The Standard Model, the Higgs and beyond

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My life as a boson: by Professor Peter Higgs
http://www.swan.ac.uk/media-centre/livestreaming/higgs-boson/

Based in part on lectures by Professor Graham Ross

Visit www.cp3-origins.dk for various lectures and info

Nordita Master Class in Physics July-August 2012
2 bumps

\[ H \rightarrow \gamma \gamma \]

Selected diphoton sample

- Data 2011 and 2012
- Sig + Bkg inclusive fit \( m_H = 126.5 \text{ GeV} \)
- 4th order polynomial

\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 4.8 \text{ fb}^{-1} \]

\[ \sqrt{s} = 8 \text{ TeV}, \int L dt = 5.9 \text{ fb}^{-1} \]

**ATLAS Preliminary**

\[ H \rightarrow ZZ^{(*)} \rightarrow 4l \]

**ATLAS** Preliminary

- Data
- Background ZZ
- Background Z+jets, \( t\bar{t} \)
- Signal \( m_H = 125 \text{ GeV} \)
- Signal \( m_H = 150 \text{ GeV} \)
- Signal \( m_H = 190 \text{ GeV} \)
- Syst.Unc.
What is the world made of?

Visible Matter ~ 5%

Dark Matter ~ 25%

Dark Energy (?) ~ 70%

See lectures by Elgarøy for discussions of dark matter and dark energy
What is the world made of?

Two outstanding problems of the Standard Models of particle physics and cosmology:

What is the origin of mass? What is the nature of Dark Matter?

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Dark Matter ~ 25%

Dark Energy ~ 70%
What is the world made of?

Two outstanding problems of the Standard Models of particle physics and cosmology, to do with mass:

What is the origin of mass? What is the nature of Dark Matter?

Visible matter ~ 5%

Dark Matter ~ 25%

Dark Energy ~ 70%

No obvious particle physics scale associated with the problem of dark energy

Many proposed particle physics scales associated with the nature and origin of DM

A definite particle physics scale related to (part of!) the origin of mass, i.e. Higgs-mechanism

...though not necessarily the Higgs boson!
What is the world made of?

Two outstanding problems of the Standard Models of particle physics and cosmology, to do with mass:

**What is the origin of mass?**

**What is the nature of Dark Matter?**

- Visible matter \(\sim 5\%\)
- Dark Matter \(\sim 25\%\)
- Dark Energy \(\sim 70\%\)

In these lectures we will discuss the SM describing the visible matter in the universe, and the origin of mass for the SM particles – the Higgs mechanism.
The SM, the Higgs and beyond

Tentative Outline

• Lecture 1 – Fundamental particles and interactions, Higgs teaser
• Lecture 2 - Symmetries, Quantum Field Theory, Gauge Theory
• Lecture 3 - The SM, the Higgs Mechanism of the Standard Model
• Lecture 4 – Beyond the SM, curing the ills of the SM Higgs boson?

The accompanying notes and exercises, which you should work through will provide the details omitted in the lecture slides
The Standard Model on a stamp

The standard model
Elementary particles

Quarks
- $u$: up
- $c$: charm
- $t$: top
- $d$: down
- $s$: strange
- $b$: bottom

Leptons
- $\nu_e$: electron neutrino
- $\nu_\mu$: muon neutrino
- $\nu_\tau$: tau neutrino
- $e$: electron
- $\mu$: muon
- $\tau$: tau

Force carriers
- $\gamma$: photon
- $W^+$: W boson
- $Z^0$: Z boson
- $g$: gluon

Quarks

U(1)

SU(2)

SU(3)

\[ \begin{align*}
\text{Strong} & \quad \alpha_s = \frac{g_s^2}{4\pi\hbar c} \sim 1^† \\
\text{Electromagnetic} & \quad \alpha_{em} = \frac{e^2}{4\pi\hbar c} \sim \frac{1}{137} \\
\text{Weak} & \quad G_F m_p^2 \sim 10^{-5}\dagger \\
\text{Gravitational} & \quad G_N m_p^2 \sim 10^{-36}
\end{align*} \]

\[ \dagger \text{Short range} \quad \text{(Do you know why?)} \]

4 known Fundamental Interactions

Source: AAAS

*Yet to be confirmed
The Standard Model

Each particle defined by a few charges or quantum numbers:

- **U(1)** Electric-, weak-, strong charge, mass and in addition spin.

