Exploring the Baryon Landscape with Real Photons

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and

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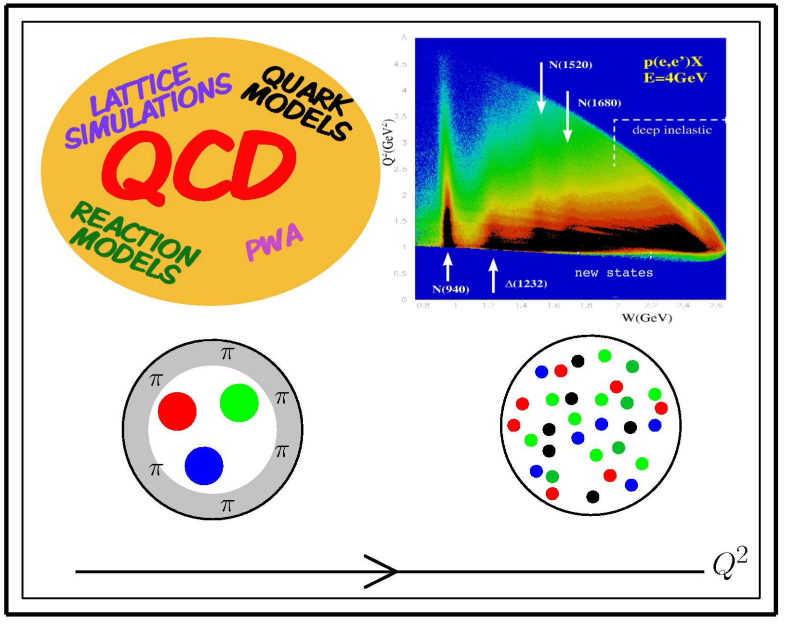


- Objectives
- Methodology
- Status of N^* and Δ^* studies
- Extension to strange Baryons (Λ, Σ, Ξ)
- Extension to charmed Baryons ($\Lambda_c, \Sigma_c, \Xi_c$)
- Outlook

Jefferson Lab JSA

Objectives

- Establish the baryon spectra
- Investigate the structure of baryon resonances

$\longrightarrow$

Understand non-perturbative QCD

- confinement mechanisms
- Meson cloud associated with the spontaneously and dynamically broken chiral symmetry of QCD
- $\cdots\cdot$

Methodology

Ideal situation :

1. At a given energy (E), perform complete/over complete measurements at all angles (θ) :

   Example: Pseudo-scalar photoproduction :

   8 observables (Tabakin and collaborators) :

   - $d\sigma/d\omega$
   - Single polarization: Σ, T, P
   - Double polarization: G, H, E, F

2. extract amplitudes $F_{\lambda_{N_f},\lambda_\gamma\lambda_{N_i}}(E,\theta)$

   Note : need to solve inverse bi-linear equations

3. Project out partial-wave amplitudes $f_{[LS]J}(E)$ from $F_{\lambda_{N_f},\lambda_\gamma\lambda_{N_i}}(\theta,E)$

4. Extract resonance poles and residues from $f_{[LS]J}(E)$:

   - Speed-plot method (Hohler)
   - Time-delayed method (Wigner)
   - Analytical continuation to complex-E plane :
     - Dispersion relations
     - Isobar and/or K-matrix Equations
     - Dynamical Scattering Equations

       (Based on Hamiltonian or Bethe-Salpeter formulation)

Reality :

Lack of complete measurements

$\longrightarrow$ ‘

Model assumptions are not avoidable

$\longrightarrow$

One must be aware of the model assumptions in interpreting

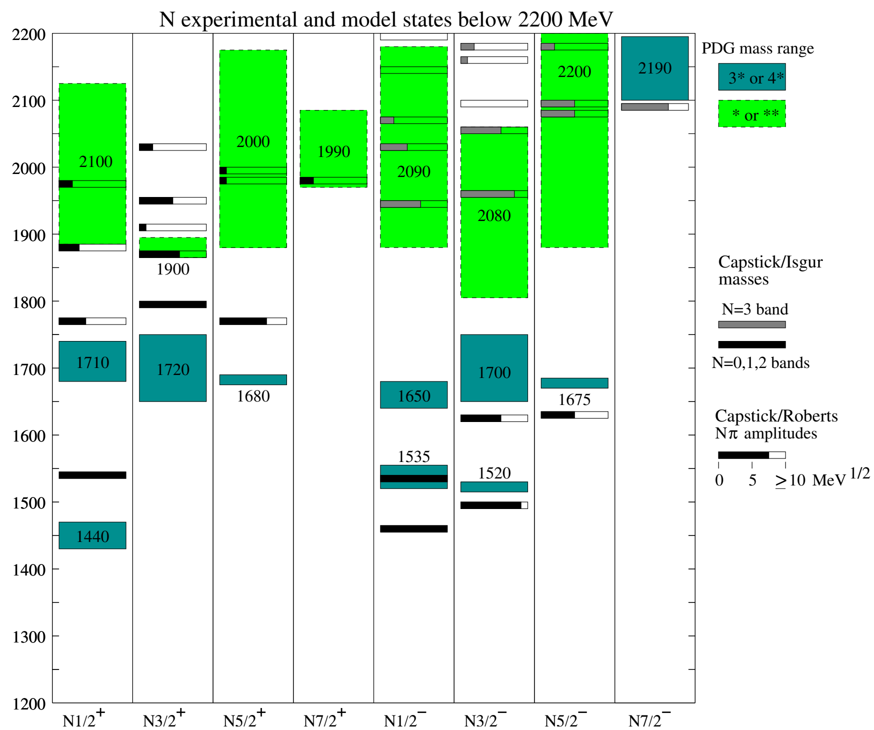
the extracted resonance parameters.

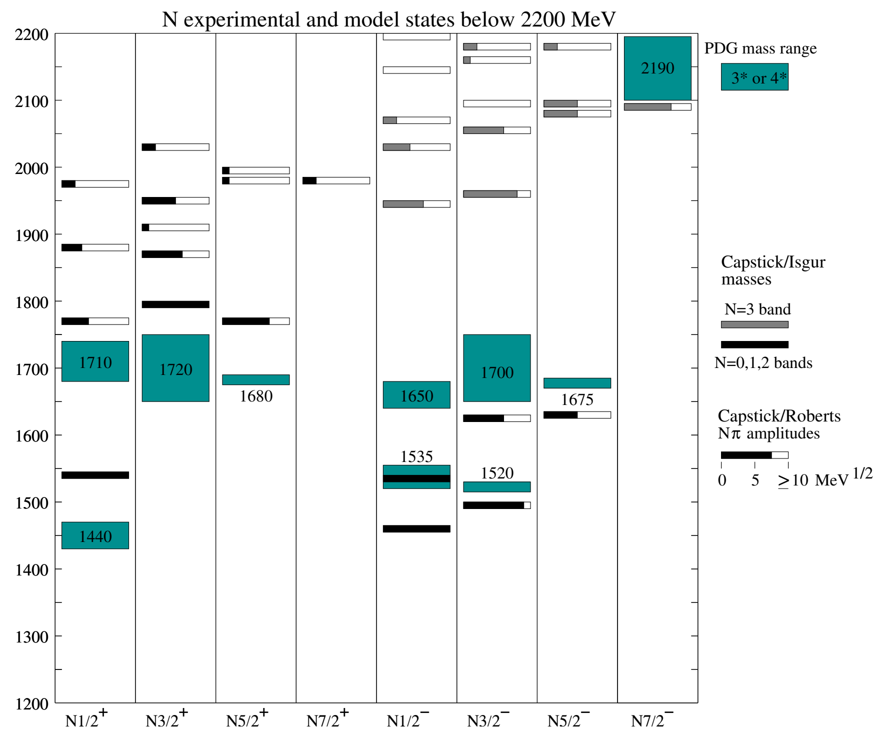
Status of N^* and Δ^* states

2007 PDG :

All 2-star and 1-star states are doubtful

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





Recent efforts :

Hope to make progress by performing a coupled-channel analysis of

ALL available data of

1. $\pi N \rightarrow \pi N, \pi\pi N, \eta N, KY, \omega N$

2. Photo-production and electro-production of $\pi N, \pi\pi N, \eta N, KY, \omega N$

Being pursued by several groups at Giessen, Bonn, and EBAC

- All agree that polarization observables are crucial
- Complete/over-complete measurements are highly desirable :
  - Can be achieved in pseudoscalar meson photoproduction (i.e. $K\Lambda$ production measurements to be conducted at JLab)
- Hope to have more hadronic meson production data :

  Possibility : develop collaborations with JPARC

  $\longrightarrow$

  A 2009 US-Japan workshop is being organized by Joo, Hick, Lee, Nakano, Sato)

Effort at EBAC :

Based on a set of dynamical coupled-channel equations :

$$T_{\alpha,\beta}(p_0,p_0;E) = V_{\alpha,\beta}(p_0,p_0) + \sum_{\gamma}\int_0^{\infty} dp' V_{\alpha,\gamma}(p_0,p')G_{\gamma}(p',E)T_{\gamma,\beta}(p',p_0,E)$$

$$V_{\alpha,\beta} = v_{\alpha,\beta} + \sum_{N^*}\frac{\Gamma^{\dagger}_{N^*,\alpha}\Gamma_{N^*,\beta}}{E-M^*}$$

- $\alpha,\beta,\gamma = \gamma N, \pi N, \eta N, \omega N, KY, \pi\pi N$ ($\pi\Delta, \rho N, \sigma N$)
- $v_{\alpha,\beta}$: Meson-exchange mechanisms
- $\Gamma_{N^*,\beta}$, M^* : Hadron structure calculations
  - Hadron models with effective degrees of freedom
  - Lattice QCD

Reaction Amplitudes

$$T_{a,b}(E) = t_{a,b}(E) + t^R_{a,b}(E)$$

$a, b = \gamma N, \pi N, \eta N, \pi\Delta, \rho N, \sigma N$

Non-resonant term :

