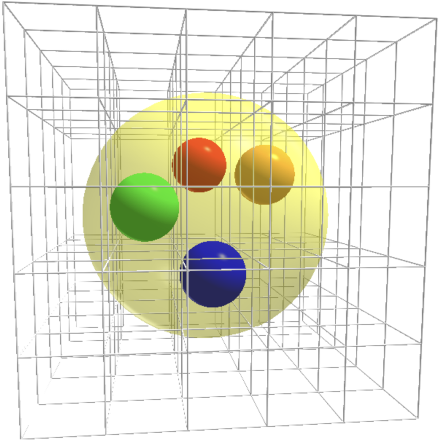
Exotic heavy hadrons from lattice QCD

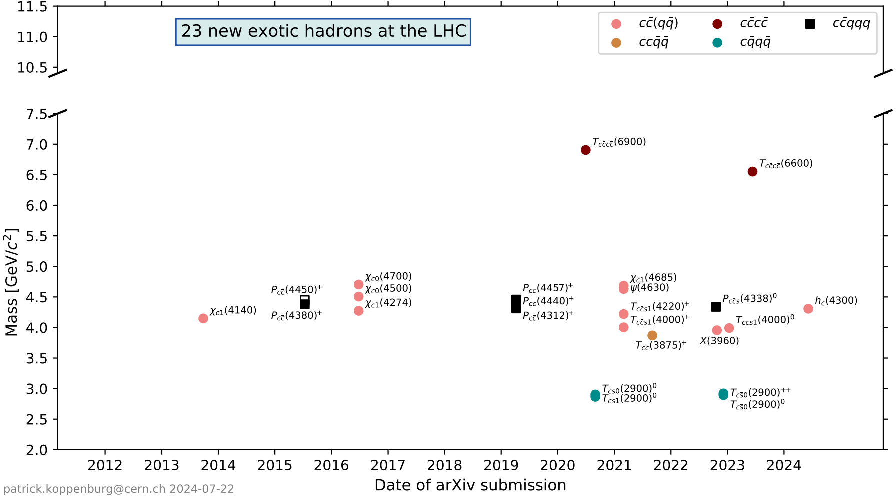
LepageFest, 2024



Randy Lewis, York University, Toronto

New exotic hadrons are being discovered every year

For example,



P. Koppenburg (LHCb collaboration), www.nikhef.nl/∼pkoppenb/particles.html

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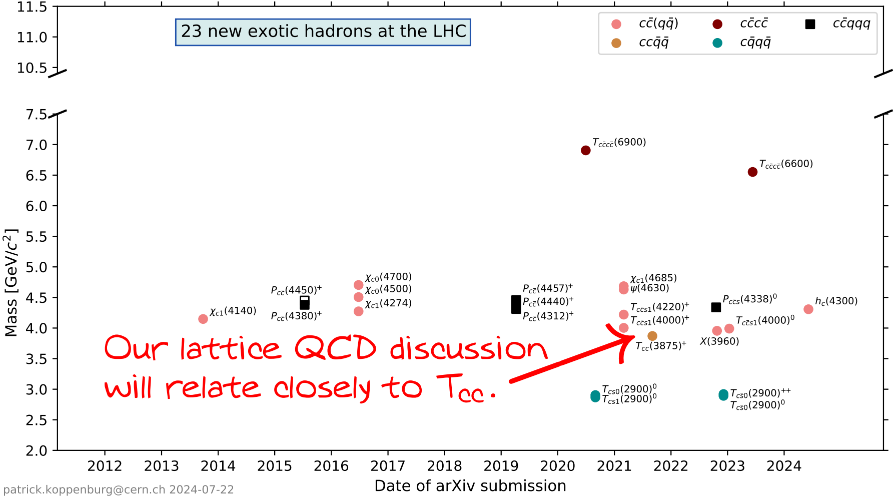

