Recent progress on the molecular tetraquarks, pentaquarks and di-baryons

---

王 波

河北大学

第三届LHCb前沿物理研讨会

2023年4月16日

Outline

✓Background：experimental observations

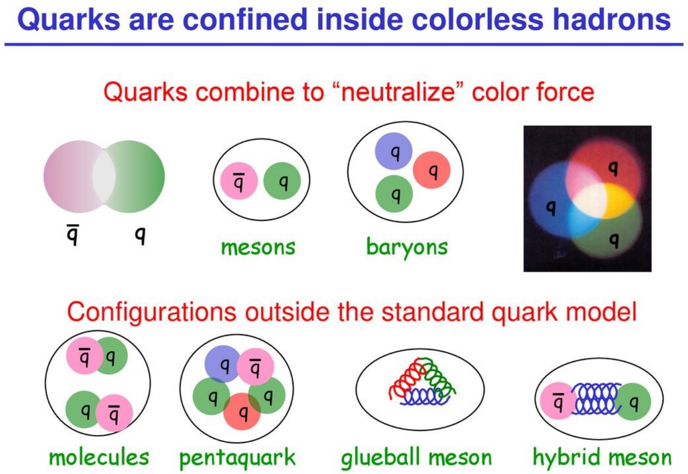
- $Z_c(3900), Z_c(4020), Z_b(10610), Z_b(10650)$
- $Z_{cs}(3985), Z_{cs}(4000)$
- $P_c(4312), P_c(4440), P_c(4457)$
- $P_{cs}(4459), P_{cs}(4338)$
- $X_{0,1}(2900)$, $T_{cc}(3875)$ and $T_{cs}(2900)$

✓Theoretical aspects:

- Molecular tetraquarks
- Molecular pentaquarks
- Molecular hexaquarks (dibaryons)

✓Summary and outlook

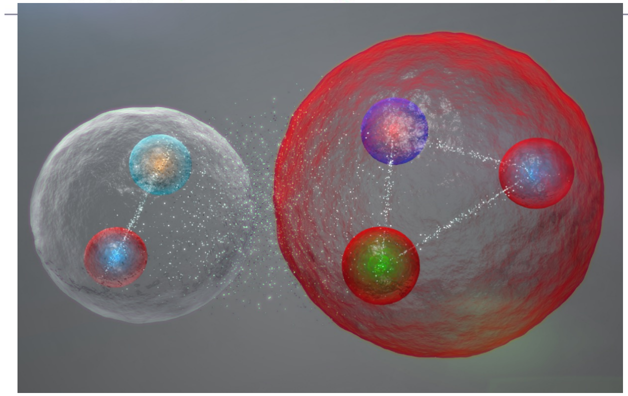
Conventional and exotic hadrons

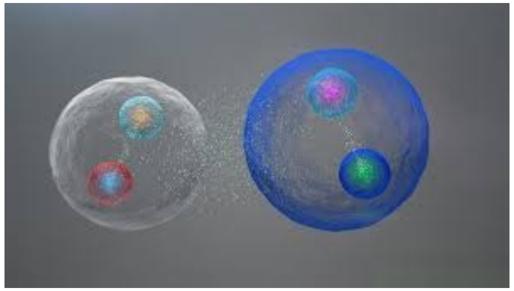


Quarks are confined inside colorless hadrons

Quarks combine to “neutralize” color force

Configurations outside the standard quark model





$X(3872)$
$Z_c(3900)$
$Z_c(4020)$
$Z_b(10610)$
$Z_b(10650)$
$P_c(4312)$
$P_c(4440)$
$P_c(4457)$
……

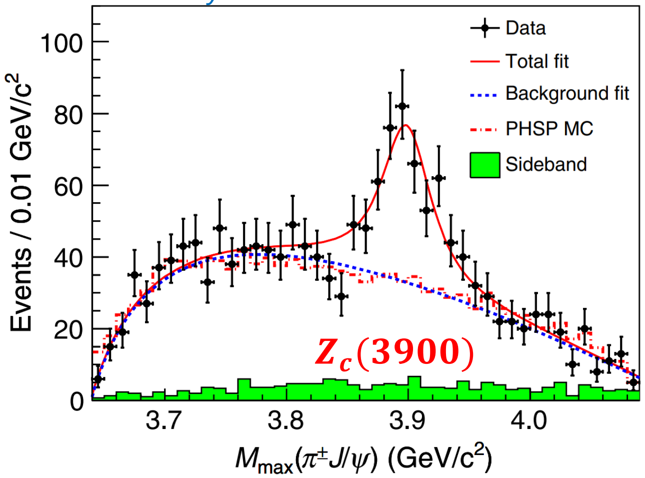
Recent reviews:

- ✓**H.-X. Chen** et al, Phys. Rept. 639, 1 (2016)
- ✓**R. Lebed** et al, Prog. Part. Nucl. Phys. 93, 143 (2017)
- ✓**A. Esposito** et al, Phys. Rept. 668, 1(2017)
- ✓**F.-K. Guo** et al, Rev. Mod. Phys. 90, 015004 (2018)
- ✓**Y.-R. Liu** et al, Prog. Part. Nucl. Phys. 107, 237 (2019)
- ✓**N. Brambilla** et al, Phys. Rept. 873, 1 (2020)
- ✓**S. Chen** et al, Front. Phys. 18, 44601 (2023)
- ✓**H.-X. Chen** et al, Rept. Prog. Phys. 86, 026201 (2023)
- ✓**L. Meng** et al, arXiv:2204.08716

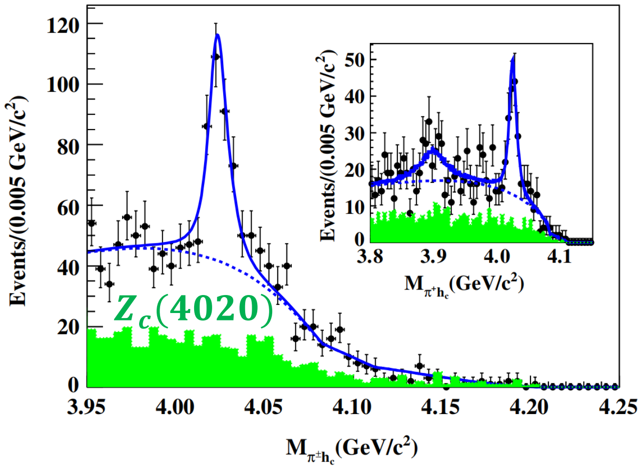
Experimental observations

- **Charmonium energy region:** $Z_c(3900)$ (Z_c) and $Z_c(4020)$ (Z_c')

Phys.Rev.Lett.**110**.252001



Phys.Rev.Lett.**111.**242001

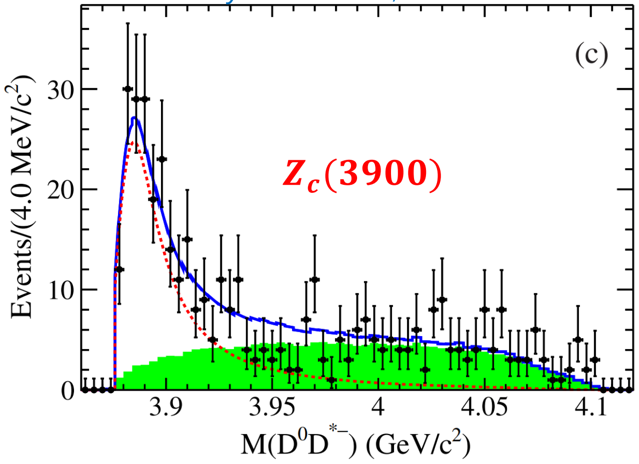


- **BESIII**: $e^+e^- \to J/\psi\pi^+\pi^-$ and $e^+e^- \to h_c\pi^+\pi^-$, respectively.
- $Z_c(3900)$: subsequently confirmed by the Belle [Phys. Rev. Lett. **110**, 252002] and Xiao *et al* [Phys. Lett. B **727**, 366].

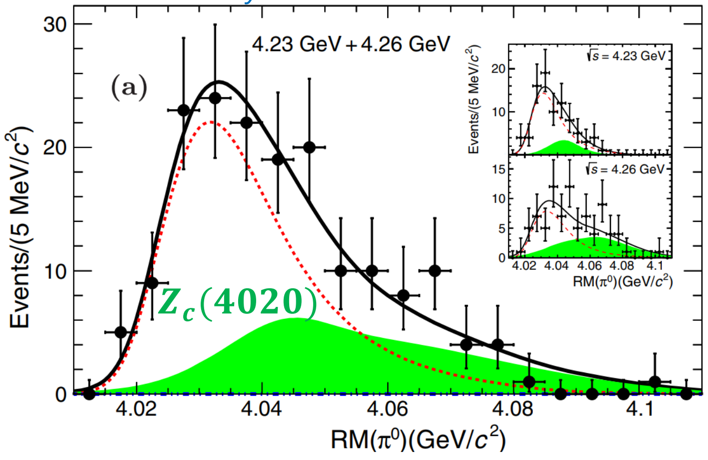
Experimental observations

- **Charmonium energy region: $Z_c(3900)$ and $Z_c(4020)$**

Phys.Rev.D.**92**, 092006



Phys.Rev.Lett.**115.**182002

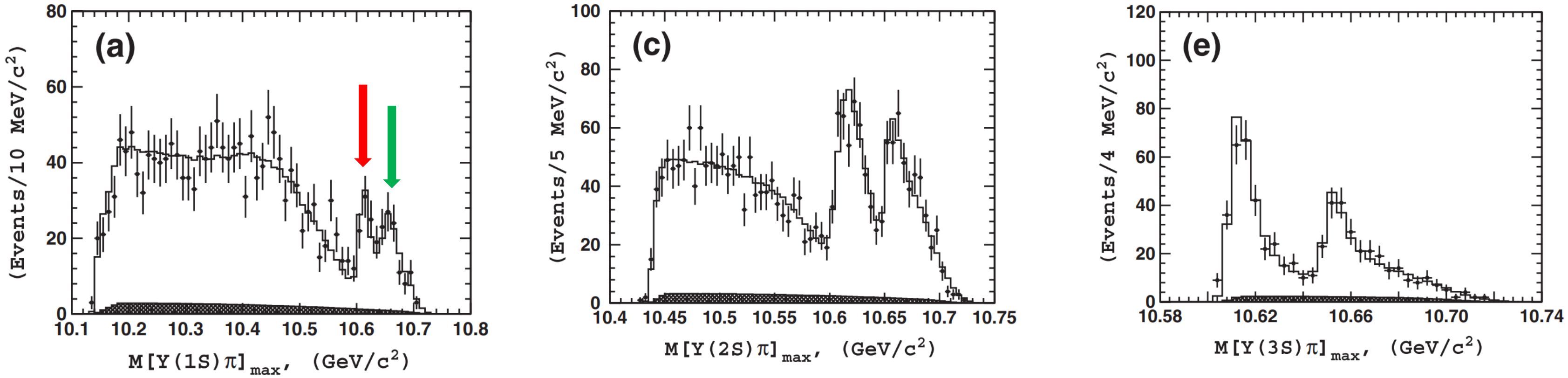


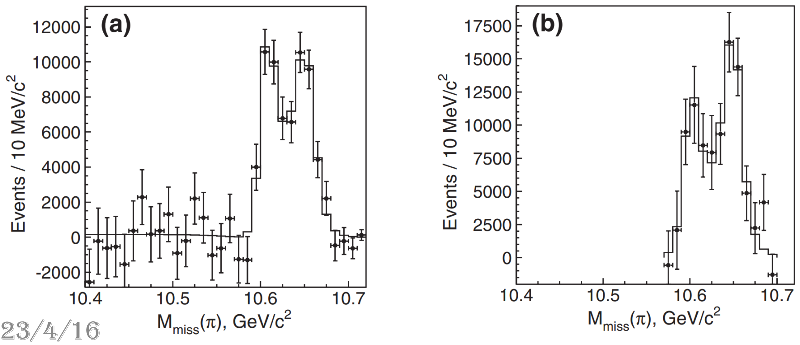
- **BESIII**: $e^+e^- \to \bar{D}D^*\pi$ and $e^+e^- \to \bar{D}^*D^*\pi$, respectively.

