Progress in understanding subunits of matter and forces among them

1957: A small “zoo” of particles existed which could be listed on wallet cards. These included the neutron, proton, pi meson, and “strange” relatives

Four fundamental forces: strong, weak, electromagnetic interactions and gravity. Parity (mirror symmetry) violation was discovered in the weak interactions.

Since then, the “zoo” grew to over 400 particles understood in terms of a few basic “quark” constituents. Two of the fundamental forces – weak and electromagnetic – were unified. Theory of strong interactions (QCD) was proposed and verified.

Heavy quarks $Q$: valuable tests of QCD and its manifestations

Today: What we can learn from heavy quarkonia ($c\bar{c}$, $b\bar{b}$)

Including some CLEO searches for $b\bar{b}$ spin singlets in $\Upsilon(nS)$ decays

Unexpected results can give insights into strong interactions or new physics
THE CHARMED QUARK

Lepton “doublets”: \( \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \) (1956); \( \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \) (1962). Rabi: “Who ordered that?”

These doublets participate in weak interactions, e.g., \( n \rightarrow p e^- \bar{\nu}_e \)

1964: Bjorken–Glashow, … proposed quark–lepton analogy, \( \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix} \) for greater lepton–quark symmetry, with weak interactions involving the transitions

\[ u \leftrightarrow d' = d \cos \theta + s \sin \theta, \quad c \leftrightarrow s' = -d \sin \theta + s \cos \theta \]

So charmed quarks would decay mainly to strange quarks.


1974: Charmed quark \( c \) \([M(c) \simeq 1.5 \text{ GeV}]\) identified via \( J/\psi = c \bar{c} \). Charmonium \((c \bar{c})\) spectrum is still evolving; many new states discovered in past three years

1975-6: Particles containing a single charmed quark, e.g. \( \Lambda_c = cud \), \( D^0 = c \bar{u} \), \( D^+ = c \bar{d} \), \( D^+_s = c \bar{s} \). Today: rich spectrum of states; new every year.
At the same time as charm: the $\tau$ lepton (M. Perl, 1974)

Electron-positron ($e^-e^+$) annihilation produces all fermions $f$ and their antiparticles $\bar{f}$ with rates ($Q_f =$ charges):

$$
\sigma = \frac{4\pi\alpha^2}{3E_{c.m.}^2} Q_f^2
$$

One can measure the ratio $R \equiv \frac{\sigma(e^+e^-\to \text{hadrons})}{\sigma(e^+e^-\to \mu^+\mu^-)} = \sum Q_q^2$

$Q_q$ is the charge of quark $q$: $2/3$ for $u, c; -1/3$ for $d, s$.

$R$ increased more above charm threshold than expected.

Production of $\tau^+\tau^- \ [m(\tau) \simeq 1.8 \text{ GeV}/c^2]$ contributed to $R$. 
Quark-lepton analogy:

\[
\begin{pmatrix}
\nu_e \\
e^-
\end{pmatrix}
\begin{pmatrix}
\nu_\mu \\
\mu^-
\end{pmatrix}
\begin{pmatrix}
\nu_\tau \\
\tau^-
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
u \\
u_d \\
\tau^-
\end{pmatrix}
\begin{pmatrix}
c \\
s \\
b
\end{pmatrix}
\begin{pmatrix}
t \\
b \\
b
\end{pmatrix}
\]

Existence of a third lepton pair \((\nu_\tau, \tau^-)\) implied existence of a third quark pair \((t [top], b [bottom])\), predicted by Kobayashi and Maskawa.

1977 (Fermilab): A family of spin–1 \(b\bar{b}\) particles produced in \(pp\) interactions, decaying to \(e^+e^-, \mu^+\mu^-\): lightest at 9.46 GeV/\(c^2\).

Rich \(b\bar{b}\) spectroscopy as well as “\(B\)” mesons containing a single \(b\) quark: \(B^+ = \bar{b}u\), \(B^0 = \bar{b}d\) (Cornell, early 1980s), \(B_s = \bar{b}s\), excited states; baryon \(\Lambda_b = bud\), \ldots today: \(b\bar{b}\) discoveries and issues.

