Applications of QCD

Varying coupling constant

Jets and Gluons

Quark-Gluon plasma

Colour counting

The proton structure function (not all of section 5.8!)
At small distances (high momentum transfers)
- The strength of strong interaction is significantly diminished

Analog with EM interactions:
- a) Electrons can emit/reabsorb virtual photons
- b) Can happen in reverse modifying the strength of EM interaction
  - Known as vacuum polarisation – small increase in $\alpha_{\text{EM}}$

Leads to $O(10^{-7})$ change in hydrogen atom energy levels
- At highest energy electron scattering $\alpha_{\text{EM}} \sim 1/128$
QCD Vacuum Polarisation

- Same thing happens in QCD for quark (or gluon) interactions
  - Quantum fluctuations influence leading order interaction strength
  - Existence of extra diagram (gluon loop) leads to opposite effect on the QCD interaction strength → gets weaker at short distances
  - Overall effect is also larger in QCD → Asymptotic freedom
    - Leads to a running coupling constant: $\alpha_s = \alpha_s(Q^2)$
Running Coupling Constants

![Graph showing the running of the coupling constant vs. μ (GeV/c)]
Running Coupling Constants

New particles around here?
Jets from Gluons

- Already discussed the principle of fragmentation
  - The process that converts the energy in colour-fields between quarks (or gluons) and produced additional quarks → making colourless hadrons in all final states.

- Jet production is a two stage process:
  - Initially $e^+e^- \rightarrow q \overline{q}$
  - Followed by $q/\overline{q} \rightarrow$ jets of hadrons

- Direction and momentum of jet preserves original direction/momentum of quark
  - A consequence of asymptotic freedom
    - QCD relatively weak at short distances (inside the jet as hadrons are being formed)

- Predict angular distribution of outgoing quarks precisely in QED
  - Matches well with the observed jet angular distribution
Pair production of quarks dominates
But the probability to produce an extra gluon is easy to estimate
A bremsstrahlung photon can appear with probability $\alpha_{EM} \approx 1/137$
An extra gluon can be radiated from a quark with prob. $\approx \alpha_s/\pi$
Produces 3-jet events

The emission of a spin-1 gluon from back-to-back spin-$\frac{1}{2}$ quarks
Has a relatively simple angular distribution
Agrees with direction/energy/frequency of 3rd jets in $e^+e^-$ collisions
Quark and gluons are normally confined inside hadrons
- At ‘normal’ energy densities \( \approx \) mass of the hadrons over a few fm\(^3\)
- Attempting to knock a quark (or gluon) out of a hadron produces additional colourless hadrons

At high energy densities it should be possible for quarks and gluons to exist over extended volumes (100+ fm\(^3\))
- Need multi-particle interactions over large volumes to achieve sufficient energy density
- Only possible in heavy-ion collisions (Pb-Pb) – now being studied at LHC
- May be the state of matter in the core of neutron stars
- Thought to have existed at an early epoch in the big bang

Understanding this is traditionally in realm of nuclear physics
- Understanding transition from multi-nucleon nuclei \( \rightarrow \) plasma of quarks/glue
Formation of Quark Gluon Plasma

(a) Heavy nucleus

(b) Colour field

(c) Hadrons

(d) Formation process
Detecting Quark Gluon Plasma

- The gluons in plasma would have $\approx$ GeV energy at threshold
  - Enough to produce $\bar{s}s$ quark pairs
  - Leading to an excess of $\Phi$ mesons relative to normal nucleon-nucleon collisions (which produce lots of $\pi^+$ and $\pi^0$)
  - Charmonium and Beautyonium ($c\bar{c}$ and $b\bar{b}$) suppressed
  - Local energy density not high enough to produce these pairs

- Also starting to study the nature of the plasma formed
  - Energy densities and volumes are consistent with incompressible medium (i.e., a liquid)
  - Originally anticipated that it would be compressible – like a gas

