Course on Physics at the LHC

Lecture 1

João Varela
A specialized course on the Physics at the Large Hadron Collider is organized by LIP in the framework of the International Doctorate Network in Particle Physics, Astrophysics and Cosmology (IDPASC).

The course is intended for under-graduate or graduate students with basic training in Particle Physics.

The objective of the Course is to introduce the physics, analysis methods and results on the physics areas covered by the LHC experiments.
Topics

• Experimental program at the LHC
• Standard Model at the LHC
• Detectors
• Statistics
• Top quark physics
• Higgs Physics
• Supersymmetry
• Exotic processes and Dark Matter
• Heavy flavor physics and rare decays searches
• Matter at high density and temperature
Students are recommended to refresh their knowledge in particle physics prior to the Course. Suggested bibliography:

- D. Griffiths, 'Introduction to Elementary Particles', John Wiley and Sons (1987)
The LHC physics case
Particle physics is a modern name for the centuries old effort to understand the basics laws of physics.

Edward Witten

Aims to answer the two following questions:

What are the elementary constituents of matter?

What are the forces that determine their behavior?

Experimentally

Get particles to interact and study what happens
Constituents of matter along History

Different Kinds of Basic Matter

- Sulfur, Salt
- Mercury
- Air
- Fire
- Earth
- Water

Chemical Elements

Subatomic Particles

Quarks and Leptons

BC

AC

1800 1900 1950 1980 2000 2020

Quarks

Forces

Leptons

Couse on Physics at the LHC
The Standard Model

Over the last ~100 years: The combination of Quantum Field Theory and discovery of many particles has led to

- The Standard Model of Particle Physics
  - With a new “Periodic Table” of fundamental elements

One of the greatest achievements of 20th Century Science

\[
L_H = \frac{1}{2} \left( \partial_\mu H \right)^2 - m_H^2 H^2 - h \lambda H^3 - \frac{h}{4} H^4 + \frac{g^2}{4} (W_\mu^+ W_\mu + \frac{1}{2 \cos^2 \theta_W} Z_\mu Z_\mu) (\lambda^2 + 2 \lambda H + H^2) + \sum_{l,q,q'} \left( \frac{m_l}{\lambda} \bar{l} l + \frac{m_q}{\lambda} \bar{q} q + \frac{m_{q'}}{\lambda} \bar{q'} q' \right) H
\]
SM confirmed by data

**Standard Model of Elementary Particles**

**Quarks**
- **u** (up) mass: 2.4 MeV/c², charge: 2/3, spin: 1/2, name: up
- **c** (charm) mass: 1.27 GeV/c², charge: 2/3, spin: 1/2, name: charm
- **t** (top) mass: 171.2 GeV/c², charge: 2/3, spin: 1/2, name: top
- **d** (down) mass: 4.8 MeV/c², charge: -1/3, spin: 1/2, name: down
- **s** (strange) mass: 104 MeV/c², charge: -1/3, spin: 1/2, name: strange
- **b** (bottom) mass: 4.2 GeV/c², charge: -1/3, spin: 1/2, name: bottom
- **g** (gluon) mass: 91.2 GeV/c², charge: 0, spin: 1/2, name: gluon

**Leptons**
- **e** (electron) mass: 0.511 MeV/c², charge: 1/2, spin: 1/2, name: electron
- **μ** (muon) mass: 105.7 MeV/c², charge: 1/2, spin: 1/2, name: muon
- **τ** (tau) mass: 1.777 GeV/c², charge: 1/2, spin: 1/2, name: tau

**Gauge Bosons**
- **Z** (Z boson) mass: 91.2 GeV/c², charge: 0, spin: 1, name: Z boson
- **W** (W boson) mass: 80.4 GeV/c², charge: ±1, spin: 1, name: W boson

