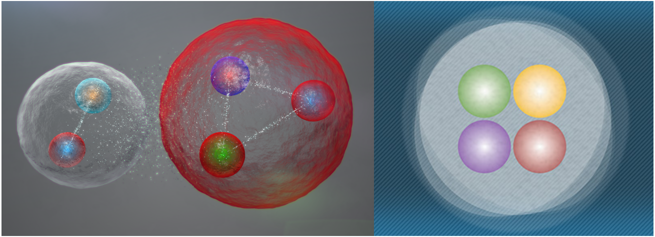
# DOUBLY HEAVY TETRAQUARKS BY LATTICE QCD

meson baryon tetraquark



images: CERN, Fermilab

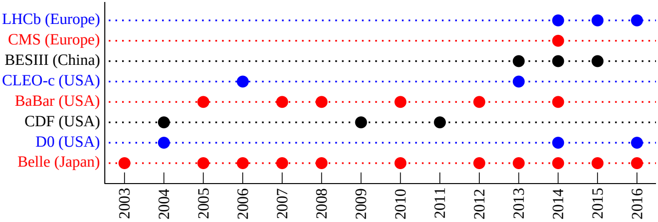
*My main reference today will be*

Anthony Francis, Renwick J. Hudspith, Randy Lewis and Kim Maltman
Physical Review Letters 118, 142001 (2017)

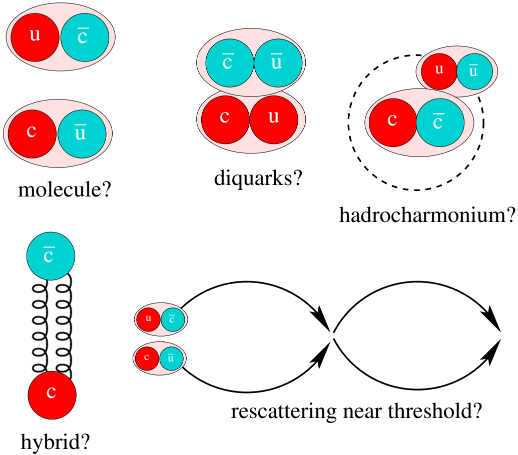
## Original expectations:

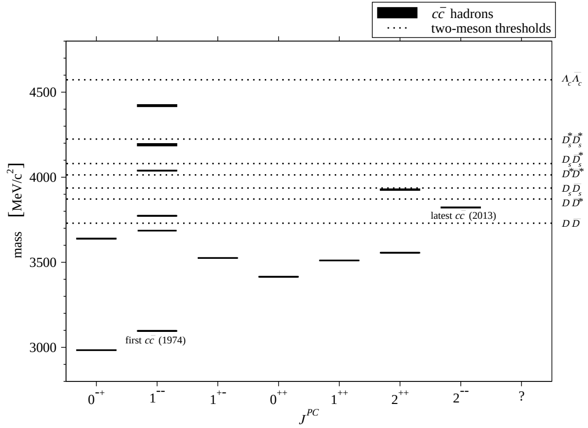
`Baryons can now be constructed from quarks by using the combinations (qqq), (qqqq`$\bar{\text{q}}$`), etc., while mesons are made out of (q`$\bar{\text{q}}$`), (qq`$\bar{\text{q}}\bar{\text{q}}$`), etc.` Murray Gell-Mann, Phys.Lett.8,214(1964)

## Many observations:



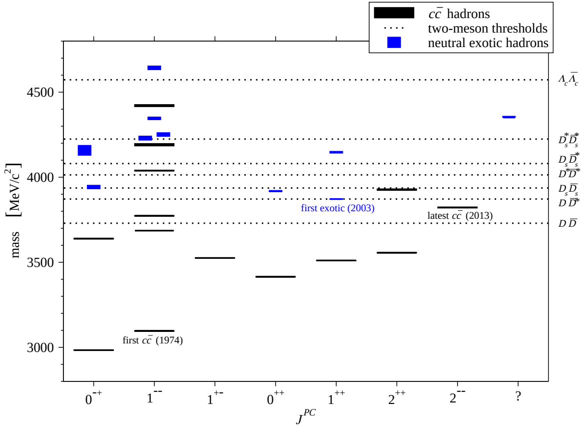
# INSIDE A $c\bar{c}$ EXOTIC?



