AT THE FRONTIER OF DISCOVERY

John Womersley
Fermi National Accelerator Laboratory

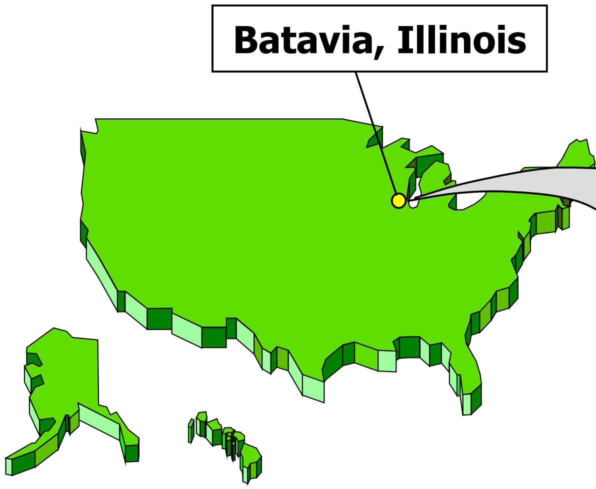
Outline

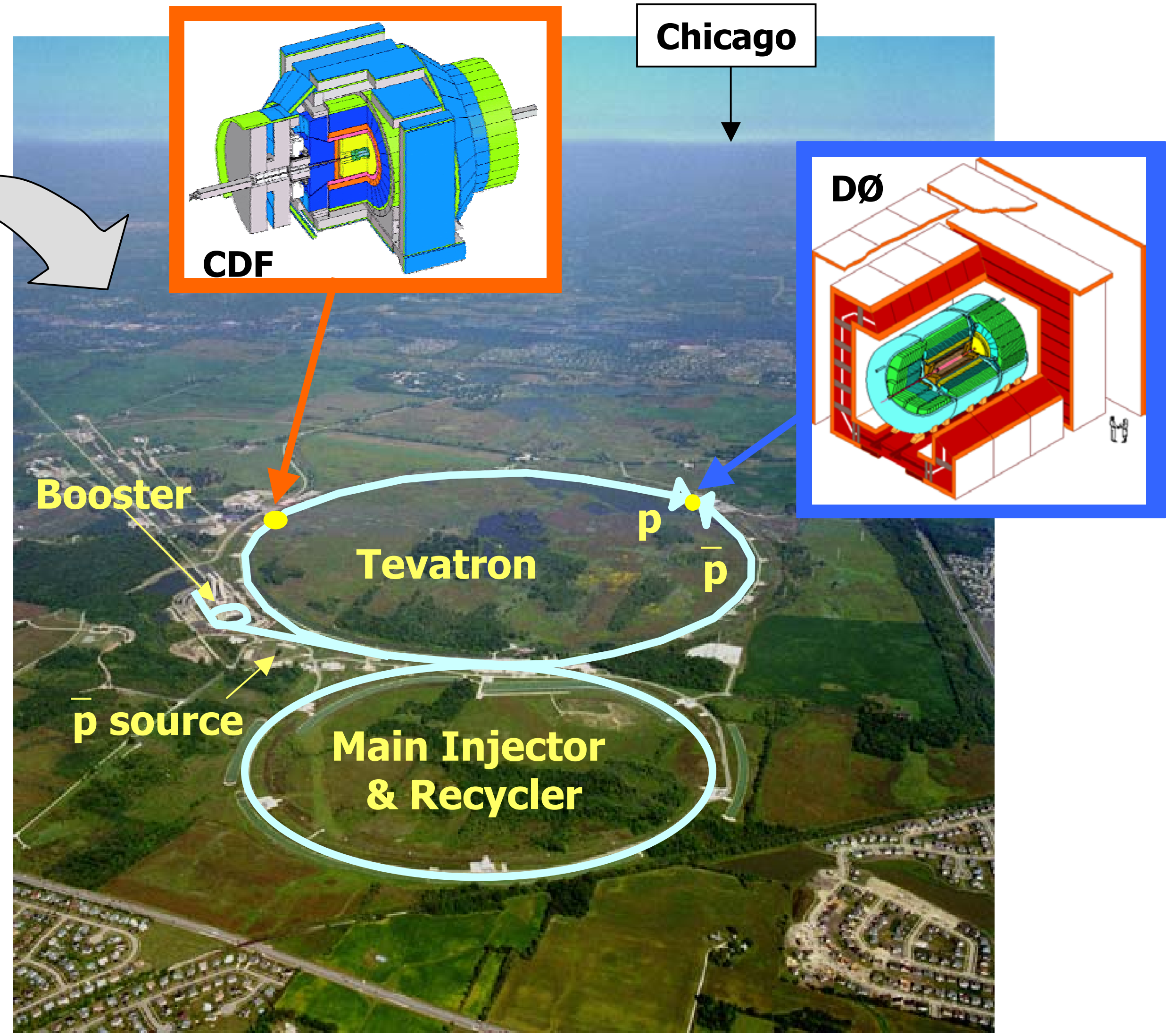
- I'm going to be talking about the Fermilab Tevatron collider, the world's highest energy particle accelerator
- After a somewhat slow start, we are now up and running, accumulating large amounts of data
- I will describe
  - How we do experiments at a high energy accelerator
  - Some of the latest results from the DØ Experiment
  - How these relate to some big questions about the universe

Note on Units

- I will use GeV interchangeably for mass, energy and momentum
- I will express "integrated luminosity" (total number of collisions observed) in terms of Inverse Picobarns (pb^{-1})
  - Where 100 pb^{-1} = sufficient data to observe 100 events for a process having 1pb cross section, *etc.*

Fermilab





p → ← **$\bar{p}$**

$\sqrt{s}$ =1.96 TeV
Δt = 396 ns

Run I 1992-95
Run II 2001-09(?)

50 × larger dataset
at increased energy

What is the universe made of?

- **A very old question, and one that has been approached in many ways**
- **The only <u>reliable</u> way to answer this question is by directly enquiring of nature, through experiments**
  - **Perhaps the greatest human invention**
  - **An activity that is open to all peoples, all nations**

Experiment has taught us:

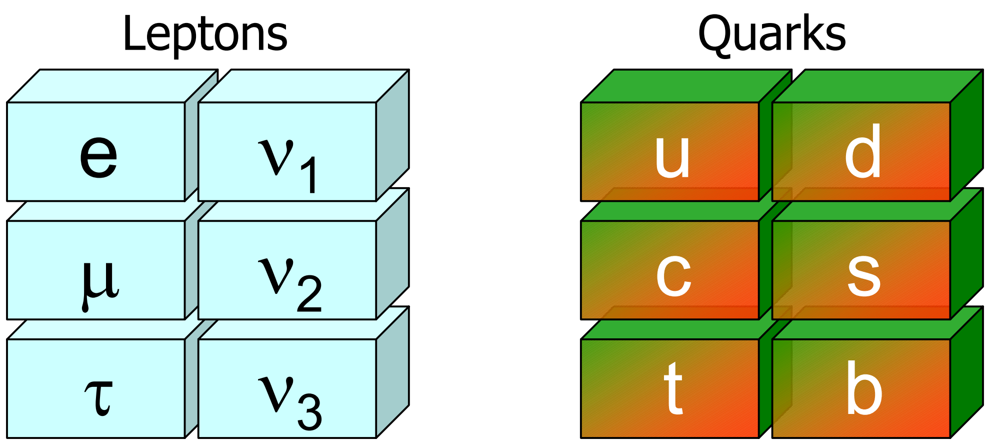
- Complex structures in the universe are made by combining simple objects in different ways
  - Periodic Table
- Apparently diverse phenomena are often different manifestations of the same underlying physics
  - Orbits of planets and apples falling from trees
- Almost everything is made of small objects that like to stick together
  - Particles and Forces
- Everyday intuition is not necessarily a good guide
  - We live in a quantum world, even if it’s not obvious to us

Particles and Forces Timeline

- **1897-1920's**
  - The electron (vacuum tubes)
  - Atomic physics, X-rays, quantum mechanics
- **1930's**
  - The nucleus (Rutherford's experiment)
- **1940's**
  - Nuclear physics
- **1950's**
  - Particle physics (explosion of mesons and baryons)
  - Quantum Field Theory (Feynman et al.)
- **1960's – 1970's**
  - Discovery of quarks (quarks and leptons as fundamental particles)
- **1980's**
  - Electroweak Unification (weak force carried by W and Z bosons)
- **1990's**
  - Consolidation of the Standard Model, discovery of top quark
  - Increasing interest in "Quarks to the Cosmos"

“Standard Model” of Particles and Forces

- **A quantum field theory describing point like, spin-½ constituents**



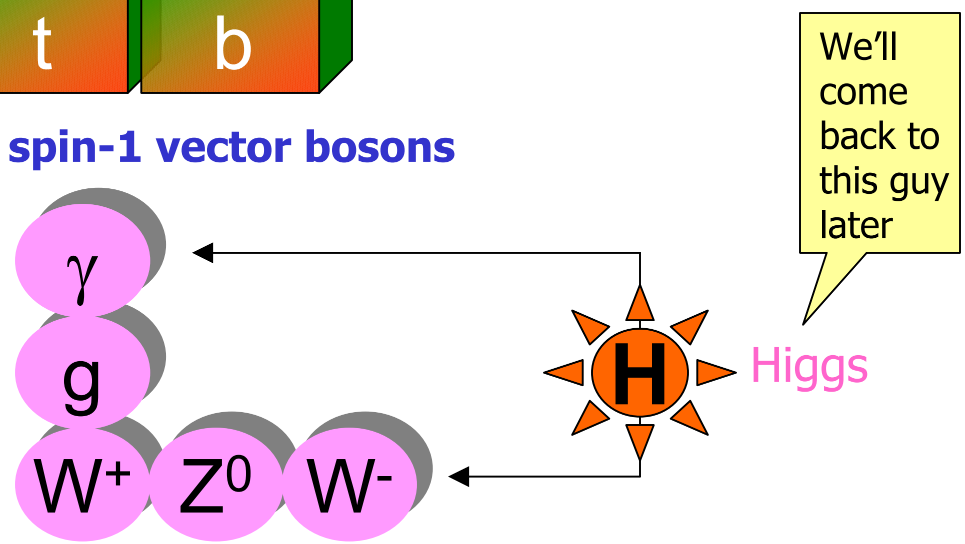
- **Which interact by exchanging spin-1 vector bosons**

Electromagnetic 10^{-2}

Strong 1

Weak 10^{-6}

Gravity 10^{-40}

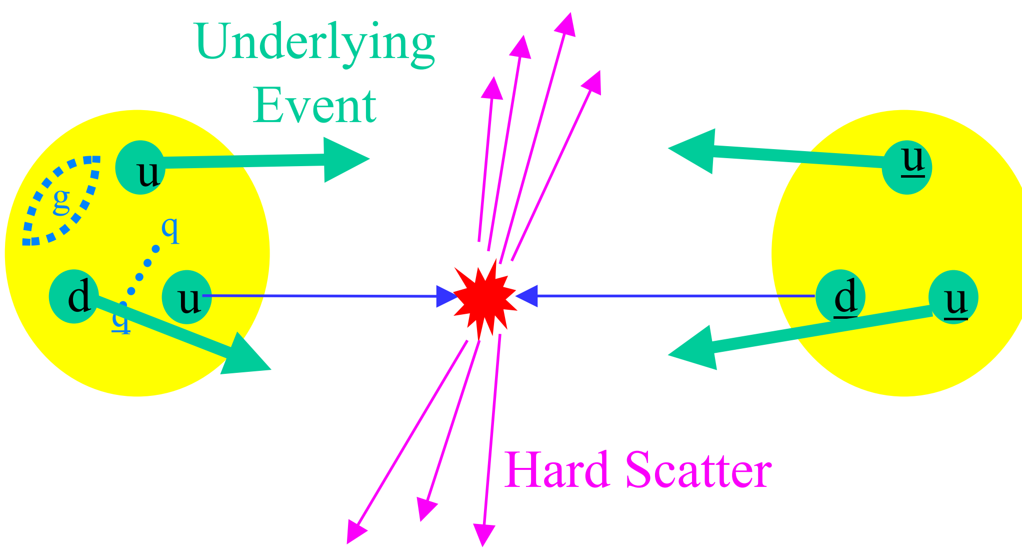


Relative strengths

John Womersley

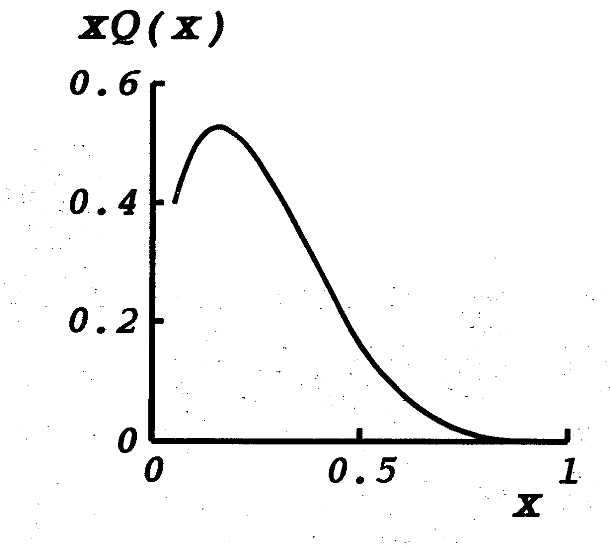
Particle Accelerators

- Accelerators allow us to explore the interactions of particles at high energies
  - See the underlying physics not the dressing
- We can collide beams of either electrons or protons
  - Because electron beams radiate when accelerated, proton accelerators are the best way to reach very high energies (electron accelerators play an important complementary role)
- Proton-antiproton collision:

