From HERA to the LHC

From Quantum Chromodynamics to Quantum Gravity

Dr. Eram Rizvi
Over 100 years of discovery and experimentation

Discovery of electron - Thompson, 1897
Birth of quantum physics - Planck, 1900
Relativity - Einstein, 1905
Nuclear scattering experiment - Rutherford, 1911

... what have we learnt?
Particle Physics is a global enterprise: experiments in all continents (incl. Antarctica!)
I will concentrate on H1 and ATLAS

... But what have we learnt?
The Standard Model

Worlds most successful theory to date - Describes fundamental constituents of matter

- **quarks:** strong, weak, electromagnetic
- **charged leptons:** weak, electromagnetic
- **neutrinos:** weak

**Strong:** holds atomic nucleus together

**Electromagnetic:** binds atom together

**Weak:** radioactive decay processes

No description of Gravity at sub-atomic level

Electromagnetic & Weak parts of Standard Model are known extremely precisely

Theory of strong interactions is less well known

Eram Rizvi

PsiStar
The complete Standard Model Lagrangian
Based on perturbation theory & relativistic quantum mechanics given us the language of Feynman diagrams to calc cross sections

Potential = V + V'

V gives rise to stationary stable, time independent states

V' is a weak additional potential leading to transitions between states \( \psi_i \rightarrow \psi_f \)

\[
\sigma = \frac{2\pi}{\hbar} |V'_{fi}|^2 \rho(E_f)
\]

\( V'_{fi} = \int \psi_f^* V_{fi} \psi_i dV \) is known as the matrix element for the scattering process

V' contains the standard model Lagrangian describes the dynamics of all interactions

Series expansion in powers of couplings \( \alpha \) between particles for each force
Quantum mechanics predicts the gyromagnetic ratio of the electron \( g = 2 \) (ratio of magnetic dipole moment to its spin). Experiment measures \( g_{\text{exp}} = 2.0023193043738 \pm 0.0000000000082 \).

Discrepancy of \( g - 2 \) due to radiative corrections. Electron emits and reabsorbs additional photons. Corresponds to higher terms in perturbative series expansion.

\[
\frac{g_{\text{theory}} - 2}{2} = 1159652140(28) \times 10^{-12}
\]

\[
\frac{g_{\text{exp}} - 2}{2} = 1159652186.9(4.1) \times 10^{-12}
\]

Phenomenal agreement between theory and experiment! 4 parts in \( 10^8 \).

QED (quantum electrodynamics) is humanity's most successful theory. Demonstrates understanding of our universe to unprecedented precision.

Equivalent to measuring distance from me to centre of moon and asking if we should measure from top of head or my waist!

... but all is not well...
Standard Model is lacking:
- why 3 generations of particles?
- why do particles have the masses they do?
- no consideration of gravity on quantum level
- where is all the antimatter in the universe?

Too many free parameters - need to be determined from experiment:
(Compare to Newtonian gravity - one free parameter: G)
- 12 particle masses: 6 quarks, 3 charged leptons, 3 neutrinos
- 3 boson masses ($W^\pm$, $Z^0$, $H^0$)
- 3 coupling constants: EM, Strong, Weak
- 4 quark mixing parameters
- 4 neutrino mixing parameters

What are the current collider experiments doing?
HERA probes t-channel of gauge boson exchange
- sensitive to propagator masses and EW couplings
- requires Parton Distribution Functions (PDFs)
HERA collides e (27 GeV) and p (~1 TeV)
study strong, electromagnetic & weak forces through Deep Inelastic Scattering

At fixed $\sqrt{s}$: two kinematic variables: $x$ & $Q^2$

$Q^2 = s \times y$

$Q^2 =$ “resolving power” of probe
High $Q^2$: resolve 1/1000$^{th}$ size of proton

$x =$ momentum fraction of proton carried by quark
HERA: $\sim 10^{-6} - 1$
Electro-Weak Unification

At high energy, masses small – forces are equal

\[ \frac{d\sigma_{NC}^{\pm}}{dx dQ^2} \approx e^4 \frac{1}{8 \pi x} \left[ \frac{1}{Q^2} \right]^2 \left[ Y_+ \tilde{F}_2 \pm Y_- \tilde{F}_3 \right] \]

\[ \frac{d\sigma_{CC}^{\pm}}{dx dQ^2} \approx g^4 \frac{1}{64 \pi x} \left[ \frac{1}{M_W^2 + Q^2} \right]^2 \left[ Y_+ \tilde{W}_2^{\pm} \mp Y_- \tilde{W}_3^{\pm} \right] \]

