A study of exotic heavy baryons

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Contents

a Introduction: Exotic resonances

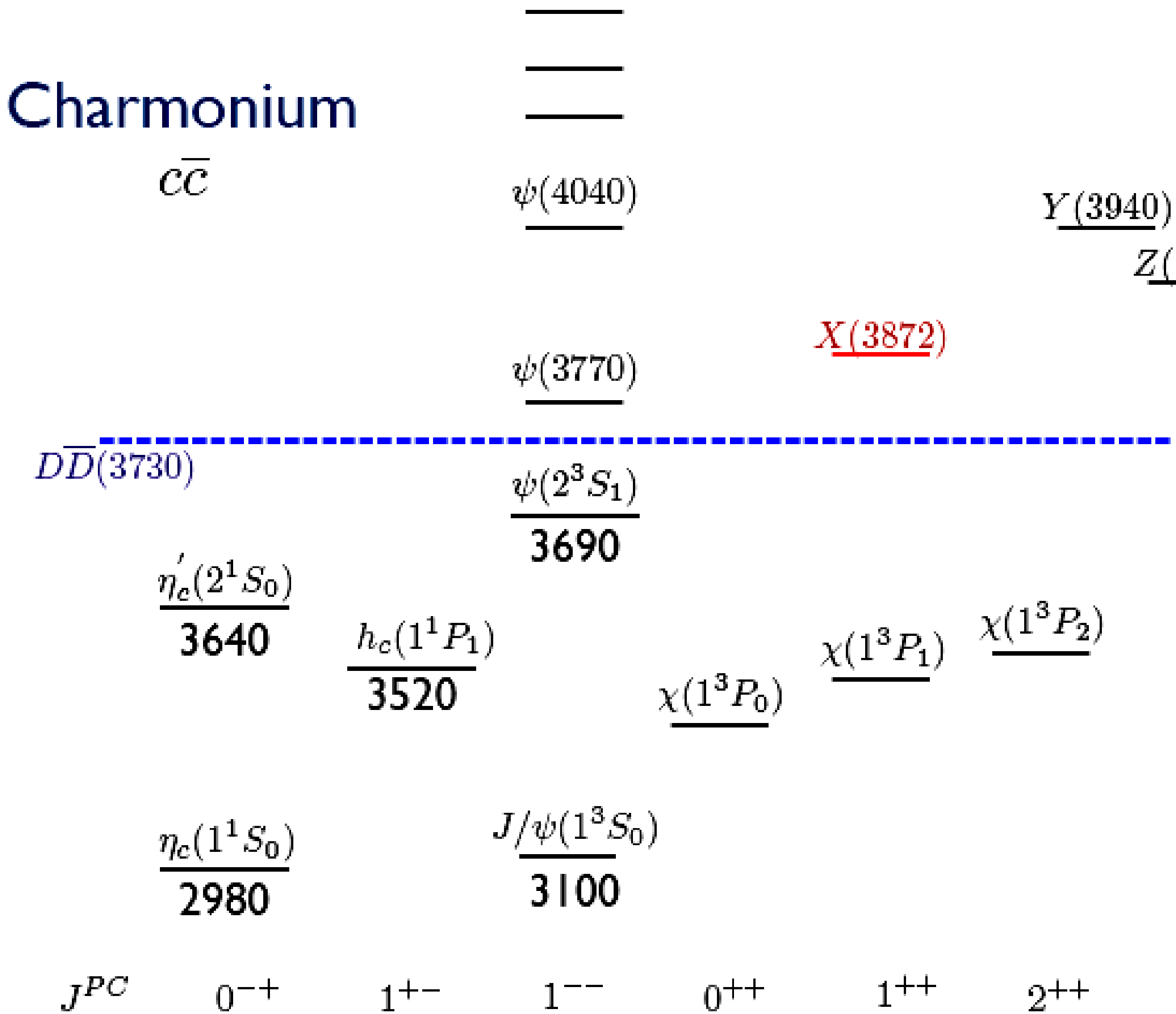
b Molecule scenario and exotic mesons

c New exotic baryon resonance of $\Lambda_c(2940)$

d Its production

e Summary..(JPARC)

