Crypto-exotic baryons with charm

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✔ **Dynamic generation of resonances:** *40 years of history!*

- $\Lambda(1405) \longleftrightarrow (\bar{K}\,N)$: Dalitz, Wyld, Rajasekaran, Weise, Siegel, ...
- $N(1535) \longleftrightarrow (K\,\Sigma)$: Dalitz, Wyld, Weise, Kaiser, Oset, ...
- $\Lambda(1520) \longleftrightarrow (\bar{K}_\mu\,N)$: Ball, Frazer, Aaron, Amado, ...
- $f_0(980) \longleftrightarrow (K\,\bar{K})$: Van Beveren, Isgur, Pelaez, ...

✔ **Conjecture:** Found. Phys. (2001)

Excited baryon and meson resonances generated by coupled-channel dynamics

Do charmed pentaquarks states exist?

- **Lipkin 1987:** discusses pentaquarks with $C = -1$ and $J^P = \frac{1}{2}^-$
  favours $S = -1$ and $S = -2$ channels — Phys. Lett. B195

- **Genovese et al 1998:** not sufficient binding in quark model — Phys. Lett. B425

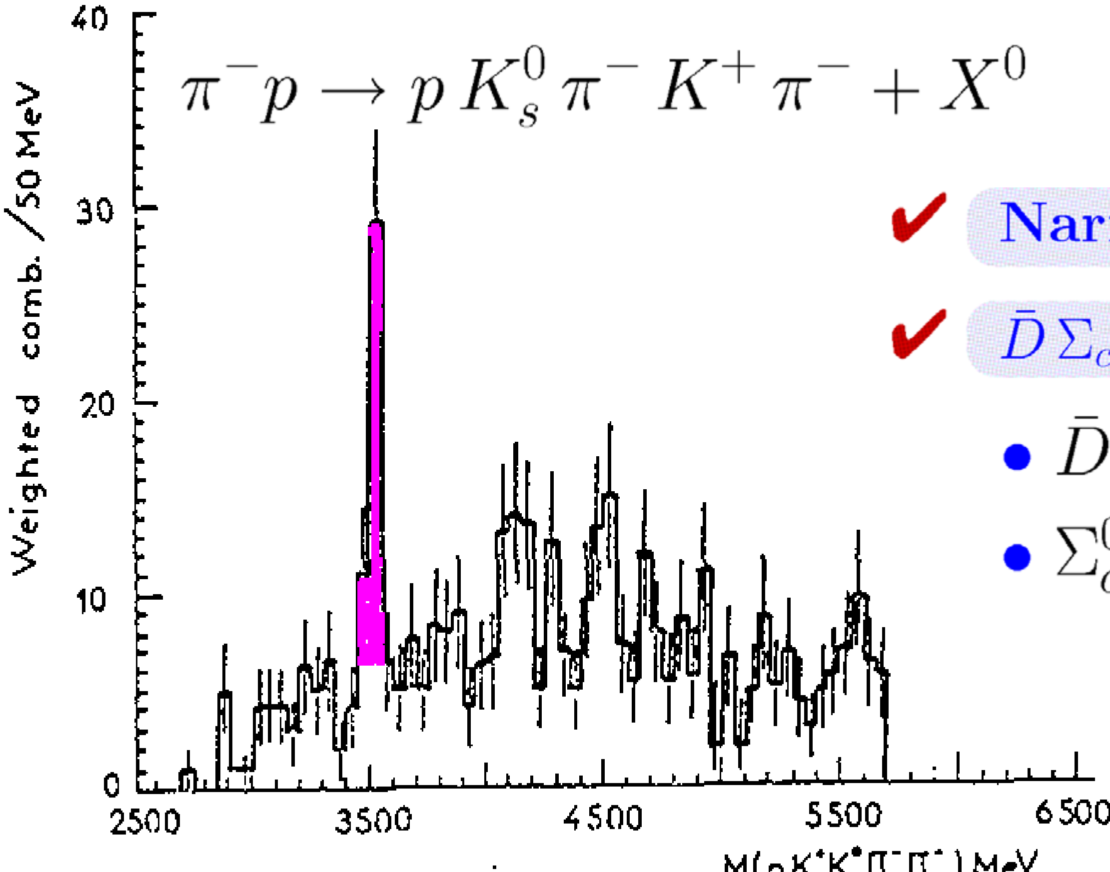
- **H1 collaboration 2004:** signal in $D^*_- p$ and $\bar{D}^*_+ \bar{p}$ invariant mass at 3.099 GeV — Phys. Lett. B588

- **Kim et al. 2004:** QCD sum rules suggest H1 signal $J^P = \frac{1}{2}^+$ — Phys. Lett. B595

- **FOCUS collaboration 2005:** no signal in $D^*_- p$ and $D_- \, p$ invariant mass — Phys. Lett. 2005

Do crypto exotic baryons exist?

