兰州大学
LANZHOU UNIVERSITY

$X(3872)$和$\Lambda_C(2940)$的内部结构及其辐射衰变性质研究

PHYSICAL REVIEW D 109, 094002 (2024)

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蘭州大學 LANZHOU UNIVERSITY

目录

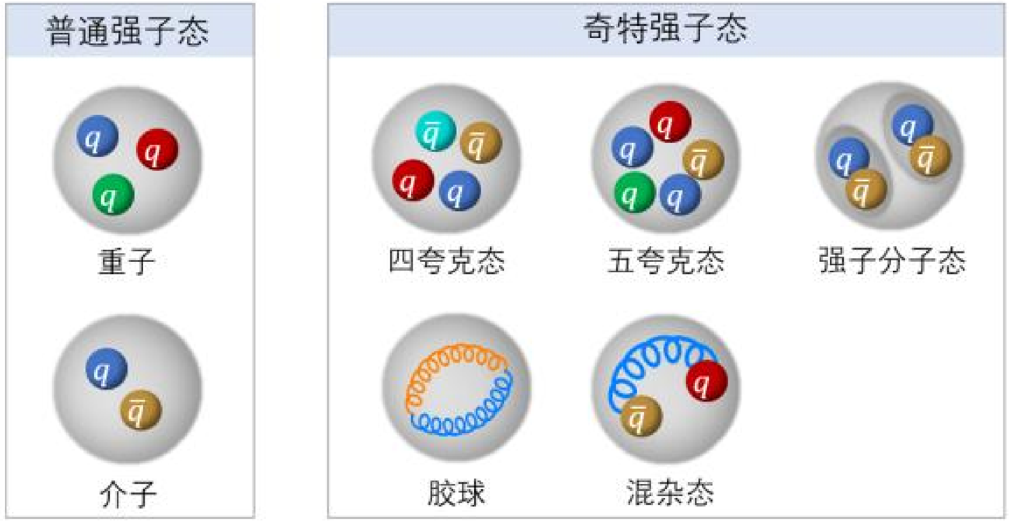
自强不息 獨樹一幟

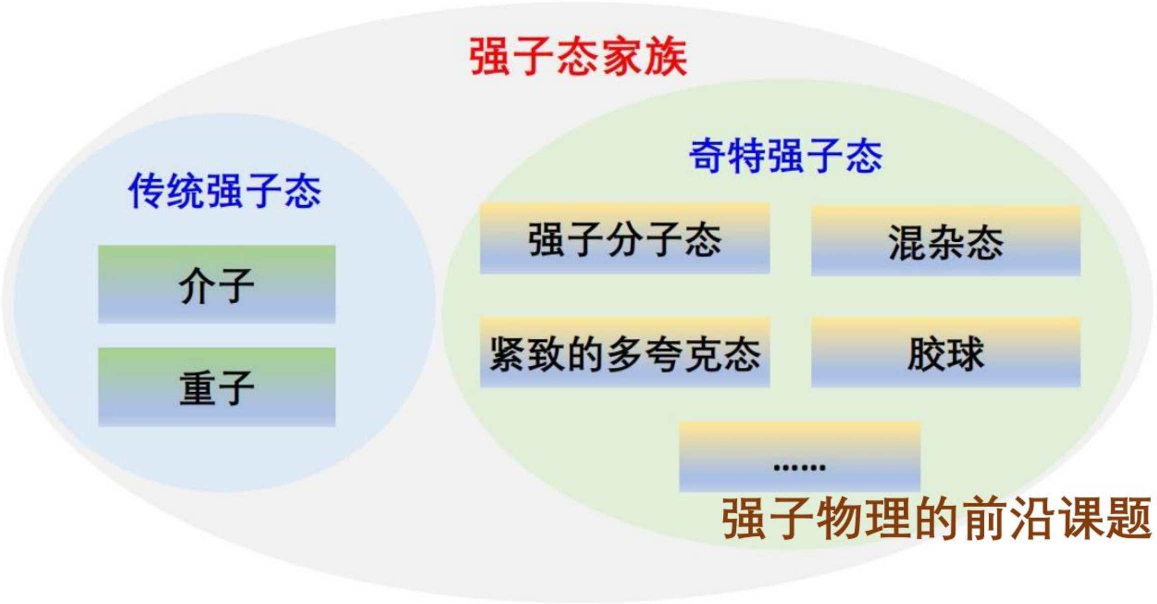
1. 研究背景

自强不息　独树一帜

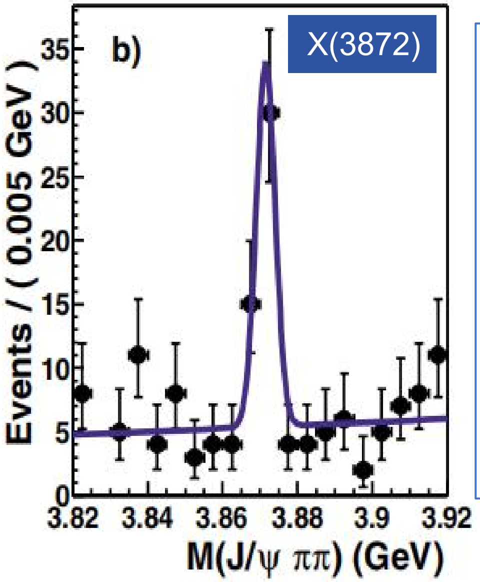
奇特强子态的发现

- 1964年，盖尔曼和茨威格提出SU(3)对称的夸克模型；
- 20世纪70年代-21世纪初，实验上发现了与夸克模型预言一致的介子和重子；
- 2003年，实验上逐步发现了超出势模型所预言的强子。



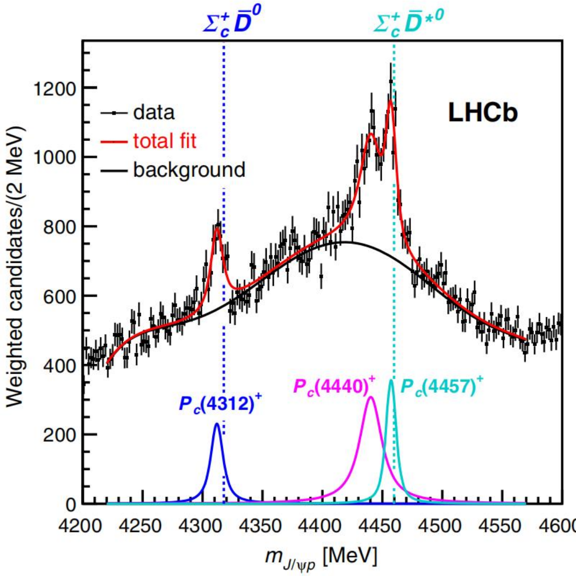


奇特强子态的发现



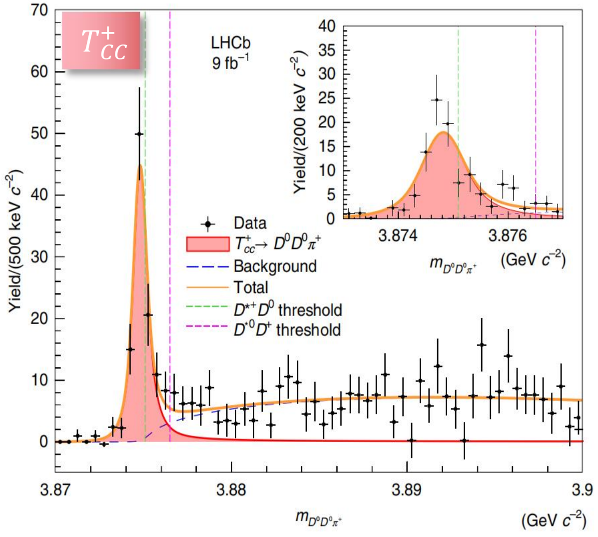
首个发现的类粲偶素

PRL 91 262001 (2003)



发现P_c的子结构

PRL 122 222001 (2019)



首次发现双粲四夸克态

Nature Phys. 18, no.7, 751 (2022)

Short range structure in the $X(3872)$

Is X(3872) really a molecular state?

Yan-Rui Liu, Xiang Liu, Wei-Zhen Deng & Shi-Lin Zhu

Dynamics study of Z+(4430) and X(3872) in molecular picture

Is $X(3872)$ a molecule?

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(Received 2 July 2008; published 8 August 2008)

We show that the literature on pion exchange between charm and bottom mesons is inconsistent. We derive the formalism explicitly, expose differences between papers in the literature, and clarify the implications. We show that the $X(3872)$ can be a bound state but that results are very sensitive to a poorly constrained parameter. We confirm that bound states in the $B\bar{B}$ sector are possible. The circumstances

Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon*

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LIU Xiang(刘翔)[2,4;2)] ZHU Shi-Lin(朱世琳)[1;3)]

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Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not.

