Status report
B.2 Hadron Spectroscopy

Bing-Song Zou, Ying Chen, Shi-Lin Zhu

July 20th, 2023

Many young researchers particitpated in and benefitted from CRC110 (since Jan 2020)

7 Ph D students:

- Zi-Yang Lin, Yan-ke Chen, Liang-Zhen Weng
- Yao Ma, Xin-Zheng Weng, Lu Meng, Bin Yang

10 Postdocs:

- Yao Ma, Hui-Min Yang, Zhun-Zhang Wang
- Guang-Juan Wang, Bo Wang, Rui Chen, Kan Chen, Bo-Lin Huang, Qi Wu, Jian-Bo Cheng

2 Visitors:

- Chengrong Deng, Zhi-Hui Wang

Outline of B2 project

- Goal: study the hadron spectroscopy and structure with lattice QCD, EFT and various models
- 2020-2023 tasks/milestones: Pc, Tcc…
- Hadronic molecules (Zou)
- Exotics from Lattice QCD (Chen)
- Tcc/T4c/Pcs (Zhu)

My group and external collaborators

(Xiang Liu, Hua-Xing Chen, Wei Chen, Jia-Jun Wu, Zhi Yang…)

- Loosely bound Tcc
- Pcc/Hcc
- X3872/Zc/Zcs/Pcs
- Compact Tcc/T4c
- $D_{s0}(2317)$, B_{s0}
- Glueball and hybrid meson
- Light meson spectrum
- Various hadron scattering

Theoretical tools

- Chiral perturbation theory
- Chiral effective field theory
- Pionless effective field theory
- QCD sum rules
- Quark model (Gaussian expansion *vs* Resonance group method)
- Complex scaling method (bound state, resonance and virtual state)

Publication list for B2 – 3rd term

- **Chiral perturbation theory**

1) B.L.Huang, Z.Y.Lin, K.Chen and S.L.Zhu,Phase shifts of the light pseudoscalar meson and heavy meson scattering in heavy meson chiral perturbation theory, Eur. Phys. J. C 83, 76 (2023)
2) B.L.Huang, Z.Y.Lin and S.L.Zhu, Light pseudoscalar meson and heavy meson scattering lengths to O(p4) in heavy meson chiral perturbation theory, Phys. Rev. D 105, 036016 (2022)
3) B.L.Huang, J.B.Cheng and S.L.Zhu, Peripheral nucleon-nucleon scattering at next-to-next-to-leading order in SU(3) heavy baryon chiral perturbation theory, Phys. Rev. D 104, 116030 (2021)
4) B.Yang, B.Wang, L.Meng and S.L.Zhu,Isospin violating decay $D^*_s \to D_s \pi^0$ in chiral perturbation theory, Phys. Rev. D 101, 054019 (2020)

Publication list for B2 – 3rd term

- **Chiral effective field theory for hadronic molecules (Bo Wang's talk)**

1) L. Meng, B. Wang, G. J. Wang and S. L. Zhu, Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules, Phys. Rept. 1019, 1 (2023)
2) B.Wang and S.L.Zhu,How to understand the X(2900)?, Eur. Phys. J. C 82, 419 (2022)
3) B. Wang, L. Meng and S. L. Zhu, Decoding the nature of Zcs(3985) and establishing the spectrum of charged heavy quarkoniumlike states in chiral effective field theory, Phys. Rev. D 103, L021501 (2021)
4) K.Chen, B.Wang and S.L.Zhu,Exploration of the doubly charmed molecular pentaquarks, Phys. Rev. D 103,116017 (2021)
5) B. Wang, L. Meng and S. L. Zhu, Deciphering the charged heavy quarkoniumlike states in chiral effective field theory, Phys. Rev. D 102, 114019 (2020)
6) B. Wang, L. Meng and S. L. Zhu, Spectrum of the strange hidden charm molecular pentaquarks in chiral effective field theory, Phys. Rev. D 101, no.3, 034018 (2020)
7) L. Meng, B. Wang and S. L. Zhu, Σ_cN interaction in chiral effective field theory, Phys. Rev. C 101, 064002 (2020)
8) B.Wang, L.Meng and S.L.Zhu,$D^{(\ast)}N$ interaction and the structure of $\Sigma_c(2800)$ and $\Lambda_c(2940)$ in chiral effective field theory,Phys. Rev. D 101, 094035 (2020)
9) K.Chen, B.L.Huang, B.Wang and S.L.Zhu, $\Sigma_c\Sigma_c$ interactions in chiral effective field theory,arXiv:2204.13316

