Asymptotic Freedom: color antiscreeing behavior of chromodynamics

\[ \frac{1}{\alpha_s(Q)} = \frac{1}{\alpha_s(\mu)} + \frac{(33 - 2n_f)}{6\pi} \ln \left( \frac{Q}{\mu} \right) \]
Dimensional transmutation

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

\[Q \text{ [GeV]}\]
Insight from QCD

\[ M_{\text{proton}} = C \cdot \Lambda + \ldots \]

- calculable on lattice
- quark masses, EM self-energy
- from dimensional transmutation

“Mass without Mass”
\[ 3 \left( \frac{m_u + m_d}{2} \right) = 10 \pm 2 \text{ MeV} \]

The source of your weight problem is quantum chromodynamics.
Lattice QCD: quark confinement origin of nucleon mass has explained nearly all visible mass in the Universe.
## New determinations of $\alpha_s$

<table>
<thead>
<tr>
<th>Author</th>
<th>Source</th>
<th>Scale</th>
<th>$\alpha_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malaescu</td>
<td>$\tau$ decay</td>
<td>$m_\tau$</td>
<td>0.344 ± 0.0086</td>
</tr>
<tr>
<td>Gehrmann-De Ridder</td>
<td>event shapes @ NNLO</td>
<td>$M_Z$</td>
<td>[0.1240 ± 0.0032$^a$]</td>
</tr>
<tr>
<td>Becher/Schwartz</td>
<td>event shapes @ NNLO</td>
<td>$M_Z$</td>
<td>0.1172 ± 0.0021</td>
</tr>
<tr>
<td>Jiménez</td>
<td>HERA jets</td>
<td>$M_Z$</td>
<td>0.1198 ± 0.0032</td>
</tr>
<tr>
<td>Bethke</td>
<td>compilation</td>
<td>$M_Z$</td>
<td>0.1189 ± 0.001</td>
</tr>
<tr>
<td>Bethke</td>
<td>jets</td>
<td>$M_Z$</td>
<td>0.121 ± 0.005</td>
</tr>
<tr>
<td>PDG</td>
<td>compilation</td>
<td>$M_Z$</td>
<td>0.1176 ± 0.002</td>
</tr>
<tr>
<td>LEP EWWG</td>
<td>global fit</td>
<td>$M_Z$</td>
<td>0.1185 ± 0.0026</td>
</tr>
</tbody>
</table>

$^a$ Awaiting resummation
Extraction of $\alpha_s$

Result for all ALEPH event shapes of LEP1/LEP2

$\alpha_s(M_Z) = 0.1240 \pm 0.0008\text{(stat)} \pm 0.0010\text{(exp)} \pm 0.0011\text{(had)} \pm 0.0029\text{(theo)}$

$e^+e^- \rightarrow 3\text{ jets and event shapes at NNLO – p.12}$

improve parton/hadron matching
(Heavy Quark 1987)

\[
\frac{\Delta m}{\Gamma} \propto f_{B_d}^2 |V_{td}|^2 B_{B_d} \tau_{B_d} m_t^2
\]

\[
\frac{\Delta m}{\Gamma} \propto f_{B_s}^2 |V_{ts}|^2 B_{B_s} \tau_{B_s} m_t^2
\]

... every factor was unknown
The $f_{D_s}$ Puzzle

\[ B(D_s \to \ell \nu) = \frac{M_{D_s} \tau_{D_s}}{8\pi} \left( f_{D_s}^2 \right) \left| G_F V_{cs} m_\ell \right|^2 \left( 1 - m_\ell^2 / M_{D_s}^2 \right)^2 \]
<table>
<thead>
<tr>
<th>Model</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO $D_s \rightarrow \mu \nu, \tau \nu$</td>
<td>$274 \pm 10 \pm 5$</td>
</tr>
<tr>
<td>CLEO $D_s \rightarrow \tau \nu$</td>
<td>$223 \pm 17 \pm 3$</td>
</tr>
<tr>
<td>CLEO average</td>
<td>$1.23 \pm 0.10 \pm 0.03$</td>
</tr>
</tbody>
</table>

Unquenched LQCD
- Foilana [arXiv:0706.1726]
  - $241(3)$

Unquenched LQCD
- Aubin, PRL 95, 122002 (2005)
  - $208(4)$

Quenched L. (QCDSF)
- Ali Khan, hep-lat/0701015

Quenched L. (Taiwan)
- Chiu, PLB 624, 31 (2005)

Quenched L. (UKQCD)
- Lellouch, PRD 64, 094501 (2001)

Quenched Lattice
- Becirevic, PRD 60, 074501 (1999)

