LHC

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What principles govern the energy, the matter, the space and the time at the most elementary level?

- Ancient Greeks: Earth, Air, Fire, Water
- By 1900, nearly 100 elements
- By 1936, back to three particles: proton, neutron, electron

High Energy Physics tries to answer these synergy with other fields to push back frontiers of knowledge!

It also brings in technological spin-offs.
The heavier elementary particles existed in nature when the universe was very hot.

They can be created in the laboratory by garnering energy, and their properties can be studied in detail.
BUT MATTER IN THE UNIVERSE IS NEUTRAL, because positive and negative charges cancel each other precisely.

THEREFORE:
Gravitation is the dominant force in the Universe
By the 1940s it was pretty clear that fundamental interactions are due to the exchange of virtual particles...

**Carriers of forces**

Long-range interactions (electromagnetic, gravitational) are mediated by **massless** particles.

Short-range interactions (eg. Weak) are mediated by **massive** particles.
All behaviour of matter particles (fermions) can be explained in terms of few forces carried by exchange or carrier particles (bosons).
Energy = kT, Length scale = hc/E

- Quantum gravity era: $t \approx 10^{-43}$ s
  $10^{32}$ K ($10^{19}$ GeV, $10^{-34}$ m)

- Grand Unification Era: $t \approx 10^{-35}$ s
  $10^{27}$ K ($10^{16}$ GeV, $10^{-32}$ m)

- ElectroWeak era: $t \approx 10^{-10}$ s
  $10^{15}$ K ($100$ GeV, $10^{-18}$ m)

- Protons and neutrons formed: $t \approx 10^{-4}$ s
  $10^{13}$ K ($1$ GeV, $10^{-16}$ m)

- Nuclei are formed $t = 3$ minutes
  $10^9$ K ($0.1$ MeV, $10^{-12}$ m)

- Today: $t = 13.7 \times 10^9$ years
  $T = 3$ K
Lack of wisdom about fundamental particles

Some of the puzzles we need to resolve:
1. why 3 families of quarks and leptons?
2. the masses cannot be predicted!

Mass of the hydrogen atom ~ proton = 1 Giga eV/c^2 = 10^9 eV/c^2

1 eV = 1.6*10^{-19} Joules

Mass of top quark ~ 175 GeV/c^2
Mass of electron ~ 0.5 Million eV/c^2
neutrino ~ 0

Masses of carrier particles:
photon mass = 0
W/Z mass ~ 80/90 GeV/c^2

No obvious pattern among mass values!

Resolving the issue of mass generation is of utmost importance today in High Energy Physics.
Highlights of 20th century physics

- Special relativity
- General Relativity
- Quantum Mechanic
- Quantum Field Theory
- Standard Model of elementary particles and their interactions

→ Role of symmetries in physics was recognized and utilized in mathematical formulations.

First example of embedded symmetry in physical law:
Newton’s law: \[ \mathbf{F} = m \mathbf{a} \]

Covariant under rotations \( \Rightarrow \) \( \mathbf{F}, \mathbf{a} \) changes in the same way under rotation.

Invariant under Galilean transformations \( \Rightarrow \) \( \mathbf{F}, \mathbf{a} \) does not change.

Mathematics ↔ Physics
- Calculus
- Complex numbers/functions
- Differential geometry
- Group theory
- Hermitian operators, Hilbert space
- ….
A symmetry of a physical system is a physical or mathematical feature of the system (observed or intrinsic) that is "preserved" under some change, leading to conservation of a property of the system.

Ex.1: The temperature of a room is invariant under a shift in the measurer's position, translational symmetry.

Ex.2: Symmetry of mathematical functions: $a^2c + 3ab + b^2c$ remain unchanged under exchange of $a$ and $b$.

Quantum Field Theoretical considerations: $E = mc^2$ allows creation of particles, could be a pair as well.

Connection with experiment: scattering in quantum mechanics:
- time evolution of a system from $t = -\infty$ to its evolution till observed time $t = +\infty$

In experiment compare theoretical predictions with measurements.
Dogma of Symmetry

Reflection/Bilateral symmetry
Five fold symmetry
Radial symmetry

Symmetry has practical uses too. ➔
(a) position of pivot in load balance
(b) 2 eyes of human face gives correct judgment of distance.
To see that we need to define scalar ($\phi$) and vector ($\vec{A}$) potentials.

These are related to the electric and magnetic fields via

$$\vec{E} = -\nabla \phi - \frac{\partial \vec{A}}{\partial t} \quad \text{and} \quad \vec{B} = \nabla \times \vec{A}.$$  

We get the same electric field $\vec{E}$ and the same magnetic field $\vec{B}$, even if we change the potentials as: $\phi' = \phi - \frac{\partial \Lambda}{\partial t}$

Thus, $\vec{A}' = \vec{A} + \nabla \Lambda$, where $\Lambda$ is a function of (x, t).
Gauge Invariance, proposed by Hermann Weyl, is the cornerstone of modern day particle physics.

