On baryon resonances and chiral symmetry

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Quark mass dependence of of s-wave baryon resonances

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4 Baryon resonances and coupled-channel dynamics

4 Chiral coupled-channels: the χ-BS(3) approach

4 Predictions for:
- $J^P = \frac{1}{2}^-$ baryon resonances
- $J^P = \frac{3}{2}^-$ baryon resonances

4 Conclusion

Resonances and coupled-channel dynamics

- **Coupled-channels dynamics:**

  - $\Lambda(1405)$ resonance as $\bar{K}N$ quasi-bound state
    - Dalitz, Wyld, Rajeskaran, Logan, Weise, Siegel, Kaiser, Oset, Ramos, Lutz, Kolomeitsev, ...
  - known good candidates: $N(1535)$, $N(1520)$ and $\Lambda(1520)$
  - similar arguments for $N(1440)$ - Jülich group
  - 0^+ meson resonances - Beveren, Weinstein, Isgur, Janssen, Pearce, Holinde, Speth, Oller, Oset, Pelaez, ...

- **Conjecture:**

  excited baryonic and mesonic resonances generated by coupled channel dynamics

- **Extension to charm sector**

Chiral SU(3) interaction terms and large-N_c QCD

- **Large-N_c ground states:**

  - Goldstone boson octet $\Phi_{[8]} = \left(\pi\,, K\,, \overline{K}\,, \eta\right)$
  - Vector meson nonet $\Phi^{\mu}_{[9]} = \left(\rho^{\mu}\,, K^{\mu}\,, \overline{K}^{\mu}\,, \omega^{\mu}\,, \phi^{\mu}\right)$
  - Baryon octet $B_{[8]} = \left(N\,, \Sigma\,, \Lambda\,, \Xi\right)$
  - Baryon decuplet $B_{[10]} = \left(\Delta\,, \Sigma^*\,, \Xi^*\,, \Omega\right)$

- **Systematic approximation strategy:**

expand in *powers* of the small current quark masses, momenta and $1/N_c$

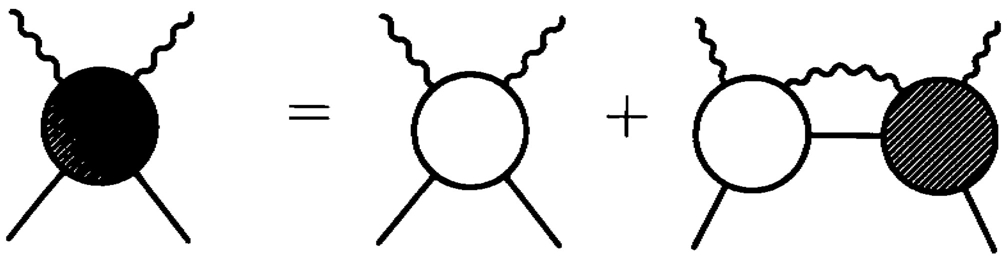
$$\frac{m_{\rm quark}}{\Lambda_{\chi SB}} \ll 1\,, \qquad \frac{1}{N_c} \ll 1$$

  - heavy fields: $M_{[8,9,10]} \sim \Lambda_{\chi SB}$ but $M_{[10]} - M_{[8]} \sim \frac{1}{N_c}$
  - light Goldstone bosons: $m_{[8]} \sim m^{1/2}_{\rm quark}$

Coupled-channel Bethe-Salpeter equation

- **Scattering amplitude:**

$$\langle M(\bar{q})\, B(\bar{p})|\, T\, |M(q)\, B(p)\rangle = (2\pi)^4\, \delta^4(q+p-\bar{q}-\bar{p})$$
$$\times \bar{u}_B(\bar{p})\, T_{MB\to MB}(\bar{q},\bar{p};q,p)\, u_B(p)\,,$$

