$D_s^{+}(2317)$, $D^{*}(2308)$ and $D_s^{+*}(2632)$ as candidates for tetraquarks?

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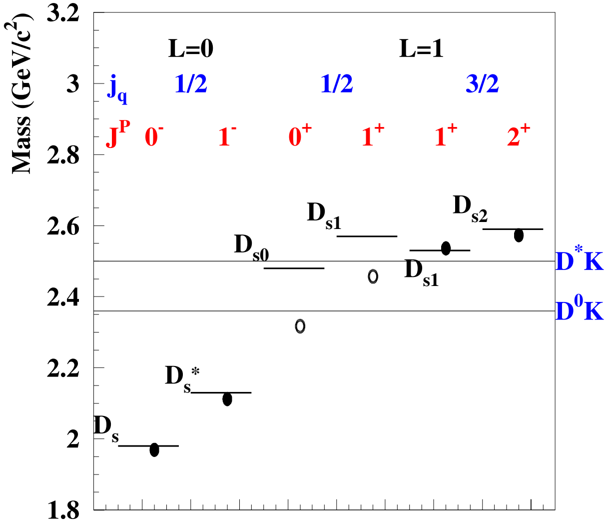
Outline:

- **Introduction: scalar D mesons**
- **'t Hooft interaction in the constituent quark model (CQM)** Ann.Phys.321, 355 (06)
- Charm tetraquark spectrum in CQM: $D^+(2308)$ - $D_s^+(2317)$ Mass Puzzle
  PRD70,096011 (04); PRL94,162002 (05);
- **Exotic spectrum predicted** MPLA21, 533 (06)
- **Alternative 4Q models**
- **Summary**

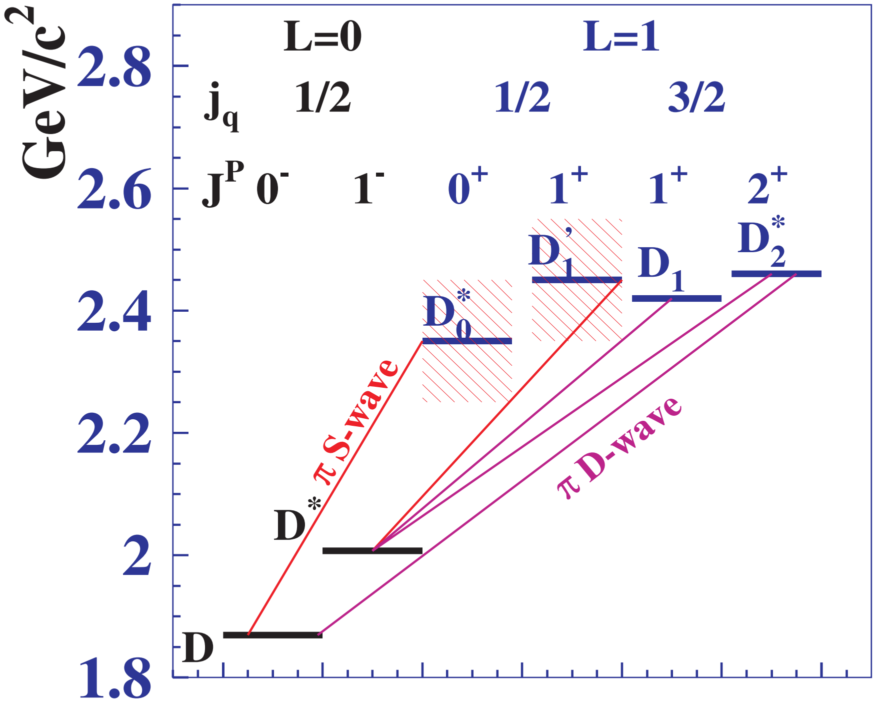
Charmed strange mesons

- Predicted spectrum in potential models:
- Two observed scalar (0^+) strange states: $D_s^+(2317)$ (BaBar) and $D_s^+(2632)$ (SELEX);
- Too light and too many!?!



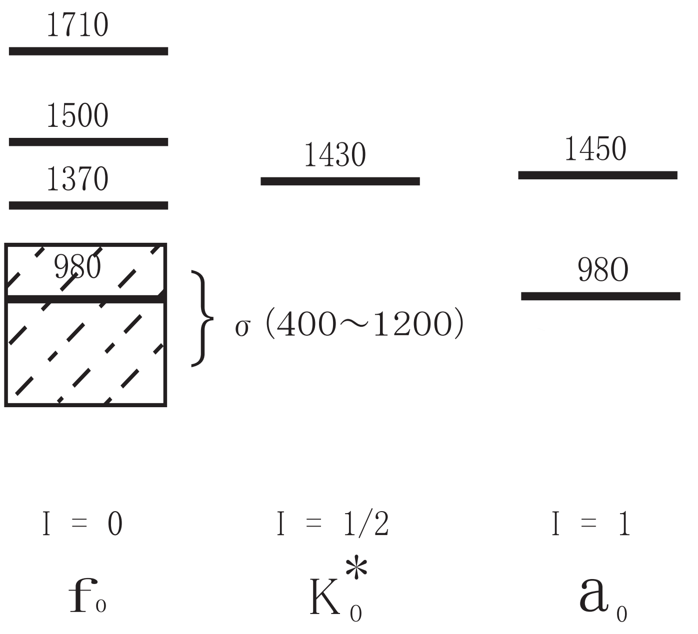
Charmed nonstrange mesons

- Spectrum predicted in potential models:
- Two observed scalar (0^+) nonstrange states: $D^+(2308)$ (Belle), $D^+(2405)$ (FOCUS)
- Too light and too many!
- Strange (2317) and nonstrange (2308) states degenerate!?!