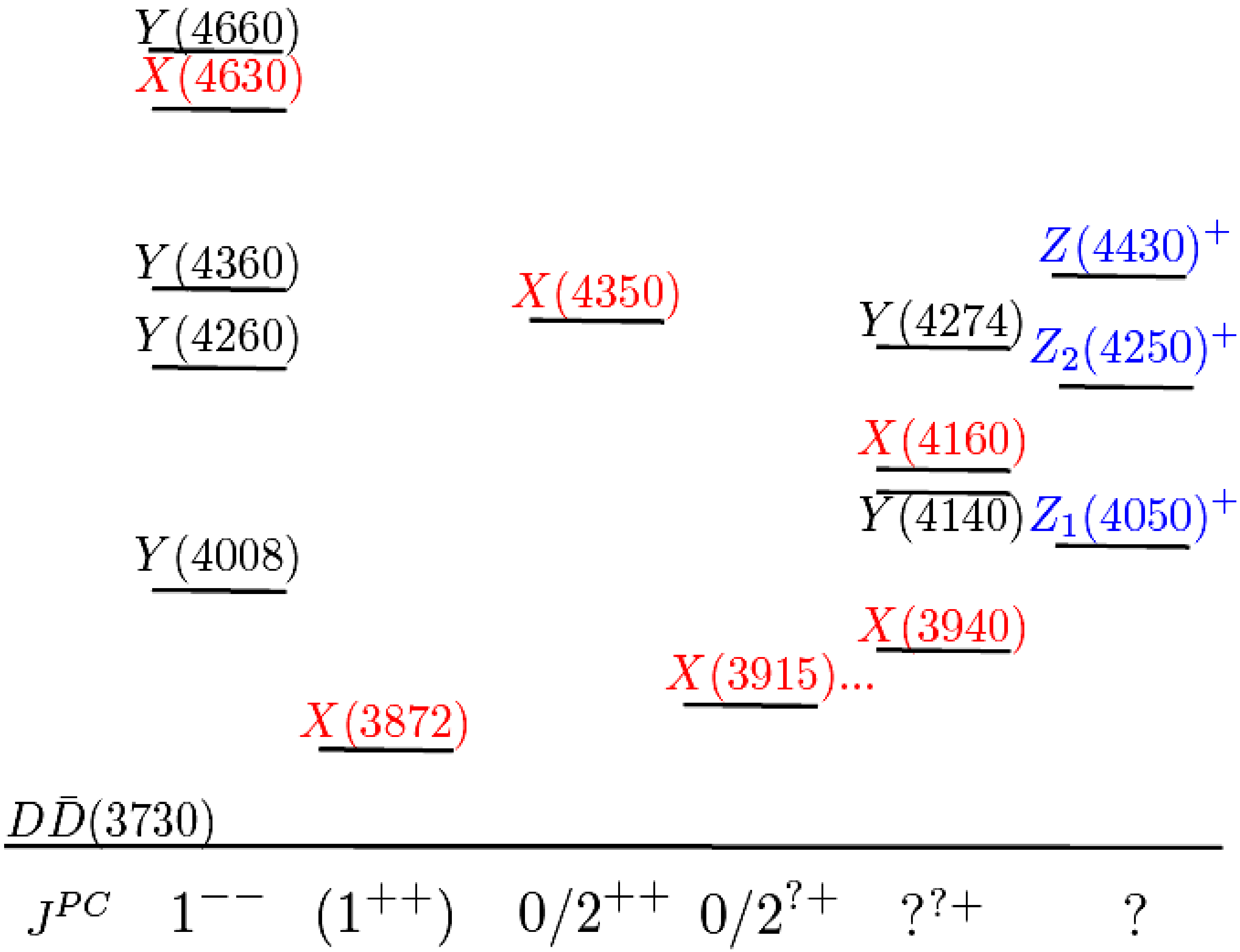
a, Introduction

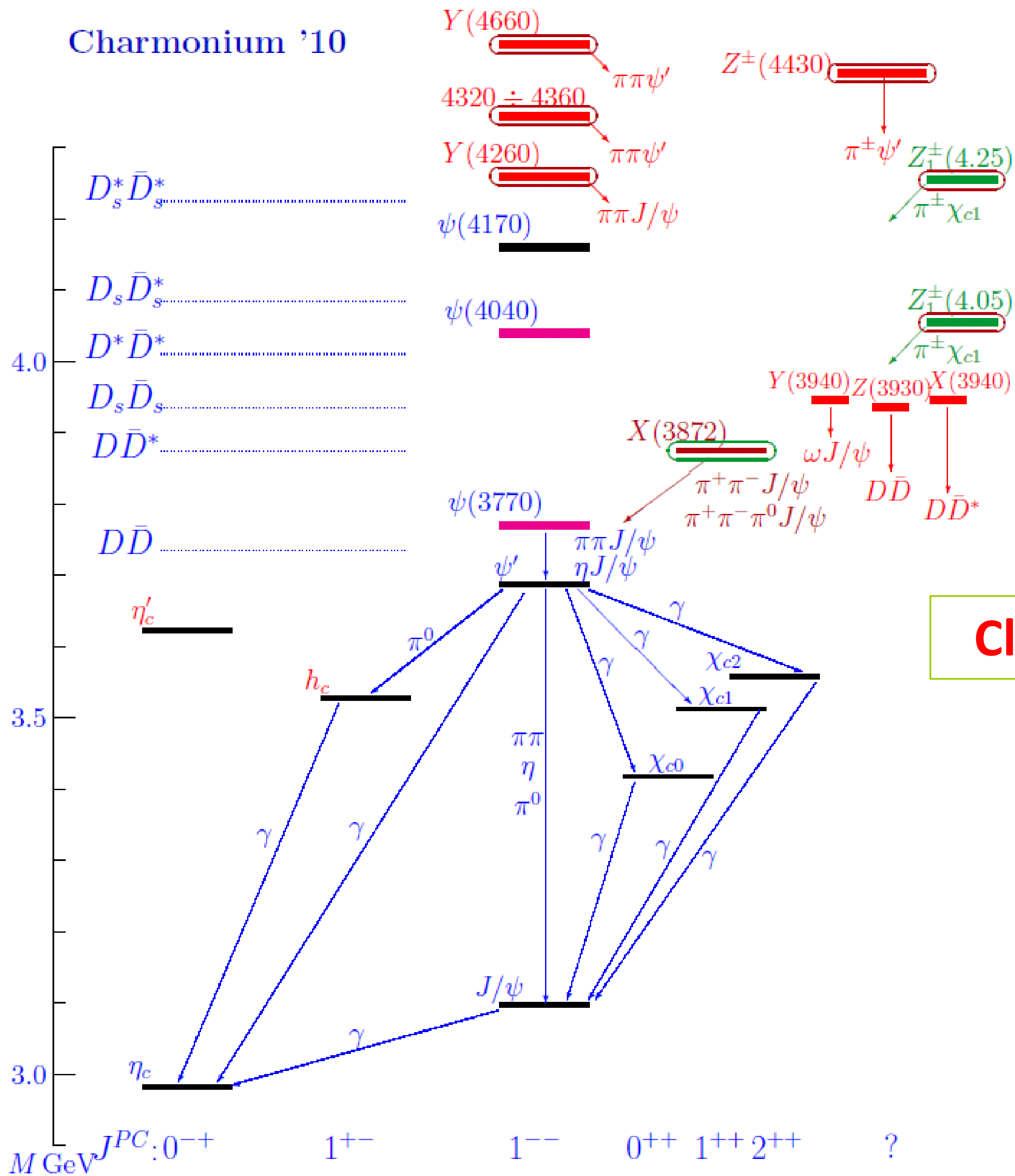


Potential models worked well for charmonium specrtoscopy

X, Y, Z states from

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

Charged heavy quarkonium states observed in exp.

State	Mass (MeV)	Width (MeV)	J^{PC}	Observation channel	Experiment
$Z_c(3900)$	3898 ± 5	51 ± 19	$1^{?-}$	$Y(4260) \to \pi^{\pm}(J/\psi\pi^{\mp})$	BESIII(2013), Belle(2013
				$\psi(4170) \to \pi^{\pm}(J/\psi\pi^{\mp})$	Xiao *et al.*(2013)
	3883 ± 1.5	25 ± 3	1^{+-}	$Y(4260) \to \pi D\bar{D}^*$	BESIII(2013)
$Z_c(4020)$	$4021.8 \pm 1.0 \pm 2.5$	$5.7 \pm 3.4 \pm 1.1$	$1^{?-}$	$e^+e^- \to \pi^{\pm}(\pi^{\mp}h_c(1P))$	BESIII(2013)
				$E_{cm} = 4.26$ and 4.36 GeV	
$Z_c(4025)$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$1^{?-}$	$e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp} + c.c.$	BESIII(2013)
				$E_{cm} = 4.26$ GeV	
$Z_1(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K + (\chi_{c1}(1P)\pi^+)$	Belle(2008)
$Z_2(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K + (\chi_{c1}(1P)\pi^+)$	Belle(2008)
$Z(4430)$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K + (\psi(2S)\pi^+)$	Belle(2007)
$Z_b(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi^{\pm}(\Upsilon(nS)\pi^{\mp})$	Belle2011
				$\Upsilon(5S) \to \pi^{\pm}(h_b(mS)\pi^{\mp})$	Belle2011
				$\Upsilon(5S) \to \pi^-(B^+\bar{B}^{*0} + \bar{B}^0B^{*+})$	Belle2013
$Z_b(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^{\pm}(\Upsilon(nS)\pi^{\mp})$	Belle2011
				$\Upsilon(5S) \to \pi^{\pm}(h_b(mS)\pi^{\mp})$	Belle2011
				$\Upsilon(5S) \to \pi^-(B^{*+}\bar{B}^{*0})$	Belle2013

XYZ resonances [Hidden-charm(bottom)]

1, Conventional quark model ×

2, Narrow width

3, Near threshold of two mesons…

Interpretations:

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

Molecular scenario

Quark and hadron level

Frame Works:

- QCD sum rule
- Non relativistic QCD
- Heavy quark effective theory
- Heavy hadron chiral perturbation theory
- Potential models
- Lattice calculations

Hadronic molecules

- Weekly bound state of two or three hadrons
- Obvious examples: Nuclei (deuteron) or hyper-nucleon
- Baryon-baryon bound state: $M_H < M_1 + M_2$

- Dynamical Generation of molecular bound states/ resonances

Long-range one-pion exchange (Tornqvist, 1991)

