蘭州大學
LANZHOU UNIVERSITY

含奇异夸克的隐粲分子态类型五夸克态的特征能谱与电磁性质

王福来

合作者：刘翔、刘占伟、周虹妍

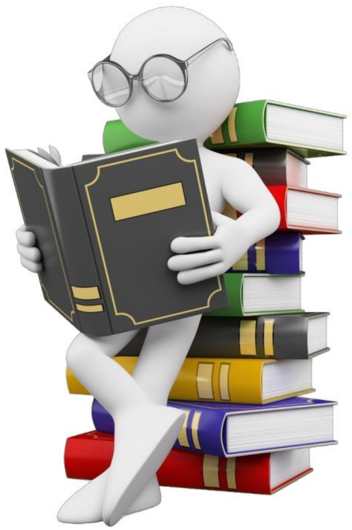
第八届XYZ粒子研讨会 2023年7月25-30日 吉林·长春

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

F. L. Wang and Xiang Liu, arXiv:2307.08276

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

提 纲



1. 研究背景

2. $\Xi_c\bar{D}^{(*)}$分子态的特征能谱

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

3. $\Xi_c^{(\prime,*)}\bar{D}_1/\Xi_c^{(\prime,*)}\bar{D}_2^*$分子态的预言

F. L. **Wang** and Xiang Liu, arXiv:2307.08276

4. $\Xi_c\bar{D}^{(*)}$分子态的的电磁性质

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

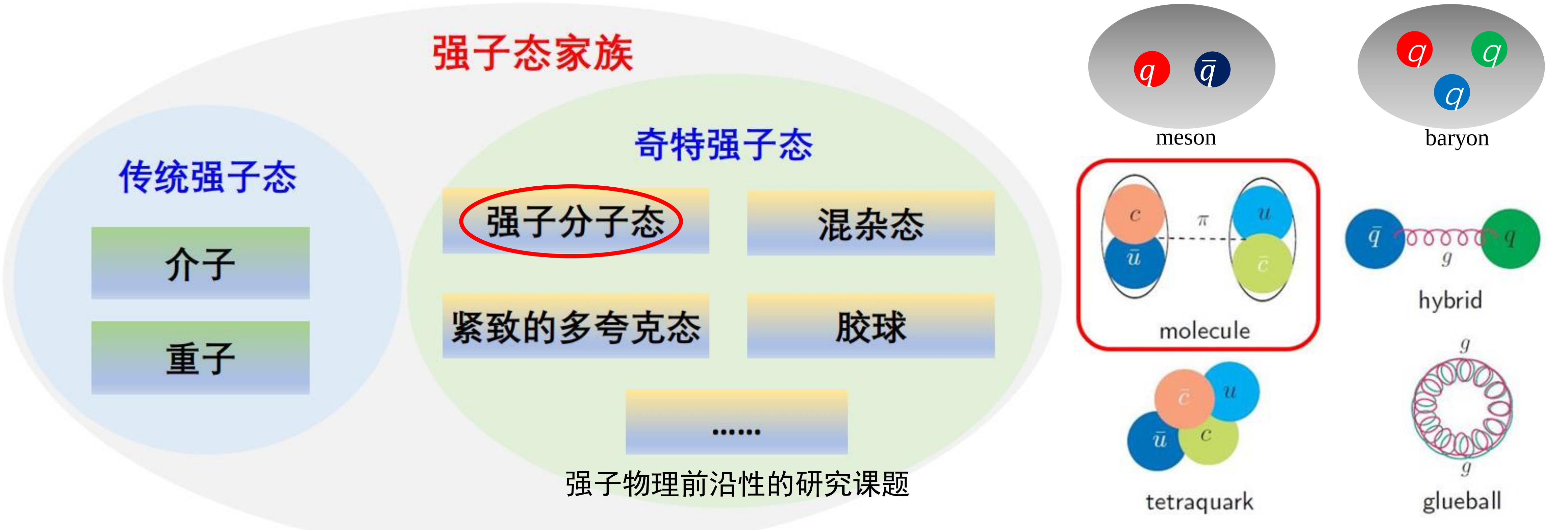
5. 总结

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、相互作用等问题。



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

- 在奇特强子态的研究中，强子分子态引起了大家的广泛关注。

强子分子态

- 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。

$P_c(4312)$
$P_c(4440)$ $\Sigma_c\bar{D}^{(*)}$分子态
$P_c(4457)$
[LHCb], PRL 122, 222001 (2019)

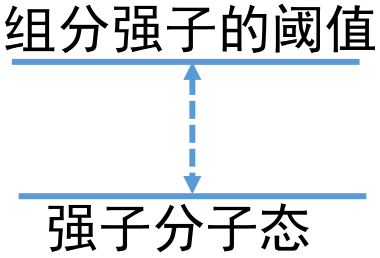
T_{cc}^{+} DD^*分子态
[LHCb], Nature Physics (2022)

- 强子分子态的典型特征：

a）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；

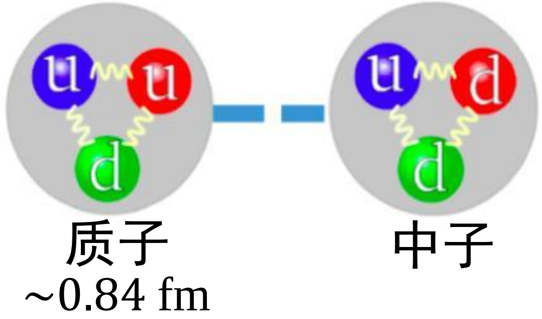
b）强子分子态的束缚较松散（较小的束缚能和较大的尺寸）。

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



- 氘核是由质子与中子形成的典型的分子态，有较小的束缚能($\sim$ 2.225 MeV)和较大的尺寸($\sim$3.9 fm)。

R. Machleidt, PRC 63, 024001 (2001)



在强子物理中，对隐粲分子态类型多夸克态的理论研究

- 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”

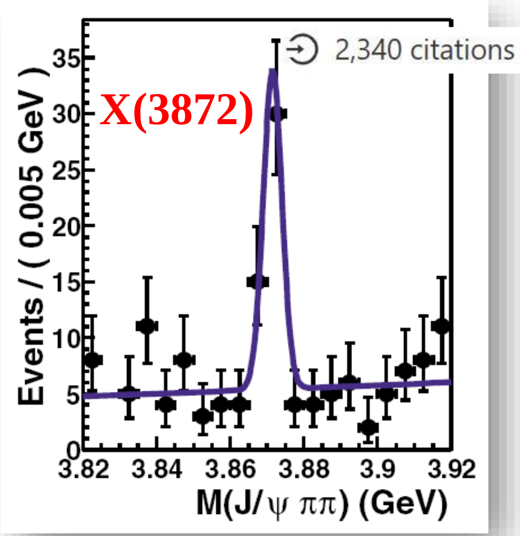
- 自2003年Belle实验组发现了类粲偶素$X(3872)$，强子物理中关于奇特强子态的研究发展得特别迅速，特别是重味强子分子态的研究。

$X/Y/Z/P_c/P_{cs}$态

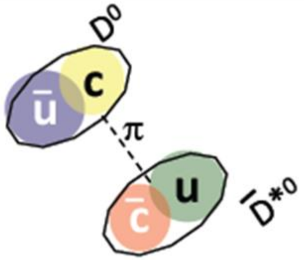
2003	$X(3872)$
2004	$Y(3940)$
2005	$Z(3930)$, $Y(4260)$
2006	
2007	$X(3940)$, $Y(4660)$, $Y(4360)$, $Y(4008)$
2008	$Y(4160)$, $Y(4630)$, $Z^+(4248)$, $Z^+(4051)$, $Z^+(4430)$
2009	$Y(4140)$
2010	$X(4350)$, $X(3915)$
2011	
2012	

大量新强子态的实验发现掀起了理论上研究奇特强子态的热潮！

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



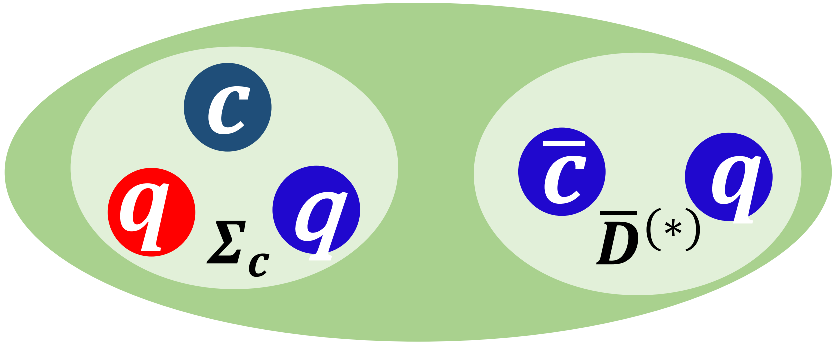
[Belle] PRL 91, 262001(2003)



- 在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

- 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, Chin. Phys. C 36, 6 (2012);
  - J. J. Wu, T.-S. H. Lee and B. S. Zou, Phys. Rev. C 85, 044002 (2012);
  - C. W. Xiao, J. Nieves, E. Oset, Phys. Rev. D 88 056012 (2013) ;
  - M. Karliner, J. L. Rosner, Phys. Rev. Lett. 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

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$P_c(4380)$与$P_c(4450)$@2015年

Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

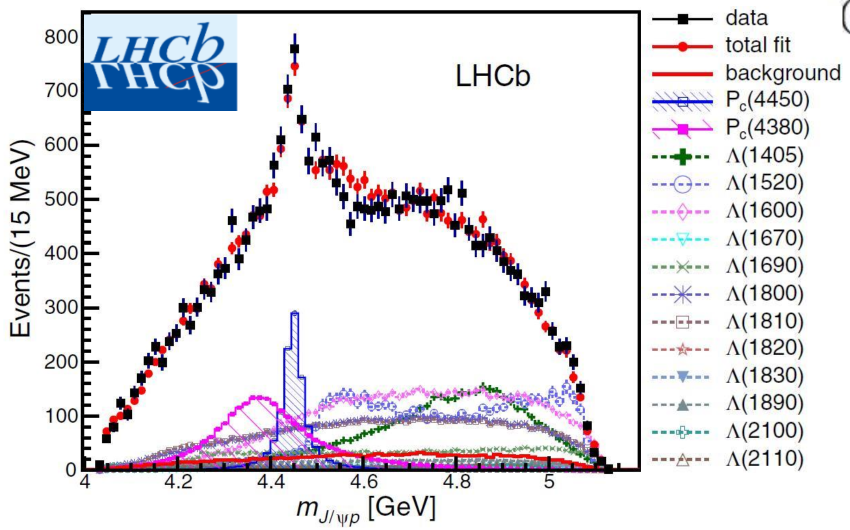
Run1

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

实验上首次发现五夸克物质

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

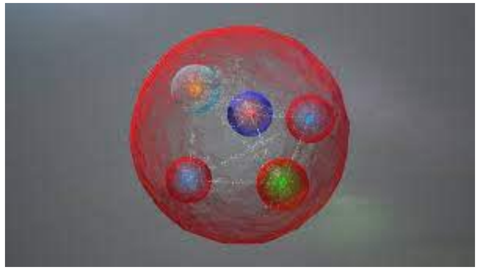
$\Lambda_b^0 \longrightarrow J/\psi p K^-$

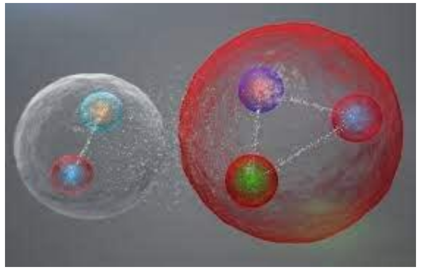


$$M_{P_c(4380)} = 4380 \pm 8 \pm 29\,\mathrm{MeV},$$
$$\Gamma_{P_c(4380)} = 205 \pm 18 \pm 86\,\mathrm{MeV},$$
$$M_{P_c(4450)} = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV},$$
$$\Gamma_{P_c(4450)} = 39 \pm 5 \pm 19\,\mathrm{MeV}$$

$P_c(4380)/P_c(4450)$的自旋宇称量子数J^P中的P宇称相反：
- 最好结果$(3/2^-, 5/2^+)$；
- 可接受结果$(3/2^+, 5/2^-)/(5/2^+, 3/2^-)$。

S波$\Sigma_c^{(*)}\bar{D}^{(*)}$系统的$P$宇称为负。


紧致五夸克态


分子态类型五夸克态

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。

2019年关于P_c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

Run1+Run2

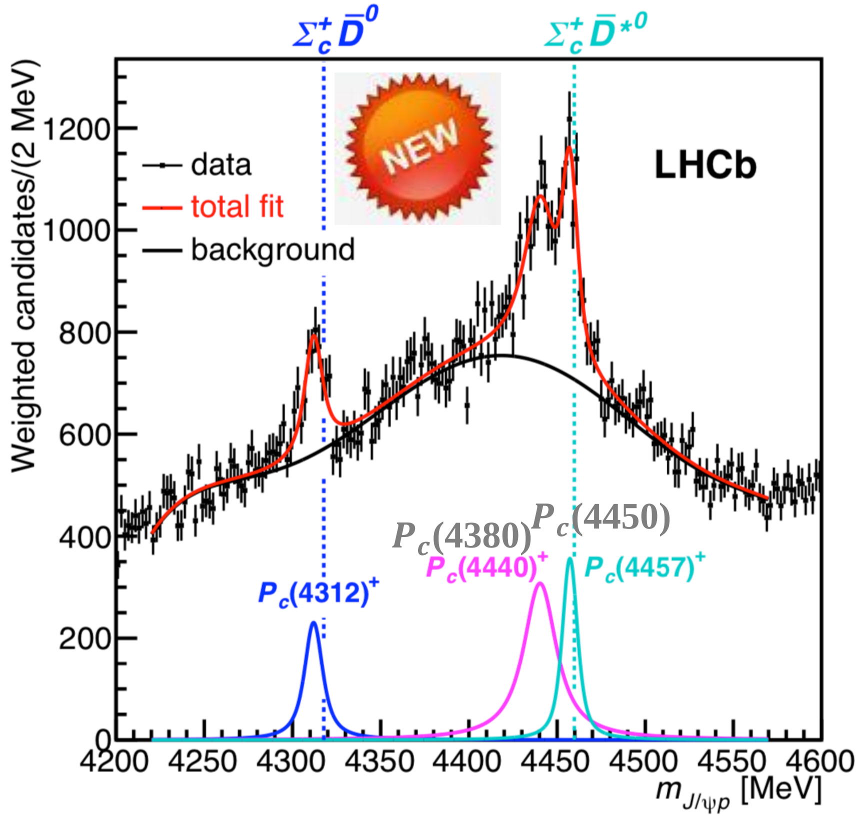
Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

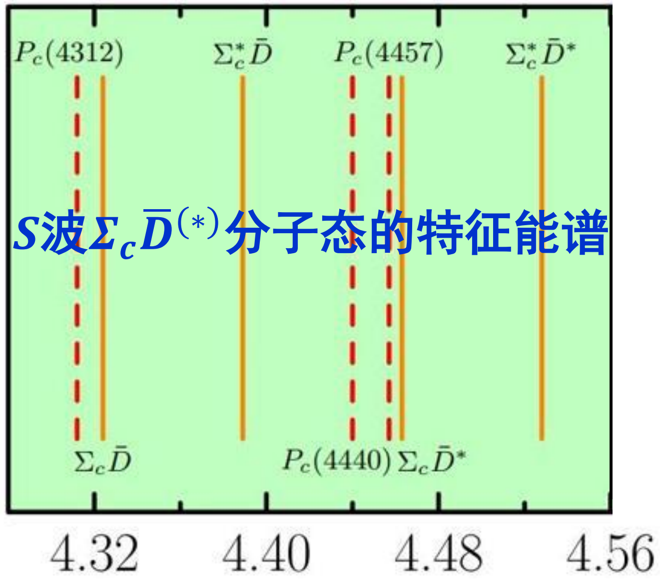
R. Aaij *et al.**
(LHCb Collaboration)

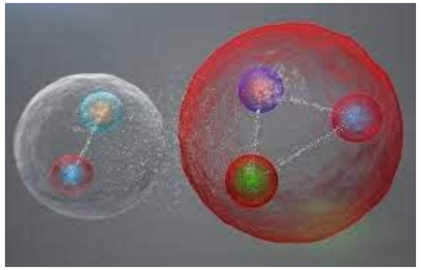
(Received 6 April 2019; published 5 June 2019)

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

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







分子态类型五夸克态

特征能谱的研究对于奇特强子态的寻找与鉴别具有重要的作用。

含奇异夸克的隐粲五夸克态$P_{cs}(4459)$的实验证据@2020年

Science Bulletin 66 (2021) 1278–1287

arXiv:2012.10380

Contents lists available at ScienceDirect

Science Bulletin

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

ELSEVIER

Science Bulletin
www.scibull.com

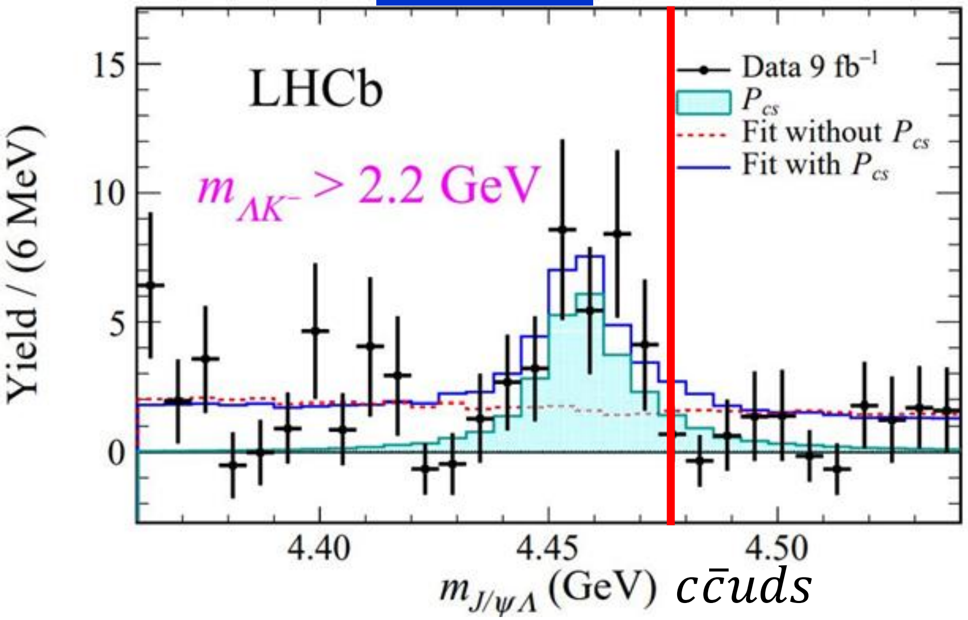
Article

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]

