STRUCTURE OF POSITIVE-PARITY CHARM MESONS

November 7, 2025 | Eric B. Gregory | Jülich Supercomputing Centre, FZ Jülich

INTRODUCTION

Based on work with:

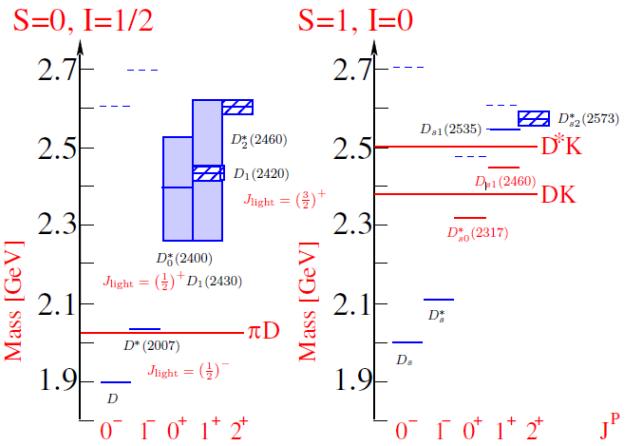
- Feng-Kun Guo (Chinese Academy of Sciences)
- Stefan Krieg (FZ Jülich)
- Christoph Hanhart (FZ Jülich)
- Tom Luu (FZ Jülich)

Published in *Eur. Phys. J. A* **61**, 226 (2025).

OVERVIEW

- Motivation: Exotics with open charm
- Hadronic molecule and tetraquark model predictions
- Lattice simulation
- Results and interpretation

PHENOMENOLGY

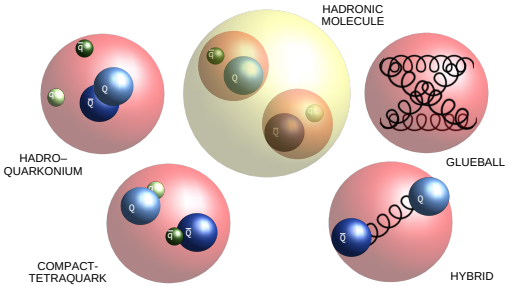


Suspicion: These are not $c\bar{q}$ and $c\bar{s}$ states, something exotic....

Puzzles:

- 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.

EXOTICS

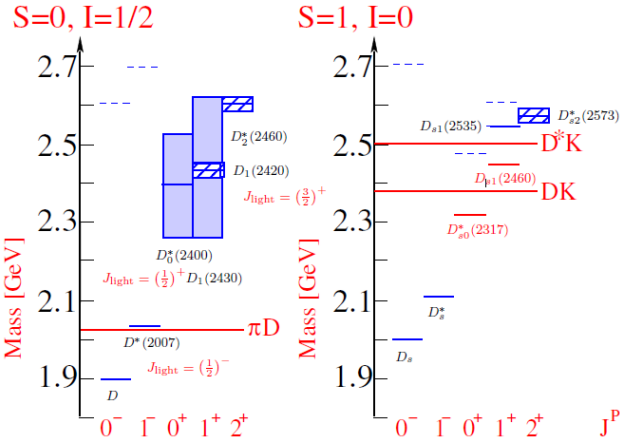


Many possible non-$q\overline{q}$ hadrons.

Strongest candidates to explain states like $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$:

- Hadronic molecules
- Compact tetraquarks

$c\bar{q}q\bar{q}$ INTERPRETATION:



For scalar sector:

- Evidence that scalar $D_0^*(2300)$ is two poles 2105 MeV and 2451 MeV.[a]
- Lighter pole is part of an $SU(3)$ $[\bar{3}]$ with the $D_{s0}^*(2317)$, with correct mass hierarchy.
- 2451 MeV pole is part of [6]

Likewise for 1^+ states:

- Theoretical suggestion that $D_1(2420)$ is two poles 2247 MeV and 2555 MeV [b]
- 2247 MeV pole is in $[\bar{3}]$ with $D_{s1}(2460)$

