Hidden-charm pentaquark states in a molecular picture

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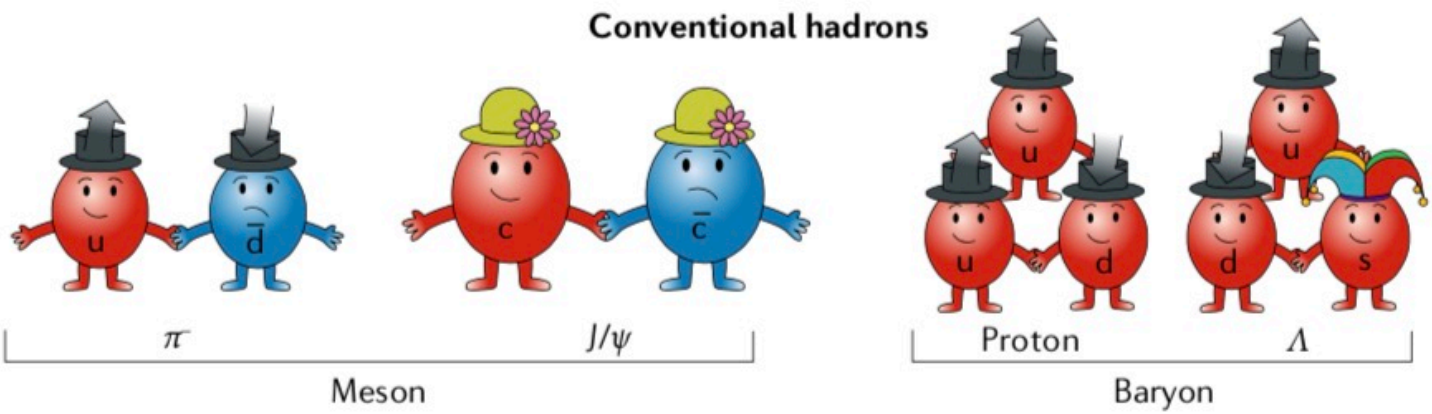
Outline

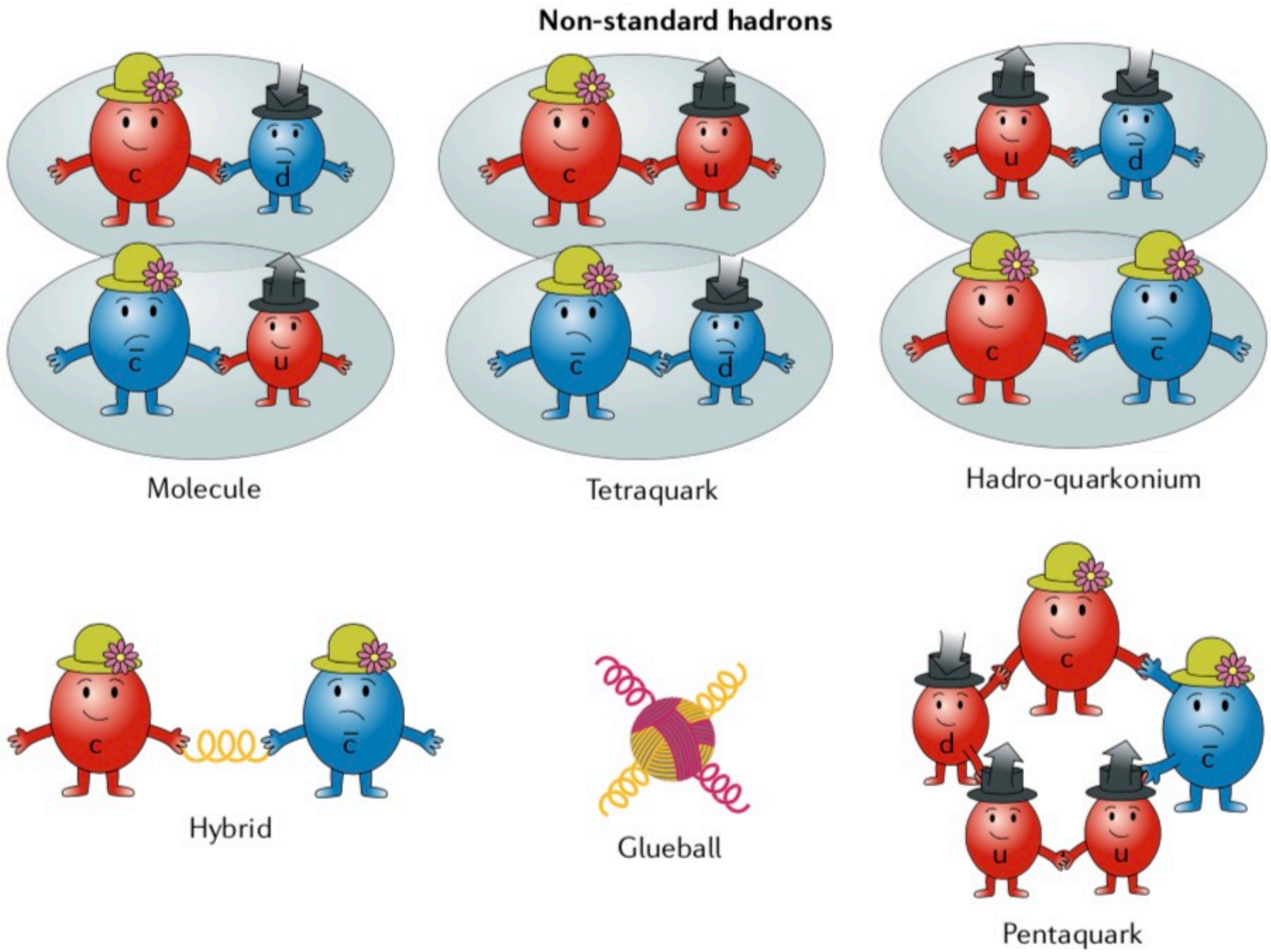
- Exotic hadrons and new pentaquark states
- Method of the QCD sum rules
- Reproduce the masses of several Pc states and predict their spin-parity quantum numbers
- Challenges for hidden-charm pentaquark states
- Summary

Quark model and exotic hadrons



- **Quark model** is established to classify hadrons: mesons ($q\bar{q}$) and baryons (qqq).
- Hadrons with exotic quantum numbers are exotic hadron states.
- **QCD** may allow for hadrons which lie outside the naive quark model. Hadron structures are more complicated in **QCD**: $N_{\text{quarks}} \neq 2, 3$.
- $SU(3)_c$ **gauge symmetry**: $(N_q - N_{\bar{q}})$ is divisible by 3, plus any number N_g of valence gluons can form a color singlet.

