Hadron 2011

The Future of Hadrons: 
The Nexus of Subatomic Physics

Chris Quigg

Fermilab
Impressions . . .

Enormous diversity and reach of experimental programs (insights from unexpected quarters)

Remarkable progress in theory; emergence of LQCD (insights from unexpected quarters)

Many puzzles, opportunities; much work to do

Still “simple” questions that we cannot answer
Musings . . .

Value of integration across hadronic physics

Connect with the rest of subatomic physics
(look for insights from unexpected quarters)
*You* may answer questions that seem far afield

Look beyond nuclear and particle physics

Seek new ways to address hadronic questions

How are we prisoners of conventional thinking?
In contrast to biological evolution, unsuccessful lines in theoretical physics do not become extinguished, never to rise again. We are free to borrow potent ideas from the past and to apply them in new settings, to powerful effect.

S-matrix style unitarity for multiparton amplitudes

? Multi-Regge analysis ?

... if predictions unsuccessful, why?
Our picture of matter

Pointlike ($r \lesssim 10^{18}$ m) quarks and leptons

Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries
QCD: the basis of hadronic physics

Fundamental fields: quarks and gluons, manifest in
- Proton structure [high resolution, hard scattering
- Matter at high density
- Lattice calculations

Effective degrees of freedom, manifest in
- Constituent quarks, Goldstone bosons, . . .
- Effective field theories
- Isobar (resonance) models
- Nuclei and nuclear structure
Asymptotic Freedom

\[ \frac{1}{\alpha_s} \approx \frac{27}{6\pi} \ln \left( \frac{2m_c}{\Lambda} \right) \]
Insight from QCD: $M_p = E_0/c^2$

$M_p = C \cdot \Lambda + \ldots \ll M_p$

New kind of matter: mass $\neq$ sum of parts

$3 \cdot \frac{1}{2} (m_u + m_d) \approx 10 \pm 2$ MeV

Jüttner
Influence of the fermion spectrum: $M_p \propto m_t^{2/27}$
Unified theories: SU(5)

Unification of Forces?

\[ \log_{10} \left( \frac{E}{1 \text{ GeV}} \right) \]

\[ \frac{1}{\alpha} \]

- SU(3)_c
- SU(2)_L
- U(1)_Y

Chris Quigg (FNAL)
The Future of Hadrons
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Unified theories: SU(5) + light SUSY

Unification of Forces?

\[ \log_{10} \left( \frac{E}{1 \text{ GeV}} \right) \]

\[ \frac{1}{\alpha} \]

SU(3)_c
SU(2)_L
U(1)_Y
Unified theories: SU(5) + light SUSY

\[ \text{SM: } \frac{7}{2}\pi \]

\[ \text{MSSM: } \frac{3}{2}\pi \]
Toward Controlled Approximations

- NRQCD for heavy-heavy systems \((Q_1 \bar{Q}_2)\)
  \(m_{Q_i} \gg \Lambda_{QCD}\)
  expansion parameter \(v/c\)

- HQET for heavy-light systems \((Q \bar{q})\)
  \(m_Q \gg \Lambda_{QCD}; \, \vec{j}_q = \vec{L} + \vec{s}_q\)
  expansion parameter \(\Lambda_{QCD}/M_Q\)

- Chiral symmetry for light quarks \((q_1 \bar{q}_2)\)
  \(m_{q_i} \ll \Lambda_{QCD}\)
  expansion parameter \(\Lambda_{QCD}/4\pi f_\pi\)

- Lattice QCD
What is a proton?

(For hard scattering) a broad-band, unseparated beam of quarks, antiquarks, gluons, & perhaps other constituents, characterized by parton densities

\[ f_i^{(a)}(x_a, Q^2), \]

...number density of species \( i \) with momentum fraction \( x_a \) of hadron \( a \) seen by probe with resolving power \( Q^2 \).

\( Q^2 \) evolution given by QCD perturbation theory

\[ f_i^{(a)}(x_a, Q^0_0^2) \): nonperturbative

Historically: No correlations, only longitudinal d.o.f.
Beyond traditional parton distributions

GPDFs, TMDs, 3-d images, . . .

