中国科学院高能物理研究所
Institute of High Energy Physics, CAS

Chiral quark model for meson production in the resonance region

Qiang Zhao

Institute of High Energy Physics, CAS

and Theoretical Physics Center for Science Facilities (TPCSF), CAS

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Outline

- The “missing baryon resonances” problem
- Effective chiral Lagrangian for quark-pseudoscalar-meson interaction
- Baryon resonances in pseudoscalar meson photoproduction and meson-nucleon scatterings
- Prospects

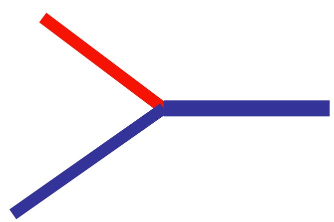
1. “Missing baryon resonances in πN scattering

- The non-relativistic constituent quark model (NRCQM) makes great success in the description of hadron spectroscopy:

  meson ($q\bar{q}$), baryon (qqq).

- However, it also predicted a much richer baryon spectrum, where some of those have not been seen in πN scatterings.

  – “Missing Resonances”.



$P_{33}(1232)$ Δ
$P_{11}(1440)$
$S_{11}(1535)$
$D_{13}(1520)$
…

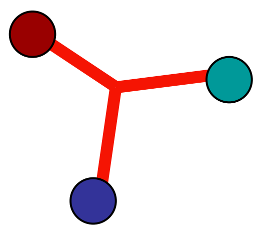
PDG2008: 22 nucleon resonances (uud, udd)

Particle	$L_{2I \cdot 2J}$	Overall status	Status as seen in — $N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						

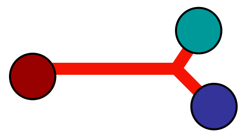
(**) not well-established

Dilemma:

a) The NRCQM is WRONG:



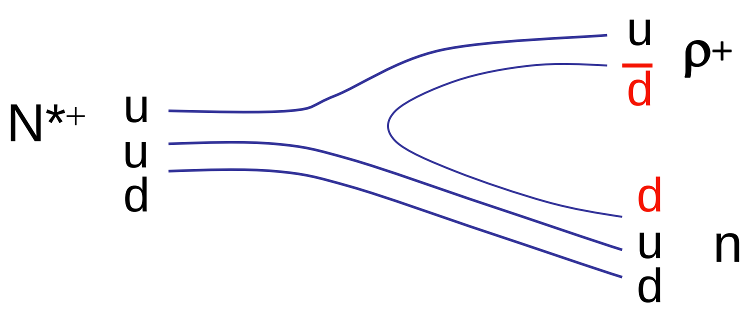
quark-diquark configuration? …



b) The NRCQM is CORRECT, but those missing states have only weak couplings to πN, i.e. small $g_{\pi N^* N}$. (Isgur, 1980)

Looking for "missing resonances" in $N^* \rightarrow \eta N$, $K\Sigma$, $K\Lambda$, ρN, ωN, ϕN, γN …

(Exotics …)



Questions:

Should we take the naïve quark model seriously?

How far one can go with it?

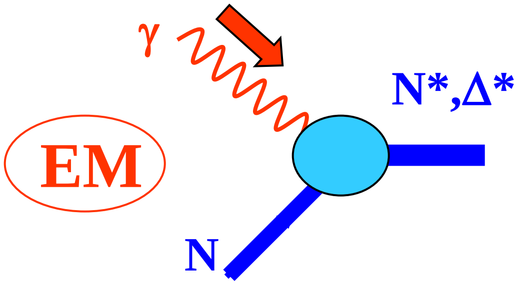
What is the success and what is the failure?

… …

❑ The first orbital excitation states in the NRCQM

Existing features with the first orbital excitation states:

i) In the light quark sector, the NRCQM allows the groundstate [56, ^{2}8] (*p* and *n*) to be excited to [70, ^{2}8] and [70, ^{4}8] octets, and [70, ^{2}10] decuplet via single photon absorption.



$|\mathbf{70},\ {}^2\mathbf{8},\ 1,1,J\rangle$ • $S_{11}(1535)$ (****), $D_{13}(1520)$ (****)

$|\mathbf{70},\ {}^4\mathbf{8},\ 1,1,J\rangle$ • $S_{11}(1650)$ (****), $D_{13}(1700)$ (***), $\boxed{D_{15}(1675)\ (****)}$

$|\mathbf{70},\ {}^2\mathbf{10},\ 1,1,J\rangle$ • $S_{31}(1620)$ (****), $D_{33}(1670)$ (****)

$\boxed{|\mathbf{70},\ {}^2\mathbf{1},\ 1,1,J\rangle \quad \bullet\ \Lambda(1405)\ S_{01}\ (****),\ \Lambda(1520)\ D_{03}\ (***)}$

The SU(6)⊗O(3) symmetry must be broken due to spin-dependent forces. Thus, state mixings are inevitable.

Several NRCQM selection rules are violated:

- **Moorhouse selection rule** (Moorhouse, PRL16, 771 (1966))

$$\gamma + p(|\mathbf{56}, {}^2\mathbf{8}; 0, 0, 1/2\rangle) \not\leftrightarrow \quad N^*(|\mathbf{70}, {}^4\mathbf{8}\rangle)$$

$$\gamma + n(|\mathbf{56}, {}^2\mathbf{8}; 0, 0, 1/2\rangle) \leftrightarrow N^*(|\mathbf{70}, {}^4\mathbf{8}\rangle)$$

- **Λ selection rule** (Zhao & Close, PRD74, 094014(2006)) in strong decays

$$N^*(|\mathbf{70}, {}^4\mathbf{8}\rangle) \not\leftrightarrow \quad K(K^*) + \Lambda$$

- **Faiman-Hendry selection rule** (Faiman & Hendry, PR173, 1720 (1968)).

$$\Lambda^*(|\mathbf{70}, {}^4\mathbf{8}\rangle) \not\leftrightarrow \quad N(|\mathbf{56}, {}^2\mathbf{8}; 0, 0, 1/2\rangle) + \bar{K}$$

2. Effective chiral Lagrangian for quark-pseudoscalar meson interactions

For pion photoproduction, the low energy theorem (LET) provides a crucial test near threshold. In order to recover the LET, one has to rely on the low energy QCD Lagrangian which keeps the meson-baryon interaction invariant under the chiral transformation. Combining the low energy QCD Lagrangian with the quark model, we introduce the quark-meson interaction through the effective Lagrangian:

$$\mathcal{L} = \overline{\psi}[\gamma_\mu(i\partial^\mu + V^\mu + \gamma_5 A^\mu) - m]\psi + \cdots,$$

where the vector and axial currents are

$$\begin{aligned} V_\mu &= \frac{1}{2}(\xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger), \\ A_\mu &= i\frac{1}{2}(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger), \end{aligned}$$

A. Manohar and H. Georgi, Nucl. Phys. **B234**, 189 (1984).

and the chiral transformation is,

$$\xi = e^{i\phi_m/f_m}, \tag{77}$$

where f_m is the decay constant of the meson. The quark field ψ in the SU(3) symmetry is

$$\psi = \begin{pmatrix} \psi(u) \\ \psi(d) \\ \psi(s) \end{pmatrix}, \tag{78}$$

and the meson field ϕ_m is a $3\otimes 3$ matrix:

$$\phi_m = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \overline{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}, \tag{79}$$

where the pseudoscalar mesons π, η and K are treated as Goldstone bosons. Thus, the Lagrangian in Eq. (121) is invariant under the chiral transformation. Expanding the nonlinear field ξ in Eq. (77) in terms of the Goldstone boson field ϕ_m, i.e. $\xi = 1 + i\phi_m/f_m + \cdots$, we obtain the standard quark-meson pseudovector coupling at tree level:

$$H_m = \sum_j \frac{1}{f_m}\overline{\psi}_j \gamma_\mu^j \gamma_5^j \psi_j \partial^\mu \phi_m \ , \tag{80}$$

where ψ_j ($\overline{\psi}_j$) represents the jth quark (anti-quark) field in the nucleon.

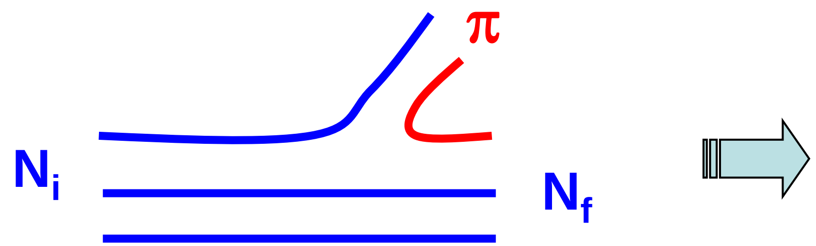
Test of Goldberger-Treiman relation:

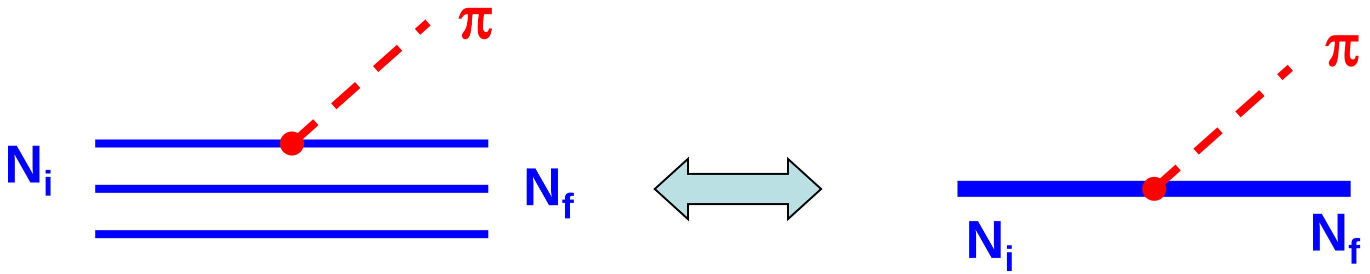
Note that, g_A, the axial vector coupling, relates the hadronic operator $\boldsymbol{\sigma}$ to the quark operator $\boldsymbol{\sigma}_j$ for the j-th quark, and is defined by

$$\langle N_f | \sum_j \hat{I}_j \boldsymbol{\sigma}_j | N_i \rangle \equiv g_A \langle N_f | \boldsymbol{\sigma} | N_i \rangle .$$

To equate the quark-level coupling to the hadronic level one for the πNN vertex, i.e. axial current conservation, one has

$$\boxed{g_{\pi NN} = \frac{g_A M_N}{f_\pi}}$$





❑ Baryon excitations in pi *p* → eta *n*

The process $\pi^- p \to \eta n$ can be expressed in term of the Mandelstam variables:

$$\mathcal{M} = \mathcal{M}_s + \mathcal{M}_u + \mathcal{M}_t.$$

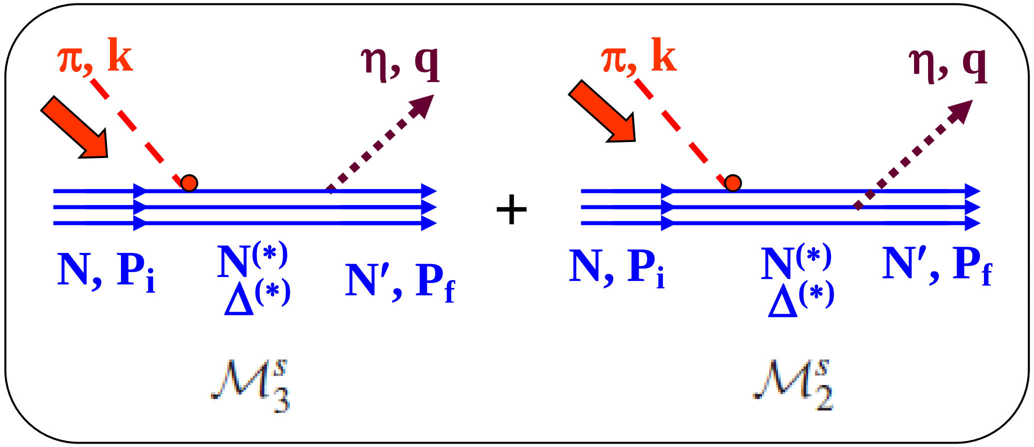
The s- and u-channel transitions are given by

$$\mathcal{M}_s = \sum_j \langle N_f | H_\eta | N_j \rangle \langle N_j | \frac{1}{E_i + \omega_\pi - E_j} H_\pi | N_i \rangle$$

$$\mathcal{M}_u = \sum_j \langle N_f | H_\pi \frac{1}{E_i - \omega_\eta - E_j} | N_j \rangle \langle N_j | H_\eta | N_i \rangle.$$

