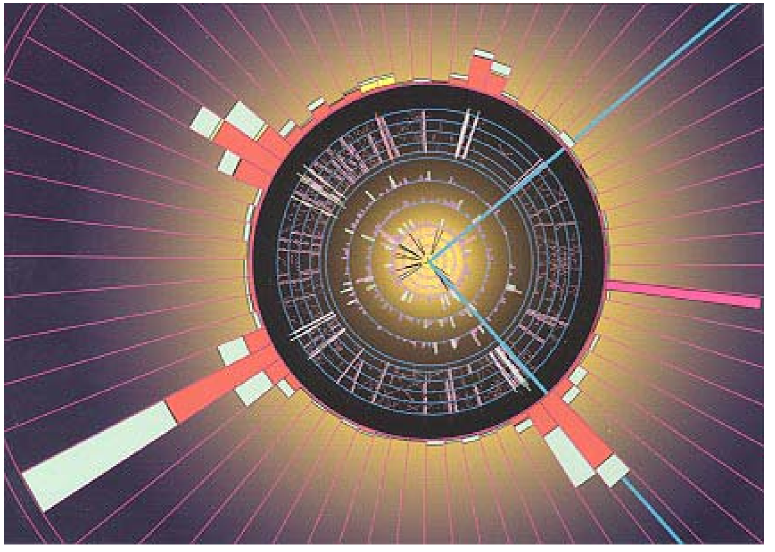
Physics at Hadron Colliders
Selected Topics: Lecture 1



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http://d0server1.fnal.gov/users/klima/Vietnam/Hue/Lecture_1.pdf

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, J. Womersley,...)

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" (recently 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**

Outline

- **Lecture 1: QCD**
  - Brief introduction to QCD
  - Detectors: Calorimetry
  - Jets — experimental issues
    - jet algorithms
    - jet energy scale
  - Jet cross sections
- **Lecture 3: The top quark**
  - mass
  - cross section
  - decay properties
- **Lecture 2: QCD**
  - Other Jet measurements
  - Vector bosons
  - Photons
  - Heavy flavour production
  - α_s
  - Hard diffraction
  - Concluding remarks on QCD
- **Lecture 4: Higgs and Supersymmetry**
  - what is mass?
  - Tracking detectors and b-tagging
  - Higgs search in Run 2
  - Supersymmetry searches

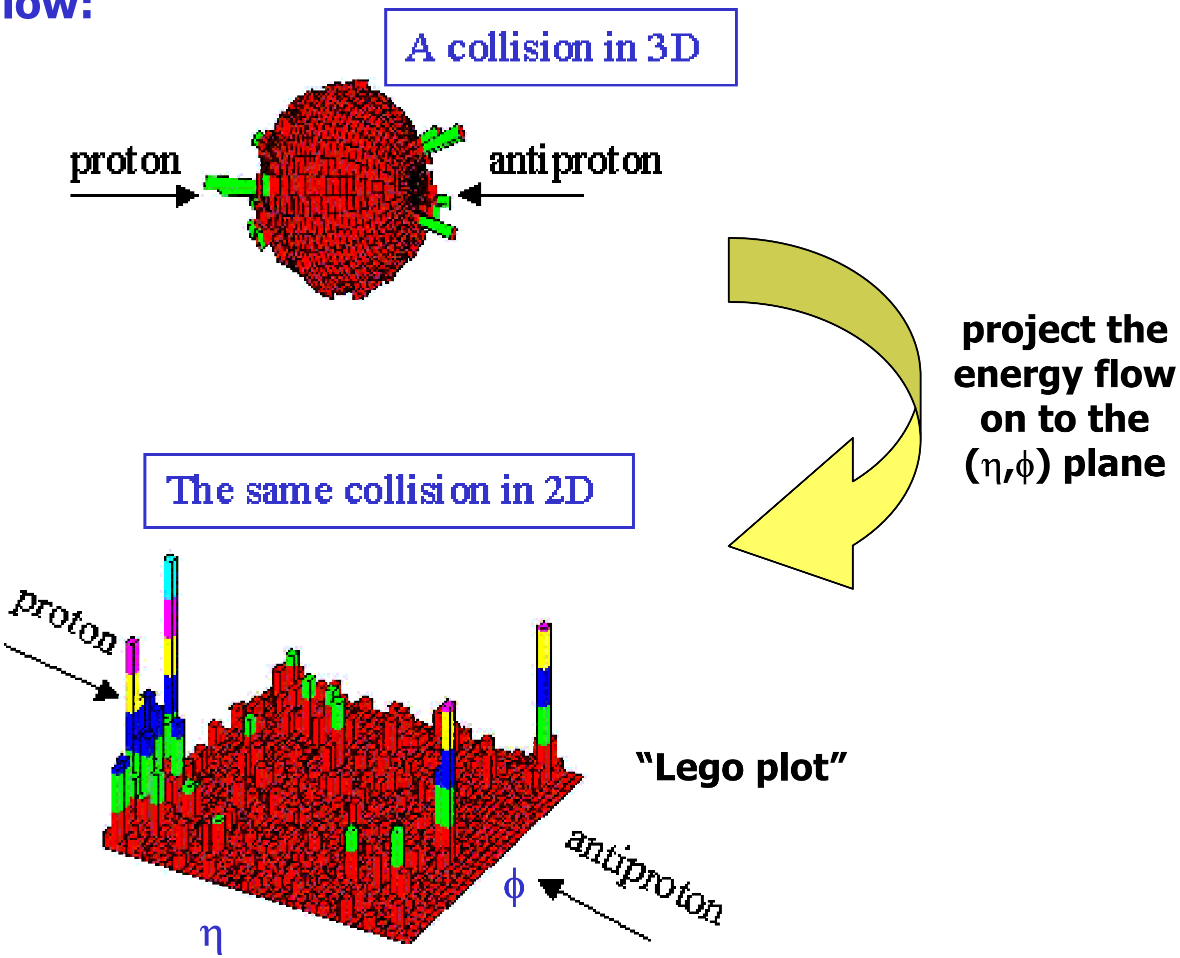
QCD

Before we can try to search for new physics at hadron colliders, we have to understand Quantum Chromo Dynamics (QCD)

The interactions between quarks and gluons

Hadron-hadron collisions are messy

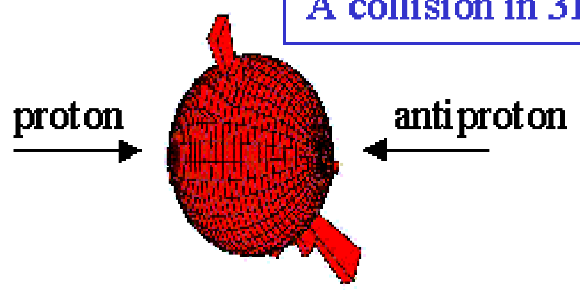
- **Energy flow:**



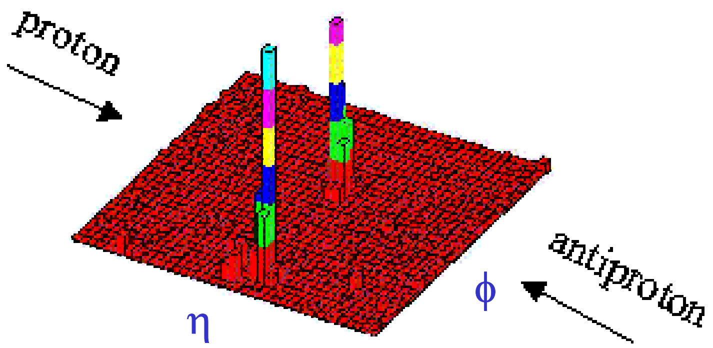
But become simple at high energies

- **Jets are unmistakable:**

A collision in 3D



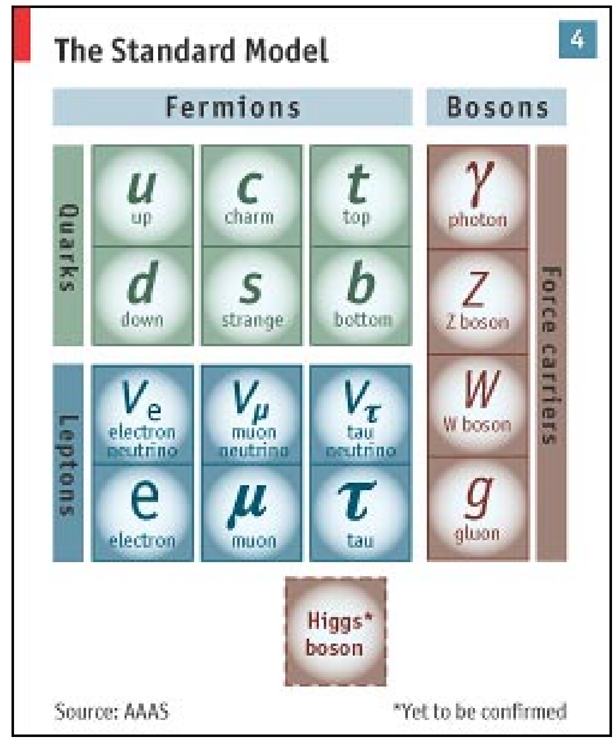
The same collision in 2D



Quantum Chromo Dynamics

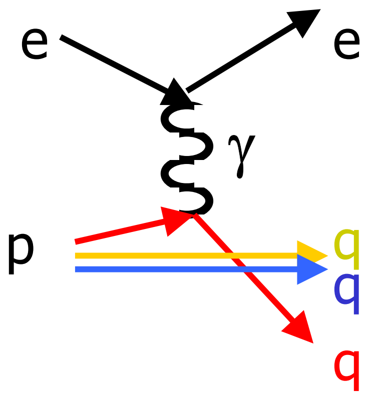
- **Gauge theory (like electromagnetism) describing fermions (quarks) which carry an SU(3) charge (color) and interact through the exchange of vector bosons (gluons)**
- **Interesting features:**
  - **gluons are themselves colored**
  - **interactions are strong**
  - **coupling constant runs rapidly**
    - **becomes weak at momentum transfers above a few GeV**

$$\alpha_s(q^2) = \frac{12\pi}{(33 - 2n_f)\ln q^2/\Lambda^2}$$

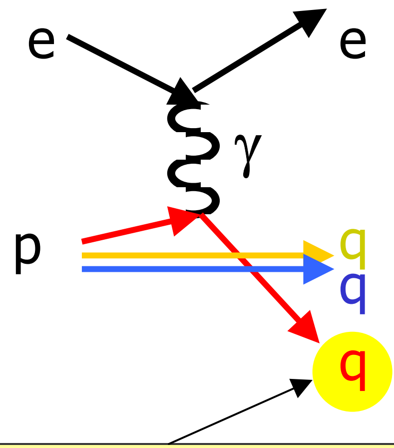


Quarks

- **These features lead to a picture where quarks and gluons are bound inside hadrons if left to themselves, but behave like "free" particles if probed at high momentum transfer**
  - **this is exactly what was seen in deep inelastic scattering experiments at SLAC in the late 1960's which led to the genesis of QCD**
  - **electron beam scattered off nucleons in a target**
    - **electron scattered from pointlike constituents inside the nucleon**
    - **~ 1/sin^4(θ/2) behavior like Rutherford scattering**
    - **other (spectator) quarks do not participate**



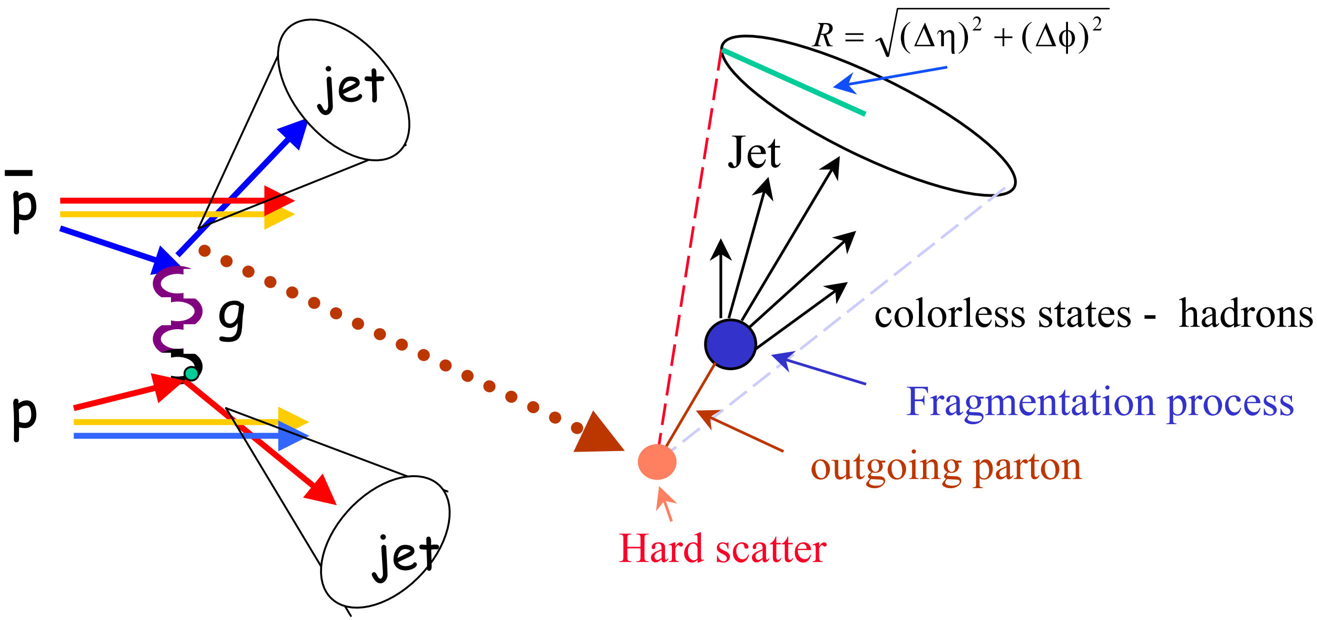
Fragmentation



So what happens to this quark that was knocked out of the proton?

- α_s is large
  - lots of gluon radiation and pair production of quarks in the color field between the outgoing quark and the colored remnant of the nucleon
- these quarks and gluons produced in the "wake" of the outgoing quark recombine to form a "spray" of roughly collinear, colorless hadrons: a jet
  - "fragmentation" or "hadronization"

What are jets?



