QCD with a broad brush ("Cartoon of QCD"): Symmetries, Fundamental Dynamics and Asymptotic Limits

- Asymptotic freedom and confinement
- Chiral $SU(2) \times SU(2)$ as an effect field theory.
- Large $N_c$ systematics (carefully selected).
  Captures some important aspects of QCD dynamics (see, eg., A. Manohar), but misses others (eg. $U_A(1)$, baryon resonance spectrum, non-resonant scattering, etc.)
- QCD string
  Captures a few aspects of QCD (leading Regge trajectories, $s, t$ duality, . . . ) but misses much (baryons, light hadron spectroscopy, parton and deep inelastic physics)
Ancient Mysteries/Urban Legends:

Phenomenologically important regularities which are not obvious consequences of basic symmetries or fundamental dynamics.

★ Vector dominance
To a good approximation the vector mesons, $\rho(770)$ act like gauge bosons of a spontaneously broken $SU(2)_{\text{isospin}}$ gauge invariance.

★ The $SU(6) \times O(3)$ Quark Model
The spectrum of light baryons and mesons looks like $Q\bar{Q}$ or $Q^3$ moving non-relativistically in a mean field.

★ The OZI* Rule
The mapping from current ($Q^2 \to \infty$) quarks to constituent ($Q^2 \to 0$) quarks is nearly trivial in flavor for light quarks.

* Okubo, Zweig, Iizuki
Ancient Mysteries/Urban Legends (continued):

“Bloom-Gilman Duality” ≡ “Precocious scaling”
The “scaling” phenomena predicted by asymptotic freedom set in a very low $Q^2$. To first approximation there are no important higher twist effects in deep inelastic QCD!

Parity Doubling
The spectrum of non-strange baryons in the $1300\text{MeV} < M < 2300\text{MeV}$ range shows indications restoration of $U(1)_A$ symmetry.

The Scalar Mesons – $0^{++}$ – are Special
Different from all other mesons. Light: $M < 1\text{Gev}$, very strongly coupled to $\pi\pi, K\bar{K}$ etc.
Sakurai in 1960 (in more modern language Bando, Kugo, and Yamawaki): If the $I = J = 1$ $\rho$ meson, prominent in low energy scattering, saturates the vector form factors of light hadrons, then it behaves like the massive vector boson of a spontaneously broken (vector) local isospin symmetry.

- Some consequences:

  - $\rho$ couples universally:
    \begin{equation}
    g_{\rho\pi\pi} \approx g_{\rho NN} \approx g_{\rho\rho\rho}
    \end{equation}

  - Kawarbayashi, Suzuki, Fayyazuddin, Riazuddin (KSFR) relation:
    \begin{equation}
    m_\rho^2 = 2g_{\rho\pi\pi}^2 f_\pi^2
    \end{equation}

  - $\rho^0 - \rho^\pm$ mass difference predicted in same fashion as $Z^0 - W^\pm$ mass difference.
• If $\rho$-pole saturates all light hadron vector form factors then

  ⋆ Dimension $\leq 4$ effective lagrangian for $\rho$ hadron physics is exactly Yang-Mills in unitary gauge.

  ⋆ Pion and nucleon form factors are well described at $Q^2 \leq 1 \text{ GeV}^2$
**SU(6) × O(3) Quark Model**

The spectrum of $uds$ meson and baryon resonances was worked out in the 1960’s by Dalitz, Gursey, and others using the non-relativistic spin × flavor $SU(6)$ plus orbital excitation $O(3)$ quark model.

- The old classification:

  - $0^+[56]: \quad 8^2 \oplus 10^3$

  - $1^-[70]: \quad 8^2 \oplus 8^2 \oplus 10^1 \oplus 1^1$

  - Extends to positive parity baryon resonances and to meson resonances as well

- Isgur/Karl: Electromagnetic transitions, pseudoscalar meson decays, etc., work well.

- Questions:
  
  Non-relativistic dynamics? Remember $SU(6)$ is not a relativistic symmetry (Coleman-Mandula) Definite quark number?
Okubo-Zweig-Iizuki Rule

Transition from the current quarks of deep inelastic phenomena \( (Q^2 \to \infty) \) to the constituent quarks of the quark model \( (Q^2 \sim 0) \) appears to be nearly diagonal in flavor.

- **Quarks** are the quasiparticles of QCD!

- Long range RG evolution and chiral symmetry violation would be expected to heavily renormalize if not entirely obscure quark degrees of freedom.

- \( u \longrightarrow U = u + u(q\bar{q}) + u(q\bar{q})^2 + \ldots \)

- Sources of flavor mixing:
  - Gluon pair creation: \( q\bar{q} = u\bar{u} + d\bar{d} + s\bar{s} \)
  - Chiral symmetry breaking via instantons: \( \mathcal{L} \propto \det(\bar{q}_R q_L) + \text{h.c.} \propto \bar{u}u\bar{d}d\bar{s}s \)
    Mixes flavors skew-symmetrically
However many measurements of local quark densities give:

\[ \langle U | \bar{s} \Gamma_{s} s | U \rangle \ll \langle U | \bar{u} \Gamma_{u} u | U \rangle, \text{ etc.} \]

For a variety of Dirac structures \( \Gamma \).

