

A wide-angle photograph of the Lanzhou University campus and surrounding city. The image shows a mix of modern high-rise buildings and older university structures, with green trees interspersed throughout. In the background, rolling hills are visible under a clear blue sky. The text "自强不息 獨樹一幟" is written in a blue, calligraphic font in the upper right corner.

自强不息 獨樹一幟

WELCOME TO LANZHOU UNIVERSITY

第八届粒子物理天问论坛@广西师范大学

三体强子分子态及三体力研究

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Phys. Rev. Lett. **135** (2025) 031902
Phys. Rev. Lett. **136** (2026) 151901

2026-8-28

目录

- 强相互作用的非微扰效应
- 具有C宇称的三体强子分子态
- 三体强子系统中的三体力
- 总结

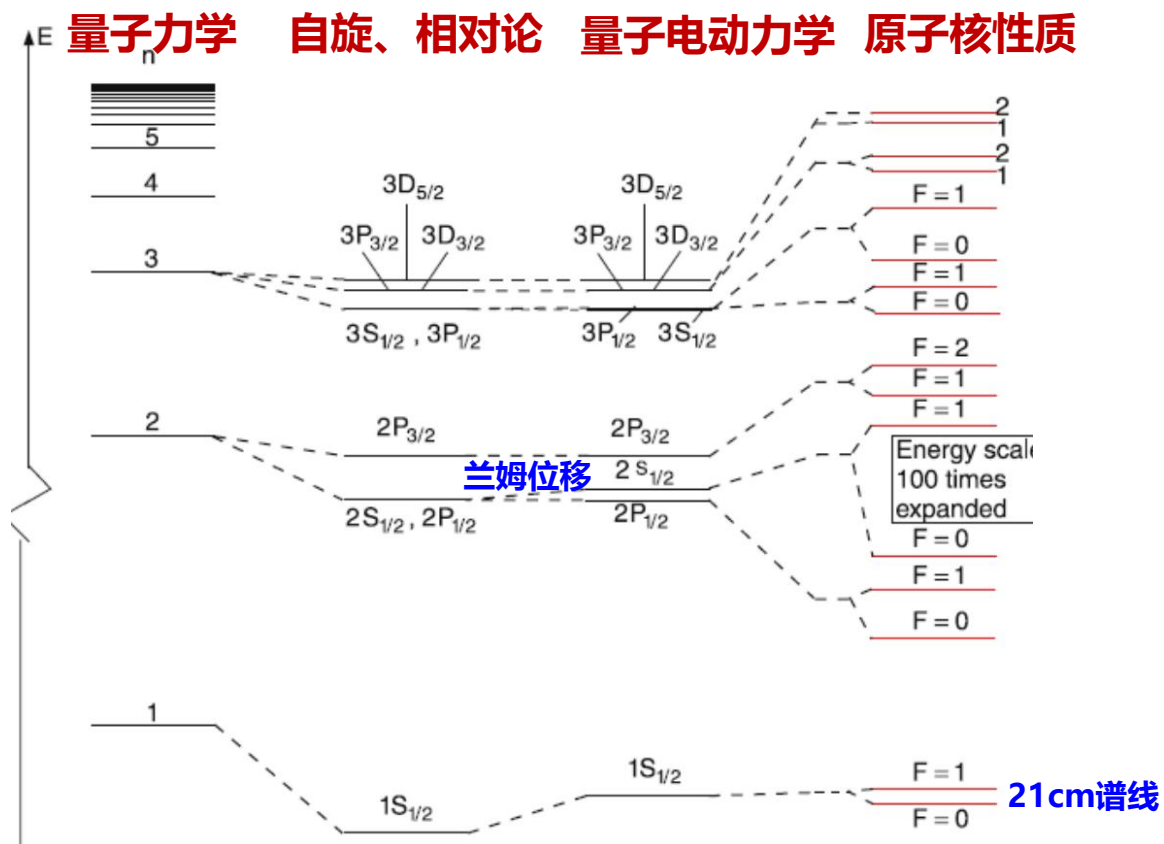


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粲偶素谱学——强相互作用

氢原子谱学



泡利所言：“氢原子是量子力学的‘氢弹’。” 其研究至今仍是探索新物理（如暗光子、额外维度）的重要窗口

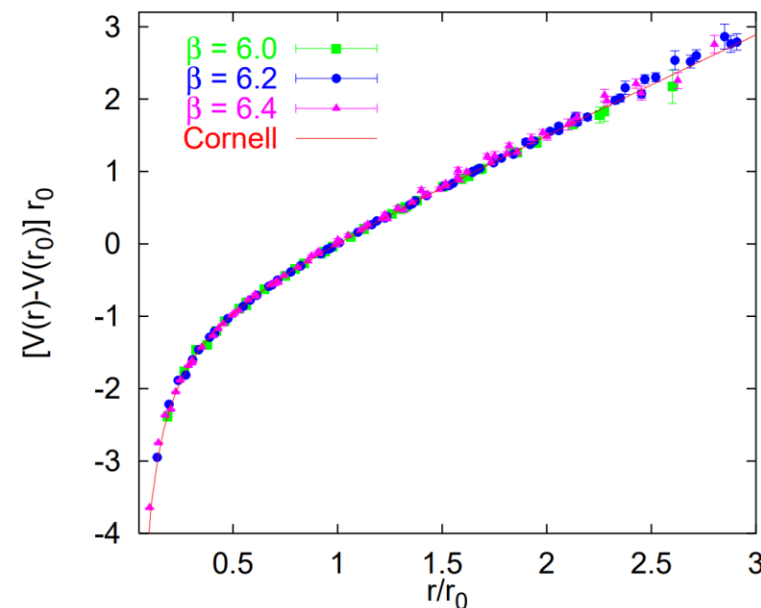
强子谱学

康奈尔势
$$V_0(r) = -\frac{4\alpha_s}{3r} + \sigma r$$

E. Eichten et al., Phys. Rev. Lett. 34 (1975) 369-372

强相互作用

格点QCD检验



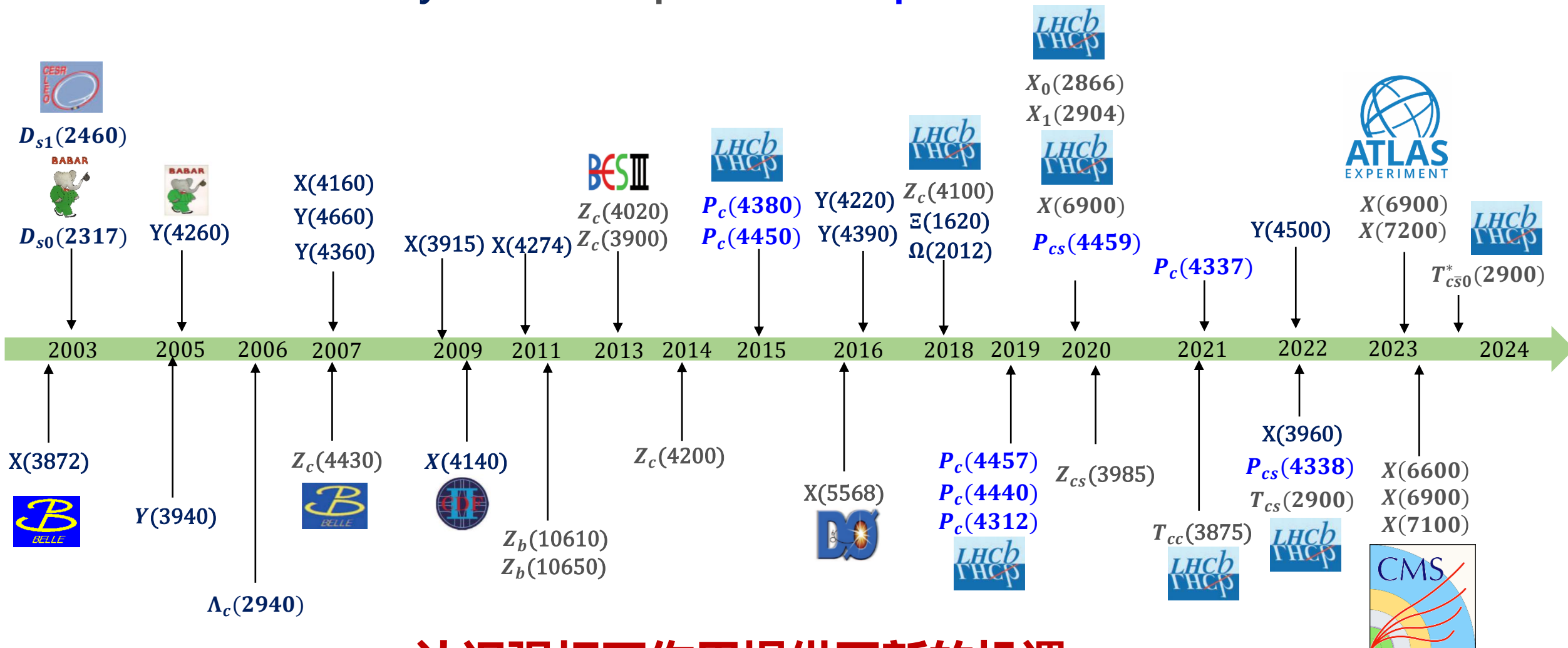
Gunnar S. Bali, Phys. Rept. 343 (2001) 1-136

