LHC Detectors and their Physics Potential

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Part 1
Introduction to the LHC
Detector Requirements & Design Concepts
What is the Large Hadron Collider?

- Circular proton-proton collider under construction at CERN
  - Collide counter-rotating beams of protons head-on
    - Centre-of-mass energy
      \[ \sqrt{s} = 2\times E_{\text{beam}} \approx 2\times p_{\text{beam}} \]
    - Compare to fixed-target
      \[ \sqrt{s} \approx \sqrt{(2\times m\times E_{\text{beam}})} \]
      \[ m \approx 1 \text{ GeV for proton target} \]
- Will also operate some of the time with heavy-ion beams
  - e.g. Pb-Pb collisions
- First proton-proton collisions expected in Summer 2007
Energy and intensity

- Want very high **energy** and very high **intensity** to maximize the sensitivity to new physics
  - Energy needed to produce new massive particles such as the Higgs boson
  - Intensity needed because some of the processes that one would like to study are very rare (e.g. small $\sigma.B$ for decay modes visible above background)
LHC uses existing CERN complex

- LHC is being built in the existing tunnel previously used for LEP
  - Circumference = 27 km
    - Radius = 4.3 km
- Use existing accelerators as injection system
- Four major “experiments”
  - ATLAS and CMS are “general-purpose” detectors optimised for exploring new physics in pp collisions
  - LHCb is a specialized detector optimised for B-physics studies
  - ALICE is a specialized detector optimised for heavy-ion physics
Path of the CERN LEP/LHC tunnel

Circumference of ring ~ 27 km
Illustration with ATLAS detector
Beam Energy

- Energy of protons is limited by the magnets that guide the beams on circular path
  - Beam energy \( \equiv \) momentum:
    \[
    p = 0.3 \times B \times r
    \]
    \( p \) = momentum [GeV],
    \( B \) = magnetic field [Tesla],
    \( r \) = radius [metres]

- Since the radius of the ring is fixed, one has to use very high-field magnets to reach high energy...
  - and fill as large a fraction as possible of the circumference with magnets
    - Achieve \( \sim 2/3 \) of ring with dipole magnets
    - Need other magnets for focusing, etc
    - Need straight sections for acceleration, detectors
    - Also require space for beam injection and ejection systems
Need very high-field “two-in-one” magnets

- Use 15-meter long superconducting magnet coils cooled to 1.9 K with super-fluid Helium
  - Field > 8 Tesla
    - Compared to 4–5 Tesla at Tevatron and HERA
- Since LHC collides beams of protons (not proton-antiproton as at Tevatron), one needs double magnets
  - Note: Use two proton beams because antiprotons cannot be produced, accumulated and cooled in sufficient numbers to reach desired beam intensity
Luminosity

- Want highest *luminosity* possible: *Rate* ≡ \( \sigma \times L \)
  - Access to rare (i.e. low cross-section) processes

\[
\mathcal{L} = \frac{N_{b1} N_{b2} f_{\text{rev}} k_b}{2\pi \sqrt{(\sigma_{x1}^2 + \sigma_{x2}^2)(\sigma_{y1}^2 + \sigma_{y2}^2)}} \cdot \exp \left\{ -\frac{(\bar{x}_1 - \bar{x}_2)^2}{2(\sigma_{x1}^2 + \sigma_{x2}^2)} - \frac{(\bar{y}_1 - \bar{y}_2)^2}{2(\sigma_{y1}^2 + \sigma_{y2}^2)} \right\}
\]

- Beam parameters at LHC
  - \( N \approx 10^{11} \); \( \sigma \approx 15 \text{ \( \mu \)m} \) in ATLAS and CMS; \( f = 11 \text{ kHz} \); \( k = 2808 \)
Some LHC parameters

• Centre-of-mass energy
  – $\sqrt{s} = 14$ TeV for proton-proton collisions
    • c.f. 2 TeV at Tevatron collider
    • Equivalent to $\sim 100,000$ TeV or $10^{17}$ eV fixed-target beam energy
  – $\sqrt{s} = 6$ TeV *per nucleon* for Pb-Pb collisions

• Luminosity
  – $L = 10^{34}$ cm$^{-2}$s$^{-1}$ for proton-proton collisions in ATLAS and CMS
    • c.f. $L = 10^{32}$ cm$^{-2}$s$^{-1}$ at Tevatron
  – $L = 10^{27}$ cm$^{-2}$s$^{-1}$ for Pb-Pb collisions (in ALICE and also ATLAS+CMS)

