应用QCD求和规则研究五夸克态

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1 引言

In 2015, the LHCb collaboration observed the $P_c(4380)$ and $P_c(4450)$ in the $J/\psi p$ mass spectrum in the $\Lambda_b^0 \to J/\psi K^- p$ decays. The preferred spin-parity assignments are $J^P = \frac{3}{2}^-$ and $\frac{5}{2}^+$, respectively.

In 2019, the LHCb collaboration studied the $\Lambda_b^0 \to J/\psi K^- p$ decays, and observed the $P_c(4312)$ in the $J/\psi p$ mass spectrum. And confirmed the $P_c(4450)$, which consists of two narrow peaks $P_c(4440)$ and $P_c(4457)$.

In 2021, the LHCb collaboration reported an evidence for the $P_{cs}(4459)$ with the strangeness $S = -1$ in the $J/\psi\Lambda$ mass spectrum in the $\Xi_b^- \to J/\psi K^-\Lambda$ decays.

In 2022, the LHCb collaboration observed an evidence for the $P_c(4337)$ in the $J/\psi p$ and $J/\psi\bar{p}$ systems in the $B_s^0 \to J/\psi p\bar{p}$ decays.

In 2023, the LHCb collaboration observed an evidence for the $P_{cs}(4338)$ in the $J/\psi\Lambda$ mass spectrum in the $B^- \to J/\psi\Lambda\bar{p}$ decays. The favored spin-parity is $J^P = \frac{1}{2}^-$.

2 重子QCD求和规则一般计算步骤

首先构造重子流 (for details: arXiv:2502.11351)

质子流是典型的重子流，五夸克态具有分数自旋，可以归结为重子。

质子流：最简单的流

$$J(x) = \varepsilon^{ijk} u_i^T(x) C \gamma_\alpha u_j(x) \gamma^\alpha \gamma_5 d_k(x) \,. \qquad (1)$$

The $J(x)$ has the spin-parity $J^P = \frac{1}{2}^+$, then the $i\gamma_5 J(x)$ would have the spin-parity $J^P = \frac{1}{2}^-$, as multiplying $i\gamma_5$ changes the parity of the $J(x)$.

其次，写出关联函数，完成算符乘积展开。

$$\Pi_{\pm}(p) = i \int d^4x e^{ip\cdot x} \langle 0 | T\left\{ J_{\pm}(x) \bar{J}_{\pm}(0) \right\} |0\rangle \,, \quad (2)$$

where we add the subscripts $\pm$ to denote the positive and negative parity, respectively, $J_- = i\gamma_5 J_+$.

We decompose the correlation functions $\Pi_{\pm}(p)$,

$$\Pi_{\pm}(p) = \not{p}\Pi_1(p^2) \pm \Pi_0(p^2) \,, \quad (3)$$

according to Lorentz covariance, because

$$\Pi_-(p) = -\gamma_5 \Pi_+(p) \gamma_5 \,. \quad (4)$$

The currents J_+ couple to both the positive- and negative-parity baryons,

$$\langle 0|J_+|B^\pm\rangle\langle B^\pm|\bar{J}_+|0\rangle = -\gamma_5\langle 0|J_-|B^\pm\rangle\langle B^\pm|\bar{J}_-|0\rangle\gamma_5\,,$$

where the $B^\pm$ denote the positive and negative parity baryons, respectively.

$$\begin{aligned}\langle 0|J_\pm(0)|B^\pm(p)\rangle &= \lambda_\pm U^\pm(p,s)\,,\\ \langle 0|J_\pm(0)|B^\mp(p)\rangle &= \lambda_\mp i\gamma_5 U^\mp(p,s)\,.\end{aligned} \quad (5)$$

正负宇称的重子，可能互相污染。

为了区分正负宇称重子的贡献，这三篇原始文献，提出了半解析方法。

Y. Chung, H. G. Dosch, M. Kremer and D. Schall, *Baryon Sum Rules and Chiral Symmetry Breaking*, Nucl. Phys. **B197** (1982) 55.

E. Bagan, M. Chabab, H. G. Dosch and S. Narison, *Baryon sum rules in the heavy quark effective theory*, Phys. Lett. **B301**, 243 (1993).

D. Jido, N. Kodama and M. Oka, *Negative parity nucleon resonance in the QCD sum rule*, Phys. Rev. **D54** (1996) 4532.

Then

$$\Pi_+(p) = \lambda_+^2 \frac{\not p + M_+}{M_+^2 - p^2} + \lambda_-^2 \frac{\not p - M_-}{M_-^2 - p^2} + \cdots . \quad (6)$$

If we take $\vec{p} = 0$, then

$$\mathrm{limit}_{\epsilon\to 0} \frac{\mathrm{Im}\Pi_+(\mathrm{p}_0 + \mathrm{i}\epsilon)}{\pi} = \lambda_+^2 \frac{\gamma_0 + 1}{2} \delta(p_0 - M_+) + \lambda_-^2 \frac{\gamma_0 - 1}{2} \delta(p_0 - M_-) + \cdots = \gamma_0 A(p_0) + B(p_0) + \cdots ,$$

where

$$A(p_0) = \frac{1}{2} \left[\lambda_+^2 \delta(p_0 - M_+) + \lambda_-^2 \delta(p_0 - M_-) \right] ,$$
$$B(p_0) = \frac{1}{2} \left[\lambda_+^2 \delta(p_0 - M_+) - \lambda_-^2 \delta(p_0 - M_-) \right] . \quad (7)$$

$A(p_0) + B(p_0)$ $(A(p_0) - B(p_0))$ contains contributions from the positive parity (negative parity) states only.

$$\int_\Delta^{\sqrt{s_0}} dp_0 \left[A(p_0) \pm B(p_0)\right] \exp\left[-\frac{p_0^2}{T^2}\right] = \int_\Delta^{\sqrt{s_0}} dp_0 \left[\rho^A_{QCD}(p_0) \pm \rho^B_{QCD}(p_0)\right] \exp\left[-\frac{p_0^2}{T^2}\right] ,$$

$$\int_\Delta^{\sqrt{s_0}} dp_0 \left[A(p_0) \pm B(p_0)\right] p_0^2 \exp\left[-\frac{p_0^2}{T^2}\right] = \int_\Delta^{\sqrt{s_0}} dp_0 \left[\rho^A_{QCD}(p_0) \pm \rho^B_{QCD}(p_0)\right] p_0^2 \exp\left[-\frac{p_0^2}{T^2}\right] .$$

我们改造上述方法，拓展成解析方法，[Eur. Phys. J. C76 (2016) 70]，适用于五夸克态与传统重子。

Setting $\Pi(p^2) = \Pi_-(p)$, we obtain the spectral densities through the dispersion relation,

$$
\begin{aligned}
\frac{\mathrm{Im}\Pi(s)}{\pi} &= \not{p}\left[\lambda_-^2\delta\left(s-M_-^2\right)+\lambda_+^2\delta\left(s-M_+^2\right)\right] \\
&\quad +\left[M_-\lambda_-^2\delta\left(s-M_-^2\right)-M_+\lambda_+^2\delta\left(s-M_+^2\right)\right] \, , \\
&= \not{p}\,\rho_H^1(s)+\rho_H^0(s)\, , \qquad (8)
\end{aligned}
$$

where the subscript H denotes the hadron side.

