The Next 20 Years of the LHC

- The Standard Model
- LHC & ATLAS
- Results from Run 1
- Search for the Higgs Boson
- Cracks in the Standard Model
- Supersymmetry
- Quantum Gravity
- Status of Searches for New Physics
- LHC programme to 2035

#LHCnext20y

Eram Rizvi

School of Physics & Astronomy Public Lecture
2nd March 2016
**The Standard Model**

The Standard Model describes 3 of the 4 fundamental forces of nature with unprecedented accuracy: electromagnetic force / weak nuclear force / strong nuclear force.

<table>
<thead>
<tr>
<th>Electric Charge</th>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2/3</td>
<td>u u u</td>
<td>e νe</td>
</tr>
<tr>
<td>-1/3</td>
<td>d d d</td>
<td>μ νμ</td>
</tr>
<tr>
<td>-1</td>
<td>t t t</td>
<td>τ ντ</td>
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</table>

<table>
<thead>
<tr>
<th>Fermions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin = ½</td>
</tr>
<tr>
<td>Constitute matter</td>
</tr>
<tr>
<td>g g g</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bosons</th>
<th>8 gluons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin = 0 / 1</td>
<td>Propagate strong force</td>
</tr>
<tr>
<td>Electromagnetism &amp; weak force unified into electroweak</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3 electroweak bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>W Z γ</td>
</tr>
<tr>
<td>Propagate electroweak force</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gravity is completely missing here!</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Higgs boson</td>
</tr>
<tr>
<td>Gives fundamental particles a mass</td>
</tr>
</tbody>
</table>

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(what universe would look like with no Higgs boson)
Higgs also saves the SM from some embarrassing predictions
Examine theoretically predicted 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

![Diagram of Higgs Boson](image)

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 Large Hadron Collider

- 27 km circumference tunnel in France / Switzerland - near Geneva
- Highest energy accelerator in the world
- Protons accelerated to 6,500 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
The ATLAS experiment at the LHC
3500 physicists
174 universities
38 countries

7000 tonnes
Mass of the Eiffel Tower
Half the size of Notre Dame
data rate: 20,000,000 Gb/s

25 m

45 m
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

Quarks/gluons detected as a collimated jet of many particles leaving energy in hadron calorimeter
The LHC

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
The LHC Performance

proton beam = 4 TeV  proton beam = 4 TeV

$\sqrt{s} = \text{collision energy} = 8 \text{ TeV}$

$\sqrt{s}$ has strange units “inverse femtobarns”

Luminosity was reduced compared to 2012
Carefully testing LHC machine’s capability!

In 2015 LHC almost doubled beam energy

Amount of data recorded

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Why collide protons in LHC?
- easy to produce
- easy to accelerate (compared to electrons)
- are composite - bags of fundamental quarks and gluons

In reality the LHC is a quark / gluon collider

We measure reaction rates for different collision processes between quarks / gluons

Many different types of process occur

Compare measurement to predictions using Feynman diagrams

Fermion diagram pieces
- fermion (quark or lepton)
- boson (W, Z, photon)
- gluon
- Higgs boson
- vertex: coupling of boson to fermion = strength of interaction \( \alpha \)

Momentum is transferred from quark pair to muon pair
\( \Rightarrow \) Z has transmitted a force!

Feynman Diagram is an equation
- Allows calculation of reaction rate

More complicated loop diagrams also contribute
\( \rightarrow \) quantum fluctuations

Complex diagrams have more vertices
\( \rightarrow \) smaller contributions
Examples of processes / Feynman diagrams measured at the LHC and compared to theory calculations
Approximately ordered in decreasing reaction rate (see next page)

- **Dominant process**
  - Dijets
  - Z production
  - WW (VV)
  - ZZ (VV)

- Extremely rare
  - H → WW
  - B_s → μμ
The Standard Model in Run 1
Probing electroweak & QCD sector of the Standard Model over 14 orders of magnitude!

Experimental verification of electroweak symmetry breaking mechanism
Dijets

Jets

±

WW

±

WZ

−

WW

−

W

±

t

Jets

±

Zjj

EWK

±

γ

±

γ

R=0.4

R=0.4

3

10

2

LHC pp

√s = 7, 8, 13 TeV

Everything is consistent with unity

I personally was involved in some of these measurements with my PhD students

Ratio of measurement to prediction

Everything is consistent with unity

→ Data and theory agree!

