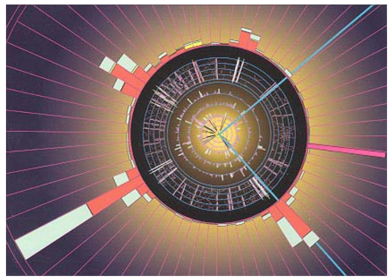
Tevatron Physics



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Introduction

- **These lectures are a personal survey of some selected topics in experimental high energy physics at hadron colliders**
  - **detectors**
  - **analysis issues**
  - **physics results (what's new, what's topical, and where there are problems)**
- **Hadron colliders = proton-antiproton / proton-proton**
  - **the next decade belongs to these machines:**
    - **Tevatron at Fermilab 2001-2007**
    - **LHC at CERN 2006 -**
- **Thanks to the many people whose work I have drawn on in putting these lectures together**
  (M. Narain, N. Varelas, J. Ellison, H. Montgomery...)

Colliders

Hadron-Hadron

- Past
  - ISR at CERN
  - SPS at CERN
- Present
  - Tevatron at Fermilab
- Future
  - LHC at CERN
- Emphasis on maximum energy = maximum physics reach for new discoveries

Electron-Positron

- Past
  - SPEAR at SLAC
  - PETRA at DESY
  - . . .
- Present (just ended)
  - LEP at CERN
- Future
  - Linear Collider
- Emphasis on precision measurements

Both approaches are complementary

Hadron Colliders

- Advantages
  - Protons can easily be accelerated to very high energies and stored in circular rings
- Disadvantages
  - Antiprotons must be collected from the results of lower energy collisions and stored
    - problem is avoided by using proton-proton collisions at the cost of a second ring
  - Protons are made of quarks and gluons
    - the whole of the beam energy is not concentrated in a single point-like collision
  - Quarks and gluons are strongly interacting particles
    - collisions are messy
- Despite these problems, hadron colliders are the best way to explore the highest mass scales for new physics

The Tevatron and the World HEP program

- **The overarching question: What sets the mass scale of the weak interactions to be about 100 GeV?**
  - **This question is addressed solely with colliders operating at the energy frontier.**
- **In the 1990's there were four such machines:**
  - **Tevatron Run 1**
  - **LEP**
  - **SLC**
  - **HERA**
- **In contrast, from 2002 to 2007 the Tevatron is the only machine that can address the central problems in the field**
  - **SLC and LEP have closed. HERA will end its run in 2006.**
  - **Increased luminosity and slightly higher energy make possible a new round of experimentation with the Tevatron.**

The Fermilab Tevatron collider

- **Run 1 (1992-95) ~100 pb^{-1}**
- **Run 2a (2001-03) 2 fb^{-1}**
  - **9 month shutdown to install new silicon layers**
- **Run 2b (2003-07?) ~ 15 fb^{-1}**

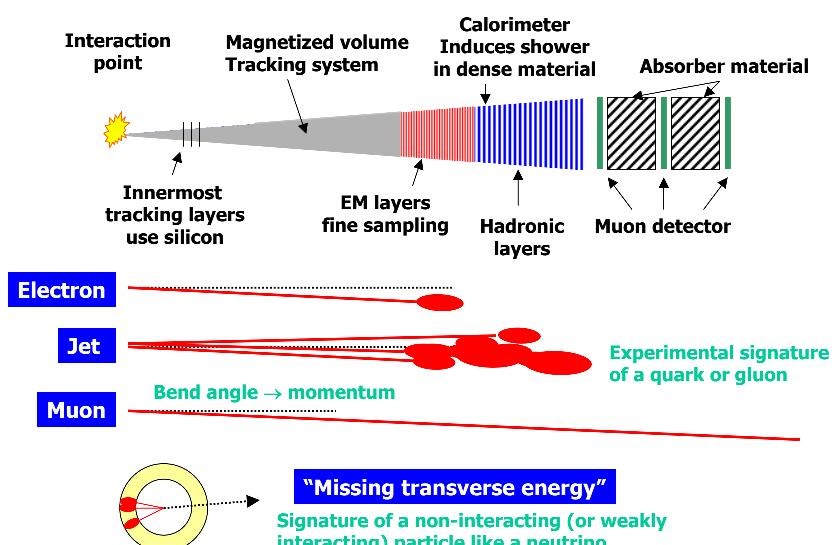
The Tevatron Physics Program

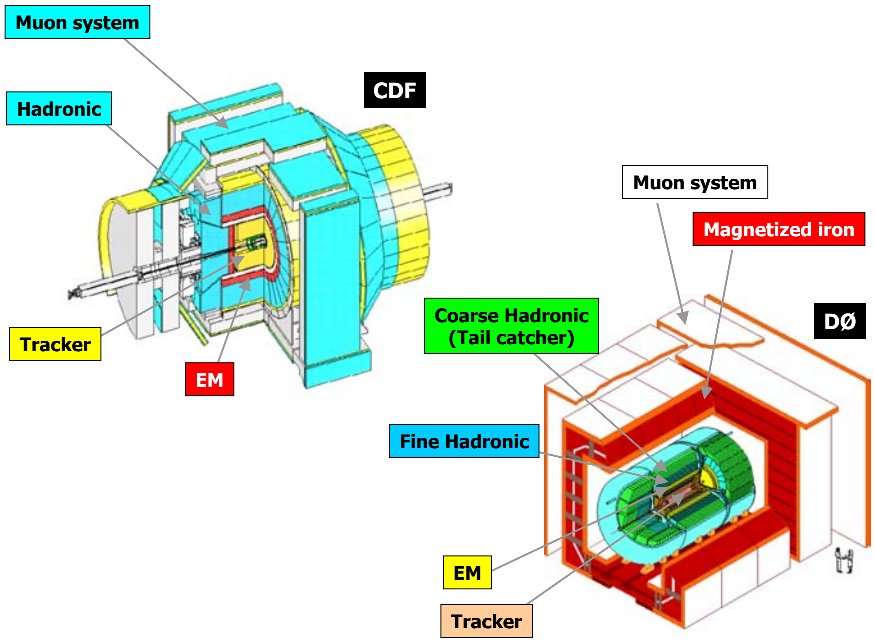
1. **Precise measurements of the known quanta of the Standard Model**
   – indirect hints (or constraints) on new particles and forces

2. **Direct searches for new physics**
   – i.e. beyond the known Standard Model particles and forces

