Towards exotic hidden-charm pentaquarks in QCD

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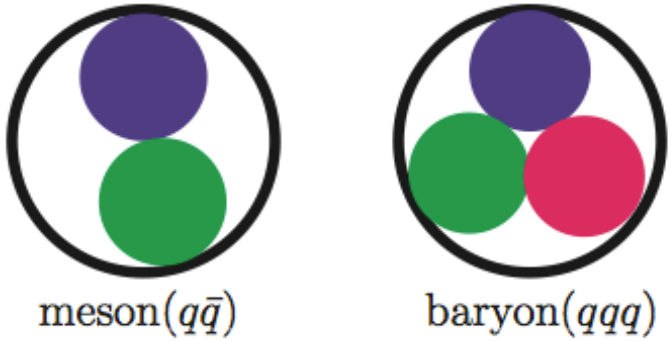
Outline

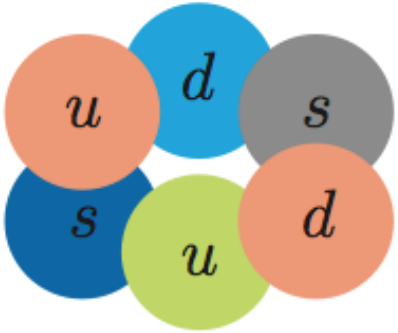
- Exotic hadrons and pentaquark states
- Method of the QCD sum rules
- Reproduce the Pc(4380) and Pc(4450) masses and predict their spin-parity quantum numbers
- Challenges for hidden-charm pentaquark states
- Summary

Quark model and **exotic hadrons**

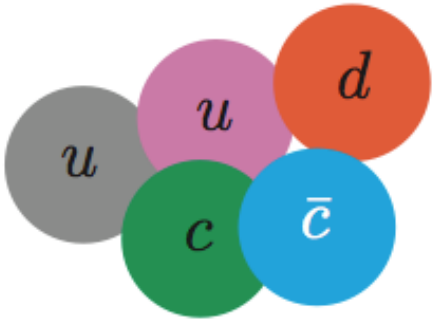


- **Quark model** is established to classify hadrons: J^{PC} quantum numbers and flavour quantum numbers.
- However, the hadron structures are more complicated in **QCD**. It may allow for hadrons which lie outside the naive quark model.
- Mesons with exotic J^{PC} quantum numbers:
  $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$
- Baryons with exotic flavour quantum numbers:
  dibaryon, pentaquark,...

