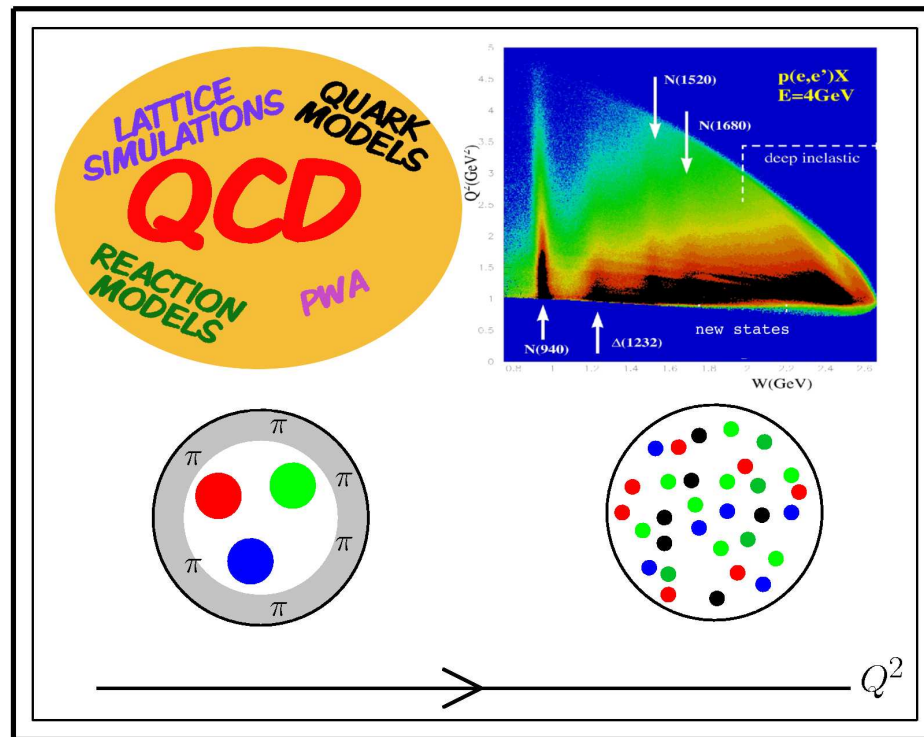


# Excited Baryon Program: Theoretical Developments

T.-S. H. Lee

Argonne National Laboratory  
and

Excited Baryon Analysis Center (EBAC) at JLab



Objectives :

Perform **theoretical** analyses of meson production data

→

- **Extract**  $N^*$  parameters :  
Masses, Widths, Form factors
- **Interpret**  $N^*$  parameters :
  - Hadron models with **effective degrees of freedom**
  - Lattice QCD

→

Understand **non-perturbative** QCD :

- **Confinement** mechanism
- Chiral dynamics of **meson** cloud of baryons
- . . . .