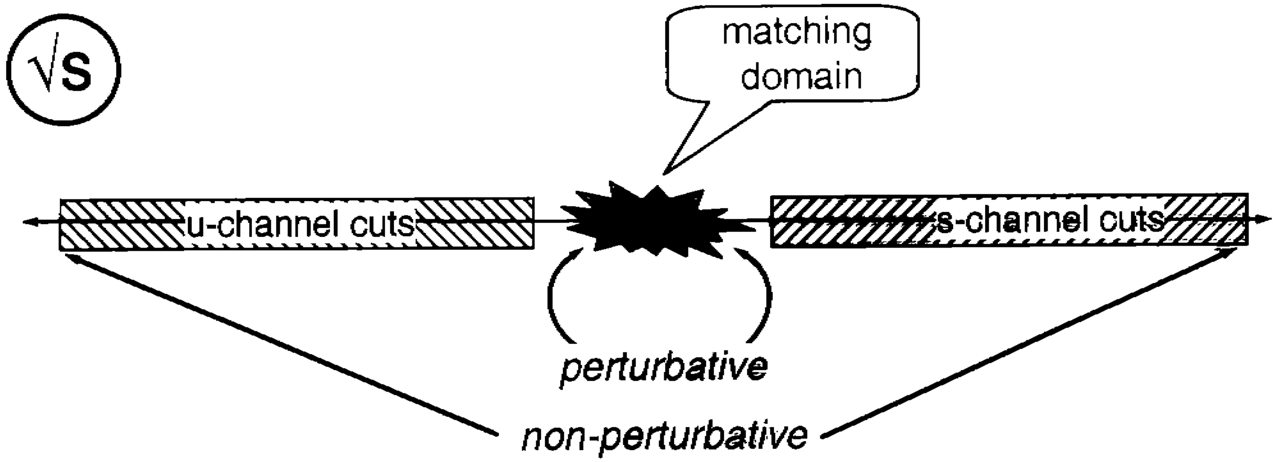


- **Compact notation:** $T = K + K\cdot G\cdot T$

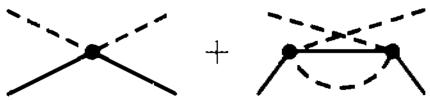
  – K – interaction kernel
  – G – two-particle propagator

- **Strategy:** Chiral expansion of interaction kernel K

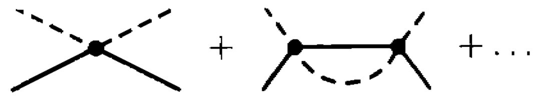
Matching of s- and u-channel unitarized amplitudes



- **Approximated crossing symmetry:**



$$+\cdots \Longrightarrow T_{\mathrm{u-chan.}}(\mu) \sim T_{\mathrm{s-chan.}}(\mu) \Longleftarrow$$



$$T = \begin{cases} T_{\mathrm{s-chan.}} & \text{if} \quad \sqrt{s} > \mu \\ T_{\mathrm{u-chan.}} & \text{if} \quad \sqrt{s} < \mu \end{cases}$$

- **Renormalization condition:** $T^{(J,P)}(\sqrt{s} = \mu) = V^{(J,P)}(\sqrt{s} = \mu)$

- **Optimal subtraction point** e.g., for πH-scattering $\rightarrow \mu = m_H$

Optimal subtraction point for pion-hadron scattering

- **chiral counting** only if $\mu \sim m_H$ the loop-function J satisfies chiral counting

- **constrains from regularization scheme**

  - dimensional regularization relates loop-functions of different partial waves
    $\Longrightarrow$ μ should be the same in all partial waves

- **hadron exchange processes**

  - balance of s- and u-channel exchanges
    $\Longrightarrow$ protect s-channel pole ! $\longrightarrow \mu = m_H$

- **constraints from photon channels**

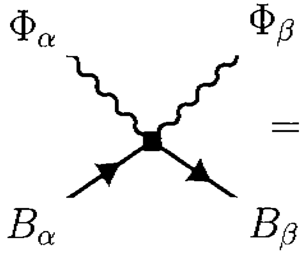
  - $\pi H \to \pi H$ contributes to $\gamma H \to \gamma H$ due to $\gamma H \to \pi H$
    crossing symmetry for $\gamma H \to \gamma H \longrightarrow \mu = m_H$

    e.g. $\pi N \to \pi N$: $\mu = m_N$; $\pi \Lambda \to \pi \Lambda$: $\mu = m_\Lambda$

