Summary of Tcc workshop

Shi-Lin Zhu
School of Physics, Peking University
Lyon, Nov 23, 2021

Outline

- Overview of the talks
- Compact Tcc/T4c
- Hadronic molecules
- Summary

So many excellent talks…

History

- Luciano Maiani: From GIM to Tcc, a brief history of charm
- Robert L. Jaffe: Tetraquarks and other exotics, a brief history

Experimental progress

- Yanxi Zhang: LHCb results and perspectives
- Chengping Shen: Belle II results and perspectives
- Ryan Mitchell: Belle III results and perspectives
- Peter Braun-Muntzinger: ALICE and hadron physics

Theory on compact Tcc/Tbb (1)

Lattice QCD

- Pedro Bicudo: Lattice QCD and tetraquarks
- Kim Maltman: Results from lattice QCD

Symmetry

- Chris Quigg: Heavy quark symmetry

PQCD potential

- Nora Brambilla: QCD and exotic hadrons

String picture

- Gian Carlo Rossi: String picture of exotic hadrons

QCD sum rules

- Marina Nielsen: Exotics in QCD with sum rules

Holography

- Stan Brodsky: Light-Front holography

Theory on compact Tcc/Tbb (2)

Quark model

- Makoto Oka: Tcc: structure, decay, and production
- Eric Braaten: Heavy exotics in the Born-Oppenheimer picture
- Javier Vijiande: Constituent model
- Angelo Esposito: Tetraquark: successes, challenges and new avenues
- Jean-Marc Richard: Stability of tetraquarks, lessons from atomic physics

Decays

- Eliecer Hernandez: Lifetime and main decay modes of Tbb
- Ahmed Ali: Weak decays of heavy flavors

Hadronic molecules (3)

- Tesuo Hyodo: Hadron-hadron interaction from heavy-ion results
- Bing Song Zou: Hadronic molecules with charm

Compact tetraquarks vs hadronic molecules

- The dominant part of QCD strong interaction is flavor independent. Color configuration is unique in conventional baryons and meson
- → flavor multiplets in baryons and meson
- Mass splittings are induced by various chromo-magnetic interactions: spin-spin, spin-orbital, tensor, …
- For multiquark states such as Tcc/T4c, there should exist color-flavor dual multiplets since two types of color configurations are allowed
- Once a member state is observed, all the other states with different isospin and strangeness should also exist.
- Their mass splittings can be calculated from chromo-magnetic interactions
- Compact tetraquarks are formed by the quark-gluon COLOR interaction

◆ In contrast, hadronic molecules are very sensitive to the isospin

◆ States with the lowest isospin are favored

◆ Hadronic molecules are bound by the hadron-hadron color-less interaction

Compact Tcc/T4c

- Spatial configuration
- Color configuration
- Confinement
- non-Abelian triple-gluon and quartic-gluon interactions

Spatial configurations of Tbb/Tcc

There are three types of spatial configurations:

- (1) Two heavy quarks are close to each other and look like compact heavy di-quark
- These Tbb/Tcc systems are similar to heavy baryons (Qqq) and Helium atom in QED

◆ (2) Two heavy quarks are not close to each other (separation around 1 fm?). They share light quark pair and form QCD valence bond

◆ similar to valence bond in Hydrogen molecule in QED where two protons are bound by electron cloud

✓ (3) Two heavy quarks are separated far away

✓ Hadronic molecules are similar to Deuteron

Color configurations of Tcc and T4c

- Color configuration unique for conventional baryons (qqq) and mesons (qqbar)
- Color configurations complicated for multiquarks
- For tetraquarks, there are two color confihurations: triplet and sextet. (the quark pair and anti-quark pair form color-singlet through 3cX3c_bar=1c or 6cX6c_bar=1c)
- Linear confinement and Coulomb force from one-gluon-exchange do not mix different color configurations if we ignore the running of coupling constant alpha_s
- However, various fine and hyperfine interaction induce mixing of color configurations

Color configuration mixing in S-wave Tcc/Tbb

TABLE IV. Masses and eigenvectors of the $nn\bar{c}\bar{c}$, $nnbb$ and $nn\bar{c}b$ tetraquarks. The masses are all in units of MeV.

