Masses of Scalar & Axial-Vector B Mesons: A Challenge to the Quark Model ?

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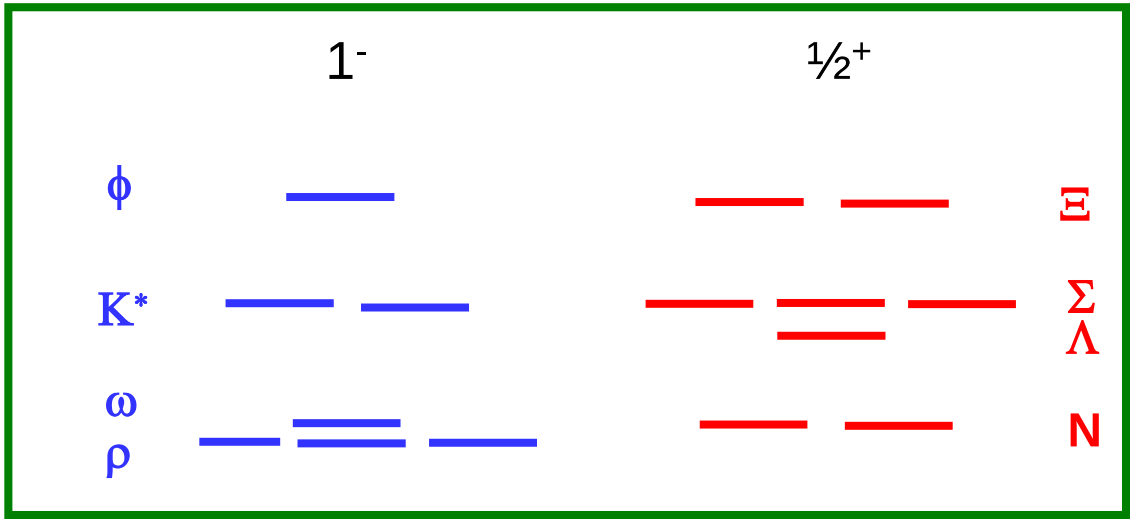
Although the quark model has been applied successfully to describe the properties of hadrons, it often encounters a great challenge in understanding even-parity 0^+ & 1^+ mesons, especially scalars.

$\phi = s\underline{s}$

$K^* = q\underline{s}$

$\omega = 1/\sqrt{2}(u\underline{u}+d\underline{d})$

$\rho^+ = u\underline{d}$



Ξ = ssq

Σ,Λ = sqq

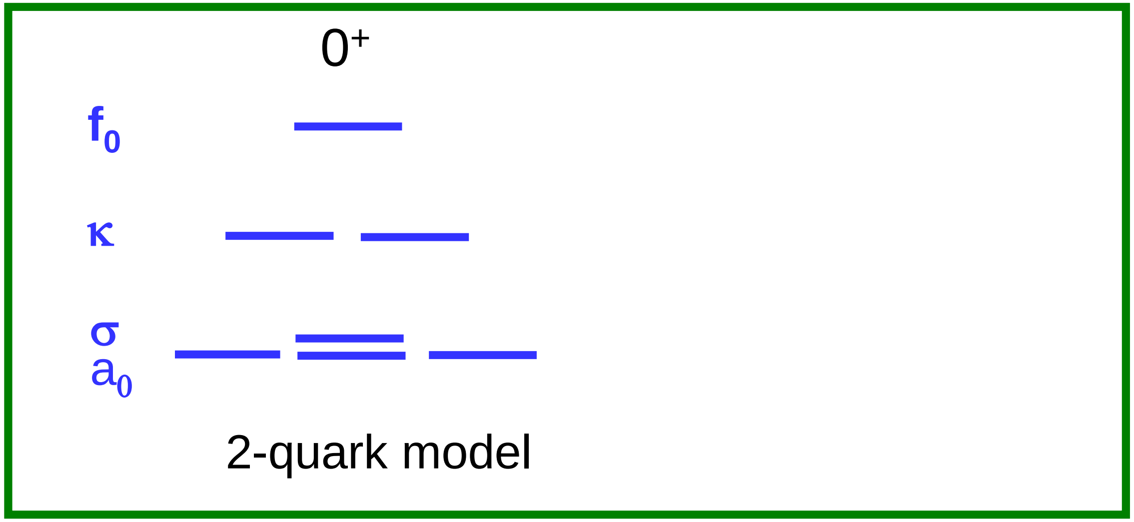
N = qqq

$f_0 = s\underline{s}$

$\kappa = q\underline{s}$

$\sigma = 1/\sqrt{2}(u\underline{u}+d\underline{d})$

$a_0^+ = u\underline{d}$

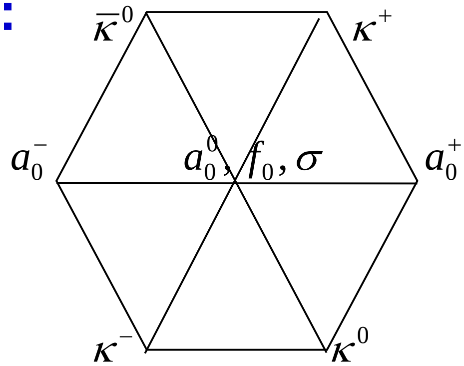


2-quark model

Scalar Mesons are p-wave mesons in $q\underline{q}$ quark model

Consider $J^P=0^+$ scalar mesons ⇒ L=1 if they are made of $q\bar{q}$

Two nonets (nonet=octet+singlet) have been observed:



- **light nonet (< 1 GeV)**

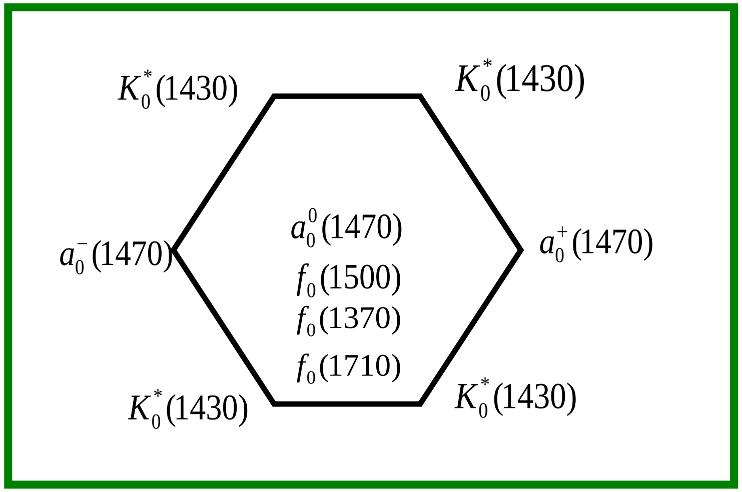
  I=0: σ(500), f_0(980), I=1/2: κ(800), I=1: a_0(980),

