CONFIRMATION OF THE EXISTENCE OF AN EXOTIC STATE IN THE πD SYSTEM

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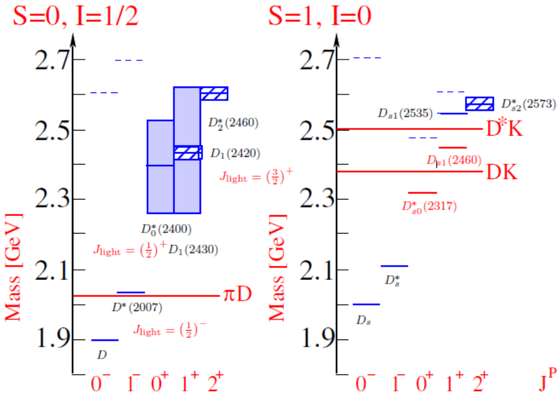
OVERVIEW

- Background
- Lattice simulation
- Results

PHENOMENOLGY

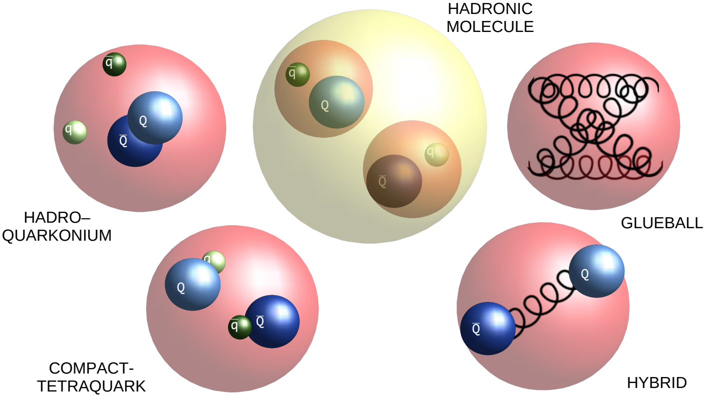


QM: Di Pierro and Eichten, PRD64(2001)114004

- Experiment: $D^*_{s0}(2317)$ and $D_{s1}(2460)$ states lower than QM predictions
- Expect corresponding non-strange states to be $\sim$ 150MeV lighter than strange states, but quite close in energy.

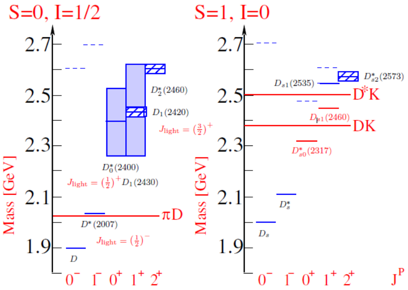
Suspicion: These are not $c\overline{q}$ and $c\overline{s}$ states, something exotic....

EXOTICS


HADRONIC
MOLECULE
HADRO–
QUARKONIUM
GLUEBALL
COMPACT-
TETRAQUARK
HYBRID

EVIDENCE

UχPT calculations[1] suggest:



QM: Di Pierro and Eichten, PRD64(2001)114004

- $D^*_{s0}(2317)$ is a DK molecule
- Broad $D^*_0(2300)$ structure is two poles: $\sim$2105 MeV and $\sim$2451 MeV
- $D^*_{s0}(2317)$ is SU(3) flavor partner of lower pole
- Upper pole is member of SU(3) sextet

Mohler *et. al*[2] and DK scatterning $D^*_{s0}(2317)$
Regensburg group calculated[3] $D^*_{s0}(2317)$ and $D^*_{s1}(2460)$ masses.
Hadron Spectrum Collaboration LQCD calculation[4] predicted the lightest D^*_0 should be below 2300MeV.

