# Couplings of the low-lying $S_{11}$ resonances to pseudoscalar meson and baryons

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# Outline

1. Introduction
2. Framework: Chiral quark model
   - The wave function model
   - The transition amplitudes
3. Numerical Results
   - $qqq$ model: $SU(6) \otimes O(3)$ conserved
   - $qqq$ model: $SU(6) \otimes O(3)$ broken
   - Results includ contributions of 5Q
4. Conclusion

# 1 INTRODUCTION

## Structure of $S_{11}(1535)$ and $S_{11}(1650)$ & Coupling constants: Previous Works

Structure of $S_{11}(1535)$ and $S_{11}(1650)$:

- Hadronic level
  - PWA: S-wave resonances
  - SU(3)dynamics: Dynamically generated $K\Sigma - K\Lambda$ quasi-bound state
    - N. Kaiser, P. B. Siegel and W. Weise, Phys. Lett. B 362, 23 (1995).
    - N. Kaiser, T. Waas and and W. Weise, Nucl. Phys. A 612, 297 (1997).
    - T. Inoue, E. Oset, and J. Vincente Vacas, Phys. Rev. C 65, 035204 (2002).
    - P. C. Bruns, M. Mai and Ulf-G. Meissner, Phys. Lett. B 697, 254 (2011).
- Quark Model: first orbitally excited states

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## Structure of $S_{11}(1535)$ and $S_{11}(1650)$ & Coupling constants: Previous Works

Coupling constants:

- $SU(3)$ dynamics
  - $S_{11}(1535)$: $|g_{\pi N}| < |g_{K\Lambda}| < |g_{\eta n}| \sim |g_{K\Sigma}|$
    [T. Inoue, E. Oset, and J. Vincente Vacas, Phys. Rev. C 65, 035204 (2002).]
  - $S_{11}(1535)$ : $|g_{\pi^0 p}| \sim |g_{K^+\Sigma^0}| < |g_{\pi^+ n}| \sim |g_{K^0\Sigma^+}| < |g_{\eta P}| < |g_{K^+\Lambda}|$
    $S_{11}(1650)$ : $|g_{K^+\Lambda}| < |g_{\pi^0 p}| < |g_{\pi^+ n}| \sim |g_{K^+\Sigma^0}| < |g_{\eta p}| < |g_{K^0\Sigma^+}|$
    P. C. Bruns, M. Mai and Ulf-G. Meissner, Phys. Lett. B 697, 254 (2011).
- Isobar model to reproduce $J/\Psi \to \bar{p}p\eta$ and $J/\Psi \to \bar{p}K^+\Lambda$: $S_{11}(1535)$: $|g_{\pi N}| < |g_{\eta N}| < |g_{K\Lambda}|$ and $\frac{g_{K\Lambda}}{g_{\eta N}} \sim 1.3 \pm 0.3$
  [B. C. Liu and B. S. Zou, Phys. Rev. Lett 96, 042002 (2006)]

## Structure of $S_{11}(1535)$ and $S_{11}(1650)$ & Coupling constants: Previous Works

Higher Fock components:

$|S_{11}(1535)\rangle = A_3|qqq\rangle + A|qqqs\bar{s}\rangle$
$\Rightarrow M_{\Lambda(1405)} < M_{Roper} < M_{S_{11}(1535)}$
[B. C. Liu and B. S. Zou, Phys. Rev. Lett 96, 042002 (2006)]

Sizable strangeness components in $S_{11}(1535) \Rightarrow$ good description for $\gamma^* N \rightarrow S_{11}(1535)$
[C. S. An and B. S. Zou, Eur. Phys. J. A **39**, 195 (2009)]
[C. S. An, Chinese. Phys. C **33**, 1393 (2009).]

Strong decays?
Coupling constants $g_{S_{11}MB}$, $MB = \pi N, \eta N, K\Lambda, K\Sigma, \eta' N$?