c.f. light scalar mesons

- Two isovector states (980 and 1450 MeV)!?!
- Too light and too many states!?! (“dimesons”)
- Strange (1430) and nonstrange (1450) states degenerate!?!
- Supernumerary flavour singlets: glueballs!?!



Two multiquark scenarios

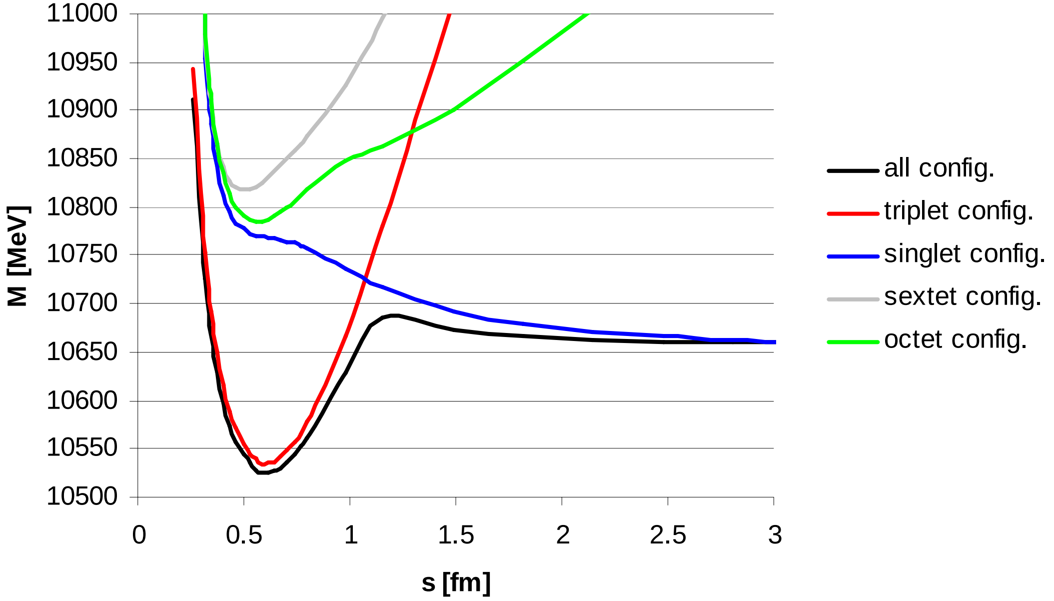
- Colorless: hadronic molecules, “bootstrap” models, Bethe-Salpeter equation models (v. Beveren & Rupp, Kolomeitsev & Lutz, Sassen & Krewald)
- With color d.o.f.: constituent quarks, need a model of confinement (“F.F” 2-body, 3-body force, “flip-flop”)

