The Higgs and Beyond

- The Standard Model
- The Higgs Boson
- Hunting for the Higgs Boson
- What next?

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PsiStar - QMUL - London
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The Standard Model

<table>
<thead>
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<th>Electric Charge</th>
<th>Quarks</th>
<th>Leptons</th>
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<td>g, g, g</td>
</tr>
</tbody>
</table>

Fermions and Bosons:
- 8 gluons
- 3 electroweak bosons
- 1 Higgs boson

Our new baby is just 4 months old
The Exchange Model

Momentum is transferred between particles A and B

In some cases particles can even exchange identity!

The interaction must:
- exchange momentum
- exchange electric charge?
An exchange particle is forbidden; it violates energy-momentum conservation.

Particle cannot emit anything in its own rest-frame.

**Saved by the Heisenberg Uncertainty Principle:**

\[ \Delta E \Delta t > h \]

Small energy \( \Delta E \) can be ‘borrowed’ for a time \( \Delta t = h / \Delta E \)!

This process is an interaction - it is the expression of a force of nature.

Newton: force = rate of change of momentum (\( F=ma \))

**What can we predict about the exchange particle?**

\( \Delta E \) is ‘used’ to produce the particle with mass - what is it?

Weak force acts in \( \beta \) decay - has a range of \( 10^{-3} \) fm

Assume it travels at light speed \( c \) - how long does it live for?

\[ c \Delta t = 10^{-3} \text{ fm} \quad \& \quad \Delta E = mc^2 \]

\[ mc^2 \approx \frac{hc}{c \Delta t} \]

So \( m = 100,000 \text{ MeV/c}^2 \)  
100 times proton mass!

But we don’t understand why \( W, Z \) are heavy and photon is massless! ....
Transition due to the exchange of a gauge boson
Exchanges momentum & quantum numbers
Strength of the interaction is parameterised by couplings $\alpha$
One $\alpha$ for each fundamental force

$M_{fi} = \text{sum of transitions of initial state } \psi_i \text{ to final state } \psi_f$

For each diagram calculate the transition amplitude
Add all transition amplitudes
Square the result to get the reaction rate

Simplest interaction is single boson exchange
More complicated loop diagrams also contribute
Potentially infinite series of diagrams for $2 \rightarrow 2$ scattering process

Feynman Rules: start from left side

1. Write a free particle wave function for each particle
   $\psi = Ae^{i(kx-\omega t)}$

2. Multiply by an exchanged boson write $\frac{1}{q^2-m^2}$ for particle of momentum $q$ and mass $m$

3. For each vertex multiply by coupling $\sqrt{\alpha} = e$

Sum over all allowed particle states i.e. all quark flavours / colours / spins

reaction rate / probability $\propto |M_{fi}|^2$
Feynman Diagrams

\[ |M_{fi}|^2 = \frac{e^4}{q^4} \frac{1}{4} \sum_{\text{spin}} \left\{ \overline{u}(k') \gamma^\mu u(k) \right\} \left\{ \overline{u}(p') \gamma_\nu u(p) \right\} \]

\[ k, k' = \text{incoming, outgoing electron momentum} \]
\[ p, p' = \text{incoming, outgoing muon momentum} \]
\[ q = \text{momentum transfer} \]
\[ e = \text{strength of electromagnetic interaction (electric charge)} \]

For electromagnetism \( \alpha_{\text{EM}} = \frac{1}{137} \sim e^2 \)
Small enough for perturbation theory to work

For strong interaction \( \alpha_s \sim 0.1 \)
Perturbation theory works but need to calc more diagrams for precision - difficult!
For QCD it took 10 years to calculate second order diagrams!
Aim to unify all forces

At high energy/momentum \( Q \):

masses \( M_W \) & \( M_Z \) are small

forces are \( \sim \) equal

\[
\frac{d\sigma_{\text{NC}}^\pm}{dx dQ^2} \approx \frac{e^4}{8\pi x} \left[ \frac{1}{Q^2} \right]^2 \\
\frac{d\sigma_{\text{CC}}^\pm}{dx dQ^2} \approx \frac{g^4}{64 \pi x} \left[ \frac{1}{M_W^2 + Q^2} \right]^2 \\
[ Y_+ \tilde{F}_2^\pm + Y_- x \tilde{F}_3^- ] \\
[ Y_+ \tilde{W}_2^\pm + Y_- x \tilde{W}_3^- ]
\]

 propagator term

(Increasing \( Q^2 \))
Higgs boson **required** to explain why $W^\pm$ and $Z^0$ bosons are very heavy
And why the photon is massless
In a symmetric theory all force particles should be massless

