Jet Physics
Lecture II

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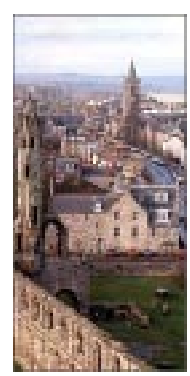


Outline

- Introduction
  - Processes under study (ee, ep, pp)
  - 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
  - Jet Calibration
  - Inclusive jet cross sections (cone and K_T)
  - Jet cross section scaling
  - Dijet production and search for quark substructure
- Final Remarks

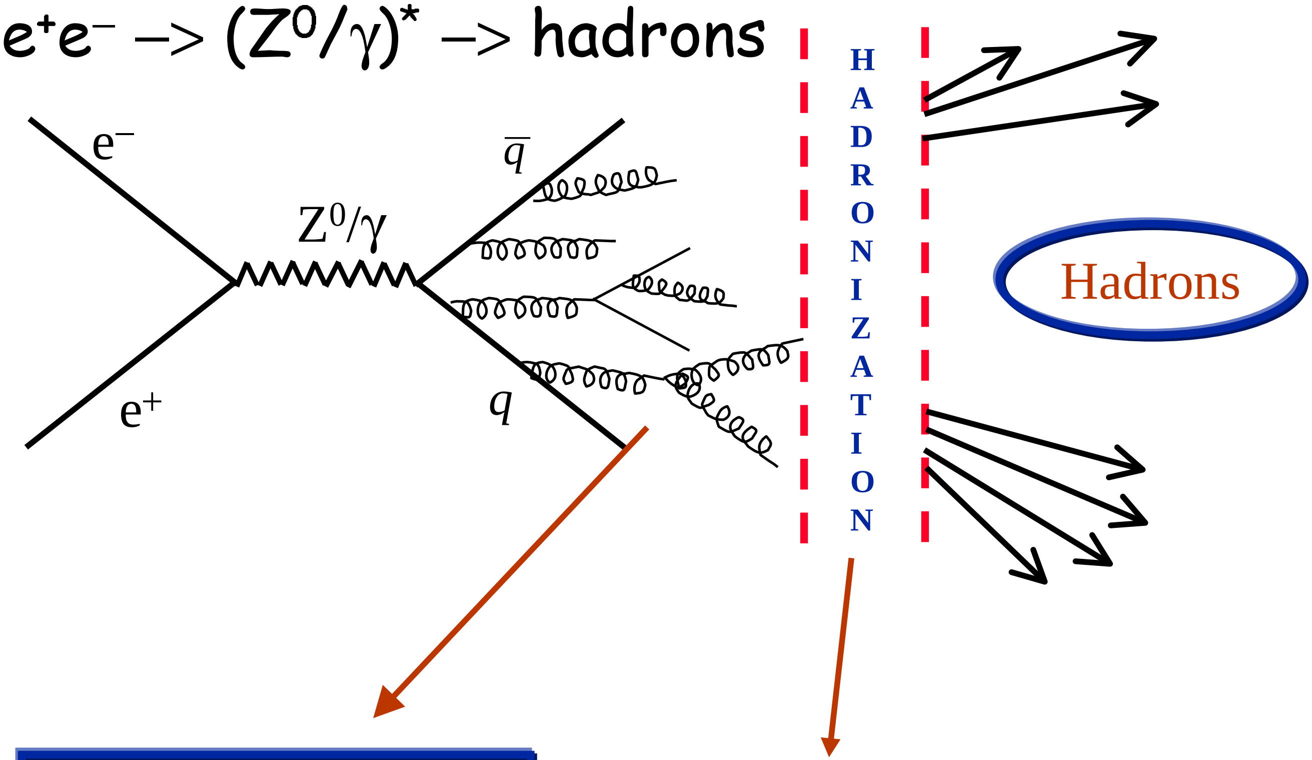
Disclaimer

This talk is NOT an inclusive survey of Tevatron QCD results. It is meant to be an intellectual "appetizer" on jet physics rather than the "main course". Some plots may not be the absolute final results; it is what I was able to find on the web!

e^+e^- Annihilations

LEP1/SLC $E_{cm}=M_Z=91.2$ GeV
LEP2: $M_Z<E_{cm}<\sim 200$ GeV

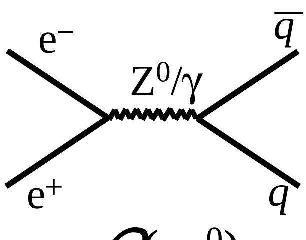
$e^+e^- \to (Z^0/\gamma)^* \to$ hadrons



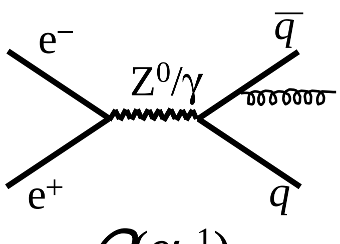
Perturbative phase
$\alpha_s<1$ (Parton Level)

Non-perturbative phase
$\alpha_s\geq 1$

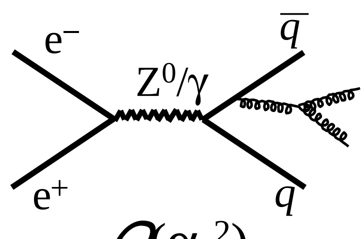
Fixed Order QCD



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

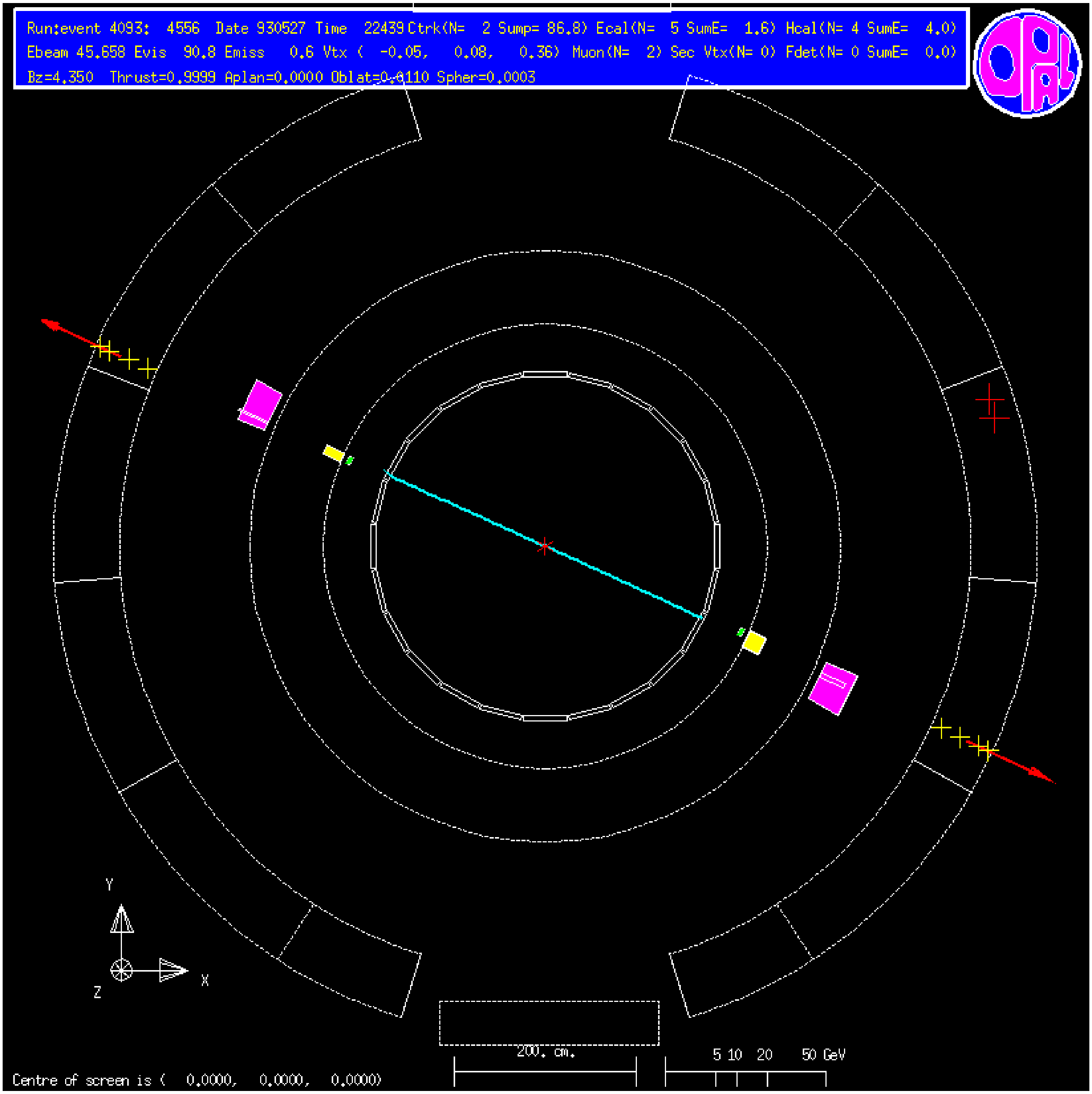


$\mathcal{O}(\alpha_s^1)$

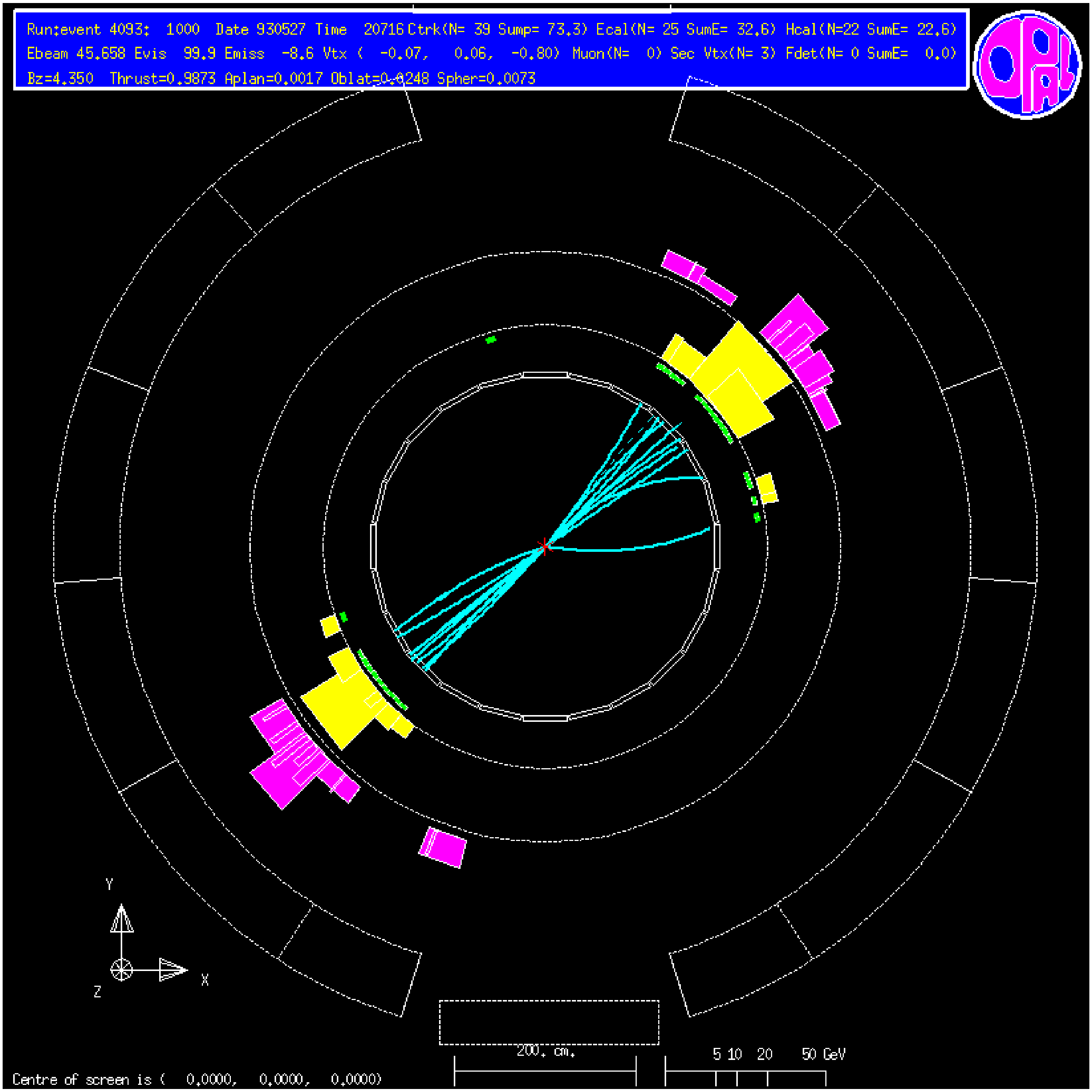


$\mathcal{O}(\alpha_s^2)$

$e^+e^- \rightarrow \mu^+\mu^-$

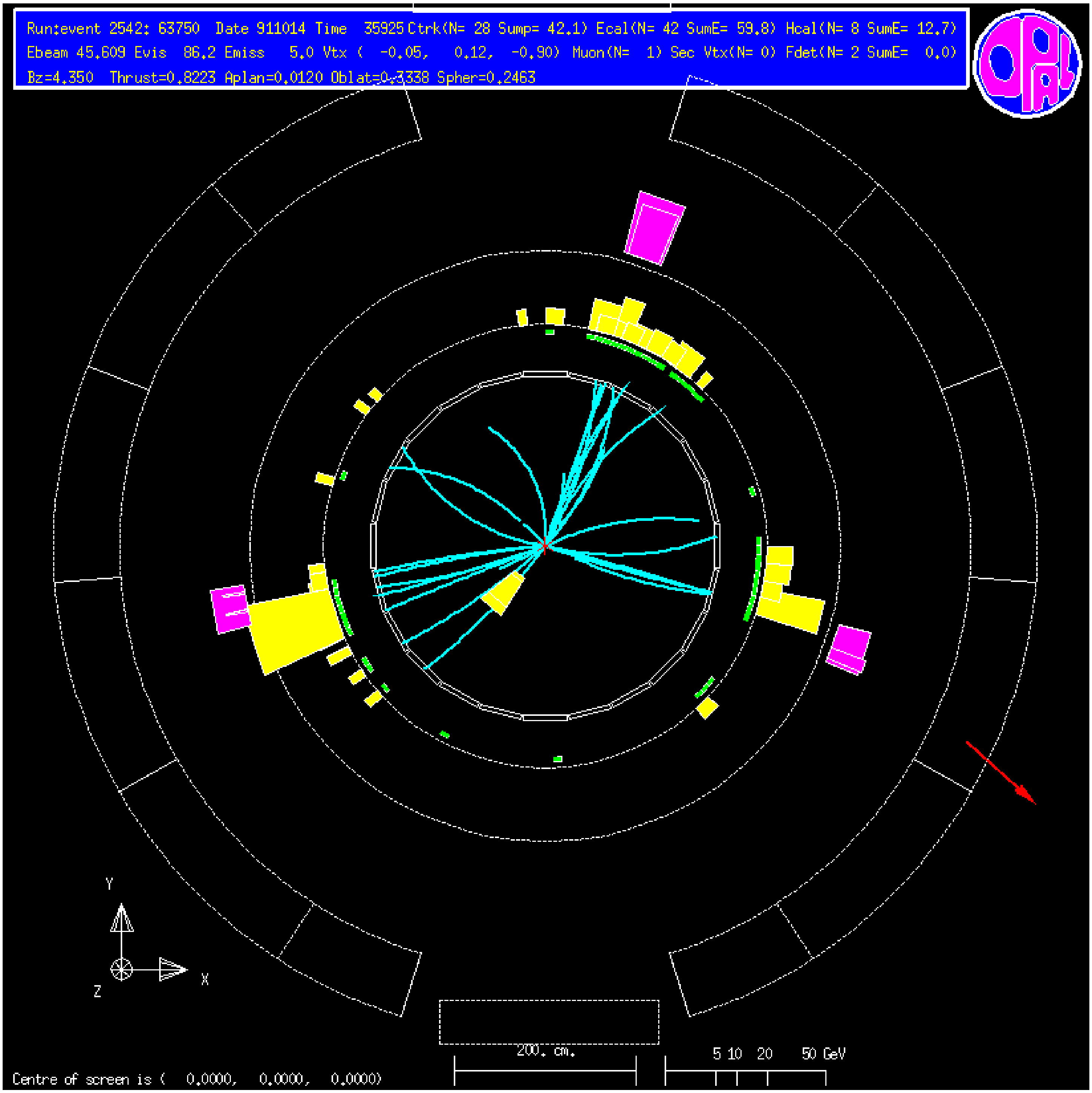


$e^+e^- \to q\bar{q}$

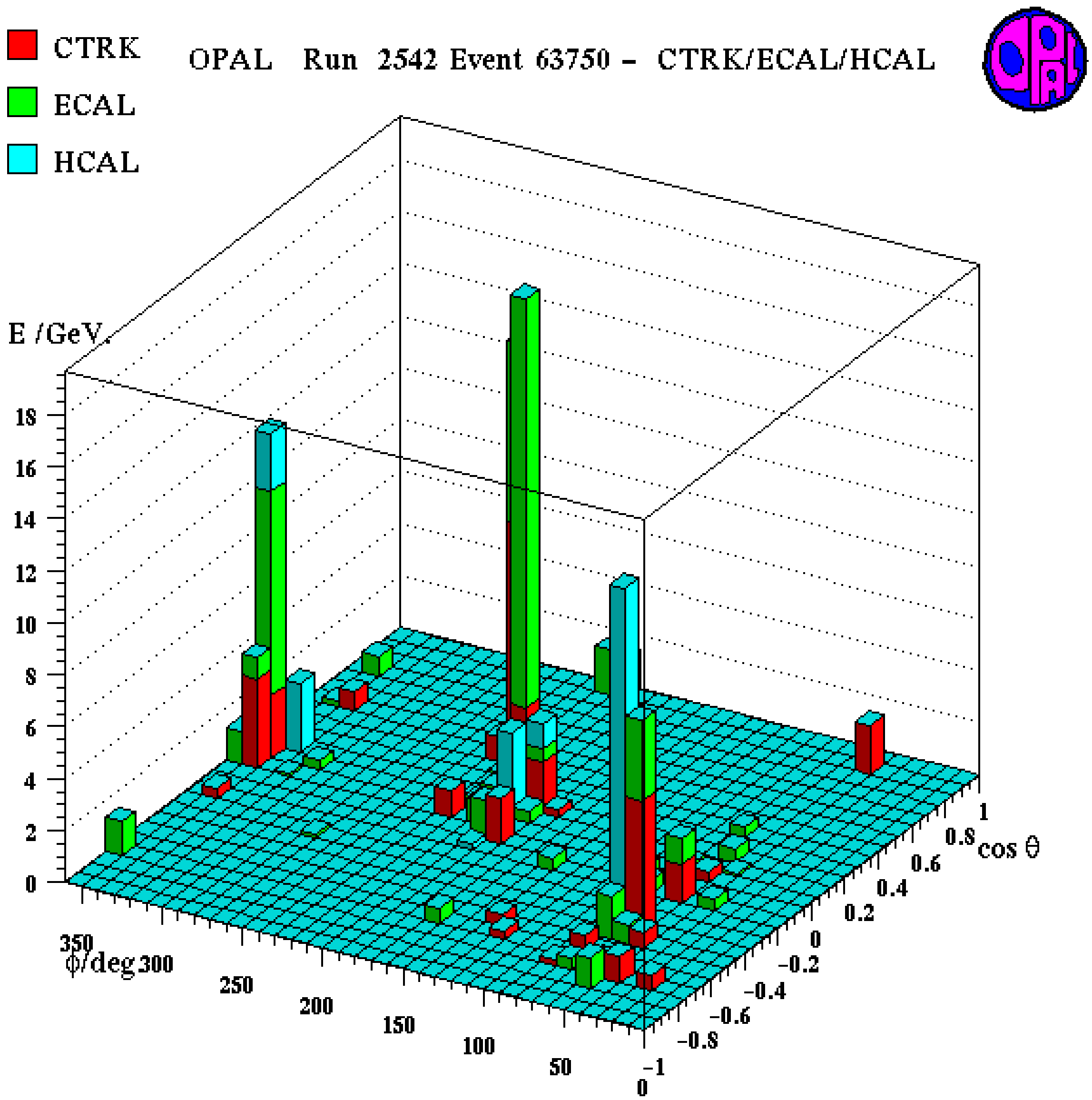


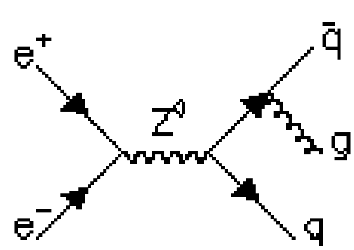
Run:event 4093: 1000 Date 930527 Time 20716 Ctrk(N= 39 Sump= 73.3) Ecal(N= 25 SumE= 32.6) Hcal(N=22 SumE= 22.6)
Ebeam 45.658 Evis 99.9 Emiss -8.6 Vtx (-0.07, 0.06, -0.80) Muon(N= 0) Sec Vtx(N= 3) Fdet(N= 0 SumE= 0.0)
Bz=4.350 Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
OPAL
Y
Z
X
200. cm.
5 10 20 50 GeV
Centre of screen is (0.0000, 0.0000, 0.0000)