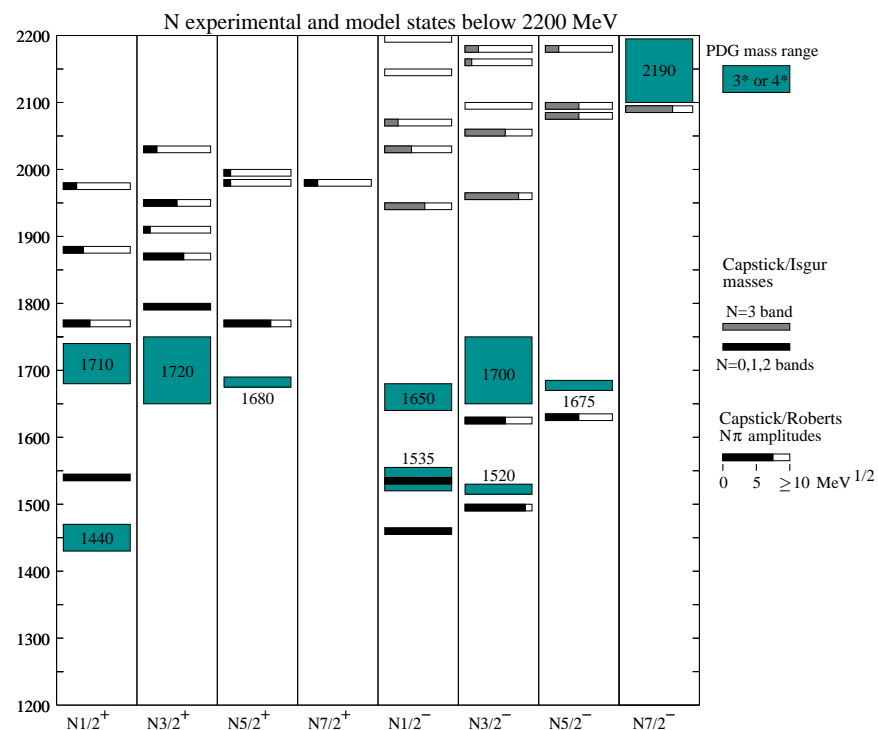
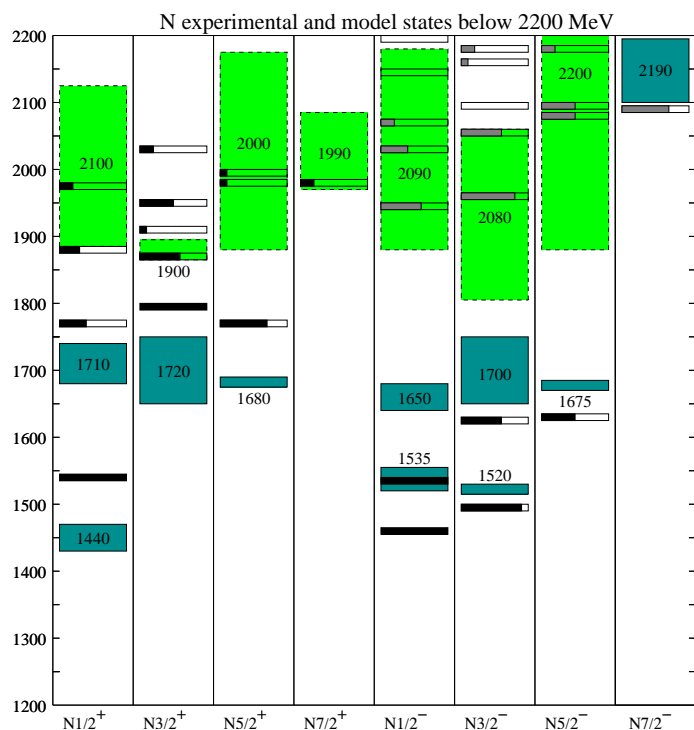
## Current focus:

- Identify baryon excited states at  $W > 1.7$  GeV

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Establish symmetry property ( $SU(6) \oplus O(3)$  or ?????)

————— old ————— >>>>> ————— current —————



Recent **PDG** assessment : 1- and 2-star states are **doubtful**

- Extract and interpret  $N$ - $N^*$  form factors

→

Reveal

- The quark sub-structure of baryon excited states
- The meson cloud effects

## General Considerations

- Baryon excited states are **coupled** to meson-baryon reaction channels to form **resonances** ( $N^*$ )

→

Reaction amplitude :  $T = t^R + t^{nr}$

- $t^R$  : **changes of internal structure** ( $N \rightarrow \Delta, N(1440), \dots$ )
- $t^{nr}$  : **non-resonant** interactions between reaction channels (Meson exchanges  $\dots$ )

