



Description of Heavy Exotic Resonances

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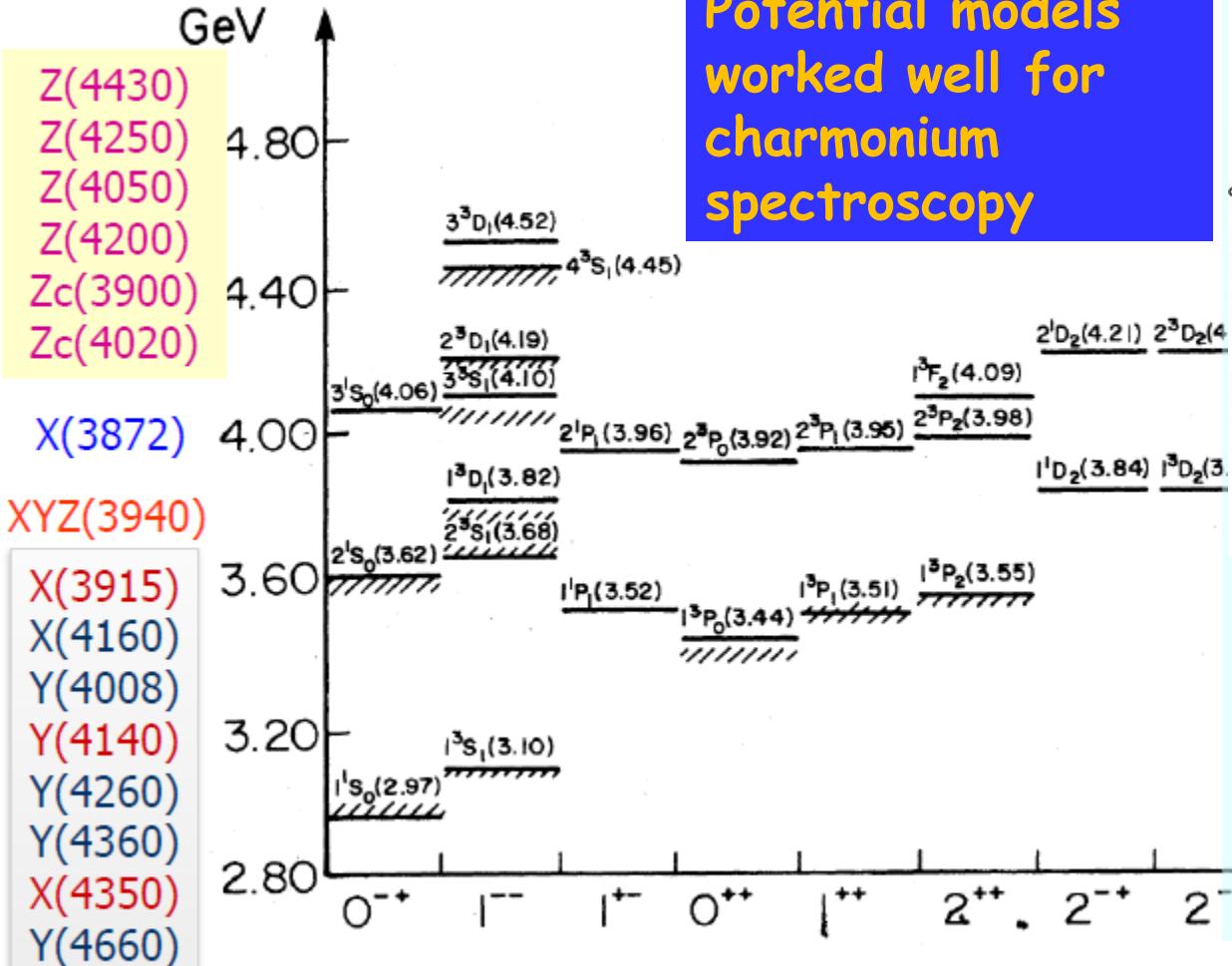
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- 1 A Brief Introduction (multi-quark states):**
- 2 Our approach: New resonances (I): $X(3872)$**
- 3 New exotic resonances (II) $\Lambda^+ c(2940)$**
- 4 $\Lambda^+ c(2940)$ productions @ PANDA & JPARC**
- 5 Summary**

1, Introduction (multi-quark)

The XYZ states

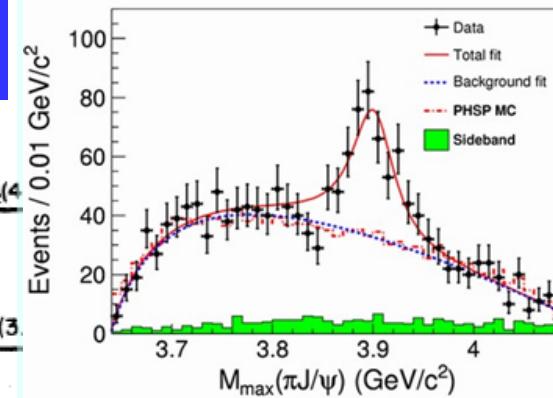


Potential models
worked well for
charmonium
spectroscopy

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

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

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



Charmonium?
Hybrid?
Tetraquark?
Molecule?

Not all XYZ states are charmonia!

Sept.16-24, Erice2015, Italy

(New resonances, five-quark)

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

$\Lambda_c(2940)^+$



The LHCb collaboration

PRL 98, 012001 (2007)

PHYSICAL REVIEW LETTERS

week ending
5 JANUARY 2007

Abstract

Observations of exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b^0 \rightarrow J/\psi K^- p$ 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 $4380 \pm 8 \pm 29 \text{ MeV}$ and a width of $205 \pm 18 \pm 86 \text{ MeV}$, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$ and a width of $39 \pm 5 \pm 19 \text{ MeV}$. The preferred J^P assignments are of opposite parity, with one state having spin $3/2$ and the other $5/2$.

Five-quark

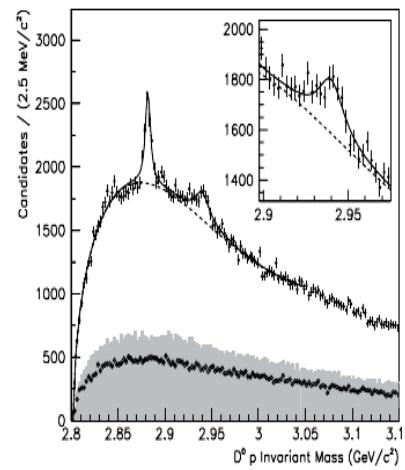


$\Sigma_c \bar{D}$, $\Sigma_c^* \bar{D}$, $\Sigma_c \bar{D}^*$, $\Sigma_c^* \bar{D}^*$, $p \chi_{c1}$
 $3^- / 2$, $5^+ / 2$ ($J^P ?$)

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

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

(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

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

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

d^{*}(2380), six-quark (light quarks)

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

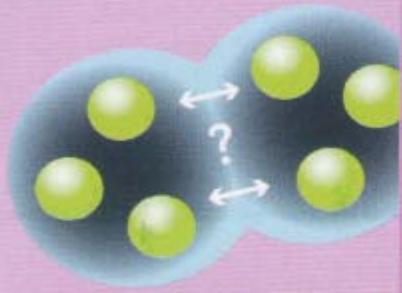
CERN COURIER

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/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: $M_H < M_1 + M_2$

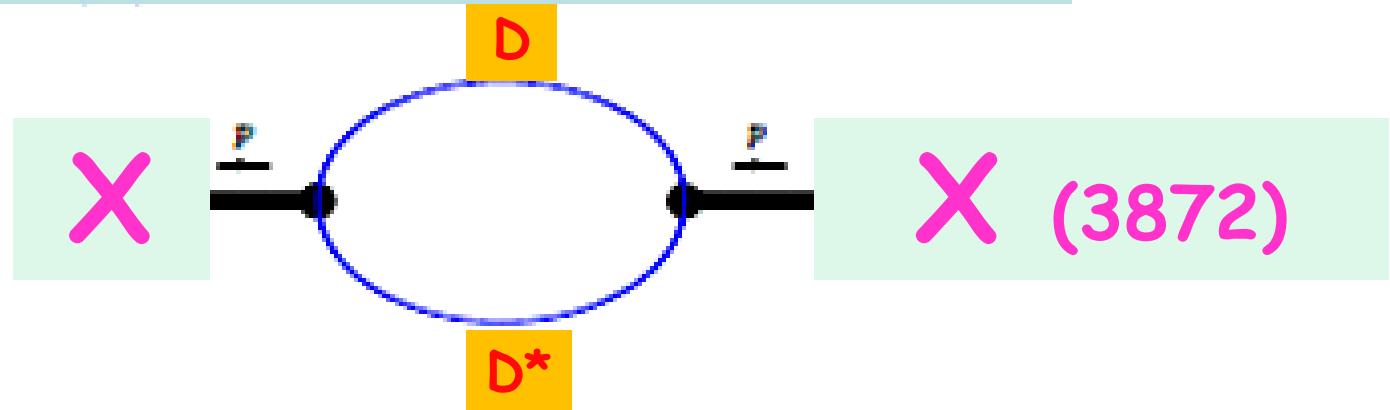
- The Molecule idea has a long history

- 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+

2, Our approach:

Molecule scenario

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



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

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

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

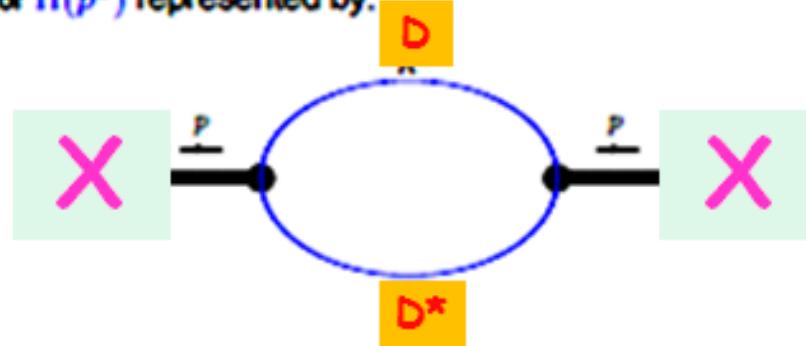
$$Z_M = 1 - \Sigma'_M(m_M^2) = 0$$

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 $\bar{\Pi}(p^2)$ represented by:



Vertex function

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

Gaussian-type is chosen for the function

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

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

Parameter: Gaussian with free size parameter Λ

Four-dimensional covariant calculation

New resonance(1): X(3872)

Basics about X(3872)

first seen in

$X(3872) \rightarrow J/\psi \pi^+ \pi^-$ by BELLE (2003),
also seen by CDF, D0 (2004) and BABAR (2005).

