Particle and Hadron Collider Physics: One Experimentalist's Overview

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Thanks to Bob Hirosky, Virginia

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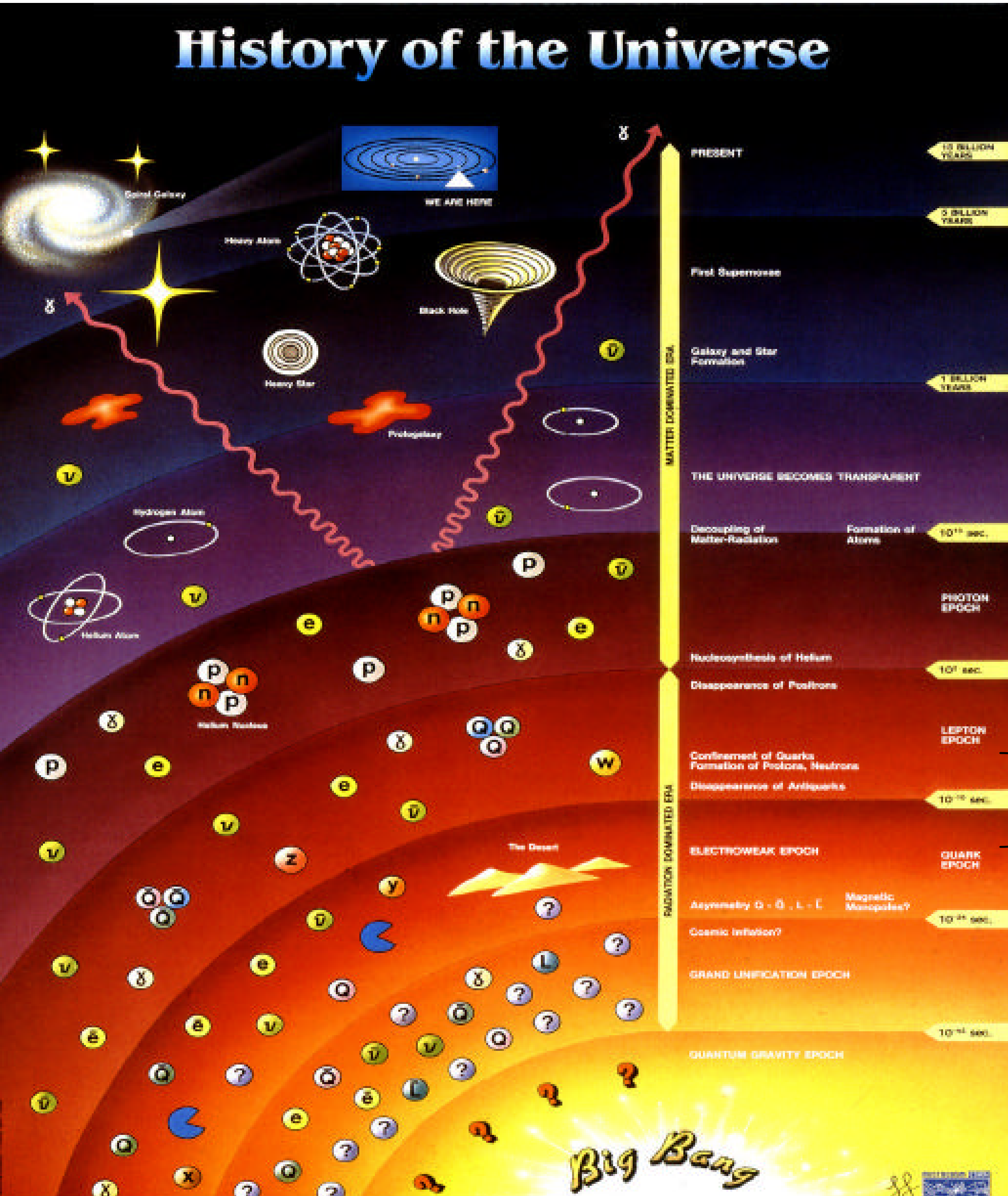
Cosmic Context



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
~10^{-12} seconds

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The Universe at 10^{-12} s → The Standard Model

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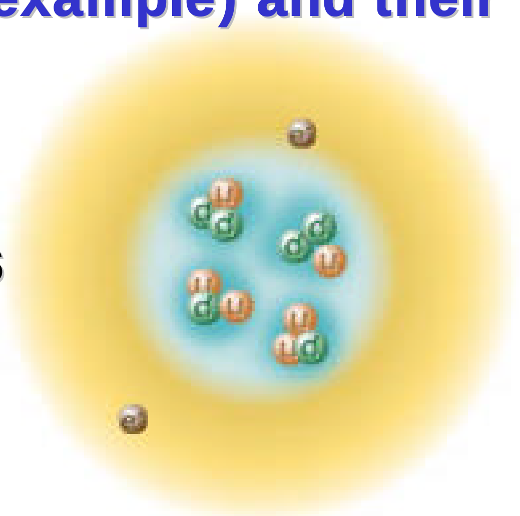
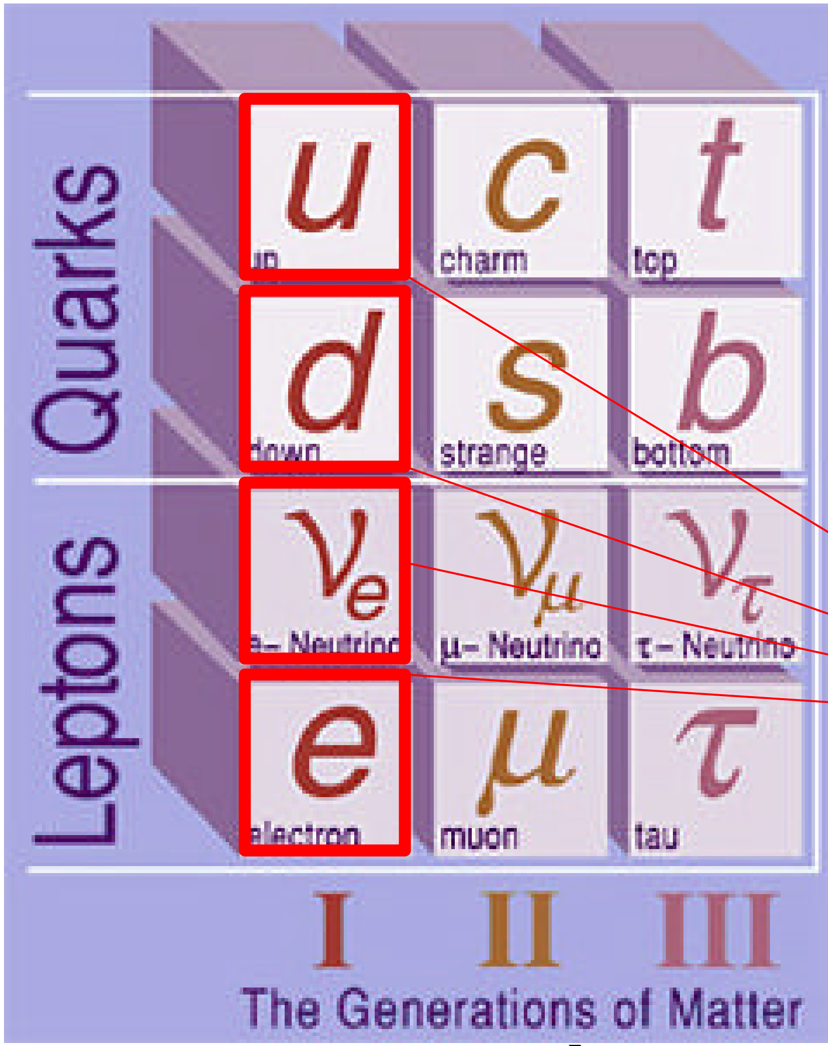
In a few words...

- **Simple: "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 (those little fellows 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."**



Periodic Table of Fundamental Particles



Mass →

Charge

+2/3

−1/3

0

−1

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

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Standard Model Interactions Mediated by Boson Exchange

Unification (Weak, Electromagnetic)

	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

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

Explained by Standard Model (Weak, Electromagnetic, Strong)

We could stop here but…..

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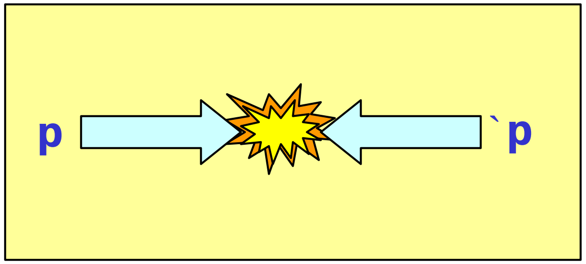
How do we test these theories at a hadron collider?

The Two Basic Ideas:

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

The Sources:

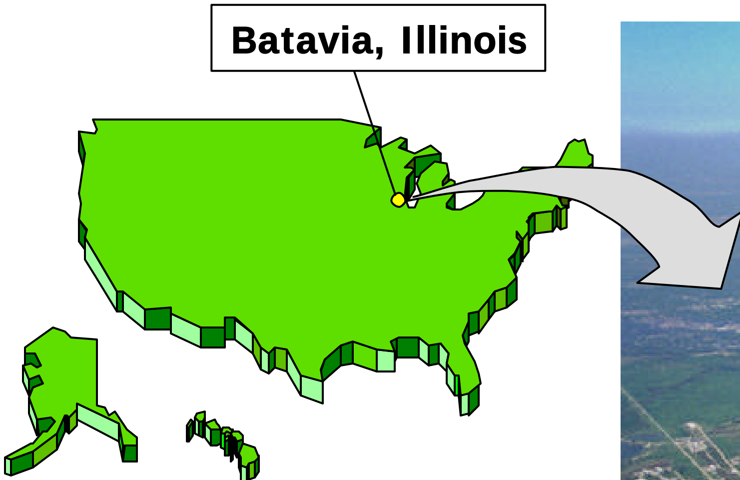


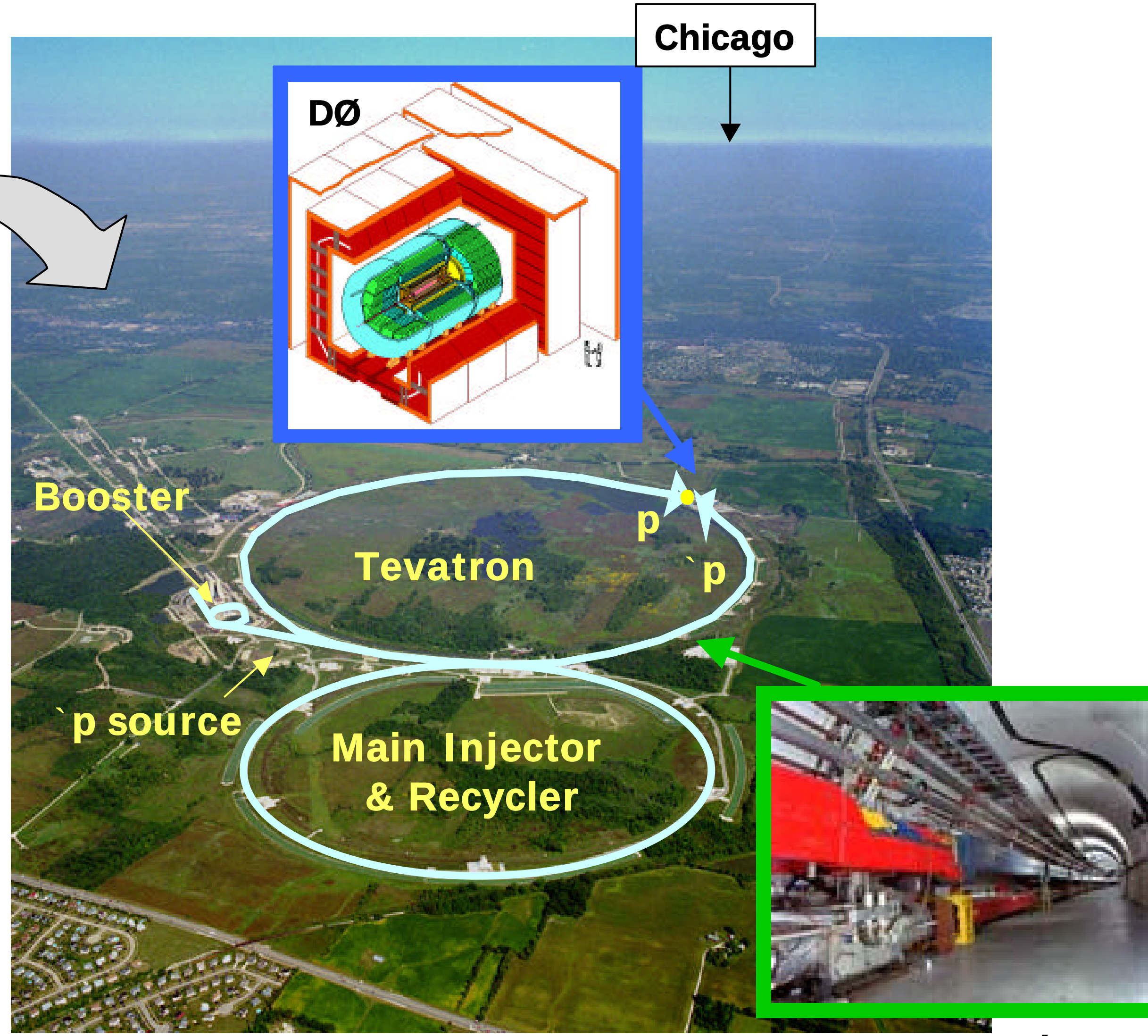
- Cosmic Rays
- Accelerators
- The higher the energy the more numerous the number and types of particles.