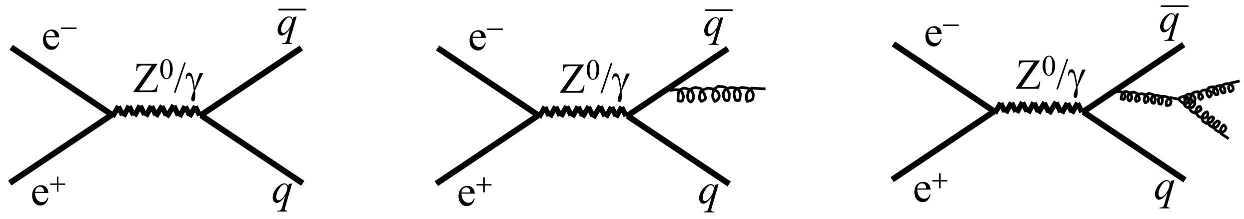
- **The hadrons in a jet have small transverse momentum relative to the parent parton's direction and the sum of their longitudinal momenta is roughly the parent parton momentum**
- **Jets are the experimental signatures of quarks and gluons and manifest themselves as localized clusters of energy**

Timeline

		← Introduction of Color and the Quark Model
SLAC		← Experimental evidence of quarks in DIS scattering, Bjorken scaling
ISR	1970	← Birth of QCD: Renormalizability, Asymptotic Freedom, Confinement
		← Discovery of the charm quark (SLAC, BNL)
		← Observation of jets in e^+e^- as manifestation of quarks (SLAC,1975) and gluons (DESY,1979)
PETRA		← Discovery of the bottom quark (FNAL)
	1980	← Violation of Bjorken scaling, Evolution of Parton Distribution and Fragmentation Functions
Sp$\bar{p}$S		← QCD calculations start to become available for many processes
		← Discovery of W and Z (CERN)
LEP *HERA*	1990	← Next to Leading Order predictions for jet production
Tevatron Run I		← Discovery of the top quark (FNAL)
Tevatron Run II	2000	← Next to Next to Leading Order predictions for jet production

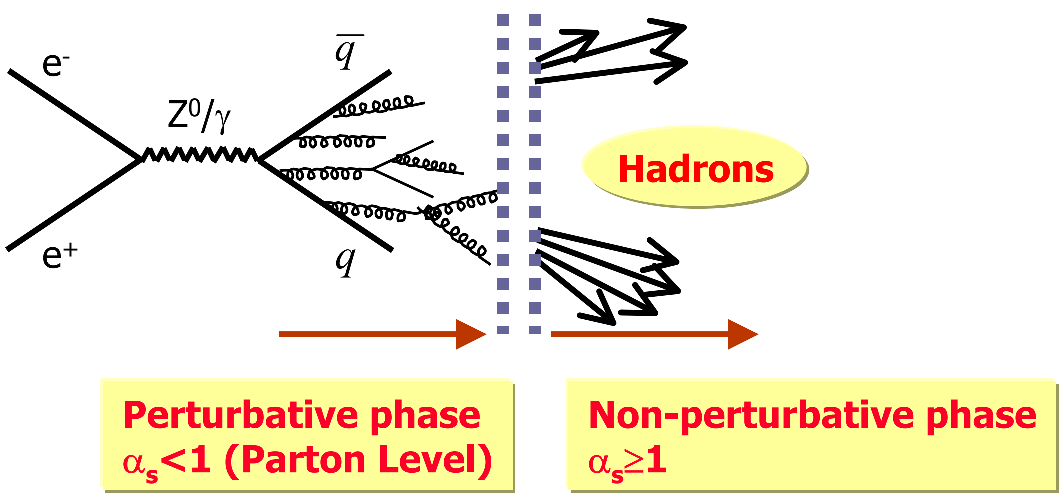
e^+e^- annihilation

- **Fixed order QCD calculation of $e^+e^- \rightarrow (Z^0/\gamma)^* \rightarrow$ hadrons :**

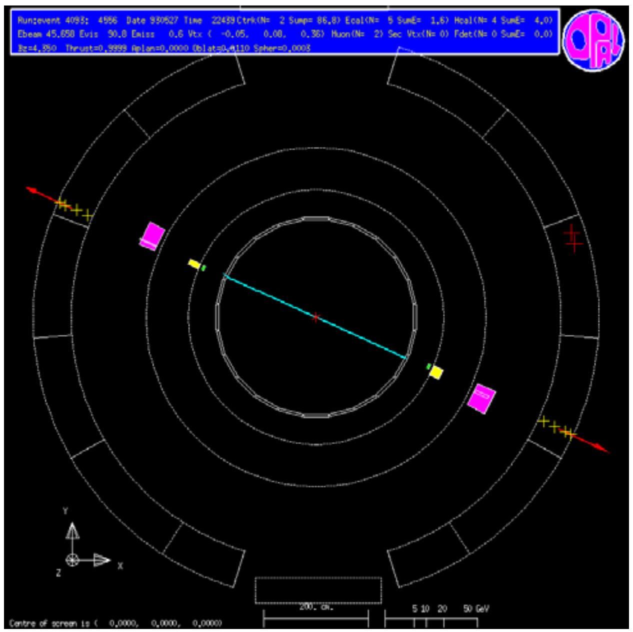


$\mathcal{O}(\alpha_s^{\,0})$ $\mathcal{O}(\alpha_s^{\,1})$ $\mathcal{O}(\alpha_s^{\,2})$

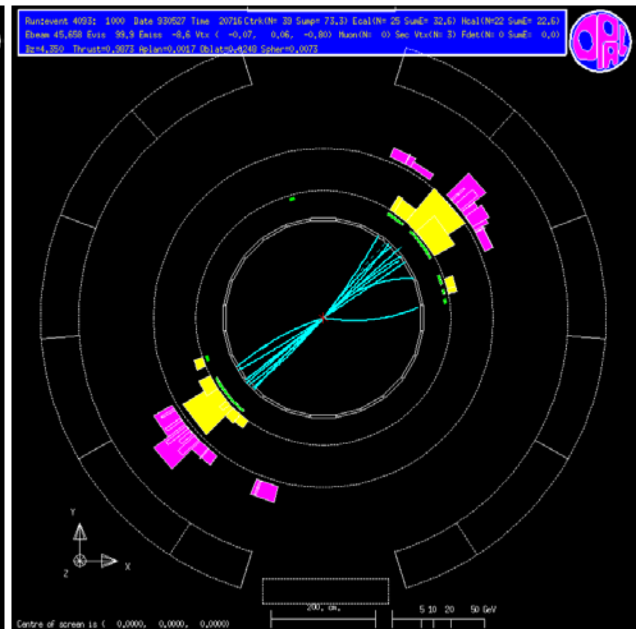
- **Monte Carlo approach (PYTHIA, HERWIG, etc.)**



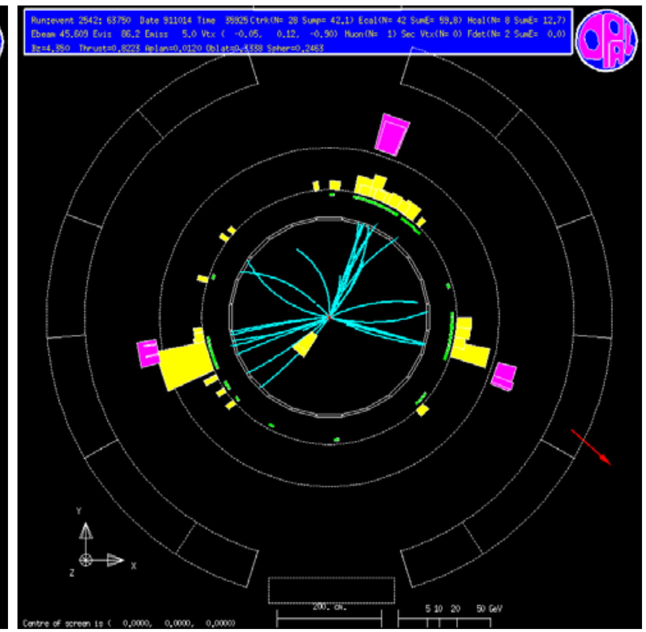
$e^+e^- \to \mu^+\mu^-$



$e^+e^- \to \bar{q}q$



$e^+e^- \to \bar{q}qg$



The Fermilab Tevatron collider

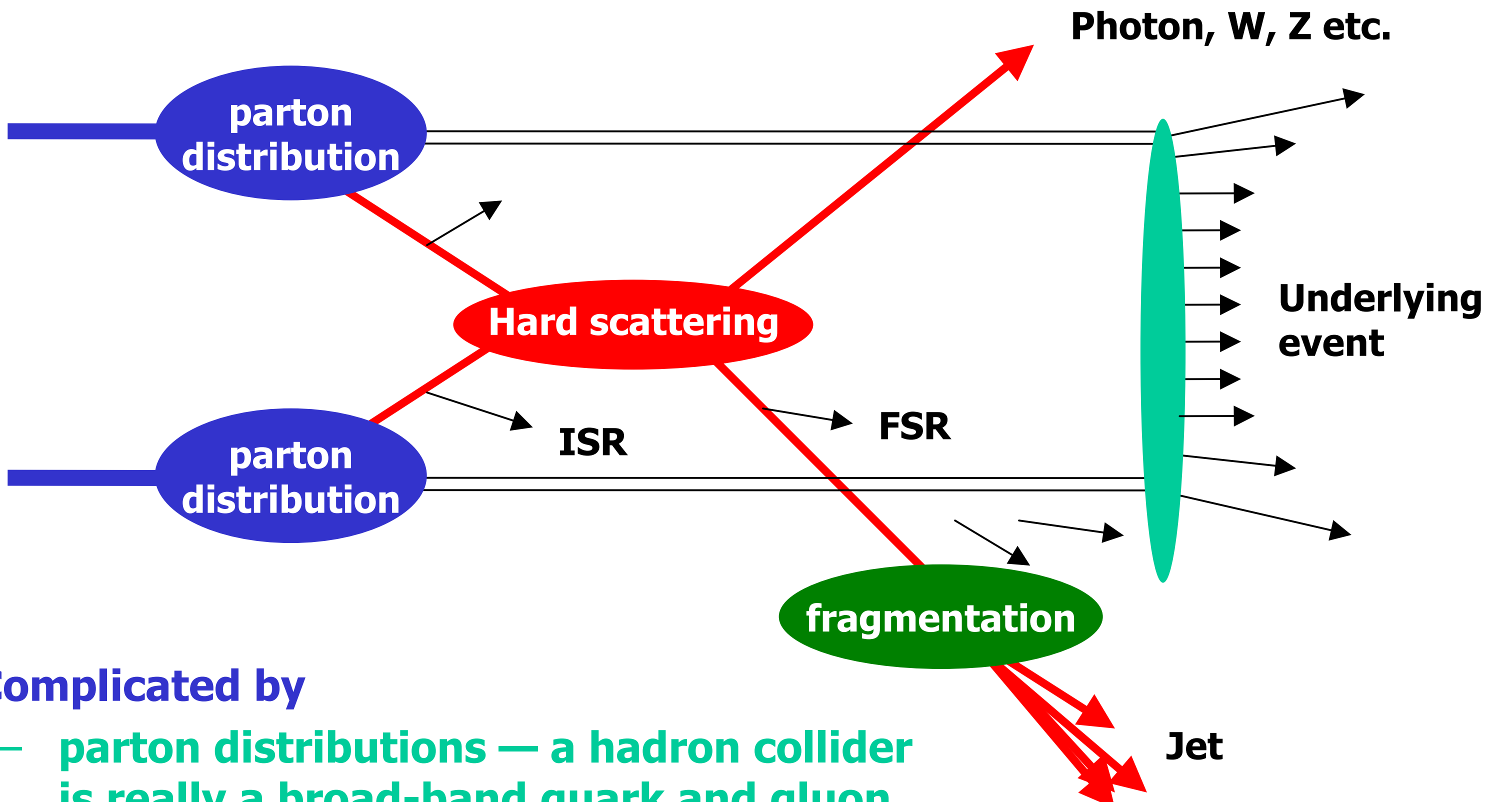
- **Run I (1992-96) ~ 100 pb^{-1}**
- **Run IIa (2001-05) ~ 2 fb^{-1}**

  Several months shutdown to install new silicon detectors +…

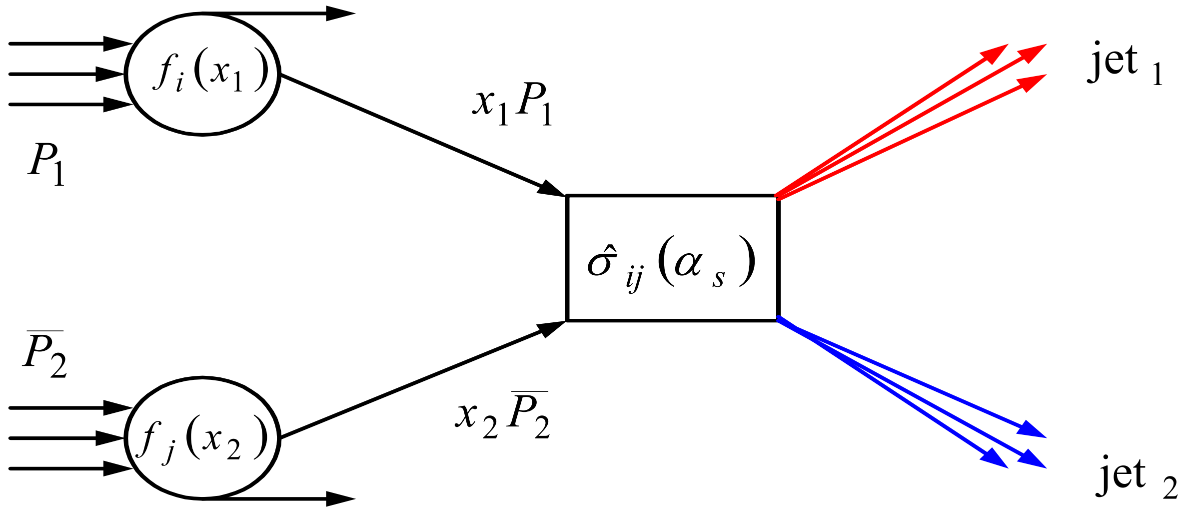
- **Run IIb (2006-09?) ~ 10-15 fb^{-1}**

  Until LHC produces physics

Hadron-hadron collisions



- **Complicated by**
  - parton distributions — a hadron collider is really a broad-band quark and gluon collider
  - both the initial and final states can be colored and can radiate gluons
  - underlying event from proton remnants



$$\sigma = \sum_{ij} \int dx_1 dx_2 \, f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right) \hat{\sigma}_{ij}\left(\alpha_s^m\left(\mu_R^2\right), x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Sum over initial states

Parton Distributions

Factorization Scale

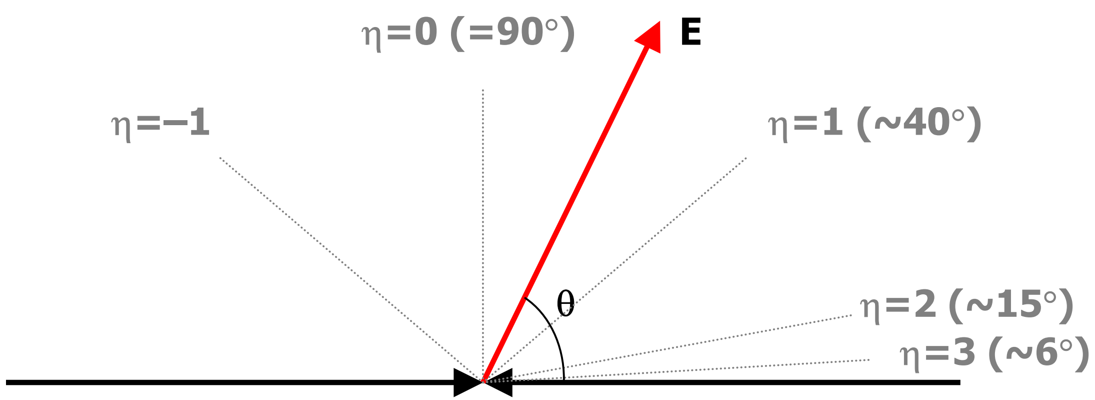
Point Cross Section

Order α_s^m

Renormalization Scale

Hadron Collider variables

- The incoming parton momenta x_1 and x_2 are unknown, and usually the beam particle remnants escape down the beam pipe
  - longitudinal motion of the centre of mass cannot be reconstructed

