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Lanzhou Center for Theoretical Physics

量子理论及应用基础
教育部重点实验室
Key Laboratory of Quantum Theory and Applications of MoE

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Key Laboratory of Theoretical Physics of Gansu Province

含奇异夸克的隐粲分子态类型五夸克态

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兰州大学
LANZHOU UNIVERSITY

第三届强子与重味物理理论与实验联合研讨会 4月5-9日 湖北·武汉

F. L. Wang and Xiang Liu, Phys. Lett. B 835, 137583 (2022)

F. L. Wang, Hong-Yan Zhou, Zhan-Wei Liu, and Xiang Liu, Phys. Rev. D, 106, 054020 (2022)

F. L. Wang and Xiang Liu, Phys. Rev. D 108, 054028 (2023)

F. L. Wang and Xiang Liu, Phys. Rev. D 109, 014043 (2024)

提　纲

1. 研究背景

2. $\Xi_c\bar{D}^{(*)}$分子态的特征能谱

3. $\Xi_c\bar{D}^*$分子态的电磁性质

4. $\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$以及$\Xi_cD^*$分子态候选者的理论预言

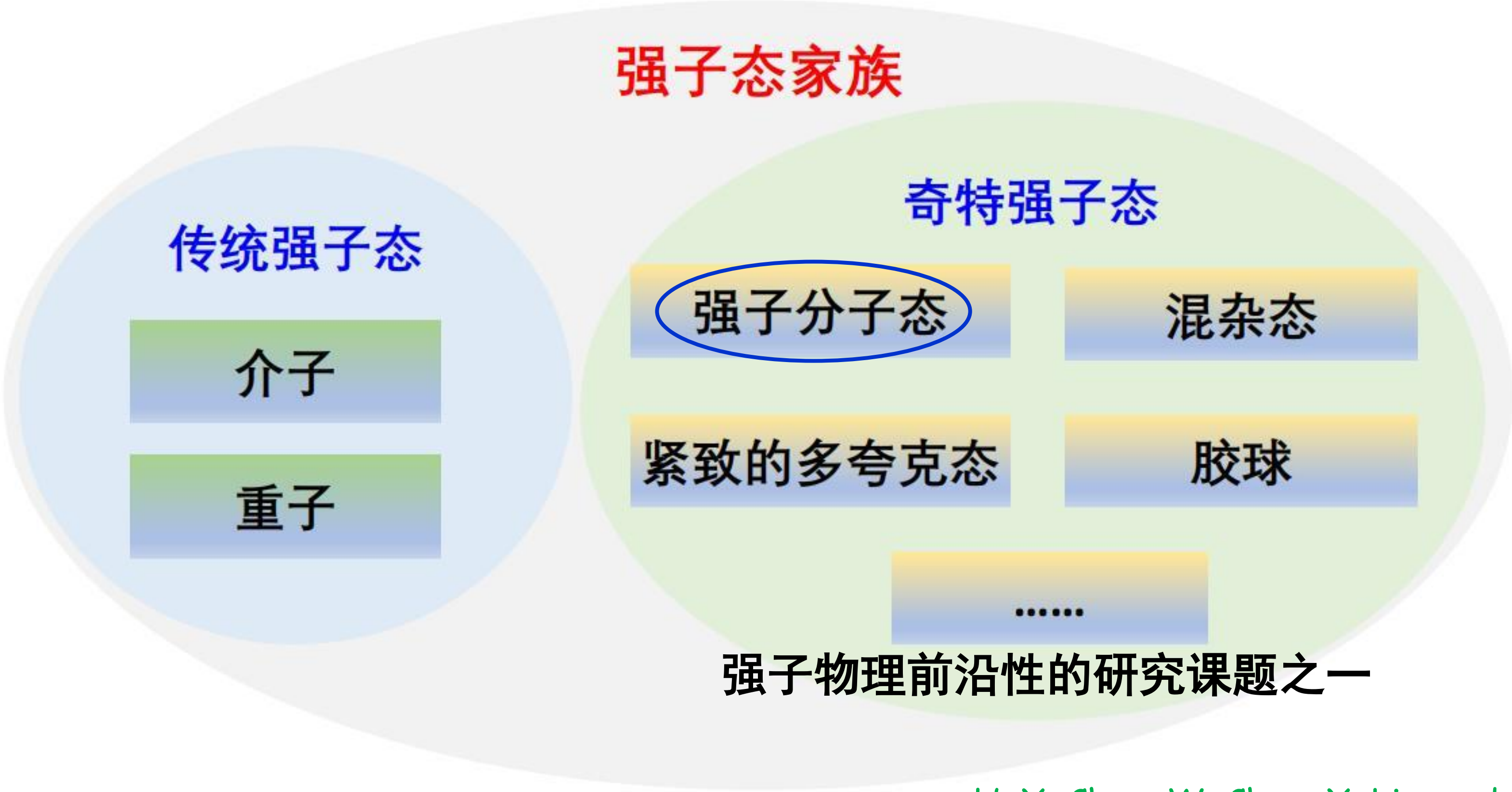
5. 总结

1

研究背景

强子物理的研究对象——强子态（夸克与胶子）

- 强子物理主要关注强子态的谱学、结构等问题。



强子态家族

传统强子态

介子

重子

奇特强子态

强子分子态

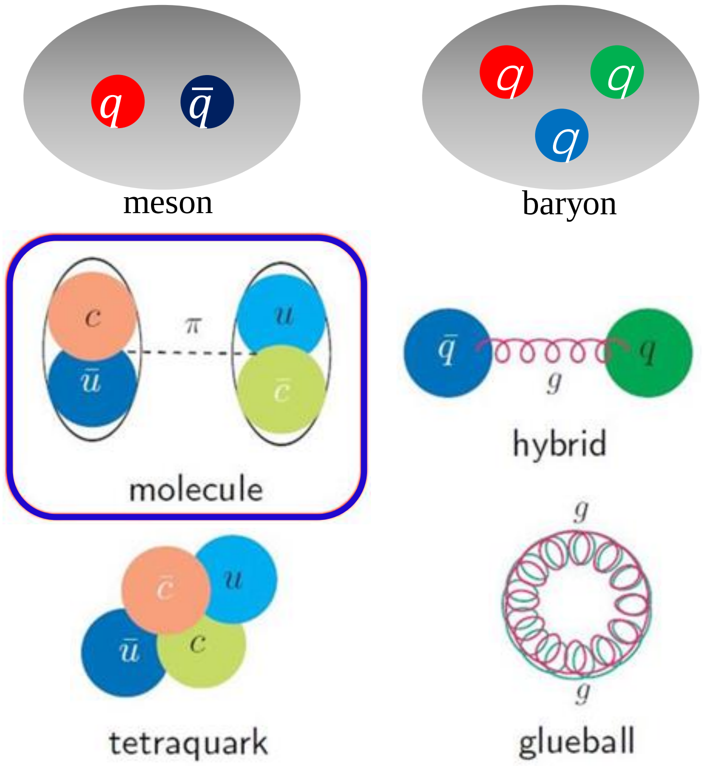
混杂态

紧致的多夸克态

胶球

……

强子物理前沿性的研究课题之一



H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rept. 639, 1 (2016)

- 为理解强子的内部结构与强相互作用的非微扰问题提供重要的信息；
- 在奇特强子态的研究中，过去二十年强子分子态引起了大家的广泛关注。

强子分子态的定义和典型特征

- 强子分子态是由两个(多个)色单态的强子形成的松散束缚态。

$P_{\psi}^{N}(4312)$
$P_{\psi}^{N}(4440)$ $\Sigma_c\bar{D}^{(*)}$分子态
$P_{\psi}^{N}(4457)$

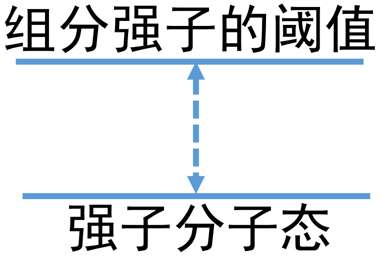
[LHCb], PRL 122, 222001 (2019)

$T_{cc}^{+}(3875)$ DD^* 分子态

[LHCb], Nature Physics (2022)

- 强子分子态的典型特征：
  - ➢ 强子分子态是束缚态，组分强子的阈值大于强子分子态的质量；
  - ➢ 强子分子态的束缚较松散（较小的束缚能和较大的尺寸）。

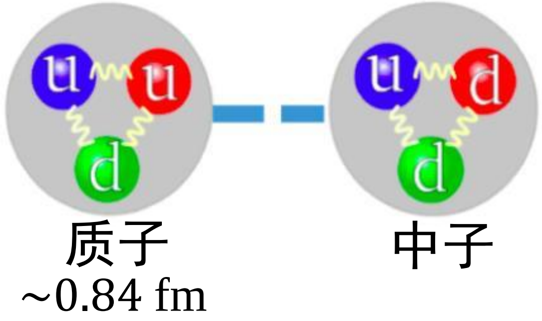
H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rept. 639, 1 (2016)


组分强子的阈值

强子分子态

- 氘核是由质子与中子形成的分子态类型六夸克态，有较小的束缚能(~ 2.225 MeV)和较大的尺寸(~3.9 fm)。

R. Machleidt, PRC 63, 024001 (2001)



质子
~0.84 fm

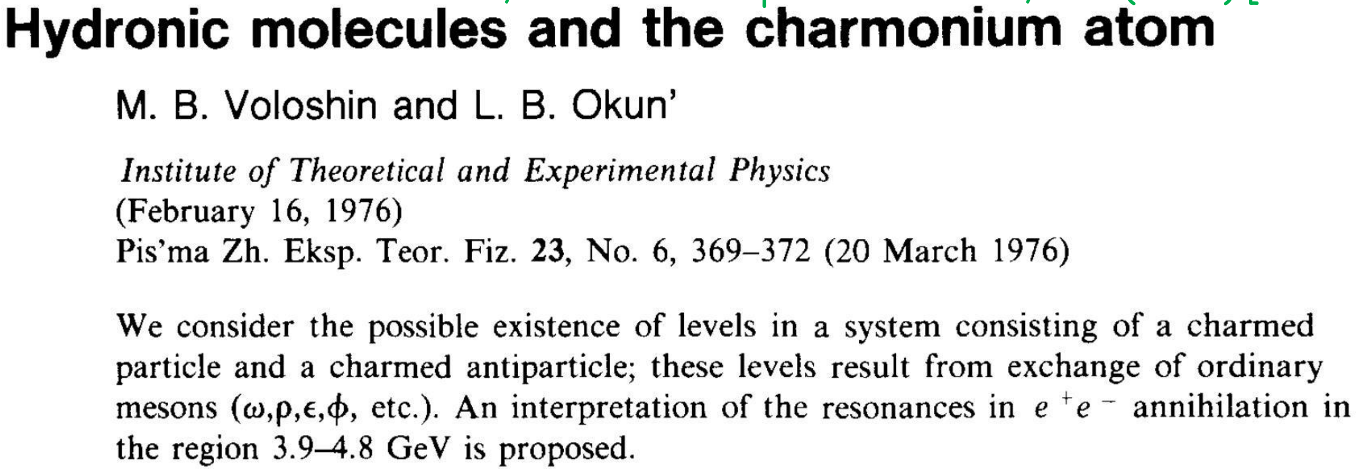
中子

在强子物理中，对隐粲分子态类型多夸克态的理论研究始于上世纪七十年代

- 由粲介子与反粲介子形成的松散束缚态。

预言

M. B. Voloshin and L. B. Okun, Pisma Zh. Eksp. Teor. Fiz. 23, 369 (1976) [JETP Lett. 23, 333 (1976)]



Hydronic molecules and the charmonium atom

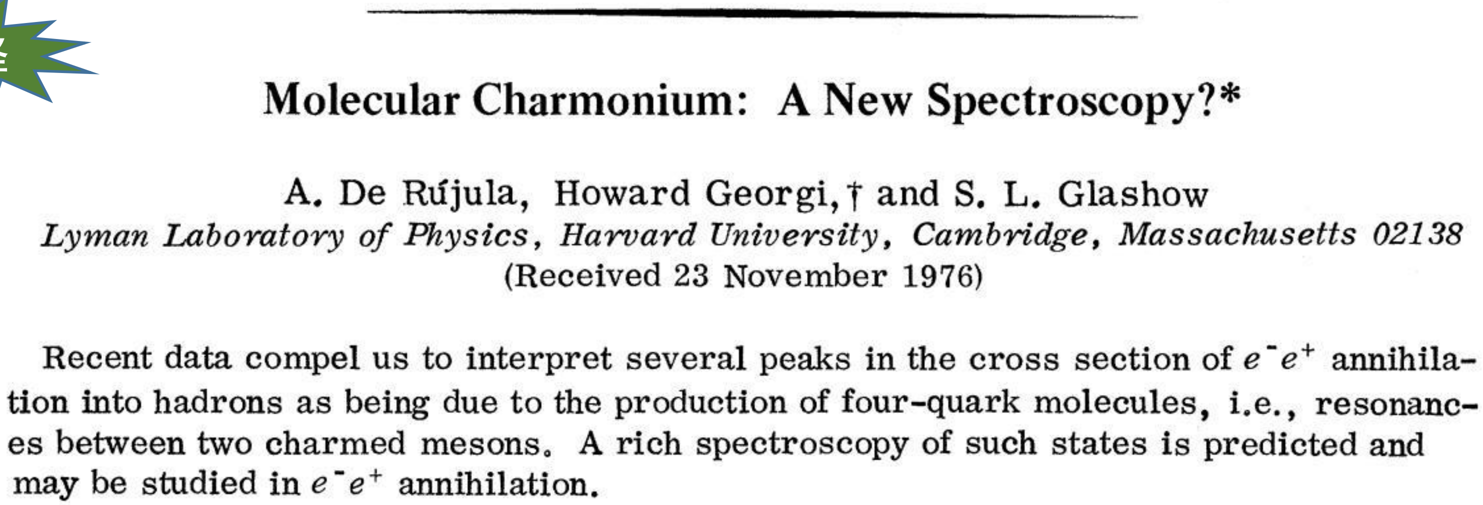
M. B. Voloshin and L. B. Okun'

Institute of Theoretical and Experimental Physics
(February 16, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 6, 369–372 (20 March 1976)

We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons ($\omega,\rho,\epsilon,\phi$, etc.). An interpretation of the resonances in e^+e^- annihilation in the region 3.9–4.8 GeV is proposed.

- $\Psi(4040)$: P波 $D^*\overline{D}^*$分子态。A.D. Rújula , H. Georgi, and S. L. Glashow, PRL 38, 317(1977)

解释



Molecular Charmonium: A New Spectroscopy?*

A. De Rújula, Howard Georgi,† and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 23 November 1976)

Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.

然而，早期对隐粲分子态类型多夸克态的理论研究没有得到较明确的实验验证。

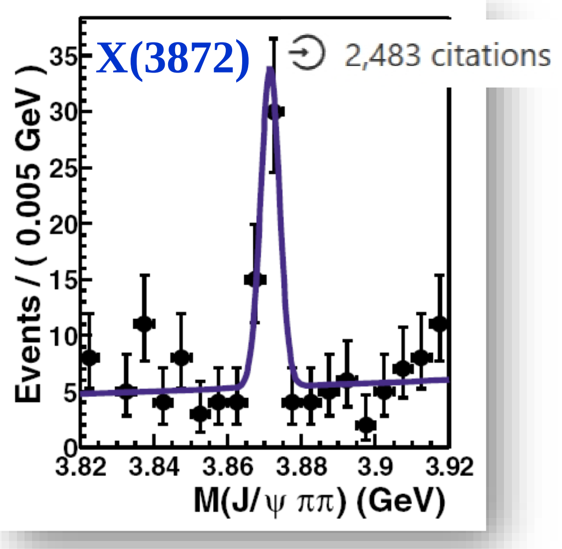
进入本世纪，奇特强子态的理论与实验研究进入到“黄金时期”

- 自2003年Belle实验组发现了类粲偶素$X(3872)$，强子物理中奇特强子态的理论与实验研究发展得特别迅速，特别是重味强子分子态的研究。

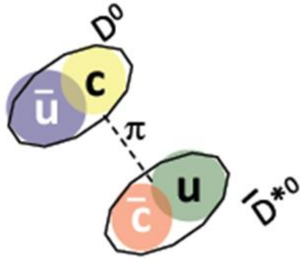
$X/Y/Z/P_{\psi}^{N}/P_{\psi s}^{\Lambda}/T_{cc}^{+}$态

2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
$X(3872)$	$Y(3940)$	$Z(3930)$ $Y(4260)$		$X(3940)$ $Y(4660)$ $Y(4360)$ $Y(4008)$	$Y(4160)$ $Y(4630)$ $Z^+(4248)$ $Z^+(4051)$ $Z^+(4430)$	$Y(4140)$	$X(4350)$ $X(3915)$		

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
$Z_c(3900)$ $Z_c(4020)$	$Z_c(4025)$ $Z_c(3885)$ $Z^+(4240)$ $Z_c^+(4200)$	$P_c(4450)$ $P_c(4380)$		$Z_c(4032)$ $X^*(3860)$ $Y(4390)$ $Y(4320)$ $Y(4220)$ $X(4700)$ $X(4500)$ $Y(4274)$	$Z_c^-(4100)$	$P_c(4457)$ $P_c(4440)$ $P_c(4312)$	$P_{cs}(4459)$ $Z_{cs}(3985)$	T_{cc}^+ $Z_{cs}(4220)$ $Z_{cs}(4000)$ $X(4685)$ $X(4630)$	$X(3960)$ $P_{\psi s}^{\Lambda}(4338)$



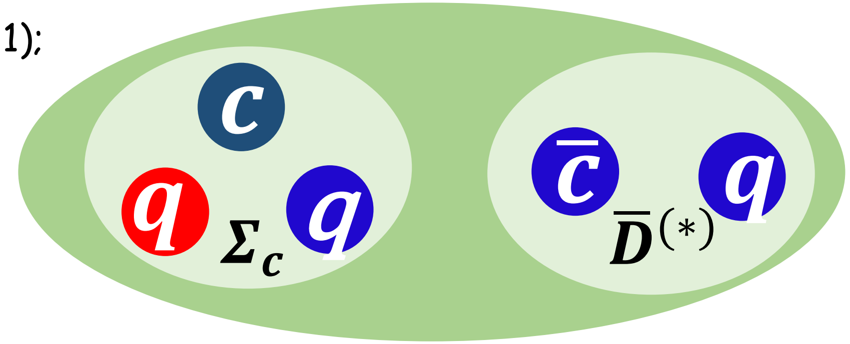
[Belle] PRL 91, 262001(2003)