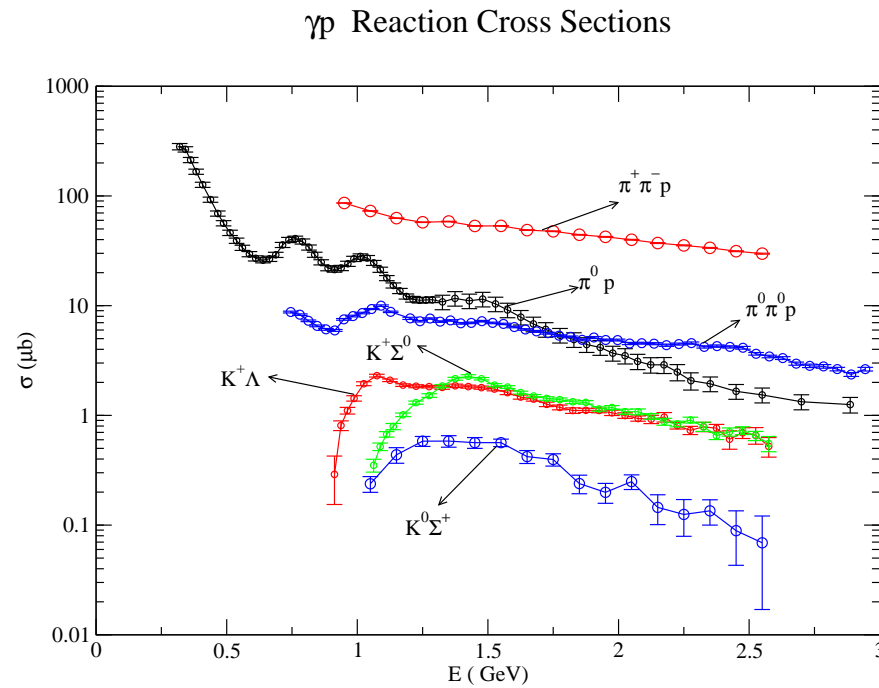
- **Many** reaction channels

$\gamma N, \pi N, \eta N, \omega N, K\Lambda, K\Sigma, \pi\pi N(\pi\Delta, \rho N, \sigma N)$

→

A **multi**-channel and **multi**-resonance reaction problem

Example:  $\gamma N \rightarrow KY$



Must include:

- coupled-channel effects :
  - $\gamma p \rightarrow \pi N \rightarrow KY$
  - $\gamma p \rightarrow \pi\pi N \rightarrow KY$
- at least about 10 known  $N^*$  resonances

## Theoretical Development

Very far from predicting meson-baryon reactions from QCD

→

Current effort:

- Develop reaction models to extract  $N^*$  parameters
- Interpret  $N^*$  parameters using available hadron structure calculations

Note :

Analysis based on **dispersion relations** is difficult :

- can not handle **multi**-particle channels ( $\pi\pi N$ )
- not applicable at **high**  $Q^2$  region

→

Develop alternative reaction models

- K-matrix models (On-shell approximation, PWA)

$$S = \frac{1 + iK}{1 - iK}$$
$$K \sim V(\text{tree} - \text{diagram})$$

- GWU-VPI (**SAID**), Mainz (**MAID**), JLab-Yerevan, CMU (**PWA**)  
Giessen, GWU, KVI, Bonn-Gatchina, JLab-MSU (**JM06**),  
Valencia, Hiroshima-Onomichi, . . .



- Dynamical Models

$$\begin{aligned} S &= 1 + 2iT \\ T &= V + \int VGT \end{aligned}$$

→

Account for reaction mechanisms in the short-range (**off-shell**) region where we want to **map out**  $N^*$  structure

- Sato-Lee, Gross-Surya, Dubna-Mainz-Taipei, Fuda-Alharbi, Ohio-Utrecht, Saclay-Pitt-ANL, Pascalutsa-Vanderhaeghen, Julich, ..

Two approaches are **complementary** :

- K-matrix models solve **algebraic** equations

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very **efficient** in processing **multi-channel** data to get  
**first-run** results of  $N^*$  parameters

- Dynamical models account for short-range (**off-shell**) mechanisms

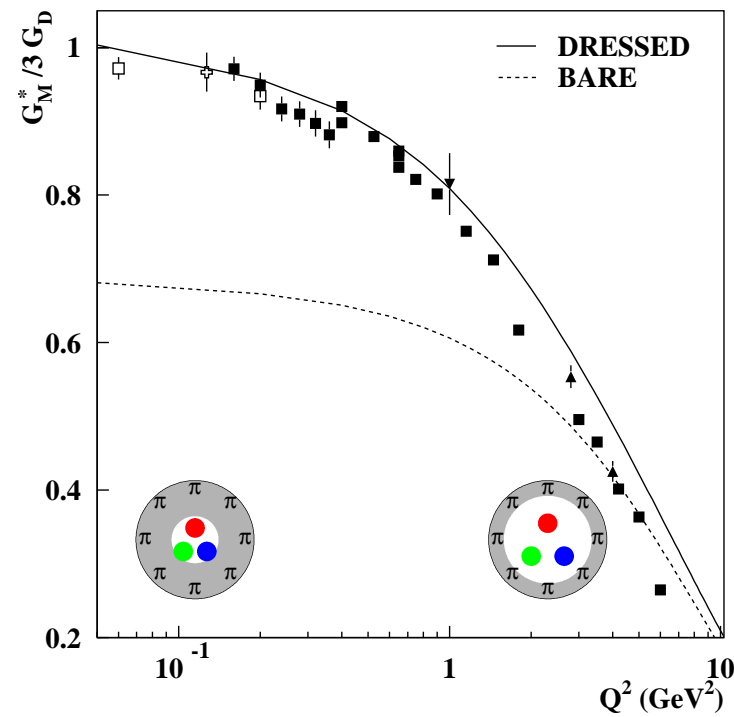
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related to hadron structure calculations for **interpreting**  $N^*$  parameters