Publication list for B2 – 3rd term

● Pionless EFT for hadronic molecules (Kan Chen's talk)

1) K. Chen, Z. Y. Lin and S. L. Zhu, Comparison between the P_ψ^N and $P_{\psi s}^{\Lambda}$ systems, Phys. Rev. D 106, 116017 (2022)
2) L. Meng, B. Wang and S. L. Zhu, Double thresholds distort the line shapes of the Pcs (4338) resonance, Phys. Rev. D 107, 014005 (2023)
3) K. Chen, B. Wang and S. L. Zhu, Heavy flavor molecular states with strangeness, Phys. Rev. D 105, 096004 (2022)
4) K. Chen, R. Chen, L. Meng, B. Wang and S. L. Zhu, Systematics of the heavy flavor hadronic molecules, Eur. Phys. J. C 82, 581 (2022)
5) L. Meng, G. J. Wang, B. Wang and S. L. Zhu, Revisit the isospin violating decays of X(3872), Phys. Rev. D 104, 094003 (2021)
6) L. Meng, G. J. Wang, B. Wang and S. L. Zhu, Probing the long-range structure of the Tcc+ with the strong and electromagnetic decays, Phys. Rev. D 104, 051502 (2021)
7) L. Meng, B. Wang, G. J. Wang and S. L. Zhu, Implications of the Zcs(3985) and Zcs(4000) as two different states, Sci. Bull. 66, 2065 (2021)
8) L. Meng, B. Wang and S. L. Zhu, Predicting the Ds(*)Ds(*) bound states as the partners of X(3872), Sci. Bull. 66, 1288 (2021)
9) L. Meng, B. Wang and S. L. Zhu, Zcs(3985)- as the U-spin partner of Zc(3900)- and implication of other states in the SU(3)_F symmetry and heavy quark symmetry, Phys. Rev. D 102, 111502 (2020)

Publication list for B2 – 3rd term

- **QCD sum rules for glueballs and hybrid states (Hua-Xing Chen or Wei Chen's talk)**

1) N. Su, W. H. Tan, H. X. Chen, W. Chen and S. L. Zhu, Light double-gluon hybrid states with the exotic quantum numbers $J^{PC}=1^{-+}$ and 3^{-+}, Phys. Rev. D 107, 114005 (2023)

2) N. Su, H. X. Chen, W. Chen and S. L. Zhu, Light double-gluon hybrid states from QCD sum rules, Phys. Rev. D 107, 034010 (2023)

3) H. X. Chen, N. Su and S. L. Zhu, QCD Axial Anomaly Enhances the $\eta\eta'$ Decay of the Hybrid Candidate $\eta_1(1855)$, Chin. Phys. Lett. 39, 051201 (2022)

4) H. X. Chen, W. Chen and S. L. Zhu, New hadron configuration: The double-gluon hybrid state, Phys. Rev. D 105, L051501 (2022)

5) H. X. Chen, W. Chen and S. L. Zhu, Two- and three-gluon glueballs of C=+, Phys. Rev. D 104, 094050 (2021)

6) H. X. Chen, W. Chen and S. L. Zhu, Toward the existence of the odderon as a three-gluon bound state, Phys. Rev. D 103, L091503 (2021)

7) H. X. Chen, W. Chen, X. Liu and S. L. Zhu, Strong decays of fully-charm tetraquarks into di-charmonia, Sci. Bull. 65, 1994 (2020)

Publication list for B2 – 3rd term

- **Complex scaling method for resonances (Zi-Yang Lin's talk)**

1) J. B. Cheng, D. x. Zheng, Z. Y. Lin and S. L. Zhu, Double-charm and hidden-charm hexaquark states under the complex scaling method, Phys. Rev. D 107, 054018 (2023)
2) J. B. Cheng, Z. Y. Lin and S. L. Zhu, Double-charm tetraquark under the complex scaling method, Phys. Rev. D 106, 016012 (2022)
3) Z.Y.Lin, J.B.Cheng, B.L.Huang and S.L.Zhu, P_c states and their open-charm decays with the complex scaling method,arXiv:2305.19073
4) J.B.Cheng, B.L.Huang, Z.Y.Lin and S.L.Zhu, Z_{cs}, Z_c and Z_b states under the complex scaling method,arXiv:2305.15787
5) Z.Y.Lin, J.B.Cheng and S.L.Zhu, T_{cc}^+ and $X(3872)$ with the complex scaling method and $DD(\bar{D})\pi$ three-body effect,arXiv:2205.14628