[a] Phys. Rev. D110, 030001

[b] Albaladejo, *et al.* Phys.Lett.B 767 (2017)
Du *et al.* Phys.Rev.D 98 (2018)

HADRONIC MOLECULES WITH FLAVOR SYMMETRY

Flavor $SU(3)$

$$c\bar{q}\ q\bar{q}$$

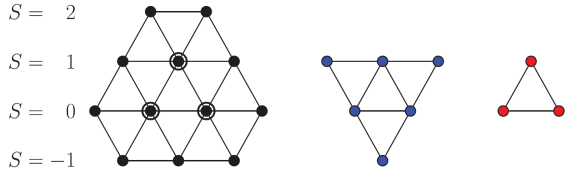
$$[\bar{3}] \otimes \big([3] \otimes [\bar{3}]\big) = [\bar{3}] \otimes ([8] \oplus [1]) = [\overline{15}] \oplus [6] \oplus [\bar{3}] \oplus [\bar{3}]\ .$$

We disregard the much heavier $[\bar{3}]$ states, $\{c\bar{q}\}$ scattering off flavor-singlet η'. We are left with :

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

c-meson anti-triplet

$q\bar{q}$ Goldstone mesons



HADRONIC MOLECULE PREDICTION

Hadronic molecule predictions based on unitarized chiral perturbation theory (UChPT)[1]
Generally:

- $[\bar{3}]$ deeply attractive
- [6] attractive virtual state
- $[\overline{15}]$ repulsive

Confirmed in scalar sector with flavor $SU(3)$-symmetric LQCD by HadSpec [2]

Expect similar behavior for scalar and axialvector sectors, up to spin-symmetry violations.

[1] see: E.E. Kolomeitsev, M.F.M. Lutz, Phys. Lett. B 582, 39 (2004), hep-ph/0307133
[2] HadSpec, Yeo *et al.* JHEP 07 (2024) 012

TETRAQUARK PICTURE WITH FLAVOR $SU(3)$

Arguments here are laid out by **Guo & Hanhart**[3]

See, *e.g.*[4] for TQ description of $c\bar{q}q\bar{q}$ states.

$SU(3)$ $cq\bar{q}\bar{q}$ states $=$ diquark $+$ anti-diquark:

$$\{cq\}\ \{\overline{qq}\}$$

Flavor decomposition: same reps as before, but can associate them with *diquarks*

$$\begin{aligned}[3]\otimes[\bar{3}]\otimes[\bar{3}] &= [3]\otimes\left([3]_A\oplus[\bar{6}]_S\right)\\ &= [\bar{3}]_A\oplus[6]_A\oplus[\bar{3}]_S\oplus[\overline{15}]_S\end{aligned}$$

The $[3]_A$ and $[\bar{6}]_S$ arising from $[\bar{3}]\otimes[\bar{3}]$ are commonly referred to as the *good* and *bad* (anti-) diquark.

[3] Guo & Hanhart, Comm. Th. Phys. 77 (2025) 125201
[4] V. Dmitrašinović, PRL 94.162002

DIQUARKS

$$qq \longrightarrow [3] \otimes [3] = [\bar{3}] \oplus [6]$$

J^P	C	F	
0^+	$\bar{3}$	$\bar{3}$	'good diquark'
1^+	$\bar{3}$	6	' bad diquark'

From phenomenology we generally expect $\sim$ 150 MeV difference between 0^+ and 1^+ diquarks.

$$M_{cq}[1^+] \approx M_{cq}[0^+] + 150 \text{ MeV} \quad \text{c.f. } M_{D_{s1}} - M_{D^*_{s0}} = 142 \text{ MeV}$$
$$M_{\overline{qq}}[1^+] \approx M_{\overline{qq}}[0^+] + 150 \text{ MeV} \quad \text{c.f. } M_{\Sigma_c} - M_{\Lambda_c} = 167 \text{ MeV}$$