$\Gamma_X \approx 3 \text{ MeV}$

quantum numbers:

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

$J^{PC} = 1^{++}$ or $J^{PC} = 2^{-+}$ from $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ helicity am

$X(3872.2 \pm 0.8)$ close to $D^0 \bar{D}^{*0}$ threshold with $m_{thr} = 3871.81 \pm 0$

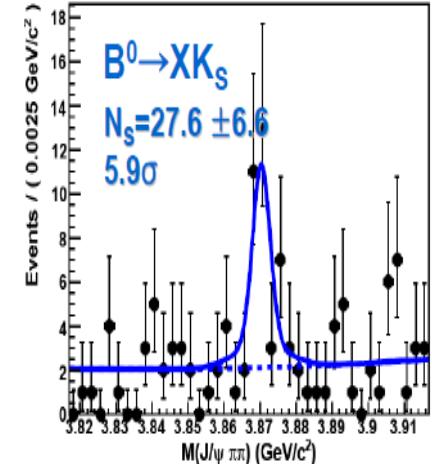
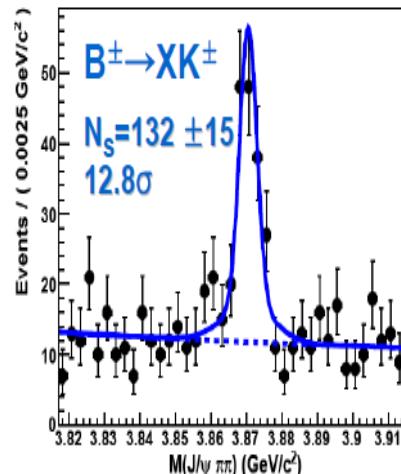
S-wave $D^0 \bar{D}^{*0}$ hadron molecule favors $J^{PC} = 1^{++}$

charmonium interpretation disfavored, $1^{++}(2^3 P_1)$ too low in mass compared to
 $m(2^3 P_2) \approx m(Z(3930))$

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

arXiv:0809.1224 605 fb⁻¹

recent results



$M(X(3872)) = (3871.46 \pm 0.37 \pm 0.07) \text{ MeV}$
by combining two modes together



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

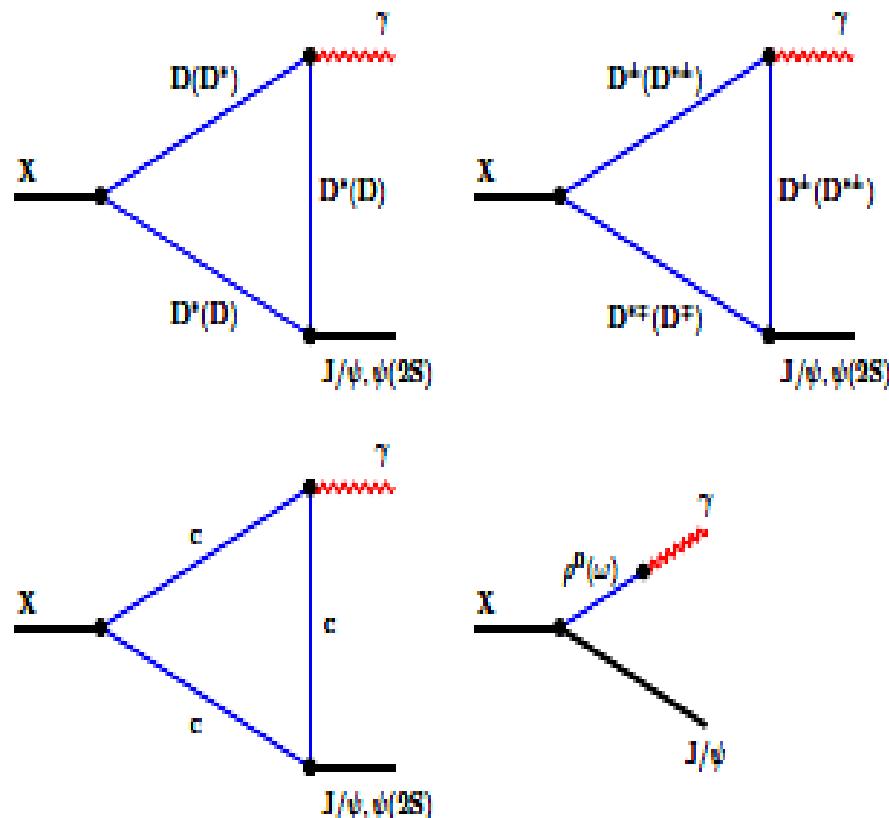
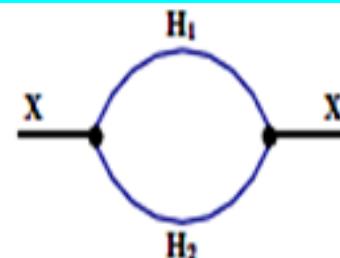
Decay modes

Basics about $X(3872)$, Decay Modes

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

Radiative decays

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



on-loop diagrams contributing to the mass operator of the $X(3872)$ meson.

Decay width (keV)

Approach	$\Gamma(X(3872) \rightarrow \gamma J/\psi)$
[$\alpha\bar{c}$], Ref. [9]	11
[$\alpha\bar{c}$], Ref. [33]	71
[$\alpha\bar{c}$], 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, 2008

Strong decay (two-body, three-body)

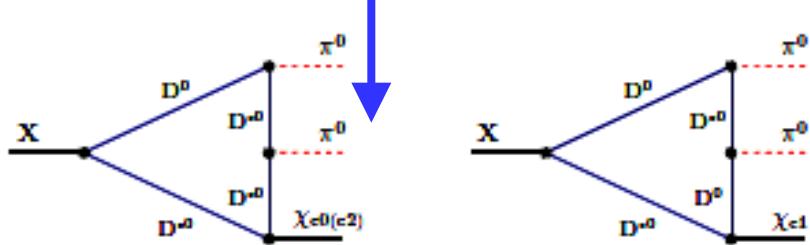
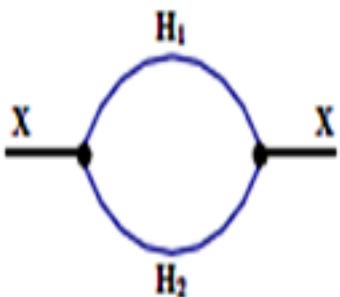


FIG. 1: $H_1 H_2$ hadron-loop diagrams contributing to the mass operator of the $X(3872)$ meson.

PRD79,094013 2009

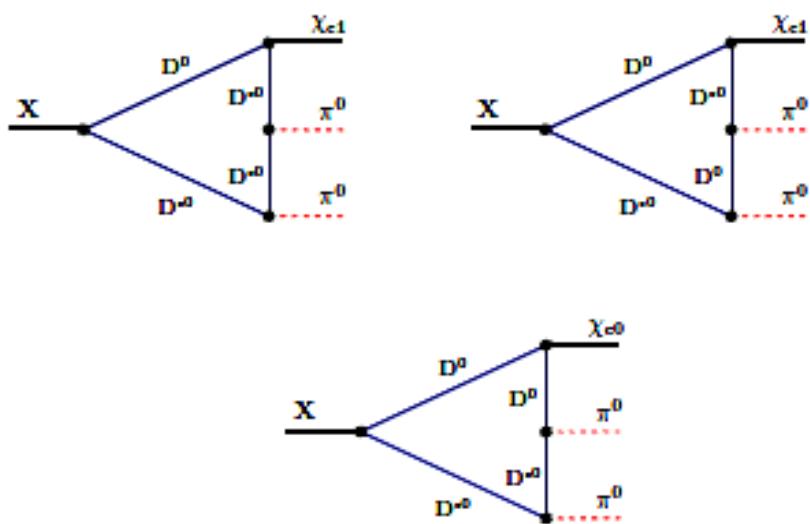
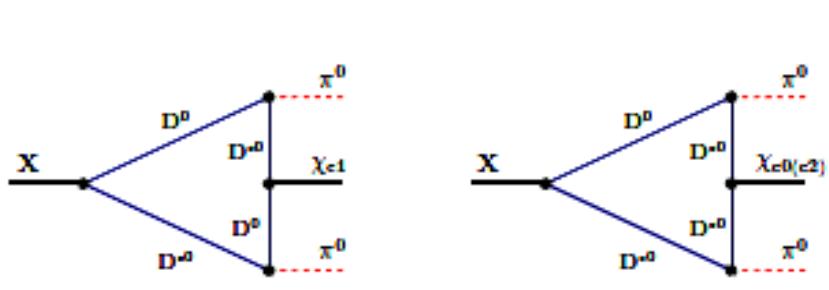
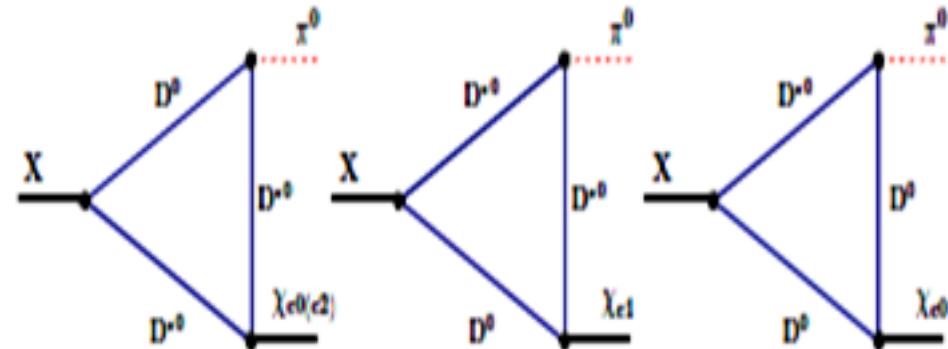


FIG. 2: Diagrams contributing to the hadronic transitions $X(3872) \rightarrow \chi_{cJ} + \pi^0$.

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

Strong decay (two-body, three-body)

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

$$\frac{\Gamma(X \rightarrow J/\psi \pi^+ \pi^- \pi^0)}{\Gamma(X \rightarrow J/\psi \pi^+ \pi^-)} = 1.0 \pm 0.4(\text{stat}) \pm 0.3(\text{syst}) \quad (1)$$

and

$$\frac{\Gamma(X \rightarrow J/\psi \gamma)}{\Gamma(X \rightarrow J/\psi \pi^+ \pi^-)} = 0.14 \pm 0.05(\text{Belle}); \\ 0.33 \pm 0.12(\text{BABAR}). \quad (2)$$

TABLE III. Properties of $X \rightarrow J_\psi + h$ 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
$\Gamma(X \rightarrow J/\psi \pi^+ \pi^-)$, keV	$7.5 \times 10^3 Z_{J_\psi \rho}(45.0)$	$9.0 \times 10^3 Z_{J_\psi \rho}(54.0)$
$\Gamma(X \rightarrow J/\psi \pi^+ \pi^- \pi^0)$, keV	$1.92 \times 10^3 Z_{J_\psi \omega}(78.9)$	$1.38 \times 10^3 Z_{J_\psi \omega}(56.6)$
$\Gamma(X \rightarrow J/\psi \pi^0 \gamma)$, keV	$0.32 \times 10^3 Z_{J_\psi \omega}(13.2)$	$0.23 \times 10^3 Z_{J_\psi \omega}(9.4)$
$\Gamma(X \rightarrow J/\psi \gamma)$, 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

New measurement of LHCb

• $\Gamma(X \rightarrow \psi(2S)\gamma)/\Gamma(X \rightarrow J/\psi\gamma) = 3.5 \pm 1.4$

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 $X(3872) \rightarrow J/\psi \gamma, \psi'\gamma$