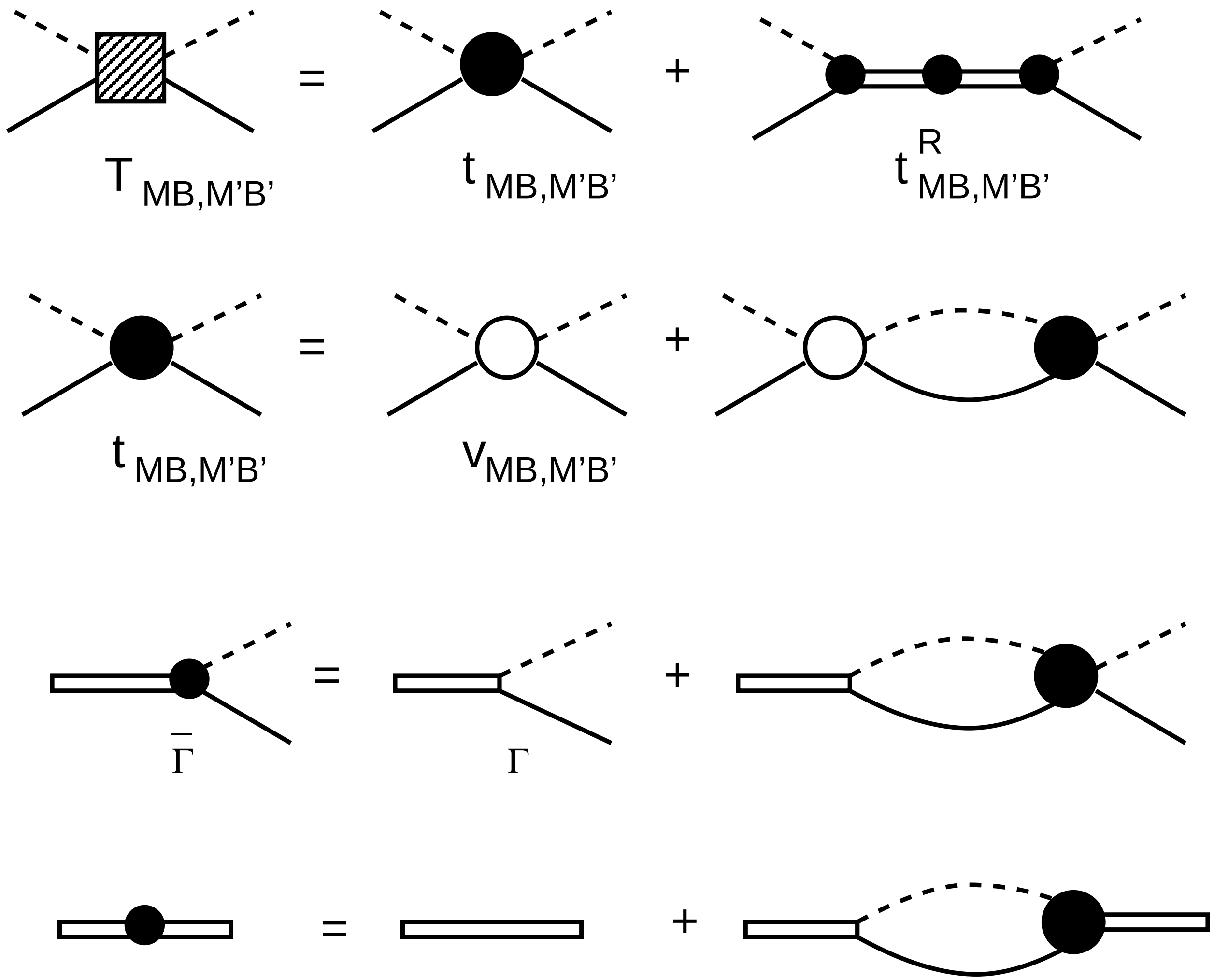
$$t_{a,b}(E) = v_{a,b} + \sum_c v_{a,c} G_c(E) t_{c,b}(E)\,,$$

Resonant term:

$$t^R_{a,b}(E) = \sum_{N^*_i, N^*_j} \bar{\Gamma}^\dagger_{N^*_i,a}(E)[G^*(E)]_{i,j} \bar{\Gamma}_{N^*_j,b}(E)\,.$$

Dressed vertex:

$$\bar{\Gamma}_{N^*,a}(E) = \Gamma_{N^*,a} + \sum_b \Gamma_{N^*,b} G_b(E) t_{b,a}(E)\,,$$

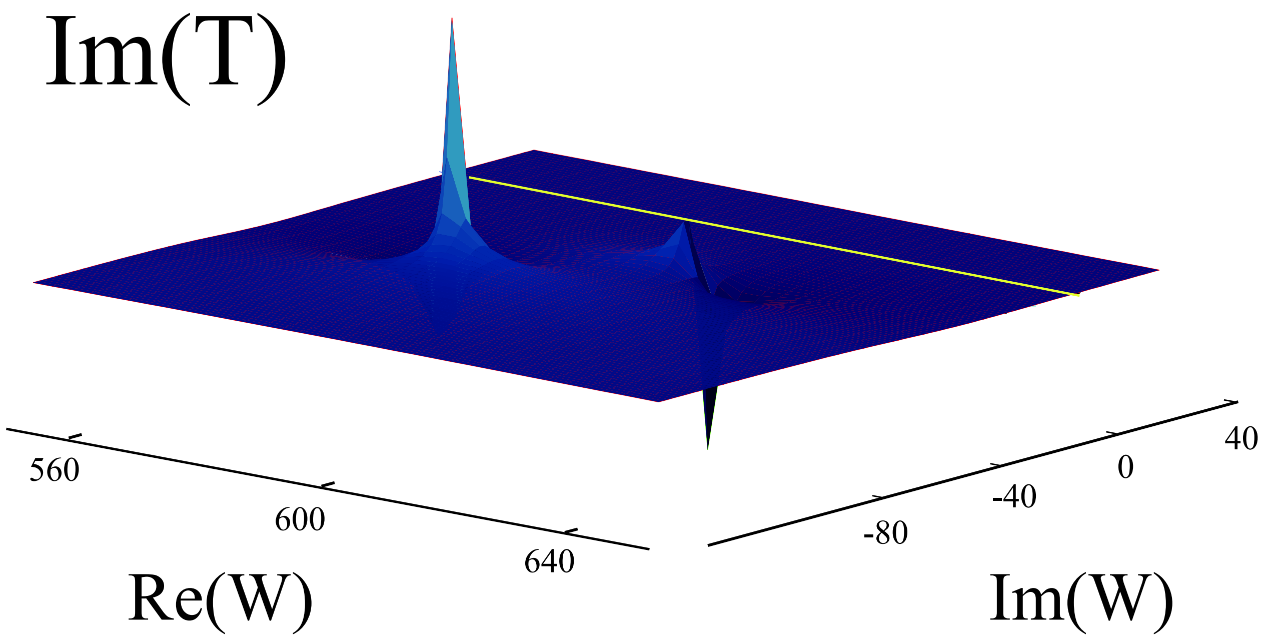


=
+
$T_{MB,M'B'}$
$t_{MB,M'B'}$
$t^R_{MB,M'B'}$
=
+
$t_{MB,M'B'}$
$v_{MB,M'B'}$
=
+
$\bar{\Gamma}$
Γ
=
+

Most recent progress:

Extract resonance poles from the πN scattering data by solving the dynamical coupled-channel equations in complex-E plane using the method of analytical continuation

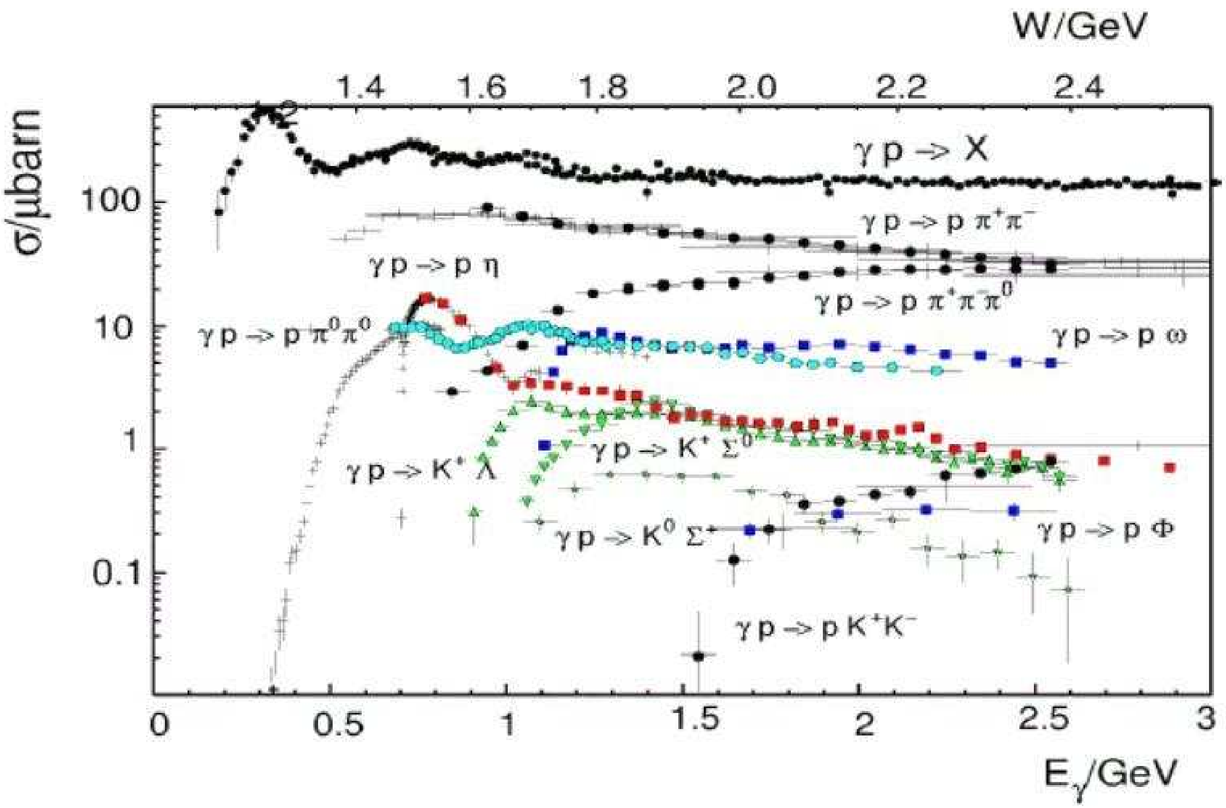
(N. Suzuki, T. Sato, T.-S. H. Lee, in preparation)



