# New Developments in Heavy-Light Systems

Estia Eichten

- QCD Dynamics
- Relativistic Potential Models — M. Di Pierro
- $D_s(0^+)$, $D_s(1^+)$ and Chiral Dynamics — W. Bardeen, C. Hill
- Open Issues and Opportunities
- Summary

# Toolbox for QCD Dynamics

- HQET for Heavy-Light Systems

  $\bar{Q}q \qquad m_Q >> \Lambda_{QCD}$ $\qquad$ $j_l = l+s$

  Expansion parameter $\frac{\Lambda_{\mathrm{QCD}}}{m_Q}$

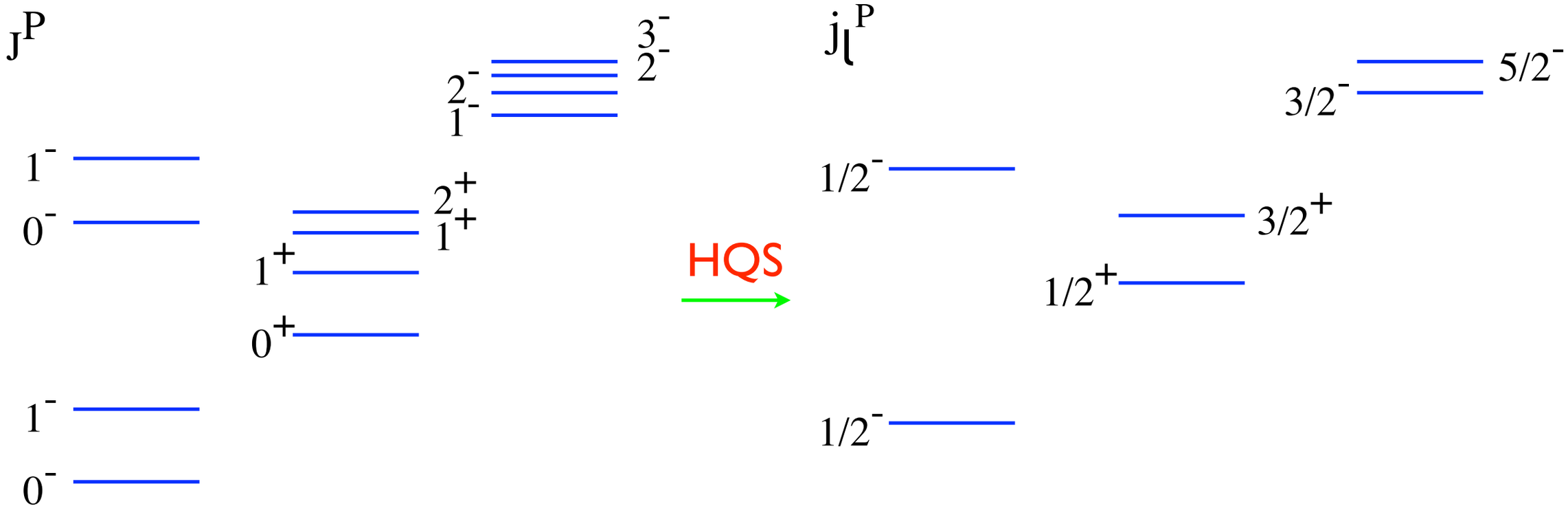
- Chiral Symmetry for Light Quarks

  $\bar{q}_1 q_2 \qquad m_{q_1}$ and $m_{q_2} << \Lambda_{\mathrm{QCD}}$

  Expansion parameter $\frac{\Lambda_{\mathrm{QCD}}}{4\pi f_\pi}$

- Lattice QCD

# Heavy-Light Spectrum



# Relativistic Potential Models

Godfrey and Isgur, PRD32 (1985)32
Goity and Roberts, PRD60 (1999) 034001
Di Pierro and EE, PRD64 (2001) 114004

$$\mathcal{H}\Psi_{n,\ell,j,J,M} = E_{n,\ell,j,J}\Psi_{n,\ell,j,J,M}$$

$$\mathcal{H} = \mathcal{H}^{(0)} + \frac{1}{m_h}\mathcal{H}^{(1)} + \frac{1}{m_h^2}\mathcal{H}^{(2)} + \ldots$$

- kinetic terms
- spin-orbit terms
- hyperfine terms

$$\mathcal{H}^{(0)} = \gamma^0(-i\partial\!\!\!/ + m_q) + V(r)$$

$$V(r) = M_h + \gamma^0 V_s(r) + V_v(r)$$

Same potential form as in NRQCD

$$V_v(r) = -\frac{4}{3}\int |\Phi(x)|^2 \frac{\alpha_s}{|\mathbf{r}-\mathbf{x}|}\mathrm{d}^3x = -\frac{4}{3}\frac{\alpha_s}{r}\mathrm{erf}(\lambda r)$$

$$V_s(r) = br + c$$

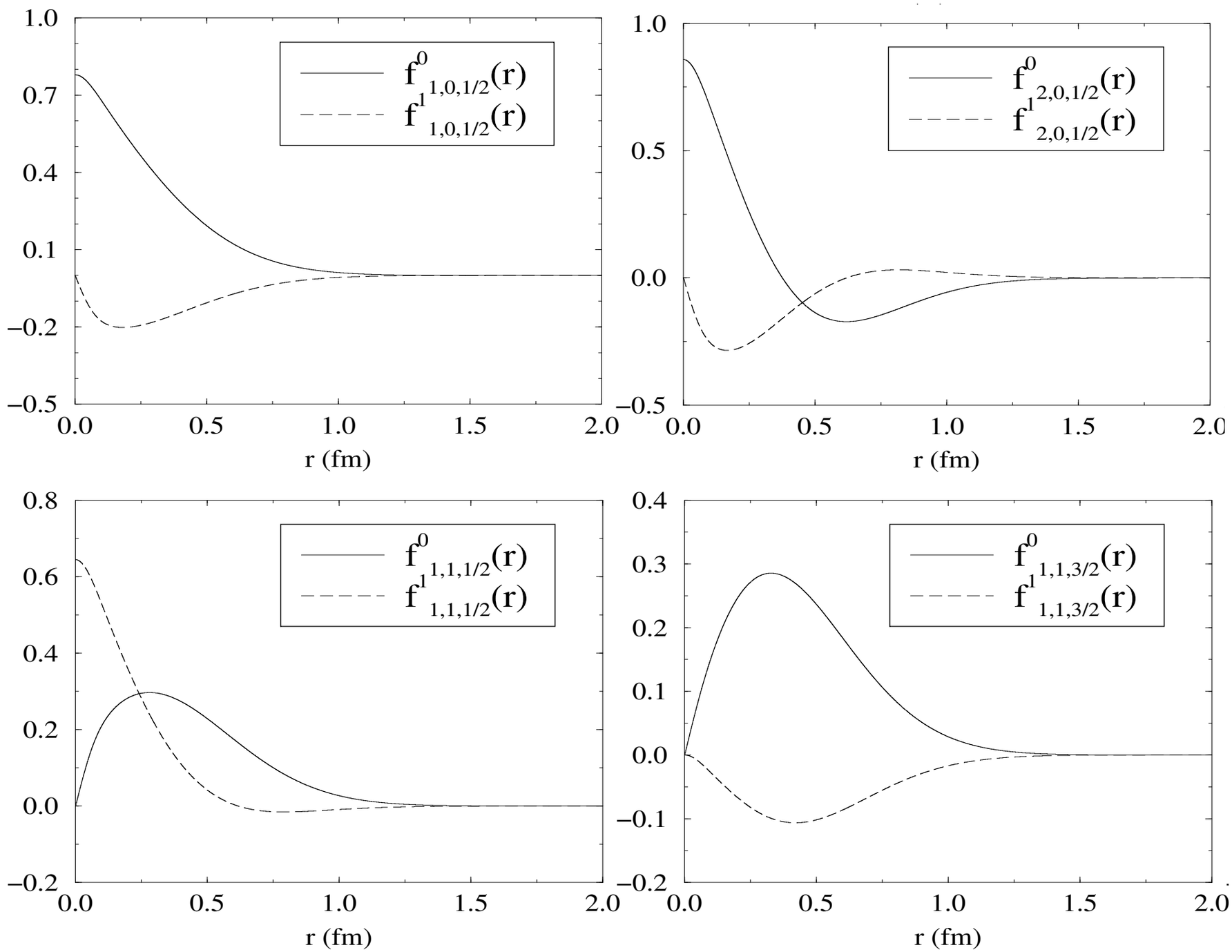
Absorb into mass

$$\alpha_s, \lambda, b, m_u, m_s, m_c, M_c, m_b, M_b$$

QCD coupling | Softener | slope | quark masses | Meson masses

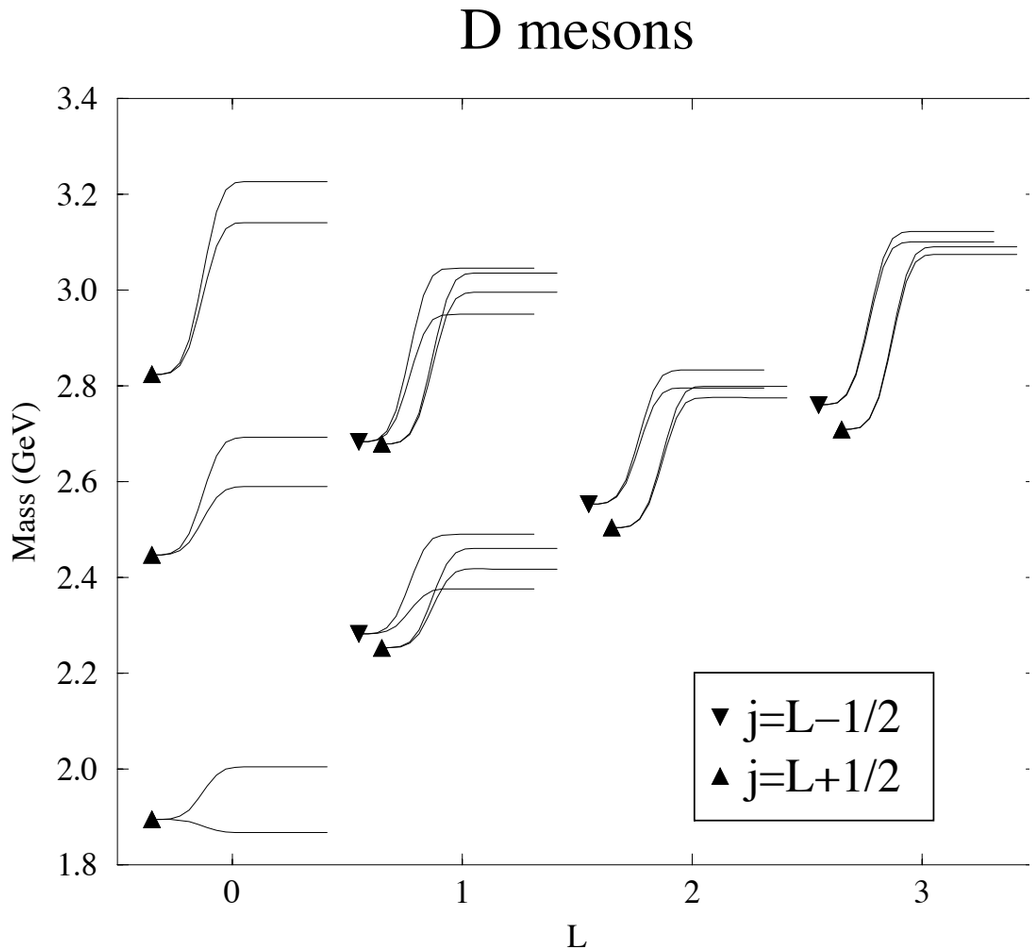
0.339 2.823 0.257 0.071 0.216 1.511 4.655 1.292 4.685

