FYST17 Lecture 5
LHC Physics 1

Thanks to A. Hoecker, V. Hedberg
Today, (tomorrow) & Next week

- The LHC accelerator and the motivations
- Challenges
- The experiments (mainly CMS and ATLAS)
- More on important variables
- Preparations
- Soft physics
- EWK physics
- LHCb
- A few more recent results
The LHC Physics Programme

1. Mass
   — Search for the Higgs Boson, measurement of its properties

2. Electroweak unification and strong interactions
   — Precision measurements \((M_W, m_{\text{top}})\) and tests of the Standard Model
   — Tests of perturbative QCD at the highest energy scales

3. Hierarchy in the TeV domain
   — Search for new phenomena moderating the hierarchy problem

4. Flavour
   — \(B\) mixing, rare decays and \(CP\) violation as tests of the Standard Model
Motivation behind the Large Hadron Collider

Advantage of hadron collider

- Can reach higher energies in ring (less synchrotron radiation)

Energy loss per turn:

\[-\Delta E \approx \frac{4\pi\alpha}{3\cdot R}\left(\frac{E}{m}\right)^4\]

\[\approx \begin{cases} 
3.5 \text{ GeV for LEP-II at } E_{\text{beam}} = 104.5 \text{ GeV} \\
6.2 \text{ keV for LHC at } E_{\text{beam}} = 7000 \text{ GeV} 
\end{cases}\]

Disadvantages

- Hadrons are composites → parasitic collisions beyond hard parton scattering
- Energy and type of colliding parton unknown → kinematics partially unconstrained
Driving the SM to the Planck Scale: Or why we expected the Higgs boson to be discovered at the LHC

The SM Higgs must steer a narrow course between two disastrous situations if it is to survive up to the Planck scale \( M_p \sim 2 \times 10^{18} \text{ GeV} \)

Perturbativity and (meta)stability bounds versus the SM cut-off scale \( \Lambda \)

Figure uses NLO Higgs potential. The widths of bands account for errors in \( \alpha_S, m_t \) and theory.
The accelerator

Large Hadron Collider
27 km circumference

Lake Geneva

CMS

LHCb

ALICE

ATLAS
CERN accelerator complex

<table>
<thead>
<tr>
<th>Top energy/GeV</th>
<th>Circumference/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac</td>
<td>0.12</td>
</tr>
<tr>
<td>Booster</td>
<td>1.4</td>
</tr>
<tr>
<td>PS</td>
<td>26</td>
</tr>
<tr>
<td>SPS</td>
<td>450</td>
</tr>
<tr>
<td>LHC</td>
<td>7000</td>
</tr>
</tbody>
</table>

- 30
- 157
- 628 = 4 x Booster
- 6'911 = 11 x PS
- 26'657 = 27/7 x SPS

(>50 years old! )
LHC Layout

8 arcs and 8 long (~700 m) straight sections
Each main sector:
154 dipoles
47 quadrupoles.

Limits stored energy + facilitates commissioning sector by sector

The beams exchange positions (inside /outside) in 4 points to ensure both rings have the same circumference!

Injection energy: 450 GeV per beam
The LHC environment

- The search for new phenomena exploits **ever smaller distances ⇒ ever larger energies**
- The LHC collides protons at $E_{CM} = 13$ TeV → probing a distance of $1 \times 10^{-18}$ cm?  
  ... not quite, since protons are composites: the energy is distributed among its partons

- **Proton energy is limited by magnets that guide the circular beams**
  
  $E_{proton} \sim 0.3 \cdot B \cdot r$: since radius is fixed (4.3 km), use as strong fields as possible (> 8 T), and fill all free LHC sections with dipole magnets (~2/3)

Protons are circling in bunches, (~3000 at full intensity) with up to $10^{11}$ protons/bunch
Bunch size ~1mm x few cm
16µm width at collision points
Made to collide every 25ns!
LHC data handling, GRID computing

Trigger system selects ~200 "collisions" per sec.