Discovery of top in 1994: Fermilab Tevatron collided protons with antiprotons to produce \(t\bar{t}\) pairs; \(m_t \sim 171\) GeV/\(c^2\). Top decays too quickly for toponium \((t\bar{t})\) spectroscopy to be of much interest.
This may be all the quarks and leptons. Attention has turned to the pattern of weak charge-changing transitions among them, in order to understand CP violation. Today we will discuss $c\bar{c}$ and $b\bar{b}$ spectra.

Exercise: *Explain* the pattern of masses and transitions!
Today: Selected topics with emphasis on CLEO contributions and questions for theory (particularly lattice): (1) $\psi(2S) \rightarrow \gamma \eta_c$; (2) $h_c$ observation; (3) $X, Y, Z$ states near 3940 MeV; (4) $Y(4260)$ and (5) $Z(4430)$ and their relation to thresholds.
CLEO is studying exclusive and inclusive $\psi(2S) \rightarrow \gamma \eta_c$

Exclusive:

Inclusive:

Measure $B[\psi(2S) \rightarrow \gamma \eta_c] = (4.02 \pm 0.11 \pm 0.52) \times 10^{-3}$ (preliminary)

Unusual $\eta_c$ line shape: enhancement at large $E_\gamma$. Can lattice reproduce this?

Since $\langle 1S | j_0(E_\gamma r/2) | 2S \rangle \sim E_\gamma^2$, expect $\Gamma \sim E_\gamma^3(E_\gamma^2)^2 = E_\gamma^7$ (need cutoff)
Hyperfine splittings test spin-dependence and spatial behavior of $Q\bar{Q}$ force

$S$-wave $\Delta M$'s: $M(J/\psi) - M(\eta_c) \simeq 115$ MeV (1S), $M(\psi') - M(\eta_c') \simeq 49$ MeV (2S).

Expect $\leq$ few MeV $P$-wave splittings (Coulombic vector $c\bar{c}$ interaction; $\sqrt{s}$ lattice)

CLEO: Observation in $\psi(2S) \to \pi^0 h_c$, $h_c \to \gamma \eta_c$ [PRL 95, 102003 (2005); PRD 72, 092004 (2005)]

Inclusive, exclusive analyses saw a signal near $\langle M(^3P_J) \rangle = 3525.36 \pm 0.06$ MeV/$c^2$

Exclusive analysis reconstructed $\eta_c$ in 7 decay modes ($\sim 10\%$ of all $\eta_c$ decays)

Inclusive: No $\eta_c$ reconstruction: better statistics but more background

Hyperfine interaction $\sim \nabla^2 V_V(r)$

Small $P$-wave $\Delta M$ favors local $\nabla^2 V_V(r)$ (one-gluon exchange)
19 candidates identified; 17.5 ± 4.5 events above background.

Excl.+incl.: $M(h_c) = (3524.4 \pm 0.6 \pm 0.4)$ MeV, $B_1 B_2 = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$

Mass was $(1.0 \pm 0.6 \pm 0.4)$ MeV below $\langle M(3P_J) \rangle$; $B_1 B_2 \sqrt{\text{theory}} (10^{-3} \cdot 0.4)$
NEW $h_c$ RESULTS

Earlier results were based on 3 M $\psi(2S)$; now 24.5 M additional

Inclusive:                   Exclusive (18 modes):

Inclusive process yields product of branching ratios (preliminary)
\[ \mathcal{B}[\psi(2S) \to \pi^0 h_c]\mathcal{B}[h_c \to \gamma \eta_c] = (3.96 \pm 0.41 \pm 0.55) \times 10^{-4} \]
**X(3872):** \(1^{++}\) MOLECULE

Discovered \(\rightarrow \pi^+\pi^- J/\psi\) by Belle in \(B \rightarrow K X(3872)\) (BaBar, CDF, D0, \ldots \sqrt{\cdot})

Details of \(J^{PC}\) conclusion: Belle analysis, ang. dists. PRD 70, 094023

Well above \(D \bar{D}\) threshold; favors unnatural \(J^P = 0^-, 1^+, 2^-\) \((J \geq 3\) unlikely)

hep-ex/0505038: \(J^{PC} = 1^{++}\) favored (angular dists.; \(\rho J/\psi\) and \(\omega J/\psi\) decays)

