The Standard Model of Particle Physics
Forces of Nature
Problems of The Standard Model
Particle Accelerators & Experiments
The Large Hadron Collider
The Higgs Boson and Extra Dimensions
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?

Thompson  Planck  Rutherford
**Introduction**

![Graph showing the evolution of particle physics experiments over time. The graph plots resolved size [fm] on the y-axis against year. Key points include:
- **Rutherford: nucleus** in 1900.
- **Hostadter: proton radius** in 1950.
- **CERN: scaling violations** in 1970.
- **HERA: rising F2** in 1980.
- **LHC?** in 2000.

The graph illustrates the progression of particle physics from early experiments to contemporary projects like the Large Hadron Collider (LHC).]
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

**Gluons**

**Photons**

**W & Z bosons**

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
1 eV = Energy of electron accelerated through 1 Volt

1 MeV = $10^6$ eV  
1 GeV = $10^9$ eV  
1 TeV = $10^{12}$ eV

Through $E=mc^2$ we can freely convert energy ↔ mass (exchange rate = $c^2$ !!!)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up Quark</td>
<td>~ 0.002</td>
</tr>
<tr>
<td>Charm Quark</td>
<td>1.25</td>
</tr>
<tr>
<td>Top Quark</td>
<td>175</td>
</tr>
<tr>
<td>Down Quark</td>
<td>~ 0.005</td>
</tr>
<tr>
<td>Strange Quark</td>
<td>~ 0.095</td>
</tr>
<tr>
<td>Bottom Quark</td>
<td>4.2</td>
</tr>
<tr>
<td>Electron</td>
<td>0.0005</td>
</tr>
<tr>
<td>Muon</td>
<td>0.105</td>
</tr>
<tr>
<td>Tau</td>
<td>1.78</td>
</tr>
<tr>
<td>Electron Neutrino</td>
<td>~ 0</td>
</tr>
<tr>
<td>Muon Neutrino</td>
<td>~ 0</td>
</tr>
<tr>
<td>Tau Neutrino</td>
<td>~ 0</td>
</tr>
<tr>
<td>Proton</td>
<td>0.938</td>
</tr>
</tbody>
</table>

These are relative masses not size - they have no measurable size

For reference:

Originally thought to be massless but now not
How does exchanging particles transmit a force?

if skaters exchange a ball they will move apart
acts like a repulsive force (if we don't see the ball!)
The Standard Model

Strong Force
Strength: 1
Range: $10^{-15}$ m
Exchange: Gluon

Electromagnetic Force
Strength: 0.01
Range: Infinite
Exchange: Photon

Weak Force
Strength: $10^{-6}$
Range: $10^{-18}$ m
Exchange: $W^\pm Z^0$

Gravity
Strength: $6\times10^{-39}$
Range: Infinite
Exchange: Graviton?
At high energy, masses small – forces are equal.

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

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

Aim to unify all forces.
The complete Standard Model formula
Quantum mechanics predicts the gyromagnetic ratio of the electron $g=2$
(ratio of magnetic dipole moment to it's 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
\[
\frac{g_{\text{theory}} - 2}{2} = 1159652140(\pm 28) \times 10^{-12}
\]
\[
\frac{g_{\text{exp}} - 2}{2} = 1159652186.9(\pm 4.1) \times 10^{-12}
\]
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?
Use large Particle Accelerators e.g. CERN.

Either annihilate two particles and use the total energy to create new particles using $E=mc^2$.

Or scatter one particle off something inside the other to see what it’s made of.

The more energy you start with, the heavier the new particles you can make or the further you can see inside. 
*(Compare firing a bullet to throwing a bullet at something)*
Two beams of particle are accelerated in opposite directions and collide at interaction regions where the detectors are:

Circular Accelerator

Linear Accelerator
Particle Physics is a global enterprise: experiments in all continents (incl. antarctica!)
I will concentrate on LHC and the ATLAS experiment
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 Higgs Boson

Higgs particle postulated to explain masses of fundamental particles

Theory predicts force carrier particles to be massless
But $W^\pm$ & $Z^0$ boson have large masses ~80-90 GeV

Higgs properties are well known except its mass!

Direct searches: $m_H > 114$ GeV

Massless Particle - Travels at the speed of light

Low Mass Particle - Travels slower

High Mass Particle - Travels slower still
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

- quarks (spin $\frac{1}{2}$) ↔ squarks (spin 0)
- leptons (spin $\frac{1}{2}$) ↔ sleptons (spin 0)
- photon (spin 1) ↔ photino (spin $\frac{1}{2}$)
- W, Z (spin 1) ↔ Wino, Zino (spin $\frac{1}{2}$)
- Higgs (spin 0) ↔ Higgsino (spin $\frac{1}{2}$)

None of these has been observed
105 new parameters required by theory - So why bother??
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 dimesional 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 ($\sim 0.1$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
Black Holes on Demand

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here’s the idea:

Particles collide in three dimensional space, shown below as a flat plane.

As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.
LHC Turns On
LHC Starts Collisions!

Atlas Experiment sees collision data

Data used to cross check if detector is operating correctly

Long “physics run” of data taking starts this Spring for ~ 1 year!
We're living in exciting times
Discovery potential of the LHC is huge
Higgs discovery
mini black holes
extra dimensions
supersymmetry
new phases of matter
quantum gravity
secret of dark matter
... something we haven't thought of yet

Lots of work to be done in next few years!
The LHC started operation November 2009
Data taking will start in earnest Feb 2010
In just a few years you could be working with us!
The LHC turned on and the earth did not get eaten by a black hole! Has taken over 2 decades to finally get to this point. Beam operators injected protons into one ring only complete circuit of the ring no acceleration to high energy means ~1000 magnets working, cryogenics OK, diagnostic systems ok vacuum inside beam pipe is ok...

Great success!
In following days CERN attempted to accelerate protons up to 5 TeV

On Friday 19th September an accident caused a “magnet quench”

To steer the beams powerful supercooled magnets are required
Cooled by liquid Helium to just above absolute zero
Magnets become superconducting - no electrical resistance!
Currents ~ 10,000 A

One electrical connection between magnets gained small resistance ~10x10^{-9} \Omega
power = I^2R = 10 \text{ watts}
enough to heat helium above critical temperature - no more cooling
magnets become resistive and dissipate power
  protection systems operated ok - magnets not damaged

sudden increase in pressure due to helium boiling
ruptured helium container and safety valves failed
  designed to withstand 8 tonnes of force from helium pressure
400m section under investigation
This is what a few nano-ohms resistance in a superconducting magnet can do...