- $X(3872) \rightarrow J/\psi \gamma, E_\gamma = 775$ MeV
VMD contributes (ρ, ω)
- $X(3872) \rightarrow \psi' \gamma, E_\gamma = 186$ MeV
can only proceed through
light quark annihilation
→ expected small
→ BaBar measurement surprising
- **New measurement by Belle Preliminary, QWG10, 711/fb**

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

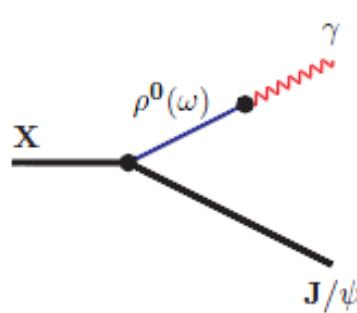
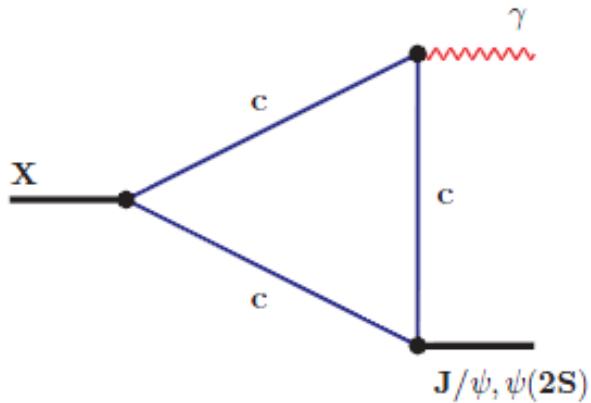
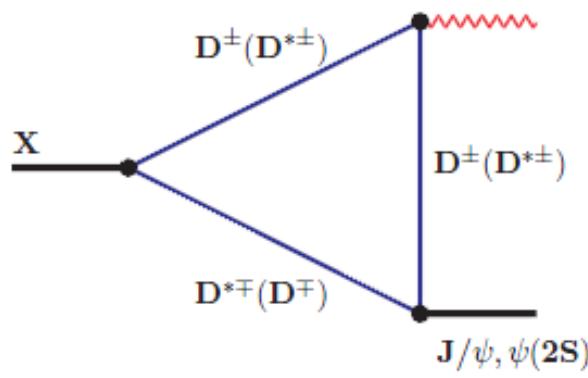
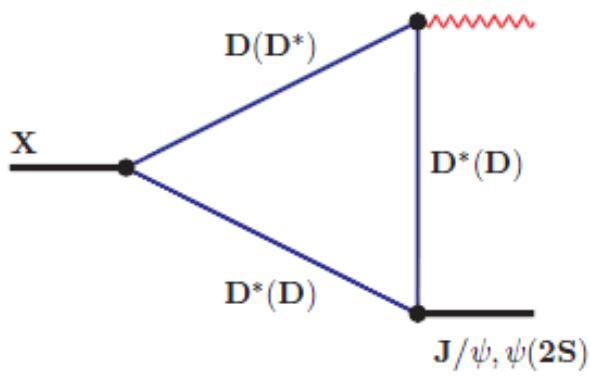
$$R_{\psi\gamma} = \frac{B(X(3872) \rightarrow \psi(2S)\gamma)}{B(X(3872) \rightarrow J/\psi\gamma)},$$

as a constraint on the charmonium content of the $X(3872)$. The branching fraction $B(X(3872) \rightarrow \psi(2S)\gamma)$ is in fact expected to be very small for a pure molecule ($O(10^{-3})$) [8-10], but it could be enhanced for an admixture of a $D^{*0}\bar{D}^0$ molecule and charmonium. The BaBar collaboration has measured a relative large branching fraction for the $X(3872)$ into $\psi(2S)\gamma$, with $R_{\psi\gamma} = 3.4 \pm 1.4$ [11], a result generally inconsistent with a pure molecular interpretation; in contrast, no significant signal was found by Belle [12].

$$\bar{R}_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29,$$

Including of $c\bar{c}$

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



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

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

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

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}	$3.5 (\theta = -20.2^\circ)$

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

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

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

BABAR

$$\bar{R}_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29,$$

LHCb

Brief summary (1)

- 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: $D_s(2317)$

Other applications:

2), Y-type: $\Upsilon(4260)$, $\Upsilon(3940)$; Z-type: $Z(4430)$, $Z_c(3900)$

3, New baryon resonance of $\Lambda_c(2940)^+$

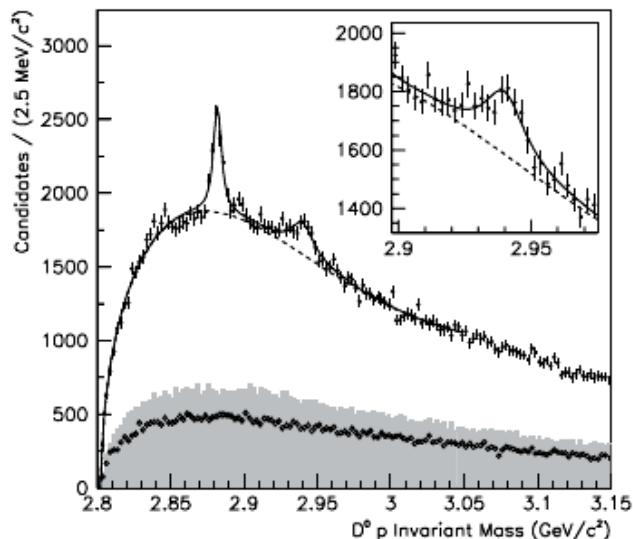
PRL 98, 012001 (2007)

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

(*BABAR* Collaboration)



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$$\Gamma = [17.5 \pm 5.2(\text{stat}) \pm 5.9(\text{syst})] \text{ MeV}.$$

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 $\Sigma_c(2455)^{0,++} \pi^\pm \rightarrow \Lambda_c^+ \pi^+ \pi^-$ by Belle

Measurement

PRL 98, 262001 (2007)

PHYSICAL REVIEW LETTERS

week ending
29 JUNE 2007

PDG

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 $\Lambda_c(2880)^+ \rightarrow \Sigma_c(2455)^{0,++} \pi^{+-}$ 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 $\Lambda_c(2880)^+ \rightarrow \Sigma_c(2520)^{0,++} \pi^{+-}$ 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 $\Lambda_c(2940)^+ \rightarrow \Sigma_c(2455)^{0,++} \pi^{+-}$ 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 Y(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}	$2938.0 \pm 1.3^{+20}_{-4.0}$	13^{+8+27}_{-5-7}

CHARMED BARYONS (C=+1)

$$\begin{aligned}\Lambda_c^+ &= u d c, & \Sigma_c^{++} &= u u c, & \Sigma_c^+ &= u d c, & \Sigma_c^0 &= d d c, \\ \Xi_c^+ &= u s c, & \Xi_c^0 &= d s c, & \Omega_c^0 &= s s c\end{aligned}$$

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)
$p D^0$	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)

+

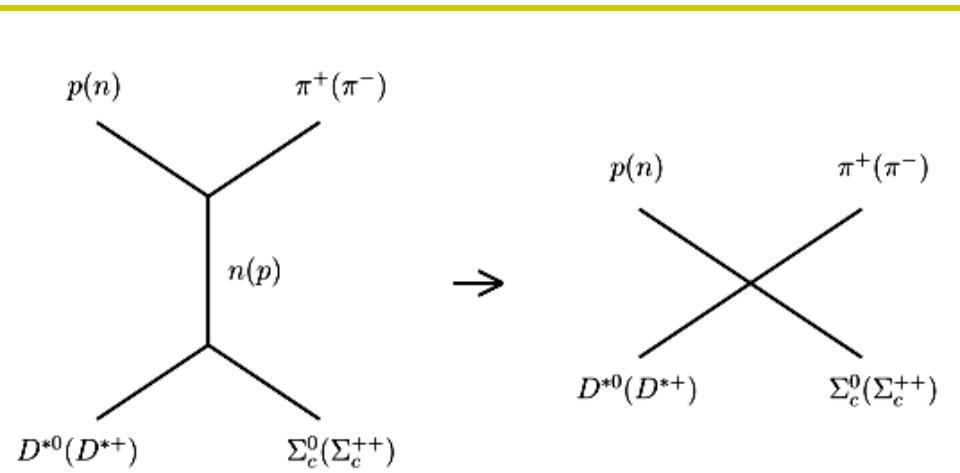
The assignment of the resonance

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

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

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

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



2015/9/18

Sept.16-24, Erice2015, Italy

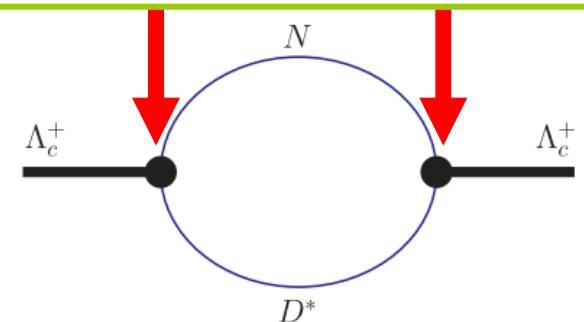


FIG. 1 (color online). Diagram describing the $\Lambda_c(2940)^+$ mass operator.

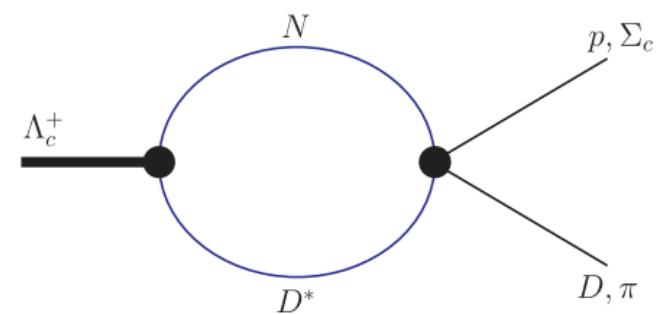


FIG. 2 (color online). Diagrams contributing to the decays $\Lambda_c(2940)^+ \rightarrow pD^0, \Sigma_c^{++}\pi^-, \Sigma_c^0\pi^+$.