- **heavy nonet (> 1 GeV)**

  I=0: f_0(1370), f_0(1500), f_0(1710), I=1/2: K^*_0(1430), I=1: a_0(1450)

	f_0(500)	K_0^*(800)	f_0(980)	a_0(980)
mass (MeV)	400-550	682±29	990±20	980±20
width (MeV)	400-700	547±24	10-100	50-100

- **Why are f_0(980) & a_0(980) degenerate in mass ?**
- **Why are σ (or f_0(500)) & κ (or K_0^*(800)) much broader than f_0 & a_0 ?**



$K_0^*(1430)$ $K_0^*(1430)$

$a_0^-(1470)$ $a_0^0(1470)$ $a_0^+(1470)$

$f_0(1500)$

$f_0(1370)$

$f_0(1710)$

$K_0^*(1430)$ $K_0^*(1430)$

Scalar mesons above 1 GeV

$K_0^*(1430)$

$a_0(1450)$

$f_0(1370)$, $f_0(1500)$, $f_0(1710)$

- **The mass of $K_0^*(1430)$ is almost degenerate with $a_0(1450)$**

  $m(a_0(1450)) = 1474 \pm 19$ MeV, $m(K_0^*(1430)) = 1425 \pm 50$ MeV

  Why?

- **Nonet in the QM has only 9 states, but there are 10 observed scalar states. Why an extra state?**

Even-parity Heavy Mesons

- Light even-parity mesons are classified according to quantum numbers L,S,J:

  ${}^{2S+1}L_J={}^3P_0$(scalar), ${}^1P_1$, ${}^3P_1$ (axial-vector), ${}^3P_2$ (tensor)

- For heavy mesons, S_Q decouples in heavy quark limit

  $\Rightarrow$ S_Q & j_q are separately good quantum numbers, $J=j_q+S_Q$

  $\Rightarrow$ classified according to $j_q=1/2, 3/2$

  $L_J^j=P_0^{1/2}$ (scalar), $P_1^{1/2}$, $P_1^{3/2}$ (axial-vector), $P_2^{3/2}$ (tensor)

L=1

j_q	**1/2**	**3/2**
J^P	**0^+ $1'^+$**	**1^+ 2^+**

D_0^*, D'_1, D_1, D_2^*

B_0^*, B'_1, B_1, B_2^*

J^P	State	M (MeV)	Γ (MeV)	QM	Γ
0^+	$D_0^*(2400)^0$ $D_0^*(2400)^\pm$	2318±29 2351±7	267±40 230±17	2340~ 2410	large
$1'^+$	$D'_1(2430)^0$	2427±25	$384^{+107}_{-75}\pm74$	2470~ 2530	large
1^+	$D_1(2420)^0$ $D_1\ (2420)^\pm$	2420.8±0.5 2432.2±2.4	31.7±2.5 25±6	2417~ 2434	small
2^+	$D_2^*(2460)^0$ $D_2^*(2460)^\pm$	2460.57±0.15 2465.4±1.3	47.7±1.3 46.7±1.2	2460~ 2467	small

J^P	State	M (MeV)	Γ (MeV)	QM	Γ
0^+	$D_{s0}^*(2317)$	2317.7±0.6	<3.8	2400~ 2510	large
$1'^+$	$D'_{s1}(2460)$	2459.6±0.6	<3.5	2528~ 2536	large
1^+	$D_{s1}(2536)$	2535.10±0.06	0.92±0.05	2543~ 2605	small
2^+	$D_{s2}^*(2573)$	2569.1±0.8	16.9±0.8	2569~ 2581	small

- Predicted D_{s0}^*, D_0^*, D'_{s1}, D'_1 are too heavy in QM
- Physical D_{s0}^* is below DK threshold, D'_{s1} below D*K threshold
- $D_0^*(2400)^\pm$ is heavier than $D_{s0}^*(2317)$

A new chapter of hadron spectroscopy in 2003:

- D_{s0}^{*}**(2317) by BaBar**
- **X(3872) by Belle**
- Θ^{+} **pentaquark by LEPS**

A new chapter in 2003: D_{s0}^{*}(2317) & X(3872)

$D_{s0}^{*}(2317)$

- A narrow scalar charmed meson D_{s0}^{*}(2317) with mass of 2317 MeV was observed by BaBar.

It is much smaller than the predictions of ~ (2480-2510) MeV from potential models for D_{s0}^{*}(2317) in a ($c\underline{s}$) bound state

⇒ D_{s0}^{*} state expected to be very broad in QM is actually very narrow as it is below DK threshold; the only allowed strong decay is isospin-violating $D_s\pi$

Wei-Shu Hou and I ('03) proposed an S-wave four-quark ($c\underline{s}n\underline{n}$) picture for D_{s0}^{*}(2317) , hoping that it is lighter than 2-quark D_{s0}^{*}($c\underline{s}$)

Barnes, Close, Lipkin ('03) proposed a $D\underline{K}$ molecule for D_{s0}^{*}

X(3872)

- First XYZ particle observed by Belle (2003) in B→ K + ($J/\psi\pi^+\pi^-$) decay. Its quantum numbers $J^{PC}= 1^{++}$ are fixed by LHCb ('13) Its mass = 3871.69±0.17 MeV is very close to m($D^0\underline{D}^{*0}$) = 3871.80±0.12 MeV, while D^+D^{*-} is heavier than $D^0\underline{D}^{*0}$ by 8.1 MeV

- It cannot be identified as $\chi_{c1}(1^3P_1)$ with mass 3511 MeV or $\chi_{c1}(2^3P_1) = \chi'_{c1}$ with predicted mass ~ 3950 MeV

- The extreme proximity of X to the threshold suggests that a loosely bound molecule state $D^0\underline{D}^{*0}$ of X(3872). This explains (i) the mass of X(3872), (ii) the narrow width, $\Gamma(X) \sim \Gamma(D^{*0}) < 1.2$ MeV, (iii) comparable rates of X(3872)→ $J/\psi\pi^+\pi^-$ and X(3872) → $J/\psi\pi^+\pi^-\pi^0 \Rightarrow$ sizable isospin violation

Arguments against a pure molecule picture:

- cannot explain prompt production of X in high energy collisions

Prompt production cross section of X(3872) in $p\underline{p}$ collisions: theoretical upper bound 0.085 nb is too small compared to 3.1±0.7 nb measured by CDF

Suzuki ('05)
Bignamini et al. PRL 103, 162001 ('09)
Artoisenet, Bratten, 0911.2016
Bignamini et al. 0912,5064

- molecule X(3872) $\Rightarrow \Gamma(\underline{B}^0 \to \underline{K}^0 X) << \Gamma(B^- \to K^- X)$

$X(3872) = D^0\underline{D}^{*0}\cos\alpha + D^+D^{*-}\sin\alpha$ with $\tan\alpha << 1$ due to mass difference