Exotic hadron configurations

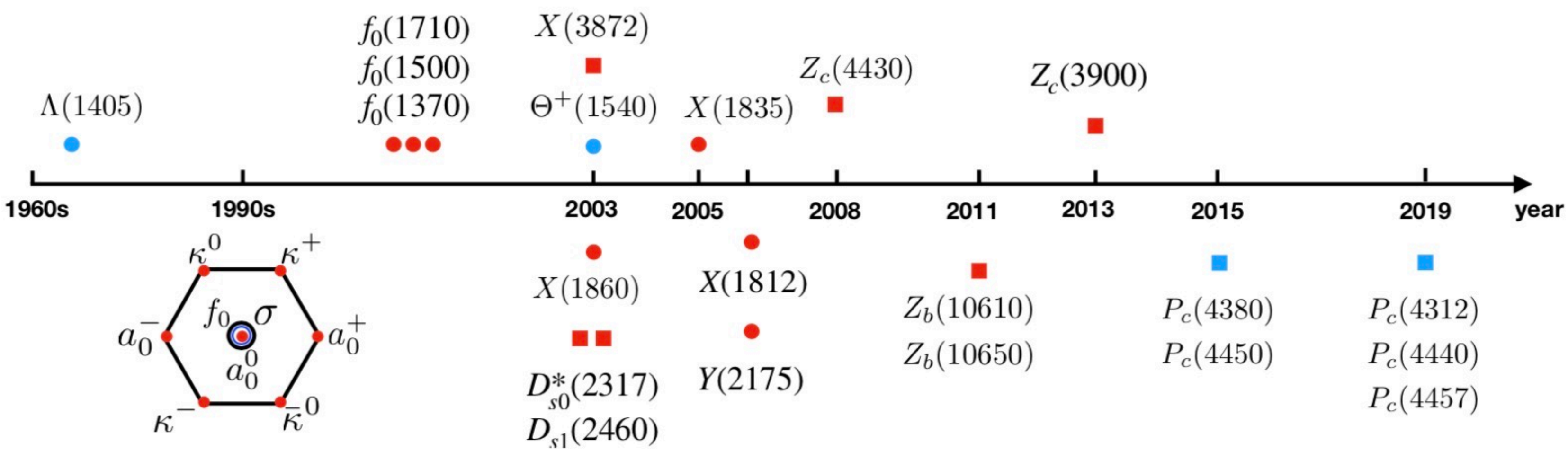


Light hadron sector:

- **Dibaryon**: Deuteron, H states, $d^*(2380)$.
- **Hybrid** candidates: $\pi_1(1400)$, $\pi_1(1600)$ and $\pi_1(2015)$ (dispute).
- **Glueball** candidates: $a_0(980)$ and $f_0(980)$.
- **Tetraquark** candidates: light scalar mesons.
- **Pentaquark**: $\Theta^+(1540)$ ($S = 1$, long story of appeared and disappeared)

Heavy hadron sector: **breakthough in multiquarks!**

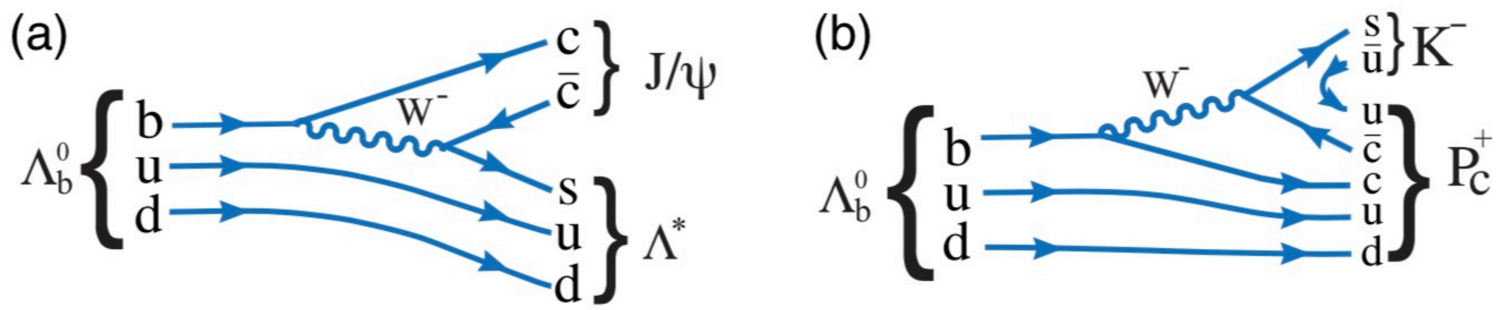
- $P_c(4380)$, $P_c(4312)$, $P_c(4440)$, $P_c(4457)$: hidden-charm pentaquark states.
- Plenty of **XYZ states**: candidates of molecules, tetraquarks, hybrids...

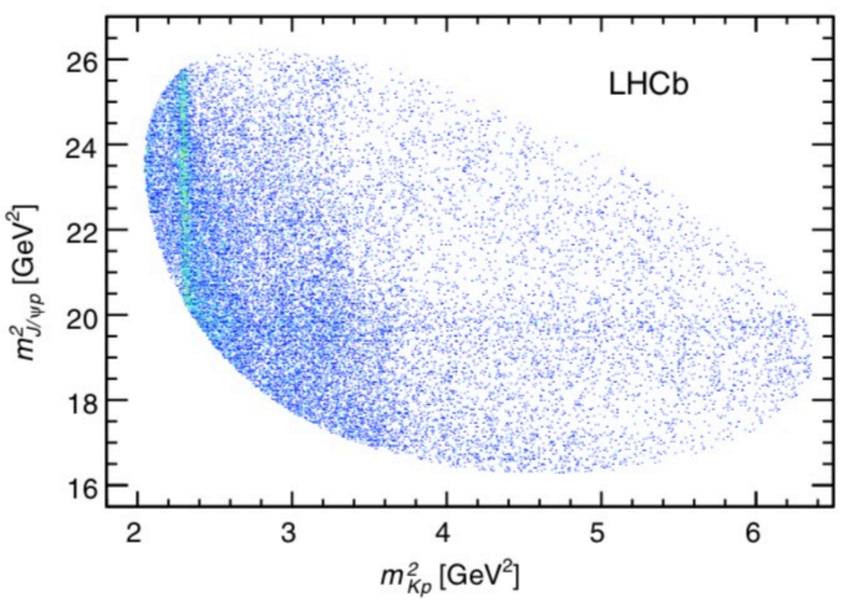


Y.R.Liu, H.X.Chen, W. Chen, X.Liu, S.L.Zhu, PPNP 107 (2019) 237-320

LHCb's observation in 2015

Two hidden-charm Pc states were observed in $\Lambda_b^0 \to J/\psi K^- p$ process