(within their uncertainties)
Higgs Hunting

subtle ‘bump’ on top of large background

clear peak, low background, but low rate too

small excess, large background, high rate
Higgs Hunting: Properties of the Higgs

Is the Higgs coupling to particles $\propto$ mass?

\[ \text{Coupling strength of Higgs to particle} \]

\[ \text{Particle mass [GeV]} \]

Have we found it? yes!
We still need to measure all of it’s properties
Are there more Higgs-like particles? Any signs of new physics??

Is the Higgs being produced at the expected rate?

**ATLAS Preliminary**

- $W, Z H \rightarrow bb$
  - $\sqrt{s} = 7 \text{ TeV}$, $L_{\text{int}} = 4.7 \text{ fb}^{-1}$
  - $\sqrt{s} = 8 \text{ TeV}$, $L_{\text{int}} = 13 \text{ fb}^{-1}$
- $H \rightarrow \tau\tau$
  - $\sqrt{s} = 7 \text{ TeV}$, $L_{\text{int}} = 4.6 \text{ fb}^{-1}$
  - $\sqrt{s} = 8 \text{ TeV}$, $L_{\text{int}} = 13 \text{ fb}^{-1}$
- $H \rightarrow WW^{(*)} \rightarrow 4\ell$
  - $\sqrt{s} = 7 \text{ TeV}$, $L_{\text{int}} = 4.6 \text{ fb}^{-1}$
  - $\sqrt{s} = 8 \text{ TeV}$, $L_{\text{int}} = 20.7 \text{ fb}^{-1}$
- $H \rightarrow \gamma\gamma$
  - $\sqrt{s} = 7 \text{ TeV}$, $L_{\text{int}} = 4.6 \text{ fb}^{-1}$
  - $\sqrt{s} = 8 \text{ TeV}$, $L_{\text{int}} = 20.7 \text{ fb}^{-1}$
- $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$
  - $\sqrt{s} = 7 \text{ TeV}$, $L_{\text{int}} = 4.6 \text{ fb}^{-1}$
  - $\sqrt{s} = 8 \text{ TeV}$, $L_{\text{int}} = 20.7 \text{ fb}^{-1}$

Combined

- $\mu = 1.30 \pm 0.20$

The Higgs particle is being produced at about the predicted Standard Model rate

$\mu = \frac{m_H}{m_Z}$

$m_H = 125.5 \text{ GeV}$
### The Standard Model

<table>
<thead>
<tr>
<th>Perl</th>
<th>Gross</th>
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<td>Gell-man</td>
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<td>Glashow</td>
<td>Taylor</td>
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<tr>
<td>Wilczek</td>
<td>Salam</td>
<td>Lee</td>
<td>t’Hooft</td>
</tr>
</tbody>
</table>

2013 Nobel prize for
Peter Higgs
François Englert

31 Nobel prizes awarded for the Standard Model!
The Problematic Standard Model

$$\frac{-1}{2} \frac{1}{2} \delta_{ij} \frac{1}{2} f_{abc} \partial_i \partial_j \partial_k \frac{1}{2} d_i = \frac{g_s}{2} \frac{1}{2} f_{abc} \frac{1}{2} f_{ade} \partial_j \partial_k \frac{1}{2} d_i$$

$$\frac{3}{2} \partial_i \partial_j \partial_k \frac{1}{2} d_i + \frac{M_2}{2} \frac{1}{2} M_2 \partial_i \partial_j \partial_k \frac{1}{2} d_i = \frac{g_s}{2} \frac{1}{2} f_{abc} \frac{1}{2} f_{ade} \partial_j \partial_k \frac{1}{2} d_i$$

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
The Standard Model has 22 parameters to be measured:
- 6 quark masses
- 3 charged leptons masses
- 3 couplings $\alpha_1, \alpha_2, \alpha_3$ for 3 forces
- 4 quark mixing parameters
- 4 neutrino mixing parameters
- 1 weak boson mass (1 predicted from other EW params)
- 1 Higgs mass

We feel this is too much for a fundamental theory (but better than 105 params of supersymmetry)

We have no idea what 96% of the universe is!
- unknown form of dark energy (74% of universe's mass!)
- unknown form of dark matter (22% of universe's mass!)