Could be S-wave bound state of \((D^0 \bar{D}^{*0} + \bar{D}^0 D^{*0})/\sqrt{2} \sim c\bar{u}u\bar{c}; c\bar{d}d\bar{c}\) channel closed. Decays to \(\gamma J/\psi\) (hep-ex/0505037) \(\Rightarrow\) some \(c\bar{c}\) in wave function. BaBar [PRL 96, 052002 (2006)] finds \(B(\pi^+\pi^- J/\psi) > 0.042\) \((90\% \text{ c.l.})\). CDF: \(2^{-+}\)?

Two mesons sharing \(q, \bar{q}\) always form \(\geq 1\) resonance below \(p_{cm} = 350\) MeV [PRD 6, 2717 (1972)] but may be much lower if neither is a \(\pi\)
\textbf{\(c\bar{c}\) ABOVE THRESHOLD}

\textbf{\(X(3940)\): Candidate for \(\eta_c''(3^1S_0)\)}

Belle, PRL 98, 082001 (2007); arXiv: 0708.3812: updated \(M, \Gamma = (37^{+26}_{-15} \pm 8)\)

\(X(3940)\) recoiling against \(J/\psi\) decays to \(D\bar{D}^* + \text{c.c.}, \) not \(\omega J/\psi\)

All lower recoiling states have \(J = 0\): \(\eta_c(2980), \chi_{c0}(3415), \eta'_c(3637)\) (but what about recent Belle observation of a state at 4160 decaying to \(D^*\bar{D}^*\)?)

\textbf{\(Y(3940)\): Candidate for excited \(J = 1\) state \(\chi'_{c1}(2^3P_1)\)}

Belle: \(B \rightarrow KY \rightarrow K\omega J/\psi\) [PRL 94 182002 (2005)]; BaBar √: arXiv:0711.2047

A similar decay was seen by CLEO in the \(b\bar{b}\) system: \(\chi'_b \rightarrow \omega \Upsilon\)

\textbf{\(Z(3930)\): Excited \(J = 2\) state \(\chi'_{c2}(2^3P_2)\)}

Belle [PRL 96, 082003 (2006)]: \(\gamma\gamma \rightarrow D\bar{D}\) spectrum shows a peak at \(M = 3929\pm5\pm2\) MeV, \(\Gamma = 29\pm10\pm2\) MeV, \(\Gamma_{ee}\mathcal{B}(D\bar{D}) = 0.18\pm0.05\pm0.03\) keV

Angular distribution consistent with \(\sin^4 \theta^* \) (\(J = 2, \lambda = \pm2\))

\(X, Y, Z\) should have \(E1\) transitions to lower charmonium states

Barnes + PRD 72, 054026 (2005); Eichten + PRD 73, 014014 (2006)
**Y(4260): HYBRID?**

BaBar: $Y(4260)$ in radiative return to $\pi^+\pi^- J/\psi$: PRL 95, 142001 (2005).

CLEO (Q. He +, PR D 74, 091104), Belle (PRL 99, 182004): $\sqrt{ }$ radiative return

CLEO evidence for $Y(4260)$ in direct scan:

- $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ (11$\sigma$)
- $\pi^0\pi^0 J/\psi$ (5.1$\sigma$), $K^+K^- J/\psi$ (3.7$\sigma$)
- $\psi(4160) \rightarrow \pi^+\pi^- J/\psi$ (3.6$\sigma$), $\pi^0\pi^0 J/\psi$ (2.6$\sigma$), consistent with $Y(4260)$ tail
- $\psi(4040) \rightarrow \pi^+\pi^- J/\psi$ (3.3$\sigma$)

T. E. Coan +, PRL 96, 162003:
- $\pi^0\pi^0 J/\psi$: not $\rho^0 J/\psi$ molecule
- Small $\Delta R$: not likely 4S state

$cq\bar{c}q$ also proposed; how to tell from hybrid $c\bar{c}g$?