QCD Sum Rules
- Bordes, hep-ph/0507241

Quark Model
- Ebert, PLB 635, 93 (2006)

Quark Model
- Cvetic, PLB 596, 84 (2004)

Light Front QM Linear
- Chol, hep-ph/0701263

Light Front QM HO
- Chol, hep-ph/0701263

Potential Model

Light Front QCD

Isospin Splittings
- Amundsen, PRD 47, 3059 (1993)

$\text{Stone} \quad \text{Haas } n_f = 2$
Outlook for $D_s$

Experiments limited by statistics
Systematize radiative corrections
Other lattice calculations using different dynamical fermions: $n_f = 2 + 1$, perhaps even $2 + 1 + 1$
Continue testing methodology

(Existence proofs of new physics to accommodate)
New physics in $b \rightarrow s$ transitions?

\[ A_{CP}(B^0 \rightarrow \pi^- K^+) = -9.7(12)\% \quad A_{CP}(B^+ \rightarrow \pi^0 K^+) = 5.0(25)\% \]
\[ \Delta A_{K\pi} \neq 0 \quad @ 5.3\sigma \]

EW penguin + 4th generation quarks?

\[ \sim \sin 2\Phi_{B_s} \approx (-0.5, -0.7) \]

\[ \bar{B} \rightarrow X_s \ell^+ \ell^- \quad @ \text{NLO} \]

Color-suppressed $B$ decays in SCET

Zwicky Hou

UTfit

Huber

Lu
New physics in \((g-2)_{\mu}\)?

\[
a^\text{exp}_\mu = (11 659 208.0 \pm 6.3) \times 10^{-10}
\]

\[
a^\text{SM}_\mu = (11 659 180.5 \pm 5.6) \times 10^{-10}
\]

\[
a^\text{exp}_\mu - a^\text{SM}_\mu = (27.5 \pm 8.4) \times 10^{-10}
\]
Meticulous comparison of $e^+e^-$, $\tau$ decays

Benayoun, Hoecker

Vainshtein
New physics within the standard model?

Heavy ion collisions: new realms of QCD

$\epsilon_{\text{RHIC}} = 15 \text{ GeV/fm}^3, \times (3-5) \@ \text{LHC}$
New physics within the standard model?

Searches underway for Wess-Zumino term

NA48, Belle, …

Apt subject for a tutorial at Moriond 2009?

Related: low-energy manifestation of sphaleron
(nonperturbative B violation linked to B-current anomaly)

EW baryogenesis
low-E vN signal?
Astrophysical?
Friendly criticism from a Lagrangian friend …

Hadron phenomenology and spectroscopy does not test SM
We have a qualitative understanding of QCD phenomenology
Many aspects are not calculable from first principles
We make models for new states
  
  \textit{approximations such as potential models}

  \textit{intuitive pictures of substructure}

  \textit{competing pictures are not mutually exclusive}

  \textit{quantum superpositions are possible}

We won’t discard QCD if these pictures fail for a new state
We do learn how to refine our approximations to QCD
How do you respond?

Fundamental vs. applied science?
Models vs. controlled approximations?
Are we testing theories or theorists?
$\mathcal{L}_{\text{QCD}}$ or random numbers?

The value of a physical picture …
can give an answer (whether or not precise and controlled),
or show that simplifying assumptions are unwarranted

*Chiral quark model* anticipates
asymmetry in light-quark sea,
negative polarization of strange
(but not antistrange) sea …

What is a hadron? What are apt degrees of freedom?
What symmetries are fruitful? QCD under unusual conditions
New states associated with charmonium

If confirmed, $Z^+(4430)$ cannot be quark-antiquark $^3D_2(3831?)$ and $^1D_2(3838)$ still missing

$Z(3930)$ fits $2^3P_2$ assignment

$Y(3940)$ favors $2^3P_1$ assignment

$X(3943)$ fits $3^1S_0$ assignment

[Y(4260), Y(4350)] and $Y(4660)$ may be hybrids, with $Y(4660)$ the radial (q-qbar) excitation

$X(3872)$ may be $D^0D^{0*}$ bound state, driven by nearby $2^3P_1$ level
Building Theoretical Apparatus for the LHC

Differential Higgs-boson production @ NNLO

Anastasiou, Grazzini

\[ \sigma \] [pb]

\[ p_T^{\text{H,max}} \] [GeV]

MRST2004 NNLO
\[ \frac{m_H}{2} \leq \mu_R = \mu_F \leq 2m_H \]
\[ m_H = 165 \text{ GeV} \]

NNLO+NNLL

R(MC@NLO)

Anastasiou

we also compare the inclusively rescaled generator spectra (HERWIG, MC@NLO) to the 'best' prediction:
Building Theoretical Apparatus for the LHC