No treatment of gravity in the Standard Model...

In a symmetric theory gauge bosons are massless

Higgs mechanism explains EW symmetry breaking

$\rightarrow$ 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 $\sim 10^{19}$ 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...

(Actually SM can account for only 1000th of this asymmetry)
The Hierarchy Problem

• Why is gravity \( \sim 10^{33} \) weaker than EW interactions?
• Why is \( m_H \) Higgs mass (125 GeV) so much smaller than \( \Lambda \) Planck mass (10^{19} \text{ GeV})?

Leads to fine tuning problem:
Corrections to Higgs mass rapidly diverge up to \( 10^{19} \text{ GeV} \)

\[
\text{physical Higgs mass } = \text{bare mass } + \text{“loops” } m_H^2 = m_0^2 + \Delta m_H^2
\]

For Higgs 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: \( \Delta m_H^2 = +c\Lambda^2 \)

\( a, b, c \) are couplings of particles to Higgs

\( \Lambda \) 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 \(~ 100 \text{ GeV} \) Higgs mass
### Supersymmetry

Every Standard Model particle gets a supersymmetric partner sparticle with opposite spin

<table>
<thead>
<tr>
<th>Electric Charge</th>
<th>Squarks</th>
<th>-1/3</th>
<th>Sleptons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+2/3</td>
<td>-1/3</td>
<td>-1</td>
</tr>
<tr>
<td>Bosons spin = 1</td>
<td>u</td>
<td>d</td>
<td>e</td>
</tr>
<tr>
<td></td>
<td>u</td>
<td>d</td>
<td>νₑ</td>
</tr>
<tr>
<td></td>
<td>u</td>
<td>d</td>
<td>I</td>
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<td></td>
<td>c</td>
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<td>μ</td>
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<td>b</td>
<td>τ</td>
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<td></td>
<td>t</td>
<td>b</td>
<td>νₜ</td>
</tr>
<tr>
<td></td>
<td>t</td>
<td>b</td>
<td>III</td>
</tr>
<tr>
<td>Fermions spin = 1/2</td>
<td>g</td>
<td>g</td>
<td>g</td>
</tr>
</tbody>
</table>

None of these has been observed

105 new parameters required by theory - So why bother??

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Astronomers observations show Dark Matter is:
- probably a particle
- electrically neutral (does not interact with photons)
- cold (non-relativistic)
- stable (does not decay to anything else)
- weakly interacting (else galaxies won’t form)
- cannot be neutrons (they’re unstable)
- cannot be neutrinos (mass too small)

In LHC pp collision SUSY sparticles could be produced
In some models only sparticle & anti-sparticle pairs can be formed
This means the lightest neutralino cannot decay into ordinary SM particle
It is stable!
This Lightest Supersymmetric Particle (LSP) could be Dark Matter!

In this case gluino pair is created
Each decays to two quarks, $W$ and a stable neutralino
Search for this experimental signature in ATLAS
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 up to 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 SUSY’s charms:
Three force couplings extrapolated to Planck scale do not intersect

Incorporating SUSY into extrapolation causes couplings to coincide below Planck scale!
Forces are unified ?!

Current measurements at 1000 GeV

16 orders of magnitude extrapolation!
Involves including all particle loops

New SUSY particles = different loops = different extrapolation
What are GUTs?

Grand unified theories: electroweak + QCD
TOE = Theory of everything = GUT + quantum gravity

Occurs 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: $c, \hbar, \mathcal{G}$

- 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

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>speed of light</td>
<td>$c$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>Gravitational constant</td>
<td>$G$</td>
<td>m$^3$ Kg$^{-1}$ s$^{-2}$</td>
</tr>
<tr>
<td>Planck constant</td>
<td>$\hbar$</td>
<td>Kg m$^{-2}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

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

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

$$T_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^5}} = 10^{-44} \text{ s}$$

This exercise very roughly tells us what energy or length scale we need to see effects of quantum gravity

These are all equivalent: experiments probing the Planck energy, also probe distances of Planck length

$$10^{19} \text{ GeV} = 10,000,000,000,000,000,000 \text{ GeV} \quad \text{No chance to build a collider at this energy!}$$

$$10^{-35} \text{ m} = 0.000 \ 000 \ 000 \ 000 \ 000 \ 000 \ 000 \ 000 \ 000 \ 000 \ 001 \text{ m}$$
Extra spatial dimensions of size < 1 mm could exist; gravity has only been tested down to this scale!

