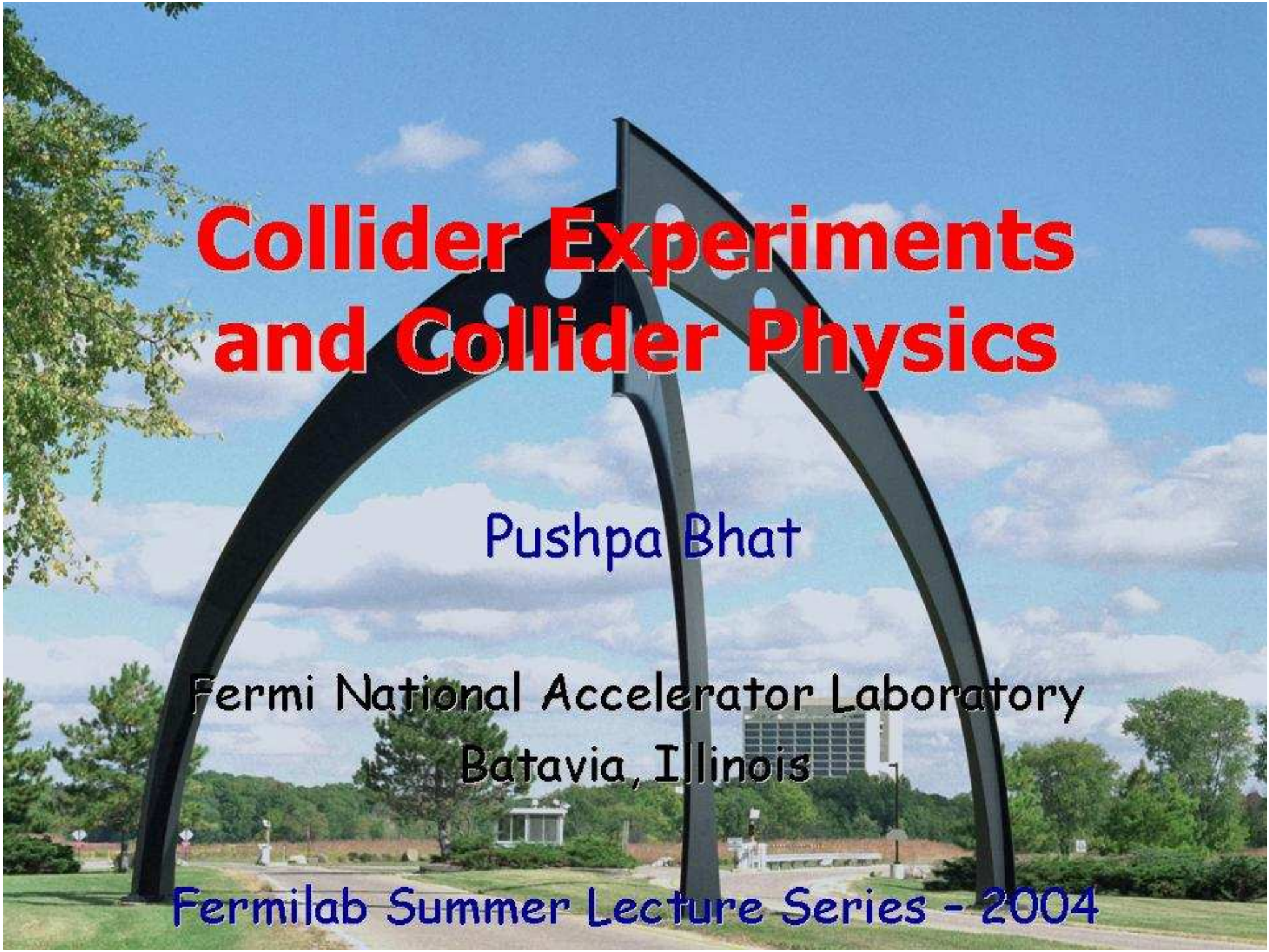


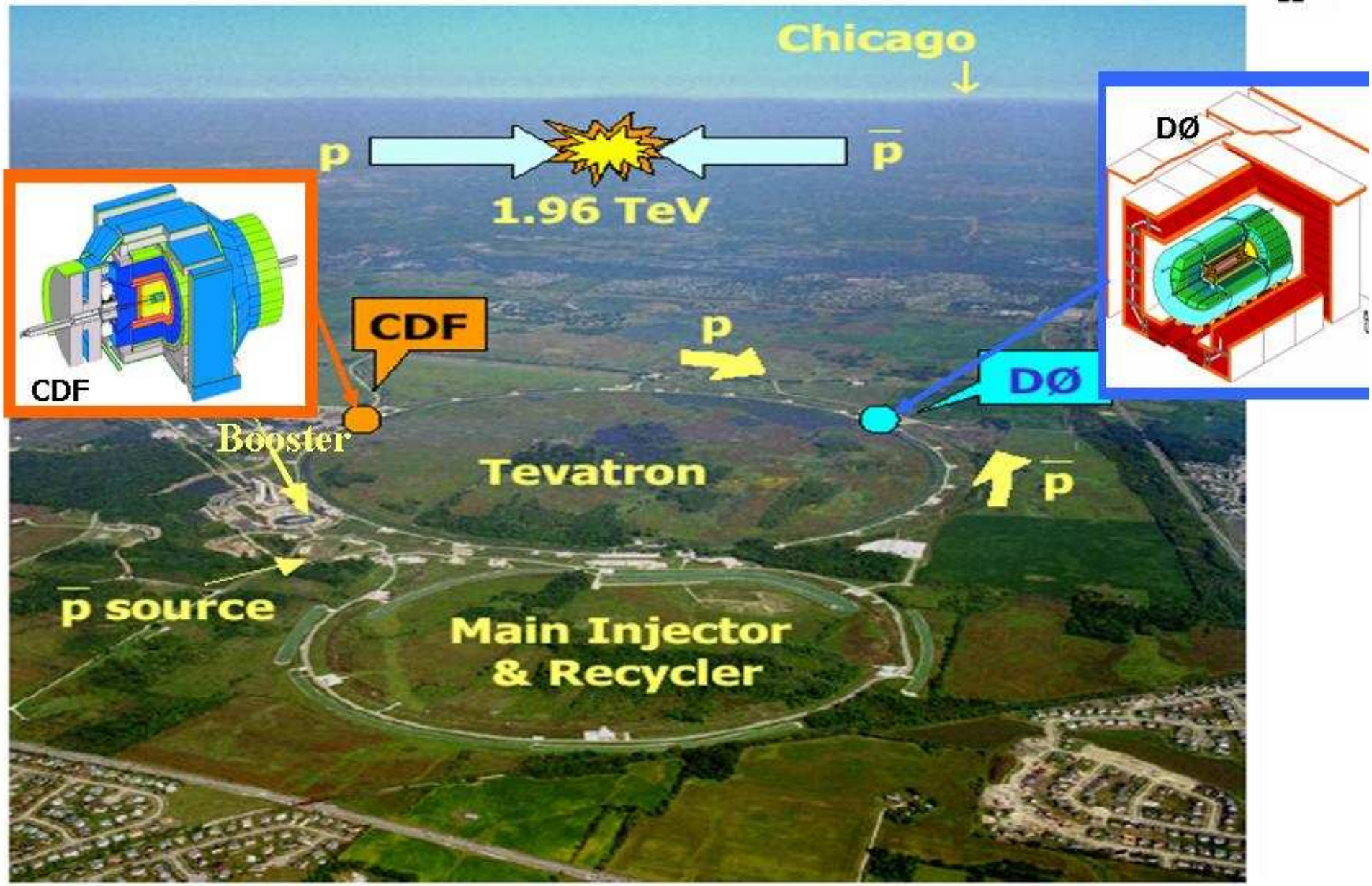
Collider Experiments and Collider Physics

Pushpa Bhat

Fermi National Accelerator Laboratory
Batavia, Illinois

Fermilab Summer Lecture Series - 2004

World's Pre-eminent HEP Laboratory



So far, ... You have heard about

- Historic Particle Physics Experiments - Lederman
- Discoveries ahead in particle physics - Witherell
  - Experiment must lead the way.
- The Universe → Quarks et al., and the cosmos are intricately connected - Kolb
- How the Particle Accelerators work - McGinnis

This talk -

- How do we actually perform the experiments in this day and age, to answer the profound and important questions? ← A sneak-peek

  I'll believe it when I see it!

  Experiment ≡ Observe + analyze

What are things made of?

- All great minds think alike!
- Basic Elements :
  - Greeks: 4 elements – air, water, fire, earth
  - Hindus: 5 elements – air, water, fire, earth, space
- All matter was suspected to be made up of "fundamental" building blocks that would be "uncuttable"

  Greeks → "Atomos" Democritus 470 – 380 B.C.

  Hindus → "Atma" Vedas, Gita 3000- 1000 B.C.

  Anu, Paramanu Atomic Theory → Kanada 600 B.C.

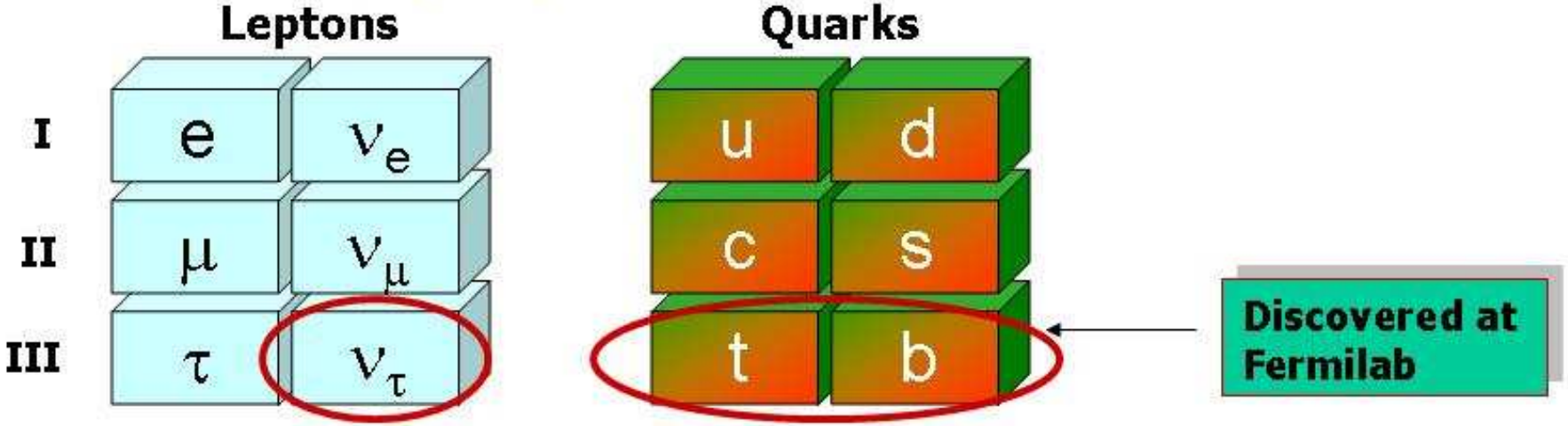
  (basic building blocks of all matter)

- And then … fast forward →→ to the periodic table (1869), the modern atom (late 1800's +early 1900's), the Nucleus (1911, Rutherford), …

The "Standard Model"

The Prevailing Theory of Matter and Forces

- Point like, spin-$\frac{1}{2}$ fermionic constituents



which interact by exchanging spin-1 vector bosons

Electromagnetic	10^{-2}	γ
Strong	1	g
Weak	10^{-6}	W^+ Z^0 W^-
For Comparison, Gravity	10^{-40}	

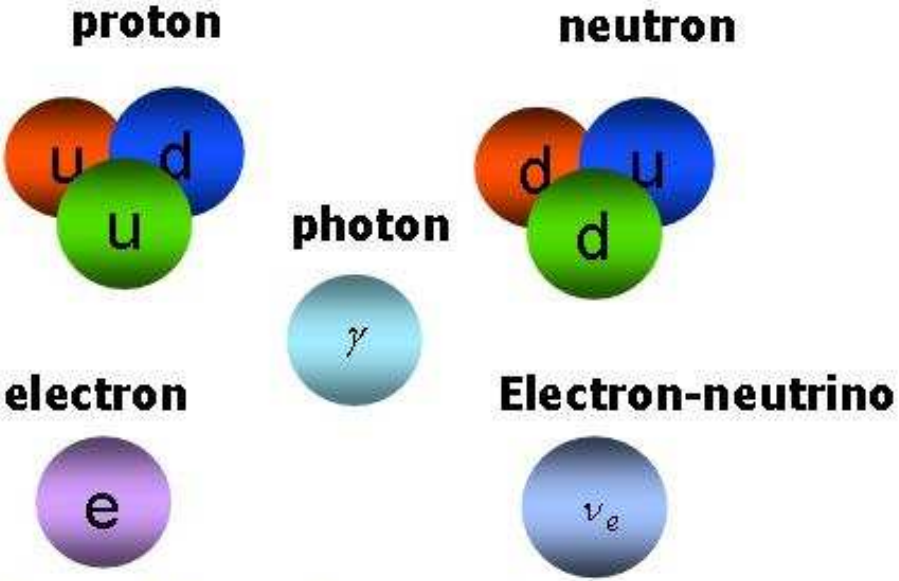
Relative strengths

Higgs

- Ordinary Matter

Matter

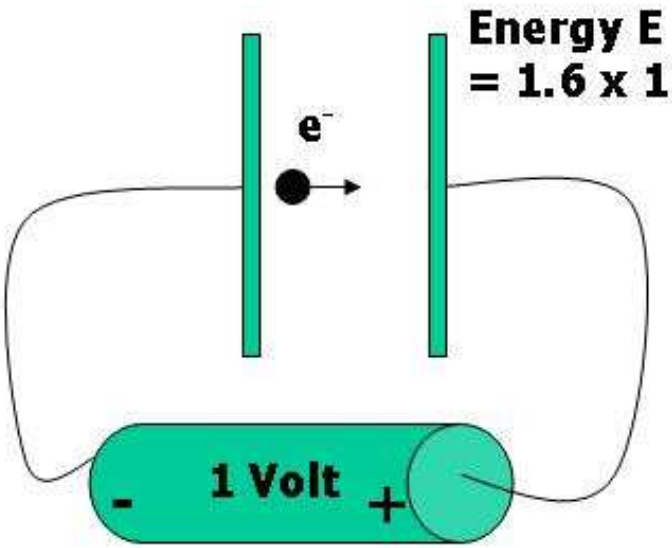
Anti-Matter



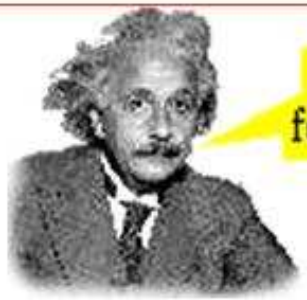
For every type of particle there exists an antiparticle type

- Fermilab makes antiprotons, stores them and collides protons and antiprotons head-on at nearly the speed of light to produce extra-ordinary matter
- The Tevatron is the most powerful microscope
  - Allows you to look at the tiniest things
- It is also the most powerful telescope
  - Allows you to look back in time (similar to looking deep into space) at the events that may have taken place in the early universe

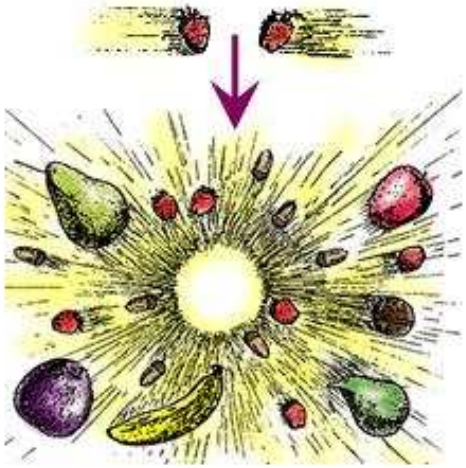
- Energy Units



1 KeV = 10^3 eV
1 MeV = 10^6 eV ~ 2 x mass of the electron
1 GeV = 10^9 eV ~ mass of the proton, neutron
1 TeV = 10^{12} eV ~ energy of protons and pbars in the Fermilab Tevatron
Energy density in the Universe at < 10^{-9} sec after the Big Bang



So, create matter From energy



Run 1 900 GeV beams speed: c-586 km/h
Run 2 980 GeV speed: c-495 km/h
Run 1 → Run 2 Improvement : 91 km/h

- Chris Quigg, Fermilab

Luminosity

- Collider Luminosity

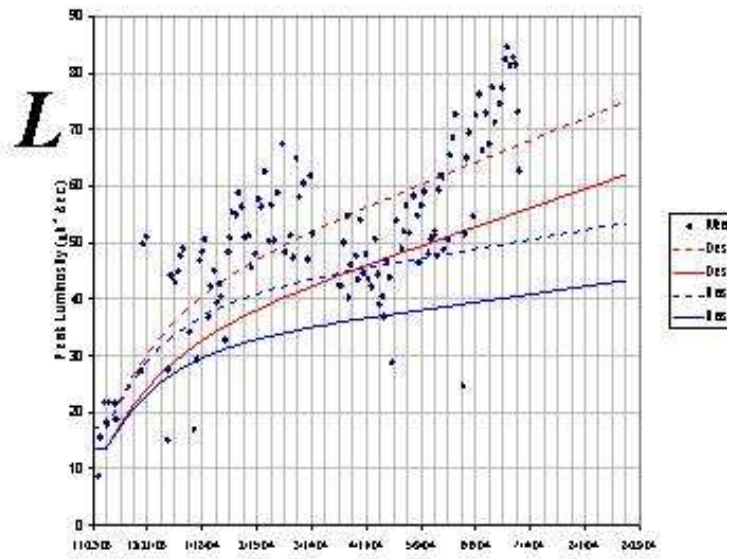
Instantaneous Luminosity $L \approx \dfrac{\text{Rev. Freq.} \times Nbunches \times \text{Np} \times \text{N}\bar{\text{p}}}{\text{Trans. Beam Area}}$