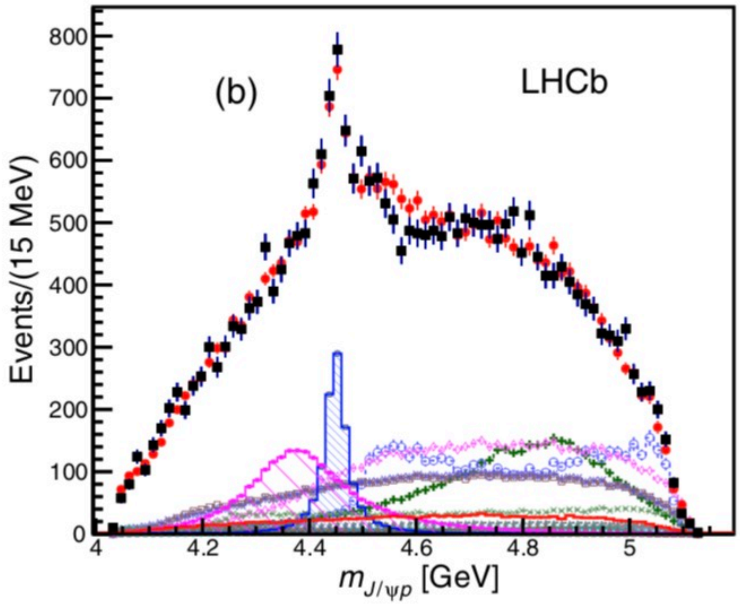




Vertical band for Lambda(1520)

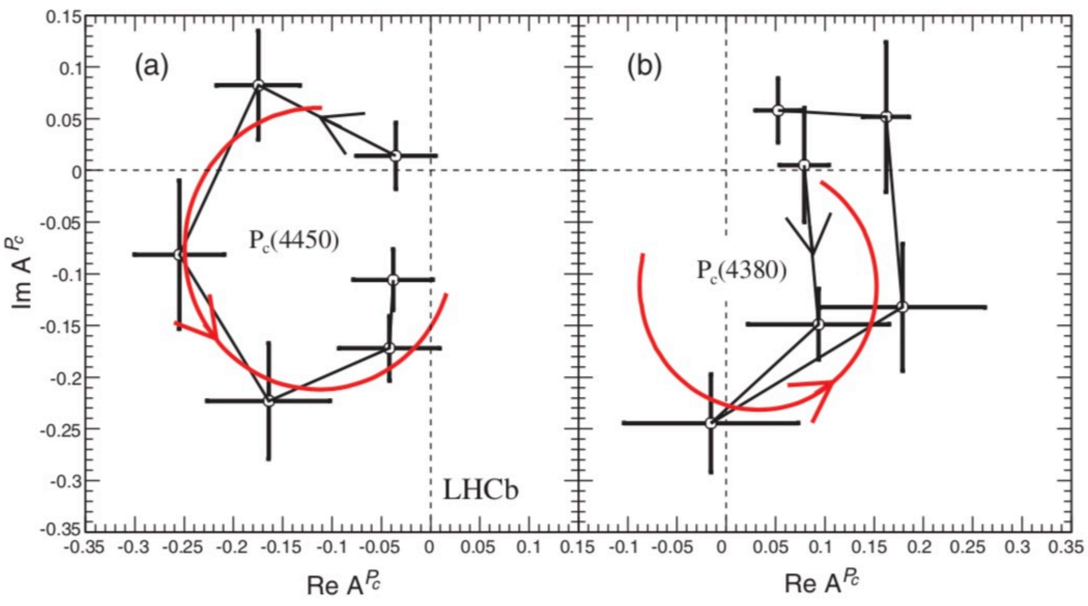
Horizontal band for Pc structures

PRL 115 (2015) 072001.



$P_c(4380)$ and $P_c(4450)$ in $J/\psi p$ structure (PRL115, 072001(2015))

$$M_1 = (4380 \pm 8 \pm 29)\,\mathrm{MeV}\,,$$
$$\Gamma_1 = (205 \pm 18 \pm 86)\,\mathrm{MeV}\,,$$
$$M_2 = (4449.8 \pm 1.7 \pm 2.5)\,\mathrm{MeV}\,,$$
$$\Gamma_2 = (39 \pm 5 \pm 19)\,\mathrm{MeV}\,.$$



Prefer quantum numbers:

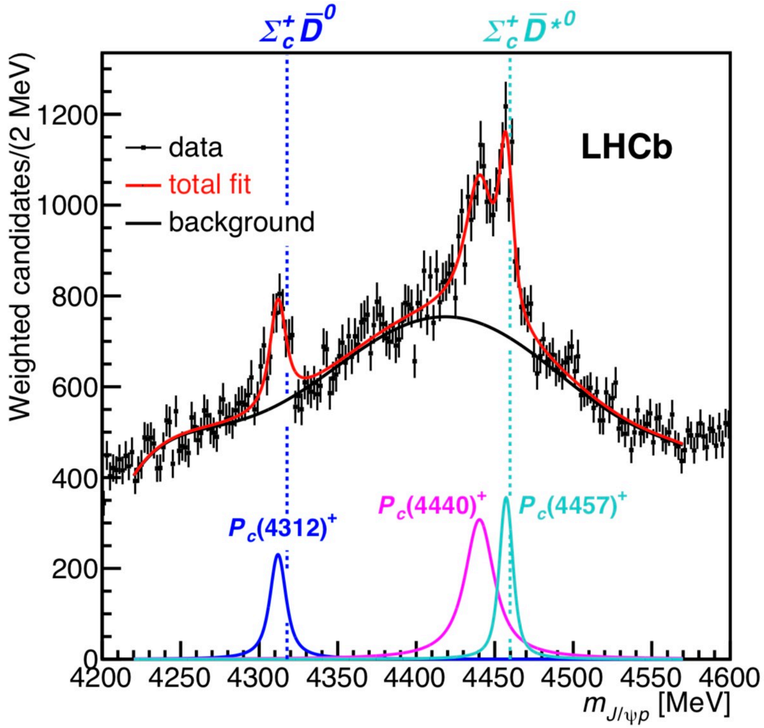
their parities are opposite

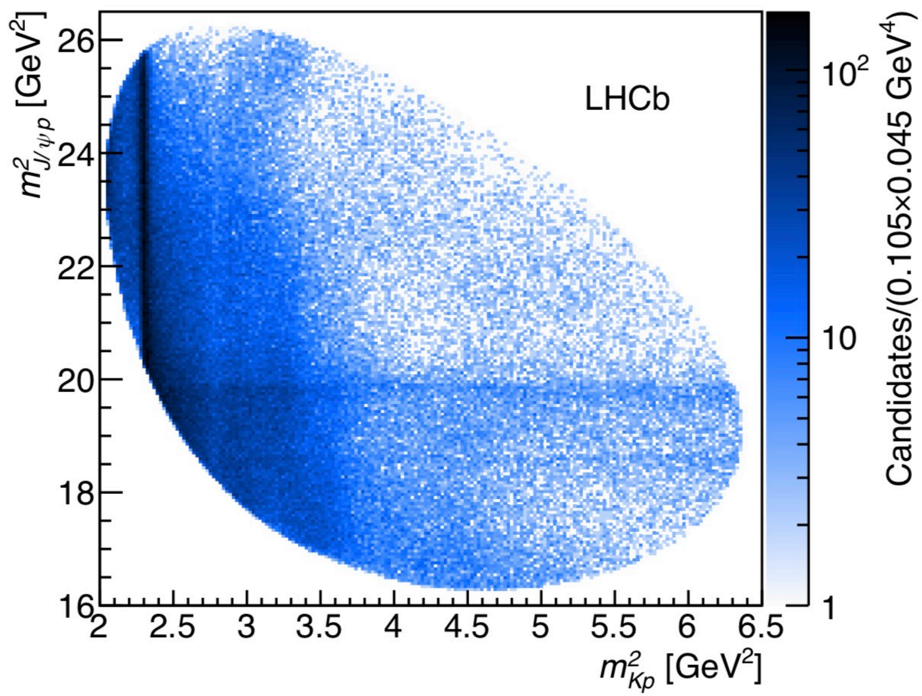
and spins are 3/2 for one

and 5/2 for another.

Combined Run 2 data in 2019:

PRL 122 (2019) 222001



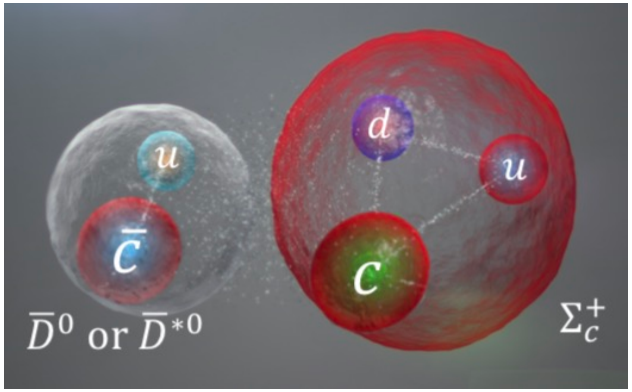


State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Theoretical predictions before 2015

There are many theoretical predictions for the existence of $\Sigma_c^+ \bar{D}^0$ $(\Sigma_c^+ \bar{D}^{*0})$ before 2015, some of the predictions are in good agreement with the LHCb's observations.

- Wu, Molina, Oset, Zou, PRL105, 232001 (2010);
- **Wang, Huang, Zhang, Zou, PRC84, 015203 (2011);**
- **Yang, Sun, He, Liu, Zhu, CPC36, 6 (2012);**
- **Wu, Lee, Zou, PRC85, 044002 (2012);**
- Karliner, Rosner, PRL115, 122001 (2015);
- Some others…

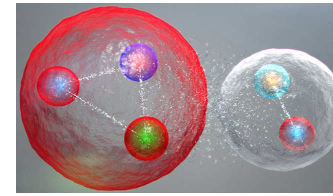


Theoretical progress on Pc states after 2015

B.S.Zou's slide

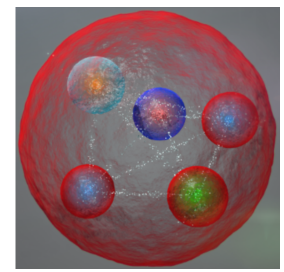
Thresholds $\bar{D}\Sigma_c^*$ **(4383MeV),** $\bar{D}^*\Sigma_c$ **(4460MeV),** $p\chi_{c1}$ **(4449MeV)**

1) $\bar{D}\Sigma_c^*$ **,** $\bar{D}^*\Sigma_c$ **,** $\bar{D}^*\Sigma_c^*$ **molecular states**



R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;H.X.Chen,W.Chen,X.Liu,S.L.Zhu,PRL115(2015),172001;

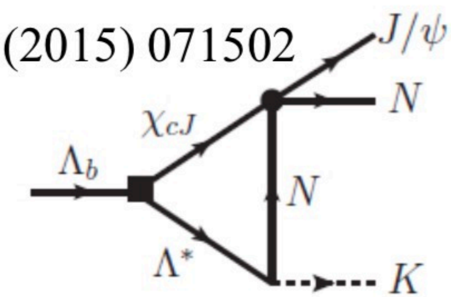
2) diquark *cu* & triquark $\bar{c}(ud)$ states



L.Maiani, A.D.Polosa, V. Riquer, PLB749 (2015) 289;
R.Lebed, PLB749 (2015) 454;
G.N.Li, M.He, X.G.He, JHEP 1512 (2015) 128;
R.Zhu, C.F.Qiao, PLB756 (2016) 259;

3) Kinematic triangle-singularity

F.K.Guo, Ulf-G.Meißner, W.Wang, Z.Yang, PRD92 (2015) 071502
X.H.Liu, Q.Wang, Q.Zhao, PLB757 (2016) 231



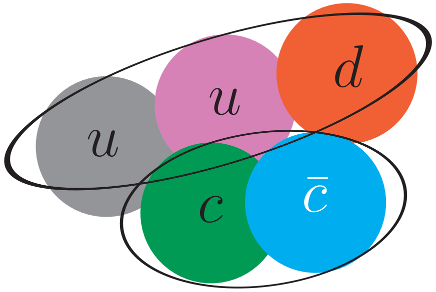
For comprehensive reviews, cf.:

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1
F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou, RMP 90 (2018)015004
Y.R.Liu, H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Prog.Part.Nucl.Phys. 107 (2019) 237

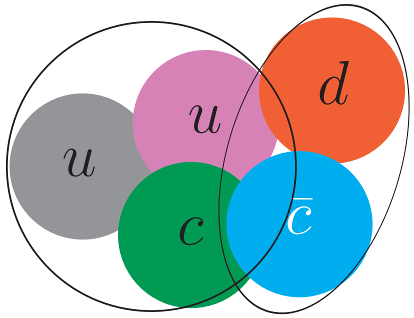
Molecular Configurations for Pc states

Two possible **configurations**:

- Combination of J/ψ and p $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$:



- Configuration $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$:



QCD sum rules

- Study two-point correlation function of current $J_\mu(x)$ with the same quantum numbers with hadron state:

$$\Pi_{\mu\nu}(q^2) = i \int d^4x e^{iq\cdot x} \langle \Omega | T[J_\mu(x) J_\nu^\dagger(0)] | \Omega \rangle$$

- Classify states $|X\rangle$ by coupling to current $\langle \Omega | J_\mu(x) | X \rangle \neq 0$
- Currents are probes of spectrum and might not overlap with state
- Hadron level: described by the dispersion relation

$$\Pi(q^2) \;=\; \frac{(q^2)^N}{\pi} \int \frac{\mathrm{Im}\Pi(s)}{s^N(s - q^2 - i\epsilon)} ds + \sum_{n=0}^{N-1} b_n (q^2)^n,$$

QCD sum rules

- Quark-gluon level: evaluated via operator product expansion(OPE)

$$\rho(s) = \rho^{pert}(s) + \rho^{\langle\bar{q}q\rangle}(s) + \rho^{\langle GG\rangle}(s) + \rho^{\langle\bar{q}q\rangle^2}(s) + \rho^{\langle\bar{q}g_s\sigma\cdot Gq\rangle}(s) + \dots,$$

- Apply Borel transform to correlation functions
- Quark-hadron duality: Laplace Sum Rules with QCD spectral function

$$\mathcal{L}_k\left(s_0, M_B^2\right) = \int_{4m_Q^2}^{s_0} ds e^{-s/M_B^2}\rho(s)s^k = f_X^2 m_X^{2k} e^{-m_X^2/M_B^2},$$

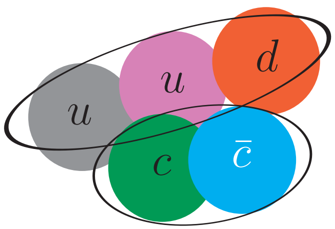
- Predict Hadron mass via:

$$m_X\left(s_0, M_B^2\right) = \sqrt{\frac{\mathcal{L}_1\left(s_0, M_B^2\right)}{\mathcal{L}_0\left(s_0, M_B^2\right)}}.$$

Pentaquark Sum Rules

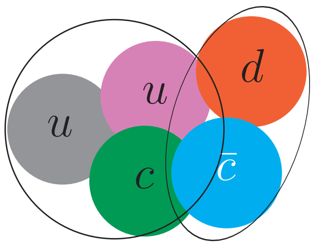
Two possible **configurations** (PRL115, 172001(2015)):

- Combination of J/ψ and p $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$:



$$
\begin{aligned}
\eta_{1\mu}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C d_b)\gamma_5 u_c]\,,\\
\eta_{2\mu}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C \gamma_5 d_b) u_c]\,,\\
\eta_{3\{\mu\nu\}}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C \gamma_\nu \gamma_5 d_b) u_c] + \{\mu \leftrightarrow \nu\}\,.
\end{aligned}
$$

- Configuration $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$:



$$
\begin{aligned}
J_\mu^{\bar{D}^*\Sigma_c} &= [\bar{c}_d \gamma_\mu d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b)\gamma^\nu \gamma_5 c_c]\,,\\
J_\mu^{\bar{D}\Sigma_c^*} &= [\bar{c}_d \gamma_5 d_d][\epsilon_{abc}(u_a^T C \gamma_\mu u_b) c_c]\,,\\
J_{\{\mu\nu\}}^{\bar{D}^*\Sigma_c^*} &= [\bar{c}_d \gamma_\mu d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b)\gamma_5 c_c] + \{\mu \leftrightarrow \nu\}\,,\\
J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*} &= [\bar{c}_d \gamma_\mu \gamma_5 d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b) c_c] + \{\mu \leftrightarrow \nu\}\,,\\
J_{\{\mu\nu\}}^{\bar{D}^*\Lambda_c} &= [\bar{c}_d \gamma_\mu u_d][\epsilon_{abc}(u_a^T C \gamma_\nu \gamma_5 d_b) c_c] + \{\mu \leftrightarrow \nu\}\,.
\end{aligned}
$$

These two color configurations are related via Fierz transformation and color rearrangement:

$$\delta^{de}\epsilon^{abc} = \delta^{da}\epsilon^{ebc} + \delta^{db}\epsilon^{aec} + \delta^{dc}\epsilon^{abe} .$$

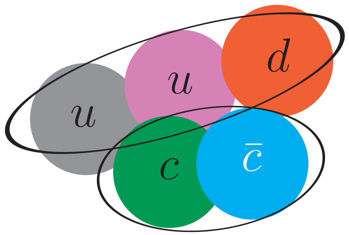
$$\eta^{c\bar{c}uud}_{12\mu} \xrightarrow{f.t.\&c.r.} \frac{1}{8} J^{\bar{D}^*\Sigma_c}_{\mu} + \frac{1}{8} J^{\bar{D}\Sigma_c^*}_{\mu} + \cdots ,$$

$$\eta^{c\bar{c}uud}_{3\{\mu\nu\}} \xrightarrow{f.t.\&c.r.} -\frac{1}{8} J^{\bar{D}^*\Sigma_c^*}_{\{\mu\nu\}} - \frac{1}{8} J^{\bar{D}\Sigma_c^*}_{\{\mu\nu\}} - \frac{3}{8} J^{\bar{D}^*\Lambda_c}_{\{\mu\nu\}} + \cdots .$$

These relations suggest that these structures coupled by the currents, if exist, would naturally decay into J/ψ and proton final states.

