The Large Hadron Collider

The American International Club of Geneva

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What constitutes our universe - what makes it work at all scales of energy, distance and time?

Cosmology and particle physics are disciplines that address these questions today but the questions are very old...
Starting around 600 B.C. the Greeks began to make very good use of observations

- Seeing that food is converted to bone, sinew, muscle... led Anaxagoras to conclude that there must exist common basic elements.

- Noting that streets and stone walkways wear out over time in imperceptible increments led Lucretius to deduce that matter can be broken down into invisibly small pieces.

- From eclipses they deduced:
  - The sun is more distant than the moon and larger than earth.
  - The earth is round and larger than the moon.

- The Pythagoreans showed that musical harmony is the result of simple numerical ratios.
Brilliant Insights

- The Sun is at the center of the solar system - Aristarchus
  - Demonstrated in 1543 (Copernicus, Brahe)
- All things are composed of Atoms - Leucippus, Democritus
  - Proven at the end of the 19th century (Boltzmann)
- The Universe is filled with an invisible substance which gives matter its qualities - Stoics
  - Particles acquire mass as a result of the Higgs field which permeates the entire Universe (Glashow, Salam, Weinberg, ...1970s)
- The basis of reality is number and harmony - Pythagoreans
  - Almost all mathematics has some relationship to physical reality
  - Particles are now thought of as vibrating strings (string theory)
and not so brilliant...

• The earth is the center of the Universe ...
  • Refuted in 1543 (Copernicus, Brahe)

• Heavier objects fall faster ...
  • Refuted in the 17th century (Galileo)

• Rest is the natural state of motion of objects. Movement requires the continual application of a force
  • Corrected by Galileo

• Wrong ideas are correlated with an absence of observation. These ideas prevailed for over 1000 years!

• Some people understood but were ignored...
  • Philoponus of Alexandria (6th century) realized Aristotle was wrong and came up with the right concepts of impetus and inertia.
  • Giordano Bruno realized that stars are like our sun and could also have planets. He was burned at the stake...
The Quantitative Era

- **Middle Ages**: progress mostly in Arab world.
- **Picked up again in the West in the 16\(^{th}\) century**.
  - *Copernicus* and then *Kepler* rediscovered the powerful combination of observation and mathematical analysis.
  - They started a revolution!
  - *Galileo* expanded upon this to invent the modern scientific method: **Simplify, Hypothesize, Observe**
    - His writings very clear and he made many contributions:
      - time as a coordinate, relative motion and inertia
  - *Newton* later created the 1\(^{st}\) complete theory
    - He *unified* all mechanical phenomena.
    - His equations and new mathematics allowed detailed predictions.
    - *He also understood this was not the whole story.*
Beyond Common Sense

• Electric and Magnetic Phenomena were studied extensively in the 18th and 19th century.
  • A variety of laws were established.

• *Faraday* made detailed measurements that revealed its true nature

• *Maxwell* paid very close attention …
  • He unified all electric and magnetic phenomena into the mathematically complete theory of Electromagnetism.
  • At that time, all common sense was “mechanical”.
  • But *Maxwell* could not describe all of the data in mechanical terms.
  • He made a leap of faith and arrived at the idea of displacement current
    \[ \nabla \times B = J + (1/c) \frac{\partial E}{\partial t} \]

• Scientists began to think more abstractly.
Relativity

• Michelson & Moreley showed there is no “aether”, which means there is no fundamental frame of reference.