“True” tetraquarks

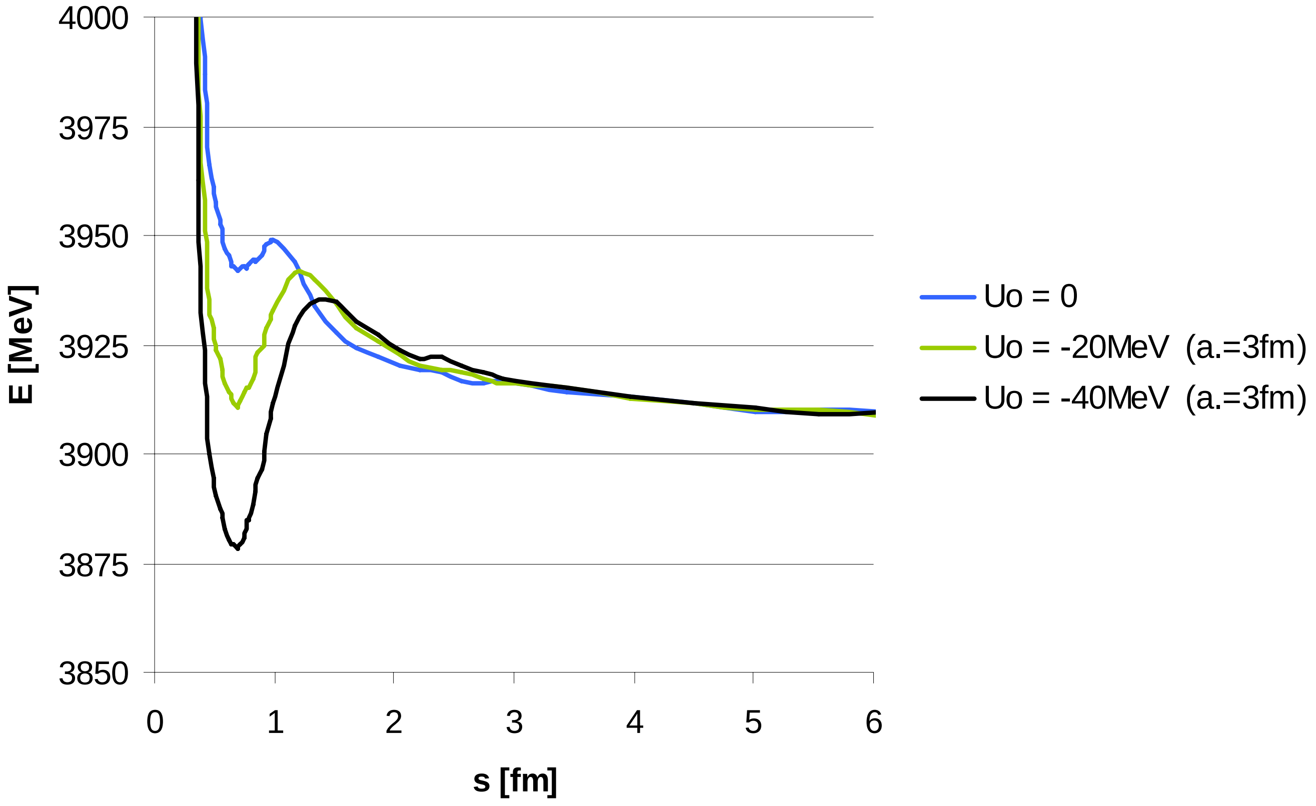
- The $D^+(2308)$, $D_s^+(2317)$, $D^*(2405)$, $D_s^+(2632)$, and $X(3872) = (q^2 q^{*2})$ are “true tetraquarks”?
- Colour quark force important: Multiquarks related to multiple colour singlets (expected since 1976)
- “F.F” 2-body confinement model leads to the $q^2 q^{*2}$ in the colour state $\left|\bar{3}_{12} 3_{34}\right\rangle$

Example of a bound two-meson state due to two-body colour potential

- Tetraquarks bound for large enough q/q* mass ratio. [Ader, J.M. Richard and Taxil PRD25,2370('82)]
- Double-b heavy-light tetraquark mass as a function of separation. (Courtesy D. Janc)
- The hidden-colour state is confined. Saturation visible in the two-meson state.



Effect of three-quark colour force on double-charm tetraquarks (D. Janc)

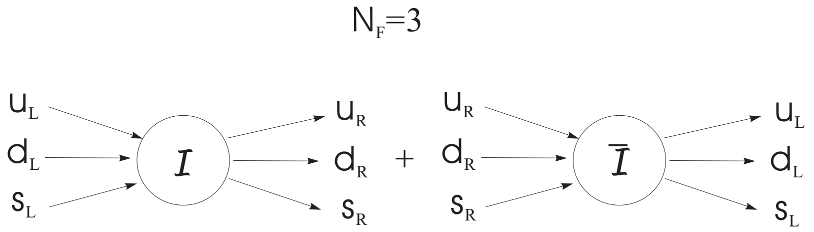


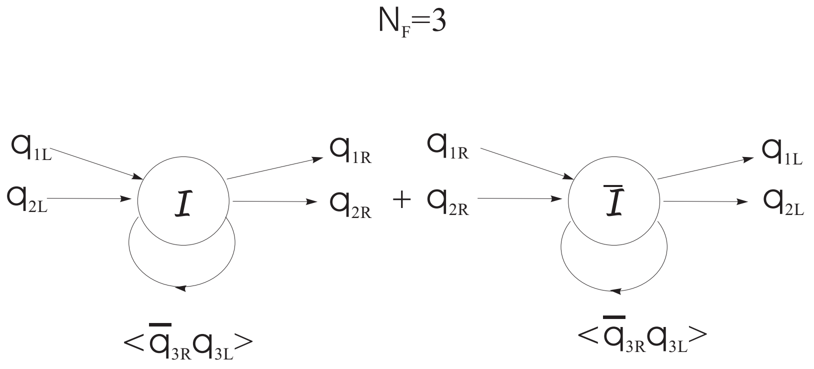
Hyperfine interactions in the CQM

- The "color-magnetic" CS (Fermi-Breit) interaction believed to be the main source of SU(6) multiplet splittings in CQM.
- CS HFI cannot solve the "$U_A(1)$ problem" in mesons (and lesser problems in baryons).
- The 't Hooft interaction solves the $U_A(1)$ problem, and improves baryon spectra.
- "Calibrate" HFI in mesons and baryons, then use it in multiquarks Ann.Phys.321, 355 (06)

Instanton-induced ‘t Hooft interaction in QCD

- Instantons induce a new three-quark, flavour-dependent, contact interaction
- Closing one pair of “legs” leads to a two-quark HF interaction that depends on flavour and spin.