Then we introduce the weight function $\exp\left(-\frac{s}{T^2}\right)$ to obtain the QCD sum rules at the hadron side,

$$2M_{\mp}\lambda_{\mp}^2 \exp\left(-\frac{M_{\mp}^2}{T^2}\right) = \int_{\Delta^2}^{s_0} ds \left[\sqrt{s}\rho_H^1(s) \pm \rho_H^0(s)\right] \exp\left(-\frac{s}{T^2}\right) .$$

$$M_{\mp}^2 = \frac{-\int_{4m_c^2}^{s_0} ds \frac{d}{d(1/T^2)} \left[\sqrt{s}\rho_{QCD}^1(s) \pm \rho_{QCD}^0(s)\right] \exp\left(-\frac{s}{T^2}\right)}{\int_{4m_c^2}^{s_0} ds \left[\sqrt{s}\rho_{QCD}^1(s) \pm \rho_{QCD}^0(s)\right] \exp\left(-\frac{s}{T^2}\right)} . \quad (9)$$

对于隐粲(或隐美或双重)五夸克流$J(x)$,

$$\Pi(p^2) = i\int d^4x e^{ip\cdot x}\langle 0|T\left\{J(x)\bar{J}(0)\right\}|0\rangle\,, \quad (10)$$

做维克收缩，得到五个完全传播子，两个重夸克传播子，三个轻夸克传播子。如果每个重夸克传播子贡献一个胶子，每个轻夸克传播子贡献一个夸克对，则得到一个维度为13 的算符，所以算符乘积展开应该到维度为13的真空凝聚。但实际计算，一般展开到维度为8或者10。

算符乘积展开如果达不到指定的维度，影响计算的准确度。对于高维真空凝聚，采取因子化的假设，因子化为低维真空凝聚。

3 QCD求和规则中参数的选取

The correlation functions $\Pi(p^2)$ do not depend on the energy scale μ, that is

$$\frac{d}{d\mu}\Pi(p^2) \;=\; 0\,, \tag{11}$$

至少对裸关联函数如此，但并不能保证基态贡献不依赖能标，$\rho_{QCD}(s,\mu)=\frac{\mathrm{Im}\Pi(s)}{\pi}$，

$$\frac{d}{d\mu}\int_{4m_Q^2(\mu)}^{s_0} ds\frac{\rho_{QCD}(s,\mu)}{s-p^2}\rightarrow 0\,, \tag{12}$$

due to the following two reasons inherited from the QCD sum rules:

- 微扰修正项被略去，高维真空凝聚因子化为低维真空凝聚，高维真空凝聚的能标依赖性被修正了；
- 引入截断 s_0，阈值 $4m_Q^2(\mu)$ 和连续态阈值 s_0 之间的关联是未知的，强子-夸克对偶只是一个假设。

我们得不到不依赖于能标的QCD求和规则，但我们提出一个能标公式，可以协调地把QCD谱密度的能标定下来。

We perform the Borel transformation with respect to the variable $P^2 = -p^2$ and obtain

$$\int_{4m_Q^2(\mu)}^{s_0} ds \frac{\rho_{QCD}(s,\mu)}{s-p^2} \rightarrow \int_{4m_Q^2(\mu)}^{s_0} ds \frac{\rho_{QCD}(s,\mu)}{T^2} \exp\left(-\frac{s}{T^2}\right) . \quad (13)$$

The integrals are sensitive to the heavy quark masses m_Q.

重夸克质量的变化，或者说能标的变化，可以引起积分区间 $\underbrace{4m_Q^2(\mu) - s_0}$ 和QCD谱密度 $\underbrace{\rho_{QCD}(s,\mu)}$ 的变化，这也就引起布莱尔窗口的变化，并由此产生强子质量和极点留数的变化。具体的计算表明：微小的重夸克质量 m_Q 变化，可以起比较大强子质量变化。

从上面的分析，我们可以得出结论：能标的选取很重要，对结果影响很大。

对于隐粲(隐美或双重)四(五)夸克态的QCD求和规则，我们区分轻重自由度，提出能标公式

$$\mu = \sqrt{M^2_{X/Y/Z/P} - (2\mathbb{M}_Q)^2} - \kappa \mathbb{M}_s \,, \quad (14)$$

the κ is the number of the s-quark.

我们首次研究了四夸克态$q\bar{q}Q\bar{Q}$的QCD求和规则的能标依赖性，发现能标公式适用于所有四夸克系统$q\bar{q}Q\bar{Q}$与五夸克系统$qqqQ\bar{Q}$。

我们把所有夸克质量和真空凝聚演化到这个特定的能标 μ，然后提取强子质量 $M_{X/Y/Z/P}$ 和极点留数。或者说 μ 和 $M_{X/Y/Z/P}$ 满足一个特定的关系，参数 $\mathbb{M}_Q$ 是一定的，对所有过程适用。能标公式既能显著提高极点项贡献，又能显著改善算符乘积展开收敛性，并首次使隐粲五夸克态的极点贡献达到 $(40-60)\%$.

The vacuum condensates are taken to be the standard values $\langle\bar{q}q\rangle = -(0.24 \pm 0.01\,\text{GeV})^3$, $\langle\bar{s}s\rangle = (0.8 \pm 0.1)\langle\bar{q}q\rangle$, $\langle\bar{q}g_s\sigma Gq\rangle = m_0^2\langle\bar{q}q\rangle$, $\langle\bar{s}g_s\sigma Gs\rangle = m_0^2\langle\bar{s}s\rangle$, $m_0^2 = (0.8 \pm 0.1)\,\text{GeV}^2$, $\langle\frac{\alpha_s GG}{\pi}\rangle = (0.33\,\text{GeV})^4$ at the energy scale $\mu = 1\,\text{GeV}$.