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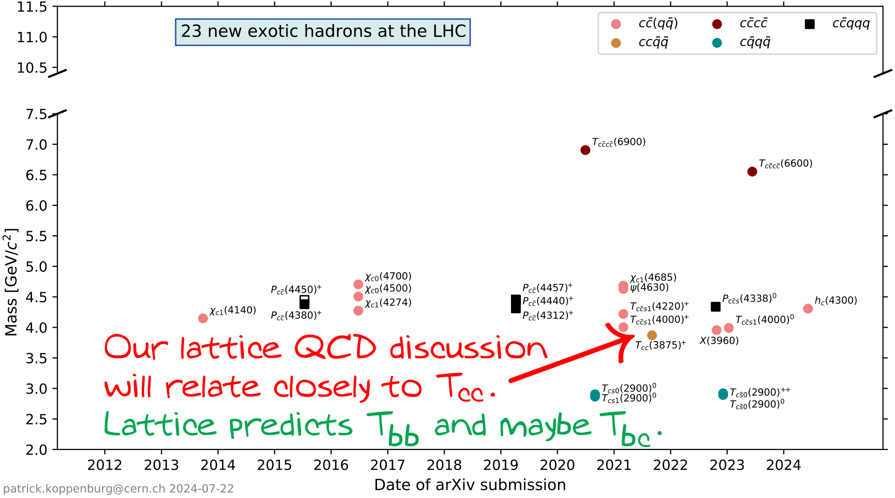

Our lattice QCD discussion will relate closely to T_{cc}.

Lattice predicts T_{bb} and maybe T_{bc}.

P. Koppenburg (LHCb collaboration), www.nikhef.nl/∼pkoppenb/particles.html

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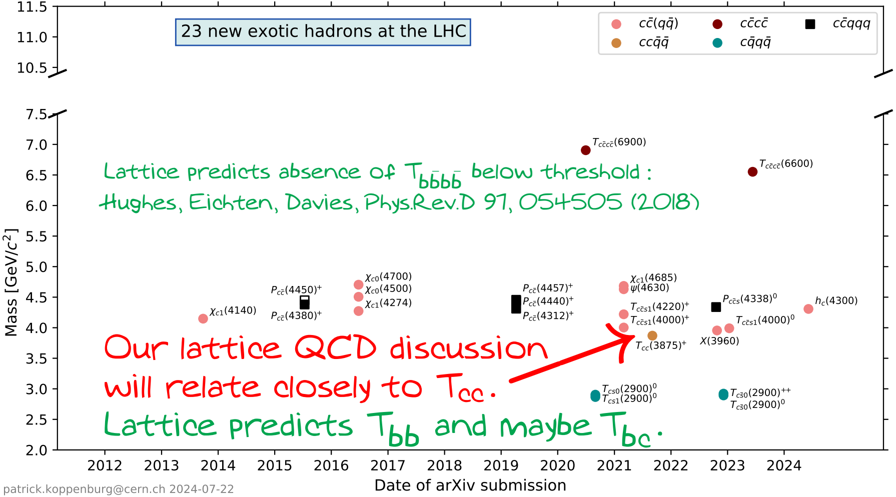
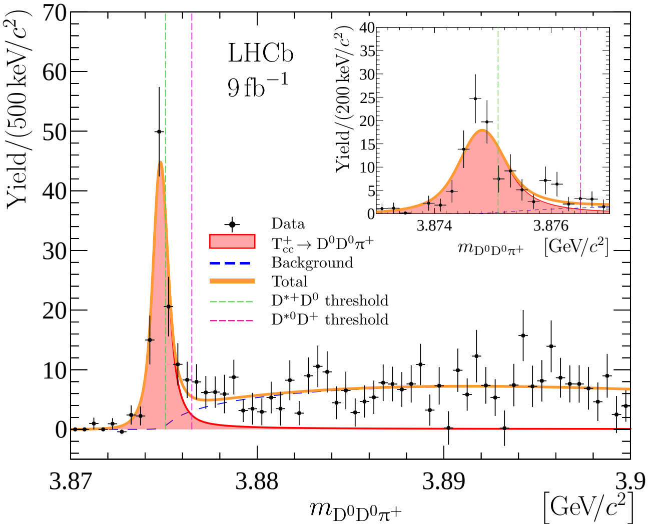


P. Koppenburg (LHCb collaboration), www.nikhef.nl/~pkoppenb/particles.html

Experimental observation of T_{cc}



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

- T_{cc} is slightly below threshold:

$$\delta m \sim \frac{1}{4}\ \text{MeV}$$

- Predictions varied widely:

$$-300\ \text{MeV} \lesssim \delta m \lesssim 300\ \text{MeV}$$

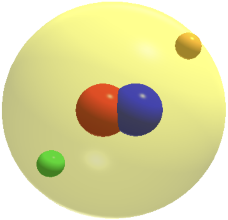
- Directly from lattice QCD?

