# Excited $D_s$ (and Pentaquarks) in Chiral Perturbation Theory

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# Recently Discovered Hadrons

- $D_s(2317), D_s(2460)$ $0^+, 1^+$ $c\bar{s}$ mesons — CLEO, BaBar, BELLE
- $D_s(2632)$ $J^P = ?^?$ $SU(3)\,?$ — SELEX
- Exotic Pentaquarks

  $\Theta^+(1540)$ $(\bar{s}uudd)$

  $\Xi^{--}$ $(ssdd\bar{u})$

  Charm Pentaquark $(\bar{c}dduu)$
- New Charmonium state $X_{c\bar{c}}(3870)$ — BELLE, CDF
- Doubly Charm Baryons — SELEX
- ...

- Heavy Hadron Chiral Perturbation Theory for Excited Charm

T.M., R. Springer, PRD 70:074014 (2004),
work in progress

- strong/em decays of $D_s(2317), D_s(2460)$

- ruling out DK molecule interpretation

- spectroscopy, one loop mass corrections

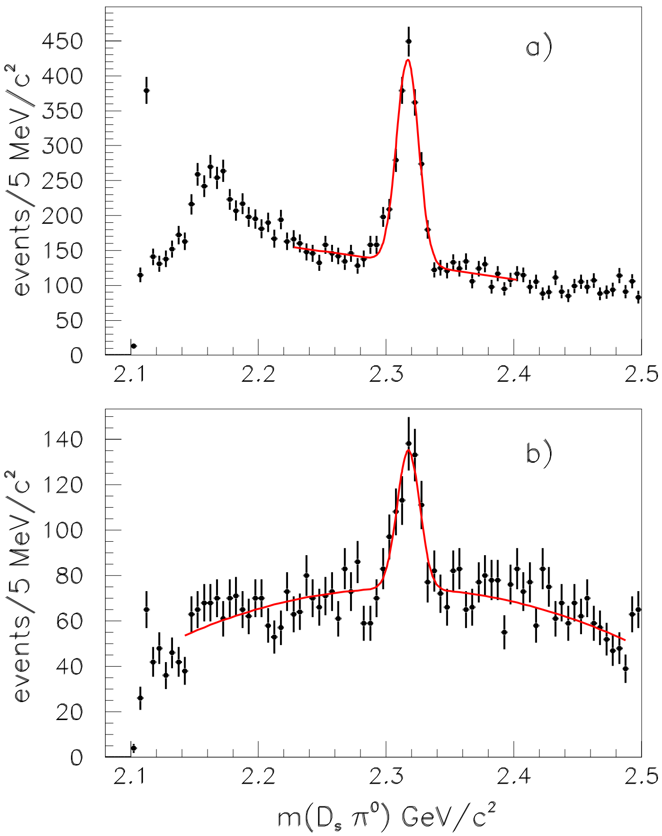
- naturalness and parity doubling models

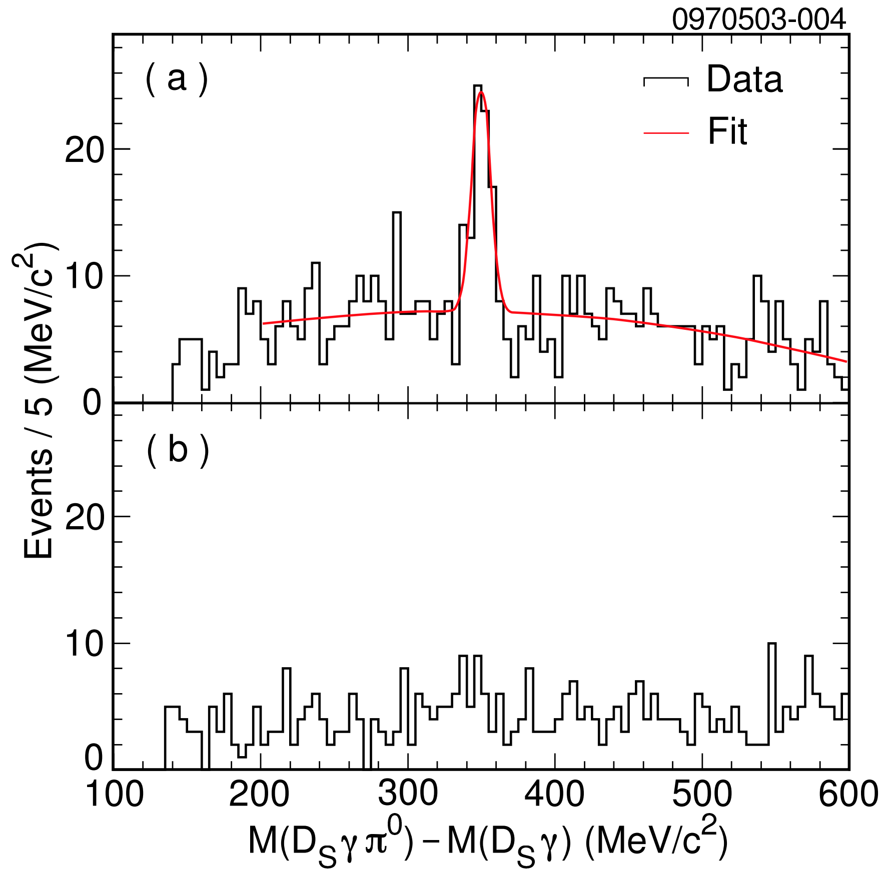
- $SU(3)$ predictions for Strong Pentaquark Decays