• Note: enormous energy stored in proton beams
  – 331 MJ/beam (enough to melt 500 kg of copper)!
    • Rely on safe ejection of beams into beam dumps at end of coast
    • Most of the protons used up in beam-beam collisions in experimental areas
More LHC parameters

• Protons circulate in bunches (i.e. not continuous beam)
  – Bunch spacing is 25 ns in time (i.e. 7.5 meters in distance)
    • Bunch-crossing rate is 40 MHz

• Total proton-proton cross-section $\sigma \sim 100$ mb
  – Interaction rate at $L = 10^{34}$ cm$^{-2}$s$^{-1}$ is $R \sim 10^{9}$ Hz
    • On average $\sim 25$ interactions per bunch crossing
      – Background activity that complicates analysis of what happened in the interaction of interest
  – LHC$b$ uses $L = 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ to maximize rate of single-interaction bunch crossings
    • Different focusing of beams to ATLAS and CMS
  – Rate much lower for heavy-ion case
    • $R \sim 10^{4}$ Hz for Pb-Pb (low luminosity)
      – Much less than bunch-crossing rate (BC period = 125 ns for Pb ions)
Luminosity for LHCb $L = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

- LHCb can operate concurrently with ATLAS and CMS
  - Different “optics” – less focussed beams – larger $\sigma$

$$L = \frac{N_{b1} N_{b2} f_{rev} k_b}{2\pi \sqrt{(\sigma_{x_1}^2 + \sigma_{x_2}^2)(\sigma_{y_1}^2 + \sigma_{y_2}^2)}} \cdot \exp \left\{ -\frac{(\bar{x}_1 - \bar{x}_2)^2}{2(\sigma_{x_1}^2 + \sigma_{x_2}^2)} - \frac{(\bar{y}_1 - \bar{y}_2)^2}{2(\sigma_{y_1}^2 + \sigma_{y_2}^2)} \right\}$$

- Beam sizes at the IP (horizontal & vertical)
- Beam-beam offsets (horizontal & vertical)
- Bunch intensities
- Number of bunches
Illustration with CMS detector
Multiple interactions per BC = “pile-up”
Has strong impact on detector designs

- Need detectors with fast time response ~ “exposure time”
  - Pile up in a single bunch crossing already presents a challenge!
  - Except in the case of ALICE where the rate of heavy-ion collisions is much less than the bunch-crossing frequency
- Need fine detector granularity to be able to reconstruct the “event”
  - Minimize the probability of pile-up in the same detector element as an interesting object
    - E.g. probability for energy from the “pile-up” interactions being deposited in the calorimeter cell hit by a photon in an H → γγ decay
Physics Objectives (ATLAS and CMS)  
(see lectures of Michelangelo)

- Search for and study of new physics in ATLAS and CMS
  - Origin of electro-weak symmetry breaking ($m_W$ and $m_Z$)
    - Higgs boson (or bosons)
    - Alternative schemes
  - SUSY
    - squark and gluinos have large cross sections
  - Compositeness
  - Leptoquarks
  - $W'$ and $Z'$
  - Extra dimensions
    - KK excitations, black holes
  - The unpredicted!
    - Very important to be open to this in our event selection and analysis
      - LHC has an order of magnitude more centre-of-mass energy and two orders of magnitude more luminosity compared to today’s most powerful machine
Physics Objectives (ATLAS and CMS)

- **Standard Model production processes**
  - W, Z, direct-photon production
  - Jet production (including multi-jet production)
  - Interesting in their own right
  - Must be understood as backgrounds to new physics
  - Can be done with comparatively very little integrated luminosity
    - It will take some time before the LHC is tuned to reach its full luminosity

- **Precision measurements**
  - W mass and top mass
    - Important for consistency checks with Higgs studies
Physics Objectives (ALICE)

Heavy-ion programme

- Heavy-ion collisions will produce extremely high energy density
  - Search for evidence of quark-gluon plasma using simultaneous signatures
  - ALICE experiment is dedicated to this activity
  - ATLAS and CMS will also contribute in a few areas
Physics Objectives (LHCb)

• LHCb aims to perform a broad programme of B-physics studies
  – ATLAS and CMS will also contribute significantly in some areas, although this is not their top priority and the detectors are not optimised for these studies
• \( CP \) violation in many channels with very high statistics
  – Extend precision beyond \( e^+e^- \) B factories
  – Including \( B_s \) decays
• \( B_s \) mesons
  – Precise measurement of oscillation period and lifetime difference between mass eigenstates
• Measurements of rare decays
  – Provide indirect tests on physics beyond the Standard Model
What do we actually measure?