T_{cc} is an extreme challenge

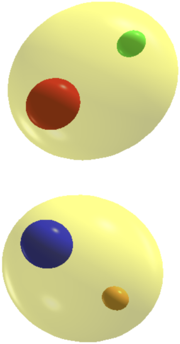
T_{bb} and T_{bc} are more accessible

Intuition for a very heavy diquark

tetraquark

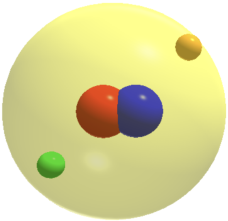


pair of mesons



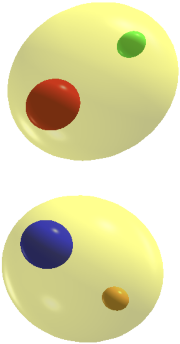
Intuition for a very heavy diquark

tetraquark



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

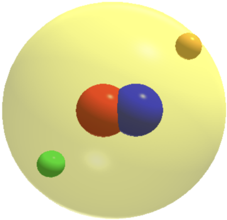
pair of mesons



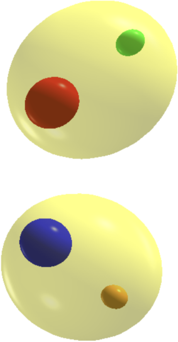
Therefore, for $m_Q \to \infty$, the tetraquark is a stable particle in QCD.

Intuition for a very heavy diquark

tetraquark



pair of mesons



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

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

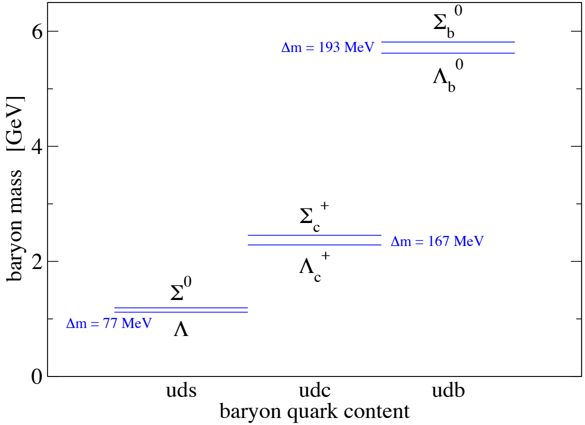
G. Peter Lepage
Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853

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

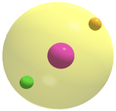
Intuition for a good light diquark

Recall some standard heavy baryons.

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



baryon

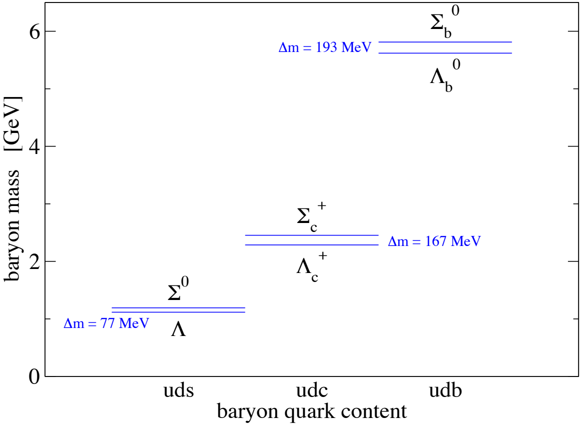


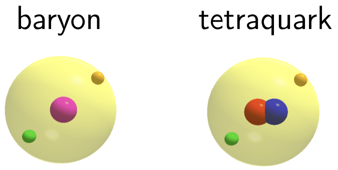
Intuition for a good light diquark

Recall some standard heavy baryons.

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

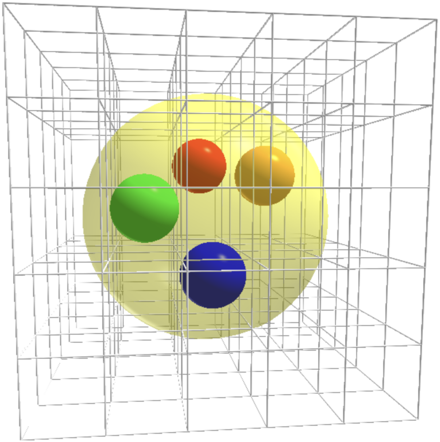
A tetraquark can have this same Λ-type light diquark.