Large-N_C and chiral SU(3) at leading order

- **Weinberg–Tomazawa term**

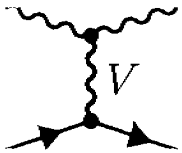
$$\mathcal{L}_{\rm WT} = \frac{i}{8\,f^2}\,{\rm Tr}\,\bar{B}_{[8]}\,\gamma_\mu \left[\left[\Phi_{[8]}, (\partial^\mu \Phi_{[8]})\right]_-, B_{[8]}\right]_-$$
$$+ \frac{3\,i}{8\,f^2}\,{\rm Tr}\,g_{\alpha\beta}\left(\bar{B}^\alpha_{[10]}\,\gamma^\mu\;B^\beta_{[10]}\right)\cdot\left[\Phi_{[8]}\,,(\partial_\mu \Phi_{[8]})\right]_-\,,$$



$$= \frac{C_{\alpha,\beta}}{4\,f^2}\left(\not{k}_\alpha + \not{k}_\beta\right)$$ ← — linear in meson 4-momentum

- **Represents vector meson t-channel exchange**

$$\sum_{\text{vector mesons}}$$



$$\Longrightarrow \quad \mathcal{K}\,C_{\alpha,\beta}\left(\not{k}_\alpha + \not{k}_\beta\right)$$

- **Pion-decay constant**

$$f \Longleftrightarrow f_K/f \sim 1.07 \pm 0.12$$
$$f_\pi \simeq 92.42 \pm 0.33 \text{ MeV and } f_K \simeq 113.0 \pm 1.3 \text{ MeV}$$

Parity-flip reactions in s-wave

- **meson-baryon**

$$0^- + \frac{1}{2}^+ \to \frac{1}{2}^- \to 0^- + \frac{1}{2}^+$$

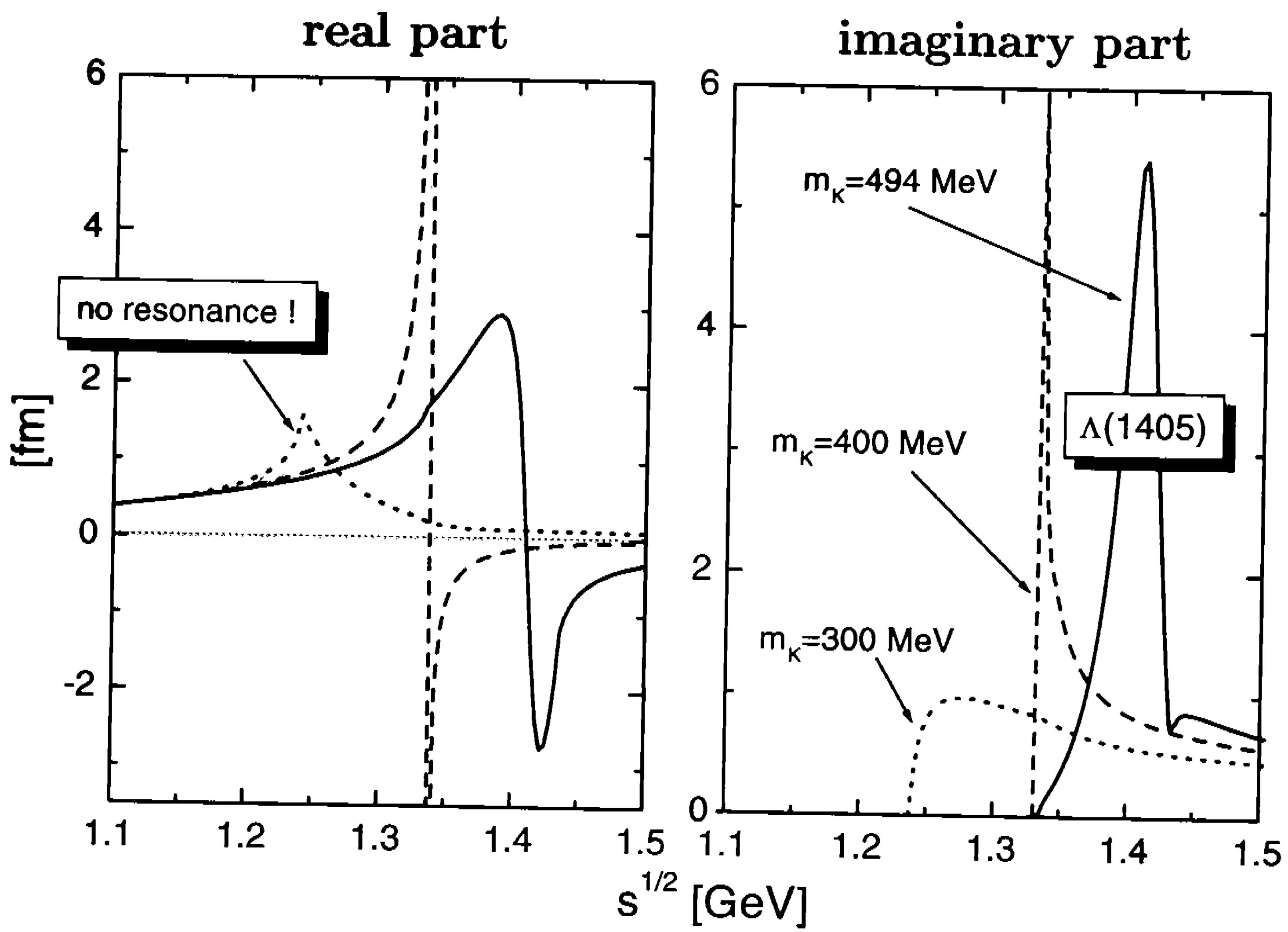
$$0^- + \frac{3}{2}^+ \to \frac{3}{2}^- \to 0^- + \frac{3}{2}^+$$

