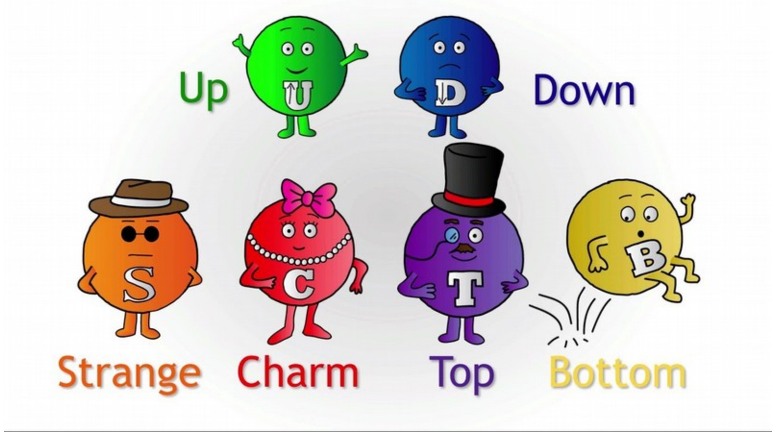


THE SOCIAL LIFE OF QUARKS

Marek Karliner

BNL Physics Colloquium, Feb 13 2018

“Who with whom,

For how long ?

A “one-night stand”,

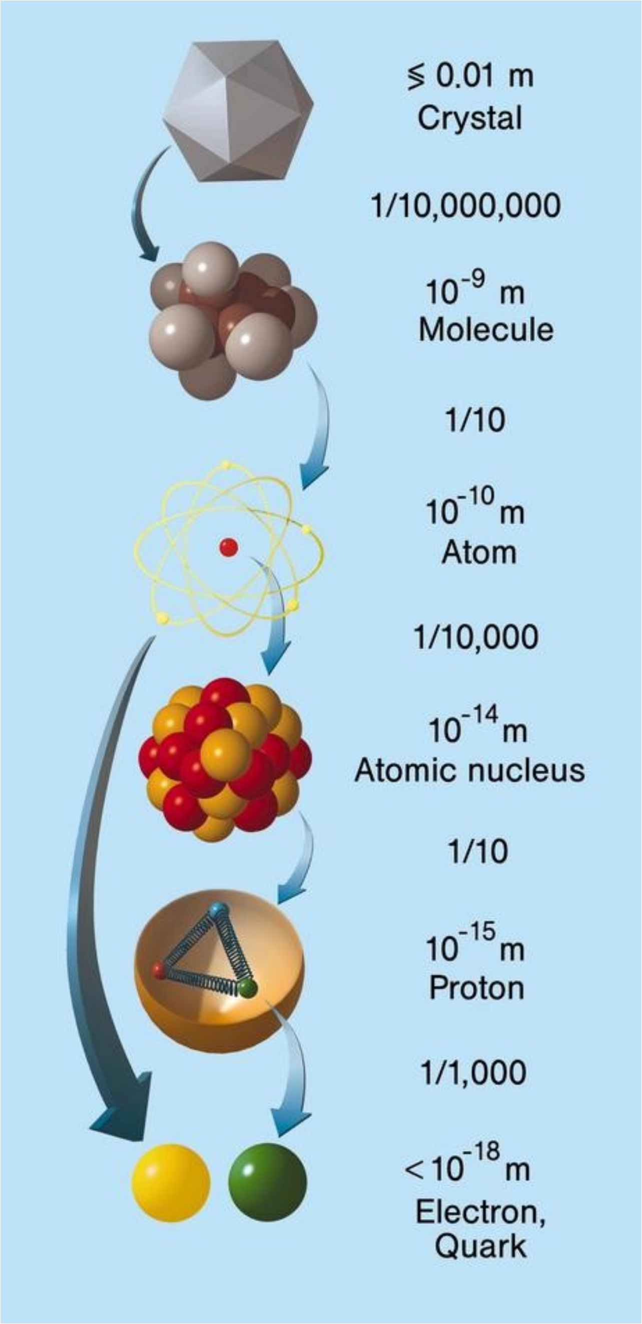
Or “Till Death Us Do Part” ?

Outline

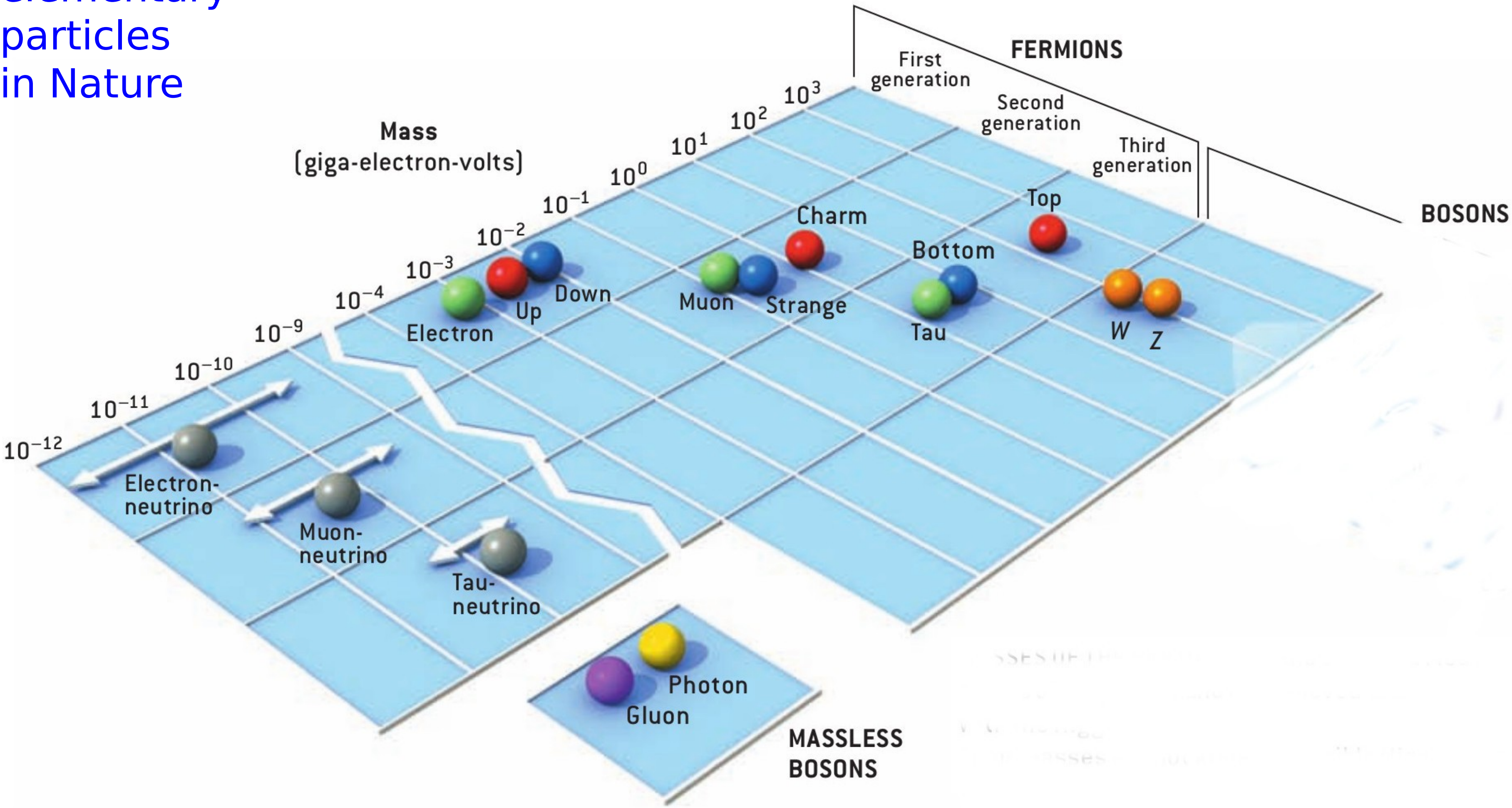
- quarks are fundamental building blocks of protons, neutrons and all hadrons
- all quarks are equal, but heavy quarks are more equal than others

new combinations with heavy quarks, incl. exotics:

- hadronic molecules, esp. LHCb pentaquark
- prediction and discovery of doubly-charmed baryon
- stable $bb\bar{u}\bar{d}$ tetraquark
- quark-level analogue of nuclear fusion
- possible similar mechanisms in dark matter sector

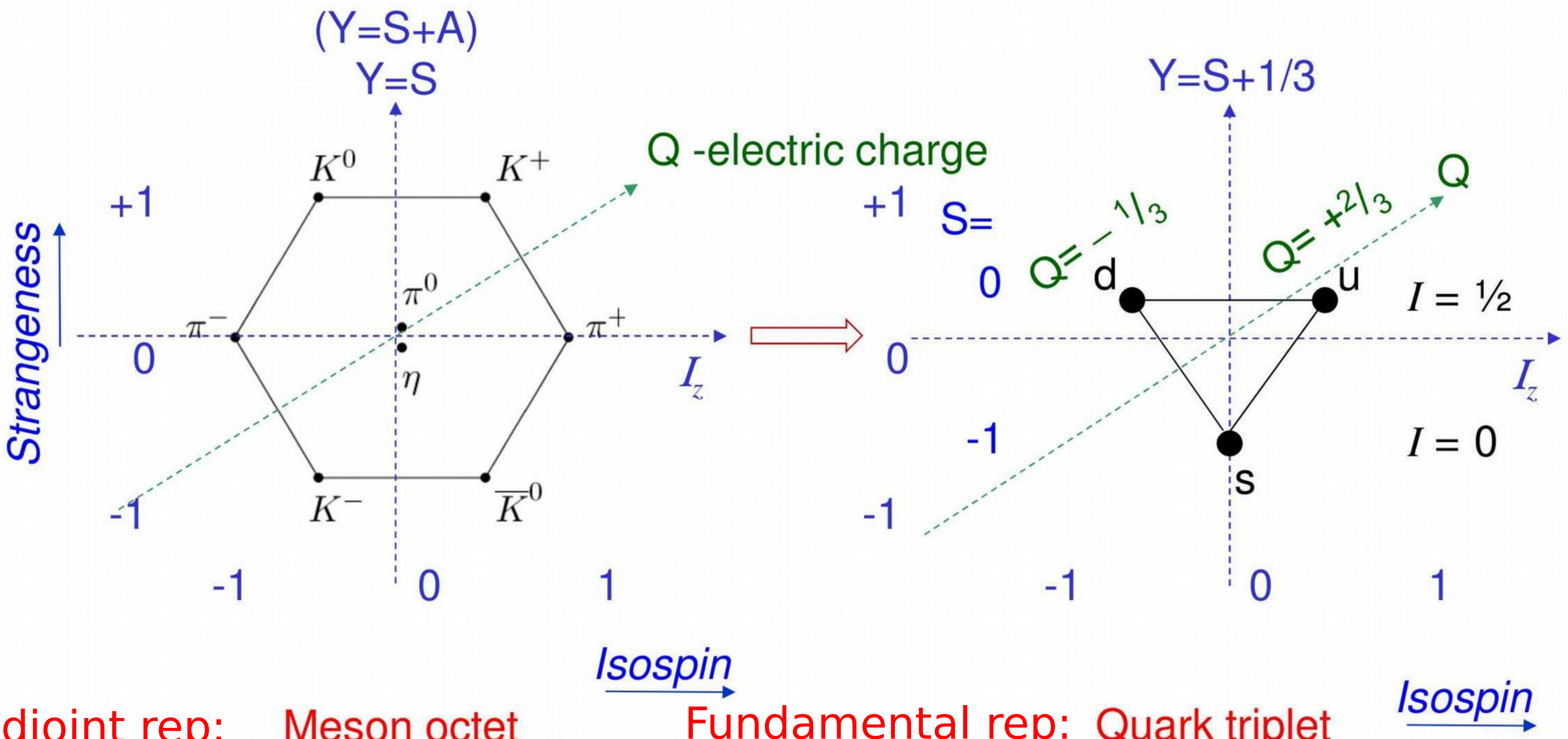

≲ 0.01 m
Crystal
1/10,000,000
10^{-9} m
Molecule
1/10
10^{-10} m
Atom
1/10,000
10^{-14} m
Atomic nucleus
1/10
10^{-15} m
Proton
1/1,000
$< 10^{-18}$ m
Electron,
Quark

masses of elementary particles in Nature



From SU(3) flavor symmetry to quarks

SU(3): Gell-Mann Ne’eman 1961 quarks: Gell-Mann 1964



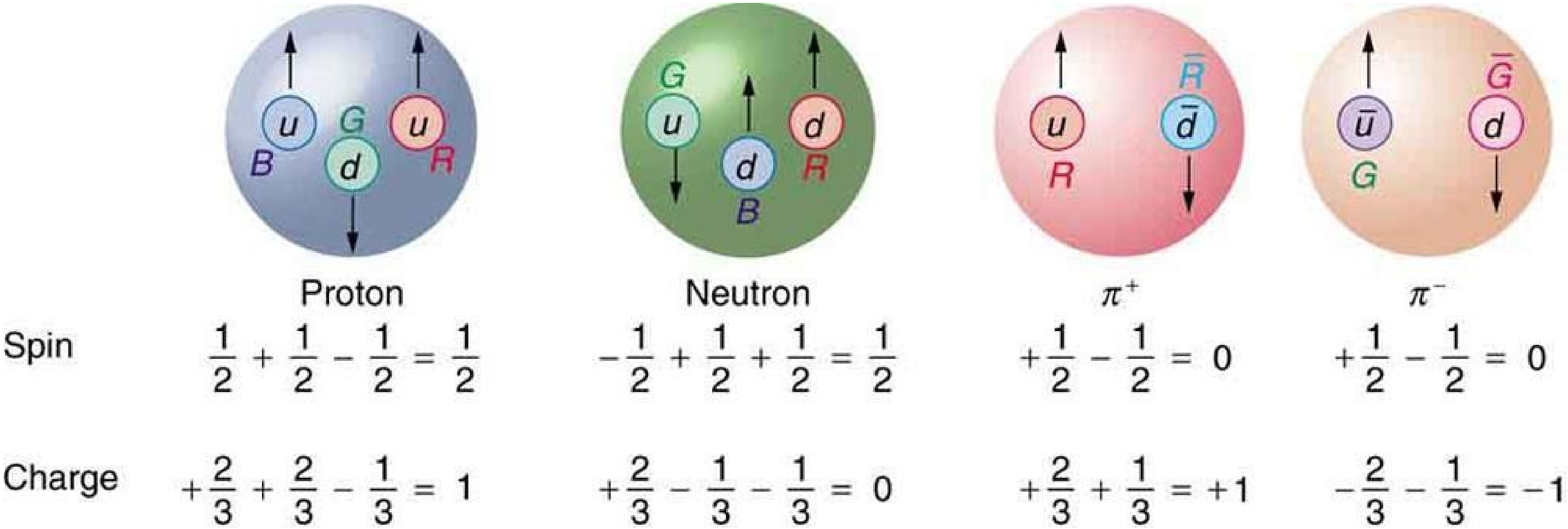
Adjoint rep: Meson octet

J = 0

Fundamental rep: Quark triplet

(also J=1/2 baryon octet and J=3/2 decuplet)

All strongly-interacting particles (=hadrons) are built from quarks



	Proton	Neutron	π^+	π^-
Spin	$\frac{1}{2}+\frac{1}{2}-\frac{1}{2}=\frac{1}{2}$	$-\frac{1}{2}+\frac{1}{2}+\frac{1}{2}=\frac{1}{2}$	$+\frac{1}{2}-\frac{1}{2}=0$	$+\frac{1}{2}-\frac{1}{2}=0$
Charge	$+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$	$+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$	$+\frac{2}{3}+\frac{1}{3}=+1$	$-\frac{2}{3}-\frac{1}{3}=-1$

Baryons, such as p and n, are composed of three quarks.

Mesons, such as pions, are composed of a quark-antiquark pair.

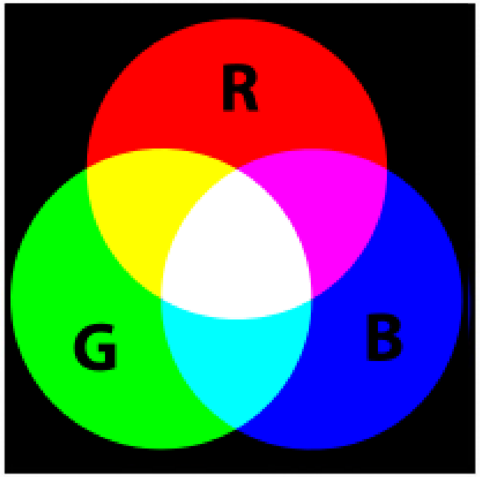
Arrows denote quark spins.

Quarks carry color charge.
Allowed combinations: in a physical object they need to add to white.

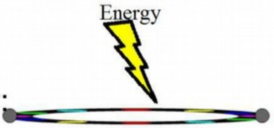
SU(3) color symmetry

- Fundamental parts of SU(3)$_{\text{flavor}}$ symmetry discovered by Gell-Mann & Zweig:
  - Quark flavor independence of strong interactions
  - Rules for making hadrons out of quarks – led to development of exact theory of strong interactions, QCD based on SU(3)$_{\text{color}}$ symmetry

Quantum Chromodynamics: QCD

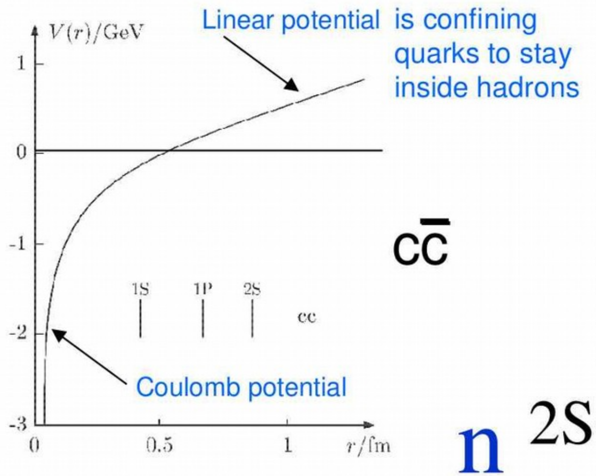


Breaking of color field flux tube by popping of $q\bar{q}$ pair:

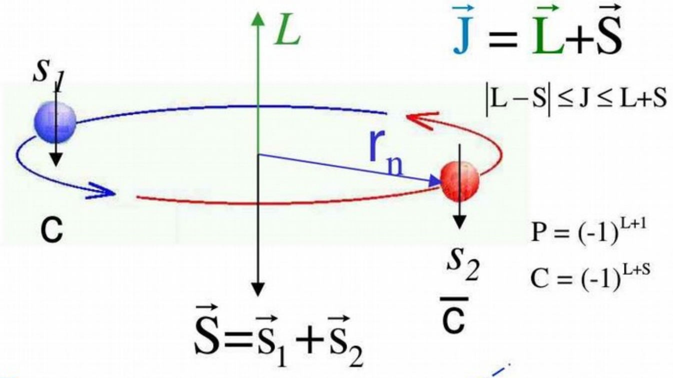


Strength of color interactions raises with separation of color charges → confinement of color charge → hadrons must be color neutral i.e. “white” ($q\bar{q}$, qqq, ….)

Charmonium – narrow (i.e. long-lived) states



Non-relativistic quantum mechanics!