Zhong, Zhao, He, and Saghai, PRC76, 065205 (2007);
Zhong and Zhao, Phys. Rev. C 79, 045202 (2009)

s-channel

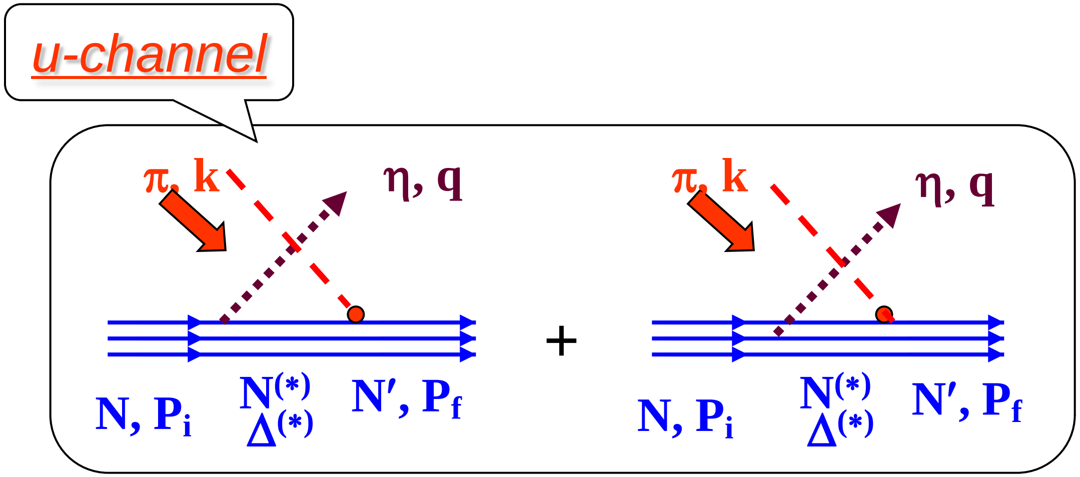


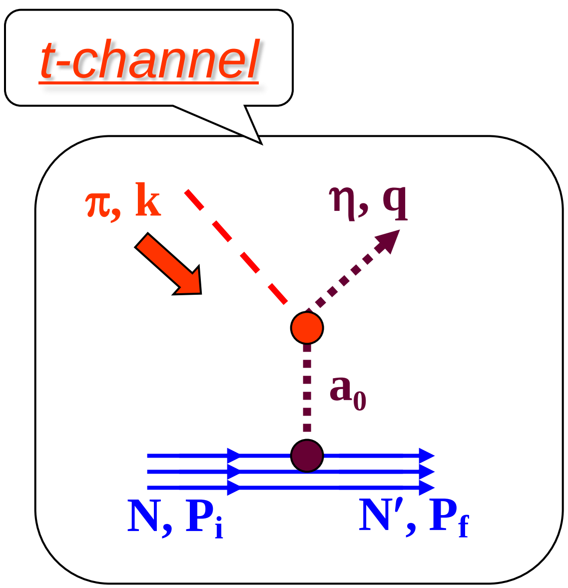
$$\mathcal{M}_s = \sum_j \langle N_f | H_\eta | N_j \rangle \langle N_j | \sum_n \frac{1}{\omega_\pi^{n+1}} (\hat{H} - E_i)^n H_\pi | N_i \rangle$$

for any operator $\mathcal{O}$, one has

$$(\hat{H} - E_i)\mathcal{O}|N_i\rangle = [\hat{H}, \mathcal{O}]|N_i\rangle$$

Refs.
Zhao, Li, & Bennhold, PLB436, 42(1998); PRC58, 2393(1998);
Zhao, Didelez, Guidal, & Saghai, NPA660, 323(1999);
Zhao, PRC63, 025203(2001);
Zhao, Saghai, Al-Khalili, PLB509, 231(2001);
Zhao, Al-Khalili, & Bennhold, PRC64, 052201(R)(2001); PRC65, 032201(R) (2002);





$$\left\{ \begin{array}{l} \mathcal{L}_{a_0\pi\eta} = g_{a_0\pi\eta} m_\pi \eta \vec{\pi}\vec{a}_0 \\[2ex] H_{a_0} = \sum_j g_{a_0 qq} m_\pi \bar{\psi}_j \psi_j \vec{a}_0 \end{array}\right.$$

$$\mathcal{M}_t = g_{a_0\pi\eta} m_\pi \langle N_f | H_{a_0} | N_i \rangle \frac{1}{t^2 - m_{a_0}^2}$$

◆ S-channel transition amplitude with quark level operators

Non-relativistic expansion:

$$H_\pi = \sum_j \frac{I_j}{g_A^\pi} \boldsymbol{\sigma}_j \cdot \left[\mathbf{A}_\pi e^{i\mathbf{k}\cdot\mathbf{r}_j} + \frac{\omega_\pi}{2m_q} \{ \mathbf{p}_j, e^{i\mathbf{k}\cdot\mathbf{r}_j} \} \right],$$

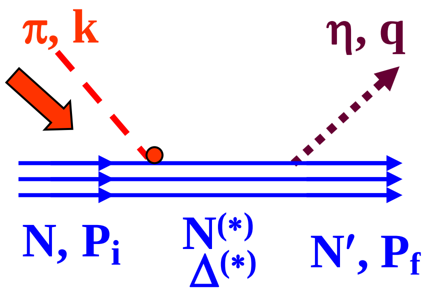
$$H_\eta = \sum_j \frac{I_j}{g_A^\eta} \boldsymbol{\sigma}_j \cdot \left[\mathbf{A}_\eta e^{-i\mathbf{q}\cdot\mathbf{r}_j} + \frac{\omega_\eta}{2m_q} \{ \mathbf{p}_j, e^{-i\mathbf{q}\cdot\mathbf{r}_j} \} \right],$$

with

$$\mathbf{A}_\pi = -\left(\frac{\omega_\pi}{E_i + M_i} + 1 \right) \mathbf{k},$$

$$\mathbf{A}_\eta = -\left(\frac{\omega_\eta}{E_f + M_f} + 1 \right) \mathbf{q}.$$

$$\mathcal{M}^s = \sum_n (\mathcal{M}_3^s + \mathcal{M}_2^s) e^{-(\mathbf{k}^2+\mathbf{q}^2)/6\alpha^2}$$



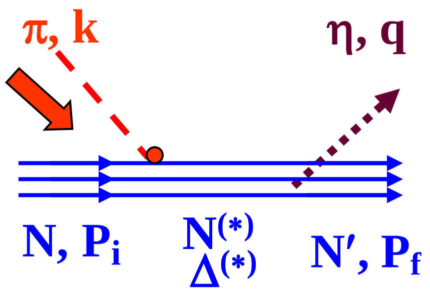
$\mathcal{M}_3^s$

with

$$\mathcal{M}_3^s = \langle N_f | \frac{3I_3}{g_A^\pi} \Bigg\{ \boldsymbol{\sigma}_3 \cdot \mathbf{A}_\eta \boldsymbol{\sigma}_3 \cdot \mathbf{A}_\pi \sum_{n=0} \frac{F_s(n)}{n!} \mathcal{X}^n + \Bigg[-\boldsymbol{\sigma}_3 \cdot \mathbf{A}_\eta \frac{\omega_\pi}{3m_q} \boldsymbol{\sigma}_3 \cdot \mathbf{q} - \frac{\omega_\eta}{3m_q} \boldsymbol{\sigma}_3 \cdot \mathbf{k} \boldsymbol{\sigma}_3 \cdot \mathbf{A}_\pi + \frac{\omega_\eta}{m_q} \frac{\omega_\pi}{m_q} \frac{\alpha^2}{3} \Bigg] \sum_{n=1} \frac{F_s(n)}{(n-1)!} \mathcal{X}^{n-1} + \frac{\omega_\eta}{3m_q} \frac{\omega_\pi}{3m_q} \boldsymbol{\sigma}_3 \cdot \mathbf{q} \boldsymbol{\sigma}_3 \cdot \mathbf{k} \sum_{n=2} \frac{F_s(n)}{(n-2)!} \mathcal{X}^{n-2} \Bigg\} | N_i \rangle$$

where $\mathcal{X} \equiv \mathbf{k} \cdot \mathbf{q} / 3\alpha^2$.

$$\mathcal{M}^s = \sum_n (\mathcal{M}_3^s + \mathcal{M}_2^s) e^{-(\mathbf{k}^2+\mathbf{q}^2)/6\alpha^2}$$



$\mathcal{M}_2^s$

with

$$\mathcal{M}_3^s = \langle N_f | \frac{3I_3}{g_A^\pi} \left\{ \boldsymbol{\sigma}_3 \cdot \mathbf{A}_\eta \boldsymbol{\sigma}_3 \cdot \mathbf{A}_\pi \sum_{n=0} \frac{F_s(n)}{n!} \mathcal{X}^n \right.$$

$$\mathcal{M}_2^s = \langle N_f | \frac{6I_1}{g_A^\pi} \left\{ \boldsymbol{\sigma}_1 \cdot \mathbf{A}_\eta \boldsymbol{\sigma}_3 \cdot \mathbf{A}_\pi \sum_{n=0} \frac{F_s(n)}{n!} \frac{\mathcal{X}^n}{(-2)^n} \right.$$
$$+ \left[-\boldsymbol{\sigma}_1 \cdot \mathbf{A}_\eta \frac{\omega_\pi}{3m_q} \boldsymbol{\sigma}_3 \cdot \mathbf{q} - \frac{\omega_\eta}{3m_q} \boldsymbol{\sigma}_1 \cdot \mathbf{k} \boldsymbol{\sigma}_3 \cdot \mathbf{A}_\pi \right.$$
$$\left. + \frac{\omega_\eta}{m_q} \frac{\omega_\pi}{m_q} \frac{\alpha^2}{3} \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_3 \right] \sum_{n=1} \frac{F_s(n)}{(n-1)!} \frac{\mathcal{X}^{n-1}}{(-2)^n}$$
$$\left. + \frac{\omega_\eta}{3m_q} \frac{\omega_\pi}{3m_q} \boldsymbol{\sigma}_1 \cdot \mathbf{q} \boldsymbol{\sigma}_3 \cdot \mathbf{k} \sum_{n=2} \frac{F_s(n)}{(n-2)!} \frac{\mathcal{X}^{n-2}}{(-2)^n} \right\} |N_i\rangle$$

where .

