LHCb hidden-charmed pentaquarks as hadronic molecular states

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Outline

1. Introduction
   - Studies about pentaquarks before LHCb experiment
   - LHCb Experiment
   - Theoretical studies after LHCb experiment
2. LHCb pentaquarks as hadronic molecular states
   - Hadronic molecular state
   - $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ interactions
   - Qusipotential Bethe-Salpeter equation
3. Results and Discussion
   - Bound states from $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ interactions
   - Could P-wave state be observed in experiment?
   - Summary

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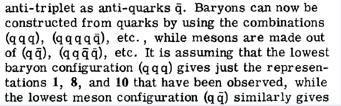
Studies about pentaquarks before LHCb experiment

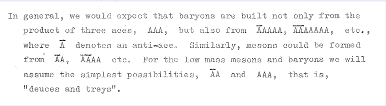
Gell-Mann and Zweig proposed not only the existence of the $q\bar{q}$ mesons and qqq baryons but also the possible existence of the tetraquarks and pentaquarks.

Gell-Mann, Phys. Lett. 8 (1964) 214



anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives

Zweig, CERN Report 8419/TH.401 (1964)



In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Theoretical studies

- The pentaquarks composed of light quarks:

  Hogaasen and Sorba, Strotmann, Nucl. Phys. B145 (1978) 119.

- Charmed Pentaquark:

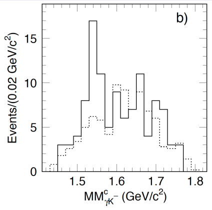
  Gignoux et al., PLB193(1987)323

  Lipkin PLB195(1987)484

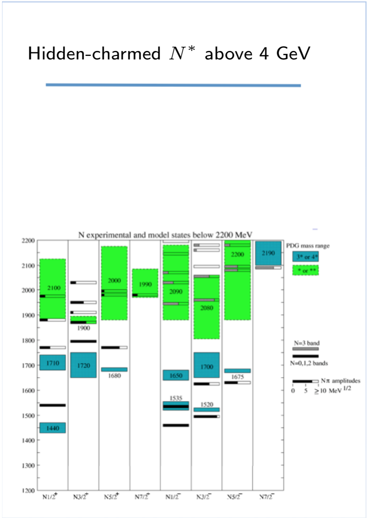
  The name "pentaquark" was proposed.

- ....

Experiment(LEPS,2003): Θ

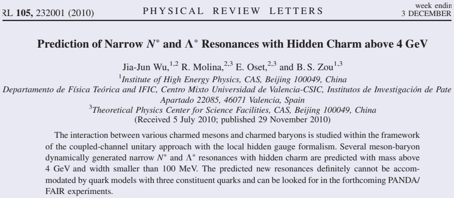


Theoretical predictions about hidden-charmed pentaquark



Hidden-charmed N^* above 4 GeV

Hidden-charmed N^* above 4 GeV



RL **105,** 232001 (2010) PHYSICAL REVIEW LETTERS week endin
3 DECEMBER

Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

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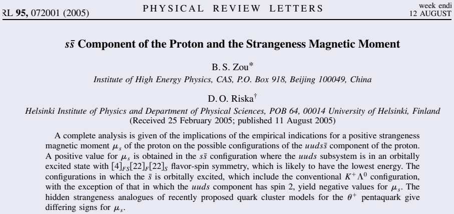
(Received 5 July 2010; published 29 November 2010)

The interaction between various charmed mesons and charmed baryons is studied within the framework of the coupled-channel unitary approach with the local hidden gauge formalism. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass above 4 GeV and width smaller than 100 MeV. The predicted new resonances definitely cannot be accommodated by quark models with three constituent quarks and can be looked for in the forthcoming PANDA/FAIR experiments.

Five quark components in N^*



RL **95,** 072001 (2005) PHYSICAL REVIEW LETTERS week endi
12 AUGUST

$s\bar{s}$ Component of the Proton and the Strangeness Magnetic Moment

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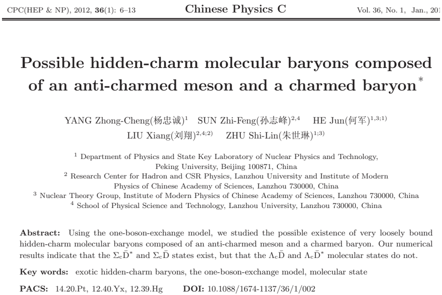
(Received 25 February 2005; published 11 August 2005)

A complete analysis is given of the implications of the empirical indications for a positive strangeness magnetic moment μ_s of the proton on the possible configurations of the $uuds\bar{s}$ component of the proton. A positive value for μ_s is obtained in the $s\bar{s}$ configuration where the $uuds$ subsystem is in an orbitally excited state with $[4]_{FS}[22]_F[22]_S$ flavor-spin symmetry, which is likely to have the lowest energy. The configurations in which the $\bar{s}$ is orbitally excited, which include the conventional $K^+\Lambda^0$ configuration, with the exception of that in which the $uuds$ component has spin 2, yield negative values for μ_s. The hidden strangeness analogues of recently proposed quark cluster models for the θ^+ pentaquark give differing signs for μ_s.