In quantum field theory all particles are described as oscillations in a field
Electrons are oscillations of the ‘electron field’ etc...
Oscillations are the particle wave functions

Higgs particle is a particle of the vacuum:
Has zero for all quantum numbers
- no charge
- no colour
- no spin
It just has mass!

Higgs field has minimum energy when field is non-zero

At the Big Bang: field = zero
As universe cooled Higgs field ‘collapsed’ to min. energy

In vacuum of empty space energy is at minimum
so Higgs field is non-zero
$\Rightarrow$ Higgs particles are everywhere!

Any particles interacting with Higgs field acquire mass - Higgs particles slow them down
Empty space filled with Higgs field

Particle with strong Higgs interaction is slowed down
Imagine walking with boots on snow
Appear to have large mass

Particle with moderate Higgs interaction travels faster
Like walking with snow shoes
Has moderate mass

Higgs particle appears as a snow-flake

Particle with no Higgs interaction travels at speed of light
⇒ massless particle
Higgs also saves the SM from some embarrassing predictions
Examine energy dependence of scattering process $e^+e^- \rightarrow W^+W^-$

Processes (a) (b) and (c) become larger than total $e^+e^-$ reaction rate! (probability greater than 100%)

Higgs-like particle is needed to cancel $e^+e^- \rightarrow W^+W^-$ theoretical inconsistency

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

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!
The Higgs Boson

Indirect sensitivity to Higgs mass:

\[ \chi^2 \] tests the statistical compatibility of data & theory
Compare data and theory with each other → extract theory parameters where \( \chi^2 \) is smallest

(\( \chi^2 \) is only valid within context of theory being tested)

Precise measurements at low energy are sensitive to Higgs loops

Loop corrections to Z/W scattering reactions:

\[ \propto M_{top}^2 \]
\[ \propto \ln M_H \]

Measurements at energy \( E < M_H \) are logarithmically (i.e. weakly) sensitive to \( M_H \)
Confront data & theory: \( \chi^2 \) test

Indicates light SM Higgs!
But large margin of error...

68% prob of SM Higgs in range \( 92^{+34}_{-26} \) GeV
95% prob of SM Higgs < 161 GeV
27 km circumference tunnel in France / Switzerland - near Geneva
Highest energy accelerator in the world
Protons accelerated to 7,000 GeV = 99.9999991% speed of light
High vacuum
Super cold superconducting magnets to achieve strong magnetic fields
17,000 A current in magnets
Four experiments:
  - Atlas
  - CMS
  - LHCb
  - Alice
Operating temperature: -271°C  One of the coldest places in universe
High energy collisions equivalent to temperatures 100,000 times hotter than sun’s core
High vacuum needed to avoid unwanted collisions with air molecules - less dense than solar system
1200 dipole magnets to bend the protons
Protons circulate 11,000 times per second
Generates up to 600 million collisions per second
LHC costs for material, construction, personnel (excluding experiments) = € 3,000,000,000
\( \sigma = \text{reaction rate} \)

Number of events (i.e. collisions) per second

Total rate of data produced by LHC: 100,000,000 events/second

Huge event rates
New physics swamped!
Need to filter events 1:10\(^7\) online

Maximum recording rate of ATLAS experiment: 200 events/second

Production rate of 125 GeV Higgs: 0.01 events/second

Like trying to find a cheap plumber from entire human population in 2 \( \mu \text{s} \)
The ATLAS experiment at the LHC

The Atlas Experiment
7000 tonnes
Mass of the Eiffel Tower
Half the size of Notre Dame
Data rate: 20,000,000 Gb/s

The Atlas Collaboration
3500 physicists
174 universities
38 countries
Measuring cross-section of a process requires recognising event properties:

- Electromagnetic energy with a charged track: e+ or e-
- Electromagnetic energy without track: photon
- Collimated ‘jet’ of particles: gluon/quark induced jet
- Penetrating charged track: \( \mu^+ \) or \( \mu^- \)
- Missing transverse energy: \( \nu \)
- Missing longitudinal energy: beam remnants
- Displaced secondary vertex: in-flight decay of 'long lived' particle

Look at the event topology...
Large experiments needed to measure outgoing particles from collisions
Experiment consists of layered detectors each sensitive to different types of particle
Look for signatures of particle types
Many possible Higgs decay modes/channels:

H → ZZ
ZZ → llll (4 lepton golden mode)
ZZ → llvv (good for high mass Higgs)
ZZ → llbb (good at high mass)

H → WW
WW → lνlν (most sensitive)
WW → lνqq (highest rate)

H → γγ
Rare, best for low mass Higgs
high background

H → ττ
Rare, good at low mass, low background

H → bb
Useful but difficult to identify b quarks

W/Z can further decay to many combinations of fermions

Each mode has different:
• sensitivity depending on mass range
• production rate
• contributions from background processes
All modes need to be studied together!
Higgs Hunting

Decay modes of the Higgs vs mass

For $m_H > 2m_W$ then WW production dominates

For $m_H > 2m_Z$ then ZZ production increases
Selected diphoton sample
- Data 2011 and 2012
- Sig + Bkg inclusive fit ($m_H = 126.5$ GeV)
- 4th order polynomial

$\sqrt{s} = 7$ TeV, $\int Ldt = 4.8$ fb$^{-1}$
$\sqrt{s} = 8$ TeV, $\int Ldt = 5.9$ fb$^{-1}$

Experiment designs were optimised for this measurement 20 years ago!

QM built & operate the trigger that collects this data (and more)
$\sqrt{s} = 7$ TeV: $\int L dt = 4.8$ fb$^{-1}$

$\sqrt{s} = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$
Higgs Hunting

\[ H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu \text{ (1 jet)} \]

- \( s = 8 \text{ TeV}, \int L dt = 13.0 \text{ fb}^{-1} \)
- \( H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu \) (1 jet)

**Diagram:**
- \( t \rightarrow \bar{t} \rightarrow H \)
- \( W \rightarrow e, \mu, q' \)
- \( e, \mu, q \)

**Legend:**
- Data
- SM (sys \( \oplus \) stat)
- WW
- WZ/ZZ/W\( \gamma \)
- \( t\bar{t} \)
- Z+jets
- W+jets
- H [125 GeV]
Probability of “no Higgs” hypothesis fluctuating to mimic Higgs signal

**ATLAS 2011 - 2012**

- Obs.
- Exp.
- ±1σ

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<th>Mass [GeV]</th>
<th>Local $p_0$</th>
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<td>150</td>
<td>10^{-4}</td>
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</table>

- **Obs.**
- **Exp.**
- ±1σ

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**ATLAS Preliminary**

- $W, Z H \rightarrow bb$
- $H \rightarrow ττ$
- $H \rightarrow WW^{(*)} \rightarrow ℓνℓν$
- $H \rightarrow γγ$
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$

**Combined**

- $\mu = 1.3 \pm 0.3$

The new particle is being produced at about the Standard Model rate

Have we found it?

Cannot say yet - we need to measure its couplings to all particles, decay width, parity (but in all likelihood this is it!)
Signal evolution with time

Wide mass range

Zoom of interesting region
The Standard Model

Perl, Gross, Rubbia, van der Meer
Reines, Lederman, Gell-man, Cronin
Steinberger, Feynman, Glashow, Taylor, Friedman
Hofstadter, Schwinger, Higgs, Veltman, Kendall
Politzer, Ting, Alvarez, Fitch
Schwarz, Richter, Weinberg, Yang
Wilczek, Salam, Lee, t’Hooft