✔ **Hints from** bubble chamber experiment with 19 GeV π^- beam



$$\pi^- p \rightarrow p\, K_s^0\, \pi^-\, K^+\, \pi^- + X^0$$

✔ **Narrow N(3520) state?**

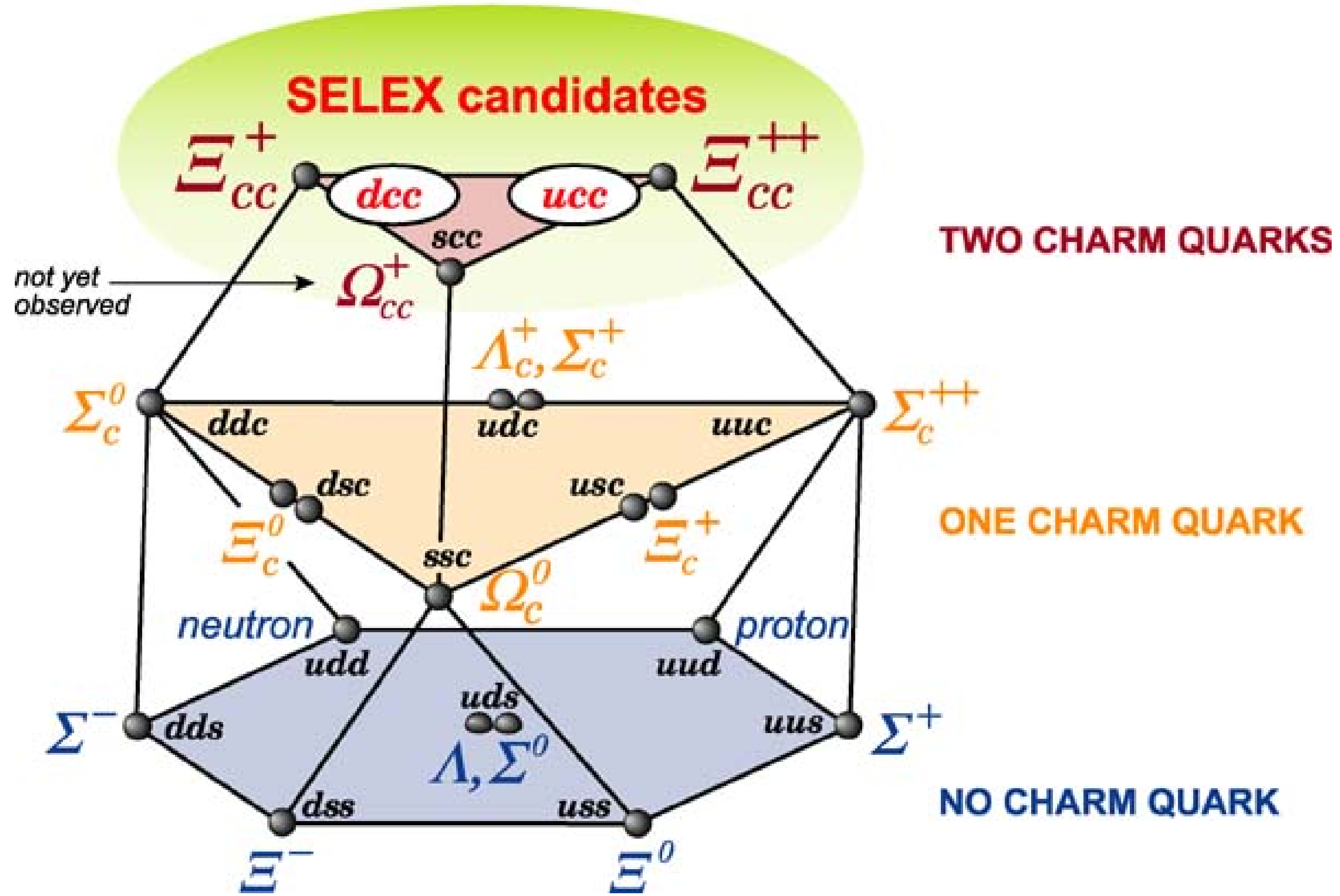
✔ **$\bar{D}\,\Sigma_c$ molecule?**

- $\bar{D}^0 \rightarrow K^+\,\pi^-$ (3.8%)
- $\Sigma_c^0 \rightarrow \Lambda_c^+\,\pi^-$ (100%)
  $\rightarrow (p\,\bar{K}^0)\,\pi^-$ (2.3%)