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

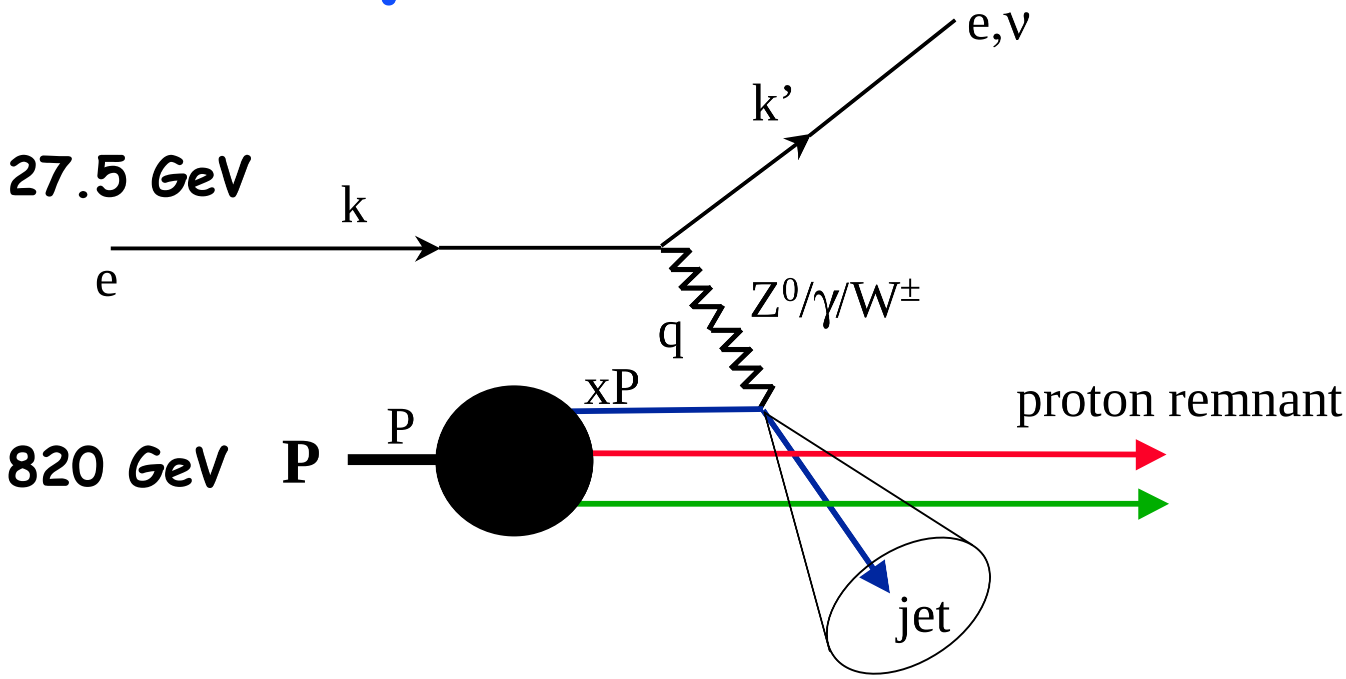


$e^+e^- \to q\bar{q}g$


CTRK
ECAL
HCAL
OPAL Run 2542 Event 63750 - CTRK/ECAL/HCAL
E /GeV
18
16
14
12
10
8
6
4
2
0
350
φ/deg 300
250
200
150
100
50
0
cos θ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1


e+
e-
Z0
q̄
g
q

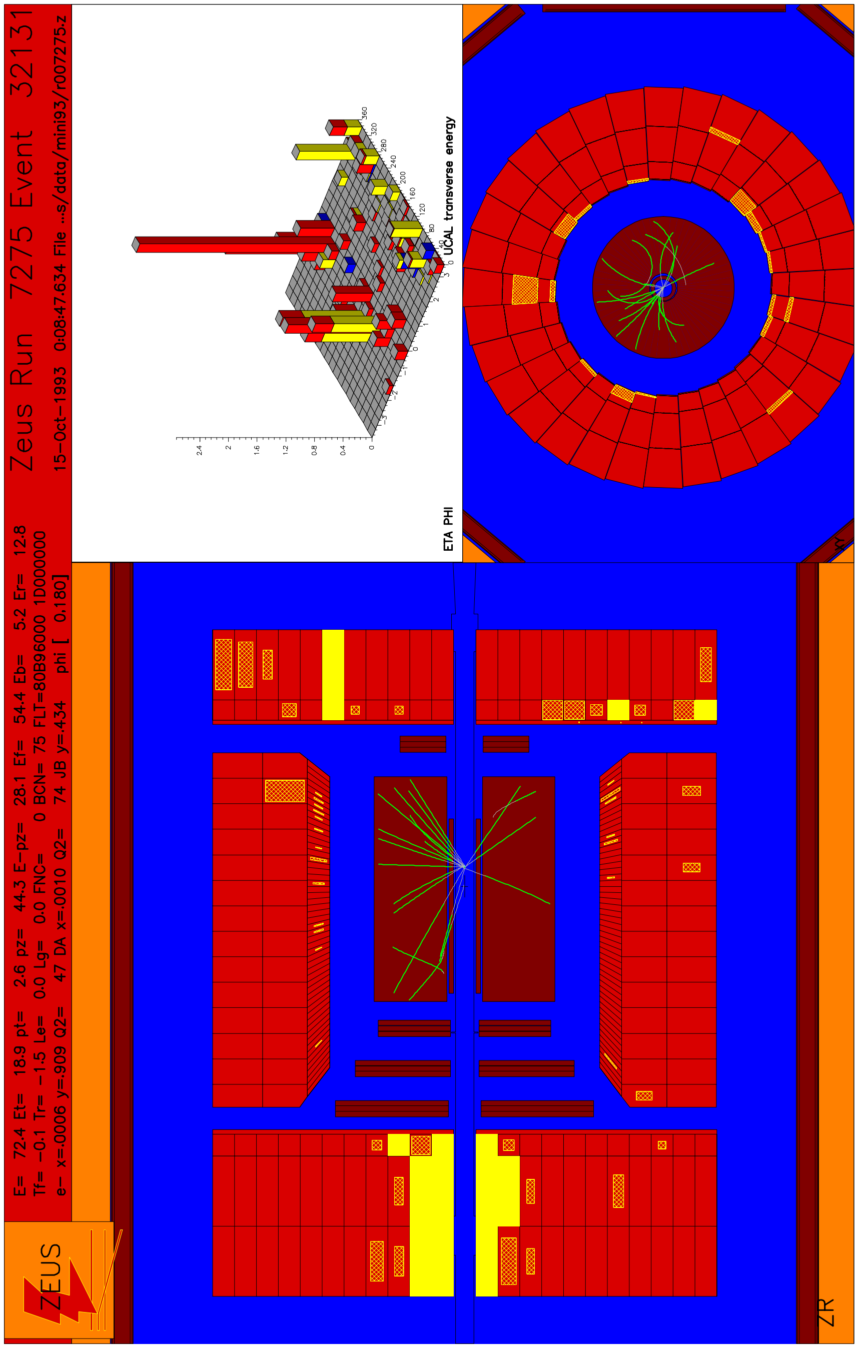
ep Interactions

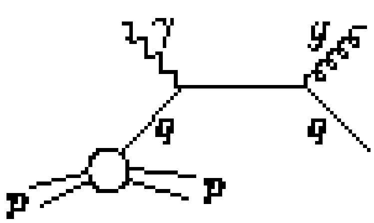


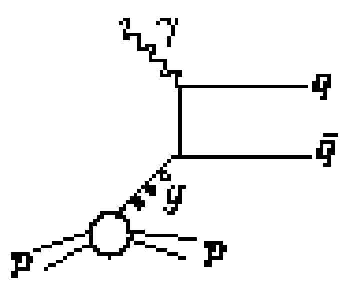
$k = (E, \boldsymbol{k})$	4-momentum for incoming e^-
$k' = (E, \boldsymbol{k}')$	4-momentum for outgoing e^-
$Q^2 = -q^2 = -(k - k')^2$	4-momentum transfer
$x = \dfrac{Q^2}{2P \cdot q}$	parton momentum fraction
$y = \dfrac{P \cdot q}{P \cdot k} = \dfrac{E - E'}{E}$	fractional energy transfer
$s = (P + k)^2 \approx 2P \cdot k = \dfrac{Q^2}{xy}$	electron-proton mass squared
$\hat{s} = (xP + k)^2 \approx sx$	electron-parton mass squared

$$\sqrt{s} = 300 \text{ GeV at HERA}$$

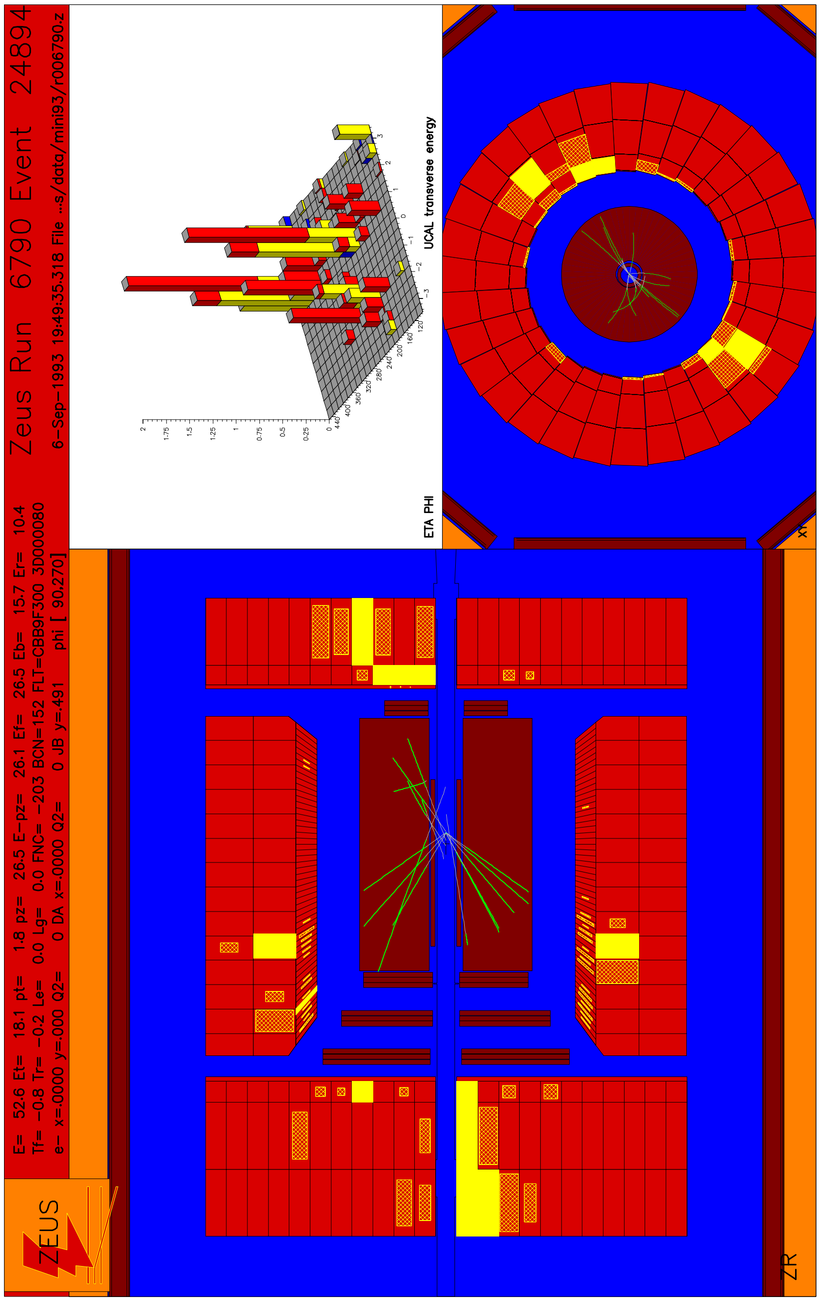
“Direct” Photon Process

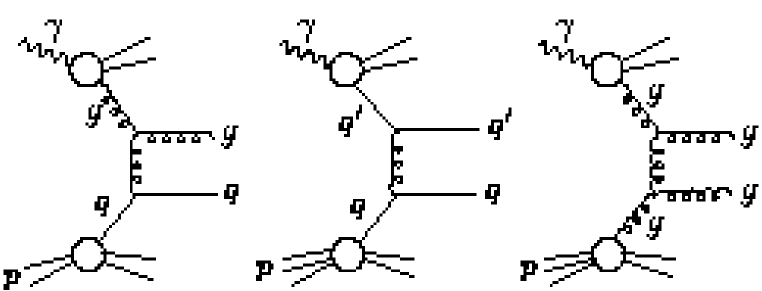






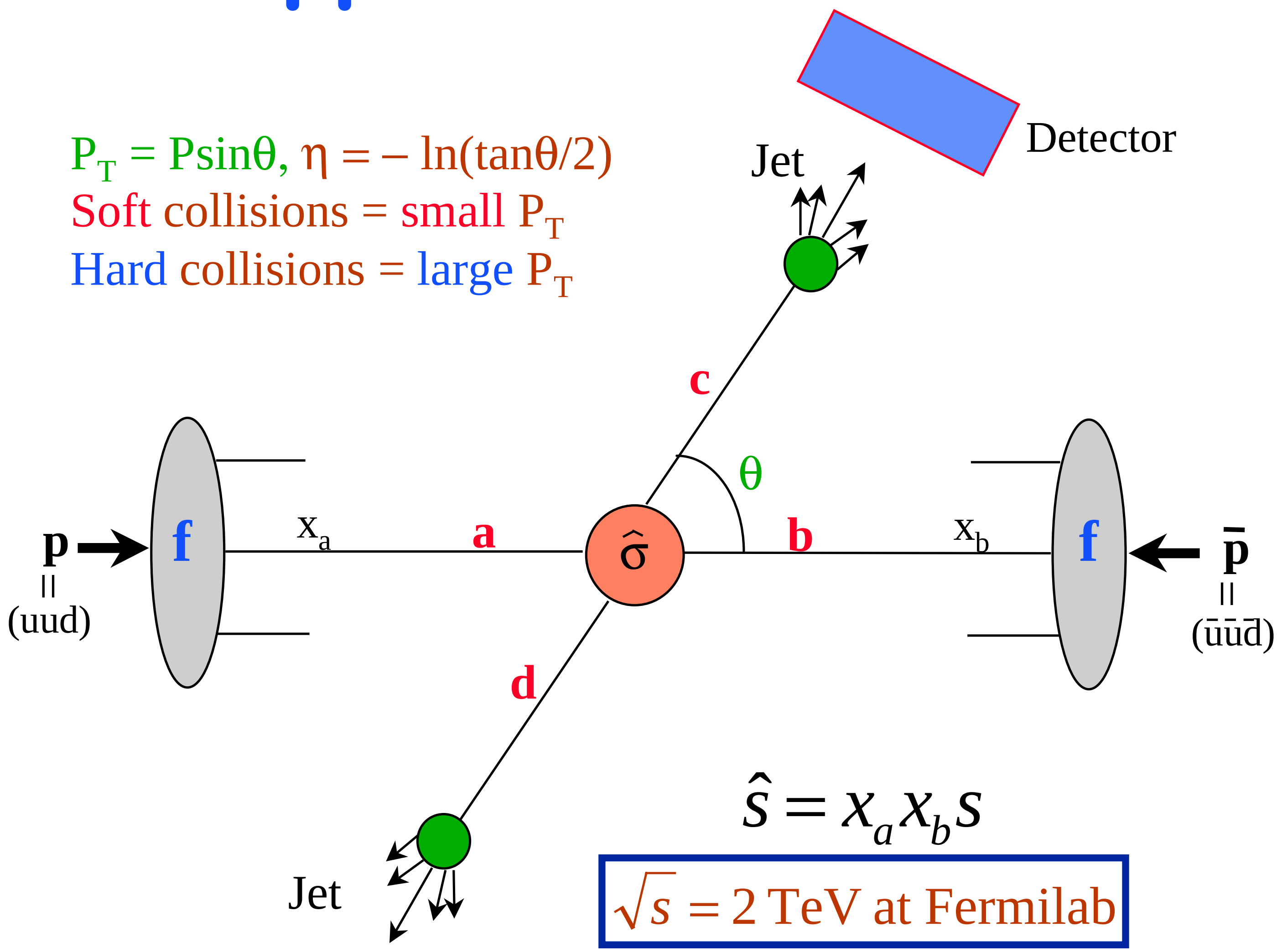
“Resolved” Photon Process





$p\bar{p}$ Interactions

$P_T = P\sin\theta$, $\eta = -\ln(\tan\theta/2)$
Soft collisions = small P_T
Hard collisions = large P_T