Effective Lagrangians

SU(4)

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

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

$$\begin{aligned}\mathcal{L}_{VPBB} = & ig_1 \bar{B}^{kmn} \gamma^\mu \gamma^5 [V_\mu, P]_k^l B_{lmn} \\ & + ig_2 \bar{B}^{kmn} \gamma^\mu \gamma^5 [V_\mu, P]_k^l B_{lnm} \\ & + ig_3 \bar{B}^{kmn} \gamma^\mu \gamma^5 ((V_\mu)_k^l P_m^s - P_k^l (V_\mu)_m^s) \\ & - ig_3 \bar{B}^{knm} \gamma^\mu \gamma^5 ((V_\mu)_k^l P_m^s - P_k^l (V_\mu)_m^s)\end{aligned}$$

$$\begin{aligned}\Gamma(\Lambda_c[1/2^+] \rightarrow B + M) = & \frac{g_{\Lambda_c BM}^2}{16\pi m_{\Lambda_c}^3} \lambda^{1/2}(m_{\Lambda_c}^2, m_B^2, m_M^2) \\ & \times ((m_{\Lambda_c} - m_B)^2 - m_M^2)\end{aligned}\quad (9)$$

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

$$\begin{aligned}\Gamma(\Lambda_c[1/2^-] \rightarrow B + M) = & \frac{f_{\Lambda_c BM}^2}{16\pi m_{\Lambda_c}^3} \lambda^{1/2}(m_{\Lambda_c}^2, m_B^2, m_M^2) \\ & \times ((m_{\Lambda_c} + m_B)^2 - m_M^2)\end{aligned}\quad (10)$$

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

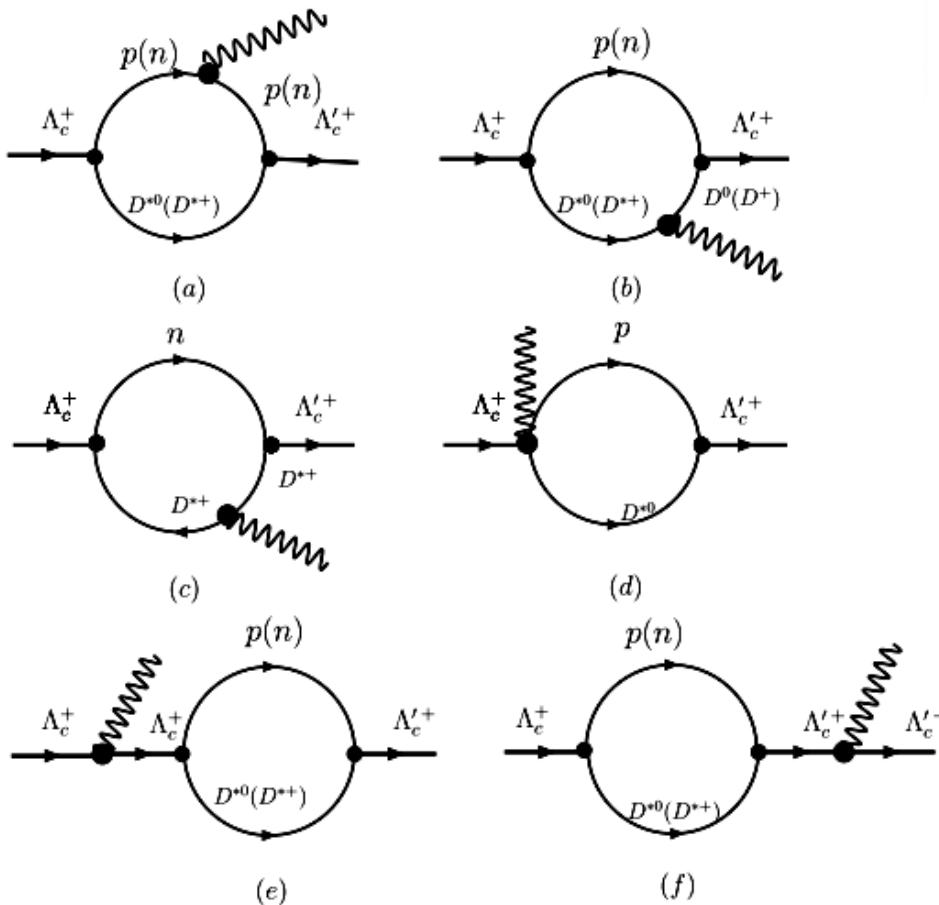
PRD81, 014006, 2010

Calculated results

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

$\cos\theta$	$\frac{1}{2}^+$ modes			$\frac{1}{2}^-$ modes		
	$\Lambda_c^+ \rightarrow p D^0$	$\Lambda_c^+ \rightarrow \Sigma_c^+ \pi^-$	$\Lambda_c^+ \rightarrow \Sigma_c^0 \pi^+$	$\Lambda_c^+ \rightarrow p D^0$	$\Lambda_c^+ \rightarrow \Sigma_c^{++} \pi^-$	$\Lambda_c^+ \rightarrow \Sigma_c^0 \pi^+$
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)



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

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

2015/9/18

Gauge Invariance

PRD82, 034035, 2010

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

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

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

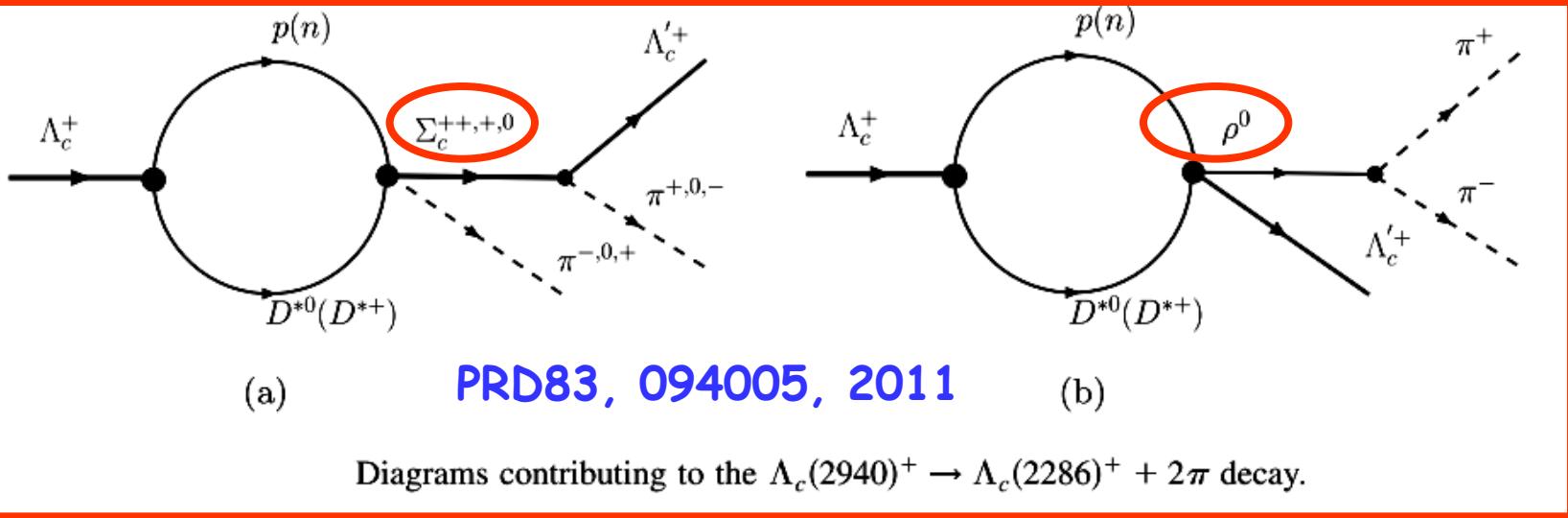
$$\mathcal{M}^\mu(p, p') = \frac{F_{\Lambda_c \Lambda'_c \gamma}}{2m_{\Lambda_c}} \bar{u}_{\Lambda'_c}(p') i \sigma^{\mu\nu} q_\nu u_{\Lambda_c}(p).$$

$$\Gamma(\Lambda_c(2940)^+ \rightarrow \Lambda_c(2286)^+ + \gamma) = \frac{\alpha P^3}{m_{\Lambda_c}^2} F_{\Lambda_c \Lambda'_c \gamma}^2,$$

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

θ (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

Three-body decay



$$\begin{aligned}
 \mathcal{L}_{\pi^- D^{*0} p \Sigma_c^{++}} &= \left[\frac{1}{4}(g_1 + g_2) - \frac{3}{2}g_3 \right] \bar{\Sigma}_c^{++} \pi^- i\gamma^\mu \gamma_5 p D_\mu^{*0} + \text{H.c.}, \quad \mathcal{L}_{\pi^- D^{*+} n \Sigma_c^{++}} = -\frac{3}{2}g_3 \bar{\Sigma}_c^{++} \pi^- i\gamma^\mu \gamma_5 n D_\mu^{*+} + \text{H.c.}, \\
 \mathcal{L}_{\pi^0 D^{*0} p \Sigma_c^+} &= \frac{1}{2} \left[\frac{1}{4}(g_1 + g_2) - 3g_3 \right] \bar{\Sigma}_c^+ \pi^0 i\gamma^\mu \gamma_5 p D_\mu^{*0} + \text{H.c.}, \quad \mathcal{L}_{\pi^0 D^{*+} n \Sigma_c^+} = \frac{1}{2} \left[\frac{1}{4}(g_1 + g_2) - 3g_3 \right] \bar{\Sigma}_c^+ \pi^0 i\gamma^\mu \gamma_5 n D_\mu^{*+} + \text{H.c.}, \\
 \mathcal{L}_{\pi^+ D^{*0} p \Sigma_c^0} &= -\frac{3}{2}g_3 \bar{\Sigma}_c^0 \pi^+ i\gamma^\mu \gamma_5 p D_\mu^{*0} + \text{H.c.}, \quad \mathcal{L}_{\pi^+ D^{*+} n \Sigma_c^0} = \left[\frac{1}{4}(g_1 + g_2) - \frac{3}{2}g_3 \right] \bar{\Sigma}_c^0 \pi^+ i\gamma^\mu \gamma_5 n D_\mu^{*+} + \text{H.c.}, \\
 \mathcal{L}_{\pi \Sigma_c \Lambda_c'} &= -\frac{1}{2} \sqrt{\frac{3}{2}} \left(g'_2 - \frac{1}{2}g'_1 \right) \bar{\Lambda}_c' i\gamma^5 \pi \Sigma_c + \text{H.c..} \quad \mathcal{L}_{D^* N \Lambda_c'} = -g_{D^* N \Lambda_c'} K_{D^* N \Lambda_c'} \bar{N} \sigma^{\mu\nu} \partial_\nu D_\mu^* \Lambda_c' + \text{H.c.},
 \end{aligned}$$

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

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

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

Three-body decay (results)

TABLE II. Three-body decay widths for $\Lambda_c(2940)^+ \rightarrow \Lambda_c(2286)^+ \pi^+ \pi^-$ (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)

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

TABLE III. Three-body decay widths $\Lambda_c(2940)^+ \rightarrow \Lambda_c(2286)^+ \pi^+ \pi^-$ (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°	$7.548(6.888 \times 10^{-3})$	$5.405(5.354 \times 10^{-3})$	$3.414(3.853 \times 10^{-3})$

4, Productions @ PANDA & JPARC



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 collision, build being able to provide precise trajectory reconstruction, energy and identification of charged particles.

What do you want to know more about?



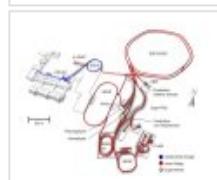
[The Physics Program](#)

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



[The Detector](#)

Detailed 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.