EXPECTATIONS FROM TETRAQUARK PICTURE

Tetraquarks		$[cq]$	$[\overline{qq}]$			
Scalar	0^+	0^+	0^+	'good'+'good'		$[\bar{3}]_A$,$[6]_A$
		1^+	1^+	'bad'+'bad'	$\longleftarrow \sim 300$ MeV heavier	$[\overline{15}_S]$
Axialvector	1^+	1^+	0^+	'bad' + 'good'	} approx. equal	$[\bar{3}_A]$,$[6]_A$
		0^+	1^+	'good'+'bad'		$[\overline{15}_S]_1$
		1^+	1^+	'bad'+'bad'		$[\overline{15}_S]_2$

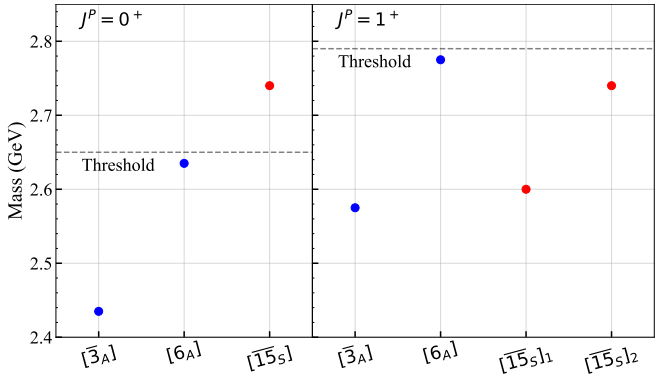
Since the [15] comes from the $\overline{qq}$ in the 1^+ 'bad' antidiquark:

$$[3] \otimes [\bar{3}] \otimes [\bar{3}] = [3] \otimes ([3]_A \oplus [\bar{6}]_S)$$
$$= [\bar{3}]_A \oplus [6]_A \oplus [\bar{3}]_S \oplus [\overline{15}]_S,$$

Guo & Hanhart:

- Start with HadSpec result for 0^+ $[\bar{3}]$ and [6]
- Add cost of "bad" $\overline{qq}$ or cq to get predictions of other states.

TETRAQUARK PREDICTIONS WITH FLAVOR $SU(3)$



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Upshot:

We expect (in the tetraquark model) quantitatively different behavior of the $[\overline{15}]$ in the scalar and axialvector sectors:

- Scalar: much heavier $[\overline{15}]$
- Axvec: *two* $[\overline{15}]$s in same neighborhood as $[\bar{3}]$ and $[6]$. (attractive)

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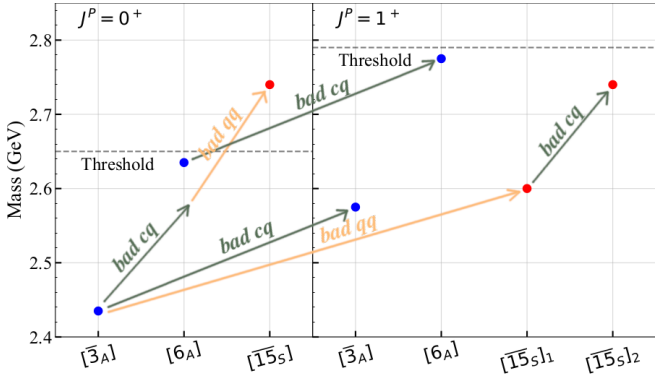

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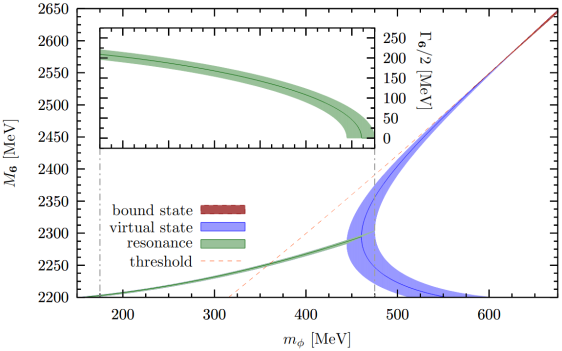
LATTICE CALCULATION



Predicted sextet state mass at the SU(3) symmetric point as a function of the Goldstone-boson mass m_ϕ from UChPT.
Du, *et al.*, Phys.Rev.D 98 (2018) 9, 094018