Tevatron getting close to 1x 10^{32} cm^{-2} sec^{-1}

Integrated Luminosity $= \int L dt$

Run 1 Int. Lum ~ 125 pb^{-1}
Run 2, already delivered ~ 500 pb^{-1}

1 barn = 10^{-24} cm^2



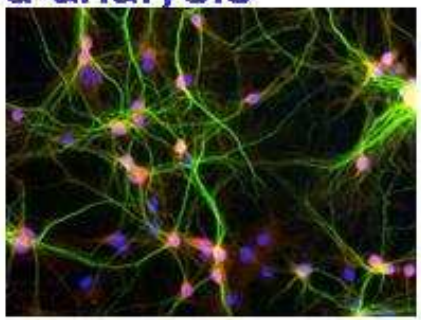
- Event Rate

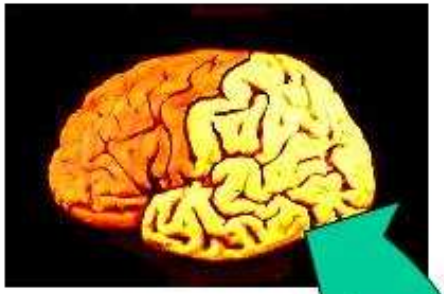
$$N = L \times \sigma$$

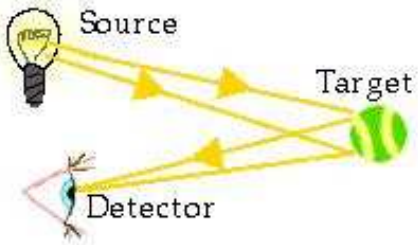
Cross-section σ **← effective area of interaction, cm^2**
← probability for a process to occur

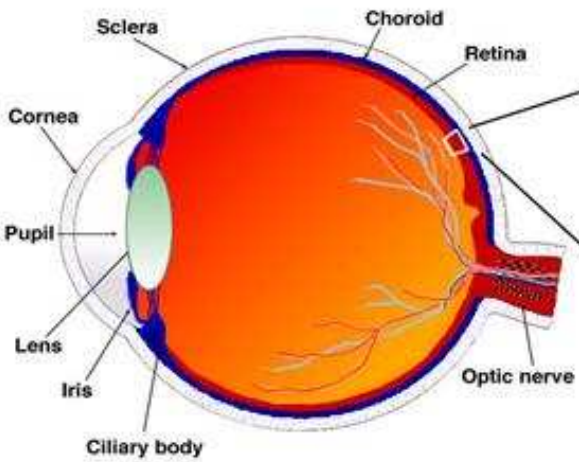
The Process of Observation

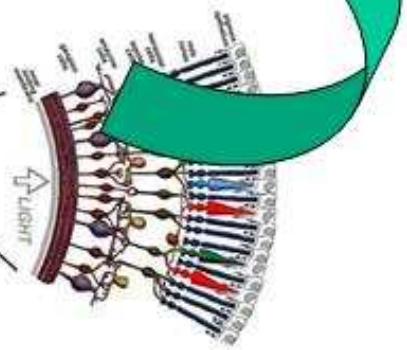
- Eye is an ingenious design of a photon detector, even though it senses only a tiny part of the electromagnetic spectrum! Along with the brain and the connectors forms a complete system for experimental observation and analysis





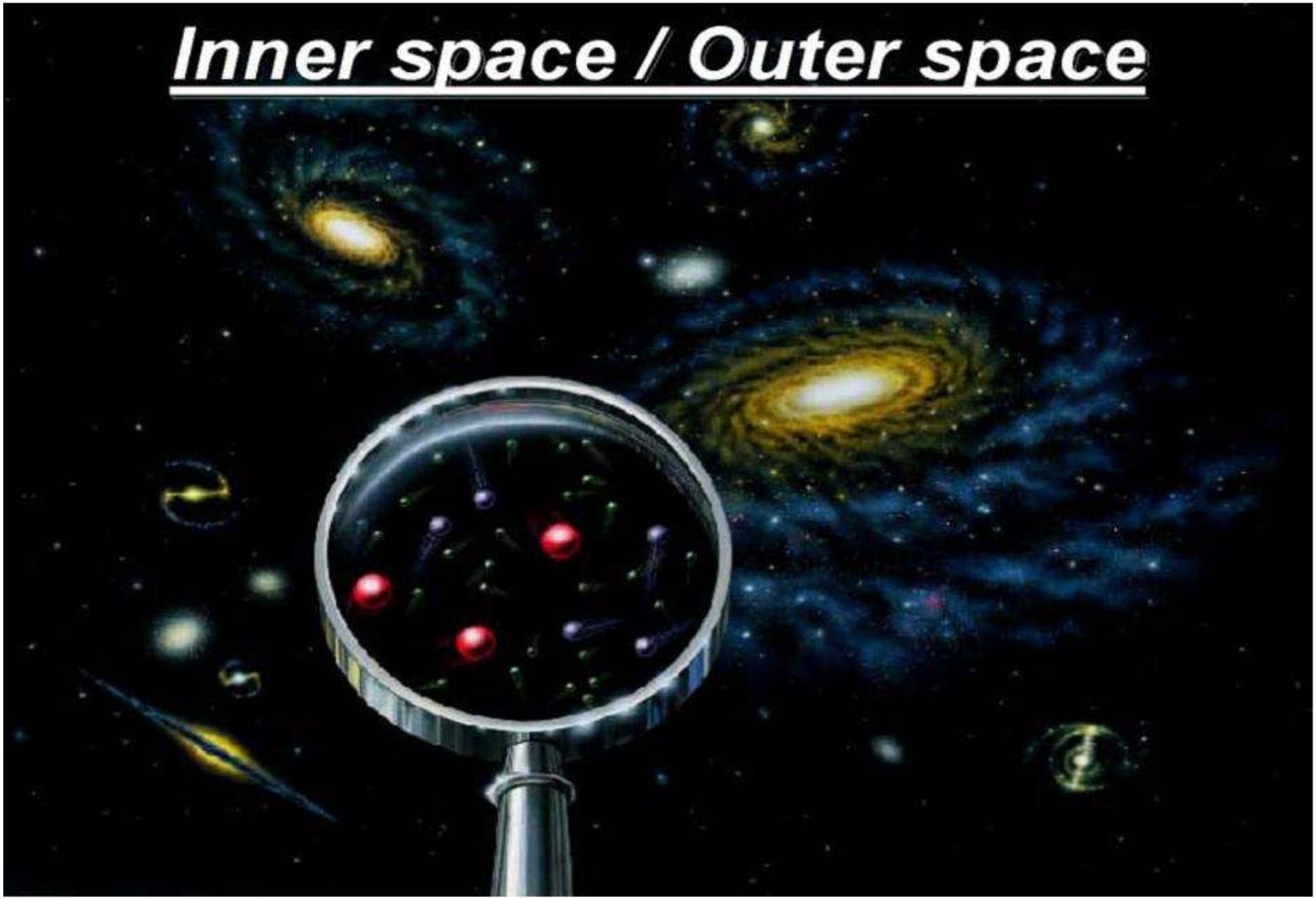




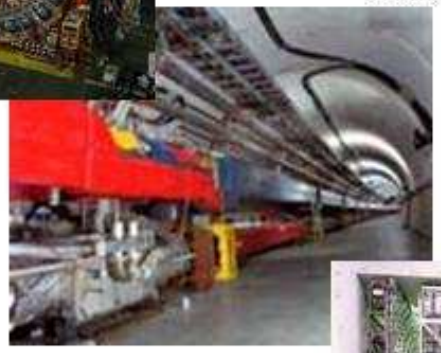


We need to see more, learn and understand! Augment our eyes and brains!

Inner space / Outer space



Analysis
Interpretation



Accelerators
& Detectors

Data

The DZero Collaboration

An international collaboration of ~ 650 physicists from 19 nations who have designed, built and operate the detector at the Tevatron

Institutions: 36 US*, 41 non-US

~ 50% from non-US institutions
(note strong European involvement)
~ 100 postdocs, 140 graduate students

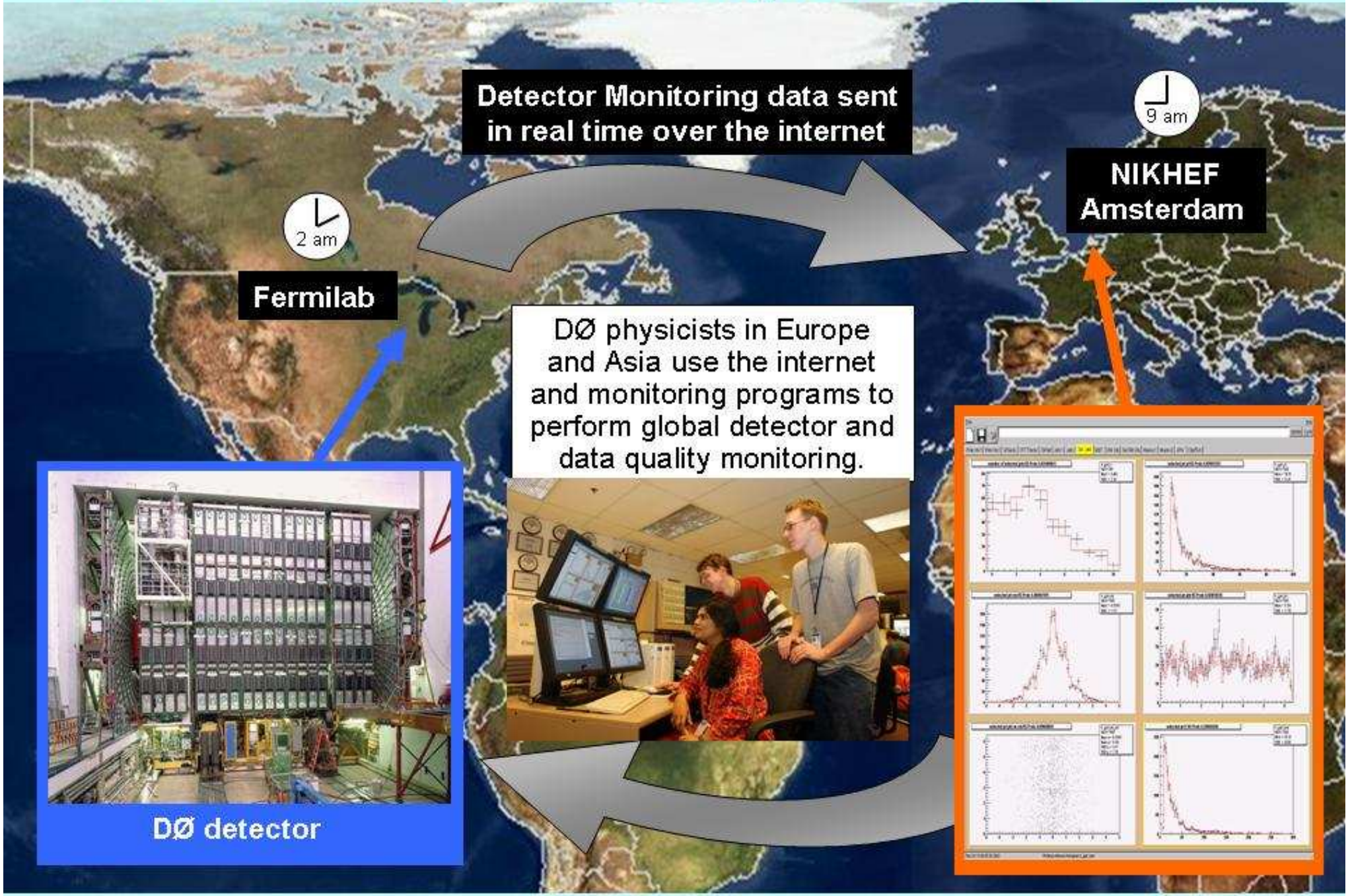
The CDF Collaboration

12 countries, 59 institutions
767 physicists

What Do Physicists Actually Do?

- Design and build hardware
  - Detectors, electronics
- Write software
- Operate the detector
- Analyze and interpret data
- Present, refine, discuss results
- Publish papers

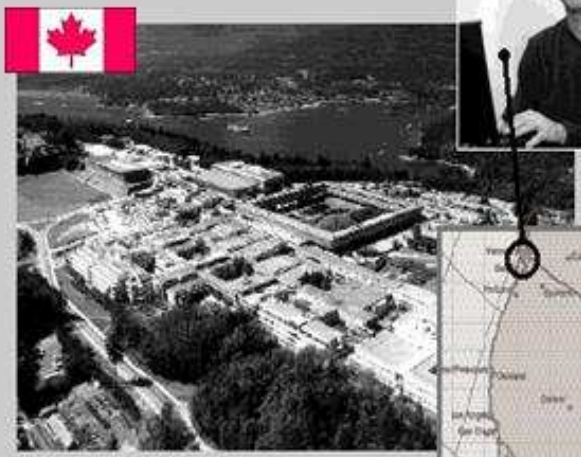
Remote International Monitoring for the DØ Experiment



All daytime monitoring shifts run from Brazil and night time from Europe, India and Vietnam.

DZero

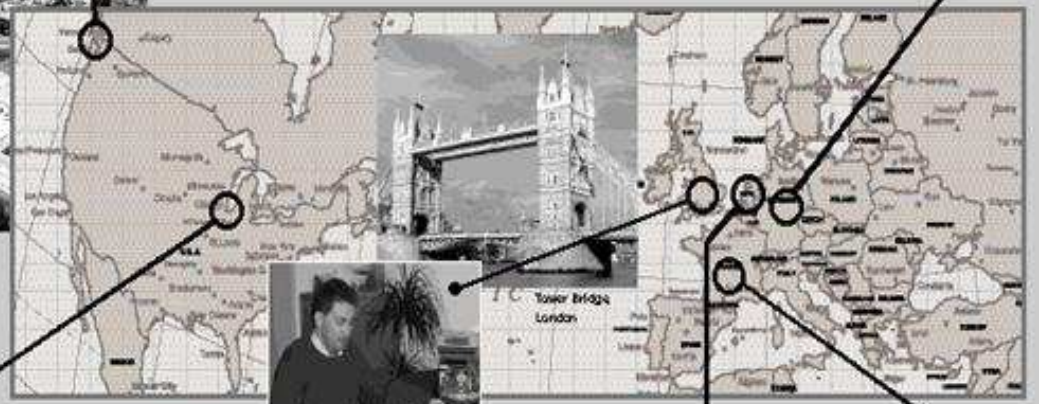
"You can't make the Grid work without motivation. It's one thing to have a vision, and it is another thing to stay up to three in the morning to make things work because they need to get done. DZero is a real application. We need to get the physics results out."
– Dugan O'Neil, Simon Fraser University, Canada



SFU campus on Burnaby Mountain, Vancouver

Wuppertal's landmark, the elevated train line

"In the past, particle physics collaborations have used remote computing sites to carry out Monte Carlo simulations. We are now one of the first experiments to process real data at remote sites. The effort has opened up many new computing resources. The evaluation of our experience will provide valuable input to the Grid development."
– Daniel Wicke, University of Wuppertal, Germany



Tower Bridge, London

"The machines at Imperial College, for example, are shared across the whole college, so it takes grid software to keep it all running smoothly." – Gavin Davies, Imperial College London, UK

Street scene in Lyon

"With the SAM software developed by the Fermilab Computing Division and DZero, a user doesn't know whether the data is stored on tape or on disk, whether it is located at Fermilab or at Karlsruhe."
– Wyatt Merritt (left), with Mike Diesburg and Amber Boehnlein, Fermilab, U.S.A.

"We've participated in large-scale Monte Carlo production in the past, but data reprocessing involves large volumes of data to be transferred in both directions on a scale that was simply unthinkable a few years ago. It will open new possibilities that we are only beginning to explore."
– Patrice Lebrun (right), with Tibor Kurca, CCIN2P3, Lyon, France

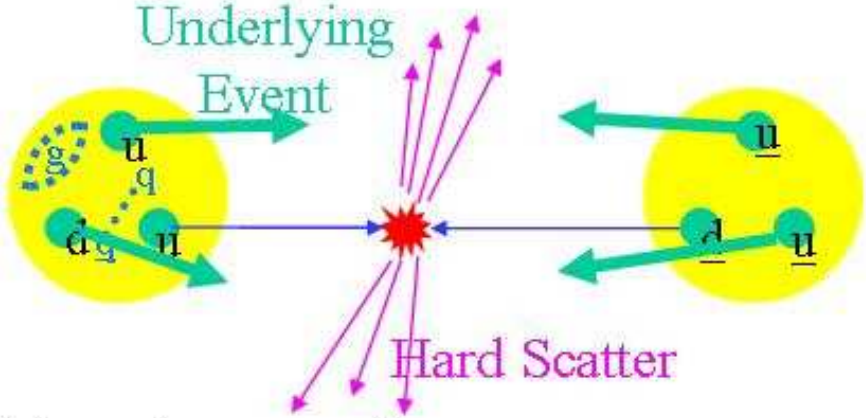
"The re-processing was a major milestone for DZero. For us it is also important that we have been able to show that we can really use the LHC Computing Grid for DZero processing. We saw jobs submitted from Wuppertal being executed on our CPUs, and we executed jobs in Karlsruhe, at Rutherford Appleton Laboratory and a few more places."
– Kors Bos (front row, second from left) and the Scientific Computing team at NIKHEF, Amsterdam, Netherlands

Amsterdam, famous for its canals

Data processing and simulations are a Worldwide effort, exploiting Grid resources

Collider Physics

- A very broad program and a rich harvest of physics
  - Quantum chromo dynamics
    - Study of quarks and gluons
  - Electroweak physics
    - W, Z bosons
  - C- and B- physics
  - Top physics
    - Strong and electroweak production of top, top properties
  - Higgs
    - Search for the SM and Supersymmetric (SUSY) Higgs
  - Searches for new phenomena and particles beyond SM
    - Supersymmetry (symmetry between fermions and bosons)
    - Technicolor (New strong interactions)
    - Leptoquarks (motivated by symmetry between quarks and leptons)
    - …
  - More Exotic possibilities → Extra dimensions, dark matter, tiny black holes



How do we do it?