**Measurements**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>Δμ/m_meas</th>
<th>Δμ/m_meas</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_{had}(m_t)</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
<td>0.02768</td>
</tr>
<tr>
<td>m_{Z} [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1874</td>
<td>91.1874</td>
</tr>
<tr>
<td>Γ_{Z} [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4959</td>
<td>2.4959</td>
</tr>
<tr>
<td>σ_{had} [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.479</td>
<td>41.479</td>
</tr>
<tr>
<td>R_{t}</td>
<td>20.767 ± 0.025</td>
<td>20.742</td>
<td>20.742</td>
</tr>
<tr>
<td>A_{FB}^{0,l}</td>
<td>0.01714 ± 0.00095</td>
<td>0.01645</td>
<td>0.01645</td>
</tr>
<tr>
<td>A_{FB}^{0,b}</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
<td>0.1481</td>
</tr>
<tr>
<td>R_{d}</td>
<td>0.21629 ± 0.00066</td>
<td>0.21579</td>
<td>0.21579</td>
</tr>
<tr>
<td>R_{b}</td>
<td>0.1721 ± 0.0030</td>
<td>0.1723</td>
<td>0.1723</td>
</tr>
<tr>
<td>A_{FB}^{0,c}</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
<td>0.1038</td>
</tr>
<tr>
<td>A_{FB}^{0,b}</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
<td>0.0742</td>
</tr>
<tr>
<td>A_{d}</td>
<td>0.923 ± 0.020</td>
<td>0.935</td>
<td>0.935</td>
</tr>
<tr>
<td>A_{b}</td>
<td>0.670 ± 0.027</td>
<td>0.668</td>
<td>0.668</td>
</tr>
<tr>
<td>A_{c}</td>
<td>0.1513 ± 0.0021</td>
<td>0.1481</td>
<td>0.1481</td>
</tr>
<tr>
<td>sin^2θ_{eff}^{l}(Q_{fb})</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
<td>0.2314</td>
</tr>
<tr>
<td>m_{W} [GeV]</td>
<td>80.399 ± 0.023</td>
<td>80.379</td>
<td>80.379</td>
</tr>
<tr>
<td>Γ_{W} [GeV]</td>
<td>2.085 ± 0.042</td>
<td>2.092</td>
<td>2.092</td>
</tr>
<tr>
<td>m_{t} [GeV]</td>
<td>173.3 ± 1.1</td>
<td>173.4</td>
<td>173.4</td>
</tr>
</tbody>
</table>

**Confirmed at sub 1% level!**
The simplest model the interactions are symmetrical and particles do not have mass.

The symmetry between the electromagnetic and the weak interactions is broken:
- Photon do not have mass
- $W, Z$ do have a mass $\sim 80-90$ GeV

**Higgs mechanism:**
mass of $W$ and $Z$ results from the interactions with the Higgs field.
The Standard Model would fail at high energy without the Higgs particle or other ‘new physics’

Based on the available data and on quite general theoretical insights it was expected that the ‘new physics’ would manifest at an energy around

$$1 \text{Tera-electronVolt} = 10^{12} \text{ electronVolt}$$

accessible at the LHC for the first time
Beyond the standard model

The Standard Model answers many of the questions about the structure of matter. But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?
Forces and expansion of the Universe

\[ E = k \cdot T \]

\[ k = 8.62 \times 10^{-5} \text{ eV K}^{-1} \]

<table>
<thead>
<tr>
<th>Temperature of universe</th>
<th>10^{32} K</th>
<th>10^{27} K</th>
<th>10^{15} K</th>
<th>10^{13} K</th>
<th>3K</th>
</tr>
</thead>
</table>

| Time after Big Bang     | 10^{-43} s | 10^{-35} s | 10^{-12} s | 10^{-6} s | 5 \times 10^{17} s ( = now) |

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The dark side of the Universe

Long standing problem:
We know that ordinary matter is only \(\sim 4\%\) of the matter-energy in the Universe.
What is the remaining 96%?

The LHC may help to solve this problem, discovering dark matter
The Universe expansion is accelerating

In 1998, two groups used distant *Supernovae* to measure the expansion rate of the universe: Perlmutter et al. (Supernova Cosmology Project), and Schmidt et al. (High-z Supernova Team)

They got the same result:

The Universe expansion is accelerating

Some form of energy (dark energy) fills space
Cosmological inflation

In the very early universe space undergoes a dramatic exponential expansion.

Explains why the Universe has a uniform Temperature (3 K) and why space-time has a flat geometry.

The inflation theory was developed independently in the late 1970’s by Alan Guth, Alexey Starobinsky, and others.
In the SM the Higgs mass is a huge problem:

- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with $\Lambda$ (upper scale of validity of the SM)
- $\Lambda$ could be huge – e.g. the Plank scale ($10^{19}$ GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV

This is known as the hierarchy problem

$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots,$$
Many possible theories

There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Compositeness

Any of this could still be found at the LHC
New fundamental symmetry:
- Every fermion should have a massive "shadow" boson
- Every boson should have a massive "shadow" fermion.

This relationship between fermions and bosons is called supersymmetry (SUSY)

Heavy versions of every quark and lepton

Supersymmetry is broken
Could DM be SUSY particles?

For every “normal” force quanta (boson), there are supersymmetric partners:

- photon \quad \text{photino}
- W, Z bosons \quad \text{Wino, Zino}
- gluon \quad \text{gluino}
- Higgs boson \quad \text{higgsino}

These “…inos” are prime suspects to be the galactic dark matter!