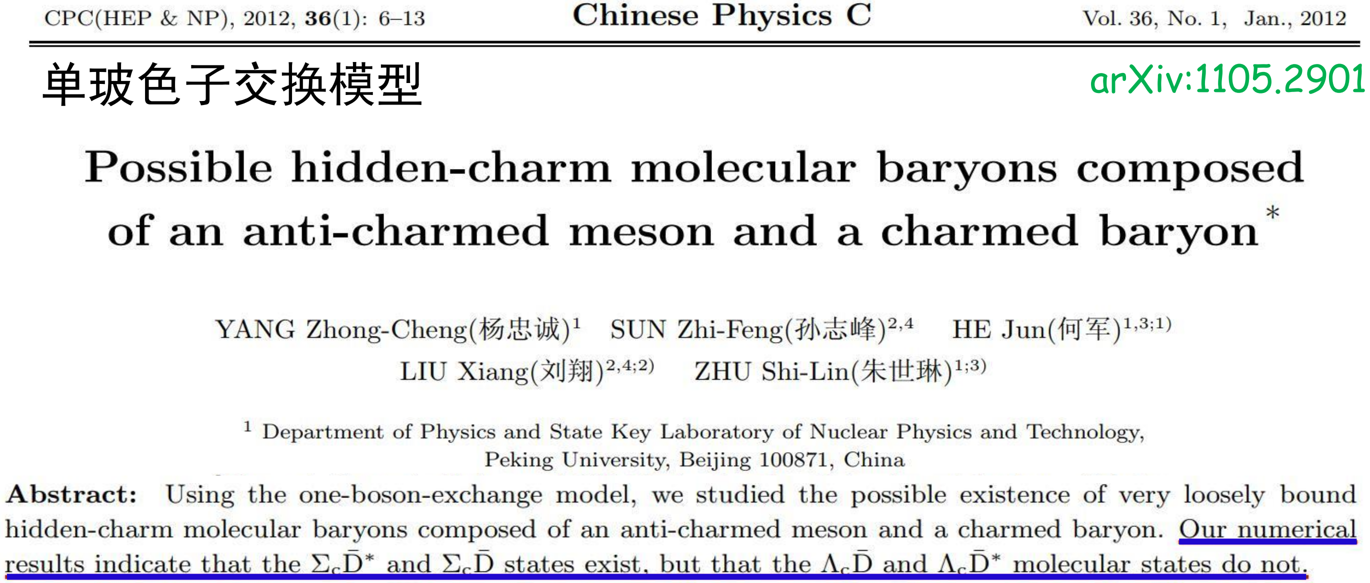
- 在重味强子分子态的研究中，近十年隐粲分子态类型五夸克态的课题取得了一系列重要的研究成果。

对$\Sigma_c\bar{D}^{(*)}$构型的隐粲分子态类型五夸克态候选者的理论预言

- 从2010年开始，一系列理论工作预言存在$\Sigma_c\bar{D}^{(*)}$构型的隐粲分子态类型五夸克态候选者：
  - ➢ J. J. Wu, Molina, Oset, and B.S. Zou, PRL 105, 232001 (2010);
  - ➢ W. L. Wang, F. Huang, Z. Y. Zhang, and B. S. Zou, PRC 84, 015203 (2011);
  - ➢ Z. C. Yang, Z. F. Sun, J. He, X. Liu, and S. L. Zhu, CPC 36, 6 (2012);
  - ➢ J. J. Wu, T.-S. H. Lee, and B. S. Zou, PRC 85, 044002 (2012);
  - ➢ C. W. Xiao, J. Nieves, and E. Oset, PRD 88 056012 (2013) ;
  - ➢ M. Karliner and J. L. Rosner, PRL 115, 122001 (2015);
  - ➢ ......



- 我们课题组的理论工作指出存在$\Sigma_c\bar{D}^{(*)}$构型的隐粲分子态类型五夸克态候选者。



CPC(HEP & NP), 2012, **36**(1): 6–13 **Chinese Physics C** Vol. 36, No. 1, Jan., 2012

单玻色子交换模型 arXiv:1105.2901

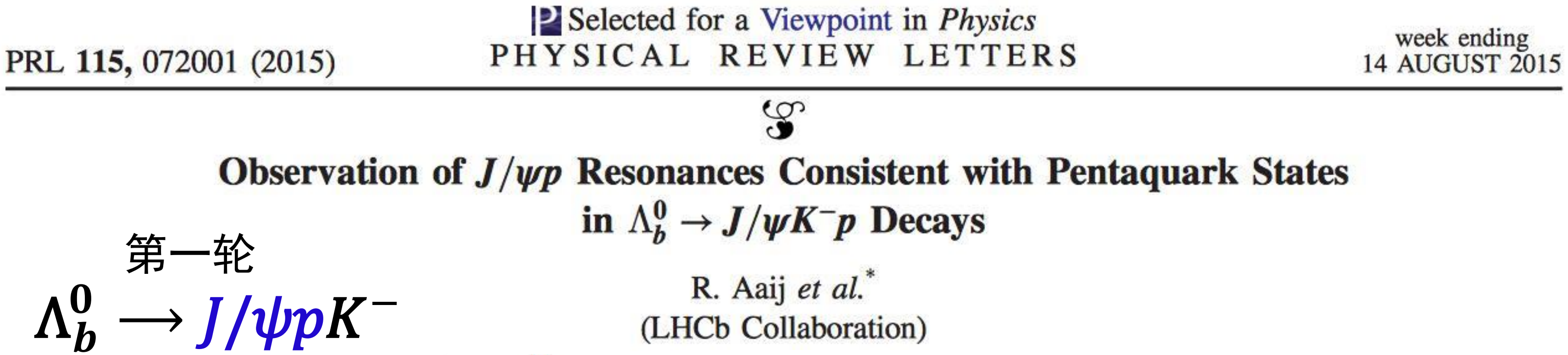
Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon *

YANG Zhong-Cheng(杨忠诚)[1] SUN Zhi-Feng(孙志峰)[2,4] HE Jun(何军)[1,3;1)]
LIU Xiang(刘翔)[2,4;2)] ZHU Shi-Lin(朱世琳)[1;3)]

[1] Department of Physics and State Key Laboratory of Nuclear Physics and Technology,
Peking University, Beijing 100871, China

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.

LHCb实验组发现$P_\psi^N(4380)$与$P_\psi^N(4450)$@2015年



Selected for a Viewpoint in *Physics*

PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

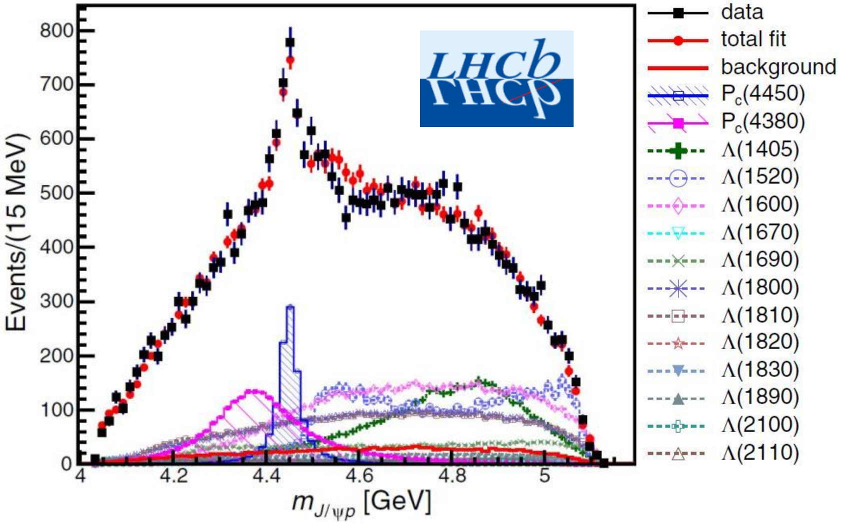
R. Aaij *et al.*[*]

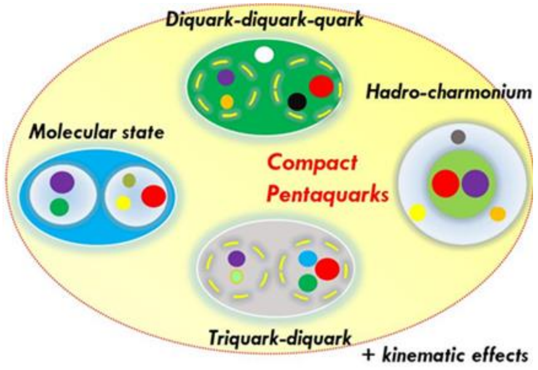
(LHCb Collaboration)

$$M_{P_c(4380)} = 4380 \pm 8 \pm 29\,\text{MeV}\,,$$
$$\Gamma_{P_c(4380)} = 205 \pm 18 \pm 86\,\text{MeV}\,,$$
$$M_{P_c(4450)} = 4449.8 \pm 1.7 \pm 2.5\,\text{MeV}\,,$$
$$\Gamma_{P_c(4450)} = 39 \pm 5 \pm 19\,\text{MeV}$$

第一轮

$\Lambda_b^0 \longrightarrow J/\psi p K^-$





$P_\psi^N(4380)/P_\psi^N(4450)$的自旋-宇称量子数中的$P$宇称相反：

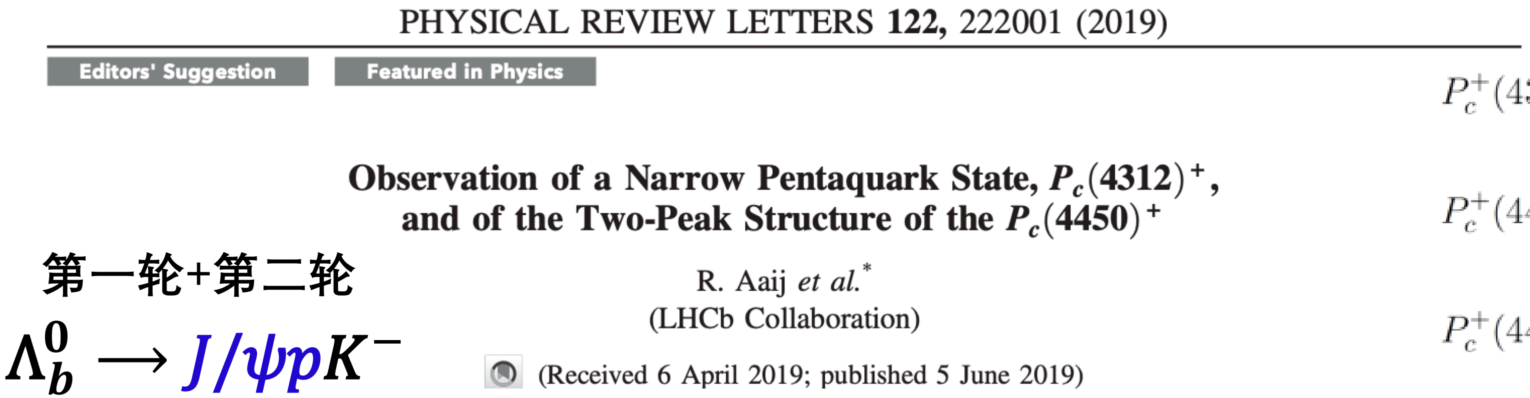
- 最好的结果($3/2^-$, $5/2^+$)；
- 可接受的结果($3/2^+$, $5/2^-$)或($5/2^+$, $3/2^-$)。

S波$\Sigma_c^{(*)}\bar{D}^{(*)}$系统的$P$宇称相同且为负。

实验宣布的隐粲五夸克态的P宇称相反与强子分子态的解释相矛盾。

2015年LHCb实验组关于$P_\psi^N(4380)$与$P_\psi^N(4450)$的实验数据不能区分不同的理论解释

2019年P_ψ^N态的高精度实验数据支持隐粲分子态类型五夸克态的解释



PHYSICAL REVIEW LETTERS **122,** 222001 (2019)

Editors' Suggestion Featured in Physics

Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

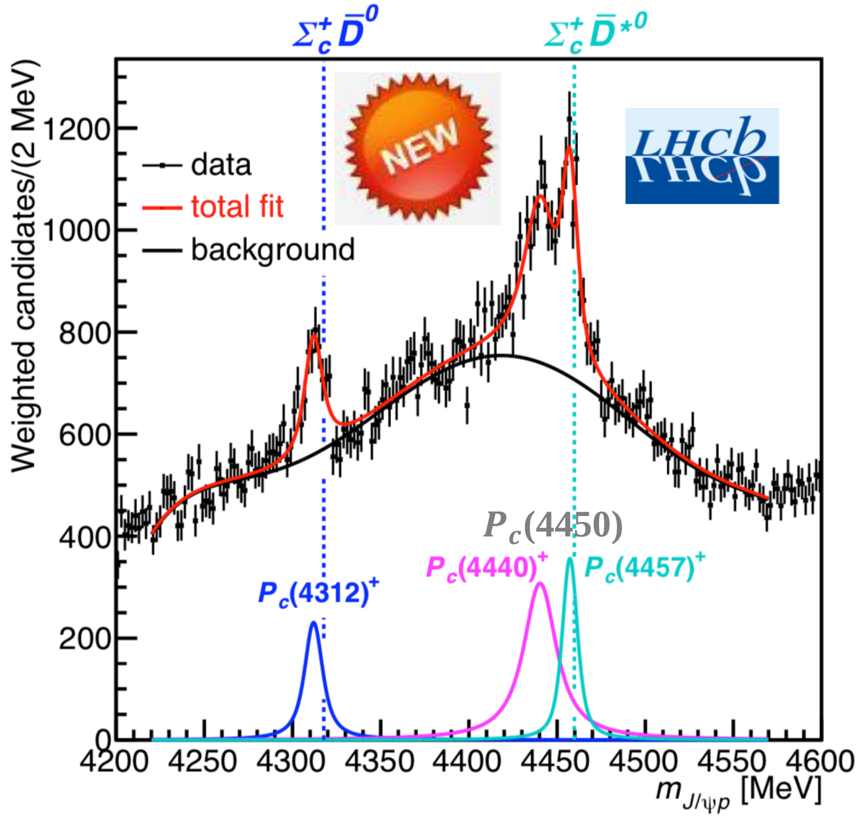
R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 6 April 2019; published 5 June 2019)

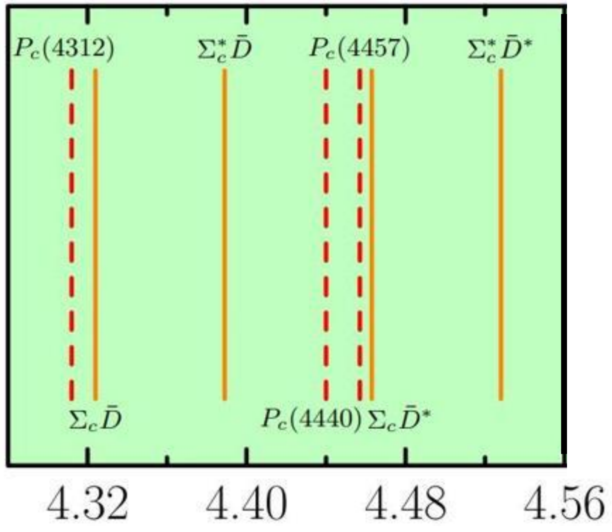
$$
\begin{aligned}
P_c^+(4312): M &= 4311.9 \pm 0.7^{+6.8}_{-0.6}\ \mathrm{MeV},\\
\Gamma &= \ \ 9.8 \pm 2.7^{+3.7}_{-4.5}\ \mathrm{MeV},\\
P_c^+(4440): M &= 4440.3 \pm 1.3^{+4.1}_{-4.7}\ \mathrm{MeV},\\
\Gamma &= \ \ 20.6 \pm 4.9^{+8.7}_{-10.1}\ \mathrm{MeV},\\
P_c^+(4457): M &= 4457.3 \pm 0.6^{+4.1}_{-1.7}\ \mathrm{MeV},\\
\Gamma &= \ \ 6.4 \pm 2.0^{+5.7}_{-1.9}\ \mathrm{MeV}.
\end{aligned}
$$

第一轮+第二轮

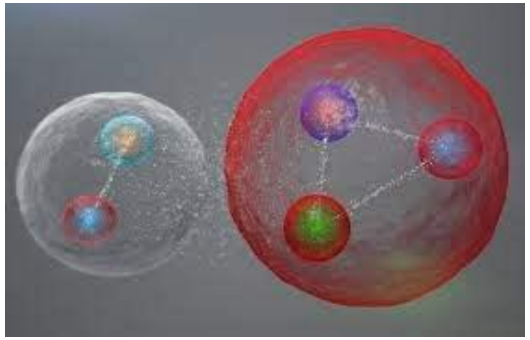
$$\Lambda_b^0 \longrightarrow J/\psi p K^-$$



S波$\Sigma_c\bar{D}^{(*)}$分子态的特征能谱



隐粲分子态类型五夸克态



含奇异夸克的隐粲五夸克态$P_{\psi s}^{\Lambda}$(4459)的实验证据@2020年

Science Bulletin 66 (2021) 1278–1287

Contents lists available at ScienceDirect

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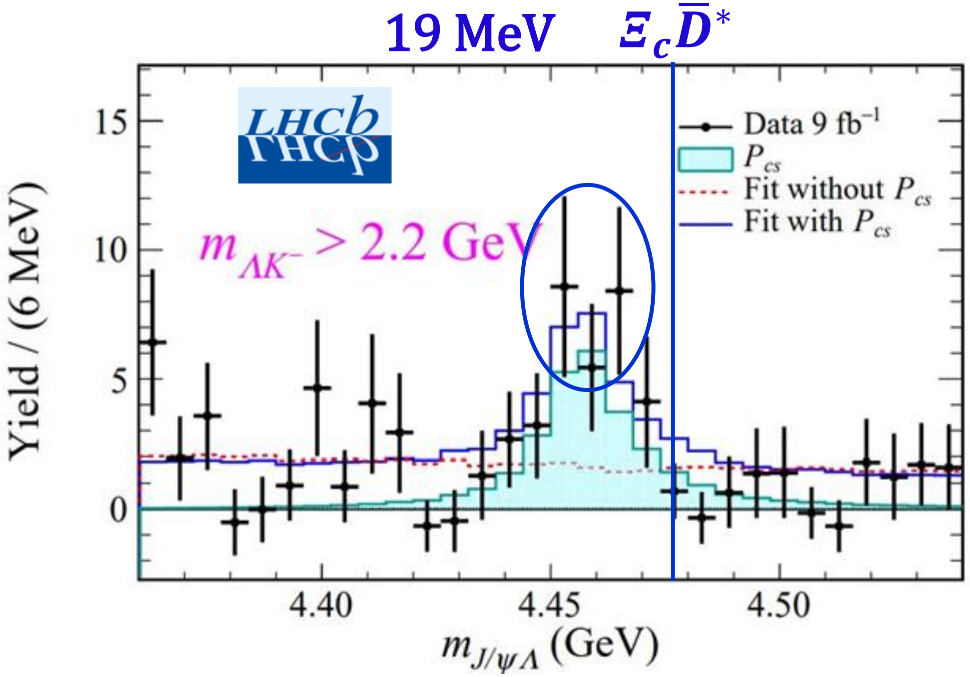
journal homepage: www.elsevier.com/locate/scib