$\vec{J} = \vec{L} + \vec{S}$

$|L - S| \leq J \leq L+S$

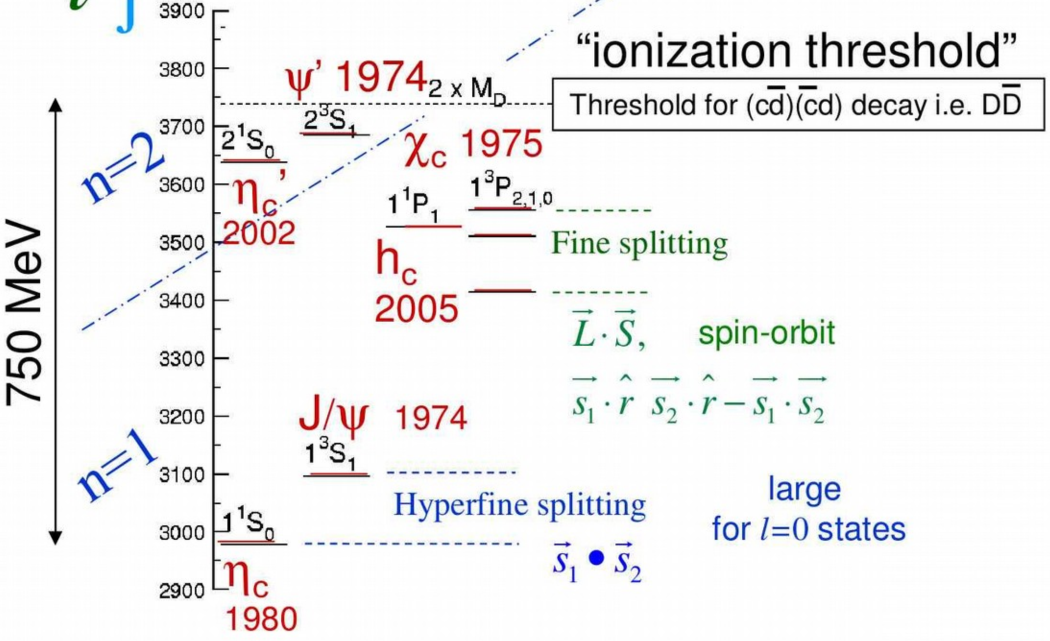
$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

$\vec{S} = \vec{s}_1 + \vec{s}_2$

$$n\,^{2S+1}l_J$$

Forces between quarks
are 10-100 times **stronger**
than between nucleons!

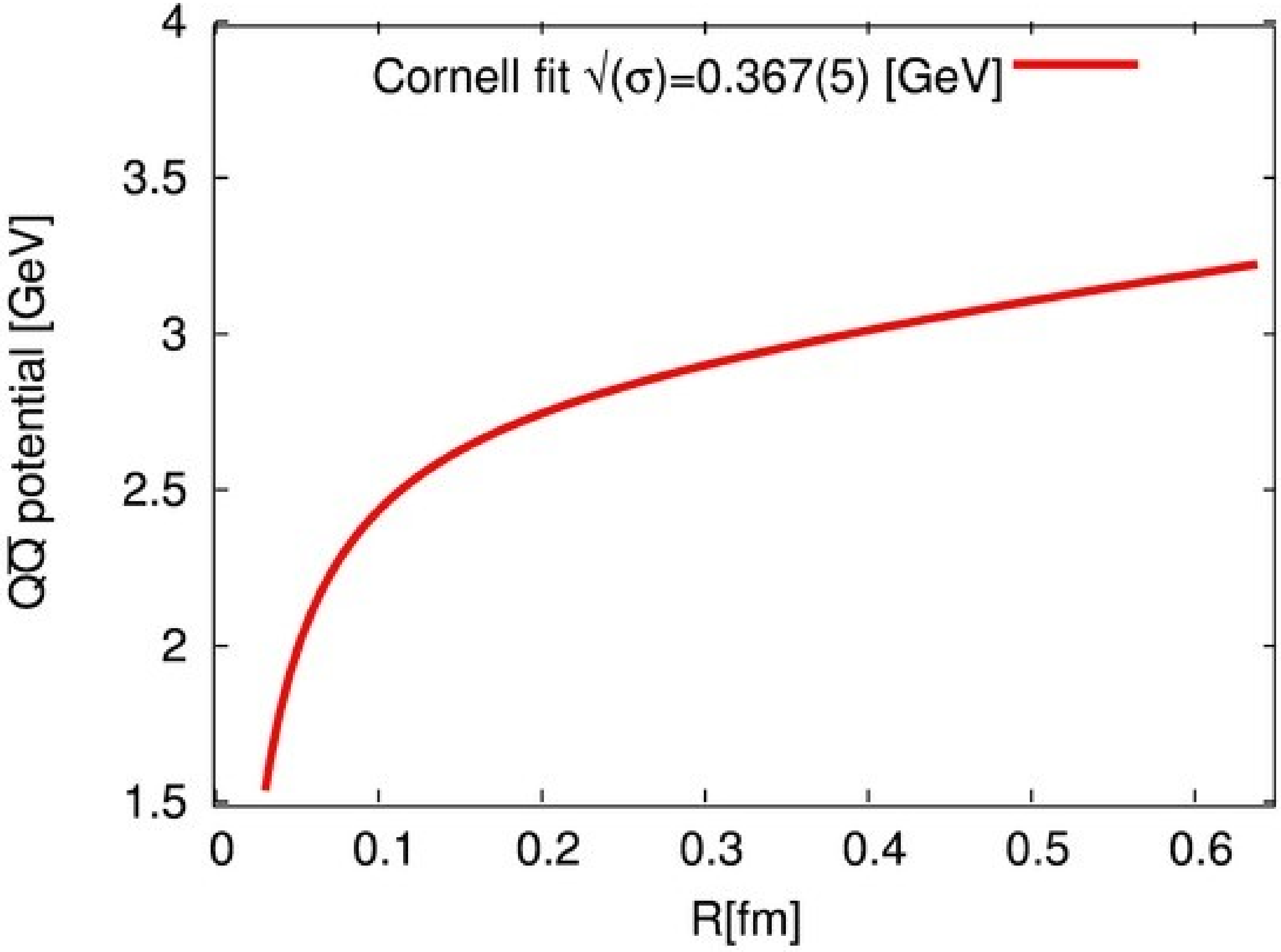


1974 November revolution:

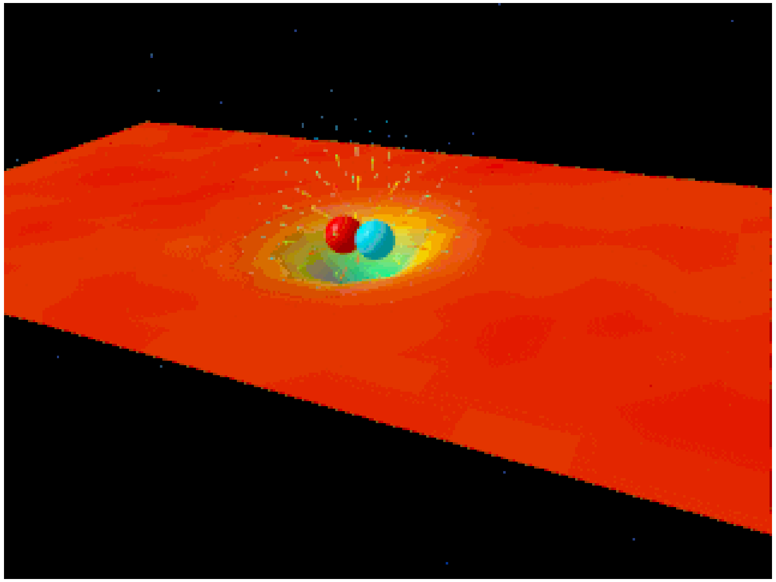
- Quark Model and qq̄ hypothesis for mesons firmly established!
- However, near mass equality of light quarks was coincidental

potential between heavy quarks: Coulomb + confinement

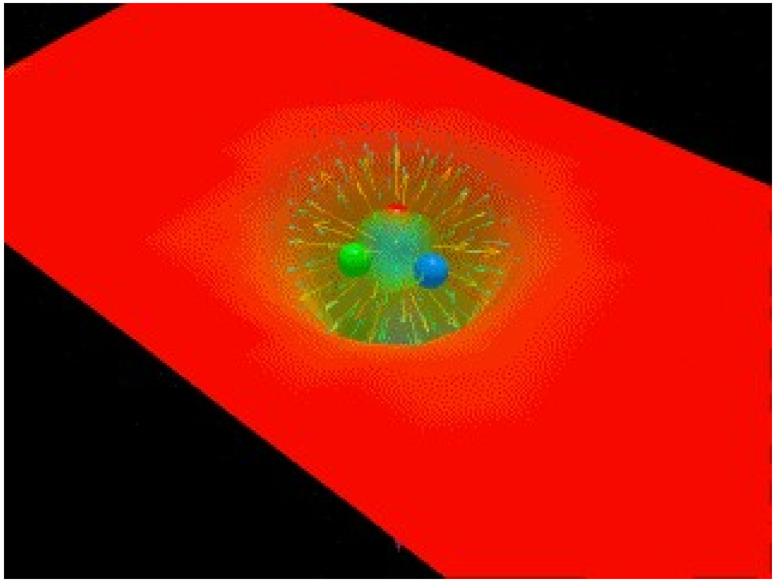
$$V(r) = -\frac{\alpha_s(r)}{r} + \sigma r$$



Confinement + Gauss Law → flux tubes

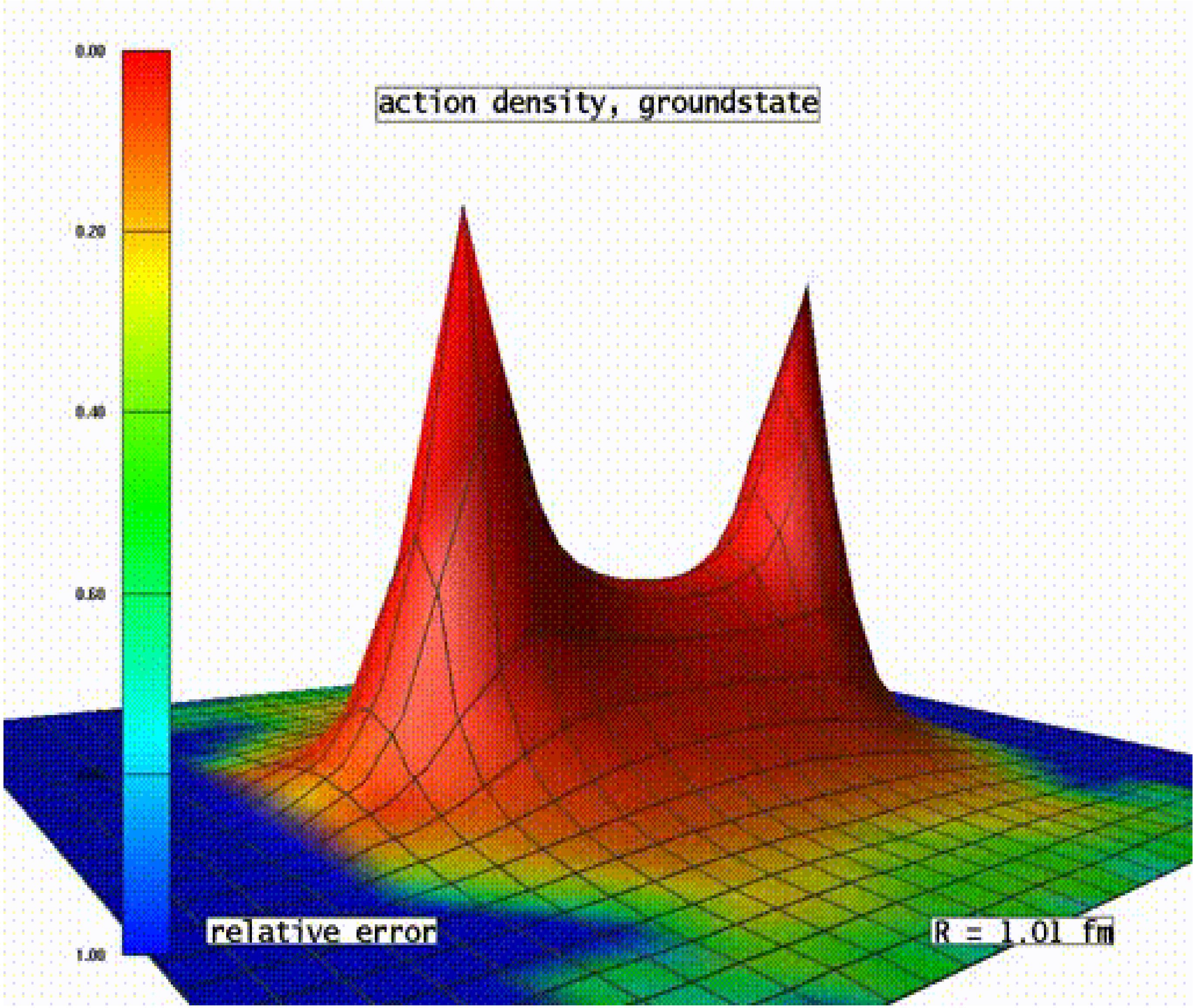


chromoelectric flux tube between a quark and an antiquark in a meson

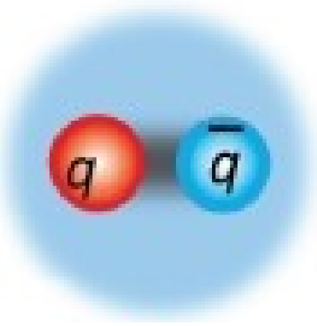


Y-shaped chromoelectric flux tube between quarks a baryon

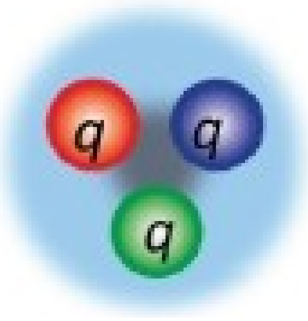
QCD string breaking



Standard Hadrons

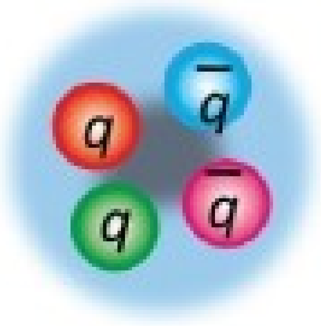


meson

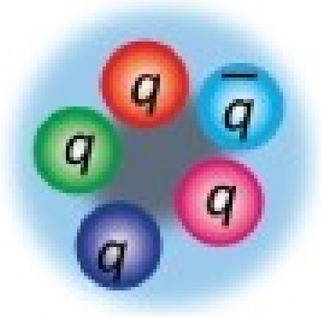


baryon

Exotic Hadrons

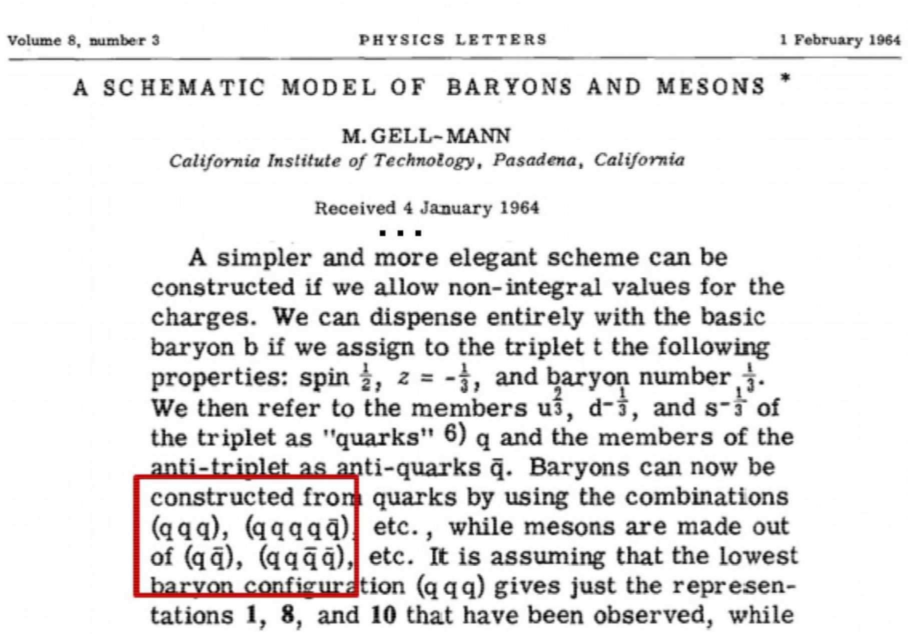


tetraquark



pentaquark

exotic hadrons – tetra and pentaquarks – discussed right from the start of the quark model



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

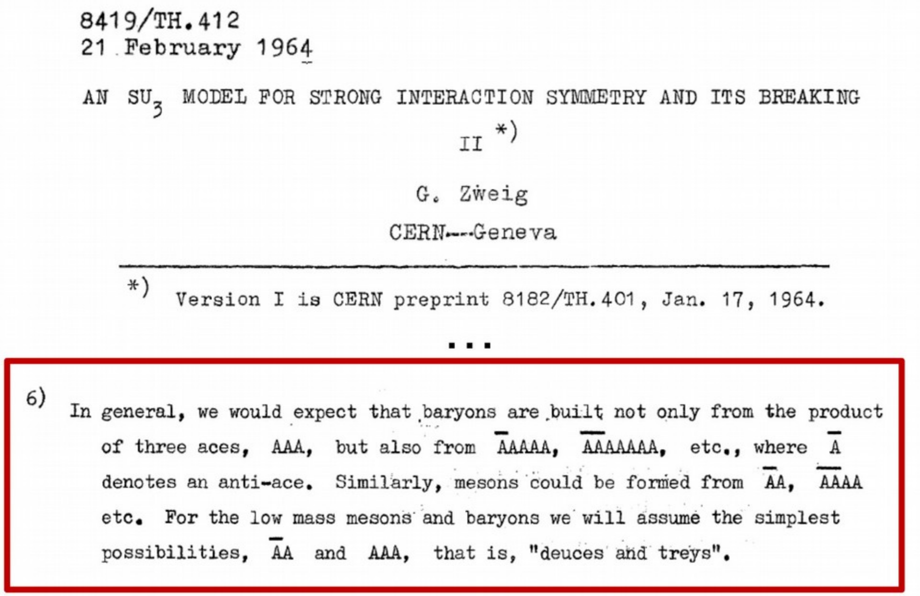
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

. . .

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig
CERN---Geneva

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*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

. . .

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

> 50 years of searches for exotics made from light (u,d,s) quarks, but no unambiguous exp. evidence

but recently clearcut evidence in heavy-light exotics

The big questions about exotic hadrons:

– do they exist ?

– if yes, which ones ?

