Heavy baryon resonace $\Lambda_c^+(2940)$ in a molecule scenario

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1、Introduction

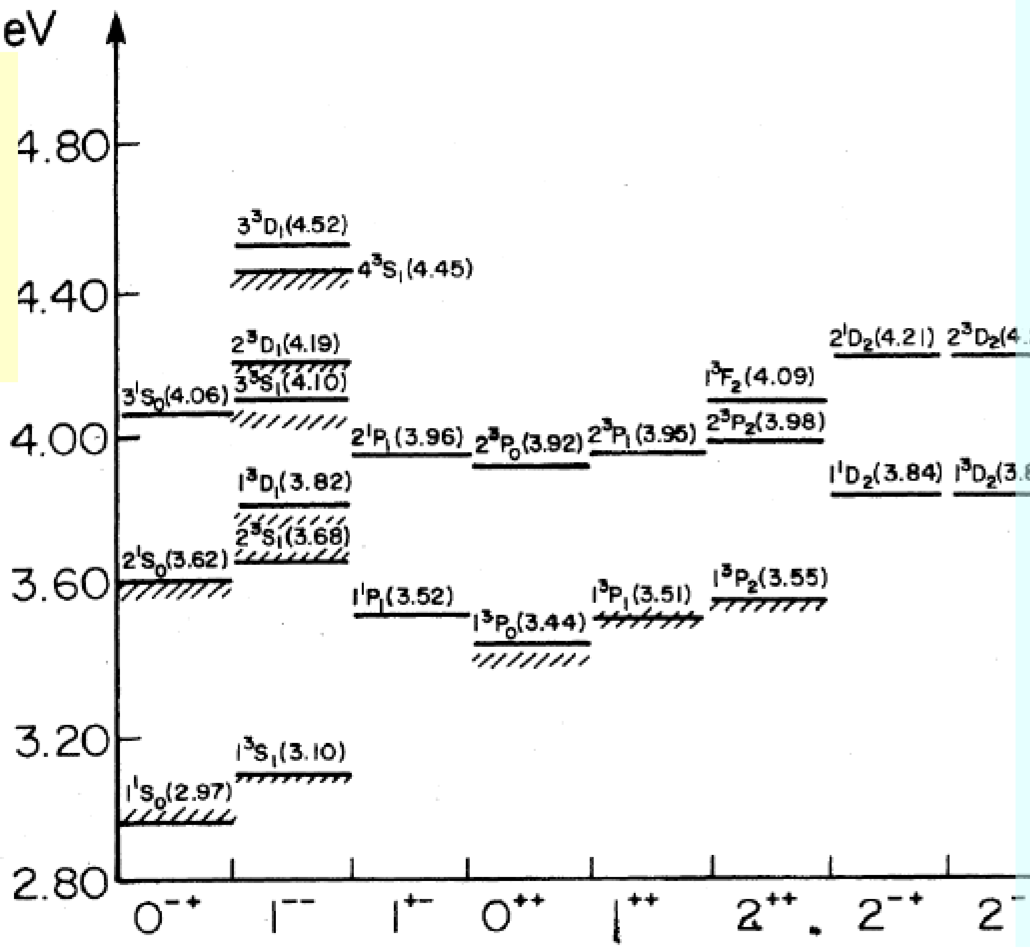
The XYZ states

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)



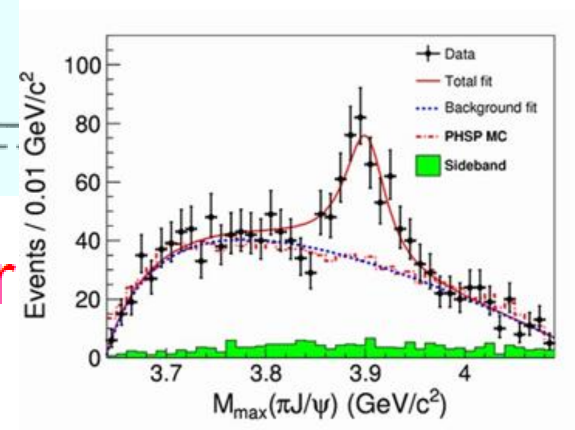
What are they ?

Potential models worked well for charmonium specrtoscopy

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



Not all XYZ states are char

Courtesy of
C. Z.Yuan

approaches/descriptions

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...

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)

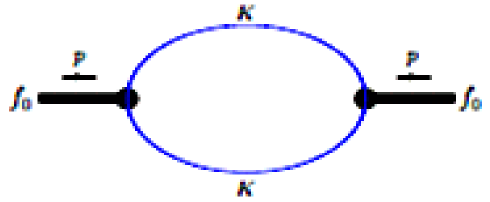
Meson-exchange models (Lohse, et al., 1990)

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

Our approach:

- Bound state description of hadronic molecules in QFT based on compositeness condition: $Z_M = 0$,
  see: Weinberg, PR 130 (1963) 776; Salam, Nuev. Cim. 25 (1962) 224; Hayashi et al., FP 15 (1967) 625;...

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



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

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

$$Z_x = 1 - g^2\Pi'(M^2) = 0$$

- Vertex function $\Phi(y^2)$ – finite size effects/distribution of constituents in bound state:

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

  momentum space: $\tilde{\Phi}(p_E^2) = \exp(-p_E^2/\Lambda^2)$, Gaussian with free size parameter Λ.

New resonances: 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:

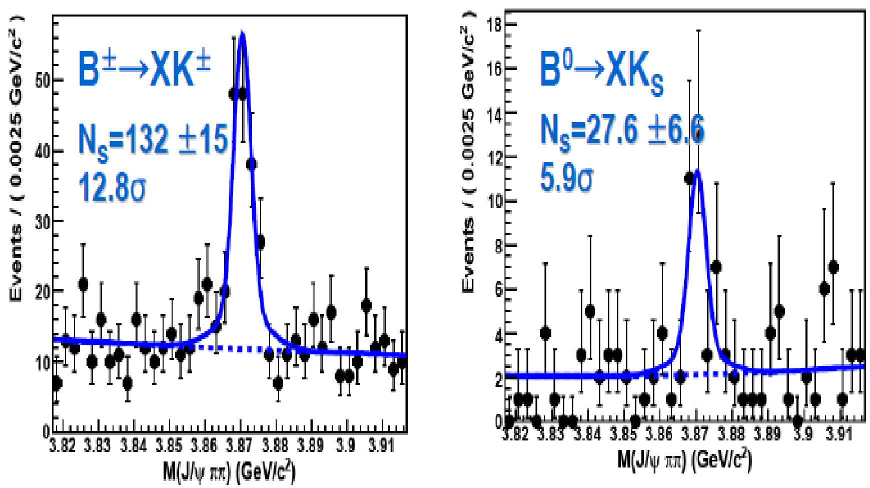
  C=+ from $X(3872) \to \gamma J/\psi$, I=0 no signal in $X \to \pi\pi^0 J/\psi$

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

$X(3872) \to \pi^+\pi^- J/\psi$

arXiv:0809.1224 605 fb^{-1}

recent results

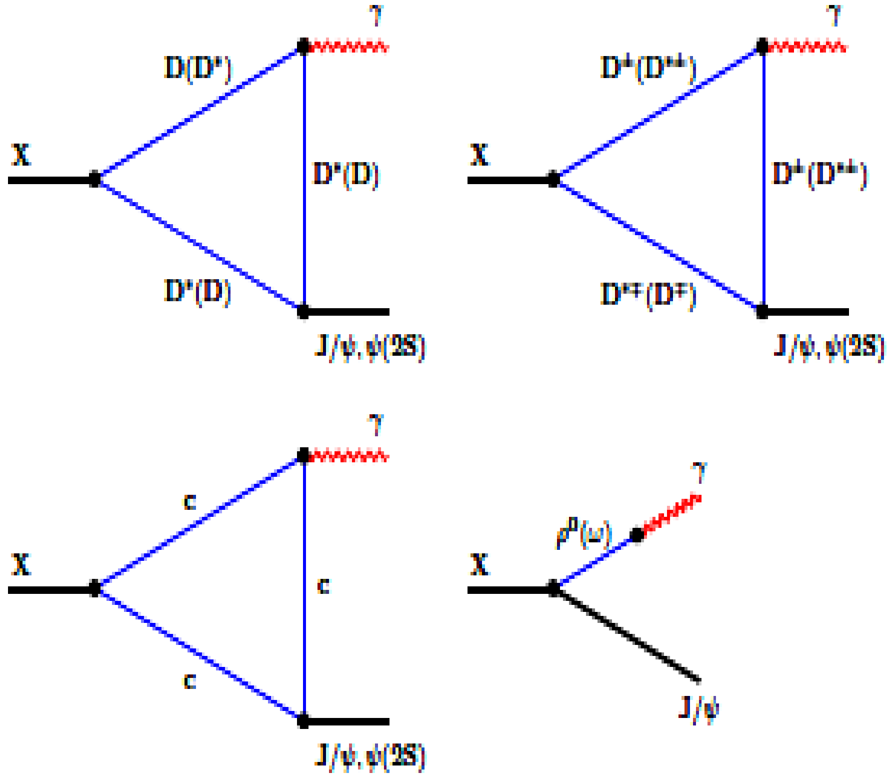


M(X(3872))=(3871.46±0.37±0.07) MeV
by combining two modes together

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

Radiative decays

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



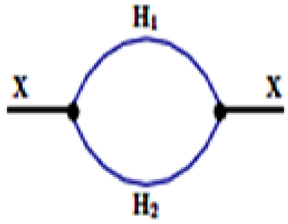


FIG. 1: H_1H_2 hadron-loop diagrams contributing to the mass operator of the $X(3872)$ meson.

Decay width (keV)

Approach	$\Gamma(X(3872) \to \gamma J/\psi)$
[$c\bar{c}$], Ref. [9]	11
[$c\bar{c}$], Ref. [33]	71
[$c\bar{c}$], Ref. [33]	139
[molecule], Ref. [33]	8
Our results	124.8 - 231.3 ($\epsilon = 0.7$ MeV) 129.8 - 239.1 ($\epsilon = 1$ MeV) 138.0 - 251.4 ($\epsilon = 1.5$ MeV)

PRD77, 094013

Strong decay(two-body, three-body)

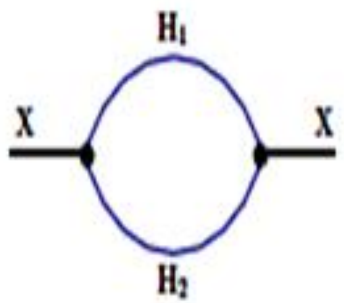


FIG. 1: H_1H_2 hadron-loop diagrams contributing to the mass operator of the $X(3872)$ meson.

PRD79,094013

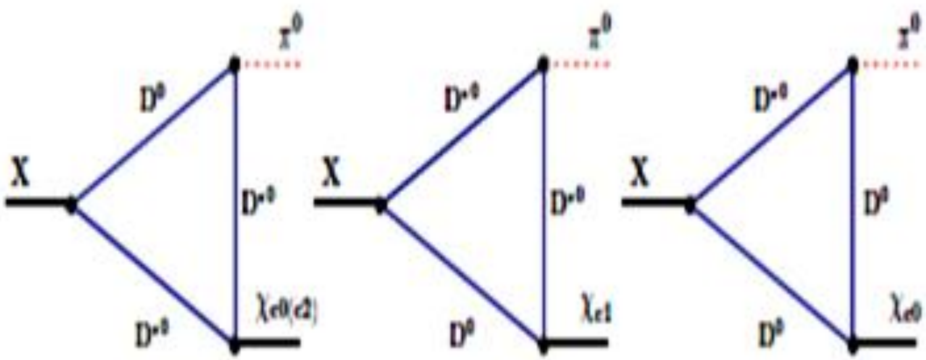


FIG. 2: Diagrams contributing to the hadronic transitions $X(3872) \to \chi_{cJ} + \pi^0$.

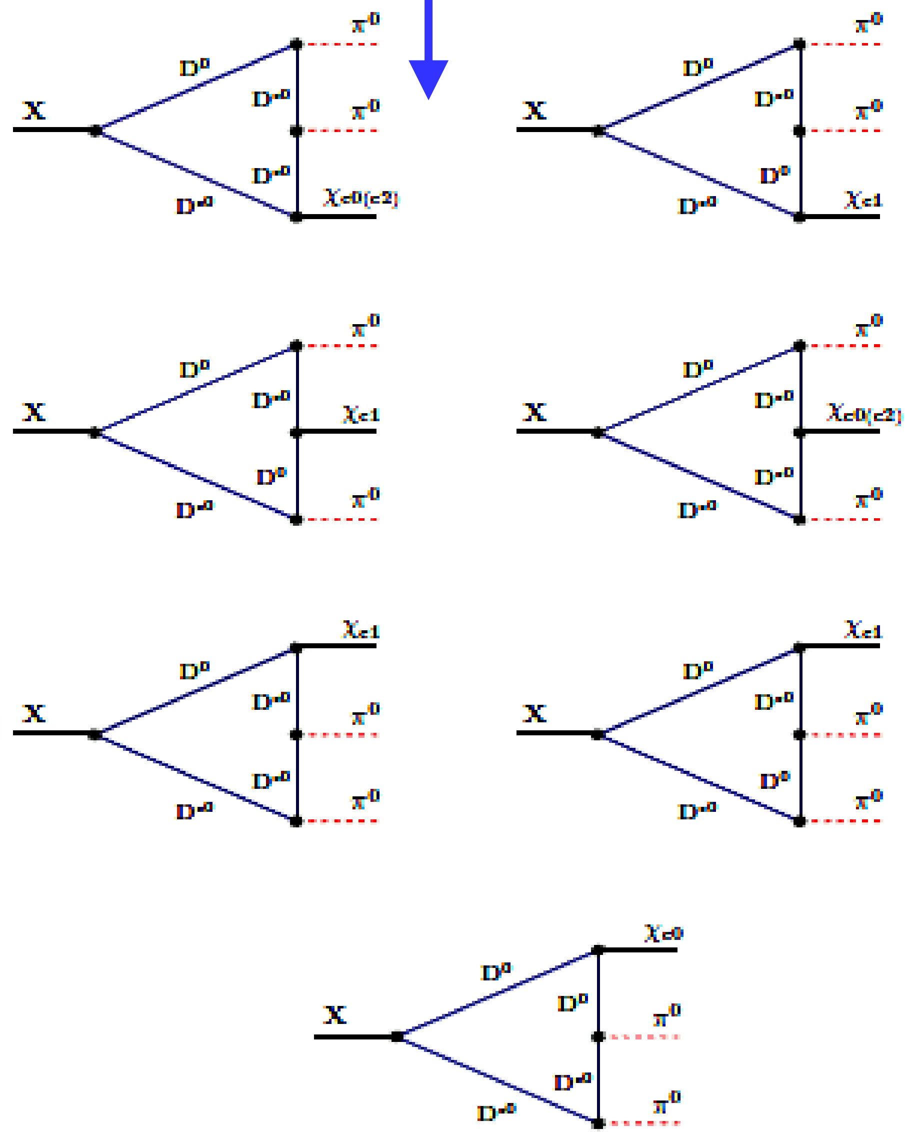


FIG. 3: Diagrams contributing to the hadronic transitions $X(3872) \to \chi_{cJ} + 2\pi^0$.

New measurement

- $\Gamma(X \to \psi(2S)\gamma)/\Gamma(X \to J/\psi\gamma) = 3.5 \pm 1.4$
  BABAR, PRL 102, (2009)
  possible evidence for charmonium component ?