奇特强子态

Exotic mesons and baryons

Tetraquark

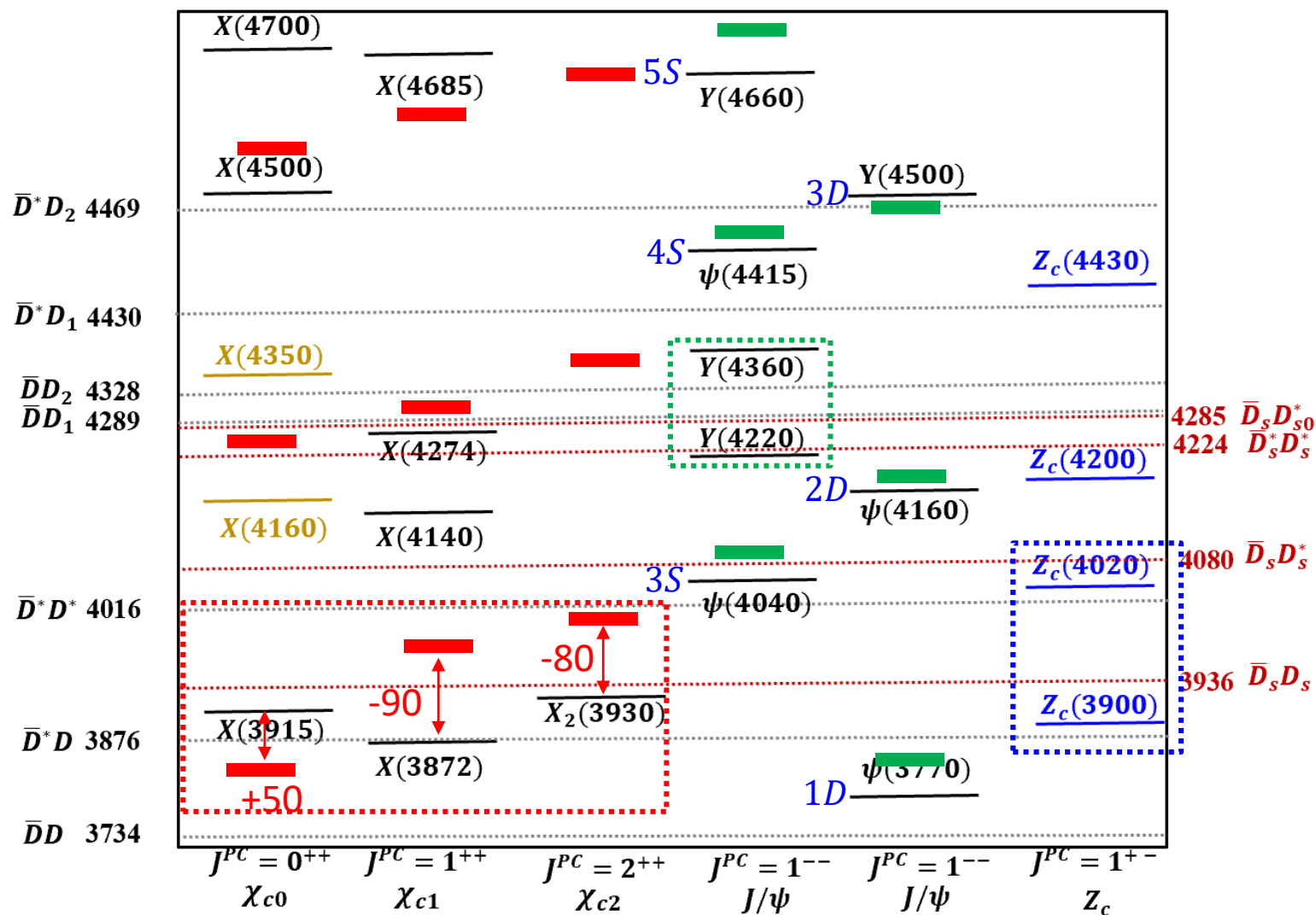
Pentaquarks



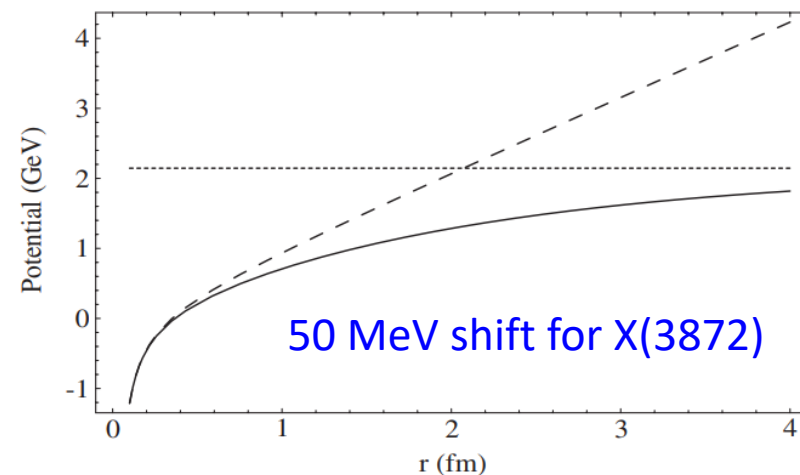
认识强相互作用提供了新的机遇

类粲偶素XYZ谱学——强子强子相互作用

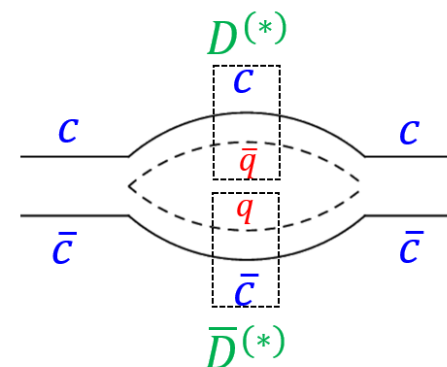
➤ 很多用传统夸克模型无法解释的粲偶素——类粲偶素 (XYZ)



屏蔽势 $br \rightarrow V^{\text{scr}}(r) = \frac{b(1 - e^{-\mu r})}{\mu}$



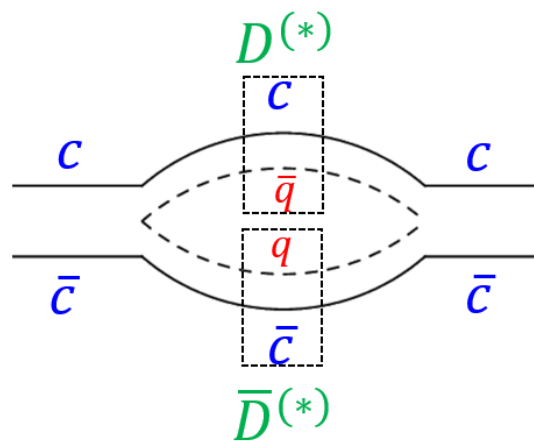
Bai-Qing Li, et al., Phys.Rev.D 79 (2009) 094004



强子-强子相互作用

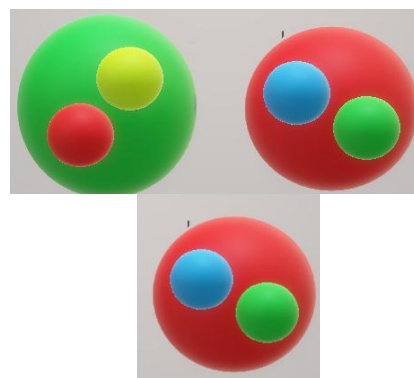
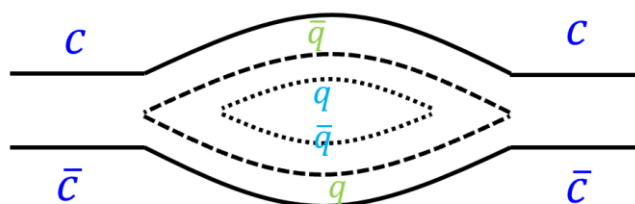
奇特强子态中可能的非微扰效应——三体力

轨道角动量 $L=1$

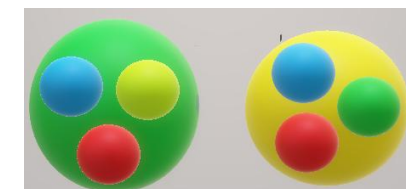


两体强子分子态
两体力

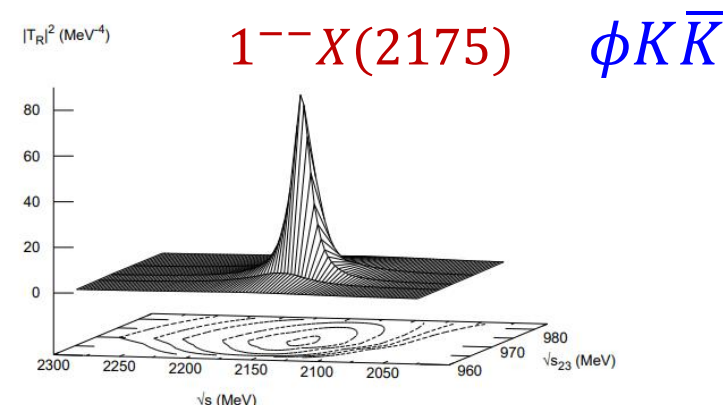
轨道角动量 $L=2/0$



三体强子分子态
两体力 + 三体力



重子-反重子分子态
两体力



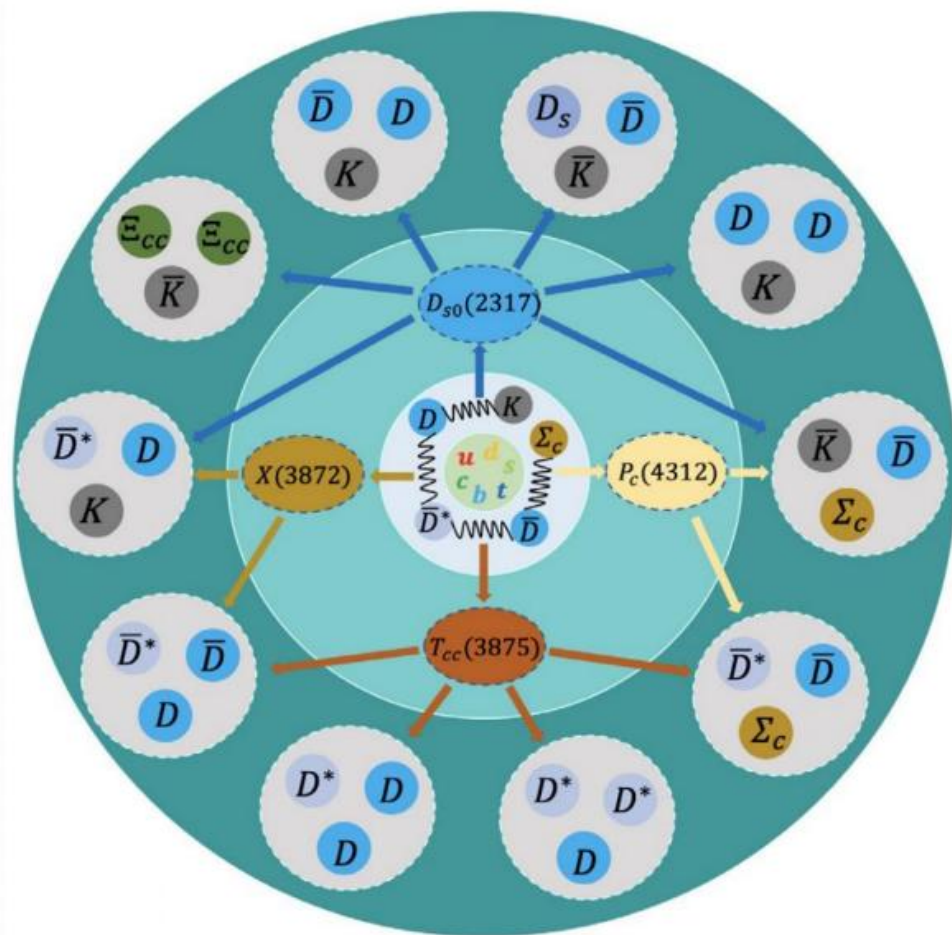
A. Martinez Torres et al., Phys.Rev.D 78 (2008) 074031

$1^{--}Y(4260)$ $J/\psi K \bar{K}$

A. Martinez Torres et al., Phys.Rev.D 80 (2009) 094012

Bing-Song Zou, Nucl. Phys. A 914 (2013) 454-460

三体强子分子态

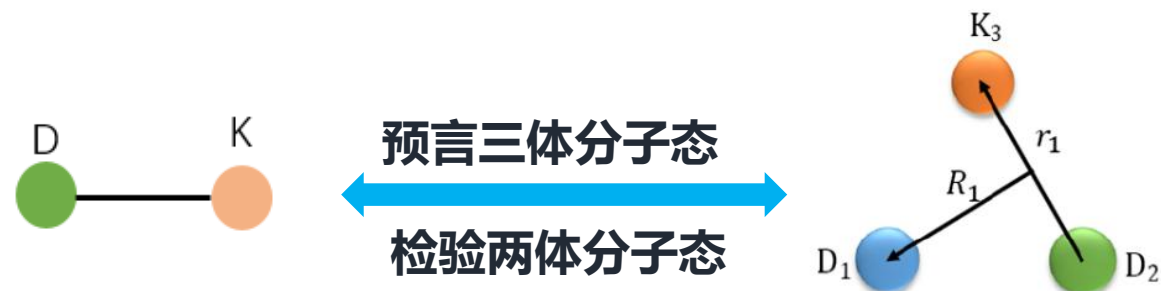


Tian-Wei Wu et al., Sci.Bull. 67 (2022) 1735-1738

Ming-Zhu Liu et al., Phys. Rept. 1108 (2025) 1-108

➤ 研究三体强子分子态的意义

- ✓ 自然界中新构型的强子态
- ✓ 检验低能强相互作用以及奇特强子态构型



➤ 实验如何确认以及寻找三体分子态?