Theoretical predictions about hidden-charmed pentaquark

Hidden-charm molecular baryons composed of anti-charmed meson and charmed baryon in the OBE mdoel.



CPC(HEP & NP), 2012, **36**(1): 6–13 **Chinese Physics C** Vol. 36, No. 1, Jan., 201

Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon*

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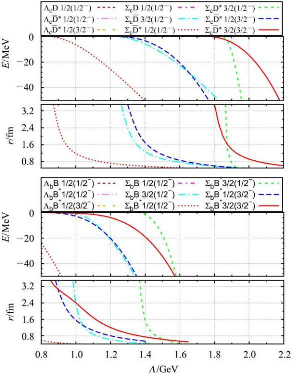
Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not.

Key words: exotic hidden-charm baryons, the one-boson-exchange model, molecular state

PACS: 14.20.Pt, 12.40.Yx, 12.39.Hg **DOI:** 10.1088/1674-1137/36/1/002



A $[\Sigma_c\bar{D}^*]_{1/2(3/2-)}$ state was predicted in our OBE model.

Theoretical predictions about hidden-charmed pentaquark

Other predictions in hadronic molecular state picture

- Wang, Huang, Zhang, and Zou, Phys. Rev. C84 (2011) 015203

  $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states in a chiral quark model

  The results show that the interaction between Σ_c and $\bar{D}$ is attractive, which consequently results in a $\Sigma_c\bar{D}$ bound state with a binding energy of about 5∼42 MeV, unlike the case of the $\Lambda_c\bar{D}$ state, which has a repulsive interaction and thus is unbound.

- Karliner, Rosner, Phys. Rev. Lett. 115 (2015) 122001

  New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules

Prediction in a multiquark picture

- Yuan, Wei, JH, Xu and Zou, Eur.Phys.J. A48 (2012) 61

  Study of $qqqc\bar{c}$ five quark system with three kinds of quark-quark hyperfine interaction

  The low-lying energy spectra of five quark systems $uud\bar{c}c$ $(I = 1/2,\ S = 0)$ and $uds\bar{c}c$ $(I = 0,\ S = -1)$ are investigated with three kinds of schematic interaction: the chromomagnetic interaction, the flavor-spin-dependent interaction and the instanton-induced interaction. In all the three models, the lowest five-quark state (uudcc or udscc) has an spin-parity $J^P = 1/2^-$; the mass of the lowest $uds\bar{c}c$ state is heavier than the lowest $uud\bar{c}c$ state.

Proposals to search for the predicted hidden-charmed pentaquark

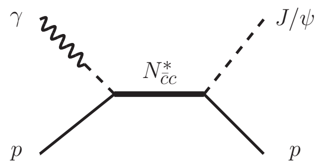
$p\bar{p} \to p\bar{p}\eta_c$ and $p\bar{p} \to p\bar{p}J/\psi$ at PANDA

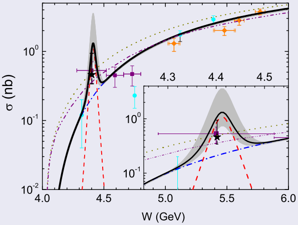
Wu, Molina, Oset, Zou, PRC84(2011)015202

- $\sigma_{\bar{p}p\to\bar{p}p\eta_c}$ and $\sigma_{\bar{p}p\to\bar{p}pJ/\psi}$: 10∼70 nb and 0.02∼2 nb.
- Main contribution comes from the predicted $N^*_{\bar{c}c}(4265)$ and $N^*_{\bar{c}c}(4418)$ states, respectively.
- About 9000∼60000 and 20∼1700 events per day at the PANDA/FAIR facility, respectively.

J/ψ photoprodusction at JLab

Huang, JH, Zhang, Chen, JPG41(2014)115004

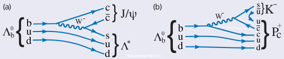




LHCb Experiment: $P_c(4450)$ and $P_c(4380)$

PRL115(2015)072001

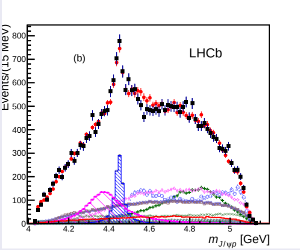
Observed in $J/\psi p$ channel of $\Lambda_b^0 \to J/\psi K^- p$ decay.