What are we up against?

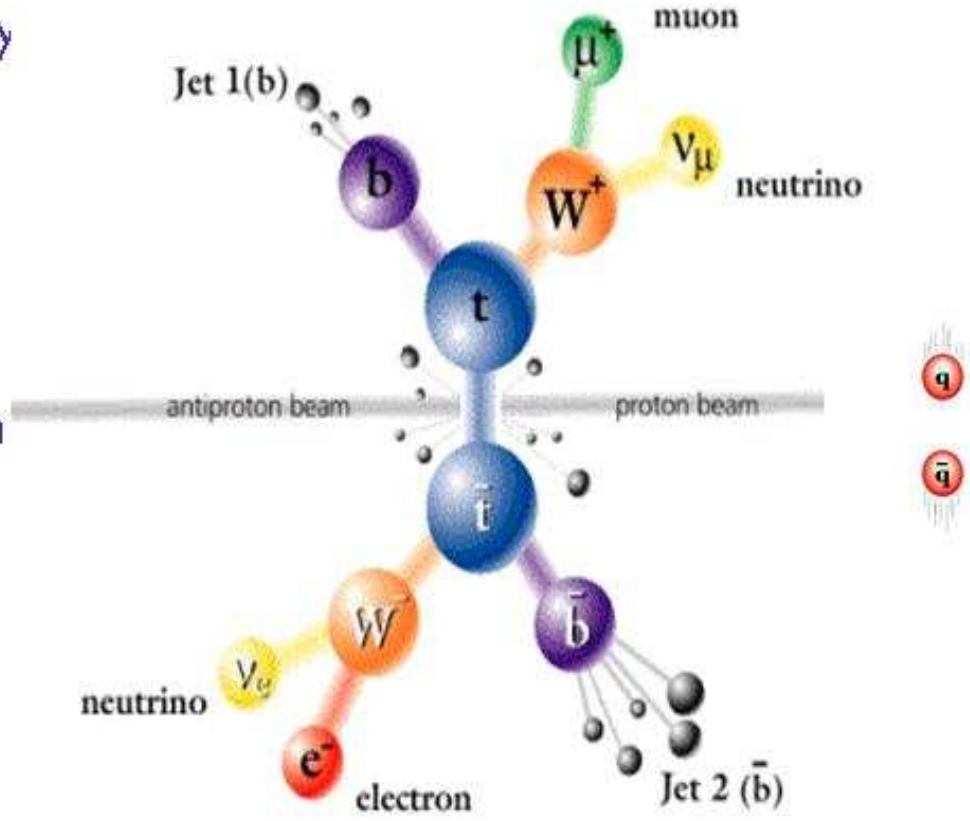
Let us take top quark production to see how it all works

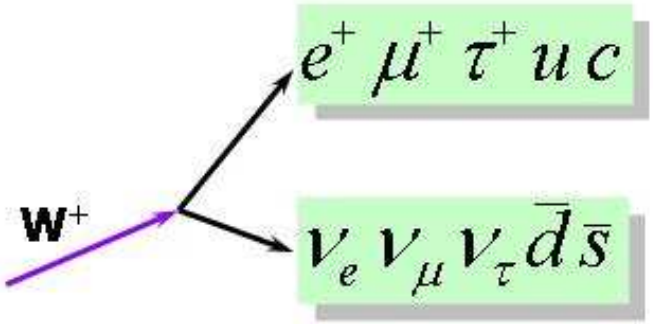
- 2.5 Million p-pbar crossings/sec most of which are "uninteresting"!
- Total inelastic cross section ~ 60 mb = 6x 10^{-2} barn
  - 1 barn = 10^{-24} cm^2
  - At $\mathcal{L}$ = 10^{32} cm^{-2} sec^{-1}, N = 6 Million interactions /sec
- Top-antitop pair production cross section $\sigma(t\bar{t})$ ~ 6.7 pb = 6.7 x 10^{-12} barn
  - 10 orders of magnitude lower!
  - 1 top pair event for every 10 billion "uninteresting" events!

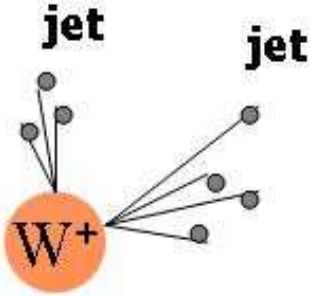
➔Finding a needle in a huge haystack!

The Top Quark
Discovered at Fermilab. 1995

- Presently, Tevatron is the only source of top quarks!
- Dominantly pair-produced via strong interactions
  - qqbar →ttbar (90%)
  - gg→ttbar (10%)
- Each top decays to a W boson and a b-quark nearly 100% of the time.
- Top quark is extremely heavy (weighs as much as a Gold atom) and extremely short-lived! Lifetime ~ 10^{-25} sec!!!!

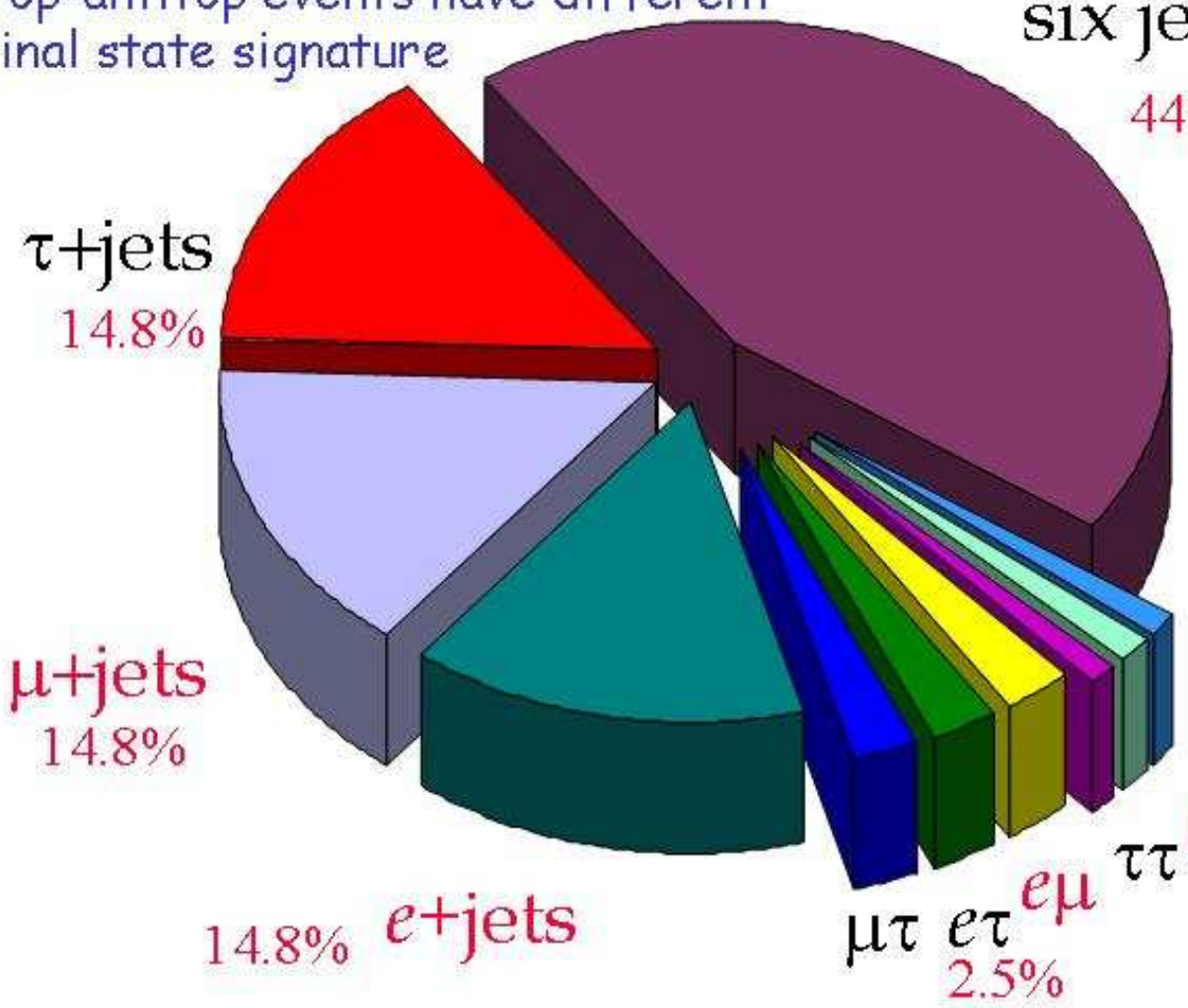






Top Quark Decay Modes

Depending on how the W's decay, Top-antitop events have different final state signature



So, to find and study top quark events, we need to find and measure leptons, jets and neutrinos.

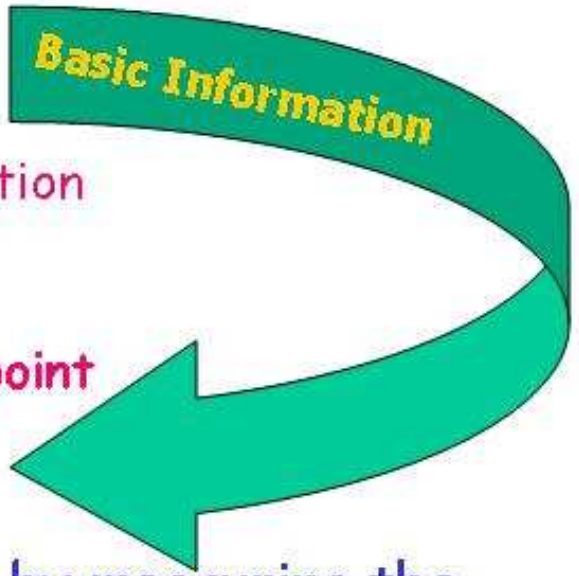
Our detectors are designed to do this

+ neutrinos in all cases except six jets mode

Identify and Measure Particles

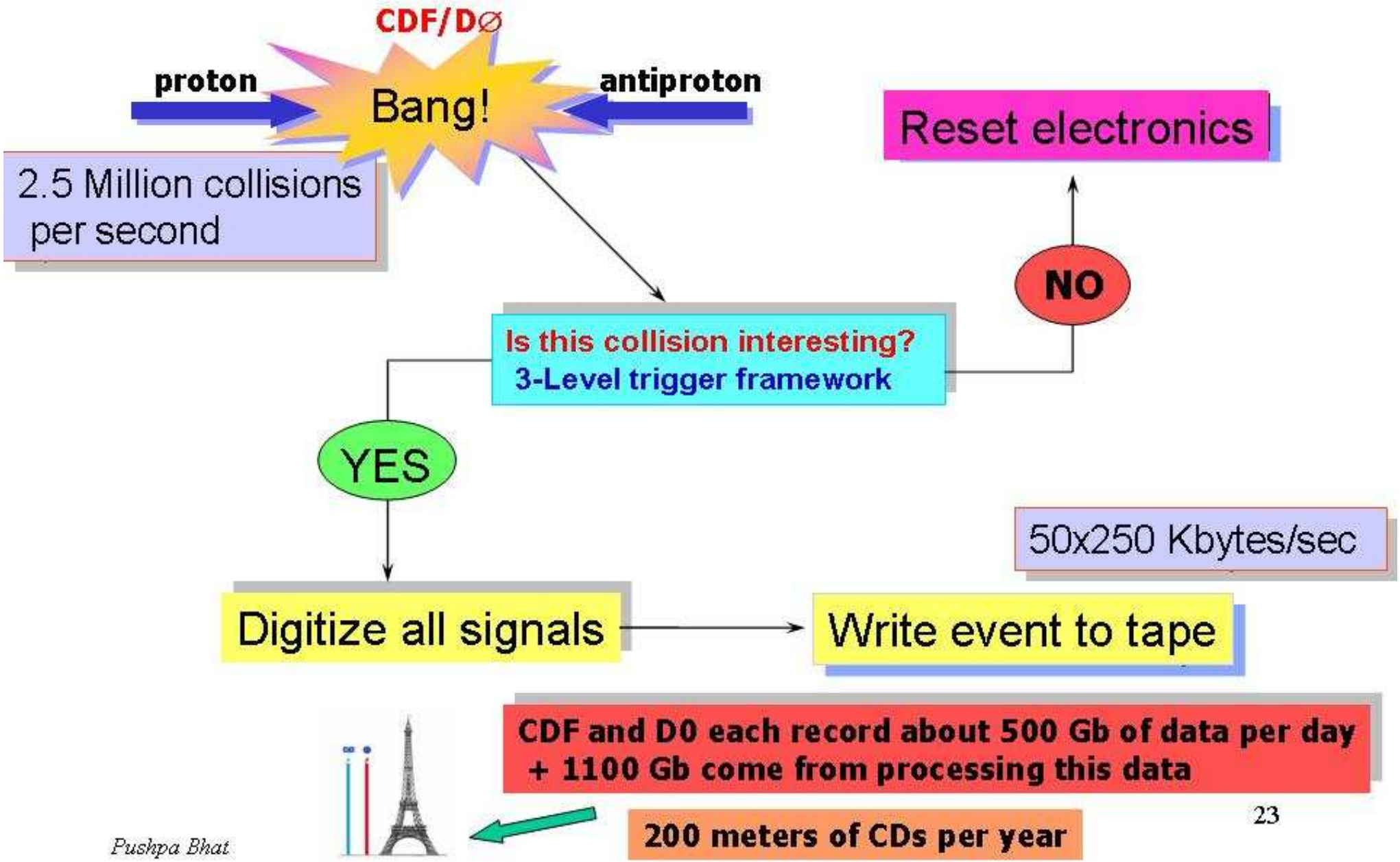
- Detectors should
  - Track, match and count particles
  - Measure energy/momentum
  - Find particle identity
  - Measure charge
  - Measure missing energy
  - Provide full solid angle coverage, fine segmentation
  - Have fast response, ideally zero deadtime

  ⇒ **Many kinds of detectors → sub-systems with several layers surrounding the collision point**