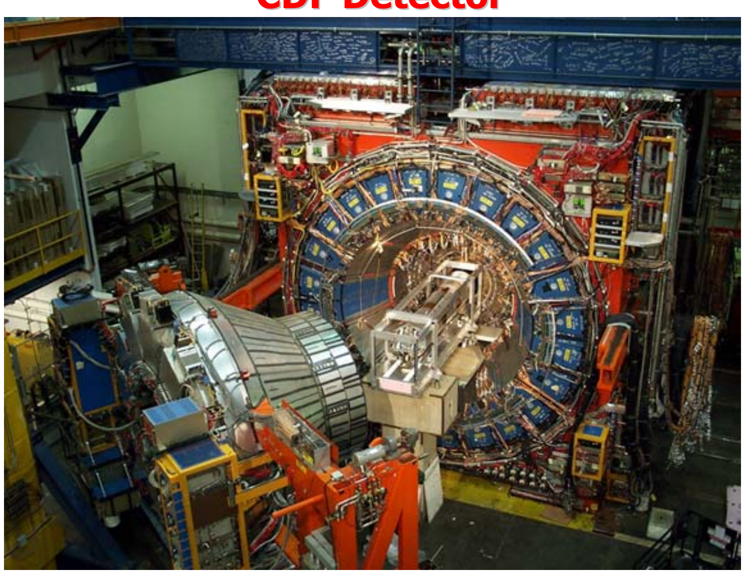
The Tevatron program has the potential for a discovery that would change the direction of particle physics.

Typical detector



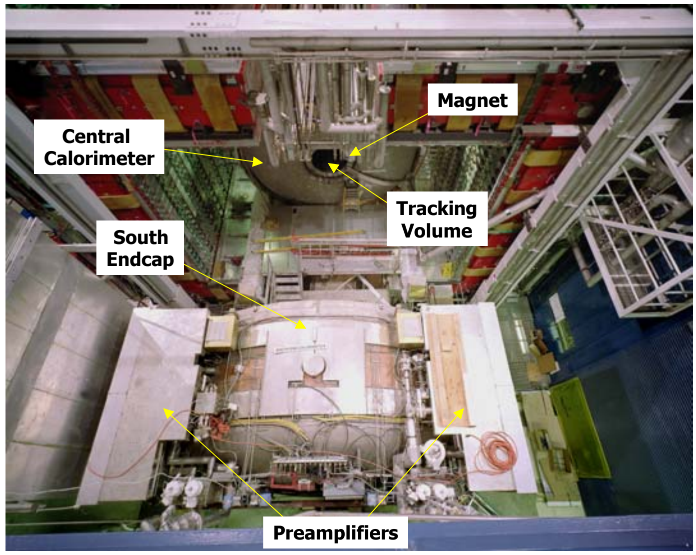


CDF Detector



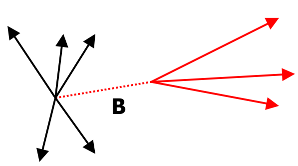
Installing silicon tracker, prior to detector roll-in

DØ



Displaced vertex tagging

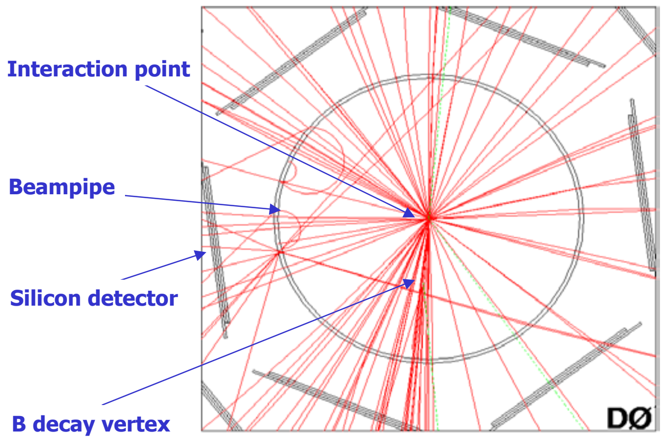
- The ability to identify b-quarks is very important in Higgs searches (also top, supersymmetry)
- b quark forms a B-meson, travels ~ 1mm before decaying



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

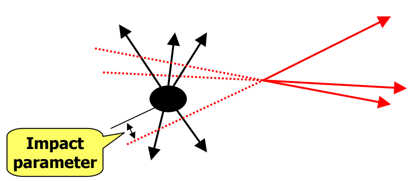
Displaced vertex tagging

The ability to identify b quark jets is very important in Higgs searches

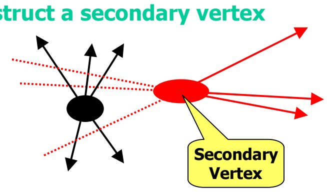


B-tagging

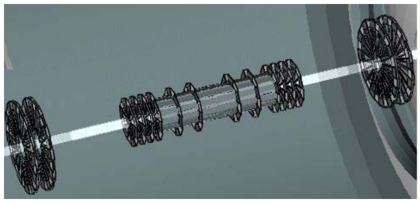
- **Typical algorithms**
  - **require 2 or 3 tracks with significant impact parameter (distance of closest approach to the fitted primary vertex)**



