Hadronic Physics & Exotics

Chris Quigg
Fermilab

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Hadronic Physics Self-Assessment

▷ Hadron phenomenology & spectroscopy does not test standard model

▷ We have a qualitative understanding of QCD phenomenology

▷ Many aspects are not calculable from first principles

▷ We make models for new (and old!) states

- *approximations such as potential models*
- *intuitive pictures of substructure*
- *competing pictures are not mutually exclusive*
- *quantum superpositions are possible*

▷ We'll never throw out QCD if these pictures don't work for the next state we find

These are fair observations . . .

- ▷ Fundamental *vs.* applied science?
- ▷ Exploration — discovering phenomena & systematics — helps us understand what are the fundamental questions
- ▷ Physics doesn't only advance by perturbation theory . . .
  One of QCD's signal achievements is explaining what sets the mass of the proton—or, if you like, what accounts for nearly all the visible mass of the Universe. Heller
- ▷ Synthesis of principles through dialogue with experiment
- ▷ Habits of mind we will cherish when the LHC brings surprises

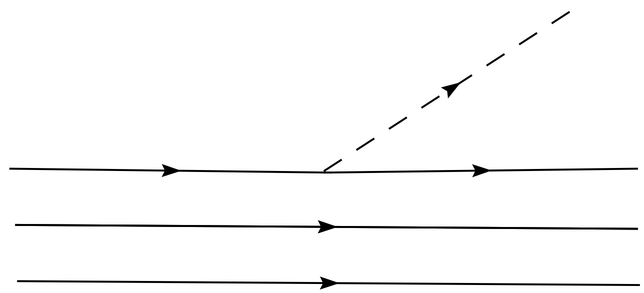
▷ Distinguish models, controlled approximations

▷ The value of a physical picture . . .

can give "answer" (whether or not precise and controlled)

or show that simplifying assumptions are unwarranted

Chiral Quark Model points to asymmetry in light-quark sea, negative polarization of strange (but not antistrange) sea.



▷ What is a hadron?

What are the apt degrees of freedom?

What symmetries are fruitful?

What implications of QCD under extreme conditions?

Where is the proton's spin?

▷ Still haven't accounted for the spin of a polarized proton

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

▷ COMPASS: improves determination $\Delta\Sigma = 0.237^{+0.024}_{-0.029}$

▷ COMPASS: $\Delta G/G$ small near $x = 0.1$ Pretz, Procureur

$$\frac{\Delta G}{G}(x_g = 0.1) = +0.024 \pm 0.089 \pm 0.057$$

▷ HERMES: Transverse-spin effects $\leadsto L_q$; Avetisyan
Belle: Fragmentation fcn of $\perp$-polarized quark Seuster

Searching for Connections

- ▷ to the Lagrangian
- ▷ to effective theories (such as chiral quark models)
- ▷ to heavy quark symmetry, HQET
- ▷ to lattice QCD
- ▷ to knowledge of nuclear forces
- ▷ to hadronic matter under extreme conditions
- ▷ among experiments, observations;
  knowing enough to notice that something *doesn't fit*

Toward Controlled Approximations

▷ NRQCD for heavy-heavy systems $(Q_1\bar{Q}_2)$

$m_{Q_i} \gg \Lambda_{\mathrm{QCD}}$

expansion parameter v/c

▷ HQET for heavy-light systems $(Q\bar{q})$

$m_Q \gg \Lambda_{\mathrm{QCD}}$; $\vec{j}_q = \vec{L} + \vec{s}_q$

expansion parameter $\Lambda_{\mathrm{QCD}}/M_Q$

▷ Chiral symmetry for light quarks $(q_1\bar{q}_2)$

$m_{q_i} \ll \Lambda_{\mathrm{QCD}}$

expansion parameter $\Lambda_{\mathrm{QCD}}/4\pi f_\pi$

▷ Lattice QCD

Seeking the Relevant Degrees of Freedom

Under what circumstances are diquarks useful / essential?

Correlations among quarks long known . . .

▷ $x \to 1$ behavior of proton parton distributions:

- $F_2^n / F_2^p \not\to \frac{2}{3}$
- Spin differs from SU(6) wave functions

▷ $\mathbf{3} \otimes \mathbf{3}$ attractive in $\mathbf{3}^*$ (half as strong as in $\mathbf{3} \otimes \mathbf{3}^* \to \mathbf{1}$?)