$$\Psi_{n,\ell,j,J,M}(r,\theta,\varphi) = \sum_{S\in\left\{-\frac{1}{2},+\frac{1}{2}\right\}} C^{J,M}_{j,m;\frac{1}{2},S} \begin{pmatrix} i f^0_{n,\ell,j}(r) k^+_{\ell,j,m}\ Y^{\ell}_{m-\frac{1}{2}}(\theta,\varphi) \\ i f^0_{n,\ell,j}(r) k^-_{\ell,j,m}\ Y^{\ell}_{m+\frac{1}{2}}(\theta,\varphi) \\ f^1_{n,\ell,j}(r) k^+_{2j-\ell,j,m} Y^{2j-\ell}_{m-\frac{1}{2}}(\theta,\varphi) \\ f^1_{n,\ell,j}(r) k^-_{2j-\ell,j,m} Y^{2j-\ell}_{m+\frac{1}{2}}(\theta,\varphi) \end{pmatrix} \otimes \xi_S \qquad k^{\pm}_{\ell,j,m} = \begin{cases} +\sqrt{\frac{\ell\pm m+\frac{1}{2}}{2\ell+1}} & \text{for } j=\ell+\frac{1}{2} \\ \pm\sqrt{\frac{\ell\mp m+\frac{1}{2}}{2\ell+1}} & \text{for } j=\ell-\frac{1}{2} \end{cases}$$



| $H\ (n^j L_J)$ | $m_{\rm exp.}$ | $E^0$ | $E^{\rm phys.}$ | $\phi(\%)$ |
|---|---|---|---|---|
| $D\ (1\frac{1}{2}S_0)$ | 1.865 | 1.895 | 1.868 | |
| $D\ (1\frac{1}{2}S_1)$ | 2.007 | 1.895 | 2.005 | |
| $D\ (1\frac{1}{2}P_0)$ | | 2.282 | 2.377 | |
| $D\ (1\frac{3}{2}P_1)$ | 2.422 | 2.253 | 2.417 | -10.92 |
| $D\ (1\frac{3}{2}P_2)$ | 2.459 | 2.253 | 2.460 | |
| $D\ (1\frac{1}{2}P_1)$ | | 2.282 | 2.490 | 10.92 |
| $D\ (2\frac{1}{2}S_0)$ | | 2.447 | 2.589 | |
| $D\ (2\frac{1}{2}S_1)$ | | 2.447 | 2.692 | 2.17 |
| $D\ (1\frac{5}{2}D_2)$ | | 2.504 | 2.775 | -5.41 |
| $D\ (1\frac{3}{2}D_1)$ | | 2.553 | 2.795 | -2.17 |
| $D\ (1\frac{5}{2}D_3)$ | | 2.504 | 2.799 | |
| $D\ (1\frac{3}{2}D_2)$ | | 2.553 | 2.833 | 5.41 |
| $D\ (2\frac{1}{2}P_0)$ | | 2.683 | 2.949 | |
| $D\ (2\frac{3}{2}P_1)$ | | 2.679 | 2.995 | -10.70 |
| $D\ (2\frac{3}{2}P_2)$ | | 2.679 | 3.035 | 1.79 |
| $D\ (2\frac{1}{2}P_1$ | | 2.683 | 3.045 | 10.70 |
| $D\ (1\frac{7}{2}F_3)$ | | 2.709 | 3.074 | -3.17 |
| $D\ (1\frac{7}{2}F_4)$ | | 2.709 | 3.091 | |
| $D\ (1\frac{5}{2}F_2)$ | | 2.760 | 3.101 | -1.79 |
| $D\ (1\frac{5}{2}F_3)$ | | 2.760 | 3.123 | 3.17 |
| $D\ (3\frac{1}{2}S_0)$ | | 2.823 | 3.141 | |
| $D\ (3\frac{1}{2}S_1)$ | | 2.823 | 3.226 | |

| $H\ (n^j L_J)$ | $m_{\rm exp.}$ | $E^0$ | $E^{\rm phys.}$ | $\phi(\%)$ |
|---|---|---|---|---|
| $D_s\ (1\frac{1}{2}S_0)$ | 1.969 | 1.988 | 1.965 | |
| $D_s\ (1\frac{1}{2}S_1)$ | 2.112 | 1.988 | 2.113 | |
| $D_s\ (1\frac{1}{2}P_0)$ | | 2.374 | 2.487 | |
| $D_s\ (1\frac{3}{2}P_1)$ | 2.535 | 2.353 | 2.535 | -11.62 |
| $D_s\ (1\frac{3}{2}P_2)$ | 2.573 | 2.353 | 2.581 | |
| $D_s\ (1\frac{1}{2}P_1)$ | | 2.374 | 2.605 | 11.62 |
| $D_s\ (2\frac{1}{2}S_0)$ | | 2.540 | 2.700 | |
| $D_s\ (2\frac{1}{2}S_1)$ | | 2.540 | 2.806 | 1.97 |
| $D_s\ (1\frac{5}{2}D_2)$ | | 2.606 | 2.900 | -6.11 |
| $D_s\ (1\frac{3}{2}D_1)$ | | 2.648 | 2.913 | -1.97 |
| $D_s\ (1\frac{5}{2}D_3)$ | | 2.606 | 2.925 | |
| $D_s\ (1\frac{3}{2}D_2)$ | | 2.648 | 2.953 | 6.11 |
| $D_s\ (2\frac{1}{2}P_0)$ | | 2.777 | 3.067 | |
| $D_s\ (2\frac{3}{2}P_1)$ | | 2.775 | 3.114 | -10.58 |
| $D_s\ (2\frac{3}{2}P_2)$ | | 2.775 | 3.157 | 1.81 |
| $D_s\ (2\frac{1}{2}P_1)$ | | 2.777 | 3.165 | 10.58 |
| $D_s\ (1\frac{7}{2}F_3)$ | | 2.812 | 3.203 | -3.60 |
| $D_s\ (1\frac{7}{2}F_4)$ | | 2.812 | 3.220 | |
| $D_s\ (1\frac{5}{2}F_2)$ | | 2.857 | 3.224 | -1.81 |
| $D_s\ (1\frac{5}{2}F_3)$ | | 2.857 | 3.247 | 3.60 |
| $D_s\ (3\frac{1}{2}S_0)$ | | 2.917 | 3.259 | |
| $D_s\ (3\frac{1}{2}S_1)$ | | 2.917 | 3.345 | |



# Decays of Excited States

For low-lying excited states the strong transitions:

$$H' \to H + (\pi,\, K,\, \eta)$$

Georgi and Manohar, NP B234 (1984) 189

Within the chiral quark model

$$\mathcal{L}_{\rm int} = \frac{g_A^8}{\sqrt{2} f_x} \bar{q}_i' X \mathcal{M}^{ij} q_j + \mathcal{O}(\partial^2)$$

$$\mathcal{M} = \sqrt{2} \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}$$

axial current $X = \not{\partial}\gamma^5$

the partial widths are

$$\Gamma_x(H' \to H + x;\ \ell_x) = \frac{p}{8\pi^2} \frac{2J+1}{2J'+1} \frac{m_H}{m_{H'}} \left| \mathcal{A}_{\ell_x}^{H'Hx}(X,p) \right|^2$$

where

Clebschs

Overlap

$$\mathcal{A}_{\ell_x}^{H'Hx}(X,p) = \frac{i g_A^8 \zeta}{\sqrt{2} f_x} \sum_{ab=\{0,1\}} \sum_k c_{\ell_x}^{ab,k}(X) \int_0^\infty f_{n',\ell',j'}^a(r) j_k(rp) f_{n,\ell,j}^b(r) r^2 {\rm d}r$$

Isospin factor

| $H' \to H + x$ | $\zeta$ | $H' \to H + x$ | $\zeta$ |
|---|---|---|---|
| $B^0 \to B^0 + \pi^0$ | $1$ | $B_s \to B_s + \eta_8$ | $-2/\sqrt{3}$ |
| $B^\pm \to B^\pm + \pi^0$ | $1$ | $B_s \to B^0 + K$ | $\sqrt{2}$ |
| $B^\pm \to B^0 + \pi^\pm$ | $\sqrt{2}$ | $B_s \to B^\pm + K^\mp$ | $\sqrt{2}$ |
| $B^0 \to B^\pm + \pi^\mp$ | $\sqrt{2}$ | $B^0 \to B_s + \bar{K}$ | $\sqrt{2}$ |
| $B^0 \to B^0 + \eta_8$ | $1/\sqrt{3}$ | $B^\pm \to B_s + K^\pm$ | $\sqrt{2}$ |
| $B^\pm \to B^\pm + \eta_8$ | $1/\sqrt{3}$ | $B_q \to B_q + \eta_1$ | $\sqrt{\frac{2}{3}} + \mathcal{O}(\frac{1}{N_c})$ |

# Some partial widths

## S wave

| channel | $l_\pi$ | $p_\pi$ (MeV) | $\Gamma_\pi/(g_A^8)^2$(keV) |
|---|---|---|---|
| $D^{\star 0}(1\frac{1}{2}S_1) \to D^0(1\frac{1}{2}S_0) + \pi^0$ | 1 | $42.8 \pm .2$ | $62 \pm 1$ |
| $D^{\star +}(1\frac{1}{2}S_1) \to D^0(1\frac{1}{2}S_0) + \pi^+$ | 1 | $39.4 \pm .5$ | $97 \pm 3$ |
| $D^{\star +}(1\frac{1}{2}S_1) \to D^+(1\frac{1}{2}S_0) + \pi^0$ | 1 | $38.1 \pm .3$ | $44 \pm 1$ |

## P wave

| $H'(n'^{j'}\ell_{J'})$ | $H(n^j\ell_J)$ | $x$ | $\ell_x$ | $p_x$ | $\Gamma_x/(g_A^8)^2$ |
|---|---|---|---|---|---|
| $D(1\frac{1}{2}P_0)$ | $D(1\frac{1}{2}S_0)$ | $\pi$ | 0 | 437 | 189 |
| $D(1\frac{3}{2}P_1)$ | $D(1\frac{1}{2}S_1)$ | $\pi$ | 0 | 355 | $(*)$ 1.7 |
| | $D(1\frac{1}{2}S_1)$ | $\pi$ | 2 | 355 | 14.5 |
| $D(1\frac{3}{2}P_2)$ | $D(1\frac{1}{2}S_0)$ | $\pi$ | 2 | 506 | 24.6 |
| | $D(1\frac{1}{2}S_1)$ | $\pi$ | 2 | 394 | 13.7 |
| $D(1\frac{1}{2}P_1)$ | $D(1\frac{1}{2}S_1)$ | $\pi$ | 0 | 420 | 181 |
| $D_s(1\frac{1}{2}P_0)$ | $D(1\frac{1}{2}S_0)$ | $K$ | 0 | 325 | 236 |
| $D_s(1\frac{3}{2}P_1)$ | $D(1\frac{1}{2}S_1)$ | $K$ | 0 | 175 | $(*)$ 1.89 |
| | $D(1\frac{1}{2}S_1)$ | $K$ | 2 | 175 | 0.3 |
| $D_s(1\frac{3}{2}P_2)$ | $D(1\frac{1}{2}S_0)$ | $K$ | 2 | 442 | 8.9 |
| | $D(1\frac{1}{2}S_1)$ | $K$ | 2 | 264 | 1.4 |
| | $D_s(1\frac{1}{2}S_0)$ | $\eta$ | 2 | 248 | 0.4 |
| $D_s(1\frac{1}{2}P_1)$ | $D(1\frac{1}{2}S_1)$ | $K$ | 0 | 302 | 224 |

** For expected masses

**

Table 8: The heavy-light 1P state hadronic transition rates for $D$ and $D_s$ mesons. $H' \to H + x$. Decays denoted with an $(*)$ are allowed only because of the order $1/m_h$ mixing of states. $p_x$ and $\Gamma_x/(g_A^8)^2$ are in MeV.

