$\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ interactions and LHCb hidden-charmed pentaquarks

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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
   - 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?
   - Discussion and 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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ 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:

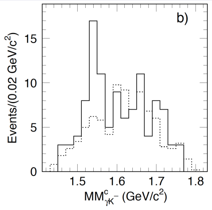
  Gignoux et al., PLB193(1987)323

  Lipkin PLB195(1987)484

  The name "pentaquark" was proposed.

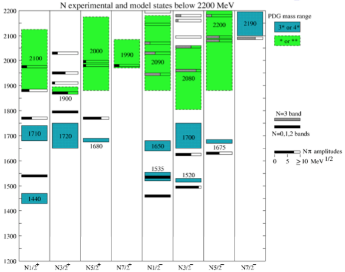
- ....

Experimental studies: Θ



Theoretical predictions about hidden-charmed pentaquark

Hidden-charmed N^* above 4 GeV



Hadronic molecular state

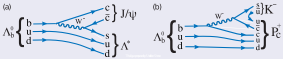
- Wu, Molina, Oset, and Zou, Phys.Rev.Lett.105 (2010) 232001
  Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV,
- Yang, Sun, JH, Liu, Zhu, Chin. Phys. C36 (2012) 6
  The possible hidden-charm molecular baryons composed of anti-charmed meson and charmed baryon,
- Wang, Huang, Zhang, and Zou, Phys. Rev. C84 (2011) 015203
  $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ states in a chiral quark model
- Karliner, Rosner, Phys. Rev. Lett. 115 (2015) 122001
  New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules

Multiquark

- 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

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

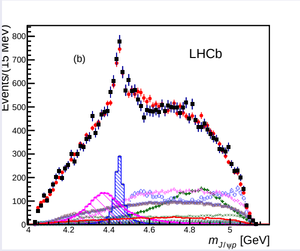
Observed in $J/\psi p$ channel of $\Lambda_b^0 \to J/\psi K^- p$ decay.

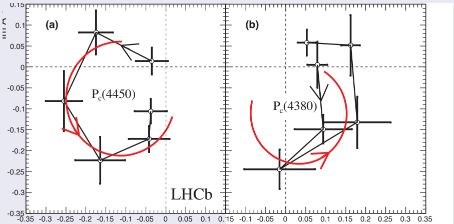


$M = 4380 \pm 8 \pm 29$ MeV, $\Gamma = 205 \pm 18 \pm 86$ MeV.
$M = 4449.8 \pm 1.7 \pm 2.5$ MeV, $\Gamma = 39 \pm 5 \pm 19$ MeV.

$P_c(4380)$	$P_c(4450)$	$\Delta(-2\ln\mathcal{L})$
$3/2^-$	$5/2^+$	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 more than 200 articles.

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
- ...

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
- ...

S-wave molecular state : negative parity

- Roca, Nieves, Oset, PRD92(2015)094003
  LHCb pentaquark as a $\bar{D}^*\Sigma_c - \bar{D}^*\Sigma^*$ molecular state
- Chen, Chen, Liu, Steele, Zhu, PRL115(2015)172001
  Towards exotic hidden-charm pentaquarks in QCD
- ...

P wave → positive parity

- Meissner and Oller, PLB751(2015)59
  Testing the $\chi_{c1}p$ composite nature of the $P_c(4450)$
  P-wave meson χ_{c1}
- JH, PLB753 (2016) 547
  $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks
  P-wave interaction