Quantum theory is invariant under constant phase transformations of wave function

\[ \psi(x) \rightarrow e^{i\theta(x)}\psi(x) \]

This symmetry leads to charge conservation.

If the phase is a function of space-time, the phase invariance is lost.

\[ \psi(x) \rightarrow e^{i\theta(x)}\psi(x) \]

• Introduce the electromagnetic field \((\phi, \vec{A})\) into the theory and identify the space-time dependent phase with \(\Lambda\).

\(\Rightarrow\) quantum theory becomes invariant under space-time dependent phase transformations.

\(\Rightarrow\) also demands existence of a massless vector field, identified as the photon, the carrier particle of electromagnetic interaction.
Half-life of tritium should be:

\( \sim 10^{-23} \text{ s} \) Strong

\( \sim 10^{-15} \text{ s} \) Electromagnetic

Actual value: 12 years!

Beta decay must be due to a very WEAK force, causing long lifetimes.

- All matter particles have weak interaction.
- Rate/strength of weak interaction is very small.

\[ ^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + ^{0}_{-1}e + ^{0}_{0}\nu \]
Enrico Fermi was the first to write down a theory of beta decay (1934)

\[ n^0 \rightarrow p^+ + e^- + \bar{\nu}_e \]

Current-Current form

\[ H_I = G_F J^\mu (n, p) J_\mu (e, \bar{\nu}) \]

Improved theory (1956):
Intermediate Vector Bosons

\[ H_I = g J^\mu (n, p) \frac{-1}{k^2 - M_W^2} gJ_\mu (e, \bar{\nu}) \]

IVB model makes sense only in a gauge theory framework
The correct gauge symmetry SU(2)xU(1) had been discovered in 1961 by Sheldon Lee Glashow.

The idea of merging SU(2)xU(1) gauge theory with the Higgs mechanism was first floated around 1966-7 by Abdus Salam.

The complete, working theory of weak interactions was worked out in 1967 by Steven Weinberg.

Standard Model has been extremely successful in explaining all the experimental observations till date.
Gauge symmetry is required to correctly describe the interaction of matter.

Quantum electrodynamics is the most complete and successful theory. The theoretical predictions match very well with experimental results. 

Eg. the fine structure constant measured up to 9 digits after decimal!

\[ \alpha = \frac{e^2}{4\pi} \]

QED obeys charge, parity (handedness) conservation.

Weak interaction violates parity! 
  explanation: only left-handed fermions take part in charged current weak interaction

Carriers of weak interaction, W+, W- should couple to photon as electron does: couplings are universal \(\Rightarrow\) unification of two forces

Carriers of weak interaction has to be massless \(\Rightarrow\) infinite range expected, like in case of EM. 
Experimentally observed: weak interaction has short range \(\Rightarrow\) the carriers must be massive!
Weak interaction carriers are about 100 times massive than a proton! What happens to the gauge symmetry???

**Spontaneous Symmetry Breaking:**

- The equations describing the system are invariant under some symmetry.
- The ground state of a system breaks the symmetry in the dynamics.
- Closing the ground state, at low energy, symmetry disappears (massive W boson) at large distance scale.
- At high energy symmetry reappears → W boson appears mass-less at short distance scale of ~ 1 fermi (10^{-13} cm).

Nambu-san made it possible to have our cake and eat it → phase transition
Nambu’s idea was taken up in earnest in 1964 by three groups to invent Higgs mechanism for mass generation in weak interaction:

1. Francois Englert and Robert Brout at Brussels
2. Peter Higgs in Edinburgh
3. Gerald Guralnik, Carl Hagen and Tom Kibble at London

But the spontaneous symmetry breaking in the Standard Model leads to the existence of a massive, spin-0, elementary particle called the Higgs boson, which is yet to be found.
Consider a ferromagnet

Interaction has rotational symmetry i.e. no preferred direction

\[ H = \sum J_{ij} S_i \cdot S_j \]

Ground state (magnetized phase) breaks the symmetry

Coleman’s demon — living inside the ferromagnet — thinks there is a preferred direction (along B)
All particles in the Standard Model acquire mass by interacting with the Higgs field...

• Until the Higgs boson is found, we do not really have full confirmation of the Standard Model.

• We do not also have any good theoretical description of nature at hand which confirm experimental findings.