Article

Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay

LHCb Collaboration [1]

$$\Xi_b^- \longrightarrow J/\psi\Lambda K^-$$



State	M_0 [MeV]	Γ_0 [MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$

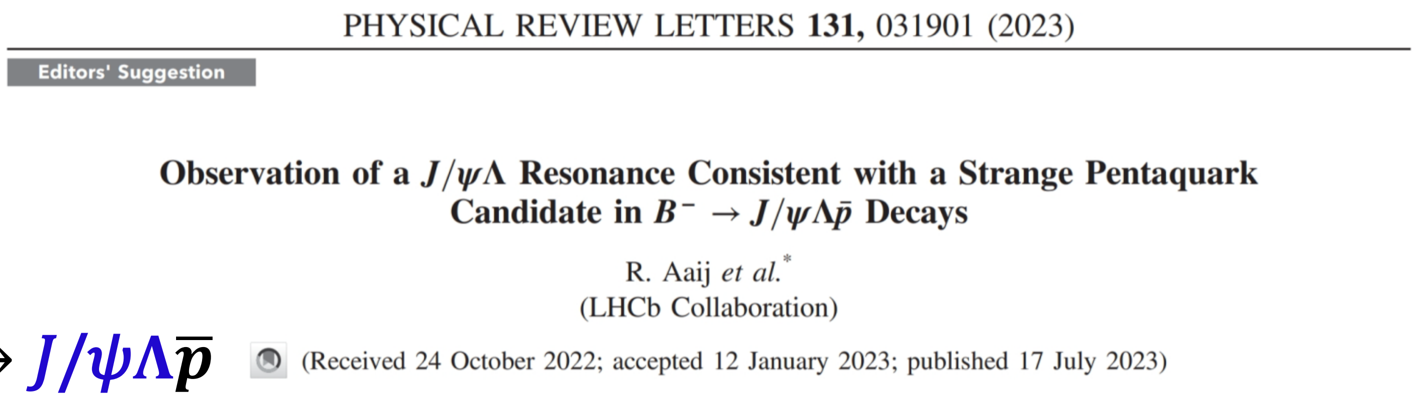
S波同位旋标量$\Xi_c\bar{D}^*$系统：$J^P = 1/2^-$与$3/2^-$（两个态）

“双峰”假设：证实&排除

困惑

$P_{\psi s}^{\Lambda}$(4459)是否存在子结构？

含奇异夸克的隐粲五夸克态$P_{\psi s}^{\Lambda}(4338)$的实验发现@2022年



PHYSICAL REVIEW LETTERS **131,** 031901 (2023)

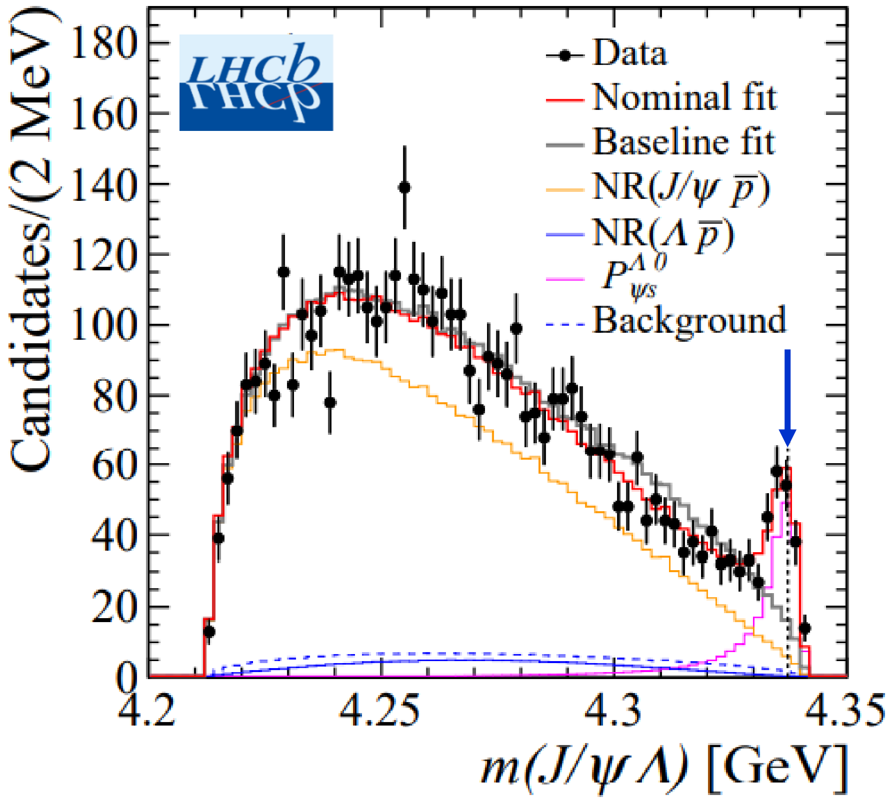
Editors' Suggestion

Observation of a $J/\psi\Lambda$ Resonance Consistent with a Strange Pentaquark Candidate in $B^- \to J/\psi\Lambda\bar{p}$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

(Received 24 October 2022; accepted 12 January 2023; published 17 July 2023)

$B^- \longrightarrow J/\psi\Lambda\bar{p}$



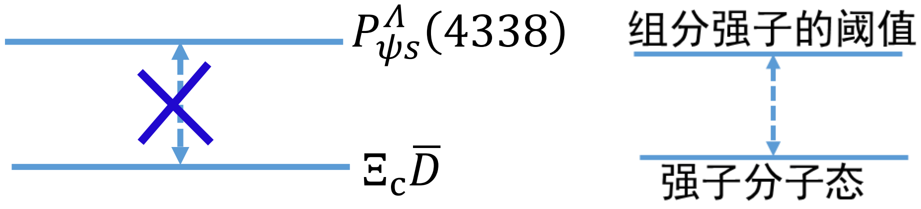
$M = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}, \quad \Gamma = 7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$

自旋-宇称量子数倾向于：$J^P = 1/2^-$。

S波同位旋标量$\Xi_c\bar{D}$系统：$J^P = 1/2^-$。

困惑

$P_{\psi s}^{\Lambda}(4338)$的质量比$\Xi_c\bar{D}$道的阈值高？



$P_{\psi s}^{\Lambda}(4338)$

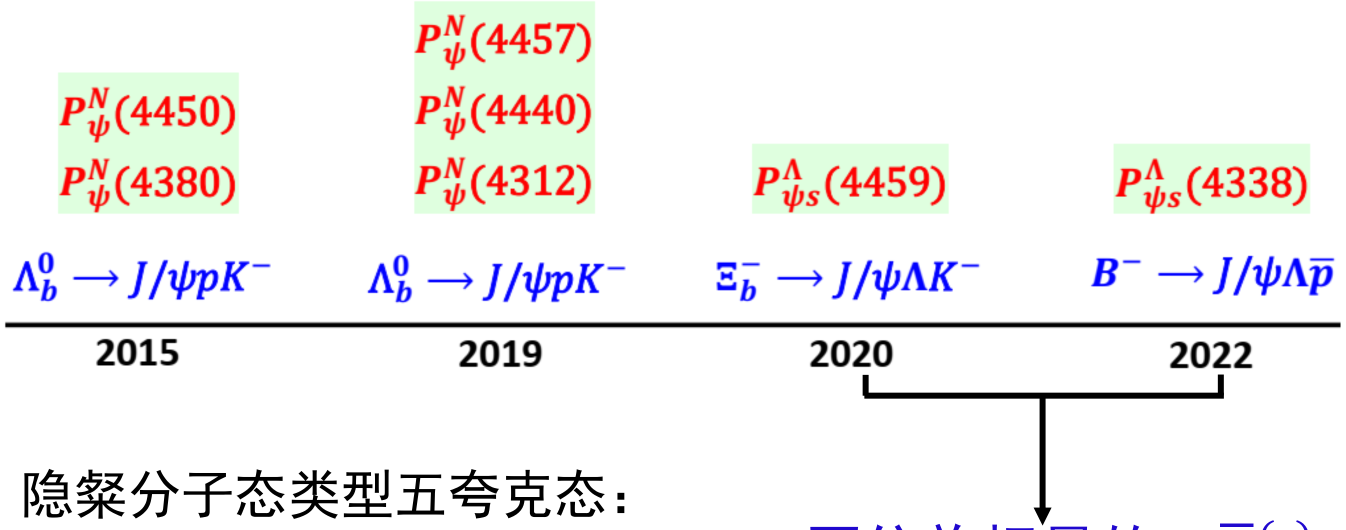
$\Xi_c\bar{D}$

组分强子的阈值

强子分子态

目前LHCb实验组发现的P_{ψ}^{N}与$P_{\psi s}^{\Lambda}$态

近十年，隐粲分子态类型五夸克态的课题取得了一系列重要的研究成果，
但是仍然存在一些问题，特别是对实验发现的含奇异夸克的隐粲五夸克态的理解。



$P_{\psi}^{N}(4450)$

$P_{\psi}^{N}(4380)$

$\Lambda_b^0 \longrightarrow J/\psi p K^-$

2015

$P_{\psi}^{N}(4457)$

$P_{\psi}^{N}(4440)$

$P_{\psi}^{N}(4312)$

$\Lambda_b^0 \longrightarrow J/\psi p K^-$

2019

$P_{\psi s}^{\Lambda}(4459)$

$\Xi_b^- \longrightarrow J/\psi \Lambda K^-$

2020

$P_{\psi s}^{\Lambda}(4338)$

$B^- \longrightarrow J/\psi \Lambda \bar{p}$

2022

隐粲分子态类型五夸克态：
特征能谱的研究对奇特强子态的
寻找和鉴别具有重要指导意义

同位旋标量的$\Xi_c \bar{D}^{(*)}$
分子态的特征能谱？

- ✓ $P_{\psi s}^{\Lambda}(4459)$是否存在子结构？
- ✓ $P_{\psi s}^{\Lambda}(4338)$的质量是否过高？

2

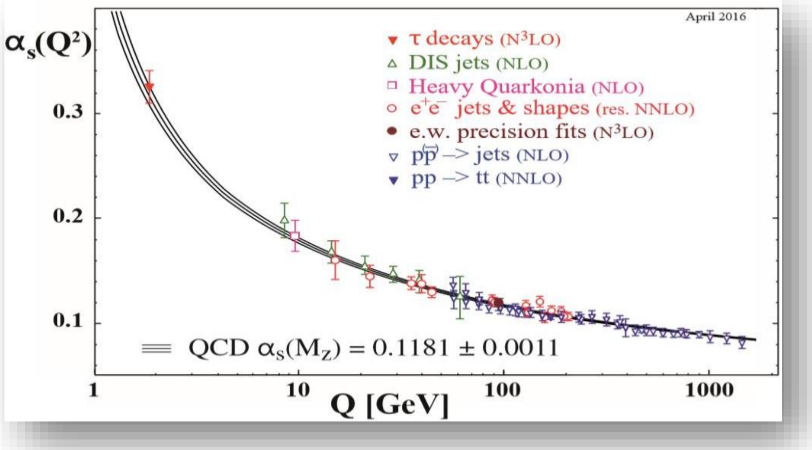
$\Xi_c\bar{D}^{(*)}$分子态的特征能谱

强子间相互作用是研究强子分子态质量谱的重要输入

- 强子间相互作用是研究强子分子态质量谱的重要输入，然而强相互作用在低能情况下不能微扰求解。

$$-\frac{1}{2\mu}\left(\nabla^2-\frac{l(l+1)}{r^2}\right)\psi(r)+\underline{V(r)}\psi(r)=E\psi(r)$$

  - ➢ 束缚能
  - ➢ 空间波函数



- 讨论强子间相互作用的模型与方法：

① 单玻色子交换模型；

② QCD求和规则；

③ 格点QCD模拟；

④ 手征微扰理论；

⑤ 组分夸克模型；

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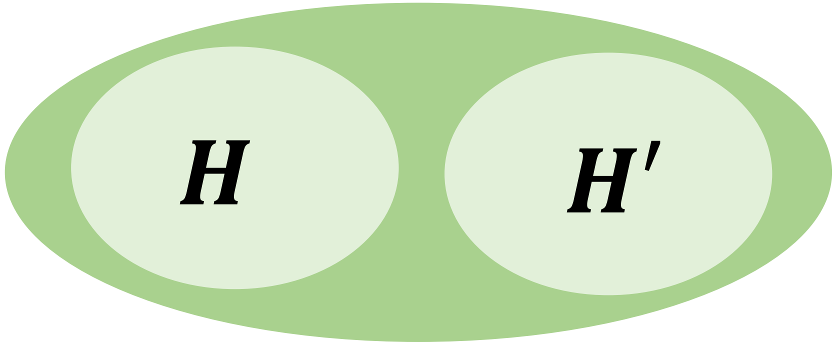
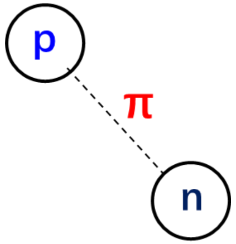


H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rept. 639, 1 (2016)

单玻色子交换模型

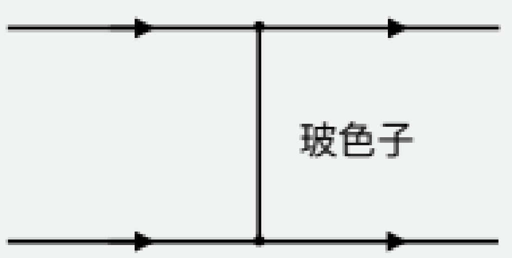
- 介子交换模型:核力是两个核子间交换pion产生的，质子和中子间通过交换pion形成氘核。pion交换只提供相互作用的长程力。



H. Yukawa, Proc. Phys. Math. Sco. Jap. 17 (1935)

- 在强子间相互作用的研究中通过考虑不同的轻味介子描述长程、中程和短程力：

$$\sigma,\quad \mathbb{P}=\begin{pmatrix}\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & \pi^+ & K^+\\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta}{\sqrt{6}} & K^0\\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}}\end{pmatrix},\quad \mathbb{V}=\begin{pmatrix}\frac{\rho^0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+}\\ \rho^- & -\frac{\rho^0}{\sqrt{2}}+\frac{\omega}{\sqrt{2}} & K^{*0}\\ K^{*-} & \bar{K}^{*0} & \phi\end{pmatrix}.$$



中程

$0.8\ \mathrm{fm} \le r \le 2.0\ \mathrm{fm}$

长程

$r \ge 2.0\ \mathrm{fm}$

短程

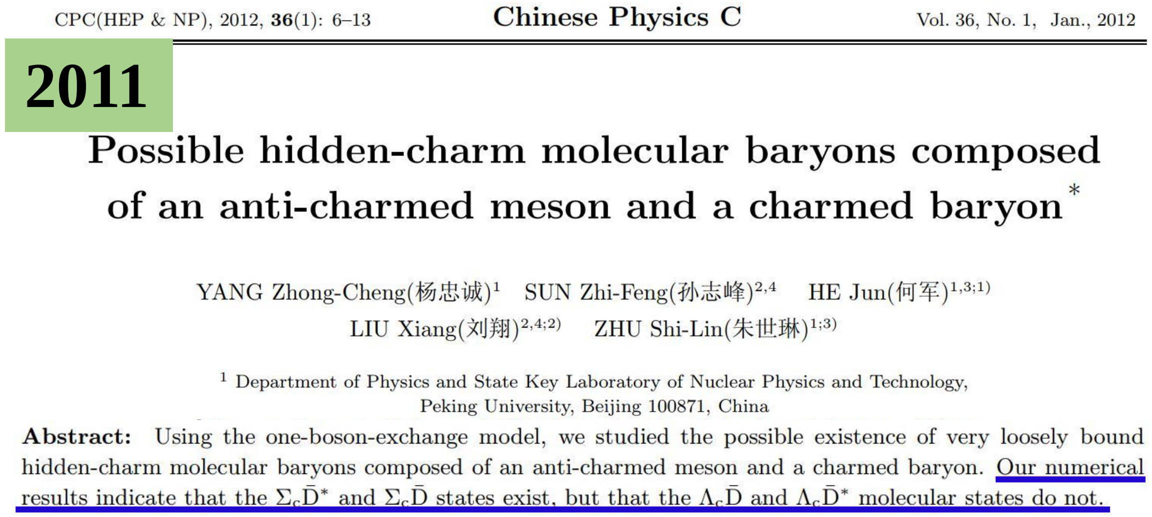
$r \le 0.8\ \mathrm{fm}$

- 在强子间相互作用的研究中考虑各种效应（修正）——更精细的结构：
  ① S–D波混合效应；② 耦合道效应；③ 同位旋破缺效应； ④ 反冲修正；……

H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rept. 639, 1 (2016)

单玻色子交换模型对实验发现的重味强子分子态候选者的成功预言

2011



CPC(HEP & NP), 2012, **36**(1): 6–13 Chinese Physics C Vol. 36, No. 1, Jan., 2012

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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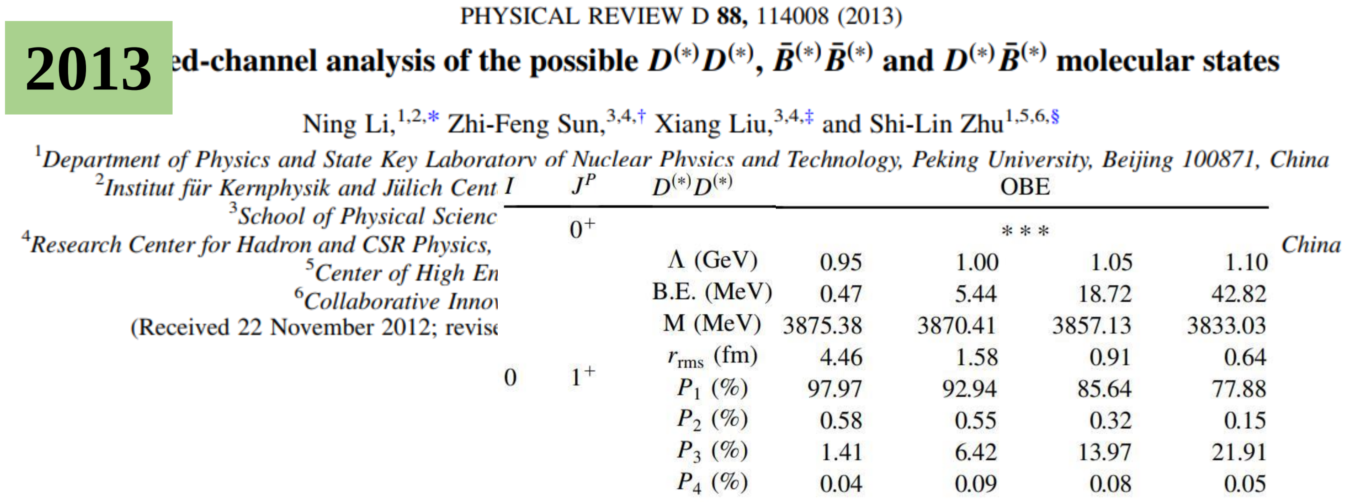
Peking University, Beijing 100871, China

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.