◆ quark level → hadron level

$$\mathcal{M}^s = \frac{1}{g_A^\pi}\Bigg\{\mathbf{A}_\eta \cdot \mathbf{A}_\pi \sum_{n=0} [g_{s1} + (-2)^{-n} g_{s2}] \frac{F_s(n)}{n!} \mathcal{X}^n$$

$$+ \left(-\frac{\omega_\pi}{3m_q}\mathbf{A}_\eta \cdot \mathbf{q} - \frac{\omega_\eta}{3m_q}\mathbf{A}_\pi \cdot \mathbf{k} + \frac{\omega_\eta}{m_q}\frac{\omega_\pi}{m_q}\frac{\alpha^2}{3}\right)$$

$$\times \sum_{n=1} [g_{s1} + (-2)^{-n} g_{s2}] \frac{F_s(n)}{(n-1)!} \mathcal{X}^{n-1}$$

$$+ \frac{\omega_\eta \omega_\pi}{(3m_q)^2}\mathbf{k} \cdot \mathbf{q} \sum_{n=2} \frac{F_s(n)}{(n-2)!}[g_{s1} + (-2$$

$$F_s(n) = \frac{M_n}{P_i \cdot k - n M_n \omega_h}$$

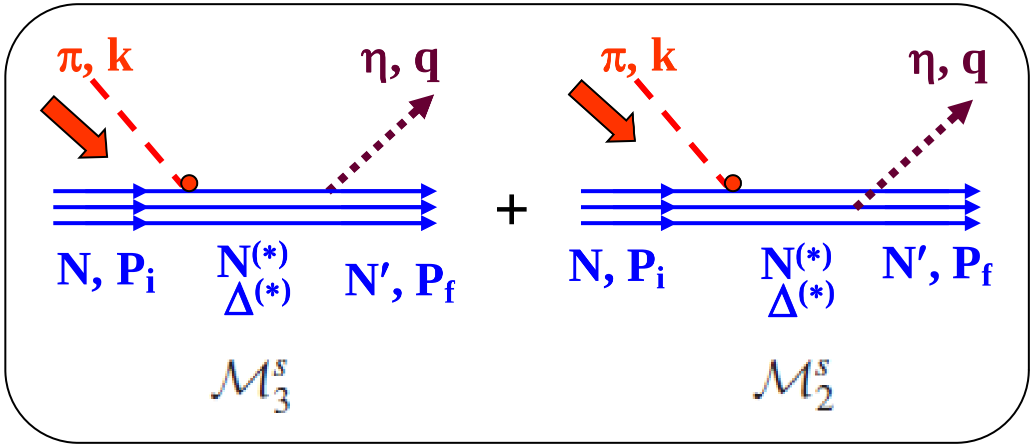
$$+ i\boldsymbol{\sigma} \cdot (\mathbf{A}_\eta \times \mathbf{A}_\pi) \sum_{n=0} [g_{v1} + (-2)^{-n} g_{v2}] \frac{F_s(n)}{\cdot} \mathcal{X}^n$$

$$\to F_s(R) = \frac{2M_R}{s - M_R^2 + i M_R \Gamma_R}$$

$$+ \frac{\omega_\eta \omega_\pi}{(3m_q)^2} i\boldsymbol{\sigma} \cdot (\mathbf{q} \times \mathbf{k})$$

$$\times \sum_{n=2} [g_{v1} + (-2)^{-n} g_{v2}] \frac{F_s(n)}{(n-2)!} \mathcal{X}^{n-2}\Bigg\} e^{-(\mathbf{k}^2+\mathbf{q}^2)/6\alpha^2}$$

s-channel



- **Compared with M^s_3, amplitude M^s_2 is relatively suppressed by a factor of $(-1/2)^n$ for each n.**
- **Higher excited states are relatively suppressed by $(k\cdot q/3\alpha^2)^n/n!$**
- **One can identify the quark motion correlations between the initial and final state baryon**
- **Similar treatment can be done for the u channel**

◆ Separate out individual resonances

A. $n = 0$ shell resonances

For $n = 0$, only the nucleon pole term contributes to the transition amplitude. Its s-channel amplitude is

$$\mathcal{M}_N^s = \mathcal{O}_N \frac{2M_0}{s - M_0^2} e^{-(\mathbf{k}^2+\mathbf{q}^2)/6\alpha^2},$$

with

$$\mathcal{O}_N = [g_{s1} + g_{s2}]\, \mathbf{A}_\eta \cdot \mathbf{A}_\pi + [g_{v1} + g_{v2}]\, i\boldsymbol{\sigma} \cdot (\mathbf{A}_\eta \times \mathbf{A}_\pi),$$

where M_0 is the nucleon mass.

B. $n = 1$ shell resonances

For $n = 1$, only S and D waves contribute in the s channel. Note that the spin-independent amplitude for D waves is proportional to the Legendre function $P_2^0(\cos\theta)$ and the spin-dependent amplitude for D waves is in proportion to $\frac{\partial}{\partial\theta}P_2^0(\cos\theta)$. Moreover, the S-wave amplitude is independent of the scattering angle.

$$\mathcal{M}^s(S) = \mathcal{O}_S F_s(R) e^{-(\mathbf{k}^2+\mathbf{q}^2)/6\alpha^2},$$

$$\mathcal{M}^s(D) = \mathcal{O}_D F_s(R) e^{-(\mathbf{k}^2+\mathbf{q}^2)/6\alpha^2},$$

with

$$\mathcal{O}_S = \left(g_{s1} - \frac{1}{2}g_{s2}\right)\left(|\mathbf{A}_\eta||\mathbf{A}_\pi|\frac{|\mathbf{k}||\mathbf{q}|}{9\alpha^2} - \frac{\omega_\pi}{3m_q}\mathbf{A}'_\eta \cdot \mathbf{q} - \frac{\omega_\eta}{3m_q}\mathbf{A}_\pi \cdot \mathbf{k} + \frac{\omega_\eta}{m_q}\frac{\omega_\pi}{m_q}\frac{\alpha^2}{3}\right),$$

$$\mathcal{O}_D = \left(g_{s1} - \frac{1}{2}g_{s2}\right)|\mathbf{A}_\eta||\mathbf{A}_\pi|(3\cos^2\theta - 1)\frac{|\mathbf{k}||\mathbf{q}|}{9\alpha^2} + \left(g_{v1} - \frac{1}{2}g_{v2}\right) i\boldsymbol{\sigma} \cdot (\mathbf{A}_\eta \times \mathbf{A}_\pi)\frac{\mathbf{k}\cdot\mathbf{q}}{3\alpha^2}.$$

$$\mathcal{M}^s(S) = [g_{S_{11}(1535)} + g_{S_{11}(1650)}]\mathcal{M}^s(S),$$
$$\mathcal{M}^s(D) = [g_{D_{13}(1520)} + g_{D_{13}(1700)} + g_{D_{15}(1675)}]\mathcal{M}^s(D).$$

In the SU(6) symmetry limit,

Factor	Value	Factor	Value	Factor	Value
g_{s1}	1	$\boxed{g_{S_{11}(1535)}}$	$\boxed{2}$	g_2	5/3
g_{s2}	2/3	$\boxed{g_{S_{11}(1650)}}$	$\boxed{-1}$	$g_{P_{11}(1710)}$	180/619
g_{v1}	5/3	$g_{D_{13}(1520)}$	2	$g_{P_{13}(1900)}$	18/619
g_{v2}	0	$g_{D_{13}(1700)}$	$-1/10$	$g_{P_{11}(2100)}$	$-16/619$
g_A^π	5/3	$g_{D_{15}(1675)}$	$-9/10$	$g_{F_{15}(1680)}$	5/3
g_A^η	1	$g_{P_{11}(1440)}$	225/619	$g_{F_{15}(2000)}$	$-2/21$
g_1	1	$g_{P_{13}(1720)}$	180/619	$g_{F_{17}(1990)}$	$-4/7$

◆ Model parameters

Goldberger-Treiman relation:

$$g_{mNN} = \frac{g_A^m M_N}{f_m}$$

$$g_{\pi NN} = 13.48,$$

$$g_{\eta NN} = 0.81$$

$$g_{a_0 NN} g_{a_0 \pi \eta} = 100$$

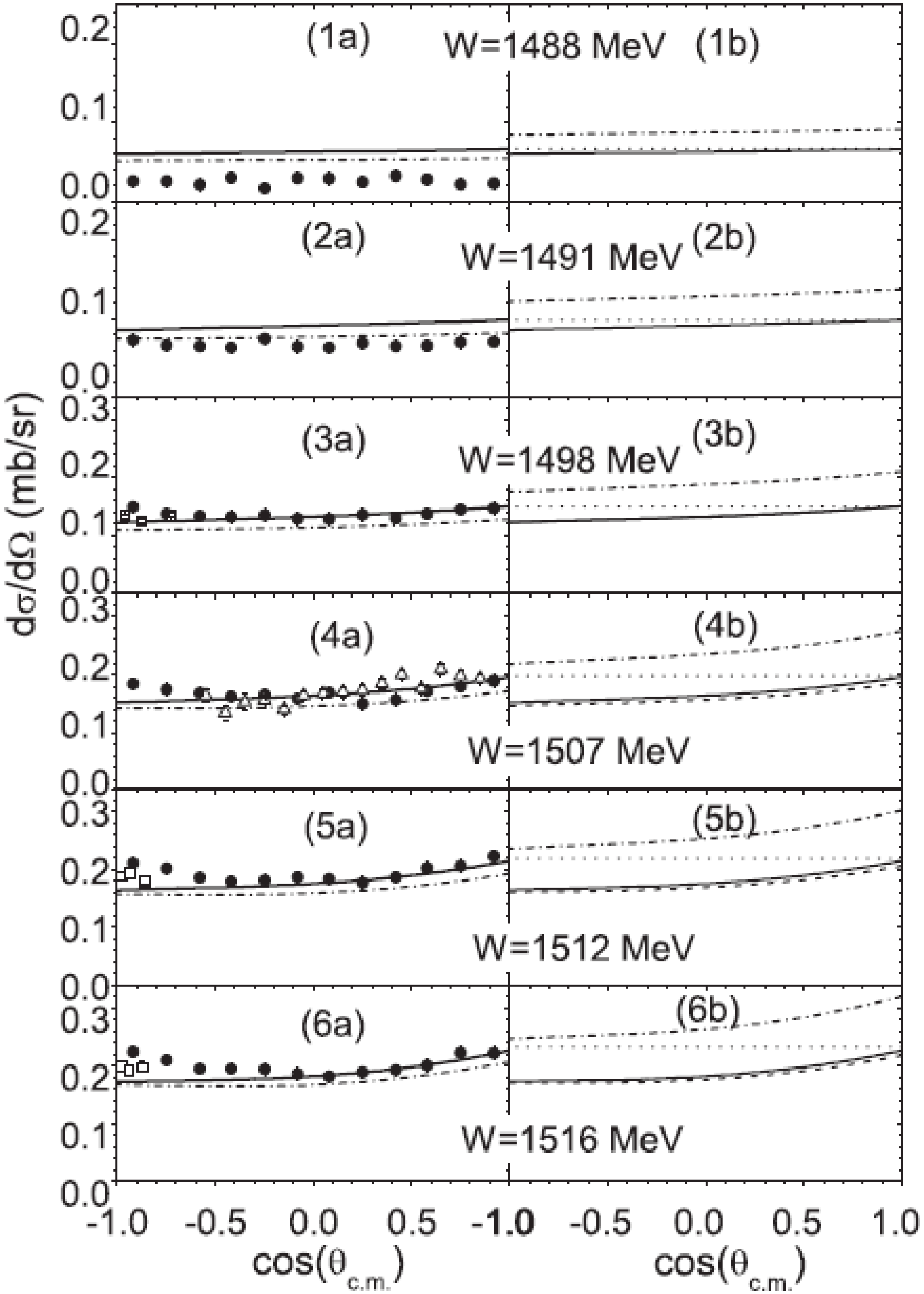
$$m_q = 330 \text{ MeV},$$

$$\alpha^2 = 0.16 \text{ GeV}^2.$$

TABLE II. Breit-Wigner masses M_R (in MeV) and widths Γ_R (in MeV) for the resonances. $n = 1$ and $n = 2$ stand for the degenerate states with quantum number $n = 1$ and $n = 2$ in the u channel.

