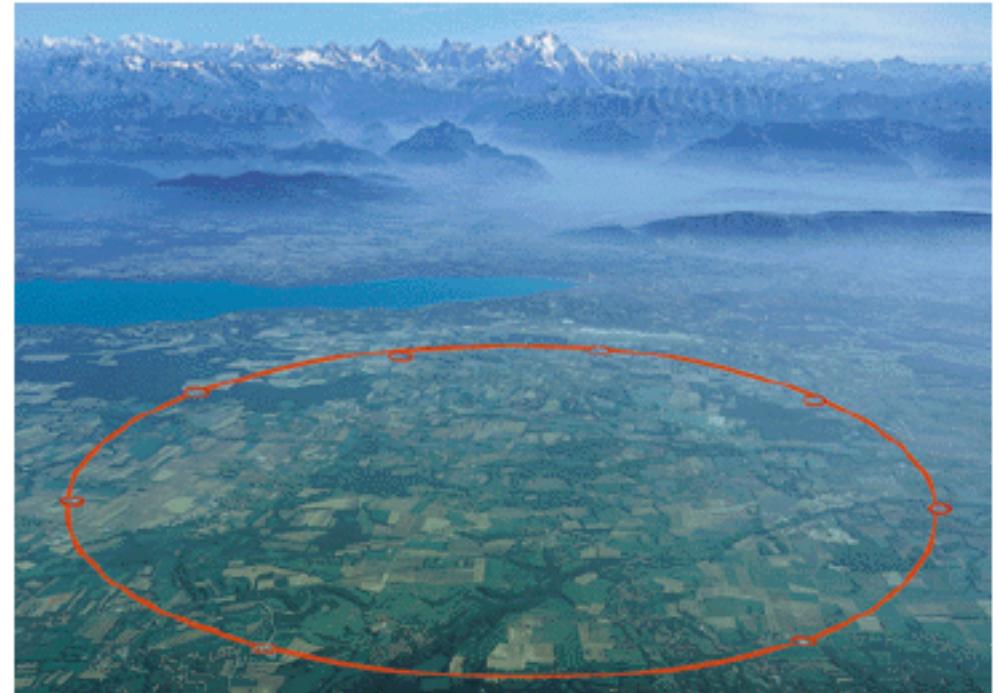


CTEQ SS04 Madison, Wisconsin

Jet Physics at Hadron-Hadron Colliders

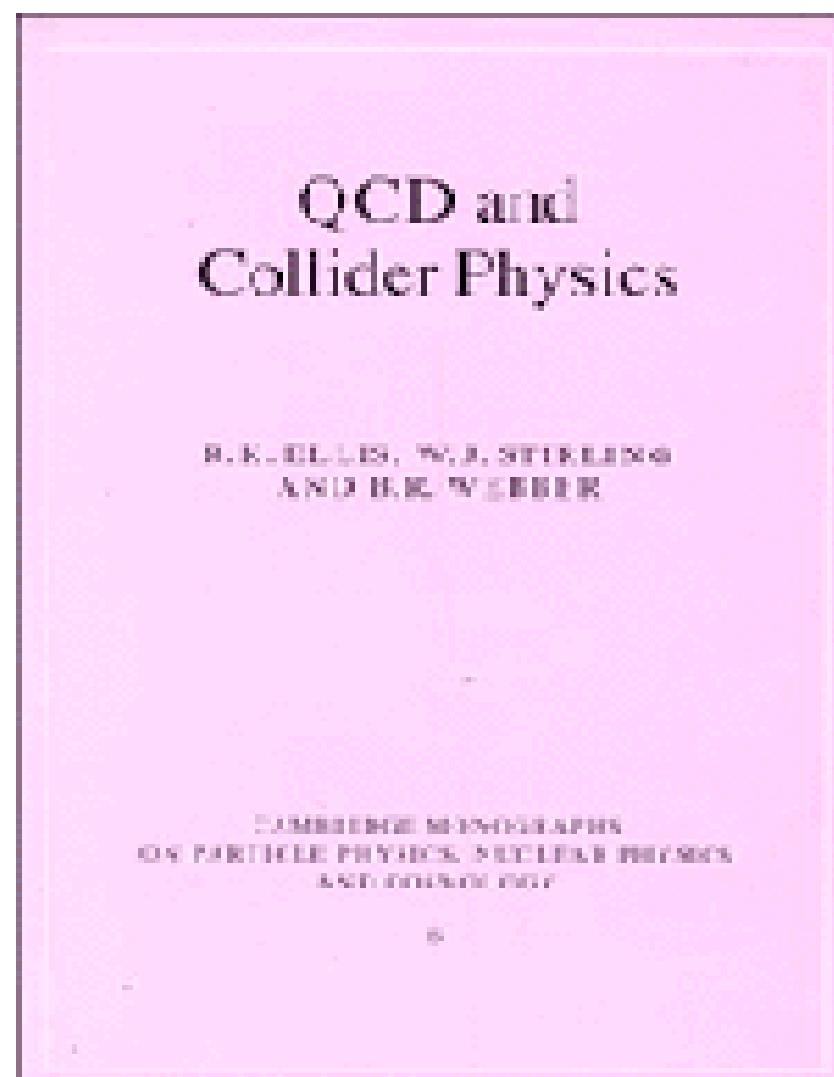
Joey Huston

Michigan State University
(CDF, CTEQ and ATLAS)



A good reference for QCD

- Available at fine book stores, Cambridge University Press, or at Fermilab
- Keith Ellis has offered to personally sign any copy that you bring to him

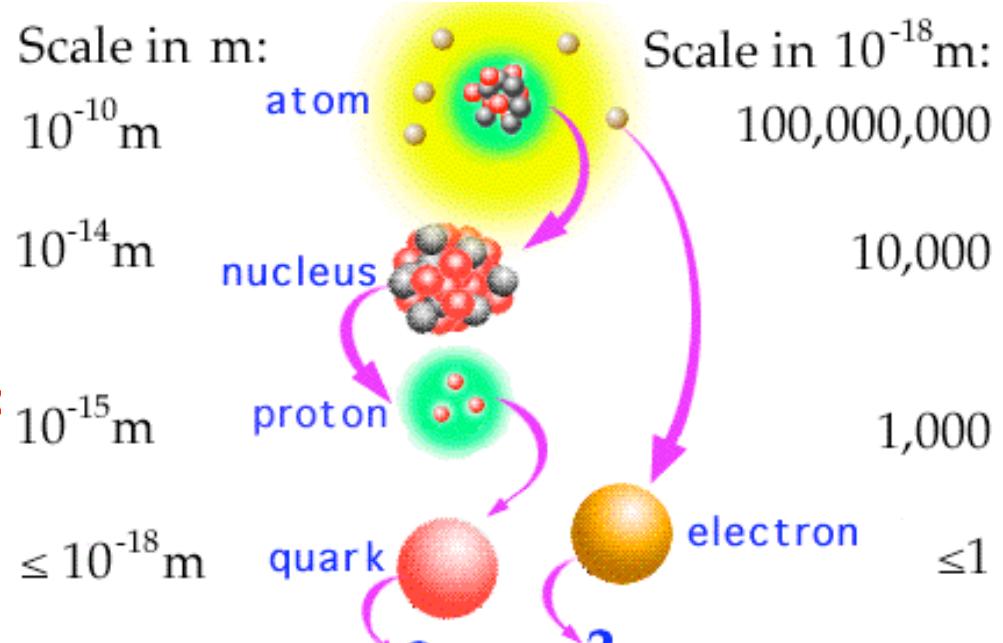


QCD at hadron colliders

- First of all, my apologies for any repetition of material that may have been presented by others at this SS
 - ◆ especially since Nikos appears to have had 3 lectures worth of material in his 1 lecture
- Some motherhood statements...
- Basically all interactions at hadron-hadron colliders are governed by or modified by QCD
 - ◆ both standard model physics
 - ◆ ...as well as possible new physics
 - ▲ new physics has backgrounds from standard model physics
 - ▲ so an understanding of QCD has to precede any searches for new physics

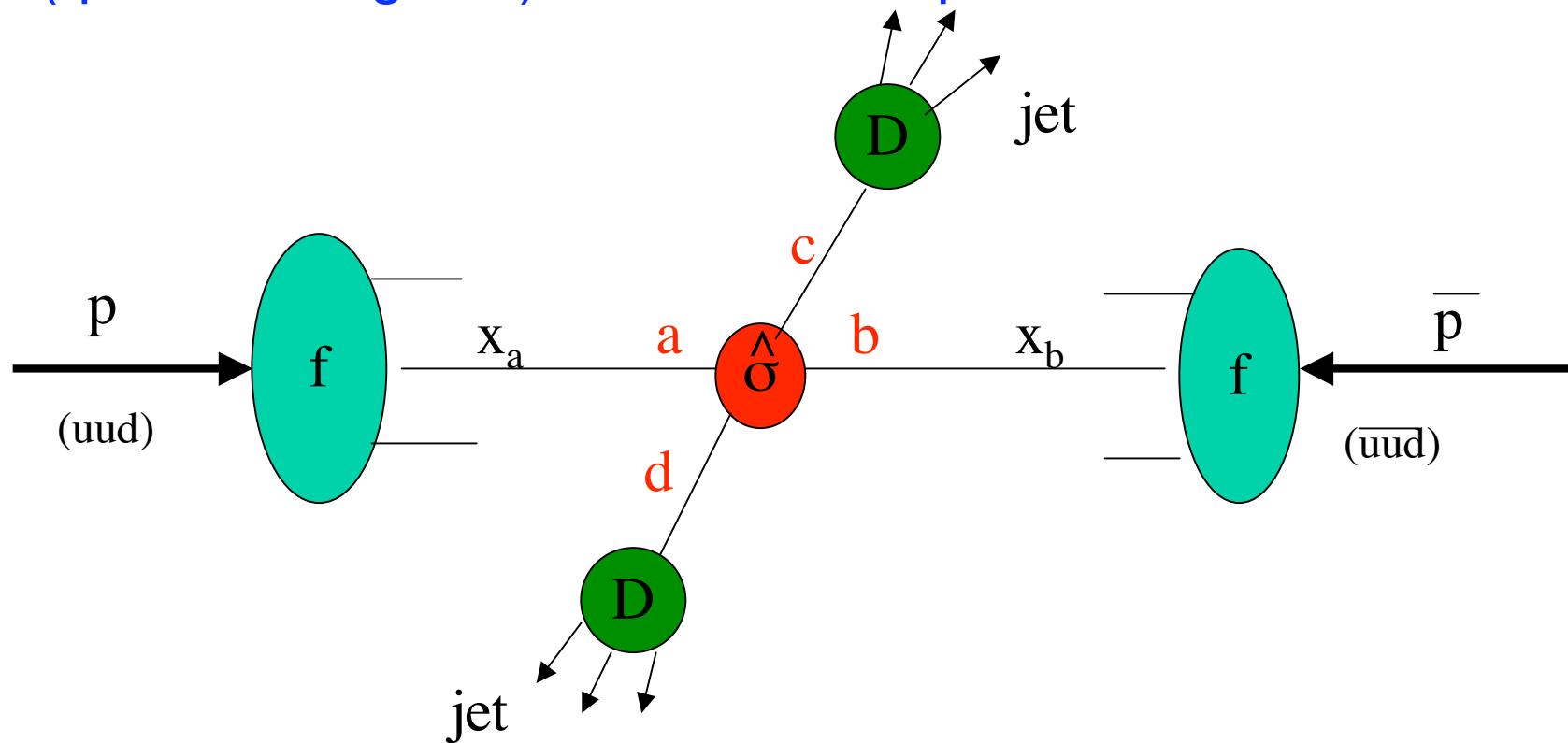
Consider jet production at hadron colliders

- Jet production at the Tevatron currently probes the most “violent” collisions currently achievable
 - ◆ smallest distance scales (10^{-17} cm)
 - ◆ some of greatest sensitivity to new physics \rightarrow quark compositeness
- New version of Rutherford scattering
 - ◆ production of jets at high p_T indicates that there must be point-like constituents within proton, i.e. quarks
 - ◆ If we observe a deviation from the expected jet cross sections at the highest jet p_T 's (smallest distance scales), this may also be an indication of something inside the quarks



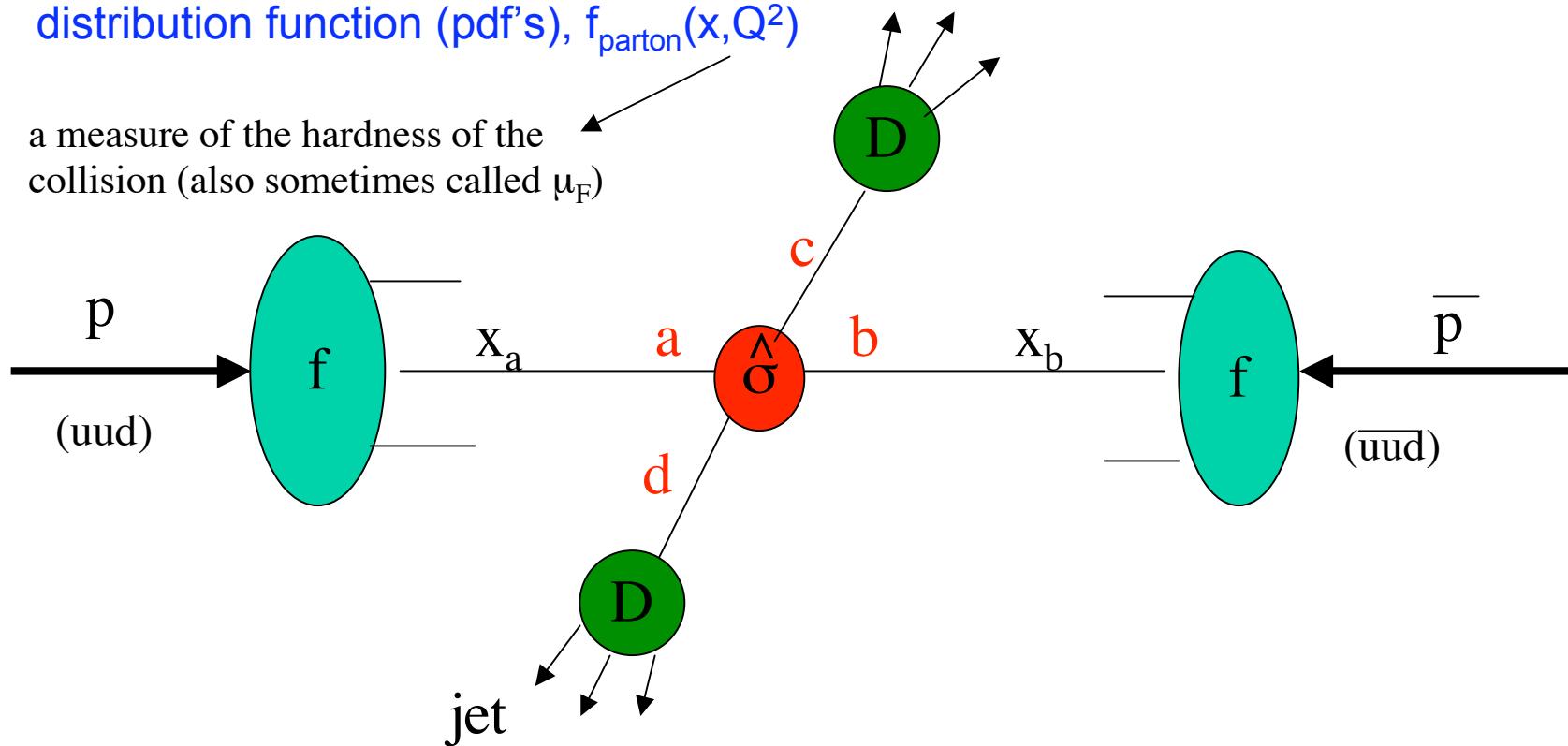
QCD at hadron colliders

- Collisions that produce jets at high transverse momentum take place at small impact parameter (the proton and the anti-proton are hitting head-on) and are more accurately hard collisions between partons (quarks and gluon) inside the two protons



So what's with the blobs, etc?

- The proton has 2 valence up quarks and 1 valence down quark (but also lots of sea quarks and gluons)
- All share the momentum of the proton; the collision is between 1 parton from the proton carrying a momentum fraction x_a and one parton from the anti-proton carrying a momentum fraction x_b
- The distribution of momentum carried by a given parton is given by parton distribution function (pdf's), $f_{\text{parton}}(x, Q^2)$



Blobs, continued

- So one parton carrying a momentum fraction x_a collides with another parton carrying a momentum fraction x_b
- The collision is given by the red blob; that's where most of the hard QCD comes in

◆ to leading order, $\sigma \propto \alpha_s^2$

◆ to next-to-leading order, $\sigma \propto \alpha_s^3$

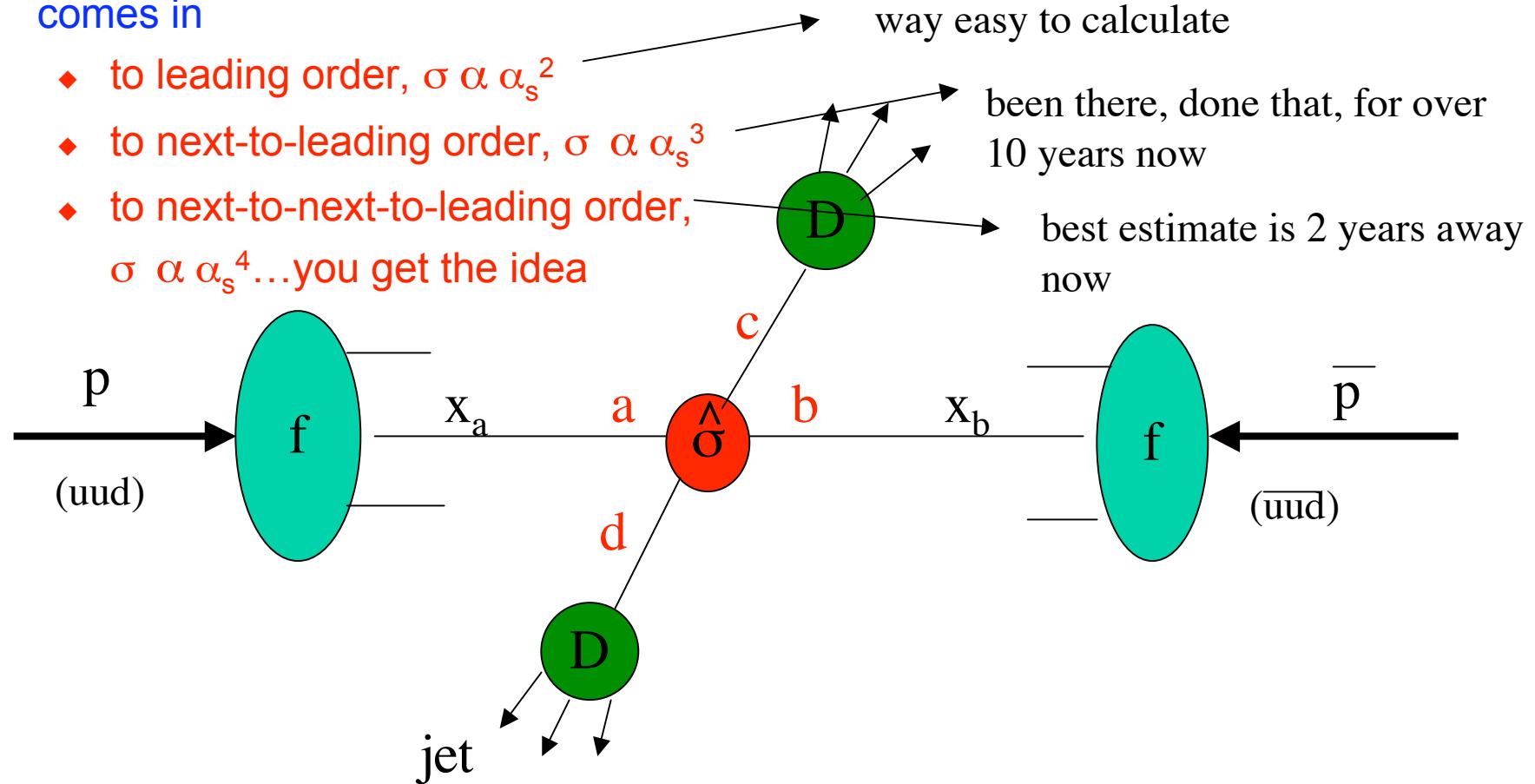
◆ to next-to-next-to-leading order,

$\sigma \propto \alpha_s^4$...you get the idea

way easy to calculate

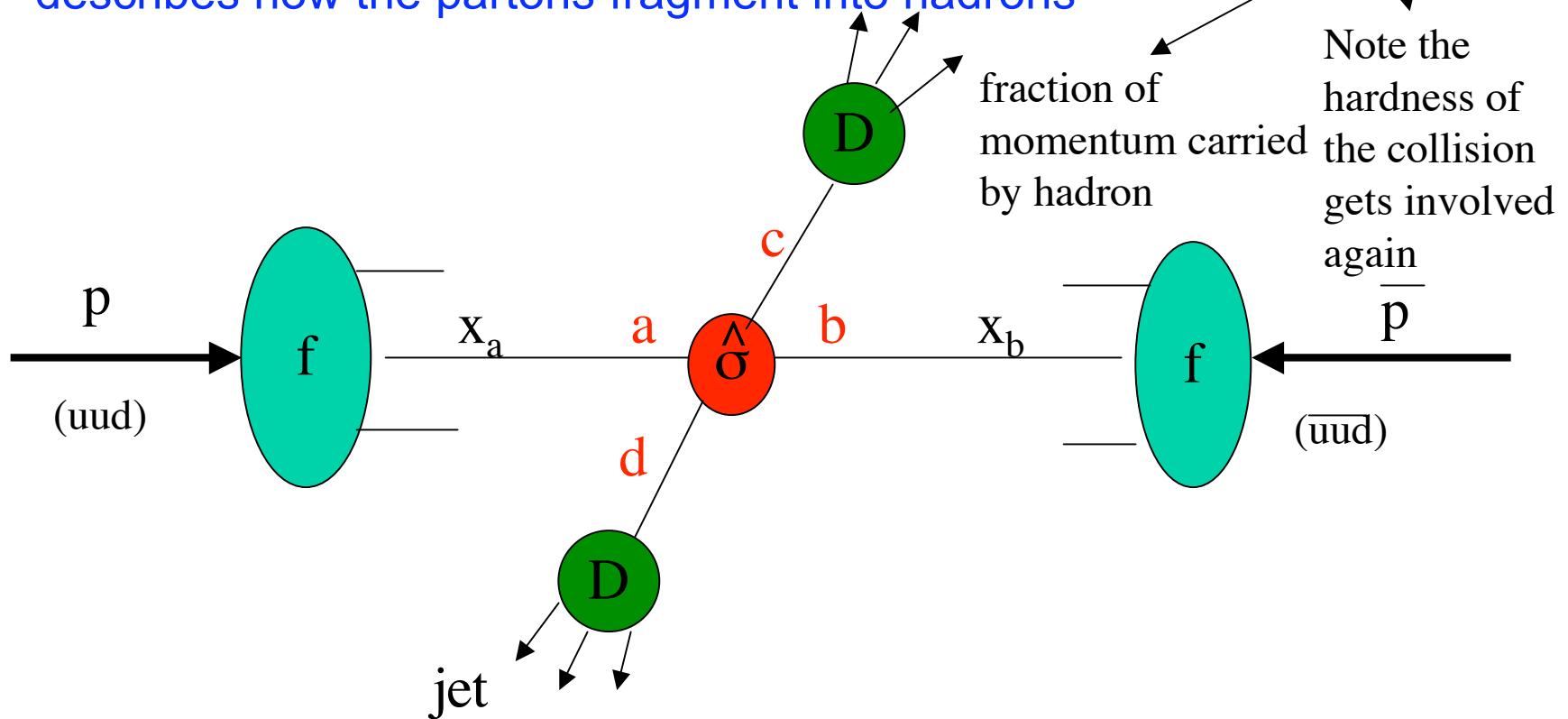
been there, done that, for over
10 years now

