The Coming Era of New Physics at the Large Hadron Collider.

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So what's a collider do, exactly?

- Colliders (accelerators) have been essential tools to understand the structure of nature.
  - ...ie, what is stuff made of?
- In a remarkably short period of time, our understanding of the basic building blocks of nature has changed.
  - Several times!
- The technique used is called scattering.
Scattering Basics

source → detector → target → Signal analysis
The eye is an incredibly sophisticated particle detector.
What you can see depends on *resolution*.

Large wavelength, Lower resolution

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

Short wavelength, Higher resolution

- Small wavelength, high energy, constituents of targets become visible.
Scattering at higher energies (shorter wavelengths)
- Microscope to Short Distances
- New Substructure and Forces
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.
Picture of the Atom ~1900

Thompson plum pudding model of the atom

Negative electron plums

Positive pudding

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Today, the plum pudding model is synonymous with the flat earth theory, but in its time it answered some important questions.

How can a heavy, overall neutral object emit light charged particles when heated (ionization?)
Rutherford Destroys the Plum Pudding Model
Rutherford Destroys the Plum Pudding Model

Brilliant example of undergraduate contribution to particle physics. Tradition continues to this day!
What Rutherford Expected

Projectiles (very fast He nuclei called *alpha particles*) will be *slightly* deflected by gold atoms
Occasionally (rarely) the projectile scattered at huge angles. Beginning of 20th century physics.
Occasionally (rarely) the projectile scattered at huge angles. Beginning of 20th century physics.

...like firing a 16-inch shell at a piece of tissue paper and seeing it bounce back.

- E Rutherford.
Things started small...

The first cyclotron...
...and got bigger

Lawrence next to the Berkeley cyclotron
...discovery of pions.
(\textit{simultaneously with cosmic rays})
...and even bigger

Princeton-Stanford accelerator (Prin-Stan).

500 MeV, 2-ring electron-electron machine
Not all were circular...

The Stanford Linear Accelerator.

Delivered 15 GeV electrons on target.
End Station A
What Kendall, Friedman, and Taylor expected...

Electrons from the Linear accelerator

Proton (target)

NO large angle scattering.
What Kendall, Friedman, and Taylor actually saw

Proton (target)

Large angle scattering can happen.

And did! Quarks!
What Kendall, Friedman, and Taylor actually saw

Electrons from the Linear accelerator

Proton (target)

Quarks!

The 1990 Nobel Prize
FIG. 1. $(d^2\sigma/d\Omega dE')/\sigma_{\text{Mott}}$, in GeV$^{-1}$, vs $q^2$ for $W = 2$, 3, and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic $e-p$ scattering divided by $\sigma_{\text{Mott}}$, $(d\sigma/d\Omega)/\sigma_{\text{Mott}}$, calculated for $\theta = 10^\circ$, using the dipole form factor. The relatively slow variation with $q^2$ of the inelastic cross section compared with the elastic cross section is clearly shown.
Aside: Antimatter

Dirac predicted antimatter as a consequence of combining relativity and quantum mechanics.

Anderson found it (an anti-electron, called positron) in cosmic ray data.
Even bigger Colliders
(now with matter-antimatter collisions!)

Most were just “let’s build it and see what’s there”. Most discoveries in the field were indeed surprises!

SppS was built to see W/Z for which there were precise predictions

LHC is built to explore electroweak energy scale which it completely covers
So what is everything made of?

**Status as of 2011**

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<th>EM Interaction</th>
<th>Strong Interaction</th>
<th>Weak Interaction</th>
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</tbody>
</table>

Everything in the universe is made of the 1st generation particles.

Quarks bind together with the strong force to make familiar particles such as protons and neutrons.
So why isn't this good enough?
Go back 100 years...

\[ \nabla \cdot \mathbf{E} = \rho / \varepsilon_0 \]
\[ \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]
\[ \nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{j}_c \]

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

\[ \Sigma_{MB} = \text{Hartree-Fock} \]
\[ \Sigma_{MB} = \text{2nd Born} \]
\[ \Sigma_{MB} = \text{GW} \]

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

Fermi theory of the 1930’s

This process violates unitarity at high energies

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

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)
Nonsensical predictions, and solutions cont.