V.M. Karnauhkov et al., Phys. Lett. B281 (1991) 148

Degrees of freedom I)

✔ $J^P = \frac{1}{2}^+$ ground states:



Picture taken from SELEX

Degrees of freedom II)

✔ $J^P = 0^-$ **ground states:**

$$\Phi_{[16]} = \begin{pmatrix} \pi_0 + \frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & \sqrt{2}\,\pi_+ & \sqrt{2}\,K_+ & \sqrt{2}\,\bar{D}^0 \\ \sqrt{2}\,\pi_- & -\pi_0 + \frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & \sqrt{2}\,K^0 & -\sqrt{2}\,\bar{D}^- \\ \sqrt{2}\,\bar{K}^- & \sqrt{2}\,\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & \sqrt{2}\,\bar{D}_s^- \\ \sqrt{2}\,D^0 & -\sqrt{2}\,D^+ & \sqrt{2}\,D_s^+ & \sqrt{2}\,\eta_c \end{pmatrix}$$

✔ $J^P = 1^-$ **ground states**

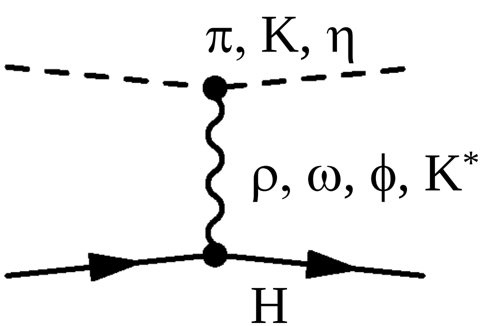
$$V^{\mu}_{[16]} = \begin{pmatrix} \rho_0^{\mu} + \omega^{\mu} & \sqrt{2}\,\rho_+^{\mu} & \sqrt{2}\,K_+^{\mu} & \sqrt{2}\,\bar{D}_0^{\mu} \\ \sqrt{2}\,\rho_-^{\mu} & -\rho_0^{\mu} + \omega^{\mu} & \sqrt{2}\,K_0^{\mu} & -\sqrt{2}\,\bar{D}_-^{\mu} \\ \sqrt{2}\,\bar{K}_-^{\mu} & \sqrt{2}\,\bar{K}_{*0}^{\mu} & \sqrt{2}\,\phi^{\mu} & \sqrt{2}\,\bar{D}_-^{s,\mu} \\ \sqrt{2}\,D_0^{\mu} & -\sqrt{2}\,D_+^{\mu} & \sqrt{2}\,D_+^{s,\mu} & \sqrt{2}\,J/\Psi^{\mu} \end{pmatrix}$$

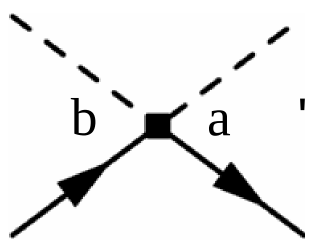
Effective interaction I)

✔ **Chiral SU(3) symmetry:** predicts s-wave interaction of Goldstone bosons with any hadron (H)

- $(\pi\,,K\,,\bar{K}\,,\eta)\otimes(D\,,D_s) \quad\leftrightarrow\quad 8\otimes\bar{3}=\bar{3}\oplus 6\oplus\overline{15}$ molecules !
- $(\pi\,,K\,,\bar{K}\,,\eta)\otimes(\Lambda_c\,,\Xi_c) \quad\leftrightarrow\quad 8\otimes 3=3\oplus \bar{6}\oplus 15$ molecules !

