Production and Evolution of High-Energy Jets

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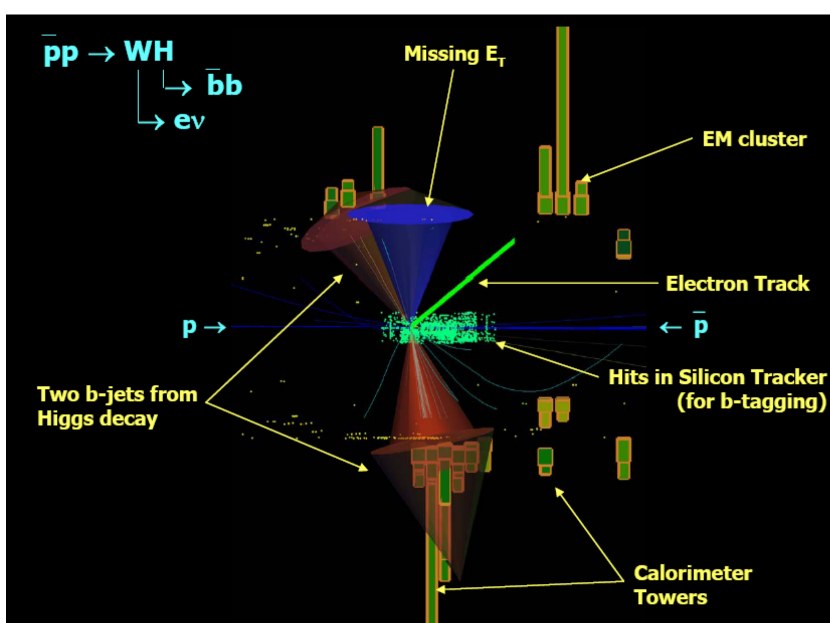
Outline

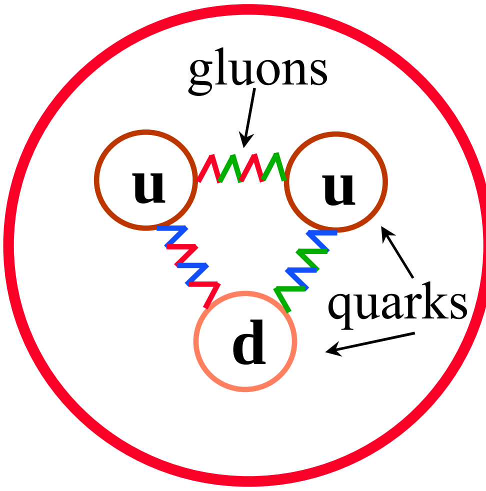
- Introduction
  - Processes under study (ee, ep, p$\bar{p}$)
  - Kinematics
  - What is a jet; jet algorithms
- Jet Characteristics
  - Jet energy profile
  - Differences between Quark and Gluon jets
  - Color coherence effects
- Jet Production at Tevatron
  - Challenges with jets
  - Inclusive jet cross sections
  - Jet cross section scaling
  - Search for quark substructure
- Outlook



Quantum ChromoDynamics (QCD)

QCD : Theory of Strong Interactions

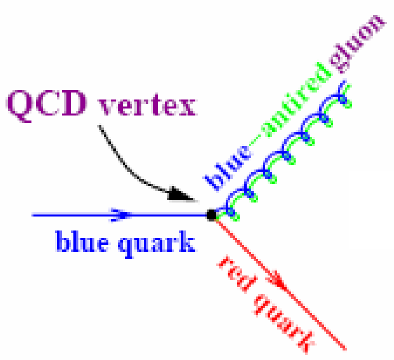
Proton



Partons = quarks & gluons

Similar to QED BUT Different

- Pointlike particles called quarks
- Six different "flavors" (u, d, c, s, t, b)
- Quarks carry "color" - analogous to electric charge
- There are three types of color (red, blue, green)
- Mediating boson is called gluon - analogous to photon
- Color charge is conserved in quark-quark-gluon vertex
- Gluons carry two color "charges" and can interact to each other – very important difference from QED - from Abelian to non-Abelian theory
- At large distances: parton interactions become large **(confinement)**
- At small distances: parton interactions become small **(asymptotic freedom)**



Coupling constant $\rightarrow \alpha_s$ (analogous to α in QED)

Free particles (hadrons) are colorless

Historic Perspective

1960

← Introduction of Color and the Quark Model

SLAC

← Experimental evidence of quarks in DIS scattering
Bjorken scaling

1970
ISR

← Birth of QCD
Renormalizability, Asymptotic Freedom, Confinement

← Discovery of the c-quark (SLAC, BNL)

← Experimental evidence of jets in e^+e^- annihilations
as manifestation of quarks (1975) and gluons (1979)

PETRA

← Discovery of the b-quark (Fermilab)

← Violation of Bjorken scaling, Evolution of Parton
Distribution and Parton Fragmentation Functions

1980
$Sp\bar{p}S$

← Computation of higher-order effects in pQCD
for many processes

← Discovery of W and Z – Confirmation of
Standard Model

Tevatron
LEP
HERA ↘
1990
D0+CDF

← Next to Leading Order pQCD predictions for jet
production

LEP 2

← Discovery of the t-quark (Fermilab)

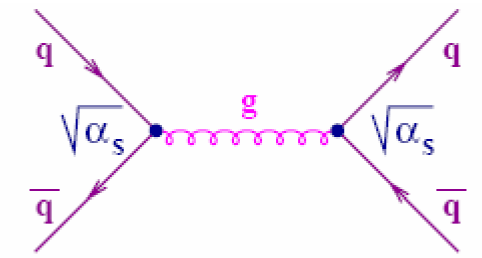
← Precision EW Data – LEP 2

2000

← Tevatron Upgrade, Run II

The "Running" α_s

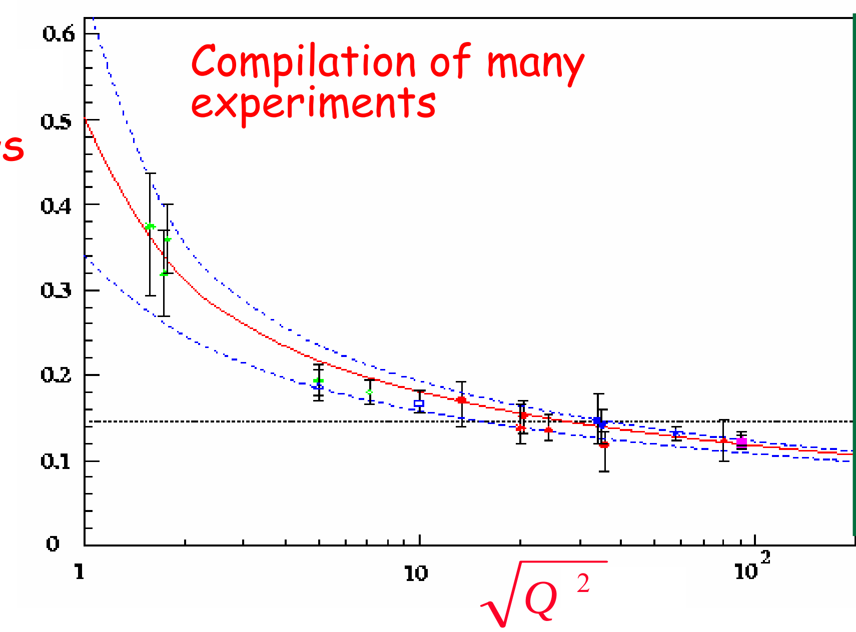
SU(3) gauge coupling constant (α_s) varies with Q^2, decreasing as Q^2 increases:



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

Leading-Log Approximation

Measurements of the strong coupling are made in many processes at different Q^2, clearly establishing the running of α_s.



Increase of α_s as $Q^2 \to 0$ means that color force becomes extremely strong when a quark or gluon tries to separate from the region of interaction (large distance=small Q^2). A quark cannot emerge freely, but is "clothed" with color-compensating quark-antiquark pairs.

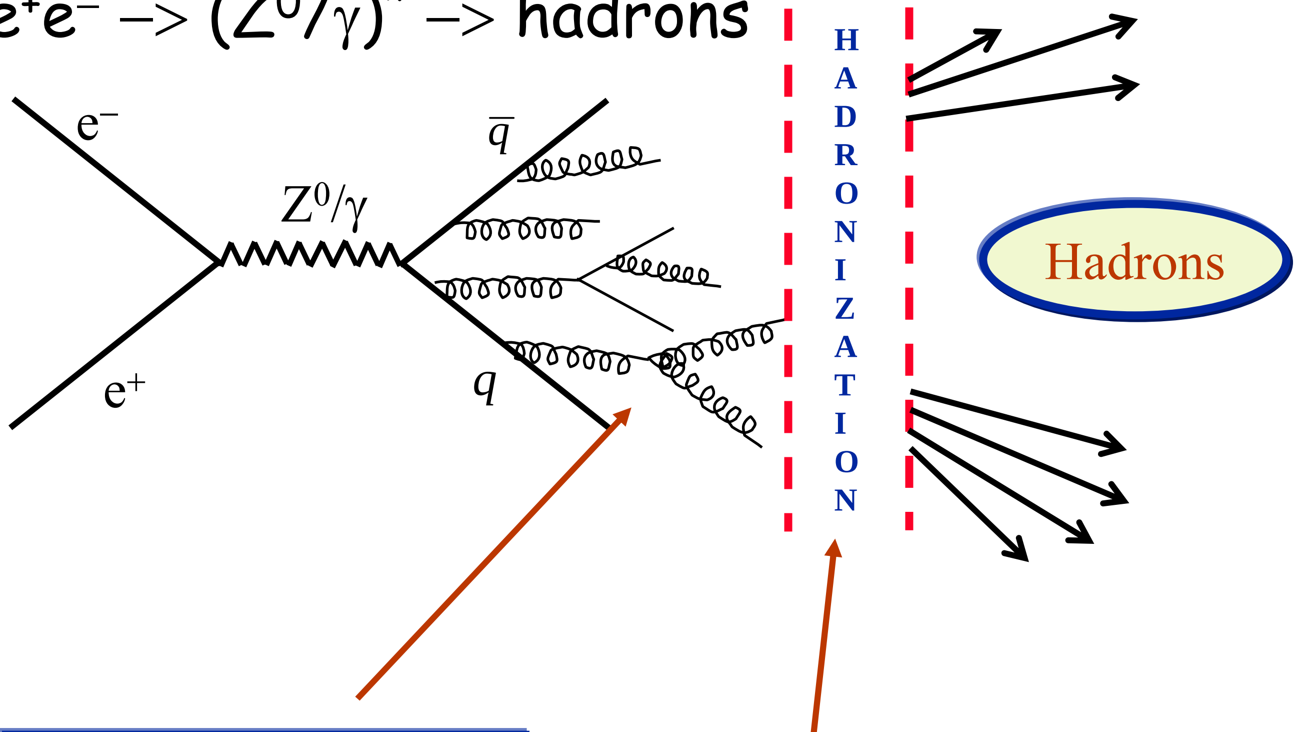
Asymptotic freedom ($\alpha_s \to 0$ as $Q^2 \to \infty$)
Infrared slavery ($\alpha_s \to \infty$ as $Q^2 \to 0$)

No free quarks or gluons ➔ origin of **jets**

QCD in e^+e^- Annihilations

LEP: 88 GeV < E_{cm} < 208 GeV
SLC: E_{cm} = 91 GeV

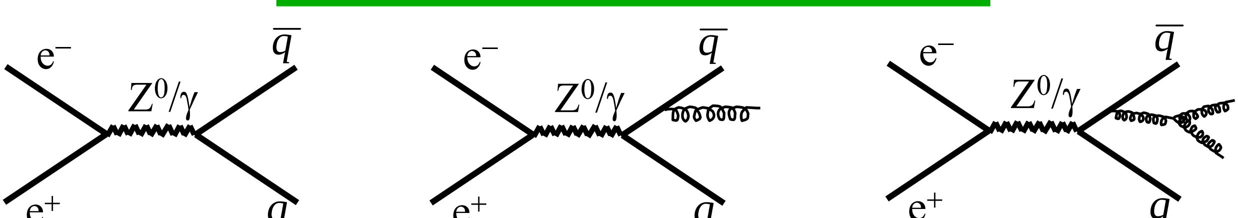
$e^+e^- \to (Z^0/\gamma)^* \to$ hadrons



Perturbative phase
$\alpha_s < 1$ **(Parton Level)**

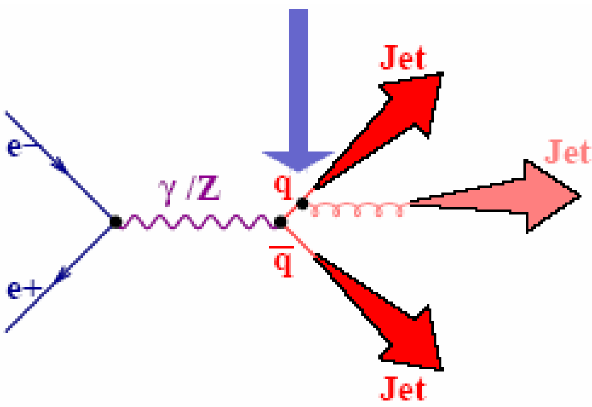
Non-perturbative phase
$\alpha_s \geq 1$ **(Hadron Level)**

Fixed Order QCD

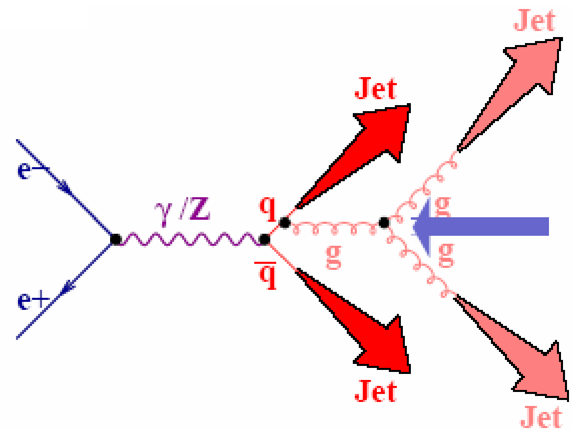


$\mathcal{O}(\alpha_s^0)$ $\mathcal{O}(\alpha_s^1)$ $\mathcal{O}(\alpha_s^2)$

Why do we Study Jets in e^+e^- ?

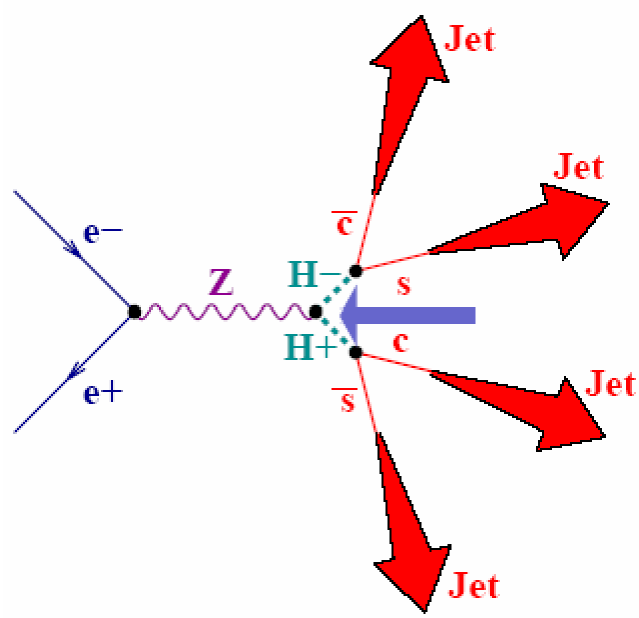


$e^+e^- \rightarrow 3\ \text{jets}$



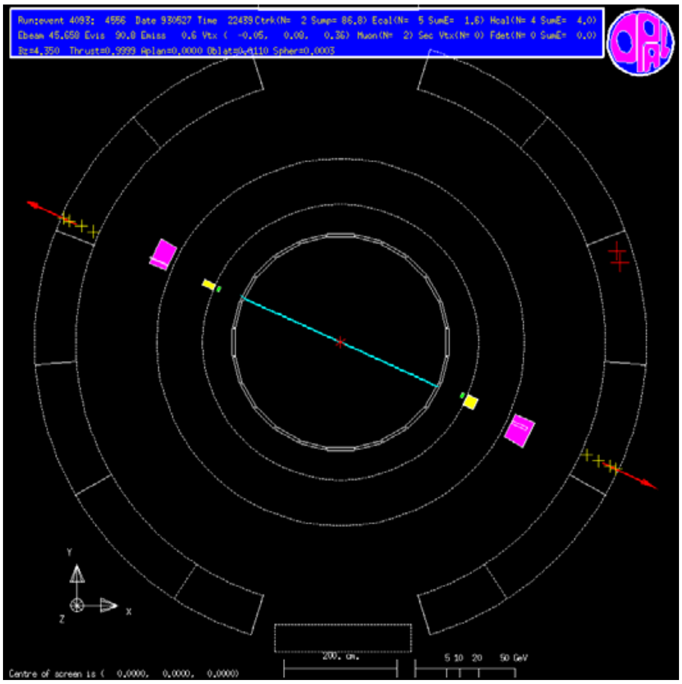
$e^+e^- \rightarrow 4\ \text{jets}$

- QCD Studies
  - Measurements of α_s
  - Fragmentation functions
  - Color/spin dynamics
  - Quark-gluon jet properties
  - Event shape variables (sphericity, thrust, …)
- Searches for the Higgs
- Searches for new physics

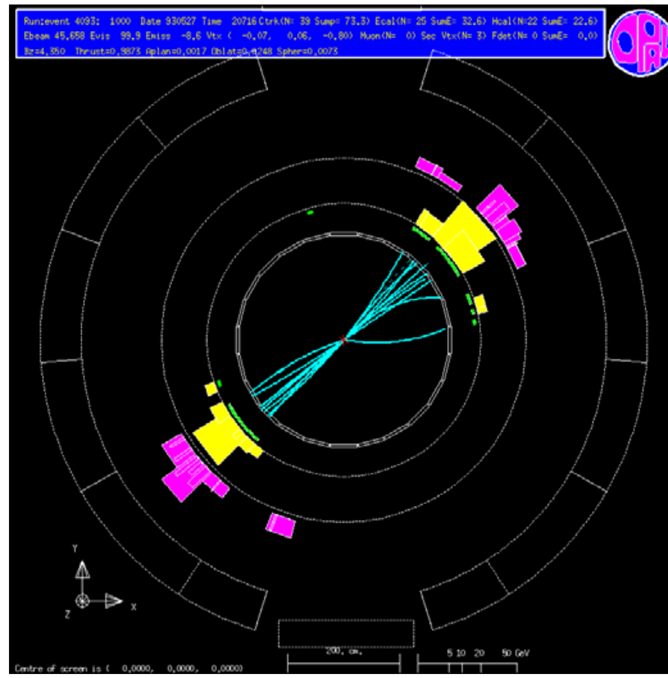


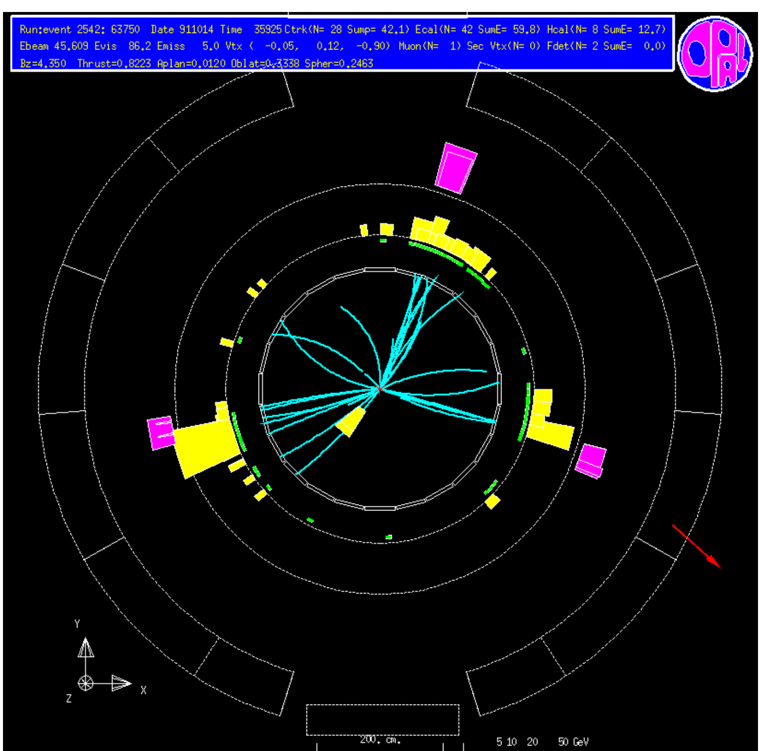
e^+e^- Event Displays

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



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

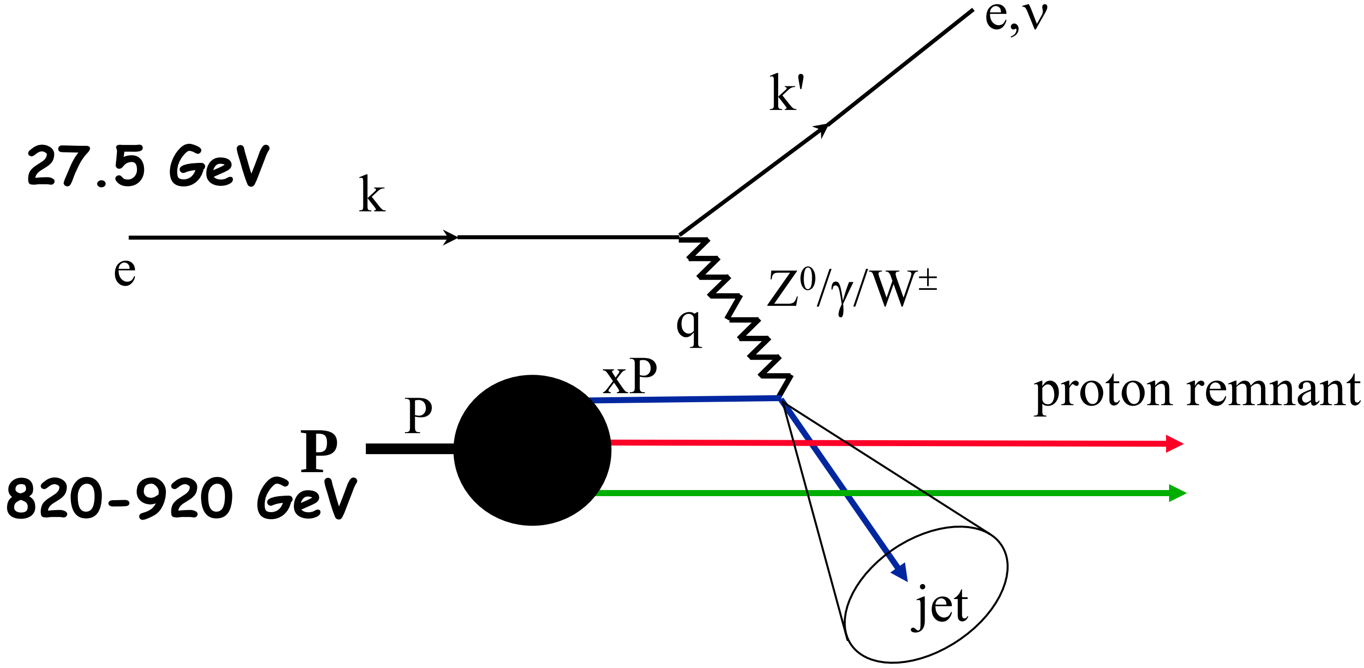




$e^+e^- \to q\bar{q}g$

Much cleaner events than hadron-hadron collisions

QCD in ep Interactions



$k = (E, \boldsymbol{k})$ 4 - momentum for incoming e^-

$k' = (E', \boldsymbol{k}')$ 4 - momentum for outgoing e^-

$Q^2 = -q^2 = -(k - k')^2$ 4 - momentum transfer

$x = \dfrac{Q^2}{2P \cdot q}$ parton momentum fraction

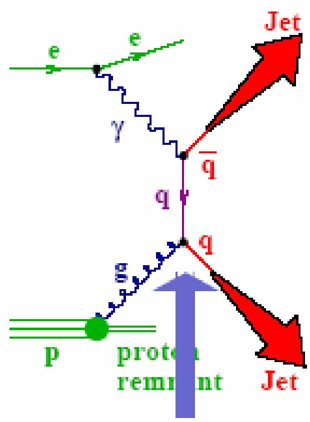
$y = \dfrac{P \cdot q}{P \cdot k} = \dfrac{E - E'}{E}$ fractional energy transfer

$s = (P + k)^2 \approx 2P \cdot k = \dfrac{Q^2}{xy}$ electron - proton mass squared

$\hat{s} = (xP + k)^2 \approx sx$ electron - parton mass squared

$$\sqrt{s} \approx 300 - 320 \text{ GeV at HERA}$$

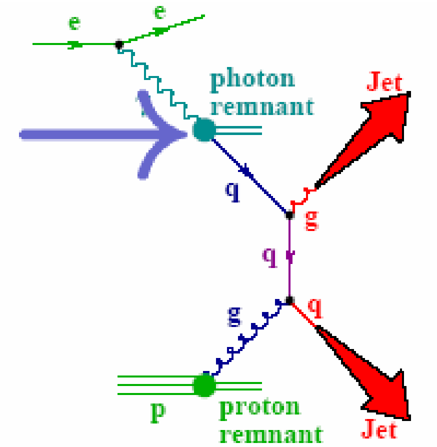
Why do we Study Jets in ep ?



→ measurements of α_s

$\gamma p \to 2\ \text{jets} + X$

Direct photoproduction

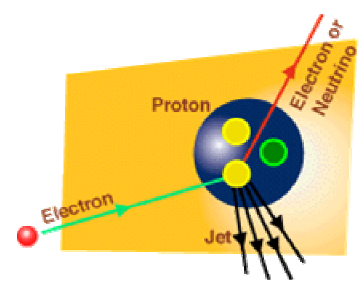


→ tests of photon structure

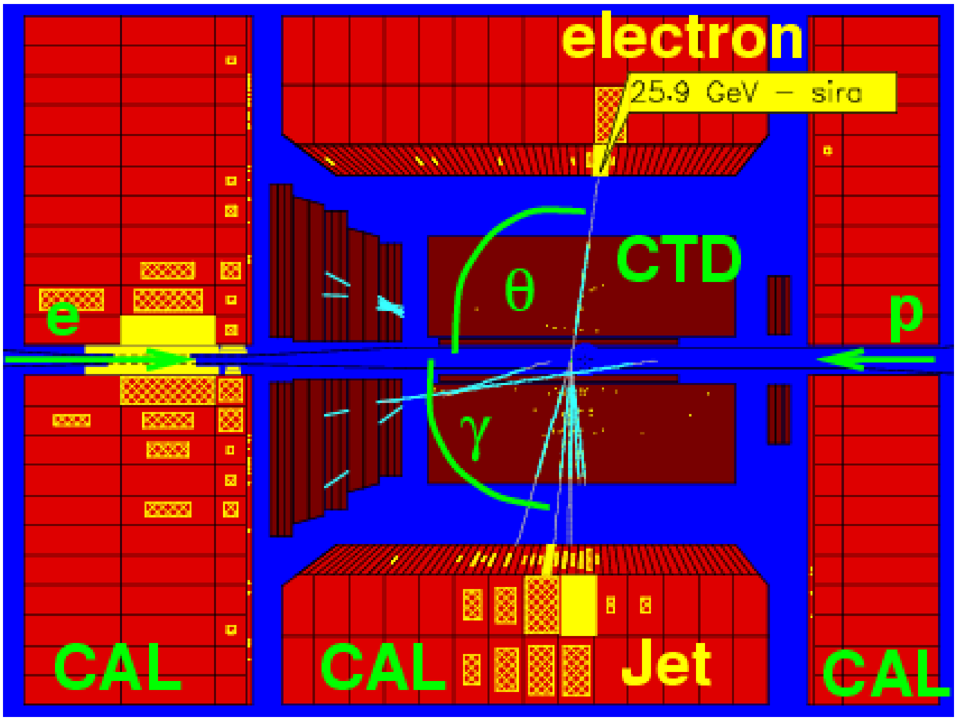
$\gamma p \to 2\ \text{jets} + X$

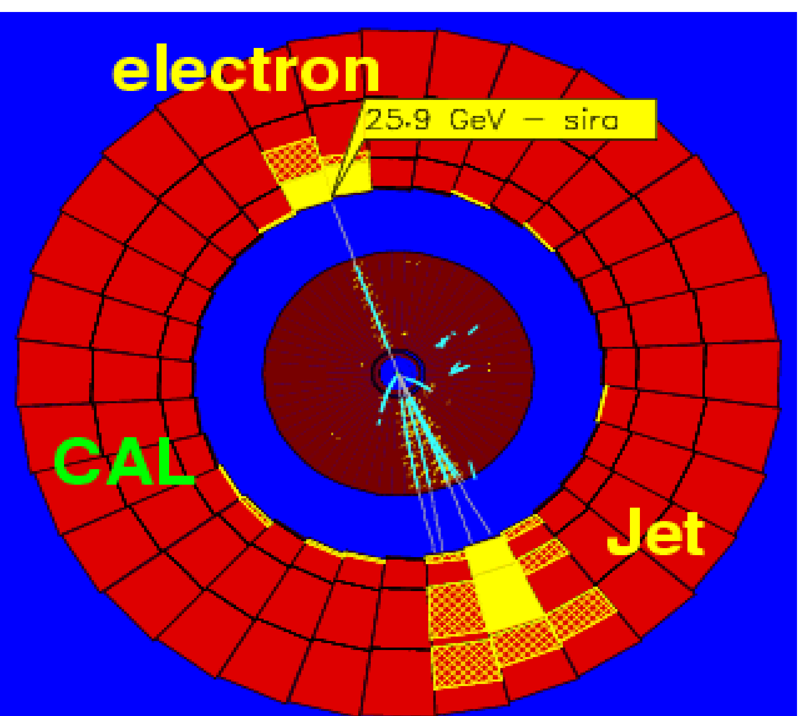
Resolved photoproduction

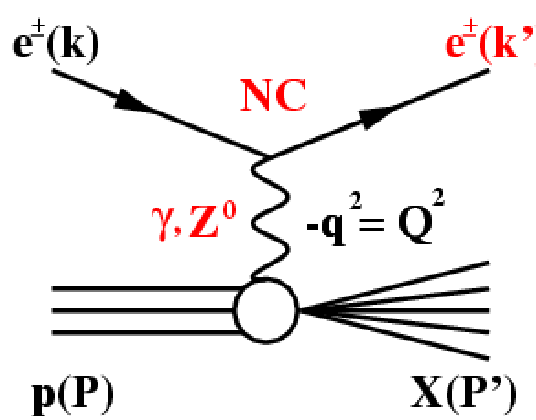
- QCD Studies
  - Measurements of α_s
  - Fragmentation functions
  - Parton Distribution Functions
  - Color/spin dynamics
  - Quark-gluon jet properties
  - Event shapes
  - Inclusive- and Multi-jet production
  - Rapidity Gaps/Diffraction
- Searches for new physics



Neutral Current ep Process

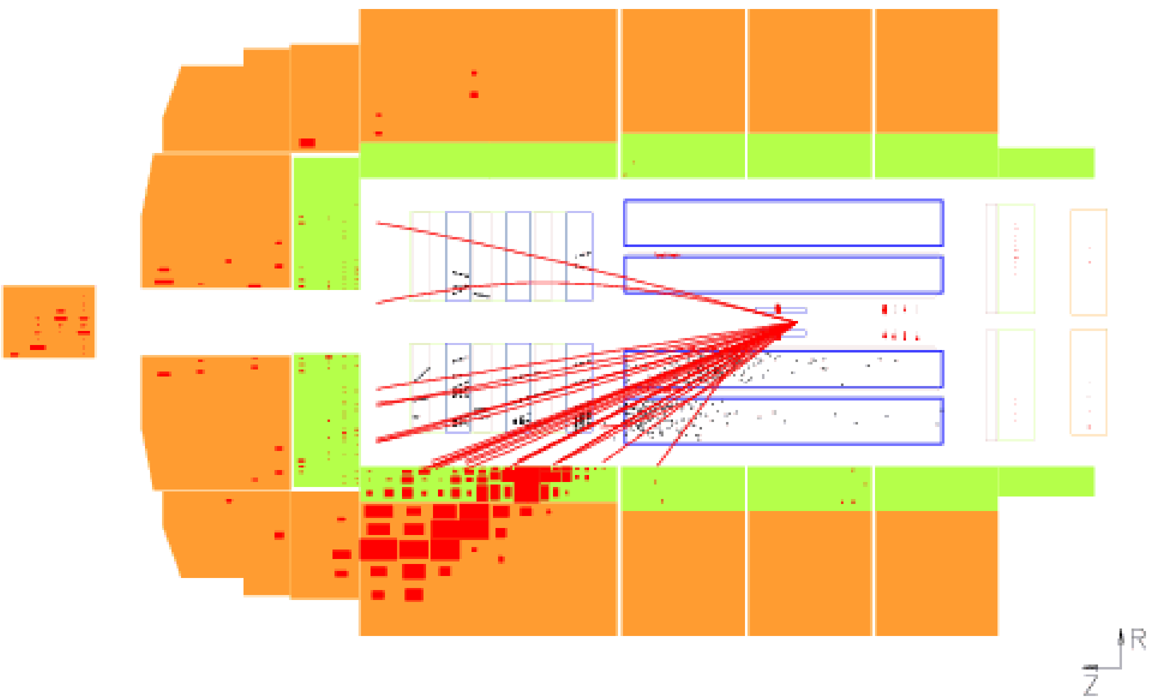


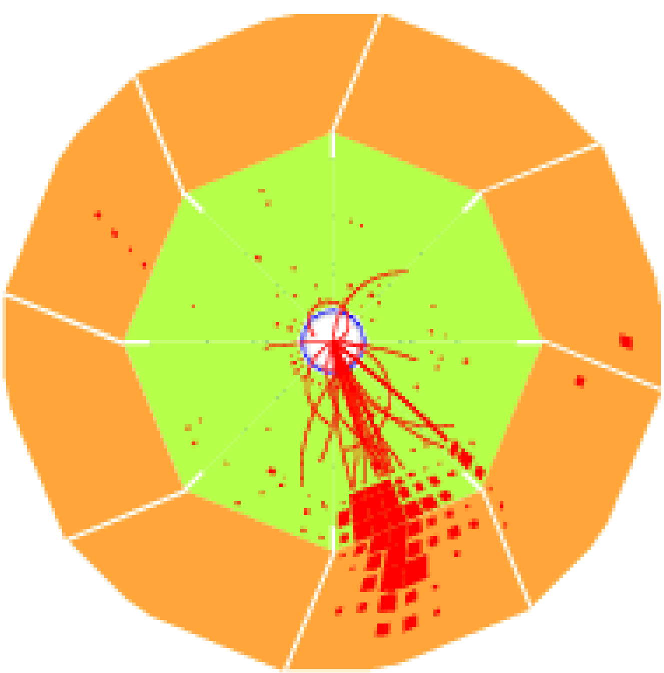


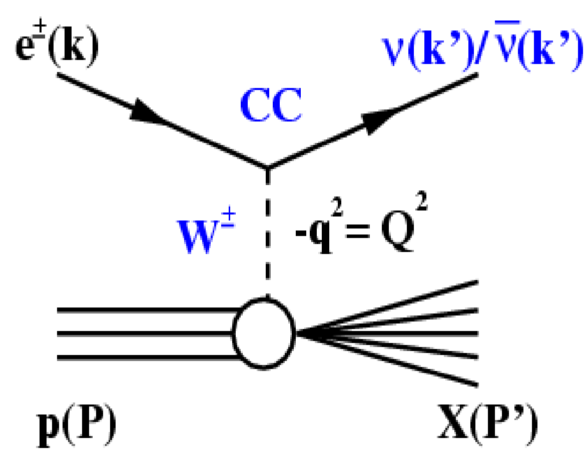


Charge Current ep Process

*Q**2 = 21475   y = 0.55   M = 198*

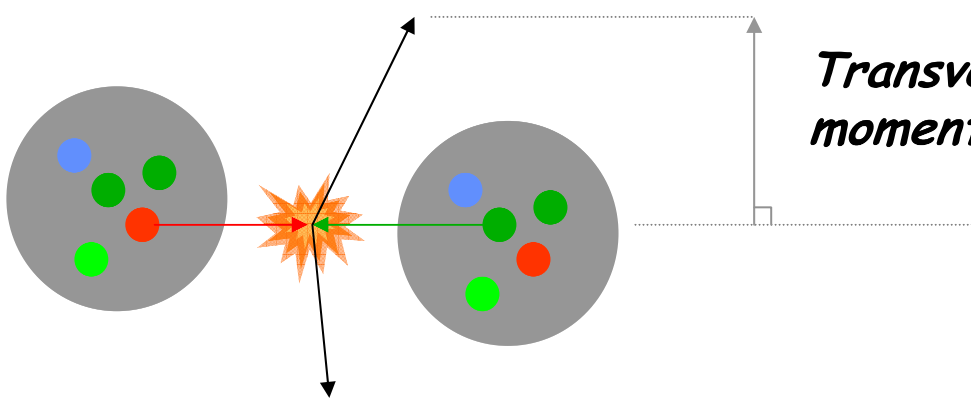






Proton-Antiproton Collisions

- **Proton beams can be accelerated to very high energies (good)**
- **But the energy is shared among many constituents – quarks and gluons (bad)**