# New Narrow States

$D_s(2317)\ \ \mathrm{I(J^P)} = 0(0^+)$

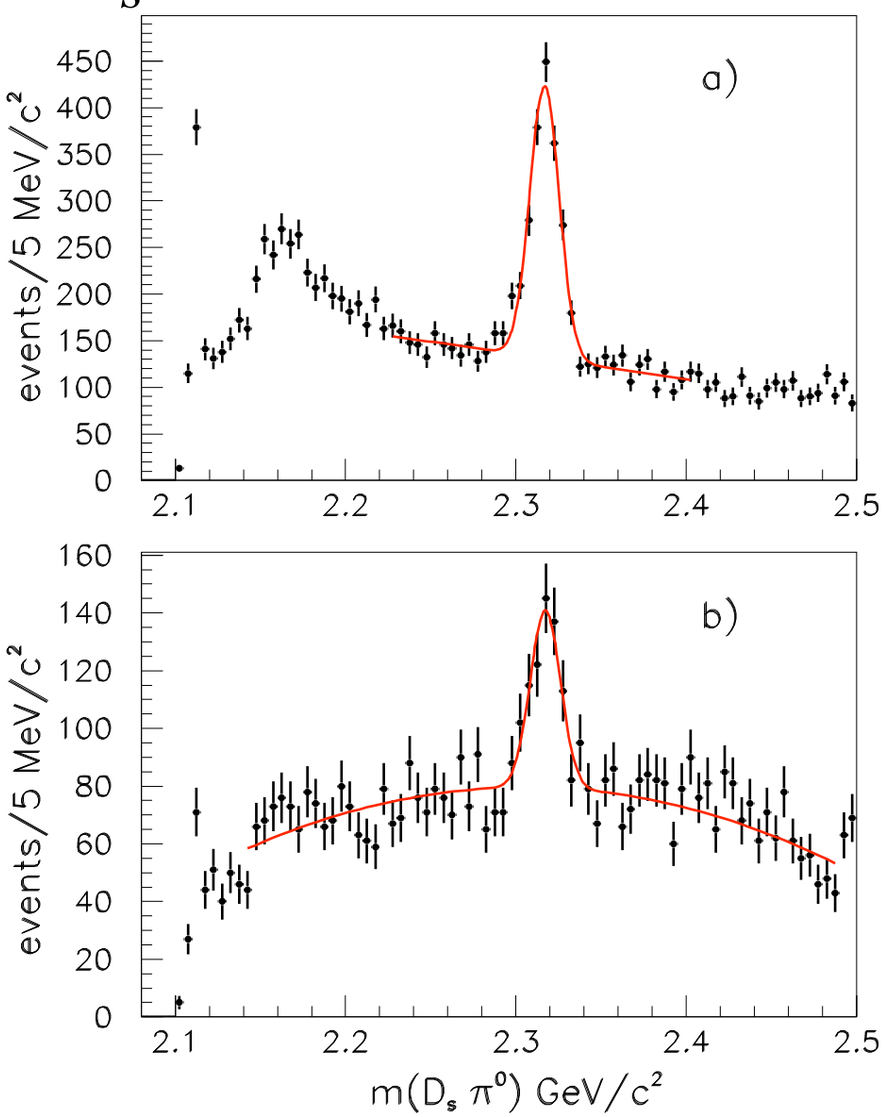



Figure 4. BaBar signal for $D_{sJ}^*(2317) \to D_s^+\pi^0$ for: a) $D_s^+ \to K^+K^-\pi^+$ for both $\phi\pi^+$ and $\bar{K}^{*0}K^+$, 1267± 63 events in the peak; and b) $D_s^+ \to K^+K^-\pi^+\pi^0$, 237± 33 events.

$D_s(2459)\ \ \mathrm{I(J^P)} = 0(1^+)$

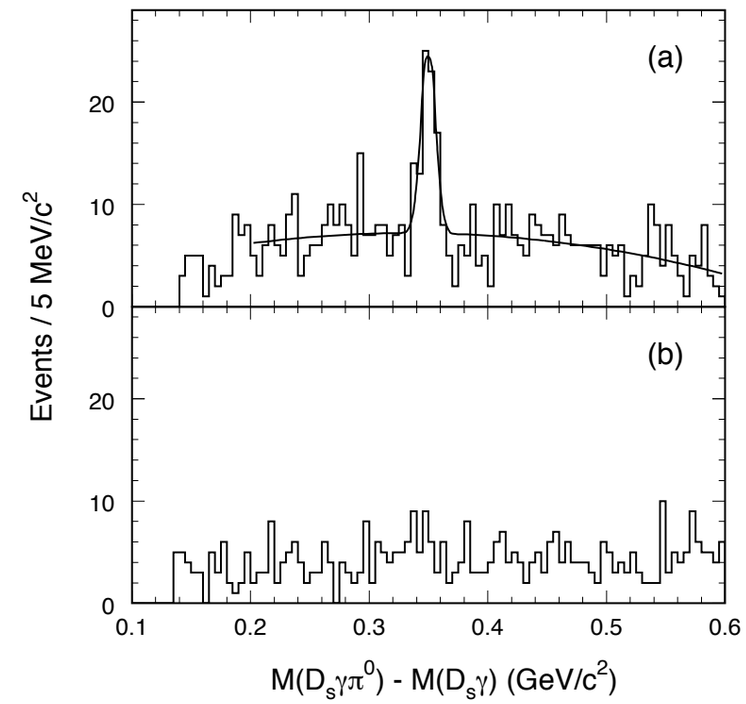



Figure 5. CLEO signal for $D_{sJ}^*(2463)$.

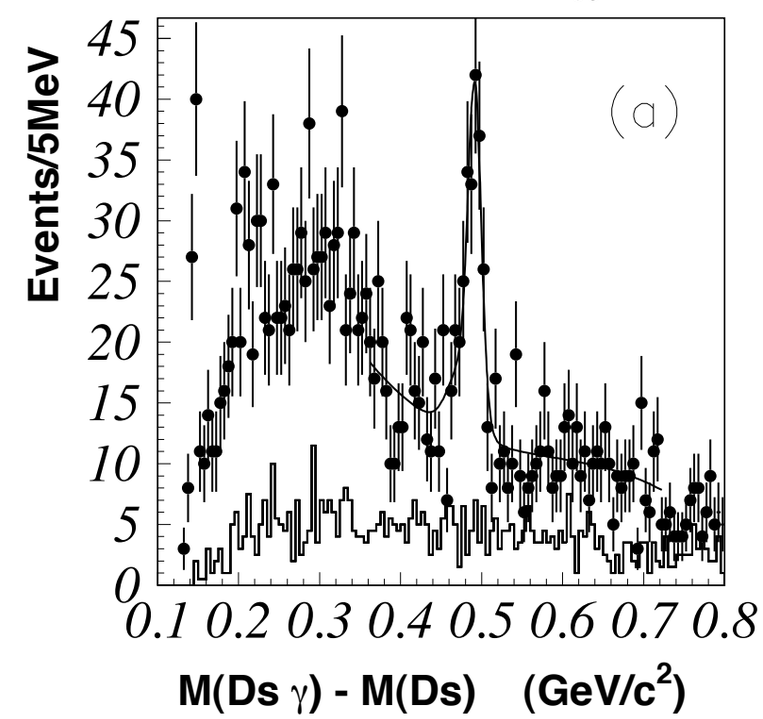
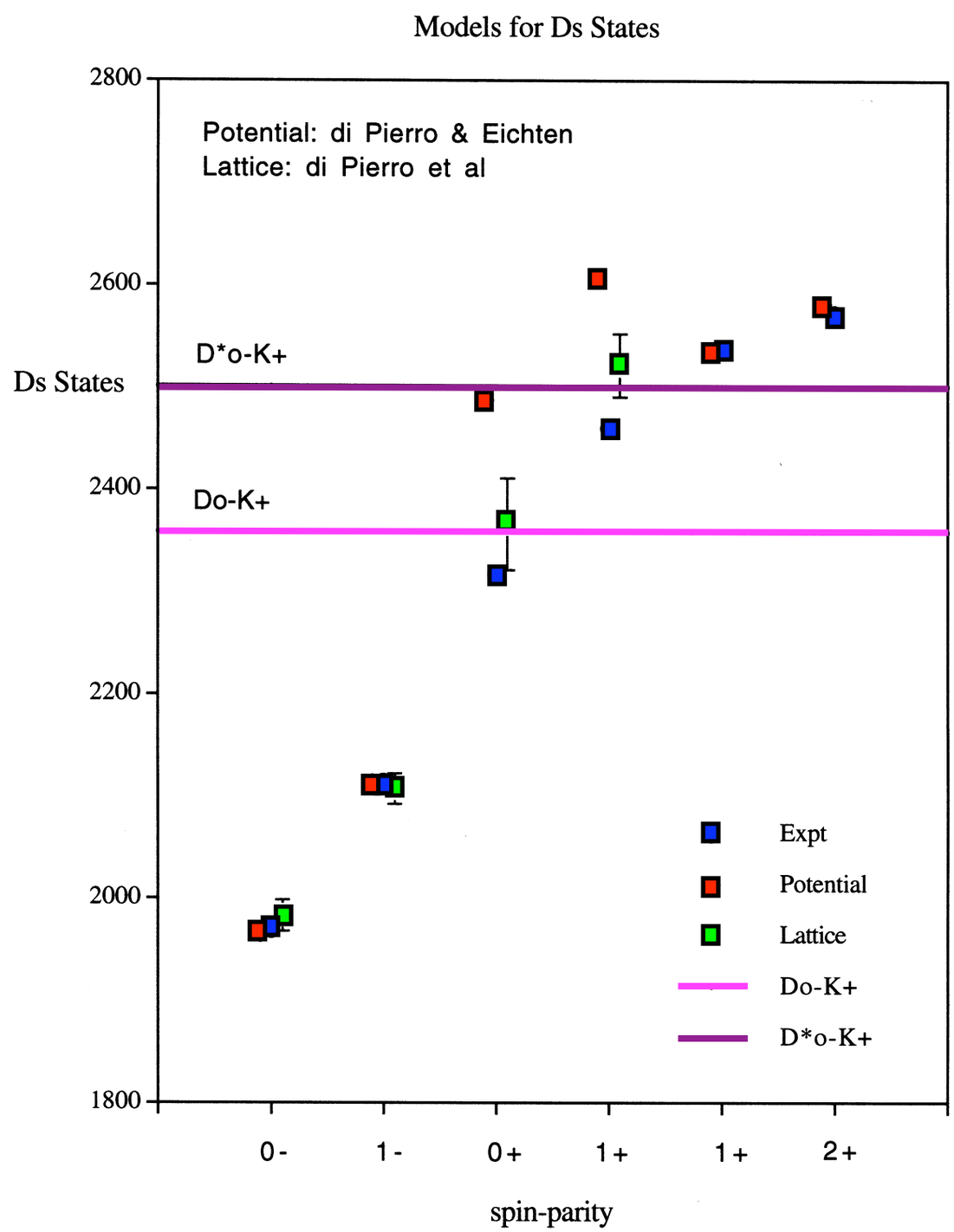



Figure 6. Belle $D_{sJ}^*(2463)$ radiative decay.