Exotic charmonium-like spectroscopy at LHCb:
a study of the X(3872) and of the Z(4430)$^-$ states

LHCb
1409.6472

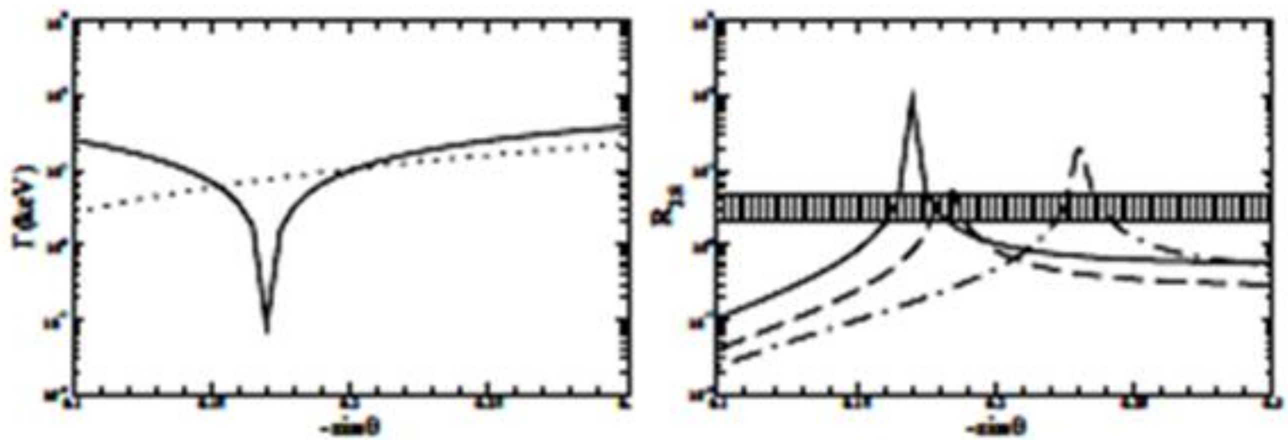
Radiative Decay X(3872) $\to$ J/ψ γ, ψ′γ

To study this further, LHCb has recently measured [7] the ratio of branching fractions

$$R_{\psi\gamma} = \frac{B(X(3872) \to \psi(2S)\gamma)}{B(X(3872) \to J/\psi\gamma)}, \quad R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29,$$

additional charmonium contribution with $Z_{c\bar{c}}^{1/2} = sin\theta \approx -0.2$ required

YBD, A. Faessler, T.Gutsche and V. Lyubovitskij, J. Phys. G38, 015001



dotted - J/ψ, solid - $\psi(2s)$ mode

$$R_{2s} = \frac{\Gamma(X \to \psi(2S) + \gamma)}{\Gamma(X \to J/\psi + \gamma)} = 3.5 \pm 1.4$$

(BABAR, 2009)

Our approach

- 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:

Other applications:

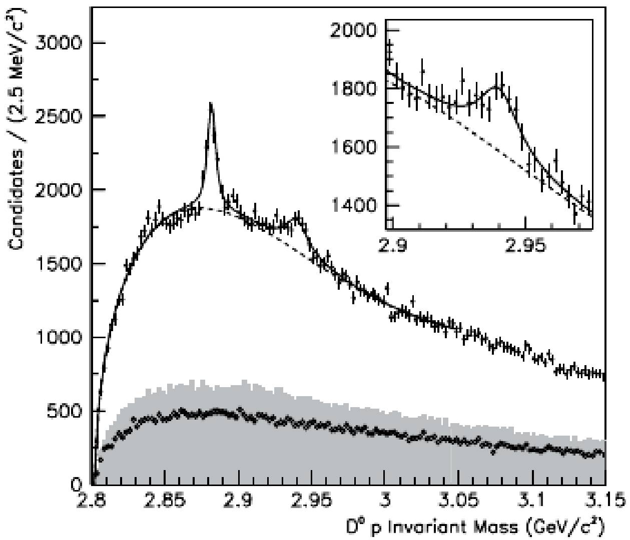
2), Y-type: Y(4260), Y(3940); Z-type: Z(4430),Zc(3900)

2, New baryon resonance of Λc(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

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

$$\Gamma = [5.8 \pm 1.5(\text{stat}) \pm 1.1(\text{syst})]\ \text{MeV}.$$

Recently a new baryon resonance $\Lambda_c(2940)^+$ has been discovered in the decay channel $D^0 p$ by the *BABAR* Collaboration [1] and confirmed as a resonant structure in the final state $\Sigma_c(2455)^{0,++}\pi^\pm \to \Lambda_c^+\pi^+\pi^-$ by Belle

Measurement

PDG

PRL 98, 262001 (2007) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2007

Experimental Constraints on the Spin and Parity of the $\Lambda_c(2880)^+$

(Belle Collaboration)

We report the results of several studies of the $\Lambda_c^+\pi^+\pi^-X$ final state in continuum e^+e^- annihilation data collected by the Belle detector. An analysis of angular distributions in $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decays strongly favors a $\Lambda_c(2880)^+$ spin assignment of $\frac{5}{2}$ over $\frac{3}{2}$ or $\frac{1}{2}$. We find evidence for $\Lambda_c(2880)^+ \to \Sigma_c(2520)^{0,++}\pi^{+,-}$ decay and measure the ratio of $\Lambda_c(2880)^+$ partial widths $\Gamma(\Sigma_c(2520)\pi)/\Gamma(\Sigma_c(2455)\pi) = 0.225 \pm 0.062 \pm 0.025$. This value favors the $\Lambda_c(2880)^+$ spin-parity assignment of $\frac{5}{2}^+$ over $\frac{5}{2}^-$. We also report the first observation of $\Lambda_c(2940)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ decay and measure $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ mass and width parameters. These studies are based on a 553 fb^{-1} data sample collected at or near the $\Upsilon(4S)$ resonance at the KEKB collider.

TABLE I. Signal yield, mass, and width for the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$. The first uncertainty is statistical, the second one systematic.

State	Yield	M (MeV/c^2)	Γ (MeV)
$\Lambda_c(2880)^+$	690 ± 50	$2881.2 \pm 0.2 \pm 0.4$	$5.8 \pm 0.7 \pm 1.1$
$\Lambda_c(2940)^+$	220^{+80}_{-60}	$2938.0 \pm 1.3^{+2.0}_{-4.0}$	13^{+8+27}_{-5-7}

CHARMED BARYONS
($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

Λ_c^+ $I(J^P) = 0(\frac{1}{2}^+)$

J is not well measured; $\frac{1}{2}$ is the quark-model prediction.

Mass $m = 2286.46 \pm 0.14$ MeV

$\Lambda_c(2940)^+$ $I(J^P) = 0(?^?)$

Mass $m = 2939.3^{+1.4}_{-1.5}$ MeV

Full width $\Gamma = 17^{+8}_{-6}$ MeV

$\Lambda_c(2940)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
pD^0	seen	420
$\Sigma_c(2455)^{0,++}\pi^\pm$	seen	–

Different interpretations

1), quark model:

Isgur-Karl (3/2+,5/2-)

Heavy-light diquark model (radial excitation of Λc)

2), Chiral quark model:

D-Wave

3), Molecular model (ratios)

the assignment of the resonance

$$\mathcal{L}_{\Lambda_c}(x) = g_{\Lambda_c}\bar{\Lambda}_c^+(x)\Gamma^\mu \int d^4y\,\Phi(y^2)(\cos\theta D^{*0}_\mu(x)p(x+y) + \sin\theta D^{*+}_\mu(x)n(x+y)) + \text{H.c.},$$

$$Z_{\Lambda_c} = 1 - \Sigma'_{\Lambda_c}(m_{\Lambda_c}) = 0.$$

$$\Gamma^\mu = \gamma^\mu \text{ for } J^P = \frac{1^+}{2} \text{ and } \Gamma^\mu = \gamma_5\gamma^\mu \text{ for } J^P = \frac{1^-}{2}$$

$$|\Lambda_c(2940)^+\rangle = \cos\theta|pD^{*0}\rangle + \sin\theta|nD^{*+}\rangle.$$

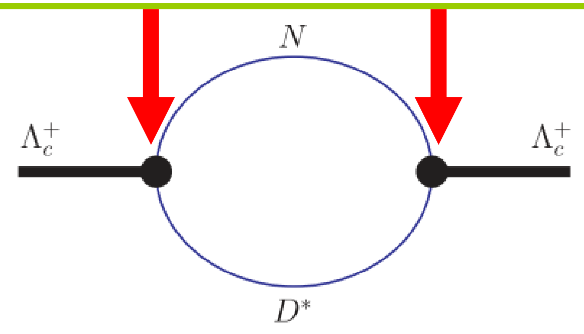


FIG. 1 (color online). Diagram describing the $\Lambda_c(2940)^+$ mass operator.

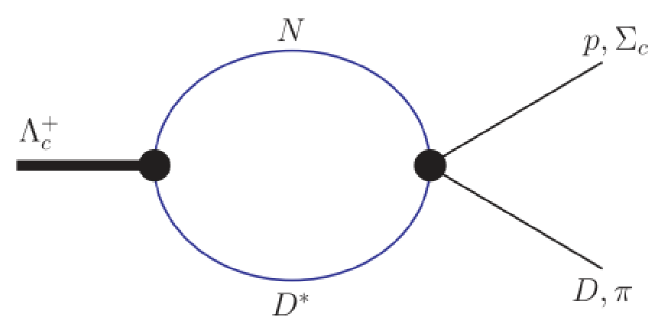
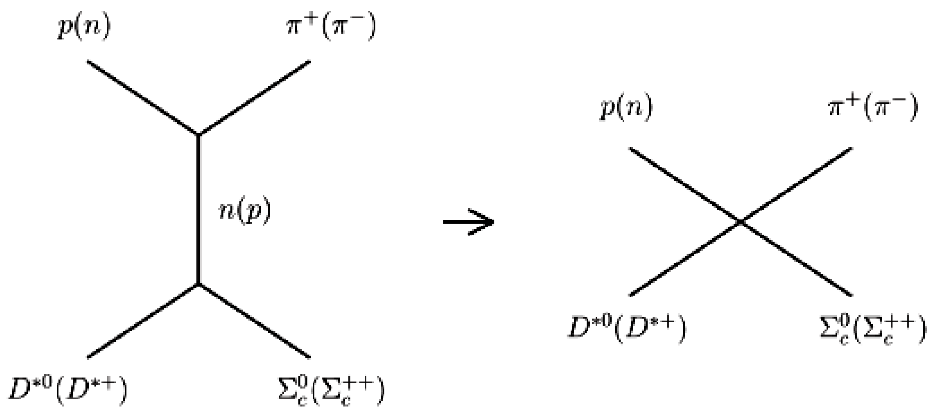


FIG. 2 (color online). Diagrams contributing to the decays $\Lambda_c(2940)^+ \to pD^0$, $\Sigma_c^{++}\pi^-$, $\Sigma_c^0\pi^+$.



Effective Lagrangians

$$\mathcal{L}_{VPBB}(x) = -\frac{G}{F_D}\bar{p}(x)i\gamma^\mu\gamma^5\Big(\frac{2}{5}p(x)D^{*0}_\mu(x) + \frac{1}{2}n(x)D^{*+}_\mu(x)\Big)\bar{D}^0(x)$$
$$+ \frac{G}{F_\pi}\bar{\Sigma}^{++}_c(x)i\gamma^\mu\gamma^5\Big(\frac{9}{10}p(x)D^{*0}_\mu(x) + n(x)D^{*+}_\mu(x)\Big)\pi^+(x)$$
$$+ \frac{G}{F_\pi}\bar{\Sigma}^{0}_c(x)i\gamma^\mu\gamma^5\Big(p(x)D^{*0}_\mu(x) + \frac{9}{10}n(x)D^{*+}_\mu(x)\Big)\pi^-(x) + \text{H.c.},$$

$$\mathcal{L}_{VPBB} = ig_1\bar{B}^{kmn}\gamma^\mu\gamma^5[V_\mu, P]^l_k B_{lmn}$$
$$+ ig_2\bar{B}^{kmn}\gamma^\mu\gamma^5[V_\mu, P]^l_k B_{lnm}$$
$$+ ig_3\bar{B}^{kmn}\gamma^\mu\gamma^5((V_\mu)^l_k P^s_m - P^l_k(V_\mu)^s_m)$$
$$- ig_3\bar{B}^{knm}\gamma^\mu\gamma^5((V_\mu)^l_k P^s_m - P^l_k(V_\mu)^s_m)$$

The strong two-body decay widths of the $\Lambda_c(2940)^+$ baryon are calculated according to the expressions

$$\Gamma(\Lambda_c[1/2^+] \to B + M) = \frac{g^2_{\Lambda_c BM}}{16\pi m^3_{\Lambda_c}}\lambda^{1/2}(m^2_{\Lambda_c}, m^2_B, m^2_M) \times ((m_{\Lambda_c} - m_B)^2 - m^2_M) \quad (9)$$

for the positive parity $\Lambda_c(2940)^+$ state and accordingly

$$\Gamma(\Lambda_c[1/2^-] \to B + M) = \frac{f^2_{\Lambda_c BM}}{16\pi m^3_{\Lambda_c}}\lambda^{1/2}(m^2_{\Lambda_c}, m^2_B, m^2_M) \times ((m_{\Lambda_c} + m_B)^2 - m^2_M) \quad (10)$$

for the negative parity choice for $\Lambda_c(2940)^+$.

PRD81, 014006

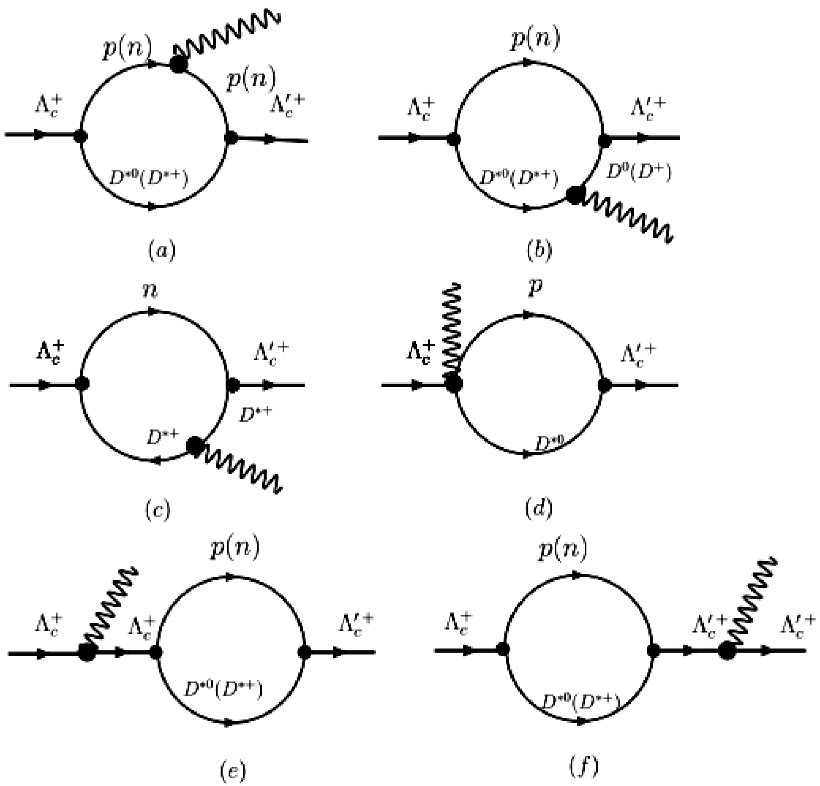
Calculated results

TABLE I. Partial decay widths of $\Lambda_c(2940)^+$ in MeV.

	$\frac{1}{2}^+$ modes			$\frac{1}{2}^-$ modes		
$\cos\theta$	$\Lambda_c^+ \to pD^0$	$\Lambda_c^+ \to \Sigma_c^{++}\pi^-$	$\Lambda_c^+ \to \Sigma_c^0\pi^+$	$\Lambda_c^+ \to pD^0$	$\Lambda_c^+ \to \Sigma_c^{++}\pi^-$	$\Lambda_c^+ \to \Sigma_c^0\pi^+$
1	0.11	0.58	0.72	19.15	612.68	756.72
0.95	0.17	0.85	0.98	29.75	907.64	1040.36
0.9	0.20	0.96	1.08	34.40	1033.00	1153.95
0.8	0.23	1.11	1.20	41.09	1208.89	1305.10
0.7	0.25	1.20	1.27	46.17	1338.06	1407.80
0.6	0.27	1.27	1.30	50.24	1437.58	1478.96
0.5	0.28	1.31	1.32	53.47	1511.85	1522.78
0.4	0.29	1.32	1.30	55.83	1560.10	1538.24
0.3	0.29	1.32	1.30	55.83	1560.10	1538.24
0.2	0.29	1.30	1.26	57.15	1577.04	1519.78
0.1	0.26	1.14	1.03	54.20	1447.05	1309.75
0.05	0.24	1.04	0.91	50.68	1334.05	1174.51
0	0.18	0.74	0.60	38.15	964.41	781.52

Radiative decay($1^+/2$)

Gauge Invariance



Diagrams contributing to the radiative decay process $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+\gamma$.

$$q_\mu \mathcal{M}^\mu(p, p') = 0$$

$$\mathcal{M}^\mu(p, p') = \bar{u}_{\Lambda_c'}(p')\Gamma^\mu(p, p')u_{\Lambda_c}(p),$$

$$\Gamma^\mu(p, p') = F_1(q^2)\gamma^\mu + F_2(q^2)i\sigma^{\mu\nu}q_\nu + F_3(q^2)q^\mu.$$

$$F_1(q^2) = F_3(q^2)\frac{q^2}{m_{\Lambda_c} - m_{\Lambda_c'}}.$$

$$\mathcal{M}^\mu(p, p') = \frac{F_{\Lambda_c\Lambda_c'\gamma}}{2m_{\Lambda_c}}\bar{u}_{\Lambda_c'}(p')i\sigma^{\mu\nu}q_\nu u_{\Lambda_c}(p).$$

$$\Gamma(\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + \gamma) = \frac{\alpha P^{*3}}{m_{\Lambda_c}^2}F^2_{\Lambda_c\Lambda_c'\gamma},$$

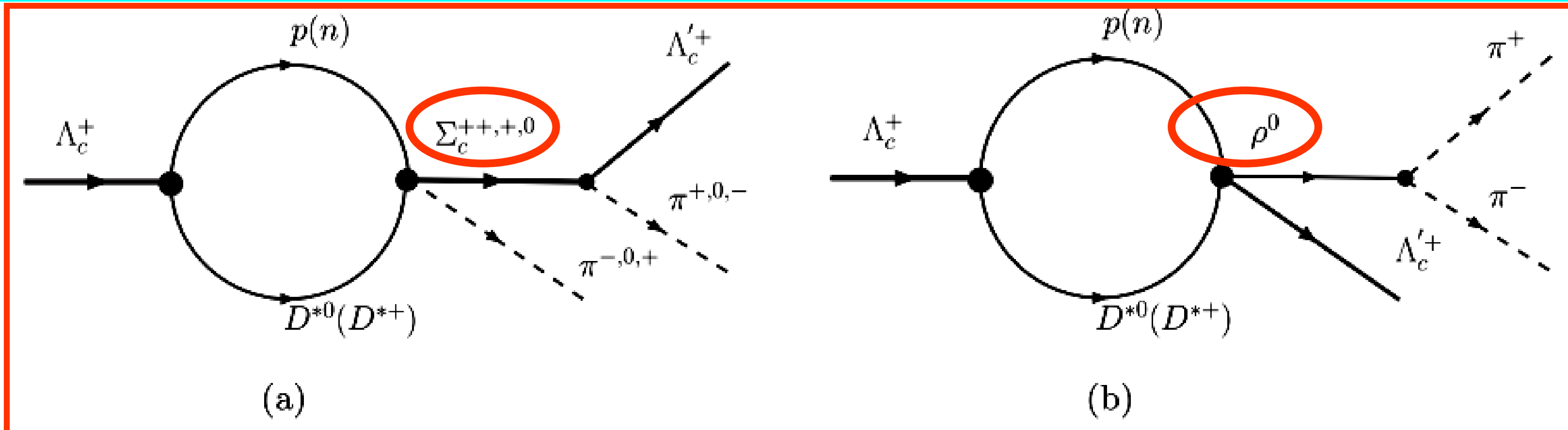
TABLE III. Radiative decay width of $\Lambda_c(2940)^+$ in keV.