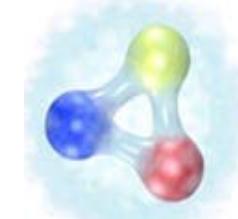


[The PANDA Collaboration](#)

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 @ PANDA

$$\mathcal{L}_{\Lambda'_c p D}^{\frac{1}{2}+} = g_{\Lambda'_c p D} \bar{\Lambda}'_c i \gamma_5 p D^0 + \text{H.c.}, \quad p \bar{p} \rightarrow p D^0 \Lambda_c^+(2286)$$

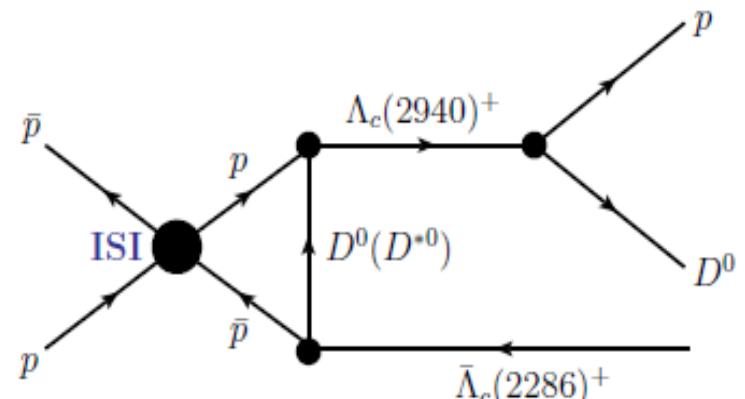
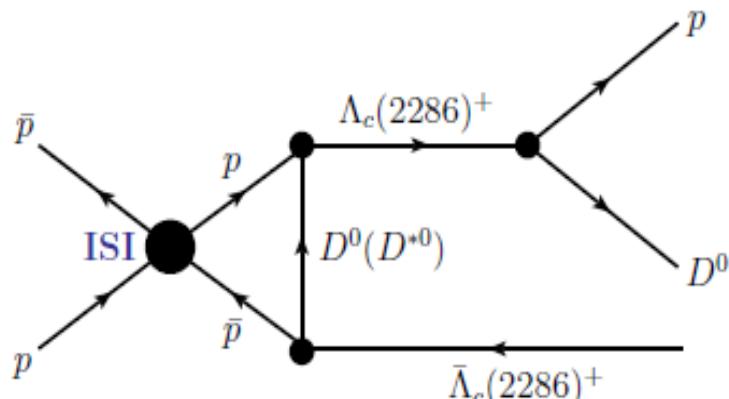
$$\mathcal{L}_{\Lambda'_c p D^*}^{\frac{1}{2}+} = g_{\Lambda'_c p D^*} \bar{\Lambda}'_c \gamma^\mu p D_\mu^{*0} + \text{H.c.} \quad |\Lambda_c(2940)\rangle = |p D^{*0}\rangle.$$

$$\frac{d\sigma}{dM_{pD}} = \frac{1}{1024\pi^4} \frac{1}{s\sqrt{s-4M_N^2}}$$

$$\mathcal{L}_{\Lambda'_c p D}^{\frac{1}{2}-} = f_{\Lambda'_c p D} \bar{\Lambda}'_c p D^0 + \text{H.c.}, \quad \times \int d\cos\theta_3 d\Omega_1^* |\vec{q}_1^*| |\vec{q}_2| |\mathcal{M}_{\text{inv}}|^2$$

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

PRD90, 094001, 2010



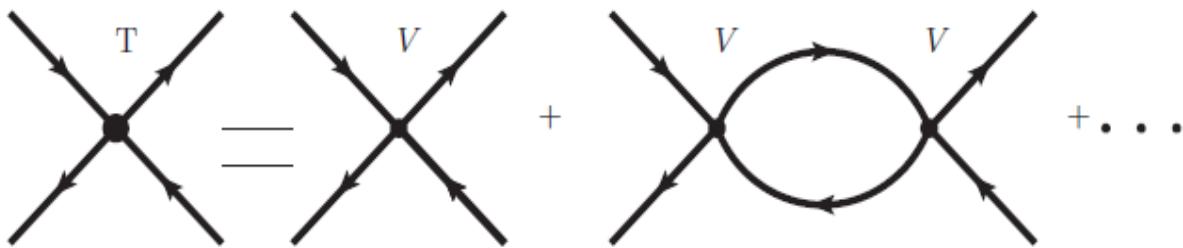
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(a)

(b)

30

Initial state interaction (ISI)



ISI

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

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

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

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

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

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

2015/9/18

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

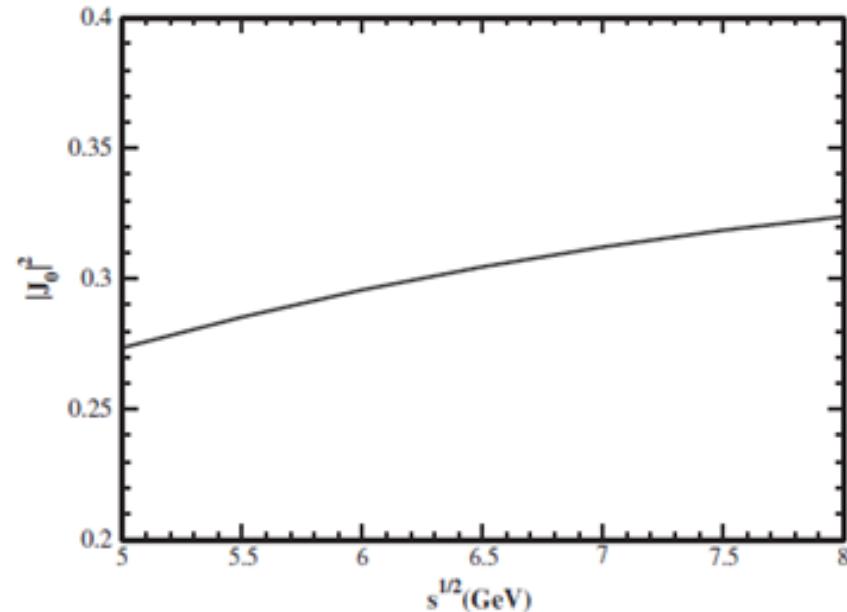
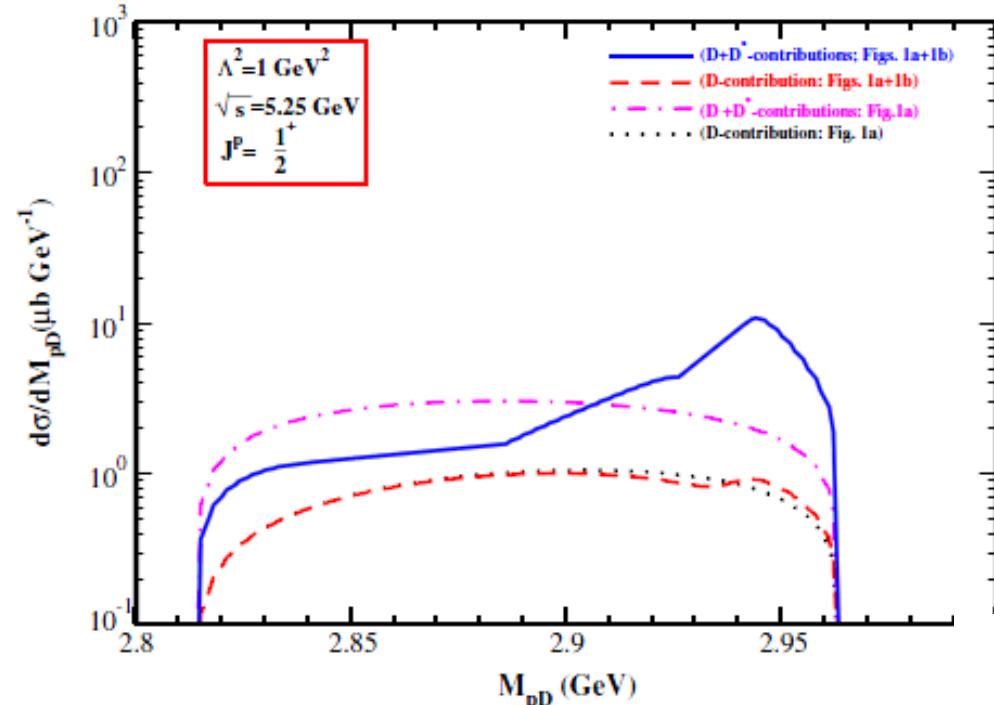
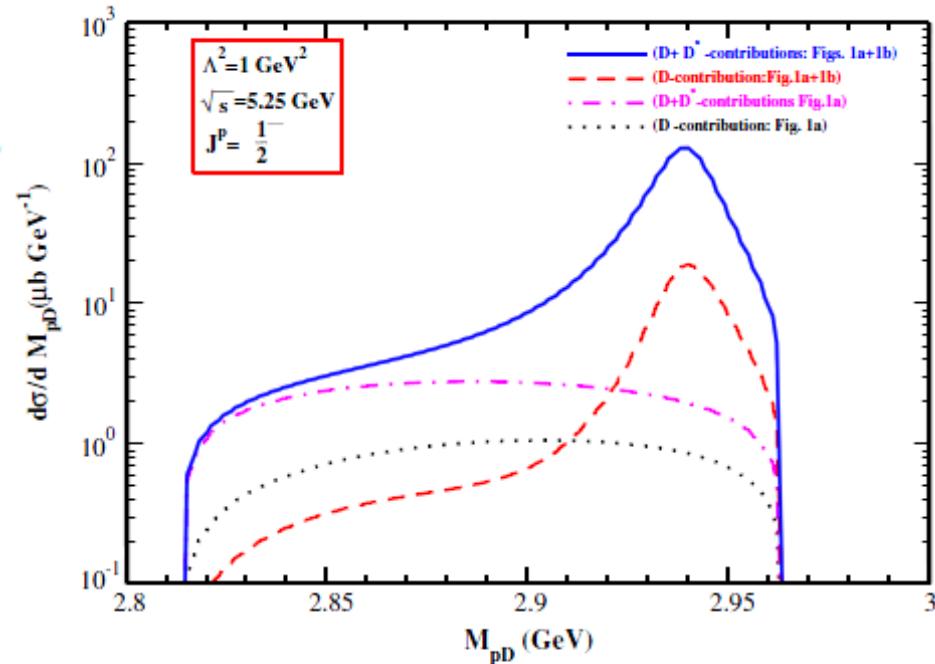


FIG. 3. Initial state interaction factor $|J_0|^2$ in dependence on $s^{1/2}$.