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

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

This is the ADD model of extra dimensions
- Proposed in 1998 by Arkani-Hamed, Dimopoulos and Dvali

Large Extra Dimensions

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With extra dimensions gravity becomes modified

\[ F = G \frac{m_1 m_2}{r^2} \]

Newton's law:

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

For \( r \) much larger than \( R \) we recover Newtonian gravity

\[ F = \left( \frac{G_D}{R^n} \right) \frac{m_1 m_2}{r^2} \]

\( G_D \) is higher dimensional Gravitational constant

\[ G = \frac{G_D}{R^n} \]

dilution due to volume of extra dimensions

Planck scale:

\[ M_P^2 = \frac{\hbar c}{G} \]

In extra dimensions full scale of gravity \( M_D^2 \) is given by

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

Thus \( M_D \) can be \( \sim 1 \) TeV when \( R^n \) is large

LHC could open the possibility of creating mini-black holes & gravitons laboratory for testing quantum gravity!!!
Large Extra Dimensions

In the Randall-Sundrum model the Standard Model is confined to a “low energy” brane.

Gravity propagates in 1 higher dimension linked to a “high energy” brane.
Gravity is weakly interacting at low energy... and interacts strongly on the high energy brane.

At high enough energy ADD models predict micro-blackhole production.

Black hole forms when quarks collide with separation \(< 2r_s\).

Black hole mass:

\[ M_{BH} = E_{LHC} \sqrt{x_a} \cdot \sqrt{x_b} \]

Depends on LHC energy & prob. of finding quarks carrying high momentum fractions of both protons, \(x\).

For “normal” objects \( r_s = \frac{2GM}{c^2} \).

With extra dimensions:

\[ r_s = \frac{2GR^n M_{BH}}{c^2} \]

\( r_s \) increased by factor \( R^n \)

Should observe continuous mass spectrum of BHs \( M > M_D \).

\( r_s = 1 \text{ cm for Earth} \).
Exotic Physics Searches

Composite Leptons

Exotic Physics Searches

Status: July 2015

\( \sqrt{s} = 7 \text{ TeV} \)

\( \sqrt{s} = 8 \text{ TeV} \)

Black Holes
Gravitons
Quantum Gravity

New heavier
W and Z bosons

Dark Matter

4th Generation
Quarks

Composite Leptons and Quarks

Anything Else!

**Only a selection of the available mass limits on new states or phenomena is shown.**

Mass scale excluded by LHC data

I was involved in these searches with my PhD students

Mass range excluded by LHC data

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### ATLAS SUSY Searches - 95% CL Lower Limits

#### Status: July 2015

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\mu$, $\tau$, $\gamma$</th>
<th>Jets</th>
<th>$E_{\text{miss}}$</th>
<th>$M_{\text{L}}$ [TeV]</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td><strong>Direct</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>MSUGRA/CMSSM</td>
<td>0-3 $c,\mu,1-2 \tau$</td>
<td>2-10 jets/3 b</td>
<td>Yes</td>
<td>20.3</td>
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<td>GMSB ($\ell$ NLS)</td>
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<td>1.34 TeV</td>
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<td>1$\tilde{g}$, $1\tilde{g}$</td>
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<td>2-3 jets</td>
<td>0.3</td>
<td>Yes</td>
<td>5.75 GeV</td>
</tr>
<tr>
<td>1$\tilde{g}$, $1\tilde{g}$</td>
<td>0</td>
<td>2-3 jets</td>
<td>0.3</td>
<td>Yes</td>
<td>6.75 GeV</td>
</tr>
<tr>
<td>1$\tilde{g}$, $1\tilde{g}$</td>
<td>0</td>
<td>2-3 jets</td>
<td>0.3</td>
<td>Yes</td>
<td>7.75 GeV</td>
</tr>
<tr>
<td>1$\tilde{g}$, $1\tilde{g}$</td>
<td>0</td>
<td>2-3 jets</td>
<td>0.3</td>
<td>Yes</td>
<td>8.75 GeV</td>
</tr>
<tr>
<td>1$\tilde{g}$, $1\tilde{g}$</td>
<td>0</td>
<td>2-3 jets</td>
<td>0.3</td>
<td>Yes</td>
<td>9.75 GeV</td>
</tr>
<tr>
<td>1$\tilde{g}$, $1\tilde{g}$</td>
<td>0</td>
<td>2-3 jets</td>
<td>0.3</td>
<td>Yes</td>
<td>10.75 GeV</td>
</tr>
<tr>
<td><strong>Indirect</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Long-lived particles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Composite Leptons and Quarks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Anything Else!</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Allowed mass range for new physics:**