θ	Λ (GeV)					
(in grad)	0.25	0.4	0.5	0.75	1	1.25
0	11.1	35.4	61.7	113.1	142.7	156.8
5	9.2	29.2	51.0	91.5	112.2	119.4
10	7.4	23.2	40.6	71.0	83.9	85.5
15	5.7	17.6	30.8	52.1	58.6	56.2
20	4.1	12.5	22.0	35.5	37.1	32.4
25	2.7	8.1	14.4	21.7	20.1	14.7

2015/7/17

PRD82, 034035

Three-body decay



Diagrams contributing to the $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ + 2\pi$ decay.

$$\mathcal{L}_{\pi^- D^{*0} p \Sigma_c^{++}} = \left[\frac{1}{4}(g_1+g_2) - \frac{3}{2}g_3\right]\bar{\Sigma}_c^{++}\pi^- i\gamma^\mu\gamma_5 p D_\mu^{*0} + \text{H.c.}, \quad \mathcal{L}_{\pi^- D^{*+} n \Sigma_c^{++}} = -\frac{3}{2}g_3\bar{\Sigma}_c^{++}\pi^- i\gamma^\mu\gamma_5 n D_\mu^{*+} + \text{H.c.},$$

$$\mathcal{L}_{\pi^0 D^{*0} p \Sigma_c^{+}} = \frac{1}{2}\left[\frac{1}{4}(g_1+g_2) - 3g_3\right]\bar{\Sigma}_c^{+}\pi^0 i\gamma^\mu\gamma_5 p D_\mu^{*0} + \text{H.c.}, \quad \mathcal{L}_{\pi^0 D^{*+} n \Sigma_c^{+}} = \frac{1}{2}\left[\frac{1}{4}(g_1+g_2) - 3g_3\right]\bar{\Sigma}_c^{+}\pi^0 i\gamma^\mu\gamma_5 n D_\mu^{*+} + \text{H.c.},$$

$$\mathcal{L}_{\pi^+ D^{*0} p \Sigma_c^{0}} = -\frac{3}{2}g_3\bar{\Sigma}_c^{0}\pi^+ i\gamma^\mu\gamma_5 p D_\mu^{*0} + \text{H.c.}, \quad \mathcal{L}_{\pi^+ D^{*+} n \Sigma_c^{0}} = \left[\frac{1}{4}(g_1+g_2) - \frac{3}{2}g_3\right]\bar{\Sigma}_c^{0}\pi^+ i\gamma^\mu\gamma_5 n D_\mu^{*+} + \text{H.c.},$$

$$\mathcal{L}_{\pi\Sigma_c\Lambda_c'^+} = -\frac{1}{2}\sqrt{\frac{3}{2}}\left(g_2' - \frac{1}{2}g_1'\right)\bar{\Lambda}_c'^+ i\gamma^5 \pi\Sigma_c + \text{H.c.}. \qquad \mathcal{L}_{D^*N\Lambda_c'} = -g_{D^*N\Lambda_c'}\kappa_{D^*N\Lambda_c'}\bar{N}\sigma^{\mu\nu}\partial_\nu D_\mu^*\Lambda_c' + \text{H.c.},$$

$$\mathcal{L}_{\rho\pi\pi} = g_{\rho\pi\pi}\rho_k^\mu \pi_i \partial_\mu \pi_j \epsilon_{ijk},$$

$$\mathcal{L}_{\rho D^* N\Lambda_c'} = \frac{g_{\rho D^* N\Lambda_c'}}{2M_N}\bar{N}D_\mu^{*+} i\sigma^{\mu\nu}\rho_\nu\Lambda_c'^+ + \text{H.c.},$$

$$\Gamma = \frac{\beta}{512\pi^3 M_{\Lambda_c}^3}\int_{4M_\pi^2}^{(M_{\Lambda_c}-M_{\Lambda_c'})^2} ds_2 \int_{s_1^-}^{s_1^+} ds_1 \sum_{\text{pol}} |M_{\text{inv}}|^2,$$

PRD83, 094003

3, Production @ PANDA

Home | News | Meetings | Collaboration | Computing | Detector | Physics | Documents | Communications

Welcome to the PANDA Experiment Website

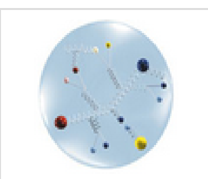
The PANDA Experiment will be one of the key experiments at the Facility for Antiproton and Ion Research (FAIR) which is under construction and currently being built on the area of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany.

The central part of FAIR is a synchrotron complex providing intense pulsed ion beams (from p to U). Antiprotons produced by a primary proton beam will then be filled into the High Energy Storage Ring (HESR) which collide with the fixed target inside the PANDA Detector.

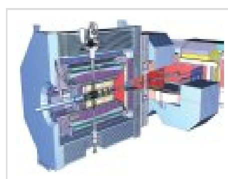
The PANDA Collaboration with more than 450 scientist from 17 countries intends to do basic research on various topics around the weak and strong forces, exotic states of matter and the structure of hadrons.

In order to gather all the necessary information from the antiproton-proton c build being able to provide precise trajectory reconstruction, energy and mo identification of charged particles.

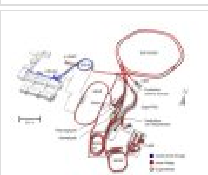
What do you want to know more about?



The Physics Program
Information about the various physics topics going to be investigated by PANDA.



The Detector
Detailled description and technical information about the different detection systems.



The Accelerator Facility
Information about host laboratory GSI, the Facility for Antiproton and Ion Research and the accelerator.

The PANDA Collaboration
Contact information, structure and working groups within the Collaboration.

Forthcoming experiments at *PANDA*, with the $\bar{p}$ momentum in the range from 1 to 15 GeV/c, which corresponds to total center-of-mass energies in the antiproton-proton system between 2.25 and 5.5 GeV, can give rich contributions to these investigations [1]. For example, $p\bar{p}$ annihilation reactions are expected to provide substantial information on the charm baryon $\Lambda_c(2286)$ as well as the baryon resonance $\Lambda_c(2940)$ recently observed by the *BABAR* Collaboration [2] and confirmed by the Belle Collaboration [3].

BEPC, BABAR, BELLE, JLab. PANDA

Production

$$|\Lambda_c(2940)\rangle = |pD^{*0}\rangle.$$

$$\mathcal{L}^{\frac{1}{2}+}_{\Lambda_c' pD} = g_{\Lambda_c' pD}\bar{\Lambda}_c' i\gamma_5 pD^0 + \text{H.c.},$$

$$\mathcal{L}^{\frac{1}{2}+}_{\Lambda_c' pD^*} = g_{\Lambda_c' pD^*}\bar{\Lambda}_c'\gamma^\mu pD^{*0}_\mu + \text{H.c.}$$

$$\frac{d\sigma}{dM_{pD}} = \frac{1}{1024\pi^4}\frac{1}{s\sqrt{s-4M_N^2}} \times \int d\cos\theta_3\, d\Omega_1^*\, |\vec{q}_1^{\,*}|\, |\vec{q}_2|\, |\mathcal{M}_{\rm inv}|^2$$

$$\mathcal{L}^{\frac{1}{2}-}_{\Lambda_c' pD} = f_{\Lambda_c' pD}\bar{\Lambda}_c' pD^0 + \text{H.c.},$$

$$\mathcal{L}^{\frac{1}{2}-}_{\Lambda_c' pD^*} = f_{\Lambda_c' pD^*}\bar{\Lambda}_c'\gamma^\mu\gamma^5 pD^{*0}_\mu + \text{H.c.}$$

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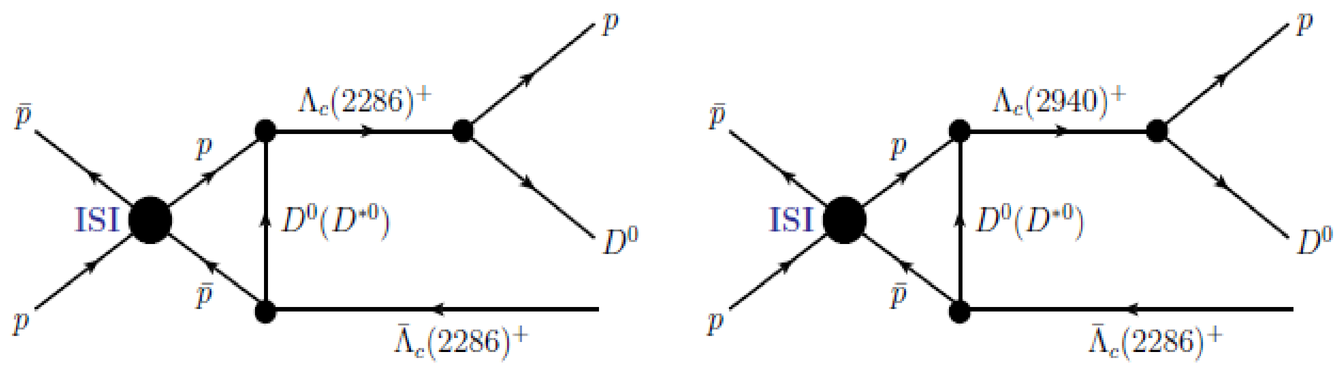
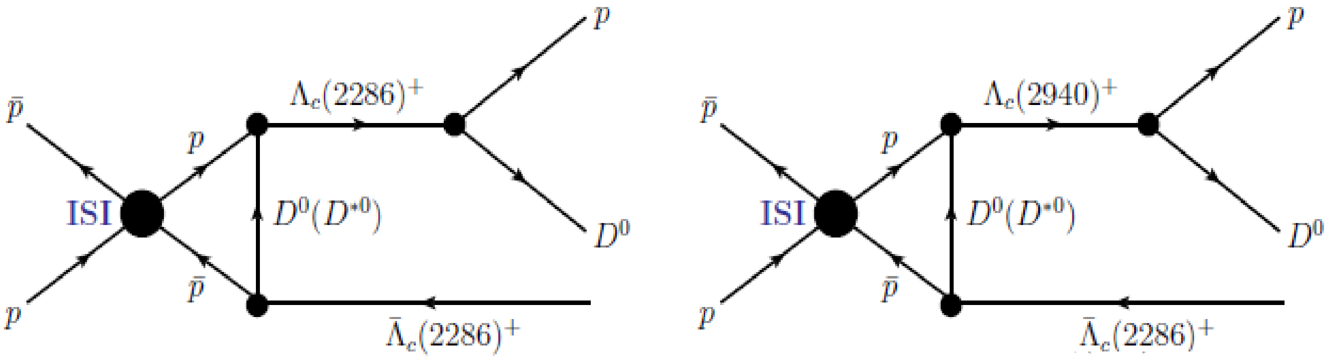


(a) (b)

Initial state interaction



(a)

ISI

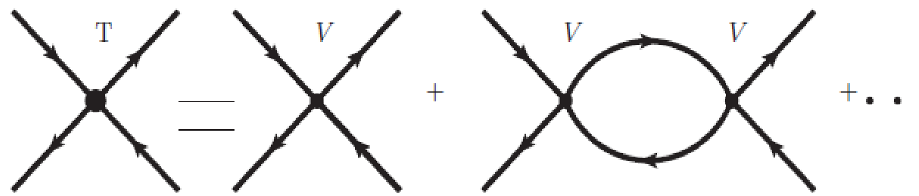


FIG. 2. Lippmann-Schwinger equation for the initial state interaction of the $N\bar{N}$ system.

$$T(\vec{q}\,',\vec{q};E) = V(\vec{q}\,',\vec{q};E) + \int \frac{d^3p V(\vec{q}\,',\vec{p})T(\vec{p},\vec{q};E)}{E(q)-E(p)+i\epsilon},$$

$$V_{N\bar{N}}(\vec{q}\,',\vec{q}) = V^{\pi}_{N\bar{N}}(\vec{q}\,',\vec{q}) + V^{\rm opt}_{N\bar{N}}(\vec{q}\,',\vec{q}).$$

The π-exchange potential is given by [23,24]

$$V^{\pi}_{N\bar{N}}(\vec{q}\,',\vec{q}) = \frac{g^2_{\pi NN}}{12M_N^2}\frac{\vec{k}_\pi^2}{M_\pi^2+\vec{k}_\pi^2} \times (\vec{\sigma}_1\cdot\vec{\sigma}_2 + \hat{S}_{12}(\vec{k}_\pi))\,(\vec{\tau}_1\cdot\vec{\tau}_2)\,F_\pi^2(\vec{k}_\pi^2),$$

