News from the Microscopic Universe and the Energy Frontier
(with a look at how art & science imitate one another)

Jerry Blazey
Northern Illinois University

University of Minnesota
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Cosmic Context

- Now (15 billion yrs)
- Stars form (1 billion yrs)
- Atoms form (300,000 yrs)
- Nuclei form (180 seconds)
- Protons and neutrons (10\(^{-10}\) s)
- Domain of current accelerators \(\sim 10^{-12}\) seconds

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Minneapolis
The Universe at $10^{-12}$ s $\rightarrow$
The Standard Model

- The essence: Bits of matter stick together by exchanging stuff.
- The great achievement of particle physics is a model that describes all particles and particle interactions. The model includes:
  - 6 quarks (the particles in the nucleus) and their antiparticles.
  - 6 leptons (of which the electron is an example) and their antiparticles
  - 4 force carrier particles
- Precisely: “All known matter is composed of composites of quarks and leptons which interact by exchanging force carriers.”
The Bits: Periodic Table of Fundamental Particles

All point-like (down to $10^{-18}$ m) spin-1/2 Fermions

Families reflect increasing mass and a theoretical organization

$u, d, n, e$ are “normal matter”

These all interact by exchanging spin 1 bosons
The Stuff: Standard Model Interactions
Mediated by Boson Exchange

Unification

- Gravity
  - Carried By: Graviton (not yet observed)
  - Acts on: All

- Weak (Electroweak)
  - Carried By: W^+ W^- Z^0
  - Acts on: Quarks and Leptons

- Electromagnetic
  - Carried By: Photon
  - Acts on: Quarks and Charged Leptons and W^+ W^-

- Strong
  - Carried By: Gluon
  - Acts on: Quarks and Gluons

10^{-37} weaker than EM, not explained

Explained by Standard Model

We could stop here but…..
Compelling Questions That Can Be Addressed by Particle Physics

(there are many others)

- How do particles get mass?
- Are there higher symmetries manifesting, themselves as new particles and forces?
- Are there hidden dimensions (perhaps explaining the weakness of gravity)?

All properties of the submicroscopic world!
Mass: The Higgs Particle

- Electroweak unification postulates the existence of the Higgs field.
- The field interacts with all other particles to impart mass, think of walking through molasses.
- The field is a microscopic property of space-time, at least one real particle will result.
- The collider programs at Fermilab, Large Hadron Collider, and International Linear Collider are dedicated, in part, to the search for and study of this particle.

Recently Hollywood gave some practical pointers on the uses of Higgs “beams”
Beyond That?

• Even with the Higgs, the Standard Model requires fine tuning of parameters to avoid infinite Higgs masses from quantum corrections – the theory is “ugly.”

• This and other theoretical thoughts lead to strong belief that the SM is merely a low energy or effective theory valid up to some scale.

• At this higher energy scale additional physics may (will?) appear.

• **Supersymmetry or SUSY** is one of the most popular theoretical options.
SUSY

- In SUSY every particle and force carrier has a massive partner: Squarks, selectrons, gluinos...
- Since they are massive they’ve not been produced in current machines.
- The discovery requires more energetic accelerators – something which is being enthusiastically pursued.
Or...Extra Dimensions!?

- Amazingly enough, a higher dimensional world (time, 3-D, plus “n” additional dimensions) can accommodate a theory with all four forces.

- Only gravity can communicate with/to other dimensions, it’s “strength” is diluted in ours. That is, or gravity carrier can spread it’s influence among all the spatial dimensions.

- Experiments are underway searching for signals of these dimensions.

The Adventures Of Buckaroo Banzai Across The Eighth Dimension - 1984

"Our World"

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How do we test these theories?

The Two Basic Ideas:

– Find a source of particles with high kinetic energy.
– Study the debris resulting from collisions inside detectors.

The Sources:

– Cosmic Rays
– Accelerators
– The higher the energy the more numerous the number and types of particles.