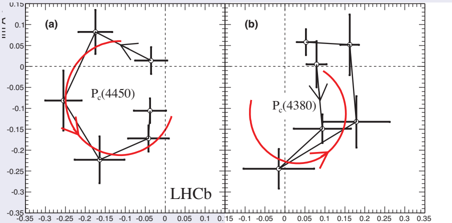


$M = 4380 \pm 8 \pm 29$ MeV, $\Gamma = 205 \pm 18 \pm 86$ MeV.
$M = 4449.8 \pm 1.7 \pm 2.5$ MeV, $\Gamma = 39 \pm 5 \pm 19$ MeV.

$P_c(4380)$	$P_c(4450)$	$\Delta(-2\ln\mathcal{L})$
$3/2^-$	$5/2^+$	0
$3/2^+$	$5/2^-$	0.9^2
$5/2^+$	$3/2^-$	2.3^2
..	..	$> 5^2$

$J/\psi p$ invariant mass spectrum and Argand diagram

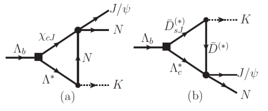




Theoretical studies after LHCb experiment

The LHCb experiment has been cited by 273 articles.

Anomalous triangle singularity



- Liu, Wang, Zhao, PLB757(2016)231
  Understanding the newly observed heavy pentaquark candidates
- Mikhail Mikhasenko, arXiv:1507.06552
  A triangle singularity and the LHCb pentaquarks

Pentaquark (a color singlet)

- Maiani, Polosa, Riquer, PLB749(2015)289 The New Pentaquarks in the Diquark Model
- Lebed, PLB749 (2015) 454
  The Pentaquark Candidates in the Dynamical Diquark Picture
- Wang, EPJC76 (2016)70
  Analysis of $P_c(4380)$ and $P_c(4450)$ as pentaquark states in the diquark model

The spin parity can be reproduced.

- Chen, Chen, Liu, Steele, Zhu, PRL115(2015)172001
  Towards exotic hidden-charm pentaquarks in QCD
  $P_c(4380)$ and $P_c(4450)$ as pentaquarks with configurations $[\bar{D}^*\Sigma_c]_{3/2-}$ and $[\bar{D}^*\Lambda_c - \bar{D}\Sigma_c^*]_{5/2+}$.

Theoretical studies after LHCb experiment

S-wave molecular state : negative parity

- Chen, Liu, Li, Zhu, PRL115(2015)132002
  Identifying exotic hidden-charm pentaquarks
  $P_c(4380)$ and $P_c(4450)$ as $[\bar{D}^*\Sigma_c]_{3/2-}$ and $[\bar{D}^*\Sigma_c^*]_{5/2-}$ molecular states.
- Roca, Nieves, Oset, PRD92(2015)094003
  LHCb pentaquark as a $\bar{D}^*\Sigma_c - \bar{D}^*\Sigma^*$ molecular state
  $P_c(4450)$ as a molecualr state of most $[\bar{D}^*\Sigma_c - \bar{D}^*\Sigma^*]_{3/2-}$ nature

The positive parity can not be reproduced from S-wave $\Sigma_c^{(*)}\bar{D}^{(*)}$ interaction.

P wave → positive parity

- Meissner and Oller, PLB751(2015)59
  Testing the $\chi_{c1}p$ composite nature of the $P_c(4450)$
  $P_c(4450)$ composed of a P-wave meson χ_{c1} and a proton
- JH, PLB753 (2016) 547 [arXiv:1507.05200]
  $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks
  $P_c(4380)$ and $P_c(4450)$ as S-wave $[\bar{D}\Sigma_c^*]_{3/2-}$ and P-wave $[\bar{D}^*\Sigma_c]_{5/2+}$ molecular states.

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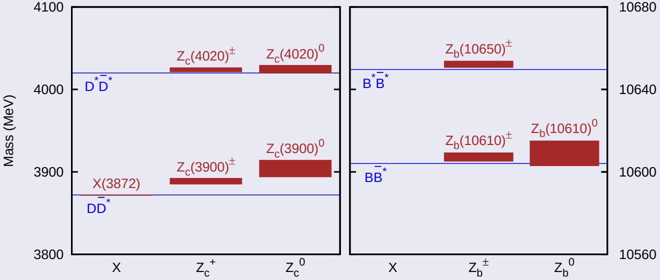
Hadronic molecular state

- Many exotic structures are close to thresholds of two hadrons.
- Theoretically, hadron-hadron interaction can produce bound state or resonance near the threshold

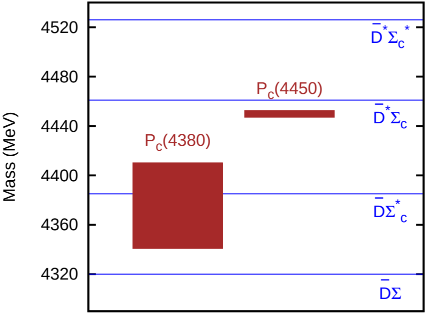
The exotic structure in experiment ↔ molecular state from hadron-hadron interaction