The two-body **'t Hooft** interaction leads to the following two-quark potential

$$
\begin{aligned}
V_{12} &= 4K\langle\bar{q}q\rangle_0 P^{\bar{3}}_{12}\,(1-\vec{\sigma}_1\cdot\vec{\sigma}_2)\,\delta(\mathbf{r}_1-\mathbf{r}_2) \\
P^{\bar{3}}_{12} &= \left[\frac{1}{3}-\frac{1}{4}\boldsymbol{\lambda}_1\cdot\boldsymbol{\lambda}_2\right]. \qquad (2)
\end{aligned}
$$

affects only spin singlets (PS mesons) and cures the $U_A(1)$ problem.

The 't Hooft interaction also leads to the three-quark potential

$$
\begin{aligned}
V_{123} &= 12KP^{1}_{123}\left(1-\sum_{i<j}^{3}\vec{\sigma}_i\cdot\vec{\sigma}_j\right)\delta(\mathbf{r}_1-\mathbf{r}_2)\delta(\mathbf{r}_3-\mathbf{r}_2) \\
P^{1}_{123} &= \frac{1}{12}\left[\frac{4}{9}-\frac{1}{3}\sum_{i<j}^{3}\boldsymbol{\lambda}_i\cdot\boldsymbol{\lambda}_j+d^{abc}\boldsymbol{\lambda}^a_1\boldsymbol{\lambda}^b_2\boldsymbol{\lambda}^c_3\right]. \qquad (3)
\end{aligned}
$$

Light mesons with ‘t Hooft interaction

- Vector and pseudoscalars
- Only p.s. change mass
- Vector mesons still ideally mixed.
- Correct ordering of states
- Only the pion (still) too heavy (non-relativistic).

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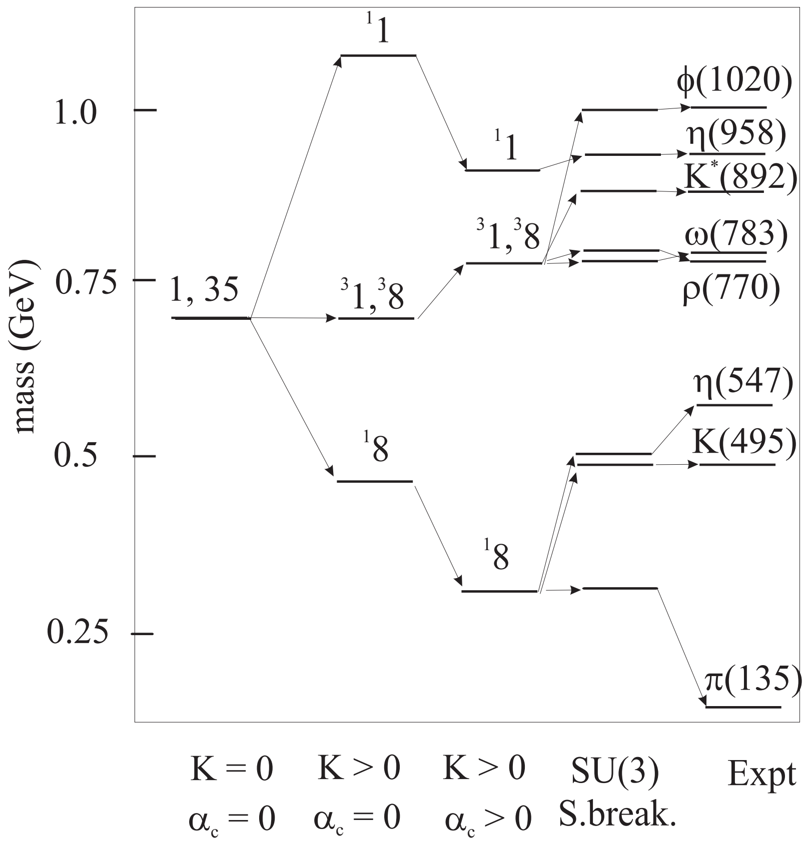
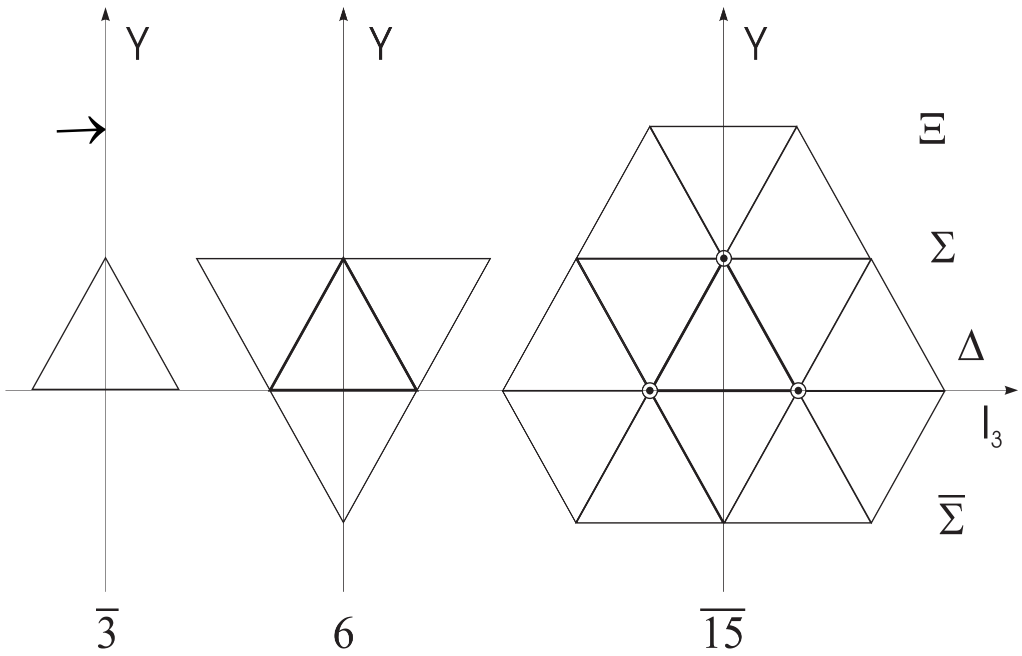