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# 2 Framework: Chiral quark model

# Three-quark system: $SU(6) \otimes O(3)$ limit

Hamitonian:

$$H = \sum_{i=1}^{3} m_i + \sum_{i=1}^{3} \frac{p_i^2}{2m_i} + \sum_{i<j} V(r_{ij}) + H_{hyp} \quad (1)$$

Potential term:

$$V(r_{ij}) = \frac{1}{2} K r_{ij}^2 + U(r_{ij}) \quad (2)$$

$SU(6) \otimes O(3)$ wave functions for $S_{11}(1535)$ and $S_{11}(1650)$:

$$|N(^2_8 P_M)_{\frac{1}{2}^-}, S_z\rangle = \frac{1}{2} \sum_{m,s_z} C^{\frac{1}{2} S_z}_{1m,\frac{1}{2} s_z} [(|N\rangle_\rho |\frac{1}{2}, s_z\rangle_\lambda + |N\rangle_\lambda |\frac{1}{2}, s_z\rangle_\rho) \varphi^\rho_{11m}(\vec{\lambda}, \vec{\rho}) + (|N\rangle_\rho |\frac{1}{2}, s_z\rangle_\rho - |N\rangle_\lambda |\frac{1}{2}, s_z\rangle_\lambda) \varphi^\lambda_{11m}(\vec{\lambda}, \vec{\rho})] , \quad (3)$$

$$|N(^4_8 P_M)_{\frac{1}{2}^-}, S_z\rangle = \frac{1}{\sqrt{2}} \sum_{m,s_z} C^{\frac{1}{2} S_z}_{1m,\frac{3}{2} s_z} [|N\rangle_\rho |\frac{3}{2}, s_z\rangle \varphi^\rho_{11m}(\vec{\lambda}, \vec{\rho}) + |N\rangle_\lambda |\frac{3}{2}, s_z\rangle \varphi^\lambda_{11m}(\vec{\lambda}, \vec{\rho})] , \quad (4)$$

# Three-quark system: $SU(6) \otimes O(3)$ breakdown

$SU(6) \otimes O(3)$ symmetry breakdown & Configurations mixing:

$$\begin{pmatrix} |S_{11}(1535), S_z\rangle \\ |S_{11}(1650), S_z\rangle \end{pmatrix} = \begin{pmatrix} cos\theta_S & -sin\theta_S \\ sin\theta_S & cos\theta_S \end{pmatrix} \begin{pmatrix} |N(^2_8P_M)_{\frac{1}{2}^-}, S_z\rangle \\ |N(^4_8P_M)_{\frac{1}{2}^-}, S_z\rangle \end{pmatrix} \tag{5}$$

$\theta_S$:

$$\begin{pmatrix} \langle N(^2_8P_M)_{\frac{1}{2}^-}, S_z|H_{hyp}|N(^2_8P_M)_{\frac{1}{2}^-}, S_z\rangle & \langle N(^2_8P_M)_{\frac{1}{2}^-}, S_z|H_{hyp}|N(^4_8P_M)_{\frac{1}{2}^-}, S_z\rangle \\ \langle N(^4_8P_M)_{\frac{1}{2}^-}, S_z|H_{hyp}|N(^2_8P_M)_{\frac{1}{2}^-}, S_z\rangle & \langle N(^4_8P_M)_{\frac{1}{2}^-}, S_z|h_{hyp}|N(^4_8P_M)_{\frac{1}{2}^-}, S_z\rangle \end{pmatrix} \tag{6}$$

# Strangeness components

Wave function for $S_{11}$ resonances with strangness components:

$$|S_{11}\rangle = N[|S_{11}\rangle_{3q} + \frac{{}_{3q}\langle S_{11}|V_{cou}|\psi_{s\bar{s}}\rangle}{M_{S_{11}} - E_{s\bar{s}}}\psi_{s\bar{s}}] \qquad (7)$$

$$\psi_{s\bar{s}} = \sum_{abc} C^{[1^4]}_{[31]_a[211]_a} C^{[31]_a}_{[211]_b[22]_c} [4]_X[211]_F(b)[22]_S(c)[211]_C(a) \times \bar{\chi}_{s_z}\varphi(\{\vec{\xi}_i\}), \qquad (8)$$