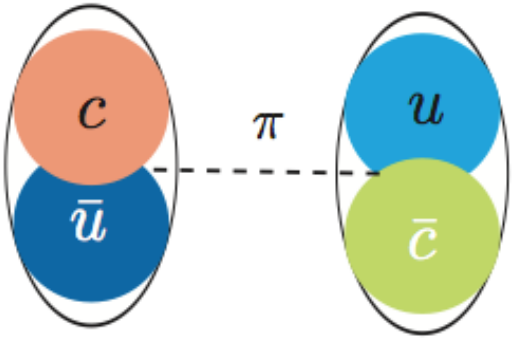
Exotic hadrons



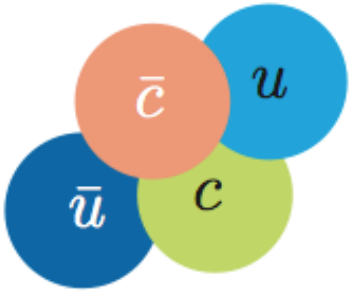
dibaryon



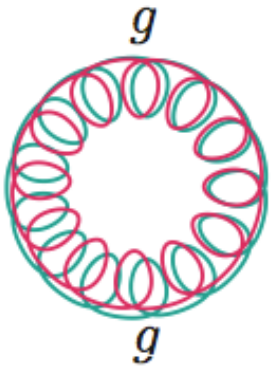
pentaquark



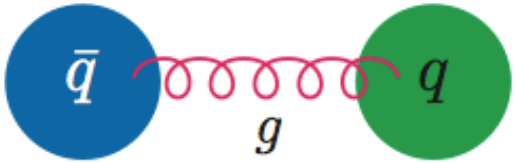
molecule



tetraquark



glueball

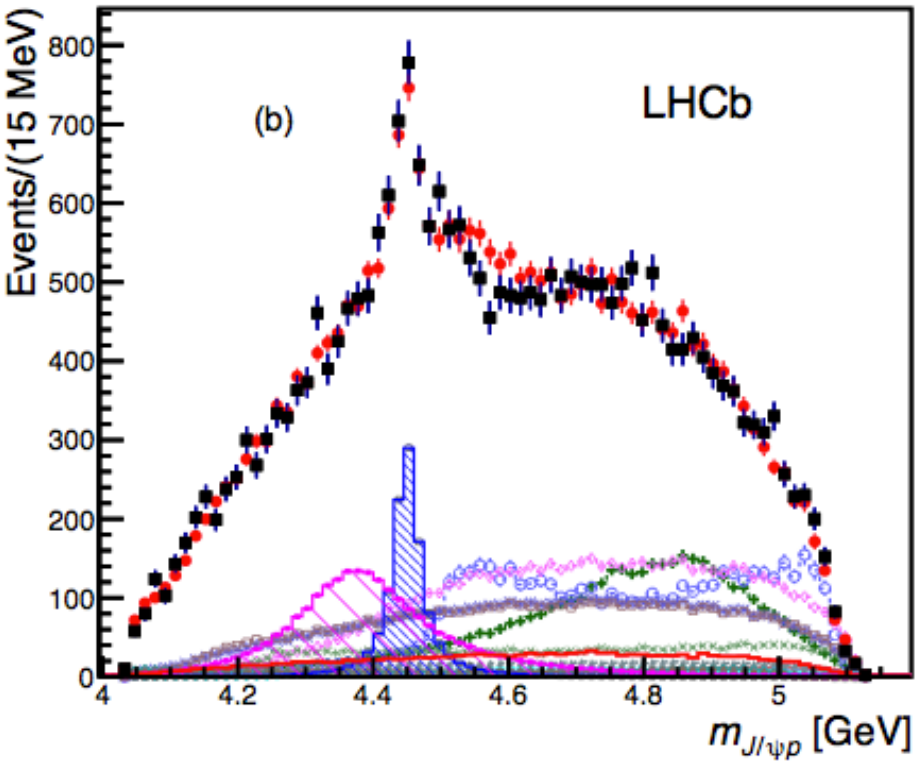


hybrid

Pentaquark states

In 2015, LHCb reported two hidden-charm pentaquark states $P_c(4380)$ and $P_c(4450)$ in $J/\psi p$ invariant mass distribution via $\Lambda_b^0 \to J/\psi K^- p$ decay (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 spins: $J = 3/2$ for $P_c(4380)$ while $J = 5/2$ for $P_c(4450)$.