2013



PHYSICAL REVIEW D **88**, 114008 (2013)

ed-channel analysis of the possible $D^{(*)}D^{(*)}$, $\bar{B}^{(*)}\bar{B}^{(*)}$ and $D^{(*)}\bar{B}^{(*)}$ molecular states

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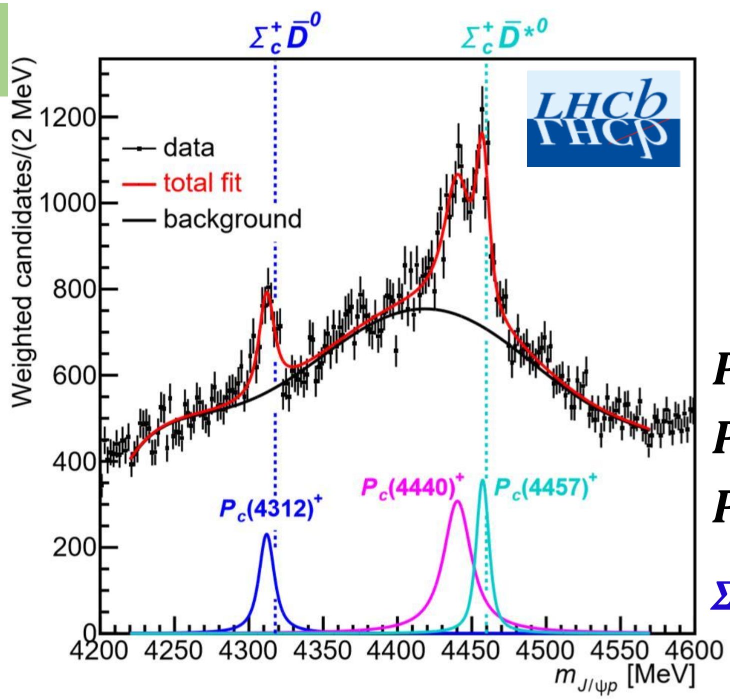
[6]Collaborative Innov

(Received 22 November 2012; revis

I	J^P	$D^{(*)}D^{(*)}$	OBE			
	0^+		* * *			
0	1^+	Λ (GeV)	0.95	1.00	1.05	1.10
		B.E. (MeV)	0.47	5.44	18.72	42.82
		M (MeV)	3875.38	3870.41	3857.13	3833.03
		$r_{\rm rms}$ (fm)	4.46	1.58	0.91	0.64
		P_1 (%)	97.97	92.94	85.64	77.88
		P_2 (%)	0.58	0.55	0.32	0.15
		P_3 (%)	1.41	6.42	13.97	21.91
		P_4 (%)	0.04	0.09	0.08	0.05

2019

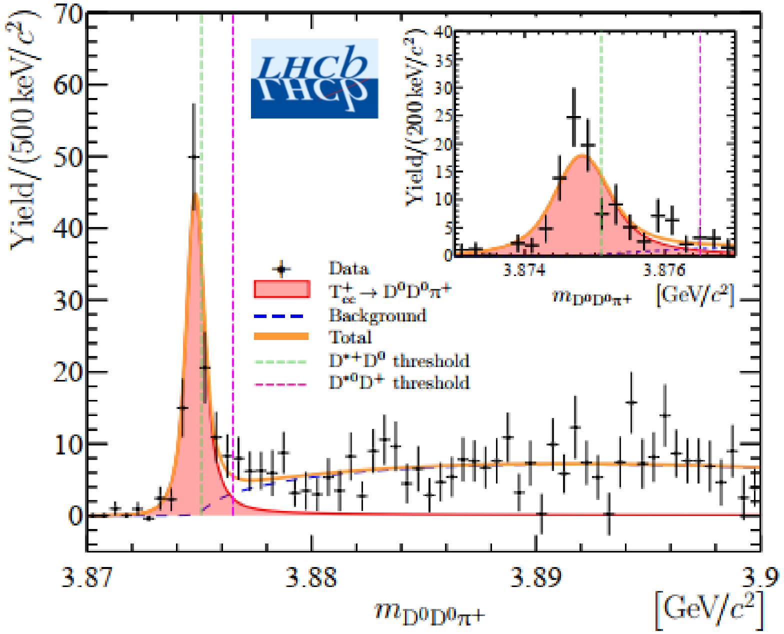


$P_\psi^N(4312)$
$P_\psi^N(4440)$
$P_\psi^N(4457)$

$\Sigma_c\bar{D}^{(*)}$分子态

[LHCb] PRL 122, 222001 (2019)

2021



$T_{cc}^+(3875)$

DD^* 分子态

[LHCb] Nature Phys. 18 (2022) 7, 751-754

在单玻色子交换模型中讨论强子分子态候选者的步骤

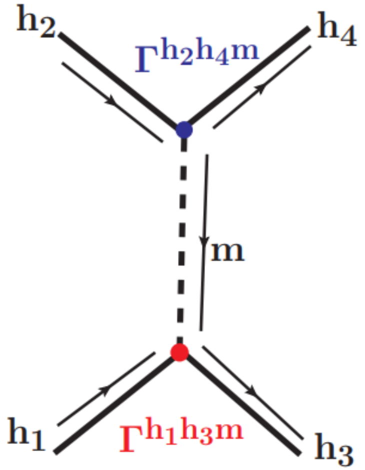
有效拉氏量方法 → 布雷特近似 → 傅里叶变换

散射振幅 → 动量空间的有效势 → 坐标空间的有效势

E. M. Lifshitz, Quantum electrodynamics, 1982

求解耦合道薛定谔方程

束缚态解: (i) 束缚能， (ii) 方均根半径，(iii) 每个道的贡献



$$i\mathcal{M}^{h_1h_2\to h_3h_4}(\boldsymbol{q}) = \sum_{m=\sigma,\mathbb{P},\mathbb{V}} i\Gamma^{h_1h_3m}_{(\mu)} P^{(\mu\nu)}_m i\Gamma^{h_2h_4m}_{(\nu)}$$

$$\mathcal{V}_E^{h_1h_2\to h_3h_4}(\boldsymbol{q}) = -\frac{\mathcal{M}^{h_1h_2\to h_3h_4}(\boldsymbol{q})}{\sqrt{\prod_i 2m_i \prod_f 2m_f}}$$

$$\mathcal{V}_E^{h_1h_2\to h_3h_4}(\boldsymbol{r}) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \mathcal{V}_E^{h_1h_2\to h_3h_4}(\boldsymbol{q}) \mathcal{F}^2(q^2, m_E^2)$$

形状因子：$\mathcal{F}(q^2, m_E^2) = \frac{\Lambda^2 - m_E^2}{\Lambda^2 - q^2}$

F. L. Wang, R. Chen, Z. W. Liu, and X. Liu, PRC 101, 025201 (2020)

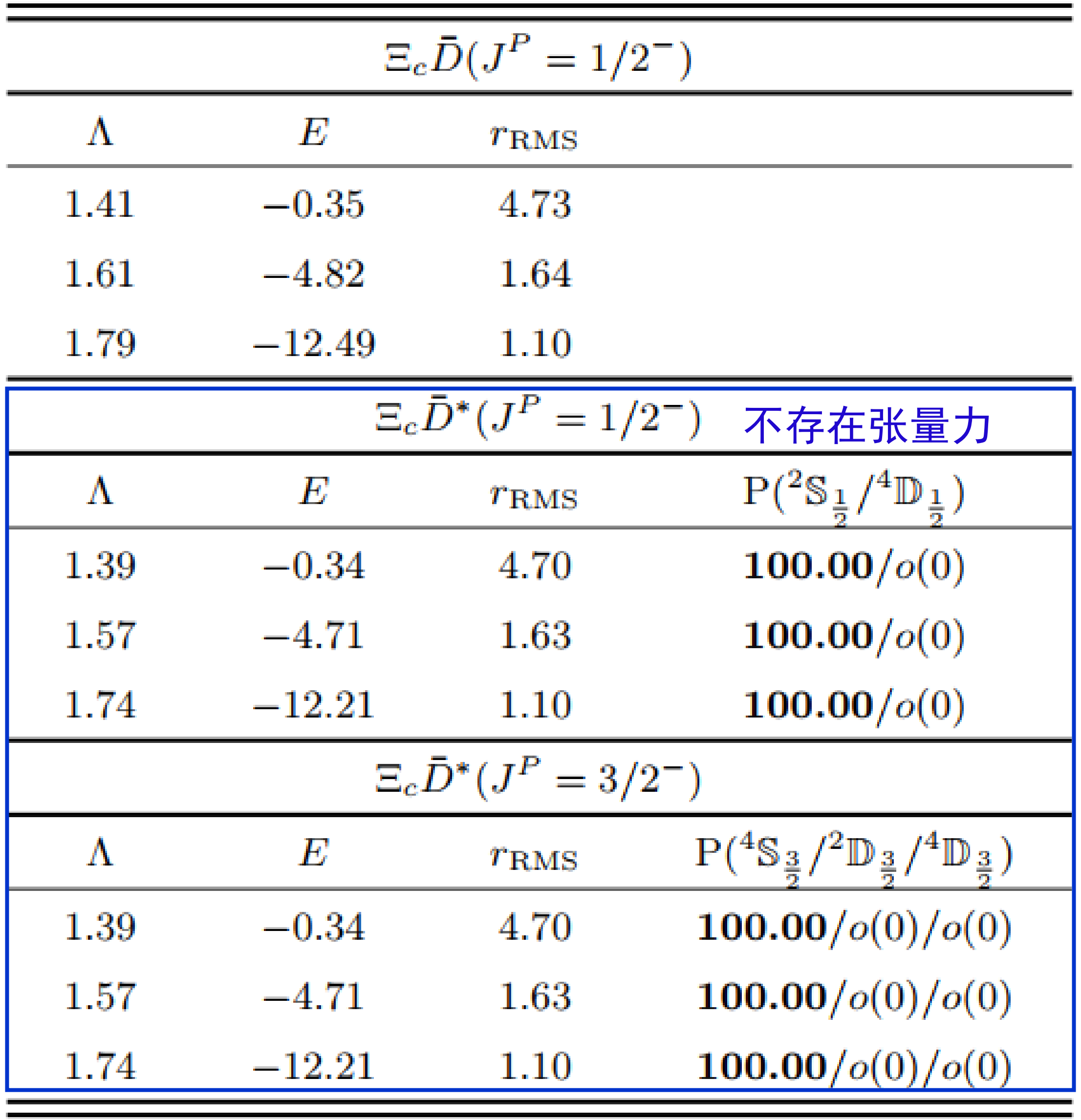
Models	Λ(MeV)	E(MeV)	$r_{\rm RMS}$(fm)
OPE($\mathbb{N}$)	/	/	/
OPE($\mathbb{Y}$)	1064	−2.23	3.74
OBE($\mathbb{N}$)	1174	−2.25	3.67
OBE($\mathbb{Y}$)	864	−2.26	3.75

Λ ~1.0 GeV

N. A. Tornqvist, Z. Phys. C 61, 525 (1994)

N. A. Tornqvist, Nuovo Cim. A 107, 2471 (1994)

同位旋标量的$\Xi_c\bar{D}^{(*)}$系统的束缚性质——单道/S-D波混合分析



Λ	E	$r_{\rm RMS}$	
	$\Xi_c\bar{D}(J^P=1/2^-)$		
1.41	−0.35	4.73	
1.61	−4.82	1.64	
1.79	−12.49	1.10	
	$\Xi_c\bar{D}^*(J^P=1/2^-)$		不存在张量力
Λ	E	$r_{\rm RMS}$	$\mathrm{P}({}^2\mathbb{S}_{\frac{1}{2}}/{}^4\mathbb{D}_{\frac{1}{2}})$
1.39	−0.34	4.70	**100.00**/$o(0)$
1.57	−4.71	1.63	**100.00**/$o(0)$
1.74	−12.21	1.10	**100.00**/$o(0)$
	$\Xi_c\bar{D}^*(J^P=3/2^-)$		
Λ	E	$r_{\rm RMS}$	$\mathrm{P}({}^4\mathbb{S}_{\frac{3}{2}}/{}^2\mathbb{D}_{\frac{3}{2}}/{}^4\mathbb{D}_{\frac{3}{2}})$
1.39	−0.34	4.70	**100.00**/$o(0)$/$o(0)$
1.57	−4.71	1.63	**100.00**/$o(0)$/$o(0)$
1.74	−12.21	1.10	**100.00**/$o(0)$/$o(0)$

$$\mathcal{V}^{\Xi_c\bar{D}^*} = 2l_B g_\sigma \mathcal{A}_1 Y_\sigma - \frac{3\beta\beta_B g_V^2}{4}\mathcal{A}_1 Y_\rho + \frac{\beta\beta_B g_V^2}{4}\mathcal{A}_1 Y_\omega$$

$$\mathcal{A}_1 = \chi_3^\dagger\left(\boldsymbol{\epsilon}_4^\dagger\cdot\boldsymbol{\epsilon}_2\right)\chi_1$$

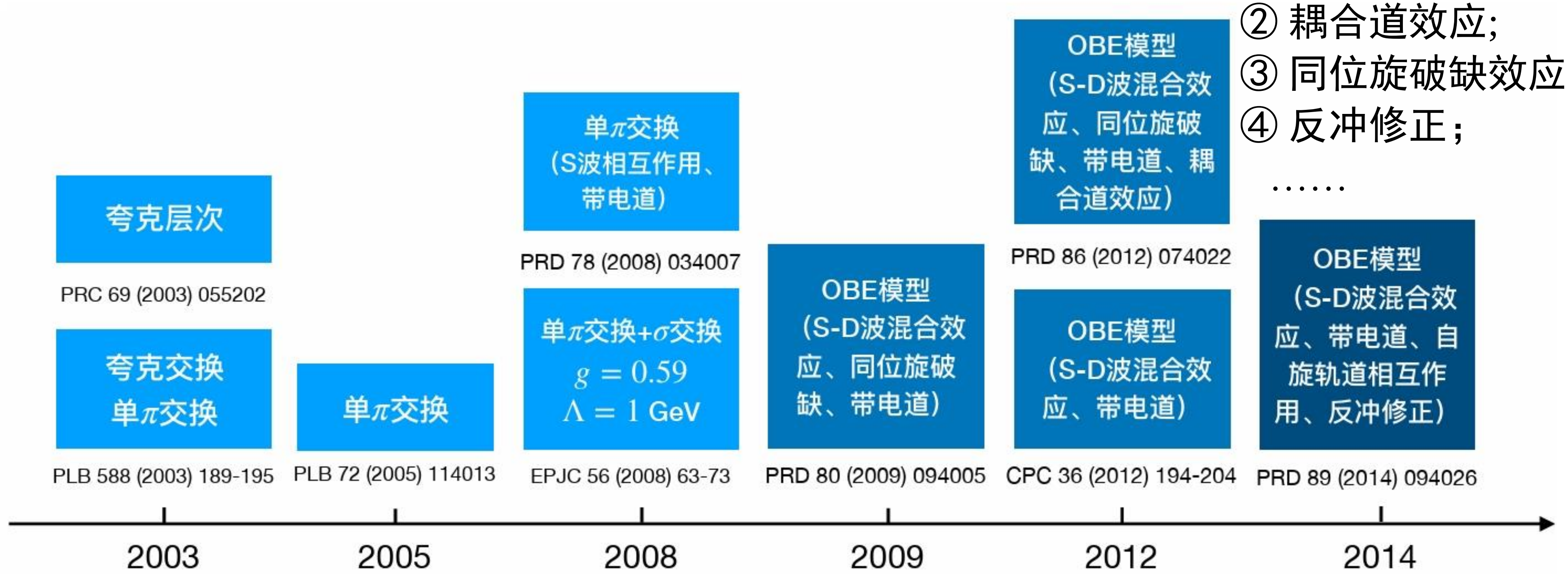
当截断参数相同时，同位旋标量的$\Xi_c\bar{D}^*$分子态出现了质量简并现象（相互作用没有自旋相互作用项）。