# Disagree with relativistic potential model expectations !



# Adjust the parameters?

Cahn and Jackson,PR D68 (2003) 037502

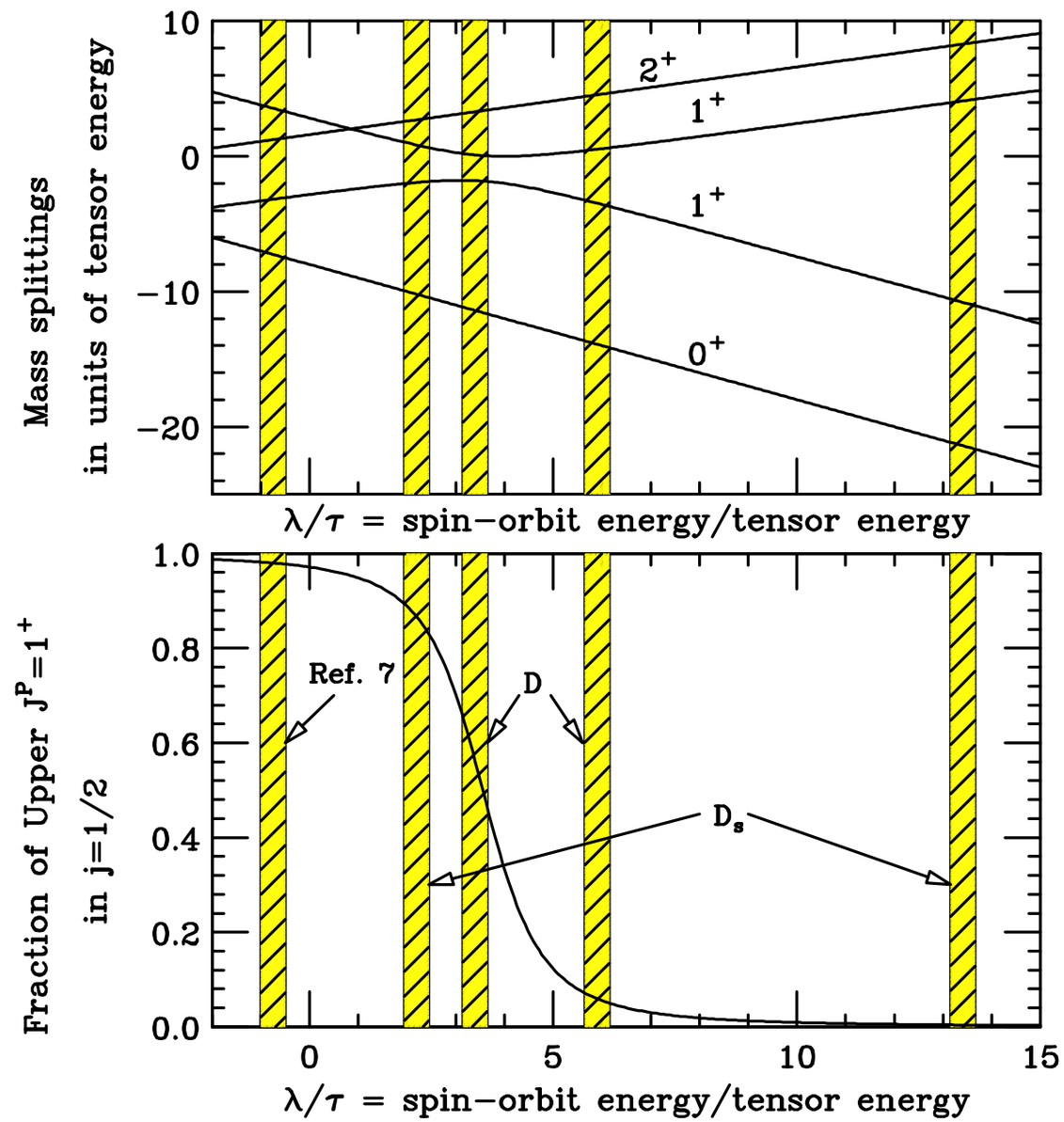
$$\mathcal{V}_{quasi-static} = V + S + \left(\frac{V' - S'}{r}\right) \boldsymbol{\ell}\cdot\left(\frac{\boldsymbol{\sigma}_1}{4m_1^2} + \frac{\boldsymbol{\sigma}_2}{4m_2^2}\right) + \left(\frac{V'}{r}\right) \boldsymbol{\ell}\cdot\left(\frac{\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2}{2m_1 m_2}\right)$$

$$+ \frac{1}{12 m_1 m_2}\left(\frac{V'}{r} - V''\right) S_{12} + \frac{1}{6 m_1 m_2} \nabla^2 V \, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

$$\lambda = \frac{1}{2m_1^2}\left[\frac{V'}{r}\left(1 + \frac{2m_1}{m_2}\right) - \frac{S'}{r}\right]$$

$$\tau = \frac{1}{4 m_1 m_2}\frac{V'}{r}.$$

Result:
Best fit for masses has problems with widths.



# Chiral Dynamics

## What's missing?

Heavy quark-antiquark systems gluons adjust quickly relative to the quark motion. In fact, this static energy can be measured in Lattice QCD.

As one quark becomes light, this is no longer true. The "string" degrees of freedom need to be included. Not just the energy but also the angular momentum

Bardeen, WIN03

## An alternative approach

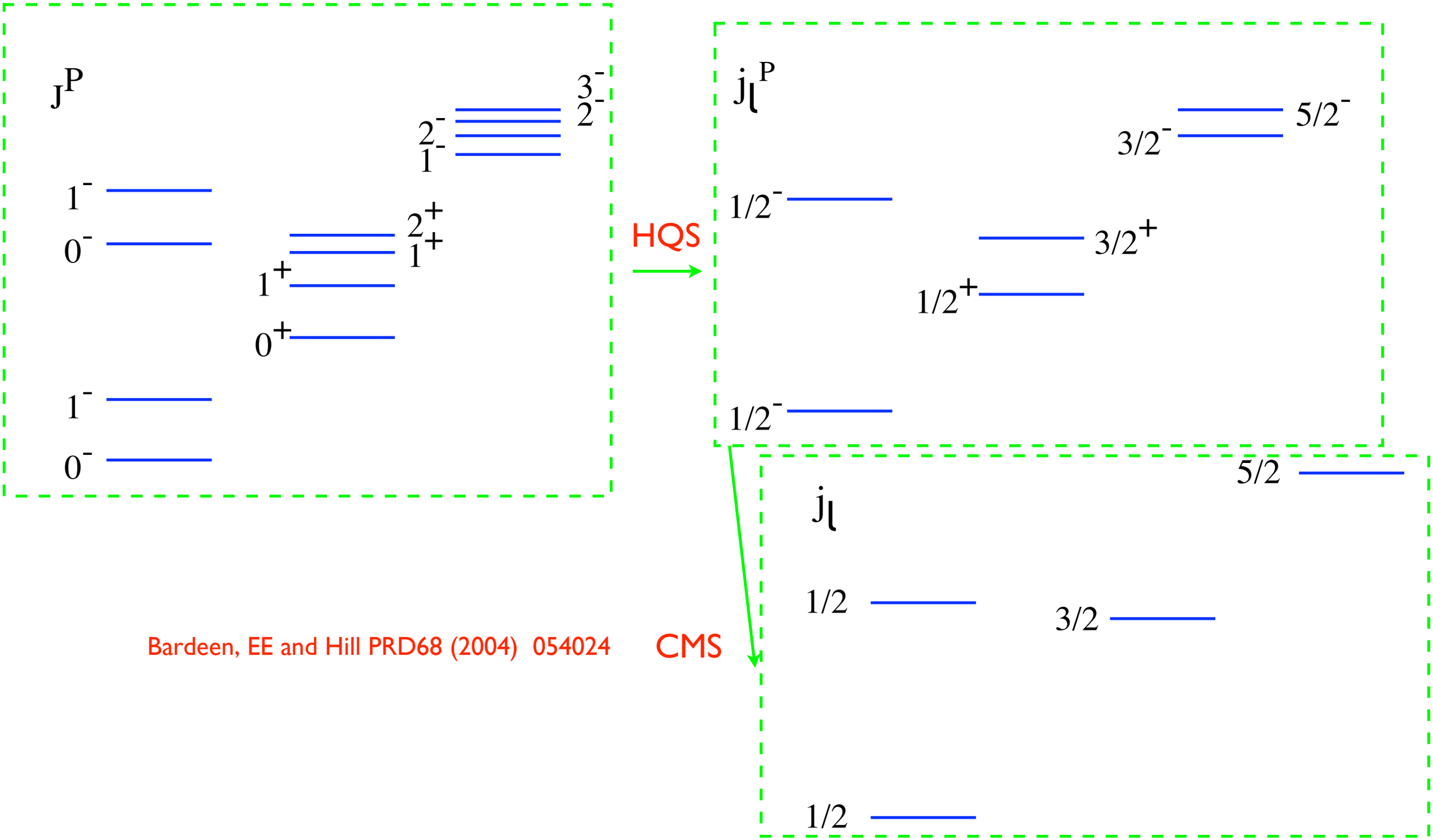
Imagine chiral symmetry and confinement could coexist. Ignore explicit chiral symmetry breaking terms. Then light hadrons could become massless but heavy-light systems are forced to remain massive.

Nowak, Rho and Zahed, PR D48 (1993) 4370
Bardeen and Hill, PR D49 (1994) 409

Heavy-Light states would be parity doubled.