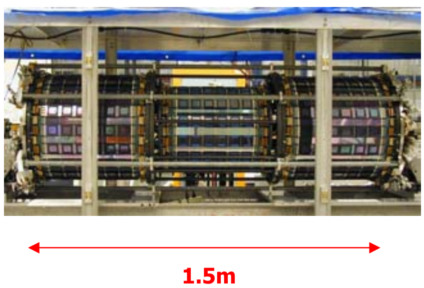
  - **reconstruct a secondary vertex**



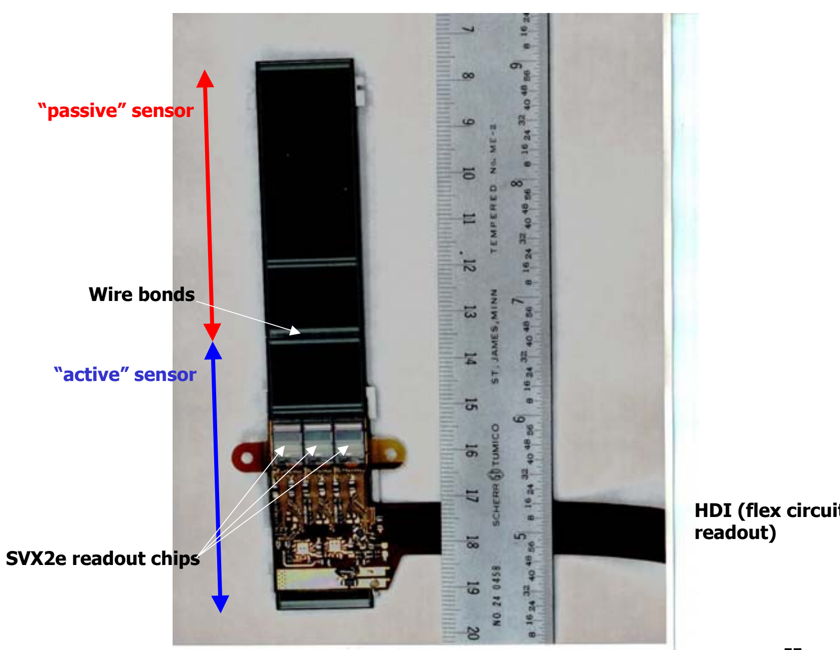
Tracking: Silicon Detectors



- **DØ:**
  - 6 barrels and 16 disks
  - Single+Double-sided SA and 90-degree stereo
  - 4 barrel layers
  - Disks track to $|\eta|<2.5$
  - ~790K channels, SVX2 chip



- **CDF**
  - 3 barrels (6-half barrels)
  - Double-sided SA and 90-degree stereo
  - Layer 00 single-sided
  - 7 layers $|\eta|<1$, 8 layers $1<|\eta|<2$
  - ~722K channels, SVX3 chip



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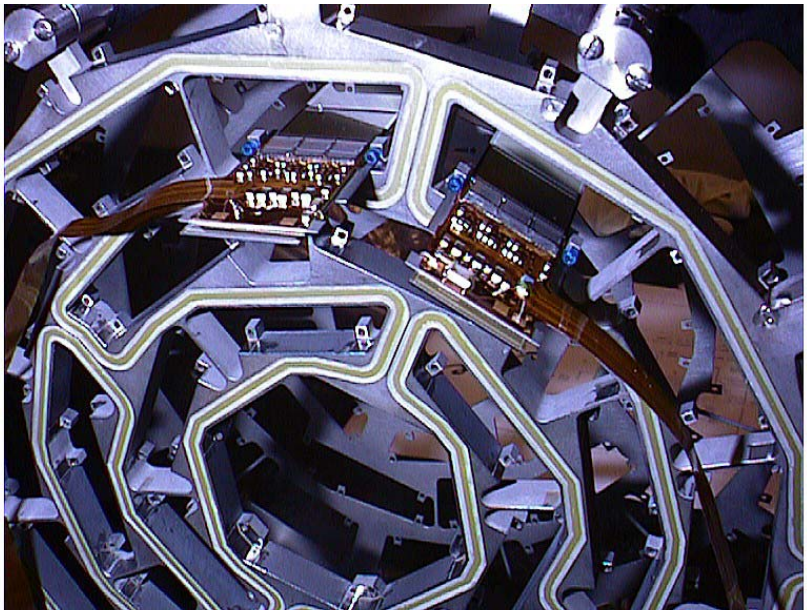
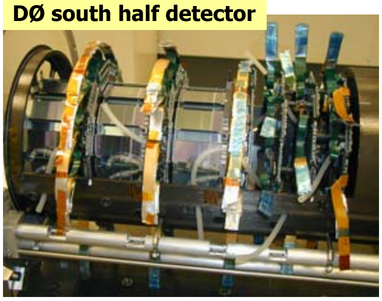
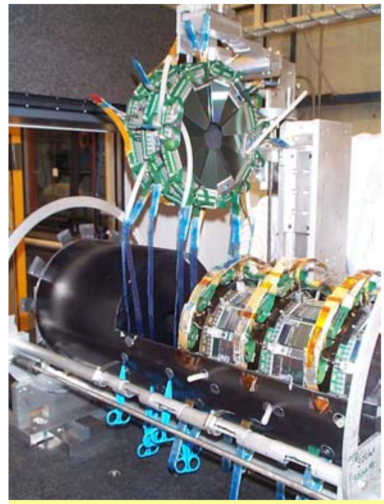


Zeiss coordinate measuring machine at Fermilab's Silicon Detector Facility

Measuring ladder position after insertion

DØ south half detector





Inserting the forward disks

Cabled up and ready for DØ

Transport to DØ

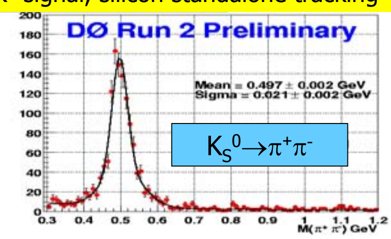
Insertion into detector

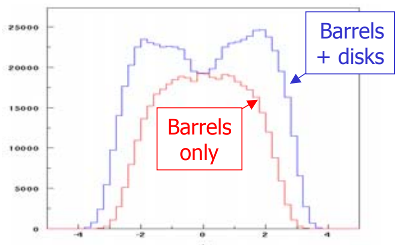
DØ Silicon Status

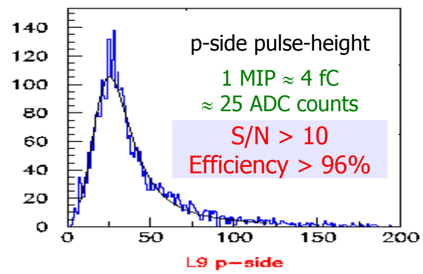
100% commissioned

Barrels: 93% operational
F-disks: 96% operational
H-disks: 89% operational

K^0 signal, silicon standalone tracking







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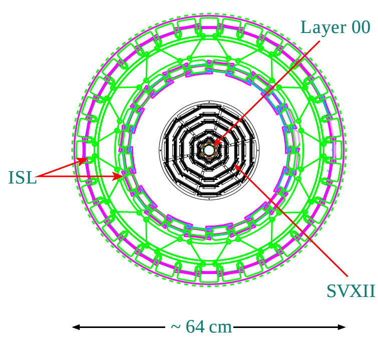
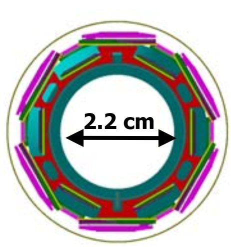
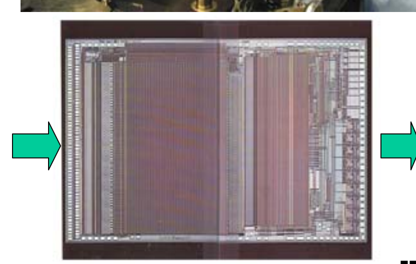
CDF Sil acker