29 Nobel prizes awarded for the Standard Model
1 more yet to come?
The Problematic Standard Model

\[
-\frac{1}{2} \partial_\mu \partial_\nu \partial_\alpha \partial_\beta f^{\alpha \beta}_{\mu \nu} + g_s f^{abc} \partial_\mu f^{\mu \nu}_{\alpha \beta} \partial_\nu f^{a \beta}_{\mu \nu} + \frac{1}{2} g_s^2 (\partial_\mu Z_\mu) \partial_\nu Z_\nu - \frac{1}{2} M^2 Z_\mu \partial_\mu Z_\mu + \frac{1}{2} \partial_\mu \partial_\nu \partial_\alpha \partial_\beta f^{\alpha \beta}_{\mu \nu} - \frac{1}{3} \partial_\mu \partial_\nu \partial_\alpha \partial_\beta f^{abc} \partial_\mu f^{\mu \nu}_{\alpha \beta} + \partial_\mu W^\mu_{\alpha \beta} \partial_\nu W^\nu_{\alpha \beta} - M^2 W^\mu_{\alpha \beta} W^\mu_{\alpha \beta} - \frac{1}{2} \partial_\mu Z_\mu \partial_\nu Z_\nu - \frac{1}{2} M^2 Z_\mu Z_\mu - \frac{1}{2} \partial_\mu A_\mu \partial_\nu A_\mu - \frac{1}{2} \partial_\mu H \partial_\nu H - \frac{1}{2} \partial_\mu \partial_\nu H \partial_\alpha \partial_\beta f^{\alpha \beta}_{\mu \nu} + \partial_\mu W^\mu_{\alpha \beta} \partial_\nu W^\nu_{\alpha \beta} - \frac{24}{g} H + \frac{1}{4} (H^2 + \partial_\mu \partial_\nu \partial_\alpha \partial_\beta f^{\alpha \beta}_{\mu \nu} + 24 \mu_0^2 \alpha - i g_s \alpha [\partial_\mu Z_\mu (W^\mu_{\nu \beta} + W^\nu_{\mu \beta}) - W^\mu_{\nu \beta} W^\nu_{\mu \beta}] - 2 g_s \alpha \alpha \alpha [W^\mu_{\nu \beta} + \alpha \alpha \alpha [W^\mu_{\nu \beta} - W^\nu_{\mu \beta}] - 2 g_s \alpha \alpha \alpha [W^\mu_{\nu \beta}]
\]

The Standard Model works beautifully! Describes all experimental data!

But it’s incomplete
Many things have to be inserted by hand
Leaves many questions unanswered
22 Parameters of the SM to be measured
- 6 quark masses
- 3 charged leptons masses
- 3 coupling constants
- 4 quark mixing parameters
- 4 neutrino mixing parameters
- 1 weak boson mass (1 predicted from other EW params)
- 1 Higgs mass

We have no idea what 96% of the universe is!
- unknown form of dark energy
- unknown form of dark matter

No treatment of gravity in the Standard Model...
- In a symmetric theory gauge bosons are massless
- Higgs mechanism explains EW symmetry breaking
  → EW bosons acquire mass

...but there must be a deeper relationship between Higgs / mass / gravity / dark energy

We know quantum gravity effects must play a role at the Planck scale i.e. energy ~ $10^{19}$ GeV
We should not exist!
For every proton/neutron/electron in universe there are $10^9$ photons (CMB - cosmic microwave background)
Thus matter/anti-matter asymmetry must be 1:10^9
We cannot see where this asymmetry lies...

In the Standard Model matter and anti-matter produced in equal quantities
In the Big Bang: for every quark, one anti-quark is also produced
As universe cools expect all particles and anti-particles to annihilate
⇒ soon after big bang all matter will have annihilated to photons

We should not exist!
For every proton/neutron/electron in universe there are $10^9$ photons (CMB - cosmic microwave background)
Thus matter/anti-matter asymmetry must be 1:10^9
We cannot see where this asymmetry lies...
Why is gravity $\sim 10^{33}$ weaker than EW interactions? 
Why is Higgs mass ($\sim 100 \text{ GeV}$) so much smaller than Planck mass ($10^{19} \text{ GeV}$)?