- **Stop / sbottom indirect production:**
- **Stop / sbottom direct production:**
- **Slepton / chargino:**
- **Long lived / stable sparticles:**

---

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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1$\sigma$ theoretical signal.*

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### Eram Rizvi

The Next 20 Years of the LHC - QMUL Public Lecture - 2nd March 2016
Effect of increasing the collision energy from 8 TeV to 13 TeV

- Gluon-gluon interactions
- Quark-antiquark interactions
- Quark-gluon interactions

The Future

Ratios of LHC parton luminosities: 13 TeV / 8 TeV

- Factor 2 increase in production rate for new particle with mass $M_X = 0.1$ TeV
- Factor 10 increase in production rate for new particle with mass $M_X = 2$ TeV
- Factor 100 increase in production rate for new particle with mass $M_X = 4$ TeV
15th December 2015 ATLAS released first tranche of new results using run 2 data

Using 2015 data only
Analysis searching for new particle decaying to 2 photons
Small deviation at mass of ~ 750 GeV
Significance ~ 2 standard deviations probability of fluctuation ~ 5%

Same odds as throwing 4 heads in a row
What are we looking for?

\[ \begin{align*}
  e+e & \quad e+\mu & \quad e+\mu+2b+2\nu & \quad e+2\mu+\nu & \quad \mu+\mu \\
  e+j & \quad e+\mu+j & \quad e+2\tau+2b+3\nu & \quad e+2\mu+\nu & \quad \mu+j+\nu \\
  2e+3j & \quad 3e+3\nu+j & \quad 2\mu+2\tau+j & \quad 2\mu+2b \\
  e+\tau+2j & \quad e+2\tau+\nu+j & \quad \tau+\tau & \quad 2\mu+2j+2\nu \\
  e+2j+\nu & \quad 2e+\tau+2\nu+2j & \quad 2\tau+2b & \quad 2b+4j \\
  \gamma+e+\nu & \quad \gamma+\mu+\nu+2j & \quad \gamma+\tau+\nu & \quad 2b+2\nu \\
  \gamma+\gamma & \quad \gamma+c+\nu & \quad \gamma+2e+\nu & \quad 2b+2j \\
  \gamma+\nu & \quad 2\gamma+2j & \quad 2\gamma+2\mu+3j & \quad \gamma+b+2j \\
  \gamma+2j & \quad j+j & \quad j+\nu \\
\end{align*} \]
What are we looking for?

- Higgs boson
- $e+e$
- $e+\mu$
- $e+\mu+2b+2\nu$
- $e+2\mu+\nu$ (muon)
- $\mu+\nu$ (muon)
- $\chi_0^0$
- $e+j$ (jet)
- $e+\mu+j$
- $e+2\tau+2b+3\nu$
- $2\tau+2b$
- $2\mu+2\tau+2b$
- $2\mu+2b$
- $2\mu+2j+2\nu$
- $2\tau+2j+2\nu$
- $2\mu+2j+2\nu$
- $e+\tau+2j$
- $\tilde{\tau}$ (neutralino)
- $\tau+\tau$
- $Z'$
- $\chi_1^-$ (charged Higgs)
- $e+2j+v$
- $2e+\tau+2v+2j$
- $2\tau+2b$
- $2\tau+2j+2\nu$
- $2\mu+2j+2v$
- $e+\mu+2b+2\nu$
- $e+2\tau+2b+3\nu$
- $2\mu+2\tau+2b$
- $2\mu+2j+2v$
- $e+\mu+3\nu$
- $e+\mu+\tau+3\nu$
- $e+\mu+\tau+2\nu$
- $e+\mu+\nu$
- $e+\mu+2\nu$
- $e+2\tau+2b+3\nu$
- $e+2\mu+\nu$
- $e+2\tau+2b+3\nu$
- $e+3\nu+j$
- $2e+3j$
- $2\gamma+2j$
- $2\gamma+2\mu+3j$
- $\gamma+2e+\nu$
- $\gamma+2\nu$
- $\gamma+\nu$
- $\gamma+\mu+2\nu$
- $\gamma+\mu+\nu$
- $\gamma+\mu+\tau+2\nu$
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- $\gamma+c+\nu$
Large increases in intensity
Requires significant changes to LHC magnets
Higher intensity means faster degradation of experiments