[An and Riska, Eur. Phys. J. A **37**, 263 (2008)]
[An and Zou, Eur. Phys. J. A **39**, 195 (2009)]
[An and Saghai, in preparation]

# Formalism

Transition amplitude for $S_{11} \to MB$:

$$\begin{aligned} T^M &= \langle B|\hat{T}^M|S_{11}\rangle \\ &= \langle B|\hat{T}^M\{A_{3q}^{S_{11}}|qqq\rangle^{S_{11}} + A_{s\bar{s}}^{S_{11}}|qqqq\bar{q}\rangle^{S_{11}}\} \\ &= A_3^{S_{11}}\langle B|\hat{T}_3^M|qqq\rangle^{S_{11}} + A_{s\bar{s}}^{S_{11}}\langle B|\hat{T}_{53}^M|qqqq\bar{q}\rangle^{S_{11}} \\ &= \langle\hat{T}_D^M\rangle + \langle\hat{T}_{ND}^M\rangle \end{aligned} \tag{9}$$

Meson-quark-quark coupling:

$$\mathcal{L}_{Mqq} = i\frac{g_A^q}{2f_M}\bar{\psi}_q\gamma_5\gamma_\mu\partial^\mu m_a\lambda_a\psi_q\,. \tag{10}$$

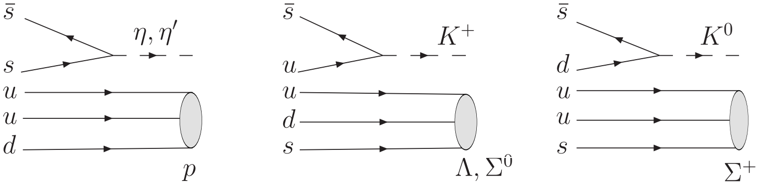
$\Rightarrow$ Diagonal transition operator:

$$\hat{T}_D^M = \sum_j \frac{g_A^q}{2f_M}\left(\frac{\omega_M}{E_f + M_f}\sigma\cdot\vec{P}_f - \sigma\cdot\vec{k}_M + \frac{\omega_M}{2\mu}\sigma\cdot\vec{p}_j\right)X_M^j\exp\{-i\vec{k}_M\cdot\vec{r}_j\}\,. \tag{11}$$

# Formalism

Non-diagonal transtion operator:

$$\hat{T}^{M}_{ND} = \sum_i \frac{g^q_A}{2f_M} C^i_{XFSC} (m_i + m_f) \bar{\chi}^{\dagger}_z \begin{pmatrix} 1 & -0 \\ 0 & 1 \end{pmatrix} \chi^i_z X^i_M \exp\{-i\vec{k}_M \cdot \vec{r}_j\} \,, \qquad (12)$$

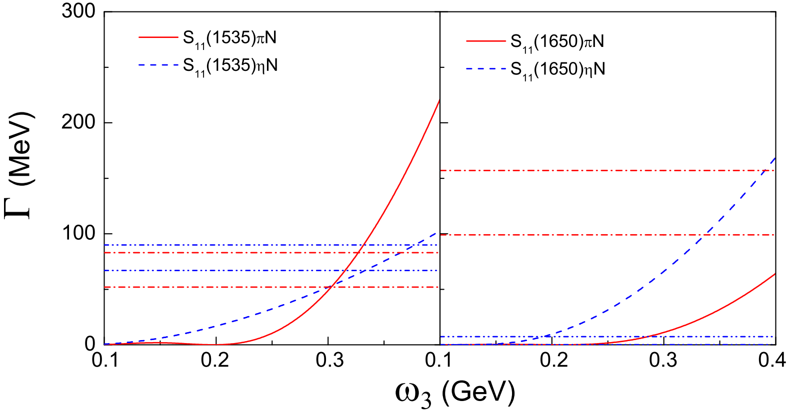


# 3 Numerical Results

## 3.1 $qqq$ model: $SU(6) \otimes O(3)$ conserved

Model parameters
(1) Constituent quark masses: $m = 0.34$, $m_s = 0.46$ GeV;
(2) Harmonic oscillator parameter: $\omega_3$ in range $0.1 - 0.4$ GeV

