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
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

• H₂O – Water is a molecule containing 2 hydrogen atoms and 1 oxygen atom

• proton = $uud$  neutron = $ddu$

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

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

$\Rightarrow$ H₂O is 28 $u$ quarks 26 $d$ quarks 10 electrons
The History of Discoveries

Quarks

- $u$, $c$, $t$, $d$, $s$, $b$

Leptons

- $e$, $\mu$, $\tau$, $\nu_e$, $\nu_\mu$, $\nu_\tau$

Forces

- $Z$, $\gamma$, $W$, $g$

Higgs boson

Timeline:

- 1884: $e$
- 1920: $\gamma$
- 1937: $\mu$
- 1950: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- 1956-1962: $u$, $d$, $s$
- 1956-1968: $c$, $b$, $g$, $W$, $Z$
- 1974-1978: $t$
- 1995-2000: $\nu_\tau$
- 2008: $H$
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!

GeV/c$^2$ is a unit of mass:
$1$ GeV/c$^2 = 1.8 \times 10^{-27}$ kg = mass of $1$ proton
The Higgs Boson: What Do We Know

![Graph showing m_W versus m_t with regions of 68% confidence level for Higgs boson mass (m_H) and the difference in the electron mass (Δm) at different m_t values.](image-url)
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
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 $= 7,000,000,000,000$ eV $= 7$ TeV
  - $\Rightarrow$ Collision: $7$ TeV + $7$ TeV = $14$ TeV

**So what? What is a TeV?**
Collision Energy

• Each beam 7 TeV = 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…

LHC = Giant Mosquito Collider?

![Graph showing luminosity vs. center-of-mass energy for different experiments including ISR, LEP1, LEP2, HERA, TeVatron, and SppS, with LHC at x7 and x100 compared to previous experiments.](image)
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?

4.3 km
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

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

Map of Charlottesville

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

How large is the LHC really?

Big enough to fit entire UVa campus and much of CVille inside its ring!
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:
- Confirm what we think we already know
- Probe what we know we are missing
- Search for things yet only imagined
Detecting Particles: How It Is Done

How is a Higgs created?

How is a Higgs detected?

Through its decay products!
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, up to 20.
  – 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
Colliding Beam Experiment

- Beam Energy
  - Luminosity
  - Bunches/Beam
  - Protons/Bunch

- 7x10^16 eV
- 10^{24} cm^2 s^{-1}
- 2835
- 10^{11}

- Bunch Crossing
  - 4 \times 10^7 Hz

- Proton Collisions
  - 10^8 Hz

- Parton Collisions

- New Particle Production
  - (Higgs, SUSY, ...)

- Selection of 1 event in 10,000,000,000,000,000

(the rest are less interesting)
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?
Intriguing Possibility

- Collisions could be so energetic that it is possible to create a *black hole*
Intriguing Possibility

• Collisions could be so energetic that it is possible to create a **black hole**

• **Before you run out of the room:**
  – Such a black hole would be **tiny** – unlike the supermassive black holes at the center of galaxies
  – Such a black hole **would not stick around for very long** – it would decay away very rapidly to a bunch of mundane familiar particles

  – **We are not in any danger**
    • Ultra-high energy cosmic rays bombard the Earth frequently, at collision energies much higher than that of the LHC
    • These cosmic rays (unknown in origin, interesting in their own right) have been around for billions of years
    • Since we have survived this long…even higher energy collisions have done no catastrophic damage
    • Hence the LHC’s meager collisions are not going to pose any significant threat
Intriguing Possibility

• Collisions could be so energetic that it is possible to create a black hole

• Before you run out of the room:
  – Such a black hole would be tiny – unlike the supermassive black holes at the center of many galaxies
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  – We have been around for billions of years and even higher energy collisions have done no catastrophic damage
  – Hence the LHC’s meager collisions are not going to pose any significant threat

A cool possibility though that could help our understanding of gravity and how these objects form.
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
  – Single beam complete orbit
  – A huge success! We threw a party
    10am GVA time = 4am here @ UVa

Lots of international press attention
First Beam Coverage

TIME's Best Inventions of 2008

5. The Large Hadron Collider

Protons and Champagne Mix as New Particle Collider Is Revved Up

by DENNIS OVERBEY Published: September 19, 2008

BATAVIA, Ill. — Science rode a beam of subatomic particles and a river of Champagne into the future on Wednesday. After 14 years of labor, scientists at the CERN laboratory outside Geneva successfully activated the Large Hadron Collider, the world's largest, most powerful particle collider and, at $8 billion, the most expensive scientific experiment to date.
Beam Incident – September 19, 2008

• Just 9 days later an electrical fault was discovered during tests to bring the LHC beam up to full energy

65,000 electrical joints are formed by induction-heated soldering and ultrasonic welding.

40,000 electrical cryogenic junctions with helium tightness

NOTE: on September 19, 2008 a fault developed in a connection between a dipole and quadrupole resulting in mechanical damage to some magnets.

3/11/09

Christopher Neu
LHC Schedule for First Collisions

• Damage caused by faulty electrical connection
• LHC shutdown to repair and inspect all other such connections
• Several magnets had to be brought to the surface for fixing

• Given the complexity of the series of machines it is not surprising that some hiccups will occur along the way
• Repairs and tests proceeding ahead of original schedule

• New schedule is for first colliding beams to occur at the LHC in October 2009!
  – A “long” initial run of ~1 year is planned…
  – Potentially enough data in this first year to see some spectacular things… if they are there!
Outlook for Students

• First collisions in October of this year
• 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 – Want to stay in Cville?
    • Make the CMS ECAL ready for taking data
  – Data analysis: can be done from anywhere: CERN, UVa, LPC@FNAL
    • 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
• Further afield: preparations for the Super LHC “SLHC”
  – Building the physics case for defining the CMS detector for the SLHC era
  – Photodetector R&D here at UVa
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.

• If you are interested come see me!