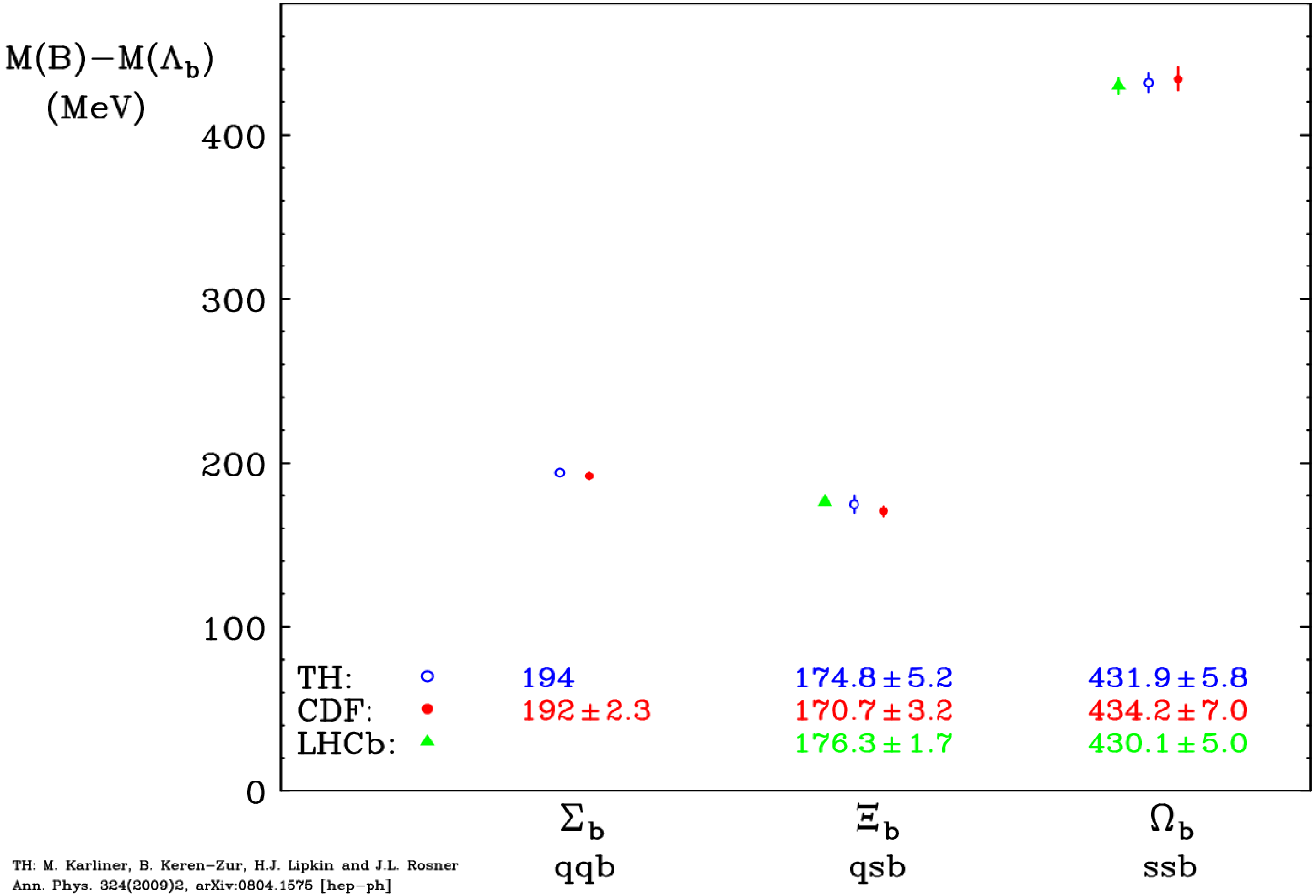
– what is their internal structure ?

– how best to look for them ?

hadrons w. heavy quarks are *much simpler:*

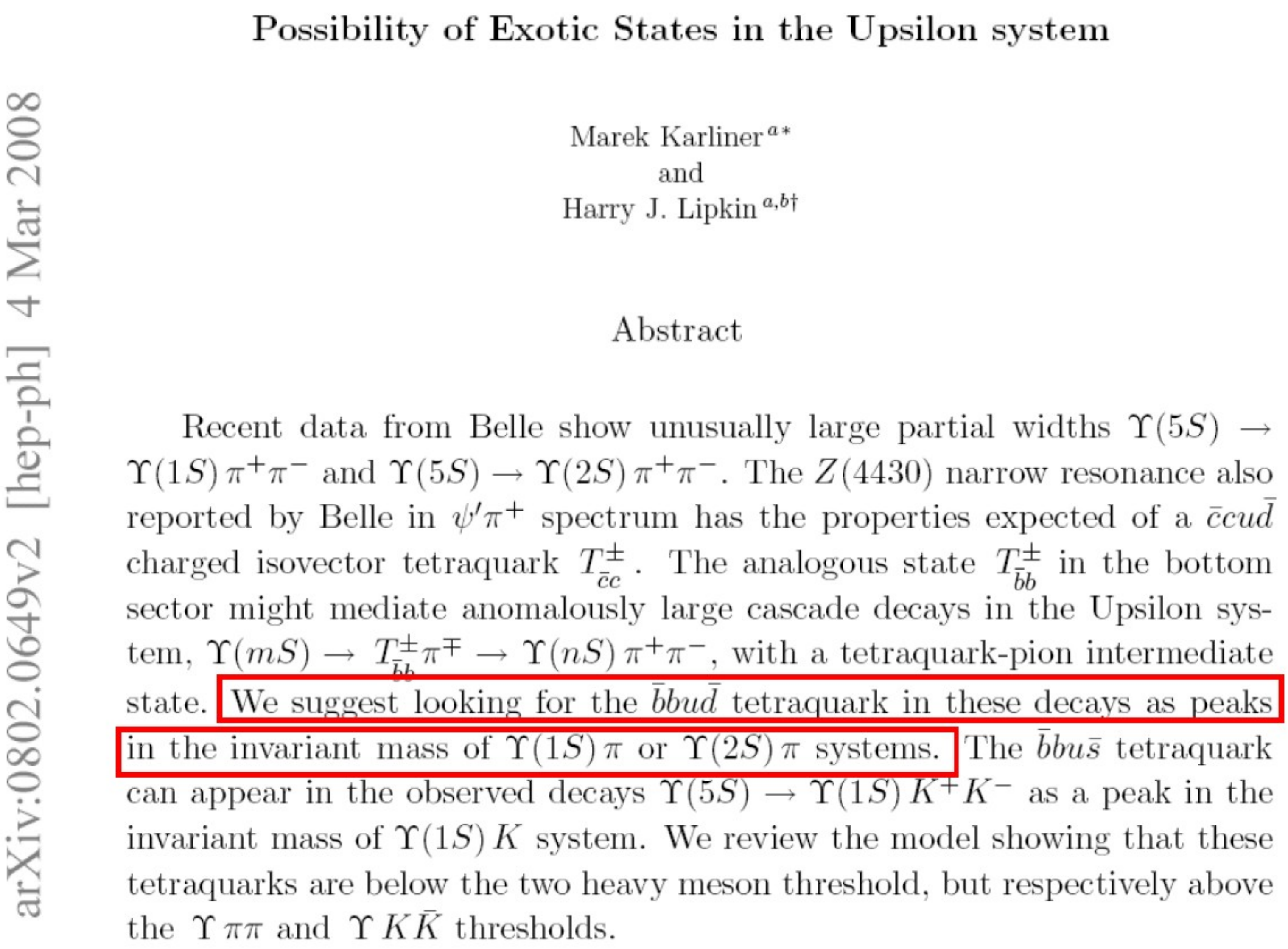
- heavy quarks almost static
- smaller spin-dep. interaction $\propto 1/m_Q$
- key to accurate prediction of b quark baryons

b−baryons spectrum − TH predictions vs EXP



TH: M. Karliner, B. Keren−Zur, H.J. Lipkin and J.L. Rosner
Ann. Phys. 324(2009)2, arXiv:0804.1575 [hep−ph]

2008: Anomaly in Belle data → tetraquark (MK & HJ Lipkin)



Possibility of Exotic States in the Upsilon system

Marek Karliner[a*]
and
Harry J. Lipkin[a,b†]

Abstract

Recent data from Belle show unusually large partial widths $\Upsilon(5S) \to \Upsilon(1S)\,\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-$. The $Z(4430)$ narrow resonance also reported by Belle in $\psi'\pi^+$ spectrum has the properties expected of a $\bar{c}cu\bar{d}$ charged isovector tetraquark $T^{\pm}_{\bar{c}c}$. The analogous state $T^{\pm}_{\bar{b}b}$ in the bottom sector might mediate anomalously large cascade decays in the Upsilon system, $\Upsilon(mS) \to T^{\pm}_{\bar{b}b}\pi^{\mp} \to \Upsilon(nS)\,\pi^+\pi^-$, with a tetraquark-pion intermediate state. We suggest looking for the $\bar{b}bu\bar{d}$ tetraquark in these decays as peaks in the invariant mass of $\Upsilon(1S)\,\pi$ or $\Upsilon(2S)\,\pi$ systems. The $\bar{b}bu\bar{s}$ tetraquark can appear in the observed decays $\Upsilon(5S) \to \Upsilon(1S)\,K^+K^-$ as a peak in the invariant mass of $\Upsilon(1S)\,K$ system. We review the model showing that these tetraquarks are below the two heavy meson threshold, but respectively above the $\Upsilon\,\pi\pi$ and $\Upsilon\,K\bar{K}$ thresholds.

2011: Belle exp. in Japan and BESIII in China

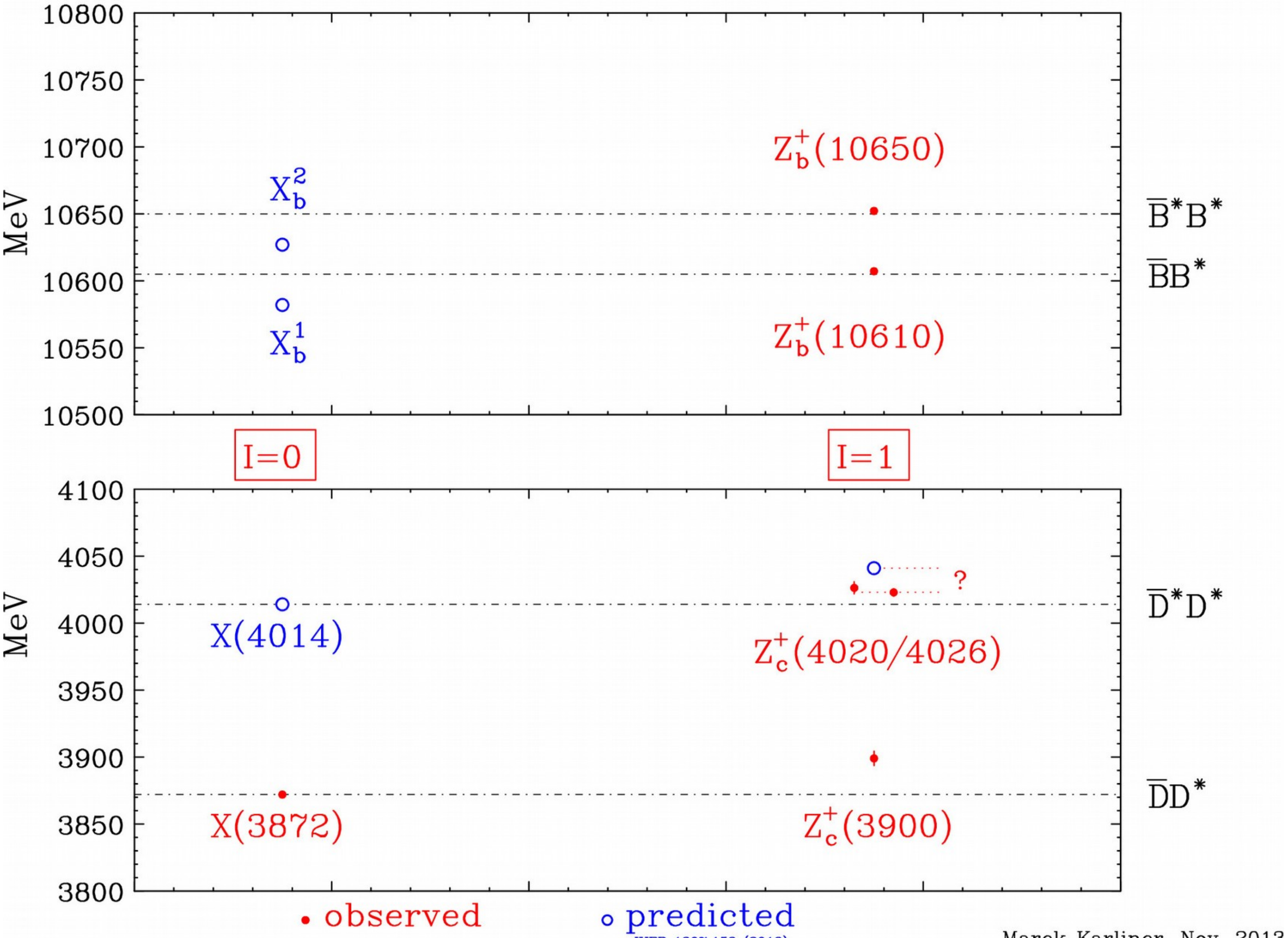
discovered Z_b and Z_c resonances

which decay into $\bar{b}b\,\pi^+$ and $\bar{c}c\,\pi^+$

$\Longrightarrow$ must contain $\bar{b}bu\bar{d}$ or $\bar{c}cu\bar{d}$

$\Longrightarrow$ manifestly exotic

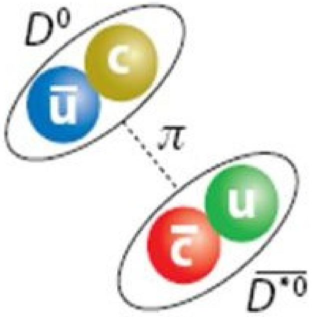
exotic heavy quarkonia vs. two meson thresholds



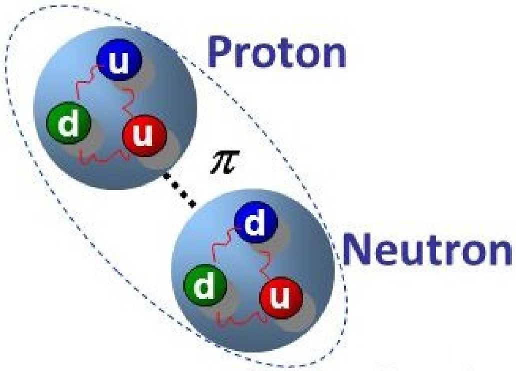
JHEP 1307,153 (2013)

Marek Karliner, Nov. 2013

Hadronic molecules: deuteron-like

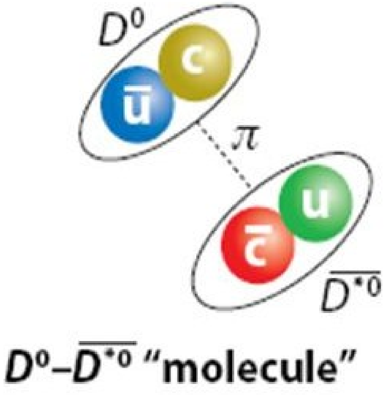


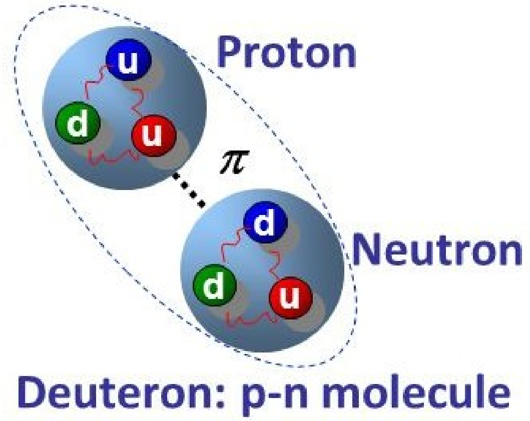
D^0–$\overline{D}^{*0}$ "molecule"



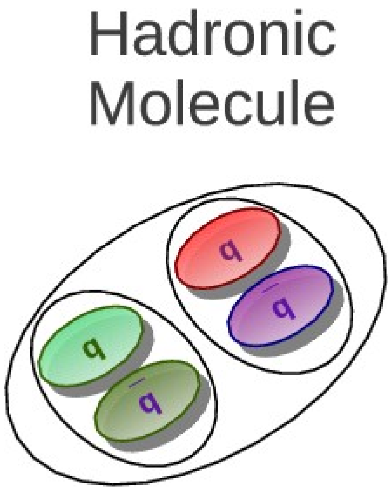
Deuteron: p-n molecule

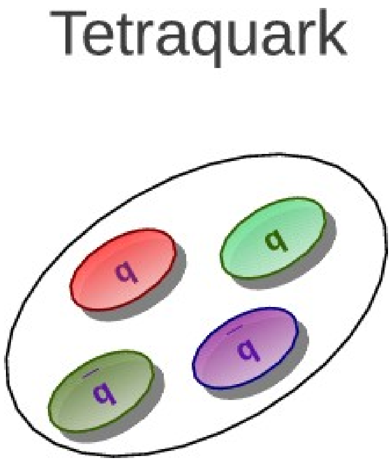
Hadronic molecules: deuteron-like





Tetraquarks: same 4 quarks, but tightly bound:





Belle, PRL 116, 212001 (2016):

$$\frac{\Gamma(Z_b(10610) \to \bar{B}B^*)}{\Gamma(Z_b(10610) \to \Upsilon(1S)\pi)} \approx \frac{86\%}{0.54\%} = \mathcal{O}(100)$$

despite 1000 MeV of phase space

for $\Upsilon(1S)\pi$ vs few MeV for $\bar{B}B^*$!

overlap of Z_c wave function with $J/\psi\pi$
much smaller than with $\bar{D}D$ ⇒ indicates an extended object

also

$$\frac{\Gamma(Z_c(3885) \to \bar{D}D^*)}{\Gamma(Z_c(3885) \to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$

(BESIII/Yu-Ping Guo @EQCD, Jinan 6/2015)

4 pieces of experimental evidence in support of molecular interpretation of Z_Q and $X(3872)$:

1. masses near thresholds and J^P of S-wave
2. narrow width despite very large phase space
3. BR(fall apart mode) $\gg$ BR(quarkonium $+\ X$)
4. no states which require binding through
   3 pseudoscalar coupling

necessary* conditions for hadronic molecule

(a) both hadrons heavy, as $E_{kin} \sim 1/\mu_{RED}$

(b) both couple to pions;
one of them can have $I = 0$, e.g.
$\Sigma_c \bar{\Lambda}_c \xrightarrow[\pi]{} \Lambda_c \bar{\Sigma}_c$.

(c) spin & parity which allow the state
go into itself under one π exchange

(d) $\Gamma(h_1) + \Gamma(h_2) \ll \Gamma(\text{molecule})$

---

*may not be sufficient

the binding mechanism can in principle

apply to any two heavy hadrons

which couple to isospin

and satisfy these conditions,

be they mesons or baryons

M. Karliner and J. L. Rosner,
Phys. Rev. Lett. **115**, no. 12, 122001 (2015)

doubly-heavy hadronic molecules: most likely candidates with $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

$D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$,

$\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, the lightest of new kind

$\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$.

$c\bar{c}$ and $b\bar{b}$ states decay strongly to $\bar{c}c$ or $\bar{b}b$ and π-(s)
$b\bar{c}$ and $c\bar{b}$ states decay strongly to $B_c^\pm$ and π-(s)

QQ' candidates – dibaryons:

$\Sigma_c\Sigma_c$, $\Sigma_c\Lambda_c$, $\Sigma_c\Lambda_b$, $\Sigma_b\Sigma_b$, $\Sigma_b\Lambda_b$, and $\Sigma_b\Lambda_c$.

Zakopane Summer School, Poland, 26 June 2015:

prediction of doubly heavy baryon with hidden charm:

$\Sigma_c \bar{D}^* \equiv \Theta_{\bar{c}c}, \quad m_{\Theta_{\bar{c}c}} \approx 4460$ MeV,

possible decay mode: $\Theta_{cc} \to J/\psi\, p$

$(S_1 \cdot S_2)$ $(I_1 \cdot I_2)$ interaction: $I = 1/2 \to J = 3/2$

S-wave $\to J^P = 3/2^-$

small overlap of molecular state with $J/\psi p$

$\Longrightarrow$ narrow width $\lesssim$ few tens of MeV

despite > 400 MeV phase space

$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\, uud$

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$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\, uud \equiv P_c(4450)$

a molecule, not a tightly-bound pentaquark

Thresholds for $Q\bar{Q}'$ molecular states

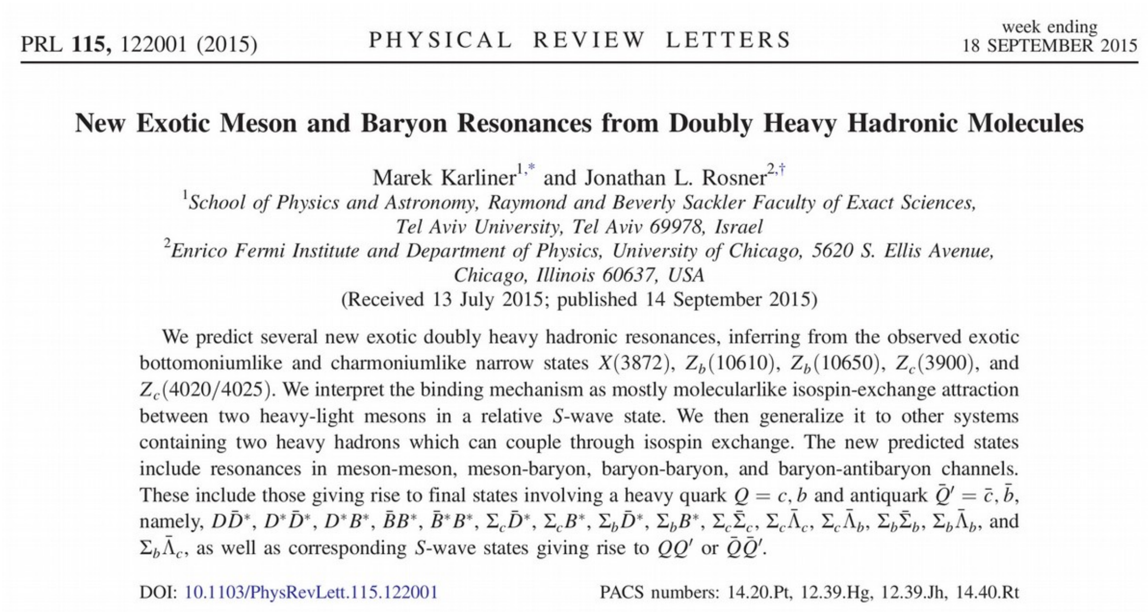
Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	$\Upsilon(nS)\pi\pi$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$\Upsilon(nS)\pi\pi$
$\Sigma_c\bar{D}^*$	$1/2$	$c\bar{c}qqq'$	4462.4	$J/\psi\, p$
$\Sigma_c B^*$	$1/2$	$c\bar{b}qqq'$	7779.5	$B_c^+ p$
$\Sigma_b\bar{D}^*$	$1/2$	$b\bar{c}qqq'$	7823.0	$B_c^- p$
$\Sigma_b B^*$	$1/2$	$b\bar{b}qqq'$	11139.6	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$\Upsilon(nS)\pi\pi$

[a] Ignoring annihilation of quarks.