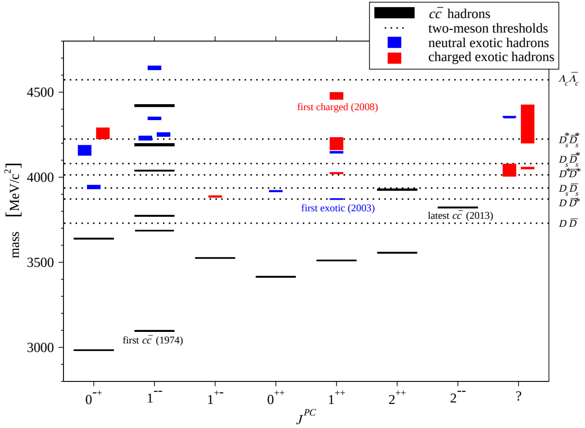


$c\bar{c}$ hadrons
two-meson thresholds
4500
4000
3500
3000
mass [MeV/c$^2$]
$\Lambda_c\bar{\Lambda}_c$
$D_s^*\bar{D}_s^*$
$D_s\bar{D}_s^*$
$D^*\bar{D}^*$
$D_s\bar{D}_s$
$D\bar{D}^*$
$D\bar{D}$
latest $c\bar{c}$ (2013)
first $c\bar{c}$ (1974)
$0^{-+}$
$1^{--}$
$1^{+-}$
$0^{++}$
$1^{++}$
$2^{++}$
$2^{--}$
?
$J^{PC}$

# $c\bar{c}$ HADRONS AND NEUTRAL EXOTICS



# $c\bar{c}$ HADRONS AND EXOTICS 



$$S = \int \mathcal{L}\ d^4x$$

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{q}(i\gamma^\mu D_\mu - m_q)q$$

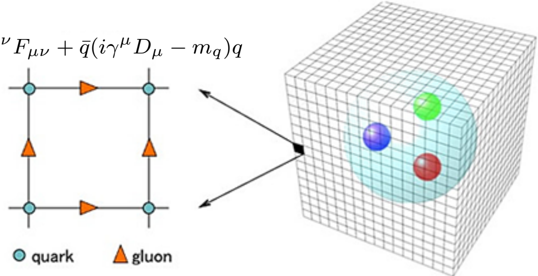
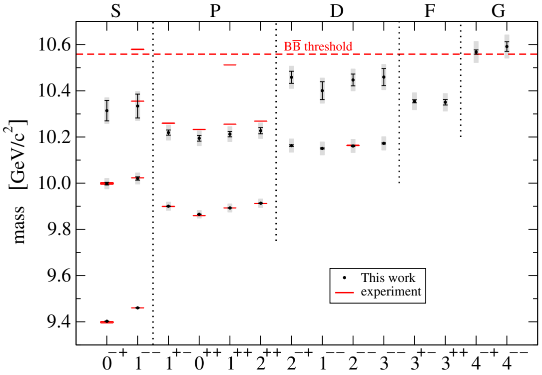



image: http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg

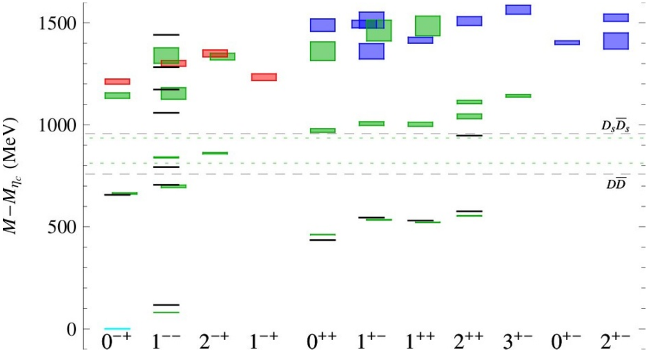
Your supercomputer will do this:

$$\left\langle \underset{\uparrow}{H(x)}\underset{\uparrow}{H^\dagger(y)} \right\rangle = \frac{1}{Z}\int e^{-S} H(x)H^\dagger(y)\mathcal{D}U_\mu\mathcal{D}\bar{\psi}\mathcal{D}\psi$$

Destroy and create one hadron.