Publication list for B2 – 3rd term

- **Quark model (Yan-Ke Chen's and Yao Ma's talks)**

1) G. J. Wang, Z.Yang, J.J.Wu, M.Oka and S.L.Zhu, New insight into the exotic states strongly coupled with the D\bar{D}^* from the T^+_{cc}, arXiv:2306.12406
2) Y.Ma, L.Meng, Y.K.Chen and S.L.Zhu, Ground state baryons in the flux-tube three-body confinement model using diffusion MonteCarlo,Phys. Rev. D 107, 054035 (2023)
3) Z. Yang, G. J. Wang, J. J. Wu, M. Oka and S. L. Zhu, The investigations of the P-wave Bs states combining quark model and lattice QCD in the coupled channel framework, JHEP 01, 058 (2023)
4) C. R. Deng and S. L. Zhu, Decoding the double heavy tetraquark state T^+_{cc}, Sci. Bull. 67, 1522 (2022)
5) C. Deng and S. L. Zhu, Tcc+ and its partners, Phys. Rev. D 105, 054015 (2022)
6) Z. Yang, G. J. Wang, J. J. Wu, M. Oka and S. L. Zhu, Novel Coupled Channel Framework Connecting the Quark Model and Lattice QCD for the Near-threshold Ds States, Phys. Rev. Lett. 128, 11 (2022)
7) G. J. Wang, L. Meng, M. Oka and S. L. Zhu, Higher fully charmed tetraquarks: Radial excitations and P-wave states, Phys. Rev. D 104, 036016 (2021)
8) X. Z. Weng, X. L. Chen, W. Z. Deng and S. L. Zhu, Systematics of fully heavy tetraquarks, Phys. Rev. D 103, 034001 (2021)
9) G. J. Wang, L. Y. Xiao, R. Chen, X. H. Liu, X. Liu and S. L. Zhu, Probing hidden-charm decay properties of P_c states in a molecular scenario, Phys. Rev. D 102, 036012 (2020)

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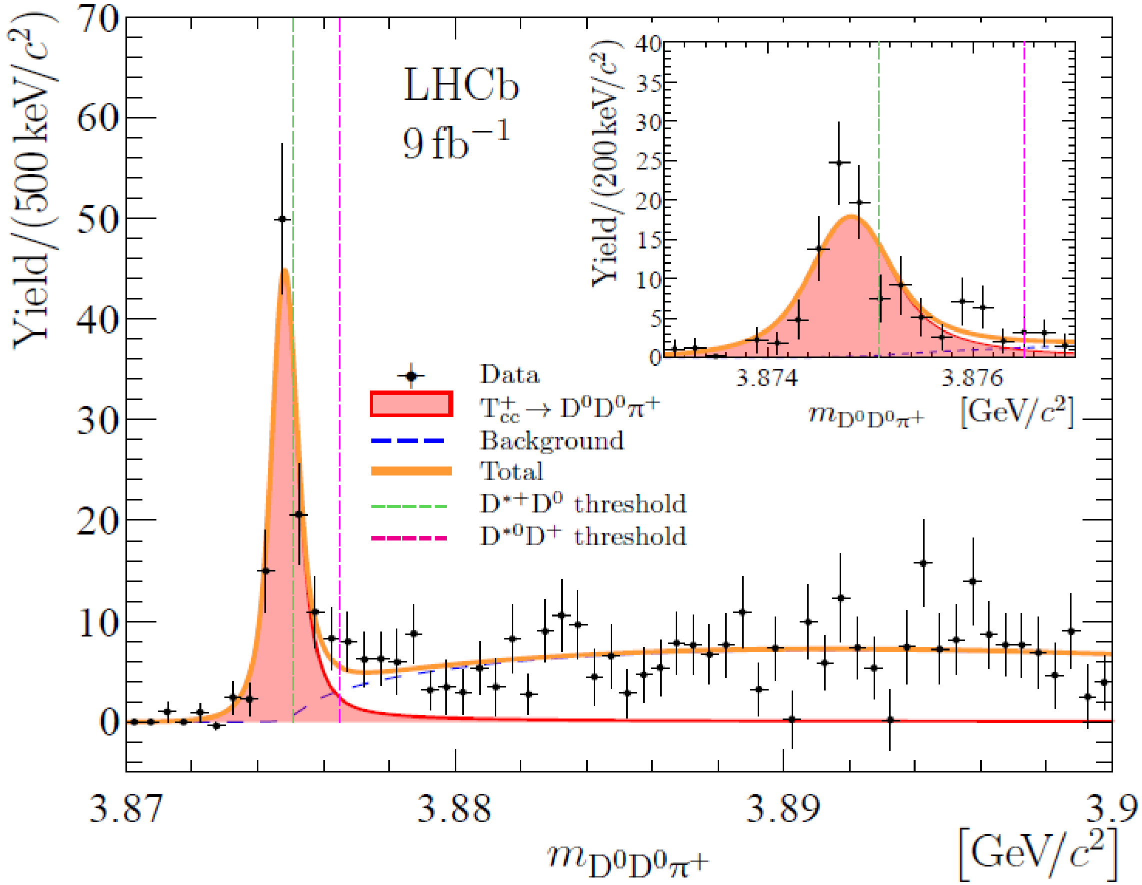
Observation of T_{cc}^{+} by LHCb, **Nature Physics Letters**