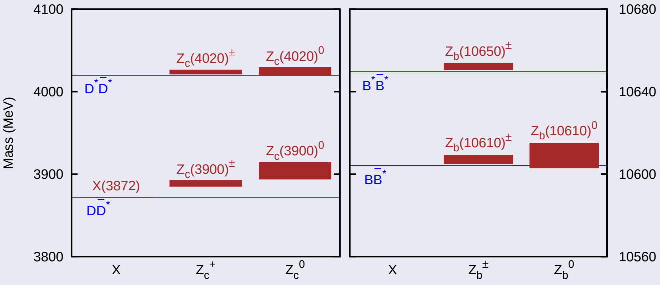
Outline

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

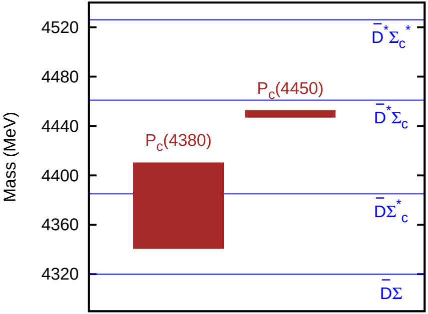
The exotic structure in experiment ↔ molecular state from hadron-hadron interaction

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



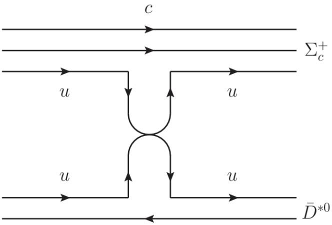
The LHCb hidden-charmed pentaquarks

- $P_c(4380)$ 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
→ Heavy meson (J/ψ) exchange suppressed
→ Only light meson exchange considered

Vertex of charmed baryon and light meson

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} = -\frac{g_1}{4f_\pi}\epsilon^{\alpha\beta\lambda\kappa}\langle\bar{\mathcal{B}}_6\overleftrightarrow{\partial}^\kappa\gamma_\alpha\gamma_\lambda\partial_\beta\mathbb{P}\,\mathcal{B}_6\rangle,$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{V}} = -i\frac{\beta_S g_V}{2\sqrt{2}}\langle\bar{\mathcal{B}}_6\overleftrightarrow{\partial}\cdot\mathbb{V}\,\mathcal{B}_6\rangle - \frac{im_{\mathcal{B}_6}\lambda_S g_V}{3\sqrt{2}}\langle\bar{\mathcal{B}}_6\gamma_\mu\gamma_\nu(\partial^\mu\mathbb{V}^\nu-\partial^\nu\mathbb{V}^\mu)\mathcal{B}_6\rangle,$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\sigma} = -\ell_S m_{\mathcal{B}_6}\langle\bar{\mathcal{B}}_6\,\sigma\,\mathcal{B}_6\rangle,$$

Vertex of anticharmed meson and light meson

$$\mathcal{L}_{\tilde{\mathcal{P}}\tilde{\mathcal{P}}\mathbb{V}} = \frac{\beta g_V}{\sqrt{2}}\tilde{\mathcal{P}}_a^\dagger\overleftrightarrow{\partial}_\mu\tilde{\mathcal{P}}_b\mathbb{V}_{ab}^\mu,$$

$$\mathcal{L}_{\tilde{\mathcal{P}}\tilde{\mathcal{P}}\sigma} = -2g_s m_{\mathcal{P}}\tilde{\mathcal{P}}_b\tilde{\mathcal{P}}_b^\dagger\sigma,$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\mathbb{P}} = -\frac{g}{f_\pi}\varepsilon_{\alpha\beta\lambda\kappa}\tilde{\mathcal{P}}_a^{*\beta\dagger}\overleftrightarrow{\partial}^\alpha\tilde{\mathcal{P}}_b^{*\kappa}\partial^\lambda\mathbb{P}_{ab},$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\mathbb{V}} = -i\frac{\beta g_V}{\sqrt{2}}\tilde{\mathcal{P}}_a^{*\dagger\mu}\overleftrightarrow{\partial}^\nu\tilde{\mathcal{P}}_{b\mu}^*\mathbb{V}_{ab\nu} - i2\sqrt{2}m_{\mathcal{P}^*}\lambda g_V\tilde{\mathcal{P}}_a^{*\mu\dagger}\tilde{\mathcal{P}}_b^{*\nu}(\partial_\mu\mathbb{V}_\nu-\partial_\nu\mathbb{V}_\mu)_{ab},$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\sigma} = 2g_s m_{\mathcal{P}^*}\tilde{\mathcal{P}}_b^*\cdot\tilde{\mathcal{P}}_b^{*\dagger}\sigma$$

