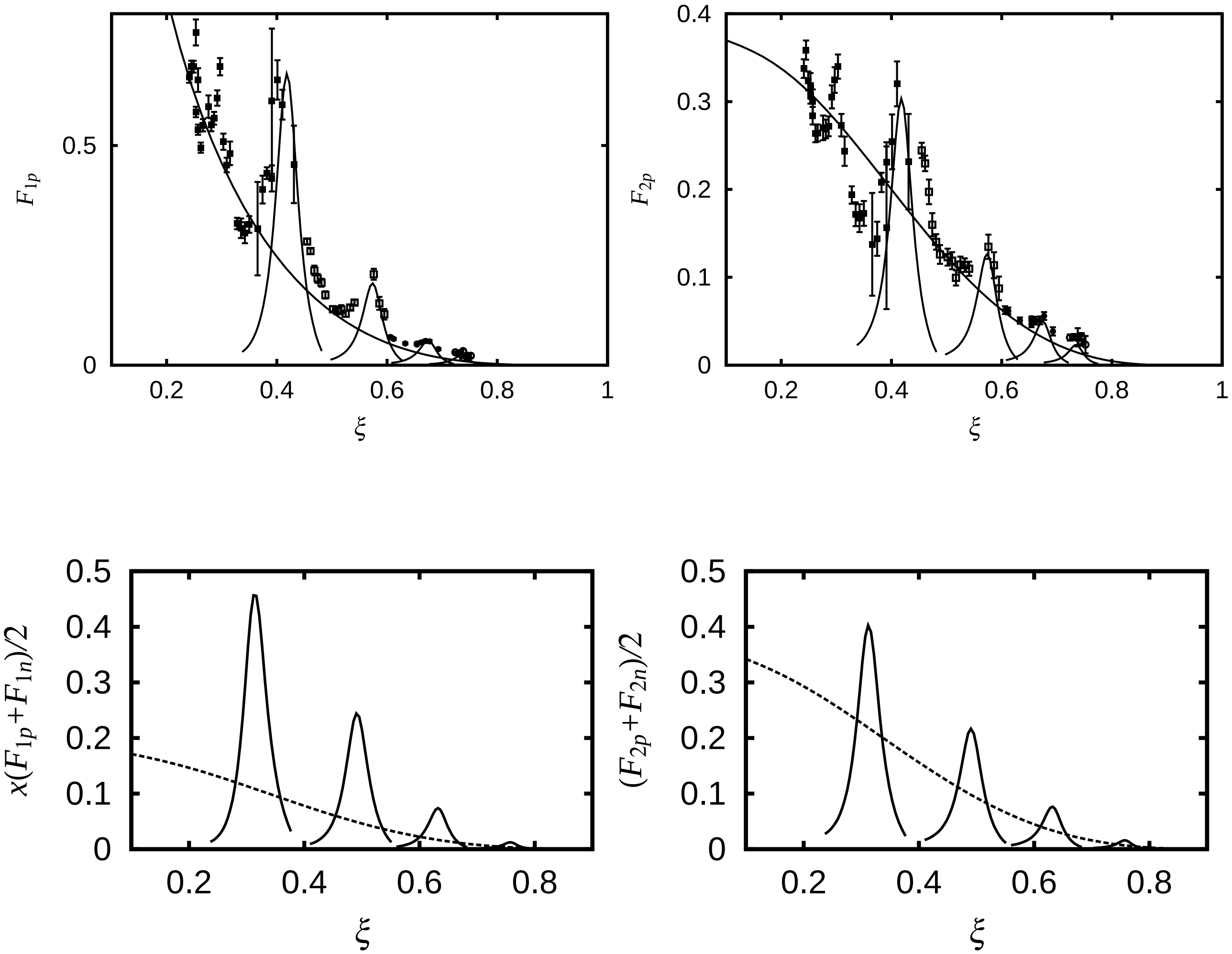
$\rightarrow$

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

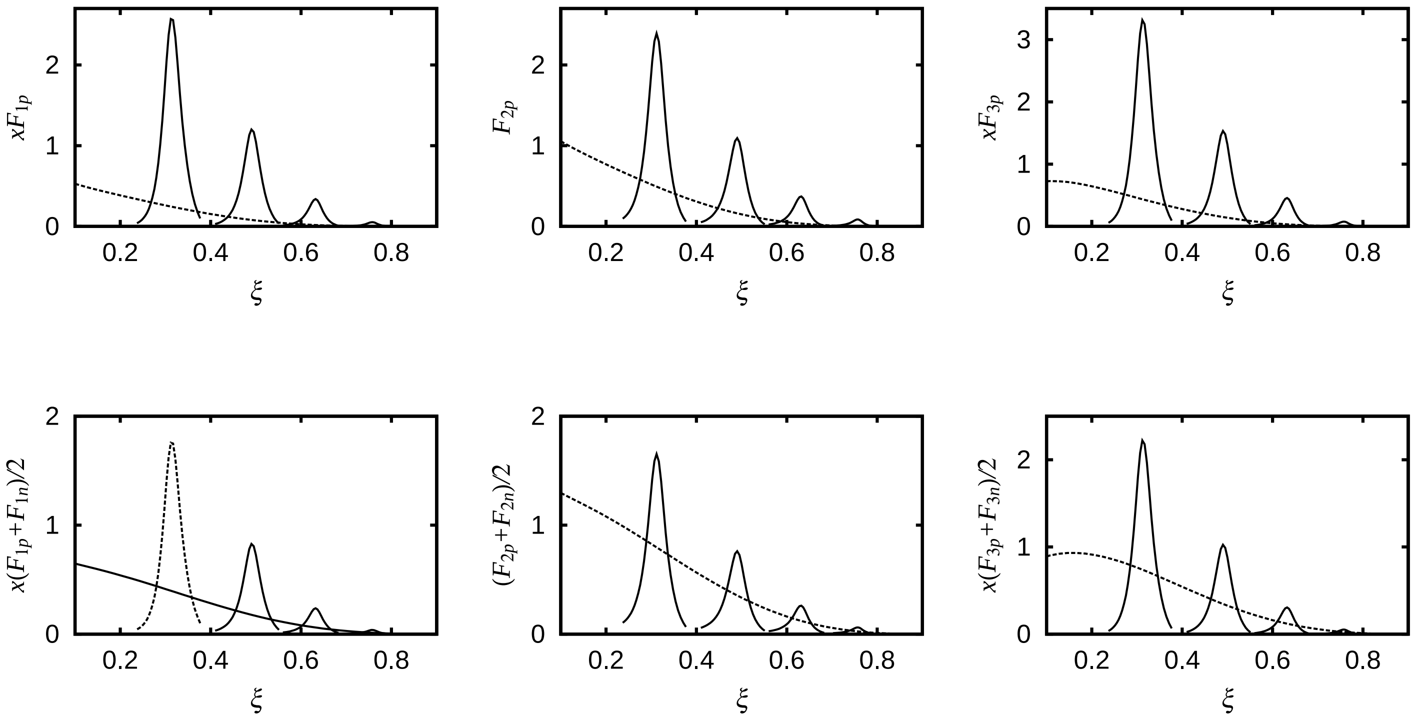
$N(e, e')$



Upper : proton taget

Lower : neutron target

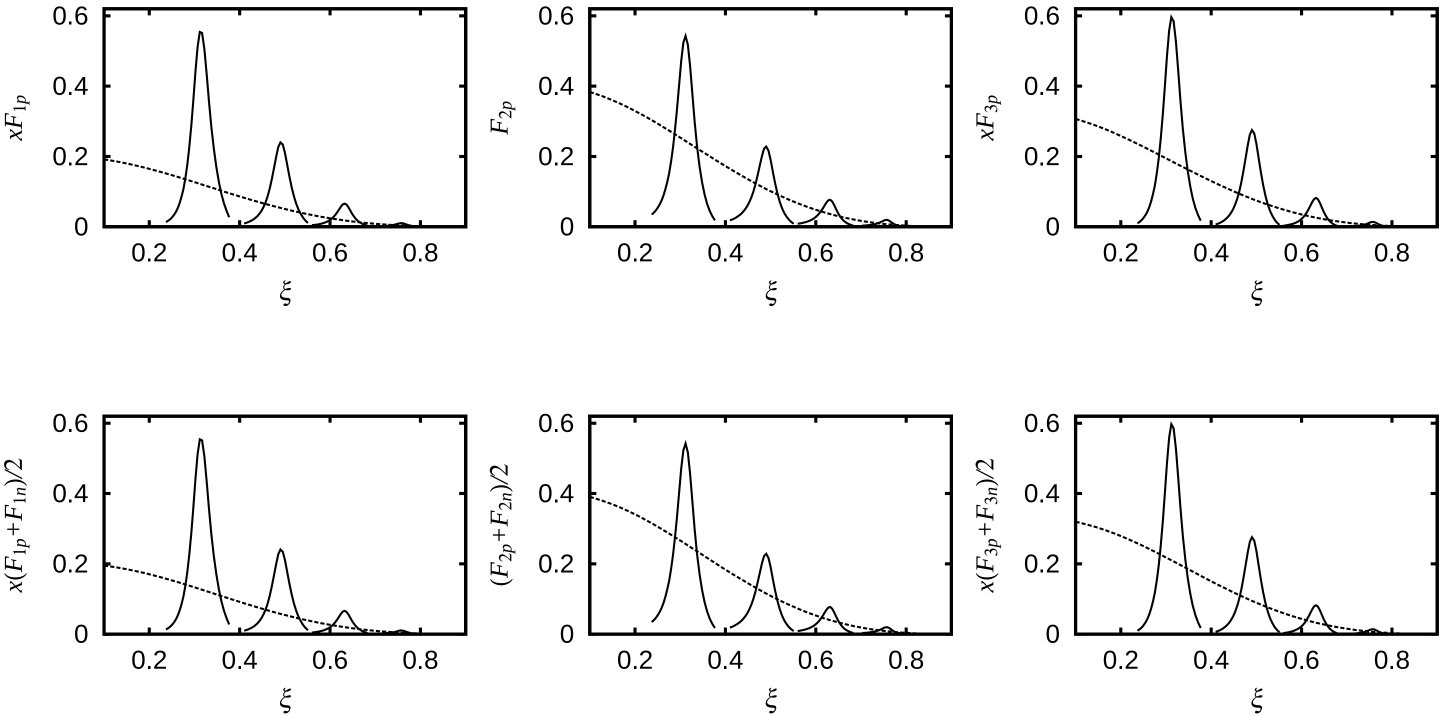
Predictions for $N(\nu, \mu)$



Upper : proton taget

Lower : neutron target

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



Upper : proton taget

