Course on Physics at the LHC Lecture 1 Derimental program at the LHC

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The LHC physics case

 $\begin{aligned} \mathcal{I} &= -\frac{1}{4} \int_{AV} F^{AV} \\ &+ i \mathcal{F} \mathcal{D} \mathcal{F} + h.c. \\ &+ \mathcal{F} \mathcal{G} \mathcal{F} \mathcal{G} \mathcal{F} + h.c. \\ &+ \mathcal{F} \mathcal{G} \mathcal{G} \mathcal{F} \mathcal{G} + h.c. \\ &+ |\mathbf{D} \mathcal{G}|^2 - V(\mathcal{G}) \end{aligned}$



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



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

$${}_{H} = \frac{1}{2} (\partial_{\mu}H)^{2} - m_{H}^{2}H^{2} - h\lambda H^{3} - \frac{h}{4}H^{4} + \frac{g^{2}}{4} (W_{\mu}^{+}W^{\mu} + \frac{1}{2\cos^{2}\theta_{W}}Z_{\mu}Z^{\mu})(\lambda^{2} + 2\lambda H + H^{2}) + \sum_{l,q,q'} (\frac{m_{l}}{\lambda}\bar{l}l + \frac{m_{q}}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q'}q')$$

H(

11

2.4 MeV/c²

1/2 U

up

4.8 MeV/c²

down

<2.2 eV/c²

neutrino

0.511 MeV/c²

e

electron

-1 ½

-eptons

e electron

 ${}^{0}_{1/2}V$

-¹/₃

1/2

mass

charge $\rightarrow \frac{2}{3}$

spin →

Quarks

name

1.27 GeV/c²

charm

104 MeV/c²

strange

<0.17 MeV/c

 ${f V}_{\mu}$

muon

neutrino

105.7 MeV/c²

muon

1⁄2

-1

 $\frac{1}{1/2}$

^{-1/3} ^{1/2}**S**

²/₃ ¹/₂ **C**

Ш

171.2 GeV/c²

t

top

4.2 GeV/c²

1-1/3h

bottom

<15.5 MeV/c²

 V_{τ}

tau

neutrino

1.777 GeV/c²

τ

tau

1/2

0

1/2

-1

1/2

²/3 1/2

0

0

0

0

0

photon

gluon

91.2 GeV/c²

Z boson

80.4 GeV/c²

W boson

Gauge bosons

SM confirmed by data

STANDARD MODEL **EMENTARY PAR** CLES OF E

	Measurement	Fit	IO ^{meas} –O ^{fit} I/o ^{meas}
$\Delta \alpha_{\rm had}^{(5)}({\rm m_{z}})$	0.02758 ± 0.00035	0.02768	
m _z [GeV]	91.1875 ± 0.0021	91.1874	
Γ _Z [GeV]	2.4952 ± 0.0023	2.4959	
σ ⁰ _{had} [nb]	41.540 ± 0.037	41.479	
R _I	20.767 ± 0.025	20.742	
A ^{0,I}	0.01714 ± 0.00095	0.01645	
A _l (P _r)	0.1465 ± 0.0032	0.1481	
R _b	0.21629 ± 0.00066	0.21579	
R _c	0.1721 ± 0.0030	0.1723	
A ^{0,b}	0.0992 ± 0.0016	0.1038	
A ^{0,c}	0.0707 ± 0.0035	0.0742	
A _b	0.923 ± 0.020	0.935	
A _c	0.670 ± 0.027	0.668	
A _l (SLD)	0.1513 ± 0.0021	0.1481	
$sin^2 \theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m _w [GeV]	80.399 ± 0.023	80.379	
Г _w [GeV]	2.085 ± 0.042	2.092	
m _t [GeV]	173.3 ± 1.1	173.4	
July 2010			0 1 2 3

Confirmed at sub 1% level!





The Higgs

In the simplest model the interactions are symmetrical and particles do not have mass

The symmetry between the electromagnetic and the week interactions is broken:

- Photon do not have mass
- W, Z do have a mass ~ 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 Tera-electronVolt = 10¹² 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?





Long standing problem:

We know that ordinary matter is only ~4% of the matterenergy in the Universe.