[b] Plus other charge states when $I \neq 0$.

[c] Based on isospin-averaged masses.

[d] Thresholds differ by 27.6 MeV.



PRL **115,** 122001 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

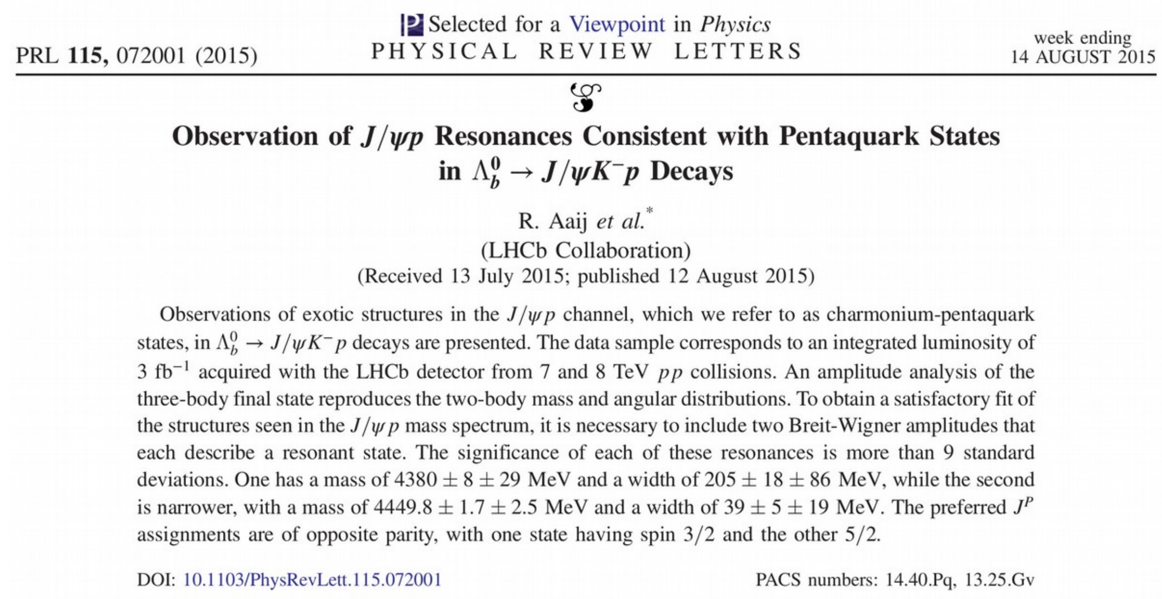
New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]
[1] *School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*
[2] *Enrico Fermi Institute and Department of Physics, University of Chicago, 5620 S. Ellis Avenue, Chicago, Illinois 60637, USA*

(Received 13 July 2015; published 14 September 2015)

We predict several new exotic doubly heavy hadronic resonances, inferring from the observed exotic bottomoniumlike and charmoniumlike narrow states $X(3872)$, $Z_b(10610)$, $Z_b(10650)$, $Z_c(3900)$, and $Z_c(4020/4025)$. We interpret the binding mechanism as mostly molecularlike isospin-exchange attraction between two heavy-light mesons in a relative S-wave state. We then generalize it to other systems containing two heavy hadrons which can couple through isospin exchange. The new predicted states include resonances in meson-meson, meson-baryon, baryon-baryon, and baryon-antibaryon channels. These include those giving rise to final states involving a heavy quark $Q = c, b$ and antiquark $\bar{Q}' = \bar{c}, \bar{b}$, namely, $D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$, as well as corresponding S-wave states giving rise to QQ' or $\bar{Q}\bar{Q}'$.

DOI: 10.1103/PhysRevLett.115.122001 PACS numbers: 14.20.Pt, 12.39.Hg, 12.39.Jh, 14.40.Rt



Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

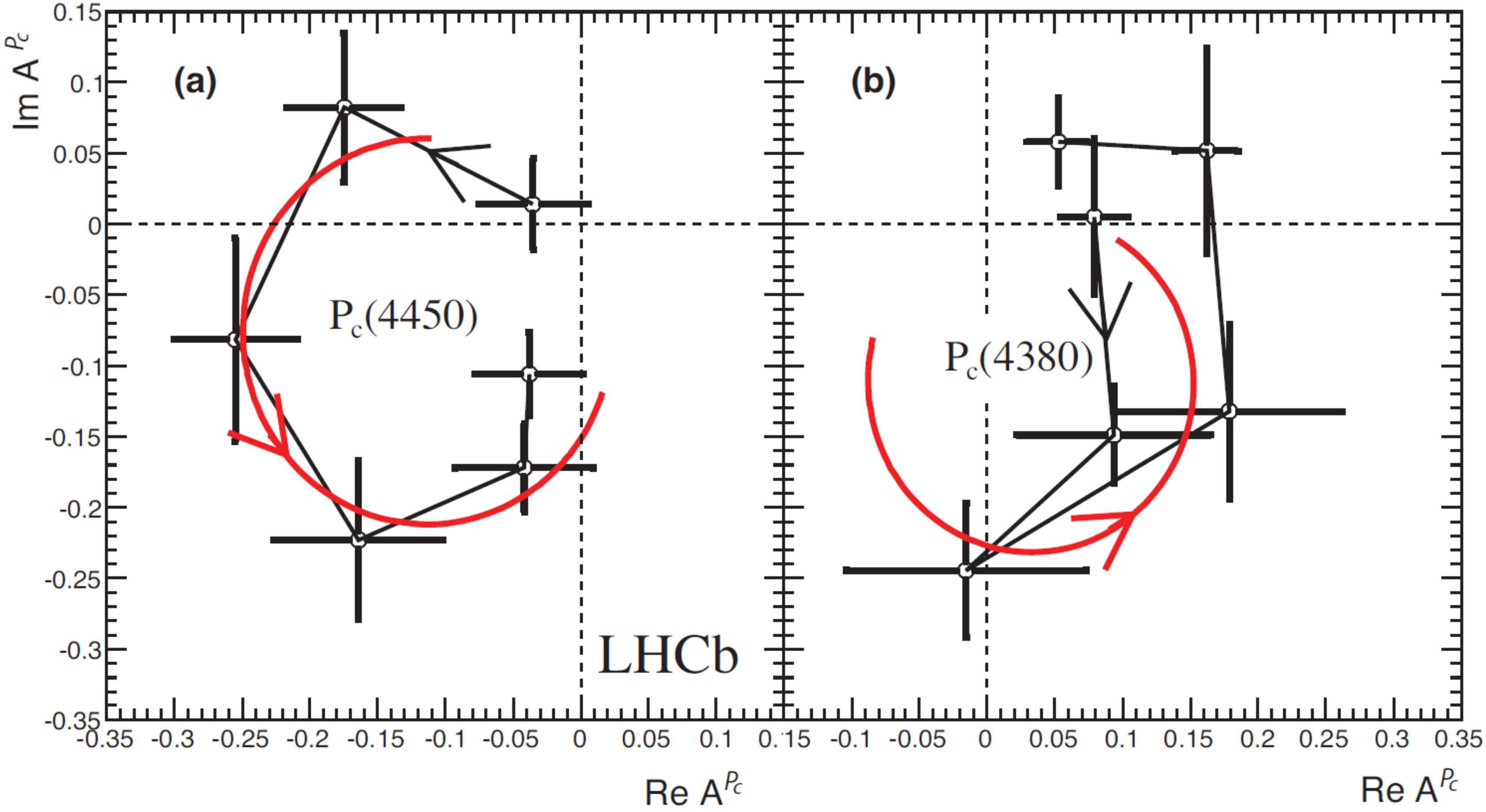
Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 13 July 2015; published 12 August 2015)

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

DOI: 10.1103/PhysRevLett.115.072001 PACS numbers: 14.40.Pq, 13.25.Gv

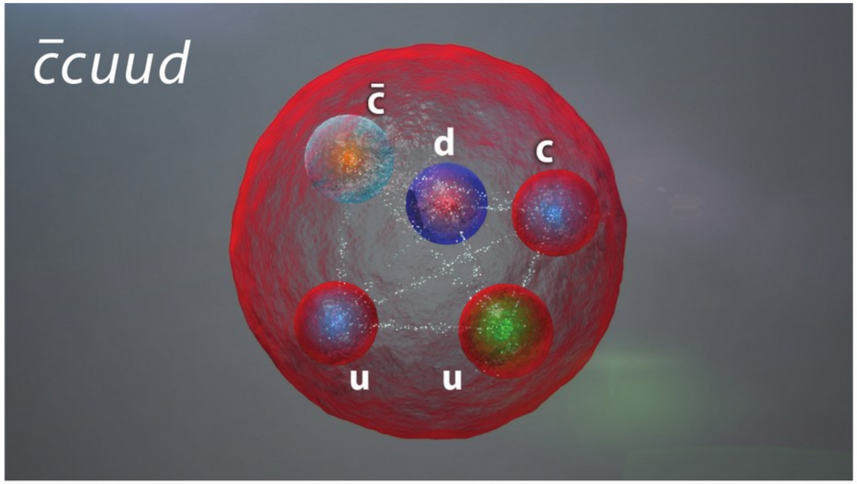


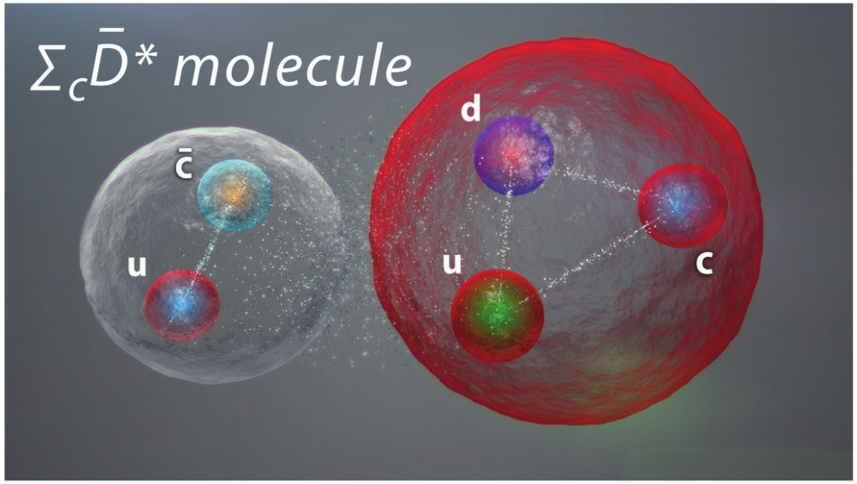
$P_c(4450)$: predicted,
narrow: $\Gamma = 39 \pm 5 \pm 19$,
10 MeV from $\Sigma_c \bar{D}^*$ threshold
perfect Argand plot: a molecule

$P_c(4380)$: not predicted,
wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
Argand plot not resonance-like
???

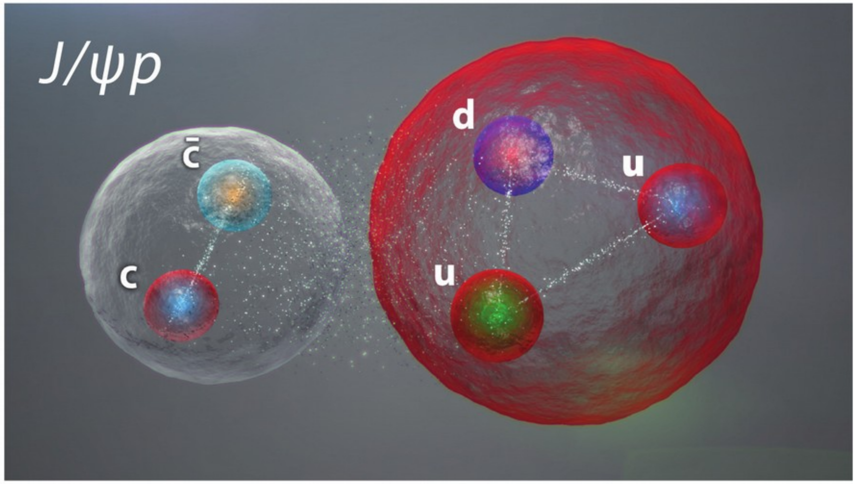
$\mathrm{P_c}(4450)$ might be just the first of many "heavy deuterons"

Decay of a tightly bound pentaquark vs. hadronic molecule to $J/\psi p$





narrow width of molecule automatic



$$|\langle \Sigma_c\bar{D}^* \,|\, J/\psi p\rangle| \ll |\langle \bar{c}cuud \,|\, J/\psi p\rangle|$$

$\Sigma_b^+ \Sigma_b^-$ dibaryon:

$\Sigma_b^+ \Sigma_b^-$ vs. $\bar{B} B^*$:

$m_{\Sigma_b} > m_B$, $I = 1$ vs. $I = \frac{1}{2}$ $\rightarrow$ stronger binding via π

$\Rightarrow$ deuteron-like $J = 1$, $I = 0$ bound state, “*beautron*”

extra ~ 3 MeV binding from EM interaction

EXP signature: $\rightarrow \Lambda_b \Lambda_b \pi^+ \pi^-$

$\Gamma(\Sigma_b) \sim 5 \div 10$ MeV, so might be visible

should be seen in lattice QCD

also $\Sigma_c \, \Sigma_c$, etc.

MK and J.L. Rosner,
Phys. Rev. D **90**, no. 9, 094007 (2014)

doubly heavy baryons QQq:

ccq, bcq, bbq, $\quad q = u, d$

must exist, and now have been seen

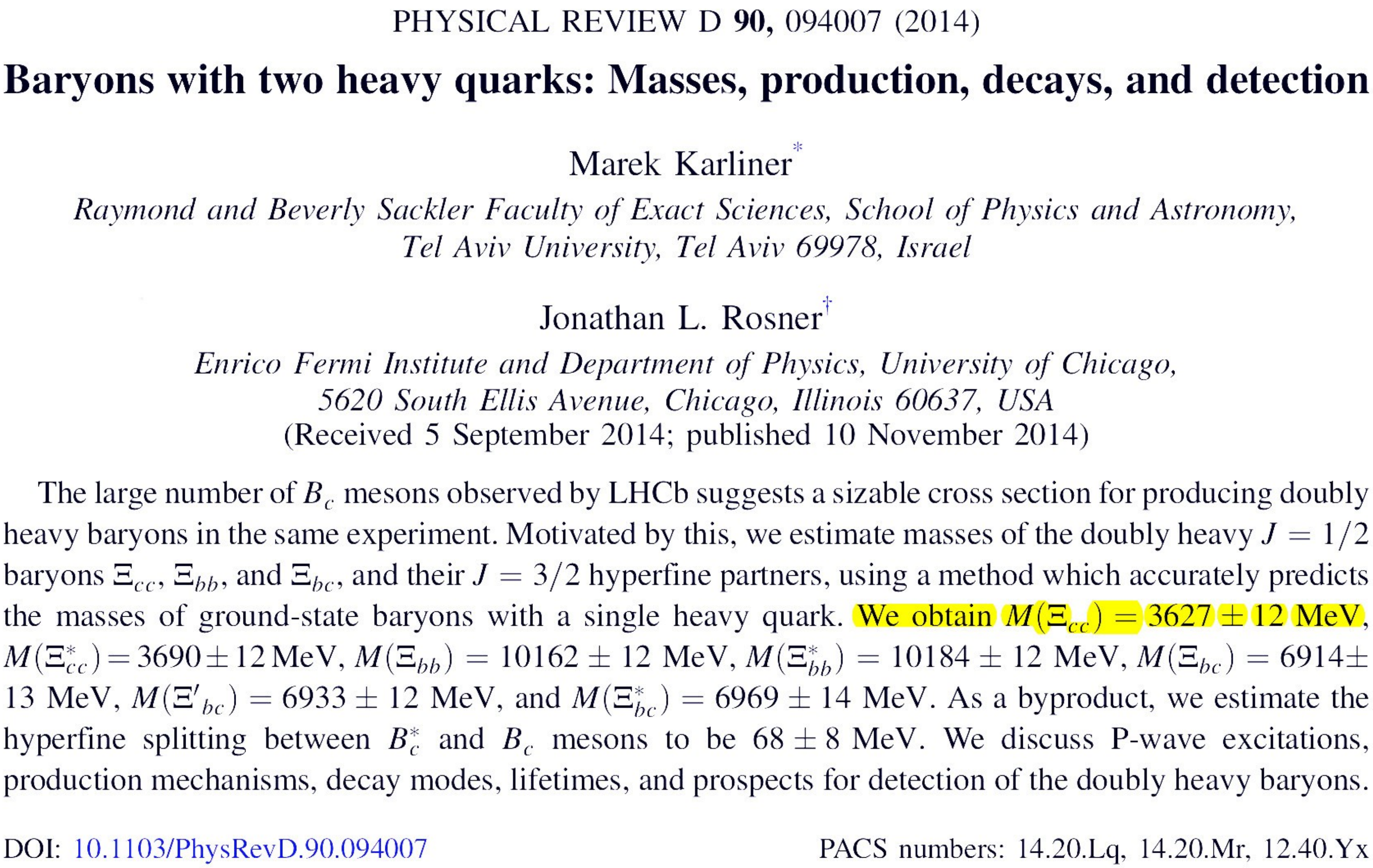
fascinating challenge for EXP & TH

LHCb sees thousands of B_c-s
$\Longrightarrow$ should see bcq, ccq, etc.

masses of doubly-heavy baryons:

use same toolbox that predicted

b baryon masses.