In both hadrons, the light diquark sees a heavy color triplet.

Roles for lattice QCD



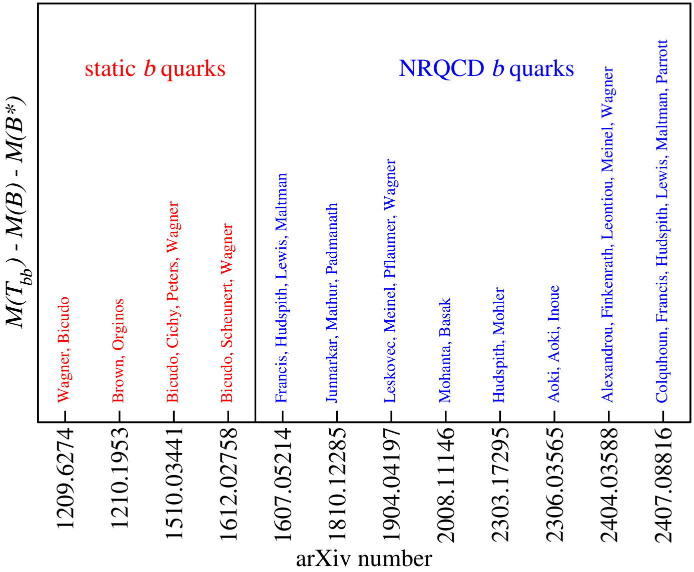
Computing directly from QCD is the goal.

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

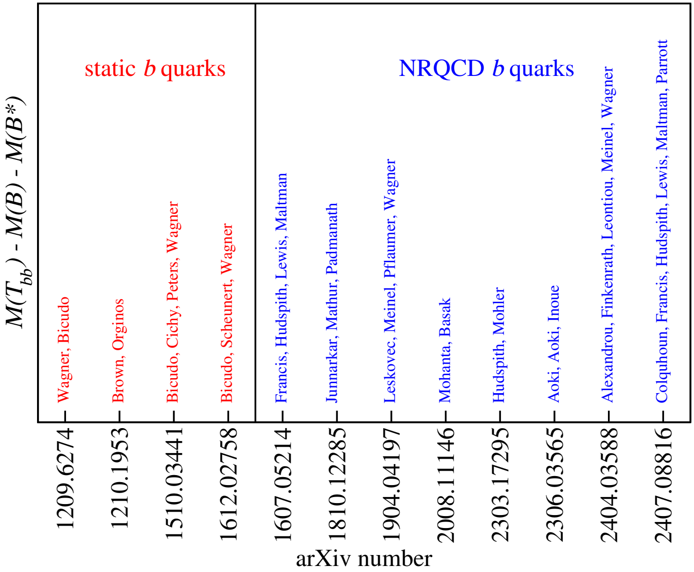
Choices made by different authors give valuable insight into systematic effects.

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

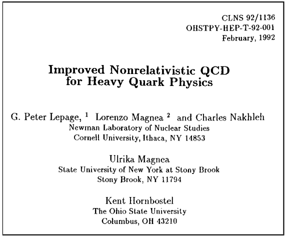
T_{bb} binding energy for $ud\bar{b}\bar{b}$ from lattice QCD



T_{bb} binding energy for $ud\bar{b}\bar{b}$ from lattice QCD



Defining lattice NRQCD



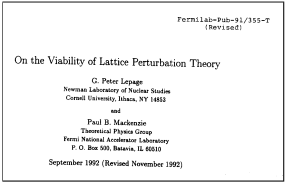
CLNS 92/1136
OHSTPY-HEP-T-92-001
February, 1992

Improved Nonrelativistic QCD for Heavy Quark Physics

G. Peter Lepage,[1] Lorenzo Magnea[2] and Charles Nakhleh
Newman Laboratory of Nuclear Studies
Cornell University, Ithaca, NY 14853