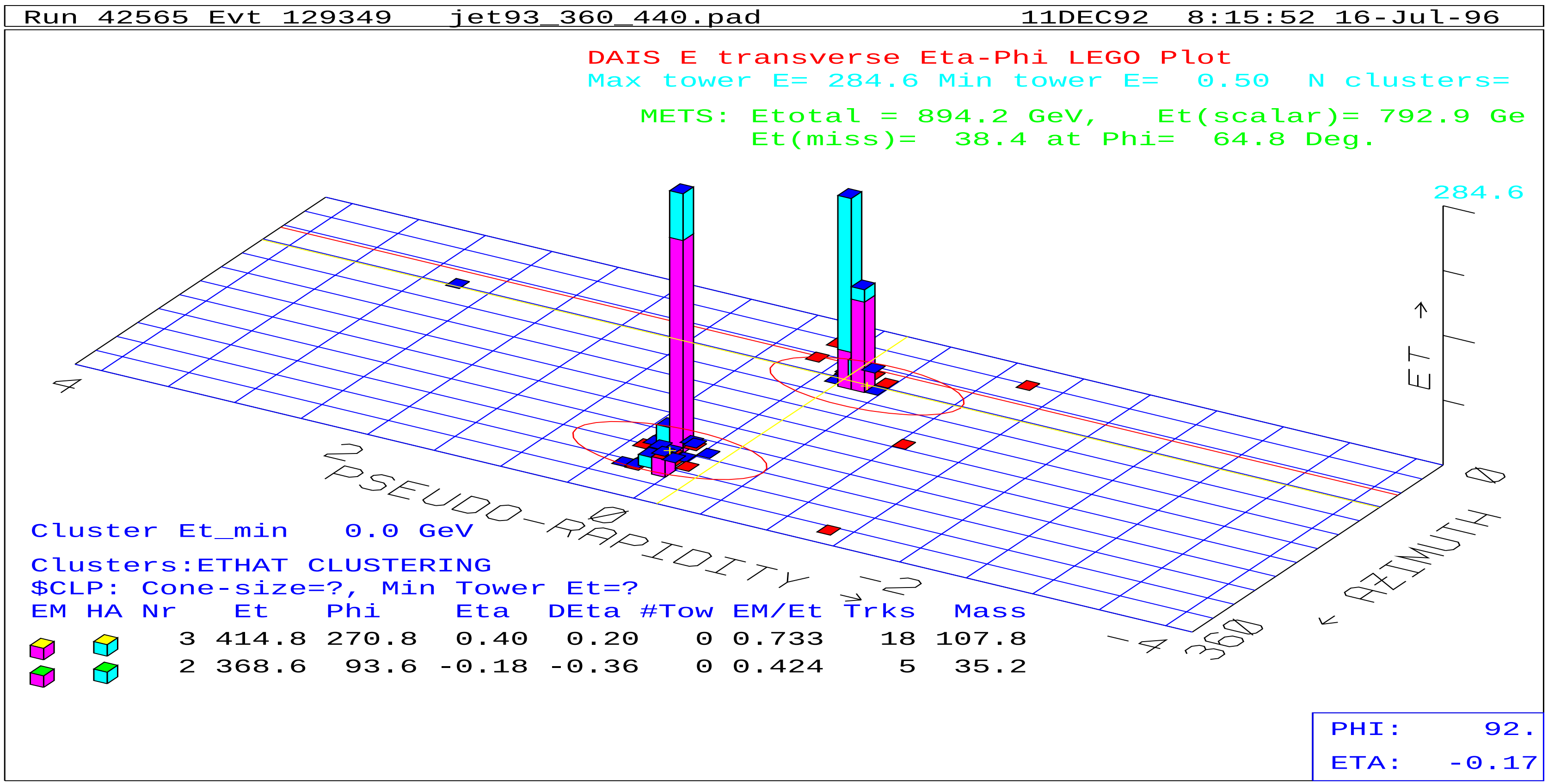


- Focus on transverse variables
  - Transverse Energy $E_T = E \sin\theta$ (= p_T if mass = 0)
- and longitudinally boost-invariant quantities
  - Pseudorapidity $\eta = -\log(\tan\theta/2)$ (= rapidity y if mass = 0)
  - particle production typically scales per unit rapidity

Simplifying things . . .

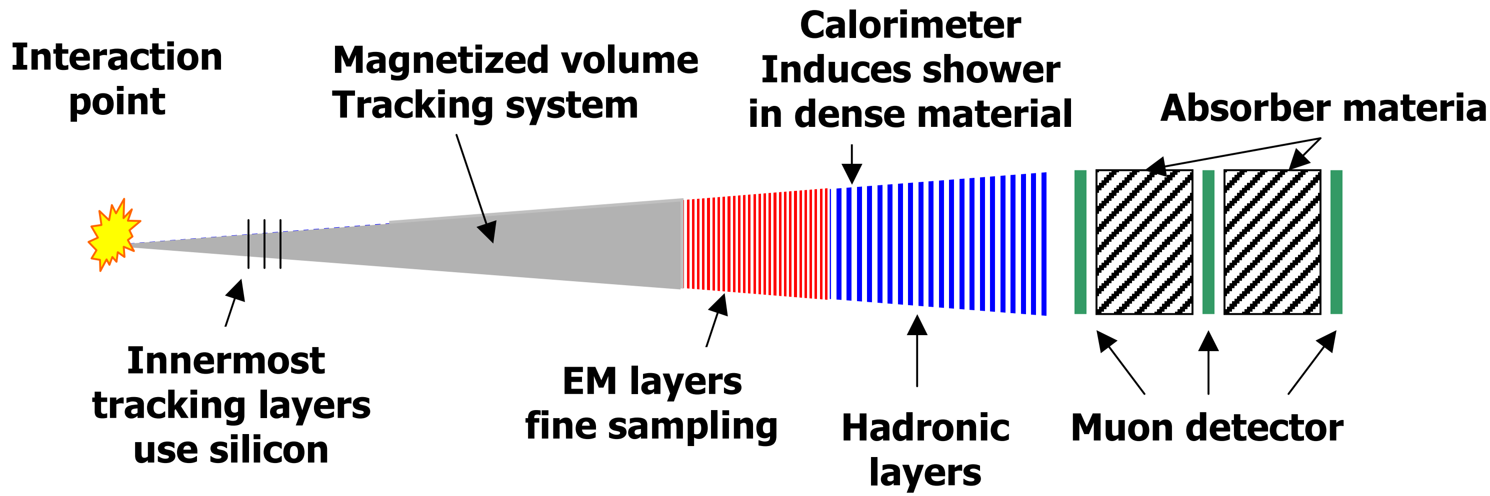
- It is a general feature of particle physics that many interactions become simpler to understand at high energies
- In the case of QCD
  - coupling constant becomes smaller at high momentum transfer
  - jet structure becomes more obvious (jets become narrower, stand out more clearly from underlying energy flow)
  - many measurement related systematic effects get smaller
- We tend to start with high E_T or high momentum transfer (Q^2) processes and try to use them to help us understand lower energy scales, rather than the reverse
- The most basic high momentum transfer process to understand is the hard scattering of the colored constituents of the hadrons to produce <u>high E_T jets</u>

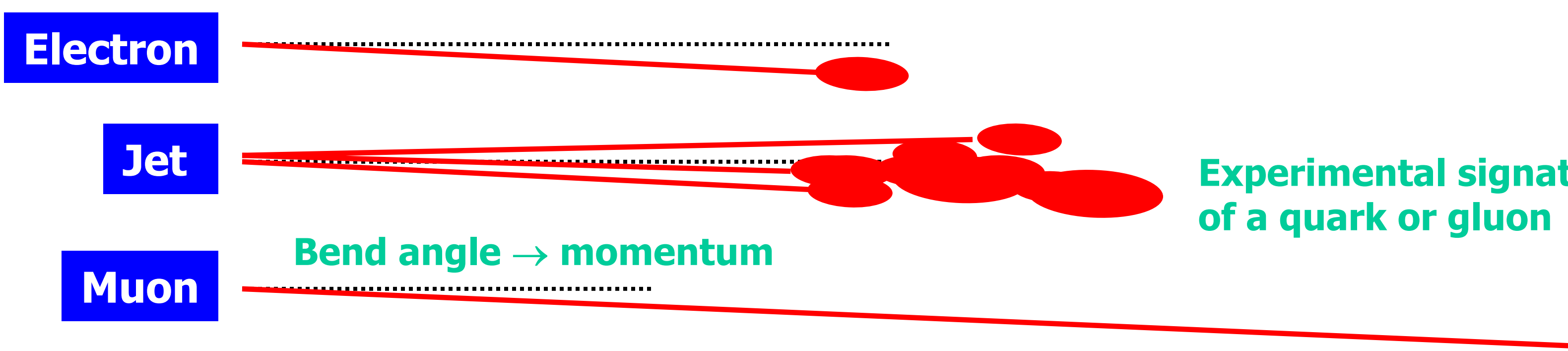
A high-E_T event at CDF



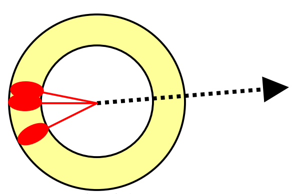
Detectors

Typical detector



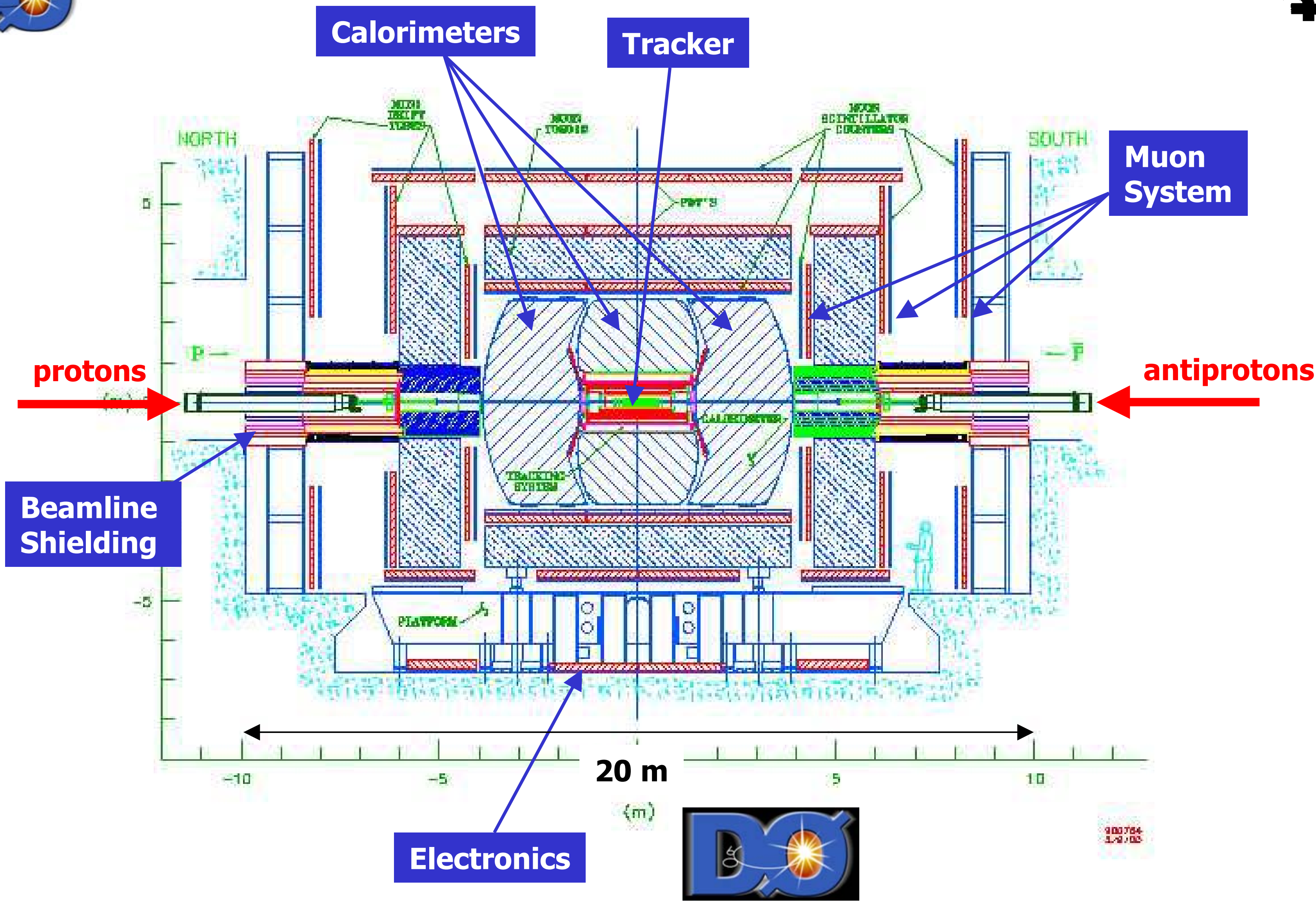


Experimental signature of a quark or gluon



"Missing transverse energy"

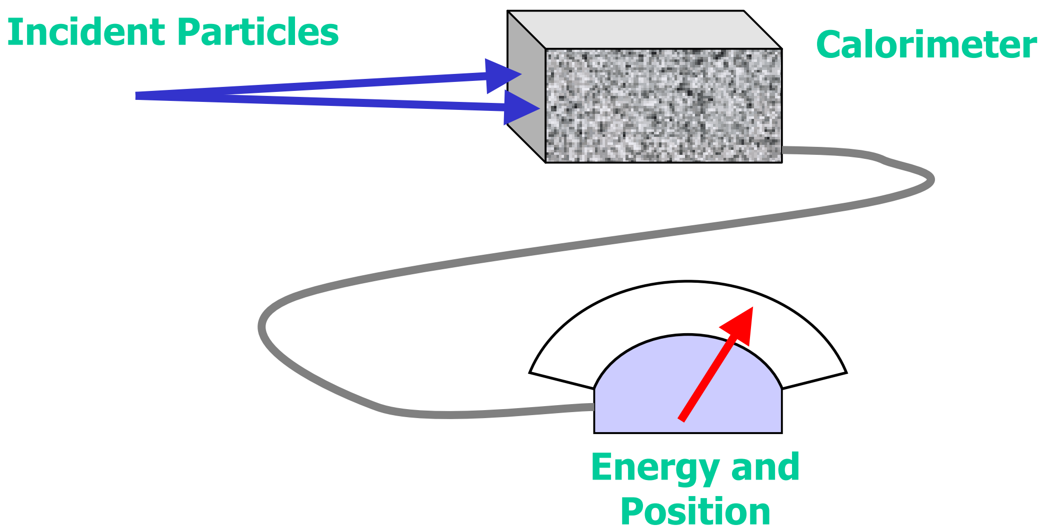
Signature of a non-interacting (or weakly interacting) particle like a neutrino


