NIKHEF Theory Seminar

Topics in Hadronic Physics

Chris Quigg

Fermilab

Impressions of *Hadron 2011* . . .

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)
Perhaps 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?

Learning from History

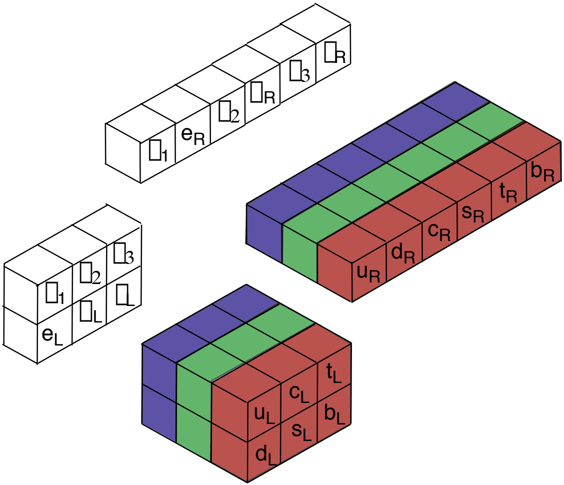
In contrast to biological evolution, unsuccessful lines in theoretical physics do not become extinguished, never to rise again. We are free to borrow potent ideas from the past and to apply them in new settings, to powerful effect.

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

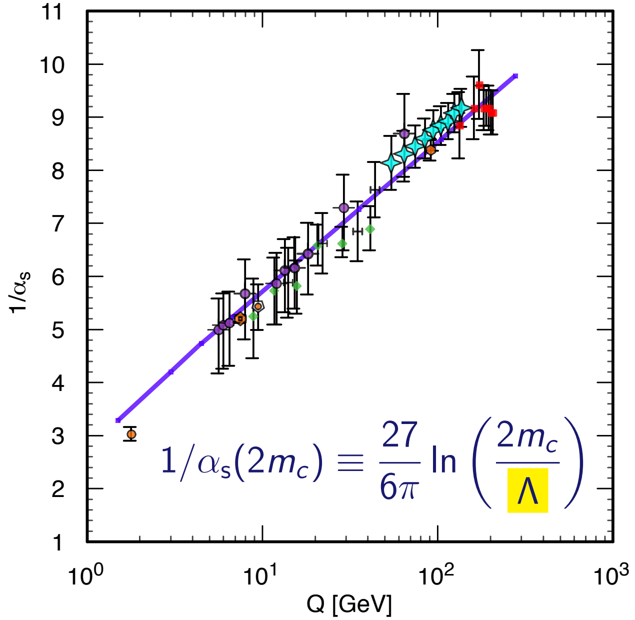
Fundamental fields: quarks and gluons, manifest in

- 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



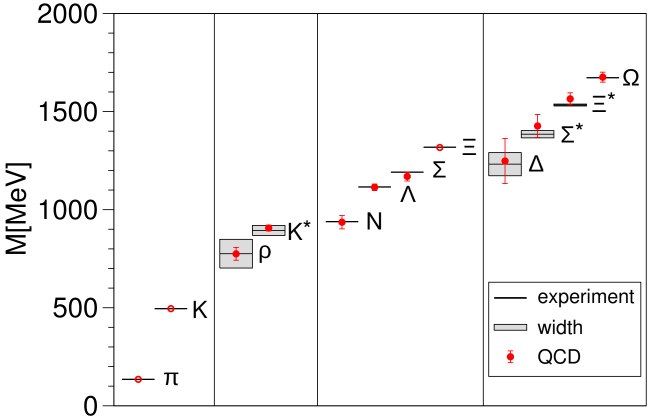
$$1/\alpha_s(2m_c) \equiv \frac{27}{6\pi} \ln\left(\frac{2m_c}{\Lambda}\right)$$