- Unexpectedly discovered how quarks/gluons behave as they traverse such a hot/dense quark/gluon medium
  - Jet Quenching – discovered in ATLAS
In addition to Pb-Pb collision
- Which produced a plasma

- One additional hard scattering
- Produced back-to-back jets
- One jet had to traverse the plasma before exiting collision region
- It energy/momentum was degraded and spread out in angle leading to a diffuse jet on the opposite side
ATLAS Observation from 2010

A Pb-Pb collision event in the ATLAS detector at the LHC with a highly asymmetric pair of jets. One of the jets lost energy as it traversed the hot, dense medium produced in the collision. Selected for an Editors’ Suggestion and a Viewpoint in Physics. [G. Aad et al. (ATLAS Collaboration), Phys. Rev. Lett. 105, 252303 (2010)]
Quantum mechanics predicts all possible reactions proceed at equal rates (subject to selection rules and energy available)

- In $e^+e^-$ collisions $\mu^+\mu^-$ production occurs at same rate as $q\bar{q}$ production scaled by relative charges ($q_u = 2/3$ $q_\mu$)
- Consider cross-section ratio: $R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$
- Only difference charge of quarks

At high energies should be possible to make all quarks

$$R_0 \equiv N_c(q_u^2 + q_d^2 + q_s^2 + q_c^2 + q_b^2) = \frac{11}{9}N_c$$

At lower energies should see only quarks that are kinematically accessible (ie. light enough to be produced in $e^+e^-$ collisions)
Cross Section Ratio vs. Collision energy
Number of Colours?

- Consistent with $11/3$
- Expectation for $N_c = 3$
- Slight variation as function of energy
  - From change of strong coupling constant $R = R_0(1 + \alpha_s/\pi)$
  - $\alpha_s$ lower at higher energies

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The Proton Structure Function

- Textbook spends half of Chapter 5 on “Deep Inelastic Scattering”
  - Explains how we know, what we know, about the structure of the proton
  - Electron-proton scattering experiments have been going on for 50 yrs

- Modern collider experiments (pp or p\overline{p}) rely heavily on the momentum distributions of quarks and gluons inside the proton
  - These determine the actual collision energies explored at the LHC
  - Many measurements depend on not only u/d quark momenta
  - But also on gluon momentum distribution and/or ‘sea quark’ distributions
    - Proton actually contains (virtual) s, b, c (and all \(\overline{q}\)) with small prob.
    - Many rare physics processes (including Higgs production) depend critically on knowing/predicting these probabilities

- Understanding/Using ep scattering data requires extrapolations based on QCD predictions to different energy collisions (Q\(^2\))
Proton Parton Density Functions

Parton Density Function of Proton \([Q^2=(10 \text{ GeV})^2]\)

CTEQ6L

\(x_f(x, Q^2)\)

- \(u\)
- \(d\)
- \(\bar{u}\)
- \(s\)
- \(c\)
- \(b\)
- \(g\)
classic example: pp scattering

\[ \sigma(p(P_1) + p(P_2) \rightarrow t\bar{t} + X) = \int_0^1 dx_1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \rightarrow t\bar{t}) + O\left(\frac{\Lambda_{QCD}}{2m_t}\right) \]

(calculable)

(Feynman, Bjorken)

incalculable, but measurable
Summary

- Colour interactions provide a rich array of physical phenomena
  - Self-coupling of gluons leads to asymptotic freedom and running strong coupling constant
  - Quark/gluon fragmentation leads to jets of hadrons that make manifest the production of quarks in the original interaction
  - Quark-gluon plasma is an interesting phase of matter that is a key ingredient to understanding the evolution of the big bang
  - Constrain the number of quark flavours and the number of colours from ‘simple’ e⁺e⁻ interaction cross-sections

- Proton structure is understood through the lens of QCD predictions for gluon and virtual quark distributions inside the proton