✔ **Universally coupled vector mesons:** recovers chiral constraints





$$\frac{C_{ab}^{(I,S,C)}}{8\,f_\pi^2}\left(2\,\sqrt{s}-M_a-M_b\right)$$

Weinberg-Tomozawa theorem

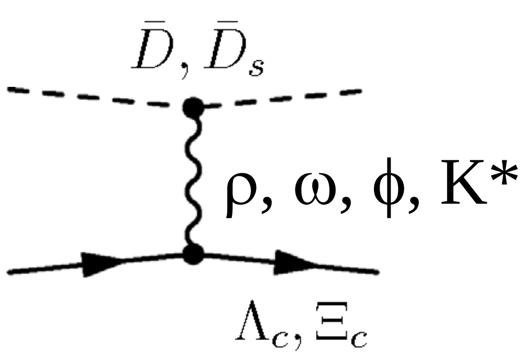
Effective interaction II)

✔ **Effective Lagrangian density**

$$\mathcal{L}^{\mathrm{SU}(4)}_{\mathrm{int}} = \frac{i}{4}\, g\, \mathrm{tr}\left(\left[(\partial_\mu \Phi_{[16]}), \Phi_{[16]} \right]_- V^\mu_{[16]} \right) + \frac{1}{4}\, g \sum_{i,j,k,l=1}^{4} \bar{B}^{[20]}_{ijk}\, \gamma^\mu \left(V^{[16],k}_{\mu,l}\, B^{ijl}_{[20]} + 2\, V^{[16],j}_{\mu,l}\, B^{ilk}_{[20]} \right)$$

- Univeral vector coupling constant g
- KSFR relation: $g = \frac{m_\rho}{\sqrt{2}\, f_\pi}$

} consistent with chiral constraints !



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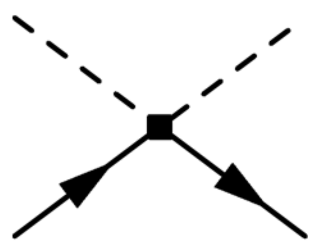


$$\simeq \sum_{V \in [16]} \frac{g^2}{m_V^2}\, C_V \left(2\sqrt{s} - M - \bar{M} \right)$$

SU(4) breaking pattern

✔ **Determination of universal coupling constant**

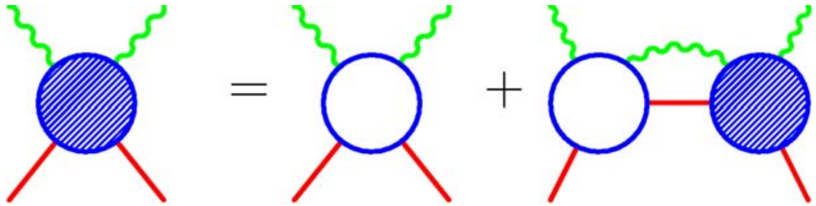
- from $\rho^0 \to \pi^+\pi^-$ decay: $g \simeq 5.8 \pm 0.4$
- from $D_*^+ \to D^0\,\pi^+$ decay: $g \simeq 10.4 \pm 1.4$
- from KSFR relation: $g \simeq 7.0 \pm 1.0$