• Einstein then postulated that the speed of light is constant in all reference frames
  • Contradicts Galilean relativity with important consequences
  • Simultaneity is not well defined
  • Space and time cannot be separated

• Everything moves at the speed of light in 4-dimensional space-time
  • The faster you are moving, the slower time is passing.
  • For something moving at the speed of light, time stops altogether.
Quantum Mechanics

- **Planck** Energy is not continuous
- **Heisenberg** Uncertainty Principle

Some Consequences for the sub-atomic realm

- We can’t know exactly what will happen, but we can know the probability that it will happen.
- There’s a limit to what we can measure.
- Matter can come into and out of existence.
- An material particle has also a wavelike identity
“There was a time when the newspapers said that only twelve men understood the theory of relativity. I do not believe there ever was such a time. There might have been a time when only one man did because he was the only guy who caught on, before he wrote his paper. But after people read the paper a lot of people understood the theory of relativity in one way or other, certainly more than twelve. On the other hand I think I can safely say that nobody understands quantum mechanics.”

Richard Feynman
Relativistic Quantum Mechanics

- Energy and matter are equivalent (E = mc^2)
- Particles have charges. Fields are associated with charges. Fields are themselves made up of particles.
  - The repulsion of two electrons by the exchange of a photon

- A particle-antiparticle pair can pop out of the vacuum even if the particles are very massive - but only for a short time. Called virtual particles.
- Real particles can also sometimes disintegrate into virtual particles for a short time even if the virtual particles are more massive.

*Consequence of the Heisenberg uncertainty principle*
The Birth of Particle Physics

- In the late 19th century and early 20th century
  - Boltzmann - Greek atomists were right: Atoms exist!
  - Thompson discovered the electron in 1897
  - Lenard used electrons to show matter is mostly empty
  - Einstein (c. 1907) & Compton (c. 1922) demonstrated the existence of the photon
  - Rutherford (1910) fired alpha particles at gold foils and some bounced back, proving the existence of the nucleus

Electron (e): Thompson & Lenard

Nucleus: Rutherford

Photon (γ) : Einstein & Compton
Particle physics

• For ~100 years our focus has been sub-atomic, sub-nuclear, and now even smaller particles and their interactions.

  • Symmetry has been a key to much of our understanding
    • E.g. The laws of physics are the same at all times and all locations
      ⇒ The law of conservation of Energy and Momentum

• For every symmetry there is something that is conserved - Noether.
  • In the sub-atomic realm we have found a number of conservation laws that relate not to our familiar space-time but to some other space - sometimes refers to as an “internal space”
The history of the Standard Model (SM)
The Standard Model

Confirmed at sub% level!

| Measurement                     | Measurement     | Fit          | $|\Delta \sigma_{\text{had}}^{(5)}(m_Z)|$ | $|\Delta \sigma_{\text{had}}^{(5)}(m_Z)|$ |
|---------------------------------|-----------------|--------------|-------------------------------------|-------------------------------------|
| $m_Z [\text{GeV}]$              | 91.1875 ± 0.0021| 91.1874      |                                     |                                     |
| $\Gamma_Z [\text{GeV}]$         | 2.4952 ± 0.0023 | 2.4957       |                                     |                                     |
| $\sigma_{\text{had}}^{(5)} [\text{nb}]$ | 41.540 ± 0.037 | 41.477       |                                     |                                     |
| $R_l$                            | 20.767 ± 0.025  | 20.744       |                                     |                                     |
| $A_{\tau_b}^{(5)}$               | 0.01714 ± 0.00095| 0.01640     |                                     |                                     |
| $A_{\tau_c}(P_{\tau})$          | 0.1465 ± 0.0032 | 0.1479       |                                     |                                     |
| $R$                             | 0.21629 ± 0.00066| 0.21585     |                                     |                                     |
| $R_c$                           | 0.1721 ± 0.0030 | 0.1722       |                                     |                                     |
| $A_{\tau_b}^{(5)}$              | 0.0992 ± 0.0016 | 0.1037       |                                     |                                     |
| $A_{\tau_c}$                    | 0.0707 ± 0.0035 | 0.0741       |                                     |                                     |
| $A_{\beta}$                     | 0.923 ± 0.020  | 0.935        |                                     |                                     |
| $A_c$                           | 0.670 ± 0.027  | 0.668        |                                     |                                     |
| $A_{\beta}(\text{SLD})$         | 0.1513 ± 0.0021| 0.1479       |                                     |                                     |
| $\sin^2 \theta_{\text{eff}}^{(Q_{\beta})}$ | 0.2324 ± 0.0012| 0.2314       |                                     |                                     |
| $m_W [\text{GeV}]$              | 80.392 ± 0.029 | 80.371       |                                     |                                     |
| $\Gamma_W [\text{GeV}]$         | 2.147 ± 0.060  | 2.091        |                                     |                                     |
| $m_t [\text{GeV}]$              | 171.4 ± 2.1    | 171.7        |                                     |                                     |