VIEWS & COMMENTS

Perfect DD^* Molecular Prediction Matching the T_{cc} Observation at LHCb

Ning Li[1], Zhi-Feng Sun[2,3,4], Xiang Liu[2,3,4] and Shi-Lin Zhu[5]

Chinese Physics Letters, Volume 38, Number 9

Citation Ning Li *et al* 2021 *Chinese Phys. Lett.* **38** 092001

DOI 10.1088/0256-307X/38/9/092001

在构建2.0版本强子家族中起着重要的作用！

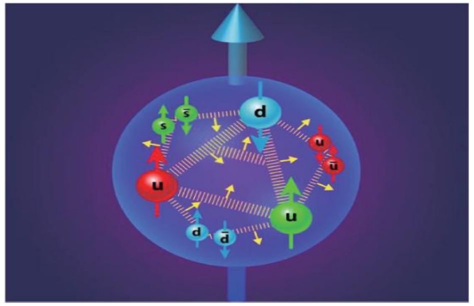
强子的电磁性质

- 反常磁矩

1933年，Otto Stern测量了质子磁矩， 实验结果远小于点电荷理论预期，证明质子存在内部结构。

- 电磁形状因子

高能轻子-核子散射 → 核子内部夸克-胶子分布函数。



- 辐射衰变

辐射衰变为我们了解强子内部结构提供电磁探针。

$D_{s0}^{*}(2317) \to \gamma D_s^{*}$

$X(3872) \to \gamma J/\psi$

$D_{s1}^{'}(2460) \to \gamma D_s$

$X(3872) \to \gamma \psi(2S)$

$D_{s1}^{'}(2460) \to \gamma D_s^{*}$

$\Lambda_c(2940) \to \gamma \Lambda_c(2286)$

……

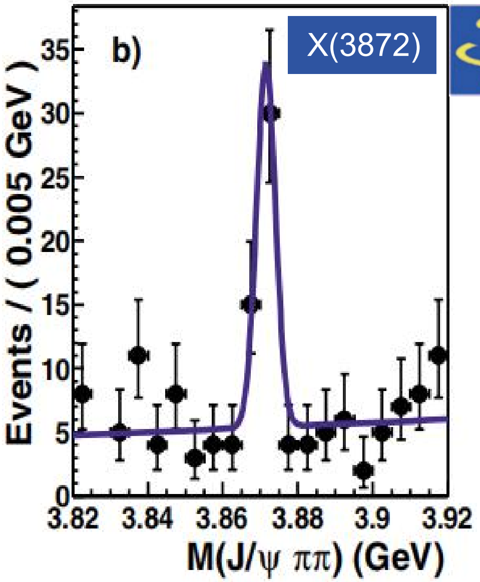
- Amand Faessler *et.al.*, PRD 76 (2007) 014005.
- Martin Cleven *et.al.*, Eur.Phys.J.A 50 (2014) 149 .
- Hai-long Fu *et.al.*, Eur.Phys.J.A 58 (2022) 70.
- Eric S. Swanson, Phys.Lett.B 598 (2004).
- Feng-Kun Guo *et.al.*, Phys.Lett.B 740 (2015).
- Yu-Bing Dong *et.al.*, Phys.Rev.D 82 (2010) 034035.
- ……

2. $X(3872)$的内部结构及辐射衰变

Based on Ping Chen, Zhan-Wei Liu, Zi-Le Zhang, Si-Qiang Luo, Fu-Lai Wang, Jun-Zhang Wang and Xiang Liu, Role of electromagnetic interactions in the $X(3872)$ and its analogs, Phys. Rev. D 109, 094002 (2024).

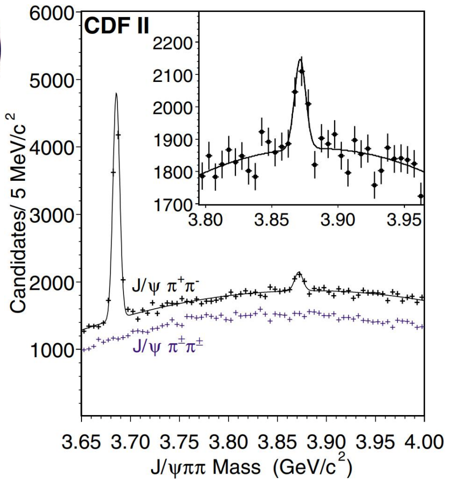
$X(3872)$的发现

- Belle PRL 91 262001 (2003)

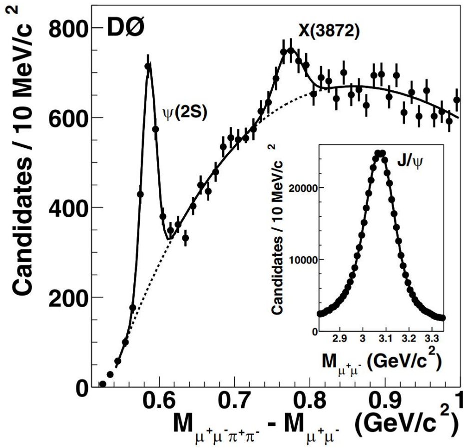


$$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$$

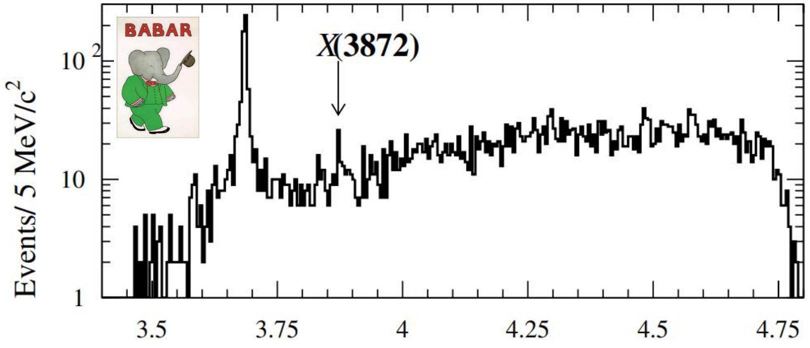
- CDF PRL 93 072001 (2004)



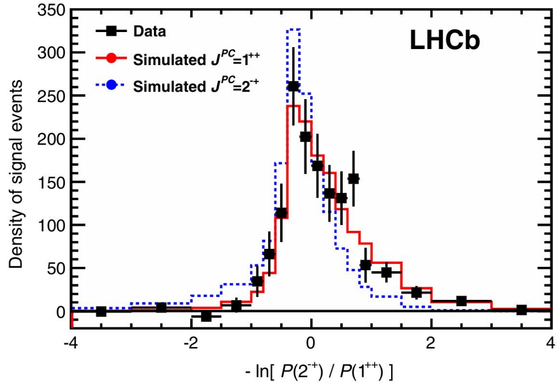
- D0 PRL 93 162002 (2004)



- Babar PRD 71 071103 (2005)



- LHCb PRL 110, 222001 (2013)



$X(3872)$的理论解释

$X(3872)$的基本性质		
量子数	$I^G(J^{PC}) = 0^+(1^{++})$	$B^+ \to X(3872)K^+, X(3872) \to \pi^+\pi^- J/\psi$
质量	$M_{(3872)} = 3871.65 \pm 0.06$ MeV	$M_{D^0} + M_{\bar{D}^{*0}} = 3871.69 \pm 0.10$ MeV
宽度	$\Gamma_{(3872)} = (1.19 \pm 0.21)$ MeV	LHCb: $\Gamma_{(3872)} = (1.39 \pm 0.24 \pm 0.10)$ MeV

PRL 107 091803 （2011）
PRL110 222001 （2013）
PRL 102 092005 （2020）

夸克模型下$c\bar{c}$的质量

Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
1S	$J/\psi(1^3S_1)$	3096.87 ± 0.04	3097	3090	3098
	$\eta_c(1^1S_0)$	2979.2 ± 1.3	2979	2982	2975
2S	$\psi'(2^3S_1)$	3685.96 ± 0.09	3686	3672	3676
	$\eta_c'(2^1S_0)$	3637.7 ± 4.4	3638	3630	3623
3S	$\psi(3^3S_1)$	4040 ± 10	4040	4072	4100
	$\eta_c(3^1S_0)$			4043	4064
4S	$\psi(4^3S_1)$	4415 ± 6	4415	4406	4450
	$\eta_c(4^1S_0)$			4384	4425
1P	$\chi_2(1^3P_2)$	3556.18 ± 0.13	3556	3556	3550
	$\chi_1(1^3P_1)$	3510.51 ± 0.12	3511	3505	3510
	$\chi_0(1^3P_0)$	3415.3 ± 0.4	3415	3424	3445
	$h_c(1^1P_1)$	see text		3516	3517
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$			3852	3916
	$h_c(2^1P_1)$			3934	3956
3P	$\chi_2(3^3P_2)$			4317	4337
	$\chi_1(3^3P_1)$			4271	4317
	$\chi_0(3^3P_0)$			4202	4292
	$h_c(3^1P_1)$			4279	4318

PRD 72 054026 (2005)