Calorimeters
Tracker
Muon System
protons
antiprotons
Beamline Shielding
Electronics
20 m
NORTH
SOUTH
-10
-5
5
10
(m)

Jet detection

Jet structure = energy flow

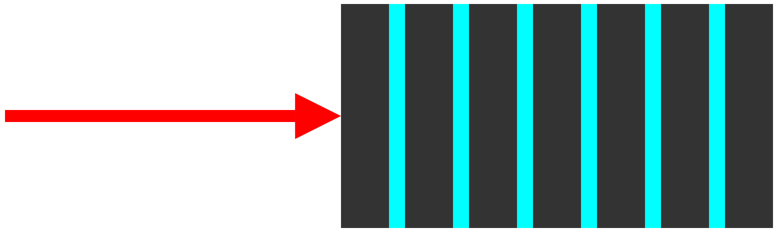
- **Therefore the basic tool for jet detection and measurement is a segmented calorimeter surrounding the interaction point**



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

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)

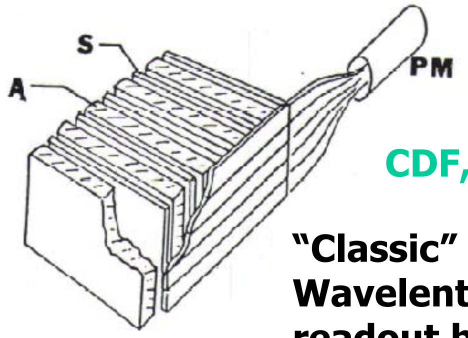
Energy Resolution

- 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 "$X\%/\sqrt{E}$" (E in GeV)
- Typical real-life values:
  - $15\%/\sqrt{E(GeV)}$ for electrons
  - $50\%/\sqrt{E(GeV)}$ for single hadrons
  - $80\%/\sqrt{E(GeV)}$ 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

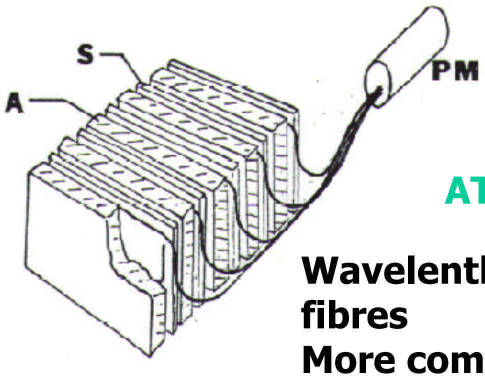
Scintillator calorimeters

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



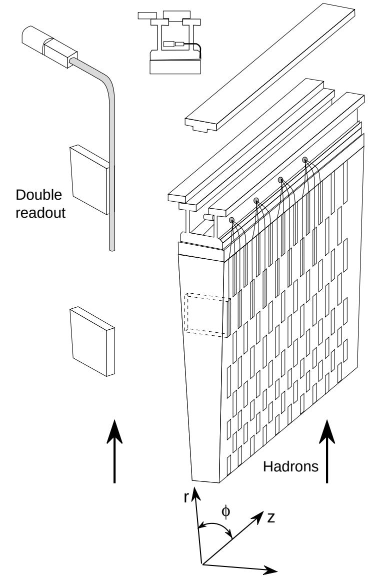
CDF, ZEUS

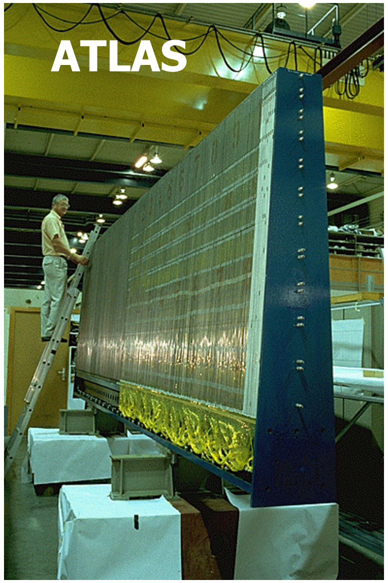
"Classic" design
Wavelenth-shifter readout bars



ATLAS, CMS

Wavelenth-shifting fibres
More compact, more flexible

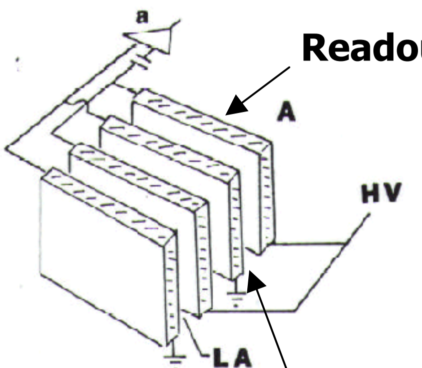




Liquid Argon

- **Stable, linear, radiation hard**
- **BUT operates at 80K: cryostat and LN_2 cooling required**

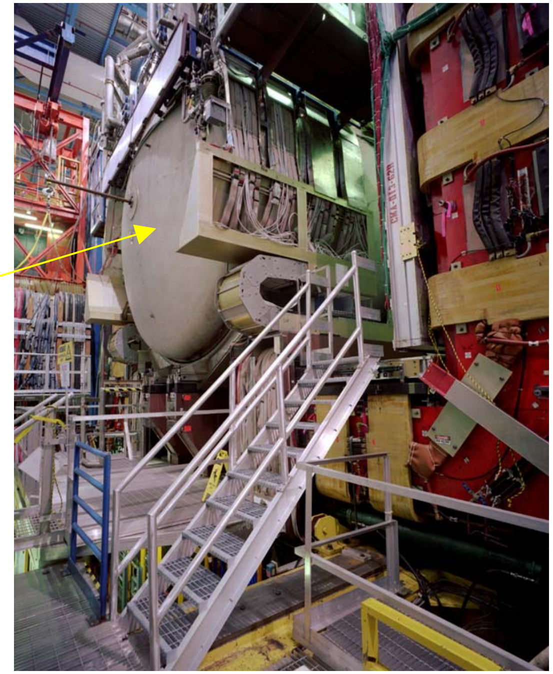
  e.g. H1, SLD, DØ, ATLAS

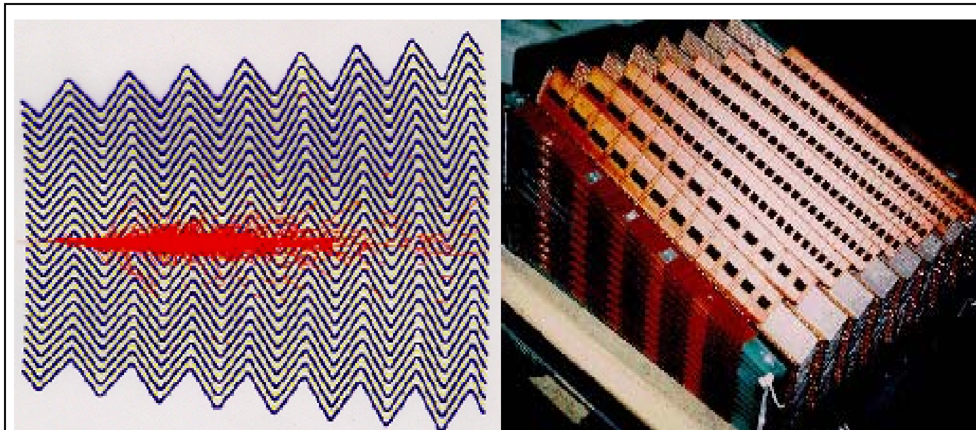


Readout boards

Absorber plates

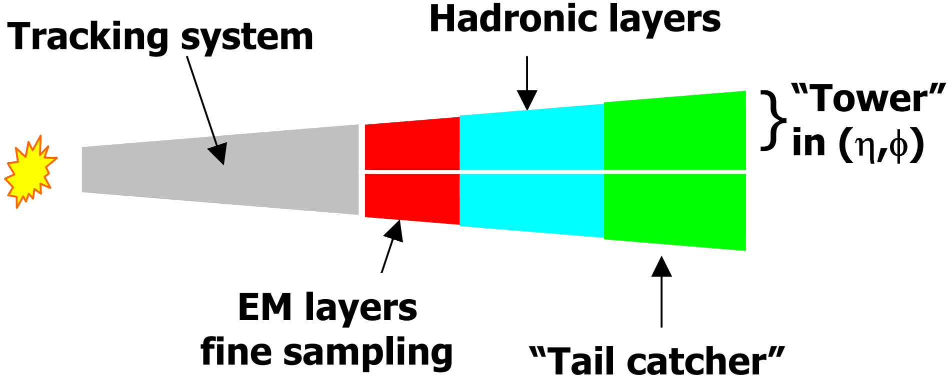
DØ North endcap liquid argon cryostat vessel