Summer, 2006

One missing piece
A Missing Ingredient: The Higgs

- **Massless force carriers** ⇒ infinite range:
  - photon, 8 types of gluons, and graviton are all massless
- **Massive force carriers** ⇒ short range:
  - Weak nuclear force is short range
- **Quantum field theory doesn’t accept massive force carriers!**
  - But there’s a loophole: If the universe is filled with a field that attenuates the weak force, that would make it short-ranged.
- This is the *Higgs* field.
  - ’70’s: Using this concept theorists predicted $W^\pm$ & $Z$ particles exist with masses of 80 & 91 times the mass of the proton.
  - ‘80’s: They are found at CERN with the expected masses!
W&Z - right where they should be...

March 2008:
http://lepewwg.web.cern.ch/LEPEWWWG/
Peter Higgs at CERN - April 4, 2008
The relationship with Cosmology

- **The beginning of time:**
  - Higher energy $\Rightarrow$ more massive particles and smaller distance scales
  - E.g. Top quark discovered at Fermilab in 1995.
    - Almost as heavy as gold atom even though it’s the smallest particle ever found.
  - Real top quarks had not existed since the first moments of the universe.
Why all the excitement about LHC?
A Dilemma

- **In the most fundamental areas of observation:**
  - **Experimental Particle Physics**
    - No discrepancies with the Standard Model (SM)
  - **Experimental Astrophysics and Cosmology**
    - Abundant evidence for physics beyond the standard model (BSM)
      - Dark energy and dark matter
      - Neutrino oscillations
      - Cosmic matter-antimatter asymmetry
      - Cosmic density fluctuations consistent with inflation
Possible Implications

• This dilemma is a clue in itself and constrains theory
  • Some models have lost while others have gained in viability
• Many of the most compelling models that satisfy these constraints while solving outstanding theoretical problems have similar features:
  • A new symmetry and a spectrum of new particles at the TeV energy scale (for which the LHC is designed)
  • The new particles at the TeV scale cure problems with the Higgs mass
    • SM particles contribute to the mass of the Higgs as “virtual” particles
    • The mass cannot be stabilized because of this
    • The new particles cancel out the effects of SM particles!
The common structure can produce similar phenomenology.
We may see something that is not so easy to interpret.
Nevertheless, the case for Supersymmetry (SUSY) is compelling.

And so we take it very seriously as a prototype of what we might find at the LHC.
SUSY and the Higgs Mass

- **Higgs mass:**
  - correction has quadratic divergence!
  - $\Lambda$ a huge quantity! Planck scale

- **Superpartners fix this:**
  - Need same coupling $\lambda$
  - Need superpartners at the weak scale
    - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.