System	J^P	Scheme I		Scheme II	
		Mass	Eigenvector	Mass	Eigenvector
$(nn\bar{c}\bar{c})^{I=1}$	0^+	3833.2	$\{0.515, 0.857\}$	3969.2	$\{0.350, 0.937\}$
		4127.4	$\{0.857, -0.515\}$	4364.9	$\{0.937, -0.350\}$
	1^+	3946.4	$\{1\}$	4053.2	$\{1\}$
	2^+	4017.1	$\{1\}$	4123.8	$\{1\}$
$(nn\bar{c}\bar{c})^{I=0}$	1^+	3749.8	$\{0.354, -0.935\}$	3868.7	$\{0.212, -0.977\}$
		3976.1	$\{0.935, 0.354\}$	4230.8	$\{0.977, 0.212\}$
$(nn\bar{b}\bar{b})^{I=1}$	0^+	10468.8	$\{0.123, 0.992\}$	10569.3	$\{0.086, 0.996\}$
		10808.9	$\{0.992, -0.123\}$	11054.6	$\{0.996, -0.086\}$
	1^+	10485.3	$\{1\}$	10584.2	$\{1\}$
	2^+	10507.9	$\{1\}$	10606.8	$\{1\}$
$(nn\bar{b}\bar{b})^{I=0}$	1^+	10291.6	$\{0.058, -0.998\}$	10390.9	$\{0.043, -0.999\}$
		10703.4	$\{0.998, 0.058\}$	10950.3	$\{0.999, 0.043\}$

Lowest isoscalar state dominated by 3cX3c_bar in Tcc/Tbb

Weng, Deng, Zhu, CPC(2021), arXiv:2108.07242

Color configuration mixing in S-wave Tcccc

TABLE IV. The mass spectrum (MeV), the percentage of different color configurations, and the root mean square radius (fm) of the S-wave tetraquark states.

0^{++}	Mass	$\bar{3}_c \otimes 3_c$	$6_c \otimes \bar{6}_c$	$1_c \otimes 1_c$	$8_c \otimes 8_c$	r_{12}/r_{34}	r	r_{13}/r_{24}	r'
1S	6405	31.9%	68.1%	96.9%	3.13%	0.52	0.31	0.48	0.37
	6498	67.7%	32.3%	5.7%	94.3%	0.51	0.36	0.51	0.36
2S	6867	10.6%	89.4%	80.6%	19.4%	0.65	0.35	0.58	0.46
	7007	89.7%	10.3%	26.0%	74.0%	0.49	0.47	0.59	0.35
1^{+-}	Mass	$\bar{3}_c \otimes 3_c$	$6_c \otimes \bar{6}_c$	$1_c \otimes 1_c$	$8_c \otimes 8_c$	r_{12}/r_{34}	r	r_{13}/r_{24}	r'
1S	6481	100%	0%	33.3%	66.7%	0.48	0.37	0.51	0.34
2S	6954	100%	0%	33.3%	66.7%	0.61	0.44	0.61	0.43
3S	7024	100%	0%	33.3%	66.7%	0.66	0.42	0.62	0.46
2^{++}	Mass	$\bar{3}_c \otimes 3_c$	$6_c \otimes \bar{6}_c$	$1_c \otimes 1_c$	$8_c \otimes 8_c$	r_{12}/r_{34}	r	r_{13}/r_{24}	r'
1S	6502	100%	0%	33.3%	66.7%	0.49	0.39	0.53	0.35
2S	6917	100%	0%	33.3%	66.7%	0.55	0.60	0.72	0.39
3S	7030	100%	0%	33.3%	66.7%	0.64	0.46	0.64	0.45