理论解释

- $D^0\bar{D}^{*0}$组成的分子态
- 含$D\bar{D}^* + c\bar{c}$的混合态
- 紧致的四夸克态
- 混杂态

→

修正效应

- $S - D$波混合效应
- 同位旋破缺效应
- 耦合道效应
- 反冲修正效应

$X(3872)$的内部结构

- 系统$D\bar{D}^*$和$D_s\bar{D}_s^*$可能形成的束缚态，$D\bar{D}^*$：$J^{PC}=1^{+\pm}$，$D_s\bar{D}_s^*$：$J^{PC}=1^{+\pm}$

电磁相互作用 → 中性:$D^0\bar{D}^{*0}/D^{*0}\bar{D}^0$

带电:D^+D^{*-}/D^-D^{*+}

J^{PC}	Cases	Channels 1	2	3	4	5	6	7	8
1^{++}	I	$[D\bar{D}^*]\|^3S_1\rangle$	$[D\bar{D}^*]\|^3D_1\rangle$						
	II	$[D^0\bar{D}^{*0}]\|^3S_1\rangle$	$[D^0\bar{D}^{*0}]\|^3D_1\rangle$	$[D^+D^{*-}]\|^3S_1\rangle$	$[D^+D^{*-}]\|^3D_1\rangle$				
	III	$[D^0\bar{D}^{*0}]\|^3S_1\rangle$	$[D^0\bar{D}^{*0}]\|^3D_1\rangle$	$[D^+D^{*-}]\|^3S_1\rangle^C$	$[D^+D^{*-}]\|^3D_1\rangle^C$				
1^{+-}	I	$[D\bar{D}^*]\|^3S_1\rangle$	$[D\bar{D}^*]\|^3D_1\rangle$	$[D^*\bar{D}^*]\|^3S_1\rangle$	$[D^*\bar{D}^*]\|^3D_1\rangle$				
	II	$[D^0\bar{D}^{*0}]\|^3S_1\rangle$	$[D^0\bar{D}^{*0}]\|^3D_1\rangle$	$[D^+D^{*-}]\|^3S_1\rangle$	$[D^+D^{*-}]\|^3D_1\rangle$	$[D^{*0}\bar{D}^{*0}]\|^3S_1\rangle$	$[D^{*0}\bar{D}^{*0}]\|^3D_1\rangle$	$[D^{*+}\bar{D}^{*-}]\|^3S_1\rangle$	$[D^{*+}\bar{D}^{*-}]\|^3D_1\rangle$
	III	$[D^0\bar{D}^{*0}]\|^3S_1\rangle$	$[D^0\bar{D}^{*0}]\|^3D_1\rangle$	$[D^+D^{*-}]\|^3S_1\rangle^C$	$[D^+D^{*-}]\|^3D_1\rangle^C$	$[D^{*0}\bar{D}^{*0}]\|^3S_1\rangle$	$[D^{*0}\bar{D}^{*0}]\|^3D_1\rangle$	$[D^{*+}\bar{D}^{*-}]\|^3S_1\rangle^C$	$[D^{*+}\bar{D}^{*-}]\|^3D_1\rangle^C$

单玻色子交换模型

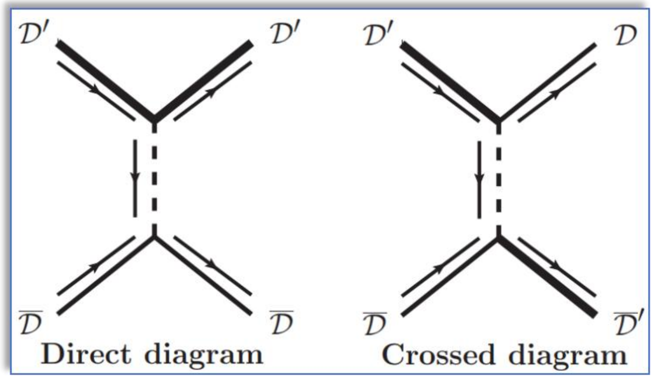
有效拉氏量方法得到散射振幅:

$$\mathcal{M}(h_1 h_2 \to h_3 h_4)$$

$$\mathcal{V}_E(\boldsymbol{q}) = -\frac{\mathcal{M}(h_1 h_2 \to h_3 h_4)}{\sqrt{\prod_i 2M_i \prod_f 2M_f}}$$

$$\mathcal{V}_E(\boldsymbol{r}) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \mathcal{V}_E(\boldsymbol{q}) \mathcal{F}^2(q^2, m_E^2)$$

对于$X(3872)$, $D\bar{D}^*$系统的相互作用有效势为:



$$\mathcal{V}_{\text{total}}(r) = \mathcal{V}_D(r) + c\mathcal{V}_C(r)$$

- 对于$D\bar{D}^* \to D\bar{D}^*$:

$$\begin{aligned} V_\sigma(r) &= -C_\sigma(i,j) g_s^2 \mathcal{A}_1 Y(\Lambda_i, m_{\sigma_i}, r), \\ V_{\rho/\omega}(r) &= -C_{\rho/\omega}(i,j) \frac{\beta^2 g_v^2}{2} \mathcal{A}_1 Y(\Lambda_i, m_{\rho_i/\omega_i}, r). \end{aligned}$$

- 对于$D\bar{D}^* \to D^*\bar{D}$:

$$\begin{aligned} V_\pi(r) &= -C_\pi(i,j) \frac{1}{3} \frac{g^2}{f_\pi^2} [\mathcal{A}_2 \nabla^2 + \mathcal{A}_3 \mathcal{T}] U(\Lambda_i, m_{\pi_i}, r), \\ V_\eta(r) &= -C_\eta(i,j) \frac{1}{3} \frac{g^2}{f_\pi^2} [\mathcal{A}_2 \nabla^2 + \mathcal{A}_3 \mathcal{T}] Y(\Lambda_i, m_{\eta_i}, r), \\ V_{\rho/\omega}(r) &= C_{\rho/\omega}(i,j) \frac{4}{3} \lambda^2 g_v^2 \mathcal{A}_2 \nabla^2 Y(\Lambda_i, m_{\rho_i/\omega_i}, r) \\ &\quad -C_{\rho/\omega}(i,j) \frac{2}{3} \lambda^2 g_v^2 \mathcal{A}_3 \mathcal{T}] Y(\Lambda_i, m_{\rho i/\omega i}, r). \end{aligned}$$

考虑S-D波混合，同位旋破缺，(耦合道)和库仑修正效应$D\bar{D}^*$系统的势能和动能项可以表示为:

$$\mathcal{V} = \begin{pmatrix} \mathcal{V}^{D^0\bar{D}^{*0}|^3S_1\rangle \to D^0\bar{D}^{*0}|^3S_1\rangle} & \mathcal{V}^{D^0\bar{D}^{*0}|^3S_1\rangle \to D^0\bar{D}^{*0}|^3D_1\rangle} & \mathcal{V}^{D^0\bar{D}^{*0}|^3S_1\rangle \to D^+D^{*-}|^3S_1\rangle} & \mathcal{V}^{D^0\bar{D}^{*0}|^3S_1\rangle \to D^+D^{*-}|^3D_1\rangle} \\ \mathcal{V}^{D^0\bar{D}^{*0}|^3D_1\rangle \to D^0\bar{D}^{*0}|^3S_1\rangle} & \mathcal{V}^{D^0\bar{D}^{*0}|^3D_1\rangle \to D^0\bar{D}^{*0}|^3D_1\rangle} & \mathcal{V}^{D^0\bar{D}^{*0}|^3D_1\rangle \to D^+D^{*-}|^3S_1\rangle} & \mathcal{V}^{D^0\bar{D}^{*0}|^3D_1\rangle \to D^+D^{*-}|^3D_1\rangle} \\ \mathcal{V}^{D^+D^{*-}|^3S_1\rangle \to D^0\bar{D}^{*0}|^3S_1\rangle} & \mathcal{V}^{D^+D^{*-}|^3S_1\rangle \to D^0\bar{D}^{*0}|^3D_1\rangle} & \mathcal{V}^{D^+D^{*-}|^3S_1\rangle \to D^+D^{*-}|^3S_1\rangle} & \mathcal{V}^{D^+D^{*-}|^3S_1\rangle \to D^+D^{*-}|^3D_1\rangle} \\ \mathcal{V}^{D^+D^{*-}|^3D_1\rangle \to D^0\bar{D}^{*0}|^3S_1\rangle} & \mathcal{V}^{D^+D^{*-}|^3D_1\rangle \to D^0\bar{D}^{*0}|^3D_1\rangle} & \mathcal{V}^{D^+D^{*-}|^3D_1\rangle \to D^+D^{*-}|^3S_1\rangle} & \mathcal{V}^{D^+D^{*-}|^3D_1\rangle \to D^+D^{*-}|^3D_1\rangle} \end{pmatrix}$$

$$\begin{aligned} \mathcal{K} &= \text{diag}\left(-\frac{\nabla^2}{2\mu_1}, -\frac{\nabla^2}{2\mu_1}, -\frac{\nabla^2}{2\mu_2} + \Delta m, -\frac{\nabla^2}{2\mu_2} + \Delta m\right) \\ \mathcal{K}_L &= \text{diag}\left(0, \frac{3}{\mu_1 r^2}, 0, \frac{3}{\mu_2 r^2}\right) \end{aligned}$$