Also $\pi^+\pi^- \psi(2S')$ states at 4360$^*$, 4660$^+$ MeV (*BaBar, $^+$Belle) in rad. return
If $Y(4260)$ is a hybrid $(c\bar{c} + \text{gluon})$, one expects it to couple to $D\bar{D}_1 + \text{c.c.}$, where $D_1$ is a P-wave $c\bar{q}$ pair. Dip in $R_{e^+e^-}$ just below threshold!

$D\bar{D}_1$ threshold is $\sim 4287$ MeV: $Y(4260)$ a $D\bar{D}_1(\rightarrow D\pi\bar{D}^*)$ “molecule”?

B. Lang [for CLEO], arXiv:0710.0165: No $D\pi\bar{D}^*$ enhancement at 4260 MeV
Dip is just below threshold of lowest-mass charmed meson pair $D^0\bar{D}_1^*$ produced in an $S$-wave. 
(Lower thresholds: $P$-wave production.)

This channel is the expected decay of $Y(4260)$ if it is a hybrid. But it is closed, so other modes (such as $\pi\pi J/\psi$) may be favored instead.

Many other dips are correlated with thresholds [e.g., in $\pi\pi$ $S$-wave near $2M(K)$; $\gamma^* \to 6\pi$ near $2M(p)$; see PR D 74, 076006 (2006).]

BaBar [PRD 74, 091103]: Analogous structure in $e^+e^- \to \phi f_0(980)$ at 2175 MeV

$X(2175)$ as hybrid $s\bar{s}$ candidate in the same way that $Y(4260)$ is a hybrid $c\bar{c}$ candidate? Makes sense if $m_c - m_s \simeq (M_Y - M_X)/2 = 1.04$ GeV

Dip in $e^+e^- \to D^*\bar{D}^*$ (major charm channel) [Belle PRL 98, 092001] at 4250 MeV
**Z(4430) AS THRESHOLD EFFECT**

Belle [arXiv:0708:1790] sees a resonance-like structure in $\pi^\pm \psi(2S)$ with mass $M = 4433 \pm 4 \pm 2$ MeV and width $\Gamma = 44^{+17+30}_{-13-11}$ MeV

First evidence for a genuine “tetraquark” (e.g., $c\bar{c}u\bar{d}$)

Seen in $B \rightarrow K \pi^\pm \psi(2S)$

Example: Mass is very close to threshold for $D^*(2010) + D_1(2420)$

If it is related to the S-wave combination of them then $J^P = (0, 1, 2)^-$

Analogous system with (e.g.) $b\bar{b}u\bar{d}$ would exist near threshold for $B^*(5325) + B_1(5723)$ or 11048 MeV. Could see it in $e^+e^- \rightarrow Z_b(11048)^\pm \pi^\mp$; CLEO has data at suitable energies

Will emphasize CLEO searches for transitions giving $b\bar{b}$ spin-singlets

In M1 transition $\Upsilon(1S') \to \gamma \eta_b(1S')$, 60 MeV $\gamma$ overwhelmed by background

Search for forbidden M1 transitions $\Upsilon(2S,3S') \to \gamma \eta_b(1S')$, reconstructing $\eta_b$ in many (!) multiparticle modes; compare with $\Upsilon(2S,3S') \to \gamma \chi_b^{(f)}$
\textbf{\textit{b\bar{b}} SPIN SINGLETS}

No \textit{b\bar{b}} spin-singlets have been seen yet.

Lattice: predict (i) hyperfine splittings and rates for (ii) allowed M1 transitions; (iii) forbidden M1 transitions; (iv) hadronic transitions (many listed below)

Expect 1S, 2S, 3S hyperfine splittings to be approximately 60, 30, 20 MeV; Lowest P-wave singlet state ("\(h_b\)"") expected to be near \(\langle M(1^3P_J) \rangle \simeq 9900\) MeV/\(c^2\)

Several searches have been performed or are under way in 1S, 2S, 3S CLEO data

\textbf{Searches for \(\eta_b(nS')\) (mixing with pseudoscalar Higgs?)}

Direct search using allowed (soft) M1 photon in \(\Upsilon(1S) \to \gamma \eta_b(1S)\): Reconstruct exclusive final states in \(\eta_b(1S')\) decays. Likely to be high-multiplicity. Expected branching ratio a few parts in \(10^4\): S. Godfrey + JLR, PR D \textbf{64}, 074011 (2001).