Tian-Wei Wu et al., Phys. Rev. Lett. 135 (2025) 031902



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理想的三体强子系统

➤ $J^{PC} = 0^{--} \bar{D}_s DK$ 三系统

✓ 具有 charge parity

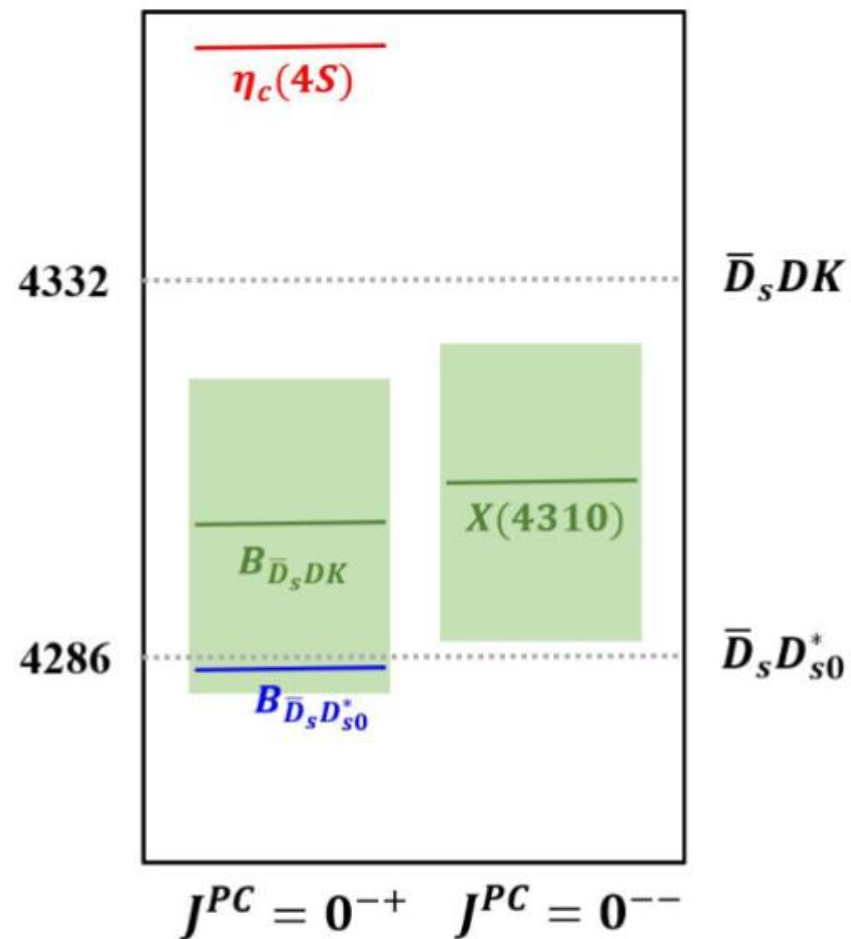
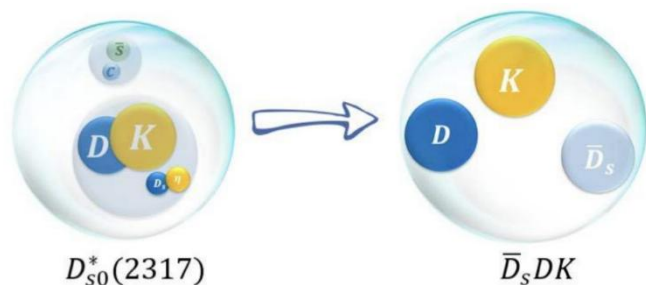
- 这个系统是电中性

✓ 其它强相互作用非微扰效应较小

- 不会与传统的 $c\bar{c}$ 混合
- 不会与两体分子态 $J^{PC} = 0^{--} \bar{D}_s D_{s0}^*$ 混合

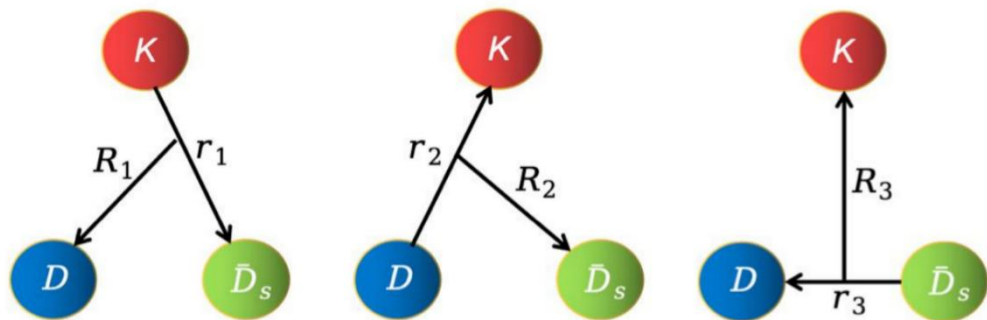
✓ 具有隐粲量子数能够被实验探测

- 可以在 e^+e^- 和 pp 碰撞过程中



Tian-Wei Wu et al., Phys. Rev. Lett. 135 (2025) 031902

$J^{PC} = 0^{--} \bar{D}_s DK$ 三体系统谱学



➤ $DK\bar{D}_s$ 系统的波函数

$$\Psi^C = \frac{1}{\sqrt{2}}(\Psi_{\bar{D}_s DK} + C\Psi'_{D_s \bar{D} \bar{K}}) \quad C = \pm 1$$

➤ $DK\bar{D}_s$ 系统的有效哈密顿量

$$H = T + T' + V + V' + V^C$$

$$H = T + V + V_C$$

$$\langle \Psi^C | (H - E) | \Psi^C \rangle = 0$$

➤ 两体相互作用

$$V(r) = C_a \frac{e^{-(r/R_c)^2}}{\pi^{3/2} R_c^3}$$

✓ $D_{s0}^*(2317)$ 和 SU(3)-flavor 对称性

$$V = \begin{pmatrix} C_a + \frac{\alpha}{\sqrt{s} - m_{bare}} & -\frac{\sqrt{3}}{2} C_a \\ -\frac{\sqrt{3}}{2} C_a & 0 \end{pmatrix}$$

$$V_{\bar{D}_s K}(r) = \frac{1}{2} V_{DK}(r)$$

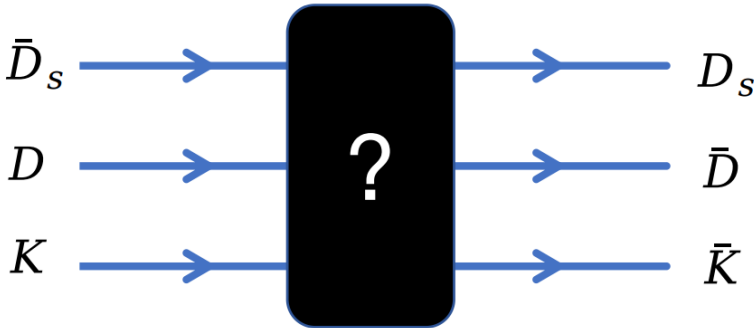
✓ X(3872) 结合 SU(3)-flavor 和 HQSS

$$V_{D_s \bar{D}} = C_a$$

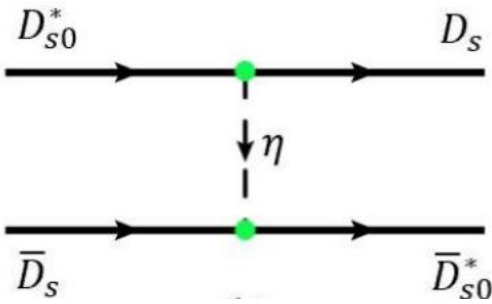
$$C_a^{DK} : C_a^{\bar{D}_s K} : C_a^{\bar{D}_s D} \approx 1 : 0.5 : 0.1$$

$J^{PC} = 0^{--} \bar{D}_s DK$ 三体系统谱学

➤ 三体相互作用



✓ 准两体系统 $\bar{D}_s D_{s0}^* - D_s \bar{D}_{s0}^*$



单 eta 介子交换

$$V^{C=\pm} = \mp \frac{2}{3} \frac{k^2}{f_\pi^2} q_0^2 \left(\frac{e^{-mr} - e^{-\Lambda r}}{4\pi r} - \frac{\Lambda^2 - m^2}{8\pi \Lambda} e^{-\Lambda r} \right)$$

$$\Lambda = \alpha \Lambda_{QCD} + m_{eff}$$

➤ $DK\bar{D}_s$ 分子态的结果

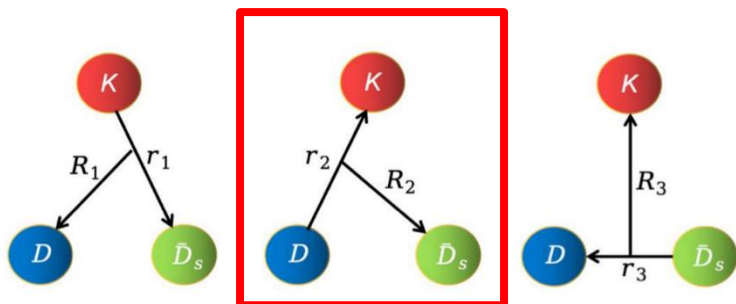
Scenarios	B.E.(0^{--})	$P_{\bar{D}_s K - D}$	$P_{DK - \bar{D}_s}$	$P_{\bar{D}_s D - K}$
$\alpha = 1$	22^{+23}_{-14}	$11^{+1}_{-1} \%$	$78^{+1}_{-2} \%$	$11^{+0}_{-1} \%$
$\alpha = 2$	20^{+22}_{-13}	$10^{+1}_{-1} \%$	$80^{+1}_{-2} \%$	$10^{+0}_{-1} \%$
Scenarios	$r_{\bar{D}_s K}$	r_{DK}	$r_{\bar{D}_s D}$	$\langle T \rangle$
$\alpha = 1$	$1.6^{+0.9}_{-0.4}$	$1.2^{+0.5}_{-0.3}$	$1.4^{+0.8}_{-0.3}$	177^{+81}_{-74}
$\alpha = 2$	$1.7^{+1.4}_{-0.4}$	$1.2^{+0.7}_{-0.3}$	$1.6^{+1.3}_{-0.5}$	169^{+82}_{-78}
Scenarios	$\langle V_{D_s \bar{K}} \rangle$	$\langle V_{DK} \rangle$	$\langle V_{D_s \bar{D}} \rangle$	$\langle V_{D_s \bar{D}_{s0}^*}^{C=-} \rangle$
$\alpha = 1$	-40^{+20}_{-25}	-147^{+62}_{-73}	-14^{+6}_{-7}	2^{+0}_{-1}
$\alpha = 2$	-37^{+22}_{-25}	-143^{+64}_{-73}	-13^{+7}_{-6}	3^{+2}_{-1}