T.M., C. Schat, PLB 588:67 (2004)

- constraining pentaquark $J^P$ quantum numbers

# Discovery of $D_s(2317)$ and $D_s(2460)$




BaBar

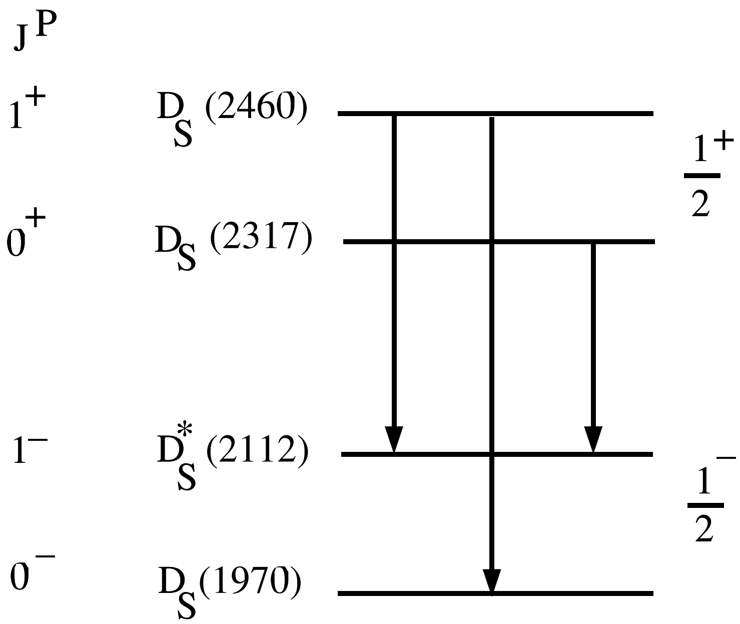
CLEO

$D_s(2317) \rightarrow D_s\pi^0$

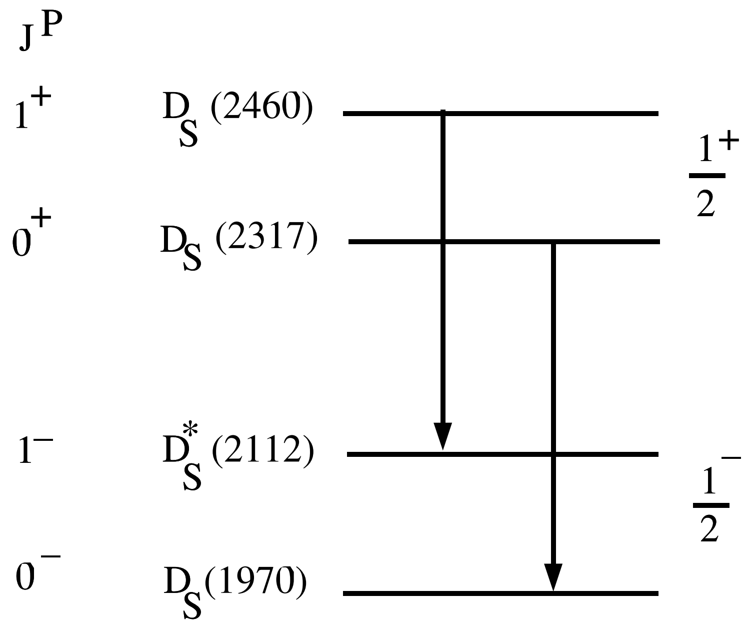
$D_s(2460) \rightarrow D_s^*\pi^0 \rightarrow D_s\pi^0\gamma$

Belle confirms $D_s(2317), D_s(2460)$, also observes $D_s(2460) \rightarrow D_s\gamma$

$D_s(0^+, 1^+) \to D_s(0^-, 1^-) + \gamma$ $\quad$ $D_s(0^+, 1^+) \to D_s(0^-, 1^-) + \pi^0$




EM Decays




Strong Decays

- Quark models, Lattice predicted

$$m_{0+} > m_D + m_K \quad m_{1+} > m_{D^*} + m_K \;\Rightarrow \Gamma \sim 250\,\mathrm{MeV}$$

- Reality: below kaon threshold, isospin violating decays, $\Gamma < 5.5$ MeV
- Hyperfine Splittings; $m_{D^*} - m_D \approx m_{1+} - m_{0+} \approx$ 142 MeV

• DK Molecule Interpretation

- $D_s(2460)[D_s(2317)] \sim 40\,\mathrm{MeV} < D^*[D]K$

- Are they molecular bound states of $DK$?