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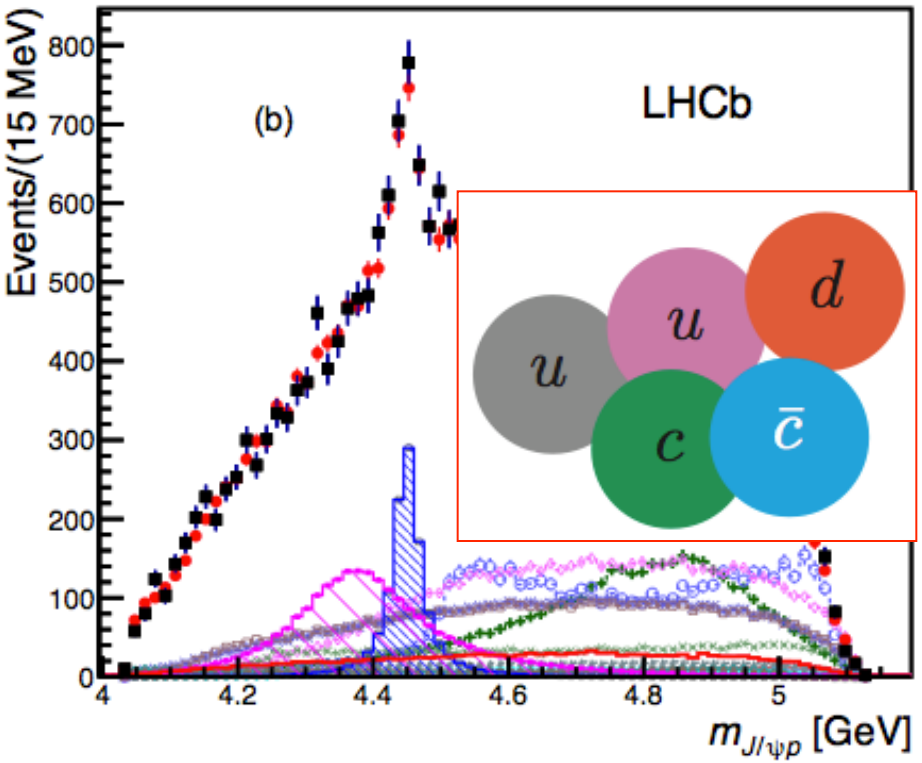

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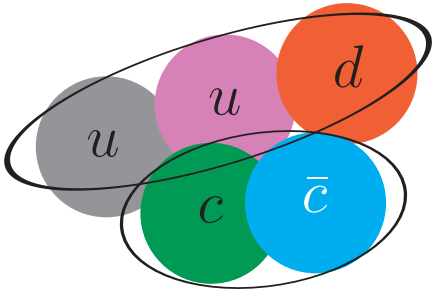
Theoretical interpretations

- **Molecular scheme:** (OBE and OPE models)
  CPC36,6(2012), PRL115,122001(2015), PRL115,132002(2015), PLB753,547(2016),…
- **Dynamically generated resonances:** (couple channel unitary approach)
  PRL105,232001(2010), PRC84,015202(2011), PRD92,114002(2015),…
- **QCD sum rules:**
  PRL115,172001(2015), EPJC76,43(2016), EPJC76,70(2016), 1602.02433,…
- **Tightly bound pentaquarks:** antiquark-diquark-diquark, diquark-triquark pictures (chiral quark model)
  PLB749,289(2015), MPA30,1550190(2015), JHEP1512,128(2015), PLB749,454(2015),…
- **Non-resonance explanations (Kinematical effect):**
  PRD92,071502(2015), PLB757,231(2016),1507.06552,…
- **Other theoretical scheme:** topological soliton model, two channel framework, doublet-exotic molecule structure,…
  PRD92,051501(2015),PLB751,59(2015),JETPL102,271(2015), EPJA51,152(2015),…

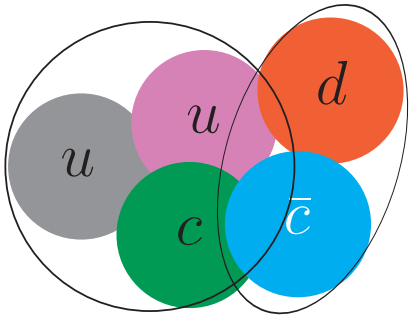
Pentaquark Configurations

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)

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

- 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 states

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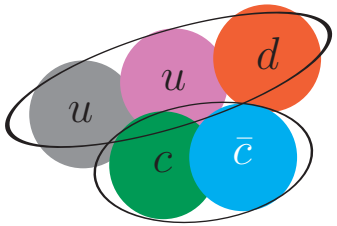
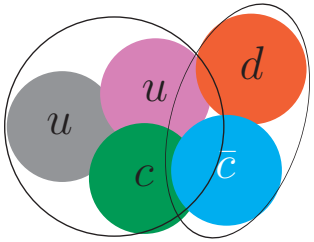


$$
\begin{aligned}
\eta_{1\mu}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C d_b)\gamma_5 u_c]\,, \\
\eta_{2\mu}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C \gamma_5 d_b) u_c]\,, \\
\eta_{3\{\mu\nu\}}^{c\bar{c}uud} &= [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T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

