P-wave states T_{bb}^{-} from diquarks

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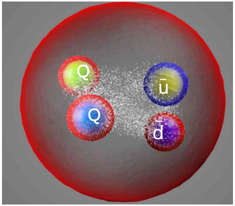
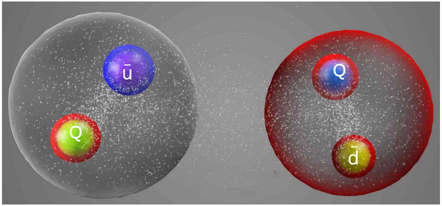
Outline

1. Background

- Theoretical explorations
  - In the early 1980s, the states $QQ\bar{q}\bar{q}$ were pioneered
  - Subsequently, various theoretical frameworks
    $T_{bb}^{-}(bb\bar{u}\bar{d})$ with 01^{+}: the promising state.



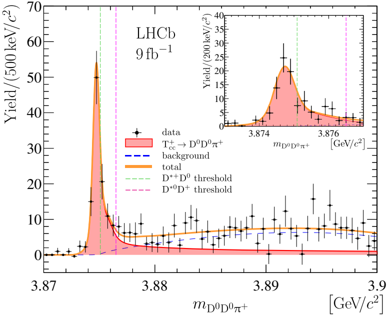
Diquark configuration



Meson-meson configuration

1. Background

- Discoveries in experiments
  - In 2017, the doubly charmed baryon Ξ_{cc}^{++} Phys. Rev. Lett. 119, 112001 (2017)
  - In 2021. the doubly charmed state T_{cc}^{+} , Nature Commun. 13, 3351 (2022)



Its binding energy and decay width are

$$E_b = -361 \pm 40 \text{ keV}, \ \Gamma = 47.8 \pm 1.9 \text{ keV}.$$

May be deuteronlike structure.

2. Quark model

- Model Hamiltonian

$$H_n = \sum_{i=1}^{n} \left(m_i + \frac{\mathbf{p}_i^2}{2m_i} \right) - T_c + \sum_{i>j}^{n} \left(V_{ij}^{oge} + V_{ij}^{con} + V_{ij}^{obe} + V_{ij}^{\sigma} \right)$$

- One-gluon-exchange and quark confinement

$$V_{ij}^{oge} = \frac{\alpha_s}{4} \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c \left(\frac{1}{r_{ij}} - \frac{2\pi\delta(\mathbf{r}_{ij}) \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{3m_i m_j} \right), \quad V_{ij}^{con} = -a_c \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c r_{ij}^2$$

- One Goldstone boson exchange

$$V_{ij}^{obe} = V_{ij}^{\pi} \sum_{k=1}^{3} \mathbf{F}_i^k \mathbf{F}_j^k + V_{ij}^{K} \sum_{k=4}^{7} \mathbf{F}_i^k \mathbf{F}_j^k + V_{ij}^{\eta} (\mathbf{F}_i^8 \mathbf{F}_j^8 \cos\theta_P - \sin\theta_P)$$

$$V_{ij}^{\chi} = \frac{g_{ch}^2}{4\pi} \frac{m_\chi^3}{12 m_i m_j} \frac{\Lambda_\chi^2}{\Lambda_\chi^2 - m_\chi^2} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \left(Y(m_\chi r_{ij}) - \frac{\Lambda_\chi^3}{m_\chi^3} Y(\Lambda_\chi r_{ij}) \right), \quad \chi = \pi,\ K,\ \eta$$

- σ-meson exchange

$$V_{ij}^{\sigma} = -\frac{g_{ch}^2}{4\pi} \frac{\Lambda_\sigma^2 m_\sigma}{\Lambda_\sigma^2 - m_\sigma^2} \left(Y(m_\sigma r_{ij}) - \frac{\Lambda_\sigma}{m_\sigma} Y(\Lambda_\sigma r_{ij}) \right)$$

2. Quark model

- Meson spectrum and adjustable parameters Phys. Rev. D 90, 054009 (2014)

Mass unit in MeV and root-mean-square unit in fm.

State	D	D^*	D_s	D_s^*	$\bar{B}$	$\bar{B}^*$	$\bar{B}_s$	$\bar{B}_s^*$
Model prediction	1867	2002	1972	2140	5259	5301	5377	5430
PDG	1869	2007	1968	2112	5280	5325	5366	5416
$\langle r^2\rangle^{\frac{1}{2}}$	0.68	0.82	0.52	0.69	0.73	0.77	0.57	0.62

Quark mass and Λ_0 unit in MeV, a_c unit in MeV·fm^{-2}, r_0 unit in MeV·fm and α_0 is dimensionless.