The optical potential for the $N\bar{N}$ scattering state is

$$V^{\rm opt}_{N\bar{N}}(r) = (u_0 + iw_0)e^{-\vec{r}^2/2r_0^2}$$

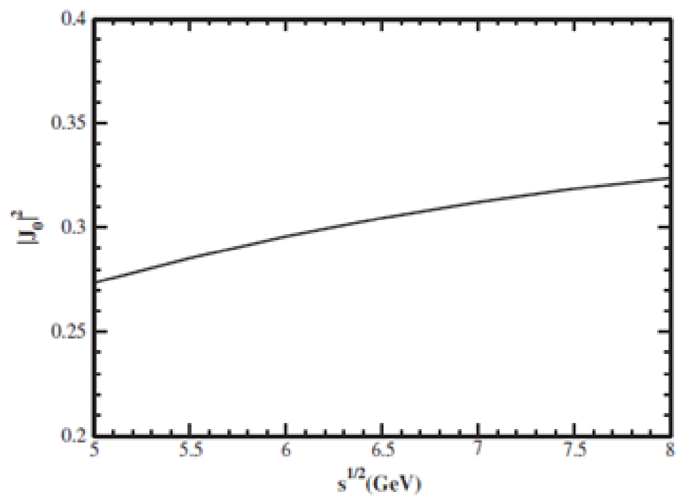
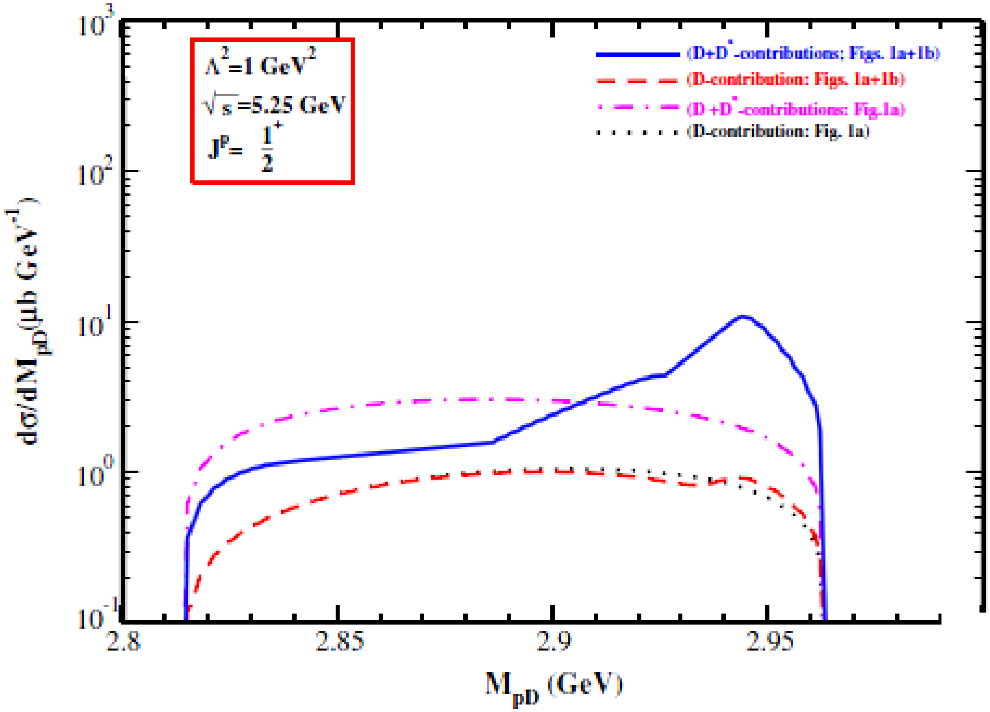
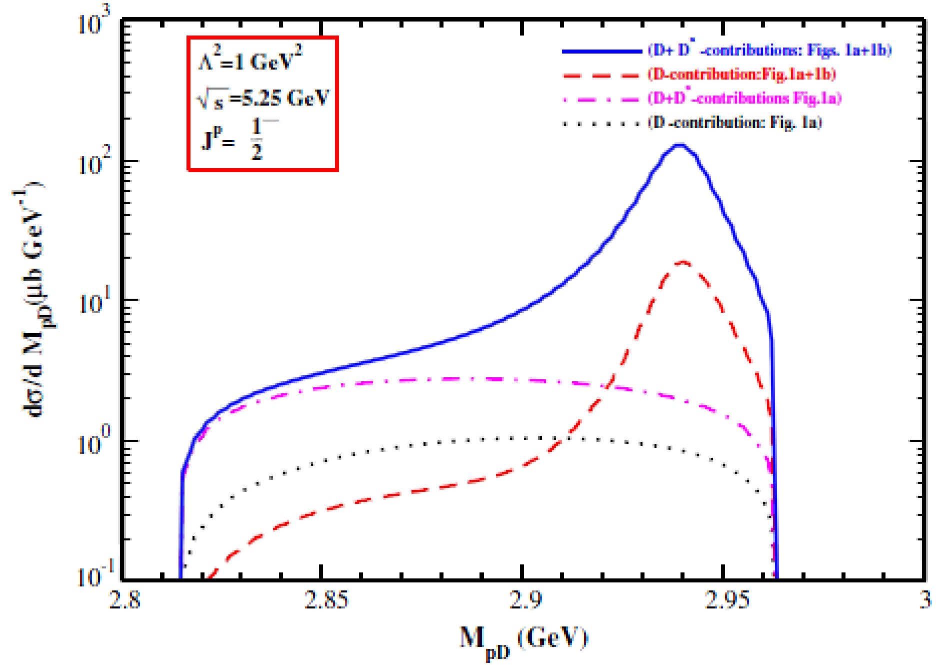


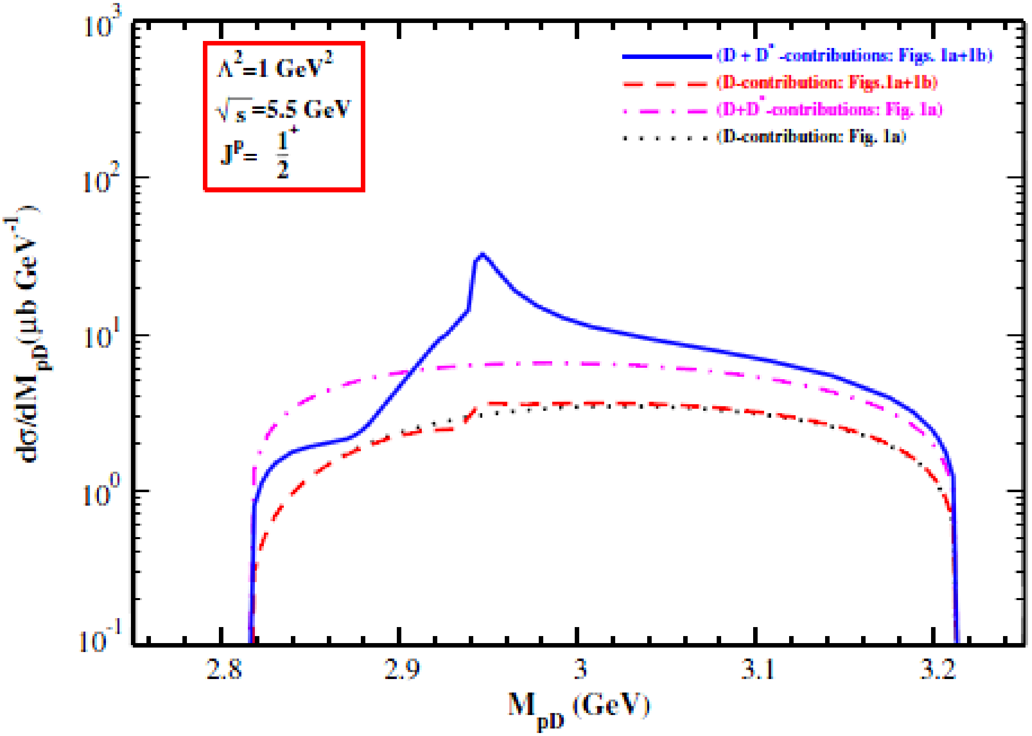
FIG. 3. Initial state interaction factor $|J_0|^2$ in dependence on $s^{1/2}$.



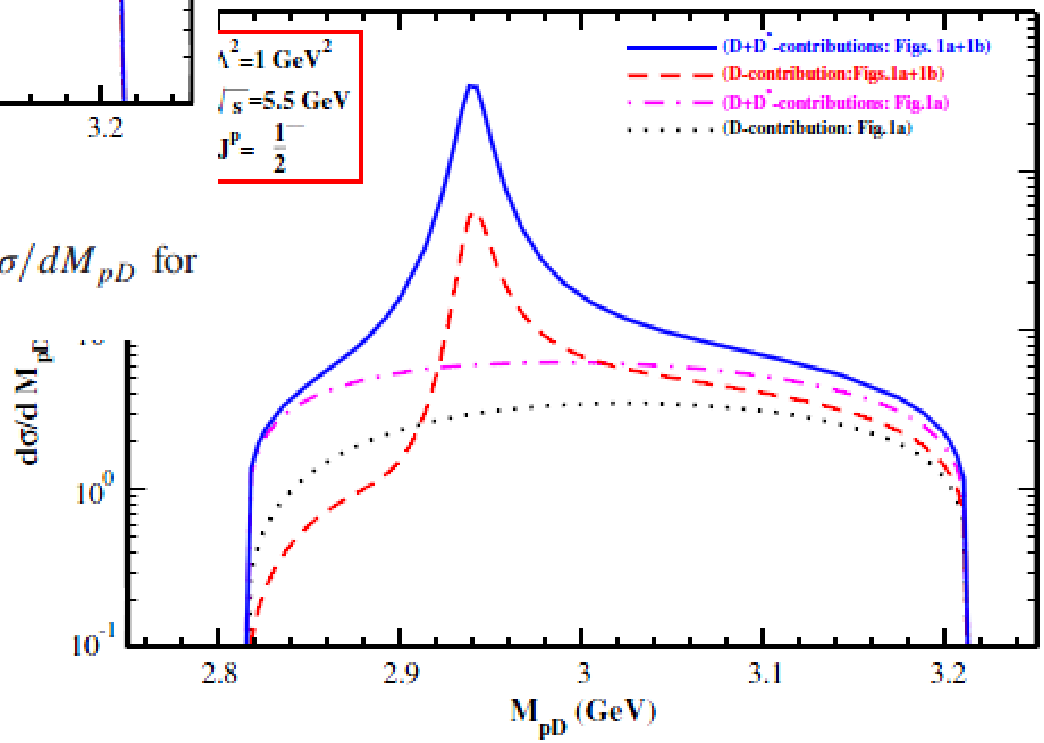
Differential cross section $d\sigma/dM_{pD}$ $s^{1/2} = 5.25$ GeV for $J^P = \frac{1}{2}^+$ of the $\Lambda_c(2940)$.



Differential cross section $d\sigma/dM_{pD}$ for $s^{1/2} = 5.25$ GeV for $J^P = \frac{1}{2}^-$ of the $\Lambda_c(2940)$.



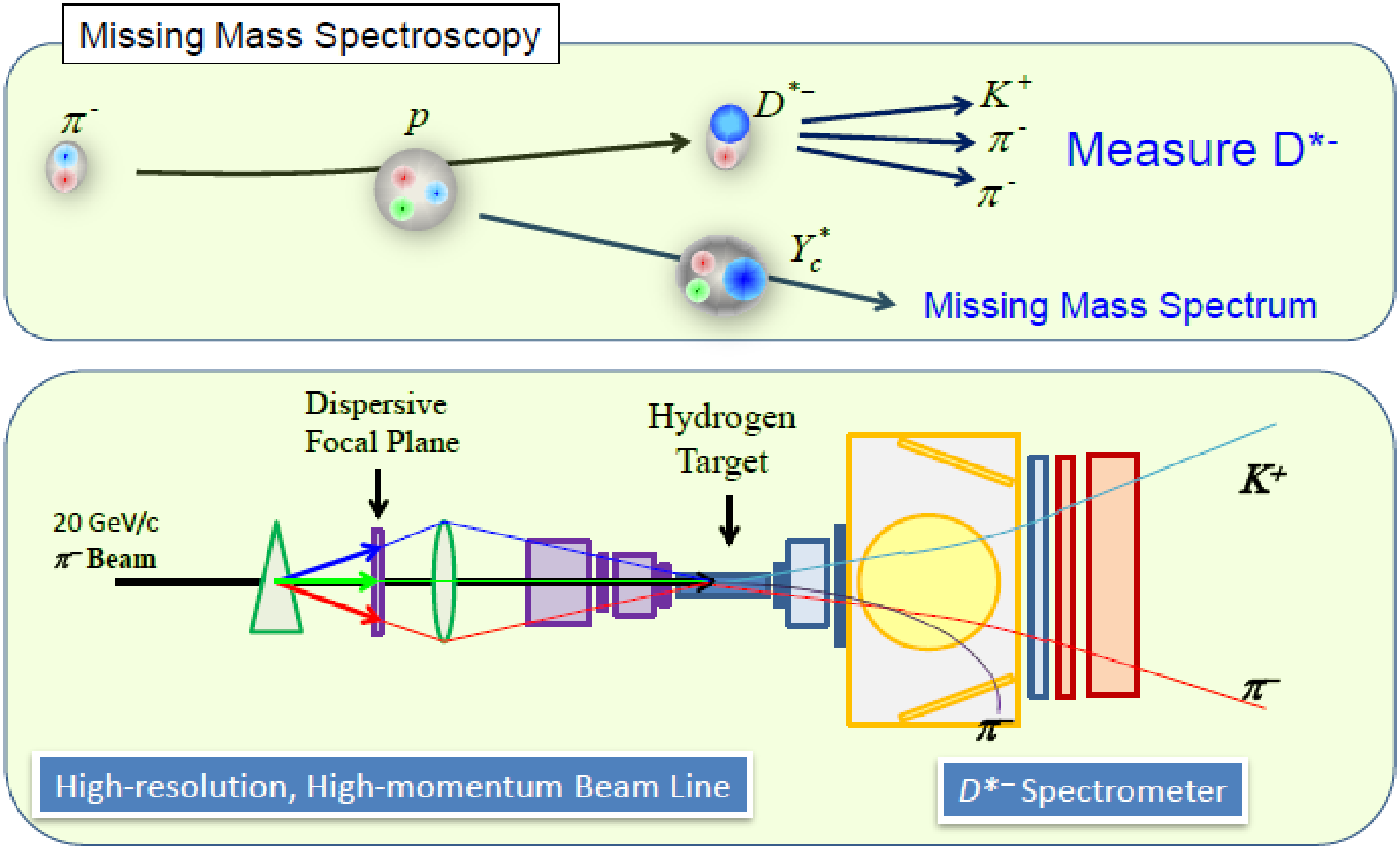
Differential cross section $d\sigma/dM_{pD}$ for $s^{1/2} = 5.5$ GeV for $J^P = \frac{1}{2}^+$ of the $\Lambda_c(2940)$.



Differential cross section $d\sigma/dM_{pD}$ for $s^{1/2} = 5.5$ GeV for $J^P = \frac{1}{2}^-$ of the $\Lambda_c(2940)$.

4, Production @ JPARC (Hadron Hall)

Charmed Baryon Spectroscopy



Courtesy of S.Sawada

Nucl-1506.01133

$$|\Lambda_c(2940)\rangle = |pD^{*0}\rangle.$$

$$d\sigma(\pi^- p \to D^- D^0 p) = \frac{1}{2\sqrt{(p_1 \cdot p_2)^2 - m_{\pi^-}^2 m_p^2}} \sum_{s_i, s_f} |\mathcal{M}|^2$$

$$\times \frac{d^3 p_3}{2E_3} \frac{d^3 p_4}{2E_4} \frac{m_p d^3 p_5}{E_5} \delta^4(p_1 + p_2 - p_3 - p_4 - p_5),$$

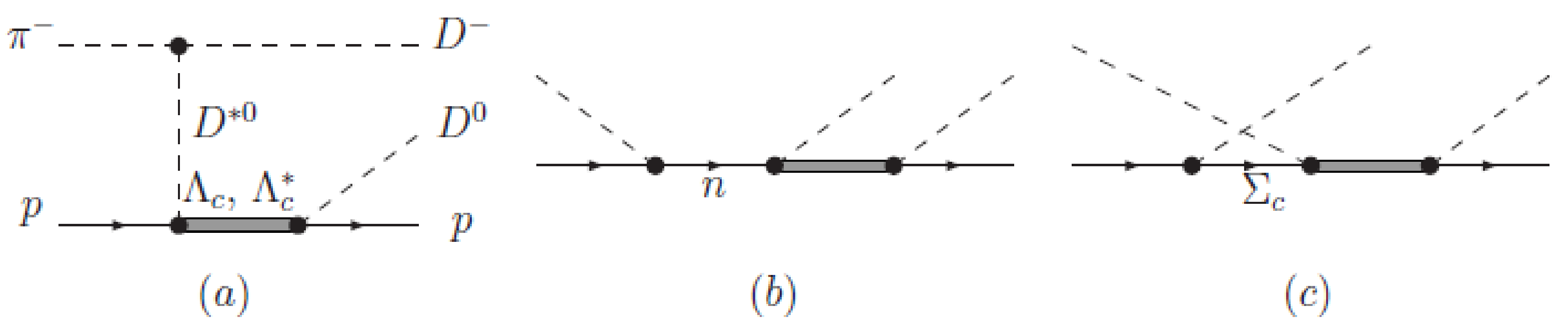


FIG. 1: Feynman diagrams for the $\pi^- p \to D^- D^0 p$ reaction.