## How far away is QCD from this point?

# Heavy-Light Spectrum




Bardeen, EE and Hill PRD68 (2004) 054024

# Chiral Multiplets of Heavy-Light Mesons

Bardeen, EE and Hill, PR D68 (2003) 054024

## Heavy quark multiplet notation:

$$\xi = exp(i\pi \cdot \lambda/2f_\pi)$$

$$\mathcal{H}_{\rm Swave} = (i\gamma^5 {\rm P} + \gamma_\mu {\rm V}^\mu)(\frac{1+\not{v}}{2})$$

$$\mathcal{H}_{\rm Pwave} = (i{\rm S} + \gamma^5\gamma_\mu {\rm A}^\mu)(\frac{1+\not{v}}{2})$$

HQS states

$$\mathcal{H}_L = \frac{1}{\sqrt{2}}\xi^\dagger(\mathcal{H}_{\rm Swave} - i\gamma^5\mathcal{H}_{\rm Pwave})$$

$$\mathcal{H}_R = \frac{1}{\sqrt{2}}\xi(\mathcal{H}_{\rm Swave} + i\gamma^5\mathcal{H}_{\rm Pwave})$$

Chiral states

Properties of ground S wave states and orbital excited P wave states with the same $j_l = 1/2$ are related.

Armed with these ideas the full effective lagrangian can be deduced.

# Light mesons only

$$\mathcal{L}_L = \frac{1}{4}\,\mathrm{Tr}(\partial_\mu \Sigma^\dagger \partial^\mu \Sigma) + \frac{1}{2}\kappa\,\mathrm{Tr}(\mathcal{M}_q \Sigma + h.c.)$$

with

$$\Sigma = f_\pi \exp(i\pi^a \cdot \lambda^a / f_\pi)$$

contains

$$\mathcal{L}_L = \ldots + \frac{m_\pi^2 (m_u - m_d)}{\sqrt{3}(m_u + m_d)} \pi^0 \eta$$

# Include heavy-light mesons

$$\begin{aligned}
\mathcal{L}_{LH} = & -\frac{1}{2}\,\mathrm{Tr}(\overline{\mathcal{H}} v \cdot (i\partial + \mathcal{V})\mathcal{H}) - \frac{1}{2}\,\mathrm{Tr}(\overline{\mathcal{H}}' v \cdot (i\partial + \mathcal{V})\mathcal{H}') \\
& + i\frac{1}{2} G_A\,\mathrm{Tr}(\overline{\mathcal{H}}' v \cdot \mathcal{A}\mathcal{H}) - i\frac{1}{2} G_A\,\mathrm{Tr}(\overline{\mathcal{H}} v \cdot \mathcal{A}\mathcal{H}') \\
& + \frac{g_\pi}{4}\left[\mathrm{Tr}(\overline{\mathcal{H}}' \tilde{\sigma} \mathcal{H}') - \mathrm{Tr}(\overline{\mathcal{H}} \tilde{\sigma} \mathcal{H})\right] \\
& + \frac{g_A}{2 f_\pi}\left[\mathrm{Tr}(\overline{\mathcal{H}}' \gamma^5 \gamma_\mu \{\mathcal{A}^\mu, \tilde{\sigma}\} \mathcal{H}') - \mathrm{Tr}(\overline{\mathcal{H}} \gamma^5 \gamma_\mu \{\mathcal{A}^\mu, \tilde{\sigma}\} \mathcal{H})\right] \\
& + \frac{g_A}{2 f_\pi}\,\mathrm{Tr}(\overline{\mathcal{H}}' \gamma^5 \gamma_\mu (\partial^\mu \tilde{\sigma} - i[\mathcal{V}^\mu, \tilde{\sigma}])\mathcal{H}) \\
& + \frac{g_A}{2 f_\pi}\,\mathrm{Tr}(\overline{\mathcal{H}} \gamma^5 \gamma_\mu (\partial^\mu \tilde{\sigma} - i[\mathcal{V}^\mu, \tilde{\sigma}])\mathcal{H}')
\end{aligned}$$

defines

$G_A$, $g_A$, $g_\pi$

with

$$\mathcal{V}_\mu = \frac{1}{2}(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger) = \frac{i}{8 f_\pi^2}[\tilde{\pi}, \partial_\mu \tilde{\pi}] + \ldots$$

$$\mathcal{A}_\mu = i\frac{1}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger) = -\frac{1}{2 f_\pi}\partial_\mu \tilde{\pi} + \ldots$$

# Chiral Supermultiplets

States

$j_l$=1/2 $$\mathcal{H} = (H_S + \gamma^5 H_P + \gamma_\mu H_V^\mu + \gamma^5\gamma_\mu H_A^\mu)\left(\frac{1+\not{v}}{2\sqrt{2}}\right)$$ 1S ($0^-$,$1^-$) 1P ($0^+$,$1^+$)

$$\mathcal{H}' = (H'_S + \gamma^5 H'_P + \gamma_\mu H'^\mu_V + \gamma^5\gamma_\mu H'^\mu_A)\left(\frac{1+\not{v}}{2\sqrt{2}}\right)$$ 2S ($0^-$,$1^-$) 2P ($0^+$,$1^+$)

Falk and Mehen, PR D53 (1996) 231 [hep-ph/9507311]

$j_l$=3/2 $$\mathcal{P}^\mu = \left(\sqrt{3/2}(\delta^\mu_\nu - \frac{1}{3}\gamma_\nu\gamma^\mu + \frac{1}{3}\gamma_\nu v^\mu)(P_V^\nu + i\gamma^5 P_A^\nu) + (K_T{}^{\mu\nu} + i\gamma^5 K_{T5}^{\mu\nu}\gamma_\nu)\right)\left(\frac{1+\not{v}}{2\sqrt{2}}\right)$$

1P ($1^+$,$2^+$) 1D ($1^-$,$2^-$)

# Lagrangian Form

Bardeen, EE and Hill PRD68 (2004) 054024

$$\mathcal{L}_0 = -i\,\mathrm{Tr}(\overline{\mathcal{H}}\not{v}\, v\cdot\partial\mathcal{H}) - i\,\mathrm{Tr}(\overline{\mathcal{H}}\not{v}\,\Delta_0\mathcal{H})$$

Chiral Multiplet Symmetry (CMS)

$$-\frac{1}{2}g_\pi^{(0)}\,\mathrm{Tr}(\overline{\mathcal{H}}\Sigma\mathcal{H}) + i\frac{g_A^{(0)}}{f_\pi}\left[\mathrm{Tr}(\overline{\mathcal{H}}\not{v}\,(\not{\partial}\,\Sigma)\mathcal{H})\right] \quad + \ldots$$

Broken Phase

$$\Sigma = \xi\tilde{\sigma}\xi \qquad \xi = \exp(i\pi\cdot\lambda/2f_\pi) \qquad \tilde{\sigma} = \sqrt{\frac{2}{3}}\sigma I_3 + \sigma^a\lambda^a \qquad \langle\sigma\rangle = \sqrt{3/2}f_\pi$$

# Mass splittings

$\Delta M = g_\pi f_\pi$ Goldberger-Treiman Relation

$\Delta M = M(D_s(0^+) - D_s(0^-)) = 349$ MeV Determines $g_\pi = 3.73$

$$\mathcal{L}_{LH,hyperfine} = k\frac{\Lambda_{QCD}^2}{12m_Q}\left[\mathrm{Tr}(\overline{\mathcal{H}}'\sigma_{\mu\nu}\mathcal{H}'\sigma^{\mu\nu}) + \mathrm{Tr}(\overline{\mathcal{H}}\sigma_{\mu\nu}\mathcal{H}\sigma^{\mu\nu})\right]$$

$M(D_s(1^+) - D_s(0^+)) = M(D_s(1^-) - D_s(0^-))$ Symmetry relation

# Pion transitions

One pion isospin violating transitions.

Two pion transition.

Form determined by chiral lagrangian

Coefficients set by fit by other known transitions

# Electromagnetic transitions

define

$$r_{\overline{Q}q} = \left(1 - \frac{m_q^* e_{\overline{Q}}}{m_{\overline{Q}}^* e_q}\right)$$

use

$$r_{\overline{c}u} = 1.23$$
$$r_{\overline{c}d} = 0.54$$
$$r_{\overline{c}s} = 0.38$$

fit

## M1 transitions rate

$$\Gamma_{\mathrm{M1}}(i \to f\gamma) = \frac{4\alpha}{3}\mu_{\overline{Q}q}^2 k^3 (2J_f + 1)|\langle f|j_0(kr)|i\rangle|^2$$

$$\mu_{\overline{Q}q} = \frac{m_Q^* e_q - m_q^* e_{\overline{Q}}}{2m_Q^* m_q^*} = \frac{e_q}{2m_q^*} r_{\overline{Q}q}$$

## E1 transitions rate

$$\Gamma_{\mathrm{E1}}(i \to f + \gamma) = \frac{4\alpha < e_{\mathrm{avg}} >^2}{27} k^3 (2J_f + 1)|\langle f|r|i\rangle|^2 \mathcal{S}_{if}$$

$$< e_{\mathrm{avg}} > = \frac{m_Q^* e_q - m_q^* e_{\overline{Q}}}{m_Q^* + m_q^*} = \frac{e_q m_Q^* r_{\overline{Q}q}}{m_Q^* + m_q^*}$$