- \( \sqrt{s} = 7 \text{ TeV} \)
  \( \mathcal{L} \sim 5 \text{ fb}^{-1} \)

- \( \sqrt{s} = 8 \text{ TeV} \)
  \( \mathcal{L} \sim 20 \text{ fb}^{-1} \)

- \( \sqrt{s} = 13 \text{ TeV} \)
  \( \mathcal{L} \sim 100 \text{ fb}^{-1} \)

- \( \sqrt{s} = 14 \text{ TeV?} \)
  \( \mathcal{L} \sim 300 \text{ fb}^{-1} \)

- \( \sqrt{s} = 14 \text{ TeV?} \)
  \( \mathcal{L} \sim 3000 \text{ fb}^{-1} \)

Peak LHC Intensity

\( \mathcal{L} = \text{Total amount of data collected} \)

LS = Long Shutdown for repairs and upgrades

Year End
In 2023 LHC will shutdown for 2 years
Upgrade machine/magnets to provide more data (luminosity)
Magnets accelerate, bend and focus the beams

Protons collide in ‘bunches’ every 25ns
Can gain luminosity by rotating bunches
Use superconducting ‘crab cavities’

Require better magnets to focus proton beams at collision points → more interactions!

New high performance superconducting magnets needed all around LHC ring
Magnetic field 8T → 12 T

Upgrade cryogenics systems to keep magnets cold

simulation of proton beams merging & separating inside ATLAS
Current LHC operation yields typically 23 overlapping collisions every 25ns.

Large flux of particles in 10 years of operation causes damage to detector, for example: silicon wafer crystal structure is deformed and electrical properties degraded.

Future LHC operation will yield typically 200 overlapping collisions every 25ns!!!

ATLAS will entirely replace inner tracker in 2023.

Upgrade ‘trigger electronics’ to select interesting collision events online to record to disk for offline analysis.

Queen Mary group strongly involved in both efforts.
Summary & Conclusions

• Run 2 restarts in April - expect 100 fb$^{-1}$ by 2018 (five times more data than now)
• By 2023 we will have 300 fb$^{-1}$ — allows us to search for rarer processes
• Many new physics models still to be tested
• Experimental data is the final arbiter of truth!
• Some models appear contrived....
• ... but nature is weird (who could have predicted quantum mechanics?)
• Nevertheless, we should continue to look because we can!
• The ‘holy grail’ of quantum gravity may be experimentally within reach
• Plenty more work to be done

The Game is On!
# The Standard Model - Quarks & Leptons

### Quarks

<table>
<thead>
<tr>
<th>Quark</th>
<th>Symbol</th>
<th>Mass (MeV/c²)</th>
<th>Electric Charge</th>
<th>Weak Charge</th>
<th>Colour Charge</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>down</td>
<td>d</td>
<td>2</td>
<td>(-\frac{1}{3})</td>
<td>yes</td>
<td>yes</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>up</td>
<td>u</td>
<td>5</td>
<td>(+\frac{2}{3})</td>
<td>yes</td>
<td>yes</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>strange</td>
<td>s</td>
<td>100</td>
<td>(-\frac{1}{3})</td>
<td>yes</td>
<td>yes</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>charm</td>
<td>c</td>
<td>1300</td>
<td>(+\frac{2}{3})</td>
<td>yes</td>
<td>yes</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>bottom</td>
<td>b</td>
<td>4300</td>
<td>(-\frac{1}{3})</td>
<td>yes</td>
<td>yes</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>top</td>
<td>t</td>
<td>173000</td>
<td>(+\frac{2}{3})</td>
<td>yes</td>
<td>yes</td>
<td>(\frac{1}{2})</td>
</tr>
</tbody>
</table>

Quarks interact through all three quantum forces:
- Electromagnetism
- Weak force
- Strong force

All matter particles (quark and leptons) have spin \(\frac{1}{2}\).