The Detectors:

- A series of special purpose devices that track and identify collision products

An example:
Fermilab Proton-Antiproton Collider





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

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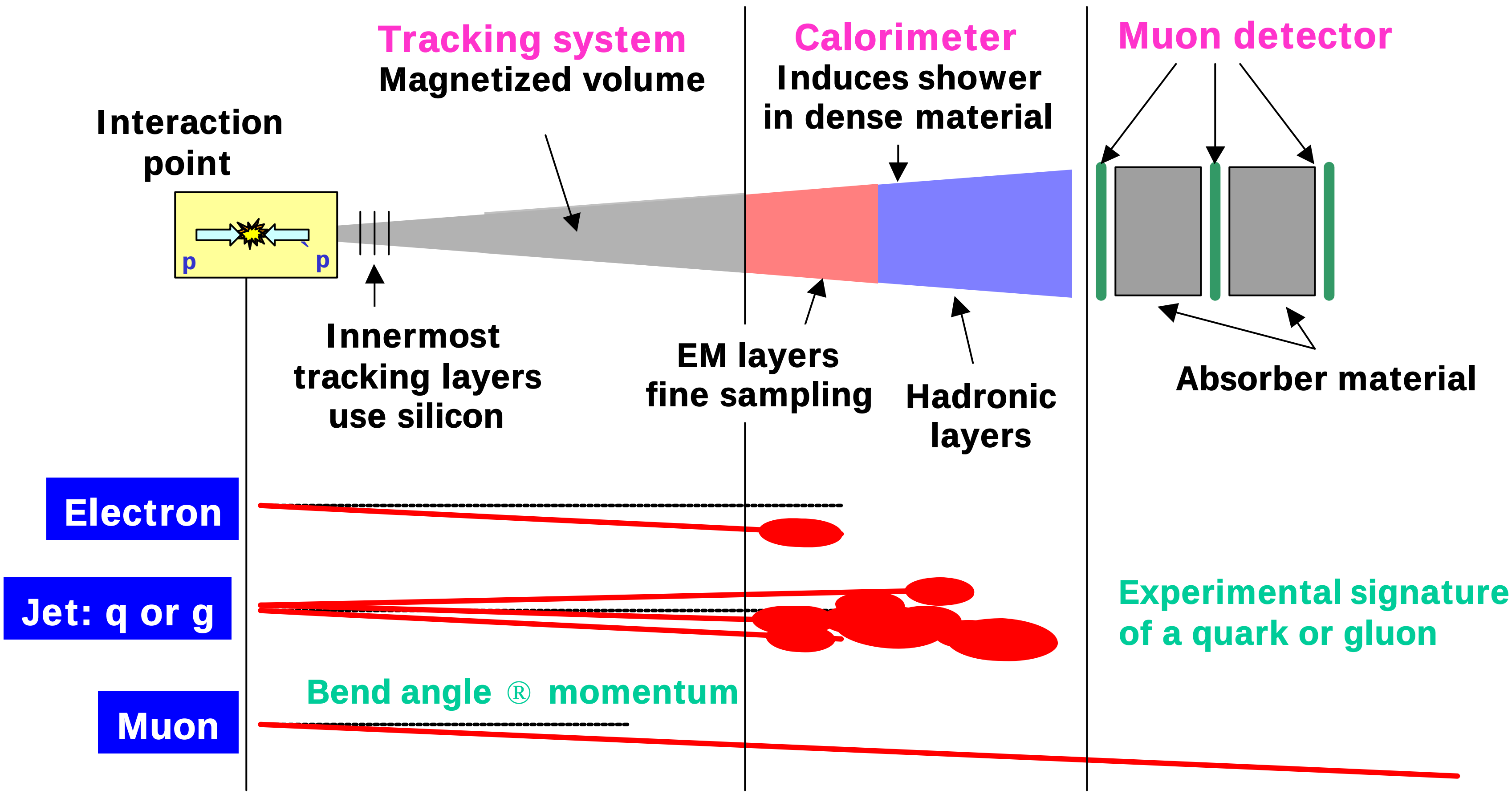
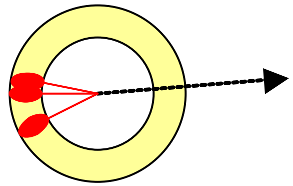
A Schematic Hadron Collider Detector





"Missing transverse energy"

Signature of a non-interacting (or weakly interacting) particle like a neutrino

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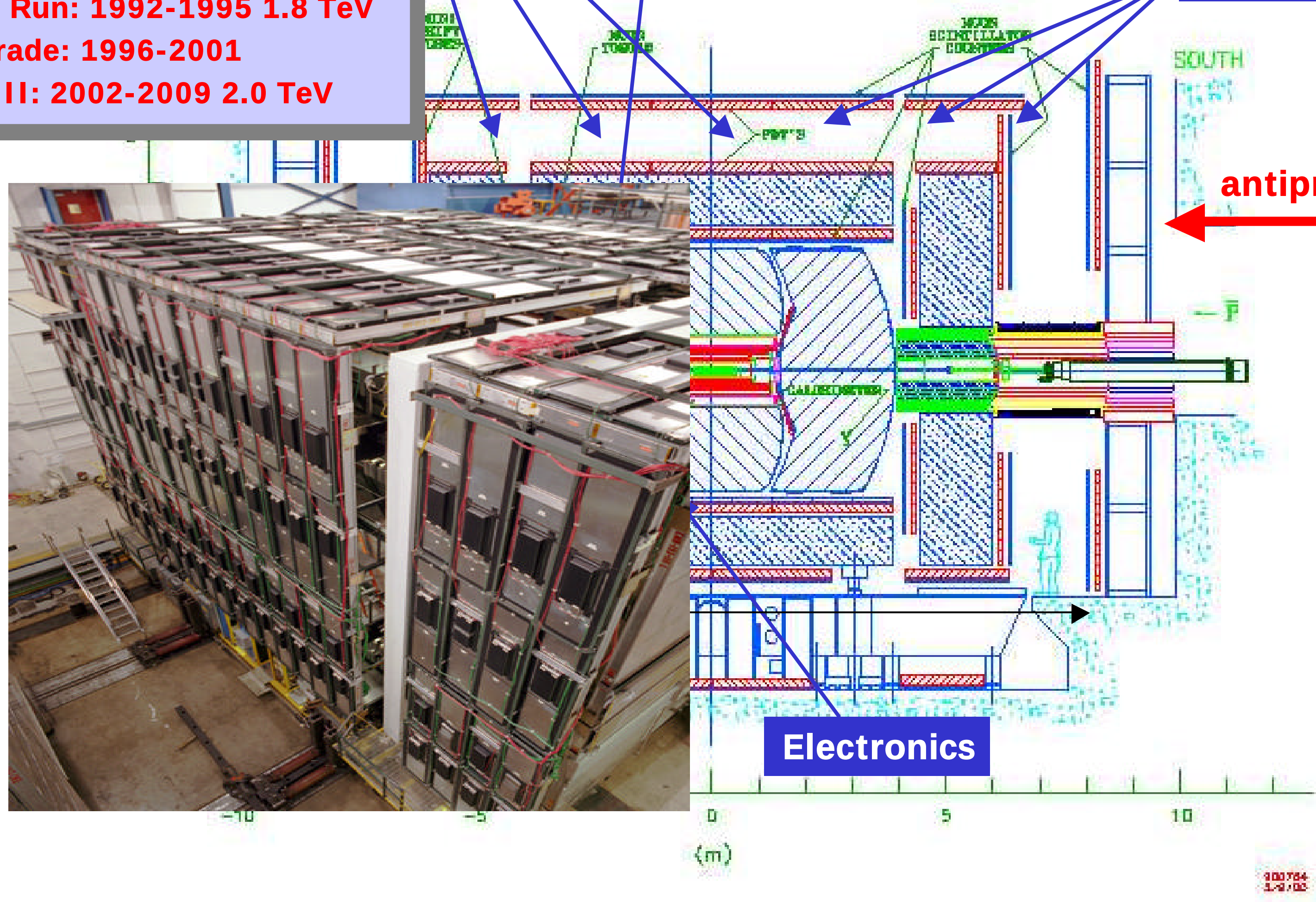
- **A Real Experiment: DZero**
  - **Proposed 1982**
  - **First Run: 1992-1995 1.8 TeV**
  - **Upgrade: 1996-2001**
  - **Run II: 2002-2009 2.0 TeV**



International

- **19 countries**
- **80 institutions**
- **650+ physicists**

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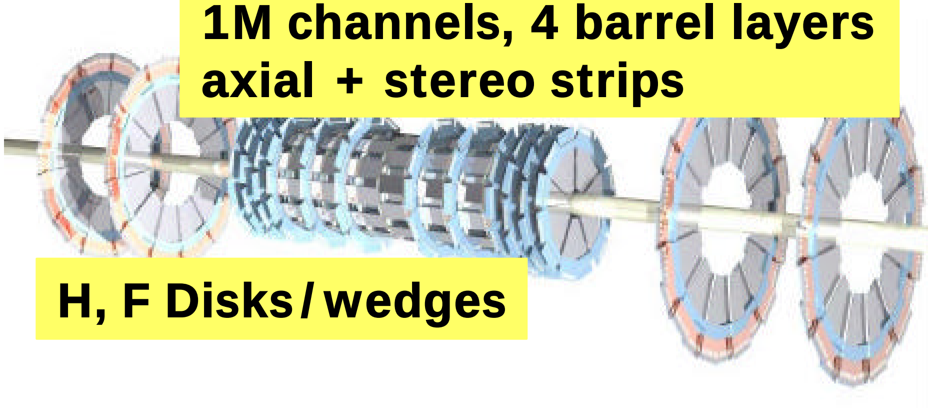