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

19 MeV $\Xi_c\bar{D}^*$(4477 MeV)



$c\bar{c}uds$

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：$J^P = 1/2^-, 3/2^-$。

“双峰”假设：证实、排除。

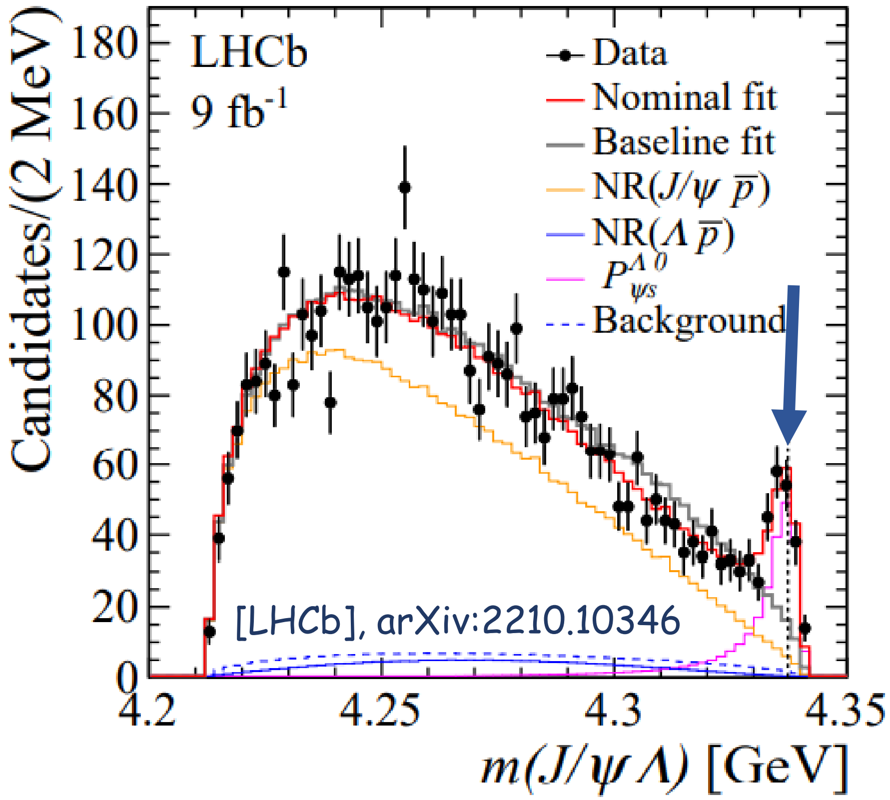
困惑

$P_{cs}(4459)$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

CERN-EP-2022-198
LHCb-PAPER-2022-031
October 19, 2022

Observation of a $J/\psi\Lambda$ resonance consistent with a strange pentaquark candidate in $B^- \to J/\psi\Lambda\bar{p}$ decays



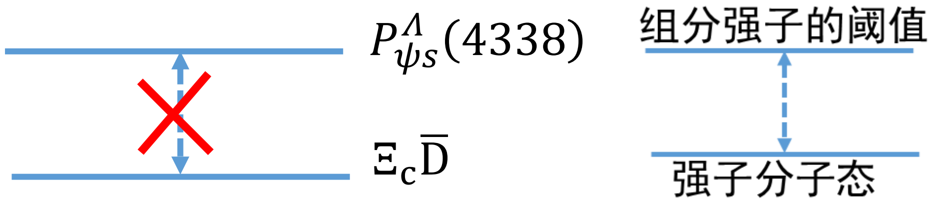
$M = 4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}, \quad \Gamma = 7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$

自旋-宇称量子数倾向：$J^P = 1/2^-$

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？



目前LHCb实验组发现的P_c态与P_{cs}态

近十年，关于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，但是仍然存在些许困惑。

2015	2019	2020	2022
$P_\psi^N(4450)$, $P_\psi^N(4380)$	$P_\psi^N(4457)$, $P_\psi^N(4440)$, $P_\psi^N(4312)$	$P_{\psi s}^\Lambda(4459)$	$P_{\psi s}^\Lambda(4338)$
$\Lambda_b^0 \to J/\psi p K^-$	$\Lambda_b^0 \to J/\psi p K^-$	$\Xi_b^- \to J/\psi \Lambda K^-$	$B^- \to J/\psi \Lambda \bar{p}$

同位旋标量的$\Sigma_c\bar{D}^{(*)}$分子态的特征能谱

在强子谱学中存在粲重子与反粲介子形成的隐粲分子态类型五夸克态

同位旋标量的$\Xi_c\bar{D}^{(*)}$分子态的特征能谱？

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

2

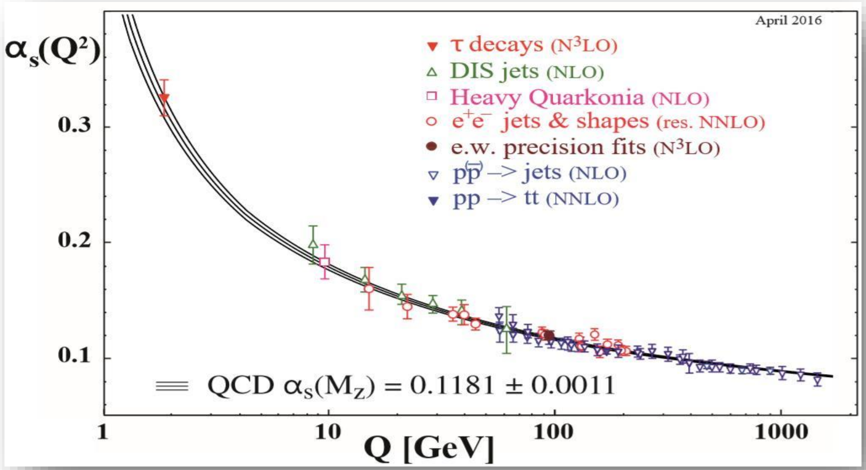
$\Xi_c\bar{D}^{(*)}$分子态的特征能谱

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

强子间相互作用是研究强子分子态谱学的重要输入

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

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



- 讨论强子间相互作用的模型与方法：

① 单玻色子交换模型；

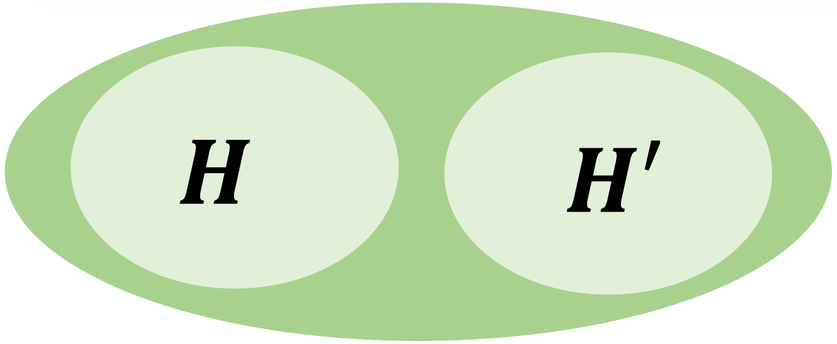
② QCD求和规则；

③ 格点QCD模拟；

④ 手征微扰理论；

⑤ 组分夸克模型；

……

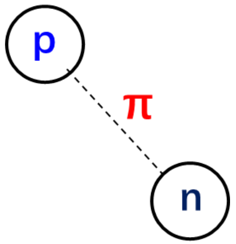


H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rept. 639, 1 (2016)

单玻色子交换模型

- pion交换模型:核力是两个核子间交换pion形成的，质子和中子间通过交换pion形成氘核，它只给出相互作用的长程力。

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



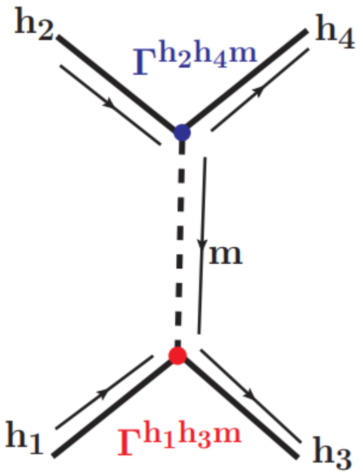
- 在强子间相互作用的研究中考虑长程、中程和短程力:

σ,

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

中程 | 长程 | 短程

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



- 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)