PHYSICAL REVIEW D **90,** 094007 (2014)

Baryons with two heavy quarks: Masses, production, decays, and detection

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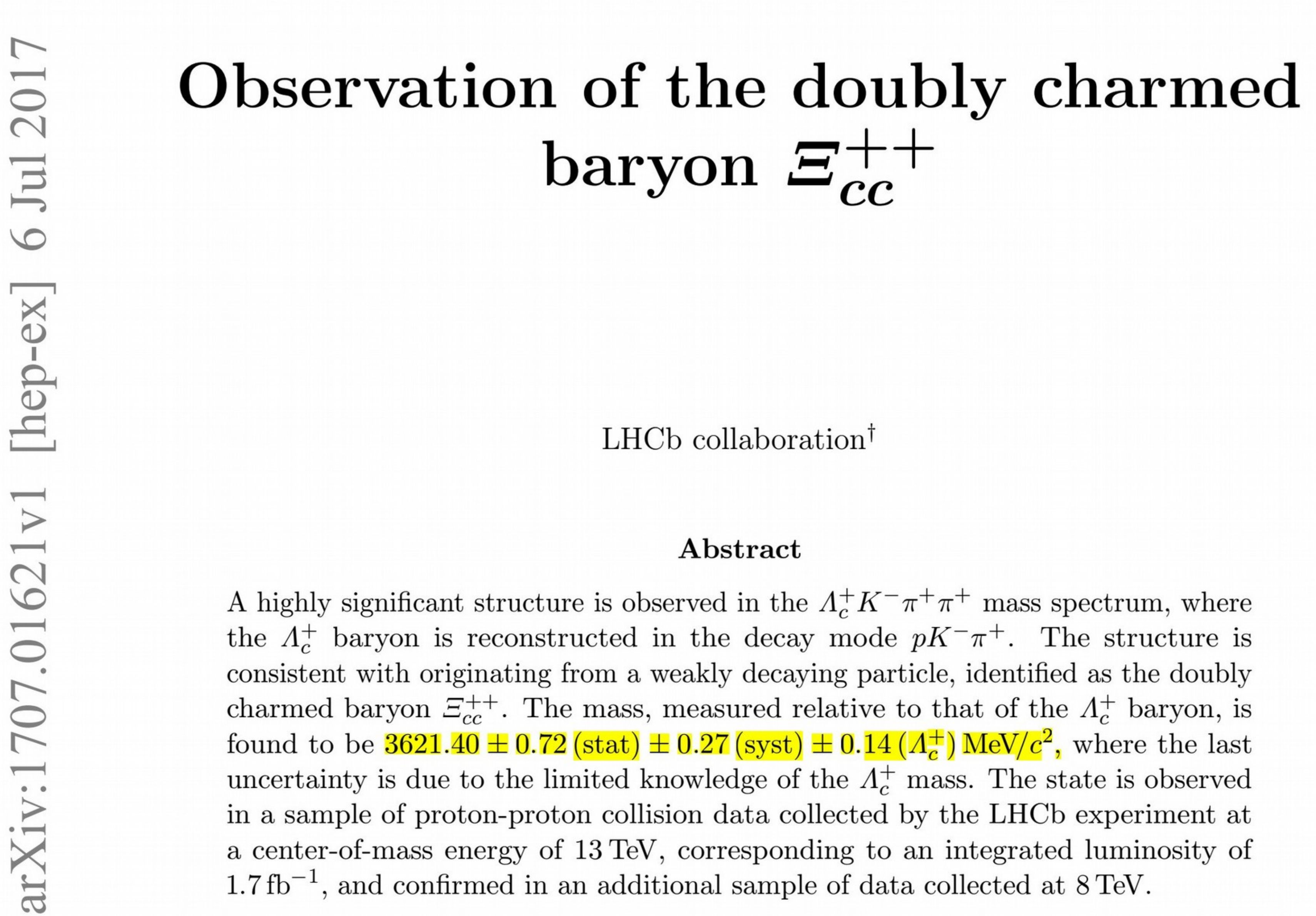
(Received 5 September 2014; published 10 November 2014)

The large number of B_c mesons observed by LHCb suggests a sizable cross section for producing doubly heavy baryons in the same experiment. Motivated by this, we estimate masses of the doubly heavy $J = 1/2$ baryons Ξ_{cc}, Ξ_{bb}, and Ξ_{bc}, and their $J = 3/2$ hyperfine partners, using a method which accurately predicts the masses of ground-state baryons with a single heavy quark. We obtain $M(\Xi_{cc}) = 3627 \pm 12$ MeV, $M(\Xi^*_{cc}) = 3690 \pm 12$ MeV, $M(\Xi_{bb}) = 10162 \pm 12$ MeV, $M(\Xi^*_{bb}) = 10184 \pm 12$ MeV, $M(\Xi_{bc}) = 6914 \pm 13$ MeV, $M(\Xi'_{bc}) = 6933 \pm 12$ MeV, and $M(\Xi^*_{bc}) = 6969 \pm 14$ MeV. As a byproduct, we estimate the hyperfine splitting between B^*_c and B_c mesons to be 68 ± 8 MeV. We discuss P-wave excitations, production mechanisms, decay modes, lifetimes, and prospects for detection of the doubly heavy baryons.

DOI: 10.1103/PhysRevD.90.094007

PACS numbers: 14.20.Lq, 14.20.Mr, 12.40.Yx

3627+-12 MeV



Observation of the doubly charmed baryon Ξ_{cc}^{++}

LHCb collaboration†

Abstract

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The mass, measured relative to that of the Λ_c^+ baryon, is found to be $3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14\,(\Lambda_c^+)\,\text{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $1.7\,\text{fb}^{-1}$, and confirmed in an additional sample of data collected at 8 TeV.

3621+-1 MeV

- Phenomenological approach
- Identify eff. d.o.f. & their interactions
- Extract model parameters from exp
- Then use them to make predictions

ccq mass calculation

sum of :

- $2m_c$
- V_{cc} in 3_c^*
- $V_{HF}(cc)$
- $V_{HF}(cq)$
- m_q

ccq mass calculation

sum of :

- $2m_c$
- V_{cc} in 3^*_c
- $V_{HF}(cc)$
- $V_{HF}(cq)$
- m_q

$$\left.\begin{array}{l} V_{cc} \text{ in } 3^*_c \\ V_{HF}(cc) \end{array}\right\} \text{no exp info !}$$

Effective masses

in mesons:

$$m_u^m = m_d^m = m_q^m = 310 \text{ MeV}, \; m_c^m = 1663.3 \text{ MeV}$$

in baryons:

$$m_u^b = m_d^b = m_q^b = \; 363 \text{ MeV}, \; m_c^b = 1710.5 \text{ MeV}$$

$V(cc)$ from $V(c\bar{c})$:

$$\bar{M}(c\bar{c}:1S) \equiv [3M(J/\psi) + M(\eta_c)]/4 = 3068.6 \text{ MeV}$$

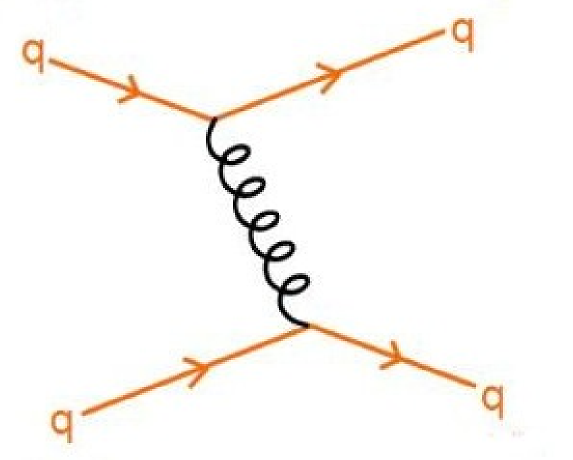
$$V(c\bar{c}) = \bar{M}(c\bar{c}:1S) - 2m_c^m = -258.0 \text{ MeV}.$$

$$V(cc) = \tfrac{1}{2}V(c\bar{c}) = -129.0 \text{ MeV}.$$

in weak coupling follows
from color algebra in 1gx

here a *dynamical assumption*:

$V(cc)$ and $V(c\bar{c})$ factorize
into color×space



gluon exchange by 2 quarks

$V_{HF}(cc)$ from $V_{HF}(c\bar{c})$:

$$V_{HF}(cc) = \frac{a_{cc}}{m_c^2}$$

$$V_{HF}(c\bar{c}) = M(J/\psi) - M(\eta_c) = 113.2\ \text{MeV} = \frac{4a_{\bar{c}c}}{m_c^2}$$

assume $a_{cc} = \frac{1}{2} a_{c\bar{c}}$,

$$\Rightarrow \quad \frac{a_{cc}}{m_c^2} = 1/2 \cdot \frac{M(J/\psi) - M(\eta_c)}{4} = 14.2\ \text{MeV}$$

Contributions to Ξ_{cc} mass

Contribution	Value (MeV)
$2m_c^b + m_q^b$	3783.9
cc binding	-129.0
$a_{cc}/(m_c^b)^2$	14.2
$-4a/m_q^b m_c^b$	-42.4
Total	3627 ± 12

The ± 12 MeV error estimate from
ave. error for Qqq baryons

doubly heavy baryons: mass predictions

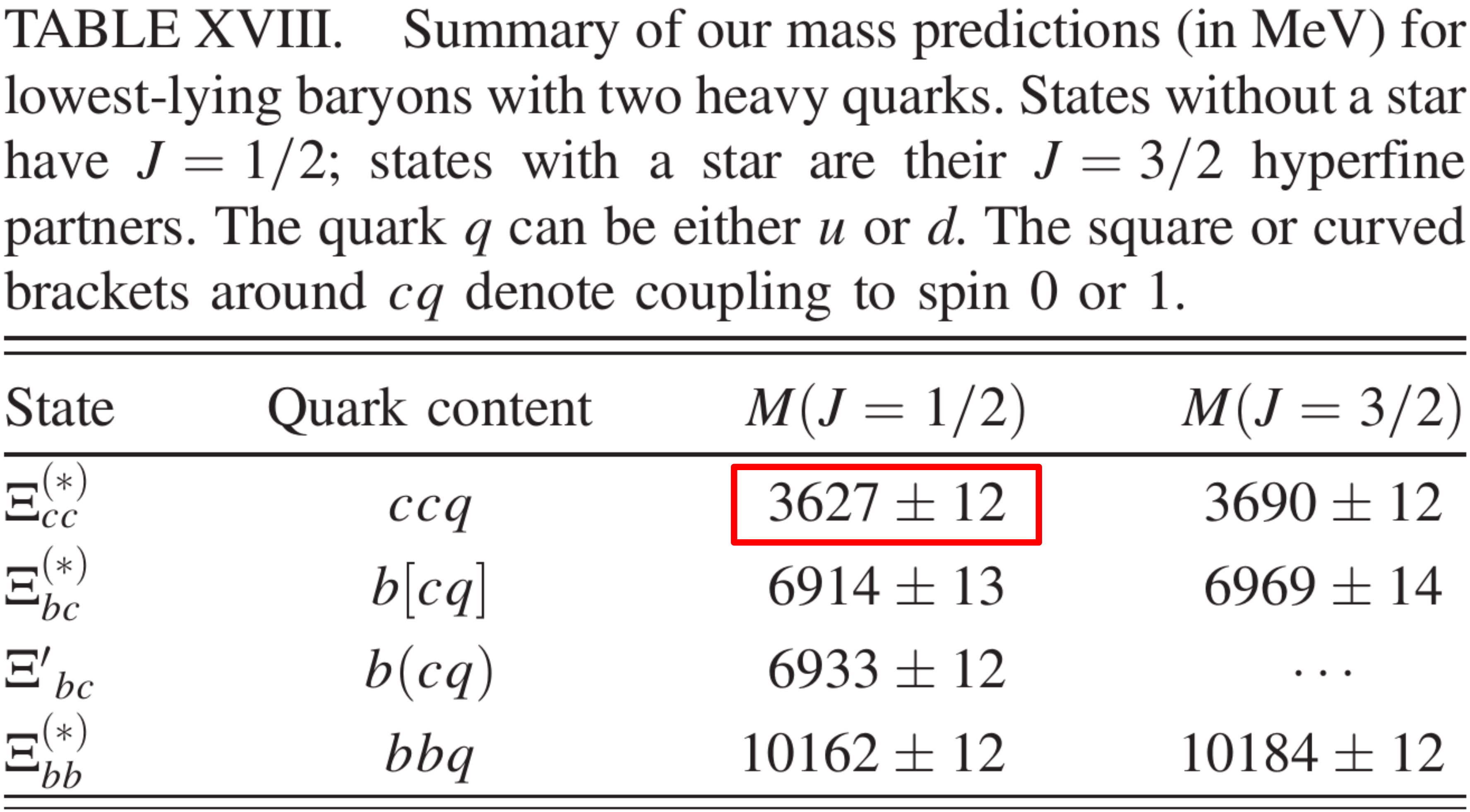
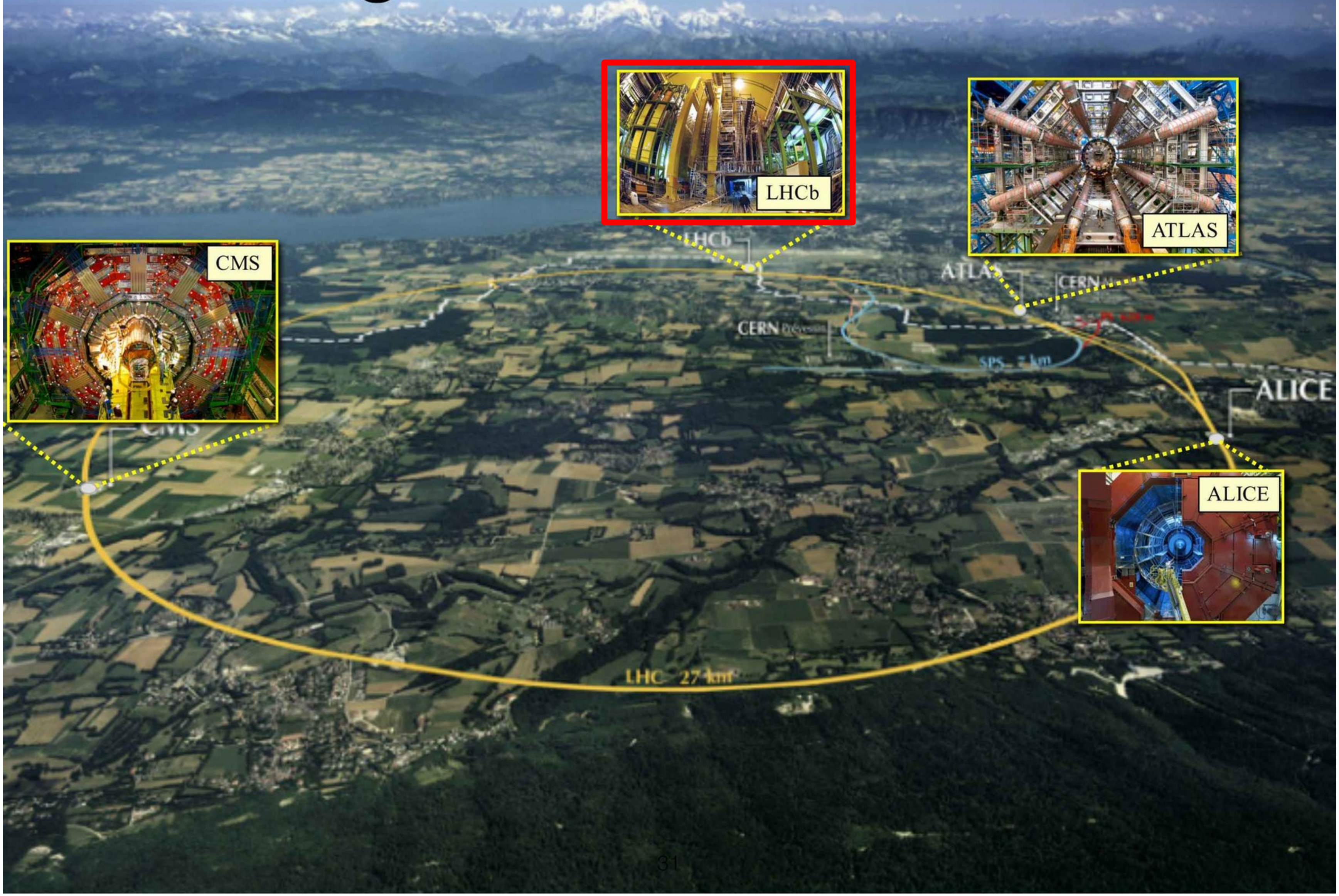


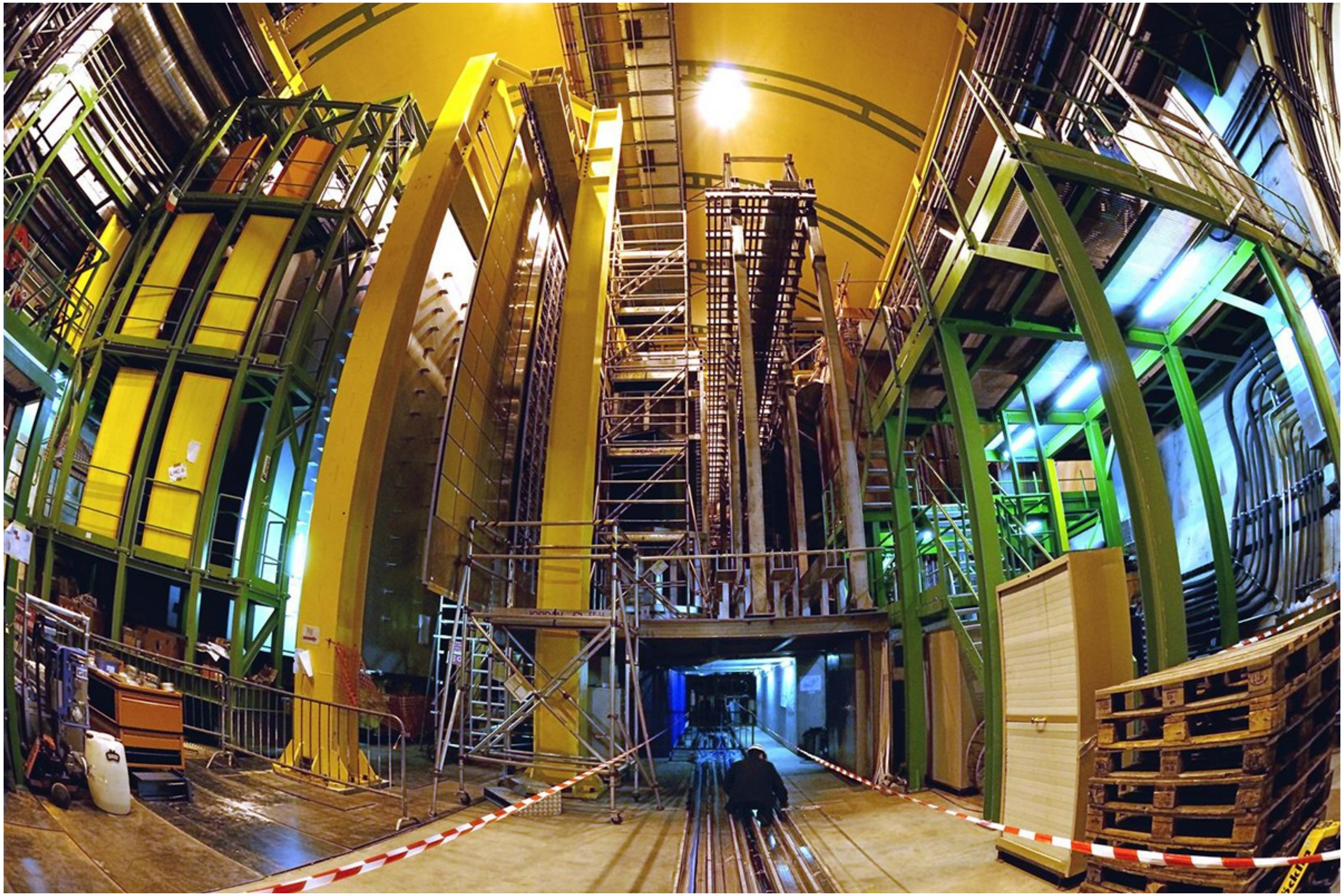
TABLE XVIII. Summary of our mass predictions (in MeV) for lowest-lying baryons with two heavy quarks. States without a star have $J = 1/2$; states with a star are their $J = 3/2$ hyperfine partners. The quark q can be either u or d. The square or curved brackets around cq denote coupling to spin 0 or 1.