Parameter	$m_{u,d}$	m_s	m_c	m_b	a_c	α_0	Λ_0	r_0
Value	280	512	1602	4936	40.78	4.55	9.17	35.06

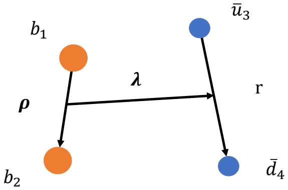
- Applied to the T_{cc}^+, the model can match the experimental data well.

C.R. Deng and S.L. Zhu, T_{cc}^+ and its partners, Phys. Rev. D 105, 054015 (2022);

C.R. Deng and S.L. Zhu, Decoding the double heavy tetraquark state T_{cc}^+, Science Bulletin 67, 1522

3. Diquark configuration of T_{bb}^{-}

- Orbit of T_{bb}^{-}



$$\boldsymbol{\rho} = \mathbf{r}_{b_1} - \mathbf{r}_{b_2}, \quad \mathbf{r} = \mathbf{r}_{\bar{u}_3} - \mathbf{r}_{\bar{d}_4}, \quad \boldsymbol{\lambda} = \frac{\mathbf{r}_{b_1} + \mathbf{r}_{b_2}}{2} - \frac{\mathbf{r}_{\bar{u}_3} + \mathbf{r}_{\bar{d}_4}}{2}$$

- Gaussian expansion method

$$\phi_{l_x m_x}(\mathbf{x}) = \sum_{n_x=1}^{n_{xmax}} c_{n_x} N_{n_x l_x} x^{l_x} e^{-\nu_{n_x} x^2} Y_{l_x m_x}(\hat{\mathbf{x}}), \ \ \mathbf{x} = \boldsymbol{\rho}, \ \mathbf{r} \ and \ \boldsymbol{\lambda}$$

- Three P-wave excited modes

A ρ-mode, $l_\rho = 1$, $l_r = l_\lambda = 0$; B r-mode, $l_r = 1$, $l_\rho = l_\lambda = 0$;
C λ-mode, $l_\lambda = 1$, $l_r = l_\rho = 0$.

3. Diquark configuration of T_{bb}^-

- Color of T_{bb}^-

$$(\bar{\mathbf{3}}_{bb}\oplus\mathbf{6}_{bb})\otimes(\mathbf{3}_{\bar u\bar d}\oplus\bar{\mathbf{6}}_{\bar u\bar d})=\underbrace{(\bar{\mathbf{3}}_{bb}\otimes\mathbf{3}_{\bar u\bar d})}_{\mathbf{1}\oplus\mathbf{8}}\oplus\underbrace{(\bar{\mathbf{3}}_{bb}\otimes\bar{\mathbf{6}}_{\bar u\bar d})}_{\mathbf{8}\oplus\overline{\mathbf{10}}}\oplus\underbrace{(\mathbf{6}_{bb}\otimes\mathbf{3}_{\bar u\bar d})}_{\mathbf{8}\oplus\mathbf{10}}\oplus\underbrace{(\mathbf{6}_{bb}\otimes\bar{\mathbf{6}}_{\bar u\bar d})}_{\mathbf{1}\oplus\mathbf{8}\oplus\mathbf{27}}$$

  - Only $\bar{\mathbf{3}}\otimes\mathbf{3}\to 1$ and $\mathbf{6}\otimes\bar{\mathbf{6}}\to 1$ are permitted. Color $\bar{\mathbf{3}}$ or $\mathbf{3}$: $\mathbf{c}_{bb}=\mathbf{c}_{\bar u\bar d}=0$; Color $\mathbf{6}$ or $\bar{\mathbf{6}}$: $\mathbf{c}_{bb}=\mathbf{c}_{\bar u\bar d}=1$.