Insight from QCD: $M_p = E_0/c^2$

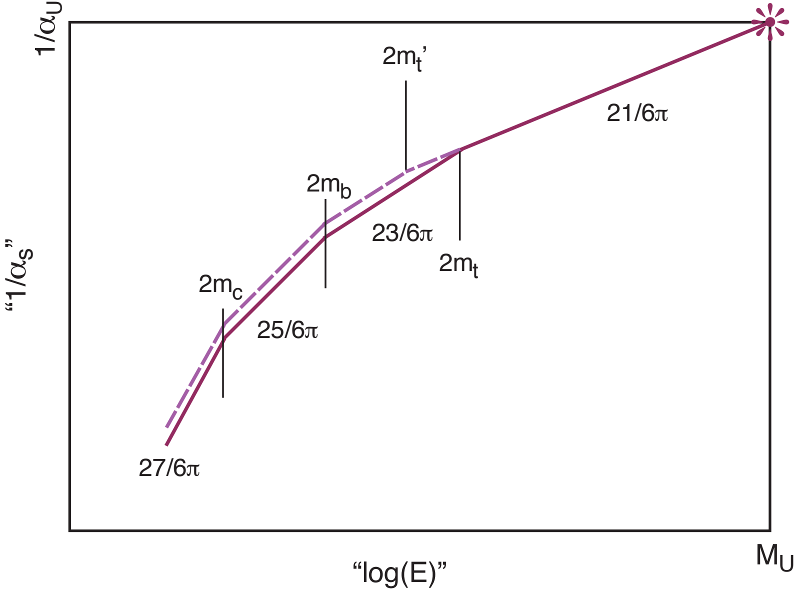
$$M_p = C \cdot \Lambda + \ldots \ll M_p$$

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

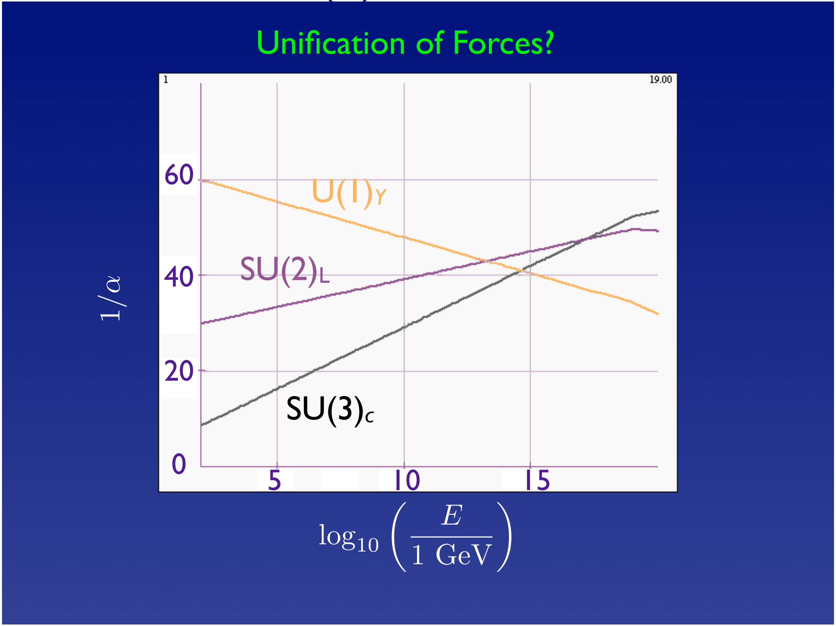
$$3 \cdot \tfrac{1}{2}(m_u + m_d) \approx 10 \pm 2 \text{ MeV}$$