(Barnes, Lipkin, Close; Nussinov,...)

- Rescue Potential Models, Lattice simulations

- Explain equality of hyperfine splittings

• Test DK molecule hypothesis using chiral perturbation theory

(T.M., R. Springer)

- **Heavy Quark Symmetry** $m_Q \gg \Lambda_{\rm QCD}$

HQ spin decouples, degenerate doublets classified by $j^p$ of light degrees of freedom

| l.d.o.f ($j^p$) | Heavy Quark Doublet ($J^P$) | Quark Model |
|---|---|---|
| $\frac{1}{2}^-$ | $0^-, 1^-$ | $\bar{q}$ in S-wave |
| $\frac{1}{2}^+$ | $0^+, 1^+$ | $\bar{q}$ in P-wave |
| $\frac{3}{2}^+$ | $1^+, 2^+$ | $\bar{q}$ in P-wave |

- **Decays**

$$\left.\begin{array}{l} 1^+ \to 1^- + \gamma \\ 1^+ \to 0^- + \gamma \\ 0^+ \to 1^- + \gamma \end{array}\right\} \frac{1}{2}^+ \to \frac{1}{2}^- + \gamma \qquad \left.\begin{array}{l} 1^+ \to 1^- + \pi^0 \\ 0^+ \to 0^- + \pi^0 \end{array}\right\} \frac{1}{2}^+ \to \frac{1}{2}^- + \pi^0$$

# Heavy Hadron Chiral Perturbation Theory

- **Heavy Quark Fields** combine $0^-, 1^-$ heavy mesons in single field

$$H_a = (c\,\bar{q}_a) = \frac{(1+\not{v})}{2}\left[D_a^{*\mu}\gamma_\mu - D_a\gamma^5\right]$$

- **Goldstone Bosons** $(\pi, K, \eta)$ $\qquad SU(3)\times SU(3)_R \to SU_{L+R}(3)$

$$\xi = e^{i\Pi/f} \qquad \Sigma = \xi^2$$

$$D^\mu_{ab} = \delta_{ab}\,\partial^\mu - V^\mu_{ab} \quad V^\mu_{ab} = \frac{1}{2}(\xi^\dagger\partial^\mu\xi + \xi\partial^\mu\xi^\dagger) \qquad A^\mu_{ab} = \frac{i}{2}(\xi^\dagger\partial^\mu\xi - \xi\partial^\mu\xi^\dagger)$$

- **Transformations** (HQ spin, $SU_F(3)$)

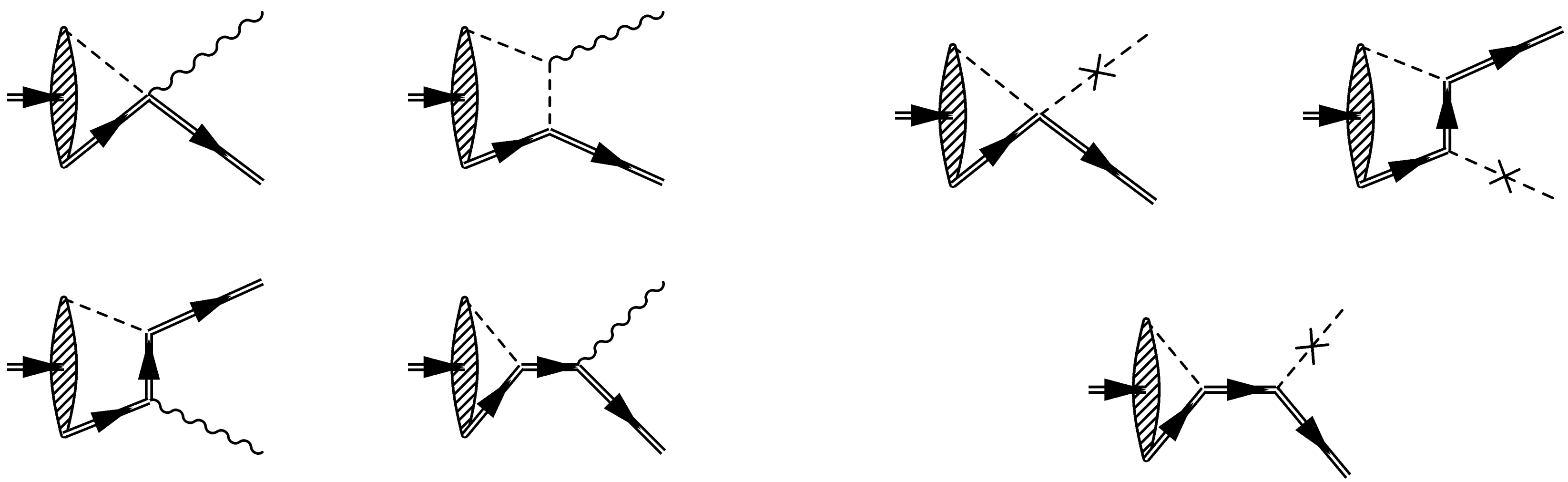
$$H \to S(\Lambda)H \qquad H \to HU^\dagger \qquad \xi \to U\xi R^\dagger = L\xi U^\dagger$$