$Z_c(3900)$: $I^G(J^{PC}) = 1^+(1^{+-})$ is measured
$Z_c(4020)$: $I^G(J^{PC}) = 1^+(1^{+-})$ is favored

Experimental observations

- Bottomonium energy region: $Z_b(10610)$ (Z_b) and $Z_b(10650)$ (Z_b')



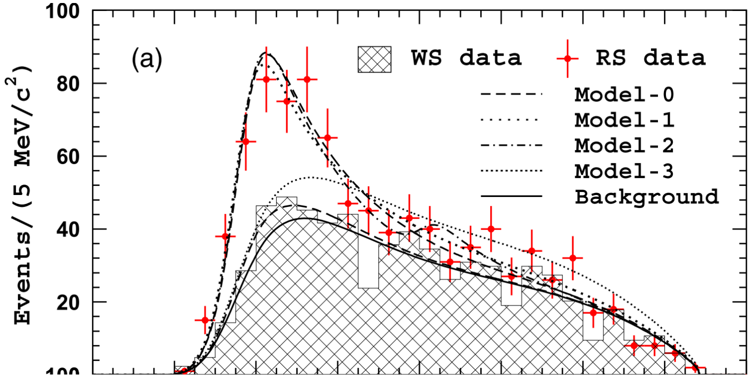


Phys.Rev.Lett. **108.**122001

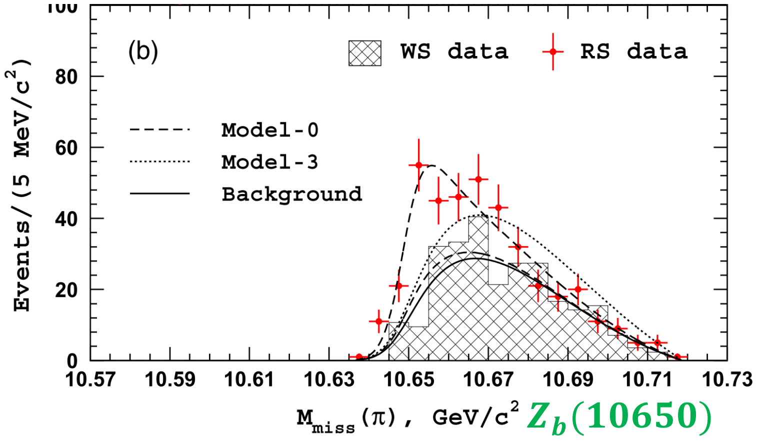
Belle: $e^+e^- \to \Upsilon(nS)\pi^+\pi^- (n=1,2,3)$ and $e^+e^- \to h_b(mP)\pi^+\pi^- (m=1,2)$, respectively.

Experimental observations

- Bottomonium energy region: $Z_b(10610)$ and $Z_b(10650)$



$Z_b(10610)$



$Z_b(10650)$

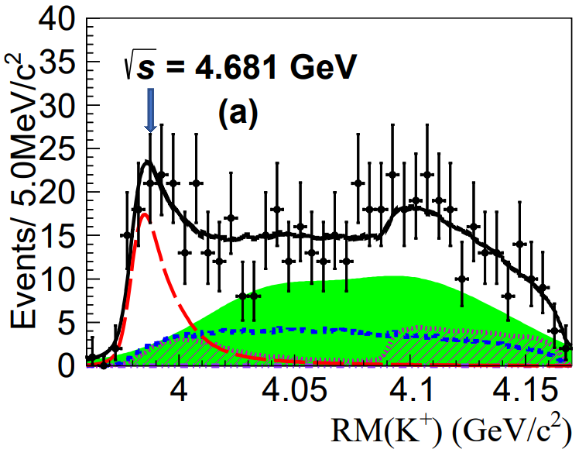
Phys.Rev.Lett. **116.**212001

Belle: $e^+e^- \to \bar{B}B^*\pi$ and $e^+e^- \to \bar{B}^*B^*\pi$, respectively.

$Z_b(10610)$: $I^G(J^{PC}) = 1^+(1^{+-})$ is measured
$Z_b(10650)$: $I^G(J^{PC}) = 1^+(1^{+-})$ is measured

Experimental observations

- Charmonium energy region: $Z_{cs}(3985)$ and $Z_{cs}(4000)$

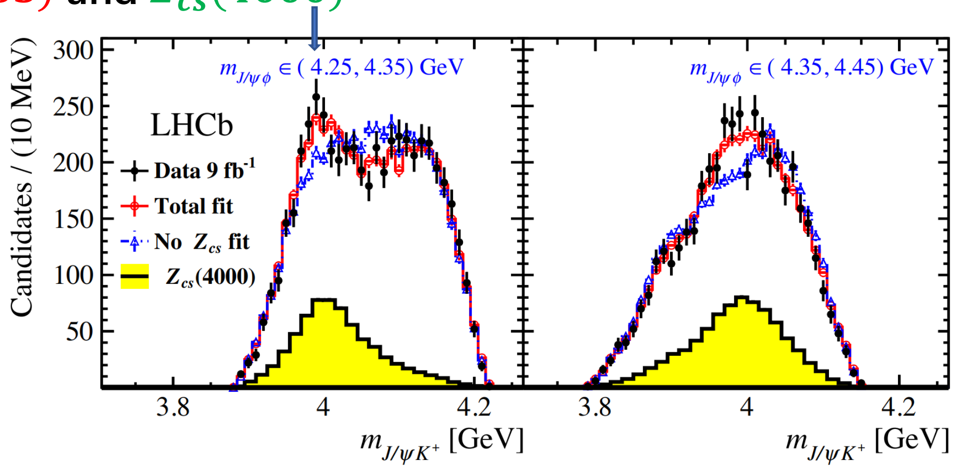


PhysRevLett.126.102001

BESIII: $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

$m_{Z_{cs}} = 3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV

$\Gamma_{Z_{cs}} = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV



PhysRevLett.127.082001

LHCb: $B^+ \to J/\psi\phi K^+$

$m_{Z_{cs}} = 4003 \pm 6^{+4}_{-14}$ MeV

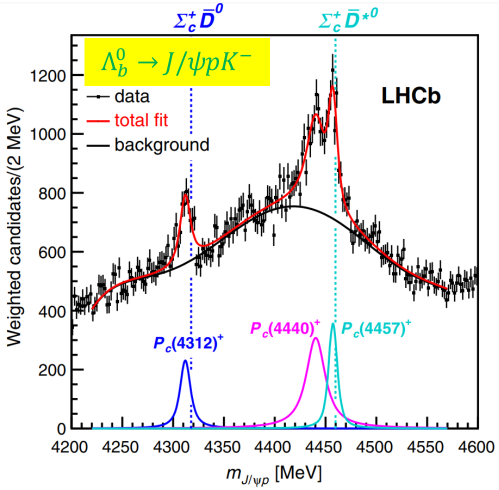
$\Gamma_{Z_{cs}} = 131 \pm 15 \pm 26$ MeV

A broder $Z_{cs}(4220)$ was also reported

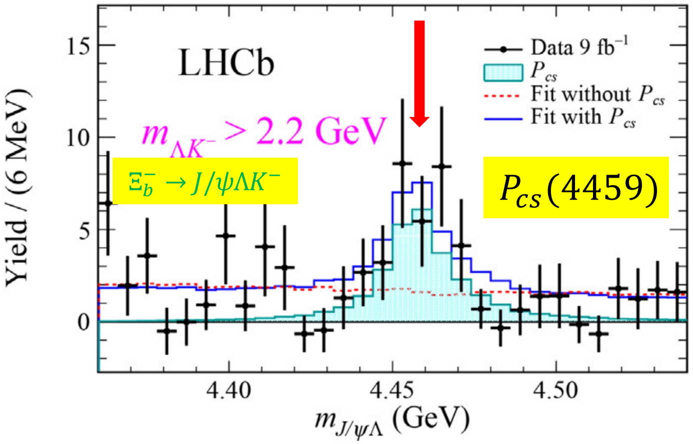
Experimental observations

- Charmonium energy region: $\boldsymbol{P_c(4312)}$, $\boldsymbol{P_c(4440)}$, $\boldsymbol{P_c(4457)}$ and $\boldsymbol{P_{cs}}$

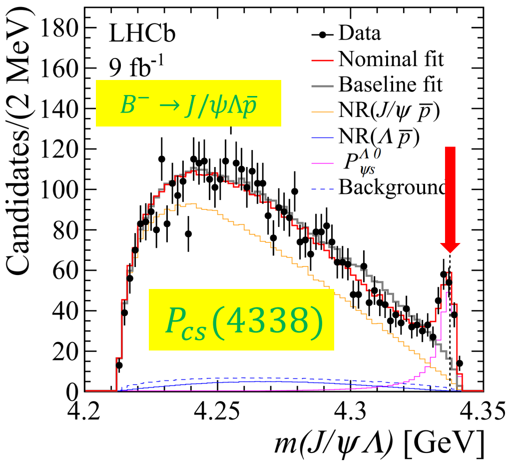
Phys.Rev.Lett.**122**.222001



Science Bulletin **66** (2021) 1278–1287



arXiv: 2210.10346

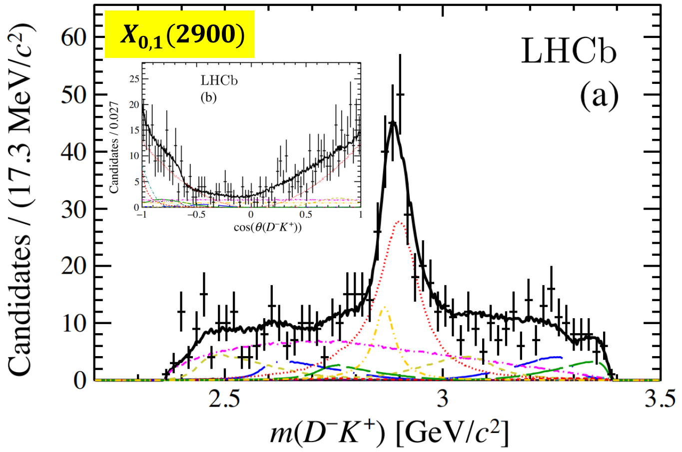


- A $P_c(4337)$ was also reported by the LHCb in $B_s^0 \to J/\psi p\bar{p}$ decay [Phys.Rev.Lett. **128** (2022) 062001].
- LHCb: the J^P quantum numbers of $\boldsymbol{P_c}$s and $\boldsymbol{P_{cs}(4459)}$ are undetermined yet, while $\frac{1}{2}^-$ is preferred for $\boldsymbol{P_{cs}(4338)}$ with 90% CL.

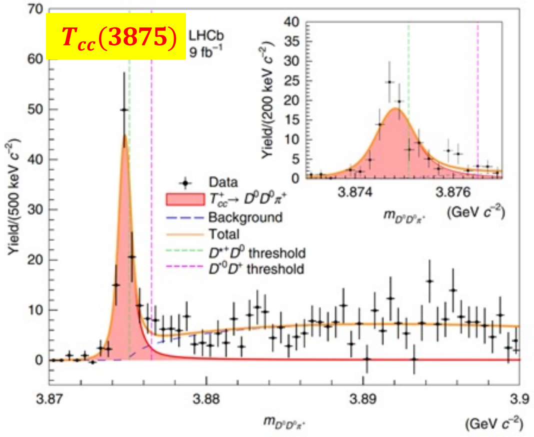
Experimental observations

$X_{0,1}(2900)$, $T_{cc}(3875)$ and $T_{c\bar{s}}(2900)$

$B^+ \to D^+ D^- K^+$

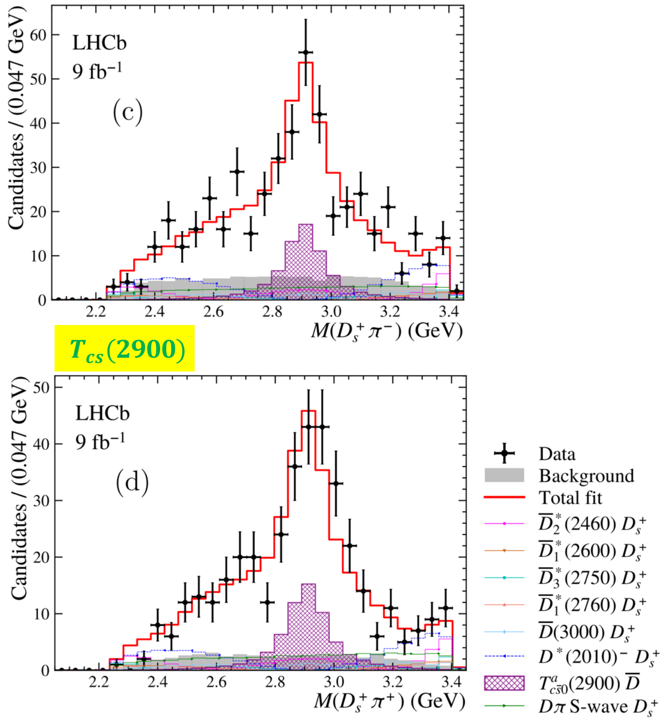


PhysRevD.102.112003



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

$B \to D_s \bar{D} \pi$



arXiv: 2212.02716

The fits of the lineshapes of $X_{0,1}(2900)$ is given in **B. Wang** *et al*, Eur.Phys.J.C 82 (2022) 419. For $T_{c\bar{s}}(2900)$, see **W. Chen's** talk.