在单玻色子交换模型中讨论强子分子态候选者的步骤

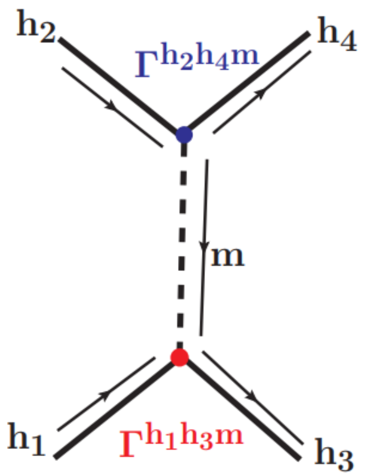
有效拉氏量方法 → 布雷特近似 → 傅里叶变换

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

N. A. Tornqvist, Z. Phys. C 61, 525 (1994)
N. A. Tornqvist, Nuovo Cim. A 107, 2471 (1994)

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**

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

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

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

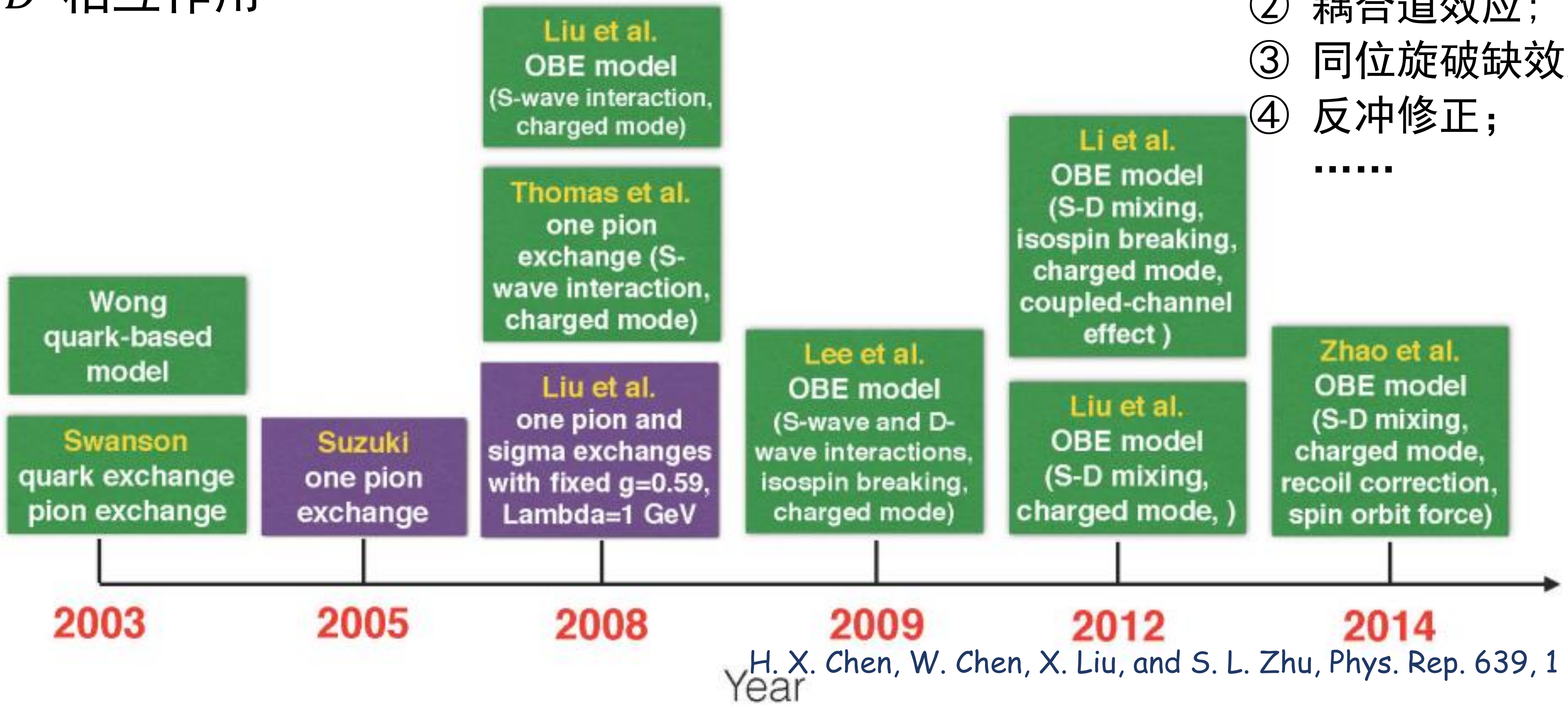
$$\mathcal{A}_1=\chi_3^\dagger\left(\epsilon_4^\dagger\cdot\epsilon_2\right)\chi_1$$

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

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

$D\bar{D}^*$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；
……



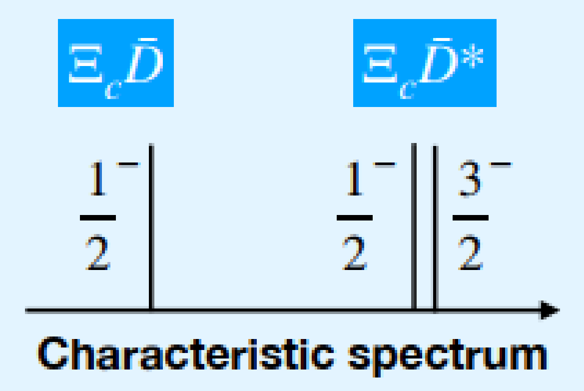
H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rep. 639, 1 (2016)

将$X(3872)$解释为强子分子态时，在讨论强子间相互作用时考虑了越来越精细的结构。

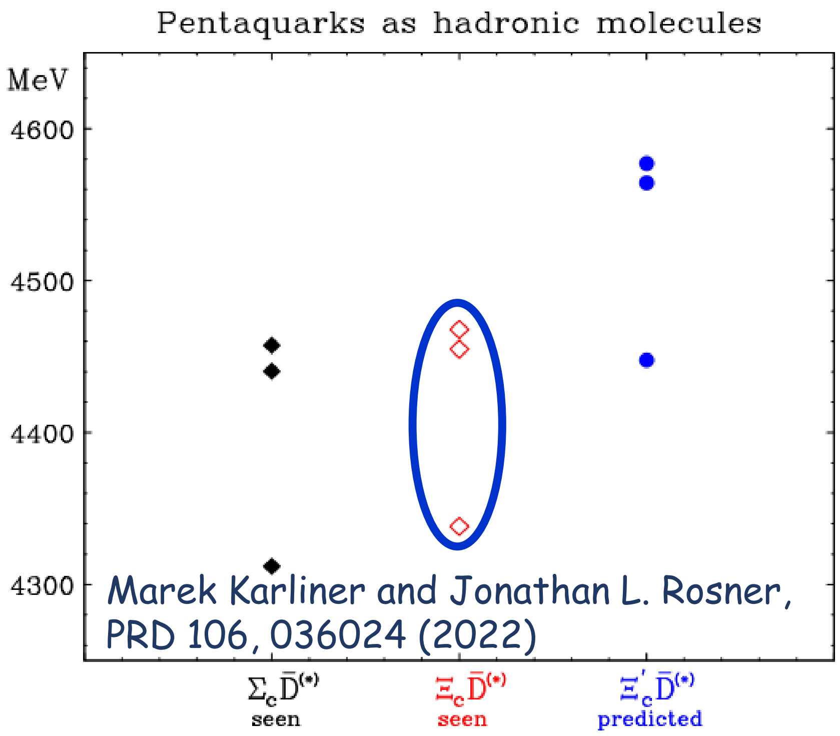
同位旋标量的$\Xi_c\bar{D}^*$系统的束缚性质——耦合道效应

Λ	Λ'	E	$r_{\rm RMS}$	$P(\Xi_c\bar{D}^*/\Xi_c'\bar{D}^*)$
		$\Xi_c\bar{D}^*(J^P=1/2^-)$		
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。

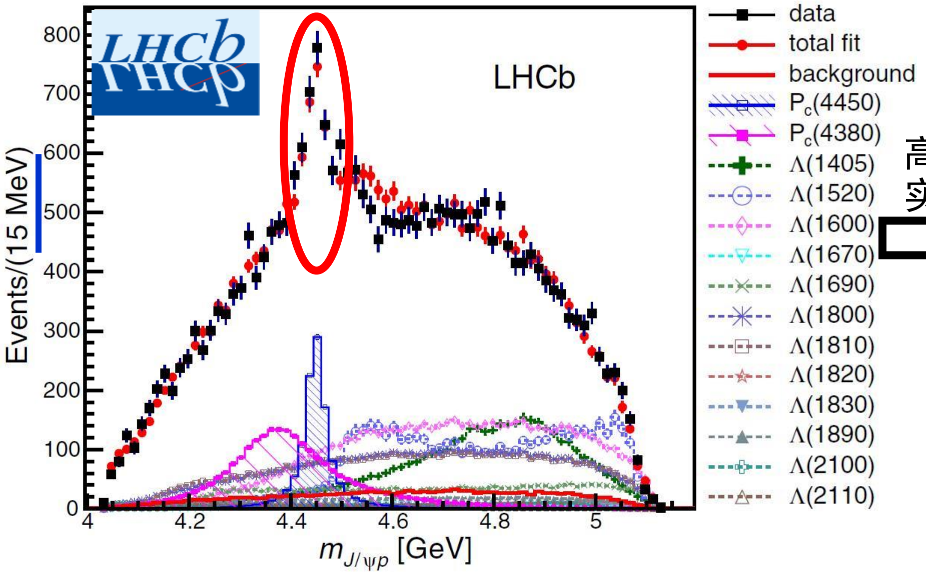


S波同位旋标量的$\Xi_c\bar{D}^{(*)}$分子态的特征能谱



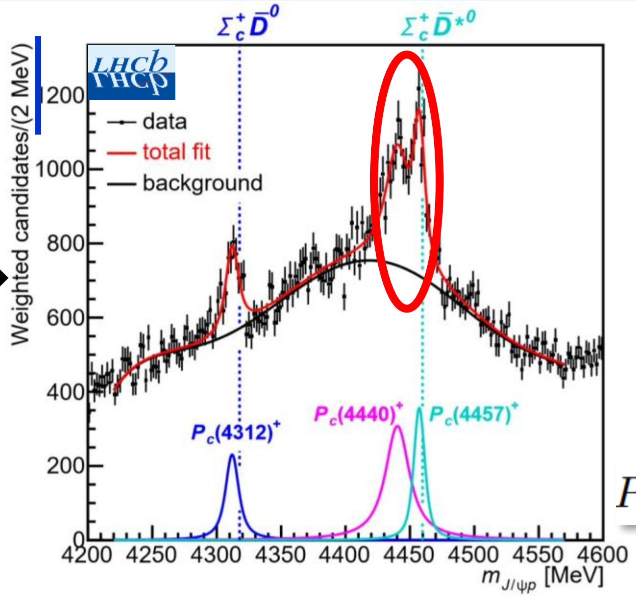
Marek Karliner and Jonathan L. Rosner, PRD 106, 036024 (2022)