Single-charm tetraquark SU(3) contents

- Tetraquark SU(3) C.G. series: two 3*-, 6-, 15*-plets.
  V.D. PRD70,096011 (2004)
- The two 3*-plets and the “inner” triplet in the 15*-plet may mix!

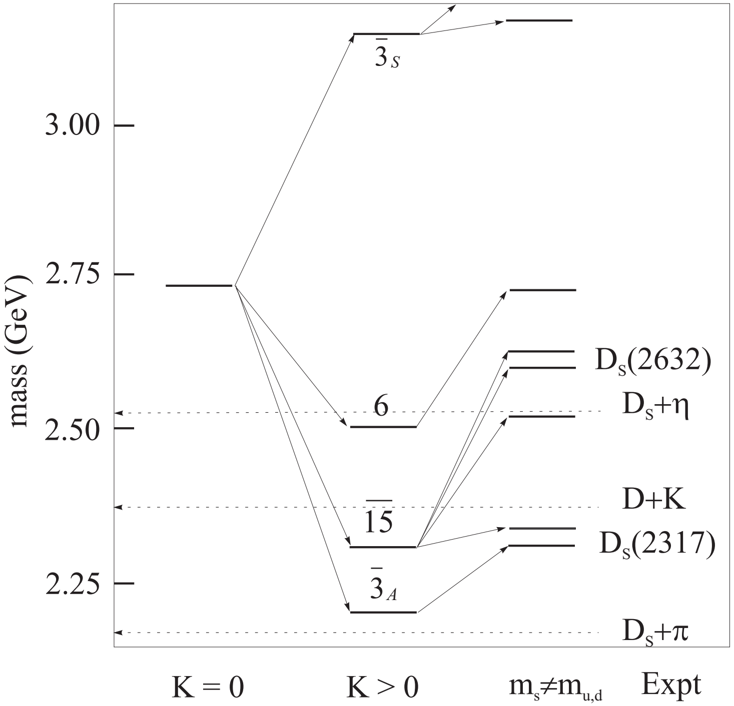


$$\bar{3}\times\bar{3}\times 3=\bar{3}_A+\bar{3}_S+6+\overline{15}$$

Single-charm tetraquark masses

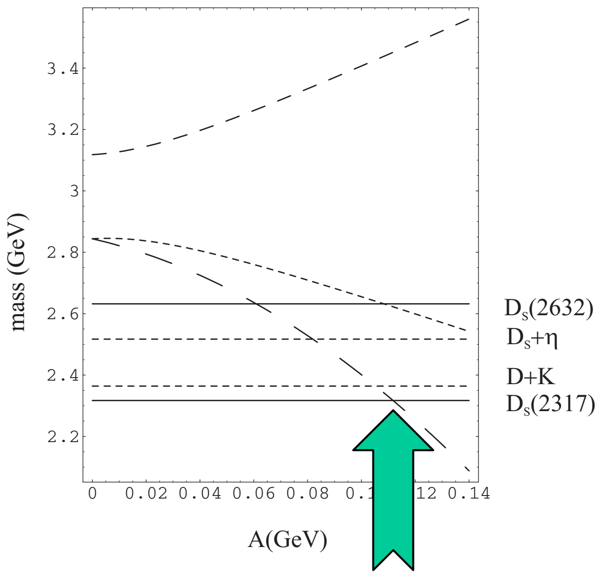
- ‘t Hooft interaction breaks degeneracy.
- SU(3) symmetry breaking s-u/d quark mass difference adds to the splitting.

PRD70,096011 (2004)



$\bar{3}_S - \overline{15}$ mixing

- Symmetric 3*-plet mixes with the 15*-plet
- Mixing splits the two states
- Lowest mass is the asymm. 3*-plet



$D^+(2308)$ - $D_s^+(2317)$ Mass Puzzle I

- All members of the antisymmetric 3*-plet and 6-plet are degenerate irrespective of their strangeness!
  PRL94,162002 (2005)
- Hidden strangeness in flavour w.f.

$$\left|D_{n3A}\right\rangle = \frac{1}{2}\left|c(s(\overline{u}\overline{s} - \overline{s}\overline{u}) - d(\overline{d}\overline{u} - \overline{u}\overline{d}))\right\rangle$$

$$\left|D_{s3A}\right\rangle = \frac{1}{2}\left|c(u(\overline{u}\overline{s} - \overline{s}\overline{u}) - d(\overline{d}\overline{s} - \overline{s}\overline{d}))\right\rangle$$

$D^+(2308)$ - $D_s^+(2317)$ Mass Puzzle II

- Explains the degeneracy of $D^+(2308)$ and $D_s^+(2317)$. PRL94,162002 (2005)
- This mass pattern is due to the SU(3) flavour wave function permutation antisymmetry.
- Such multiplets exist only in multiquarks: the first and the simplest are found in tetraquarks!
- Similar to $a_0(1450)$ – $K_0^*(1430)$ degeneracy in light scalars.