L00





SVX3 chip

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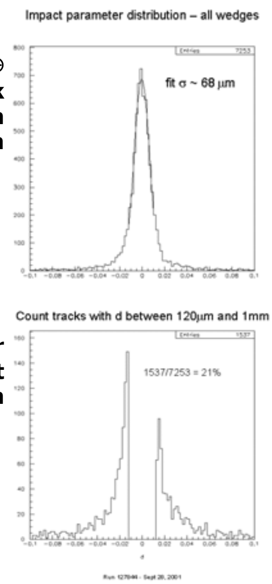
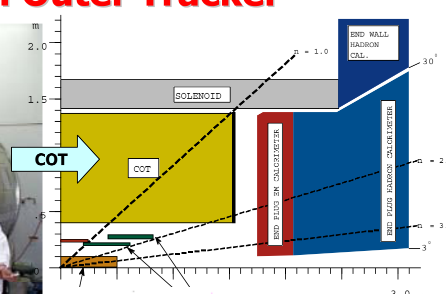
CDF Impact Parameter Trigger

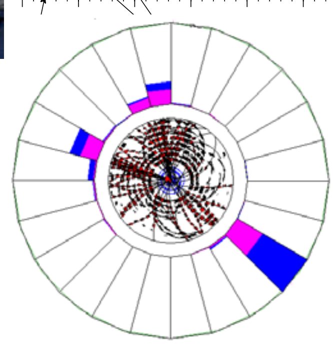
beam spot ⊕ track resolution 68 μm

SVT trigger cutting at 120 μm



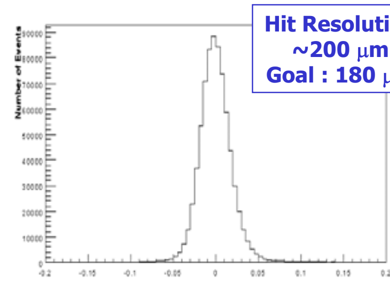
CDF: Central Outer Tracker





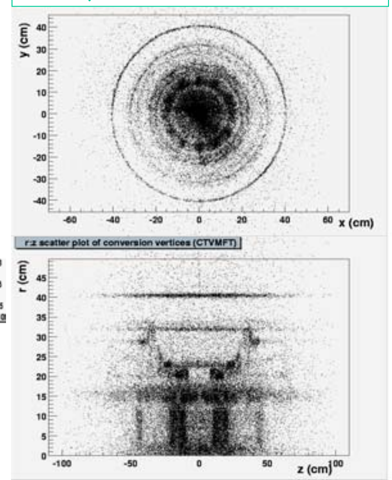
- **96 wire planes**
  - **(8 superlayers)**
  - **50% are 3° stereo**
  - **Uniform drift (0.88 cm cell)**
  - **Cells tilted 35°**
  - **30,240 sense wires**

COT performance

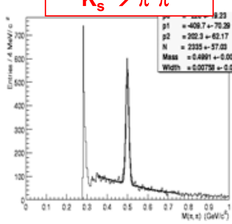


Hit Resolution
~200 μm
Goal : 180 μm

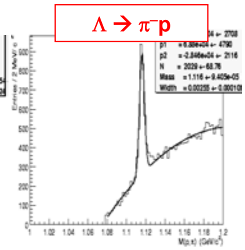
"X-ray" the detector with
$\gamma \rightarrow e^+e^-$ conversions



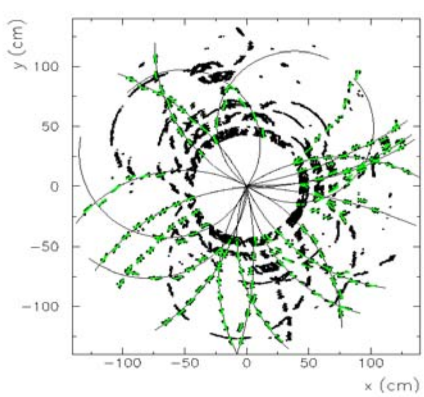
$K_s \rightarrow \pi^+\pi^-$



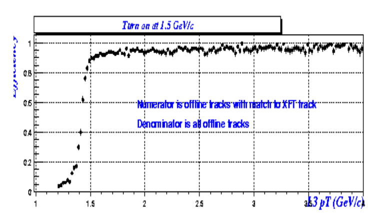
$\Lambda \rightarrow \pi^- p$



Online track trigger (XFT)



Trigger efficiency vs. p_T



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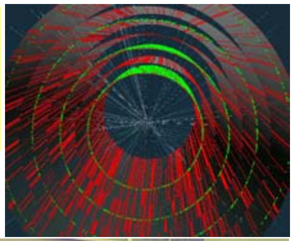
DØ Scintillating Fiber Tracker

Tracker geometry and simulation of particle tracks



Cylinder nesting

Ribbon manufacture

Tracker Installation

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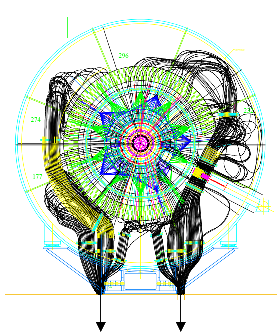
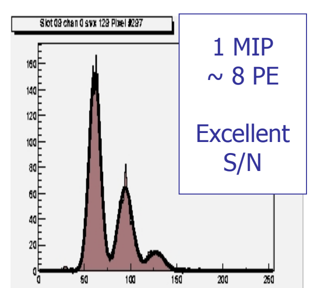
Fiber tracker readout



Readout under detector



Photoelectron peaks in Run 2 operation

1 pe ~ 7 fC

Clear Fiber Waveguides carry the signals to VLPC's

Solid state photon counters Operate at LHe temperature

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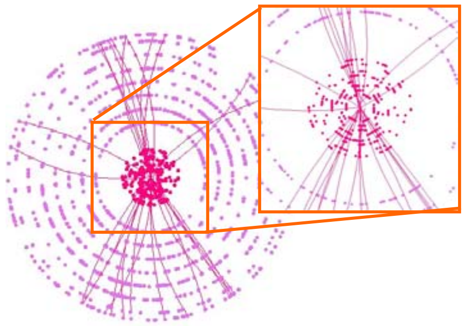
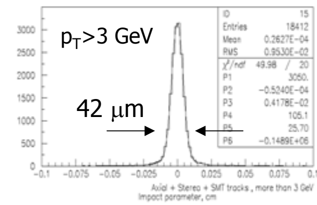
DØ Tracking Status

