High Energy Experiments: A Smashing good time

is out there

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Meet the Group: CMS and D-Zero Projects

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Michael Balazs (student)

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The basic questions

What are the basic building blocks of everything?

What are the forces of nature?
Some things we know about matter:

Elementary Particles

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<th>II</th>
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<tbody>
<tr>
<td>Leptons</td>
<td>ν_e</td>
<td>ν_μ</td>
<td>ν_τ</td>
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<tr>
<td>Quarks</td>
<td>u</td>
<td>c</td>
<td>t</td>
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Charge = +2/3
Charge = -1/3
Charge = 0
Charge = -1

The “periodic table of fermions.”

(quantized fields)

EM
Strong
Weak
Some things we know about matter:

Electroweak Unification

EM/Weak interactions unified at large energy/momentum transfer
Some things we know about matter:

Quantum Chromodynamics

Gauge theory (like electromagnetism) describes fermions (quarks) which carry an SU(3) charge (color) and interact through the exchange of vector bosons (gluons)

Interesting features:
- gluons themselves have color
- interactions are strong
- coupling constant runs rapidly
  - becomes weak at momentum transfers above a few GeV

In a more general theory (GUT), expect unification w/ electroweak force
Some things we don’t know about matter:

Masses

Second and third generations of quarks and leptons are much more massive than first.

Origin of mass difference for bosons in EW force?

mass = 80.4 GeV

Electroweak asymmetry

>12 orders of magnitude in mass!
The Higgs Mechanism

In the Standard Model
(Glashow, Weinberg, Salam, ‘t Hooft, Veltmann)

- “electroweak symmetry breaking” through introduction of a scalar field $\phi$
  $\rightarrow$ masses of $W$ and $Z$
- Higgs field permeates space with a finite vacuum expectation value
  - cosmological implications! (inflation)
- If $\phi$ also couples to fermions $\rightarrow$ generates fermion masses

An appealing picture: is it correct?

- One clear and testable prediction: there exists a neutral scalar particle
  which is an excitation of the Higgs field
- All its properties (production and decay rates, couplings) are fixed except
  its own mass

Highest priority of worldwide high energy physics program: find it!
W's, Z's, Top's, and Higgs's (oh my!):

- Fundamental parameters of Standard Model (SM)
- Affect predictions of SM via radiative corrections:
  - BB mixing
  - W and Z mass
  - Large mass of top quark
    - may provide clues about electroweak symmetry breaking

- Measurements of $M_W$, $m_t$ constrain $M_H$
The Standard Model is incomplete:

**Theoretical problems**
- Mass scale for $M_{EW}$?
- How to achieve grand unification?
- How to include gravity?
- What explains proliferation of quark and lepton types and determines their mixings?

**Experimental problems**
- SM fit to electro-weak data has probability of 4.4% 
- What is dark matter?
  - New type of matter? – can be produced at the LHC!
  - “Dark” because of undiscovered properties of space-time? – can be probed at LHC!

More general theories make predictions that can be tested at the Tevatron & LHC
Beyond the Higgs:

Standard Model works well for observed phenomena and would be completed by the discovery of the Higgs, but the Higgs may be the first window on to a new domain of physics at the electroweak scale.

This Higgs is unlike any other particle in the SM (no other elementary scalars).

SM Higgs would have a mass unstable to radiative corrections (quantum effects): $m_H$ would become very large $m_H \sim 10^{15}$ GeV, unless parameters fine tuned at the level of 1 part in $10^{26}$.

The patterns of the fundamental particles suggest a deeper structure: the SM is a low energy approximation to some more general theory.

Theoretically the most attractive option is supersymmetry.
Now (15 billion years)

Large scale galactic clustering, mass deficit in universe, lensing

where/what is dark matter?
Supersymmetry

- Introduce a symmetry between bosons and fermions:
  - more massive super-partners for all particles
  - Allows a fundamental scalar (the Higgs) at low mass
    - cancels the divergences in $m_H$
    - closely approximates the standard model at low energies
    - allows unification of forces with common couplings at higher energies
    - provides a path to the incorporation of gravity and string theory: Local Supersymmetry = Supergravity

- lightest neutral superpartner (neutralino, etc) is massive, weakly interacting + stable → cosmic dark matter candidate!

- Connections w/ gravity: allows TEV scale affects for processes probing extra spacial dimensions
- Flexible framework & calculable!
But, SUSY or other extensions to the Standard Model aren't obvious

Numerous specific models proposed

Many tunable parameters affect phenomenology w/o breaking SM as observed.

Majority of proposed models must be wrong, but this is a good thing...

