

Understanding the Fundamental Nature of the Universe using the ATLAS Detector at the LHC

Quarknet Workshop
NC A&T State University, Greensboro, NC

Mark Kruse

Professor and Director of Graduate Studies
Department of Physics, Duke University
<https://webhome.phy.duke.edu/~mkruse/>

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Overview

- Introductions
- Review of the SM – what it tells us, and what it doesn't
- Broad overview of the LHC and the ATLAS experiment
- The Higgs mechanism for fundamental mass generation
- Some recent results and future prospects

A bit about myself...

- Professor at Duke since 2001 (before that, grad student and postdoc working at Fermilab)
- Research in HEP, joined ATLAS in 2005
- Up until 2022 was US-ATLAS Outreach and Education Coordinator, and continue to be passionate about outreach and education

Key points:

- Particle physics, in addition to it's attempt to fundamentally understand why the universe (and us!) exists, teaches a large array of skills that can benefit a number of professional outcomes. Our students have been successful in teaching, finance, data mining, programming, and academic professions.
- Particle Physics provides an ideal gateway to inspire students to study physics.

The Standard Model of Particle Physics

- The theory that currently best describes our fundamental understanding of the universe is known as the **Standard Model**

- **Matter (fermions – spin 1/2):**

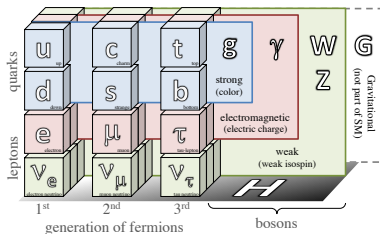
- ▶ **Quarks:** fractionally charged, constituents of mesons ($q\bar{q}$) and baryons (qqq)
- ▶ **Leptons:** charged (e, μ, τ) or neutral (ν 's)

- **Interactions (bosons – spin 1):**

- ▶ **gluons** are massless and mediate the strong interaction (act on **color charge**)
- ▶ **photon** is massless and mediates the EM interaction (acts on **electric charge**)
- ▶ **$W^\pm, Z$ bosons** are massive and mediate the weak interaction (act on **weak isospin**)
- ▶ **Interaction strengths:**

$\alpha_s = 1$	Strong interaction, short range
$\alpha = 10^{-2}$	EM interaction, long range
$\alpha_W = 10^{-6}$	Weak interaction, short range
$\alpha_G = 10^{-38}$	Gravitational interaction, long range

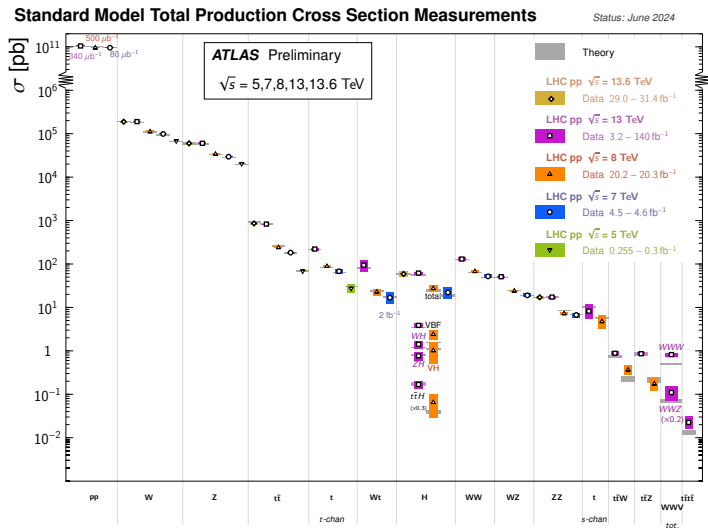
Fundamental constituents of the SM:



Intrinsic charges of fermions determine the interactions they experience.

The SM – experimental tests

So far, there has been no conclusive evidence contradicting the predictions of the SM



Despite its success, the SM has many open questions:

● Fundamental fermions:

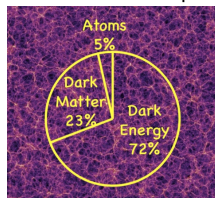
- ▶ Are they truly fundamental ?
- ▶ Why are there 3 generations ?
- ▶ Why are their masses (Higgs couplings) so different ?
- ▶ Are neutrinos Dirac or Majorana ?

● Fundamental interactions:

- ▶ Why do some symmetries and conservation laws not apply to all interactions ?
- ▶ Is Higgs sector really as simple as it seems ?
- ▶ **Gravity**: can it be included ? Is it fundamental ? Why so much weaker ?
- ▶ Are there other fundamental interactions, symmetries ?
- ▶ Can all the interactions be unified ? Should we believe this to be important ?

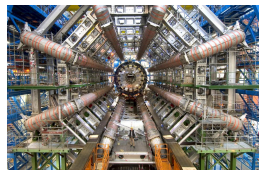
● Other questions:

- ▶ What is Dark Matter ?
- ▶ What is Dark Energy ?
- ▶ What caused matter-antimatter asymmetry ?



....and many more !!