Decay widths $\Gamma_{\pi N}$ and $\Gamma_{\eta N}$ of $S_{11}(1535)$ and $S_{11}(1650)$ as functions of the oscillator parameter $\omega_3$:

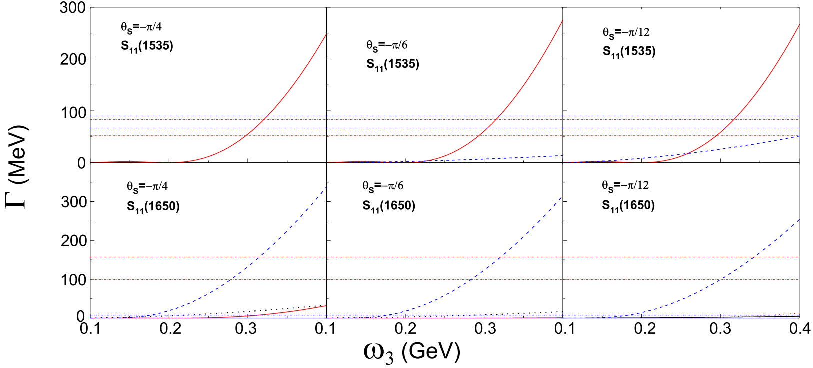


## 3.2 *qqq* model: $SU(6) \otimes O(3)$ broken

Model parameters
(1) Constituent quark masses: $m = 0.34$, $m_s = 0.46$ GeV;
(2) Harmonic oscillator parameter: $\omega_3$ in range $0.1 - 0.4$ GeV
(3) The mixing angle: $\theta_S$, $OGE \Rightarrow 32°$, $OBE \Rightarrow -13°$, we treat it as free parameter in the range $-\frac{\pi}{4}$ to $\frac{\pi}{4}$;

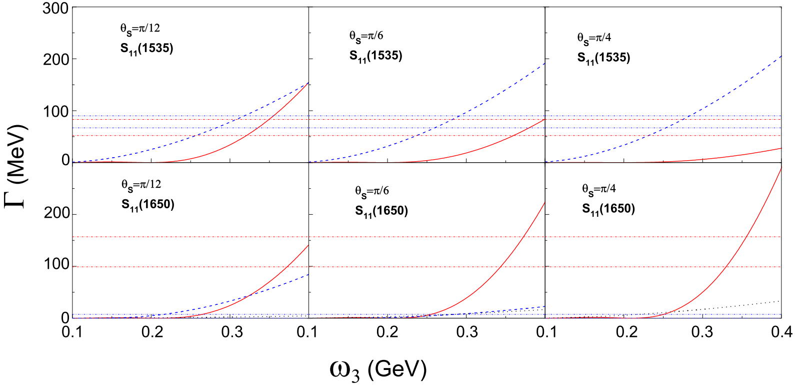
# *qqq* model with $SU(6) \otimes O(3)$ broken: $\theta_S < 0$

$S_{11}(1535)$ and $S_{11}(1650)$ decay widths as functions of $\omega_3$, $\theta_S$ is taken to be $-45°$, $-30°$ and $-15°$, respectively



# *qqq* model with $SU(6) \otimes O(3)$ broken: $\theta_S > 0$

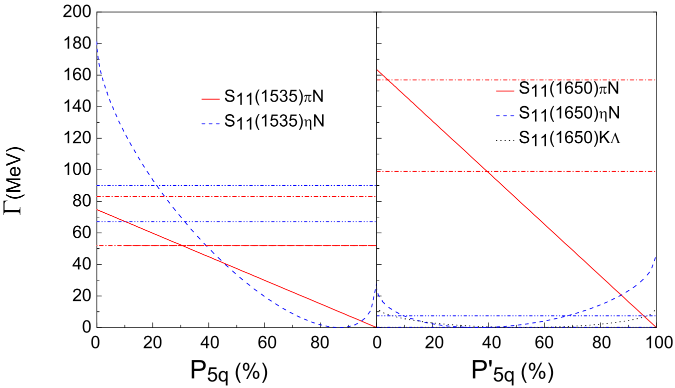
$S_{11}(1535)$ and $S_{11}(1650)$ decay widths as functions of $\omega_3$, $\theta_S$ is taken to be 15°, 30° and 45°, respectively



