Strong decay mode J/ψ p for the pentaquark states $P_c(4380)$,$P_c(4450)$

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Contents

1, Introduction (recent multi-quark)

The XYZ states

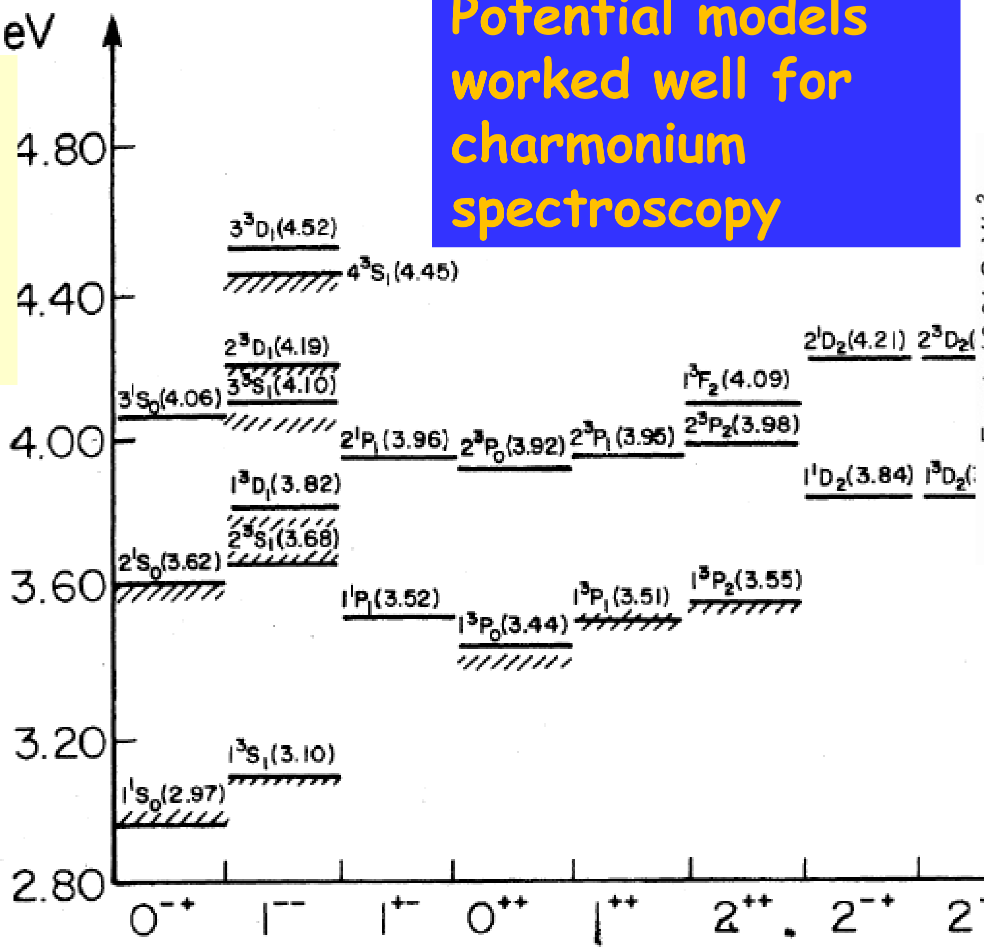
Z(4430)
Z(4250)
Z(4050)
Z(4200)
Zc(3900)
Zc(4020)

X(3872)

XYZ(3940)

X(3915)
X(4160)
Y(4008)
Y(4140)
Y(4260)
Y(4360)
X(4350)
Y(4660)

Potential models worked well for charmonium spectroscopy

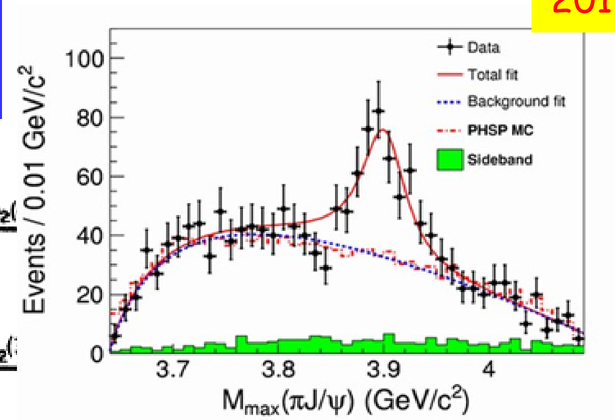


BESIII, Belle and CLEO-c → $Z_c(3900)$

$M_{Zc(3900)} = (3899 \pm 3.6 \pm 4)$ MeV

$\Gamma_{Zc(3900)} = (46 \pm 10 \pm 20)$ MeV

2013



Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

Not all XYZ states are charmonia!

Courtesy of C. Z.Yuan

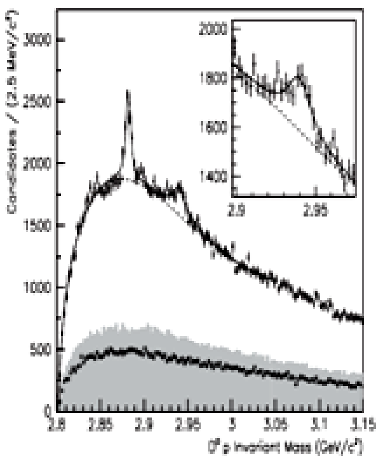
(New resonances, five-quark)

$\Lambda_c(2940)^+$

PRL 98, 012001 (2007) PHYSICAL REVIEW LETTERS week ending 5 JANUARY 2007

Observation of a Charmed Baryon Decaying to $D^0 p$ at a Mass Near 2.94 GeV/c^2

(BABAR Collaboration)



The results for the $\Lambda_c(2940)^+$ baryon are

$$m = [2939.8 \pm 1.3(\text{stat}) \pm 1.0(\text{syst})]\ \text{MeV}/c^2,$$
$$\Gamma = [17.5 \pm 5.2(\text{stat}) \pm 5.9(\text{syst})]\ \text{MeV}.$$

For the $\Lambda_c(2880)^+$ baryon the results are

$$m = [2881.9 \pm 0.1(\text{stat}) \pm 0.5(\text{syst})]\ \text{MeV}/c^2,$$
$$\Gamma = [5.8 \pm 1.5(\text{stat}) \pm 1.1(\text{syst})]\ \text{MeV}.$$

$$|\Lambda_c(2940)^+\rangle = \alpha\,|pD^{*0}\rangle + \beta\,|nD^{*+}\rangle$$

$1^\pm/2,\quad 3^\pm/2$

arXiv:1507.03414v1 [hep-ex] 13 Jul 2015

Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

The LHCb collaboration[†]

Abstract

Observations of exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis is performed on the three-body final-state that reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

Five-quark

$\Sigma_c\bar{D},\ \Sigma_c^*\bar{D},\ \Sigma_c\bar{D}^*,\ \Sigma_c^*\bar{D}^*,\ p\chi_{c1},\ \psi(2S)p$

$3^-/2,\qquad 5^+/2(J^P?)$

$P_c(4380),\qquad P_c'(4449)$

d*(2380), six-quark (light quarks)

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

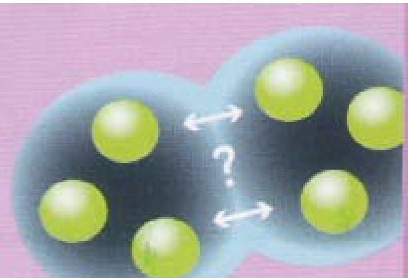
CERN COURIER

VOLUME 54 NUMBER 6 JULY/AUGUST 2014

Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers $I(J^P) = 0(3^+)$. The structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic compact particle or a hadronic molecule. The result answers the long-standing question of whether there are more eigenstates in the two-baryon system than just the deuteron ground-state. This fundamental question has been awaiting an answer since at least 1964, when first Freeman Dyson and later Robert Jaffe envisaged the possible existence of non-trivial six-quark configurations.

EXOTICS

COSY's new evidence for a six-quark state



Approaches/ Interpretations

QCD sum rule

Non relativistic QCD

Heavy quark effective theory

Heavy hadron chiral perturbation theory

Potential models

Lattice calculations

- Molecule, baryonium
- tetraquark
- Hybrids
- Coupling channel, CUSPs,tringle singularity, …

Quark
+degrees
of freedom

Hadronic molecules

- Weekly bound state of two or three hadrons
- Typical examples: Nuclei and hyper-nuclei
- Baryon-baryon bound state: $M_H < M_1 + M_2$

- The Molecule idea has a long history

Voloshin, Okun (1976)

- De Rujula, George, and Glashow (1977)

Long-range one-pion exchange (Tornqvist, ZPC1993)

Meson-exchange models (Lohse, et al., 1990)

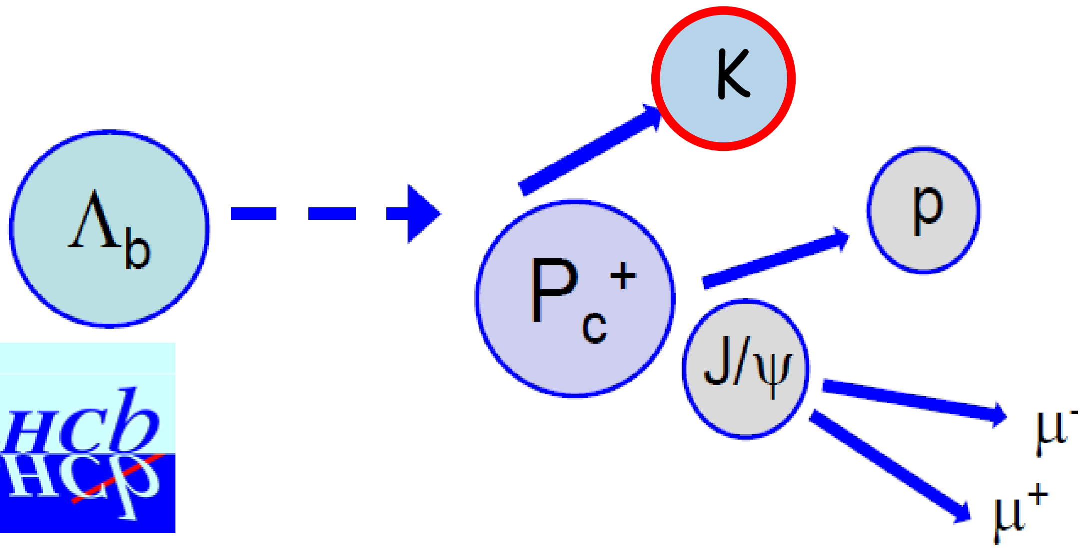
Unitarized coupled channel models with chiral Lagrangians (Olier, et al., 1997; Jido et al., 2005, Gammermann et al., 08)+……Chinese+

2, Molecule scenario
Of Two Pentaquark states
Pc(4380)+, and Pc(4450)+

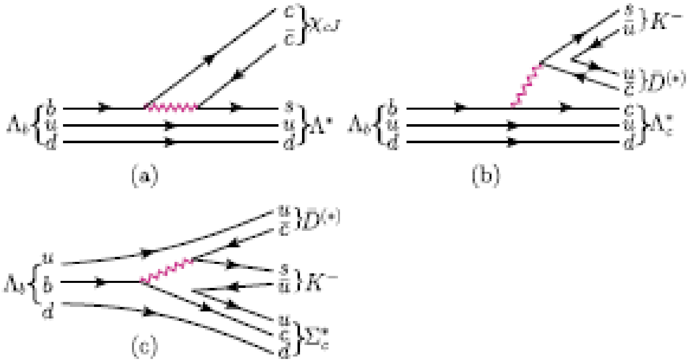
Observation of J/ψp resonances consistent with pentaquark states