LHC data volume per year: 10-15 Petabytes

= 10-15 \cdot 10^{15} \text{ Byte}

A typical Tier-2 GRID center (example: Tokyo University)
”the trigger does not determine which physics model is right, only which physics model is left” A. Bocci

ATLAS trigger has 3 levels (CMS similar with 2 levels)
- Level-1: hardware, ~3 μs decision time, 40 MHz → 100 kHz
- Level-2: software, ~40 ms decision time, 100 kHz → 2 kHz
- Level-3: software, ~4 s decision time, 2 kHz → 200 Hz

i.e. no time for input from tracking
Example: Higgs

L1

Coarse granularity

L1: This is not Higgs
Example: Higgs

L2

Improved reconstruction, improved ability to reject events

L2: This is not Higgs
Example: Higgs

EF

high quality reconstruction, improved ability to reject events

L3/EF: This is not Higgs
Trigger efficiency

Enters in calculation of cross section:

$$\sigma = \frac{N}{A \cdot \varepsilon \cdot \int L \, dt}$$

Examples: ATLAS trigger:

- $\int L \, dt = 20.3 \text{ fb}^{-1}$
- $\int L \, dt = 2.4 \text{ fb}^{-1}$
Online analysis: by-passing the trigger?

If we relax storage requirement
Analysis can be done directly on first level trigger output

Detector performance/ resolution degraded
-but not always a show stopper

First analyses/ attempts on-going at the LHC experiments

Raw data still not stored …
Requirements from Physics Programme

- Some benchmark analyses
- Design challenges:

  - $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$
  - W mass
  - top mass
  - $H \rightarrow \gamma\gamma$, 4e, 4$\mu$, $\tau\tau$ (WBF)
  - SUSY with R-parity, SUSY Higgs
  - RS KK modes

**Trigger efficiency** $(p_T > 3 \text{ GeV})$ and purity (HLT tracking reconstructs charge, vertex and $B$ mass)

**Hadronic top mass** with 2 $b$-tags $p_T$ spectrum $W$ decays

- Some benchmark analyses

**Design challenges:**

- MC = 4 TeV
- $100 \text{ fb}^{-1}$

Broad KK resonance in RS model
## Requirements from LHC Conditions

**LHC and data conditions:**

- **40 MHz bunch crossing rate** \((25\text{ns} = 7.5\text{m bunch spacing})\)
- **~1 GHz interaction rate at** \(L = 10^{34}\text{ cm}^{-2}\text{s}^{-1}\) \((\sim 25 \text{ ias. per bunch crossing})\)
- **~300 Mbytes/seconds data rate** \((200 \text{ Hz} \Rightarrow O(1.5 \text{ MB/event}))\)
- **Irradiation rate / 10 LHC years:** \(5 \times 10^{14}\text{ n}_{eq}/\text{cm}^{2}\) \((300 \text{ kGray} [= \text{J/kg}])\)
- **High charged multiplicity** \((O(1000) \text{ tracks per event, } 10^{12} / \text{sec})\)
- **High background rates** \((\text{beam halo muons, neutrons, beam-gas collisions})\)

**Design challenges:**

- **Fast trigger, precise timing and “pipeline” electronics:** Level-1 latency \(< 2.5\mu\text{s}\)
- **Efficient pattern recognition to reduce:** GHz @ L1 \(\rightarrow 75 \text{ kHz @ HLT } \rightarrow 200 \text{ Hz to disk}\)
- **Powerful data processing farms:** distribute data analysis to computing centres worldwide
- **Radiation hard inner tracker** \((\text{pixel with large } S/B)\) and forward calorimeter technology
- **High-granular pixel/silicon or fine-grained straw tracker technologies**
- **Precise muon timing**, redundant pattern recognition, radiation hardness
A large Toroidal Lhc Apparatus

ATLAS
Compact Muon Solenoid

- Total weight: 12500 t
- Overall diameter: 15 m
- Overall length: 21.6 m

ECAL: 76k scintillating PbWO₄ crystals
HCAL: Scintillator/brass sandwich

Pixels & Tracker:
- Pixels (100x150 μm²) ~ 1 m²
- 66M channels
- Silicon Microstrips ~210 m²
- 9.6M channels

4T Solenoid
MUON BARREL
- Drift Tubes (DT) and Resistive Plate Chambers (RPC)

Iron Yoke
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

CMS
ALICE + LHCb

A Large Ion Collider Experiment

LHCb
From the construction of ATLAS

Installing pixels

Installing ECAL
From the installation of CMS

Installing pixels
LHCb + ALICE

LHCb magnet

Graduate student Tuva pulling cables for ALICE
Why CMS stands for 'compact'