▷ Scalar nonet $f_0(600) = \sigma, \kappa(900), f_0(980), a_0(980)$ as $qq\bar{q}\bar{q}$ organized into diquark–antidiquark $\mathbf{3} \otimes \mathbf{3}^*$

Chew–Frautschi systematics for N, Δ Selem & Wilczek

If light baryons *are usefully viewed as* $q[qq]_{\mathbf{3}^*}$ ...

Test and extend the idea:

- $\rightsquigarrow QQq$ baryons (and comparison with $Q\bar{q}$)
- systematics of $qq \cdot \bar{q}\bar{q}$ states; extension to $Qq \cdot \bar{Q}\bar{q}$ states
- shape of baryons (at least high-spin?) in lattice QCD
- comparison with $1/N_c$ systematics?
- configurations beyond qqq and $\bar{q}q$?
- role of diquarks in color–flavor locking, color superconductivity, etc.
- colorspin as an organizing principle? mass effects ...

Exotic Baryons (Pentaquarks)

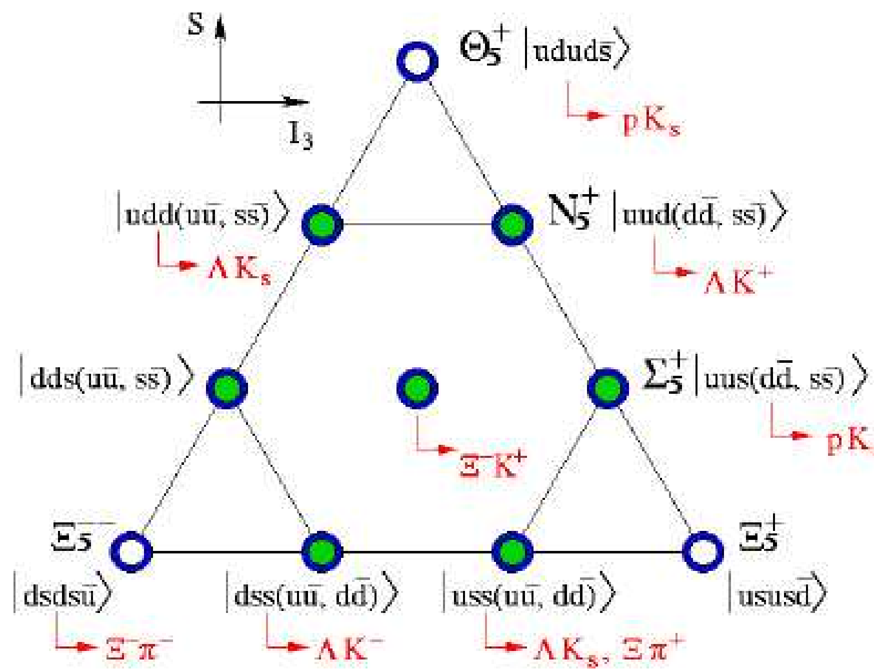
Claims for narrow exotic baryons:

$\Theta^{+}(\approx 1540)$: many sightings . . .

