What Is This?
And how did we get here?
Two Paradigms of Particle Physics

Remarkable facts about the LHC

The LHC is the most powerful microscope ever constructed, able to see the smallest things ever seen by mankind!

... I can use the LHC to see new fundamental particles

Just as I can use a microscope to see cells....

The Higgs Boson

BACK TO THE BIG BANG:
INSIDE THE LARGE HADRON COLLIDER
How do you see what something is made of?

Answer: *Scattering.*
Scattering Diagram.

**Low Resolution**

Incoming projectile

Target

Outgoing projectile

Detector

Large wavelength, low energy, target looks like a big blob.

**High resolution**

Small wavelength, high energy, constituents of targets become visible

What’s wavelength?
Visible light is a tiny, tiny part of the electromagnetic spectrum. But only recently have we become aware of that.
Scattering Experiments

High Energy Collisions of Particles
- Microscope to Short Distances
- New Substructure and Forces

- Weak Interactions
  - Origin of Mass
    - New Symmetries, Dark Matter, Quantum Dimensions, …

logarithmic scale

1 metre
1 millimetre
1 micrometre
1 nanometre
1 picometre
1 femtometre
1 attometre
1 zeptometre
1 yoctometre

10^0 m
10^{-3} m
10^{-6} m
10^{-9} m
10^{-12} m
10^{-15} m
10^{-18} m
10^{-21} m
10^{-24} m
10^{-27} m
10^{-30} m
10^{-33} m
10^{-3} m

- person
- blood cell
- atom
- nuclear
- Origin of Mass
  - (New Symmetries, Dark Matter, Quantum Dimensions, …)

- Leptons
  - Quarks
- Force Carriers
- Three Generations of Matter
Unification of Particles and Forces

Atomic Scale
$10^{-10}$ m

Nuclear Scale
$10^{-15}$ m

Sub-Nuclear Scale
$10^{-18}$ m
What are things made of ~1900

- Dmitrii Mendeleev:
  Periodic Table of Elements.
  - Everything is made up of mixtures of pure elements (ATOMS).

- JJ Thompson:
  electron.
  - ATOMS can eject these small, negatively charged bits that are also the carrier of electric current.

- But why is helium 4 times heavier than hydrogen?
Picture of the Atom ~1900

Thompson plum pudding model of the atom

Negative electron plums

Positive pudding

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Rutherford Destroys the Plum Pudding Model

Note: Marsden was an undergraduate in Rutherford's lab
What Rutherford Expected

Projectiles (very fast He nuclei called *alpha particles*) will be slightly deflected by gold atoms.
What Rutherford Saw

Occasionally (rarely) the projectile scattered at huge angles. *What did this mean?*
The Early 20\textsuperscript{th} Century Atom

\textit{...like firing a 16” shell at a piece of tissue paper and seeing it bounce back.}
- E Rutherford.

- An atom's mass must be concentrated in a \textbf{small positively charged nucleus} as only a very small number of alpha particles either deflected or rebounded off the foil.
  - \textit{Atom: Yankee Stadium :: Nucleus: grain of sand.}

- Most of the atom must be \textbf{empty space}. This space must contain the electrons.
  - The electrons orbit the nucleus like planets around the sun.

- Nucleus found to be made of \textit{protons} and \textit{neutrons}.
  - Chadwick, 1932.
  - \textit{Fixes Mendeleev’s problem of masses of elements!}
The Mid-20th Century Nucleus

• The nucleus is very small:
  \[1 \text{fm} = 10^{-15} \text{ m}!\]

• What keeps the protons from flying apart?
  – The STRONG force.

• Some combinations of neutrons+protons are happy (stable)...but some are not (unstable).
  – Radioactivity!