Ulrika Magnea
State University of New York at Stony Brook
Stony Brook, NY 11794

Kent Hornbostel
The Ohio State University
Columbus, OH 43210



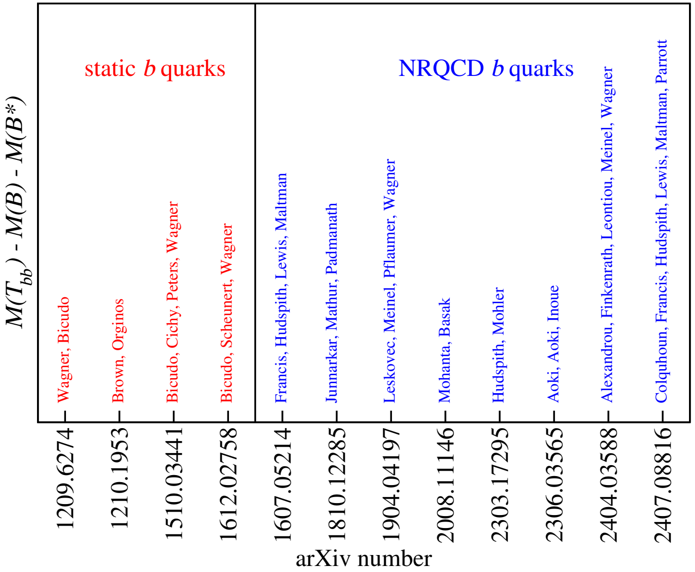
Fermilab-Pub-91/355-T
(Revised)

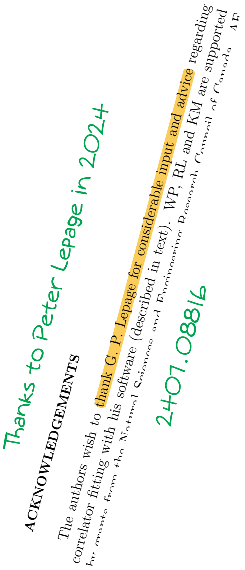
On the Viability of Lattice Perturbation Theory

G. Peter Lepage
Newman Laboratory of Nuclear Studies
Cornell University, Ithaca, NY 14853
and
Paul B. Mackenzie
Theoretical Physics Group
Fermi National Accelerator Laboratory
P. O. Box 500, Batavia, IL 60510

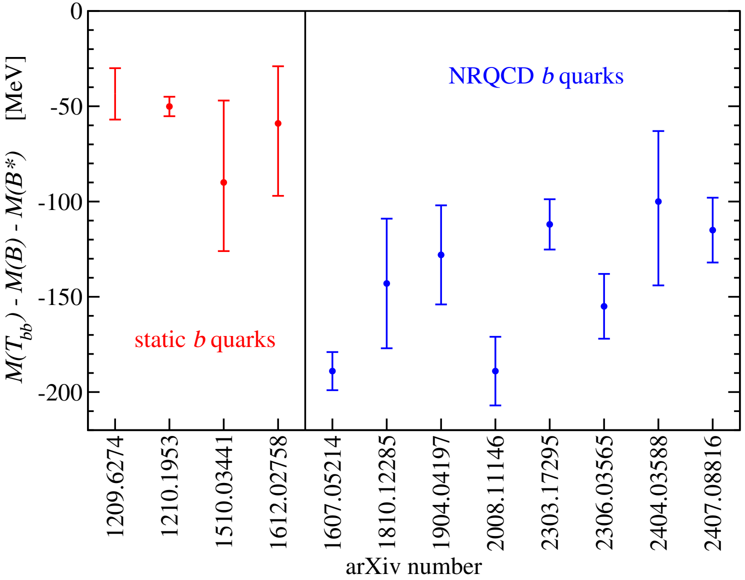
September 1992 (Revised November 1992)