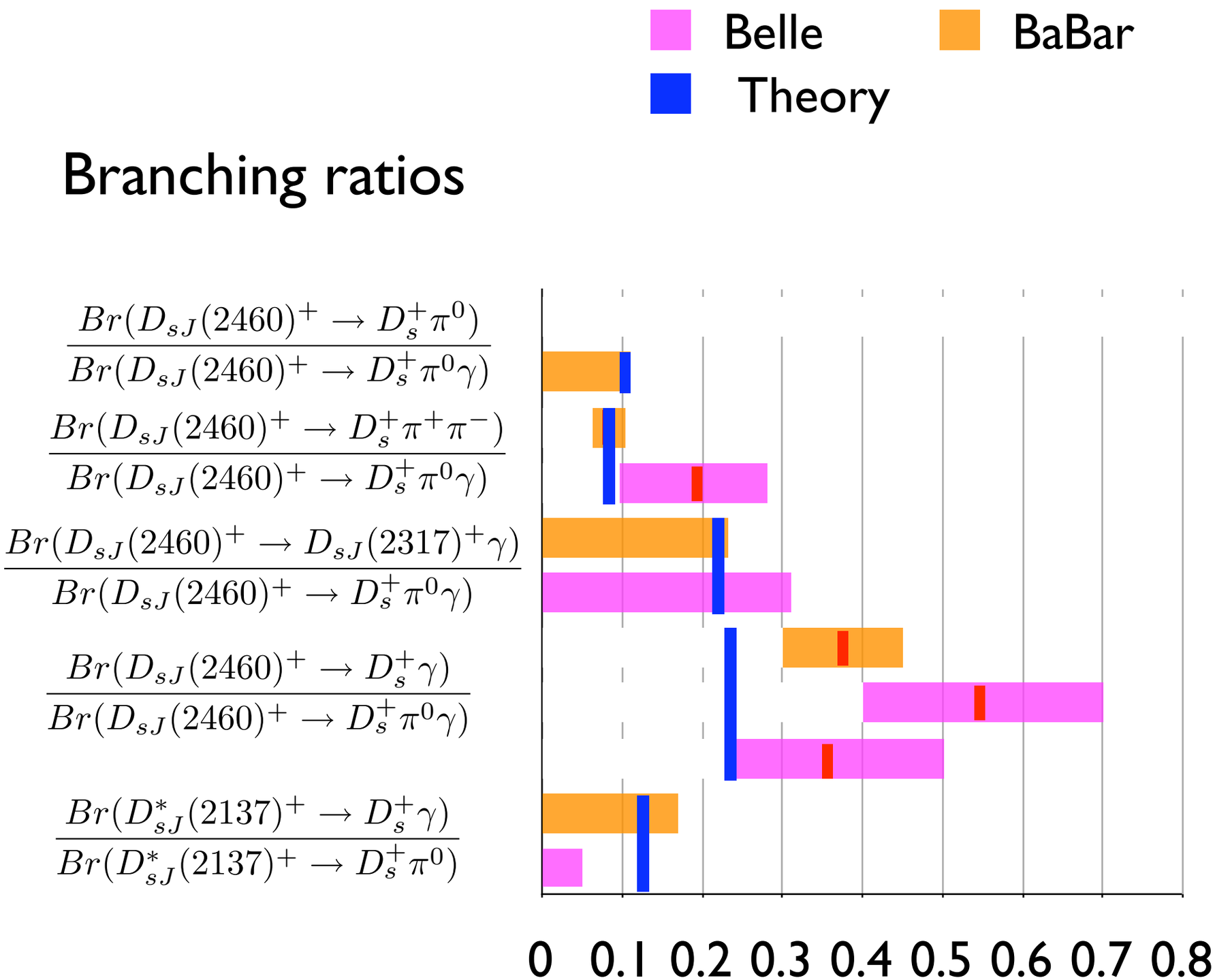
$\mathcal{S}_{if}$

$(0^+, 1^-)$ is 1
$(1^+, 1^-)$ is 2/3
$(1^+, 0^-)$ is 1

# BEH predictions for decays

| system | transition | Q(keV) | overlap | dependence | $\Gamma$ (keV) | exptl BR |
|---|---|---|---|---|---|---|
| $(c\overline{u})$ | $1^- \to 0^- + \gamma$ | 137 | 0.991 | $r_{\overline{c}u}$ | 33.5 | $(38.1 \pm 2.9)\%$ |
| | $1^- \to 0^- + \pi^0$ | 137 | | $g_A$ | 43.6 | $(61.9 \pm 2.9)\%$ |
| | total | | | | 77.1 | |
| $(c\overline{d})$ | $1^- \to 0^- + \gamma$ | 136 | 0.991 | $r_{\overline{c}d}$ | 1.63 | $(1.6 \pm 0.4)\%$ |
| | $1^- \to 0^- + \pi^0$ | 38 | | $g_A$ | 30.1 | $(30.7 \pm 0.5)\%$ |
| | $1^- \to 0^- + \pi^+$ | 39 | | $g_A$ | 65.1 | $(67.7 \pm 0.5)\%$ |
| | total | | | | 96.8 | $96 \pm 22$ |
| $(c\overline{s})$ | $1^- \to 0^- + \gamma$ | 138 | 0.992 | $r_{\overline{c}s}$ is 1. | 0.43 | $(94.2 \pm 2.5)\%$ |
| | $1^- \to 0^- + \pi^0$ | 48 | | $g_A\delta_{\eta\pi 0}$ | 0.0079 | $(5.8 \pm 2.5)\%$ |
| | total | | | | 0.44 | |
| $(c\overline{s})$ | $0^+ \to 1^- + \gamma$ | 212 | 2.794 | $r_{\overline{c}s}$ | 1.74 | |
| | $0^+ \to 0^- + \pi^0$ | 297 | | $G_A\delta_{\eta\pi 0}$ | 21.5 | |
| | total | | | | 23.2 | |
| $(c\overline{s})$ | $1^+ \to 0^+ + \gamma$ | 138 | 0.992 | $r'_{\overline{c}s}$ | 2.74 | |
| | $1^+ \to 0^+ + \pi^0$ | 48 | | $g_A\delta_{\eta\pi 0}$ | 0.0079 | |
| | $1^+ \to 1^- + \gamma$ | 323 | 2.638 | $r_{\overline{c}s}$ | 4.66 | |
| | $1^+ \to 0^- + \gamma$ | 442 | 2.437 | $r_{\overline{c}s}$ | 5.08 | |
| | $1^+ \to 1^- + \pi^0$ | 298 | | $G_A\delta_{\eta\pi 0}$ | 21.5 | |
| | $1^+ \to 0^- + 2\pi$ | 221 | | $g_A\delta_{\sigma_1\sigma_3}$ | 4.2 | |
| | total | | | | 38.2 | |

# Comparison with experiment



# Open Issues and Opportunities

Opportunities for further study with $D_s(0^+)$, $D_s(1^+)$

Measure the remaining decay rates

Analogy states in the Bs system

Expect radiative transitions to dominate pion transitions

$r_{\overline{c}u} = 1.23$ $\quad$ $r_{\overline{b}u} = 0.85$

$r_{\overline{c}d} = 0.54$ $\quad$ $r_{\overline{b}d} = 1.07$ $\quad$ pion transition rates unchanged

$r_{\overline{c}s} = 0.38$ → $r_{\overline{b}s} = 1.10$ $\quad$ E1 rates ~ r*r

| system | transition | Q(keV) | overlap | dependence | Γ (keV) |
|---|---|---|---|---|---|
| $(b\overline{s})$ | $0^+ \to 1^- + \gamma$ | 293 | 2.536 | $r_{\overline{b}s}$ | 58.3 |
| | $0^+ \to 0^- + \pi^0$ | 297 | | $G_A \delta_{\eta\pi 0}$ | 21.5 |
| | total | | | | 79.8 |
| $(b\overline{s})$ | $1^+ \to 0^+ + \gamma$ | 47 | 0.998 | $r'_{\overline{b}s}$ | 0.061 |
| | $1^+ \to 1^- + \gamma$ | 335 | 2.483 | $r_{\overline{b}s}$ | 56.9 |
| | $1^+ \to 0^- + \gamma$ | 381 | 2.423 | $r_{\overline{b}s}$ | 39.1 |
| | $1^+ \to 1^- + \pi^0$ | 298 | | $G_A \delta_{\eta\pi 0}$ | 21.5 |
| | $1^+ \to 0^- + 2\pi$ | 125 | | $g_A \delta_{\sigma_1 \sigma_3}$ | 0.12 |
| | total | | | | 117.7 |

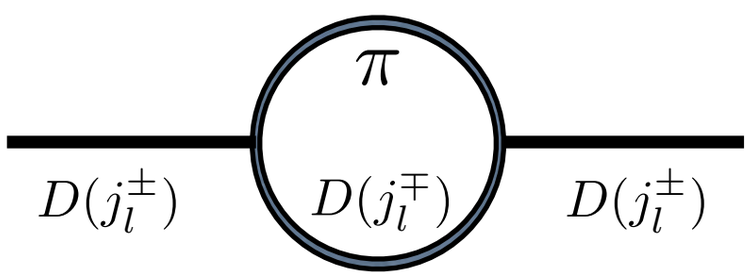
Striking Prediction

# Analogy states in the D system

| $\Delta M$ $(c\bar{q})$ (MeV) | $\Delta M$ $(c\bar{s})$ (MeV) |
|---|---|
| $M_{D_1'^0} - M_{D_0^{*0}} = 119 \pm 26 \;\; (87 \pm 40)$ | $M_{D_{sJ}(2460)} - M_{D^*_{sJ}(2317)} = 141.4 \pm 1.2$ |
| $M_{D_1'^0} - M_{D^{*0}} = 417 \pm 36 \;\; (428 \pm 30)$ | $M_{D_{sJ}(2460)} - M_{D_s^*} = 346.4 \pm 1.2$ |
| $M_{D_0^{*0}} - M_{D^0} = 444 \pm 36 \;\; (487 \pm 27)$ | $M_{D^*_{sJ}(2317)} - M_{D_s} = 348.9 \pm 0.8$ |

Expect coupling to decay channels to play a major role in explaining the differences in the P wave splittings in these systems.

Compute one loop chiral corrections for heavy-light transitions.




$$\Omega = \frac{1}{2\pi^2}\int_0^\infty k^2 dk \frac{|<1E_1, \pi E_\pi|H_I|0M_0>|^2}{M_0 - E_1 - E_\pi + i\epsilon}$$

$$\Omega = \mathrm{M(shift)} + i\ \Gamma(\mathrm{width})$$

Introduce a cutoff to study sensitivity to wavefunctions.

$$|<1,\pi|H_I|0>|^2 = C^2 \exp -(k^2/\Lambda^2_{\mathrm{cutoff}})$$

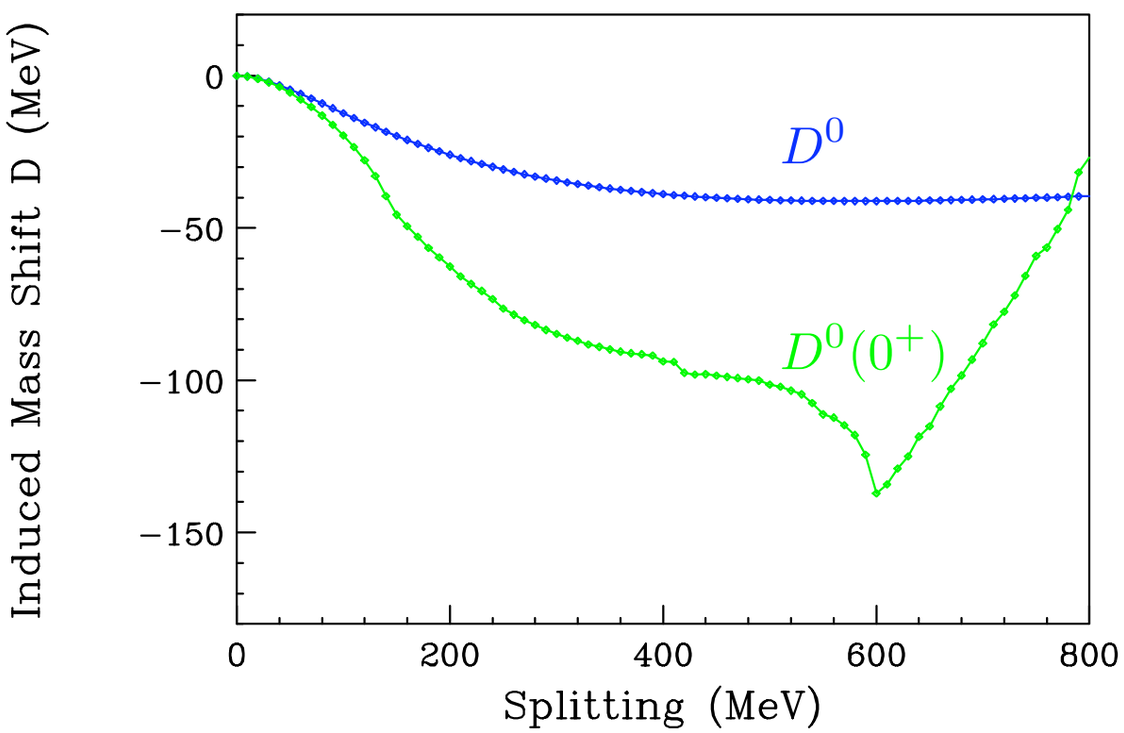
Restrict calculations to S-wave transitions.