Leads to fine tuning problem: 
Corrections to Higgs mass rapidly diverge up to $10^{19}$ GeV 

$$ \text{physical mass} = \text{bare mass} + \text{"loops"} \quad m_H^2 = m_0^2 + \Delta m_H^2 $$

Since Higgs is scalar field we get:

- top quark loop: $\Delta m_H^2 = -a\Lambda^2$
- W/Z boson loop: $\Delta m_H^2 = +b\Lambda^2$
- Higgs loop: $\Delta m_H^2 = +c\Lambda^2$

$\Lambda$ is the energy up to which the SM is valid 
... or the energy at which new physics appears

If $\Lambda^2 \sim (10^{19} \text{ GeV})^2$ and $m_H^2 \sim (100 \text{ GeV})^2$

$$ m_H^2 = m_0^2 + (-a + b + c)\Lambda^2 $$

$$ m_H^2 = m_0^2 + (-a + b + c) \cdot 10^{38} \approx 100^2 $$

If SM is valid to energy scale $\Lambda$ (i.e. no new physics from $10^3 \text{ GeV} - 10^{19} \text{ GeV}$) incredible fine tuning required between bare mass and the corrections to maintain $\sim 100 \text{ GeV}$ Higgs mass
What are the alternatives to the Standard Model?

“*The LHC opens a door to a new room, but we’ve got to have a good look around in that new room. The Higgs particle is a very important question but it’s far from the only one.*”

Jon Butterworth

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 super-partner sparticle

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

None of these has been observed
105 new parameters required by theory - So why bother??
**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 $\frac{1}{2}$ particle-antiparticle pairs in the vacuum

Higgs mass quantum corrections diverge up to $10^{19}$ 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
Incorporating SUSY into extrapolation brings unification below Planck scale!

Current measurements at 1000 GeV

16 orders of magnitude extrapolation!
Involves including all particle loops

New SUSY particles = different loops = different extrapolation

Incorporating SUSY into extrapolation brings unification below Planck scale!
Supersymmetry “died” on Monday!

Experiments search for new physics (NP):
look for influence of new heavy particles via quantum loops
Choose a process heavily suppressed by Standard Model
(low contamination from SM background)

New physics quantum loop effects visible if
NP loops are similar size to SM loops

Measure the decay rate of the $B_s^0$ meson
Decay to $\mu^+\mu^-$ is very suppressed in SM - SM predicts fraction of decays is $\sim 10^{-9}$ !

New heavy particles can enter the loops and alter decay rate

On Monday LHCb experiment announced world's first measurement of this very rare decay rate

Agrees with SM :(

Supersymmetry has few places left to hide!

Decay fraction ($B_s^0 \rightarrow \mu^+\mu^-$) = $3.2^{+1.5}_{-1.2} \times 10^{-9}$

SM predicts: $(3.54 \pm 0.30) \times 10^{-9}$
There is plenty more work to be done!
Many exciting projects underway:
  T2K
  SNO+
  Super-LHC
  LHeC
Join us and click here:

http://pprc.qmul.ac.uk/postgraduate/phd-programme
Quantum fluctuations affect all reaction rate measurements
Effects are subtle but measurable
Consider $e^-$ scattering process:

\[ e^- e^- \rightarrow e^- + e^- + e^- + e^- + \alpha^2 + \alpha^3 + \alpha^4 + \alpha^2 + \alpha^2 + \ldots \]

An infinite number of diagrams contribute to this scattering process
Result is finite due to cancellations

All these and more diagrams are required to calc g-2 of the electron with high precision
Precision measurements are weakly sensitive to existence of new particles modifying “loop corrections”
Particle masses also affected by such quantum fluctuations
Particles have fixed mass, but experimentally measured mass = “bare” mass + quantum fluctuations

\[ m^2_H = m^2_0 + \Delta m^2_H \]

quantum fluctuations affect a “bare” particle mass resulting in experimentally measurable mass
Almost all the visible mass of universe is due to massless QCD effects
Energy associated with quark and gluon interactions $\rightarrow$ 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 $W^\pm$ & $Z^0$ boson have large masses $\sim$80-90 GeV (proton $\sim$1 GeV)
Higgs mechanism explains why $W^\pm$ & $Z^0$ bosons are not massless

Higgs properties are well known except its mass!