## Selected Recent Results

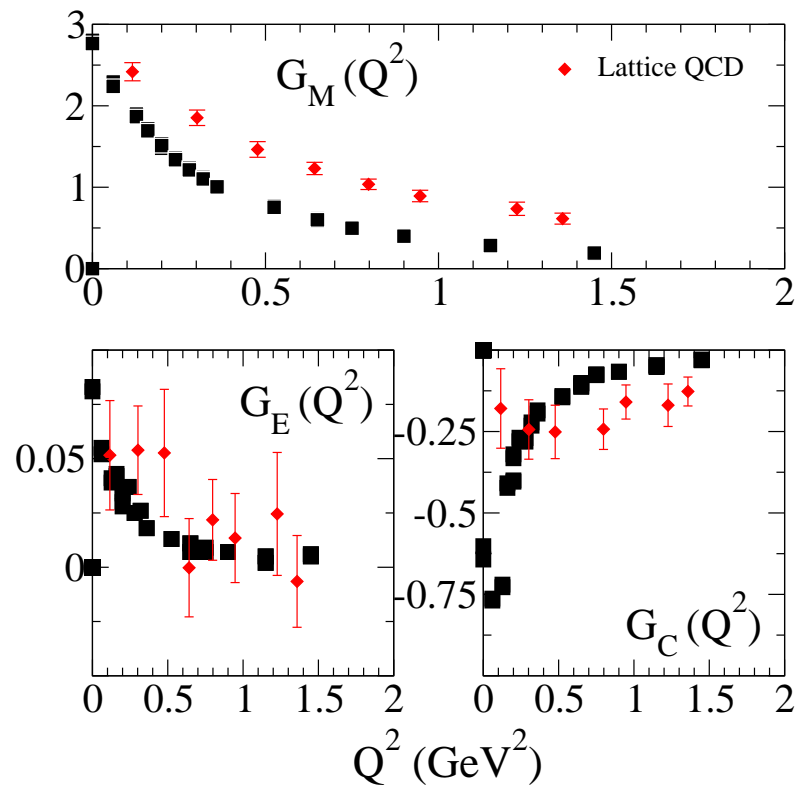
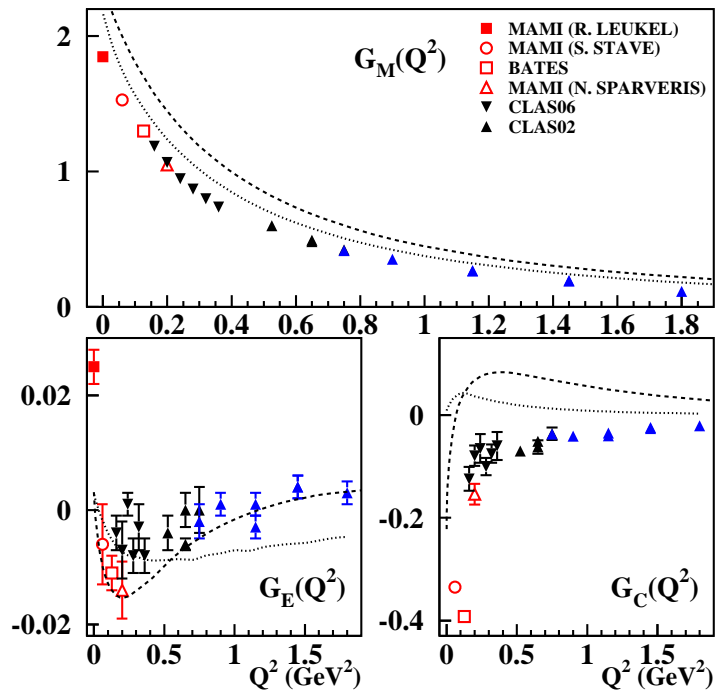
### 1. $\gamma N \rightarrow \Delta(1232)$ form factors