Possible combinations

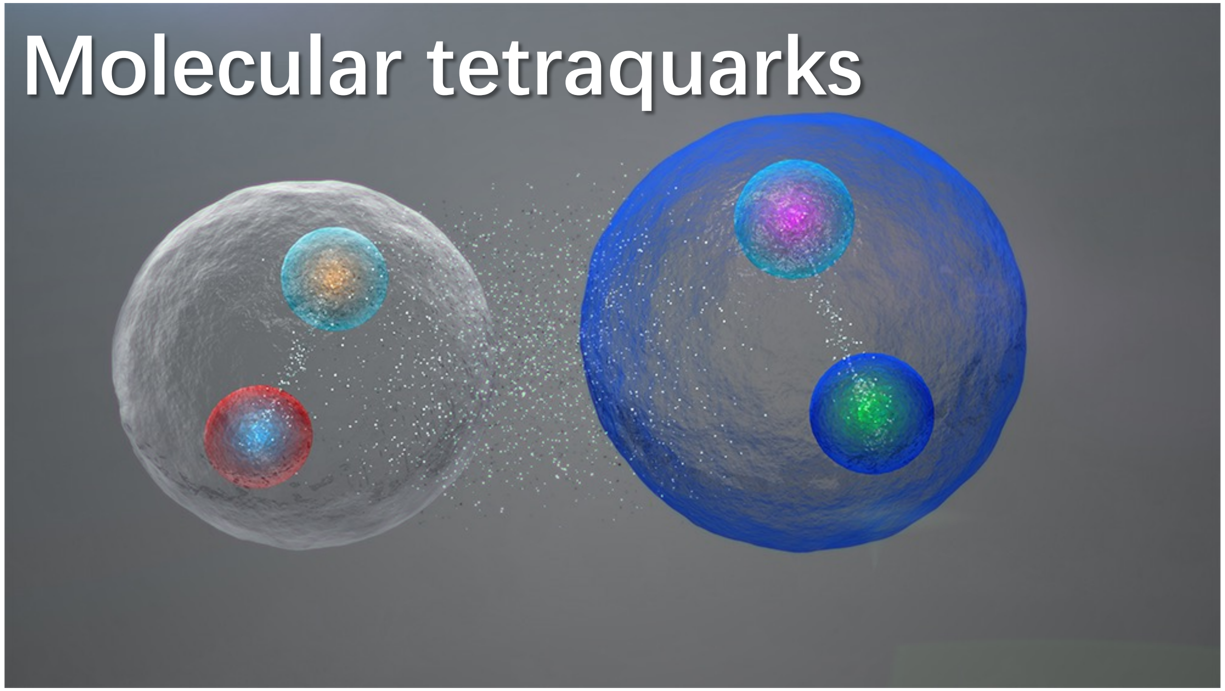
$$\begin{bmatrix} \mathrm{N} \\ \mathrm{M_Q} \\ \mathrm{B_Q} \\ \mathrm{B_{QQ}} \end{bmatrix} \hat{\otimes} \begin{bmatrix} \mathrm{N} \\ \mathrm{M_Q} \\ \mathrm{B_Q} \\ \mathrm{B_{QQ}} \\ \bar{\mathrm{N}} \\ \bar{\mathrm{M}}_\mathrm{Q} \\ \bar{\mathrm{B}}_\mathrm{Q} \\ \bar{\mathrm{B}}_\mathrm{QQ} \end{bmatrix}^T \Rightarrow \begin{bmatrix} \mathrm{NN} & \mathrm{NM_Q} & \mathrm{NB_Q} & \mathrm{NB_{QQ}} & \mathrm{N\bar{N}} & & & \\ & \mathrm{M_QM_Q} & \mathrm{M_QB_Q} & \mathrm{M_QB_{QQ}} & \mathrm{M_Q\bar{N}} & \mathrm{M_Q\bar{M}_Q} & & \\ & & \mathrm{B_QB_Q} & \mathrm{B_QB_{QQ}} & \mathrm{B_Q\bar{N}} & \mathrm{B_Q\bar{M}_Q} & \mathrm{B_Q\bar{B}_Q} & \\ & & & \mathrm{B_{QQ}B_{QQ}} & \mathrm{B_{QQ}\bar{N}} & \mathrm{B_{QQ}\bar{M}_Q} & \mathrm{B_{QQ}\bar{B}_Q} & \mathrm{B_{QQ}\bar{B}_{QQ}} \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} \text{deuteron} & \Lambda(2940)?,\ldots & \square & \square & X(1835)? & & & \\ & T_{cc},\ldots & \square & \square & \square & X(3872), Z_{c(s)}^{(\prime)}, Z_b^{(\prime)},\ldots & & \\ & & \square & \square & \square & P_{c(s)},\ldots & \square & \\ & & & \square & \square & \square & \square & \square \end{bmatrix},$$

- Sometimes, the K^* meson may be regarded as the heavy matter field to some extent ($m_{K^*} \sim m_N$). The $X_{0,1}(2900)$ [1, 2] and $T_{cs}(2900)$ [3] observed by the LHCb are very close to the $\bar{D}^*K^*$ and D^*K^* thresholds, respectively.

[1] Phys. Rev. D 102 (2020) 112003 [2] Phys. Rev. Lett. 125 (2020) 242001 [3] arXiv: 2212.02716 [hep-ex] [4] arXiv: 2212.02717 [hep-ex]

Molecular tetraquarks



$X(3872)$ and its possible partners

In Refs. [**J. Nieves** *et al*, Phys.Rev.D 86 (2012) 056004; **F-.K. Guo** *et al*, Phys.Rev.D 88 (2013) 054007; **V. Baru** *et al*, Phys.Lett.B 763 (2016) 20-28], the heavy quark spin symmetry (HQSS) partners of $X(3872)$ with the J^{PC} quantum numbers 2^{++} was proposed.

$$\left|\frac{1}{\sqrt{2}}(D\bar{D}^* - D^*\bar{D})\right\rangle_{1^{++}} = -|1_h^{--} \otimes 1_\ell^{--}\rangle$$

$$|D^*\bar{D}^*\rangle_{2^{++}} = -|1_h^{--} \otimes 1_\ell^{--}\rangle$$

$$\xrightarrow{\hat{H}_{\text{eff}} \equiv \tilde{c}_1 + \tilde{c}_2 \boldsymbol{\ell}_1 \cdot \boldsymbol{\ell}_2}$$

$$\begin{aligned} V^{\alpha}_{1^{++}} &= C^{\alpha}_1 = \tilde{c}_1 + \frac{1}{4}\tilde{c}_2, \\ V^{\alpha}_{2^{++}} &= C^{\alpha}_1 = \tilde{c}_1 + \frac{1}{4}\tilde{c}_2. \end{aligned}$$

$SU(3)_F$ symmetry and HQSS for di-meson systems

L. Meng, B. Wang, S-.L. Zhu, Sci.Bull. 66 (2021) 1288-1295

$$\begin{aligned} &D_s^{(*)} - D^{(*)} \simeq 100 \text{ MeV}, \\ &D^*_{(s)} - D_{(s)} \simeq 140 \text{ MeV}, \end{aligned}$$

$$V_{q\bar{q}} = c_1 + c_2 \boldsymbol{s}_1 \cdot \boldsymbol{s}_2 + c_3 \mathbb{C}_2 + c_4 (\boldsymbol{s}_1 \cdot \boldsymbol{s}_2)\mathbb{C}_2$$

$$m_{D^0} + m_{D^{*0}} - m_{X(3872)} = (0.00 \pm 0.18) \ \text{MeV}.$$

It can be approximately regarded as a pure $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}$ dimeson, then its flavor wave function in the light part will be $|\bar{u}u\rangle$.

$$\boxed{\langle \mathbb{C}_2 \rangle_{u\bar{u}} = \langle \mathbb{C}_2 \rangle_{s\bar{s}}}$$

$$V_{q\bar{q}} = \tilde{c}_1 + \tilde{c}_2 \boldsymbol{s}_1 \cdot \boldsymbol{s}_2,$$

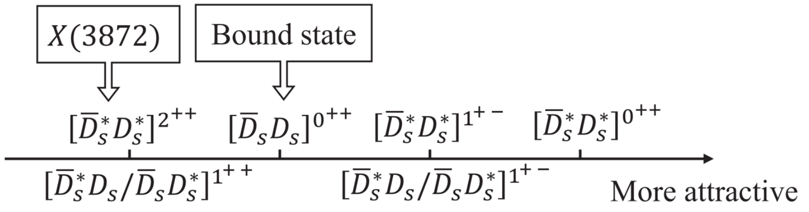
$$\langle \boldsymbol{s}_1 \cdot \boldsymbol{s}_2 \rangle^{0^{++}}_{\{\mathtt{PP},\mathtt{VV}\}} = \begin{bmatrix} 0 & \frac{\sqrt{3}}{4} \\ \frac{\sqrt{3}}{4} & -\frac{1}{2} \end{bmatrix},$$

$$\langle \boldsymbol{s}_1 \cdot \boldsymbol{s}_2 \rangle^{1^{+-}}_{\{\mathtt{PV},\mathtt{VV}\}} = \begin{bmatrix} -\frac{1}{4} & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{4} \end{bmatrix},$$

$$\langle \boldsymbol{s}_1 \cdot \boldsymbol{s}_2 \rangle^{1^{++}}_{\{\mathtt{PV}\}} = \frac{1}{4}, \quad \langle \boldsymbol{s}_1 \cdot \boldsymbol{s}_2 \rangle^{2^{++}}_{\{\mathtt{VV}\}} = \frac{1}{4},$$

$$\Longrightarrow$$

$$\left(V^{1^{++}}_{\mathtt{PV}} - V^{0^{++}}_{\mathtt{PP}}\right) : \left(V^{0^{++}}_{\mathtt{VV}} - V^{0^{++}}_{\mathtt{PP}}\right) : \left(V^{1^{+-}}_{\mathtt{PV/VV}} - V^{0^{++}}_{\mathtt{PP}}\right) = 1 : -2 : -1.$$



$X(3872)$

Bound state

$[\bar{D}_s^* D_s^*]^{2^{++}}$ $[\bar{D}_s D_s]^{0^{++}}$ $[\bar{D}_s^* D_s^*]^{1^{+-}}$ $[\bar{D}_s^* D_s^*]^{0^{++}}$

$[\bar{D}_s^* D_s/\bar{D}_s D_s^*]^{1^{++}}$ $[\bar{D}_s^* D_s/\bar{D}_s D_s^*]^{1^{+-}}$

More attractive

$X(3872)$ and its possible partners

Two prerequisites:

- The $X(3872)$ is the molecular state with its mass coinciding exactly with the $\overline{D}_0^* D_0$ threshold;
- There exist the $\overline{D}_s D_s$ bound states with $J^{PC} = 0^{++}$.

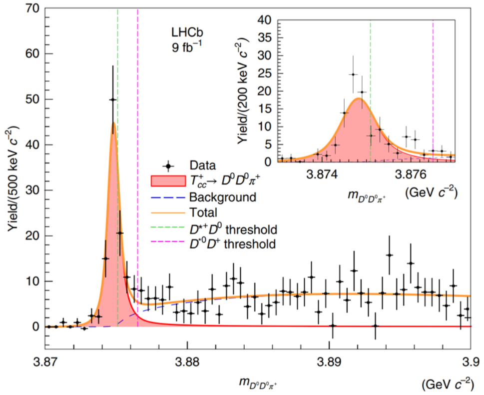
The recent lattice QCD calculation yielded a shallow $[D_s\overline{D}_s]^{0^{++}}$ bound state with $\Delta E = -6.2^{+3.8}_{-2.0}$ MeV [JHEP 06 (2021) 035]

$$T(p\prime, p; E) = V(p\prime, p) + \int \frac{\mathrm{d}^3 p\prime\prime}{(2\pi)^3} \frac{V(p\prime, p\prime\prime) T(p\prime\prime, p; E)}{E - p^2/(2\mu) + i\epsilon},$$

$X(3872)_{\text{input}}$	$[\overline{D}_s D_s]^{0^{++}}_{\text{input}}$		$[\overline{D}_s^* D_s^*]^{0^{++}}$		$[\overline{D}_s^* D_s/\overline{D}_s D_s^*]^{1^{+-}}$		$[\overline{D}_s^* D_s^*]^{1^{+-}}$	
ΔE (MeV)	ΔE (MeV)	M (MeV)	ΔE (MeV)	M (MeV)	ΔE (MeV)	M (MeV)	ΔE (MeV)	M (MeV)
0.0	−2.4	3934.3	−20.3	4204.1	−9.5	4071.0	−11.4	4213.0
0.0	−6.2	3930.5	−45.5	4178.9	−22.5	4058.0	−25.2	4199.2
0.0	−8.2	3928.5	−57.6	4166.8	−29.0	4051.5	−32.0	4192.4
0.0	-12.9	3923.8	−84.3	4140.1	−43.7	4036.8	−47.2	4177.2
−1.0	−2.4	3934.3	−8.3	4216.1	−4.9	4075.6	−6.3	4218.1
−1.0	−6.2	3930.5	−28.9	4195.5	−15.9	4064.6	−18.2	4206.2
−1.0	−8.2	3928.5	−39.6	4184.8	−21.7	4058.8	−24.4	4200.0
−1.0	−12.9	3923.8	−64.1	4160.3	−35.2	4045.3	−38.5	4185.9
Cutoff-I [49]	−13	3924	−84	4140	−46	4035	−47	4177
Cutoff-II [49]	−9	3928	−84	4140	−41	4040	−44	4180

[49] C. Hidalgo-Duque *et al*, Phys.Rev.D 87 (2013) 7, 076006.