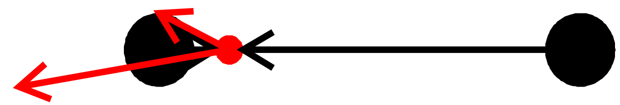


Proton-Antiproton Collisions

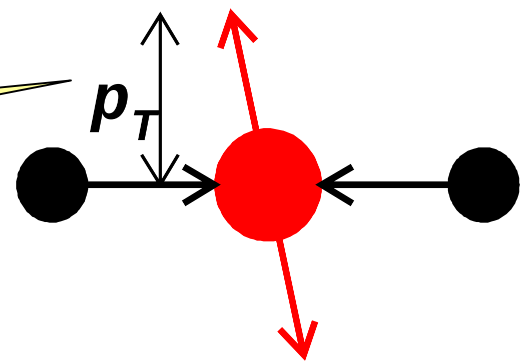
For every proton there is a probability for a single quark (or gluon) to carry a fraction "x" of the proton momentum



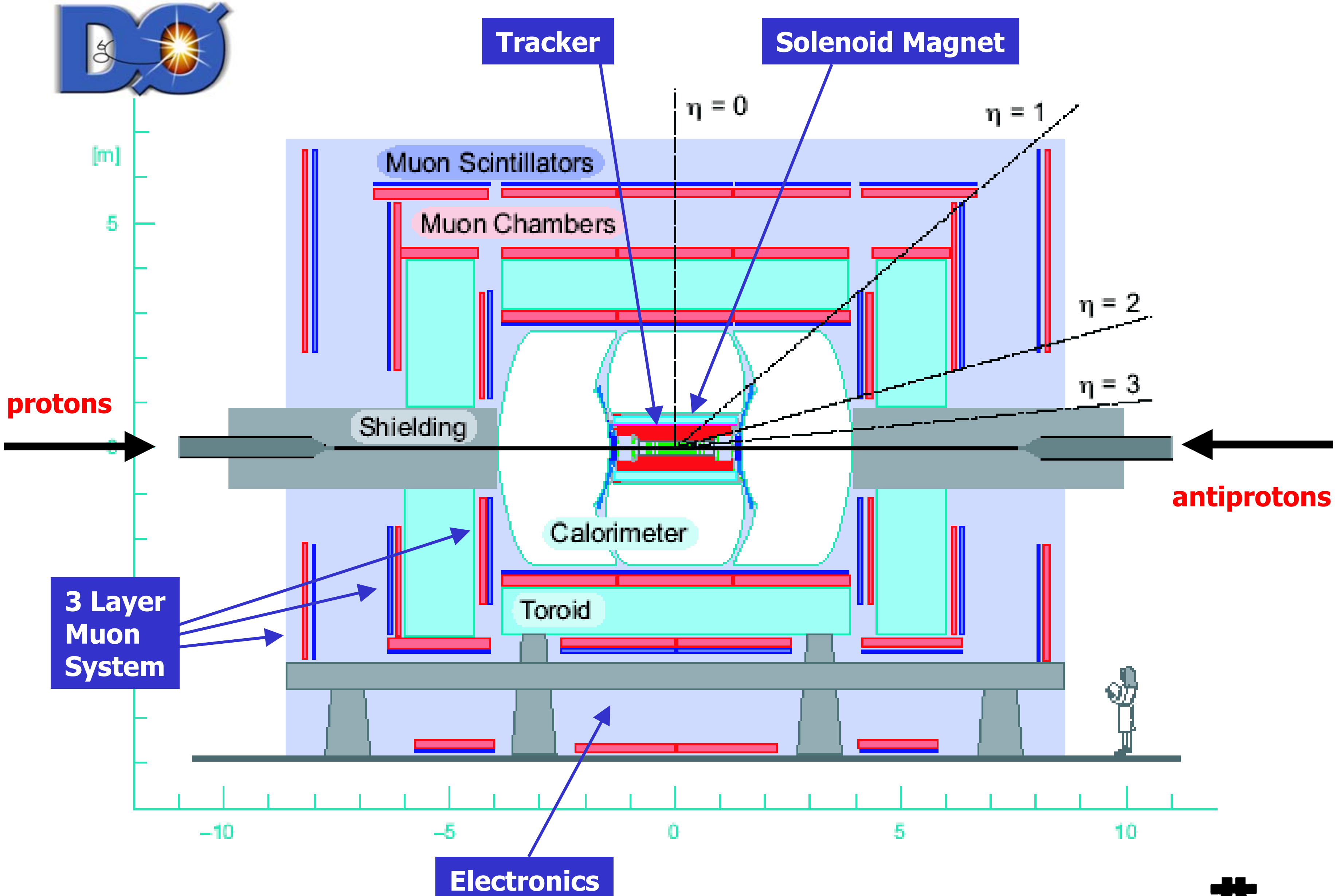
Small x = small energy, products boosted along beam direction



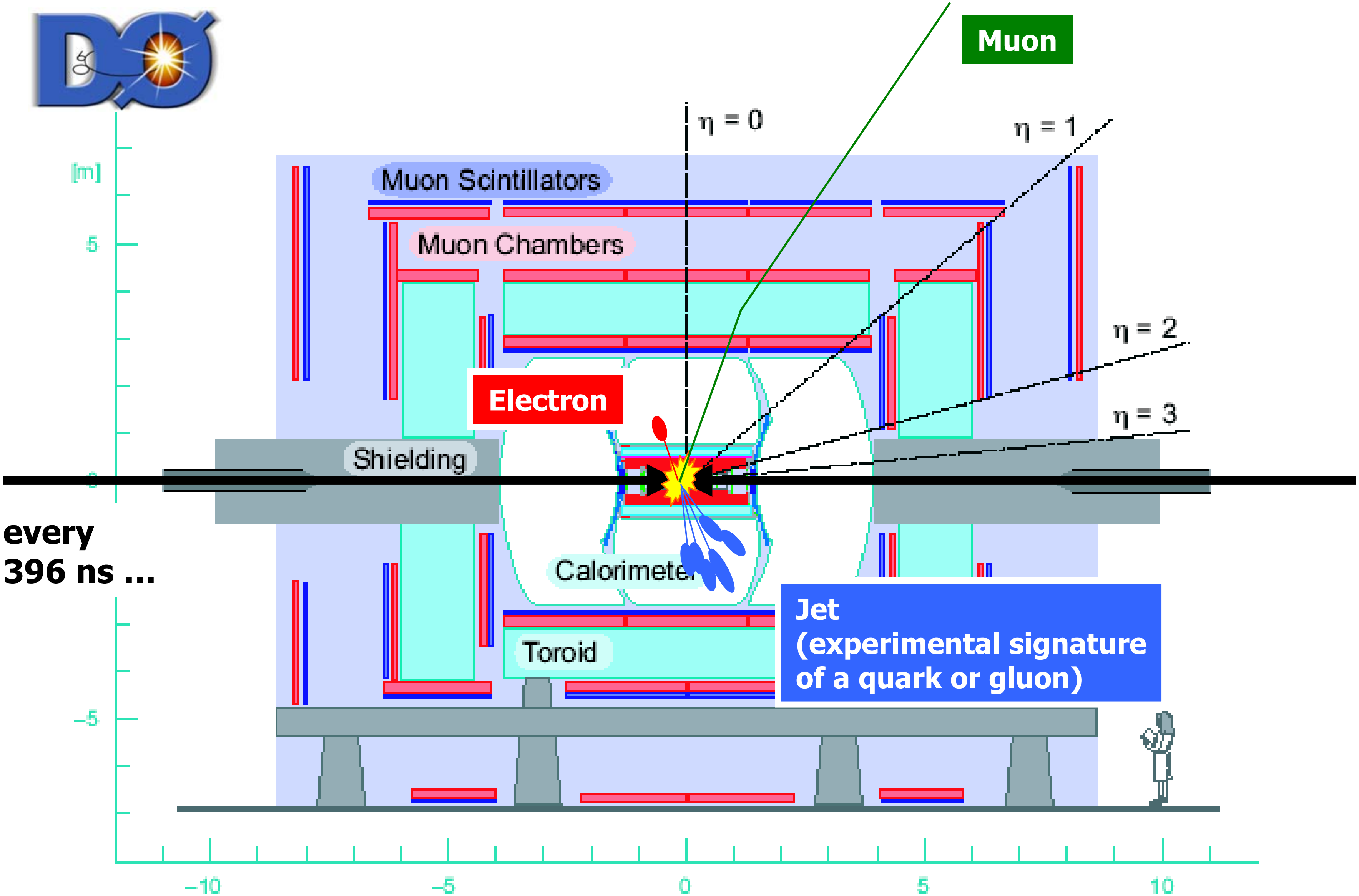
Large x = large energy, can create massive objects whose decay products have a large momentum transverse to the beam



A good way to tell that a hard (and therefore interesting) collision occurred.
Forms the basis of on-line event selection ("triggering")