对$P_{cs}(4459)$态的实验研究的理论建议



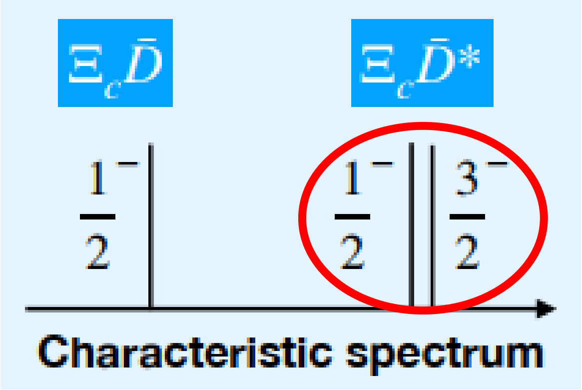
[LHCb], PRL 115, 072001 (2015)

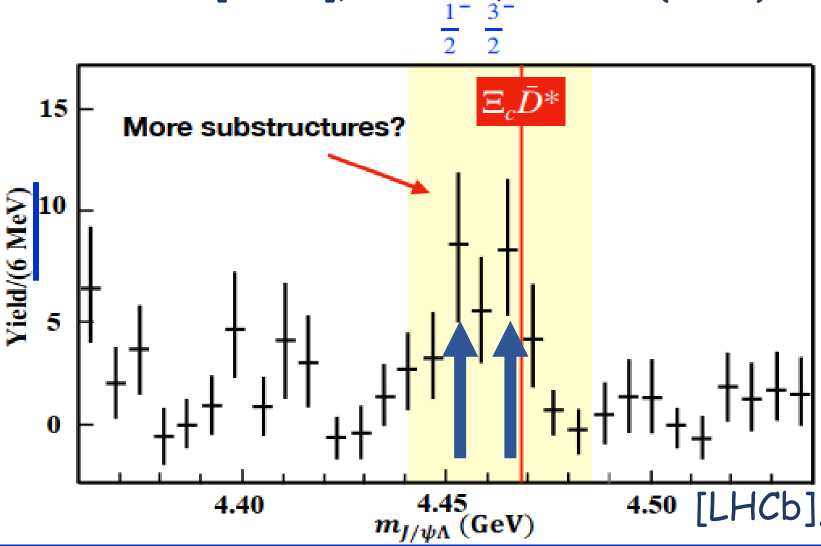
高精度的
实验数据



[LHCb], PRL 122, 222001 (2019)

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

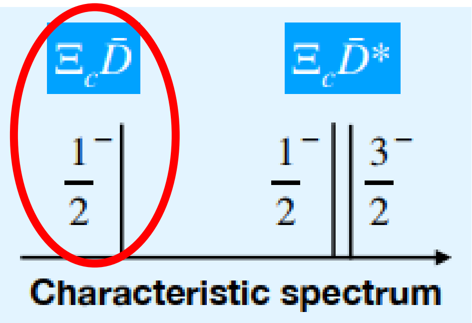


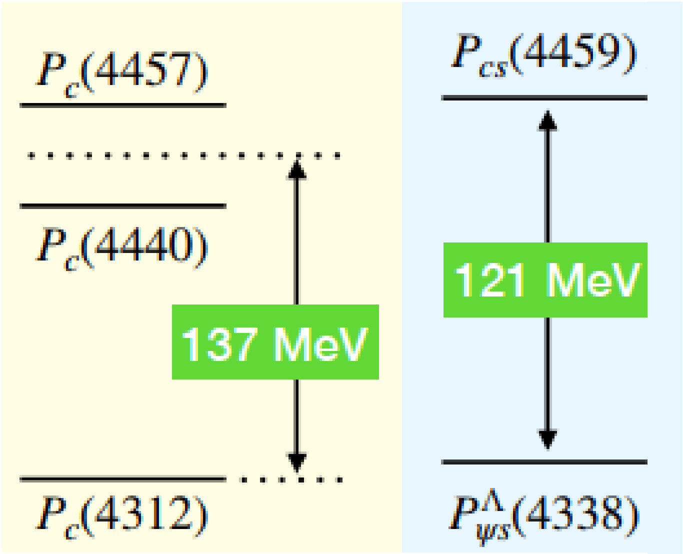


[LHCb], Sci. Bull. 66, 1278-1287 (2021)

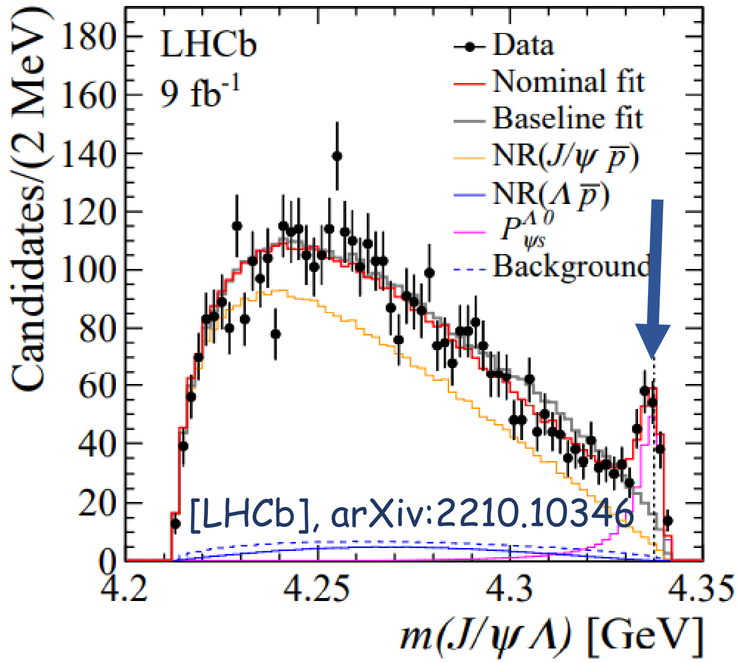
建议实验用高精度的实验数据研究$\Xi_c\bar{D}^*$道附近的增长结构

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





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



- ✓ 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, arXiv:2209.10413 [**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**] ;
- ✓ ……

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

$P_{cs}(4459)$和$P^{\Lambda}_{\psi s}(4338)$的广泛讨论

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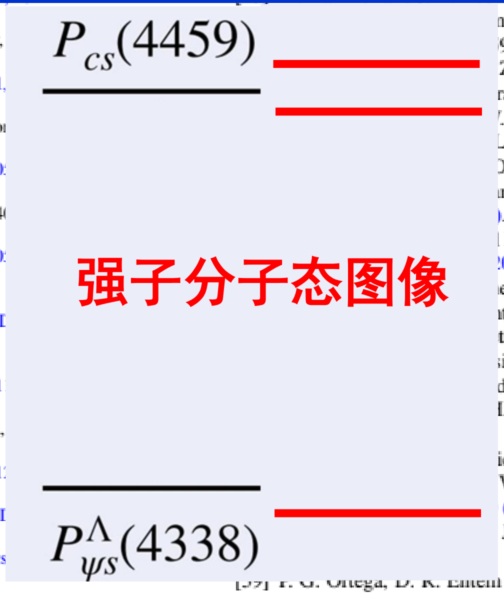
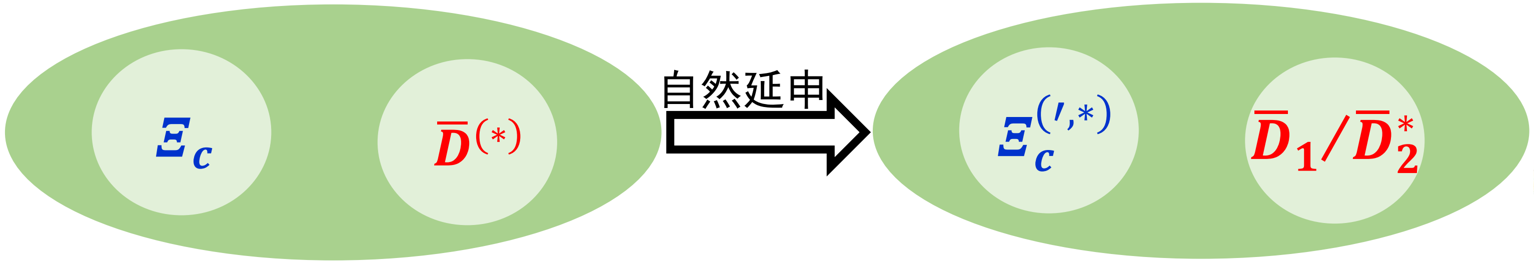
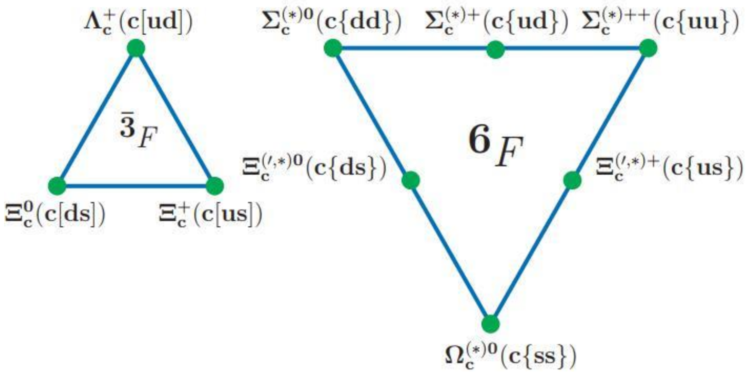
$P_{cs}(4459)$和$P^{\Lambda}_{\psi s}(4338)$的“双峰”和“质量”问题在理论上被广泛研究，理论结果需要实验证实，可能需要高精度高统计量的实验数据。