✔ **Moderate SU(4) breaking in 3-point vertices !?**

✔ **To be addressed by Lattice QCD**

Coupled-channel Bethe-Salpeter equation

✔ **Scattering amplitude:**



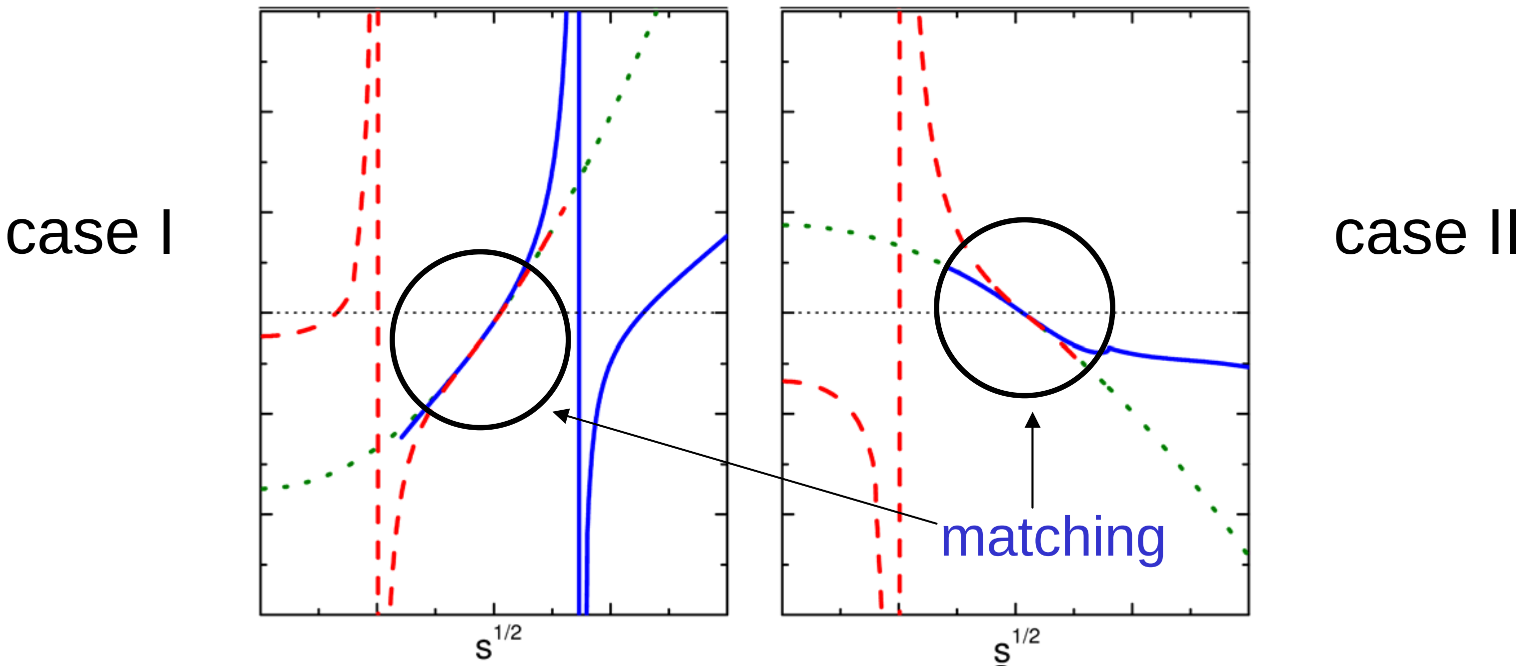
✔ **Strategy:** *chiral and large-N_c expansion of effective interaction kernel*

✔ **Covariant projection operators:** *covariant partial wave expansion*

✔ **Crossing symmetry:** Match u- and s-channel amplitudes

Crossing-symmetric scattering amplitudes

Typical forward scattering amplitude



✔ **Gluing of s- and u-channel unitarized amplitudes:**

- requires good matching properties
- by construction: exact crossing symmetry in physical region
- approximate crossing symmetry at subthreshold energies

Coupled-channel dynamics for C=-1 molecules

$C=-1: \ (I, \ S)$	state	M_R [MeV] Γ_R [MeV]	$\lvert g_R \rvert$	M_R [MeV] Γ_R [MeV]	$\lvert g_R \rvert$
$(\frac{1}{2}, -1)$	$\bar{D}_s N$	2687	3.8	2780	3.3
	$\bar{D}\,\Lambda$	0	1.4	0	1.1
	$\bar{D}\,\Sigma$		5.4		4.9
$(0, -2)$	$\bar{D}_s \Lambda$	2763	3.4	2838	3.0
	$\bar{D}\,\Xi$	0	6.1	0	5.6