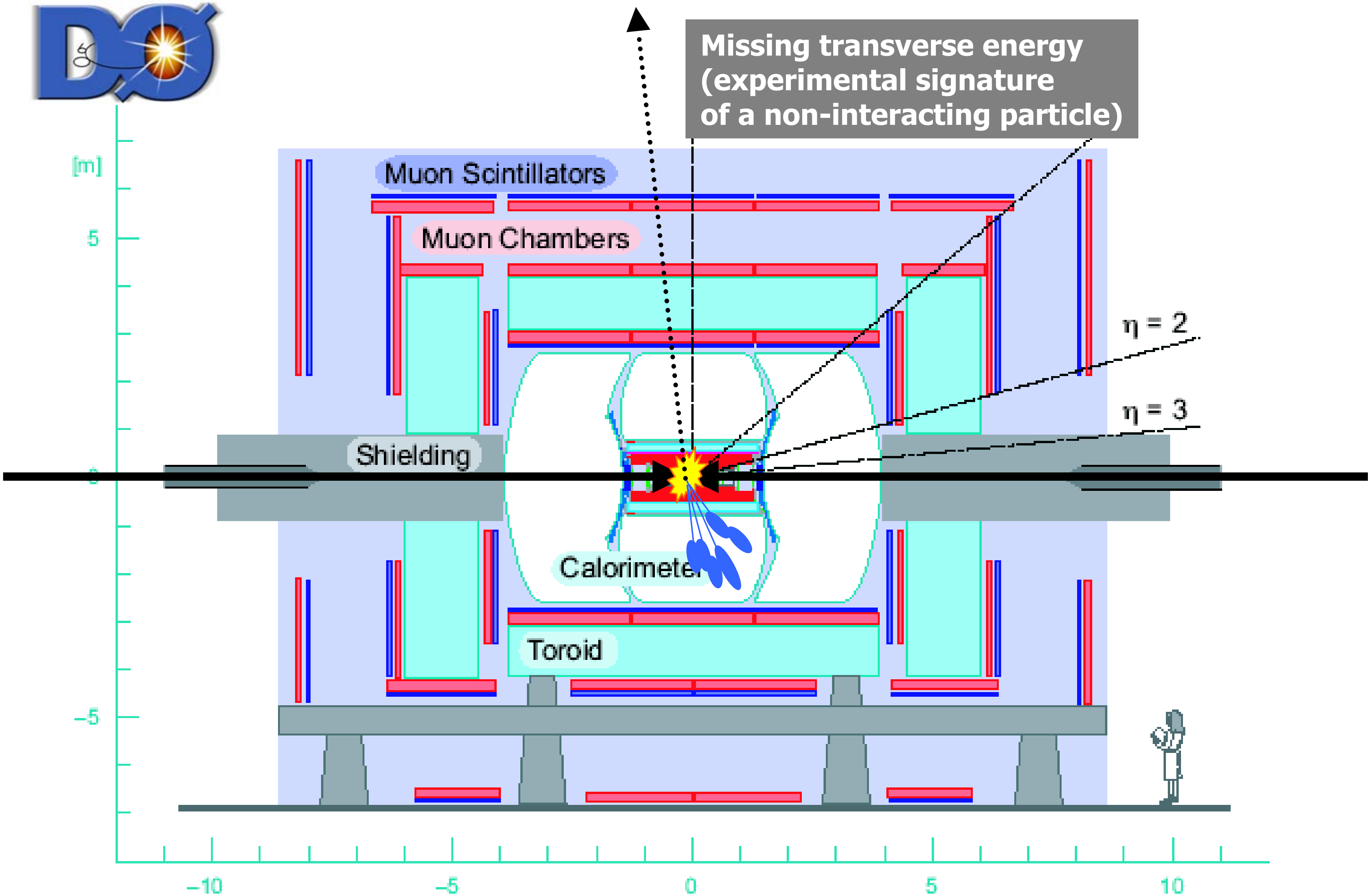


John Womersley



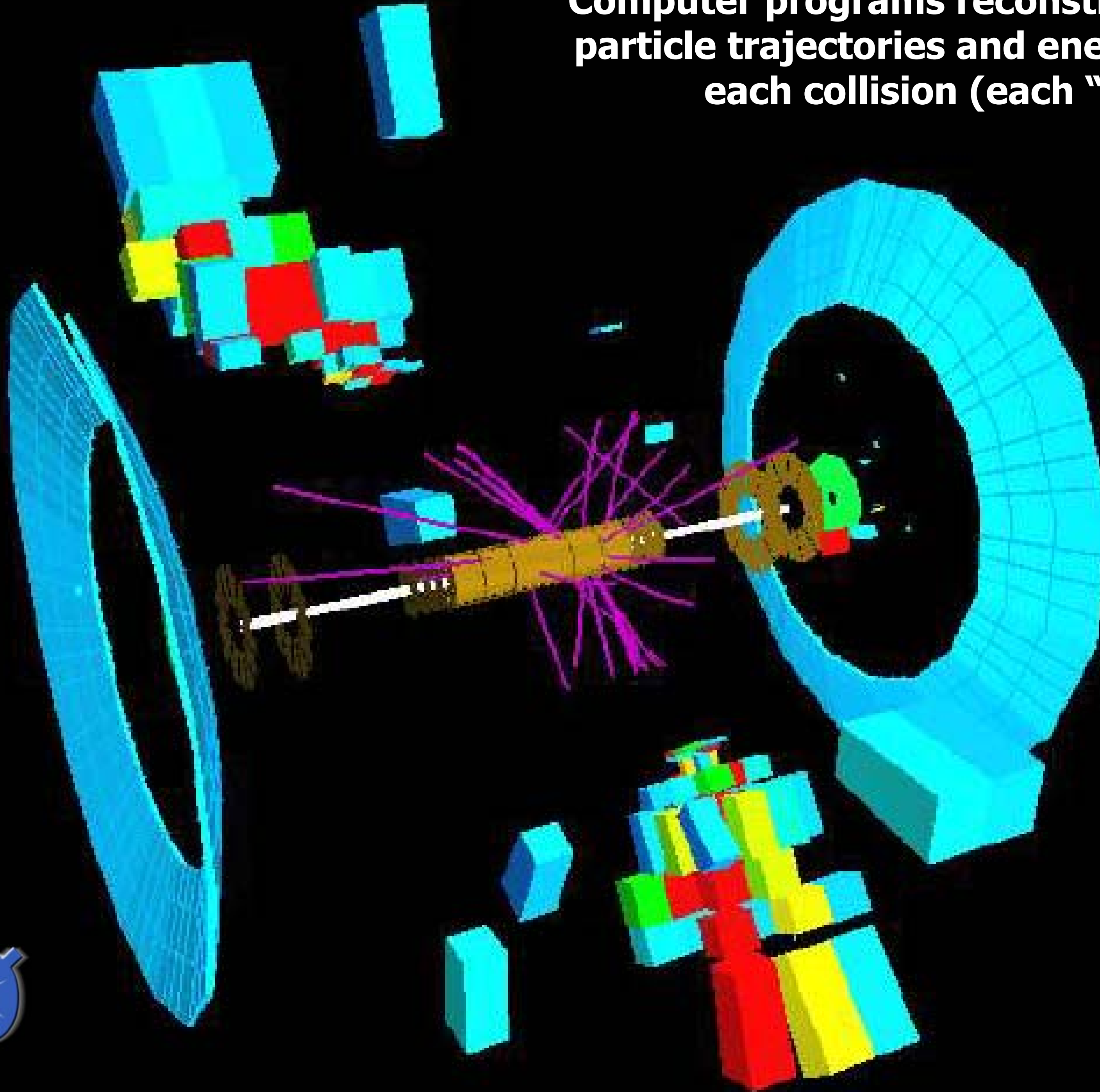
Muon
η = 0
η = 1
η = 2
η = 3
[m]
5
0
−5
Muon Scintillators
Muon Chambers
Electron
Shielding
Calorimeter
Toroid
Jet
(experimental signature of a quark or gluon)
−10
−5
0
5
10

every 396 ns …


Missing transverse energy
(experimental signature
of a non-interacting particle)
[m]
5
0
−5
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid
η = 2
η = 3
−10
−5
0
5
10

DØ detector installed in the Collision Hall, January 2001

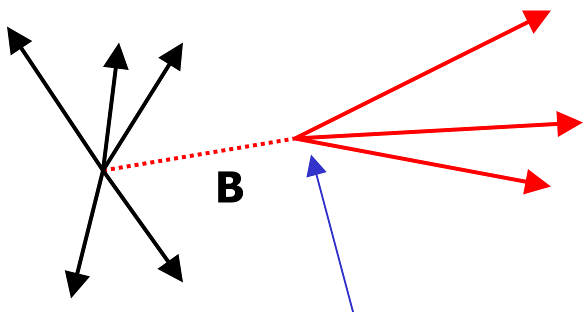
Computer programs reconstruct the particle trajectories and energies in each collision (each “event”)



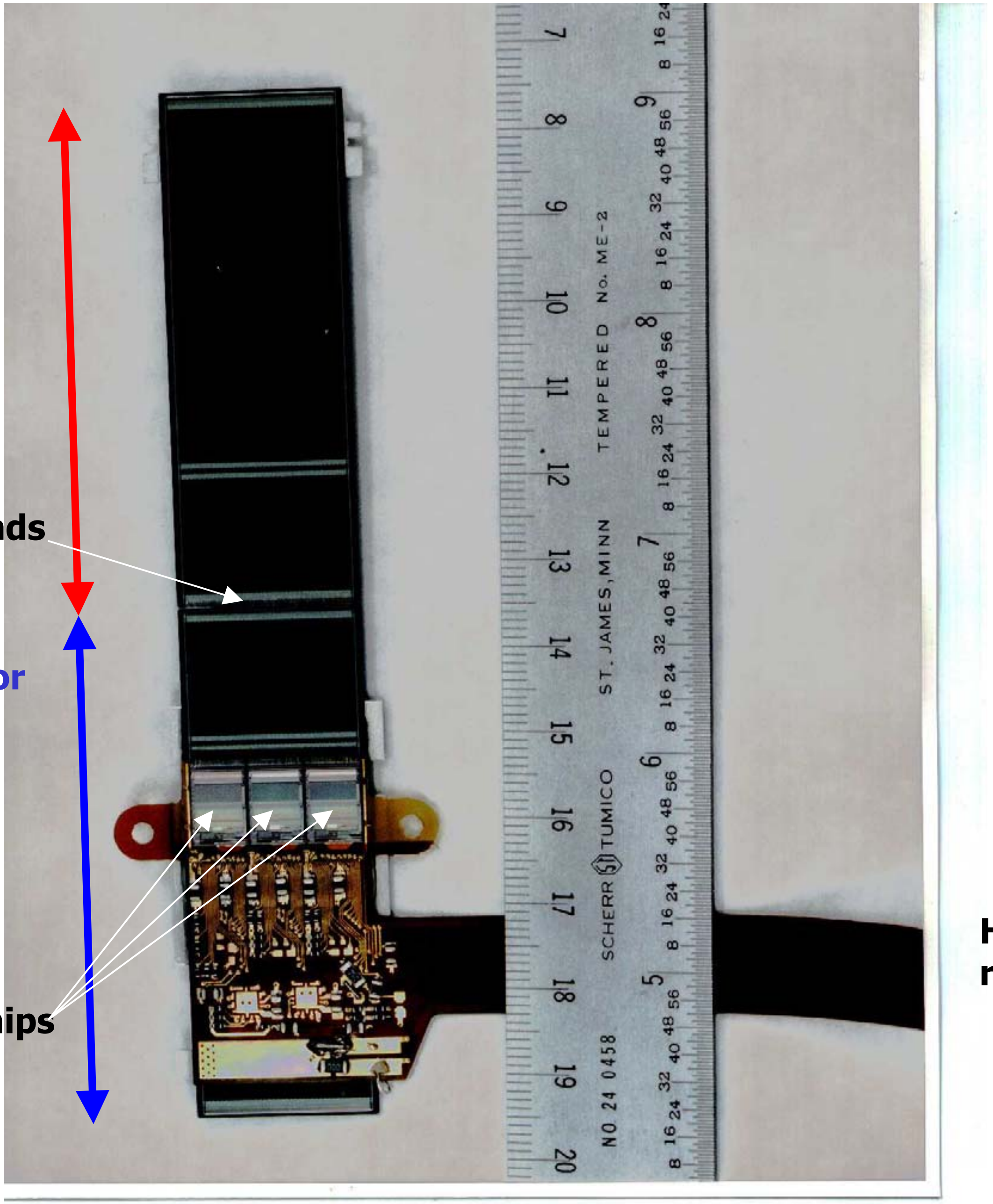
Displaced vertex tagging

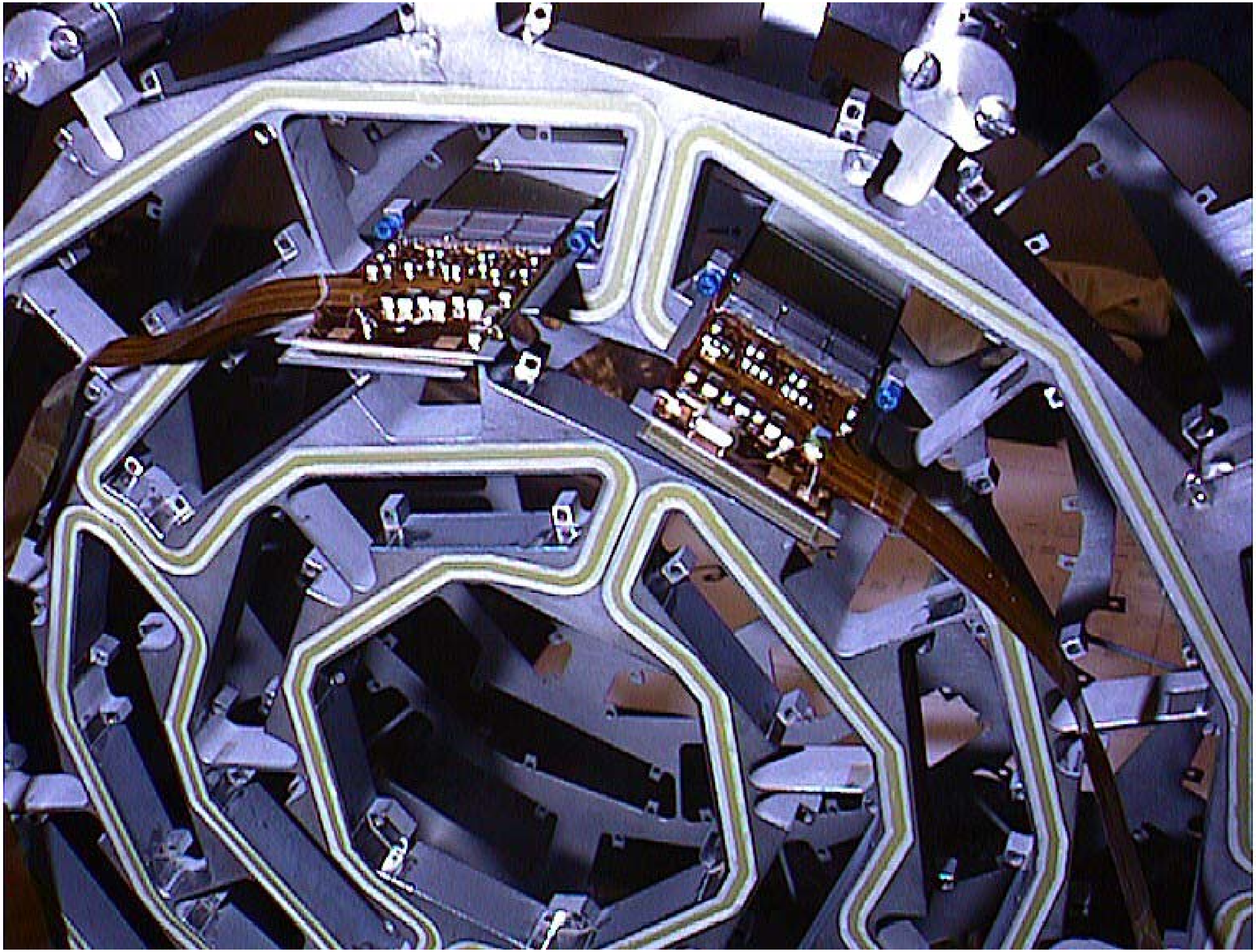
- **The ability to identify b-quarks is very important in collider physics**
  - **signatures for the top quark, supersymmetry, Higgs boson**

- **b quark forms a B-meson, travels ~ 1mm before decaying**



to reconstruct this decay, need to measure tracks with a precision at the 10μm level


Silicon sensor
Wire bonds
Silicon sensor
SVX2e readout chips
HDI (flex circuit readout)

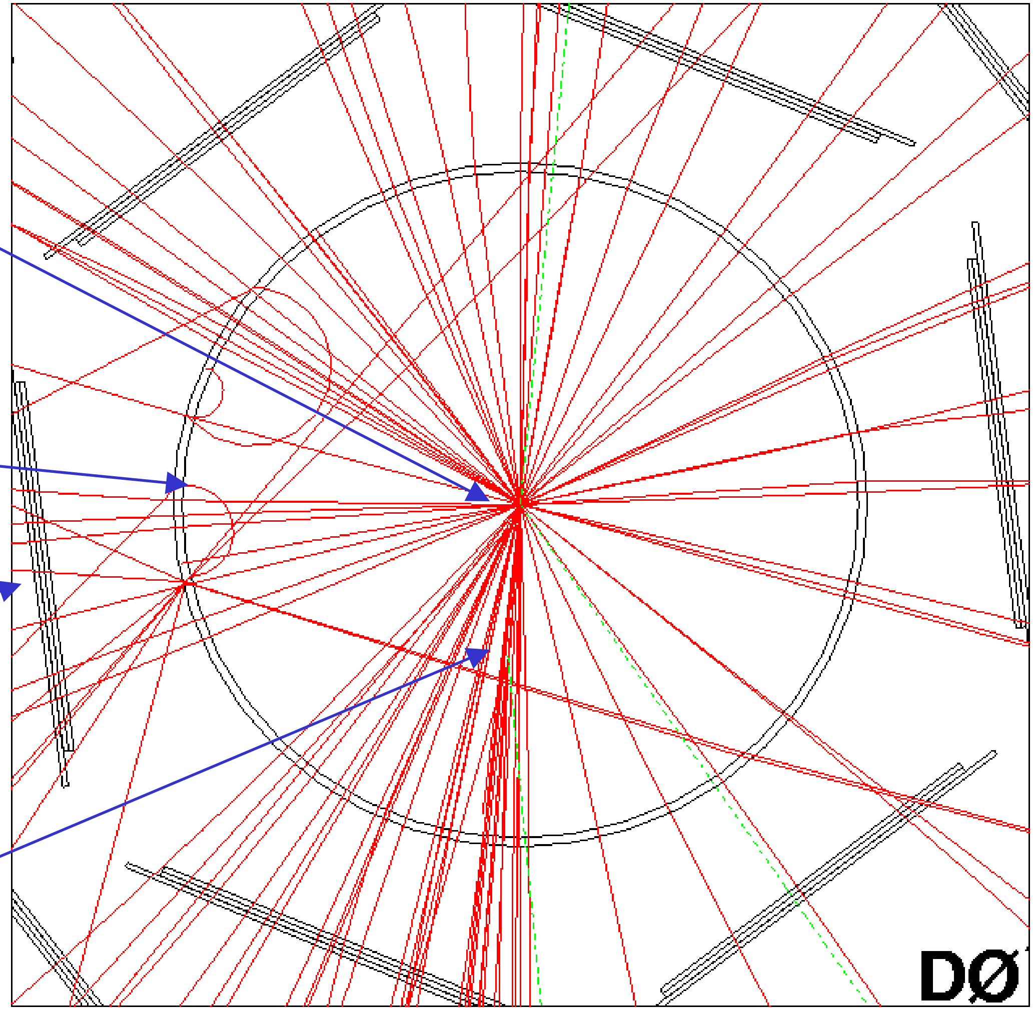


Interaction point ("primary vertex")