Whatever is out there (and it's ~5x more plentiful than normal matter) will be a surprise!
How do we see any of this?

Analyze states produced in proton-(anti)proton collisions at high energy $E=Mc^2$, so Big $E$ = Large reach in creating new matter states.

Study dynamics of collisions – How do the forces work...

Only by understanding the Standard Model precisely can we hope to find new physics in the dynamics of our collisions.

Study massive states – What kinds of things can exist, what are there properties...

Precise knowledge of $W$, top properties are central to understanding where the Higgs may be...

Collider physics = precision studies + direct access to new physics

Literally 100's of thesis topics
The Labs

Fermilab (Near Chicago)
The Tevatron
proton-antiproton collider
at c.o.m. Energy = ~2TeV

6.3 km circumference

CERN (Geneva, Switzerland)
The LHC
proton-proton collider
at c.o.m. Energy = 14TeV

27 km circumference
The Experiments

**DØ - Fermilab**
Weighs 5000 tons
~$10^6$ channels of information
Inspects ~$3-30 \times 10^6$ collisions/sec.
Running now

**CMS - CERN**
Weighs 12,500 tons
~$10^7$ channels of information
Inspects ~$40-1000 \times 10^6$ collisions/sec.
First beam: end of 2008
The Calorimeter

The full cube, w/ muon chambers
Slice of CMS

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

Iron return yoke interspersed with Muon chambers
Accumulate world's largest data sets at highest energies before LHC era

massive physics menu includes:

- Precision top physics (first ever)
- Precision EW physics (order of magnitude increase W statistics)
- Searches: Higgs* and for new physics (explore much of SUSY phase space, extra-dimensions, exotic matter states)
- QCD and proton hadronic structure (new levels of precision, smallest distance scales yet)
- Heavy flavor physics (Precision measurements in heavy quark sector, relationship between generations, matter antimatter asymmetry,...

The best HEP program happening!

Dukes, Hirosky

LHC: The New Frontier

massive physics menu includes:

- Copious top production
- Test of EW physics to “unitarity limit”
- Copious Higgs production, test SM vs. SUSY Higgs
- Direct observations of SUSY states* or elimination of the lifetime work of many theorists :)  
- Order of magnitude increase in reach to physics at smallest distance scales*
- Open to weirdness: black hole production, extremely massive exotic states, new types of strong interactions, extra-dimensions*....

A new era for HEP is only a couple 1 year away!

Conetti, Cox, Hirosky

* general group interests at present
Various Technical Projects
At the CMS test beam
Workshops and Physics Schools
Where do HEP students go?

HEP students and postdocs go many places after completing their research, some (very few really) examples:

- **Industry**
  - Industrial research and instrumentation design
  - Wireless technology and network infrastructure
  - IT Consulting
  - Financial analysis, modeling
  - Design of medical treatment devices

- **Non-Industry**
  - Private and public “think tanks”
  - National research laboratories (not only HEP)
  - Law, Media

- **Academia**
  - 4-year undergraduate colleges
  - Tier-1 research universities

But, you should only choose this or any other research area because you are interested in the physics!

no passion, no progress!
What can you learn along w/ physics?

Lots:
- detector technologies, typical HEP experiments can easily employ many varieties of particle detection – enormous amount of practical physics in development of detector systems
- high performance data readout systems, electronics (HEP detectors must typically process 10's of TB of data each second)
- high performance computing:
  - need to cull above data rate to manageable levels in real time
  - handle data sets at many PetaByte level
- sophisticated data analysis techniques, statistical reasoning, multivariate approaches for problems -> extracting maximal information from data
- working with engineers and detector/accelerator physics experts to bring experiments on-line
- experience w/ detailed simulations of detector systems and physics processes
- working in a large expert physics community, amazing access to expertise in world wide community + opportunities to contribute

...
## Interested in Experimental HEP?

Expected opportunities for graduate students this year:

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<th>Experiment</th>
<th>~Advisor</th>
<th>Colleagues</th>
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<tr>
<td>CMS</td>
<td>Hirosky</td>
<td>(w/ Cox and Conetti)</td>
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<tr>
<td>DØ/NOvA</td>
<td>Dukes</td>
<td>(w/ Hirosky)</td>
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To learn more (start by doing some homework):
- seminars, colloquia, ...
- Symmetry Magazine: [http://www.symmetrymagazine.org](http://www.symmetrymagazine.org)
- CERN Courier: [http://cerncourier.com](http://cerncourier.com)

Contact me or another group member if you have questions about the group and our projects.

Interested in signing up? I'll be happy to interview interested students after the Fall semester.