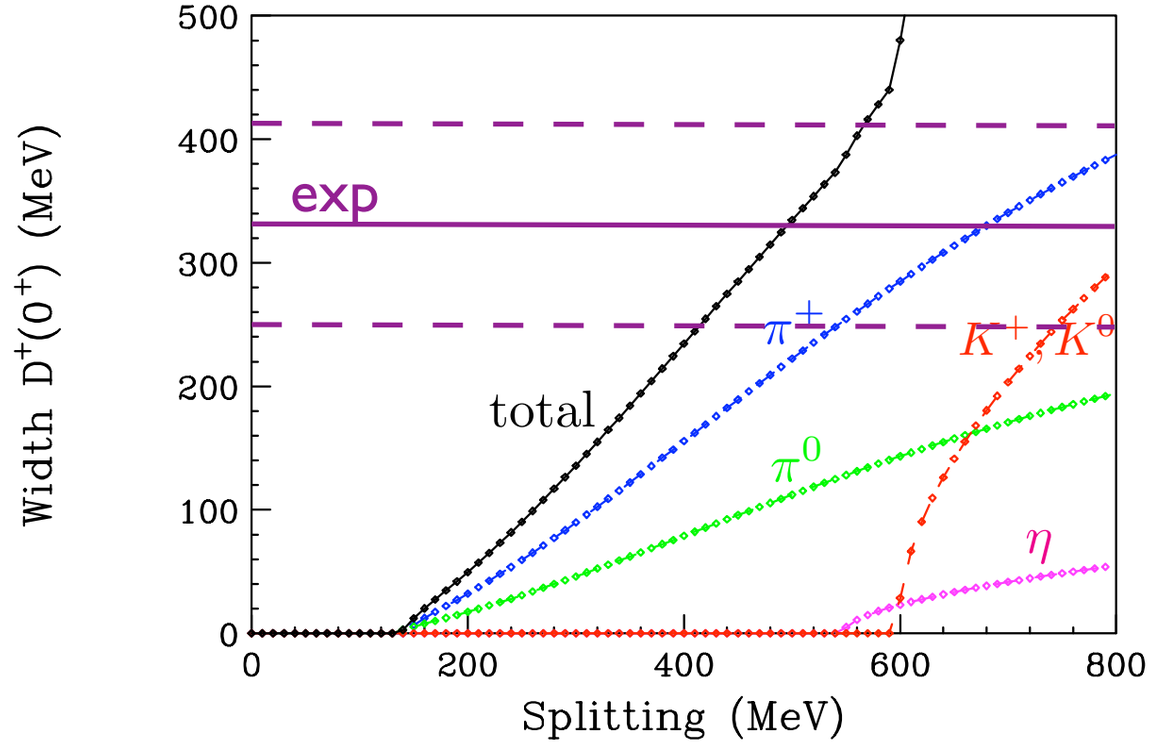
$$C^2 = CG \times [\frac{G_A \delta M}{f_\pi}]^2 \qquad G_A \approx 1$$

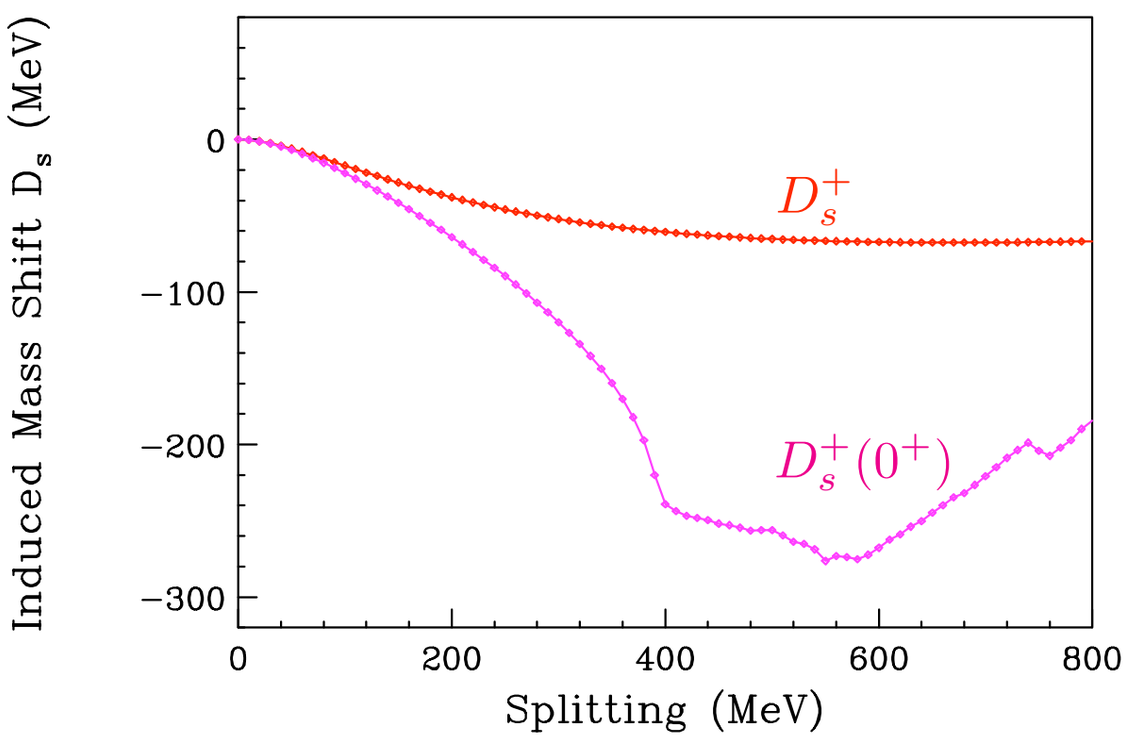
Related recent works

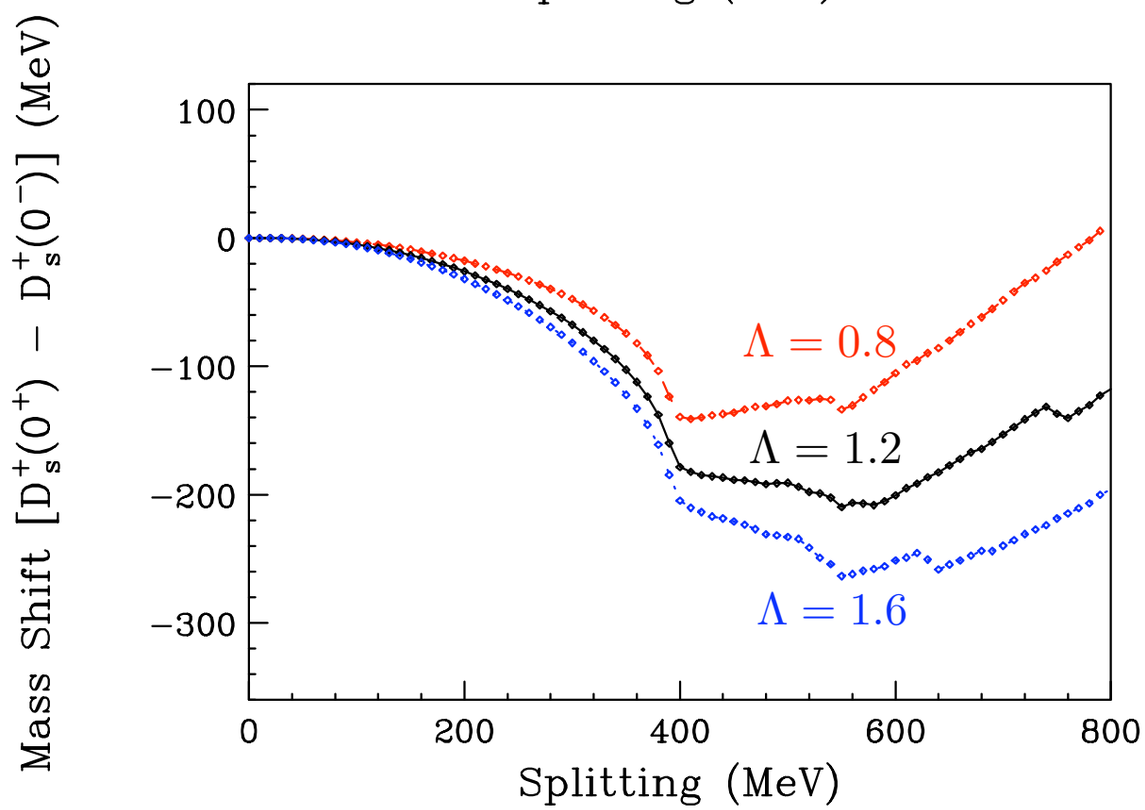
CCM :
Simonov,Tjon [hep-ph/0409361]
Hwang, Kim [hep-ph/0408154]

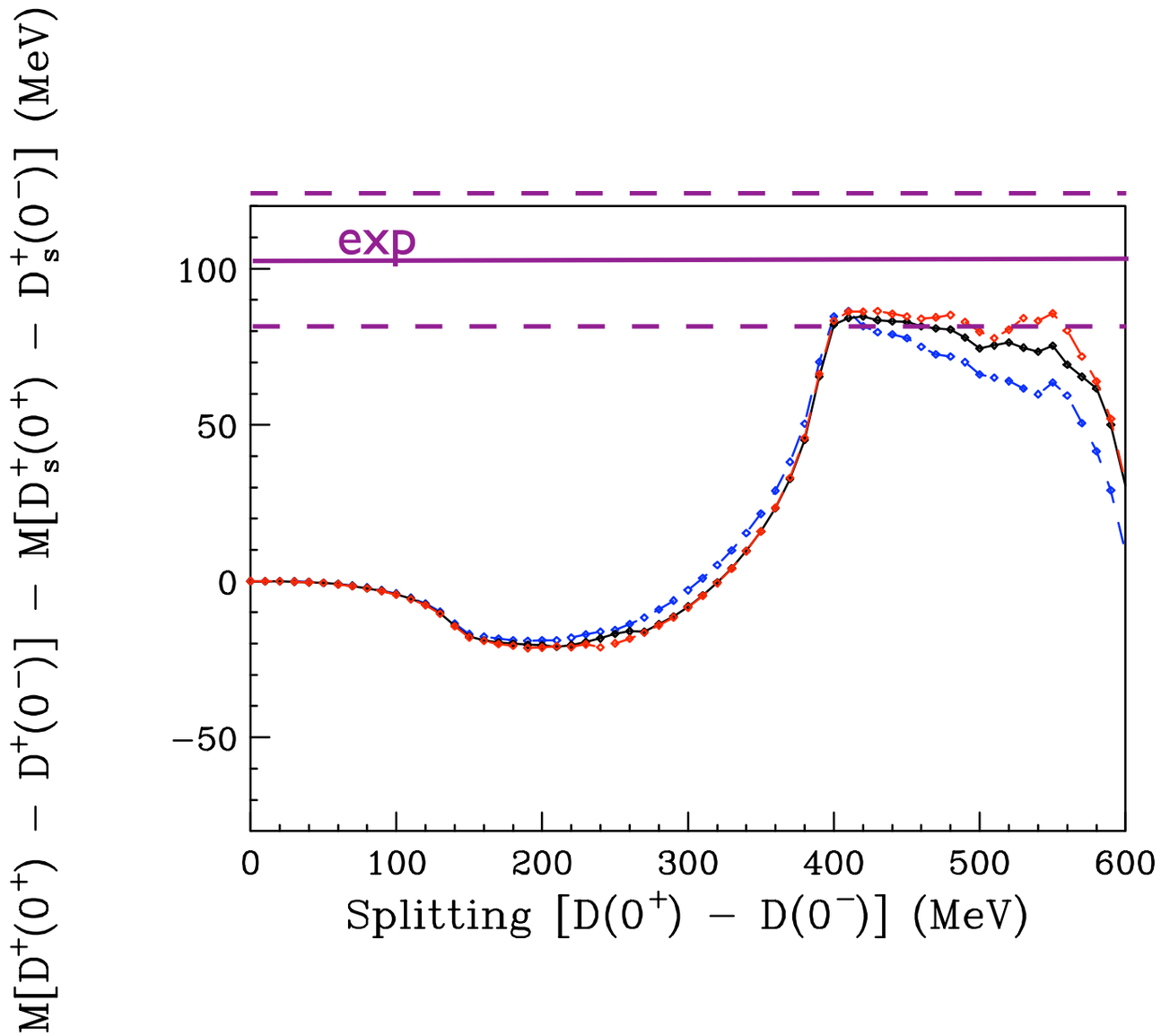
Chiral loop :
Becirevic, Fajfer, Prelovsek [hep-ph/0406296]