$$\hat{s} = x_a x_b s$$

$$\boxed{\sqrt{s} = 2\text{ TeV at Fermilab}}$$

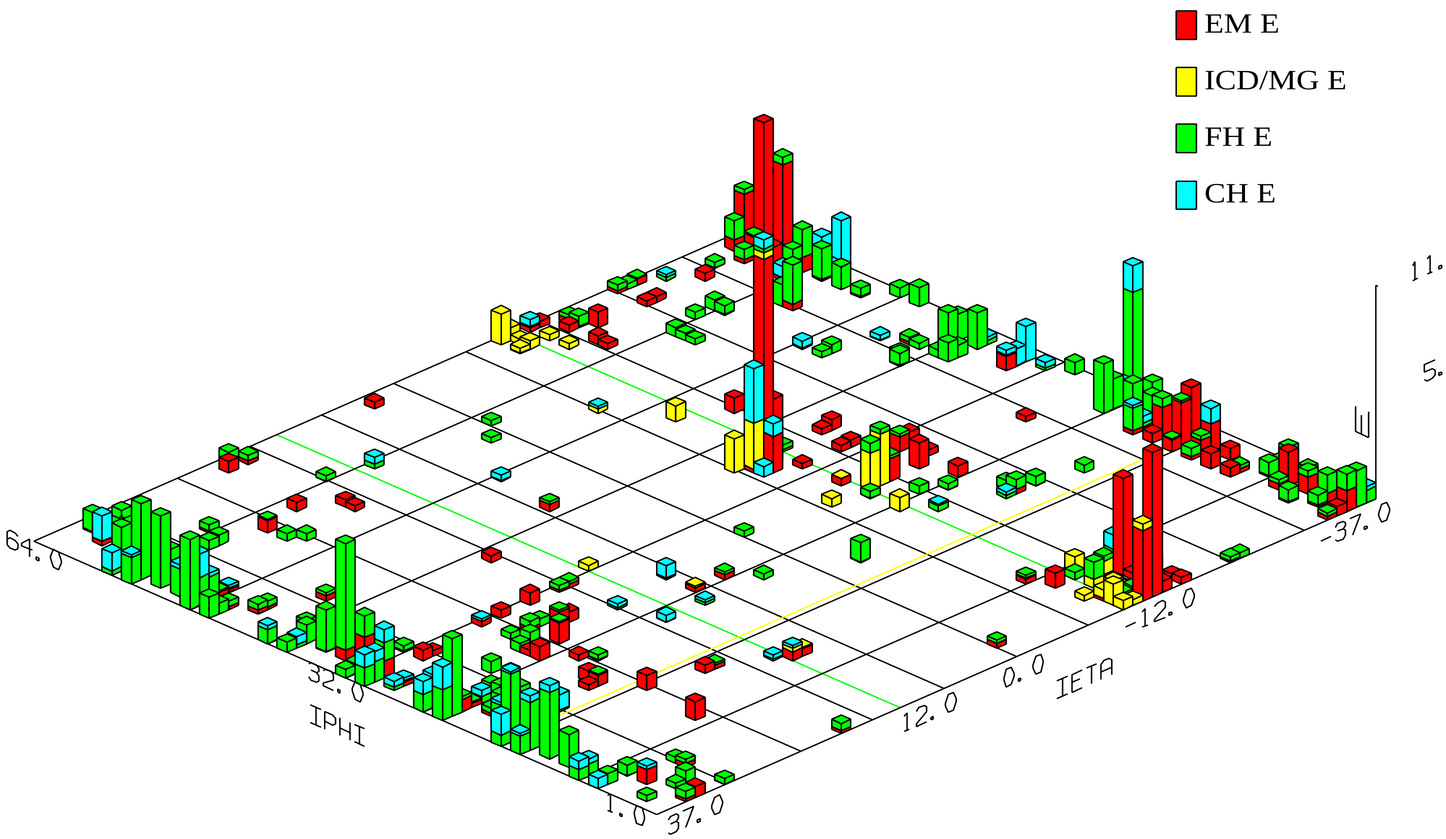
- $f_{a/A}(x_a,\mu)$: Probability function to find a parton of type **a** inside hadron **A** with momentum fraction x_a - ***Parton Distribution Functions***

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

  μ: 4-momentum transfer related to the "scale" of the interaction

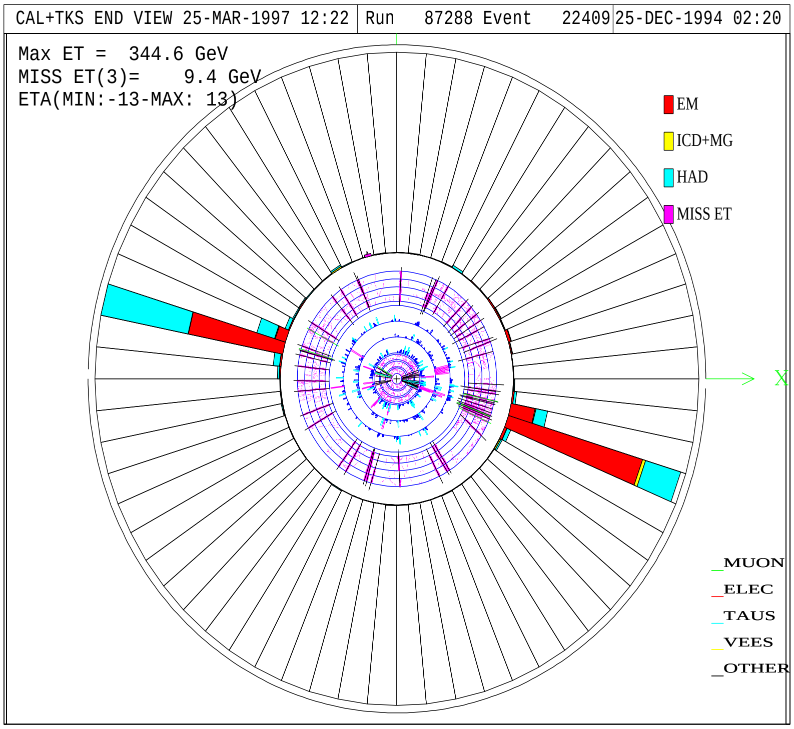
- $\hat{\sigma}$: Partonic level cross section

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



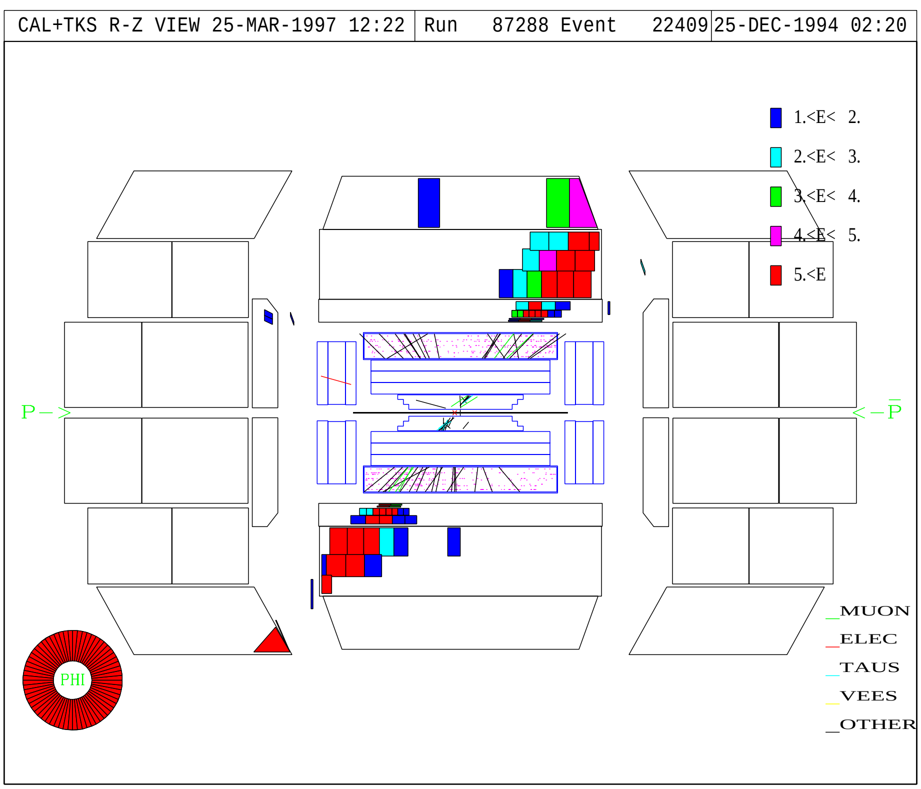
- **Complications due to:**
  - Parton Distribution Functions (PDFs)
  - "Colored" initial and final states
  - Remnant jets - Underlying event (UE)

High-E_T DØ Event

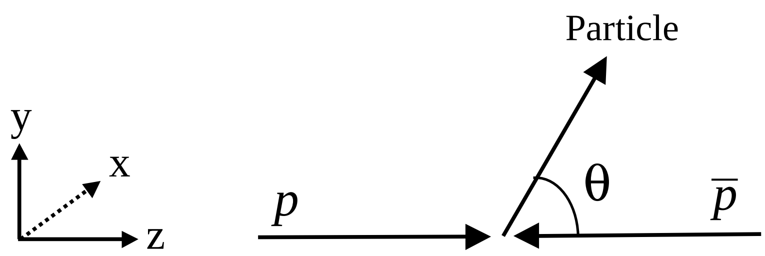


$E_{T,1}$ = 475 GeV,
η_1 = –0.69, x_1=0.66
$E_{T,2}$ = 472 GeV,
η_2 = 0.69, x_2=0.66

M_{JJ} = 1.18 TeV
Q^2 = 2.2x10^5 GeV^2



Kinematics in Hadronic Collisions



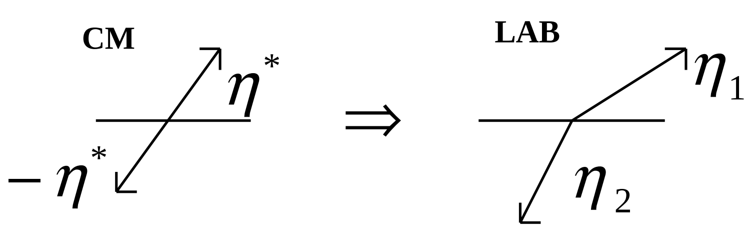
Rapidity (y) and Pseudo-rapidity (η)

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

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

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

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



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

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

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

Kinematics in Hadronic Collisions cont'd

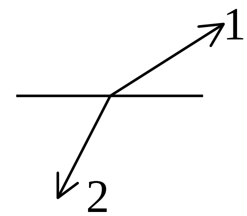
Transverse Energy/Momentum

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

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

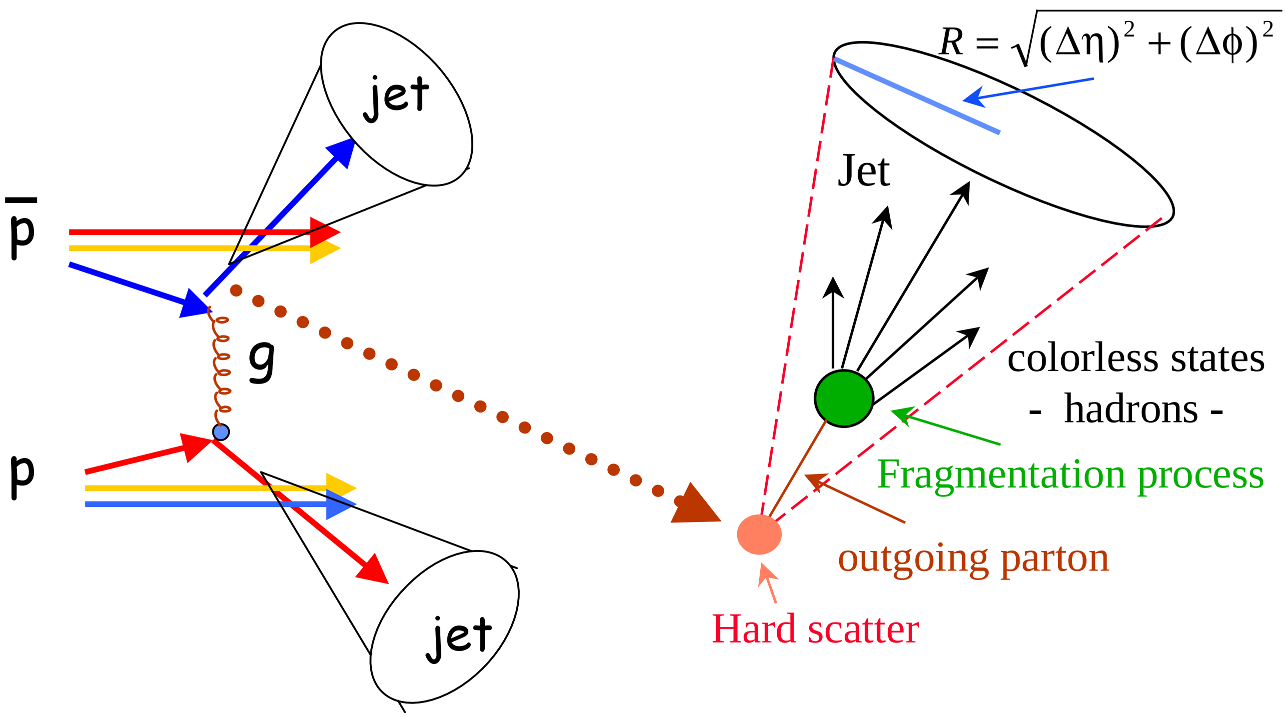
$$p_z = E \tanh y$$
$$E = E_T \cosh y$$
$$p_z = E_T \sinh y$$

Invariant Mass



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

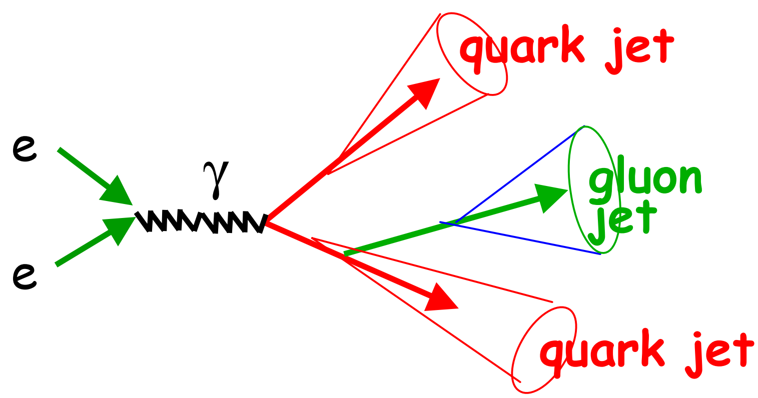
What are Jets ?



- 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

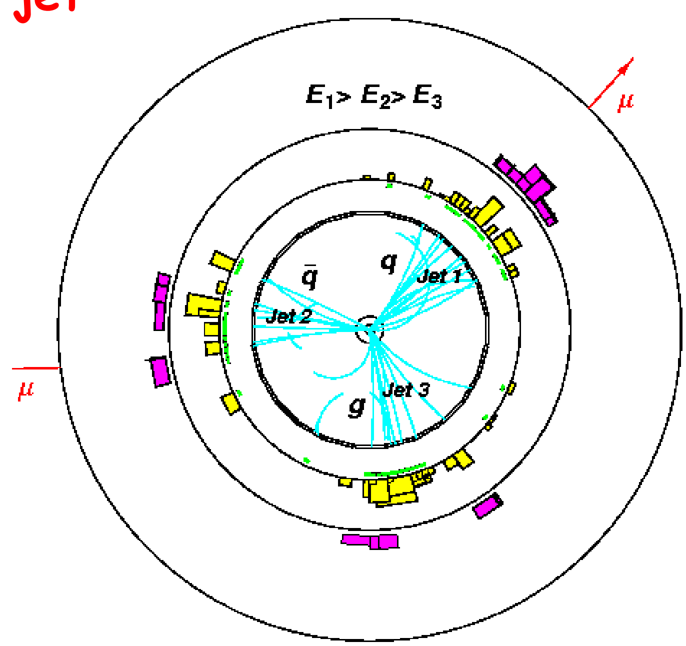
Evidence for Jets

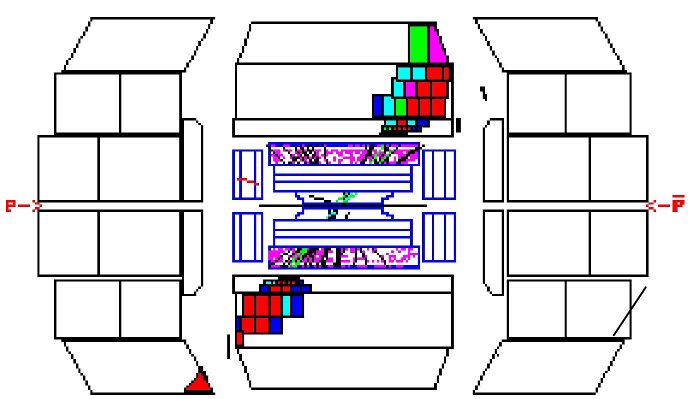
e $^+$e $^-$ collisions proceed through an intermediate state of a photon (or Z); such collisions lead to quark antiquark. Presence of 3rd jet signals gluon radiation



(gluon jets are broader than quark jets)

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





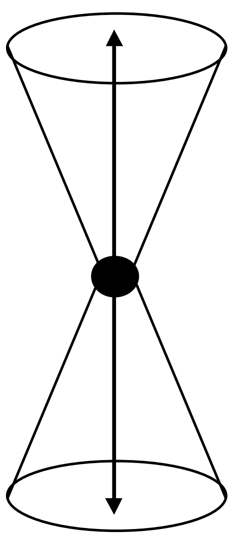
Quark-quark collisions produce clear jets as well: two 500 GeV E_T quark jets from q q scattering in D0. (color indicates energy deposit)