Beampipe

Silicon detector

B decay ("secondary vertex")

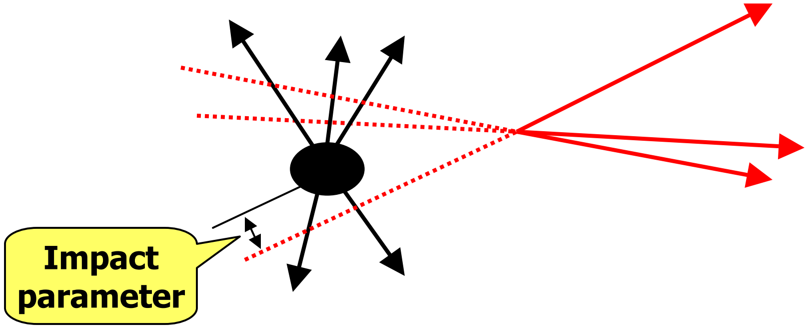


This green track clearly does not originate at the primary vertex

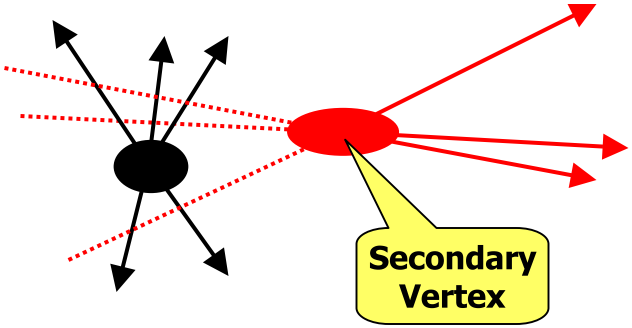
1 inch

B-tagging

- Typical algorithms
  - require 2 or 3 tracks with significant impact parameter (distance of closest approach to the fitted primary vertex)



  - reconstruct a secondary vertex



What do physicists actually do?

- Design and build hardware
  - Detectors, electronics
- Write software
- Operate the detector
- Interpret data
- Present, refine, discuss our results among ourselves
- Publish papers

The work of many people…

The DØ detector was built and is operated by an international collaboration of ~ 670 physicists from 80 universities and laboratories in 19 nations

> 50% non-USA
~ 120 graduate students

How do students work in DØ?

- Almost all the research we do involves graduate students
  - from universities all over the world
- Your research is done using data from DØ
- You work in a small analysis group
  - Present progress, discuss problems, get guidance
- Work on your own analysis but also develop tools for common use, carry out detector work for benefit of others, etc.
  - In return, you can use datasets, software, developed by others
- Your analysis will be probably be published as a paper by the whole experiment
- An opportunity for young people, from all over the world, to work at the real frontier of discovery

FERMI NEWS

FERMILAB A U.S. DEPARTMENT OF ENERGY LABORATORY

Photo by Reidar Hahn

ALL USERS ISSUE

Volume 26

Friday, June 13, 2003

Number 10

INSIDE:

2 World at Work

4 Users: Numbers...

5 ...and Faces

8 The Old DOE-Re-Mi

10 All Work, No Play?

12 Users Office in High Demand.

Remote International Monitoring for the DØ Experiment

Detector Monitoring data sent in real time over the internet

9 am

NIKHEF Amsterdam

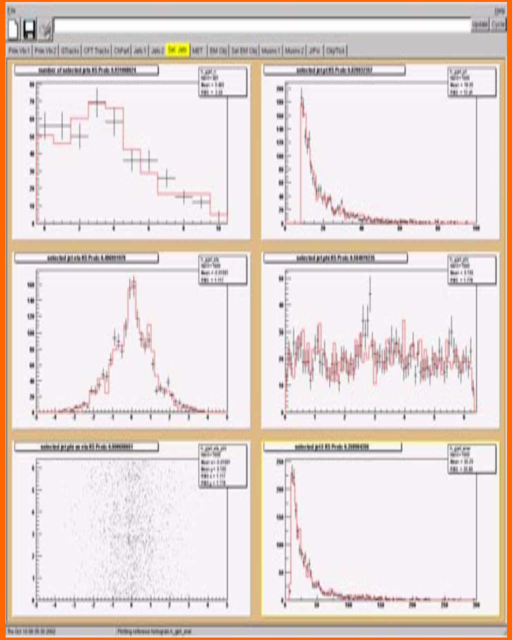
2 am

Fermilab

DØ physicists in Europe use the internet and monitoring programs to examine collider data in real time and to evaluate detector performance and data quality.

They use web tools to report this information back to their colleagues at Fermilab.

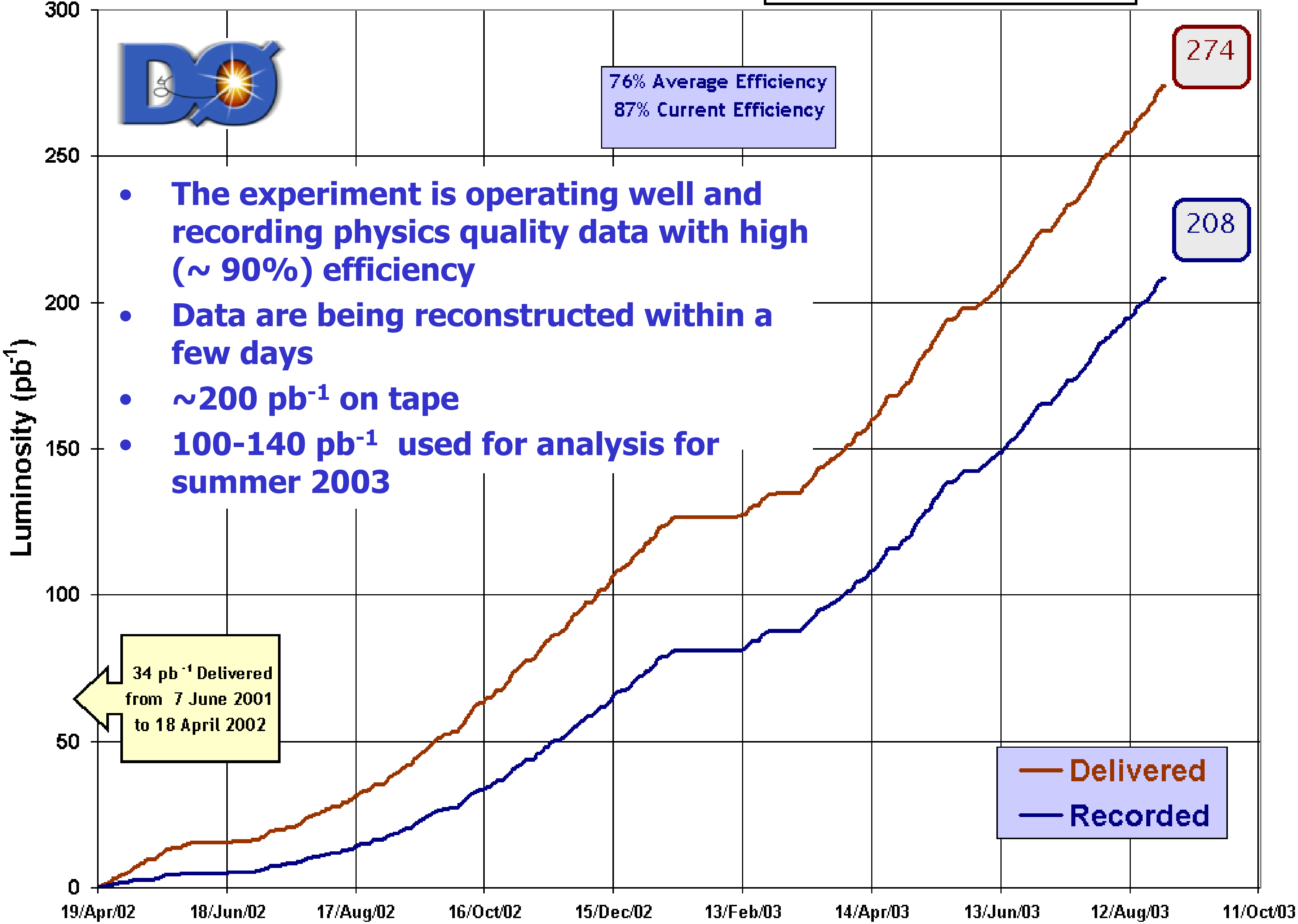
DØ detector



No reason we can not do the same thing with physicists in Latin America!

Run II Integrated Luminosity

- The experiment is operating well and recording physics quality data with high (~ 90%) efficiency
- Data are being reconstructed within a few days
- ~200 pb^{-1} on tape
- 100-140 pb^{-1} used for analysis for summer 2003



What next?

- You've got this great standard model and you know all about all of the particles and forces involved. So why do you need to do these experiments? Isn't it all done?
  - Yes, we know a lot, but we know a lot less than we would like, and we know enough now to ask some deeper questions
  - The paradox of the "circumference of knowledge"

- We can now list the standard model particles and forces, just as biologists can now list DNA sequences; like them, we need to move on to ask "why is it this way" and "what does it encode" questions like:
  - Why are some forces weak and others strong?
  - What is the dark matter that seems to be responsible for cosmic structure?
  - What is the structure of spacetime?

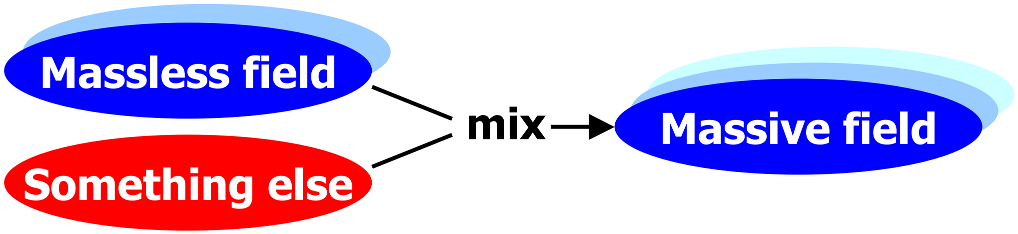
Particle physics is the DNA of the universe

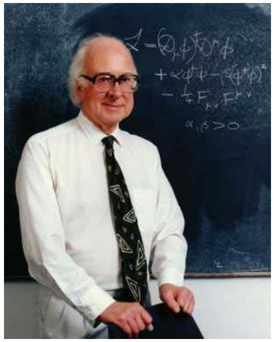
Q:

- **Why are some forces weak and others strong?**
  - **Is the Universe filled with an energy field?**
  - **Is this the reason particles have mass?**

Electroweak Symmetry Breaking

- Photons and W/Z bosons couple to particles with the same strength
  - Electroweak unification
- Yet while the universe (and this room) is filled with photons, W's and Z's mediate a weak force that occurs inside nuclei in radioactive beta decay
  - This is because the W and Z are massive particles
  - The unification is "broken"
- Where does this mass (the symmetry breaking) come from?
  - Not like the mass of the proton, which is the binding energy of its constituents
- In the Standard Model, the W and Z get their mass because the universe is filled with an energy field, called the Higgs field, with which they interact (and in fact mix)
  - The universe is a refractive medium for W's and Z's





The "Higgs Mechanism"

The Higgs Mechanism

- **In the Standard Model** (Glashow, Weinberg, Salam, 't Hooft, Veltmann)
  - "electroweak symmetry breaking" occurs through a scalar field which permeates all of space with a finite vacuum expectation value
    - Cosmological implications: a source of "Dark Energy"
    - but 10^{54} times too much energy density!
  - If the same field couples to quarks and leptons → generates fermion masses

- **Is this picture correct?**
  - One clear and testable prediction: there exists a **neutral scalar particle** which is an excitation of the Higgs field
    - The "Higgs boson"
  - All its properties (production and decay rates, couplings) are fixed within the SM, except for its own mass


University of Durham
THE HIGGS BOSON
1964
Peter Higgs suggested introducing
The Higgs boson is the only missing ingredient of the Standard Model
2008
Ogden Centre for Fundamental Physics

As of summer 2003, we cannot be sure that the Tevatron will deliver sufficient data to permit a direct observation of the Higgs boson at Fermilab

Fermilab said unlikely to uncover 'God particle'

Science magazine says equipment may not be good enough

BY ART GOLAB
Staff Reporter

Fermilab's search for the elusive Higgs boson—an elusive, theorized subatomic bit of matter known as "the God particle"—has suffered a significant blow, according to two scientific publications that analyzed a new report submitted by the west suburban lab to the U.S. Energy Department.

Though Fermilab scientists say they still believe they have a 50 percent chance of discovering the Higgs boson before a new, more powerful particle accelerator being built in Switzerland beats them to it, there's good reason to doubt that will happen, New Scientist magazine reports.

The magazine said data in the lab's report to the Department of Energy shows it will be "virtually impossible" for Fermi's Tevatron particle accelerator to produce enough of the powerful collisions between protons and anti-protons thought to be needed to flush out the particle.

Another scientific journal, Nature, said Fermilab, which is in Batavia, has downgraded the number of collisions between protons and anti-protons it expects to achieve by 60 to 80 percent.

Fermilab spokeswoman Judy Jackson called the New Scientist article "way off-base."

And Fermilab scientist John Womersley said the number of collisions would be down, but by about 47 percent, still leaving plenty of leeway to find the particle that is the Holy Grail of modern physics.

"If the Higgs does exist with the properties predicted, it has maybe a 50 percent chance of being in the range we can explore here," Womersley said. "That's a good enough shot. If there's a 50 percent chance of rain, you take an umbrella."

In 1995, during an earlier run of the Tevatron, Fermilab discovered the top quark, one of the building blocks of matter.

But the current run, started in 2001 with the goal of discovering the Higgs, has been less successful.

The recent downgrade, Womersley said, is due to technical problems with the aging

The four-mile underground ring at Fermilab, in Batavia, enables scientists to accelerate anti-protons to near-light speed in hopes that collisions with protons will reveal the "God particle."