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



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

Pentaquark Configurations

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

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

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

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

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

Pentaquark Configurations

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

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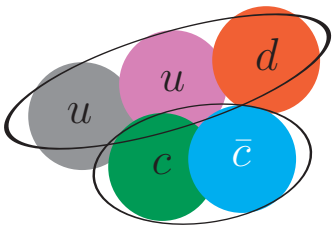

$$\eta_{1\mu}^{c\bar{c}uud} = [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C d_b)\gamma_5 u_c]\,,$$
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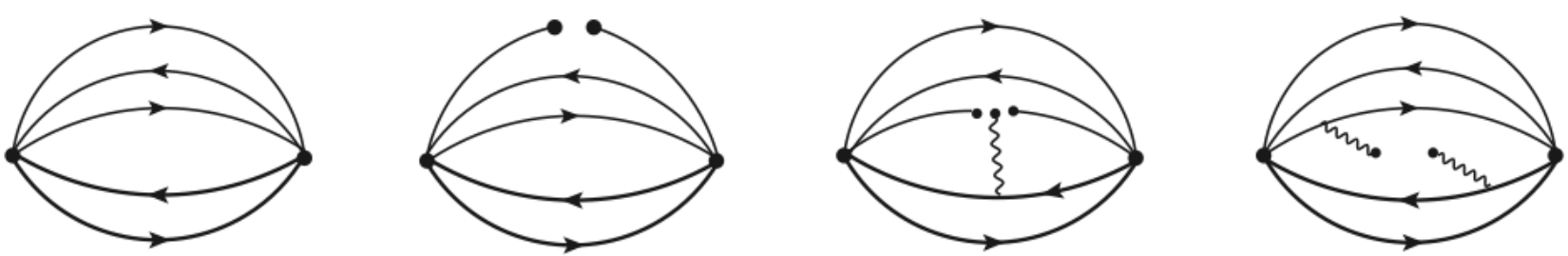
$$\eta_{3\{\mu\nu\}}^{c\bar{c}uud} = [\bar{c}_d \gamma_\mu c_d][\epsilon_{abc}(u_a^T C \gamma_\nu \gamma_5 d_b) u_c] + \{\mu \leftrightarrow \nu\}\,.$$

OPE is too simple to give reliable mass predictions!



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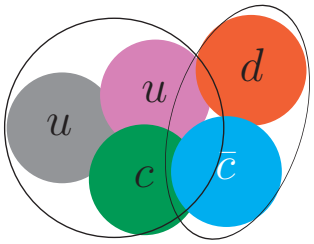

- Configuration $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$:

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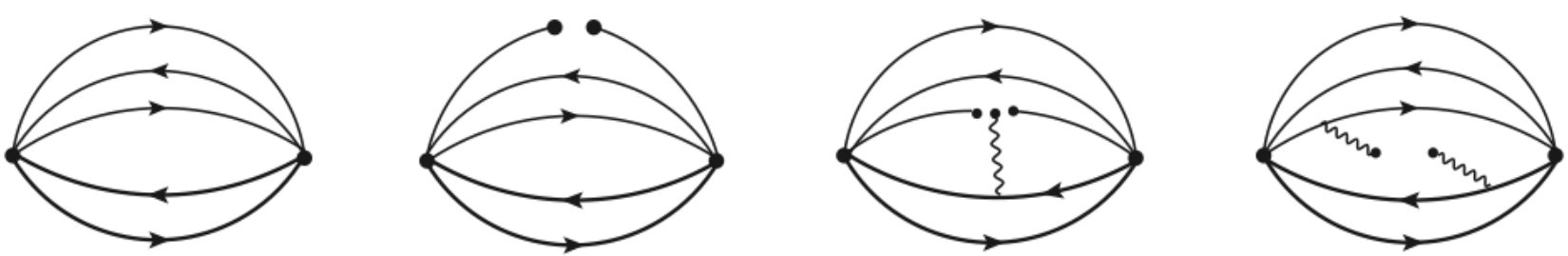
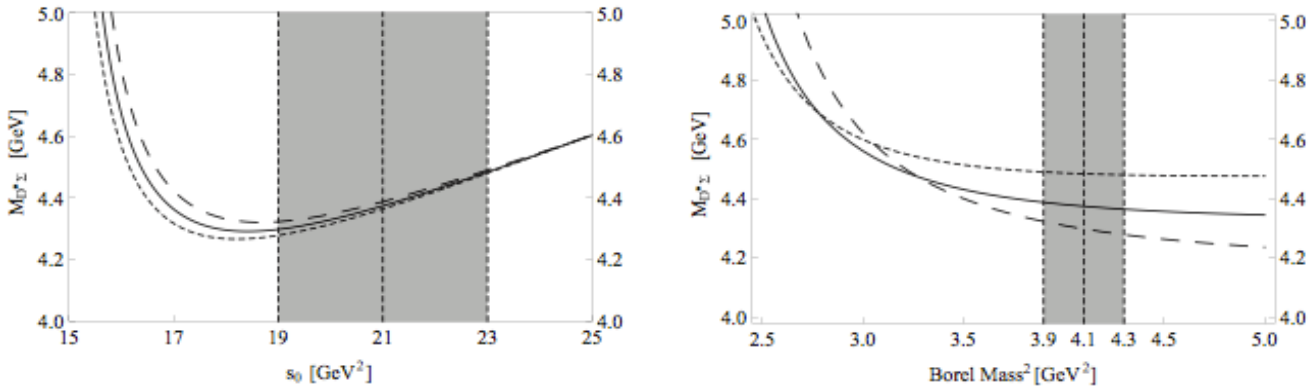
J_{\{\mu\nu\}}^{\bar{D}^*\Lambda_c} &= [\bar{c}_d\gamma_\mu u_d][\epsilon_{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)c_c] + \{\mu\leftrightarrow\nu\}\,.
\end{aligned}
$$



Pc(4380) and Pc(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 $\theta = -51 \pm 5^\circ$.

We also predict their hidden-bottom partners

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

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

Challenges

- The **Pc(4380)** and **Pc(4450)** are only reported by LHCb, should be confirmed in other processes and analyses. BelleII, CMS, 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 the two Pc states is crucial for the discrimination of various models.
- Identification of the dominant decay modes of the two Pc states is important!
- Is it possible to produce the hidden-bottom pentaquarks experimentally?
- Other hidden-charm multiquark systems may also exist!

Summary

- LHCb reported two exotic hidden-charm pentaquark states in 2015: Pc(4380) and Pc(4450).
- Studied the Pcs in two possible configurations: J/psi+proton and charmed-baryon+charmed-meson.
- Using charmed-baryon+charmed-meson configuration, we reproduced the masses of two Pc states and predicted their spin-parity quantum numbers.
- Remain many theoretical and experimental challenges!

Thank you!

Backup

Other pentaquark states

TABLE I: Numerical results for the spin $J = 1/2$ hidden-charm pentaquark states.

Current	Defined in	Structure	s_0 [GeV^2]	Borel Window [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	$4.59^{+0.17}_{-0.12}$	$(1/2, -)$

arXiv: 1602.02433

Other pentaquark states

TABLE II: Numerical results for the spin $J = 3/2$ hidden-charm pentaquark states.

