Exotic heavy hadrons from lattice QCD

LepageFest, 2024



Randy Lewis, York University, Toronto







For example, 11.5 cc(aā) cčcč cēaaa 23 new exotic hadrons at the LHC 11.0 ccāā cāaā 10.5 7.5-Tcccc (6900) 7.0 Teres(6600) Lattice predicts absence of Think below threshold : 6.5 Hughes, Eichten, Davies, Phys. Rev. D 97, 054505 (2018) 6.0 Mass [GeV/c²] 5.5 5.0 $\chi_{c1}(4685)$ P.= (4450)* -(4457)4.5 Xc1(4274 -(4440) h_(4300) Tcts1(4220) $\chi_{c1}(4140)$ P - (4380) .(4312) ● ⁷ccs1(400000 Tces1(4000) 4.0 Our lattice QCD discussion T_{cc}(3875)+ X(3960) 3.5 will relate closely to Tro. 3.0 $T_{cs0}(2900)^{0}$ (2900)++ Lattice predicts The and maybe The. 2.5 2.0 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 Date of arXiv submission patrick.koppenburg@cern.ch 2024-07-22

Experimental observation of T_{cc}



- T_{cc} is slightly below threshold: $\delta m \sim \frac{1}{4} \ {\rm MeV} \label{eq:deltambda}$
- Predictions varied widely: $-300 \text{ MeV} \lesssim \delta m \lesssim 300 \text{ MeV}$
- Directly from lattice QCD?

 T_{cc} is an extreme challenge T_{bb} and T_{bc} are more accessible

Aaij et al. [LHCb], Nature Phys.18,751(2022)

Intuition for a very heavy diquark



Intuition for a very heavy diquark

tetraquark

pair of mesons



The heavy diquark is compact with binding energy $\sim \alpha_s^2 m_Q \sim \frac{m_Q}{\ln^2(m_Q)}$.



Therefore, for $m_Q \rightarrow \infty$, the tetraquark is a stable particle in QCD.

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tetraquark



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Recall the quarkonium discussion:

July 1994

Rigorous QCD Analysis of Inclusive Annihilation and Production

of Heavy Quarkonium

Geoffrey T. Bodwin

High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439

Eric Braaten*

Theory Group, Fermilab, Batavia, IL 60510

G. Peter Lepage

Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853

Therefore, for $m_Q \rightarrow \infty$, the tetraquark is a stable particle in QCD.

pair of mesons





Intuition for a good light diquark

Recall some standard heavy baryons.

Each Λ_Q is more deeply bound than its Σ_Q partner, especially as $m_Q \to \infty$.



Intuition for a good light diquark

Recall some standard heavy baryons.

Each Λ_Q is more deeply bound than its Σ_Q partner, especially as $m_Q \to \infty$. A tetraquark can have this same Λ -type light diquark.



Roles for lattice QCD



Computing directly from QCD is the goal.

Extrapolations are required in lattice spacing, volume and some quark masses.

Choices made by different authors give valuable insight into systematic effects.

A consensus from the lattice community will provide confidence for tetraquark physics.

8*)	\$	static	<i>b</i> quai	rks			N	RQC	ıarks	Wagner	man, Parrott	
$M(T_{bb})$ - $M(B)$ - $M(E)$	- Wagner, Bicudo	- Brown, Orginos	- Bicudo, Cichy, Peters, Wagner	- Bicudo, Scheunert, Wagner	- Francis, Hudspith, Lewis, Maltman	Junnarkar, Mathur, Padmanath	- Leskovec, Meinel, Pflaumer, Wagner	– Mohanta, Basak	- Hudspith, Mohler	– Aoki, Aoki, Inoue	 Alexandrou, Finkenrath, Leontiou, Meinel, 	- Colquhoun, Francis, Hudspith, Lewis, Mal
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8/20



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T_{bc} binding energies for u d ar c ar b from lattice QCD



Additional systematics:

- larger threshold effects
- relativistic charm quark [variants of El-Khadra,Kronfeld,Mackenzie Phys.Rev.D55. 3933 (1997)]

T_{bc} binding energies for u d ar c ar b from lattice QCD



Operators and energies for lattice T_{bc} with $J^P=0^+$

Alexandrou, Finkenrath, Leontiou, Meinel, Pflaumer, Wagner, PhysRevLett132,151902 = 2312.02925