Target:

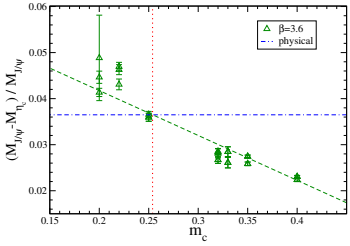
- $m_c \sim$ physical charm mass
- m_q to give $M_\pi \sim 600$ — 700 MeV

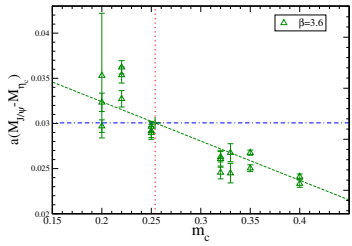
We use:

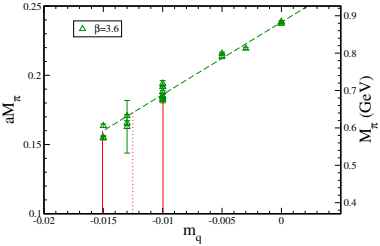
- $N_f = 3 + 1$ dynamical clover fermions
- 6 stout iterations
- Chroma + QUDA

TUNING

Three-step process for each value of β:







Tune m_c so:

$$\frac{M_{J/\psi} - M_{\eta_c}}{M_{J/\phi}} = 0.0365(\mathrm{phys})$$

Extract a:

$$a = \frac{M_{J/\psi}^{\mathrm{latt}} - M_{\eta_c}^{\mathrm{latt}}}{M_{J/\psi}^{\mathrm{exp}} - M_{\eta_c}^{\mathrm{exp}}}$$

Tune m_q so:

$$600 < M_\pi < 700 \text{ MeV}$$

SIMULATION TARGET POINT

@ $\beta = 3.6$

$m_q = -0.013$
$m_c = 0.25$

$M_\pi = 613 \pm 1\text{MeV}$
$M_D = 1890 \pm 2\text{MeV}$
$M_{D^*} = 2037 \pm 4\text{MeV}$
$a = 0.053\ \text{fm} = 0.27\ \text{GeV}^{-1}$

We generated ensembles with:

$N_x^3 \times N_t$	$M_\pi L$	trajecs
$32^3 \times 64$	5.3	5130
$40^3 \times 64$	6.6	5052
$48^3 \times 64$	7.9	4135
$64^3 \times 64$	10.6	9960

$\longleftarrow$ used for results in today's discussion

CONTRACTIONS

[6] and [15] are identical up to $+$ or $-$;

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

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

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

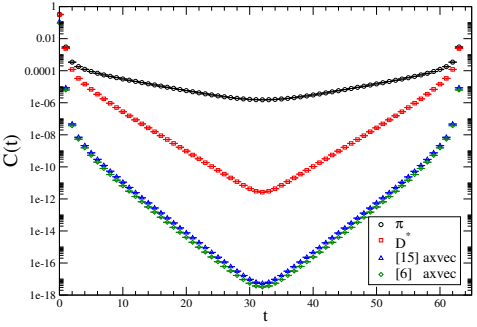
	Γ_A	Γ_B
Scalar:	γ_5	γ_5
Axialvector:	γ_5	$\gamma_x, \gamma_y, \gamma_z$

FIT CORRELATORS

- $q\overline{q}$ states: $P = \pi, D, D^*$

$$C_{P,s}(t) = \sum_{j=0}^{(N-1)} A_{P,s,j} \cosh\left(E_{P,j}(t - L_t/2)\right)$$

with $s =$ {point, smeared} sinks



- For the $SU(3)$ states:

$$C_{P,s}(t) = B_s \cosh\left((M_{\bar{q}c} - M_\pi)(t - L_t/2)\right) + \sum_{j=0}^{(N-1)} A_{P,s,j} \cosh\left(E_{p,j}(t - L_t/2)\right).$$

Fit with $N = 2, 3, 4$

Extract the ground state mass shifts:

Scalar	Axial-vector
$\Delta E_{[6]_{\rm sca}} \equiv E_{[6]_{\rm sca}} - (M_D + M_\pi)$	$\Delta E_{[6]_{\rm axv}} \equiv E_{[6]_{\rm axv}} - (M_{D^*} + M_\pi)$
$\Delta E_{[\overline{15}]_{\rm sca}} \equiv E_{[\overline{15}]_{\rm sca}} - (M_D + M_\pi)$	$\Delta E_{[\overline{15}]_{\rm axv}} \equiv E_{[\overline{15}]_{\rm axv}} - (M_{D^*} + M_\pi)$

ANALYSIS

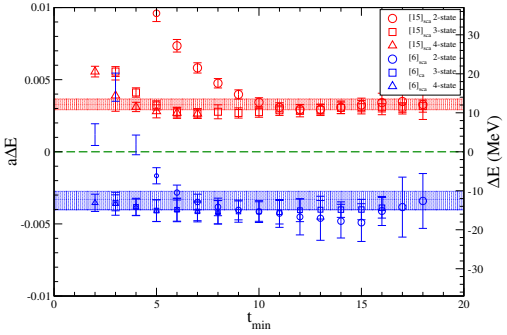
- Perform a weighted average over fits using Akaike Information Criterion (AIC)

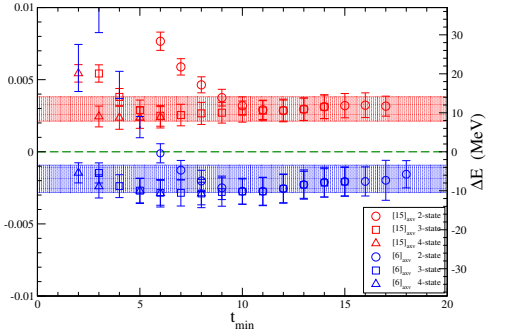
$$\mathrm{AIC}_i = \chi_i^2 + 2N_{\mathrm{param}} - 2N_{\mathrm{data}}$$

$$W_i = \frac{\exp\left(\mathrm{AIC}_i/2\right)}{\sum_i \exp\left(\mathrm{AIC}_i/2\right)}$$

- Binned jackknife error analysis

RESULTS





$$\Delta E_{[6]_{\mathrm{sca}}} = (-13 \pm 2)\ \mathrm{MeV}$$

$$\Delta E_{[\overline{15}]_{\mathrm{sca}}} = (12 \pm 1)\ \ \mathrm{MeV}\ ,$$

$$\Delta E_{[6]_{\mathrm{axv}}} = (-7 \pm 4)\ \mathrm{MeV}$$

$$\Delta E_{[\overline{15}]_{\mathrm{axv}}} = (11 \pm 3)\ \ \mathrm{MeV}$$

Statistical uncertainties only.

Nearly identical behavior of the $[\overline{15}]$ in scalar and axial-vector sectors!

CONCLUSIONS

- From flavor-symmetric LQCD study, we calculate spectrum of open-charm $SU(3)$ [6] and $[\overline{15}]$ states in 0^+ and 1^+ channels.
- In both scalar and axialvector cases we see attractive [6] and repulsive interaction in $[\overline{15}]$.
  - In agreement with hadronic molecule model.
  - Stark contrast with the prediction of the tetraquark model, which predicts repulsive 0^+ $[\overline{15}]$, but deeply attractive 1^+ $[\overline{15}]$.
- Our interpretation is exclusion of tetraquark model.

Thank you for your attention!

