A History of the Standard Model

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Preamble

• What is the Standard Model?

• How were fundamental particles first motivated?

• Key experimental discoveries

• The future
The Standard Model

- The standard model of particle physics is the mathematical theory which describes how matter is composed from its ‘building block’ particles
- And how these particles interact with one another
- Interactions can be forces (pushes and pulls) and also more subtle e.g. decay of unstable particles
Standard Model Lagrangian
New fundamental particles?

- A ‘zoo’ of new particles discovered in cosmic rays having different properties to p, n and e⁻
- $\Omega^-$ predicted by Murray Gell-Mann prior to its discovery by looking at mathematical patterns
Discovery of Quarks

- Discovered in 1968 at SLAC using high energy electrons to probe matter at a deeper level

- Similar to Rutherford’s alpha particle scattering experiment
• Quarks and leptons are ‘building blocks’ of all matter
• Stable matter formed from u, d, e
• All the rest form unstable particles which decay
Success of the Standard Model

- From 1970s onwards, particle physics experiments have made measurements which agree with theoretical predictions of Standard model.

- LEP Collider (1989-2000) tested many of these prediction to exquisite precision - 1 part in 1 million.
**Discovery of W and Z particles**

- Electroweak unification predicted the existence of three vector bosons (force carriers): $W^\pm$, $Z^0$, and $\gamma$

- Existence demonstrated in proton-anti-proton collisions in UA1, UA2 experiments on SPS collider in 1982
**LEP – a factory making Z⁰s**

**Z line shape**

**Moriond 1990:**

\[ m_Z = 91171 \pm 12 \pm 32 \text{ (incl. } \Delta E_{\text{LEP}}) \text{ MeV} \]
\[ \Gamma_Z = 2538 \pm 26 \pm 28 \text{ MeV} \]
\[ N_{\nu} = 3.04 \pm 0.12 \]

*first evidence 3 generations*

**Now:**

\[ m_Z = 91187.5 \pm 2.1 \text{ MeV} \]
\[ \Gamma_Z = 2495.2 \pm 2.3 \text{ MeV} \]
\[ N_{\nu} = 2.9841 \pm 0.0083 \]
SM part of a bigger theory?

- Unsatisfactory aspects to SM e.g.
- Why are the 3 generations of quarks and leptons?
- What (or Who) sets the 19 free parameters?
- WHY do the particles have a mass?
The Higgs Mechanism

• A room is full of physicists ...

• A famous person enters the room, and walks among them

• Physicists cluster round him and he acquires mass
The Higgs Mechanism

• This time a rumour is spread around the room

• it creates the same kind of clustering, but this time among the scientists themselves
The God Particle

• The Higgs boson has been called the ‘God Particle’ as it gives the building block particles their characteristic masses

• First glimpses seen in experiments at CERN in 2011 ...

• If the Standard Model is correct, the Higgs Boson *had* to exist
Discovery of Higgs Boson 2012

• Build the most powerful **accelerator** ever and smash particles (protons) together with enough energy to produce it
• Build the biggest ever **experiments** (detector) surrounding the interaction point to detect the products of the collision
• These don’t include Higgs Boson itself...
• ...only remnants of its decay
• Large Hadron Collider (LHC)
• 100m underground
• 27km in circumference
• Accelerates protons to 7TeV
Experiments (Detectors)
Job of the experiment

- Provide raw data
- Which are read out via optical fibre and used by computer programs to reconstruct particle trajectories (TRACKERS) and assign energy deposits (CALORIMETERS)
• Charged particles cause ionisation – ‘hits’ reconstructed to fit trajectory
• Apply a magnetic field to measure momentum
• $p = BqR$
Calorimetry / Particle ID
How do we know if the Higgs Boson was there?

- Higgs itself is unstable so must look for decay products
- Must find a plausible group of tracks amongst many to identify candidates
- Can you reconstruct enough decays to give a statistically significant signal over a background of ‘fake’ Higgses?
Not as easy as it looks

- Simulated data (Monte Carlo=MC) lets you train your algorithms to see if they work
- ‘Truth’ tracks created (not the same set each time) then smeared to account for detector resolution
- Apply kinematical selection cuts to clean up the sample
- This rejects some real Higgs but a much higher proportion of ‘fake’ candidates
Can calculate the (invariant) mass of the Higgs candidates from momentum and energy of decay products; REAL Higgses should form a visible peak above background noise

Clean decay channels $H \rightarrow ZZ^* \rightarrow l^- l^+ l^- l^+$

High purity but low statistics

‘Noisier’ decay $H \rightarrow \gamma\gamma$

High statistics ‘bump’ hunting
$ATLAS$

$H \rightarrow ZZ^* \rightarrow 4l$

$\sqrt{s} = 7 \text{ TeV}: \int \Ldt = 4.5 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}: \int \Ldt = 20.3 \text{ fb}^{-1}$

- **Data**
- **Signal ($m_H = 124.5 \text{ GeV} \mu = 1.66$)**
- **Background ZZ**
- **Background Z+jets, $t\bar{t}$**
- **Systematic uncertainty**
The first hints of a bump...
More data → More reliable!

ATLAS

- Data
- Combined fit:
  - Signal+background
  - Background
  - Signal

Mass measurement categories

\[
\int L dt = 4.5 \text{ fb}^{-1} \quad \sqrt{s} = 7 \text{ TeV} \\
\int L dt = 20.3 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV}
\]
Neutrinos – Cosmic Messengers

- Theorized in 1930 (Pauli); $\bar{\nu}_e$ discovered 1956 (Reines)
- Technically, neutrinos are ‘building blocks’
- They also interact very weakly and so are not seen easily in experiments
- They are produced in abundance by the Sun’s nuclear fusion
- 100 billion of them pass through your thumbnail every second
- You don’t notice even them!
Beyond MSM – Neutrino Oscillations

• The Minimal standard model does not accommodate massive neutrinos
• Neutrinos actually change flavour in flight. This oscillation was first observed in 1960s but was not understood as such until 2001
• In special relativity, a particle moving at v=c is necessarily massless. Furthermore, it has no sense of the passage of time and therefore cannot oscillate
• When neutrinos were found to oscillate, this proved that they have mass
• Problem for MSM!
Supersymmetry remains just an interesting, if mathematically elegant, hypothesis right now. It would explain why particles have the masses they do and shed light on dark matter. Many versions of the theory suggest the LHC’s current experiments will be energetic enough to produce the heavier supersymmetric particles — if they exist.
Conclusion

• The standard model is a very successful theory, and many predictions have been accurately tested
• There are unsatisfactory aspects, and certain phenomena are excluded in the Minimal Standard Model
• Adjustments necessary to e.g. accommodate massive neutrinos and supersymmetric particles
• Much work still to be done – PhD anyone??