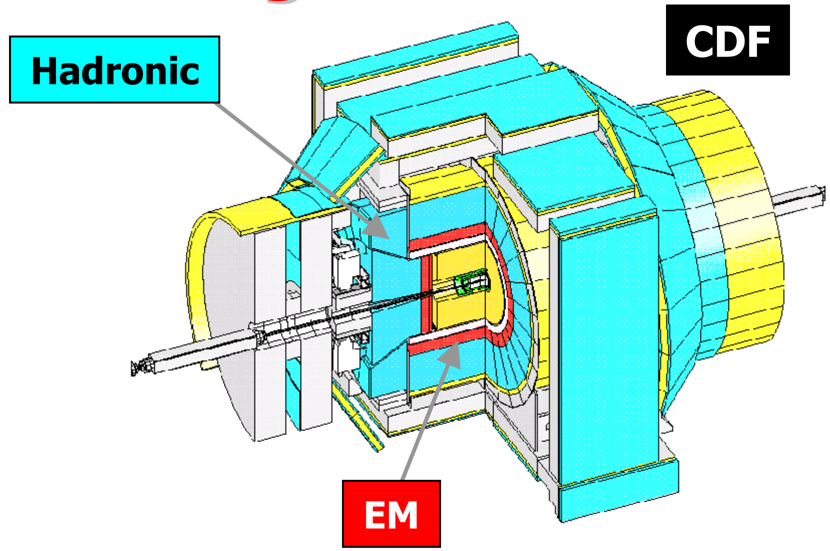


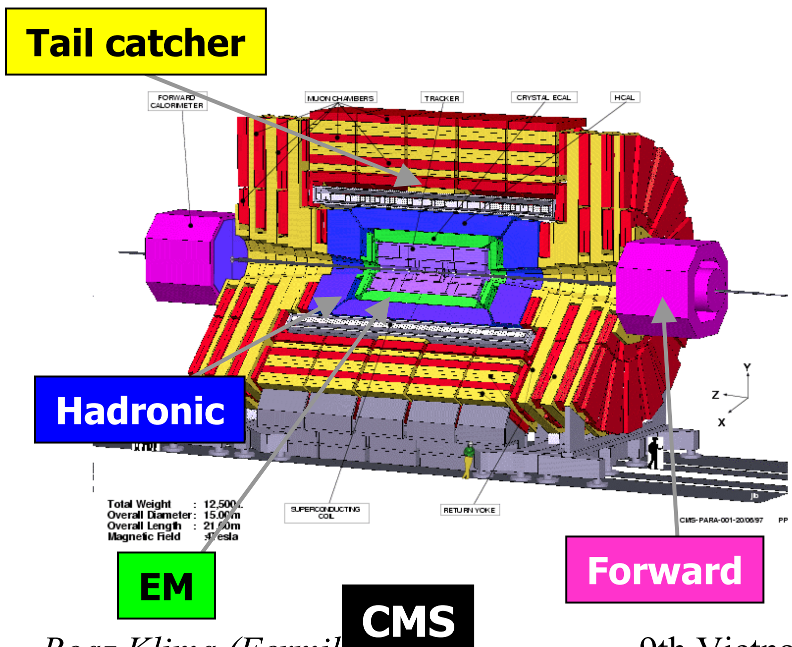


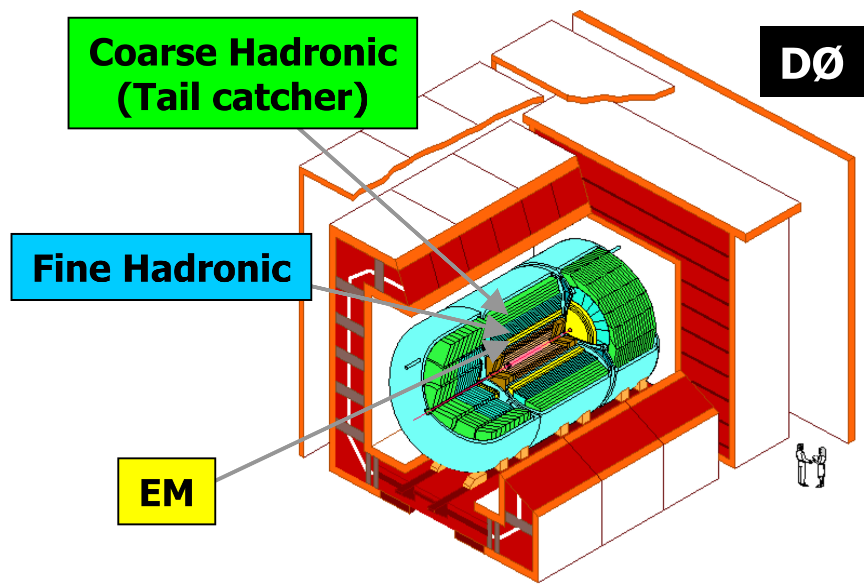
ATLAS "accordion" EM calorimeter

Typical calorimeter arrangement



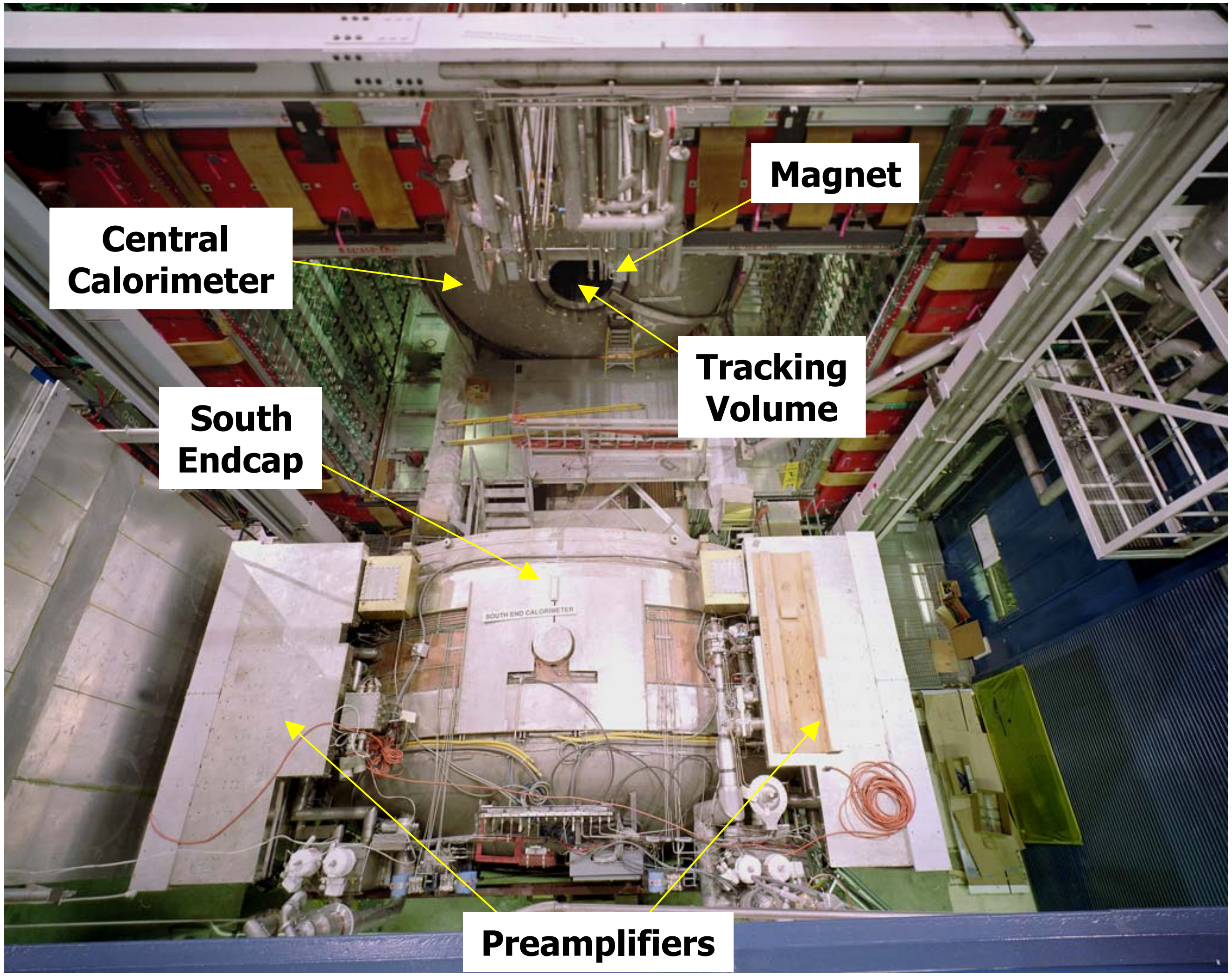






CDF

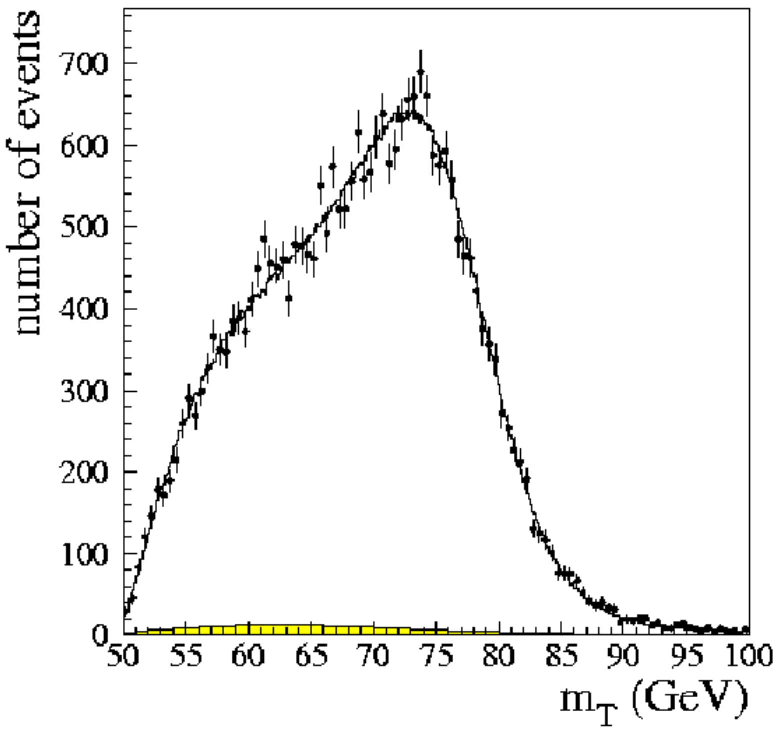
DØ



Magnet
Central Calorimeter
Tracking Volume
South Endcap
SOUTH END CALORIMETER
Preamplifiers

DØ Calorimeter Performance

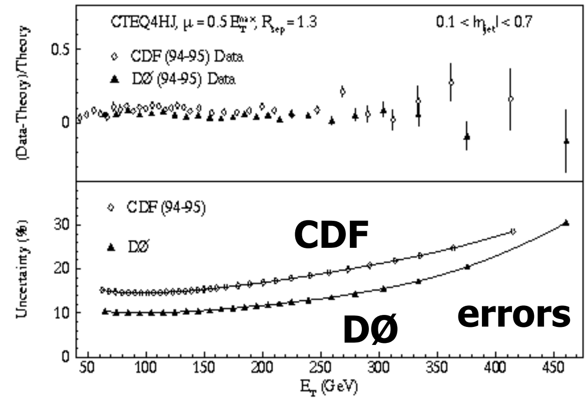
Electrons



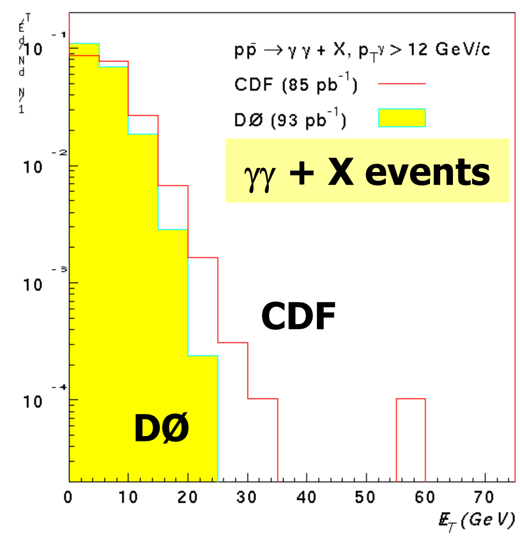
m_W = 80.483 ± 0.084 GeV
DØ electrons

Jets

Inclusive jet cross section

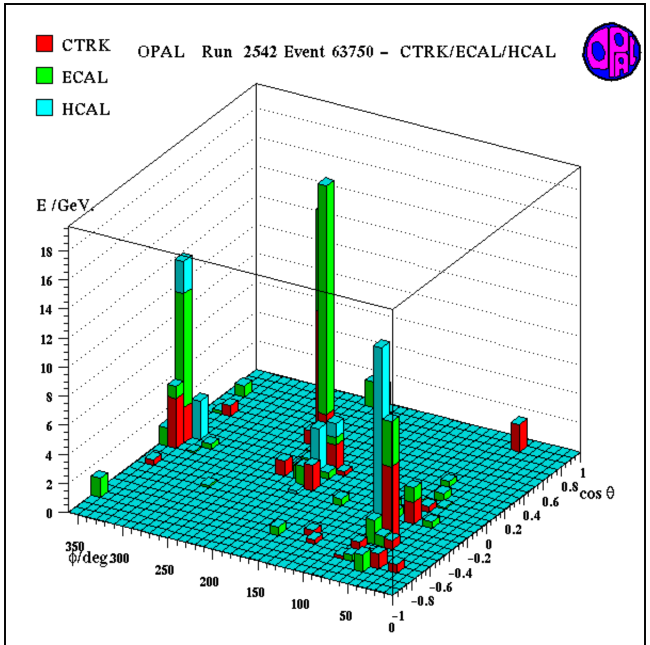


Missing E_T resolution



Using Additional Information

- It is possible to augment the calorimetric measurements using charged track information in various ways:
  - $E(jet) = \Sigma\, E(\text{towers without tracks}) + \Sigma\, p(\text{tracks})$
  - $E(jet) = a_{EM}\, \Sigma\, E(\text{towers without tracks}) + a_{had}\, \Sigma\, E(\text{towers with tracks})$
  - $E(jet) = a_{EM}\, \Sigma\, E(\text{identified } \pi^0 \text{ clusters}) + a_{had}\, \Sigma\, E(\text{other cells})$
- Usually in e^+e^- colliders, E(jet) is defined from a constrained fit to the overall event kinematics including the requirement that $\Sigma\, E = \sqrt{s}$



OPAL 3-jet event

Jet energies are calculated including charged particle momenta from the tracker (red bars)

Jet Cross Sections

Triggering

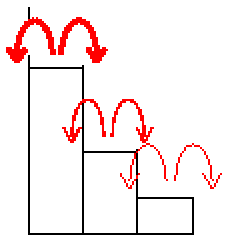
- **Accelerator luminosity is driven by physics goals**
  - e.g. to find the Higgs we will need ~ 10 fb^{-1} of data
  - requires collision rate ~ 2×10^{32} cm^{-2} s^{-1}
- **But low-E_T inelastic cross sections are much much higher than the processes we are interested in saving**
  - even with beam bunches crossing in the detector every 132 ns, get >1 inelastic collision per crossing
- **Triggering challenge**
  - Real-time selection of perhaps 50 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…)

Typical trigger scheme

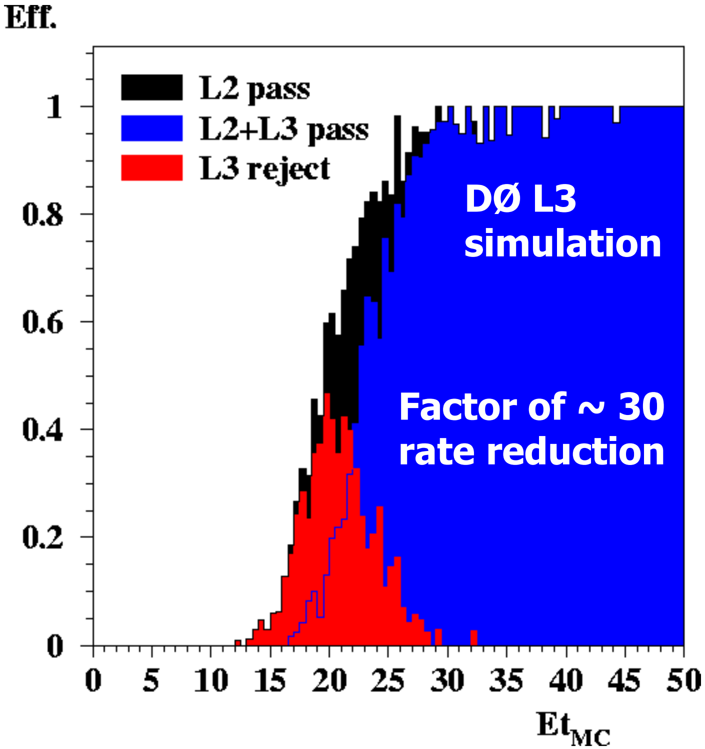
- **Detector**
    - **10MHz collisions**
- **Level 1 trigger**
    - **hardware based, looks at fast outputs from specialized detectors**
        - **accepts 10kHz**
- **Level 2 trigger**
    - **microprocessors, fast calculations on a small subset of the data**
        - **accepts 1 kHz**
- **Level 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**
    - **Reprocessing with newer versions of the reconstruction program**

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 ("smearing")



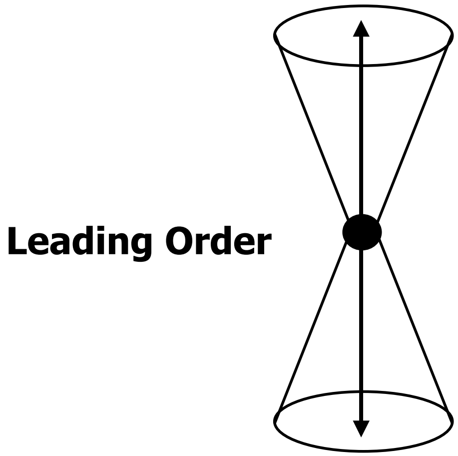
- Multi-level trigger system with increasingly refined estimates of jet E_T
- Large dynamic range of cross section demands that many trigger thresholds be used e.g.
  - 15 GeV prescaled 1/1000
  - 30 GeV prescaled 1/100
  - 60 GeV prescaled 1/10
  - 100 GeV no prescale

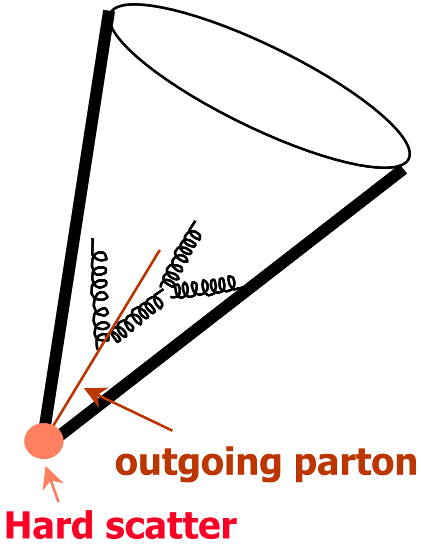


Jet Algorithms

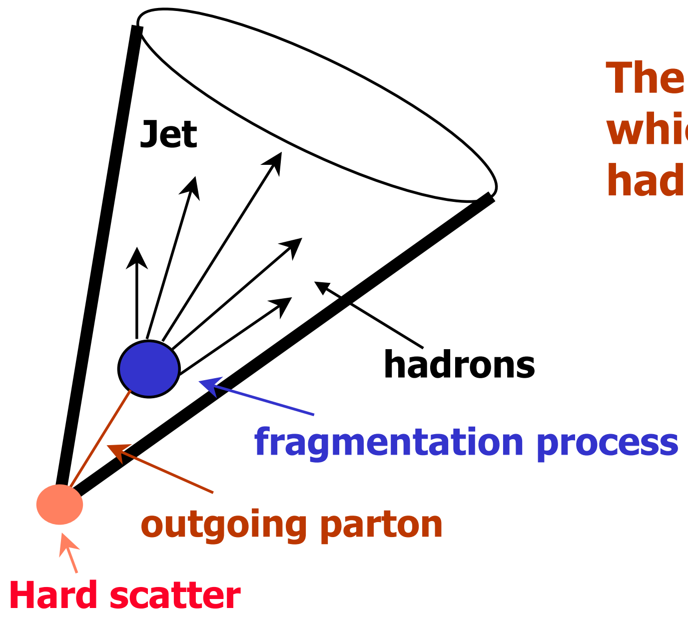
- The goal is to be able to apply the "same" jet clustering algorithm to data and theoretical calculations without ambiguities.