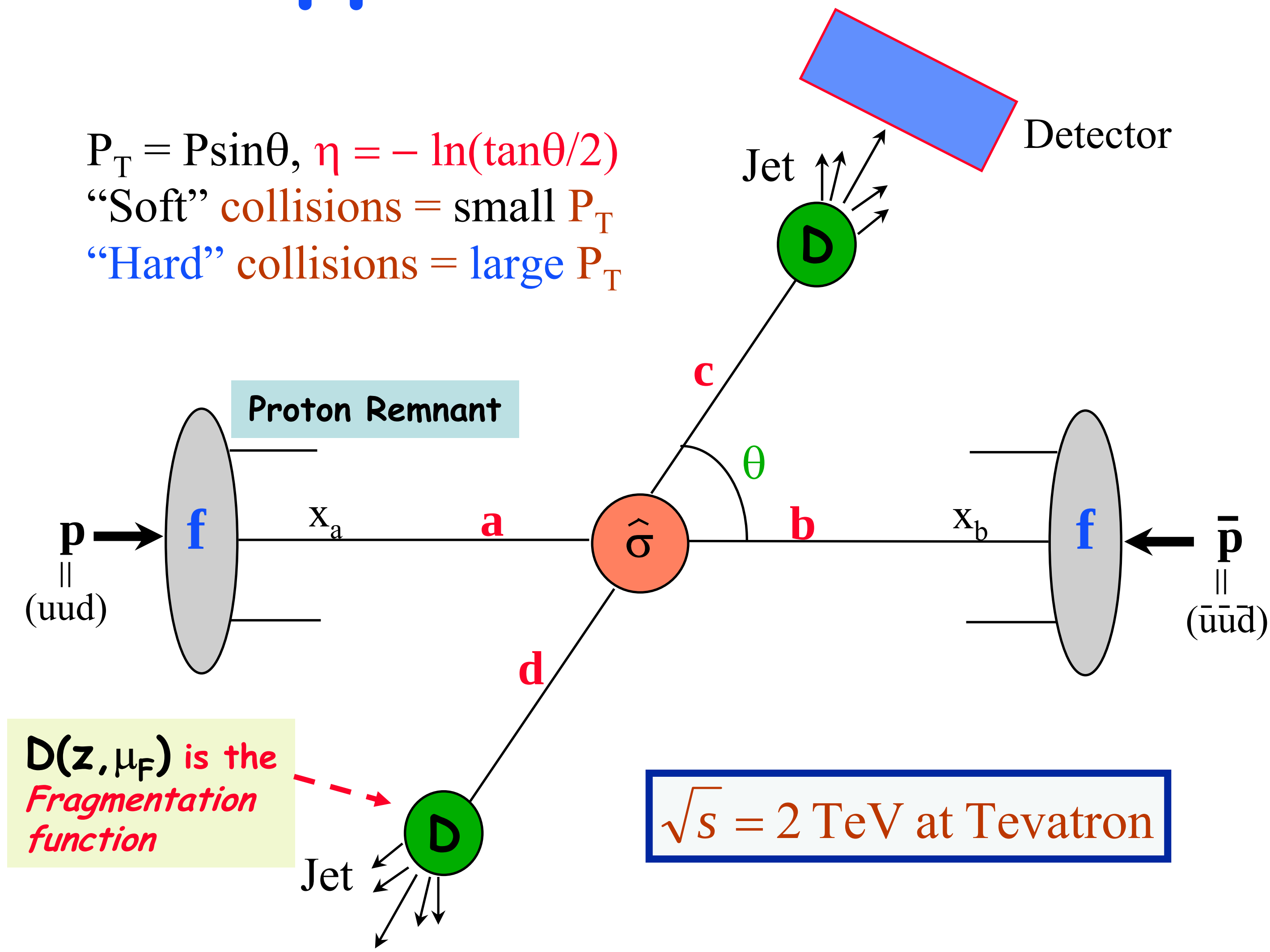
- **To select high-energy collisions: look for outgoing particles produced with high momentum perpendicular to the beamline ("transverse momentum") → *hard collisions***
  - *Hard collisions* take place at small impact parameter and are more accurately collisions between partons inside the two protons
  - Analog of Rutherford's experiment
  - Forms the basis of the on-line event selection ("triggering")

$p\bar{p}$ Interactions

$P_T = P\sin\theta$, $\eta = -\ln(\tan\theta/2)$

"Soft" collisions = small P_T

"Hard" collisions = large P_T



$\sqrt{s} = 2$ TeV at Tevatron

- $f_{a/A}(x_a,\mu_F)$: Probability function to find a parton of type **a** inside hadron **A** with momentum fraction x_a - ***Parton Distribution Functions***

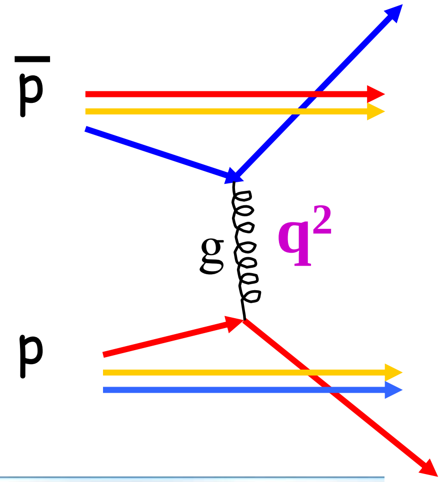
  x_a: Fraction of hadron's momentum carried by parton **a**

  μ_F: related to the "hardness" of the interaction ***"Factorization Scale"***

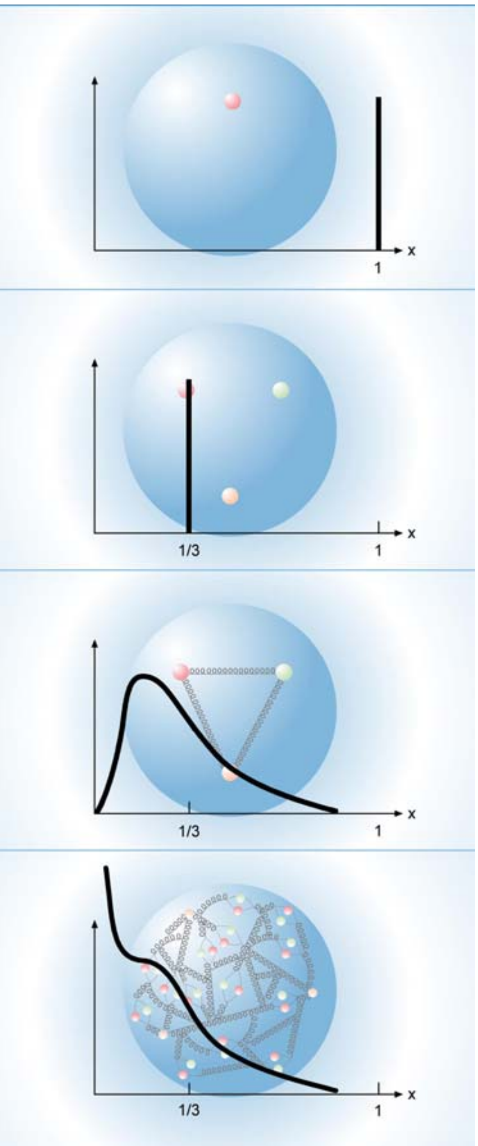
- $\hat{\sigma}(ab \rightarrow cd)$ Partonic level cross section

$p\bar{p}$ Interactions cont'd

Probing the Proton



Q is the *"four-momentum transfer"* or the *"scale"* of the interaction $Q^2 = -q^2 > 0$



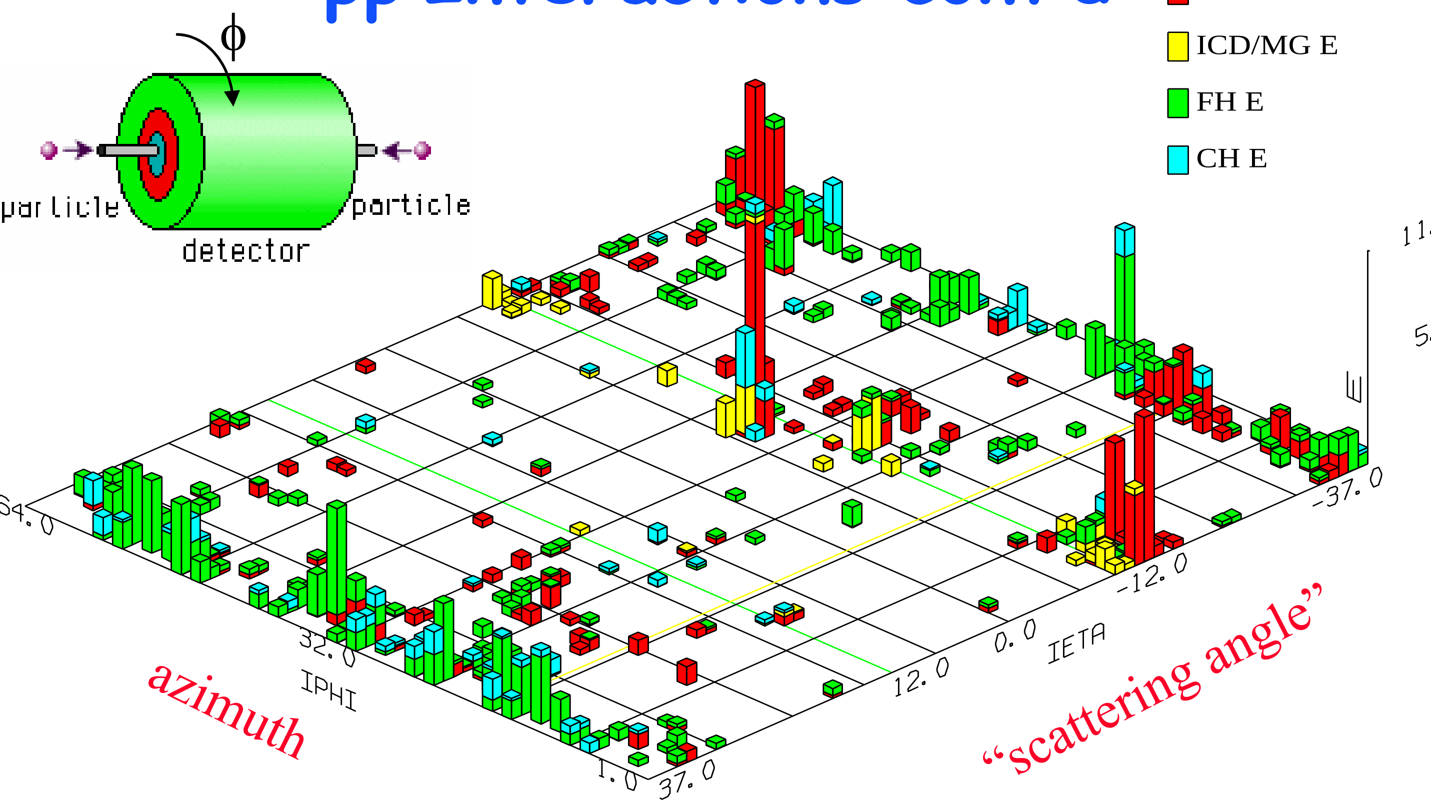
Low value

Q^2

High value

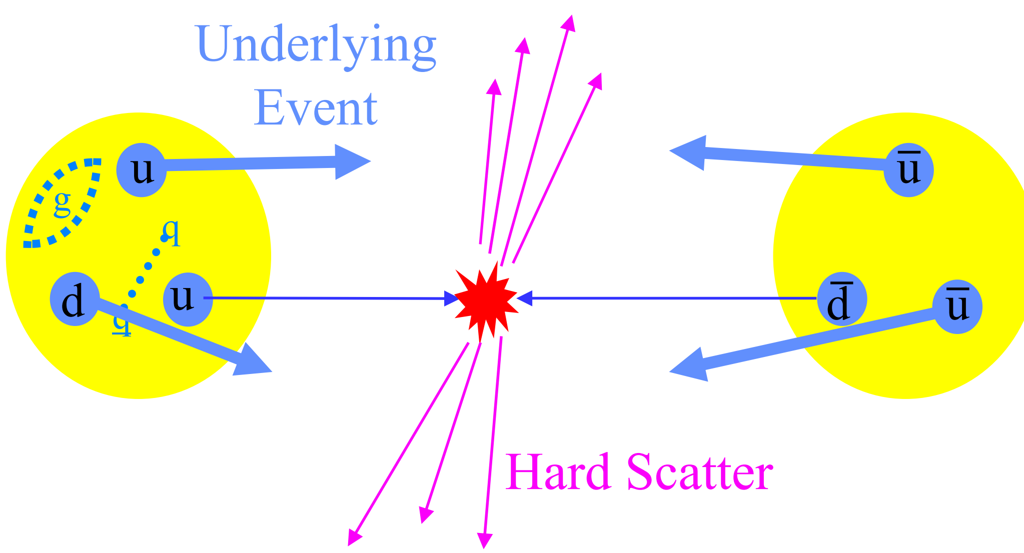
- For every proton there is a probability for a single quark (or gluon) to carry a fraction "x" of the proton's momentum
- This probability depends on the scale of the interaction Q^2.

$p\bar{p}$ Interactions cont'd



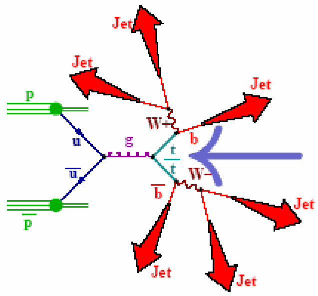
Complications from the e^+e^- due to:

- Parton Distribution Functions (PDFs)
- "Colored" initial and final states
- Remnant jets - Underlying event (UE)



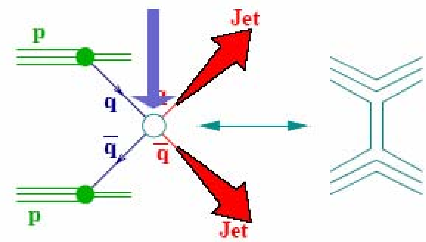
Why do we Study Jets in $p\bar{p}$?

Study of heavy particles:

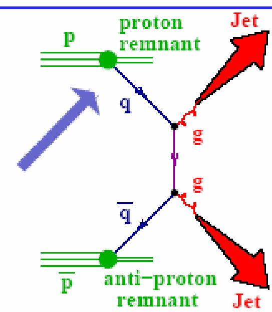


→ measurements of top quark production
$p\bar{p} \rightarrow 6 \text{ jets} + X$

Search for quark substructure:



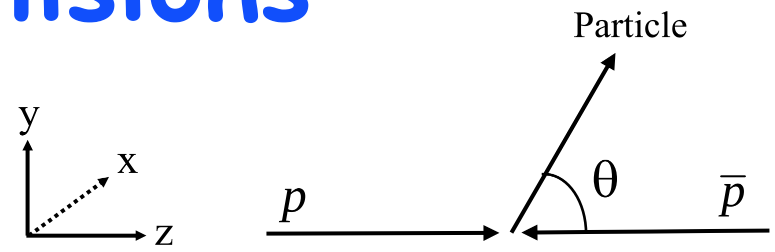
→ search for quark compositeness
$p\bar{p} \rightarrow 2 \text{ jets} + X$



→ tests of the proton structure function
$p\bar{p} \rightarrow 2 \text{ jets} + X$

- QCD Studies
  - Measurements of α_s
  - Fragmentation functions
  - Parton Distribution Functions
  - Color/spin dynamics
  - Quark-gluon jet properties
  - Event shapes
  - Inclusive- and Multi-jet production
  - Rapidity Gaps/Diffraction
  - Production of Vector Bosons + jets
- Study of heavy particles (e.g. top production)
- Searches for Higgs
- Searches for new physics
  - Quark sub-structure + …
- And much more …

Kinematics in Hadronic Collisions



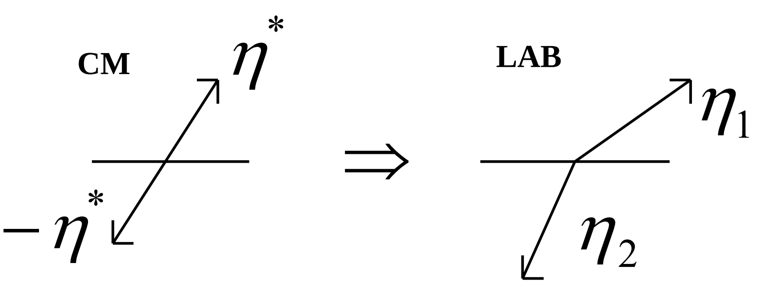
Rapidity (y) and Pseudo-rapidity (η)

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

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

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

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



LAB System ≠ parton-parton CM system

$$\eta_{boost} = \frac{1}{2}(\eta_1 + \eta_2)$$

$$\eta^* = \frac{1}{2}(\eta_1 - \eta_2)$$

$$\eta_{Lab} = \eta^* + \eta_{boost}$$

Kinematics in Hadronic Collisions cont'd

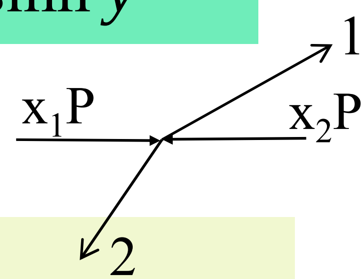
Transverse Energy/Momentum

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

$$p_T \equiv p \sin\theta$$

$$p_z = E \tanh y$$
$$E = E_T \cosh y$$
$$p_z = E_T \sinh y$$

Invariant Mass



$$M_{12}^2 \equiv (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu})$$
$$= m_1^2 + m_2^2 + 2(E_1 E_2 - \boldsymbol{p}_1 \cdot \boldsymbol{p}_2)$$
$$\xrightarrow[m_1, m_2 \to 0]{} 2E_{T1}E_{T2}(\cosh\Delta\eta - \cos\Delta\phi)$$

Partonic Momentum Fractions

$$x_1 = \left(e^{\eta_1} + e^{\eta_2}\right)E_T / \sqrt{s}$$
$$x_2 = \left(e^{-\eta_1} + e^{-\eta_2}\right)E_T / \sqrt{s}$$

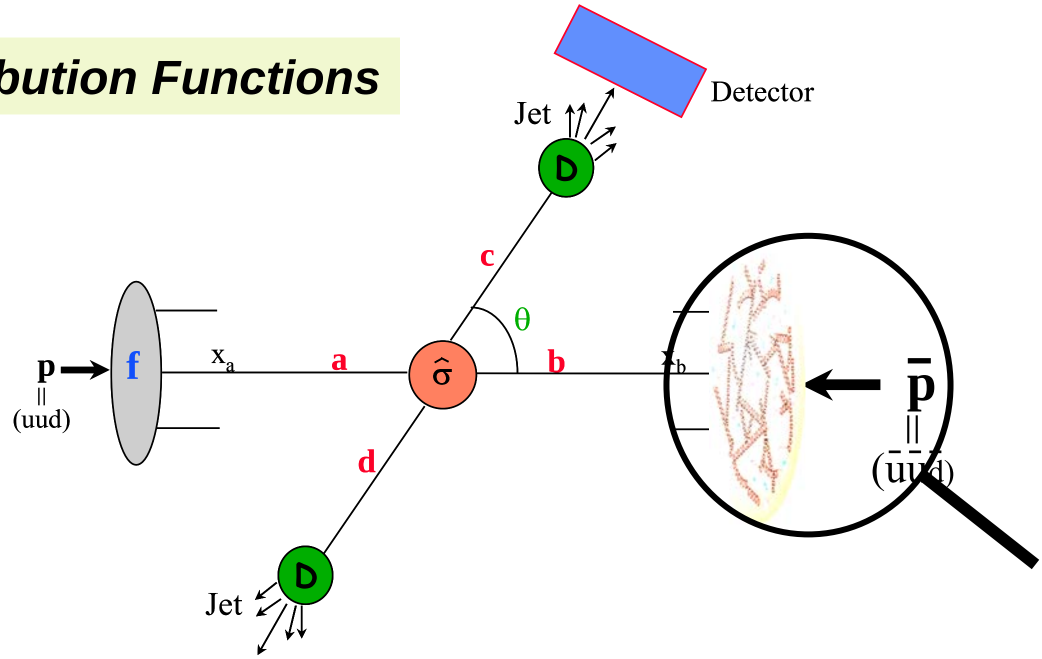
Parton CM (energy)^2 $\rightarrow \hat{s} = x_a x_b s$

$$x_T \equiv 2E_T / \sqrt{s} = x_{1,2}(\eta_{1,2} = 0)$$

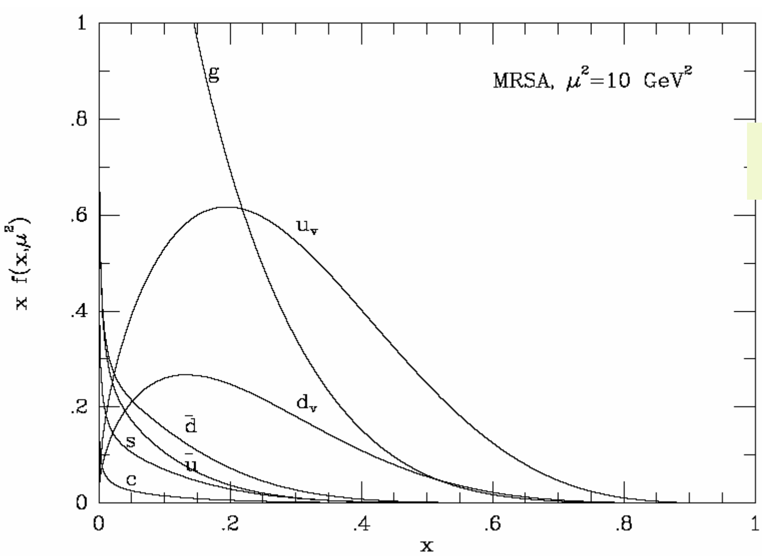
$$0 < x_1, x_2 < 1$$
$$x_T^2 < x_1 x_2 < 1$$

Explanation of the blob's

Parton Distribution Functions



- *Parton Distribution Functions* of the proton are measured at a some "hard scale" and evolved via pertrurbative QCD to the "scale" of the interaction
- PDFs are determined doing Global Fits of data from DIS (Deep Inelastic Scattering), DY (Drell-Yan), Direct Photons, and production of jets



$$xf(x,Q_o) = A_o\, x^{A1}\, (1-x)^{A2}\, P(x)$$

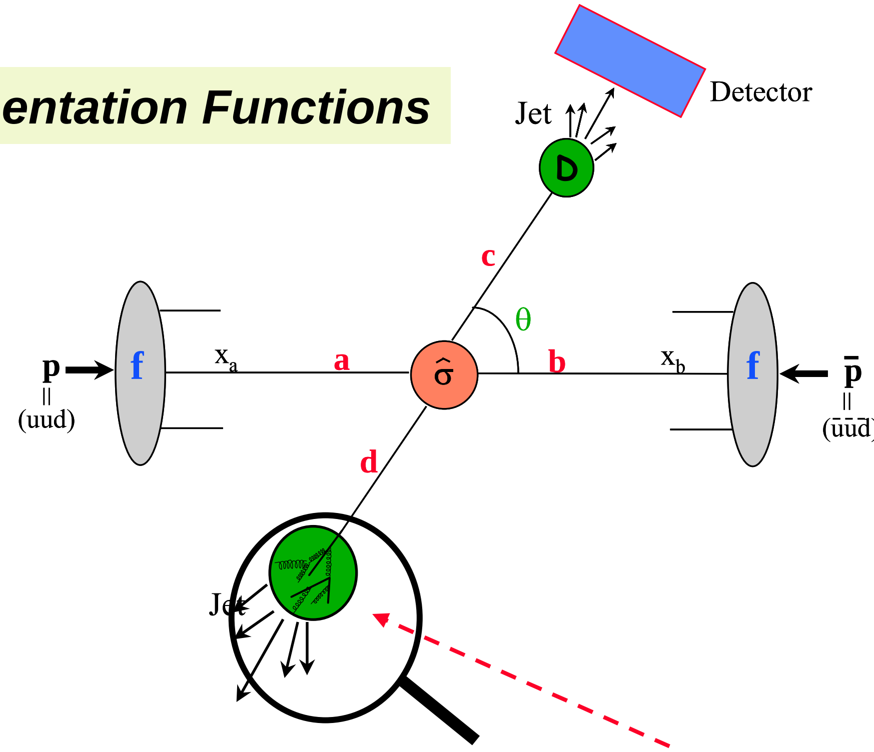
small x behavior

large x behavior

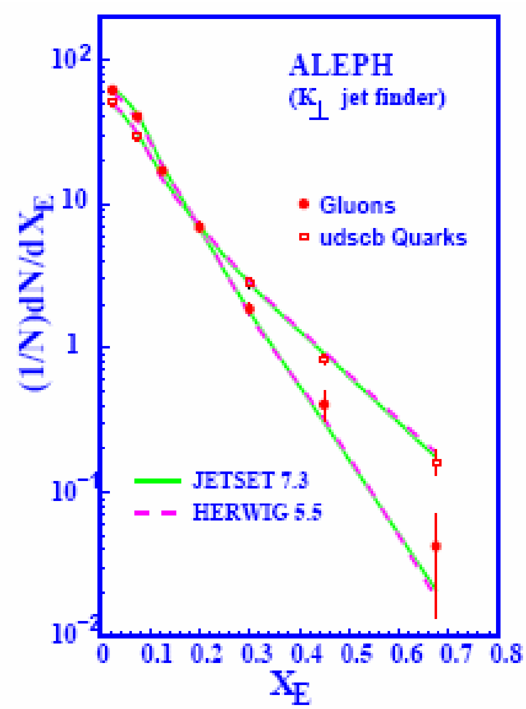
in between

Explanation of the blob's cont'd

Particle Fragmentation Functions

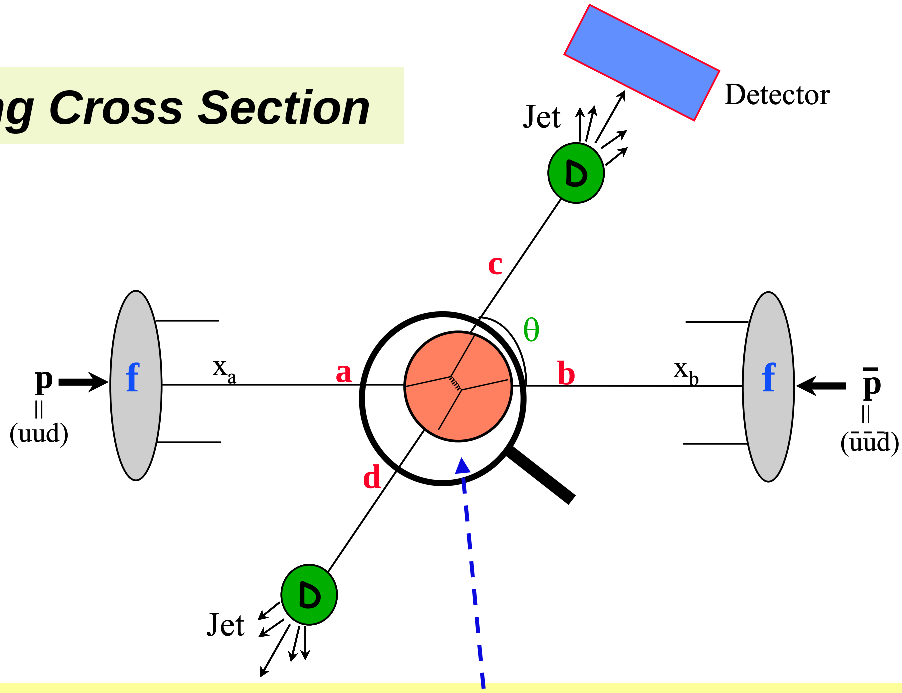


- Particle Fragmentation Functions $D_{A/a}(z_A, \mu_F)$ measure the probability of finding a particle of type A with momentum fraction z_A of parent parton a
- Fragmentation functions are determined doing Global Fits of data from DIS and e^+e^-
- Most of the particles within a jet have a small fraction of the total jet momentum
- The "evolution" of the Fragmentation functions can be calculated in pQCD



Explanation of the blob's cont'd

Hard Scattering Cross Section

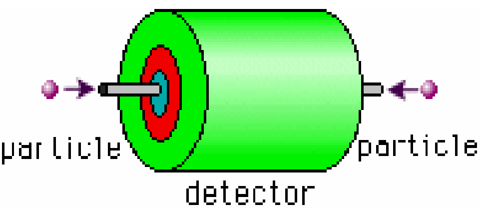


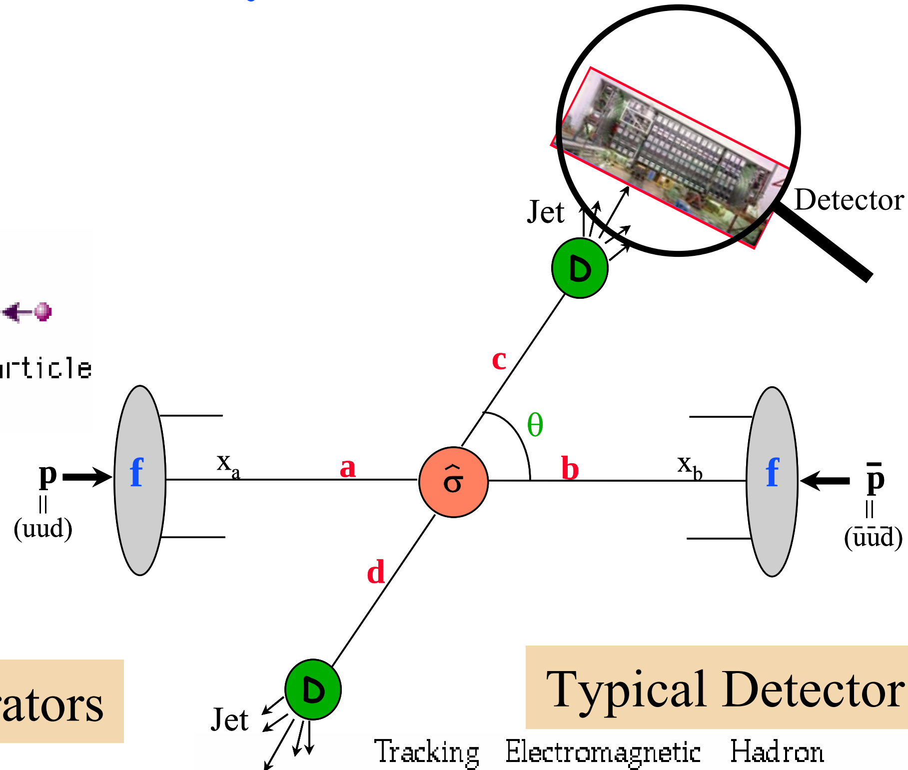
$$\sigma_X = \sum_{i,j} \int_0^1 dx_a dx_b\, f_i\left(x_a, \mu_F^2\right) f_j\left(x_b, \mu_F^2\right) \hat{\sigma}_{ij}\left(p_a, p_b, \alpha_s\left(\mu_R^2\right), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2} \right)$$

- σ_X = (PDF's for p and $\bar{p}$) ⊗ (partonic level cross section)
  - Separate the long-distance pieces (PDF's) from the short-distance cross section → **Factorization**
- What's the deal with the various scales?
  - μ_F is the factorization scale that enters in the evolution of the PDF's and the Fragmentation functions (could be two different scales). It is an arbitrary parameter that can be thought as the scale which separates the long- and short-distance physics
  - μ_R is the renormalization scale that shows up in the strong coupling constant
  - Q is the hard scale which characterizes the parton parton interaction
  - Typical choice: $\mu_F = \mu_R = Q \sim E_T/4 - 2E_T$ of the jets