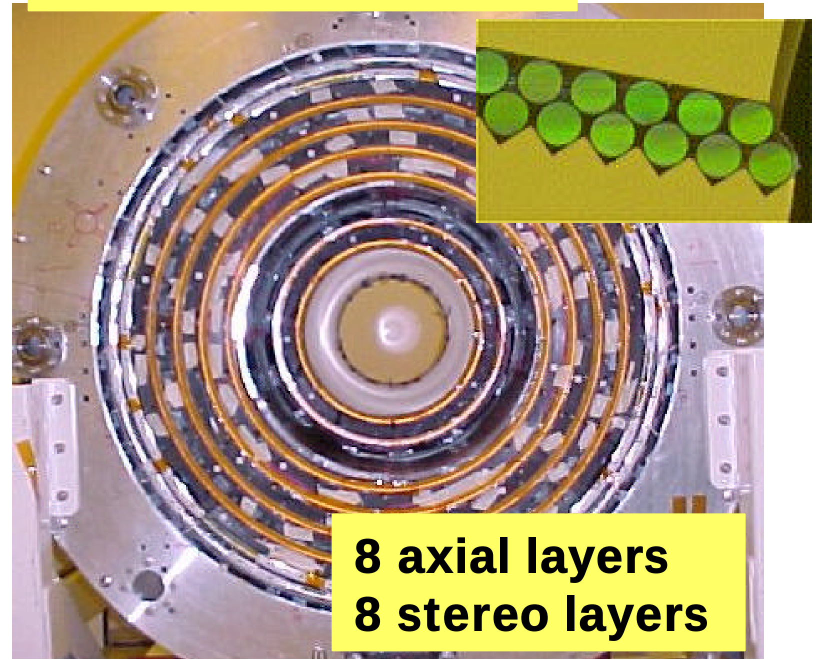

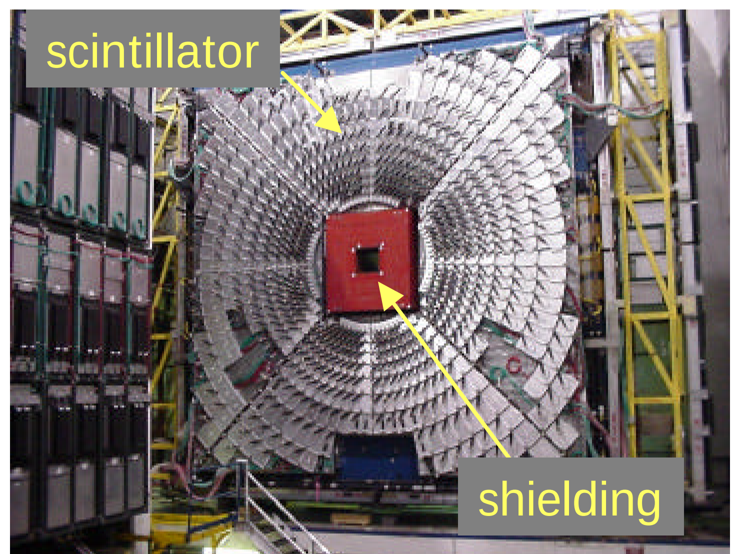

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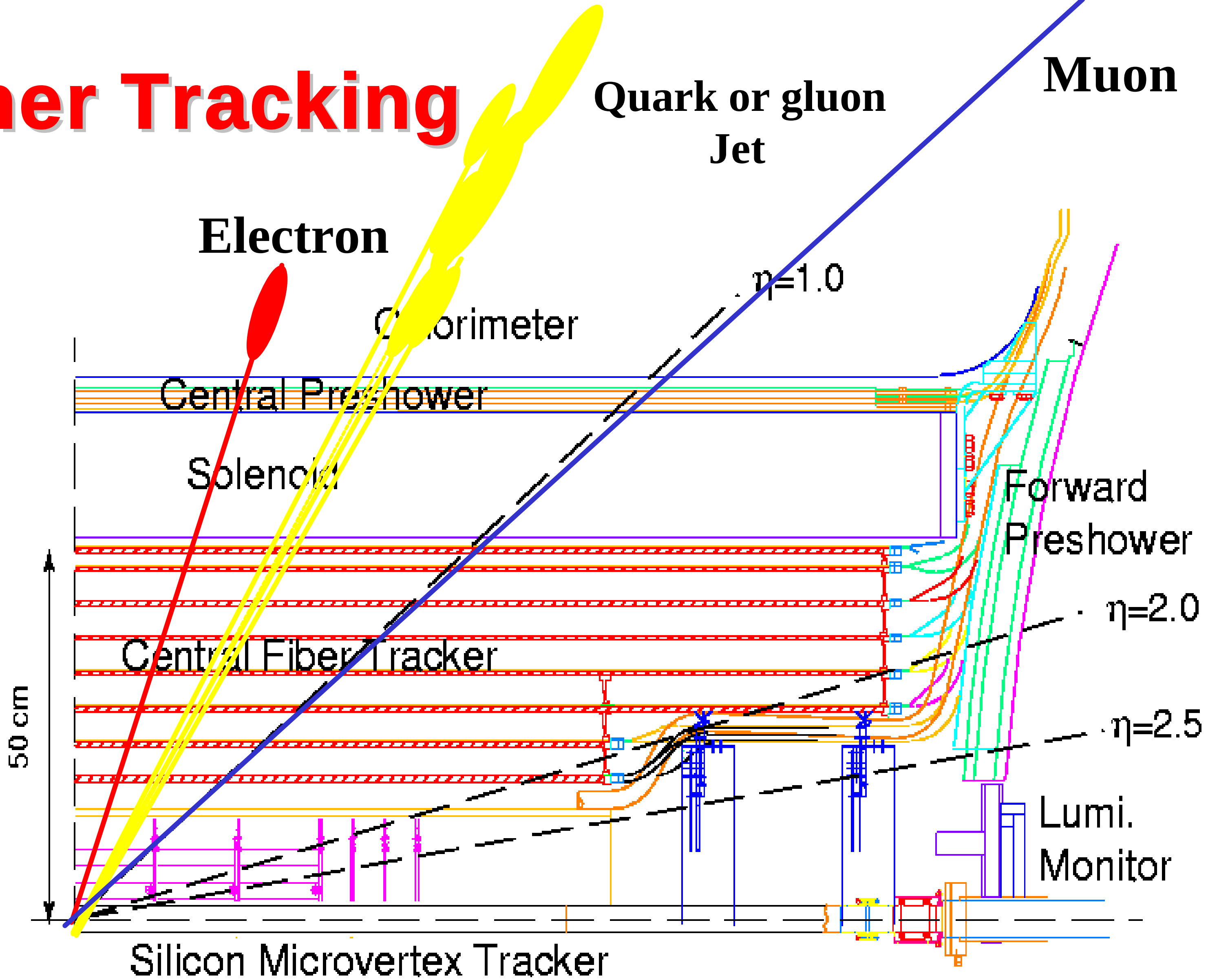
Inner Tracking



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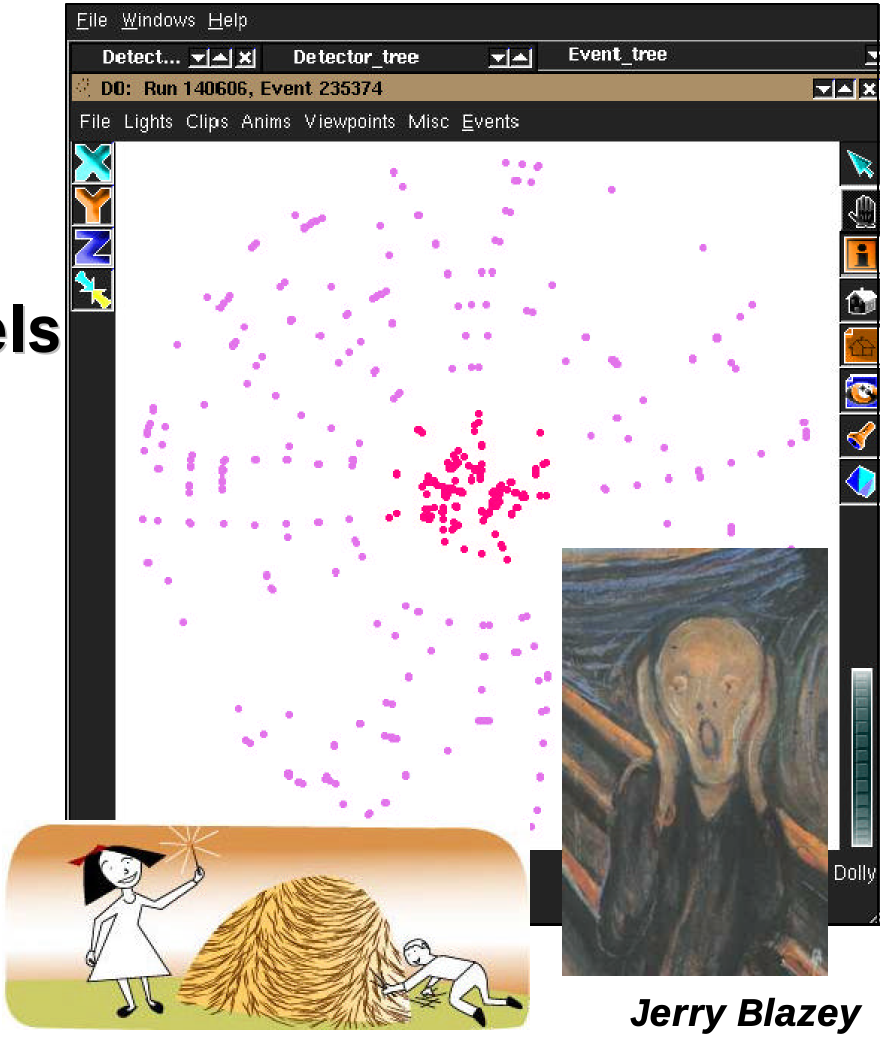
Run II: 24/7 Event Collection