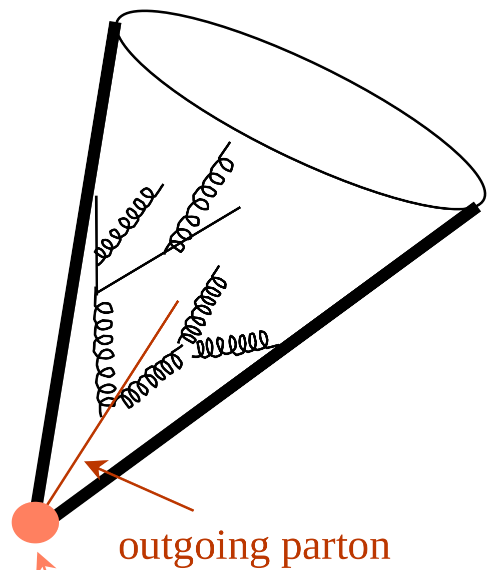
Jet Algorithms

- **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

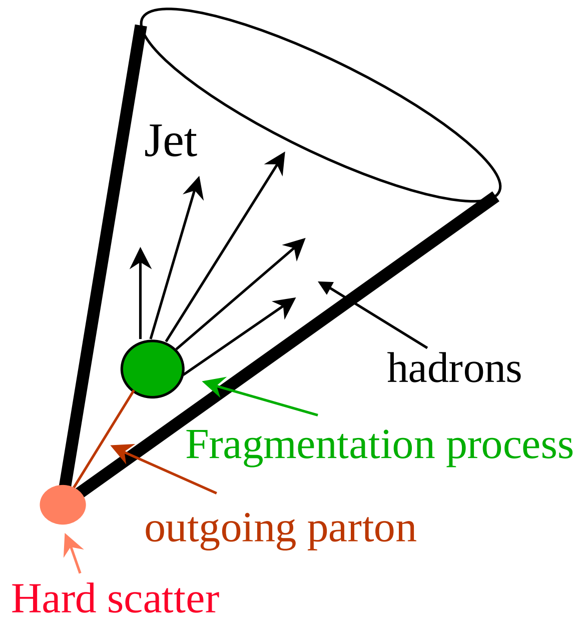
Leading Order



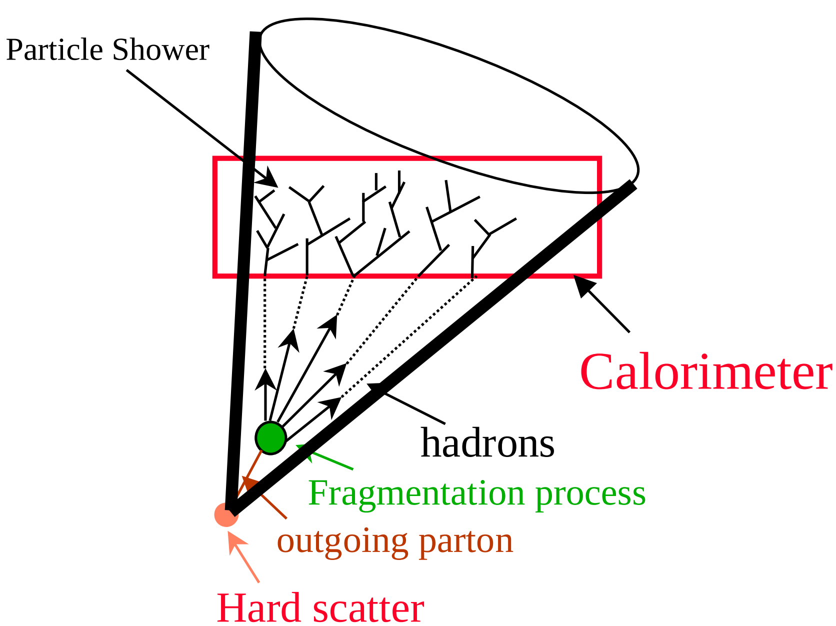


Jet Algorithms cont'd

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

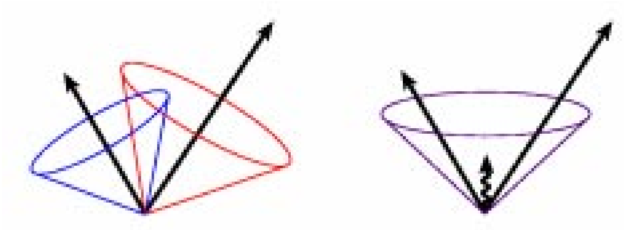


- Jets at the "Detector Level"

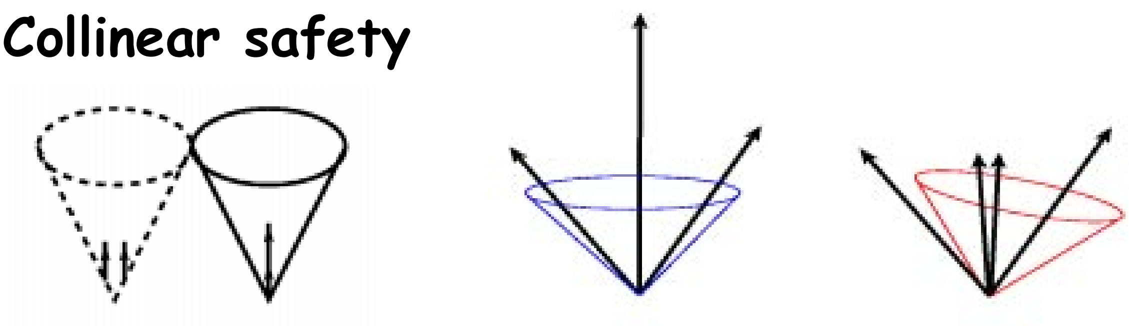


Jet Algorithms - Requirements

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



  - **Collinear safety**



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

Jet Algorithms - Requirements cont'd

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

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: $E_k = E_i + E_j$

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

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

The JADE Algorithm

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

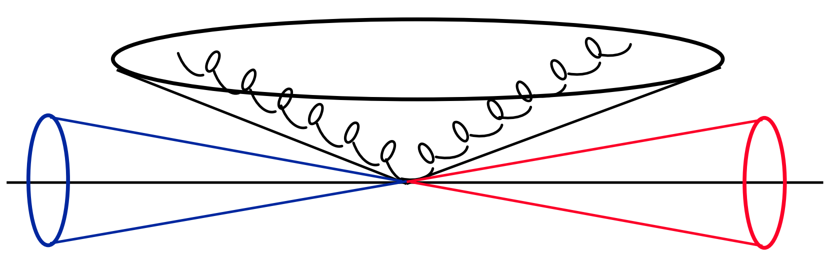
$$\min(y_{ij}) = \min(\frac{M_{ij}^2}{E_{vis}^2}) < y_{cut}$$

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

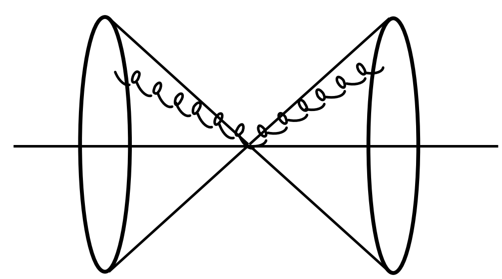
- Recombination: $p_k = p_i + p_j$
- Problems with this algorithm
  - It doesn't allow resummation when y_{cut} is small
  - Tendency to reconstruct "spurious" jets

    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

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

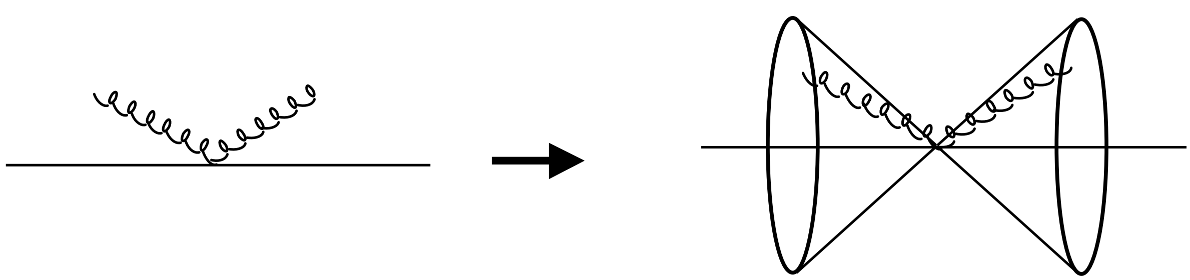
$$\min(y_{ij}) = \frac{M_{ij}^2}{E_{vis}^2} < y_{cut}$$

For small θ_{ij}

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

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

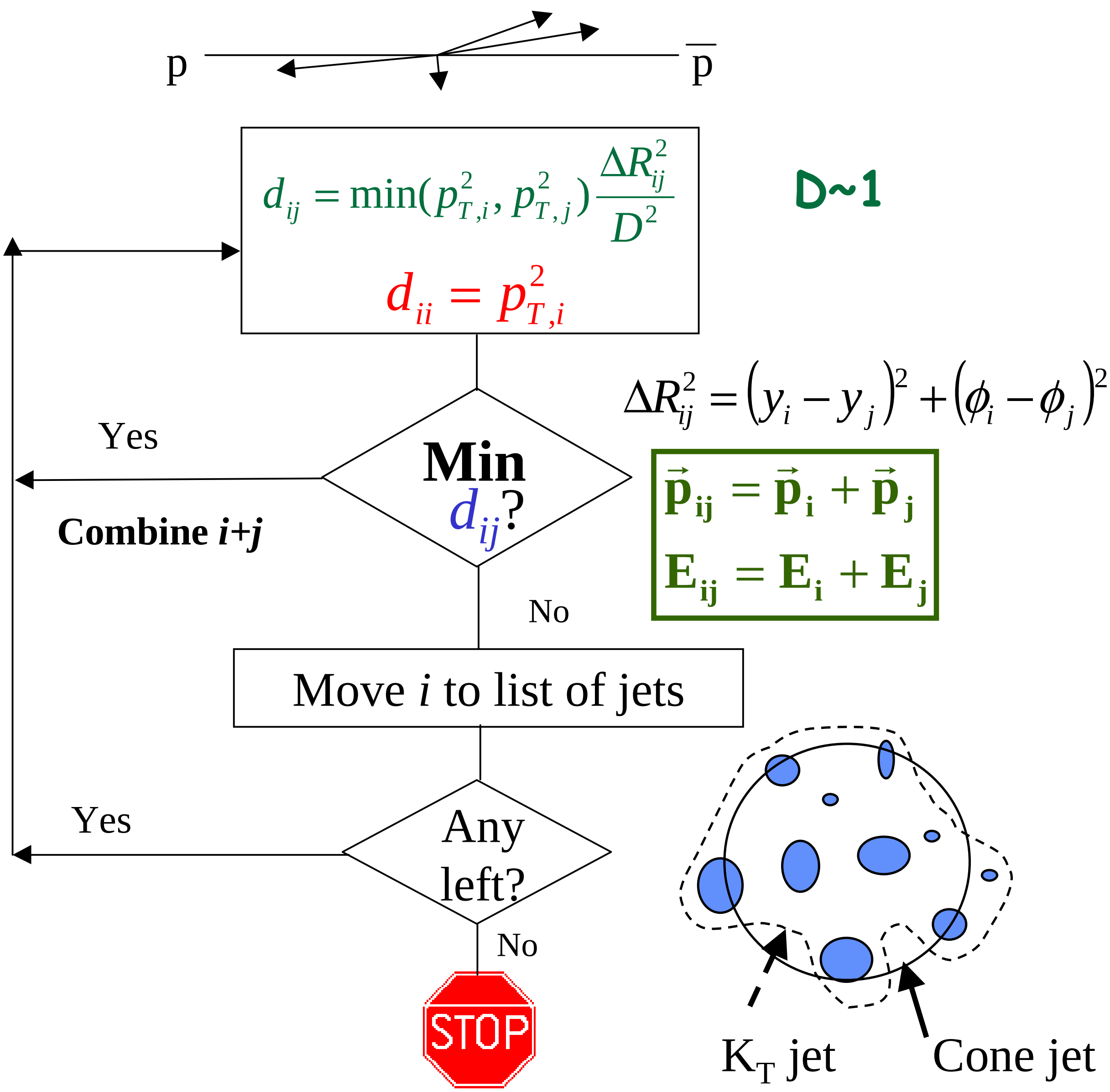
- Recombination: $p_k=p_i+p_j$
- It allows the resummation of leading and next-to-leading logarithmic terms to all orders for the regions of low y_{cut}



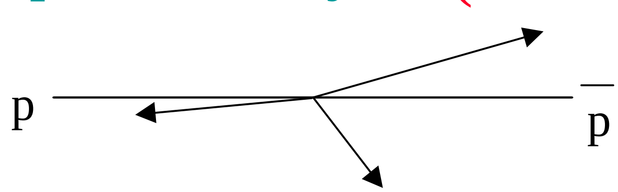
√ 2-Jet event

A "K_T" Algorithm for hadron colliders

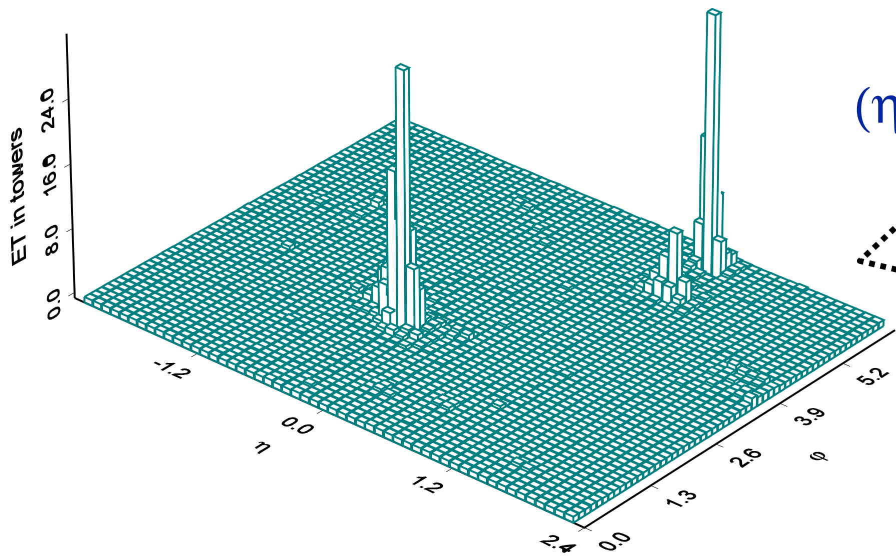
Input: List of Energy preclusters $(\Delta R = 0.2)$

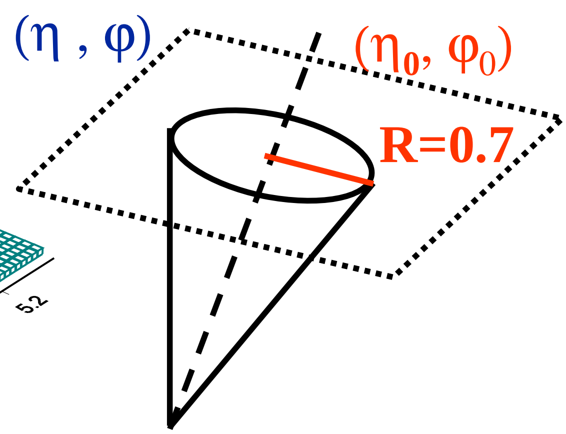


Output: List of jets $(\Delta R \geq D)$

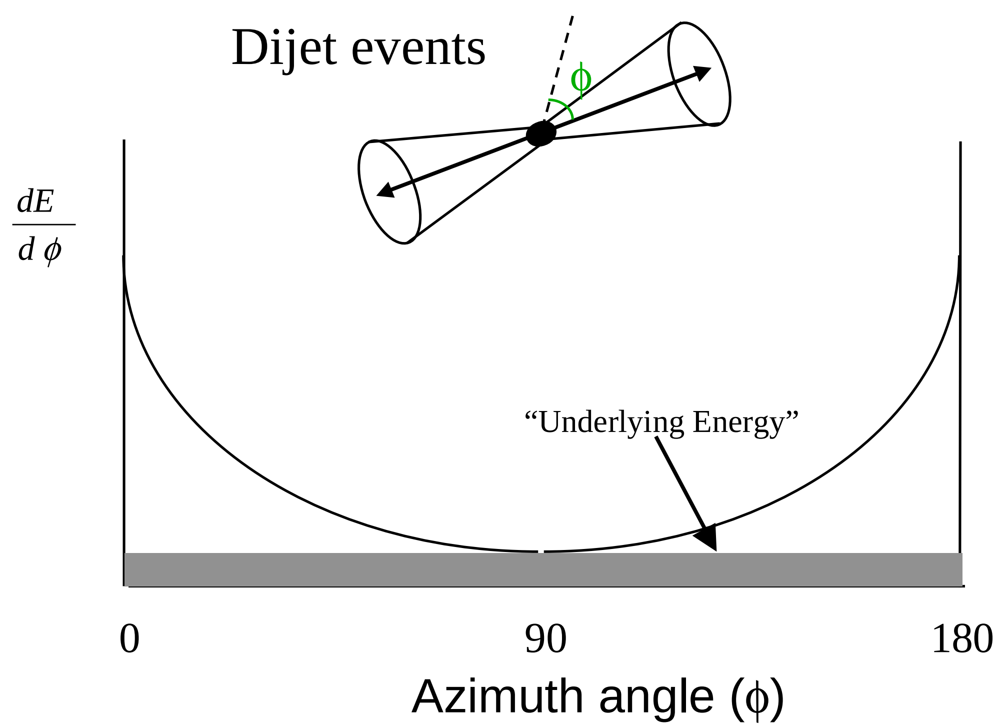


The "Cone" Algorithm



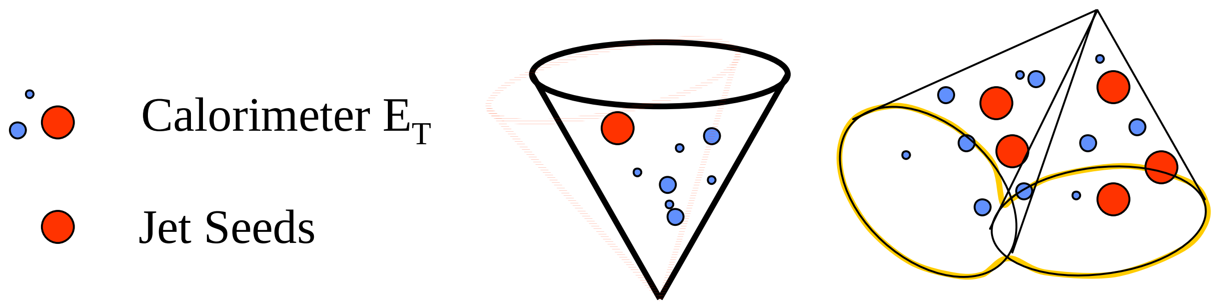


- A more intuitive representation of a jet that is given by recombination jet finders
- It clusters particles whose trajectories lie in an area $A=\pi R^2$ of (η,ϕ) space