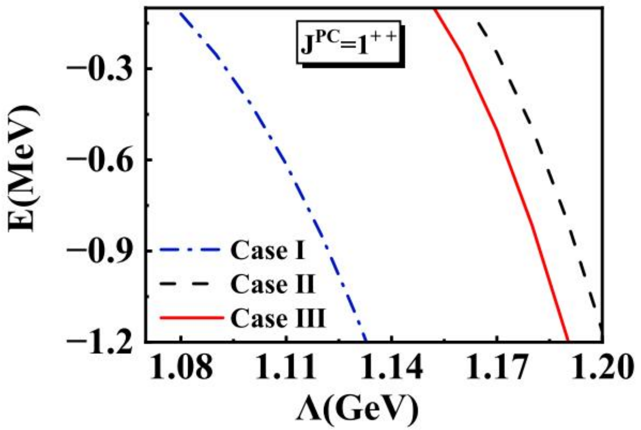
耦合道薛定谔方程: $(\mathcal{K} + \mathcal{K}_L + \mathcal{V})\,\hat{\phi}(r) = E\hat{\phi}(r)$

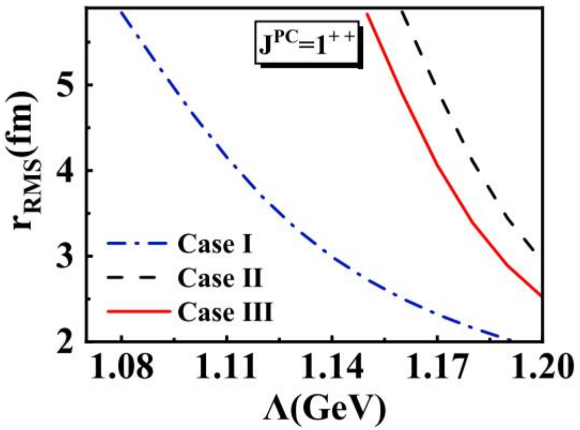
$$\hat{\phi}(r) = (\phi_{[D^0\bar{D}^{*0}]|^3S_1\rangle}, \phi_{[D^0\bar{D}^{*0}]|^3D_1\rangle}, \phi_{[D^+D^{*-}]|^3S_1\rangle}, \phi_{[D^+D^{*-}]|^3D_1\rangle})^T$$

$X(3872)$作为可能的$D\bar{D}^*(1^{++})$分子态的束缚解

$$\mathcal{F}(q^2, m_E^2) = (\Lambda^2 - m_E^2)/(\Lambda^2 - q^2)$$

Λ (GeV)	Case I				Case II						Case III					
	E (MeV)	r_{RMS} (fm)	P_1	P_2	E (MeV)	r_{RMS} (fm)	P_1	P_2	P_3	P_4	E (MeV)	r_{RMS} (fm)	P_1	P_2	P_3	P_4
1.08	−0.12	5.84	99.16	0.84	✗						✗					
1.16	−2.13	2.51	98.24	1.76	✗						−0.25	4.90	86.82	0.49	12.19	0.50
1.17	−2.54	2.32	98.14	1.86	−0.25	4.94	88.02	0.48	11.01	0.49	−0.50	4.06	83.17	0.61	15.61	0.61
1.18	−2.98	2.16	98.04	1.96	−0.49	4.12	84.67	0.60	14.13	0.60	−0.82	3.39	79.68	0.71	18.89	0.72
1.19	−3.46	2.03	97.95	2.05	−0.80	3.44	81.40	0.70	17.19	0.71	−1.19	2.89	76.51	0.81	21.86	0.81





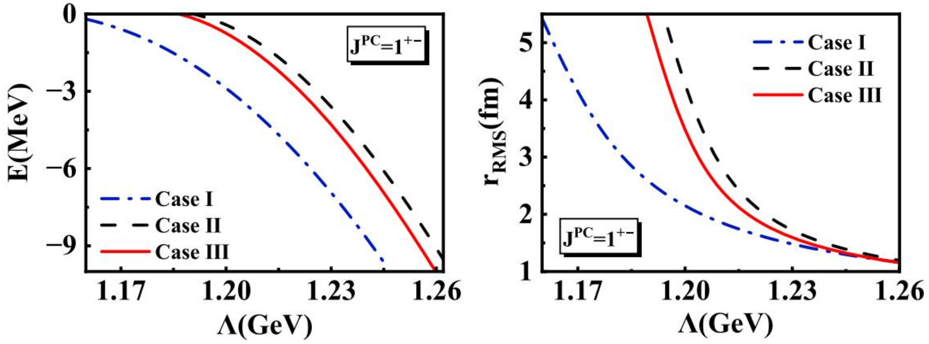
$E(\text{CaseI}) > E(\text{CaseIII}) > E(\text{CaseII})$

$r_{EMS}(\text{CaseII}) > r_{EMS}(\text{CaseIII}) > r_{EMS}(\text{CaseI})$

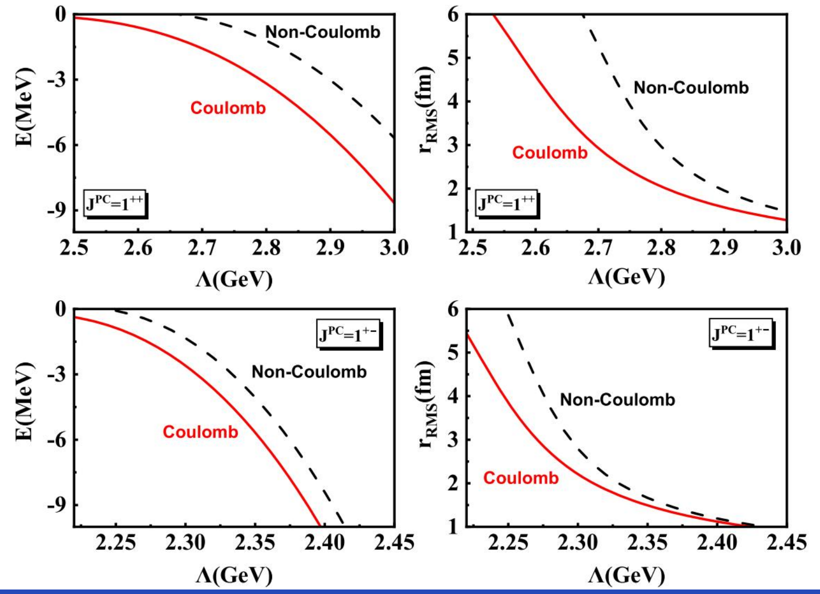
同位旋破缺削弱了组分粒子之间的相互作用，
而库仑相互作用增强两带电粒子间的吸引，
库仑相互作用的影响小于质量差的影响。

$X(3872)$伙伴态的束缚能

$D\bar{D}^*(1^{+-})$的束缚解



$X(3872)$伙伴态$D_s\bar{D}_s^*$的束缚解



- $X(3872)$的C 宇称伙伴态比$X(3872)$束缚浅，由于$D\bar{D}^*(1^{+-})$与$D^*\bar{D}^*$的耦合，带电道的占比增加。

$$E(\text{CaseI}) > E(\text{CaseIII}) > E(\text{CaseII})$$

- $D_s^{(*)}$介子是同位旋单态，只有带电组分，相比于$D\bar{D}^*$系统，库仑相互作用在$D_s\bar{D}_s^*$系统更明显。

- 由带电粒子组成的系统中，库仑修正将更明显

$[D_s^+D_s^-]$ ➡ $X(3960)$　　$[D_s^+D_{s0}^-]$ ➡ X(4274)

$[D_s^{*+}D_s^{*-}]$ ➡ $X(4140)$　　$[D_s^{*+}D_{s0}^{*-}]$ ➡ $X(4350)$

$X(3872)$的辐射衰变

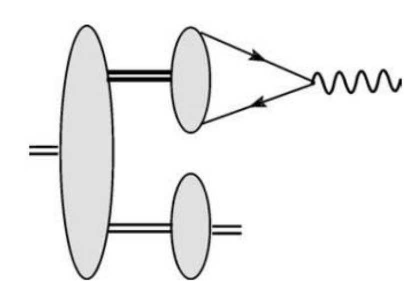


Fig. 1. Vector meson dominance diagram.

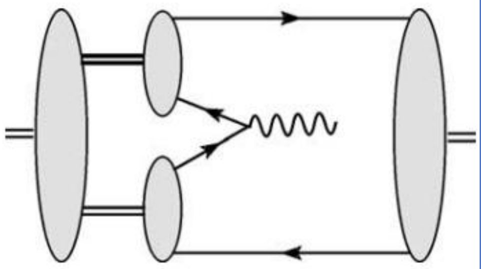


Fig. 2. Annihilation diagram.