• Some disintegrations of unstable nuclei can cause their unstable neighbors to disintegrate.
  – Fission, chain reaction.
History repeats itself
(Stanford Linear Accelerator)
Hit protons with *(high energy)* electrons

End Station A

Liquid hydrogen target

detector
What Kendall, Friendman, Taylor et al. Expected

Projectiles (high energy electrons from the 2 mile long SLAC accelerator) will be slightly deflected by protons
What Kendall, Friedman, Taylor et al Saw

Occasionally (rarely) the projectile scattered at huge angles. *What did this mean?*
What Kendall, Friedman, Taylor et al. Saw

Occasionally (rarely) the projectile scattered at huge angles. What did this mean?
Substructure inside the proton!
(eventually called quarks)
Strangeness

$s = 0\quad \Delta^- \quad \Delta^0 \quad \Delta^+ \quad \Delta^{++}$

$q = 2$

$s = -1\quad \Sigma^{*-} \quad \Sigma^{*0} \quad \Sigma^{*+}$

$q = 1$

$s = -2\quad \Xi^{*-} \quad \Xi^{*0}$

$q = 0$

$s = -3\quad \Omega^-$

$q = -1$
Charm

High school students (Rutgers Quarknet)
Bottom
(originally called beauty)

Upsilon (bb) discovery at FNAL experiment E-288 (1977)
W boson
(carrier of weak force)

Figure 11: Distribution of the missing transverse energy for events in which there is a single electron with $E_T > 15$ GeV.

Figure 12: Transverse momentum distribution of the W.
Z boson
(carrier of weak force)

Experimental discovery of the electroweak force carriers at CERN (1983)
Muon

Neutrino

b–jet

Fit produced by S. Chen (Rutgers Undergrad)
Isn’t this good enough?
Isn’t this good enough?
Even before QED, we knew that classical electrodynamics could not be the whole story . . .

The classical theory predicts its own demise with an infinite electron self-energy

(This is a recurring and important theme)
Nonsensical predictions, and solutions

- Fermi theory of the 1930's

\[ \nu \mu \rightarrow e \nu_e \]

- This process violates unitarity at high energies

\[ \nu \mu \rightarrow \mu \]

- What do we do?
- Modify the diagram to cancel the divergence

\[ \nu \mu \rightarrow W \rightarrow \mu \]

- the W boson
- (observed at CERN in 1983)
Nonsensical predictions, and solutions cont.

• But now this process violates unitarity at high energies!

• What do we do?
  • Introduce another diagram that cancels the divergence

• the Z boson
  • (also observed at CERN in 1983)

But Z diagrams diverge---need higgs...
Problems of Particle Physics

Problem 1: while discovering “building blocks” of matter we have found more pieces that we need

Problem 2: Extra pieces bring more problems (and even with the extra pieces, we can explain only 5% of what we see in the Universe... )
Mass

Higgs Mechanism

- Separate piece of SM
  - introduced “by hand”
- Mass ↔ Rest energy
- If we make particle interact with vacuum it will acquire additional energy \( \rightarrow \text{ MASS} \)

- If one just puts the masses into Lagrangian the theory breaks: loses gauge invariance and becomes unrenormalizable
  - no viable theoretical alternatives

- This “Higgs Field” means every little volume of space has mass (even if it completely empty!)
Hadron Colliders

• The new particles are heavy – need a lot of energy
• Easiest way to achieve high center-of-mass energy is colliding beams of protons or anti-protons
  – heavy, so no synchrotron radiation
  – stable, so can take time accelerating
• But: messy!
  – quark/gluon colliders
  – remnants of the proton get in the way
  – multiple pp collisions in the same event

“constituents” of proton that carry small fraction of its energy

“constituents” of proton that carry large fraction of its energy

9/2/2009
Newest Discovery announced July 4 2012

HIGGS BOSON: THE VERY ESSENCE OF WHAT WE ARE

THE Higgs boson is part of a theory that explains why the tiny particles that make up atoms have mass. It states that a fraction of the second after the building blocks of life were created in the Big Bang, particles pass through it, they pick up mass. Without this mass, they would whizz around space at the speed of light. The mass makes them slow down and allows them to bind together to make the atoms and elements in a bid to detect the particle. The eureka moment came July last year, when scientists at the Large Hadron Collider in Geneva announced they had found its footprint. The find was described as being the philosophical equivalent of Columbus discovering America.

Professor Higgs said that he had never expected the theory to be made in his lifetime.

Hallada “la más sólida evidencia” de la existencia del bosón de Higgs

The possible detection of the particle is a late encore in the pursuit of angels of the mass

WHAT IS HIGGS BOSON

More than 5,000 scientists help find clue

New York

NEW YORK, THURSDAY, JULY 5, 2012

Physicists Find Elusive Particle Seen as Key to Universe

Rutgers University

September 7, 2005
What is this Higgs Boson anyway?

The higgs boson is an excitation of the higgs field.