PRL 115, 07201, arXiv:1507.03414

Exotic Hadron Spectroscopy at LHCb:
Candidates for Tetra- and Pentaquark States



$$b \to c + \bar{c}s$$

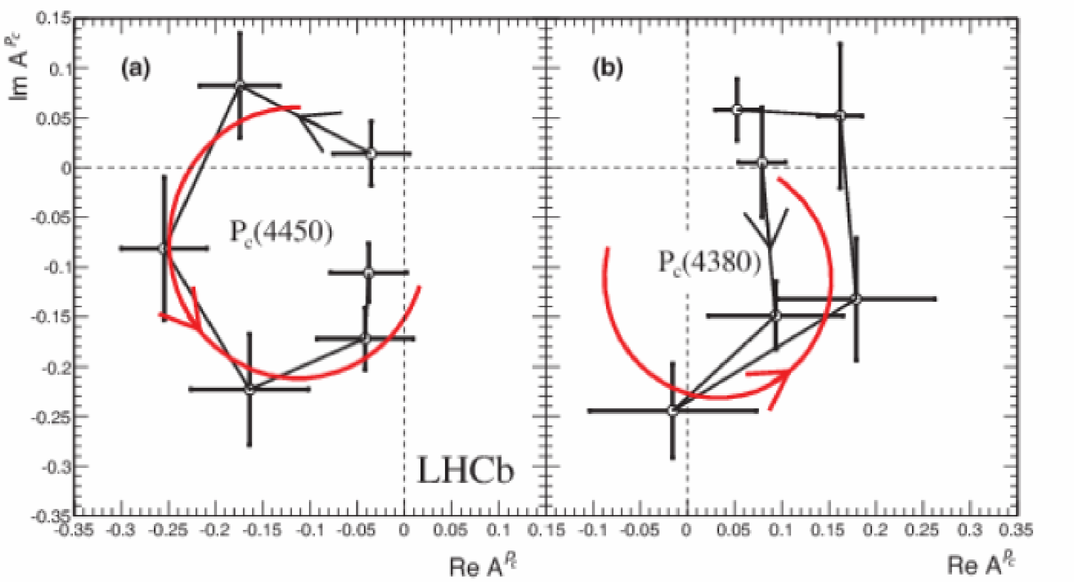


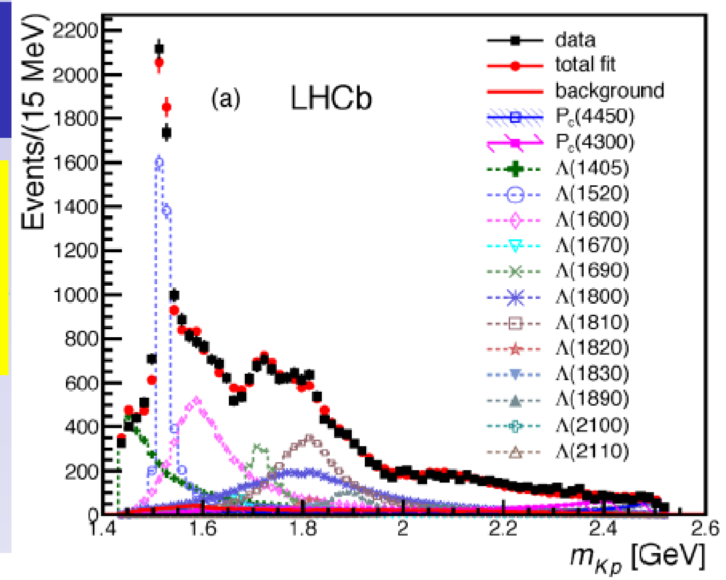
Pentaquark states

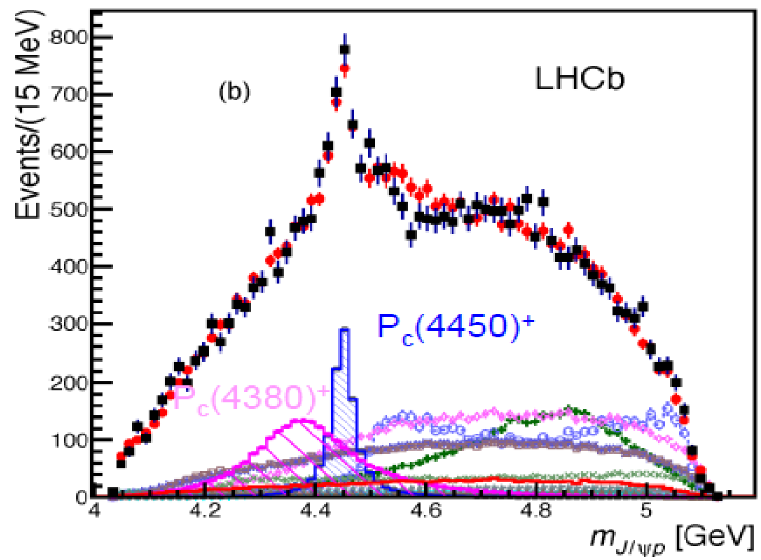
$P_c^+(4380):(M;\Gamma)=(4380\pm8\pm29;205\pm18\pm86)MeV$

$P_c^+(4450):(M;\Gamma)=(4449.8\pm1.7\pm2.5;39\pm5\pm19)MeV$

Spin-parity: $(3/2^-,5/2^+)$, $(3/2^+,5/2^-)$, or $(5/2^+,3/2^-)$.







$P_c(4450)^+$	12σ
$P_c(4380)^+$	9σ
$P_c(4450)$ & $P_c(4380)$	15σ

Phys. Rev. Lett. 115, 072001 (2015).

$$\mathcal{B}(\Lambda_b^0\to J/\psi K^- p) = 3.04\pm0.04\pm0.06\pm0.33^{+0.43}_{-0.27}\times10^{-4},$$

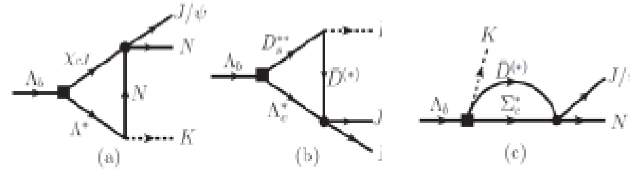
$$\mathcal{B}(\Lambda_b^0\to P_c^+(4380)K^-)\mathcal{B}(P_c^+(4380)\to J/\psi p) = 2.56\pm0.22\pm1.28^{+0.46}_{-0.36}\times10^{-5},$$

Interpretations of two Pc

*kinematic effects in non-perturbative rescattering processes
(CUSPS or triangle singularity)

e.g. arXiv:1507.04950, 1507.05359, 1507.06552, et.al..

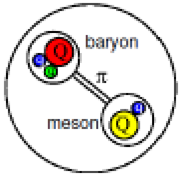
from arXiv:1507.05359



*bound states(or resonances) by open-charm baryon and meson

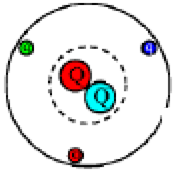
4.g. arXiv: 1507.03717, 1507.03704,1507.05200, 1507.4249 et. al.

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



*baryon+charmonia

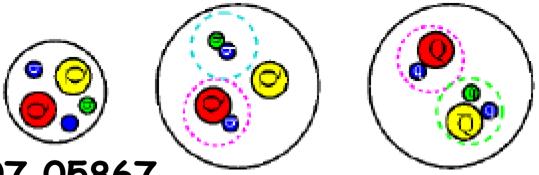
e.g. arXiv:1507.07478,1508.00888, 1512.00426



$\chi_{c1}p$, $\psi(2S)p$

*Tightly bound pentaquark states

e.g.arXiv; 1201.0807,1507.04980,1507.07652,1508.00356,1507.05867,
1507.08252, 1508.01468,1508.04189



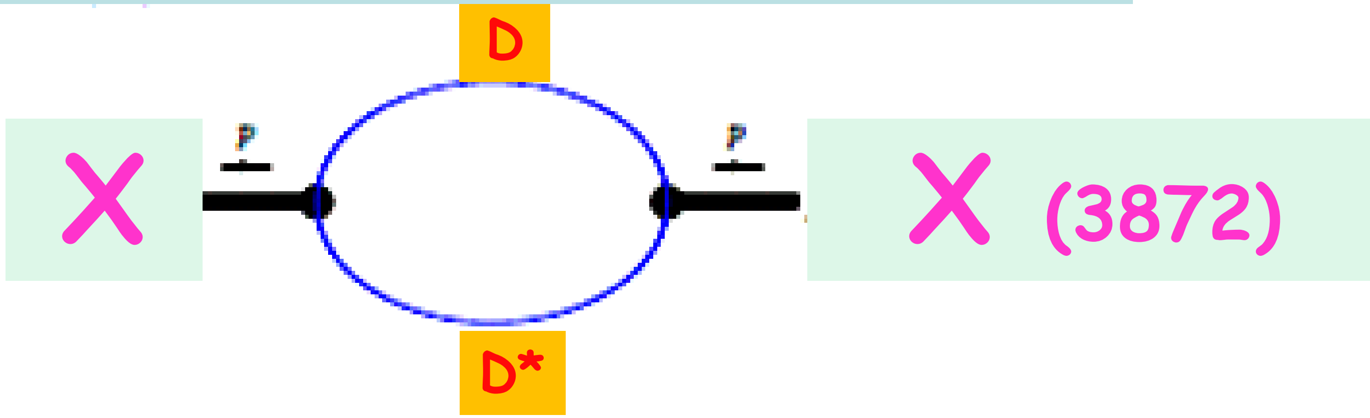
*coupled-channle unitary approach: A series of meson-baryon dynamically generators

e.g. arXiv:PRL105,232001; PRC84,015202, PRD92,094003, etl.al…

Our Phenomenological approach:

Molecule scenario PRD77,094013+…

The mass operator represented by $\widetilde{\Pi}(p^2)$



in Collaboration with Amand Faessler, Thomas Gutsche, and V. E. Lyubovitskij

$$L_{XDD} = X_\mu J^\mu$$

$$= \frac{g_X}{\sqrt{2}} X_\mu \int d^4y\, \Phi_X(y^2)[D(x+y/2)\bar{D}^{*\mu}(x-y/2)+\bar{D}(x+y/2)D^{*\mu}(x-y/2)]$$

Correlation function

Two fields

Compositeness condition:

Bound state description of hadronic molecules in QFT based on compositeness condition: Weinberg,PR1963;Salam, Nuov.Cim. 1962 Heyashi et al.,Fortsch. Phys. 1967

The coupling g is determined by the condition

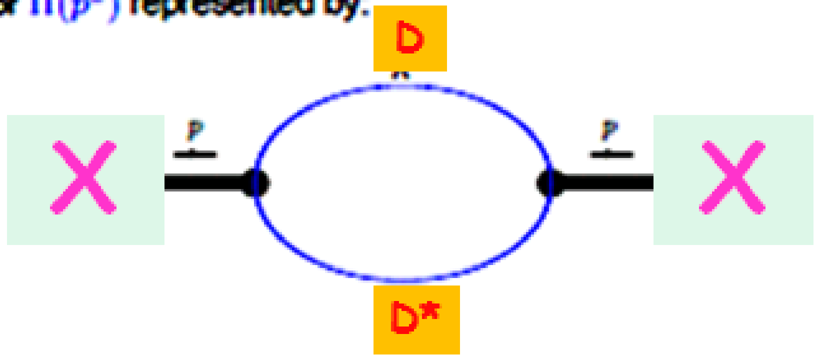
$$Z_M = 1 - \Sigma'_M(m_M^2) = 0$$

with the derivative of the mass operator

$$\Sigma'_M(m_M^2) = g_M^2 \Pi'_M(m_M^2) = g_M^2 \frac{d\Pi_M(p^2)}{dp^2}\Big|_{p^2=m_M^2}$$