M. Campanelli
### ATLAS & CMS: Design & Performance Overview

<table>
<thead>
<tr>
<th>ATLAS (7 ktons)</th>
<th>CMS (12.5 ktons)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INNER TRACKER</strong></td>
<td><strong>INNER TRACKER</strong></td>
</tr>
<tr>
<td>• Silicon pixels + strips</td>
<td>• Silicon pixels + strips</td>
</tr>
<tr>
<td>• TRT with particle identification</td>
<td>• No dedicated particle identification</td>
</tr>
<tr>
<td>• $B = 2,T$</td>
<td>• $B = 3.8,T$</td>
</tr>
<tr>
<td>• $\sigma(p_T) \sim 3.8%$ (at 100 GeV, $\eta = 0$)</td>
<td>• $\sigma(p_T) \sim 1.5%$ (at 100 GeV, $\eta = 0$)</td>
</tr>
<tr>
<td><strong>MAGNETS</strong></td>
<td><strong>MAGNETS</strong></td>
</tr>
<tr>
<td>• 4 Magnets</td>
<td>• 1 Magnet</td>
</tr>
<tr>
<td>• Solenoid + Air-core muon toroids</td>
<td>• Solenoid</td>
</tr>
<tr>
<td>• Calorimeters outside solenoid field</td>
<td>• Calorimeters inside field</td>
</tr>
<tr>
<td><strong>EM CALORIMETER</strong></td>
<td><strong>EM CALORIMETER</strong></td>
</tr>
<tr>
<td>• Pb / Liquid Ar sampling accordion</td>
<td>• PbWO₄ scintillation crystals</td>
</tr>
<tr>
<td>• $\sigma(E) \sim 10\text{–}12% / \sqrt{E} \oplus 0.2\text{–}0.35%$</td>
<td>• $\sigma(E) \sim 3\text{–}5.5% / \sqrt{E} \oplus 0.5%$</td>
</tr>
<tr>
<td>• Longitudinal segmentation</td>
<td>• No longitudinal segmentation</td>
</tr>
<tr>
<td>• Saturation at $\sim 3,\text{TeV}$</td>
<td>• Saturation at $1.7,\text{TeV}$</td>
</tr>
<tr>
<td><strong>HAD CALORIMETER</strong></td>
<td><strong>HAD CALORIMETER</strong></td>
</tr>
<tr>
<td>• Fe / Scint. tiles (EC: Cu-liquid Ar)</td>
<td>• Cu (EC: brass) / Scint. tiles</td>
</tr>
<tr>
<td>• $\sigma(E) \sim 45% / \sqrt{E} \oplus 1.3%$ (Barrel)</td>
<td>• Tail catchers outside solenoid</td>
</tr>
<tr>
<td>• $\sigma(E) \sim 100% / \sqrt{E} \oplus 8%$ (Barrel)</td>
<td>• $\sigma(p_T) \sim 13% / 4.5%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)</td>
</tr>
<tr>
<td><strong>MUON</strong></td>
<td><strong>MUON</strong></td>
</tr>
<tr>
<td>• Drift tubes &amp; CSC (fwd) + RPC/TGC</td>
<td>• Drift tubes &amp; CSC (EC) + RPC</td>
</tr>
<tr>
<td>• $\sigma(p_T) \sim 10.5% / 10.4%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)</td>
<td>• $\sigma(p_T) \sim 13% / 4.5%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)</td>
</tr>
</tbody>
</table>
Luminosity is purely a function of the LHC beam parameters (formula similar to luminosity of stars)

\[ L = \frac{f_{\text{rev}} n_{\text{bunch}} N_{p,1} N_{p,2}}{A} = \frac{f_{\text{rev}} n_{\text{bunch}} N_{p,1} N_{p,2}}{4\pi \sigma_x \sigma_y} \]

- \( f_{\text{rev}} = 11245.5 \text{ Hz} \) is the bunch revolution frequency
- \( n_{\text{bunch}} = 1...2808 \) is the number of bunches in the machine
- \( N_{p,1/2} = 1.1 \times 10^{11} \) is the number of protons in each beam
- \( \sigma_{x/y} = 16...50 \mu m \) is the Gaussian transverse beam width
- \( L_{\text{max}} = 1.3 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2} \)

Luminosity determines the rate of physics processes by unit time and hence drives our ability to detect new processes

\[ N_{\text{obs}} = \text{cross section} \times \text{efficiency} \times \int L \cdot dt \]