$$\begin{aligned}\mathcal{L} \;=\; & \frac{f^2}{8}\mathrm{Tr}\,\partial^\mu\Sigma\,\partial_\mu\Sigma^\dagger + \frac{f^2 B_0}{4}\mathrm{Tr}(m_q\Sigma + m_q\Sigma^\dagger) \\ & -\mathrm{Tr}\,\bar{H}_a iv\cdot D_{ba}H_b + g\,\mathrm{Tr}\,\bar{H}_a H_b\gamma_\mu\gamma_5 A^\mu_{ba} + \ldots\end{aligned}$$

- **Expand in** $\dfrac{p}{\Lambda_\chi} \sim \dfrac{m_\pi}{\Lambda_\chi} \sim \dfrac{\Lambda_{\mathrm{QCD}}}{m_c}$

- Nonrelativistic bound state ($p_K \sim \sqrt{2\mu B} \sim 190\,\mathrm{MeV}$) decay rate is

$$\begin{aligned}\mathcal{M}[D_s(2317) \to D_s^*\gamma] &\propto \int d^3p|\tilde{\psi}(\vec{p})|^2 \mathcal{M}[D(\vec{p})K(-\vec{p}) \to D_s^*\gamma] \\ &\propto |\psi(0)|^2 \mathcal{M}[DK \to D_s^*\gamma]\end{aligned}$$



- Strong isospin violation due to $\eta - \pi^0$ mixing

- Branching Ratios in $DK$ Molecule Scenario

| | Exp. | Theory |
|---|---|---|
| $\frac{\Gamma[D_s(2460) \to D_s^* \gamma]}{\Gamma[D_s(2460) \to D_s^* \pi^0]}$ | $< 0.16$ | $3.23$ |
| $\frac{\Gamma[D_s(2460) \to D_s \gamma]}{\Gamma[D_s(2460) \to D_s^* \pi^0]}$ | $0.44 \pm 0.09$ | $2.21$ |
| $\frac{\Gamma[D_s(2317) \to D_s \gamma]}{\Gamma[D_s(2317) \to D_s \pi^0]}$ | $< 0.059$ | $2.96$ |

- electromagnetic branching ratios too large
- $D_s(2460) \to D_s \gamma$ smallest, not largest

- Even-Parity Fields $$S_a = \frac{(1+\not{v})}{2}\left[D_{1a}'^{\mu}\gamma_\mu\gamma^5 - D_{0a}^*\right]$$

$$\mathcal{L} = \mathcal{L}_H + \mathrm{Tr}\,\bar{S}_a(iv\cdot D_{ba} - \delta_S)S_b + g'\,\mathrm{Tr}\,\bar{S}_a S_b\gamma_\mu\gamma_5 A^\mu_{ba}$$
$$+h\,\mathrm{Tr}\,\bar{H}_a S_b\gamma_\mu\gamma_5 A^\mu_{ba} + \frac{e\tilde{\beta}}{4}\mathrm{Tr}[\overline{H}_a S_b\sigma^{\mu\nu}F_{\mu\nu}Q^\xi_{ba}]$$

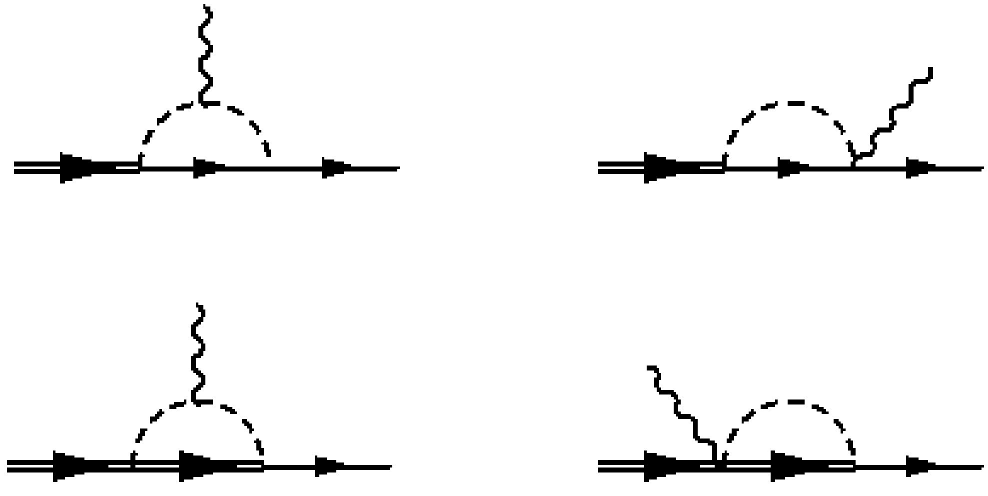
- Natural sized parameters $h \approx 0.7,\ \tilde{\beta} \approx 0.4\,\mathrm{GeV}^{-1}$