- **meson-meson**

$$0^- + 0^- \to 0^+ \to 0^- + 0^-$$

$$0^- + 1^- \to 1^+ \to 0^- + 1^-$$

Antikaon-Nucleon S-wave amplitude (Q^1)



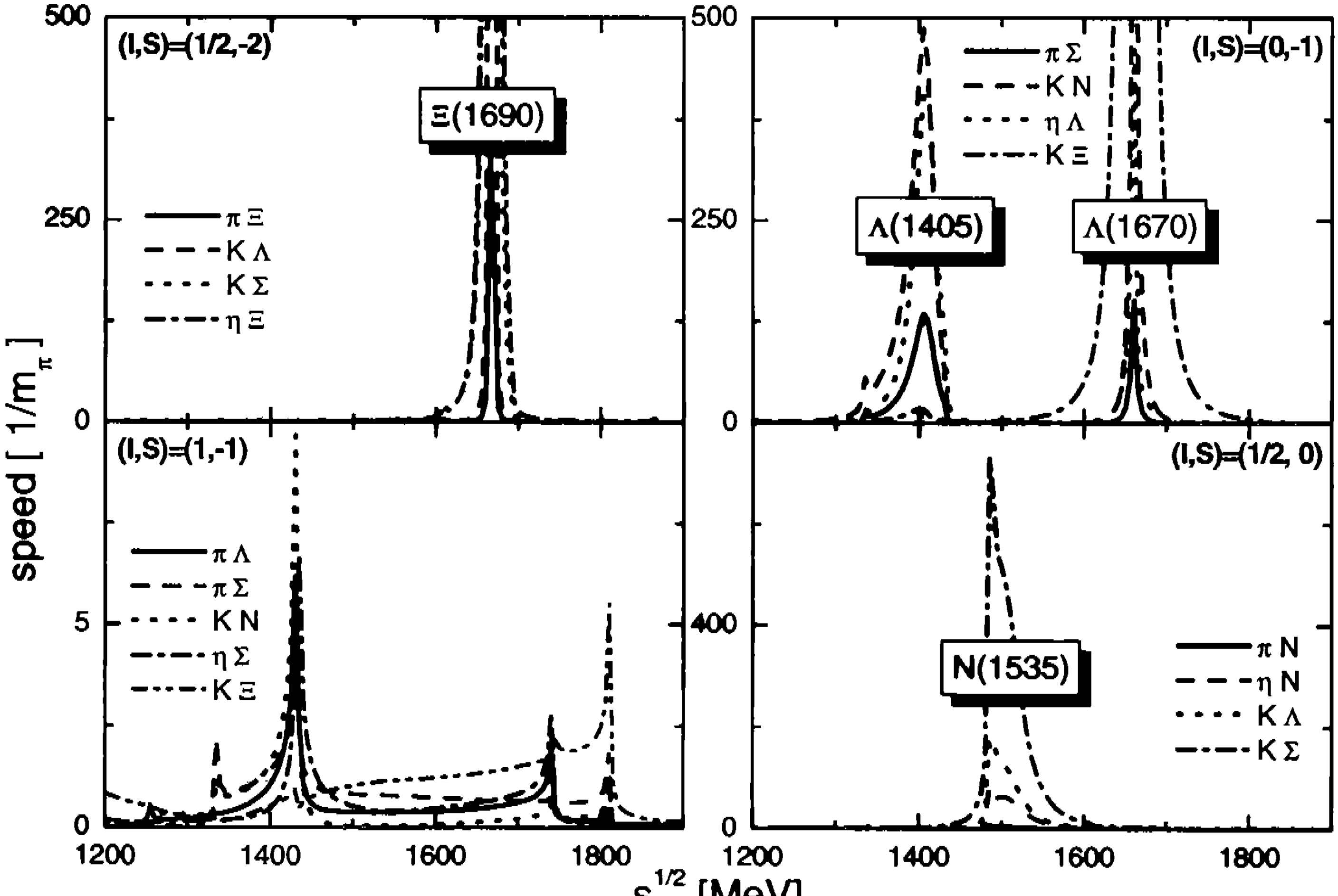
Found. Phys. **31** (2001)

- **Parameter free result:** use $f_\pi = 93$ MeV

- Λ(1405) **resonance dynamically generated:**

  disappears at $m_K = 300$ MeV

$J^P = \frac{1}{2}^-$ baryon resonances (Q^1)



nucl-th/0305100, nucl-th/0305101

- **Parameter free result:** use $f_\pi = 90$ MeV
- **Chiral SU(3) symmetry:** 2 octets and singlet

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \overline{\mathbf{10}} \oplus \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$$

- **Predictions:**
  - strong signals: $N(1535)$, $\Lambda(1405)$, $\Lambda(1670)$ and $\Xi(1690)$
  - weak signals: $N(1650)$, $\Xi(1620)$ and $\Sigma(1620)$, $\Sigma(1750)$

