Heavy-light hadrons: Old laces & new pieces

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“Solomon saith: There is no new thing upon the earth. So that as Plato had an imagination, that all knowledge was but remembrance; so Solomon giveth his sentence, **that all novelty is but oblivion.**
Francis Bacon: Essays, LVIII”

— Jorge Luis Borges, The Aleph and Other Stories

Outline:

- Old Laces – Chiral dynamics, summarized in e.g. "Nuclear Chiral Dynamics" (M. Rho, I. Zahed, MAN; Singapore 1996)

- Two revolutions (exp. and theoretical)

- New Pieces – Holographic ML Chiral Effective Action
  - Y. Liu, I. Zahed; PRD 95 (2017) 056022, PRD 96 (2017) 116012
  - Y. Liu, MAN, I. Zahed; PRD 100 (2019) 126023; PRD .. (2022) in press (Tetraquarks)
  - Y. Liu, MAN, I. Zahed; PRD 104 (2021), 114021; PRD 104 (2021) 114022 (Pentaquarks)
  - Y. Liu, K. Mamo, MAN, I. Zahed; PRD 104 (2021) 114023. (Photoproduction of Pentaquarks)

Heavy and light.

2 (3) quarks (u, d, s) $m_{u/d} \ll \Lambda_{QCD}$, $m_s \sim \Lambda_{QCD}$

3 heavy quarks (c, b, t) $m_h \gg \Lambda_{QCD}$

- Light sector: SBXS $SU_L(n_\ell) \times SU_R(n_\ell) \to SU_V(n_\ell)$

  Effective chiral actions (σ-model, NJL, χPT..)

- Heavy sector: heavy spin decouples as $m_h \to \infty$

  Then $(0^-, 1^-)$ becomes degenerated in the $m_h \to \infty$ limit

$$H = \frac{1+\slashed{v}}{2}\left(i\gamma_5 D + \gamma^\mu D_\mu^*\right)$$

- Expansion in $1/N_c$

Light sector:

- Goldstone particles (pions)

$$\mathcal{L}_6 \sim \frac{f_\pi^2}{4} \mathrm{Tr}\, \partial_\mu U \partial^\mu U + \ldots \qquad U = e^{i/f_\pi \vec{\tau} \cdot \vec{\pi}}$$

- What about baryons? "Ergonomic solution": Skyrme
  Baryon is a solition, Baryon number is topological (winding)

$$\vec{\pi} = f(r) \frac{\vec{r}}{r} \quad , \quad \mathcal{L} = \mathcal{L}_6 + \mathcal{L}_{Skyrme} + \mathcal{L}_{WZW}$$

$\mathcal{L}_{WZW} \to (\pi^0 \to \gamma\gamma)$

$\mathcal{L}_{Skyrme} \to$ stabilizer

- Such classical solution has zero modes (rotations $U \to A(t) U A^\dagger(t)$)
- Quantization of collective coordinates in moduli space (Witten, Adkins, Napp[...]

$$H = M_0 + \frac{I^2}{2\Omega_{sol}} = M_0 + \frac{J^2}{2\Omega_{sol}}$$

- Two parameters, good phenomenology

Strange sector

- SU(2) → SU(3) : Mazur, MAN, Prasza\l owicz → "elegant disaster" (1984)
- Way-out : m_s is too heavy:
  BORN-Oppenheimer approx: fast vibrations of Kaon in SU(2) solitonic background. Then slow rotation of the bound state happens in presence of Berry phase from Kaon

$$H = M_0 + \underline{\text{binding}} + \frac{\left(\vec{J} - (1 - c_K)\, \mathrm{tr}\, K \vec{I} K^{+}\right)^2}{2\,\Omega_{sol}}$$

(isospin-spin transmutation)

Callan-Klebanov-(Hornbostel) 1985

- Successful phenomenology (also, no pentaquark)

Heavy sector:

- One has to remember about heavy spin symmetry

$$H = M_0 + \text{binding} + \frac{\left[(\vec{J}-\vec{S}_H) - (1-c_D)\,\mathrm{tr}\, D\vec{I}D^\dagger - (1-c_{D^*})\,\mathrm{tr}\, D^*\vec{I}D^{*\dagger}\right]^2}{2\Omega_{sol}}$$