并考虑随能标的演化：

$$
\begin{aligned}
\langle\bar{q}q\rangle(\mu) &= \langle\bar{q}q\rangle(1\text{GeV})\left[\frac{\alpha_s(1\text{GeV})}{\alpha_s(\mu)}\right]^{\frac{12}{33-2n_f}}, \\
\langle\bar{s}s\rangle(\mu) &= \langle\bar{s}s\rangle(1\text{GeV})\left[\frac{\alpha_s(1\text{GeV})}{\alpha_s(\mu)}\right]^{\frac{12}{33-2n_f}}, \\
\langle\bar{q}g_s\sigma Gq\rangle(\mu) &= \langle\bar{q}g_s\sigma Gq\rangle(1\text{GeV})\left[\frac{\alpha_s(1\text{GeV})}{\alpha_s(\mu)}\right]^{\frac{2}{33-2n_f}}, \\
\langle\bar{s}g_s\sigma Gs\rangle(\mu) &= \langle\bar{s}g_s\sigma Gs\rangle(1\text{GeV})\left[\frac{\alpha_s(1\text{GeV})}{\alpha_s(\mu)}\right]^{\frac{2}{33-2n_f}}, \qquad (15)
\end{aligned}
$$

We take the $\overline{MS}$ masses $\underbrace{m_c(m_c) = (1.275 \pm 0.025)\,\mathrm{GeV}}$, $\underbrace{m_b(m_b) = (4.18 \pm 0.03)\,\mathrm{GeV}}$ and $\underbrace{m_s(\mu = 2\,\mathrm{GeV}) = (0.095 \pm 0.005)\,\mathrm{GeV}}$ from the Particle Data Group, and take into account the energy-scale dependence of the $\overline{MS}$ masses from the renormalization group equation,

$$
\begin{aligned}
m_Q(\mu) &= m_Q(m_Q)\left[\frac{\alpha_s(\mu)}{\alpha_s(m_Q)}\right]^{\frac{12}{33-2n_f}}, \\
m_s(\mu) &= m_s(2\mathrm{GeV})\left[\frac{\alpha_s(\mu)}{\alpha_s(2\mathrm{GeV})}\right]^{\frac{12}{33-2n_f}}, \\
\alpha_s(\mu) &= \frac{1}{b_0 t}\left[1 - \frac{b_1}{b_0^2}\frac{\log t}{t} + \frac{b_1^2(\log^2 t - \log t - 1) + b_0 b_2}{b_0^4 t^2}\right]. \quad (16)
\end{aligned}
$$

4 QCD求和规则对双夸克-双夸克-反夸克型五夸克态质量谱的计算

首先给出夸克结构、J^P、布莱尔参数、QCD谱密度能标(满足能标公式)、阈值参数、极点贡献、最高维凝聚贡献

其次给出质量的理论值以及对现有P粒子的可能确认。还有实验检验。

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$[qq'][q''c]\bar{c}\,(S_L,\,S_H,\,J_{LH},\,J)$	J^P	Currents
$[ud][uc]\bar{c}\,(0,\,0,\,0,\,\frac{1}{2})$	$\frac{1}{2}^-$	$J^1(x)$
$[ud][uc]\bar{c}\,(0,\,1,\,1,\,\frac{1}{2})$	$\frac{1}{2}^-$	$J^2(x)$
$[uu][dc]\bar{c}+2[ud][uc]\bar{c}\,(1,\,0,\,1,\,\frac{1}{2})$	$\frac{1}{2}^-$	$J^3(x)$
$[uu][dc]\bar{c}+2[ud][uc]\bar{c}\,(1,\,1,\,0,\,\frac{1}{2})$	$\frac{1}{2}^-$	$J^4(x)$
$[ud][uc]\bar{c}\,(0,\,1,\,1,\,\frac{3}{2})$	$\frac{3}{2}^-$	$J^1_\mu(x)$
$[uu][dc]\bar{c}+2[ud][uc]\bar{c}\,(1,\,0,\,1,\,\frac{3}{2})$	$\frac{3}{2}^-$	$J^2_\mu(x)$
$[uu][dc]\bar{c}+2[ud][uc]\bar{c}\,(1,\,1,\,2,\,\frac{3}{2})$	$\frac{3}{2}^-$	$J^3_\mu(x)$
$[uu][dc]\bar{c}+2[ud][uc]\bar{c}\,(1,\,1,\,2,\,\frac{3}{2})$	$\frac{3}{2}^-$	$J^4_\mu(x)$
$[uu][dc]\bar{c}+2[ud][uc]\bar{c}\,(1,\,1,\,2,\,\frac{5}{2})$	$\frac{5}{2}^-$	$J^1_{\mu\nu}(x)$
$[ud][uc]\bar{c}\,(0,\,1,\,1,\,\frac{5}{2})$	$\frac{5}{2}^-$	$J^2_{\mu\nu}(x)$

The S_L and S_H denote the spins of the light and heavy diquarks respectively, $\vec{J}_{LH}=\vec{S}_L+\vec{S}_H$, $\vec{J}=\vec{J}_{LH}+\vec{J}_{\bar{c}}$, the $\vec{J}_{\bar{c}}$ is the angular momentum of the $\bar{c}$-quark.

$$
\begin{aligned}
J^1(x) &= \varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}u_j^T(x)C\gamma_5 d_k(x)\,u_m^T(x)C\gamma_5 c_n(x)\,C\bar{c}_a^T(x)\,,\\
J^2(x) &= \varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}u_j^T(x)C\gamma_5 d_k(x)\,u_m^T(x)C\gamma_\mu c_n(x)\,\gamma_5\gamma^\mu C\bar{c}_a^T(x)\,,\\
J^3(x) &= \frac{\varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}}{\sqrt{3}}\left[u_j^T(x)C\gamma_\mu u_k(x)d_m^T(x)C\gamma_5 c_n(x) + 2u_j^T(x)C\gamma_\mu d_k(x)u_m^T(x)C\gamma_5 c_n(x)\right]\gamma_5\gamma^\mu C\\
J^4(x) &= \frac{\varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}}{\sqrt{3}}\left[u_j^T(x)C\gamma_\mu u_k(x)d_m^T(x)C\gamma^\mu c_n(x) + 2u_j^T(x)C\gamma_\mu d_k(x)u_m^T(x)C\gamma^\mu c_n(x)\right]C\bar{c}_a^T(
\end{aligned}
$$