- 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.**



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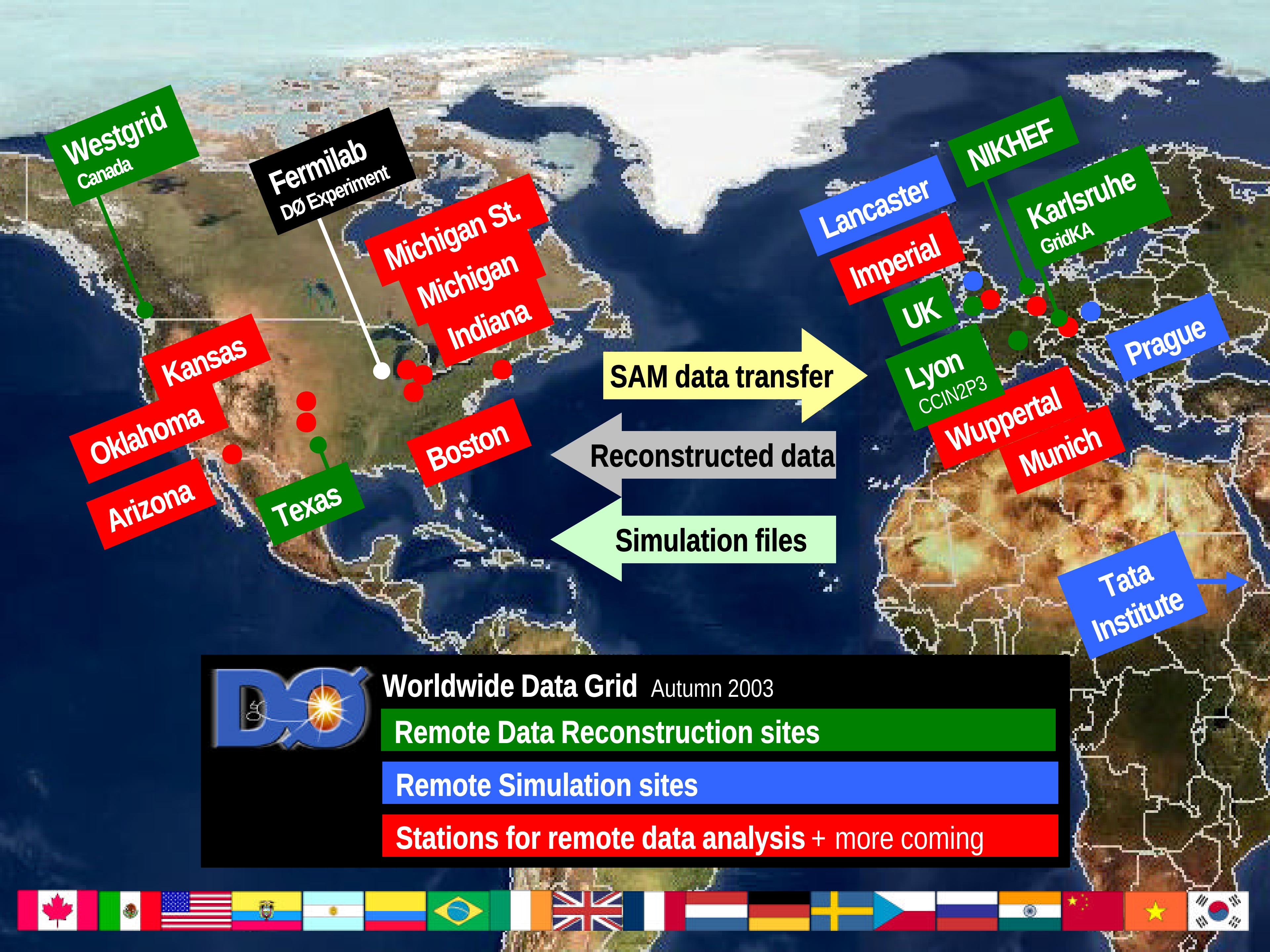
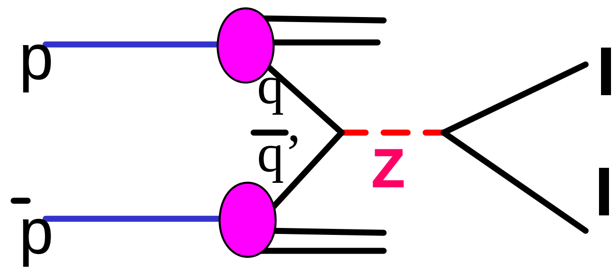
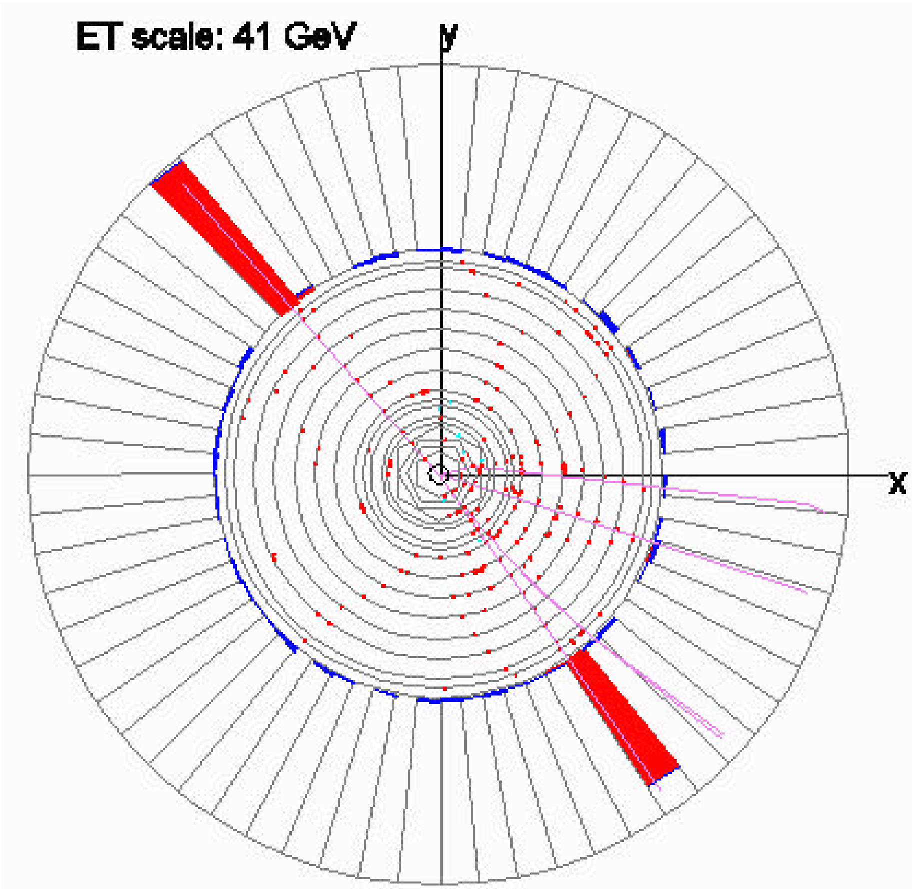
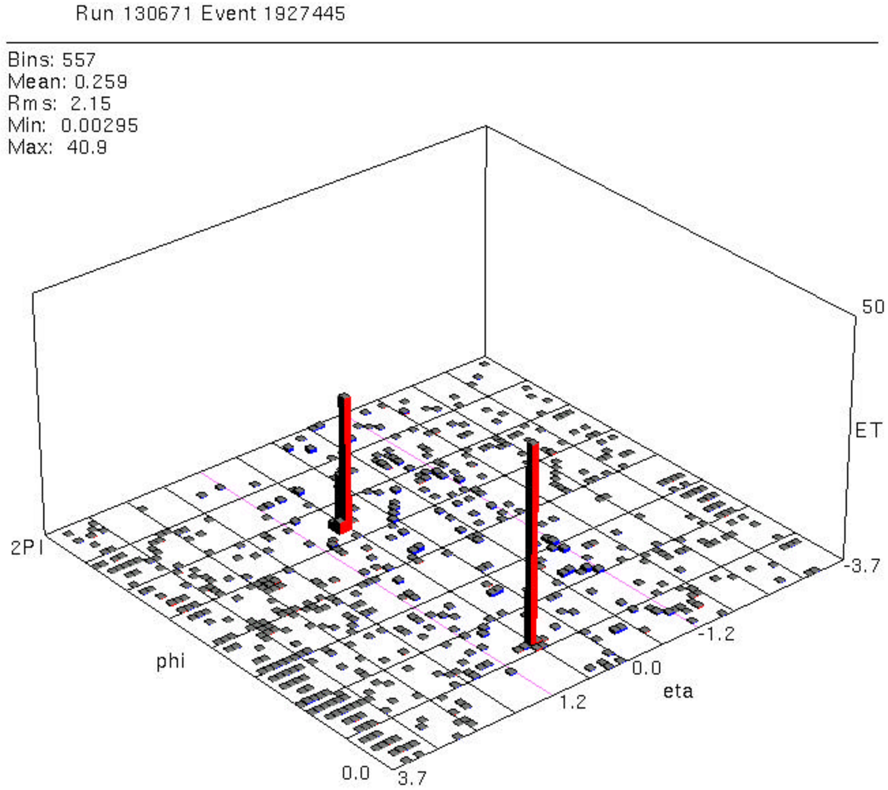

Westgrid
Canada
Fermilab
DØ Experiment
Michigan St.
Michigan
Indiana
Kansas
Oklahoma
Arizona
Texas
Boston
SAM data transfer
Reconstructed data
Simulation files
Lancaster
Imperial
UK
NIKHEF
Karlsruhe
GridKA
Lyon
CCIN2P3
Prague
Wuppertal
Munich
Tata
Institute
DØ
Worldwide Data Grid Autumn 2003
Remote Data Reconstruction sites
Remote Simulation sites
Stations for remote data analysis + more coming

A Sample Event: $Z \rightarrow e^+e^-$

Feynman Diagram







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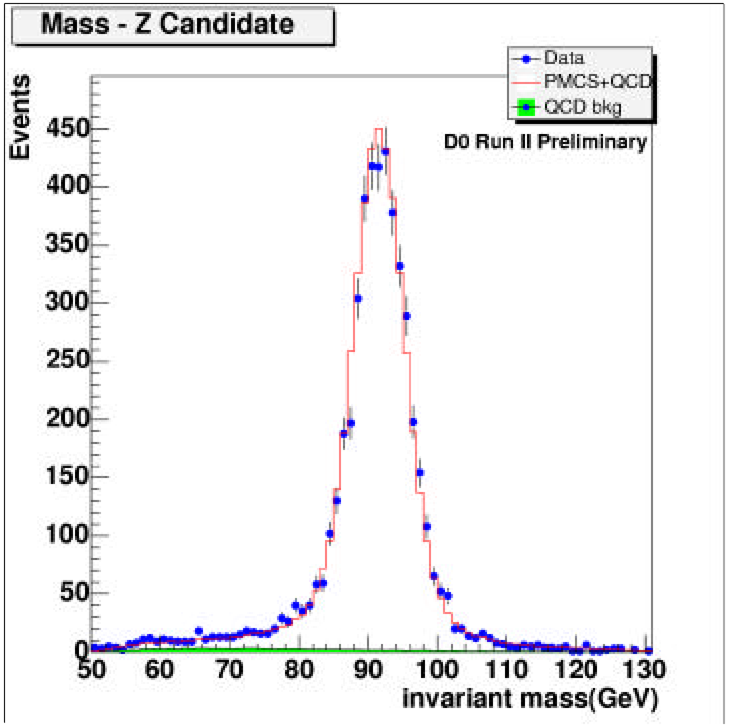
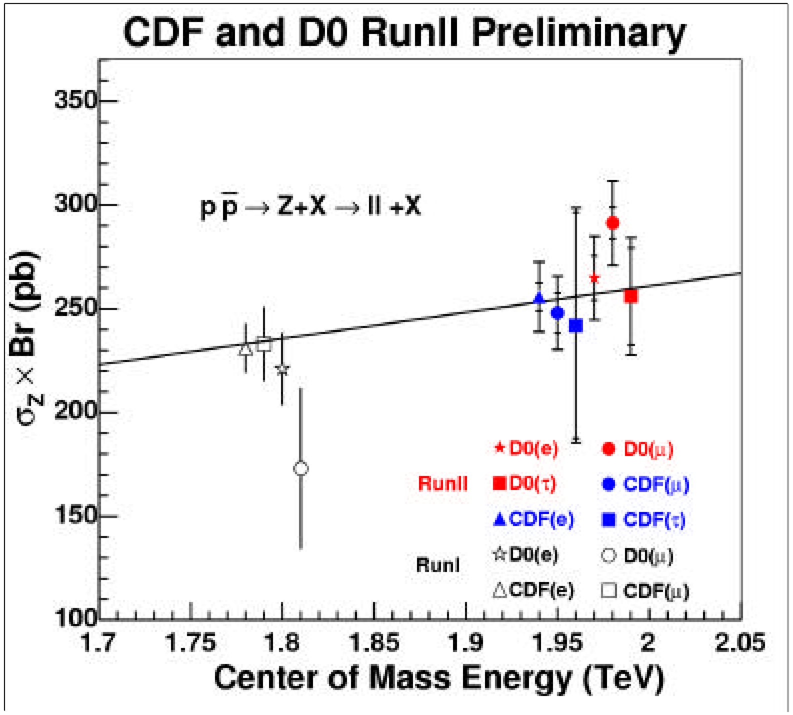
Sample Distribution: Z mass





- **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.**

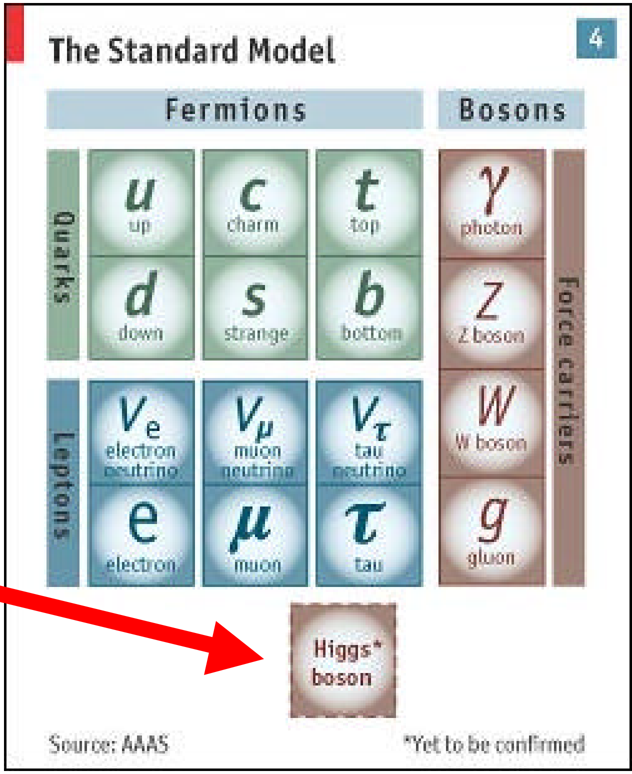
Compelling Questions That Can Be Addressed by Hadron Collider Physics

(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)?

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 the International Linear Collider are dedicated, in part, to the search for and study of this particle.**



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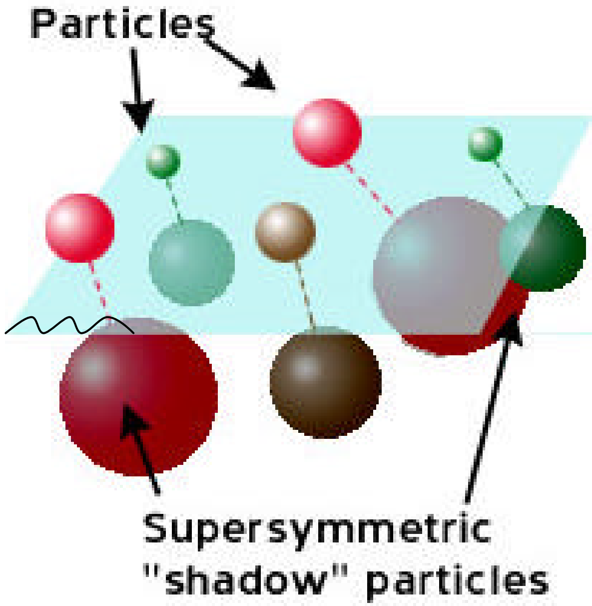
Beyond That?