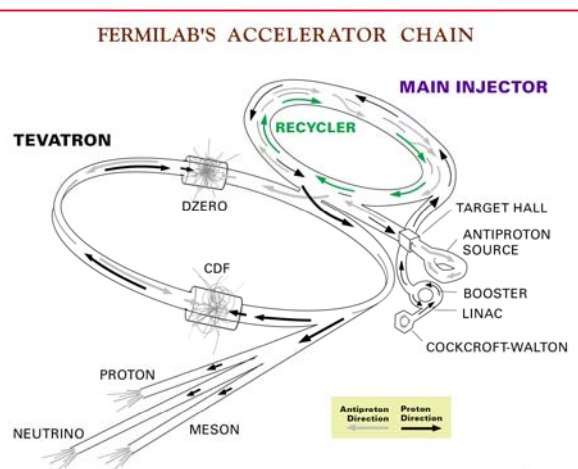
Explanation of the blob's cont'd

Detector

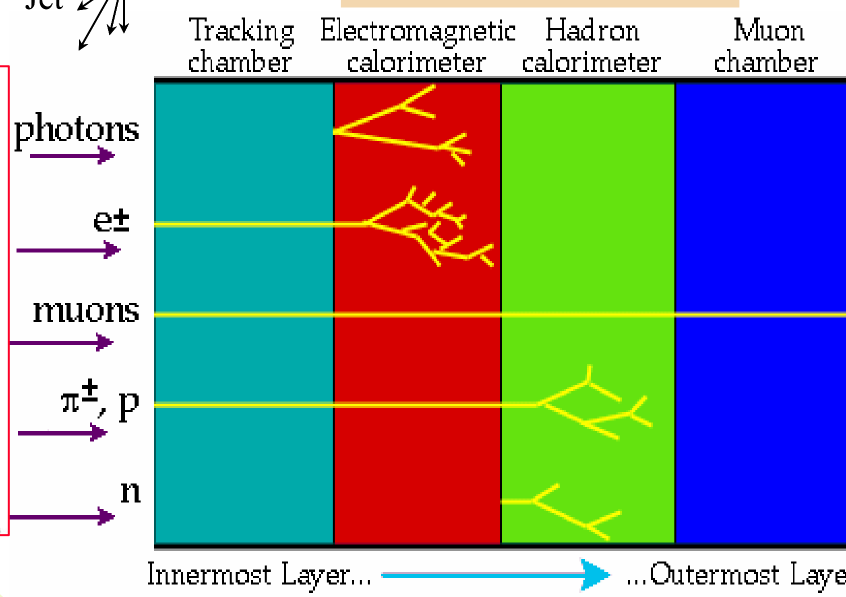




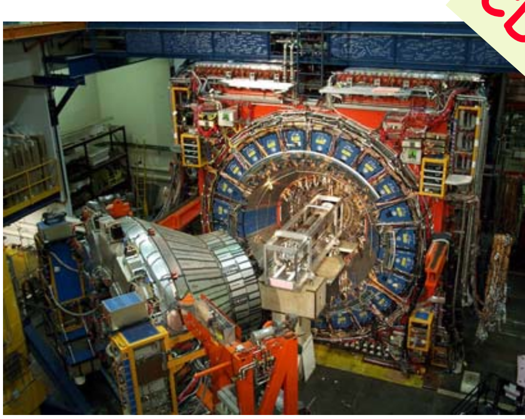
Fermilab Accelerators



Typical Detector

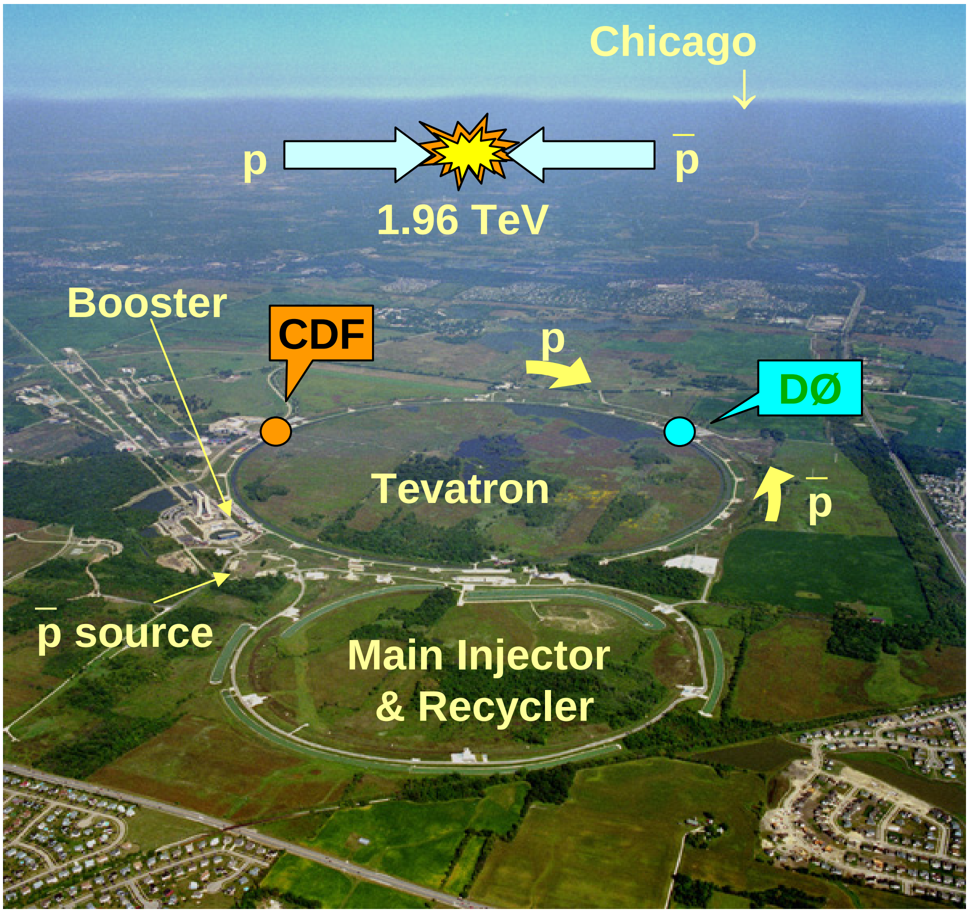


CDF



DØ

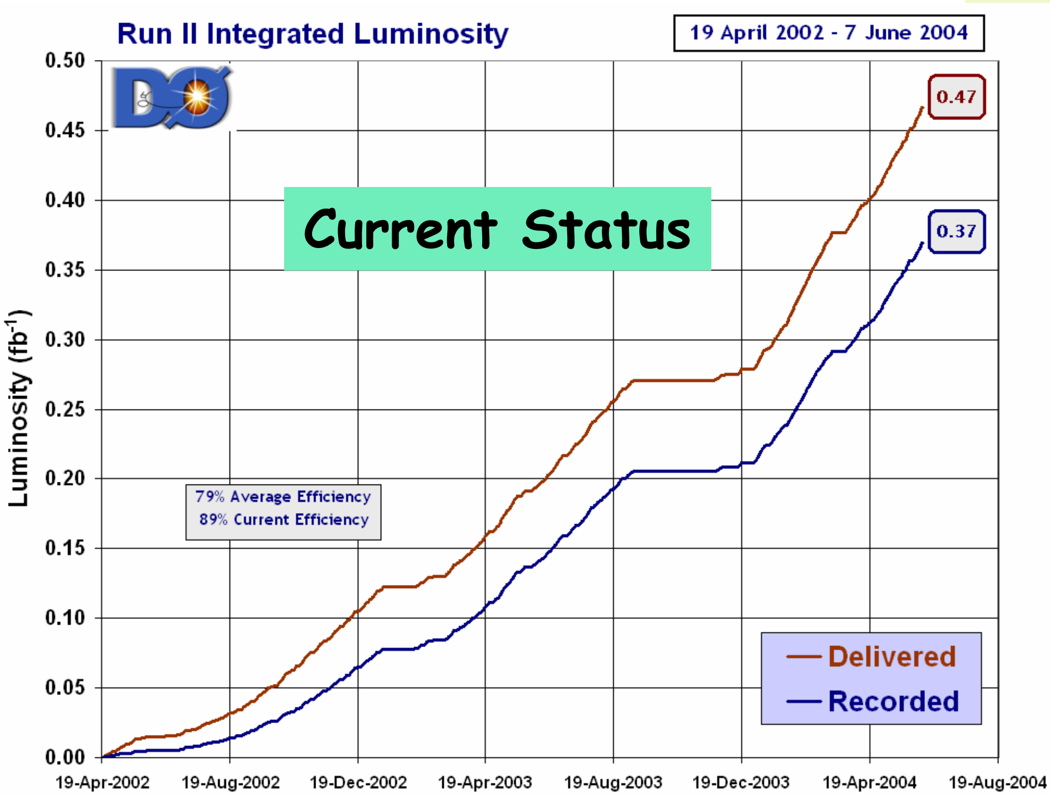
Tevatron Runs



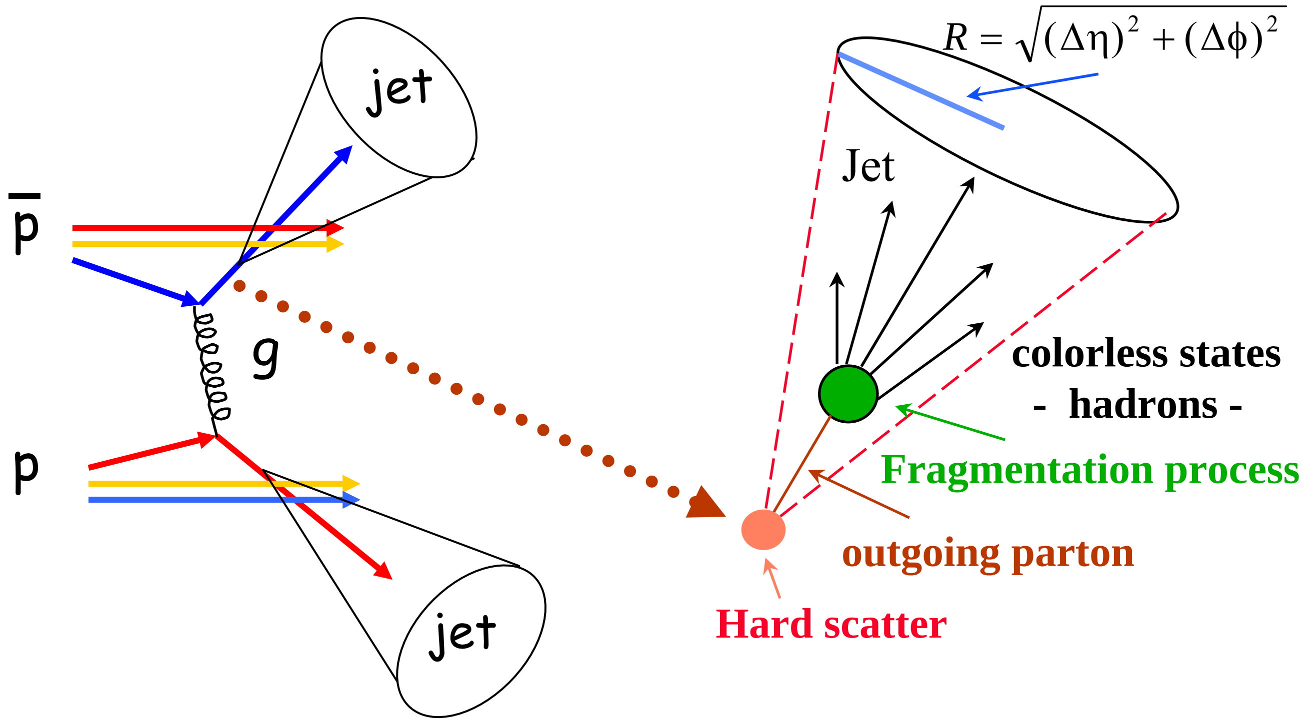
Run I
1992-1996
1.8 TeV
~120 pb^{-1}
(0.63 TeV ~600 nb^{-1})

Run IIa
2002-2005
1.96 TeV
~ 1 fb-1

Run IIb
2006-2010
1.96 TeV
~4-8 fb^{-1}



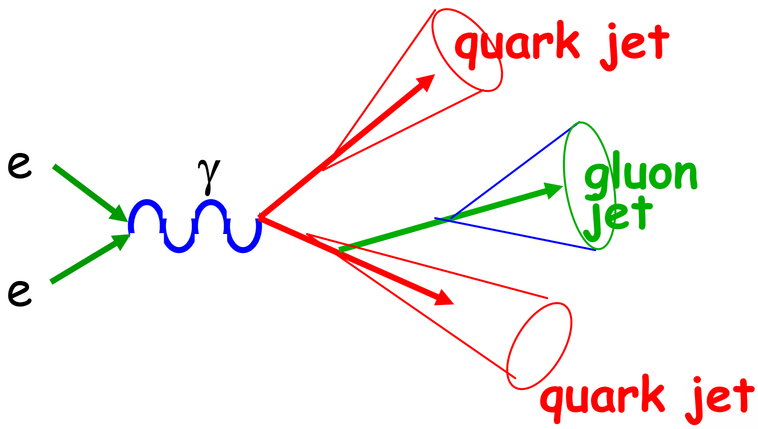
What are Jets ?



- 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 manifest themselves as localized clusters of energy
- **JETS are the experimental signatures of quarks and gluons**

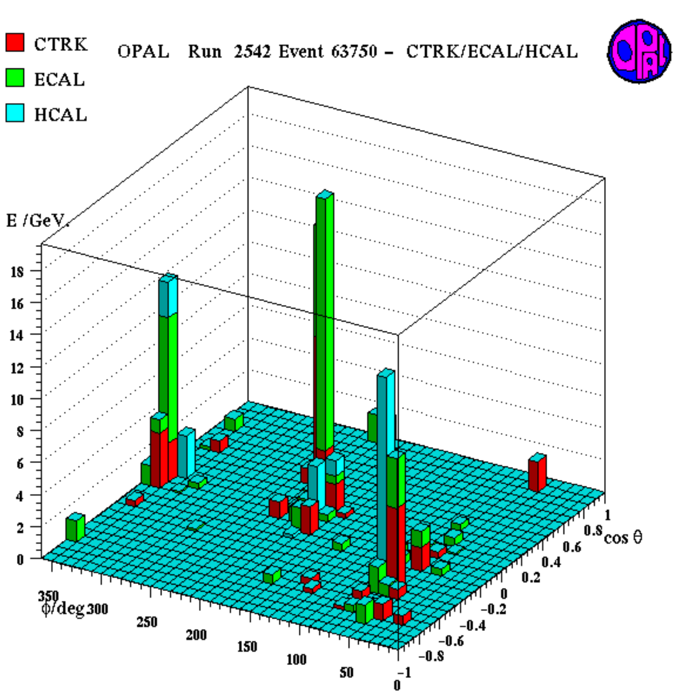
Evidence for Jets

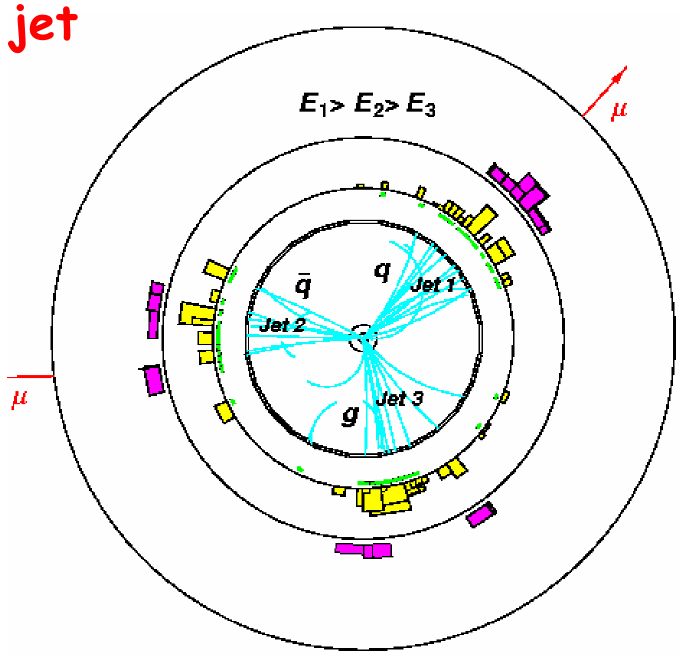
e^+e^- collisions proceed through an intermediate state of a photon (or Z); such collisions lead to quark antiquark. Presence of 3rd jet signals gluon radiation



(gluon jets are broader than quark jets)

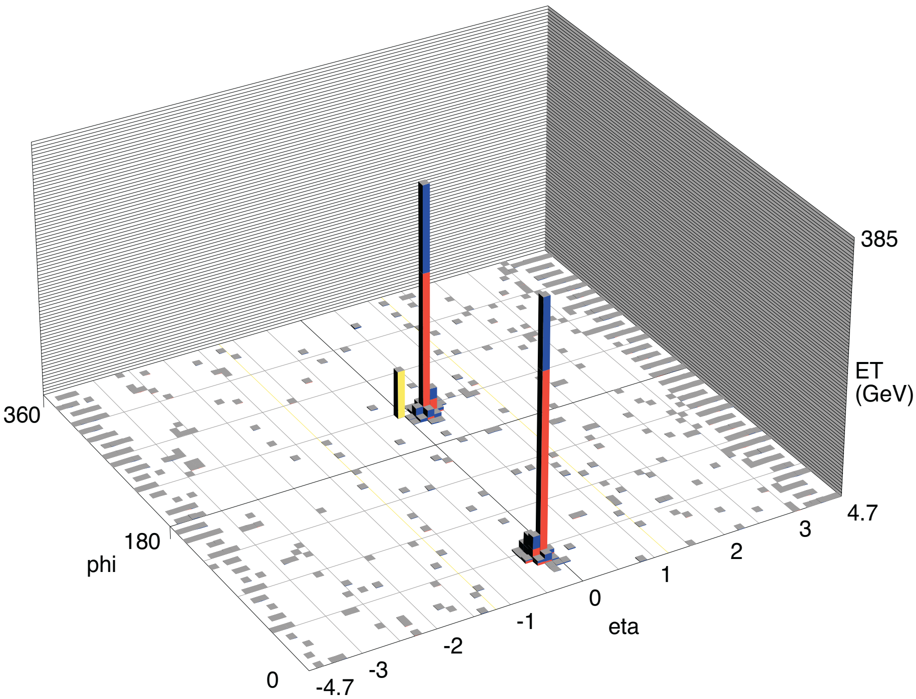
Typical ee event with 2 quarks and one gluon. (**Gluons exist** and are manifested as jets).





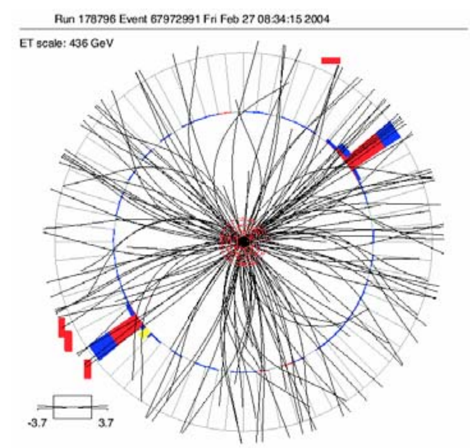
Gluons jets were discovered at PETRA in 1979

Recent Tevatron High-E_T Events

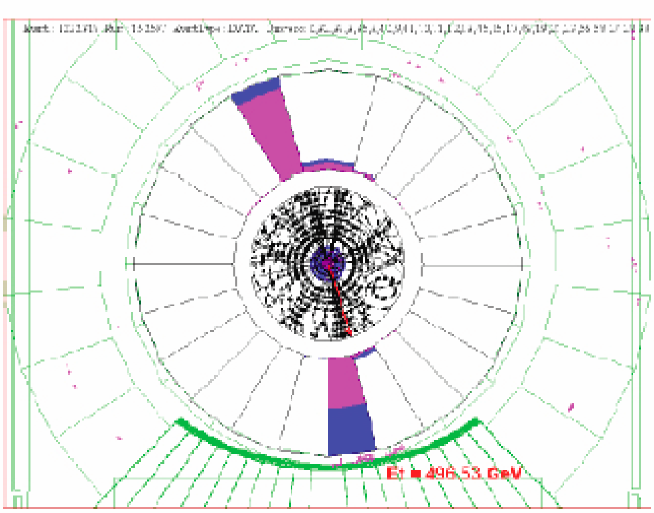


DØ Event

E_{T1} ~ 620 GeV
E_{T2} ~ 560 GeV
M_{JJ} ~ 1.2 TeV

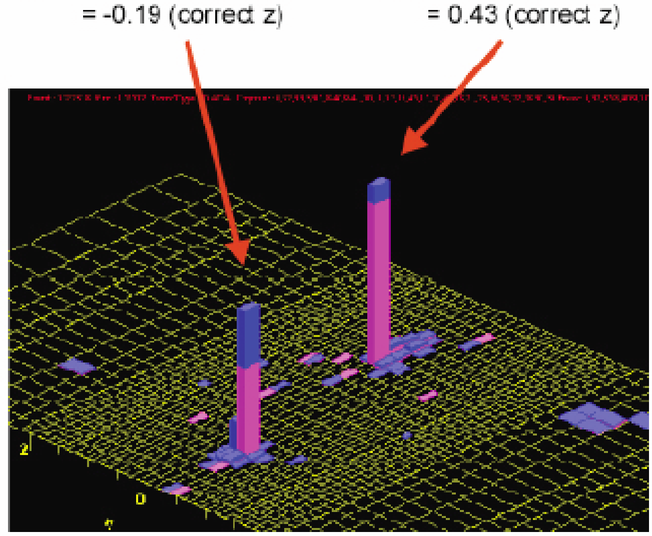


Run 152507 event 1222318
Dijet Mass = 1364 GeV (corr)
cos θ* = 0.30
z vertex = -25 cm



J2 E_T = 633 GeV (corr)
546 GeV (raw)
J2 η = -0.30 (detector)
= -0.19 (correct z)

J1 E_T = 666 GeV (corr)
583 GeV (raw)
J1 η = 0.31 (detector)
= 0.43 (correct z)



CDF Run 2 Preliminary

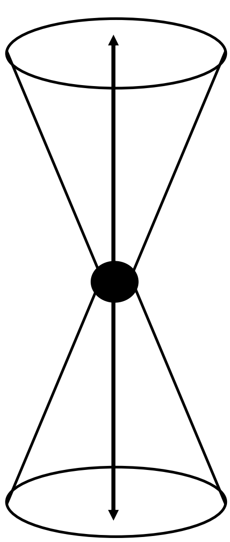
Jet Algorithms

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

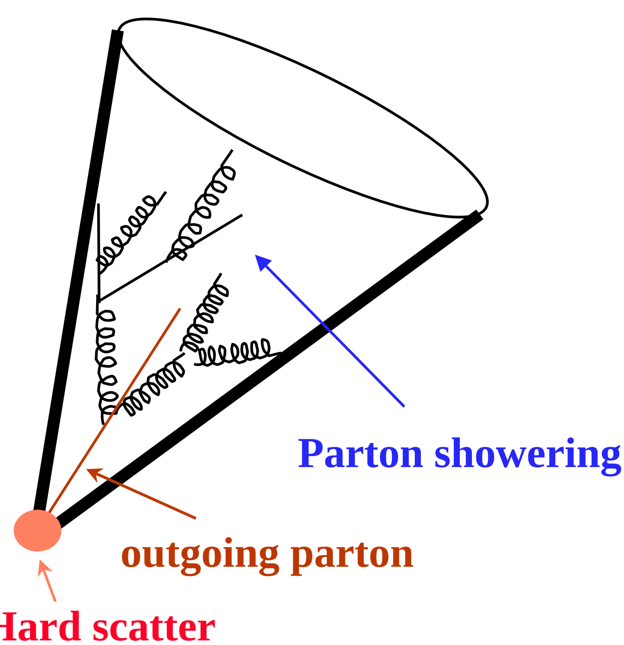
- **Jets at the "Parton Level" (i.e., before hadronization)**
  - Fixed order QCD or (Next-to-) leading logarithmic summations to all orders

2 → 2 process
Leading Order QCD

leading contributions of
gluon/quark radiation to all orders



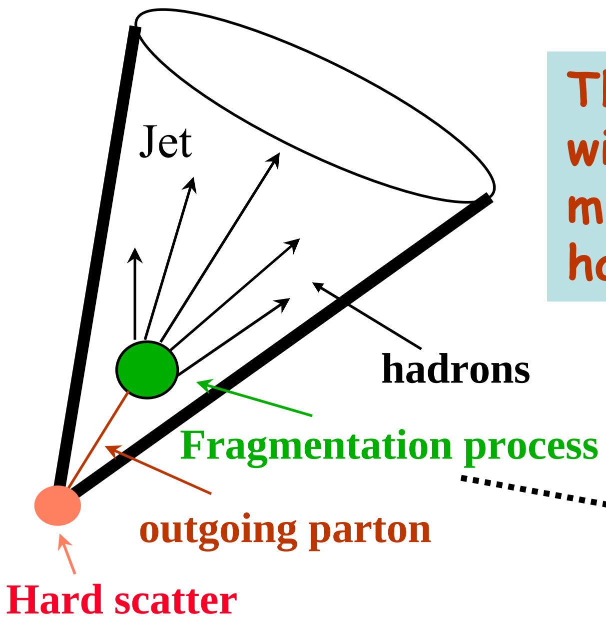
2-jet final state
1 parton/jet



multi-jet final state

Jet Algorithms cont'd

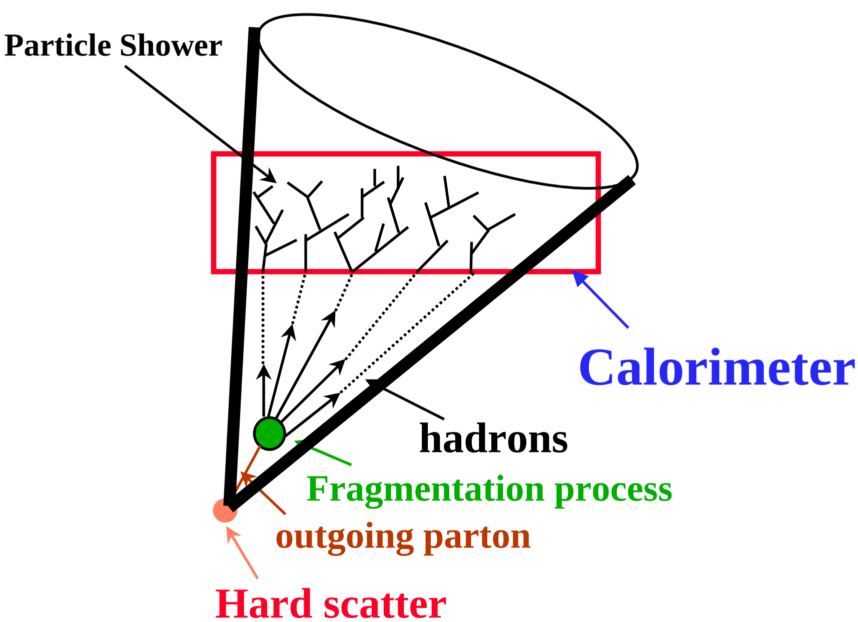
- **Jets at the "Particle (or hadron) Level"**

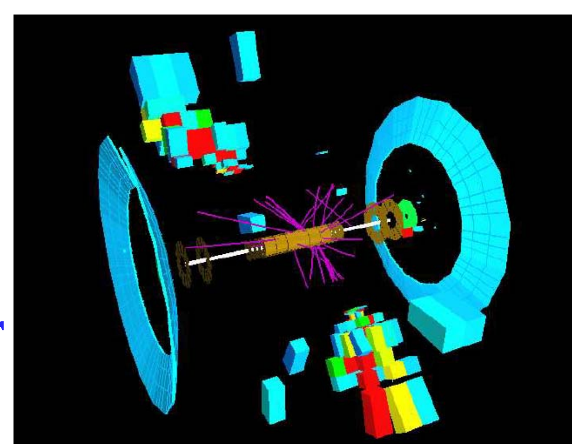


The idea is to come up with a jet algorithm which minimizes the non-perturbative hadronization effects

Parton showering
+ Hadronization

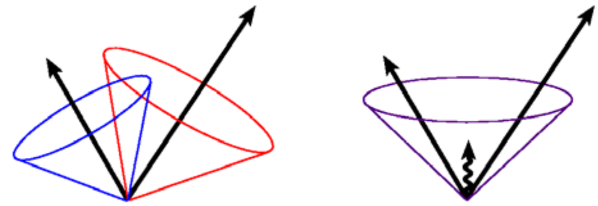
- **Jets at the "Detector Level"**
  - *Calorimeter - clusters of energy "towers"*
  - *Tracking - clusters of tracks*



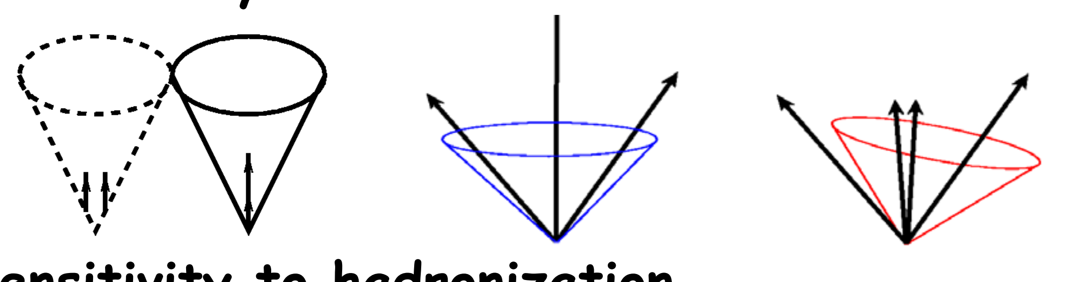


Jet Algorithms - Requirements

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



  - **Collinear safety**



  - **Low sensitivity to hadronization**
  - **Invariance under boosts**
  - **Order independence**
    - Same jets at parton/particle/detector levels
  - **Straight forward implementation**

- **Experimental:**
  - **Detector independence - Can everybody implement this?**
  - **Minimization of resolution smearing/angle bias**
  - **Stability w/ luminosity**
  - **Computational efficiency**
  - **Maximal reconstruction efficiency**

Jet Finders

(Generic Recombination)

- Define a resolution parameter y_{cut}
- For every pair of particles (i,j) compute the "separation" y_{ij} as defined for the algorithm
- $$y_{ij} = \frac{M_{ij}^2}{E_{vis}^2}$$
- If $\min(y_{ij}) < y_{cut}$ then combine the particles (i,j) into k
  - E scheme: $p_k = p_i + p_j$ -> massive jets
  - E_0 scheme: $E_k = E_i + E_j$ -> massless jets

$$\boldsymbol{p}_k = E_k \frac{\boldsymbol{p}_i + \boldsymbol{p}_j}{\left|\boldsymbol{p}_i + \boldsymbol{p}_j\right|}$$

- Iterate until all particle pairs satisfy $y_{ij} > y_{cut}$
- No problems with jet overlap
- Less sensitive to hadronization effects

The JADE Algorithm

$$M_{ij}^2 = 2E_iE_j(1-\cos\theta_{ij})$$

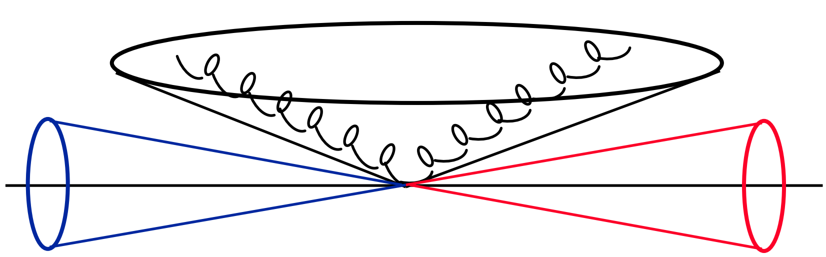
$$\min(y_{ij}) = \min(\frac{M_{ij}^2}{E_{vis}^2}) < y_{cut}$$

(E_{vis} is the sum of all particle energies)

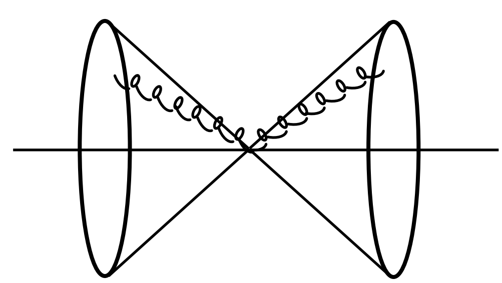
- Recombination: $p_k=p_i+p_j$
- Problems with this algorithm
  - It doesn't allow resummation when y_{cut} is small
  - Tendency to reconstruct "spurious" jets

i.e. consider the following configuration where two soft gluons are emitted close to the quark and antiquark

The gluon-gluon invariant mass can be smaller than that of any gluon-quark and therefore the event will be characterized as a 3-jet one instead of a 2-jet event



✗ 3-Jet event



√ 2-Jet event

The Durham or "K_T" Algorithm

$$M_{ij}^2 = 2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})$$

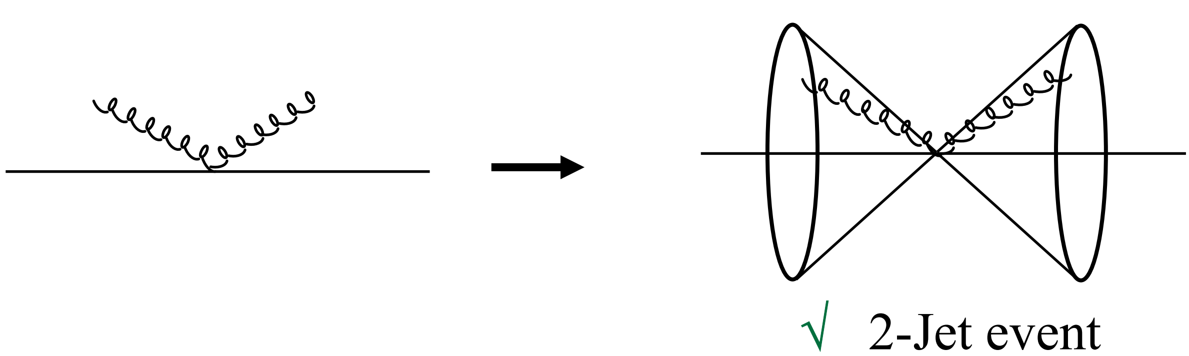
$$\min(y_{ij}) = \frac{M_{ij}^2}{E_{vis}^2} < y_{cut}$$

For small θ_{ij}

$$M_{ij}^2 \approx 2\min(E_i^2, E_j^2)\left(1-(1-\frac{\theta_{ij}^2}{2}+\cdots)\right)$$

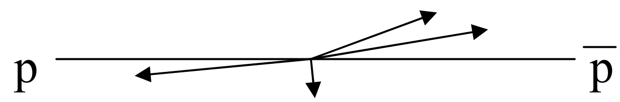
$$\approx 2\min(E_i^2, E_j^2)\left(\frac{\theta_{ij}^2}{2}\right) \approx \min(k_{Ti}^2, k_{Tj}^2)$$

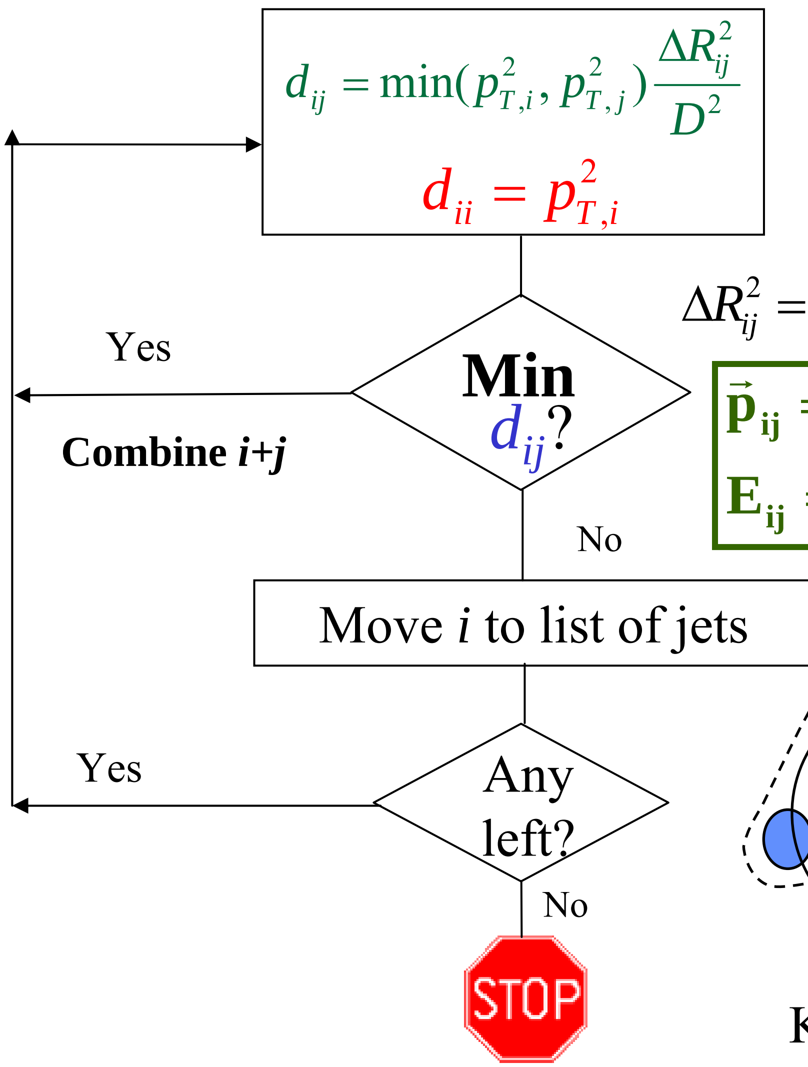
- Recombination: $p_k=p_i+p_j$
- It allows the resummation of leading and next-to-leading logarithmic terms to all orders for the regions of low y_{cut}



A "K_T" Algorithm for hadron colliders

Input: List of Energy preclusters $(\Delta R_{precluster} \approx 0.2)$

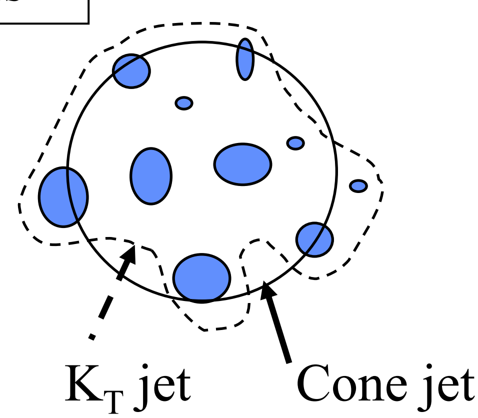




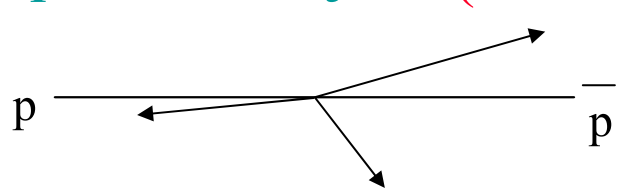
D~1

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

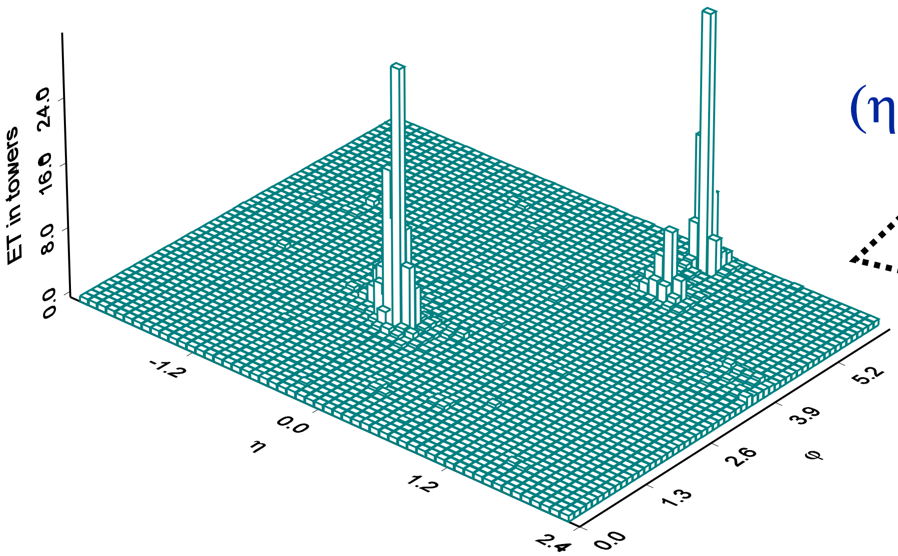
$$\vec{\mathbf{p}}_{ij} = \vec{\mathbf{p}}_i + \vec{\mathbf{p}}_j$$
$$\mathbf{E}_{ij} = \mathbf{E}_i + \mathbf{E}_j$$