Effective interactions

$$\mathcal{L}_{D^*D\pi} = g_{D^*D\pi} D^*_\mu \vec{\tau} \cdot (D\partial^\mu \vec{\pi} - \partial^\mu D \vec{\pi}), \qquad (1)$$

$$\mathcal{L}_{\pi NN} = -i g_{\pi NN} \bar{N} \gamma_5 \vec{\tau} \cdot \vec{\pi} N, \qquad (2)$$

$$\mathcal{L}_{DN\Sigma_c} = -i g_{DN\Sigma_c} \bar{N} \gamma_5 D \Sigma_c + \mathrm{H.c.}, \qquad (3)$$

$$\mathcal{L}_{\Lambda_c pD} = i g_{\Lambda_c pD} \bar{\Lambda}_c \gamma_5 p D^0 + \mathrm{H.c.}, \qquad (4)$$

$$\mathcal{L}_{\Lambda_c pD^*} = g_{\Lambda_c pD^*} \bar{\Lambda}_c \gamma^\mu p D^{*0}_\mu + \mathrm{H.c.}, \qquad (5)$$

$$\mathcal{L}_{\Lambda_c \pi \Sigma_c} = i g_{\Lambda_c \pi \Sigma_c} \bar{\Lambda}_c \gamma_5 \vec{\pi} \cdot \vec{\Sigma}_c + \mathrm{H.c.}. \qquad (6)$$

$$F_{D^*}(q^2_{ex}, M_{ex}) = \frac{\Lambda^2_{D^*} - M^2_{D^*}}{\Lambda^2_{D^*} - q^2_{D^*}}, \qquad F_B(q^2_{ex}, M_{ex}) = \frac{\Lambda^4_B}{\Lambda^4_B + (q^2_{ex} - M^2_{ex})^2}.$$

Matrix elements

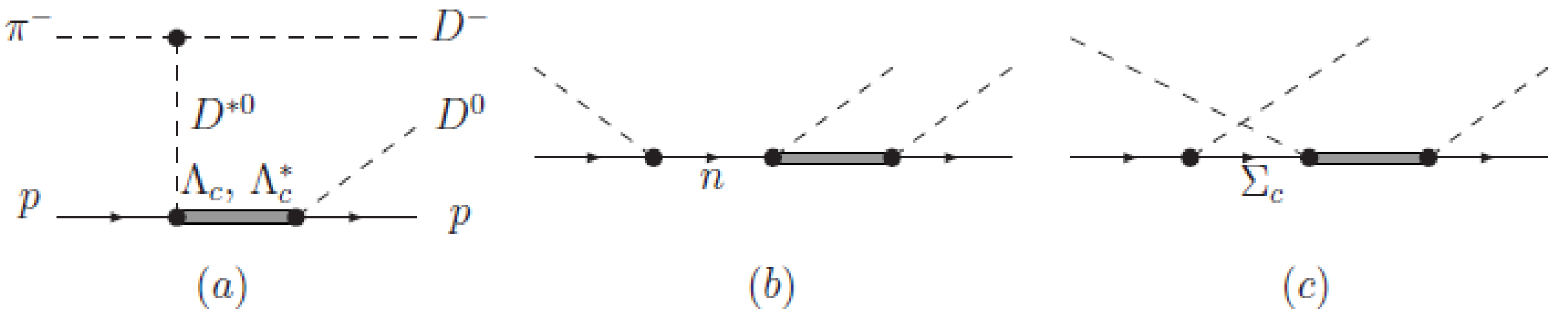


FIG. 1: Feynman diagrams for the $\pi^- p \to D^- D^0 p$ reaction.

$$\mathcal{M}_a^{\frac{1}{2}^\pm} = \frac{i g_a^{\frac{1}{2}^\pm}}{(q^2 - M_{\Lambda_c'}^2 + i M_{\Lambda_c'} \Gamma_{\Lambda_c'})(t - M_{D^*}^2)} \times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda_c'})(\not{p}_1 - \frac{p_1 \cdot k_t \not{k}_t}{M_{D^*}^2})\gamma_5 u(p_2, s_i),$$

$$\mathcal{M}_b^{\frac{1}{2}^\pm} = \frac{\sqrt{2} g_b^{\frac{1}{2}^\pm}}{(q^2 - M_{\Lambda_c'}^2 + i M_{\Lambda_c'} \Gamma_{\Lambda_c'})(s - m_n^2)} \times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda_c'})(\not{k}_s + m_n)\gamma_5 u(p_2, s_i),$$

$$\mathcal{M}_c^{\frac{1}{2}^\pm} = \frac{g_c^{\frac{1}{2}^\pm}}{(q^2 - M_{\Lambda_c'}^2 + i M_{\Lambda_c'} \Gamma_{\Lambda_c'})(u - M_{\Sigma_c}^2)} \times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda_c'})(\not{k}_u + M_{\Sigma_c})\gamma_5 u(p_2, s_i),$$

Results (1:total cross sections)

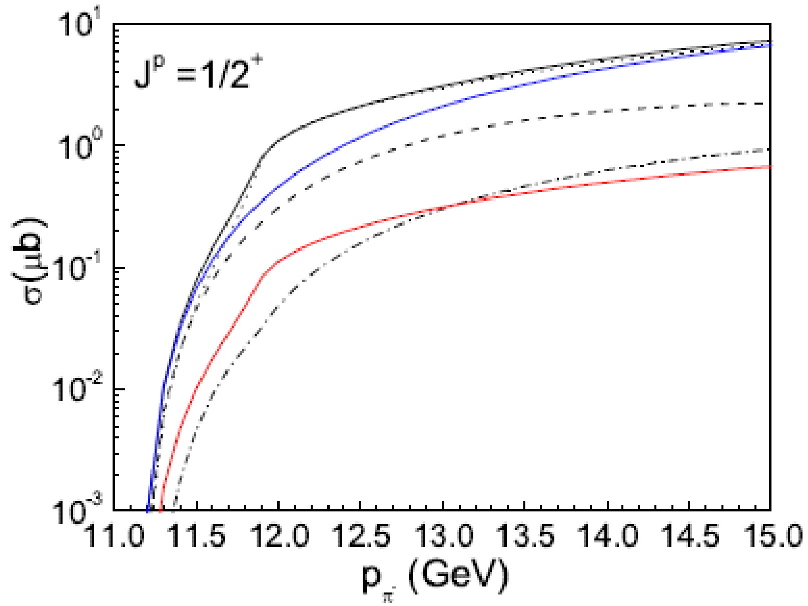


FIG. 2: (Color online) Total cross sections for the $\pi^- p \to D^- D^0 p$ reaction as a function of the beam momentum p_{π^-} for $J^P = \frac{1}{2}^+$ of the $\Lambda_c^+(2940)$. The dashed, dotted, and dash-dotted curves stand for the contributions from the s-channel, t-channel, and u-channel, respectively. Their total contribution is shown by the solid line. The blue line stands for the contributions from the ground $\Lambda_c^+(2286)$ state.

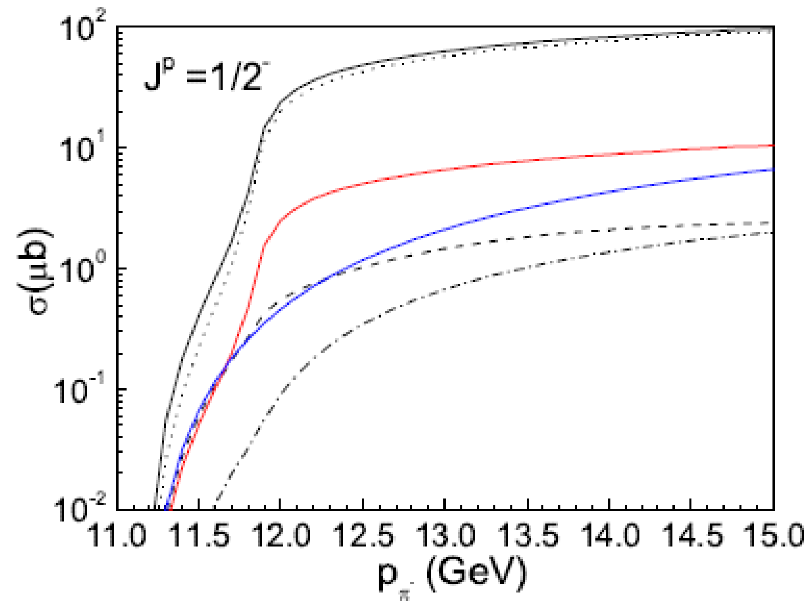


FIG. 3: (Color online) As shown in Fig. 2 but for $J^P = \frac{1}{2}^-$ of the $\Lambda_c^+(2940)$.

Results (2: differential cross sections)

$$\frac{d^2\sigma}{dM_{D^0p}d\Omega} = \frac{m_p^2}{2^9\pi^5\sqrt{s[(p_1\cdot p_2)^2 - m_\pi^2 - m_p^2]}} \times \int \sum_{s_i,s_f} |\mathcal{M}|^2 |\vec{p}_3||\vec{p}_5^{\,*}|d\Omega^*,$$

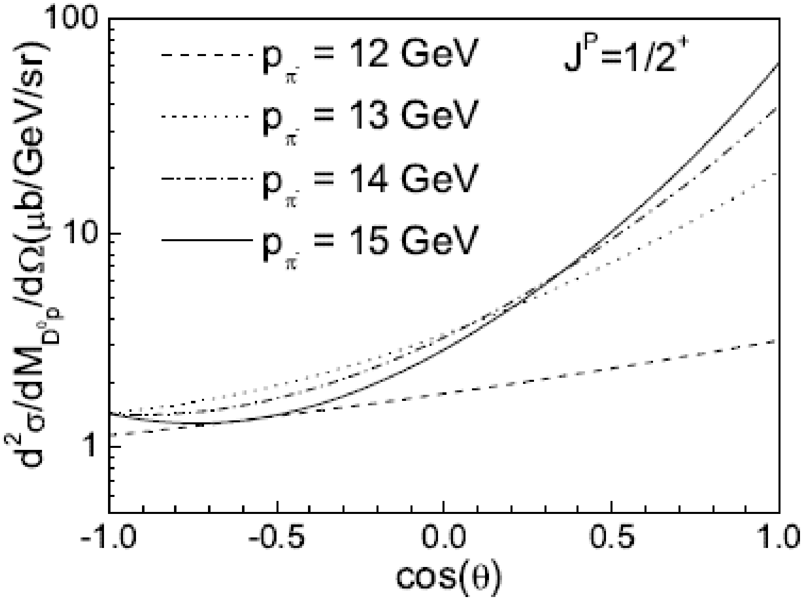


FIG. 4: Differential cross sections for the $\pi^- p \to D^- D^0 p$ reaction as a function of the scattering angle (θ) of the outgoing D^- meson in the CM frame of $\pi^- p$ system for $J^P = \frac{1}{2}^+$ of the $\Lambda_c^+(2940)$.

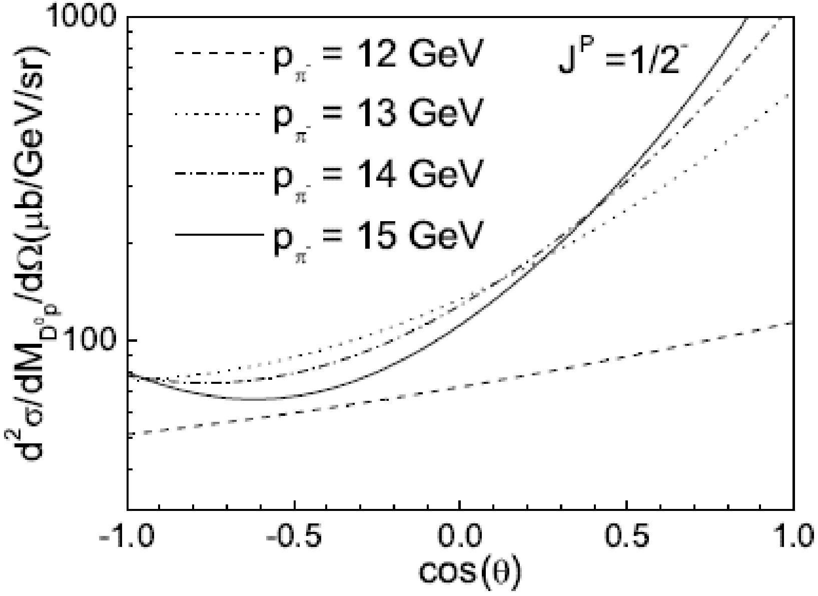


FIG. 5: As shown in Fig. 4 but for $J^P = \frac{1}{2}^-$ of the $\Lambda_c^+(2940)$.

Results (3: Ratio)

$$R = \frac{\frac{d^2\sigma}{dM_{D^0p}d\Omega}(J^P = \frac{1}{2}^-)}{\frac{d^2\sigma}{dM_{D^0p}d\Omega}(J^P = \frac{1}{2}^+)},$$

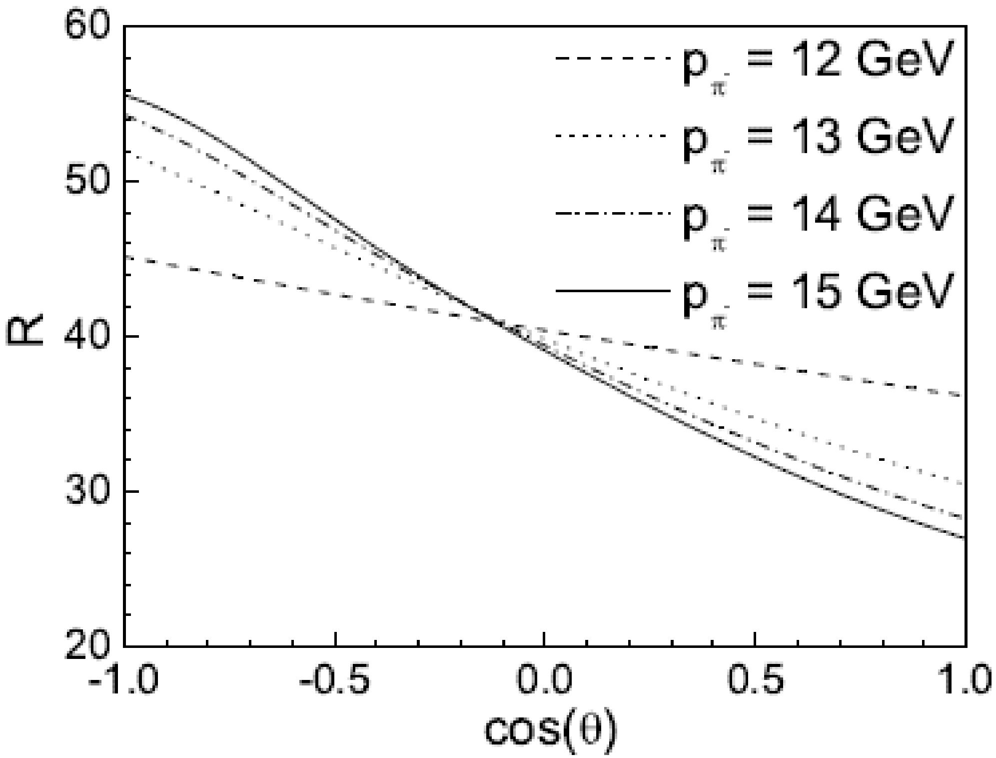


FIG. 6: Ratio of the differential cross sections for $J^P = \frac{1}{2}^-$ and $J^P = \frac{1}{2}^+$.

5, Summary

1), Molecule scenario

Our approach with hadronic loop
Compositness condition +
Other Effective Lagrangians
X(3872), Zc(3900), Y(4260), Zb(10610), Z 'b (10650)

2), Baryon resonance $\Lambda^{+}_{c}(2940)$

3), Productions of $\Lambda^{+}_{c}(2940)$

@ PANDA
@ JPARC

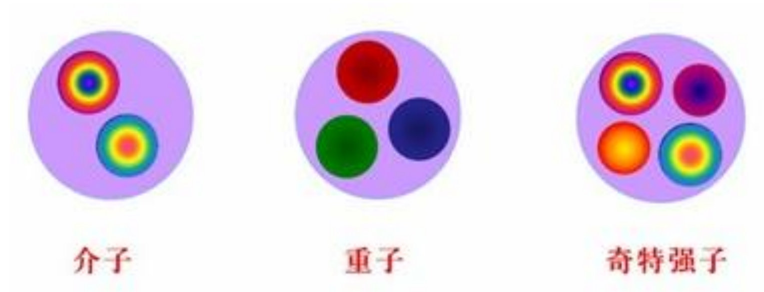
Thanks! Organizer for the HNP2015 conference

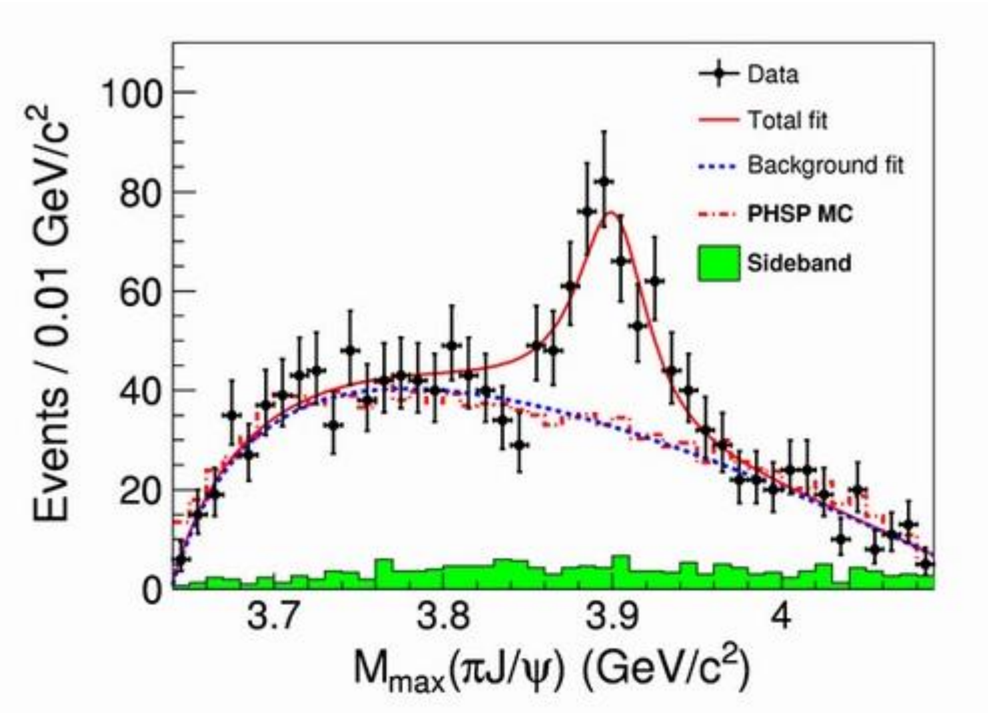
4, New resonances of Zc (3900)

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





2015/7/17

北京谱仪III实验发现的新的共振结构$Z_c(3900)$

Zc (3900) two-body decay

$$|Z_c^+\rangle = \frac{1}{\sqrt{2}}|D^{*+}\bar{D}^0 + \bar{D}^{*0}D^+\rangle, \quad |Z_c^{+\prime}\rangle = |D^{*+}\bar{D}^{*0}\rangle.$$

1+, its bottomia states Zb(10610) and Z'b(10650)

Zc(Zc')→ψ(nS)+π, Zc(Zc')→h c(mP)+π

$$\mathcal{L}_{Z_c}(x) = \frac{g_{Z_c}}{\sqrt{2}} M_{Z_c} Z_c^\mu(x) \int d^4y \Phi_{Z_c}(y^2)(D(x+y/2) \times \bar{D}^*_\mu(x-y/2) + D^*_\mu(x+y/2)\bar{D}(x-y/2)),$$

$$\mathcal{L}_{Z_c'}(x) = \frac{g_{Z_c'}}{\sqrt{2}} i\epsilon_{\mu\nu\alpha\beta}\partial^\mu Z_c'^\nu(x) \int d^4y \Phi_{Z_c'}(y^2) D^{*\alpha}(x+y/2) \times \bar{D}^{*\beta}(x-y/2),$$

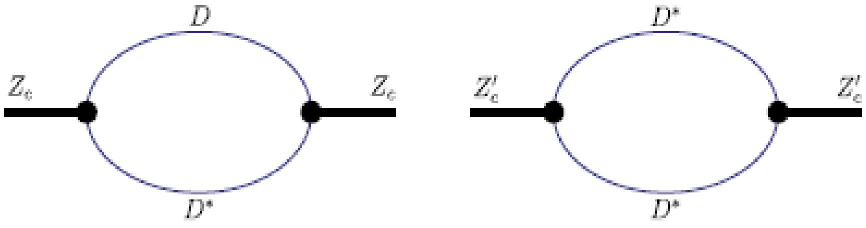


FIG. 1 (color online). Mass operators of Z_c^+ and $Z_c'^+$.