“Cross section” given by Nature

“Efficiency” of detection optimised by experimentalist
Recorded Luminosity

Measured with forward detectors, calibrated with beam separation scans

\[ \text{10}^{32} \text{ cm}^{-2}\text{s}^{-1} \text{ instantaneous luminosity corresponds to an integrated luminosity of 0.1 nb}^{-1} \text{ per second} \]
\[ \Rightarrow 180 \text{ pb}^{-1} \text{ per month (assuming 70\% LHC efficiency for physics)} \]
Schedule (preliminary)

LHC roadmap: according to MTP 2016-2020 V1

<table>
<thead>
<tr>
<th>Year</th>
<th>LS2 starting in 2019</th>
<th>LS3 LHC: starting in 2024</th>
<th>Injectors: in 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Run 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Run 2</td>
<td>LS 2</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>Run 2</td>
<td>LS 2</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>Run 2</td>
<td>LS 2</td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td>Run 2</td>
<td>LS 2</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>Run 2</td>
<td>LS 2</td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td>Run 2</td>
<td>LS 2</td>
<td></td>
</tr>
</tbody>
</table>

Heavy ion runs most Novembers (not this year, though)

Frederick Bordry to the SPC
The basic concept

LUCID
a luminosity monitor

An array of aluminum tubes filled with $\text{C}_4\text{F}_{10}$ gas acts as Cherenkov counters.

The Cherenkov light is produced with a $3^\circ$ angle and makes typically 3 reflections while passing down the tube.

The Cherenkov threshold (10 MeV for elec. and 2.8 GeV for pions) and the pointing of the tubes suppresses background.

No Landau fluctuations makes it easier to count several particles going through the same tube.

A good time resolution makes it possible to study individual beam crossings.
The basic concept

The rate of the pp interactions ($R_{pp}$) seen by LUCID is proportional to the luminosity ($L$):

$$R_{pp} = \mu_{LUCID} \cdot f_{BX} = \sigma_{pp} \cdot \varepsilon_{LUCID} \cdot L$$

Number of pp interactions per bunch-crossing (BX) as measured by LUCID.

Bunch crossing rate = \frac{2808}{3564} \times 40 \text{ MHz}

Efficiency (and acceptance) of LUCID to detect a pp interaction ($\sim 21\%$ for single sided detection and $\sim 5\%$ for detection on both the A and C side).

Zero Counting
Count bunch crossings with no interactions:

$$\mu_{LUCID} = -\ln\left(\frac{N_{\text{zero BX}}}{N_{\text{total BX}}}\right)$$

Hit Counting
Count the number of tubes with a signal (hit):

$$\mu_{LUCID} = \frac{<N_{\text{hits/BX}}>}{<N_{\text{hits/pp}}>}$$

Particle Counting
Count the number of particles in LUCID by doing several cuts on the pulseheight distributions:

$$\mu_{LUCID} = \frac{<N_{\text{particles/BX}}>}{<N_{\text{particles/pp}}>}$$
Cross sections at a hadron collider

- For proton collisions, cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element

\[
\sigma_{pp \rightarrow X} = \sum_{\text{partons}} \text{PDF} \otimes \sigma_{\text{hard scatter}} = \sum_{a,b} \int_0^1 dx_1 dx_2 \cdot f_a(x_1, Q^2) \cdot f_b(x_2, Q^2) \cdot \hat{\sigma}_{ab \rightarrow X}^{x_1, x_2, \alpha(S), Q^2}
\]

here chose: \( Q = \mu_F = \mu_R \)

- For inclusive processes and at short distance, \( \sigma(pp \rightarrow X) \) can be computed in pQCD with factorization theorem, separating hard scattering and PDFs

- Large \( \alpha_s \) requires (complicated) higher order calculations

p-p event is superposition of: hard subprocess (matrix element) + initial and final state radiation, multiple parton–parton interactions with additional radiation
Kinematic of Proton Collisions

- Proton is complicated composite of valence quarks, gluons and sea quarks

- PDF depends on 2D mixture of
  - $Q^2$ (evolution in $\ln(Q^2)$ predicted by QCD)
  - Bjorken $x$ momentum fraction

- CM energy of parton collision:
  \[ \hat{s} = M^2_X = x_1 \cdot x_2 \cdot s_{\text{LHC}} \]