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%

- **Not all particles are necessarily assigned to a jet**

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

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

D0 and CDF's Angles:

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

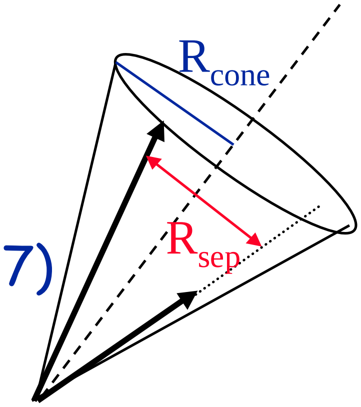
CDF's E_T:

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

D0's E_T:

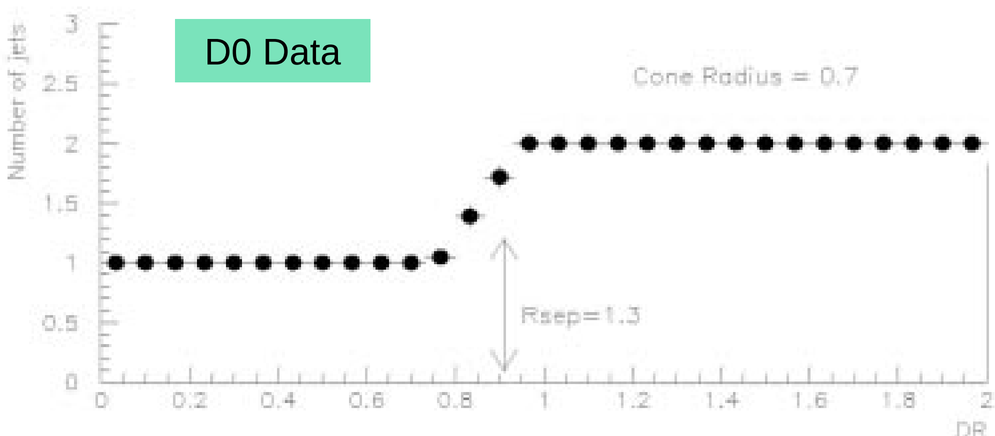
$$E_T^J = \sum_{i \subset J} E_T^i$$

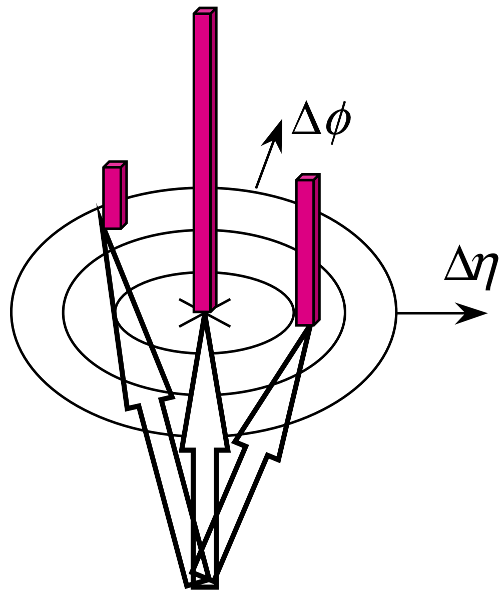
The "Cone" Algorithm at the NLO Parton Level



- Apply Snowmass recipe
  - Each parton must be within R_{con} (=0.7) of centroid
- The two partons must be within $R_{sep} \times R_{cone}$ 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:





Jet Characteristics

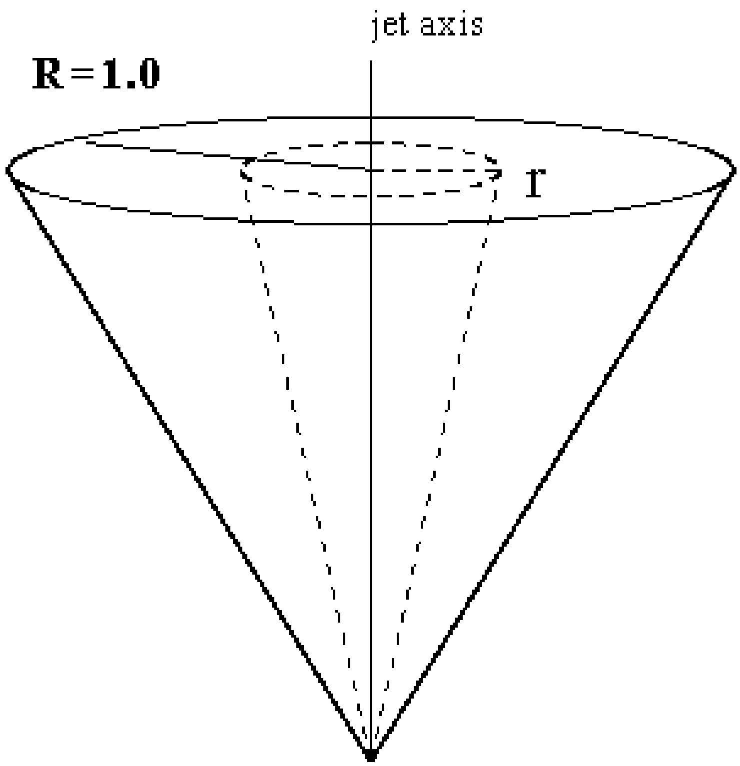
Jet Profiles:

- How fat/thin jets are?
- Can we tell the difference between quark and gluon initiated jets?

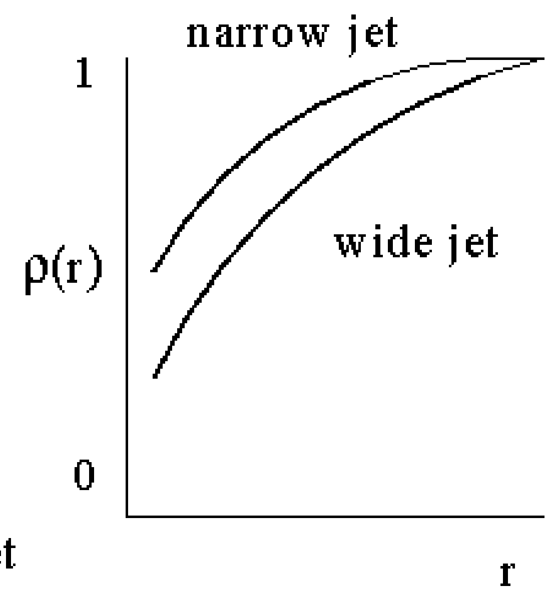
Color Coherence:

- Is there any preferred direction of soft jet emission?
- Can color coherence effects survive the hadronization process?
- What is the relative importance of perturbative vs. non-perturbative effects?

Jet Shape Measurement



Measure radial E_T flow in 10 subcones around jet axis in $\Delta r = 0.1$ increments

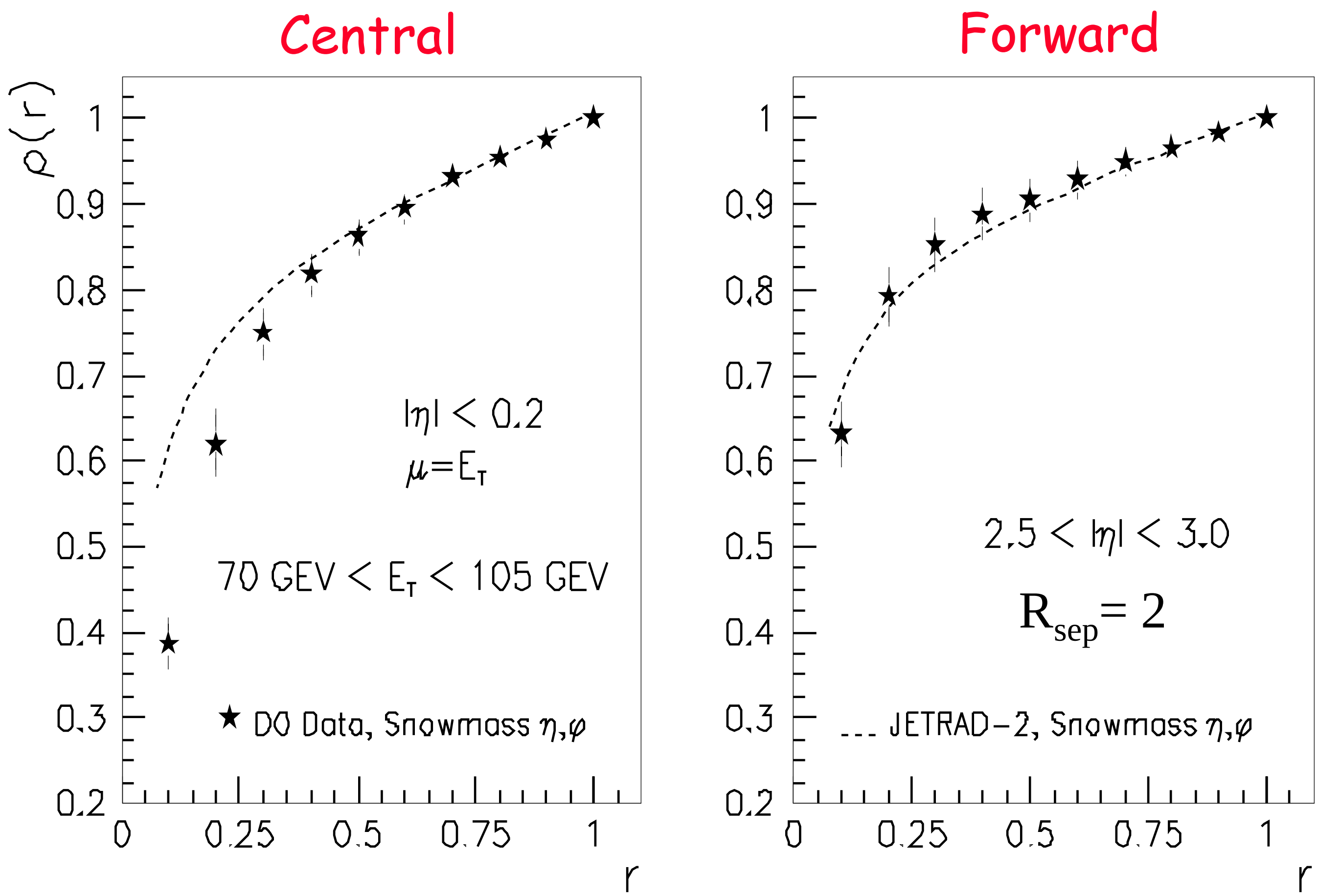


Calculate average integrated jet E_T fraction as a function of radial distance from jet axis:

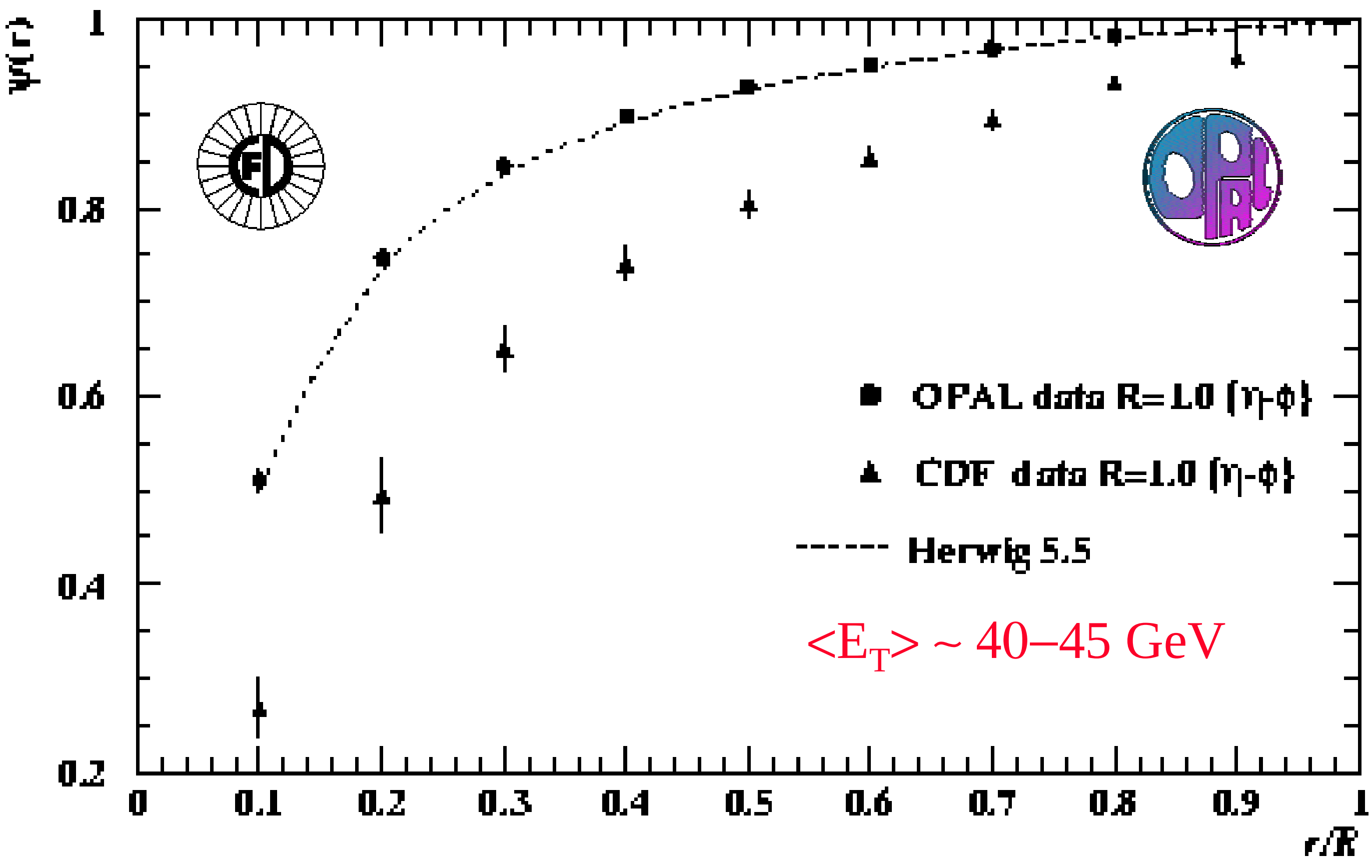
$$\rho(r) = 1/N_{jets}\left[\Sigma_{jets}\left(E_T(r)/E_T(R)\right)\right]$$

The investigation of jet profiles gives insights into the transition between the parton produced in the hard process and the observed spray of hadrons

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)
- Jets become narrower with increasing E_T (not shown)
- 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

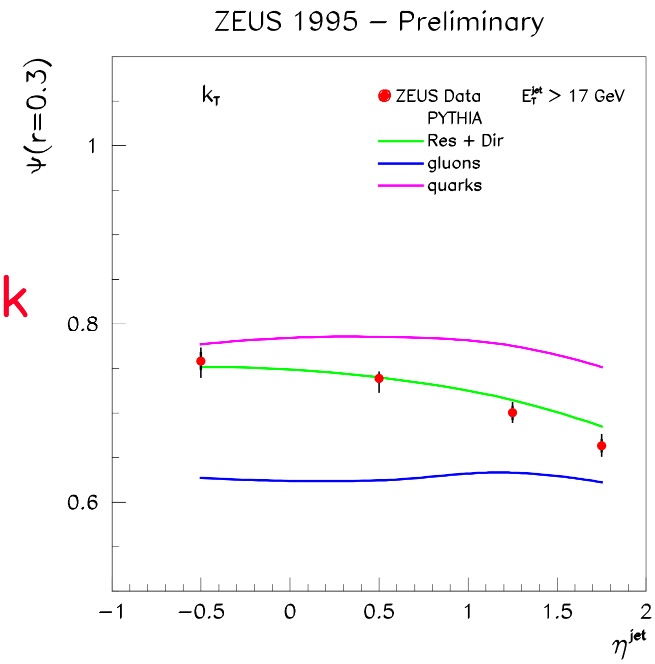


Jet Energy Profiles at e^+e^-

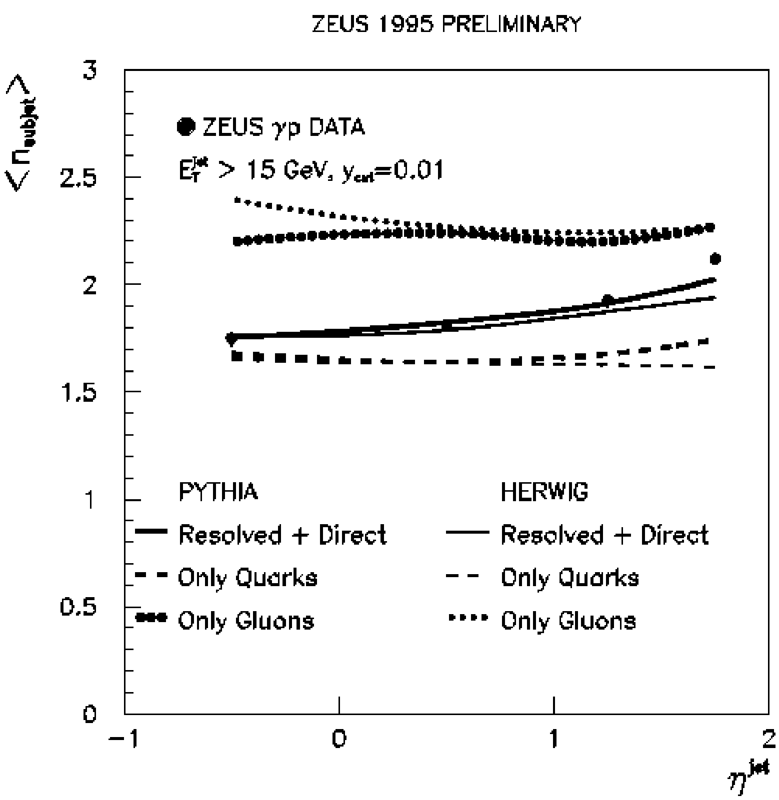
- OPAL performed an analysis technique similar to CDF for comparison purposes
- e^+e^- jets are narrower than $p\bar{p}$ jets
- Can it be the underlying event or "splash-out"?
  - Although the CDF data include underlying event, its effect to the energy profile is not large enough to account for the difference
- 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 ep

- **Subjet multiplicity rises as jets become more forward**
- **Consistent with expectations (more gluons) and HERWIG/PYTHIA**