F. L. Wang and Xiang Liu, PLB 835, 137583 (2022)

根据研究$X(3872)$的经验，强子间相互作用的高精度研究中考虑更精细的结构

$D\bar{D}^*$系统相互作用

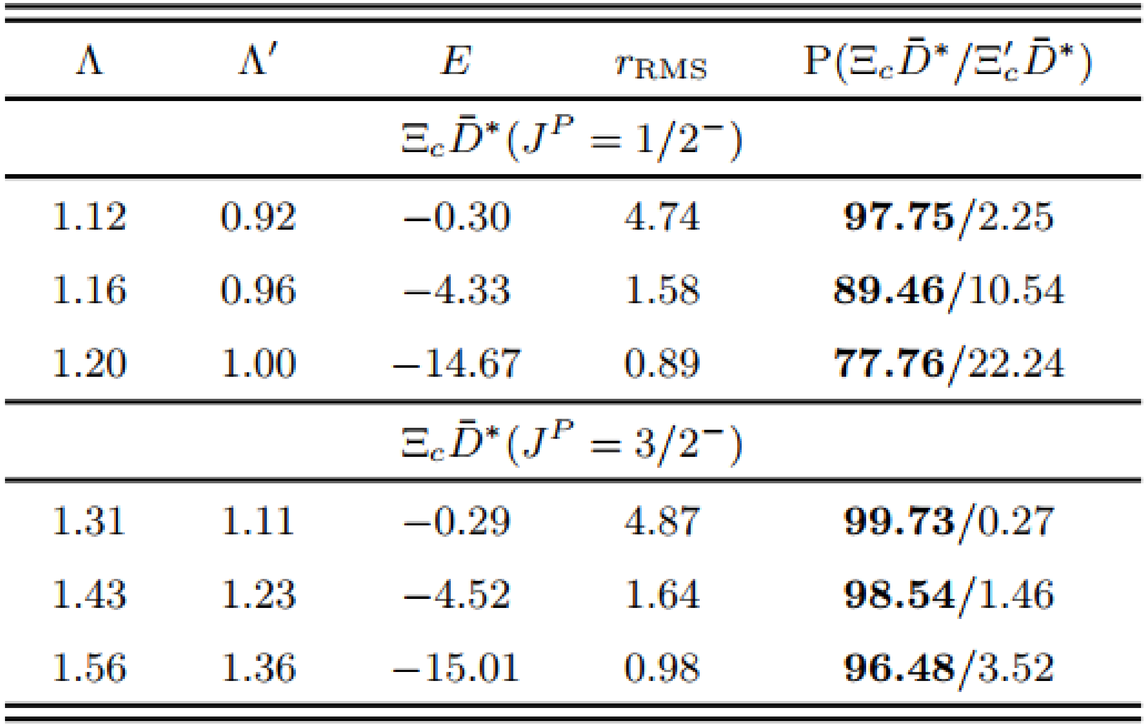
① S-D波混合效应;
② 耦合道效应;
③ 同位旋破缺效应;
④ 反冲修正；
……



H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rep. 639, 1 (2016)

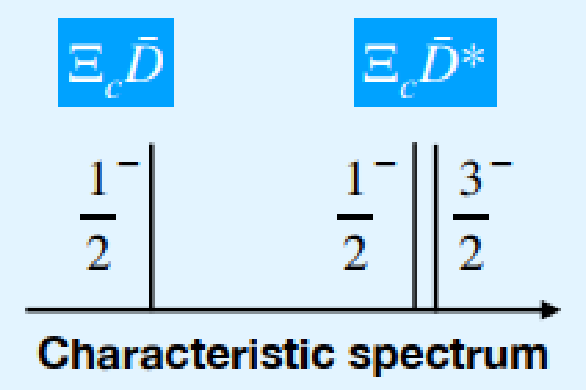
将$X(3872)$解释为$D\bar{D}^*$分子态时，$D\bar{D}^*$系统相互作用的高精度研究中考虑了越来越精细的结构。

同位旋标量的$\Xi_c\bar{D}^*$系统的束缚性质——耦合道分析



Λ	Λ'	E	$r_{\rm RMS}$	$\mathrm{P}(\Xi_c\bar{D}^*/\Xi_c'\bar{D}^*)$
		$\Xi_c\bar{D}^*(J^P=1/2^-)$		
1.12	0.92	−0.30	4.74	**97.75**/2.25
1.16	0.96	−4.33	1.58	**89.46**/10.54
1.20	1.00	−14.67	0.89	**77.76**/22.24
		$\Xi_c\bar{D}^*(J^P=3/2^-)$		
1.31	1.11	−0.29	4.87	**99.73**/0.27
1.43	1.23	−4.52	1.64	**98.54**/1.46
1.56	1.36	−15.01	0.98	**96.48**/3.52

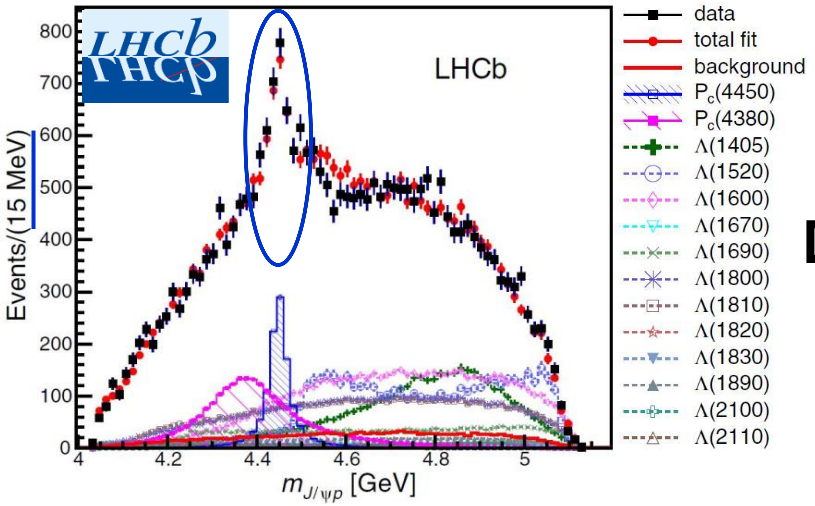
耦合道效应使同位旋标量的$\Xi_c\bar{D}^*$分子态的质量简并现象消失，分裂为两个态。



S波同位旋标量的$\Xi_c\bar{D}^{(*)}$分子态的特征能谱

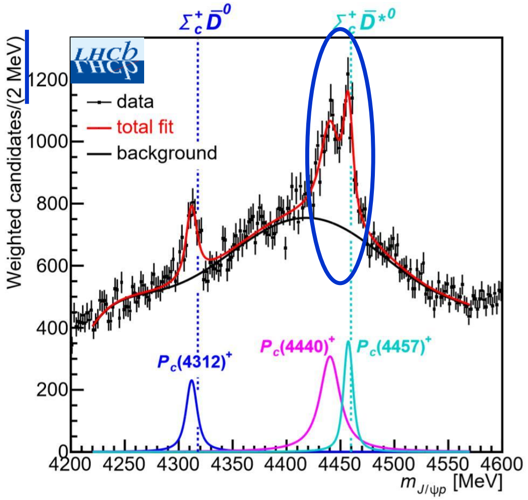
F. L. Wang and Xiang Liu, PLB 835, 137583 (2022)

对$P_{\psi s}^{\Lambda}(4459)$实验研究的理论建议



[LHCb], PRL 115, 072001 (2015)

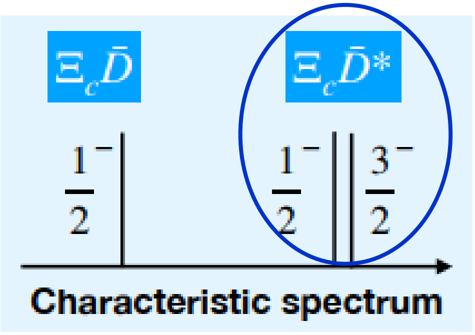
高精度的
实验数据

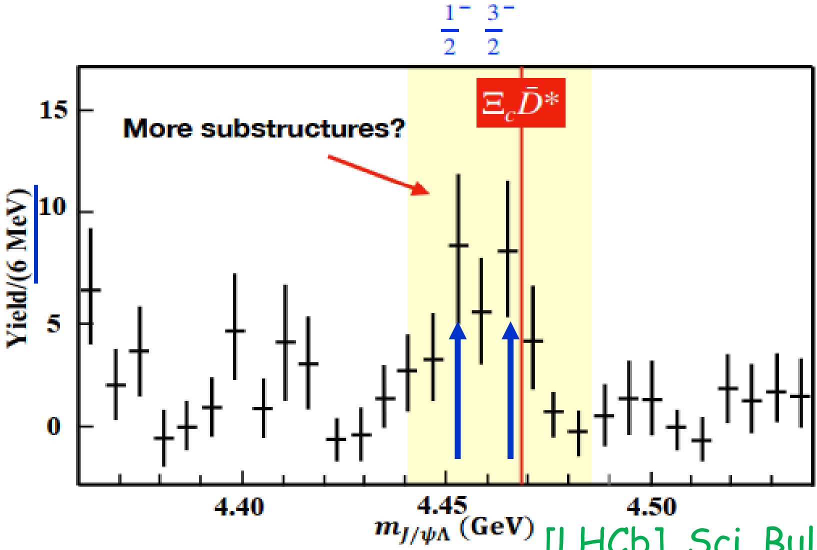


[LHCb], PRL 122, 222001 (2019)

$$P_c(4450) \Rightarrow P_c(4440) + P_c(4457)$$

类似情况在$P_{\psi s}^{\Lambda}$的研究中再次出现





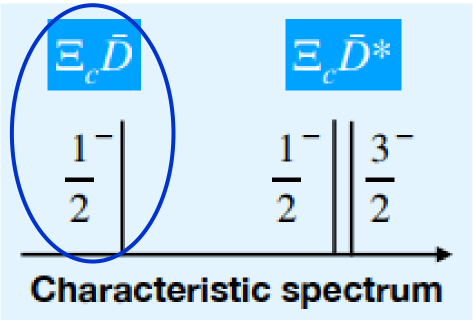
包含两个子结构

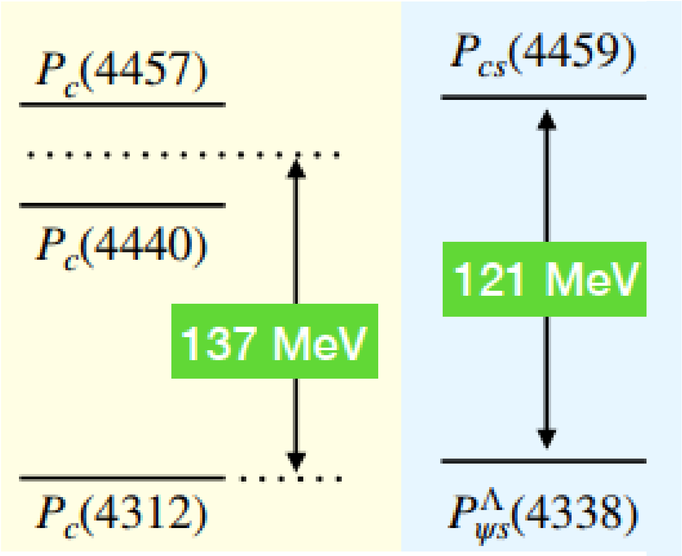
[LHCb], Sci. Bull. 66, 1278-1287 (2021)

建议实验上用高精度高统计量的实验数据研究$\Xi_c\bar{D}^*$道附近的增长结构

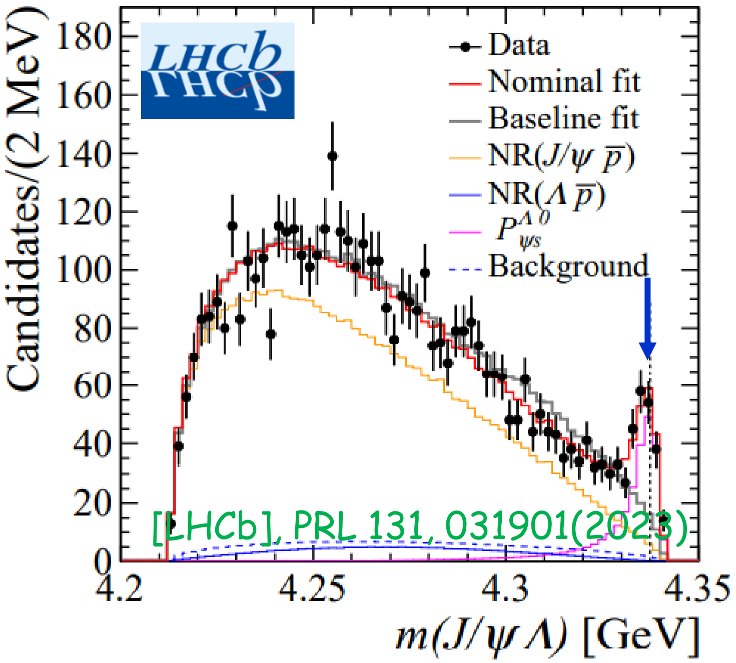
F. L. Wang and Xiang Liu, PLB 835, 137583 (2022)

对$P_{\psi s}^{\Lambda}(4338)$实验研究的理论建议





$P_{\psi s}^{\Lambda}(4322)$



[LHCb], PRL 131, 031901(2023)

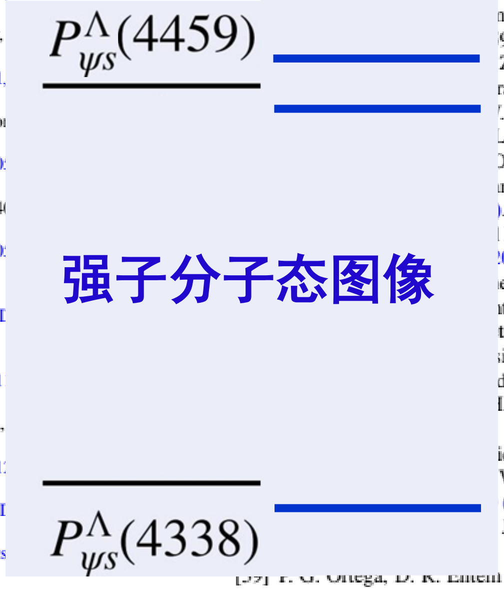
- Marek Karliner and Jonathan L. Rosner, PRD 106, 036024 (2022) ;
- M. J. Yan, F. Z. Peng, M. S´anchez S´anchez, and M. Pavon Valderrama, PRD 107, 074025 (2023) [**4326 MeV**];
- A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, and Y. Yamaguchi, PRD 108, 074012(2023) [**4336.34 MeV**];
- P. G. Ortega, D. R. Entem, and F. Fernandez, PLB 838 (2023) 137747 [**4318.1 MeV**];
- J. T. Zhu, S. Y. Kong, and J. He, PRD 107, 034029 (2023) [**4335 MeV**];
- K. Chen, Z. Y. Lin, and S. L. Zhu, PRD 106, 116017 (2022) [**4328.5 MeV**] ;
- Z. Y. Yang, F. Z. Peng, M. J. Yan, Mario S´anchez S´anchez, and Manuel Pavon Valderrama, arXiv:2211.08211 [**4327.4 MeV**] ;
- ……

建议实验上通过$\Xi_b^- \longrightarrow J/\psi\Lambda K^-$过程确认$P_{\psi s}^{\Lambda}(4338)$对应的增长结构的共振态参数

F. L. Wang and Xiang Liu, PLB 835, 137583 (2022)

$P_{\psi s}^{\Lambda}(4459)$和$P_{\psi s}^{\Lambda}(4338)$的“双峰”和“质量”问题被广泛讨论

$P_{\psi s}^{\Lambda}(4459)$和$P_{\psi s}^{\Lambda}(4338)$的“双峰”和“质量”问题在理论上被广泛讨论，
理论研究结果需要高精度高统计量的实验数据的研究



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Lett. B **799**, 135051 (2019).
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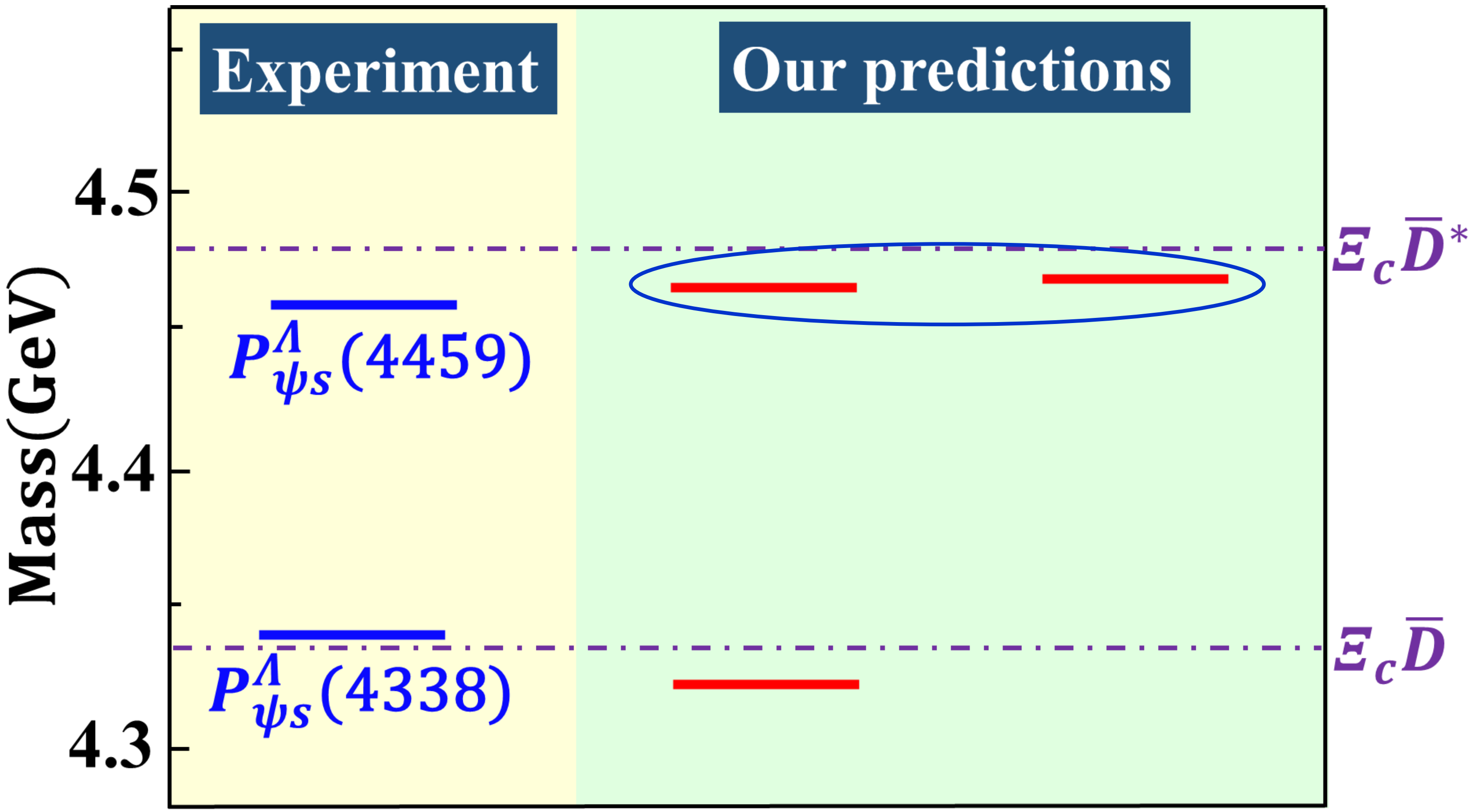
$\Xi_c\bar{D}^*$分子态的自旋-宇称量子数的确定