$\Theta^{++}(1530)$: STAR

$\Xi^{--,0}(1862)$: NA49

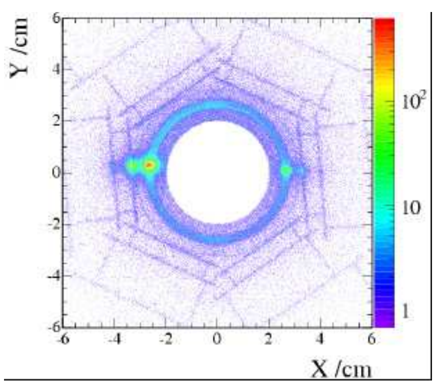
$\Theta_c^{0}(3099)$: H1

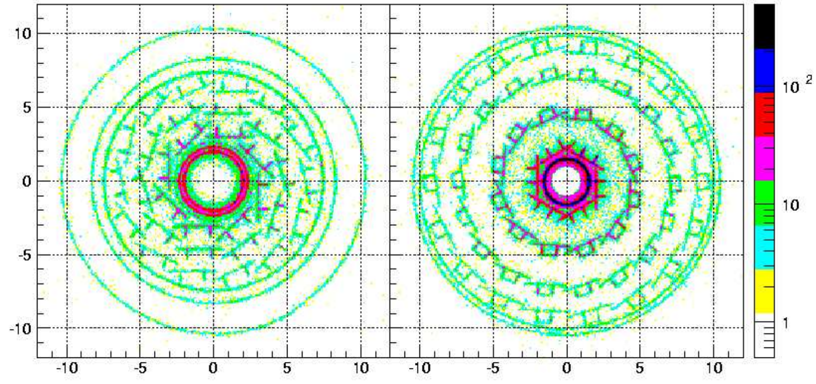


No claim is unchallenged!

Hard to argue that every experiment is significant, correctly interpreted.

- CLAS (JLab) $\gamma p \to K_S K^+ n$: ~ 1500 counts / 4-MeV bin: no signal
- CLAS (JLab) $\gamma d \to K^- p K^+ n$: no signal; increased estimate of background reduces significance of original claim to $\sim 3\sigma$
- DELPHI limits in Z decay — Pukhaeva
- HERA-B no observation of Θ^+, Ξ^{--} — Živko
- Status reports on H1, ZEUS — Chekanov, Ozerov
- BaBar & Belle interactions with detector elements — Graugés, Mizuk

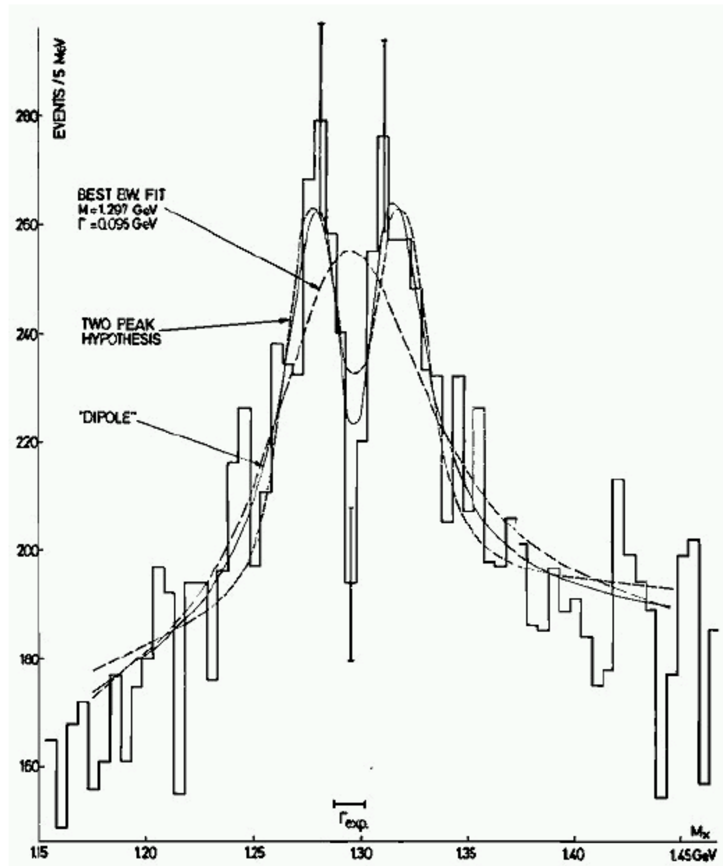




The case for exotic baryons remains unproved . . .

Details: V. Burkert @ Uppsala

"Split A_2"