- **SU(2)** For each charge there is a corresponding force acting on the charge – described by a gauge theory

- **SU(3)** Matter particles are spin-1/2

- **SU(3)** Force particles are spin -1

*Higgs Boson* in the SM is spin-0

**Fundamental Interactions**

**Strength**

- **Strong – SU(3)** \( \alpha_s = \frac{g_s^2}{4\pi\hbar c} \approx 1^{1+} \)
- **EM – U(1)** \( \alpha_{em} = \frac{e^2}{4\pi\hbar c} \approx \frac{1}{137} \)
- **Weak – SU(2)** \( G_F m_p^2 \approx 10^{+5} \)
- **Gravitational** \( G_N m_p^2 \approx 10^{-36} \)
### The Periodic Table

**Leptons**

<table>
<thead>
<tr>
<th></th>
<th>(e)</th>
<th>(\nu_e)</th>
<th>(d)</th>
<th>(u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV)</td>
<td>0.511</td>
<td>&lt; 0.000003</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>106</td>
<td>&lt; 0.2</td>
<td>120</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>1777</td>
<td>&lt; 20</td>
<td>4300</td>
<td>175,000</td>
</tr>
</tbody>
</table>

| Charge | -1 | 0 | -1/3 | 2/3 |

**Quarks (each in 3 “colors”)**

Terms:
- **Particles like the electron** (fermions, spin 1/2)
- **Particles like the photon** (bosons, spin 1)

**Note:**
- “electromagnetism”
- “strong interaction”
- “weak interaction”
Forces

Can we understand forces as particle exchange classically?
Forces

Can we understand forces as particle exchange classically?

Repulsive force as particle exchange:

What about an attractive force?
The strength of the force

Electromagnetism

\[ V_{em}(r) = \frac{e_1 e_2}{4\pi} \frac{1}{r} \]

In momentum space:

\[ V_{em}(|q|) \sim \int V_{em}(|r|) e^{-i k \cdot r} d^3r \sim \frac{\alpha}{|k|^2} \]
Exchange forces

Electromagnetism

\[ V_{em}(r) = \frac{e_1 e_2}{4\pi} \frac{1}{r} \]

Experiments conducted in momentum space:

\[ V_{em}(|q|) \sim \int V_{em}(|r|) e^{-i k \cdot r} d^3 r \sim \frac{\alpha}{|k|^2} \]

\[ Q^2 \equiv -k^2 \]

"virtual photon"
Application to a scattering process

\[ e^+ e^- \rightarrow \mu^+ \mu^- \]

\[
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 E_{CM}^2} |M|^2
\]

Feynman diagram

\[ QM : \text{Transition amplitude} \quad <\text{final state}|H_I|\text{initial state}> \]

\[
M \propto <\mu^+\mu^-|H_I|\gamma>^\alpha <\gamma|H_I|e^+e^->^\alpha
\]

\[
<\gamma|H_I|e^+e^->^\alpha \propto e (0,1,i,0)
\]

\[
<\mu^+\mu^-|H_I|\gamma>^\alpha \propto e (0,\cos\theta,i,\sin\theta)
\]

\[
M (RL \rightarrow RL) = e^2 (1 + \cos \theta)
\]
The Standard Model

Each particle defined by a few charges or quantum numbers:

- \( U(1) \): Electric-, weak-, strong charge, mass and in addition spin.
- \( SU(2) \): For each charge there is a corresponding force acting on the charge – described by a gauge theory.
- \( SU(3) \): Matter particles are spin - 1/2
  - Force particles are spin - 1
  - Higgs Boson in the SM is spin - 0

Fundamental Interactions

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Force Carriers</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong - ( SU(3) )</td>
<td>( \alpha_s = \frac{g_s^2}{4\pi\hbar c} \sim 1^{1\dagger} )</td>
<td></td>
</tr>
<tr>
<td>Electromagnetic - ( U(1) )</td>
<td>( \alpha_{em} = \frac{e^2}{4\pi\hbar c} \sim \frac{1}{137} )</td>
<td></td>
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<tr>
<td>Weak - ( SU(2) )</td>
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<td>Gravitational</td>
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Higgs Boson looks special but more generally Mass is a special charge!... can you give a reason why?
Mass and the elementary particles

i) There is no anti-charge for mass!
   But here we completely neglect gravity which is unimportant for elementary particle processes and we don't have a quantum theory of gravity...there's plenty to do!
Mass and the elementary particles

i) There is no anti-charge for mass!
   But here we completely neglect gravity which is unimportant for elementary particle processes and we dont have a quantum theory of gravity...theres plenty to do!