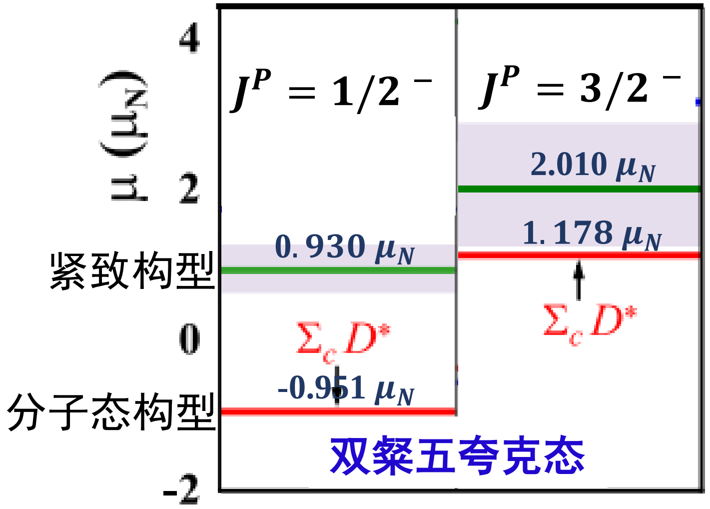
- 分波分析是实验上确定强子自旋-宇称量子数的有效途径，但是目前对隐粲五夸克态的分波分析仍然缺乏。
- 理论上需要为实验上讨论$\Xi_c\bar{D}^*$分子态的自旋-宇称量子数提供更多的研究途径。

3

$\Xi_c\bar{D}^*$分子态的电磁性质

强子的电磁性质——磁矩与辐射衰变宽度

- 磁矩与辐射衰变宽度是反映强子内部结构的重要电磁性质。
- 磁矩与辐射衰变宽度为确定强子的量子数与构型提供重要参考。
- 强子的磁矩与辐射衰变宽度是重要的实验可观测量。



H. Y. Zhou, **F. L. Wang**, Z. W. Liu, and X. Liu, PRD 106,034034 (2022)

- 强子电磁性质的研究模型与方法：

① 组分夸克模型；

② QCD求和规则；

③ 格点QCD模拟；

④ 手征微扰理论；

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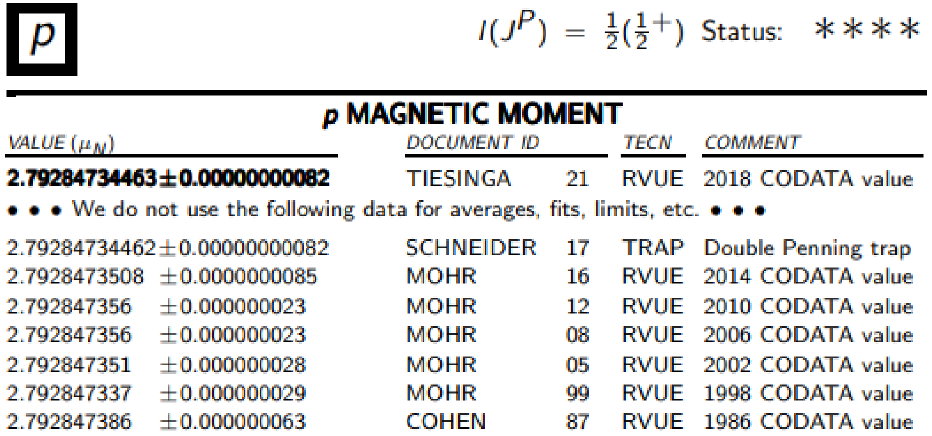


p $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

p MAGNETIC MOMENT

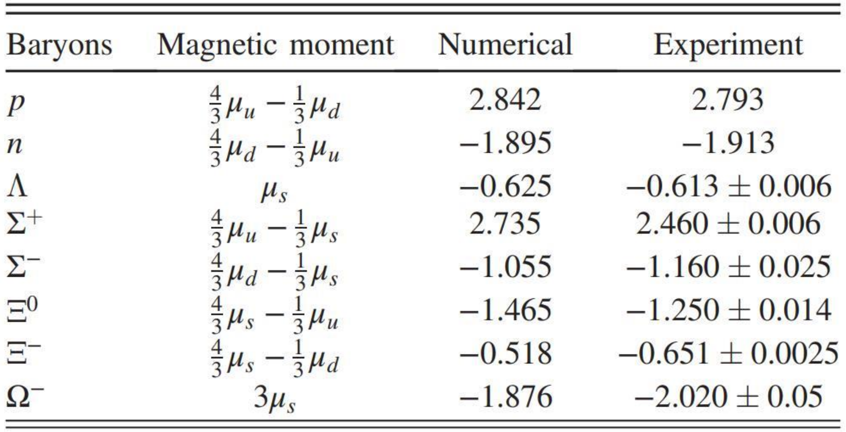
VALUE (μ_N)	DOCUMENT ID	TECN	COMMENT
2.79284734463±0.00000000082	TIESINGA 21	RVUE	2018 CODATA value

• • • We do not use the following data for averages, fits, limits, etc. • • •

2.79284734462±0.00000000082	SCHNEIDER 17	TRAP	Double Penning trap
2.7928473508 ±0.0000000085	MOHR 16	RVUE	2014 CODATA value
2.792847356 ±0.000000023	MOHR 12	RVUE	2010 CODATA value
2.792847356 ±0.000000023	MOHR 08	RVUE	2006 CODATA value
2.792847351 ±0.000000028	MOHR 05	RVUE	2002 CODATA value
2.792847337 ±0.000000029	MOHR 99	RVUE	1998 CODATA value
2.792847386 ±0.000000063	COHEN 87	RVUE	1986 CODATA value

组分夸克模型被广泛的用于讨论强子的电磁性质

- 组分夸克模型成功的描述了轻味重子的磁矩。



Baryons	Magnetic moment	Numerical	Experiment
p	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_d$	2.842	2.793
n	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_u$	−1.895	−1.913
Λ	μ_s	−0.625	-0.613 ± 0.006
Σ^+	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_s$	2.735	2.460 ± 0.006
Σ^-	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_s$	−1.055	-1.160 ± 0.025
Ξ^0	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_u$	−1.465	-1.250 ± 0.014
Ξ^-	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_d$	−0.518	-0.651 ± 0.0025
Ω^-	$3\mu_s$	−1.876	-2.020 ± 0.05

G. J. Wang, R. Chen, L. Ma, X. Liu, and S. L. Zhu, PRD 94, 094018 (2016)

- 组分夸克模型被广泛的用于讨论分子态类型五夸克态的磁矩与辐射衰变宽度。
  - G. J. Wang, R. Chen, L. Ma, X. Liu, and S. L. Zhu, PRD 94, 094018 (2016)
  - M. W. Li, Z. W. Liu, Z. F. Sun, and R. Chen, PRD 104, 054016 (2021)
  - F. L. Wang, H. Y. Zhou, Z. W. Liu, and X. Liu, PRD 106, 054020 (2022)
  - H. Y. Zhou, F. L. Wang, Z. W. Liu, and X. Liu, PRD 106, 034034 (2022)
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  - F. L. Wang, S. Q. Luo, H. Y. Zhou, Z. W. Liu, and X. Liu, PRD 108, 034006 (2023)
  - F. L. Wang and X. Liu, PRD 108, 074022 (2023)
  - F. Guo and H. S. Li, arXiv:2304.10981
  - F. L. Wang and X. Liu, PRD 109, 014043 (2024)
  - H. S. Li, F. Guo, Y. D. Lei, and F. Gao, arXiv:2401.14767
  - B. J. Lai, F. L. Wang, and X. Liu, PRD 109, 054036(2024)
  - ……

强子磁矩的研究模型——组分夸克模型

- 在组分夸克模型中，强子的磁矩是其组分的自旋磁矩与轨道磁矩的矢量和。

$$\hat{\mu}_z = \hat{\mu}_z^{\text{spin}} + \hat{\mu}_z^{\text{orbital}}$$

$$\hat{\mu}_z^{\text{spin}} = \sum_i \frac{e_i}{2M_i}\hat{\sigma}_{iz}$$

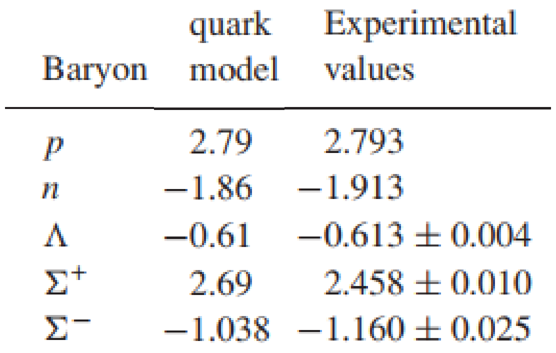
$$\hat{\mu}_z^{\text{orbital}} = \mu_{bm}^L \hat{L}_z = \left(\frac{M_m}{M_b+M_m}\frac{e_b}{2M_b} + \frac{M_b}{M_b+M_m}\frac{e_m}{2M_m}\right)\hat{L}_z$$

Y. R. Liu, P. Z. Huang, W. Z. Deng, X. L. Chen, and S. L. Zhu, PRC 69, 035205 (2004)
P. Z. Huang, Y. R. Liu, W. Z. Deng, X. L. Chen, and S. L. Zhu, PRD 70, 034003 (2004)

- 强子的磁矩通过计算磁矩算符的期望值得到：

$$\mu_H = \langle J_H, J_H | \hat{\mu}_z | J_H, J_H \rangle \qquad \psi = \omega_{\text{color}} \otimes \chi_{\text{flavor}} \otimes \chi_{\text{spin}} \otimes R_{\text{space}}$$

构造强子的波函数！



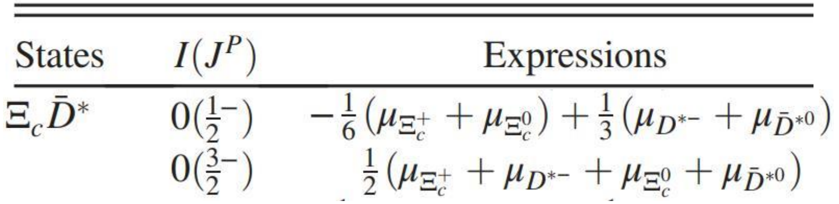
Baryon	quark model	Experimental values
p	2.79	2.793
n	−1.86	−1.913
Λ	−0.61	−0.613 ± 0.004
Σ^+	2.69	2.458 ± 0.010
Σ^-	−1.038	−1.160 ± 0.025

- 输入的参数——组分夸克质量：

$$m_u = 0.336\ \text{GeV},\quad m_d = 0.336\ \text{GeV},\ m_s = 0.450\ \text{GeV},\ m_c = 1.680\ \text{GeV}$$

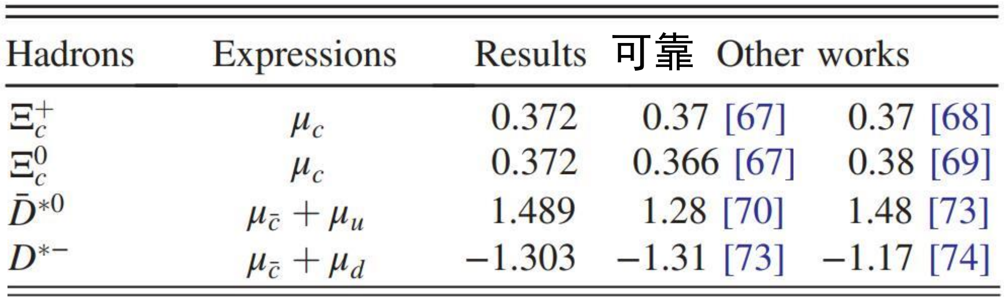
S. Kumar, R. Dhir, and R. C. Verma, J. Phys. G 31, 141-147 (2005)

$\Xi_c\bar{D}^*$分子态的磁矩



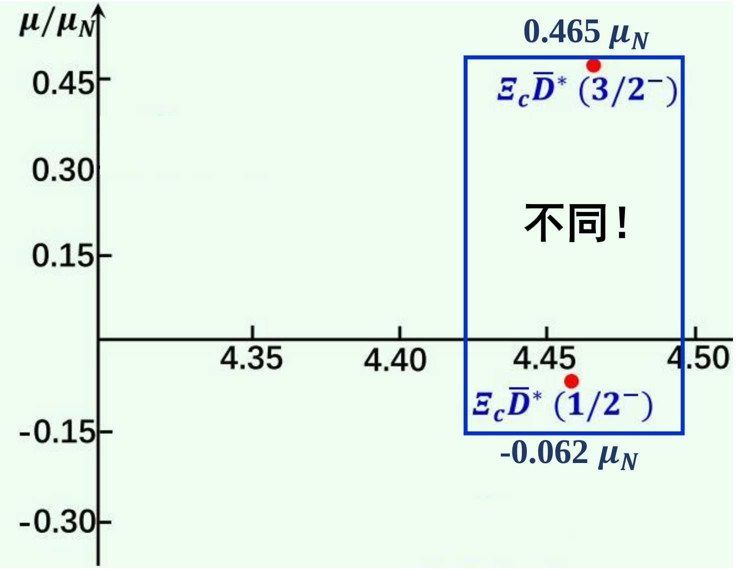
States	$I(J^P)$	Expressions
$\Xi_c\bar{D}^*$	$0(\frac{1}{2}^-)$	$-\frac{1}{6}(\mu_{\Xi_c^+}+\mu_{\Xi_c^0})+\frac{1}{3}(\mu_{D^{*-}}+\mu_{\bar{D}^{*0}})$
	$0(\frac{3}{2}^-)$	$\frac{1}{2}(\mu_{\Xi_c^+}+\mu_{D^{*-}}+\mu_{\Xi_c^0}+\mu_{\bar{D}^{*0}})$

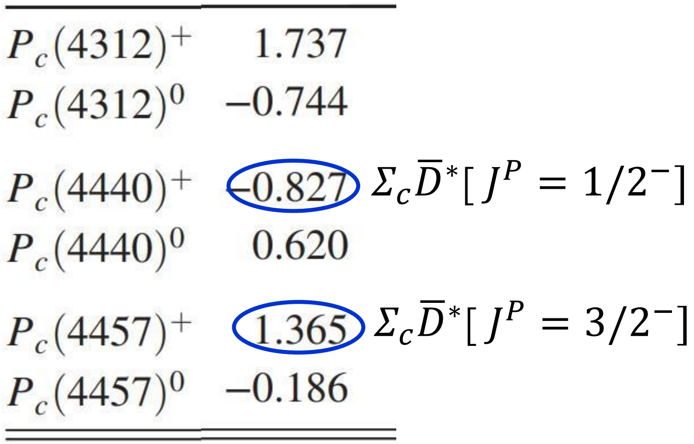
强子分子态的磁矩是其组分强子磁矩的线性组合



Hadrons	Expressions	Results	可靠 Other works	
Ξ_c^+	μ_c	0.372	0.37 [67]	0.37 [68]
Ξ_c^0	μ_c	0.372	0.366 [67]	0.38 [69]
$\bar{D}^{*0}$	$\mu_{\bar{c}}+\mu_u$	1.489	1.28 [70]	1.48 [73]
D^{*-}	$\mu_{\bar{c}}+\mu_d$	−1.303	−1.31 [73]	−1.17 [74]

[67] S. Kumar, R. Dhir, and R. C. Verma, J. Phys. G 31, 141 (2005); [68] A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Korner, V. E.Lyubovitskij, D. Nicmorus, and K. Pumsa-ard, PRD 73, 094013 (2006); [69] L. Y. Glozman and D. O. Riska, Nucl. Phys. A603, 326(1996); A620, 510 (1997); [70] V. Simonis, arXiv:1803.01809; [73] B. Wang, B. Yang, L. Meng, and S. L. Zhu, PRD 100, 016019 (2019);[74] S. K. Bose and L. P. Singh, PRD 22, 773 (1980).