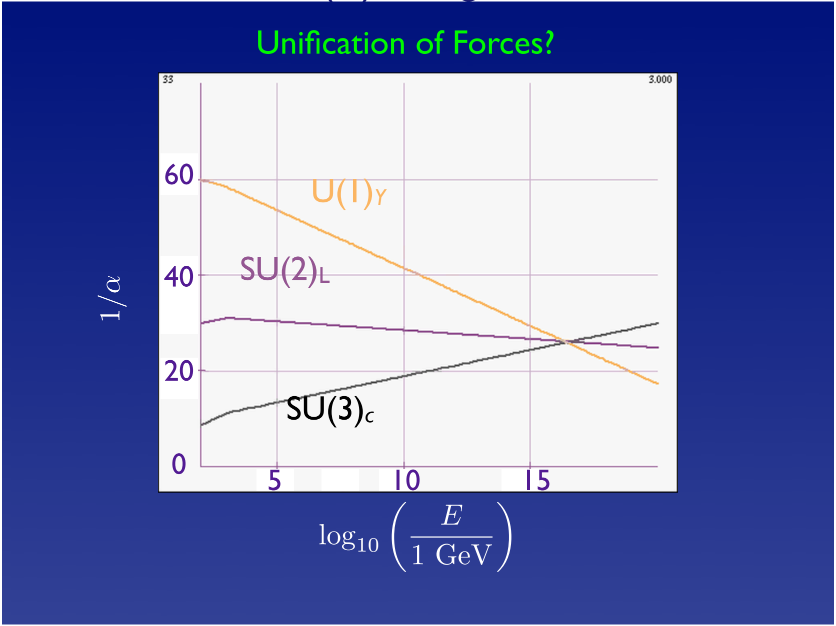
Influence of the fermion spectrum: $M_p \propto m_t^{2/27}$



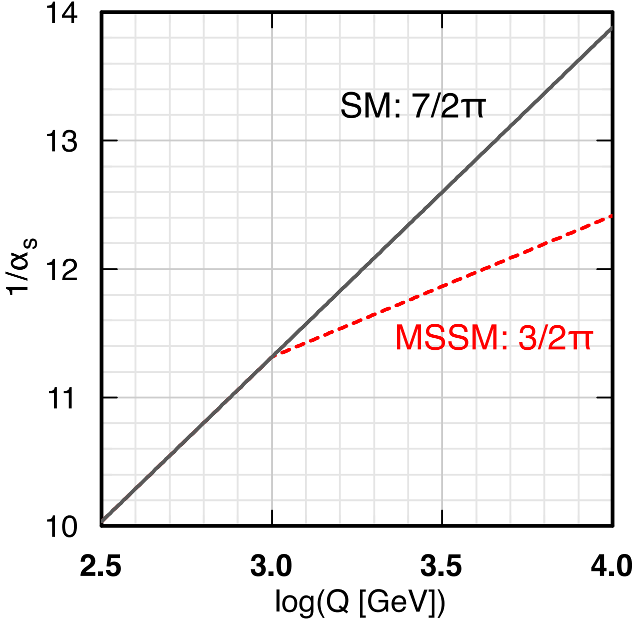
Unified theories: SU(5)



Unified theories: SU(5) + light SUSY



Unified theories: SU(5) + light SUSY



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 $(Q\bar{q})$
  $m_Q \gg \Lambda_{\mathrm{QCD}}$; $\vec{\jmath}_q = \vec{L} + \vec{s}_q$
  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

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

$f_i^{(a)}(x_a, Q_0^2)$: nonperturbative

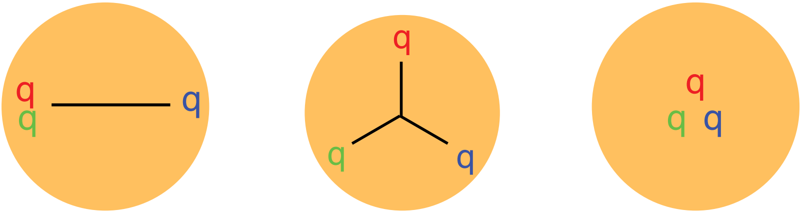
Historically: No correlations, only longitudinal d.o.f.

Beyond traditional parton distributions

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

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

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



Bjorken, 2010

Signatures in LHC event structures?

Ken Wilson's Ancient Program CLNS-131 (1970)

Some Experiments in Multiple Production

- Multiplicities: diffractive + multiperipheral?
- Feynman scaling: $\rho_1(x \equiv k_z/E, k_\perp, E)$ indep. of E?
- Factorization: πp, 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?