- **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 the most popular theoretical option.**

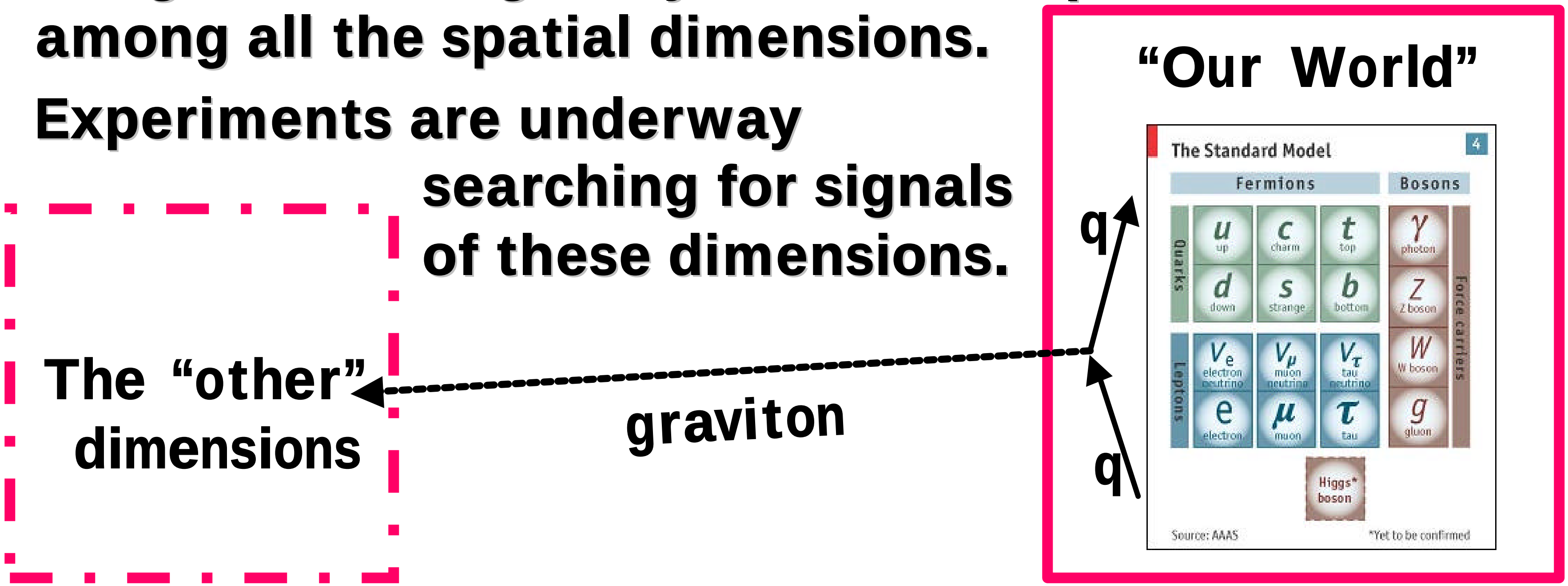
SUSY

- In SUSY every particle and force carrier has a massive partner: Squarks, slectrons, 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, the graviton, or gravity carrier can spread it's influence among all the spatial dimensions.**
- **Experiments are underway searching for signals of these dimensions.**



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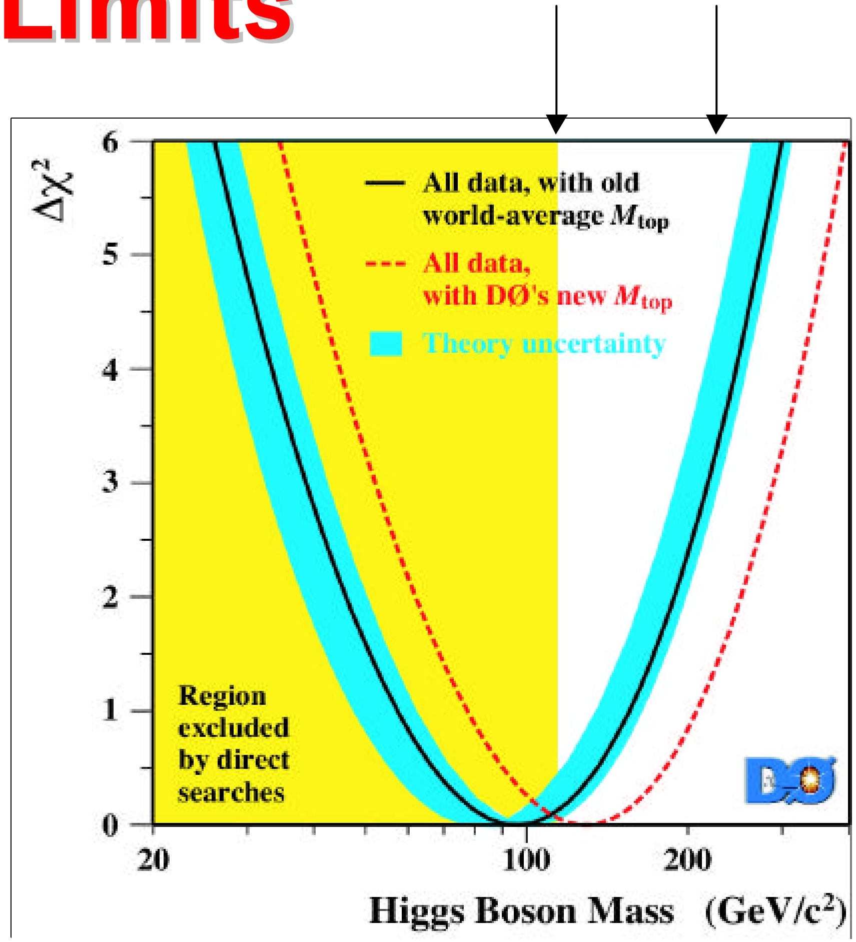
Past Higgs Searches and Current Limits

- 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 new* Run I top quark mass measurement, favor $m_H = 117$ GeV with an upper limit of $m_H = 251$ GeV.



* Nature 10 June 2004

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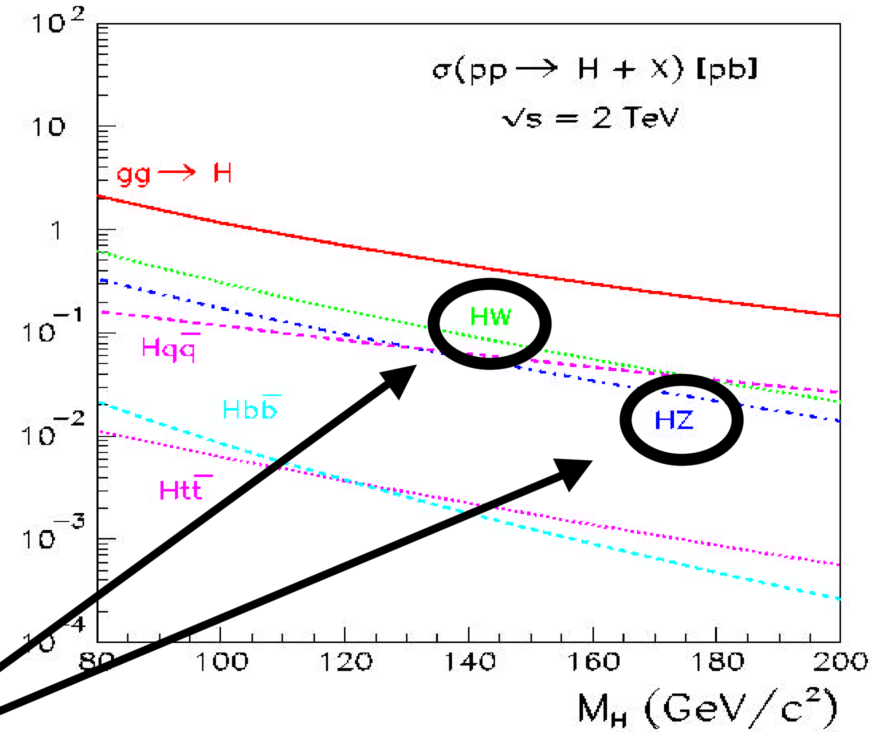
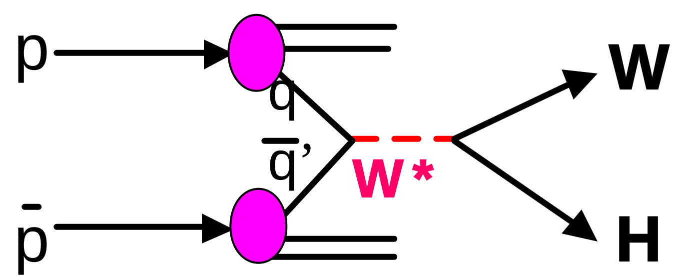
A Current Tevatron Searches

- **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 m decays of W/Z help distinguish the signal**





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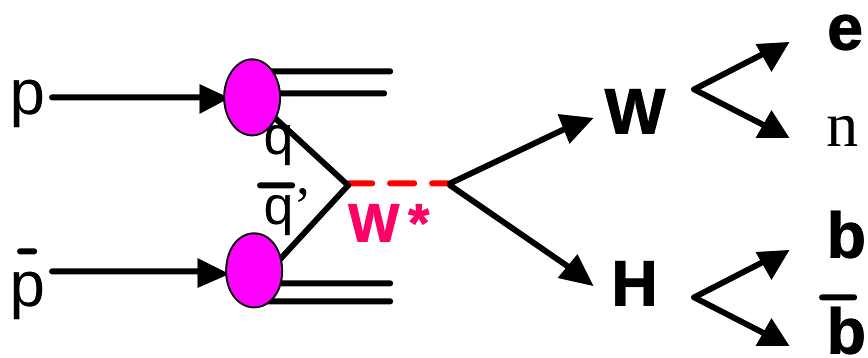
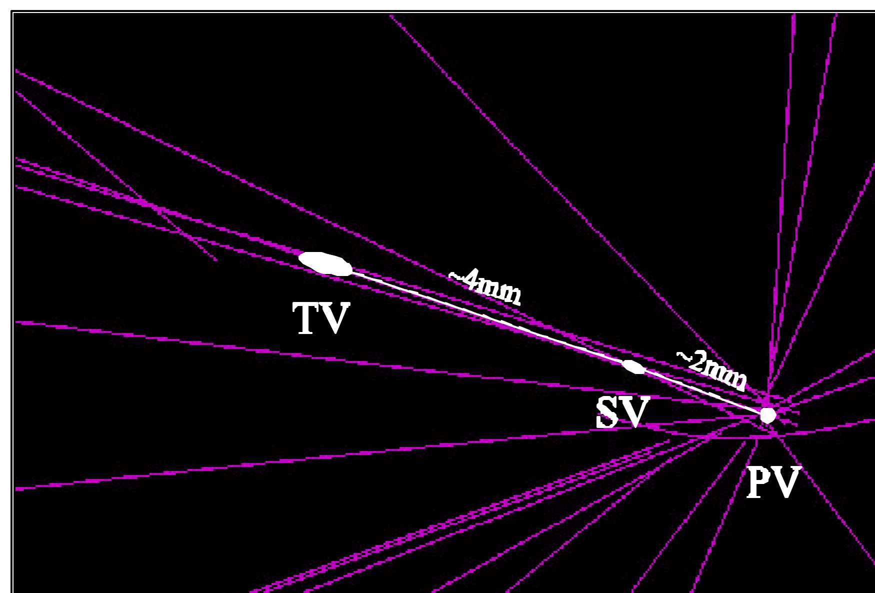
Search for HW production