The Detectors:

– A series of special purpose devices that track and identify collision products.
Fermilab Proton-Antiproton Collider

Batavia, Illinois

You are here

1) Hydrogen Bottle
2) Linear Accelerator
3) Booster
4) Main/Injector
5) Antiproton Source
6) Tevatron @ 2 TeV
A Schematic detector

- Tracking system
  - Magnetized volume
- Calorimeter
  - Induces shower in dense material
- Muon detector
  - Absorber material

- Interaction point
- Innermost tracking layers use silicon
- EM layers
  - Fine sampling
  - Hadronic layers
- Electron
- Jet: q or g
- Muon
  - Bend angle → momentum

"Missing transverse energy"
Signature of a non-interacting (or weakly interacting) particle like a neutrino

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- A Real Experiment: DZero
  - Proposed 1982
  - First Run: 1992-1995 1.8 TeV
  - Upgrade: 1996-2001
  - Run II: 2002-2009 2.0 TeV

Star Trek First Contact -1996

Calorimeters
Tracker
Muon System
Electronics

antiprotons

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Earthquake: Low β Quad Tiltmeters
International

- 19 countries
- 80 institutions
- 650+ physicists

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Silicon Microstrip Tracker
1M channels, 4 barrel layers
axial + stereo strips

H, F Disks/wedges

Calorimeter, 50k Channels
Liquid argon calorimeter
with uranium absorber

Central Fiber Tracker
80k Channels

8 axial layers
8 stereo layers

scintillator

shielding
**Inner Tracking**

- Electron
- Quark or gluon Jet
- Muon
- Central Preshower
- Solenoid
- Central Fiber Tracker
- Silicon Microvertex Tracker
- Forward Preshower
- Lumi. Monitor

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Run II: 24/7 Event Collection

- Proton-antiprotons collide at 7MHz or seven million times per second
- Tiered electronics pick successively more interesting events
  - Level 1 2 kHz
  - Level 2 1 kHz
- About 100 crates of electronics readout the detectors and send data to a Level 3 farm of 100+ CPUs that reconstruct the data
- Level 3: 50 events or 12.5 Mbytes of data to tape per second
- Per year: 500 million events
Physics: Event Analysis

- Events are “reconstructed” offline by farms of ~100 CPUs.
- Each detector samples position, energy, or momentum, 1M+ channels.
- Then computers build or reconstruct full event characteristics based upon these samples.
- Interesting events or signals are culled from the background usually 100’s out of millions.
Fermilab DØ Experiment

Worldwide Data Grid Autumn 2003

Remote Data Reconstruction sites
Remote Simulation sites
Stations for remote data analysis + more coming
A Sample Event: \( Z \rightarrow e^+e^- \)
Sample Distribution: Z mass

- Collect events and calculate mass for each event, then plot distributions
- Extract or measure properties such as mass or production rate as a function of beam brightness or luminosity.
- For example 1pb⁻¹ of luminosity means 1 event will be produced for a process of 1pb cross section.
Now back to our three scheduled questions!
Past Higgs Searches and Current Limits

- Over the last decade or so, experiments at LEP or the European e⁺e⁻ collider have been searching for the Higgs.
- Direct searches for Higgs production, similar to our Z mass measurement exclude $m_H < 114$ GeV.
- Precision measurements of electroweak parameters combined with DZero’s newest Run I top quark mass measurement, favor $m_H = 117$ GeV with an upper limit of $m_H = 251$ GeV.

* Nature 10 June 2004
A current Tevatron Search

- For any given Higgs mass, the production cross section, decays are calculable within the Standard Model
- There are a number of ongoing searches in a number of production and decay channels
- In the ~120 GeV region a good bet would be to look for Higgs and associated W or Z production
  - Cross section ~ 0.1-0.2 pb
  - e or µ decays of W/Z help distinguish the signal

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Search for HW production

- **One very striking and distinctive signature**

- **Look for**
  - an electron = track + EM calorimeter energy
  - neutrino = missing transverse energy
  - two b quarks = two jets each with a secondary vertex from the long lived quarks.
The $b\bar{b}$ jet mass distribution

Details:

- **W selection:**
  - Isolated, central electron, $p_T > 20$ GeV
  - Missing transverse energy $> 25$ GeV

- **Two Jet Selection:**
  - $E_T > 20$ GeV
  - Two tracks
  - Large impact parameter

- Efficiency about 1%
- Expect: $4.4 \pm 1.2$
- Observe: 6

![Dijet Mass (GeV) vs Events](image)
Limits

- Mass distribution consistent with Standard Model $Wb\bar{b}$, $t$, $W$, $Z$ production
- 9 pb upper cross section limit at $m_H=115$ GeV for $pp\rightarrow WH$ and $H\rightarrow bb$.

In the mass window 85-135 still factor of 20 from expectation, but by the end of Run II and combining all channels, we should have sensitivity to $\sim 130$ GeV.
A candidate
A second candidate
Well actually... there’s at least one Higgs, in Scotland

...but we will keep looking for more!
The Search for Extra Dimensions

• The strengths of the electromagnetic, strong, and weak forces change with energy, suggesting grand unification of these forces.

• It is believed that gravity becomes as strong as the other forces and unifies with them at the energy known as the Planck scale.