$E_T^{jet} > 17$ GeV
(K_T Algorithm) $y_{cut} = 0.01$
- Majority of jets are quark originated for $\eta^{jet}<0$
- Fraction of gluon jets increase with η^{jet}



LO Processes:

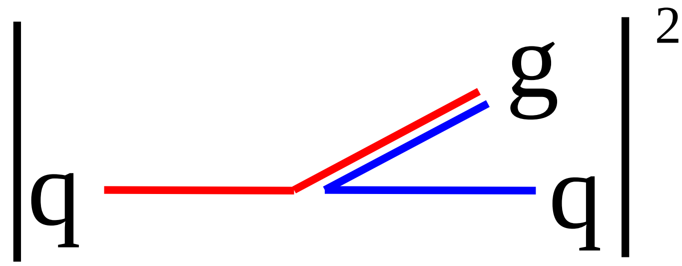
$$\gamma g \rightarrow q\bar{q}$$

$$q_\gamma g_p \rightarrow qg$$

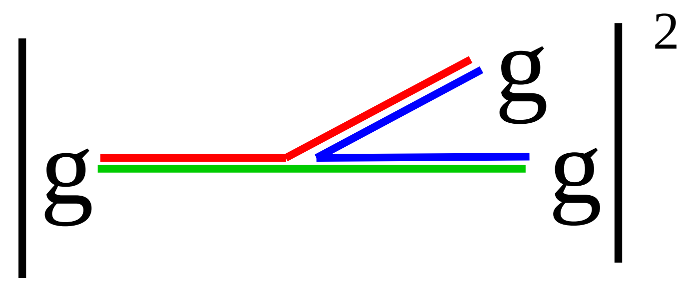
Quark vs Gluon Jets

Deepen understanding of jet substructure

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



$\sim C_F = 4/3$



$\sim C_A = 3$

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

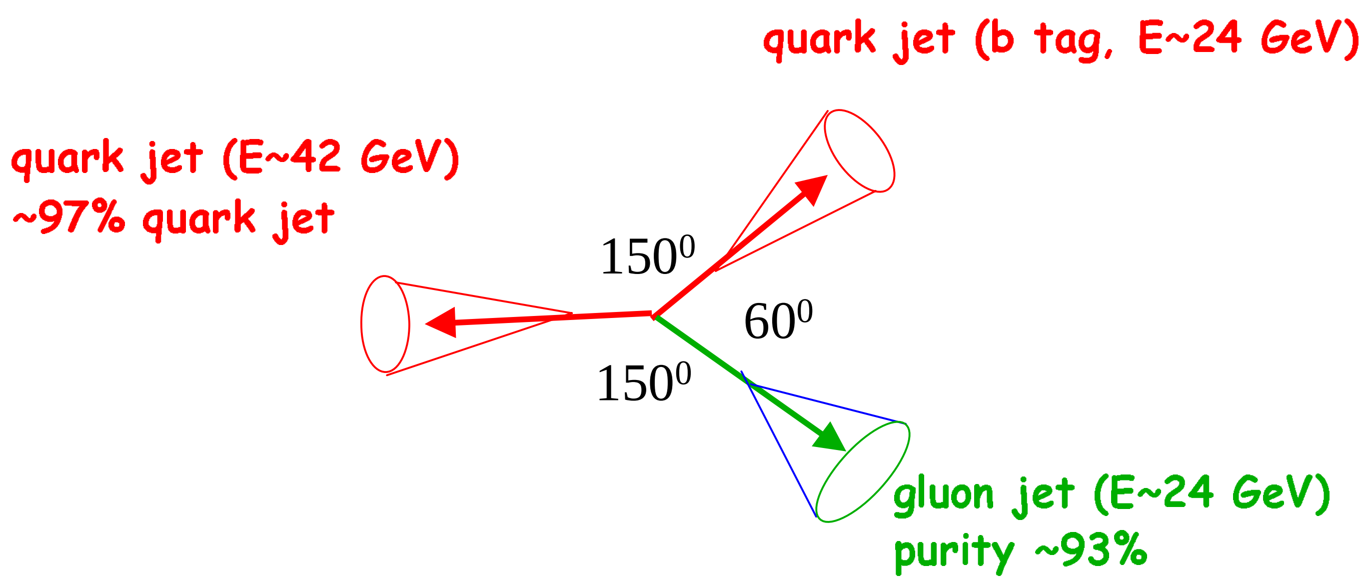
At Leading Order: $r \sim \frac{C_A}{C_F} = \frac{9}{4} = 2.25$

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: $r \sim 1.7$

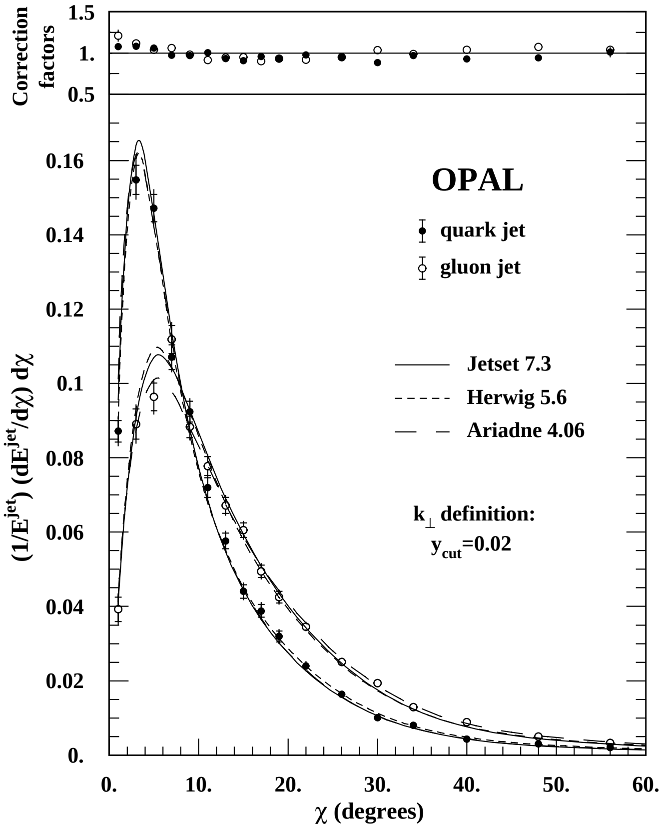
Quark vs Gluon Jets (LEP1)

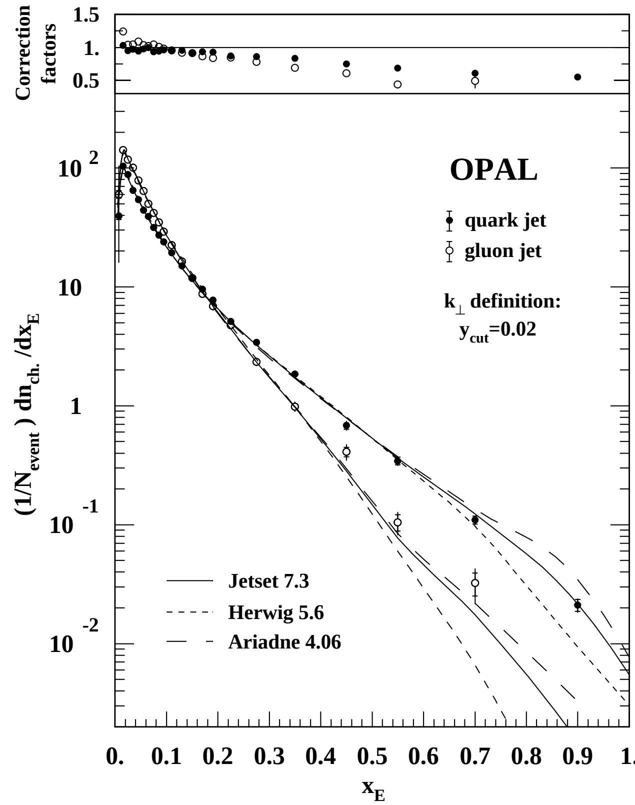
- Expectation:
  - Gluon jets are broader than quark jets
  - Gluon jets have softer fragmentation function than quark jets
- LEP1 measurement (OPAL)
  - Select three jet events

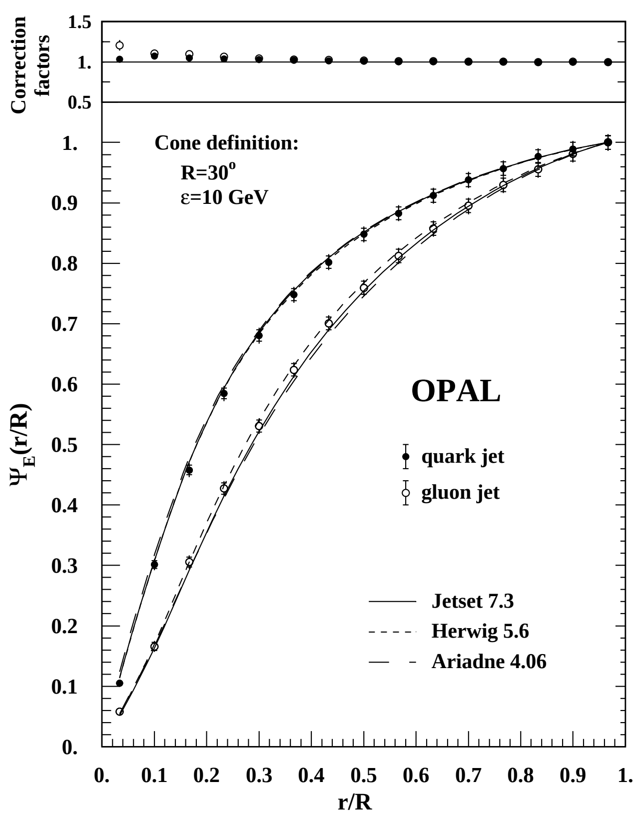


  - Repeat analysis with a "KT" (Durham) and "cone" jet algorithm in order to compare with Tevatron results

Quark vs Gluon Jets







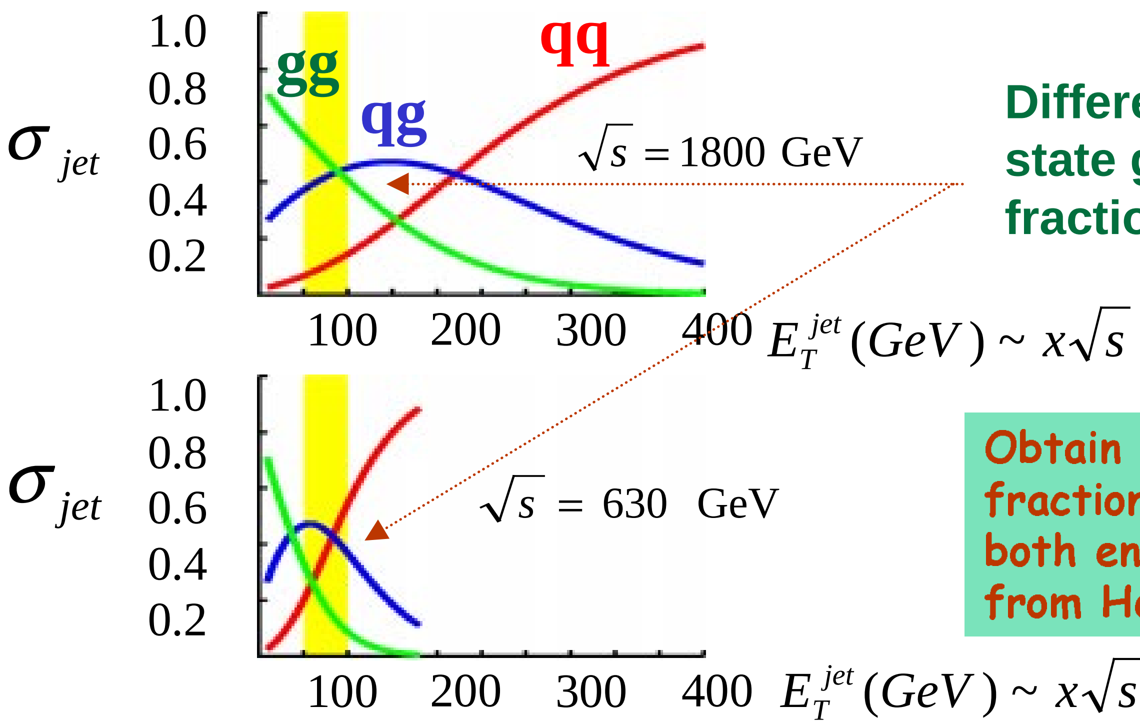
r (K_T, charged prtc)=1.25±0.04
r (cone, R=30^0, ch prtc)=1.10 ±0.02
for R=50^0, r~1.26

=> result sensitive to jet algorithm!

OPAL has published an analysis on gluon vs quark jets which is almost entirely independent of the choice of the jet finding algorithm used
Eur. Phys. J. C11 (1999) 217

Quark vs Gluon Jets

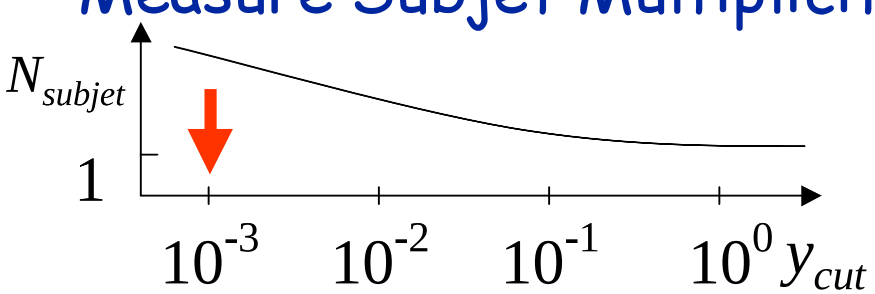
- Basic Idea:
  - Compare the subjet multiplicity of jets with same E_T and η at center of mass energies 630 and 1800 GeV and infer q and g jet differences



Different final state gluon fraction

Obtain gluon fractions for both energies from Herwig

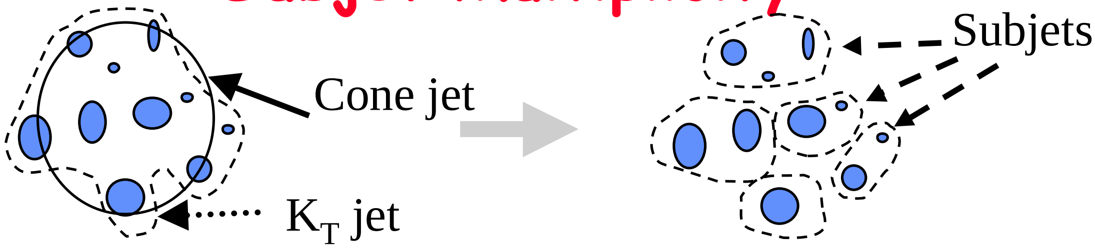
- Rerun k_T algorithm on all 4-vectors merged into jet:
  - Recombine energy clusters into subjets separated by y_{cut} (a resolution parameter)
- Measure Subjet Multiplicity:

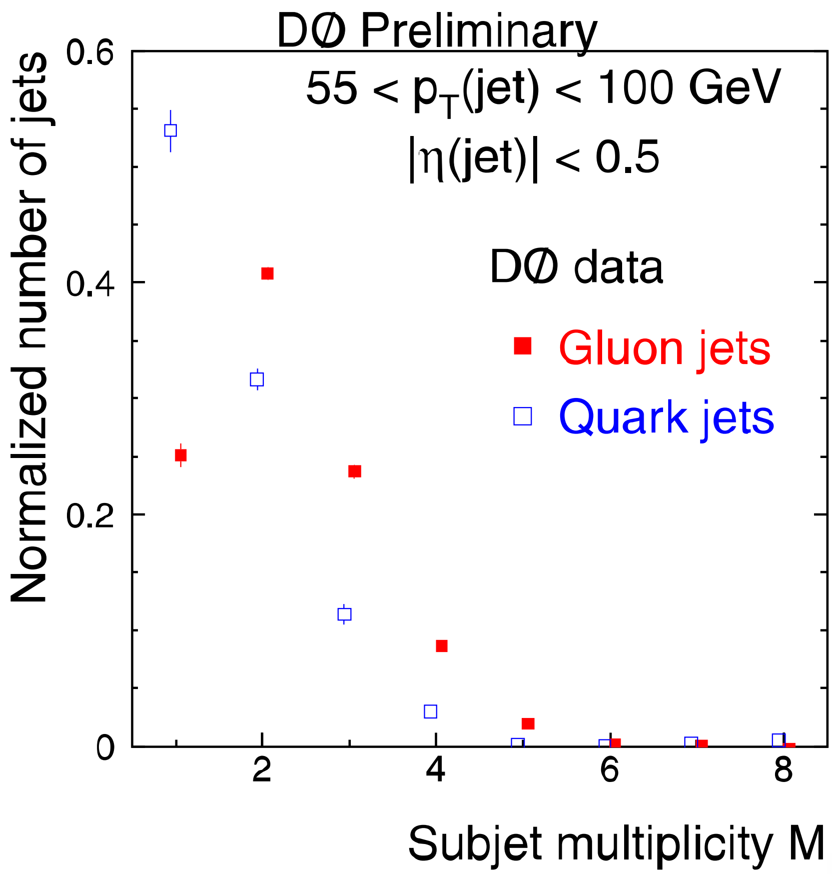


$$d_{i,j} = \min(p_{T,i}^2, p_{T,j}^2)\frac{\Delta R_{ij}^2}{D^2} > y_{cut}\, p_{T,Jet}^2$$

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

Subjet Multiplicity





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

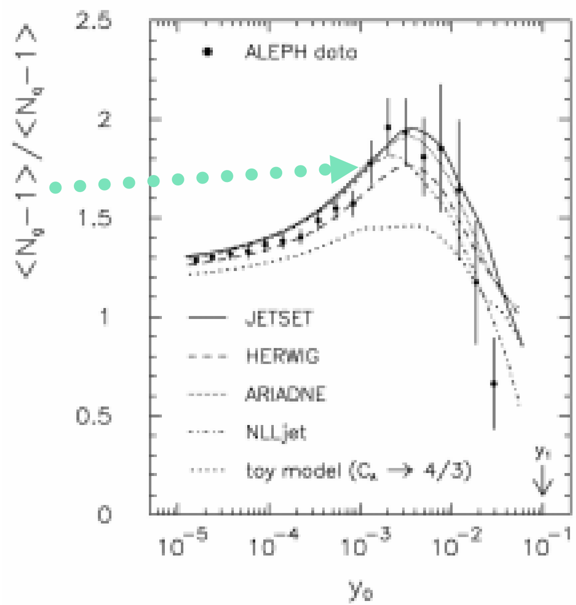
$$= 1.84 \pm 0.15\,(stat) \pm {}^{0.22}_{0.18}\,(sys)$$