- Jets at the "Parton Level"
  - i.e., before hadronization
  - Fixed order QCD or (Next-to-) leading logarithmic summations to all orders



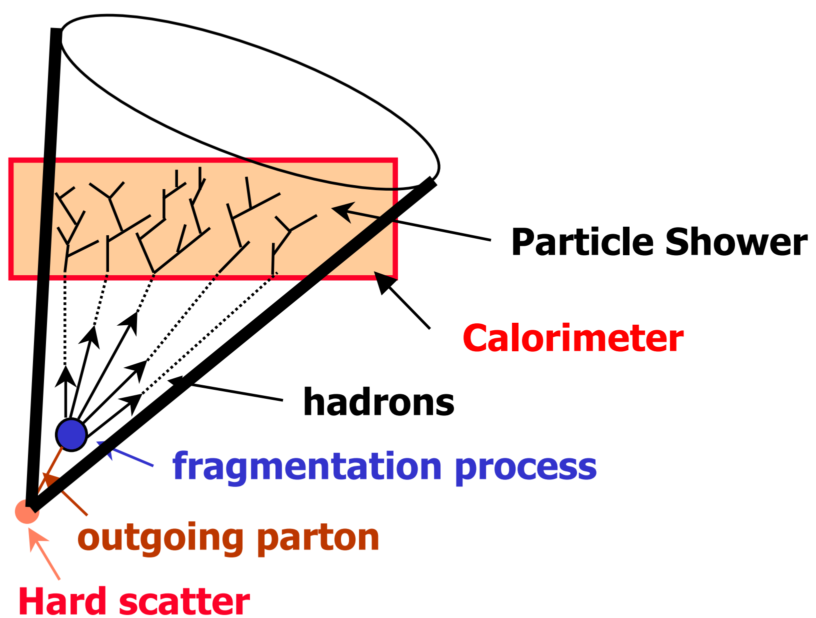


- **Jets at the particle (hadron) level**



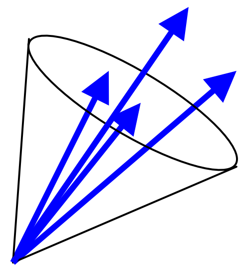
The idea is to come up with a jet algorithm which minimizes the non-perturbative hadronization effects

- **Jets at the "detector level"**



Jet Algorithms

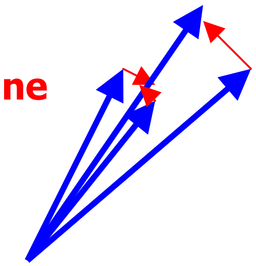
- Traditional Choice at hadron colliders: cone algorithms
  - Jet = sum of energy within $\Delta R^2 = \Delta\eta^2 + \Delta\phi^2$



Sum contents of cone

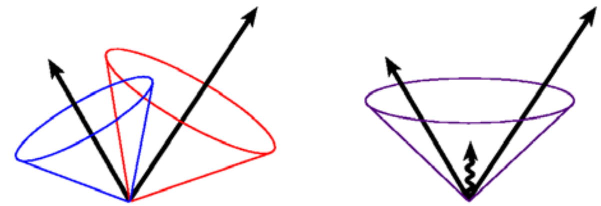
- Traditional choice in e^+e^-: successive recombination algorithms
  - Jet = sum of particles or cells close in relative k_T

Recombine

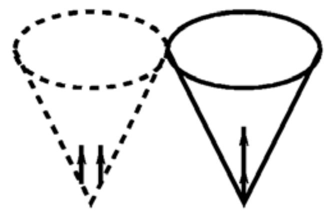


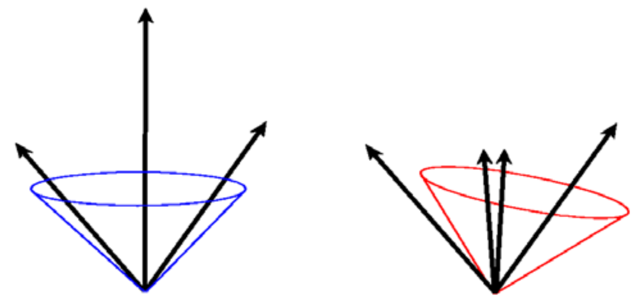
Theoretical requirements

- **Infrared safety**
  - **insensitive to "soft" radiation**



- **Collinear safety**



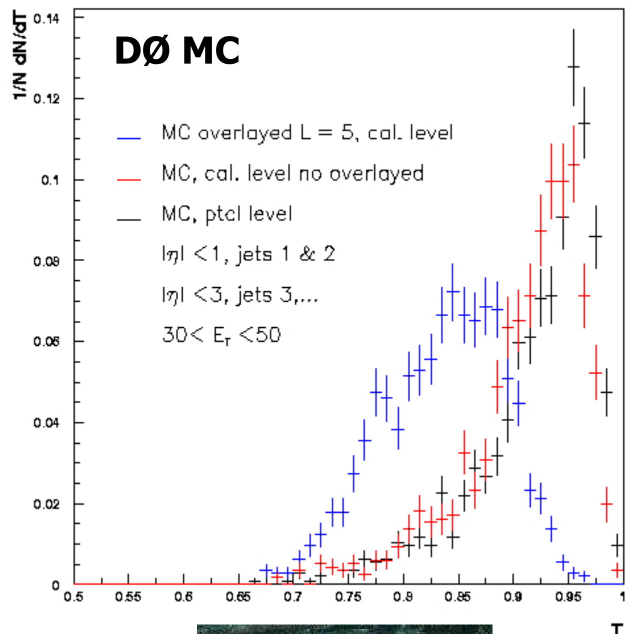


- **Low sensitivity to hadronization**
- **Invariance under boosts**
  - **Same jets solutions independent of boost**
- **Boundary stability**
  - **maximum $E_T = \sqrt{s}/2$**
- **Order independence**
  - **Same jets at parton/particle/detector levels**
- **Straightforward implementation**

Experimental requirements

- Detector independence
  - can everybody implement this?
- Best resolution and smallest biases in jet energy and direction
- Stability
  - as luminosity increases
  - insensitive to noise, pileup and small negative energies
- Computational efficiency
- Maximal reconstruction efficiency
- Ease of calibration
- ...

Effect of pileup on Thrust
k_T algorithm jets, E_T > 30 GeV



Cone Jets

- **Use DØ as an example:**

Cone jets are defined by a number of algorithm parameters

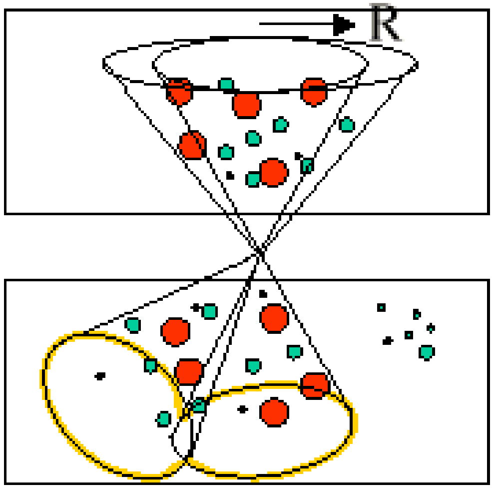
• Cone Size (ie radius, R = 0.3,0.5,0.7 in η x φ space)

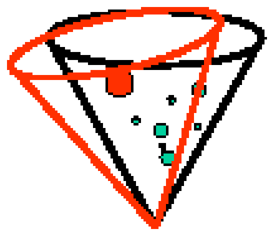
• Seed or starting point for iterations (DØ uses 1 GeV E_T towers)

Calorimeter E_T

Jet Seeds

•Minimum ET requirement = 8 GeV





•Clustering begins w/ seed tower > 1 GeV

•Preclusters are formed by combining seed towers w/ their neighbors (reduces # of jet computations)

•Draw cone around seed/precluster, find ET weighted centroid, recalculate jet centroid, repeat until stable

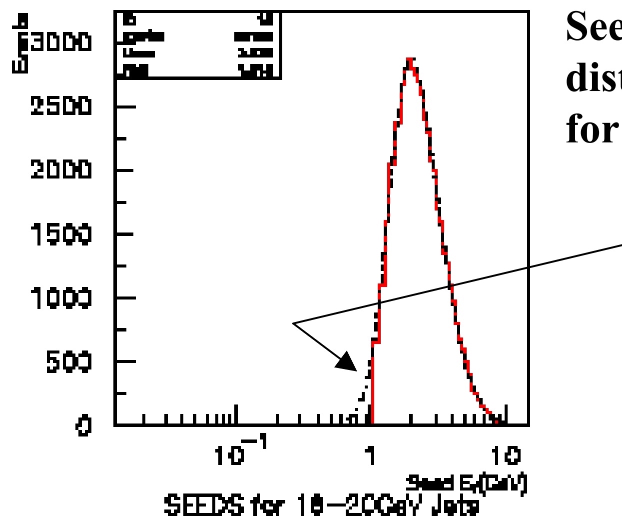
Standard Snowmass definitions

$$\eta_{jet} = \frac{\sum_i E_T^i \eta^i}{\sum_i E_T^i}$$

$$\phi_{jet} = \frac{\sum_i E_T^i \phi^i}{\sum_i E_T^i}$$

$$E_T = \sum_i E_T^i = \sum_i E_i \sin(\theta_i)$$

Lost jets



Seed tower energy distribution for 18-20 GeV jets

Inefficiency

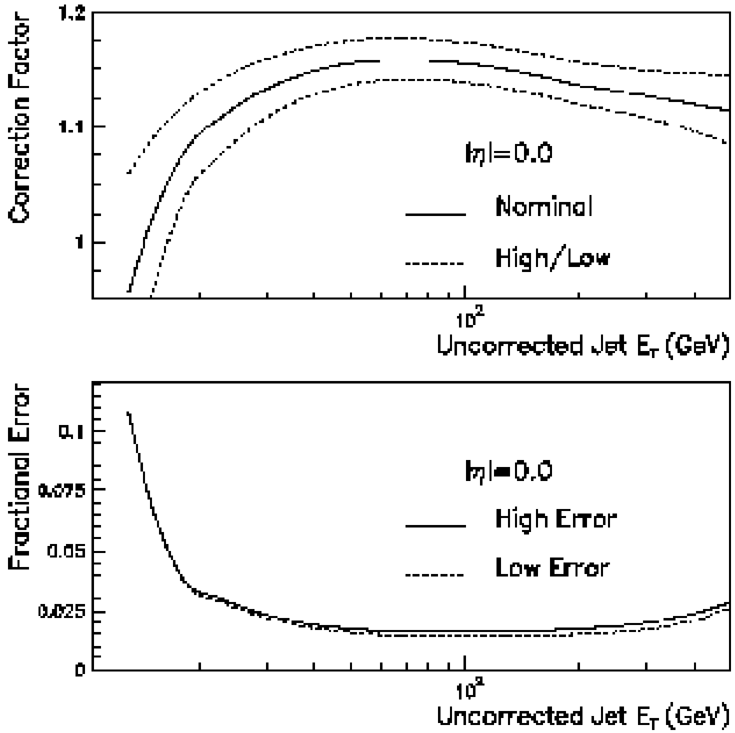
Jet Energy Calibration

1. **Establish calorimeter stability and uniformity**
   - pulsers, light sources
   - azimuthal symmetry of energy flow in collisions
   - muons

2. **Establish the overall energy scale of the calorimeter**
   - Testbeam data
   - Set E/p = 1 for isolated tracks
     - momentum measured using central tracker
   - EM resonances ($\pi^0 \rightarrow \gamma\gamma$, J/$\psi$, Υ and Z $\rightarrow e^+e^-$)
     - adjust calibration to obtain the known mass

3. **Relate EM energy scale to jet energy scale**
   - Monte Carlo modelling of jet fragmentation + testbeam hadrons
     - CDF
   - E_T balance in jet + photon events
     - DØ

Overall Correction Factor



E_T (GeV)	CorrFac
20	1.08 ± 0.030
100	1.15 ± 0.017
450	1.12 ± 0.025

Uncertainty reduced

by 50% in 1996-1998

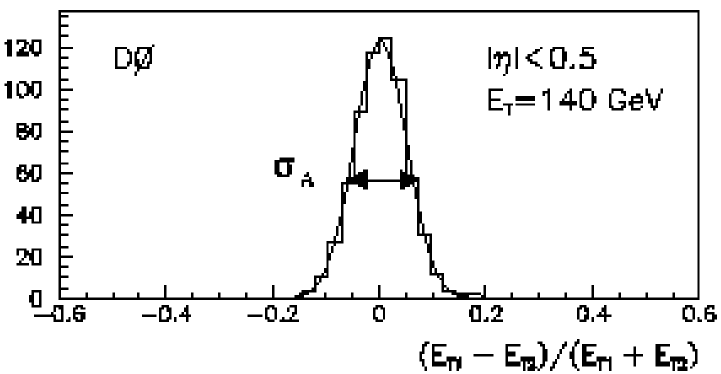
. . . thanks to a lot of hard work

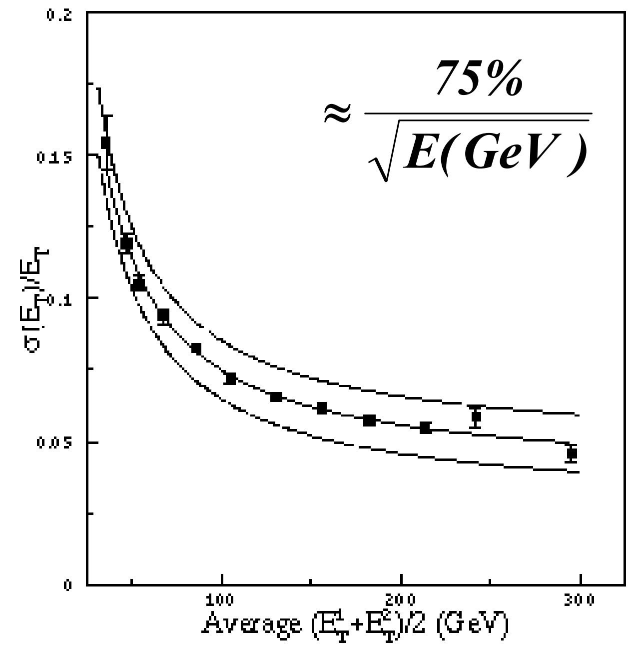
Jet Resolutions

- **Determined from collider data using dijet E_T balance**

$$A = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \Longrightarrow \frac{\sigma_{ET}}{E_T} = \sqrt{2}\sigma_A$$

