In Pursuit of Discovery at
The Large Hadron Collider

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An Introduction

• My name is Chris Neu
  – Experimental high energy physics
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  – I collaborate currently on 2 experiments:
    • CMS operating at CERN
    • CDF operating at Fermilab
  – My main interests:
    • The search, discovery and understanding of the Higgs boson
    • Detailed studies of the top quark
    • Searches for exotic new phenomena
What is Particle Physics?

Particle physics is the study of the fundamental building blocks of the universe and how those building blocks interact.

My overriding question:  What is the world made of?

Personal curiosity about how the world works. We have a pretty good handle on things, developed over the last 100 years.
The Standard Model

- Model states that the world is comprised of 2 types of particles, quarks and leptons.
- Quarks and leptons interact through 3 of the 4 known forces.
- Interactions are represented as the exchange of force-carrying bosons.
- Bound states of quarks are allowed – hadrons, like the proton.

Everyday matter around us is made entirely of u and d quarks and electrons.
An Example – Water

• $H_2O$ – Water is a molecule containing 2 hydrogen atoms and 1 oxygen atom

• proton = $uud$  
  neutron = $ddu$

• **hydrogen:** 1 proton = $2u$ quarks  
  1 $d$ quarks  
  1 electron

• **oxygen:** 8 protons = $2u$ quarks  
  1 $d$ quarks  
  8 neutrons = $1u$ quarks  
  2 $d$ quarks  
  8 electrons

$\Rightarrow H_2O$ is 28 $u$ quarks  
  26 $d$ quarks  
  10 electrons
The History of Discoveries

Quarks

Leptons

Forces


Christopher Neu
The History of Discoveries

One remaining piece to complete the puzzle

H: the Higgs boson -- the last piece of the standard model yet to be discovered.
The Electromagnetic and Weak Forces

**Feature:**
- Electromagnetic and Weak forces are unified

**Force carriers:**
- Photon massless
- $W, Z$ very massive
- Why?

**Higgs Mechanism:**
- Explains masses of $W, Z$
- Other particles interact with the Higgs field and acquire mass
- Additional consequence: new particle, the Higgs boson - *not yet discovered!*

1 GeV/c$^2 = 1.8 \times 10^{-27}$ kg = mass of 1 proton
Mass – What’s the Big Deal?

• Higgs boson credited with the “origin of mass”

• This is not the complete story
  – Most of the visible universe is protons and neutrons
  – Protons \((p)\) and neutrons \((n)\) are a bound state of \(u, d\) quarks (~3-8 MeV apiece)
  – The \(p, n\) masses (938 and 940 MeV) come mostly from the strong force holding the quarks together
  – Strong force proceeds with or without the Higgs

• However, what if the fundamental particles were massless?
  – If \(m_u = m_d = 0\), then \(M_{\text{proton}} > M_{\text{neutron}}\)
  – \(p \rightarrow ne^+\nu_e\) – This would be bad.
  – If \(m_e = 0\), the Bohr radius of atoms would be large
    • Chemistry as we know it would not exist! This too would be bad.
So how do we hunt for the Higgs?
The Large Hadron Collider: An Introduction

- The Large Hadron Collider (LHC) is a massive new particle accelerator located on the French-Swiss border near Geneva, Switzerland.

- The LHC will accelerate protons to nearly the speed of light and collide them together.

- Experimenters seek to use the LHC to explore the frontiers of human understanding of the fundamental world.

Located at CERN (Org. Européenne pour la Recherche Nucléaire)
- Geneva, Switzerland

We are at the threshold of an exciting new era.
The Large Hadron Collider

• Why the name?

“Large”

27 km (!) in circumference and ~100 m underground

“Hadron”

The LHC accelerates *protons*...and protons are categorized in particle physics* as *hadrons*

“Collider”

The LHC will SMASH the protons together!

* more on this in a bit
Collisions

• Orbits of the protons are mostly circular except...

• Four collision locations
  – Each location is equipped with independent experiments

• Collision energy:
  – proton with \( v = 99.999999\% \) of the speed of light \( \Rightarrow \)
    energy = 3,500,000,000,000 eV
    \( = 3.5 \text{ TeV} \)
  – \( \Rightarrow \) Collision: 3.5 TeV + 3.5 TeV = 7 TeV

So what? What is a TeV?
Collision Energy

• Each beam @ 3.5 TeV = 7 TeV (eventually go up by x2 to 14 TeV of energy)
• How much energy is this?
  – Really not that much
  – About the same as the kinetic energy of a flying mosquito BUT confined to a space 1,000,000 times smaller!
• Is this useful?
  – Yes, our old friend, Einstein, taught us $E=mc^2$
  – Energy can be transferred into the mass of new particles!
  – 14 TeV = highest energy ever achieved!
  – That’s why the LHC has to be so large…
The Large Hadron Collider: A Sense of Scale

The LHC has to be large in order to get the protons to such high energy.