best estimate is 2 years away
now



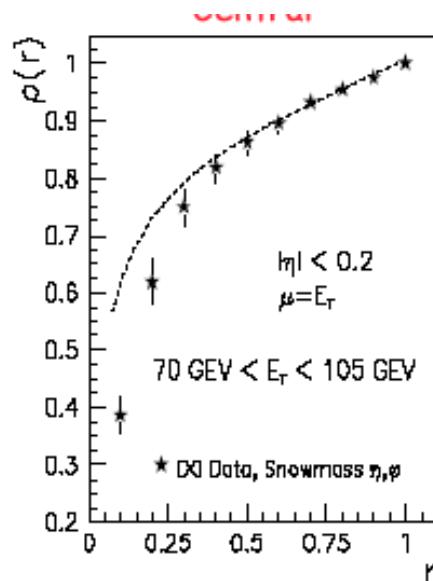
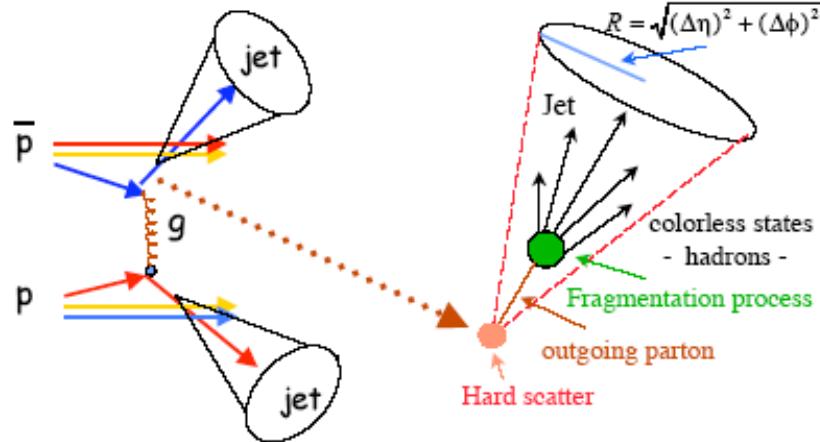
Blobs, continued

- c and d are the outgoing partons, but problem: they carry color; we don't observe the quarks or gluons themselves (don't see naked color) but instead the partons fragment into jets of hadrons (pions, kaons, and protons)
- it's the jets of hadrons that we can observe experimentally; $D(z, Q^2)$ describes how the partons fragment into hadrons



Jets

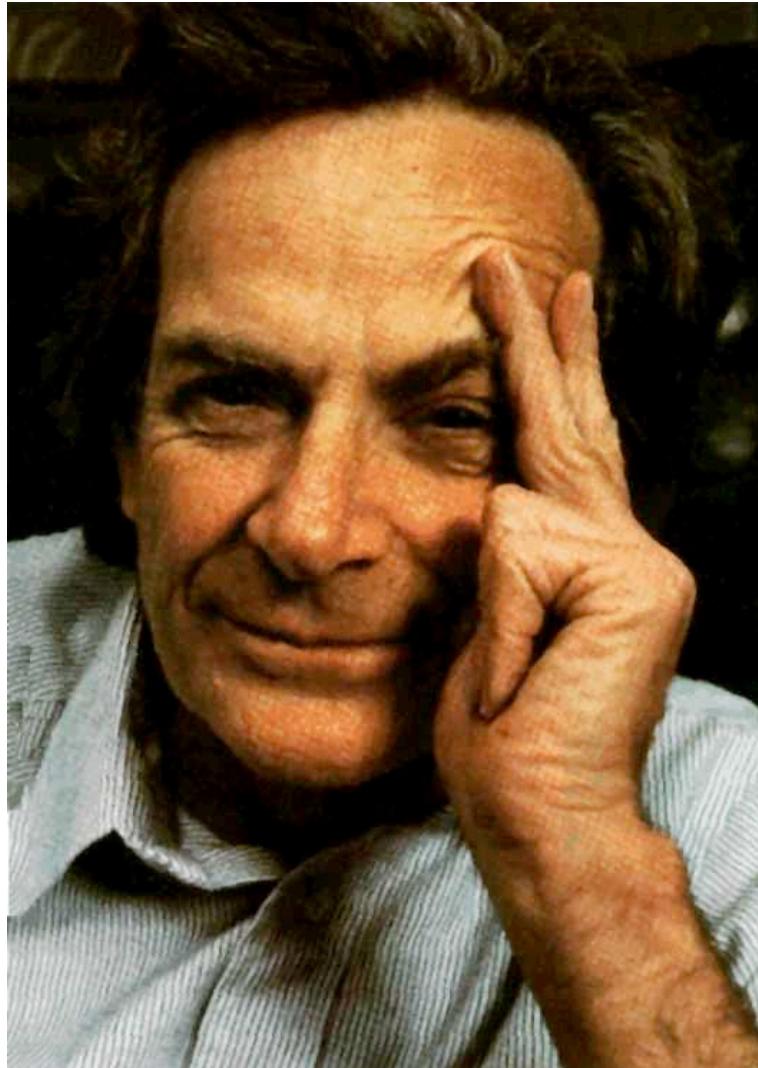
What are Jets ?



- Colored partons from the hard scatter evolve via soft quark and gluon radiation and hadronization process to form a "spray" of roughly collinear colorless hadrons → **JETS**
- The hadrons in a jet have small transverse momenta relative to their parent parton's direction and the sum of their longitudinal momenta roughly gives the parent parton momentum
- JETS are the experimental signatures of quarks and gluons
- Jets manifest themselves as localized clusters of energy

The exact definition of that localized cluster is important for precision measurements.

Original description of fragmentation done by Feynman and Field



Who's now working with me on CDF



and who has a famous sister

Rick's famous sister



Rick's wife

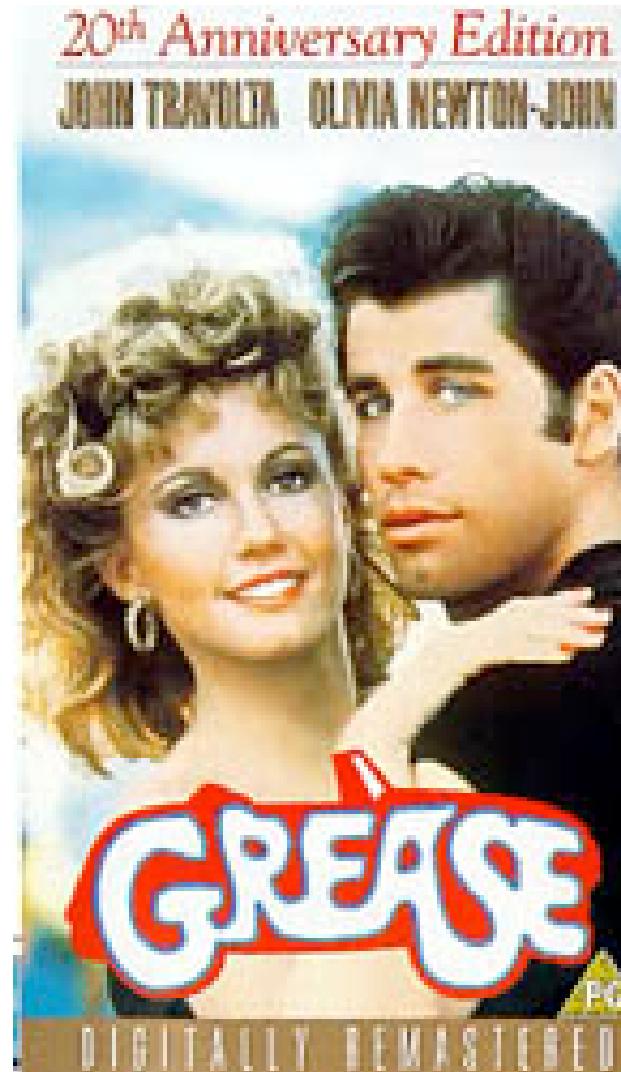
Rick's sister

Rick

Trivia question: who is Max Born's famous grand-daughter?

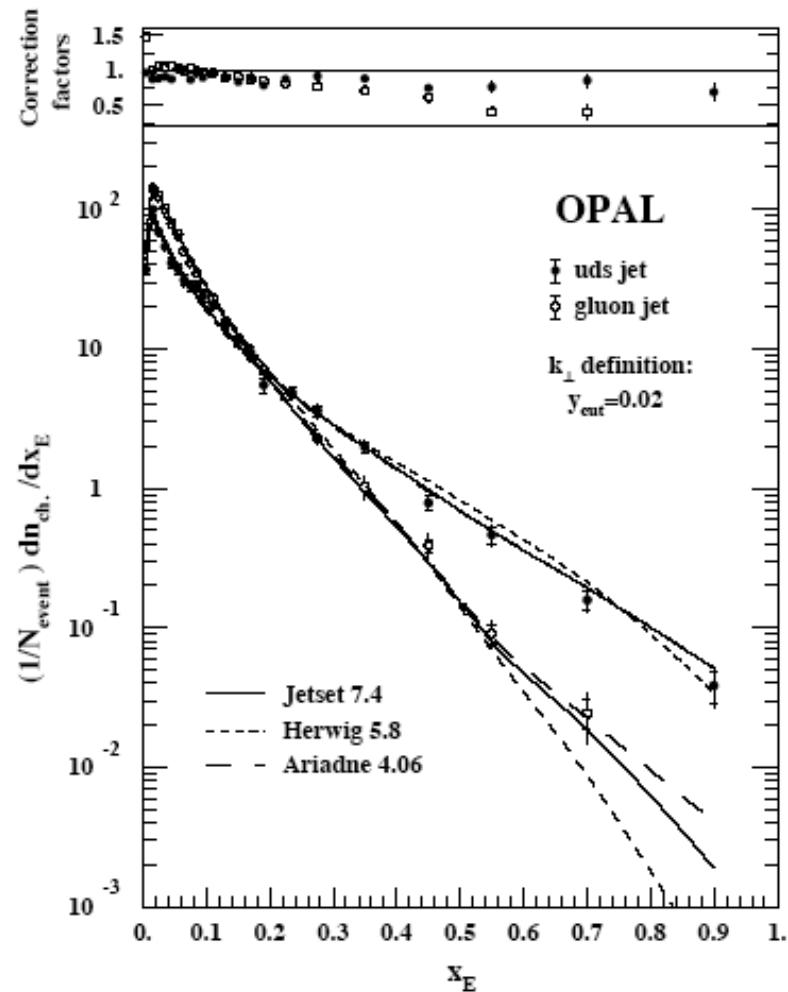
Olivia Newton-John

- John Travolta is not related to any famous physicist
 - ◆ as far as I know



Jet Fragmentation Functions

- The parton that gives rise to the jet fragments into a fairly large number of particles (increasing as the jet E_T increases)
 - ◆ say 20 particles for a jet with E_T of 100 GeV
- Most of the jet particles have a small fraction (z) of the total jet momentum
 - ◆ and the gluon fragmentation is softer than the quark fragmentation
- We can't calculate the fragmentation functions perturbatively; have to measure them
 - ◆ mostly at LEP
 - ◆ we can calculate how they change with Q , though

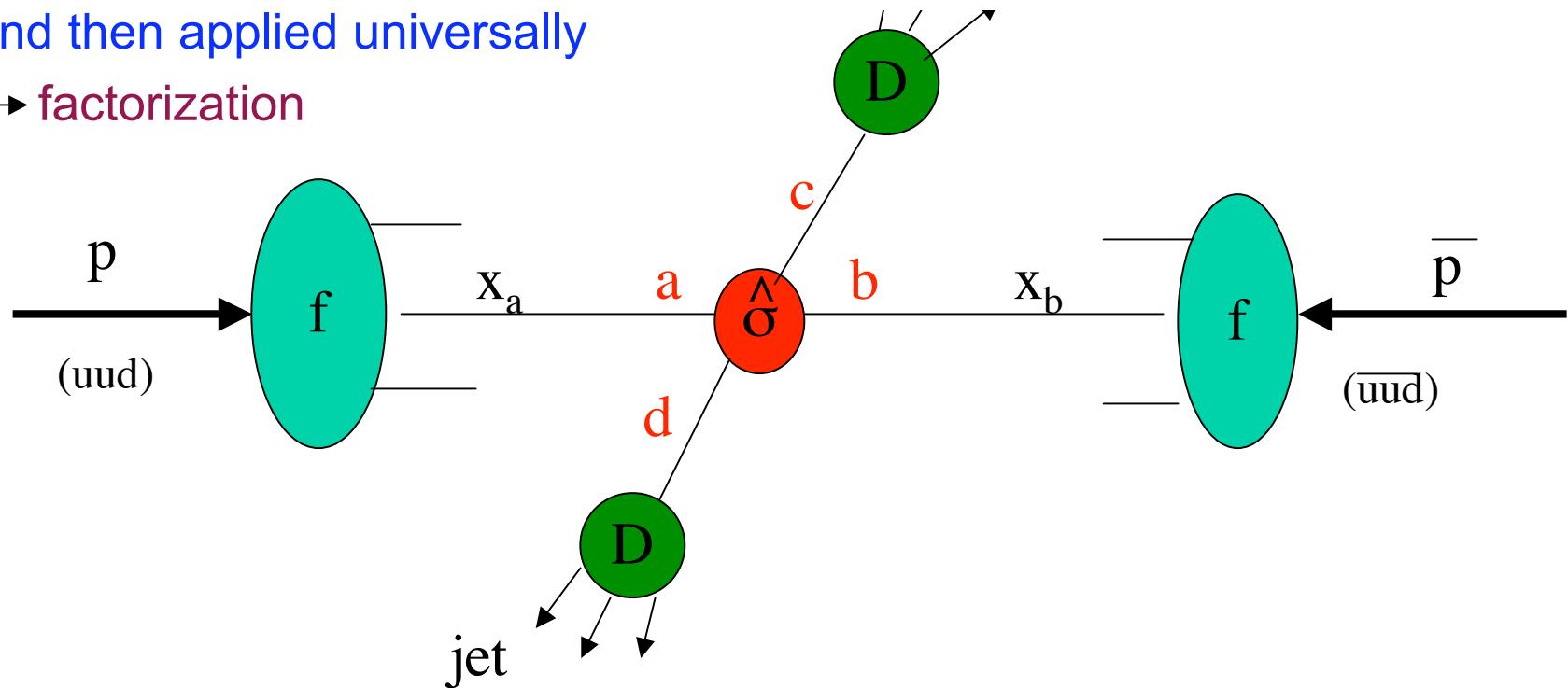


Blobs, continued

- The cross section for jet production to occur depends on a convolution of $f_{\text{parton}}(x_a, Q^2)$, $f_{\text{parton}}(x_b, Q^2)$ and the hard scattering cross section $\hat{\sigma}$

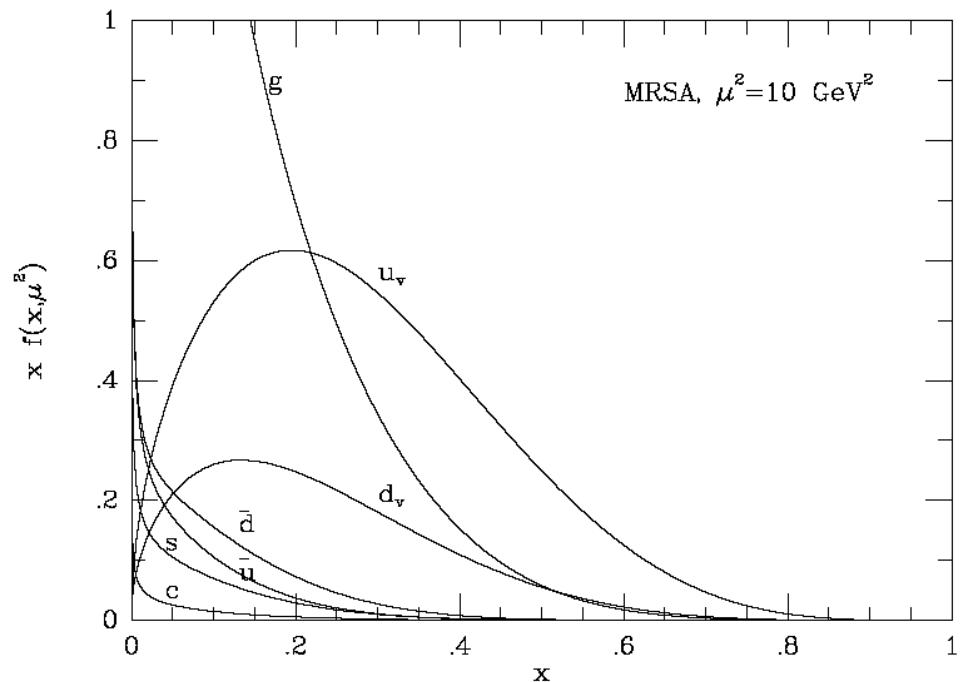
- The parton distribution functions can be determined from one process and then applied universally
→ factorization

$$\begin{aligned}\sigma_X &= \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \\ &\times \hat{\sigma}_{ab \rightarrow X} \left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right)\end{aligned}$$