[1] Liu,*et. al* , PRD 87 014508 (2012); Albaladejo *et. al*, PLB 767, 465, (2017); Du, *et. al* PRD 98,094018(2018)
[2] Mohler *et. al* PRL 111, 222001(2013)
[3] Bali, *et. al*, PRD 96, 074501 (2017)
[4] Moir *et. al*, JHEP 10, 011 (2016) & Gayer *et. al*,JHEP 07 ((2021) 2021.04973

FLAVOR SYMMETRY

In $SU(3)$ flavor symmetric world, 4-quark state with c and $\bar{q}q\bar{q}$:

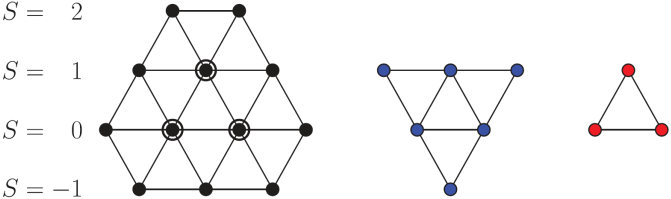
$$[\bar{3}] \otimes [3] \otimes [\bar{3}] = [\bar{3}] \otimes ([8] \oplus [1]) = [15] \oplus [6] \oplus [\bar{3}] \oplus [\bar{3}] \; .$$

We do not consider the $[\bar{3}]$ states,light anti-quark of the D-meson with the singlet $q\bar{q}$

$$[\bar{3}] \otimes [8] = [15] \oplus [6] \oplus [\bar{3}] \; .$$

$\uparrow$ c-meson anti-triplet

$\uparrow$ $q\bar{q}$ Goldstone mesons



QUARK MODEL VS TETRAQUARKS VS MOLECULES

- QM: $[\bar{3}] \otimes [1] = [\bar{3}] \longrightarrow$ no [6]
- Tetraquarks: *all* flavor multiplets are attractive.[5]
- Hadronic molecules: $[\bar{3}]$ most attractive, then [6], with repulsive [15] [6]

A LQCD calculation of [6] and [15] could shed some light....

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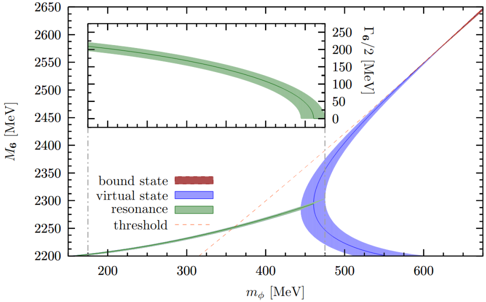
[5] see, e.g., Dmitrasinovic, PRL 94, 162002

[6] Kolomeitsev& Lutz PLB 582; Guo *et al.* PLB 641, 278 (2006); Guo *et al.* Eur. Phys. J.A. 40, 171 (2009)

LQCD WITH $SU(3)$ FLAVOR SYMMETRY

To understand the system we simulate $N_f = 3 + 1$:



(Du, *et. al* PRD 98,094018(2018))

- physical m_c quarks
- 3 flavors of light quarks with m_q, such that $M_\pi \approx 600$ –700 MeV

May show bound or virtual [6] state.

ENSEMBLES

Clover Wilson + 6 iterations of stout smearing (CHROMA + qPHIX or QUDA)
For tuning:

- $\sim$ 63 short ($\sim$ 500 trajecs) tuning ensembles
- 3 different β values

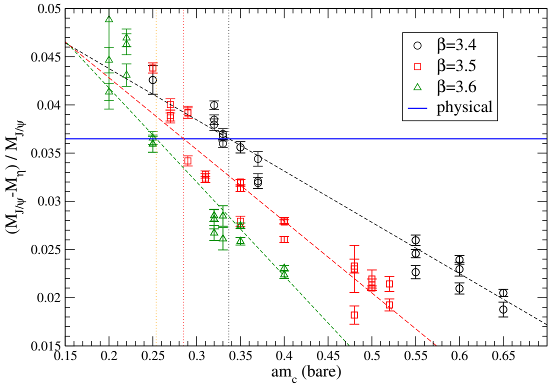
Ultimately, measurements & conclusions from single point in parameter space:

- $\beta = 3.6$ (no continuum extrapolation)
- $a = 0.27\text{GeV}^{-1}$
- $am_q = -0.013$, $am_c = 0.25$
- $m_\pi \sim 612$ MeV (by design!).
- Three volumes: $L_s = 32, 40, 48 \longrightarrow 1.6, 2.1, 2.6$ fm
- $\sim$ 2500 — 2700 trajecs

Not precision spectroscopy!

TUNING m_c

Step 1: Get $\frac{M_{J/\psi} - M_\eta}{M_{J/\psi}} = 0.365$ right.