• Difficult to find a natural way to make gravity much weaker than other forces at lower energy scales.

• It has been suggested that there are extra, compact, spatial dimensions, in which only gravity can propagate, and which are therefore hidden from our everyday experience.

• Gravity would therefore be as strong as other forces, but appears diluted and weak from our four space-time dimensional viewpoint in which we are “confined”...but once again...
A Model with “n” Dimensions.

- Gravity communicating with these extra dimensions could produce an unexpectedly large number of electron or photon pairs.
- Thus, analysis of the production rate of electrons and photons provides sensitivity to these extra dimensions.
- Large energies are required to produce such pairs.
• Di-electro-ge magnetic objects (>25 GeV) are collected as the mass calculated (just as in our Z plot a few minutes ago).

• The observed mass spectrum is compared to a linear combination of
  – SM signals
  – Instrumental backgrounds
  – Extra Dimension Signals

• No evidence is found for hidden dimensions, @ 95%CL
  – $n = 2, 170 \, \mu m$
  – $n = 3, 1.5 \, \text{nm}$
  – $n = 4, 5.7 \, \text{pm}$
  – $n = 5, 0.2 \, \text{pm}$
  – $n = 6, 21 \, \text{fm}$
  – $n = 7, 4.2 \, \text{fm}$

Note the long mass tail
Or a Single TeV$^{-1}$ size Extra Dimension

- Another idea introduces a single dimension of the size of $\sim 10^{-19}$ m (or $\sim 1$ TeV$^{-1}$ in “natural” units), where the carriers of the electroweak and strong force (photons, W and Z particles, and gluons) can propagate.
- We also see no evidence for a single extra dimension of $\sim 1$ TeV$^{-1}$ size.
- At 95% CL size limit $1.75 \times 10^{-19}$ m

Note the long mass tail
Once again there are interesting events!
(way out on the mass tail.)

ee pair

γγ pair
Supersymmetry

• Reminder: Postulates a symmetry between bosons and fermions such that all the presently observed particles have new, more massive super-partners.

• Theoretically attractive:
  – Additional particles cancel divergences in $m_H$
  – SUSY closely approximates the standard model at low energies
  – Allows unification of forces at much higher energies
  – Provides a path to the incorporation of gravity and string theory: Local Supersymmetry = Supergravity
  – Lightest stable particle cosmic dark matter candidate

• Masses depend on unknown parameters, but expected to be 100 GeV - 1 TeV
The Golden Tri-lepton Supersymmetry Signature

- In one popular model the charged and neutral partners of the gauge and Higgs bosons, the charginos and neutralinos, are produced in pairs.
- Decay into fermions and the Lightest Supersymmetric Particle (LSP), a candidate for dark matter.

- The signature is particularly striking:
  - Three leptons = track + EM calorimeter energy or tracks + muon tracks (could be eee, eeμ, eμμ, μμμ, eeτ, etc...).
  - Neutrino = missing transverse energy.
Trilepton Search Results

- Four tri-lepton channels
  - Electron, electron, lepton
  - Muon, muon, lepton
  - Electron, muon, lepton
  - Like sign muon-muon

- Cuts
  - Two leptons
  - Pt > 5-12 GeV
  - Missing Et > 22 GeV
  - Track above 3 GeV

- About 320 pb$^{-1}$
- Expected: 2.9 +/- 0.8
- Observe: 3 events
Interesting events do turn up...but we are now severely constraining the allowed SUSY parameter space.
Adding e+\tau+lepton and \mu+\tau+lepton
More than just interesting events… SUSY provides an attractive plot device for the fourth season of Angel, 2002. Consider this synopsis: While Fred [lead female] is speaking [at a conference about her article on SUSY], a portal opens above her head and a tentacle demon tries to kill her!!!!!!

Don’t you sometimes wish!?
The Future: A Huge Data Set to Explore

- These analyses ~400 pb\(^{-1}\), have already logged 0.6 fb\(^{-1}\)
- Expect to see 8 fb\(^{-1}\) this run.

These hints and events should become even more interesting…
Prospects

- The Tevatron is stretching the boundaries of the observed universe:
  - Constrain the SM and place limits on the Higgs mass or
  - Better yet: observe/discover the Higgs
  - Discover new physics ... SUSY
  - Communicate with extra dimensions....

- A thoroughly exciting challenge to answer the most basic questions...
  - What is the history of the universe?
  - What is the composition of the universe?
  - What is the structure of the universe?
  - It seems some answers are already in Hollywood!

“To the [Microscopic] Universe.... and Beyond!”

Toy Story - 1995