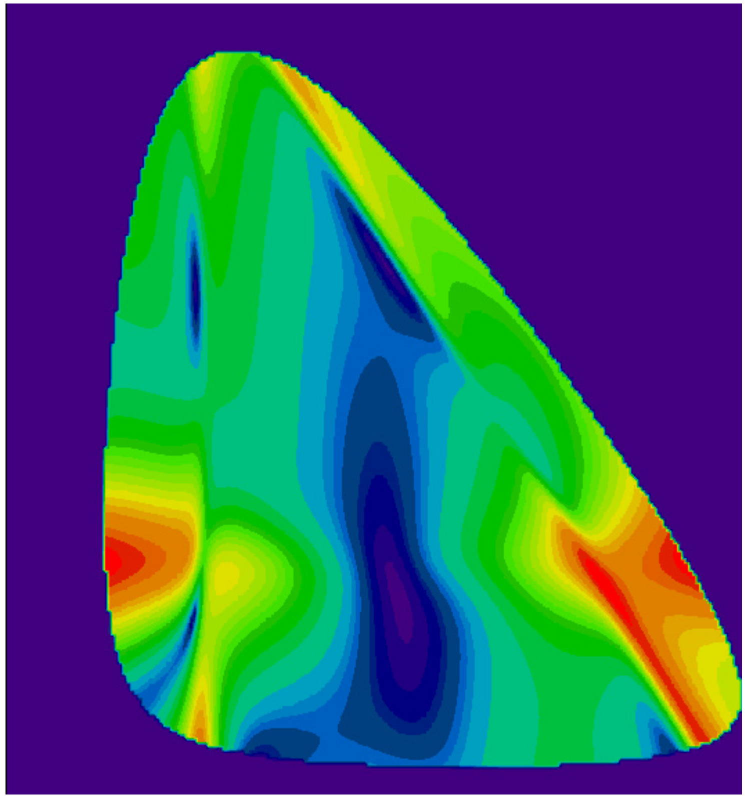


. . . 1969 Lund Conference

Dalitz-Plot Analyses

Access to amplitudes and phases

Selen



$(D^0 \to K^- \pi^+ \pi^0)$

CLEO-c goal: determine strong phase between $D^0 \to K^\pm K^{*\mp}$ for extraction of $\phi_3 = \gamma$ from $B^\pm \to K^\pm K^{*\mp} K^\pm$

Dalitz-Plot Analyses

BaBar study of $D^0 \to \bar{K}^0 K^+ K^-$ Altenburg

Partial-wave analysis on the Dalitz plot

$\leadsto$ dominant channels $D^0 \to \bar{K}^0 a_0(980), \bar{K}^0 \varphi, K^- a_0^+(980)$

Exploring the scalar nonet

KLOE study of $e^+e^- \to \varphi \to \gamma f_0(980), \gamma a_0(980)$ Gauzzi

$e^+e^- \to \varphi \to \gamma\eta$ slope parameters in 5-, 7-γ final states

$$\mathcal{B}(\eta \to \pi^0\gamma\gamma) = (8.4 \pm 2.7 \pm 1.4) \times 10^{-5}$$

$1/10\times$ GAMS result (1984), in line with chiral perturbation theory

Stretching our models, calculations

Leaving the comfort zone, looking for unseen effects

Extend descriptions of ψ, Υ to B_c

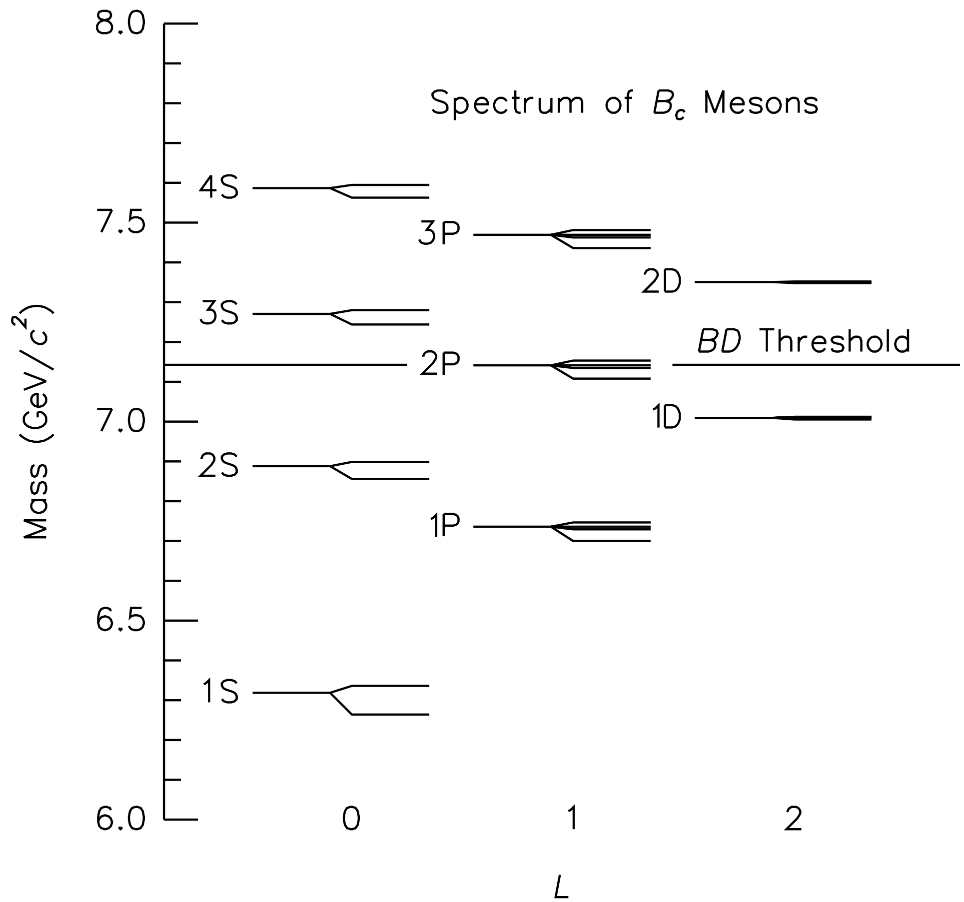
$B_c \to \pi J/\psi, a_1 J/\psi, J/\psi \ell \nu$