✓ 预言存在一个三体分子态X(4310)

✓ $DK-\bar{D}_s$ 这种构型占主导

$$J^{PC} = 0^{--} \bar{D}_s DK$$

$J^{PC} = 0^{--} \bar{D}_s D K$ 分子态的强衰变

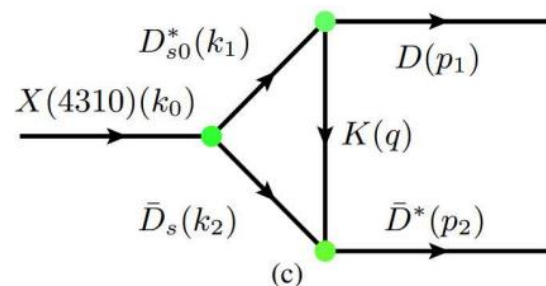
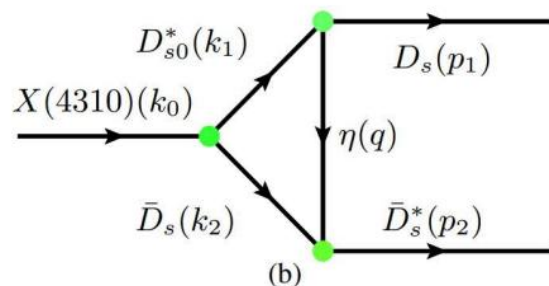
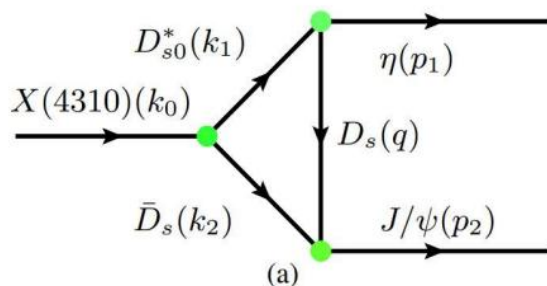


$$1 - Z = g^2 \frac{\partial G(s)}{\partial s}$$

80%

准两体近似

➤ 末态相互作用方法



$$i\mathcal{M}_a = g_{XD_s^* \bar{D}_s} g_{D_s^* D_s \eta} g_{\psi \bar{D}_s D_s} \int \frac{d^4 q}{(2\pi)^4} (k_2^\mu - q^\mu) \frac{1}{k_1^2 - m_{D_s^*}^2} \frac{1}{k_2^2 - m_{\bar{D}_s}^2} \frac{1}{q^2 - m_{D_s}^2} \varepsilon_\mu(p_2) F(q^2),$$

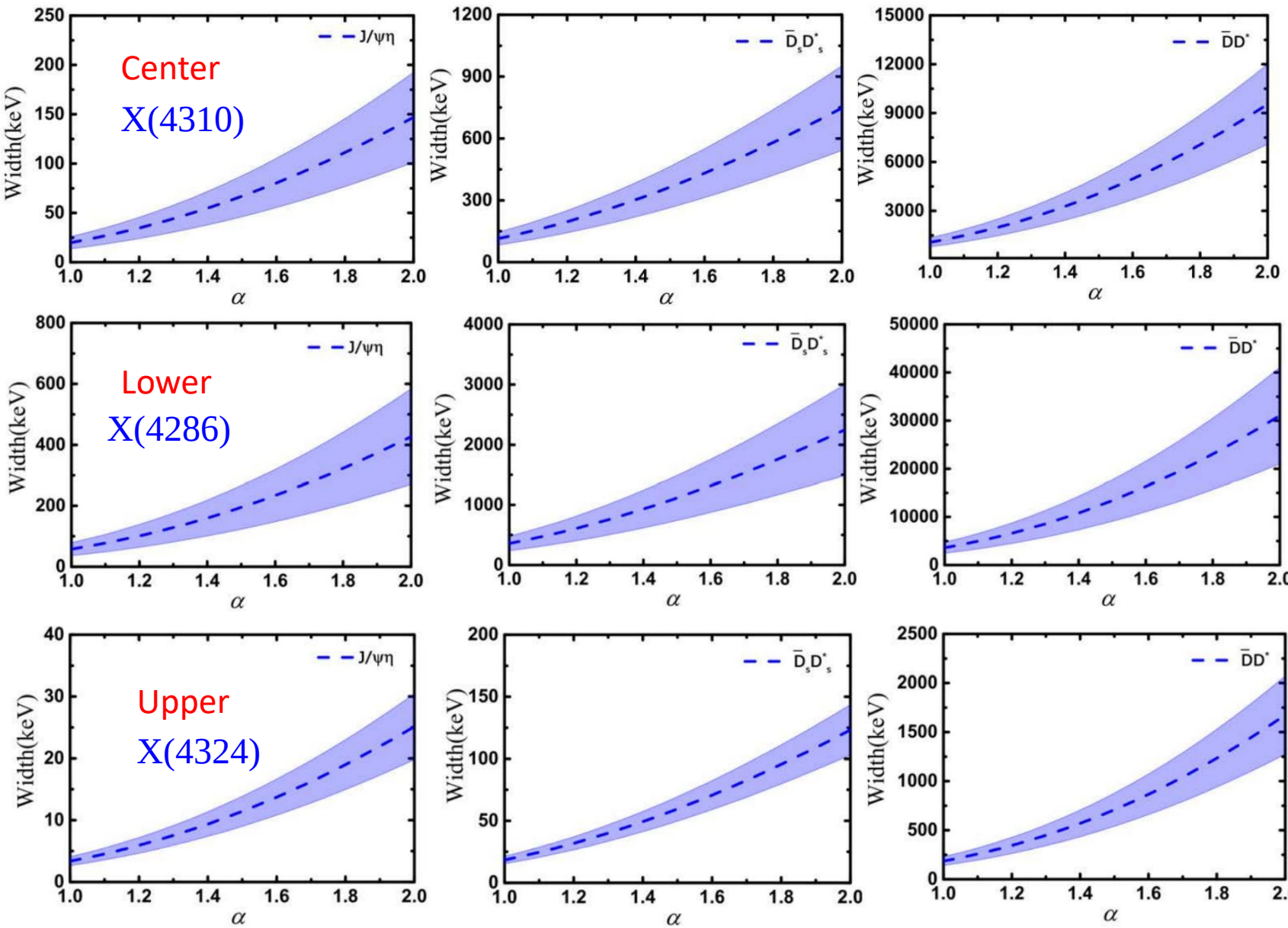
$$i\mathcal{M}_b = g_{XD_s^* \bar{D}_s} g_{D_s^* D_s \eta} g_{\bar{D}_s D_s^* \eta} \int \frac{d^4 q}{(2\pi)^4} q^\mu \frac{1}{k_1^2 - m_{D_s^*}^2} \frac{1}{k_2^2 - m_{\bar{D}_s}^2} \frac{1}{q^2 - m_\eta^2} \varepsilon_\mu(p_2) F(q^2),$$

$$F(q, \Lambda, m) = \left(\frac{\Lambda^2 - m_E^2}{\Lambda^2 - q^2} \right)^2$$

$$i\mathcal{M}_c = g_{XD_s^* \bar{D}_s} g_{D_s^* D K} g_{\bar{D}_s D^* K} \int \frac{d^4 q}{(2\pi)^4} q^\mu \frac{1}{k_1^2 - m_{D_s^*}^2} \frac{1}{k_2^2 - m_{\bar{D}_s}^2} \frac{1}{q^2 - m_K^2} \varepsilon_\mu(p_2) F(q^2),$$

$$\Lambda = \alpha \Lambda_{QCD} + m_E$$

$J^{PC} = 0^{--} \bar{D}_s D K$ 分子态的强衰变



➤ 最主要的衰变道

Center	Lower	Upper
$\Gamma(X \rightarrow \bar{D}^* D) / \Gamma(X \rightarrow \bar{D}_s^* D_s)$		
9.3~12.6	9.9~13.6	8.7~11.8
$\Gamma(X \rightarrow \bar{D}_s^* D_s) / \Gamma(X \rightarrow J/\psi \eta)$		
5.1~5.7	5.2~6.1	4.9~5.4

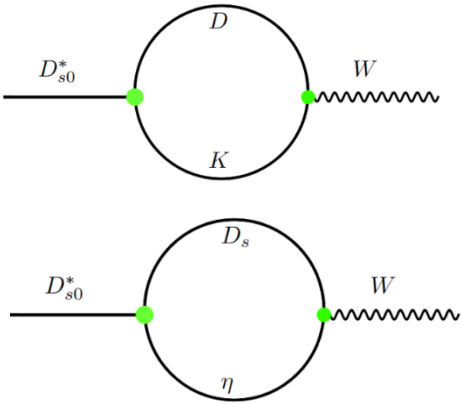
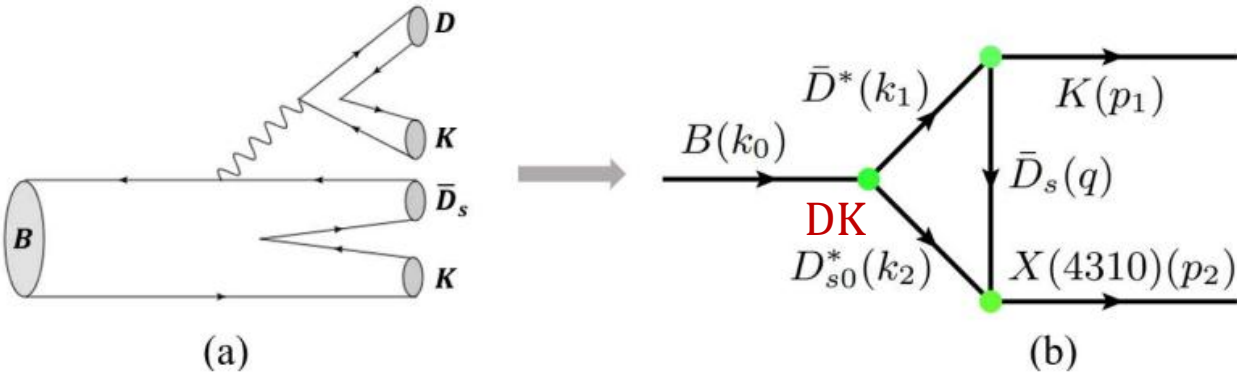
$$\Gamma(X \rightarrow \bar{D}^* D) : \Gamma(X \rightarrow \bar{D}_s^* D_s) : \Gamma(X \rightarrow J/\psi \eta)$$

$$50 : 5 : 1$$

$$X \rightarrow \bar{D}^* D$$

$J^{PC} = 0^{--} \bar{D}_s DK$ 分子态在B介子衰变中的产生

末态相互作用方法



Ming-Zhu Liu et al., Phys. Rev. D 109 (2024) 056014

弱相互作用顶点

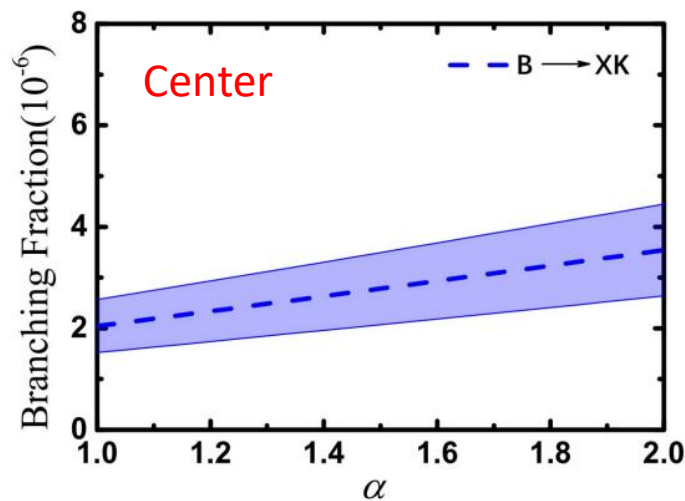
$$\mathcal{A}(B \rightarrow D_{s0}^* \bar{D}^*) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs} a_1 f_{D_{s0}^*} \left\{ -q_1 \cdot \varepsilon(q_2) (m_{D^*} + m_B) A_1(q_1^2) + (k_0 + q_2) \cdot \varepsilon(q_2) q_1 \cdot (k_0 + q_2) \right. \\ \left. \frac{A_2(q_1^2)}{m_{D^*} + m_B} + (k_0 + q_2) \cdot \varepsilon(q_2) [(m_{D^*} + m_B) A_1(q_1^2) - (m_B - m_{D^*}) A_2(q_1^2) - 2m_{D^*} A_0(q_1^2)] \right\}$$