Tevatron, which was built in 1985. The complex equipment required to cool the ring's superconducting magnets and maintain a vacuum is failing more often than expected, causing down time, he said. There also have been difficulties with a new recycler ring that's meant to boost the production of scarce anti-protons.

"We've had a somewhat disappointingly slow startup," Womersley said. "This new plan accounts for the fact that you can't run the accelerator all the time, 24 hours a day. You have to have maintenance periods. You have to have time to put in the upgrades and new instrumentation."

Fermilab hopes to find the Higgs by accelerating anti-protons to near-light speed in the four-mile underground ring of the Tevatron and slamming them into protons going in the opposite direction. The more collisions, the better the chance of a Higgs particle showing up. If it does, detectors built into the ring should be able to spot its traces.

The Higgs boson represents the missing link in physicists' so-called "standard theory" of how the universe works. That theory accounts for just about everything, but it contains no proof for why atoms have mass. Physicists theorize that there must be a subatomic particle that gives atoms mass and have dubbed this theorized particle the Higgs boson.

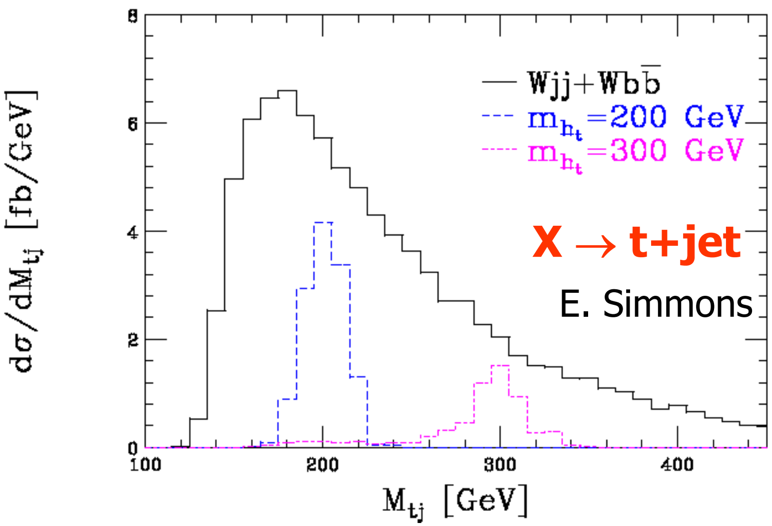
But, though scientists here and in Europe have been searching for years, nobody has found it yet.

We will also pursue this physics through indirect routes

John Womersley

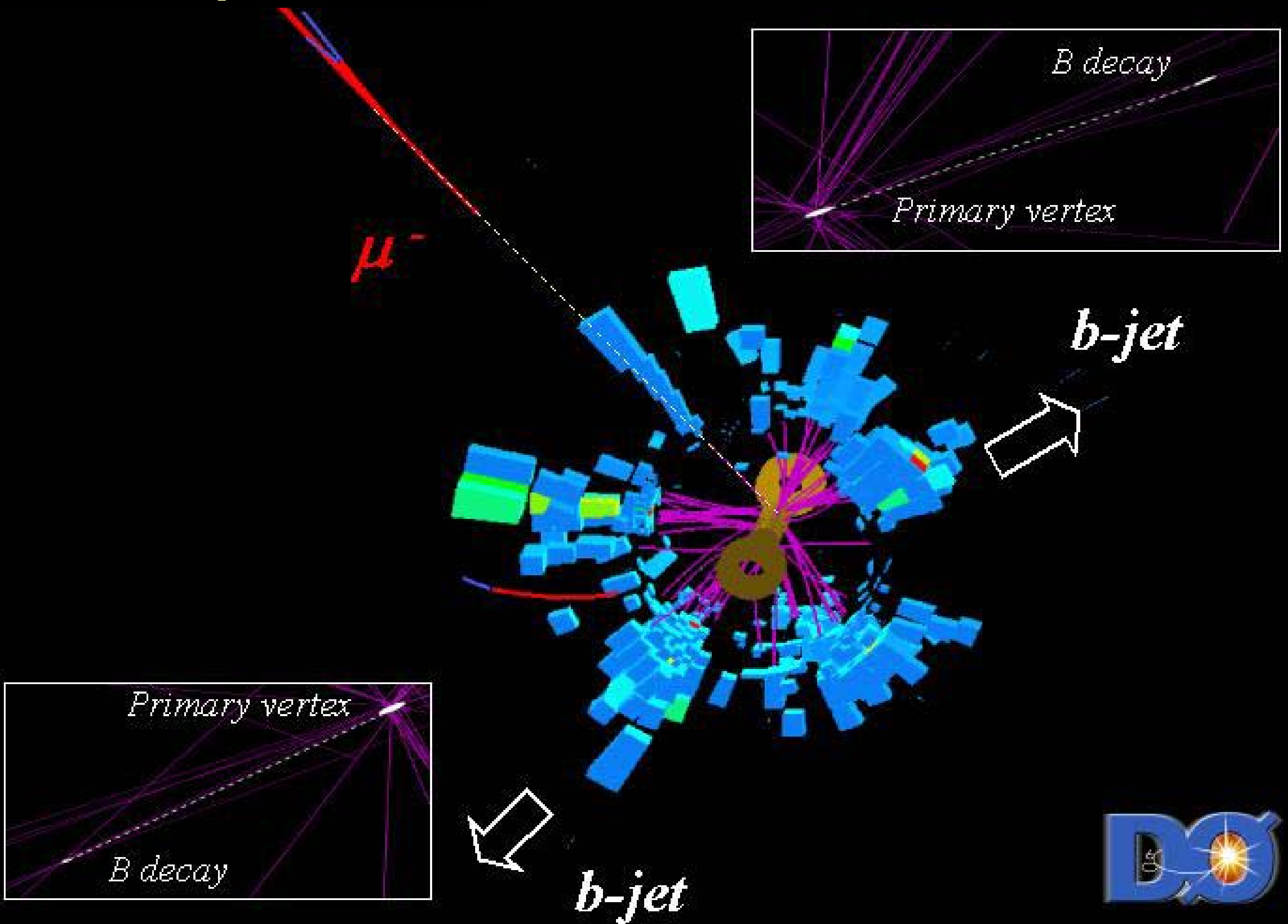
The Top Quark

- Why, alone among the elementary fermions, does the top quark couple strongly to the Higgs field?
  - Is nature giving us a hint here?
    - Is the mechanism of fermion mass generation indeed the same as that of EW symmetry breaking?
  - The top is a window to the origin of fermion masses
- The Tevatron Collider is the world's only source of top quarks
- We are measuring its
  - Mass
  - Production cross section
  - Spin
    - Through top-antitop spin correlations
  - Electroweak properties
    - Through single top production
- Any surprises, anomalies?



The Run II Top Physics Program has begun

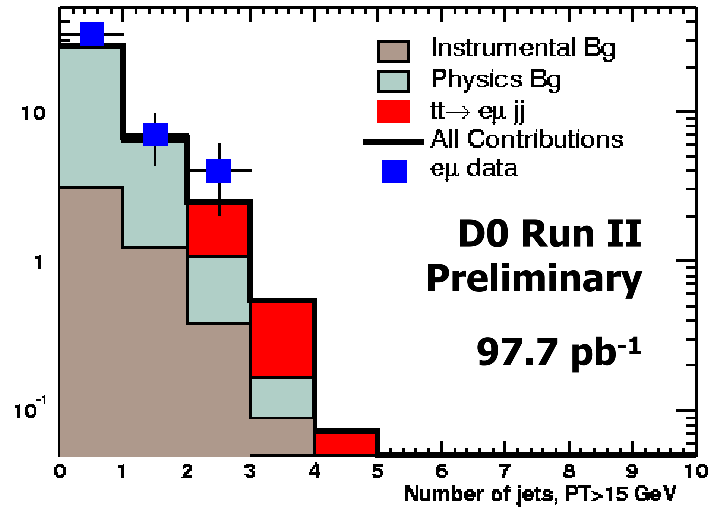
Run II top candidate



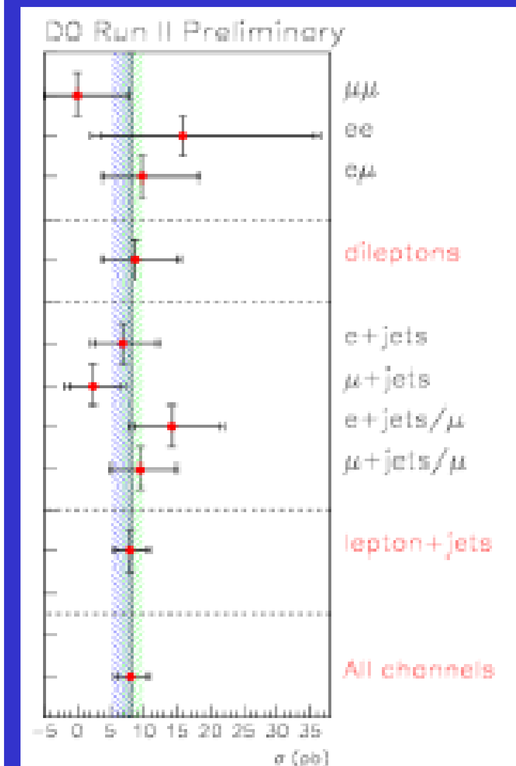
Top Production Cross Section

We measure

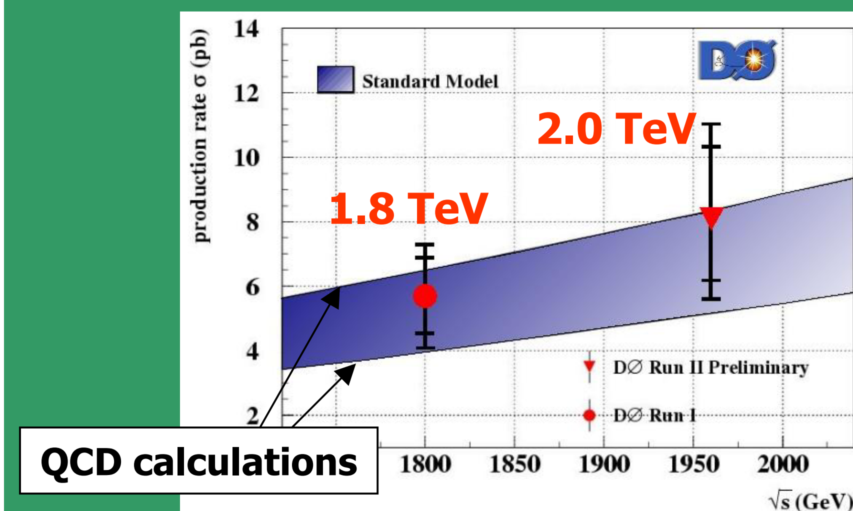
$$\sigma = 8.1\,^{+2.2}_{-2.0}\,(stat)\,^{+1.6}_{-1.4}\,(syst) \pm 0.8\,(lumi)\,pb$$



Is it consistent across all the various decay modes of the top quark?



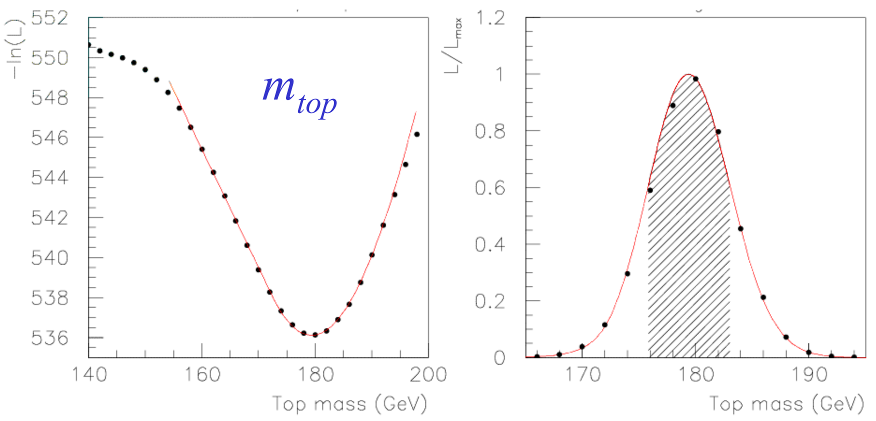
Is it as expected from QCD?



