Introduction to QCD and the physics of the LHC

Lake Baikal Summer School

July 23-30 2009

Michelangelo L. Mangano
TH Unit, Physics Dept, CERN
michelangelo.mangano@cern.ch
Questions still left unanswered by the SM

- what’s the origin of electroweak symmetry breaking and of mass?
  - SM Higgs mechanism?
  - Supersymmetry?
  - new strong forces (technicolor)? .....
- why Universe dominated by matter? Sources of CP violation?
- what is the origin of dark matter?
- why SU(3)xSU(2)xU(1)? are there are fundamental forces?
- why 3 generations? are there other elementary fermions?
- what about gravity? why 4 dimensions?
- ..... and many more!!

The goal of the next generation of experiments is to start answering these questions.
The Large Hadron Collider (LHC)

http://hcc.web.cern.ch/hcc/
The LHC accelerator

- $E_{\text{beam}} = 7000 \text{ GeV} \sim 7 \times 10^{12} \text{ eV} \sim 5 \text{ trillions } 1.5\text{V} \text{ batteries}$
  
  - ~ $100 \text{ M km of batteries},$ about $d[\text{Earth-Sun}]$

- $E_{\text{beam}} = 7000 \text{ GeV} \sim 7500 \ m_{\text{proton}} \ c^2$
  
  - $E=mc^2/\sqrt{1-v^2/c^2} \Rightarrow v = 0.999\ 999\ 999\ 99\ c$

- $N_{\text{proton}} \sim 10^{11}/\text{bunch} \times 2800 \text{ bunches/beam} \times 2 \text{ beams} \sim 10^{14}$

- Energy stored $\sim 350 \text{ MJ} \sim 80\text{kg of TNT} \sim$ Train running full speed
Booster, 157m (1972)

Proton Synchrotron, 628m (1959)

Super-Proton Synchrotron, 7km (1976)

LHC, 27 km (1989 as LEP, 2008 as LHC)
Steering protons

\[ B: \text{Magnetic field line perpendicular to the screen} \]
The LHC dipole

- 1232 LHC dipoles, plus ~600 other smaller magnets
- B field = 83,000 Gauss (Earth’s field ~ 0.5 Gauss)
  - Ni Ti SC cable
- T = 1.9K₀ = – 456 °F
  - superfluid liquid Helium
- 35 tonnes
- 15 m long
- Stress at the collar: 150 MPa
  - ~ 22,000 psi
  - ~ 1,500 kg/cm²
- Stored energy: 7 MJoule/dipole => ~ 10G Joule total

A great lecture on LHC dipoles:
L.Rossi, slides: http://indico.cern.ch/materialDisplay.py?sessionId=18&materialId=0&confId=a042016
video: http://indico.cern.ch/materialDisplay.py?sessionId=18&materialId=1&confId=a042016
Atlas detector

Detector characteristics:
- Width: 44m
- Diameter: 22m
- Weight: 7000t
The experimental challenge

• Bunch crossing repetition rate: 40 MHz (25 ns $\leftrightarrow$ 7.5 m)
  • can only write out $\sim$200 events/sec $\Rightarrow$ trigger keeps only $10^{-5}$ of the events

• 1 top quark produced / sec
  • like finding 1 needle in a 10 tonnes stack of needles, with 1 second of time to do it

• 1 Higgs boson produced / hr
  • like finding 1 needle in a 10,000 tonnes stack of needles
The expected timeline

• Completion of the work on the accelerator by end-November

• Start of LHC commissioning with beam before end of the year

• Collisions until Fall 2010, for an expected $O(100) \text{ pb}^{-1}$ of integrated luminosity at CM energies in the range of 6–10 TeV

• Further consolidation work during one or more shut-downs, to reach the full energy (14 TeV) and full luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$) within 2012
The goals of the LHC

• To firmly establish the “what”:  
  • discover the crucial missing element of the Standard Model, namely the **Higgs boson**  
  • discover direct evidence for the particle responsible for the **Dark Matter** in the Universe  
  • establish the sources of CP violation  
  • search for possible new fundamental interactions, too weak to have been observed so far  
  • search for possible new generations of quarks or leptons  
  • confirm/disprove the elementary nature of quarks/leptons  

• To firmly establish the “how”: the observation of the Higgs boson, and the determination of its properties, will complete the dynamical picture of the Standard Model, confirming (hopefully!) our presumed understanding of “how” particles acquire a mass.