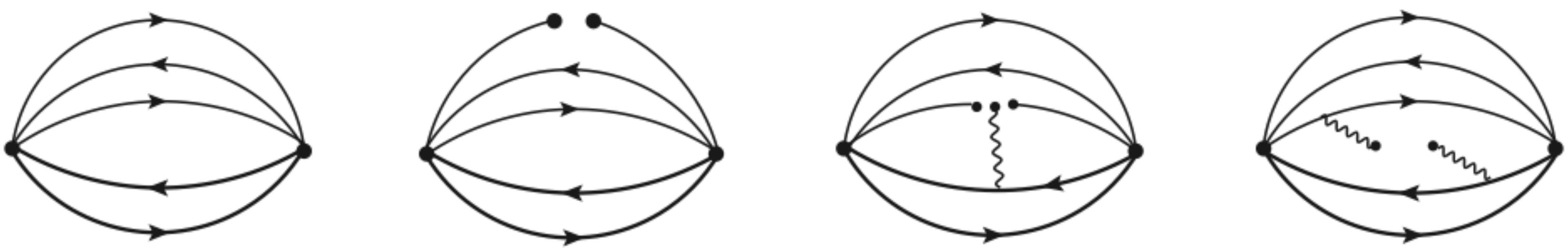
The first configurations (PRL115, 172001(2015)):

- Combination of J/ψ and p $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$:

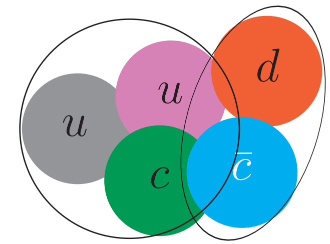


$$
\begin{aligned}
\eta_{1\mu}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C d_b)\gamma_5 u_c] \, , \\
\eta_{2\mu}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C \gamma_5 d_b) u_c] \, , \\
\eta_{3\{\mu\nu\}}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C \gamma_\nu \gamma_5 d_b) u_c] + \{\mu \leftrightarrow \nu\} \, .
\end{aligned}
$$

OPE is too simple to give reliable mass predictions!

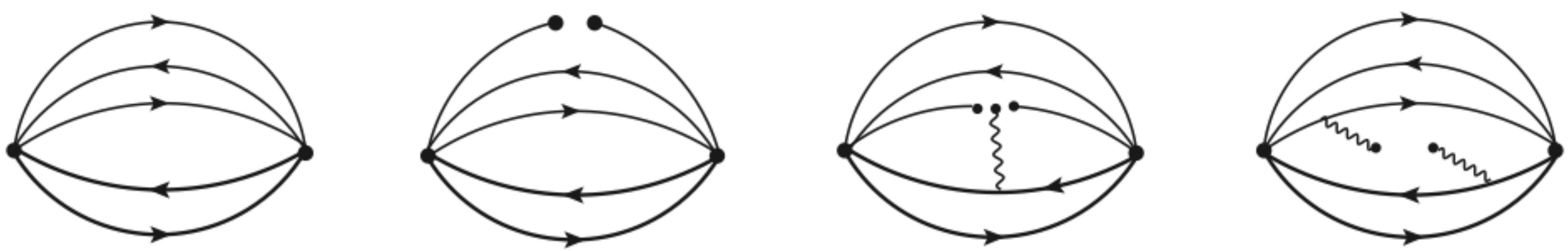


The second configurations (PRL115, 172001(2015)):



- Configuration $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$:

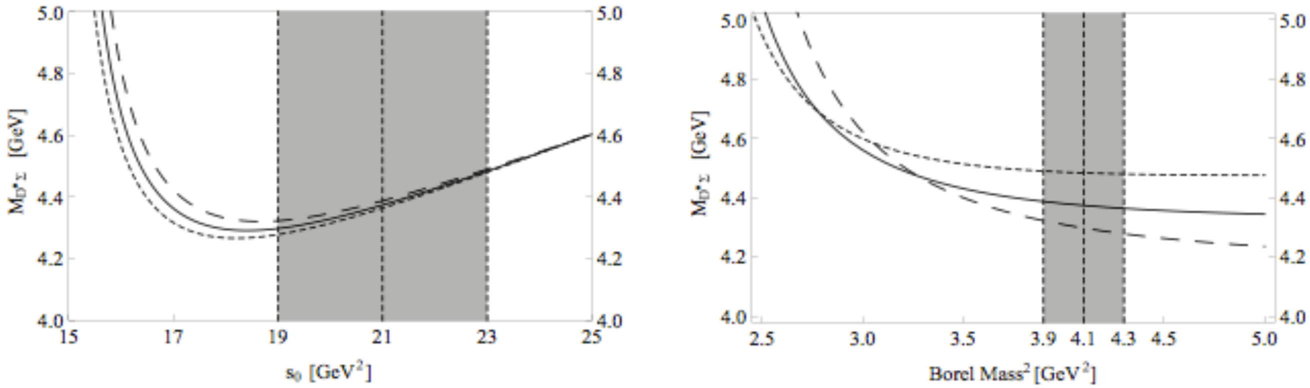
$$
\begin{aligned}
J_\mu^{\bar{D}^*\Sigma_c} &= [\bar{c}_d \gamma_\mu d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b)\gamma^\nu \gamma_5 c_c]\,,\\
J_\mu^{\bar{D}\Sigma_c^*} &= [\bar{c}_d \gamma_5 d_d][\epsilon_{abc}(u_a^T C \gamma_\mu u_b) c_c]\,,\\
J_{\{\mu\nu\}}^{\bar{D}^*\Sigma_c^*} &= [\bar{c}_d \gamma_\mu d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b)\gamma_5 c_c] + \{\mu \leftrightarrow \nu\}\,,\\
J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*} &= [\bar{c}_d \gamma_\mu \gamma_5 d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b) c_c] + \{\mu \leftrightarrow \nu\}\,,\\
J_{\{\mu\nu\}}^{\bar{D}^*\Lambda_c} &= [\bar{c}_d \gamma_\mu u_d][\epsilon_{abc}(u_a^T C \gamma_\nu \gamma_5 d_b) c_c] + \{\mu \leftrightarrow \nu\}\,.
\end{aligned}
$$



Good behaviors of the mass sum rule predictions!