Top mass

- We can look forward to improved precision on m_t in the near future
  - Expect ~ 500 b-tagged lepton+jets events per experiment per fb^{-1}
    - cf. World total at end of Run I ~ 50

- Improved techniques
  - e.g. new DØ Run I mass measurement extracts a likelihood curve for each event
  - equivalent to a factor 2.4 increase in statistics:
  - m_{top} = 180.1 ± 5.4 GeV



cf 174.3 ± 5.1 GeV (all previous measurements combined)

Precision electroweak measurements

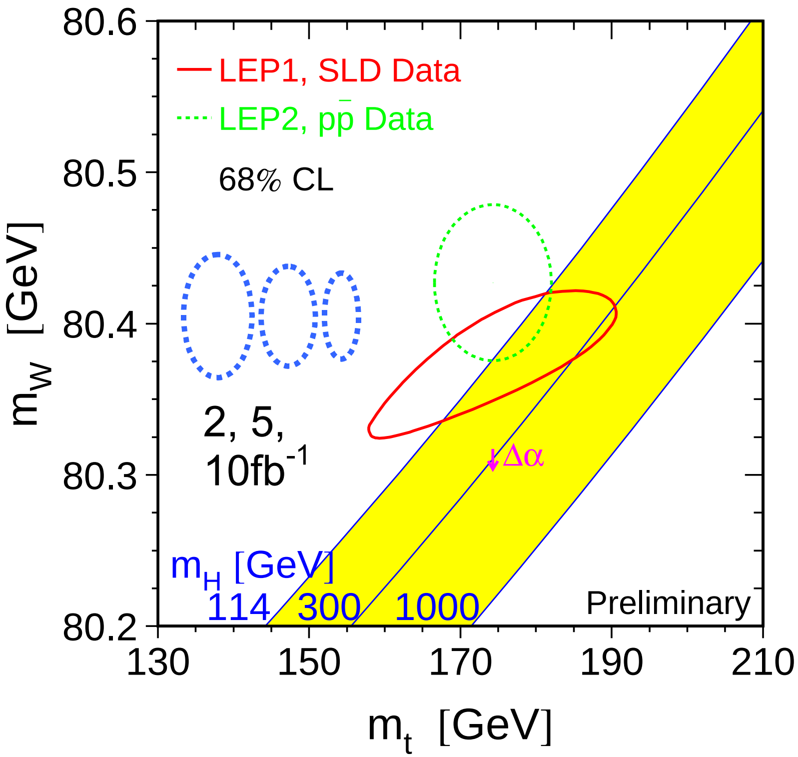
- **The top mass and the mass of the W boson provide important constraints on the self-consistency of the Standard Model, and allow limits to be set on the mass of the Higgs boson**

Δm_t	l + jets	dilepton
2 fb^{-1}	± 2.7 GeV	± 2.8 GeV
5 fb^{-1}	± 2.2 GeV	± 2.2 GeV

per experiment, using the "classic" technique

[from M. Grunewald et al., hep-ph/0111217 (2001)]

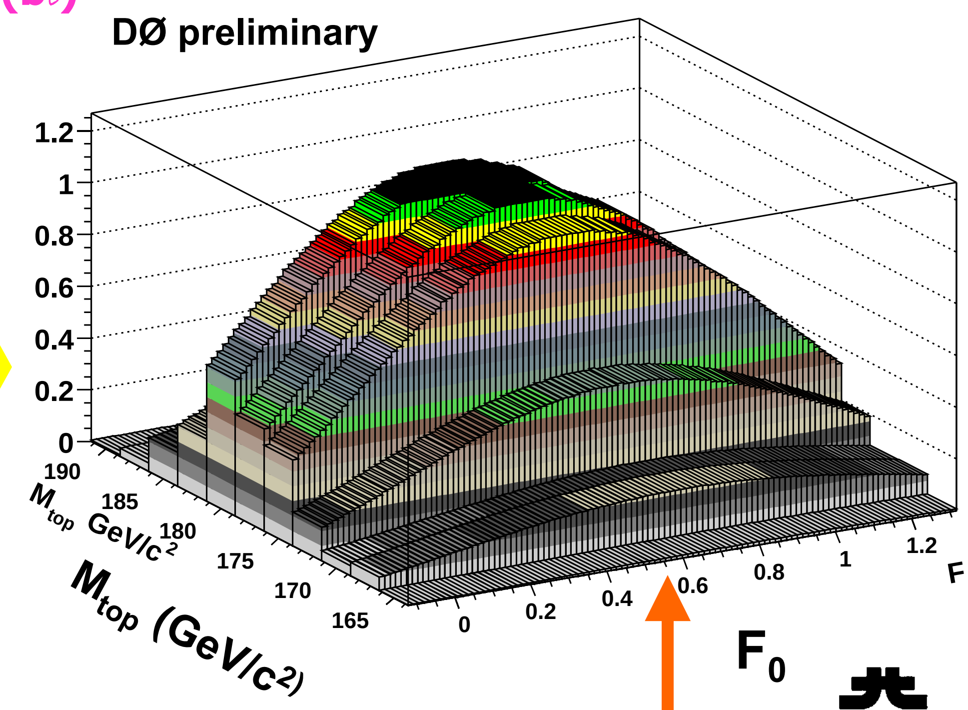
$dm_H/dm_t \sim$ 50 GeV/4 GeV



Top decays

- **Because its mass is so large, the top quark is expected to decay very rapidly (~ ys)**
- **If this is true, there is no time to form a hadron before it decays**
- **Top → Wb decay should then preserve the spin information**
  - **Helicity of the W is predicted in the Standard Model**
  - **Reflected in several kinematic variables**
    - **W, ℓ momenta, mass (bℓ)**

- **Can extract fraction of longitudinally polarized W's from top quark sample**
  - **SM predicts $F_0 = 0.70$**
  - **We measure $F_0 = 0.56 \pm 0.31$**
    (68% CL, stat ⊕ sys)



Q:

- **What is the dark matter that seems to be responsible for structure in the universe?**
  - **Is it a new kind of particle?**
  - **Does this point to a previously undiscovered symmetry of the universe?**

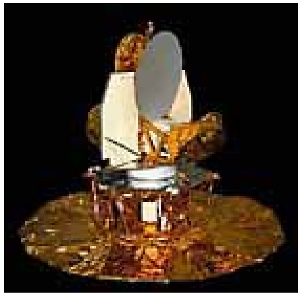
Mass shapes the Universe

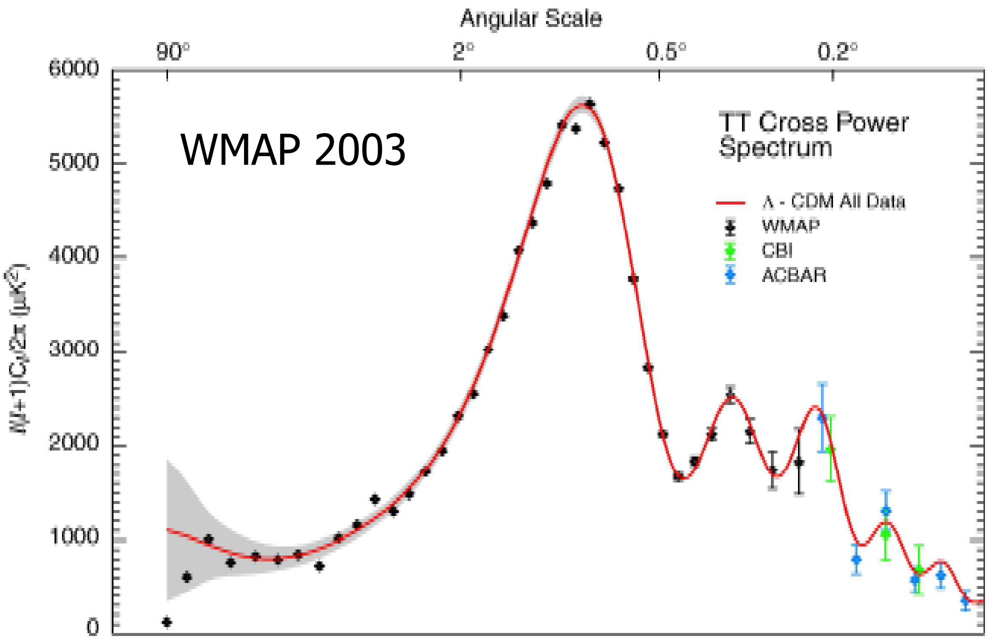
…through gravitation, the only force that is important over astronomical distances

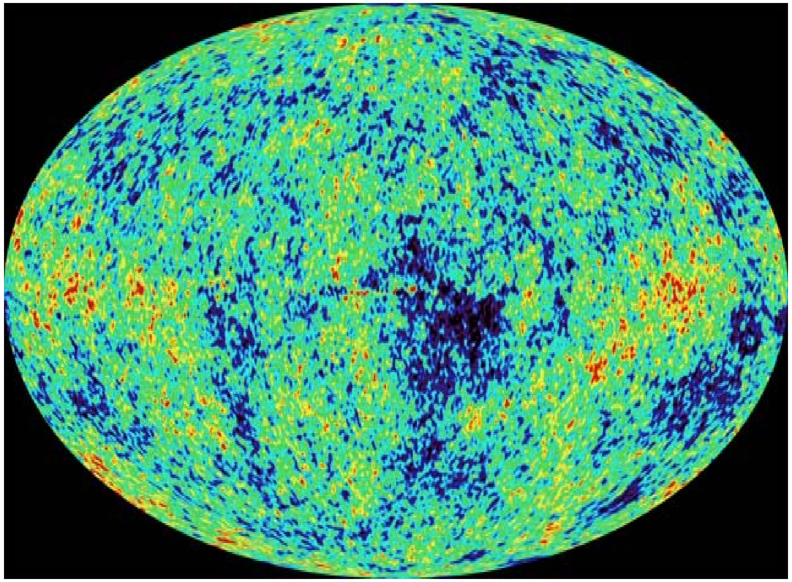
- **Masses of Atoms**
  - **binding energies from the strong force (QCD)**
- **Dark Matter**
  - **Long known that dynamical mass much greater than visible luminous material**
  - **Primordial nucleosynthesis, D/He abundance measures baryon density**

Cosmic Microwave Background

- Recent measurements of “acoustic peaks” vs. multipole number







John Womersley

What is Dark Matter?

Compare with cosmological models

- Size of DM “potential wells” into which matter fell
- Allows matter and DM densities to be extracted

→ About six to seven times more mass (27±4%) than there is baryonic matter (4.4±0.4%)

- new particles?
  - Weakly interacting, massive relics from the very early universe

- Two experimental approaches:
  - Search for dark matter particles impinging on earth
  - Try to create such particles in our accelerators

Supersymmetry

- Postulate a symmetry between bosons and fermions:
  - all the presently observed particles have new, more massive superpartners (SUSY is a broken symmetry)
- Theoretically nice:
  - additional particles cancel divergences in the Higgs mass
    - solves a deficiency of the SM
  - 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
- Predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos
  - masses depend on unknown parameters, but expected to be 100 GeV - 1 TeV

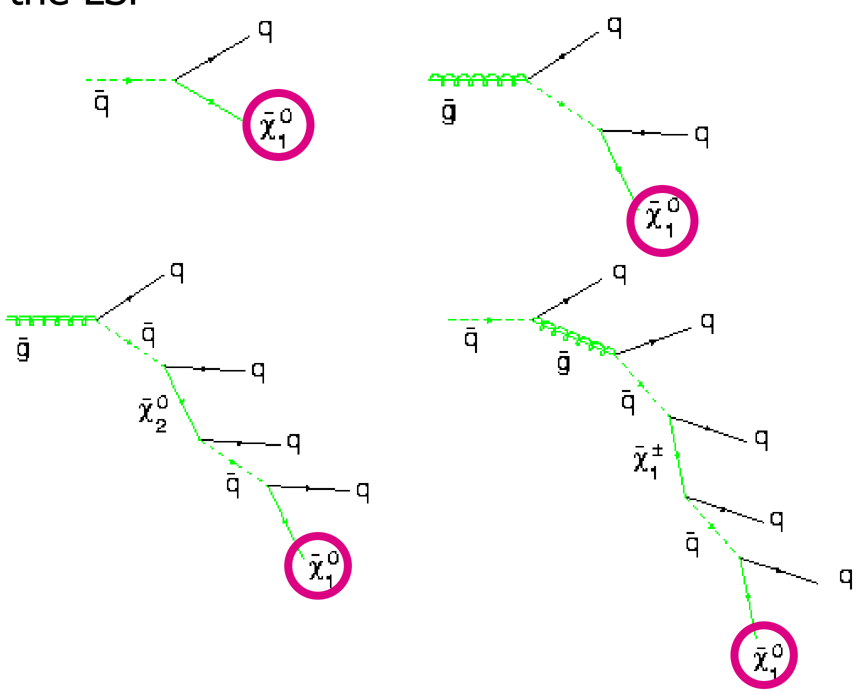
Lightest neutralino is a good explanation for cosmic dark matter
Potentially discoverable at the Tevatron

Supersymmetry signatures

- **Squarks and gluinos are the most copiously produced SUSY particles**
- **As long as R-parity is conserved, cannot decay to normal particles**
  - **missing transverse energy from escaping neutralinos (lightest supersymmetric particle or LSP)**

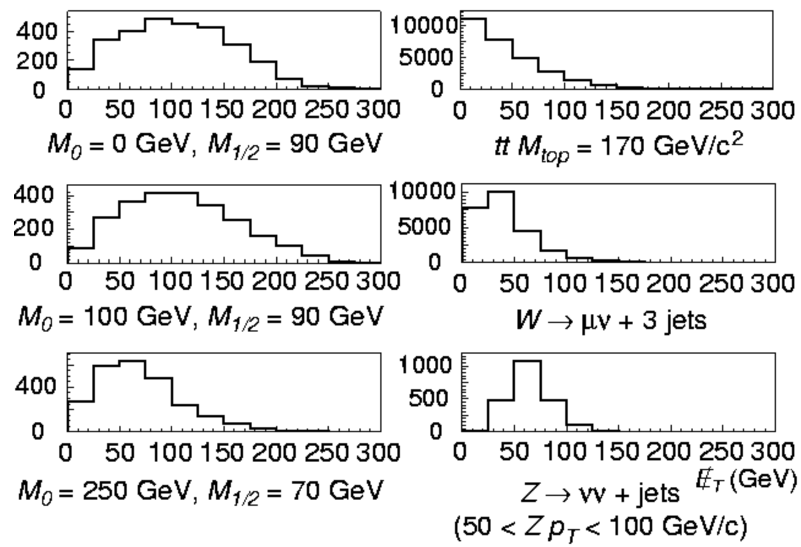
Make dark matter at the Tevatron! → **Detect its escape from the detector**