Current	Defined in	Structure	s_0 [GeV^2]	Borel Window [GeV^2]	Mass [GeV]	(J, P)
$\eta_{5\mu} - \eta_{7\mu}$	Eq. (A1)	$[pJ/\psi]$	–	–	–	–
$\eta_{18\mu}$	Eq. (A2)	$[N^*\eta_c]$	–	–	–	–
$\eta_{19\mu}$	Eq. (A3)	$[N^*J/\psi]$	–	–	–	–
$\xi_{5\mu} - \xi_{7\mu}$	Eq. (A4)	$[\Lambda_c\bar{D}^*]$	–	–	–	–
$\xi_{18\mu}$	Eq. (A5)	$[\Sigma_c^*\bar{D}]$	21 – 25	3.93 – 4.51	$4.56^{+0.16}_{-0.13}$	$(3/2, -)$
$\xi_{20\mu}$	Eq. (A6)	$[\Lambda_c^*\bar{D}]$	23 – 27	4.12 – 4.63	$4.56^{+0.18}_{-0.22}$	$(3/2, +)$
$\xi_{25\mu}$	Eq. (A7)	$[\Sigma_c^*\bar{D}^*]$	21 – 25	3.85 – 4.30	$4.67^{+0.21}_{-0.12}$	$(3/2, -)$
$\xi_{27\mu}$	Eq. (A8)	$[\Lambda_c^*\bar{D}^*]$	23 – 27	4.07 – 4.50	$4.68^{+0.15}_{-0.18}$	$(3/2, +)$
$\xi_{33\mu}$	Eq. (A9)	$[\Sigma_c\bar{D}^*]$	20 – 24	3.97 – 4.41	$4.46^{+0.18}_{-0.13}$	$(3/2, -)$
$\xi_{35\mu}$	Eq. (A10)	$[\Lambda_c\bar{D}^*]$	27 – 31	4.32 – 5.11	$5.18^{+0.16}_{-0.12}$	$(3/2, +)$
$\psi_{2\mu}$	Eq. (A11)	$[\Sigma_c^*\bar{D}]$	20 – 24	3.88 – 4.41	$4.45^{+0.16}_{-0.13}$	$(3/2, -)$
$\psi_{5\mu}$	Eq. (A12)	$[\Sigma_c^*\bar{D}^*]$	21 – 25	3.86 – 4.46	$4.61^{+0.18}_{-0.12}$	$(3/2, -)$
$\psi_{9\mu}$ ($J_\mu^{\bar{D}^*\Sigma_c}$ in Ref. [46])	Eq. (A13)	$[\Sigma_c\bar{D}^*]$	19 – 23	3.94 – 4.27	$4.37^{+0.18}_{-0.13}$	$(3/2, -)$

arXiv: 1602.02433

Other pentaquark states

TABLE III: Numerical results for the spin $J = 5/2$ hidden-charm pentaquark states.

Current	Defined in	Structure	s_0 [GeV^2]	Borel Window [GeV^2]	Mass [GeV]	(J, P)
$\eta_{11\mu\nu}$	Eq. (B1)	$[N^* J/\psi]$	–	–	–	–
$\xi_{13\mu\nu}$	Eq. (B2)	$[\Sigma_c^* \bar{D}^*]$	20 – 24	3.51 – 4.00	$4.50^{+0.18}_{-0.12}$	(5/2, –)
$\xi_{15\mu\nu}$ ($J^{\bar{D}^*\Lambda_c}_{\{\mu\nu\}}$ in Ref. [46])	Eq. (B3)	$[\Lambda_c^* \bar{D}^*]$	24 – 28	4.09 – 4.59	$4.76^{+0.15}_{-0.19}$	(5/2, +)
$\psi_{3\mu\nu}$	Eq. (B4)	$[\Sigma_c^* \bar{D}^*]$	21 – 25	3.88 – 4.40	$4.59^{+0.17}_{-0.12}$	(5/2, –)
$\psi_{4\mu\nu}$ ($J^{\bar{D}\Sigma_c^*}_{\{\mu\nu\}}$ in Ref. [46])	Eq. (B5)	P-wave $[\Sigma_c^* \bar{D}]$	25 – 29	4.30 – 4.73	$4.82^{+0.15}_{-0.14}$	(5/2, +)
$J^{\rm mix}_{\mu\nu}$ ($J^{\bar{D}\Sigma_c^*\&\bar{D}^*\Lambda_c}_{\{\mu\nu\}}$ in Ref. [46])	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, +)

arXiv: 1602.02433