Testing the SM: The Large Hadron Collider (LHC)



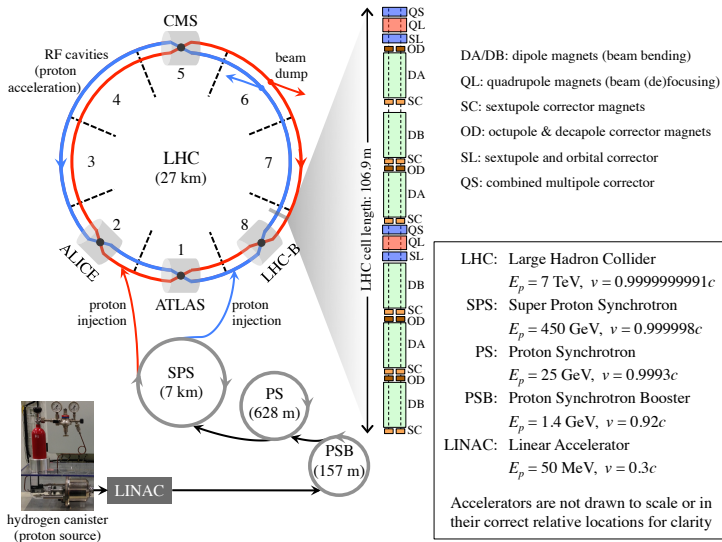
● Basic Idea:

Create the largest amount of energy technologically possible from controlled particle collisions in order to recreate some of the particles and phenomena that existed in the very early universe (less than a trillionth of a second after the Big Bang) to figure out what existed then, why, and how it affected the subsequent evolution of the Universe. That is, why we or anything exists!

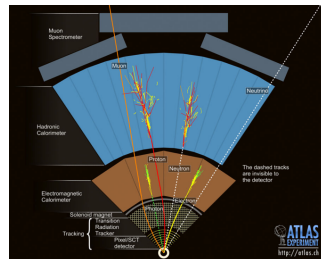
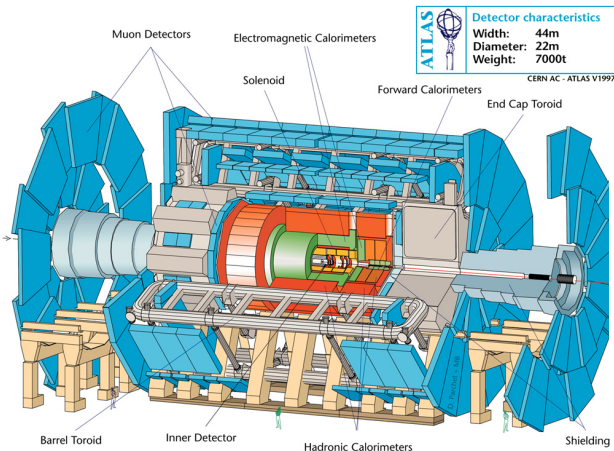
● Basic principles:

- ▶ Protons better than electrons
- ▶ Circular is better than linear
- ▶ Proton kinetic energy → mass/energy of new particles
- ▶ Electric fields accelerate protons, magnetic fields bend and focus them
- ▶ Bunches of ~ 10 billion protons (< 1 mm wide) are made to collide 40 million times a second in the centres of huge detectors (e.g. ATLAS) designed to record the resulting debris

The Large Hadron Collider



The ATLAS experiment

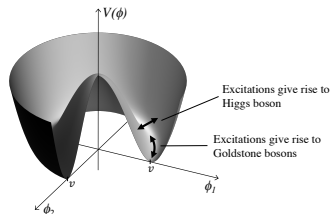


The Higgs mechanism and mass generation

- One of the great successes of the SM is the **unification** of the **weak** and **electromagnetic** interactions → **electroweak interaction**
- The **electroweak interaction** is described by:
 - ▶ **three massless bosons** that act on **T** (weak isospin), **W_1 , W_2 , W_3** , and
 - ▶ **one massless boson** that acts on **$Y = 2(Q - T_3)$** (weak hypercharge), **B**
- The **electroweak interaction** is described by a **Lagrangian** (essentially the sum of all the energy terms associated with the interaction) that possesses an **underlying symmetry**.
(Technical aside: in QFTs so-called gauge symmetries **require the existence of** interaction bosons – the electroweak interaction is described by a $SU(2)_L \otimes U(1)_Y$ symmetry)
- For the **$W^\pm$** and **Z^0** bosons to **have mass**, this underlying symmetry of the electroweak interaction (by which we really mean the underlying symmetry in the expression for the electroweak Lagrangian) **must be broken**
- In the mid-1960s it was found by **Robert Brout, Francois Englert, and Peter Higgs**, that the **simplest way** to do this was to add a potential energy term to the electroweak Lagrangian of the form: **$V(\phi) = a\phi^4 - b\phi^2$** , where **$\phi$** is a 4-dimensional (has 4 components) scalar field what we now call the **Higgs field**.

The Higgs mechanism and mass generation (cont.)