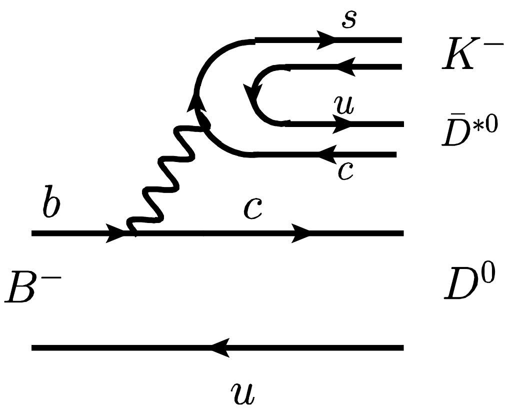
Suzuki ('05); Braaten, Kusunoki ('05),…

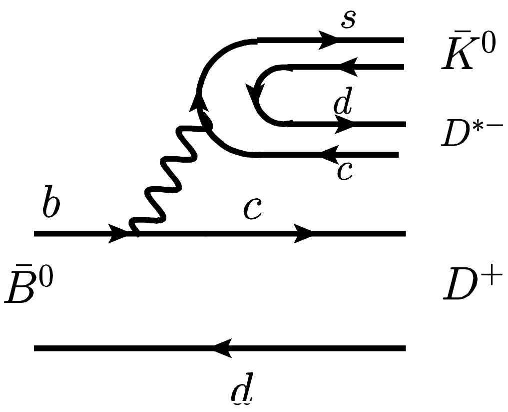
$\Rightarrow R_1 = \Gamma(\underline{B}^0 \to \underline{K}^0 X)/\Gamma(B^- \to K^- X) \approx \tan^2\alpha$

Expt: $R_1 = 0.50 \pm 0.30 \pm 0.05$ by BaBar, $1.26 \pm 0.65 \pm 0.06$ by Belle

- $R_2 = \Gamma$

$= \{$





LHCb

re DD* molecule

Suzuki ('05)
Li, Meng, Chao ('09)
Matheus et al. ('09)

$$|X(3872)\rangle = c_0|c\underline{c}\rangle + c_1|D^0\underline{D}^{*0}\rangle + c_2|D^+D^{*-}\rangle + \ldots$$

a mixture of $D\underline{D}^*$ (S-wave) and χ'_{c1} (P-wave, core) charmonium

- Mass degeneracy of $f_0(980)$ & $a_0(980)$; Narrowness of them vs broadness of $f_0(500)$ & $K_0^*(800)$.

- Near degeneracy between $a_0(1450)$ & $K_0^*(1430)$
  $m(a_0(1450)) = 1474 \pm 19$ MeV, $m(K_0^*(1430)) = 1425 \pm 50$ MeV

- Mass similarity of $D_{s0}^*(2317)$ & $D_0^*(2400)^0$. Physical D_{s0}^* is below DK threshold, D'_{s1} below D*K threshold.

- B_{s0}^* & B_0^* have not been observed yet, but the closeness of their masses is strongly expected.

Near mass degeneracy of scalar mesons seems to be a universal phenomenon !

- If X(3872) is dominated by the $c\underline{c}$ component, how do we understand its mass?

If 0^+ or 1^+ mesons are simple $q\underline{q}$ states, quark model will be always in trouble!

A common wisdom: strong coupled channel effects will distort quark model calculations

- Mixing between $c\underline{s}$ & $D\underline{K}$ threshold $\Rightarrow$ low mass of $D_{s0}^*(2317)$
  $c\underline{q}$ & $D\pi$ state $\Rightarrow$ low mass of $D_0^*(2400)$
  [van Beveren, Rupp ('03)]

This conjecture is realized by

- QCD sum rules [Dai, Zhu et al ('06, '08)]
- Lattice [Mohler et al, PRL ('13), PRD('14)]

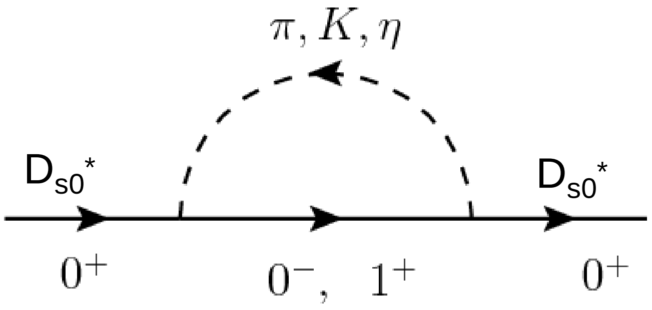
$c\underline{s}$ & $D\underline{K}$ interpolating fields $\Rightarrow$ $D_{s0}^*(2317)$ below $D\underline{K}$ threshold

$c\underline{q}$ & $D\pi$ interpolating fields $\Rightarrow$ $D_0^*(2400)$ above $D\pi$ threshold

$$|D_{s0}^*(2317)\rangle \sim |c\underline{s}\rangle + |D\underline{K}\rangle + \ldots$$

$$|D_0^*(2400)\rangle \sim |c\underline{q}\rangle + |D\pi\rangle + \ldots$$

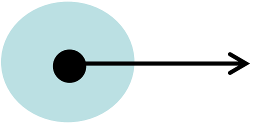
- Consider mass shifts due to self-energy chiral loops



Fajfer et al. ('04,'06,'16)
Mehen, Springer ('05)
Guo, Krewald, Meissner ('08)
HYC, Yu ('14)
Alhakami ('16)

and see if self energies can pull down scalar meson masses significantly and mass is shifted down more in the strange sector than in the nonstrange partner.

Heavy quark effective theory (HQET) & Heavy meson chiral perturbation theory (HMChPT)



on-shell quark: p=m_Qv

off-shell quark: p=m_Qv+k   k: residual momentum

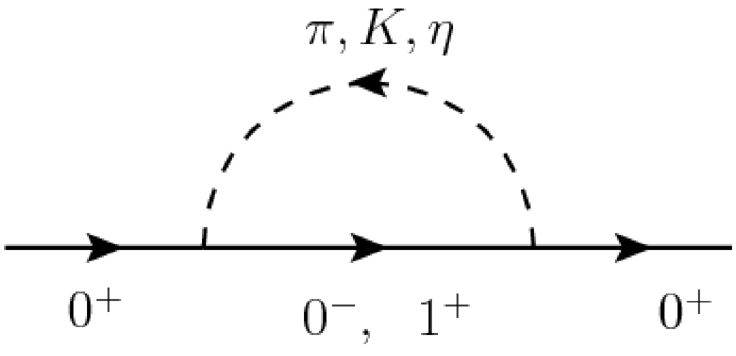
$$\frac{i}{\not{p}-m_Q+i\epsilon}=\frac{i(\not{p}+m_Q)}{p^2-m_Q^2+i\epsilon}=\frac{i(1+\not{v})\,\mathrm{m_Q}}{(m_Qv+k)^2-m_Q^2+i\epsilon}\to(1+\not{v})\frac{i}{2v\cdot k+i\epsilon}$$