- When $m_h \to \infty$, phases cancel $\frac{(J-S_H)^2}{2\Omega_{sol}} = \frac{I^2}{2\Omega_{sol}}$

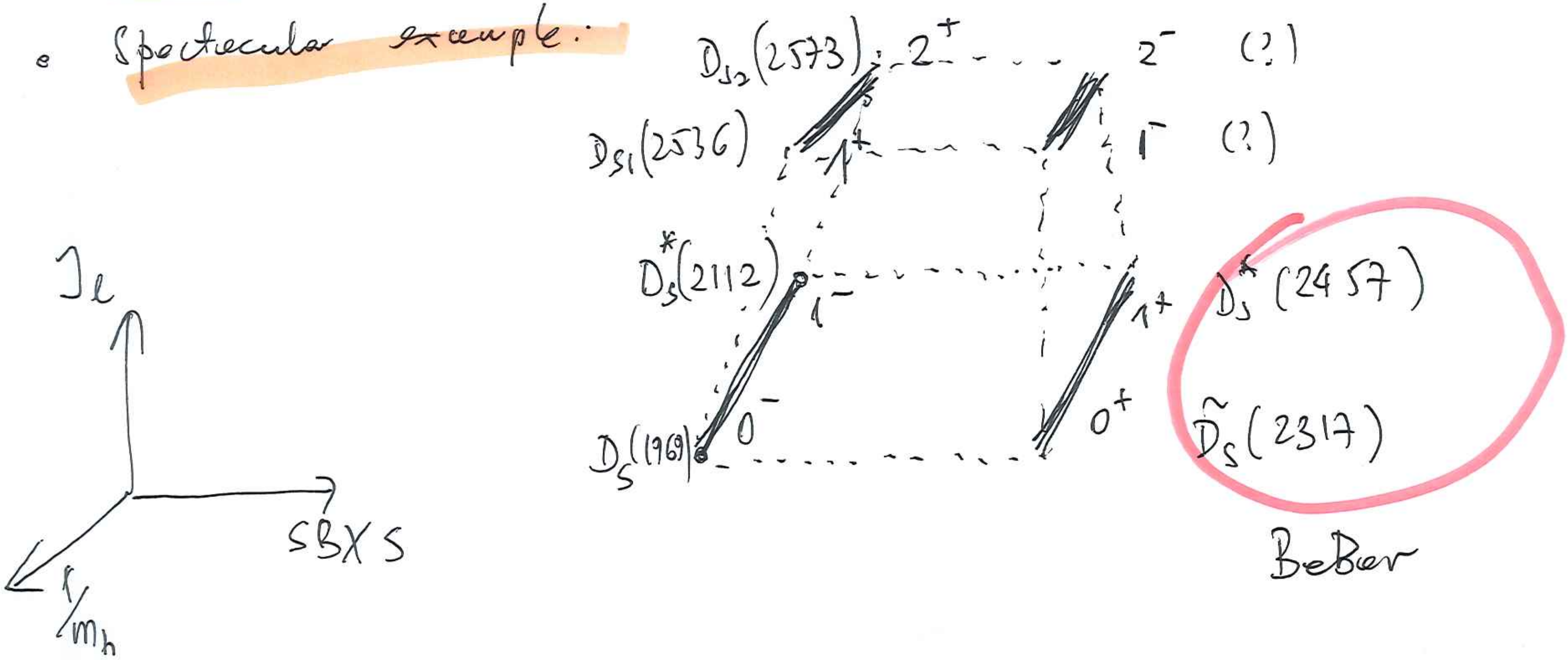
  (Heavy spin symmetry at the baryonic level)

- Soliton can capture more than one meson (exotics), Savage-Wise symmetry

- Same happens (a priori) for χ doublers

Chiral doublers scenario (MAN, M. Rho, I. Zahed (1992), Bardeen–Hill (1993))

- Requirement of simultaneous presence of both symmetries enforces the emergence of opposite to H, multiplet $G = \frac{1+\slashed{v}}{2}\left(\tilde{D} + \gamma^\mu \gamma_5 \tilde{D}^*_\mu\right)$
- Doublers communicate via axial current
- $m_G - m_H \sim O(\Sigma_{light}) \sim 350$ MeV
- Reorganization, not doubling the hadronic states
- Spectacular example:



Meson–Baryon "supersymmetry"

- QQ  $\longrightarrow$ Diquark with color $\bar{3}$, alike $\bar{Q}$
- Such symmetry relates spin-splittings of $\bar{H}L$ to HHL

  $\left(\Delta M_{HHL} = \frac{3}{4} \Delta M_{\bar{H}L} \right)$ Savage & Wise (1990)
- Iterating duality $HH \leftrightarrow \bar{H}$ leads to further correspondence

  e.g. $HLL \to \overline{HH}\,LL$ (heavy baryon – doubly heavy tetraquark)

New zoo.... (alike quark chemistry)

- soliton captures H meson
- soliton —"— G meson
- soliton captures $\bar{H}$ (heavy pentaquark)
- soliton —"— $\bar{G}$ (doubler of h. pentaquark)
- soliton captures more than one ....
- etc ....

Exotica

	States
	2866 2909
$\bar{c}du\bar{s}$	$X_0(2900)$, $X_1(2900)$ [21, 22]
$c\bar{c}q\bar{q}$	$\chi_{c1}(3872)$ [6]
$c\bar{c}u\bar{d}$	$Z_c(3900)$ [23], $Z_c(4020)$ [24, 25], $Z_c(4050)$ [26], $X(4100)$ [27], $Z_c(4200)$ [28], $Z_c(4430)$ [29–32], $R_{c0}(4240)$ [31]
$c\bar{c}u\bar{s}$	$Z_{cs}(3985)$ [33], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [34]
$c\bar{c}s\bar{s}$	$\chi_{c1}(4140)$ [35–38], $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ [38], $X(4630)$, $X(4685)$ [34], $X(4740)$ [39]
$c\bar{c}c\bar{c}$	$X(6900)$ [14]
$b\bar{b}u\bar{d}$	$Z_b(10610)$, $Z_b(10650)$ [40]
$c\bar{c}uud$	$P_c(4312)$ [41], $P_c(4380)$ [42], $P_c(4440)$, $P_c(4457)$ [41], $P_c(4357)$ [43] 36 \ weakend
$c\bar{c}uds$	$P_{cs}(4459)$ [44]
$cc\bar{u}\bar{d}$	T_{cc}^{+}

2007 1864.9 but wider
$D^{*0}\bar{D}^0$ threshold O(120 keV)

DD^{*+}
$c\bar{u}$ $c\bar{d}$
1
1865 2010
3875

• Gravity / Gauge duality (holography, AdS/CFT)

In the 70'-ties:

QCD

<u>Fundamental</u> theory of quarks & gluons

strings - flux tubes

<u>effective</u>, alike LUND model

Maldacena

Gauge theory in 4 dim $\simeq$ String theory in higher dimensions

Witten:

Application of duality to QCD - pure YM in 3+1 at large N and $\lambda = g_{YM}^2 N$

Surprising similarity of spectrum of glueballs to large N lattice

Sakai & Sugimoto 2005

- Adding N_f massless fermions: $SU_L(N_f) \times SU_R(N_f) \to SU_V(N_f)$ SBχS

- Low energy limit $S = S_{YM} + S_{CS}$

$$S_{YM} = \varkappa \int d^4x \, dz \, \mathrm{Tr} \left(\frac{1}{2} k(z)^{-1/3} F_{\mu\nu}^2 + k(z) F_{\mu z}^2 \right) \qquad k(z) = 1 + z^2$$

Mode expansion:

$$A_\mu(x^\mu, z) = \sum_n B_\mu^{(n)}(x^\mu) \, \psi_n(z)$$
$$A_5(x^\mu, z) = \sum_n \varphi^{(n)}(x^\mu) \, \Phi_n(z).$$

- Keeping only $\varphi^{(0)}$ gives $\mathcal{L} = \mathcal{L}_\sigma + \mathcal{L}_{Skyrme} + \mathcal{L}_{WZ}$, i.e. Skyrme model

$B_\mu^{(1)} \sim \rho$, $B_\mu^{(2)} \sim a_1$ give hidden gauge model

- Successful phenomenology with very few parameters.