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

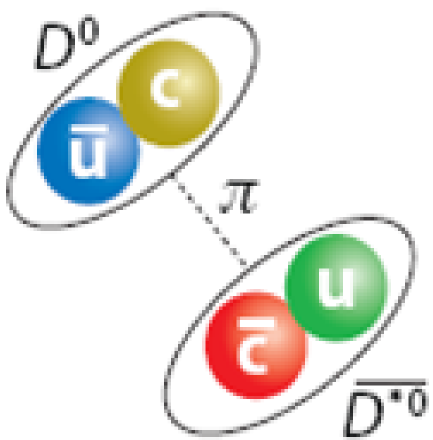
Unitarized coupled channel models with chiral Lagrangians (Olier, et al., 1997;

Jido et al., 2005,

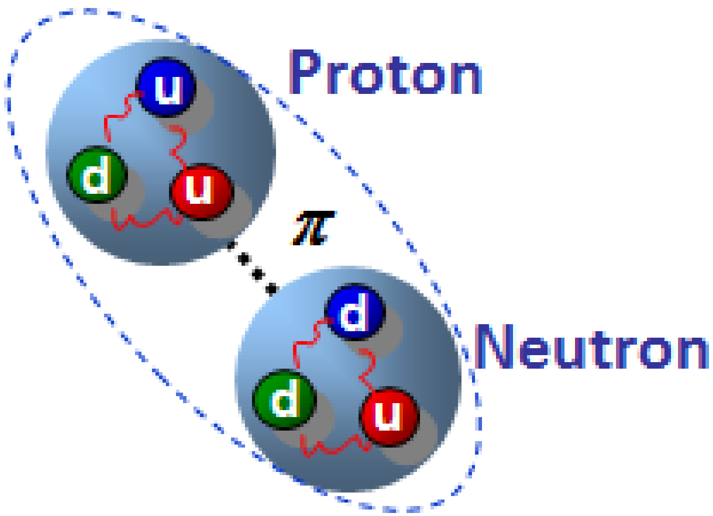
Gammermann et al., 08)

Hadronic molecule – an analogue to Deuteron

Heavy-light quark-antiquark pairs form heavy mesons, and the meson-antimeson pair moves at distances longer than the typical size of the meson. The mesons are interacting through exchange of light quarks and gluons, similar to nuclear force.



D^0–$\overline{D^{*0}}$ "molecule"



Deuteron: p-n molecule

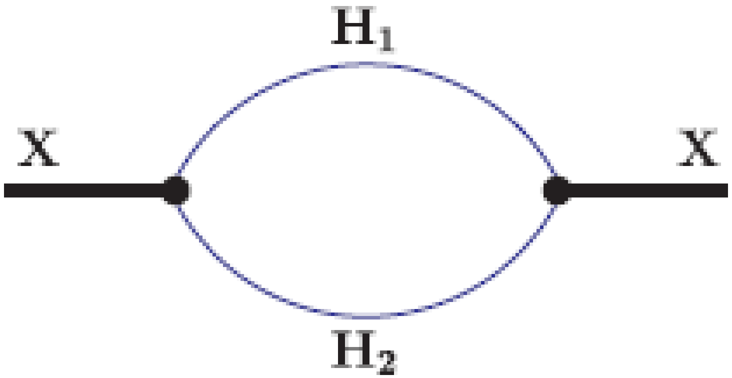
b, Molecule scenario: X(3872)

Bound state description of hadronic molecule on QFT based on the Compositeness condition: $Z_M=0$

(See Weinberg: PR130 (1966),776; Salam, Nuov. Cim. 25 (1962),224…)

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

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



Mass operator

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

Example: New resonances: X(3872) (meson)

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 $m_{thr} = 3871.81 \pm 0.36$

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

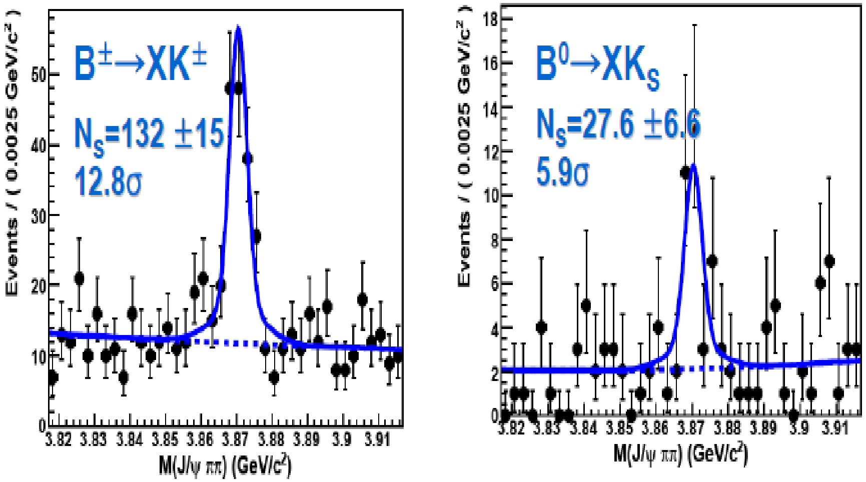
- charmonium interpretation disfavored, $1^{++}(2^3P_1)$ too low in mass compared to

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

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

arXiv:0809.1224 605 fb^{-1}

recent results



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

Decay modes of X(3872)

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 ?

□

Calculation: Molecular scenario

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

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

$(m_{D^0}=1864.85$ 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,
  $Z_{D^0D^{*0}}=0.92\,,\quad Z_{D^\pm D^{*\mp}}=0.033\,,\quad Z_{J_\psi\omega}=0.041\,,\quad Z_{J_\psi\rho}=0.006$
- 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

Effective Lagrangians

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

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

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

Non-local ones

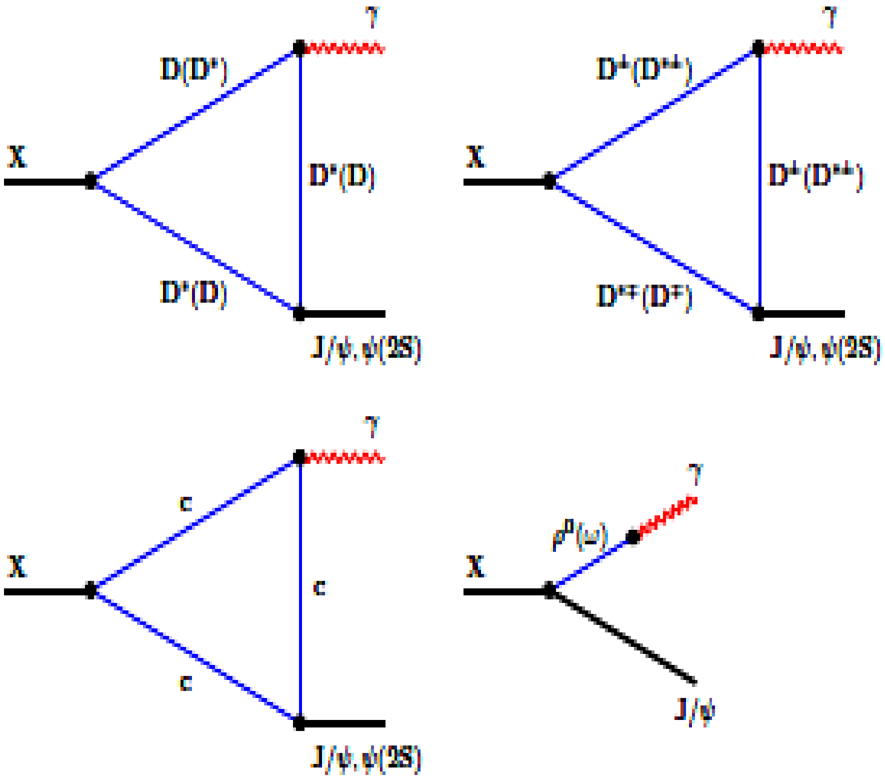
$$J^\mu_{D\bar{D}^*}(x) \to \mathcal{J}^\mu_{D\bar{D}^*}(x) = \frac{1}{\sqrt{2}} \int d^4y \Phi_{DD^*}(y^2)(D(x+y/2) \times \bar{D}^{*\mu}(x-y/2) + \bar{D}(x+y/2)D^{*\mu}(x-y/2)),$$

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

Radiative decays

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

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

PRD79, 094013

Strong decay(two-body, three-body)

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) → J/ψ γ, ψ´γ

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

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

as a constraint on the charmonium content of the $X(3872)$. The branching fraction $B(X(3872) \to \psi(2S)\gamma)$ 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 $D^{*0}\overline{D^0}$ 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].