LHC is built to discover the Higgs particle. Otherwise, LHC will observe signatures of Spontaneous Symmetry Breaking.
LHC motivations: explore, search, measure

- LHC is the world’s most powerful microscope doing nano-nano physics to study how the universe was 13.7 billion years ago. → simulating the situation of the universe when it was as old as $10^{-12}$ s !!

- LHC results are likely to change the way we consider the world.

Till now no Higgs boson and no departure from established physics!

One of the fastest race tracks: protons zipping past with 99.999999% of velocity of light around 27 km of LHC ring 11000 times/sec.
Study physics laws of first moments after Big Bang

- studying a distance scale of about $10^{-18}$ m
- LHC is a facility to study the situation which existed $\sim 10^{-12}$ s after the creation of the universe
Probing shorter than ever length scales

Required energy

\[ 10^{-20} \text{ m} \approx 10^{+13} \text{ eV} \]

\[ = 10 \text{ TeV} \]

(1 TeV = \(10^{12}\) electronVolt

= \(1.6 \times 10^{-7}\) Joule)

Electronic Eye

10 million electronic channels
recording data every 25 nano sec.

LARGE HADRON COLLIDER

20 years to plan, build, 20 more to work with

\(\rightarrow\) we need you!

Presently, LHC provides energy up to 7 TeV, equivalent to the kinetic energy of a fly!
LHC: The Giant Marvel of Technology

- 100-150 m under the surface
- 27 km at 1.9 K (superfluid He)
- Vacuum ~ $10^{-13}$ Atm.
- Superconducting coils: 12000 tonnes/7600

- Temperature generated at LHC due to proton-proton collision
  ~$10^{16}$ °C, compare with sun: 5506 °C, a matchstick: 250 °C

LHC machine to be maintained at -271 °C vs. Home freezer: -8 °C
Boomerang nebula: -272 °C, Antarctica: -89.2 °C,

Indian contributions in LHC magnet components

Largest ever human endeavour, require huge resources to be put in.
To be passed on to younger generations of today and tomorrow: YOU!
What happens in LHC experiment

Mammoth detectors register signals for energetic, mostly (hard) inelastic collisions involving large momentum transfer.

Proton-Proton          1400 bunch/beam
Protons/bunch          $2 \times 10^{11}$
Beam energy             3.5 – 4 TeV
(1TeV = $10^{12}$ eV)
Luminosity            $3 \times 10^{33} - 6.6 \times 10^{33} / \text{cm}^2 / \text{s}$
Crossing rate                 20 MHz
Collisions                       $10^8$ Hz

Selection of 1 in $10,000,000,000,000,000$
Mass of particles comes from energy of the reaction.
The larger the energy the greater the variety of particles.

Equal amount of matter and antimatter is produced when energy is converted to matter.

Pair production: $\gamma$ rays \(\rightarrow\) e+ e-
Entering a New Era in Fundamental Science

Exploration of a new energy frontier

CMS
ALICE
LHCb
ATLAS

28th February 2011

India
CERN
Mumbai

LHC ring:
27 km circumference
~190 Institutions with about 3500 scientists and engineers.

Indian contributions in HO and Si-preshower detectors
Hadron Outer Calorimeter installation

432 trays consisting of plastic scintillators (40 cm X 30 cm) + wave length shifting fibres
Brief history of collisions at LHC

• Protons circulated in maiden LHC tunnel on August 2008
• Accident occurs soon → implications on our spending

• LHC operation restarted after machine consolidation in September 2009
• Collisions at 7 TeV from April 2010, lead ion collisions for several weeks

• Very good operation in 2011, 2012

• LHC operation to stop for upgradation for ~ 20 months after 2012.

Event rate

\[ R = \sigma L \]

crosssection, \ Luminosity

⇒ Very few interesting events corresponding to rare processes within limited time.
Nobel prize winning particle physics of last century being utilized at LHC for detector calibration.

$\rho, \omega, \phi, J/\psi, \psi', Y(1,2,3S)$

$\mu^+\mu^-$ widths:
- $J/\psi$: 30 MeV
- $Y$: 70 MeV

CMS Preliminary

$\sqrt{s} = 7$ TeV, $L_{int} = 40$ pb$^{-1}$

Invariant mass resolution at the Z peak $\sim 1\%$
Most important physics harvest from LHC

Search for standard model Higgs boson exclusion as of January 2012: $127 \pm 600 \text{ GeV}/c^2$

• excess at $\sim 125 \text{ GeV}$
• need more data to conclude about existence of Higgs boson
• absence of Higgs will also be a discovery!