$P_c(4380)$ and $P_c(4450)$

PRL115 (2015), 172001



$$M_{[\bar{D}^*\Sigma_c],3/2^-} = 4.37^{+0.19}_{-0.12}\ \text{GeV},$$

$$M_{[\bar{D}\Sigma_c^*\&\bar{D}^*\Lambda_c],5/2^+} = 4.47^{+0.20}_{-0.13}\ \text{GeV},$$

which supports $P_c(4380)$ as a $[\bar{D}^*\Sigma_c]$ hidden-charm pentaquark with $J^P = 3/2^-$ while $P_c(4450)$ as an admixture of $[\bar{D}^*\Lambda_c]$ and $[\bar{D}\Sigma_c^*]$ with $J^P = 5/2^+$ and the mixing angle is fine-tuned to be $\theta = -51 \pm 5°$.

We also predict their hidden-bottom partners

$$M_{[\bar{B}^*\Sigma_b],3/2^-} = 11.55^{+0.23}_{-0.14}\ \text{GeV},$$

$$M_{[\bar{B}\Sigma_b^*\&\bar{B}^*\Lambda_b],5/2^+} = 11.66^{+0.28}_{-0.27}\ \text{GeV}.$$

Pc(4312), Pc(4440) and Pc(4457)

We compose the following interpolating currents:

$$\begin{aligned}
\xi_{14} &= [\epsilon^{abc}(u_a^T C\gamma_\mu d_b)\gamma_\mu\gamma_5 c_c][\bar{c}_d\gamma_5 u_d]\,,\\
\psi_2 &= [\epsilon^{abc}(u_a^T C\gamma_\mu u_b)\gamma_\mu\gamma_5 c_c][\bar{c}_d\gamma_5 d_d]\,,\\
\xi_{33\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d\gamma_\mu u_d]\,,\\
\psi_{2\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu u_b)c_c][\bar{c}_d\gamma_5 d_d]\,,\\
\psi_{9\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu u_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d\gamma_\mu d_d]\,,\\
\xi_{13\mu\nu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu d_b)c_c][\bar{c}_d\gamma_\nu u_d] + \{\mu \leftrightarrow \nu\}\,,
\end{aligned}$$

Pc(4312), Pc(4440) and Pc(4457)

EPJC76, 572 (2016); PRD100 (2019), 051501(R)

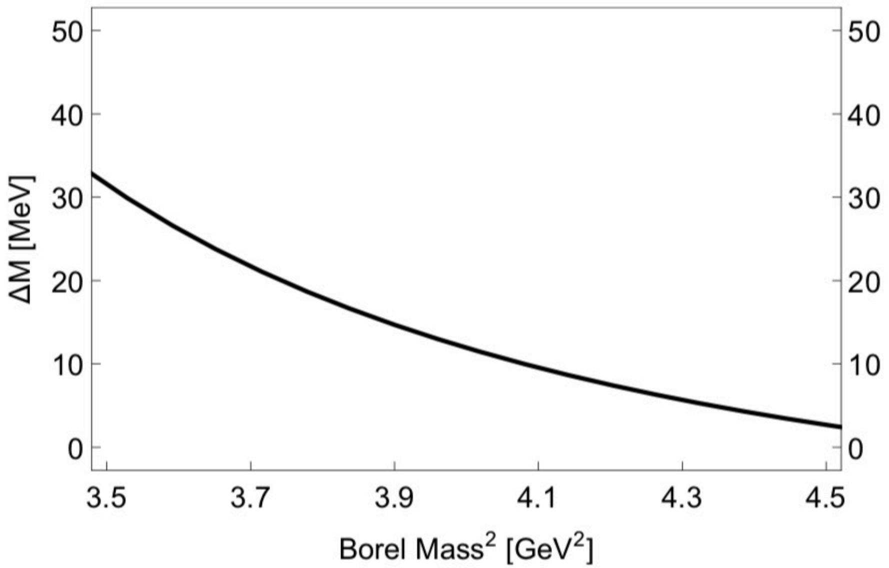
Current	Defined in	Structure	s_0 [GeV^2]	Borel Mass [GeV^2]	Mass [GeV]	(J, P)
ξ_{14}	Eq. (2)	$[\Sigma_c^+ \bar{D}^0]$	$20-24$	$4.12-4.52$	$4.45^{+0.17}_{-0.13}$	$(1/2, -)$
ψ_2	Eq. (3)	$[\Sigma_c^{++} \bar{D}^-]$	$19-23$	$3.95-4.47$	$4.33^{+0.17}_{-0.13}$	$(1/2, -)$
$\xi_{33\mu}$	Eq. (4)	$[\Sigma_c^+ \bar{D}^{*0}]$	$20-24$	$3.97-4.41$	$4.46^{+0.18}_{-0.13}$	$(3/2, -)$
$\psi_{2\mu}$	Eq. (5)	$[\Sigma_c^{*++} \bar{D}^-]$	$20-24$	$3.88-4.41$	$4.45^{+0.16}_{-0.13}$	$(3/2, -)$
$\psi_{9\mu}$	Eq. (6)	$[\Sigma_c^{++} \bar{D}^{*-}]$	$19-23$	$3.94-4.27$	$4.37^{+0.18}_{-0.13}$	$(3/2, -)$
$\xi_{13\mu\nu}$	Eq. (7)	$[\Sigma_c^{*+} \bar{D}^{*0}]$	$20-24$	$3.51-4.00$	$4.50^{+0.18}_{-0.12}$	$(5/2, -)$

- $P_c(4312)$: molecular state $[\Sigma_c^{++} D^-]$ with $J^P = \frac{1}{2}^-$;
- $P_c(4440)$: molecular state $[\Sigma_c^{*++} D^-]$ with $J^P = \frac{3}{2}^-$;
- $P_c(4457)$: molecular state $[\Sigma_c^+ \bar{D}^{*0}]$ with $J^P = \frac{3}{2}^-$;
- There is still a place for $P_c(4380)$: molecular state $[\Sigma_c^{++} D^{*-}]$ with $J^P = \frac{3}{2}^-$.