hadronic, γ cascades to B_c

interpolates $Q\bar{Q}$, $Q\bar{q}$, but c more relativistic than in $c\bar{c}$, unequal-mass kinematics: $\rightsquigarrow$ enhanced sensitivity to effects beyond NRQM?

CDF: $M(B_c) = 6287 \pm 5$ MeV

Lattice: 6304 ± 20 MeV



D_{sJ} Levels

▷ Two states well established, properties converging

J^{PC} seem consistent with $j_q = \frac{1}{2}$ $c\bar{s}$ levels,

but centroid well below $j_q = \frac{3}{2}$, so quite narrow

disagrees with relativistic potential models

$$0^+ : \; D_{sJ}^*(2317) \to D_s\pi^0;\; 1^+ : \; D_{sJ}(2460) \to D_s\gamma, D_s^*\pi^0$$

$$1^+ : \; D_{s1}^*(2536);\; 1^+ : \; D_{s2}^*(2573)$$

Is there a simple, graceful interpretation?

$c\bar{s}$ or DK or tetraquark

Radiative decays to distinguish Colangelo

What happens in B_s system?

(Meson classification schemes)

Compare LS and jj coupling in atoms

Choice of basis (mis)guides our thinking . . .

▷ Equal-mass $q\bar{q}$ or $Q\bar{Q}$: Couple $\vec{L}$ with $\vec{S} = \vec{s}_q + \vec{s}_{\bar{q}}$

Standard for light mesons, now familiar for $c\bar{c}$, $b\bar{b}$

$\Rightarrow$ $^1\mathrm{S}_0$ – $^3\mathrm{S}_1$; $^1\mathrm{P}_1$ – $^3\mathrm{P}_{0,1,2}$; $^1\mathrm{D}_2$ – $^3\mathrm{D}_{1,2,3}$; ^1L_L – $^3L_{L-1,L,L+1}$

▷ Heavy=light $Q\bar{q}$: Couple $\vec{s}_Q$ with $\vec{j}_q = \vec{L} + \vec{s}_q$

$L = 0$: $j_q = \frac{1}{2}$: 0^- – 1^-

$L = 1$: $j_q = \frac{3}{2}$: 1^+ – 2^+ (d-wave decay);

$j_q = \frac{1}{2}$: 0^+ – 1^+ (s-wave decay)

Strange particles ($s\bar{q}$): Traditional $q\bar{q}$ classification, but maybe insights from considering as $Q\bar{q}$? PRL **71,** 4116 ('93)

Hint of Configuration Mixing

Belle: Angular analysis of $(j_\ell = \frac{3}{2})\ D_{s1}(2536) \to D^{*+}K_S$ indicates large s-wave amplitude (not pure d-wave), yet $\Gamma < 2.3$ MeV Drutskoy

Mixing with $D_{sJ}(2460)$?

(Phase space limited)

A New Element?

▷ Could chiral symmetry and confinement coexist?