	bare values		Analytical Continuation		PDG
S_{11}	1800		(1535, 157)		(1490 - 1530 , 45 - 125)
	1880		(1642, 41)		(1640 - 1670, 75 - 90)
P_{11}	1763		being determined		(1350 - 1380, 80 - 110)
	2037		(1820, 248)		(1670 - 1770, 40 - 190)
P_{13}	1711		being determined		(1660 - 1690, -57 - 138)
D_{13}	1899		(1521, 58)		(1505 - 1515 , 52 - 60)
D_{15}	1898		(1654, 77)		(1655 - 1665 , 62 - 75)
F_{15}	2187		(1674, 53)		(1665 - 1680 , 55 - 68)

	Bare values		Analytical Continuation		PDG
S_{31}	1850		(1563, 95)		(1590 - 1610, 57 - 60)
P_{31}	1900		No		(1830 - 1880, 100 - 250)
P_{33}	1391		(1211, 50)		(1209 - 1211, 49 - 51)
D_{33}	1976		(1604, 106)		(1620 - 1680, 80 - 120)
F_{35}	2162		(1928, 165)		(1825 - 1835, 132 - 150)

Data of γp reaction cross sections



$\rightarrow$

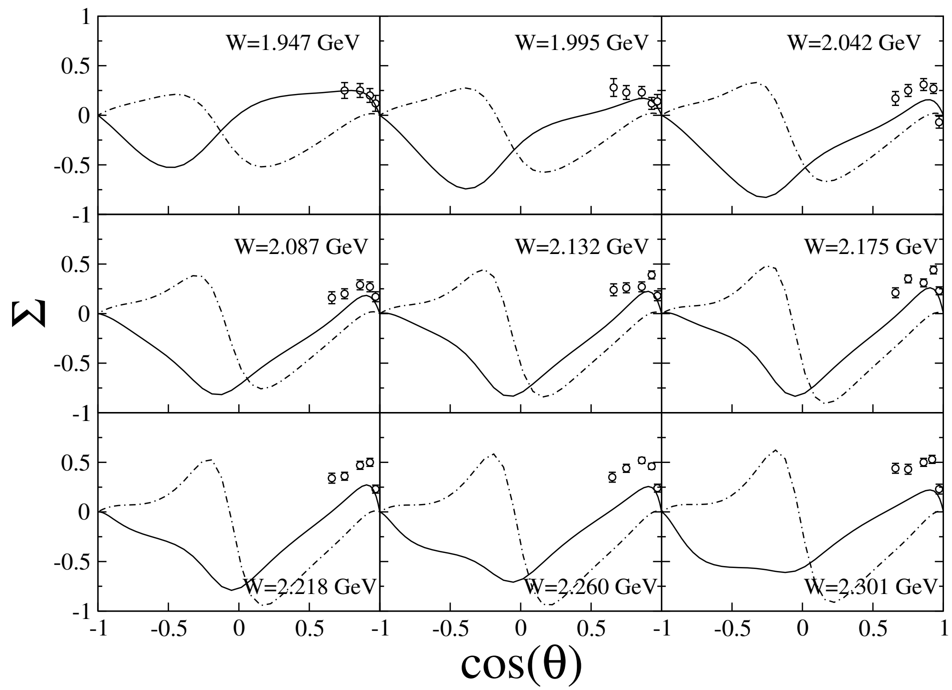
Main next task :

Include two-pion production data in the fit for confirming/discovering N^* and Δ^* in the third resonance region

Importance of polarization observables: consider $\gamma p \rightarrow K^+\Lambda$

(B. Julia-Diaz, B. Saghai, T.-S. H. Lee, F. Tabakin, Phys. Rev. 2007)

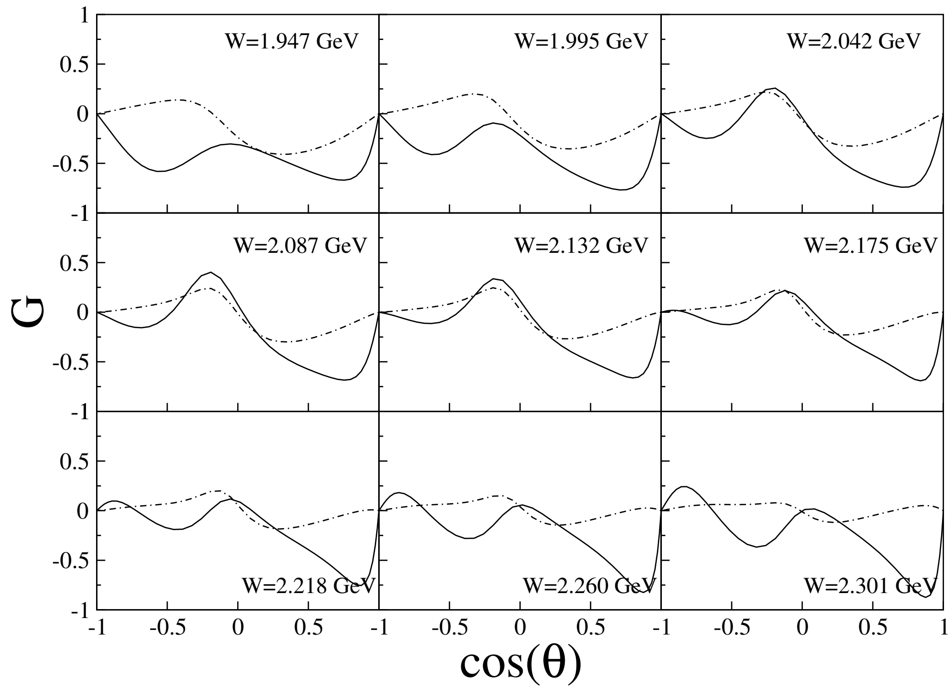
1. Asymmetry Σ_γ of linearly polarized photons



dashed : no N^*

2. Double polarization $G = (\sigma(t,z) - \sigma(t,-z))/(\sigma(t,z) + \sigma(t,-z))$

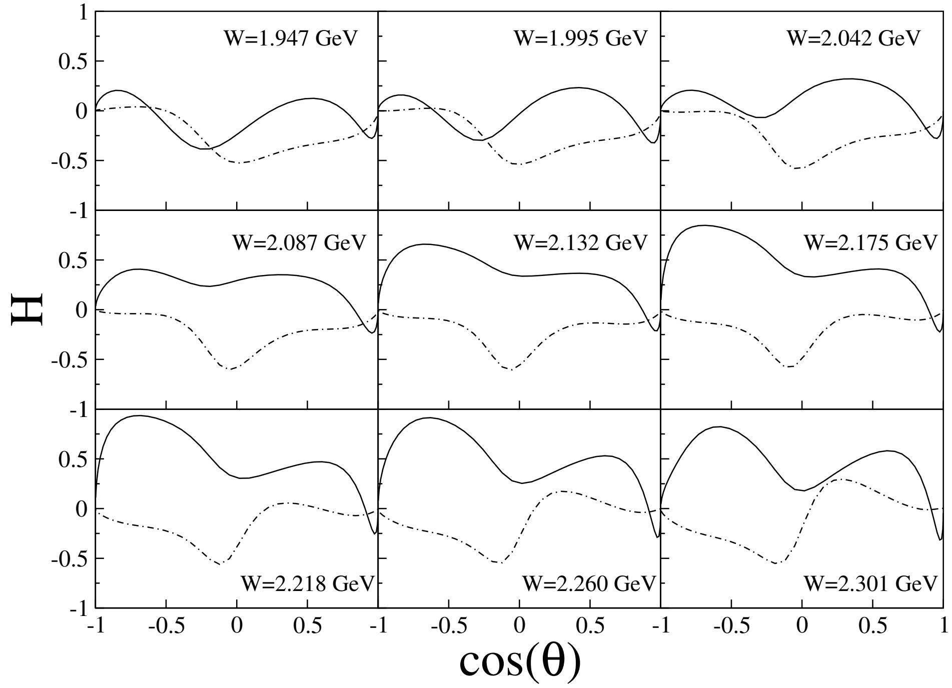
($t : cos^{-1}(\vec{\epsilon}_\gamma \cdot \hat{x}) = \pm 45^0$)



dashed : no N^*

3.Double polarization $H = (\sigma(t,x) - \sigma(t,-x))/(\sigma(t,x) + \sigma(t,-x))$

$(t : cos^{-1}(\vec{\epsilon}_\gamma \cdot \hat{x}) = \pm 45^0)$



dashed : no $N*$

$\longrightarrow$

Need more complete data of single and double polarization of

$\vec{\gamma} + N \rightarrow \pi N, \pi\pi N, \eta N, KY, \omega N$ at $E_\gamma \leq 3$ GeV

$\longrightarrow$

Fix the starting point of analyzing electro-production data for extracting form factors

$F_{\gamma N, N^*}(Q^2)$: quark distributions in baryons

Status of Λ^*, Σ^*, Ξ^* states

2007 PDG :

A number of 1-star and 2-star entries may eventually disappear , but there are certainly many resonances yet to be discovered underlying the established ones.