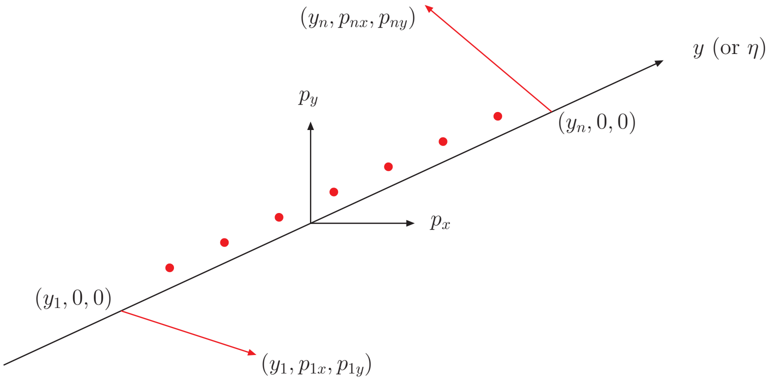
Diffractive scattering + short-range order

- (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

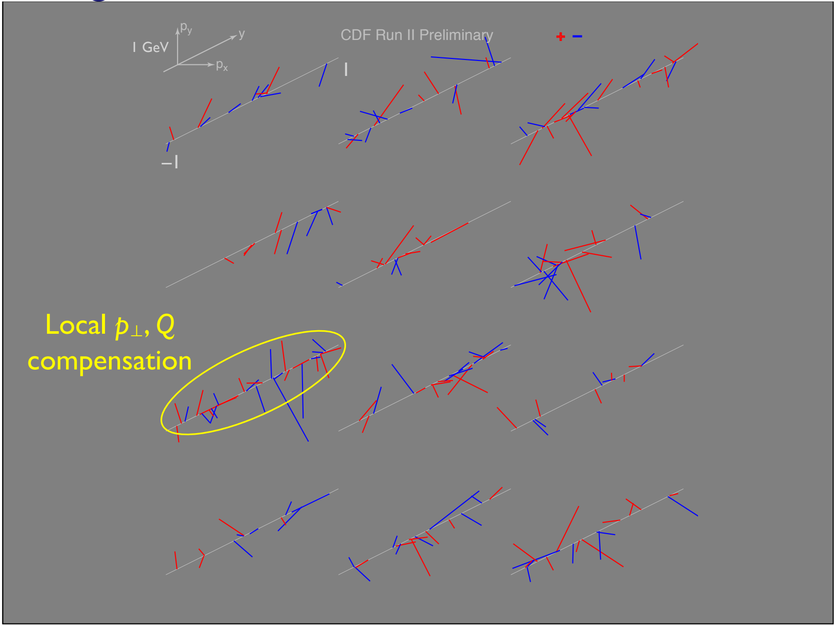
(Avoid pathological attachment to blind analysis!)



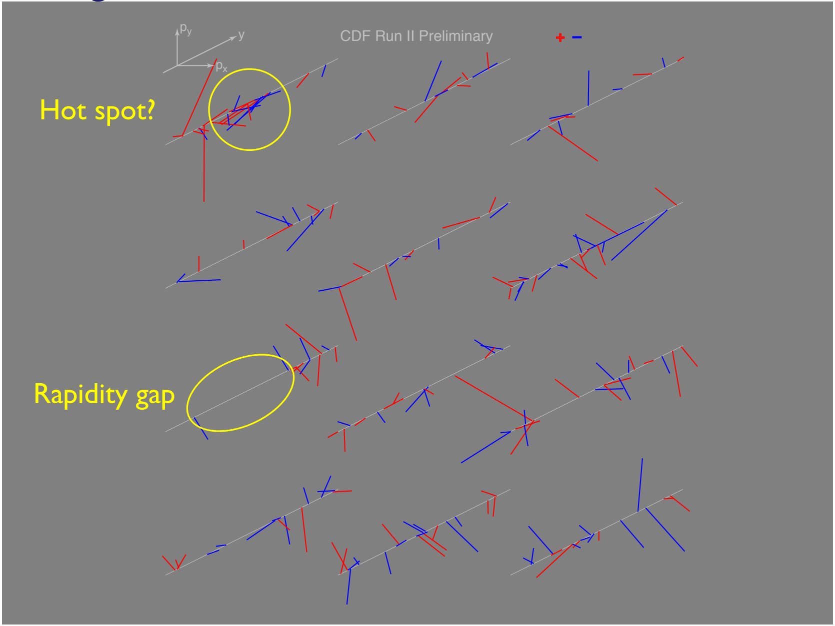
(unwrapped LEGO plot for particles)