(DØ Data)

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

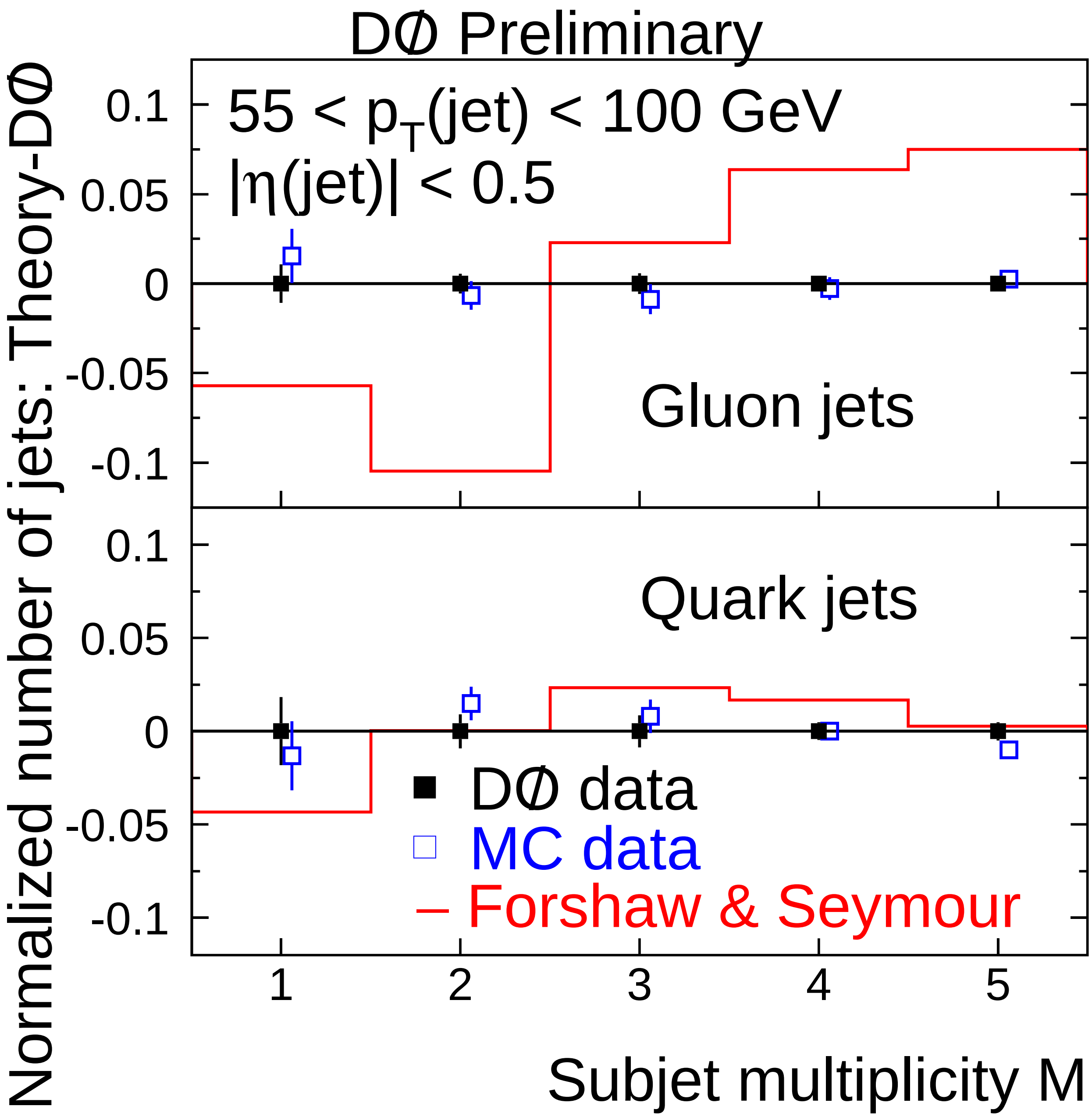
(HERWIG 5.9)

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



Subjet Multiplicity of Quark/Gluon Jets

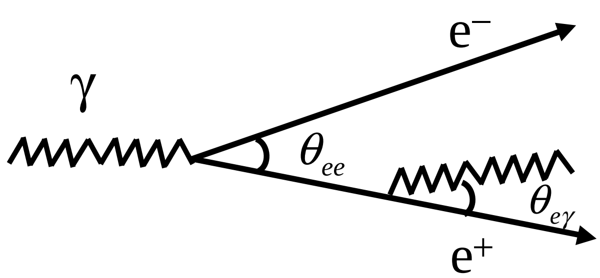
Data vs Theory



- Nice agreement with Herwig
- Analytic resummed calculation predicts slightly higher multiplicities

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**
  - It results in a suppression of large-angle soft gluon radiation in partonic cascades
- **Two types of Coherence:**
  - **Intrajet Coherence**
    - Angular Ordering of the sequential parton branches in a partonic cascade
  - **Interjet Coherence**
    - String or Drag effect in multijet hadronic events

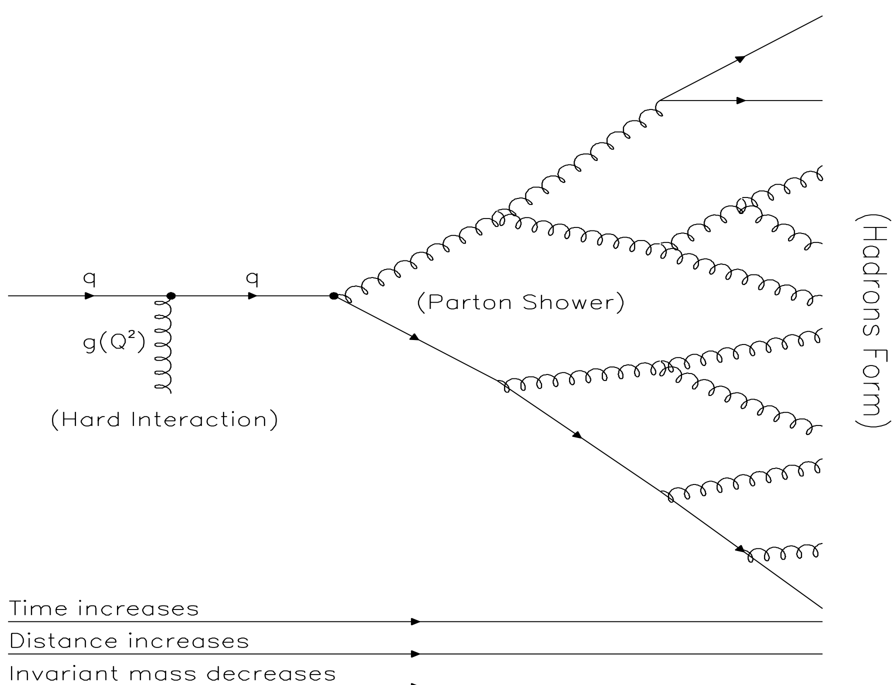
Shower Development

"Traditional Approach"

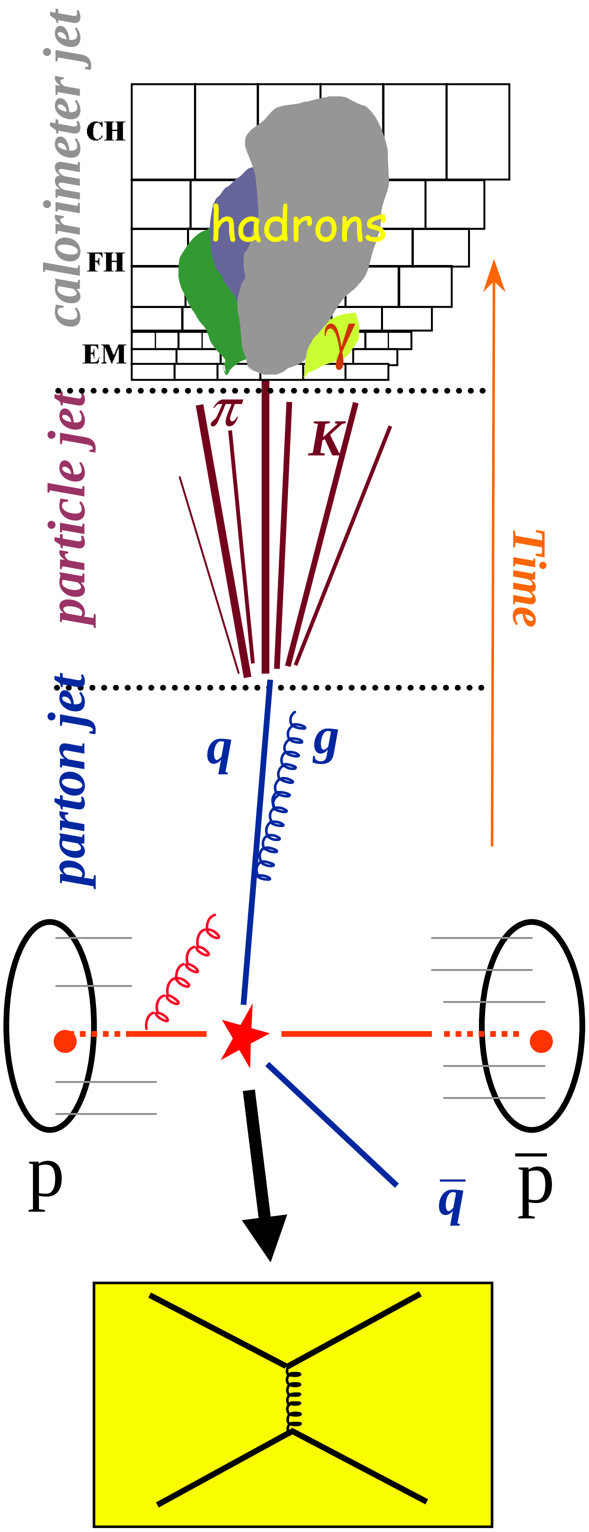
- Shower develops according to pQCD into jets of partons until a scale of Q_0 ~ 1 GeV.
- Thereafter, non-perturbative processes take over and produce the final state hadrons

"Local Parton Hadron Duality (LPHD) Approach"

- Parton cascade is evolved further down to a scale of about Q_0 ~ 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 ?

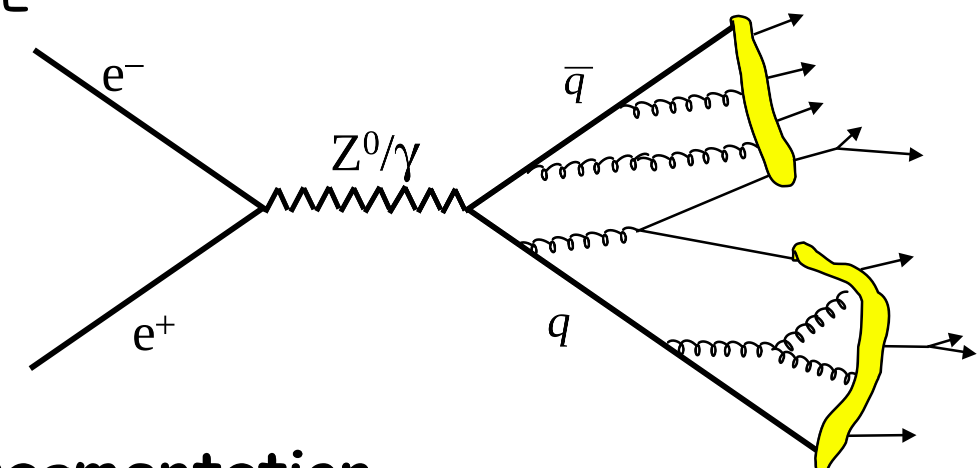


- A "Fortran" program (typically 1-50k lines of code) that generates events, trying to simulate Nature!
- Events vary from one to the next (random numbers)
- Expect to reproduce average behavior and fluctuations of real data
- Event Generators include:
  - Parton Distribution functions
  - Initial state radiation
  - Hard interaction
  - Final state radiation
  - Beam jet structure
  - Hadronization and decays
- Some programs in the market:
  - JETSET, PYTHIA, LEPTO, ARIADNE, HERWIG, COJETS...
- Parton-level only:
  - VECBOS, NJETS, JETRAD, HERACLES, COMPOS, PAPAGENO, EUROJET...

Hadronization Models

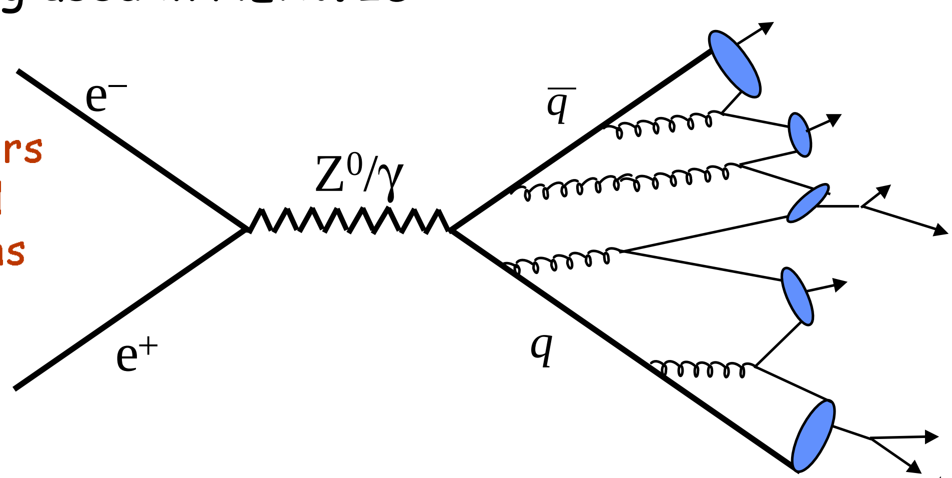
- **Independent fragmentation**
  - it is being used in ISAJET and COJETS
  - simplest scheme - each parton fragments independently following the approach of Fied and Feynman
- **String fragmentation**
  - it is being used in JETSET, PYTHIA, LEPTO, ARIADNE

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 <u>neighboring</u> partons combine into color singlets..

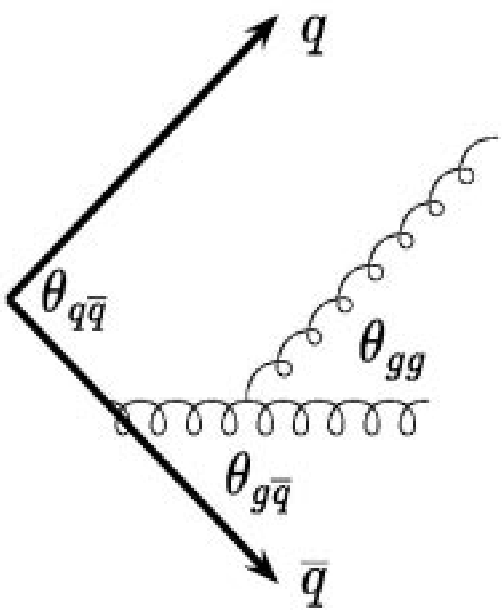


Intrajet Coherence

- Color Coherence (CC) effects in partonic cascades

- Angular Ordering of soft gluon radiation

uniform *decrease* of successive emission angles of soft gluons as partonic cascade evolves away from the hard process



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

Intrajet Coherence

Theoretical Framework:

- Analytic Approach:

PQCD + LPHD → **DLA, MLLA...**

LPHD ⇒ at low evolution scales the hadronic distributions are expected to be proportional to the partonic ones

PQCD ⇒ Resummed analytical calculations (DLA, MLLA) incorporate leading coherence effects

- MC Approach:

Perturbative: Include CC effects probabilistically by means of AO for both initial and final state evolutions

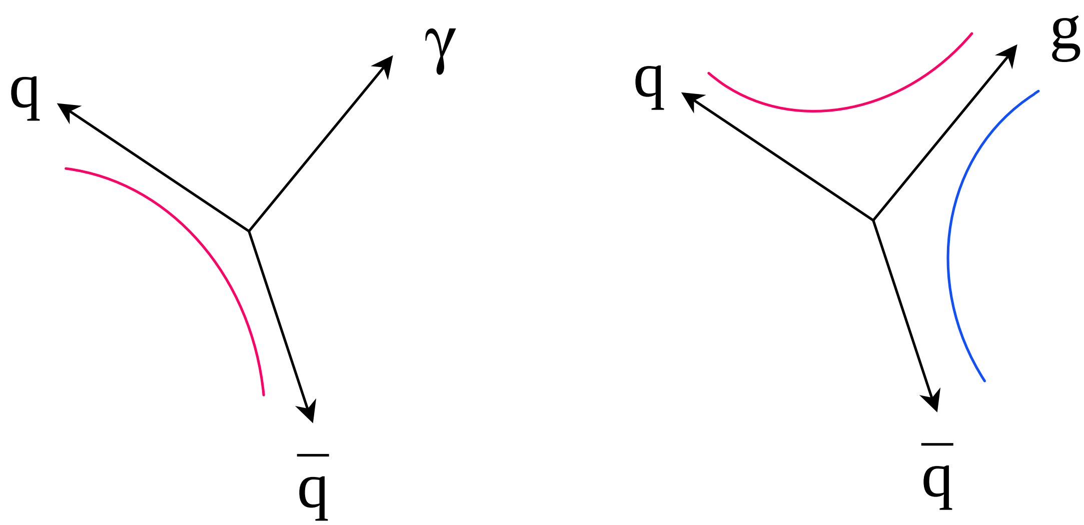
Non-Perturbative: Use phenomenological models to simulate the non-perturbative hadronization stage, e.g. the LUND string model or the cluster fragmentation model.