Resonance	M_R	Γ_R	Resonance	M_R	Γ_R
$S_{11}(1535)$	1535	150	$P_{11}(1440)$	1440	300
$S_{11}(1650)$	1655	165	$P_{11}(1710)$	1710	100
$D_{13}(1520)$	1520	115	$P_{13}(1720)$	1720	200
$D_{13}(1700)$	1700	115	$P_{13}(1900)$	1900	500
$D_{15}(1675)$	1675	150	$P_{11}(2100)$	2100	150
$n = 1$	1650	230	$F_{15}(1680)$	1685	130
$n = 2$	1750	300	$F_{15}(2000)$	2000	200
–	–	–	$F_{17}(1990)$	1990	350

Differential cross sections

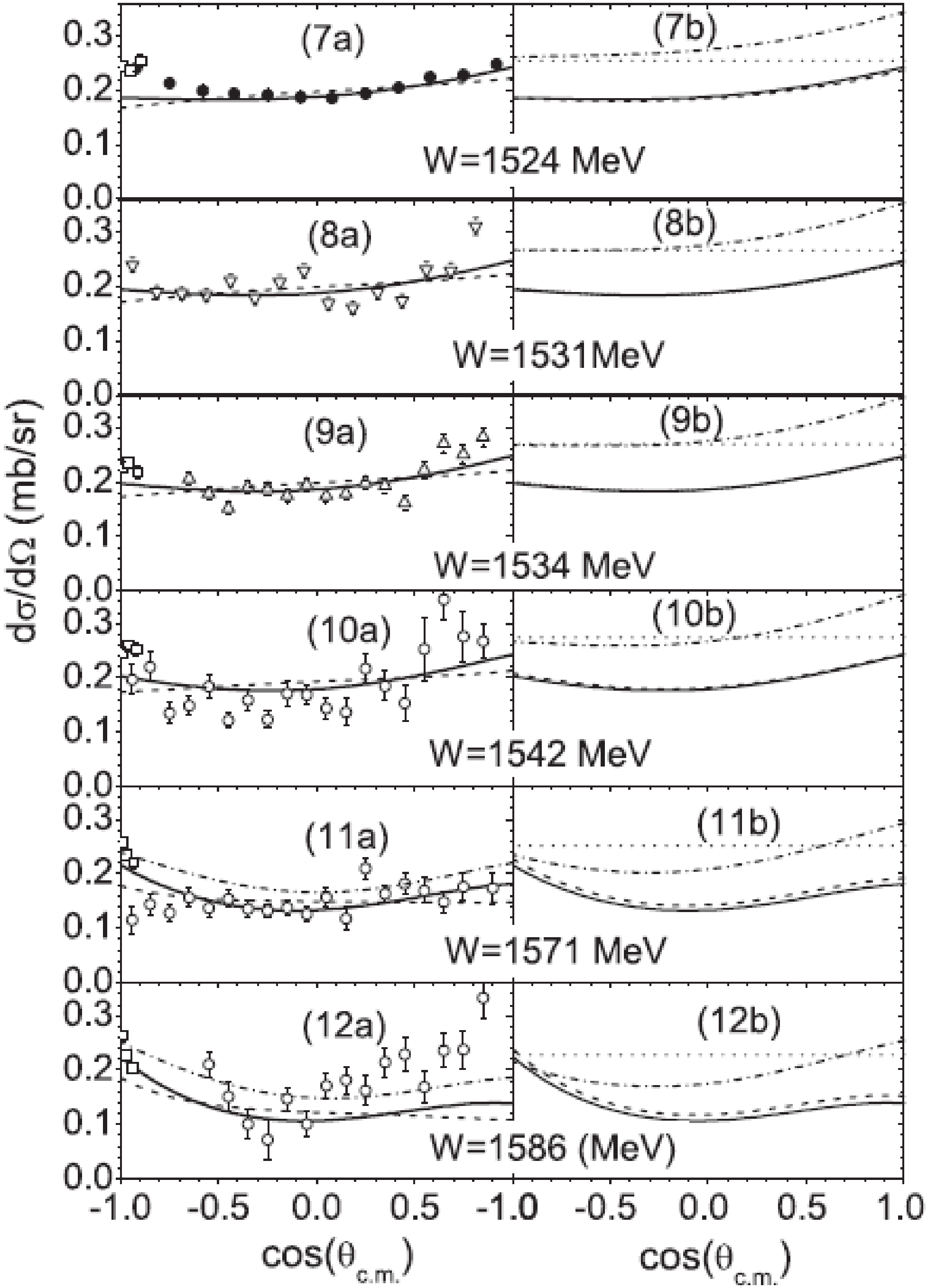


Left panel:

- Solid: full calculation
- Dot-dashed: without nucleon Born term

Right panel:

- Solid: full calculation
- Dotted lines: exclusive S11(1535)
- Dot-dashed: without S11(1650)
- Dashed: without t-channel



Left panel:

- Solid: full calculation
- Dot-dashed: without nucleon Born term
- Dashed: without D13(1520)

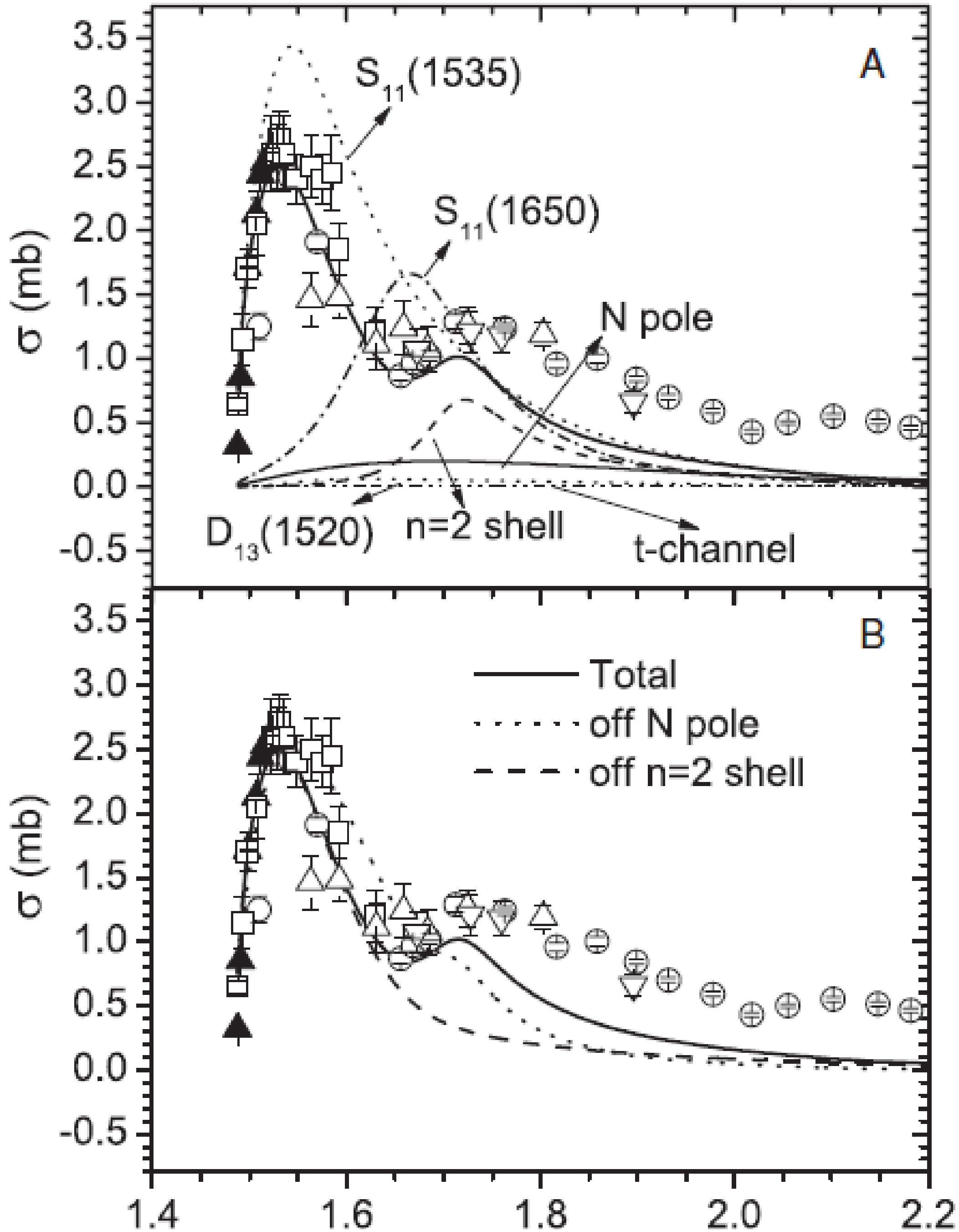
Right panel:

- Solid: full calculation
- Dotted lines: exclusive S11(1535)
- Dot-dashed: without S11(1650)
- Dashed: without t-channel

Total cross sections

- **S11(1535) is dominant near threshold. The exclusive cross section is even larger than the data.**
- **S11(1650) has a destructive interference with the S11(1535), and appears to be a dip in the total cross section.**
- **States from n=2 shell account for the second enhancement around 1.7 GeV.**

Zhong, Zhao, He, and Saghai, PRC76, 065205 (2007)



❑ S-channel resonance excitations in $K^- p \to \Sigma^0 \pi^0$

$$\mathcal{O}_S = [g_{S_{01}(1405)} + g_{S_{01}(1670)}]\mathcal{O}_S,$$
$$\mathcal{O}_D = [g_{D_{03}(1520)} + g_{D_{03}(1690)}]\mathcal{O}_D,$$

$$\frac{g_{S_{01}(1405)}}{g_{S_{01}(1670)}} = \frac{\langle N_f|I_3^\pi \sigma_3|S_{01}(1405)\rangle\langle S_{01}(1405)|I_3^K \sigma_3|N_i\rangle}{\langle N_f|I^\pi \sigma_3|S_{01}(1670)\rangle\langle S_{01}(1670)|I_3^K \sigma_3|N_i\rangle}$$

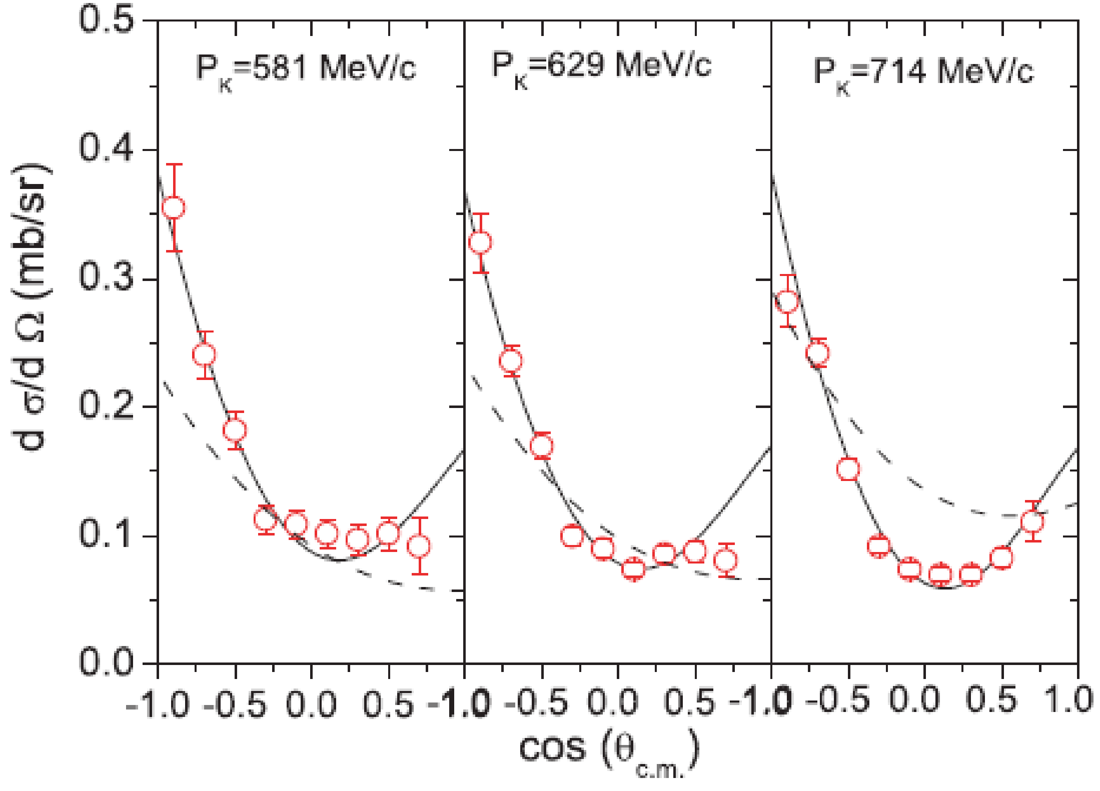
$$|S_{01}(1405)\rangle = \cos(\theta)|\mathbf{70},{}^2\mathbf{1}\rangle - \sin(\theta)|\mathbf{70},{}^2\mathbf{8}\rangle$$
$$|S_{01}(1670)\rangle = \sin(\theta)|\mathbf{70},{}^2\mathbf{1}\rangle + \cos(\theta)|\mathbf{70},{}^2\mathbf{8}\rangle$$