HQET: effective theory of QCD with $m_Q \to \infty$ and fixed v_μ; it possesses heavy quark spin-flavor symmetry

Consider the strong decay $D^* \to D\pi$. We shall use HMChPT to describe its dynamics; heavy quark symmetry (HQS) & chiral symmetry are synthesized

Yan, HYC, Cheung, Lin, Lin, Yu ('92)
Wise ('92)
Burdman, Donoghue ('92)

Mass shift in HMChPT



propagator of D_{s0}^*

$$\Pi(v\cdot k) = \left(\frac{2h^2}{f_\pi^2}\right)\frac{i}{2}\int\frac{d^4q}{(2\pi)^4}\,\frac{(v\cdot q)^2}{(q^2-m^2+i\epsilon)(v\cdot q+\omega+i\epsilon)}$$

$$\Pi'(v\cdot k) = -\left(\frac{2g'^2}{f_\pi^2}\right)\frac{i}{2}\int\frac{d^4q}{(2\pi)^4}\,\frac{q^2-(v\cdot q)^2}{(q^2-m^2+i\epsilon)(v\cdot q+\omega_{D_1'}+i\epsilon)}$$

h: coupling of 0^+0^- with ϕ

g': coupling of 0^+1^+ with ϕ

$$\frac{i}{2(v\cdot k-\Delta_S+\frac{3}{4}\Delta M_{D_0^*}-\tilde{\Delta}_s)-[2\,\Pi_{DK}(\omega_D)+\frac{2}{3}\,\Pi_{D_s\eta}(\omega_{D_s})+2\,\Pi'_{D_1'K}(\omega'_{D_1'})+\frac{2}{3}\,\Pi'_{D_{s1}'\eta}(\omega'_{D_{s1}'})]}$$

Δ_S: mass splitting between even- & odd-parity doublets
ΔM_S: mass splitting between spin partners of scalar doublet

on-shell mass condition $\Rightarrow$ denominator is set to zero $\Rightarrow$ $v\cdot\tilde{k}$

$$m = m_0 + v\cdot\tilde{k} = m_0 + \frac{1}{2}\mathrm{Re}\,\Pi(v\cdot\tilde{k})$$

- Loop divergence is absorbed by counterterms
- There is a log term $\ln(\Lambda^2/m^2)$ with an arbitrary renormalization scale Λ, which is often chosen to be Λ_χ, the chiral symmetry breaking scale

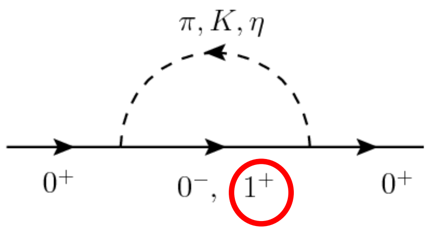
In our original 2014 paper we didn’t consider 1’+ intermediate states. We argued that near degeneracy cannot be explained by HMChPT. Mass shift is overshooting for D_{s0}^*, and the predicted mass of order 2240 MeV is too small compared to experiment.

$h = 0.56$, $\Lambda = 1.3$ GeV

	Bare mass	**δM**	**M_{phys}**	**Γ**	**Bare mass**	**δM**	**M_{phys}**	**Γ**
D_{s0}^*	2487	-249	2238		2480	-235	2245	
D_0^*	2377	-34	2343	103	2400	-80	2320	75
B_{s0}^*	5804	-100	5704		5830	-152	5678	
B_0^*	5706	-101	5605	73	5760	-23	5737	477

Bare masses taken from potential model calculations:
Godfrey, Kokoski (’91); Di Pierro, Eichten (’01)

Mass shift: $\delta M = M_{phys} - M_{bare}$



We have missed a contribution from 1^+ states before.
By adjusting couplings h, g' and renormalization scale Λ,
we can achieve degeneracy in the charm sector

1^+ contribution characterized by g' is destructive. M(D_{s0}^*) is sensitive to g', while M(D_0^*) is stable.

h=0.51, g'= 0.25, Λ= 1.27 GeV

	Bare mass	δM	M_{phys}
D_{s0}^*	2480	-162	2318
D_0^*	2400	-79	2321
B_{s0}^*	5831	-136	5694
B_0^*	5706	-55	5701

	Bare mass	δM	M_{phys}
D'_{s1}	2550	-98	2452
D'_1	2460	-41	2419
B'_{s1}	5857	-85	5772
B'_1	5777	-34	5743

- Self-energy correction will push down the masses of B_{s0}^* and D_{s0}^* more than that of B_0^* & D_0^*
- Mass degeneracy is working in B sector

- The coupling h extracted from D_0^*, $D'_1 \to D\pi$

$$\left\{\begin{array}{ll} 0.60\pm0.07 & \text{from } D_0^*(2400)^0 \\ 0.514\pm0.017 & \text{from } D_0^*(2400)^+ \\ 0.79\pm0.17 & \text{from } D'_1(2430) \end{array}\right.$$

- The coupling g’ is unknown

Our results differ from Guo, Krewald, Meissner ('08) who considered similar loop calculation

$$\Pi(\omega) = \left(\frac{2h^2}{f_\pi^2}\right)\frac{m^2}{32\pi^2}\left[-2\omega\ln\frac{\Lambda^2}{m^2} - 2\omega + 4\omega F\left(-\frac{m}{\omega}\right)\right]$$

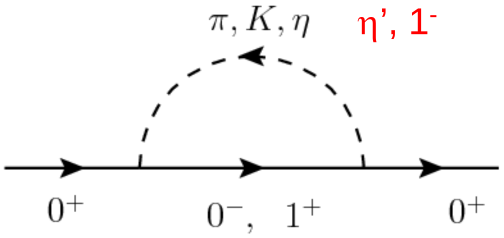
$$\omega = v\cdot k + M_{D^*_{s0}} - M_D + \frac{3}{4}\Delta M_D$$

GKM concluded that self energy vanishes in chiral limit

Correct expression:

$$\Pi(\omega) = \left(\frac{2h^2}{f_\pi^2}\right)\frac{\omega}{32\pi^2}\left[(m^2-2\omega^2)\ln\frac{\Lambda^2}{m^2} - 2\omega^2 + 4\omega^2 F\left(-\frac{m}{\omega}\right)\right]$$

Low masses of D_{s0}^* & D_0^* and near mass degeneracy can be qualitatively understood as a result of self-energy effects due to strong coupled channels. However, we should not take them as quantitative predictions due to many uncertainties:



1.unknown input bare masses

2.contributions from other channels

3.very sensitive to the renormalization scale Λ

Near degeneracy in B sector is implied by chiral loop calculations. Now we wish to make quantitative predictions on scalar B meson masses.