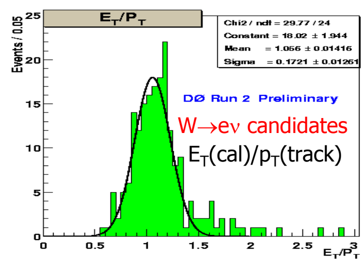


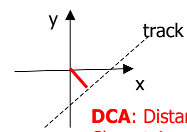


DCA resolution ~ 42 μm (using SMT + axial & stereo fibers)

beam spot ~ 30 μm

Global Tracking
CFT → SMT and
SMT → CFT



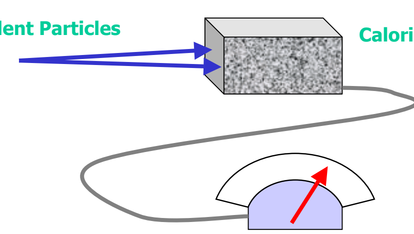


DCA: Distance of Closest Approach

Energy detection

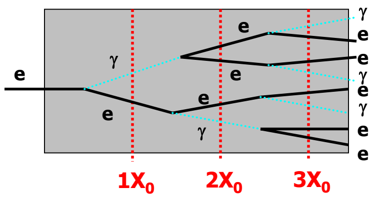
Jet structure = energy flow

- **The basic tool for jet detection and measurement is a segmented calorimeter surrounding the interaction point**



- **Basic idea: induce a shower of interactions between the incident particle and dense material; measure the energy deposited**

Electromagnetic showers



- Above ~100 MeV, pair production and bremsstrahlung dominate energy loss
- shower development scales with radiation lengths X_0
  - $1\ X_0 \approx 180A/Z^2\ g/cm^2$
- Number of particles at depth t (in X_0) is $N(t) = 2^t = e^{t \ln 2}$
- Average energy of shower particle is $E(t) = E_0/N(t)$
  - E_0 = incident energy
- Shower propagates until $E(t) < E_c$, where E_c = critical energy for other energy loss mechanisms to become dominant
- At this point
  - $N_{max} = E_0/E_c$ and $t_{max} = \ln (E_0/E_c)/\ln 2$
- The sum of all charged track lengths in the calorimeter is then
  - $L = 2/3 \int N(t)\,dt = E_0/E_c$
    - factor 2/3 is because equal numbers of e^+, e^- and γ
- Consequently:

> – Total charged track length $\propto$ incident energy
> – Sum of ionization in material $\propto$ incident energy

- Calorimeters measure energy by measuring the sum of ionization from charged tracks in the shower

Hadronic Showers

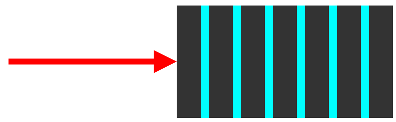
- Strongly interacting particles also cascade in material, but many more processes are involved
  e.g. 10 GeV pion in an iron/Ar calorimeter:

ionization of secondary hadrons	40%
EM cascade from $\pi^0 \rightarrow \gamma\gamma$ (rises with energy)	21%
nuclear binding and neutrinos	21%
neutrons	9%
nuclear excitation	4%
ionization by nuclear fragments	2%
ioinization by primary particle	2%

- Hadronic showers scale with the nuclear interaction length
- Showers longer, wider, start later, with more fluctuations, than an EM shower of the same energy
- Response to a hadron is usually lower than to an electron of the same energy (referred to as the "e/π ratio")

Sampling calorimeters

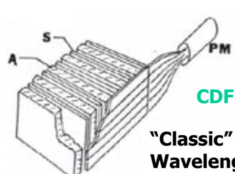
- For reasons of cost and compactness, typically measure only a fixed fraction of the ionization (the "sampling fraction")



- Alternate dense absorber with sensitive medium
- Absorber can be
  - lead, uranium (for maximum density), steel, copper, iron (for magnetic field), tungsten (costly)
- Sensitive layers can be
  - scintillator, wire chambers, liquid argon, silicon (cost, specialized applications only)

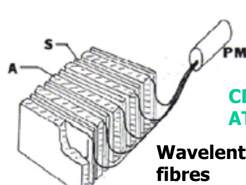
Scintillator calorimeters

- Cheap, straightforward to build, but suffer from radiation damage



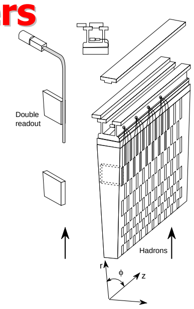
CDF central, ZEUS

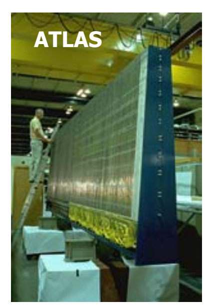
"Classic" design
Wavelength-shifter readout bars



CDF forward
ATLAS, CMS

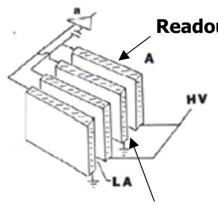
Wavelenth-shifting fibres
More compact, more flexible

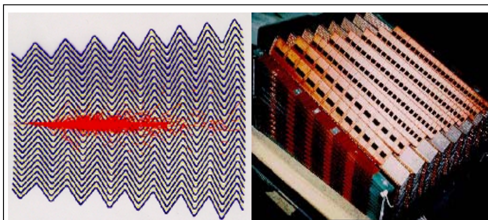




Liquid Argon

- Stable, linear, radiation hard
- BUT operates at 80K: cryostat and LN_2 cooling required
  e.g. H1, SLD, DØ, ATLAS





ATLAS "accordion" EM calorimeter

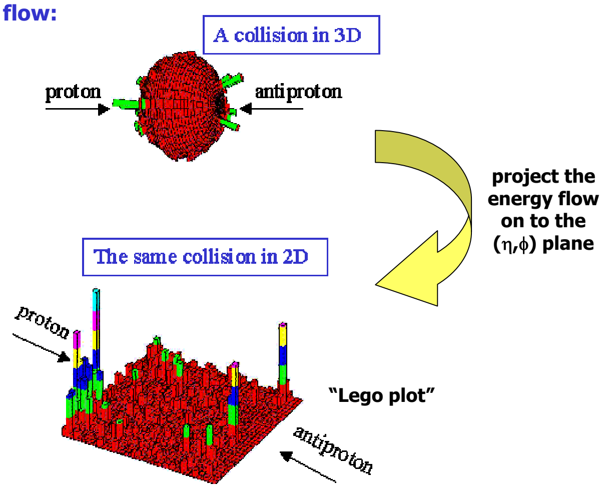
Energy Resolution

- Usually dominated by statistical fluctuations in the number of shower particles
  - $N \propto E_0$
  - $\delta N/N \propto 1/\sqrt{E_0}$
- Often quoted as "X%/√E" (E in GeV)
- Typical real-life values:
  - 15%/√E(GeV) for electrons
  - 50%/√E(GeV) for single hadrons
  - 80%/√E(GeV) for jets