Physics Letters B 598 (2004) 197–202

$D\bar{D}^* + \rho J/\psi + \omega J/\psi$ ➡ $R_{\gamma\psi} = 4 \times 10^{-3}$

What can radiative decays of the $X(3872)$ teach us about its nature?

CrossMark

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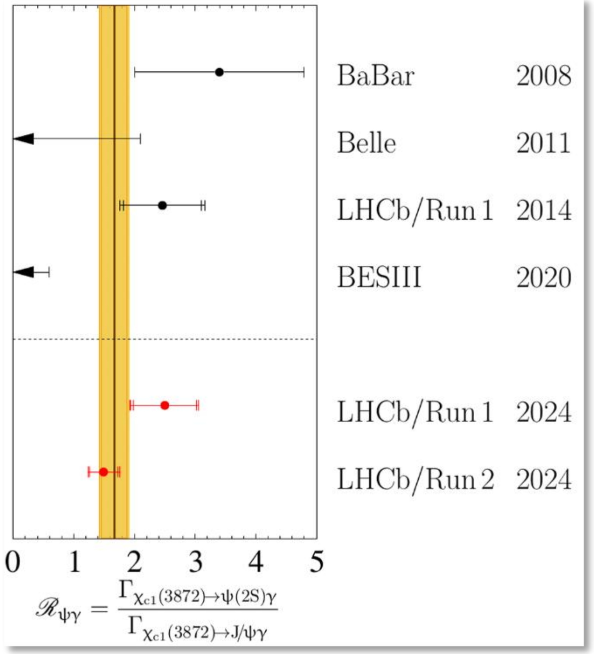
ABSTRACT

Starting from the hypothesis that the $X(3872)$ is a $D\bar{D}^*$ molecule, we discuss the radiative decays of the $X(3872)$ into $\gamma J/\psi$ and $\gamma\psi'$ from an effective field theory point of view. We show that radiative decays are very weakly sensitive to the long-range structure of the $X(3872)$. In particular, contrary to earlier claims, we argue that the experimentally determined ratio of the mentioned branching fractions is not in conflict with a wave function of the $X(3872)$ that is dominated by the $D\bar{D}^*$ hadronic molecular component.

实验上测得的$X(3872)$两种辐射衰变的分支比的比值：

$3.4 \pm 1.4\ \ (3.5\sigma)$	BaBar
$< 2.1\ \ (90\%\ \mathrm{C.L.})$	Belle
$2.46 \pm 0.64\ \pm 0.29\ \ (3.5\sigma)$	LHCb
$< 0.59\ \ (90\%\ \mathrm{C.L.})$	BESIII
$1.67 \pm 0.21 \pm 0.12 \pm 0.04$	LHCb



$X(3872)$及伙伴态的辐射衰变

- 求解耦合道薛定谔方程，得到初态波函数，计算束缚态的辐射衰变。

$X(3872) \to \gamma J/\psi$

$X(3872) \to \gamma \psi(2S)$

➡

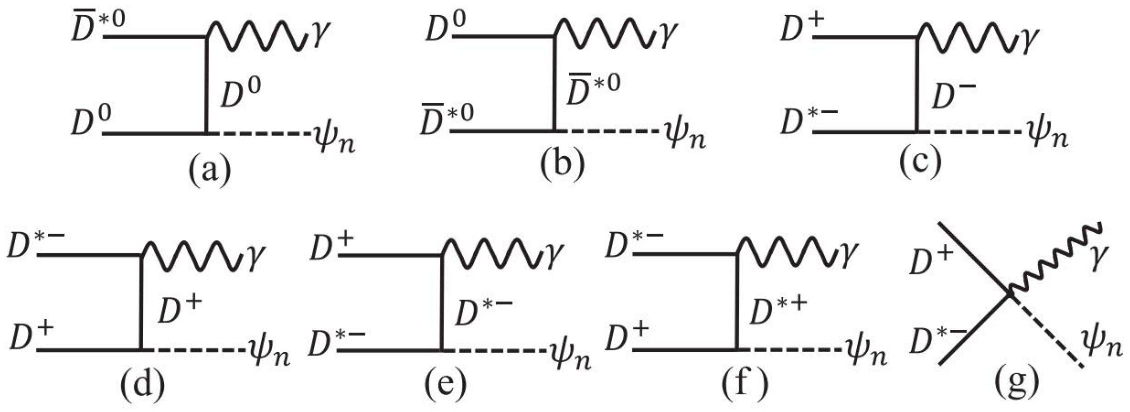
$$R_{\gamma\psi} = \frac{\mathcal{B}(X \to \gamma\psi(2S))}{\mathcal{B}(X \to \gamma J/\psi)}$$

$1^{+-}\ D_{(s)}\bar{D}^*_{(s)} \to \gamma\eta_c(1S)$

$1^{+-}\ D_{(s)}\bar{D}^*_{(s)} \to \gamma\eta_c(2S)$

➡ $R_{\gamma\eta}$

- 有效拉氏量方法研究$X(3872)$的辐射衰变过程：



- 空间波函数：

$$\hat{\phi}^{JM}_{[AB]}(\mathbf{p}) = \left\{\phi_{[AB]|^3L_J\rangle}(|\mathbf{p}|)\ C^{S,m_S}_{1m_1,1m_2}\, C^{J,M}_{Sm_S,Lm_L}\ Y_{L,m_L}(\theta,\phi)\right.$$

- 衰变振幅：

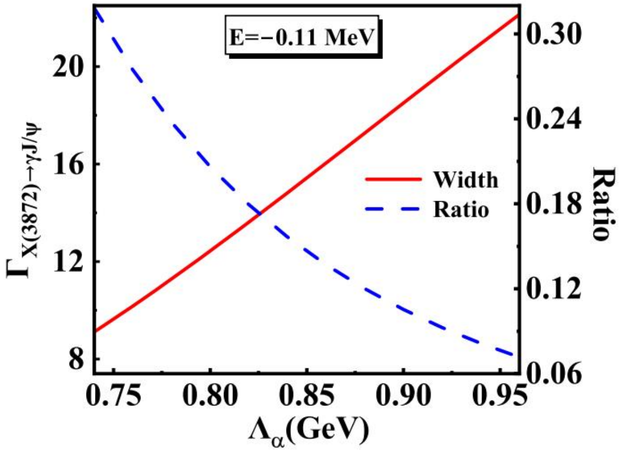
$$\mathcal{M}^{JM}_{[AB]\to CD} = \frac{\sqrt{2m_{[AB]}}}{\sqrt{2m_A}\sqrt{2m_B}}\int\frac{d^3\mathbf{p}}{(2\pi)^{3/2}}\,\hat{\phi}^{JM}_{[AB]}(\mathbf{p}) \otimes \hat{\mathcal{M}}_{AB\to CD}.$$

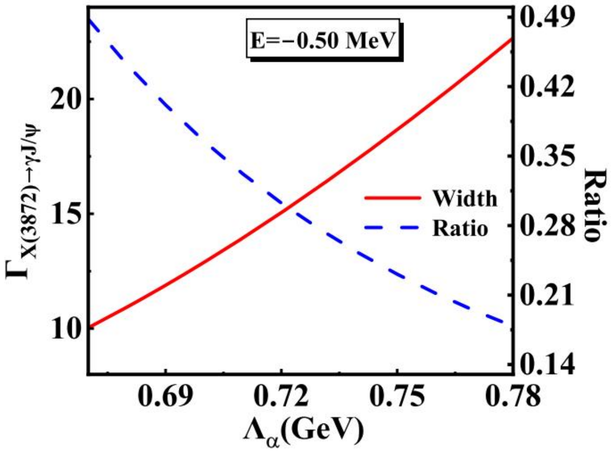
- 衰变宽度：

$$\Gamma_{[AB]\to CD} = \frac{1}{3}\frac{|\mathbf{k}|}{32\pi^2 m_X^2}\sum_M\int\left|\mathcal{M}^{JM}_{[AB]\to CD}\right|^2 d\Omega_{\mathbf{k}}.$$