These are \( 1/N_c \) effects, so one might account for OZI as an \( N_c \to \infty \) result, however:

- Long range perturbative evolution clearly overcomes \( N_c \) suppression, as pairs mix into nucleon wavefunction.

- So does chiral symmetry breaking via instantons, and \( N_c \to \infty \) has other problems with \( U_A(1) \) phenomena: eg. \( m_{\eta'}/M_N \sim 1/N_c^2 \)!
Absence of Higher Twist in DIS

Nearly coincident with the discovery of Bjorken scaling, Bloom and Gilman pointed out that scaling set in at very low $Q^2$ in an average sense.

In modern language: the structure function obtained by the inverse Mellin transform of the data at large $Q^2$, where twist-two operators alone are important, can be devolved* to very low $Q^2$ – well below one GeV – where it interpolates the data which are dominated by resonances.

- Where are the effects of the matrix elements of twist-four (and beyond) operators? They appear to be characterized by a very small mass scale.

- Careful studies of $F_2$ and more recently, of $g_2$.

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* Target mass corrections (= improved scaling variable) are essential.
• Wandzura-Wilczek prescription: higher twist structure functions are well approximated by kinematic reflection of leading twist, with no true higher twist correlation functions.

• Bag-like: quarks behave as perturbative down to a scale where they encounter a confining “wall”.

S. Liuti, R. Ent, C.E. Keppel, I. Niculescu, hep-ph/0111063

Arrows denote $Q^2 = 0.4$ below which treatment breaks down. Solid curve is NLO+TMC, dashed is NLO, dotted is 200 GeV^2.
Comparison of pQCD+TMC calculations at NLO (dashed lines) and with resummation (full lines), with current large $x$ data. The full dots are in the resonance region, $1.3 \leq W^2 \leq 3.4$ GeV$^2$; the open triangles correspond to $W^2 \leq 1.3$ GeV$^2$. The dotted lines represent the regions where TMC contributions are uncertain.
The structure function $xg_2$ for all spectrometers combined (solid circle) and data from E143 (open diamond) and E155 (open square). The errors are statistical; the systematic errors are shown at the bottom. Also shown is our twist-2 $g_2^{WW}$ at the average $Q^2$ of this experiment at each value of $x$ (solid line). The curves are the bag model calculations of Stratmann (dash-dot) and Song (dot) and the chiral soliton models of Weigel and Gamberg (short dash) and Wakamatsu (long dash).
Parity Doubling

- Non-strange baryon resonances show significant, but far from universal pairing of states with identical spin and isospin and opposite parity.

- Well established states below 2000 MeV:
• Less well-established states at higher masses:

\[
\begin{align*}
\frac{9}{2} \pm & : N(2220) - N(2250) & \frac{7}{2} \pm & : N(1990) - N(2190) \\
\frac{5}{2} \pm & : N(2000) - N(2200) & \frac{3}{2} \pm & : N(1900) - N(2080) \\
\frac{9}{2} \pm & : \Delta(2300) - \Delta(2400) & \frac{7}{2} \pm & : \Delta(1950) - \Delta(2200) \\
\frac{5}{2} \pm & : \Delta(1905) - \Delta(1930) & \frac{3}{2} \pm & : \Delta(1920) - \Delta(1940) \\
\frac{1}{2} \pm & : \Delta(1910) - \Delta(1900) \\
\end{align*}
\]

• Data on strange baryons and mesons is sparse, but scalar and pseudoscalar nonets at 1300 MeV - 1500 MeV are striking:

\[
\begin{align*}
I = 1 & : a_0(1450) - \pi(1300) \\
I = 1/2 & : K^*_0(1430) - K(1450) \\
I = 0 & : f_0(1370) - \eta(1295) \\
I = 0 & : f_0(1500) - \eta(1440) \\
\end{align*}
\]

• Certainly fails at low mass.

• A spontaneously broken $SU(2) \times SU(2)$ cannot be “restored” high in the spectrum:

$Q_5^a |B\rangle \propto |M^a B\rangle$.

• $U(1)_A$ is not spontaneously broken, no obstruction to “restoration”?
The Light Scalar Mesons are Different

There is a nonet of $uds$ scalar mesons at masses below 1 GeV that are different from other hadrons. [Well – so are the pseudoscalars.]

- They are not $\bar{q}q$ states.

- They are very strongly coupled to $\pi\pi, \bar{K}K, \pi K, \pi\eta, K\eta$ and bound the domain of chiral dynamics.

- Present picture: $\bar{q}qqq$ states strongly mixed with meson-meson continuum.

- Review and references: RLJ hep-ph/0001123

- QCD most attractive channel:

$$[qq] : \bar{3}_c \bar{3}_f \ J = 0$$
• \([qq] \times [\bar{q}q]\) uniquely 0\(^{++}\) nonet

• Mass structure is inverted due to “hidden” \(\bar{s}s\) pairs. Agrees with data – subject of considerable activity both in experiment and theory.

\[
\sigma(600) \kappa(850) a_0(980) f_0(980)
\]

• Standard quark model 0\(^{++}\) states are \(p\)-waves and now have been discovered at 1300 – 1500 MeV.