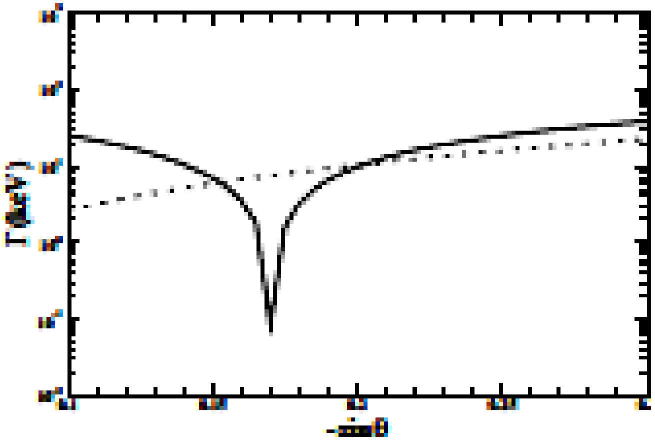
$$R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29,$$

Results

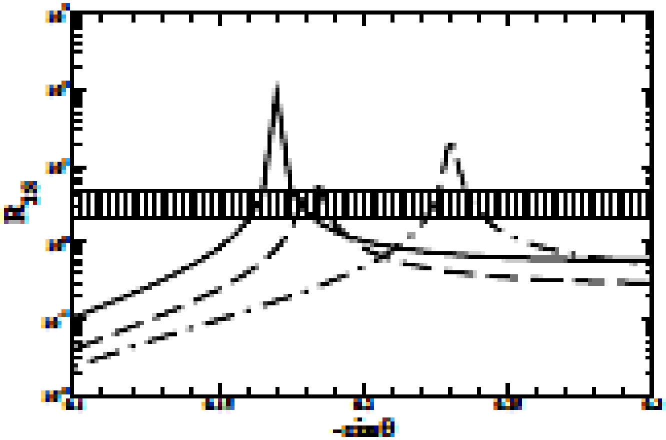
Results for $X(3872) \to \gamma J/\psi$ and $\psi(2s)$

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)

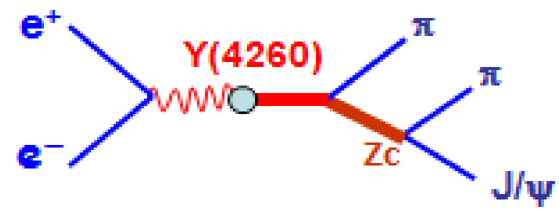
Some resonances

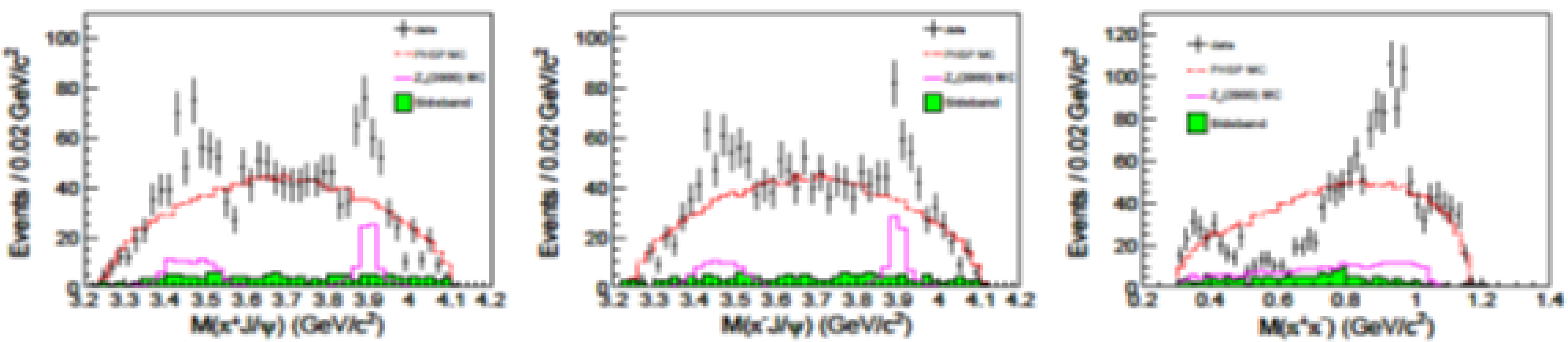
X(3872), neutral

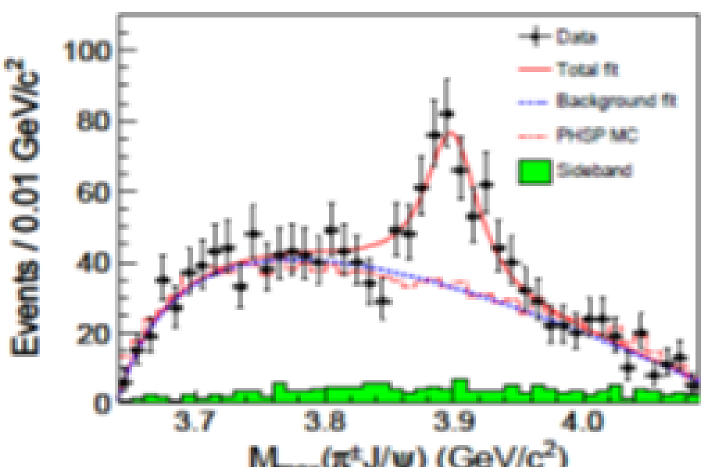
Zc(3900)+ , Y(4260)

Zb(10610), Z ‘b (10650)

Observation of a charged charmoniumlike structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV







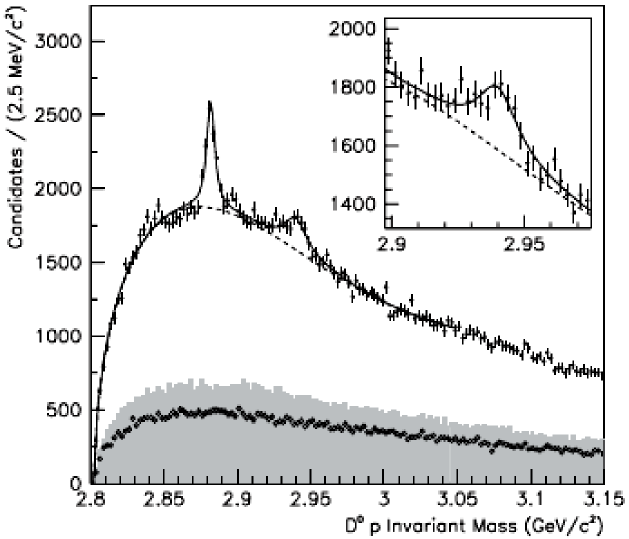
- The mass of the charged charmonium-like structure Zc(3900) is about 3.899 GeV, close to DD* threshold!
- It could be an opportunity for understanding the mysterious Y(4260).