Aim to unify all forces
Introduction

The H1Collaboration (1995)
Make measurements of highest possible precision
Search for deviations from expectation
Can use highest $Q^2$ photons to look for quark sub-structure

Already data exclude quark radius $> 1.6 \times 10^{-18}$ m
Proton Structure

Proton = 1 quark

Proton = 3 independent quarks

Proton = 3 coupled quarks

Proton = 3 coupled quarks bound by dynamic gluons creating “sea” of quark/anti-quark pairs at small momentum fractions
This is the region explored by HERA
HERA data show a rising number of quarks & gluons with small momentum fractions $x$

Number increases as $Q^2$ increases
Proton Structure

At low $x$ the proton is exploding with particles!

Measurements well described by QCD theory

HERA has given us a precise map of the proton
- a good understanding of QCD

Low $x$: gluon splitting

High $x$: gluon emission
At high energy (small distances) QCD coupling is small.

QCD is more difficult to understand than QED or Weak processes.

At low energies QCD coupling is large. Perturbation theory fails!
Quark & Gluon Density Functions

Fit data: extract momentum weighted quark / gluon distributions

$Q^2 = 10 \text{ GeV}^2$

Gluon scaled down factor 20!!

x dependence can only be determined from data
Proton Structure at the LHC

Large Hadron Collider: next generation proton accelerator being built in Geneva

HERA densities extrapolate into LHC region

LHC = gluon collider

HERA data crucial in calculations of new physics & measurements at LHC
The Large Hadron Collider
LHC will collide protons at 7 TeV (7000 GeV)
27 km circumference ring
1200 superconducting dipole magnets ~ 9 T field
3000 tons of magnets supercooled to 1.9K
Each beam has energy equivalent to 100 kph Eurostar train
Proton bunches collide in bunches every 25 ns
Beams have transverse size ~15 µm (human hair ~20 µm)
20 interactions every bunch crossing
Particles from one collision still travelling when next collision occurs!
One of the largest scientific / technological projects ever undertaken

> $10^8$ electronic channels
$8 \times 10^8$ proton-proton interactions/second
$2 \times 10^{-4}$ Higgs per second
10 Petabytes of data a year
(10 Million GBytes = 14 Million CDs)
The Large Hadron Collider

Huge event rates

New physics swamped!

Need to filter events 1:10^7 online

Like trying to find a cheap plumber from entire human population in 2 µs

Rate of 100 GeV Higgs production

What are we looking for?
Almost all the visible mass of universe is due to massless QCD effects. Energy associated with quark and gluon interactions → proton & neutron mass

Higgs particle postulated to explain masses of fundamental particles

Gauge theory predicts force carrier particles to be massless e.g. photon & gluon. But $W^\pm & Z^0$ bosons have large masses ~80-90 GeV (proton~1 GeV)

Higgs properties are well known except its mass!

Direct searches: $m_H > 114$ GeV
Examine energy dependence of scattering processes
Process (a) and (b) are well behaved as energy increases
Process (c) becomes larger than total $e^+e^-$ cross section! (unitarity is violated)

Higgs-like particle is needed to cancel $e^+e^\rightarrow W^+W^-$ scattering divergences

Requires Standard Model Higgs to be $< \sim 1$TeV

If Standard Model is correct we will find the Higgs at the LHC!

If Standard Model is wrong some new particle must do this job

win-win situation!
Even if Standard Model Higgs doesn't exist, a Higgs-like particle must! Place bounds on mass of Higgs-like particle by requiring self consistency of theory.
But we should have already seen it!

Precise measurements at low energy are sensitive to Higgs loops

Perturbations on a perturbation!

Measurements at $E < m_H$ are logarithmically sensitive to $m_H$

Confront data & theory: $\chi^2$ test

Indicates light Higgs!

68% prob of SM Higgs in range $85^{+39}_{-28}$ GeV

95% prob of SM Higgs < 166 GeV
Likelihood of **NOT** being a statistical fluctuation vs Higgs mass

Standard Model Higgs discovered over full mass range within ~3 years data taking

In most cases >1 channel for discovery
What are the alternatives to the Standard Model?