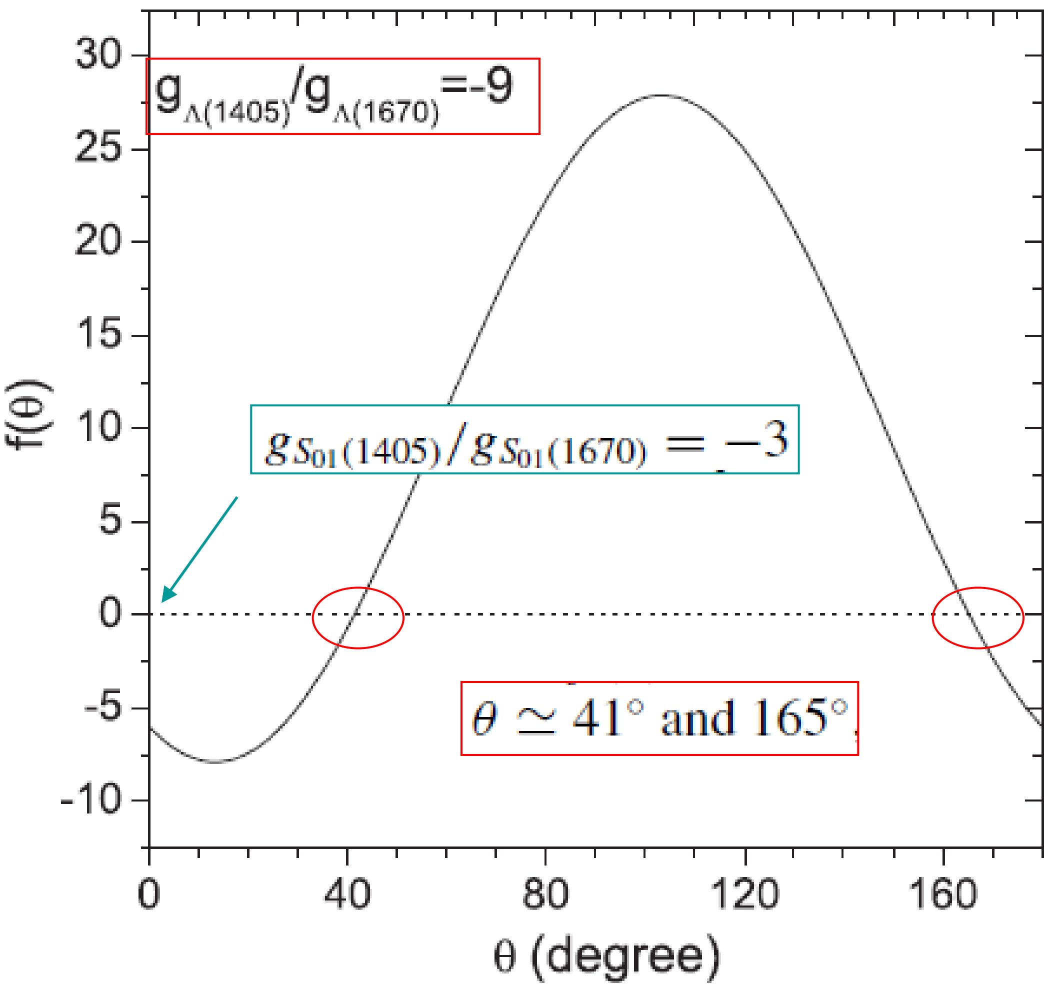
$$\frac{g_{S_{01}(1405)}}{g_{S_{01}(1670)}} = \frac{[3\cos(\theta) - \sin(\theta)][\cos(\theta) + \sin(\theta)]}{[3\sin(\theta) + \cos(\theta)][\sin(\theta) - \cos(\theta)]}$$

$g_{S_{01}(1405)}/g_{S_{01}(1670)} = -3$ leads to $\theta = 0^\circ$, i.e., no configuration mixing between $[\mathbf{70},{}^2\mathbf{1}]$ and $[\mathbf{70},{}^2\mathbf{8}]$.

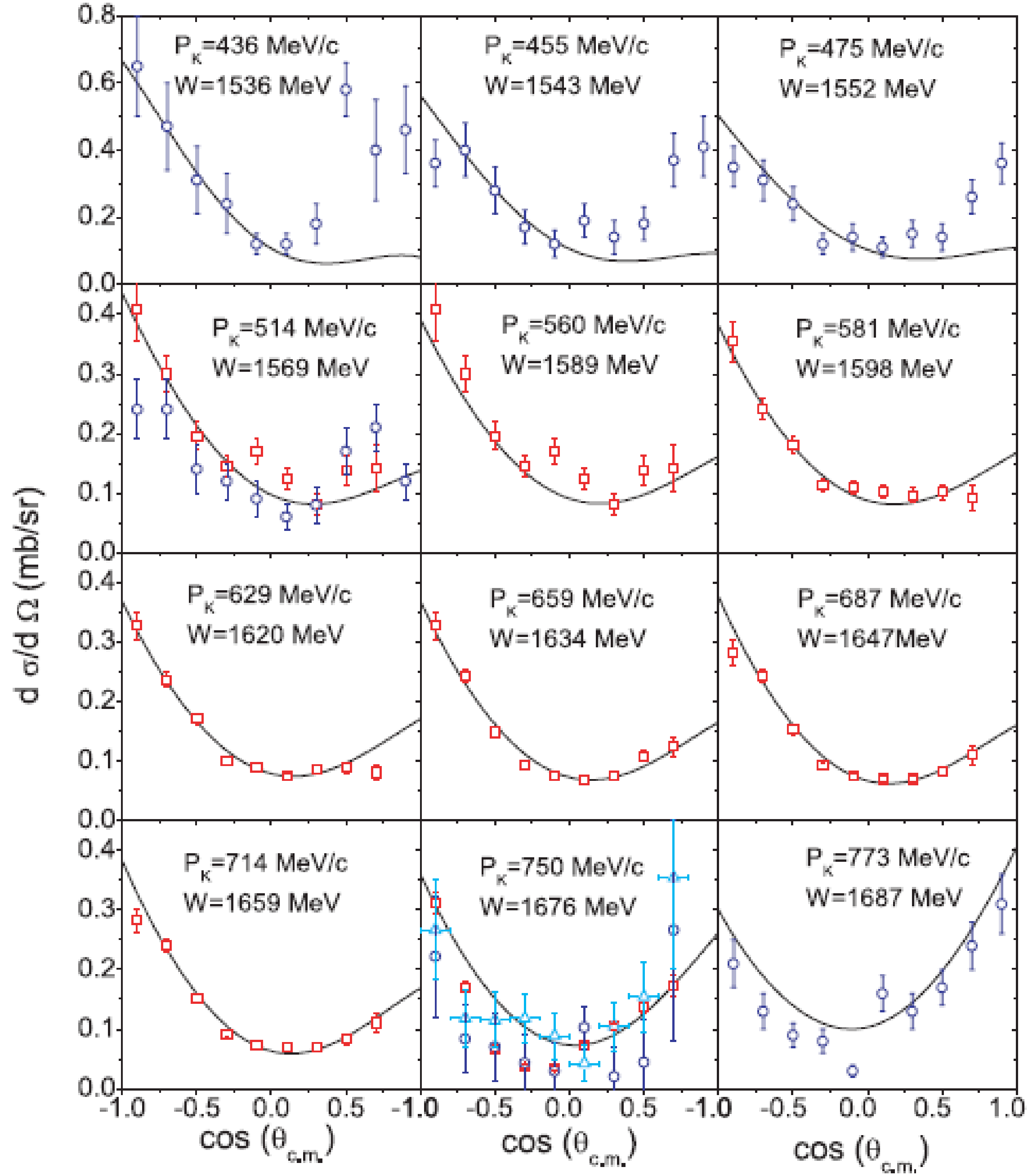
Zhong and Zhao, PRC79, 045202 (2009)

We thus determine the mixing angle by experimental data which requires $g_{S_{01}(1405)}/g_{S_{01}(1670)} \simeq -9$



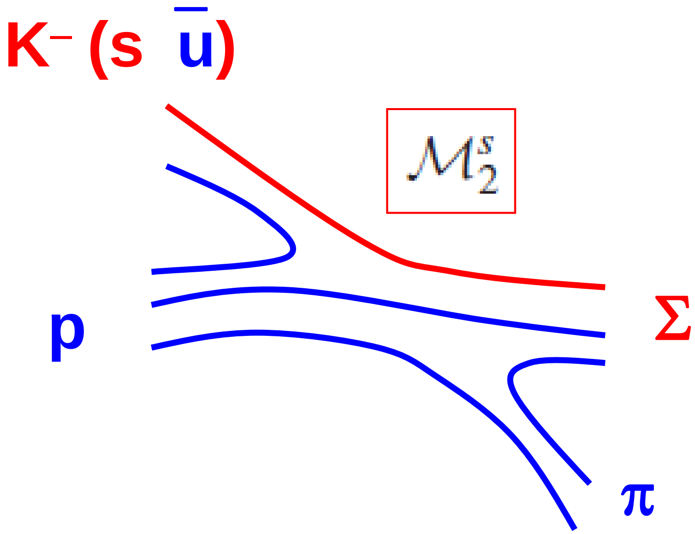


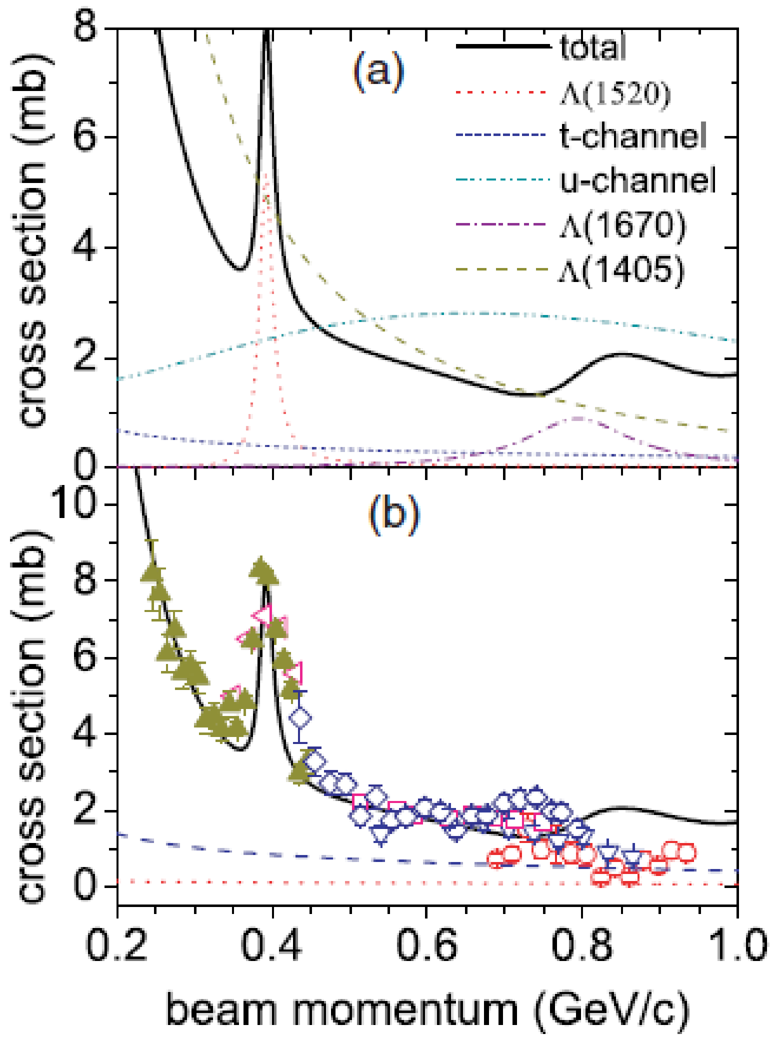
$g_{\Lambda(1405)}/g_{\Lambda(1670)}$=-9
$g_{S_{01}(1405)}/g_{S_{01}(1670)} = -3$
$\theta \simeq 41^\circ$ and 165°
f(θ)
θ (degree)
30
25
20
15
10
5
0
-5
-10
0
40
80
120
160



P$_K$=436 MeV/c
W=1536 MeV
P$_K$=455 MeV/c
W=1543 MeV
P$_K$=475 MeV/c
W=1552 MeV
P$_K$=514 MeV/c
W=1569 MeV
P$_K$=560 MeV/c
W=1589 MeV
P$_K$=581 MeV/c
W=1598 MeV
P$_K$=629 MeV/c
W=1620 MeV
P$_K$=659 MeV/c
W=1634 MeV
P$_K$=687 MeV/c
W=1647MeV
P$_K$=714 MeV/c
W=1659 MeV
P$_K$=750 MeV/c
W=1676 MeV
P$_K$=773 MeV/c
W=1687 MeV
d σ/d Ω (mb/sr)
cos (θ$_{c.m.}$)

s-channel





- $\mathcal{M}_3^s$ =0
- $\mathcal{M}_2^s$ is the only s-channel amplitude
- U-channel turns to be important

Prospects - I

1. For the purpose of searching for individual resonance excitations, it is essential to have a quark model guidance for both known and “missing” states. And then allow the data to tell:

   i) which state is favored;

   ii) whether a state beyond the conventional quark model is needed;

   iii) how quark model prescriptions for N*NM form factors complement with isobaric models.