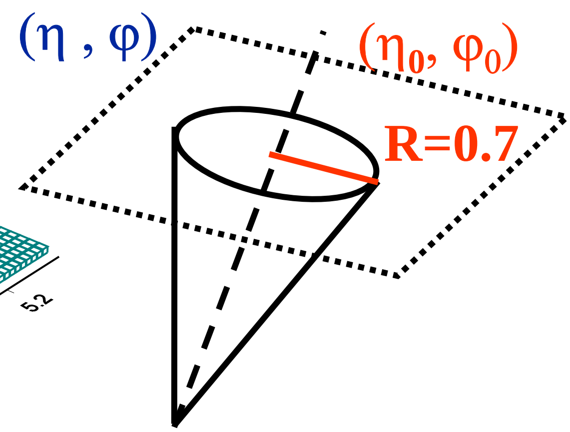


Output: List of jets $(\Delta R \geq D)$

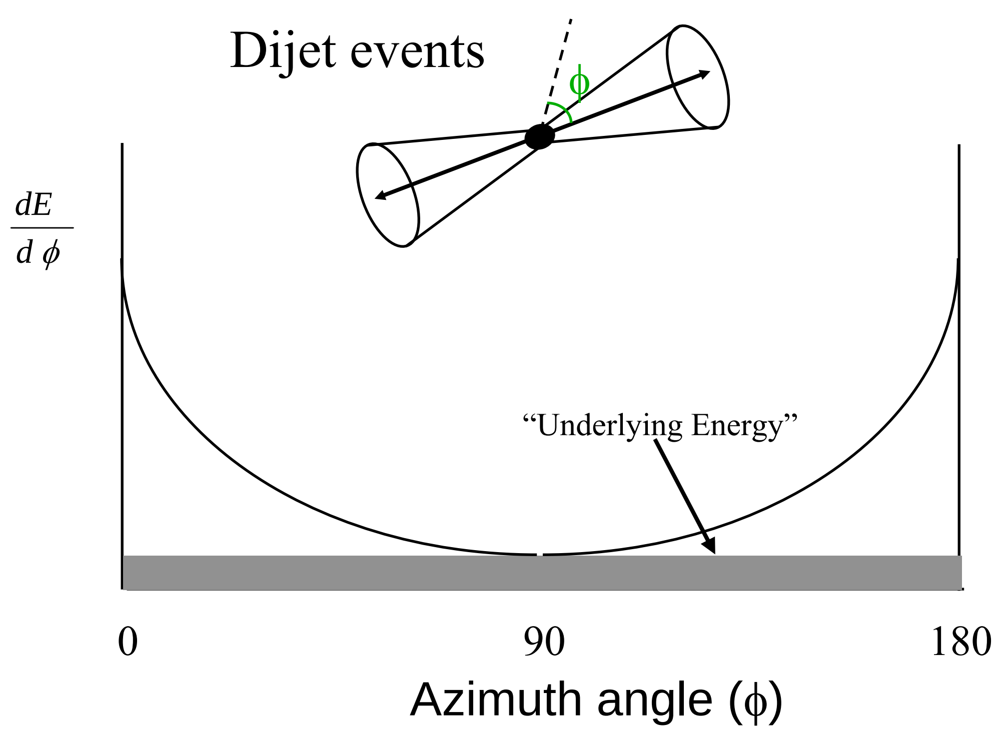


The "Cone" Algorithm



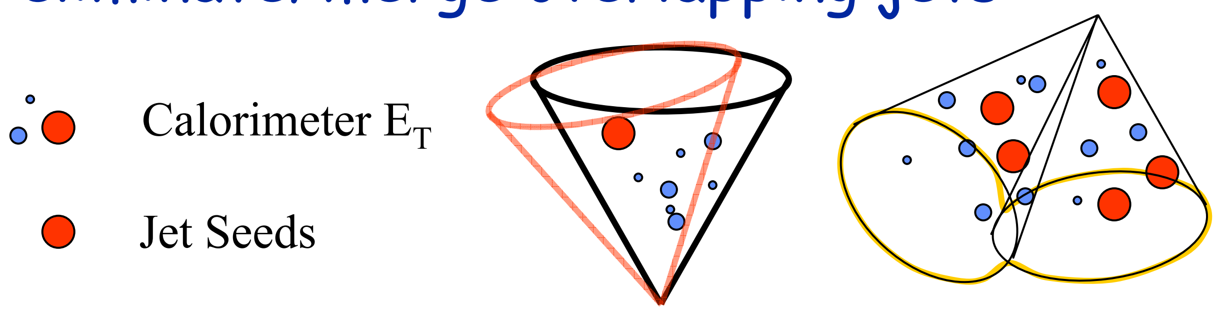


- A more intuitive representation of a jet that is given by recombination jet finders
- It clusters particles whose trajectories lie in an area $A=\pi R^2$ of (η,ϕ) space



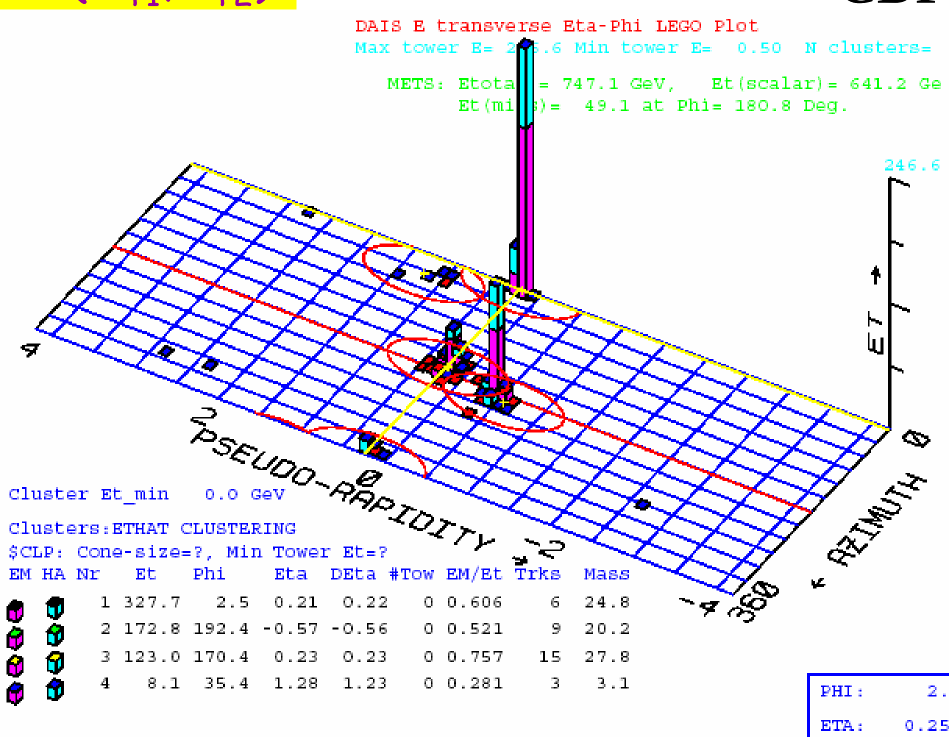
The "Cone" Algorithm cont'd

- It requires "seeds" with a minimum energy of ~ few hundred MeV (to save computing time)
  - Preclusters are formed by combining seed towers with their neighbors
- Jet cones may overlap so need to eliminate/merge overlapping jets



Merge if shared $E_T > 0.5 \times \min(E_{T1}, E_{T2})$

Merge/split criterion: D0 –> 50%
CDF –> 75%



The D0/CDF "Cone" Algorithm *for Run I*

In Run I: D0 and CDF used Snowmass clustering and defined angles via momentum vectors

$$
\begin{aligned}
E_x^i &= E_T^i \cdot \cos(\phi^i)\ , \\
E_y^i &= E_T^i \cdot \sin(\phi^i)\ , \\
E_z^i &= E^i \cdot \cos(\theta^i)\ , \\
E_{x,y,z}^J &= \sum_{i \subset J = C} E_{x,y,z}^i\ , \\
\theta^J &= \tan^{-1}\left(\frac{\sqrt{(E_x^J)^2 + (E_y^J)^2}}{E_z^J}\right) .
\end{aligned}
$$

$$i \subset C \quad : \quad \sqrt{(\eta^i - \eta^C)^2 + (\phi^i - \phi^C)^2} \leq R. \qquad (1)$$

In the Snowmass algorithm a "stable" cone (and potential jet) satisfies the constraints

$$\eta^C = \frac{\sum_{i \subset C} E_T^i \eta^i}{E_T^C}, \quad \phi^C = \frac{\sum_{i \subset C} E_T^i \phi^i}{E_T^C} \qquad (2)$$

(*i.e.*, the geometric center of the previous equation is identical to the E_T-weighted centroid) with

$$E_T^C = \sum_{i \subset C} E_T^i\ . \qquad \textbf{(Snowmass scalar } E_T\textbf{)} \qquad (3)$$

D0 and CDF's Angles:

$$
\begin{aligned}
\eta^J &= -\ln\left(\tan\left(\frac{\theta^J}{2}\right)\right)\ , \\
\phi^J &= \tan^{-1}\left(\frac{E_y^J}{E_x^J}\right) .
\end{aligned}
$$

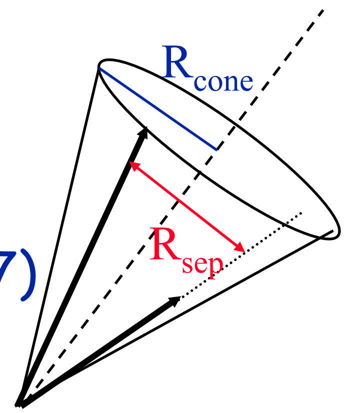
CDF's E_T:

$$E_T^J = E^J \cdot \sin(\theta^J), \quad E^J = \sum_{i \subset J} E^i\ .$$

D0's E_T:

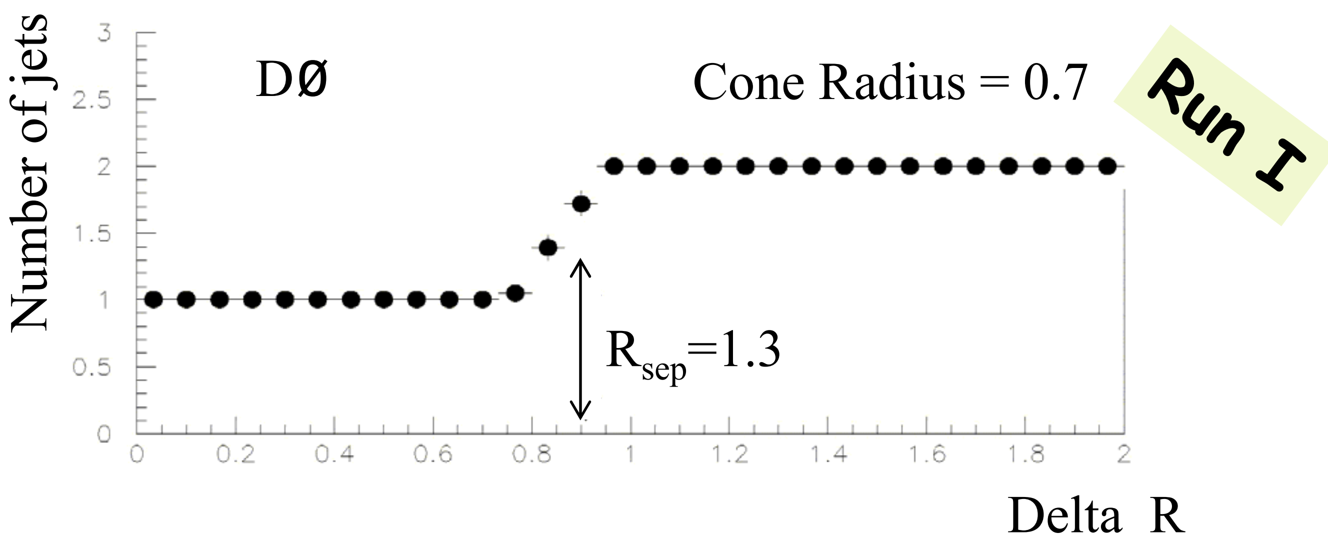
$$E_T^J = \sum_{i \subset J} E_T^i$$

The "Cone" Algorithm at the NLO Parton Level



- Apply Snowmass recipe
  - Each parton must be within R_{con} (=0.7) of centroid
- The two partons must be within R_{sep}xR_{cone} of one another, where R_{sep} varies from 1 - 2 (R_{sep}=1.3 for DO/CDF)
  - introduce ***ad-hoc*** parameter R_{sep} to control parton recombination in the theoretical jet algorithm
  - it **doesn't** generalize to higher orders

If jets from separate events are overlaid then they can be distinguished at 1.3xR_{cone}=0.9 for 0.7 cone jets:

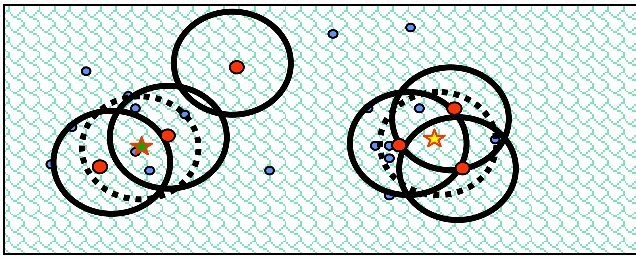


"Midpoint" or Improved Legacy Cone Algorithm (*Run II*)

"particle" = {experiment: calorimeter towers / MC: stable particles / pQCD: partons}

three parameters: $R_{\text{cone}} = 0.7$, $p_{T\,\text{min}} = 8$ GeV, overlap fraction $f = 50\%$

- Use all particles as **seeds**
  — make cone of radius $\Delta R = \sqrt{(\Delta y^2 + \Delta\phi^2)} < R_{\text{cone}}$ around seed direction
  — proto jet: add particles within cone in the "E-scheme" (adding four-vectors)
  — iterate until stable solution is found with: cone axis = jet-axis
- Use all **midpoints** between pairs of jets as **additional seeds** $\Longrightarrow$ infrared safety!!!
  — (repeat procedure as described above)



- Take all solutions from the first two steps:
  — remove identical solutions
  — remove proto-jets with $p_{T\,\text{jet}} < p_{T\,\text{min}}$
- Look for jets with **overlapping cones**:
  — merge jets, if more than a fraction f of $p_{T\,\text{jet}}$ is contained in the overlap region
  — otherwise split jets: assign the particles in the overlap region to the nearest jet
  ($\rightarrow$ and recompute jet-axes)

the cone algorithm used by DØ in Run I differed in the following ways:

- Particles were combined to jets in the "E_T-scheme" ("snowmass convention") instead of the "E-scheme" (adding four-vectors)

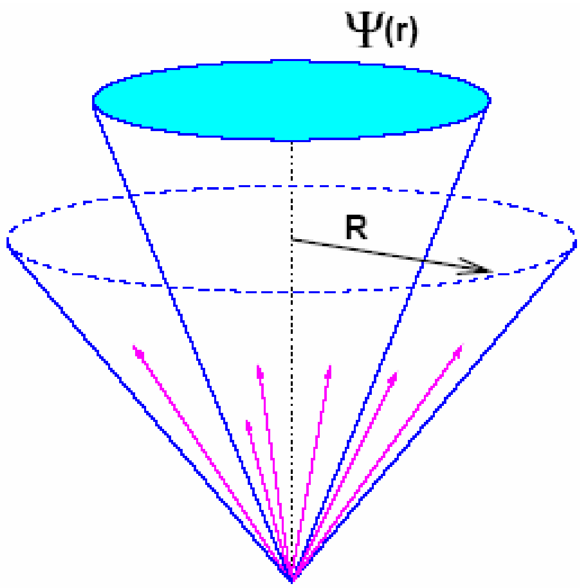
  $\Rightarrow$ in Run I by definition jet four-vectors were massless
  $\rightarrow$ pseudorapidity η was used instead of rapidity y
  $\rightarrow$ transverse energy $E_T = E \cdot \sin\theta$ was used instead of transverse momentum p_T

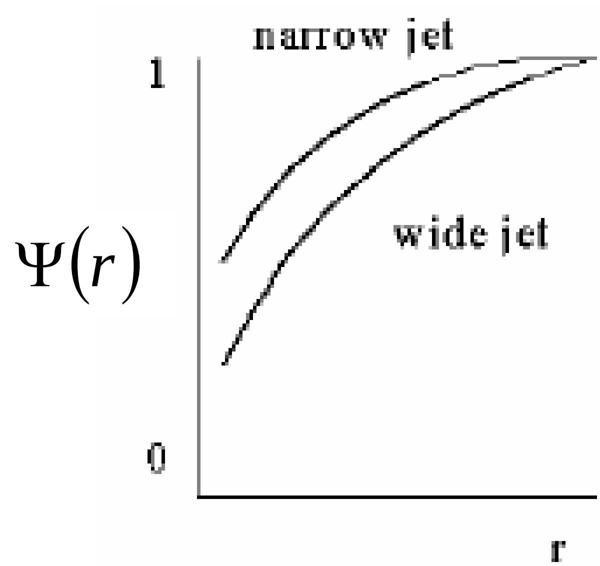
  please note: $E_T^{E_T-\text{scheme}} \geq p_T^{E-\text{scheme}}$ and $M_{\text{dijet}}^{E_T-\text{scheme}} \leq M_{\text{dijet}}^{E-\text{scheme}}$

- no midpoints were used as additional seeds
  $\Rightarrow$ procedure not infrared safe $\Rightarrow$ no predictions from perturbative QCD possible

Energy Flow in Jets

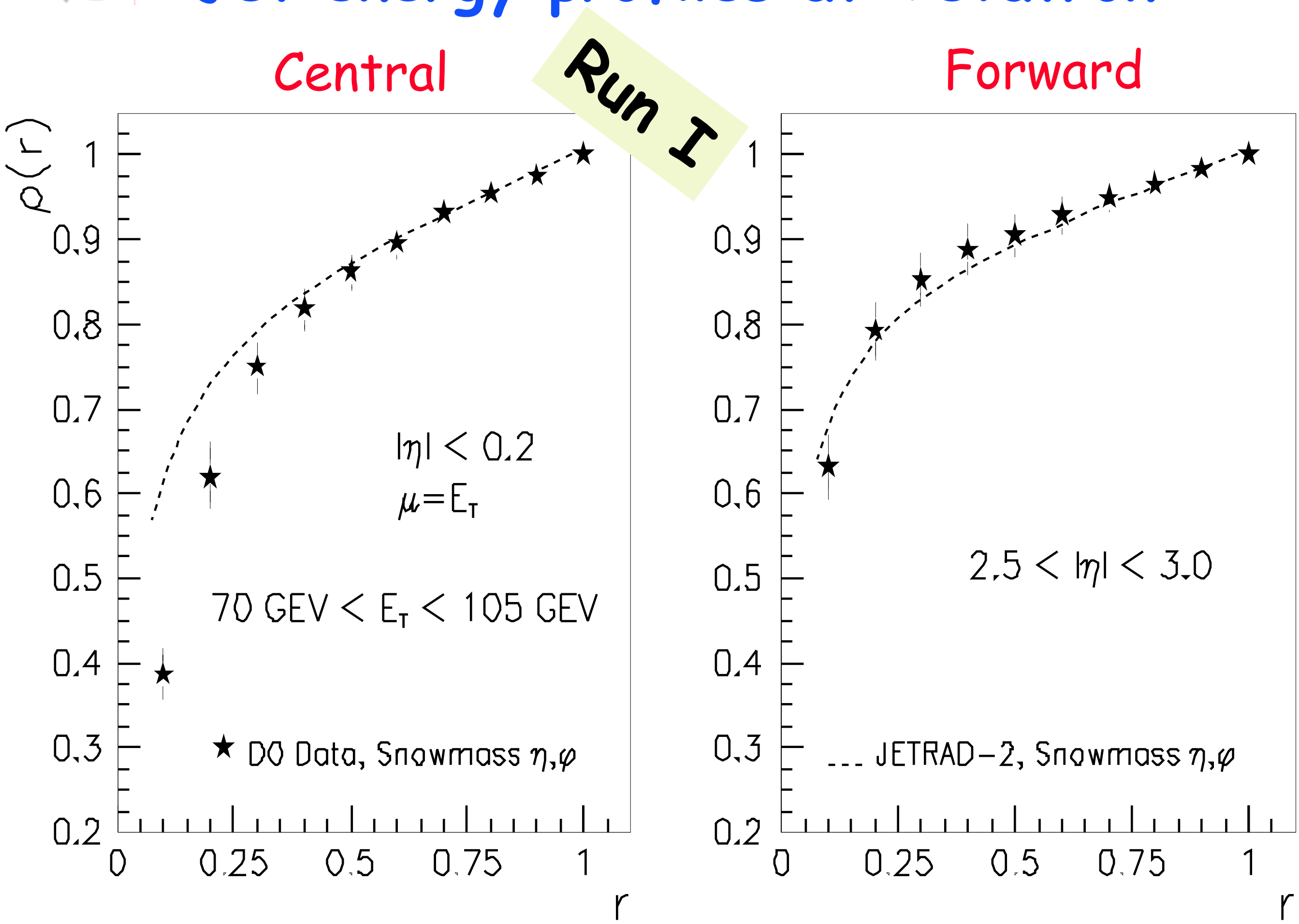
$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{P_T(0,r)}{P_T(0,R)}$$



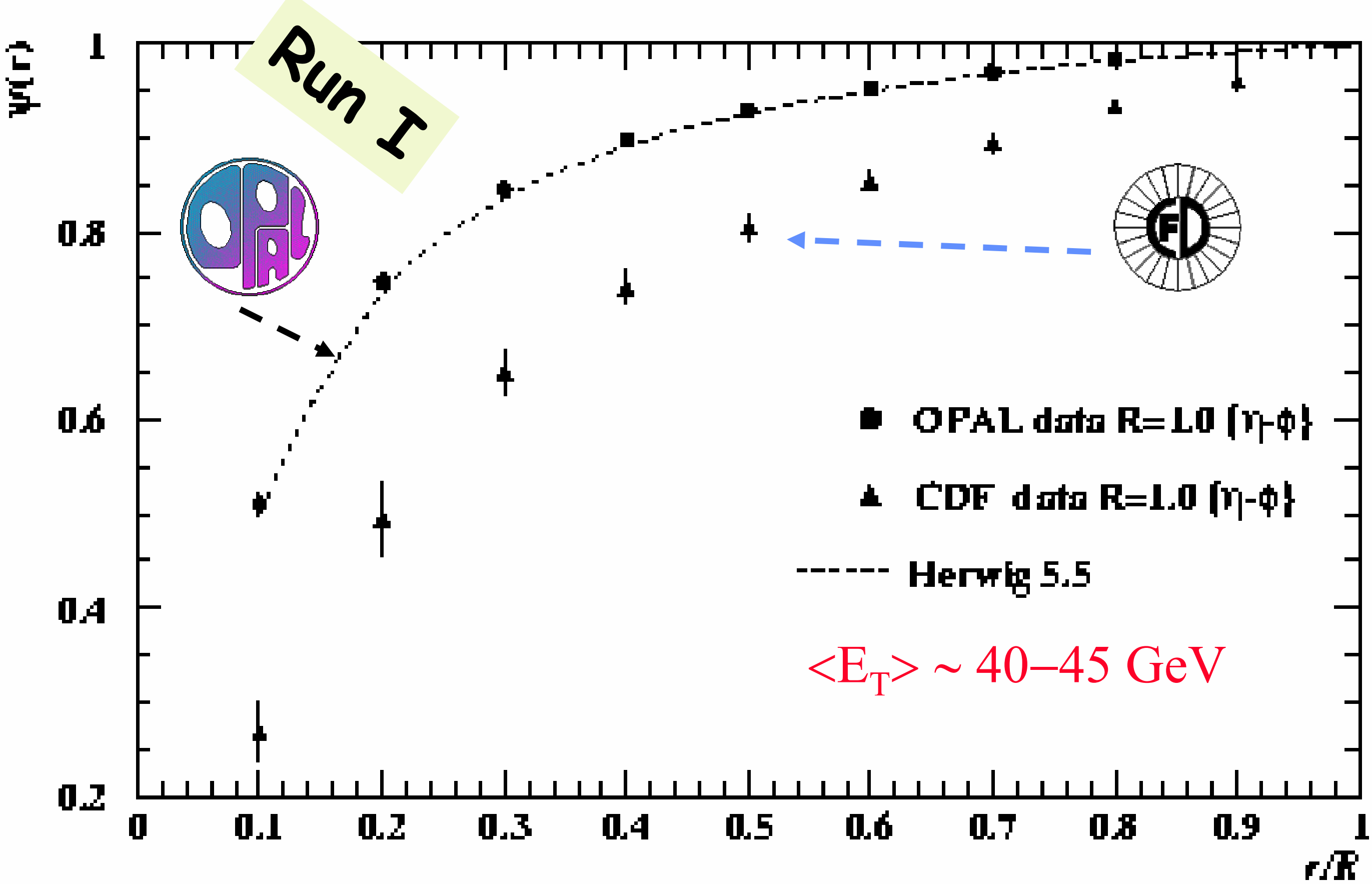


- The investigation of jet profiles gives insights into the transition between the parton produced in the hard process and the observed spray of hadrons
- Sensitive to the quark/gluon jet mixture
- **Jet Shape:**
  - *Measure the average energy flow in subcones as a function of radial distance from the jet axis*
  - *Use calorimeter towers or charged tracks*

Jet energy profiles at Tevatron



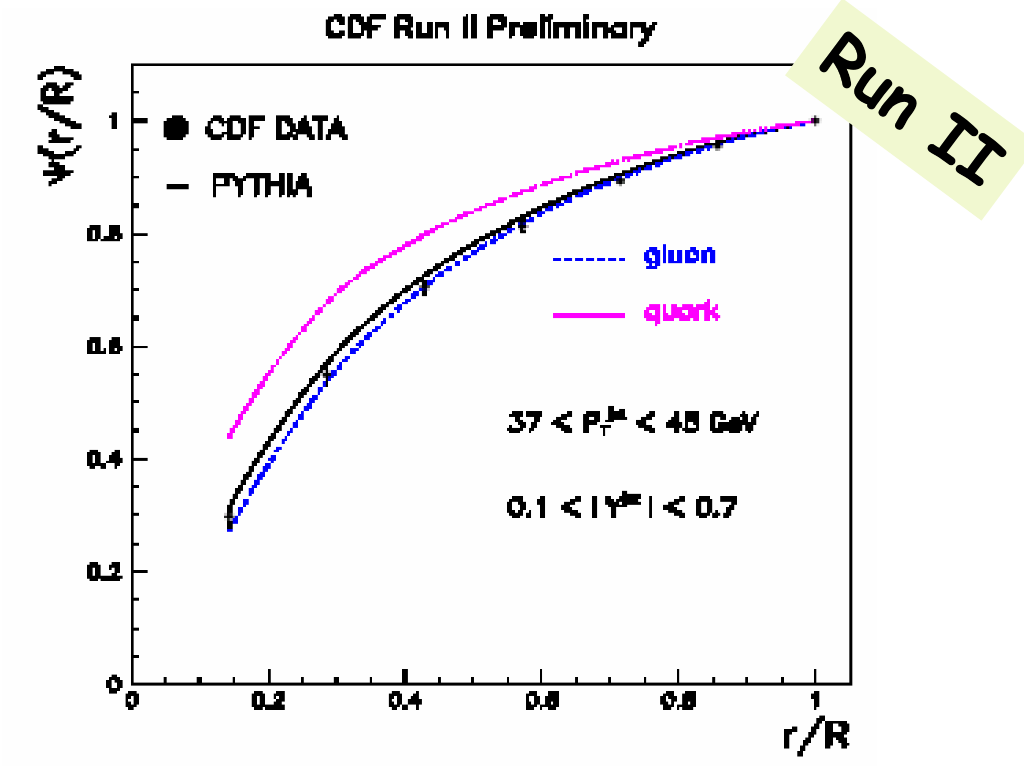
- Forward jets are narrower than jets in the central region for similar E_T
  - forward jets are quark enriched (high-x region) whereas central jets are mostly gluons (low-x region)
- NLO (JETRAD) QCD predictions reproduce the general features of the data, however...
  - Since the jet shape measurement is a LO prediction at partonic NLO calculation, the theoretical result is very sensitive to renormalization scale and to the details of the jet algorithm

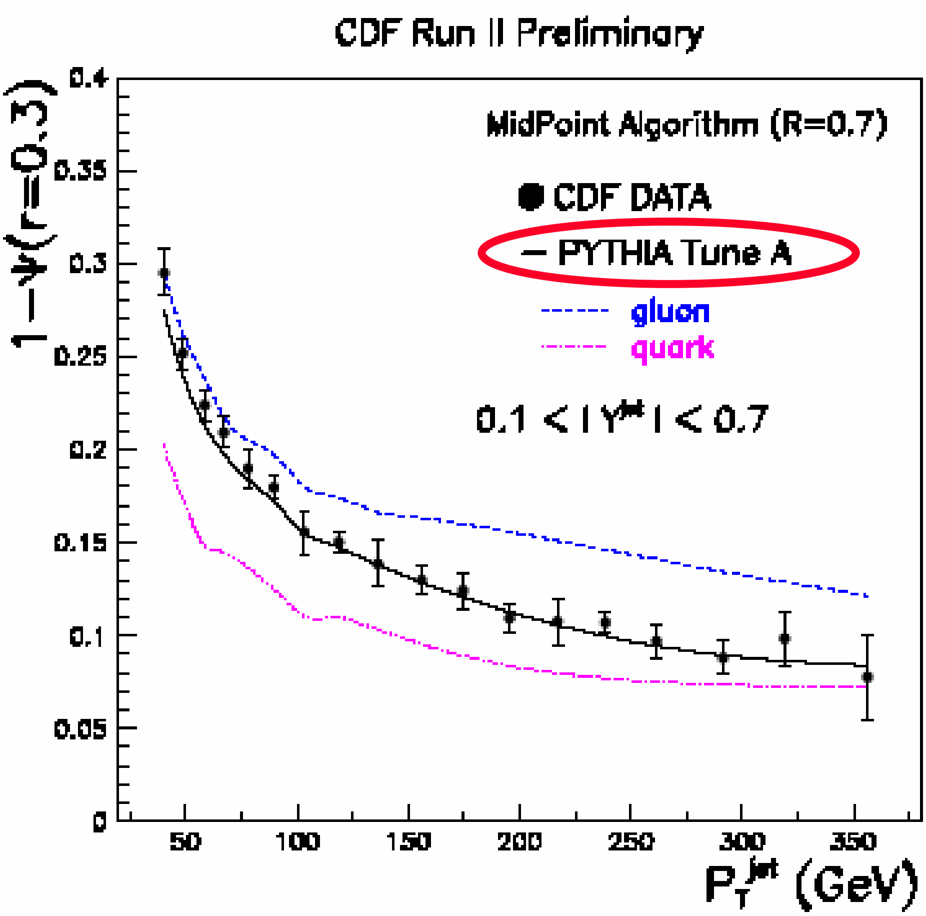


Jet Energy Profiles at e^+e^-

- OPAL performed an analysis similar to CDF for comparison purposes
- e^+e^- jets are narrower than $p\bar{p}$ jets
- Can it be the underlying event or "splash-out"?
  - Although the CDF data include underlying event, its effect to the energy profile is not large enough to account for the difference
- Can it be due to quark/gluon jet differences?
  - Most probable explanation
    - based on MC studies OPAL jets are ~ 96% quark jets, whereas CDF jets are ~75% gluon-induced

Jet energy profiles at Tevatron



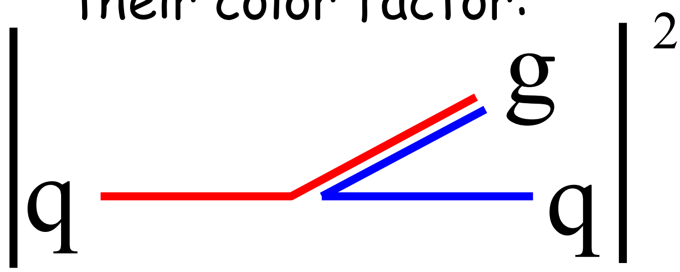


More about Pythia tuning later

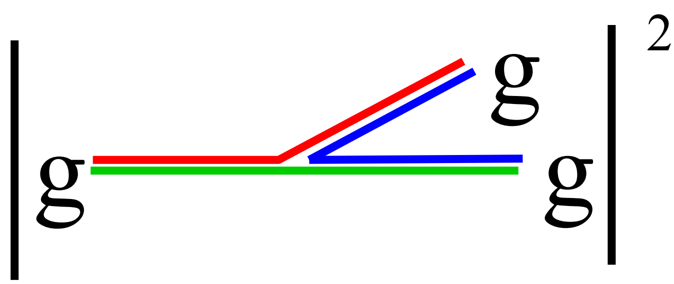
Quark vs Gluon Jets

Deepen understanding of jet substructure

- Quark & Gluon jets radiate proportional to their color factor:



$\sim C_F = 4/3$



$\sim C_A = 3$

$$r \equiv \frac{<n_g>}{<n_q>} \equiv \frac{<\text{gluon jet multiplicity}>}{<\text{quark jet multiplicity}>}$$

At Leading Order ($E_{jet} \rightarrow \infty$): $r \sim \frac{C_A}{C_F} = \frac{9}{4} = 2.25$

N.N.L.O: $r \sim \frac{C_A}{C_F}\left(1 - O(\alpha_s)\right) \xrightarrow[\text{LEP1 energies}]{} 0.9\frac{C_A}{C_F} \sim 2$

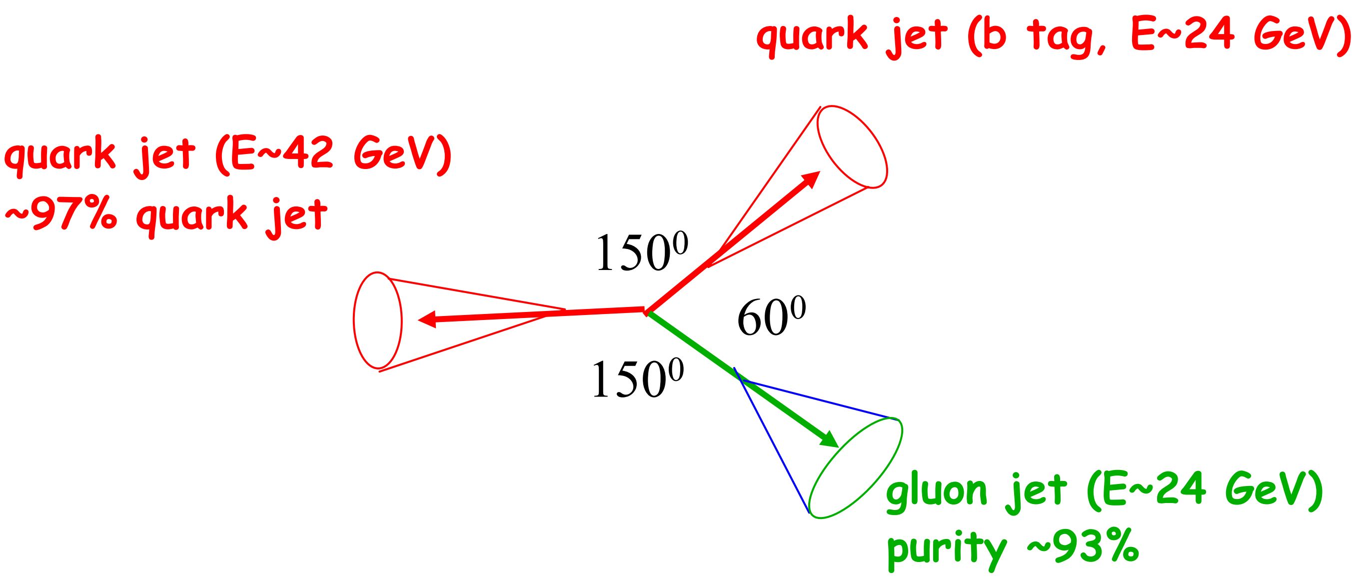
N.N.L.O w/ energy conservation: $r \sim 1.7$

Numerical Solutions (E_{jet} (LEP) ~ 40 GeV): $r \sim 1.5$

(more accurate energy conservation and phase space limits)

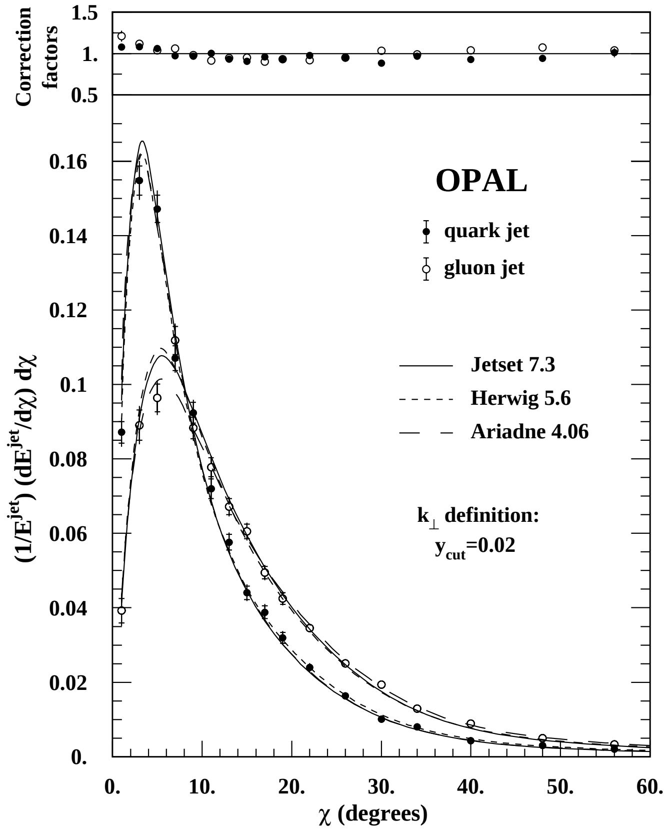
Quark vs Gluon Jets (LEP1)

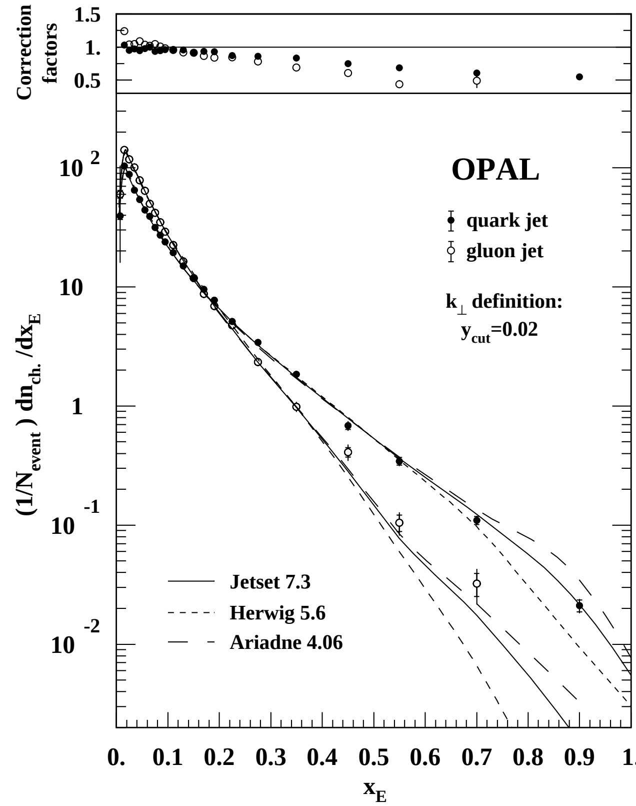
- Expectation:
  - Gluon jets are broader than quark jets
  - Gluon jets have softer fragmentation function than quark jets
- LEP1 measurement (OPAL)
  - Select three jet events

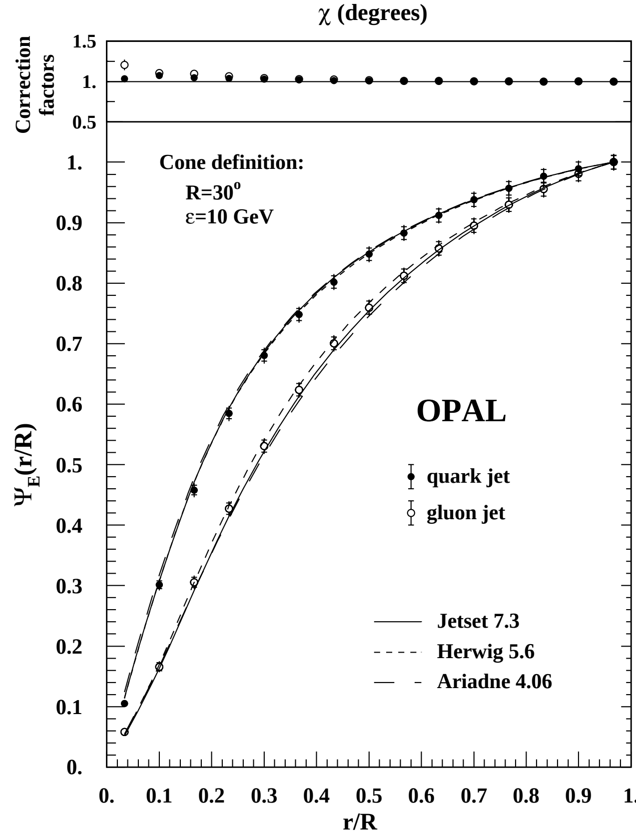


  - Repeat analysis with a "KT" (Durham) and "cone" jet algorithm in order to compare with Tevatron results

Quark vs Gluon Jets







r (K_T, charged prtc)=1.25±0.04

r (cone, R=30^0, ch prtc)=1.10 ±0.02

for R=50^0, r~1.26

⇒ result sensitive to jet algorithm!