T_{cc} and its decays



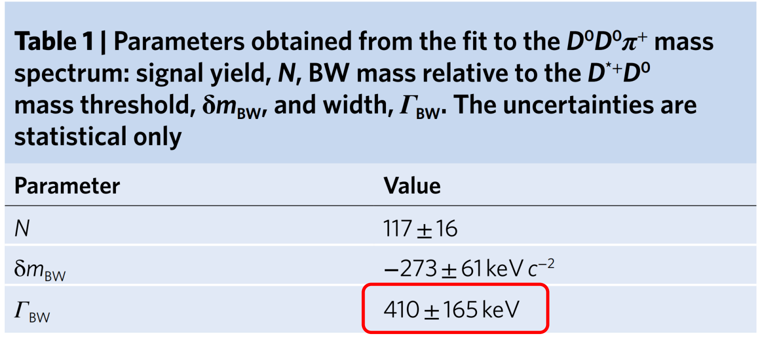


Table 1 | Parameters obtained from the fit to the $D^0D^0\pi^+$ mass spectrum: signal yield, N, BW mass relative to the $D^{*+}D^0$ mass threshold, δm_{BW}, and width, Γ_{BW}. The uncertainties are statistical only

Parameter	Value
N	117 ± 16
δm_{BW}	−273 ± 61 keV c^{-2}
Γ_{BW}	410 ± 165 keV

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

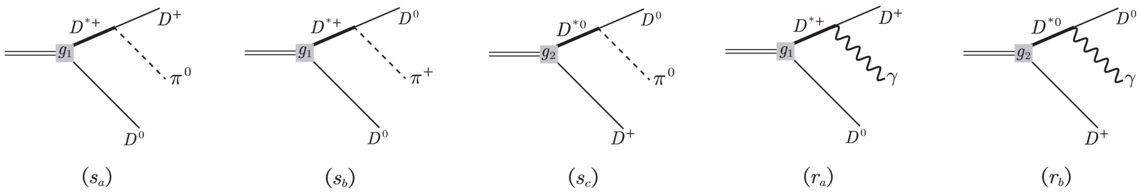
- ✓ Within the contact EFT [**L. Meng** *et al*, Phys.Rev.D 104 (2021) , L051502]

$$|T_{cc}^+\rangle = \cos\theta|D^{*+}D^0,\phi_1\rangle + \sin\theta|D^{*0}D^+,\phi_2\rangle,$$

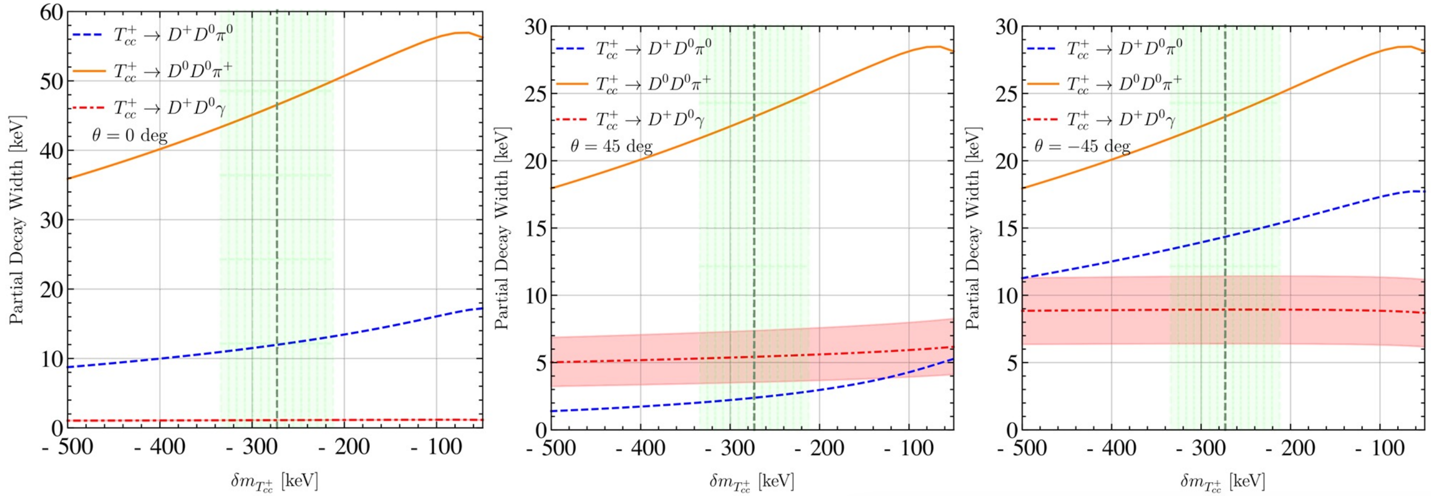
$$\lim_{E\to E_0}(E-E_0)t_{ij} = \lim_{E\to E_0}\left[\frac{d(t_{ij})^{-1}}{dE}\right]^{-1} = \frac{1}{8M_T^2\mu}g_ig_j$$

$$g_1 = \frac{4M_T\sqrt{\pi\kappa_1}}{\sqrt{\mu}}\cos\theta, \qquad g_2 = \frac{4M_T\sqrt{\pi\kappa_2}}{\sqrt{\mu}}\sin\theta.$$

$$\theta = \begin{cases} 0 & \mathrm{pure}D^{*+}D^0 \\ \frac{\pi}{4} & I=1, I_3=0\,. \\ -\frac{\pi}{4} & I=0, I_3=0 \end{cases}$$



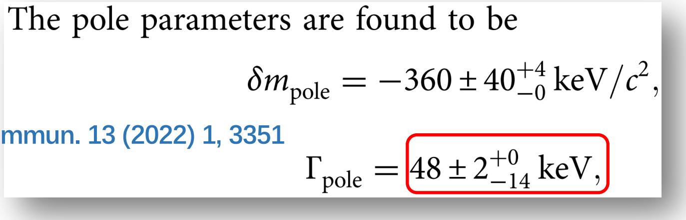
T_{cc} and its decays



$$\text{Single-channel limit}: \Gamma_{\text{str}} + \Gamma_{\text{EM}} = 59.7^{+4.6}_{-4.4}\ \text{keV}.$$

$$\boxed{\text{Isospin singlet}: \Gamma_{\text{str}} + \Gamma_{\text{EM}} = 46.7^{+2.7}_{-2.9}\ \text{keV},}$$

$$\text{Isospin triplet}: \Gamma_{\text{str}} + \Gamma_{\text{EM}} = 31.2^{+2.2}_{-2.4}\ \text{keV}.$$


The pole parameters are found to be

$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}\ \text{keV}/c^2,$$

$$\Gamma_{\text{pole}} = \boxed{48 \pm 2^{+0}_{-14}\ \text{keV},}$$

Nature Commun. 13 (2022) 1, 3351

isoscalar assignment for T_{cc} is supported!

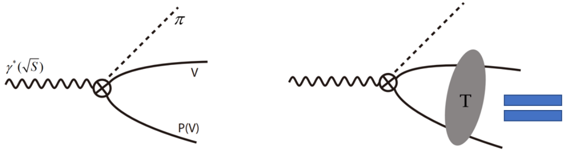
The improved calculations for the DD^* interactions that based on the χEFT up to N^{2}LO was given in **B. Wang** *et al*, arXiv:2212.08447 [accepted by PRD].

Isospin violating decays of $X(3872)$ was revisited in **L. Meng** *et al*, PhysRevD.104.094003

$Z_{c,b}$ and their strange partners

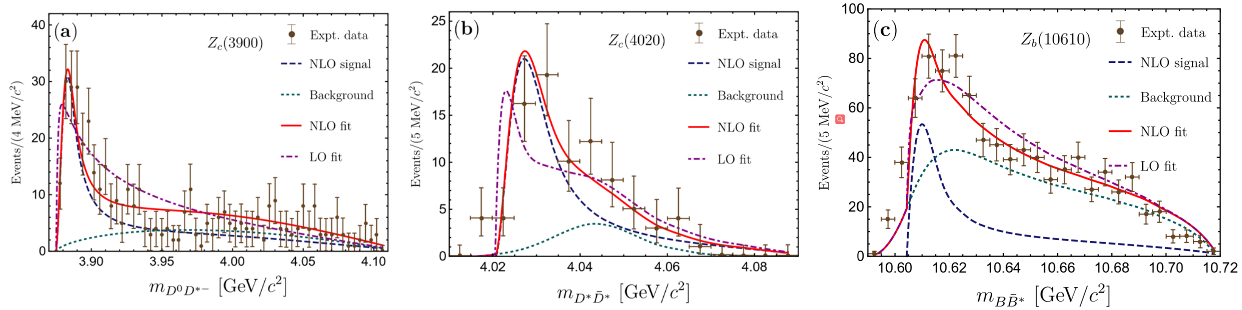
Comprehensive review on χEFTs in heavy sectors: arXiv:2204.08716

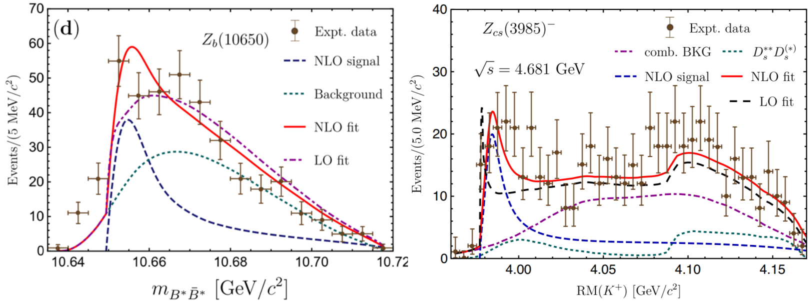
1. Simulate the production process:



= χEFT

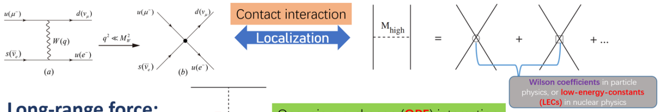
2. Fit the lineshapes in experiments:





Search for the poles in the Riemann sheets:

- **Short-range force:**

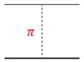


Contact interaction

Localization

Wilson coefficients in particle physics, or low-energy-constants (LECs) in nuclear physics

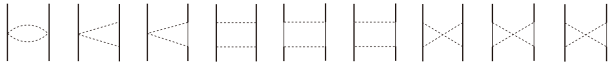
- **Long-range force:**



One-pion-exchange (**OPE**) interaction

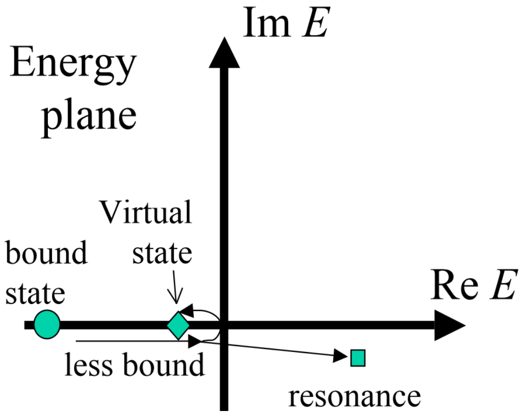
- **Mid-range force:**

Two-pion-exchange (**TPE**) interaction



$$\mathcal{U}(E,\boldsymbol{p}) = \mathcal{M}(E,\boldsymbol{p}) + \int \frac{d^3\boldsymbol{q}}{(2\pi)^3}\mathcal{V}(E,\boldsymbol{p},\boldsymbol{q})\mathcal{G}(E,\boldsymbol{q})\mathcal{U}(E,\boldsymbol{q}),$$