## 3.3 Results includ contributions of 5Q

Model parameters
(1) Constituent quark masses: $m = 0.29$, $m_s = 0.43$ GeV;
(2) Harmonic oscillator parameter: $\omega_3 = 0.34$ GeV, $\omega_5 = 0.6$ GeV;
(3) The mixing angle: $\theta_S$ in $0 - \frac{\pi}{4}$;
(4) Probabilities of 5Q: $P_{s\bar{s}} = 0 - 100\%$, $P'_{s\bar{s}} = 0 - 100\%$.

$\theta_S = 28°$:


Γ(MeV)
200
180
160
140
120
100
80
60
40
20
0
S11(1535)πN
S11(1535)ηN
S11(1650)πN
S11(1650)ηN
S11(1650)KΛ
0
20
40
60
80
100
P5q (%)
P'5q (%)

26.9°$< \theta_S <$ 29.8°;

$S_{11}(1535)$: $P_{s\bar{s}}$=21-30%; $S_{11}(1650)$: $P'_{s\bar{s}}$=11-18% $\Rightarrow$

Table: Strong decay widths for $S_{11}(1535)$ and $S_{11}(1650)$.

| $N^*$ | $\Gamma_{tot}$ | $\pi N$ | $\eta N$ | $K\Lambda$ | Ref |
|---|---|---|---|---|---|
| $S_{11}(1535)$ | 150 | 52 - 83 | 67 - 90 | | PDG2010 |
| | | 53 - 62 | 68 - 90 | | Present work |
| $S_{11}(1650)$ | 165 | 99 - 157 | 0.2 - 7.4 | 4.1 - 5.4 | PDG2010 |
| | | 138 - 148 | 1.7 - 7.3 | 4 - 5 | Present work |

# Numerical results for the coupling constants

Table: Coupling constants.

| $N^*$ | $\pi^0 p$ | $\pi^+ n$ | $\eta p$ | $K^+\Lambda$ | Ref. |
|---|---|---|---|---|---|
| 1535 | $\pm(0.68 \pm 0.08)$ | $\pm(0.96 \pm 0.11)$ | $\pm(2.07 \pm 0.15)$ | | Data |
| | -0.63 $\pm$ 0.03 | 0.89 $\pm$ 0.04 | -2.07 $\pm$ 0.15 | 1.76 $\pm$ 0.02 | $3Q + 5Q$ |
| | -0.54 $\pm$ 0.03 | 0.77 $\pm$ 0.04 | -2.67 $\pm$ 0.03 | 1.39 $\pm$ 0.03 | $3Q$ |
| 1650 | $\pm(0.89 \pm 0.10)$ | $\pm(1.26 \pm 0.14)$ | $\pm(0.27 \pm 0.20)$ | $\pm(0.53 \pm 0.04)$ | Data |
| | -0.94 $\pm$ 0.02 | 1.33 $\pm$ 0.03 | 0.35 $\pm$ 0.12 | 0.51 $\pm$ 0.03 | $3Q + 5Q$ |
| | -0.75 $\pm$ 0.02 | 1.06 $\pm$ 0.03 | 0.70 $\pm$ 0.10 | 0.78 $\pm$ 0.05 | $3Q$ |

Data:

$$\Gamma^{PDG}_{S_{11}\to MB} = \frac{1}{4\pi} g^2_{S_{11}MB} \frac{E_f + M_f}{M_i} |\vec{k}_M| \,, \tag{13}$$

# Continued:

Table: Coupling constants.