Example: The XYZ particles near the $D^{(*)}\bar{D}^*/B^{(*)}\bar{B}^*$ threshold



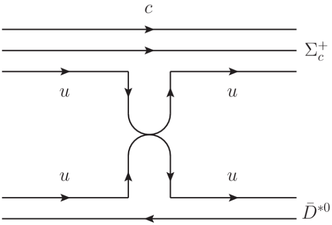
The LHCb hidden-charmed pentaquarks

- $P_c(4380)$ and $P_c(4450) \leftrightarrow \bar{D}\Sigma_c^*(2520)$ and $\bar{D}^*\Sigma_c(2455)$ thresholds
- Mass gaps: about 5 MeV and 15 MeV



- S wave provides only negative parity state.
- It conflicts with the LHCb experiment: opposite parities for two P_c states.
- Higher-wave interaction will be included.

$\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ interactions



No OZI suppression for light meson exchange
→ Heavy meson (J/ψ) exchange suppressed
→ Only light meson exchange considered

Vertex of charmed baryon and light meson

$$\begin{aligned}
\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} &= -\frac{g_1}{4f_\pi}\,\epsilon^{\alpha\beta\lambda\kappa}\langle\bar{\mathcal{B}}_6\,\overleftrightarrow{\partial}^{\kappa}\gamma_\alpha\gamma_\lambda\partial_\beta\mathbb{P}\,\mathcal{B}_6\rangle,\\
\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{V}} &= -i\frac{\beta_S g_V}{2\sqrt{2}}\,\langle\bar{\mathcal{B}}_6\,\overleftrightarrow{\partial}\cdot\mathbb{V}\,\mathcal{B}_6\rangle\\
&\quad-\frac{im_{\mathcal{B}_6}\lambda_S g_V}{3\sqrt{2}}\,\langle\bar{\mathcal{B}}_6\gamma_\mu\gamma_\nu(\partial^\mu\mathbb{V}^\nu-\partial^\nu\mathbb{V}^\mu)\mathcal{B}_6\rangle,\\
\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\sigma} &= -\ell_S m_{\mathcal{B}_6}\langle\bar{\mathcal{B}}_6\,\sigma\,\mathcal{B}_6\rangle,
\end{aligned}$$

Vertex of anticharmed meson and light meson

$$\begin{aligned}
\mathcal{L}_{\tilde{\mathcal{P}}\tilde{\mathcal{P}}\mathbb{V}} &= \frac{\beta g_V}{\sqrt{2}}\tilde{\mathcal{P}}_a^\dagger\overleftrightarrow{\partial}_\mu\tilde{\mathcal{P}}_b\mathbb{V}_{ab}^\mu,\\
\mathcal{L}_{\tilde{\mathcal{P}}\tilde{\mathcal{P}}\sigma} &= -2g_s m_{\mathcal{P}}\tilde{\mathcal{P}}_b\tilde{\mathcal{P}}_b^\dagger\sigma,\\
\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\mathbb{P}} &= -\frac{g}{f_\pi}\varepsilon_{\alpha\beta\lambda\kappa}\tilde{\mathcal{P}}_a^{*\beta\dagger}\overleftrightarrow{\partial}^\alpha\tilde{\mathcal{P}}_b^{*\kappa}\partial^\lambda\mathbb{P}_{ab},\\
\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\mathbb{V}} &= -i\frac{\beta g_V}{\sqrt{2}}\tilde{\mathcal{P}}_a^{*\dagger\mu}\overleftrightarrow{\partial}^\nu\tilde{\mathcal{P}}_{b\mu}^*\mathbb{V}_{ab\nu}\\
&\quad-i2\sqrt{2}m_{\mathcal{P}^*}\lambda g_V\tilde{\mathcal{P}}_a^{*\mu\dagger}\tilde{\mathcal{P}}_b^{*\nu}(\partial_\mu\mathbb{V}_\nu-\partial_\nu\mathbb{V}_\mu)_{ab},\\
\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\sigma} &= 2g_s m_{\mathcal{P}^*}\tilde{\mathcal{P}}_b^*\cdot\tilde{\mathcal{P}}_b^{*\dagger}\sigma
\end{aligned}$$

$\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ potential

JH, PLB753(2016)547

The $\bar{D}\Sigma_c^*$ interaction

$$\mathcal{V}_{\mathbb{V}} = i\frac{\beta g_V^2}{2}\left[\frac{\beta_S}{2}(k_2+k_2)\cdot(k_1+k_1')\bar{\Sigma}_c^*\cdot\Sigma_c^* - m_{\Sigma_c^*}\lambda_S(\bar{\Sigma}^*\cdot q\right.$$
$$\left.\cdot\ \Sigma_c^*\cdot(k_1+k_1') - \bar{\Sigma}_c^*\cdot(k_1+k_1')\,\Sigma_c^*\cdot q\right]\ P_{\mathbb{V}}(q^2),$$
$$\mathcal{V}_\sigma = i2\ell_S g_s m_D m_{\Sigma_c^*}\Sigma_c^*\cdot\Sigma^* P_\sigma(q^2).$$