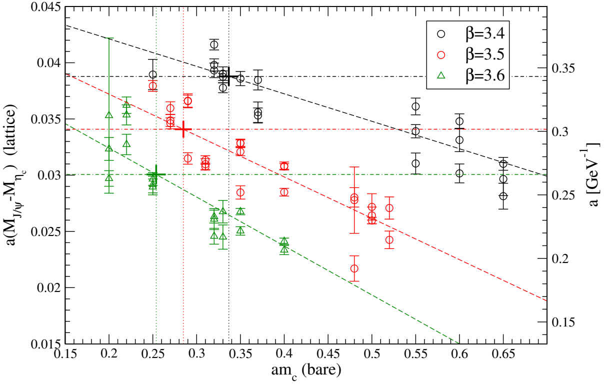


Neglect disconnected diagrams $\longrightarrow \sim$10% error.

DETERMINE LATTICE SPACING

Harder to calibrate far from physical point!

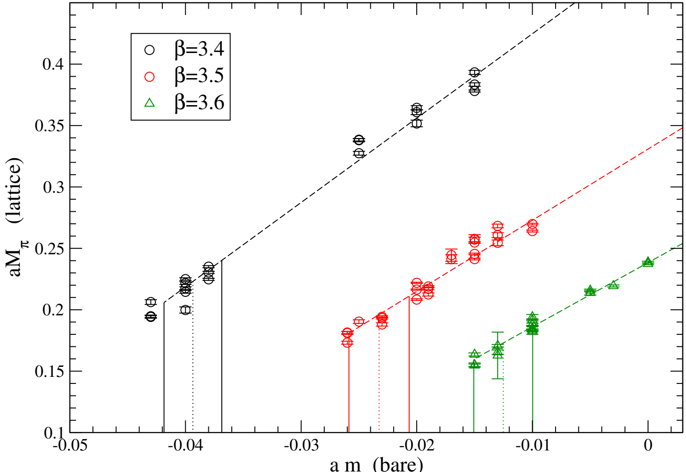
$$a = \left(aM_{J/\psi}^{\mathrm{latt}} - aM_{\eta}^{\mathrm{latt}} \right) / 0.113 \mathrm{GeV}$$



(again ∼ 10% error..)

TUNING m_q

Aim for 650MeV pions.



[6] REPRESENTATION STATES

state	components	T_a^2	I_z	Y
1	$-\lvert u\bar{u}\bar{d}\rangle\frac{1}{2}+\lvert u\bar{d}\bar{u}\rangle\frac{1}{2}-\lvert s\bar{d}\bar{s}\rangle\frac{1}{2}+\lvert s\bar{s}\bar{d}\rangle\frac{1}{2}$	$\frac{10}{3}$	$+\frac{1}{2}$	$-\frac{1}{3}$
2	$\lvert d\bar{u}\bar{d}\rangle\frac{1}{2}-\lvert d\bar{d}\bar{u}\rangle\frac{1}{2}-\lvert s\bar{u}\bar{s}\rangle\frac{1}{2}+\lvert s\bar{s}\bar{u}\rangle\frac{1}{2}$	$\frac{10}{3}$	$-\frac{1}{2}$	$-\frac{1}{3}$
3	$\lvert u\bar{u}\bar{s}\rangle\frac{1}{2}-\lvert u\bar{s}\bar{u}\rangle\frac{1}{2}-\lvert d\bar{d}\bar{s}\rangle\frac{1}{2}+\lvert d\bar{s}\bar{d}\rangle\frac{1}{2}$	$\frac{10}{3}$	0	$+\frac{2}{3}$
4	$\lvert d\bar{s}\bar{u}\rangle\frac{1}{\sqrt{2}}-\lvert d\bar{u}\bar{s}\rangle\frac{1}{\sqrt{2}}$	$\frac{10}{3}$	-1	$+\frac{2}{3}$
5	$\lvert u\bar{s}\bar{d}\rangle\frac{1}{\sqrt{2}}-\lvert u\bar{d}\bar{s}\rangle\frac{1}{\sqrt{2}}$	$\frac{10}{3}$	$+1$	$+\frac{2}{3}$
6	$\lvert s\bar{d}\bar{u}\rangle\frac{1}{\sqrt{2}}-\lvert s\bar{u}\bar{d}\rangle\frac{1}{\sqrt{2}}$	$\frac{10}{3}$	0	$-\frac{4}{3}$

$$O^5_{[6]}(x';x)=\frac{1}{\sqrt{2}}\left\{\left[\bar{s}(x')\Gamma c(x')\right]\left[\bar{d}(x)\Gamma u(x)\right]-\left[\bar{d}(x')\Gamma c(x')\right]\left[\bar{s}(x)\Gamma u(x)\right]\right\}$$