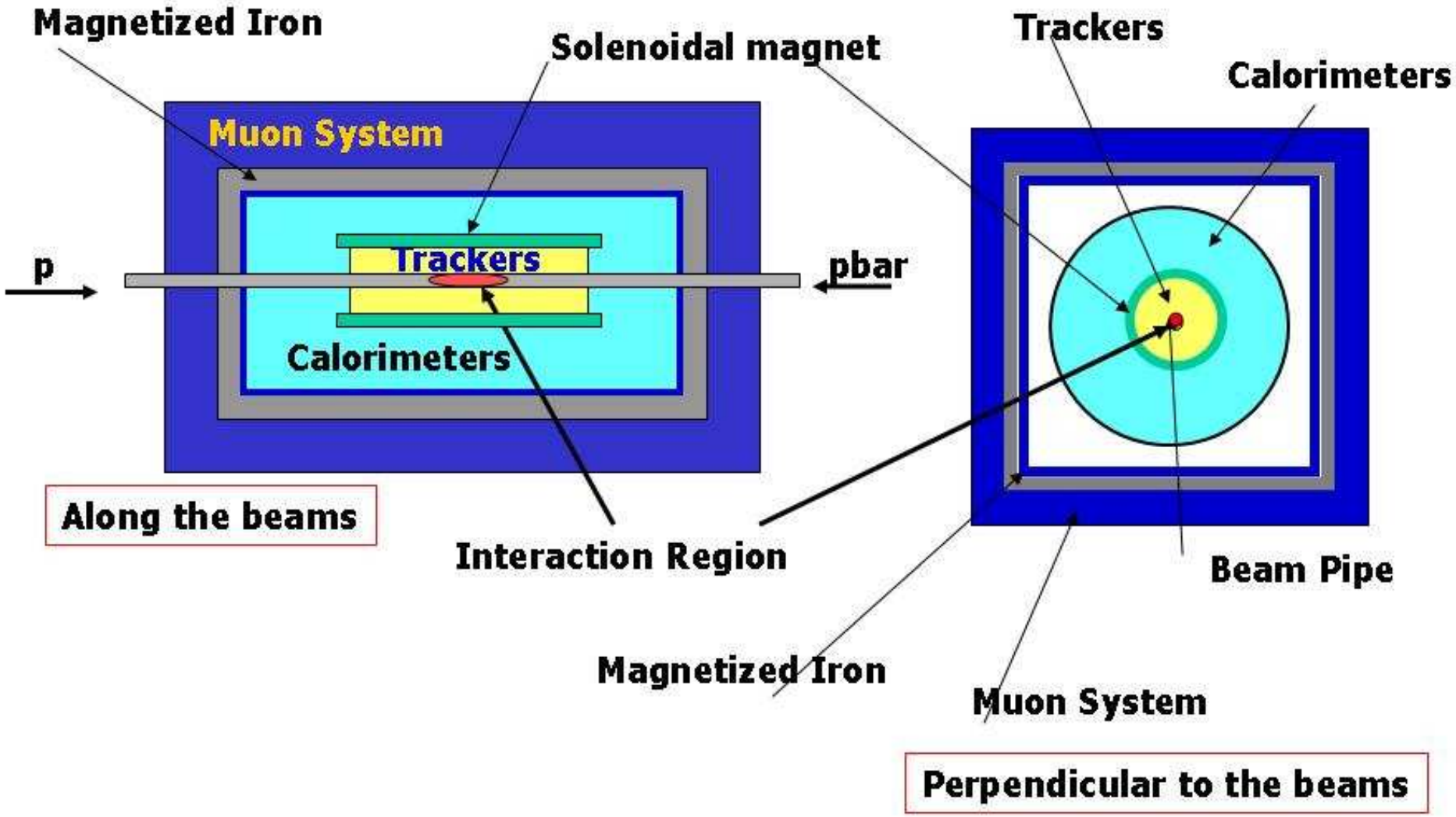


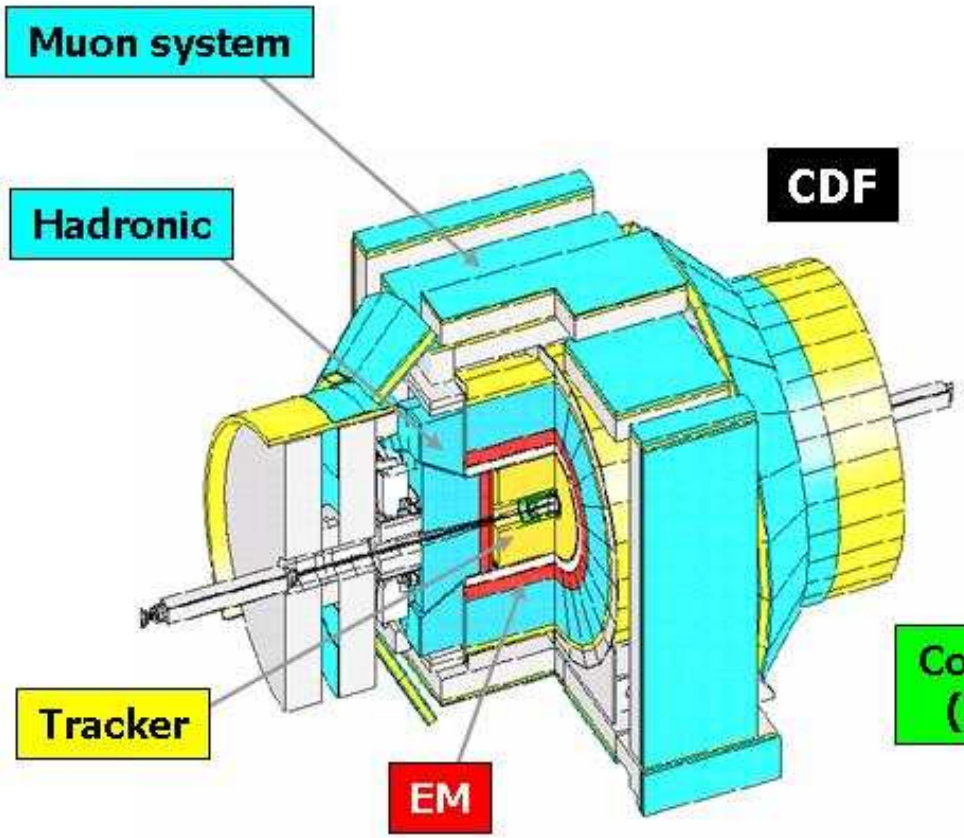
- Find Collision vertex
- Find and measure short-lived parent particles by measuring the children
- Perform analysis to understand the process that produced the event

Trigger on Interesting Events

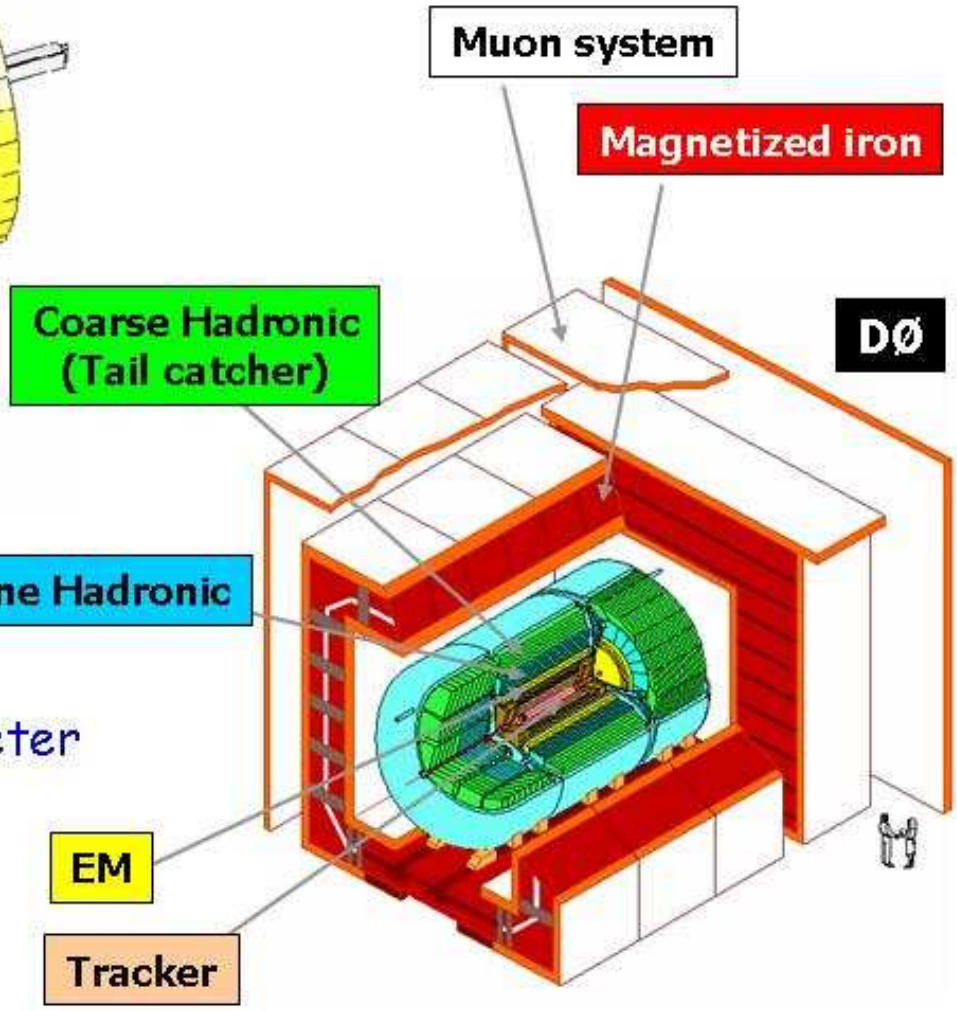


General Layout of a Collider Detector

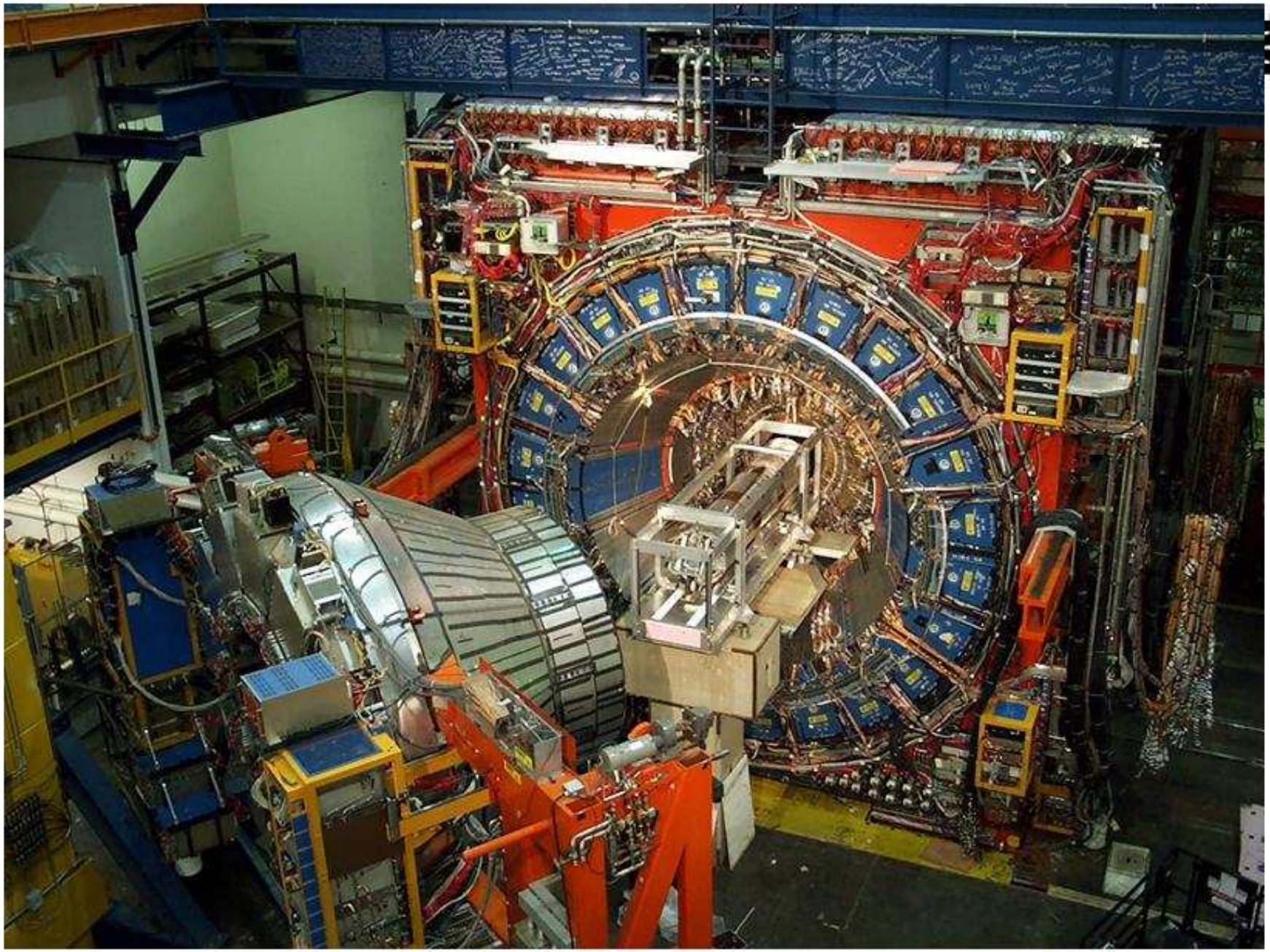




Arrays of sensitive instrumentation
> Million electronic channels each



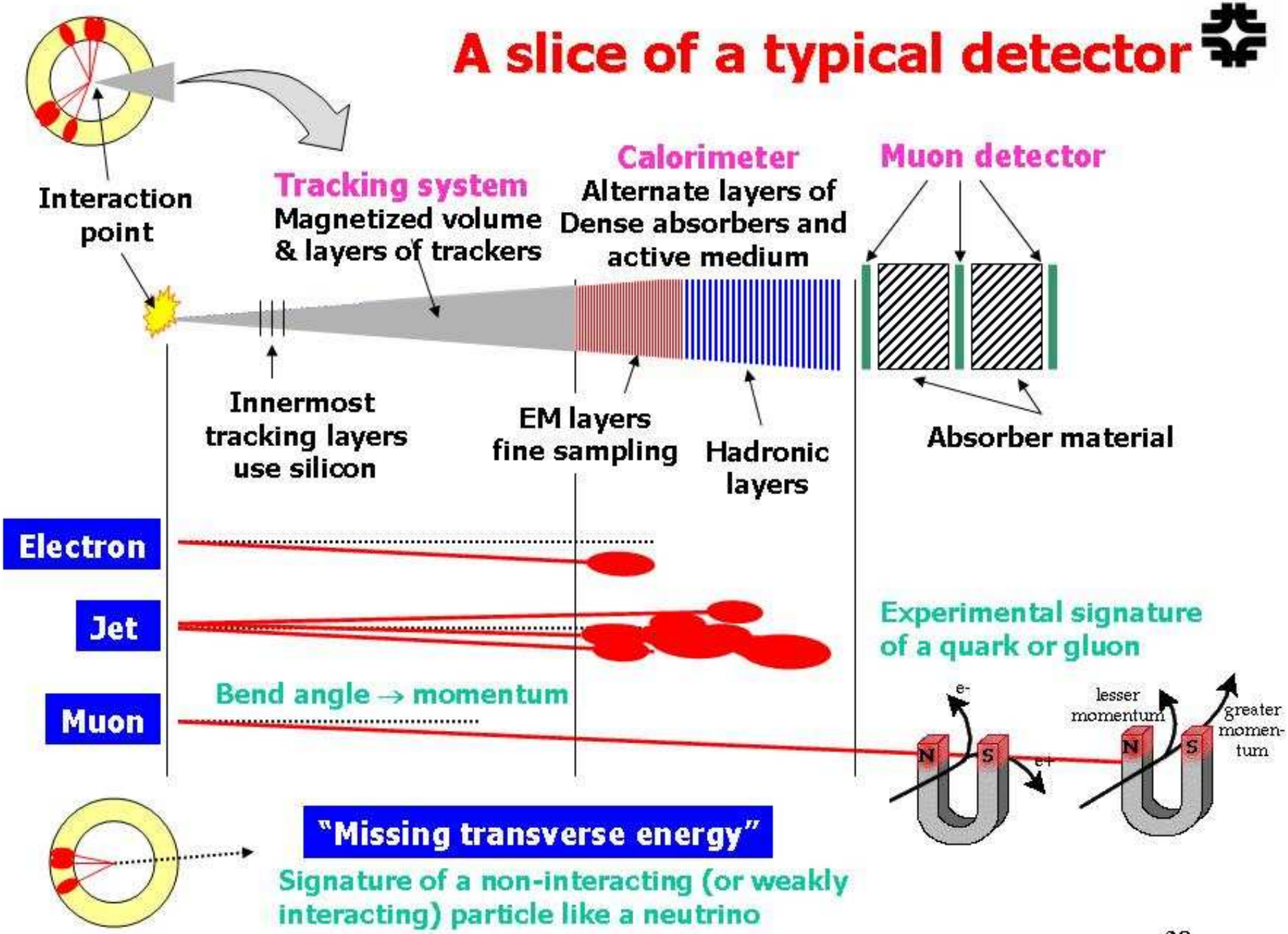
- "Transparent" central tracking in a magnetic field
- Energy measurement of photons, electrons and hadrons in the calorimeter (most particles absorbed)
- Muons measured in the outermost magnetic spectrometer
- Missing energy (neutrinos) from measuring everything else



Installing silicon tracker, prior to CDF detector roll-in

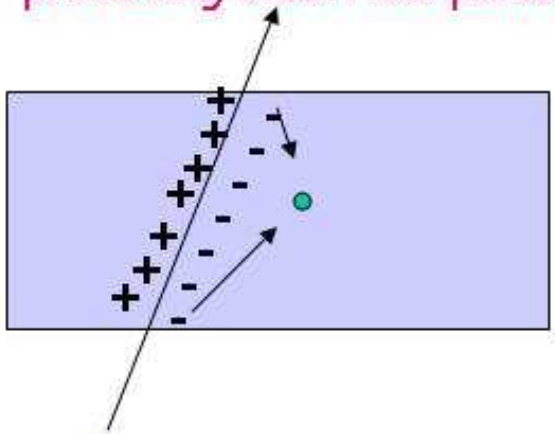
DØ detector installed in the Collision Hall, January 2001

A slice of a typical detector



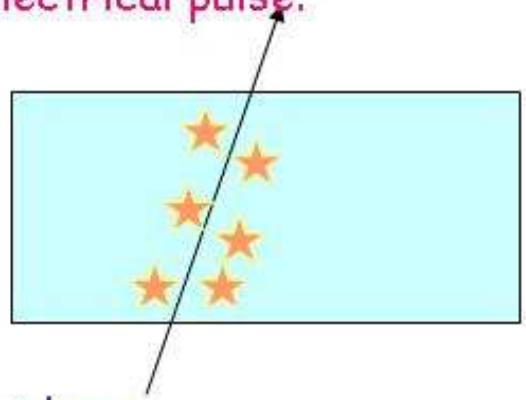
Tracking the Particles

- Ionization detectors
  - Energetic charged particles ionize the medium. Charges are collected at an electrode producing electrical pulses



- Examples:
  - CDF/D0 Silicon detectors, Hit Res: 10-15 um
  - CDF Central Outer Tracker, Hit Res: 180 um
  - CDF/D0 muon chambers Hit Res: 500 um

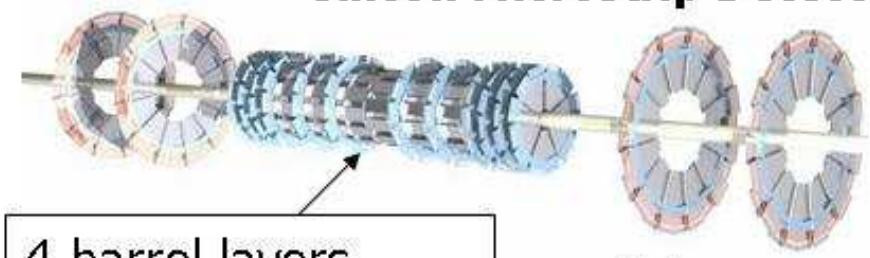
- Scintillation detectors
  - High energy particles excite molecules which scintillate producing light. Light is collected and converted into an electrical pulse.