- $Q^2$ -evolution of **meson cloud** is discovered

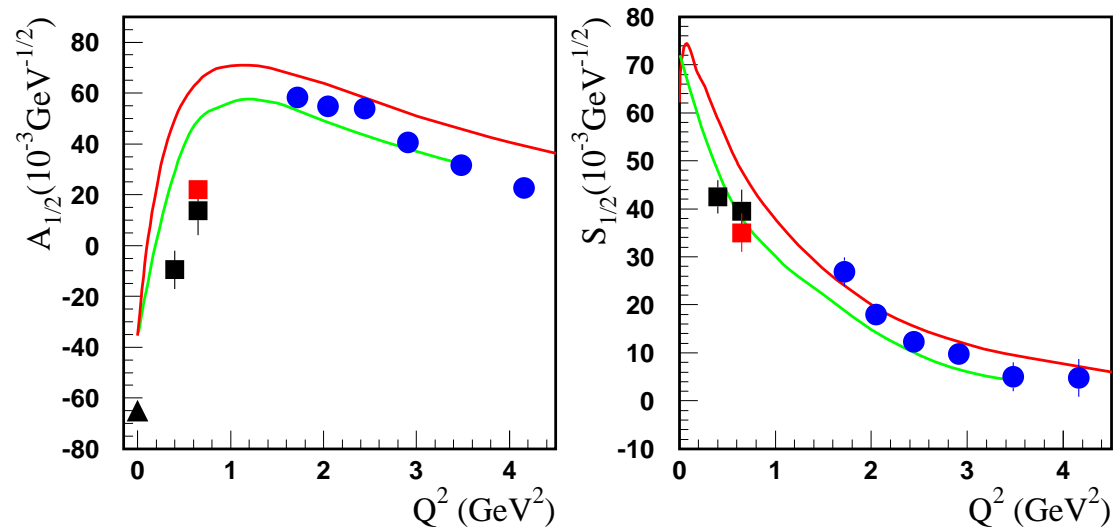


- Hadron structure calculations are **tested**

————— Quark Model ————— LQCD —————  
 ————— ( Bare ) ————— ( Dressed ) —————



## 2. $N$ - $N^*(1440)$ form factors agree with Quark Model



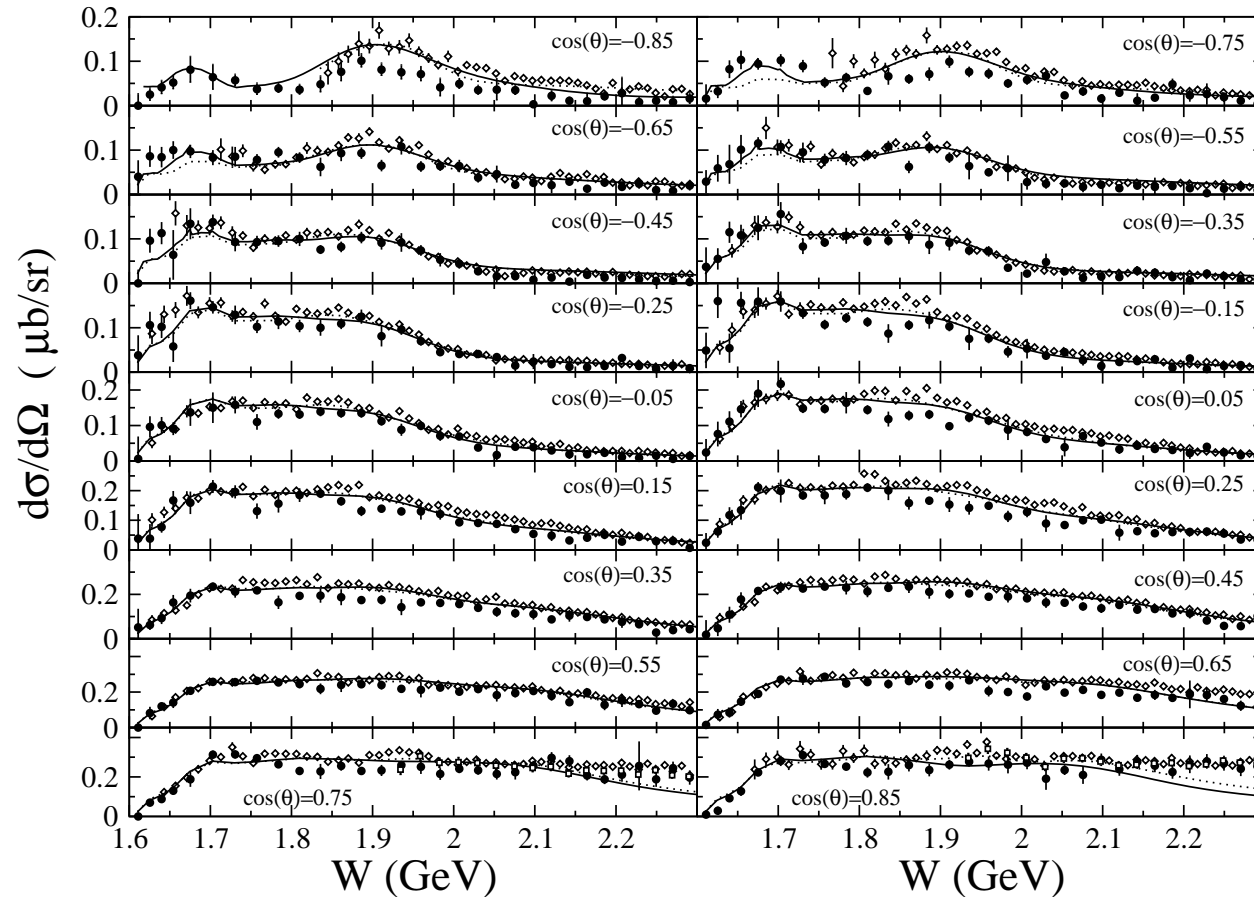
Red curves :S. Capstick and B.D. Keister