Parton distribution function fits

- Since all hadron-hadron cross sections depend on pdf's, the determination of them is an important aspect of QCD phenomenology
 - ◆ non-perturbative physics, although evolution of pdf's with Q^2 can be calculated perturbatively
- Can determine pdf's using data from DIS (deep-inelastic scattering), DY (Drell-Yan pair production), and the production of jets
- There are two major groups that provide pdf's to the world
 - ◆ MRST
 - ◆ CTEQ



$$x f(x, Q_0) = A_0 x^{A_1} (1-x)^{A_2} P(x)$$

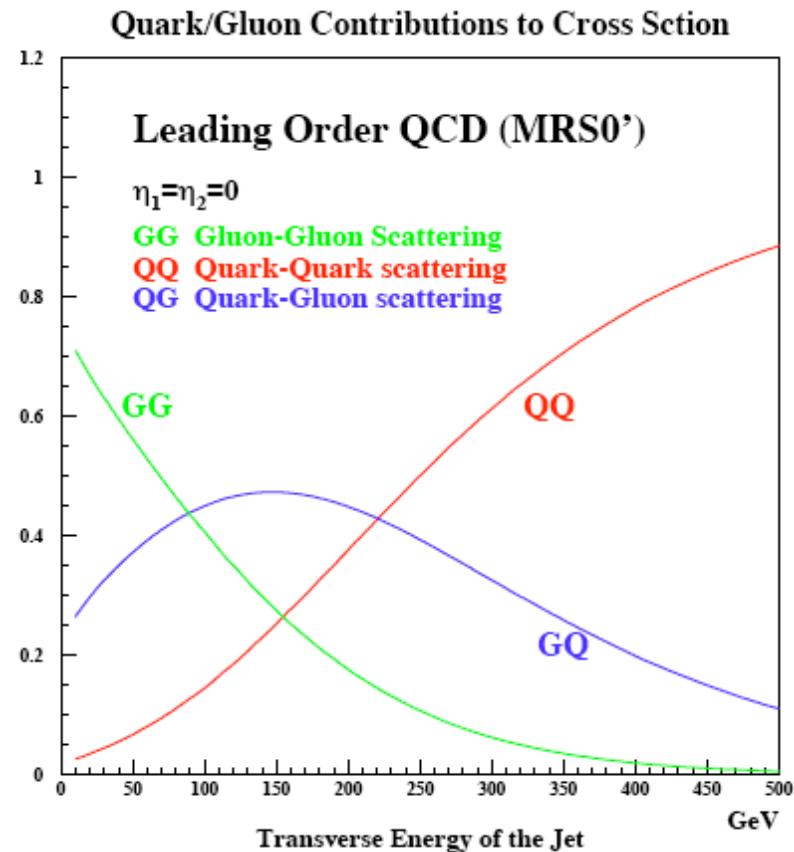
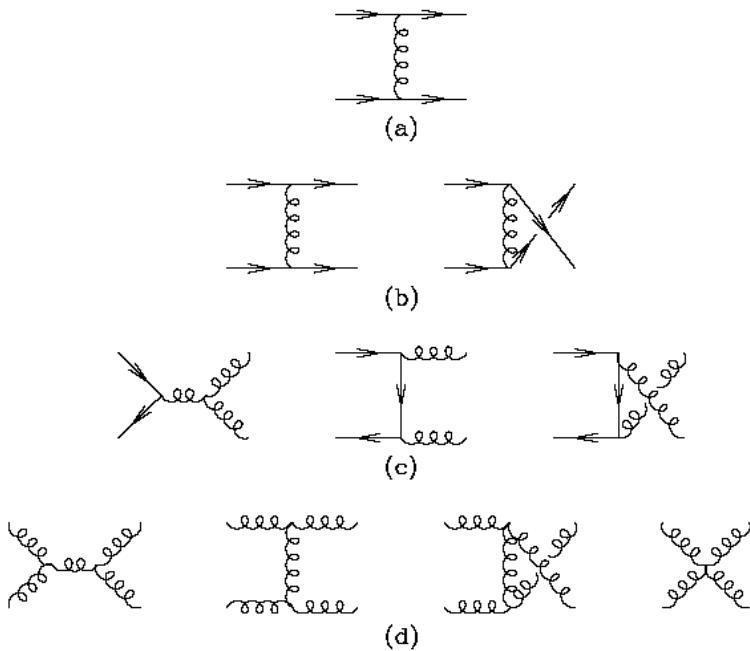
small x behavior

in between

large x behavior

Jet production at LO

- There are many subprocesses that contribute to jet production at hadron colliders
 - gg scattering
 - gq scattering
 - qq (or qq scattering)
 - qq scattering



mostly gg scattering at low E_T , which corresponds to low values of parton x (where the gluon dominates); we'll see later that jet production is important in global pdf fits, especially at high x

Jet production beyond LO

- Calculating jet cross sections at LO is a graduate student exercise
- Several programs (EKS, JETRAD) for NLO available
 - ◆ this is the first order at which you can believe the normalization of the cross section
- Calculating the cross section to NLO is a 5 year (or more) exercise involving ten's of people

Why go beyond NLO? (1)

- Better estimate of size of cross section
- | | | |
|--------|---|--|
| ● LO | → | order of magnitude estimate ($\mu?$) |
| ● NLO | → | reliable estimate of σ ($\Delta\mu?$) |
| ● NNLO | → | reliable estimate of $\Delta\sigma$ |

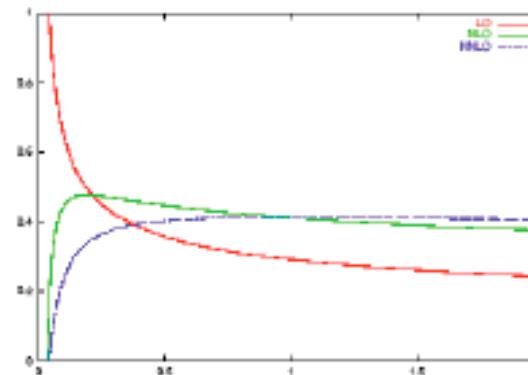


Figure 1: Jet cross section $d\sigma/dE_T$ for $E_T = 100$ GeV versus renormalisation scale μ/E_T . NNLO is the renormalisation group predictable part. We see that for renormalisation scales within a factor of two of the jet energy, the renormalisation scale uncertainty is reduced from 20% to 9% to 1%.

Elements of NNLO calculation

- 2 loop, 2 parton final state



- | 1 loop |², 2 parton final state



- 1 loop, 3 parton final states
or 2+1 parton final state



- tree, 4 parton final states
or 3+1 parton final states
or 2+2 parton final state

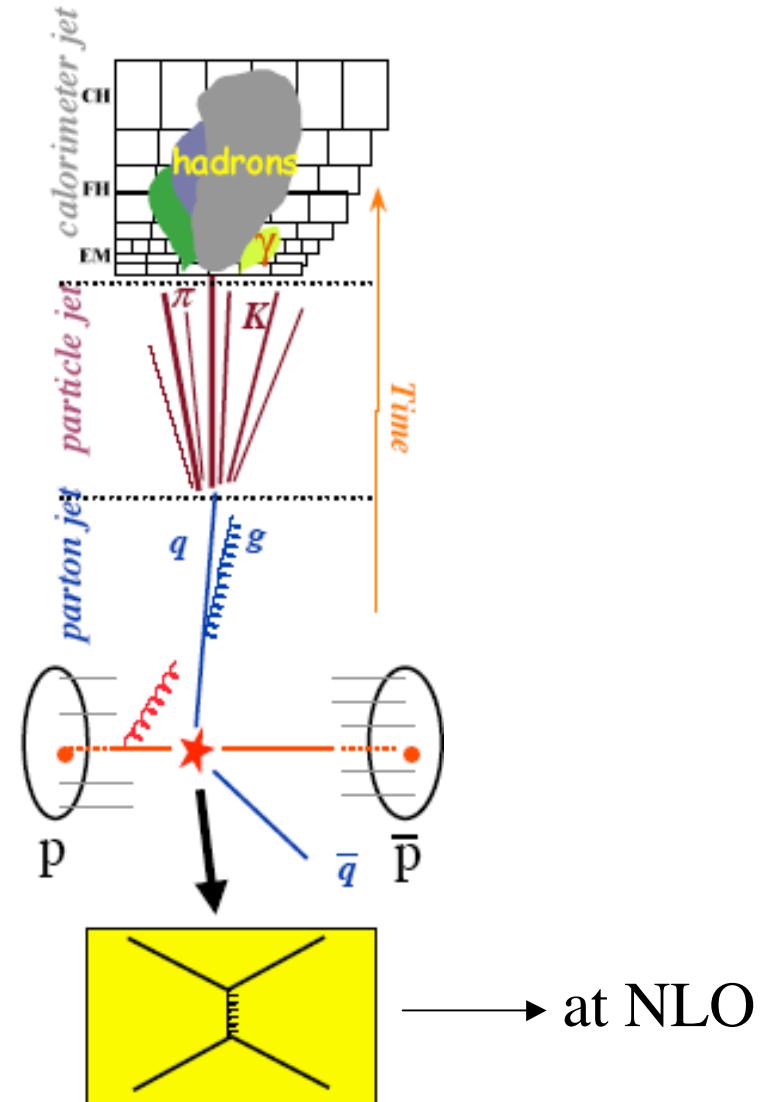


(where **n** theoretically unresolved soft or collinear partons are indicated as **+n**)

⇒ rapid progress in last two years [**many authors**]: many $2 \rightarrow 2$ scattering processes with up to one off-shell leg now calculated at two loops — these must then be combined with the tree-level $2 \rightarrow 4$, the one-loop $2 \rightarrow 3$ and the self-interference of the one-loop $2 \rightarrow 2$ to yield physical NNLO cross sections

Something to look forward to

- MC @ NLO combines the best features of parton shower Monte Carlos and NLO calculations
- The hard cross section is calculated to NLO and then passed on to Herwig for additional gluon radiation and hadronization
- Inclusive jet production will be included by this fall



Jet algorithms beyond LO

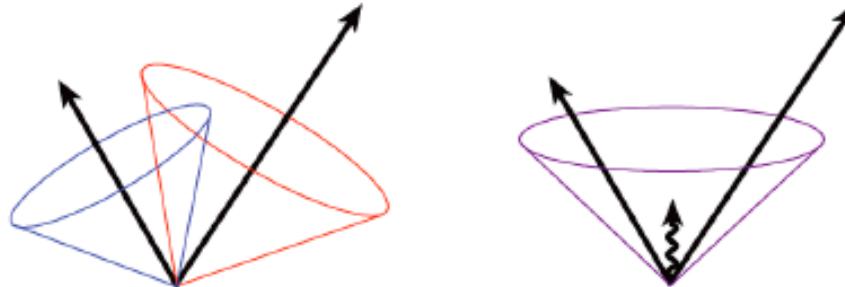


FIG. 1: Two partons in two cones or in one cone with a (soft) seed present.

Also have to better understand details of comparisons between jet algorithms at the parton level and at the detector level
See, for example, hep-ph/0111434
Building Better Cone Jet Algorithms

To be discussed more during Steve Ellis visit in March

Thus far, Tevatron jet algorithms have been corrected to hadron, but not parton, level

Will include hadronization corrections in Run II

Eagerly waiting for inclusive jet production in MC@NLO

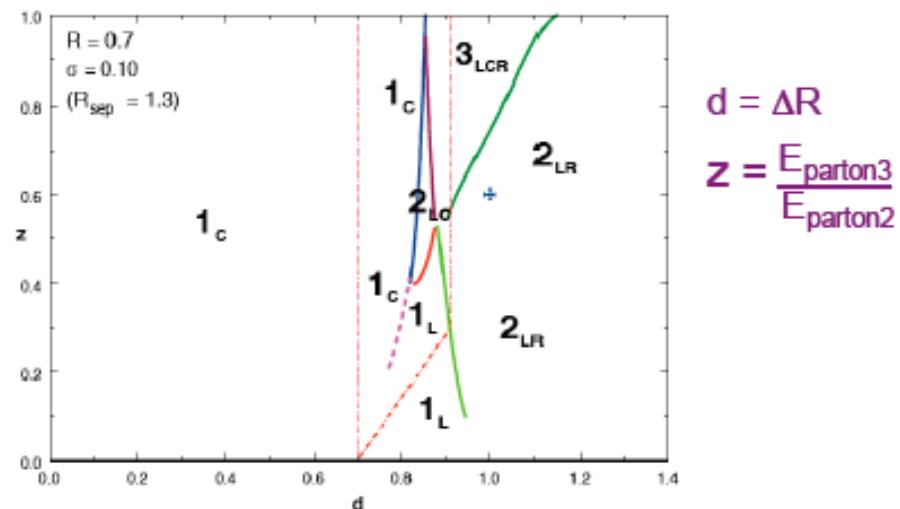
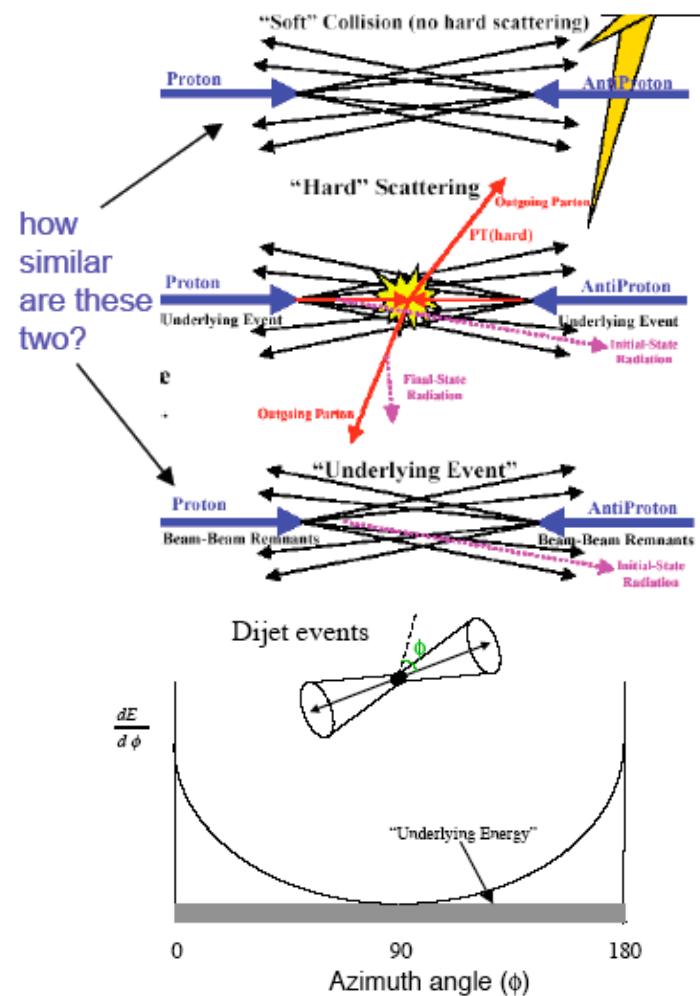


FIG. 10: Stable cone structure found by the cone jet algorithm with underlying partons including gaussian smearing with width $\sigma = 0.1$. The dashed-dotted lines indicated the unsmeared, perturbative result with $R_{\text{sep}} = 1.3$.

A complication

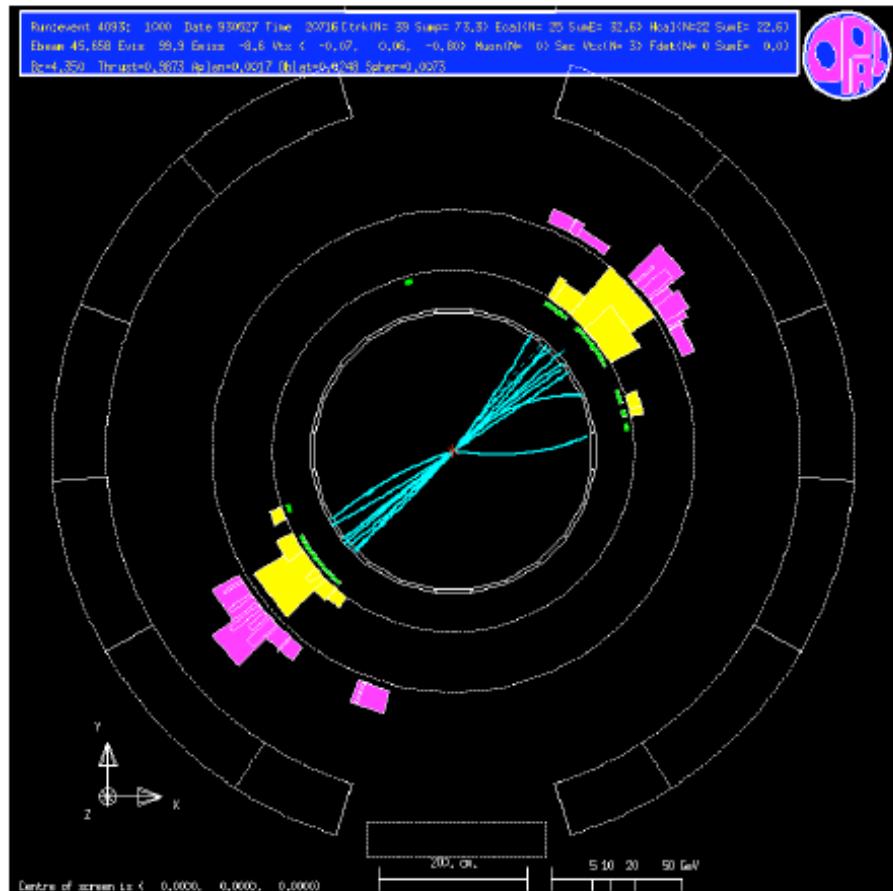
- Remember that it's not only the two main partons that are interacting with each other; the rest of the proton and anti-proton are interacting as well (but softly)
- The result is a kind of low energy underlying event filling the detector
 - ◆ this underlying event must be subtracted from the jet energy as best as possible
 - ◆ the assumption that we make is that the underlying event in a jet event is similar to the ambient level observed in minimum bias events with a small impact parameter
 - ◆ this is kind of a murky statement and results in an appreciable systematic error at low E_T

- Have to subtract underlying event from hard scatter in order to compare jet cross sections to parton-level calculations

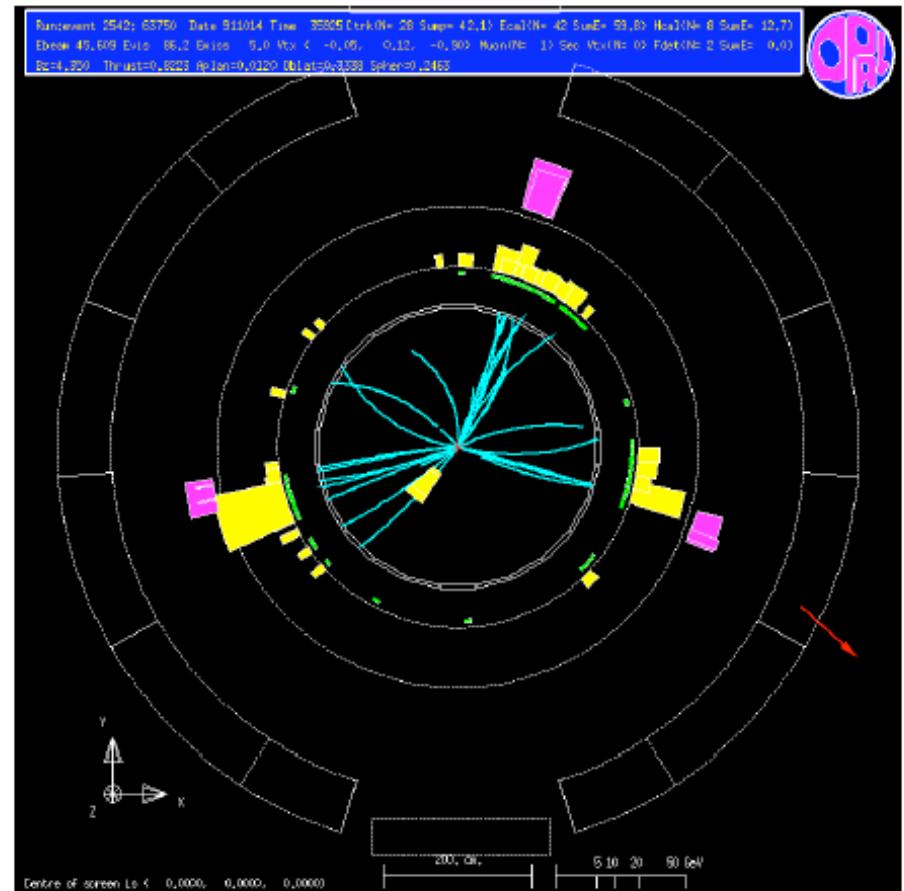


Hadron-hadron collider not as clean an environment as an e+e- machine

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

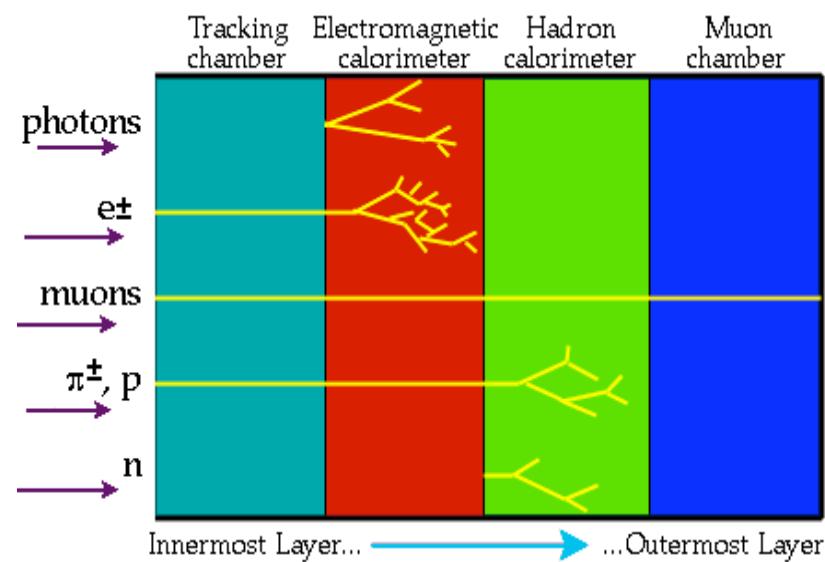
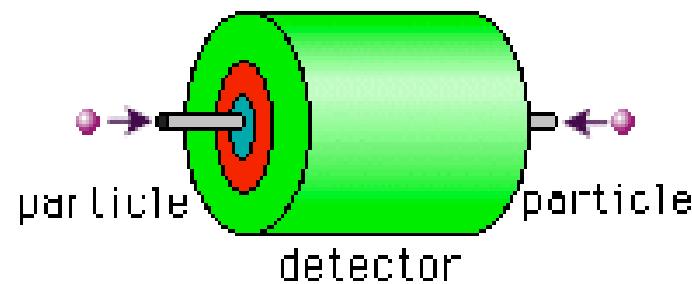