Lowest S-wave state dominated by 6cX6c_bar

Wang, Meng, Oka, Zhu, PRD 104 (2021) 036016

Color configuration mixing in P-wave T4c

TABLE V. The mass spectrum (MeV) and the percentages of different color configurations in the P-wave T_c states obtained with leading potentials, including the Coulomb, linear confinement and hyperfine potentials in Eq. (2). The eigenstates are labeled by $|\rho/\lambda_i^C\rangle$,where C is the C-parity and $i = 1, 2, 3$ represent different states in the ascending order of the mass.

J^{-+}	Mass	$\|3_\lambda^+;{}^3P_{0,1,2}\rangle$	$\|3_\rho^+;{}^3P_{0,1,2}\rangle$	$\|6_\rho^+;{}^3P_{0,1,2}\rangle$	$1_c \otimes 1_c$	$8_c \otimes 8_c$	$6_\rho^+ < 3_\lambda^+ < 3_\rho^+$
$\|\lambda_1^+\rangle$	6746	99.5%	0.4%	0.1%	33.4%	66.6%	
J^{-+}	Mass	$\|3_\lambda^+;{}^3P_{0,1,2}\rangle$	$\|3_\rho^+;{}^3P_{0,1,2}\rangle$	$\|6_\rho^+;{}^3P_{0,1,2}\rangle$	$1_c \otimes 1_c$	$8_c \otimes 8_c$	
$\|\rho_1^+\rangle$	6599	0.1%	24.5%	75.4%	58.5%	41.5%	
$\|\rho_2^+\rangle$	6894	0.5%	72.0%	27.5%	42.5%	57.5%	
J^{--}	Mass	$\|3_\lambda^-;{}^1P_1\rangle$	$\|6_\lambda^-;{}^1P_1\rangle$	$\|3_\lambda^-;{}^5P_{1,2,3}\rangle$	$1_c \otimes 1_c$	$8_c \otimes 8_c$	$6_\rho^- < 3_\lambda^- < 6_\lambda^- < 3_\rho^-$
$\|\lambda_1^-\rangle$	6740	98.9%	1.1%	0%	33.7%	66.3%	
$\|\lambda_2^-\rangle$	6741	0%	0%	100%	33.3%	66.7%	
$\|\lambda_3^-\rangle$	6885	1.4%	98.6%	0%	66.2%	33.8%	
J^{--}	Mass	$\|3_\rho^-;{}^3P_{0,1,2}\rangle$	$\|6_\rho^-;{}^3P_{0,1,2}\rangle$		$1_c \otimes 1_c$	$8_c \otimes 8_c$	
$\|\rho_1^-\rangle$	6561	27.1%	72.9%		57.6%	42.4%	
$\|\rho_2^-\rangle$	6913	72.1%	27.9%		42.6%	57.4%	

Some P-wave states dominated by 3cX3c_bar

Wang, Meng, Oka, Zhu, PRD 104 (2021) 036016

Confinement mechanism

- Conventional hadron spectrum and lattice QCD simulations favor linear confinement between the color-singlet (qqbar)_1c pair or color-triplet (qq)_3c_bar pair within color-singlet hadrons
- Long-distance force between the color-octet (qqbar)_8c pair or color-sextet (qq)_6c pair within multiquarks is still unknown
- Need more data to explore confinement force: do we still expect the linear confinement force with the same color factor as in Coulomb potential? Or flux tube with universal string tension? Or …

non-Abelian triple-gluon and quartic-gluon interactions in Tcc

- In the traditional quark model, in addition to the long-ranged confining force, one generally considers the two-body short-ranged interaction from the gluon exchange, which follows similar formalism in atomic physics
- non-Abelian SU(3) gauge group of QCD differs from the U(1) of QED
- There exist the triple-gluon and quartic-gluon interactions in QCD
- Very luckily, these non-Abelian interactions do not contribute to the traditional meson and baryon spectrum due to their unique color configuration in quark model
- However, the situation is very different for the Tcc/T4c . The color wave function of any three quarks within the Tcc/T4c is color-triplet 3c or 3c_bar
- the genuine three-body interaction from the triple-gluon or quartic-gluon interaction does not vanish
- This effect has seldom been investigated in the literature
- Multiquarks may provide an ideal platform to study non-Abelian guage interactions