Prospects - II

2. Understanding the non-resonance background

   A reliable estimate of the non-resonance background, such as the t- and u-channel. Their interferences with the resonances are essentially important.

3. Unitarity constraint

   A coherent study of the pseudoscalar photoproduction and meson-baryon scattering is needed. In particular, a coupled channel study will put a unitary constraint on the theory.

Photoproduction of pseudoscalar mesons (π, η, η', K); and $\pi N \rightarrow \eta N$; $K^- p \rightarrow \pi\Sigma$, and more are coming out soon…

Q. Z., **PRC 63**, 035205 (2001) ;
Q. Z., J.S. Al-Khalili, Z.P. Li, and R.L. Workman, **PRC 65**, 065204 (2002);
Q. Z., B. Saghai and Z.P. Li, **JPG 28**, 1293 (2002);
X.H. Zhong, Q. Z., J. He, and B. Saghai, **PRC 76**, 065205 (2007)
X.H. Zhong and Q. Z., arXiv:0811.4212, **PRC79**, 045202(2009)

Thanks !

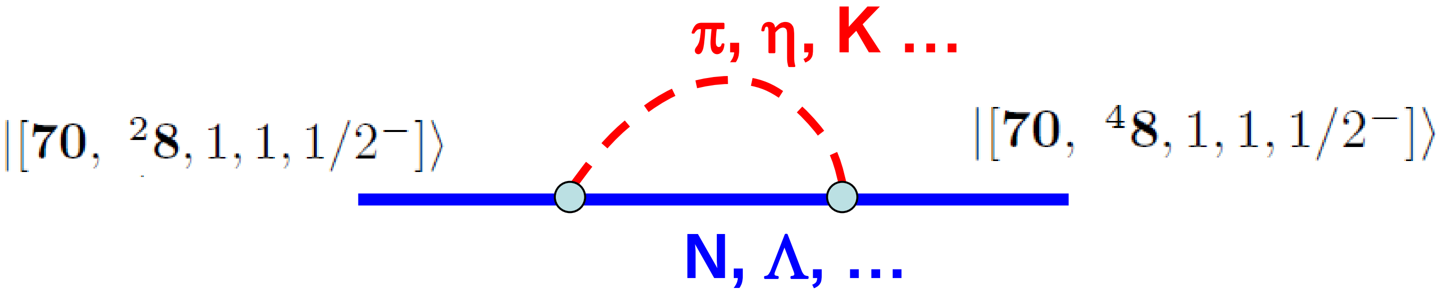
◆ A revisit to the S-wave state mixing

The mixing between pure $[\mathbf{70},\ ^2\mathbf{8}]$ and $[\mathbf{70},\ ^4\mathbf{8}]$ states is defined as

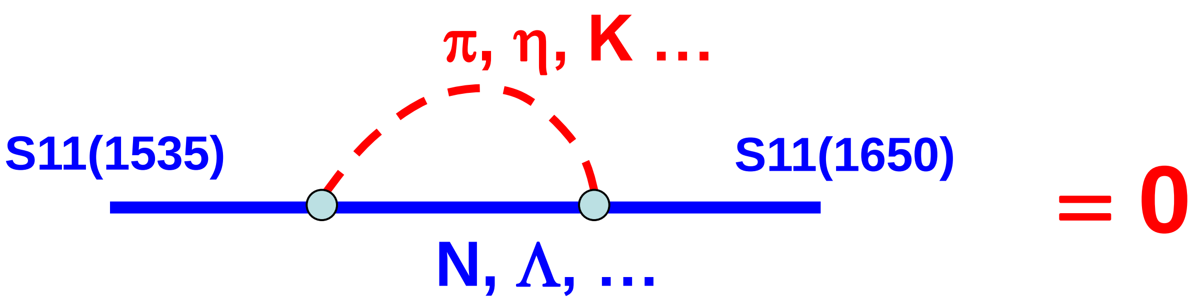
$$\begin{pmatrix} S_{11}(1535) \\ S_{11}(1650) \end{pmatrix} = \begin{pmatrix} \cos\theta_S & -\sin\theta_S \\ \sin\theta_S & \cos\theta_S \end{pmatrix} \begin{pmatrix} |[\mathbf{70},\ ^2\mathbf{8}, 1, 1, 1/2^-]\rangle \\ |[\mathbf{70},\ ^4\mathbf{8}, 1, 1, 1/2^-]\rangle \end{pmatrix}$$

Similarly, the D-wave mixing can be written as

$$\begin{pmatrix} D_{13}(1520) \\ D_{13}(1700) \end{pmatrix} = \begin{pmatrix} \cos\theta_D & -\sin\theta_D \\ \sin\theta_D & \cos\theta_D \end{pmatrix} \begin{pmatrix} |[\mathbf{70},\ ^2\mathbf{8}, 1, 1, 3/2^-]\rangle \\ |[\mathbf{70},\ ^4\mathbf{8}, 1, 1, 3/2^-]\rangle \end{pmatrix}$$



The physical states should be orthogonal which means:



This expectation can be examined by the K-matrix propagator between [70, ^{2}8] and [70, ^{4}8] mixing states:

$$G = \frac{1}{D_a D_b - |D_{ab}|^2} \begin{pmatrix} D_a & D_{ab} \\ D_{ab} & D_b \end{pmatrix}$$

$$\begin{cases} D_a = s - m_a^2 + i\sqrt{s}\,\Gamma^a(s) \\ D_b = s - m_b^2 + i\sqrt{s}\,\Gamma^b(s) \end{cases} \qquad \begin{cases} \Gamma^a(s) = \Gamma^a_{\pi N} + \Gamma^a_{\eta N} + \ldots\,, \\ \Gamma^b(s) = \Gamma^b_{\pi N} + \Gamma^b_{\eta N} + \ldots\,. \end{cases}$$

$$D_{ab} \simeq \frac{i}{16\pi}[\rho_{\pi N} g^a_{S_{11}N\pi} g^b_{S_{11}N\pi} + \rho_{\eta N} g^a_{S_{11}N\eta} g^b_{S_{11}N\eta}]$$

Recalling that

$$\alpha \equiv \langle \psi^s_{000} | q e^{i\sqrt{\frac{2}{3}} q \lambda_z} | \psi^\lambda_{110} \rangle = i \frac{q^2}{\sqrt{3}\alpha_h} e^{-q^2/6\alpha_h^2},$$

$$\beta \equiv \langle \psi^s_{000} | e^{i\sqrt{\frac{2}{3}} q \lambda_z} \hat{p}_{3-} | \psi^\lambda_{111} \rangle = -\langle \psi^s_{000} | e^{i\sqrt{\frac{2}{3}} q \lambda_z} \hat{p}_{3+} | \psi^\lambda_{11-1} \rangle$$

$$= -i\sqrt{\frac{2}{3}} \alpha_h e^{-q^2/6\alpha_h^2},$$

$$\gamma \equiv \langle \psi^s_{000} | e^{i\sqrt{\frac{2}{3}} q \lambda_z} \hat{p}_{3z} | \psi^\lambda_{110} \rangle = i \frac{\alpha_h}{\sqrt{3}} \left(1 + \frac{q^2}{3\alpha_h^2} \right) e^{-q^2/6\alpha_h^2},$$

$$H_m^{NR} = \sum_j \left\{ \frac{\omega_m}{E_f + I \ldots} \right.$$

The N* → NM tra

$$\left\{ \begin{aligned} \mathcal{M}_{S_{11}\to NM} &= \frac{1}{f_m} [C_1 \langle \hat{H}_1 \rangle \alpha(q) + C_2 \langle \hat{H}_2 \rangle (\gamma(q) - \sqrt{2}\beta(q))], \\ \mathcal{M}_{D_{13}(D_{15})\to NM} &= \frac{1}{f_m} \left[C_1 \langle \hat{H}_1 \rangle \alpha(q) + C_2 \langle \hat{H}_2 \rangle \left(\gamma(q) + \frac{\beta(q)}{\sqrt{2}} \right) \right] \end{aligned} \right.$$

with $C_1 \equiv -3 \left(\frac{\omega_m}{E_f + M_f} + 1 \right), \quad C_2 \equiv \frac{3\omega_m}{2\mu_q}.$

$\hat{H}_1(\alpha), \hat{H}_2(\gamma - \sqrt{2}\beta)$	$S_{11}^+ \to \Lambda K^+$	$S_{11}^+ \to p\eta$	$S_{11}^+ \to n\pi^+$	$S_{11}^+ \to p\pi^0$	$S_{11}^+ \to \Sigma^+ K^0$
$\langle N, J_z = \frac{1}{2} \| \hat{H}_1 \| S_{11}^+, J_z = \frac{1}{2} \rangle$	$-\frac{1}{6}$	$-\frac{\cos\theta}{3\sqrt{3}}$	$-\frac{2\sqrt{2}}{9\sqrt{3}}$	$\frac{2}{9\sqrt{3}}$	$-\frac{1}{9\sqrt{6}}$
$\langle N, J_z = \frac{1}{2} \| \hat{H}_2 \| S_{11}^+, J_z = \frac{1}{2} \rangle$	$-\frac{1}{6}$	$-\frac{\cos\theta}{3\sqrt{3}}$	$-\frac{2\sqrt{2}}{9\sqrt{3}}$	$\frac{2}{9\sqrt{3}}$	$-\frac{1}{9\sqrt{6}}$