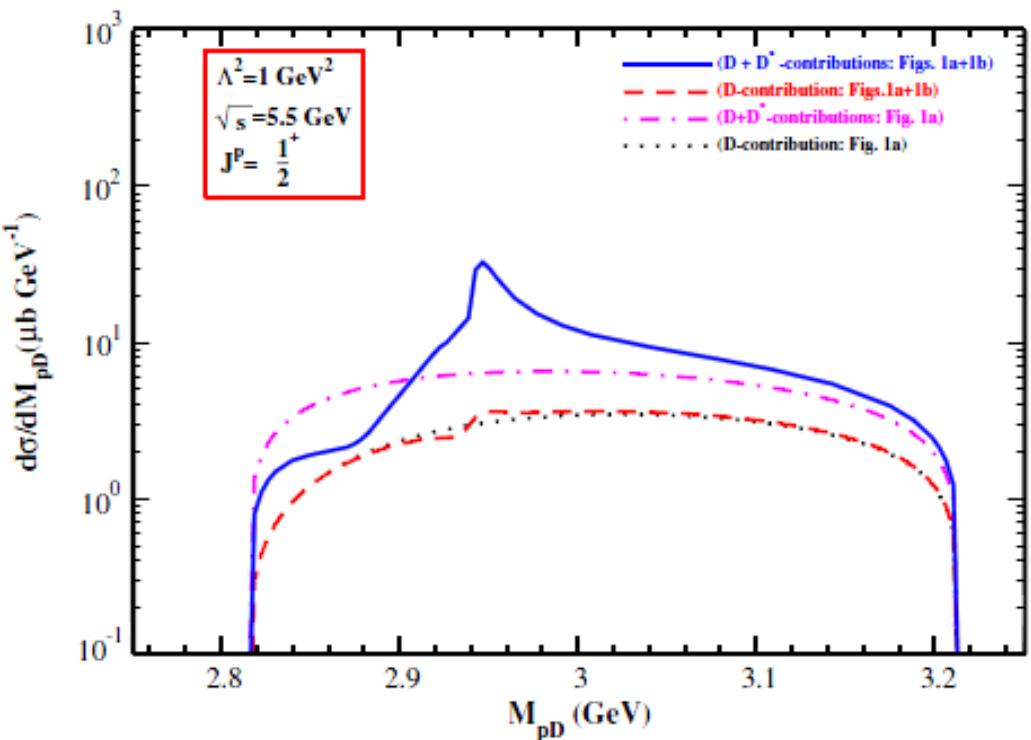
Differential cross sections



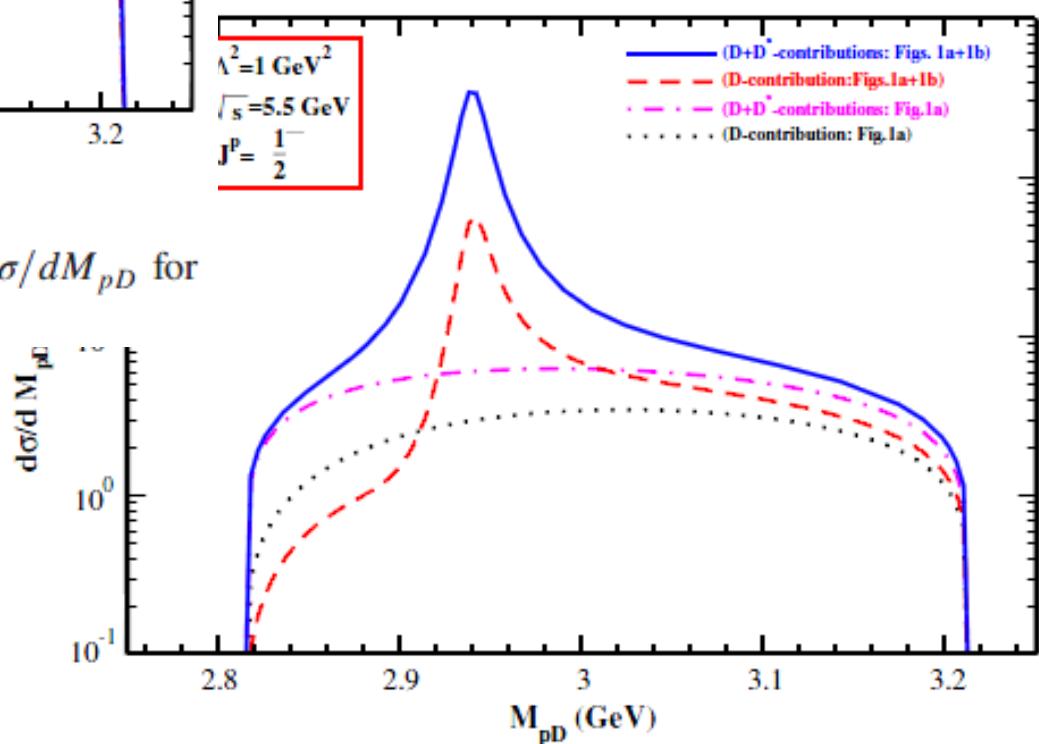
Differential cross section $d\sigma/dM_{pD}$
 $s^{1/2} = 5.25 \text{ GeV}$ for $J^P = \frac{1}{2}^+$ of the $\Lambda_c(2940)$.



Differential cross sections



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



2015/9/18

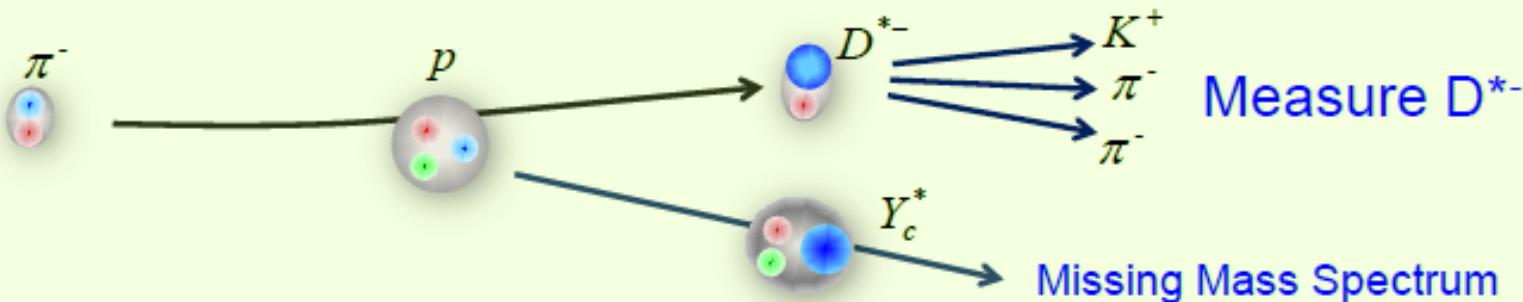
Differential cross section $d\sigma/dM_{33_D}$ for $s^{1/2} = 5.5 \text{ GeV}$ for $J^P = \frac{1}{2}^-$ of the $\Lambda_c(2940)$.

Production@ JPARC (Hadron Hall)

1

Charmed Baryon Spectroscopy

Missing Mass Spectroscopy



Dispersive
Focal Plane

20 GeV/c
 π^- Beam

Hydrogen
Target

K^+

π^-

High-resolution, High-momentum Beam Line

D^{*-} -Spectrometer

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

Nucl-1506.01133
PRD92, 034029

$$\begin{aligned} d\sigma(\pi^- p \rightarrow D^- D^0 p) &= \frac{1}{2\sqrt{(p_1 \cdot p_2)^2 - m_{\pi^-}^2 m_p^2}} \sum_{s_i, s_f} |\mathcal{M}|^2 \\ &\times \frac{d^3 p_3}{2E_3} \frac{d^3 p_4}{2E_4} \frac{m_p d^3 p_5}{E_5} \delta^4(p_1 + p_2 - p_3 - p_4 - p_5), \end{aligned}$$

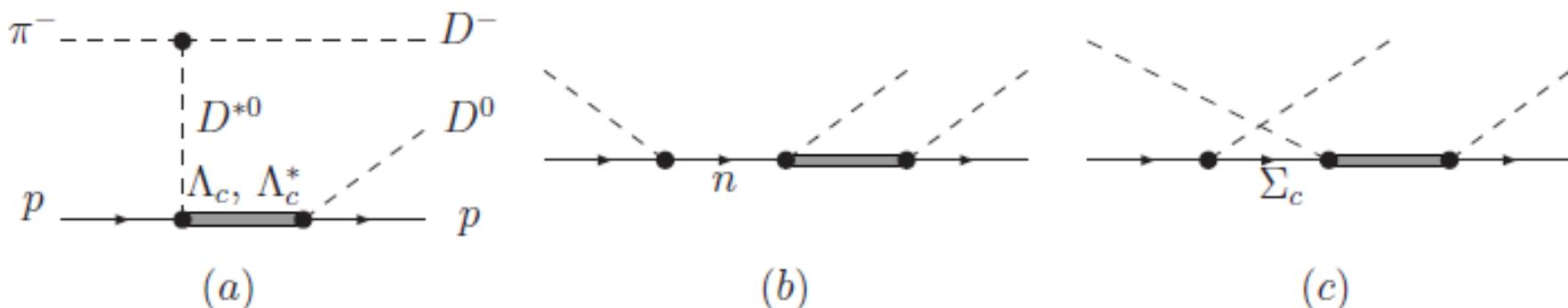


FIG. 1: Feynman diagrams for the $\pi^- p \rightarrow D^- D^0 p$ reaction.

Effective interactions

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

$$\mathcal{L}_{\pi N N} = -ig_{\pi N N} \bar{N} \gamma_5 \vec{\tau} \cdot \vec{\pi} N, \quad (2)$$

$$\mathcal{L}_{D N \Sigma_c} = -ig_{D N \Sigma_c} \bar{N} \gamma_5 D \Sigma_c + \text{H.c.}, \quad (3)$$

$$\mathcal{L}_{\Lambda_c p D} = ig_{\Lambda_c p D} \bar{\Lambda}_c \gamma_5 p D^0 + \text{H.c.}, \quad (4)$$

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

$$\mathcal{L}_{\Lambda_c \pi \Sigma_c} = ig_{\Lambda_c \pi \Sigma_c} \bar{\Lambda}_c \gamma_5 \vec{\pi} \cdot \vec{\Sigma}_c + \text{H.c..} \quad (6)$$

$$F_{D^*}(q_{ex}^2, M_{ex}) = \frac{\Lambda_{D^*}^2 - M_{D^*}^2}{\Lambda_{D^*}^2 - q_{D^*}^2} \quad F_B(q_{ex}^2, M_{ex}) = \frac{\Lambda_B^4}{\Lambda_B^4 + (q_{ex}^2 - M_{ex}^2)^2}.$$

Matrix elements

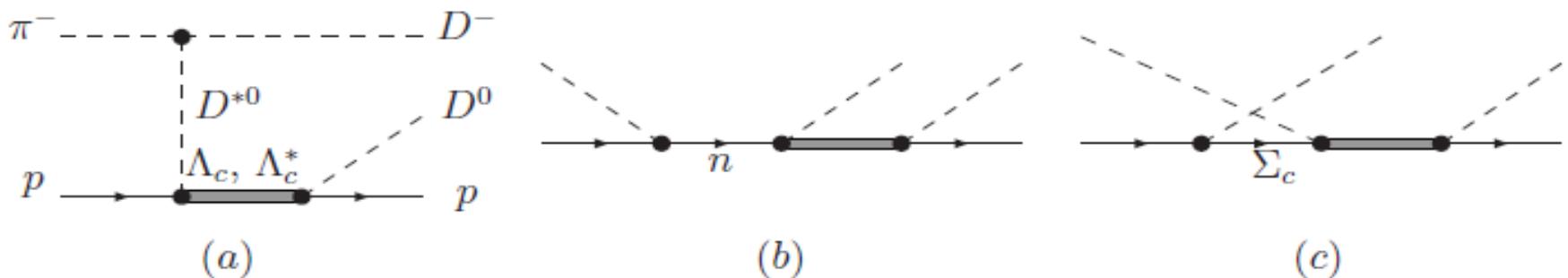


FIG. 1: Feynman diagrams for the $\pi^- p \rightarrow D^- D^0 p$ reaction.