The $\bar{D}^*\Sigma_c^*$ interaction

$$\begin{aligned}
\mathcal{V}_{\mathbb{P}} &= -i\frac{3gg_1}{4f_\pi^2}\epsilon^{\alpha\beta\lambda\kappa}\bar{D}_\beta^{*\dagger}(k_1+k_1')_\alpha\bar{D}_\kappa^* q_\lambda\\
&\cdot\ \epsilon^{\alpha'\beta'\lambda'\kappa'}(k_2+k_2')_{\kappa'}q_{\beta'}\ \bar{\Sigma}_{c\alpha'}^*\Sigma_{c\lambda'}^*\ P_{\mathbb{P}}(q^2),\\
\mathcal{V}_{\mathbb{V}} &= ig_V^2\Big\{-\frac{\beta\beta_S}{4}(k_1+k_1')\cdot(k_2+k_2')\bar{D}^{*\dagger}\cdot\bar{D}^*\bar{\Sigma}_c^*\cdot\Sigma_c^*\\
&+ 2m_{\Sigma_c^*}m_{D^*}\lambda\lambda_S[\bar{D}^{*\dagger}\cdot q(\bar{\Sigma}_c^*\cdot q\Sigma_c^*\cdot\bar{D}^* - \bar{\Sigma}_c^*\cdot\bar{D}^*\Sigma_c^*\cdot q)\\
&- \bar{D}^*\cdot q(\bar{\Sigma}_c^*\cdot q\Sigma_c^*\cdot\bar{D}^{*\dagger} - \bar{\Sigma}_c^*\cdot D^{*\dagger}\Sigma_c^*\cdot q)] + \frac{m_{\Sigma_c^*}\beta\lambda_S}{2}\\
&\cdot\ [q^\mu(k_1+k_1')^\nu - q^\nu(k_1+k_1')^\mu]\bar{D}^{*\dagger}\cdot\bar{D}^*\bar{\Sigma}_{c\mu}^*\Sigma_{c\nu}^* - \lambda\beta_S m_{P^*}\\
&\cdot\ [q_\mu(k_1+k_1')_\nu - q_\nu(k_1+k_1')_\mu]\bar{D}^{\mu\dagger}\bar{D}^{*\nu}\bar{\Sigma}_c^*\cdot\Sigma_c^*\Big\}P_{\mathbb{V}}(q^2),\\
\mathcal{V}_\sigma &= -i2g_s\ell_S m_{\bar{D}^*}m_{\Sigma_c^*}\bar{\Sigma}_c^*\cdot\Sigma_c^*\ \bar{D}^{*\dagger}\cdot\bar{D}^*P_\sigma(q^2).
\end{aligned}$$

The $\bar{D}^*\Sigma_c$ interaction

$$\mathcal{V}_{\mathbb{P}} = i\frac{gg_1}{4f_\pi^2}\epsilon_{\alpha\beta\lambda\kappa}\bar{D}^{*\beta\dagger}(k_1+k_1')^\alpha\bar{D}^{*\kappa}q^\lambda\epsilon^{\alpha'\beta'\lambda'\kappa'}(k_2+k_2')_{\kappa'}$$
$$q_{\beta'}\ \bar{\Sigma}_c\ \gamma_{\alpha'}\gamma_{\lambda'}\ \Sigma_c\ P_{\mathbb{V}}(q^2),$$
$$\mathcal{V}_{\mathbb{V}} = ig_V^2\Big\{\frac{\beta\beta_S}{4}(k_1+k_1')\cdot(k_2+k_2')\bar{D}^{*\dagger}\cdot\bar{D}^*\ \bar{\Sigma}_c\Sigma - \frac{m_{\Sigma_c}\beta\lambda_S}{6}[q^\mu$$
$$\cdot\ (k_1+k_1')^\nu - q^\nu(k_1+k_1')^\mu]\bar{\Sigma}_c\gamma_\mu\gamma_\nu\Sigma_c\ \bar{D}^{*\dagger}\cdot\bar{D}^* + \lambda\beta_S m_{D^*}$$
$$\cdot\ [q_\mu(k_1+k_1')_\nu - q_\nu(k_1+k_1')_\mu]\bar{D}^{\mu\dagger}\bar{D}^{*\nu}\ \bar{\Sigma}_c\Sigma_c - \frac{2m_{\Sigma_c}m_{D^*}\lambda\lambda_S}{3}$$
$$\cdot\ \bar{\Sigma}_c[\gamma\cdot q(q^\mu\gamma^\nu - q^\nu\gamma^\mu) - (q^\mu\gamma^\nu - q^\nu\gamma^\mu)\gamma\cdot q]\Sigma_c\bar{D}_\mu^\dagger\bar{D}_\nu^*\Big\}\ P_{\mathbb{V}}(q^2),$$
$$\mathcal{V}_\sigma = i2g_s\ell_S m_{D^*}m_{\Sigma_c^*}\bar{\Sigma}_c\Sigma_c\ \bar{D}^{*\dagger}\cdot\bar{D}^*P_\sigma(q^2).$$