Exp. input

with the mass operator $\tilde{\Pi}(p^2)$ represented by:



2016/8/10

Vertex function

Characterize the finite size of the hadron
the distributions in the hadron

Gaussian-type is chosen for the function

$$\Phi_M(y^2) = \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot y} \tilde{\Phi}(-k^2), \qquad \tilde{\Phi}(-k_E^2) = exp\left(-k_E^2/\Lambda_M^2\right)$$

local limit $\Phi(y^2) \to \delta^{(4)}(y)$

Parameter: Gaussian with free size parameter Λ

Four-dimensional covariant calculation

New resonance: X(3872)

Basics about $X(3872)$

- first seen in
  $X(3872) \to J/\psi\pi^+\pi^-$ by BELLE (2003),
  also seen by CDF, D0 (2004) and BABAR (2005).
- $\Gamma_X \approx 3$ MeV
- quantum numbers:

  C=+ from $X(3872) \to \gamma J/\psi$, I=0 no signal in $X \to \pi\pi^0 J/\psi$

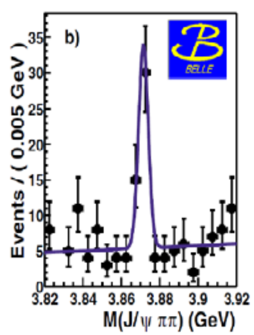
  $J^{PC} = 1^{++}$ or $J^{PC} = 2^{-+}$ from $X(3872) \to J/\psi\pi^+\pi^-$ helicity amplitude analysis
- $X(3872.2 \pm 0.8)$ close to $D^0 D^{*0}$ threshold with $m_{thr} = 3871.81 \pm 0.36$ MeV;
- S-wave $D^0 D^{*0}$ hadron molecule favors $J^{PC} = 1^{++}$
- charmonium interpretation disfavored, $1^{++}(2^3P_1)$ too low in mass compared to $m(2^3P_2) \approx m(Z(3930))$

Discovery of X(3872)

Belle 2003, Phys. Rev. Lett. 91, 2620

$$B^\pm \to K^\pm \underbrace{J/\psi\pi^+\pi^-}$$

- Very narrow resonance (Γ<1.2 MeV) close to $D^0\bar{D}^{0*}$ threshold.
- Nature unclear: conventional charmonium state, exotic state ($D^0\bar{D}^{0*}$ molecule, tetraquark), or a mixture
- Determination of J^{PC} important



LHCb

PRL 110, 222001 (2013).	*PR D 92, 011102 (2015).*
$B^+ \to X(3872)K^+$ w/ $X(3872) \to J/\psi\pi\pi$	Update: w/o assumption on L
$\to J^{PC} = 1^{++}$, $J^{PC} = 2^{-+}$ rejected w/ >8σ	Confirms $J^{PC} = 1^{++}$
(analysis assumed lowest possible L)	

$$\mathcal{B}(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$

Decay modes

Basics about $X(3872)$, Decay Modes

- $\Gamma(X \to J/\psi\pi^+\pi^-\pi^0)/\Gamma(X \to J/\psi\pi^+\pi^-) = 1.0 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})$
  BELLE (hep-ex/0505037)
  isospin violating decay modes
  decays dominated by subthreshold decays of $\omega J/\psi$ and $\rho J/\psi$
- $\Gamma(X \to J/\psi\gamma)/\Gamma(X \to J/\psi\pi^+\pi^-) = 0.14 \pm 0.05$ (Belle); 0.33 ± 0.12 (BABAR)
  BELLE (hep-ex/0505037), BABAR PRL 102 (2009)
  large radiative decay mode !!
- $\Gamma(X \to \psi(2S)\gamma)/\Gamma(X \to J/\psi\gamma) = 3.5 \pm 1.4$
  BABAR, PRL 102, (2009)
  possible evidence for charmonium component ?

Strong decay   Radiative decay

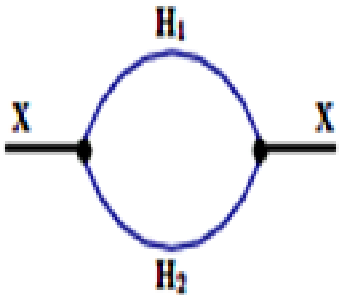
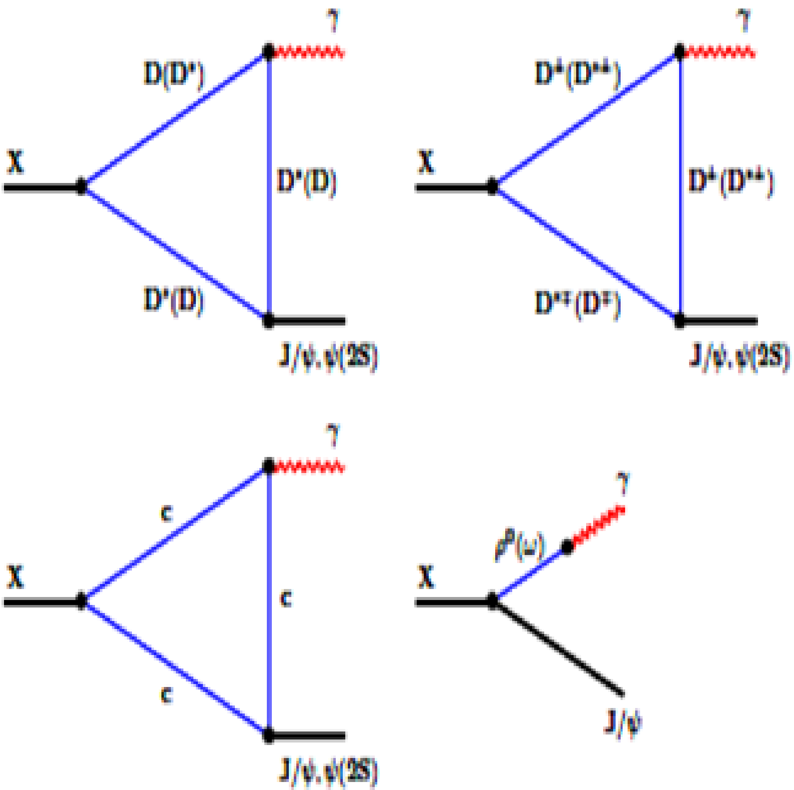
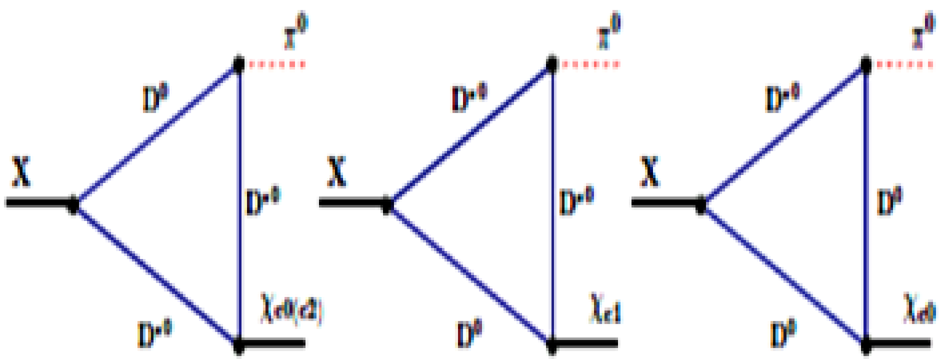


FIG. 1: H_1H_2 hadron-loop diagrams contributing to the mass operator of the $X(3872)$ meson.

PRD79,094013   2009

$$X(3872) \to J/\psi, \psi(2S) + \gamma$$





 ...ams contributing to the hadronic transitions $X(3872) \to \chi_{cJ} + \pi^0$.

Strong decay (two-body, three-body)

$$|X(3872)\rangle = \frac{Z^{1/2}_{D^0D^{*0}}}{\sqrt{2}}(|D^0\bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle) + \frac{Z^{1/2}_{D^\pm D^{*\mp}}}{\sqrt{2}}(|D^+D^{*-}\rangle + |D^-D^{*+}\rangle) + Z^{1/2}_{J_\psi\omega}|J_\psi\omega\rangle + Z^{1/2}_{J_\psi\rho}|J_\psi\rho\rangle,$$

$$\frac{\Gamma(X\to J/\psi\pi^+\pi^-\pi^0)}{\Gamma(X\to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})$$

and

$$\frac{\Gamma(X\to J/\psi\gamma)}{\Gamma(X\to J/\psi\pi^+\pi^-)} = 0.14 \pm 0.05(\text{Belle});$$

$$0.33 \pm 0.12(BABAR).$$

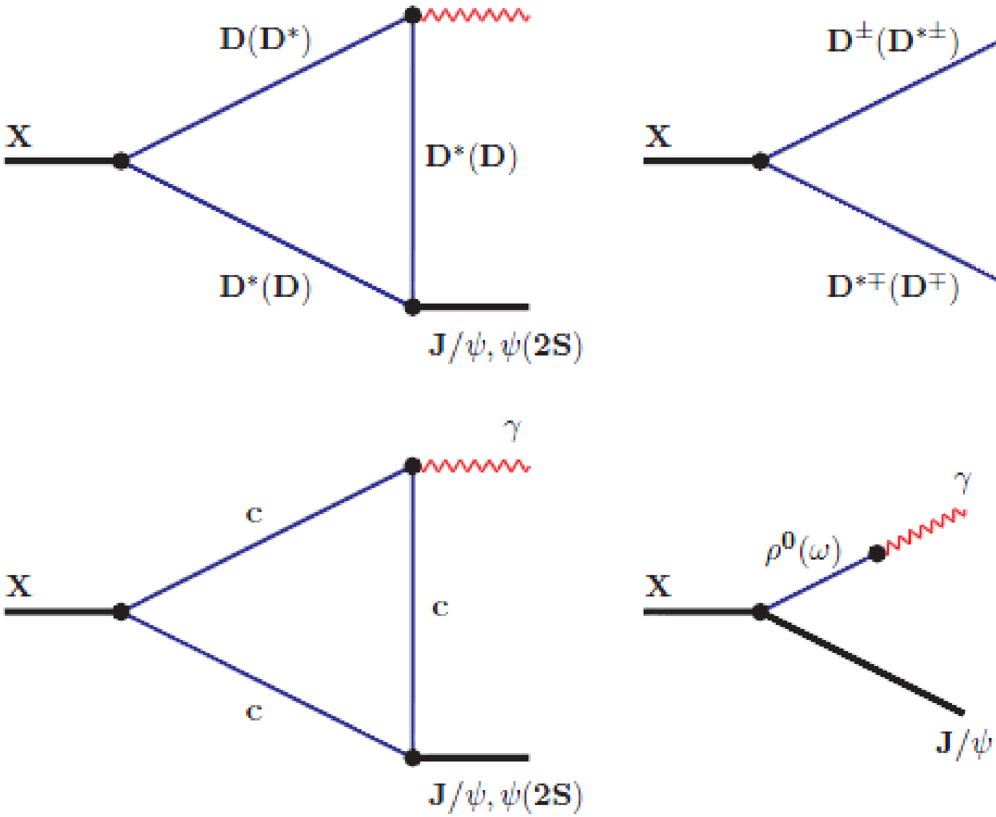
TABLE III. Properties of $X \to J_\psi + h$ decays. The numbers in brackets and for the ratios R_1, R_2 from explicit values for $Z_{J_\psi\rho}$, $Z_{J_\psi\omega}$ and $\sigma = (Z_{J_\psi\rho}/Z_{J_\psi\omega})^{1/2}$ of Eq. (34).