Searches for suppressed M1 photons in \(\Upsilon(2S, 3S) \to \gamma \eta_b(1S)\): expected \(E_\gamma \sim 600, 910\) MeV; expected \(B\) few parts in \(10^4\) (Godfrey + JLR) sensitive to relativistic effects. CLEO: \(B[\Upsilon(2S) \to \gamma \eta_b(1S)] < 5.1 \times 10^{-4}\); \(B[\Upsilon(3S) \to \gamma \eta_b(1S)] < 4.3 \times 10^{-4}\); \(B[\Upsilon(3S) \to \gamma \eta_b(2S)] < 6.2 \times 10^{-4}\) [PRL \textbf{94}, 032001 (2005)].

With \(B[\Upsilon(2S) \to \gamma \chi_{b0,1,2}] \simeq (4, 7, 7)\%\), should reconstruct \(\sim 100\) \(\chi_{b0,1,2}\) per \(\eta_b\)
OTHER $\eta_b, h_b$ SEARCHES

Voloshin’s proposed process $\Upsilon(3S) \rightarrow \gamma \chi'_{b0}(2P) \rightarrow \gamma \eta \eta_b(1S)$

We know $B[\Upsilon(3S) \rightarrow \gamma \chi'_{b0}(2P)] \simeq 6\%$

Voloshin estimates $B[\chi'_{b0}(2P) \rightarrow \eta \eta_b]$ could be as large as $10^{-3}$

Warm-up exercise is to identify other rare processes involving $\eta$. We do this in looking for $\Upsilon(2S, 3S) \rightarrow \eta \Upsilon(1S)$.

Search using sequential process $\Upsilon(3S) \rightarrow \pi^0 h_b(1^1 P_1) \rightarrow \pi^0 \gamma \eta_b(1S)$

Expect $B[h_b(1) \rightarrow \gamma \eta_b(1S)] \simeq 40\%$ (allowed E1 transition related to $\chi_b \rightarrow \gamma \Upsilon(1S)$)

Voloshin estimates $B[\Upsilon(3S) \rightarrow \pi^0 h_b(1P)] > 20B[\Upsilon(3S) \rightarrow \pi^+ \pi^- h_b(1P)]$ and could be in the range of $10^{-4}$ to $10^{-3}$

Discovery of $h_c$ was easier: $M(\eta_c)$ was known! If $\eta_b$ is seen in transitions from $\Upsilon(2S, 3S)$, the sequential process holds promise for $h_b(1P)$ discovery.

Search using $\Upsilon(3S) \rightarrow \omega \eta_b(1S)$

Inclusive $\omega \rightarrow \pi^+ \pi^- \pi^0$ signal from $\Upsilon(3S)$ is not impressive

This process may be observable once we learn to select $\eta_b$ final states
\[ \Upsilon(2S) \rightarrow (\eta, \pi^0) \Upsilon(1S) \]

Using scaling laws \( \Gamma \sim (p^*)^3/m_Q^4 \), Yan 1980, Kuang 2006 predict

\[
R' = \frac{\Gamma[\Upsilon(2S) \rightarrow \eta \Upsilon(1S)]}{\Gamma[\psi(2S) \rightarrow \eta J/\psi(1S)]} = 0.0025, \quad R'' = \frac{\Gamma[\Upsilon(3S) \rightarrow \eta \Upsilon(1S)]}{\Gamma[\psi(2S) \rightarrow \eta J/\psi(1S)]} = 0.0013,
\]

\[ \mathcal{B}[\Upsilon(2S, 3S) \rightarrow \eta \Upsilon(1S)] = (8.1 \pm 0.8, \ 6.7 \pm 0.7) \times 10^{-4} \ (b \text{ spin flip!}) \]

\( \Upsilon(2S) \rightarrow \eta (\rightarrow \gamma \gamma) \Upsilon(1S) \) Monte Carlo: \hspace{1cm} Data (CLEO preliminary):