Form factor

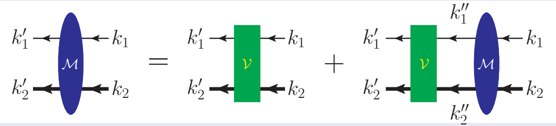
Propagator:

$$\begin{aligned}
P_{\mathbb{P}}(q^2) &= \left(\frac{-1}{q^2-m_\pi^2}+\frac{1}{6}\frac{1}{q^2-m_\eta^2}\right),\\
P_{\mathbb{V}}(q^2) &= \left(\frac{-1}{q^2-m_\rho^2}-\frac{1}{2}\frac{1}{q^2-m_\omega^2}\right),\\
P_\sigma(q^2) &= \frac{1}{q^2-m_\sigma^2}.
\end{aligned}$$

A form factor is introduced to compensate the off-shell effect of exchange meson as $f(q^2) = (\frac{\Lambda^2}{\Lambda^2-q^2})^4$

Bethe-Salpeter equation (BSE)

A 4D integral equation in Minkowski space



$$\begin{aligned}\mathcal{M}(k_1'k_2', k_1k_2; P) &= \mathcal{V}(k_1'k_2', k_1k_2; P)\\ &+ \int \frac{d^4k''}{(2\pi)^4}\mathcal{V}(k_1'k_2', k_1''k_2''; P)G(k_1''k_2'')\mathcal{M}(k_1''k_2'', k_1k_2; P).\end{aligned}$$

Reduction to a 3D integral equation

- Direct solution of the BSE is complicated and much computer time is required.
- Integrate out the zero component of momentum k'', k''^0.
- The 4D integral equation is reduced to a familiar 3D equation on 3-vector momentum $\boldsymbol{k}''$.

How to do it?

Quaipotential approximation: 4D BSE → 3D BSE

Gross, PRC26(1982)2203

The BSE is equivalent to a pair of equations

$$\begin{aligned}\mathcal{M} &= U - UG_0\mathcal{M}\\ U &= V - V(G-G_0)U\end{aligned}$$

Quasipotential approximation

Choose G_0 in a way that

- $G - G_0$ is small, so $U \approx V$.
- k''^0 can be integrated out.
- G_0 satisfies the unitarity condition

Infinite choices:

- BSLT approximation
- K-matrix method
- Instantaneous approximation

The covariant spectator theory(CST)

$$G_0 = 2\pi i \frac{\delta^+(k_1^2 - m_1^2)}{k_2^2 - m_2^2}$$

- Maintains manifest covariance
- BS and CST are equivalent when both are solved exactly.
- Gives the correct "one body limit".
- Preserves cluster separability.
- converges more rapidly that the BSE.
- CST have been applied successfully to the study of Deuteron and the NN scattering.

The interested audience is referred to the works by Gross et al.

Partial wave analysis: reduce 3D BSE to 1D BSE

JH, PRD90 (2014)076008

- The partial wave decomposition is done directly into the quantum number J^P.
- All partial waves based on L related to a certain J^P are included.
- Advantage: the experiment result is usually provided with spin parity J^P.

The BSE for a fixed spin parity J^P

$$\mathcal{M}^{J^P}_{\lambda\lambda'}(\mathrm{p},\mathrm{p}') = \mathcal{V}^{J^P}_{\lambda,\lambda'}(\mathrm{p},\mathrm{p}') + \sum_{\lambda''}\int \frac{\mathrm{p}''^2 d\mathrm{p}''}{(2\pi)^3}\mathcal{V}^{J^P}_{\lambda\lambda''}(\mathrm{p},\mathrm{p}'')G_0(\mathrm{p}'')\mathcal{M}^{J^P}_{\lambda''\lambda'}(\mathrm{p}'',\mathrm{p}').$$

where λ, λ' and $\lambda'' \geq 0$ and $\hat{M}^{J^P}_{\lambda'\lambda} = f_{\lambda'} f_{\lambda} M^{J^P}_{\lambda'\lambda}$, with $f_0 = \frac{1}{\sqrt{2}}$ and $f_{\lambda\neq 0} = 1$.