| | Exp. | Theory |
|---|---|---|
| $\frac{\Gamma[D_s(2460)\to D_s^*\gamma]}{\Gamma[D_s(2460)\to D_s^*\pi^0]}$ | $< 0.16$ | $0.37 \pm 0.07$ |
| $\frac{\Gamma[D_s(2460)\to D_s\gamma]}{\Gamma[D_s(2460)\to D_s^*\pi^0]}$ | $0.44 \pm 0.09$ | $0.44$ (fit) |
| $\frac{\Gamma[D_s(2317)\to D_s\gamma]}{\Gamma[D_s(2317)\to D_s\pi^0]}$ | $< 0.059$ | $0.13 \pm 0.03$ |

- consistent with $D_s(2460) \to D_s\gamma$ largest

LO prediction overestimates e.m. branching ratios ($\sim 2.5\,\sigma$)

- Chiral Loops



- $O(\Lambda_{\rm QCD}/m_Q)$ counterterms

$$\mathcal{L} = \frac{iee_Q\tilde{\beta}'}{8m_Q}{\rm Tr}[\overline{H}_a\sigma^{\mu\nu}S_a\gamma_5]F^{\alpha\beta}\epsilon_{\mu\nu\alpha\beta} + \frac{ee_Q\tilde{\beta}''}{8m_Q}{\rm Tr}[\overline{H}_a\sigma^{\mu\nu}S_a\gamma^\alpha]i\partial_\alpha F_{\mu\nu}$$
$$+\frac{h'}{2m_Q}{\rm Tr}[\overline{H}_a\sigma^{\mu\nu}S_b\gamma^\alpha]A^\beta_{ba}\epsilon_{\mu\nu\alpha\beta}$$

- Unknown parameters $g', \tilde{\beta}, \tilde{\beta}', \tilde{\beta}''$

- corrections can reproduce data, not predictive

- DK molecule interpretation of $D_s(2317)$ and $D_s(2460)$ disfavored
- Quark model interpretation (e.g. P-wave $c\bar{s}$) consistent with data
- Mixed State (Nussinov;Browder, Pakvasa, Petrov)

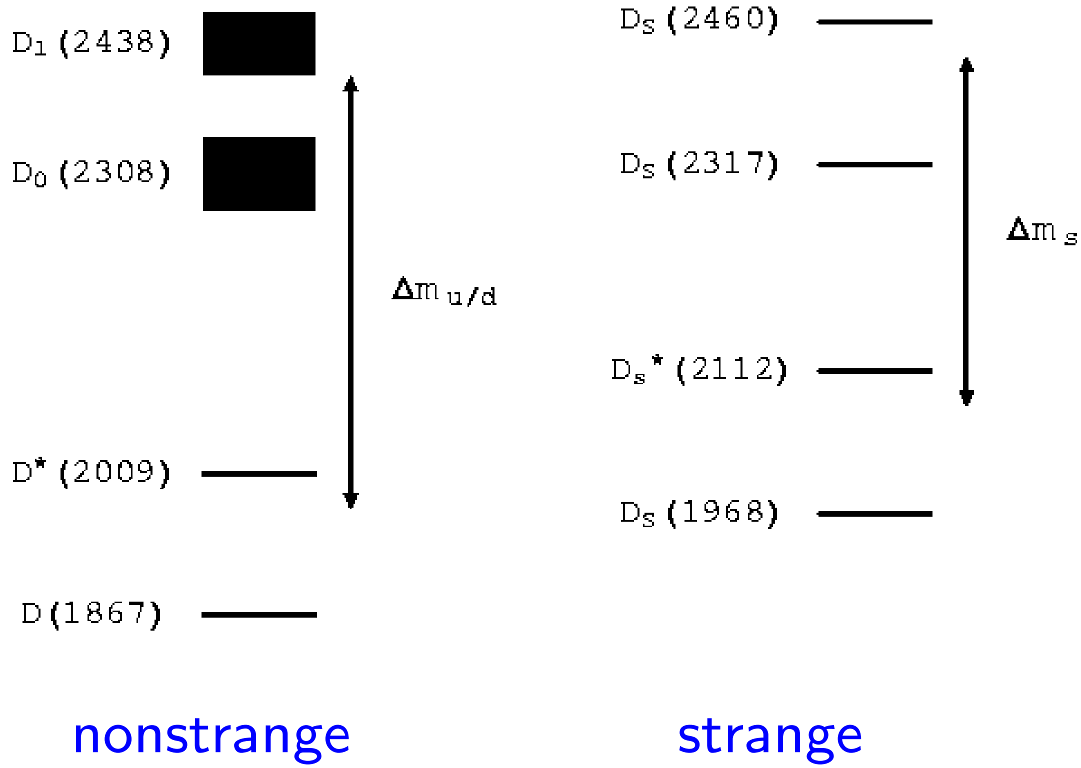
$$|D_s(2317)\rangle = \alpha|c\bar{s}\rangle + \beta|c\bar{s}s\bar{s}\rangle + \gamma|DK\rangle$$

$$\text{Enhances} \quad \frac{\Gamma[D_s(2460) \to D_s^* \gamma]}{\Gamma[D_s(2460) \to D_s^* \pi^0]}, \frac{\Gamma[D_s(2317) \to D_s \gamma]}{\Gamma[D_s(2317) \to D_s \pi^0]}$$

$$\text{relative to} \quad \frac{\Gamma[D_s(2460) \to D_s \gamma]}{\Gamma[D_s(2460) \to D_s^* \pi^0]}$$