State	Quark content	$M(J = 1/2)$	$M(J = 3/2)$
$\Xi_{cc}^{(*)}$	ccq	$\boxed{3627 \pm 12}$	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

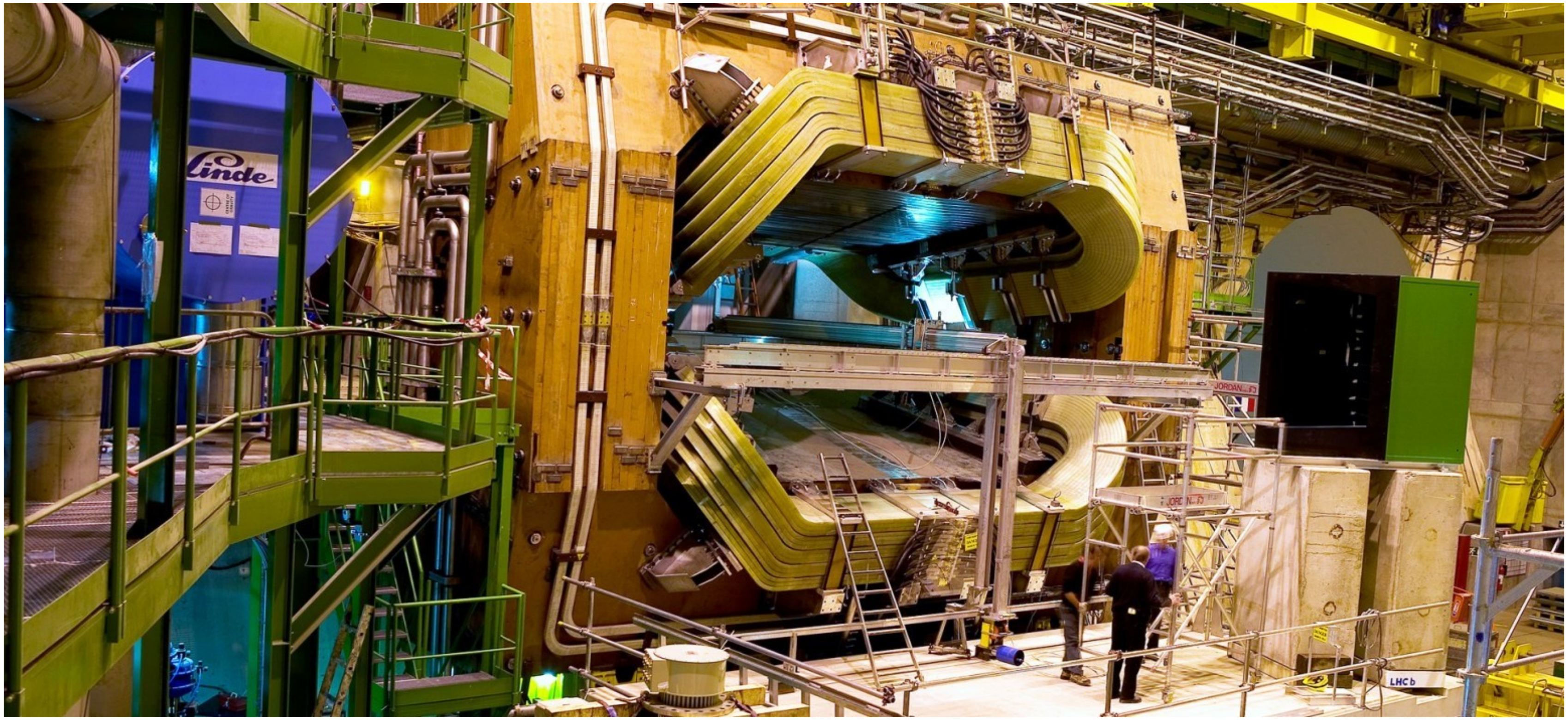
LHCb: 3621 ± 1

Large Hadron Collider





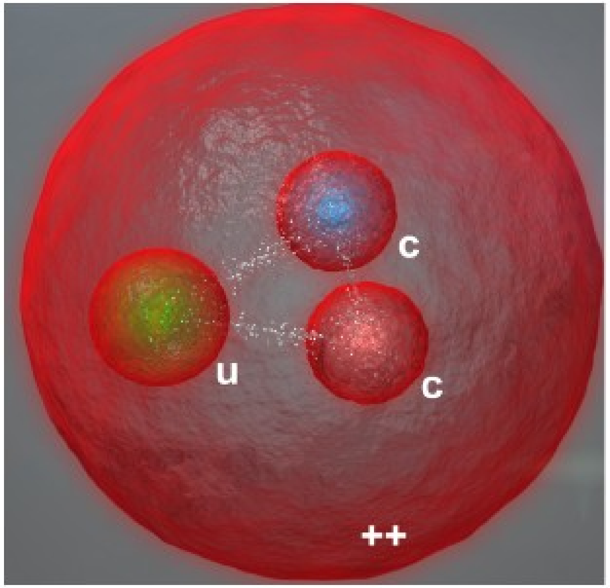
LHCb experiment



LHCb experiment

Observation of the doubly charmed baryon Ξ_{cc}^{++}

arXiv: 1707.01621



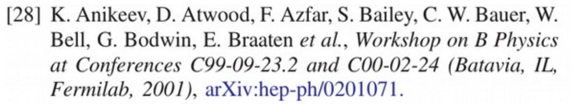
$\Xi_{cc}^{++} : ccu$

CERN seminar (11/07/2017)

Heavy Baryons at LHCb (Yanxi ZHANG)

doubly heavy baryons
predicted lifetimes (fs)

Baryon	This work	[28]	[51]	[71]	[72]
$\Xi_{cc}^{++} = ccu$	185	430±100	460±50	500	~ 200
$\Xi_{cc}^{+} = ccd$	53	120±100	160±50	150	~ 100
$\Xi_{bc}^{+} = bcu$	244	330±80	300±30	200	–
$\Xi_{bc}^{0} = bcd$	93	280±70	270±30	150	–
$\Xi_{bb}^{0} = bbu$	370	–	790±20	–	–
$\Xi_{bb}^{-} = bbd$	370	–	800±20	–	–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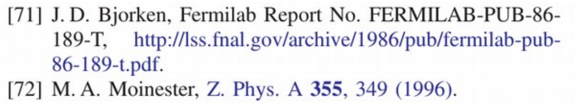
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The same theoretical toolbox

that led to the accurate Ξ_{cc} mass prediction

now predicts

a stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark,

215 MeV below BB^* threshold

The same theoretical toolbox

that led to the accurate Ξ_{cc} mass prediction

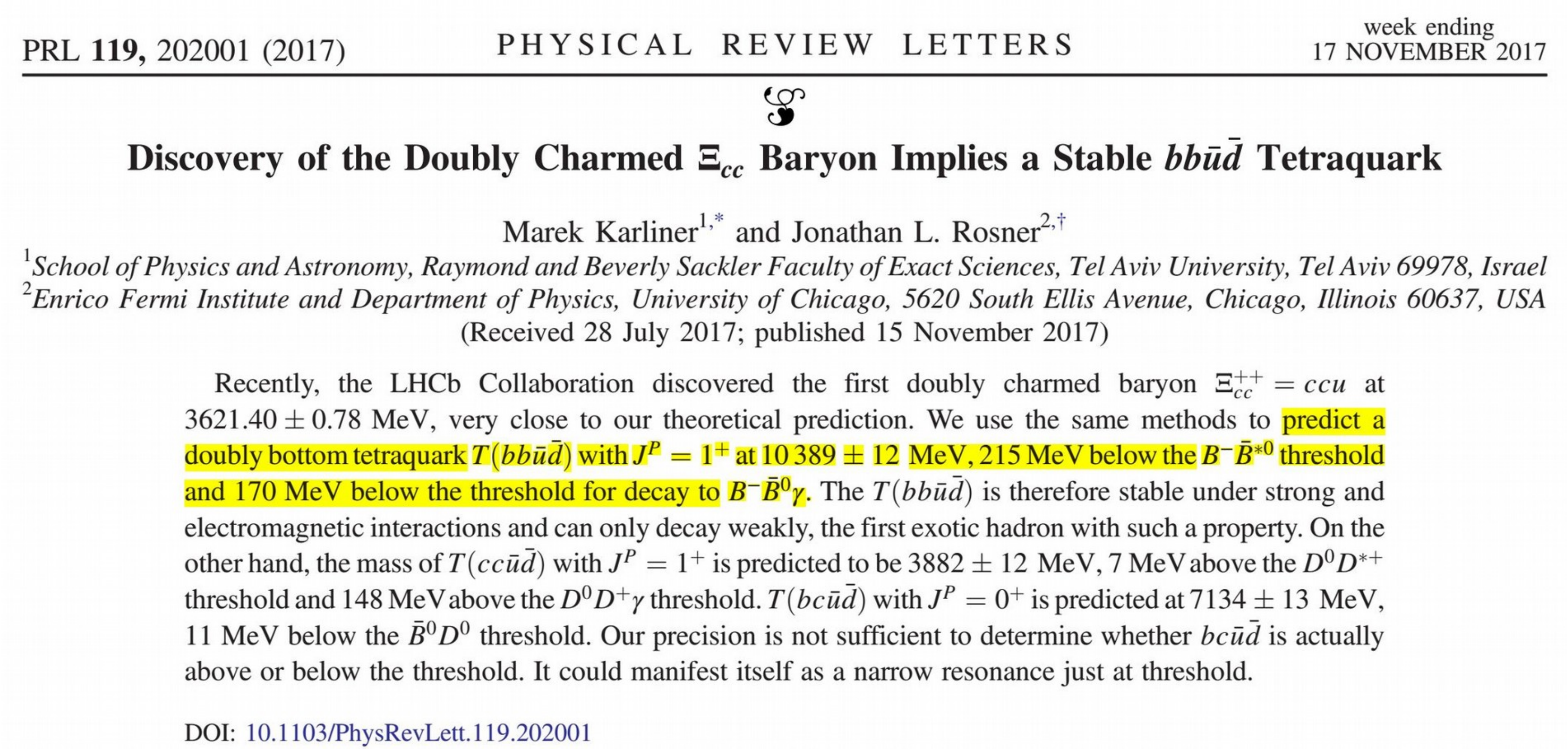
now predicts

a stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark,

215 MeV below BB^* threshold

the first manifestly exotic stable hadron

Editors’ Suggestion



PRL **119,** 202001 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

Discovery of the Doubly Charmed Ξ_{cc} Baryon Implies a Stable $bb\bar{u}\bar{d}$ Tetraquark

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]

[1] *School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*
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(Received 28 July 2017; published 15 November 2017)

Recently, the LHCb Collaboration discovered the first doubly charmed baryon $\Xi_{cc}^{++} = ccu$ at 3621.40 ± 0.78 MeV, very close to our theoretical prediction. We use the same methods to predict a doubly bottom tetraquark $T(bb\bar{u}\bar{d})$ with $J^P = 1^+$ at $10\,389 \pm 12$ MeV, 215 MeV below the $B^-\bar{B}^{*0}$ threshold and 170 MeV below the threshold for decay to $B^-\bar{B}^0\gamma$. The $T(bb\bar{u}\bar{d})$ is therefore stable under strong and electromagnetic interactions and can only decay weakly, the first exotic hadron with such a property. On the other hand, the mass of $T(cc\bar{u}\bar{d})$ with $J^P = 1^+$ is predicted to be 3882 ± 12 MeV, 7 MeV above the D^0D^{*+} threshold and 148 MeV above the $D^0D^+\gamma$ threshold. $T(bc\bar{u}\bar{d})$ with $J^P = 0^+$ is predicted at 7134 ± 13 MeV, 11 MeV below the $\bar{B}^0D^0$ threshold. Our precision is not sufficient to determine whether $bc\bar{u}\bar{d}$ is actually above or below the threshold. It could manifest itself as a narrow resonance just at threshold.

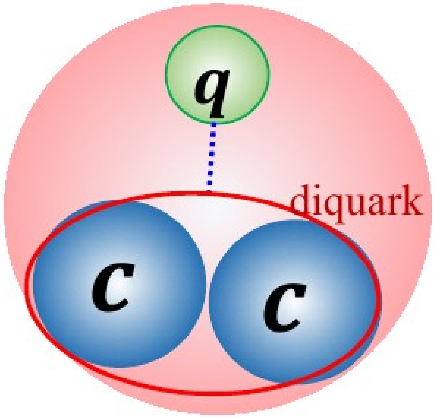
DOI: 10.1103/PhysRevLett.119.202001

Calculation of tetraquark $bb\bar{u}\bar{d}$ mass

build on accuracy of the Ξ_{cc} mass prediction

$$\boxed{V(bb) = \tfrac{1}{2}V(\bar{b}b)}$$

bbq baryon



to obtain lowest possible mass, assume:

- $bb\bar{u}\bar{d}$ in S-wave
- $\bar{u}\bar{d}$: $\mathbf{3}_\mathbf{c}$ "good" antidiq., $S{=}0$, $I{=}0$

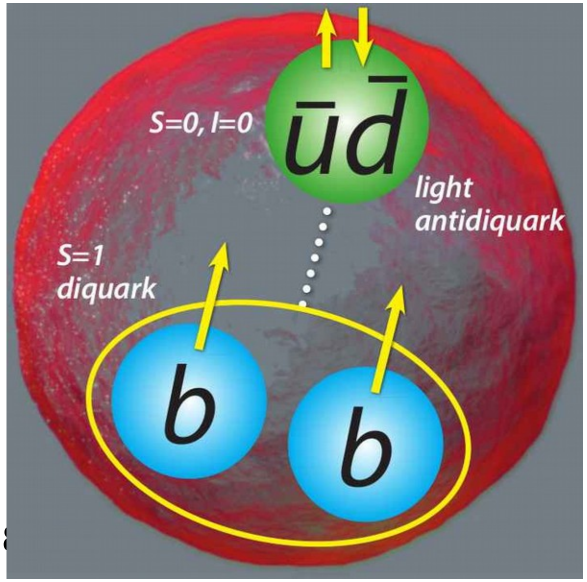
(it's the lightest one)

$\Rightarrow$ bb must be $\overline{3}_\mathbf{c}$; Fermi stats: spin 1

$(bb)_{S=1}\,(\bar{u}\bar{d})_{S=0} \Rightarrow J^P = 1^+$.

$\Rightarrow$ $(bb)\,(\bar{u}\bar{d})$ very similar to bbq baryon:

$q \leftrightarrow (\bar{u}\bar{d})$



Contributions to mass of $(bb\bar{u}\bar{d})$ Tq with $J^P = 1^+$

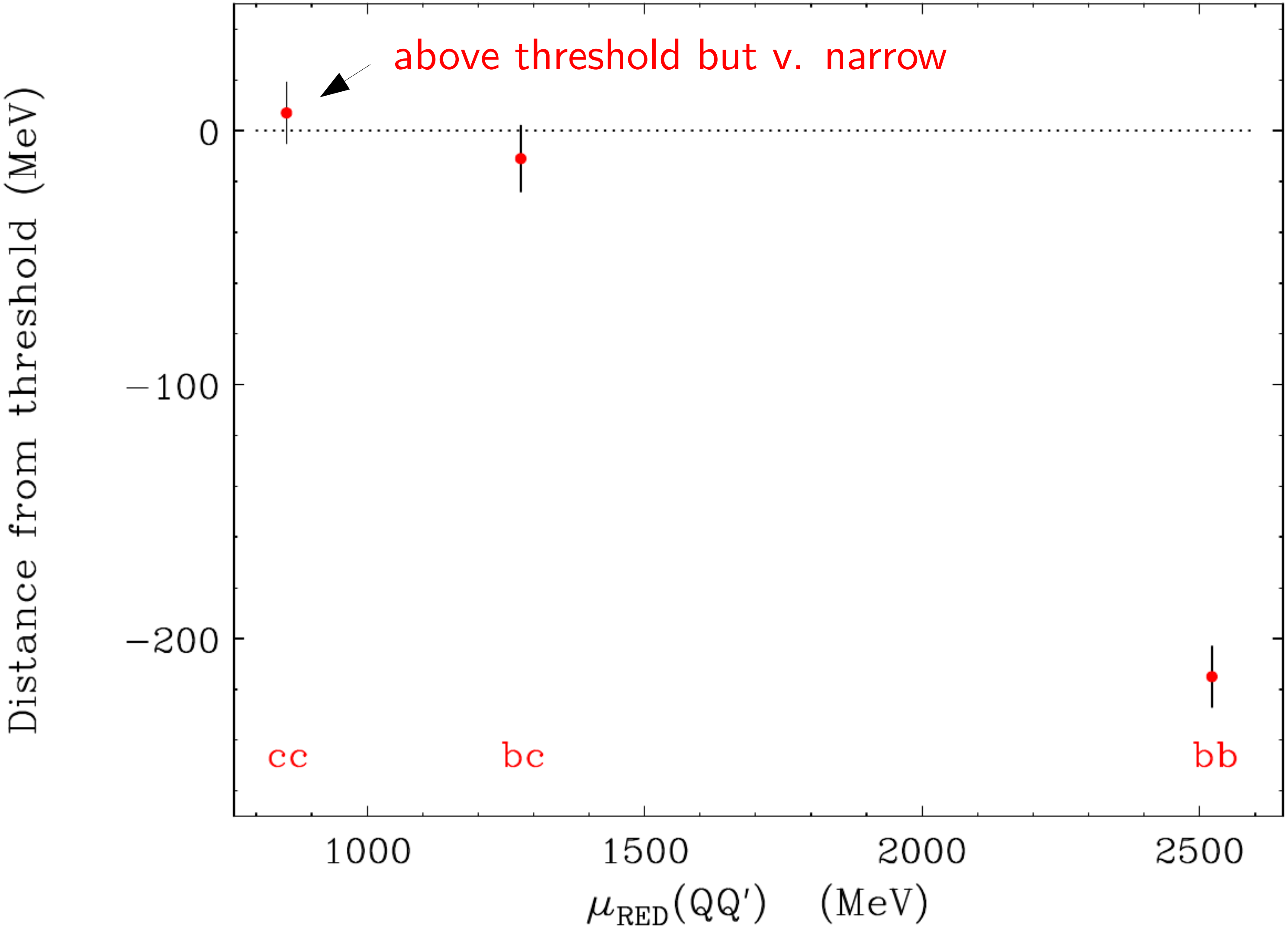
Contribution	Value (MeV)
$2m_b^b$	10087.0
$2m_q^b$	726.0
$a_{bb}/(m_b^b)^2$	7.8
$-3a/(m_q^b)^2$	−150.0
bb binding	−281.4
Total	10389.4 ± 12

Contributions to mass of $(bc\bar{u}\bar{d})$ Tq* with $J^P = 0^+$

Contribution	Value (MeV)
$m_b^b + m_c^b$	6754.0
$2m_q^b$	726.0
$-3a_{bc}/(m_b^b m_c^b)$	-25.5
$-3a/(m_q^b)^2$	-150.0
bc binding	-170.8
Total	7133.7 ± 13

*lowest-mass bc diquark has $S=0$, so $J=0$

Distance of the $QQ'\bar{u}\bar{d}$ Tq masses from the relevant two-meson thresholds (MeV).