| $N^*$ | $K^0\Sigma^+$ | $K^+\Sigma^0$ | $\eta' p$ | Ref. |
|---|---|---|---|---|
| $S_{11}(1535)$ | | | | |
| | 1.81 $\pm$ 0.06 | -1.28 $\pm$ 0.04 | 3.33 $\pm$ 0.10 | $3Q + 5Q$ |
| | 1.03 $\pm$ 0.04 | -0.73 $\pm$ 0.03 | 3.20 $\pm$ 0.04 | $3Q$ |
| $S_{11}(1650)$ | | | | |
| | -2.17 $\pm$ 0.05 | 1.53 $\pm$ 0.04 | -1.62 $\pm$ 0.14 | $3Q + 5Q$ |
| | -1.36 $\pm$ 0.04 | 0.96 $\pm$ 0.03 | -1.35 $\pm$ 0.17 | $3Q$ |

$S_{11}(1535) \Rightarrow |g_{\pi^0 p}| < |g_{\pi^+ n}| < |g_{K^+\Sigma^0}| < |g_{K^+\Lambda}| \sim |g_{K^0\Sigma^+}| \leq |g_{\eta P}| < |g_{\eta' p}|$
$S_{11}(1650) \Rightarrow |g_{\eta p}| < |g_{K^+\Lambda}| < |g_{\pi^0 p}| < |g_{\pi^- p}| \leq |g_{K^+\Sigma^0}| \sim |g_{\eta' p}| < |g_{K^0\Sigma^+}|$

# Conclusion

- By *qqq* model without or with $SU(6) \otimes O(3)$ breaking, strong decays data cannot be reproduced;
- 26.9°$< \theta_S <$ 29.8°, $P_{s\bar{s}} = 21 - 30\%$ and $P'_{s\bar{s}} = 11 - 18\%$: With the contributions of the 5Q components, results are in excellent agreement with data;
- The two resonances couple strongly to strangeness channels;
- Role of the five-quark components in the meson production dominated by these two resonances is under investigation.

Thank you very much for your attention!

Hyperfine interaction between the quarks:

$$H_{hyp}^{OGE} = \sum_{i<j} \frac{2\alpha_s}{3m_i m_j} \{ \frac{8\pi}{3} \vec{S}_i \cdot \vec{S}_j \delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3} [ \frac{3\vec{S}_i \cdot \vec{r}_{ij} \vec{S}_j \cdot \vec{r}_{ij}}{r_{ij}^2} - \vec{S}_i \cdot \vec{S}_j ] \} \tag{14}$$

[N. Isgur and G. karl, Phys. Rev. D 18, 4187 (1978).]

$$H_{hyp}^{OBE} = [\sum_{i<j}\sum_{F}\frac{g^2}{4\pi}\frac{1}{12m_im_j}\vec{\sigma}_i\cdot\vec{\sigma}_j\vec{\lambda}_i^F\cdot\vec{\lambda}_j^F(\mu^2\frac{e^{-\mu r_{ij}}}{r_{ij}} - 4\pi\delta(\vec{r}_{ij}))] + H_T \quad (15)$$

$$H_T = \sum_{i<j}\sum_{F}\frac{g^2}{4\pi}\frac{1}{12m_im_j}\frac{\mu^2 e^{-\mu r_{ij}}}{r_{ij}}(1+\frac{3}{\mu r_{ij}}+\frac{3}{\mu^2 r_{ij}^2})\vec{\lambda}_i^F\cdot\vec{\lambda}_j^F(\frac{3\vec{\sigma}_i\cdot\vec{r}_{ij}\vec{\sigma}_j\cdot\vec{r}_{ij}}{r_{ij}^2} - \vec{\sigma}_i\cdot\vec{\sigma}_j) \quad (16)$$

[Glozman and Riska, Phys. Rept. **268**, 263 (1996).]