$e^+e^- \rightarrow q\bar{q}g$



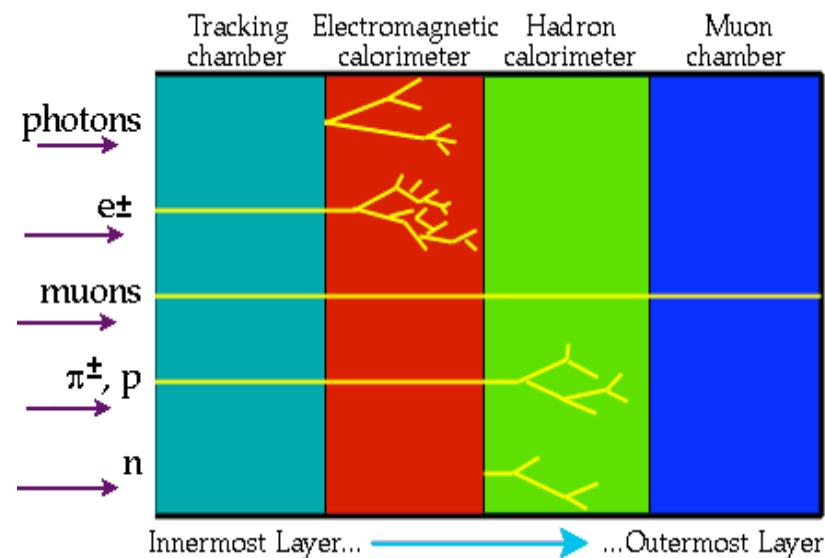
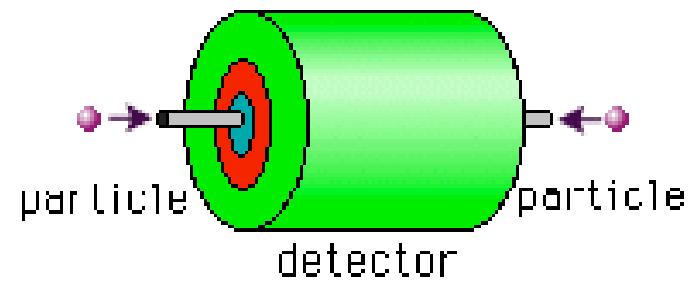
Detectors at colliders

- Collider detectors usually have a cylindrical symmetry
- They try to reconstruct as much information from the collision as possible using silicon vertex detectors, tracking chambers, and calorimetry



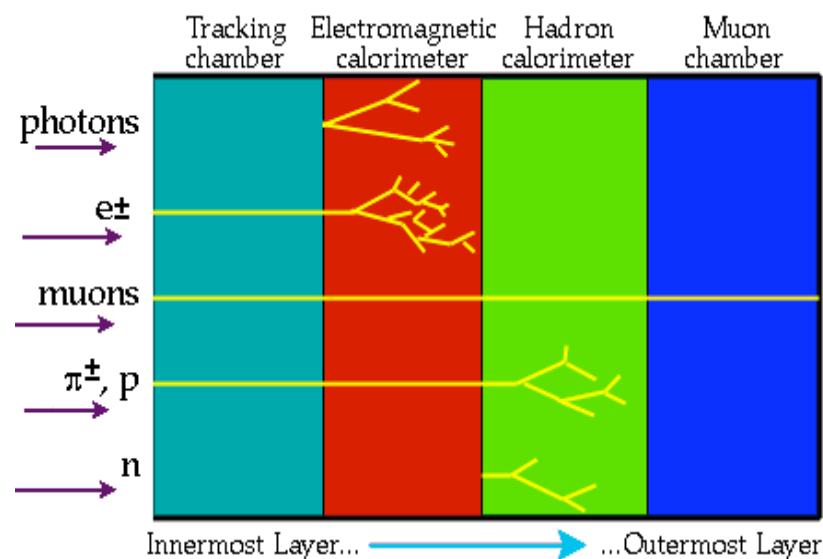
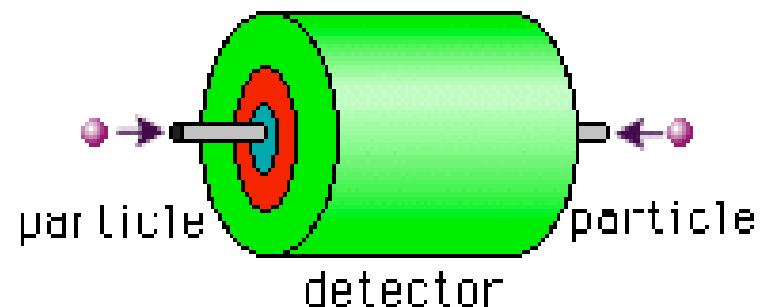
Detectors at colliders

- Silicon vertex detectors look for particles (like b quarks) that live for a relatively long time ($\sim 10^{-11}$ s)
- Tracking chambers measure the trajectories of charged particles (through ionization of the gas in the chamber)
 - ◆ `trajectory+magnetic field=momentum measurement for particle



Detectors at colliders

- Calorimetry is used to measure the energy of particles
 - ◆ it's a destructive process, i.e. energy of particle is used up
 - ▲ calorimeters can be either homogenous, or
 - ▲ sampling, i.e. a sandwich
 - ◆ calorimeters usually divided into 2 compartments, electromagnetic (measure energies of electrons and photons) and hadronic (measure energies of pions, kaons, protons, neutrons)
- Calorimetry has a projective tower structure (in η ($=-\ln(\tan\theta/2)$) and ϕ) that points back towards the interaction point
 - ◆ see lego plots later



The Tevatron (in Run 2)

Main injector (150 GeV proton storage ring) replaces main ring

New permanent magnet storage ring for pbar accumulation (under commissioning)

Increased center-of-mass energy ($1.8 \Rightarrow 1.96 \text{ TeV}$)

More bunches (protons and antiprotons are in bunches a few tens of cm long)
($6 \Rightarrow 36, 396 \text{ ns crossing time}$)

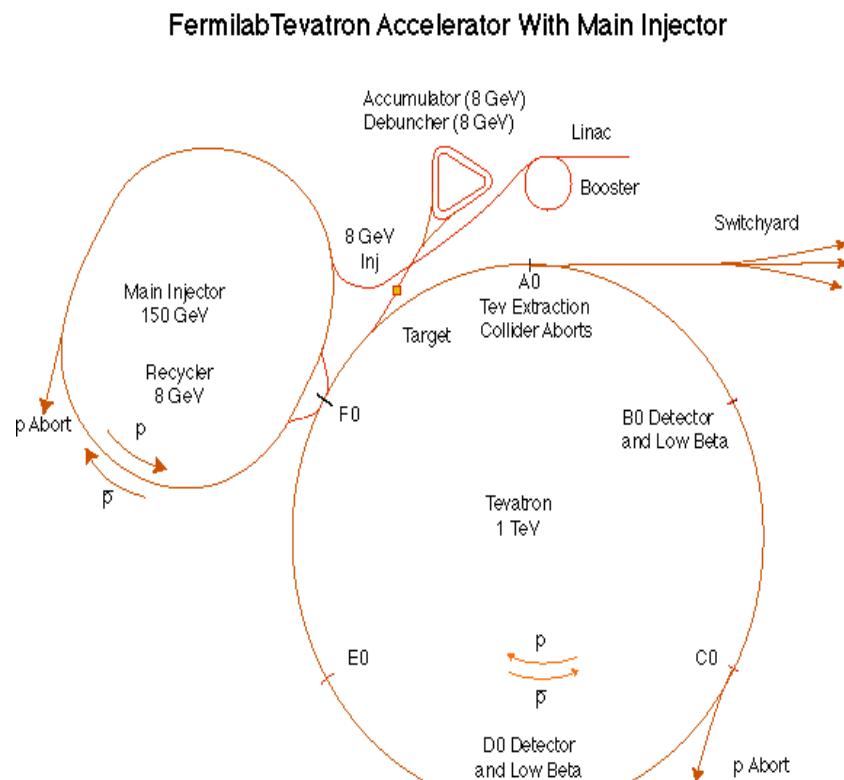
Higher luminosity

Run 2 goal: $3 - 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

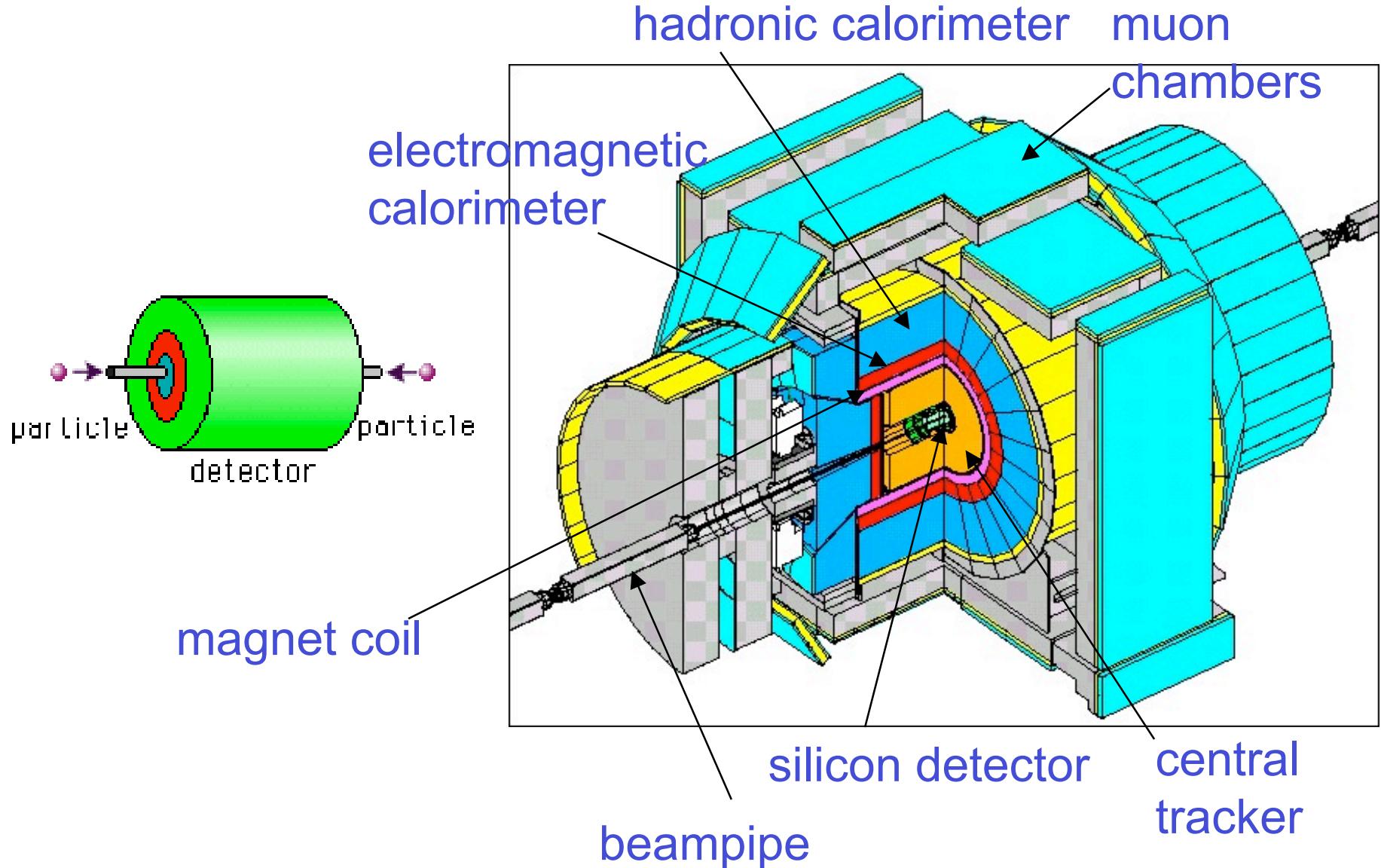
Run 2 maximum: $\sim 7 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
(to date)

Run 1 maximum: $2.4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

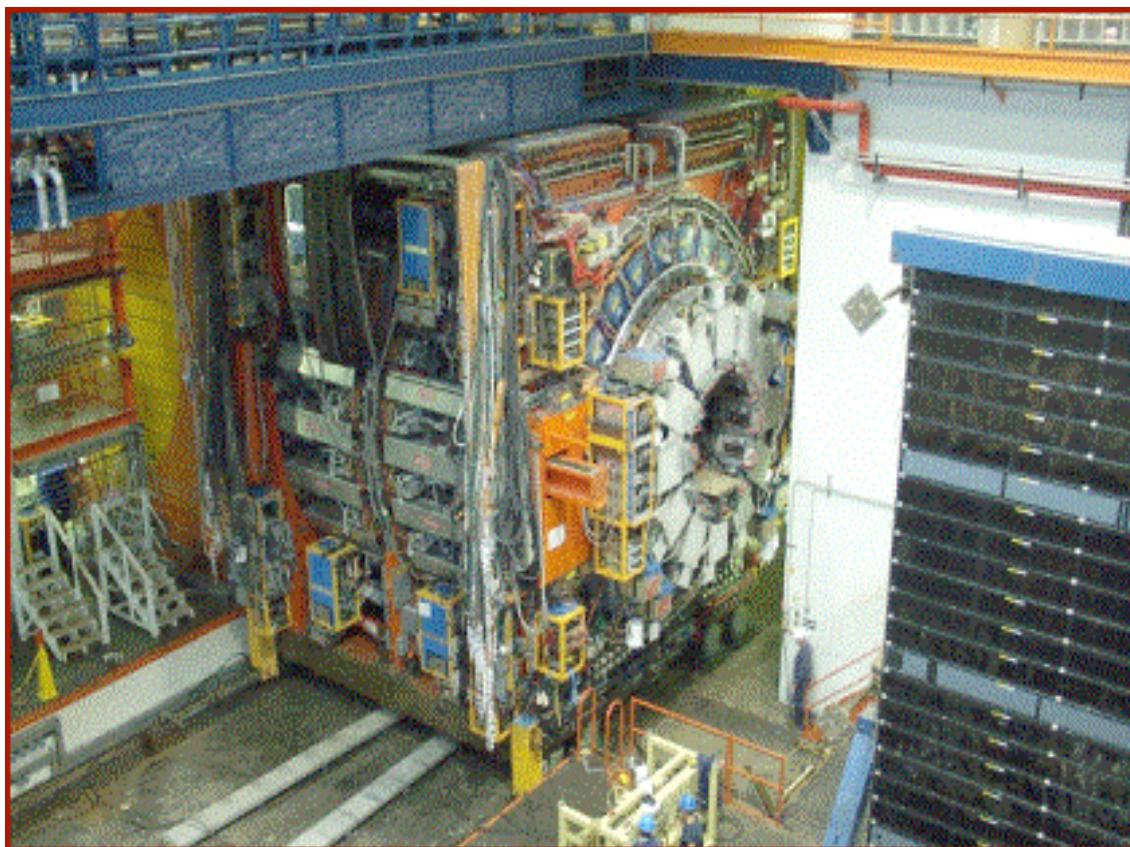
$$\sigma \times L = \# \text{ events}$$



CDF Detector in Run II



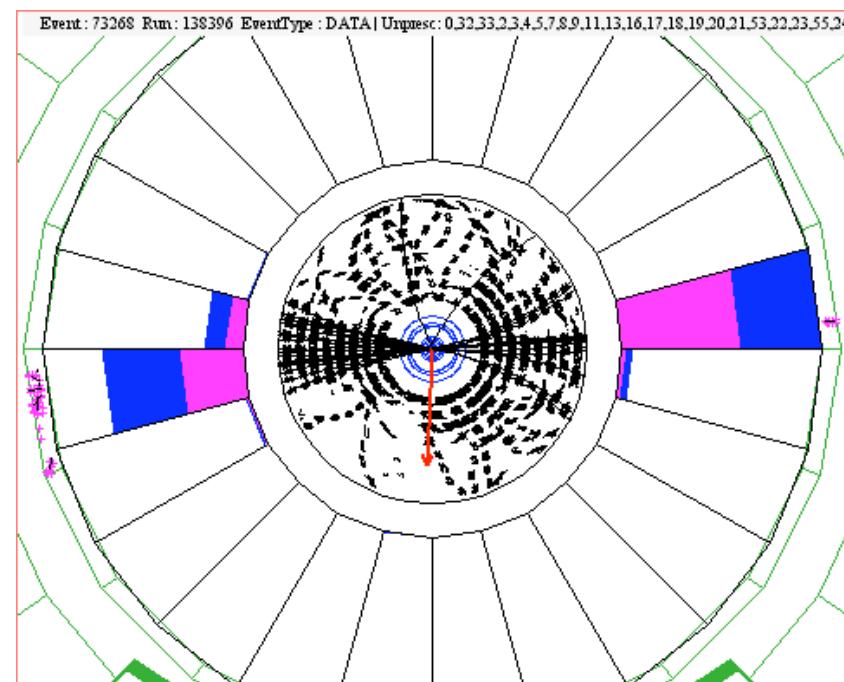
Rolling into the collision hall



Nov. 2001 - R. Erbacher

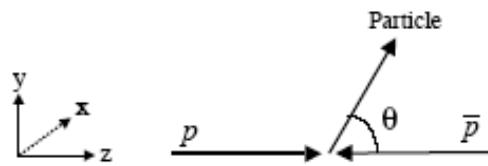
How do I know a jet when I see it?

- At some level, it's simple
- Two *streams* of particles coming from the interaction point
- Precision determinations are more difficult and depend on the details of jet algorithms
 - ◆ see Jay's talk tomorrow



Some definitions

Kinematics in Hadronic Collisions



Transverse Energy/Momentum

$$E_T^2 \equiv p_x^2 + p_y^2 + m^2 = p_T^2 + m^2 = E^2 - p_z^2$$

$$p_T \equiv p \sin \theta \qquad p_z = E \tanh y$$

$$E = E_T \cosh y$$

$$p_z = E_T \sinh y$$

Rapidity (y) and Pseudo-rapidity (η)

$$y \equiv \frac{1}{2} \ln \frac{E + p_z}{E - p_z} = \frac{1}{2} \ln \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta}$$

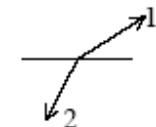
$$\beta \cos \theta = \tanh y \text{ where } \beta = p/E$$

In the limit $\beta \rightarrow 1$ (or $m \ll p_T$) then

$$\eta \equiv y|_{m=0} = \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta} = -\ln \tan \frac{\theta}{2}$$

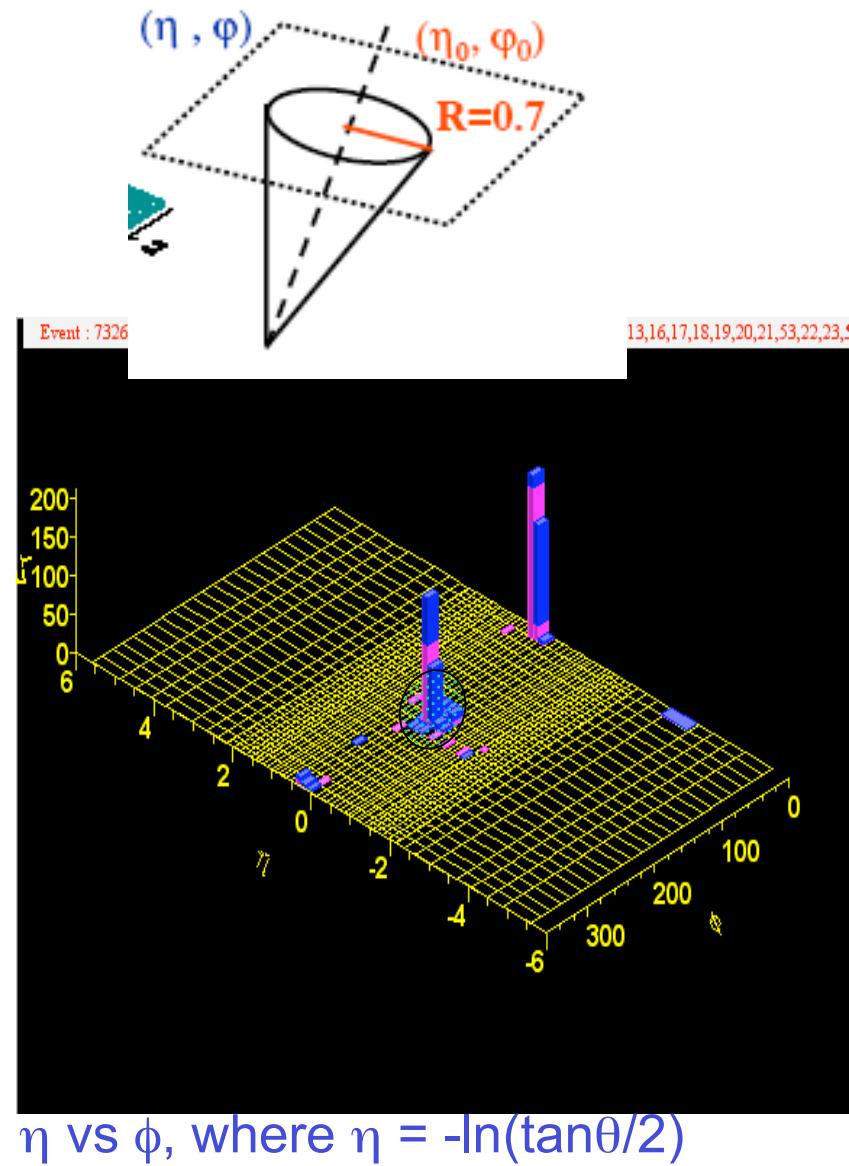
Invariant Mass

$$\begin{aligned} M_{12}^2 &\equiv (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu}) \\ &= m_1^2 + m_2^2 + 2(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2) \\ &\xrightarrow{m_1, m_2 \rightarrow 0} 2E_{T1}E_{T2}(\cosh \Delta\eta - \cos \Delta\phi) \end{aligned}$$