Direct searches at the LEP $e^+e^-$ collider
No Higgs found within energy range of LEP $\Rightarrow$ mass $m_H > 114$ GeV

4 LEP experiments combined their data points = data after many selection criteria
yellow = simulation of background contribution
red = simulation of potential Higgs contribution
Not statistically conclusive!
LEP was shutdown to start LHC construction
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.
Recap

- A quantum mechanical particle is associated with a wave function $\psi$
- The wave function encapsulates all information about the particle
- The wave function squared is proportional to probability of finding the particle at a particular place, time, energy, momentum etc..

$$\psi = A e^{i(kx - \omega t)}$$

The equation involves “derivative” operators:

$$\frac{\partial}{\partial t}$$

⇒ mathematical operators acting on wave function

They calculate slopes - or how the wave function changes per meter, or per second

$$\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$$

operators act on something, just like $+ \text{ or } \div \text{ or } \sqrt{}$

In this case they act on the wave function $\psi$

Schrödinger equation describes the particle $\psi$ behaves under influence of an energy field $V(x,y,z)$

$x,y,z,t$ are co-ordinates in space and time

$V(x,y,z)$ could be e.g. another particle’s electric field

$$-\frac{\hbar^2}{2m} \nabla^2 \psi + V(x,y,z)\psi = i\hbar \frac{\partial}{\partial t} \psi$$

kinetic energy + potential energy = total energy

Symmetry:

A transformation which leaves an experiment unchanged

Each quantum symmetry is related to a conservation law

- Translation in time
- Translation in space
- Rotations
- Angular Momentum conservation
- Energy conservation
- Momentum conservation
- Gauge Transformation
- Charge conservation
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 $\delta$ of EM radiation. All experiments can only measure phase differences. Could globally change the phase at all points in universe. Yields no observable change => global gauge transformation. (In electromagnetism this is the gauge symmetry expressed by the U(1) group).

What happens if we demand local phase transformations? $\delta \rightarrow \delta(x,t)$ i.e. $\delta$ is no longer a single number, it depends on position $x$ and time $t$.

$$\frac{-\hbar^2}{2m} \nabla^2 \psi + V(x, y, z) \psi = i\hbar \frac{\partial}{\partial t} \psi$$

Wave functions of all particles get an extra piece from the change in $\delta$. This spoils the Schrödinger equation (actually, relativistic versions are the Klein-Gordon and Dirac equations).

$\delta(x,t)$ spoils the spatial & time derivatives.
\[ \psi = Ae^{-i(kx-\omega t)} \rightarrow \psi = Ae^{-i\delta(x,t)} e^{-i(kx-\omega t)} \]

...and since energy (E) and momentum (p) measurements are represented by operators in quantum mechanics

\[ i\hbar \frac{\partial}{\partial t} \psi = E\psi \quad \text{and} \quad \hbar \frac{i}{\partial x} \psi = p_x \psi \]

The derivatives cause nuisance terms to appear in equations arising from \( \delta(x,t) \)

But we still want physics to work the way it did before the gauge transformation!
We want the Schrödinger equation to still work!

So - add an additional term to the equation to cancel out those nuisance terms
After adding these to the equation we ask ourselves: what do the new equation pieces look like?

The alterations required to accommodate these changes introduce a new quantum field
This field has a ‘spin’ = 1
This field interacts with charged particles
This field no charge itself
The field particle has zero mass
- it is the photon!

Our consideration of local symmetry leads us to predict the photon
This can be applied to other quantum interactions:
local gauge invariance introduces new fields
oscillations in the fields are the probability wave functions of particles

<table>
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<th>Gauge particle</th>
<th>Gauge group</th>
<th>Symbol</th>
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<td>(q, W^\pm, e^\pm, \mu^\pm, \tau^\pm)</td>
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These are not simply abstract mathematical manipulations - the particles exist!
Weak bosons (spin 1 particles) discovered in 1983 at CERN’s UA1 experiment

Energy of electrons from the decay of the \(W^-\) particle: \(W \rightarrow e\nu_e\)

Fig. 19c. The electron transverse energy distribution. The two curves show the results of a fit of the enhanced transverse mass distribution to the hypotheses \(W\rightarrow\nu\nu\) and \(X\rightarrow\nu\nu\). The first hypothesis is clearly preferred.

(In 2011 LHC has 40x more data than in 2010)
So far theory predicted new particle’s existence
How do we calculate particle reaction rates?
e.g. reaction rate of electron - positron scattering??