Anselmino, Aschenauer, Pretz

$\gamma^* \rightarrow \gamma$ probes $q$; $\gamma \rightarrow V$ probes $g$ in $\perp$ plane

Compare impact-parameter distributions from $pp \rightarrow pp$?

Signatures in LHC event structures?
Some Experiments in Multiple Production

- Multiplicities: diffractive + multiperipheral?
- Feynman scaling: $\rho_1(x \equiv k_z/E, k_\perp, E)$ indep. of $E$?
- Factorization: $\pi p, pp$ same in backward hemisphere?
- $dx/x$ spectrum (flat rapidity plateau)?
- Double Pomeron exchange?
- Short-range order:
  $$\rho_2(y_1, y_2) - \rho_1(y_1)\rho_1(y_2) \propto \exp(-|y_1 - y_2|/L)?$$
- Factorization test with central trigger (no diffraction)
Isn’t “Soft” Particle Production Settled?

Diffractive scattering + short-range order

- (Not exhaustively studied at Tevatron)
- Long-range correlations?
- High density of $p_z = 5$ to $10$ GeV partons
  $\rightsquigarrow$ hot spots, thermalization, . . . ?
- Multiple-parton interactions, perhaps correlated $q(qq)$ in impact-parameter space, . . .
- PYTHIA tunes miss $2.36$-TeV data (ATLAS & CMS)

Few percent of minimum-bias events ($\sqrt{s} \gtrsim 1$ TeV) might display an unusual event structure
We should look! How?
Learning to See at the LHC

(Avoid pathological attachment to blind analysis!)

\[(y_n, p_{nx}, p_{ny})\]

\[(y_1, p_{1x}, p_{1y})\]

\[(y_1, 0, 0)\]

\[(y_n, 0, 0)\]

\[(y_n, p_{nx}, p_{ny})\]

\[\text{(unwrapped LEGO plot for particles)}\]

Bjorken, SLAC-PUB-0974 (1971)
Learning to See at the LHC

Local $p_\perp$, $Q$ compensation
Learning to See at the LHC

Hot spot?

Rapidity gap
Seeking the Relevant Degrees of Freedom

Under what circumstances are diquarks useful / essential?

Correlations among quarks long known . . .

- $x \rightarrow 1$ behavior of proton parton distributions:
  - $F_2^n / F_2^p < \frac{2}{3}$
  - Spin differs from SU(6) wave functions

- $3 \otimes 3$ attractive in $3^*$ (half as strong as in $3 \otimes 3^* \rightarrow 1$?)

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

Hadron Spectrum Collab.: no sign of $[qq]_3^*$ (Edwards)
Test, extend idea of diquarks

- $Q\bar{Q}q$ 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.
- color–spin as an organizing principle? mass effects . . .
Doubly Heavy Baryons

Spectroscopy

- Analogy: $[QQ^{(i)}]_{3*} q$ and $\bar{Q}q$ as heavy-light systems
- One-gluon-exchange: $V_{[QQ^{(i)}]_{3*}}(r) = \frac{1}{2} V_{(\bar{Q}q)_1}(r)$; deviations beyond?
- Learn about $[QQ^{(i)}]_{3*}$ dynamics through excitation spectrum?
- As in $b\bar{c}$, unequal masses in $bcq$ may expose limitations of NRQM

Weak decays

- Rich set of heavy $\rightarrow$ heavy, heavy $\rightarrow$ light transitions
- Isolate different pieces of $H_{\text{weak}}^{\text{eff}}$
Doubly Heavy Baryons

Strong and electromagnetic cascades

- Two-scale problem: \( r_H = \langle r^{2}_{(QQ^{(i)})} \rangle^{1/2} \), \( r_{\ell} = \langle r^{2}_{(QQ^{(i)}q)} \rangle^{1/2} \)

- Expect some extremely narrow states

Production dynamics

- Extend fragmentation models to new regimes
- Compare with quarkonium production dynamics
Stretching our models, calculations