Possible decay chains always end in the LSP



Missing E_T

SUSY **backgrounds**



Search region typically > 75 GeV

John Womersley

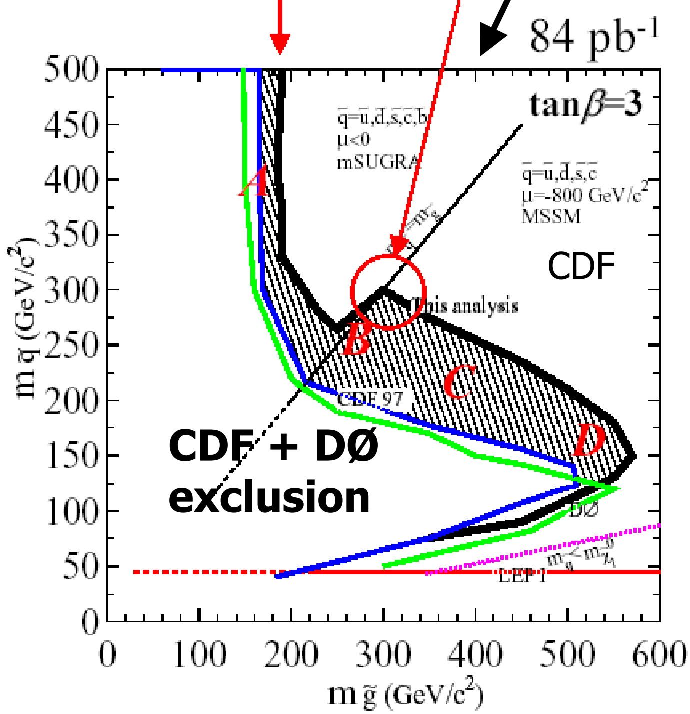
Searching for squarks and gluinos

Run I

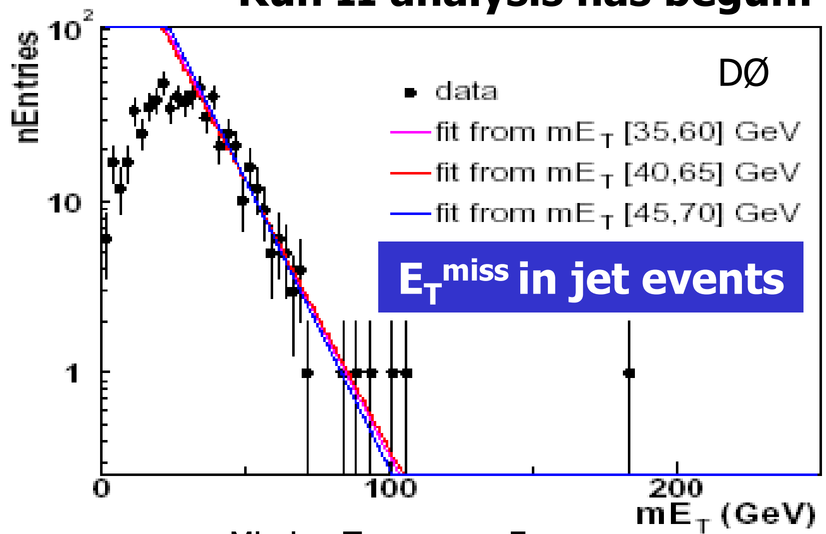
$M_{\tilde{g}} > 300\ \mathrm{GeV/c^2} \quad M_{\tilde{q}} \approx M_{\tilde{g}}$

$M_{\tilde{g}} > 195\ \mathrm{GeV/c^2}$

With 2 fb^{-1}: Reach in gluino mass ~ 400 GeV



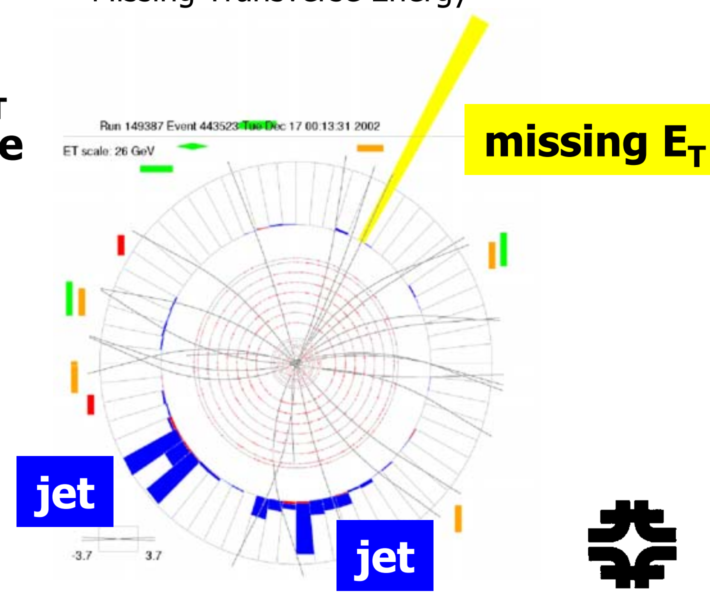
Run II analysis has begun:



Missing Transverse Energy

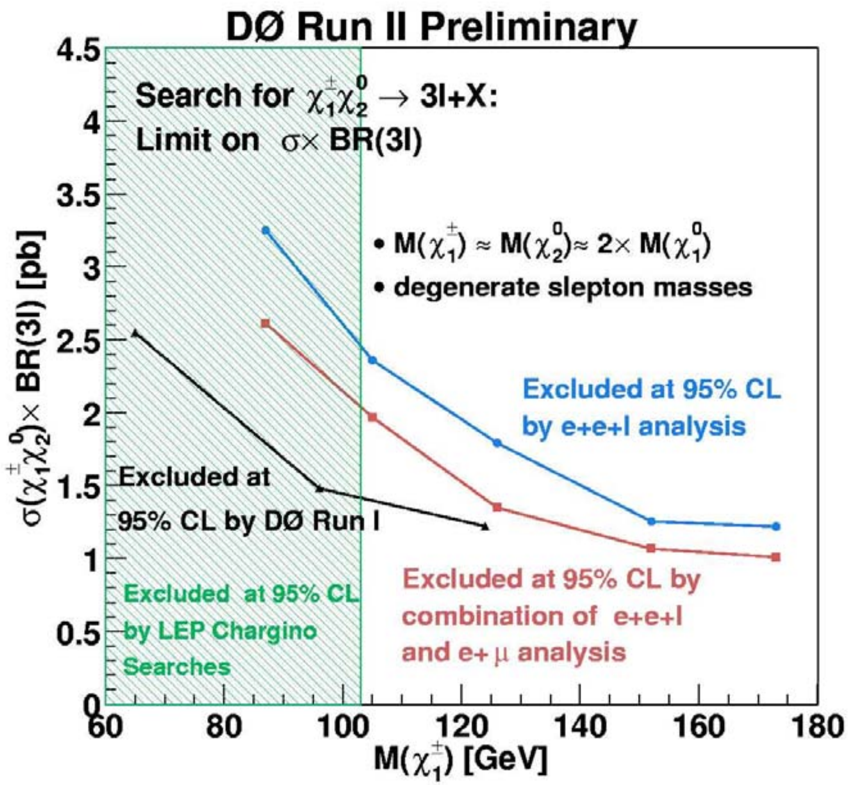
High ME$_T$ candidate event

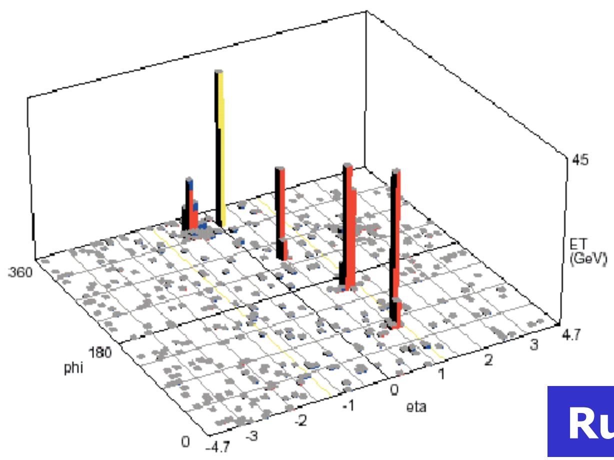
DØ



Chargino/neutralino production

- "Golden" signature
  - Three leptons
    - very low standard model backgrounds
- Increasingly important as squark/gluino production reaches its kinematic limits (masses ~ 400-500 GeV)
- Reach on $\chi^{\pm}$ mass
  ~ 180 GeV ($\tan\beta = 2, \mu < 0$)
  ~ 150 GeV (large $\tan\beta$)



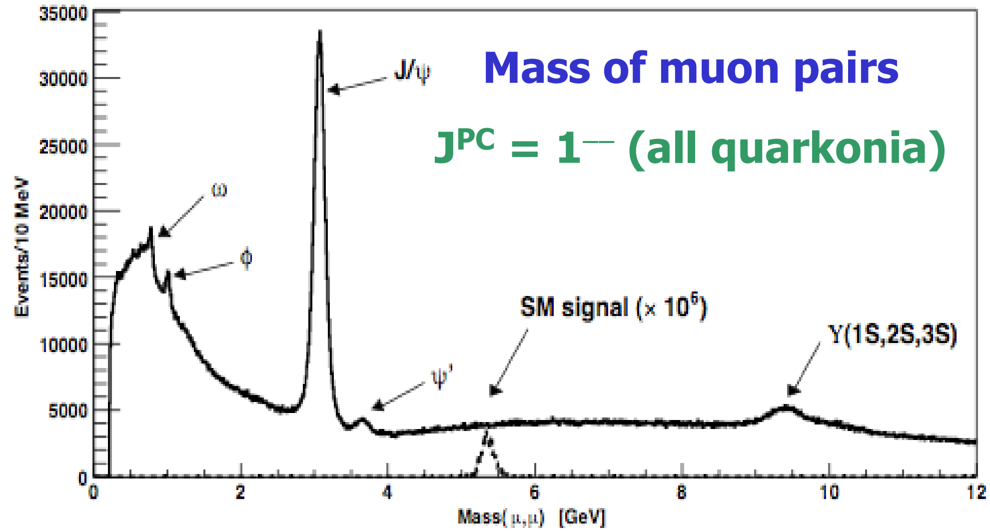


We have entered unexplored territory in terms of sensitivity to new physics

Run II Trilepton candidate event

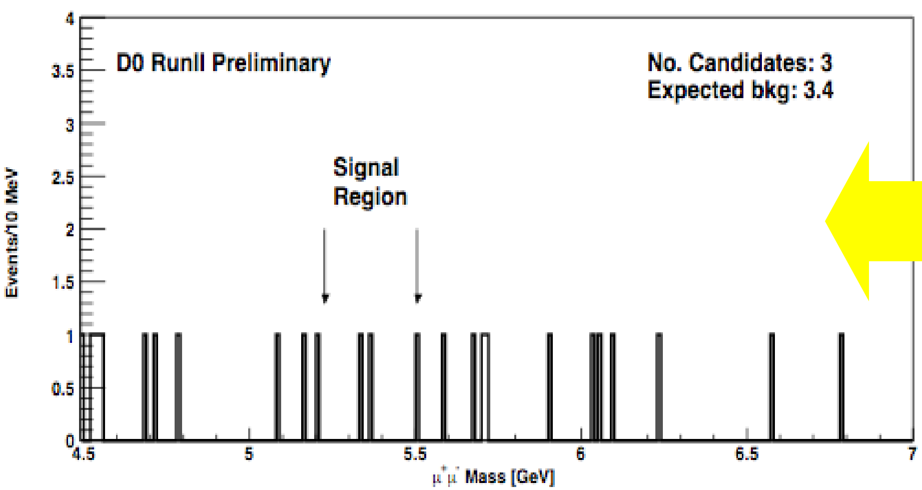
Indirect searches for new particles

- Measure the rate of the rare decay $B_s \to \mu^+\mu^-$
- In the Standard Model, cancellations lead to a very small branching ratio
  - SM BR= 3.7×10^{-9}
- New particles (e.g. SUSY) contribute additional Feynman diagrams, increase BR
  - up to 10^{-6}



Mass of muon pairs

$J^{PC} = 1^{--}$ (all quarkonia)



- In $100 pb^{-1}$ of data, after all cuts, in B_s mass region
  - Observe 3 events
  - Expect 3.4 ± 0.8 background
  - BR $(B_s \to \mu^+\mu^-) < 1.6 \times 10^{-6}$ (90% CL)

    cf. 2.0×10^{-6} (PDG)

John Womersley

Q:

- **What is the structure of spacetime?**
  - **How many dimensions are there?**
  - **Is geometry the way to connect gravity to the other forces?**

Connections with Gravity

- **While gravity can be unified with the other forces plus supersymmetry, it was usually assumed that any unification of forces would occur at the Planck scale ~ 10^{19} GeV**
  - **very large hierarchy between the electroweak scale and gravitational scales**

- **Powerful new idea:**
  Gravity may propagate in extra dimensions, while the gauge particles and fermions (i.e. us) remain trapped in 3+1 dimensional spacetime
  - **extra dimensions not necessarily small in size (millimeters!)**
  - **true Planck scale may be as low as the electroweak scale**
  - **Gravity could start to play a role in experiments at ~ TeV**

- **Many different theoretical ideas, with different topologies possible**
  - **large extra dimensions (ADD)**
  - **TeV scale extra dimensions**
  - **warped extra dimension (RS)**

New York Times

A Far-Out Theory Describing What's Out There

Physicists have long sought a unified theory to explain all the forces and matter in the universe. Superstring theory is an attempt at such a unification, and now "brane" theory expands on it, proposing that our universe is one of many membranes that "float" in a multidimensional megaverse.

SUPERSTRING THEORY

At its most basic level, the universe consists of tiny loops of string that vibrate at different frequencies.

Since matter can be described in terms of energy, each frequency (energy) corresponds to a type of particle (matter) just as different frequencies coming from a violin's strings produce different notes.

STRING SIZE

The strings are to an atom…

…as an atom is to the solar system.