Rate \( \simeq 1/4 \) of Yan/Kuang prediction. \( \mathcal{B}[\Upsilon(2S) \rightarrow \pi^0 \Upsilon(1S)] < 1.6 \times 10^{-4} \)
\[ \Upsilon(3S) \rightarrow (\eta, \pi^0) X \] 

TRANSITIONS

In contrast to \( \Upsilon(2S) \rightarrow \eta \Upsilon(1S) \), where \( \eta \) is nearly at rest, for \( \Upsilon(3S) \rightarrow \eta \Upsilon(1S) \) the \( \eta \) has energy 871 MeV and its photons in \( \eta \rightarrow \gamma \gamma \) can have energies overlapping those in transitions \( \Upsilon(3S) \rightarrow \gamma \chi_b^{(n)} \rightarrow \gamma \gamma \Upsilon(1S) \).

Selection of photons with \( 140 \leq E_\gamma \leq 380 \) MeV and \( 500 \leq E_\gamma \leq 725 \) MeV eliminates most of these backgrounds.

Looks like one will have similar sensitivities in \( \eta \rightarrow \gamma \gamma \) and \( \eta \rightarrow \pi^+\pi^-\pi^0 \) modes, the former having background most likely from radiative Bhabha events and the latter having little background but less efficiency. (We are always demanding \( \Upsilon(1S) \rightarrow \ell^+\ell^- \)).

Searches for \( \Upsilon(3S) \rightarrow \pi^0 \Upsilon(1S, 2S) \) necessarily involve background from radiative Bhabha events unless we restrict attention to \( \Upsilon(1S) \rightarrow \mu^+\mu^- \).

BaBar may have a shot at some of these transitions if it can concentrate on \( \Upsilon(1S) \rightarrow \mu^+\mu^- \) and adequately understand backgrounds.

Mass resolution appears to be very good, especially in \( \Upsilon(3S) \rightarrow \eta(\rightarrow \pi^+\pi^-\pi^0) \Upsilon(1S) \), where \( \sigma[M(\eta)] < 2 \) MeV.
Typical spectra in $\psi(2S) \to \pi\pi J/\psi$, $\Upsilon(2S) \to \pi\pi \Upsilon(1S)$ are peaked at high $M(\pi\pi)$.

This has usually been ascribed to an “Adler zero” associated with couplings of soft pions to other matter with factors $p_\pi/f_\pi$ which vanish as $p_\pi \to 0$.

However, $M(\pi\pi)$ spectrum in $\Upsilon(3S) \to \pi\pi \Upsilon(1S)$ has a double-hump structure. Nodes in wave functions; coupled channels?

This appears to be so for $\Upsilon(4S) \to \pi\pi \Upsilon(2S)$ whereas $\Upsilon(4S) \to \pi\pi \Upsilon(1S)$ spectrum peaks at high $M(\pi\pi)$. $\Upsilon(5S’) \to \pi\pi (1S, 2S, 3S), K\bar{K} 1S$: Belle, arXiv:0710.2517
Rates are much greater than anticipated; role of open channels?
FUTURE PROSPECTS

CLEO has about 800 pb$^{-1}$ at 3770 MeV and 600 pb$^{-1}$ at 4170 MeV; run ended last Monday.

24.5 million \( \psi(2S) \) (about 8 times the previous CLEO sample) were collected in summer 2006; analyses of 21M \( \Upsilon(1S) \), 9M \( \Upsilon(2S) \), 6M \( \Upsilon(3S) \) still in progress.

Belle has taken 2.9 fb$^{-1}$ of data at \( \Upsilon(3S) \) for “invisible” decays of \( \Upsilon(1S) \) [CLEO search] tagged via \( \Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S) \) but potentially valuable for spectroscopy. BaBar will collect 30 fb$^{-1}$ at 3S. CLEO has (1.1, 1.2, 1.2) fb$^{-1}$ at 1S, 2S, 3S.