ii) There is another peculiar feature of mass in a quantum theory:
    Scattering of massive spin one-states:

Do you remember any spin-1 states (Lorentz vector) from classical or quantum physics? How many degrees of freedom? How many physical degrees of freedom does a massless spin-1 field have? How about a massive spin-1 vector. Can you explain why?
Scattering of massive W-bosons

\[
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 E_{\text{CM}}^2} |M|^2
\]

QM: Transition amplitude

\[
M \propto \langle W^+W^- | H_I | W^+W^- \rangle
\]

\[
M(W_L^+W_L^- \rightarrow W_L^+W_L^-) \sim \frac{E^2}{m_W^2}
\]

Where \( E \) is the energy...what does this imply for High energy scatterings such as at LHC?
Scattering of massive $W$-bosons

$W_L^+ \rightarrow W_L^- + W_L^+$

$Q M$ : Transition amplitude

\[
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 E_{CM}^2} |M|^2
\]

$M \propto <W^+W^- | H_I | W^+W^- >$

$M(W_L^+W_L^- \rightarrow W_L^+W_L^+) \sim E^2 / m_W^2$

Where $E$ is the energy...what does this imply for High energy scatterings such as at LHC?

 Either $QM$ breaks down or we discover something new at LHC...seems that we already are starting to see it
The Higgs mechanism

*Gauge theories* do not suffer from the *unitarity* problem, spin-1 gauge fields are massless

In fact we take *gauge symmetry* as a fundamental symmetry of the SM. However, the *W/Z Bosons are still observed to be massive*

The way out is to invoke the Higgs-mechanism and mass as an emergent phenomenon via *Spontaneous symmetry breaking*

We will (hopefully) see towards the end how the Higgs boson can unitarize WW scattering
Consider a theory with a real scalar field $\phi(x,t)$ (you can think of it just as a classical particle. Next lecture will introduce Quantum Field Theory)

$$V(\phi) = \mu^2 \phi^2 + \frac{1}{2} \lambda^2 \phi^4$$

What symmetry, i.e. a non-trivial transformation of $\phi(x,t)$ leaves the potential invariant?:

$$P : \phi \rightarrow \phi' ; \quad V(\phi) = V(\phi')$$
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The Higgs mechanism - teaser

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This is our first example of *Spontaneous symmetry breaking or the Higgs mechanism*
The Higgs mechanism - teaser

Now consider the same theory coupled to another field $\psi$ via

$$V(\phi) = \mu^2 \phi^2 + \frac{1}{2} \lambda^2 \phi^4 + \frac{1}{2} \psi^2 \phi$$

To do perturbation theory in the broken phase we expand $\phi = v + \delta \phi$

$$V(\phi) \rightarrow \frac{1}{2} \psi^2 v + \ldots$$

The field $\psi$ has acquired a mass!

This is our first example of Spontaneous symmetry breaking and the Higgs mechanism

$\nu$ is a ‘preferred direction’ in field space – compare alignment of magnets, Hansson’s lecture
It turns out that there is one essential feature need for the SM Higgs mechanism that our toy model does not capture – *Goldstone bosons*

Our example was of spontaneous breaking of a *discrete symmetry* we need to consider. Spontaneous breaking of a *continuous symmetry*

**Goldstone’s Theorem:**

*For every spontaneously broken global continuous symmetry there will be an associated massless particle*
Goldstone Theorem - examples

This is simpler than it might sound!
What are the symmetries before and after we bend a (nearly) rigid rod attached at both ends?

Can you identify a ‘massless excitation’ existing after but not before symmetry breaking?
Goldstone Theorem

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What are the symmetries before and after we bend a (nearly) rigid rod attached at both ends?

Can you identify a ‘massless excitation’ existing after but not before symmetry breaking?

What about water freezing to ice, can you identify a ‘massless excitation’ there?

Generally related to phase transitions as in Hansson’s lectures –
What drives the Higgs mechanism? -> Beyond the Standard Model!
Goldstone Theorem

Goldstones Theorem:
For every *spontaneously broken* *global continuous* symmetry there will be an associated *massless* particle

The Higgs Mechanism:
If the spontaneously broken global symmetries are *gauged* the corresponding gauge fields will acquire mass.

In fact the longitudinal mode of those gauge fields ‘are’ the Goldstone bosons which are *eaten*

All of these statements and toy examples are what we now aim to concretize in the SM Quantum Field Theory and beyond!