- Examples:
  - D0 Central Fiber Tracker
  - D0 Muon pixel detectors

DØ Trackers

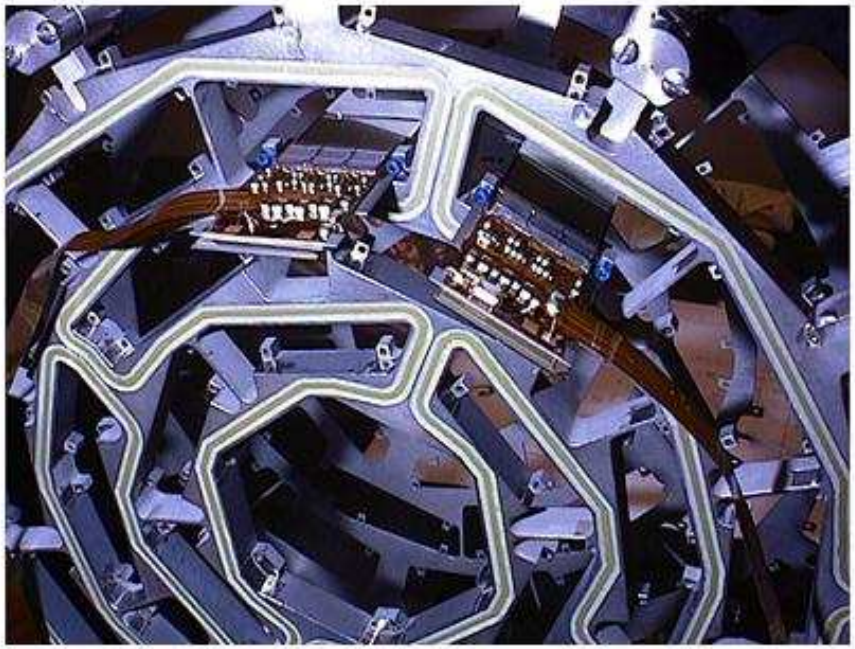
Silicon Microstrip Detector



4 barrel layers
axial + stereo strips

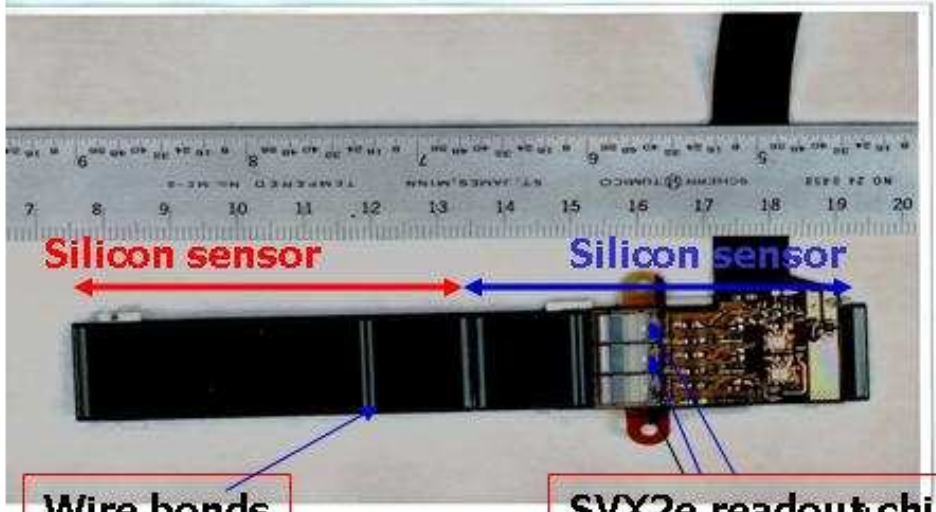
16 disks

Total of 800,000 Si channels



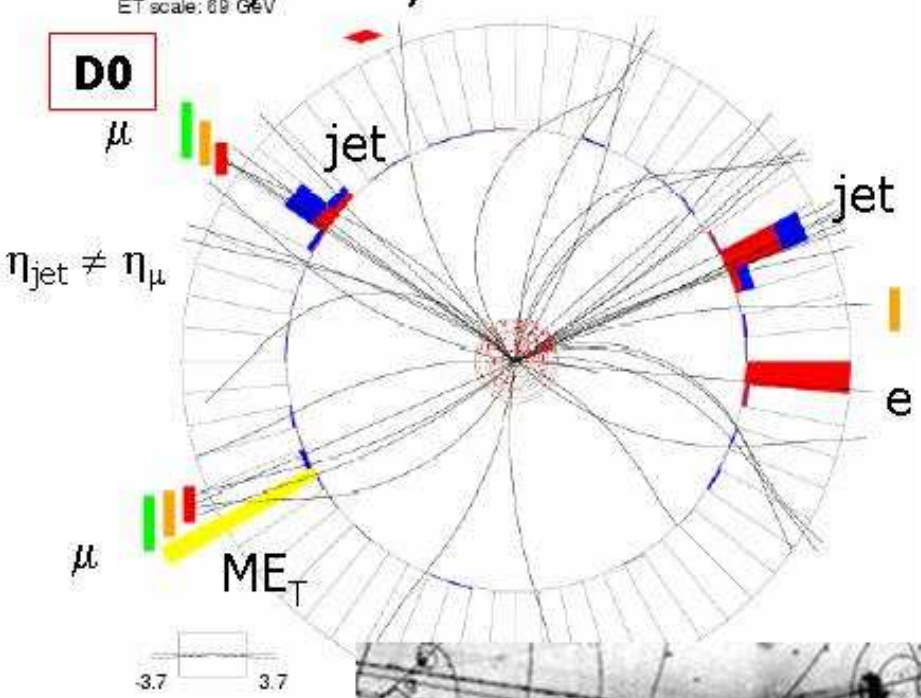
Central Fiber Tracker

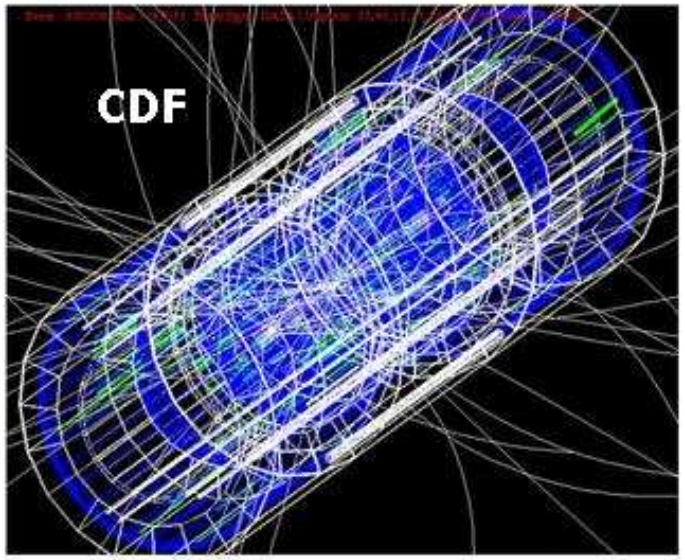
80,000 channels in the CFT

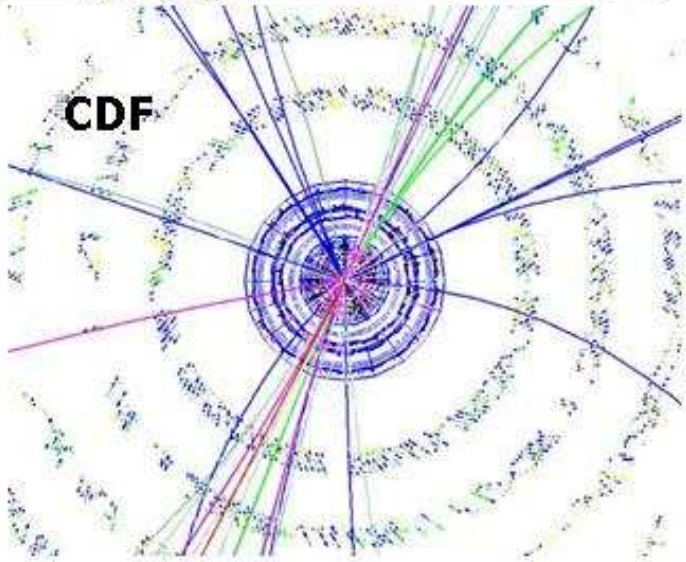


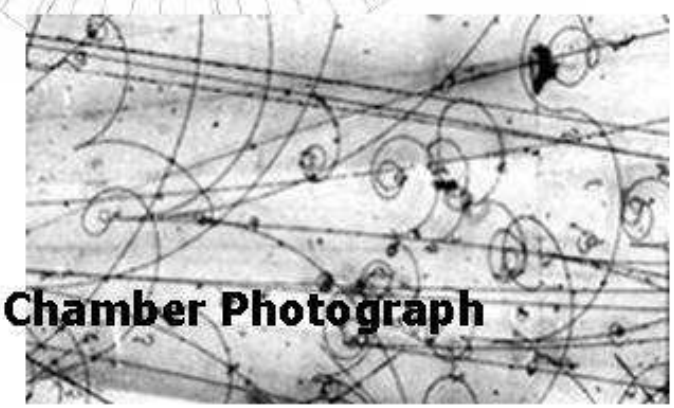
Tracks Reconstructed

Modern trackers:
Tracks reconstructed from electronic signals (hits) from the readout cells
In Silicon, fibres, drift tubes or scintillators



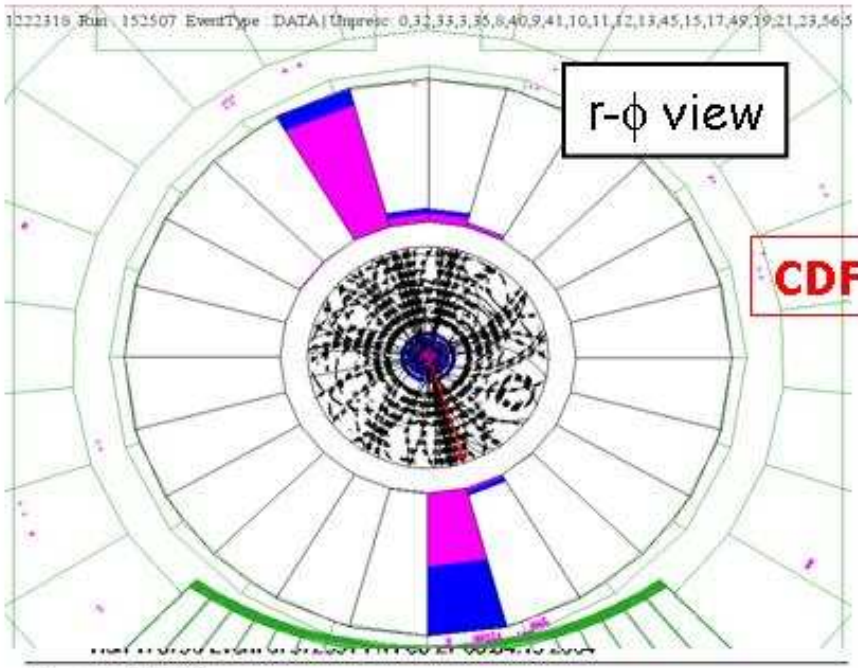




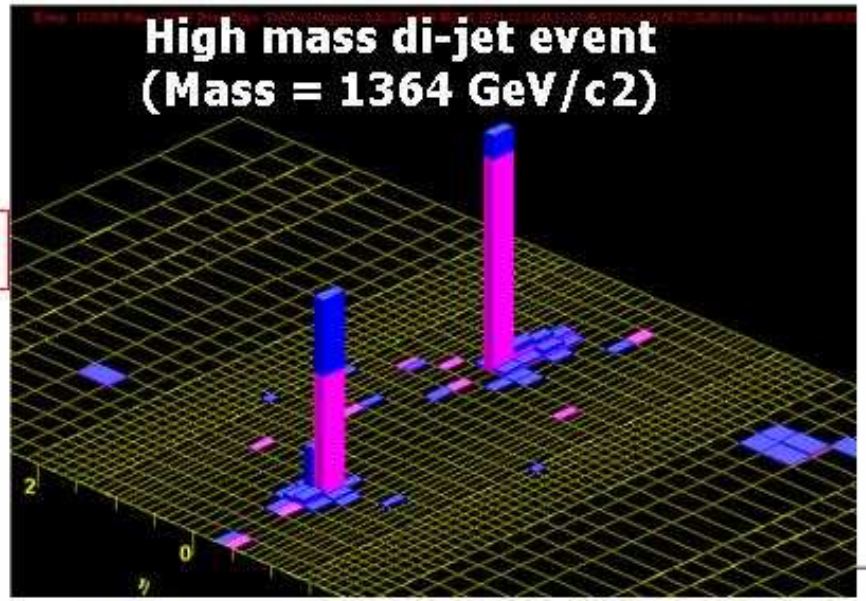


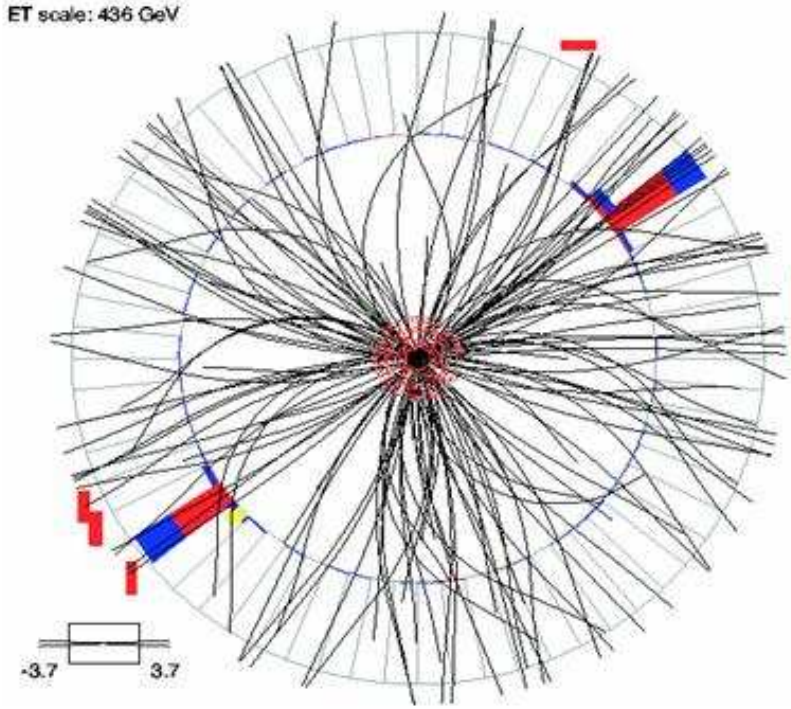
Old Bubble Chamber Photograph

Pushpa Bhat

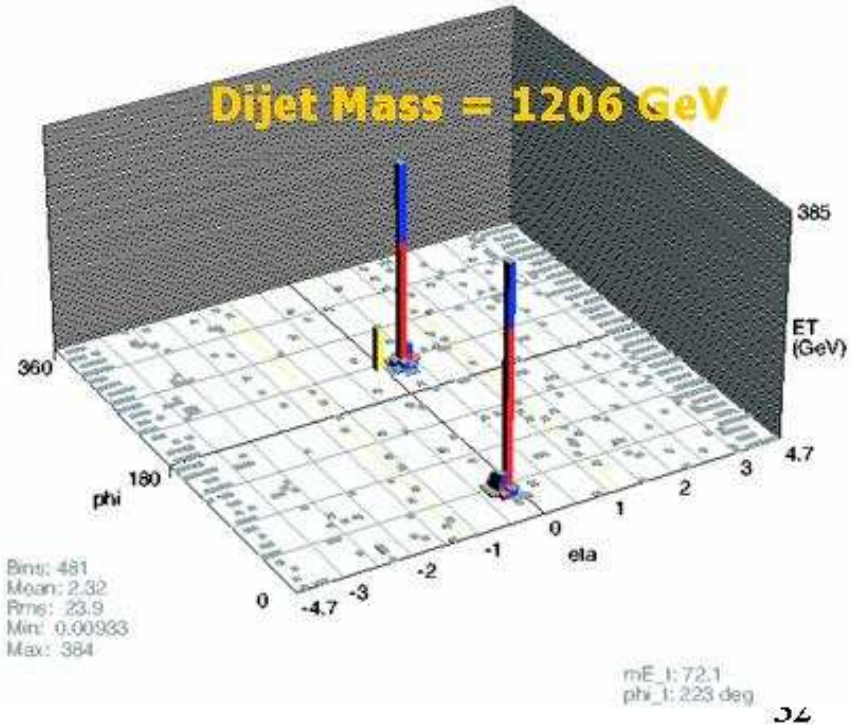

r-ϕ view

CDF


High mass di-jet event
(Mass = 1364 GeV/c2)