$$
\begin{aligned}
J_\mu^1(x) &= \varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}u_j^T(x)C\gamma_5 d_k(x)\,u_m^T(x)C\gamma_\mu c_n(x)\,C\bar{c}_a^T(x)\,,\\
J_\mu^2(x) &= \frac{\varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}}{\sqrt{3}}\left[u_j^T(x)C\gamma_\mu u_k(x)d_m^T(x)C\gamma_5 c_n(x) + 2u_j^T(x)C\gamma_\mu d_k(x)u_m^T(x)C\gamma_5 c_n(x)\right]C\bar{c}_a^T(x\\
J_\mu^3(x) &= \frac{\varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}}{\sqrt{3}}\left[u_j^T(x)C\gamma_\mu u_k(x)d_m^T(x)C\gamma_\alpha c_n(x) + 2u_j^T(x)C\gamma_\mu d_k(x)u_m^T(x)C\gamma_\alpha c_n(x)\right]\gamma_5\gamma^\alpha C\\
J_\mu^4(x) &= \frac{\varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}}{\sqrt{3}}\left[u_j^T(x)C\gamma_\alpha u_k(x)d_m^T(x)C\gamma_\mu c_n(x) + 2u_j^T(x)C\gamma_\alpha d_k(x)u_m^T(x)C\gamma_\mu c_n(x)\right]\gamma_5\gamma^\alpha C
\end{aligned}
$$

$$
\begin{aligned}
J_{\mu\nu}^1(x) &= \frac{\varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}}{\sqrt{6}}\left[u_j^T(x)C\gamma_\mu u_k(x)d_m^T(x)C\gamma_\nu c_n(x) + 2u_j^T(x)C\gamma_\mu d_k(x)u_m^T(x)C\gamma_\nu c_n(x)\right]\\
&\quad C\bar{c}_a^T(x) + (\mu\leftrightarrow\nu)\,,\\
J_{\mu\nu}^2(x) &= \frac{1}{\sqrt{2}}\varepsilon^{ila}\varepsilon^{ijk}\varepsilon^{lmn}u_j^T(x)C\gamma_5 d_k(x)\left[u_m^T(x)C\gamma_\mu c_n(x)\,\gamma_5\gamma_\nu C\bar{c}_a^T(x)\right.\\
&\quad \left.+u_m^T(x)C\gamma_\nu c_n(x)\,\gamma_5\gamma_\mu C\bar{c}_a^T(x)\right]\,, \qquad (17)
\end{aligned}
$$

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	T^2GeV^2)	$\sqrt{s_0}$(GeV)	μ(GeV)	pole	D_{13}
$J^1(x)$	$3.1-3.5$	4.96 ± 0.10	2.3	$(41-62)\%$	$<1\%$
$J^2(x)$	$3.2-3.6$	5.10 ± 0.10	2.6	$(42-63)\%$	$<1\%$
$J^3(x)$	$3.2-3.6$	5.11 ± 0.10	2.6	$(42-63)\%$	$\ll 1\%$
$J^4(x)$	$2.9-3.3$	5.00 ± 0.10	2.4	$(40-64)\%$	$\leq 1\%$
$J^1_\mu(x)$	$3.1-3.5$	5.03 ± 0.10	2.4	$(42-63)\%$	$\leq 1\%$
$J^2_\mu(x)$	$3.3-3.7$	5.11 ± 0.10	2.6	$(40-61)\%$	$\ll 1\%$
$J^3_\mu(x)$	$3.4-3.8$	5.26 ± 0.10	2.8	$(42-62)\%$	$\ll 1\%$
$J^4_\mu(x)$	$3.3-3.7$	5.17 ± 0.10	2.7	$(41-61)\%$	$<1\%$
$J^1_{\mu\nu}(x)$	$3.2-3.6$	5.03 ± 0.10	2.4	$(40-61)\%$	$\leq 1\%$
$J^2_{\mu\nu}(x)$	$3.1-3.5$	5.03 ± 0.10	2.4	$(42-63)\%$	$\leq 1\%$

成功实现极点项贡献$(40-60)\%$。

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$[qq'][q''c]\bar{c}\,(S_L, S_H, J_{LH}, J)$	$M(\text{GeV})$	$\lambda(10^{-3}\text{GeV}^6)$	Assignments	Currents
$[ud][uc]\bar{c}\,(0, 0, 0, \frac{1}{2})$	4.31 ± 0.11	1.40 ± 0.23	$?\,P_c(4312)$	$J^1(x)$
$[ud][uc]\bar{c}\,(0, 1, 1, \frac{1}{2})$	4.45 ± 0.11	3.02 ± 0.48	$?\,P_c(4440/4457)$	$J^2(x)$
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 0, 1, \frac{1}{2})$	4.46 ± 0.11	4.32 ± 0.71	$?\,P_c(4440/4457)$	$J^3(x)$
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 1, 0, \frac{1}{2})$	4.34 ± 0.14	3.23 ± 0.61	$?\,P_c(4312/\mathbf{4337})$	$J^4(x)$
$[ud][uc]\bar{c}\,(0, 1, 1, \frac{3}{2})$	4.39 ± 0.11	1.44 ± 0.23	$?\,P_c(4440)$	$J^1_\mu(x)$
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 0, 1, \frac{3}{2})$	4.47 ± 0.11	2.41 ± 0.38	$?\,P_c(4440/4457)$	$J^2_\mu(x)$
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 1, 2, \frac{3}{2})$	4.61 ± 0.11	5.13 ± 0.79		$J^3_\mu(x)$
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 1, 2, \frac{3}{2})$	4.52 ± 0.11	4.49 ± 0.72		$J^4_\mu(x)$
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 1, 2, \frac{5}{2})$	4.39 ± 0.11	1.94 ± 0.31	$?\,P_c(4440)$	$J^1_{\mu\nu}(x)$
$[ud][uc]\bar{c}\,(0, 1, 1, \frac{5}{2})$	4.39 ± 0.11	1.44 ± 0.23	$?\,P_c(4440)$	$J^2_{\mu\nu}(x)$