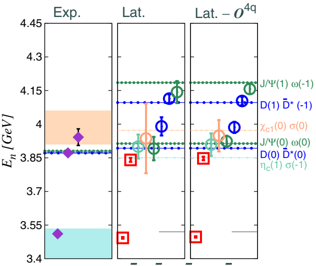

Wurtz,Lewis,Woloshyn Phys.Rev.D92,054504 (2015)



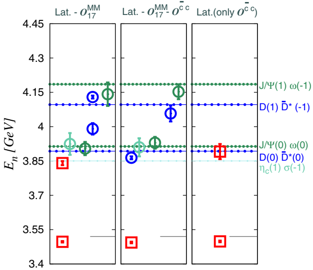

black = experiment
green = mesons from lattice
red,blue = hybrids from lattice

Hadron Spectrum Collaboration, JHEP 07,126 (2012)

difficulties: X(3872) is an excited state.
X(3872) is very near a threshold.
X(3872) is surrounded by many states.
$c\bar{c}$ annihilation is too expensive.



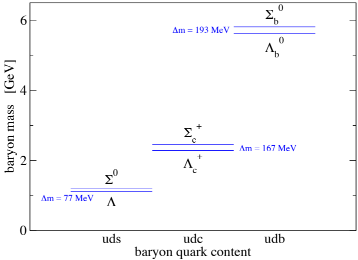

(a) $I=0$ : $\bar{c}c$ ( $\bar{u}u + \bar{d}d$ ) & $\bar{c}c$




Padmanath,Lang,Prelovsek Phys.Rev.D92,034501 (2015)

difficulties: X(3872) is an excited state. $\Rightarrow$ Find a ground state exotic.
X(3872) is very near a threshold. $\Rightarrow$ Use good diquarks.
X(3872) is surrounded by many states. $\Rightarrow$ good diquarks.
$c\bar{c}$ annihilation is too expensive. $\Rightarrow$ Use $\bar{c}\bar{c}$ or $\bar{b}\bar{b}$.

Here is a clue from experiment:




Is there a deeply bound $ud\bar{b}\bar{b}$ tetraquark?

# FOUR-QUARK OPERATORS



- Our $ud\bar{b}\bar{b}$ tetraquark operator should be symmetric in both color and flavor, like the $ud$ in a $\Lambda$ baryon.

$$O(x) = u_a^T(x)C\gamma_5 d_b(x)\bar{b}_a(x)C\gamma_i\bar{b}_b^T(x)$$

This operator has $I = 0$ and $P = +$. The ground state is spin 1.

- The lightest two-meson state with $I(J^P) = 0(1^+)$ is

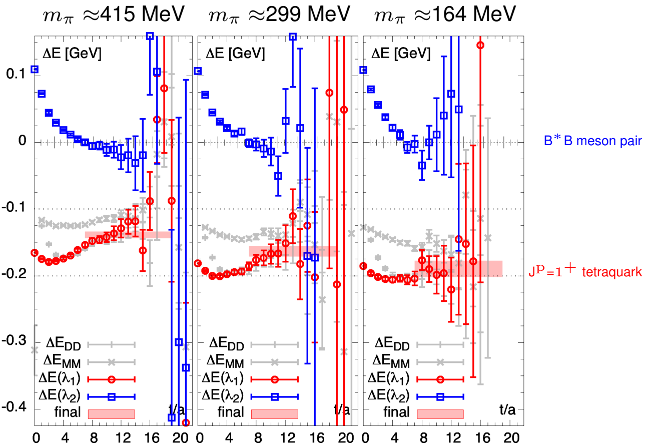
$$P(x) = \bar{b}_a(x)\gamma_5 u_a(x)\bar{b}_b(x)\gamma_i d_b(x) - \bar{b}_a(x)\gamma_5 d_a(x)\bar{b}_b(x)\gamma_i u_b(x)$$

- Our lattice study allows for mixing between the two operators.