From S. Sugimoto talk

mass

mass	ρ	a_1	ρ'	(a_1')	ρ''
exp.(MeV)	776	1230	1465	(1640)	1720
our model	[776]	1189	1607	2023	2435
ratio	[1]	1.03	0.911	(0.811)	0.706

↑ input ($M_{KK} \simeq 949$ MeV)

coupling

coupling		fitting m_ρ and f_π	experiment
f_π	$1.13 \cdot \kappa^{1/2} M_{KK}$	[92.4 MeV]	92.4 MeV
L_1	$0.0785 \cdot \kappa$	0.584×10^{-3}	$(0.1 \sim 0.7) \times 10^{-3}$
L_2	$0.157 \cdot \kappa$	1.17×10^{-3}	$(1.1 \sim 1.7) \times 10^{-3}$
L_3	$-0.471 \cdot \kappa$	-3.51×10^{-3}	$-(2.4 \sim 4.6) \times 10^{-3}$
L_9	$1.17 \cdot \kappa$	8.74×10^{-3}	$(6.2 \sim 7.6) \times 10^{-3}$
L_{10}	$-1.17 \cdot \kappa$	-8.74×10^{-3}	$-(4.8 \sim 6.3) \times 10^{-3}$
$g_{\rho\pi\pi}$	$0.415 \cdot \kappa^{-1/2}$	4.81	5.99
g_ρ	$2.11 \cdot \kappa^{1/2} M_{KK}^2$	0.164 GeV^2	0.121 GeV^2
$g_{a_1\rho\pi}$	$0.421 \cdot \kappa^{-1/2} M_{KK}$	4.63 GeV	$2.8 \sim 4.2$ GeV

Baryon in Sakai & Sugimoto

4 dim pion Skyrmion (static solution)

↓

5 dim gauge field BPST instanton in x_1, x_2, x_3, z in <u>flavor</u>

Topological number $\equiv$ baryon number

Direct realization of 1989 Atiyah–Manton idea

$$U(\bar{x}) = P\exp\left(i\int dz\, A_z(\bar{x}, z)\right)$$

8 zero modes $(SU(2), \vec{X}, Z, \rho)$ lead to moduli space

quantization

$$M = M_0 + \left(\sqrt{\left(\frac{l+1}{6}\right)^2 + \frac{2}{15}N_c^2} + \sqrt{\frac{2}{3}}\left(n_\rho + n_z + 1\right)\right) M_{KK}$$

$$l = 2I = 2J = 1, 3, 5 \ldots$$

From S. Sugimoto talk

- If we choose $M_{\rm KK} \simeq 500$ MeV
  and use nucleon mass ($\simeq 940$ MeV) to fix the constant M_0 ,
  (we only consider the mass difference), we obtain

(n_ρ, n_z)	$(0,0)$	$(1,0)$	$(0,1)$	$(1,1)$	$(2,0)/(0,2)$	$(2,1)/(0,3)$	$(1,2)/(3,0)$
$N\,(l=1)$	$[940]^+$	1348^+	1348^-	1756^-	$1756^+, 1756^+$	$2164^-, 2164^-$	$2164^+, 2164^+$
$\Delta\,(l=3)$	1240^+	1648^+	1648^-	2056^-	$2056^+, 2056^+$	$2464^-, 2464^-$	$2464^+, 2464^+$

↑ States appeared in the Skyrme model

($\pm$: parity)

- $I = J$ states from Particle Data Group look like....

(n_ρ, n_z)	$(0,0)$	$(1,0)$	$(0,1)$	$(1,1)$	$(2,0)/(0,2)$	$(2,1)/(0,3)$	$(1,2)/(3,0)$
$N\,(l=1)$	940^+	1440^+	1535^-	1655^-	1710^+, ?	2090^-_*, ?	2100^+_*, ?
$\Delta\,(l=3)$	1232^+	1600^+	1700^-	1940^-_*	1920^+, ?	?, ?	?, ?