- One very striking and distinctive signature



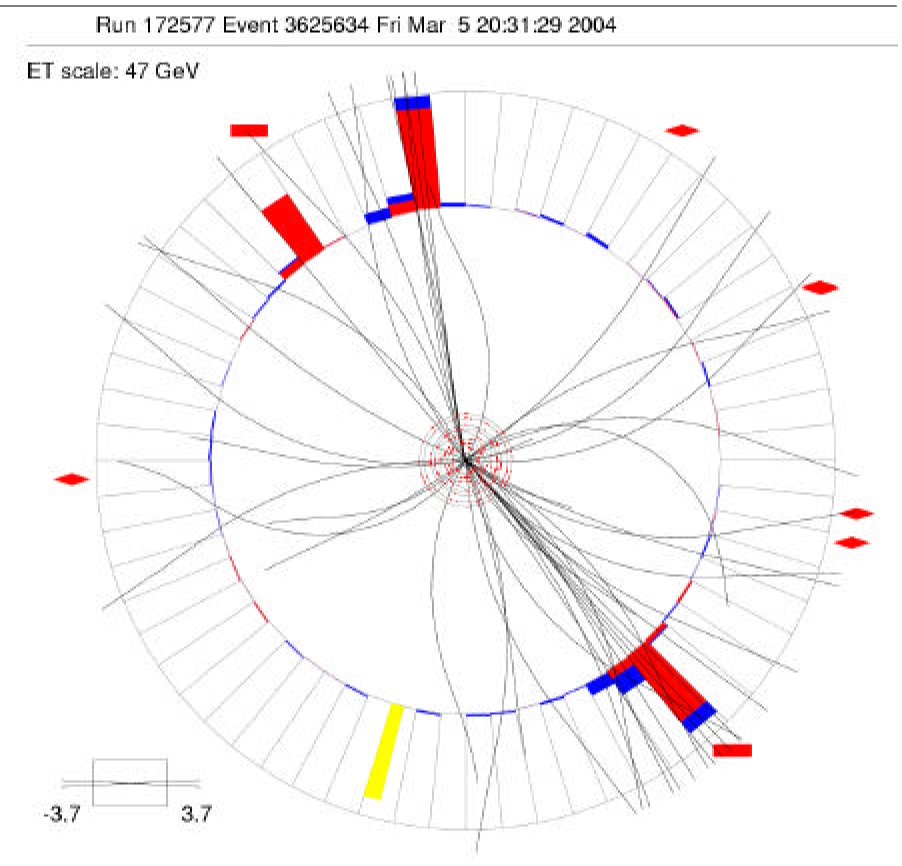
- Look for
  - an electron = track + EM calorimeter energy
  - neutrino= missing transverse energy
  - two b quarks =

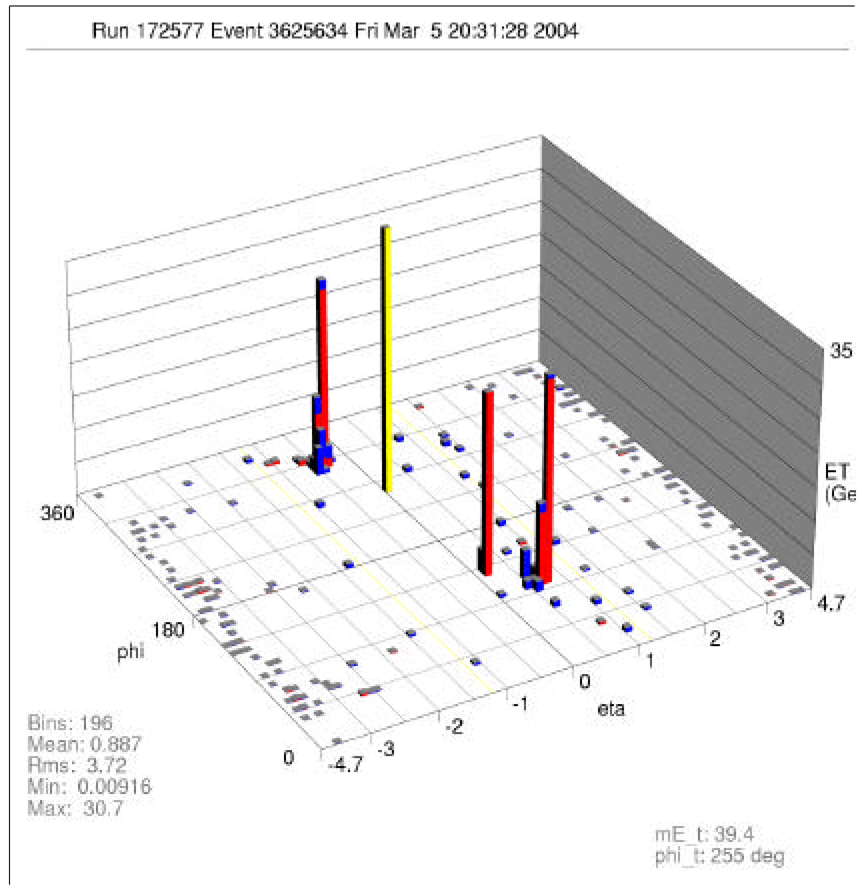
    two jets each with a secondary vertex from the long lived quarks.



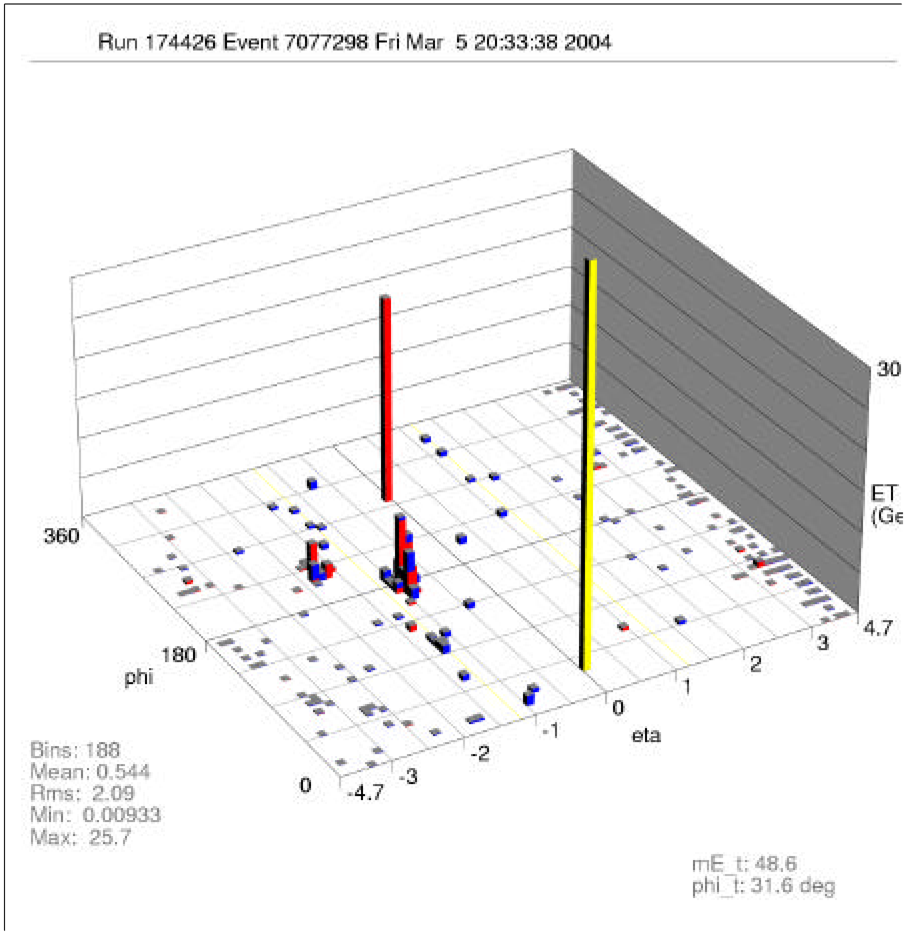
Results

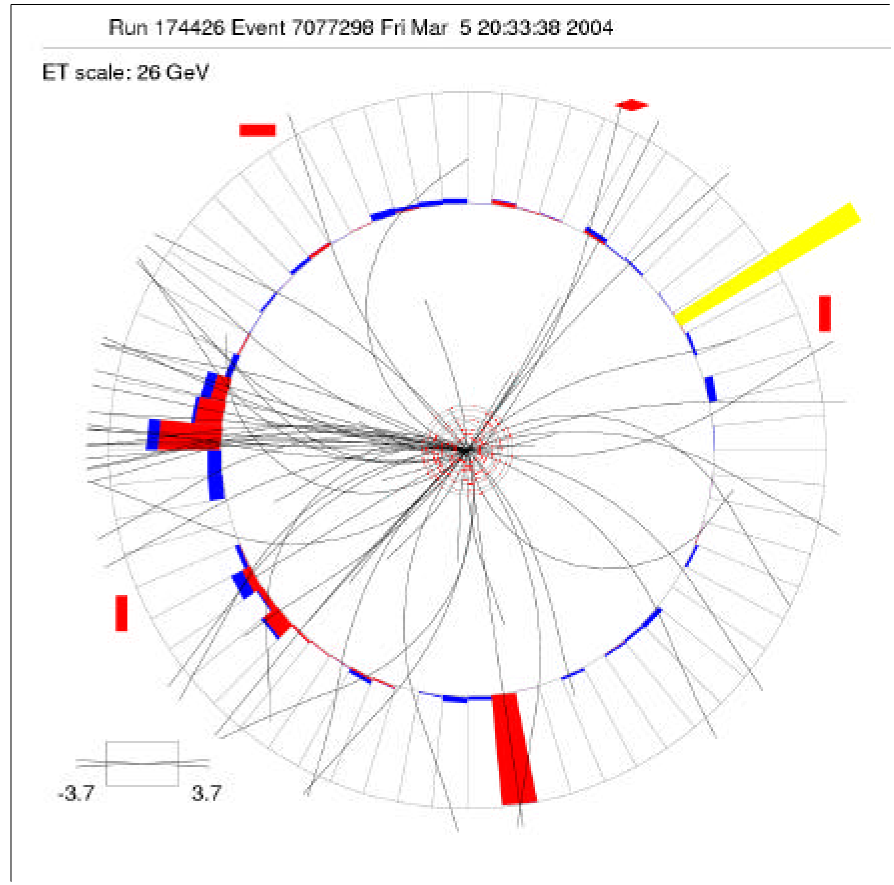
- Two events found, consistent with Standard Model Wb$\bar{b}$ production
- 12.5 pb upper cross section limit for pp→WH where H→bb m_H=115 GeV.
- By the end of Run II an combining all channels, we should have sensitivity to ~130 GeV.



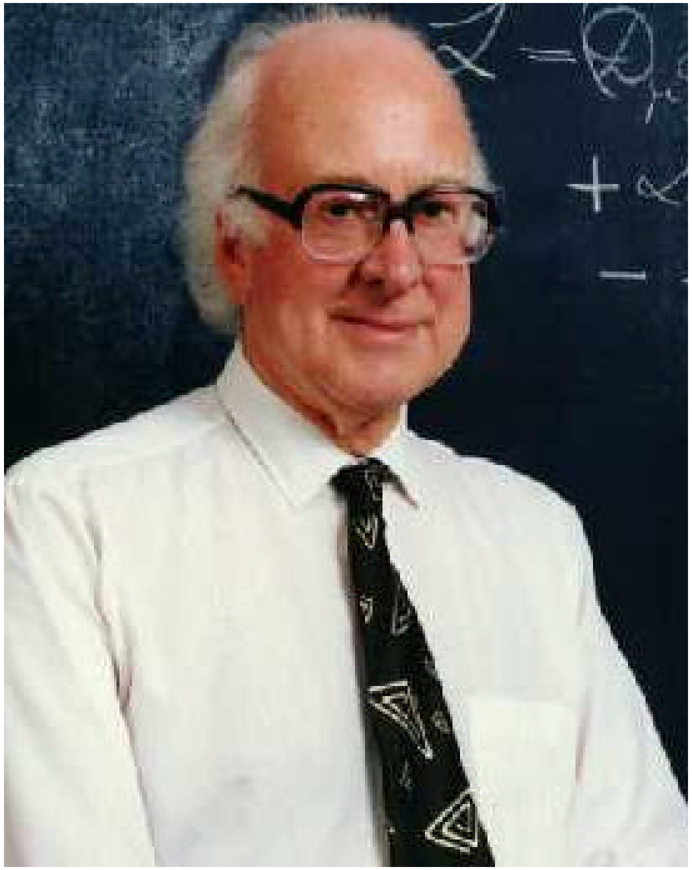


The other candidate….