$$\begin{aligned} M_a^{\frac{1}{2}\pm} &= \frac{i g_a^{\frac{1}{2}\pm}}{(q^2 - M_{\Lambda'_c}^2 + i M_{\Lambda'_c} \Gamma_{\Lambda'_c})(t - M_{D^*}^2)} \\ &\times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda'_c})(\not{p}_1 - \frac{\not{p}_1 \cdot \not{k}_t \not{k}_t}{M_{D^*}^2}) \gamma_5 u(p_2, s_i), \end{aligned}$$

$$\begin{aligned} M_b^{\frac{1}{2}\pm} &= \frac{\sqrt{2} g_b^{\frac{1}{2}\pm}}{(q^2 - M_{\Lambda'_c}^2 + i M_{\Lambda'_c} \Gamma_{\Lambda'_c})(s - m_n^2)} \\ &\times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda'_c})(\not{k}_s + m_n) \gamma_5 u(p_2, s_i), \end{aligned}$$

$$\begin{aligned} M_c^{\frac{1}{2}\pm} &= \frac{g_c^{\frac{1}{2}\pm}}{(q^2 - M_{\Lambda'_c}^2 + i M_{\Lambda'_c} \Gamma_{\Lambda'_c})(u - M_{\Sigma_c}^2)} \\ &\times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda'_c})(\not{k}_u + M_{\Sigma_c}) \gamma_5 u(p_2, s_i), \end{aligned}$$

Results (1:total cross sections)

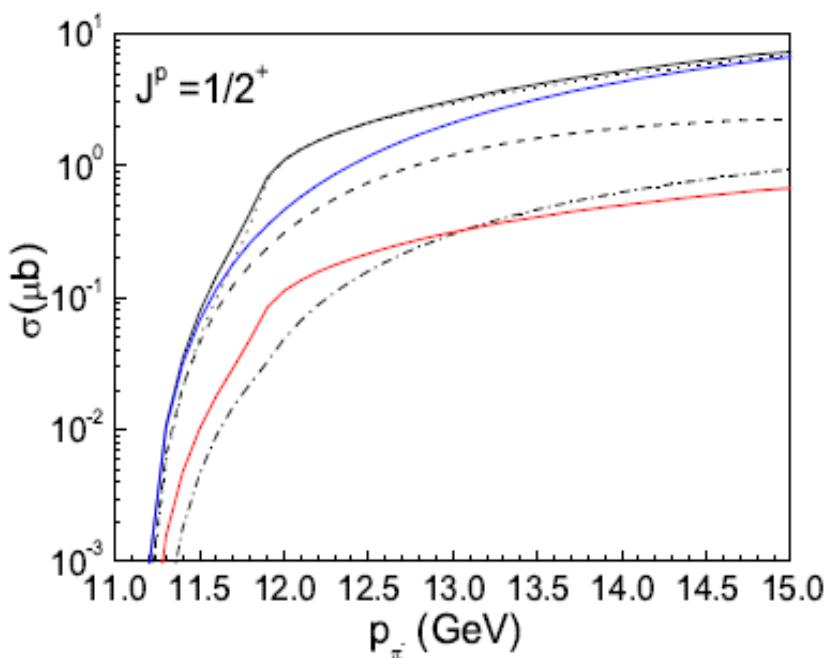


FIG. 2: (Color online) Total cross sections for the $\pi^- p \rightarrow D^- D^0 p$ reaction as a function of the beam momentum p_{π^-} for $J^P = \frac{1}{2}^+$ of the $\Lambda_c^+(2940)$. The dashed, dotted, and dash-dotted curves stand for the contributions from the s -channel, t -channel, and u -channel,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

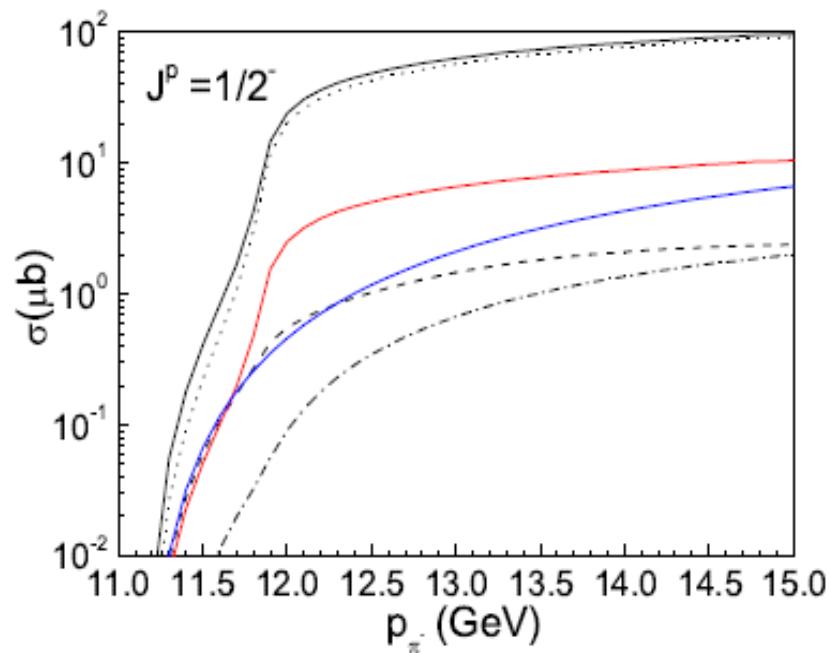


FIG. 3: (Color online) As shown in Fig. 2 but for $J^P = \frac{1}{2}^-$ of the $\Lambda_c^+(2940)$.

Results (2: differential cross sections)

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

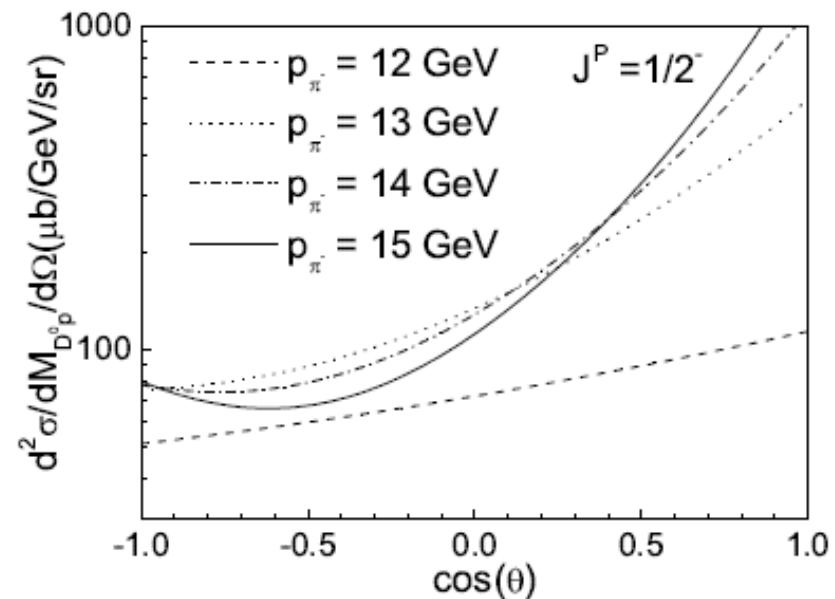
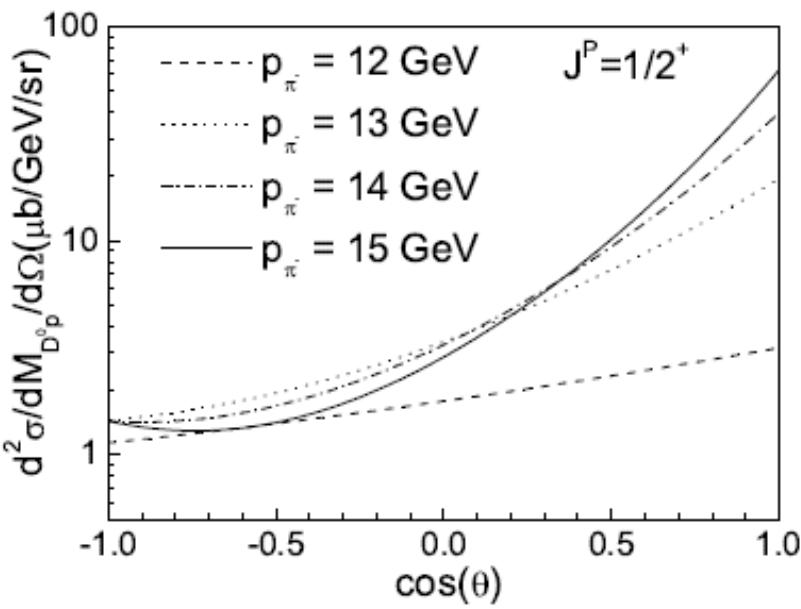
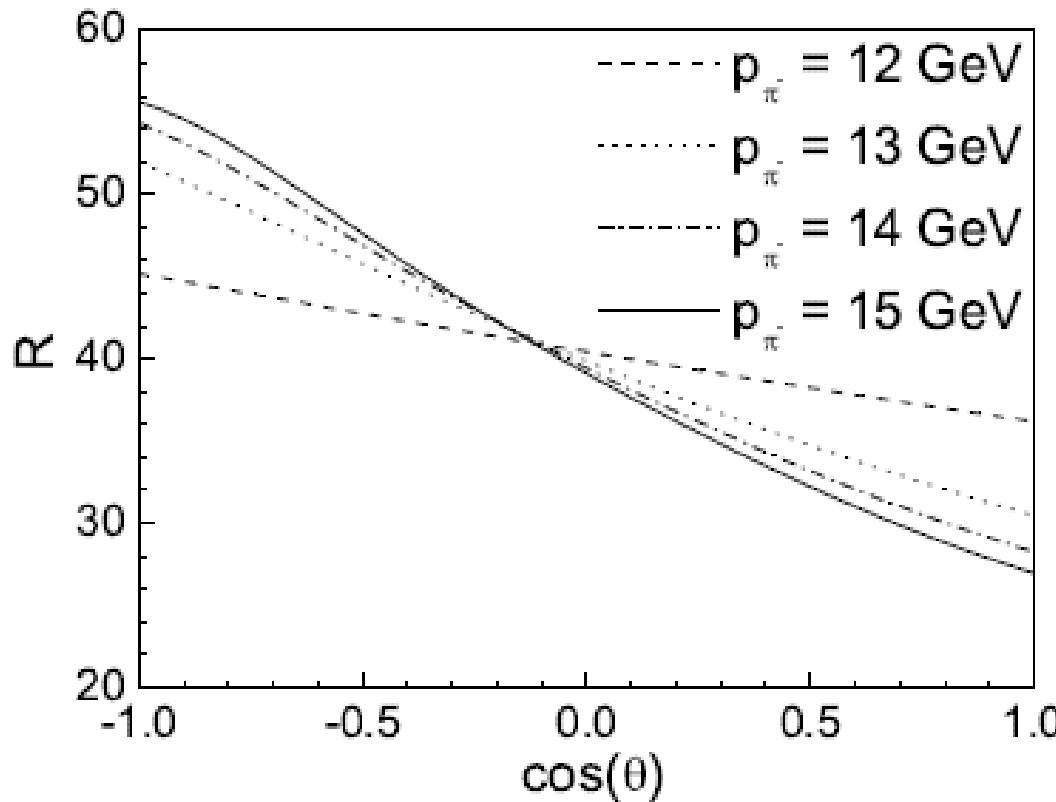


FIG. 4: Differential cross sections for the $\pi^- p \rightarrow D^- D^0 p$ reaction as a function of the scattering angle (θ) of the outgoing D^- meson in the CM frame of $\pi^- p$ system for $J^P = \frac{1}{2}^+$ of the $\Lambda_c^+(2940)$.