In the limit of no soft radiation

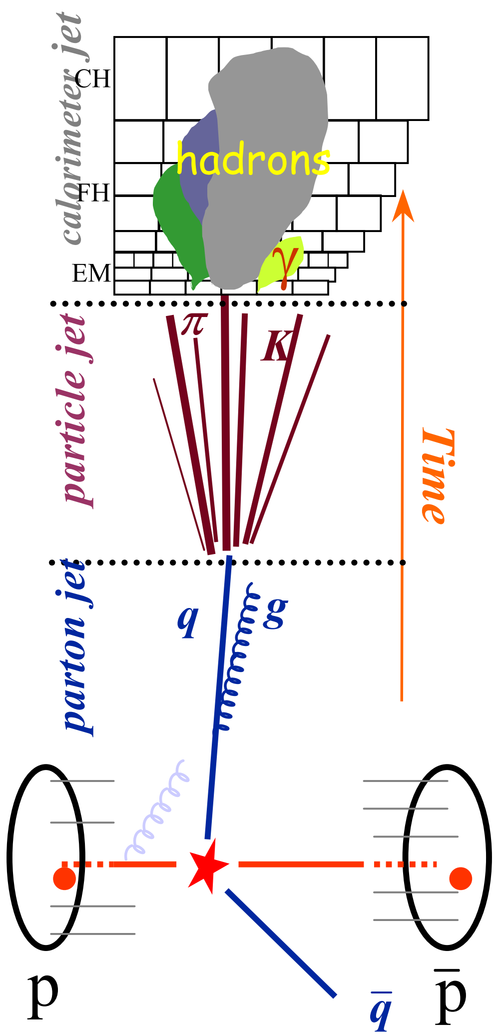




ET :	50 GeV	100 GeV	450 GeV
σ_{ET} /ET:	0.105	0.075	0.035

Simulation tools

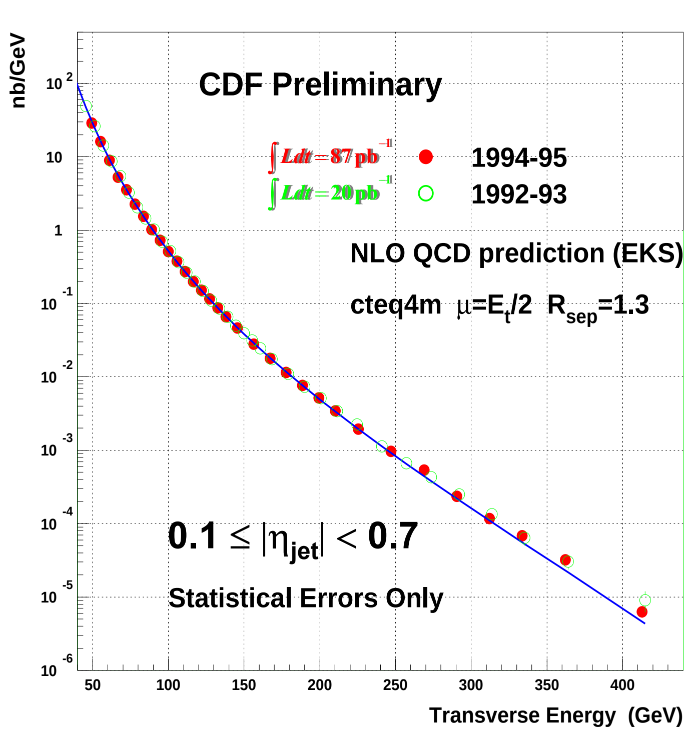
- A "Monte Carlo" is a Fortran or C++ program that generates events
- Events vary from one to the next (random numbers) — expect to reproduce both the average behavior and fluctuations of real data
- <u>Event Generators</u> may be
  - parton level:
    - Parton Distribution functions
    - Hard interaction 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

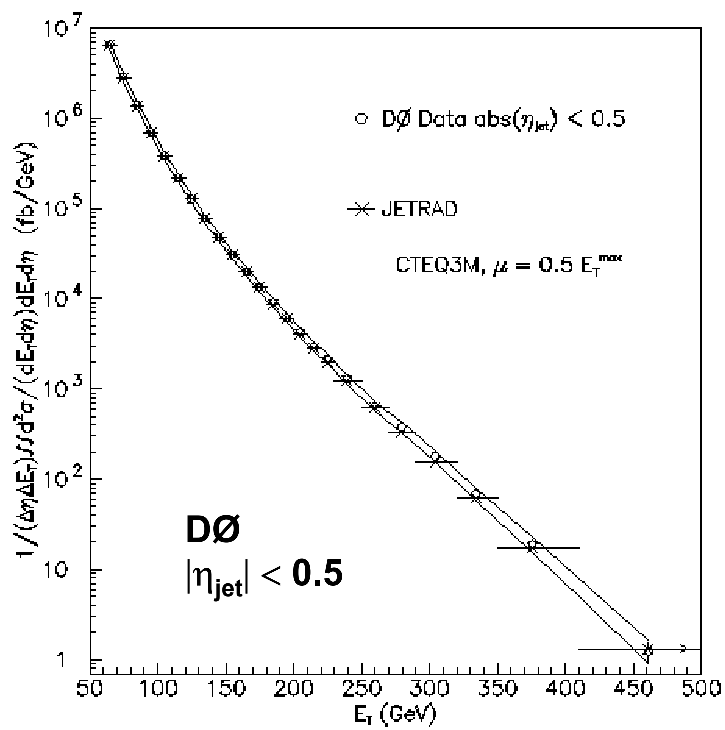


Jet cross sections at $\sqrt{s}$ = 1.8 TeV

R = 0.7 cone jets

- **Cross section falls by seven orders of magnitude from 50 to 450 GeV**
- **Pretty good agreement with NLO QCD over the whole range**



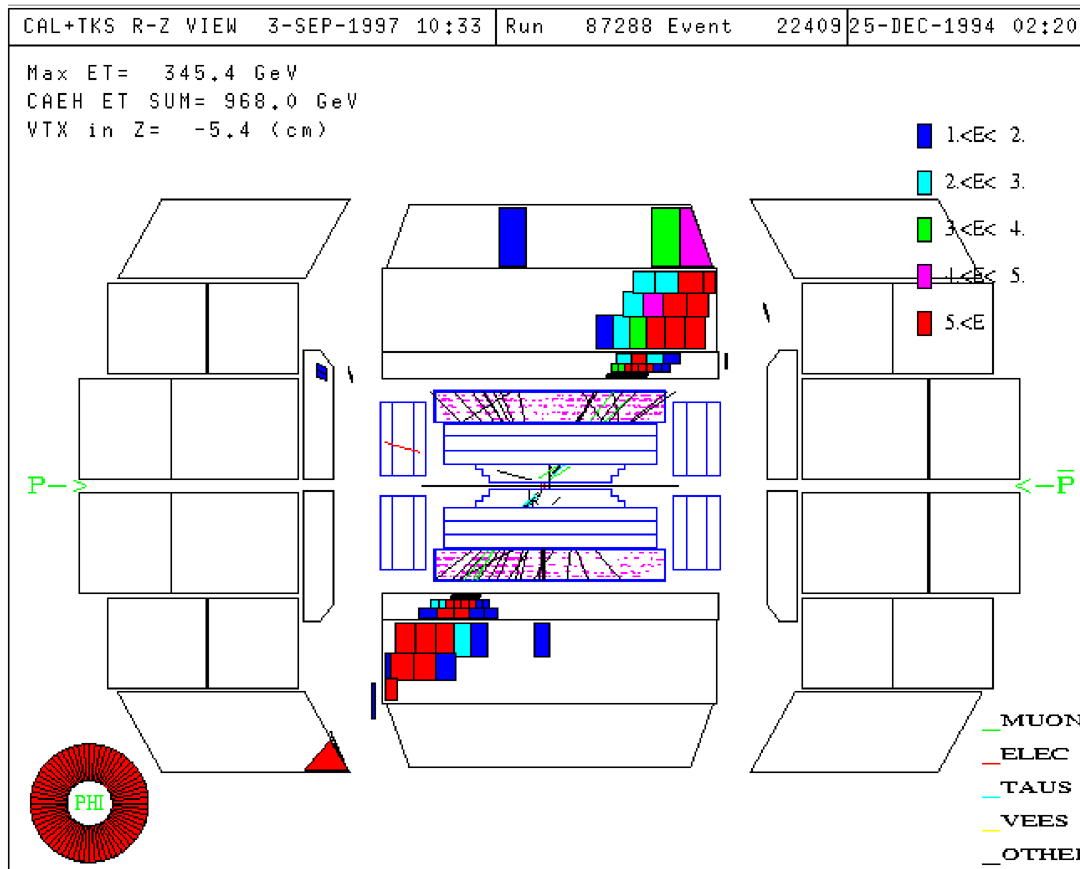


Highest E_T jet event in DØ

Quotes from Postcards sold at Fermilab with this event's displays:

1. These two jets of particles recorded by the DØ experiment at Fermilab probe distances a billion times smaller than an atom

2. Two jets of particles observed in the DØ experiment at Fermilab probe the smallest distances ever examined by humans

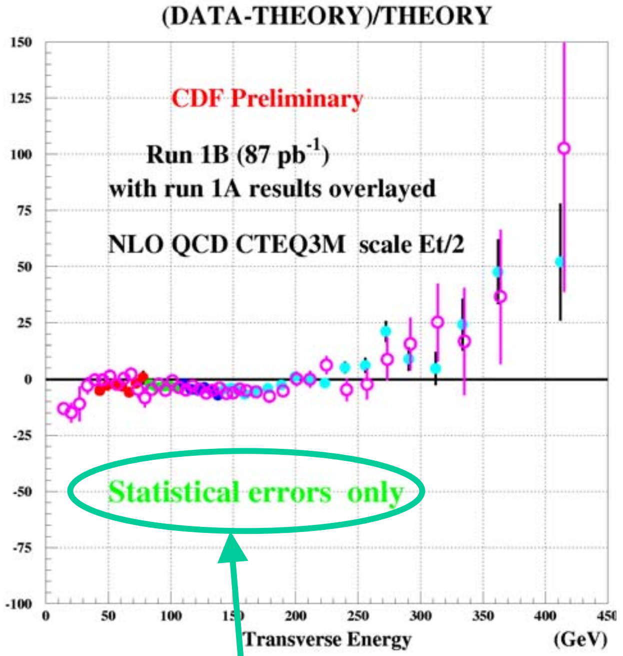


E_{T1} = 475 GeV, η_1 = -0.69, x_1=0.66
E_{T2} = 472 GeV, η_2 = 0.69, x_2=0.66

M_{JJ} = 1.2 TeV
$Q^2 = 2.2\text{x}10^5\ \text{GeV}^2$

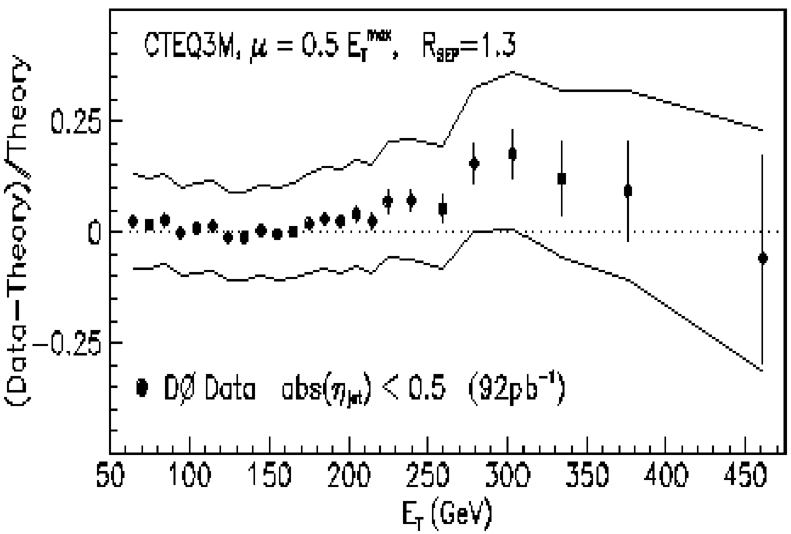
What's happening at high E_T?

CDF $0.1<|\eta|<0.7$



NB Systematic errors not plotted

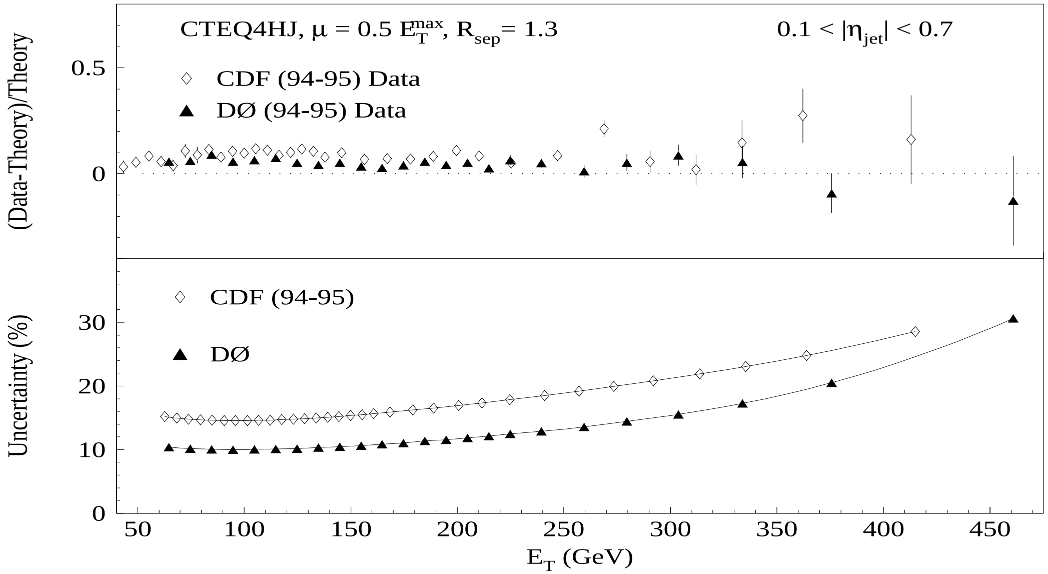
DØ $|\eta|<0.5$



So much has been said about the high-E_T behaviour of the cross section that it is hard to know what can usefully be added

The DØ and CDF data agree

- DØ analyzed $0.1 < |\eta| < 0.7$ to compare with CDF
  - Blazey and Flaugher, hep-ex/9903058 Ann. Rev. article

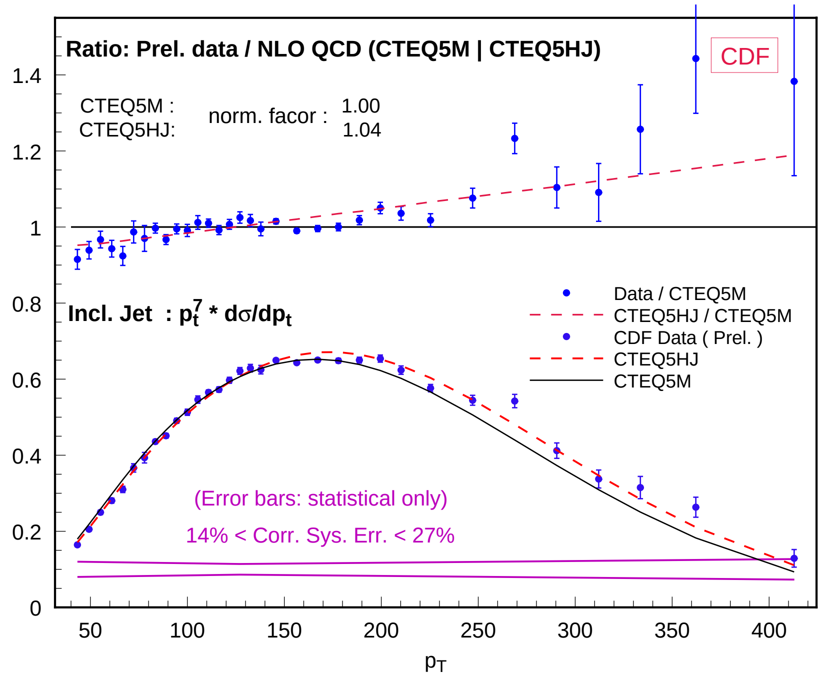


- Studies (e.g. CTEQ4HJ distributions shown above) show that one can boost the gluon distribution at high-x without violating experimental constraints*; results are more compatible with CDF data points