Tetraquark production

$$\sigma(pp \to T(bb\bar{u}\bar{d}) + X \lesssim \sigma(pp \to \Xi_{bb} + X)$$

same bottleneck: $\sigma(pp \to \{bb\} + X)$

hadronization:

$$\left.\begin{array}{l} \{bb\} \to \{bb\}q \\ \{bb\} \to \{bb\}\bar{u}\bar{d} \end{array}\right\} \quad \begin{array}{ccc} P(\bar{u}\bar{d}) & \lesssim & P(q) \\ \mathbf{3}_c & & \mathbf{3}_c \end{array}$$

LHCb observed $ccu = \Xi_{cc}^{++}$

$$\sigma(pp \to \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \to \Xi_{cc} + X)$$

$\Rightarrow$ Ξ_{bb} and $T(bb\bar{u}\bar{d})$ accessible,
with much more $\int \mathcal{L} dt$

Tetraquark production

$\sigma(pp \to T(bb\bar{u}\bar{d}) + X \lesssim \sigma(pp \to \Xi_{bb} + X)$

same bottleneck: $\sigma(pp \to \{bb\} + X)$

hadronization:

$$\left.\begin{array}{l}\{bb\} \to \{bb\}q \\ \{bb\} \to \{bb\}\bar{u}\bar{d}\end{array}\right\} \quad \begin{array}{ccc} P(\bar{u}\bar{d}) & \lesssim & P(q) \\ \mathbf{3}_c & & \mathbf{3}_c \end{array}$$

LHCb observed $ccu = \Xi_{cc}^{++}$

$\sigma(pp \to \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \to \Xi_{cc} + X)$

⇒ Ξ_{bb} and $T(bb\bar{u}\bar{d})$ accessible,
with much more $\int \mathcal{L} dt$

$T(cc\bar{u}\bar{d})$
likely narrow
accessible *now*.
Being searched for.

crude estimate of $bb\bar{u}\bar{d}$ lifetime

$M_{initial} = M(bb\bar{u}\bar{d}) = 10{,}389.4$ MeV

$M_{final} = M(\bar{B}) + M(D) = 7,144.5$ MeV,

$W^{-*} \to e\bar{\nu}_e,\ \mu\bar{\nu}_\mu,\ \tau\bar{\nu}_\tau$, 3 colors of $\bar{u}d$ and $\bar{c}s$,

a kinematic suppression factor
$F(x) = 1 - 8x + 8x^3 - x^4 + 12x^2 \ln(1/x)$,
$x \equiv \{[M(\bar{B}) + M(D)]/M(bb\bar{u}\bar{d})\}^2$,

$|V_{cb}| = 0.04$, factor of 2 to count each decaying b quark.

$$\Rightarrow\ \Gamma(bb\bar{u}\bar{d}) = \frac{18\, G_F^2 M(bb\bar{u}\bar{d})^5}{192\pi^3} F(x)|V_{cb}|^2 = 17.9\times10^{-13}\ \text{GeV}\ ,$$

$\tau(bb\bar{u}\bar{d}) = 367$ fs $= 3.7 \times 10^{-13}$ sec, typical $\tau_{\text{weak}}(b)$

$bb\bar{u}\bar{d}$ decay channels

(a) “standard process” $bb\bar{u}\bar{d} \to cb\bar{u}\bar{d} + W^{*-}$.

$(bb\bar{u}\bar{d}) \to D^0\bar{B}^0\pi^-,\ D^+B^-\pi^-$

$(bb\bar{u}\bar{d}) \to J/\psi K^-\bar{B}^0,\ J/\psi\bar{K}^0B^-$.

In addition, a rare process where *both* $b \to c\bar{c}s$,

$(bb\bar{u}\bar{d}) \to J/\psi J/\psi K^-\bar{K}^0$.

striking signature: $2J/\psi$-s from same 2ndary vertex

(b) The W-exchange $b\bar{d} \to c\bar{u}$

e.g. $(bb\bar{u}\bar{d}) \to D^0B^-$,

$T(bb\bar{u}\bar{d})$ Summary

- stable, deeply bound $bbu\bar{d}$ tetraquark
- $J^P = 1^+$, $M(bb\bar{u}\bar{d}) = 10389 \pm 12$ MeV
- 215 MeV below BB^* threshold
- $\boxed{\text{first manifesty exotic stable hadron}}$
- $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^-,\ J/\psi \bar{K}\bar{B},$
  $J/\psi J/\psi K^- \bar{K}^0,\ D^0 B^-$
- $(bc\bar{u}\bar{d})$: $J^P = 0^+$, borderline bound
  7134 ± 13 MeV, 11 MeV below $\bar{B}^0 D^0$
- $(cc\bar{u}\bar{d})$: $J^P = 1^+$, borderline unbound
  3882 ± 12 MeV, 7 MeV above the $D^0 D^{*+}$

two v. different types of exotics:

$Q\bar{Q}q\bar{q}$

$QQ\bar{q}\bar{q}$

e.g.

$Z_b(10610)$

$\bar{B}B^*$

molecule

$T(bb\bar{u}\bar{d})$

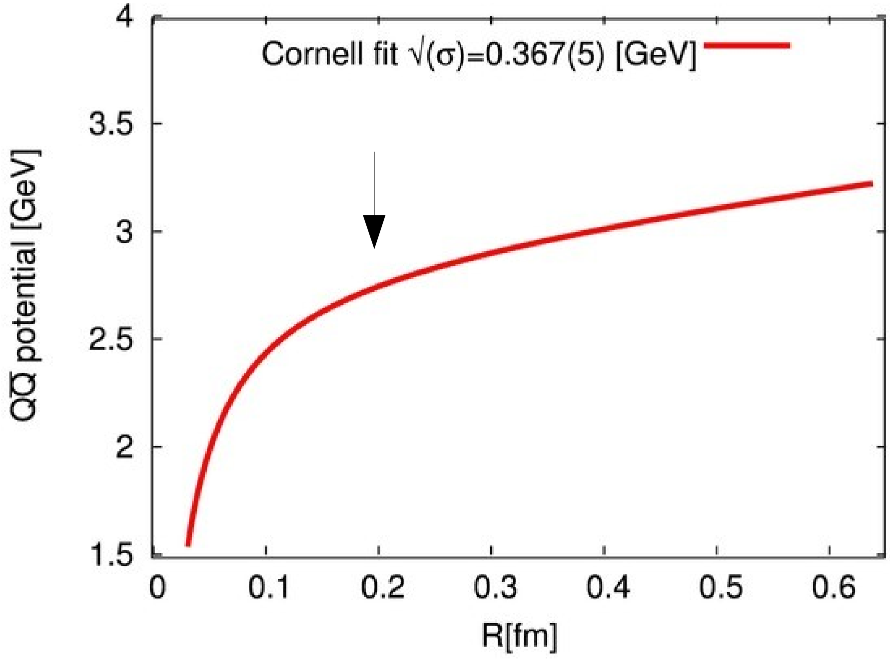
tightly-bound

tetraquark

$T(bb\bar{u}\bar{d})$:
$m_b \approx 5$ GeV
$\Rightarrow R(bb) \sim 0.2$ fm

$$V(r) = -\frac{\alpha_s(r)}{r} + \sigma r$$

$\Rightarrow B(bb) \approx -280$ MeV
tightly bound, but $\bar{3}_c$,
so cannot disangage from $\bar{u}\bar{d}$



$Z_b(10610)$: $b\bar{b}u\bar{d}$

very different!

if $b\bar{b}$ compact $\Rightarrow$ color singlet:
decouple from $u\bar{d}$, $Z_b \to \Upsilon\pi^+$
so only semi-stable config.,
"hadronic molecule:" $\bar{B}B^* \sim 1$ GeV above $\Upsilon\pi$
yet narrow ~ 15 MeV, because $R(\bar{B}B^*)/R(\Upsilon) \gg 1$

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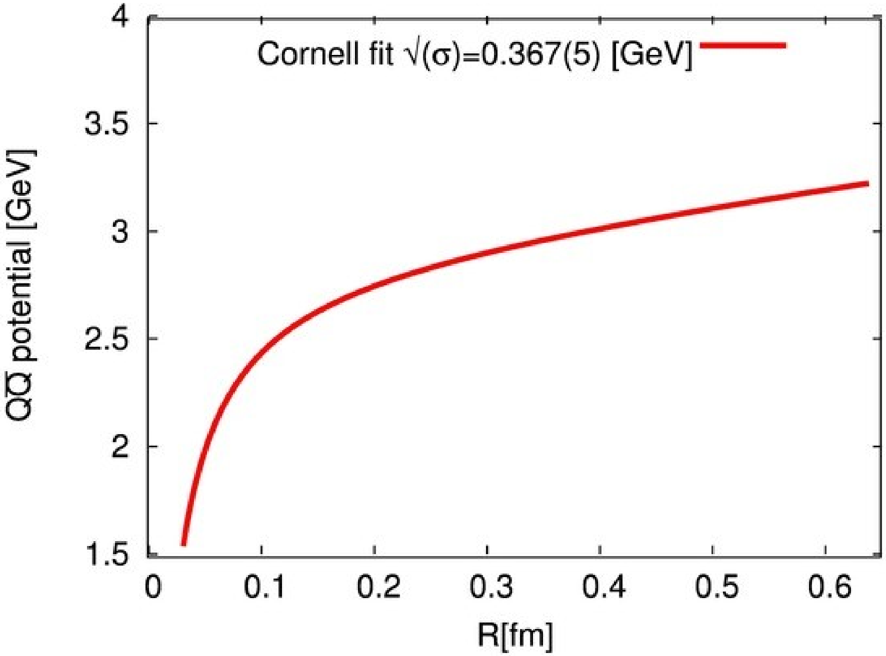

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bottom line: $T(bb\bar{u}\bar{d})$ a tetraquark, $Z_b(b\bar{b}u\bar{d})$ a molecule

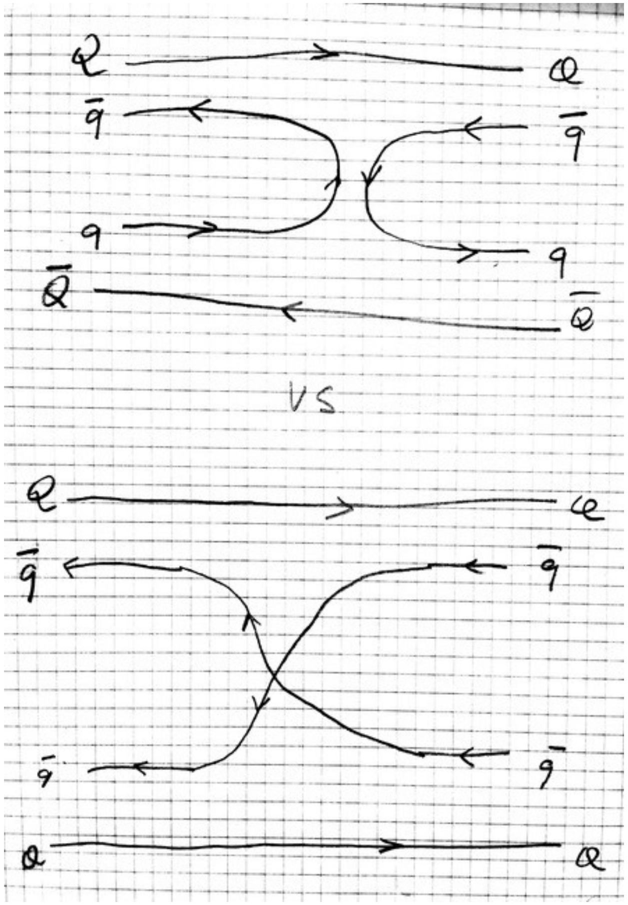
molecular binding $\equiv$ meson x-change

$Q\bar{Q}q\bar{q}$ vs. $QQ\bar{q}\bar{q}$

Tornqvist (1994):

molecular binding only in $Q\bar{q}\,\bar{Q}q$ channels.

$Q\bar{q}\,Q\bar{q}$ repulsive or very weakly bound, except maybe B^*B^*.



$QQ\bar{Q}\bar{Q}$ States

Phys. Rev. D **95**, 034011 (2017) MK, J.L. Rosner, S.Nussinov

Toolbox borrowed from QQq baryons

$M_{(cc\bar{c}\bar{c})} = 6{,}192 \pm 25$ MeV, 225 ± 25 MeV above $\eta_c \eta_c$

unlikely to be narrow, nor to have significant non-hadronic decays

$M_{(bb\bar{b}\bar{b})} = 18{,}826 \pm 25$ MeV, 28 ± 25 MeV above $\eta_b \eta_b$

could be narrow & exhibit non-hadronic decays if estim. $> 1\sigma$ high

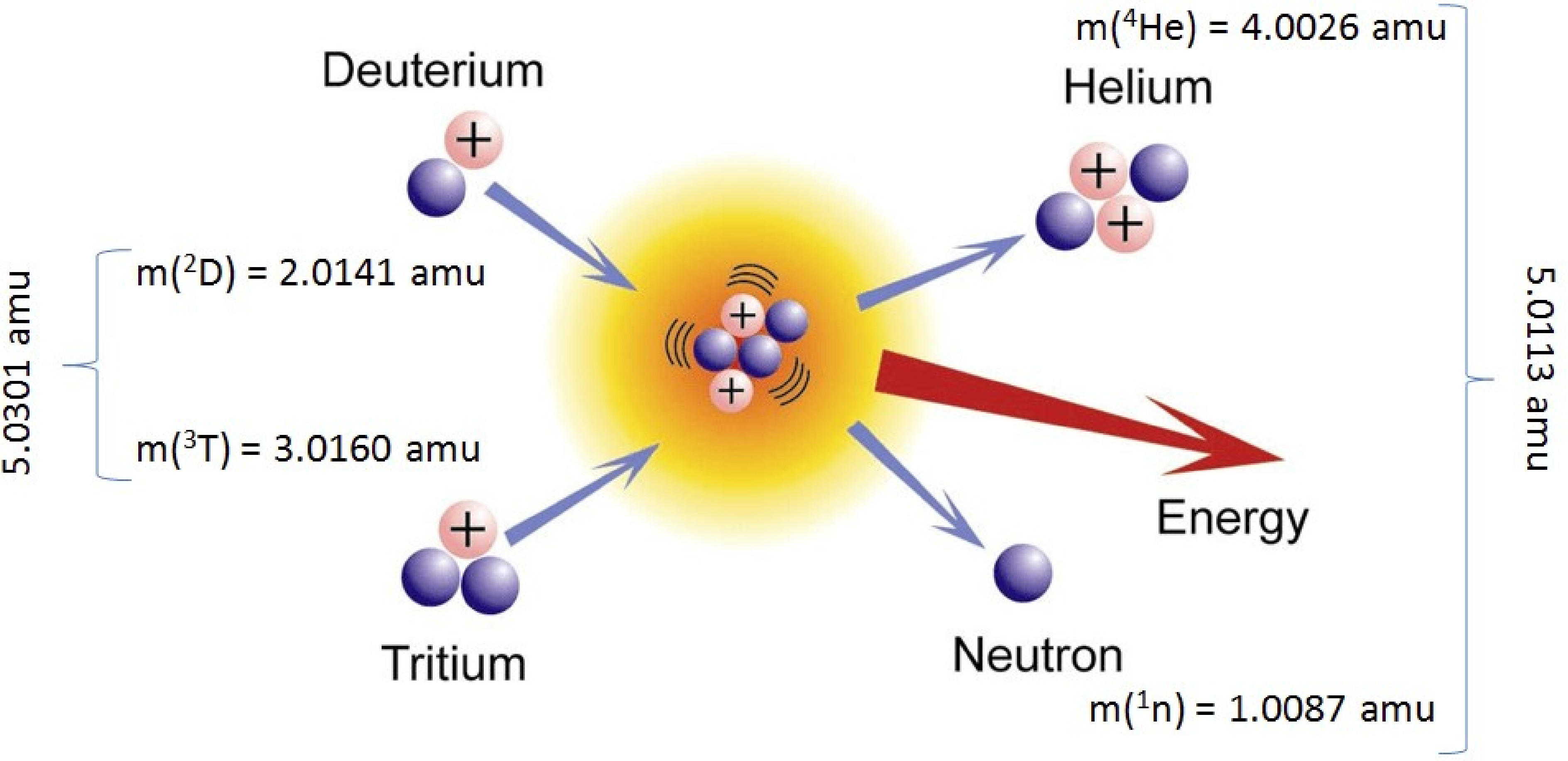
production of an extra $Q\bar{Q}$: probabillity $\sim 0.1\%$

CMS (arXiv:1610.07095) sees double $\Upsilon(1S)$; production;
38 events, each $\Upsilon \to \mu^+\mu^-$, in 20.7 fb^{-1} at $\sqrt{s} = 8$ TeV

$\Rightarrow$ Inspect neutral 4ℓ final states for possible evidence of $bb\bar{b}\bar{b}$ state; most likely $J^{PC} = 0^{++}$

Quark-level analogue of nuclear fusion with doubly-heavy baryons

DT fusion: $\mathrm{DT} \to {}^4\mathrm{He}\,\mathrm{n}$



m(^{2}D) = 2.0141 amu

m(^{3}T) = 3.0160 amu

5.0301 amu

m(^{4}He) = 4.0026 amu

m(^{1}n) = 1.0087 amu

5.0113 amu

Q = 0.0188 amu x 931.481 MeV/amu = 17.5 MeV

Nuclear fusion reactions w. light nuclei

$$\begin{aligned}
D\,T &\to {}^4\mathrm{He}\,n & Q &= 17.59\ \mathrm{MeV},\\
D\,D &\to {}^3\mathrm{He}\,n & Q &= 3.27\ \mathrm{MeV},\\
D\,D &\to T\,p & Q &= 4.04\ \mathrm{MeV},\\
T\,T &\to {}^4\mathrm{He}\,2n & Q &= 11.33\ \mathrm{MeV},\\
D{}^3\mathrm{He} &\to {}^4\mathrm{He}\,p & Q &= 18.35\ \mathrm{MeV},\\
{}^3\mathrm{He}{}^3\mathrm{He} &\to {}^4\mathrm{He}\,2p & Q &= 12.86\ \mathrm{MeV}.
\end{aligned}$$

LHCb measured $M(X_{cc}^{++}) = 3621.4 \pm 0.78$ MeV

$\Rightarrow$ Q-value of the reaction:

$$\begin{array}{ccccc} \Lambda_c\ \Lambda_c & \rightarrow & \Xi_{cc}^{++}\ n, & & Q = 12\ \text{MeV} \\ cud\ cud & & ccu\ ddu & & \end{array}$$

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robust estimate of Ξ_{bb}^{0} mass, so expect

$$\begin{array}{lcll} \Lambda_b\ \Lambda_b & \to & \Xi_{bb}^{0}\ n, & Q = 138\ \text{MeV} \\ bud\ bud & & bbu\ ddu & \end{array}$$

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$$cud\ cud \qquad\qquad ccu\ ddu$$