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

\[
m_h^2 = (m_h^2)_0 + \frac{1}{16\pi^2} (m_f^2 - m_f^2) \ln(\Lambda / m_f),
\]
Relation to top and W

- Top and W masses appear in corrections to Higgs mass.
- Turned around, precise measurements of the W and top mass constrain the standard model Higgs.
Higgs Mass Bounds

- **SM Higgs**
  - Precision Electroweak Data:
    - $M_H \lesssim 180$ GeV
  - Direct searches:
    - $M_H \geq 114$ GeV
- **In SUSY there are at least 5 Higgs particles!**
  - But the lightest is a lot like the SM Higgs, just a little less easy to make
  - Direct searches:
    - $M_H \geq 91$ GeV
  - Theory
    - $M_H \lesssim 150$ GeV
Reasons to like basic SUSY

- It is a very basic symmetry and it unifies all forces at high energy
- The top quark has an explanation:
  - Causes the Higgs mechanism!
- Predicts a heavy neutral particle that is stable & doesn’t interact much.
  - Such particles would have been made in abundance in the early universe and should be a significant part of the universe now but they would not be part of the visible universe....
Dark Matter
Dark Matter

M33 rotation curve

observed

expected from luminous disk

Vera Rubin

v (km/s)

50

100

5

10

R (kpc)
The Dark Side

~25% of universe is dark matter:
  • This value is what you’d predict with SUSY!
  • (Ordinary matter is ~5%)

  • SUSY is our best guess at present
    • Provides a natural dark matter candidate (neutralino)
    • Leads to remarkable gauge coupling unification
    • Can provide an explanation for why SU(2) is broken
    • Fixes the Higgs mass problem
Beyond SUSY

• Though basic SUSY looks very compelling, it also has problems (that I will not go into) and theorists have proposed many alternatives.

• We do not know which if any is the right one ...
  • More complicated SUSY models
  • Strong dynamics
  • Grand Unified theories
  • String-theory motivated models
    • Large extra dimensions
    • Warped extra dimensions
    • Hidden Valley theories
The TeV Scale

• The main thing is that there are many reasons to expect important new findings at around the TeV energy scale

⇒ We need to probe all around this energy level.

• The LHC is well-suited to this task
The Process

• Accelerate beams of protons
• Collide the beams
• Detect what comes out and store the data
• Analyzing the Data
A proton-proton collider

- Electric fields accelerate while magnetic fields are used to focus and bend the particle trajectories.

Energy is limited by magnet strength and ring size.
⇒ We use really strong magnets and really big rings.
The LHC injector complex

Energy gain per step is $x10$ to $x20$
Important components of the accelerator

- **Superconducting dipoles**
  - Magnetic field 8.33 Tesla
  - 1232 magnets, each 15 meters long operated at 1.9 K (-271 Celsius)

**Largest cryogenic system in the world**

**Acceleration gradient of 5 MV/m**
LHC Is two accelerators in tandem
• **Dipoles and quadrupoles stabilize trajectory**
• **Sextupoles and higher multipoles adjust and refine**
• **Like optics (and it’s called “beam optics”)**
Vast stored energy!

- **LHC magnets:**
  - 1 dipole magnet \(E_{\text{stored}} = 7 \text{ MJ}\)
  - All magnets \(E_{\text{stored}} = 10.4 \text{ GJ}\)
- 90 kg of TNT • 15 kg of chocolate

Compared to previous accelerators:
- A factor \(\frac{1}{2}\) in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored energy

Melt 12 tons of Copper!

- **Kinetic energy of 2808 p bunches:**
  - \(E_{\text{bunch}} = N_p \times E_p = (1.15 \times 10^{11}) \times 7 \text{ TeV} = 129 \text{ kJ}\)
  - \(E_{\text{beam}} = k \times E_{\text{bunch}} = 2808 \times E_{\text{bunch}} = 362 \text{ MJ}\)
Colliding Beams

- Beam bunches contain billions of particles
- Only a few pairs of protons collide when bunches cross
Protons have structure

- Proton collisions are really collisions of quarks or gluons
“Minimum Bias” Events

- Vast majority of collisions
- Tend to throw particles forward and backward and less in between

Example shown here is for pp but pp is similar
Hard Collisions

Much more interesting and much more rare

Example: W production and decay to a positron and a neutrino
So how do we reconstruct what happened in the collision?

We look at what comes out and where it goes.
A slice of CMS

7 meter lever arm for tracking muons
And why are the detectors so big?