SU(3) limit

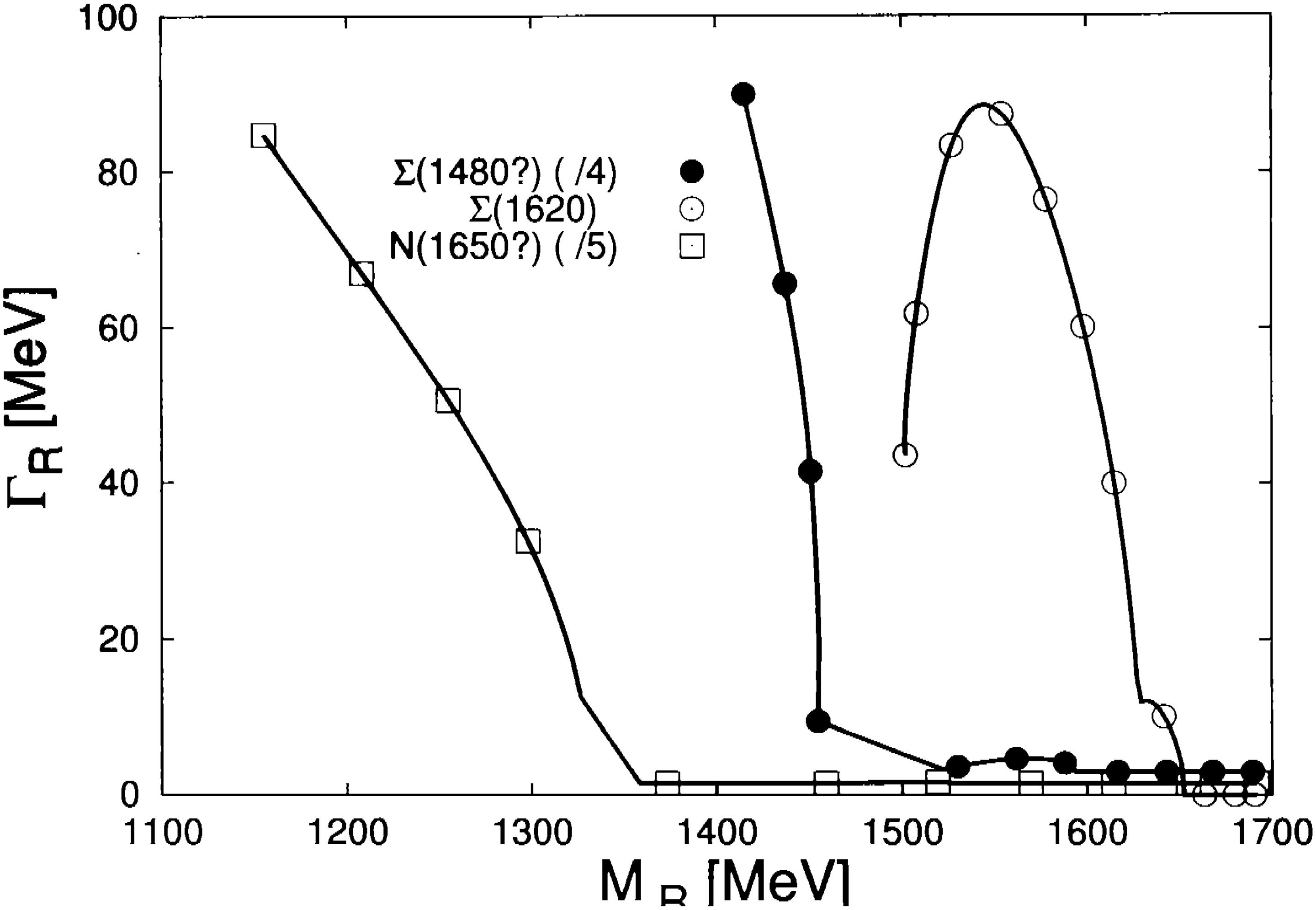
- **"heavy" SU(3) limit** :

$$m_\pi = m_\eta = m_K = 495 \text{ MeV}$$

- **"light" SU(3) limit** :