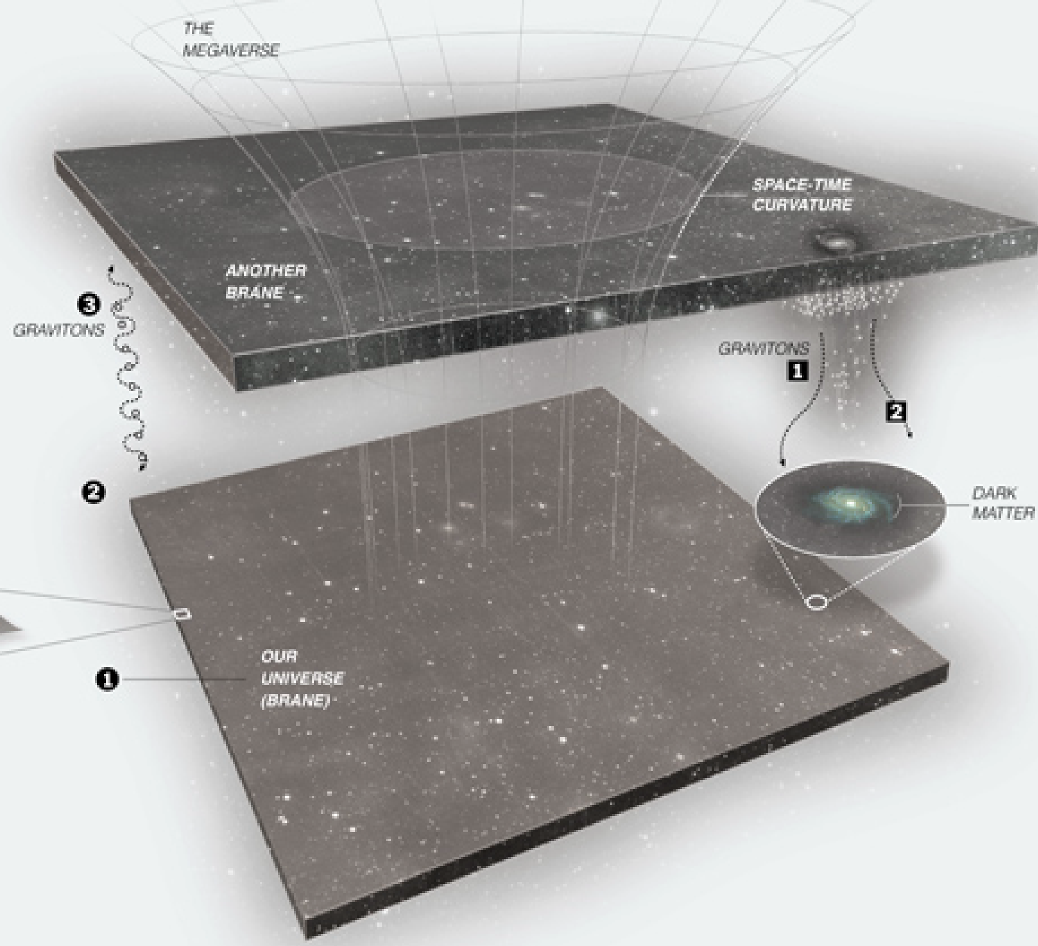
Brane Theory

It expands superstring theory to include vibrating membranes, or branes, which may have many dimensions.

❶ *Our universe can be thought of as a three-dimensional brane floating inside a four-dimensional megaverse.*

❷ *Most strings that compose our universe are attached to the brane's surface, and so most particles that exist on our brane are confined to its three-dimensional space.*

❸ *However, the particles that convey gravity, gravitons, are not tightly confined to any particular brane, and some of them roam across to other branes in the megaverse.*



BRANE THEORY AND GRAVITY

Gravity is described by relativity theory as curved space-time, and it is the weakest of the forces in our universe. Brane theory contains a possible explanation.

1 *Gravitons, conveyors of gravity, may be concentrated on a different brane where the space-time of the megaverse is severely curved. Only a small number of gravitons make their way here, so gravity is felt as a weak force.*

DARK MATTER

Cosmologists suggest that it makes up 90 percent of our universe. It neither emits or absorbs light, but it exerts gravity. According to brane theory, it may just be ordinary matter concentrated on other branes, and its light cannot shine through to this universe.

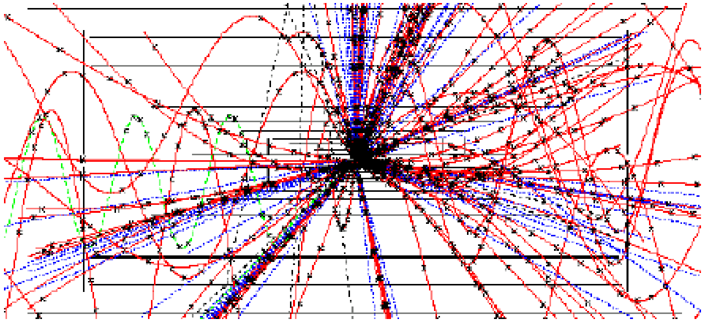
2 *The light from dark matter, conveyed by particles called photons, would cling to the surface of the foreign brane, but gravitons might seep across the divide. Pulled by our galaxies' local gravitational force, the gravitons would cluster into halos around the galaxies.*

Sources: "Q is for Quantum," by John Gribbin; "The Ideas of Particle Physics," by J.E. Dodd

Steve Duenes/The New York Times

TeV-scale gravity

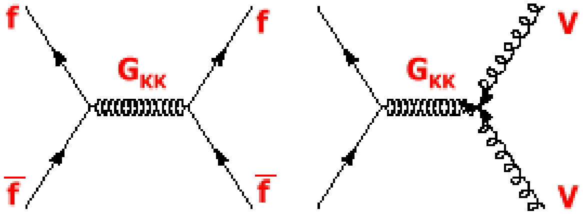
- **Observable effects can be direct and spectacular . . .**



Production of Black Holes may even occur

Decay extremely rapidly (Hawking radiation) with spectacular signatures

- **Or indirect . . .**
  - **Virtual graviton exchange can enhance the production rate for e^+e^- and $\gamma\gamma$ pairs with large masses and angle relative to the beamline**



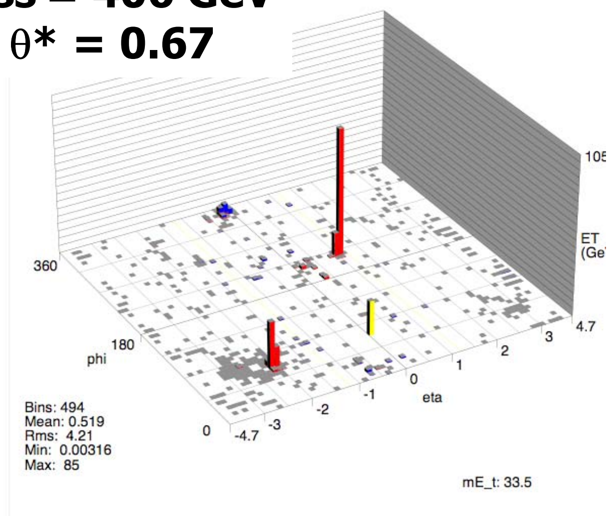
Indirect effects likely to be seen first
→ focus on these at the Tevatron

Searching for Extra Dimensions

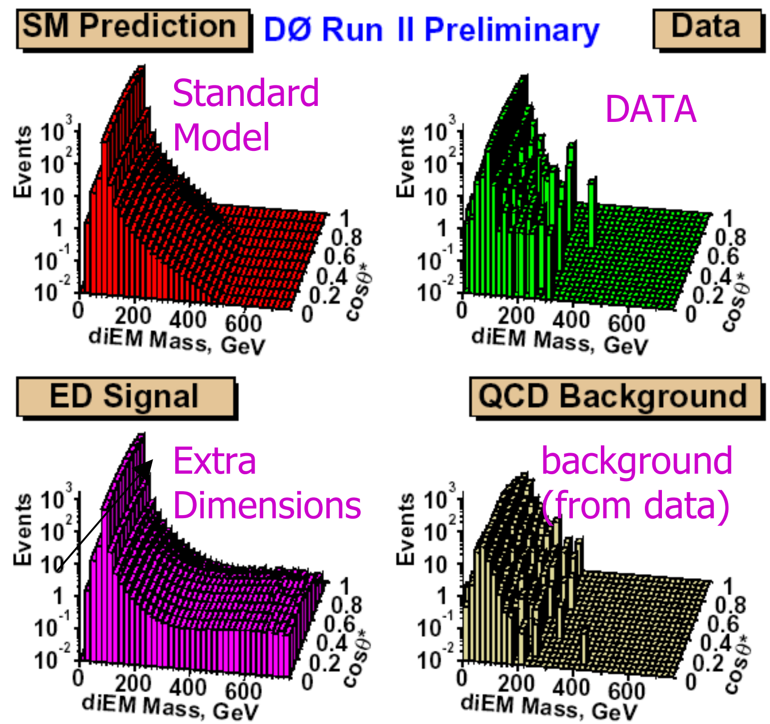
- **Signal would be an excess of ee, μμ, γγ events at large mass and large angle, due to virtual graviton exchange**

High-mass electron pair event

mass = 406 GeV
cos θ* = 0.67



$p\bar{p} \rightarrow$ ee and γγ



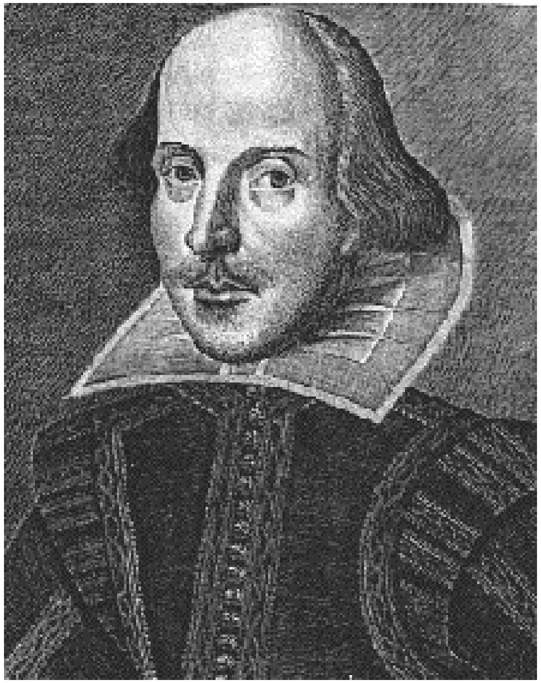
DØ limits from $p\bar{p} \rightarrow$ ee, μμ, γγ
(Summer 2003)

M_S(GRW) > 1.28 TeV (128 pb^{-1}, 95% CL)
> 1.37 TeV (Run I + Run II combined)
most stringent limit to date on large extra dimensions

John Womersley

Are we asking the right questions?

There are more things in heaven
and earth, Horatio,
Than are dreamt of in your
philosophy. — W.S.



- **We need a way to search for new phenomena that is not constrained by our preconceptions of what might be "out there."**

Sleuth

- **A new approach from DØ: attempt at a model-independent analysis framework to search for new physics**
  - **will never be as sensitive to a particular model as a targeted search, but open to anything**
  - **searches for deviations from standard model predictions**
- **Systematic study of 32 final states involving electrons, muons, photons, W's, Z's, jets and missing E_T in the DØ 1992-95 data**
- **Only two channels with some hint of disagreement**
  - **2 electrons + 4 jets**
    - **observe 3, expect 0.6± 0.2, CL = 0.04**
  - **2 electrons + 4 jets + Missing E_T**
    - **observe 1, expect 0.06±0.03, CL = 0.06**
- **While interesting, these events are not an indication of new physics, given the large number of channels searched**
  - **Run I data shows 89% probability of agreement with the Standard Model (alas!)**
  - **With significantly more data in Run II, sensitive to smaller deviations… The analysis has begun!**

New DØ Results Summer 2003

I've shown just a small fraction of our program

- masses, or scale limits
  - $M(B^{**}_d) = 5.71 \pm 0.016$ GeV
  - $m(\chi_0^1) > 80$ GeV
  - $m_{1/2} > 150$ GeV
  - M_S(GRW) > 1.28 TeV ($ee/\gamma\gamma$)
  - M_S(GRW) > 0.88 TeV ($\mu\mu$)
  - $M_{LQ}(\mu\mu) > 184$ GeV
  - $M_{LQ}(e\nu) > 159$ GeV
  - $M_{LQ}(ee) > 231$ GeV
  - $M_{Z'}(ee) > 719$ GeV
  - $M_{Z'}(\mu\mu) > 620$ GeV
  - $M(H^{\pm\pm}) > 115$ GeV
- BR and R
  - $BR(B_s \to \mu\mu) < 1.6\times10^{-6}$
  - $R_{W/Z} = 10.34 \pm 0.35 \pm 0.48$
- lifetimes
  - τ(incl. B) = $1.562 \pm 0.013 \pm 0.045$ ps
  - $\tau(B^+) = 1.65 \pm 0.083\ ^{+0.096}_{-0.1233}$ ps
  - $\tau(B_d) = 1.52\ ^{+0.19}_{-0.17}$ ps
  - $\tau(B_s) = 1.19\ ^{+0.19}_{-0.14}$ ps
  - $\tau_{\Lambda b} = 1.05\ ^{+0.21}_{-0.18} \pm 0.12$ ps
  - $\tau(B \to D l\nu) = 1.46 \pm 0.08$ ps
- cross sections, or limits
  - $\sigma(tt) = 8.1^{+2.2}_{-2.0}\ ^{+1.6}_{-1.4} \pm 0.8$ pb
  - $\sigma(Z\mu\mu) = 261.8 \pm 5.0 \pm 8.9 \pm 26.2$ pb
  - $\sigma(Z\tau\tau$, π–type) = 235 ± 137 pb
  - $\sigma(Z\tau\tau$, ρ-type) = 222 ± 71 pb
  - $\sigma(W+bb) < 33.4$ pb
  - σ*BR(H->WW->$ee/e\mu$) < 0.45 to 2.8 pb
  - σ*BR(H->WW->$\mu\mu$) < 0.2 to 0.7pb

Conclusions

- The Tevatron Collider at Fermilab is the world's highest energy accelerator
- In studying high energy collisions between the fundamental constituents of matter, we are not just trying to understand these constituents, we are trying to address big questions about the universe

  For example
  - What is the cosmic dark matter?
  - Is the universe filled with energy?
  - What is the structure of spacetime?
- This physics program is based on the detailed understanding of Standard Model particles and forces that we have obtained over the last few decades
  - we are guided by theory but also open to the unexpected
- We have now entered unexplored territory—who knows what we will find!

"Imagina que viajas millones y millones de kilómetros hasta llegar a los niveles más profundos del espacio interior de los quarks y los leptones. Jóvenes científicos pueden ser pilotos del más poderoso acelerador del mundo como miembros del EQUIPO ANDINO en la estación D-cero de Fermilab"

Leon Lederman
Premio Nobel de Física
Director Emérito de
Fermilab

Si eres un joven de la región andina, HOY tienes la oportunidad de participar en uno de los proyectos de investigación en física fundamental más interesantes e importantes del mundo.

Mira más detalles en la siguiente página web:

www-d0.fnal.gov/andes.html