Peter Skands  
(CERN-TH)

L = $\bar{\psi}_q^i (i \gamma^\mu)(D_\mu)_{ij} \psi_j^i - m_q \bar{\psi}_q^i \psi_q^i - \frac{1}{4} F^a_{\mu \nu} F^{a \mu \nu}$

“Nothing”

Gluon action density: 2.4x2.4x3.6 fm

QCD Lattice simulation from D. B. Leinweber, hep-lat/0004025
A huge variety of phenomena

\[ \mathcal{L} = \bar{\psi}_q^i (i \gamma^\mu) (D_\mu)_{ij} \psi_q^j - m_q \bar{\psi}_q^i \psi_q^i - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} \]

Still only partially solved ...
Data ↔ Theory

“It is a huge mistake to theorize before one has data - One tends to twist fact to suit theory, instead of theory to suit fact”

Sherlock Holmes (2009)
Collider Physics

Comparisons to Collider observables

L=...
Collider Physics

Comparisons to Collider observables

L=...

A) Theoretical Idea is wrong
Collider Physics

Comparisons to Collider observables

A) Theoretical Idea is wrong

B) SM Physics Model is wrong
Disclaimer

Focus on QCD for collider physics
- Factorization, Hard Processes
- Jets and Matching
- Monte Carlo Event Generators
- Underlying Event, Hadronization, Min-Bias, ...

Still, some topics not touched, or only briefly
- Heavy flavor physics (e.g., B mesons, J/Psi, ...)
- Physics of hadrons, Lattice QCD
- Heavy ion physics
- DIS
- New Physics
- Prompt photon production, polarized beams, forward physics, diffraction, BFKL, ...
Overview

1. Fundamentals of QCD
2. QCD in the Ultraviolet
3. QCD in the Infrared
4. Monte Carlo Generators
5. Jets & Matching
6. Getting (kick)started with PYTHIA 8
QCD
Lecture 1
Fundamentals
Before QCD

Some Theorems

E.g., Lorentz inv., unitarity and the optical theorem

$SS^\dagger = 1 \Rightarrow \sigma_{\text{tot}}(s) = \sum_X \int d\Phi_X |M_X|^2 = \frac{8\pi}{\sqrt{s}} \text{Im}[M_{\text{el}}(\theta = 0)]$

"something will happen" note: includes "no" scattering

Total $\sigma = \text{Sum over everything that can happen} = \text{"Square Root" of nothing happening}
Before QCD

Some Theorems

E.g., Lorentz inv., unitarity and the optical theorem

\[ SS^\dagger = 1 \implies \sigma_{\text{tot}}(s) = \sum_X \int d\Phi_X |M_X|^2 = \frac{8\pi}{\sqrt{s}} \text{Im} [M_{\text{el}}(\theta = 0)] \]

“something will happen”
note: includes “no” scattering

Total \( \sigma = \) Sum over everything that can happen = “Square Root” of nothing happening

+ Some models

E.g., potential models, Regge theory, Pomerons, string models, the early parton model, ...
After QCD

Some Theorems

E.g., Lorentz inv., unitarity and the optical theorem

\[ SS^\dagger = 1 \implies \sigma_{\text{tot}}(s) = \sum_X \int d\Phi_X |M_X|^2 = \frac{8\pi}{\sqrt{s}} \text{Im}[M_{\text{el}}(\theta = 0)] \]

“something will happen”
note: includes “no” scattering

More Theorems

\[ \mathcal{L} = \bar{\psi}_q(i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i\psi_q^i - \frac{1}{4}F_{\mu\nu}^aF^{a\mu\nu} \]

+ Factorization, Perturbative Quantum Field Theory,
  \[ \Rightarrow \text{Resummation, Coherence, Infrared Safety, ...} \]
+ Lattice Discretization
+ Phenomenological Models

+ Some models
  E.g., potential models, Regge theory, Pomerons, string models, constituent quark model, ...