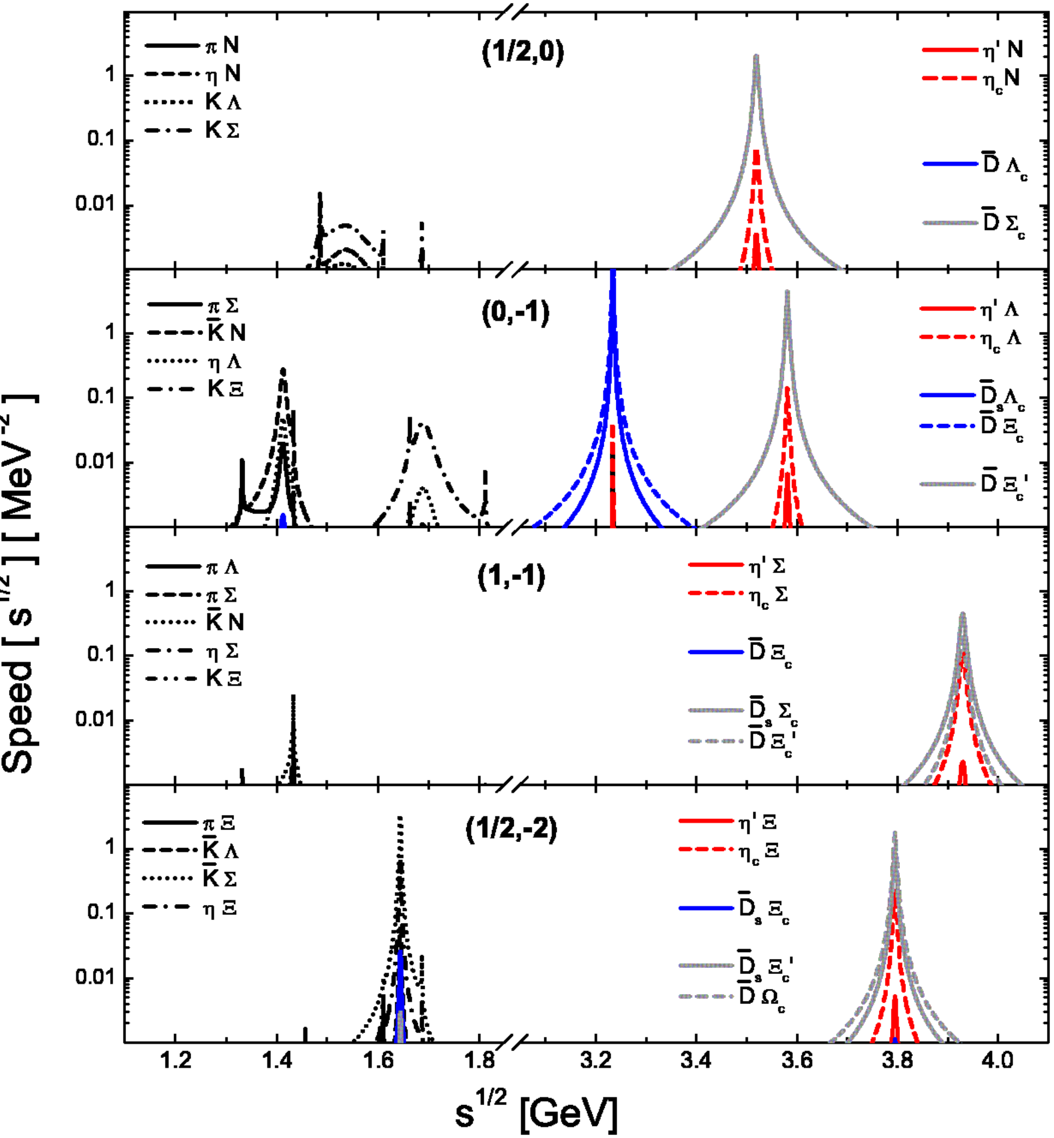
✔ **Leading-order interaction:** universally coupled vector mesons ($g = 6.6$)

$3 \otimes 8 = 3 \oplus \bar{6} \oplus 15$ strong attraction in 3 with $J^P = \frac{1}{2}^-$