⇒ r>1 is established!

OPAL has published an analysis on gluon vs quark jets which is almost entirely independent of the choice of the jet finding algorithm used

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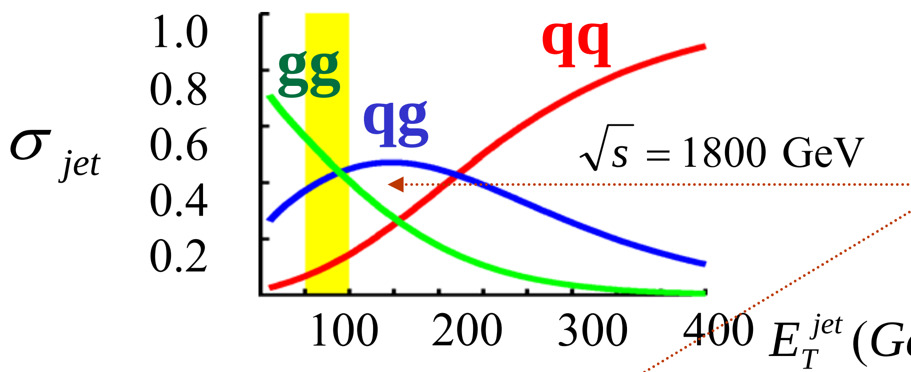
r (E_{jet} = 40 GeV) = 1.514±0.039

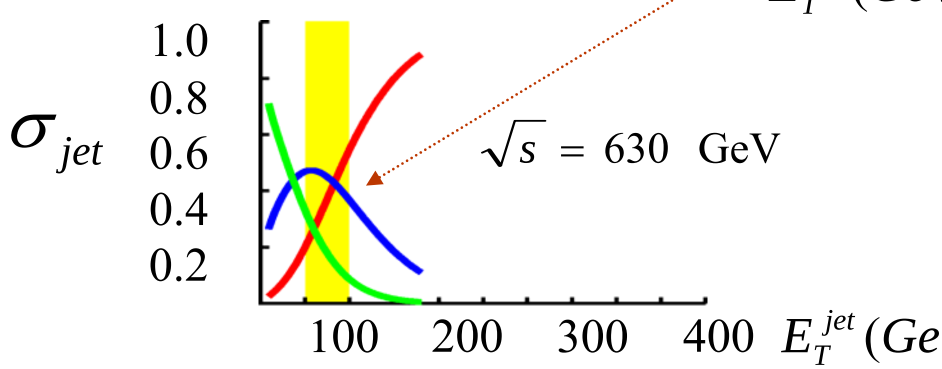
Quark vs Gluon Jets

- Basic Idea:
  - Compare the subjet multiplicity of jets with same E_T and η at center of mass energies 630 and 1800 GeV and infer q and g jet differences



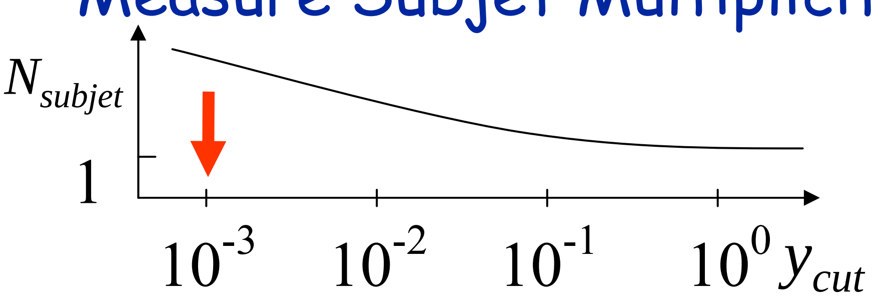
Different final state gluon fraction

- 50% gluon jets @ 1800GeV
- 33% @ 630 GeV



Obtain gluon fractions for both energies from Herwig

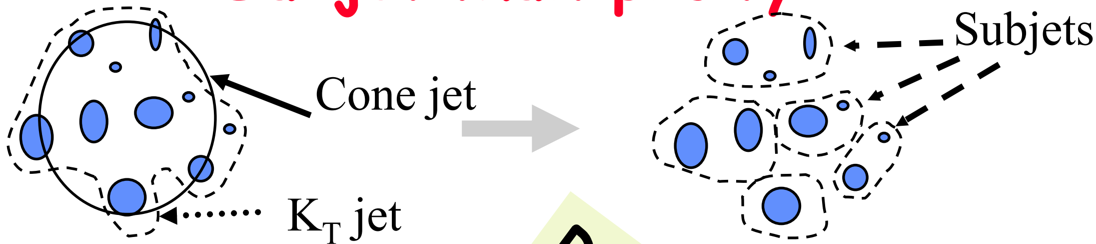
- Rerun k_T-algorithm on all 4-vectors merged into jet:
  - Recombine energy clusters into subjets separated by y_{cut} (a resolution parameter)
- Measure Subjet Multiplicity:



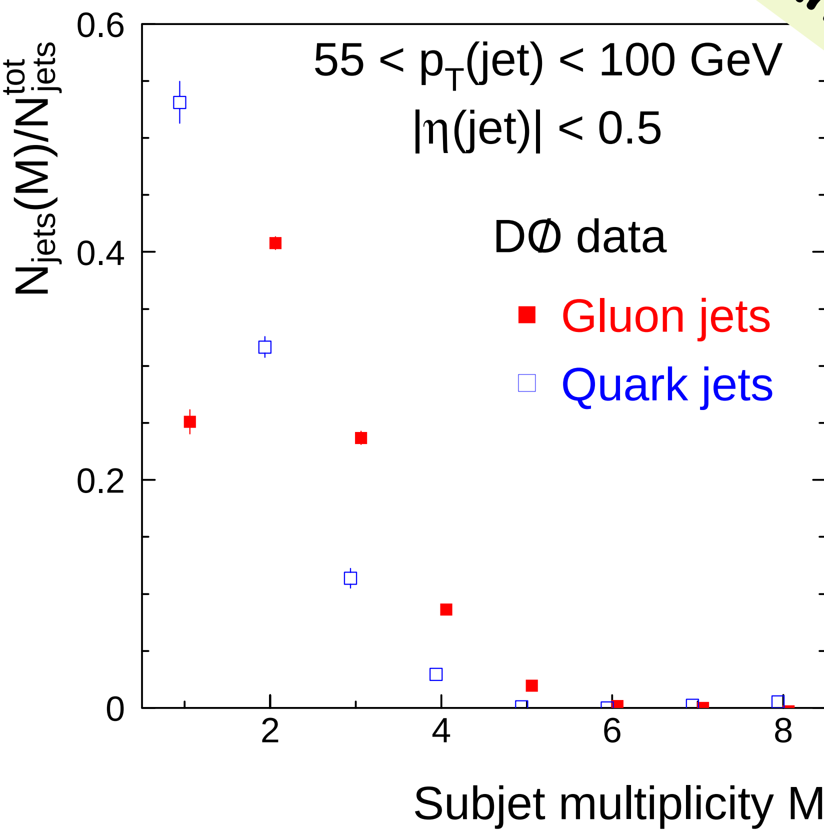
$$d_{i,j} = \min(p_{T,i}^2, p_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2} > y_{cut}\, p_{T,Jet}^2$$

$y_{CUT} \to 1$, $N_{subjet} \to 1$,
$y_{CUT} \to 0$, $N_{subjet} \to \infty$

Subjet Multiplicity



Run I



$$r = \frac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1}$$

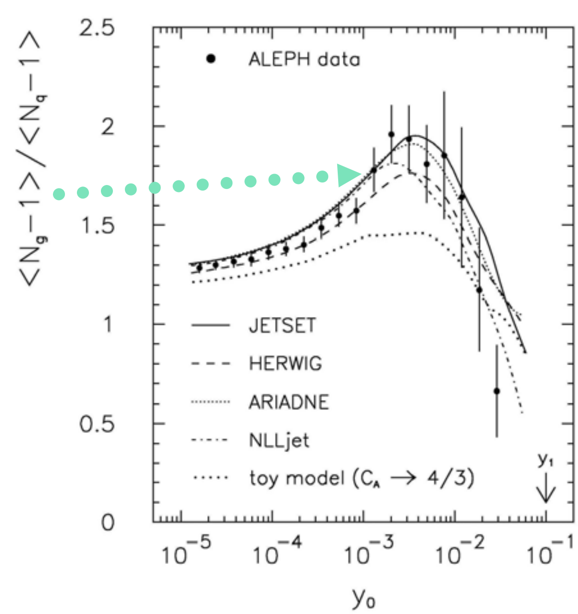
$$r = 1.84 \pm 0.15\,(stat) \pm^{0.22}_{0.18}\,(sys)$$

(DØ Data)

$$r = 1.91 \pm 0.16\,(stat)$$

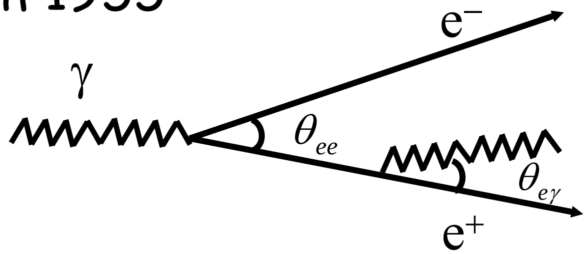
(HERWIG 5.9)

Result is consistent with ALEPH measurement for $y_0 \sim 10^{-3}$



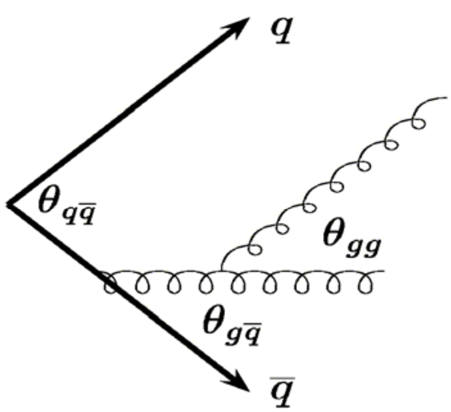
Coherence

- **Property of gauge theories.** Similar effect in QED, the "Chudakov effect" observed in cosmic ray physics in 1955



$$\theta_{ee} > \theta_{e\gamma}$$

- In QCD color coherence effects are due to the interference of soft gluon radiation emitted along color connected partons
- **Two types of Coherence:**
  - **Intrajet Coherence**
    - Angular Ordering of the sequential parton branches in a partonic cascade
      - Suppression of large-angle soft gluon radiation in partonic cascades – Hump backed plateau



$$\theta_{gg} < \theta_{g\bar{q}} < \theta_{q\bar{q}}$$

  - **Interjet Coherence**
    - String or Drag effect in multijet hadronic events

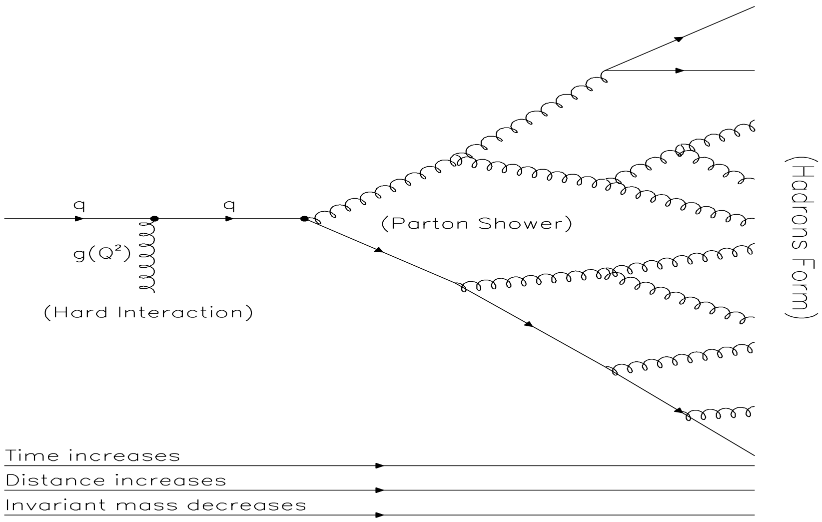
Shower Development

"Traditional Approach"

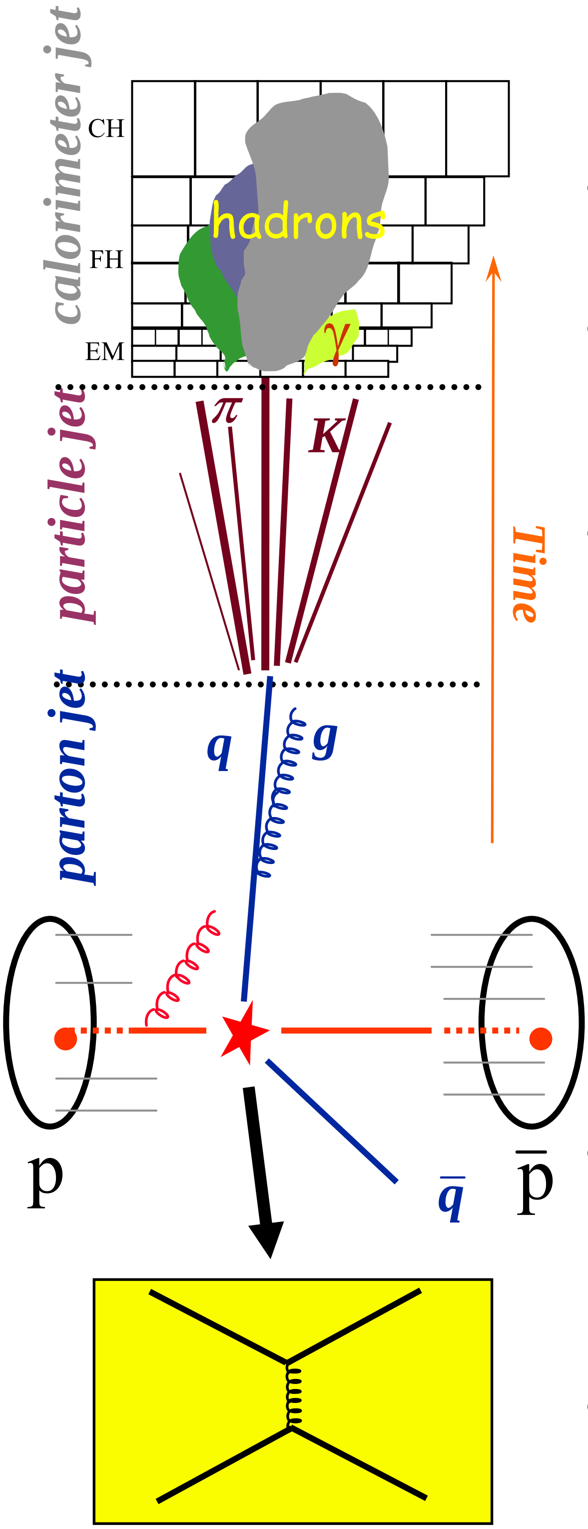
- Shower develops according to pQCD into spray of partons until a scale of $Q_0 \sim 1$ GeV.
- Thereafter, non-perturbative processes take over and produce the final state hadrons
- Coherence effects are included probabilistically (i.e., Angular Ordering) and in the hadronization model

"Local Parton Hadron Duality (LPHD) Approach"

- Parton cascade is evolved further down to a scale of about $Q_0 \sim 250$ MeV.
- No hadronization process.
  Hadron spectra = Parton spectra
- Simplicity. Only two essential parameters (Λ_{QCD} and Q_0) and an overall normalization factor



What is an Event Generator ?

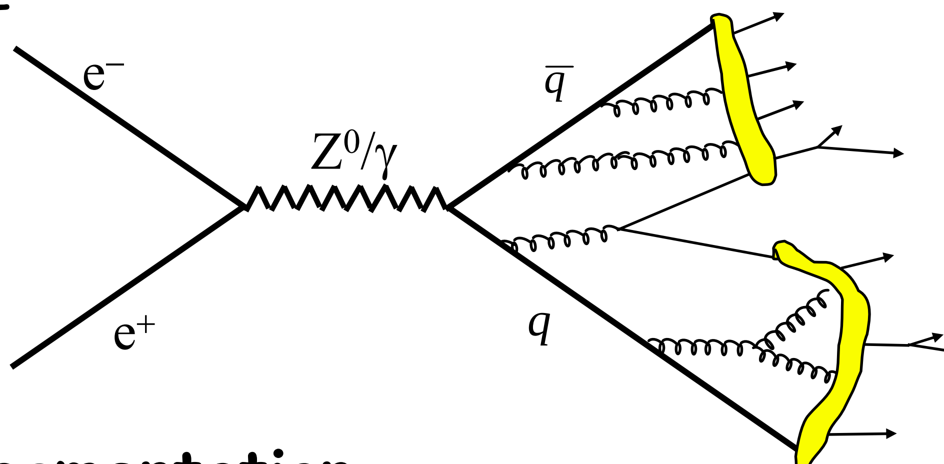


- A "Fortran" ("C") program that generates events, trying to simulate Nature!
- Events vary from one to the next (random numbers)
- Expect to reproduce average behavior and fluctuations of real data
- Event Generators include:
  - Parton Distribution functions
  - Initial state radiation
  - Hard interaction
  - Final state radiation
  - Beam jet structure
  - Multiple Parton Interactions
  - Hadronization and decays
- Some programs in the market:
  - JETSET, PYTHIA, LEPTO, ARIADNE, HERWIG, COJETS...
- Parton-level only:
  - VECBOS, NJETS, JETRAD, HERACLES, COMPOS, ALPGEN, PAPAGENO, EUROJET...

Hadronization Models

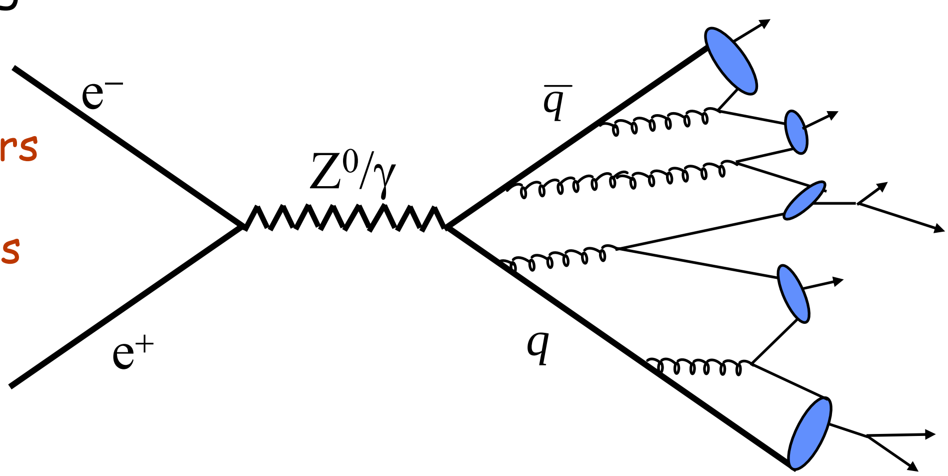
- **Independent fragmentation**
  - it is being used in ISAJET and COJETS
  - simplest scheme - each parton fragments independently following the approach of Field and Feynman
- **String fragmentation**
  - it is being used in JETSET, PYTHIA, LEPTO, ARIADNE

String Fragmentation: Separating partons connected by color string which has uniform energy per unit length.



- **Cluster fragmentation**
  - it is being used in HERWIG

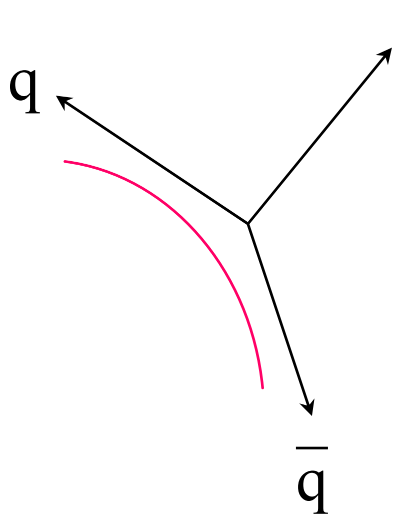
Cluster Fragmentation: Pairs of color connected neighboring partons combine into color singlets.



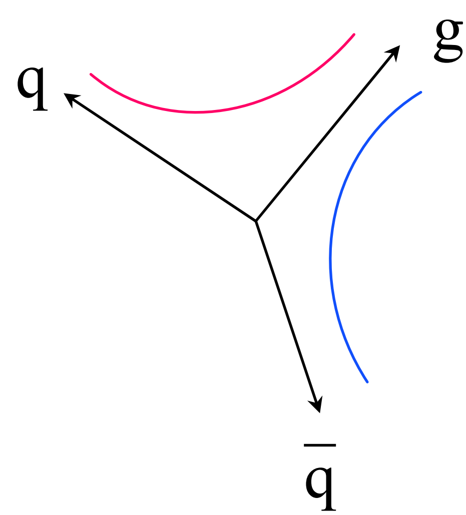
Coherence Observations

e^+e^- interactions:

First observations of final state color coherence effects in the early '80's (JADE, TPC/2g, TASSO, MARK II Collaborations) ("string" or "drag" effect)



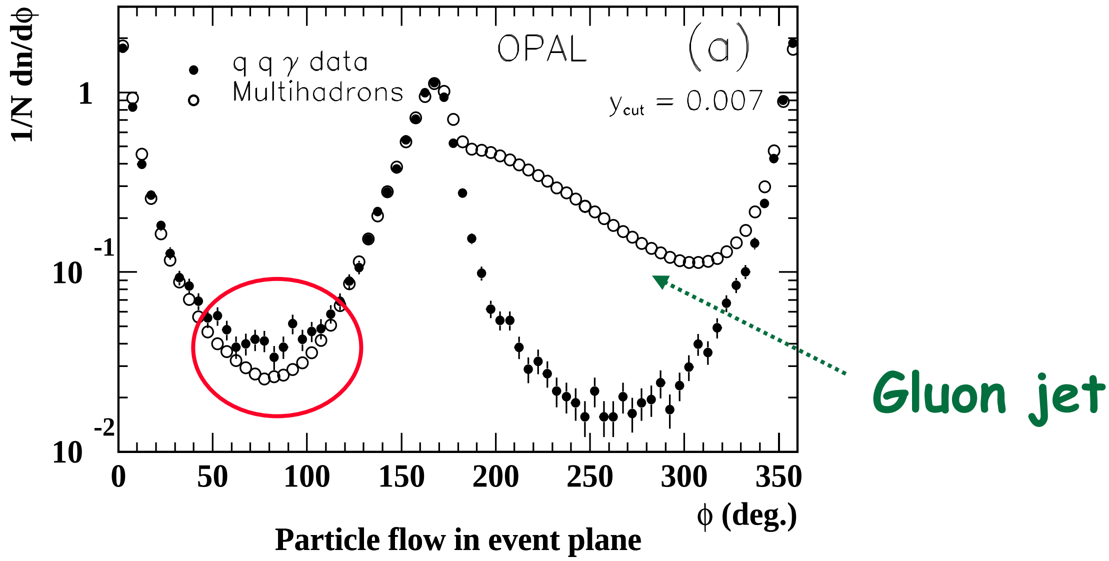
$$e^+e^- \to q\,\bar{q}\,\gamma$$

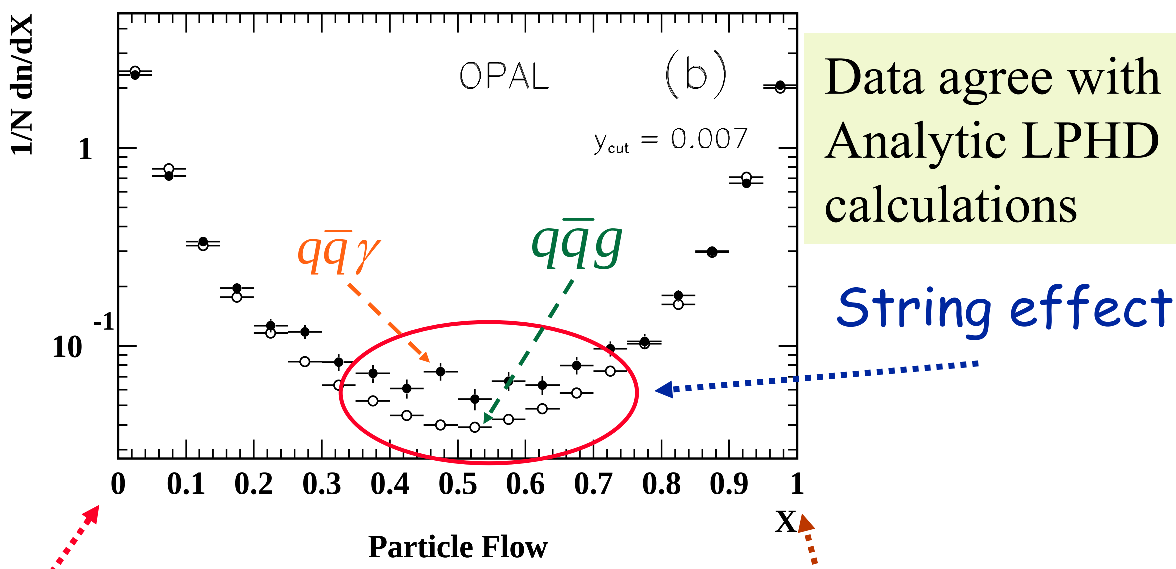


$$e^+e^- \to q\,\bar{q}\,g$$

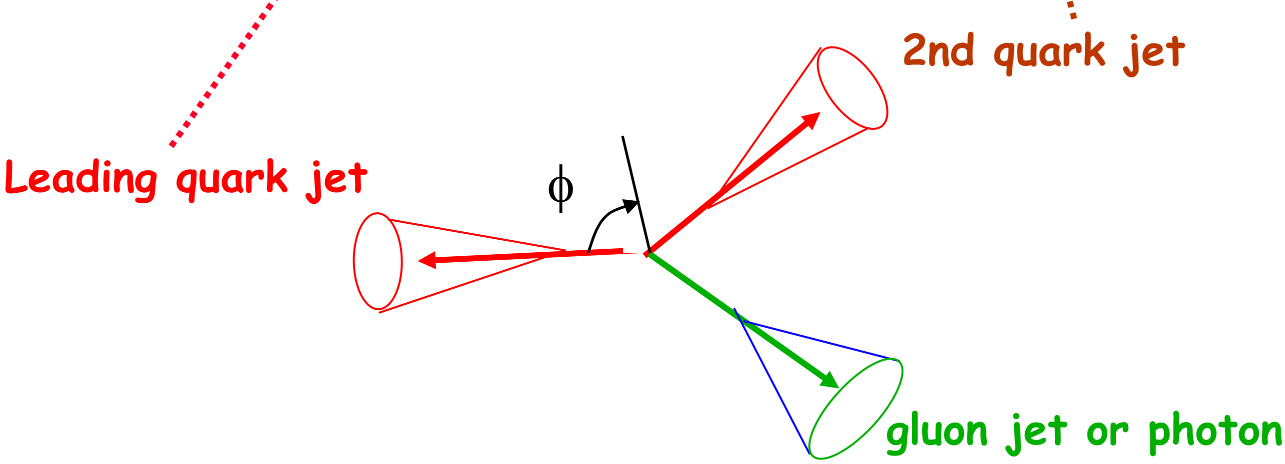
Depletion of particle flow in region between q and $\bar{q}$ jets for $q\bar{q}g$ events relative to that of $q\bar{q}\gamma$ jets.