Bjorken, SLAC-PUB-0974 (1971)

Learning to See at the LHC



Learning to See at the LHC



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:
  - $F_2^n / F_2^p < \frac{2}{3}$
  - 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 $\mathbf{3} \otimes \mathbf{3}^*$

Hadron Spectrum Collab.: no sign of $[qq]_{3^*}$ (lattice)

Test, extend idea of diquarks

- $\rightsquigarrow$ 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 . . .

Doubly Heavy Baryons

Spectroscopy

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

Weak decays

- Rich set of heavy $\longrightarrow$ heavy, heavy $\longrightarrow$ light transitions
- Isolate different pieces of $\mathcal{H}^{\text{eff}}_{\text{weak}}$

Doubly Heavy Baryons

Strong and electromagnetic cascades

- Two-scale problem: $r_{\mathrm{H}} = \langle r^2_{(QQ^{(\prime)})} \rangle^{\frac{1}{2}}$, $r_\ell = \langle r^2_{(QQ^{(\prime)}q)} \rangle^{\frac{1}{2}}$
- Expect some extremely narrow states

Production dynamics

- Extend fragmentation models to new regimes
- Compare with quarkonium production dynamics

Stretching our models, calculations

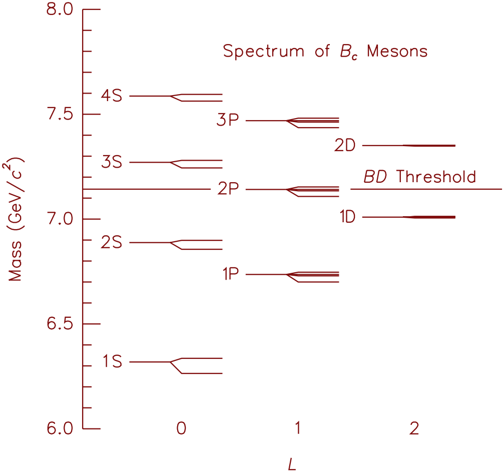
Leaving the comfort zone, looking for unseen effects

Extend descriptions of ψ, Υ to B_c

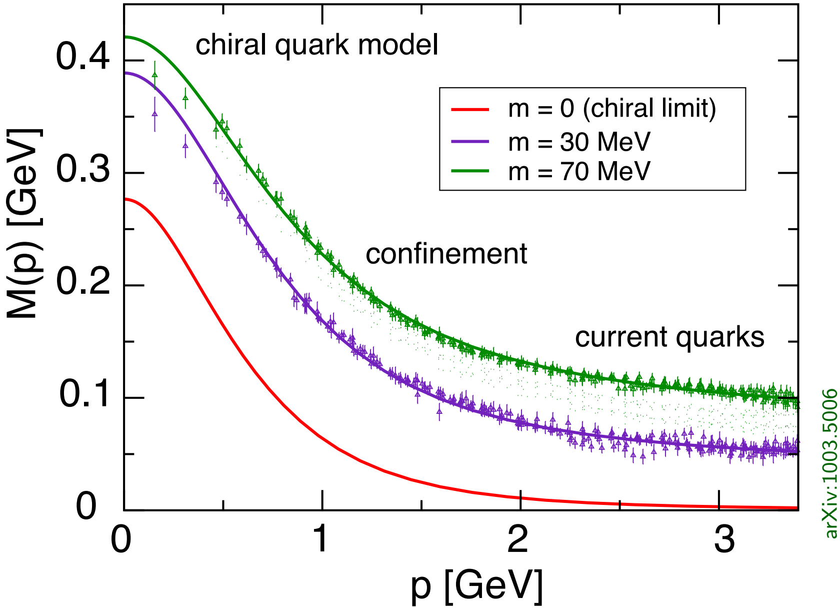
$B_c \to \pi J/\psi, a_1 J/\psi, J/\psi \ell \nu$
hadronic, γ cascades to B_c