Quantity	Local case	Nonlocal case
$\Gamma(X\to J/\psi\pi^+\pi^-)$, keV	$7.5\times 10^3 Z_{J_\psi\rho}(45.0)$	$9.0\times 10^3 Z_{J_\psi\rho}(54.0)$
$\Gamma(X\to J/\psi\pi^+\pi^-\pi^0)$, keV	$1.92\times 10^3 Z_{J_\psi\omega}(78.9)$	$1.38\times 10^3 Z_{J_\psi\omega}(56.6)$
$\Gamma(X\to J/\psi\pi^0\gamma)$, keV	$0.32\times 10^3 Z_{J_\psi\omega}(13.2)$	$0.23\times 10^3 Z_{J_\psi\omega}(9.4)$
$\Gamma(X\to J/\psi\gamma)$, keV	$49.18 Z_{J_\psi\omega}(1+1.94\sigma)^2(6.1)$	$35.19 Z_{J_\psi\omega}(1+2.51\sigma)^2(5.5)$
R_1	1.75	1.05
R_2	0.14	0.10

Including of $c\bar{c}$

$$|X(3872)\rangle = \cos\theta\left[\frac{Z^{1/2}_{D^0 D^{*0}}}{\sqrt{2}}(|D^0\bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle) + \frac{Z^{1/2}_{D^\pm D^{*\mp}}}{\sqrt{2}}(|D^+ D^{*-}\rangle\right.$$

$$\left. + |D^- D^{*+}\rangle) + Z^{1/2}_{J_\psi\omega}|J_\psi\omega\rangle + Z^{1/2}_{J_\psi\rho}|J_\psi\rho\rangle\right] + \sin\theta\;|c\bar{c}\rangle.$$



$$\mathcal{L}_{cc\gamma}(x) = \frac{2e}{3}A_\mu(x)\bar{c}(x)\gamma^\mu c(x),$$

YBD, Faessler, Gutsche & Lyubovitskij, J. Phys. G38, 015001

Diagrams contributing to the radiative transitions $X(3872) \to J/\psi + \gamma$ and $X(3872) \to \psi(2S) + \gamma$.

Results (including $c\bar{c}$)

YBD, Faessler, Gutsche & Lyubovitskij, J. Phys. G38, 015001

Quantity	$c\bar{c}$	DD^*	$J/\psi V$	$DD^* + J/\psi V$	Total
Γ_{J_ψ}, keV	45	3.6	1.5	8	1.94
Γ_{ψ}, keV	64	0.01	0	0.01	6.8
R	1.1	3.3×10^{-3}	0	1.5×10^{-3}	$3.5\ (\theta = -20.2^0)$

$$|X(3872)\rangle = \cos\theta \left[\frac{Z^{1/2}_{D^0D^{*0}}}{\sqrt{2}} (|D^0\bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle) + \frac{Z^{1/2}_{D^\pm D^{*\mp}}}{\sqrt{2}} (|D^+D^{*-}\rangle + |D^-D^{*+}\rangle) + Z^{1/2}_{J_\psi\omega}|J_\psi\omega\rangle + Z^{1/2}_{J_\psi\rho}|J_\psi\rho\rangle \right] + \sin\theta\ |c\bar{c}\rangle.$$

BABAR

$$R = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 3.5 \pm 1.4.$$

$$R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29,$$

LHCb

Interference effect, by the admixture θ, plays crucial role to understand the measured ratio

Discussions

- 1), Hadronic molecules: old expectations-
- renewed interest in heavy mesons
- 2), Effective approach is applied
- to the states (Compositeness)
- 3), Hadronic loop is considered
- 4), Decay modes: some c\bar{c}
- +dominate hadronic picture

1), Open charmed mesons: Ds(2317)

Other applications:

2), Y-type: Y(4260), Y(3940);
Z-type: Z(4430),Zc(3900); Zb(10610), Zb(10650)

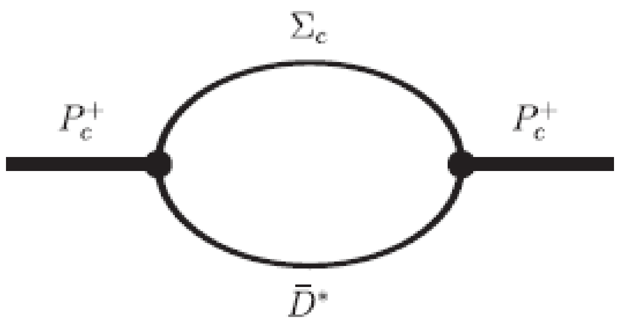
3), $\Lambda_c(2940)$, $\Sigma_c(2800)$

Applications to the two Pc $P_c(\Sigma_c\bar{D}^*)$ (PRD93,074020)

$$\mathcal{L}^{3/2^{\pm}}_{P_c\Sigma_c\bar{D}^*}(x) = -ig_{P_c\Sigma_c\bar{D}^*}\int d^4y\Phi(y^2)\bar{\Sigma}_c(x+\omega_{\bar{D}^*}y)\Gamma^{(\pm)} \times \bar{D}^*_\mu(x-\omega_{\Sigma_c}y)P^\mu_c(x) + \text{H.c.},$$

$$\mathcal{L}^{5/2^{\pm}}_{P_c\Sigma_c\bar{D}^*}(x) = g_{P_c\Sigma_c\bar{D}^*}\int d^4y\Phi(y^2)\bar{\Sigma}_c(x+\omega_{\bar{D}^*}y)\Gamma^{(\mp)} \times \partial_\mu\bar{D}^*_\nu(x-\omega_{\Sigma_c}y)P^{\mu\nu}_c(x) + \text{H.c.},$$

where $\omega_{\bar{D}^*} = m_{\bar{D}^*}/(m_{\Sigma_c}+m_{\bar{D}^*})$ and $\omega_{\Sigma_c} = m_{\Sigma_c}/(m_{\Sigma_c}+m_{\bar{D}^*})$. The vertex $\Gamma^{(\pm)}$ matrix is defined as $\Gamma^+ = \gamma_5$ and $\Gamma^- = 1$. The effective correlation function $\Phi(y^2)$ is chosen to describe the distribution of Σ_c and $\bar{D}^*$ in P_c



$P_c(\Sigma_c\bar{D}^*)$

FIG. 1. The mass operator of P_c^+ states.

$M_{\Sigma_c\bar{D}^*} \sim 4465$ MeV $\rightarrow (1^+/2;1^-)$

$Parity \sim (-1)^{1+l}$

Compositeness condition

For the generic hadronic molecule $H = (M_1M_2)$, the compositeness condition is:

$$Z_H = 1 - \Sigma'_H(m_H^2) = 0$$

where $\Sigma'_H(m_H^2)$ is the derivative of the mass operator, and m_H is the mass of the hadronic molecule.

S. Weinberg, Phys. Rev. 130, 776 (1963).
A. Salam, Nuovo Cimento 25, 224 (1962).

$$Z_{P_c} = 1 - \frac{\partial\Sigma^{T(\pm)}_{P_c}(p)}{\partial \not p}\Big|_{\not p = m_{P_c}} \equiv 0,$$

where the $\Sigma^{T(\pm)}_{P_c}(p)$ is the transverse part of the mass operator $\Sigma^{\mu\nu(\pm)}_{P_c}(p)$ with the $J^P = 3/2^{\pm}$ assumption and $\Sigma^{\mu\nu\alpha\beta(\pm)}_{P_c}(p)$ with the $J^P = 5/2^{\pm}$ assumption of the molecule P_c states, The relation between the transverse part and the corresponding mass operator can be defined as

$$\Sigma^{\mu\nu(\pm)}_{P_c}(p) = g^{\mu\nu}_\perp\Sigma^{T(\pm)}_{P_c}(p) + \frac{p^\mu p^\nu}{p^2}\Sigma^{L(\pm)}_{P_c}(p),$$

$$\Sigma^{\mu\nu\alpha\beta(\pm)}_{P_c}(p) = \frac{1}{2}(g^{\mu\alpha}_\perp g^{\nu\beta}_\perp + g^{\mu\beta}_\perp g^{\nu\alpha}_\perp)\Sigma^{T(\pm)}_{P_c}(p) + \cdots,$$

The diagram describing the mass operator of the P_c states is presented in Fig. 1. From the effective Lagrangian, we can obtain the concrete forms of $\Sigma^{\mu\nu(\pm)}_{P_c}(p)$ and $\Sigma^{\mu\nu\alpha\beta(\pm)}_{P_c}(p)$,

$$\Sigma^{\mu\nu(\pm)}_{P_c}(p) = \pm g^2_{P_c\Sigma_c\bar{D}^*}\int \frac{d^4q}{(2\pi)^4 i}\tilde{\Phi}^2(q-\omega_{\bar{D}^*}p)\Gamma^{(\pm)}\frac{1}{\not{q}-m_{\Sigma_c}} \times\Gamma^{(\pm)}\frac{-g^{\mu\nu}+(p-q)^\mu(p-q)^\nu/m^2_{\bar{D}^*}}{(p-q)^2-m^2_{\bar{D}^*}},$$

$$\Sigma^{\mu\nu\alpha\beta(\pm)}_{P_c}(p) = \pm g^2_{P_c\Sigma_c\bar{D}^*}\int \frac{d^4q}{(2\pi)^4 i}\tilde{\Phi}^2(q-\omega_{\bar{D}^*}p)\Gamma^{(\mp)} \times\frac{1}{\not{q}-m_{\Sigma_c}}\Gamma^{(\mp)}(p-q)^\alpha(p-q)^\mu \times\frac{-g^{\beta\nu}+(p-q)^\beta(p-q)^\nu/m^2_{\bar{D}^*}}{(p-q)^2-m^2_{\bar{D}^*}},$$

where q is the 4-momentum of Σ_c baryon.

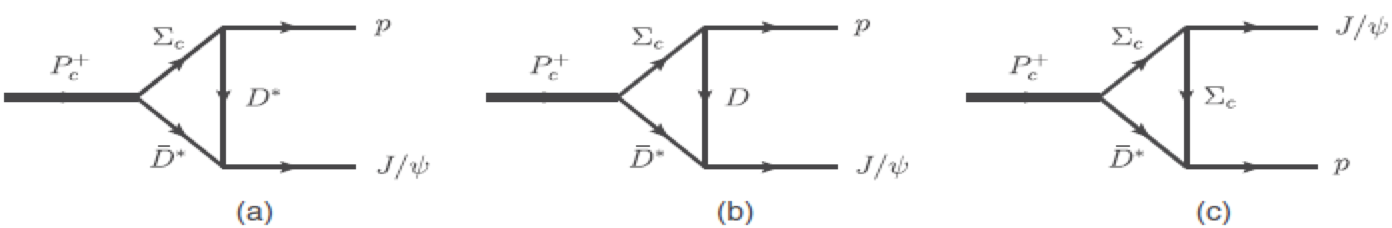
$$\begin{aligned}\mathcal{L}_{\psi D^{(*)}D^{(*)}} &= -ig_{\psi DD}\psi_\mu(\partial^\mu D D^\dagger - D\partial^\mu D^\dagger)\\ &\quad + g_{\psi D^* D}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(D^*_\alpha\overleftrightarrow{\partial}_\beta D^\dagger - D\overleftrightarrow{\partial}_\beta D^{*\dagger}_\alpha)\\ &\quad + ig_{\psi D^* D^*}\psi^\mu(D^*_\nu\partial^\nu D^{*\dagger}_\mu - \partial^\nu D^*_\mu D^{*\dagger}_\nu\\ &\quad - D^*_\nu\overleftrightarrow{\partial}_\mu D^{*\nu\dagger}),\end{aligned}$$

$$\mathcal{L}_{\Sigma_c N D^*} = g_{\Sigma_c N D^*}\bar{N}\gamma_\mu\vec{\tau}\cdot\vec{\Sigma}_c D^{*\mu} + \text{H.c.},$$

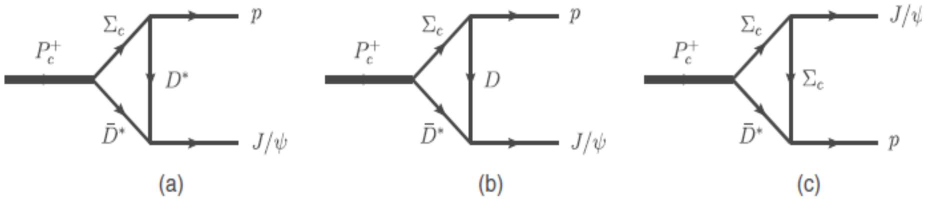
$$\mathcal{L}_{\Sigma_c N D} = -ig_{\Sigma_c N D}\bar{N}\gamma_5\vec{\tau}\cdot\vec{\Sigma}_c D + \text{H.c.},$$

$$\mathcal{L}_{\Sigma_c\Sigma_c\psi} = g_{\Sigma_c\Sigma_c\psi}\bar{\Sigma}_c\gamma_\mu\Sigma_c\psi^\mu.$$

$$\begin{aligned}g_{\psi DD} &= 2g_2\sqrt{m_\psi}m_D,\\ g_{\psi D^* D} &= 2g_2\sqrt{m_D m_{D^*}/m_\psi},\\ g_{\psi D^* D^*} &= 2g_2\sqrt{m_\psi}m_{D^*},\end{aligned}$$



Feynman diagrams for the $P_c^+ \to J/\psi p$ decay process.