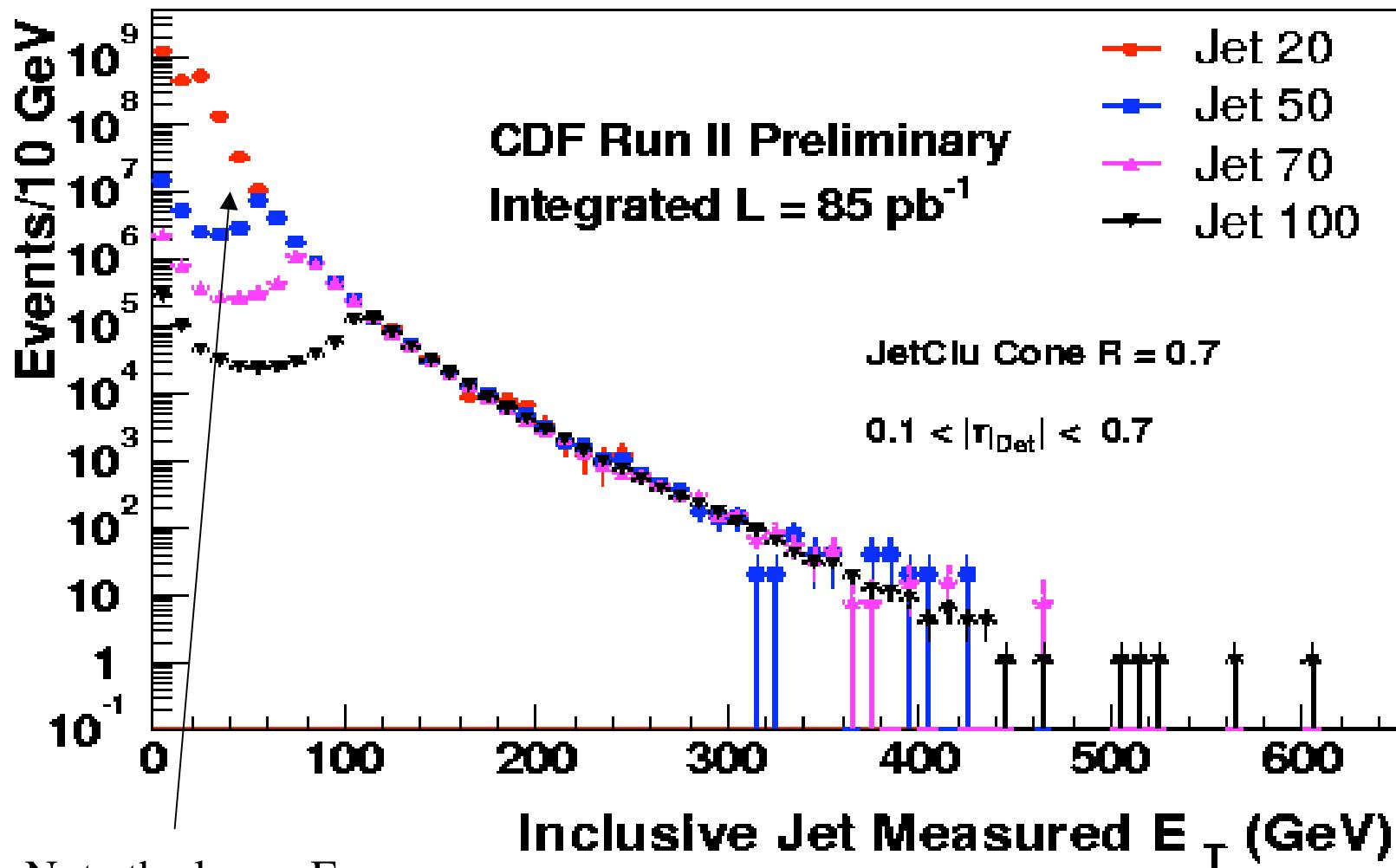


Jet defined in η - ϕ space

- Calorimeter towers are laid out in η and ϕ (for CDF $\Delta\eta=0.1$ and $\Delta\phi=15^\circ$)
- Energy deposited in the electromagnetic section of the calorimeter is colored red and energy deposited in the hadronic section is colored blue
- The two “jets” produced in this event have deposited energy both in the electromagnetic and in the hadronic calorimeter
- Most commonly used jet algorithm in CDF or D0 is cone algorithm, where jet energy is contained in a cone of radius R in η - ϕ space
 - ◆ but also have k_T algorithm which looks at closeness in momentum space
 - ◆ see Nikos’ talk



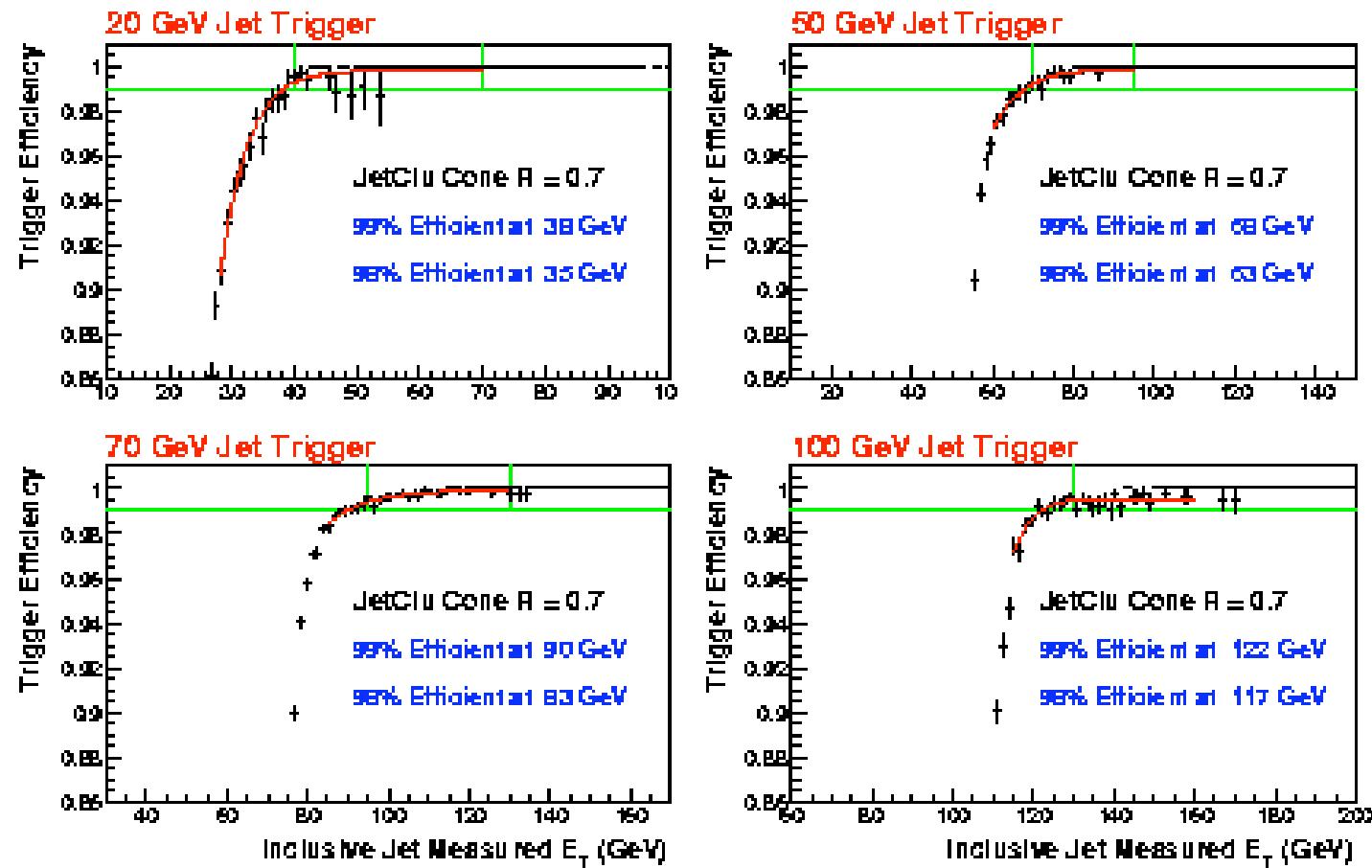
Measuring the inclusive jet cross section



Note the lower E_T
cross section has to be measured by pre-scaled triggers

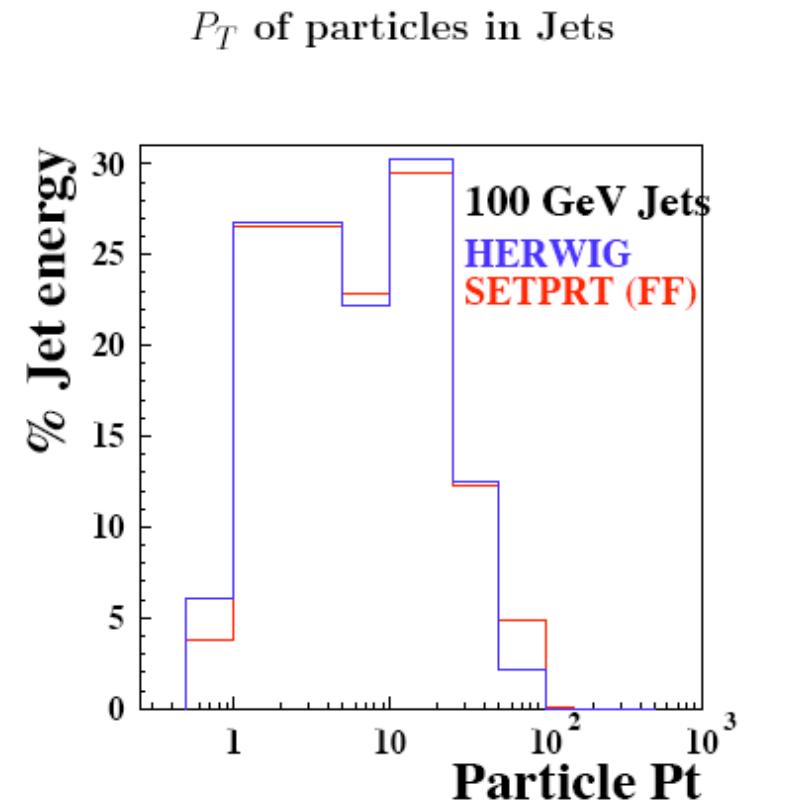
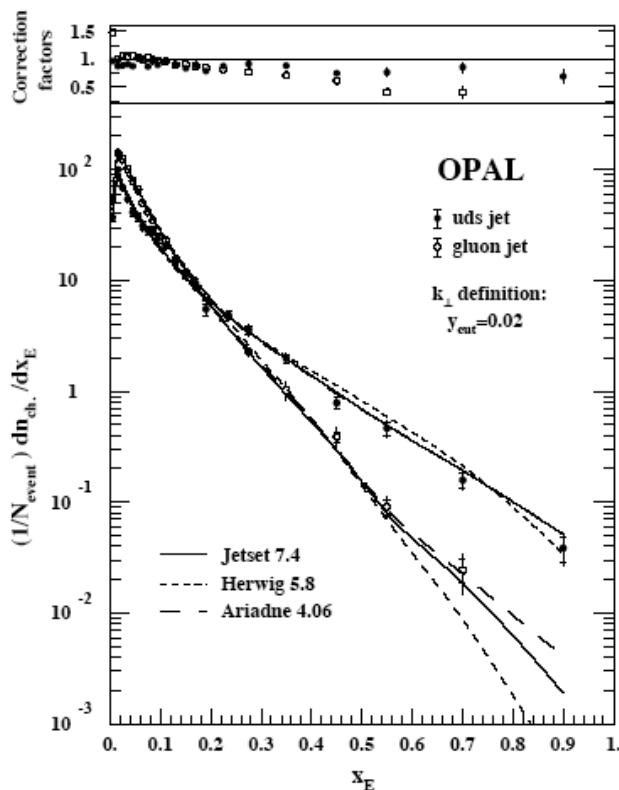
Looking at trigger efficiencies

CDF Run II Preliminary



Jet Fragmentation

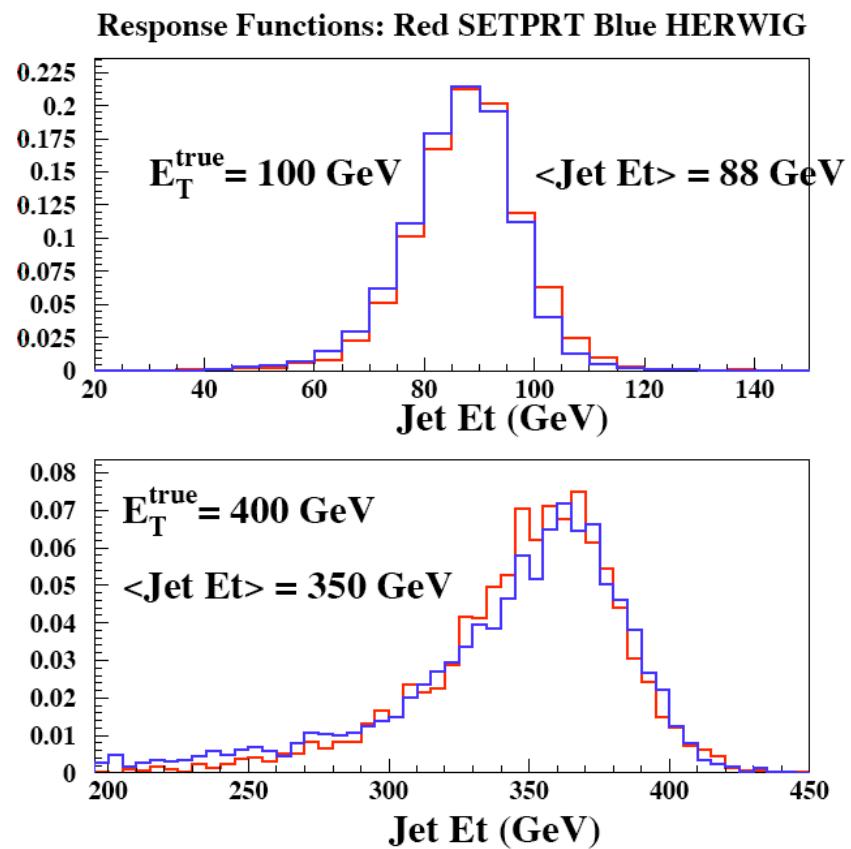
- Most of the energy of the jet is in the form of low p_T particles



100 GeV Jets are primarily (90%) particles with $P_T < 50 \text{ GeV}$.

Calorimeter measurement of a jet

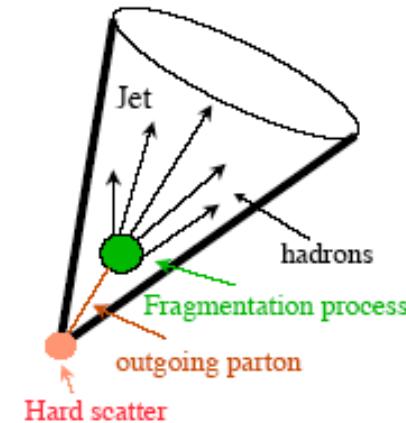
- The photons and electrons deposit energy in the electromagnetic calorimeter
- Hadrons (pions, protons, etc) deposit most of their energy in the hadronic calorimeter (but some in the electromagnetic calorimeter)
- The response of the 2 calorimeters is different; in addition there are cracks in between detectors
- Thus, jets of the same energy can give a different response in the calorimeters depending on exactly how they have fragmented



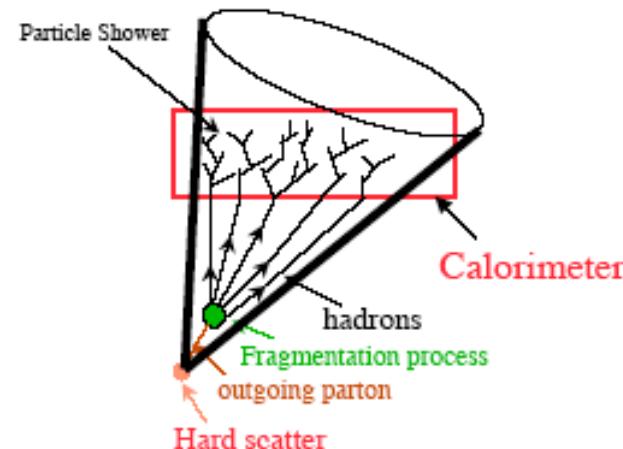
Determining the corrected distribution

- Knowing the response distribution of the detector to particles of given energies, and knowing how jets fragment, we can determine from the measured jet E_T distribution what the corrected or true distribution looks like
 - ◆ that knowledge of fragmentation can come from a direct measurement by the experiment or by the use of parton shower Monte Carlos
- The corrected distribution can then be compared to theoretical predictions
- We can correct back to the hadron level (sum of p_T 's of all of the hadrons in the jet cone) or to the original parton level (taking account of the energy deposited outside of the jet cone)

- Jets at the "Particle (or hadron) Level"

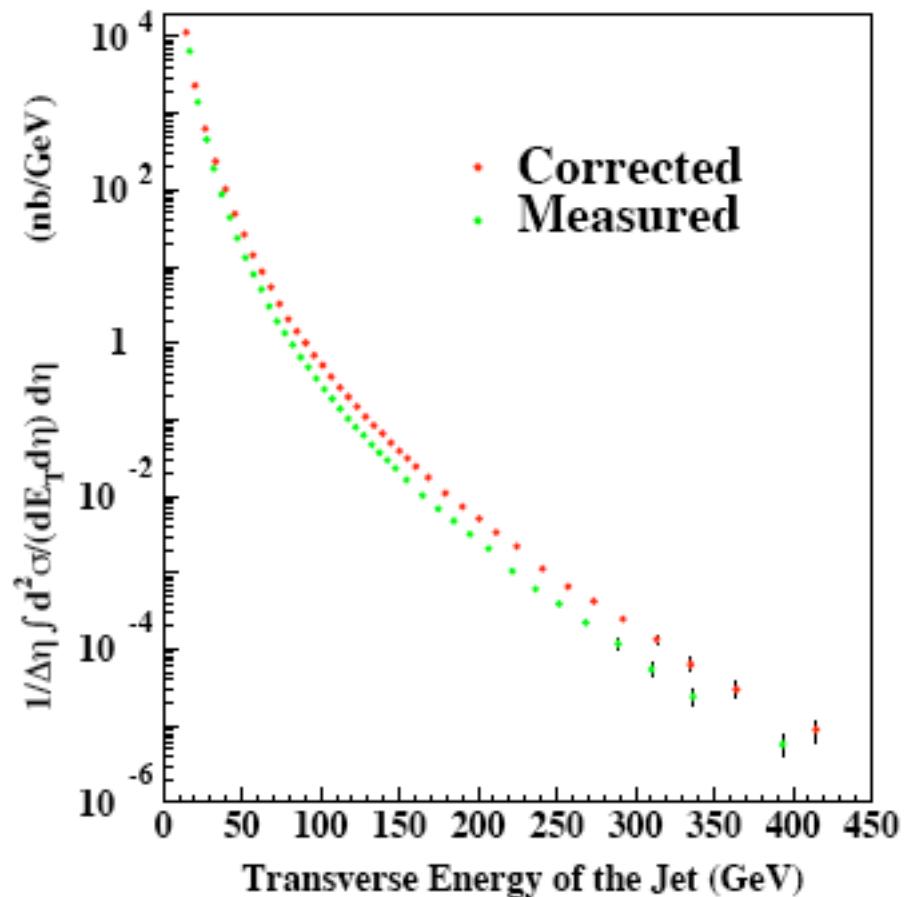


- Jets at the "Detector Level"