$P_c(4312)^+$	1.737	
$P_c(4312)^0$	−0.744	
$P_c(4440)^+$	−0.827	$\Sigma_c\bar{D}^*[J^P=1/2^-]$
$P_c(4440)^0$	0.620	
$P_c(4457)^+$	1.365	$\Sigma_c\bar{D}^*[J^P=3/2^-]$
$P_c(4457)^0$	−0.186	

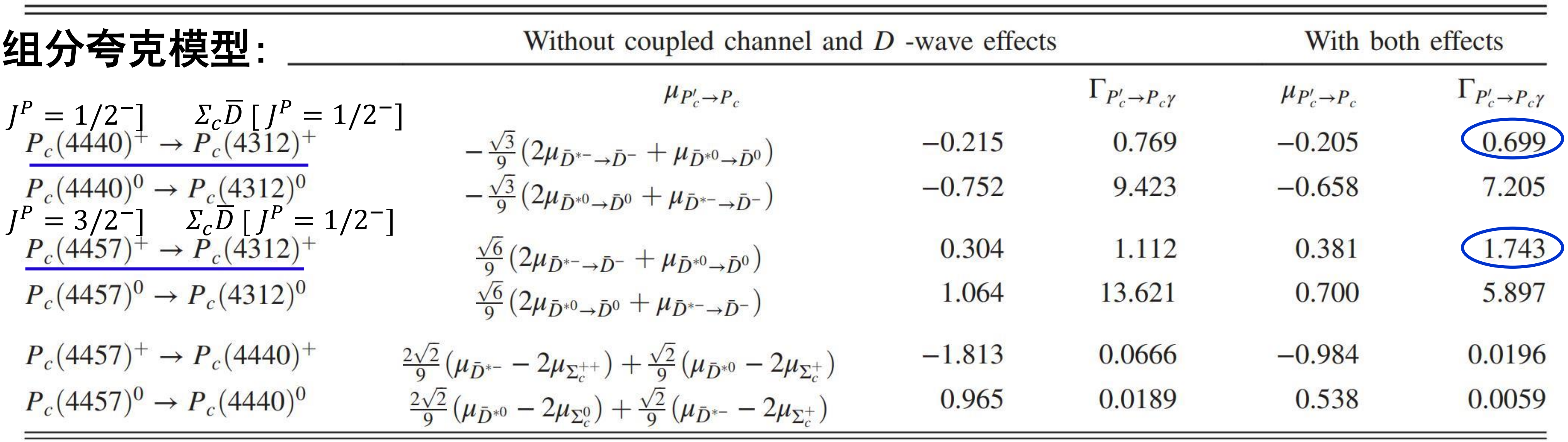
M. W. Li, Z. W. Liu, Z. F. Sun and R. Chen, PRD 104, 054016 (2021)

磁矩是实验上讨论$\Xi_c\bar{D}^*$分子态的自旋-宇称量子数的可行途径

F. L. Wang, Hong-Yan Zhou, Zhan-Wei Liu, and Xiang Liu, PRD, 106, 054020 (2022)

辐射衰变行为是研究$P_\psi^N(4440)$与$P_\psi^N(4457)$自旋-宇称量子数的可行途径

组分夸克模型：



$\Sigma_c\bar{D}^*[J^P=1/2^-]$ $\Sigma_c\bar{D}[J^P=1/2^-]$

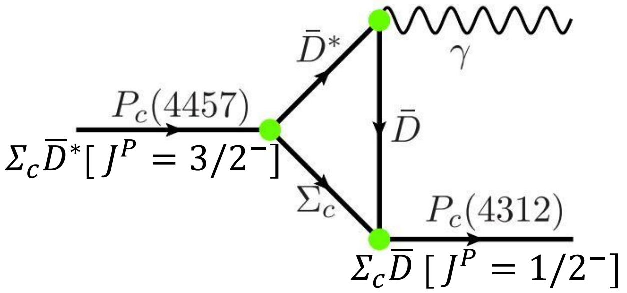
$\Sigma_c\bar{D}^*[J^P=3/2^-]$ $\Sigma_c\bar{D}[J^P=1/2^-]$

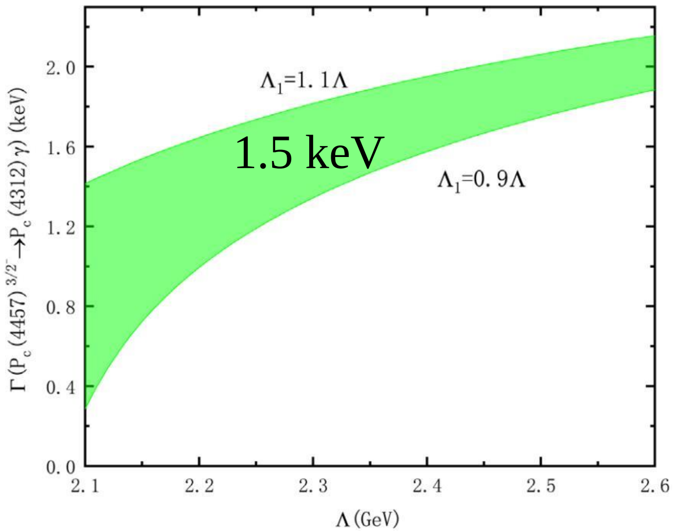
		Without coupled channel and D -wave effects		With both effects	
	$\mu_{P_c'\to P_c}$		$\Gamma_{P_c'\to P_c\gamma}$	$\mu_{P_c'\to P_c}$	$\Gamma_{P_c'\to P_c\gamma}$
$P_c(4440)^+\to P_c(4312)^+$	$-\frac{\sqrt{3}}{9}(2\mu_{\bar{D}^{*-}\to\bar{D}^-}+\mu_{\bar{D}^{*0}\to\bar{D}^0})$	−0.215	0.769	−0.205	0.699
$P_c(4440)^0\to P_c(4312)^0$	$-\frac{\sqrt{3}}{9}(2\mu_{\bar{D}^{*0}\to\bar{D}^0}+\mu_{\bar{D}^{*-}\to\bar{D}^-})$	−0.752	9.423	−0.658	7.205
$P_c(4457)^+\to P_c(4312)^+$	$\frac{\sqrt{6}}{9}(2\mu_{\bar{D}^{*-}\to\bar{D}^-}+\mu_{\bar{D}^{*0}\to\bar{D}^0})$	0.304	1.112	0.381	1.743
$P_c(4457)^0\to P_c(4312)^0$	$\frac{\sqrt{6}}{9}(2\mu_{\bar{D}^{*0}\to\bar{D}^0}+\mu_{\bar{D}^{*-}\to\bar{D}^-})$	1.064	13.621	0.700	5.897
$P_c(4457)^+\to P_c(4440)^+$	$\frac{2\sqrt{2}}{9}(\mu_{\bar{D}^{*-}}-2\mu_{\Sigma_c^{++}})+\frac{\sqrt{2}}{9}(\mu_{\bar{D}^{*0}}-2\mu_{\Sigma_c^+})$	−1.813	0.0666	−0.984	0.0196
$P_c(4457)^0\to P_c(4440)^0$	$\frac{2\sqrt{2}}{9}(\mu_{\bar{D}^{*0}}-2\mu_{\Sigma_c^0})+\frac{\sqrt{2}}{9}(\mu_{\bar{D}^{*-}}-2\mu_{\Sigma_c^+})$	0.965	0.0189	0.538	0.0059

可靠

M. W. Li, Z. W. Liu, Z. F. Sun, and R. Chen, PRD 104, 054016 (2021)

强子圈机制：





X. Z. Ling, J. X. Lu, M. Z. Liu, and L. S. Geng, PRD 104, 074022 (2021)

$\Xi_c\bar{D}^*$分子态的跃迁磁矩与辐射衰变行为

$$\mu_H = \langle J_H, J_H|\hat{\mu}_z|J_H, J_H\rangle$$

$$\mu_{H\to H'} = \langle J_{H'}, J_z|\hat{\mu}_z|J_H, J_z\rangle^{J_z=\text{Min}\{J_H, J_{H'}\}}$$

$$\Gamma_{H\to H'\gamma} = \frac{E_\gamma^3}{M_P^2}\frac{\alpha_{\text{EM}}}{2J_H+1}\frac{\sum_{J_{H'z},J_{Hz}}\begin{pmatrix} J_{H'} & 1 & J_H\\ -J_{H'z} & 0 & J_{Hz}\end{pmatrix}^2}{\begin{pmatrix} J_{H'} & 1 & J_H\\ -J_z & 0 & J_z\end{pmatrix}^2}\frac{|\mu_{H\to H'}|^2}{\mu_N^2} \qquad E_\gamma = \frac{M_H^2 - M_{H'}^2}{2M_H}$$

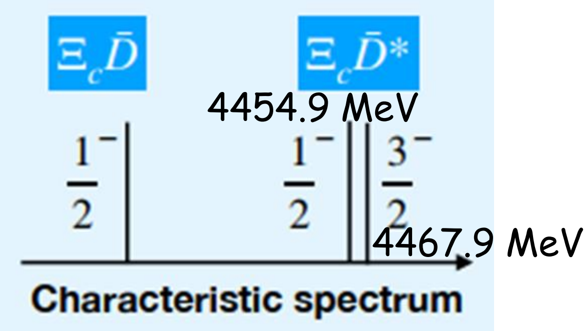
F. L. Wang, S. Q. Luo, H. Y. Zhou, Z. W. Liu, and X. Liu, PRD 108, 034006 (2023)

Decay modes	Expressions	Results
$\Xi_c\bar{D}^*\lvert\frac{1}{2}^-\rangle \to \Xi_c\bar{D}\lvert\frac{1}{2}^-\rangle\gamma$	$\frac{1}{2\sqrt{3}}(\mu_{D^{*-}\to D^-}+\mu_{\bar{D}^{*0}\to\bar{D}^0})$	−0.484
$\Xi_c\bar{D}^*\lvert\frac{3}{2}^-\rangle \to \Xi_c\bar{D}\lvert\frac{1}{2}^-\rangle\gamma$	$\frac{1}{\sqrt{6}}(\mu_{D^{*-}\to D^-}+\mu_{\bar{D}^{*0}\to\bar{D}^0})$	−0.684

强子分子态的跃迁磁矩是其组分强子跃迁磁矩的线性组合

Decay modes	Expressions	Results 可靠	Other works
$\bar{D}^{*0}\to\bar{D}^0\gamma$	$\mu_{\bar{c}}-\mu_u$	−2.234	−2.13 [73]
$D^{*-}\to D^-\gamma$	$\mu_{\bar{c}}-\mu_d$	0.558	0.54 [73]

[73] B. Wang, B. Yang, L. Meng, and S. L. Zhu, PRD 100, 016019 (2019)



[LHCb], Sci. Bull. 66, 1278-1287 (2021)

$$\Gamma(\Xi_c\bar{D}^*|1/2^-\rangle \to \Xi_c\bar{D}|1/2^-\rangle\gamma) = 3.596\ \text{keV}$$
$$\Gamma(\Xi_c\bar{D}^*|3/2^-\rangle \to \Xi_c\bar{D}|1/2^-\rangle\gamma) = 4.813\ \text{keV}$$

不同！

辐射衰变行为是实验上讨论$\Xi_c\bar{D}^*$分子态的自旋-宇称量子数的可行途径

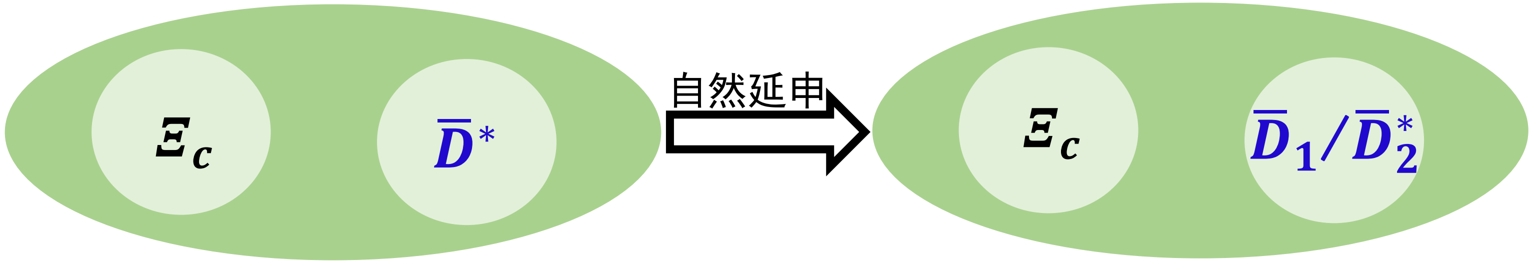
F. L. Wang, Hong-Yan Zhou, Zhan-Wei Liu, and Xiang Liu, PRD, 106, 054020 (2022)

4

$\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$以及$\Xi_c D^*$分子态候选者的理论预言

类似于$\Xi_c\bar{D}^*$分子态的质量谱行为是否存在于其它构型的$P_{\psi s}^{\Lambda}$分子态

- 通过研究$\Xi_c\bar{D}^*$分子态的自身性质讨论$P_{\psi s}^{\Lambda}(4459)$的“双峰”问题(直接途径)。
- 类似于 $\Xi_c\bar{D}^*$ 分子态的质量谱行为是否存在于其它构型的 $P_{\psi s}^{\Lambda}$ 分子态（间接途径）？



$$\underline{P\text{-波粲介子:}}\ S_l \equiv S_q + L = \frac{1}{2}\otimes 1 = \frac{1}{2}\oplus\frac{3}{2}$$

$$J \equiv S_l + S_Q = \frac{1}{2}\otimes\frac{1}{2} = 0\oplus 1 \qquad S = \left(0^+, 1^+\right)$$

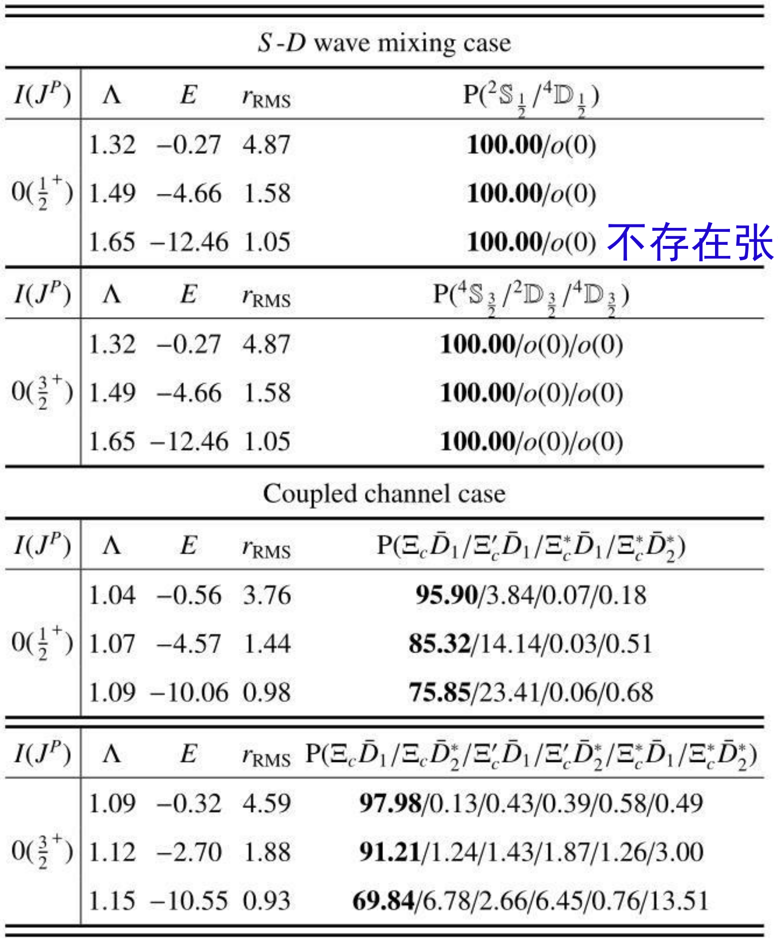
$$\boxed{D_1(2420)} \quad I(J^P) = \tfrac{1}{2}(1^+)$$

$$J \equiv S_l + S_Q = \frac{3}{2}\otimes\frac{1}{2} = 1\oplus 2 \qquad \boxed{T = \left(1^+, 2^+\right)}$$

$$\boxed{D_2^*(2460)} \quad I(J^P) = \tfrac{1}{2}(2^+)$$

$\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$分子态的谱学行为相同于$\Xi_c\bar{D}^*$分子态

- $\Xi_c\bar{D}_1$ 系统的束缚性质：



S-*D* wave mixing case

$I(J^P)$	Λ	E	$r_{\rm RMS}$	$P({}^2\mathbb{S}_{\frac{1}{2}}/{}^4\mathbb{D}_{\frac{1}{2}})$
$0(\frac{1}{2}^+)$	1.32	−0.27	4.87	**100.00**/$o(0)$
	1.49	−4.66	1.58	**100.00**/$o(0)$
	1.65	−12.46	1.05	**100.00**/$o(0)$

不存在张量力

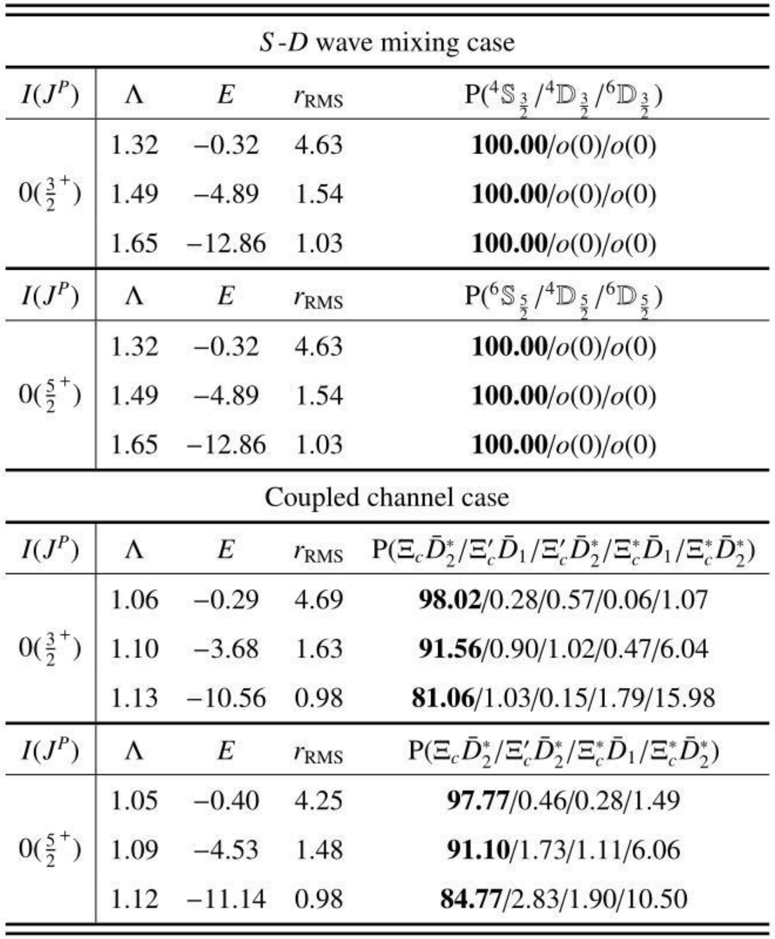
$I(J^P)$	Λ	E	$r_{\rm RMS}$	$P({}^4\mathbb{S}_{\frac{3}{2}}/{}^2\mathbb{D}_{\frac{3}{2}}/{}^4\mathbb{D}_{\frac{3}{2}})$
$0(\frac{3}{2}^+)$	1.32	−0.27	4.87	**100.00**/$o(0)$/$o(0)$
	1.49	−4.66	1.58	**100.00**/$o(0)$/$o(0)$
	1.65	−12.46	1.05	**100.00**/$o(0)$/$o(0)$

Coupled channel case

$I(J^P)$	Λ	E	$r_{\rm RMS}$	$P(\Xi_c\bar{D}_1/\Xi_c'\bar{D}_1/\Xi_c^*\bar{D}_1/\Xi_c^*\bar{D}_2^*)$
$0(\frac{1}{2}^+)$	1.04	−0.56	3.76	**95.90**/3.84/0.07/0.18
	1.07	−4.57	1.44	**85.32**/14.14/0.03/0.51
	1.09	−10.06	0.98	**75.85**/23.41/0.06/0.68

$I(J^P)$	Λ	E	$r_{\rm RMS}$	$P(\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*/\Xi_c'\bar{D}_1/\Xi_c'\bar{D}_2^*/\Xi_c^*\bar{D}_1/\Xi_c^*\bar{D}_2^*)$
$0(\frac{3}{2}^+)$	1.09	−0.32	4.59	**97.98**/0.13/0.43/0.39/0.58/0.49
	1.12	−2.70	1.88	**91.21**/1.24/1.43/1.87/1.26/3.00
	1.15	−10.55	0.93	**69.84**/6.78/2.66/6.45/0.76/13.51