- Expect chiral supermultiplets: states with $L, L+1$, same j_q:

  $j_q = \frac{1}{2}$: 1S$(0^-, 1^-)$ and 1P$(0^+, 1^+)$

  $j_q = \frac{3}{2}$: 1P$(1^+, 2^+)$ and 1D$(1^-, 2^-)$

- Hyperfine splitting $M_{D_s(1^+)} - M_{D_s(0^+)} = M_{D_s(1^-)} - M_{D_s(0^-)}$
- Predictions for decay rates match experiment (so far)
- How far is QCD from this situation?

Bardeen, Eichten, Hill, PRD **68,** 054024 (2004)

Quarkonium Spectroscopy

A flood of beautiful new results

- CLEO discovery of $h_c(1^1\mathrm{P}_1)$ in $\psi' \to \pi^0 h_c$ Miller
  $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV $\approx \langle M(1^3\mathrm{P}_J)\rangle - 1$ MeV
- Belle $\gamma\gamma \to \eta_c, \chi_{c0}, \chi_{c2} \to h^+h^-, h^+h^-h^+h^-$ Sokolov
  rates $\Gamma(\eta_c \to \gamma\gamma)\mathcal{B}(\eta_c \to f)$ about $1/3\times$ PDG rates
- CLEO observation of $\psi(3770) \to \pi\pi J/\psi$ Miller
  $\mathcal{B}(\psi(3770) \to \pi^+\pi^- J/\psi) = (189 \pm 22^{+7}_{-4}) \times 10^{-5}$
  and $\Gamma(\psi(3770) \to \gamma\chi_{c1}) = 78 \pm 19$ keV
- CLEO $\mathcal{B}(\Upsilon(5S) \to B_s^{(*)}\bar{B}_s^{(*)}) = 16.0 \pm 2.6 \pm 6.3\%$ Duboscq
  $\Gamma(\Upsilon(1\mathrm{S}) \to e^+e^-) = 1.336 \pm 0.009 \pm 0.019$ keV (+ 2S,3S)