In the calculation of the two-body decays of $Z_c^+ (Z_c'^+) \to H + \pi^+$ where $H = \Psi(nS)$, $h_c(mP)$ we generate the four-particle $DD^* H\pi^+$ and $D^*D^*H\pi^+$ vertices by a phenomenological Lagrangian

$$\mathcal{L}_{\mathcal{D}\bar{\mathcal{D}}\mathcal{H}\mathcal{P}}(x) = ig_F \,\mathrm{tr}(\bar{\mathcal{D}}(x)[\mathcal{H}(x), \mathcal{P}(x)]\mathcal{D}(x)) + g_D \,\mathrm{tr}(\bar{\mathcal{D}}(x)\{\mathcal{H}(x), \mathcal{P}(x)\}\mathcal{D}(x)),$$

where g_F and g_D are effective coupling constants, $[\cdots]$ and $\{\cdots\}$ denote the commutator and anticommutator, respectively.

The H is the heavy charmonia field; D is the superposition of isodoublets of open-charm mesons with $J^P = 0^-$, 1^- and 1^+; $\mathcal{P}$ is the chiral field:

$$\mathcal{H} = J^\mu \gamma_\mu + h^\mu \gamma_\mu \gamma_5 + \frac{g_H}{M_H}(J^{\mu\nu}\sigma_{\mu\nu} + h^{\mu\nu}\sigma_{\mu\nu}\gamma_5),$$

$$\mathcal{D} = Di\gamma_5 + D^{*\mu}\gamma_\mu + D_1^\mu \gamma_\mu \gamma_5,$$

$$\mathcal{P} = \frac{1}{2}\not{u}\gamma^5 + \frac{1}{2}[u^\dagger, \partial_\mu u]\gamma^\mu,$$

$$\mathcal{L}_{DD^*J\pi}(x) = -\frac{8g_F g_H}{F_\pi M_J} J^{\mu\nu}(x)\bar{D}_\nu^*(x)\partial_\mu \hat{\pi}(x)D(x) + \mathrm{H.c.},$$

$$\mathcal{L}_{D^*D^*J\pi}(x) = \frac{4g_D}{F_\pi}\varepsilon^{\mu\nu\alpha\beta} J_\mu \bar{D}_\beta^*(x) i\partial_\nu \hat{\pi}(x) D_\alpha^*(x),$$

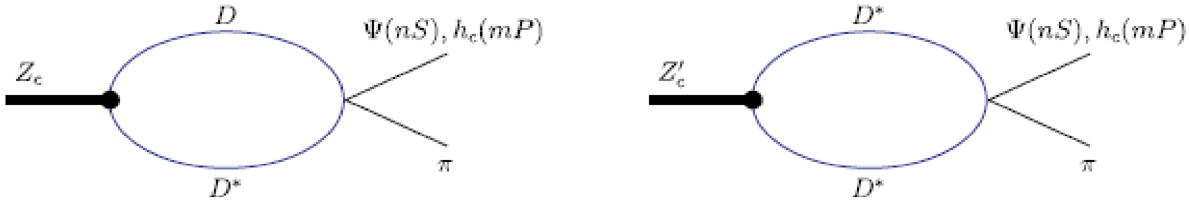
$$\mathcal{L}_{DD^*h_c\pi}(x) = -\frac{4g_F g_H}{F_\pi M_J}\varepsilon^{\mu\nu\alpha\beta} h_{\mu\nu}(x)\bar{D}_\alpha^*(x)\partial_\beta \hat{\pi}(x)D(x) + \mathrm{H.c.},$$

$$\mathcal{L}_{D^*D^*h_c\pi}(x) = \frac{4g_F}{F_\pi}\bar{D}^{*\nu}(x)(h_\mu(x)i\partial_\nu \hat{\pi}(x) - h_\nu(x)i\partial_\mu \hat{\pi}(x))D^{*\mu}(x).$$

The three-particle coupling $g_{D^*D\pi}$ of the pion to charmed D mesons is defined by the phenomenological Lagrangian:

$$\mathcal{L}_{D^*D\pi}(x) = \frac{g_{D^*D\pi}}{\sqrt{2}}\bar{D}^{*\mu}(x)\partial_\mu \hat{\pi}(x)D(x) + \mathrm{H.c.},$$

where the value $g_{D^*D\pi} = 17.9$ has been determined from data on $D^* \to D\pi$ decay [15].



Two-body decays $Z_c^+ \to \Psi(nS),\ h_c(mP) + \pi$ and $Z_c'^+ \to \Psi(nS),\ h_c(mP) + \pi$.

$$\Gamma_{Z_c^+ \to h_c(mP)\pi^+} \simeq \frac{g^2_{Z_c h_c(mP)\pi}}{96\pi M^3_{Z_c}} \lambda^{3/2}(M^2_{Z_c}, M^2_{h_c}, M^2_{\pi})\left(1 + \frac{M^2_{h_c}}{2M^2_{Z_c}}\right),$$

$$\Gamma_{Z_c'^+ \to h_c(mP)\pi^+} \simeq \frac{g^2_{Z_c' h_c \pi}}{96\pi M^3_{Z_c'}} \lambda^{3/2}(M^2_{Z_c'}, M^2_{h_c}, M^2_{\pi}),$$

TABLE III. Predictions for the strong decay widths of Z_c^+ and $Z_c'^+$ states in MeV.

ϵ (MeV)	$\Gamma_{Z_c}(1S)$	$\Gamma_{Z_c'}(1S)$	$\Gamma_{Z_c}(2S)$	$\Gamma_{Z_c'}(2S)$	$\Gamma_{Z_c}(1P)$	$\Gamma_{Z_c'}(1P)$
5	7.45–13.63	11.50–26.60	1.47–2.70	8.26–19.1	0.68–1.25	1.02–2.36
10	8.53–19.15	15.33–34.49	1.48–3.32	10.81–24.23	0.76–1.70	1.34–3.00
15	9.55–21.66	17.85–40.64	1.41–3.21	12.32–28.06	0.82–1.86	1.53–3.49
20	10.43–23.89	19.47–45.11	1.28–2.94	13.16–30.48	0.87–1.98	1.65–3.81

5, Summary

1), Molecule scenario

Our approach with hadronic loop

Compositness condition

Other Effective Lagrangians

2), Some resonances

X(3872), Λc(2940), Zc(3900), deuteron, Y(4260)

3), Other resonances can also be studied.

Thanks!

5, New resonances of Zb(10610), Zb(10650)'

- Observed by Belle, (2011)
- Z^+b(10610) : M=10608.4±2.0MeV,
- Γ=15.6±2.5MeV
- Z^+b(10650): M=10653.2±1.5MeV
- Γ=14.4±3.2MeV

Analysis of the charged pion angular distributions :

- $I^G(J^p)$= $1^+(1^+)$
- Charged , Zb→ $\pi(\pm)$+$\Upsilon(nS), (n = 1,2,3)$

Diagrams

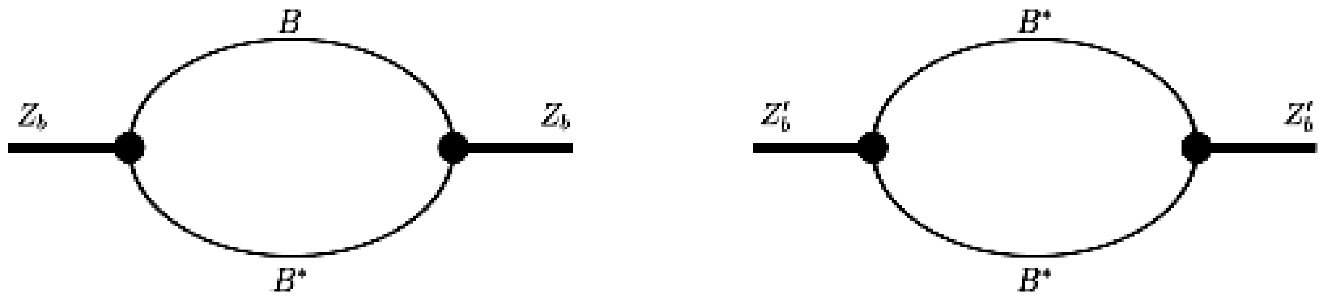


FIG. 1: Mass operators of Z_b^+ and $Z_b'^+$.

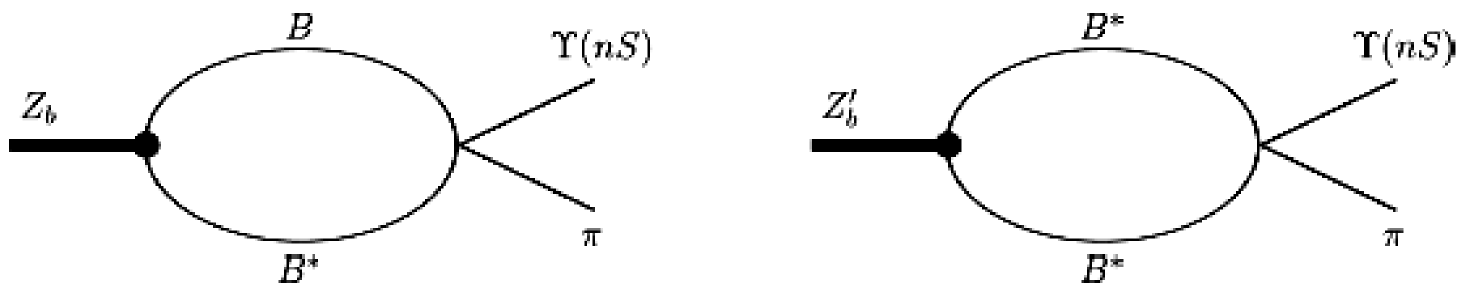


FIG. 2: Two-body decays of $Z_b^+ \to V + \pi$ and $Z_b'^+ \to V + \pi$, where $V = \Upsilon(nS), h_b(mP)$

Effective Lagrangians

$$|Z_b^+(10610)\rangle = \frac{1}{\sqrt{2}}\Big|B^{*+}\bar{B}^0 + \bar{B}^{*0}B^+\Big\rangle,$$
$$|Z_b^{+\prime}(10650)\rangle = |B^{*+}\bar{B}^{*0}\rangle.$$

$$\mathcal{L}_{Z_b}(x) = \frac{g_{Z_b}}{\sqrt{2}} M_{Z_b} Z_b^\mu(x)\int d^4y\, \Phi_{Z_b}(y^2)\Big(B(x+y/2)\bar{B}^*_\mu(x-y/2) + B^*_\mu(x+y/2)\bar{B}(x-y/2)\Big),$$
$$\mathcal{L}_{Z_b'}(x) = \frac{g_{Z_b'}}{\sqrt{2}} i\epsilon_{\mu\nu\alpha\beta}\partial^\mu Z_b^{\prime\nu}(x)\int d^4y\, \Phi_{Z_b'}(y^2) B^{*\alpha}(x+y/2)\bar{B}^{*\beta}(x-y/2),$$

$$\mathcal{L}_{BB^*\Upsilon\pi}(x) = g_{BB^*\Upsilon\pi}\Upsilon_\mu(x)\bar{B}^{*\mu}(x)\vec{\pi}(x)\cdot\vec{\tau}B(x) + \text{H.c.}\,,$$
$$\mathcal{L}_{B^*B^*\Upsilon\pi}(x) = i\epsilon_{\mu\nu\alpha\beta}\Big(g_{B^*B^*\Upsilon\pi}\Upsilon^\mu(x)\bar{B}^{*\beta}(x)\partial^\nu\vec{\pi}(x)\cdot\vec{\tau}B^{*\alpha}(x) + f_{B^*B^*\Upsilon\pi}\partial^\nu\Upsilon^\mu(x)\bar{B}^{*\beta}(x)\vec{\pi}(x)\cdot\vec{\tau}B^{*\alpha}(x)\Big).$$

$$\mathcal{L}_{BB^*h_b\pi}(x) = \epsilon_{\mu\nu\alpha\beta}\, g_{BB^*h_b\pi}\,\partial^\nu h_b^\mu(x)\bar{B}^{*\beta}(x)\partial^\alpha\vec{\pi}(x)\cdot\vec{\tau}B(x) + \text{H.c.}\,,$$
$$\mathcal{L}_{B^*B^*h_b\pi}(x) = g_{B^*B^*h_b\pi}h_b^\mu(x)\bar{B}^{*\beta}(x)\partial^\nu\vec{\pi}(x)\cdot\vec{\tau}B^{*\alpha}(x)\Big(g_{\mu\nu}g_{\alpha\beta} - g_{\mu\alpha}g_{\nu\beta} - g_{\nu\alpha}g_{\mu\beta}\Big)$$
$$+\; f_{B^*B^*h_b\pi}\partial^\nu h_b^\mu(x)\bar{B}^{*\beta}(x)\vec{\pi}(x)\cdot\vec{\tau}B^{*\alpha}(x)\Big(g_{\mu\beta}g_{\nu\alpha} - g_{\nu\beta}g_{\mu\alpha}\Big),$$

Results (I)

Table I. $Z_b^+ \to \Upsilon(nS) + \pi^+$ decay properties.

ϵ(MeV)	g_{Z_b}	Γ_{1S}(MeV)	Γ_{2S}(MeV)	Γ_{3S}(MeV)
1	3.3, 3.4, 3.6, 3.7	11.6, 16.4, 22.3, 29.5	13.7, 19.4, 26.4, 34.9	7.2, 10.2, 13.9, 18.4
5	4.0, 4.0, 4.1, 4.2	11.0, 16.5, 22.4, 29.5	13.0, 19.4, 26.3, 34.7	6.7, 10.1, 13.6, 18.0
10	5.0, 4.9, 4.8, 4.8	11.7, 16.9, 22.7, 29.7	13.7, 19.8, 26.6, 34.8	7.0, 10.1, 13.5, 17.6
20	7.2, 6.6, 6.3, 6.0	13.3, 18.3, 24.0, 30.8	15.4, 21.2, 27.8, 35.7	7.4, 10.2, 13.4, 17.3
30	9.4, 8.5, 7.9, 7.4	14.5, 19.6, 25.4, 32.3	16.7, 22.5, 29.2, 37.1	7.7, 10.3, 13.4, 17.0
40	11.7, 10.4, 9.5, 8.8	15.4, 20.4, 26.7, 33.7	17.5, 23.2, 30.3, 38.3	7.5, 10.0, 13.1, 16.5
50	13.9, 12.3, 11.1, 10.2	15.9, 21.2, 27.6, 34.9	17.8, 23.9, 31.1, 39.2	7.1, 9.6, 12.5, 15.7
Exp.		$22.9 \pm 7.3 \pm 2$	$21.1 \pm 4^{+2}_{-3}$	$12.2 \pm 1.7 \pm 4$

Results (II)

Table II. $Z_b'^{+} \to \Upsilon(nS) + \pi^{+}$ decay properties.