• The detectors give information on comparatively long-lived particles that are generally the decay products of the fundamental objects that we wish to study
  – We do not directly “see”:
    • Up, down, charm, strange and beauty quarks, and gluons (that manifest themselves as jets of hadrons)
    • Top quarks that decay rapidly (e.g. $t \rightarrow bW$)
    • W and Z bosons that decay rapidly to quarks or leptons
    • Higgs bosons
    • Etc
  – We do “see” somewhat more directly:
    • Electrons
    • Muons
    • Photons
    • Long-lived charged and neutral hadrons (which may form jets)
    • Missing transverse momentum (e.g. due to high transverse momentum neutrinos)
Generic concept of detector

• Collisions take place in centre of detector
  – Collision products move outwards from the centre

• Trajectories of charged particles are measured
  – Solenoid magnetic field, so particles follow helical paths
    • \( p = 0.3 \times B \times r \times Q \) used to determine momentum from radius of curvature
      (assuming charge \( Q = 1 \))

• Calorimeters measure energy deposited by electrons, photons, and hadrons
  – Calorimeters are sufficiently thick that almost all energy is absorbed, apart from muons (only minimally ionising) and neutrinos [and possibly other particles beyond those of the Standard Model]

• Trajectories of remaining charged particles (= muons) are measured
  – Provides muon identification and additional information on momentum
Generic detector (simplified)
Additional information

• The inner tracking detectors may provide additional information for particle identification
  – Hadron identification by Cerenkov or time-of-flight techniques
    • Important in LHCb, e.g. for $K/\pi$ separation in B decays
    • Important in ALICE, e.g. for strangeness-enhancement studies
  – Electron identification via transition-radiation signature
    • Used in ATLAS to enhance purity of electron selection
  – Particle identification from ionisation $(dE/dx)$ measurements

• Reconstructed tracks can be extrapolated to search for primary and secondary vertices
  – Determine time of decay of short-lived particles
    • Important for B-physics studies (e.g. time-dependent $CP$ violation)
  – Separate $b$-quark jets from light-quark and gluon jets
    • Important in top and Higgs physics studies
Particle identification: Time of Flight

- Charged particles can be identified from their mass that can be determined by measuring their velocity in addition to their momentum.
- A rather direct way to measure velocity is to measure the time taken by the particles to move between two points.

E.g. multi-gap RPC detectors

Technique used in ALICE
Particle identification: Cerenkov light

- Charged particles that traverse a medium with a velocity higher than the speed of light in that medium radiate Cerenkov light
  - Determine velocity from Cerenkov angle
  - Technique used in ALICE and in LHCb

\[
\cos \theta_c = \frac{1}{\beta n} = \frac{1}{\frac{v}{c} n}
\]
Particle identification: Transition Radiation

- When an ultra-relativistic charged particle (i.e. electron with $\beta \gamma > 1000$) traverses boundaries between materials of different refractive indices, they emit transition radiation.
- The TR X-rays can be detected and used to identify electrons.
- This technique is used in ALICE and ATLAS.

![Figure 3-25 Pion efficiency as a function of $p_T$ in various pseudorapidity intervals for 90% electron efficiency.](image)
Particle identification: $dE/dx$
Definition of term “event”

• In high-energy particle colliders (Tevatron, HERA, LEP, LHC), the particles in the counter-rotating beams are bunched
  – Bunches cross at regular intervals
    • Interactions only occur during the bunch-crossings
  – The “trigger” (an on-line system of electronics and computers – see later) has the job of selecting the bunch-crossings potentially of interest for physics analysis, i.e. those containing interactions of interest

• I will use the term “event” to refer to the record of all the products of a given bunch-crossing (plus any activity from other bunch-crossings that gets recorded along with this)
  – Be aware (beware!): the term “event” is not uniquely defined!
    • Some people use the term “event” for the products of a single interaction between the incident particles
      – People sometimes unwittingly use “event” interchangeably to mean different things!
Transverse momentum and pseudo-rapidity