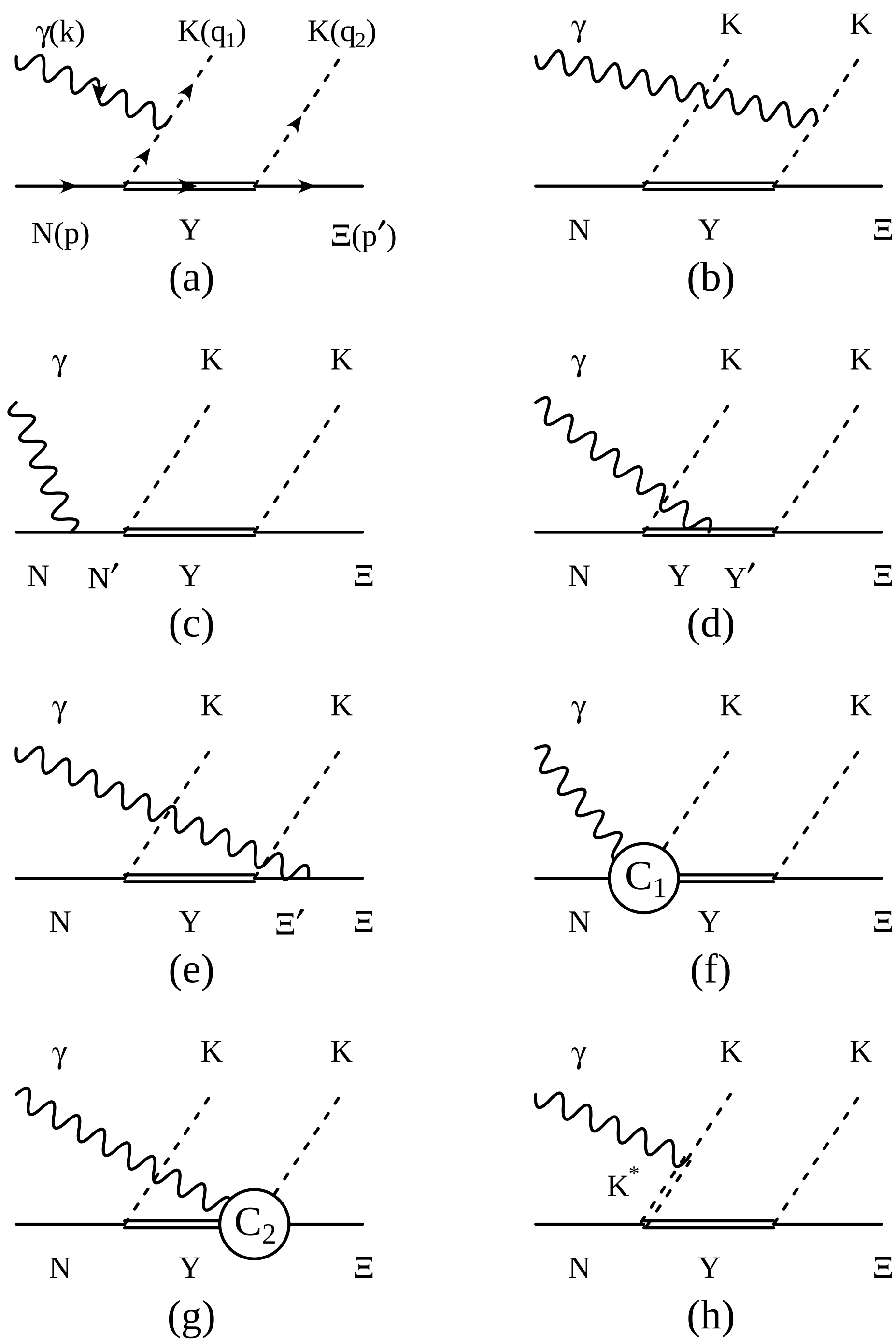
$\longrightarrow$

Need to investigate $KK, K\bar{K}$ production processes

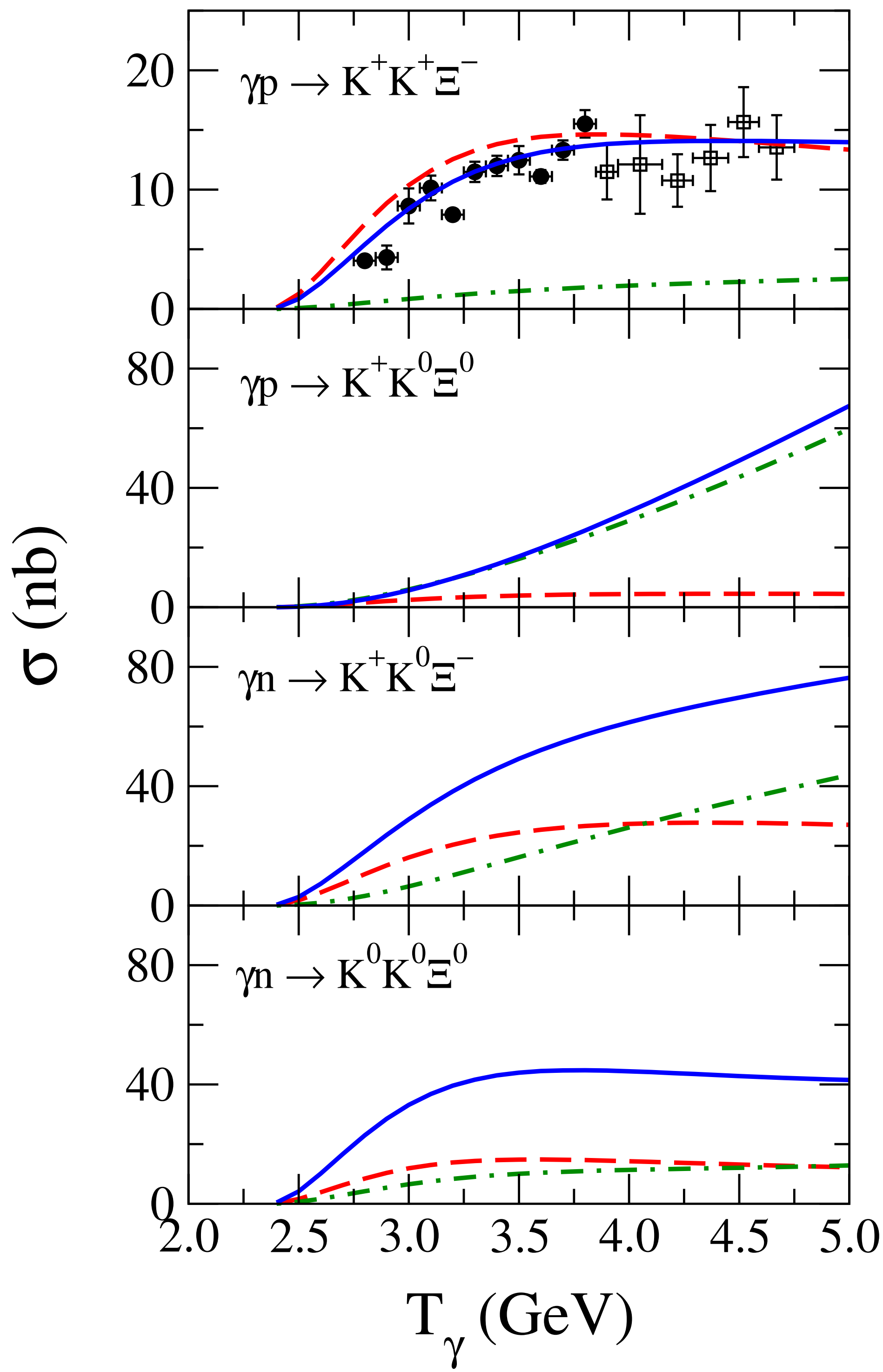
- $\gamma N \to K(\Lambda^*, \Sigma^*) \to K\bar{K}N$
- $\gamma N \to KK\Xi^* \to$ 3-meson or 4-mesons final sates

Example : $\gamma N \longrightarrow KK\Xi$

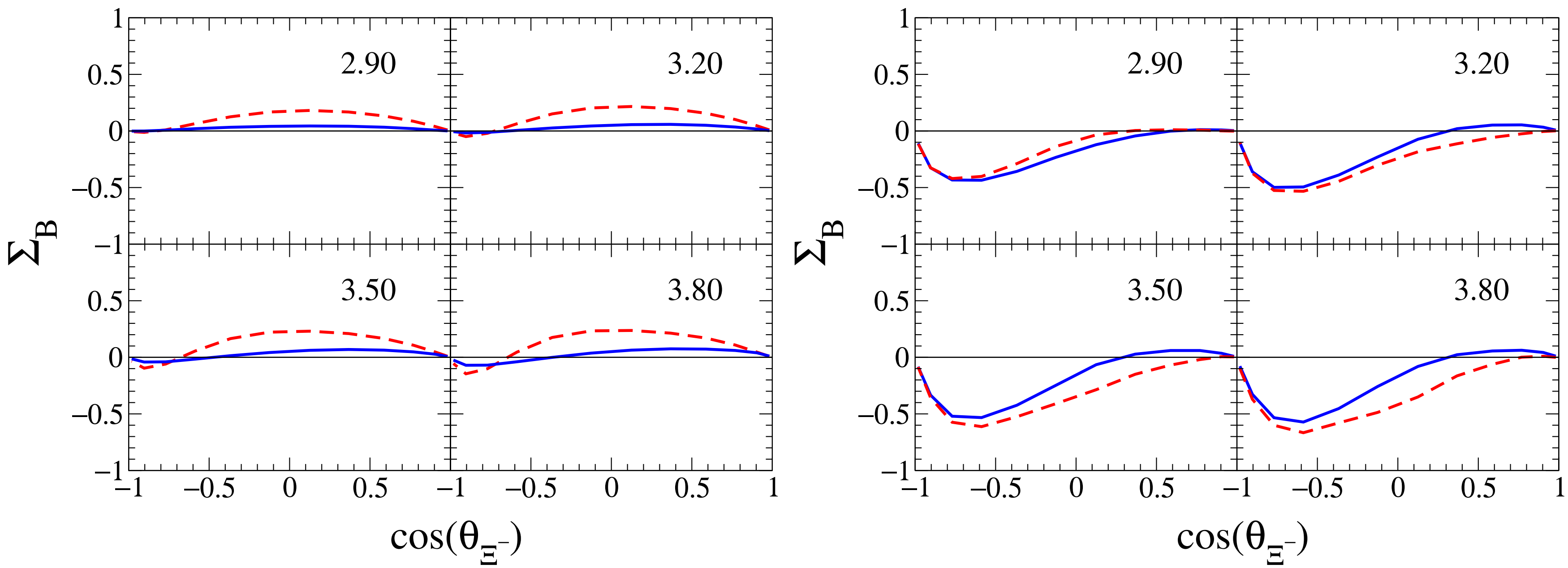
(Y. Oh, K. Nakayama, H. Haberzettl, PRC, 2007)