Green curves : I. Aznauryan

### 3. New states at $W > 1.7$ GeV are suggested

Example: Coupled-channel fit to  $\gamma p \rightarrow K^+ \Lambda$  data of JLab

(B. Julia-Diaz et al. 2006)



→

| New states | Mass  | Width |
|------------|-------|-------|
| $S_{11}$   | 1.833 | 0.288 |
| $P_{13}$   | 1.974 | 0.108 |
| $D_{13}$   | 1.912 | 0.316 |

Several **new states** have also been suggested in the **K-matrix** analyses by Giessen group, GWU group, Bonn-Gatchina group, CLAS collaboration (**JM06** )

**Note :**

- Need to be further **confirmed** by analyses including **polarization** data and more complete coupled-channel analyses.
- Need to be **verified** by dynamical model analyses

Necessary next step :

Strengthen the collaborations between

empirical analyses (PWA, K-matrix analyses )

and

theoretical efforts (dynamical models, hadron structure calculations )

→

Establish Excited Baryon Analysis Center (EBAC )

at the Theory Center of Jefferson Laboratory



## Excited Baryon Analysis Center (EBAC )

Theory Center, Jefferson Laboratory

- Established: January, 2006
- Goal : Reach a DOE milestone by 2009

”Complete the combined analysis of available single pion, eta and kaon photo-production data for nucleon resonances and incorporate analysis of two-pion final states into the coupled channel analysis of resonances.”