•
$$\sum_{\vec{x}} \left[\bar{b}^a(\vec{x}) \gamma_5 C \bar{c}^{b,T}(\vec{x}) \right] \left[u^{a,T}(\vec{x}) C \gamma_5 d^b(\vec{x}) \right] - (d \leftrightarrow u)$$

• $\sum_{\vec{x}} B^+(\vec{x}) D^-(\vec{x}) - \sum_{\vec{x}} B^0(\vec{x}) \bar{D}^0(\vec{x})$

•
$$\sum_{\vec{x},j} B_j^{*+}(\vec{x}) D_j^{*-}(\vec{x}) - \sum_{\vec{x},j} B_j^{*0}(\vec{x}) \bar{D}_j^{*0}(\vec{x})$$

•
$$B^+(\vec{q})D^-(-\vec{q}) - B^0(\vec{q})\bar{D}^0(-\vec{q})$$
 for $\frac{|\vec{q}|L}{2\pi} \in \{0, 1, \sqrt{2}, \sqrt{3}\}$

where

$$egin{aligned} B^+(x) &= ar{b}(ec{x})\gamma_5 u(ec{x}) \ B^+(ec{q}) &= rac{1}{\sqrt{V}}\sum_{ec{x}}B^+(x)e^{2\pi iec{q}\cdotec{x}/L} \end{aligned}$$

etc.



Toward the T_{cc} binding energy from lattice QCD

An early attempt:

1810.12285	Junnarkar, Mathur, Padmanath	-23 ± 11 MeV
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Recent studies: (DD* scattering via volume dependence or effective potentials)

2202.10110	Padmanath, Prelovsek	$-9.9^{+3.6}_{-7.1}$ MeV
2206.06185	Chen, Shi, Chen, Gong, Liu, Sun, Zhang	I=0 attractive but $I=1$ repulsive
2302.04505	Lyu, Aoki, Doi, Hatsuda, Ikeda, Meng	$-59\left(^{+53}_{-99} ight)\left(^{+2}_{-67} ight)$ keV
2402.14715	Collins, Nefediev, Padmanath, Prelovsek	"a very delicate fine tuning" is observed
2405.15741	Whyte, Wilson, Thomas	-41 ± 31 MeV (virtual bound state)

Reminder:

Physical pion masses will be necessary because pion exchange contributions are significant. Note: Available lattice studies of T_{cc} use $m_{\pi} > m_{D^*} - m_D$, meaning D^* mesons are stable.

Dreams for the distant future

Real-time evolution in lattice QCD?



Image from https://physics.aps.org/articles/v10/100

Image from arXiv:2201.00202

Dense matter in lattice QCD?

SDO

Nuclotron-M

conductor

n_=0.16 fm-

arvon density n/

RHIC-BES

Hadrons

Compact Stars

One small step for tetraquarks...

PHYSICAL REVIEW RESEARCH 5, 033184 (2023)

Simulating one-dimensional quantum chromodynamics on a quantum computer: Real-time evolutions of tetra- and pentaquarks

Yasar Y. Atas ⁰,^{1,2,*,†} Jan F. Haase,^{1,2,3,*,‡} Jinglei Zhang,^{1,2,§} Victor Wei ⁰,^{1,4} Sieglinde M.-L. Pfaendler ⁰,⁵ Randy Lewis,⁶ and Christine A. Muschik^{1,2,7}

QCD in one spatial dimension



Staggered fermions:

Each site needs 3 gubits. Gauge fields provide interactions among them.

Two staggered sites in the strong coupling limit:



Time evolution at intermediate coupling

Oscillations among the eigenstates were computed on ibm_peekskill.



This study required the mitigation of hardware errors.

Practical error mitigation was crucial



The mitigation method was developed with three students at York University:

A Rahman, Lewis, Mendicelli, Powell, Phys.Rev.D 106, 074502 (2022).

Conclusions

- Lattice NRQCD (by Lepage et al) is the foundation for T_{bb} and T_{bc} studies.
- There is clearly a bound T_{bb} with $ud\overline{b}\overline{b}$ and with $us\overline{b}\overline{b}$. The systematic errors are being determined through multiple lattice studies.
- T_{bc} does not yet have a consensus among lattice groups. Several studies exist and real progress has been made.
- T_{cc} is a challenge for lattice QCD because binding energy $\sim \frac{1}{4} \text{ MeV} \ll \Lambda_{QCD}$. Nevertheless, impressive efforts have been reported.
- Quantum computers have opened new opportunities for the coming decades.