If instead I was interested in state 6 I would get

$$O^6_{[6]}(x';x)=\frac{1}{\sqrt{2}}\left\{\left[\bar{d}(x')\Gamma c(x')\right]\left[\bar{u}(x)\Gamma s(x)\right]-\left[\bar{u}(x')\Gamma c(x')\right]\left[\bar{d}(x)\Gamma s(x)\right]\right\}$$

We use $\Gamma=\gamma_5$.

T_a^2=Casimir op., I_z=Isospin, Y=hypercharge

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CONTRACTIONS

Regardless of the state chosen from table, the contractions are the same at the $SU(3)$ point

$$\langle O^i_{[d]}(y';y)\bar{O}^i_{[d]}(x;x)\rangle^{[6]} = \mathrm{Tr}\left[\Gamma\gamma_5\mathcal{S}^\dagger_{y';x}\gamma_5\Gamma\mathcal{S}_{y';x}\right]\mathrm{Tr}\left[\Gamma\gamma_5\mathcal{S}^\dagger_{y;x}\gamma_5\Gamma\mathcal{C}_{y;x}\right] + \mathrm{Tr}\left[\Gamma\gamma_5\mathcal{S}^\dagger_{y;x}\gamma_5\Gamma\mathcal{S}_{y';x}\Gamma\gamma_5\mathcal{S}^\dagger_{y';x}\gamma_5\Gamma\mathcal{C}_{y;x}\right]$$

$$\langle O^i_{[d]}(y';y)\bar{O}^i_{[d]}(x;x)\rangle^{[15]} = \mathrm{Tr}\left[\Gamma\gamma_5\mathcal{S}^\dagger_{y';x}\gamma_5\Gamma\mathcal{S}_{y';x}\right]\mathrm{Tr}\left[\Gamma\gamma_5\mathcal{S}^\dagger_{y;x}\gamma_5\Gamma\mathcal{C}_{y;x}\right] - \mathrm{Tr}\left[\Gamma\gamma_5\mathcal{S}^\dagger_{y;x}\gamma_5\Gamma\mathcal{S}_{y';x}\Gamma\gamma_5\mathcal{S}^\dagger_{y';x}\gamma_5\Gamma\mathcal{C}_{y;x}\right]$$

...and [6] and [15] are similar up to $+$ or $-$.

$\mathcal{S}$ is light quark propagator
$\mathcal{C}$ is charm quark propagator

CORRELATORS

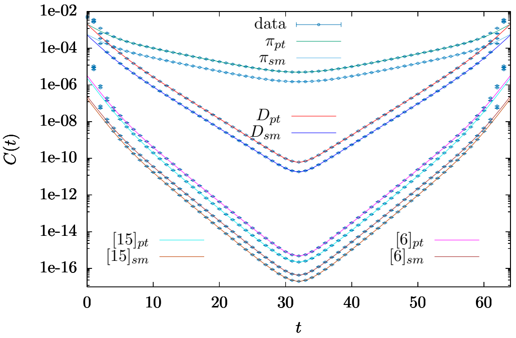
Simultaneously fit correlators:

$$\mathcal{C}(t,P,s) = \delta_{P,P'}\delta_{s,s'}C_{P',s'}(t)$$

with

s ={point, smeared} sinks

and



$$C_{P,s}(t) = \sum_{j=0}^{(N-1)} A_{P,s,j}\cosh\left(M_{P,j}(t - L_t/2)\right) \qquad \text{for } P = \{\pi, D\}$$