✔ **OZI violation:** allow small $\phi D \bar{D}$ vertex

pushes up the masses of the triplet states

Coupled-channel dynamics for $C = 0$ molecules



✔ **Leading-order interaction:**

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

- recover $N(1535)$, $\Lambda(1405)$
  $\Lambda(1670)$, $\Xi(1690)$

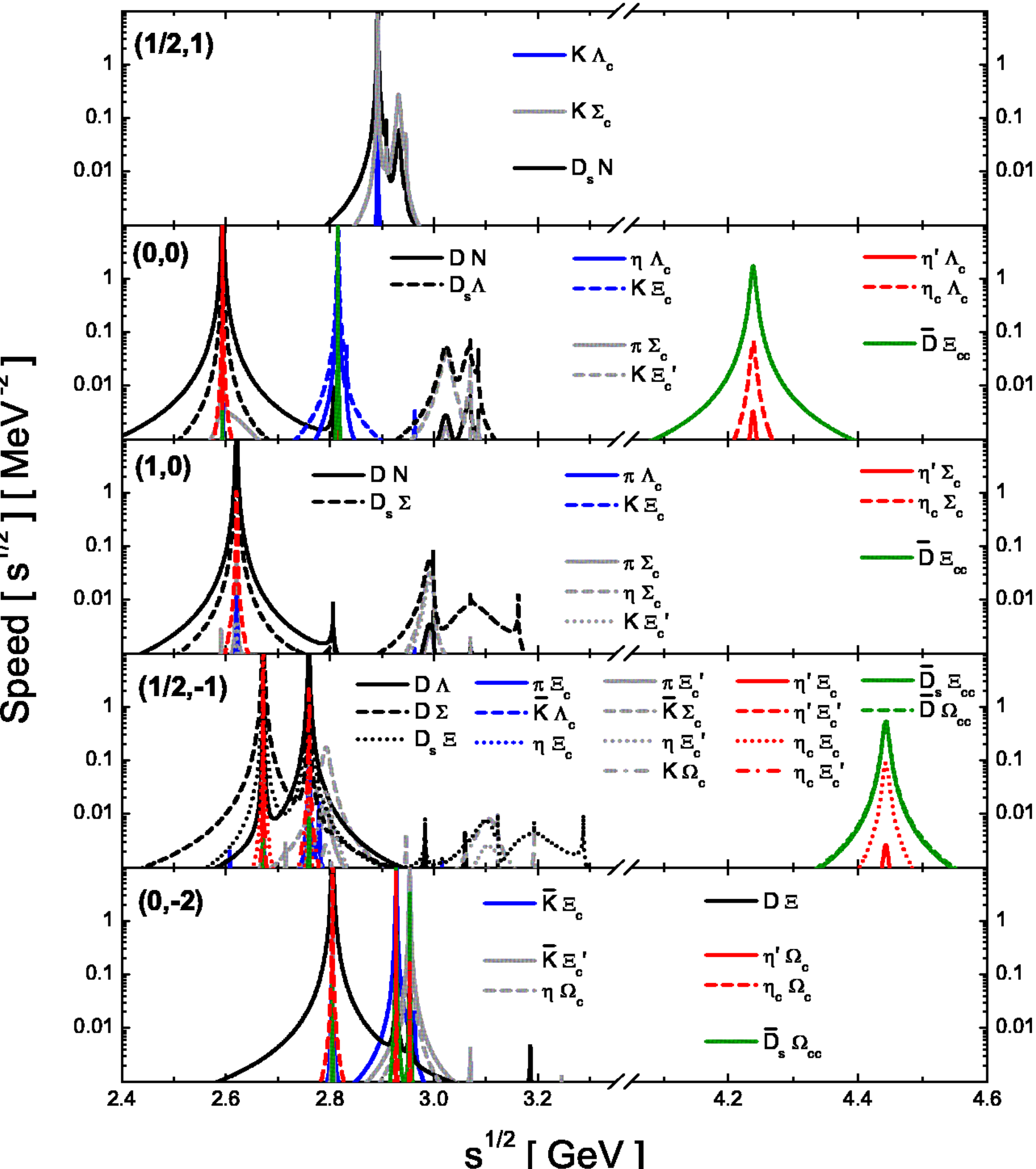
$3\otimes\bar{3} = 1\oplus 8$ $\quad\bar{c}c$ pair

- predict crypto-exotic $\Lambda(3234)$
  width about 1 MeV
  equal branching into
  $\pi\Sigma$, $\bar{K}N$, $\eta\Lambda$, $K\Xi$

$3\otimes 6 = 8\oplus 10$ $\quad\bar{c}c$ pair

- predict crypto-exotic $N(3524)$,
  $\Lambda(3581)$, $\Sigma(3930)$, $\Xi(3798)$,
  width about 10 MeV
  decay dominantly into η'