How large is the LHC really?

4.3 km
The Large Hadron Collider: A Sense of Scale

Map of LHC Layout

The LHC has to be large in order to get the protons to such high energy.

How large is the LHC really?
The LHC has to be large in order to get the protons to such high energy.

How large is the LHC really?
The Large Hadron Collider: A Sense of Scale

How large is the LHC really? Big enough to fit entire UVa campus and much of CVille inside its ring!

The LHC has to be large in order to get the protons to such high energy.
So the LHC can make a Higgs….how do we observe it?
The Compact Muon Solenoid Experiment

- UVa collaborates on CMS
- One of 2 Higgs-hunting exp’s at the LHC
- Wide-ranging program of measurements and searches

Three-fold mission:

- **Confir**m what we think we already know
- **Probe** what we know we are missing
- **Search** for things yet only imagined

- Total weight: 12500 T
- Overall diameter: 15.0 m
- Overall length: 21.5 m
- Magnetic field: 4 Tesla
Detecting Particles: How It Is Done

How is a Higgs created?

Through its decay products!

How is a Higgs detected?
Detecting Particles: Challenges

• Okay, so this is simple, right?
  – 1. Accelerate protons in LHC
  – 2. Smash them together
  – 3. Use CMS to see the Higgs decay products, infer Higgs production
  – 4. Collect Nobel Prize

• Well….it is not so simple
  – Protons collide inside CMS 40 million times per second
  – Every 40 millionths of a second, more than one p-p collision occurs. Lots actually, 20 or more!
  – Electronics of the detector are still recording the previous collision when the next one occurs
  – Lots of mundane particles leave a decay signature JUST LIKE the Higgs
This is what we see:

And this is a (simulation of a) mundane event! Higgs events are just as complicated.

**Moral:**
This is going to be hard!

Discoveries at LHC are not a slam dunk and may take time.
Unsolved Mysteries

• We need to look for the Higgs to understand the important issue of mass
• However the Higgs is not the only potential for discovery at the LHC.
• Lots of other open questions in particle physics

A few things I find interesting:
– Standard Model does not include gravity, which is really weak in strength. *Why is gravity so weak?*
  • Hypothesis: *Yet-unseen extra dimensions of space time*

– 96% of the visible universe is made of entities that we cannot accommodate in the standard model
  *What the heck is the so-called *Dark Matter*?*
  • Hypothesis: *Additional new particles from Supersymmetry*

– What else is there? Is there any wild new stuff out there that *we’ve only dreamed of?*

Energy Density of the Universe

- = understood
- = dark matter
- = dark energy
LHC Timeline

• **Timeline:**
  – The idea for the LHC was hatched in the early 80s
  – Its experiments were conceived in the early 90s
  – Construction of the LHC began in 2001
  – Experiments designed and fabricated around the globe, assembled at CERN, over last 10 years
  – Last steering magnet delivered in April 2007
  – Detector construction ~complete mid 2008

• **First beam:** September 10, 2008
  – Followed by accident…
  – 13 month recovery

• **First beam redux:**
  November 20, 2009 – exciting at CERN

• **First collisions:**
  November 23, 2009

• **Record-breaking collision energy:**
  November 30, 2009 (overcame Fermilab Tevatron)
First LHC pp Collision at CMS
Celebration
Outlook for Students

• First collisions delivered late last year
• More coming …starting next week!
  – Beginning of a 18-24 month run at 7 TeV collision energy = lots of opportunities
• There’s so much to do!
  – Hardware:
    • Commission the CMS detector – Want to work at CERN? Want to live in Europe?
    • Fully characterize the performance of the CMS ECAL
    • Make the CMS ECAL ready for taking data
  – Data analysis:
    • Three-fold strategy:
      – Rapid results on early data – look at phenomena we already are familiar with
        » top quark production
        » $W+b$-jet
      – Results on my main interest in 2-3 years:
        » Higgs!
      – Longer-term results on exotics searches
Want to Know More?

• Exciting times are ahead in particle physics – *you can be a part of it*
  – Want to do research that *will change the way we understand the universe*?
  – The kind of stuff that will *force us to rewrite textbooks*?
  – Or even force us to rethink everything entirely?

• I have devised a research program on CMS that will provide for multiple PhD thesis topics over the next several years.

• **However spots are limited…** no guarantee of positions.

• If you are interested come see me!