Hadronic molecules

- Only two talks on hadronic molecules

Chiral effective field theory for hadronic molecules

- Chiral symmetry and its spontaneous breaking play an important role both in the light and heavy hadron systems
- In the eyes of the pions, the heavy mesons and baryons are the **SAME matter fields** as the nucleons
- Modern nuclear force was built upon the chiral effective field theory (ChEFT) proposed by Weinberg
- The same chiral dynamics not only governs the nuclei and forms the deuteron, but also dictates the shallow bound states or resonances such as Pc/Pcs/Tcc/Zc/Zcs/Zb…
- ChEFT is modeled by One-Boson-Exchange Model (OBE)

OBE vs ChEFT

	OBE	ChEFT
Long distance	1 pion	1 pion
Medium range	Sigma meson exchange	2- pion loop
Short distance	Vector meson exchange	Low-energy constants

Pc states were predicted in OBE model

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*

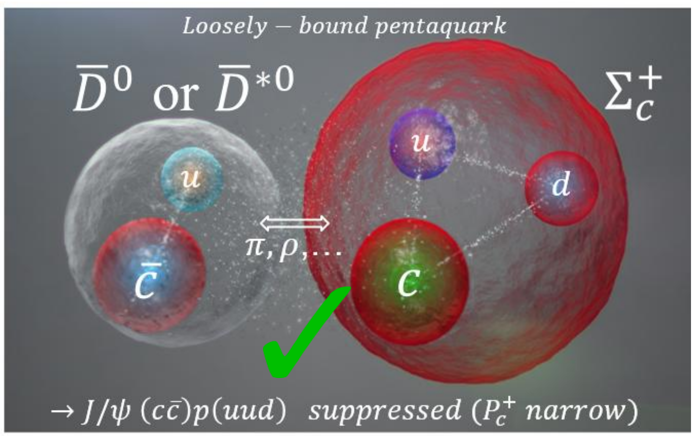
YANG Zhong-Cheng(杨忠诚)[1] SUN Zhi-Feng(孙志峰)[2,4] HE Jun(何军)[1,3;1)]
LIU Xiang(刘翔)[2,4;2)] ZHU Shi-Lin(朱世琳)[1;3)]