Yeah, that clears it right up.
Break it down.

• The **higgs** boson is an excitation of the higgs field.

• **Higgs**: Peter Higgs
Break it down.

• The higgs **boson** is an excitation of the higgs field.

• **Boson**: Satyendra Nath Bose.
Break it down.

• The higgs boson is an excitation of the higgs field.

• Excitation: exactly what you think it means.
Break it down.

• The higgs boson is an excitation of the higgs field.

• Field:
  – *This one requires some explanation.*
What is a field (in physics)?

• Let’s talk about something familiar
  – The electric field.

• 19th century answer:
  – Accounting trick to add up distributed sources.
Magnetic Field
Magnetic Field

Moving charge (current) creates a magnetic field.
Electric $\rightarrow$ Magnetic

1) Electric charge creates electric field

2) *Moving* electric charge creates magnetic field
Magnetic $\Rightarrow$ Electric?

3) Moving magnetic field creates electric field
Electromagnetic Field

2) Moving electric charge creates magnetic field

3) Moving magnetic field creates electric field
Moving electric field creates magnetic field

Moving magnetic field creates electric field

Light!
The original field theory

\[ \nabla \times E = -\frac{\partial B}{\partial t}, \]

\[ \nabla \times B = \frac{1}{c^2} \frac{\partial E}{\partial t}. \]
The Mystery of Mass

- Masses can be given in terms of energy.
  - Einstein said: $E=mc^2$.
- Neutrinos have $m \sim 0$.
- Electron is very light.
  - $M_e = 0.511$ Million eV/c$^2$.
- Top quark is very heavy.
  - $M_t = 175$ Billion eV/c$^2$. 
One Idea: Higgs

Popular person enters a crowded room. People cluster. The person has a difficult time getting across the room. **HEAVY**

Unknown person enters a crowded room. No one notices. The person has no problem getting across the room. **LIGHT**
To find the higgs boson

Higgs fluid permeates all space (vacuum).

But fundamental excitation is NOT massless (unlike photon)

So to find it, have to hit the vacuum really hard
Our version of the hammer

Rutherford → High Energy Collider
Probes Short Distances - New Substructure and Forces
Produce New Particles → Decay → Observed

E > 10,000,000 Rutherford
Large Hadron Collider

27 km Tunnel

Counter Rotating Proton Beams

7, 8, 13 TeV Collision Energy

$\frac{1}{2}$ nanogram in Beam = Kinetic Energy of High Speed TGV Train Paris-Geneva 300 km/hr

$T = 1.9$ K
$I = 12,000$ Amps
$B = 8.3$ Tesla
$E = 7 \text{ MJ} / \text{ Dipole}$
Detector Mass in Perspective

CMS is 30% heavier than the Eiffel tower
High Energy Collider Detectors

**Central detector**
- Tracking, $p_T$, MIP
- Em. shower position
- Topology
- Vertex

**Hermetic calorimetry**
- Missing $E_t$ measurements

**Muon detector**
- $\mu$ identification

**Light materials**

**Heavy materials**

**Electromagnetic and Hadron calorimeters**
- Particle identification ($e, \gamma$ Jets, Missing $E_t$)
- Energy measurement

**Materials with high number of protons + Active material**

**Heavy materials (Iron or Copper + Active material)**
CMS Detector Transverse Slice

Particle Identification
But before we talk about physics...

... a few technical details on analyzing the data!
Very large background from gluon scattering

- jets are everywhere
- jets fluctuate A LOT
- there is always a “cloud” of soft particles from multiple interactions and proton remnants

Jets can mimic all possible rare particles – electrons, muons, photons

- photons are especially tricky
Standard Model Versus New Physics Processes

Yesterday’s Discovery
Today’s Background
Tomorrow’s Calibration

100,000,000 Top Quarks / yr  Design Luminosity

Huge Background to New Physics Searches

May Have to Enhance Recorded S/B by $10^{4-5}$
Typically Look in Low Background Channels
Now we are ready to talk about physics...
Can we measure old *Standard Model* stuff well?
Can we measure Standard Model stuff well?