c, 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

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^+ $\quad I(J^P) = 0(\frac{1}{2}^+)$

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

Mass $m = 2286.46 \pm 0.14$ MeV

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

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(2286))

2), Chiral quark model:
D-Wave

3), Molecular Model
near threshold of pD*

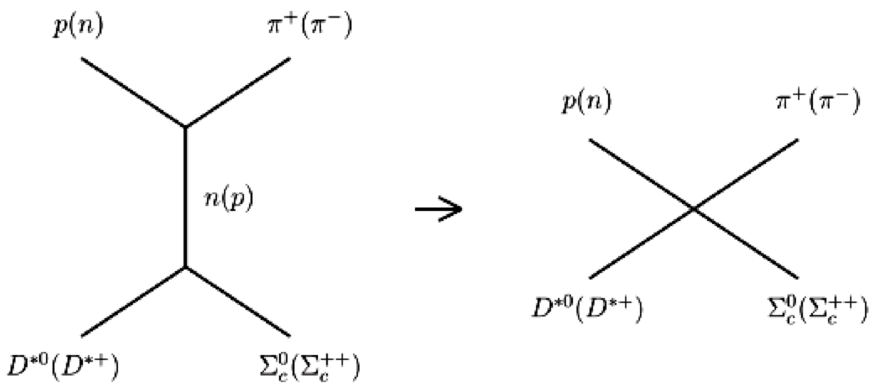
The assignment of this resonance

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

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

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

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



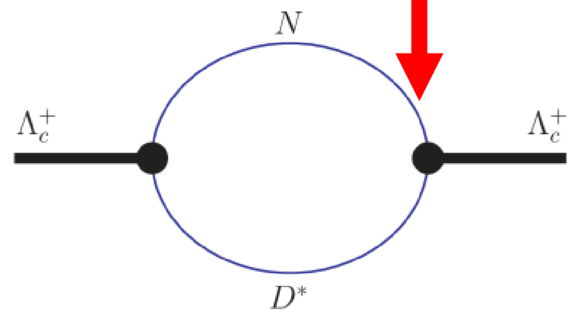


FIG. 1 (color online). Diagram describing the $\Lambda_c(2940)^+$ mass operator.

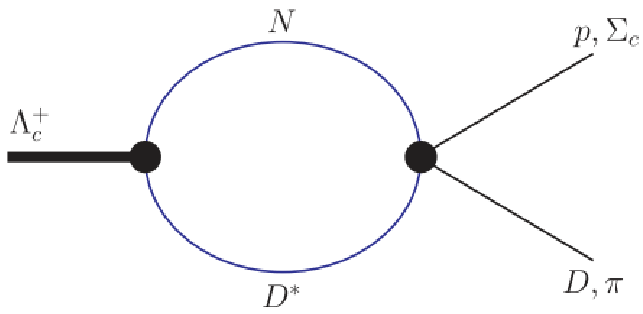


FIG. 2 (color online). Diagrams contributing to the decays $\Lambda_c(2940)^+ \to pD^0, \Sigma_c^{++}\pi^-, \Sigma_c^0\pi^+$.

Effective Lagrangians

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

PRD81, 014006

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 $\Lambda_c(2940)^+$.

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($1^+/2$)

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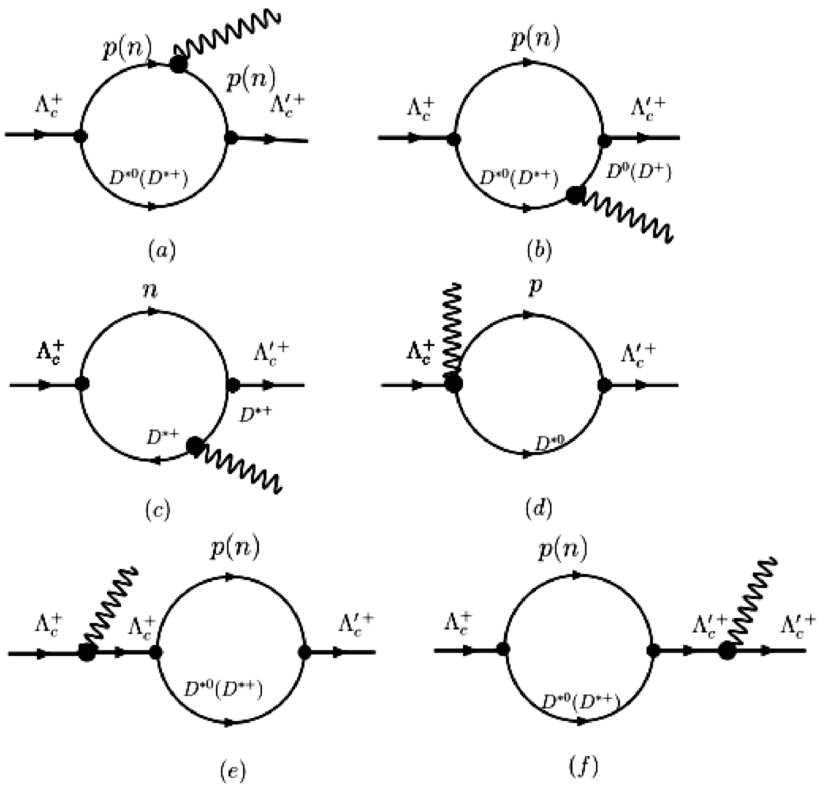
Gauge Invariance



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

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

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

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

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

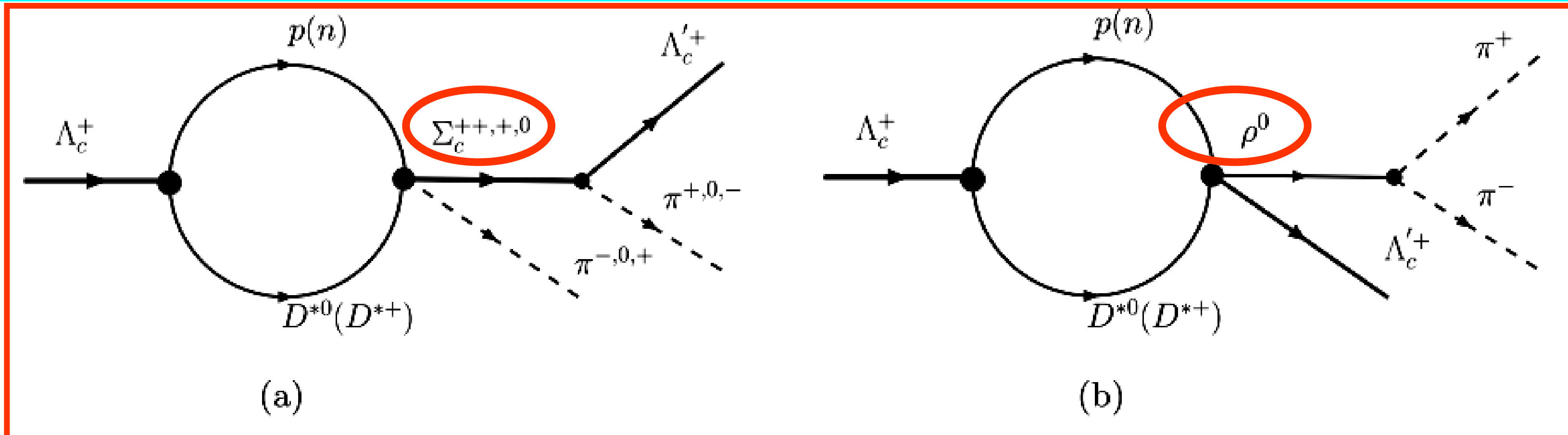
$$\mathcal{M}^\mu(p, p') = \frac{F_{\Lambda_c\Lambda_c'\gamma}}{2m_{\Lambda_c}}\bar{u}_{\Lambda_c'}(p')i\sigma^{\mu\nu}q_\nu u_{\Lambda_c}(p).$$

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

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

Three-body decay



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

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

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

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

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

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

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

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

Hadron physics at J-PARC, Japan

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d, Production @ PANDA

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

Welcome to the PANDA Experiment Website

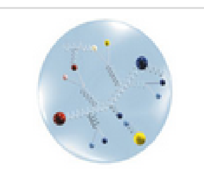
The PANDA Experiment will be one of the key experiments at the Facility for Antiproton and Ion Research (FAIR) which is under construction and currently being built on the area of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany.