- Very often use transverse momentum ($p_T$) and pseudo-rapidity ($\eta$) as variables in hadron-collider physics
  - $p_T$ is momentum transverse to the beam direction
    - Not same definition as in $e^+e^-$ experiments
      \[ \eta \equiv - \ln(\tan(\theta/2)) \equiv y \equiv \frac{1}{2} \ln((E+p_z)/(E-p_z)) \]
      - In central region, hadron $\eta$ distribution is approximately flat at fixed $p_T$
    - In central region, hadron $\eta$ distribution is approximately flat at fixed $p_T$

- Considering particle distribution in polar angle $\theta$, there is a high concentration of high-momentum (but low-$p_T$) particles at small angles relative to the two proton beams
  - The high flux of particles originating from proton-proton collisions creates a challenging radiation environment for detectors and electronics
    - Radiation-resistant detectors
    - Radiation-hard (or tolerant) electronics
    - Need to consider “noise” signals induced in detectors by the radiation as well as conventional noise signals
How do we reconstruct an “event”...

- **Start with signals seen in the detectors**
  - Points in space along charged particle trajectories
  - Energies measured in calorimeter cells
  - Signals from particle-identification detectors

- **Reconstruct quantities more closely related to particles**
  - Parametrize trajectory of charged-particle “tracks” in the inner tracking detectors and in the external muon detectors
    - Position and direction at some “start point”; radius of curvature
      - Infer charge sign and momentum (assuming $|Q| = 1$)
  - Parametrize energy deposits in the calorimeters in terms of “clusters”
    - Energy
    - Longitudinal and lateral shape
      - Can (e.g.) test consistency with shower from isolated electron or photon
    - Direction of energy flow
Generic detector (simplified)
Reconstruction of muons

- Combine information from muon detection system and the inner tracking detectors to get information on muon candidates
  - Muon charge sign and momentum vector at a given point in space
- Know with some confidence that this is really a muon, but there are backgrounds at some level
  - E.g. decays in flight of charged pions and kaons ($\pi \rightarrow \mu \nu$, $K \rightarrow \mu \nu$)
- Small probability to match the wrong inner-detector track to the muon-spectrometer track
  - Very small probability for fake muon-spectrometer tracks due to spurious hits
Reconstruction of electrons and photons

- **Reconstruct electrons and photons**
  - Combine information from the calorimeters and the inner tracking detectors
    - Electrons and photons identified as narrow clusters in electromagnetic calorimeters
    - Electrons have associated track; can check consistency of parameters between cluster and track \((p / E, \text{impact point} / \text{cluster centre}, \text{etc.})\)
    - Photons have no associated track
  - For many interesting processes, the electrons and photons are “isolated”, whereas the candidates are often in jets for background processes
    - Genuine electrons from charm and beauty decays
    - Photons from \(\pi^0\) decays (which may “convert” to given electrons)
    - Misidentified hadrons
  - Background comes from misidentified jets (dominant high-\(p_T\) process)
    - Also electrons may be misidentified as photons and vice versa
Reconstruction of jets

- Jets are the dominant high-$p_T$ process at LHC
  - Interesting in their own right
  - Important source of background when searching for other physics processes
- Reconstruction is rather straightforward in principle
  - Comparatively broad clusters of energy in the calorimeters
  - Associated tracks in the inner detectors for the charged hadrons
- Very high rate of jets extending to extremely large transverse momentum
Features that distinguish interesting processes from pile-up and background

• Most of the particles from random (“minimum-bias”) proton-proton interactions are low-$p_T$ hadrons
  – Applying a cut on the reconstructed tracks / clusters of $p_T \sim 2$ GeV eliminates almost all of the activity
  – Concentrating on electrons, muons and photons gives particularly clean signatures for extracting physics signals
    • Requiring “isolation” reduces the background from hadronic jets
  – Missing transverse energy (i.e. momentum imbalance in the transverse plane) is also a very powerful signature

• Extensive studies of the physics potential of the experiments have demonstrated that in many cases the most important remaining backgrounds to new physics will involve events with genuine W or Z bosons, or top quarks
18 superimposed pp collisions, as seen by internal part of CMS silicon central tracker. Among them 4 muons from a higgs decay.

“Exposure time” of one BC (25 ns)

Reconstructed tracks of $p_t > 2$ GeV. Among them well visible 4 muons from the higgs decay

Muons coloured in yellow