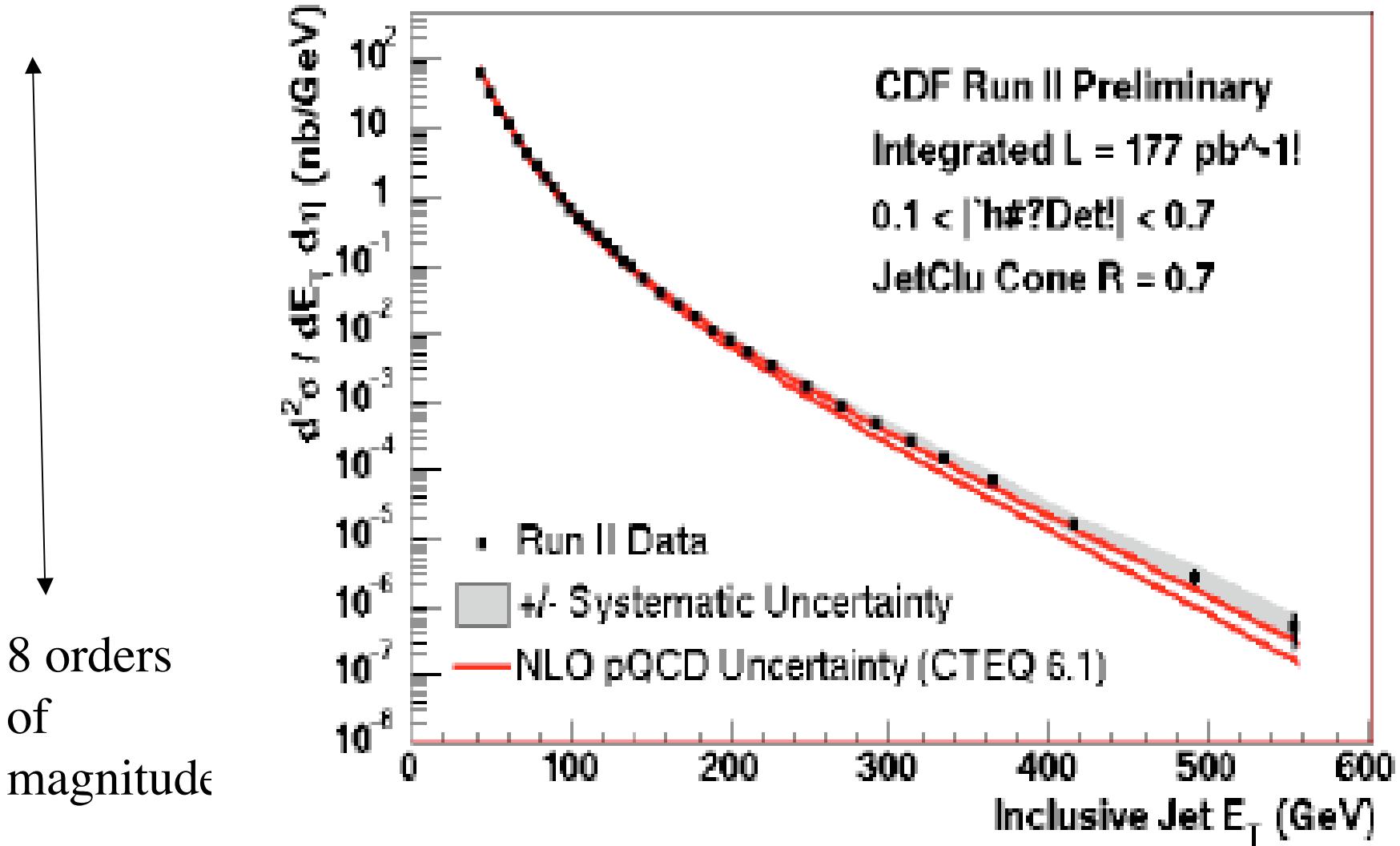


Determining the corrected distribution

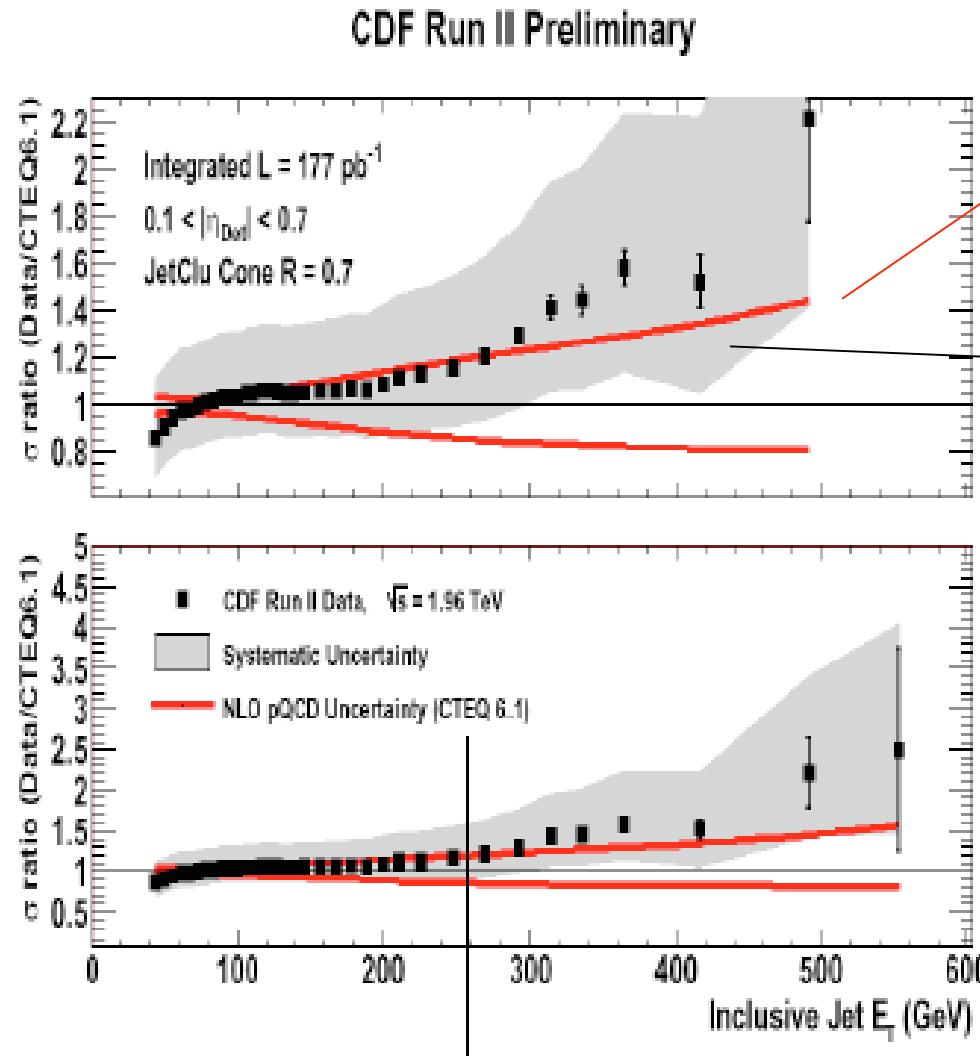
- Knowing the response distribution of the detector to particles of given energies (from test beam and in situ data), and knowing how jets fragment, we can determine from the measured jet E_T distribution what the corrected or true distribution looks like
 - ◆ that knowledge of fragmentation can come from a direct measurement by the experiment or by the use of parton shower Monte Carlos
- The corrected distribution can then be compared to theoretical predictions
- We can correct back to the hadron level (sum of p_T 's of all of the hadrons in the jet cone) or to the original parton level (taking account of the energy deposited outside of the jet cone)



Resulting in, for example, the inclusive jet cross section from Run 2



Data compared to theory



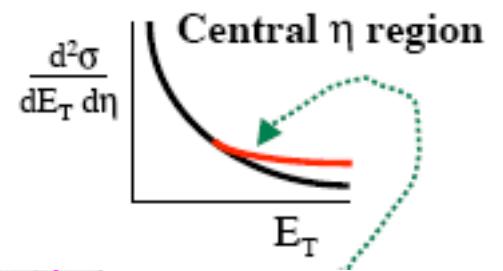
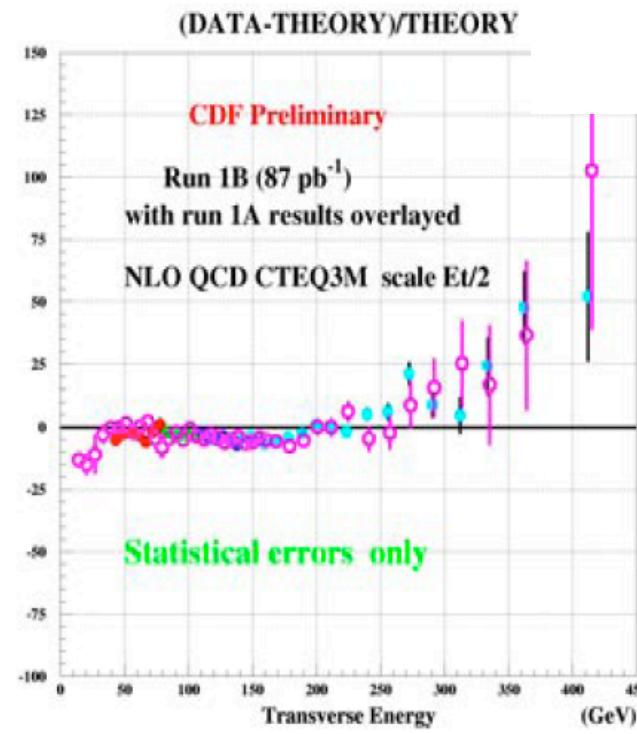
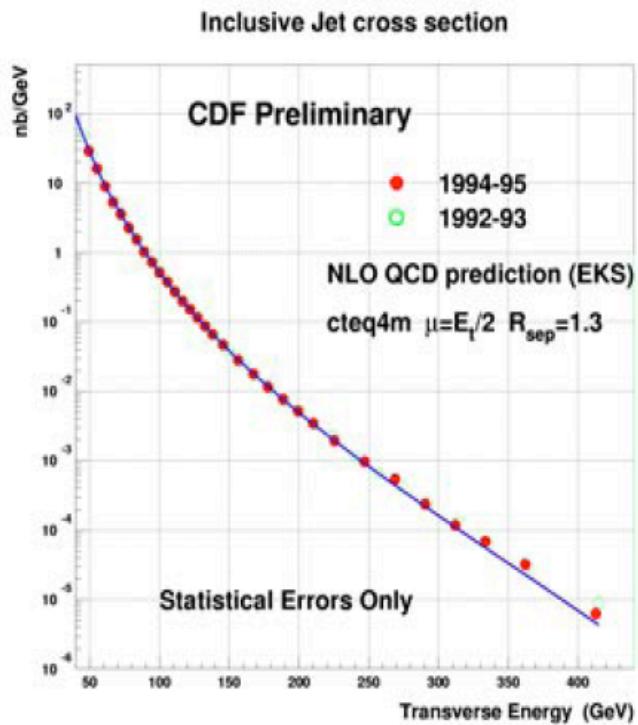
theory
uncertainty

(current)
experimental
uncertainty

could
this be
sign of
something
interesting?

Historical aside

An excess at high E_T was observed by CDF in Run 1 when comparing to NLO predictions using the topical pdf's



Rutherford
scattering all
over again

Possible new physics explanations

Possible Explanations of High E_T Excess

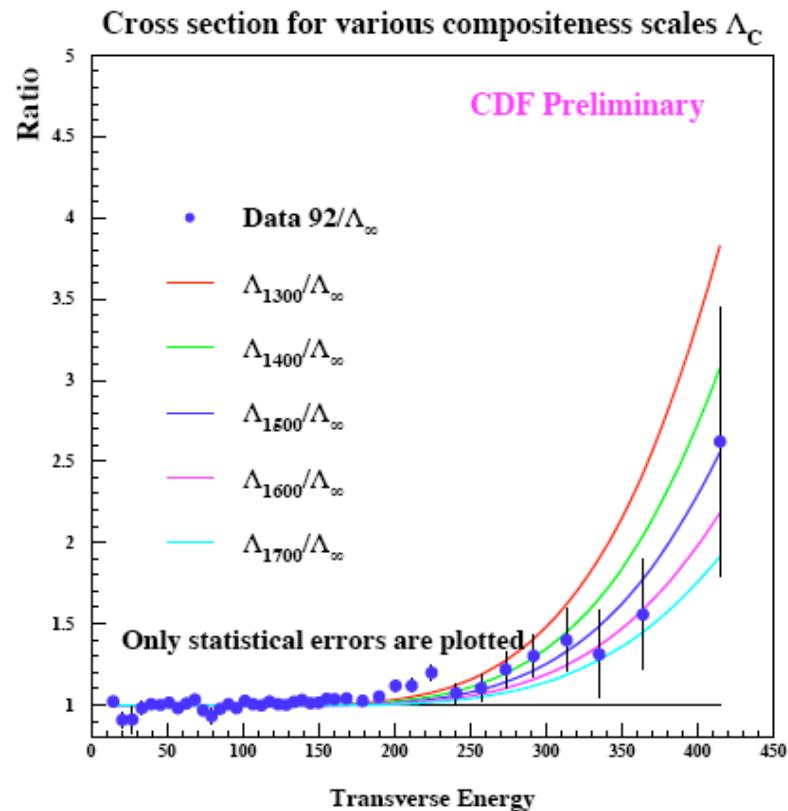
Until uncertainties within the realm of QCD are better understood any claim of NEW PHYSICS is INDEFENSIBLE!

However, the new physics possibilities include:

Composite quarks: a contact term is added to LO QCD Lagrangian \rightarrow increased cross section for high E_T jets

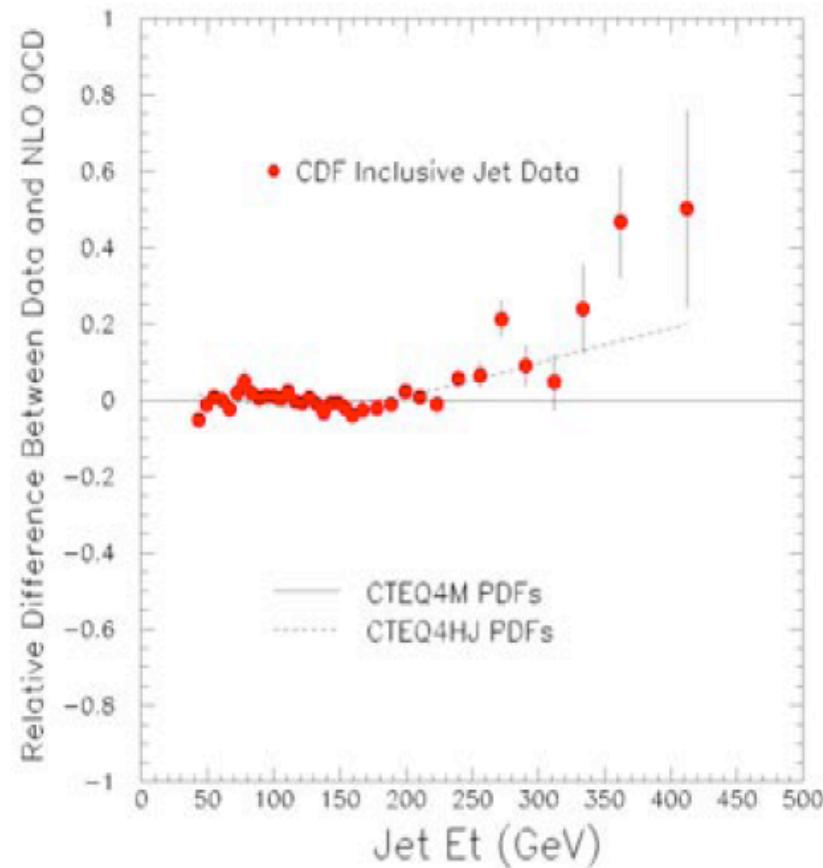
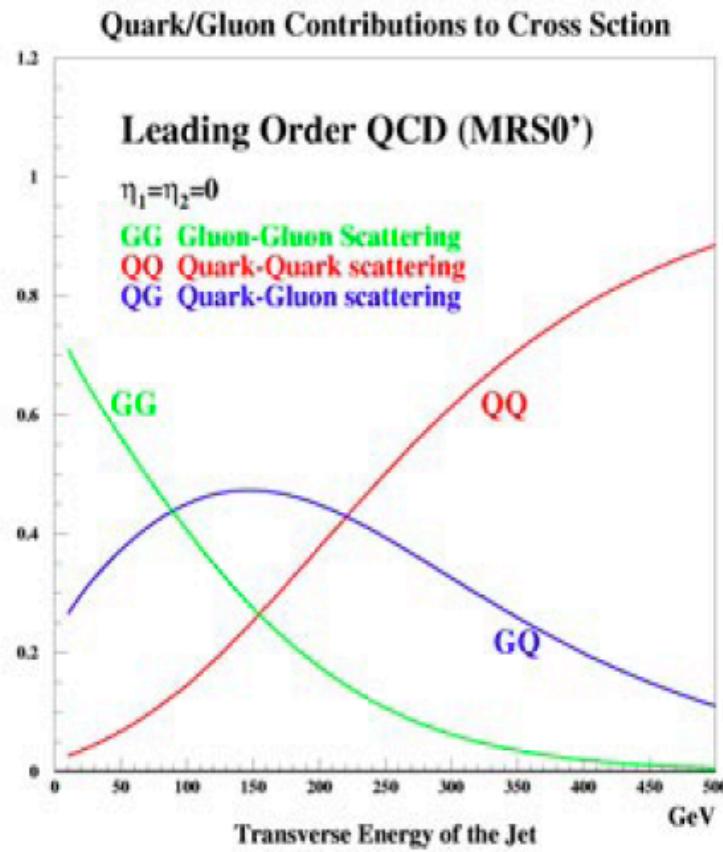
α_s stops running: possible conspiracy between new particles Susy (hep-ph9512325, hep-ph9601279), color sextet (Alan White ANL)

New Particle Z' : leptophobic Z', this could also possibly explain the charm/bottom problem at LEP (hep-ph/9601324)



A non-exotic explanation

Modify the gluon distribution at high x



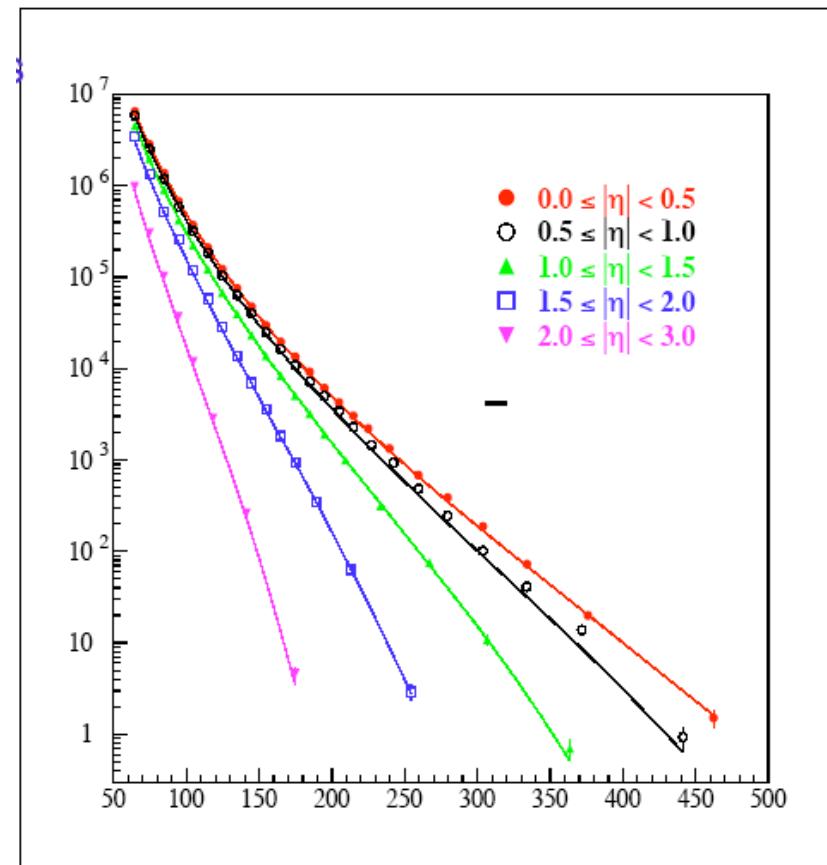
Which is now the accepted explanation

How do I determine pdf's?

- Calculation of production cross sections at the Tevatron relies upon knowledge of pdfs in relevant kinematic range
- pdfs are determined by global analyses of data from DIS, DY and jet production
 - ◆ global analyses dominated by DIS data but jet data from the Tevatron are now playing a crucial role
- Two major groups that provide semi-regular updates to parton distributions when new data/theory becomes available
 - ◆ MRS->MRST98->MRST99->MRST2001->MRST2002
 - ◆ CTEQ->CTEQ5->CTEQ5(1)->CTEQ6->CTEQ6.1
 - ◆ also GKK and Alekhin, but not widely used
- All of the above groups provide a way to estimate the error on the central pdf
 - ◆ new methodologies enable full characterization of parton parametrization space in neighborhood of global minimum
 - ▲ Hessian method
 - ▲ Lagrange Multiplier
 - ◆ both of above techniques used by CTEQ and MRST

pdf explanation

- The high x gluon was artificially increased in order to provide a better description of the CDF high E_T jet data
 - ◆ or rather the high E_T data was given more weight to see what budged...and it turned out to be the gluon
- The pdf explanation (a larger gluon at high x) worked for the D0 jet cross section measured in 5 different rapidity intervals
 - ◆ expect new physics to be mostly central but a pdf explanation has to work everywhere
- In fact, if the D0 jet data is included in a global pdf fit, then the larger gluon is the central fit



Run 1 D0 jet data

- CTEQ4 and CTEQ5 had CDF and D0 central jet cross sections in fit
- Statistical power not great enough to strongly influence high x gluon
 - ◆ CTEQ4HJ/5HJ required a special emphasis to be given to high E_T data points
- Central fit for CTEQ6 is naturally HJ-like
- χ^2 for CDF+D0 jet data is 113 for 123 data points
- Note the value of having *search for new physics regions as well as control regions*
 - ◆ new physics should be central
 - ◆ pdf explanation works everywhere

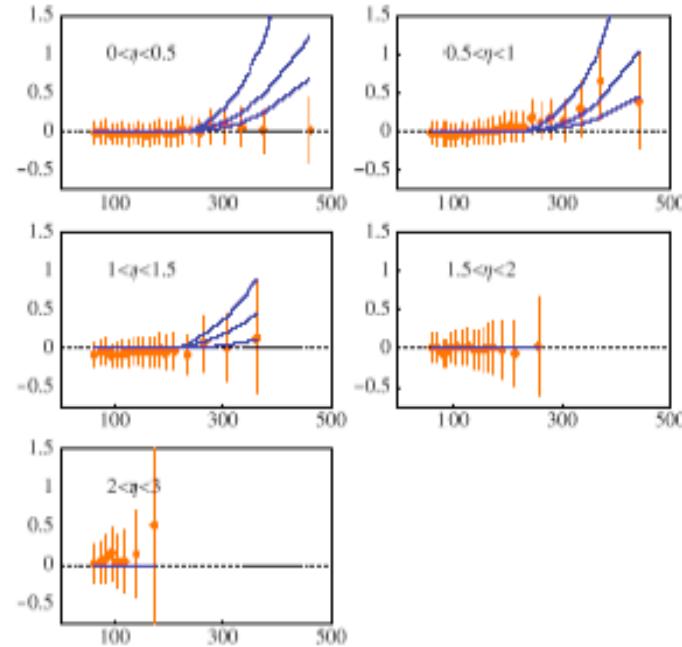
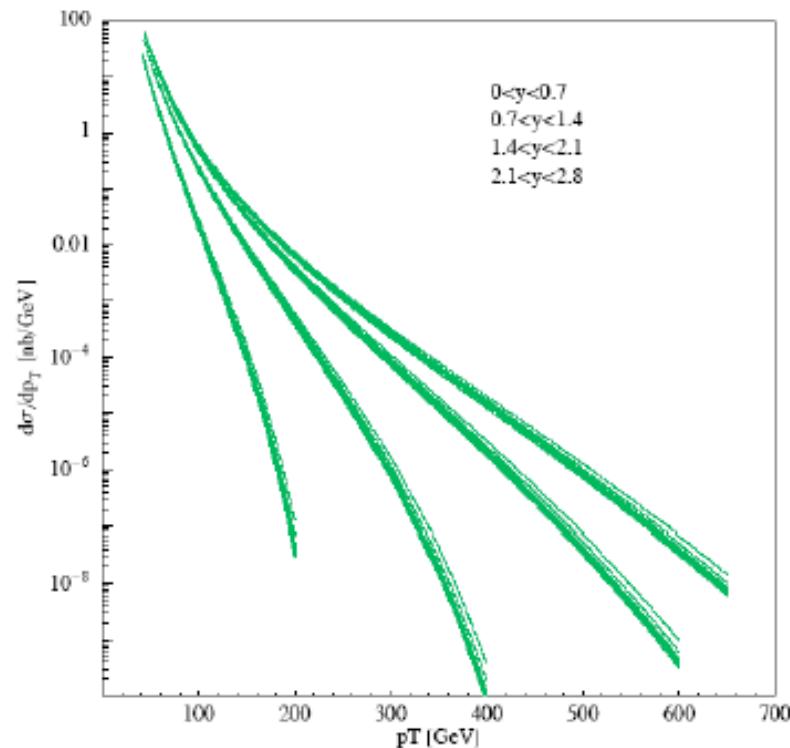


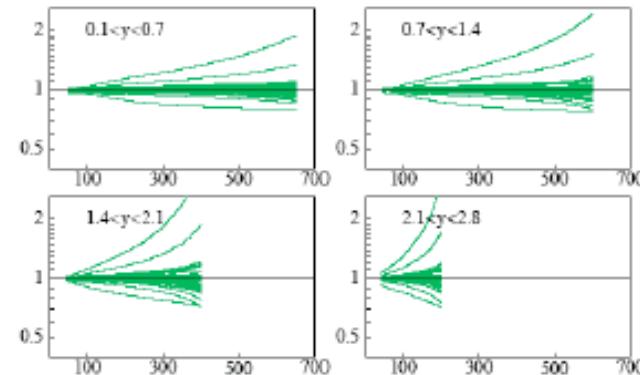
FIG. 23: Comparison of three models in which a hypothetical contact interaction contributes to jet production. The ordinate is the fractional difference between the model and the standard theory; the abscissa is the jet E_T in GeV. The contact interaction has $\Lambda = 1.5$, 2.0, and 2.4 TeV for the three curves. In all cases the PDF's are the standard CTEQ6.1N. The D0 data are superimposed for comparison.