- Other terms contribute in quadrature
  - "noise term" (independent of E; dominant at low E)
    - electronic noise
  - "constant term" (constant fraction of E, dominant at high E)
    - calibration uncertainties, nonlinear response, unequal response to hadrons and electrons

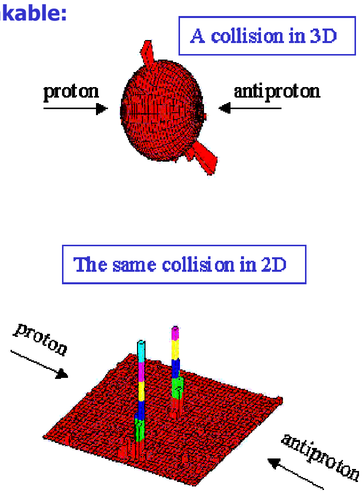
Hadron-hadron collisions are messy

- **Energy flow:**

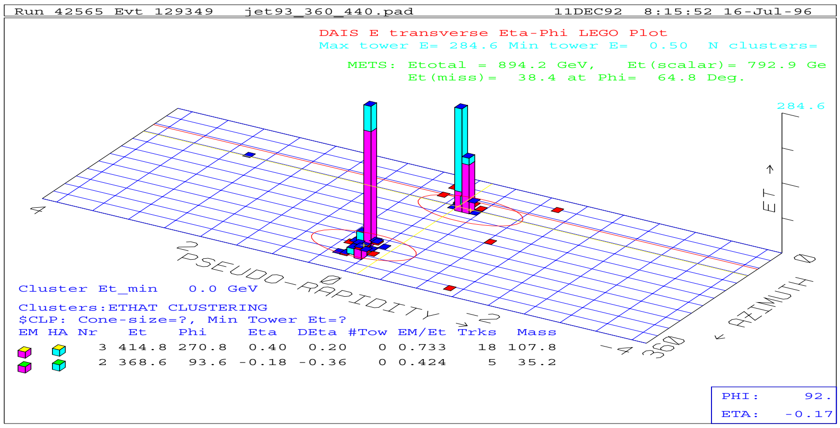


But become simple at high energies

- **Jets are unmistakable:**



A high-E_T event at CDF



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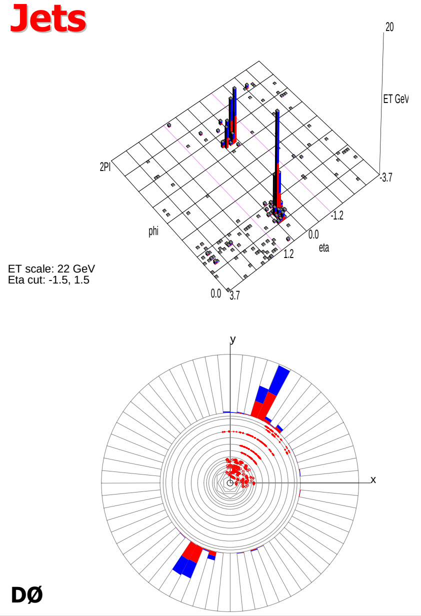
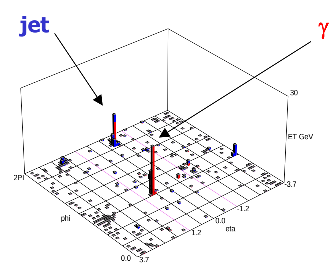
Jets