$$m_K = m_\eta = m_\pi = 139 \text{ MeV}$$

Quark-mass dependence of $J^P = \frac{1}{2}^-$ states



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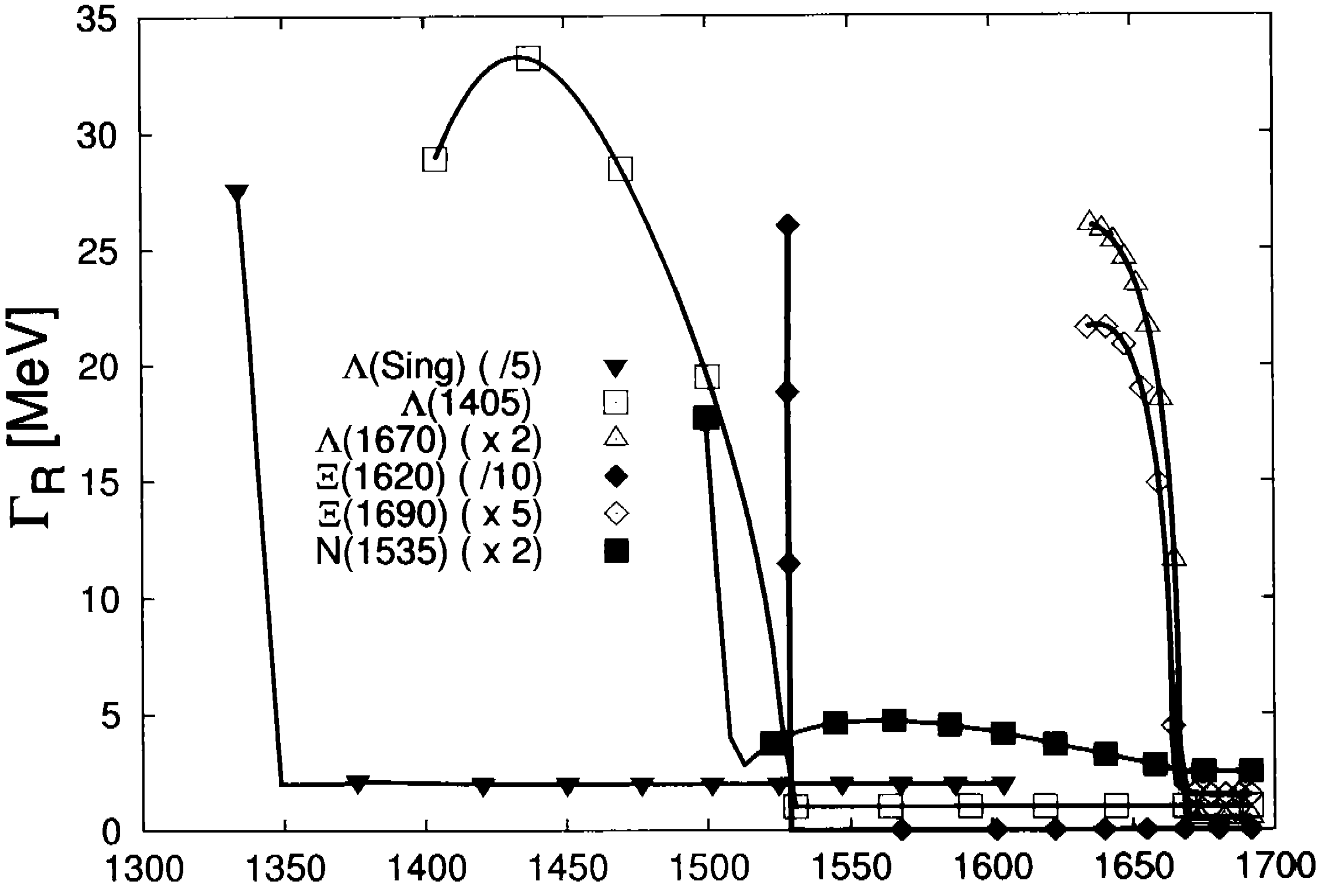
- **Parameter free result:** use $f_\pi = 90$ MeV

- **Quark-mass dependence via:**

$$m_\pi^2\big|_{\mathrm{SU}(3)} = m_\pi^2 + x(m_K^2 - m_\pi^2), \quad x \in [0,1]\,. \qquad (2)$$

- **Physical quark masses:**
  - weak signals: $N(1650)$, $\Xi(1620)$ and $\Sigma(1620)$, $\Sigma(1750)$