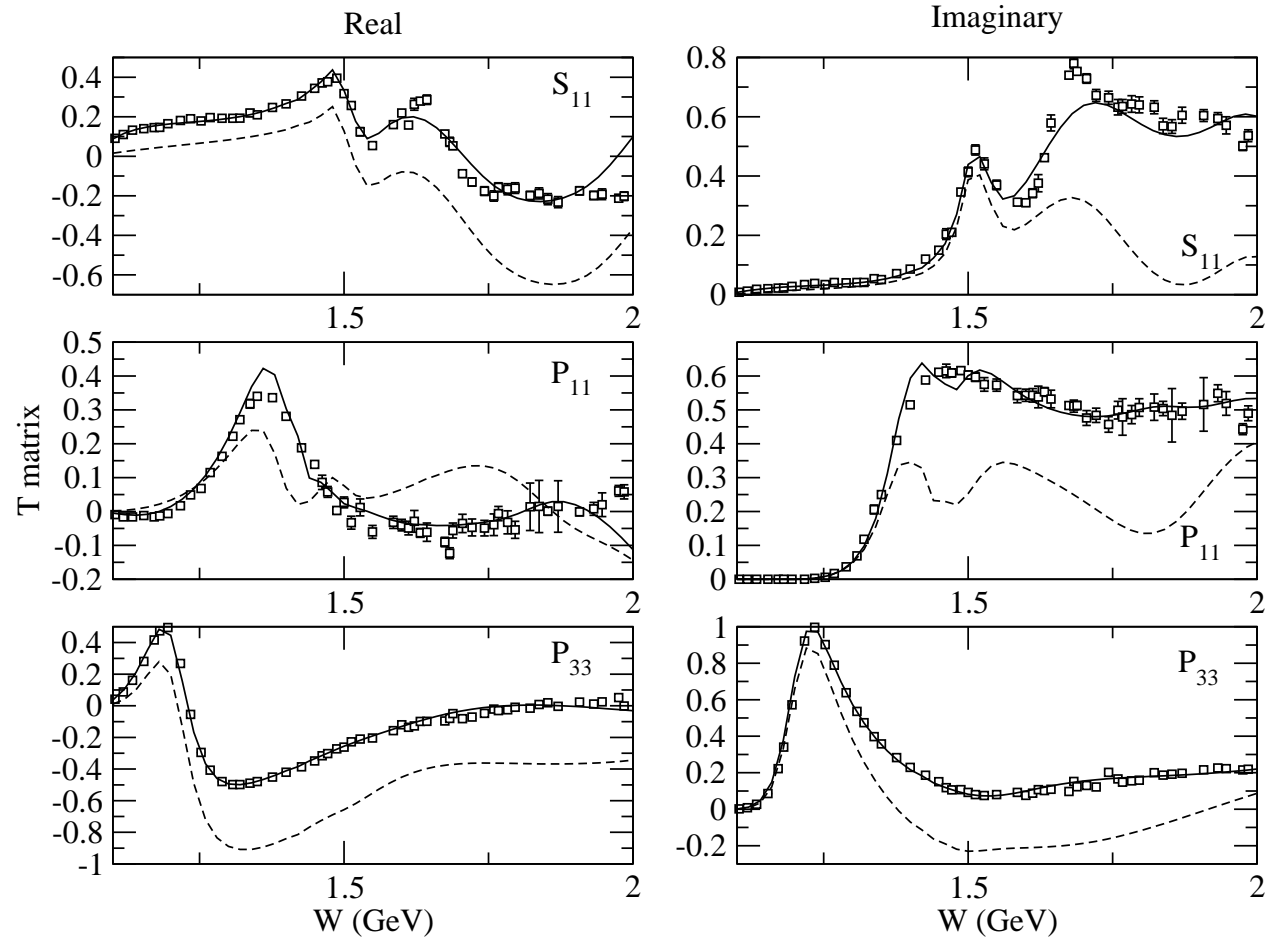


## 1. On-going theoretical projects :

- Perform Dynamical Coupled-Channel Analysis  
(B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, M. Paris, T. Sato, K. Tsushima)
  - $\pi N$ ,  $\eta N$ ,  $\pi\pi N$  production
  - $\omega N$ ,  $K\Lambda$  production
- Develop collaborations with other theoretical efforts
  - Coupled-channel analysis by the **Julich** group  
(J. Haidenbauer, C. Hanhart, S. Krewald, Ulf-G. Meißner, A. Sibirtsev, K. Nakayama, H. Haberzettl )
  - **EBAC-Saclay** Coupled-channel analysis of  $\eta$ ,  $K$  photoproduction  
(J.-C. David, J. Durand, Jun He, B. Julia-Diaz, T.-S. H. Lee, B. Saghai, T. Sato)