$D_{s0}^*(2317)$ 衰变常数

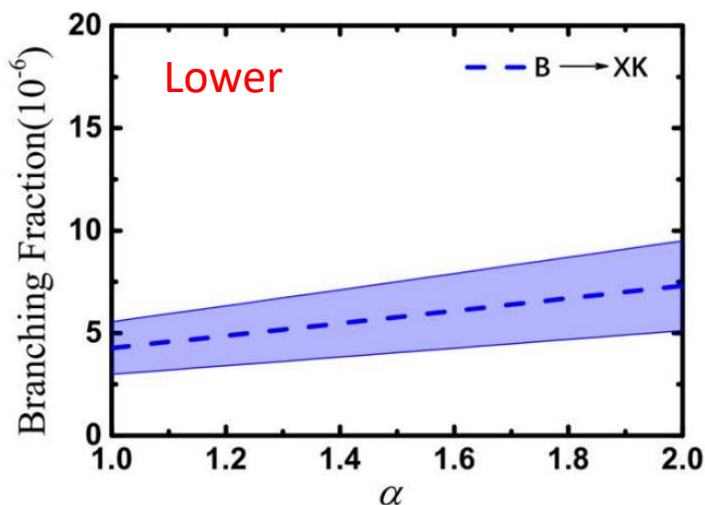
分子态图像

Decay Constants	$\mu = 1000$	$\mu = 1500$	$\mu = 2000$
$f_{D_{s0}^*(2317)}$	59.36	58.74	58.59

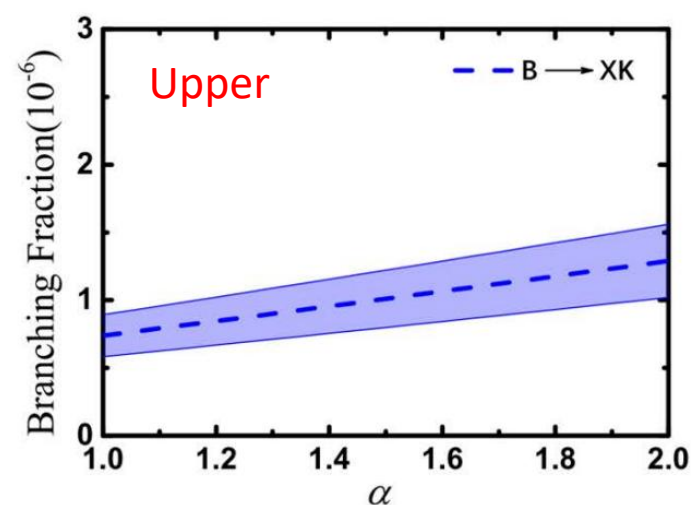
$J^{PC} = 0^{--} \bar{D}_s DK$ 分子态在B介子衰变中的产生



$$\mathcal{B}(B \rightarrow X(4310)K) \approx 10^{-6}$$



$$\mathcal{B}(B \rightarrow D_{s0}^*(2317)\bar{D}^{(*)}) \approx 10^{-3}$$



➤ 比较两体分子态和三体分子态产率的比值

$$\mathcal{B}(B \rightarrow \bar{D}_s DK X) / \mathcal{B}(B \rightarrow D_{s0}^*(2317)\bar{D}^{(*)}) \approx 10^{-3}$$

$$Y(e^+e^- \rightarrow \bar{D} DK X) / \mathcal{B}(e^+e^- \rightarrow D_{s0}^*(2317)X) \approx 10^{-3}$$

Tian-Chen Wu et al., Phys. Rev. D 108 (2023) 014015

两个比值一致性说明了我们估计的三体分子态产率是合理的

$J^{PC} = 0^{--} \bar{D}_s DK$ 分子态在LHCb实验上的事例数

➤ 估计事例数

$$\mathcal{B}(B \rightarrow X(4310)K) \approx 2 \times 10^{-6}$$

✓ $B \rightarrow D^{(*)} \bar{D} K$

$$\mathcal{B}(X(4310) \rightarrow D^{*\pm} D^{\mp}) \approx 0.25$$

$$\mathcal{B}(B^+ \rightarrow (X(4310) \rightarrow D^{*\pm} D^{\mp}) K^+) \approx 5 \times 10^{-7}$$

$$\mathcal{B}(B^+ \rightarrow D^{*\pm} D^{\mp} K^+) \approx 6 \times 10^{-4}$$

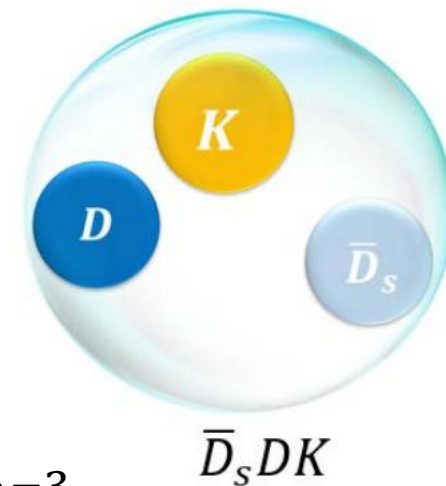
$$\mathcal{B}(B^+ \rightarrow (X(4310) \rightarrow D^{*\pm} D^{\mp}) K^+) / \mathcal{B}(B^+ \rightarrow D^{*\pm} D^{\mp} K^+) \approx 10^{-3}$$

LHCb Collaboration 9 fb^{-1} $N(B^+ \rightarrow D^{*\pm} D^{\mp} K^+) \approx 2 \times 10^3$

$$N(B^+ \rightarrow (X(4310) \rightarrow D^{*\pm} D^{\mp}) K^+) \approx 2$$

LHCb Collaboration 50 fb^{-1} $N(B^+ \rightarrow (X(4310) \rightarrow D^{*\pm} D^{\mp}) K^+) \approx 10$

LHCb Collaboration 350 fb^{-1} $N(B^+ \rightarrow (X(4310) \rightarrow D^{*\pm} D^{\mp}) K^+) \approx 100$





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- 总结

为什么引入三体力

➤ **轻核结合能** 尽管现代两体核力（如Argonne v18、CD-Bonn、手征势）能够高精度拟合核子-核子散射数据，但仅考虑两体相互作用无法准确描述轻核的结合能

	Λ	^3H				^4He			
		E	T	V_{NN}	V_{3N}	E	T	V_{NN}	V_{3N}
NLO	500	-8.54	30.76	-39.30	—	-29.57	61.42	-91.00	—
	600	-7.53	39.24	-46.77	—	-23.87	77.61	-101.47	—
NNLO	500	-8.68	31.07	-39.43	-0.318	-29.51	61.83	-89.59	-1.753
	600	-8.68	34.44	-42.41	-0.712	-29.98	71.49	-97.44	-4.025
“Expt”	—	-8.68	—	—	—	-29.8 ± 0.1	—	—	—

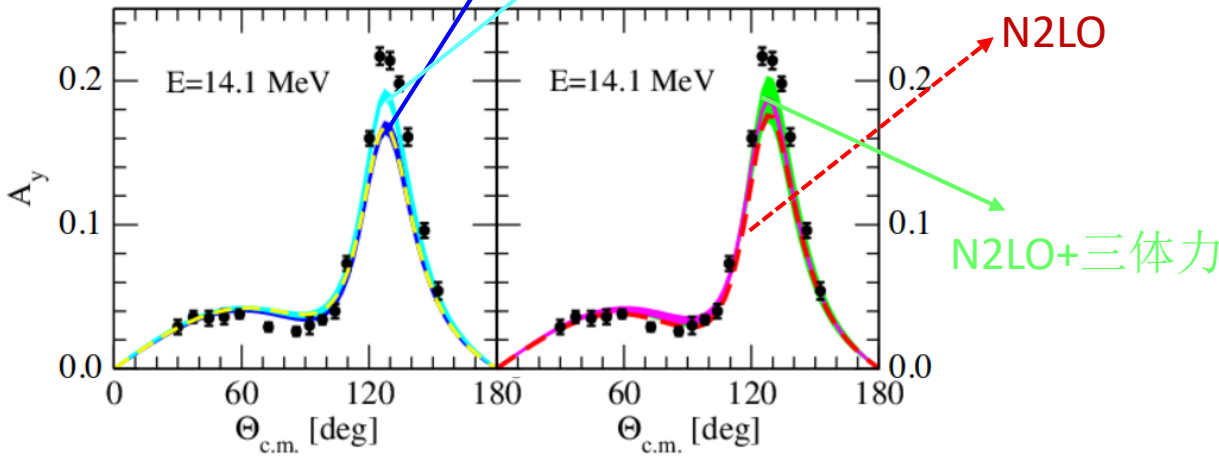
E. Epelbaum et al., Phys. Rev. C 66 (2002) 064001

	B (MeV)	T (MeV)	$P_{S'}$ (%)	P_D (%)	P_P (%)	2a (fm)	4a (fm)
^3H							
AV18	7.61	46.66	1.30	8.50	0.07	1.27	6.33
AV18+UR	8.49	51.34	1.05	9.31	0.13	0.63	6.33
^3He							
AV18	6.91	45.62	1.53	8.46	0.06	1.17	13.6
AV18+UR	7.75	50.27	1.24	9.26	0.13	-0.02	13.7