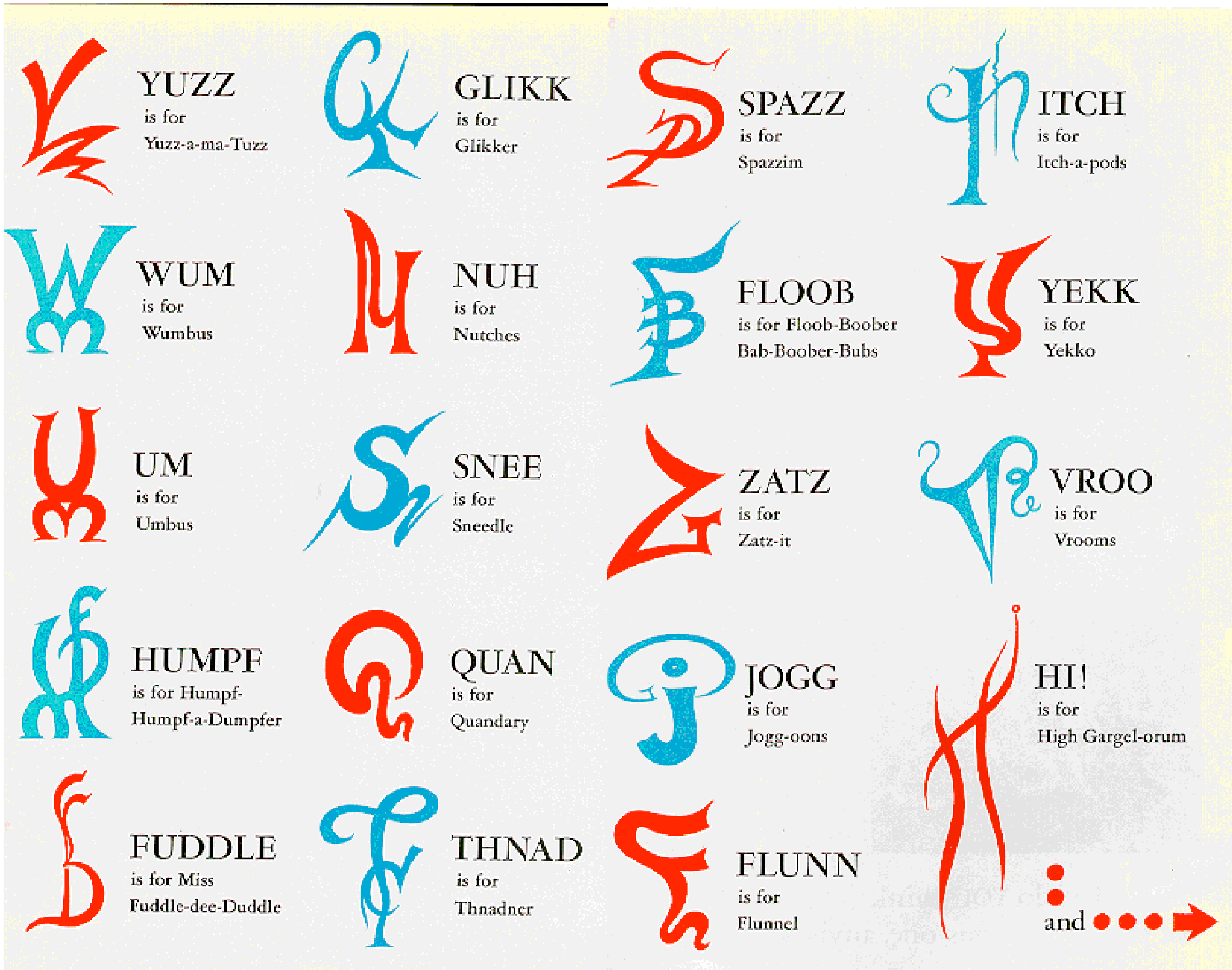
- KEDR $M(\psi') = 3686.117 \pm 0.012 \pm 0.015$ MeV   Todyshev
  $M(\psi(3770) = 3773.5 \pm 0.9 \pm 0.6$ MeV
- Belle Observe $\Upsilon(4\mathrm{S}) \to \pi^+\pi^-\Upsilon(1\mathrm{S})$ Sokolov
  38 ± 6.9 events, $\mathcal{B} = (1.1 \pm 0.2 \pm 0.4) \times 10^{-4}$
- CLEO Observe $\chi_b'(2^3\mathrm{P}_{2,1}) \to \pi^+\pi^-\chi_b(1^3\mathrm{P}_{2,1})$ Duboscq
  $\Gamma \approx 0.9$ keV (first non-$^3\mathrm{S}_1$ transition seen)

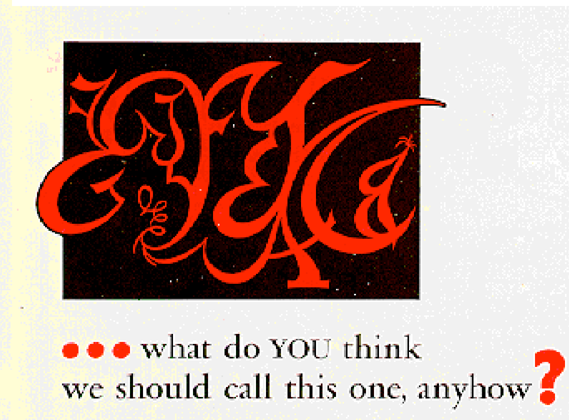
New States Associated with Charmonium

- $\eta_c'(3637)$: $2^1\mathrm{S}_0$
- $h_c(3524)$: $1^1\mathrm{P}_1$ — CLEO (E835)
- $X(3872)$: $J^{PC} = 1^{++}$, *probably not charmonium* — Pakhlov
- $Y(3940 \pm 11)$: seen in $B \to K\omega J/\psi$; $\Gamma = 92 \pm 24$ MeV — Belle
- $X(3936 \pm 14)$: seen in $e^+e^- \to J/\psi + X$ — Belle, hep-ex/0705019
  $\Gamma = 39 \pm 24$ MeV; $\to D\bar{D}^*, \not\to D\bar{D}$ — $\eta_c''(3^1\mathrm{S}_0)$ candidate
- $Z(3931 \pm 4 \pm 2)$: seen in $\gamma\gamma \to D\bar{D}$ — Belle, hep-ex/0507033
  $\Gamma \approx 20$ MeV, consistent with 2^{++} — χ_{c2}' $(2^3\mathrm{P}_2)$ candidate
- $Y(4260)$: 1^{--} seen in $e^+e^- \to \gamma\pi^+\pi^- J/\psi$ — BaBar, hep-ex/0506081
  $\Gamma \approx 50 \sim 90$ MeV; also in $B \to K^- J/\psi\pi\pi$ — hep-ex/0507090