+ More models
  Soft / non-perturbative effects
    Fragmentation models
    Diffraction models, Min-Bias models, soft Underlying-Event models
    Soft final-state interactions, hydrodynamics, ...
  Approximations to higher-order perturbative effects
    Jet (sub)structure and multiple emissions: shower models
    Multiple parton interactions: “hard” UE models
    Hard Diffraction (e.g., diffractive Higgs), ... work in progress
    interesting inputs from LHC
QCD as Discovery Physics

1951: the first hint of colour

Discovery of the $\Delta^{++}$ baryon

| $\Delta^{++}$ \rangle = | u_\uparrow u_\uparrow u_\uparrow \rangle 

Symmetric in space, spin & flavor
Antisymmetric in ???

Meson-Nucleon Scattering and Nucleon Isobars*

KEITH A. BRUECKNER
Department of Physics, Indiana University, Bloomington, Indiana
(Received December 17, 1951)

Phys.Rev.86(1952)106

satisfactory agreement with experiment is obtained. It is concluded that the apparently anomalous features of the scattering can be interpreted to be an indication of a resonant meson-nucleon interaction corresponding to a nucleon isobar with spin $\frac{3}{2}$, isotopic spin $\frac{3}{2}$, and with an excitation of 277 Mev.

~ 1960: Eightfold Way

Isospin: Wigner, Heisenberg
Strangeness (’53): Gell-Mann, Nishijima
Eightfold Way (’61): Gell-Mann, Ne’eman
Quarks (’63): Gell-Mann, Zweig, (Sakata)
The $\Delta$ Baryon

1951: the first hint of colour

Discovery of the $\Delta^{++}$ baryon

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1965: $|\Delta^{++}\rangle = \varepsilon_{ijk} | u_i \uparrow u_j \uparrow u_k \uparrow \rangle$

Symmetric in space, spin & flavor
Antisymmetric in a new ($\geq$3D) Quantum Number
+ postulate only overall singlets observed in nature
E.g., $| u_R u_R \rangle$ not a “physical” particle

Additional SU(3):
Han, Nambu, Greenberg
The Width of the $\pi^0$

$\Delta^{++}, \Delta^-, \text{ and } \Omega^-$

Strictly speaking, we only know $N \geq 3$

$\pi \rightarrow \gamma\gamma$ decays

Get pion decay constant $f_\pi$ from

$\pi^- \rightarrow \mu^- \nu_\mu$

$\Rightarrow \quad \Gamma(\pi^0 \rightarrow \gamma^0\gamma^0)_{th} = \frac{N^2 C}{9} \frac{\alpha_{em}^2}{\pi^2} \frac{1}{64\pi} \frac{m^3_{\pi}}{f^2_{\pi}} = 7.6 \left( \frac{NC}{3} \right)^2 \text{ eV}$

See, e.g., Ellis, Stirling, & Webber, “QCD and Collider Physics”, Cambridge Monographs
The R ratio

\[ R = \frac{\sigma(e^+e^- \rightarrow q\bar{q})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

First

\[ = n_u \left( \frac{2}{3} \right)^2 + n_d \left( -\frac{1}{3} \right)^2 \]

Last

\[ = \begin{cases} 
2 \left( \frac{N_C}{3} \right) & q = u, d, s \\
3.67 \left( \frac{N_C}{3} \right) & q = u, d, s, c, b 
\end{cases} \]

Question: why does \( \pi^0 \rightarrow \gamma^0 \gamma^0 \) go with \( N_C^2 \) and \( R \) only with \( N_C \)?
The $R$ ratio

$$R = \frac{\sigma(e^+e^- \rightarrow q\bar{q})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = \begin{cases} 2 \left( \frac{N_C}{3} \right) & q = u, d, s \\ 3.67 \left( \frac{N_C}{3} \right) & q = u, d, s, c, b \end{cases}$$

Plot from PDG
So What?
New Physics Pipeline

Data Phenomenological Models

Discriminating Observables

Individual Essential Features

Fits

Quark Model, Eightfold Way, ...