But now *these* processes violate unitarity at high energies!

What do we do?

Introduce *other* diagrams to cancel the divergence

*the Higgs boson*
Thus far we have no direct evidence for the Higgs boson*

but let’s keep going:

If the Higgs exists, these types of processes violate unitarity at high energies unless a parameter is “unnaturally” fine-tuned (“fine-tuning problem”)

What do we do?

Introduce other diagrams to cancel the divergence without fine-tuning

\{ supersymmetry, strong dynamics, extra dimensions \}
Symmetries

Symmetries are the Central Organizing Principle in Our Understanding of Fundamental Physics !!!

Spatial Translation Invariance (Momentum)
Time Translation Invariance (Energy)
Spatial Rotation Invariance (Angular Momentum)

Space-Time Rotation / Boost Invariance

Electromagnetic Waves
velocity = constant

(Lorentz, ... , Einstein)
Supersymmetry

Every SM particle gets a super-partner to cancel inconvenient divergences. Superpartners of fermions are bosons (add an “s”: selectron, squark…) Superpartners of bosons are fermions (add an “ino”: wino, gluino, photino…) Superpartners more massive than SM, but should be around ~TeV or so...

Hunting grounds of the LHC!

Dark matter candidates!
The Large Hadron Collider
Large Hadron Collider

Radio Frequency Klystron Cavities
1232 Super Conducting Dipole Magnets

$T = 1.9 \text{ K}$ \quad $I = 12000 \text{ Amps}$

$B = 8.3 \text{ Tesla}$ \quad $E = 7 \text{ MJ / Dipole}$

$\frac{1}{2} \text{ nanogram in Beam -}$

Kinetic Energy of 100,000 Ton Aircraft Carrier at Cruising Speed
Vue d'ensemble des expériences LHC.
High Energy Collider Detectors

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

Hermetic calorimetry
- Missing Et measurements

Muon detector
- $\mu$ identification

Light materials

Heavy materials

Materials with high number of protons + Active material

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

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

Particle Identification

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g., Pion)
- Light Green: Neutral Hadron (e.g., Neutron)
- Blue dashed: Photon

Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers

Transverse slice through CMS
CMS Detector

- **ECAL**: Scintillating PbWO4 crystals
- **SUPERCONDUCTING COIL**: Graduated Student
- **HCAL**: Plastic scintillator/brass sandwich
- **IRON YOKE**: Cathode Strip Chambers (CSC)
- **MUON ENDCAPS**: Resistive Plate Chambers (RPC)
- **TRACKER**: Silicon Microstrips, Pixels
- **MUON BARREL**: Drift Tube Chambers (DT), Resistive Plate Chambers (RPC)

**Dimensions and Properties**
- Length: 21.6 m
- Diameter: 15 m
- Weight: ~12,500 tons
- Magnetic Field: 4 Tesla
- 1% Momentum Resolution
LHC and CMS operations in 2010.

About $47\text{pb}^{-1}$ delivered by LHC and $\sim43\text{pb}^{-1}$ of data collected by CMS. Overall data taking efficiency $\sim92\%$. 6$\text{pb}^{-1}$ of data integrated in a good fill. Excellent performance in coping with more than 5 order of magnitude increase in instantaneous luminosity.

Average fraction of operational channels per CMS sub-system still $\sim99\%$. A few problems here and there. Last few days of pp running tested 50ns filling scheme. Vacuum (e-cloud) worse than at 150ns. 75ns vacuum much better. 800 bunches OK.