- Spin of T_{bb}^-
  - $\mathbf{s}_{bb}=0$ or 1, $\mathbf{s}_{\bar u\bar d}=0$ or 1;
  - Total spin $s=s_{bb}\oplus s_{\bar u\bar d}$;

$$s=\begin{cases}0, & 1\oplus 1 \text{ or } 0\oplus 0\\ 1, & 1\oplus 1,\ 1\oplus 0 \text{ or } 0\oplus 1\\ 2, & 1\oplus 1\end{cases}$$

- Isospin of T_{bb}^-
  - $\mathbf{i}_{bb}=0$, $\mathbf{i}_{\bar u\bar d}=0$ or 1

3. Diquark configuration of T_{bb}^{-}

- Constraints due to the Pauli principle

$$[bb]: \ \mathbf{s}_{bb} + \mathbf{c}_{bb} + \mathbf{i}_{bb} + \mathbf{l}_{\rho} = odd$$
$$[\bar{u}\bar{d}]: \ \mathbf{s}_{\bar{u}\bar{d}} + \mathbf{c}_{\bar{u}\bar{d}} + \mathbf{i}_{\bar{u}\bar{d}} + \mathbf{l}_{r} = even$$

- Total wavefunction

$$\Phi_{IJ}^{T_{bb}^{-}} = \sum_{\alpha} c_{\alpha} \left[\Psi_{i_1 j_1 c_1 l_\rho}^{[bb]} \Psi_{i_2 j_2 c_2 l_r}^{[\bar{u}\bar{d}]} \phi_{l_\lambda m_\lambda}(\boldsymbol{\lambda}) \right]_{IJ}^{T_{bb}^{-}}$$

- Solving the four-body Schrödinger equation

$$(H_4 - E_4)\Phi_{IJ}^{T_{bb}^{-}} = 0$$

in the orbit-color-spin-isospin space composed of 1280 bases.

4. Natures of diquarks and correlations

- Average values of each interaction in the s-wave T_{bb}^{-}

$$\langle V_{ij} \rangle = \langle \Phi_{IJ}^{T_{bb}^{-}} | V_{ij} | \Phi_{IJ}^{T_{bb}^{-}} \rangle$$

$n^{2S+1}L_J$	Parts	T	$V^{\rm con}$	$V^{\rm cm}$	$V^{\rm coul}$	V^{η}	V^{π}	V^{σ}	Parts	T	$V^{\rm con}$	$V^{\rm cm}$	$V^{\rm coul}$	V^{η}	V^{π}	V^{σ}
1^3S_1	$[bb]_{\bar{\mathbf{3}}}^{1}$	124	16	1	−199	0	0	0	$[bb]_{\mathbf{6}}^{0}$	51	−19	1	59	0	0	0
	$[\bar{u}\bar{d}]_{\mathbf{3}}^{0}$	789	55	−289	−257	57	−335	−40	$[\bar{u}\bar{d}]_{\bar{\mathbf{6}}}^{1}$	249	−70	−10	68	−2	20	−14
	$[bb]_{\bar{\mathbf{3}}}^{1}$-$[\bar{u}\bar{d}]_{\mathbf{3}}^{0}$	210	124	−2	−340	0	0	0	$[bb]_{\mathbf{6}}^{0}$-$[\bar{u}\bar{d}]_{\bar{\mathbf{6}}}^{1}$	303	372	0	−764	0	0	0

- Natures of diquarks in s-wave
  - Good diquark $[bb]$: $\mathbf{s}_{bb}=1$, $\mathbf{c}_{bb}=0$ $(\bar{\mathbf{3}}_c)$, $\mathbf{l}_\rho=0$;
    Coulomb interaction
  - Good antidiquark $(\bar{u}\bar{d})$: $\mathbf{s}_{\bar{u}\bar{d}}=0$, $\mathbf{c}_{\bar{u}\bar{d}}=0(\mathbf{3}_c)$, $\mathbf{l}_r=0$, and $\mathbf{i}_{\bar{u}\bar{d}}=0$;
    Color magnetic, Coulomb, π-meson exchange
  - Stronger correlation in the configuration $[bb]_{\mathbf{6}}^{0}$-$[\bar{u}\bar{d}]_{\bar{\mathbf{6}}}^{1}$.