Exotic tetraquark mass predictions

	D_{sJ}^{+}	D_{J}^{+}	$D_{s^*J}^{0}$	D_{sJ}^{++}	D_{ssJ}^{+}	D_{J}^{++}
$\bar{3}_A$	2317	2317	-	-	-	-
6	2724	2724	2724	2724	-	-
$\overline{15}$	2632	2561	2520	2520	2657	2383
$\bar{3}_S$	3437	3224	-	-	-	-

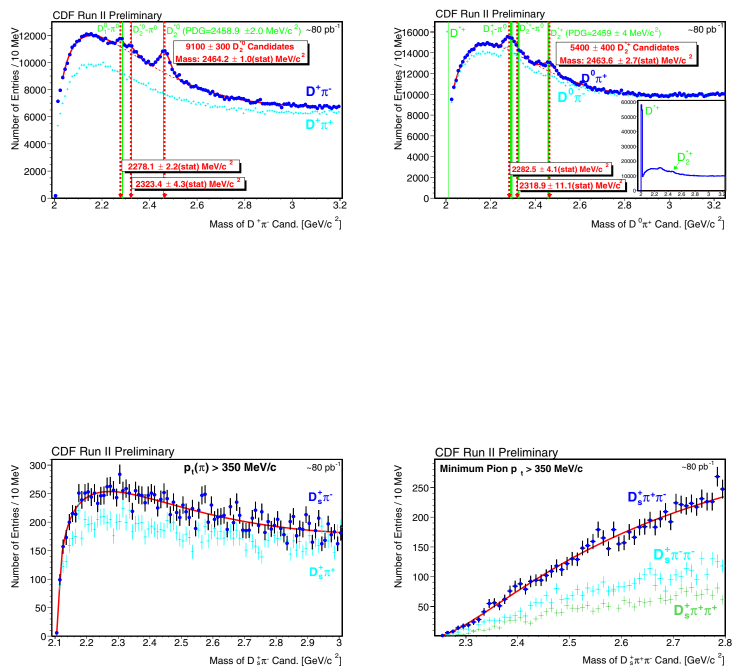
•Many exotic states, most of them within exptl reach of Belle and BaBar

Alternative models of tetraquarks

- Terasaki assumes CS HFI; that leads to $D_s^+(2317)$ being not an isosinglet, but an isotriplet! He predicts degenerate iso-partners.
- ‘t Hooft HFI also leads to isotriplets, and many other exotics, but at higher masses.
- Model independent searches for exotica at present accelerators suggested by Cheng&Hou, PLB566, 193 (‘03). Only one exp. search so far (CDF).

Search for isotriplet D_{sJ} mesons

- M. Shapiro (CDF) has conducted a search for isopartners of $D_s^+(2317)$ eConfC030603:MAR06,2003
- without success: no visible structure in the isotriplet spectra (lower figures)
- descriptive: not a quantitative measure of isopartners' absence.



Decays as tetraquark signature?

- Two kinds of decays measured so far (still incomplete): hadronic and EM.
- $D_s^+(2317)$ is very narrow due isospin conservation: main hadronic decay channel ($D_s^+(1969)\ \pi^0$) violates isospin.
- Other predicted tetraquarks should be wider due to their being above the allowed decay thresholds.
- $D_s^+(2632)$ partial decays indicate unusual flavour multiplet (15-plet?) that exists only in tetraquarks. Liu et al. PRD70, 094009,2004
- $B \longrightarrow D_s + \overline{D}_s$ decays in agreement with tetraquark assumption.
- Most EM decays of $D_s^+(2317)$ consistent with cs content, however.

Summary and outlook

- One antitriplet: [D_s^+(2317) (BaBar), D^+(2308)(Belle)] might be tetraquarks lowered in mass due to KKMT interaction.
- Small strange-nonstrange meson mass difference D_s^+(2317) - D^+(2308) is a “smoking gun” evidence for tetraquark structure!
- Another antitriplet: [D^+(2405) (FOCUS), D_s^+(2632) (SELEX)] might be a mixture of cq bar and tetraquark
- D_s^+(2632) partial decays indicate unusual flavour multiplet (15-plet?) that exists only in tetraquarks.
- Models predict many exotic tetraquarks. Experiment?
- Many theoretical uncertainties

Outlook: theoretical uncertainties in multiquark calculations

- Colour confining dynamics
- Hyperfine interactions
- Relativity
- Chiral symmetry
- Dynamical pair production

Colour in Multiquarks

- Color interactions must confine quarks.
- Confinement must not act between quarks in two separate color singlets (“color saturation”), except perhaps for the v.d.Waals force.
- There are multiple color singlets and the interactions mix them. Color singlet eigenstates are mixtures that depend on the spatial separation.
- All color singlets ought to be stable, as all of them may be admixed. All color eigenstates ought to be observable: new (“hidden color”) hadrons.