$X(3872)$辐射衰变的数值结果

$X(3872) \to \gamma\psi_n$辐射衰变宽度及比值





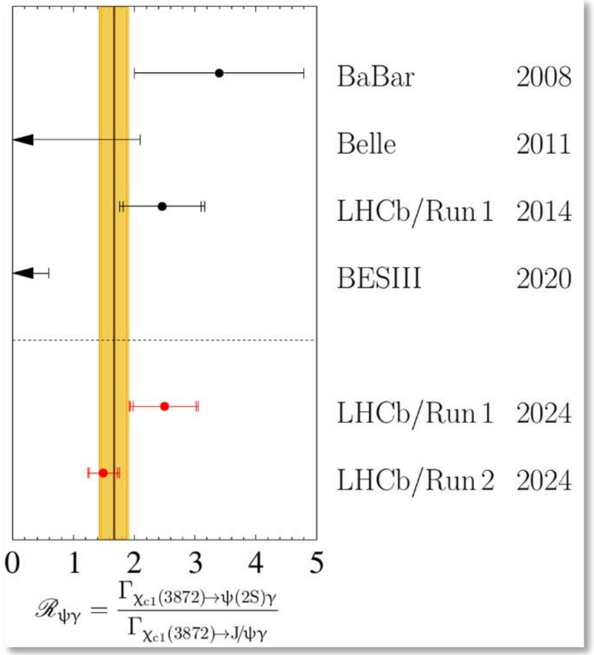
由Belle和BaBar实验组的测量结果，得到

$X(3872) \to \gamma J/\psi$的辐射衰变宽度：

$$\Gamma_{X(3872)\to\gamma J/\psi} = \begin{cases} 10.1^{+4.6}_{-4.5}\ \text{keV} & \text{Belle} \\ 15.5 \pm 7.3\ \text{keV} & \text{BaBar} \end{cases}$$

$R_{\gamma\psi} < 1$，和Belle, BESIII实验组测量结果一致。

实验上测得的$X(3872)$两种辐射衰变的分支比的比值：



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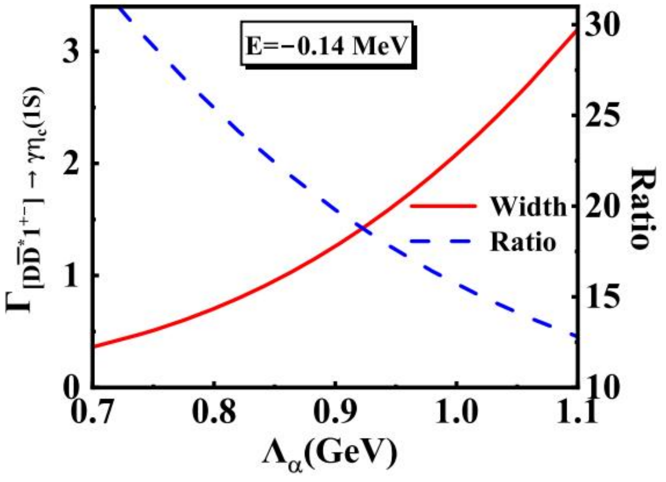
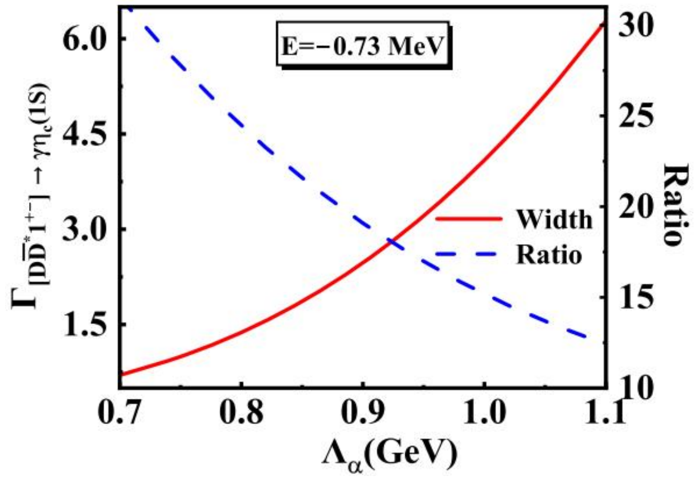
$X(3872)$伙伴态辐射衰变的数值结果

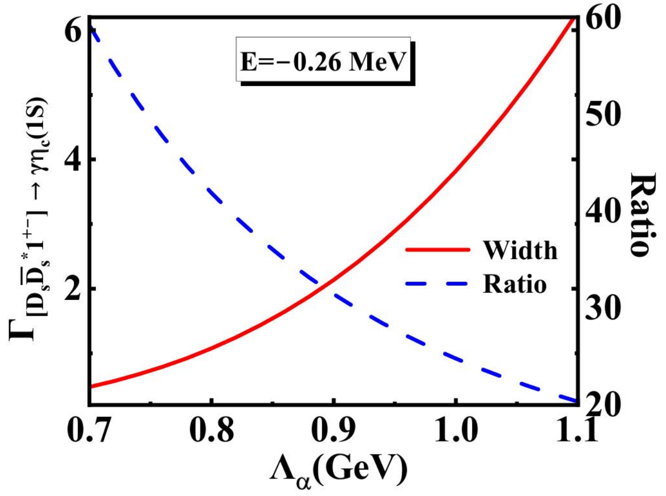
$D\bar{D}^*(1^{+-}) \to \gamma\eta_c(1S)$辐射衰变宽度及比值



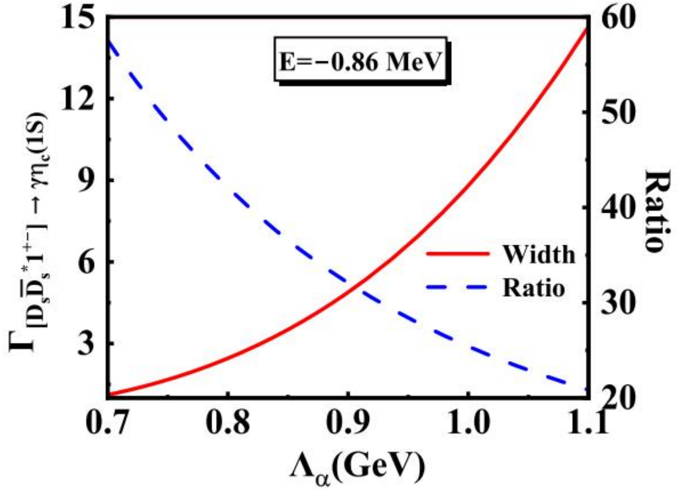
$$R_{\gamma\eta_c} = \frac{\Gamma_{[D\bar{D}^*]\to\gamma\eta_c(2S)}}{\Gamma_{[D\bar{D}^*]\to\gamma\eta_c(1S)}}$$



$D_s\bar{D}_s^*(1^{+-}) \to \gamma\eta_c(1S)$辐射衰变宽度及比值



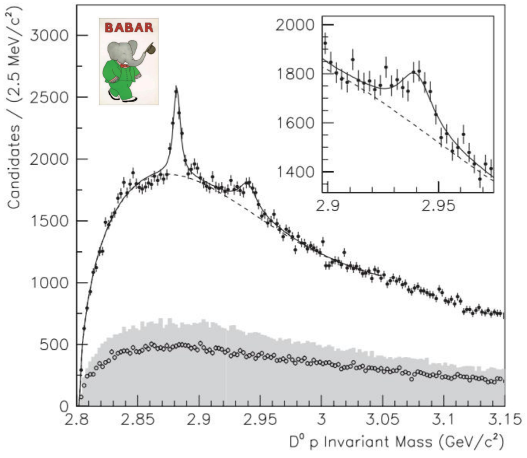
$$R^s_{\gamma\eta_c} = \frac{\Gamma_{[D_s\bar{D}_s^*]\to\gamma\eta_c(2S)}}{\Gamma_{[D_s\bar{D}_s^*]\to\gamma\eta_c(1S)}}$$