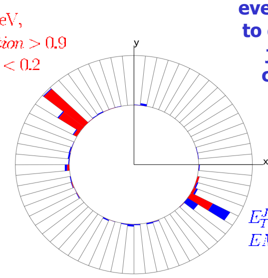
Gamma + Jet Candidate

Run 128309 Event 256324



γ candidate

E_T^{γ}=27 GeV,
$EM fraction > 0.9$
$Isolation < 0.2$



This type of event is used to derive the jet energy calibration

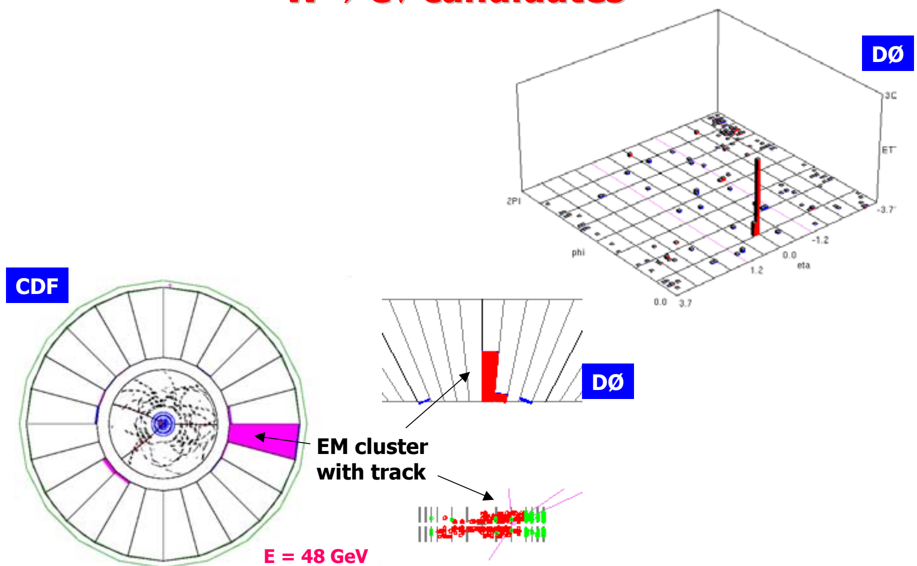
jet

E_T^{Jet}=24 GeV
$EM fraction = 0.48$

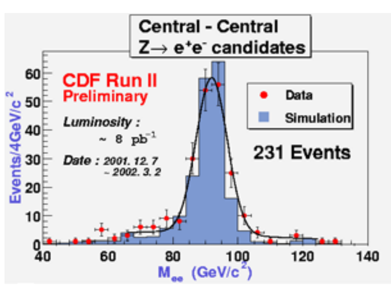
DØ

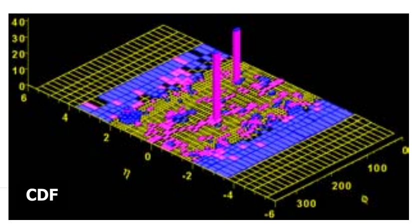
John Womersley

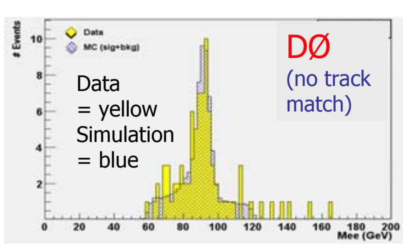
W→ eν candidates

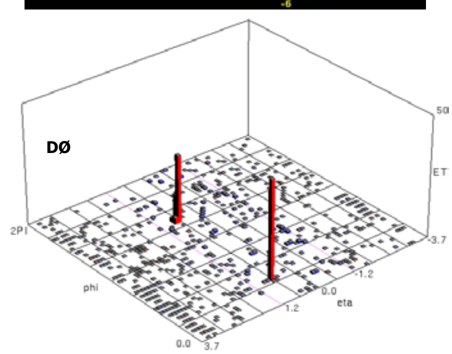


Z → e⁺e⁻ candidates









Forward muon truss (supports C layer detectors and shielding)

Muon Detectors

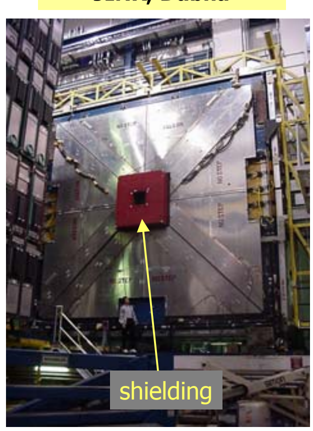
Forward mini drift tube detectors (from JINR, Dubna, Russia)

Forward muon trigger scintillators (From Protvino, Russia)

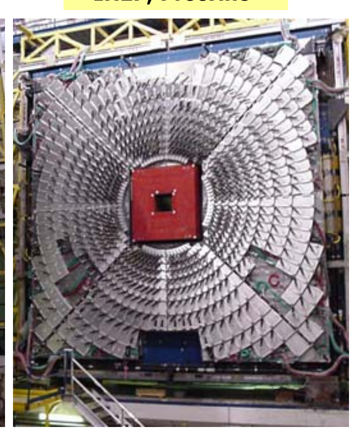
DØ Forward Muon Detector Upgrade

Shielding mounted on support truss

Mini drift tube plane (10m × 10m) JINR, Dubna



Trigger scintillator Plane (10m × 10m) IHEP, Protvino

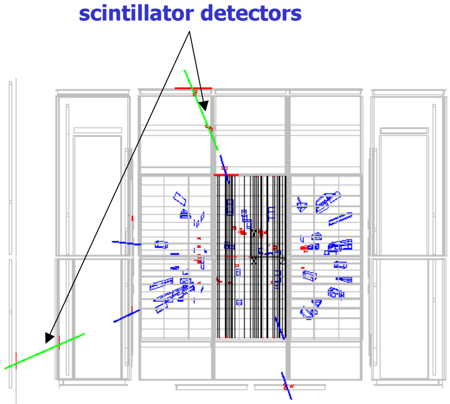


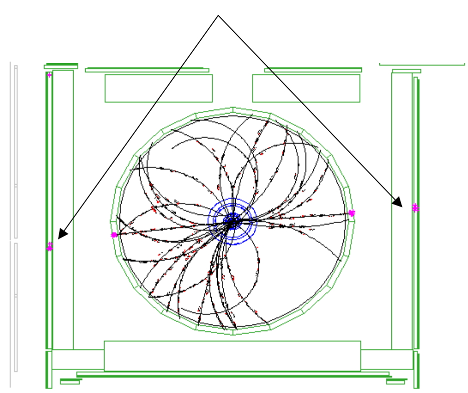
DØ detector installed in the Collision Hall, January 2001

$Z \rightarrow \mu^+\mu^-$ candidates

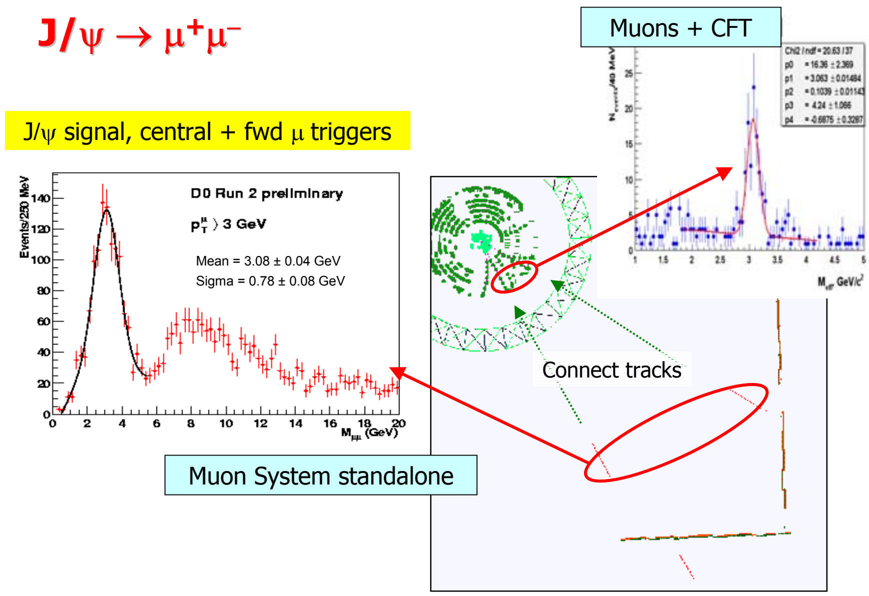
DØ: muons reconstructed with hits in drift tubes and scintillator detectors

CDF: muons reconstructed in muon system and COT





$J/\psi \rightarrow \mu^+\mu^-$



Triggering

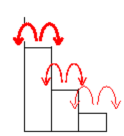
- **Accelerator luminosity is driven by physics goals**
  - **e.g. to find the Higgs we will need ~ 10 fb^{-1} of data**
  - **requires collision rate ~ 2×10^{32} cm^{-2} s^{-1}**
- **But low-E_T inelastic cross sections are much much higher than the processes we are interested in saving**
  - **even with beam bunches crossing in the detector every 132 ns, get >1 inelastic collision per crossing**
- **Triggering challenge**
  - **Real-time selection of perhaps 20 events per second (maximum that can be written to a tape) from a collision rate of 10,000,000 events per second**
  - **usually based on rapid identification of**
    - **high energy particles**
    - **comparatively rare objects (electrons, muons…)**

