The “Super” Era of Sub-Atomic Particle Physics

Jay Hauser

Abstract:
Particle physics has now moved into the "Super" era, in which Supersymmetry, Supergravity, and Superstring theories will be investigated by Supercolliders.

A Supercollider is being built in Europe which may produce Dark Matter and other particles predicted by the Super-theories. This machine will produce a huge amount of data, and finding these particles will be like finding a few needles in a 100-million-ton haystack. This amazing machine and the upcoming search for these particles will be described.
Science Tools: the Very Large and the Very Small

**Einstein relativity:**
\[ E = \sqrt{(m \cdot c^2)^2 + (p \cdot c)^2} \]

not
\[ E = m \cdot c^2 \]

**Quantum Mechanics:**
\[ \lambda = \frac{h \cdot c}{p} \]

Physics of the very small is physics of high momentum and hence high energy.
Outline of Talk

• Fundamental physics of the latter 20th Century
• Fundamental physics of the 21st Century
• Particle physics with Supercolliders
  Two important experiments: CDF and CMS
• Cosmic connections to particle physics
• String theory and particle physics
The 4 Forces of Nature:

**Strong**
- Gluons (8)
- Quarks
- Mesons
- Baryons
- Nuclei

**Electromagnetic**
- Photon
- Atoms
- Light
- Chemistry
- Electronics

**Gravitational**
- Graviton ?
- Solar system
- Galaxies
- Black holes

**Weak**
- Bosons (W, Z)
- Neutron decay
- Beta radioactivity
- Neutrino Interactions
- Burning of the sun

*The particle drawings are simple artistic representations*
History and Ideas of Force Unification

1686 Newton, 1915 Einstein

1873 Maxwell

1967 theory W&S
1983 experiment

-Higgs
Electro-Weak Unification

- The theory has been extensively verified above ~100 GeV in measurements with W and Z bosons
- But - the theory hinges on the “Higgs” particle
  $105 \text{ GeV} < m_H c^2 < 1000 \text{ GeV}$
- Higgs is not yet observed, does it exist?
- LHC “no-lose” theorem: either it will be found, or a new force of nature (“5th Force”) will be found.
• “Grand” unification adds the Strong force:
  • All these forces have the same strength at $10^{15}$ GeV.
  • Protons very slowly decay away - gulp!
  • Theory needs *Supersymmetric* particles with $mc^2 < 1000$ GeV to “stabilize” theory to keep the Higgs energy $<<10^{15}$ GeV
What’s Supersymmetry?

• Elementary particles have “spin”, a fundamental quantum number
• Supersymmetry is a kind of “Spin symmetry”

<table>
<thead>
<tr>
<th>Spin Type</th>
<th>“Ordinary”</th>
<th>Supersymmetric</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Matter”: 1/2-integer</td>
<td>Electron</td>
<td>Photino</td>
</tr>
<tr>
<td>“Force”: Integer</td>
<td>Photon</td>
<td>Selectron</td>
</tr>
</tbody>
</table>

With ordinary matter, force is carried only by integer-spin particles:

Supersymmetry doubles the list of elementary particles
Making New (Heavy) Particles:
Convert Energy to Mass

Particles produced if \[ E_{CM} > (m_1+m_2+\ldots)c^2 \]

I) Old way: beam hits stationary target

\[ E_{beam} \]

II) For more energy: use *colliding* beams
Colliding Proton/Antiproton Beams

- In the proton, there are quarks and gluons (that hold them together).
- Collisions are like throwing bags of marbles at each other at high velocity:
  - Quark-quark etc. collisions are more interesting than bag-bag collisions.
- Fortunately, the arrangement of quarks and gluons has been measured by many experiments.
Particle Physics Detectors

- A tracking chamber measures the energies of charged particles (with aid of a big magnet to bend them)
- A calorimeter measures energies of neutral particles
- A muon system sees only penetrating muon particles
- Used to take pictures (bubble chambers), now we use fully electronic readout
Proton-Antiproton Collisions at Fermilab (near Chicago)

The Tevatron accelerator, 6 km circumference

The CDF (Collider Detector at Fermilab) experiment
Discovery of the top quark in 1995

The top quark has a mass of 175 GeV, as much as an atom of gold
The UCLA Group Looked for Supersymmetric Quarks and Gluons
High Energy Physics Accelerators
The LHC Accelerator at the CERN Laboratory

- 14 TeV energy (7x higher than Fermilab 2 TeV)
- 100 times as many collisions
The CERN Laboratory near Geneva, Switzerland

The first particle accelerator by E. Lawrence (10 cm diameter):
**Data Analysis**

Start from:
- 40 million events/sec
- x10 million sec/year (30% run eff.)
- x10 years
- =4x10\(^{15}\) events

**End result:**
Search for Higgs particle
Look for data > background rate
~40 events excess

10\(^{-14}\) factor:
Each Higgs event is like a 1g needle in a 100 million metric ton haystack
Finding Needles in Large Haystacks...