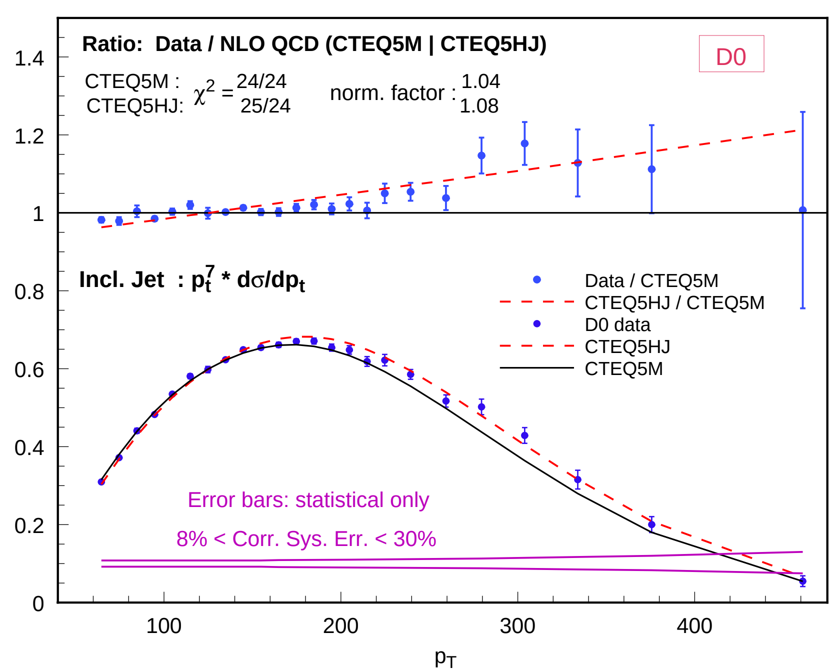
  *except maybe fixed-target photons, which require big k_T corrections before they can be made to agree with QCD (see later)

Jet data with latest CTEQ5 PDF's

- **CDF data**

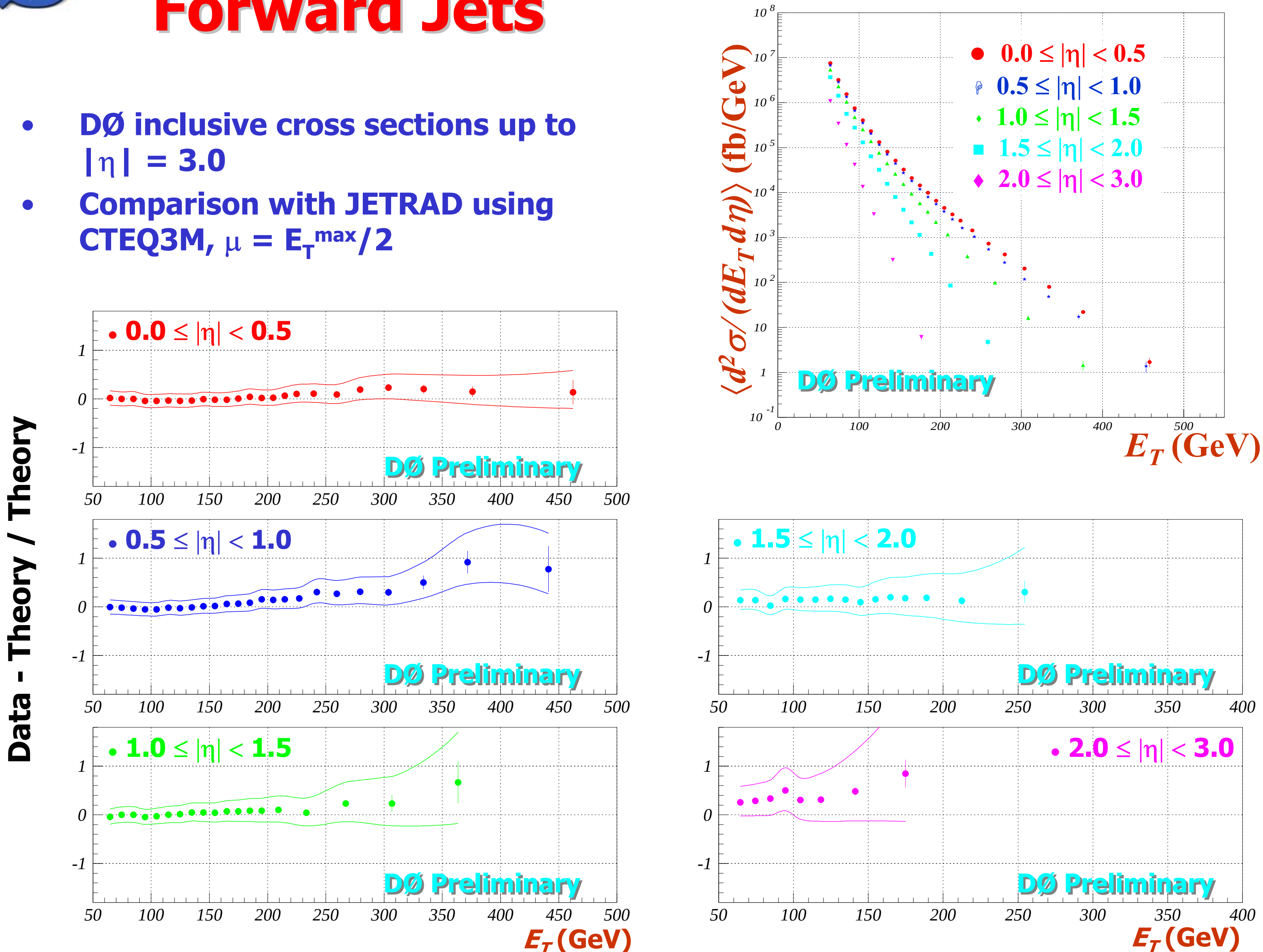


- **DØ data**

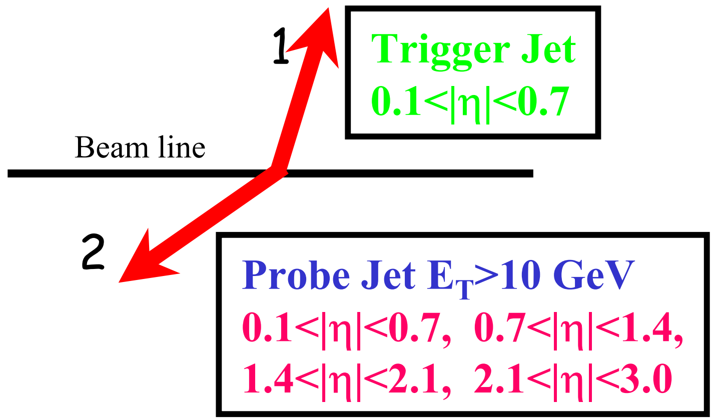


Forward Jets

- DØ inclusive cross sections up to $|\eta| = 3.0$
- Comparison with JETRAD using CTEQ3M, $\mu = E_T^{max}/2$

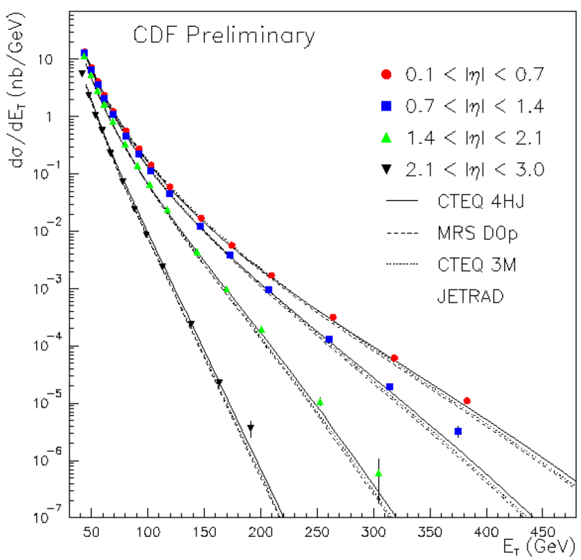


Triple differential dijet cross section

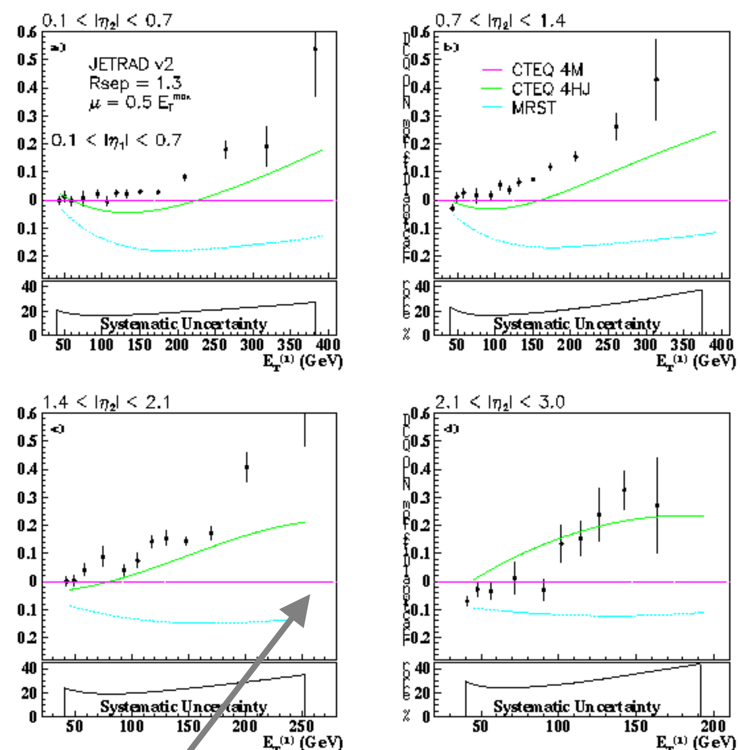


$$\frac{d^3\sigma}{dE_1^T\, d\eta_1 d\eta_2}$$

Can be used to extract or constrain PDF's

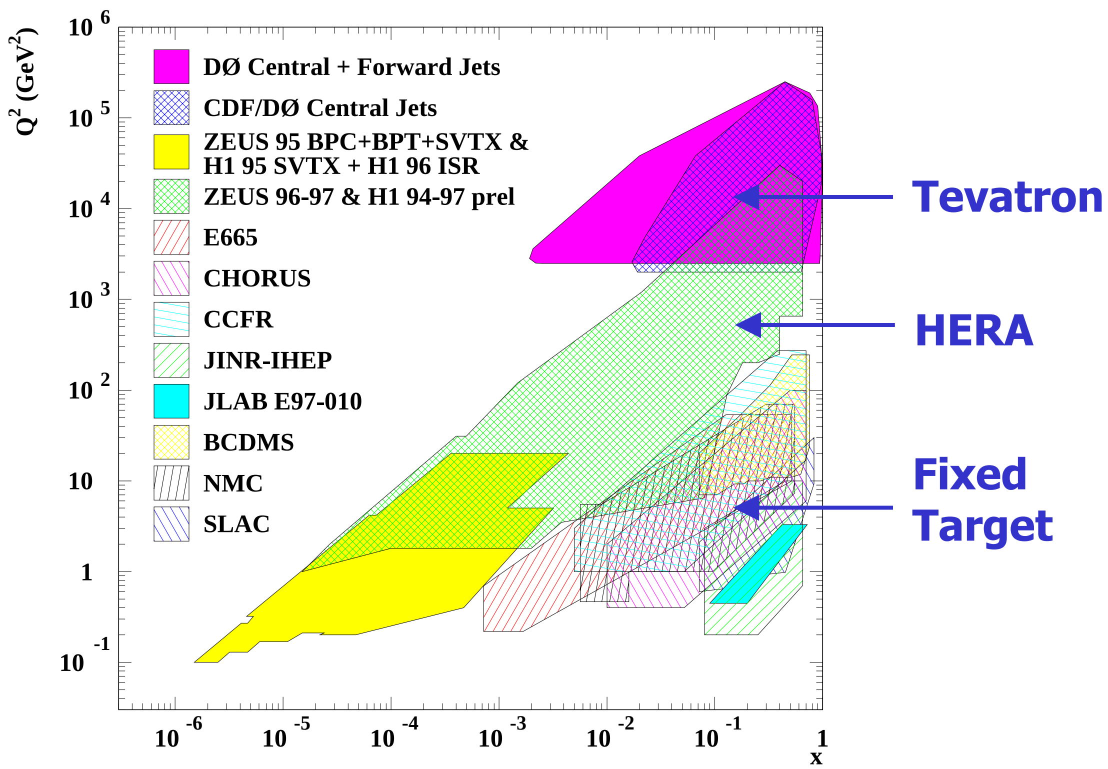


CDF Preliminary



At high E_T, the same behaviour as the inclusive cross section, presumably because largely the same events

Tevatron jet data can constrain PDF's

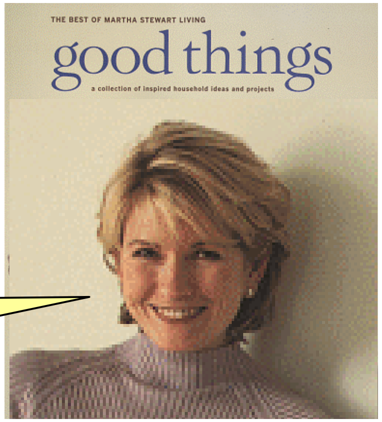


- **For dijets:**

$$x_{1(2)} = \sum_{i=1}^{2} +(-)\frac{E_{T,i}}{\sqrt{s}} exp(\eta_i) \quad and \quad Q^2 = E_{T,1}E_{T,2}$$

What have we learned from all this?

- **Whether nature has actually exploited the "freedom" to enhance gluon distributions at large x will only be clear with the addition of more data**
  - with 2fb^{-1} at the Tevatron the reach in E_T will increase by ~70 GeV and should make the asymptotic behaviour clearer
  - With higher Ecm there will be a significant increase in the number of high ET jets
- **whatever the Run II data show, this has been a useful lesson:**
  - parton distributions have uncertainties, whether made explicit or not
  - we should aim for a full understanding of experimental systematics and their correlations



It's a good thing

- **We can then use the jet data to reduce these uncertainties on the parton distributions**