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.

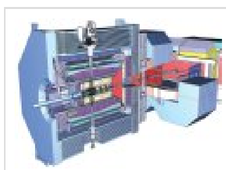
The PANDA Collaboration with more than 450 scientist from 17 countries intends to do basic research on various topics around the weak and strong forces, exotic states of matter and the structure of hadrons.

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



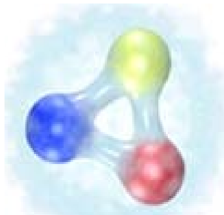
The Detector
Detailled description and technical information about the different detection systems.

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 $\bar{P}$ANDA, 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

$$|\Lambda_c^{'}(2940)>=|pD^{*0}>$$

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1+/2

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

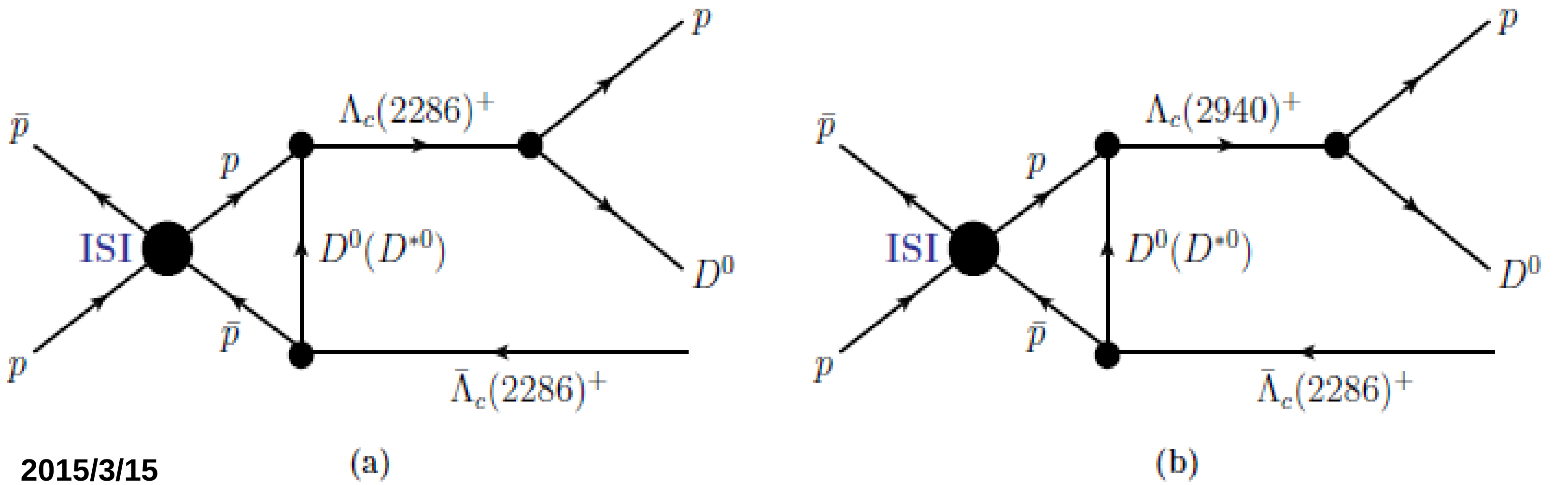
$$\mathcal{L}^{\frac{1}{2}+}_{\Lambda_c' pD^*} = g_{\Lambda_c' pD^*}\bar{\Lambda}_c'\gamma^\mu pD^{*0}_\mu + \text{H.c.}$$

1-/2

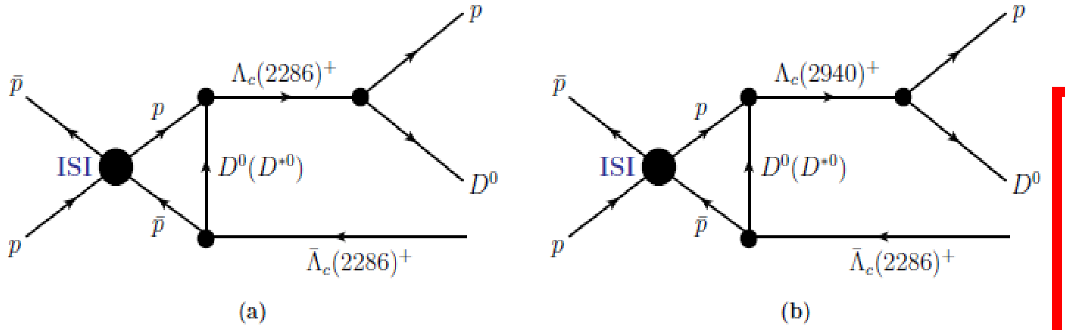
$$\mathcal{L}^{\frac{1}{2}-}_{\Lambda_c' pD} = f_{\Lambda_c' pD}\bar{\Lambda}_c' pD^0 + \text{H.c.},$$

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

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



Initial state interaction



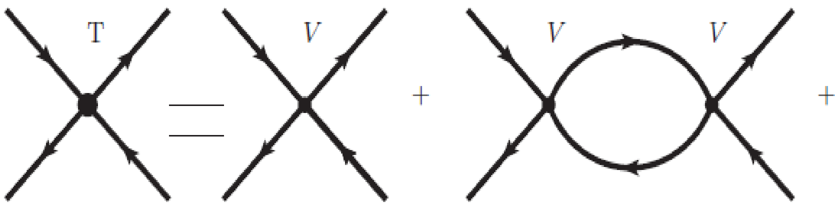


FIG. 2. Lippmann-Schwinger equation for the initial state interaction of the $N\bar{N}$ s