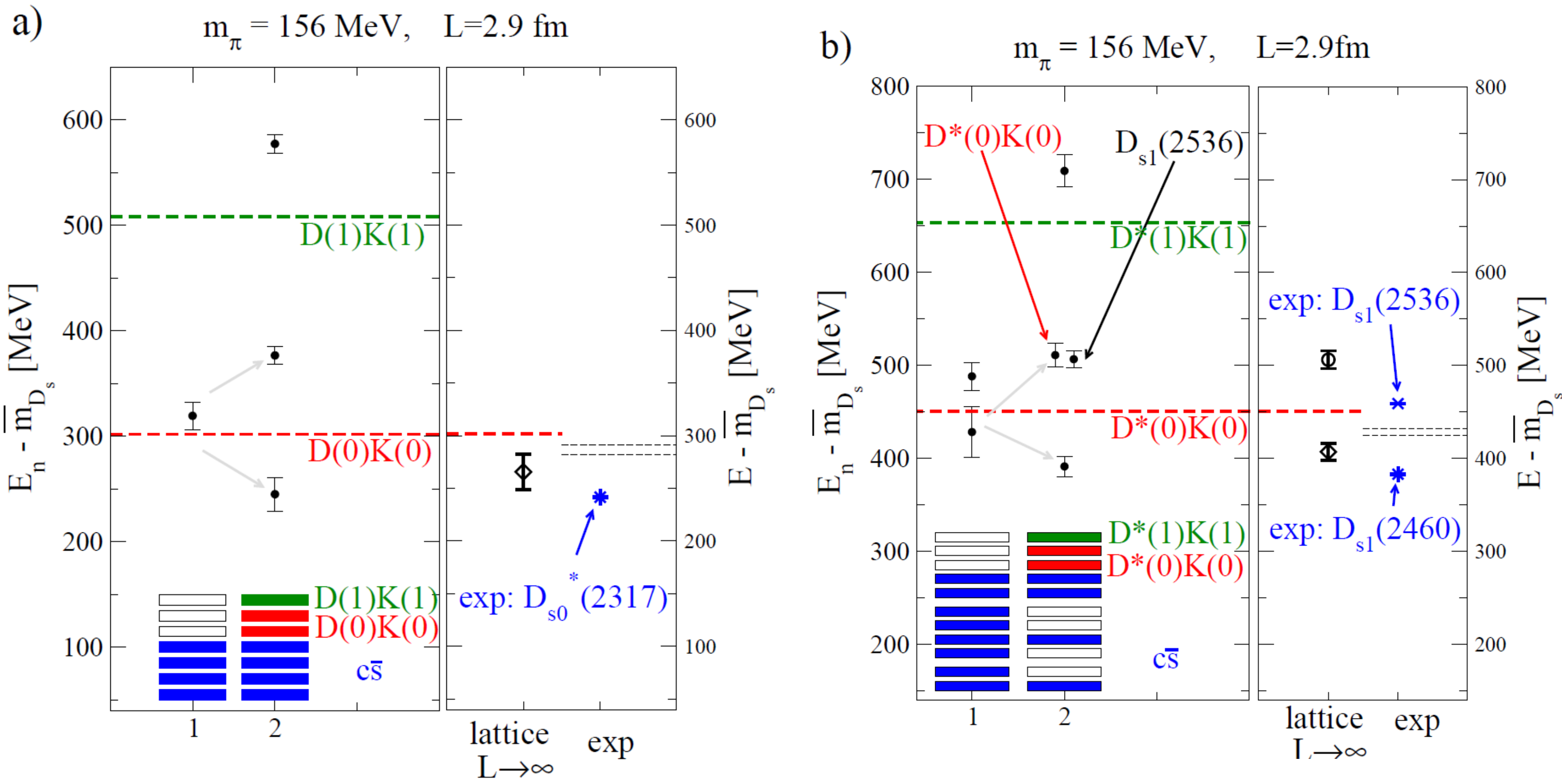
Lattice studies of $D_{s0}^{*}(2317)$

Most of lattice QCD studies of D_{s0}^{*} are based on $q\underline{q}$ interpolators.

Early (quenched) lattice QCD calculations found energy levels substantially above the physical DK threshold. Recent dynamical LQCD simulations taking sea quark contributions into account are also not definitive due to closeness of DK threshold.

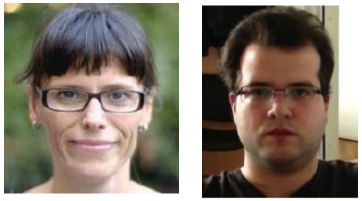
Lang, Leskovec, Mohler, Prelovsek, Woloshyn ('13,'14)

improved Wilson fermions for u, d, s but not for c; $N_f = 2+1$



$M(D_{s0}^*) = 2326 \pm 17$ MeV

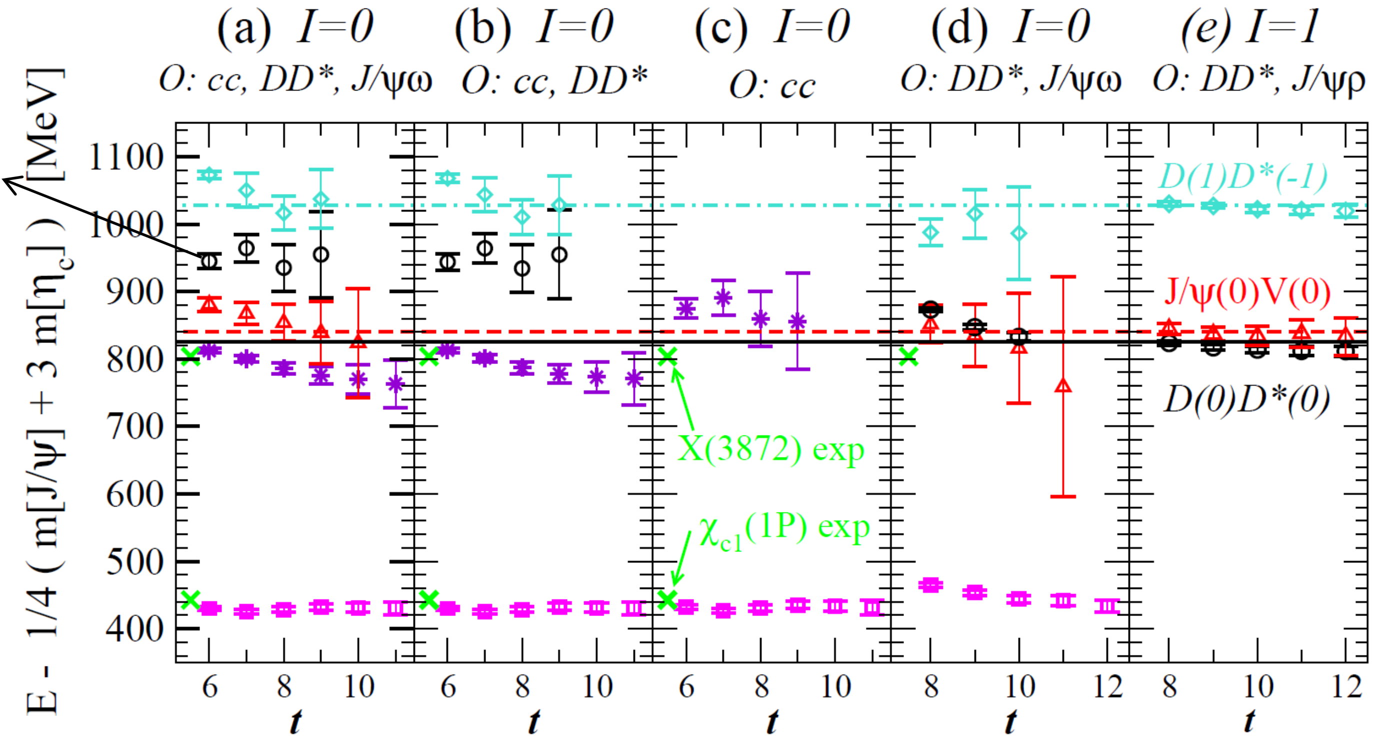
Lattice studies of X(3872)