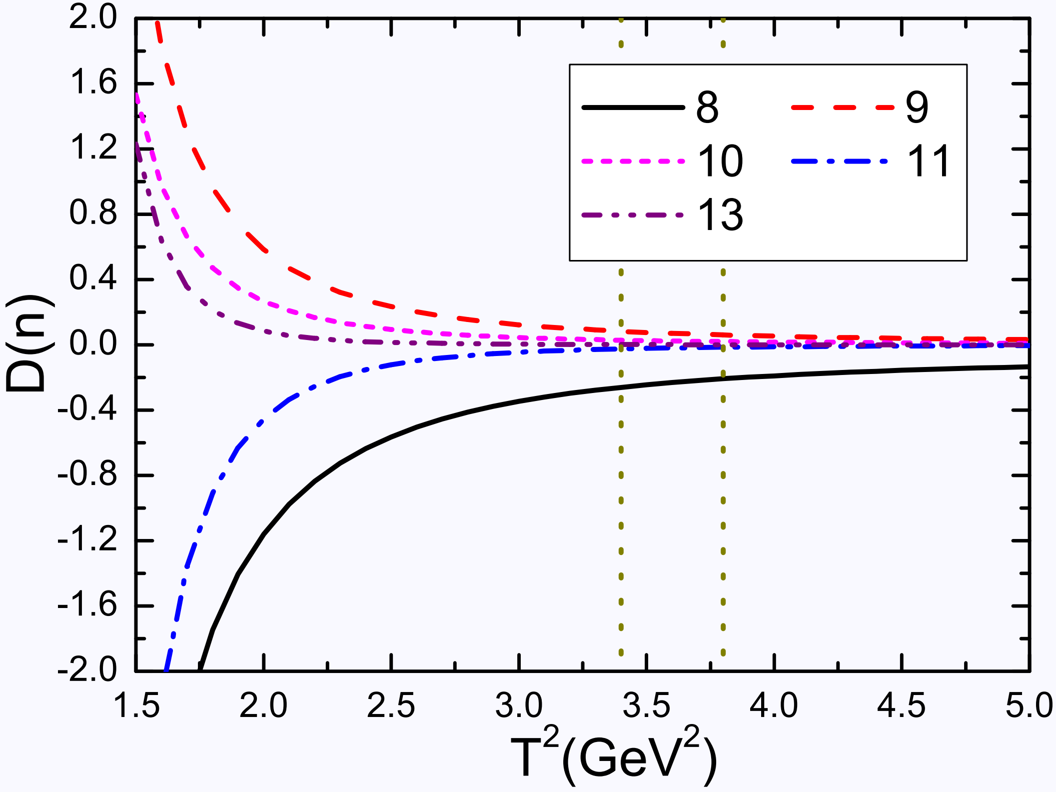
We predict a pentaquark state with the mass $4.34 \pm 0.14\,\text{GeV}$ and $J^P = \frac{1}{2}^-$ before the LHCb's observation of the $P_c(4337)$.

- Int. J. Mod. Phys. A36 (2021) 2150071, based on the $SU(3)$ symmetry.

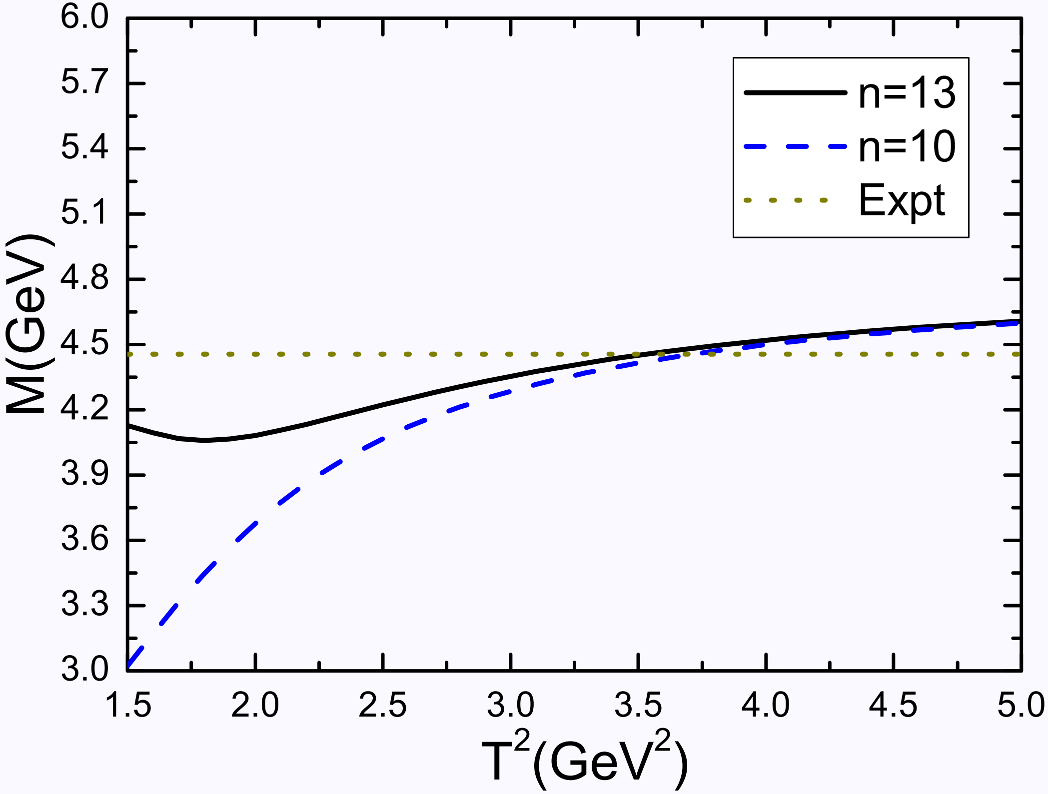
$[qq'][q''c]\bar{c}\,(S_L, S_H, J_{LH}, J)$	New analysis	u or $d \to s$	Assignments
$[ud][uc]\bar{c}\,(0, 0, 0, \frac{1}{2})$	4.31 ± 0.11	4.46 ± 0.11	? $P_{cs}(4459)$
$[ud][uc]\bar{c}\,(0, 1, 1, \frac{1}{2})$	4.45 ± 0.11	4.60 ± 0.11	
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 0, 1, \frac{1}{2})$	4.46 ± 0.11	4.61 ± 0.11	
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 1, 0, \frac{1}{2})$	4.34 ± 0.14	4.49 ± 0.14	
$[ud][uc]\bar{c}\,(0, 1, 1, \frac{3}{2})$	4.39 ± 0.11	4.54 ± 0.11	
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 0, 1, \frac{3}{2})$	4.47 ± 0.11	4.62 ± 0.11	
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 1, 2, \frac{3}{2})$	4.61 ± 0.11	4.76 ± 0.11	
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 1, 2, \frac{3}{2})$	4.52 ± 0.11	4.67 ± 0.11	
$[uu][dc]\bar{c} + 2[ud][uc]\bar{c}\,(1, 1, 2, \frac{5}{2})$	4.39 ± 0.11	4.54 ± 0.11	
$[ud][uc]\bar{c}\,(0, 1, 1, \frac{5}{2})$	4.39 ± 0.11	4.54 ± 0.11	

There is no room for the $P_{cs}(4338)$. For more literatures, see: arXiv:2502.11351。