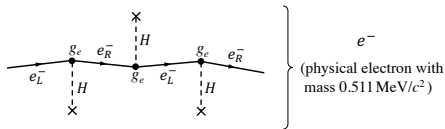
- **Relation between particles and fields:** In QFTs, fields are the fundamental entities and quantum fluctuations in these fields are what we are calling **particles** (roughly speaking)
- The Higgs potential introduces **four new scalar fields**, $\phi_1, \phi_2, \phi_3, \phi_4$, that correspond to **four new scalar (spin-0) bosons**: **one massive Higgs boson** and **three massless “Goldstone bosons”**
- **Stable fluctuations** can only occur at the vacuum expectation value (v , at the minimum of $V(\phi)$)
- In what is an almost miraculous collusion between the **three additional massless Goldstone bosons**, and the **massless electroweak boson fields**, the “degrees of freedom” afforded by the Goldstone bosons are now what we observe as the **masses of the W and Z bosons**.
- **This is often described in the following way:** the combinations of the W_1, W_2 fields that result in the $W^\pm$ fields, absorbed (or “ate”) two of the Goldstone boson fields that is now observed as the mass of the W^+ and W^- weak bosons. The combinations of the W_3 and B fields that lead to the Z^0 and photon fields ate the third Goldstone boson field that we now observe as the Z^0 mass, while leaving the photon field massless. **The way this works out mathematically is one of the triumphs of the SM**



The Higgs mechanism and mass generation (cont.)

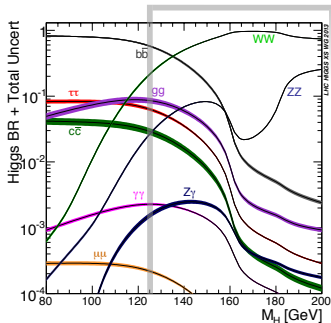
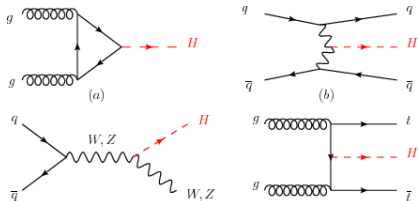
- EW symmetry breaking occurs at energies of order 1 TeV, corresponding to an age of the universe of around 10^{-13} s. At earlier times all particles in the universe were massless!
- As the universe expanded and cooled, this symmetry (in the electroweak Lagrangian) was broken by $V(\phi)$, leading to the massive Higgs boson and the massive $W^\pm$ and Z^0 from the Goldstone bosons associated with $V(\phi)$
- So, the Higgs fields are now mixed/absorbed by the electroweak boson fields to give what we observe today – separate Electromagnetic and Weak interaction fields, and the (single) Higgs field, for which the predicted particle manifestation is the Higgs boson, a massive scalar (spin-0) particle
- The Higgs field can also be used to generate the masses of the fundamental fermions
- The fermion masses are generated through their interactions with (or couplings to) the Higgs field. For example:

- The coupling g_e determines the observed particle mass
- Interaction with the Higgs field changes the handedness of the massless e_R and e_L states. Fundamentally: $\text{mass} = L \leftrightarrow R$ oscillations

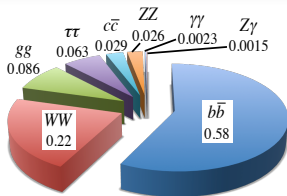


- However, we do not know why different fermions have different intrinsic Higgs couplings
- However fantastical this theory may seem at first, its main prediction, that of a neutral scalar (spin-0) Higgs boson, was discovered at the LHC in 2012!

Higgs Production and Decay at the LHC

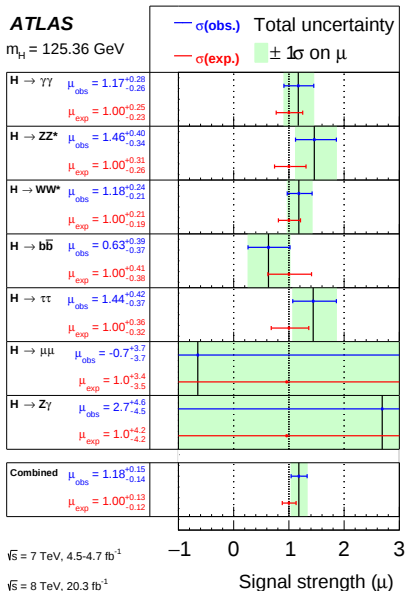


Higgs boson branching ratios for $M_H = 125 \text{ GeV}/c^2$



Higgs Results

- The Higgs discovery was made using the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ decay channels
- Has now been observed in various other decay channels
- Updated results from "Run 2" due out soon
- All still in agreement with the SM!!



Future Outlook

- Run 2 of the LHC will end next year, then after a 2-3 year shutdown for upgrades, Run 3 will start at slightly higher collision energy and greater luminosity
- Precision Higgs measurement will be an important priority, but also the first measurements of the Higgs self coupling, which will give us information about the shape of the Higgs potential (is it really as simple as assumed in the SM?)
- It's an interesting time in Particle Physics. We don't know how/when/if the SM will be broken, but new discoveries may be lurking just around the corner. Science usually advances when something completely unexpected is discovered!
- Thanks for your efforts to inspire future generations to continue the quest toward a fundamental understanding of our universe!