Prelovsek & Leskovec ('13)

$J^{PC}=1^{++}$, I=0 & I=1

D(0)D*(0) shifted up due to negative $a_0^{DD^*}$



Interpolating fields:
$c\underline{c}$, $D\underline{D}^*$, $J/\psi\omega$

Evidence of X(3872) below $D\underline{D}^*$ threshold for I=0; large & negative DD^* scattering length $a_0^{DD^*}$ = -1.7±0.4 fm is found

$|X(3872)> = c_0|c\underline{c}> + c_1|D^0\underline{D}^{*0}> + c_2|D^+D^{*-}> + c_3|J/\psi\omega> + c_4|J/\psi\rho>$

Yu-Chih Chen (陳昱至), Ting-Wai Chiu (趙挺偉) ('17)

N_f = 2 +1 +1 optimal domain wall fermions m_π=280 MeV

J^P	State	Lattice	PDG
0^+	$D_{s0}^*(2317)$	2317±15±5	2317.7±0.6
$1'^+$	$D'_{s1}(2460)$	2463±13±9	2459.6±0.6
1^+	$D_{s1}(2536)$	2536±12±4	2535.10±0.06

- They conclude that $D_{s0}^*(2317)$ is a conventional $c\underline{s}$ state, interacting through the gluons with quantum fluctuations of (u,d,s,c) quarks in the sea.

- Since (u,d,s,c) are Dirac fermions, sea quarks $u\underline{u}$ /$d\underline{d}$ popping up from vacuum at the location of $c\underline{s}$ can emulate DK, … properly. Hence, no need to introduce DK, DK^*, D_1K,… interpolators.

Masses of even-parity B mesons

J^P	State	M (MeV)	Γ (MeV)
0^+	B_0^*	?	?
$1'^+$	B'_1	?	?
1^+	$B_1(5721)^0$ $B_1(5721)^\pm$	5726.0±1.3 5725.9±2.6	27.5±3.4 25±6
2^+	$B_2^*(5747)^0$ $B_2^*(5747)^\pm$	5739.5±0.7 5737.2±0.7	24.2±1.7 20±5

J^P	State	M (MeV)	Γ (MeV)
0^+	B_{s0}^*	?	?
$1'^+$	B'_{s1}	?	?
1^+	$B_{s1}(5830)$	5830.63±0.27	0.5±0.4
2^+	$B_{s2}^*(5840)$	5839.84±0.18	1.47±0.33

Masses of B_0^* & B_{s0}^*

B_0^*, B_{s0}^*, B'_1, B'_{s1} have not been seen yet. Near degeneracy is expected to work even better in B sector.

	B_0^*	B_{s0}^*
Cleven et al ('14)		5625±45
Lutz et al ('04)	5526	5643
Torres-Rincon ('14)	5530	5748
Guo et al ('06)	Two poles	5725±39
Matsuki et al ('07)	5592	5617
Orsland et al ('99)	5592	5667
Vijande et al ('08)	5615	5679
Cleven et al ('11)		5696±40
Bardeen et al ('03)	5627±35	5718±35
T. Lee et al ('07)	5637	5634
Z.G. Wang ('08)	5720±50	5700±60
Badalian et al ('08)	5675±20	5710±15
Albaladejo et al ('16)		5709±8
Lahde et al ('00)	5678	5781
Alhakami ('16)	Mass differ	~ 8 MeV

	B_0^*	B_{s0}^*
Lu et al ('16)	5683	5756
Altenbuchinger ('14)		5726±28
Colangelo et al ('12)	5708±23	5707±1
Ortega et al ('16)		5741.4
Dmitrasinovic ('12)	5728±25	5716±25
HPQCD ('11)		5752±30
UKQCD ('08)		5760±9
Lang et al. ('15)		5713±22
Di Pierro et al ('06)	5706	5804
Godfrey et al ('16)	5720	5805
Lakhina et al ('07)	5730	5776
Liu et al ('16)	5749	5833
Ebert et al ('10)	5782	5843
Sun et al ('14)	5756	5830
Godfrey et al ('91)	5756	5831

Masses of B_0^* & B_{s0}^*

B_0^*, B_{s0}^*, B'_1, B'_{s1} have not been seen yet. Near degeneracy is expected to work even better in B sector.

	B_0^*	B_{s0}^*
Cleven et al ('14)		5625±45
Lutz et al ('04)	5526	5643
Torres-Rincon ('14)	5530	5748
Guo et al ('06)	Two poles	5725±39
Matsuki et al ('07)	5592	5617
Orsland et al ('99)	5592	5667
Vijande et al ('08)	5615	5679
Cleven et al ('11)		5696±40
Bardeen et al ('03)	5627±35	5718±35
T. Lee et al ('07)	5637	5634
Z.G. Wang ('08)	5720±50	5700±60
Badalian et al ('08)	5675±20	5710±15
Albaladejo et al ('16)		5709±8
Lahde et al ('00)	5678	5781
Alhakami ('16)	Mass differ	~ 8 MeV

	B_0^*	B_{s0}^*
Lu et al ('16)	5683	5756
Altenbuchinger ('14)		5726±28
Colangelo et al ('12)	5708±23	5707±1
Ortega et al ('16)		5741.4
Dmitrasinovic ('12)	5728±25	5716±25
HPQCD ('11)		5752±30
UKQCD ('08)		5760±9
Lang et al. ('15)		5713±22
Di Pierro et al ('06)	5706	5804
Godfrey et al ('16)	5720	5805
Lakhina et al ('07)	5730	5776
Liu et al ('16)	5749	5833
Ebert et al ('10)	5782	5843
Sun et al ('14)	5756	5830
Godfrey et al ('91)	5756	5831