研究$\Xi_c^{(\prime,*)}\bar{D}_1/\Xi_c^{(\prime,*)}\bar{D}_2^*$分子态是澄清$P_{cs}(4459)$和$P_{\psi s}^{\Lambda}(4338)$结构的间接途径

- 通过研究$P_{cs}(4459)$和$P_{\psi s}^{\Lambda}(4338)$自身性质讨论它们的“双峰”和“质量”问题(直接)。
- 类似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）？





<u>P-波粲介子:</u> $S_l \equiv S_q + L = \frac{1}{2}\otimes 1 = \frac{1}{2}\oplus\frac{3}{2}$

$J \equiv S_l + S_Q = \frac{1}{2}\otimes\frac{1}{2} = 0\oplus 1$ $\quad S = (0^+, 1^+)$ $\quad \boxed{D_1(2420)}$ $\quad I(J^P) = \frac{1}{2}(1^+)$

$J \equiv S_l + S_Q = \frac{3}{2}\otimes\frac{1}{2} = 1\oplus 2$ $\quad \boxed{T = (1^+, 2^+)}$ $\quad \boxed{D_2^*(2460)}$ $\quad I(J^P) = \frac{1}{2}(2^+)$

3

$\Xi_c^{(\prime,*)}\bar{D}_1/\Xi_c^{(\prime,*)}\bar{D}_2^*$分子态的预言

F. L. Wang and Xiang Liu, arXiv:2307.08276

$\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$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：

$I(J^P)$	Λ	E	$r_{\rm RMS}$	P($^2\mathbb{S}_{\frac{1}{2}}/^4\mathbb{D}_{\frac{1}{2}}$)
S-D wave mixing case				
	1.32	−0.27	4.87	**100.00**/$o(0)$
$0(\frac{1}{2}^+)$	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($^4\mathbb{S}_{\frac{3}{2}}/^2\mathbb{D}_{\frac{3}{2}}/^4\mathbb{D}_{\frac{3}{2}}$)
	1.32	−0.27	4.87	**100.00**/$o(0)$/$o(0)$
$0(\frac{3}{2}^+)$	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($\Xi_c\bar{D}_1/\Xi_c^{\prime}\bar{D}_1/\Xi_c^*\bar{D}_1/\Xi_c^*\bar{D}_2^*$)
	1.04	−0.56	3.76	**95.90**/3.84/0.07/0.18
$0(\frac{1}{2}^+)$	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($\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*/\Xi_c^{\prime}\bar{D}_1/\Xi_c^{\prime}\bar{D}_2^*/\Xi_c^*\bar{D}_1/\Xi_c^*\bar{D}_2^*$)
	1.09	−0.32	4.59	**97.98**/0.13/0.43/0.39/0.58/0.49
$0(\frac{3}{2}^+)$	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

$$\mathcal{V}^{\Xi_c\bar{D}_1\to\Xi_c\bar{D}_1} = -2l_Bg_\sigma^{\prime\prime}\epsilon_4^\dagger\cdot\epsilon_2\chi_3^\dagger\chi_1Y_\sigma-\frac{1}{2}\beta_B\beta^{\prime\prime}g_V^2\epsilon_4^\dagger\cdot\epsilon_2\chi_3^\dagger\chi_1\mathcal{G}(I)Y_{\mathbb{V}}$$

$\Xi_c\bar{D}_2^*$系统：

$P_{cs}(4459)$的“双峰”问题

$I(J^P)$	Λ	E	$r_{\rm RMS}$	P($^4\mathbb{S}_{\frac{3}{2}}/^4\mathbb{D}_{\frac{3}{2}}/^6\mathbb{D}_{\frac{3}{2}}$)
S-D wave mixing case				
	1.32	−0.32	4.63	**100.00**/$o(0)$/$o(0)$
$0(\frac{3}{2}^+)$	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($^6\mathbb{S}_{\frac{5}{2}}/^4\mathbb{D}_{\frac{5}{2}}/^6\mathbb{D}_{\frac{5}{2}}$)
	1.32	−0.32	4.63	**100.00**/$o(0)$/$o(0)$
$0(\frac{5}{2}^+)$	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($\Xi_c\bar{D}_2^*/\Xi_c^{\prime}\bar{D}_1/\Xi_c^{\prime}\bar{D}_2^*/\Xi_c^*\bar{D}_1/\Xi_c^*\bar{D}_2^*$)
	1.06	−0.29	4.69	**98.02**/0.28/0.57/0.06/1.07
$0(\frac{3}{2}^+)$	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($\Xi_c\bar{D}_2^*/\Xi_c^{\prime}\bar{D}_2^*/\Xi_c^*\bar{D}_1/\Xi_c^*\bar{D}_2^*$)
	1.05	−0.40	4.25	**97.77**/0.46/0.28/1.49
$0(\frac{5}{2}^+)$	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

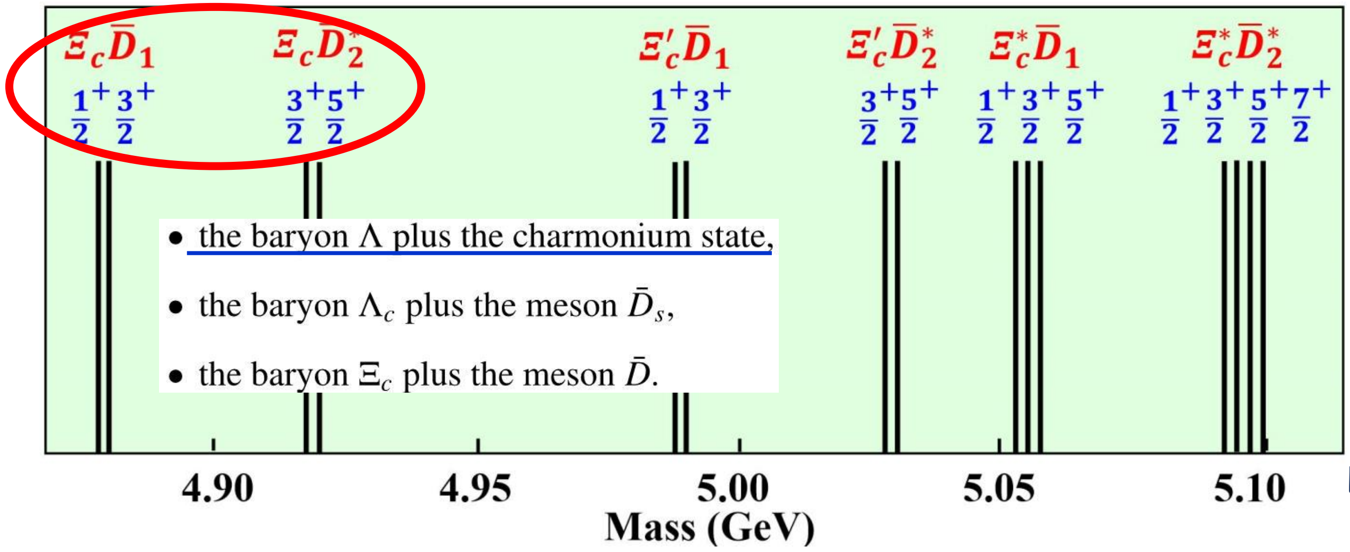
$$\mathcal{V}^{\Xi_c\bar{D}_2^*\to\Xi_c\bar{D}_2^*} = -2l_Bg_\sigma^{\prime\prime}\sum_{m,n,a,b}C_{1m,1n}^{2,m+n}C_{1a,1b}^{2,a+b}\left(\epsilon_{4m}^\dagger\cdot\epsilon_{2a}\right)\left(\epsilon_{4n}^\dagger\cdot\epsilon_{2b}\right)\chi_3^\dagger\chi_1Y_\sigma$$
$$-\frac{1}{2}\beta_B\beta^{\prime\prime}g_V^2\sum_{m,n,a,b}C_{1m,1n}^{2,m+n}C_{1a,1b}^{2,a+b}\left(\epsilon_{4m}^\dagger\cdot\epsilon_{2a}\right)\left(\epsilon_{4n}^\dagger\cdot\epsilon_{2b}\right)\chi_3^\dagger\chi_1\mathcal{G}(I)Y_{\mathbb{V}}$$