(Solvable) Theory

Complete description

Quantum Chromo-Dynamics
**Gauge Group (= local internal space)**

Special Unitary group in 3 (complex) dimensions, SU(3)

(Group of 3x3 unitary complex matrices with det=1)

**Gluons**

One gauge boson for each linearly independent such matrix

\[3^2 - 1 = 8 : \text{gluons are octets}\]

**Quarks**

One quark color for each degree of SU(3)

3 : quarks are triplets (e.g., vectors on which matrices operate)
\[ \mathcal{L} = \bar{\psi}_q^i (i \gamma^\mu) (D_\mu)_{ij} \psi_q^j - m_q \bar{\psi}_q^i \psi_q^i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \]

**Quark fields**

\[ \psi_q^j = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix} \]

**Covariant Derivative**

\[ D_{\mu ij} = \delta_{ij} \partial_\mu - ig_s T_{ij}^a A_\mu^a \]

\( \Rightarrow \) Feynman rule

**Gell-Mann Matrices**

\( (T^a = \lambda^a/2) \)

- \( \lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \)
- \( \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \)
- \( \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \)
- \( \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \)
- \( \lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \)
- \( \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \)
- \( \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \)
- \( \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & -\frac{2}{\sqrt{3}} \end{pmatrix} \)

(Antonio used \( G_\mu \) instead of \( T A_\mu \) and \( G_\mu \) instead of \( A_\mu \)
Interactions in Colour Space

Quark-Gluon interactions

\[ \psi_j = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix} \]

\[ \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \]
Interactions in Colour Space

Quark-Gluon interactions

\[ \psi_j q \]

\[ \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix} \]

\[ \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \]

\[ \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \]

\[ \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \]
Interactions in Colour Space

**Colour Factors**

We already saw pion decay and the "R" ratio depended on how many "color paths" we could take. All QCD processes have a "colour factor". It counts the enhancement from the sum over colours.

\[
\sum_{\text{colours}} |M|^2 = \delta_{ij} \delta^{*}_{ji} = \text{Tr} [\delta_{ij}] = N_C
\]

\[
\psi_i q \psi_j = \delta_{ij} \sum_{\text{colours}} |M|^2 = \propto \delta_{ij} \delta^{*}_{ji} = \text{Tr} [\delta_{ij}] = N_C
\]

\[i,j \in \{R,G,B\}\]
Interactions in Colour Space

**Colour Factors**

We already saw pion decay and the “R” ratio depended on how many “color paths” we could take. All QCD processes have a “colour factor”. It counts the enhancement from the sum over colours.

\[
\sum_{\text{colours}} |M|^2 = \delta_{ij} \quad \propto \delta_{ij} \delta^*_{ji} = \text{Tr}[\delta_{ij}] = NC
\]

Z Decay:
Interactions in Colour Space

**Colour Factors**

We already saw pion decay and the “R” ratio depended on how many “color paths” we could take. All QCD processes have a “colour factor”. It counts the enhancement from the sum over colours.

\[
\sum_{\text{colours}} |M|^2 = \delta_{ij} \propto \delta_{ij} \delta_{ji} = \text{Tr}[\delta_{ij}] = NC
\]
Interactions in Colour Space

Colour Factors

We already saw pion decay and the “R” ratio depended on how many “color paths” we could take.

All QCD processes have a “colour factor”. It counts the enhancement from the sum over colours.

\[
\frac{1}{9} \sum_{\text{colours}} |M|^2 = \delta_{ij} \propto \delta_{ij}\delta_{ji}^* = \text{Tr}[\delta_{ij}] = NC
\]

\(i,j \in \{R,G,B\}\)
Interactions in Colour Space

**Colour Factors**

We already saw pion decay and the “R” ratio depended on how many "color paths" we could take.