Feynman diagrams for the $P_c^+ \to J/\psi p$ decay process.

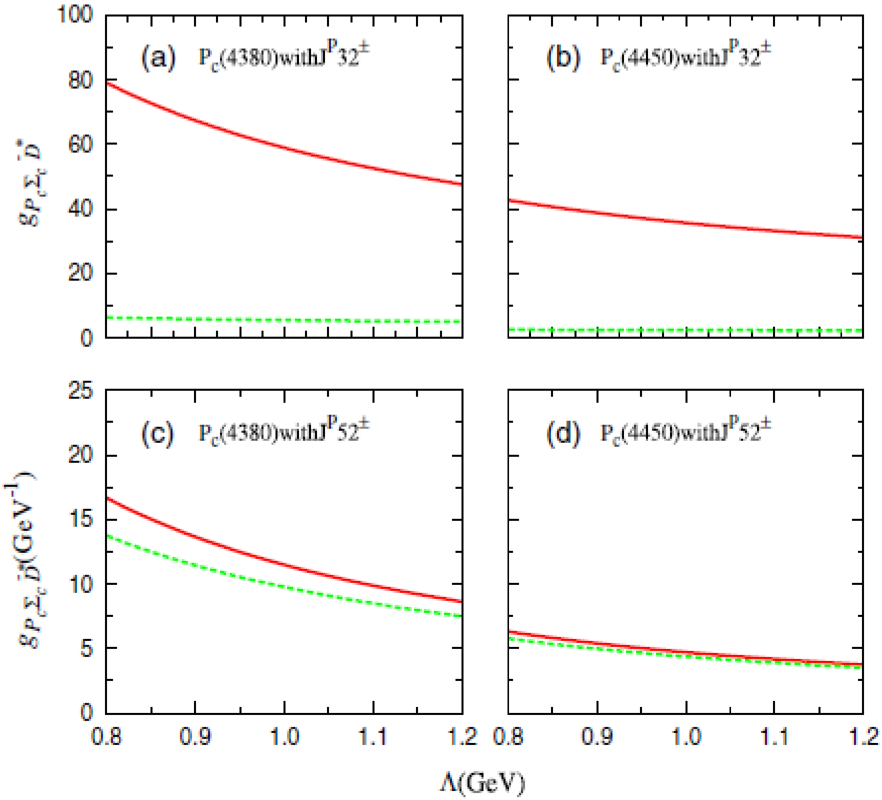


FIG. 3. The coupling constants of P_c states with different J^P assignments depending on the parameter Λ. The red solid line stands for $P = +$, and the green dashed line corresponds to $P = -$ cases.

Then, the total amplitudes of the $P_c^+ \to J/\psi p$ process are

$$\mathcal{M} = \mathcal{M}_a + \mathcal{M}_b + \mathcal{M}_c .$$

TABLE I. Coupling constants of $P_c\Sigma_c\bar{D}^*$ with different J^P assignments with $\Lambda = 1$ GeV.

State	$3/2^+$	$3/2^-$	$5/2^+$ (GeV^{-1})	$5/2^-$ (GeV^{-1})
$P_c(4380)$	58.91	5.48	11.49	9.77
$P_c(4450)$	35.66	2.38	4.71	4.39

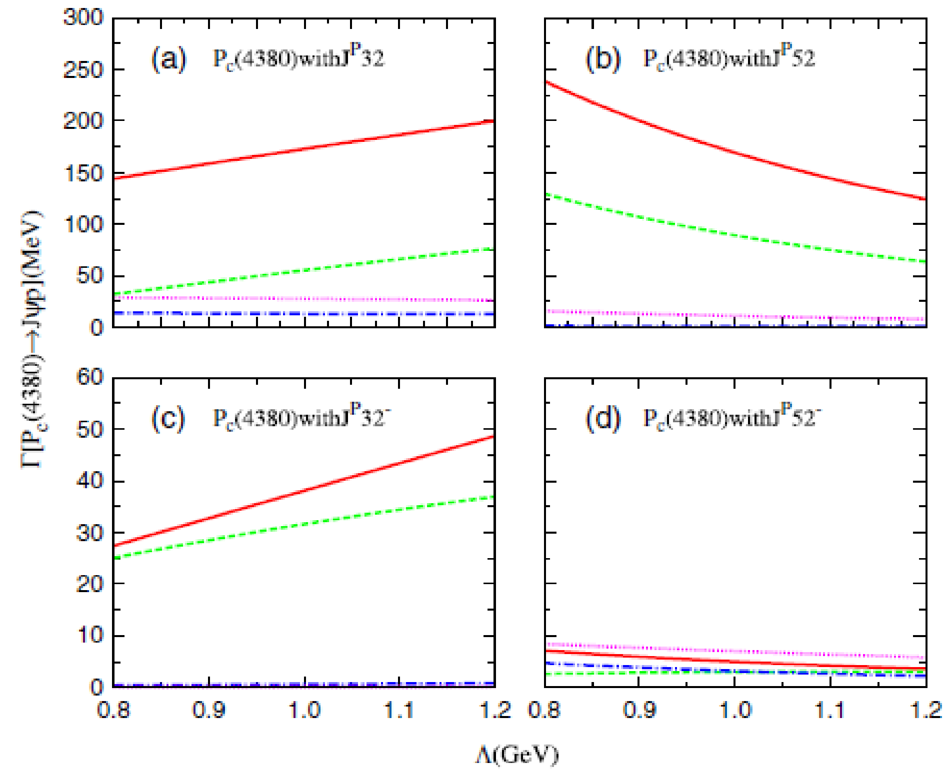


FIG. 6. The individual contributions of the D^*, D, and Σ_c exchanges for the $P_c^+(4380) \to J/\psi p$ with different J^P assignments. The red solid, green dotted, blue dotted-dashed, and pink short dotted lines stand for the total, D^*, D, and Σ_c contributions, respectively.

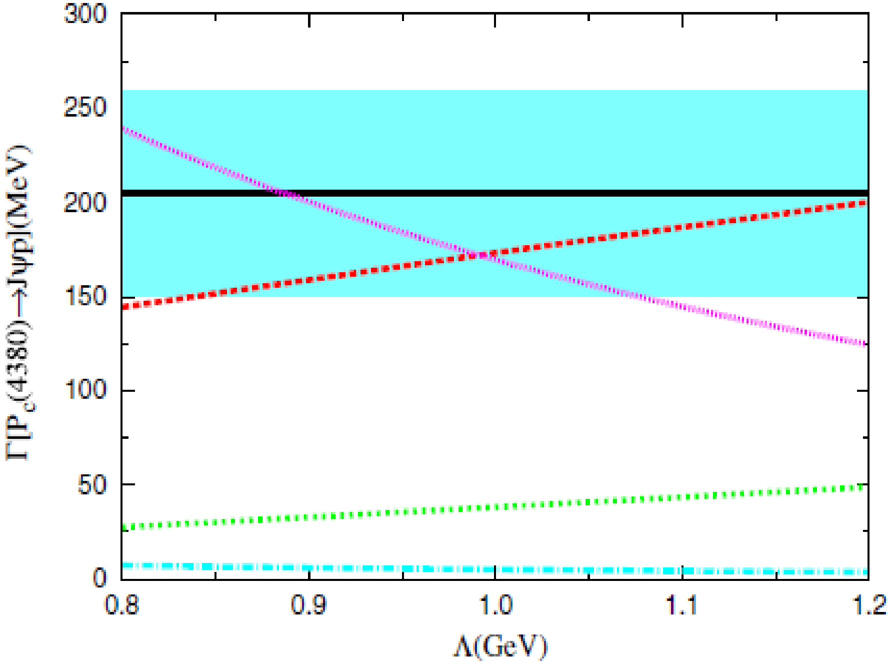


FIG. 4. The partial decay widths of the $P_c^+(4380) \to J/\psi p$ with different J^P assignments depending on the parameter Λ. The red dashed, green dotted, pink short dotted, and blue dotted-dashed lines stand for the $J^P = 3/2^+, 3/2^-, 5/2^+$ and $5/2^-$ cases, respectively. The black solid line and blue error band correspond to the total width observed by experiment.

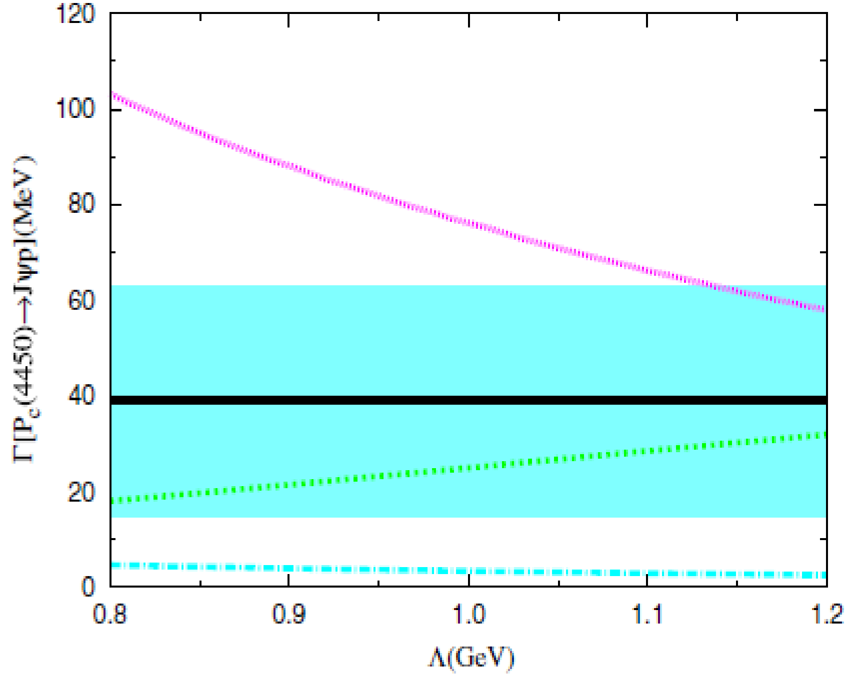


FIG. 5. The same as Fig. 4, but for the $P_c^+(4450) \to J/\psi p$. The partial decay width of the $J^P = 3/2^+$ case is much larger than the experimental data and neglected here.