ϵ(MeV)	$g_{Z_b'}$	Γ_{1S}(MeV)	Γ_{2S}(MeV)	Γ_{3S}(MeV)
1	3.2, 3.4, 3.6, 3.7	12.0, 16.9, 23.0, 30.4	14.7, 20.8, 28.3, 37.4	9.0, 12.8, 17.4, 23.0
5	3.9, 4.0, 4.1, 4.2	12.1, 17.0, 23.0, 30.3	14.9, 20.8, 28.2, 37.2	9.0, 12.6, 17.1, 22.6
10	5.0, 4.8, 4.8, 4.7	12.7, 17.4, 23.4, 30.6	15.4, 21.3, 28.5, 37.3	9.2, 12.7, 17.1, 22.3
20	7.2, 6.6, 6.3, 6.0	14.0, 18.8, 24.6, 31.7	16.9, 22.7, 29.8, 39.3	9.8, 13.2, 17.3, 22.3
30	9.4, 8.5, 7.8, 7.3	15.1, 20.1, 26.1, 33.1	18.1, 24.1, 31.3, 39.7	10.2, 13.5, 17.6, 22.3
40	11.7, 10.4, 9.4, 8.7	15.8, 21.1, 27.3, 34.5	18.9, 25.1, 32.4, 41.0	10.2, 13.6, 17.6, 22.2
50	13.9, 12.3, 11.0, 10.1	16.2, 21.7, 28.2, 35.6	19.1, 25.5, 33.2, 41.9	9.9, 13.3, 17.3, 21.8
Exp.		$12 \pm 10 \pm 3$	$16.4 \pm 3.6^{+4}_{-6}$	$10.9 \pm 2.6^{+4}_{-2}$

Some known candidates

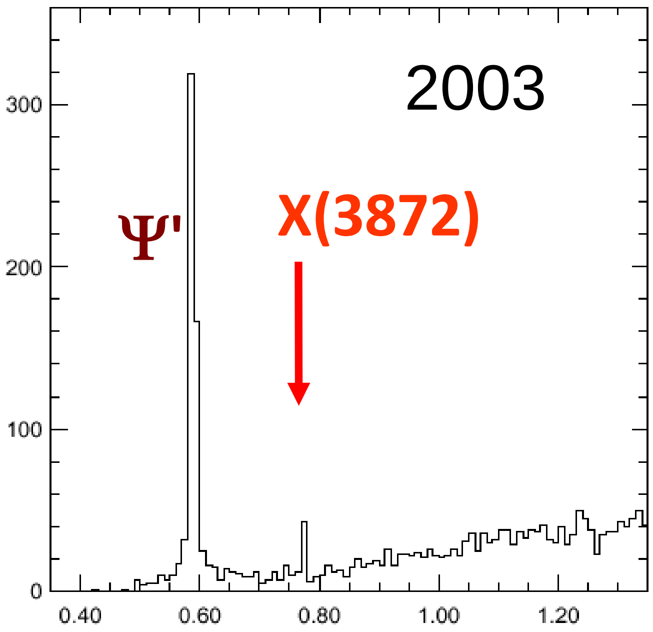
for hadronic meson-meson molecules

- a0(980), f0(980)→K $\bar{K}$
- D*s0(2317)→DK; Ds1→D*K
- X(3872)→D $\bar{D}$*+c.c
- Z(4430)→D*(2010) $\bar{D}$1(2420)

$X(3872)$	$\overline{D}^0 D^{*0}$
$X(3915)$	$\overline{D}^{*0} D^{*0} + D^{*+} D^{*-}$
$Y(4140)$	$D_s^{*+} D_s^{*-}$
$Y(4260)$	$D_0 \overline{D}^*$, $\psi(2S) f_0(980)$ $\Lambda_c \overline{\Lambda}_c, \chi_{c0}\rho, \chi_{c1}\omega, D_1 \overline{D}$
$Z(4430)^+$	$D^{*+} \overline{D}_1^0$
$X(4630)$	$\psi(2S) f_0(980)$
$Y(4660)$	$\psi(2S) f_0(980)$

In the current nomenclature, the neutral(charged) states observed in B decays are labeled $X(Z)$, whereas the Y are the neutral, $J^{PC} = 1^{--}$ states observed in initial-state radiation e^+e^- processes.

Observation of X(3872)



$M(\pi^+\pi^- l^+ l^-) - M(l^+ l^-)$

Observed by Belle in $B^\pm \to K^\pm \pi^+\pi^- J/\psi$

Confirmed by CDF, D0, BaBar

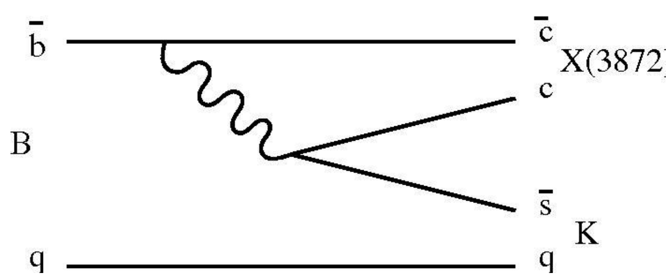
	M(X(3872)), MeV/c^2
BELLE B→XK	3871.46±0.37±0.07
B→XK	3871.4±0.6±0.1
CDF $X \to J/\psi\pi^+\pi^-$	3871.61±0.16±0.19
Our average	3871.50±0.19
$M(D^0)+M(D^{*0})$	3871.81±0.36

Mass of X(3872) is close to *DD**

Not fittable to any known cc-bar states

What is it:

charmonium, *DD**-molecule, tetraquark...?



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Measurement

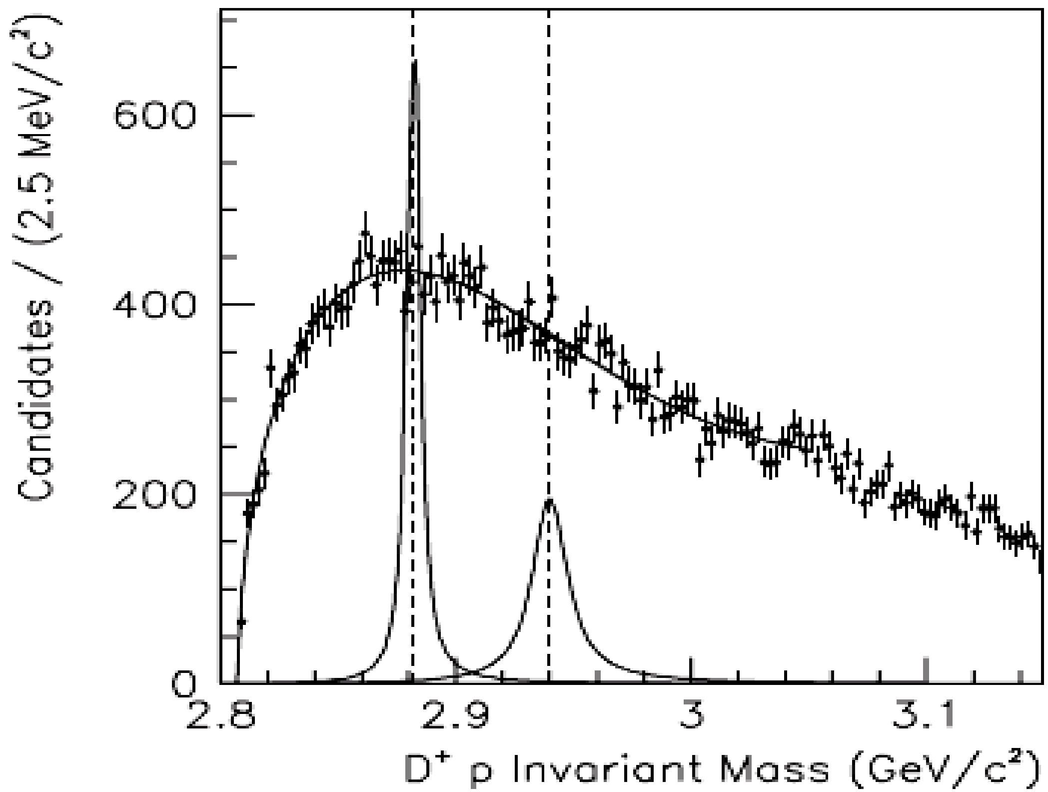


FIG. 3. The invariant mass distribution of selected D^+p candidates. The curve is the result of the fit described in the text. The curves below are the line shapes of the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ baryons obtained from the D^0p data, drawn approximately to scale after correcting for selection efficiency and D^0 and D^+ branching fractions.

approaches/descriptions

QCD sum rule

Non relativistic QCD

Heavy quark effective theory

Heavy hadron chiral perturbation theory

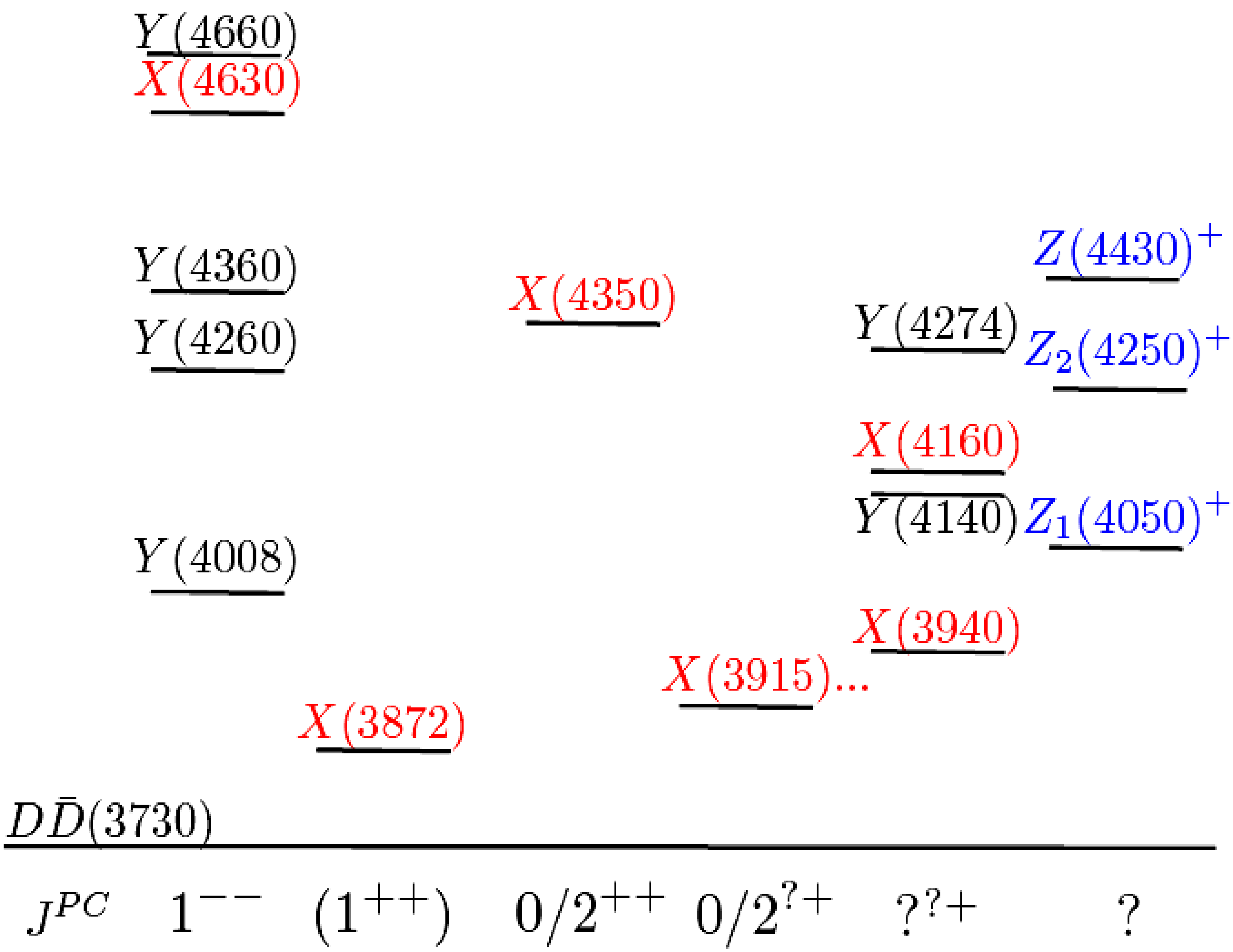
Potential models

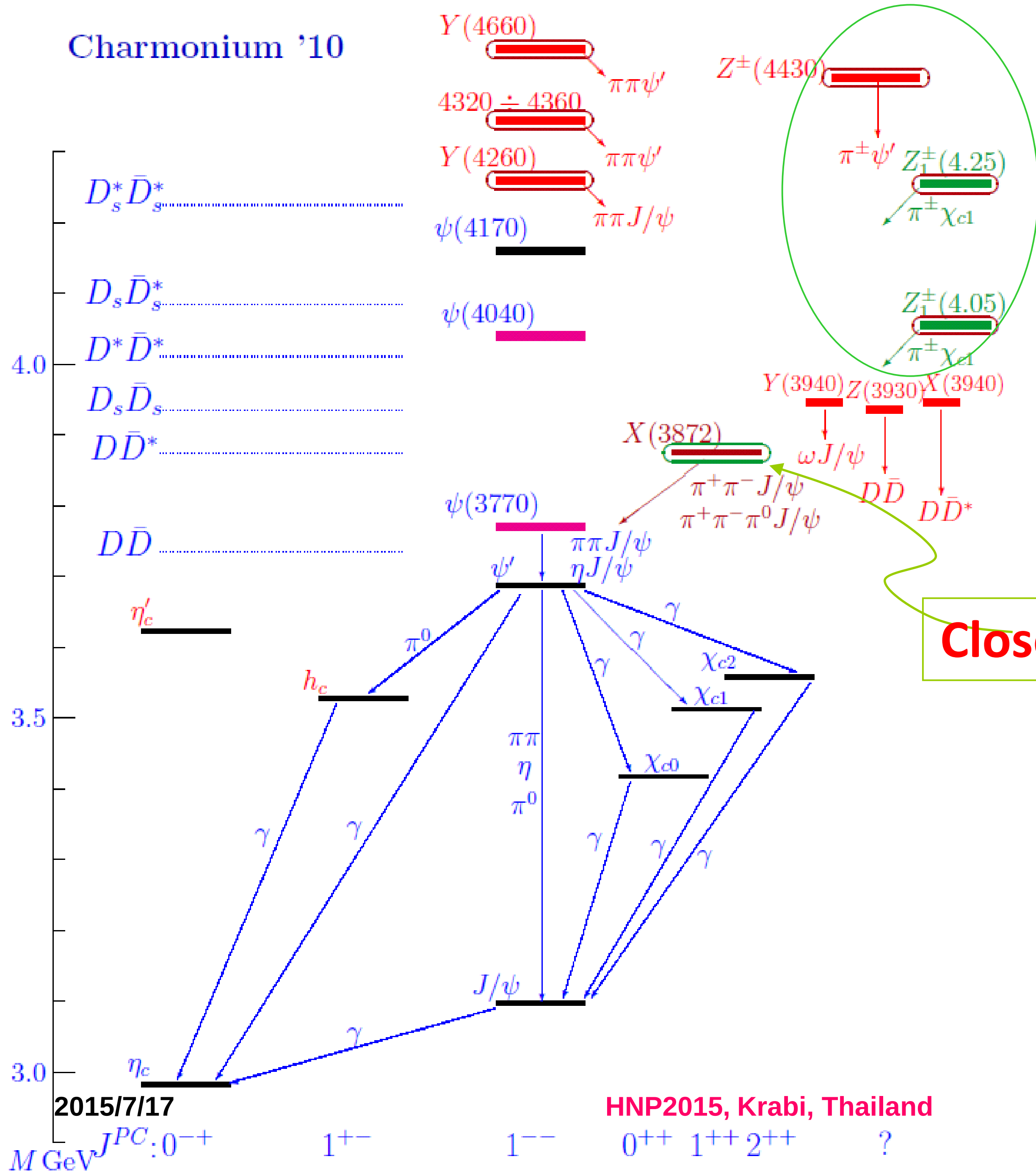
Lattice calculations

- Molecule, baryonium
- tetraquark
- Hybrids
- Coupling channel…

X, Y, Z states

Courtesy of Brambilla et al., 1010.5827





Charged charmonium spectrum

-- A completely new scenario of strong QCD!

States close to open thresholds

-- The role played by open D meson channels?

Close to DD* threshold

XYZ resonances [Hidden-charm(bottom)]

1, Conventional quark model ×

2, Narrow width

3, Near threshold of two mesons...

Many interpretations:

Molecular scenario

Quark and hadron level

- Molecule, baryonium
- tetraquark
- Hybrids
- Coupling channel…

QCD sum rule

Non relativistic QCD

Heavy quark effective theory

Heavy hadron chiral perturbation theory

Potential models

Lattice calculations

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 ?

Numerical results

TABLE Three-body decay widths for $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ \pi^+ \pi^-$ (in MeV) with the diagram Fig. 1(a) for different values of θ and Λ. The values in the parentheses represent the contributions from Σ_c^0 and Σ_c^{++}, respectively.