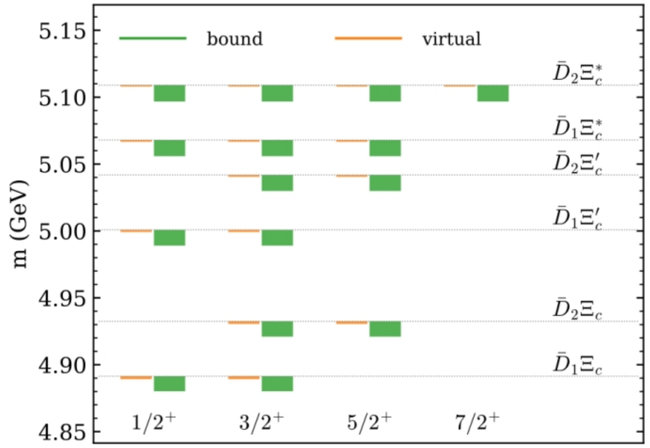
当截断参数相同时，同位旋标量的$\Xi_c\bar{D}_1/\Xi_c\bar{D}_2^*$分子态发生了质量简并的现象（没有自旋相互作用项）。

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。

$\Xi_c^{(\prime,*)}\bar{D}_1/\Xi_c^{(\prime,*)}\bar{D}_2^*$分子态的特征能谱

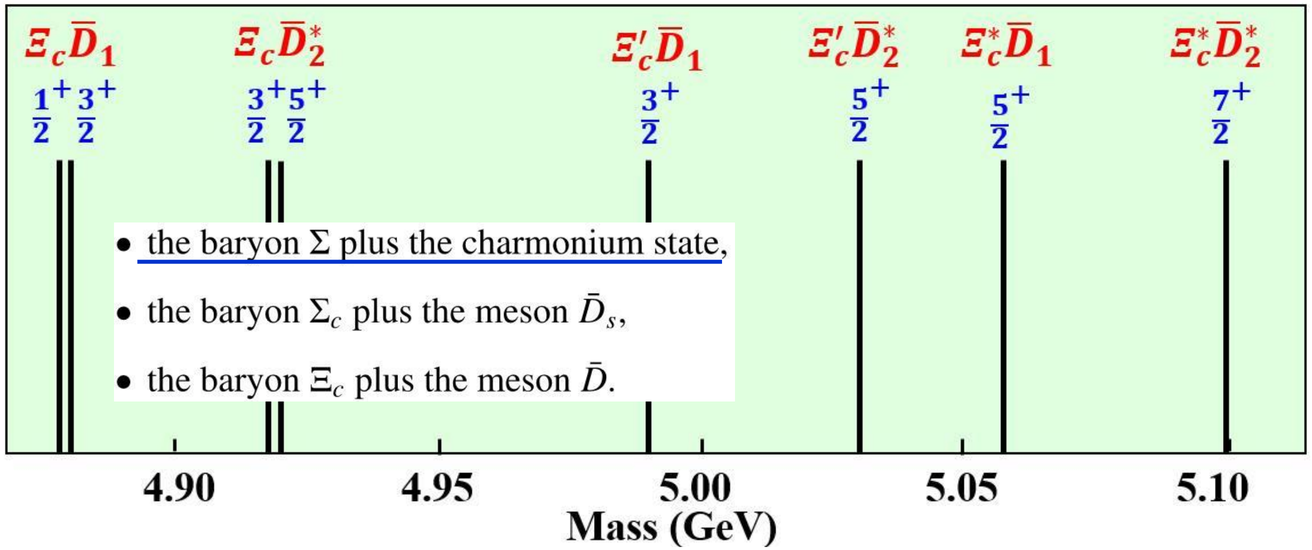
- 最可能的同位旋标量的含奇异夸克的隐粲分子态类型五夸克候选者：





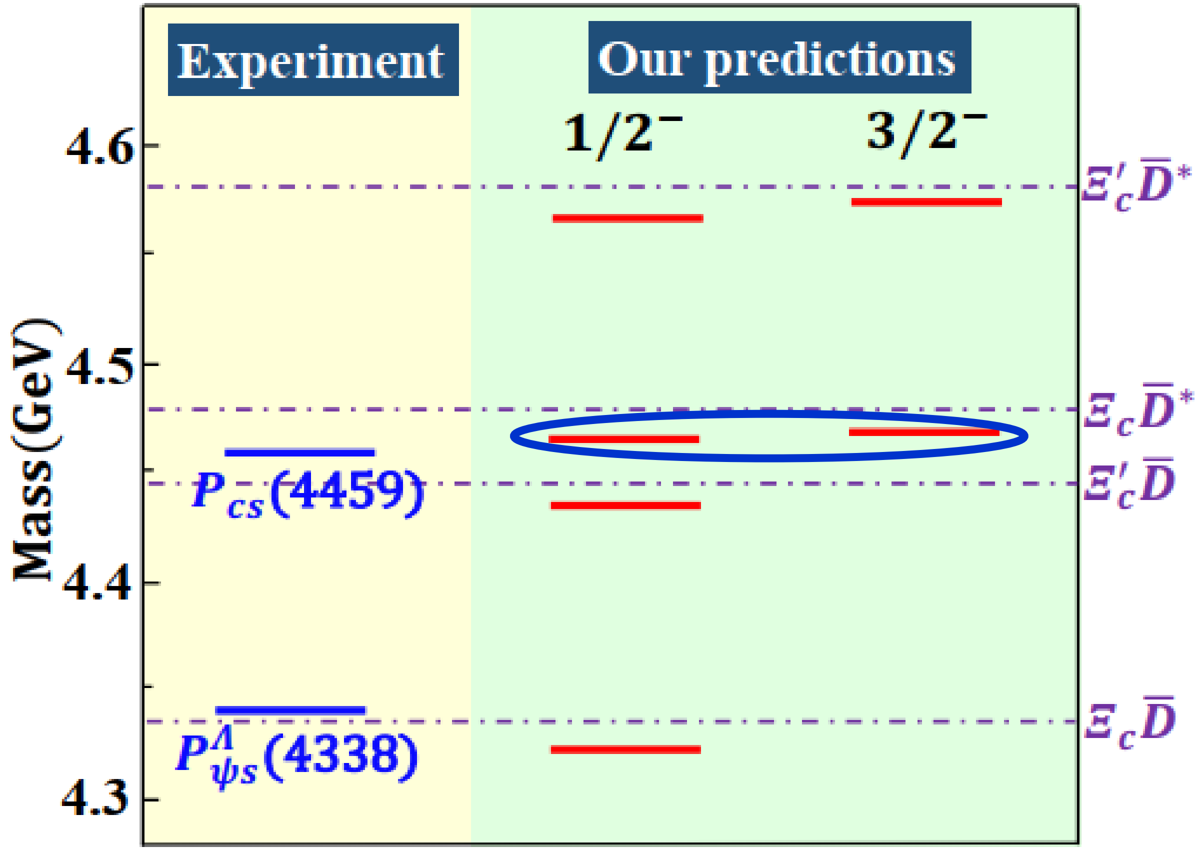
K. Dong, F. K. Guo, and B. S. Zou, Progr. Phys. 41, 65-93 (2021)

- 可能的同位旋矢量的含奇异夸克的隐粲分子态类型五夸克候选者：



$$\Xi_b^- \longrightarrow P_{cs}K^-$$

P_{cs}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P_c/P_{cs}态的分波分析仍然缺乏。
- ✓ 理论上需要为实验上讨论P_{cs}态的自旋-宇称量子数提供更多的途径。

4

$\Xi_c\bar{D}^{(*)}$分子态的电磁性质

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

强子的磁矩

- 磁矩是表征强子电磁性质的重要物理量，可以反映强子的内部结构。
- 磁矩为确定强子的量子数与构型等性质提供重要的信息。
- 强子的磁矩是实验上重要的可观测量。
- 强子磁矩的研究模型与方法：

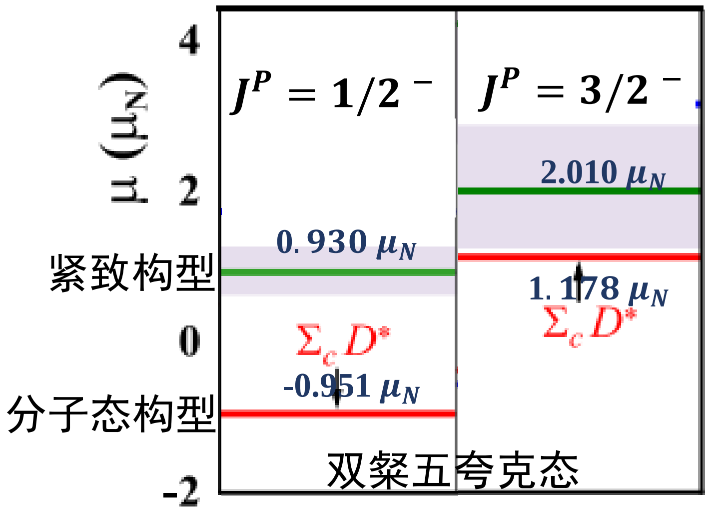
  ① 组分夸克模型；

  ② QCD求和规则；

  ③ 格点QCD模拟；

  ④ 手征微扰理论；

  ……



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

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

组分夸克模型广泛的用于讨论强子的磁矩

- 组分夸克模型成功的描述轻味重子的磁矩。

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)

- 组分夸克模型用于讨论各种构型的分子态类型五夸克态的磁矩。

PHYSICAL REVIEW C **69**, 035205 (2004)

Pentaquark magnetic moments in different models

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[1]*Department of Physics, Peking University, Beijing 100871, China*
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PHYSICAL REVIEW D **94**, 094018 (2016)

Magnetic moments of the hidden-charm pentaquark states

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PHYSICAL REVIEW D **104**, 054016 (2021)

Magnetic moments and transition magnetic moments of P_c and P_{cs} states

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Chinese Physics C Vol. 46, No. 12 (2022) 123111