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**, confirmed by LHCb in July 2021

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)

Highlight 1

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 $(46.7^{+2.7}_{-2.9})$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

Highlight 2

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, P_{cs}(4338) in 2022**

Highlight 3

IOP Publishing Reports on Progress in Physics

Rep. Prog. Phys. **86** (2023) 026201 (96pp) https://doi.org/10.1088/1361-6633/aca3b6

Review

An updated review of the new hadron states

Hua-Xing Chen[1,*], Wei Chen[2], Xiang Liu[3,4], Yan-Rui Liu[5] and Shi-Lin Zhu[6,*]

Abstract

The past decades witnessed the golden era of hadron physics. Many excited open heavy flavor mesons and baryons have been observed since 2017. We shall provide an updated review of the recent experimental and theoretical progresses in this active field. Besides the conventional heavy hadrons, we shall also review the recently observed open heavy flavor tetraquark states $X(2900)$ and $T_{cc}^{+}(3875)$ as well as the hidden heavy flavor multiquark states $X(6900)$, $P_{cs}(4459)^0$, $Z_{cs}(3985)^-$, $Z_{cs}(4000)^+$, and $Z_{cs}(4220)^+$. We will also cover the recent progresses on the glueballs and light hybrid mesons, which are the direct manifestations of the non-Abelian $SU(3)$ gauge interaction of the Quantum Chromodynamics in the low-energy region.

Highlight 4

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Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules

Lu Meng [a,1], Bo Wang [b,c,d,1], Guang-Juan Wang [e,f,1], Shi-Lin Zhu [g,*]

A R T I C L E I N F O

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A B S T R A C T

Chiral symmetry and its spontaneous breaking play an important role both in the light hadron and heavy hadron systems. The chiral perturbation theory (χPT) is the low energy effective field theory of the Quantum Chromodynamics. In this work, we shall review the investigations on the chiral corrections to the properties of the heavy mesons and baryons within the framework of χPT. We will also review the scatterings of the light pseudoscalar mesons and heavy hadrons, through which many new resonances such as the $D^*_{s0}(2317)$ could be understood.

Moreover, many new hadron states were observed experimentally in the past decades. A large group of these states is near-threshold resonances, such as the charged charmoniumlike Z_c and Z_{cs} states, bottomoniumlike Z_b states, hidden-charm pentaquark P_c and P_{cs} states and the doubly charmed T_{cc} state, etc. They are very good candidates of the loosely bound molecular states composed of a pair of charmed (bottom) hadrons, which are very similar to the loosely bound deuteron. The modern nuclear force was built upon the chiral effective field theory (χEFT), which is the extension of the χPT to the systems with two matter fields. The long-range and medium-long-range interactions between two nucleons arise from the single- and double-pion exchange respectively, which are well constrained by the chiral symmetry and its spontaneous breaking. The short-distance interactions can be described by the low energy constants. Such a framework works very well for the nucleon–nucleon scattering and nuclei. In this work, we will perform an extensive review of the progress on the heavy hadronic molecular states within the framework of χEFT. We shall emphasize that the same chiral dynamics not only govern the nuclei and forms the deuteron, but also dictates the shallow bound states or resonances composed of two heavy hadrons.

Summary

- Using different tools (lattice QCD, EFT and various models), B2 family are working on important topics with common interest: **Tcc, Hcc, $\eta_1(1855)$, glueball**
- 2020/2021 milestones on Pc/Tcc achieved
- Trained many postdocs and Ph D students
- 40~50 publications
- Very smooth progress
- Expect more exciting results in 2022/2023