Also not consistent with data

- Belle, CLEO also observe nonstrange $0^+, 1^+$ excited charm



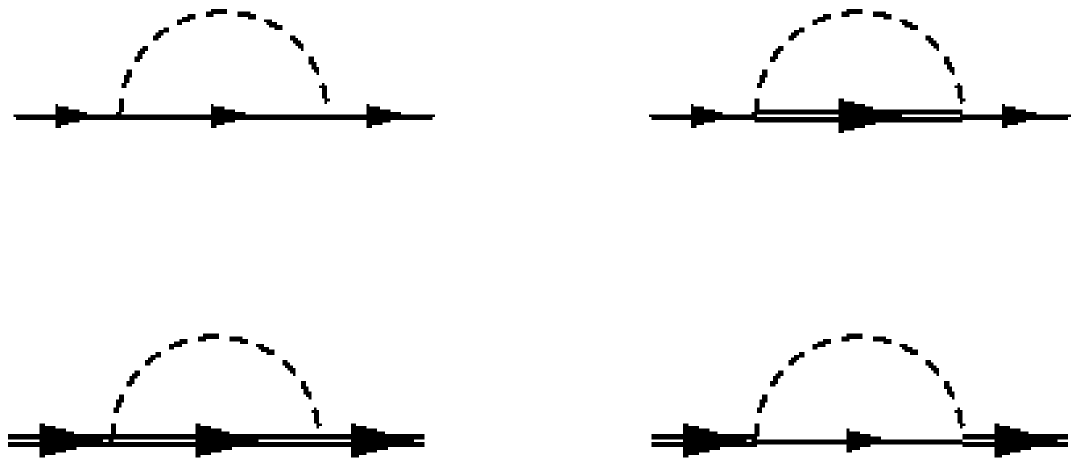

- Spectroscopy Puzzles:

  Hyperfine splittings all ≈ 142 MeV Why?

  $\Delta m_{u/d} \approx 430$ MeV $> \Delta m_s = 348$ MeV

  ⇒ Why is $SU(3)$ breaking so small for $0^+, 1^+$ charm mesons?

- One loop mass corrections:



In $m_Q \to \infty$ limit $\Delta m_{u/d} - \Delta m_s \approx -100\,\mathrm{MeV}$ not +100 MeV !

Becerevic et. al. PLB 599:55 (2004)

- Include $O(\Lambda_{\mathrm{QCD}}/m_c)$ corrections, virtual $J^P = 1^+, 2^+$ mesons

T.M., R. Springer, to appear

underpredict $0^+, 1^+$ charm nonstrange masses by about 180 MeV!

- Hybrid Approaches

(Hwang, Kim; Simonov, Tjonn; Lee, Lee, Min, Park)

- add chiral couplings to quark potential model

- claim better agreement with data

- use $e^{-k^2/\Lambda_{\rm UV}^2}$ cutoff rather than dimensional regularization

- rather sensitive to cutoff

- Perhaps NNLO HH$\chi$PT corrections resolve discrepancy?

- Hyperfine Splittings

$$\mathcal{L} = -\frac{\Delta_H}{8}\mathrm{Tr}[\overline{H}_a \sigma^{\mu\nu} H_a \sigma_{\mu\nu}] + \frac{\Delta_S}{8}\mathrm{Tr}[\overline{S}_a \sigma^{\mu\nu} S_a \sigma_{\mu\nu}]$$

- Why $\Delta_S = \Delta_H$?

- Parity doubling models (Bardeen, Eichten, Hill; Nowak, Rho, Zahed)