(? : not found, $*$: evidence of existence is poor)

S. Sugimoto talk (Moriond)

Table 2: $\left\langle r^2 \right\rangle_{I=0}$, $\left\langle r^2 \right\rangle_{I=1}$ and $\left\langle r^2 \right\rangle_A$ are isoscalar, isovector and axial mean square radii, respectively. $g_{I=0}$ and $g_{I=1}$ are isoscalar and isovector g-factors. g_A is the axial coupling.

	our model	experiment
$\left\langle r^2 \right\rangle_{I=0}$	$(0.74\ \text{fm})^2$	$(0.81\ \text{fm})^2$
$\left\langle r^2 \right\rangle_{I=1}$	$(0.74\ \text{fm})^2$	$(0.94\ \text{fm})^2$
$\left\langle r^2 \right\rangle_A$	$(0.54\ \text{fm})^2$	$(0.67\ \text{fm})^2$
$g_{I=0}$	1.7	1.8
$g_{I=1}$	7.0	9.4
g_A	0.73	1.3

Holographic H-L effective theory (Liu, Zahed; 2017)

- "CK"-like scheme based on adding ∞-heavy flavor ($m_H = \infty$)

$$M = M_0 + (N_Q + N_{\bar{Q}})\, m_H + \left[\frac{(l+1)^2}{6} + \frac{2}{15} N_c^2 \left(1 - \frac{15(N_Q - N_{\bar{Q}})}{4N_c} + \frac{5(N_Q - N_{\bar{Q}})^2}{3N_c^2}\right)^2\right]^{1/2} M_{KK} + \sqrt{\frac{2}{3}}(n_\rho + n_z + 1) M_{KK}$$

- Various combinations of q-numbers give all types of H-L hadrons.

$N_Q = 1 \quad N_{\bar{Q}} = 0$ — baryons HLL

$N_Q = 2 \quad N_{\bar{Q}} = 0$ — " — HHL

$N_Q = N_{\bar{Q}} = 1$ — Pentaquarks $H\bar{H}LLL$

$n_z \neq 0$ excited, $n_\rho \neq 0$ odd parity ...

- Three parameters: M_{KK}, M_0, m_H

Adding spin-effects (subleading terms in m_H^{-1}) Liu, MAN, Zahed (2021)a

- 3 parameters $M_0 \to m_{N}$, $M_{KK} \to m_{\Lambda_c}$, $m_H = M_D$ for c
  $m_H = M_B$ for b

- 3 Pentaquarks $\frac{1}{2}\frac{1}{2}^-$, $\frac{1}{2}\frac{1}{2}^-$ $\frac{1}{2}\frac{3}{2}^-$ IJ^{Π}
  $S=1$ $S=0$ $S=1$

  ($\frac{1}{2}\frac{5}{2}^{\pm}$ ruled out), consistent with $P_c(4312, 4440, 4457)$ (LHCb)

- Recently reported $P_c(4337)$ at 3σ significance is not supported

- Open and hidden decay widths Liu, MAN, Zahed (2021)b
  e.g. $P_c \to \Lambda_c + \bar{D}$ $\Gamma(S=0, J=\frac{1}{2}) : \Gamma(S=1, J=\frac{1}{2}) : \Gamma(S=1, J=\frac{3}{2}) = \frac{1}{2} : \frac{5}{6} : \frac{1}{3}$

- Formfactors (Liu, Mamo, MAN, Zahed; 2022), consistent with recent GLUEX result.
  $\gamma p \to J/\psi\, p$ (P_c^+)

TABLE I. Charm baryons and Pentaquarks

B	IJ^P	l	n_ρ	n_z	N_Q	$N_{\bar{Q}}$	Mass-MeV	Exp-MeV
Λ_c	$0\frac{1}{2}^+$	0	0	0	1	0	2286	2286
Σ_c	$1\frac{1}{2}^+$	2	0	0	1	0	2557	2453
	$1\frac{3}{2}^+$	2	0	0	1	0	2596	2520
Λ_c^*	$0\frac{1}{2}^-$	0	0	1	1	0	2683	2595
	$0\frac{1}{2}^+$	0	1	0	1	0	2726	2765
Σ_c^*	$1\frac{1}{2}^-, 1\frac{3}{2}^-$	2	0	1	1	0	[2947/2986]	–
	$1\frac{1}{2}^+, 1\frac{3}{2}^+$	2	1	0	1	0	[2948/2995]	–
P_c	$\frac{1}{2}\frac{1}{2}^-, \frac{1}{2}\frac{3}{2}^-$	1	0	0	1	1	[4340/4360/4374]	[4312/4440/4457]
P_c^*	$1\frac{1}{2}^-, 1\frac{3}{2}^-$	1	0	1	1	1	[4732/4752/4767]	–
	$1\frac{1}{2}^+, 1\frac{3}{2}^+$	1	1	0	1	1	[4725/4746/4763]	–