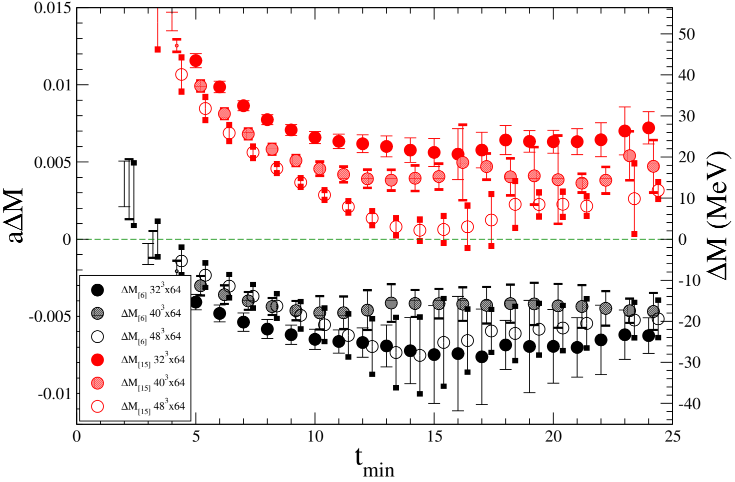
and

$$C_{P,s}(t) = B_s \cosh\left((M_D - M_\pi)(t - L_t/2)\right) + A_{P,s,0}\cosh\left((\Delta_{M_P} + M_{D,0} + M_{\pi,0})(t - L_t/2)\right) + \sum_{j=1}^{(N-1)} A_{P,s,j}\cosh\left(M_{p,j}(t - L_t/2)\right) \qquad \text{for } P = \{[6],[15]\}$$

Then, extract the ground state mass shifts

$$\Delta M_{[6]} \equiv M_{[6]} - (M_D + M_\pi)$$
$$\Delta M_{[15]} \equiv M_{[15]} - (M_D + M_\pi)$$

RESULTS



$N = 2$ fits

- Repulsive [15]
- Bound (or virtual) [6]

$\longrightarrow$ Hadronic molecule

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CONCLUSIONS & FUTURE WORK

Conclusions:

- Bound or virtual [6] state consistent with hadronic molecule.
- Repulsive [15] evidence against tetraquarks

Future efforts:

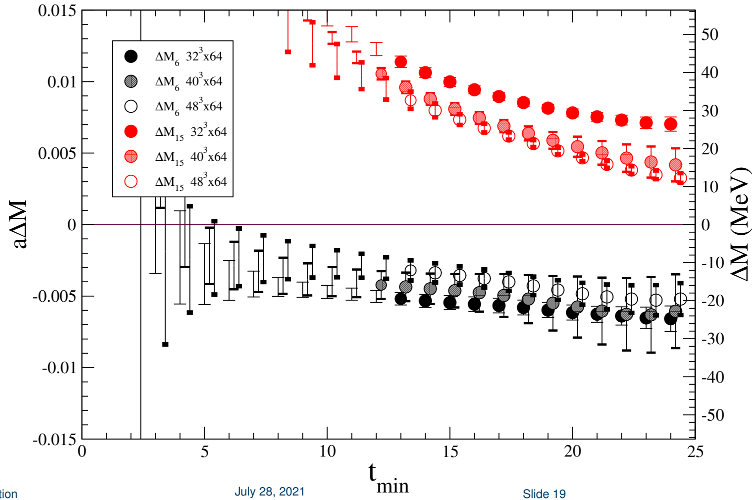
- 4th volume, more statistics, to discern virtual/bound state
- Lüscher analysis
- additional β values for continuum extrapolation
- $[\bar{3}]$ state (disconnected diagrams!)
- η_c & J/ψ disconnected diagrams to better understand scale systematics

Thanks for your attention!

BACKUP SLIDES

RESULTS

$N = 1$ fits



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RESULTS

$N = 1$ fits

$D\pi$ **S-wave from** $B^- \to D^+\pi^-\pi^-$

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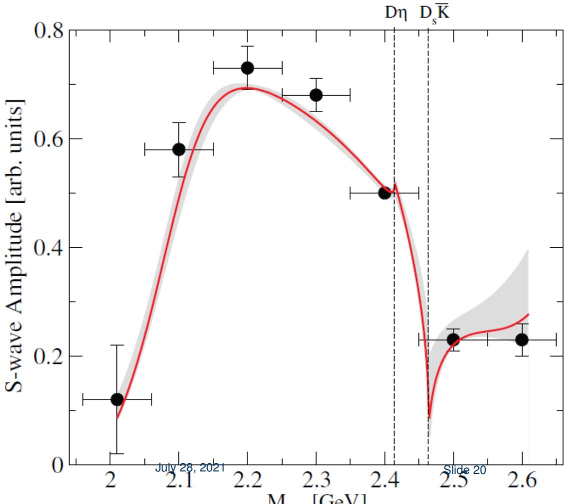