Well actually... there's at least one Higgs, in Scotland



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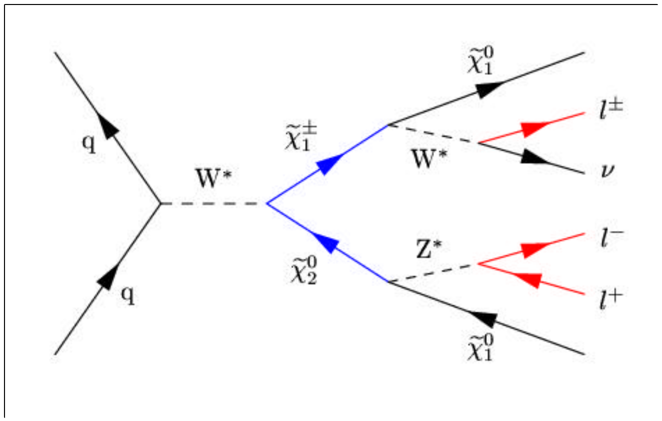
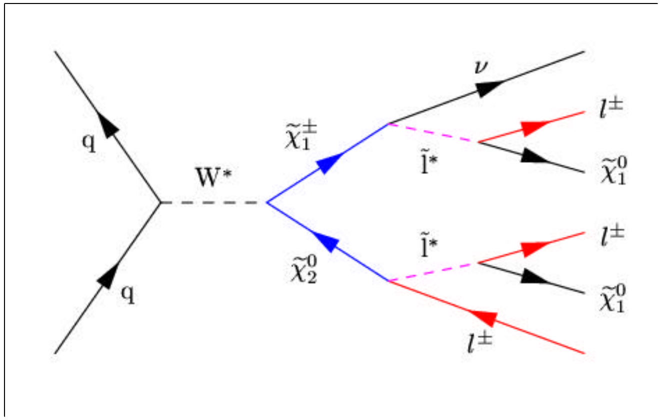
Supersymmetry

- **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.**

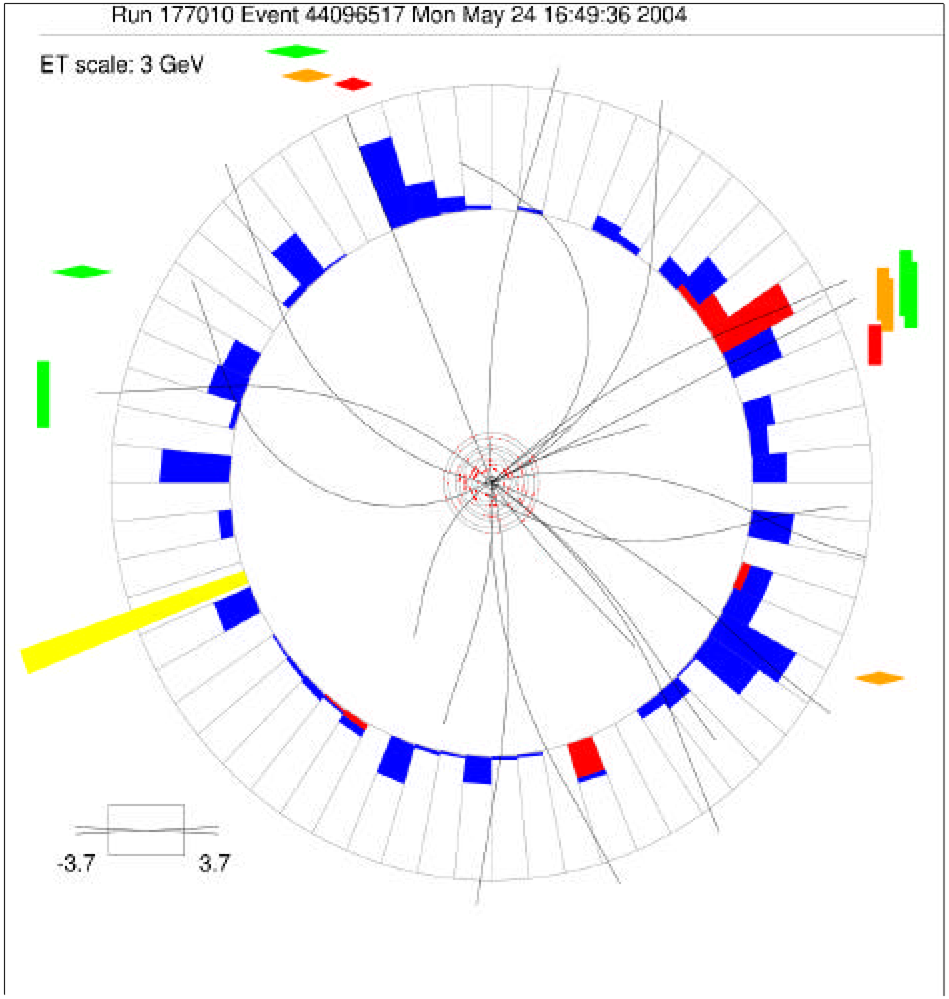




- **The signature is particularly striking:**
  - **Three leptons = track + EM calorimeter energy or tracks + muon tracks (could be eee, eem, emm, mmm, eet , etc…).**
  - **Neutrino+neutralino= missing transverse energy**

Trilepton Search Results

- **In four tri-lepton channels three events total found.**
- **Consistent with Standard Model expectation of 2.9 events.**
- **Here is a like-sign muon candidate**



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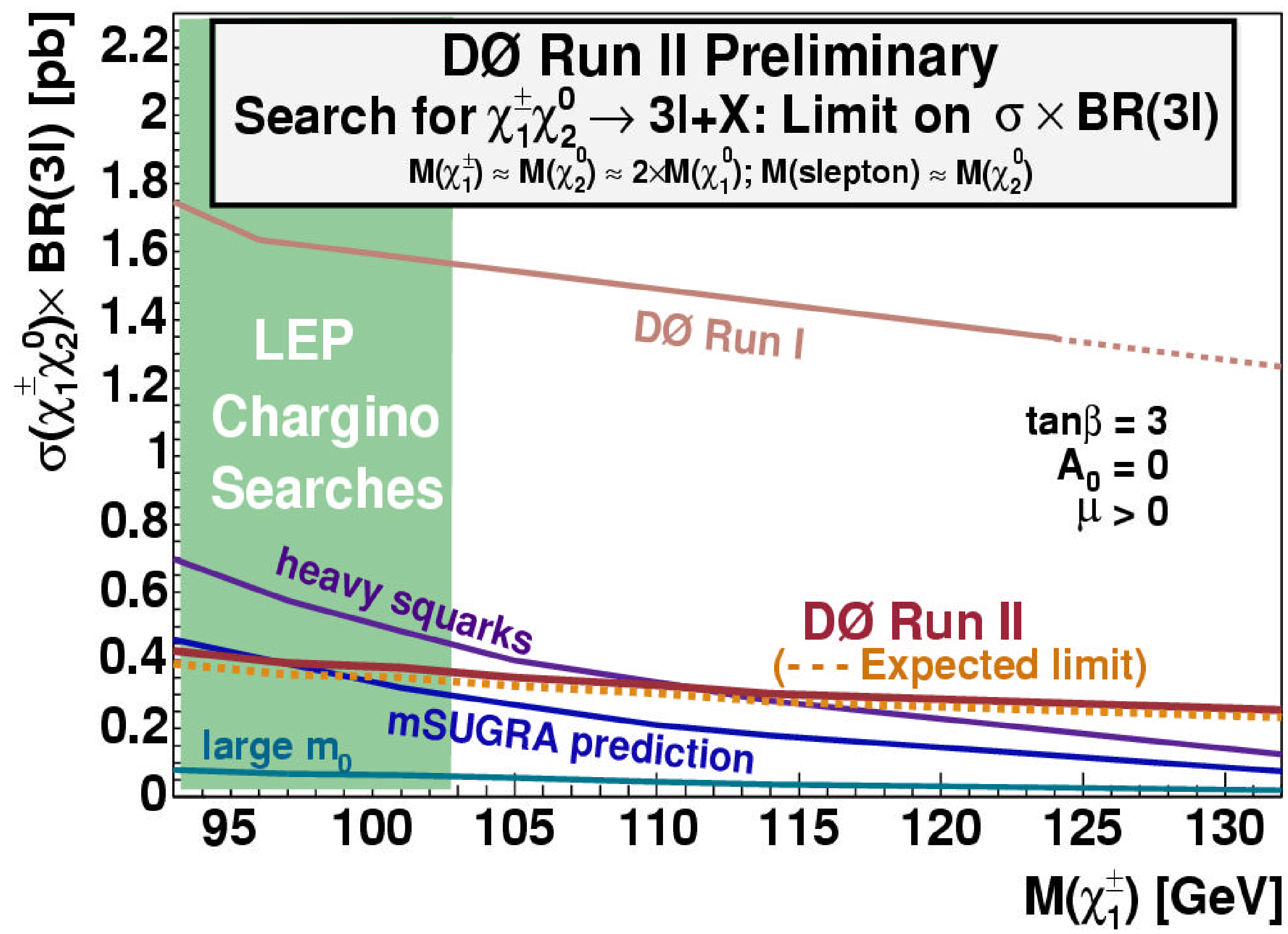
Interesting events do turn up…but we are now severely constraining the allowed SUSY parameter space.



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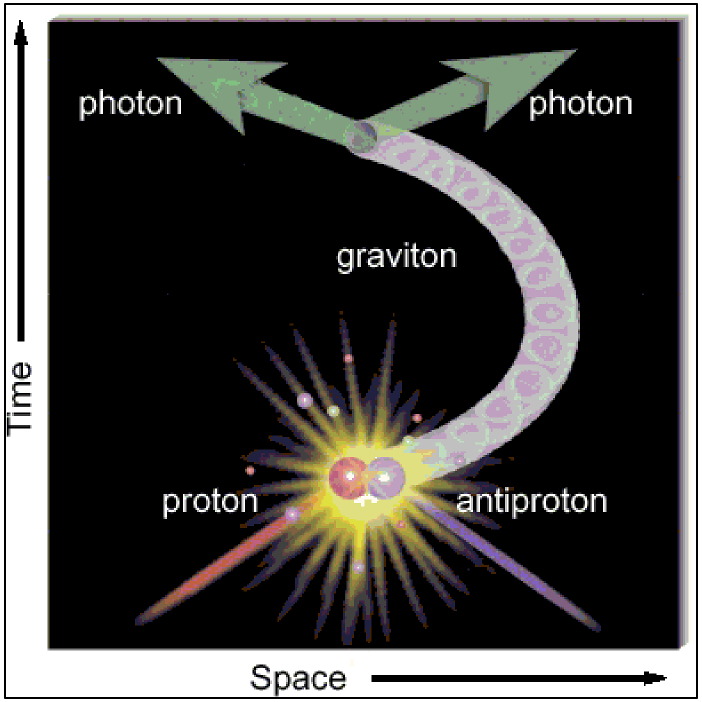
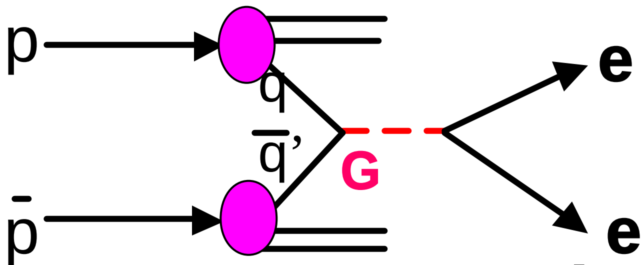
The Search for Extra Dimensions

- 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 photon provides sensitivity to these extra dimensions.
- Large energies are required to produce such pairs.