• To seek new elements which can help us shedding light on the most difficult question, namely **WHY?**
Observables and fundamental quantities

- **Mass:**
  - Composite particles -> dynamical origin, calculable: \( M = \frac{E}{c^2}, E = T + U \)
  - Fundamental particles -> assigned parameter; origin ???
  - **Measurement:**
    - in decays: \( P = \sum p_i \), \( M^2 = P^2 \)
    - in production: \( M = \text{minimum energy necessary for creation} \)

- **Charge:**
  - Which type (electric, weak, strong)?
  - Are there other charges?? What is the origin of charge??
  - **Measurement: interaction strength**
    - lifetime of a particle before its decay (or its width)
    - reaction probabilities (rate counting)

- **Spin** (intrinsic angular momentum):
  - Integer-> bosons, Semiinteger -> fermions
  - Origin??
  - Pauli principle (two identical fermions cannot occupy the same quantum state) at the origin of matter stability and diversity
  - **Measurement: angular distributions in scattering or decay processes**
Examples of mass determination: 
M = energy at production threshold

Production rate for $e^+e^- \rightarrow \text{hadrons}$, as a function of the center of mass energy

The peaks represent the appearance of a new possible final state, made it possible by having enough CM energy to create it.
Examples of mass determination: top quark kinematic reconstruction

top → bottom + W
  → e nu
  → μ nu
  → τ nu
  → q antiq
Inside the proton we can find, in addition to the component $uud$ quarks, also **gluons** as well as **quark-antiquark** pairs.

If we probe the proton at energies high enough, we take a picture of the proton with a very sharp time resolution, and we can “detect” the presence of these additional components. In particular, the gluons and antiquarks present inside will participate in the reactions involving proton.

Notice that, if $\Delta t$ is small enough, even pairs of quark-antiquark belonging to the heavier generations (e.g. s-sbar, c-cbar) can appear!! The proton can contain quarks heavier than itself!!
Examples of reactions in proton collisions

**quark-quark scattering:**

Real-life example from p-pbar collisions at the Tevatron, 1.96 TeV CM energy:

\[ M(\text{dijet}) = 1370 \text{ GeV} \]
Real data (Tevatron) vs theoretical expectations

If quarks are pointlike (QCD: solid line)

Possible deviations if quarks have a substructure apparent at a distance scale equal to $1/\Lambda$

Data exclude $\Lambda < 2.4$ TeV $\Rightarrow$
quarks are pointlike at least down to $10^{-17}$ cm

The LHC will probe distances a factor of 10 smaller!!
Examples of reactions in proton collisions

quark-antiquark annihilation:
\[ u \overline{d} \rightarrow W \]

A real-life event from the tevatron:

In principle the “force carrier” of new interactions could be created in the same way, provided their mass is not too large.
Examples of reactions in proton collisions

gluon-gluon reactions:

$gg \rightarrow \text{top antitop}$
## Rates for some processes

<table>
<thead>
<tr>
<th>Process</th>
<th>events/s</th>
<th>events/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>30</td>
<td>$3 \times 10^8$</td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$</td>
<td>3</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.8</td>
<td>$8 \times 10^6$</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>$5 \times 10^5$</td>
<td>$5 \times 10^{12}$</td>
</tr>
<tr>
<td>jets, $E_t &gt; 1$ TeV</td>
<td>$1.5 \times 10^{-2}$</td>
<td>$5 \times 10^5$</td>
</tr>
<tr>
<td>$H \left(m_H = 130 \text{ GeV}\right)$</td>
<td>0.02</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>$\tilde{g}\tilde{g} \left(m_\tilde{g} = 1 \text{ TeV}\right)$</td>
<td>$10^{-3}$</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>
QCD: quantum chromodynamics

Understanding the physics of proton-proton collisions requires the understanding of the proton structure, and of the interactions among its elementary constituents, quarks and gluons.

These interactions are described by quantum chromodynamics, a gauge theory, with SU(3) symmetry group, whose charge is called color.

Gluons: force carriers, in the adjoint representation, 8, of SU(3)
Quarks: matter fields, in the fundamental representation, 3, of SU(3)

QCD is characterized by

confinement: the potential grows linearly at large distance, confining colored objects into color-singlet systems (hadrons)

asymptotic freedom: the strength of the coupling constant decreases at short distance, where colored partons can be treated as free particles
Applications of QCD

- nuclear structure
- proton structure (DIS, polarized DIS, diffraction, ..... )
- hadronic spectroscopy and transitions (scattering, decays, etc)
- EW properties of quarks ("CKM physics"): K, D, B decays
- $e^+ e^-$ to hadrons (determination of $\alpha_s$, non-PT effects, ... )
- jet physics (in ee, ep and pp(bar) collisions)
- quark-gluon plasma (relativistic heavy-ion collisions)
- ....
Remainder of these lectures

- review the proton structure at short distance
  - Factorization theorem
  - Parton densities

- applications at the LHC
  - Production of W and Z bosons
  - Production of jets and top quarks

A useful reference review:

J. Campbell, J. Huston, J. Stirling: *Hard Interactions of Quarks and Gluons: a Primer for LHC Physics*