4. Natures of diquarks and correlations

- Average values of each interaction in the P-wave T_{bb}^{-} with λ-mode

$n^{2S+1}L_J$	Parts	T	$V^{\rm con}$	$V^{\rm cm}$	$V^{\rm coul}$	V^{η}	V^{π}	V^{σ}	Parts	T	$V^{\rm con}$	$V^{\rm cm}$	$V^{\rm coul}$	V^{η}	V^{π}	V^{σ}
1^3S_1	$[bb]^1_{\bar{\mathbf{3}}}$	124	16	1	−199	0	0	0	$[bb]^0_{\mathbf{6}}$	51	−19	1	59	0	0	0
	$[\bar{u}\bar{d}]^0_{\mathbf{3}}$	789	55	−289	−257	57	−335	−40	$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$	249	−70	−10	68	−2	20	−14
	$[bb]^1_{\bar{\mathbf{3}}}$-$[\bar{u}\bar{d}]^0_{\mathbf{3}}$	210	124	−2	−340	0	0	0	$[bb]^0_{\mathbf{6}}$-$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$	303	372	0	−764	0	0	0
$1^3P^{\lambda}_{0,1,2}$	$[bb]^1_{\bar{\mathbf{3}}}$	115	18	1	−193	0	0	0	$[bb]^0_{\mathbf{6}}$	41	−24	1	52	0	0	0
	$[\bar{u}\bar{d}]^0_{\mathbf{3}}$	739	59	−273	−250	53	−316	−38	$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$	203	−85	−7	60	−1	14	−11
	$[bb]^1_{\bar{\mathbf{3}}}$-$[\bar{u}\bar{d}]^0_{\mathbf{3}}$	282	216	−1	−232	0	0	0	$[bb]^0_{\mathbf{6}}$-$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$	449	552	0	−604	0	0	0

- Natures of $[bb]$ and $[\bar{u}\bar{d}]$ are unchanged.
- Strong correlation becomes weak in the configuration $[bb]^0_{\mathbf{6}}$-$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$.

4. Natures of diquarks and correlations

- Average values of each interaction in the P-wave T_{bb}^- with ρ-mode

$n^{2S+1}L_J$	Parts	T	$V^{\rm con}$	$V^{\rm cm}$	$V^{\rm coul}$	V^{η}	V^{π}	V^{σ}	Parts	T	$V^{\rm con}$	$V^{\rm cm}$	$V^{\rm coul}$	V^{η}	V^{π}	V^{σ}
1^3S_1	$[bb]^1_{\bar{\mathbf{3}}}$	124	16	1	-199	0	0	0	$[bb]^0_{\mathbf{6}}$	51	-19	1	59	0	0	0
	$[\bar{u}\bar{d}]^0_{\mathbf{3}}$	789	55	-289	-257	57	-335	-40	$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$	249	-70	-10	68	-2	20	-14
	$[bb]^1_{\bar{\mathbf{3}}}$-$[\bar{u}\bar{d}]^0_{\mathbf{3}}$	210	124	-2	-340	0	0	0	$[bb]^0_{\mathbf{6}}$-$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$	303	372	0	-764	0	0	0
$1^1P^{\rho}_1$	$[bb]^0_{\bar{\mathbf{3}}}$	138	39	0	-107	0	0	0	$[bb]^1_{\mathbf{6}}$	97	-28	-7	44	0	0	0
	$[\bar{u}\bar{d}]^0_{\mathbf{3}}$	775	55	-283	-253	56	-328	-40	$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$	248	-70	-10	68	-2	20	-14
	$[bb]^0_{\bar{\mathbf{3}}}$-$[\bar{u}\bar{d}]^0_{\mathbf{3}}$	200	140	-4	-320	0	0	0	$[bb]^1_{\mathbf{6}}$-$[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$	302	396	-24	-740	0	0	0

- P-wave $[bb]^0_{\bar{\mathbf{3}}}$ is a good diquark, Coulomb interaction.
- $[\bar{u}\bar{d}]$ and the correlation between $[bb]$ and $[\bar{u}\bar{d}]$ just change a little bit.

4. Natures of diquarks and correlations

- Average values of each interaction in the P-wave T^-_{bb} with r-mode

$n^{2S+1}L_J$	Parts	T	$V^{\rm con}$	$V^{\rm cm}$	$V^{\rm coul}$	V^η	V^π	V^σ	Parts	T	$V^{\rm con}$	$V^{\rm cm}$	$V^{\rm coul}$	V^η	V^π	V^σ
1^3S_1	$[bb]^1_{\bar{3}}$	124	16	1	-199	0	0	0	$[bb]^0_{6}$	51	-19	1	59	0	0	0
	$[\bar{u}\bar{d}]^0_{3}$	789	55	-289	-257	57	-335	-40	$[\bar{u}\bar{d}]^1_{\bar{6}}$	249	-70	-10	68	-2	20	-14
	$[bb]^1_{\bar{3}}$-$[\bar{u}\bar{d}]^0_{3}$	210	124	-2	-340	0	0	0	$[bb]^0_{6}$-$[\bar{u}\bar{d}]^1_{\bar{6}}$	303	372	0	-764	0	0	0
$1^1P^r_1$	$[bb]^1_{\bar{3}}$	116	17	1	-195	0	0	0	$[bb]^0_{6}$	41	-24	0	50	0	0	0
	$[\bar{u}\bar{d}]^1_{3}$	435	218	4	-93	1	2	-5	$[\bar{u}\bar{d}]^0_{\bar{6}}$	375	-125	4	42	-1	-5	-4
	$[bb]^1_{\bar{3}}$-$[\bar{u}\bar{d}]^1_{3}$	165	228	-6	-240	0	0	0	$[bb]^0_{6}$-$[\bar{u}\bar{d}]^0_{\bar{6}}$	257	552	-2	-596	0	0	0