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





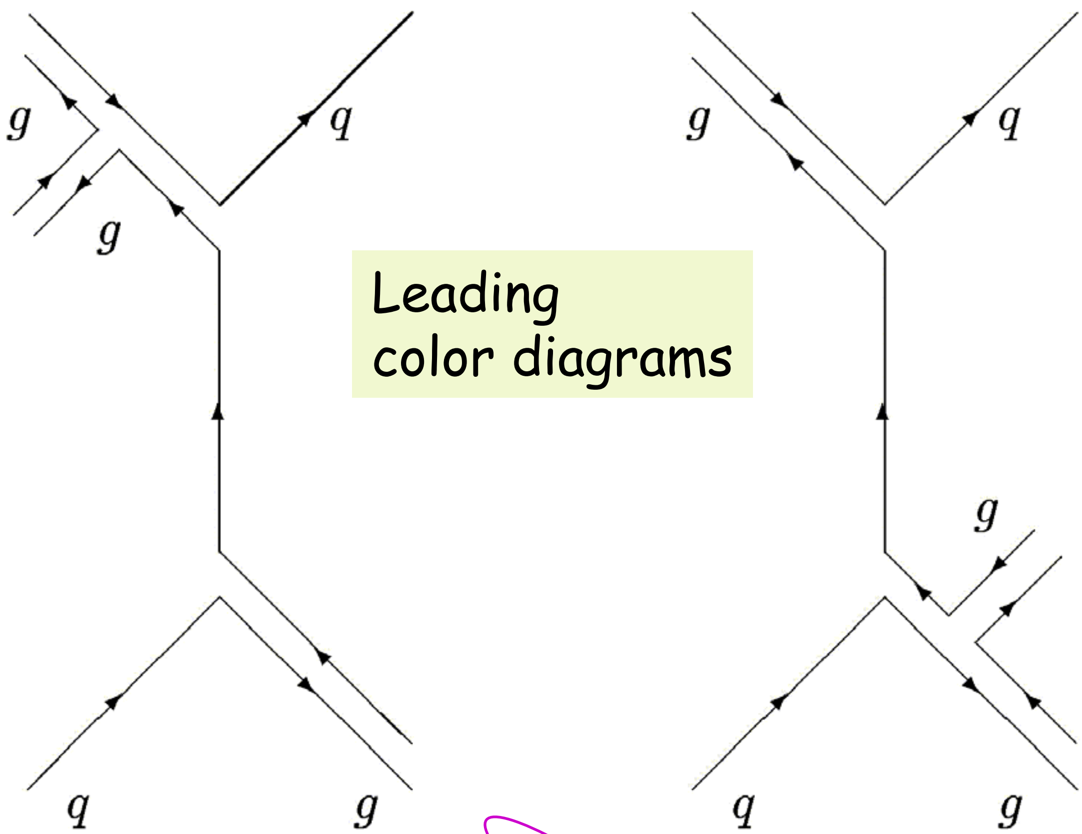
Data agree with Analytic LPHD calculations

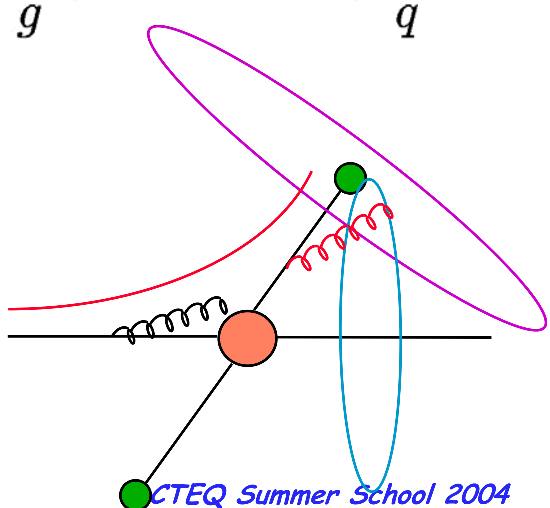


Coherence Observations cont'd

$p\bar{p}$ interactions:

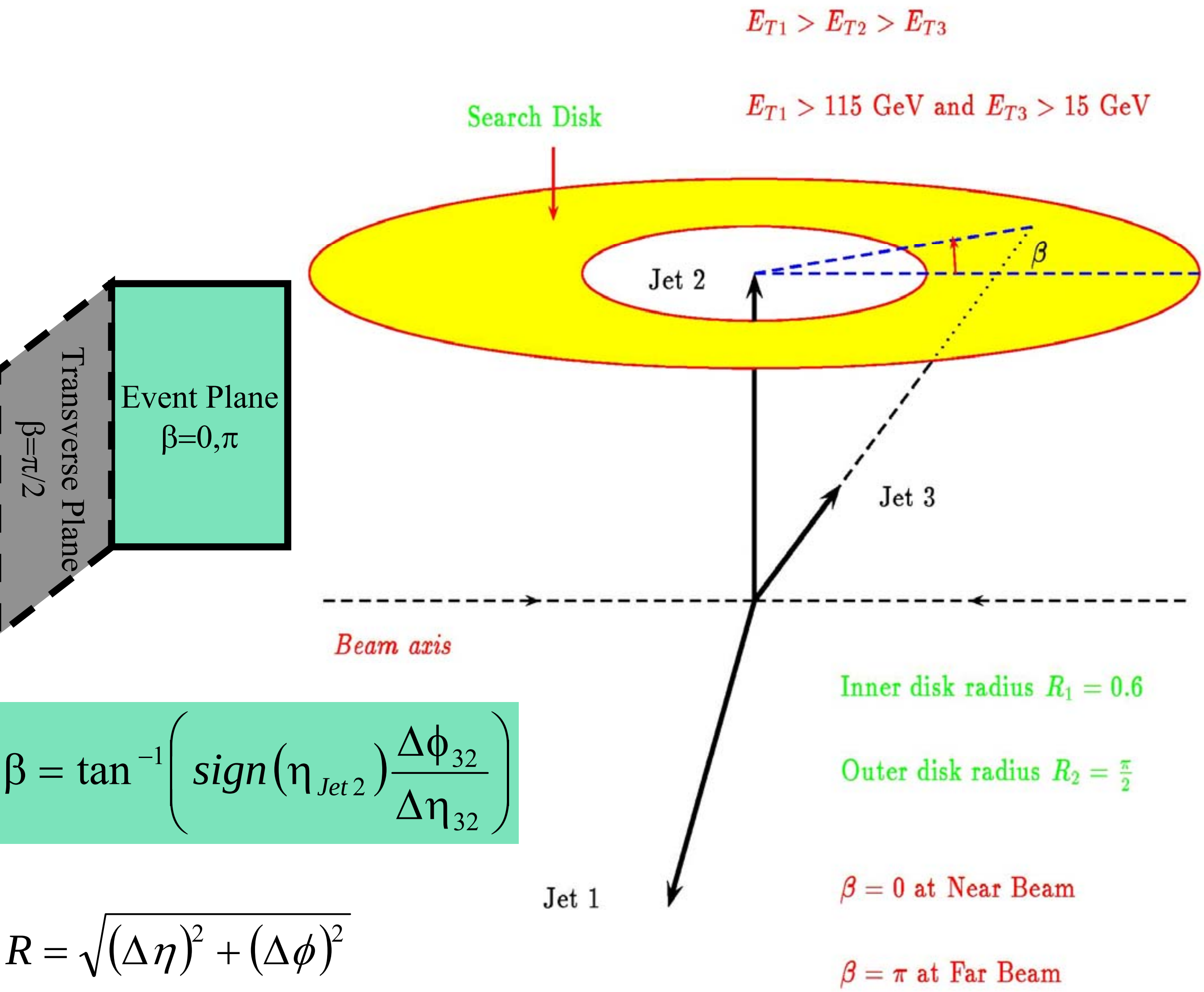
- Colored constituents in initial *and* final state (more complicated that e^+e^-)
- Probes initial-initial, final-final and **initial-final** state color interference





$p\bar{p} \to 3\,jets + X$

- Select events with three or more jets
- Measure the angular distribution of "softer" 3rd jet around the 2nd highest-E_T jet in the event



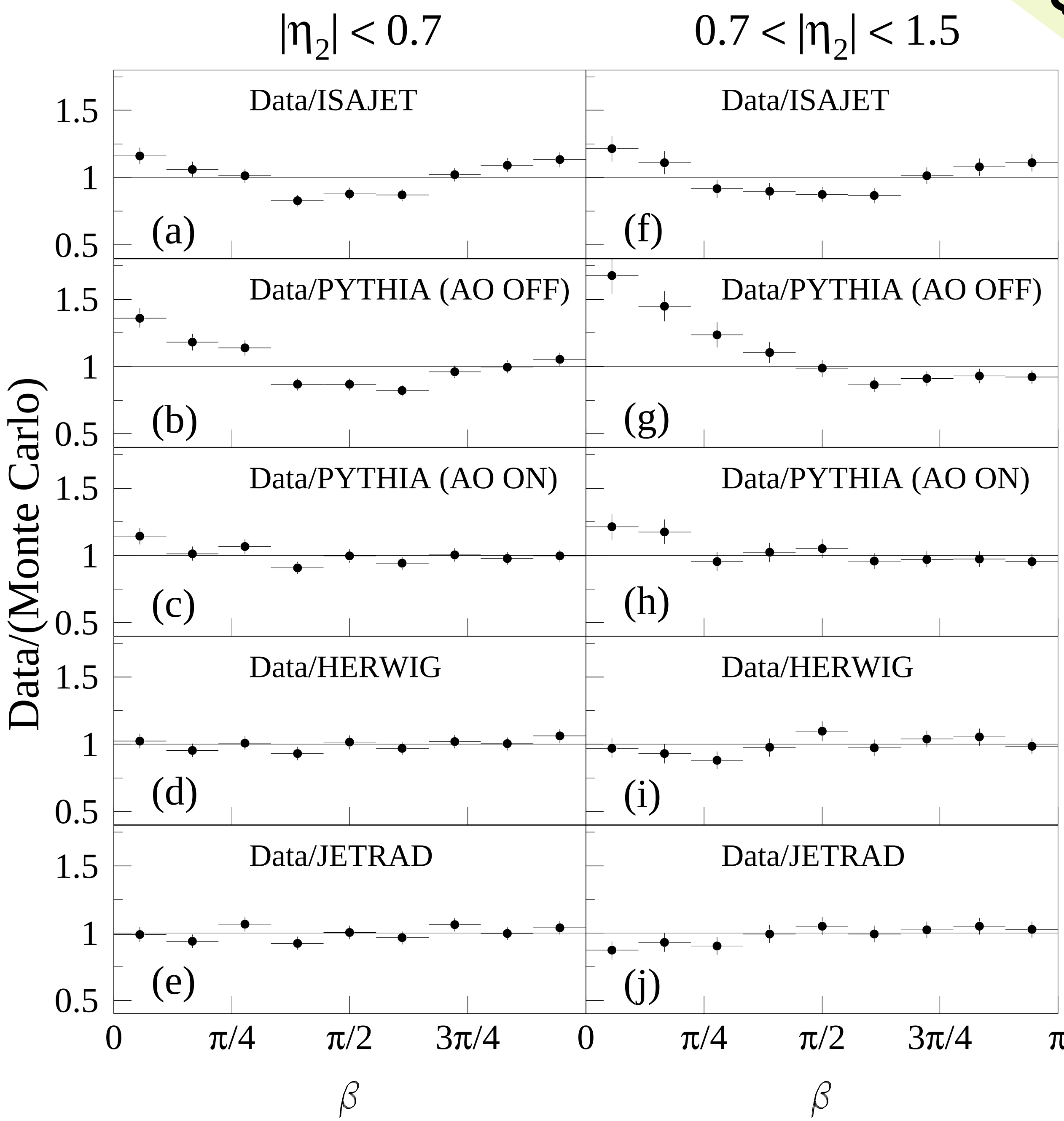
$$\beta = \tan^{-1}\left(sign(\eta_{Jet\,2}) \frac{\Delta\phi_{32}}{\Delta\eta_{32}} \right)$$

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- Compare data to several event generators with different color coherence implementations

3-jet Data/Monte Carlo

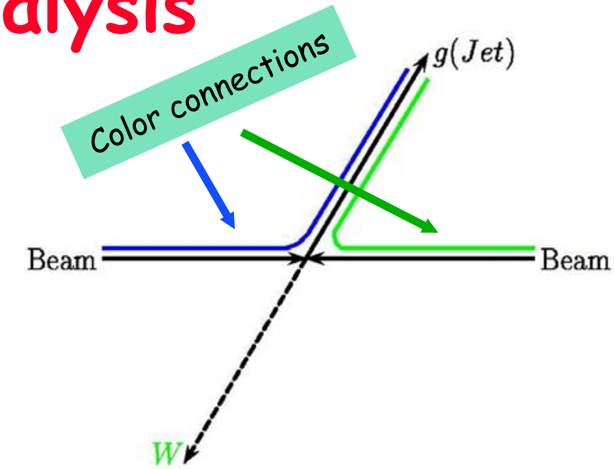
Run I

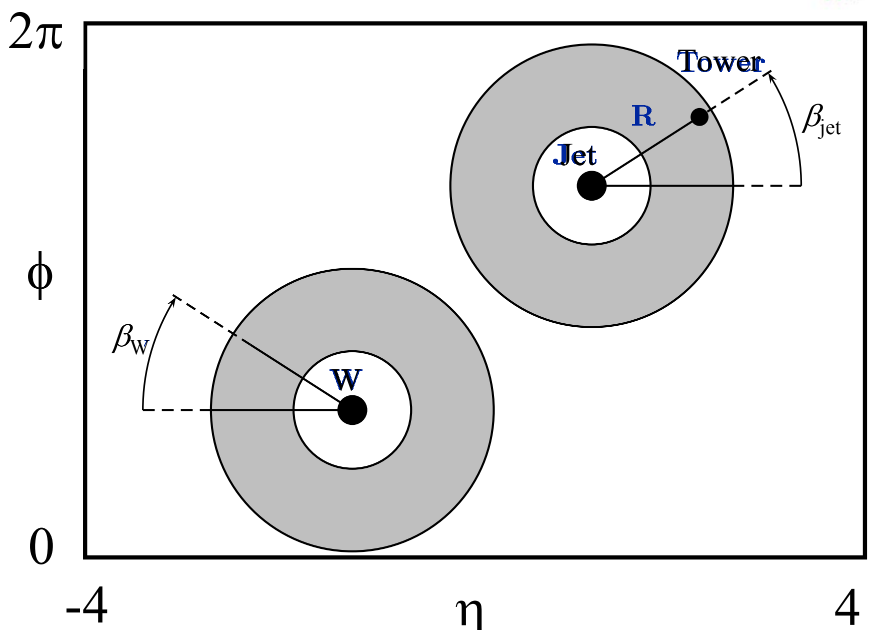


- HERWIG and JETRAD agree best with the data
- MC models w/o CC effects disagree with the data

W+Jet Analysis

Compare pattern of soft particle flow around jet to that around (colorless) W





At LO:

$$qg \rightarrow q'W$$

$$q\bar{q}' \rightarrow gW$$

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Search disks: R(*inner*)=0.7
R(*outer*)=1.5

$$\beta_{W,Jet} = \tan^{-1}\left(sign(\eta_{W,Jet}) \frac{\Delta\phi}{\Delta\eta} \right)$$

- In each annular region, measure number of calorimeter towers (~ particles) with $E_T > 250$ MeV
- Plot $N^{Tower}_{Jet} / N^{Tower}_{W}$ vs. β
- Annuli "folded" about ϕ symmetry axis

β range: $0 \rightarrow \pi$

$\beta = 0 \rightarrow$ "near beam", $\beta = \pi \rightarrow$ "far beam"

W + Jet - Monte Carlo Samples

- PYTHIA v5.7 Monte Carlo
  - Full detector simulation
  - 3 samples with different color coherence:

  "Full coherence": AO + String Fragmentation

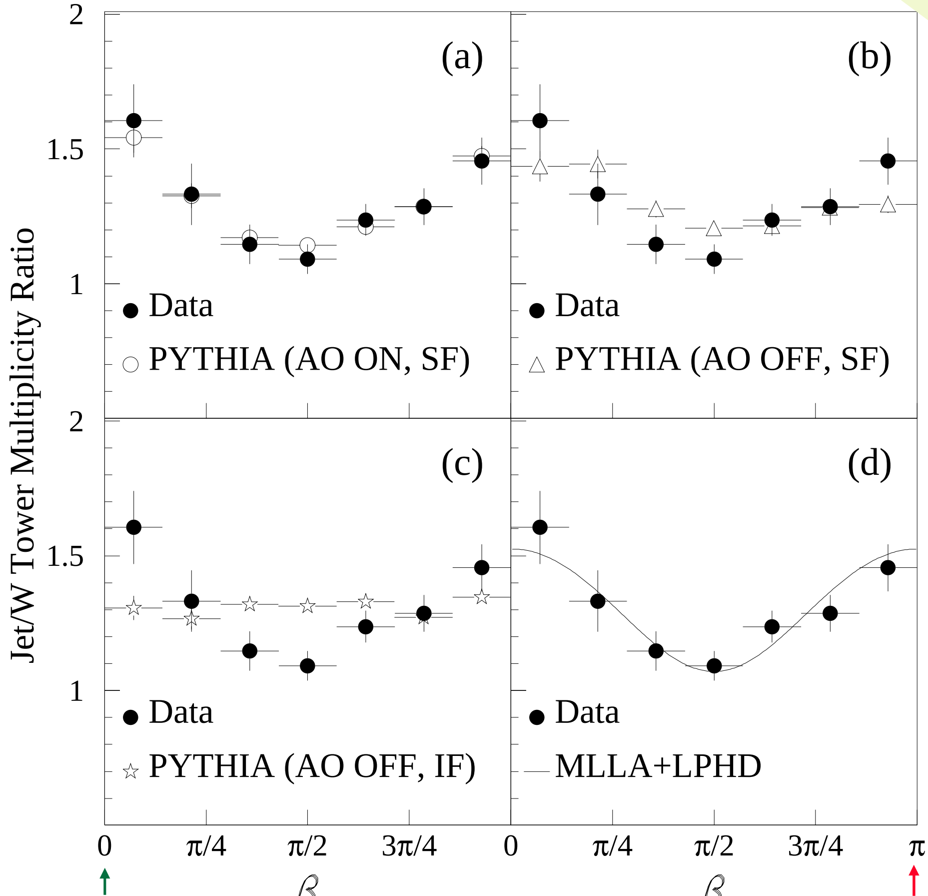
  "Partial": No AO + String Fragmentation

  "No coherence": No AO + Independent Frag.

- Analytic Predictions by Khoze and Stirling
  - MLLA + LPHD
  - $q\bar{q}$–>Wg and qg–>Wq processes

W+Jet Results

Run I

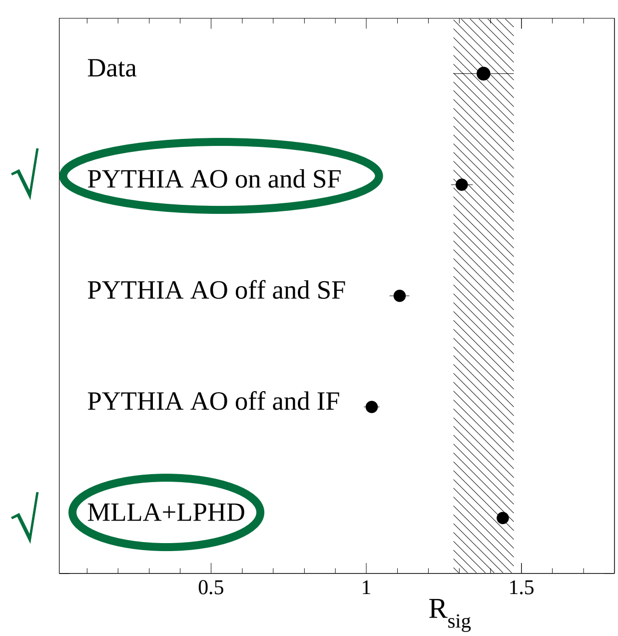


Near Beam

Far Beam

Plot the ratio or ratios

$$R_{signal} \equiv \frac{\text{Event Plane Multiplicity Ratio}}{\text{Transverse Plane Multiplicity Ratio}} = \frac{R(\beta = 0, \pi)}{R(\beta = \pi/2)}$$



Jet Production @ Tevatron

Motivation:

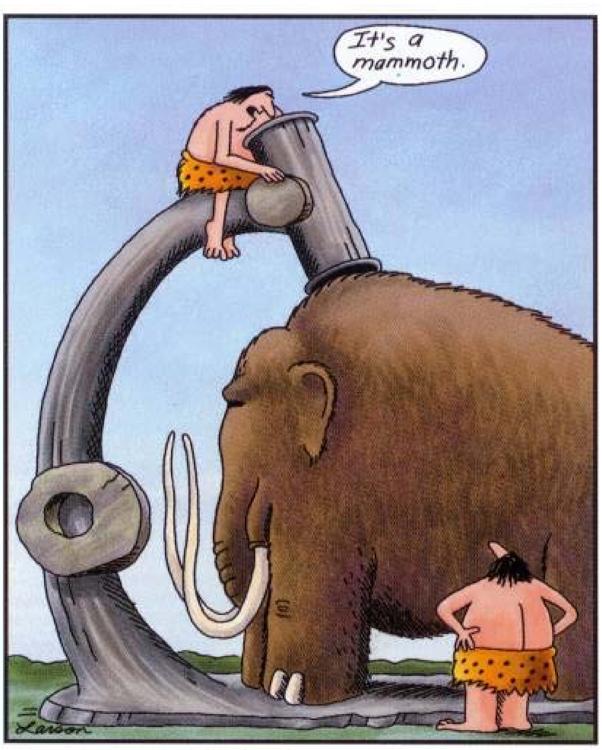
- Search for breakdown of the Standard Model at shortest distances
    - At Tevatron energies:

$$p_T \sim 500\,GeV$$

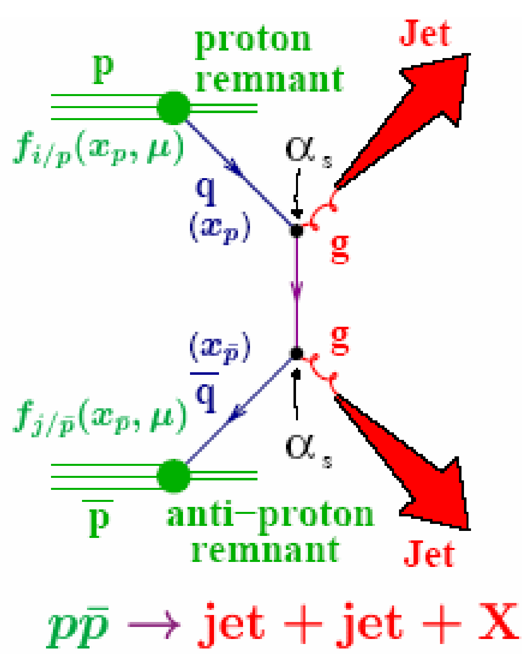
$$\Rightarrow \text{distance} \sim \frac{\hbar c}{p_T} \sim \frac{200\ \text{MeV}\cdot\text{fm}}{500\ \text{GeV}} \sim 4\times10^{-19}\,m$$

World's best microscope !

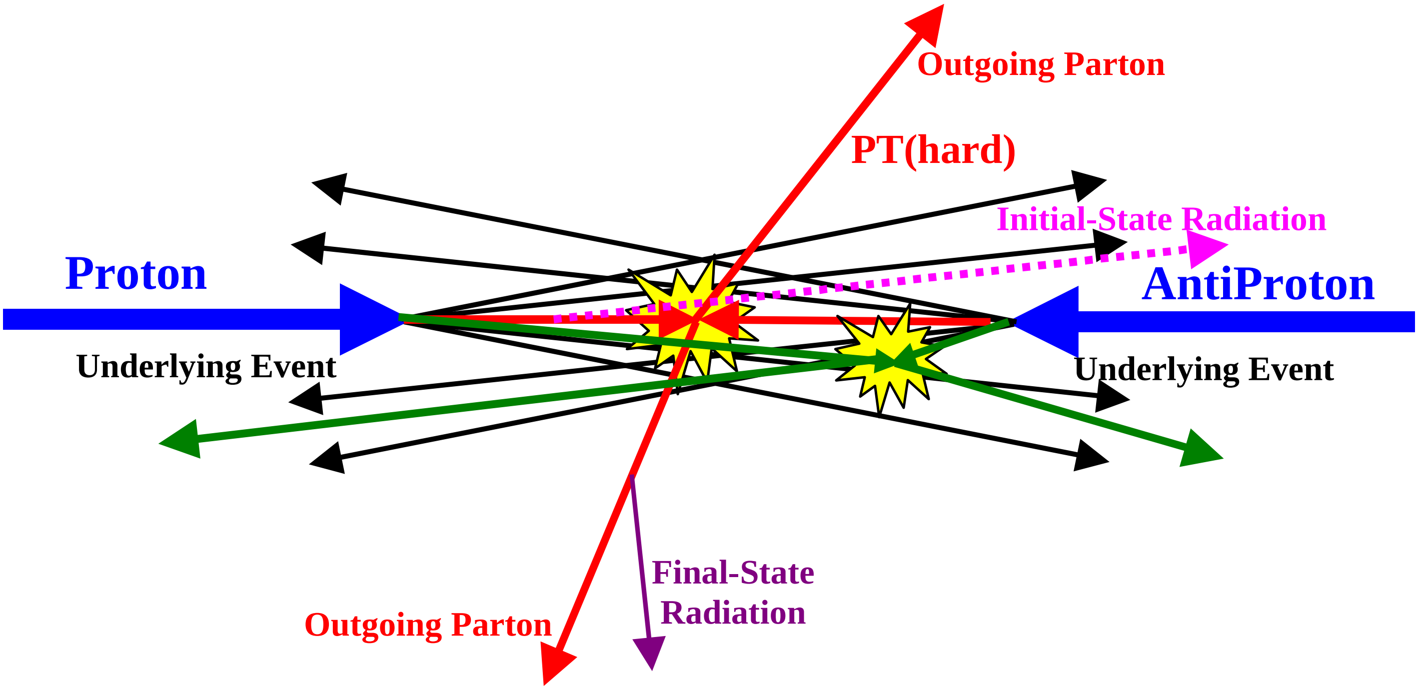
- Search for new particles decaying into jet final states
- Search for quarks substructure
- Constrain gluon density at high x
- Precision studies of QCD



Early microscopes



$p\bar{p} \rightarrow jets$



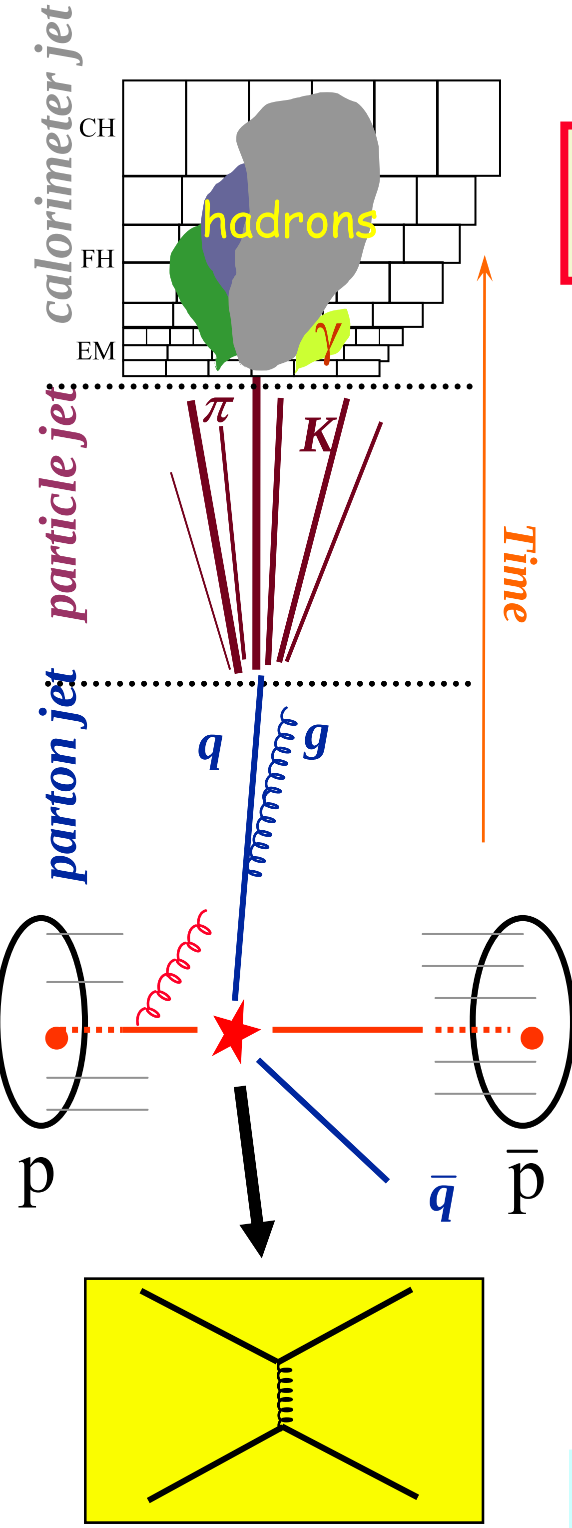
- Initial State Radiation (ISR)
  - Incoming partons emit soft gluons
- Final State Radiation (FSR)
  - Outgoing partons emit soft gluons
- Underlying Event
  - Remnants of proton and antiproton interact producing low-p_T particles
- Multiple-Parton Scattering
  - Collisions between more than one parton within each incoming proton-antiproton
- Multiple Interactions
  - Collisions between more than one proton-antiproton pair

Challenges with Jets

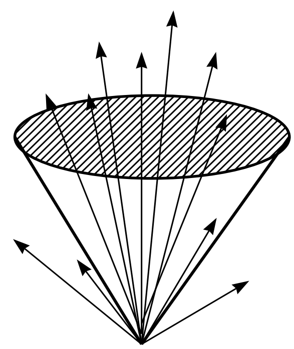
- Triggering on Jets
  - reduce rate from ~10^6 to ~ tens of Hz
  - multiple triggering stages; Level-1,2,3
  - fast/crude jet clustering algorithms for L1/2
- Selection of a Jet Algorithm
  - detector, particle, parton/NLO level
- Jet Reconstruction, Selection, Trigger Efficiencies
- Jet Calibration
  - vs E, η
  - underlying event definition (subtract or not?)
  - out-of-cone showering effects
  - correction back to particle jet or original parton ?
- Jet Resolution
  - difficulties with low-E_T region and near reconstruction threshold
- Simulation of Jet/Event/Detector Characteristics
  - precision of detector modeling vs CPU time
  - ability to overlay zero/minimum-bias events from data
  - tuning of fragmentation model
  - selection of PDF, hard scale parameter Q, …
  - Interface a higher-order parton-based program with a LO parton-shower simulation
  - ...

Jet Energy Scale

An example



Jet energy scale correction: "calorimeter" → "particle" jet



$$E^{true} = \frac{E^{meas} - E_O}{R_{jet}\ R_{OOC}}$$

E^{true} **"True" Jet Energy; particle level**

E^{meas} **Measured Jet Energy**

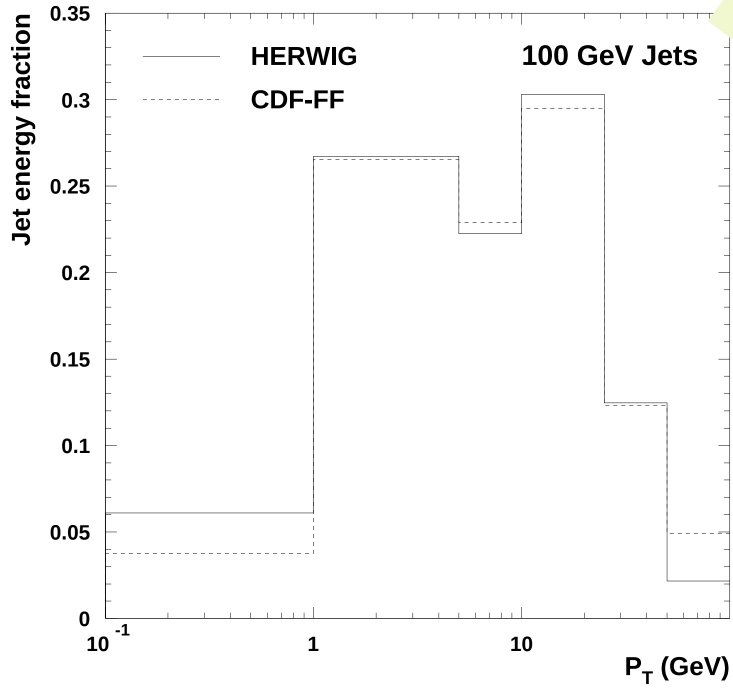
E_O **Offset** **(Mult. Int., pile-up, UE)**

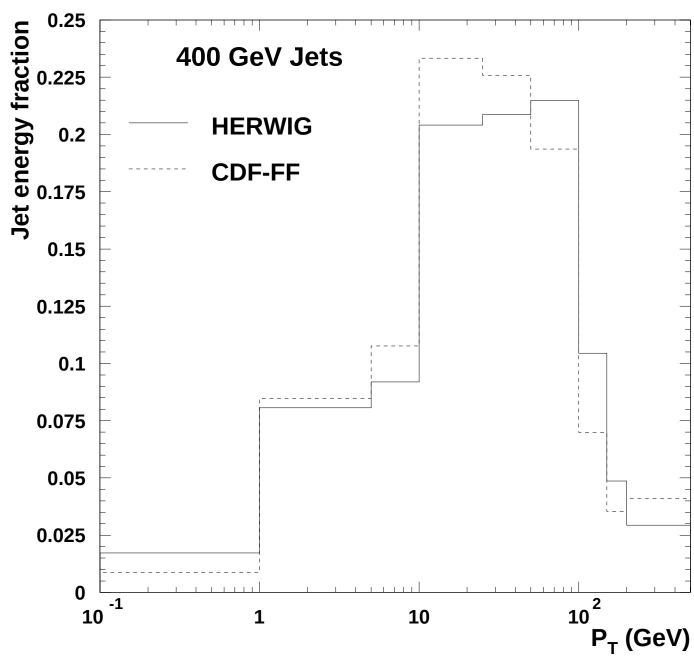
R_{jet} **Calorimeter Jet Response**
Measured in situ using γ – Jet P_T balance

R_{OOC} **Out of Cone Calorimeter**
Showering *(energy leaking in/out of jet cone)*

Particle p_T distribution in Jets

Run I

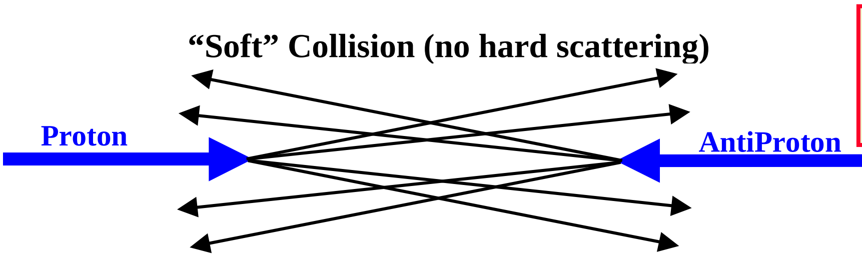




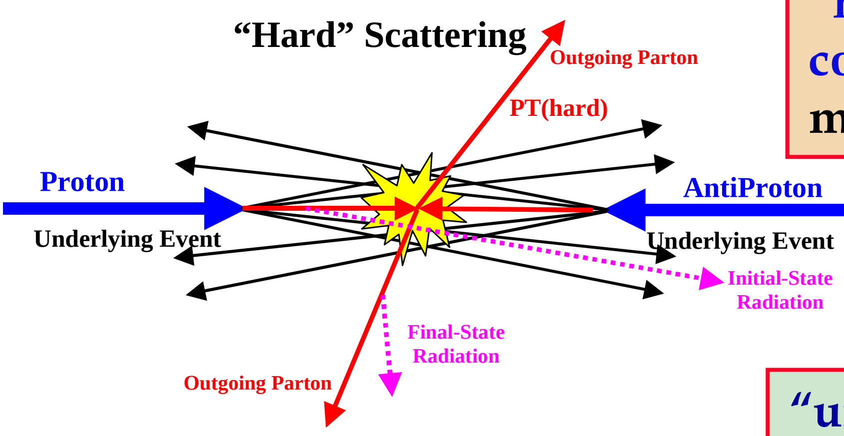
- Particle P_T spectrum inside jet picks at about ~10% of jet E_T
- there is significant contribution from low energy particles

Underlying Event (UE)

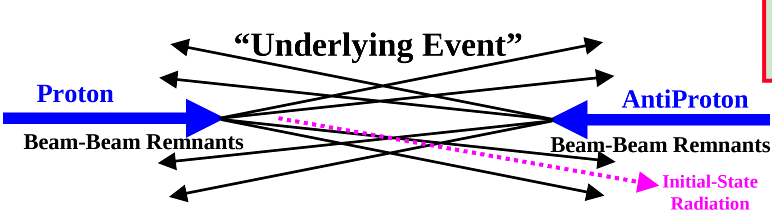
The UE event is the ambient energy from fragmentation of partons not associated with the hard scattering



No hard scattering.
"Min-Bias" event.



"hard" parton-parton collision : large transverse momentum outgoing jets.



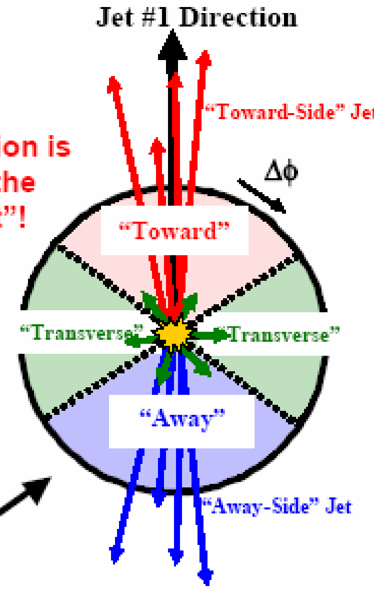
"underlying event": everything but the two outgoing hard scattered "jets".

- Underlying event is not the same as a minimum bias event
- Includes ISR/FSR/MPI – not completely independent of hard scatter

Underlying Event cont'd

- Underlying event pollutes many analyses
- Basic in order to understand the jet fragmentation

"Transverse" region is very sensitive to the "underlying event"!