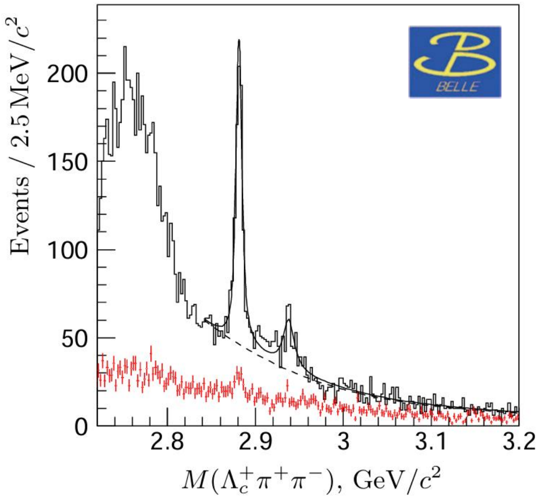
3. $\Lambda_c(2940)$的内部结构及辐射衰变

自强不息　獨樹一幟

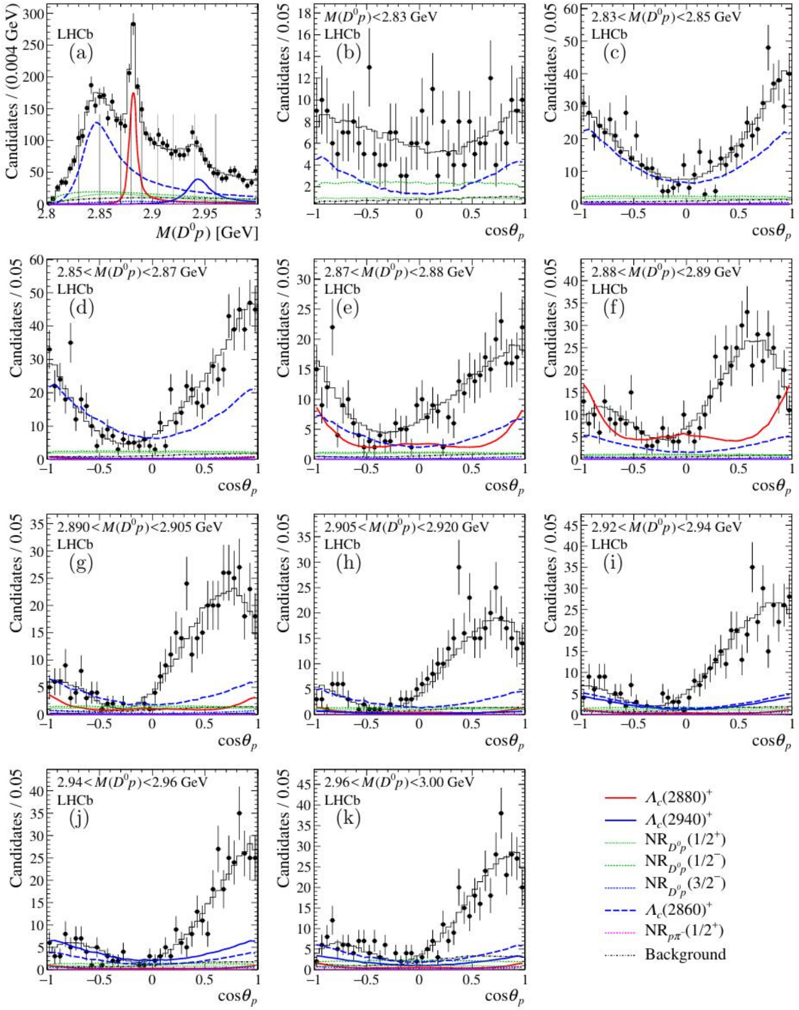
$\Lambda_c(2940)$的发现及内部结构



Phys. Rev. Lett. 98, 012001 (2007)



Phys. Rev. Lett.98, 262001 (2007)



量子数偏向于3/2−

LHCb JHEP 05 (2017) 030

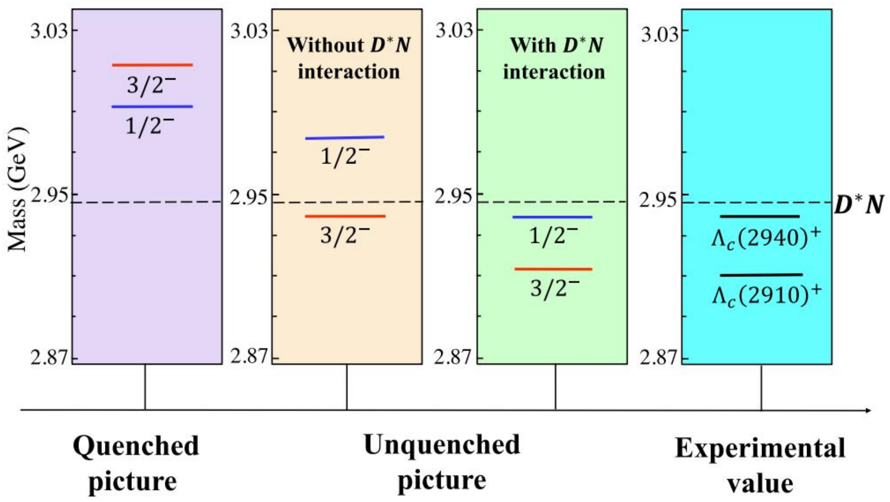
□ 低质量疑难

TABLE II: The predicted masses of the Λ_c^+ baryons (in MeV). We also collect the experimental values [1] and other theoretical results [9, 50, 51] for comparison.

$J^P(nL)$	Exp. [1]	This work	Ref. [9]	Ref. [50]	Ref. [51]
$\frac{1}{2}^+(1S)$	2286.86	2286	2286	2286	2265
$\frac{1}{2}^+(2S)$	2766.6	2766	2769	2791	2775
$\frac{1}{2}^+(3S)$		3112	3130	3154	3170
$\frac{1}{2}^+(4S)$		3397	3437		
$\frac{1}{2}^-(1P)$	2592.3	2591	2598	2625	2630
$\frac{3}{2}^-(1P)$	2628.1	2629	2627	2636	2640
$\frac{1}{2}^-(2P)$	2939.3	2989	2983		[2780]
$\frac{3}{2}^-(2P)$		3000	3005		[2840]
$\frac{1}{2}^-(3P)$		3296	3303		[2830]
$\frac{3}{2}^-(3P)$		3301	3322		[2885]
$\frac{3}{2}^+(1D)$		2857	2874	2887	2910
$\frac{5}{2}^+(1D)$	2881.53	2879	2880	2887	2910
$\frac{3}{2}^+(2D)$		3188	3189	3120	3035
$\frac{5}{2}^+(2D)$		3198	3209	3125	3140
$\frac{5}{2}^-(1F)$		3075	3097	[2872]	[2900]
$\frac{7}{2}^-(1F)$		3092	3078		3125
$\frac{7}{2}^+(1G)$		3267	3270		3175
$\frac{9}{2}^+(1G)$		3280	3284		

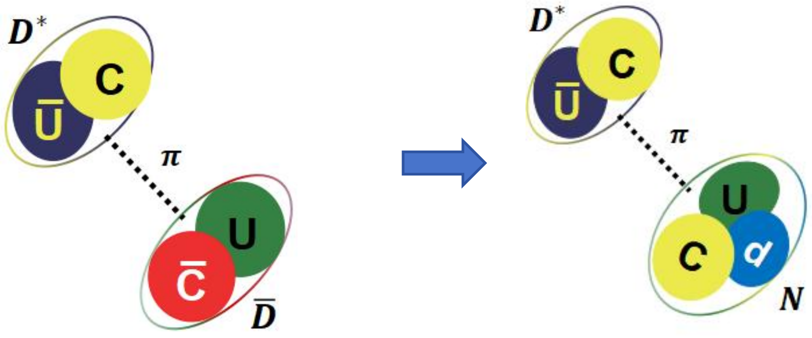
Bing Chen et.al. Eur. Phys. J. A (2015) 51: 82

$\Lambda_C(2940)$的理论解释



Phys. Rev. D 107, 034036 (2023)

$\Lambda_C(2940)$存在低质量疑难，$\bar{D}$替换为N，它可以被解释为D^*N的分子态。



☐ D^*N强子分子态

➢ 质量谱

- Xiang Liu *et al.* ,Eur. Phys. J. C 51, 883–889 (2007).
- Jun He *et al.*, Phys.Rev.D 82, 114029 (2010).
- Bo Wang *et al.* ,Phys.Rev.D 101, 094035 (2020).
- P.G. Ortega *et al.*, PLB 718 1381–1384 (2013).
- Jian-Rong Zhang *et al.*, Phys.Rev.D 89, 096006 (2014).
- ......

➢ 产生和衰变

- Yubing Dong *et al.*, Phys.Rev.D 82, 034035 (2010).
- Yubing Dong *et al.*, Phys.Rev.D 90, 094001 (2014) .
- Xiao-Yun Wang *et al.*, Phys.Rev.D 92, 094032 (2015) .
- Yin Huang *et al.*, Phys.Rev.D 99, 014045 (2019).
- Dian-Yong Chen *et al.*, Phys.Rev.D 109, 094049 (2024).
- Kai-Sa Qiao, Bing-Song Zou, Phys.Rev.D 111, 056029 (2025).
- ......

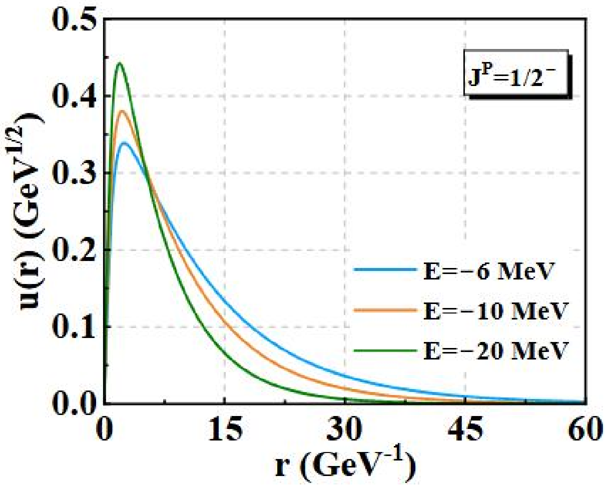
$\Lambda_c(2940)$的束缚能

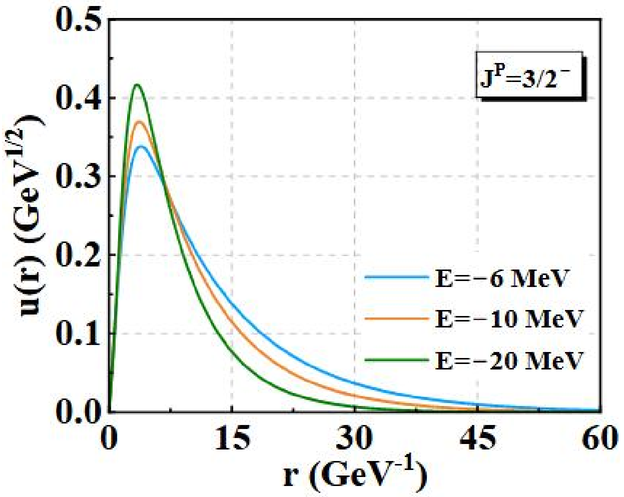
- 将$\Lambda_c(2940)$考虑为可能的D^*N分子态，分别计算自旋为$1/2^-$和$3/2^-$时的束缚能。