3/2+

3/2-

5/2+

5/2-

Discussions (1)

1), Individual contributions of the D*, D and Σc
For S and P waves, D* plays dominated role
and the interferences are still sizeable

2), Λ=0.8~ 1.2 GeV, Γ increases with Λ for $J^p = 3^{\pm}/2$
decreases with Λ for $J^p = 5^{\pm}/2$

3), Pc(4380), the obtained in all four cases are small than the data; $J^p = 5^-/2$ →D-wave (is disfavored by LHCb)

4), Pc(4450), $J^p = 3^+/2$ is excluded (Exp.+Γ(large))
$J^p = 5^+/2$ is excluded (Γ(large))
$J^p = 5^-/2$ (D-wave)

With various spin-parity assignments, the partial decay widths of P_c states are significantly different. All the P wave $\Sigma_c \bar{D}^*$ assignments are excluded, while S-wave $\Sigma_c \bar{D}^*$ pictures for $P_c(4380)$ and $P_c(4450)$ are both possible.

TABLE II. Partial decay widths of $P_c^+ \to J/\psi p$ with different J^P assignments with $\Lambda = 1$ GeV. The unit is in MeV.

State	3/2+	3/2−	5/2+	5/2−
$P_c(4380)$	× 173.12	38.12	× 169.51	4.96
$P_c(4450)$	× 369.82	25.00	× 76.15	× 3.39

$$P_c^+(4380):(M;\Gamma)=(4380\pm8\pm29;205\pm18\pm86)MeV$$

$$P_c^+(4450):(M;\Gamma)=(4449.8\pm1.7\pm2.5;39\pm5\pm19)MeV$$

Discussions (2)

We consider $\Sigma_c \bar{D}^*$, Other scenarios of $\Sigma_c^* \bar{D}, \Sigma_c^* \bar{D}^*$

Heavy quark sym.
Spin rearrangement

PRD93, 034031: In the heavy quark limit, the S-wave D and D^* mesons can be categorized into a doublet as well as the heavy baryons Σ_c and Σ_c^*. With the heavy quark symmetry and spin rearrangement scheme, there is an interesting work studying the ratios of partial decay widths in different molecular scenarios The model-independent result shows that for the three S-wave $\Sigma_c \bar{D}^*$, $\Sigma_c^* \bar{D}$, and $\Sigma_c^* \bar{D}^*$ molecules with $J^P = 3/2^-$ the ratios of their $J/\psi p$ decay widths satisfy $\Gamma[(\Sigma_c \bar{D}^*)] : \Gamma[(\Sigma_c^* \bar{D})] : \Gamma[(\Sigma_c^* \bar{D}^*)] = 1.0 : 2.7 : 5.4$. Simply employing those ratios

$$\Gamma^{3/2^-}_{P_c^+(4380)\to J/\psi p}[(\Sigma_c^* \bar{D})] = 102.92 \text{ MeV},$$
$$\Gamma^{3/2^-}_{P_c^+(4380)\to J/\psi p}[(\Sigma_c^* \bar{D}^*)] = 205.85 \text{ MeV},$$
$$\Gamma^{3/2^-}_{P_c^+(4450)\to J/\psi p}[(\Sigma_c^* \bar{D})] = 67.50 \text{ MeV},$$
$$\Gamma^{3/2^-}_{P_c^+(4450)\to J/\psi p}[(\Sigma_c^* \bar{D}^*)] = 135.00 \text{ MeV}.$$

The much larger partial decay width $\Gamma^{3/2^-}_{P_c^+(4450)\to J/\psi p} \times [(\Sigma_c^* \bar{D}^*)]$ excludes the possibility of $P_c(4450)$ as an S-wave $J^P = 3/2^-$ $\Sigma_c^* \bar{D}^*$ molecule. Also, the $P_c(4450)$ as the $\Sigma_c^* \bar{D}$ system is not favored due to its higher mass over the threshold and a slightly large partial decay width. The above discussion shows that if the $P_c(4450)$ state has the spin parity $J^P = 3/2^-$ only the $\Sigma_c \bar{D}^*$ system of the three molecular scenarios is allowed. This result is consistent with the interpretations of Ref. [26], in which the $P_c(4450)$ is a $J^P = 3/2^-$ $\Sigma_c \bar{D}^*$ resonance and $P_c(4380)$ may not be a genuine state.

$$M_{\Sigma_c^* \bar{D}} \sim 4390\, MeV \to (3^+/2, 0^-)$$
$$M_{\Sigma_c^* \bar{D}^*} \sim 4530\, MeV \to (3^+/2, 1^-)$$

PRD93, 034031: The $J^P = 3/2^-$ $\Sigma_c^* \bar{D}$ and $\Sigma_c^* \bar{D}^*$ molecular pictures are also discussed in heavy quark limit, and only $\Sigma_c^* \bar{D}$ for $P_c(4380)$ is allowed.

3, Production of neutral Pc states

1. b quark decay process: $\Lambda_b^0 \to J/\psi p K^-$, and $\Upsilon(1S) \to J/\psi p\bar{p}$. **@LHCb**
2. Photon and electron production: $\gamma p \to J/\psi p$, and $ep \to epJ/\psi$. **@Jlab.**
3. Hadron induced production: $\pi^- p \to J/\psi n$, $pp \to ppJ/\psi$, and $p\bar{p} \to p\bar{p}J/\psi$. **@PANDA**

Here, we focus on $\pi^- p \to J/\psi n$ reaction.

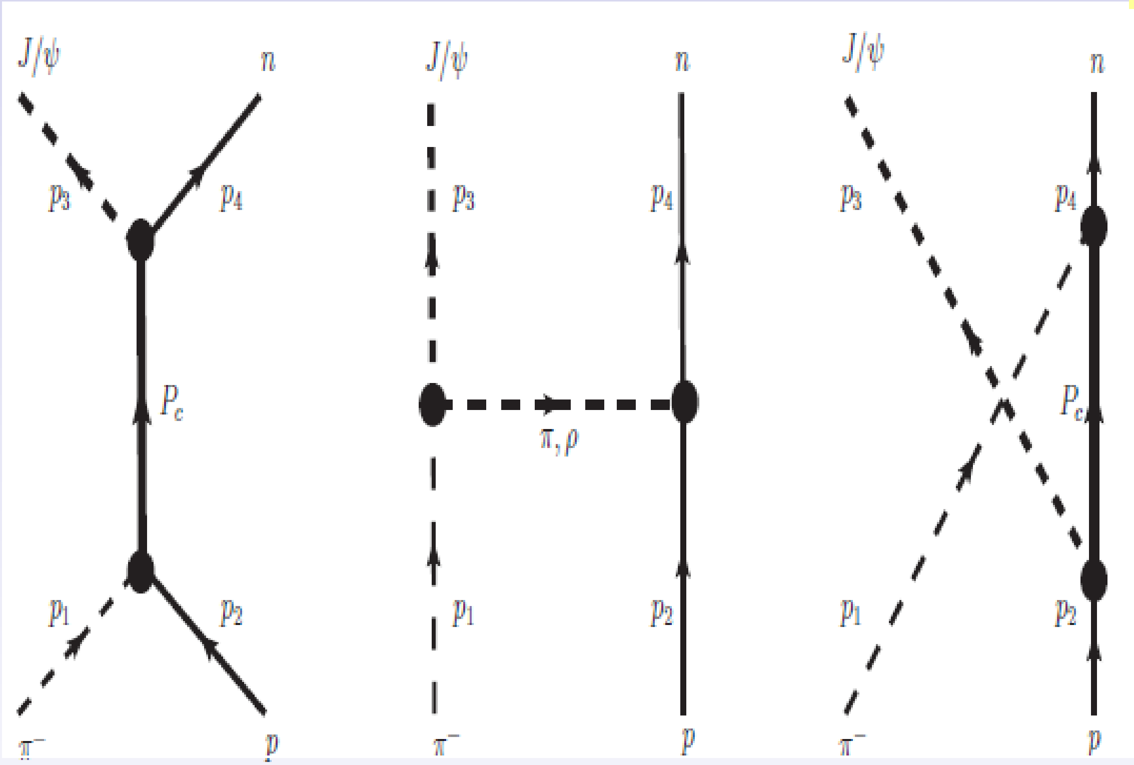
@J-PARC

Neutral states production via $\pi^- p \to J/\psi n$ reaction

LHCb, $\Lambda_b^0 \to J/\psi K^- p$

@J-PARC

$E_{max}(\pi^-) \sim 20 \;\; GeV$



Neutral Pc states

Feynman diagrams for $\pi^- p \to J/\psi n$ reaction.

PRD93,034009

Effective Lagrangians

The effective Lagrangians for $P_c N J/\psi$ couplings can be written as

$$\mathcal{L}^{3/2^\pm}_{P_c N J/\psi} = -\frac{ig_1}{2M_N}\overline{N}\Gamma^{(\pm)}_\nu \psi^{\mu\nu} P_{c\mu} - \frac{g_2}{(2M_N)^2}\partial_\nu \overline{N}\Gamma^{(\pm)}\psi^{\mu\nu}P_{c\mu} + \frac{g_3}{(2M_N)^2}\overline{N}\Gamma^{(\pm)}\partial_\nu\psi^{\mu\nu}P_{c\mu} + \text{H.c.},$$

$$\mathcal{L}^{5/2^\pm}_{P_c N J/\psi} = \frac{g_1}{(2M_N)^2}\overline{N}\Gamma^{(\mp)}_\nu \partial^\alpha\psi^{\mu\nu}P_{c\mu\alpha} - \frac{ig_2}{(2M_N)^3}\partial_\nu\overline{N}\Gamma^{(\mp)}\partial^\alpha\psi^{\mu\nu}P_{c\mu\alpha} + \frac{ig_3}{(2M_N)^3}\overline{N}\Gamma^{(\mp)}\partial^\alpha\partial_\nu\psi^{\mu\nu}P_{c\mu\alpha} + \text{H.c.},$$

where the vertex Γ matrix is defined as

$$\Gamma^{(\pm)}_\mu \equiv \begin{pmatrix}\gamma_\mu\gamma_5 \\ \gamma_\mu\end{pmatrix},$$

$$\Gamma^{(\pm)} \equiv \begin{pmatrix}\gamma_5 \\ 1\end{pmatrix},$$

for positive and negative parities.

$$\mathcal{L}^{3/2^+}_{P_c N\pi} = \frac{g_{P_c N\pi}}{m_\pi}\overline{N}\vec{\tau}\cdot\partial_\mu\vec{\pi}P^\mu_c + \text{H.c.},$$

$$\mathcal{L}^{3/2^-}_{P_c N\pi} = \frac{g_{P_c N\pi}}{m_\pi^2}\overline{N}\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\partial_\nu\vec{\pi}P^\nu_c + \text{H.c.},$$

$$\mathcal{L}^{5/2^+}_{P_c N\pi} = \frac{g_{P_c N\pi}}{m_\pi^3}\overline{N}\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\partial_\nu\partial_\lambda\vec{\pi}P^{\nu\lambda}_c + \text{H.c.},$$

$$\mathcal{L}^{5/2^-}_{P_c N\pi} = \frac{g_{P_c N\pi}}{m_\pi^2}\overline{N}\vec{\tau}\cdot\partial_\mu\partial_\nu\vec{\pi}P^{\mu\nu}_c + \text{H.c.}$$

$$\mathcal{L}_{J/\psi\pi\pi} = -ig_{J/\psi\pi\pi}(\partial^\mu\pi^-\pi^+ - \partial^\mu\pi^+\pi^-)\psi_\mu,$$

$$\mathcal{L}_{J/\psi\pi\rho} = -\frac{g_{J/\psi\pi\rho}}{m_{J/\psi}}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\rho_\nu\partial_\alpha\psi_\beta\pi,$$

$$\mathcal{L}_{\pi NN} = -\frac{g_{\pi NN}}{2M_N}\overline{N}\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi}N,$$

$$\mathcal{L}_{\rho NN} = -g_{\rho NN}\overline{N}\left(\gamma_\mu + \frac{\kappa}{2M_N}\sigma_{\mu\nu}\partial^\nu\right)\vec{\tau}\cdot\partial^\mu\vec{\rho}N.$$