To fix the parameters for the charmed heavy baryons, we choose $M_D = 1.87$ GeV for the D-meson mass in (7) and fix $M_{KK} = 0.475$ GeV to reproduce the $M_{\Lambda_c} = 2.286$ GeV. This low value of M_{KK} is consistent with the value used to reproduce the nucleon

TABLE II. Bottom baryons and Pentaquarks

B	IJ^P	l	n_ρ	n_z	N_Q	$N_{\bar{Q}}$	Mass-MeV	Exp-MeV
Λ_b	$0\frac{1}{2}^+$	0	0	0	1	0	5608	5620
Σ_b	$1\frac{1}{2}^+$	2	0	0	1	0	5962	5810
	$1\frac{3}{2}^+$	2	0	0	1	0	5978	5830
Λ_b^*	$0\frac{1}{2}^-$	0	0	1	1	0	5998	5912
	$0\frac{1}{2}^+$	0	1	0	1	0	6029	(6072)
Σ_b^*	$1\frac{1}{2}^-, 1\frac{3}{2}^-$	2	0	1	1	0	[6351/6367]	–
	$1\frac{1}{2}^+, 1\frac{3}{2}^+$	2	1	0	1	0	[6344/6367]	–
P_b	$\frac{1}{2}\frac{1}{2}^-, \frac{1}{2}\frac{3}{2}^-$	1	0	0	1	1	[11155/11163/11167]	–
P_b^*	$1\frac{1}{2}^-, 1\frac{3}{2}^-$	1	0	1	1	1	[11544/11553/11556]	–
	$1\frac{1}{2}^+, 1\frac{3}{2}^+$	1	1	0	1	1	[11532 /11543/11579]	–