It’s because we want to detect and measure the momentum of very high energy muons.
ATLAS detector construction and installation
ATLAS Calorimeters
Cabling the ATLAS pixel detector
ATLAS Control room
Cosmic muons in ATLAS
MUON BARREL

- Silicon
- Microstrips
- 210 m² of silicon sensors
- 9.6M channels

CALORIMETERS

- ECAL
  - 76k scintillating PbWO₄ crystals

- HCAL
  - Scintillator/brass sandwich

IRON YOKE

TRACKER

- Pixels
- Silicon Microstrips
- 210 m² of silicon sensors
- 9.6M channels

4T Solenoid

MUON BARREL

- Drift Tube Chambers (DT)
- Resistive Plate Chambers (RPC)

MUON ENDCAPS

- Cathode Strip Chambers (CSC)
- Resistive Plate Chambers (RPC)

Overall diameter: 15 m
Overall length: 21.6 m
Total weight: 12500 t
Weapons to detectors
Lowering of Heavy Elements

Y80 landing in the CMS experiment hall
Tracker Insertion (15 Dec’07)
Experimental Challenges

• Collisions are frequent (~ 40 million per second)
  • Interesting collisions are rare - less than 1 per 10 billion for some of the most interesting ones
• We can write ~100 events to tape per second.
• We must pick the good ones and do it fast
  • Decision (‘trigger’) levels:
    • A first analysis is done in a few millionths of a second
    • A final analysis takes ~ 0.1 second
• We end up with lots of data
WLCG Infrastructure

- **EGEE**  Enabling Grid for E-Science
- **OSG**   Open Science Grid

1 Tier-0 + 11 Tier-1 + 67 Tier-2

T0-T1 : Dedicated 10Gbs Optical Network
Startup Program

• Prior to beam: early detector commissioning

• Early beam (up to 10pb\(^{-1}\))
  • Detector synchronization, in-situ alignment and calibration
  • Commission trigger, start “physics commissioning”:
    • Observe known particles and their decays \( J/\psi, \gamma, W, Z, t\bar{t} \)
    • First look at possible extraordinary signatures…

• Early Beam (100pb\(^{-1}\)) more SM, start to search for Higgs SUSY
  • Measure/understand backgrounds to SUSY and Higgs searches
  • Initial Higgs sensitivity
  • Early look for excesses from SUSY& \( Z'/jj \) resonances. SUSY hints (?)

• (1000 pb\(^{-1}\)) A discovery era?
Nature may have surprises in store…

- Large extra dimensions
- Possible micro black hole production
  - Decay via Hawking radiation into photons, leptons, jets…
Summary

• The question of what our Universe is made of and how it works goes back 2600 years (at least)
  • The ancients identified many of the basic concepts
  • Scientists have spent the last ~550 years refining these into mathematically complete theories.
  • We now understand the underlying forces and particles making up the phenomena of “everyday life”

• We know there is more
  • The LHC will help us resolve some very important questions, some of which are very old
Practical Benefits of Pure Research

• Pure research has no intended applications by definition.

• Nevertheless, many benefits have resulted:
  
  • Newton’s Mechanics \(\rightarrow\) the industrial revolution
  
  • Maxwell’s Electromagnetism \(\rightarrow\) electricity and the wireless transmission of information
  
  • Quantum mechanics \(\rightarrow\) chemistry, solid state physics, the transistor and computers, lasers, etc.
Some References

• History
  • Physical Thought from the Presocratics to the Quantum Physicists - *Sambursky*

• Modern Physics
  • The Dancing Wu Li Masters - *Zukav*

• String Theory
  • The Elegant Universe - *Greene*

• The Life of a Physicist
  • Surely You’re Joking Mr. Feynmann - *Feynmann*

• CERN LHC: Accelerator and experiments

• FERMILAB Tevatron: Accelerator and experiments