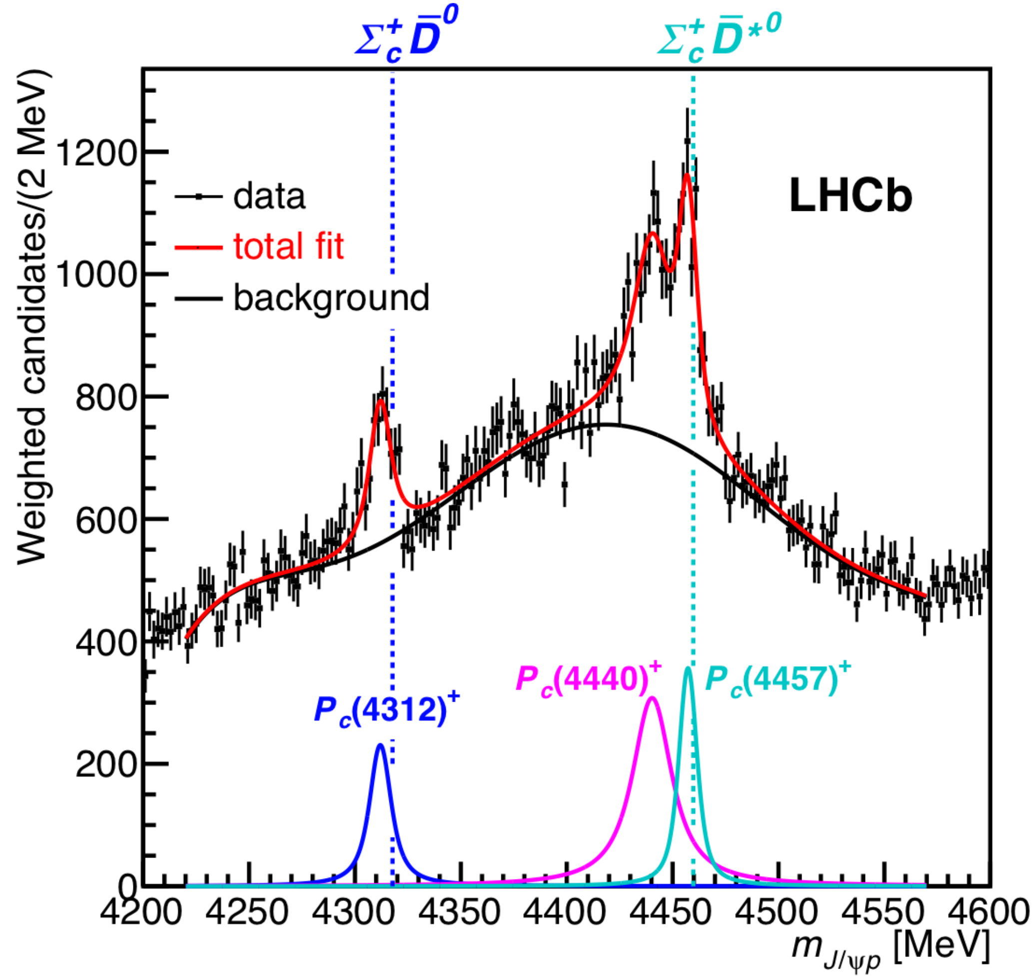
Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$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

Wu, Molina, Oset and Zou, Prediction of narrow N and resonances with hidden charm above 4 GeV, Phys. Rev. Lett. 105 (2010) 232001

Molecular picture confirmed by LHCb

- The near-threshold masses and narrow widths of $P_c(4312)^+$, $P(4440)^+$ and $P_c(4457)^+$ favor "molecular" pentaquarks with meson-baryon substructure!





PRL122, 222001 (2019)

Hidden-charm and hidden-bottom molecular pentaquarks in chiral effective field theory

Bo Wang,[a,b] Lu Meng[a] and Shi-Lin Zhu[a,b] JHEP 11 (2019) 108

ΔE	$[\Sigma_c \bar{D}]_{\frac{1}{2}}$	$[\Sigma_c \bar{D}^*]_{\frac{1}{2}}$	$[\Sigma_c \bar{D}^*]_{\frac{3}{2}}$	$[\Sigma_c^* \bar{D}]_{\frac{3}{2}}$	$[\Sigma_c^* \bar{D}^*]_{\frac{1}{2}}$	$[\Sigma_c^* \bar{D}^*]_{\frac{3}{2}}$	$[\Sigma_c^* \bar{D}^*]_{\frac{5}{2}}$
Without Λ_c	-29.05	-6.84	-2.98	-34.30	-0.16	$\times$	$\times$
With Λ_c	-4.60	-22.48	-3.19	-34.51	-14.34	-3.40	-0.30
I.S.	-7.24	-1.47	-17.44	-40.88	$\times$	-0.24	-11.20

Table 2. The binding energies ΔE for the $I = \frac{1}{2}$ hidden-charm $[\Sigma_c^{(*)} \bar{D}^{(*)}]_J$ systems in both cases with and without the Λ_c, as well as the case with $J^P = \frac{1}{2}^-$ for $P_c(4457)$ and $\frac{3}{2}^-$ for $P_c(4440)$. The values of $(\mathbb{D}_1, \mathbb{D}_2)$ for the "Without Λ_c" and "With Λ_c" cases are chosen to be $(42, -12.5)$ GeV^{-2} and $(52, -4)$ GeV^{-2}, respectively. "I.S." stands for the results when interchanging the spins of $P_c(4440)$ and $P_c(4457)$, where $(\mathbb{D}_1, \mathbb{D}_2) = (58, -31)$ GeV^{-2} in this case. "$\times$" means no binding solution (in units of MeV).