- It must be tuned as well as possible
- Default Pythia does not describe well the CDF data → Pythia CDF tune A

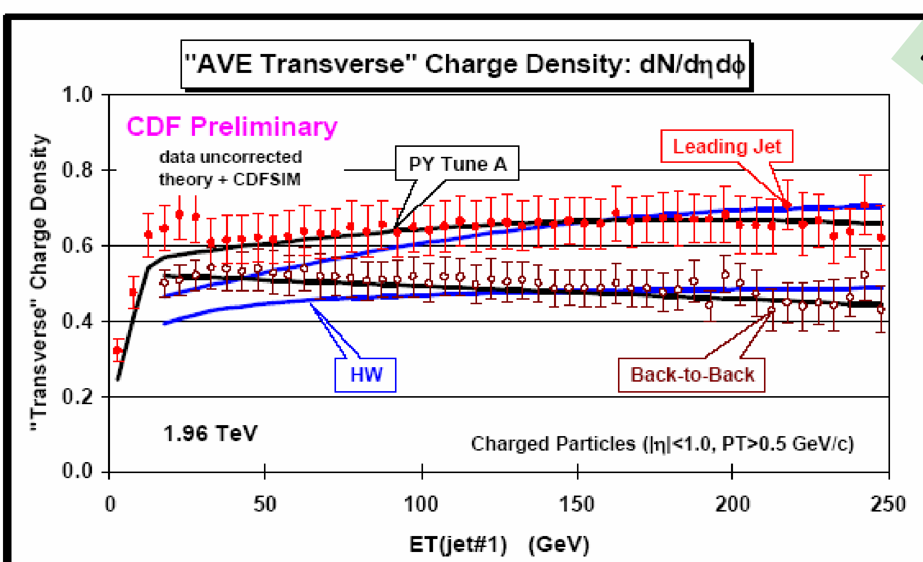
The method

The picture

- Look at charged particle correlations in the azimuthal angle $\Delta\phi$ relative to the leading calorimeter jet (JetClu R = 0.7, $|\eta| < 2$)
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away"
- All three regions have the same size in η-ϕ space, $\Delta\eta x \Delta\phi = 2x120^o = 4\pi/3$

- **PYTHIA tune A (on Run I data) reproduces well Run II data**
- **HERWIG works only at high E_{T1}**

PYTHIA Tune A has more ISR & multiple parton interactions



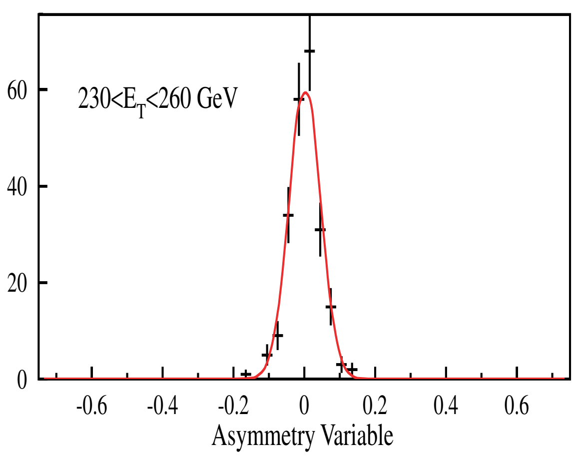
Average charged particle density, $dN/d\eta d\phi$, in the "transverse" region versus E_T(jet#1) for "Leading Jet" and "Back-to-Back" events compared with PYTHIA Tune A and HERWIG

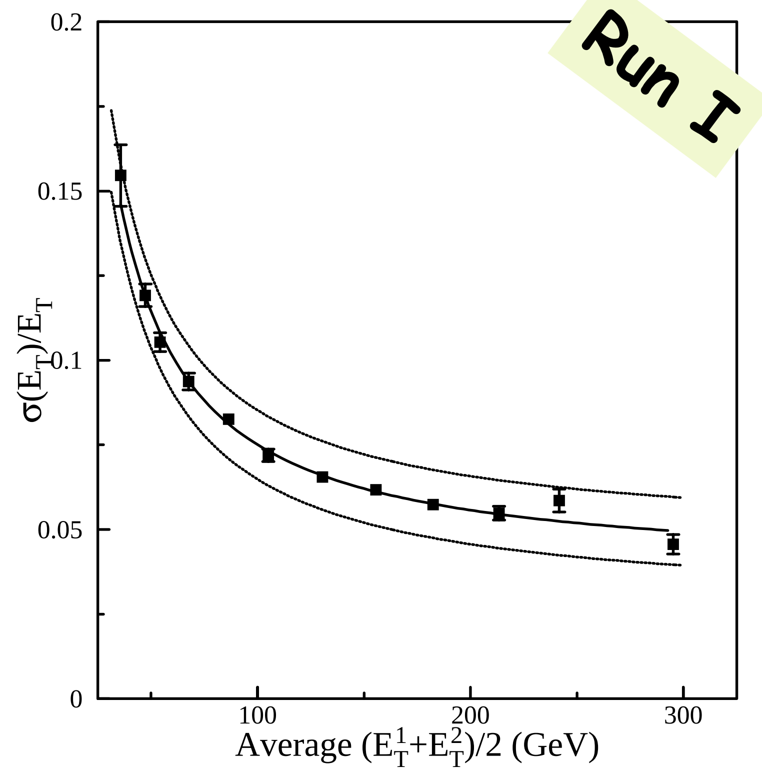
Jet Energy Resolution

- Measured from dijet collider data using E_T balance:

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

In the limit of no soft radiation





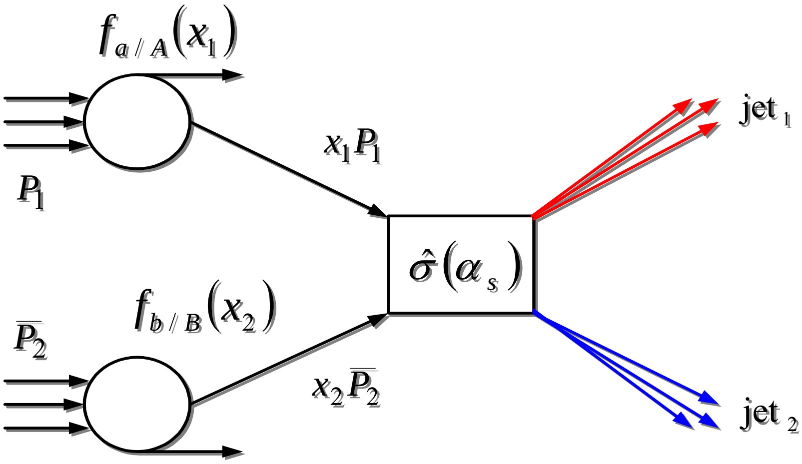
- Unsmearing procedure:
  - convolute "true cross section" $f(E_T)$ with a Gaussian smearing

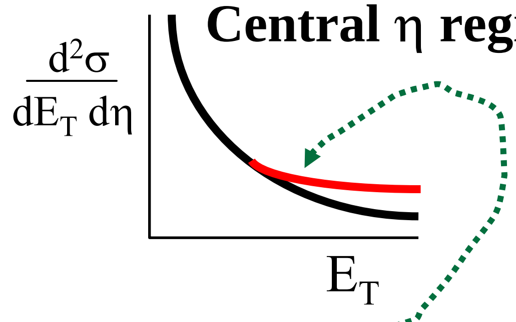
$$F(E_T) = \int \frac{1}{\sqrt{2\pi\sigma}} e^{\frac{-(E'_T - E_T)^2}{2\sigma^2}} \cdot f(E'_T)\, dE'_T$$

$$f(E'_T) = AE'^{-B}_T \left(1 - \frac{2E'_T}{\sqrt{s}}\right)^C$$

  - Fit $F(E_T)$ to the data cross section

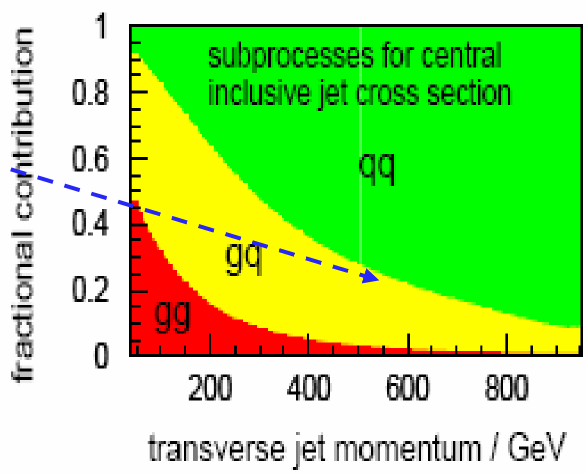
High-E_T Jet Production





Quark substructure ?
PDFs ?

Significant gluon contribution at high E_T

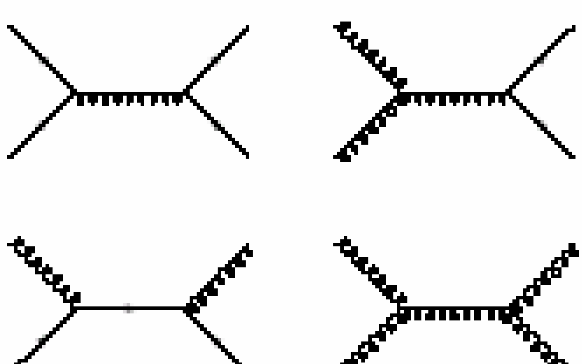


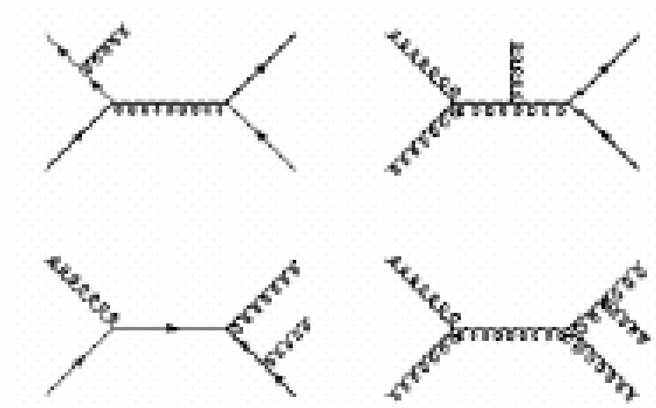
$$\frac{d\sigma}{dP_T} \approx \sum_{a,b} \int dx_a\, f_{a/A}(x_a,\mu) \int dx_b\, f_{b/B}(x_b,\mu) \frac{d\hat{\sigma}}{dP_T}$$

$$\frac{d\hat{\sigma}}{dP_T}(ab \to cd) \approx \sum_N \left(\frac{\alpha_s(\mu^2)}{\pi} \right)^N M_N$$

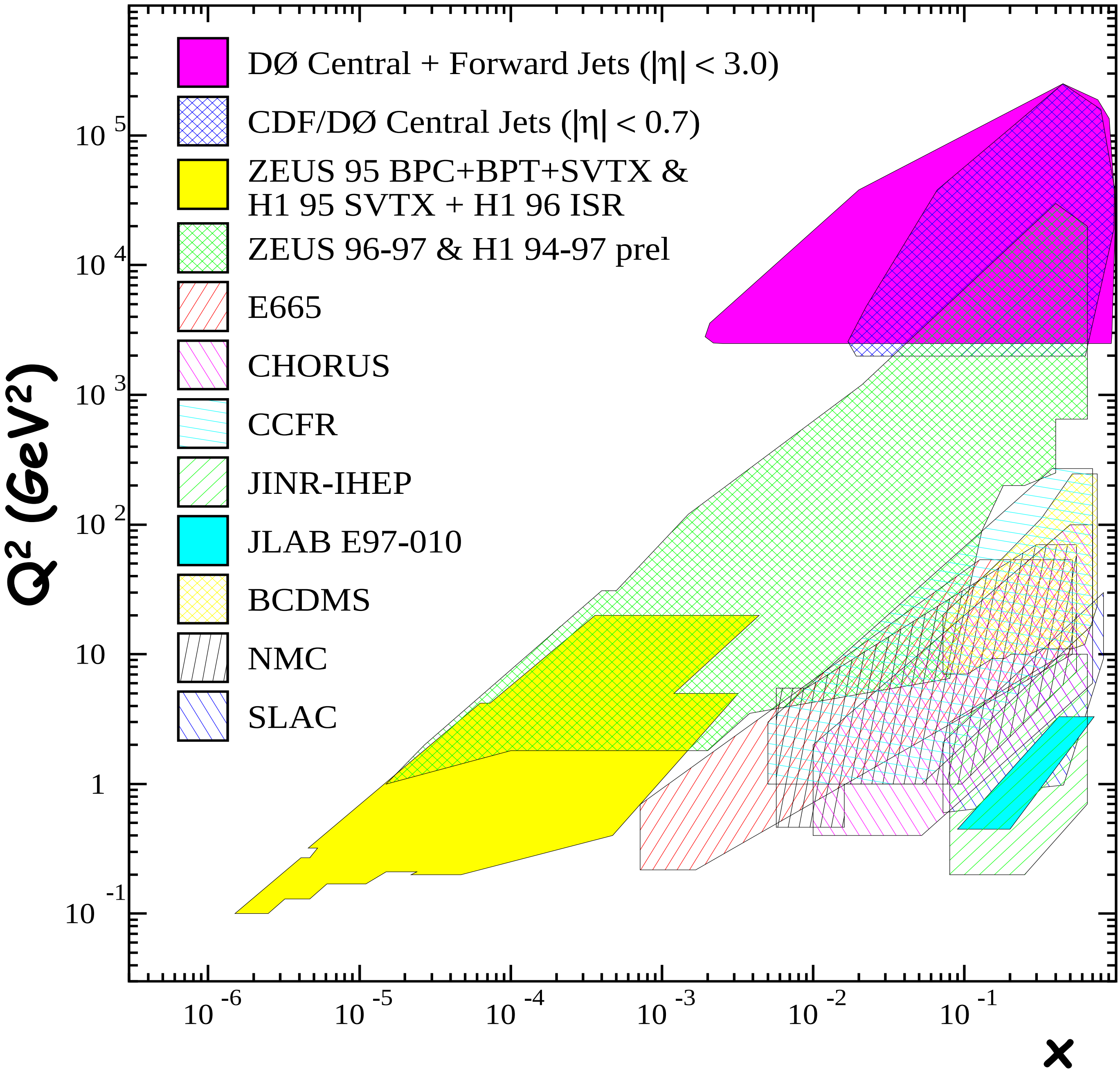
$\text{LO} = O(\alpha_s^2)$

$\text{NLO} = O(\alpha_s^2) + O(\alpha_s^3)$





Tevatron X-Q^2 Reach



Tevatron data overlaps and extends reach of DIS

Some archeology...the rise *(or exponential fall)* of jet cross sections

Jets from thrust / coarse clustering

1982-3:AFS - Direct Evidence... √s = 63 GeV, Jet CS @ y=0
qualitative comparison w/ gluon models in pdf's
" " - Further Evidence...
UA2 - Observation of... √s = 540 GeV, Jet CS @ η=0
qualitative comparison w/ QCD calc. (Horgan&Jacob)
AFS - Jet CS at √s = 45/63 GeV, y=0

1986: UA1
1991: UA2

Clustering in Cones

1992/6: CDF
1999: DØ
2000/1: D0,CDF

Tevatron Era, Cone Jets @ √s = 1.8 & 0.63 TeV, NLO QCD

$$\frac{1}{\Delta E_T \Delta\eta}\iint d\eta\, dE_T \frac{d^2\sigma}{dE_T\, d\eta} \longleftrightarrow \frac{N_{jet}}{\Delta E_T \Delta\eta\, \varepsilon \int L dt} \text{ vs. } E_T$$

$\Delta E_T \rightarrow E_T$ bin size

$\Delta\eta \rightarrow \eta$ bin size

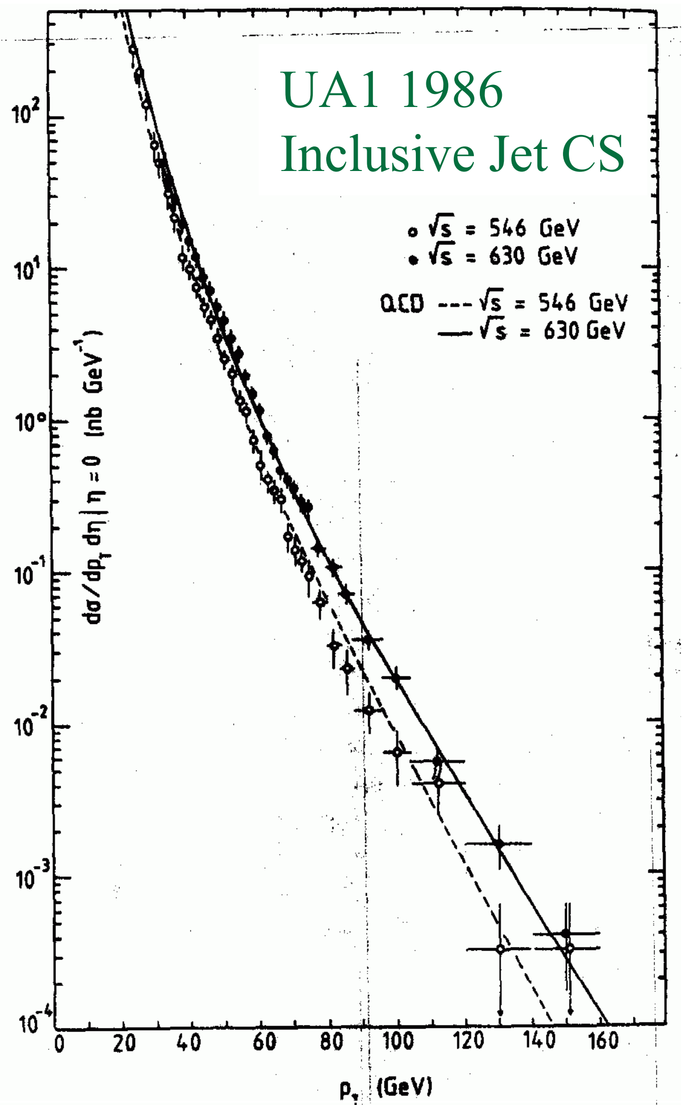
$N_{jet} \rightarrow$ # of jets in the bin

$\varepsilon \rightarrow$ selection efficiency

$L \rightarrow$ inst. Luminosity

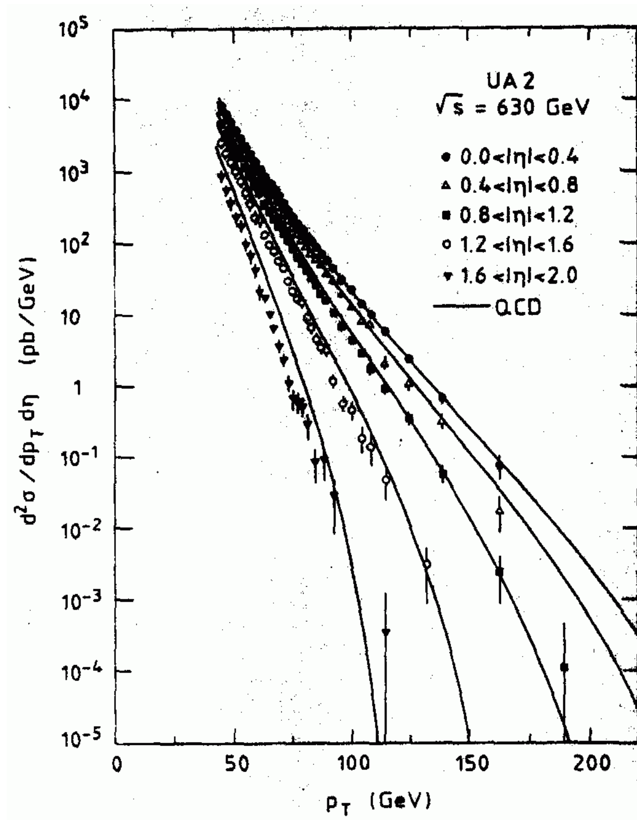
The old days…

UA1 1986
Inclusive Jet CS



Uncertainties ~ 70% on CS:
±50% accept./jet corr (smearing)
±40% calib ±10% aging ±15% Lum
Λ_C > 400 GeV “*Exp and theo. Uncerts. taken in to account*”

UA2 1991
Inclusive Jet CS

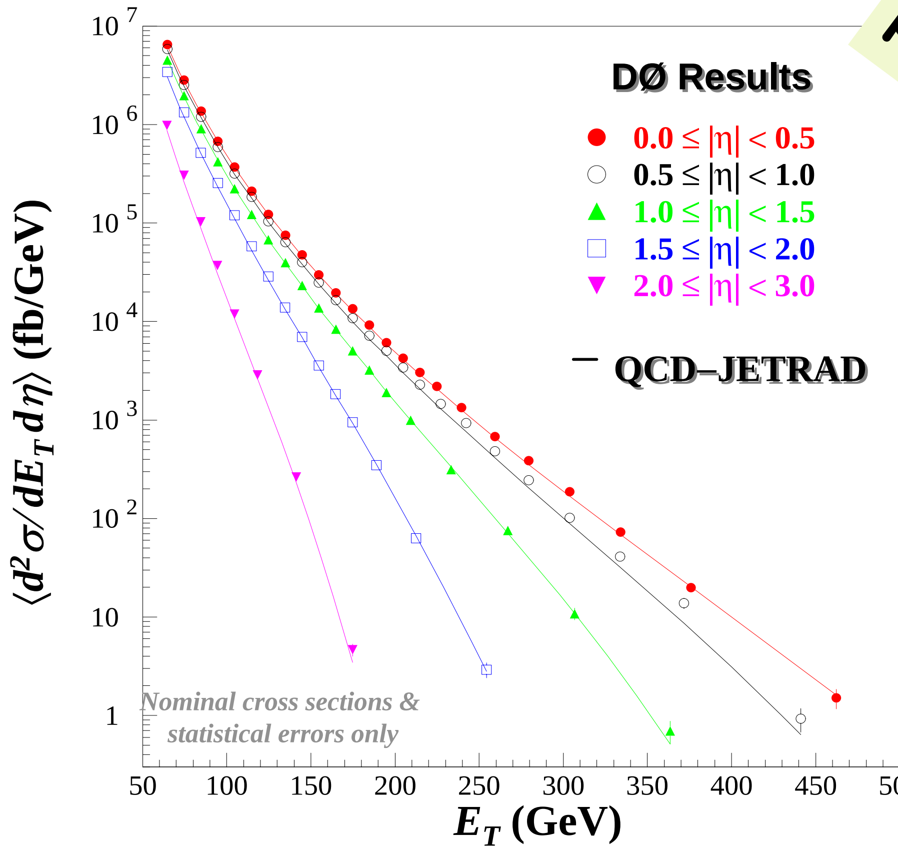


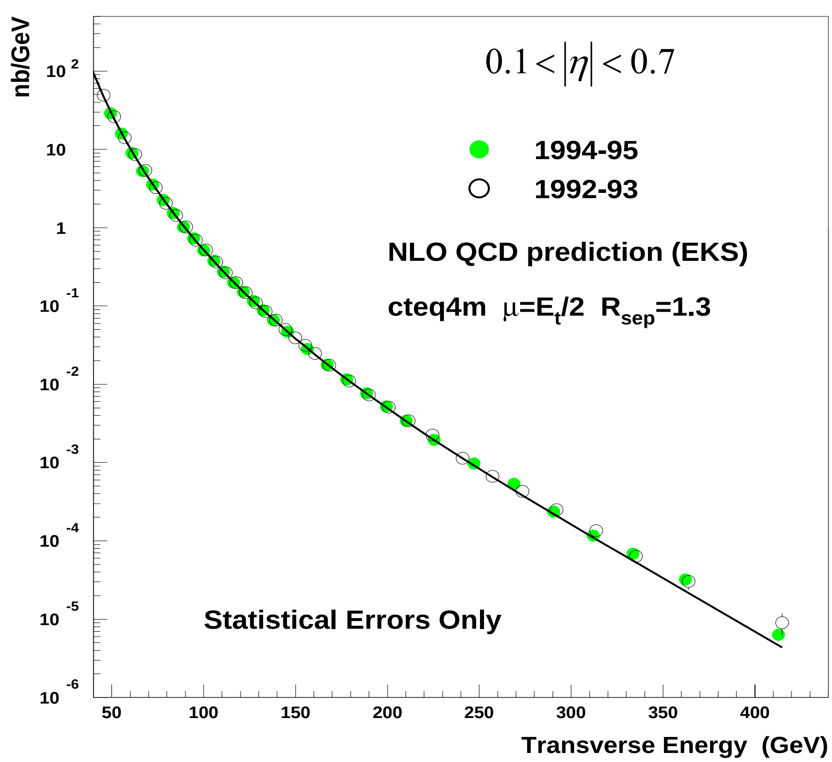
Uncertainties ~ 32% on CS:
±25% model dep. (fragmentation)
±15% jet alg/analysis params
±11% calib ±5% Lum
Λ_C > 825 GeV “*...include sys. effects which could distort the CS shape*”

$\left(\sqrt{s} = 1800 \text{ GeV}\right)$

The recent past...

Run I

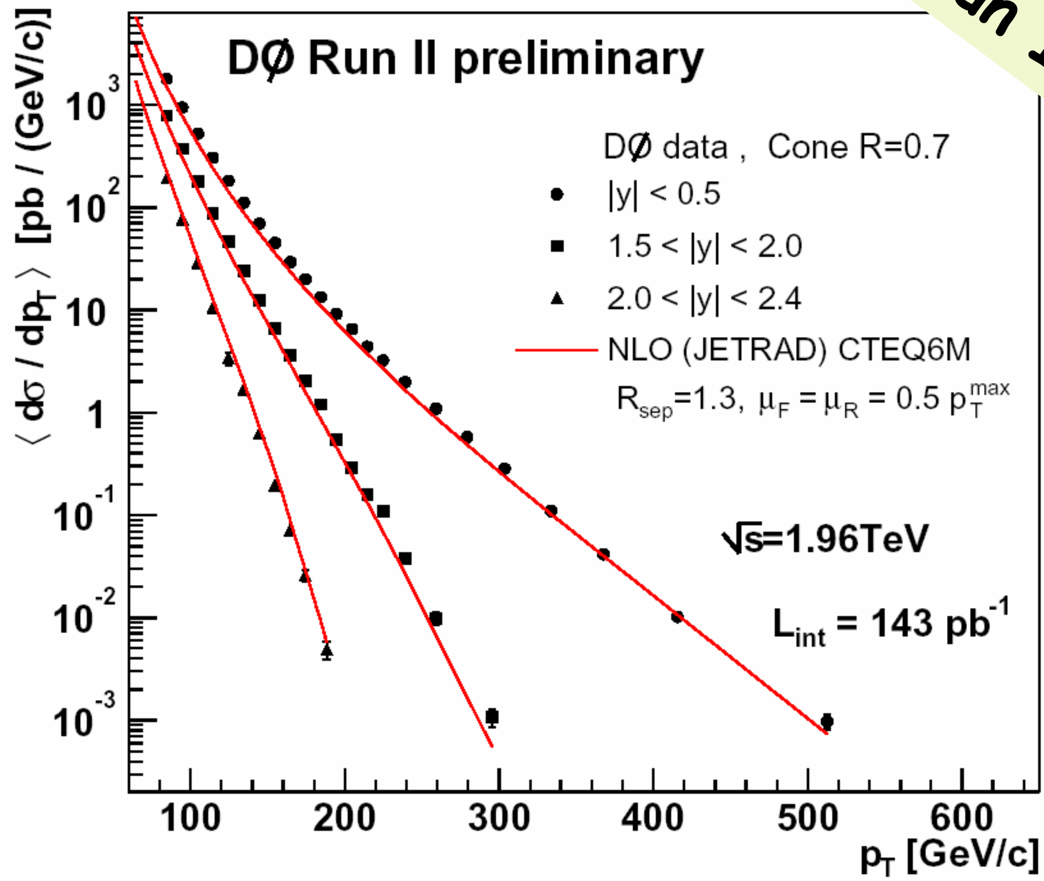


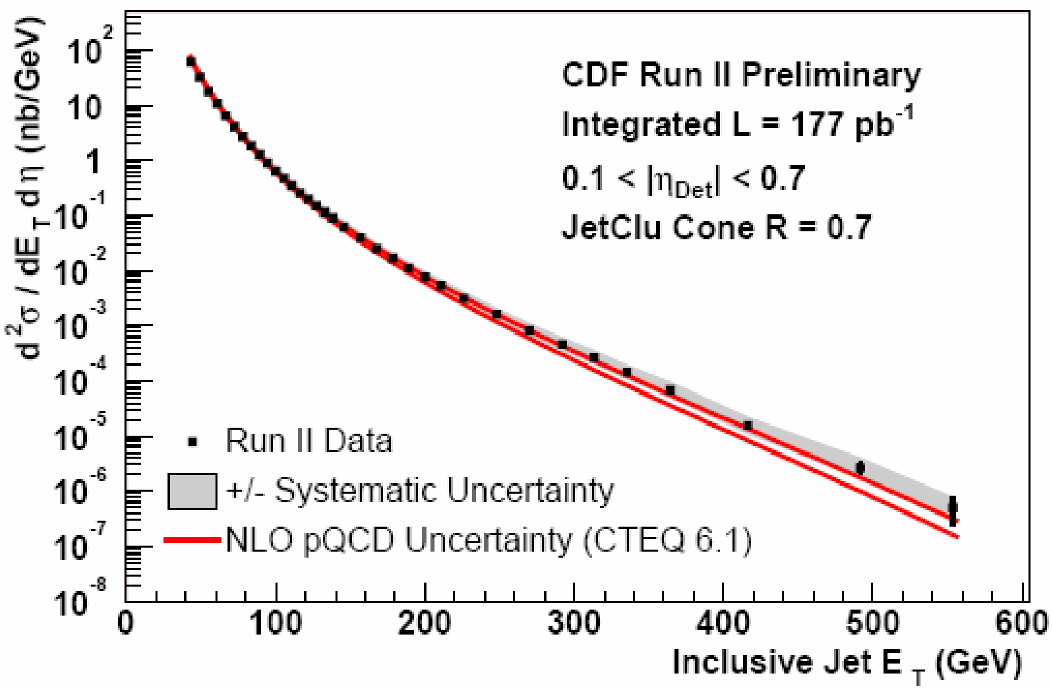


$\left(\sqrt{s} = 1960\ \text{GeV}\right)$

The present...

Run II



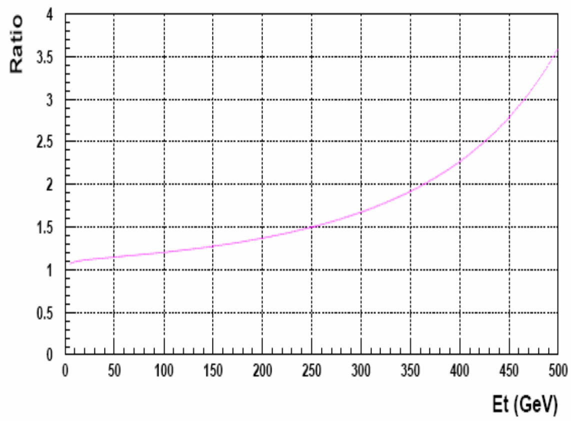


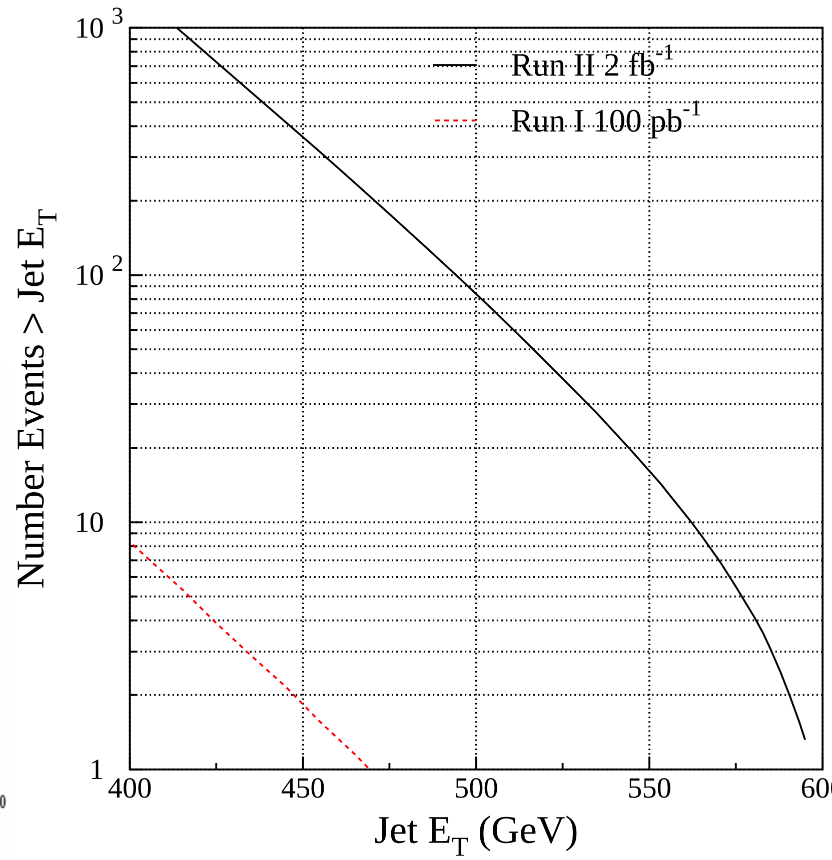
The next few years...

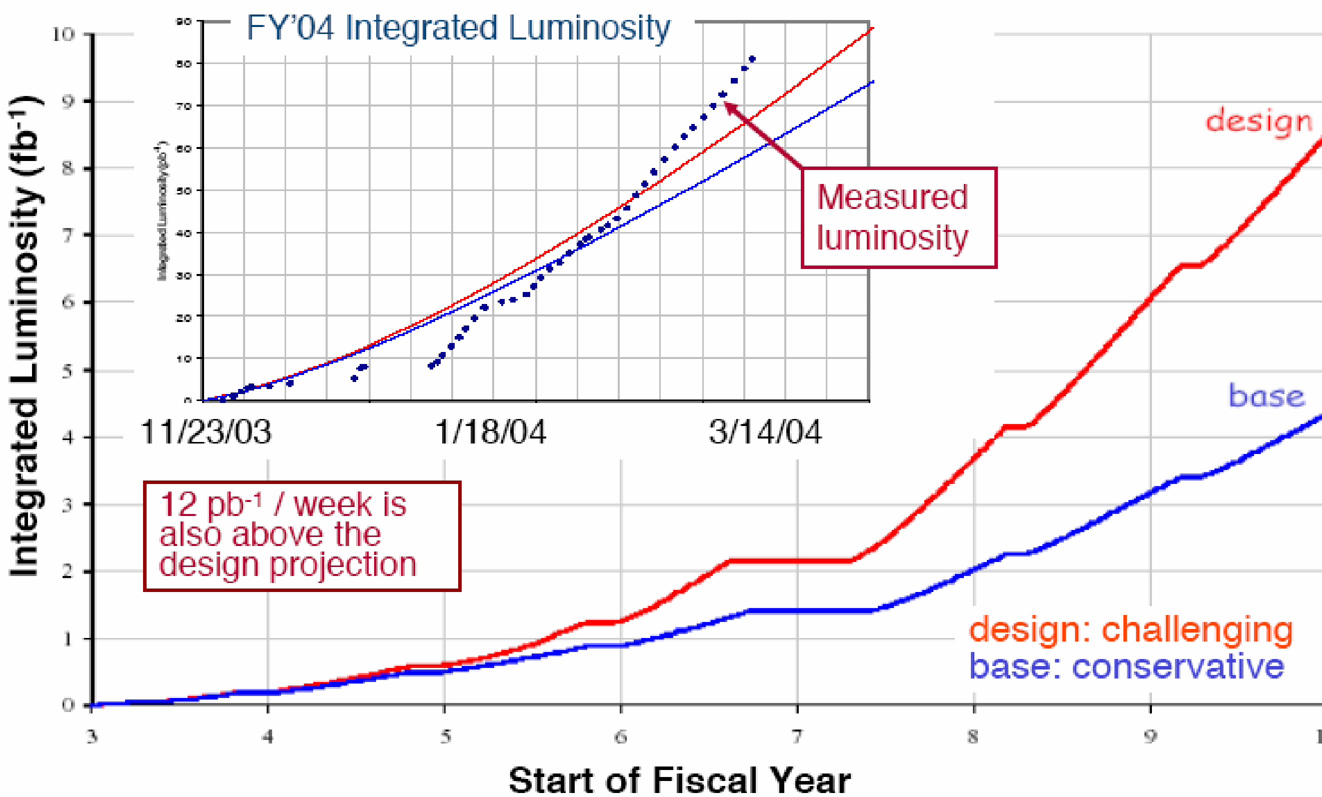
$\left(\sqrt{s} = 1960\ \text{GeV}\right)$

Great reach at high x and Q^2, the place to look for new physics!