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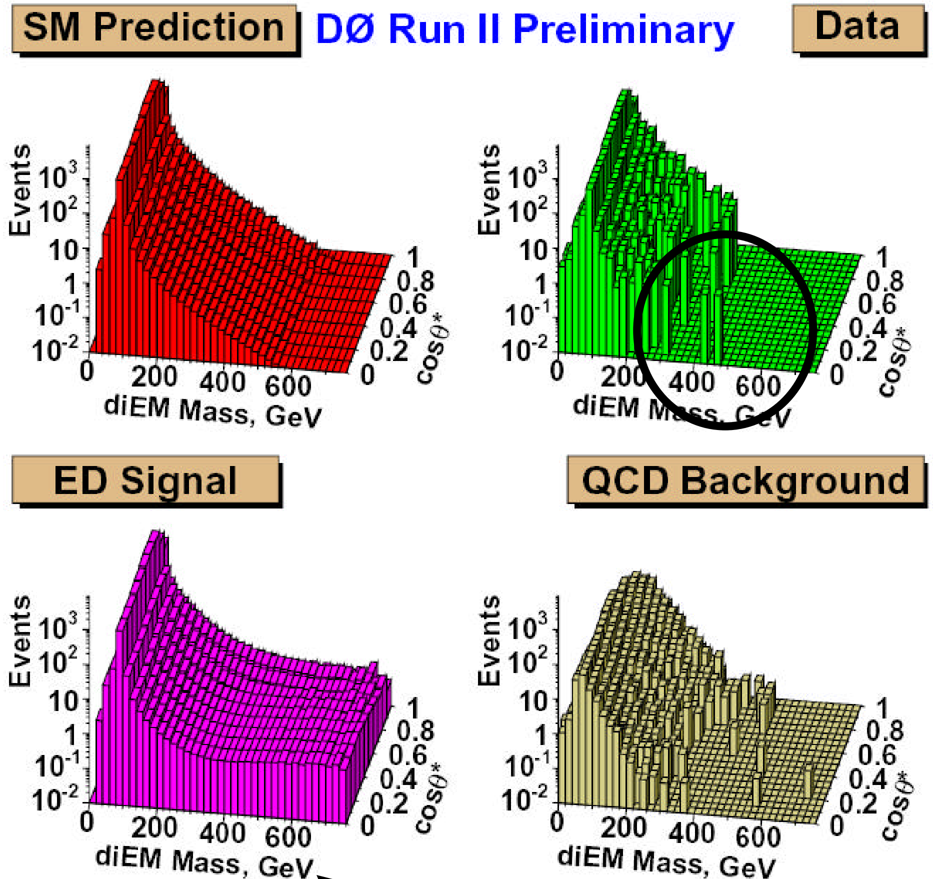

Note the long mass tail

- **Di-electrogmagnetic objects are collected an 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 mm**
  - ***n* = 3, 1.5 nm**
  - ***n* = 4, 5.7 pm**
  - ***n* = 5, 0.2 pm**
  - ***n* = 6, 21 fm**
  - ***n* = 7, 4.2 fm**

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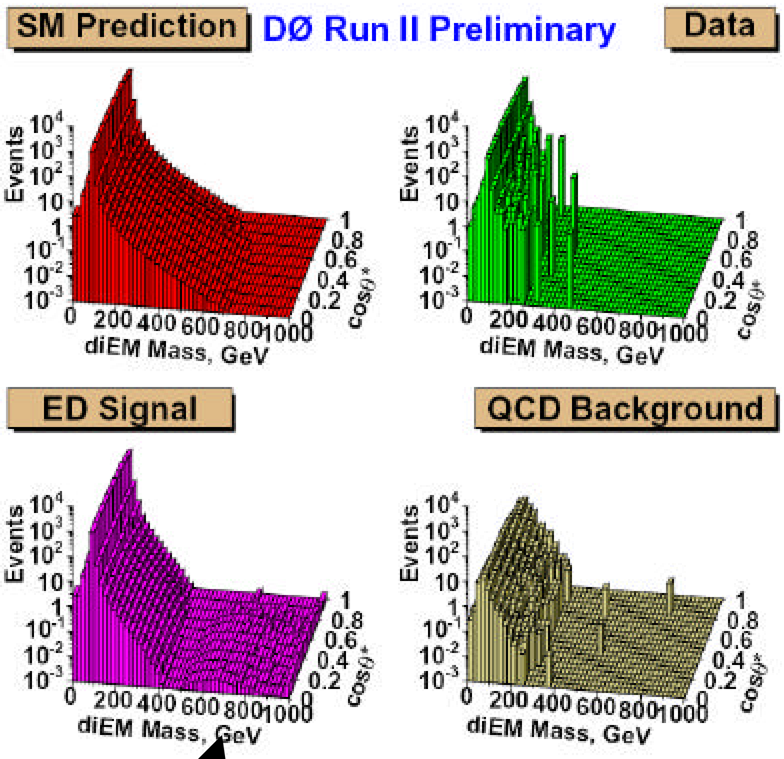
Or a Single TeV^{-1} size Extra Dimension

- **Another idea introduces a single dimension of the size of ~10^{-19} m (or ~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 ~1 TeV^{-1} size**
- **At 95% CL size limit 1.75×10^{-19} m**



Note the long mass tail

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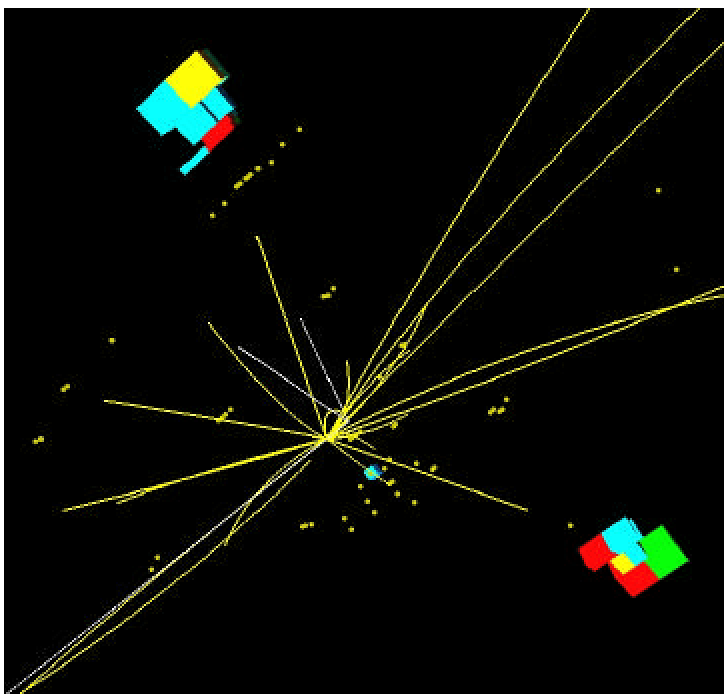
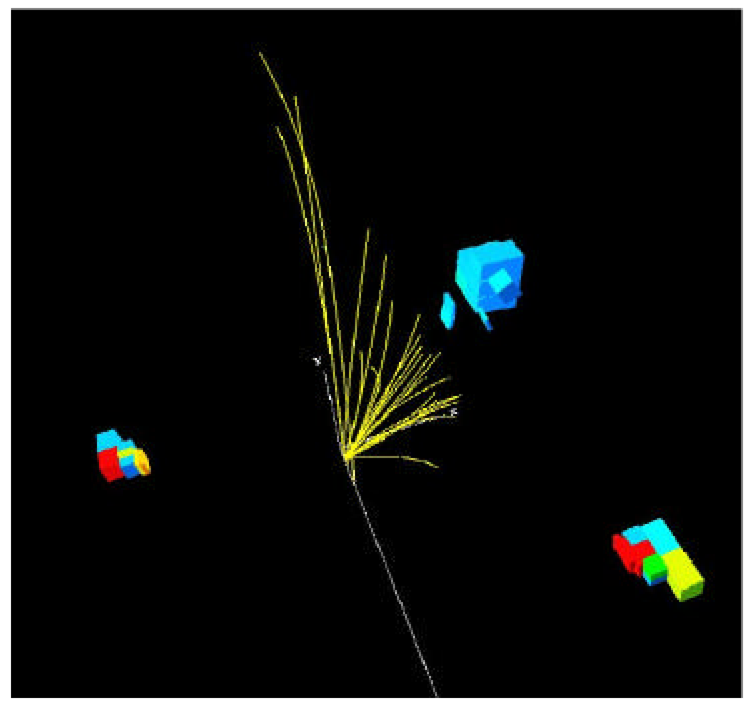
Once again there are interesting events!

(way out on the mass tail.)

ee pair



gg pair



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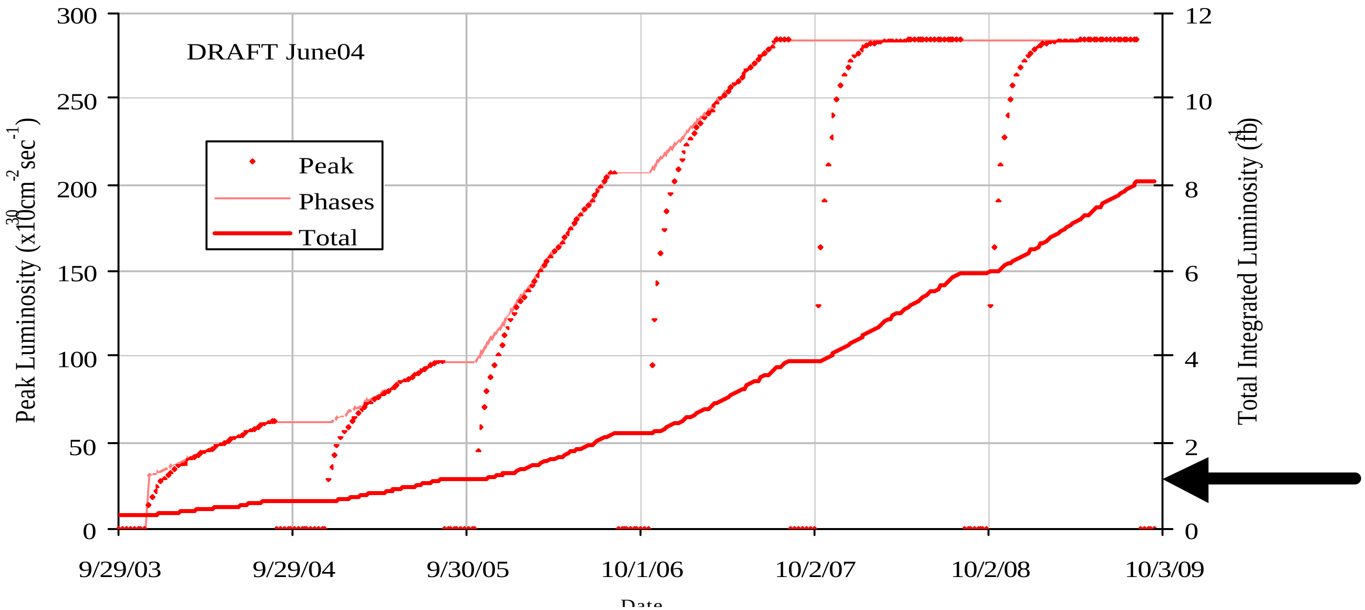
The Future: A Huge Data Set to Explore

- These analyses ~200 pb^{-1}, have already logged 471 pb^{-1}
- Expect to see 8000 pb^{-1} this run.



These hints should become even more interesting…

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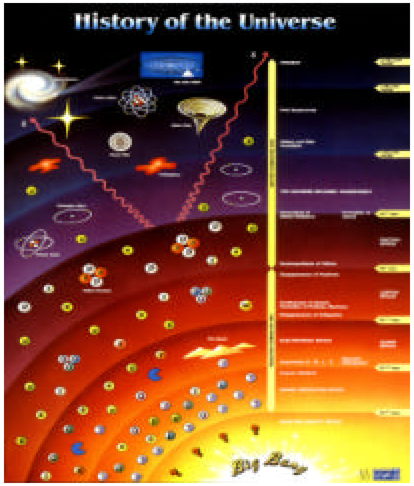
Current Prospects

- **The Tevatron (Dzero and CDF) 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....**

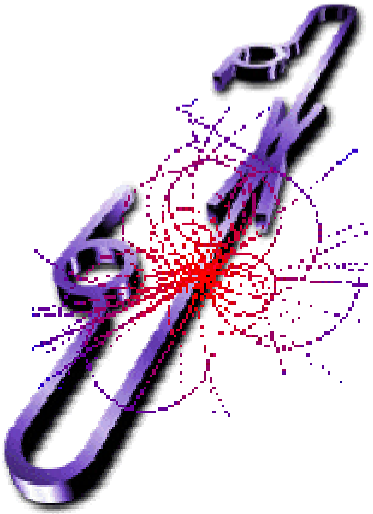
- **A thoroughly exciting challenge to answer the most basic questions...**
  - **What is the history of the universe?**
  - **What is the composition of the universe?**
  - **What is the structure of the universe?**



Jerry Blazey
January 2005
Vietnam

The Future

- Large Hadron Collider (LHC) @ CERN
- Atlas and CMS Experiments, Each with 2000+ collaborators!
- International Linear Collider, 30 miles long!



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Our Lecture Series

- ✓ Overview
- History, Accelerators, Detectors, & Cross Sections
- QCD and Electroweak Physics
- Searches for New Physics

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