Modelling Confinement

- Two-body interaction

$$V(r_{ij}) = \frac{1}{4}\sum_{a=1,..,8} \lambda_i^a \lambda_j^a v(r_{ij}) \equiv (F_i \cdot F_j) v(r_{ij})$$

- with the "saturating" colour factor has been used.

$$(F_i \cdot F_j)$$

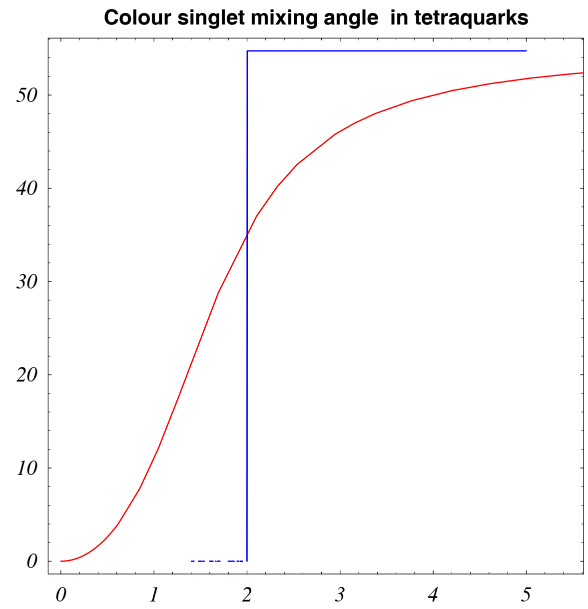
- "Saturation" of color forces = no confining forces between colour singlets (modulo v.d.Waals force)
- Lorentz *vector* confining int.: all c. singlets stable.
- Lorentz *scalar* confining int.: some c. singlets unstable!

Tetraquark colour states

$$\left|1_{13}1_{24}\right\rangle = \cos\theta\left|\bar{3}_{12}3_{34}\right\rangle + \sin\theta\left|6_{12}\bar{6}_{34}\right\rangle$$

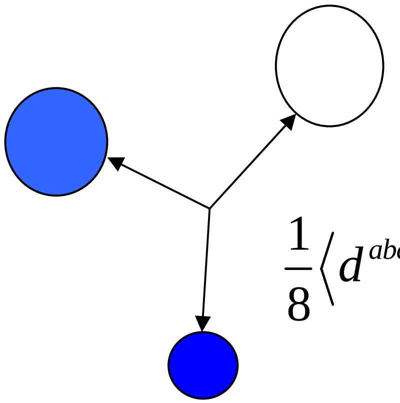
$$\left|8_{13}8_{24}\right\rangle = -\sin\theta\left|\bar{3}_{12}3_{34}\right\rangle + \cos\theta\left|6_{12}\bar{6}_{34}\right\rangle$$

- Color quark interactions mix the two colour singlets
- One state turns into two mesons at asymptotic distances; another is a confined hidden-colour (hc) tetraquark state.
- Diagonal states are orthogonal: h.c. state cannot decay into two mesons.
- No physical process in the NRCQM can turn one c. eigenstate into another. Need annihilation processes (relativity).



Three-body force: stability and saturation

- A “saturating” three-body force has been introduced, V.D. PLB499,136 (2001)
- Two scenarios: (a) Allow all color states, demand that color 8, 10 be heavy; (b) Forbid all non-singlets
- Scenario (a) demands 3-, 4- ,5-body forces etc.; (b) allows only dominant 2-body and a weak 3-body.
- PRD 67, 114007 (03).

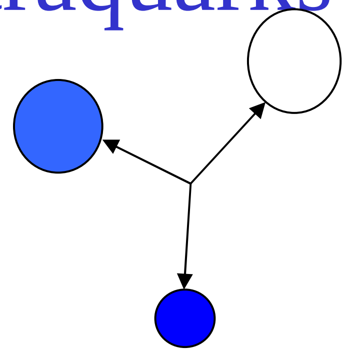


$$\frac{1}{8}\left\langle d^{abc}\lambda_i^a\lambda_j^b\lambda_k^c\right\rangle$$

$$V \to V + V_{3b}$$

$$V_{3b}\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right)=\frac{1}{8}d^{abc}\lambda_i^a\lambda_j^b\lambda_k^c U_0 \exp[-(r_i^2+r_j^2+r_k^2)/a_0]$$