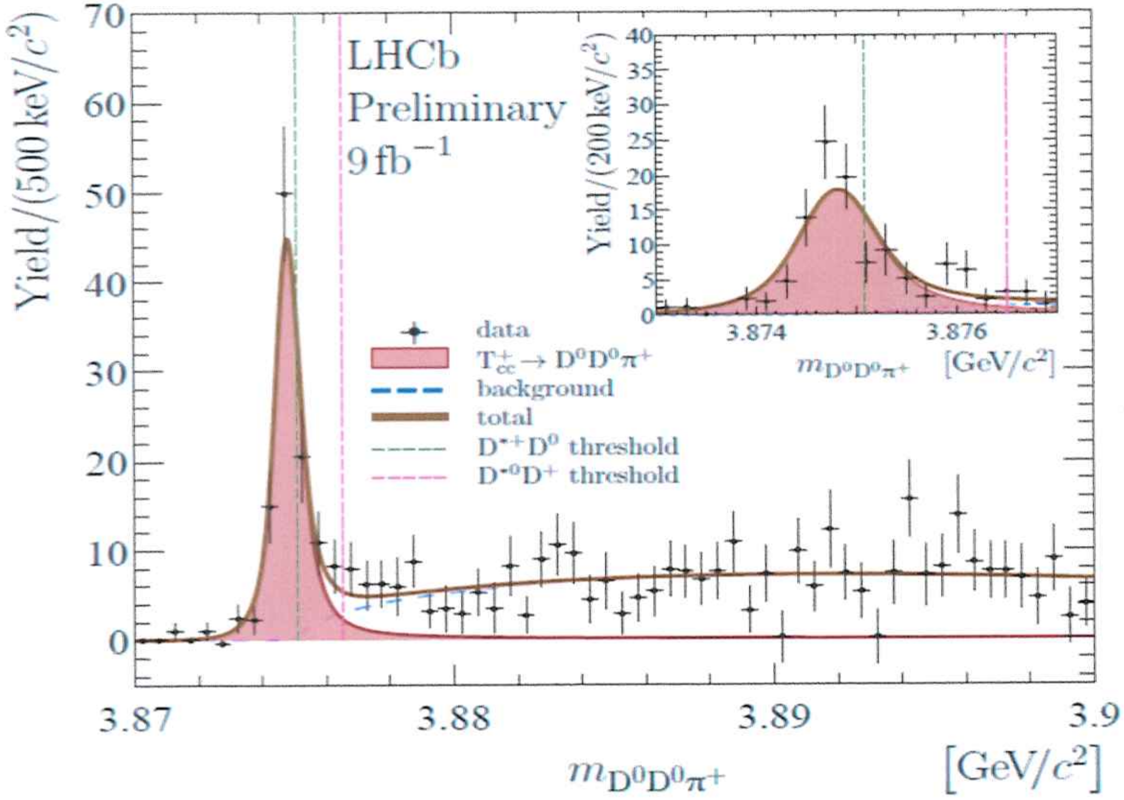


FIG. 1. Newly measured isoscalar charmed T_{cc}^{+} tetraquark by LHCb [48].

Tetraquark puzzle

- $HH\bar{L}\bar{L}$ — several predictions (positive / negative within ± 200 MeV)
- Measurement of $\Xi_{cc}^{++}(3621)$ fixed the normalization for $\bar{b}\bar{b}ud$ tetraquark. (Karliner, Rosner 2017, Eichten – Quigg (2017)), bounded up to 200 MeV (!).
- In holographic picture, role of the instanton (baryons, pentaquark) is placed by sphaleron (Baryon # = 0), binding two heavy mesons. (Liu, MAN, Zahed 2019) $bb\bar{q}\bar{q}$ bounded 80 MeV, $cc\bar{q}\bar{q}$ bounded by 40 MeV
- $T_{cc}^{+}(01^{+})$, narrow, discovered at LHCb, bounded at −360 keV, $\Gamma \sim 50$ keV
- Normalizing mass to T_{cc}^{+}, we (Liu, MAN, Zahed, 2022) predict mass of T_{bc} and T_{bb}, and calculate very narrow width. ($m_H = \infty$)

TABLE I. Binding energies for tetraquarks versus the $'$t Hooft coupling $\lambda = g_{\rm YM}^2 N_c$ with $M_{\rm KK} = 1$ GeV

λ	$QQ\bar{q}\bar{q}$ GeV	$bb\bar{q}\bar{q}$ GeV	$bc\bar{q}\bar{q}$ GeV	$cc\bar{q}\bar{q}$ GeV
10	−0.097	−0.088	−0.080	−0.072
15	−0.107	−0.091	−0.077	−0.062
20	−0.108	−0.085	−0.064	−0.041
25	−0.103	−0.073	−0.045	−0.018
30	−0.093	−0.056	−0.024	−0.0016
32	−0.089	−0.048	−0.015	0.00073

TABLE II. Binding energies for tetraquarks versus the $'$t Hooft coupling $\lambda = g_{\rm YM}^2 N_c$ with $M_{\rm KK} = 0.475$ GeV.

λ	$QQ\bar{q}\bar{q}$ GeV	$bb\bar{q}\bar{q}$ GeV	$bc\bar{q}\bar{q}$ GeV	$cc\bar{q}\bar{q}$ GeV
10	−0.046	−0.044	−0.042	−0.040
15	−0.051	−0.047	−0.044	−0.040
20	−0.051	−0.046	−0.040	−0.035
25	−0.049	−0.042	−0.035	−0.028
30	−0.045	−0.035	−0.027	−0.019
40	−0.031	−0.018	−0.0076	0.0011

Summary:

- Strongly coupled QCD could be approached via duality from string theory in large N_c and large λ limit, including spectra of heavy-light hadrons
- Few parameters and very restrictive predictions, so models are confutable
- Approach based on confinement, SBχS and heavy spin symmetry, in the limit of large N_c and large 't Hooft coupling.
- "High brow" theory boils down to relatively simple QM in moduli space
- Astonishing and deep analogies to "old" physics.

particles

Sakai - Sugimoto table

our table (I)