Lower : neutron target

$\longrightarrow$

- Duality is confirmed for the unpolarized structure functions of all electroweak processes

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

  $\longrightarrow$

  Theoretical challenges :

  – Which QCD-based model can explain these form factors ?

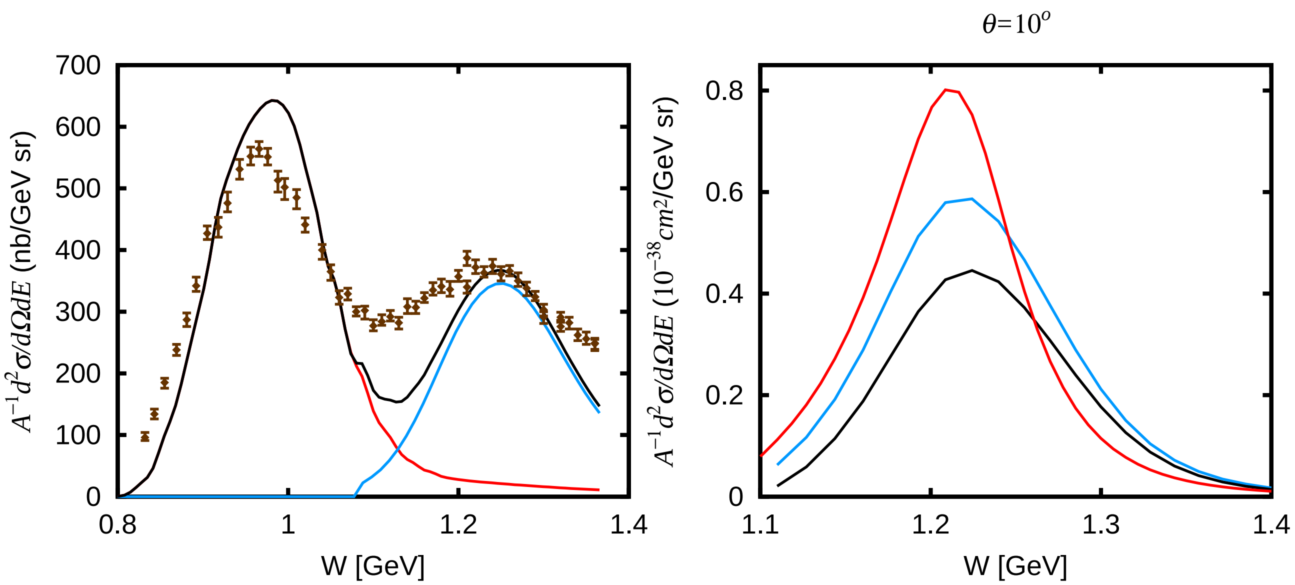
  – Can they be explained by Lattice QCD ?

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

  $\longrightarrow$

  Future experimental confirmations will be interesting !!

- 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 B. Julia-Diaz, A. Matsuyama, T. Sato, Physics Report (2007))
  - Apply the model to predict neutrino-nucleus reaction
    (with B. Szczerbinska, K. Kubodera, and T. Sato, Phys. Lett. (2007))



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