A. Kievsky et al., Phys.Rev.C 52 (1995) R15-R19

三体力对描述轻核束缚能起到一定的作用

➤ 核子-氦核散射过程

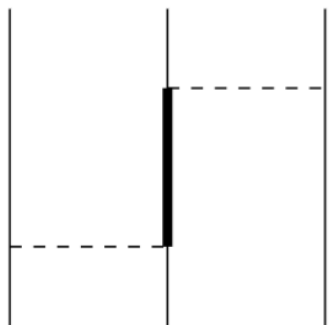


E. Epelbaum et al., Phys.Rev.C 99 (2019) 024313

只通过两核子间相互作用不能描述Ay疑难

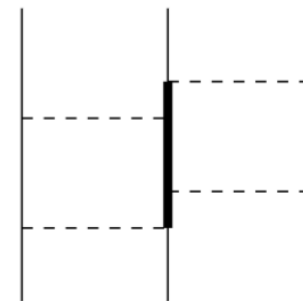
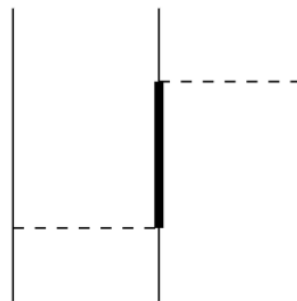
三体力的发展历史——唯象力

➤ Fujita-Miyazawa 机制——两 π 交换



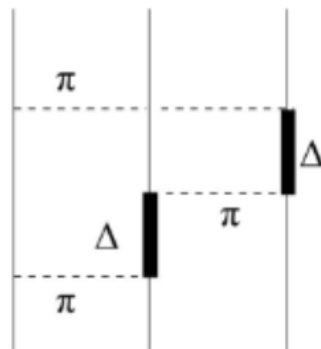
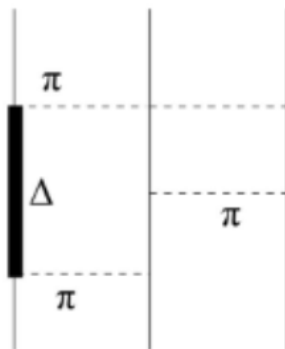
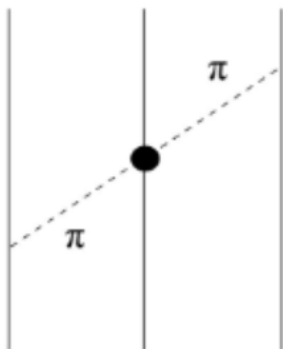
Fujita and Miyazawa, Prog.Theor.Phys. 17 (1957) 360-365

➤ Urbana力



Carlson, Pandharipande, and Wiringa, Nucl.Phys.A 401 (1983) 59-85

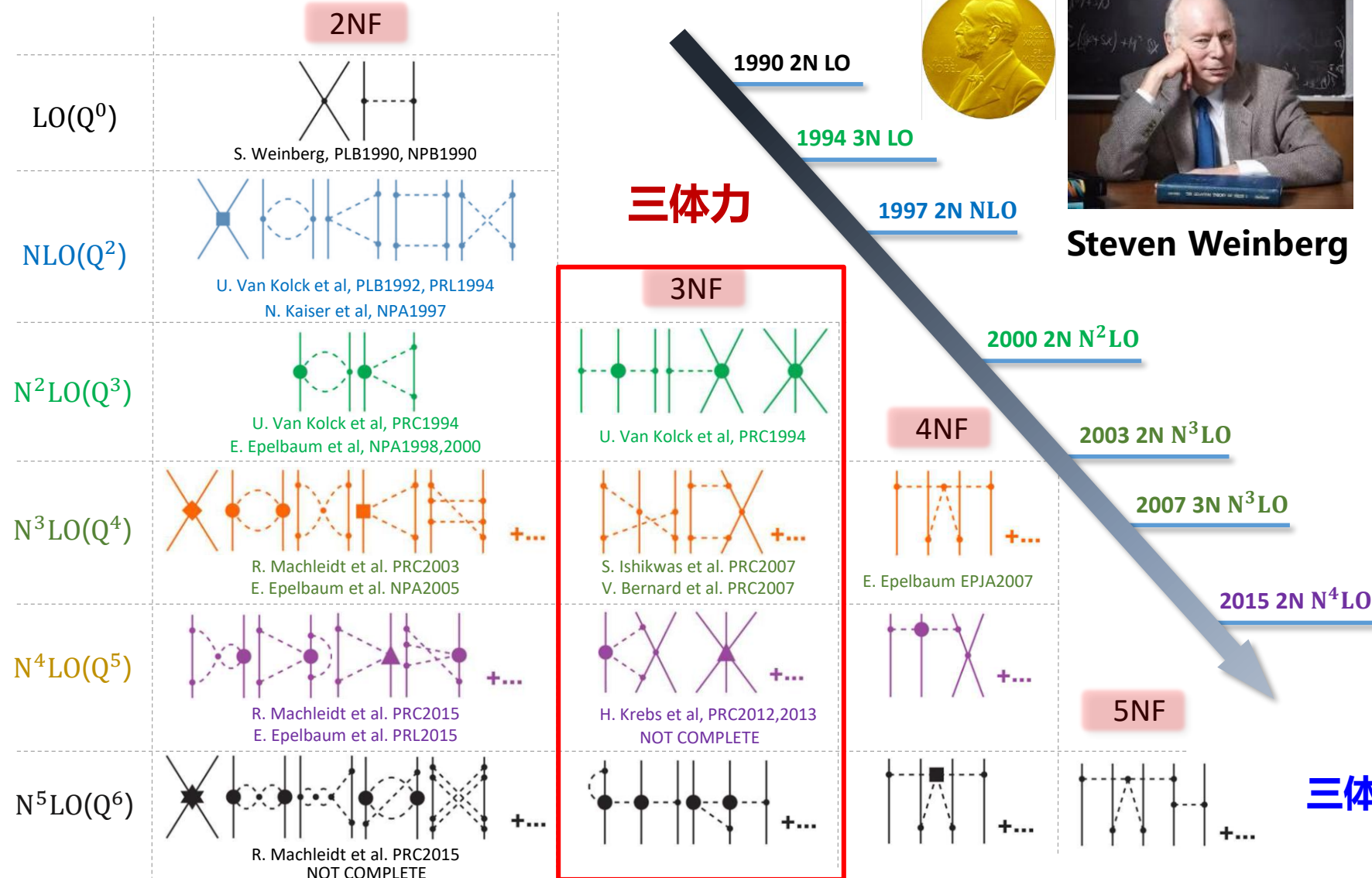
➤ Illinois力



Steven C. Pieper, V. R. Pandharipande, R. B. Wiringa, J. Carlson, Phys.Rev.C 64 (2001) 014001