Leaving the comfort zone, looking for unseen effects
Extend descriptions of $\psi, \Upsilon$ to $B_c$

\[
B_c \rightarrow \pi J/\psi, a_1 J/\psi, J/\psi \ell \nu
\]

hadronic, $\gamma$ cascades to $B_c$

interpolates $Q \bar{Q}, Q \bar{q}$

c more relativistic than in $c \bar{c}$, unequal-mass kinematics:

$\sim$ enhanced sensitivity to effects beyond NRQM?
Traditional view: appropriate degrees of freedom

![Graph showing quark mass extrapolation to the chiral limit](image)

- **Quark mass [GeV]**
- **q (GeV)**

- **Chiral quark model**
- **Confinement**
- **Current quarks**

Ken Hicks talk

Chris Quigg (FNAL)
Are quarks and gluons apt d.o.f. at large distances?

Some evidence (revisit!) that $\alpha_s \to 0.5$ at small $Q^2$:

$$\alpha_0(\mu_I) \equiv (1/\mu_I) \int_0^{\mu_I} dQ \alpha_s(Q), \quad \mu_I = 2 \text{ GeV}$$
If $\alpha_s$ “freezes,” LE perturbative analyses plausible

- Unimportance of nonvalence components for hadron properties
- De Rújula–Georgi–Glashow mass formula (color hyperfine interaction)
- Bloom-Gilman duality
- Precocious dimensional scaling
- Perturbative approach to bound states
- ...

Compare lattice, $1/N_c$; how define $\alpha_s$ below few GeV?

Hoyer, arXiv:1106.1420
Quasistatic Properties of the Nucleon

Perturbative evolution doesn’t distinguish \((q, \bar{q})\) or \((u, d)\)

*Differences must be set at low scales*

Example: Gottfried sum rule

\[
I_G(Q^2) = \int_0^1 dx \frac{F_2^p(x, Q^2) - F_2^n(x, Q^2)}{x}
\]

\[
= \int_0^1 dx \sum_i e_i^2 \left[ q_i^{(p)}(x, Q^2) + \bar{q}_i^{(p)}(x, Q^2) - q_i^{(n)}(x, Q^2) + \bar{q}_i^{(n)}(x, Q^2) \right]
\]
Quasistatic Properties of the Nucleon

Fruitful picture: chiral quark model / $\chi$FT

Constituent quark $\rightarrow$ quark + Nambu-Goldstone boson

- Pion cloud changes PDF, doesn’t enter $F_2^p - F_2^n$ ($F_2^{\pi^+} = F_2^{\pi^-}$)
- GSR Deviations arise from left-behind quarks
- Pion cloud doesn’t affect spin budget
- $\gamma_5$ coupling flips left-behind quark helicity

$\Delta d, \Delta s < 0, \Delta \bar{d}, \Delta \bar{s} = 0$
Dark matter searches ...
Dark matter searches and nucleon structure

Scale of SUSY expectations set by (spin-independent) $\sigma$

Neutralino WIMP: $\sigma$ attributed to Higgs exchange

How does $H$ interact with nucleon?

$H$ coupling to heavy flavors: $s, b, \ldots$

$\times 2$ variation among lattice calculations

Experimental attention, perhaps theoretical reconception
Nucleon structure with a millimole of muons

Neutrino factory could provide flux $> 10^{20} \, \nu/\text{year}$

- $\nu$ scattering on thin target (e.g., H, D)
- $\nu$ scattering on silicon target
- $\nu$ scattering on polarized target

Fig. 1. The kinematic region in the ($x, Q^2$) plane available at a 50 GeV neutrino factory.

Distribution, but neutrino scattering has thus far contributed complementary measurements of the valence quark distributions, as well as measurements of the strange sea. However, neutrino scattering has in the past been plagued by tiny interaction rates and large beam spot sizes, requiring targets on the order of several meters wide and several hundred tons to get appreciable statistics.