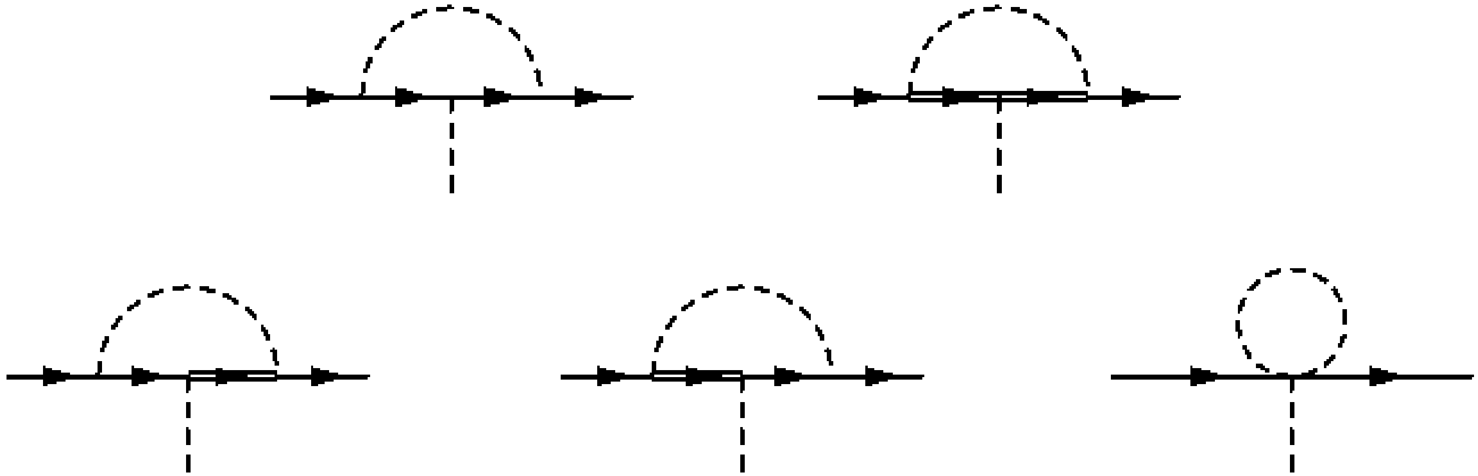
Linear sigma model: $H_L, H_R, \Sigma$ fields linearly realized $SU_L(3) \times SU_R(3)$

$\Sigma \to \langle\Sigma\rangle$, $H_L, H_R \to H, S$

Predict (tree level) $\Delta_H = \Delta_S$, $g = -g'$

- Preserved by higher order correction?

- One loop corrections to $g$ (for $g'$ $H \leftrightarrow S$): T.M., R. Springer



$$\begin{aligned}
\mu \frac{d}{d\mu}(g+g') &= -\frac{9h^2}{4\pi^2 f^2}\,\delta_S^2 (g+g') \\
\mu \frac{d}{d\mu}(g-g') &= -\frac{7h^2}{4\pi^2 f^2}\,\delta_S^2 (g-g') \\
\mu^2 \frac{d}{d\mu^2}(\Delta_S - \Delta_H) &= \frac{4}{9\pi^2 f^2}({g'}^2 \Delta_S^3 - g^2 \Delta_H^3) + \frac{2h^2}{\pi^2 f^2}(\Delta_S - \Delta_H)[\delta_S^2 + ...]
\end{aligned}$$

- $g = -g'$, $\Delta_S = \Delta_H$ stable under RG flow
- Parity doubling prediction for $\Delta_H = \Delta_S$ robust (one loop)

- Decoupling of $J^P = 1^+, 2^+$ heavy mesons?

$J^P = 1^+, 2^+$ doublets $\sim 100 - 200$ MeV heavier than $J^P = 0^+, 1^+$ doublet

$$T_a^\mu = \frac{1\ + \not{v}}{2} \left( D_{2a}^{\mu\nu} \gamma_\nu - \sqrt{\frac{3}{2}} D_{1a}^\nu \gamma_5 \left[ \delta_\nu^\mu + \frac{1}{3} \gamma_\nu (\gamma^\mu - v^\mu) \right] \right)$$

- Leading order axial coupling

$$f' \, \mathrm{Tr}[\overline{S}_a T_b^\mu \, A_{\mu ba} \gamma_5] + \mathrm{h.c.}]$$

Virtual $T_a^\mu$ loops modify masses, axial couplings of $S_a$ fields

significant corrections to parity doubling model predictions

unless $f'$ very small

# $SU(3)$ Predictions for Pentaquark Decays

- Popular Models

**Diquarks** (Jaffe, Wilczek)

$\bar{s}(ud)(ud)$: $(ud)$ in $\bar{3}$ of $SU_F(3), SU_c(3)$, $S=0$ relative P-wave

nearly degenerate $\overline{10}, 8$, $J^P = \frac{1}{2}^+$ pentaquarks

**Chiral Soliton Models** (Diakonov, Petrov, Polyakov)

predicted narrow $(\Gamma \sim 30\,\mathrm{MeV})$ $\overline{10}$ with $m_{\Theta^+} \approx 1530\,\mathrm{MeV}$ also $J^P = \frac{1}{2}^+$

- Naive CQM predicts $J^P = \frac{1}{2}^-$

some QCD sum rule, lattice analyses favor $J^P = \frac{1}{2}^-$

- Determining Pentaquark Quantum numbers
- Parity from polarized $\vec{p}\vec{p} \to \Theta^+ K^-$ at threshold (Thomas, Hicks, Osaka)