Higher dimensional vacuum condensates for the $P_{cs}(4459)$。



Mass with variation of the Borel parameter T^2 for the $P_{cs}(4459)$。



5 QCD求和规则对色单态-色单态型五夸克态质量谱的计算

利用QCD求和规则做计算，用的是定域流。对于色单态-色单态型的五夸克流，有两个色中性的集团，每个集团和一个介子或重子有相同的量子数，虽然这个集团，我们也用介子或重子描述，但并不是真正的物理介子与重子。我们说的分子态，确切地说，应该叫做色单态-色单态型五夸克态。

首次区分同位旋，用标准的介子流与Ioffe流，构造五夸克流

$$
\begin{aligned}
J^{\bar{D}\Sigma_c}_{\frac{1}{2}}(x) &= \frac{1}{\sqrt{3}} J^{\bar{D}^0}(x) J^{\Sigma_c^+}(x) - \sqrt{\frac{2}{3}} J^{\bar{D}^-}(x) J^{\Sigma_c^{++}}(x) \, , \\
J^{\bar{D}\Sigma_c}_{\frac{3}{2}}(x) &= \sqrt{\frac{2}{3}} J^{\bar{D}^0}(x) J^{\Sigma_c^+}(x) + \frac{1}{\sqrt{3}} J^{\bar{D}^-}(x) J^{\Sigma_c^{++}}(x) \, , \\
J^{\bar{D}\Sigma_c^*}_{\frac{1}{2};\mu}(x) &= \frac{1}{\sqrt{3}} J^{\bar{D}^0}(x) J_\mu^{\Sigma_c^{*+}}(x) - \sqrt{\frac{2}{3}} J^{\bar{D}^-}(x) J_\mu^{\Sigma_c^{*++}}(x) \, , \\
J^{\bar{D}\Sigma_c^*}_{\frac{3}{2};\mu}(x) &= \sqrt{\frac{2}{3}} J^{\bar{D}^0}(x) J_\mu^{\Sigma_c^{*+}}(x) + \frac{1}{\sqrt{3}} J^{\bar{D}^-}(x) J_\mu^{\Sigma_c^{*++}}(x) \, ,
\end{aligned} \tag{18}
$$

$$
\begin{aligned}
J^{\bar{D}^*\Sigma_c}_{\frac{1}{2};\mu}(x) &= \frac{1}{\sqrt{3}} J_\mu^{\bar{D}^{*0}}(x) J^{\Sigma_c^+}(x) - \sqrt{\frac{2}{3}} J_\mu^{\bar{D}^{*-}}(x) J^{\Sigma_c^{++}}(x) \, , \\
J^{\bar{D}^*\Sigma_c}_{\frac{3}{2};\mu}(x) &= = \sqrt{\frac{2}{3}} J_\mu^{\bar{D}^{*0}}(x) J^{\Sigma_c^+}(x) + \frac{1}{\sqrt{3}} J_\mu^{\bar{D}^{*-}}(x) J^{\Sigma_c^{++}}(x) \, , \\
J^{\bar{D}^*\Sigma_c^*}_{\frac{1}{2};\mu\nu}(x) &= \frac{1}{\sqrt{3}} J_\mu^{\bar{D}^{*0}}(x) J_\nu^{\Sigma_c^{*+}}(x) - \sqrt{\frac{2}{3}} J_\mu^{\bar{D}^{*-}}(x) J_\nu^{\Sigma_c^{*++}}(x) + (\mu \leftrightarrow \nu) \, , \\
J^{\bar{D}^*\Sigma_c^*}_{\frac{3}{2};\mu\nu}(x) &= \sqrt{\frac{2}{3}} J_\mu^{\bar{D}^{*0}}(x) J_\nu^{\Sigma_c^{*+}}(x) + \frac{1}{\sqrt{3}} J_\mu^{\bar{D}^{*-}}(x) J_\nu^{\Sigma_c^{*++}}(x) + (\mu \leftrightarrow \nu) \, ,
\end{aligned} \tag{19}
$$

$$
\begin{aligned}
J_0^{\bar{D}\Xi_c'}(x) &= \frac{1}{\sqrt{2}} J^{\bar{D}^0}(x) J^{\Xi_c'^0}(x) - \frac{1}{\sqrt{2}} J^{\bar{D}^-}(x) J^{\Xi_c'^+}(x)\,, \\
J_1^{\bar{D}\Xi_c'}(x) &= \frac{1}{\sqrt{2}} J^{\bar{D}^0}(x) J^{\Xi_c'^0}(x) + \frac{1}{\sqrt{2}} J^{\bar{D}^-}(x) J^{\Xi_c'^+}(x)\,, \\
J_{0;\mu}^{\bar{D}\Xi_c^*}(x) &= \frac{1}{\sqrt{2}} J^{\bar{D}^0}(x) J_\mu^{\Xi_c^{*0}}(x) - \frac{1}{\sqrt{2}} J^{\bar{D}^-}(x) J_\mu^{\Xi_c^{*+}}(x)\,, \\
J_{1;\mu}^{\bar{D}\Xi_c^*}(x) &= \frac{1}{\sqrt{2}} J^{\bar{D}^0}(x) J_\mu^{\Xi_c^{*0}}(x) + \frac{1}{\sqrt{2}} J^{\bar{D}^-}(x) J_\mu^{\Xi_c^{*+}}(x)\,,
\end{aligned} \tag{20}
$$

$$
\begin{aligned}
J_{0;\mu}^{\bar{D}^*\Xi_c'}(x) &= \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*0}}(x) J^{\Xi_c'^0}(x) - \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*-}}(x) J^{\Xi_c'^+}(x)\,, \\
J_{1;\mu}^{\bar{D}^*\Xi_c'}(x) &= \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*0}}(x) J^{\Xi_c'^0}(x) + \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*-}}(x) J^{\Xi_c'^+}(x)\,, \\
J_{0;\mu\nu}^{\bar{D}^*\Xi_c^*}(x) &= \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*0}}(x) J_\nu^{\Xi_c^{*0}}(x) - \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*-}}(x) J_\nu^{\Xi_c^{*+}}(x) + (\mu \leftrightarrow \nu)\,, \\
J_{1;\mu\nu}^{\bar{D}^*\Xi_c^*}(x) &= \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*0}}(x) J_\nu^{\Xi_c^{*0}}(x) + \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*-}}(x) J_\nu^{\Xi_c^{*+}}(x) + (\mu \leftrightarrow \nu)\,,
\end{aligned} \tag{21}
$$