T_{bb} binding energy for $ud\bar{b}\bar{b}$ from lattice QCD

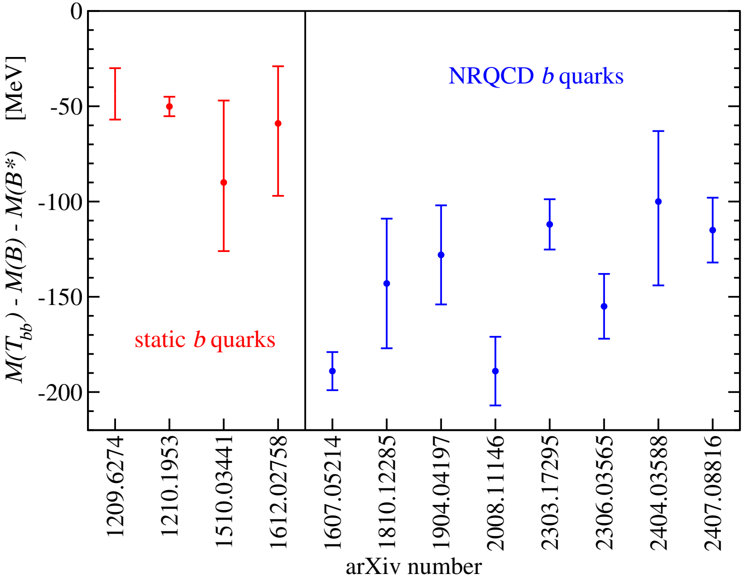




T_{bb} binding energy for $ud\bar{b}\bar{b}$ from lattice QCD



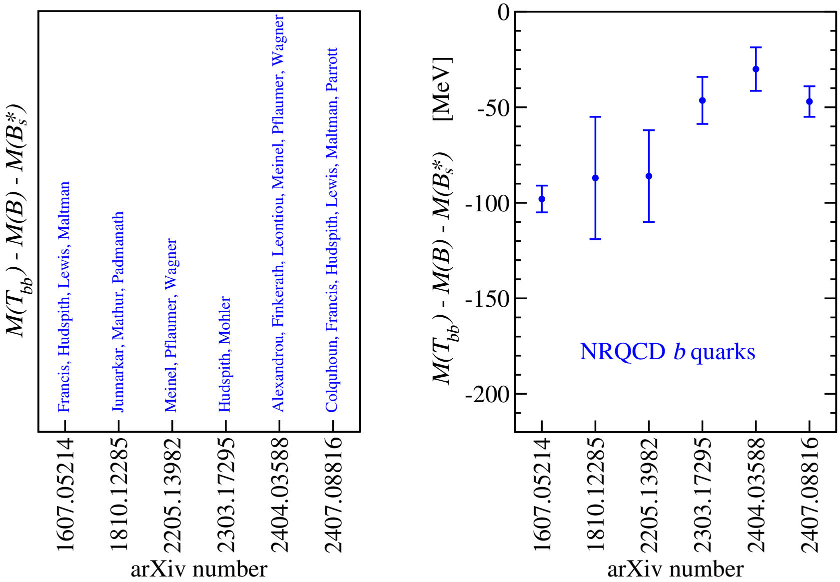
T_{bb} binding energy for $ud\bar{b}\bar{b}$ from lattice QCD



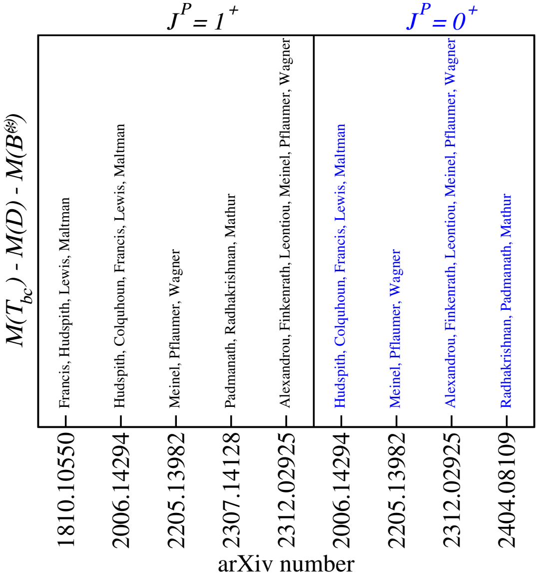
Systematic effects:

- chosen operator set (local, nonlocal, smeared, meson pair, diquark pair, scattering states)
- tuning of NRQCD
- extrapolations (lattice spacing, volume, quark masses)
- chosen lattice action (Wilson, HISQ, overlap, domain wall)