Higgs production/total interaction: $10^{-9}$

2012: $L = 3.7 \times 10^{33}$/cm$^2$/s
Expect 10-15 fb$^{-1}$ @ 8TeV
Passage of 2 galaxies 100 M years back

Rotation curve of a galaxy (1989)

LHC can shed light on the nature of the dark matter

- Lightest SuperSymmetric particle is a very good candidate of the dark matter
- SUSY is the most favourite model for physics beyond Standard model.

LHC will discover SUSY if it is relevant at EWSB scale (rescues divergence of the physical mass of the Higgs boson)
Data rates @ CMS as foreseen more than 15 years back

Collision Rate: ~ 40 MHz

Event size: ~1.5 MB

for Offline-Analysis
Tape & HDD Storage

Reduction with ASICs
Level 1 Trigger

~ 60 TB/sec

High Level Trigger
Software Data Reduction (PC Farm)

~ 150 GB/sec

Presently event size ~ 1MB (beam flux lower than design)
data collection rate ~ 300 Hz

~ 225 MB/sec
In hard numbers

LHC will collide 6-8 hundred million proton-on-proton per second for several years.

Only 1 in 20 thousand collisions will have an important tale to tell, *but we do not know which one!*

- so we have to search through all of them!

- Huge task!

- 15 PBytes ($10^{15}$ bytes) of data a year
- Analysis requires ~100,000 computers to get results in reasonable time.

GRID computing is essential
The GRID Computing Goal

• Science without borders
• Provide **Resources** and **Services** to store/serve \( O(10) \) PB data/year
• Provide **access** to all interesting physics events to \( O(4000) \) collaborators
• Minimize constraints due to **user localisation** and **resource variety**
• **Decentralize control** and **costs** of computing infrastructure
• Share resources with other LHC experiments

→ Solution through **Worldwide LHC Computing GRID**
→ Delivery of physics should be fast
→ Workhorse for production data handling

- Today >140 sites
- ~250k CPU cores
- ~100 PB disk
1. Share more than information
   Data, computing power, applications in dynamic, multi-institutional, virtual organizations (Ian Foster: Anatomy of Grid)

2. Efficient use of resources at many institutes. People from many institutions working to solve a common problem (virtual organisation).


4. Interactions with the underneath layers must be transparent and seamless to the user.

CMS in Total:
1 Tier-0 at CERN (GVA)
7 Tier-1s on 3 continents
50 Tier-2s on 4 continents

India has a CMS T2 centre at Mumbai: T2-IN-TIFR
Layered Structure of CMS GRID ➔ connecting computers across globe

Tier 0
- Experimental site
- Online data recording
- CERN computer centre, Geneva

Tier 1
- National centres
  - CERN
  - ASIA (Taiwan)
  - USA
  - Germany
  - Italy
  - France

Tier 2
- Regional groups in a continent/nation
  - India
  - China
  - Korea
  - Taiwan
  - Pakistan

Indiacms
- T2_IN_TIFR

Different Universities, Institutes in a country
- TIFR
- BARC
- Delhi Univ.
- Panjab Univ.

Individual scientist’s PC, laptop, ..
Today, the LHC is attracting immense attention, it is possibly THE most watched science project → CERN is in the spotlight.

The journey of thousand miles have already started though what awaits at the end is not known.

• Fascinating science, the curiosity provides the sustenance over time
• Addresses long standing questions of mankind
• Forefront technologies in accelerator, detector, computing
• Sociological experiment

LHC is poised to tackle some of the most profound questions very soon.

Stay Tuned!
Backup
Current idea about evolution of the Universe

• Just after the Big Bang, at unimaginably high temperatures, all interactions were merged into some unified interaction.
  ➞ Matter and radiation were one.

• As the primordial fireball cooled, radiation and matter separated out.

• The first interaction to separate out was gravity.

• Then strong interactions separated out, electroweak interactions stayed together

• Eventually, as the Universe cooled further, the weak and electromagnetic interactions separated out

• Matter (massive) began to clump together into filaments

• Eventually these condensed into galaxies, stars, planets..
• Just as the equation \( x^2 = 4 \) can have two possible solutions (\( x = 2 \) OR \( x = -2 \)), so Dirac's equation could have two solutions, one for an electron with positive energy, and one for an electron with negative energy.

• Dirac interpreted this to mean that for every particle that exists there is a corresponding antiparticle, exactly matching the particle but with opposite charge. For the electron, for instance, there should be an "antielectron" called the positron identical in every way but with a positive electric charge.

1928 Dirac predicted existence of antimatter
1932 antielectrons (positrons) found in conversion of energy into matter
1995 antihydrogen consisting of antiprotons and positrons produced at CERN
Proton-on-proton collision at LHC

\[ \sqrt{(s x_1 x_2)} = \sqrt{(s x)} \]  
[“Hard scattering partons”]