$$
\begin{aligned}
J_0^{\bar{D}\Xi_c}(x) &= \frac{1}{\sqrt{2}} J^{\bar{D}^0}(x) J^{\Xi_c^0}(x) - \frac{1}{\sqrt{2}} J^{\bar{D}^-}(x) J^{\Xi_c^+}(x)\,, \\
J_1^{\bar{D}\Xi_c}(x) &= \frac{1}{\sqrt{2}} J^{\bar{D}^0}(x) J^{\Xi_c^0}(x) + \frac{1}{\sqrt{2}} J^{\bar{D}^-}(x) J^{\Xi_c^+}(x)\,, \\
J_{\frac{1}{2}}^{\bar{D}\Lambda_c}(x) &= J^{\bar{D}^0}(x) J^{\Lambda_c^+}(x)\,, \\
J_{\frac{1}{2}}^{\bar{D}_s\Xi_c}(x) &= J^{\bar{D}_s^-}(x) J^{\Xi_c^+}(x)\,, \\
J_0^{\bar{D}_s\Lambda_c}(x) &= J^{\bar{D}_s^-}(x) J^{\Lambda_c^+}(x)\,,
\end{aligned} \tag{22}
$$

$$
\begin{aligned}
J_{0;\mu}^{\bar{D}^*\Xi_c}(x) &= \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*0}}(x) J^{\Xi_c^0}(x) - \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*-}}(x) J^{\Xi_c^+}(x)\,, \\
J_{1;\mu}^{\bar{D}^*\Xi_c}(x) &= \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*0}}(x) J^{\Xi_c^0}(x) + \frac{1}{\sqrt{2}} J_\mu^{\bar{D}^{*-}}(x) J_\mu^{\Xi_c^+}(x)\,, \\
J_{\frac{1}{2};\mu}^{\bar{D}^*\Lambda_c}(x) &= J_\mu^{\bar{D}^{*0}}(x) J^{\Lambda_c^+}(x)\,, \\
J_{\frac{1}{2};\mu}^{\bar{D}_s^*\Xi_c}(x) &= J_\mu^{\bar{D}_s^{*-}}(x) J^{\Xi_c^+}(x)\,, \\
J_{0;\mu}^{\bar{D}_s^*\Lambda_c}(x) &= J_\mu^{\bar{D}_s^{*-}}(x) J^{\Lambda_c^+}(x)\,,
\end{aligned} \tag{23}
$$

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	IJ^P	$T^2(\mathrm{GeV}^2)$	$\sqrt{s_0}(\mathrm{GeV})$	$\mu(\mathrm{GeV})$	PC
$\bar{D}\Sigma_c$	$\frac{1}{2}\frac{1}{2}^-$	$3.2-3.8$	5.00 ± 0.10	2.2	$(42-60)\%$
$\bar{D}\Sigma_c$	$\frac{3}{2}\frac{1}{2}^-$	$2.8-3.4$	4.98 ± 0.10	2.2	$(44-65)\%$
$\bar{D}\Sigma_c^*$	$\frac{1}{2}\frac{3}{2}^-$	$3.3-3.9$	5.06 ± 0.10	2.3	$(42-60)\%$
$\bar{D}\Sigma_c^*$	$\frac{3}{2}\frac{3}{2}^-$	$2.9-3.5$	5.03 ± 0.10	2.4	$(44-64)\%$
$\bar{D}^*\Sigma_c$	$\frac{1}{2}\frac{3}{2}^-$	$3.3-3.9$	5.12 ± 0.10	2.5	$(42-60)\%$
$\bar{D}^*\Sigma_c$	$\frac{3}{2}\frac{3}{2}^-$	$3.0-3.6$	5.10 ± 0.10	2.5	$(41-61)\%$
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}\frac{5}{2}^-$	$3.2-3.8$	5.08 ± 0.10	2.5	$(43-60)\%$
$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}\frac{5}{2}^-$	$3.0-3.6$	5.24 ± 0.10	2.8	$(42-61)\%$
$\bar{D}\Xi_c'$	$0\frac{1}{2}^-$	$3.4-4.0$	5.12 ± 0.10	2.2	$(41-58)\%$
$\bar{D}\Xi_c'$	$1\frac{1}{2}^-$	$3.2-3.8$	5.14 ± 0.10	2.3	$(43-61)\%$
$\bar{D}\Xi_c^*$	$0\frac{3}{2}^-$	$3.4-4.0$	5.15 ± 0.10	2.3	$(43-60)\%$
$\bar{D}\Xi_c^*$	$1\frac{3}{2}^-$	$3.3-3.9$	5.22 ± 0.10	2.4	$(44-62)\%$

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	IJ^P	$T^2(\mathrm{GeV}^2)$	$\sqrt{s_0}(\mathrm{GeV})$	$\mu(\mathrm{GeV})$	PC
$\bar{D}^*\Xi'_c$	$0\frac{3}{2}^-$	$3.5-4.1$	5.26 ± 0.10	2.5	$(42-59)\%$
$\bar{D}^*\Xi'_c$	$1\frac{3}{2}^-$	$3.4-4.0$	5.31 ± 0.10	2.6	$(43-60)\%$
$\bar{D}^*\Xi^*_c$	$0\frac{5}{2}^-$	$3.6-4.2$	5.31 ± 0.10	2.6	$(42-58)\%$
$\bar{D}^*\Xi^*_c$	$1\frac{5}{2}^-$	$3.4-4.0$	5.35 ± 0.10	2.6	$(44-61)\%$
$\bar{D}\,\Xi_c$	$0\frac{1}{2}^-$	$3.2-3.8$	5.00 ± 0.10	2.1	$(41-60)\%$
$\bar{D}\,\Xi_c$	$1\frac{1}{2}^-$	$3.1-3.7$	5.09 ± 0.10	2.3	$(42-61)\%$
$\bar{D}\,\Lambda_c$	$\frac{1}{2}\frac{1}{2}^-$	$3.2-3.8$	5.11 ± 0.10	2.5	$(42-60)\%$
$\bar{D}_s\,\Xi_c$	$\frac{1}{2}\frac{1}{2}^-$	$3.2-3.8$	5.15 ± 0.10	2.2	$(41-59)\%$
$\bar{D}_s\,\Lambda_c$	$0\frac{1}{2}^-$	$3.2-3.8$	5.13 ± 0.10	2.3	$(43-61)\%$
$\bar{D}^*\,\Xi_c$	$0\frac{3}{2}^-$	$3.2-3.8$	5.10 ± 0.10	2.3	$(43-61)\%$
$\bar{D}^*\,\Xi_c$	$1\frac{3}{2}^-$	$3.3-3.9$	5.27 ± 0.10	2.6	$(43-61)\%$
$\bar{D}^*\,\Lambda_c$	$\frac{1}{2}\frac{3}{2}^-$	$3.3-3.9$	5.23 ± 0.10	2.7	$(41-61)\%$
$\bar{D}^*_s\,\Xi_c$	$\frac{1}{2}\frac{3}{2}^-$	$3.3-3.9$	5.28 ± 0.10	2.4	$(42-59)\%$
$\bar{D}^*_s\,\Lambda_c$	$0\frac{3}{2}^-$	$3.2-3.8$	5.14 ± 0.10	2.4	$(42-60)\%$