$\Rightarrow \theta_S^{OGE} \simeq 32°, \theta_S^{OBE} \simeq -13°$

## Vector meson exchange

[L. Ya. Glozman, nucl-th/9909021 (1999)]

[R. Wagenbrunn, L. Ya. Glozman, W. Plessas, K. Varga, Nucl. Phys. A 663, 703c (2000) ]

$26.9° < \theta_S < 29.8°$;
$S_{11}(1535)$: $P_{s\bar{s}}$=21-30%; $S_{11}(1650)$: $P'_{s\bar{s}}$=11-18% $\Rightarrow$

| $N^*$ | $\Gamma_{tot}$ | $\pi N$ | $\eta N$ | $K\Lambda$ | Approach |
|---|---|---|---|---|---|
| $S_{11}(1535)$ | 150 | 52 - 83 | 67 - 90 | | PDG2010 |
| | | 53 - 62 | 68 - 90 | | Present work |
| | | 22.4 | 70.1 | | Chiral Unitary [1] |
| | | 22.1 | 60.8 | | Chiral Unitary [1] |
| | 142 | | 50 | | Disp. Rel. [2] |
| | 195 | | 50 | | Isobar [2] |
| $S_{11}(1650)$ | 165 | 99 - 157 | 0.2 - 7.4 | 4.1 - 5.4 | PDG2010 |
| | | 138 - 148 | 1.7 - 7.3 | 4 - 5 | Present work |
| | 85 | | 3.8 | | Disp. Rel. [2] |
| | 125 | | 5.5 | | Isobar [2] |
| | 197 | 177 | 20 | 0 | Meson exchange [3] |

[1] T. Inoue, E. Oset and M. J. Vincente Vacas, PRC 65, 035204 (2002).
[2] I. G. Aznauryan, Phys. Rev. C 68, 065204 (2003).
[3] K. Nakayama and H. Haberzettl, Phys. Rev. C 69, 065212 (2004).

| $N^*$ | $\pi^0 p$ | $\pi^+ n$ | $\eta p$ | $K^+\Lambda$ | $K^0\Sigma^+$ | $K^+\Sigma^0$ | $\eta' p$ | Ref. |
|---|---|---|---|---|---|---|---|---|
| $S_{11}(1535)$ | -0.63 $\pm$ 0.03 | 0.89 $\pm$ 0.04 | -2.07 $\pm$ 0.15 | 1.76 $\pm$ 0.02 | 1.81 $\pm$ 0.06 | -1.28 $\pm$ 0.04 | 3.33 $\pm$ 0.10 | |
| | $\pm$0.39 | $\pm$0.56 | $\pm$1.84 | $\pm$0.92 | $\pm$2.12 | $\pm$1.50 | | [1] |
| | 0.39 | $-$0.57 | 1.77 | $-$1.28 | $-$2.36 | 1.67 | | [1] |
| | $\pm$0.64 | | $\pm$1.88 | | | | $\pm$3.72 | [2] |
| $S_{11}(1650)$ | -0.94 $\pm$ 0.02 | 1.33 $\pm$ 0.03 | 0.35 $\pm$ 0.12 | 0.51 $\pm$ 0.03 | -2.17 $\pm$ 0.05 | 1.53 $\pm$ 0.04 | -1.62 $\pm$ 0.14 | |
| | $\pm$1.18 | | $\pm$0.68 | $\pm$0.80 | | | | [3] |
| | 0.81 | | | 0.76 | | | | [4] |

$S_{11}(1535) \Rightarrow |g_{\pi^0 p}| < |g_{\pi^+ n}| < |g_{K^+\Sigma^0}| < |g_{K^+\Lambda}| \sim |g_{K^0\Sigma^+}| \leq |g_{\eta P}| < |g_{\eta' p}|$
$S_{11}(1650) \Rightarrow |g_{\eta p}| < |g_{K^+\Lambda}| < |g_{\pi^0 p}| < |g_{\pi^- p}| \leq |g_{K^+\Sigma^0}| \sim |g_{\eta' p}| < |g_{K^0\Sigma^+}|$

[1] T. Inoue, E. Oset and m. J. Vincente Vacas, PRC 65, 035204 (2002).
[2] X. Cao and X. G. Lee, Phys. Rev. C 78, 035207 (2008).
[3] A. Sibirtsev, K. Tsushima and A. W. Thomas, Phys. Lett B 421, 59 (1998).
[4] R. Shyam, H. Lenske and U. Mosel, Phys. Rev. C 69, 065205 (2004).

$$F = \frac{\Lambda^4}{\Lambda^4 + (q_{N^*}^2 - M_{N^*}^2)^2}\,, \tag{17}$$