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

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



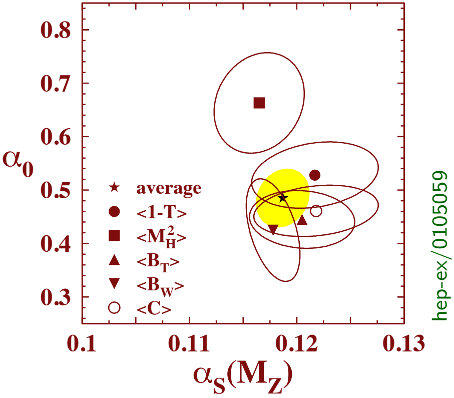
Traditional view: appropriate degrees of freedom



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 α_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 α_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

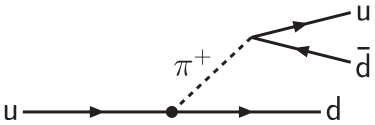
Example: Gottfried sum rule

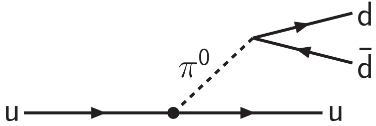
$$
\begin{aligned}
I_{\mathrm{G}}(Q^2) &= \int_0^1 dx \frac{F_2^p(x, Q^2) - F_2^n(x, Q^2)}{x} \\
&= \int_0^1 dx \sum_i e_i^2 \left[q_i^{(p)}(x, Q^2) + \bar{q}_i^{(p)}(x, Q^2) \right. \\
&\qquad \left. - q_i^{(n)}(x, Q^2) + \bar{q}_i^{(n)}(x, Q^2) \right]
\end{aligned}
$$

Quasistatic Properties of the Nucleon

Fruitful picture: chiral quark model / χFT

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

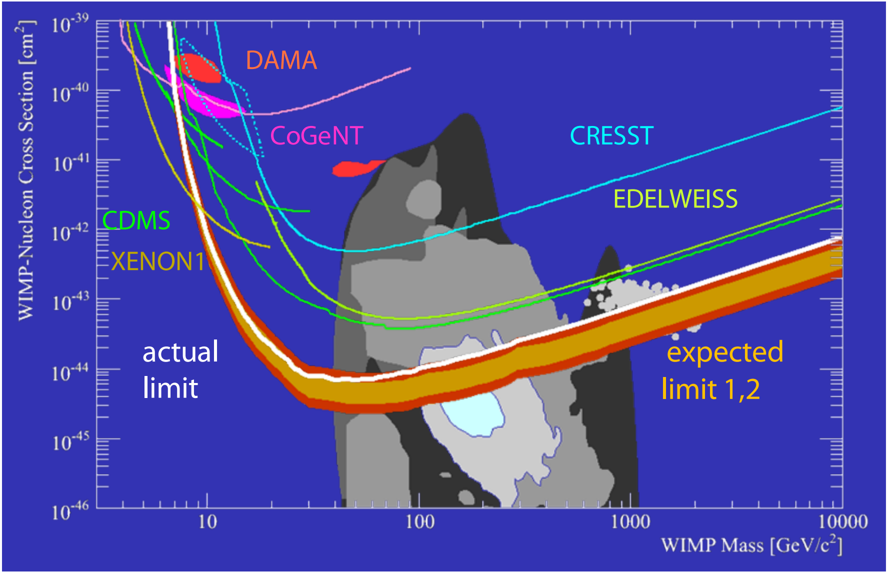




- Pion cloud changes PDF, doesn't enter $F_2^p - F_2^n$ $(F_2^{\pi^+} = F_2^{\pi^-})$
- GSR Deviations arise from left-behind quarks
- Pion cloud doesn't affect spin budget
- γ_5 coupling flips left-behind quark helicity