All QCD processes have a "colour factor". It counts the enhancement from the sum over colours.

\[ Z \rightarrow 3 \text{jets} \]

\[
\sum_{\text{colours}} |M|^2 = \delta_{ij} \delta_{ji} \propto \delta_{ij} T^j_a (T^l_a \delta_{il})^* = \text{Tr}[T_a T_a] = \frac{1}{2} \text{Tr}\delta_{ab} = 4
\]

\[ i,j \in \{R,G,B\} \]
\[ a \in \{1,...,8\} \]
Quick Guide to Colour Algebra

Colour factors squared produce traces

\[ \text{Tr}(t^A t^B) = T_R \delta^{AB}, \quad T_R = \frac{1}{2} \]

(from lectures by G. Salam)
Quick Guide to Colour Algebra

Colour factors squared produce traces

\[ \text{Tr}(t^A t^B) = T_R \delta^{AB}, \quad T_R = \frac{1}{2} \]

\[ \sum_A t^A_{ab} t^A_{bc} = C_F \delta_{ac}, \quad C_F = \frac{N_c^2 - 1}{2N_c} = \frac{4}{3} \]

(from lectures by G. Salam)
Quick Guide to Colour Algebra

Colour factors squared produce traces

\[ \text{Tr}(t^At^B) = T_R \delta^{AB} , \quad T_R = \frac{1}{2} \]

\[ \sum_A t^A_{ab} t^A_{bc} = C_F \delta_{ac} , \quad C_F = \frac{N_c^2 - 1}{2N_c} = \frac{4}{3} \]

\[ \sum_{C,D} f^{ACD} f^{BCD} = C_A \delta^{AB} , \quad C_A = N_c = 3 \]

\[ t^A_{ab} t^A_{cd} = \frac{1}{2} \delta_{bc} \delta_{ad} - \frac{1}{2N_c} \delta_{ab} \delta_{cd} \quad \text{(Fierz)} \]

(from lectures by G. Salam)
The Gluon

**Gluon-Gluon Interactions**

\[ \mathcal{L} = \bar{\psi}_q^i (i \gamma^\mu) (D_\mu)_{ij} \psi_q^j - m_q \bar{\psi}_q^i \psi_q^i - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} \]

**Gluon field strength tensor:**

\[ F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f_{abc} A_\mu^b A_\nu^c \]

Structure constants of SU(3):

\[ f_{123} = 1 \]
\[ f_{147} = f_{246} = f_{257} = f_{345} = \frac{1}{2} \]
\[ f_{156} = f_{367} = -\frac{1}{2} \]
\[ f_{458} = f_{678} = \frac{\sqrt{3}}{2} \]

Antisymmetric in all indices

All other \( f_{ijk} = 0 \)
Gluon self-interaction

\[ \psi_{q_R} = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}, \quad \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \]

Absence in QED

\[ g_1^5, g_{q_R}^4, g_{q_G}^6 \]

Twice as large as quark
The Strong Coupling

**Bjorken scaling**

To first approximation, QCD is SCALE INVARIANT (a.k.a. conformal)

A jet inside a jet inside a jet inside a jet ...

If the strong coupling did not run, this would be absolutely true (e.g., N=4 SYM)
Conformal QCD

No running

\[ Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s), \quad \beta(\alpha_s) = 0 \]

This simplification (QCD at fixed coupling) already captures some of the important properties of QCD.
Conformal QCD

Bremsstrahlung

Rate of bremsstrahlung jets mainly depends on the RATIO of the jet $p_T$ to the "hard scale"

$$\sigma_X(j \geq 5 \text{ GeV}) \approx \sigma_X(j \geq 50 \text{ GeV})$$

See, e.g.,

Plehn, Tait: 0810.2919 [hep-ph]
Alwall, de Visscher, Maltoni: JHEP 0902(2009)017
Scaling Violation

In real QCD

\[ Q^2 \frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s), \quad \beta(\alpha_s) = -\alpha_s^2 (b_0 + b_1 \alpha_s + b_2 \alpha_s^2 + \ldots), \]

\[ b_0 = \frac{11C_A - 2n_f}{12\pi}, \quad b_1 = \frac{17C_A^2 - 5C_A n_f - 3C_F n_f}{24\pi^2} = \frac{153 - 19n_f}{24\pi^2} \]

The coupling runs logarithmically with the energy

Asymptotic freedom in the ultraviolet

Infrared slavery (confinement) in the IR
“What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the weaker is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called 'asymptotic freedom'. The converse is true when the quarks move apart: the force becomes stronger when the distance increases.”
Asymptotic Freedom