Quark-mass dependence of $J^P = \frac{1}{2}^-$ states



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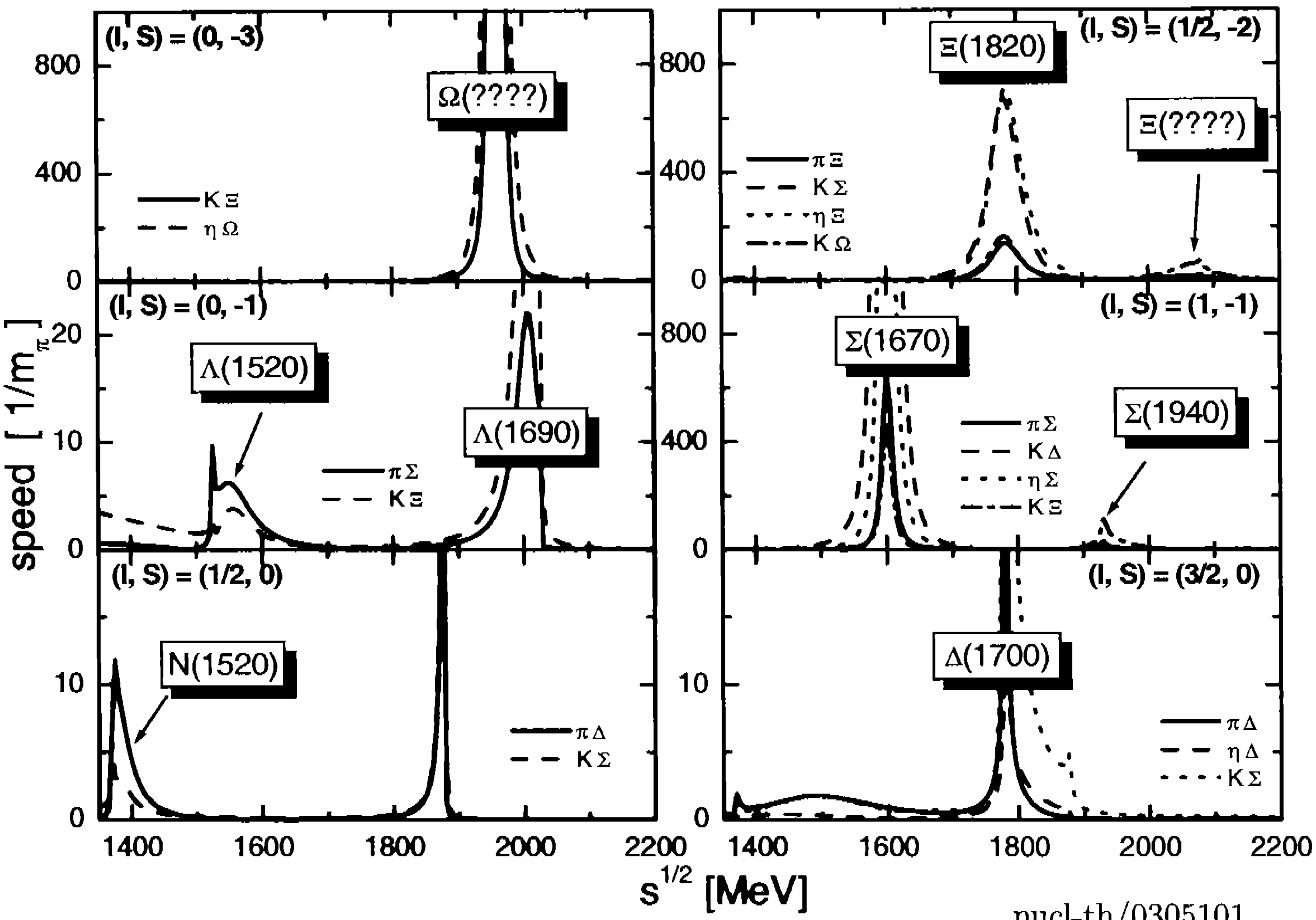
  - strong signals: $N(1535)$, $\Lambda(1405)$, $\Lambda(1670)$ and $\Xi(1690)$

$J^P = \frac{3}{2}^-$ baryon resonances (Q^1)



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- **Parameter free result:** use $f_\pi = 90$ MeV

- **Chiral SU(3) symmetry:** decuplet and octet

$$8 \otimes 10 = 35 \oplus 27 \oplus 10 \oplus 8$$

- **Predictions:**
  - a decuplet bound state in $(0, -3)$-sector
  - a 27-plet state in $(0, -1)$-sector

Summary

Conjecture: meson and baryon resonances that do not belong to the large-N_c ground states are dynamically generated by coupled-channel dynamics

- degrees of freedom: large-N_c meson and baryon ground-state fields
- chiral symmetry dynamically generates meson and baryon resonances
- at leading order: parameter-free prediction for baryon and meson resonances in light-quark and heavy-quark sectors
- prediction of new multiplets