Hidden-charm and hidden-bottom molecular pentaquarks in chiral effective field theory

Bo Wang,[a,b] **Lu Meng**[a] **and Shi-Lin Zhu**[a,b]

JHEP 11 (2019) 108

ABSTRACT: The newly observed $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ at the LHCb experiment are very close to the $\Sigma_c\bar{D}$ and $\Sigma_c\bar{D}^*$ thresholds. In this work, we perform a systematic study and give a complete picture on the interactions between the $\Sigma_c^{(*)}$ and $\bar{D}^{(*)}$ systems in the framework of heavy hadron chiral effective field theory, where the short-range contact interaction, long-range one-pion-exchange contribution, and intermediate-range two-pion-exchange loop diagrams are all considered. We first investigate the three P_c states without and with considering the Λ_c contribution in the loop diagrams. It is difficult to simultaneously reproduce the three P_cs unless the Λ_c is included. The coupling between the $\Sigma_c^{(*)}\bar{D}^{(*)}$ and $\Lambda_c\bar{D}^{(*)}$ channels is crucial for the formation of these P_cs. Our calculation supports the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ to be the S-wave hidden-charm $[\Sigma_c\bar{D}]_{J=1/2}^{I=1/2}$, $[\Sigma_c\bar{D}^*]_{J=1/2}^{I=1/2}$ and $[\Sigma_c\bar{D}^*]_{J=3/2}^{I=1/2}$ molecular pentaquarks, respectively. Our calculation disfavors the spin assignment $J^P = \frac{1}{2}^-$ for $P_c(4457)$ and $J^P = \frac{3}{2}^-$ for $P_c(4440)$, because the excessively enhanced spin-spin interaction is unreasonable in the present case. We obtain the complete mass spectra of the $[\Sigma_c^{(*)}\bar{D}^{(*)}]_J$ systems with the fixed low energy constants. Our result indicates the existence of the $[\Sigma_c^*\bar{D}^*]_J$ ($J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$) hadronic molecules. The previously reported $P_c(4380)$ might be a deeper bound one. Additionally, we also study the

PHYSICAL REVIEW D **101,** 034018 (2020)

Spectrum of the strange hidden charm molecular pentaquarks in chiral effective field theory

BO WANG, LU MENG, and SHI-LIN ZHU PHYS. REV. D **101,** 034018 (2020)

TABLE III. The predicted binding energies ΔE and masses M for the $[\Xi_c'\bar{D}^{(*)}]_J$, $[\Xi_c^*\bar{D}^{(*)}]_J$, and $[\Xi_c\bar{D}^{(*)}]_J$ systems in $I=0$ channel, where the subscript "J" denotes the total spin of the system. We correspondingly use the thresholds of $\Xi_c'^+\bar{D}^{(*)0}$, $\Xi_c^{*+}\bar{D}^{(*)0}$, and $\Xi_c^+\bar{D}^{(*)0}$ as the benchmarks to calculate the values in this table (in units of MeV). The state that denoted by "♯" means which may be nonexistent at the upper limit.