T_{bb} binding energy for $us\bar{b}\bar{b}$ from lattice QCD



T_{bc} binding energies for $ud\bar{c}\bar{b}$ from lattice QCD

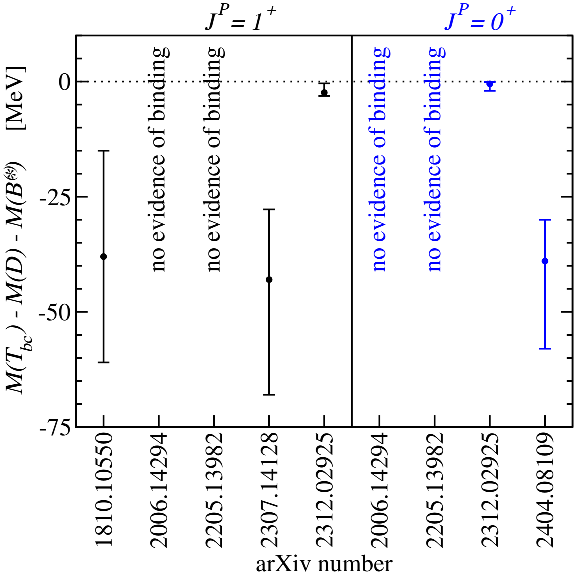


Additional systematics:

- larger threshold effects
- relativistic charm quark

  [variants of El-Khadra,Kronfeld,Mackenzie Phys.Rev.D55, 3933 (1997)]

T_{bc} binding energies for $ud\bar{c}\bar{b}$ from lattice QCD



Additional systematics:

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

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

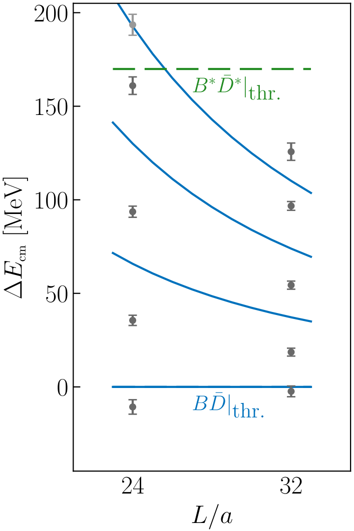
- $\sum_{\vec{x}} \left[\bar{b}^a(\vec{x})\gamma_5 C\bar{c}^{b,T}(\vec{x})\right]\left[u^{a,T}(\vec{x})C\gamma_5 d^b(\vec{x})\right] - (d \leftrightarrow u)$
- $\sum_{\vec{x}} B^+(\vec{x})D^-(\vec{x}) - \sum_{\vec{x}} B^0(\vec{x})\bar{D}^0(\vec{x})$
- $\sum_{\vec{x},j} B_j^{*+}(\vec{x})D_j^{*-}(\vec{x}) - \sum_{\vec{x},j} B_j^{*0}(\vec{x})\bar{D}_j^{*0}(\vec{x})$
- $B^+(\vec{q})D^-(-\vec{q}) - B^0(\vec{q})\bar{D}^0(-\vec{q})$ for $\frac{|\vec{q}|L}{2\pi} \in \{0, 1, \sqrt{2}, \sqrt{3}\}$

where

$$B^+(x) = \bar{b}(\vec{x})\gamma_5 u(\vec{x})$$

$$B^+(\vec{q}) = \frac{1}{\sqrt{V}} \sum_{\vec{x}} B^+(x) e^{2\pi i \vec{q}\cdot\vec{x}/L}$$

etc.



Curves are non-interacting $B\bar{D}$ energy levels.

Toward the T_{cc} binding energy from lattice QCD

An early attempt:

1810.12285	Junnarkar, Mathur, Padmanath	-23 ± 11 MeV

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	$-59 \left(^{+53}_{-99}\right) \left(^{+2}_{-67}\right)$ 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?

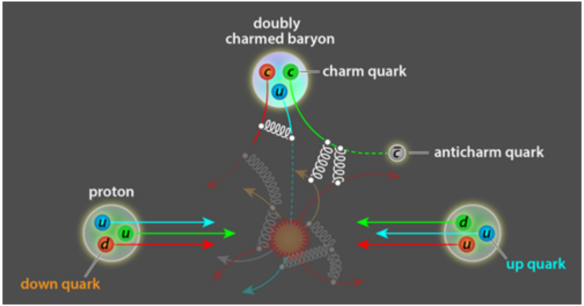


Image from `https://physics.aps.org/articles/v10/100`

Dense matter in lattice QCD?

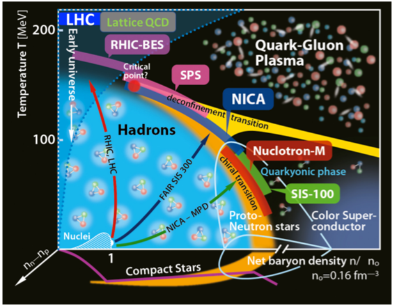


Image from `arXiv:2201.00202`

One small step for tetraquarks. . .