Three-quark colour force in tetraquarks

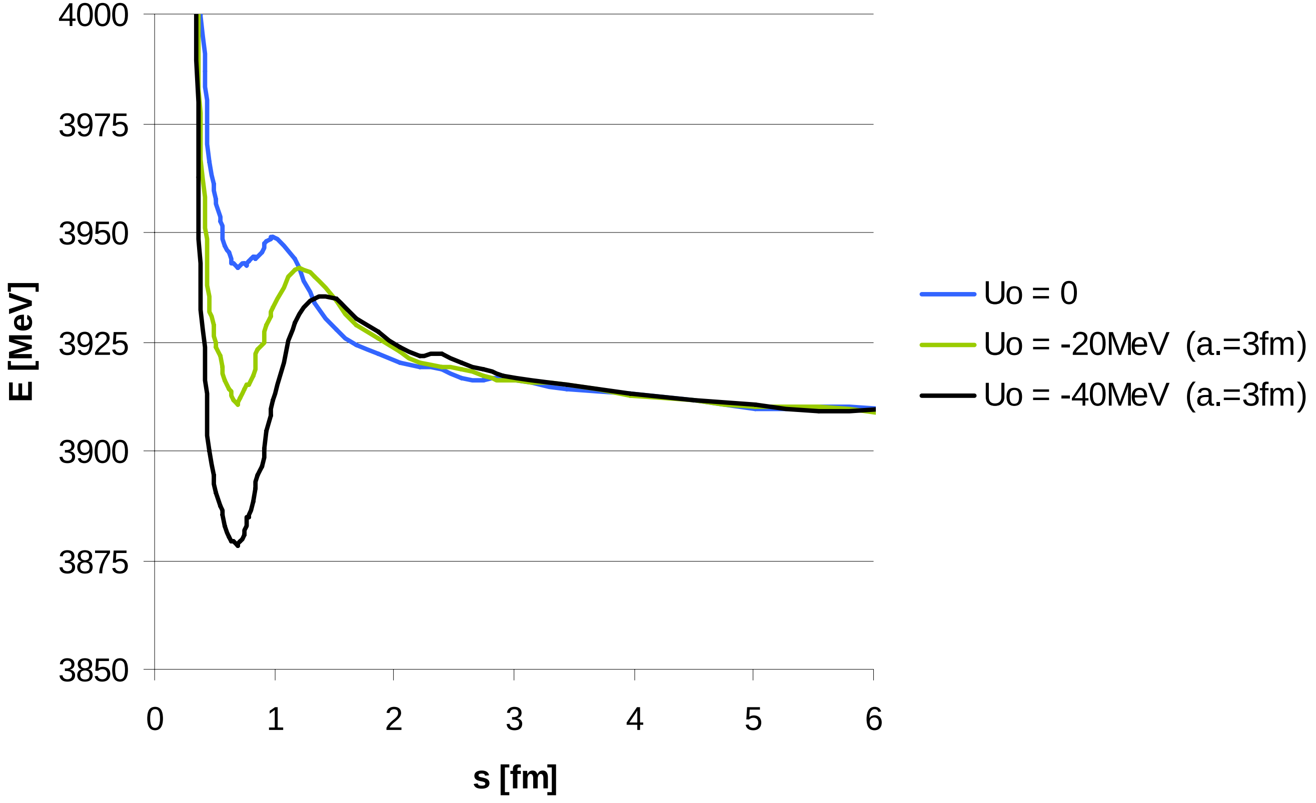


- Saturation: mixes states in the asymptotic basis, but changes only the hidden-colour state energy
- Does not mix states in the Pauli basis, but changes their energies. Unstable.
  PRD 67, 114007 (03).

$$\frac{1}{8}\left\langle d^{abc}\lambda_i^a\lambda_j^b\lambda_k^c\right\rangle$$

	$1_{12}1_{34}$	$8_{12}8_{34}$	$\bar{3}_{13}3_{24}$	$6_{13}6_{24}$
$1_{12}1_{34}$	0	$-5\sqrt{2}/18$	$5/(9\sqrt{3})$	$-5\sqrt{2}/(18\sqrt{3})$
$8_{12}8_{34}$	$-5\sqrt{2}/18$	$5/18$	$-5\sqrt{2}/(9\sqrt{3})$	$-5/(18\sqrt{3})$
$\bar{3}_{13}3_{24}$	$5/(9\sqrt{3})$	$-5\sqrt{2}/(9\sqrt{3})$	$5/9$	0
$6_{13}6_{24}$	$-5\sqrt{2}/(18\sqrt{3})$	$-5/(18\sqrt{3})$	0	$-5/18$

Effects of three-quark colour force on double-charm tetraquarks (D. Janc)



Summary of color in tetraquarks

- Two-body color-color force allows asymptotic separation of two mesons: L. vector induces the smallest v.d.Waals force.
- Three-body force induces even stronger mixing and v.d.Waals force.
- L. scalar prefered by P-wave hadron spectroscopy: unstable baryon.
- Add three-quark to L. scalar so as to stabilize the baryon: find too large v.d.Waals force
- The only simple solution is L. vector plus weak short-range three-quark force.

Flip-flop model: stability and saturation?

- A “QCD-inspired” model of confinement based on the concept of colour flux tubes.
- Color factors are not given in this model: arbitrary!
- Open questions: (a) does this model “saturate”?
  (b) are all color-singlets stable? Nobody knows!
- This scenario implies multi-quark (3-, 4-,5-body) forces: are there multiquark bound states?
- Ill-defined model, leave it for the future.