Automated evaluation of one-loop amplitudes for NLO, exploiting on-shell methods implemented for gluon amplitudes

6-γ amplitudes using modern methods

Parton showers with quantum interference aim: only approximation small-angle / soft splitting Color & spin density matrix, relaxes to standard MC

NLO + resummation for Z’ production reliable σ, test of generators
Building Theoretical Apparatus for the LHC

Uncertainties, nuclear corrections for PDFs
use nuclear data to extract nuclear PDFs

*important for heavy-quark densities*

---

The Challenge

Reference fit $Q^2 = 10 \text{ GeV}^2$
Ref+Chorus+NuTeV+E866 fit
Ref+NuTeV+E866 fit
Ref+Chorus+E866 fit
Ref+Chorus+NuTeV fit
Building Theoretical Apparatus for the LHC

Neural net PDFs to escape parametrizations and more reliably assess uncertainties

Evolution equation methodologies

\[ pp \rightarrow VV + \text{jet} \ @ \ NLO \]

Improved understanding of $\tau$ decays $\chi$PT at large $N_c$
Applications beyond the LHC
QCD influence on UHE $\nu$ detection
*Importance of wee-$x$ parton distributions*

A.M. Stasto astro-ph/0310636

$E_\nu = 10^{11}$ GeV

$Q^2 = M_W^2$

![Graph showing the relationship between $\log(x)$ and $\log_{10}(x)$ for $E_\nu$ and $Q^2$.](image)

![Graph showing the relationship between $E_\nu$ and $\sigma_{CC}$ for various parton distributions.](image)

Berger, Block, Tan unitarized
CTEQ6
EHLQ
EHLQ, unevolved

HERA

$10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$ $10^{12}$

$10^{-36}$ $10^{-35}$ $10^{-34}$ $10^{-33}$ $10^{-32}$ $10^{-31}$
While on the subject of neutrinos …

Connection between $\nu$ properties, 1-TeV scale?

$m_\nu$ not necessarily set at high scale, LHC signatures ($Z'$, other heavies) possible

Raidal, see also hep-ph/0612017
AdS/CFT Connection, holography, etc.

Powerful methods to solve strong-coupling problems that may give insight into real problems

Issue: theories we can solve are not exactly QCD, so what should we expect from these exercises?

Insights into strongly coupled theories?
Hints about universal behavior?
Reliable analogues for QCD?
(Direct tests of string theory?)

Hashimoto, Hong, Zarembo, Heller, Dung Nguyen
How realized in QCD (Pomeron \(\leftrightarrow\) gluons)?

How is Froissart bound realized?

\[ \sigma_{\text{tot}} \leq C \cdot \ln^2 s \]

Avsar
Observation of large rapidity gaps at Tevatron, HERA encourages exploration of diffractive discovery channels.
Global fits favor a Higgs boson …

… but only test its coupling to gauge bosons
Keep in mind ... 

We do not know the origin of fermion mass, so discovery may require nonstandard modes, “invisible” Higgs could be very challenging.

van der Bij conjecture (weak form) 
Something bad could happen.

van der Bij conjecture (strong form) 
It already has.
A Few Big Questions about EWSB

- What hides electroweak symmetry?
- Is there one Higgs boson? several?
- Does $H$ give mass to fermions, or only to gauge bosons? What sets $f$ masses, mixings?
- How does $H$ interact with itself?
- Does the pattern of $H$ decays imply new physics? imply new forms of matter?
- What stabilizes $M_H$ on the Fermi scale?
- Is Nature supersymmetric?
- Is EWSB controlled by new strong dynamics? by extra dimensions?
- Can light Higgs coexist with absence of new phenomena?
We think the electroweak theory is incomplete.

*Also hierarchy problem, fermion masses, etc.*
QCD could be complete, up to $M_{\text{Planck}}$

... but that doesn’t prove it must be Prepare for surprises!

10. SOME EXPERIMENTS ON MULTIPLE PRODUCTION

Kenneth G. Wilson

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

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Might we see unexpected event structure in early LHC running?

Importance of canonical expectations for multiplicities, correlations, topologies

Even without surprises, study of soft collisions, underlying events will pay great dividends in understanding multiple production and the search for new physics!
A Modest Proposal for QCD 2009:  
A Night at the Zoo

Experimental groups encouraged to share puzzling effects / “zoo events”

*Promote awareness, stimulate thinking*

Theoretical responses invited

Off the record · No reporting

*Grappa provided to all speakers*
Un très grand merci …
da tous les participants, surtout aux élèves
aux gentils organisateurs
à nos amies sauvetrices du secretariat
au personnel du Planibel
à Kim et Van
À très bientôt !