CMS Preliminary, $\sqrt{s}=7$ TeV

$D^* \rightarrow D^0(K\pi)\pi$

CMS Preliminary
$\sqrt{s} = 7$ TeV

Yield = $355.9 \pm 32.5$
Mean = $(1.864 \pm 0.001)$
Sigma = $(13.9 \pm 1.4)$ Me

$\eta$, $\phi$, $J/\psi$, $\psi'$, $Y$

CMS
$\sqrt{s} = 7$ TeV
$L_{\text{int}} = 40$ pb$^{-1}$

Dimuon mass (GeV/c$^2$)

$M(K\pi)$ [GeV/c$^2$]

$0 \ 50 \ 100$

 события / 10 MeV/c$^2$

$10^0 \ 10^1 \ 10^2 \ 10^3 \ 10^4 \ 10^5 \ 10^6$

36 pb$^{-1}$
36 pb$^{-1}$
1.1 fb$^{-1}$
4.7 fb$^{-1}$

JHEP10(2011)132
CMS-PAS-EWK-10-012
PLB701(2011)535
CMS-PAS-EWK-11-010
CMS-PAS-HIG-11-025
8 TeV DATA

4-lepton Mass : 126.9 GeV

$\mu^+(Z_1) \ p_T : 43 \ GeV$

$e^-(Z_2) \ p_T : 10 \ GeV$

$\mu^- (Z_1) \ p_T : 24 \ GeV$

$e^+ (Z_2) \ p_T : 21 \ GeV$

CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86

7 TeV DATA

4μ+γ Mass: 126.1 GeV

μ⁻(Z₁) pₜ: 14 GeV

γ(Z₁) Eₜ: 8 GeV

μ⁻(Z₂) pₜ: 28 GeV

μ⁺(Z₂) pₜ: 6 GeV

μ⁺(Z₁) pₜ: 67 GeV
What’s next?
Isn’t this good enough?

Just found in 2012
We found the Higgs and **there are problems**

- The higgs boson (mass = 125 GeV) means there is a higgs field.
  - This field is unlike any other field we know!
- This field couples to the vacuum.
  - The “source” of this field is empty space itself!
- Mass arises from stuff coupling to this field.
  - *But the field itself has mass (as we found in 2012)*
- So...every little bit of space should attract every other little bit!
  - The universe should be a tiny little bass the size of a basketball.
- **Cool observational fact:** The universe is NOT the size of a basketball.
  - *this is a good thing!*
  - *But it’s a big problem for particle physics.*
Dark Matter

Gravitational Effects of Dark Matter are Apparent from Sub-Galactic Scales ... Entire Universe

Dark Matter –

Non-Luminous, Non-dissipative Particles
Left Over from the Big Bang

Density Dark Matter / Density Normal Matter » 6
Weakly Interacting Dark Matter

Weak Scale Mass + Weak Scale Interactions »
Correct Relic Density from Big Bang

Supersymmetry:
Superpartner of Photon » Correct Properties

Light ↔ Dark
The known world of Standard Model particles

- u, c, t
- d, s, b
- e, μ, τ
- ν_e, ν_μ, ν_τ
- γ
- Z
- W

- quarks
- leptons
- force carriers

The hypothetical world of SUSY particles

- ~u, ~c, ~t
- ~d, ~s, ~b
- ~e, ~μ, ~τ
- ~ν_e, ~ν_μ, ~ν_τ
- ~γ
- ~Z
- ~W

- squarks
- sleptons
- SUSY force carriers

These can cancel out the problem diagrams
The known world of Standard Model particles

- quarks
- leptons
- force carriers

The hypothetical world of SUSY particles

- squarks
- sleptons
- SUSY force carriers

These can cancel out the problem diagrams... and the lightest one could be Dark Matter.
Supersymmetry Signatures

Depend on Ordering in Superpartner Mass Spectrum

Missing Energy, Leptons, Jets

Lots of Backgrounds

$\ell\ell$ mass ($m_{\ell\ell}^{\text{max}}$ (exp)) = 77.37 ± 0.67

$\ell\ell$ mass ($m_{\ell\ell}^{\text{max}}$ (TH)) = 78.1

Z + jets
We are Entering a **New Era**
with the Experimental Investigation of
Electroweak Symmetry Breaking.

**We have found the Origin of Mass!**

New Symmetries and Forces,
Quantum Dimensions of Space-Time,
Dark Matter,
Black Holes,
......
Don’t Be Fooled by Bright Lights

The Dark Side Rules The Universe

Dark Matter Binds It Together

Dark Energy Controls Its Destiny