(More Charmonium Levels to Be Found)

- $\psi_2(3831)$ $(1^3\mathrm{D}_2{:}2^{--}) \to \gamma\chi_{c1,2}, \pi\pi J/\psi, \not\to D\bar{D}$
- $\eta_{c2}(3838)$ $(1^1\mathrm{D}_2{:}2^{-+}) \to \gamma h_c, \pi\pi\eta_c, \not\to D\bar{D}$
- $\psi_3(3868)$ $(1^3\mathrm{D}_3{:}3^{--}) \to D\bar{D}$, $\Gamma \lesssim 1$ MeV
- $\psi_4(4054)$ $(1^3\mathrm{F}_4{:}4^{++}) \to D\bar{D}$, $\Gamma \lesssim 5$ MeV
- (not to mention hybrid $c\bar{c}g$ levels)





Dr. Seuss, *On Beyond Zebra*

What is $X(3872) \to \pi\pi J/\psi$?

- Candidate ψ_2 or ψ_3, but no radiative decays seen
- $\pi\pi$ mass spectrum suggests $J/\psi\,\rho$ decay $\leadsto$ not (pure) $I = 0$ $\boxed{\pi^0\pi^0?}$
- $J/\psi\,3\pi$ decay suggests $J/\psi\,\omega$ decay
- $J/\psi\,\gamma$ decay determines $C = +$ (4.4σ observation)
- Angular distributions support $J^{PC} = 1^{++}$;
  $2^1\mathrm{P}_1$ is too massive, especially if $Z(3931)$ is $2^3\mathrm{P}_2$

If not charmonium . . .

- s-wave cusp at $D^0\bar{D}^{*0}$ threshold — Bugg
- $D^0 - \bar{D}^{*0}$ "molecule" bound by pion exchange — Tørnqvist, Swanson
- Diquark–antidiquark "tetraquark" state $[cq][\bar{c}\bar{q}]$ — Piccinini

Distinctive Predictions?

- Threshold bumps at all thresholds (?) no excitations
- No pion exchange for $D_s \bar{D}_s^* \rightsquigarrow$ no analogue molecule
- Tetraquark interpretation suggests split $X(3872)$ and excited states
- What happens in the $b\bar{b}$ system?
- If a dynamical level and a threshold coincide? Braaten & Kusunoki

For quarkonium:

Increasing effectiveness of lattice QCD (below threshold) Davies

influence of gluons, . . .

Coupled-channel potential models are useful interpretive tools

Experiment – Theory Dialogue

BaBar suggestion (inconclusive but provocative) (hep-ex/0507090):

$B^- \to K^- X(3872)$	61.2 ± 15.3 events	$3871.3 \pm 0.6 \pm 0.1$ MeV
$B^0 \to K^0 X(3872)$	8.3 ± 4.5 events	$3868.6 \pm 1.2 \pm 0.2$ MeV
	$\Delta M =$	$2.7 \pm 1.3 \pm 0.2$ MeV

Tetraquark: two states, $\Delta M \approx 7$ MeV

$$\mathcal{R} \equiv \frac{\mathcal{B}(B^0 \to K^0 X(3872))}{\mathcal{B}(B^- \to K^- X(3872))} = 0.50 \pm 0.30 \pm 0.05$$

Tetraquark: $\mathcal{R} \approx 1$;   Molecule: $\mathcal{R} \lesssim 0.1$

Hadron physics is rich in opportunities

- ▷ Models are wonderful exploratory tools
- ▷ Make contact with lattice, symmetries at every opportunity
- ▷ Build coherent networks of understanding
- ▷ Tune between systems: models beyond their comfort zones
- ▷ Relate mesons to baryons (quarks to diquarks?)
- ▷ Look beyond qqq and $q\bar{q}$:
  exotics, matter under unusual conditions

Focus on what we can learn of lasting value