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

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

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 g

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

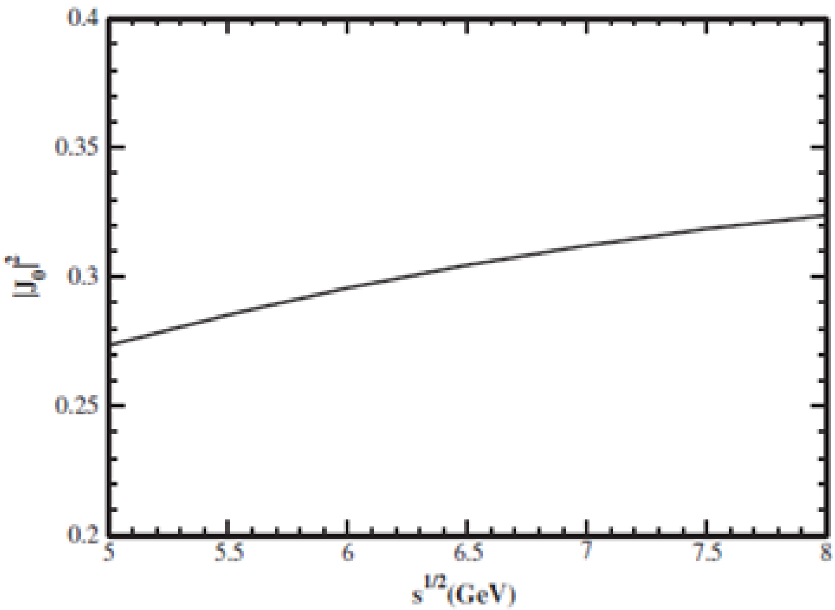
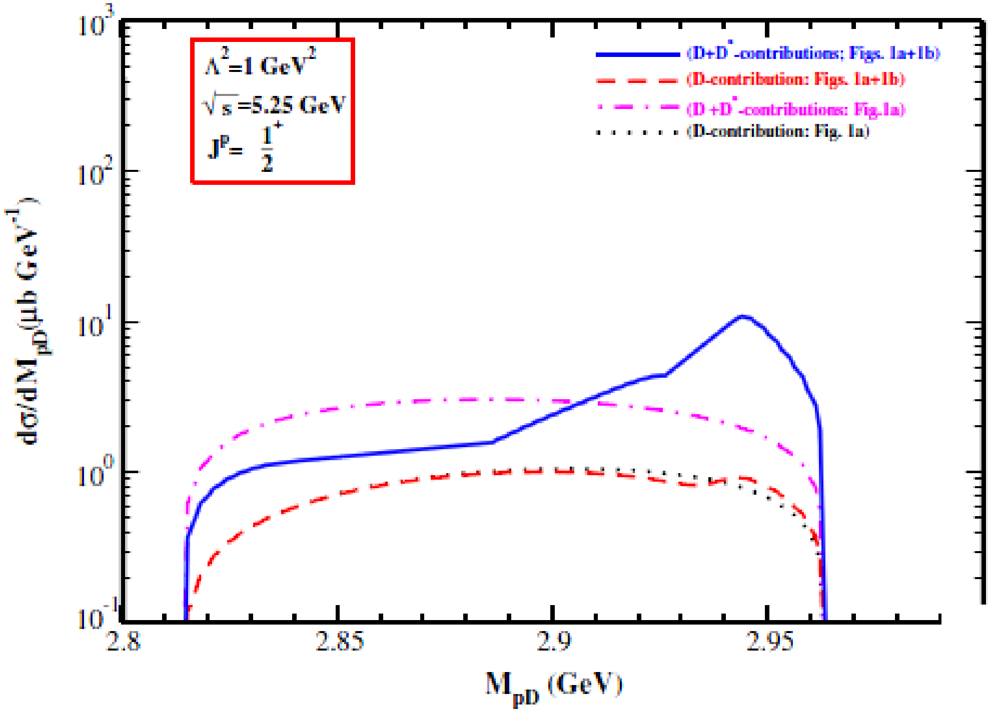
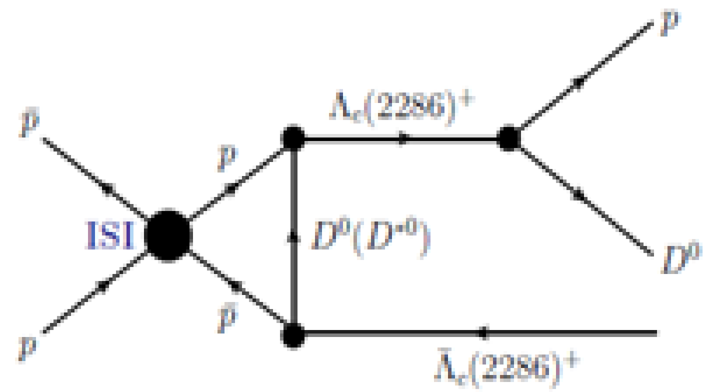


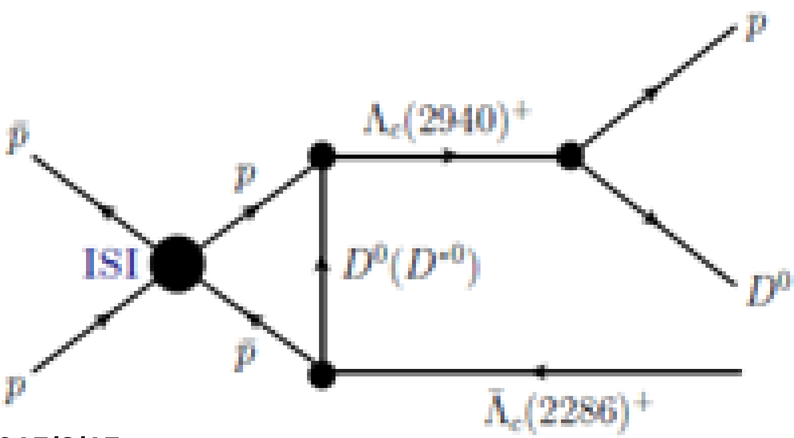
FIG. 3. Initial state interaction factor $|J_0|^2$ in dependence on $s^{1/2}$.



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



(a)