$\bar D\Sigma_c^*$, $\bar D^*\Sigma_c$ 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

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

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

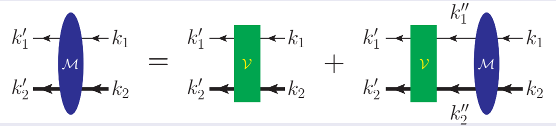
Propagator:

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

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 $\rightarrow$ 3D BSE

Gross, PRC26(1982)2203

The BSE is equivalent to a pair of equations

$$\mathcal{M} = U - UG_0\mathcal{M}$$
$$U = V - V(G - G_0)U$$

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 here is done into the quantum number J^P instead of usual orbital angular momentum L
- 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

$$G_{j>0} = \frac{w(\mathrm{p}''_j)\mathrm{p}''^2_j}{(2\pi)^3} G_0(\mathrm{p}''_j),$$

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

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

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 $P_c(4450)$

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

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:

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

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

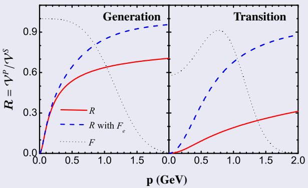
JH, arXiv:1607.03223

Two-channel scattering of scalar mesons

	Generation channel	Observation channel	Coupling
Mass of threshold $M_{1,2}$	$M_{\bar{D}^*,\Sigma_c}$	$M_{J/\psi,p}$	$--$
mass of exchanged meson m_{ex}	m_π		m_D
Potential $i\mathcal{V}$	$\frac{C}{q^2-m_\pi^2}$	0	$\frac{C'}{q^2-m_D^2}$

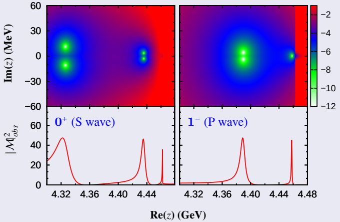
$\boldsymbol{R} = \mathcal{V}^P/\mathcal{V}^S$

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



P-wave interaction is not so small

Pole and Peak observed in Observation channel

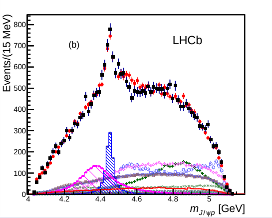


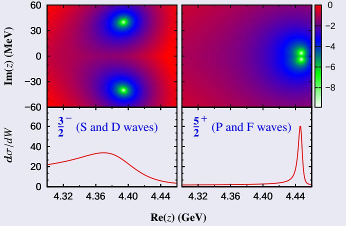
P-wave state can be observed

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

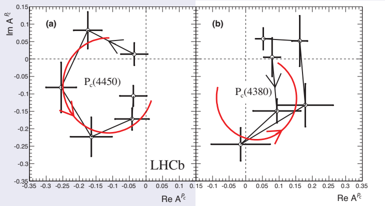
JH, arXiv:1607.03223

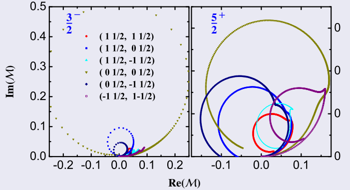
Pole





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

$P_c(4380)$: $\bar{D}\Sigma_c^*$ $[3/2^-, 0.7\text{–}1.4]$, $\bar{D}\Sigma_c^*$ $[3/2^+, 2.8\text{–}5.0]$, $\bar{D}^*\Sigma_c[3/2^-, 3.0\text{–}3.7]$;

$P_c(4450)$: $\bar{D}^*\Sigma_c[5/2^+, 2.7\text{–}2.8]$, $\bar{D}^*\Sigma_c[5/2^-, 2.8\text{–}2.9]$, $\bar{D}^*\Sigma_c^*[5/2^+, 2\text{–}2.1]$.

- 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!