- P-wave $[\bar{u}\bar{d}]^0_{\bar{6}}$ is a good diquark, good $\Rightarrow$ bad, bad $\Rightarrow$ good.
- P-wave excitation in $[\bar{u}\bar{d}]$ dramatically changes the correlation between $[bb]$ and $[\bar{u}\bar{d}]$.

5. Bound states and binding mechanism

- Binding energy

$$\Delta E = E_4 - M_{\bar{B}^{(*)}} - M_{\bar{B}^{(*)}}$$

- Contribution from each interaction

$$\Delta\langle V_{ij}\rangle = \langle\Phi_{IJ}^{T_{bb}^-}|V_{ij}|\Phi_{IJ}^{T_{bb}^-}\rangle - \langle\Phi(\bar{B}^{(*)}\bar{B}^{(*)})|V_{ij}|\Phi(\bar{B}^{(*)}\bar{B}^{(*)})\rangle$$

- S-wave state T_{bb}^-, threshold $\bar{B}\bar{B}^*$

$n^{2S+1}L_J$	Color-spin, ratio	ΔE	ΔT	$\Delta V^{\rm con}$	$\Delta V^{\rm cm}$	$\Delta V^{\rm coul}$	ΔV^{η}	ΔV^{π}	ΔV^{σ}	$\langle\boldsymbol{\rho}^2\rangle^{\frac{1}{2}}$	$\langle\mathbf{r}^2\rangle^{\frac{1}{2}}$	$\langle\boldsymbol{\lambda}^2\rangle^{\frac{1}{2}}$
1^3S_1	$[bb]^{1}_{\bar{\mathbf{3}}}[\bar{u}\bar{d}]^{0}_{\mathbf{3}}$, $>99\%$	-215	479	-50	-259	-67	57	-335	-40	0.39	0.71	0.64
	$[bb]^{0}_{\mathbf{6}}[\bar{u}\bar{d}]^{1}_{\bar{\mathbf{6}}}$, $<1\%$	119	-38	40	94	19	-2	20	-14	0.60	1.13	0.53
	Mixing	-216	481	-51	-260	-68	57	-335	-40	0.39	0.71	0.64

  - Compact bound state, $\Delta E = -216$ MeV.
  - Binding mechanism
    chromomagnetic and π-meson-exchange in the $[\bar{u}\bar{d}]^{0}_{\mathbf{3}}$.
  - Dominant configuration $[bb]^{1}_{\bar{\mathbf{3}}}[\bar{u}\bar{d}]^{0}_{\mathbf{3}}$.

5. Bound states and binding mechanism

- P-wave T_{bb}^{-} with $1^3P^{\lambda}_{0,1,2}$, no spin-orbit coupling, thresholds $\bar{B}\bar{B}^*$

$n^{2S+1}L_J$	Color-spin, ratio	ΔE	ΔT	$\Delta V^{\rm con}$	$\Delta V^{\rm cm}$	$\Delta V^{\rm coul}$	ΔV^{η}	ΔV^{π}	ΔV^{σ}	$\langle \boldsymbol{\rho}^2\rangle^{\frac{1}{2}}$	$\langle \mathbf{r}^2\rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\lambda}^2\rangle^{\frac{1}{2}}$
$1^3P^{\lambda}_{0,1,2}$	$[bb]^{1}_{\bar{\mathbf{3}}}[\bar{u}\bar{d}]^{0}_{\mathbf{3}}$, $>99\%$	55	494	49	-243	56	53	-316	-38	0.40	0.74	0.91
	$[bb]^{0}_{\mathbf{6}}[\bar{u}\bar{d}]^{1}_{\bar{\mathbf{6}}}$, $<1\%$	511	51	199	22	237	-1	14	-11	0.67	1.25	0.72
	Mixing	55	494	49	-243	56	53	-316	-38	0.40	0.74	0.90

- No bound state, P-wave excitation between $[bb]$ and $[\bar{u}\bar{d}]$
- Dominant configuration $[bb]^{1}_{\bar{3}}[\bar{u}\bar{d}]^{0}_{3}$
- Introduce spin-orbit interaction