Masses of B_1 & B_{s1}

	B'_1	B'_{s1}
Cleven et al ('14)		5671±45
Lutz et al ('04)	5590	5690
Torres-Rincon ('14)	5579	5799
Guo et al ('07)		5778±7
Matsuki et al ('07)	5649	5682
Orsland et al ('99)	5671	5737
Vijande et al ('08)		5713
Cleven et al ('11)		5742±40
Bardeen et al ('03)	5674±35	5765±35
T. Lee et al ('07)	5673	5672
Z.G. Wang ('08)	5740±50	5760±60
Badalian et al ('08)	5725±20	5730±15
Albaladejo et al ('16)		5755±8
Lahde et al ('00)	5686	5795
Alhakami ('16)	Mass differ	~ 19 MeV

	B'_1	B'_{s1}
Lu et al ('16)	5729	5801
Altenbuchinger ('14)		5778±26
Colangelo et al ('12)	5753±31	5766±1
Ortega et al ('16)		5858
Dmitrasinovic ('12)	5742±25	5763±25
HPQCD ('11)		5806±30
UKQCD ('08)		5807±9
Lang et al. ('15)		5750±26
Di Pierro et al ('06)	5742	5842
Godfrey et al ('16)	5738	5822
Lakhina et al ('07)	5752	5803
Liu ('10)	5782	5843
Ebert et al ('10)	5774	5865
Sun et al ('14)	5779	5858
Godfrey et al ('91)	5777	5857

HQS for the masses of B_{s0}^* & B_0^*

Consider the two parameters $\Delta_S = \langle M_S \rangle - \langle M_H \rangle$ & λ_2^S in HMChPT

$$\langle M_H \rangle = \frac{3M_{P^*} + M_P}{4}, \quad \langle M_S \rangle = \frac{3M_{P'_1} + M_{P_0^*}}{4}, \quad \lambda_2^S = \frac{1}{4}\left(M_{P'_1}^2 - M_{P_0^*}^2\right)$$

In heavy quark limit, both parameters are independent of heavy quark flavor

$$\Delta_S^{(b\bar{q})} = \Delta_S^{(c\bar{q})}, \quad \Delta_S^{(b\bar{s})} = \Delta_S^{(c\bar{s})}, \quad \lambda_2^{S(b\bar{q})} = \lambda_2^{S(c\bar{q})}, \quad \lambda_2^{S(b\bar{s})} = \lambda_2^{S(c\bar{s})}$$

With input from the charm spectroscopy we obtain

$M(B_0^{*\pm})=5705\pm52$, $M(B'^{\pm}_1)=5753\pm40$,

$M(B_0^{*0})=5724\pm41$, $M(B'^{0}_1)=5754\pm34$,

$M(B_{s0}^*)=5707\pm1$, $M(B'_{s1})=5766\pm1$

Colangelo et al ('12)

Near degeneracy in D sector will imply the same in scalar B sector via HQS

$1/m_Q$ and QCD corrections

- **QCD corrections**

$$\frac{\lambda_2^{H(b\bar{q})}}{\lambda_2^{H(c\bar{q})}} = \frac{m_{B^*}^2 - m_B^2}{m_{D^*}^2 - m_D^2} = \left(\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right)^{9/25}\left[1 - \mathcal{O}\left(\frac{\alpha_s}{\pi}\right)\right] + \Lambda_R\left(\frac{1}{m_c} - \frac{1}{m_b}\right)$$

$0.89 \pm 0.01 = 0.82\,[1 - O(\alpha_s)] + O(1/m_Q)$ ⇒ dominated by QCD correction

$$\lambda_2^{S(b\bar{q})} = \lambda_2^{S(c\bar{q})}\left(\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right)^{9/25}$$

- **$1/m_Q$ corrections**

In heavy quark effective theory $m_{H_Q} = m_Q + \bar{\Lambda}_{H_Q} - \frac{\lambda_1}{2m_Q} - \frac{d_H \lambda_2}{2m_Q}$

$$\Delta_S^{(b)} = \Delta_S^{(c)} + (\lambda_1^S - \lambda_1^H)\left(\frac{1}{2m_c} - \frac{1}{2m_b}\right) \equiv \Delta_S^{(c)} + \delta\Delta_S$$

$M(B_0^{*0})=5711\pm49 + \delta\Delta_S$, $M(B_0^{*\pm})=5728\pm38 + \delta\Delta_S$, $M(B_{s0}^{*})=5715\pm1 + \delta\Delta_S$

$M(B'^{\,0}_1) = 5748\pm39 + \delta\Delta_S$, $M(B'^{\,\pm}_1)=5754\pm32 + \delta\Delta_S$, $M(B'_{s1})=5763\pm1 + \delta\Delta_S$

$\delta\Delta_S$ is estimated to be of order -35 MeV or less

Near degeneracy is not spoiled by $1/m_Q$ & QCD corrections

- **An empirical mass relation**

$$M_{D'_{s1}} - M_{D^*_{s0}} \simeq M_{D^*} - M_D \simeq M_{D^*_s} - M_{D_s}, \qquad (141.8, 141.4, 143.8)\ \text{MeV}$$

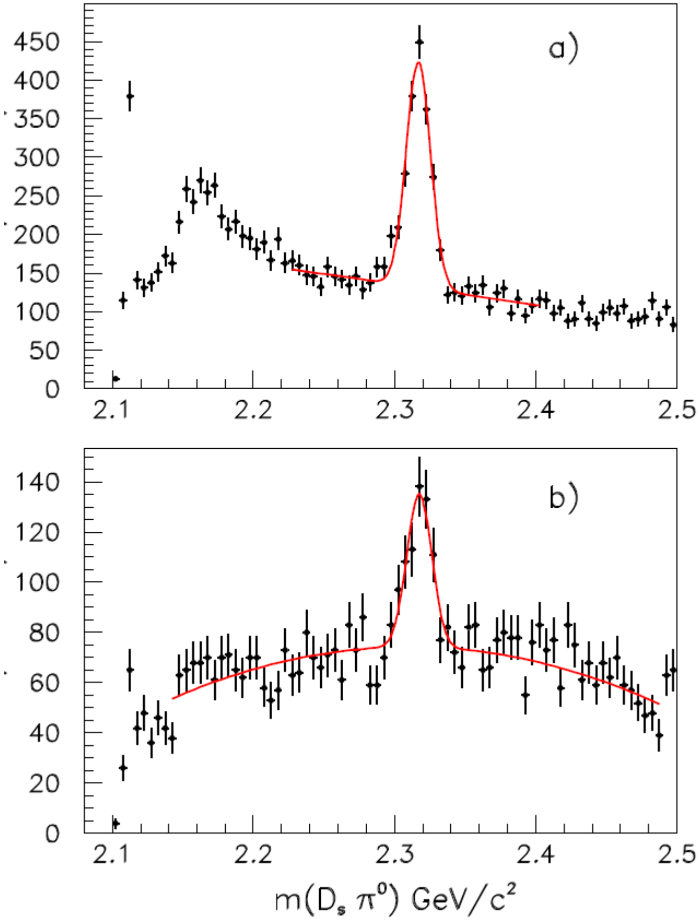
It is thus expected that $M_{B'_{s1}} - M_{B^*_{s0}} \simeq M_{B^*} - M_B \simeq M_{B^*_s} - M_{B_s}$

also holds in B sector with mass splitting 48 MeV

- **Mass splitting between B'$_{s1}$ & B'$_1$ is estimated to be 15 MeV due to self-energy effect.**

B_{s0}^* is below BK threshold, B'_{s1} below B^*K threshold. The strong decays $B_{s0}^* \to B_s\pi^0$, $B'_{s1} \to B_s^*\pi^0$ violate isospin symmetry. Hence, they are very narrow. It will be even more difficult to identify B^*_0 and B'_1 due to their broad widths.