$$\Delta d, \Delta s < 0,\ \Delta\bar{d}, \Delta\bar{s} = 0$$

Dark matter searches . . .



Dark matter searches and nucleon structure

Scale of SUSY expectations set by (spin-independent) σ

Neutralino WIMP: σ attributed to Higgs exchange

How does H interact with nucleon?

H coupling to heavy flavors: s, b, ...

$\times 2.5$ variation among lattice calculations

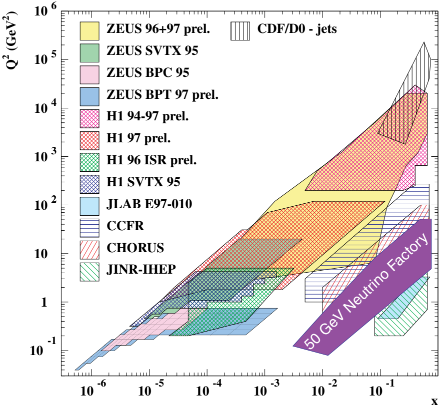
$\sigma \times \frac{1}{10}$? (Giedt, Thomas, Young, 0907.4177)

Experimental attention, perhaps theoretical reconception

Nucleon structure with a millimole of muons

Neutrino factory could provide flux $> 10^{20}$ ν/year

- ν scattering on thin target (*e.g.*, H, D)
- ν scattering on silicon target
- ν scattering on polarized target



Nucleon structure with a millimole of muons

Early studies (arXiv: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:
  $$j_q = \tfrac{1}{2}\text{: } 1S(0^-, 1^-) \text{ and } 1P(0^+, 1^+)$$
  $$j_q = \tfrac{3}{2}\text{: } 1P(1^+, 2^+) \text{ and } 1D(1^-, 2^-)$$
- 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 quarkonium

MANY new states observed!

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

Most new states are not simple charmonium!

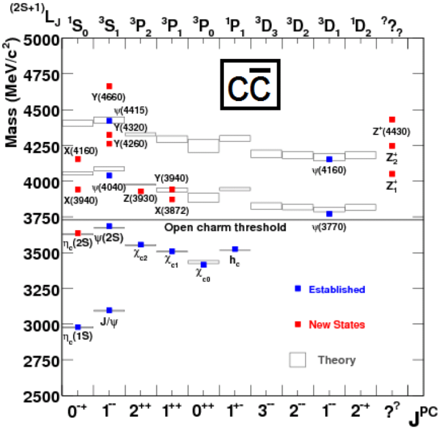
More are to be found!

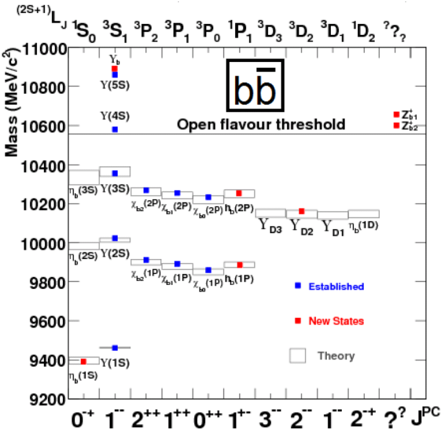
B-Meson Gateways to Missing Charmonium Levels

Estia J. Eichten,[1,*] Kenneth Lane,[1,2,†] and Chris Quigg[1,‡]
[1] *Theoretical Physics Department*
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510
[2] *Department of Physics, Boston University*
590 Commonwealth Avenue, Boston, MA 02215
(Dated: June 3, 2002)