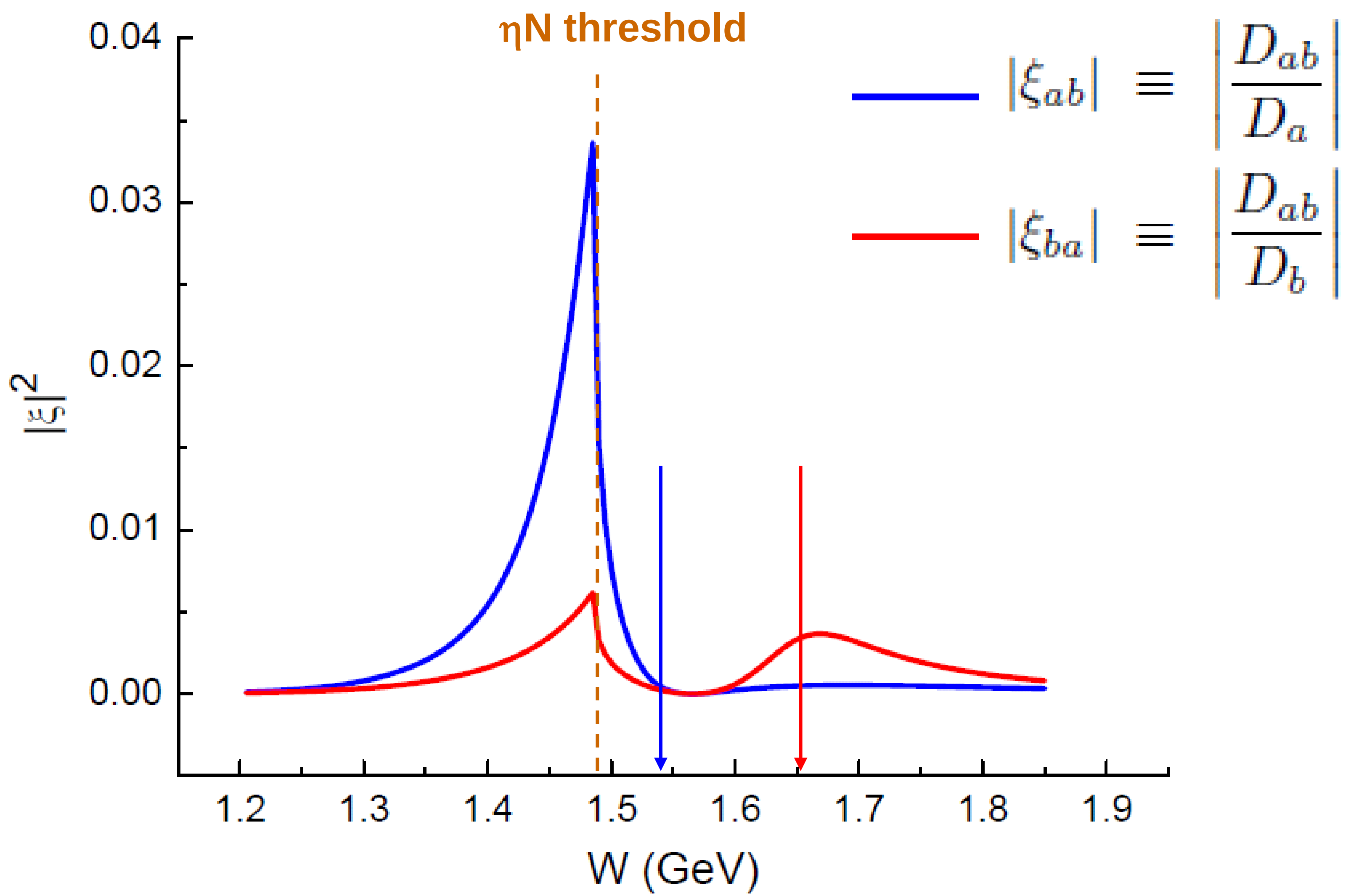
We can then extract the N*NM form factors given by the chiral effective Lagrangian in the NRCQM, e.g.

$$\sum_{spin} |\mathcal{M}_{hadron}|^2 \equiv (E_i + M_i)(E_f + M_f) \sum_{spin} |\mathcal{M}_{quark}|^2,$$

where

$$\begin{aligned} N^*(S_{11} \to NM): \quad \mathcal{M}^{S_{11}}_{hadron} &= g_{S_{11}NM} \bar{u}_N u_R, \\ N^*(D_{13} \to NM): \quad \mathcal{M}^{D_{13}}_{hadron} &= g_{D_{13}NM} \bar{u}_N \gamma_5 \gamma_\mu u_{R\nu} p^\mu_M p^\nu_M, \\ N^*(D_{15} \to NM): \quad \mathcal{M}^{D_{15}}_{hadron} &= g_{D_{15}NM} \bar{u}_N u_{R\mu\nu} p^\mu_M p^\nu_M, \end{aligned}$$

$$\Rightarrow \left\{ \begin{aligned} \mathcal{M}^{S_{11}}_{quark} &= \frac{1}{f_m}[C_1\alpha(q) + C_2(\gamma(q) - \sqrt{2}\beta(q))]\langle \hat{H} \rangle \\ &= \frac{1}{f_m} \frac{i\alpha_h e^{-q^2/6\alpha^2}}{\sqrt{3}} \left[C_1 \frac{q^2}{\alpha_h^2} + C_2 \left(3 + \frac{q^2}{3\alpha_h^2} \right) \right] \langle \hat{H} \rangle, \\ \mathcal{M}^{D_{13}/D_{15}}_{quark} &= \frac{1}{f_m}[C_1\alpha(q) + C_2(\gamma(q) + \frac{\beta(q)}{\sqrt{2}})]\langle \hat{H} \rangle \\ &= \frac{1}{f_m} \frac{iq^2 e^{-q^2/6\alpha^2}}{3\sqrt{3}\alpha_h} \langle \hat{H} \rangle, \end{aligned} \right.$$



ηN threshold
$|\xi_{ab}| \equiv \left|\frac{D_{ab}}{D_a}\right|$
$|\xi_{ba}| \equiv \left|\frac{D_{ab}}{D_b}\right|$
0.04
0.03
0.02
0.01
0.00
$|\xi|^2$
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
W (GeV)

With the data for $S_{11} \to N\pi$ and $N\eta$ [1], i.e.

$$\begin{aligned} Br(S_{11}(1535) \to N\pi) &= 35 \sim 55\% \\ Br(S_{11}(1650) \to N\pi) &= 60 \sim 95\% \ , \end{aligned}$$

$$\begin{aligned} Br(S_{11}(1535) \to N\eta) &= 45 \sim 60\% \\ Br(S_{11}(1650) \to N\eta) &= 3 \sim 10\% \ , \end{aligned}$$

$$\Rightarrow \boxed{\theta_S \approx 24.6^\circ \sim 32.1^\circ}$$

$$\theta_S^{OPE} = 25.5^\circ$$
$$\theta_S^{OGE} = -32^\circ$$

Similarly, with the data for $D_{13} \to N\pi$

$$\begin{aligned} Br(D_{13}(1520) \to N\pi) &= 55 \sim 65\% \\ Br(D_{13}(1700) \to N\pi) &= 5 \sim 15\% \ , \end{aligned}$$

$$\begin{aligned} Br(D_{13}(1520) \to N\eta) &= 0.23 \pm 0.04\% \\ Br(D_{13}(1700) \to N\eta) &= 0.0 \pm 1.0\% \ , \end{aligned}$$

$$\Rightarrow \boxed{\theta_D \approx 6.3^\circ \sim 18.3^\circ .}$$

$$\theta_D^{OPE} = -52.7^\circ$$
$$\theta_D^{OGE} = 6^\circ$$

Relative signs for the N*NM couplings are given by the NRCQM

$\theta_S(24.6^\circ \sim 32.1^\circ)$	$S_{11}^+ \to p\eta$	$S_{11}^+ \to \Lambda K^+$	$S_{11}^+ \to n\pi^+$	$S_{11}^+ \to p\pi^0$	$S_{11}^+ \to \Sigma^+ K^0$
$\mathcal{M}_{N^* \to NM}$	$6.86 \sim 7.18$	$4.32 \sim 4.07$	$3.29 \sim 2.68$	$-2.312 \sim -1.92$	$3.32 \sim 3.88$
$g_{S_{11}NM}$	$7.03 \sim 7.35$	$4.42 \sim 4.16$	$3.37 \sim 2.74$	$-2.38 \sim -1.94$	$3.41 \sim 3.99$
$g_{S_{11}NM}/g_{S_{11}p\eta}$	1	$0.63 \sim 0.57$	$0.48 \sim 0.37$	$-0.34 \sim -0.27$	$0.49 \sim 0.54$

TABLE VI: Strong coupling constants for $S_{11}(1535) \to NM$.

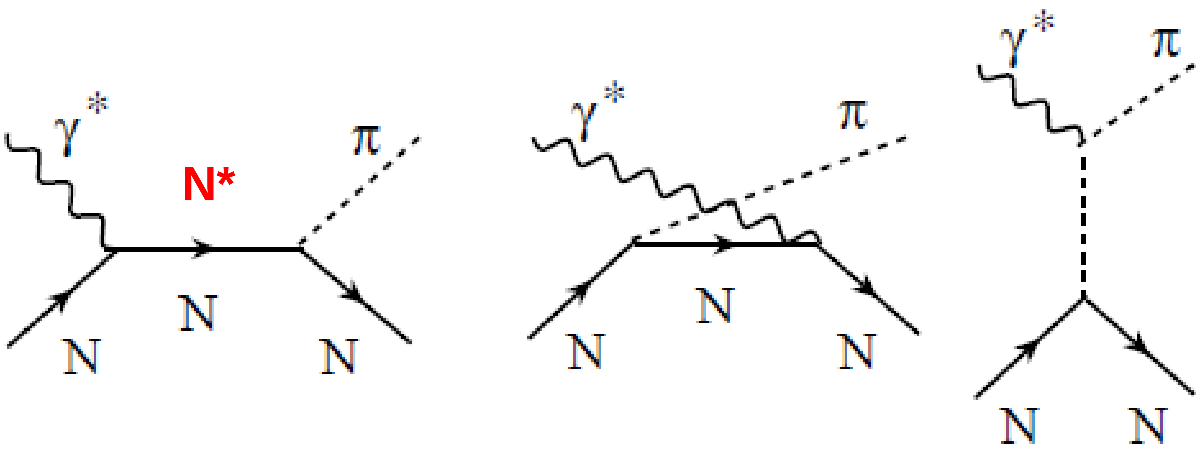
$\theta_S(24.6^\circ \sim 32.1^\circ)$	$S_{11}^+ \to p\eta$	$S_{11}^+ \to \Lambda K^+$	$S_{11}^+ \to n\pi^+$	$S_{11}^+ \to p\pi^0$	$S_{11}^+ \to \Sigma^+ K^0$
$\mathcal{M}_{N^* \to NM}$	$-2.56 \sim -1.67$	$2.0 \sim 2.57$	$4.06 \sim 4.44$	$-2.85 \sim -3.15$	$-4.19 \sim -3.75$
$g_{S_{11}NM}$	$-2.50 \sim -1.63$	$1.96 \sim 2.51$	$3.96 \sim 4.34$	$-2.80 \sim -3.07$	$-4.0 \sim -3.58$
$g_{S_{11}NM}/g_{S_{11}p\eta}$	1	$-0.78 \sim -1.54$	$-1.58 \sim -2.66$	$1.12 \sim 1.88$	$1.6 \sim 2.2$

TABLE VII: Strong coupling constants for $S_{11}(1650) \to NM$.

Indication of a destructive sign between S11(1535) and S11(1650) amplitudes in $\gamma p \to \eta p$, and $\pi^- p \to \eta n$.

arXiv: 0810.0997[nucl-th] by Aznauryan, Burkert and Lee.

It is important to have a correct definition of the common sign of amplitudes and relative sign between helicity amplitudes, i.e. A1/2, A3/2, and S1/2.

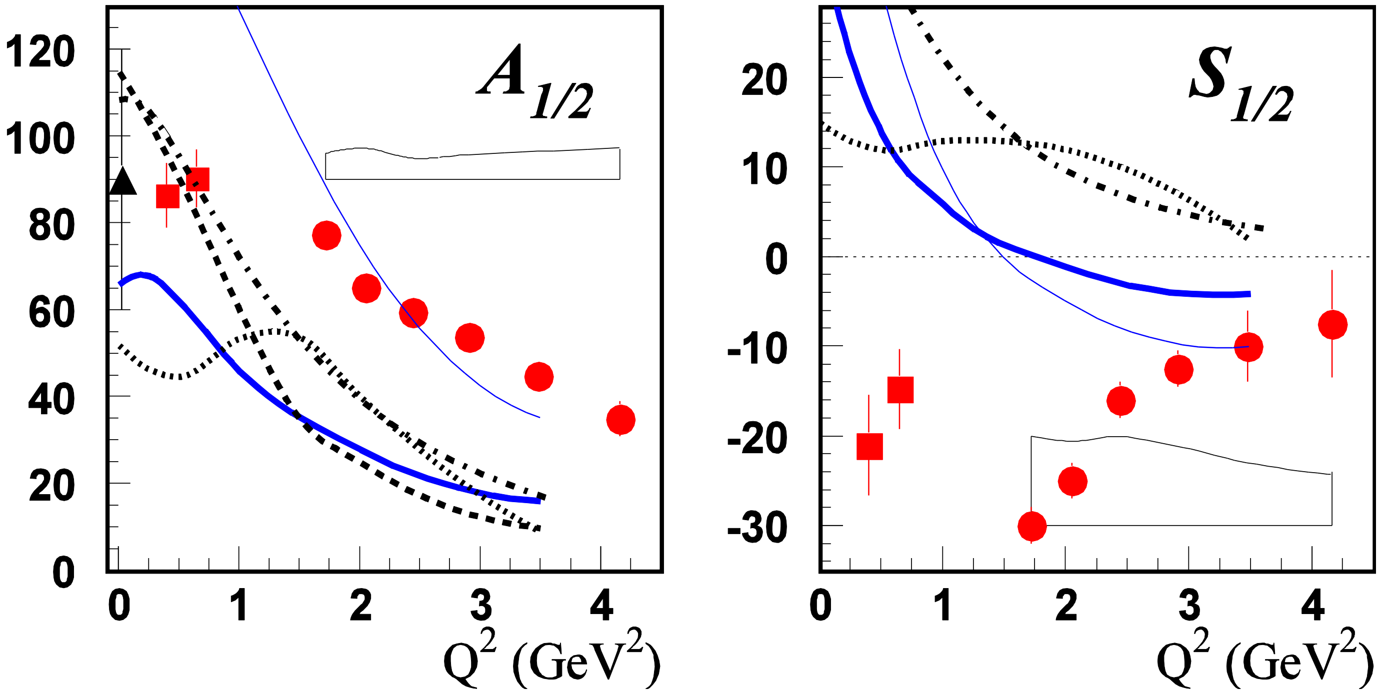


$\mathcal{A}_{1/2}$, $\mathcal{A}_{3/2}$, $\mathcal{S}_{1/2}$:

$$A_{\frac{1}{2},\frac{3}{2}} = \zeta \mathcal{A}_{\frac{1}{2},\frac{3}{2}}, \quad S_{\frac{1}{2}} = \zeta \mathcal{S}_{\frac{1}{2}}.$$

$$\boxed{\zeta = -sign(g^*/g)}$$

$\gamma^* p \rightarrow S_{11}$ (1535): 3q picture



Opposite sign of $S_{1/2}$!!!