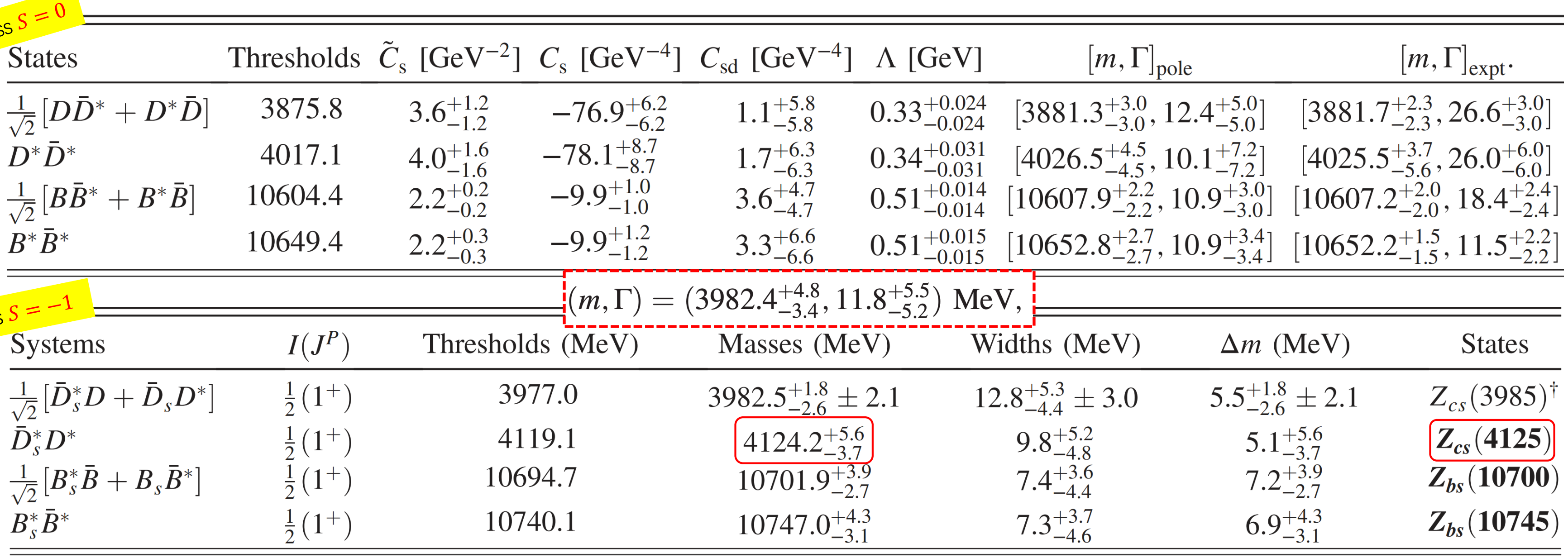
Energy plane



$Z_{c,b}$ and their strange partners

B. Wang *et al*, PhysRevD.102.114019
B. Wang *et al*, PhysRevD.103.L021501

- **Fitted parameters and predicted states**



Poles in the second Riemann sheet

Strangeness $S = 0$

States	Thresholds	$\tilde{C}_s$ [GeV^{-2}]	C_s [GeV^{-4}]	C_{sd} [GeV^{-4}]	Λ [GeV]	$[m,\Gamma]_{\rm pole}$	$[m,\Gamma]_{\rm expt}$.
$\frac{1}{\sqrt{2}}[D\bar{D}^* + D^*\bar{D}]$	3875.8	$3.6^{+1.2}_{-1.2}$	$-76.9^{+6.2}_{-6.2}$	$1.1^{+5.8}_{-5.8}$	$0.33^{+0.024}_{-0.024}$	$[3881.3^{+3.0}_{-3.0}, 12.4^{+5.0}_{-5.0}]$	$[3881.7^{+2.3}_{-2.3}, 26.6^{+3.0}_{-3.0}]$
$D^*\bar{D}^*$	4017.1	$4.0^{+1.6}_{-1.6}$	$-78.1^{+8.7}_{-8.7}$	$1.7^{+6.3}_{-6.3}$	$0.34^{+0.031}_{-0.031}$	$[4026.5^{+4.5}_{-4.5}, 10.1^{+7.2}_{-7.2}]$	$[4025.5^{+3.7}_{-5.6}, 26.0^{+6.0}_{-6.0}]$
$\frac{1}{\sqrt{2}}[B\bar{B}^* + B^*\bar{B}]$	10604.4	$2.2^{+0.2}_{-0.2}$	$-9.9^{+1.0}_{-1.0}$	$3.6^{+4.7}_{-4.7}$	$0.51^{+0.014}_{-0.014}$	$[10607.9^{+2.2}_{-2.2}, 10.9^{+3.0}_{-3.0}]$	$[10607.2^{+2.0}_{-2.0}, 18.4^{+2.4}_{-2.4}]$
$B^*\bar{B}^*$	10649.4	$2.2^{+0.3}_{-0.3}$	$-9.9^{+1.2}_{-1.2}$	$3.3^{+6.6}_{-6.6}$	$0.51^{+0.015}_{-0.015}$	$[10652.8^{+2.7}_{-2.7}, 10.9^{+3.4}_{-3.4}]$	$[10652.2^{+1.5}_{-1.5}, 11.5^{+2.2}_{-2.2}]$

$$(m, \Gamma) = (3982.4^{+4.8}_{-3.4}, 11.8^{+5.5}_{-5.2})\ \text{MeV},$$

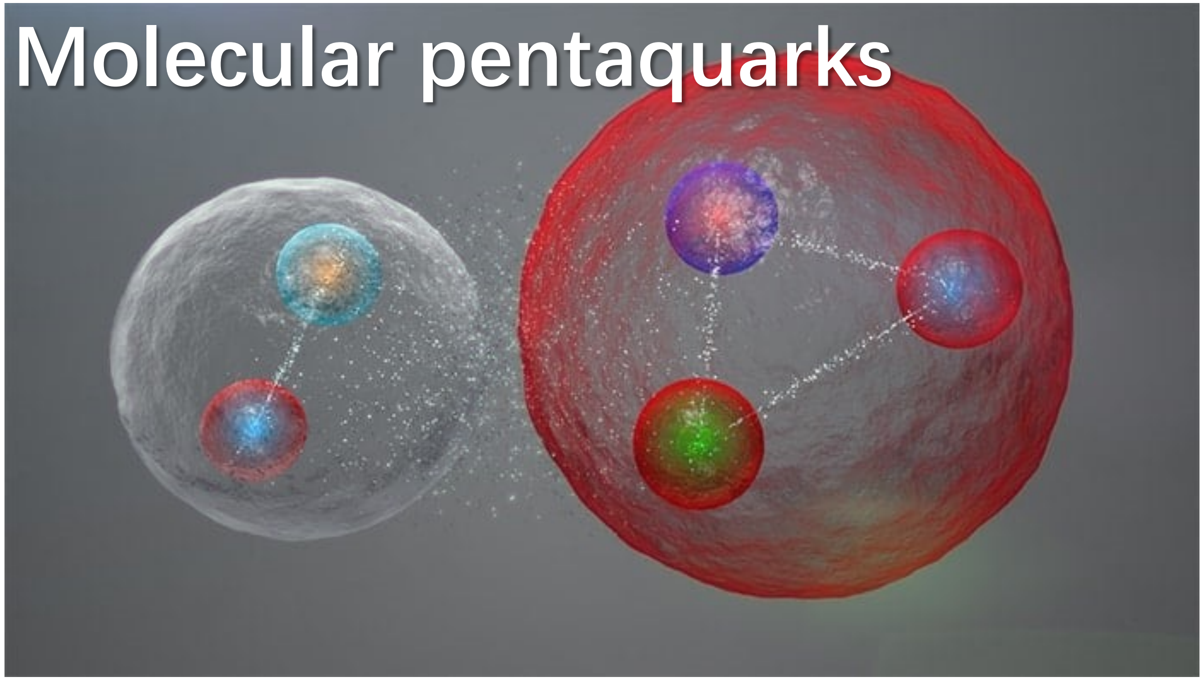
Strangeness $S = -1$

Systems	$I(J^P)$	Thresholds (MeV)	Masses (MeV)	Widths (MeV)	Δm (MeV)	States
$\frac{1}{\sqrt{2}}[\bar{D}_s^* D + \bar{D}_s D^*]$	$\frac{1}{2}(1^+)$	3977.0	$3982.5^{+1.8}_{-2.6} \pm 2.1$	$12.8^{+5.3}_{-4.4} \pm 3.0$	$5.5^{+1.8}_{-2.6} \pm 2.1$	$Z_{cs}(3985)^\dagger$
$\bar{D}_s^* D^*$	$\frac{1}{2}(1^+)$	4119.1	$4124.2^{+5.6}_{-3.7}$	$9.8^{+5.2}_{-4.8}$	$5.1^{+5.6}_{-3.7}$	$\boldsymbol{Z_{cs}(4125)}$
$\frac{1}{\sqrt{2}}[B_s^* \bar{B} + B_s \bar{B}^*]$	$\frac{1}{2}(1^+)$	10694.7	$10701.9^{+3.9}_{-2.7}$	$7.4^{+3.6}_{-4.4}$	$7.2^{+3.9}_{-2.7}$	$\boldsymbol{Z_{bs}(10700)}$
$B_s^* \bar{B}^*$	$\frac{1}{2}(1^+)$	10740.1	$10747.0^{+4.3}_{-3.1}$	$7.3^{+3.7}_{-4.6}$	$6.9^{+4.3}_{-3.1}$	$\boldsymbol{Z_{bs}(10745)}$

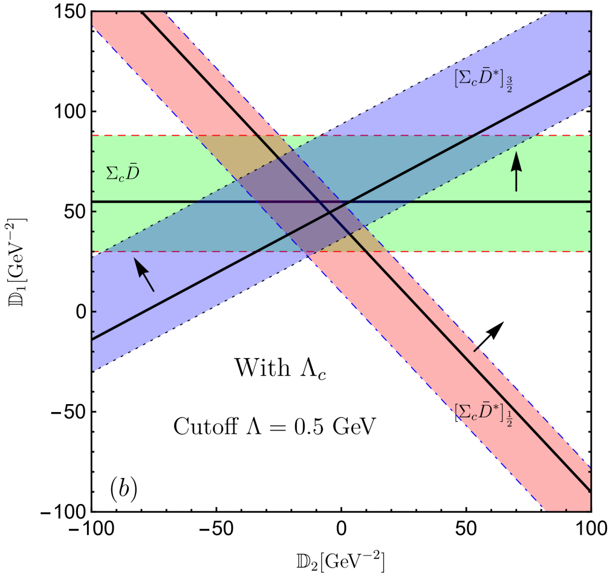
✓ **New measurement from BESIII ($e^+e^- \to K^+ D_s^{*-} D^{*0} + c.c$): Z'_{cs}, $m \sim 4123.5$ MeV, with a significance of $2.1\,\sigma$.** Chin.Phys.C 47,033001 (2023).

✓ **Implications of $Z_{cs}(4000)$ and $Z_{cs}(3985)$ as two different states are given in Ref. [L. Meng *et al*, Sci.Bull. 66 (2021) 2065-2071].**

Molecular pentaquarks

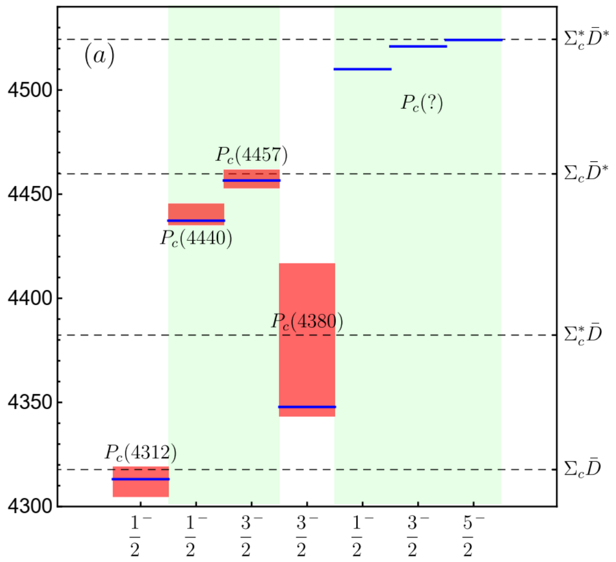


P_cs and their strange partners



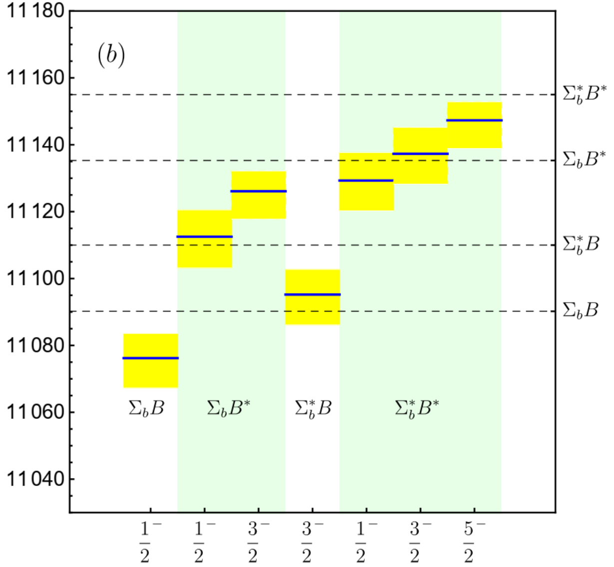
B. Wang *et al*, JHEP 1911 (2019) 108

$\Sigma_c^{(*)}\bar{D}^{(*)}$ systems



Hidden-charm spectra

$\Sigma_b^{(*)}B^{(*)}$ systems



Hidden-bottom spectra

How to observe?