三体力的发展历史——手征有效场论

➤ 手征有效场论



van Kolck



Kaiser



Epelbaum

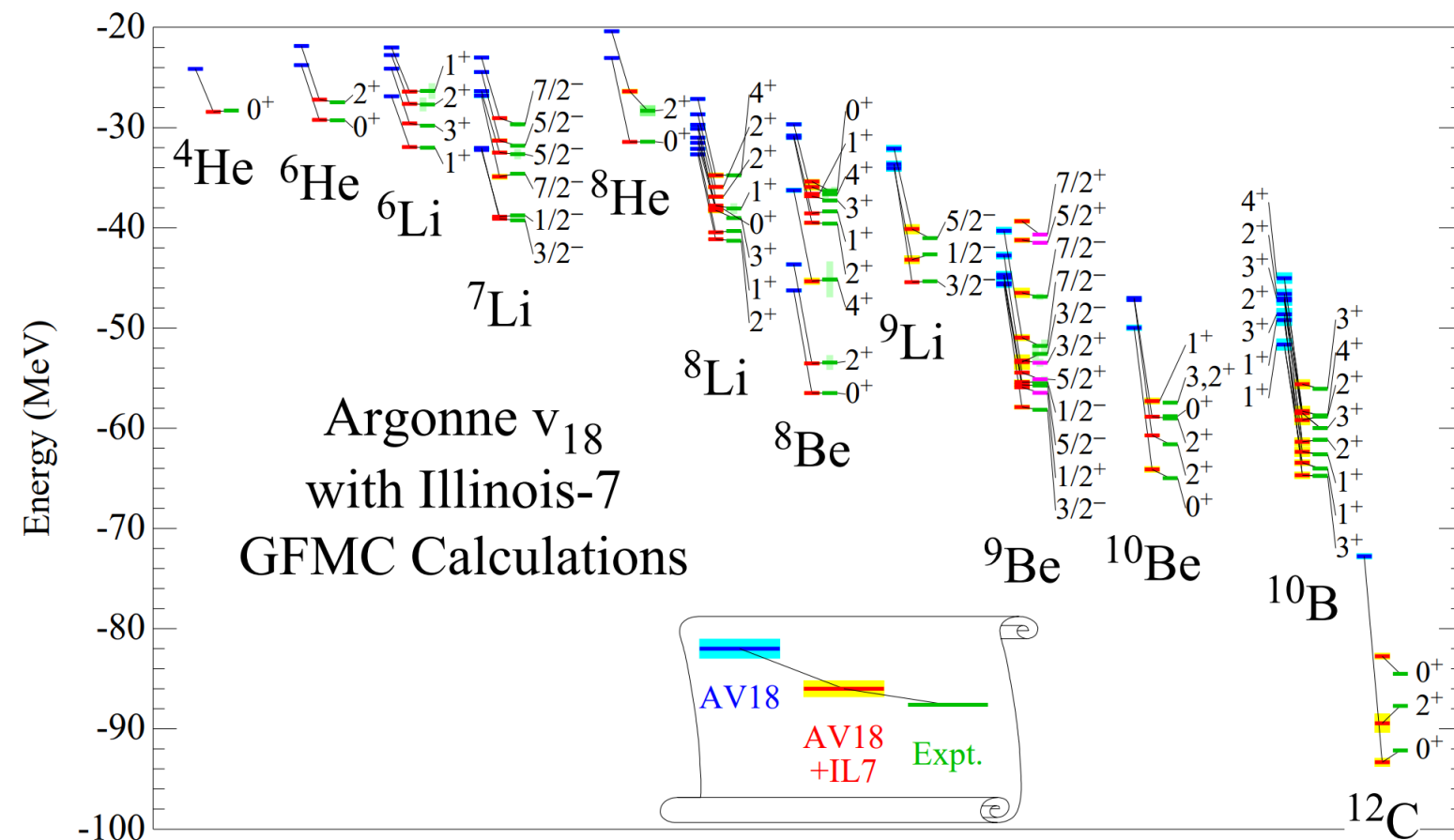


Machleidt

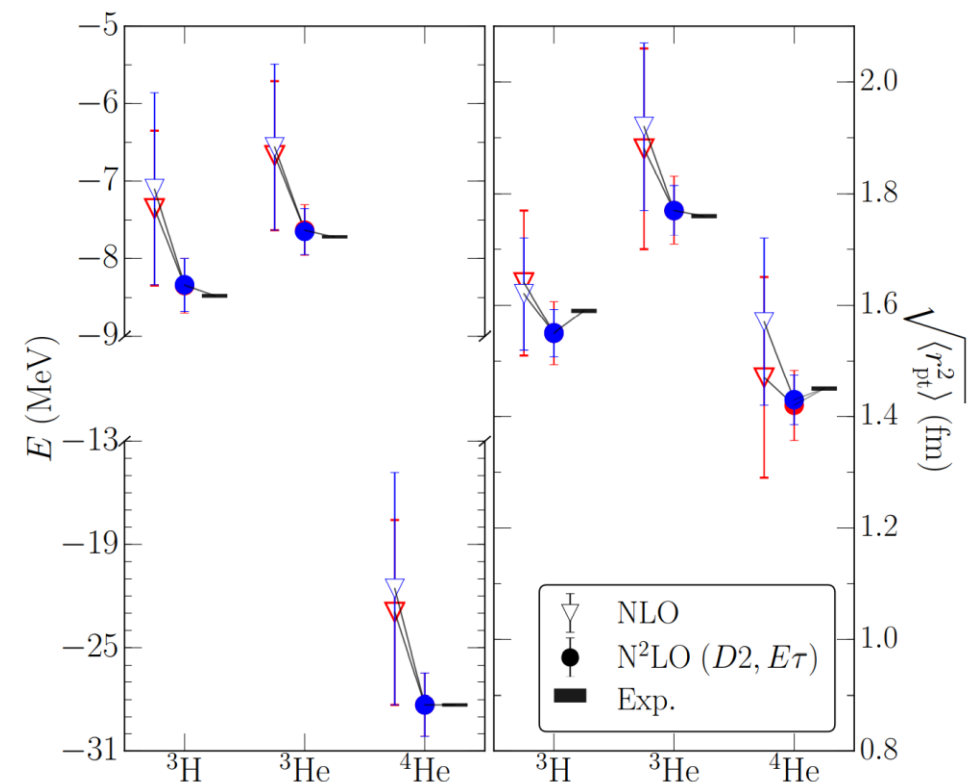
三体力在手征有效场论中自然的出现

三体力的发展历史

➤ 三体力对轻核强子谱学的影响



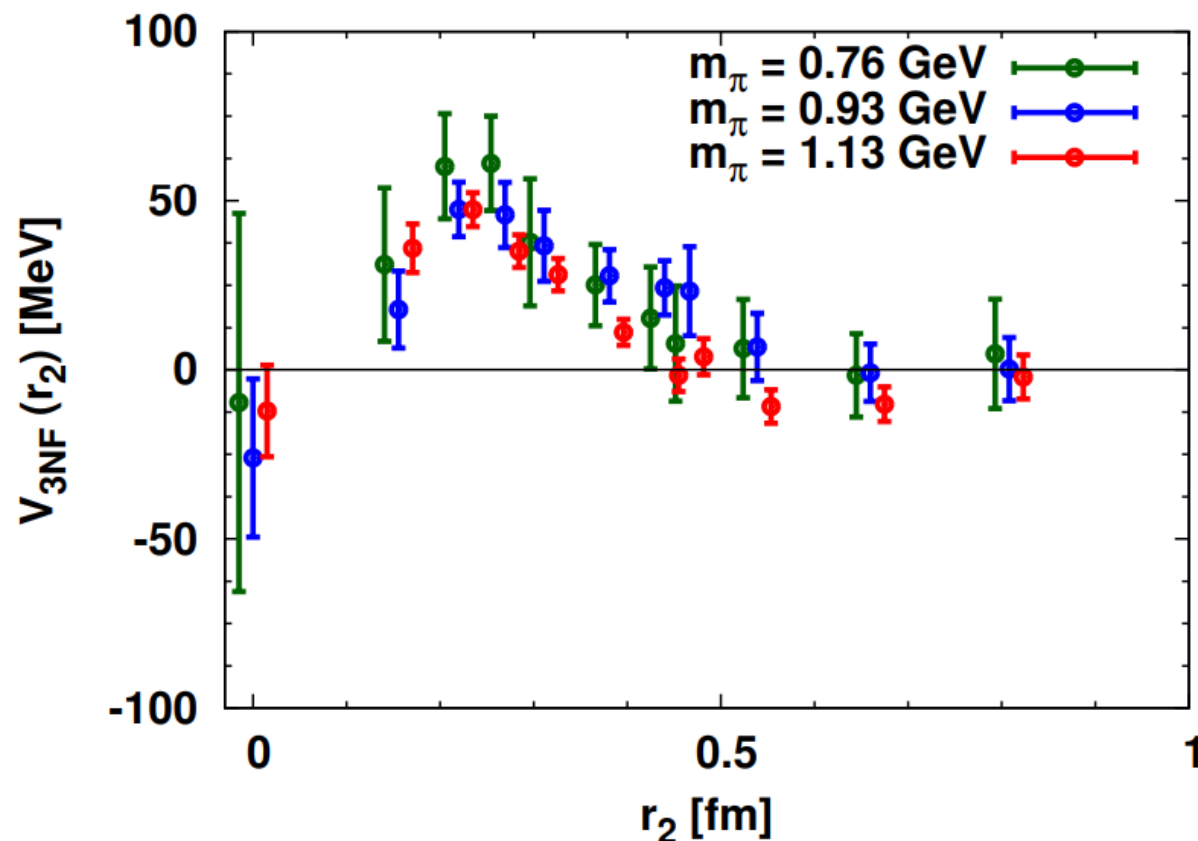
J. Carlson et al., Rev. Mod. Phys. 87 (2015) 1067



J.E. Lynn et al., Phys. Rev. Lett. 116 (2016) 062501

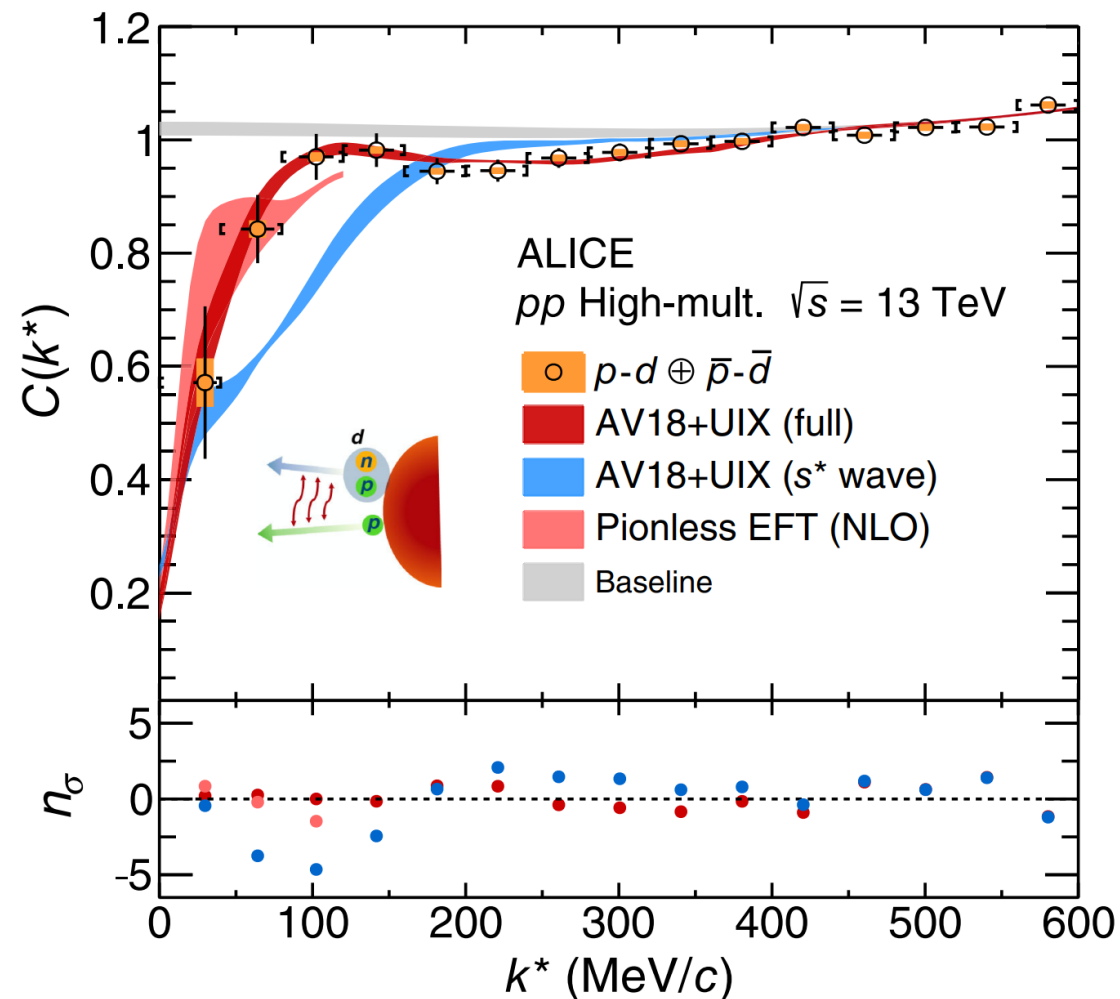
模型无关的研究三体力

➤ 格点QCD



Sinya Aoki et al., Front.in Phys. 8 (2020) 307

➤ 费米镜技术

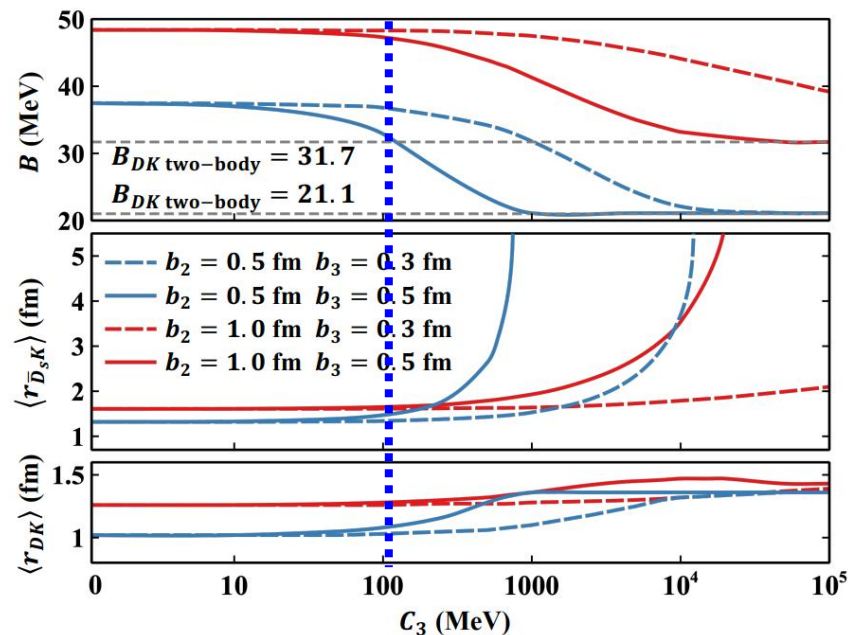
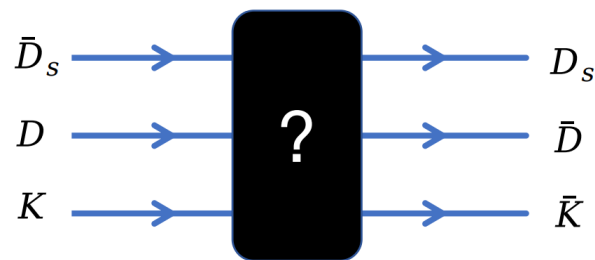