γ(k)
K(q1)
K(q2)
N(p)
Y
Ξ(p′)
(a)
γ
K
K
N
Y
Ξ
(b)
γ
K
K
N
N′
Y
Ξ
(c)
γ
K
K
N
Y
Y′
Ξ
(d)
γ
K
K
N
Y
Ξ′
Ξ
(e)
γ
K
K
C1
N
Y
Ξ
(f)
γ
K
K
C2
N
Y
Ξ
(g)
γ
K
K
K*
N
Y
Ξ
(h)



γp → K⁺K⁺Ξ⁻
γp → K⁺K⁰Ξ⁰
γn → K⁺K⁰Ξ⁻
γn → K⁰K⁰Ξ⁰
σ (nb)
T_γ (GeV)
0
10
20
40
80
2.0
2.5
3.0
3.5
4.0
4.5
5.0



Right : include $\Lambda(1800)$ and $\Lambda(1890)$

Challenge :

Need to have hadronic reaction data to fix KK, $K\bar{K}$, and KY final state interactions

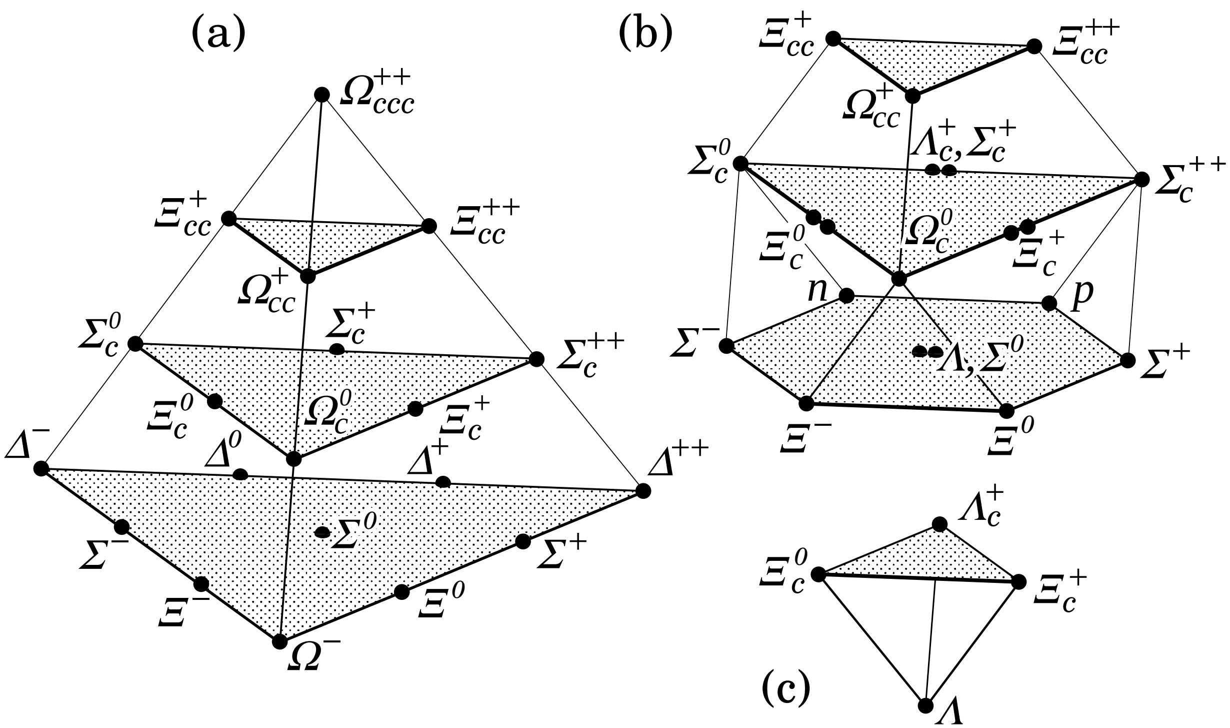
$\longrightarrow$

Possibility : Measurements at JPARC

Status of charmed baryons

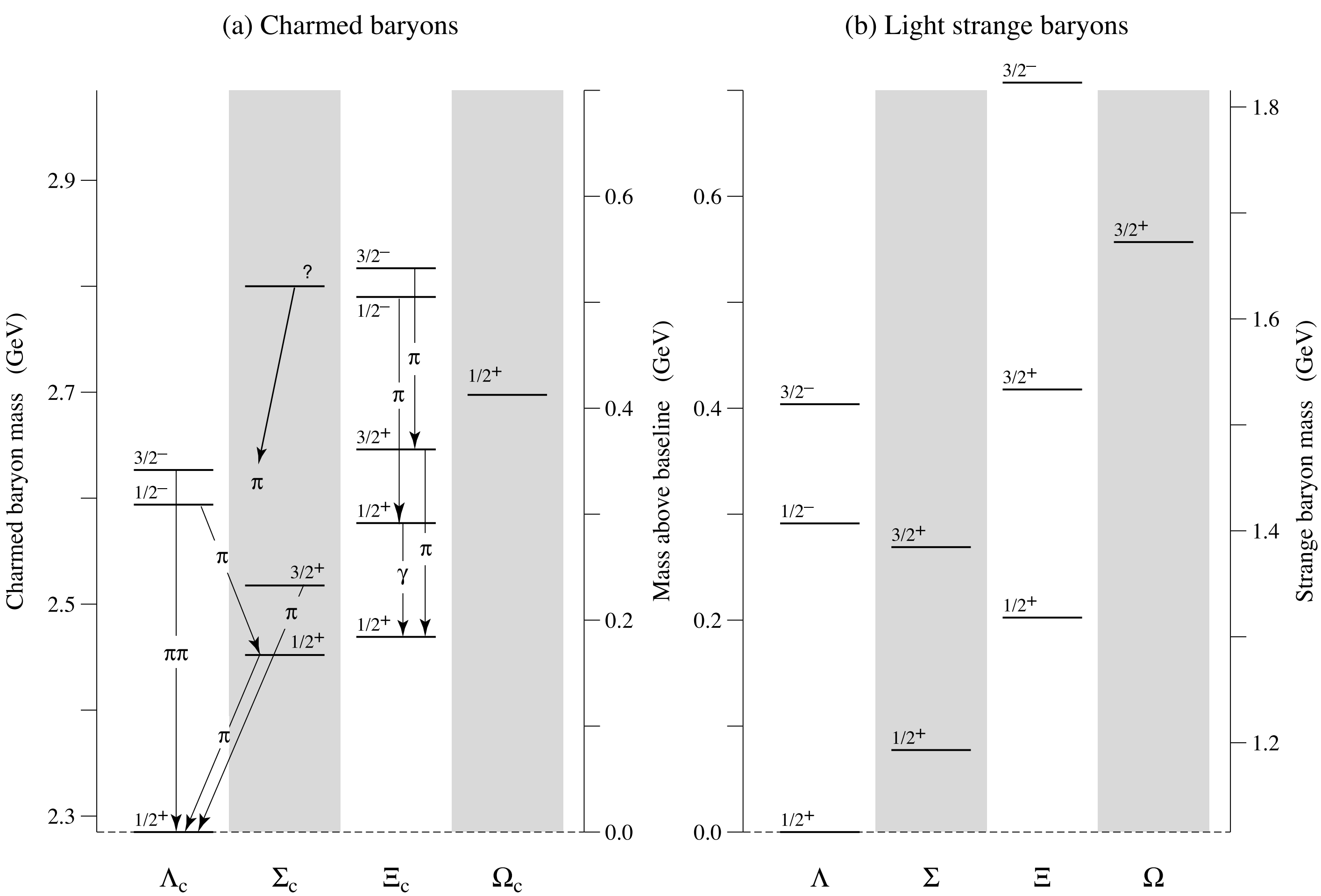
SU(4) predict :

$$4 \times 4 \times 4 = 20 + 20'_1 + 20'_2 + 4$$



2007 PDG :

- 12 charmed baryons are observed
- Their spin-parity quantum numbers are not determined


(a) Charmed baryons
(b) Light strange baryons
Charmed baryon mass (GeV)
Mass above baseline (GeV)
Strange baryon mass (GeV)
2.9
2.7
2.5
2.3
0.6
0.4
0.2
0.0
1.8
1.6
1.4
1.2
3/2−
1/2−
1/2+
3/2+
?
π
ππ
γ
Λc
Σc
Ξc
Ωc
Λ
Σ
Ξ
Ω

How can real photons be used to study charmed baryons ?

Questions :

- Reaction mechanisms ?
- What can be learned ?