Impossible to change in quark model !!!

Combined with the difficulties in the description of large width of **S_{11}(1535) → η N** and large **S_{11}(1535) → ϕN,ΛK** couplings, this shows that <u>3q picture for S_{11}(1535) should be complemented</u>

LF RQM:

Capstick, Keister, PR D51 (1995) 3598

Pace, Simula et.al., PR D51 (1995) 3598

From I. Aznauryan, Electromagnetic N-N Transition Form Factors Workshop, 2008*

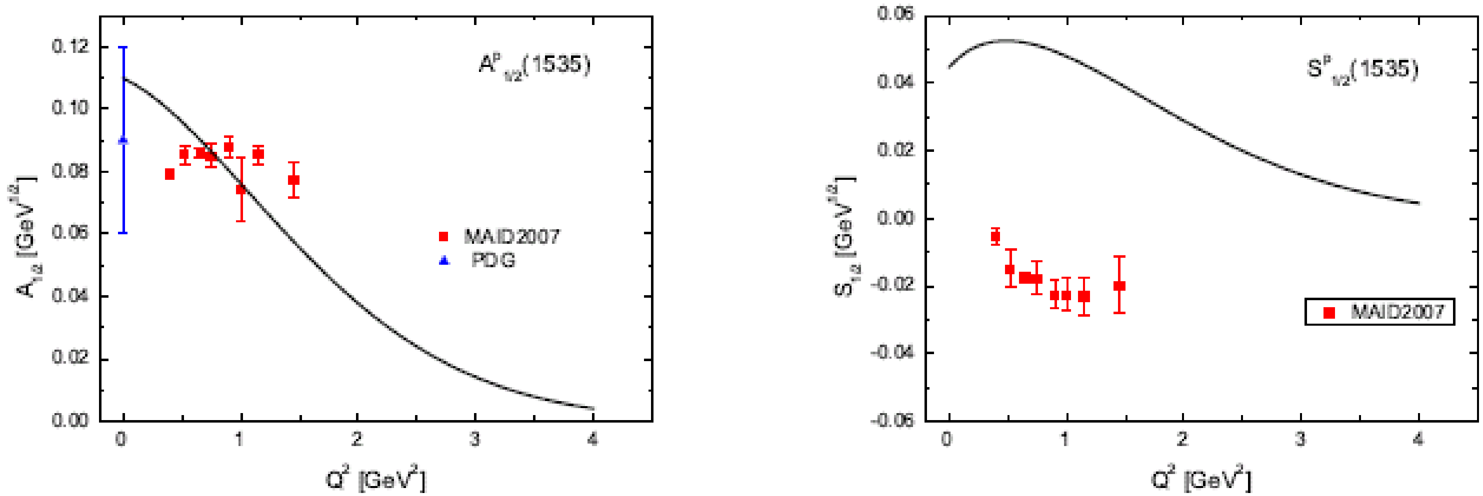


FIG. 1: Helicity amplitude for $\gamma^* p \to S_{11}(1535)$

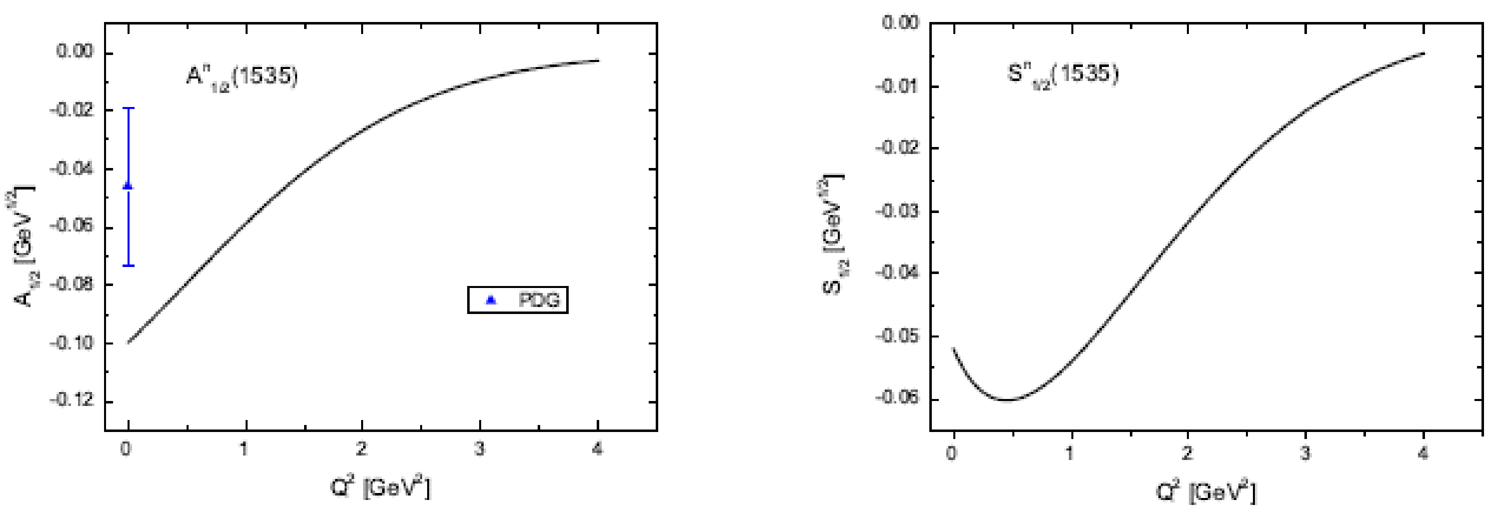


FIG. 2: Helicity amplitude for $\gamma^* n \to S_{11}(1535)$

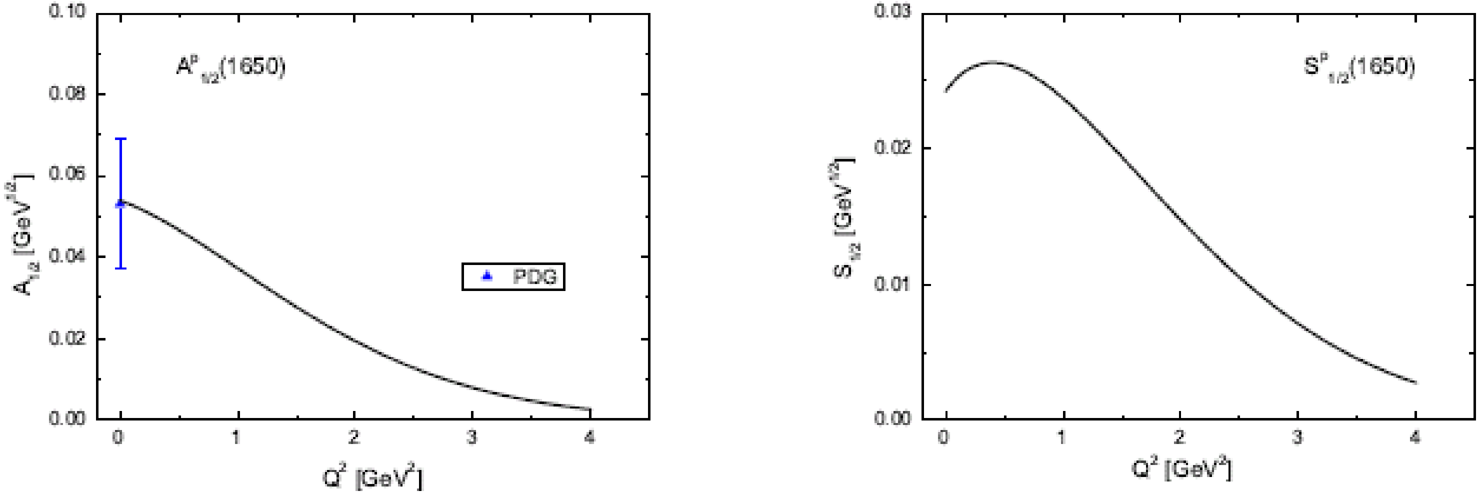


FIG. 3: Helicity amplitude for $\gamma^* p \to S_{11}(1650)$

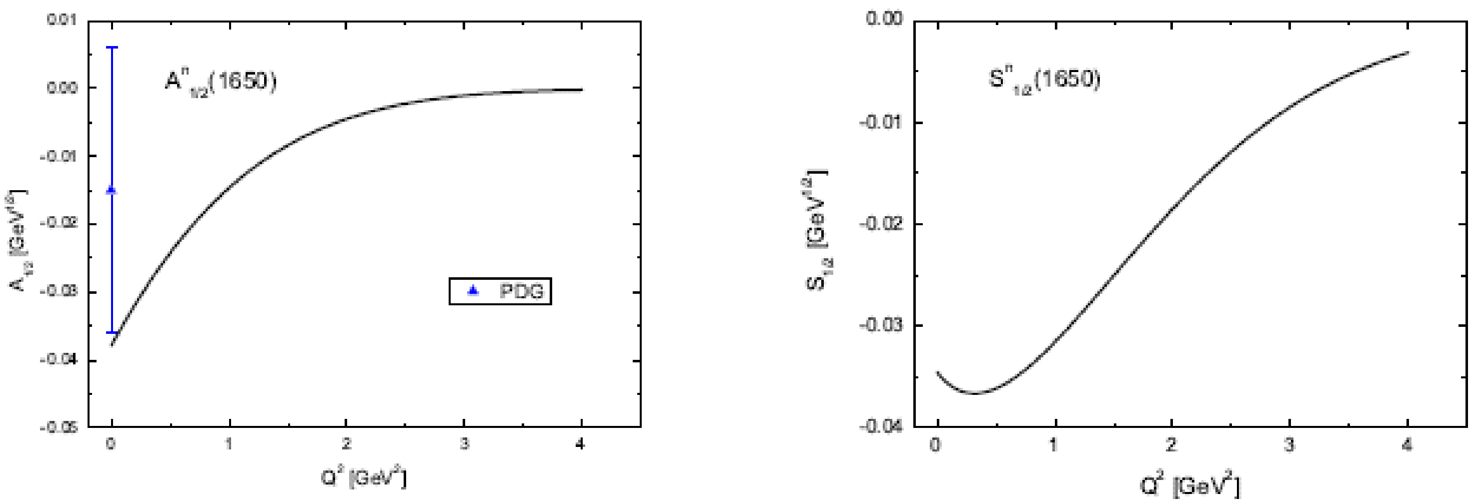


FIG. 4: Helicity amplitude for $\gamma^* n \to S_{11}(1650)$