Best bet is Supersymmetry (SUSY)

Theoretically elegant - extends symmetry ideas of the Standard Model
Invokes a symmetry between fermions and bosons
(integer and half integer spin particles)

Immediately double number of particles
Each SM particle has a superpartner sparticle

\[
\begin{align*}
\text{quarks (spin } \frac{1}{2} \text{)} & \leftrightarrow \text{ squarks (spin 0)} \\
\text{leptons (spin } \frac{1}{2} \text{)} & \leftrightarrow \text{ sleptons (spin 0)} \\
\text{photon (spin 1)} & \leftrightarrow \text{ photino (spin } \frac{1}{2} \text{)} \\
\text{W, Z (spin 1)} & \leftrightarrow \text{ Wino, Zino (spin } \frac{1}{2} \text{)} \\
\text{Higgs (spin 0)} & \leftrightarrow \text{ Higgsino (spin } \frac{1}{2} \text{)}
\end{align*}
\]

None of these has been observed
105 new parameters required by theory - So why bother??
What are GUTs?
Grand unified theories: quantum gravity
Expect this to occur at energy scales when couplings reach strength of gravity
Construct a quantity with dimensions of energy or length from constants of relativity, quantum mechanics & gravity: $c$, $\hbar$, $G$

$$E_{\text{planck}} = \sqrt{\frac{\hbar c}{G}} = 10^{19} \text{ GeV}$$

$$L_{\text{planck}} = \sqrt{\frac{G \hbar}{c^3}} = 10^{-35} \text{ m}$$

Dark Matter Candidates
Astronomical observation show that $\sim 25\%$ of universe is dark matter
It should be cold (i.e. non-relativistic) and stable (does not decay)
- Must be non-charged (or will interact with photons)
- Must be only weakly interacting
- Cannot be neutrons - free neutrons decay
- Cannot be neutrinos - mass too small
The lightest SUSY particle (LSP) is a prime dark matter candidate!
Hierarchy Problem
Why is Higgs mass (~1 TeV) so much smaller than the Planck scale (10^{19} GeV)?
Such calculations need to take account virtual fluctuations

Higgs interacts with all spin ½ particle-antiparticle pairs in the vacuum

Higgs mass quantum corrections are quadratically divergent upto 10^{19} GeV
If SM valid upto Planck scale then incredible fine-tuning of cancellations is needed to ensure ~1 TeV Higgs mass
Seems unnatural
Only a problem for the Higgs (only SM particle with spin 0)

New SUSY sparticles (e.g. stop squark) contribute and cancel identically

Higgs interaction with spin 0 sparticle cancels SM quantum corrections above
GUT Unification
Another of SUSYs charms:
Coupling constants extrapolated to Planck scale do not intersect

Incorporating SUSY into extrapolation brings unification below Planck scale!

Current measurements

16 orders of magnitude extrapolation!
Involves including all particle loops

New SUSY particles = different loops = different extrapolation
Quantum Gravity
Supersymmetry is a particular form of string theory
String theory aims to describe physics of Planck scale - domain of quantum gravity
Impossible to reach in any collider!

Some quantum gravity theories line in 10 or 11 dimensional space!
   predict gravitons propagate in extra dimensions size of Planck length
   (graviton = postulated force carrier of gravity)
Explains why gravity is $10^{23}$ times weaker than Weak force - gravity is diluted

But: If extra dimensions large ($\sim 0.1\text{mm}$) quantum gravity could be seen at TeV scale
Gravity has never been tested at such short distances!
LHC could open the possibility of creating mini-black holes & gravitons
   laboratory for testing quantum gravity!!!

Mini black holes will evaporate via Hawking radiation
   experimentally look for particle decays with Black Body spectrum at Hawking Temp

\[
T \approx \frac{(n+1)}{4\pi R}
\]
   \(n = \) number of extra dimensions
   \(R = \) radius of compacted dimension
We're living in exciting times
Discovery potential of the LHC is huge
   Higgs discovery
   physics of b quarks
   supersymmetry
   new phases of matter
   quantum gravity
   precision measurement of EW sector
   ...something we haven't thought of yet

Lots of work to be done in next few years!
A gauge transformation is one in which a symmetry transformation leaves the physics unchanged.

Both circuits behave identically.
- Circuit is only sensitive to potential differences.
- Change the ground potential of the earth and see no difference!
- Leads to concept of charge conservation.

In electromagnetism we are insensitive to phase $\alpha$ of EM radiation.
- Could globally change the phase at all points in universe: no difference.
- Leads to global gauge transformation.

What happens if we demand local phase transformations? $\alpha \rightarrow \alpha(x,t)$.
If we demand local phase invariance AND consistent physics then we must alter Maxwells equations

The alterations required to accommodate these changes introduce a new field - interaction of charged particle with an EM field - the photon!

This can be applied to many situations:
local gauge invariance introduces new fields & particles:

- Electromagnetism photon
- Quantum chromodynamics gluons
- Weak force $W^\pm$ and $Z^0$

Intimately related to symmetries and conservation laws