The potential is defined as

$$\mathcal{V}^{J^P}_{\lambda'\lambda}(\mathrm{p}',\mathrm{p}) = 2\pi\int d\cos\theta\ [d^J_{\lambda\lambda'}(\theta)\mathcal{V}_{\lambda'\lambda}(\boldsymbol{p}',\boldsymbol{p}) + \eta d^J_{-\lambda\lambda'}(\theta)\mathcal{V}_{\lambda'-\lambda}(\boldsymbol{p}',\boldsymbol{p})],$$

where $k_1 = (W-E, 0, 0, -\mathrm{p})$, $k_2 = (E, 0, 0, \mathrm{p})$ and $k_1' = (W-E', -\mathrm{p}'\sin\theta, 0, -\mathrm{p}'\cos\theta)$, $k_2' = (E', \mathrm{p}'\sin\theta, 0, \mathrm{p}'\cos\theta)$ with $\mathrm{p} = |\boldsymbol{p}|$ in order to avoid confusion with the four-momentum p.

Solving the 1D BSE for scattering amplitude

JH, PRD90 (2014)076008

We discretize the momenta p, p' and p'' by the Gaussian quadrature with weight $w(\mathrm{p}_i)$,

$$iM_{ik} = iV_{ik} + \sum_{j=0}^{N} iV_{ij} G_j iM_{jk},$$

with the discretized propagator

$$\begin{aligned} G_{j>0} &= \frac{w(\mathrm{p}''_j)\mathrm{p}''^2_j}{(2\pi)^3} G_0(\mathrm{p}''_j), \\ G_{j=0} &= -\frac{i\mathrm{p}''_o}{32\pi^2 W} + \sum_j \left[\frac{w(\mathrm{p}_j)}{(2\pi)^3} \frac{\mathrm{p}''^2_o}{2W(\mathrm{p}''^2_j - \mathrm{p}''^2_o)} \right]. \end{aligned}$$

In numerical solution, N should be large enough to produce stable result. Usually, $N = 50$ is chosen.

For a certain reaction, the initial and final particles should be on-shell. The scattering amplitude is

$$\hat{M} = M_{00} = \sum_j [(1 - VG)^{-1}]_{0j} V_{j0}. \qquad \text{pole} : |1 - VG| = 0$$

The total cross section can be written as

$$\sigma = \frac{1}{16\pi s} \frac{|\mathrm{p}'|}{|\mathrm{p}|} \sum_{J^P,\lambda\geq 0\lambda'\geq 0} \frac{2J+1}{2} \left| \frac{\hat{M}^{J^P}_{\lambda\lambda'}}{4\pi} \right|^2 .$$

Note that the second sum extends only over positive λ and λ'. Since there is no interference between the contributions from different partial waves, the total cross section can also be divided into partial-wave cross sections, allowing a direct access to the importance of the individual partial waves.

Outline

1. Introduction
   - Studies about pentaquarks before LHCb experiment
   - LHCb Experiment
   - Theoretical studies after LHCb experiment

2. LHCb pentaquarks as hadronic molecular states
   - Hadronic molecular state
   - $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ interactions
   - Qusipotential Bethe-Salpeter equation

3. Results and Discussion
   - Bound states from $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ interactions
   - Could P-wave state be observed in experiment?
   - Summary

Bound states from $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$ interactions

JH, PLB753(2016)547

Bound state relevant to $P_c(4380)$ and $P_c(4450)$

$$\begin{array}{llll} P_c(4380): & \bar{D}\Sigma_c^*\ [3/2^-, 0.7{-}1.4], & \bar{D}\Sigma_c^*\ [3/2^+, 2.8{-}5.0], & \bar{D}^*\Sigma_c[3/2^-, 3.0{-}3.7]; \\ P_c(4450): & \bar{D}^*\Sigma_c[5/2^+, 2.7{-}2.8], & \bar{D}^*\Sigma_c[5/2^-, 2.8{-}2.9], & \bar{D}^*\Sigma_c^*[5/2^+, 2{-}2.1]. \end{array}$$

The values in the bracket are spin-parity of the system and the cut offs in the unit of GeV which produces the experimental mass within uncertainties.

Identification of $P_c(4380)$ and $P_c(4450)$ based on mass and spin parity

LHCb experiment:

$$\begin{array}{lll} P_c(4380): & M = 4380 \pm 8 \pm 29 \text{ MeV}, & J^P = 3/2^-. \\ P_c(4450): & M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}, & J^P = 5/2^+. \end{array}$$

Hence, we can identify the $P_c(4380)$ and the $P_c(4450)$ as

$$P_c(4380) : \bar{D}\Sigma_c^*[3/2^-]; \quad P_c(4450) : \bar{D}^*\Sigma_c[5/2^+].$$

$P_c(4450)$ is a state from P- and F-wave $\bar{D}^*\Sigma_c$ interaction!