Multi-step approach:
I) Special-purpose 40 MHz Electronics
   “Level 1 Trigger”
   UCLA

II) Fast “online” Computers
    “Level 2 Trigger”
    UCSD & UCLA

III) “Offline” Analysis
    Crunch Petabyte data store
    (1 Million Gigabytes)
    Caltech
• SUSY will be found quickly - if it exists.

• LHC opens up the part of SUSY parameter space populated by dark matter candidates very quickly.
History of the Universe, according to the Big Bang model:
Cosmic Connections

Big Bang:
• Energy decreases w/time
• At earliest times, the universe was hot
• Particle energies were large
Proton Collider Discoveries

Timeline of accelerators, detectors, and discoveries:

- **ISR**
  - SPS Collider
  - UA1/UA2 Detectors

- **Tevatron**
  - CDF/DO Detectors

- **LHC Collider**
  - CMS/Atlas Detectors


Other possibilities: heavy Z particles, right-handed W particles, heavy stable particles, composite quarks or leptons, leptoquarks, ...
LHC Construction Underway – Examples…

- Accelerator magnets
The ATLAS Cavern
Conductor double pancakes, all 16 ready

Coil casing, 7 out of 8 at CERN

Cryostat vacuum vessel, 6 out of 8 delivered

...the ATLAS Detector Magnets
...CMS Experimental Caverns

Service: USC55 ready Jan 04

Experiment: UXC55 ready July 04
…the CMS Endcap Muon Detector

- Chambers produced at Fermilab
- Equipping with electronics and testing at UCLA
- 400,000 data channels “trigger” electronics built by UCLA
CMS Calorimeters

HE-1 re-installed on YE-1 in Jan/Feb 2003.
Mount HE+1 by end of 2003,
Field Theory versus String Theory

The “Feynman Diagram”:

- **Point particles** are represented as lines in space-time.
- Interaction (force) at point vertex, e.g.:

  ![Diagram of Feynman Diagram](image)

  Higgs particle “decay”

  Distance →

  Time ↓

  \[ Z^0 \]

  \[ H^0 \]

  \[ Z^0 \]

  Point vertex causes infinities!

  Cumbersome remedies were found... but seems to be no hope of including gravity.

Ed Witten and Colleagues:

- **Particles are strings**
- **Represented as surfaces in space-time**
- Interaction (force) as shown:

  ![String Theory Version](image)

  String theory version

  No points - infinities are gone!

  But strings require extra dimensions of space-time beyond the known 4!
More String Theory

- Connected with “Theory Of Everything” (TOE) that unifies with gravity force
- Planck energy $E_{PL} = (hc^5/G)^{1/2} = 10^{19}$ GeV is $>>$ Grand Unified Scale of $10^{15}$ GeV

<table>
<thead>
<tr>
<th>Type</th>
<th>Spacetime Dimensions</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bosonic</td>
<td>26</td>
<td>Only bosons, no fermions means only forces, no matter, with both open and closed strings. Major flaw: a particle with imaginary mass, called the tachyon</td>
</tr>
<tr>
<td>I</td>
<td>10</td>
<td>Supersymmetry between forces and matter, with both open and closed strings, no tachyon, group symmetry is SO(32)</td>
</tr>
<tr>
<td>IIA</td>
<td>10</td>
<td>Supersymmetry between forces and matter, with closed strings only, no tachyon, massless fermions spin both ways (nonchiral)</td>
</tr>
<tr>
<td>IIB</td>
<td>10</td>
<td>Supersymmetry between forces and matter, with closed strings only, no tachyon, massless fermions only spin one way (chiral)</td>
</tr>
<tr>
<td>HO</td>
<td>10</td>
<td>Supersymmetry between forces and matter, with closed strings only, no tachyon, heterotic, meaning right moving and left moving strings differ, group symmetry is SO(32)</td>
</tr>
<tr>
<td>HE</td>
<td>10</td>
<td>Supersymmetry between forces and matter, with closed strings only, no tachyon, heterotic, meaning right moving and left moving strings differ, group symmetry is $E_8 \times E_8$</td>
</tr>
</tbody>
</table>

Recent discovery: different theories are all contained in 11-dimensional M-Theory!
Just for Fun: How to do Experimental String Physics?

• Find a nearby black hole

• Get it “into the lab” without destroying everything

• Shoot particles at it!

• Particle physics of the 25th century?
Web Links

- This talk on my web site:  
  http://www.physics.ucla.edu/~hauser/homepage/present_research.html

- Particle physics tutorial:  http://ParticleAdventure.org/

- Fermilab home page:  http://www.fnal.gov/

- CERN public home page:  http://public.web.cern.ch/Public/

- Ned Wright’s cosmology tutorial:  
  http://www.astro.ucla.edu/~wright/cosmolog.htm

- Hubble Space Telescope and other astronomy pictures:  start at  
  http://dir.yahoo.com/Science/Astronomy/Pictures/