Spectroscopy at \( \psi(2S) \) bears further rich promise:

- M2/E1 ratios in \( \chi_{c1,2} \to \gamma J/\psi \Rightarrow \) charmed quark magnetic moment
- Exclusive \( \chi_c \) decays: potentially fertile ground for hybrids, glueballs
- One (tagged via \( \pi^+\pi^- \)) \( J/\psi \) decay for every 4–5 \( \psi(2S) \): Simultaneously study exclusive decays of \( J/\psi \) and \( \psi(2S) \) to same final states, guard against kinematic reflections.
Hadron spectroscopy is providing both long-awaited states like $h_c$ and surprises like $c\bar{c}$ states with light-quark admixtures like $X(3872)$; exotic $Z(4430)$; $\Upsilon(5S) \rightarrow \Upsilon \pi \pi$.

Many states are more understandable when light-quark degrees of freedom are included. Evidence for molecules, 3S, 2P, 4S or hybrid charmonium, interesting decays of states above flavor threshold.

QCD may not be the only strongly coupled theory with which we have to deal. Electroweak symmetry breaking or quark/lepton structure may require related techniques.

A big gap in our understanding is how heavy hadrons fragment to multiparticle states. For example, how does $\eta_b$ decay?

Strong interaction theories will have to cope with interplay of light- and heavy-quark degrees of freedom to satisfactorily describe the variety of phenomena in heavy quark spectra. Progress in unquenched lattice QCD is a good sign that this effort is under way.
$\psi''(3770)$ \textbf{DECAYS}

Cross sections (nb) for charm production at $\psi''(3770)$:

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>$\sigma(D^+D^-)$</th>
<th>$\sigma(D^0D^0)$</th>
<th>$\sigma(DD)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BES-II</td>
<td>$2.56 \pm 0.08 \pm 0.26$</td>
<td>$3.58 \pm 0.09 \pm 0.31$</td>
<td>$6.14 \pm 0.12 \pm 0.50$</td>
</tr>
<tr>
<td>CLEO</td>
<td>$2.79 \pm 0.07^{+0.10}_{-0.04}$</td>
<td>$3.60 \pm 0.07^{+0.07}_{-0.05}$</td>
<td>$6.39 \pm 0.10^{+0.17}_{-0.08}$</td>
</tr>
<tr>
<td>Mark III</td>
<td>$2.1 \pm 0.3$</td>
<td>$2.9 \pm 0.4$</td>
<td>$5.0 \pm 0.5$</td>
</tr>
</tbody>
</table>

$\sigma(\psi'')$ seemed $> \Sigma(D\bar{D})$ [see also BES, PL B641, 145 and PRL 97, 121801]; CLEO [PRL 96, 092002] says $\sigma(\psi'') = (6.38 \pm 0.08^{+0.41}_{-0.30})$ nb $\simeq \sigma(D\bar{D})$.

$\psi'' \rightarrow XJ/\psi$: CLEO, PRL:  \quad $\psi'' \rightarrow \gamma\chi_{cJ}$ partial widths:

<table>
<thead>
<tr>
<th>$\psi''$ mode</th>
<th>$B$ (%)</th>
<th>Mode</th>
<th>Predicted (keV)</th>
<th>CLEO (PRD 74, 031106)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^- J/\psi$</td>
<td>$0.189\pm0.020\pm0.020$</td>
<td>$\gamma\chi_{c2}$</td>
<td>3.2</td>
<td>3.9</td>
</tr>
<tr>
<td>$\pi^0\pi^0 J/\psi$</td>
<td>$0.080\pm0.025\pm0.016$</td>
<td>$\gamma\chi_{c1}$</td>
<td>183</td>
<td>59</td>
</tr>
<tr>
<td>$\eta J/\psi$</td>
<td>$0.087\pm0.033\pm0.022$</td>
<td>$\gamma\chi_{c0}$</td>
<td>254</td>
<td>225</td>
</tr>
<tr>
<td>$\pi^0 J/\psi$</td>
<td>&lt; 0.028</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Eichten-Lane-Quigg PR D 69: (a) without, (b) with coupling to open channels; (c): JLR, Ann. Phys. 319, 1 (2005). Non-$D\bar{D}$ modes at most a percent or two: negative exclusive searches [Yelton; PR D 73, 012002; PRL 96, 032003 (2006)].
Brian Lang, presented at Charm07 Workshop, Ithaca, arXiv:0710.0165

Cross sections with predictions of Eichten+.