EXTRA SLIDES

EXTRA SLIDES

15 REPRESENTATION STATES

state	components	T_a^2	I_z	Y
1	$\lvert s\bar{s}\bar{s}\rangle \frac{1}{\sqrt{3}} - \lvert u\bar{u}\bar{s}\rangle \frac{1}{\sqrt{3}} - \lvert u\bar{s}\bar{u}\rangle \frac{1}{\sqrt{3}}$	$\frac{16}{3}$	0	$+\frac{2}{3}$
2	$-\lvert d\bar{u}\bar{d}\rangle \frac{1}{2} - \lvert d\bar{d}\bar{u}\rangle \frac{1}{2} + \lvert s\bar{d}\bar{s}\rangle \frac{1}{2} + \lvert s\bar{s}\bar{d}\rangle \frac{1}{2}$	$\frac{16}{3}$	$+\frac{1}{2}$	$-\frac{1}{3}$
3	$-\lvert u\bar{u}\bar{u}\rangle \frac{1}{\sqrt{3}} + \lvert s\bar{u}\bar{s}\rangle \frac{1}{\sqrt{3}} + \lvert s\bar{s}\bar{u}\rangle \frac{1}{\sqrt{3}}$	$\frac{16}{3}$	$-\frac{1}{2}$	$-\frac{1}{3}$
4	$\lvert d\bar{s}\bar{s}\rangle$	$\frac{16}{3}$	$-\frac{1}{2}$	$+\frac{5}{3}$
5	$\lvert u\bar{s}\bar{s}\rangle$	$\frac{16}{3}$	$+\frac{1}{2}$	$+\frac{5}{3}$
6	$\lvert d\bar{u}\bar{s}\rangle \frac{1}{\sqrt{2}} + \lvert d\bar{s}\bar{u}\rangle \frac{1}{\sqrt{2}}$	$\frac{16}{3}$	-1	$+\frac{2}{3}$
7	$\lvert d\bar{d}\bar{s}\rangle \frac{1}{2} + \lvert d\bar{s}\bar{d}\rangle \frac{1}{2} - \lvert u\bar{u}\bar{s}\rangle \frac{1}{2} - \lvert u\bar{s}\bar{u}\rangle \frac{1}{2}$	$\frac{16}{3}$	0	$+\frac{2}{3}$
8	$\lvert u\bar{d}\bar{s}\rangle \frac{1}{\sqrt{2}} + \lvert u\bar{s}\bar{d}\rangle \frac{1}{\sqrt{2}}$	$\frac{16}{3}$	-1	$+\frac{2}{3}$
9	$\lvert s\bar{u}\bar{u}\rangle$	$\frac{16}{3}$	-1	$-\frac{4}{3}$
10	$\lvert s\bar{u}\bar{d}\rangle \frac{1}{\sqrt{2}} + \lvert s\bar{d}\bar{u}\rangle \frac{1}{\sqrt{2}}$	$\frac{16}{3}$	0	$-\frac{4}{3}$
11	$\lvert s\bar{d}\bar{d}\rangle$	$\frac{16}{3}$	$+1$	$-\frac{4}{3}$
12	$\lvert d\bar{u}\bar{u}\rangle$	$\frac{16}{3}$	$-\frac{3}{2}$	$-\frac{1}{3}$
13	$-\lvert u\bar{u}\bar{u}\rangle \frac{1}{\sqrt{3}} + \lvert d\bar{u}\bar{d}\rangle \frac{1}{\sqrt{3}} + \lvert d\bar{d}\bar{u}\rangle \frac{1}{\sqrt{3}}$	$\frac{16}{3}$	$-\frac{1}{2}$	$-\frac{1}{3}$
14	$-\lvert u\bar{u}\bar{d}\rangle \frac{1}{\sqrt{3}} - \lvert u\bar{d}\bar{u}\rangle \frac{1}{\sqrt{3}} + \lvert d\bar{d}\bar{d}\rangle \frac{1}{\sqrt{3}}$	$\frac{16}{3}$	$+\frac{1}{2}$	$-\frac{1}{3}$
15	$\lvert u\bar{d}\bar{d}\rangle$	$\frac{16}{3}$	$+\frac{3}{2}$	$-\frac{1}{3}$

For example

$$O^{i=9}_{[d=\overline{15}]}(x';x) = [\bar{u}(x')\Gamma_B c(x')][s(x)\Gamma_A \bar{u}(x)]$$

For scalar case: $\Gamma_A = \Gamma_B = \gamma_5$

For axial vectors, average over: $\Gamma_A = \gamma_5; \Gamma_B = \gamma_x, \gamma_y, \gamma_z$

JÜLICH Forschungszentrum