Reaction Mechanisms :

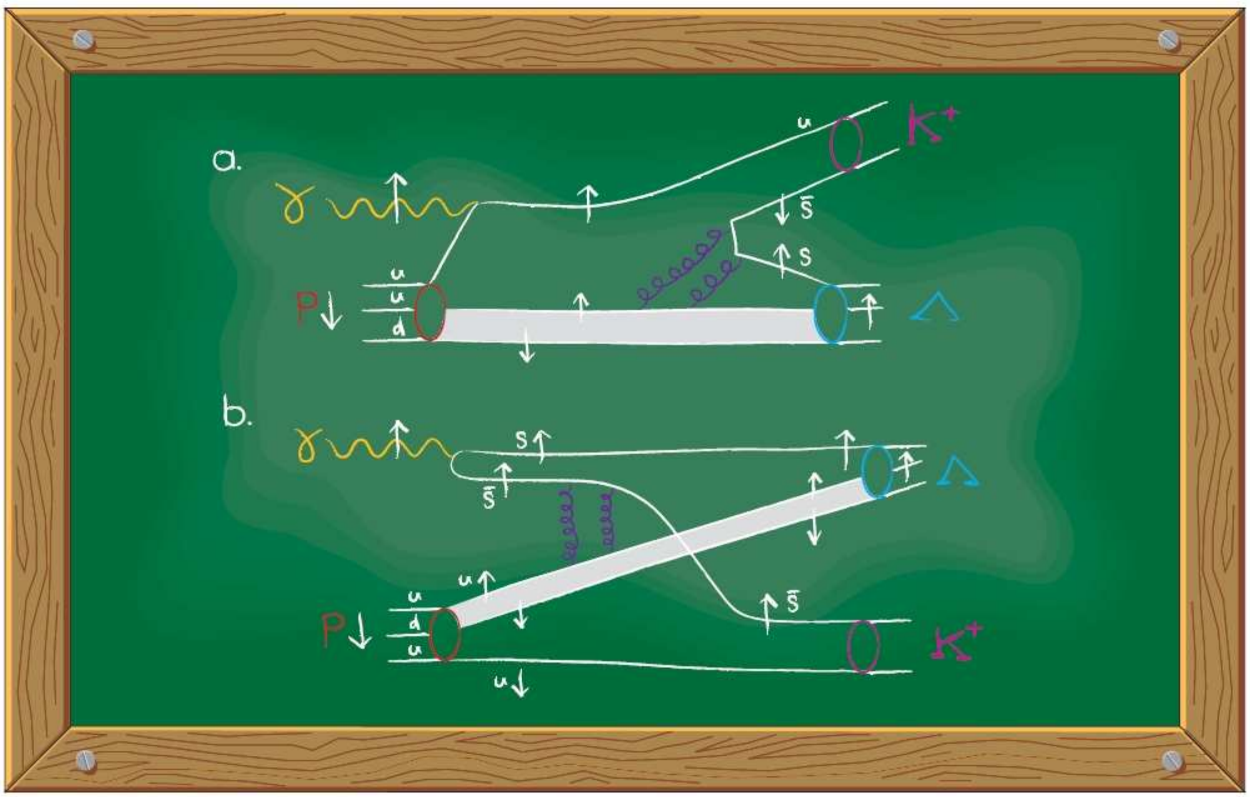
- Within the constituent quark model:

$$\vec{\gamma} p \longrightarrow \bar{D}^0(\bar{c}u)\Lambda_c^+(cud)$$

$$\vec{\gamma} p \longrightarrow K^+(\bar{s}u)\Lambda(sud)$$

$\longrightarrow$

Same quark-gluon mechanisms postulated by CLAS collaboration



a.
γ
P↓
u
u
d
u
s̄
s
K+
Λ
b.
γ
s
s̄
u
d
u
P↓
u
s̄
Λ
K+

$\longrightarrow$

It is necessary to detect D and $\bar{D}$ mesons for identifying charmed baryons

$\longrightarrow$ New opportunities :

Determine the properties of Λ_c, Σ_c, and Ξ_c

- determine their spin-parity
- discover new states
- determine their partial decay widths
- $\cdots\cdot\cdot$

Reachable goals :

- Test quark model predictions :

  T.M. Yan and collaborators, PRD 51, 1199 (1995), 56, 5483 (1997)

  – strong decays $\Lambda_{c1}^{+} \to \Lambda_c^+ \pi^+ \pi^-$ etc.
  $\Gamma(\Sigma_{c1}^{++}(\frac{1}{2}) \to \Lambda_c^+ \pi^+ \pi^0) = 106.4$ MeV
  $\Gamma(\Sigma_{c2}^{++}(\frac{3}{2}, \frac{5}{2}) \to \Lambda_c^+ + \pi^+) = 12.0$ MeV
  . . ..

  – weak radiative decays $\Lambda_c \to \Sigma^+ \gamma$ and $\Xi_c^0 \to \Xi^0 \gamma$ ($c\bar{u} \to sd\gamma$)

- Test predictions from molecular states model

  M. Lutz and J. Hofmann , 2005

  Can predict $\vec{\gamma} N \to D(\bar{D}N), D(\bar{D}\Lambda), D(\bar{D}\Sigma)$ by gauging ($\partial^\mu \to \partial^\mu - ieA^\mu$) their SU(4) Lagrangians based on chiral symmetry and large N_c limit

Outlook

- With the available data, the study of N^* and Δ^* is progressing well
  - Single and double polarization observables of photo-production are essential to coupled-channel analysis.
  - Additional hadronic meson production data are highly desirable

    $\longrightarrow$ Explore possibilities at JPARC

$\longrightarrow$

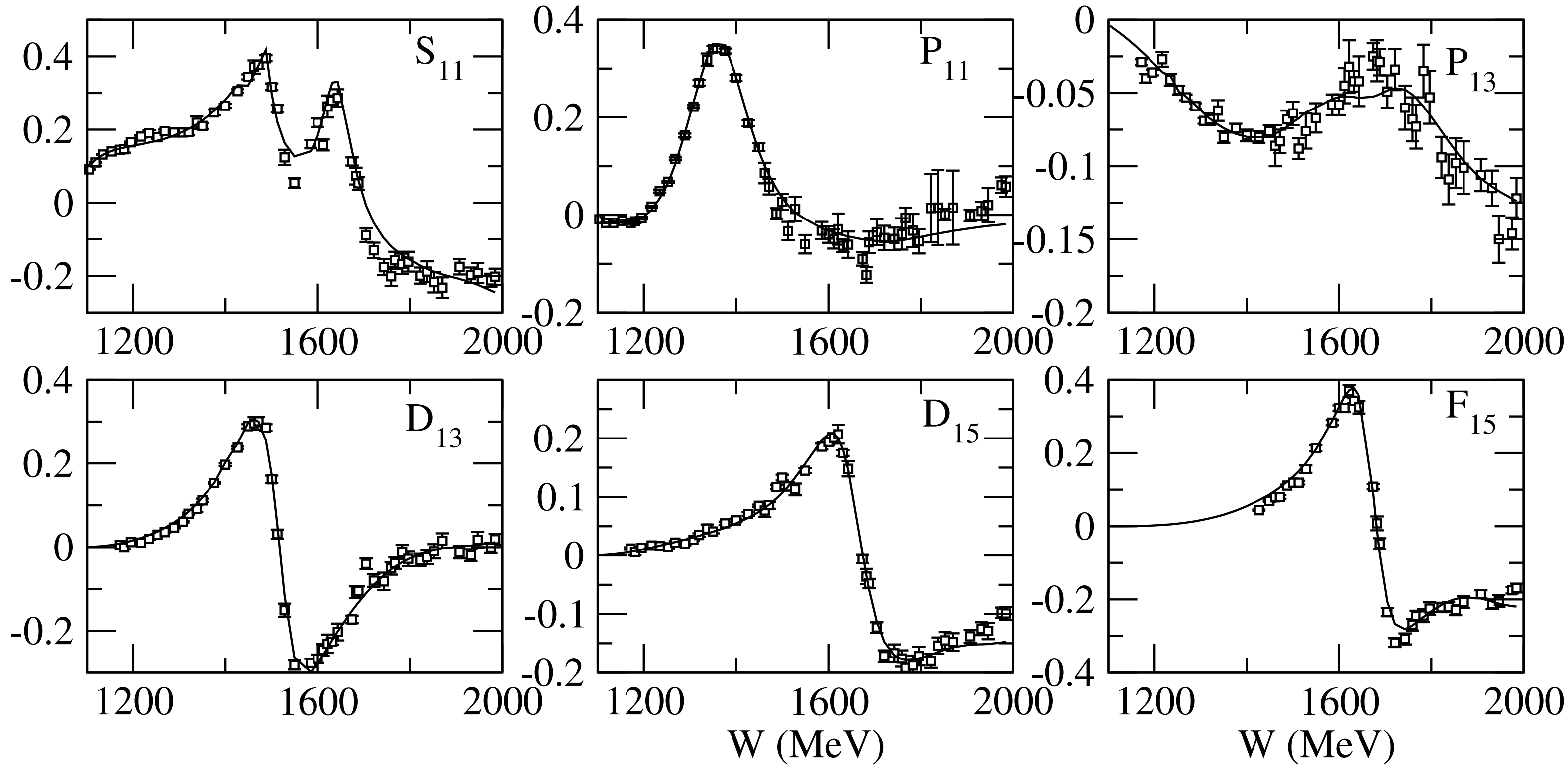
will verify/revise PDG's tables, in particular in the third resonance region

- Data of photo-production of KK and $K\bar{K}$ and $K\pi$ are needed to make significant progress in the study of strange baryons Λ^*, Σ^* and Ξ^*
- The photoproduction of charmed baryons will provide new tool to extend our knowledge of the Baryon Landscape .