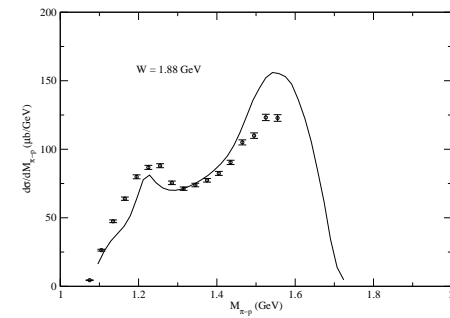
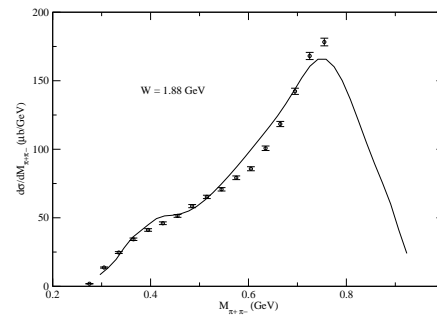
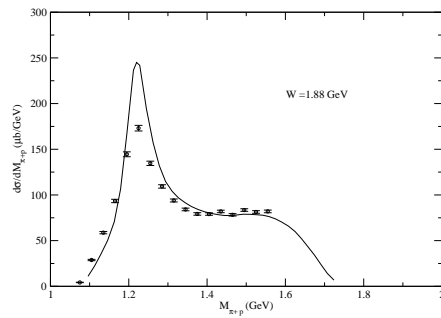
## First results from EBAC

- Fits of  $\pi N$  amplitudes



(dashed curves:  $N^*$  contributions )

- Start to analyze  $\gamma p \rightarrow \pi^+ \pi^- p$  data of JLab



## Plans :

- 2007 - 2008 : Analysis of  $\pi, \eta, \pi\pi$  production data
- 2008 -2009 : **full** coupled analysis including  $\omega, K$  production data

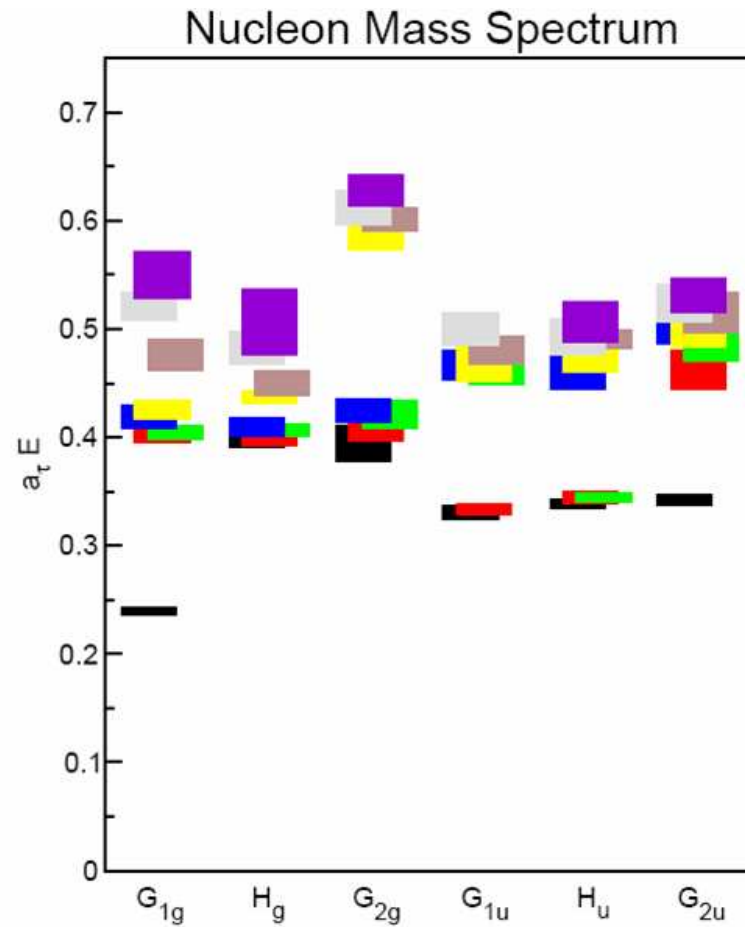
2. Provide **theoretical** input to the data analyses by **experimental** groups

- Include the coupled-channel effects in the combined analyses of  $\pi, \eta, \pi\pi$  production data by **CLAS** collaboration
- Collaborations with other experimental groups will be developed

3. Projects being developed :

- Development of reaction models at **high  $Q^2$**  region, accessible to JLab's **12 GeV upgrade**
- Investigation of the **connections** with **Lattice QCD** calculations

## Recent LQCD Calculations (Provided by LHPC)



Question :

How to compared with the extracted  $N^*$  resonance energies ?

# Dynamical Coupled-Channel Analysis at EBAC

Theory Center, JLAB