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

Results (3: Ratio)

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



2015/9/18 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

Compositeness condition +

Other Effective Lagrangians

$\Lambda(3872)$

$Z_c(3900)$, $Y(4260)$, $Z_b(10610)$, $Z'b(10650)$

2), Baryon resonance $\Lambda+c(2940)$

3), Productions of $\Lambda+c(2940)$

@ PANDA

@ JPARC

BACKUP

X, Y, Z states

Courtesy of Brambilla et al., 1010.5827

$\underline{Y(4660)}$
 $\underline{X(4630)}$

$\underline{Y(4360)}$
 $\underline{Y(4260)}$

$\underline{Y(4008)}$

$\underline{X(3872)}$

$\underline{X(4350)}$

$\underline{X(3915)}\dots$

$\underline{Z(4430)}^+$

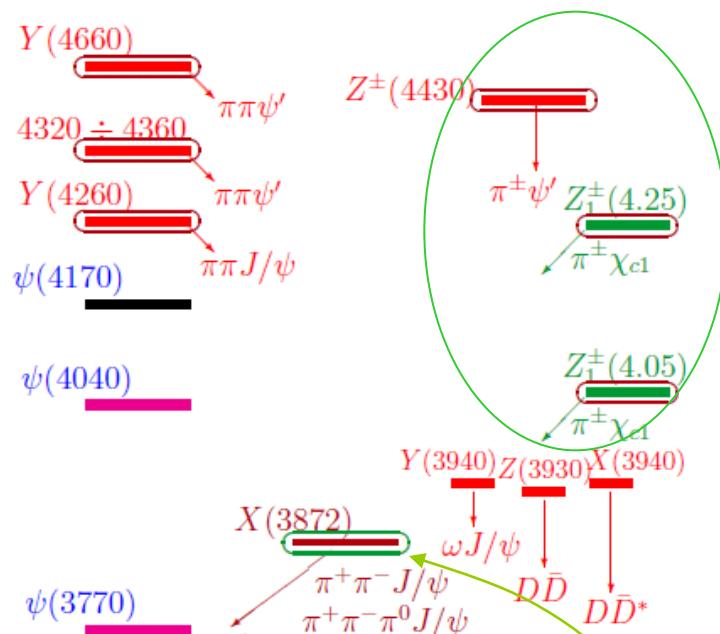
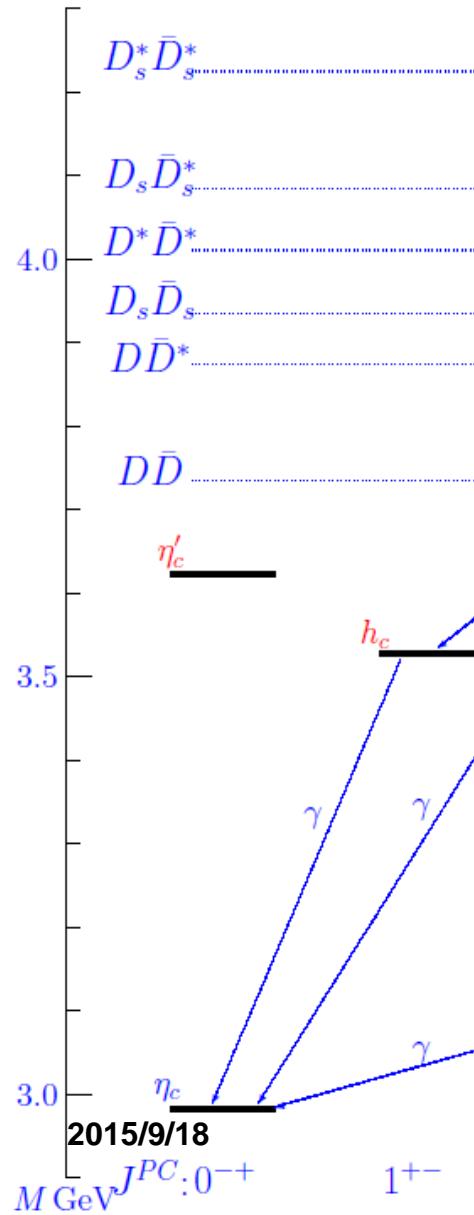
$\underline{Y(4274)}$ $\underline{Z_2(4250)}^+$

$\underline{X(4160)}$
 $\overline{Y(4140)} \underline{Z_1(4050)}^+$

$\underline{X(3940)}$

$D\bar{D}(3730)$	J^{PC}	1^{--}	(1^{++})	$0/2^{++}$	$0/2^{?+}$	$?^{?+}$	$?$

Charmonium '10



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

2015/9/18

Sept.16-24, Erice2015, Italy

Some known candidates for hadronic meson-meson molecules

• a0(980), f0(980)	$\rightarrow K \bar{K}$	$X(3872)$	$\bar{D}^0 D^{*0}$
• D*s0(2317)	$\rightarrow D\bar{K}$; $Ds1 \rightarrow D^*K$	$X(3915)$	$\bar{D}^{*0} D^{*0} + D^{*+} D^{*-}$
• X(3872)	$\rightarrow D \bar{D}^{*+} c.c.$	$Y(4140)$	$D_s^{*+} D_s^{*-}$
• Z(4430)	$\rightarrow D^*(2010) \bar{D}_1(2420)$	$Y(4260)$	$D_0 \bar{D}^*, \psi(2S) f_0(980)$ $\Lambda_c \bar{\Lambda}_c, \chi_{c0} \rho, \chi_{c1} \omega, D_1 \bar{D}$
		$Z(4430)^+$	$D^{*+} \bar{D}_1^0$
		$X(4630)$	$\psi(2S) f_0(980)$
		$Y(4660)$	$\psi(2S) f_0(980)$

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.

Decay modes

Basics about $X(3872)$, Decay Modes

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

Calculation: Molecular scenario

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

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

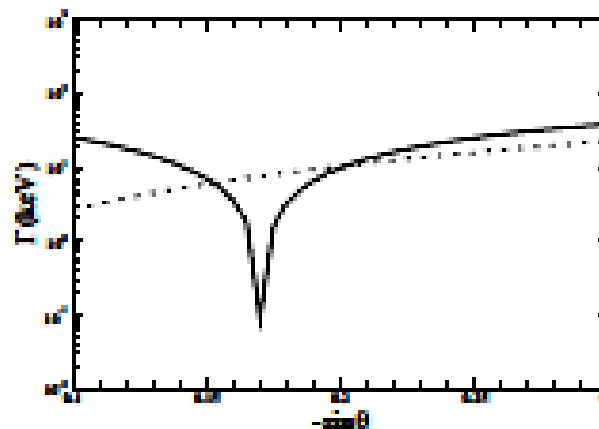
($m_{D^0} = 1864.85$ MeV, $m_{D^{*0}} = 2006.7$ MeV, $m_x = m_{D^0} + m_{D^{*0}} - \epsilon$)

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

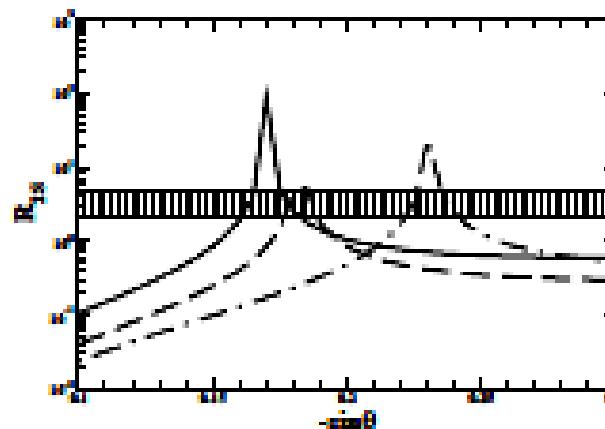
Results for $X(3872) \rightarrow \gamma J/\psi$ and $\psi(2S)$

Configuration	$\Gamma(X(3872) \rightarrow \gamma J/\psi, \gamma\psi(2S))$ 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 $Z_{cc}^{1/2} = \sin\theta \approx -0.2$ required



dotted - J/ψ , solid - $\psi(2S)$ mode



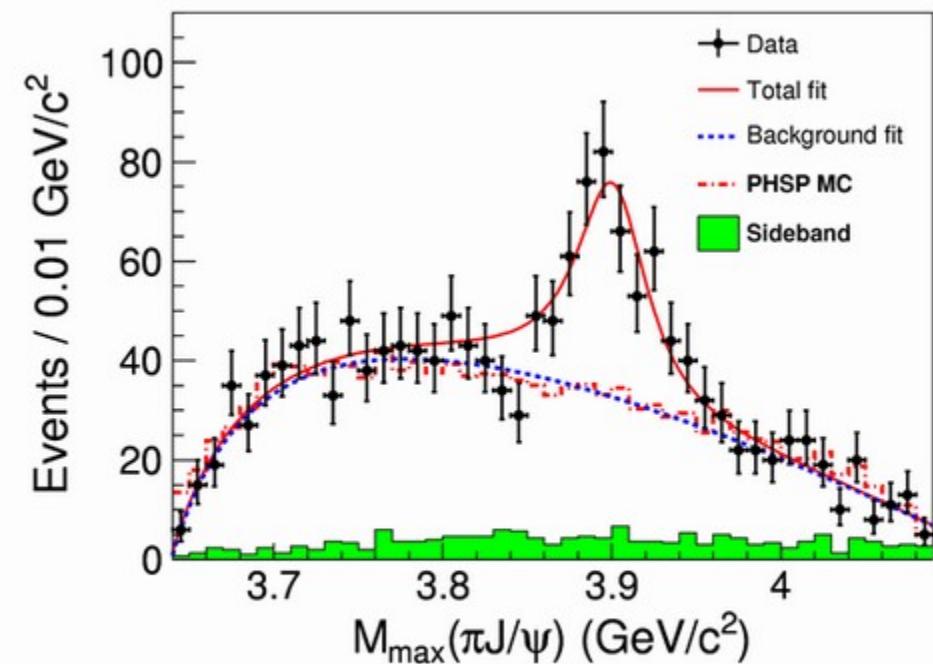
$$R_{2S} = \frac{\Gamma(X \rightarrow \psi(2S) + \gamma)}{\Gamma(X \rightarrow J/\psi + \gamma)} = 3.5 \pm 1.4 \\ (\text{BABAR, 2009})$$

BEPC, New resonances of Zc (3900)

BESIII, Belle and CLEO-c \rightarrow Zc(3900)₊

$$M_{Z_c(3900)} = (3899 \pm 3.6 \pm 4) \text{ MeV}_{+}$$

$$\Gamma_{Z_c(3900)} = (46 \pm 10 \pm 20) \text{ MeV}_{+}$$



1月，北京谱仪III实验发现了新的共振结构Zc(3900)。这是一个尚未被识别到的，可能是由中性介子和一种带电轻子组成的三体共振态。该共振态在2013年1月的物理数据中被首次观察到，直到2014年1月被确认。首先，这个新发现的共振态是什么？它的性质是什么？这是科学家们的主要研究方向。

2015/9/18
北京谱仪III实验发现的新的共振结构Zc(3900)