We outline a coherent strategy for exploring the four remaining narrow charmonium states [$\eta_c'(2^1\mathrm{S}_0)$, $h_c(1^1\mathrm{P}_1)$, $\eta_{c2}(1^1\mathrm{D}_2)$, and $\psi_2(1^3\mathrm{D}_2)$] 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 quarkonium





$+\pi^{\pm}(b\bar{b})$ states at 10 610, 10 650 GeV

States associated with quarkonium

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

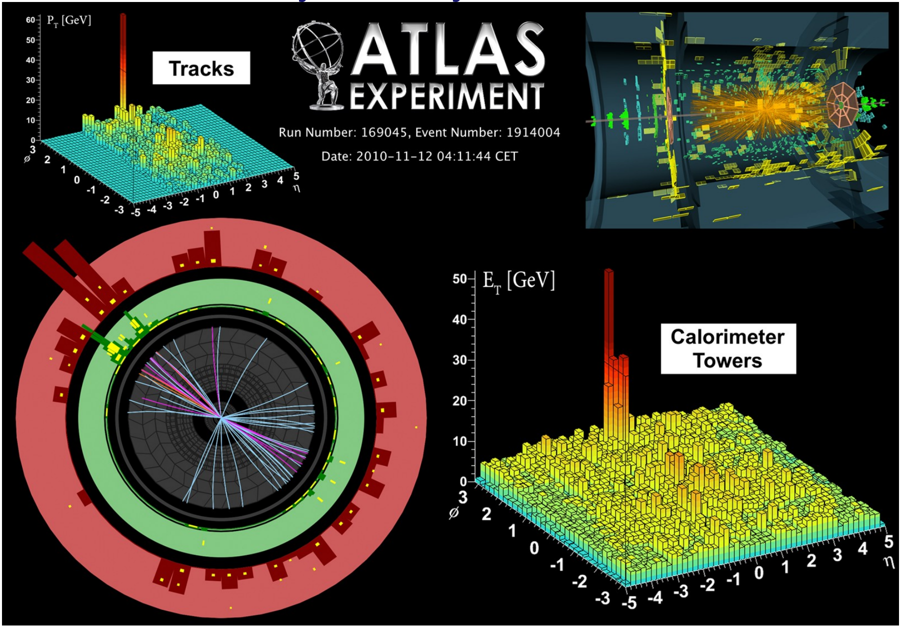
- on their own
- near would-be charmonium levels
- with attractive *s*-waves

Most states above threshold have multiple personalities

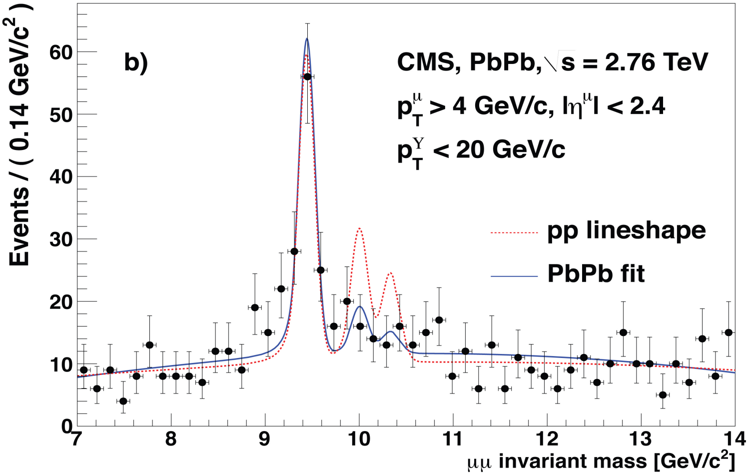
Mysteries of decays to $\pi^+\pi^-(c\bar{c})$:

Rethink our reliance on color multipole expansion

New Era of Heavy-Ion Physics



Quarkonium Melting indication (CMS 1105.4894)



Energy dependence? Compare J/ψ, Υ families;
Behavior of χ 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