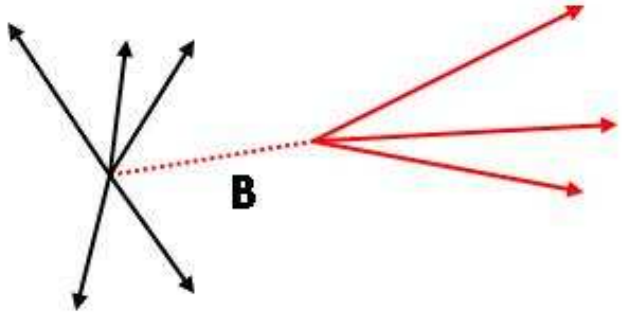

ET scale: 436 GeV
-3.7
3.7

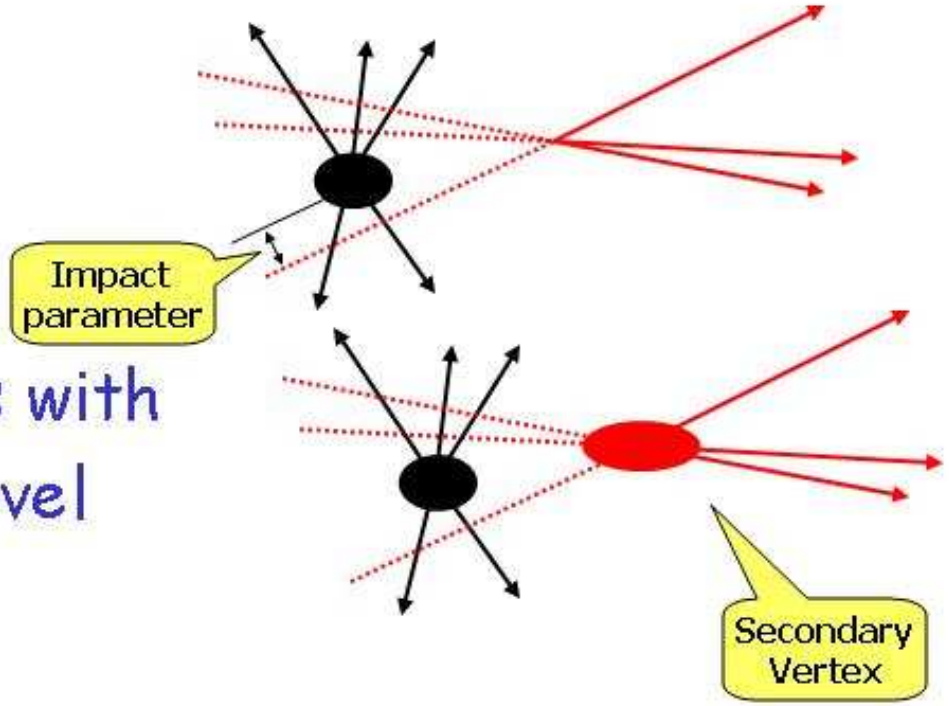
D0


Dijet Mass = 1206 GeV
385
ET
(GeV)
360
180
phi
0
-4.7
-3
-2
-1
0
1
2
3
4.7
eta
Entries: 481
Mean: 2.32
RMS: 23.9
Min: 0.00933
Max: 384
mE_t: 72.1
phi_t: 223 deg

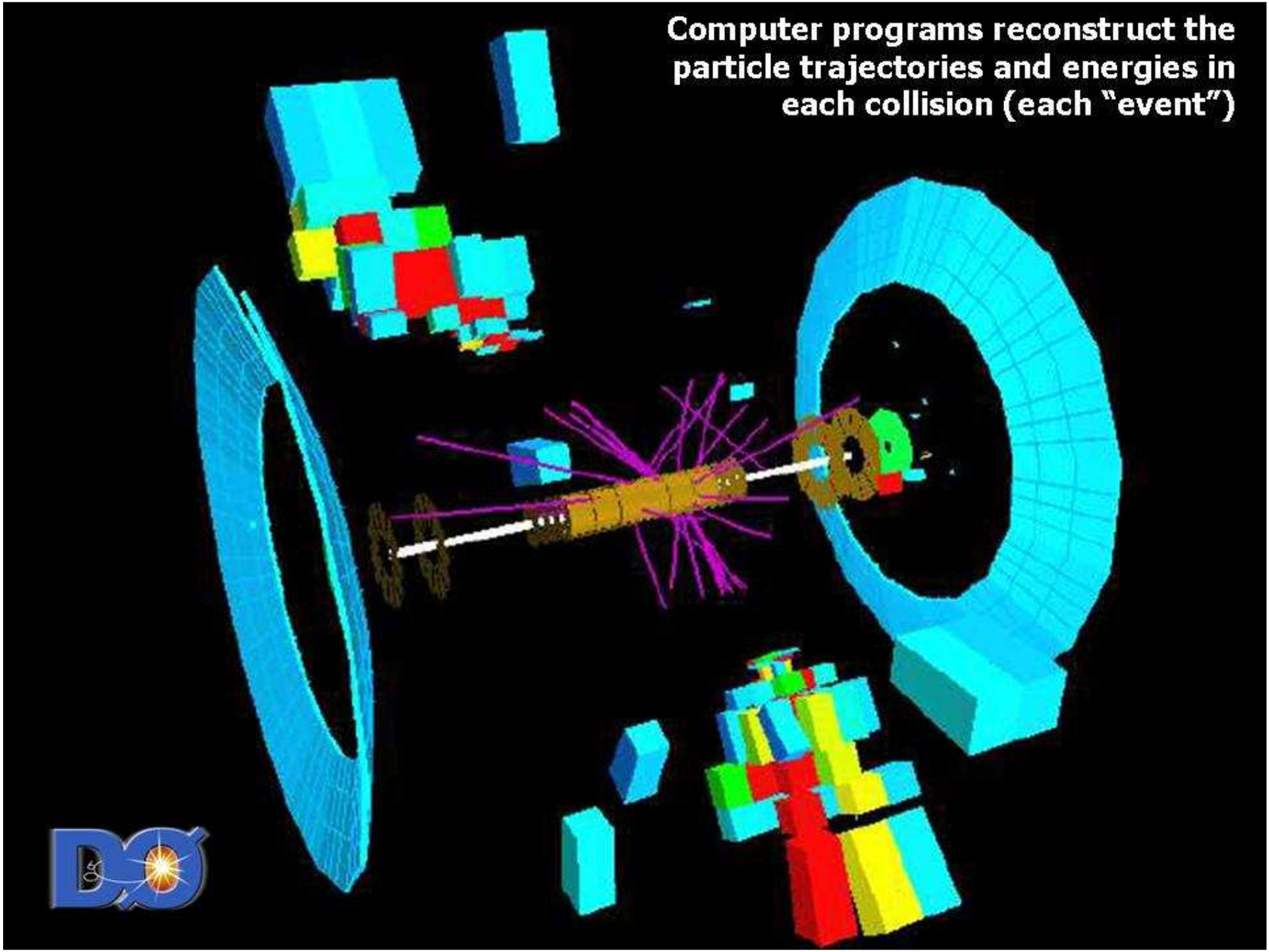
Finding b-quark jets

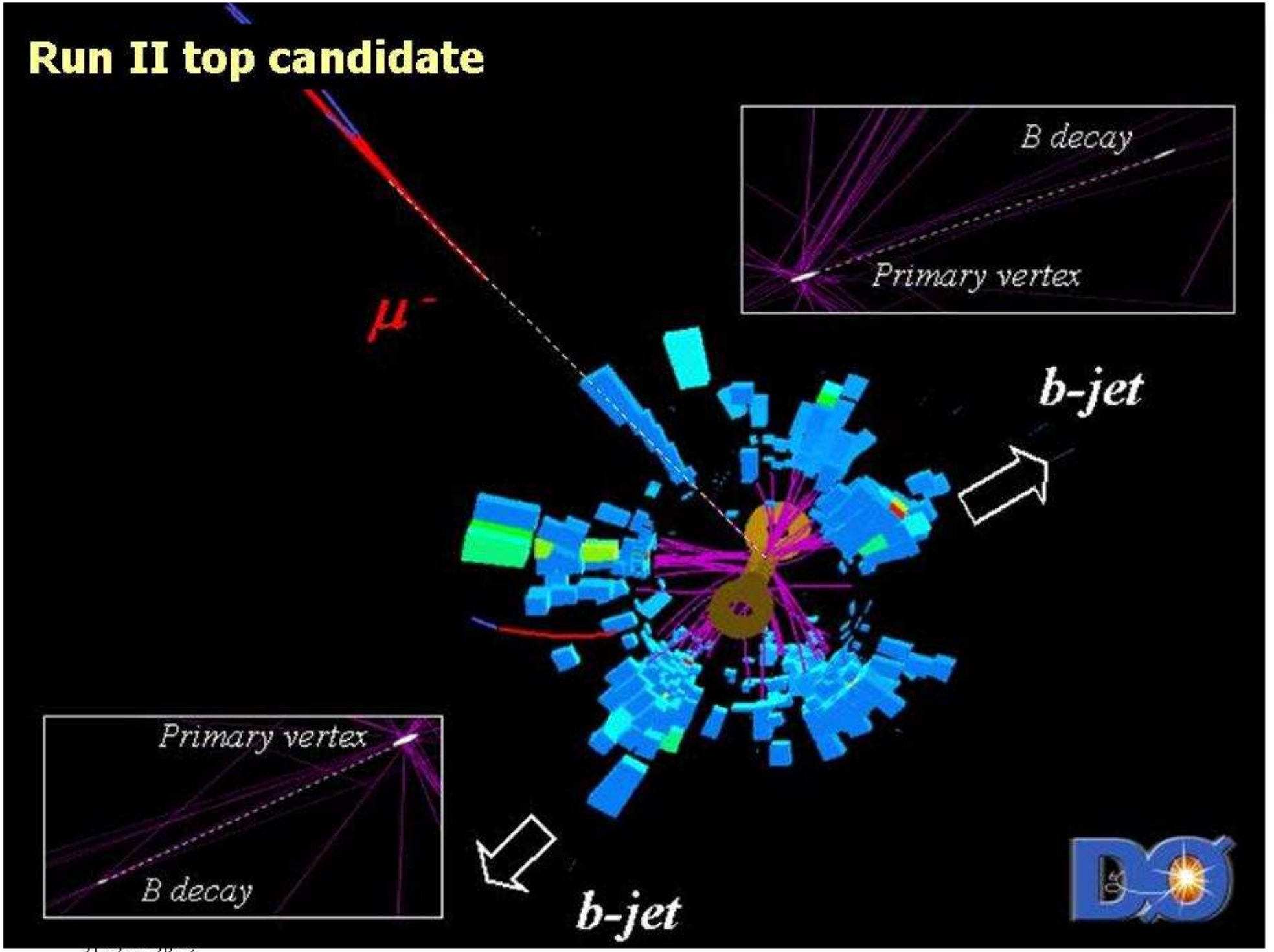
- The ability to identify b-quarks is very important
  - signatures for the top quark, supersymmetry, Higgs boson
- b quark forms a B-meson, travels a few mm before decaying





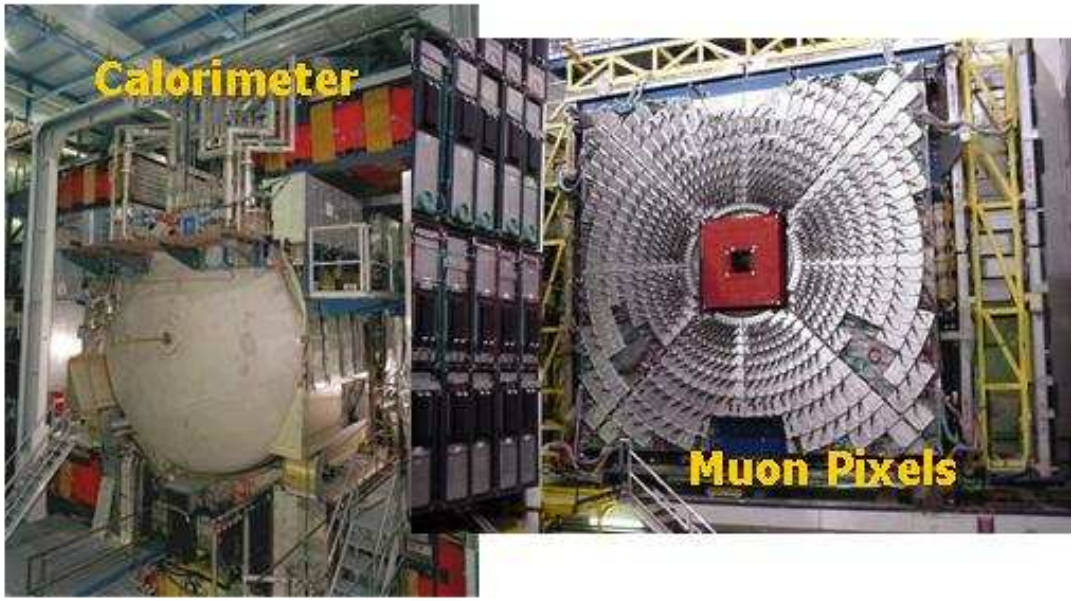
- need to measure tracks with a precision at the 10μm level

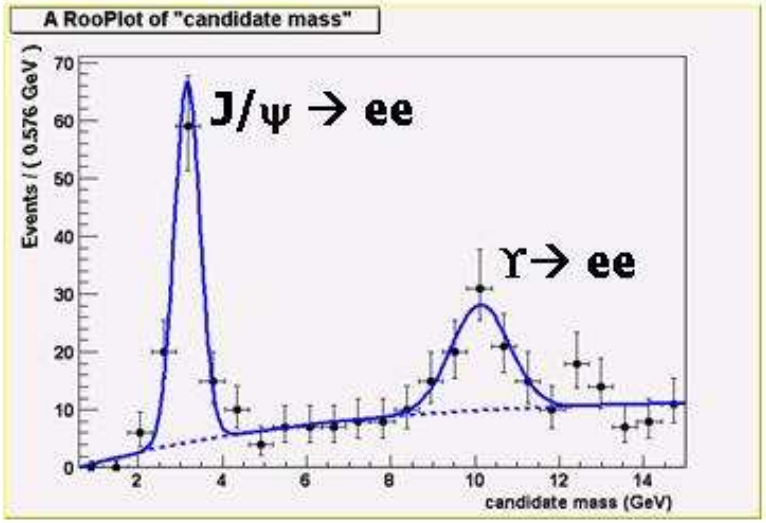

Computer programs reconstruct the particle trajectories and energies in each collision (each "event")

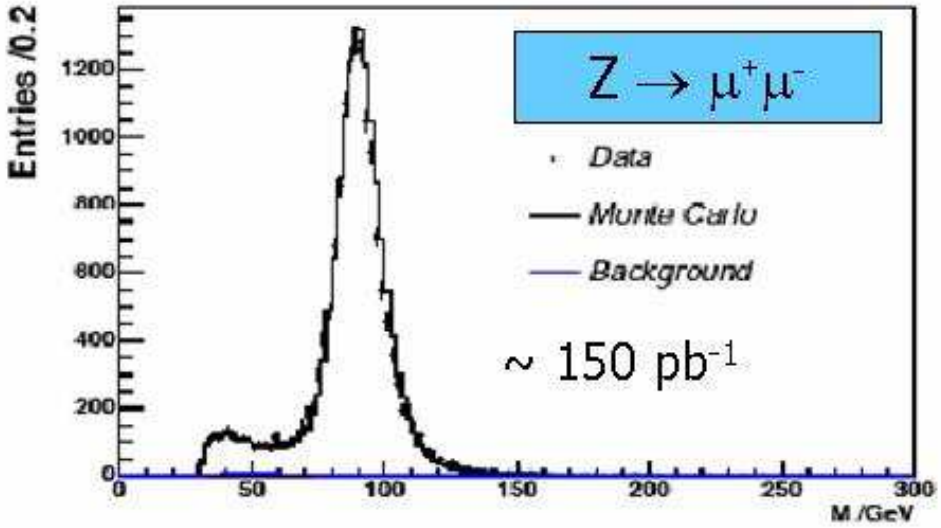

Run II top candidate
B decay
Primary vertex
μ⁻
b-jet
Primary vertex
B decay
b-jet

Are the Detectors working as they should?

- Look at "standard" or "calibration" physics signals
  - J/ψ ($c\bar{c}$) **1974** BNL/SLAC
  - ϒ($b\bar{b}$) **1976** Fermilab
  - W, Z **1983** CERN
- Today's discoveries will be tomorrow's calibration or background for new searches!