**QED:**
charge screening

**QCD:**
also has charge screening

Quark loops
But only dominant if > 16 flavors!
Asymptotic Freedom

QED:
charge screening

QCD:
color “leaking”

Gluons carry color
Dominant if < 16 flavors!
Asymptotic Freedom

At High Energies

QCD is weak $\rightarrow$ quarks and gluons almost free

Smaller coupling

$\rightarrow$ Perturbation theory better behaved

Lecture 2: QCD in the ultraviolet

$\rightarrow$ Changes in jet shapes

High-$p_\perp$ jets narrower than low-$p_\perp$ ones

Important for jet calibration (e.g., smaller “out-of-cone” corrs)

(Freedom or Unification?)

Decreasing coupling approaches EW ones ...
UV and IR

At current scales

Coupling actually runs rather fast

Explodes at a scale somewhere below $\approx 1 \text{ GeV}$

So we usually give its value at a unique reference scale that everyone agrees on
The Fundamental Parameter(s)

QCD has one fundamental parameter

\[ \alpha_s(m_Z)^\text{MS} \]

\[ \alpha_s(Q^2) = \frac{1}{1 + b_0 \alpha_s(m_Z) \ln \frac{Q^2}{m_Z^2} + O(\alpha_s^2)} \]

... and its sibling

\[ \Lambda_{QCD}^{(n_f)\text{MS}} \]

\[ \alpha_s(Q^2) = \frac{1}{b_0 \ln \frac{Q^2}{\Lambda^2}} \]

... And all their cousins

\[ \alpha_s(m_Z)_{LO} \alpha_s(m_Z)_{N^0\text{LO}} \alpha_s(m_Z)_{N^1\text{LO} + N^2\text{LL}} \alpha_s(m_Z)^\text{DIS} \alpha_s(m_Z)^\text{DR}, \ldots \]

\[ \Lambda^{(3)} \Lambda^{(4)} \Lambda^{(5)} \Lambda_{CMW} \Lambda_{FSR} \Lambda_{ISR} \Lambda_{MPI}, \ldots \]
Other parameters

The number of flavors (and quark masses)

- $n_f = 3$ (above $m_s$)
- $n_f = 4$ (above $m_c$)
- $n_f = 5$ (above $m_b$)
- $n_f = 6$ (above $m_t$)

$\alpha_s(m_Z)_{\text{MS}} = \frac{11N_C - 2n_f}{12\pi}$

+ New Physics contributions above some as yet unknown scale?
Other parameters

The emergent is unlike its components insofar as … it cannot be reduced to their sum or their difference." G. Lewes (1875)

Emergent phenomena

Cannot guess non-perturbative phenomena from perturbative QCD → “Emerge” due to confinement

- Hadron masses,
- Decay constants,
- Fragmentation functions
- Parton distribution functions,…

Difficult/Impossible to compute given only knowledge of perturbative QCD

→ Lattice QCD (only for “small” systems)
→ Experimental fits (for reference)
→ Phenomenological models (for everything else)
The Way of the Chicken

Who needs QCD? I’ll use leptons

- Sum inclusively over all QCD
  - Leptons almost IR safe by definition
  - WIMP-type DM, Z’, EWSB → may get some leptons

---

The unlucky chicken

• Put all its eggs in one basket and didn’t solve QCD
The Way of the Chicken

- Who needs QCD? I’ll use leptons
  - Sum inclusively over all QCD
    - Leptons almost IR safe by definition
    - WIMP-type DM, Z', EWSB → may get some leptons
  - Beams = hadrons for next decade (RHIC / Tevatron / LHC)
    - At least need well-understood PDFs
    - High precision = higher orders → enter QCD (and more QED)
  - Isolation → indirect sensitivity to QCD
  - Fakes → indirect sensitivity to QCD
  - Not everything gives leptons
    - Need to be a lucky chicken …

- The unlucky chicken
  - Put all its eggs in one basket and didn’t solve QCD

→ Next Lectures