成功实现极点项贡献$(40-60)\%$

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	IJ^P	$M(\mathrm{GeV})$	$\lambda(10^{-3}\mathrm{GeV}^6)$	Assignments	Thresholds (MeV)
$\bar{D}\Sigma_c$	$\frac{1}{2}\frac{1}{2}^-$	$4.31^{+0.07}_{-0.07}$	$3.25^{+0.43}_{-0.41}$	$P_c(4312)$	4321
$\bar{D}\Sigma_c$	$\frac{3}{2}\frac{1}{2}^-$	$4.33^{+0.09}_{-0.08}$	$1.97^{+0.28}_{-0.26}$		4321
$\bar{D}\Sigma_c^*$	$\frac{1}{2}\frac{3}{2}^-$	$4.38^{+0.07}_{-0.07}$	$1.97^{+0.26}_{-0.24}$	$P_c(4380)$	4385
$\bar{D}\Sigma_c^*$	$\frac{3}{2}\frac{3}{2}^-$	$4.41^{+0.08}_{-0.08}$	$1.24^{+0.17}_{-0.16}$		4385
$\bar{D}^*\Sigma_c$	$\frac{1}{2}\frac{3}{2}^-$	$4.44^{+0.07}_{-0.08}$	$3.60^{+0.47}_{-0.44}$	$P_c(4440)$	4462
$\bar{D}^*\Sigma_c$	$\frac{3}{2}\frac{3}{2}^-$	$4.47^{+0.09}_{-0.09}$	$2.31^{+0.33}_{-0.31}$		4462
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}\frac{5}{2}^-$	$4.46^{+0.08}_{-0.08}$	$4.05^{+0.54}_{-0.50}$	$P_c(4457)$	4527
$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}\frac{5}{2}^-$	$4.62^{+0.09}_{-0.09}$	$2.40^{+0.37}_{-0.35}$		4527
$\bar{D}\Xi_c'$	$0\frac{1}{2}^-$	$4.43^{+0.07}_{-0.07}$	$3.02^{+0.39}_{-0.37}$		4446
$\bar{D}\Xi_c'$	$1\frac{1}{2}^-$	$4.45^{+0.07}_{-0.08}$	$2.50^{+0.33}_{-0.31}$		4446
$\bar{D}\Xi_c^*$	$0\frac{3}{2}^-$	$4.46^{+0.07}_{-0.07}$	$1.71^{+0.22}_{-0.21}$	$P_{cs}(4459)$	4513
$\bar{D}\Xi_c^*$	$1\frac{3}{2}^-$	$4.53^{+0.07}_{-0.07}$	$1.56^{+0.20}_{-0.19}$		4513

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	IJ^P	M(GeV)	$\lambda(10^{-3}\text{GeV}^6)$	Assignments	Thresholds (MeV)
$\bar{D}^*\Xi_c'$	$0\frac{3}{2}^-$	$4.57^{+0.07}_{-0.07}$	$3.41^{+0.43}_{-0.41}$		4588
$\bar{D}^*\Xi_c'$	$1\frac{3}{2}^-$	$4.62^{+0.08}_{-0.08}$	$3.05^{+0.39}_{-0.37}$		4588
$\bar{D}^*\Xi_c^*$	$0\frac{5}{2}^-$	$4.64^{+0.07}_{-0.07}$	$4.36^{+0.54}_{-0.51}$		4655
$\bar{D}^*\Xi_c^*$	$1\frac{5}{2}^-$	$4.67^{+0.08}_{-0.08}$	$3.25^{+0.41}_{-0.39}$		4655
$\bar{D}\,\Xi_c$	$0\frac{1}{2}^-$	$4.34^{+0.07}_{-0.07}$	$1.43^{+0.19}_{-0.18}$	? $P_{cs}(4338)$	4337
$\bar{D}\,\Xi_c$	$1\frac{1}{2}^-$	$4.46^{+0.07}_{-0.07}$	$1.37^{+0.19}_{-0.18}$		4337
$\bar{D}\,\Lambda_c$	$\frac{1}{2}\frac{1}{2}^-$	$4.46^{+0.07}_{-0.08}$	$1.47^{+0.20}_{-0.18}$		4151
$\bar{D}_s\,\Xi_c$	$\frac{1}{2}\frac{1}{2}^-$	$4.54^{+0.07}_{-0.07}$	$1.58^{+0.21}_{-0.20}$		4437
$\bar{D}_s\,\Lambda_c$	$0\frac{1}{2}^-$	$4.48^{+0.07}_{-0.07}$	$1.57^{+0.21}_{-0.20}$		4255
$\bar{D}^*\,\Xi_c$	$0\frac{3}{2}^-$	$4.46^{+0.07}_{-0.07}$	$1.55^{+0.20}_{-0.19}$	? $P_{cs}(4459)$	4479
$\bar{D}^*\,\Xi_c$	$1\frac{3}{2}^-$	$4.63^{+0.08}_{-0.08}$	$1.69^{+0.22}_{-0.21}$		4479
$\bar{D}^*\,\Lambda_c$	$\frac{1}{2}\frac{3}{2}^-$	$4.59^{+0.08}_{-0.08}$	$1.67^{+0.22}_{-0.21}$		4293
$\bar{D}_s^*\,\Xi_c$	$\frac{1}{2}\frac{3}{2}^-$	$4.65^{+0.08}_{-0.08}$	$1.66^{+0.22}_{-0.21}$		4580
$\bar{D}_s^*\,\Lambda_c$	$0\frac{3}{2}^-$	$4.50^{+0.07}_{-0.07}$	$1.52^{+0.21}_{-0.19}$		4398

There is no room for the $P_c(4337)$.

6 总结

- 我们采用能标公式提高基态贡献，成功实现了极点为主与算符乘积展开收敛；这两个条件很难同时满足。
- 五夸克态不能容纳$P_{cs}(4338)$。
- 五夸克分子态不能容纳$P_c(4337)$。
- 理论与实验都有待提高，目前难以有确切结论。

谢谢大家，欢迎批评指正！