- Typical ‘$x$’ values (assume: $x_1 = x_2$)
  - **LHC ($\sqrt{s} = 14$ TeV):**
    - $M_X = 100$ GeV (1 TeV) $\Rightarrow <x> = 0.007$ (0.07)
  - **Tevatron ($\sqrt{s} = 2$ TeV):**
    - $M_X = 100$ GeV (1 TeV) $\Rightarrow <x> = 0.05$ (0.5)

- PDFs rise dramatically towards low $x$
  $\Rightarrow$ larger cross sections at LHC
  $\Rightarrow$ gluon dominated

*The LHC is a gluon collider!*
Kinematic Constraints and Variables

• Transverse momentum and missing transverse energy: \( p_T, E_{T,\text{miss}} \)
  - Particles escaping detection have low \( p_T \)
  - Visible transverse momentum conserved: \( \sum p_{T,i} \approx 0 \) useful variable!
  - Large \( E_{T,\text{miss}} \) indicates invisible particle (i.e., neutrino) escaped detector

• Longitudinal momentum and visible energy: \( p_z \)
  - Particles escaping detection have large \( p_z \)
  - Visible \( p_z \) not conserved \( \Rightarrow \) not a useful variable

• Polar angle \( \theta \) (angle between beam axis and particle)
  - Not Lorentz invariant, depends on longitudinal boost of system

• Rapidity \( y \) and Pseudorapidity \( \eta \)

\[
y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) = \frac{1}{2} \ln \left( \frac{x_1}{x_2} \right) \quad \Rightarrow \quad x_1 = x_2 \cdot e^{2y}, \quad \eta = \frac{1}{2} \ln \left( \frac{|p| + p_z}{|p| - p_z} \right) = -\ln \left( \tan \frac{\theta}{2} \right) \quad \text{for} \quad y \quad \text{M=0}
\]

- \( dN/dy \) distribution independent of Lorentz boosts along the beam axis
- Particle production in hadron colliders is \( \sim \) constant in \( y \)
Starting up an experiment
Data taking: ATLAS control room
Muon flux at surface:
~130 Hz / m² for $E_\mu > 1$ GeV
average energy ~4 GeV

Muon flux in ATLAS detector (simulation):
~4 kHz in muon fiducial volume
~15 Hz in TRT barrel

Charge ratio: $\mu^+ / \mu^- \sim 1.27$

Simulated cosmic flux in ATLAS cavern: integration over 10 msec
More Cosmic Muons in CMS (both charges!) …

Through barrel and endcap muon detectors
Studying cosmic rays

Charge ratio

Showers of muons

Cosmic Air shower in CMS, O(10-100) muons
Alignment of detectors

(Another perfect use of cosmic rays)
Muon Alignment Also Uses (Straight) Tracks

- Compare residuals for straight cosmic tracks
- Straight line fit
- Hits in outer chamber
- Hits in middle chamber
- Hits in inner chamber
- Track “residuals”
- Low-momentum muons, tails dominated by multiple scattering
- Nominal geometry:
  - Constant: 501 ± 6.2
  - Mean: -2.094 ± 0.015
  - Sigma: 1.199 ± 0.020
- Optical alignment:
  - Constant: 950.7 ± 14.5
  - Mean: 0.02156 ± 0.00673
  - Sigma: 0.4326 ± 0.0095
- Track-based alignment:
  - Constant: 925.4 ± 14.2
  - Mean: 0.1336 ± 0.0068
  - Sigma: 0.4299 ± 0.0092
- Barrel
“Weak Modes”

Residuals insensitive against some types of misalignment $\rightarrow$ effect on physics!

- Constrain weak modes via use of
  - cosmic ray, beam halo & beam collision data
  - vertex and beam spot constraints
  - resonance masses ($Z, J/\psi, \gamma, K^0, \ldots$)
  - $E/p$

Simulation exercise with misalignment
Monitored Drift Tubes (MDT)
3 layers in each barrel and endcap
Precision z measurements (80 μm / DT)

Thin Gap Chambers (TGC) / Fast (4 ns) z and φ trigger chambers

Cathode Strip Chambers (CSC)
MWPCs with cathodes segmented in strips, z (precise) and φ info

Sectors overlap in φ

Huge volumes – to be aligned at 35 μm !?
Summary of today

Mostly pretty pictures, more about physics tomorrow!