### Leptons

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Symbol</th>
<th>Mass (MeV/c²)</th>
<th>Electric Charge</th>
<th>Weak Charge</th>
<th>Colour Charge</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>e</td>
<td>0.5</td>
<td>-1</td>
<td>yes</td>
<td>no</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>(\nu_e)</td>
<td>&lt;10^{-5}</td>
<td>0</td>
<td>yes</td>
<td>no</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>muon</td>
<td>(\mu)</td>
<td>106</td>
<td>-1</td>
<td>yes</td>
<td>no</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>muon neutrino</td>
<td>(\nu_\mu)</td>
<td>&lt;10^{-1}</td>
<td>0</td>
<td>yes</td>
<td>no</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>tau</td>
<td>(\tau)</td>
<td>1780</td>
<td>-1</td>
<td>yes</td>
<td>no</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>tau neutrino</td>
<td>(\nu_\tau)</td>
<td>&lt;0.3</td>
<td>0</td>
<td>yes</td>
<td>no</td>
<td>(\frac{1}{2})</td>
</tr>
</tbody>
</table>

Leptons interact through one or two quantum forces only:
- Weak force
- Electromagnetism (not neutrinos)

The values of the weak charge and colour charge are known but not important for our discussion.
The Standard Model - Bosons

<table>
<thead>
<tr>
<th>boson</th>
<th>symbol</th>
<th>mass MeV/c²</th>
<th>electric charge</th>
<th>weak charge</th>
<th>colour charge</th>
<th>spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>photon</td>
<td>γ</td>
<td>0</td>
<td>0</td>
<td>no</td>
<td>no</td>
<td>1</td>
</tr>
<tr>
<td>W±</td>
<td>W</td>
<td>80400</td>
<td>$-\frac{1}{3}$</td>
<td>yes</td>
<td>no</td>
<td>1</td>
</tr>
<tr>
<td>Z</td>
<td>Z</td>
<td>91200</td>
<td>$\frac{2}{3}$</td>
<td>yes</td>
<td>no</td>
<td>1</td>
</tr>
<tr>
<td>gluons</td>
<td>g</td>
<td>0</td>
<td>0</td>
<td>no</td>
<td>yes</td>
<td>1</td>
</tr>
<tr>
<td>Higgs</td>
<td>h</td>
<td>125000</td>
<td>0</td>
<td>no</td>
<td>no</td>
<td>0</td>
</tr>
</tbody>
</table>

- photon cannot interact with itself (electric charge = 0)
- W/Z bosons can interact with each other (they have weak charge)
- W bosons can interact with photons (they have electric charge)
- gluons can interact with each other (they have colour charge)

- Aside from mass, the higgs boson has the quantum numbers of the vacuum i.e. all zero!

all force carrying particles have spin 1
Aim to unify all forces

At high energy/momentum ($Q$):

masses $M_W$ & $M_Z$ are small

forces are $\sim$ equal

Eram Rizvi

The Next 20 Years of the LHC - QMUL Public Lecture - 2\textsuperscript{nd} March 2016
The Exchange Model

large angle scattering

Momentum is transferred between particles A and B

In some cases particles can even exchange identity!

The interaction must:
- exchange momentum
- exchange electric charge?
The Exchange Model

Weak force is responsible for $\beta$ decay
quarks emit heavy $W$ particle which decays

An exchange particle is forbidden
violates energy-momentum conservation

Particle cannot emit anything in its own rest-frame

Saved by the Heisenberg Uncertainty Principle:

$$\Delta E \Delta t > \hbar$$

Small energy $\Delta E$ can be ‘borrowed’ for a time $\Delta t = \hbar / \Delta E$ !

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?
$c \Delta t = 10^{-3}$ fm & $\Delta E = mc^2$

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

So $m = 100,000$ MeV/c$^2$
100 times proton mass!

But we don’t understand why $W,Z$ are heavy and photon is massless! ....
Feynman Diagrams

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

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

in case you don’t believe me...

For electromagnetism \( \alpha_{EM} = 1/137 \sim e^2 \)
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!
Reminder from last week:
Quantum fluctuations affect all reaction rate measurements
Effects are subtle but measurable
Consider $e^{-}$ scattering process:

\[ e^{-} + H \rightarrow e^{-} = \alpha^0 + \alpha^1 + \alpha^2 + \alpha^3 + \alpha + \ldots \]

Measure electron scattering off Higgs
(ignoring missing lower part of diagram!)