Francis,Hudspith,Lewis,Maltman,*Phys.Rev.Lett.*118,142001(2017)

# WE SEE A STABLE $ud\bar{b}\bar{b}$ TETRAQUARK

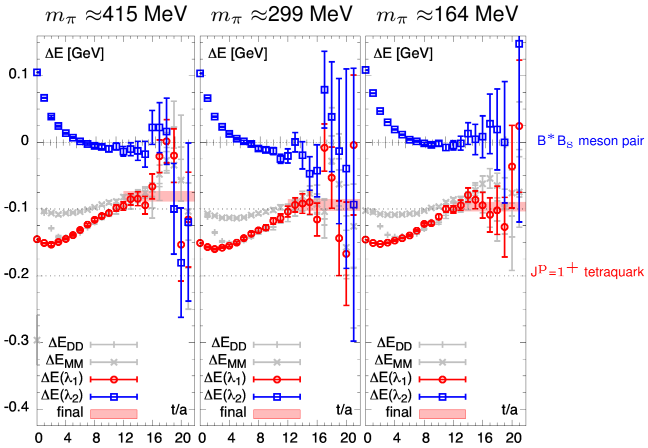





Francis,Hudspith,Lewis,Maltman,*Phys.Rev.Lett.*118,142001(2017)

# WE SEE A STABLE $\ell s\bar{b}\bar{b}$ TETRAQUARK

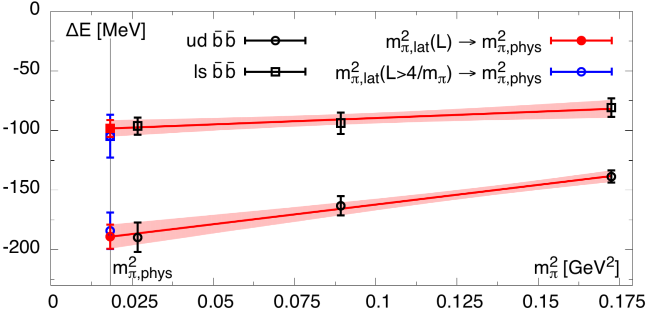





Francis,Hudspith,Lewis,Maltman,*Phys.Rev.Lett.*118,142001(2017)

# DEPENDENCE ON u,d,s MASSES






Francis,Hudspith,Lewis,Maltman,*Phys.Rev.Lett.*118,142001(2017)

Previous lattice studies of $ud\bar{c}\bar{c}$ with $m_\pi >$400 MeV found no tetraquark.

Ikeda et al, PLB729,85(2014)

Guerrieri at al, PoS LATTICE2014 (2915) 106

IMPLICATION: *Our results* rely on the large $\bar{b}$ mass and light $u$,$d$.

Previous lattice calculations of the potential between static $\bar{b}\bar{b}$ quarks were fit to a phenomenological form. This gave a smaller non-zero binding for the $ud\bar{b}\bar{b}$ tetraquark.

Brown,Orginos,PRD86,114503(2007)

Bicudo,Cichy,Peters,Wagner,PRD93,034501(2016)

IMPLICATION: *Our results* rely on using a direct lattice calculation.

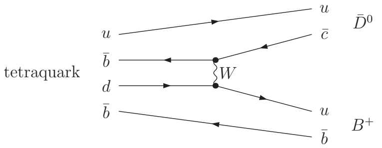
Francis,Hudspith,Lewis,Maltman,*Phys.Rev.Lett.*118,142001(2017)

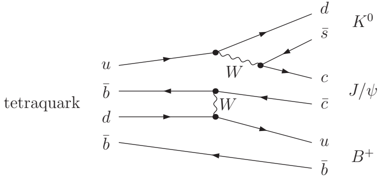
# EXPERIMENTAL SEARCH IDEAS



Good news: No strong decays and no electromagnetic decays.

Sample weak decays ↗ ↘



• Since 2003, more than two dozen exotics have been discovered.
Their inner structure is not clear. . . molecules?
diquarks?
hadroquarkonium?
hybrids?
rescattering?
Standard view: No single idea can explain all of the known exotics.

• Lattice QCD is the direct computational method for theory.
Our results indicate deeply bound $ud\bar{b}\bar{b}$ and $\ell s\bar{b}\bar{b}$ tetraquarks.
These would be true tetraquarks, not molecules nor threshold effects.

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