Relics from the Big Bang!
The temptation unification
SUSY and the Higgs mass

\[ m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2} \lambda^2 \Lambda^2 + \ldots, \]

Higgs mass:
- correction has quadratic divergence!
  - \( \Lambda \) a cut-off scale – e.g. Planck scale

Superpartners fix this:
- Need superpartners at mass \(~1-2\) TeV
  - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.
Extra dimensions

Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

How can there be extra, smaller dimensions?

The acrobat can move forward and backward along the rope: **one dimension**
The flea can move forward and backward as well as side to side: **two dimensions**
But one of these dimensions is a small closed loop.
Understanding the Universe

History of the Universe

Accelerators

LHC – Energy Frontier

Telescopes

Key:
- W, Z bosons
- photon
- quark
- meson
- gluon
- electron
- muon
- tau
- neutrino
- galaxy
- baryon
- ion
- star
- atom
- black hole

Particle Data Group, LBNL, © 2008. Supported by DOE and NSF
The LHC proton collider
Accelerator and Experiments

Underground circular tunnel
27 km circumference;
100 m underground
4 caverns for experiments
Acceleraotor and experiments layout

Tiny bunches of counter-circulating protons. Colliding head-on 40 million times each second.
Collisions at LHC

Bunch Crossing $4 \times 10^7$ Hz

Proton Collisions $10^6$ Hz

Parton Collisions

New Particle Production $10^{-5}$ Hz

(Higgs, SUSY, ....)

Beam Energy $7 \times 10^{12}$ eV
Luminosity $10^{34}$ cm$^{-2}$ s$^{-1}$
Bunches/Beam 2835
Protons/Beam $10^{11}$

7 TeV Proton Proto colliding beams
Superconducting magnetic dipole

The 15-m long LHC cryodipole
In the tunnel

Beam delivery towards interaction point
Air pressure inside the two 27Km-long vacuum pipes ($10^{-13}$ atm) is lower than on the moon.
It’s cold!

27 Km of magnets are kept at 1.9 °K, colder than outer space, using over 100 tons of liquid helium.
In a tiny volume, temperatures one billion times hotter than the center of the sun.
The Experiments
General purpose LHC experiments

Advanced detectors comprising many layers, each designed to perform a specific task.

Together these layers allow to identify and precisely measure the energies of all stable particles produced in collisions.

Photons, Electrons, Muons, Quarks (as jets of particles) Neutrinos (as missing energy)
**CMS Detector**

- **Total weight**: 14,000 tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T

**CMS Detector Specifications**

- **Steel Return Yoke**: 12,500 tonnes
- **Silicon Trackers**
  - Pixel (100x150 μm) ~16m² ~66M channels
  - Microstrips (80x180 μm) ~200m² ~9.6M channels
- **Superconducting Solenoid**
  - Niobium titanium coil carrying ~18,000A
- **Muon Chambers**
  - Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
  - Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
- **Preshower**
  - Silicon strips ~16m² ~137,000 channels
- **Forward Calorimeter**
  - Steel + Quartz fibres ~2,000 Channels
- **Crystal Electromagnetic Calorimeter (ECAL)**
  - ~76,000 scintillating PbWO₄ crystals
- **Hadron Calorimeter (HCAL)**
  - Brass + Plastic scintillator ~7,000 channels

**Course on Physics at the LHC**
Detection of hadrons, $e^\pm$, $\gamma$ and $\mu^\pm$
1993-2008: detector R&D and construction

15 years!
Superconductor solenoid at 3.8 Tesla
ATLAS Toroidal System
Silicon Tracker

214m² silicon sensors
11.4 million silicon strips
65.9 million silicon pixels

Used to reconstruct the trajectories of thousands of charge particles produced in the collisions
ECAL Electromagnetic Calorimeter

Electron and photon detection

PbWO$_4$ scintillating crystals & avalanche photodiodes

**Design Goal:** Measure the energies of photons from a decay of the Higgs boson to precision of ≤ 0.5%

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Barrel</th>
<th>Endcaps</th>
</tr>
</thead>
<tbody>
<tr>
<td># of crystals</td>
<td>61200</td>
<td>14648</td>
</tr>
<tr>
<td>Volume</td>
<td>8.14m$^3$</td>
<td>2.7m$^3$</td>
</tr>
<tr>
<td>Xtal mass (t)</td>
<td>67.4</td>
<td>22.0</td>
</tr>
</tbody>
</table>

Couse on Physics at the LHC
HCAL Hadronic Calorimeter

Detection of hadrons:
- protons, neutrons, peons, etc.