The higher partial wave terms are neglected

$(g_1, g_{P_c N\pi})$ unknown

The propagators for exchanged π and ρ mesons

$$G_\pi(q) = \frac{i}{q^2 - m_\pi^2},$$

$$G_\rho^{\mu\nu}(q) = i\frac{-g^{\mu\nu} + q^\mu q^\nu / m_\rho^2}{q^2 - m_\rho^2}.$$

For the propagator of spin-3/2 fermion, we use

$$G^{\beta\alpha}(q) = \frac{i(\not{q} + M)P^{\beta\alpha}(q)}{q^2 - M^2 + iM\Gamma},$$

with

$$P^{\beta\alpha}(q) = -g^{\beta\alpha} + \frac{1}{3}\gamma^\beta\gamma^\alpha + \frac{1}{3M}(\gamma^\beta q^\alpha - \gamma^\alpha q^\beta) + \frac{2}{3M^2}q^\beta q^\alpha,$$

and for the propagator of the spin-5/2 femion, it

$$G^{\rho\sigma\alpha\beta}(q) = \frac{i(\not{q} + M)P^{\rho\sigma\alpha\beta}(q)}{q^2 - M^2 + iM\Gamma},$$

with

$$P^{\rho\sigma\alpha\beta}(q) = \frac{1}{2}(\tilde{g}^{\rho\alpha}\tilde{g}^{\sigma\beta} + \tilde{g}^{\rho\beta}\tilde{g}^{\sigma\alpha}) - \frac{1}{5}\tilde{g}^{\rho\sigma}\tilde{g}^{\alpha\beta} - \frac{1}{10}(\tilde{\gamma}^\rho\tilde{\gamma}^\alpha\tilde{g}^{\sigma\beta} + \tilde{\gamma}^\rho\tilde{\gamma}^\beta\tilde{g}^{\sigma\alpha} + \tilde{\gamma}^\sigma\tilde{\gamma}^\alpha\tilde{g}^{\rho\beta} + \tilde{\gamma}^\sigma\tilde{\gamma}^\beta\tilde{g}^{\rho\alpha}),$$

where

$$\tilde{g}^{\alpha\beta} = g^{\alpha\beta} - \frac{p^\alpha p^\beta}{M^2}$$

and

$$\tilde{\gamma}^\alpha = \gamma^\alpha - \frac{p^\alpha}{M^2}\not{p}.$$

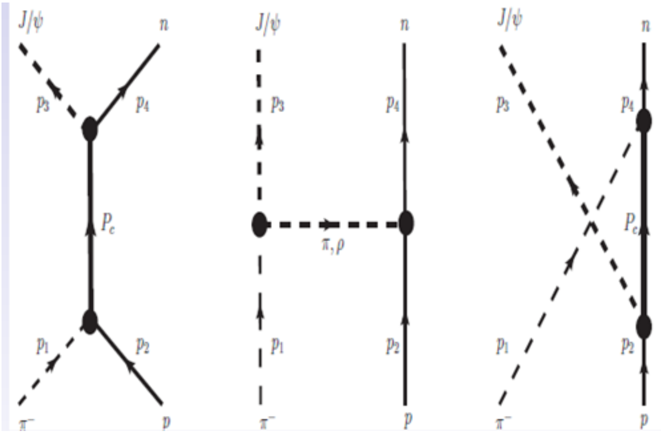
In our calculations, phenomenological form factors are needed since the hadrons are not pointlike particles. The form factors $F(q^2)$, $F_M^{NN}(q_M^2)$, and $F_M^{J/\psi\pi}(q_M^2)$ can be expressed as

$$F(q^2) = \frac{\Lambda_{P_c}^4}{\Lambda_{P_c}^4 + (q^2 - M_{P_c}^2)^2},$$

$$F_M^{J/\psi\pi}(q_M^2) = \frac{\Lambda_M^{*2} - m_M^2}{\Lambda_M^{*2} - q_M^2},$$

$$F_M^{NN}(q_M^2) = \left(\frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - q_M^2}\right)^n,$$

with $n = 1$ for the π meson and $n = 2$ for the ρ meson [49]. We use the cutoff parameters $\Lambda_{P_c} = 0.5$ GeV for P_c states [35,55], and $\Lambda_\rho^* = \Lambda_\pi^* = 1.3$ GeV, $\Lambda_\rho = 1.6$ GeV, and $\Lambda_\pi = 1.3$ GeV for mesons [49].



Not point-like particle

Two assumptions:

$B(P_c \to J/\psi N) \sim 10\%$

$B(P_c \to \pi N) \sim 1\%$

P_c from $J/\psi N$

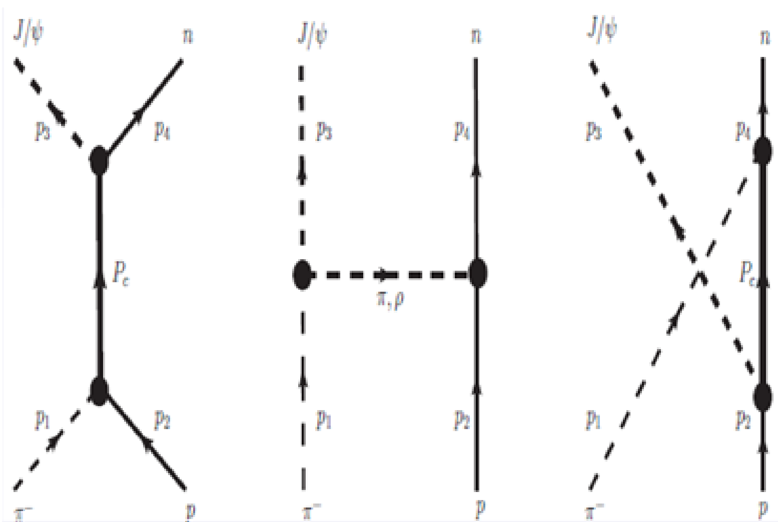
πN OZI − allowed

$c\bar{c}$ component

suppression $\sim (m_u / m_c)^2$

TABLE I. Coupling constants of $P_c N J/\psi$ and $P_c N \pi$ different J^P assignments by assuming the branching ratios are 10% and 1%, respectively.

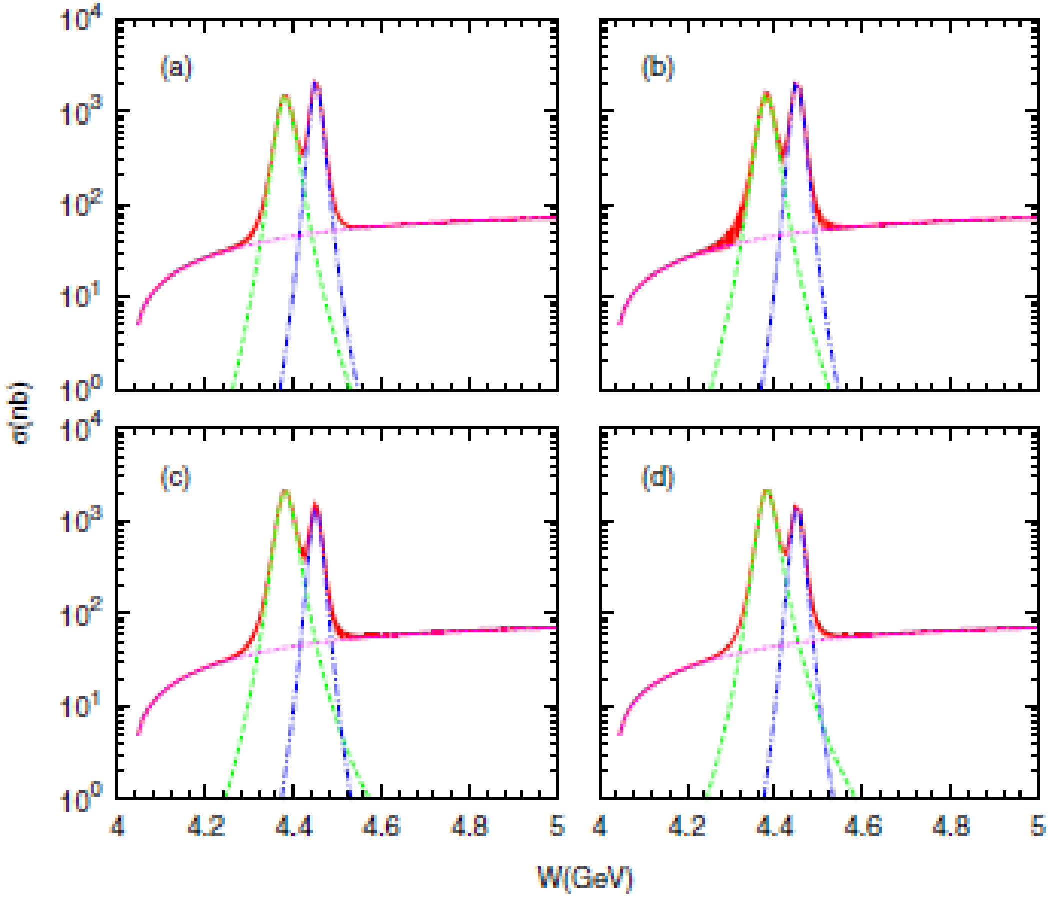
State	Channel	$3/2^+$	$3/2^-$	$5/2^+$	$5/2^-$
$P_c(4380)$	$J/\psi N$	1.09	0.49	2.17	5.13
	πN	8.56×10^{-3}	3.43×10^{-4}	3.59×10^{-5}	8.95×10^{-4}
$P_c(4450)$	$J/\psi N$	0.41	0.20	0.80	1.75
	πN	3.65×10^{-3}	1.43×10^{-4}	1.47×10^{-5}	3.75×10^{-4}



$P_c^+(4380): (M; \Gamma) = (4380 \pm 8 \pm 29; 205 \pm 18 \pm 86)\, MeV$

$P_c^+(4450): (M; \Gamma) = (4449.8 \pm 1.7 \pm 2.5; 39 \pm 5 \pm 19)\, MeV$

Total Cross Sections



$a : (3/2^+; 5/2^-)$

$b : (3/2^-; 5/2^+)$

$c : (5/2^+; 3/2^-)$

$d : (5/2^-; 3/2^+)$

Total

P(4380)

P(4450)

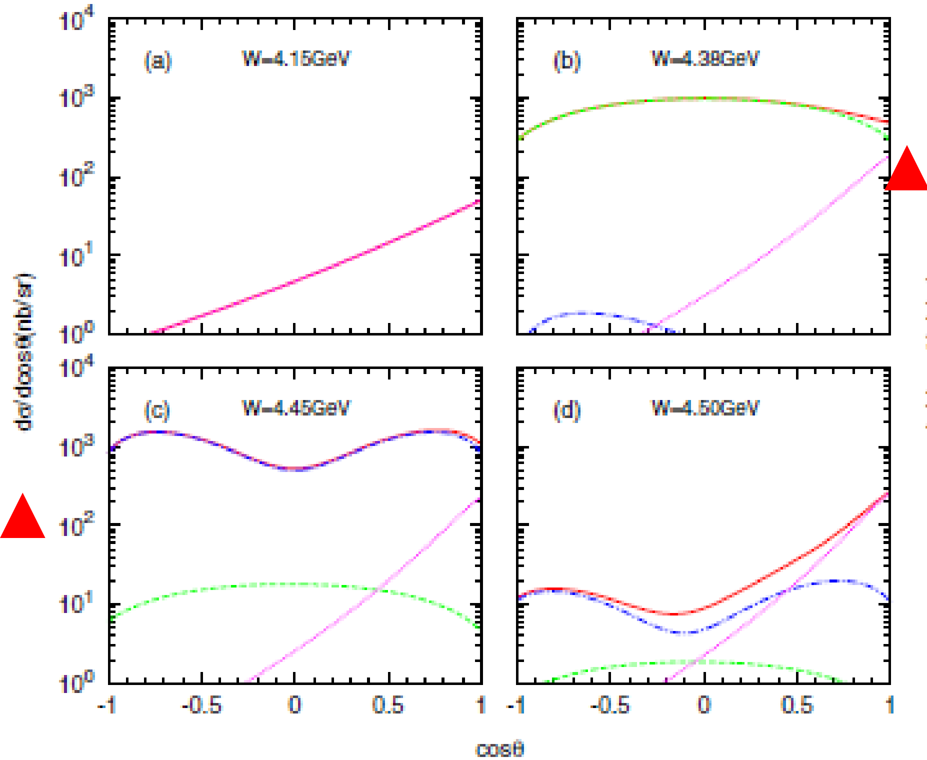
Background

The total cross sections for the $\pi^- p \to J/\psi n$ reaction with different J^P assumptions versus c.m. energy. The green dashed, blue dot-dashed, and pink short dotted lines stand for $P_c^0(4380)$, $P_c^0(4450)$, and background contributions, respectively. The thin red solid bands are total cross sections with the consideration of the interferences. Panels (a–d) correspond to $(3/2^+, 5/2^-)$, $(3/2^-, 5/2^+)$, $(5/2^+, 3/2^-)$, $(5/2^-, 3/2^+)$ assumptions for $[P_c^0(4380), P_c^0(4450)]$, respectively.