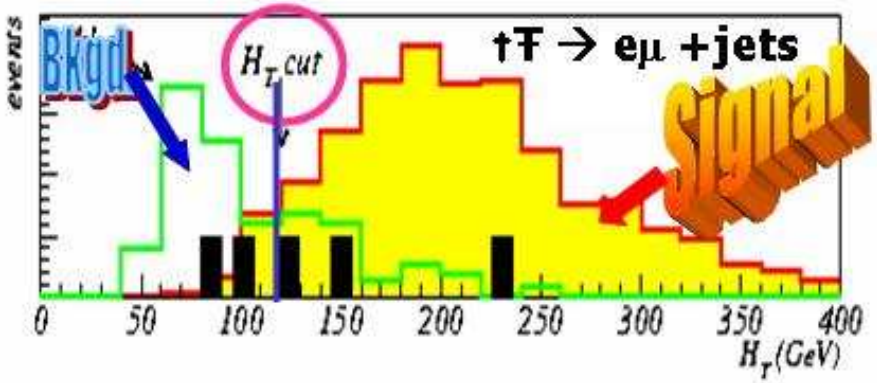


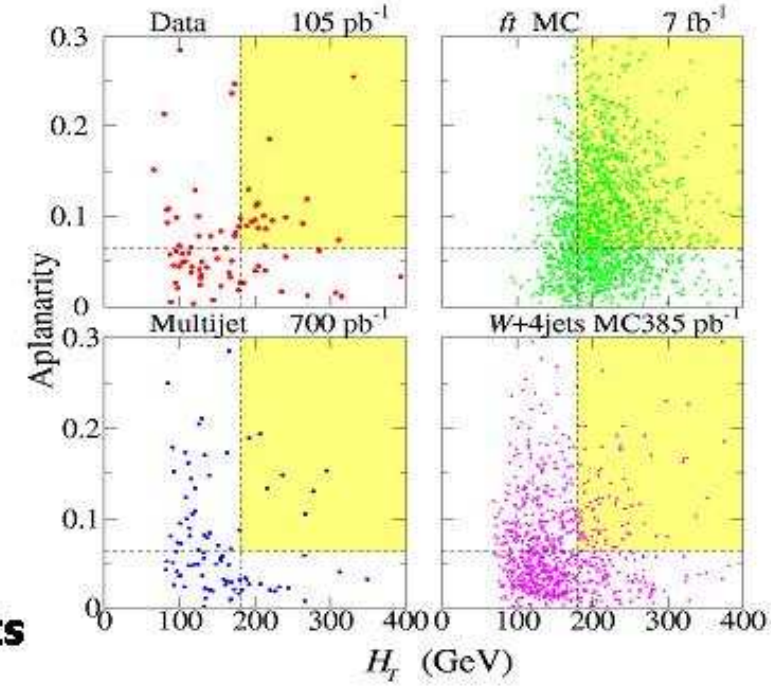
Finding the Signal

- New physics signals are tiny compared to standard background processes which mimic signal signature
- For example
  - $t\bar{t} \rightarrow Wb\ Wb \rightarrow e\ \nu$ b-jet + $\mu\ \nu$ b-jet
  - Backgrounds
    - WW +jets → $e\nu + \mu\nu$ +jets
    - $Z \rightarrow \tau\ \tau$ +jets → $e\nu + \mu\nu$ +jets
    - Instrumentation backgrounds (from mis-identification and mis-measurements)
- Therefore, we need to have good strategies for discriminating signal from background processes and the ability to estimate background contribution in the signal candidate pool (via theoretical models and simulations of detector response) .

Signal/Background Discrimination

- Select events with final state signature
- Compare kinematics (energy/momenta/angles) of objects in the signal events and background events from models/simulations
- Develop selection strategies to maximize efficiency for signal selection



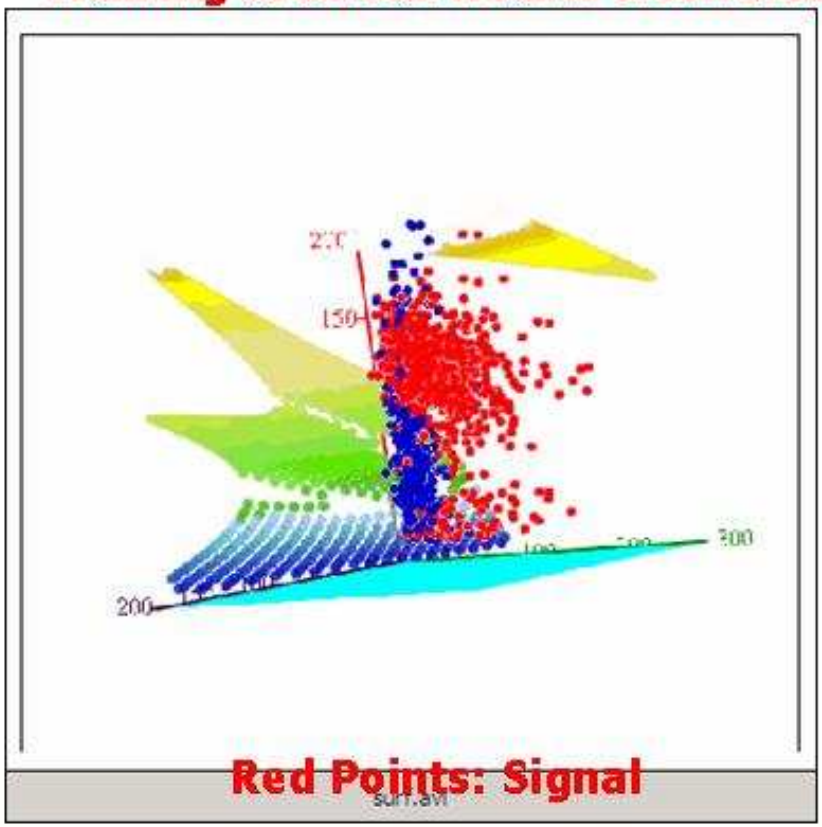


H_T = Sum Transverse energy of all objects

Multi-dimensional Methods

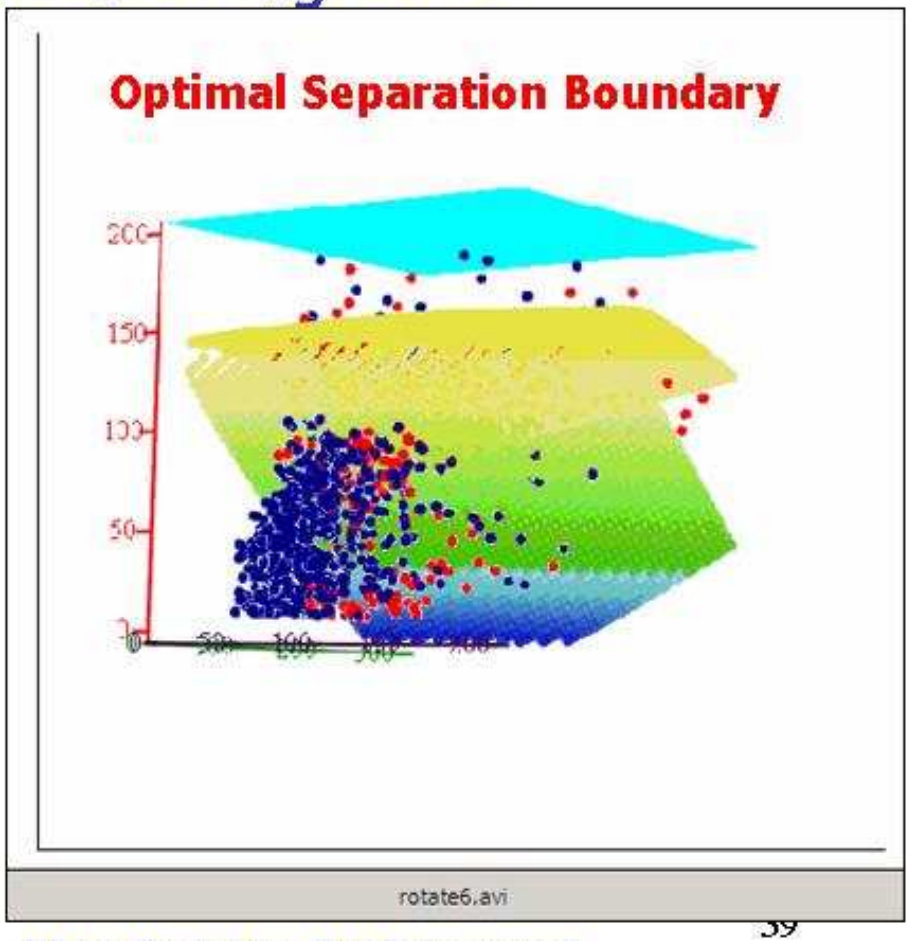
- When signals are very small, you can't afford to lose any → need sophisticated methods to handle data and separate signal from background

Training Artificial Neural Networks



Red Points: Signal

Optimal Separation Boundary



Blue Points: Background

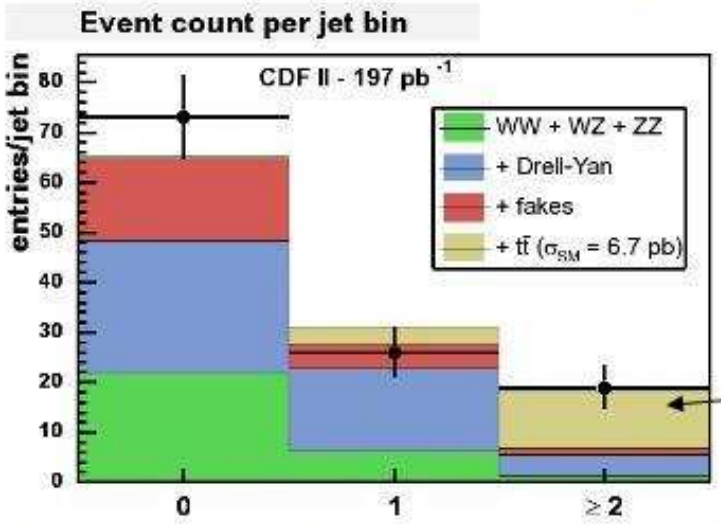
Top Cross Section (CDF, Run II)

Dilepton Channel

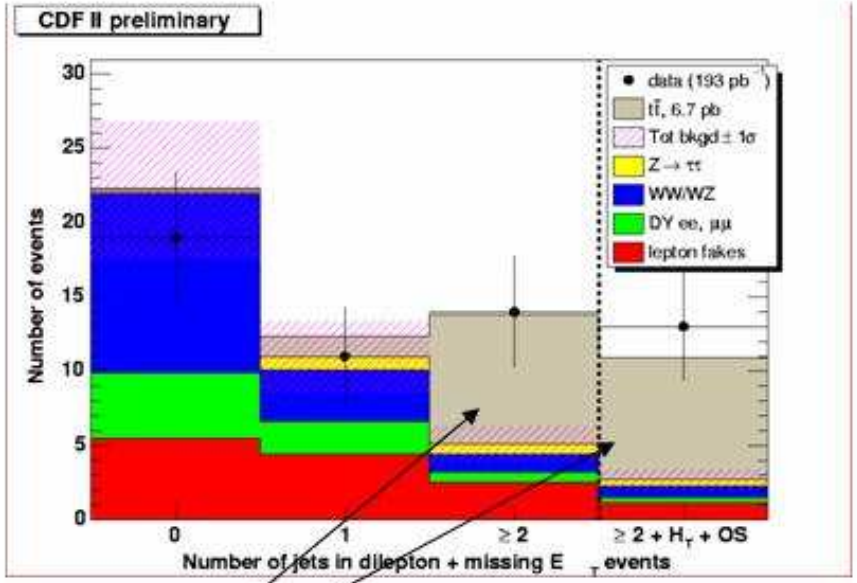
- Having observed N candidate events and estimated the background B, cross section is

$$\sigma(t\bar{t}) = \frac{N_{obs} - B}{\varepsilon . \int L.dt}$$

ε = detection efficiency



$$\sigma(t\bar{t}) = 7.0^{+2.7}_{-2.3}(stat)^{+1.5}_{-1.4}(sys)\ pb$$

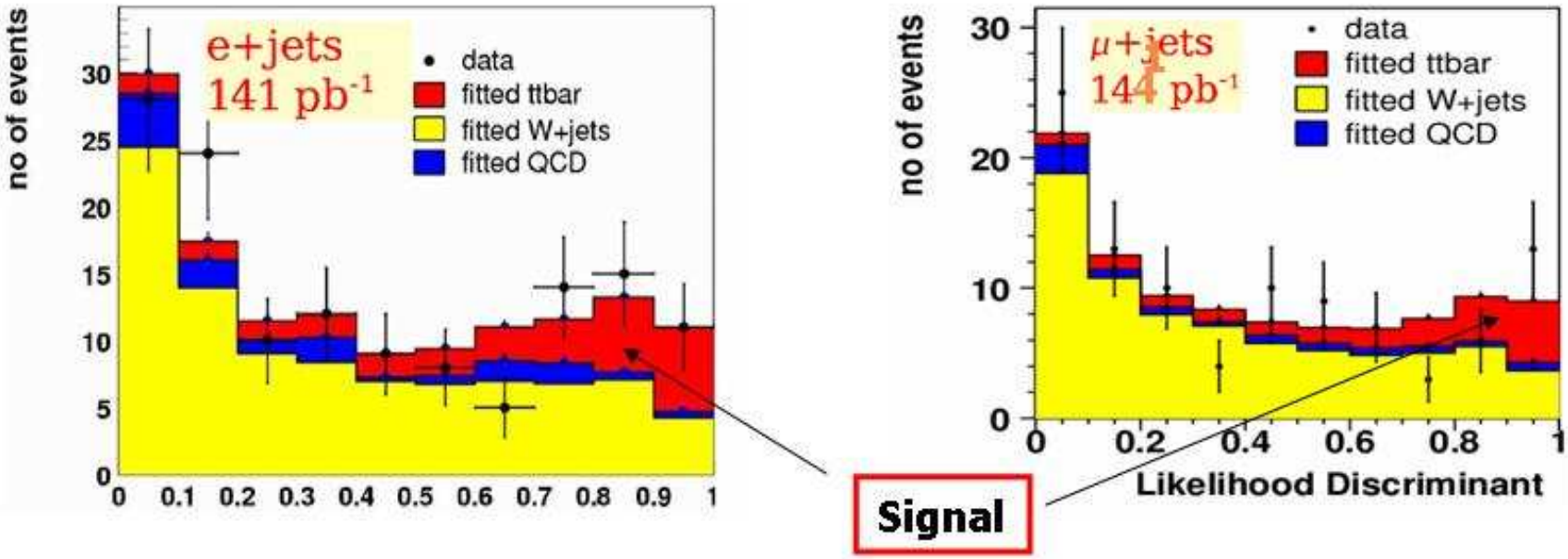


Signal Bins

$$\sigma(t\bar{t}) = 8.4^{+3.2}_{-2.7}(stat)^{+1.6}_{-1.2}(sys)\ pb$$

Top Cross Section (D0, Run II)

Lepton + jets Channel

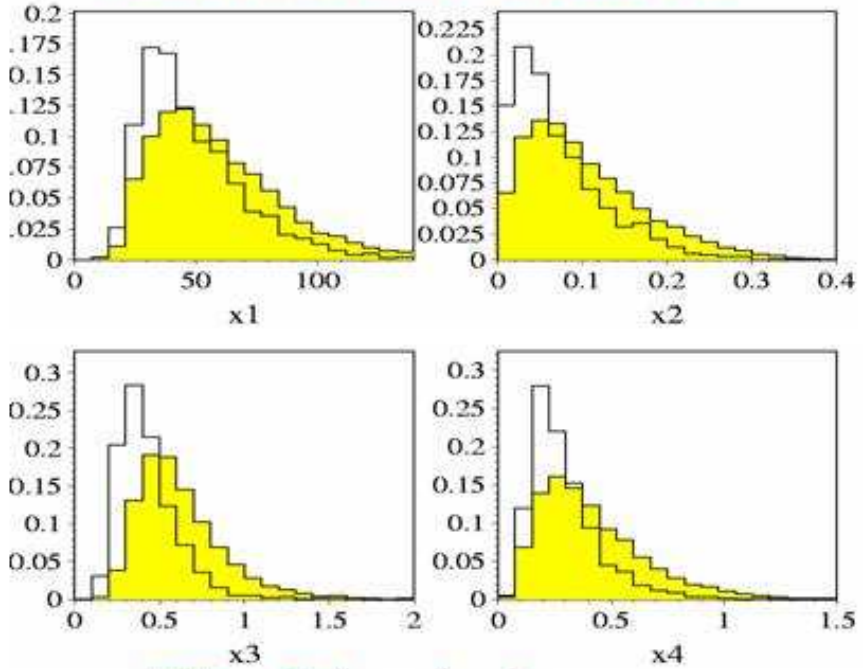


	muons	electrons
Nev	100	136
fitted N^{W}	74.7 + 12.7 – 12.0	94.6 + 15.8 - 15.0
fitted N^{QCD}	7.1 + 0.9 – 0.9	14.1 + 1.2 - 1.2
fitted N^{tt}	17.8 + 9.9 – 8.7	27.5 + 12.7 - 11.7

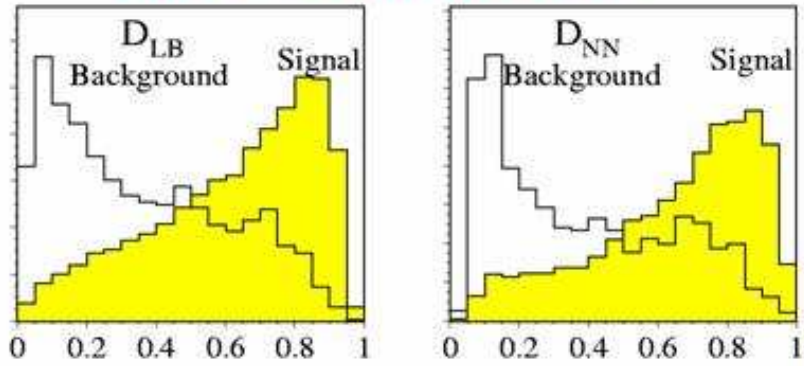
$$\sigma(t\bar{t}) = 7.2^{+2.6}_{-2.4}(stat)^{+1.7}_{-2.2}(sys)\ pb$$

Measuring the Top Quark Mass (Run 1)