- Production mechanism is unknown.
- Reconstrruction channels: $\Upsilon(nS)N$ $(n = 1{,}2)$, $\Lambda_bB^{(*)}$

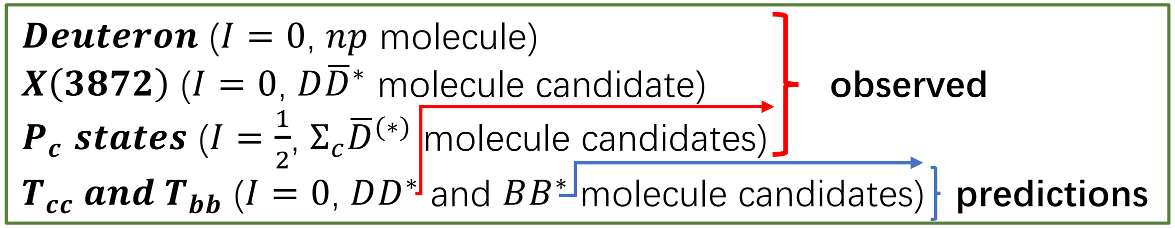
"There is plenty of room at the 'bottom' " .-R. P. Feynman

P_cs and their strange partners

- $\Xi_c^{(\prime,*)}\bar{D}^{(*)}$ systems

$XYZ: Q\bar{Q}q\bar{q}$; $P_c: Q\bar{Q}qqq$.

1. The **heavy quark core** plays an important role in stabilizing the exotic clusters [Phys. Rev. D **84**, 014031, Phys. Rev. D **86**, 014020, Eur. Phys. J. C **74**, 3198].
2. Hydrogen molecule: two protons plus two electrons, stably exists in the nature.
3. Existence of P_c ➔ more hadronic molecules in **SU(3) symmetry**?
4. Two heavy matter fields tend to form the bound states in the **lowest isospin channels**?



$\boldsymbol{Deuteron}$ ($I=0$, np molecule)
$\boldsymbol{X(3872)}$ ($I=0$, $D\bar{D}^*$ molecule candidate)
$\boldsymbol{P_c\ states}$ ($I=\frac{1}{2}$, $\Sigma_c\bar{D}^{(*)}$ molecule candidates)
$\boldsymbol{T_{cc}\ and\ T_{bb}}$ ($I=0$, DD^* and BB^* molecule candidates)

observed

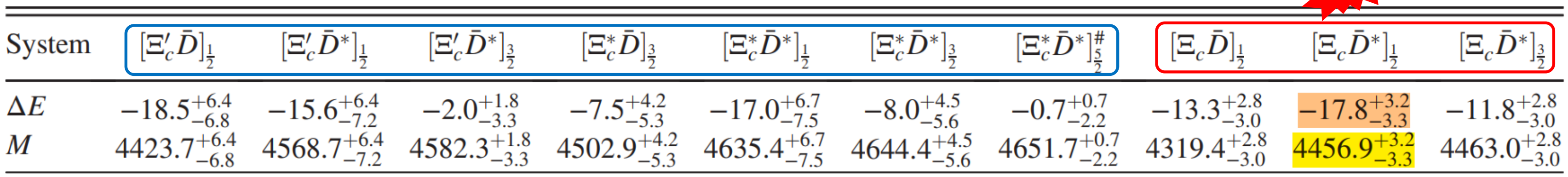
predictions

5. Whether the $\Xi_c^{(\prime,*)}\bar{D}^{(*)}$ systems can form bound states in the $\boldsymbol{I=0}$ channels?
6. May be observed in $J/\psi\Lambda$ final states of the decays $\Lambda_b(\Xi_b)\to J/\psi\Lambda K(\eta)$?

P_cs and their strange partners

- **P_{cs} spectra**

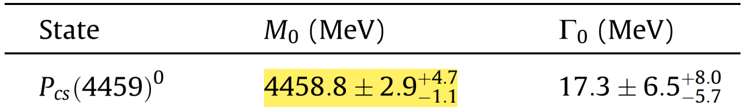
B. Wang *et al*, Phys. RevD. **101**.034018



System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{5}{2}}^{\#}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-18.5^{+6.4}_{-6.8}$	$-15.6^{+6.4}_{-7.2}$	$-2.0^{+1.8}_{-3.3}$	$-7.5^{+4.2}_{-5.3}$	$-17.0^{+6.7}_{-7.5}$	$-8.0^{+4.5}_{-5.6}$	$-0.7^{+0.7}_{-2.2}$	$-13.3^{+2.8}_{-3.0}$	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4423.7^{+6.4}_{-6.8}$	$4568.7^{+6.4}_{-7.2}$	$4582.3^{+1.8}_{-3.3}$	$4502.9^{+4.2}_{-5.3}$	$4635.4^{+6.7}_{-7.5}$	$4644.4^{+4.5}_{-5.6}$	$4651.7^{+0.7}_{-2.2}$	$4319.4^{+2.8}_{-3.0}$	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

1. Predicted ten P_{cs} states in the isoscalar channels.
2. Three new ones in $\Xi_c\bar{D}^{(*)}$ systems.
3. The new $[\Xi_c\bar{D}^*]_{1/2}$ state is VERY consistent with the newly LHCb result.

Taken from Science Bulletin **66** (2021) 1278–1287



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

- **What about the $\Lambda_c\bar{D}^{(*)}$ and other systems?**

1. The $\Lambda_c\bar{D}^{(*)}$ systems: No isospin-isospin interaction, contact (repulsive)+TPE (couple-channel, attractive)$\simeq 0$ ➔ no bound states (estimation).
2. Other systems: $\Lambda_c\bar{D}_s^{(*)}$, $\Sigma_c\bar{D}_s^{(*)}$, $\Sigma_c^*\bar{D}_s^{(*)}$ $(s=-1)$: attractive, but too weak to form bound states. $\Omega_c^{(*)}\bar{D}_s^{(*)}$ $(s=-3)$: repulsive. It is hard to form bound states in these systems!

Doubly charmed P_{cc} states

From $\Sigma_c^{(*)}\bar{D}^{(*)}$ to $\Sigma_c^{(*)}D^*$ systems

The low energy constants of the $\Sigma_c^{(*)}D^*$ systems are estimated from the $N\bar{N}$ scattering data by introducing a quark level Lagrangian:

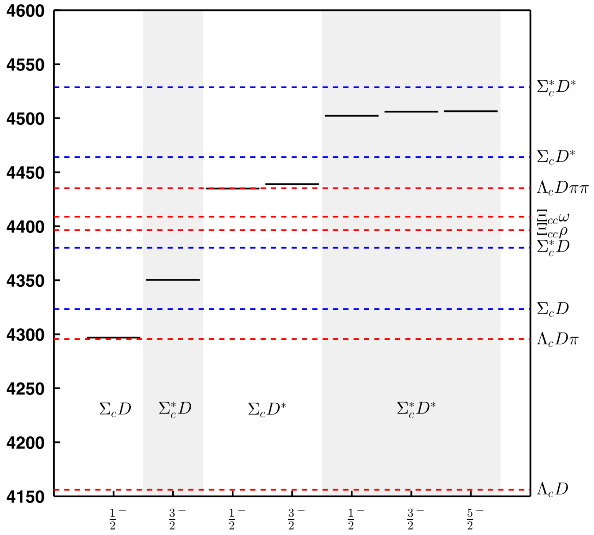
$$\mathcal{L} = g_s\bar{q}\mathcal{S}q + g_a\bar{q}\gamma_\mu\gamma^5\mathcal{A}^\mu q,$$

$$V_{q\bar{q}} = c_s(1 - 3\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2) + c_t(1 - 3\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2.$$

$$V_{\Sigma_c D^*} = 2c_s - 12c_s\mathbf{I}_1\cdot\mathbf{I}_2 - \frac{4}{3}c_t\boldsymbol{\sigma}\cdot\boldsymbol{T} + 8c_t(\mathbf{I}_1\cdot\mathbf{I}_2)(\boldsymbol{\sigma}\cdot\boldsymbol{T}).$$

		$[\Sigma_c D]_{\frac{1}{2}}$	$[\Sigma_c^* D]_{\frac{3}{2}}$	$[\Sigma_c D^*]_{\frac{1}{2}}$	$[\Sigma_c D^*]_{\frac{3}{2}}$	$[\Sigma_c^* D^*]_{\frac{1}{2}}$	$[\Sigma_c^* D^*]_{\frac{3}{2}}$	$[\Sigma_c^* D^*]_{\frac{5}{2}}$
Case 1	BE (MeV)	−15.4	−25.0	−31.8	−8.0	−32.8	−18.2	−3.5
	R_{rms} (fm)	1.45	1.25	1.20	1.65	1.20	1.38	1.91
Case 2	BE (MeV)	−31.3	−42.9	−30.3	−31.7	−26.6	−25.4	−29.7
	R_{rms} (fm)	1.23	1.11	1.22	1.20	1.26	1.27	1.22
Case 3	BE (MeV)	−26.5	−37.7	−29.1	−25.0	−26.4	−22.6	−22.2
	R_{rms} (fm)	1.27	1.14	1.23	1.27	1.26	1.31	1.30

K. Chen *et al*, PhysRevD.103.116017

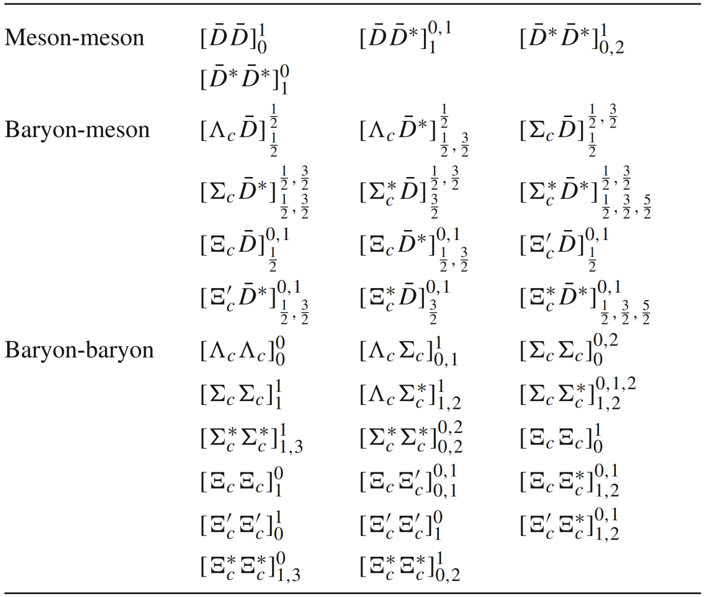


All the $\Sigma_c^{(*)}D^*$ systems with isospin $I = 1/2$ can form bound states. In addition, we also investigate the interactions of the charmed-bottom $\Sigma_c^{(*)}\bar{B}^{(*)}$, $\Sigma_b^{(*)}D^{(*)}$ and $\Sigma_b^{(*)}\bar{B}^{(*)}$systems. Among the obtained bound states, the bindings become deeper when the reduced masses of the corresponding systems are heavier.