Magnetic moments of hidden-charm strange pentaquark states*

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[4]Peng Huanwu Center for Fundamental Theory, Xi'an 710127, China

PHYSICAL REVIEW D **106**, 034034 (2022)

Probing the electromagnetic properties of the $\Sigma_c^{(*)}D^{(*)}$-type doubly charmed molecular pentaquarks

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arXiv:2210.02809

Exploring the electromagnetic properties of the $\Xi_c^{(\prime,*)}\bar{D}_s^*$ and $\Omega_c^{(*)}\bar{D}_s^*$ molecular states

Fu-Lai Wang[1,2,3,*] Si-Qiang Luo[1,2,3,†] Hong-Yan Zhou[1,2,‡] Zhan-Wei Liu[1,2,3,§] and Xiang Liu[1,2,3,4¶]
[1]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
[3]*Lanzhou Center for Theoretical Physics, Key Laboratory of Theoretical Physics of Gansu Province, and Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China*
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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夸克的自旋磁矩与轨道磁矩的和。

$$\mu = \mu_{\text{spin}} + \mu_{\text{orbital}}$$

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

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

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：

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

构造波函数！

$$\psi = \omega_{\text{color}} \otimes \underline{\chi_{\text{flavor}} \otimes \chi_{\text{spin}}} \otimes R_{\text{space}}$$

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)：

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

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

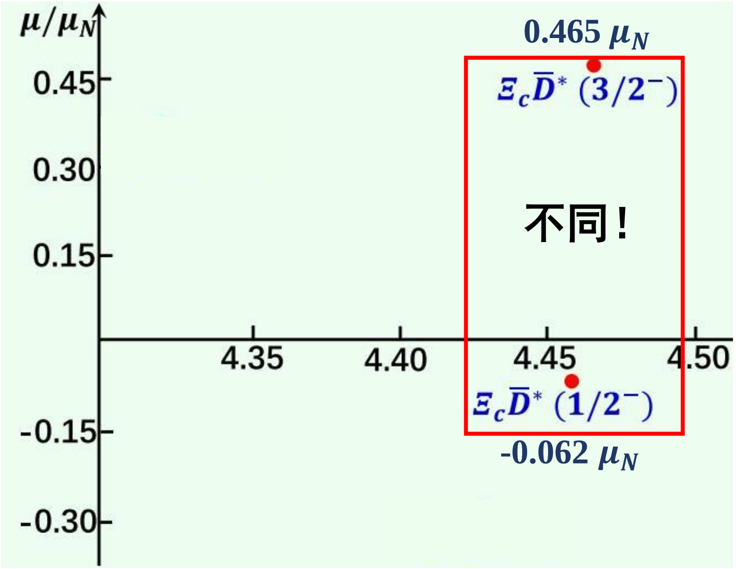
含奇异夸克的隐粲分子态类型五夸克态的磁矩

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	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)

磁矩是研究含奇异夸克的隐粲分子态类型五夸克态的自旋-宇称量子数的可行途径

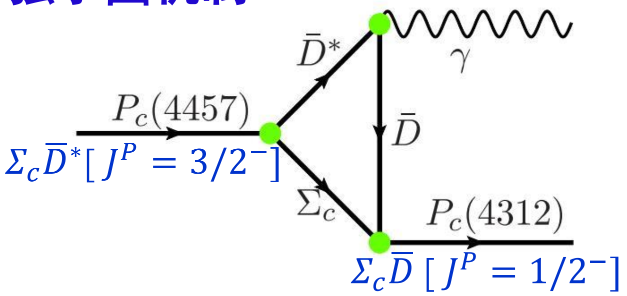
辐射衰变行为是讨论$P_c(4440)$与$P_c(4457)$自旋-宇称量子数的可行途径

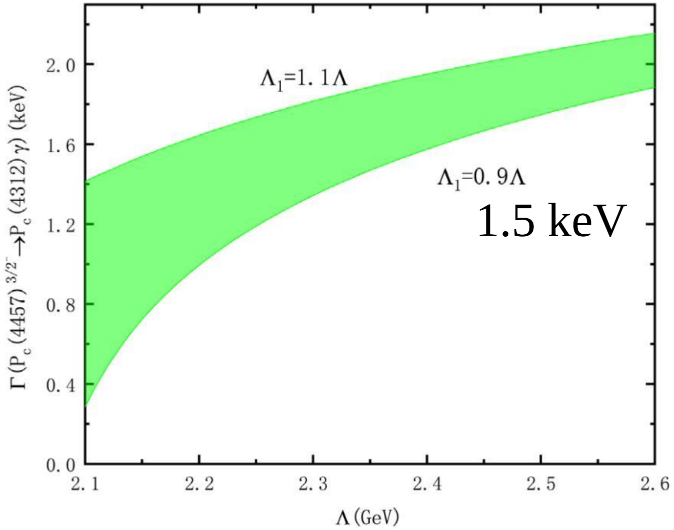
组分夸克模型:

		Without coupled channel and D -wave effects		With both effects	
	$\mu_{P'_c \to P_c}$		$\Gamma_{P'_c \to P_c\gamma}$	$\mu_{P'_c \to P_c}$	$\Gamma_{P'_c \to P_c\gamma}$
$\Sigma_c\bar{D}^*[J^P=1/2^-]$ → $\Sigma_c\bar{D}\,[J^P=1/2^-]$					
$P_c(4440)^+ \to P_c(4312)^+$	$-\frac{\sqrt{3}}{9}(2\mu_{\bar{D}^{*-}\to\bar{D}^-}+\mu_{\bar{D}^{*0}\to\bar{D}^0})$	−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
$\Sigma_c\bar{D}^*[J^P=3/2^-]$ → $\Sigma_c\bar{D}\,[J^P=1/2^-]$					
$P_c(4457)^+ \to P_c(4312)^+$	$\frac{\sqrt{6}}{9}(2\mu_{\bar{D}^{*-}\to\bar{D}^-}+\mu_{\bar{D}^{*0}\to\bar{D}^0})$	0.304	1.112	0.381	1.743 可靠
$P_c(4457)^0 \to P_c(4312)^0$	$\frac{\sqrt{6}}{9}(2\mu_{\bar{D}^{*0}\to\bar{D}^0}+\mu_{\bar{D}^{*-}\to\bar{D}^-})$	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

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)

含奇异夸克的隐粲分子态类型五夸克态的跃迁磁矩与辐射衰变行为

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

$$\Downarrow$$

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

3−j系数

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

F. L. Wang, S. Q. Luo, H. Y. Zhou, Z. W. Liu, and X. Liu, arXiv:2210.02809.

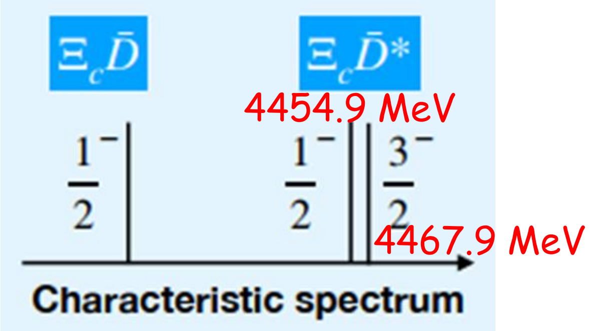
Decay modes	Expressions	Results
$\Xi_c\bar{D}^*\|\frac{1}{2}^-\rangle \to \Xi_c\bar{D}\|\frac{1}{2}^-\rangle\gamma$	$\frac{1}{2\sqrt{3}}(\mu_{D^{*-}\to D^-} + \mu_{\bar{D}^{*0}\to\bar{D}^0})$	−0.484
$\Xi_c\bar{D}^*\|\frac{3}{2}^-\rangle \to \Xi_c\bar{D}\|\frac{1}{2}^-\rangle\gamma$	$\frac{1}{\sqrt{6}}(\mu_{D^{*-}\to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

$$\frac{\mu_{\Xi_c\bar{D}^*|\frac{1}{2}^-\rangle\to\Xi_c\bar{D}|\frac{1}{2}^-\rangle}}{\mu_{\Xi_c\bar{D}^*|\frac{3}{2}^-\rangle\to\Xi_c\bar{D}|\frac{1}{2}^-\rangle}} = \frac{1}{\sqrt{2}}$$



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

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

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

不同！

辐射衰变行为是研究含奇异夸克的隐粲分子态类型五夸克态的自旋−宇称量子数的途径

5
总结

总结

$P_{cs}(4459)/P_{\psi s}^{\Lambda}(4338)$

- 特征能谱的研究对于奇特强子态的寻找与鉴别具有重要的意义。

- 目前的实验数据暗示在强子家族中存在同位旋标量的$\Xi_c\bar{D}^{(*)}$分子态的特征能谱，建议实验上用高精度的数据讨论 $\Xi_c\bar{D}^*$道附近的增长结构，并且通过$\Xi_b^- \to J/\psi\Lambda K^-$过程确认$P_{\psi s}^{\Lambda}(4338)$对应的增长结构的共振态参数。

- 讨论$\Xi_c^{(\prime,*)}\bar{D}_1/\Xi_c^{(\prime,*)}\bar{D}_2^*$分子态候选者，不仅是澄清$P_{cs}(4459)$结构的间接途径，而且可以丰富隐藏分子态类型五夸克态谱学。

- 电磁性质是实验上研究含奇异夸克的隐粲分子态类型五夸克态的自旋-宇称量子数的有效途径。

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

谢谢大家！ 敬请批评指正！