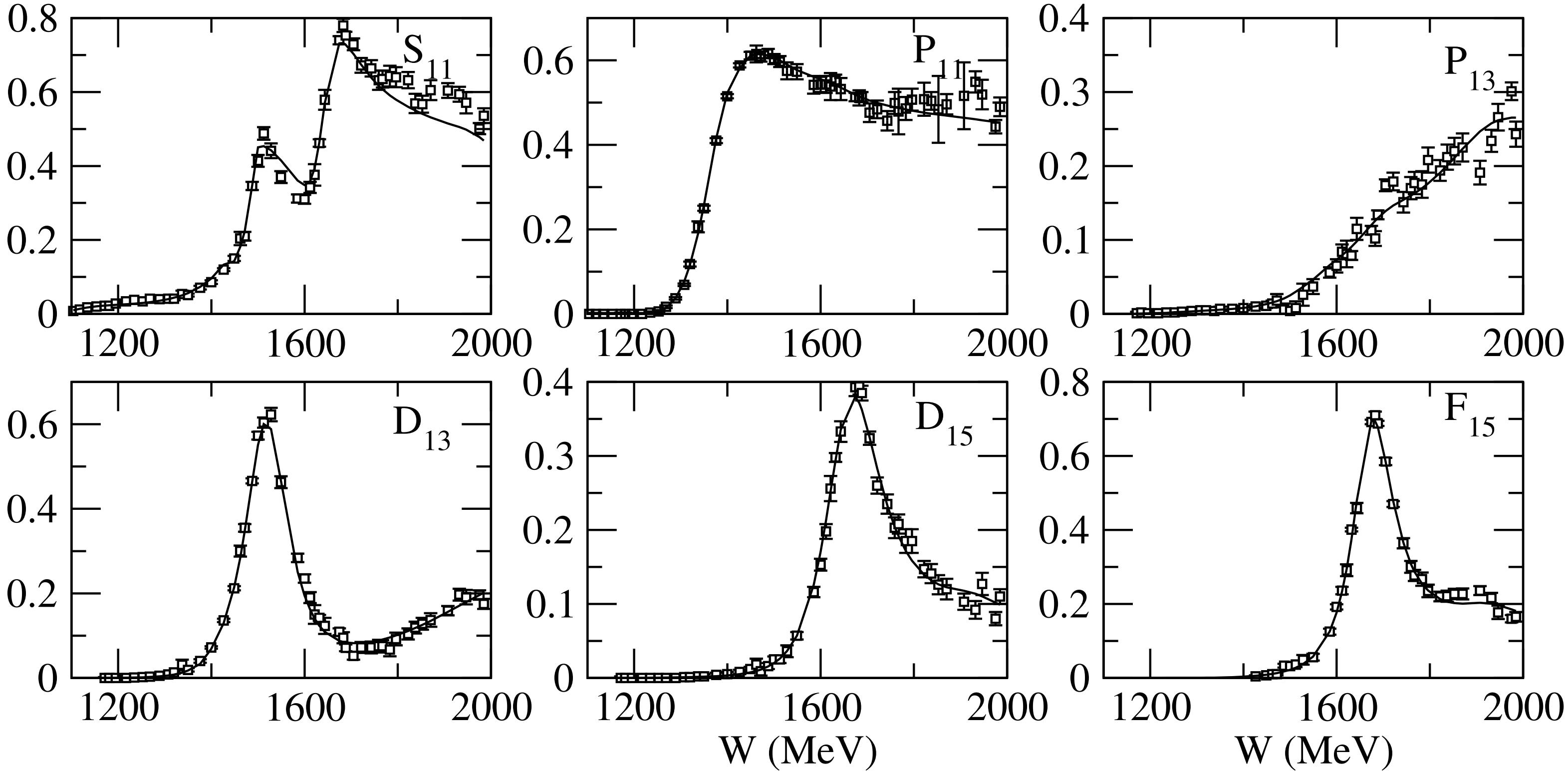
Additional materials

EBAC's fit to πN scattering data

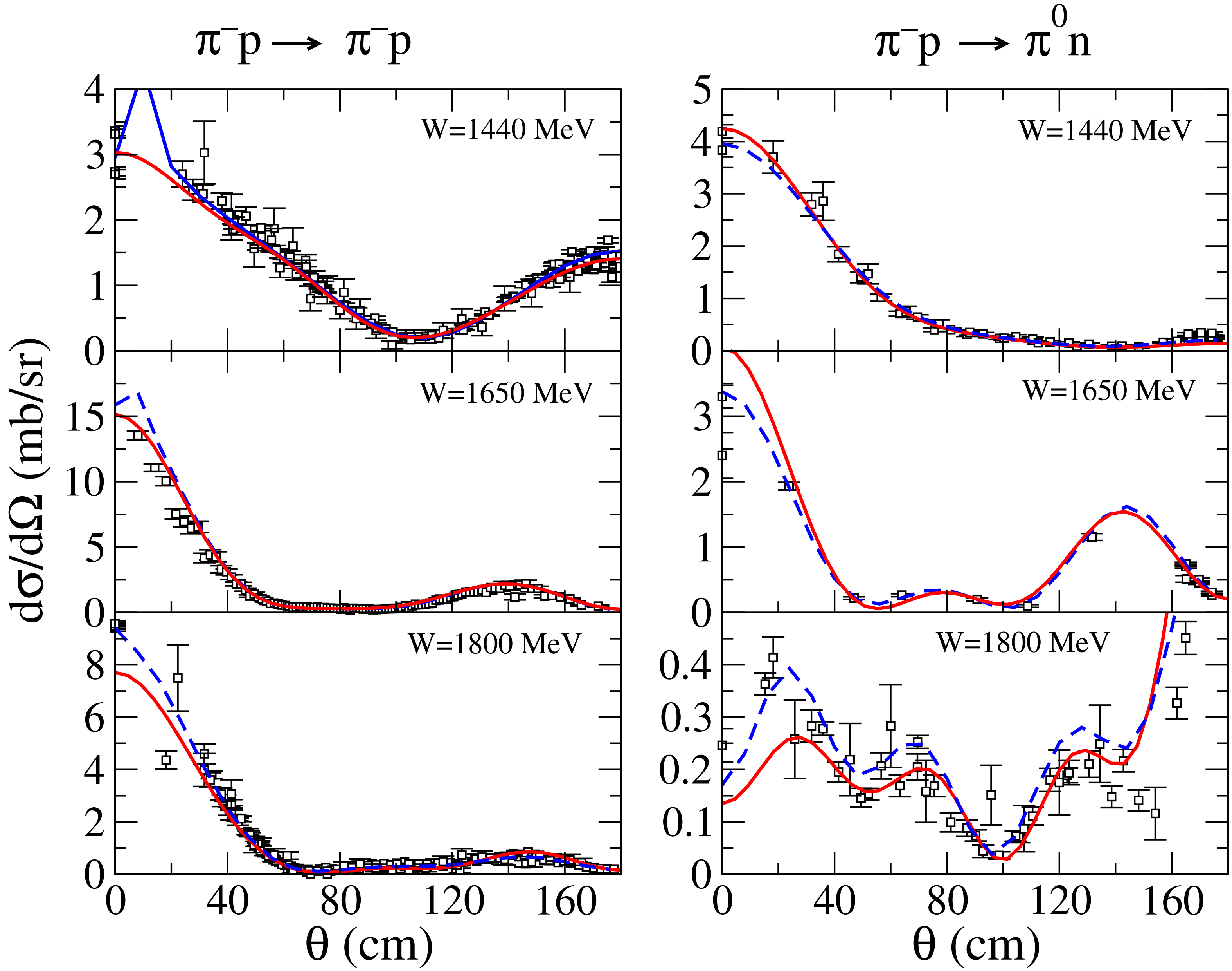
(B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, T. Sato, Phys. Rev. C, 2007)



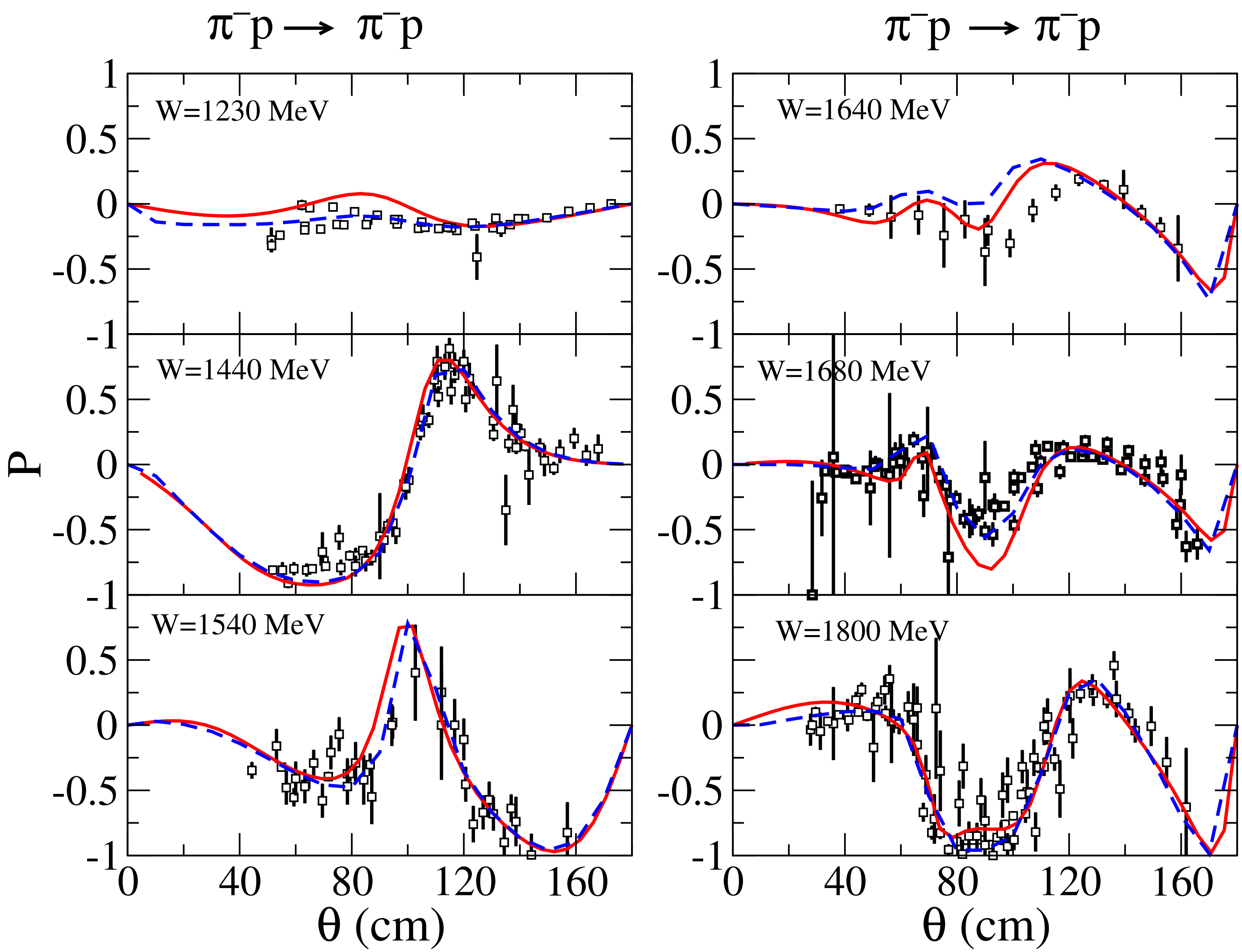
Fit to the $I = \frac{1}{2}\ Re(T_{\pi N, \pi N})$ of SAID