From G. Tonnelli talk, 6 Dec 2010
Rediscovering the Standard Model

CMS Preliminary

\[ \sqrt{s} = 7 \text{ TeV}, \quad L_{\text{int}} = 40 \text{ pb}^{-1} \]

CMS Preliminary, \( \sqrt{s} = 7 \text{ TeV} \)

\[ L_{\text{int}} = 3.1 \text{ pb}^{-1} \]

\[ \sigma = 70 \text{ MeV}/c^2 \]

\[ |t'| < 1 \]

\[ \int L \, dt = 35 \text{ pb}^{-1} \]

Events / GeV

10^6

10^5

10^4

10^3

10^2

10

1

Events / 2 GeV

\[ \pi^{0} \rightarrow \gamma \gamma \]

\[ K \rightarrow \pi \pi \]

\[ \rho, \omega, \phi, J/\psi, Y(1,2,3S), \eta, \psi', Z \]

### Dilepton mass 88 GeV/c², p_T = 138 GeV/c

- e⁻ p_T = 80 GeV/c, \( \eta = 0.5, \phi = -2.9 \)
- b-tagged jet p_T = 89 GeV/c, \( \eta = 0.5, \phi = -0.5 \)
- \( \mu^{+} \) p_T = 60 GeV/c, \( \eta = -0.7, \phi = -2.5 \)

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

100,000,000 Top Quarks / yr  Design Luminosity
Opportunity for Precision Top Physics ...
Huge Background to New Physics Searches

May Have to Enhance Recorded S/B by $10^{(4-5)}$
Skill of the Physics Analysis

Typically Look in Low Background Channels
– But what if nature doesn’t live there?
Beautiful ZZ event seen in CMS data. First found by RU postdoc R. Gray.

**Muons** ($p_T$ [GeV], $\eta$, $\phi$ [rad])

- $\mu_0^-$ $(48.1422, -0.412532, -1.92555)$
- $\mu_1^+$ $(43.4421, 0.204654, 1.79493)$
- $\mu_2^+$ $(25.8769, -0.782084, 0.774588)$
- $\mu_3^-$ $(19.5646, 2.01112, -0.980597)$

**Invariant Masses**

- $\mu_0 + \mu_1$: 92.15 GeV (total $Z$ $p_T$ 26.5 GeV, $\phi$ -3.03)
- $\mu_2 + \mu_3$: 92.24 GeV (total $Z$ $p_T$ 29.4 GeV, $\phi$ +0.06)
- $\mu_0 + \mu_2$: 70.12 GeV (total $p_T$ 27 GeV)
- $\mu_3 + \mu_1$: 83.1 GeV (total $p_T$ 26.1 GeV)

**Invariant Mass of 4$\mu$: 201 GeV**
Many other models for new physics have multiple leptons as decay signatures.

This one analysis also puts bounds on **Slepton Co-NLSP** (where the sleptons are close in mass to the lightest SUSY Particle) models with **leptonic R-Parity violations**. Both of these give 4 leptons in the final state.
Diphoton + missing momentum
Jet Physics

Highest mass dijet event

Run: 138919
Event: 32253996
Dijet Mass: 2.130 TeV

Jet 1 $p_T$: 585 GeV
Jet 2 $p_T$: 557 GeV

CMS Preliminary (120 nb$^{-1}$)
$\sqrt{s} = 7$ TeV
$M_1 > 354$ GeV
$|\eta_1, \eta_2| < 1.3$

95% CL Upper Limits
- String
- Excited quark
- Axigluon
- $E_6$ diquark
- $W'$
- Z'
- RS Graviton

QCD Pythia + CMS simulation
10% JES uncertainty
Summary

• The energy frontier has always been surprising.
  • No one expected the nucleus, heavy leptons, mesons, partons, charm...

• Incredibly beautiful data coming out of LHC detectors.
  • *Almost makes you forget how long it took*...
  • Granularity of CMS/ATLAS much finer than CDF/D0 → entirely new physics techniques.

• We have entered the era of new physics. The 2011-2012 run is being called the “discovery run”.
  • Is there a higgs? Will we create Dark Matter?
  • Whatever happens, it probably will not be what we expect.
    - Will SUSY etc go the way of S-Matrix theory?

• To the students in the audience: JOIN US!