Jet cross section ratio $\sigma(\sqrt{s} = 1.96\text{TeV})/\sigma(\sqrt{s} = 1.8\text{TeV})$



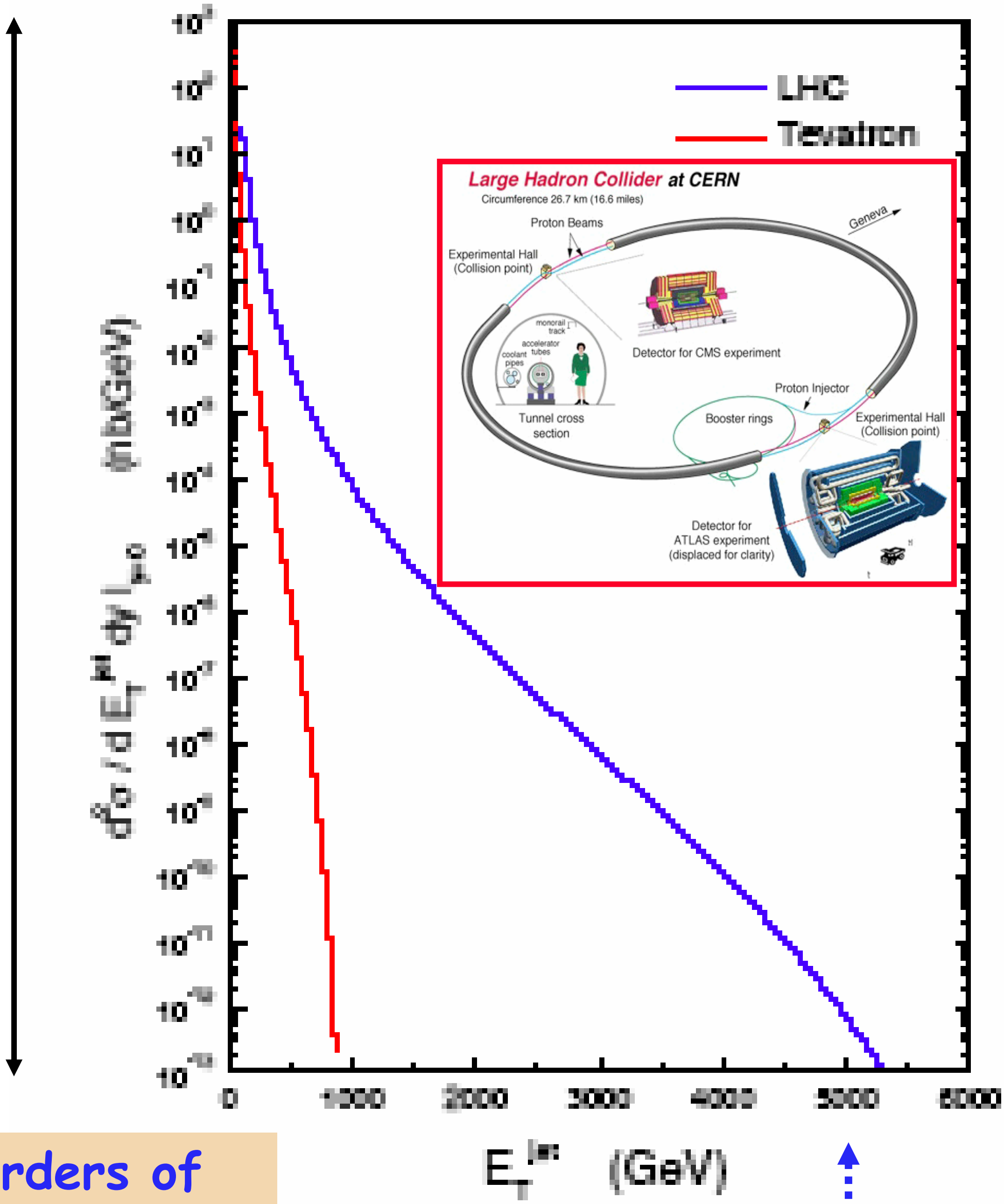




The future...

$$\begin{pmatrix} p \rightarrow\leftarrow p \\ \sqrt{s} = 14\ \text{TeV} \end{pmatrix}$$

The LHC will far beyond anything that we can measure at the Tevatron



16 orders of magnitude drop

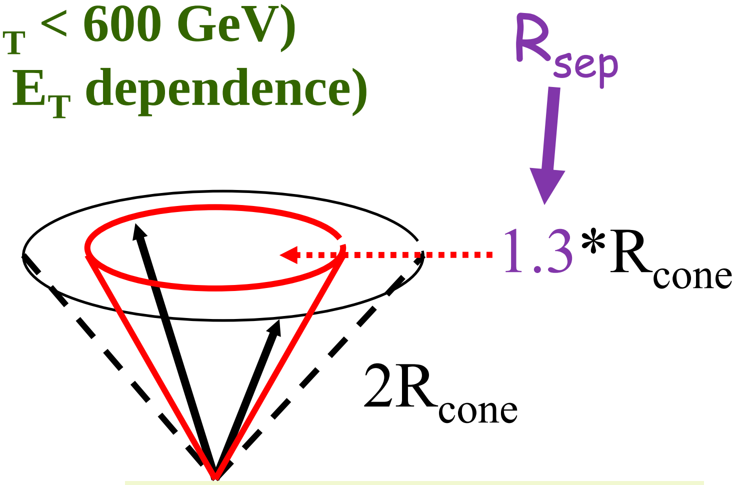
distance resolution ~10^{-20} m

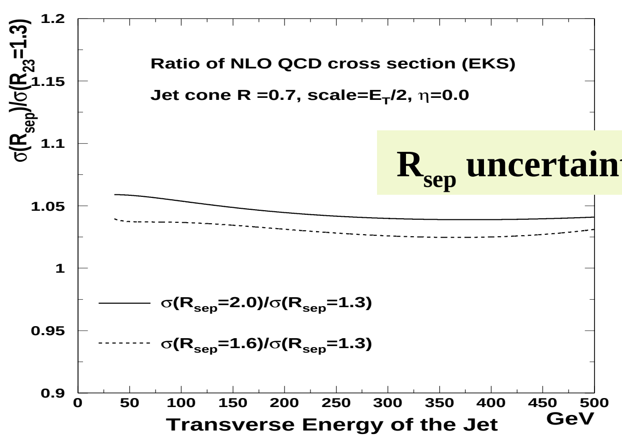
Theoretical Predictions

- **NLO QCD predictions (α_s^3) :**
  Ellis, Kunszt, Soper, Phys. Rev. D, 64, (1990) EKS
  Aversa, et al., Phys. Rev. Lett., 65, (1990)
  Giele, Glover, Kosower, Phys. Rev. Lett., 73, (1994) JETRAD

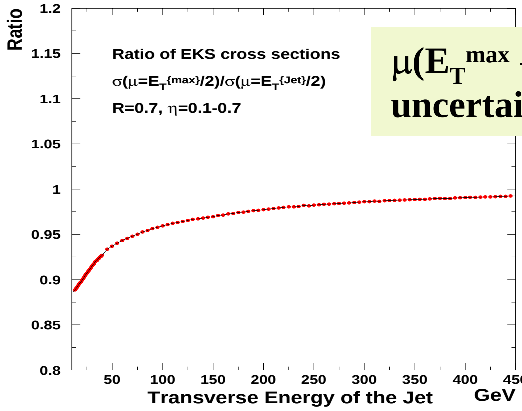
- **Choices (hep-ph/9801285, Eur. Phys. J. C. 5, 687 1998):**
  Renormalization Scale (~10% with E_T dependence)
  PDFs (~5-40% for 50 < E_T < 600 GeV)
  Clustering Alg. (5% with E_T dependence)

Jet Clustering Algorithm at NLO



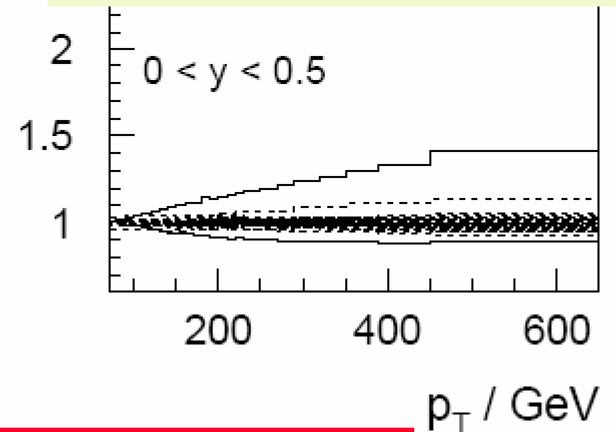


R_{sep} uncertainty



$\mu(E_T^{max} \rightarrow E_T^{jet})$ uncertainty

PDF uncertainty - CTEQ6.1



DØ uses: JETRAD
$\mu = 0.5E_T^{Max}$, R_{sep}=1.3

CDF uses: EKS
$\mu = 0.5E_T^{Jet}$, R_{sep}=1.3

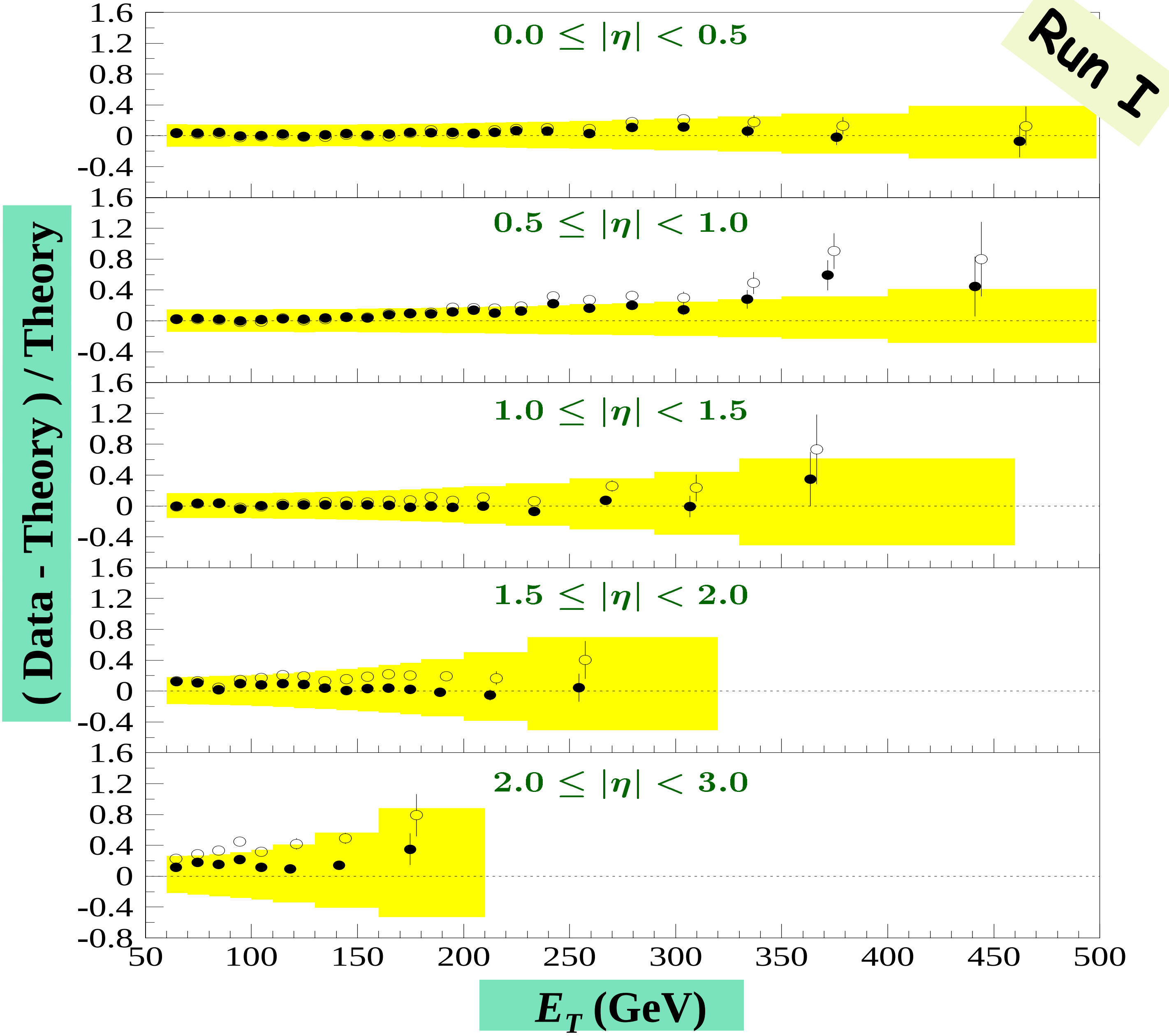
Data vs Theory

Comparisons to JETRAD with: $\mu = E_T^{max}/2$

$R_{sep} = 1.3$

○ CTEQ4M

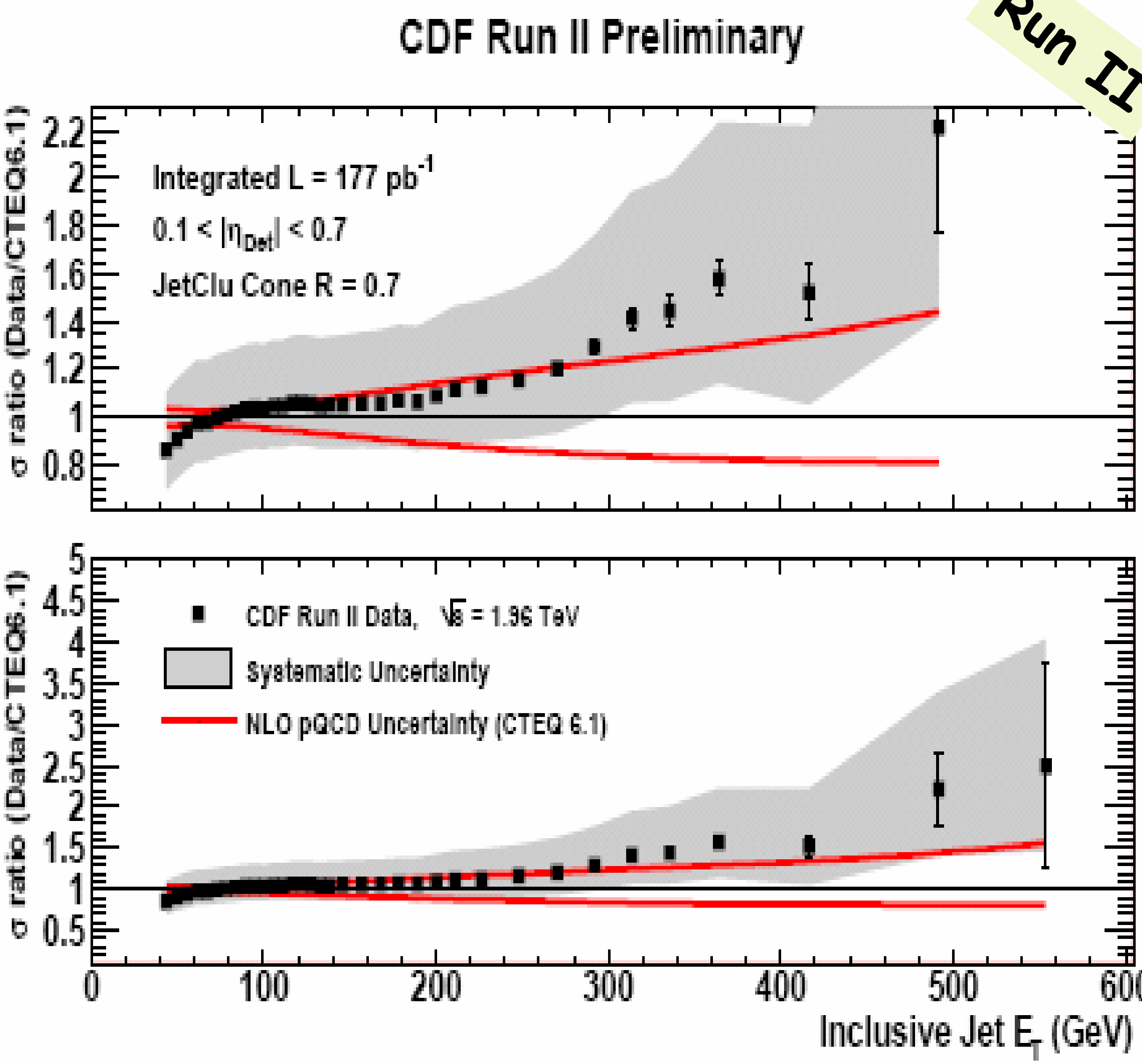
● CTEQ4HJ



- QCD prediction agrees well with data for jets out to 450 GeV (half of beam energy), over 7 orders of magnitude !
- Result is sensitive to high-x gluon density

Data vs Theory

EKS : $\mu = 0.5E_T^{Jet}$, R_{sep}=1.3



Run II

Notice the PDF uncertainty @ NLO prediction!

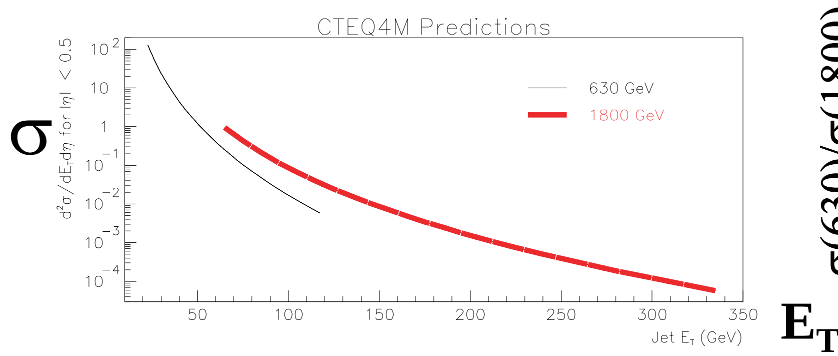
Inclusive Jet Cross Section Ratio: $\sigma(630)/\sigma(1800)$ vs X_T

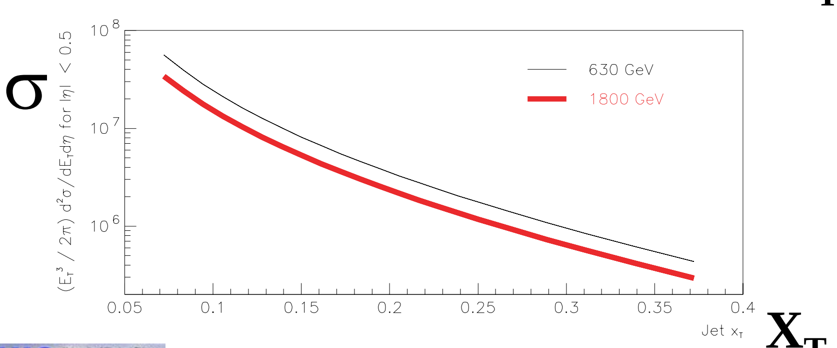
- **Cross Section Scaling**
  - At Born level ($\mathcal{O}(\alpha_s^2)$) :
- **Scaling violations**
  - PDFs, $\alpha_s(Q^2)$
- **Ratio of the scale invariant cross sections at different CM energies**
  - allows substantial reduction in uncertainties (in theory and experiment)

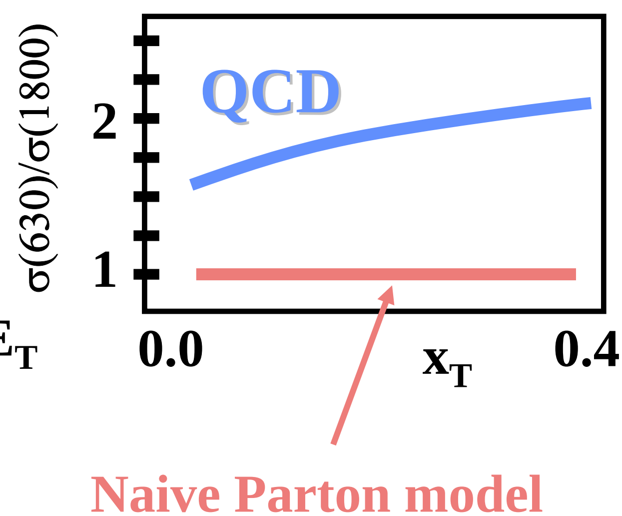
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^4} f(x_T)$$

$$\text{where } x_T = \frac{2p_T}{\sqrt{s}}$$

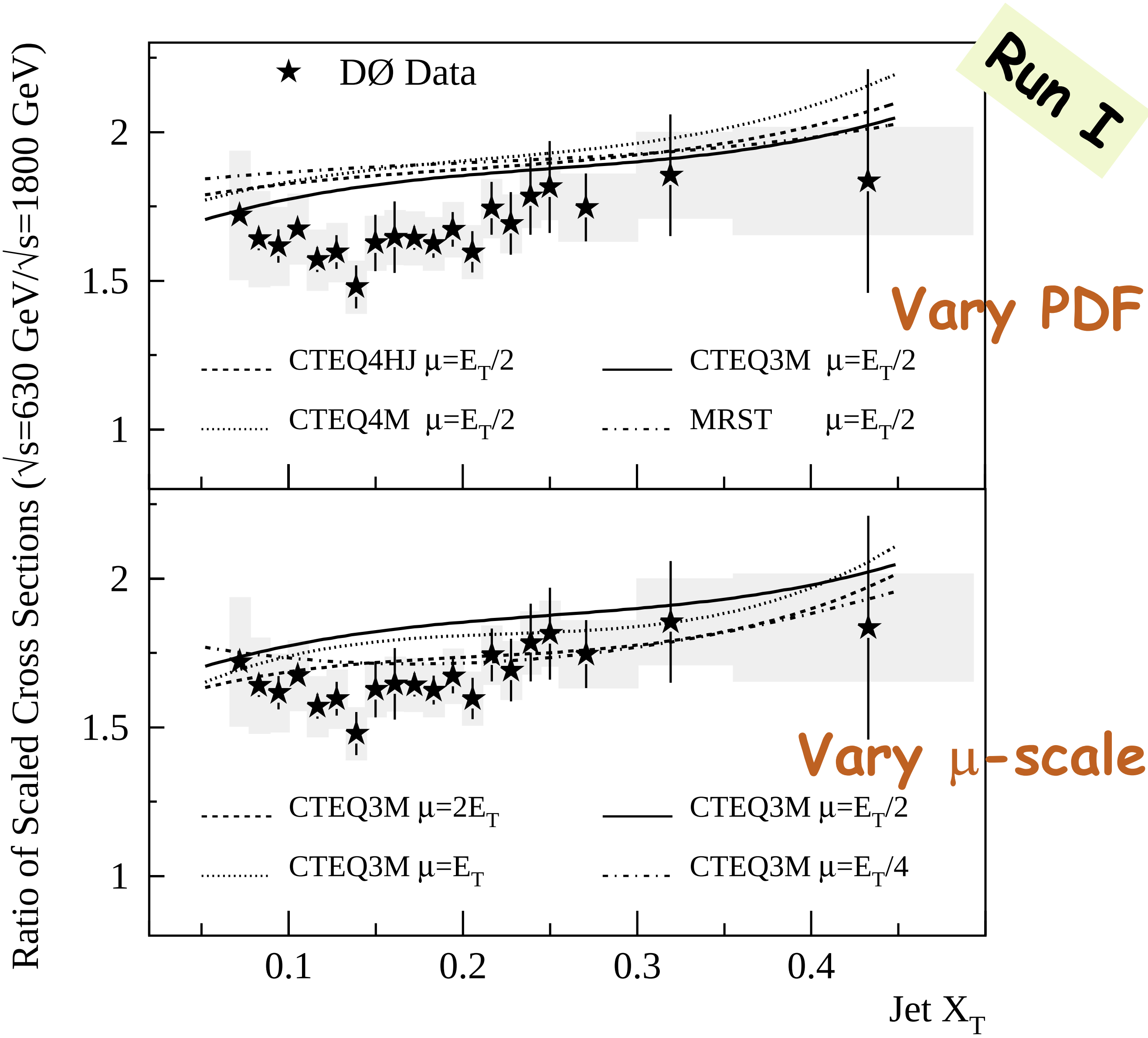
$$R(x_T) \equiv \frac{p_T^4 \cdot E\frac{d^3\sigma}{dp^3}(\sqrt{s}=630\text{ GeV})}{p_T^4 \cdot E\frac{d^3\sigma}{dp^3}(\sqrt{s}=1800\text{ GeV})} \sim 1 + \text{scaling violating terms}$$







σ(630)/σ(1800) vs X_T NLO



- **Sensitivity to the PDF's is reduced in the ratio**
  - **Test of matrix elements**
- **Better agreement with NLO QCD in shape than in normalization**

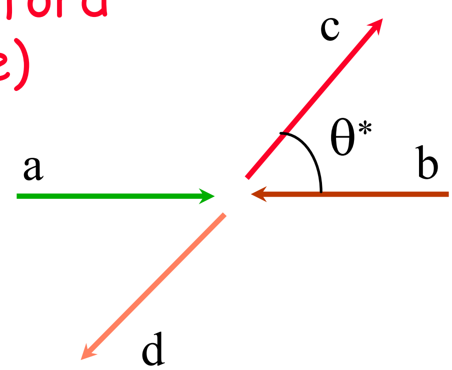
Dijet Production

The differential cross section for a jet pair of mass M_{JJ} produced at an angle θ^* at the jet-jet CM system is:

$$\frac{d^2\sigma}{dM_{JJ}^2\, d\cos\theta^*} = \sum_{a,b}\int dx_a dx_b\, f_{a/A}(x_a,\mu) f_{b/B}(x_b,\mu)\,\delta(x_a x_b s - M_{jj}^2)\,\frac{d\hat{\sigma}^{ab}}{d\cos\theta^*}$$

For small angles –> similar to Rutherford scattering (t-channel gluon exchange)

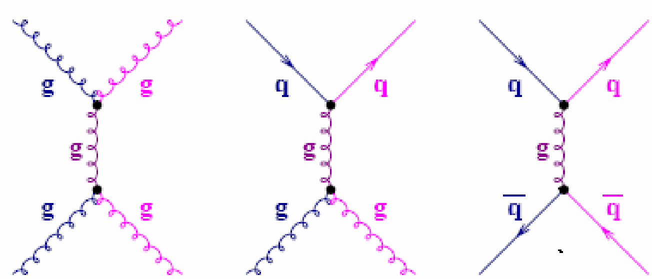
$$\frac{d\hat{\sigma}}{d\cos\theta^*} \approx \frac{1}{\left(1-\cos\theta^*\right)^2}$$



characteristic of the exchange of a vector boson
gluons have spin = 1

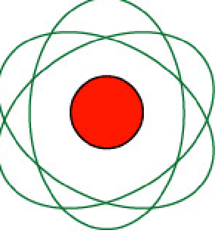
Dominant subprocesses have very similar shape for $d\hat{\sigma}/d\cos\theta^*$ with different weights:

gg –> gg	qg –> qg	$q\bar{q}$ –> $q\bar{q}$
1	4/9	$(4/9)^2$

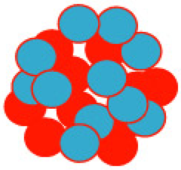


$$d\hat{\sigma}/d\cos\theta^* \sim (1 - |\cos\theta^*|)^{-2}$$

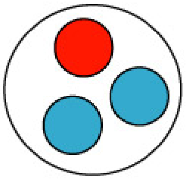
Angular Distributions –> Sensitive to Hard Scatter Dynamics



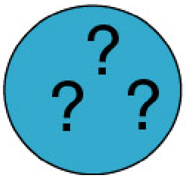
Search for Quark Substructure



Hypothesis: Quarks are bound states of preons
Preons interact by means of a new strong interaction - metacolor -



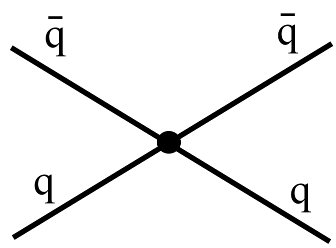
Compositeness Scale: Λ_c



$\Lambda_c = \infty$ –> point like quarks

Λ_c = finite –> Substructure at mass scale of Λ_c

For $\sqrt{\hat{s}} << \Lambda_c$ the composite interactions can be represented by contact terms



$$L_{qq} = \pm \frac{g^2}{2\Lambda_c^2} \bar{q}_L \gamma^\mu q_L \bar{q}_L \gamma_\mu q_L$$

$d\sigma \sim$ [QCD + Interference + Compositeness]

$$\downarrow \qquad \downarrow \qquad \downarrow$$

$$\alpha_s^2(\mu^2)\frac{1}{\hat{t}^2} \qquad \alpha_s(\mu^2)\frac{1}{\hat{t}} \cdot \frac{\hat{u}^2}{\Lambda_c^2} \qquad \left(\frac{\hat{u}}{\Lambda_c^2}\right)^2$$

$d\sigma \sim 1/(1-\cos\theta^*)^2$ angular distribution

$d\sigma \sim (1+\cos\theta^*)^2$ angular distribution

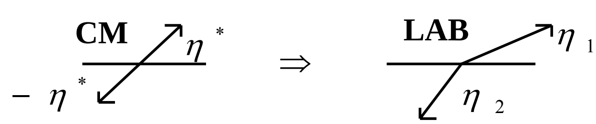
Angular Distributions –> Quark Substructure

- QCD is dominated by ~ $1/(1-\cos\theta^*)^2$
- Contact interactions:
  - dominated by ~ $(1+\cos\theta^*)^2$
  - grow linearly with $\hat{s}^2$
  - only affect (anti)quark-(anti)quark interactions, so their effect will be most apparent at high-P_T interactions

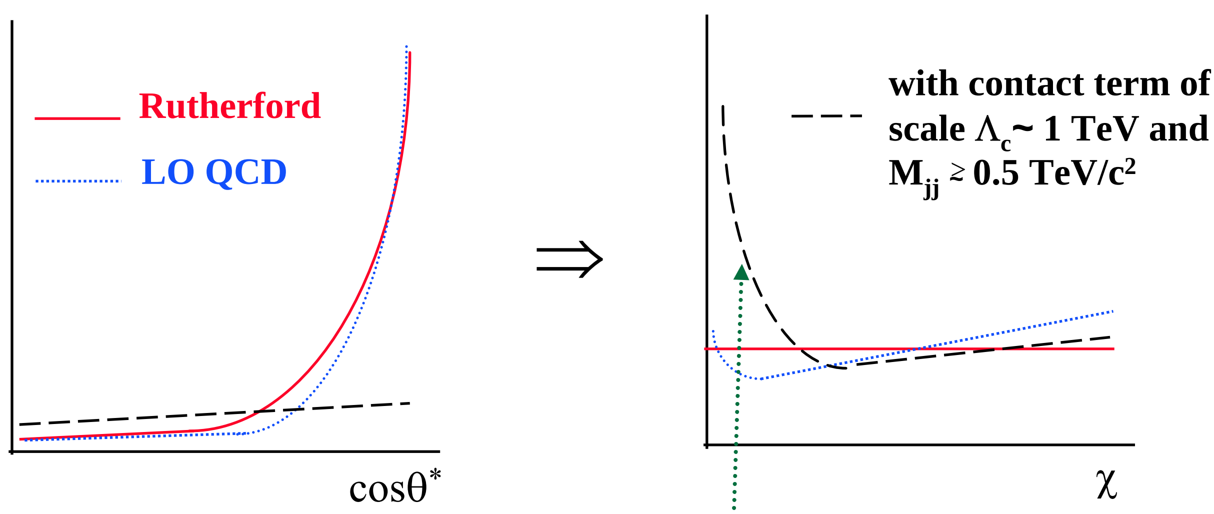
→ From $\cos\theta^*$ variable to χ

- Flatten out the $\cos\theta^*$ distribution by plotting $dN/d\chi$
- Facilitate an easier comparison to the theory

$$\chi = e^{2|\eta^*|} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



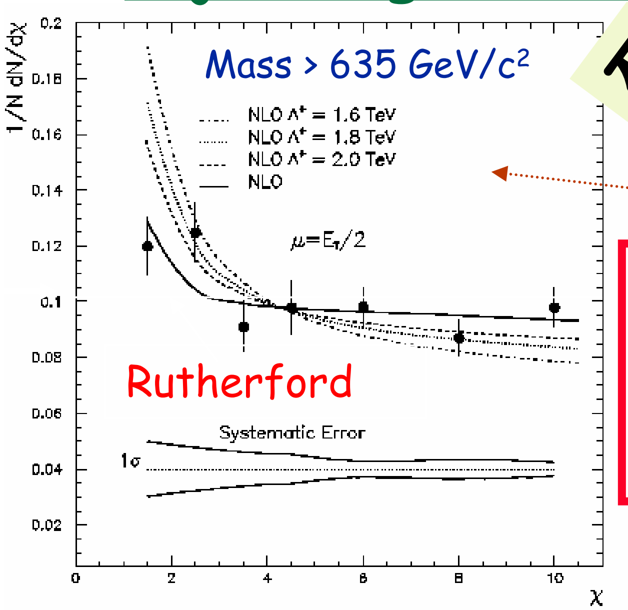
$$\cos\theta^* = \tanh\eta^* \qquad \eta^* = \frac{1}{2}(\eta_1 - \eta_2) \qquad \eta_{boost} = \frac{1}{2}(\eta_1 + \eta_2)$$



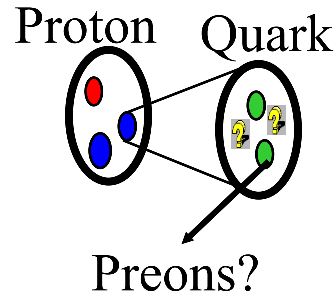
$dN/d\chi$ sensitive to contact interactions

Limits of Quark Substructure

Dijet Angular Distributions



Run I

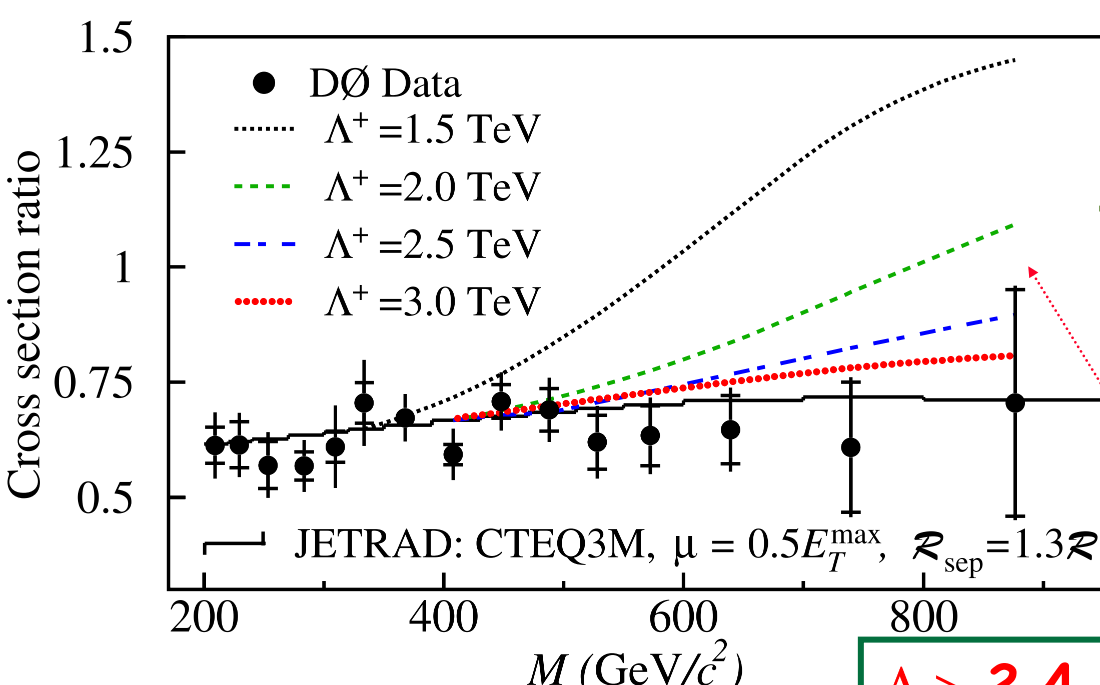


95% CL Compositeness Limit:

$\Lambda^{(+,-)} \geq 2.1 - 2.4$ **TeV**

Dijet Mass Cross Section Ratio

σ ($|\eta_{1,2}|$ **< 0.5) /** σ (**0.5 <** $|\eta_{1,2}|$< **1)** **(** $\sqrt{s}$ **=1800 GeV)**



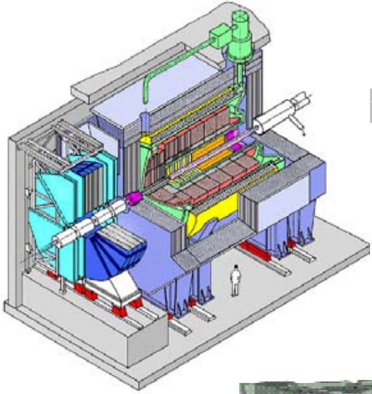
Systematic Uncertainty ~ 8%

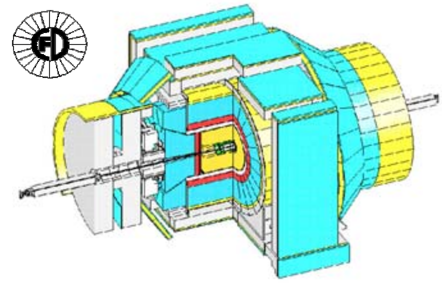
Theory uncertainty ~ 6% (μ) , 3% (PDF)

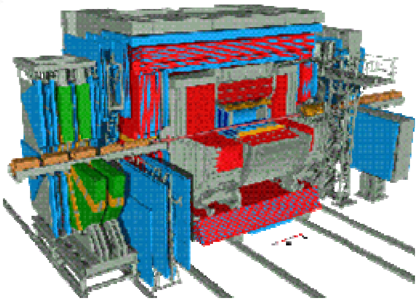
NLO QCD in good agreement with data

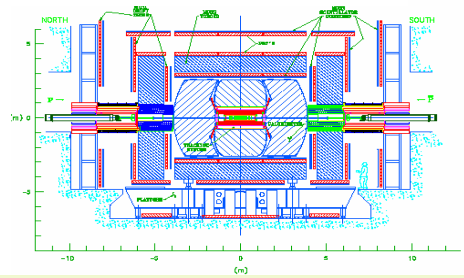
$\Lambda >$ 2.4 – 2.7 TeV (95% confidence level)

Outlook









- Jets celebrate their 29th year since first observed in e^+e^-
- QCD measurements have reached or exceeded the accuracy of theoretical predictions
- Tevatron Run II offers a big opportunity for QCD, *setting the stage for LHC*