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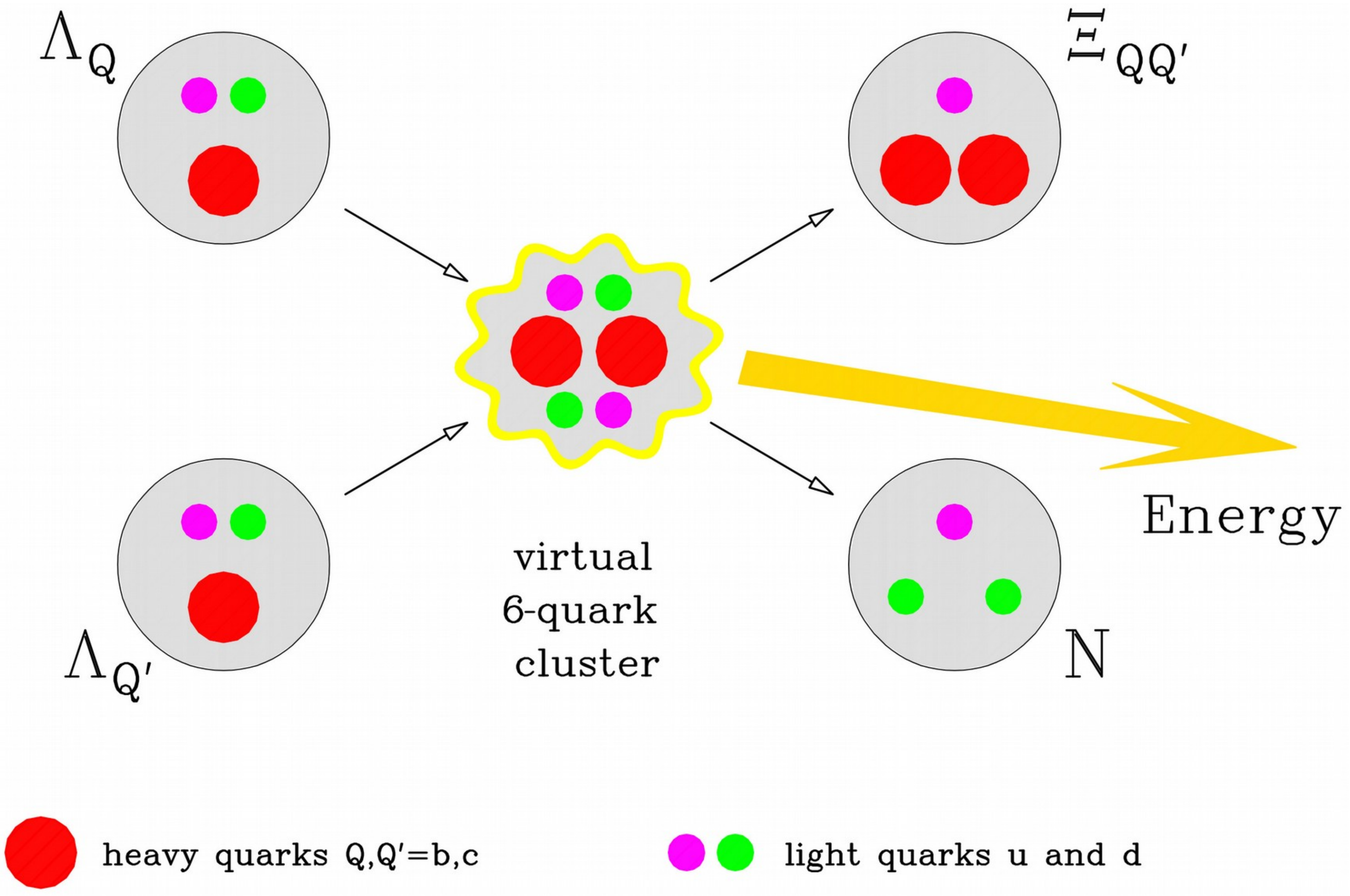
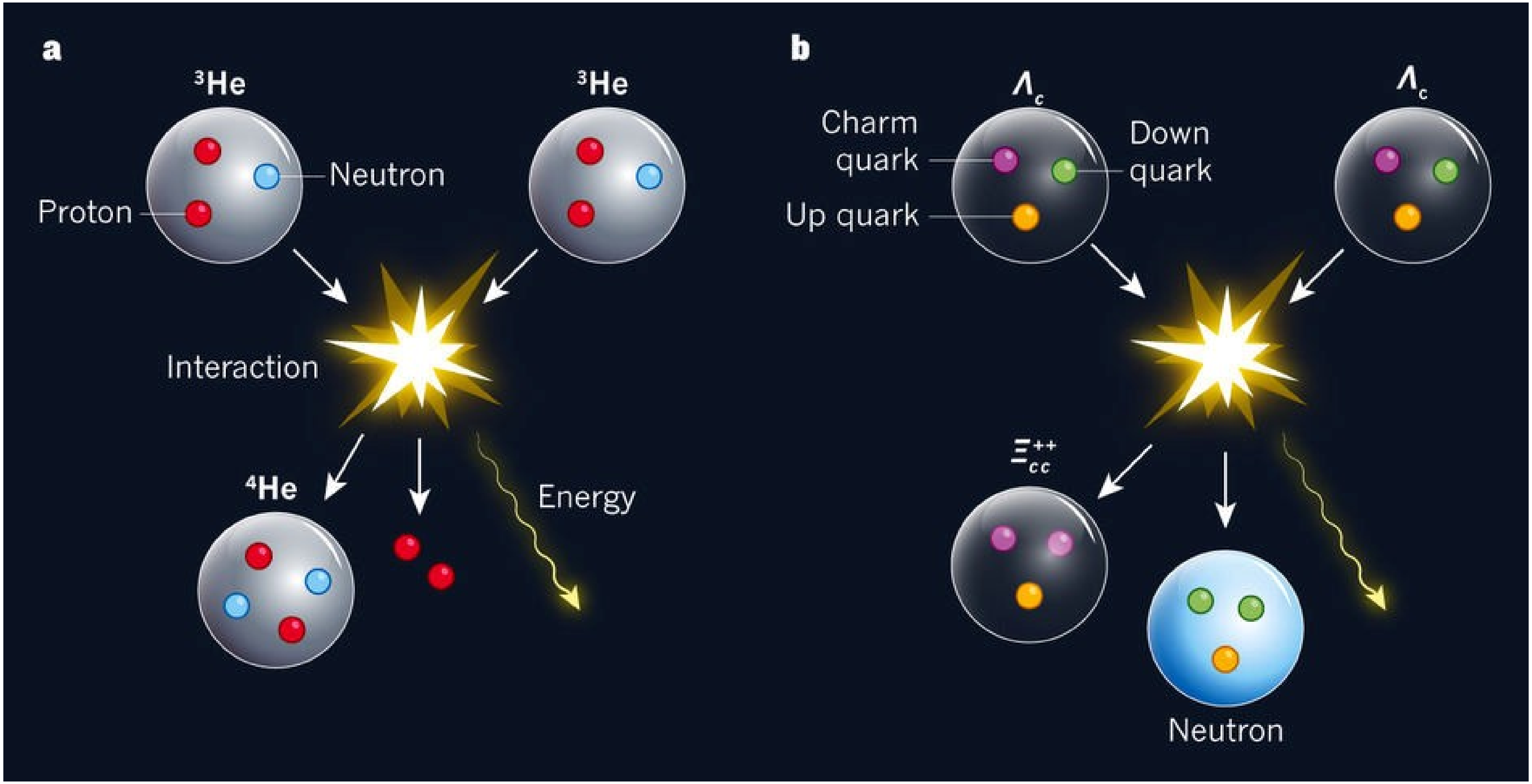
$$\Lambda_b\ \Lambda_b \quad \rightarrow \quad \Xi_{bb}^{0}\ n, \qquad Q = 138 \text{ MeV}$$

$$bud\ bud \qquad\qquad bbu\ ddu$$

But no chain reaction, as $\tau(Q) \sim 10^{-13}$ sec


Λ_Q
$\Xi_{QQ'}$
virtual 6-quark cluster
Energy
$\Lambda_{Q'}$
N
heavy quarks Q,Q′=b,c
light quarks u and d


a
^{3}He
^{3}He
Neutron
Proton
Interaction
^{4}He
Energy
b
Λ_c
Λ_c
Charm quark
Down quark
Up quark
Ξ_{cc}^{++}
Neutron

Nature,
Nov 2, 2017

LETTER

doi:10.1038/nature24289

Quark–level analogue of nuclear fusion with doubly heavy baryons

Marek Karliner[1] & Jonathan L. Rosner[2]

The essence of nuclear fusion is that energy can be released by the rearrangement of nucleons between the initial- and final-state nuclei. The recent discovery[1] of the first doubly charmed baryon Ξ_{cc}^{++}, which contains two charm quarks (c) and one up quark (u) and has a mass of about 3,621 megaelectronvolts (MeV) (the mass of the proton is 938 MeV) also revealed a large binding energy of about 130 MeV between the two charm quarks. Here we report that this strong binding enables a quark-rearrangement, exothermic reaction in which two heavy baryons (Λ_c) undergo fusion to produce the doubly charmed baryon Ξ_{cc}^{++} and a neutron n ($\Lambda_c\Lambda_c \to \Xi_{cc}^{++}n$), resulting in an energy release of 12 MeV. This reaction is a quark-level analogue of the deuterium–tritium nuclear fusion reaction (DT → ^{4}He n). The much larger binding energy (approximately 280 MeV) between two bottom quarks (b) causes the analogous reaction with bottom quarks ($\Lambda_b\Lambda_b \to \Xi_{bb}^0 n$) to have a much larger energy release of about 138 MeV. We suggest some experimental setups in which the highly exothermic nature of the fusion of two heavy-quark baryons might manifest itself. At present, however, the very short lifetimes of the heavy bottom and charm quarks preclude any practical applications of such reactions.

The mass of the doubly charmed baryon Ξ_{cc}^{++} observed in the LHCb experiment[1] 3621.40 ± 0.78 MeV is consistent with several predictions[2], including that of $3{,}627 \pm 12$ MeV (an extensive list of other predictions can be found in refs 1 and 2). The essential insight of ref. 2 is the large binding energy B of the two heavy quarks (the charm c or bottom b quarks) in a baryon, $B(cc) = 129$ MeV and $B(bb) = 281$ MeV. To a very good approximation, this binding energy is half of the quark–antiquark binding energy in their bound states, which are known as quarkonia. This 'half' rule is exact in the one-gluon-exchange limit and has now been validated by the measurement of the Ξ_{cc}^{++} mass. Its successful extension beyond weak coupling implies that the heavy quark potential factorizes into a colour-dependent and a space-dependent part, with the latter being the same for quark–quark and quark–antiquark pairs. The relative factor of 1/2 then results from the colour algebra, just as in the weak-coupling limit.

The large binding energy between heavy quarks has some important implications, such as the existence of a stable $bb\bar{u}\bar{d}$ tetraquark (where $\bar{u}$ and $\bar{d}$ are antiup and antidown quarks, respectively) with spin–parity[3] $J^P = 1^+$ 215 MeV below the $B^-\bar{B}^{*0}$ threshold and 170 MeV below the threshold for decay to $B^-\bar{B}^0\gamma$, where B^- is a spinless meson composed of $b\bar{u}$, $\bar{B}^{*0}$ is a spin-1 meson composed of $b\bar{d}$, $\bar{B}^0$ is a spinless meson composed of $b\bar{d}$ and γ is a photon. Another important consequence is the existence of a quark-level analogue of nuclear fusion. Consider the quark-rearrangement reaction

$$\underbrace{\Lambda_c}_{cud}\underbrace{\Lambda_c}_{cud} \to \underbrace{\Xi_{cc}^{++}}_{ccu}\underbrace{n}_{ddu} \qquad (1)$$

where the quarks are indicated below each baryon. This is a fusion of two singly heavy baryons into a doubly heavy baryon and a nucleon. The masses of all of the particles in reaction (1) are known and the energy release ΔE is 12 MeV, as shown in Table 1.

The exothermic reaction (1) is the quark-level analogue of the well known exothermic nuclear fusion reactions between the lightest nuclei, which contain two or three nucleons[4], with quarks playing the part of the nucleons, hadrons playing the part of the nuclei and the doubly heavy baryon playing the part of ^{4}He:

$$\begin{aligned} &\mathrm{DT} \to {}^4\mathrm{He}\,n, && \Delta E = 17.59\ \mathrm{MeV} \\ &\mathrm{DD} \to {}^3\mathrm{He}\,n, && \Delta E = 3.27\ \mathrm{MeV} \\ &\mathrm{DD} \to \mathrm{T}\,p, && \Delta E = 4.04\ \mathrm{MeV} \\ &\mathrm{TT} \to {}^4\mathrm{He}\,2n, && \Delta E = 11.33\ \mathrm{MeV} \\ &\mathrm{D}^3\mathrm{He} \to {}^3\mathrm{He}\,p, && \Delta E = 18.35\ \mathrm{MeV} \\ &{}^3\mathrm{He}^3\mathrm{He} \to {}^4\mathrm{He}\,2p, && \Delta E = 12.86\ \mathrm{MeV} \end{aligned} \qquad (2)$$

where D denotes a deuteron, T represents a triton and p stands for proton. Reaction (1) involves two hadrons with three quarks each, rather than two nuclei with two or three nucleons each, as shown schematically in Fig. 1, which also depicts the analogous reactions $\Lambda_Q\Lambda_{Q'} \to \Xi_{QQ'}N$, where $Q, Q' \in \{b, c\}$. The energy release ΔE of reaction (1) is of a similar order of magnitude to those of reactions (2).

Table 1 lists the ΔE values for four reactions $\Lambda_Q\Lambda_{Q'} \to \Xi_{QQ'}N$, where $Q, Q' \in \{s, c, b\}$. The trend is clear: ΔE increases monotonically with increasing quark mass. The reaction

$$\Lambda\Lambda \to \Xi N \qquad (3)$$

is endothermic with $\Delta E = -23$ MeV. Reaction (1) is exothermic with $\Delta E = +12$ MeV, whereas the reaction

$$\Lambda_b\Lambda_b \to \Xi_{bb}N \qquad (4)$$

is expected to be strongly exothermic with $\Delta E = +138 \pm 12$ MeV. Finally, the reaction

$$\Lambda_b\Lambda_c \to \Xi_{bc}N \qquad (5)$$

is expected to have $\Delta E = +50 \pm 13$ MeV, between the values for the cc and bb reactions (1) and (4). The latter two estimates of ΔE (for reactions (4) and (5)) rely on predictions of the Ξ_{bb} and Ξ_{bc} masses[2].

As already mentioned, the dominant effect that determines ΔE is the binding between two heavy quarks. Because these quarks interact through an effective two-body potential, their binding is determined by their reduced mass, $\mu_{\mathrm{red}} = m_Q m_{Q'}/(m_Q + m_{Q'})$, where m_Q and $m_{Q'}$ are the masses of the individual quarks. In Fig. 2, we plot ΔE versus $\mu_{\mathrm{red}}(QQ')$. The effective quark masses are as in ref. 2: $m_s = 538$ MeV, $m_c = 1{,}710.5$ MeV and $m_b = 5{,}043.5$ MeV. The straight-line fit $\Delta E = -44.95 + 0.0726\mu_{\mathrm{red}}$ (dot-dashed line) describes the data well, which shows that, to a good approximation, ΔE depends linearly on the reduced mass.

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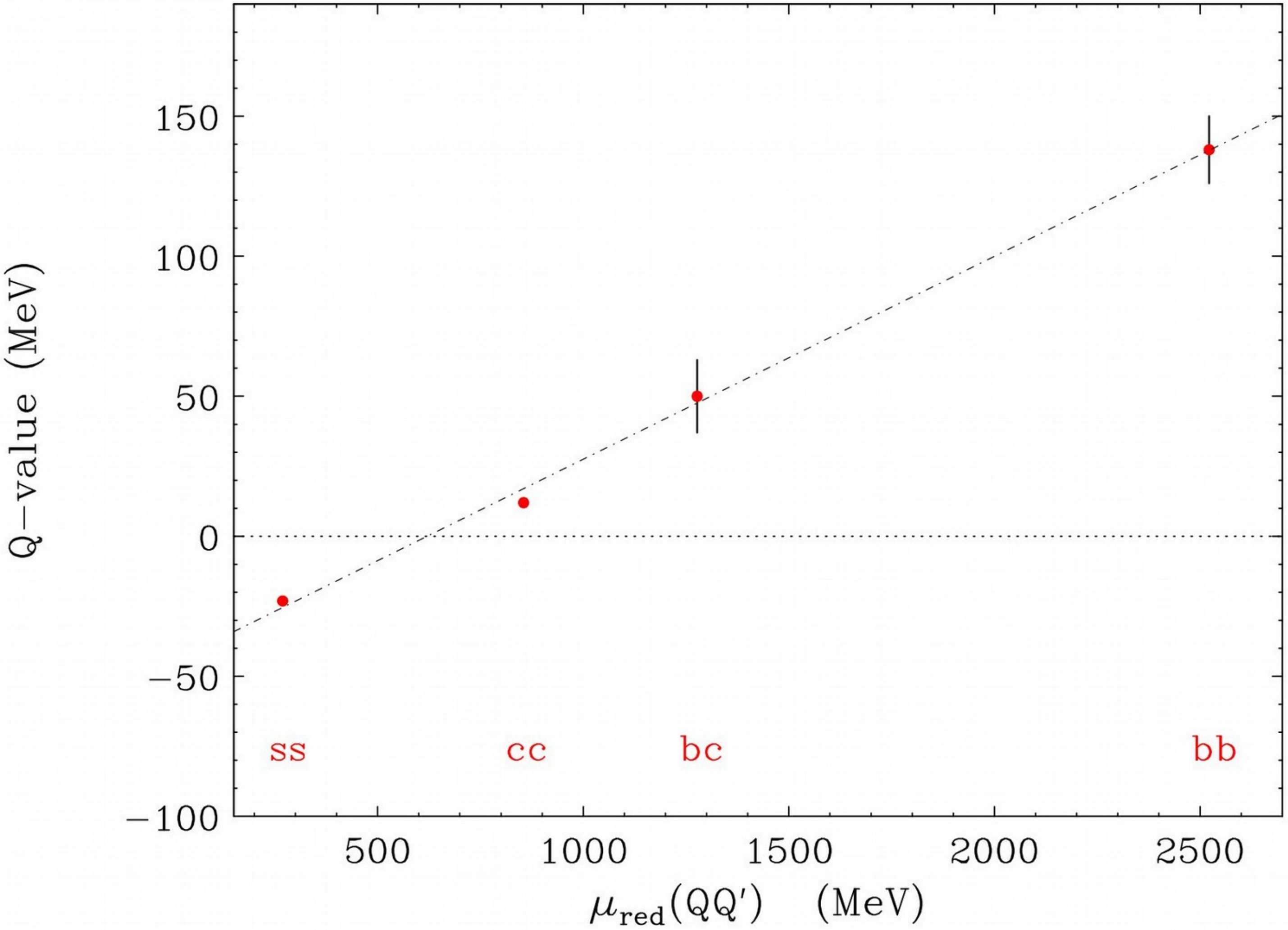

Q-value in the quark-level fusion reactions $\Lambda_Q \Lambda_{\mathcal{Q}'} \to \Xi_{\mathcal{Q}\mathcal{Q}'}\, N$, $\mathcal{Q}, \mathcal{Q}' = s, c, b$, plotted against the reduced masses of the doubly-heavy diquarks $\mu_{red}(\mathcal{Q}\mathcal{Q}')$. The dot-dashed line denotes a linear fit $Q = -44.95 + 0.0726\, \mu_{red}$.

doubly-strange hypernuclei might be produced in

$$K^- \ {}^{16}\mathrm{O} \to K^+ \ {}^{16}_{\Lambda\Lambda}\mathrm{C} \quad \equiv \quad {}^{16}\mathrm{O}(K^-, K^+){}^{16}_{\Lambda\Lambda}\mathrm{C}$$

ongoing exp. at J-PARC.

Suggest bottom analogue:

$$B^- \ {}^{16}\mathrm{O} \to B^+ \ {}^{\ 16}_{\Xi^-_{bb}}\mathrm{C}\,.$$

$E(bb) \approx 280$ MeV $\Rightarrow$ v. high Q-value

main challenge:
$\tau(B^-) = 1.6 \times 10^{-12}$ s,
$\tau(B^-) \cdot c \approx 0.5$ mm

Possibly also charm analogue

$$D^{+}\ {}^{N}\!A \rightarrow D^{-}\ \Xi_{cc}^{++}\ {}^{N}\!A'$$

both bottom and charm

in heavy ion collisions

a universal phenomenon:
heavy fermions $\tilde{\mathcal{Q}}$ in fund. rep. strongly bound;
binding increases monotonically with $m_{\tilde{\mathcal{Q}}}$

$\Rightarrow$ might be relevant for DM sector:

QCD-like theories w. confined "dark quarks" $\tilde{q}, \tilde{\mathcal{Q}}$
$m_{\tilde{q}} \lesssim \Lambda_{\widetilde{QCD}}$, $\mathrm{m}_{\tilde{\mathcal{Q}}}$ v. large

in many scenarios $\tilde{\mathcal{Q}}$ stable, unlike Q in SM

$\Rightarrow$ *stable* tightly-bound $\tilde{\mathcal{Q}}\tilde{\mathcal{Q}}\tilde{q}$

$\Rightarrow$ chain reaction involving $\tilde{\mathcal{Q}}$-level fusion

SUMMARY

- narrow exotics with $Q\bar{Q}$:
  $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$ molecules

– *heavy deuterons*: $\Sigma_c D^*$: LHCb $P_c(4450) \Rightarrow$ photoproduction
  $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$

- doubly charmed baryon found exactly where predicted

  $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq)$, (bbq)

- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb !

- $cc\bar{c}\bar{c}$ @ 6,192±25 MeV, $bb\bar{b}\bar{b}$ @ 18,826±25 MeV $\Rightarrow 4\ell$

- quark-level analogue of nuclear fusion

- possible similar mechanisms in dark matter sector

exciting new spectroscopy awaiting discovery