Alice Collaboration, Phys.Rev.X 14 (2024) 3, 031051

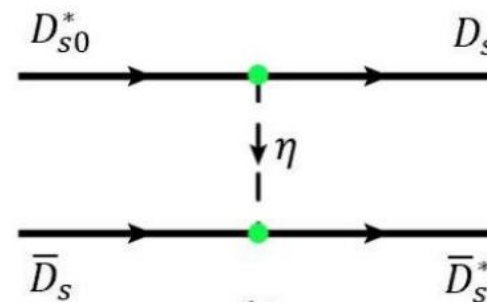
三强子系统开展三体力的研究

➤ 与C宇称相关的三体力

$$H = T + T' + V + V' + \boxed{V^C}$$



$$\Psi^C = \frac{1}{\sqrt{2}}(\Psi_{\bar{D}_s D K} + C \Psi'_{D_s \bar{D} \bar{K}})$$



$$V^{C=\pm} = \mp \frac{2}{3} \frac{k^2}{f_\pi^2} q_0^2 \left(\frac{e^{-mr} - e^{-\Lambda r}}{4\pi r} - \frac{\Lambda^2 - m^2}{8\pi\Lambda} e^{-\Lambda r} \right)$$

Marek Karliner et al., Nucl.Phys.A 954 (2016) 365-370

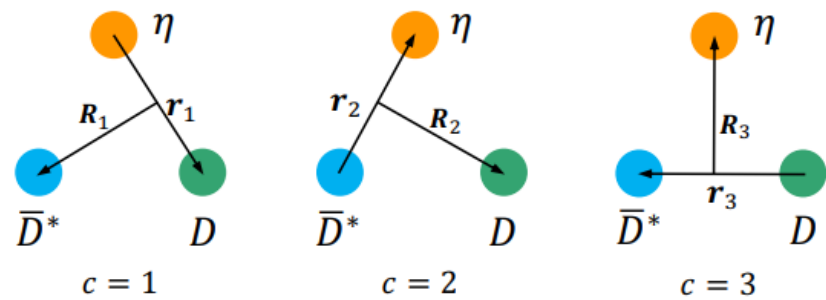
$$V^C = C_3 e^{-r^2/b_3^2} e^{-R^2/b_3^2}$$

$$\frac{|\langle V_3 \rangle|}{|\langle V_3 \rangle| + \sum_{1 \leq i < j \leq 3} |\langle V(r_{ij}) \rangle|}$$

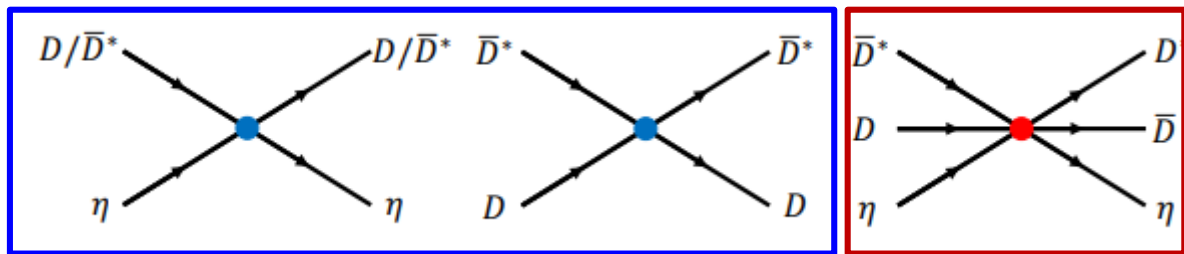
三体力的贡献大约只有4%

具有C宇称的三体系统 $I(J^{PC}) = 0(1^{-+}) \bar{D}^* D \eta$

➤ 三体系统的雅可比道



➤ 三体系统中的势能



两体相互作用

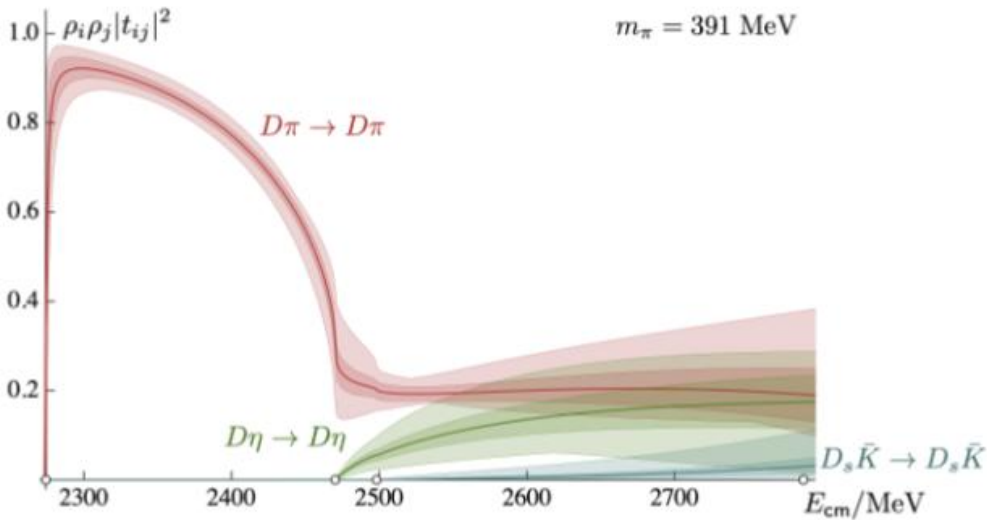
三体相互作用

$$V = C_a e^{-r^2/b_2^2}$$

格点QCD

$$V^C = C_3 e^{-r^2/b_3^2} e^{-R^2/b_3^2}$$

Charge 对称性



G. Moir et al., JHEP 10, 011 (2016)

C宇称为+的是吸引相互作用

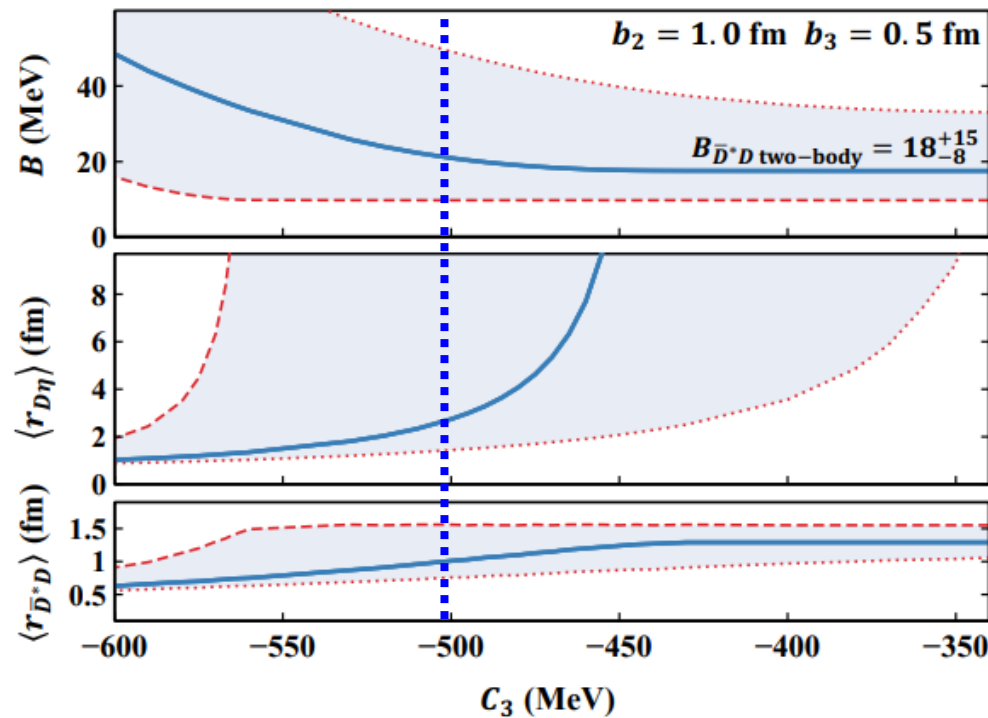
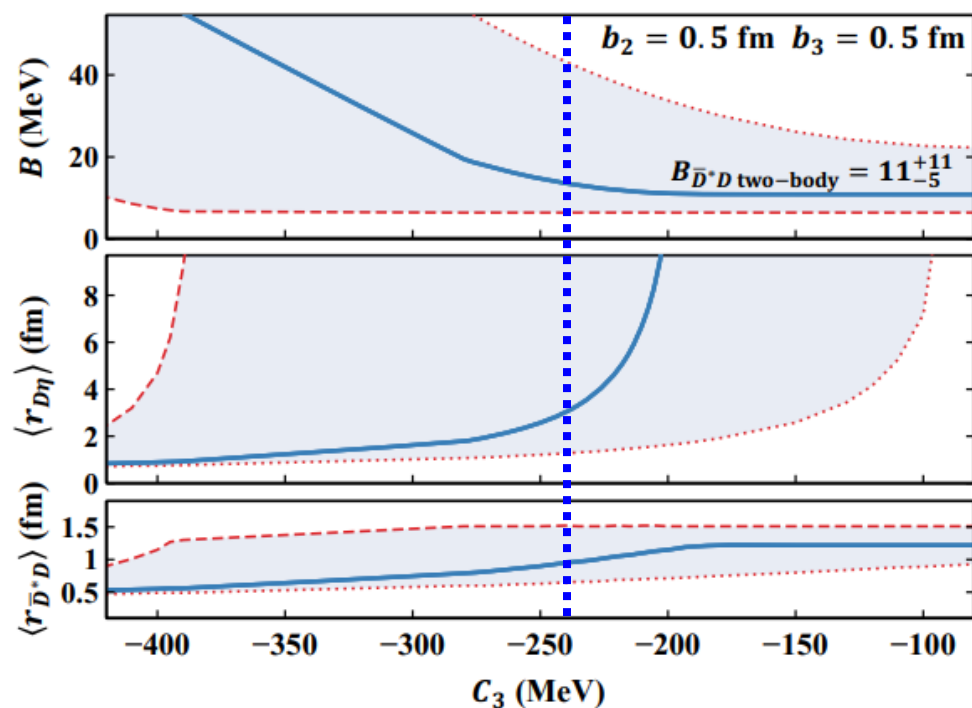
只能确定三体相互作用的正负号，其大小当作一个未知的参数

Xiang-Kun Dong et al., Phys.Rev.D 101 (2020) 076003

Chunjiang Shi et al., Phys.Rev.D 109 (2024) 094513

具有C宇称的三体系统 $I(J^{PC}) = 0(1^{-+}) \bar{D}^* D \eta$

➤ 三体系统的束缚能与均方根半径随三体力的变化



- ✓ 在三体系统 $I(J^{PC}) = 0(1^{-+}) \bar{D}^* D \eta$ 中存在一个三体分子态
- ✓ 三体力的贡献达到了20%

三体系统 $I(J^{PC}) = 0(1^{-+}) \bar{D}^* D \eta$ 是研究三体力非常理想的系统

目录

- 强相互作用的非微扰效应
- 具有C宇称的三体强子分子态
- 三体强子系统中的三体力
- 总结

- 基于有效场论方法和对称性，预测具有Charge对称性，受QCD裸态以及两体强子分子态的影响较小的三体强子分子态，并为实验寻找提供了理想的理论方案

如果这一预言获得实验证实，将是**三体强子分子态存在的首个确凿证据**，并有望为解决 $D_{s0}^*(2317)$ 粒子分子态组分的长期争议提供决定性支持

- 提出在具有C宇称的三强子系统研究强相互作用的微扰效应——三体力，为研究三体力提供了全新且更直接的途径

理论分析显示，在 $I(J^{PC}) = 0(1^{-+}) \bar{D}^* D \eta$ 的三体系统中，**三体力的贡献达到了20%**，意味着该系统是研究三体力的理想系统

谢谢大家！