System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{5}{2}}^{\sharp}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
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	$4423.7^{+6.4}_{-6.8}$	$4568.7^{+6.4}_{-7.2}$	$4582.3^{+1.8}_{-3.3}$	$4502.9^{+4.2}_{-5.3}$	$4635.4^{+6.7}_{-7.5}$	$4644.4^{+4.5}_{-5.6}$	$4651.7^{+0.7}_{-2.2}$	$4319.4^{+2.8}_{-3.0}$	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

- **We predicted Pcs around 4457MeV with ChEFT**
- **Later, LHCb reported evidence of $P_{cs}(4459)$ in 2020**

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

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

Ning Li,[1,2,*] Zhi-Feng Sun,[3,4,†] Xiang Liu,[3,4,‡] and Shi-Lin Zhu[1,5,6,§]

TABLE IV. The numerical results for the $D^{(*)}D^{(*)}$ system. "$* * *$" means the corresponding state does not exist due to symmetry while "$\cdots$" means there does not exist binding energy with the cutoff parameter less than 3.0 GeV. The binding energies for the states $D^{(*)}D^{(*)}[I(J^P)=0(1^+)]$ and $D^{(*)}D^{(*)}[I(J^P)=1(1^+)]$ are relative to the threshold of DD^* while that of the state $D^{(*)}D^{(*)}[I(J^P)=1(0^+)]$ is relative to the DD threshold.

			$D^{(*)}D^{(*)}$							
I	J^P		OPE				OBE			
	0^+		$* * *$				$* * *$			
		Λ (GeV)	1.05	1.10	1.15	1.20	0.95	1.00	1.05	1.10
		B.E. (MeV)	1.24	4.63	11.02	20.98	0.47	5.44	18.72	42.82
		M (MeV)	3874.61	3871.22	3864.83	3854.87	3875.38	3870.41	3857.13	3833.03
		$r_{\rm rms}$ (fm)	3.11	1.68	1.12	0.84	4.46	1.58	0.91	0.64
0	1^+	P_1 (%)	96.39	92.71	88.22	83.34	97.97	92.94	85.64	77.88
		P_2 (%)	0.73	0.72	0.57	0.42	0.58	0.55	0.32	0.15
		P_3 (%)	2.79	6.45	11.07	16.11	1.41	6.42	13.97	21.91
		P_4 (%)	0.08	0.13	0.14	0.13	0.04	0.09	0.08	0.05

We predicted a **very shallow DD* molecule**, which was confirmed by LHCb in July

Tcc vs X(3872)

- Tcc and X(3872) share the same one-pion-exchange potential. Their long-range dynamics is similar and strongly correlated to each other
- If X(3872) contains a large portion of molecular component or X(3872) is a loosely bound molecular state, the existence of X(3872) implies the existence of Tcc
- There should also exist partner states Tccs/Tbb…
- The difference is that X(3872) contains a short-distance ccbar core

PHYSICAL REVIEW D **104,** L051502 (2021)

Letter

Probing the long-range structure of the T_{cc}^{+} with the strong and electromagnetic decays

Lu Meng,[1] Guang-Juan Wang,[2] Bo Wang,[3,4,*] and Shi-Lin Zhu[5,†]

- LHCb first reported Tcc width to be (410±163) keV
- Within the molecular framework, we employed the couple-channel effective field theory and calculated the decay widths of Tcc
- In the isospin symmetry limit, we obtained its total decay width to be 46.7 keV
- One month later, the LHCb collaboration adopted the unitarized Breit-Wigner distribution and extracted the total width to be (47.8±1.9) keV, which further supports the molecular picture

Summary

- Tcc signal observed by LHCb is probably a shallow DD* molecule
- One may expect similar signal below D*D*/BB*/B*B*/DsD*/DDs*… thresholds
- Other molecular cousins Tccs/Tbb… should also exist
- Compact tetraquarks Tbb must exist (lattice QCD, various quark models, chromomagnetic models…)
- Need more efforts to look for compact Tcc?
- Multiquark states (T4c/Tbb) provide ideal platform to study confinement mechanism, non-Abelian 3-gluon/4-gluon QCD interaction, QCD valence bond, novel spatial/color configurations…