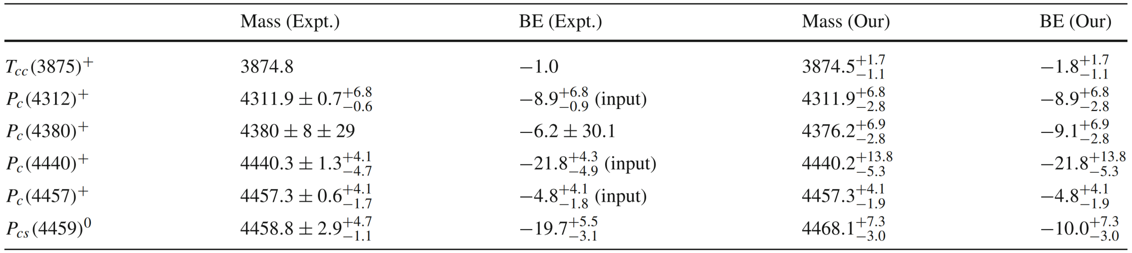
More systems

Within the same framework, we also covered more systems

K. Chen *et al*, Eur.Phys.J.C 82 (2022) 7, 581

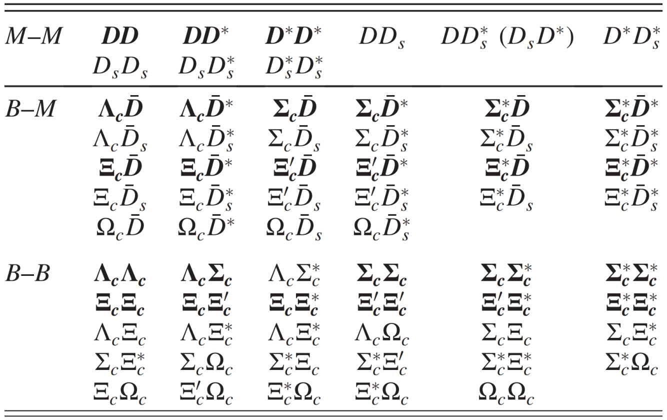


Meson-meson	$[\bar{D}\bar{D}]_0^1$	$[\bar{D}\bar{D}^*]_1^{0,1}$	$[\bar{D}^*\bar{D}^*]_{0,2}^1$
	$[\bar{D}^*\bar{D}^*]_1^0$		
Baryon-meson	$[\Lambda_c\bar{D}]_{\frac{1}{2}}^{\frac{1}{2}}$	$[\Lambda_c\bar{D}^*]_{\frac{1}{2},\frac{3}{2}}^{\frac{1}{2}}$	$[\Sigma_c\bar{D}]_{\frac{1}{2}}^{\frac{1}{2},\frac{3}{2}}$
	$[\Sigma_c\bar{D}^*]_{\frac{1}{2},\frac{3}{2}}^{\frac{1}{2},\frac{3}{2}}$	$[\Sigma_c^*\bar{D}]_{\frac{3}{2}}^{\frac{1}{2},\frac{3}{2}}$	$[\Sigma_c^*\bar{D}^*]_{\frac{1}{2},\frac{3}{2},\frac{5}{2}}^{\frac{1}{2},\frac{3}{2}}$
	$[\Xi_c\bar{D}]_{\frac{1}{2}}^{0,1}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2},\frac{3}{2}}^{0,1}$	$[\Xi_c'\bar{D}]_{\frac{1}{2}}^{0,1}$
	$[\Xi_c'\bar{D}^*]_{\frac{1}{2},\frac{3}{2}}^{0,1}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}^{0,1}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2},\frac{3}{2},\frac{5}{2}}^{0,1}$
Baryon-baryon	$[\Lambda_c\Lambda_c]_0^0$	$[\Lambda_c\Sigma_c]_{0,1}^1$	$[\Sigma_c\Sigma_c]_0^{0,2}$
	$[\Sigma_c\Sigma_c]_1^1$	$[\Lambda_c\Sigma_c^*]_{1,2}^1$	$[\Sigma_c\Sigma_c^*]_{1,2}^{0,1,2}$
	$[\Sigma_c^*\Sigma_c^*]_{1,3}^1$	$[\Sigma_c^*\Sigma_c^*]_{0,2}^{0,2}$	$[\Xi_c\Xi_c]_0^1$
	$[\Xi_c\Xi_c]_1^0$	$[\Xi_c\Xi_c']_{0,1}^{0,1}$	$[\Xi_c\Xi_c^*]_{1,2}^{0,1}$
	$[\Xi_c'\Xi_c']_0^1$	$[\Xi_c'\Xi_c']_1^0$	$[\Xi_c'\Xi_c^*]_{1,2}^{0,1}$
	$[\Xi_c^*\Xi_c^*]_{1,3}^0$	$[\Xi_c^*\Xi_c^*]_{0,2}^1$	



	Mass (Expt.)	BE (Expt.)	Mass (Our)	BE (Our)
$T_{cc}(3875)^+$	3874.8	-1.0	$3874.5_{-1.1}^{+1.7}$	$-1.8_{-1.1}^{+1.7}$
$P_c(4312)^+$	$4311.9 \pm 0.7_{-0.6}^{+6.8}$	$-8.9_{-0.9}^{+6.8}$ (input)	$4311.9_{-2.8}^{+6.8}$	$-8.9_{-2.8}^{+6.8}$
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	-6.2 ± 30.1	$4376.2_{-2.8}^{+6.9}$	$-9.1_{-2.8}^{+6.9}$
$P_c(4440)^+$	$4440.3 \pm 1.3_{-4.7}^{+4.1}$	$-21.8_{-4.9}^{+4.3}$ (input)	$4440.2_{-5.3}^{+13.8}$	$-21.8_{-5.3}^{+13.8}$
$P_c(4457)^+$	$4457.3 \pm 0.6_{-1.7}^{+4.1}$	$-4.8_{-1.8}^{+4.1}$ (input)	$4457.3_{-1.9}^{+4.1}$	$-4.8_{-1.9}^{+4.1}$
$P_{cs}(4459)^0$	$4458.8 \pm 2.9_{-1.1}^{+4.7}$	$-19.7_{-3.1}^{+5.5}$	$4468.1_{-3.0}^{+7.3}$	$-10.0_{-3.0}^{+7.3}$

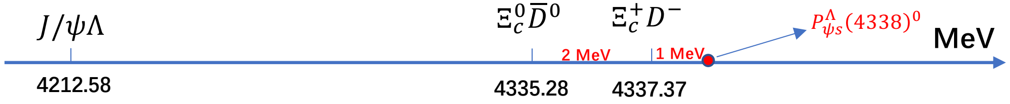
K. Chen *et al*, Phys.Rev.D 105 (2022) 9, 096004

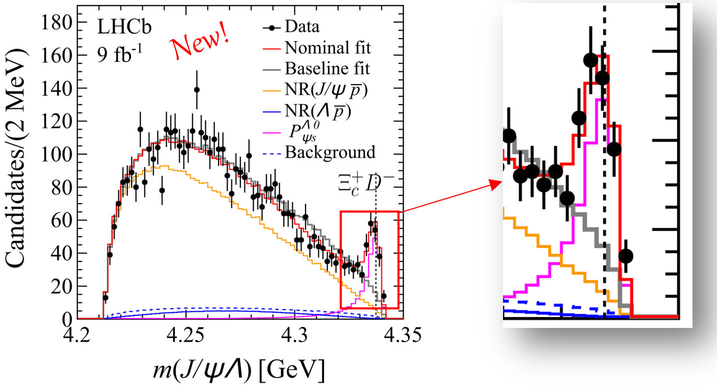


M–M	$\boldsymbol{DD}$ D_sD_s	$\boldsymbol{DD^*}$ $D_sD_s^*$	$\boldsymbol{D^*D^*}$ $D_s^*D_s^*$	DD_s	DD_s^* (D_sD^*)	$D^*D_s^*$
B–M	$\boldsymbol{\Lambda_c\bar{D}}$ $\Lambda_c\bar{D}_s$ $\boldsymbol{\Xi_c\bar{D}}$ $\Xi_c\bar{D}_s$ $\Omega_c\bar{D}$	$\boldsymbol{\Lambda_c\bar{D}^*}$ $\Lambda_c\bar{D}_s^*$ $\boldsymbol{\Xi_c\bar{D}^*}$ $\Xi_c\bar{D}_s^*$ $\Omega_c\bar{D}^*$	$\boldsymbol{\Sigma_c\bar{D}}$ $\Sigma_c\bar{D}_s$ $\boldsymbol{\Xi_c'\bar{D}}$ $\Xi_c'\bar{D}_s$ $\Omega_c\bar{D}_s$	$\boldsymbol{\Sigma_c\bar{D}^*}$ $\Sigma_c\bar{D}_s^*$ $\boldsymbol{\Xi_c'\bar{D}^*}$ $\Xi_c'\bar{D}_s^*$ $\Omega_c\bar{D}_s^*$	$\boldsymbol{\Sigma_c^*\bar{D}}$ $\Sigma_c^*\bar{D}_s$ $\boldsymbol{\Xi_c^*\bar{D}}$ $\Xi_c^*\bar{D}_s$	$\boldsymbol{\Sigma_c^*\bar{D}^*}$ $\Sigma_c^*\bar{D}_s^*$ $\boldsymbol{\Xi_c^*\bar{D}^*}$ $\Xi_c^*\bar{D}_s^*$
B–B	$\boldsymbol{\Lambda_c\Lambda_c}$ $\boldsymbol{\Xi_c\Xi_c}$ $\Lambda_c\Xi_c$ $\Sigma_c\Xi_c^*$ $\Xi_c\Omega_c$	$\boldsymbol{\Lambda_c\Sigma_c}$ $\boldsymbol{\Xi_c\Xi_c'}$ $\Lambda_c\Xi_c^*$ $\Sigma_c\Omega_c$ $\Xi_c'\Omega_c$	$\Lambda_c\Sigma_c^*$ $\boldsymbol{\Xi_c\Xi_c^*}$ $\Lambda_c\Xi_c^*$ $\Sigma_c^*\Xi_c$ $\Xi_c^*\Omega_c$	$\boldsymbol{\Sigma_c\Sigma_c}$ $\boldsymbol{\Xi_c'\Xi_c'}$ $\Lambda_c\Omega_c$ $\Sigma_c^*\Xi_c'$ $\Xi_c^*\Omega_c$	$\boldsymbol{\Sigma_c\Sigma_c^*}$ $\boldsymbol{\Xi_c'\Xi_c^*}$ $\Sigma_c\Xi_c$ $\Sigma_c^*\Xi_c^*$ $\Omega_c\Omega_c$	$\boldsymbol{\Sigma_c^*\Sigma_c^*}$ $\boldsymbol{\Xi_c^*\Xi_c^*}$ $\Sigma_c\Xi_c^*$ $\Sigma_c^*\Omega_c$

Lineshapes of the $P_{\psi s}^{\Lambda}(4338)^0$

$m = 4338.3 \pm 0.7 \pm 0.4$ MeV, $\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV.





If a pole is close to the physical sheet and far away from the threshold,

Breit-Weigner (BW): $T \propto 1/(E - M + i\Gamma/2)$

The lineshape of the resonance would be distorted from the conventional BW distribution if it appears near the threshold and strongly couples to the threshold at the same time [Phys. Lett. B 63,224(1976), Phys. Rev. D 76, 034007(2007), Phys. Rev. Lett. 115, 202001(2015)]. See also J-.J. Wu's talk.

therapies

K-matrix parameterization or LS equation

Two models for the $J/\psi\Lambda$-$\Xi_c^0\bar{D}^0$-$\Xi_c^+D^-$ interactions:

L. Meng *et al*, PhysRevD.107.014005

Model-I

$$V_{\rm I} = \frac{1}{2}\begin{bmatrix} 0 & -\tilde{c} & \tilde{c} \\ -\tilde{c} & c_1 + c_0 & c_1 - c_0 \\ \tilde{c} & c_1 - c_0 & c_1 + c_0 \end{bmatrix},$$

Model-II

$$V_{\rm II} = \frac{1}{2}\begin{bmatrix} 0 & -\tilde{c} & \tilde{c} \\ -\tilde{c} & \frac{g^2}{E^2 - m_0^2} & -\frac{g^2}{E^2 - m_0^2} \\ \tilde{c} & -\frac{g^2}{E^2 - m_0^2} & \frac{g^2}{E^2 - m_0^2} \end{bmatrix},$$

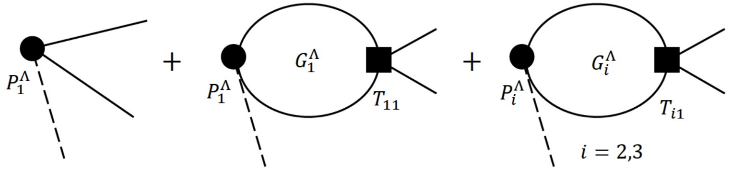
Lineshapes of the $P_{\psi s}^{\Lambda}(4338)^0$

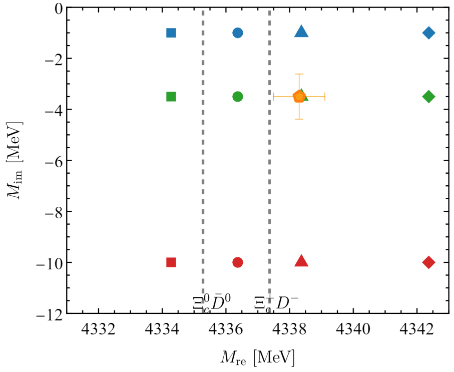
$$T = V + VGT, G = \mathrm{diag}\{G_1, G_2, G_3\}$$

$$G_i(E) = \int_0^{\Lambda} \frac{l^2 d^2 l}{(2\pi)^2} \frac{\omega_{i1}+\omega_{i2}}{\omega_{i1}\omega_{i2}[E^2-(\omega_{i1}+\omega_{i2})^2+i\epsilon]}, \ \omega_{ia} = \left(\boldsymbol{l}^2 + m_{ia}^2\right)^{1/2}.$$

Analytical continuation: $G_i \to G_i + i\frac{k_i}{4\pi E}$

Production diagrams: L. Meng *et al*, PhysRevD.107.014005



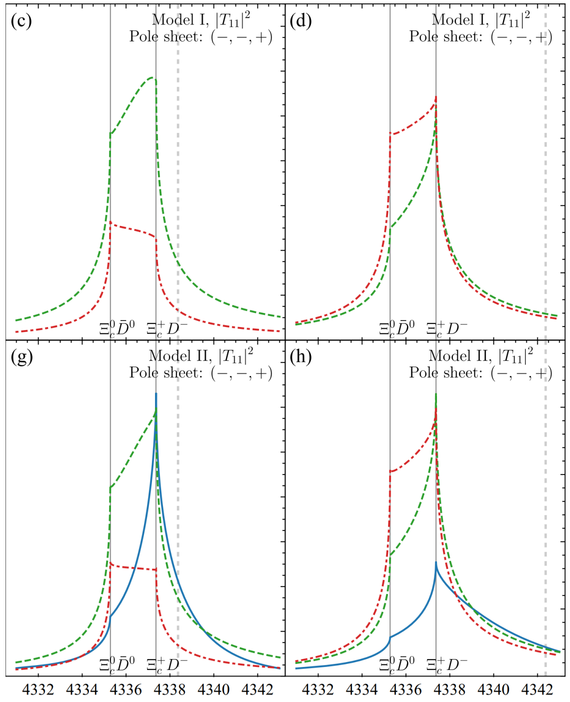


"Synthetic" poles:

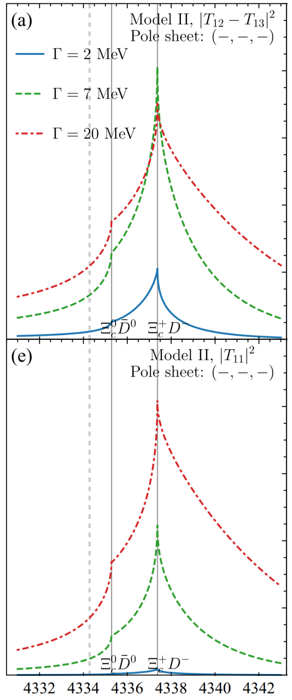
$M_{ij} = M_i - i\Gamma_j/2$

- $M_i = \{m_{\Xi_c^0 D^0} - 1, m_{\Xi_c^+ D^-} - 1, m_{\Xi_c^+ D^-} + 1, m_{\Xi_c^+ D^-} + 5\}$ MeV
- $\Gamma_i = \{2, 7, 20\}$ MeV

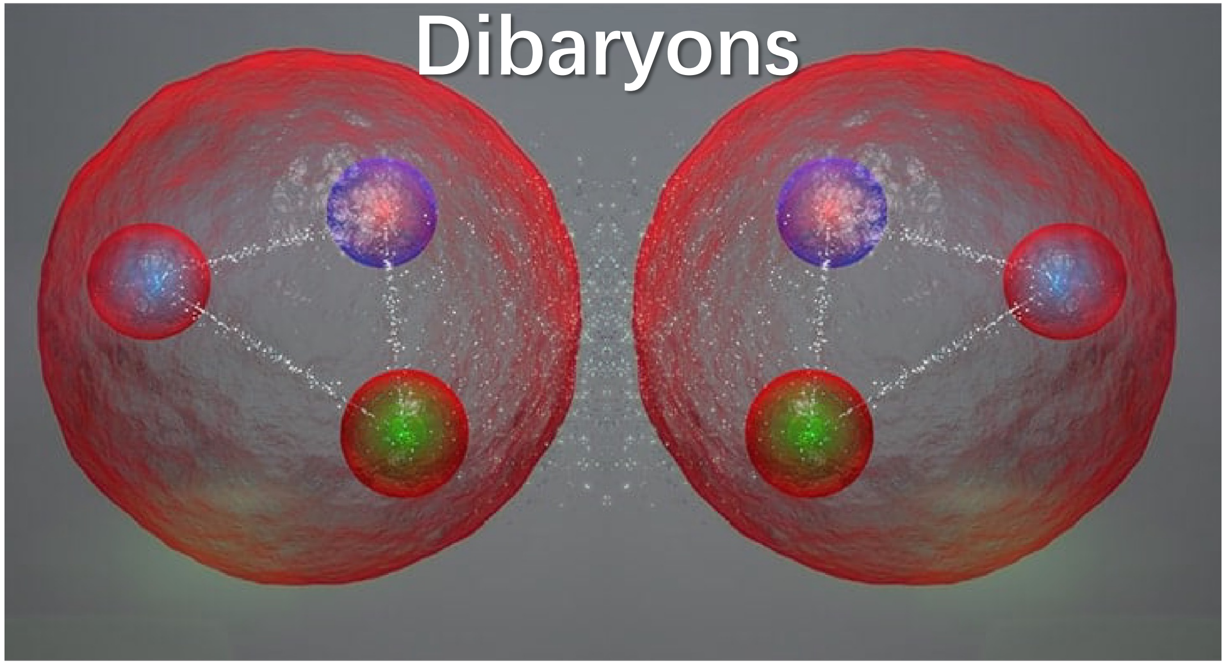
Poles well above the $\Xi_c^+ D^-$ threshold



Poles well below the $\Xi_c^+ D^-$ threshold



Dibaryons

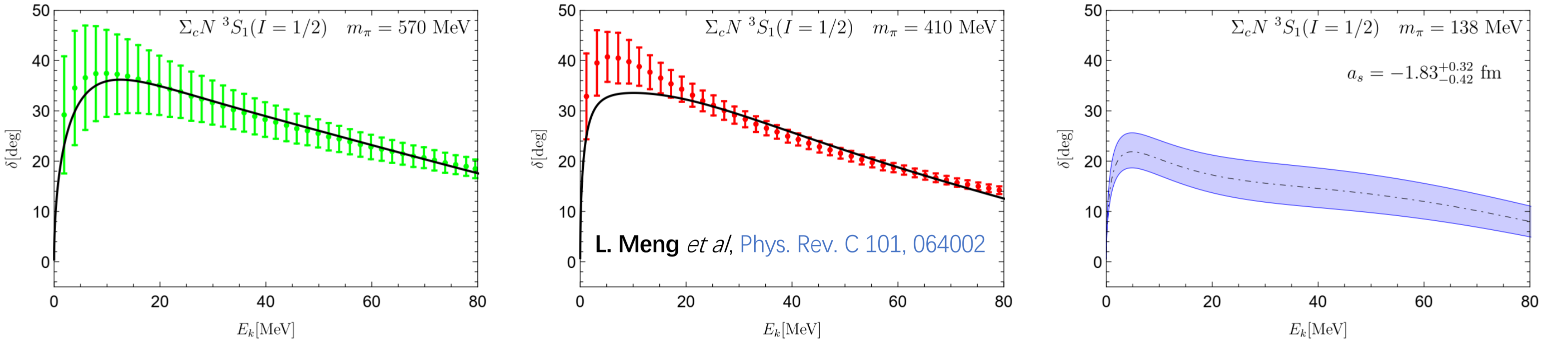


Dibaryons (molecular hexaquark)

A dibaryon is essentially a system with two baryons. There is one known dibaryon in nature-deuteron, another possible one is the ΔΔ dibaryon-$d^*(2380)$ (**disputed**).

$\mathbf{NB_Q}$ and $\mathbf{NB_{QQ}}$ systems

- ✓ The NY_c ($Y_c = \Sigma_c, \Lambda_c$) interactions are essential for understanding the in-medium properties of the charmed baryons. The experimental proposals at the J-PARC [arXiv:1706.07916] and GIS-FAIR [Prog. Part. Nucl. Phys. 66 (2011) 477–518] have stimulated many investigations on the NY_c interactions.
- ✓ In Refs. [Nucl. Phys. A 971 (2018) 113–129, PoS Hadron2017 (2018) 146], the HAL QCD Collaboration calculated the phase shifts of the $N\Lambda_c$ and $N\Sigma_c$ scatterings from lattice QCD at the unphysical pion mass $m_\pi = 410 - 570$ MeV.



L. Meng *et al*, Phys. Rev. C 101, 064002

- ✓ In Ref. [**L. Meng** *et al*, Eur. Phys. J. A 54 (9) (2018) 143], the authors predicted the bound states in the $N\Xi_{cc}$ and $\overline{N}\Xi_{cc}$ systems from the OBE model .

Dibaryons (molecular hexaquark)

$\mathrm{B_Q B_Q}$ and $\mathrm{B_Q \bar{B}_Q}$ systems

- ✓ In Ref. [**N. Lee** *et al*, PhysRevD.84.014031], the authors calculated the $\Lambda_c\Lambda_c(\bar{\Lambda}_c), \Xi_c\Xi_c(\bar{\Xi}_c), \Sigma_c\Sigma_c(\bar{\Sigma}_c), , \Xi_c'\Xi_c'(\bar{\Xi}_c'), \Omega_c\Omega_c(\bar{\Omega}_c)$ systems within the OBE model, they obtained: the H-dibaryonlike state $\Lambda_c\Lambda_c$ does not exist; there may exist loosely bound deuteronlike states for the other systems
- ✓ In Ref. [**J-.B. Cheng** *et al*, PhysRevD.107.054018], the authors investigated the double-charm and hidden-charm hexaquarks as molecules in complex scaling method with explicit three-body effect.
- ✓ In Ref. [**J-.X. Lu** *et al*, PhysRevD.99.074026], the authors found that the isoscalar $\Lambda_c\bar{\Lambda}_c$, $\Sigma_c^{(*)}\bar{\Sigma}_c^{(*)}$and isovector $\Lambda_c\bar{\Sigma}_c^{(*)}$as well as their doubly charmed and doubly bottom counterparts are good candidates of the molecular hexaquarks.
- ✓ In Ref. [**X. Z. Ling** *et al*, Eur. Phys. J. C (2021) 81:1090], the masses and strong decays of the $\Sigma_c^{(*)}\Sigma_c^{(*)}$ dibaryons were calculated.
- ✓ Calculations from other approaches, see [**H. Huang** *et al*, PhysRevC.89.035201; **T. F. Carames** *et al*, PhysRevD.92.034015; **H. Garcilazo** *et al*, Eur. Phys. J. C 80 (8) (2020) 720; **Z. Liu** *et al*, Phys.Rev.D 105 (2022) 3, 034006; **X.-K. Dong** *et al*, Commun. Theor. Phys. 73 (12) (2021) 125201; **X.-K. Dong** *et al*, Progr. Phys. 41 (2021) 65–93].

$\mathrm{B_{QQ} B_Q}$ and $\mathrm{B_{QQ} \bar{B}_{QQ}}$ systems

The $\Xi_{cc}^{(*)}$ [$\bar{\Xi}_{cc}^{(*)}$] can be related to the $\bar{D}^{(*)}$ [$D^{(*)}$] with the heavy diquark-antiquark symmetry (HDAS),

$$\Xi_{cc}^{(*)} \xrightarrow{\text{HDAS}} \bar{D}^{(*)} \qquad \bar{\Xi}_{cc}^{(*)} \xrightarrow{\text{HDAS}} D^{(*)}$$

Dibaryons (molecular hexaquark)

$\mathbf{B_{QQ}B_{Q}}$ and $\mathbf{B_{QQ}\bar{B}_{QQ}}$ systems

As a consequence of the HDAS, the $\Xi_{cc}^{(*)}D^{(*)}$, $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$and $\Xi_{cc}^{(*)}\bar{\Xi}_{cc}^{(*)}$ systems can be related to the $\bar{D}^{(*)}D^{(*)}$, $\bar{D}^{(*)}\Sigma_c^{(*)}$ and $\bar{D}^{(*)}D^{(*)}$ systems, respectively.

Thus, the existence of the molecular states in the $\bar{D}^{(*)}D^{(*)}$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$ systems should also imply the existence of the molecular states in the $\Xi_{cc}^{(*)}D^{(*)}$, $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$and $\Xi_{cc}^{(*)}\bar{\Xi}_{cc}^{(*)}$ systems.

- ✓ In Ref. [**B. Yang** *et al*, Eur. Phys. J. A56 (2) (2020) 67], Yang et al investigated the possible bound states in the $\Xi_{cc}^{(*)}\Xi_{cc}^{(*)}(\bar{\Xi}_{cc}^{(*)})$ systems, and predicted the molecular candidates in the isoscalar and isovector channels.
- ✓ In Ref. [**F.-K. Guo** *et al*, PhysRevD.88.054014], the authors predicted the triply heavy pentaquarks with $I(J^P)=0(3/2^-)$, $0(5/2^-)$ with the $X(3872)$ as input, as well as the $1(1/2^-)$ and $1(3/2^-)$ ones with the $Z_b(10650)$ as input.
  see also **R. Chen** *et al*, PhysRevD.96.114030.
- ✓ In Ref. [**Y.-W. Pan** *et al*, PhysRevD.102.011504], the authors proposed an alternative way to determine the spins of the $P_c(4440)$ and $P_c(4457)$ from the spectrum of the , $\Xi_{cc}^{(*)}\Sigma_c^{(*)}$ systems with the help of lattice QCD.

$\mathbf{B_{QQQ}B_{QQQ}}$ systems

- ✓ **Lattice**: Phys. Rev. Lett.127.072003; Phys. Rev. Lett.130.111901
- ✓ **Models**: Chin. Phys. Lett. 38, 101201; Eur. Phys. J. C 82, 805; Int. J. Mod. Phys. A 37, 2250166; arXiv: 2207.05505; arXiv: 2208.03041

Summary and outlook

1. Many near-threshold states have been observed in experiments.
2. Their spectra and decays were intensively studied within various models.
3. Most of the nowadays observed exotic states have the same origin? —The dynamically generated resonances (bound states) from the analogue of nuclear forces in different sectors.
4. What forces govern the formations of these states—the “general nuclear forces”?
5. Weak(er) model-dependent approaches need to be developed.

Thank you!