5. Bound states and binding mechanism

- P-wave T_{bb}^{-} with $1^3P_1^{\rho}$, threshold $\bar{B}\bar{B}$

$n^{2S+1}L_J$	Color-spin, ratio	ΔE	ΔT	$\Delta V^{\rm con}$	$\Delta V^{\rm cm}$	$\Delta V^{\rm coul}$	ΔV^{η}	ΔV^{π}	ΔV^{σ}	$\langle \boldsymbol{\rho}^2\rangle^{\frac{1}{2}}$	$\langle \mathbf{r}^2\rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\lambda}^2\rangle^{\frac{1}{2}}$
$1^1P_1^{\rho}$	$[bb]_{\bar{\mathbf{3}}}^{0}[\bar{u}\bar{d}]_{\mathbf{3}}^{0}$, $>99\%$	-18	409	7	-210	91	56	-331	-40	0.60	0.72	0.65
	$[bb]_{\mathbf{6}}^{1}[\bar{u}\bar{d}]_{\bar{\mathbf{6}}}^{1}$, $<1\%$	203	-53	69	39	144	-2	20	-14	0.72	1.13	0.53
	Mixing	-18	412	6	-213	89	56	-328	-40	0.60	0.72	0.65

  - Compact bound state, $\Delta E = -18$ MeV.
  - Binding mechanism
    chromomagnetic and π-meson-exchange interaction in the $[\bar{u}\bar{d}]_{\mathbf{3}}^{0}$.
  - Dominant configuration $[bb]_{\bar{\mathbf{3}}}^{0}[\bar{u}\bar{d}]_{\mathbf{3}}^{0}$.

5. Bound states and binding mechanism

- P-wave T_{bb}^{-} with $1^1P_1^r$, threshold $\bar{B}\bar{B}$

$n^{2S+1}L_J$	Color-spin, ratio	ΔE	ΔT	$\Delta V^{\rm con}$	$\Delta V^{\rm cm}$	$\Delta V^{\rm coul}$	ΔV^{η}	ΔV^{π}	ΔV^{σ}	$\langle \boldsymbol{\rho}^2\rangle^{\frac{1}{2}}$	$\langle \mathbf{r}^2\rangle^{\frac{1}{2}}$	$\langle \boldsymbol{\lambda}^2\rangle^{\frac{1}{2}}$
$1^1P_1^r$	$[bb]^1_{\bar{\mathbf{3}}}[\bar{u}\bar{d}]^1_{\mathbf{3}}$, $<1\%$	562	15	233	74	243	1	2	-5	0.40	1.42	0.71
	$[bb]^0_{\mathbf{6}}[\bar{u}\bar{d}]^0_{\bar{\mathbf{6}}}$, $>99\%$	480	-30	176	80	265	-1	-5	-4	0.67	1.53	0.57
	Mixing	480	-28	176	78	265	-1	-5	-4	0.67	1.53	0.57

  - No bound state.
    Strong chromomagnetic and π-meson-exchange interactions disappear in $[\bar{u}\bar{d}]$.
  - Dominant configuration $[bb]^0_{\mathbf{6}}[\bar{u}\bar{d}]^0_{\bar{\mathbf{6}}}$.

6. Summary

- Summary
  - Good diquark $[bb]$ and good andiquark $[\bar{u}\bar{d}]$

    S-wave: $[bb]^1_{\bar{\mathbf{3}}}$, $[\bar{u}\bar{d}]^0_{\mathbf{3}}$; P-wave: $[bb]^0_{\bar{\mathbf{3}}}$, $[\bar{u}\bar{d}]^1_{\bar{\mathbf{6}}}$
  - Diquark correlation in $[bb]_{\mathbf{6}}[\bar{u}\bar{d}]_{\bar{\mathbf{6}}}$ is stronger than $[bb]_{\bar{\mathbf{3}}}[\bar{u}\bar{d}]_{\mathbf{3}}$

    Sometimes, the color configuration $[bb]_{\mathbf{6}}[\bar{u}\bar{d}]_{\bar{\mathbf{6}}}$ is dominant.
  - Compact P-wave bound state T^-_{bb} with 00^-

    Binding energy is about 18 MeV, orbit excitation occurs in the diquark $[bb]$.

    Anti-diquark $[\bar{u}\bar{d}]^0_{\bar{\mathbf{6}}}$ is responsible for its binding mechanism.

Thank you for your attention!