With the advent of a muon storage ring the flux of neutrinos at a near detector would be several orders of magnitude higher than at present experiments, and concentrated in a much smaller spot size. Because of this one can now consider using compact hydrogen and deuterium targets, rather than iron. These targets have the advantage of allowing measurements of the valence quark distributions without nuclear effects, or conversely one can finally measure nuclear effects in valence quark distributions by comparing results using different targets. Many of these ideas (as well as other high-rate neutrino experiments at muon storage rings) are considered in references [3], [4], and [5].

Because it is expected that the storage ring will run in roughly equal running times in $\mu^+$ and $\mu^-$ mode, the fluxes for $\nu_e$ and $\bar{\nu}_e$ will be approximately equal, as will the fluxes for $\bar{\nu}_\mu$ and $\nu_\mu$. In conventional beam neutrino experiments the dominant statistical error has been the antineutrino event rate, because the typical total antineutrino event rate (on the targets used) has been only 20-25% of the neutrino event rate.
Nucleon structure with a millimole of muons

Early studies (hep-ph/0009223): determine flavor by flavor the valence and sea quark distribution functions with statistical errors of order 0.01 per bin.

Could use a modern critical evaluation
Could chiral symmetry and confinement coexist?

(Contrary to intuition for light-quark systems)

**Heavy meson systems**

- Expect chiral supermultiplets: \((L, L + 1)\), same \(j_q\):
  \[ j_q = \frac{1}{2}: \ 1S(0^-, 1^-) \text{ and } 1P(0^+, 1^+) \]
  \[ j_q = \frac{3}{2}: \ 1P(1^+, 2^+) \text{ and } 1D(1^-, 2^-) \]
- Hyperfine splitting
  \[ M_{D_s(1^+)} - M_{D_s(0^+)} = M_{D_s(1^-)} - M_{D_s(0^-)} \]
- Predictions for decay rates match experiment
- How far is QCD from this situation?
States associated with charmonium

MANY new states observed!

A few $[\chi_{c2}(2P)(3927)]$ look like simple $c\bar{c}$

Most new states are not simple charmonium!

More are to be found!

B-Meson Gateways to Missing Charmonium Levels

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(Dated: June 3, 2002)

We outline a coherent strategy for exploring the four remaining narrow charmonium states [$\eta_c'(2^1S_0)$, $h_c(1^1P_1)$, $\eta_{c2}(1^3D_2)$, and $\psi_2(1^3D_2)$] expected to lie below charm threshold. Produced in $B$-meson decays, these levels should be identifiable now via striking radiative transitions among charmonium levels and in exclusive final states of kaons and pions. Their production and decay rates will provide much needed new tests for theoretical descriptions of heavy quarkonia.
States associated with charmonium

More narrow states: $1^3D_3$, $2^3P_2$, and $1^3F_4$

Make all possible few-particle combinations

Need to better understand the role of thresholds
- on their own
- near would-be charmonium levels
- with attractive s-waves

Most states above threshold have multiple personalities

Mysteries of decays to $\pi^+\pi^- (c\bar{c})$:
   Rethink our reliance on color multipole expansion
New Era of Heavy-Ion Physics

Run Number: 169045, Event Number: 1914004
Date: 2010-11-12 04:11:44 CET
Quarkonium Melting

- Energy dependence?
- Compare $J/\psi$, $\Upsilon$ families
- Behavior of $\chi$ states?
- Any possibilities for $B_c$?
QCD could be complete to very high energies

How Might QCD Crack?

(Strong CP Problem)

(Breakdown of factorization)

Free quarks / unconfined color

New kinds of colored matter

Quark compositeness

Larger color symmetry containing QCD
Hadron Spectroscopy is rich in opportunities

- Models are wonderful exploratory tools
- Engage lattice, symmetries at every opportunity
- Build coherent networks of understanding
- Tune between systems: models beyond comfort zones
- Relate mesons to baryons
- Look beyond $qqq$ and $q\bar{q}$: heavy flavors, exotics, matter under unusual conditions

*Focus on what we can learn of lasting value*
Heartfelt thanks!

International Advisory Committee
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Contributors and Participants