In Schrödinger equation a particle interacts with a potential energy field $V$
Potential energy is energy an object has by virtue of position
Apple in a tree $\rightarrow$ it has potential energy in Earth’s gravitational field
Apple falls $\rightarrow$ it releases potential energy into kinetic energy
Total energy is constant!

In quantum mechanics the potential causes a transition from initial state to final state wave functions $\psi_i \rightarrow \psi_f$
Potential = $V + V'$
$V$ gives rise to stable, time independent quantum states $\psi_f$ and $\psi_i$
$V'$ is a weak additional perturbation leading to transitions between states

$$P = |M_{fi}|^2 = |\int \psi_f V' \psi_i \, dv|^2$$

$P = $ probability of transition from initial to final state
$M_{fi}$ is known as the matrix element for the scattering process

$V'$ contains the standard model Lagrangian - describes the dynamics of all interactions
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 live 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” (~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!!!
Why are the extra dims < 1 mm?
gravity has only been tested down to this scale!

Relative strength of gravity explained by
dilution of gravitons propagating in
very large volume of bulk space

Where are the extra dimensions?
curled up (compactified) and finite
only visible at small scales / high energies

Large Extra Dimensions

infinite extent
usual 3+1 dimensions

compactified
eextra dimension
of size R

field lines in extra
dimensions

test mass feels
gravitational field
With extra dimensions gravity becomes modified

Newton's law: \[ F = \frac{m_1 m_2}{r^2} \]

With \( n \) extra spatial dimensions each of size \( R \)

\[ F = G_D \frac{m_1 m_2}{r^{2+n}} \]

\[ F = \left( \frac{G_D}{R^n} \right) \frac{m_1 m_2}{r^2} \quad \text{i.e.} \quad G = \frac{G_D}{R^n} \]

For \( r \gg R \) we recover Newtonian gravity

Planck scale: \[ M_p^2 = \frac{\hbar c}{G} \]

In extra dimensions full scale of gravity \( M_D \) is given by

\[ M_D^{2+n} = \frac{\hbar c}{G_D} = \frac{M_p^2}{R^n} \]

Thus \( M_D \) can be \( \sim 1 \) TeV when \( R^n \) is large
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: $c$, $\hbar$, $G$

Naturally extends to quantum gravity
Provides a candidate for dark matter
SUSY solves hierarchy problem
Brings about GUT unification of couplings
Some general assumptions can reduce 105 parameters to 5

Supersymmetry

$E_{\text{Planck}} = \sqrt{\frac{\hbar c}{G}} = 10^{19}$ GeV
$L_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^3}} = 10^{-35}$ m
$T_{\text{Planck}} = \sqrt{\frac{\hbar G'}{c^5}} = 10^{-44}$ s

Planck energy
Planck length
Planck time

Dark Matter Candidates
Astronomical observation show that ~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!
Search all channels for Higgs decays
If not found then place upper limit on Higgs production rate versus $M_H$
SM predicts Higgs production rate for any given $M_H$

Solid black line = observation from data:
maximum allowed production rate
compared to SM prediction

Dashed black line = Simulation of experiment:
maximum allowed production rate
compared to prediction with no Higgs

For $M_H = 110$ GeV there is a 95% probability that
Higgs production can be no more than 1.0 times the
predicted SM rate

Any difference in solid / dashed lines is only due to:
• statistical fluctuations in the data
• Higgs

Quantify expected statistical fluctuations:
• 68% of fluctuations should lie within green band
• 95% of fluctuations should lie within yellow band

In region 122.5–129 GeV data show an excess
Excess is still consistent with fluctuation...
... but it's looking very interesting!
Search all channels for Higgs decays
If not found then place upper limit on Higgs production rate for any given $M_H$

Solid black line = observation from data:
- maximum allowed production rate compared to SM prediction

Dashed black line = Simulation of experiment:
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Eram Rizvi
In case you wanted to see the full version of this graph!

$$\int L \, dt \sim 4.6-4.9 \, fb^{-1}, \, \sqrt{s}=7 \, TeV$$

**ATLAS 2011 Preliminary**

**CLs limits**

$$m_H [GeV]$$