1, background is sizeable
2, interference is small
3, one can hadrly see
the differences among
the total cross sections

Differential Cross Sections (1)

$(3/2^{+};5/2^{-})$ $(3/2^{-};5/2^{+})$



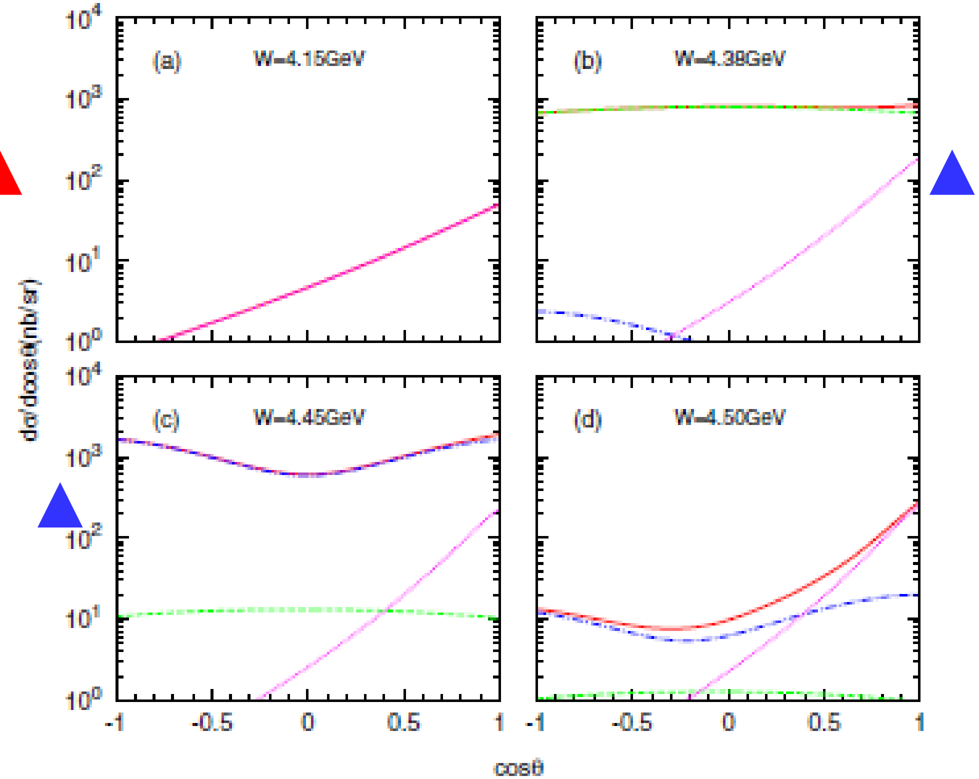


FIG. 3. The differential cross sections for the $\pi^- p \to J/\psi n$ reaction at the c.m energies W = 4.15 GeV, 4.38 GeV, 4.45 GeV, and 4.45 GeV. The $[P_c^0(4380), P_c^0(4450)]$ corresponds to the $(3/2^+, 5/2^-)$ assumption. The red solid, green dashed, blue dot-dashed, and pink short dotted lines stand for total, $P_c^0(4380)$, $P_c^0(4450)$, and background contributions, respectively.

FIG. 4. The caption is the same as that of Fig. 3, but the $[P_c^0(4380), P_c^0(4450)]$ corresponds to the $(3/2^-, 5/2^+)$ assumption.

Total
P(4380)
P(4450)
Background

$$\frac{d\sigma}{dcos\theta} = \frac{M_N^2}{16\pi s}\frac{|\vec{p}_3^{\,c.m.}|}{|\vec{p}_1^{\,c.m.}|}|\mathcal{M}_{\pi^- p\to J/\psi n}|^2,$$

W(c.m.)GeV:
(4.15,4.38,4.45, 4.5)

Differential Cross Sections (2)

$(5/2^{+};3/2^{-})$ $(5/2^{-};3/2^{+})$

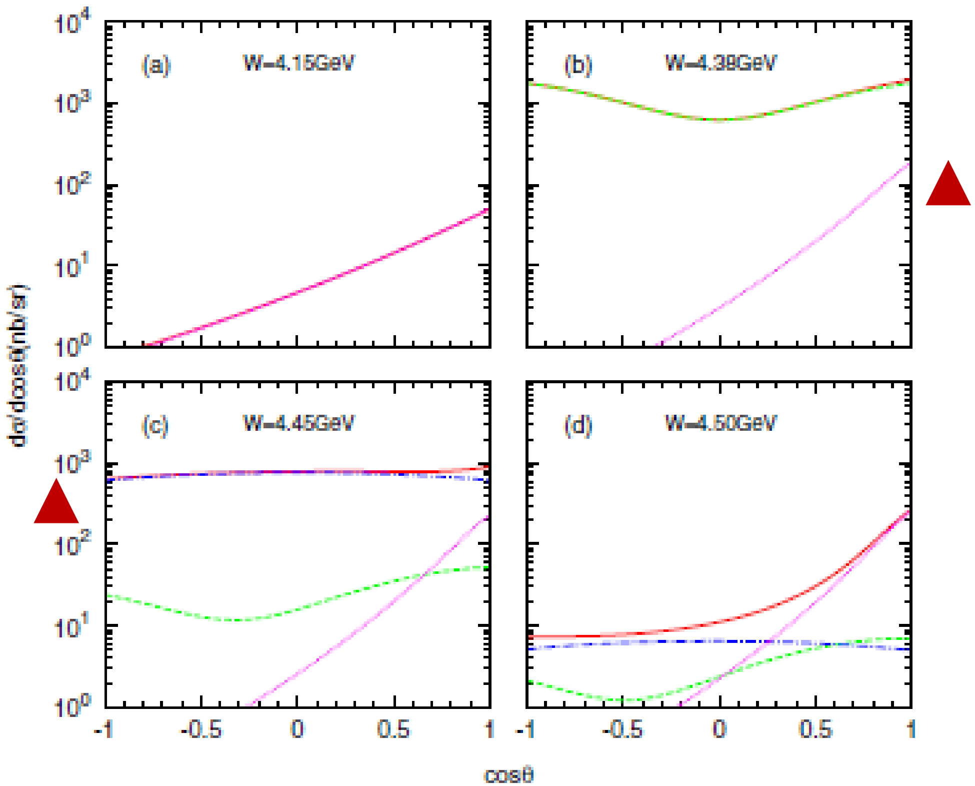


FIG. 5. The caption is the same as that of Fig. 3, but the $[P_c^0(4380), P_c^0(4450)]$ corresponds to the $(5/2^{+}, 3/2^{-})$ assumption.

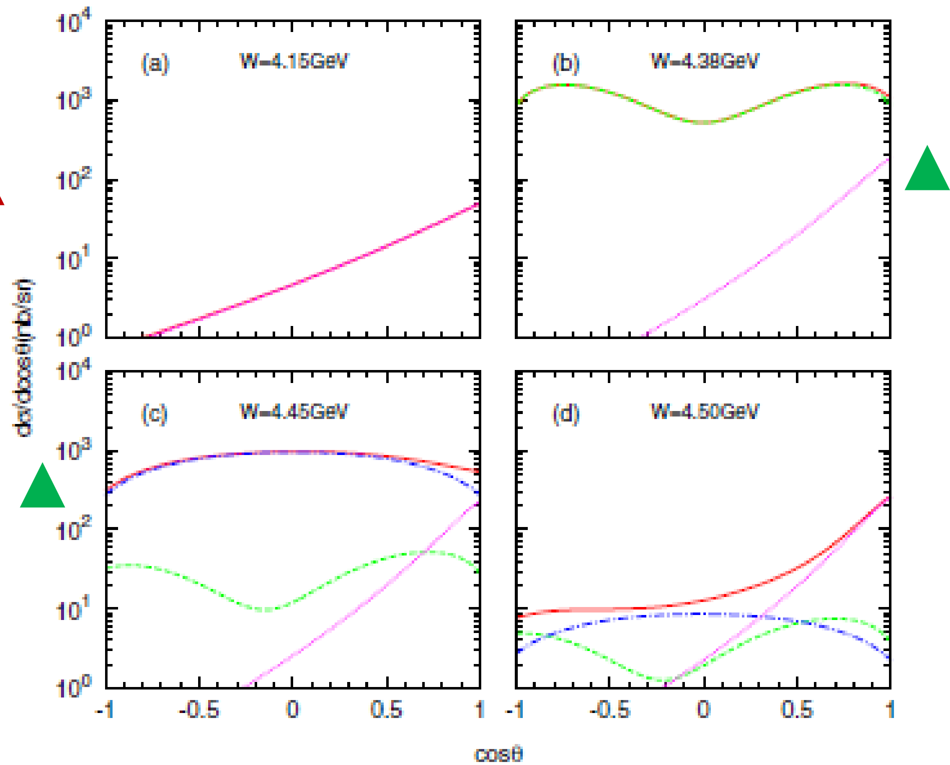


FIG. 6. The caption is the same as that of Fig. 3, but the $[P_c^0(4380), P_c^0(4450)]$ corresponds to the $(5/2^{-}, 3/2^{+})$ assumption.

Total
P(4380)
P(4450)
Background

$$\frac{d\sigma}{dcos\theta} = \frac{M_N^2}{16\pi s}\frac{|\vec{p}_3^{\,c.m.}|}{|\vec{p}_1^{\,c.m.}|}|\mathcal{M}_{\pi^- p\to J/\psi n}|^2,$$

For production

1, t-channel meson exchanges provide forward contribution

2, two Pc states contribute mainly for the differential cross sections at c. m. energy W=4.38GeV and W=4.45GeV,respectively

3, angular distributions of the two Pc resonances are obviously different than the forward background contribution

4, angular distributions display significantly different behaviors with different spin-parities assignments

5, it is expected those specific features can be tested by future J-PARC experiment with high luminosity

4, Summary

1, Production of the neutral Pc states are discussed Pc are cosidered as the point-particles with two assumptions for JPARC

$$B(P_c \to J/\psi N) \sim 10\%$$
$$B(P_c \to \pi N) \sim 1\%$$

2, Molecular scenario of $P_c(\Sigma_c \bar{D}^*)$ are employed to estimate their strong decay modes (J/ψ+P)

3, Our calculations show $3^-/2$ assignment for the two Pc

4, Other possible interpretations are also needed.

Thank you for your attention!