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[15] REPRESENTATION STATES

state	components	T_a^2	I_z	Y
1	$\|s\bar{s}\bar{s}\rangle\frac{1}{\sqrt{3}} - \|u\bar{u}\bar{s}\rangle\frac{1}{\sqrt{3}} - \|u\bar{s}\bar{u}\rangle\frac{1}{\sqrt{3}}$	$\frac{16}{3}$	0	$+\frac{2}{3}$
2	$-\|d\bar{u}\bar{d}\rangle\frac{1}{2} - \|d\bar{d}\bar{u}\rangle\frac{1}{2} + \|s\bar{d}\bar{s}\rangle\frac{1}{2} + \|s\bar{s}\bar{d}\rangle\frac{1}{2}$	$\frac{16}{3}$	$+\frac{1}{2}$	$-\frac{1}{3}$
3	$-\|u\bar{u}\bar{u}\rangle\frac{1}{\sqrt{3}} + \|s\bar{u}\bar{s}\rangle\frac{1}{\sqrt{3}} + \|s\bar{s}\bar{u}\rangle\frac{1}{\sqrt{3}}$	$\frac{16}{3}$	$-\frac{1}{2}$	$-\frac{1}{3}$
4	$\|d\bar{s}\bar{s}\rangle$	$\frac{16}{3}$	$-\frac{1}{2}$	$+\frac{5}{3}$
5	$\|u\bar{s}\bar{s}\rangle$	$\frac{16}{3}$	$+\frac{1}{2}$	$+\frac{5}{3}$
6	$\|d\bar{u}\bar{s}\rangle\frac{1}{\sqrt{2}} + \|d\bar{s}\bar{u}\rangle\frac{1}{\sqrt{2}}$	$\frac{16}{3}$	-1	$+\frac{2}{3}$
7	$\|d\bar{d}\bar{s}\rangle\frac{1}{2} + \|d\bar{s}\bar{2}\rangle\frac{1}{2} - \|u\bar{u}\bar{s}\rangle\frac{1}{2} - \|u\bar{s}\bar{u}\rangle\frac{1}{2}$	$\frac{16}{3}$	0	$+\frac{2}{3}$
8	$\|u\bar{d}\bar{s}\rangle\frac{1}{\sqrt{2}} + \|u\bar{s}\bar{d}\rangle\frac{1}{\sqrt{2}}$	$\frac{16}{3}$	-1	$+\frac{2}{3}$
9	$\|s\bar{u}\bar{u}\rangle$	$\frac{16}{3}$	-1	$-\frac{4}{3}$
10	$\|s\bar{u}\bar{d}\rangle\frac{1}{\sqrt{2}} + \|s\bar{d}\bar{1}\rangle\frac{1}{\sqrt{2}}$	$\frac{16}{3}$	0	$-\frac{4}{3}$
12	$\|s\bar{d}\bar{d}\rangle$	$\frac{16}{3}$	$+1$	$-\frac{4}{3}$
12	$\|d\bar{u}\bar{u}\rangle$	$\frac{16}{3}$	$-\frac{3}{2}$	$-\frac{1}{3}$
13	$-\|u\bar{u}\bar{u}\rangle\frac{1}{\sqrt{3}} + \|d\bar{u}\bar{d}\rangle\frac{1}{\sqrt{3}} + \|d\bar{d}\bar{u}\rangle\frac{1}{\sqrt{3}}$	$\frac{16}{3}$	$-\frac{1}{2}$	$-\frac{1}{3}$
14	$-\|u\bar{u}\bar{d}\rangle\frac{1}{\sqrt{3}} - \|u\bar{d}\bar{u}\rangle\frac{1}{\sqrt{3}} + \|d\bar{d}\bar{d}\rangle\frac{1}{\sqrt{3}}$	$\frac{16}{3}$	$+\frac{1}{2}$	$-\frac{1}{3}$
15	$\|u\bar{d}\bar{d}\rangle$	$\frac{16}{3}$	$+\frac{3}{2}$	$-\frac{1}{3}$