- $\Xi_c\bar{D}_2^*$ 系统的束缚性质：



S-*D* wave mixing case

$I(J^P)$	Λ	E	$r_{\rm RMS}$	$P({}^4\mathbb{S}_{\frac{3}{2}}/{}^4\mathbb{D}_{\frac{3}{2}}/{}^6\mathbb{D}_{\frac{3}{2}})$
$0(\frac{3}{2}^+)$	1.32	−0.32	4.63	**100.00**/$o(0)$/$o(0)$
	1.49	−4.89	1.54	**100.00**/$o(0)$/$o(0)$
	1.65	−12.86	1.03	**100.00**/$o(0)$/$o(0)$

$I(J^P)$	Λ	E	$r_{\rm RMS}$	$P({}^6\mathbb{S}_{\frac{5}{2}}/{}^4\mathbb{D}_{\frac{5}{2}}/{}^6\mathbb{D}_{\frac{5}{2}})$
$0(\frac{5}{2}^+)$	1.32	−0.32	4.63	**100.00**/$o(0)$/$o(0)$
	1.49	−4.89	1.54	**100.00**/$o(0)$/$o(0)$
	1.65	−12.86	1.03	**100.00**/$o(0)$/$o(0)$

Coupled channel case

$I(J^P)$	Λ	E	$r_{\rm RMS}$	$P(\Xi_c\bar{D}_2^*/\Xi_c'\bar{D}_1/\Xi_c'\bar{D}_2^*/\Xi_c^*\bar{D}_1/\Xi_c^*\bar{D}_2^*)$
$0(\frac{3}{2}^+)$	1.06	−0.29	4.69	**98.02**/0.28/0.57/0.06/1.07
	1.10	−3.68	1.63	**91.56**/0.90/1.02/0.47/6.04
	1.13	−10.56	0.98	**81.06**/1.03/0.15/1.79/15.98

$I(J^P)$	Λ	E	$r_{\rm RMS}$	$P(\Xi_c\bar{D}_2^*/\Xi_c'\bar{D}_2^*/\Xi_c^*\bar{D}_1/\Xi_c^*\bar{D}_2^*)$
$0(\frac{5}{2}^+)$	1.05	−0.40	4.25	**97.77**/0.46/0.28/1.49
	1.09	−4.53	1.48	**91.10**/1.73/1.11/6.06
	1.12	−11.14	0.98	**84.77**/2.83/1.90/10.50

当截断参数相同时，同位旋标量的$\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$分子态发生了质量简并现象（没有自旋相互作用项）。

耦合道效应使同位旋标量的$\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$分子态的质量简并现象消失，分裂为两个态。

F. L. Wang and Xiang Liu, PRD 108, 054028 (2023)

$\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$分子态

澄清$P_{\psi s}^{\Lambda}(4459)$“双峰”问题的间接途径

$T_{cc}^+(3875)$的实验发现@2021年

nature physics

LETTERS

https://doi.org/10.1038/s41567-022-01614-y

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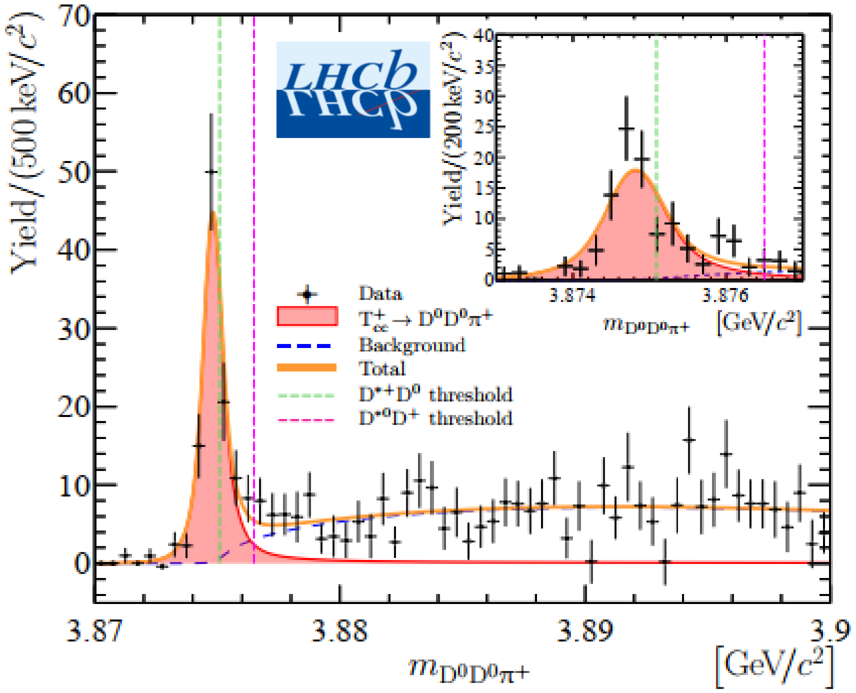
Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

双粲多夸克态



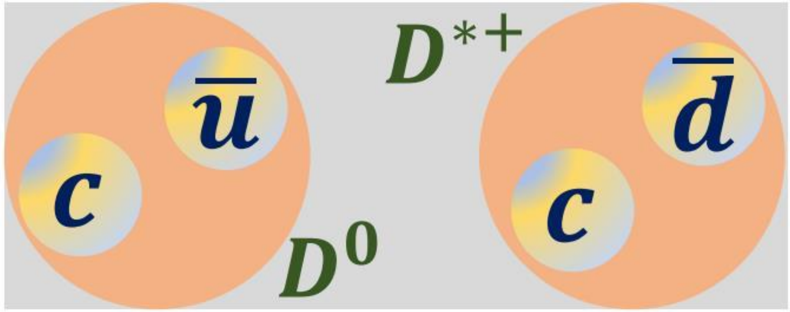
- 质量与宽度：

$$\delta m_{\rm BW} = -273 \pm 61 \pm 5\,^{+11}_{-14}\ \mathrm{keV}/c^2\,,$$

$$\Gamma_{\rm BW} = 410 \pm 165 \pm 43\,^{+18}_{-38}\ \mathrm{keV}\,,$$

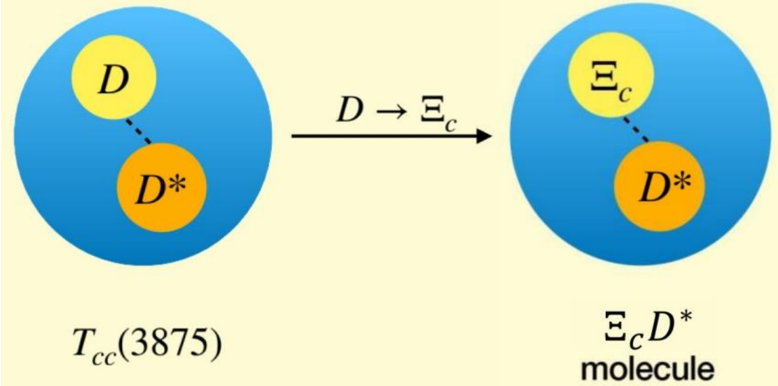
- $J^P = 1^+$的同位旋标量的态。

同位旋标量且$J^P = 1^+$的DD^*分子态



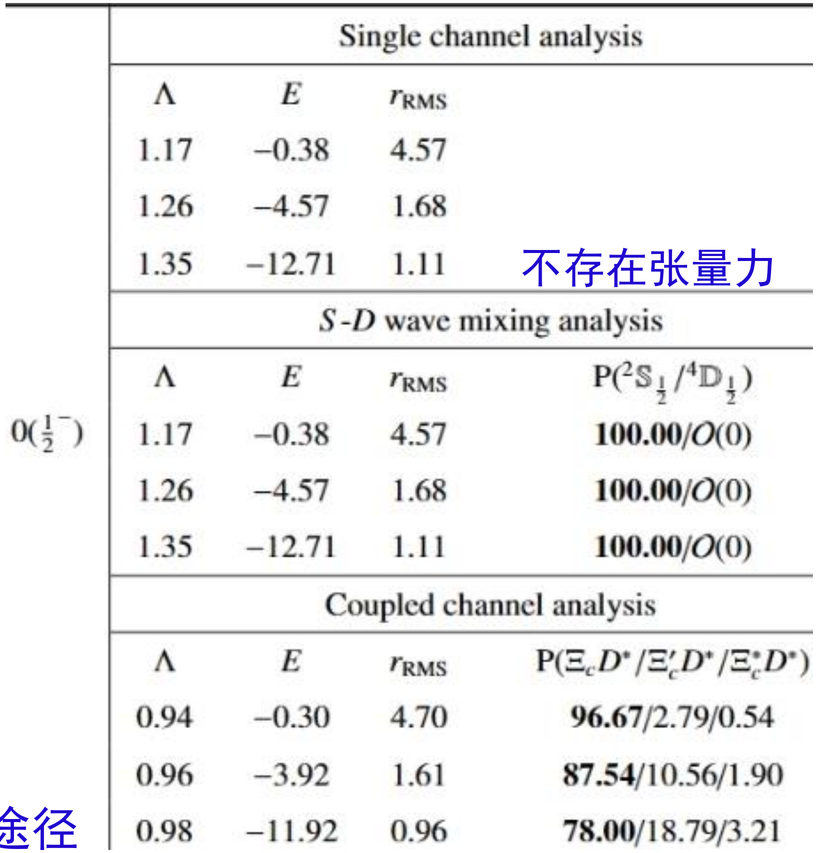
$\Xi_c D^*$分子态的谱学行为相同于$\Xi_c \bar{D}^*$分子态

- $\Xi_c D^*$系统的束缚性质：



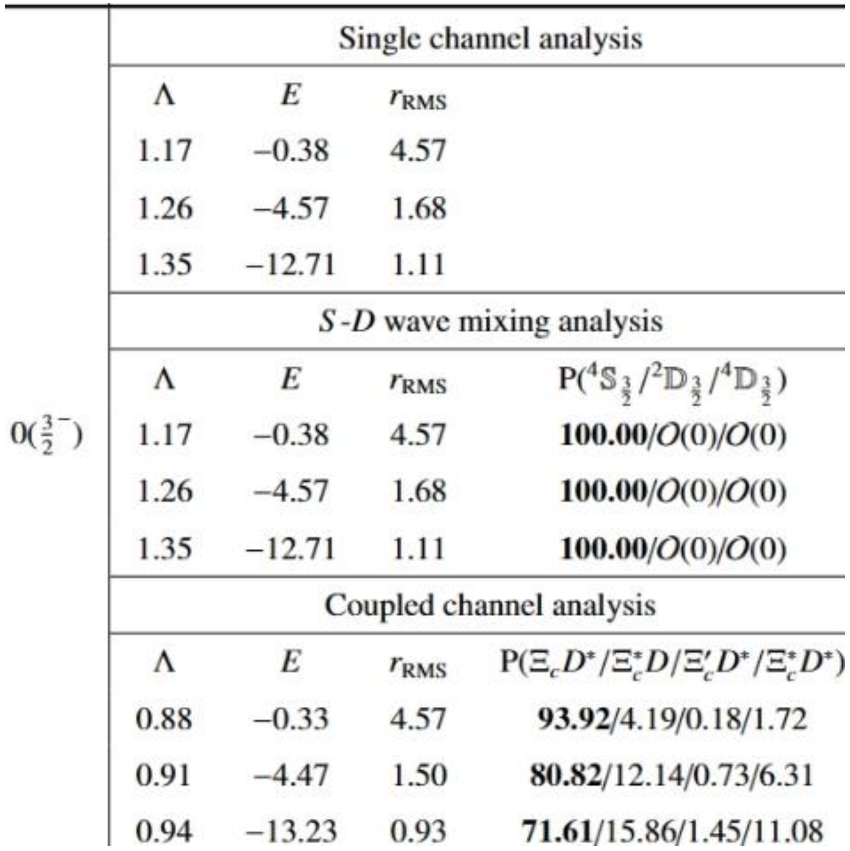
$\Xi_c D^*$分子态

澄清$P_{\psi s}^{\Lambda}(4459)$"双峰"问题的间接途径



	Single channel analysis			
	Λ	E	$r_{\rm RMS}$	
$0(\frac{1}{2}^-)$	1.17	−0.38	4.57	
	1.26	−4.57	1.68	
	1.35	−12.71	1.11	
	S-D wave mixing analysis			
	Λ	E	$r_{\rm RMS}$	$P(^2S_{\frac{1}{2}}/^4D_{\frac{1}{2}})$
	1.17	−0.38	4.57	**100.00**/O(0)
	1.26	−4.57	1.68	**100.00**/O(0)
	1.35	−12.71	1.11	**100.00**/O(0)
	Coupled channel analysis			
	Λ	E	$r_{\rm RMS}$	$P(\Xi_c D^*/\Xi_c' D^*/\Xi_c^* D^*)$
	0.94	−0.30	4.70	**96.67**/2.79/0.54
	0.96	−3.92	1.61	**87.54**/10.56/1.90
	0.98	−11.92	0.96	**78.00**/18.79/3.21

不存在张量力



	Single channel analysis			
	Λ	E	$r_{\rm RMS}$	
$0(\frac{3}{2}^-)$	1.17	−0.38	4.57	
	1.26	−4.57	1.68	
	1.35	−12.71	1.11	
	S-D wave mixing analysis			
	Λ	E	$r_{\rm RMS}$	$P(^4S_{\frac{3}{2}}/^2D_{\frac{3}{2}}/^4D_{\frac{3}{2}})$
	1.17	−0.38	4.57	**100.00**/O(0)/O(0)
	1.26	−4.57	1.68	**100.00**/O(0)/O(0)
	1.35	−12.71	1.11	**100.00**/O(0)/O(0)
	Coupled channel analysis			
	Λ	E	$r_{\rm RMS}$	$P(\Xi_c D^*/\Xi_c^* D/\Xi_c' D^*/\Xi_c^* D^*)$
	0.88	−0.33	4.57	**93.92**/4.19/0.18/1.72
	0.91	−4.47	1.50	**80.82**/12.14/0.73/6.31
	0.94	−13.23	0.93	**71.61**/15.86/1.45/11.08

当截断参数相同时，同位旋标量的$\Xi_c D^*$分子态发生了质量简并现象（没有自旋相互作用项）。

耦合道效应使同位旋标量的$\Xi_c D^*$分子态的质量简并现象消失，分裂为两个态。

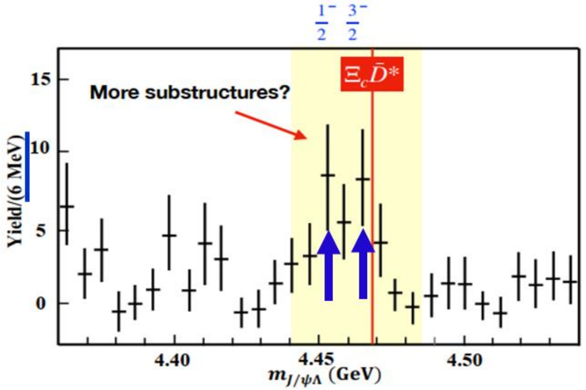
F. L. Wang and Xiang Liu, PRD 109, 014043 (2024)

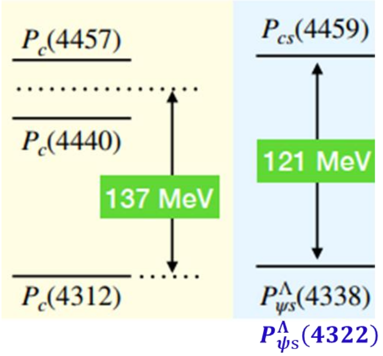
5

总 结

总结

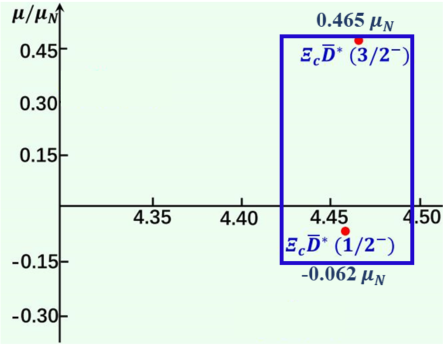
- 同位旋标量的$\Xi_c\bar{D}^{(*)}$分子态的特征能谱。





建议未来实验用高精度高统计量的实验数据讨论$\Xi_c\bar{D}^*$道附近的增长结构，通过 $\Xi_b^-\to J/\psi\Lambda K^-$过程确认$P_{\psi s}^{\Lambda}(4338)$的共振态参数。

- 电磁性质是研究$\Xi_c\bar{D}^*$分子态的自旋-宇称量子数的可行途径。

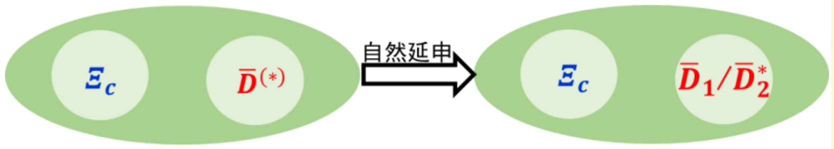


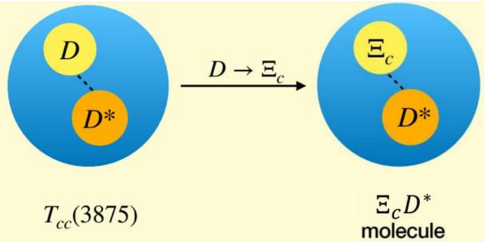
$$\Gamma(\Xi_c\bar{D}^*|1/2^-\rangle \to \Xi_c\bar{D}|1/2^-\rangle\gamma) = 3.596\ \text{keV}$$

$$\Gamma(\Xi_c\bar{D}^*|3/2^-\rangle \to \Xi_c\bar{D}|1/2^-\rangle\gamma) = 4.813\ \text{keV}$$

磁矩与辐射衰变行为是实验上讨论$\Xi_c\bar{D}^*$分子态的自旋-宇称量子数的可行途径。

- 类似于$\Xi_c\bar{D}^*$分子态的质量谱行为存在于其它构型的$P_{\psi s}^{\Lambda}$分子态。





讨论$\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$以及$\Xi_c D^*$分子态候选者，不仅是澄清$P_{\psi s}^{\Lambda}(4459)$结构的间接途径，而且丰富分子态类型重味五夸克态家族。

期望LHCb实验组的实验同仁能够关注我们的理论结果，
理论与实验紧密结合共同推动含奇异夸克的隐粲分子态类型五夸克态的研究！

谢谢大家！ 敬请批评指正！

自強不息
獨樹一幟