CDF and DØ trigger scheme

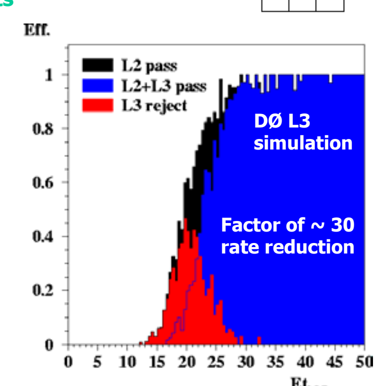
- **Detector**
    - **10MHz collisions**
- **Level 1 trigger**
    - **hardware based, looks at fast outputs from specialized detectors**
        - **accepts 10kHz (DØ), 40kHz (CDF)**
- **Level 2 trigger**
    - **microprocessors, fast calculations on a small subset of the data**
        - **accepts 1 kHz(DØ), 300 Hz (CDF)**
- **Level 3 trigger**
    - **computers, fast calculations, all the data is available**
        - **accepts 50 Hz**
- **Offline processing**
    - **computer farm to process all the data within a few days of recording**
    - **streaming and data classification**

Jet Triggering

- **Unlike most physics at hadron colliders, the principal background for jets is other jets**
    - **because the cross section falls steeply with E_T, lower energy jets mismeasured in E_T often have a much higher rate than true high E_T jets**

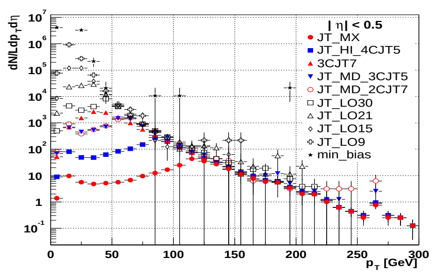


- **Multi-level trigger system makes increasingly refined estimates of jet E_T**



Prescaled triggers

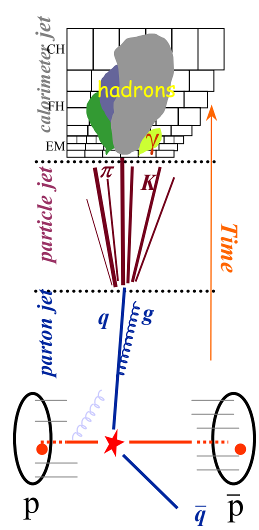
- **Large dynamic range of steeply falling cross sections often demands that many trigger thresholds be used e.g. for jets**
  - **15 GeV prescaled 1/1000**
  - **30 GeV prescaled 1/100**
  - **60 GeV prescaled 1/10**
  - **120 GeV no prescale**

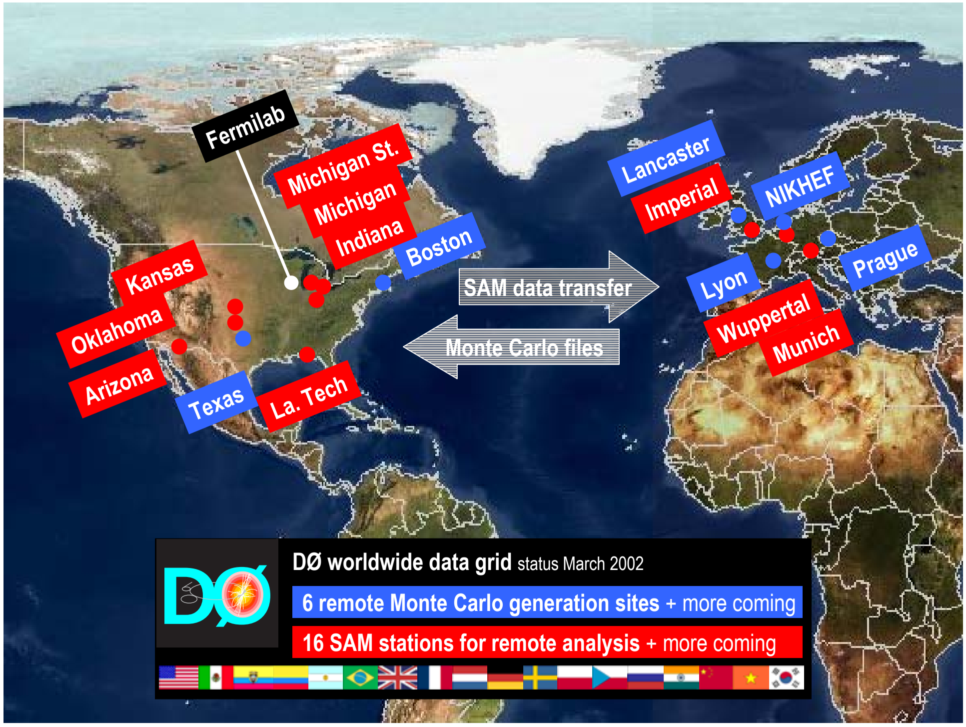


D0 Run 2 Level 1 jet triggers

Simulation tools

- **A "Monte Carlo" is a Fortran or C++ program that generates events**
- **Events vary from one to the next (random numbers) — expect to reproduce both the average behavior and fluctuations of real data**
- **<u>Event Generators</u> may be**
  - **parton level:**
    - **Parton Distribution functions**
    - **Hard interaction matrix element**
  - **and may also handle:**
    - **Initial state radiation**
    - **Final state radiation**
    - **Underlying event**
    - **Hadronization and decays**
- **Separate programs for <u>Detector Simulation</u>**
  - **GEANT is by far the most commonly used**





Complementarity between DØ and CDF

- **CDF is arguably a tracking-centred detector:**
  - **better charged track resolution and more measurement layers**
  - **some π/K separation**
  - **higher level 1 bandwidth**
- **DØ is arguably a calorimeter-centred detector:**
  - **better jet and missing E_T resolution**
  - **better muon system**
- **Experiments are roughly equal in**
  - **EM calorimeter resolution**
  - **b-tagging efficiency**
- **Run I Experience shows that the physics reach is not dramatically different**
  - **either driven by cross sections (e.g. SUSY limits), or the respective strengths tend to balance (e.g. top discovery and mass, m_W)**