We now have the technology to calculate pdf uncertainties for any cross section

- CDF will measure the inclusive jet cross section in the forward regions as well



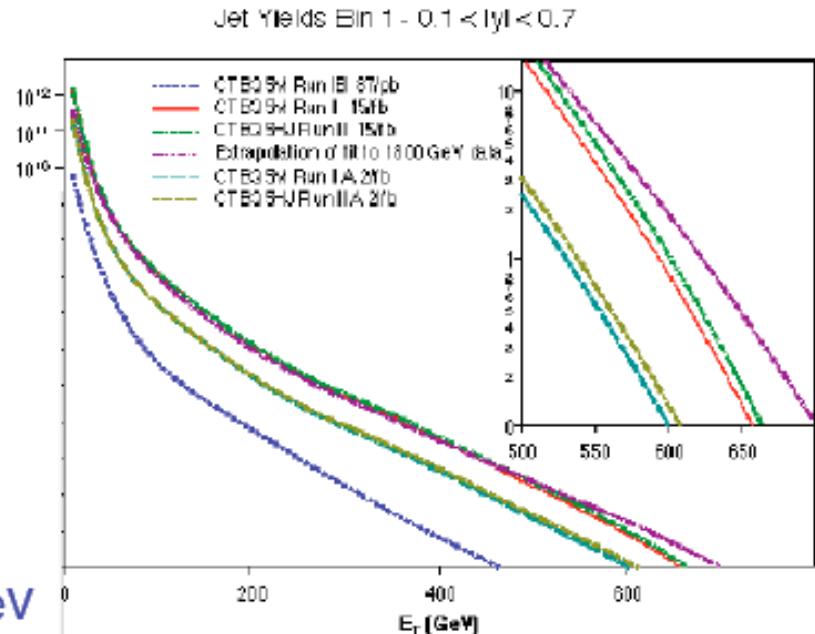
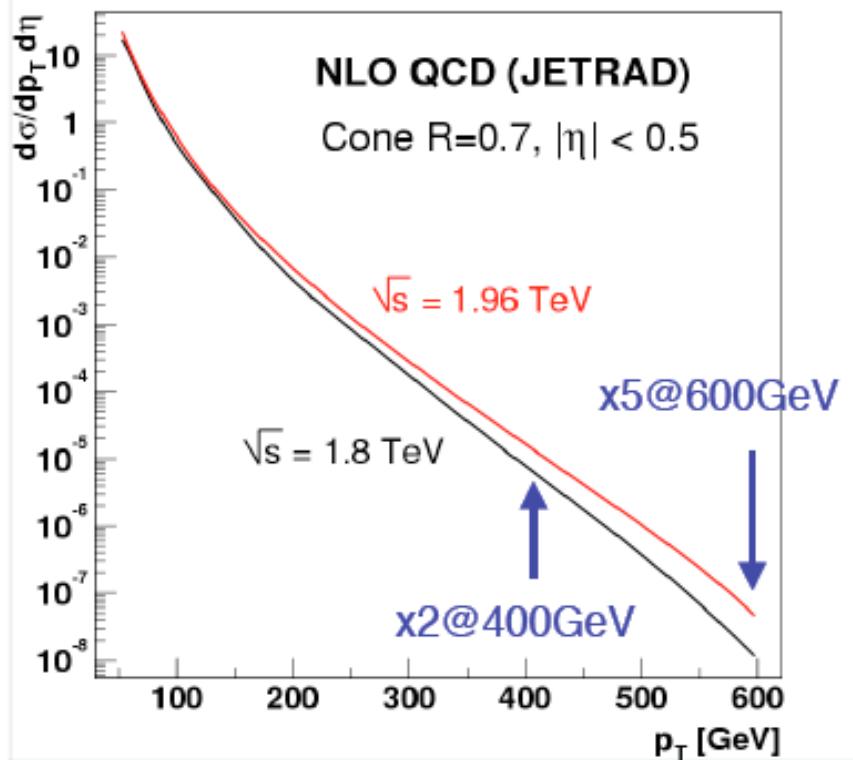
See, for example, hep-ph/0303013



NB: new physics is primarily central;
a pdf explanation should work everywhere

Jet Production in Run 2

- Nowhere else is the increase in center of mass energy appreciated so much



See

[http://www.pa.msu.edu/~huston/
run2btdr_qcd/tdr.ps](http://www.pa.msu.edu/~huston/run2btdr_qcd/tdr.ps)

Highest E_T jet observed in Run 2

Run 152507 event 1222318

Dijet Mass = 1364 GeV (corr)

$\cos \theta^* = 0.30$

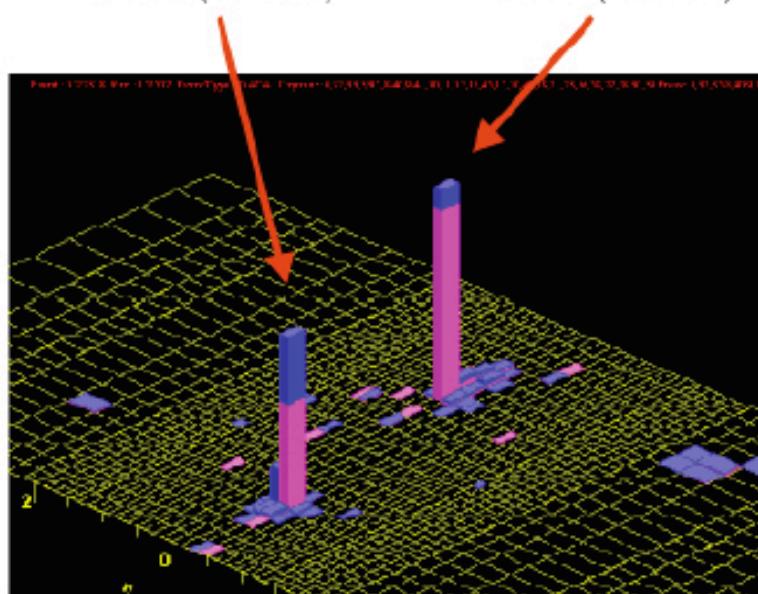
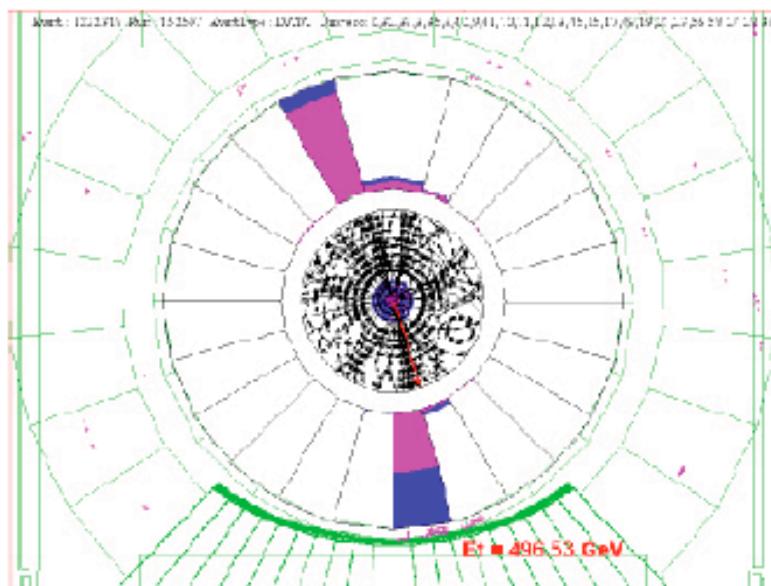
z vertex = -25 cm

$J2 E_T = 633$ GeV (corr)
546 GeV (raw)

$J2 \eta = -0.30$ (detector)
= -0.19 (correct z)

$J1 E_T = 666$ GeV (corr)
583 GeV (raw)

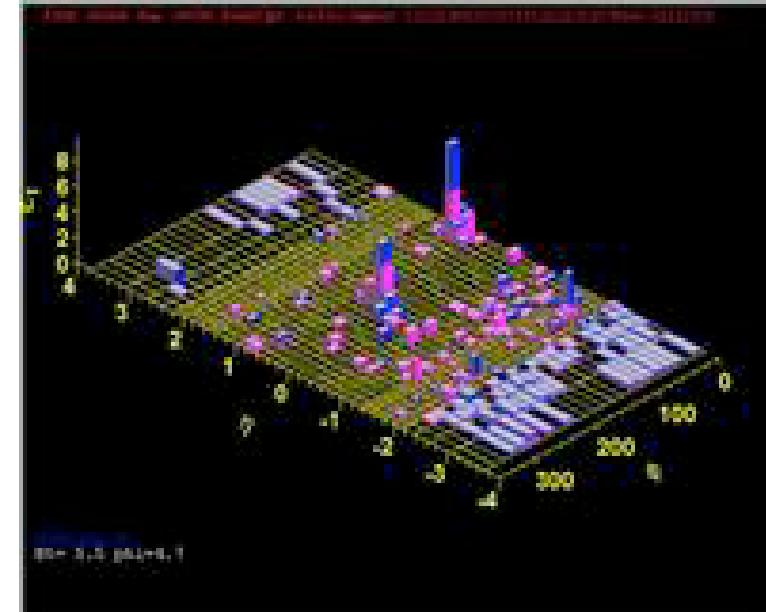
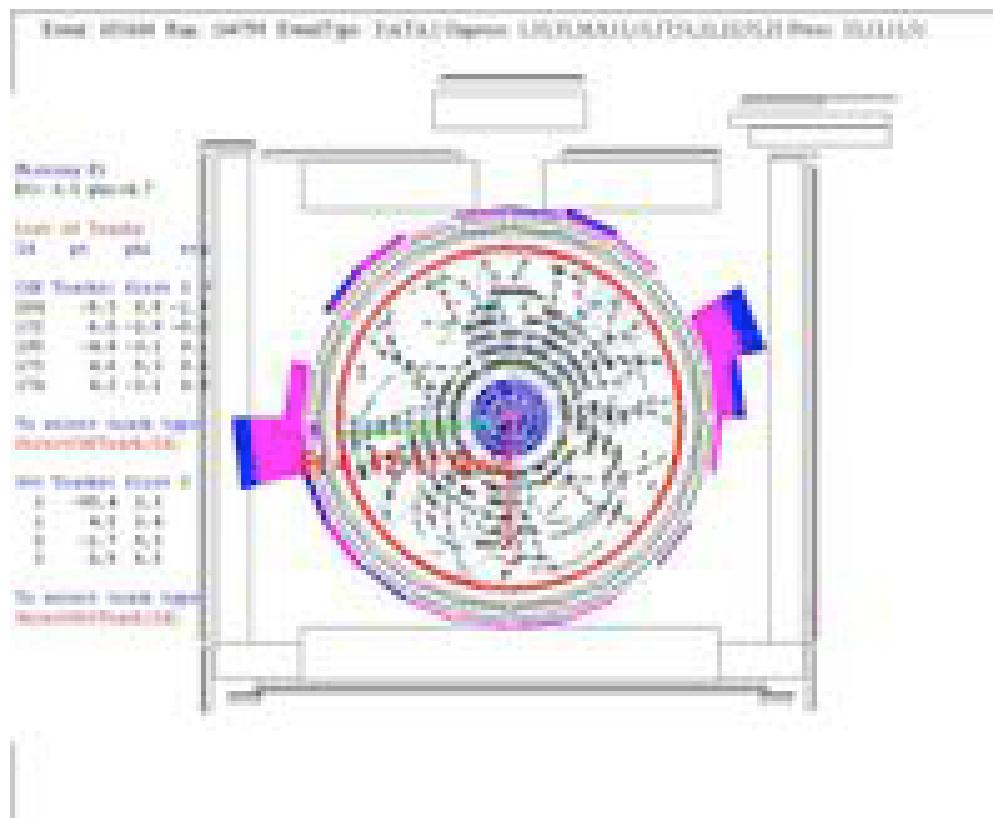
$J1 \eta = 0.31$ (detector)
= 0.43 (correct z)



CDF Run 2 Preliminary

A good screensaver

- Live events from CDF
 - ◆ http://www.fnal.gov/pub/now/live_events/index.html



LHC

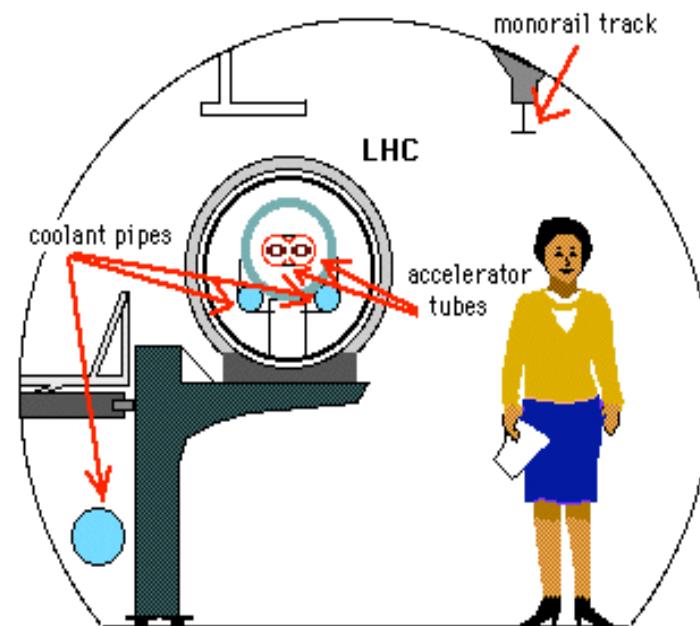
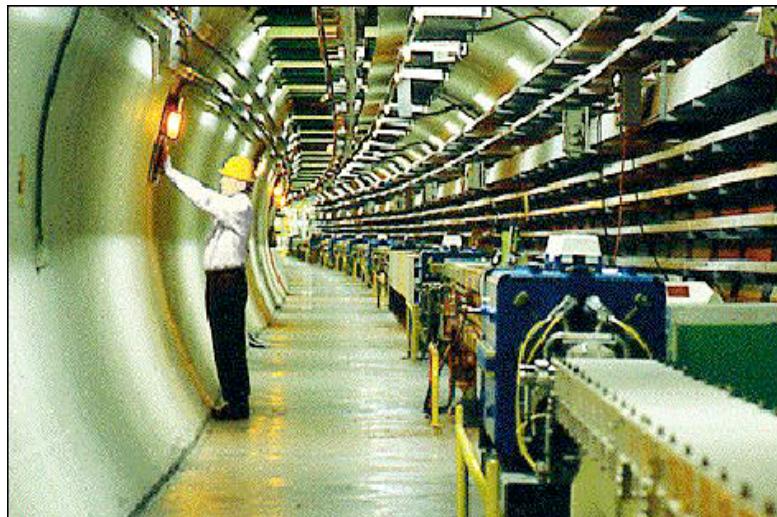
- The Large Hadron Collider (LHC) is an underground accelerator 26.7 km in circumference that collides protons on protons at a center-of-mass energy of 14 TeV

The accelerator straddles the border between France and Switzerland



LHC Tunnel

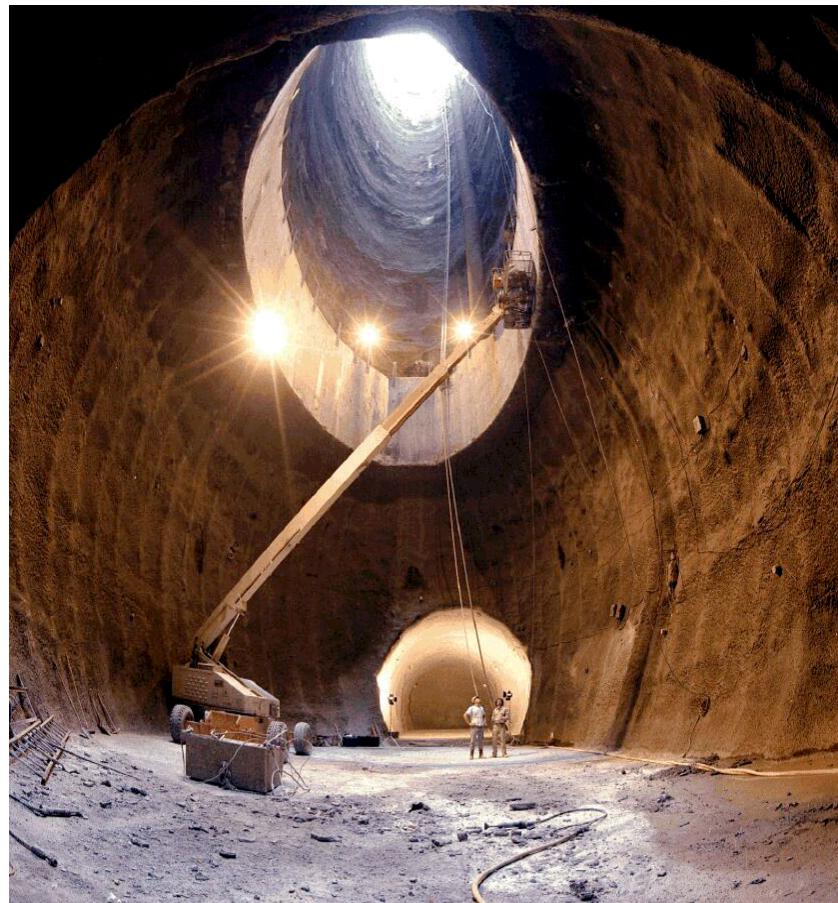
The LHC sits inside the tunnel currently occupied by LEP (an electron-positron collider)



Does anyone remember the SSC?