Could P-wave state be observed in experiment? Toy Model

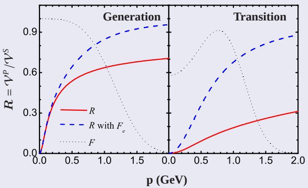
JH, arXiv:1607.03223

Two-channel scattering of scalar mesons

	Generation channel	Observation channel	Coupling
Mass of threshold M_{12}	$M_{\bar{D}^*\Sigma_c}$	$M_{J/\psi p}$	$--$
mass of exchanged meson m_{ex}	m_π		m_D
Potential $i\mathcal{V}$	$\frac{C}{q^2-m_\pi^2}$	0	$\frac{C'}{q^2-m_D^2}$

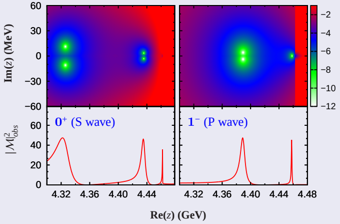
$\boldsymbol{R} = \mathcal{V}^P/\mathcal{V}^S$

$$\mathcal{V}^l_{ij}(\mathrm{p}', \mathrm{p}) = 4\pi \int d\cos\theta \; P_l(\theta)\mathcal{V}_{ij}(\boldsymbol{p}', \boldsymbol{p})$$



P-wave interaction is not so small

Pole and Peak observed in Observation channel

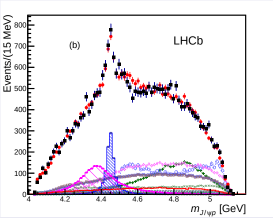


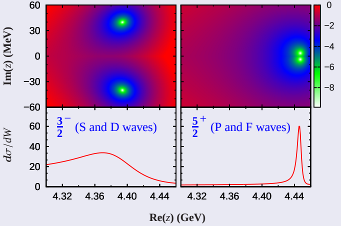
P-wave state can be observed

Application to the $\bar{D}^*\Sigma_c$ interaction

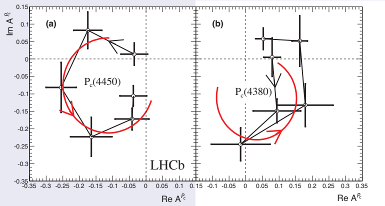
JH, arXiv:1607.03223

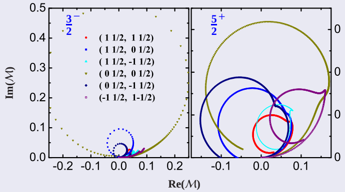
Pole





Argand





Discussion

LHCb experiment

$P_c(4380)$	$P_c(4450)$	$\Delta(-2\ln\mathcal{L})$
$3/2^-$	$5/2^+$	0
$3/2^+$	$5/2^-$	0.9^2
$5/2^+$	$3/2^-$	2.3^2
..	..	$> 5^2$

Bound state

$P_c(4380)$: $\bar{D}\Sigma_c^*\ [3/2^-, 0.7{-}1.4]$,
$\bar{D}\Sigma_c^*\ [3/2^+, 2.8{-}5.0]$,
$\bar{D}^*\Sigma_c[3/2^-, 3.0{-}3.7]$;
$P_c(4450)$: $\bar{D}^*\Sigma_c[5/2^+, 2.7{-}2.8]$,
$\bar{D}^*\Sigma_c[5/2^-, 2.8{-}2.9]$,
$\bar{D}^*\Sigma_c^*[5/2^+, 2{-}2.1]$.

- Too many bound state are produce from the interactions with different cutoffs. The cutoff for each interaction should be different and has not been determined in experiment or theory.
- It is more natural to assign the $P_c(4380)$ and the $P_c(4450)$ as $3/2^-$-wave and $5/2^+$-wave $\bar{D}^*\Sigma_c$ state. Only one cutoff is Involved.
- The existence of two or more resonant signals around 4380 MeV, especially those with spin parity $3/2^-$, can not be excluded because of the large widths for the $P_c(4380)$ obtained here and in experiment. So, it do not conflict with the identification based on mass and J^P.

Summary

We study the possibility to interpret two LHCb pentaquarks $P_c(4380)$ and $P_c(4450)$ as molecular state from the $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ interactions.

- Many bound states can be produced from the $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and the $\bar{D}^*\Sigma_c^*$ interactions
- Two possible assignments of $P_c(4380)$ and the $P_c(4450)$:
  as $3/2^-$ $\bar{D}\Sigma_c^*$ and $5/2^+$ $\bar{D}^*\Sigma_c$ molecular state based on mass and J^P.
  as $3/2^-$ and $5/2^+$ $\bar{D}^*\Sigma_c$ molecular state base on a two-channel analysis.
- The $P_c(4450)$ is a $5/2^+$ $\bar{D}^*\Sigma_c$ state.
  The $P_c(4380)$ may have more complicated origin.

- P-wave introduction can produce a bound state as well as S-wave interaction.
- The P-wave state can be observed as well as S-wave state.
- P wave may be non-negligible even when the S wave is not forbidden.

Thank you!