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

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 loop effects

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

Quantum loop fluctuations affect a “bare” particle mass resulting in different but experimentally measurable mass
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 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 minimum energy

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

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

Each $W$ can decay to $e\nu$, $\mu\nu$, $\tau\nu$, $qq'$ (x3x3)

Each $Z$ can decay to $ee$, $\mu\mu$, $\tau\tau$, $qq$ (x6x3)
Many possible Higgs decay modes/channels:

- **H → ZZ**
  - ZZ → 4l (4 lepton golden mode)
  - ZZ → llμν (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!

At LHC Higgs is produced via a loop
Higgs Hunting

\[ \begin{align*}
\text{\small \text{Eram Rizvi}} & \hspace{1cm} \text{The Next 20 Years of the LHC - QMUL Public Lecture - 2nd March 2016} \\
\end{align*} \]
At the LHC, the probability of detecting a Higgs boson-like particle is assessed using the profile likelihood ratio. The observed excess corresponds to a significance of 4.9 standard deviations for the Higgs boson mass hypothesis of 126 GeV. The contributions from the di-photon and diboson channels can be seen in the figure, with the di-photon channel providing the strongest evidence. The search for Higgs bosons is ongoing, with new data at 8 TeV expected to further refine the results.
Feynman Diagrams

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

Draw all possible Feynman diagrams for your experiment:

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

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

Feynman Rules: start from left side

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

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

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

$|M_{fi}|^2 = \frac{e^4}{4} \sum_{\text{spin}} \{[\bar{u}(k')\gamma^\mu u(k)] [\bar{u}(k')\gamma^\nu u(k)]^*\} \{[\bar{u}(p')\gamma_\mu u(p)] [\bar{u}(p')\gamma_\nu u(p)]^*\}$

Simplest interaction is single boson exchange

More complicated loop diagrams also contribute

Potentially infinite series of diagrams for $2 \rightarrow 2$ scattering process

If perturbation is small i.e. $\alpha < 1$ then contributions from extra loop diagrams is suppressed

The propagator - transfers momentum further a boson is from it’s mass $m$ the more suppressed the interaction

reaction rate / probability $\propto |M_{fi}|^2$
current LHC operating energy

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 μs
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” (~0.1mm) 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!!!
Collision produces complex state as horizon forms
Not all energy is trapped behind horizon

Extremely short lifetime \( \sim 10^{-25} \) s

Balding
Energy lost as BH settles into 'hairless' state

Evaporation
Thermal Hawking radiation in form of SM particles & gravitons
Greybody factors give emission probabilities for all particles

Plank Phase
For \( M_{BH} \sim M_D \) unknown quantum gravity effects dominates. BH left as stable remnant or final burst of particles ????
Collision produces complex state as horizon forms
Not all energy is trapped behind horizon
Extremely short lifetime $\sim 10^{-25}\,\text{s}$

On Feb 11\textsuperscript{th} 2016 the LIGO experiment announced discovery of gravitational waves
They observed two astrophysical black holes collide & merge 410 Mpc away (1 billion light years!)
Waveform of the gravity wave tells us about dynamics of the system
Ringdown is high frequency part of waveform
In this step irregularly shaped merged black hole sheds energy and stabilises
This is equivalent to ‘balding phase’ of a microscopic black hole
Searching for new physics is like searching for the Loch Ness Monster:
If you observe the Loch for 24 hours and see nothing, then either:
a) Nessie doesn’t exist
b) camera has poor efficiency for spotting animals (larger than 2m long)
c) Nessie exists but comes to the surface less than once per day
Must exclude (b) and (c) before we can conclude (a)!

In searches a model predicts a reaction rate
If you observe no such reaction rate (i.e. zero collisions) then
you can calculate upper limit on allowable reaction rate

Carefully consider your detector’s efficiency in observing similar collisions

Do you understand background processes that mimic the signal you’re looking for?

We found nothing so far...
Particle trajectories from single bunch crossing
25 collisions occurred all overlapping
ATLAS can reconstruct 25 separate interaction points
Only 1 collision is interesting - has much higher energy particles than other collisions