Mass splitting between Pc(4440) and Pc(4457)

$$\Pi^{\xi_{33\mu}\psi_{2\mu}}_{\mu\nu}(q^2) \equiv i\int d^4x e^{iqx}\langle 0|T\xi_{33\mu}(x)\psi^{\dagger}_{2\nu}(0)|0\rangle$$

$$= \left(\frac{q_\mu q_\nu}{q^2} - g_{\mu\nu}\right)(\not{q} + M^*)\Pi^{\xi_{33\mu}\psi_{2\mu}}(q^2)$$



Off-diagonal correlator vanishes, implying that this two currents should couple to different states!

$$\Delta M = M_{\xi_{33\mu}} - M_{\psi_{2\mu}} = 8.1^{+30.9}_{-18.9}\ \mathrm{MeV}$$

Some other pentaquark predictions

Current	Defined in	Structure	s_0 [GeV^2]	Borel Mass [GeV^2]	Mass [GeV]	(J, P)
$\eta_2 - \eta_4$	Eq. (8)	$[p\eta_c]$	–	–	–	–
$\eta_5 - \eta_7$	Eq. (9)	$[pJ/\psi]$	–	–	–	–
η_{13}	Eq. (10)	$[N^* J/\psi]$	–	–	–	–
$\xi_2 - \xi_4$	Eq. (13)	$[\Lambda_c \bar{D}]$	–	–	–	–
$\xi_5 - \xi_7$	Eq. (14)	$[\Lambda_c \bar{D}^*]$	–	–	–	–
ξ_{14}	Eq. (15)	$[\Sigma_c \bar{D}]$	$20 - 24$	$4.12 - 4.52$	$4.45^{+0.17}_{-0.13}$	$(1/2, -)$
ξ_{16}	Eq. (16)	$[\Lambda_c^* \bar{D}]$	$25 - 29$	$4.40 - 4.76$	$4.86^{+0.16}_{-0.19}$	$(1/2, +)$
ξ_{17}	Eq. (17)	$[\Sigma_c^* \bar{D}^*]$	$22 - 26$	$3.64 - 4.25$	$4.73^{+0.19}_{-0.12}$	$(1/2, -)$
ξ_{19}	Eq. (18)	$[\Lambda_c^* \bar{D}^*]$	$23 - 27$	$3.70 - 4.22$	$4.67^{+0.16}_{-0.20}$	$(1/2, +)$
ψ_2	Eq. (21)	$[\Sigma_c^* \bar{D}]$	$19 - 23$	$3.95 - 4.47$	$4.33^{+0.17}_{-0.13}$	$(1/2, -)$
ψ_3	Eq. (22)	$[\Sigma_c^* \bar{D}^*]$	$21 - 25$	$3.50 - 4.11$	$4.59^{+0.17}_{-0.12}$	$(1/2, -)$

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$\xi_{5\mu} - \xi_{7\mu}$	Eq. (45)	$[\Lambda_c \bar{D}^*]$	–	–	–	–
$\xi_{18\mu}$	Eq. (46)	$[\Sigma_c^* \bar{D}]$	$21 - 25$	$3.93 - 4.51$	$4.56^{+0.16}_{-0.13}$	$(3/2, -)$
$\xi_{20\mu}$	Eq. (47)	$[\Lambda_c^* \bar{D}]$	$23 - 27$	$4.12 - 4.63$	$4.56^{+0.18}_{-0.22}$	$(3/2, +)$
$\xi_{25\mu}$	Eq. (48)	$[\Sigma_c^* \bar{D}^*]$	$21 - 25$	$3.85 - 4.30$	$4.67^{+0.21}_{-0.12}$	$(3/2, -)$
$\xi_{27\mu}$	Eq. (49)	$[\Lambda_c^* \bar{D}^*]$	$23 - 27$	$4.07 - 4.50$	$4.68^{+0.15}_{-0.18}$	$(3/2, +)$
$\xi_{33\mu}$	Eq. (50)	$[\Sigma_c \bar{D}^*]$	$20 - 24$	$3.97 - 4.41$	$4.46^{+0.18}_{-0.13}$	$(3/2, -)$
$\xi_{35\mu}$	Eq. (51)	$[\Lambda_c \bar{D}^*]$	$27 - 31$	$4.32 - 5.11$	$5.18^{+0.16}_{-0.12}$	$(3/2, +)$
$\psi_{2\mu}$	Eq. (52)	$[\Sigma_c^* \bar{D}]$	$20 - 24$	$3.88 - 4.41$	$4.45^{+0.16}_{-0.13}$	$(3/2, -)$
$\psi_{5\mu}$	Eq. (53)	$[\Sigma_c^* \bar{D}^*]$	$21 - 25$	$3.86 - 4.46$	$4.61^{+0.18}_{-0.12}$	$(3/2, -)$
$\psi_{9\mu}$	Eq. (54)	$[\Sigma_c \bar{D}^*]$	$19 - 23$	$3.94 - 4.27$	$4.37^{+0.18}_{-0.13}$	$(3/2, -)$
$\xi_{13\mu\nu}$	Eq. (56)	$[\Sigma_c^* \bar{D}^*]$	$20 - 24$	$3.51 - 4.00$	$4.50^{+0.18}_{-0.12}$	$(5/2, -)$
$\xi_{15\mu\nu}$	Eq. (57)	$[\Lambda_c^* \bar{D}^*]$	$24 - 28$	$4.09 - 4.59$	$4.76^{+0.15}_{-0.19}$	$(5/2, +)$
$\psi_{3\mu\nu}$	Eq. (58)	$[\Sigma_c^* \bar{D}^*]$	$21 - 25$	$3.88 - 4.40$	$4.59^{+0.17}_{-0.12}$	$(5/2, -)$
$\psi_{4\mu\nu}$	Eq. (59)	P-wave $[\Sigma_c^* \bar{D}]$	$25 - 29$	$4.30 - 4.73$	$4.82^{+0.15}_{-0.14}$	$(5/2, +)$
$J^{\text{mix}}_{\mu\nu}$	Eq. (40)	P-wave $[\Lambda_c \bar{D}^* \& \Sigma_c^* \bar{D}]$	$20 - 24$	$3.22 - 3.50$	$4.47^{+0.18}_{-0.13}$	$(5/2, +)$

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Challenges

- These Pc states have been only reported by LHCb, they should be confirmed in other experiments and processes, GlueX,BelleII, JPARC.
- Many isospin and spin partner states were predicted by various theoretical approaches. Where and how can them be observed?
- Experimental identification of the parities for these Pc states is crucial for the discrimination of various models.
- Identifying the dominant decay modes of the Pc states.
- Are there hidden-bottom pentaquarks?
- More open questions……

Summary

- LHCb reported three hidden-charm pentaquark states in 2019: Pc(4312), Pc(4440) and Pc(4457).
- Studied the Pcs in two possible molecular configurations: J/psi+proton and charmed-baryon+charmed-meson.
- Using charmed-baryon+charmed-meson configuration, we reproduced the masses of these Pc states and predicted their spin-parity quantum numbers.
- Remain many theoretical and experimental challenges!

Thank you!