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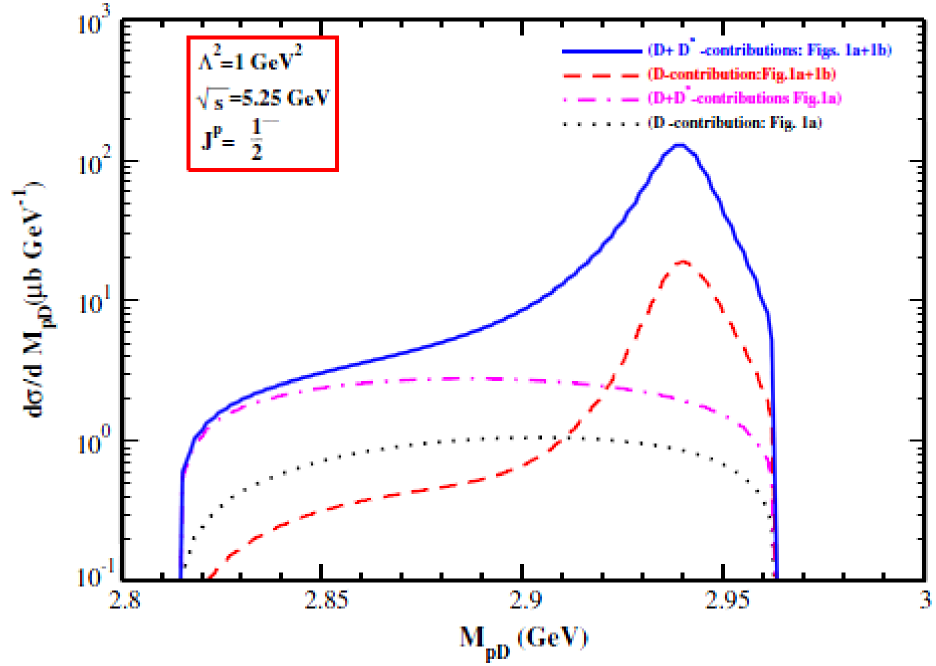
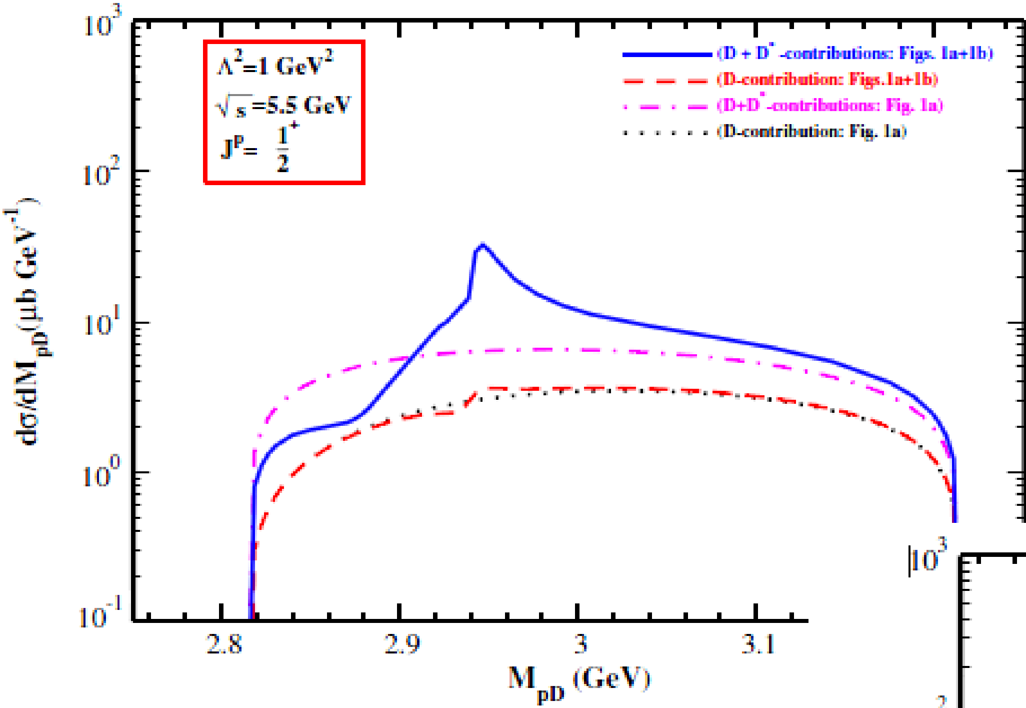
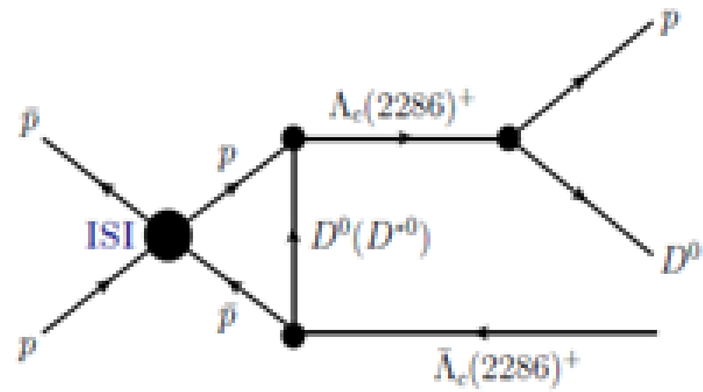
(b)



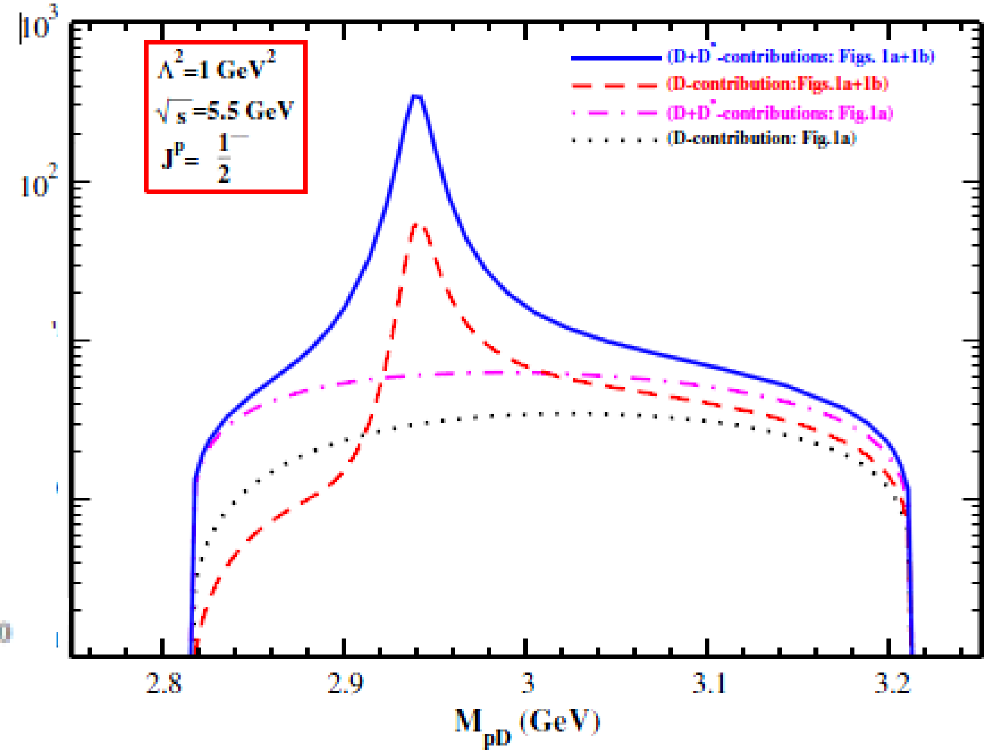
Differential cross section $d\sigma/dM_{pD}$ for
$^{1/2} = 5.25$ GeV for $J^P = \frac{1}{2}^-$ of the $\Lambda_c(2940)$.

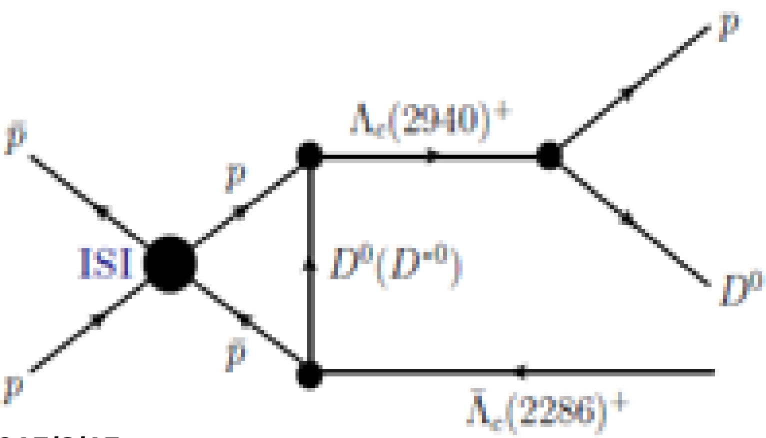


Differential cross section
$s^{1/2} = 5.5$ GeV for $J^P = \frac{1}{2}^+$ of the $\Lambda_c(2940)$.



(a)





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(b)

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

e, Summary

- 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), Production at PANDA

5), $\Sigma_c(2880)$

- 6), J-PARC $5 \sim 15 GeV, \sqrt{s} = 3 \sim 5.5 GeV$

- $$\pi^- p \to \Lambda_c^+(2940) + D^{*-} \to D^{*-} + D^0 p$$

Thanks!