θ	$\Lambda = 1.25$ GeV	$\Lambda = 1$ GeV	$\Lambda = 0.75$ GeV
0°	6.010(1.930,1.568)	4.311(1.384,1.125)	2.729(0.876,0.712)
5°	6.392(2.040,1.679)	4.583(1.462,1.204)	2.899(0.925,0.762)
10°	6.776(2.150,1.792)	4.855(1.541,1.284)	3.070(0.974,0.812)
15°	7.160(2.259,1.905)	5.129(1.618,1.364)	3.241(1.023,0.862)
20°	7.543(2.368,2.018)	5.401(1.696,1.445)	3.411(1.071,0.912)

TABLE Three-body decay widths $\Lambda_c(2940)^+ \to \Lambda_c(2286)^+ \pi^+ \pi^-$ (in MeV) with diagrams of Figs. 1(a) and 1(b) for different values of θ and Λ. Values in parentheses indicate the contributions of Fig. 1(b) with an intermediate ρ meson.

θ	$\Lambda = 1.25$ GeV	$\Lambda = 1$ GeV	$\Lambda = 0.75$ GeV
0°	$6.014(5.486 \times 10^{-3})$	$4.314(4.268 \times 10^{-3})$	$2.732(3.083 \times 10^{-3})$
5°	$6.396(5.835 \times 10^{-3})$	$4.586(4.539 \times 10^{-3})$	$2.902(3.276 \times 10^{-3})$
10°	$6.780(6.186 \times 10^{-3})$	$4.859(4.811 \times 10^{-3})$	$3.073(3.468 \times 10^{-3})$
15°	$7.165(6.537 \times 10^{-3})$	$5.133(5.083 \times 10^{-3})$	$3.244(3.661 \times 10^{-3})$
20°	$7.548(6.888 \times 10^{-3})$	$5.405(5.354 \times 10^{-3})$	$3.414(3.853 \times 10^{-3})$

Effective Lagrangians

$$\mathcal{L}^{L}_{X}(x) = g_{XD^0D^{*0}} X_\mu(x) J^{\mu}_{D^0D^{*0}}(x) + g_{XD^\pm D^{*\mp}} X_\mu(x) J^{\mu}_{D^\pm D^{*\mp}}(x) + \frac{g_{XJ_\psi\omega}}{m_X}\epsilon_{\mu\nu\alpha\beta}\partial^\nu X^\alpha(x) J^{\mu\beta}_{J_\psi\omega}(x) + \frac{g_{XJ_\psi\rho}}{m_X}\epsilon_{\mu\nu\alpha\beta}\partial^\nu X^\alpha(x) J^{\mu\beta}_{J_\psi\rho}(x),$$

Non-local ones

$$J^{\mu}_{D\bar{D}^*}(x) \to \mathcal{J}^{\mu}_{D\bar{D}^*}(x) = \frac{1}{\sqrt{2}}\int d^4y\,\Phi_{DD^*}(y^2)(D(x+y/2) \times \bar{D}^{*\mu}(x-y/2) + \bar{D}(x+y/2)D^{*\mu}(x-y/2)),$$

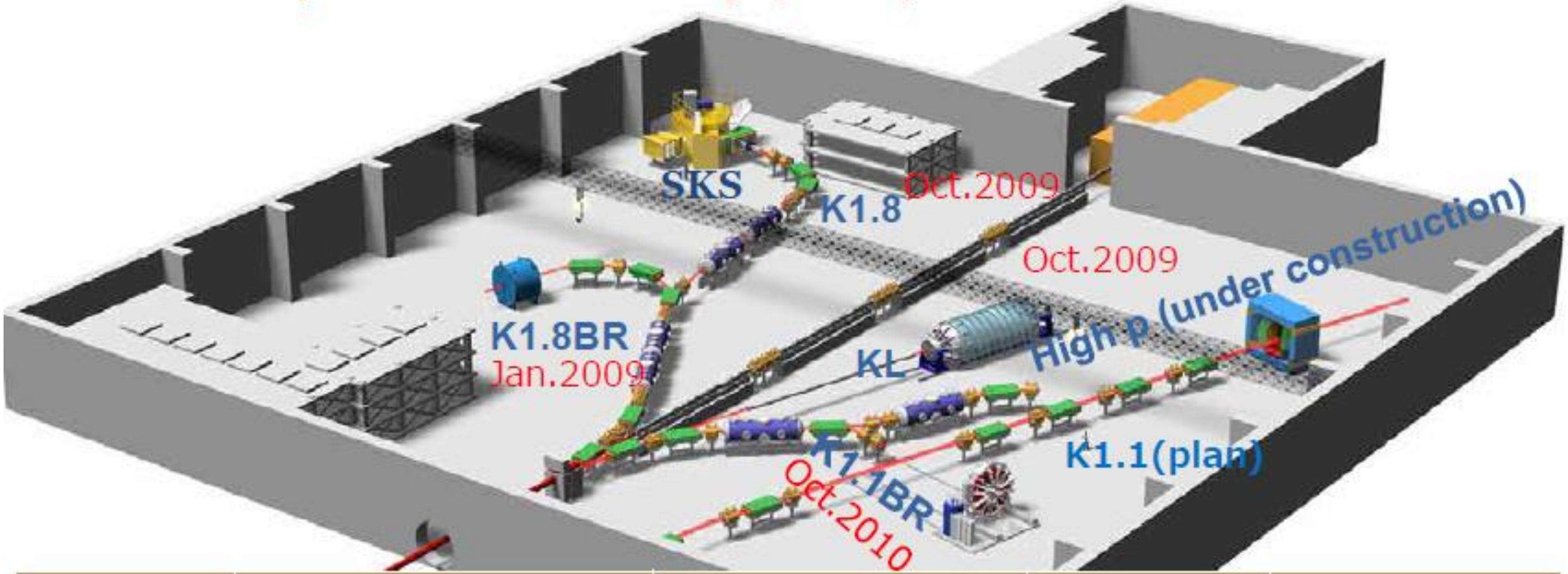
$$J^{\mu}_{D\bar{D}^*}(x) = \frac{1}{\sqrt{2}}(D(x)\bar{D}^{*\mu}(x) + \bar{D}(x)D^{*\mu}(x)),$$

$$J^{\mu\beta}_{J_\psi V} = J^{\mu}_{\psi} V^{\beta},$$

$$J^{\mu}_{J_\psi V}(x) \to \mathcal{J}^{\mu\beta}_{J_\psi V}(x) = J^{\beta}_{\psi}(x)\int d^4y\,\Phi_V(y^2)V^{\mu}(x+y)$$

4, Production @ JPARC (Hadron Hall)

Hadron Experimental Facility (HEF)



Beam Lines	Experiment	Secondary particles	Max. Mom.	Max. Intensity
K1.8	Hypernuclei, Hadron Physics with S	π, K, p (2 separators)	< 2.0 GeV/c	~10^5 Hz for K^+
K1.8BR	Hadron Physics with S	π, K, p (1 separator)	< 1.0 GeV/c	~10^4 Hz for K^+
K1.1BR	Lepton Flavor violation	π, K, p (1 separator)	< 1.1 GeV/c	~10^4 Hz for K^+
KL	Neutral K rare decay	Neural Kaon	~ 2 GeV/c	~10^6 Hz

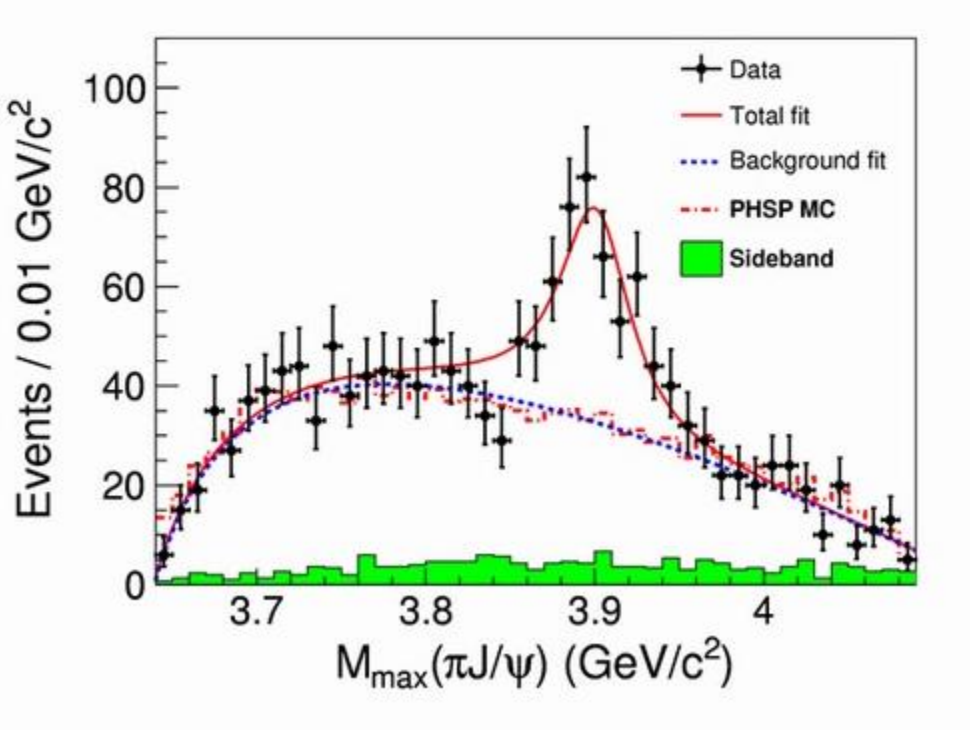
Intense Kaon Beam in the momentum range of ~ 1 GeV/c

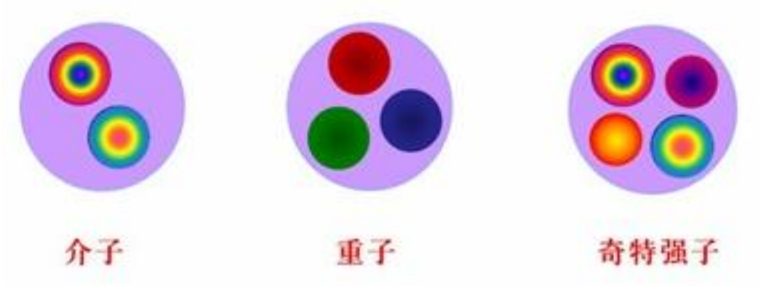
BEPC, New resonances of Zc (3900)

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





北京谱仪III实验发现的新的共振结构$Z_c(3900)$

Calculation: Molecular scenario

Ansatz: $X(3872)$ is S-wave molecule with $J^{PC} = 1^{++}$

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

$(m_{D^0} = 1864.85$ MeV, $m_{D^{*0}} = 2006.7$ MeV, $m_x = m_{D^0} + m_{D^{*0}} - \epsilon)$

- dominant $|D^0 \bar{D}^{*0}\rangle + |D^{*0} \bar{D}^0\rangle$ component
- quantitatively see Swanson (2004): for $\epsilon = 0.3$ MeV,
  $Z_{D^0 D^{*0}} = 0.92\,, \quad Z_{D^\pm D^{*\mp}} = 0.033\,, \quad Z_{J_\psi \omega} = 0.041\,, \quad Z_{J_\psi \rho} = 0.006$
- small admixture of 1^{++} $c\bar{c}$ component: $\propto \sin\theta$
- Compositeness condition: $Z_X = 1 - (\Sigma^M_X(m^2_X))' - (\Sigma^C_X(m^2_X))' = 0$ fixes coupling of X to its components

Measurement

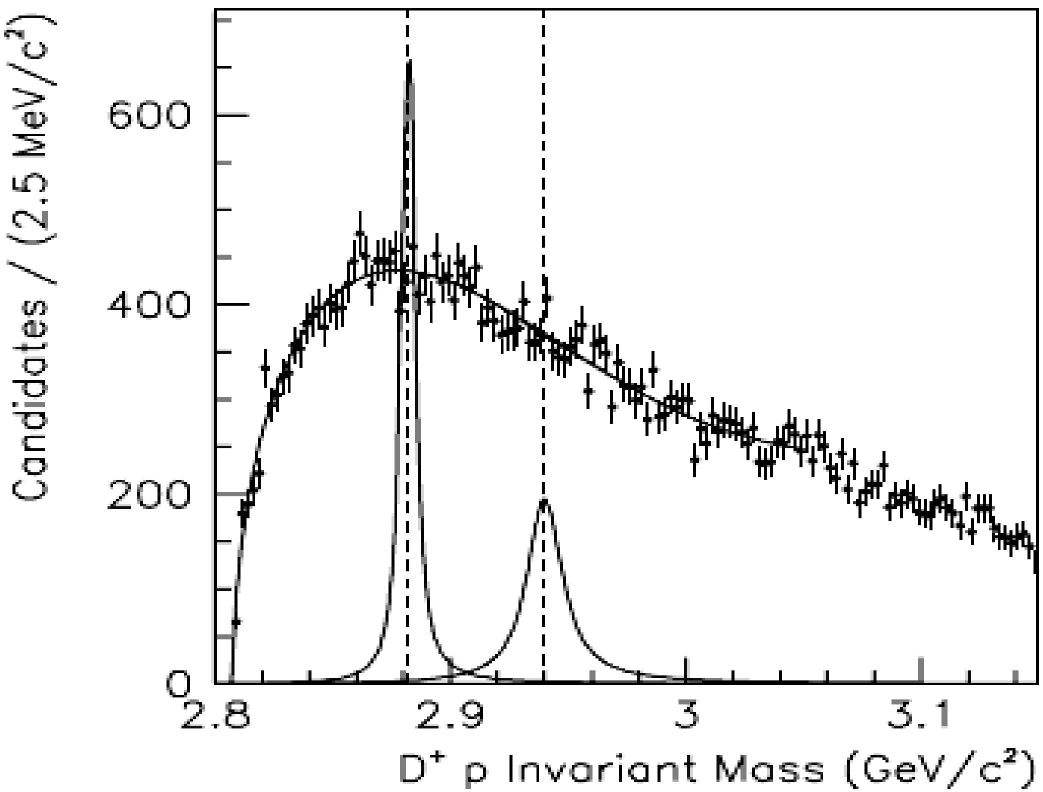
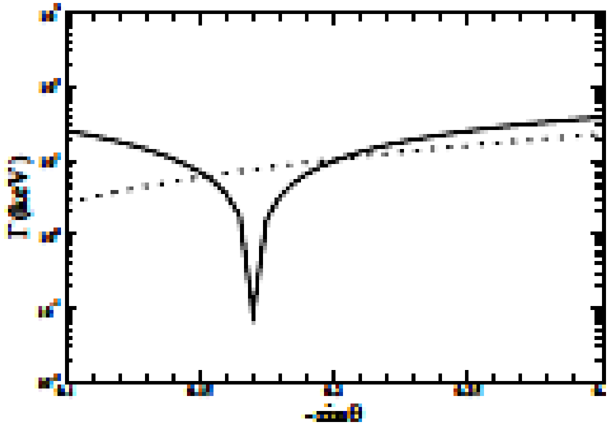


FIG. 3. The invariant mass distribution of selected D^+p candidates. The curve is the result of the fit described in the text. The curves below are the line shapes of the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ baryons obtained from the D^0p data, drawn approximately to scale after correcting for selection efficiency and D^0 and D^+ branching fractions.

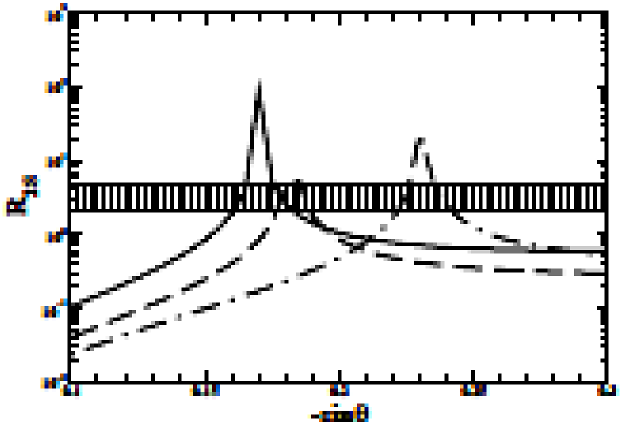
Results for $X(3872) \to \gamma J/\psi$ and $\psi(2s)$

Configuration	$\Gamma(X(3872) \to \gamma J/\psi,\ \gamma\psi(2S))$ keV	
molecular DD^* component	60 - 120(J/ψ)	0.3 ($\psi(2S)$)
pure $J/\psi V$ component	6(J/ψ)	0 ($\psi(2S)$)
interfering DD^* and $J/\psi V$ components	30 - 65 (J/ψ)	0.3 ($\psi(2S)$)

additional charmonium contribution with $Z_{c\bar{c}}^{1/2} = sin\theta \approx -0.2$ required



dotted - J/ψ, solid - $\psi(2s)$ mode



$$R_{2s} = \frac{\Gamma(X \to \psi(2S)+\gamma)}{\Gamma(X \to J/\psi+\gamma)} = 3.5 \pm 1.4$$

(BABAR, 2009)

Dong, Faessler, TG, Kovalenko, Lyubovitskij, PRD 77 (2008), 79 (2009), 0909.0380 [hep-ph]