Recall $D_{s0}^*(2317) \to D_s^+ \pi^0$



$D_s^+ \to K^+K^-\pi^+$

$D_s^+ \to K^+K^-\pi^+\pi^0$

Conclusions

- **Quark model will be always in trouble if 0^+ or 1^+ mesons are simple $q\underline{q}$ states!**

⇒ strong coupled channel effects will distort quark model calculations

- **Near degeneracy between $D_{s0}^*(2317)$ & $D_0^*(2400)$**

⇒ Qualitatively, near degeneracy can be explained in terms of self-energy effects due to strong coupled channels

- **B_{s0}^* & B_0^* have not been observed yet, but the closeness of their masses is strongly expected**

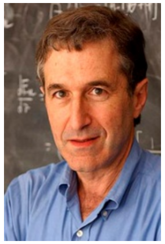
⇒ Scalar B masses can be quantitatively deduced from HQS with input

from charm spectroscopy. We predict $M(B_0^*) \sim M(B_{s0}^*) \sim 5715$ MeV $+ \delta\Delta_S$

Spare Slides

Tetraquark (4-quark)picture

Major difficulties with a_0 and f_0 can be circumvented in the four-quark model (Jaffe 1977)



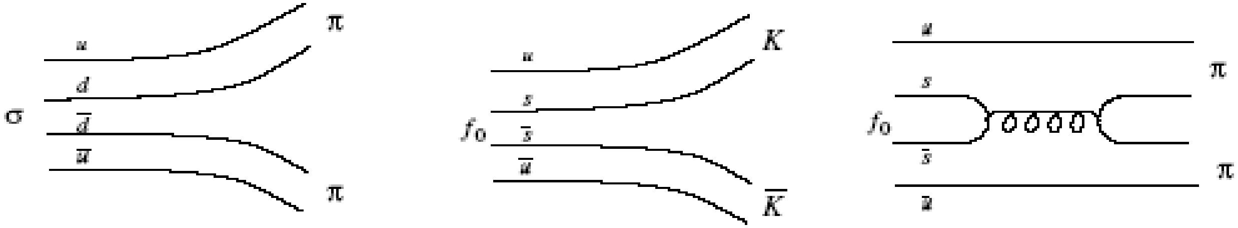
$$\sigma = ud\bar{u}\bar{d} \qquad f_0 = s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}$$

$$a_0^0 = s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}, \qquad a_0^+ = u\bar{d}s\bar{s}, \qquad a_0^- = d\bar{u}s\bar{s}$$

$$\kappa^+ = u\bar{s}d\bar{d}, \quad \kappa^0 = d\bar{s}u\bar{u}, \quad \bar{\kappa}^0 = s\bar{d}u\bar{u}, \quad \kappa^- = s\bar{u}d\bar{d}$$

- **Mass degeneracy between f_0 and a_0 is natural**
- **$\sigma \to \pi\pi$, $\kappa \to K\pi$ & $f_0, a_0 \to K\bar{K}$ are OZI allowed (fall apart) , while $f_0 \to \pi\pi$ & $a_0 \to \pi\eta_q$ are OZI suppressed so that**

Γ(4-quark)>>Γ(2-quark)



f_0(980) and a_0(980) are very close to $K\bar{K}$ threshold
⇒ f_0(980) width is dominated by $\pi\pi$, a_0 governed by $\pi\eta$ state.
This explains why $m_\sigma \sim \Gamma_\sigma \sim \Gamma_\kappa \gg \Gamma_f \sim \Gamma_a$

Poles of scattering amplitude on Riemann sheet in unitarized ChPT

[Guo et al ('06,'07); Cleven et al ('09); Torres-Rincon et al ('14); Albaladejo et al. ('16)]

pole below threshold in real axis ⇒ bound state
pole on 2nd Riemann sheet ⇒ resonance above threshold

A DK bound state is found with M=2312±41 MeV, which is precisely $D_{s0}^*(2317)$, and a BK bound state (B_{s0}^*) found with M=5725±39 MeV

Two I=1/2, S=0 resonances found for D_0^* :

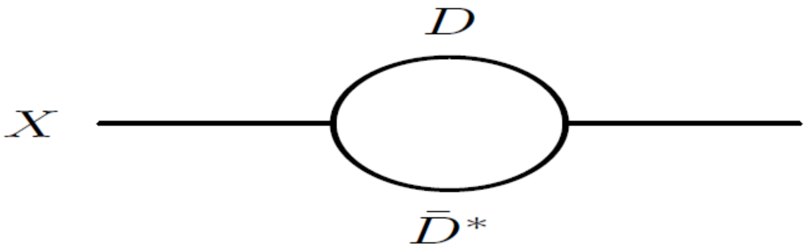
(2097± 18 – i107±40) MeV, (2448± 30 – i26± 24) MeV Guo et al ('06)

$(2105^{+6}_{-8} - i102^{+10}_{-12})$ MeV, $(2451^{+36}_{-26} - i134^{+7}_{-8})$ MeV Albaladejo et al. ('16)

Two I=1/2, S=0 resonances found for B_0^* :

(5536± 29 – i117±43) MeV, (5842± 22 – i18± 10) MeV Guo et al ('06)

$(5537^{+9}_{-11} - i116^{+14}_{-15})$ MeV, $(5840^{+12}_{-13} - i25^{+6}_{-5})$ MeV Albaladejo et al. ('16)



Achasov et al. (’15)

- Perez-Rubio, Collins, Bali ('15) : $N_f = 2+1$ without 4-quark interpolators

  $M(D_{s0}^*) = 2349 \pm 19$ MeV

- Cichy, Kalinowski, Wagner ('16): $N_f = 2+1+1$ twist mass lattice QCD

  $M(D_0^*) = 2325 \pm 19$ MeV

  $M(D_{s0}^*) = 2390 \pm 25$ MeV with 3σ discrepancy