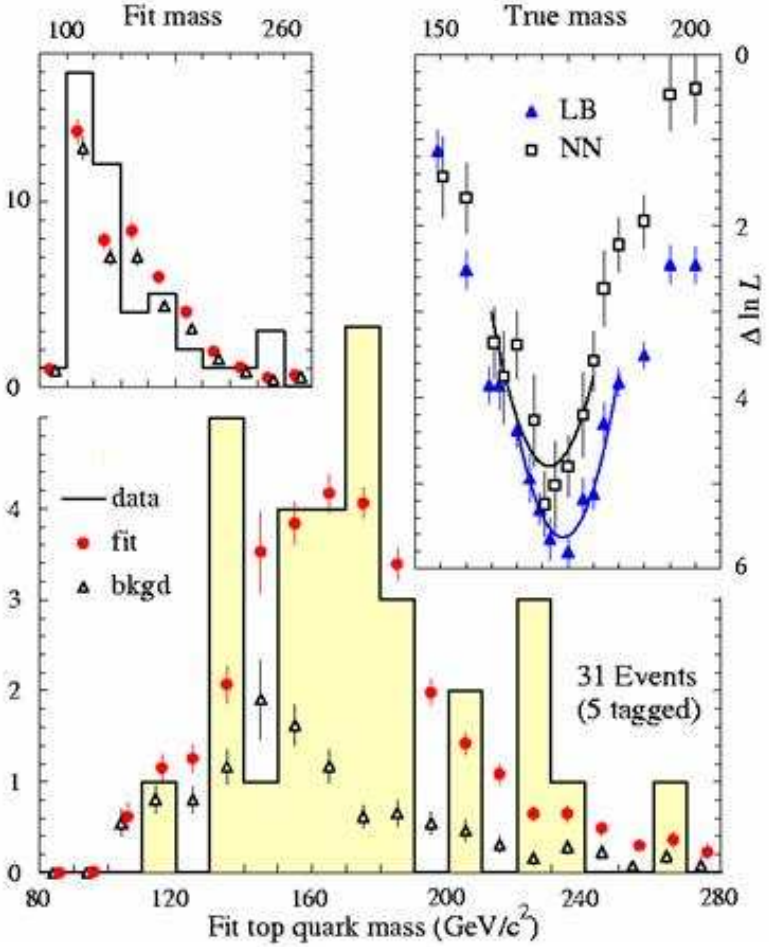
Discriminant variables



The Discriminants



DØ Lepton+jets



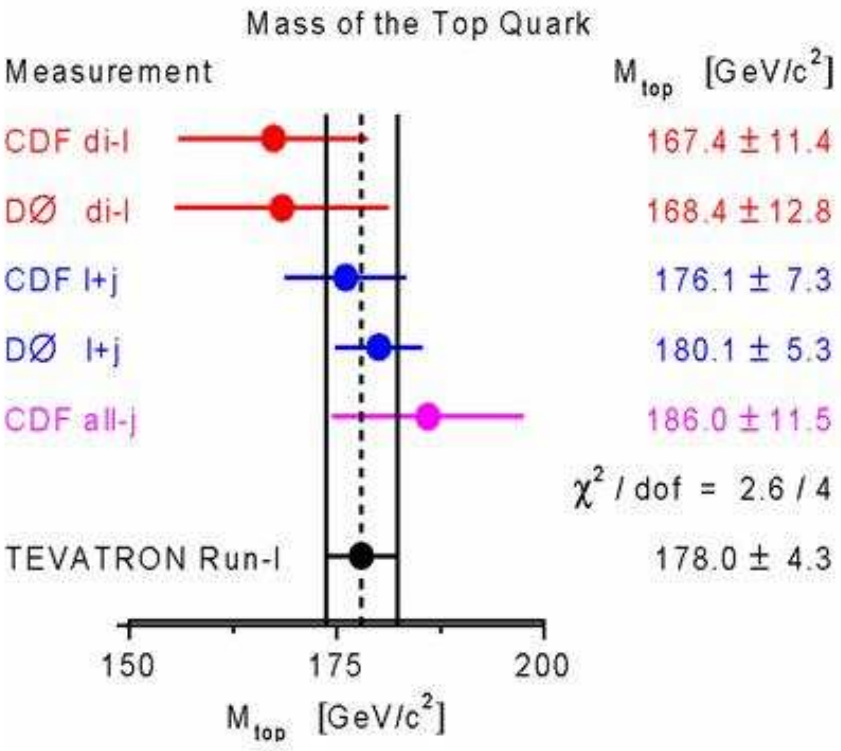
$m_t = 173.3 \pm 5.6(\text{stat.}) \pm 6.2\ (\text{syst.})\ \text{GeV}/c^2$

Fit performed in 2-D: $(D_{LB/NN}, m_{fit})$

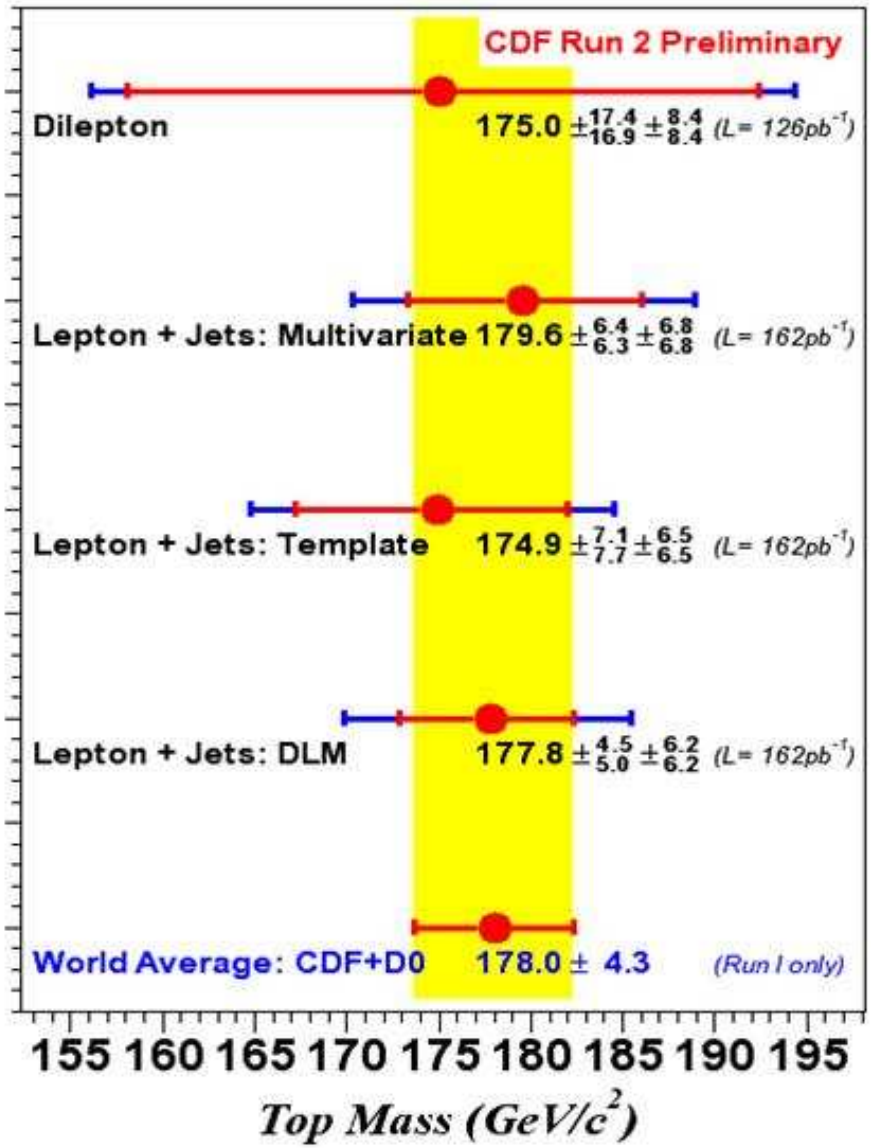
Pushpa Bhat

Top Mass Measurement (Contd.)

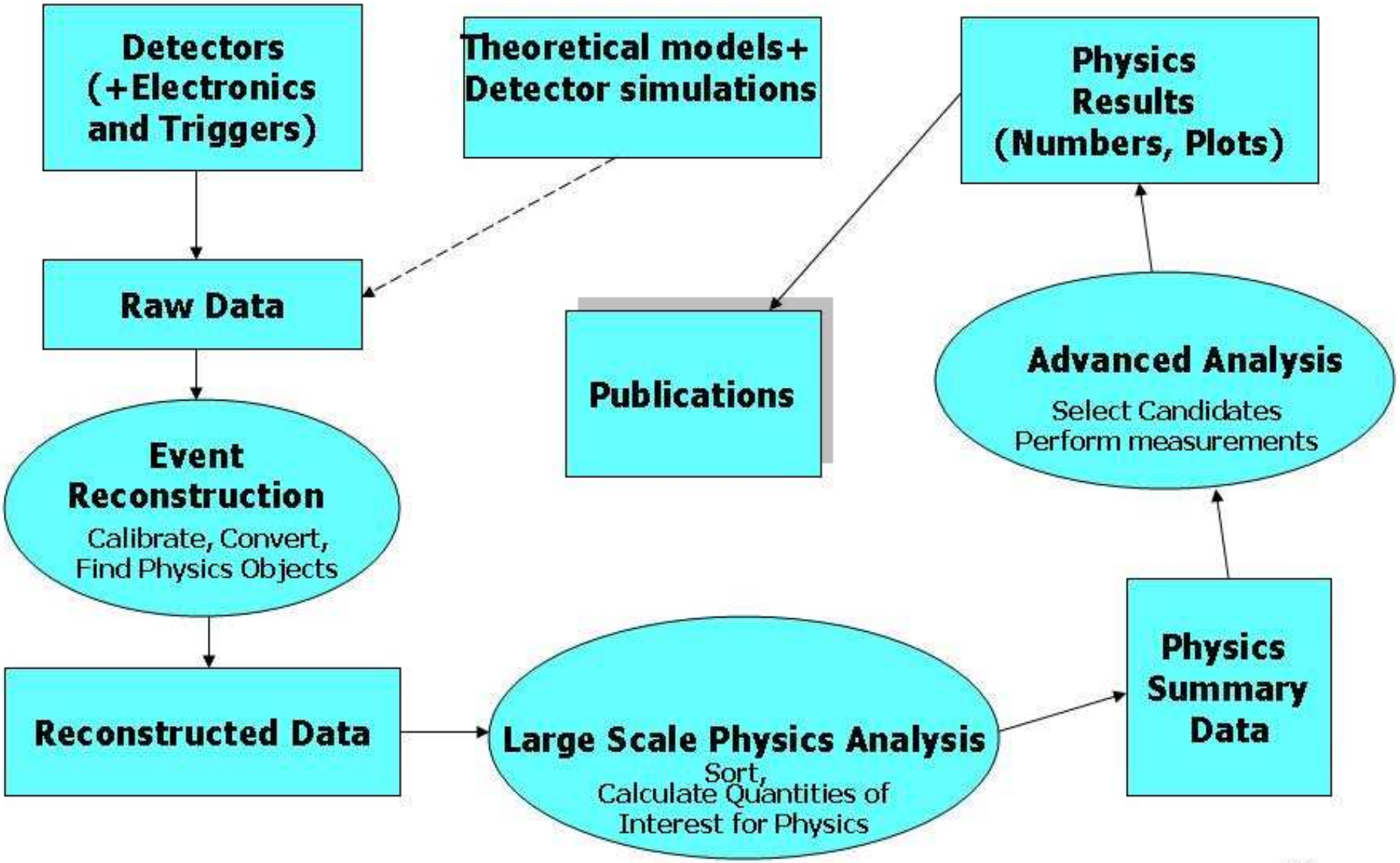
Run 1 Results (CDF, D0)



Run 2 Results (CDF)

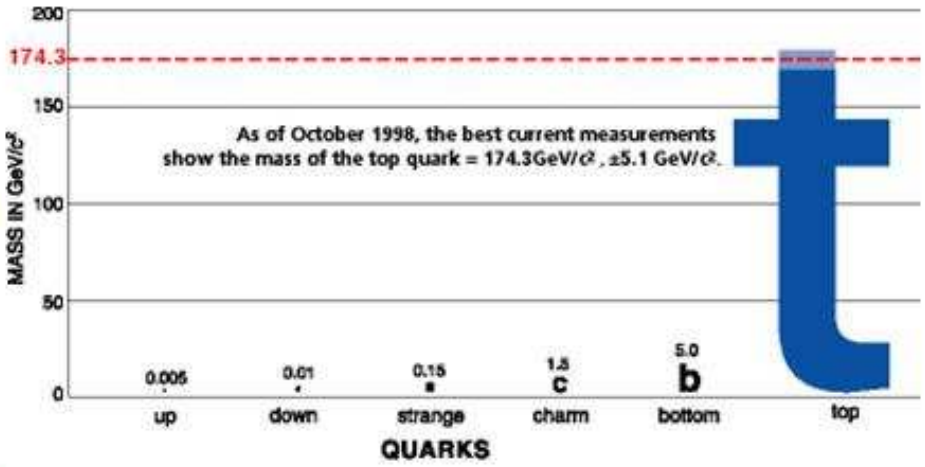


Data Processing in an HEP Experiment



Top as a window on New Physics?

- Why is the top so heavy?
  ~ 40x that of b-quark
  - It is a mystery!
- The large mass is allowed in the SM but *not required*
  - May have profound implications
  - Constrains the mass of the Higgs boson! Very important!



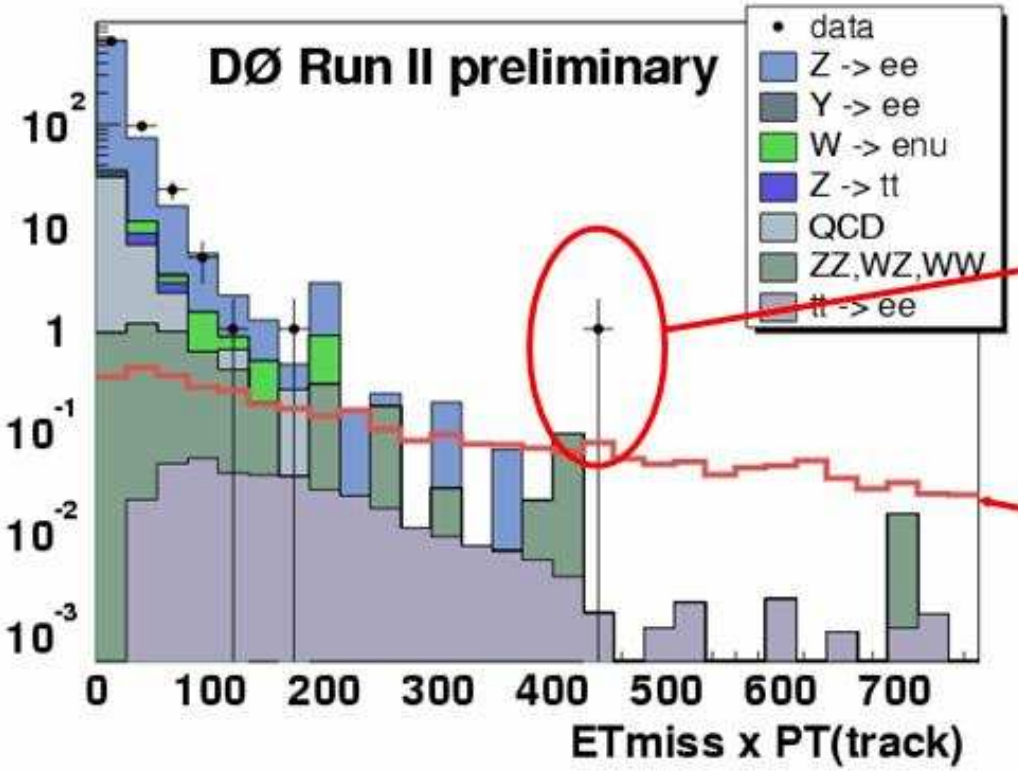
- In SUSY theories, a heavy top can induce spontaneous electroweak symmetry breaking
- $t\bar{t}$ condensate can act "Higgs-like"
- It is extremely important to measure top production rates, its decays and mass as precisely as possible.

What might CDF and D0 discover?

- Higgs is the most-wanted particle!
  - Study e.g.,WH →eν/μν + 2 b-jets, ZH →ee/μμ/νν + 2 b-jets
  - So, final state particles are similar to top events
  - We will need about 15-20 times more data than we now have to find the Higgs if its mass is below 130 GeV
    - **Maybe much lighter than the top quark but its production rate is 10 times smaller!**
- SUSY?
  - Each particle will have a sparticle (or a super-partner)
  - If SUSY exists at the TeV scale, we should see some of those particles soon!
- Other exotics – Leptoquarks, technicolor, evidence for extra-dimensions
- Something completely unexpected!

Looking at data is starting to be fun

- With >400 pb^{-1} in Run II (more than 3x that in RunI), one can imagine that new physics may be present in our data at the few event level!!!



1 trilepton candidate event
Expected background fairly small
Expected SUSY signal 1-2 events

One of the mSUGRA reference points
m_0=76 $m_{1/2}$=170 A_0=0 tan β=3 μ > 0
$m(\chi^0_1\ \chi^0_2\ \chi^\pm)$ = 59, 106, 101 GeV

Summary

- This may be as important and exciting a time in the history of physics as any other momentous time.
- In the last collider run we made a major discovery at this Lab – that of the top quark.
- We hope that some revolutionary discoveries are around the corner!
- Is there a Higgs field?
- Is nature supersymmetric?
- Are there extra spatial dimensions?
- What is the physics beyond the Standard model?

Only Experiments can tell!

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

-Shakespeare

Experiments may reveal something unexpected!