- CMS HCAL has three components:
  - Barrel HCAL (HB)
  - Endcap HCAL (HE)
  - Forward HCAL (HF)

- Plastic scintillator and brass
- Quartz fibers and steel
Muon detectors

Drift Tubes (DT)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
Trigger and readout electronics

Underground caverns

Couse on Physics at the LHC
Electronics systems in the Service Cavern. About 150 racks occupy two floors. Most electronics was designed and built specifically for the experiment on Physics at the LHC.
Sep 2008: CMS detector ready for beams
Simulation of proton-proton collision making two dark matter particles
The World Wide Web (invented at CERN) provides seamless access to information that is stored in many millions of different geographical locations.

The Grid is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe.
Experimental challenges
High collision rate

Luminosity:
\[ L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
\[ = 10^7 \text{ Hz/mb} \]

Cross section:
\[ \sigma \approx 100 \text{ mb} \]

\[ \Rightarrow N = L\sigma \approx 1 \text{ GHz} \]

However:

Bunch crossing rate: 40 MHz

\[ \therefore \text{Interactions/crossing} \approx 25 \]

This is a real challenge!
Bunch crossing frequency

- LHC has 3564 bunches (2835 filled with protons)
- Crossing rate is 40 MHz
- Distance between bunches: 27km / 3600 = 7.5m
- Distance between bunches in time: 7.5m / c = 25ns
- Proton-proton collision per bunch crossing: ~ 25

lep: $e^+e^-$ Crossing rate 30 kHz

SPS-pp Crossing rate 280 kHz

Tevatron pp Crossing rate 2.5 MHz

LHC: pp Crossing rate 40 MHz
Event pileup

- Proton bunches have a cigar shape, about 5 cm long and 20 microns diameter
- Each bunch has $1.5 \times 10^{11}$ protons
- At each crossing of bunches, about 25 collision occur
- The particles produced ($30 \times 25 = 750$ charged particles) are “seen” by the detector as a single image (event)

21 pileup events

Tracking threshold in $p_T \sim 100$ MeV. Fake rate < 1%
High radiation levels
Two-level trigger

Trigger system decide if the event is interesting to be recorded

Two-step process:
- Level 1: dedicated hardware processors
- High level: computer farm
Triggers and event selection

- Select processes that produce particles with high transverse energy
- Examples at $5 \times 10^{33}$ cm$^{-2}$s$^{-1}$
  - Single lepton and photon triggers ($P_T \sim 30$ GeV)
  - Multiple lepton and photon triggers ($P_T \sim 15$ GeV)
  - Missing transverse energy ($P_T \sim 50$-$100$ GeV)
  - Multiple jet triggers ($P_T \sim 50$-$100$ GeV)
- About 100 trigger conditions in L1 trigger table
- About 400 trigger conditions in HLT trigger table
Detector commissioning
LHC Page 1: stable beams

**PROTON PHYSICS: STABLE BEAMS**

Energy: 3500 GeV  I(B1): 5.50e+13  I(B2): 5.54e+13

Comments 22-04-2011 00:02:52:

** Stable Beams **
World record for luminosity for hadron machine
Automatic LUMI LEVELING in IP8

BIS status and SMP flags

- Link Status of Beam Permits: true, true
- Global Beam Permit: true, true
- Setup Beam: true, false
- Beam Presence: true, true
- Moveable Devices Allowed In Stable Beams: true, true
2009: First p-p collisions at LHC

November 23, 2009
First collisions at 900 GeV

December 14, 2009
First collisions at 2.36 TeV

March 30, 2010
First collisions at 7 TeV

First collision at 7 TeV in CMS
Tracking: secondary vertices

Basic variables relevant for B-tagging are well described by the simulation.

Secondary vertices compatible with heavy flavor production.
Photons and electrons

EM cluster energy

CMS

CMS 2010 Preliminary

Events

10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0

2 4 6 8 10 12 14 16 18 20

energy (GeV)

MC
Data
ECAL Barrel

Photons and electrons

Couse on Physics at the LHC

64
Jets and missing energy

Jet $p_T$ distribution

Di-jet mass

Missing Transverse Energy

Calorimeter

Particle Flow
Rediscovery of resonances

\[ \frac{m}{m_{PDG}} = 1 + (1.9 \pm 0.9) \cdot 10^{-4} \]

\[ \frac{m}{m_{PDG}} = 1 - (0.7 \pm 1.4) \cdot 10^{-4} \]
Rediscovery of the Standard Model at LHC
End of Lecture 1