$\Lambda_c(2940)$作为可能的D^*N分子态的束缚解

J^P	Λ (GeV)	E (MeV)	$M_{\rm mol}$ (MeV)	$r_{\rm RMS}$ (fm)
$\frac{1}{2}^-$	1.35	−1.36	2946.11	3.73
	1.37	−5.51	2941.96	1.95
	1.4	−18.98	2928.49	1.11
	1.42	−33.49	2913.98	0.87
$\frac{3}{2}^-$	1.08	−1.45	2946.02	3.55
	1.17	−6.06	2941.41	1.94
	1.37	−20.70	2926.77	1.25
	1.55	−36.94	2910.53	1.04

自旋为$1/2^-$和$3/2^-$时的D^*N分子态的径向波函数





$$\hat{\phi}^{JM}_{[AB]}(\mathbf{p}) = \left\{\phi_{[AB]|^3L_J\rangle}(|\mathbf{p}|)\, C^{S,m_S}_{1m_1,1m_2}\, C^{J,M}_{Sm_S,Lm_L}\, Y_{L,m_L}(\theta,\phi)\right\},$$

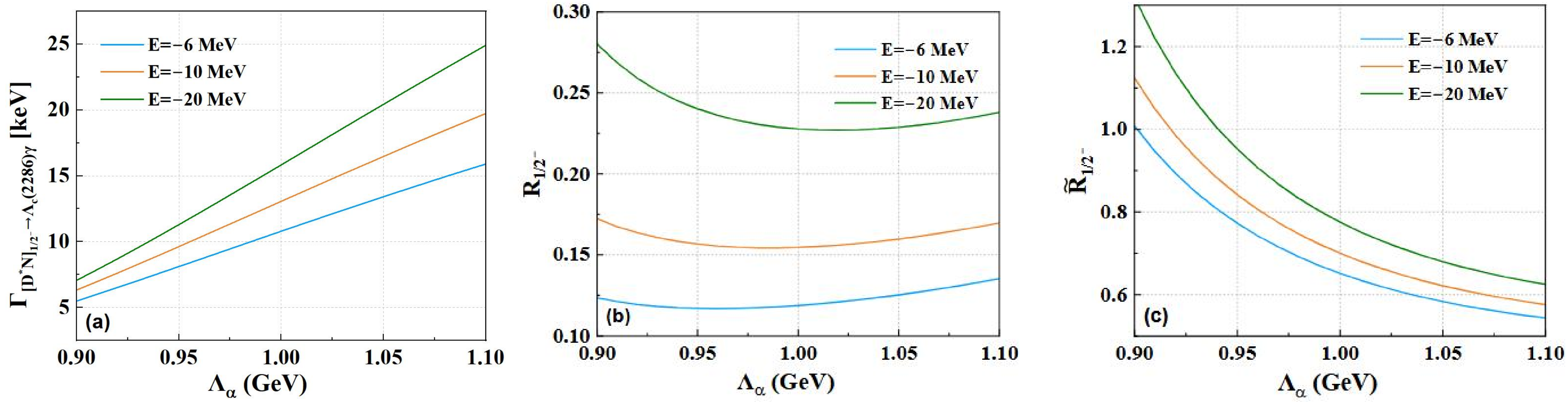
$$\mathcal{M}^{JM}_{[AB]\to CD} = \frac{\sqrt{2m_{[AB]}}}{\sqrt{2m_A}\sqrt{2m_B}} \int \frac{d^3\mathbf{p}}{(2\pi)^{3/2}}\, \hat{\phi}^{JM}_{[AB]}(\mathbf{p}) \otimes \hat{\mathcal{M}}_{AB\to CD}.$$

- 衰变宽度：

$$\Gamma_{[D^*N]\to\Lambda_c\gamma} = \frac{1}{2J+1}\frac{|\mathbf{k}|}{32\pi^2 m^2_{[D^*N]}} \sum_M \int \left|\mathcal{M}^{JM}_{[D^*N]\to\Lambda_c\gamma}\right|^2 d\Omega_{\mathbf{k}}$$

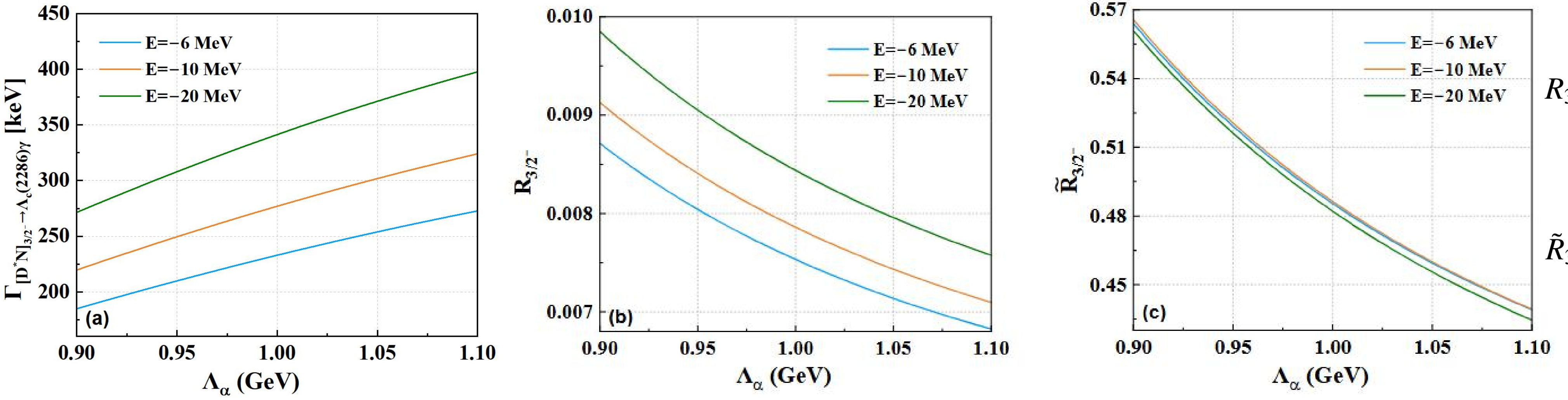
$\Lambda_c(2940)$的辐射衰变

$D^*N \to \gamma\Lambda_c$的辐射衰变宽度及比值



$$R_{1/2^-} = \frac{\Gamma_{[D^*N]_{1/2^-}\to\Lambda_c(2595)\gamma}}{\Gamma_{[D^*N]_{1/2^-}\to\Lambda_c(2286)\gamma}}$$

$$\tilde{R}_{1/2^-} = \frac{\Gamma_{[D^*N]_{1/2^-}\to\Lambda_c(2765)\gamma}}{\Gamma_{[D^*N]_{1/2^-}\to\Lambda_c(2286)\gamma}}$$



$$R_{3/2^-} = \frac{\Gamma_{[D^*N]_{3/2^-}\to\Lambda_c(2595)\gamma}}{\Gamma_{[D^*N]_{3/2^-}\to\Lambda_c(2286)\gamma}}$$

$$\tilde{R}_{3/2^-} = \frac{\Gamma_{[D^*N]_{3/2^-}\to\Lambda_c(2765)\gamma}}{\Gamma_{[D^*N]_{3/2^-}\to\Lambda_c(2286)\gamma}}$$

4. 总结

- 在分子态框架下，用单玻色子交换模型，考虑电磁修正，通过求解薛定谔方程计算了$X(3872)$及伙伴态的束缚能及波函数，电磁相互作用和夸克之间质量差对于解释同位旋破缺同样重要。

- 初态波函数作为输入，得到$X(3872)$的两个特征辐射衰变道的宽度以及比值，计算结果与Belle和BESIII实验组测量结果一致，预测了$X(3872)$的伙伴态$D_{(s)}\bar{D}^*_{(s)}(1^{+-}) \to \gamma\eta_c(nS)$的辐射衰变宽度及比值。

$X(3872) \to \gamma J/\psi$

$X(3872) \to \gamma\psi(2S)$

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

- 辐射衰变对于区分$\Lambda_c(2940)$的量子数以及内部结构有很大帮助,实验上可以通过寻找这样的衰变道对$\Lambda_c(2940)$的量子数以及内部结构做进一步区分，帮助我们更清楚地了解$\Lambda_c(2940)$的性质。

谢谢各位老师与同学！