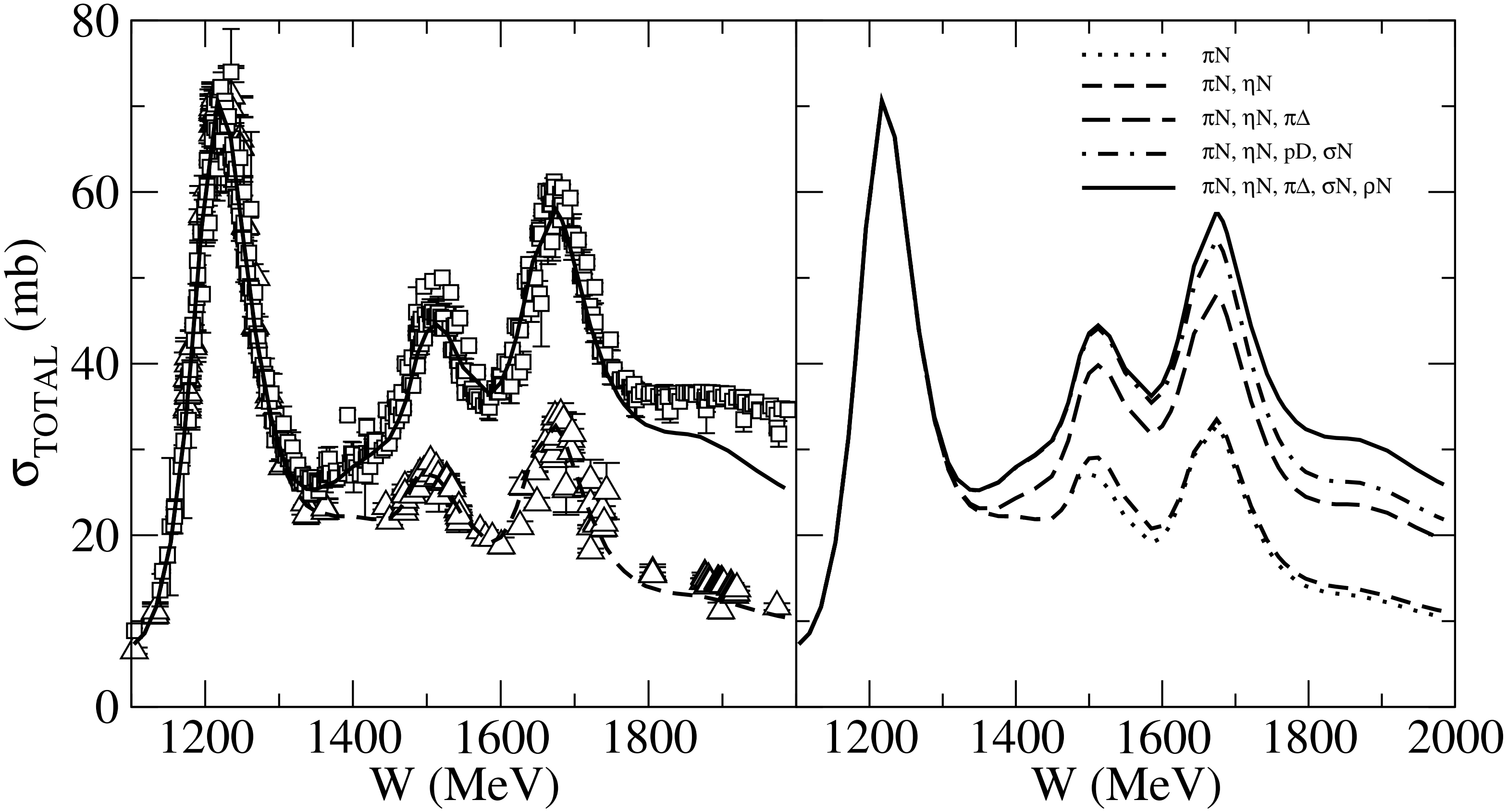
Fit to the $I = \frac{1}{2}\ Im(T_{\pi N, \pi N})$ of SAID



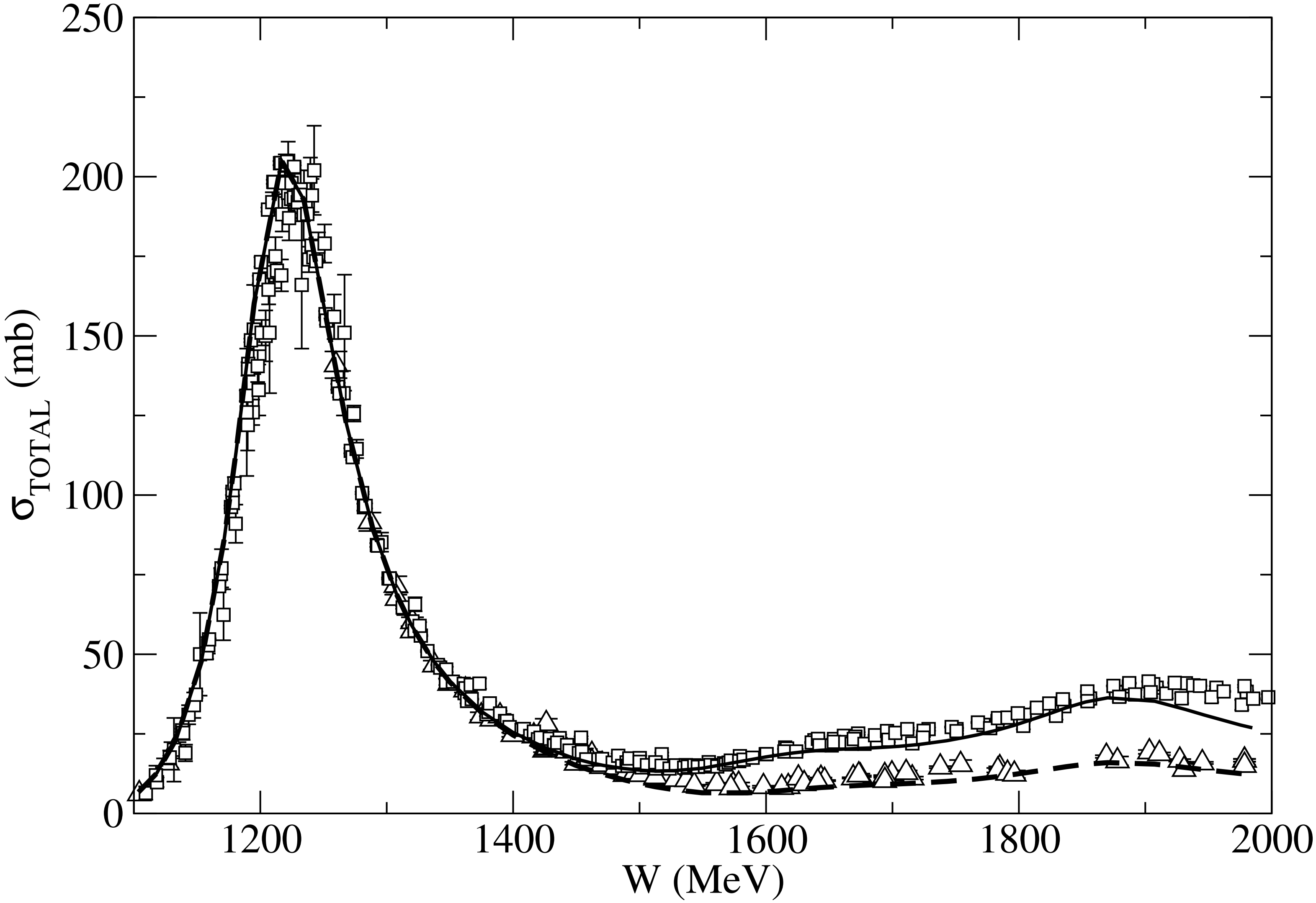
Compare with the differential cross section data of πN scattering



Compare with the target polarization data of πN scattering



Predicted $\pi^- p$ total cross sections



Predicted $\pi^+ p$ total cross sections