$\vec{p}\vec{p}$ in ${}^1S_0({}^3S_1)$ produce only $P = +(-)$ pentaquarks

- Two-Body Decays (T.M., C. Schat)

$$\Theta^+$$

$$N^0_{\overline{\mathbf{10}}} \qquad N^+_{\overline{\mathbf{10}}}$$

$$\Sigma^-_{\overline{\mathbf{10}}} \qquad \Sigma^0_{\overline{\mathbf{10}}} \qquad \Sigma^+_{\overline{\mathbf{10}}}$$

$$\Xi^{--}_{\overline{\mathbf{10}}} \qquad \Xi^-_{\overline{\mathbf{10}}} \qquad \Xi^0_{\overline{\mathbf{10}}} \qquad \Xi^+_{\overline{\mathbf{10}}}$$

$\Theta^+ \to pK^0, nK^+ \quad \Xi^{--} \to \Xi^- \pi^-, \Sigma^- K^- \quad \Xi^+ \to \Xi^0 \pi^+, \Sigma^+ \overline{K}^0$

- $p = 270\,\mathrm{MeV} - 445\,\mathrm{MeV} \sim m_K$ apply $SU(3)$ $\chi pT$
- Heavy Baryon Chiral Lagrangian (Jenkins, Manohar)
- $SU(3)$ Clebsch $\overline{B}^i{}_l M^j{}_n P_{ijk} \epsilon^{lnk}$ + phase space factors

$$\frac{m_B}{m_P} p^{2L+1} \quad (L > 0)$$

$$\frac{m_B}{m_P} E^2 p \quad (L = 0)$$

$E^2 p$ not $p$ for S-waves, Goldstone Bosons derivatively coupled

- $J^P = \frac{1}{2}^-$ S-wave, $J^P = \frac{1}{2}^+, \frac{3}{2}^+$ P-waves, $J^P = \frac{3}{2}^-, \frac{5}{2}^-$ D-waves,...

- Interesting ratios

| | $J^P$ | | |
|---|---|---|---|
| | $\frac{1}{2}^-$ | $\frac{1}{2}^+$, $\frac{3}{2}^+$ | $\frac{3}{2}^-$ |
| $\frac{\Gamma(\Xi^{--}_{\overline{\mathbf{10}}} \to \Xi^- \pi^-)}{\Gamma(\Xi^{--}_{\overline{\mathbf{10}}} \to \Sigma^- K^-)}$ | $1.2 \pm 0.4$ | $3.1 \pm 0.9$ | $4.7 \pm 1.4$ |
| $\frac{\Gamma(\Xi^{0}_{\overline{\mathbf{10}}} \to \Xi^- \pi^+)}{\Gamma(\Xi^{0}_{\overline{\mathbf{10}}} \to \Sigma^+ K^-)}$ | $1.1 \pm 0.3$ | $2.9 \pm 0.9$ | $4.2 \pm 1.3$ |
| $\frac{\Gamma(\Xi^{--})}{\Gamma(\Theta^+)}$ | $> 1.8 \pm 0.5$ | $> 5.3 \pm 1.6$ | $> 14. \pm 4.$ |

- Ratios can discriminate various $J^P$

$\Gamma[\Xi^{--}], \Gamma[\Xi^{+}] < 10\,\Gamma[\Theta^{+}]$ can rule out $J^P = \frac{3}{2}^{-}, \geq \frac{5}{2}$

- $\frac{\Gamma[\Xi^{--}\to\Xi^{-}\pi^{-}]}{\Gamma[\Xi^{--}\to\Sigma^{-}K^{-}]}, \frac{\Gamma[\Xi^{+}\to\Xi^{0}\pi^{+}]}{\Gamma[\Xi^{+}\to\Sigma^{+}\overline{K}^{0}]}$ distinguishes $J^P = \frac{1}{2}^{\pm}$

NA49 can't reconstruct $\Sigma^- \to n\pi^-$

$$\begin{aligned} \Xi^+ &\to \Xi^0\pi^+ \to \Lambda\pi^0\pi^+ \to p\pi^-\gamma\gamma\pi^+ \;, \\ &\to \Sigma^+\overline{K}^0 \to p\pi^0\pi^+\pi^- \to p\gamma\gamma\pi^+\pi^- \end{aligned}$$

- CLAS will be looking for pentaquark $\Xi$'s...

Important to measure both $K$ and $\pi$ decays of exotic $\Xi$

## Summary

- Electromagnetic branching ratios of $D_s(2317)$ and $D_s(2460)$

- disfavor $DK$ molecule interpretation

- consistent with conventional $c\bar{s}$ interpretation

- Spectroscopy puzzles

- small $SU(3)$ splittings of $J^P = 0^+, 1^+$ states

- equality of hyperfine splittings

- Parity doubling models

- naturally explains equality of even- and odd-parity hyperfine splittings

- decoupling of $J^P = 1^+, 2^+$ states?

- Very interesting to observe $B_s$ even-parity states!

- Strong Decays of $\Theta^+$ and $\Xi$

\- Measure both $\pi$ and $K$ decays of exotic $\Xi$

can discriminate between $J^P = \frac{1}{2}^-$ and $J^P = \frac{1}{2}^+$ pentaquarks