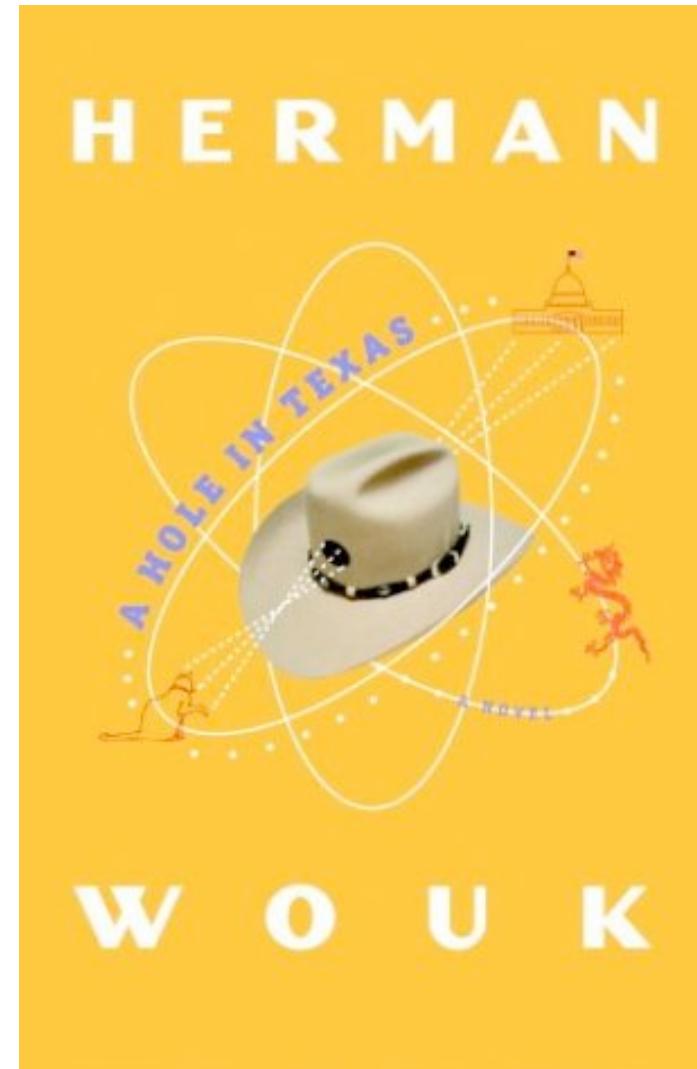
- The goal of the experiments at the LHC is to explore the TeV mass range
 - ◆ $7 \text{ TeV} \times 7 \text{ TeV} = 49 \text{ TeV}$
 - ◆ ...but the collisions are between the quarks and gluons rather than the protons per se
 - ◆ ...and the quarks and gluons only carry a fraction (typically small) of the proton's momentum
- The SSC would have had a circumference of 40 miles and an energy of 40 TeV...but with the same goal
- The LHC is stuck with the LEP tunnel (but magnets are improved over SSC design)
 - ◆ ->increase intensity of proton-proton collisions by factor of 10 over SSC design

One of the SSC shafts and experimental halls



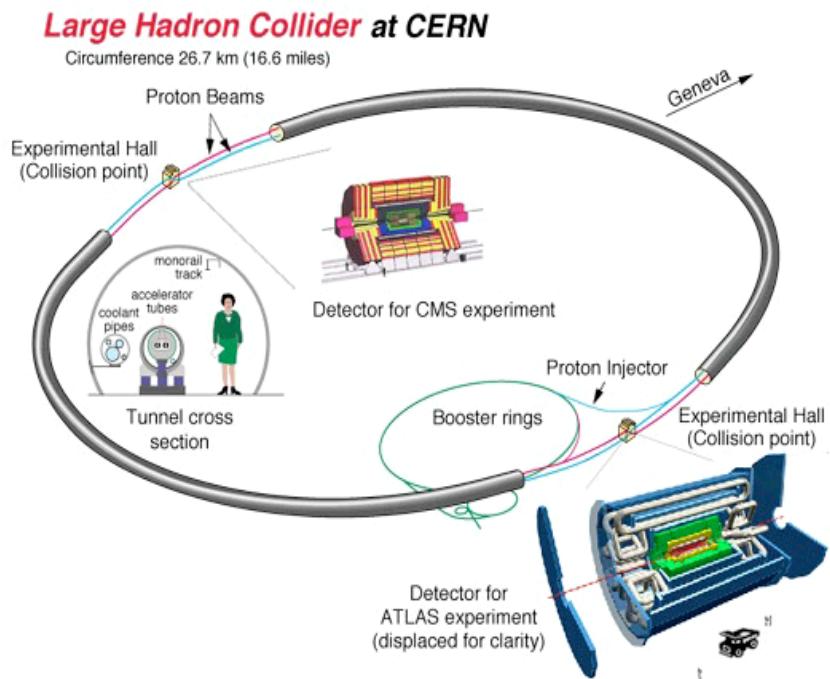
Relive the SSC

- Read “A Hole in Texas”
- Keith will also sign copies of this book



ATLAS and CMS

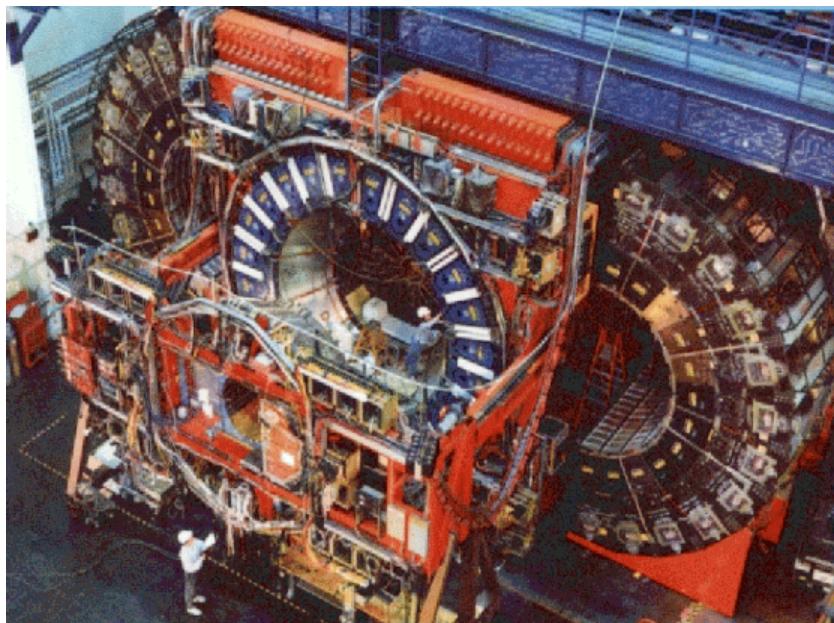
- Like the Tevatron, there are two major experiments observing the collisions at the LHC (ATLAS and CMS)



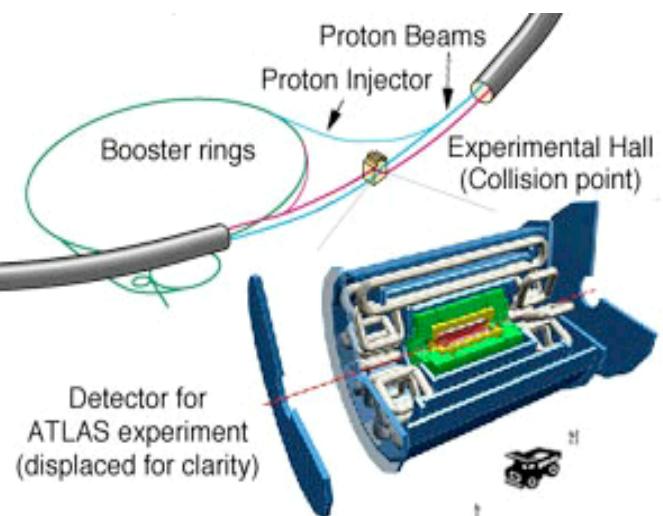
ATLAS and CDF

Typically, use a person standing next to the detector to show the scale

ATLAS uses a dump truck



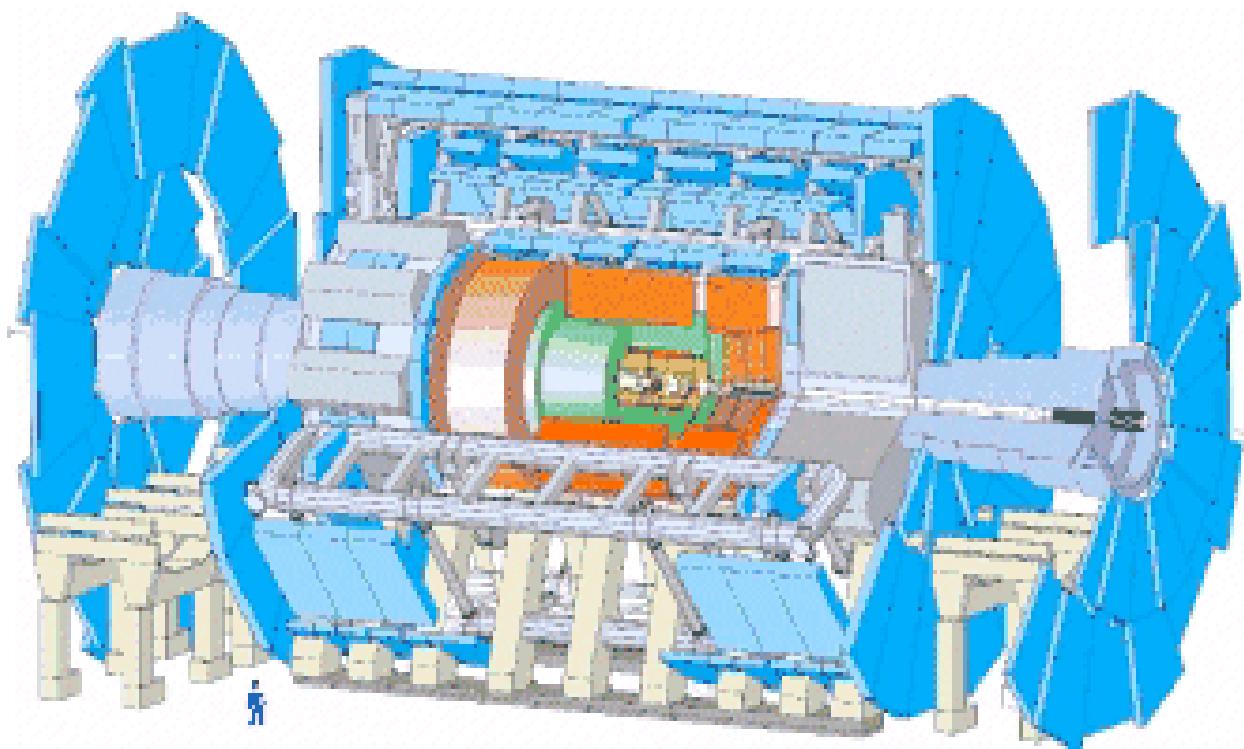
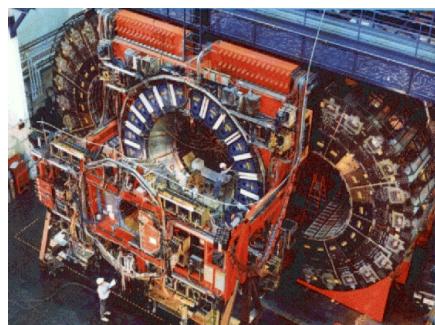
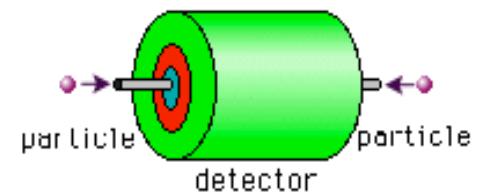
LHC
Ring



CDF

CDF and ATLAS

- Scale the size of one little man to the other



ATLAS Site

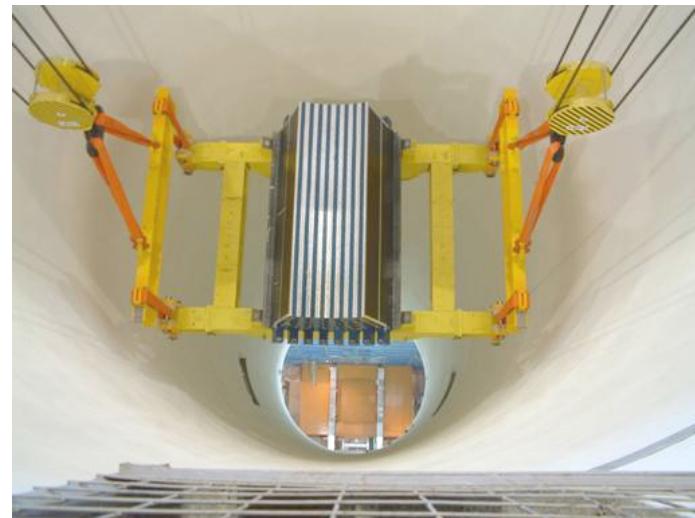


ATLAS cavern (last week)



Slow process of assembling the detector

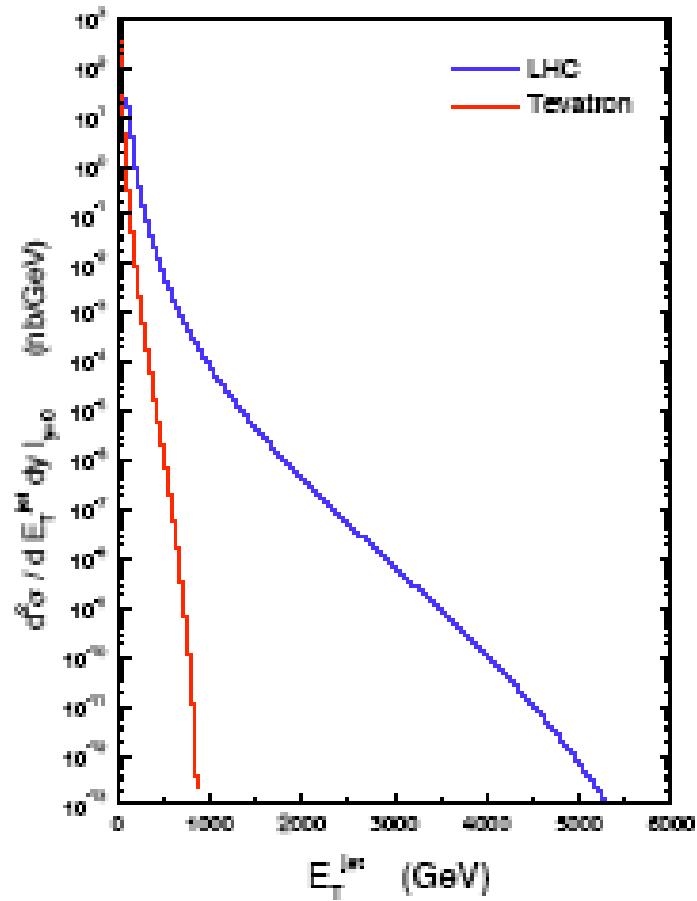
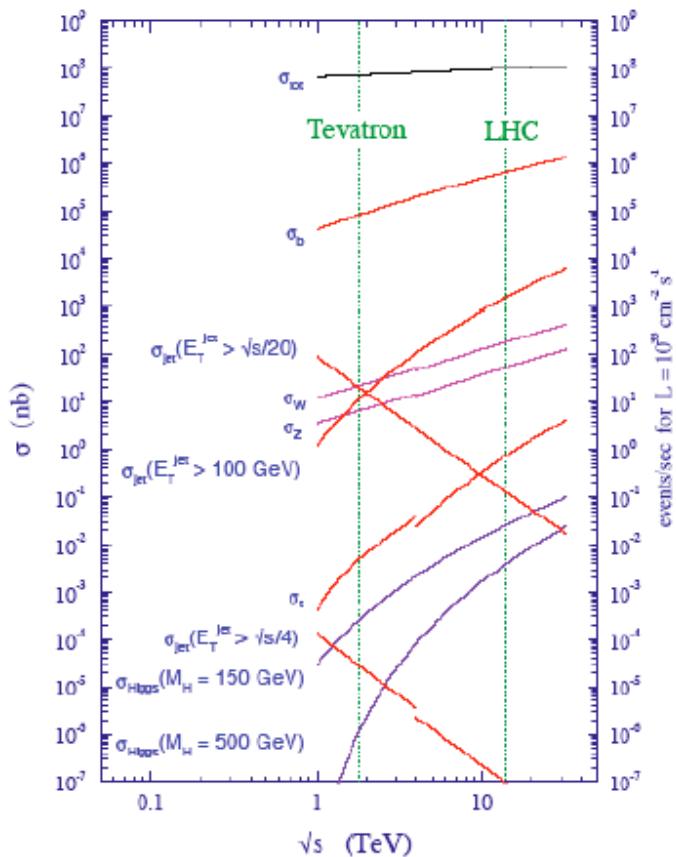
- 100 m deep access shaft to experimental hall



Jet production at the LHC

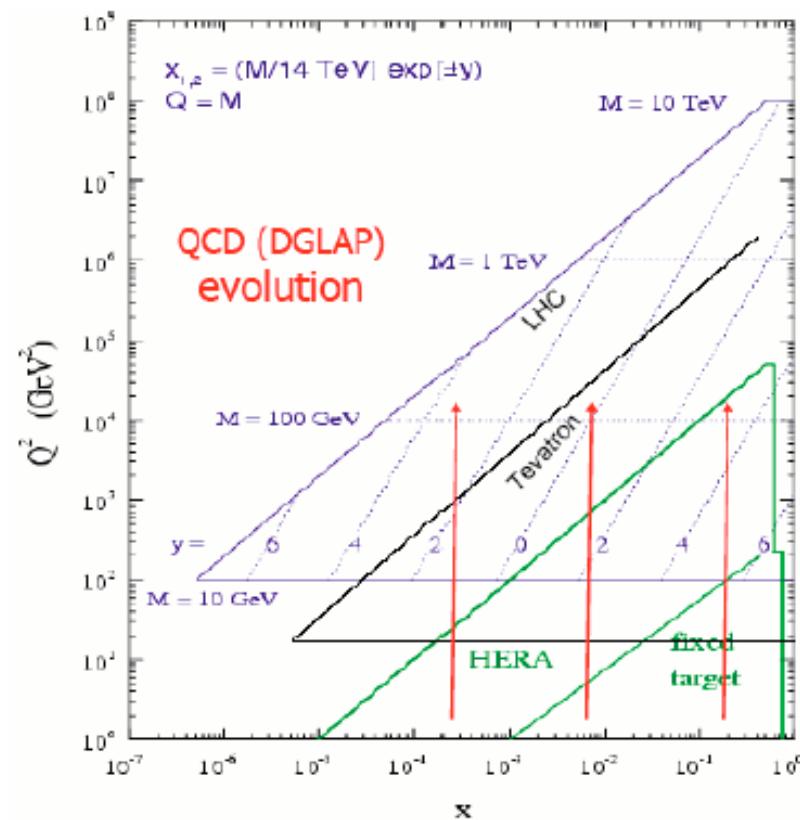
- The increased center of mass energy means the LHC will go far beyond anything that we can measure at the Tevatron

proton - (anti)proton cross sections



LHC kinematics

- Kinematic regime for LHC much broader than currently explored
 - ◆ for example, HERA covers most of the relevant x range but at much smaller values of Q^2
- Is NLO DGLAP evolution sufficient for LHC?
- Do we need NNLO? Will we ever need BFKL?
- Currently there are several approximate NNLO fits
 - ◆ MRST
 - ◆ Alekhin
- For a true NNLO fit, will need to include jet cross section at NNLO



Predictions for the LHC

- Current pdf uncertainty is similar to that for the Tevatron
- Should be greatly reduced, if not at the Tevatron, then in the early running...but how much?

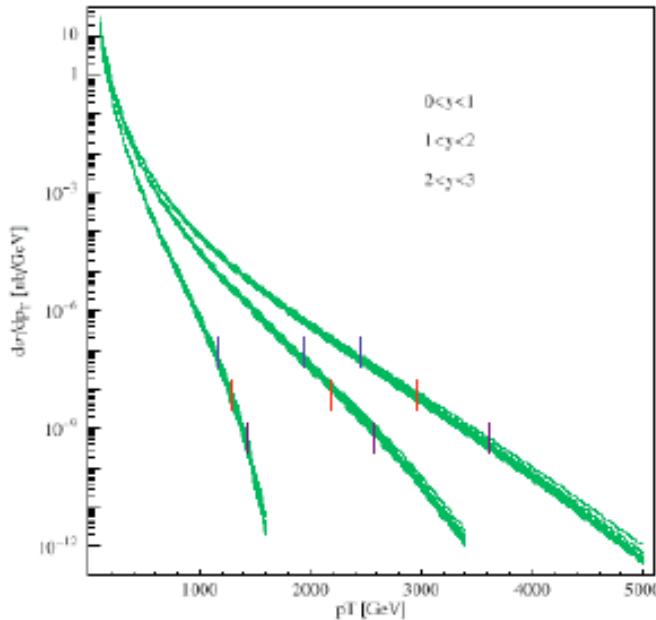


FIG. 30: The inclusive jet cross section as a function of p_T for three rapidity bins at the LHC. The three rapidity ranges are $(0,1)$, $(1,2)$ and $(2,3)$. Predictions of all 40 eigenvector basis sets are superimposed.

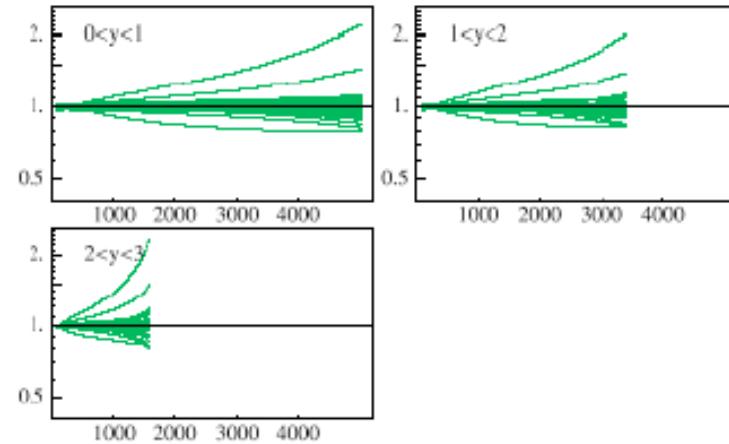


FIG. 31: The uncertainty range of the inclusive jet cross section at the LHC. The curves are graphs of the ratios of the cross sections for the 40 eigenvector basis sets compared to the central (CTEQ6.1M) prediction (ordinate) versus p_T in GeV (ordinate).

after 1 fb-1
after 10 fb-1
after 100 fb-1

at level of 1 event per
10 GeV

Looking forward to physics in 2007