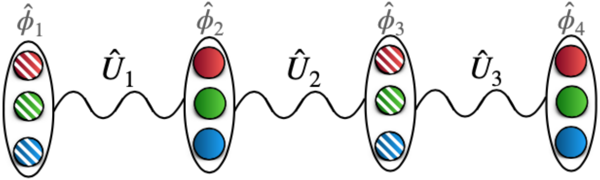
PHYSICAL REVIEW RESEARCH **5**, 033184 (2023)

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

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

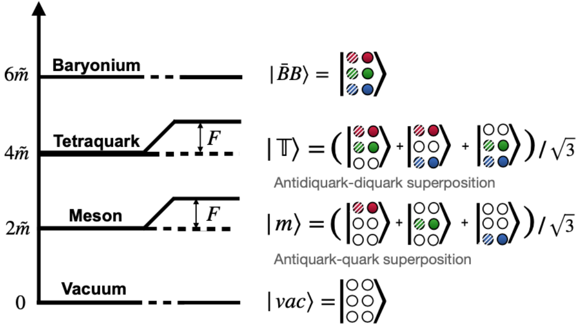
QCD in one spatial dimension

Staggered fermions:



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

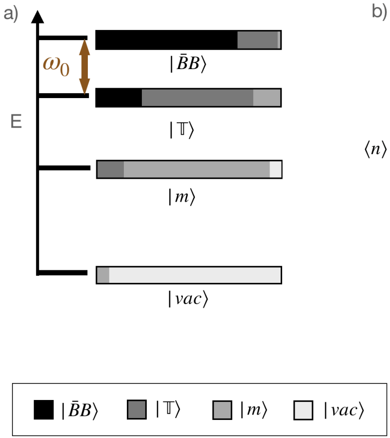
Two staggered sites in the strong coupling limit:

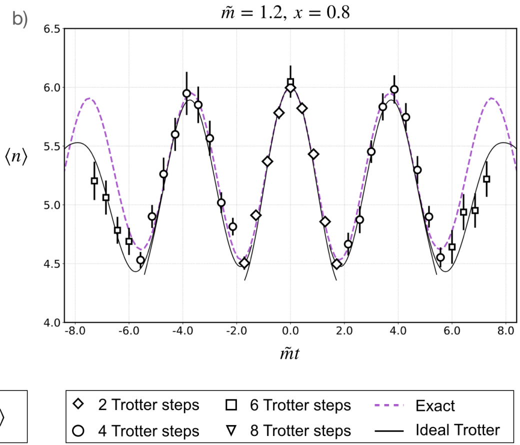


Mesons and tetraquarks have electric flux, F

Time evolution at intermediate coupling

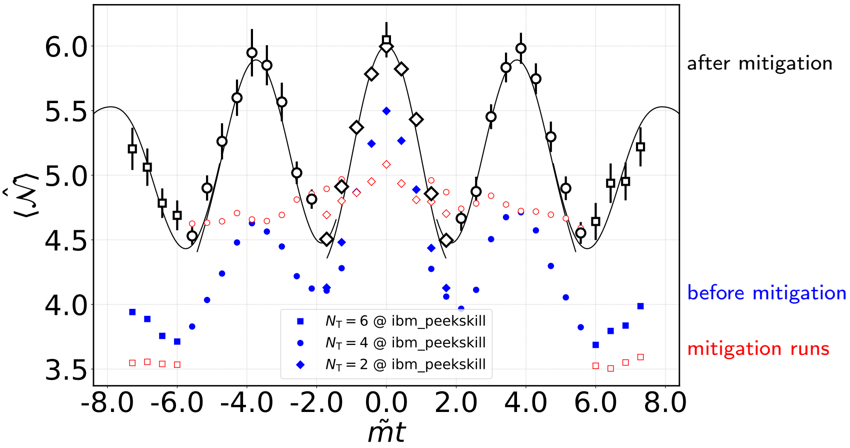
Oscillations among the eigenstates were computed on `ibm_peekskill`.





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 $ud\bar{b}\bar{b}$ and with $us\bar{b}\bar{b}$.
  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 $\sim \frac{1}{4}$ MeV $\ll \Lambda_{QCD}$.
  Nevertheless, impressive efforts have been reported.

- Quantum computers have opened new opportunities for the coming decades.