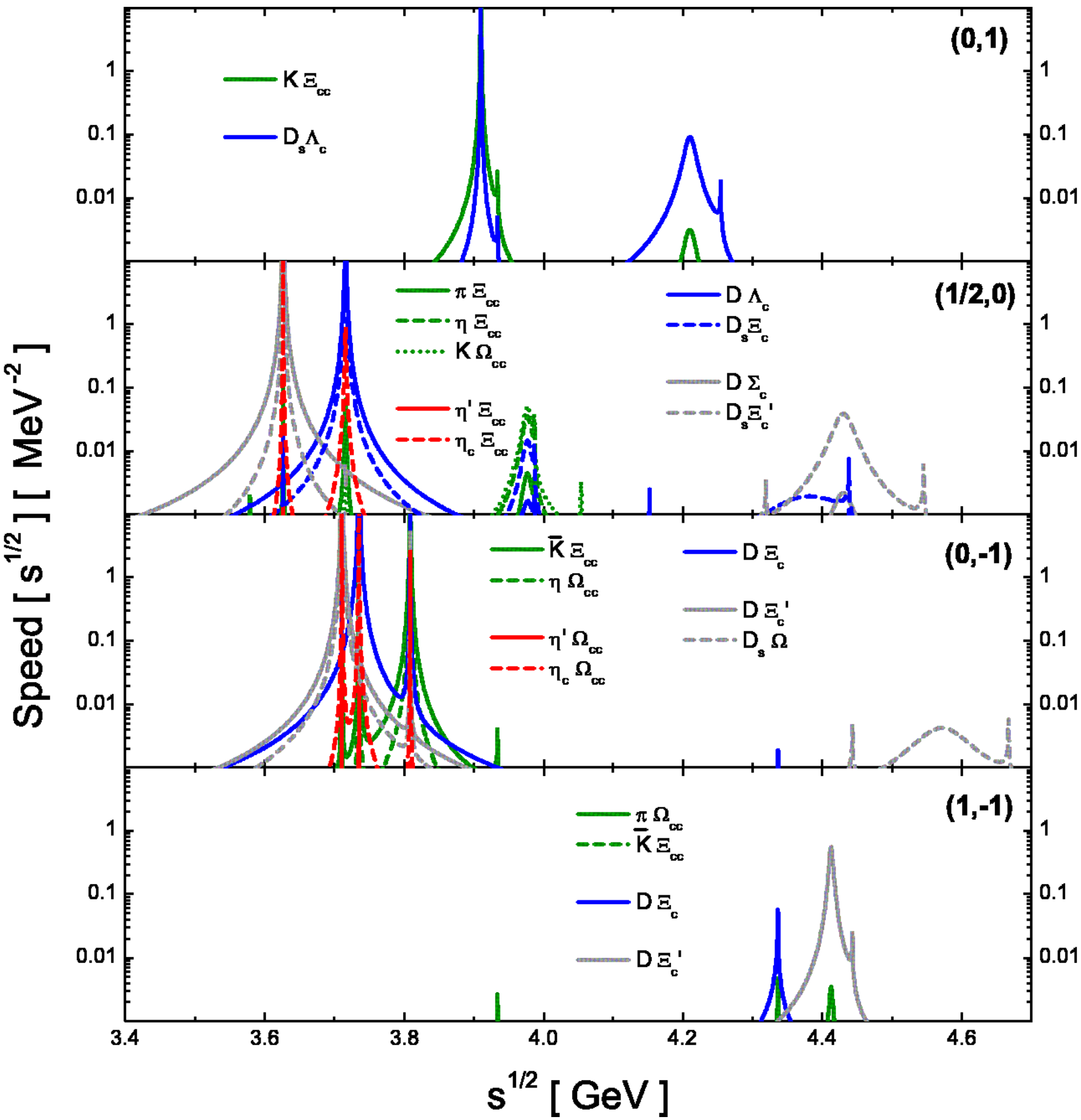
Coupled-channel dynamics for $C = 1$ molecules



✔ **Leading-order interaction:**

- $\Lambda_c(2593)$ is a $D\,N$, $D_s\,\Lambda$ molecule
- $\Lambda_c(2880)$ is not a $J^P = \frac{1}{2}^-$ state
- $\Xi_c(2790)$ is a $\bar{K}\,\Sigma_c$, $\eta\,\Xi_c'$ molecule
- predict many narrow states !

Coupled-channel dynamics for $C = 2$ molecules



✔ rich spectrum !

Summary

✔ **0^- interaction with $\frac{1}{2}^+$:** t-channel exchange of light vector mesons

- univerally coupled vector mesons $\longrightarrow$ chiral constraints recovered
- s-wave interaction $\longrightarrow J^P = \frac{1}{2}^-$ baryon spectrum

✔ **Charm -1:** strong attraction in Lipkin channels $(I, S) = (\frac{1}{2}, -1), (0, -2)$

- bound $\bar{D}_s\, N$, $\bar{D}\,\Lambda$, $\bar{D}\,\Sigma$ and $\bar{D}_s\,\Lambda$, $\bar{D}\,\Xi$ systems
- difficult to detect - to be addressed by Lattice QCD

✔ **Charm 0:** predict existence of crypto exotic baryons with hidden $\bar{c}c$

- narrow $N(3524)$, $\Lambda(3581)$, $\Sigma(3930)$, $\Xi(3798)$ baryons
- decay dominantly into η' with width about 10 MeV
- even stronger binding for $\Lambda(3234)$ - suppressed $\eta'\Lambda$ decay

✔ **Charm $+1, +2, +3$:** predict many narrow states so far unobserved