What is the remaining 96%?



The LHC may help to solve this problem, discovering dark matter

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)

The Universe expansion is accelerating

They got the same result: **The Universe expansion is accelerating**

Some form of energy (dark energy) fills space





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





Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

- Virtual particles in quantum loops contribute to the Higgs mass
- Contributions grow with A (upper scale of validity of the SM)
- Λ could be huge e.g. the Plank scale (10¹⁹ GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



This is known as the hierarchy problem



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



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

photon W, Z bosons gluon Higgs boson

photino Wino, Zino gluino higgsino

These "...inos" are prime suspects to be the galactic dark matter!

Relics from the Big Bang!



The temptation unification







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







The LHC proton collider





Accelerator and Experiments



Accelerator and experiments layout





Collisions at LHC



Superconducting magnetic dipole





In the tunnel

Beam delivery towards interaction point



It's empty!

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.





It's Hot!

In a *tiny* volume, temperatures one billion times hotter than the center of the sun.





The LHC timeline



Bound to be one of the greatest endeavors of science in the 21st century



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)







ATLAS detectors



35

Detection of hadrons, e^{\pm} , γ and μ^{\pm}





1993-2008: detector R&D and construction



Superconductor solenoid at 3.8 Tesla





ATLAS Toroidal System





Silicon Tracker



214m² silicon sensors11.4 million silicon strips65.9 million silicon pixels





ECAL Electromagnetic Calorimeter





Electron and photon detection PbWO₄ scintillating crystals & avalanche photodiodes



Design Goal: Measure the energies of photons from a decay of the Higgs boson to precision of $\leq 0.5\%$

Parameter	Barrel	Endcaps
# of crystals	61200	14648
Volume	8.14m ³	2.7m ³
Xtal mass (t)	67.4	22.0

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)







Electronics systems

Electronics systems in the Service Cavern. About 150 racks occupy two floors. Most electronics was designed and built specifically for the experiment





Sep 2008: CMS detector ready for beams





Detector simulation

Simulation of proton-proton collision making two dark matter particles



The LHC Computing Grid

The Grid unites computing resources of particle physics institutions around the world

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





- 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





- Proton bunches have a cigar shape, about 5 cm long and 20 microns diameter
- Each bunch has 1.5 10¹¹ protons
- At each crossing of bunches, about 25 collision occur
- The particles produced (30x25 = 750 charged particles) are "seen" by the detector as a single image (event)



High radiation levels







barr

mb

μb

nb

pb

fb

50

LHC

bb

jets

Event rate

Level-2 input

SUSY qã+qã+gã

 $\tan\beta = 2, \mu = m_{\tilde{a}} = m_{\tilde{a}}/2$

 $\tan\beta=2, \mu=m_{\tilde{a}}=m_{\tilde{a}}$

scalar LQ Z,→2

1000 2000

Level-3

 $\mathbb{V} \rightarrow \mathbb{S}$ elected events

z→to archive

h > yy

¬_{SM}→27

jet E_T or particle mass (GeV)

500

 $gg \rightarrow H_{SM}$

aā→aāH

Z_{SM→}3γ

100

200

 $H_{SM} \rightarrow \gamma \gamma$

inelastic Level-1 input

Event Rate

GHz

kHz

Hz

g=mq/2 Emg=mq ZARE→2ℓ mHz

μHz

10-9

MHz MHz

LV1

HLT

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



- Select processes that produce particles with high transverse energy
- Examples at 5.x10³³ cm⁻²s⁻¹
 - Single lepton and photon triggers ($P_T \sim 30 \text{ GeV}$)
 - Multiple lepton and photon triggers ($P_T \sim 15 \text{ GeV}$)
 - Missing transverse energy ($P_T \sim 50-100 \text{ GeV}$)
 - Multiple jet triggers ($P_T \sim 50-100 \text{ GeV}$)
- About 100 trigger conditions in L1 trigger table
- About 400 trigger conditions in HLT trigger table



Detector commissioning



LHC Page 1: stable beams





March 30, 2010: CMS Page 1





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





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





Jets and missing energy





Rediscovery of the Standard Model at LHC





End of Lecture 1