Induced Mass Shift D (MeV)
0
−50
−100
−150
0
200
400
600
800
Splitting (MeV)
$D^0$
$D^0(0^+)$


Width $D^+(0^+)$ (MeV)
500
400
300
200
100
0
0
200
400
600
800
Splitting (MeV)
exp
total
$\pi^\pm$
$K^+, K^0$
$\pi^0$
$\eta$


Induced Mass Shift $D_s$ (MeV)
0
−100
−200
−300
0
200
400
600
800
Splitting (MeV)
$D_s^+$
$D_s^+(0^+)$


Mass Shift $[D_s^+(0^+) - D_s^+(0^-)]$ (MeV)
100
0
−100
−200
−300
0
200
400
600
800
Splitting (MeV)
$\Lambda = 0.8$
$\Lambda = 1.2$
$\Lambda = 1.6$




S wave couplings provide about 80 MeV of relative shift.

Model insensitive.

Coupling to decay channels near threshold results in large SU(3) breaking effects arising from the light pseudoscalar meson mass differences.

# SUMMARY

- Relativistic Potential model limitations
  - Failure to incorporate chiral dynamics
  - Failure to include light quark pair dynamics
- Narrow heavy-light states:
  - The j= 1/2 S and P wave states can be view as a chiral supermultiplet.
  - HQS and Spontaneous Chiral Symmetry breaking accounts for mass splittings.
  - Many testable predictions for decay modes involving pions and photons. Looks promising.
  - Mass shifts due to coupling to decay channels may be large. Could explain the splitting pattern versus light quark mass.

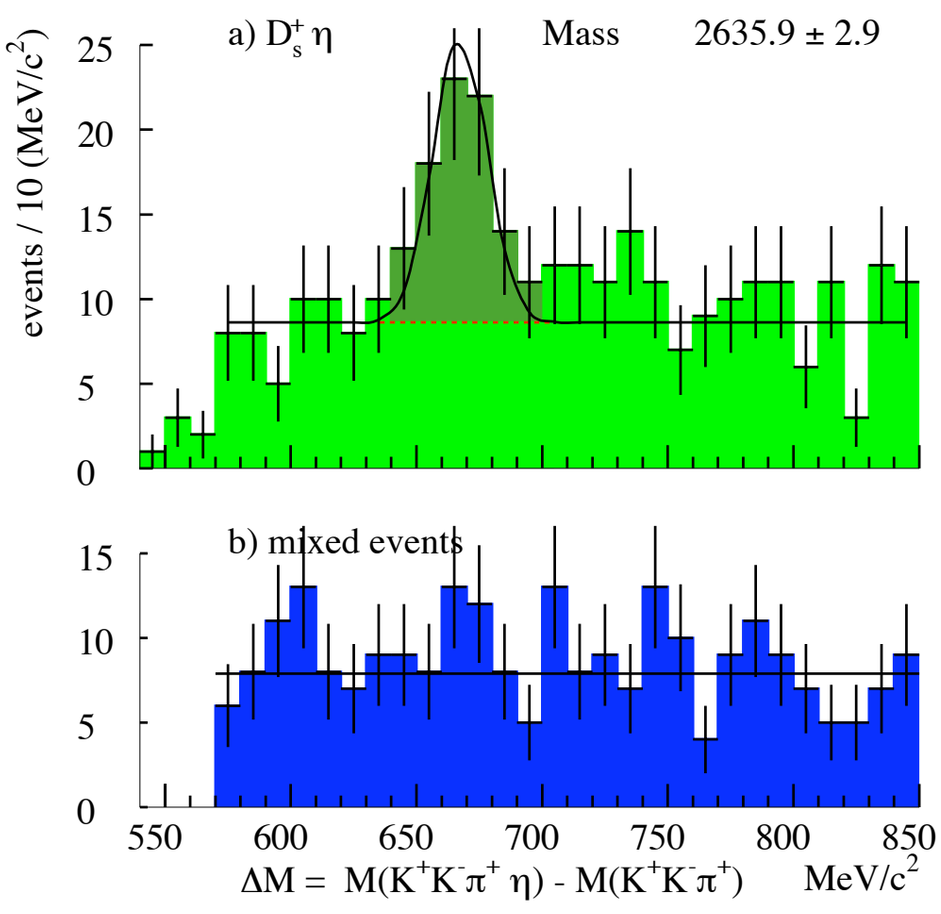
# EXTRA SLIDES

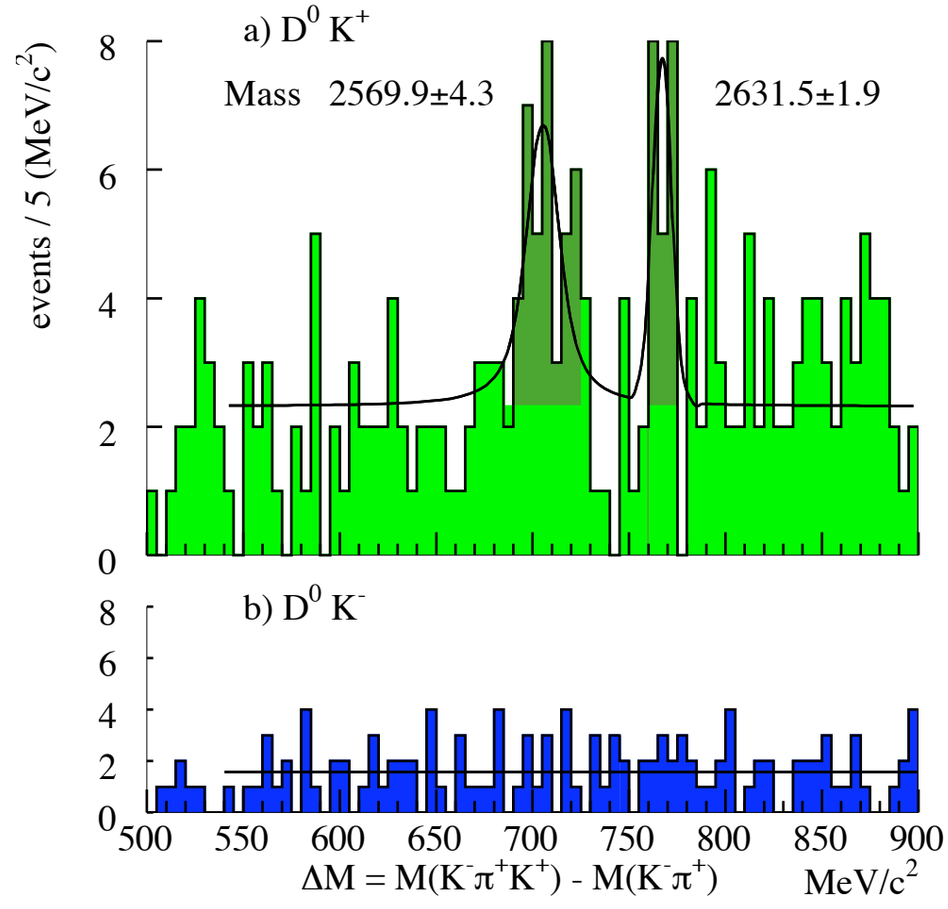
# First Observation of a Narrow Charm-Strange Meson $D_{sJ}^{+}(2632) \to D_s^{+}\eta$ and $D^0K^+$

SELEX Collaboration HEP-EX/0406045

| Fig. | state | events | $\Delta$M MeV/c$^2$ | Mass MeV/c$^2$ | Significance $(S-B)/\sqrt{B}$ | $\sigma$ MeV/c$^2$ | $\Gamma$ MeV/c$^2$ | $\chi^2/n_d$ |
|---|---|---|---|---|---|---|---|---|
| 1 | $\eta(548) \to \gamma\gamma$ | $5087 \pm 863$ | | $544.8 \pm 2.9$ | 13.9 $\sigma$ | $27.8 \pm 4.3$ | | 1.17 |
| 2 | $D_s^+(2632) \to D_s^+\eta$ | $45 \pm 9.3$ | $667.4 \pm 2.9$ | $2635.9 \pm 2.9$ | 7.2 $\sigma$ | 10.7 | | 0.95 |
| 3 | $D_s^+(2573) \to D^0K^+$ | $25 \pm 9$ | $705.4 \pm 4.3$ | $2569.9 \pm 4.3$ | 5.4 $\sigma$ | 4.9 | $14^{+9}_{-6}$ | 0.77 |
| 3 | $D_s^+(2632) \to D^0K^+$ | $14 \pm 4.5$ | $767.0 \pm 1.9$ | $2631.5 \pm 1.9$ | 5.3 $\sigma$ | 4.9 | $< 17(90\%CL)$ | |

TABLE I: Fit results for Figures 1-3.



# Properties

- Likely radial excitation of $D_s^*$ : $J^P = 1^-$ $j_l^P = 1/2^-$
  - Mass 100-175 MeV below RQM expectations.
  - Transition interaction term $g\,\mathrm{Tr}\,\overline{\mathcal{H}'}\psi\,\gamma^5\gamma_\mu\mathcal{A}^\mu\mathcal{H} + h.c.$ $\mathcal{A}_\mu = -\frac{1}{2f_\pi}\partial_\mu\tilde{\pi} + \ldots$
- Can use chiral quark model to estimate overall coupling, g(CQM), for light meson transition terms in the CMS form.

Di Pierro and EE, PRD64 (2001) 11400

- Use HQS and SU(3) to determine relations between transitions.
- HQS partner state - radial excitation of $D_s$
  - $J^P = 0^-$
  - Mass ~ 2525 MeV. Near the observed 2535 P state.
- Partial Widths (see Table)
  - $D_s(2632)$ to $D_s$ + eta transition much smaller than observed. Addition Contribution?
  - $D_s(2525)$ very narrow. Two pion transition might dominate.