Interjet Coherence

- Interjet coherence deals with the angular structure of particle flow when three or more partons are involved

- **e^+e^- interactions:**

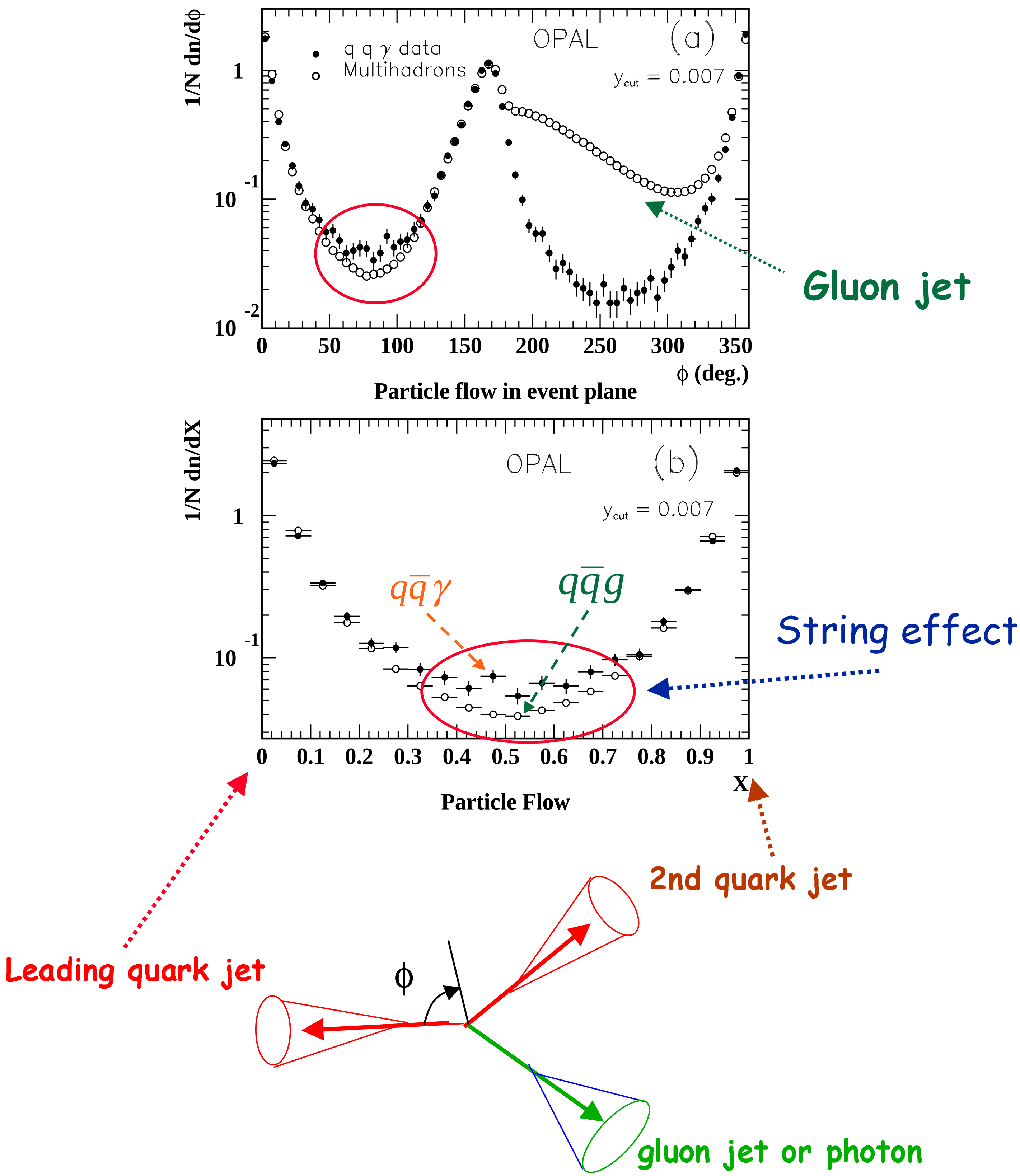
First observations of final state color coherence effects in the early '80's (JADE, TPC/2γ, TASSO, MARK II Collaborations) (**"string"** or **"drag"** effect)



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

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.

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

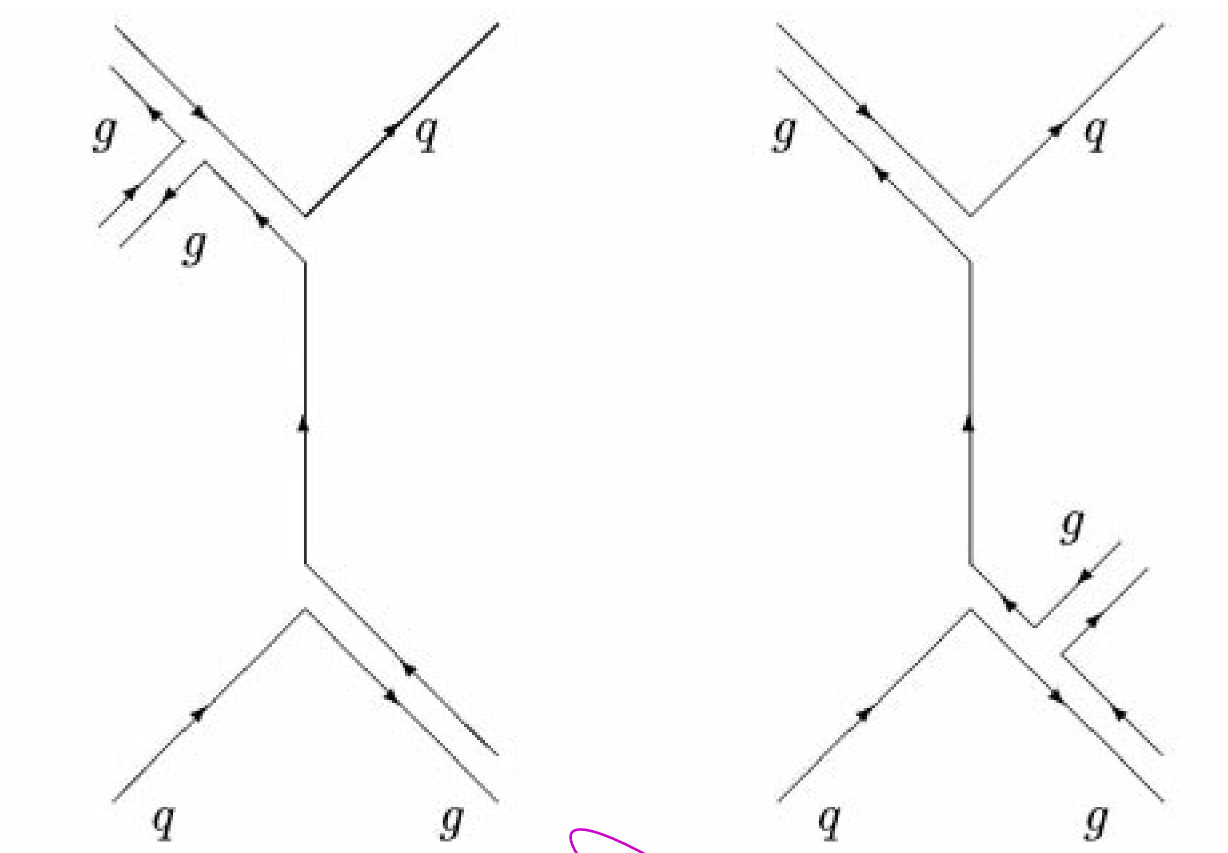


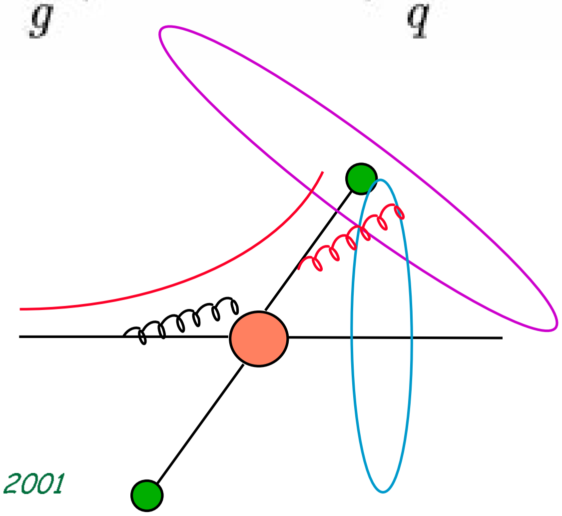
Interjet Coherence

$p\bar{p}$ interactions:

• Colored constituents in initial *and* final state (more complicated that e^+e^-)

• Probes initial-initial, final-final and **initial-final** state color interference



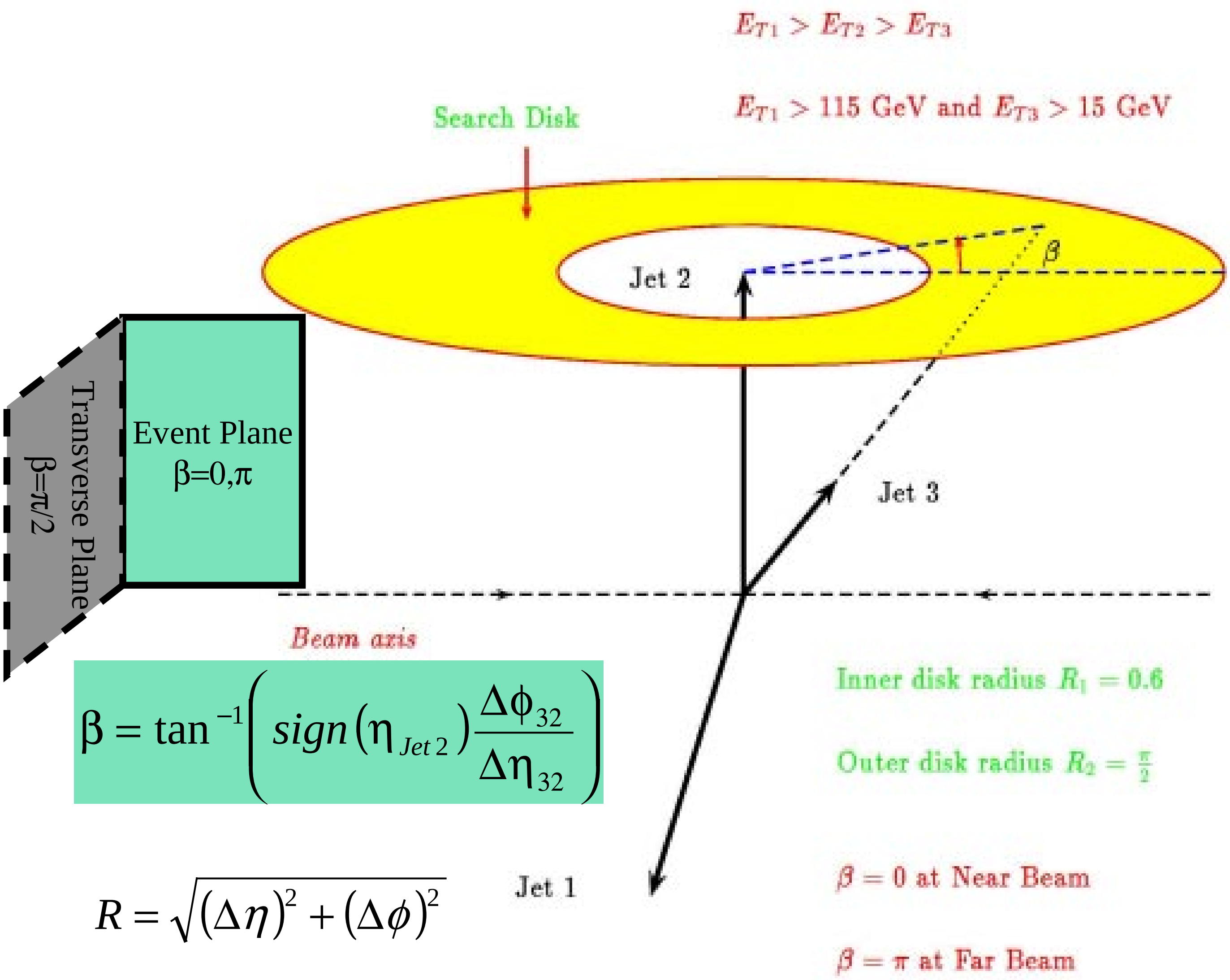


Multijets

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

- 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

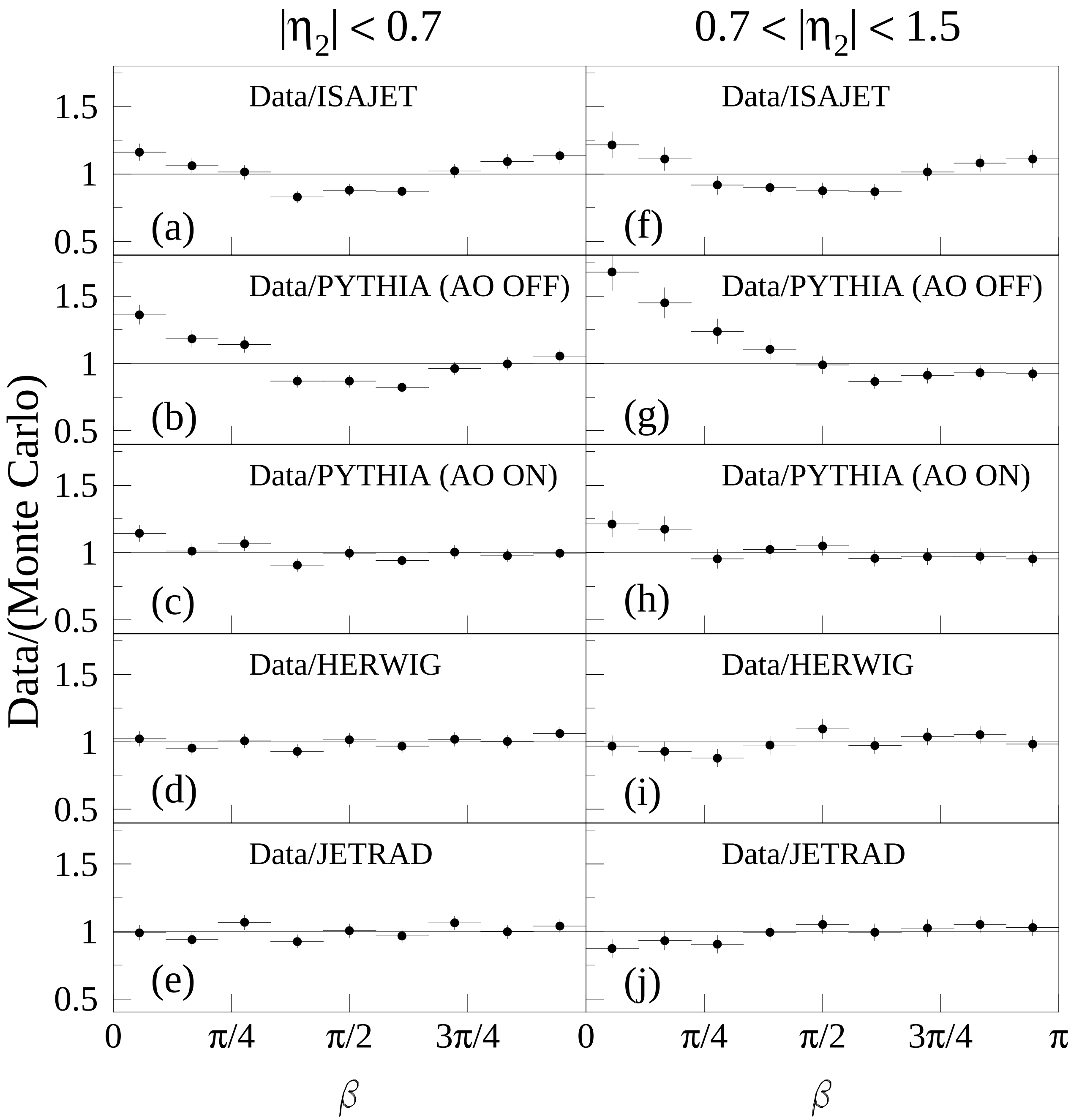
Monte Carlo Simulations

- Generate high statistics particle/parton level MC samples including detector position and energy resolution effects

- **Shower-level event generators:**
  - ISAJET v7.13
    - Does not include color coherence effects
    - Independent fragmentation
  - HERWIG v5.8
    - AO approximation
    - Cluster fragmentation
  - PYTHIA v5.7
    - AO approximation (no azimuthal correlations for ISR)
    - AO may be turned off
    - String or independent fragmentation

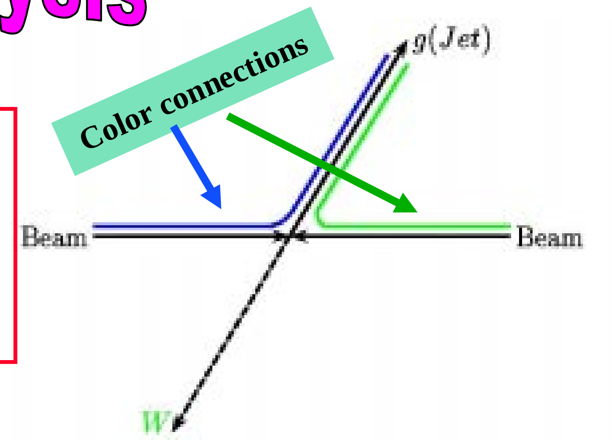
- **Parton-level pQCD calculation:**
  - JETRAD v1.1
    - $O(\alpha_s^3)$ parton level, one loop $2 \rightarrow 2$, tree level $2 \rightarrow 3$ scattering amplitudes
    - No fragmentation

3–jet Data/Monte Carlo



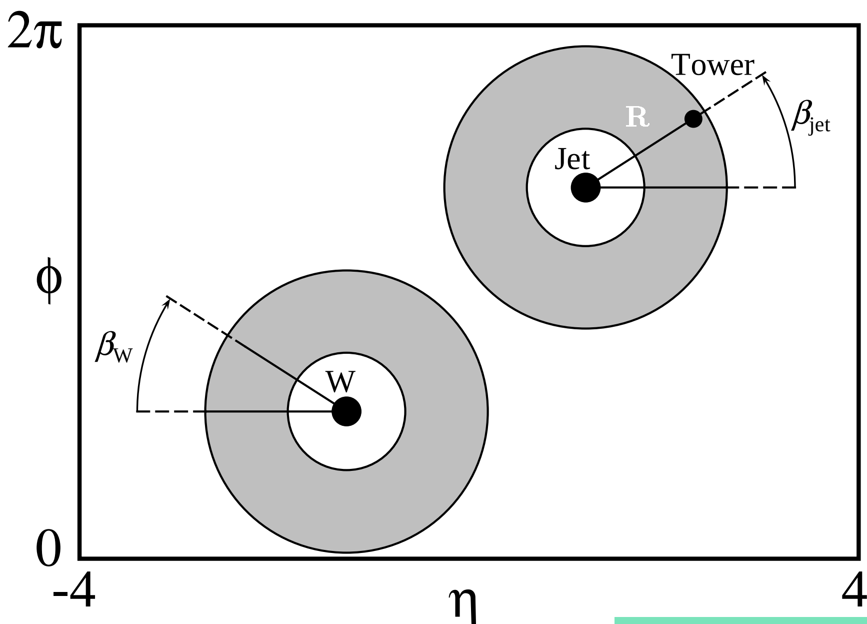
- HERWIG and JETRAD agree best with the data
- MC models w/o CC effects disagree with the data

W+Jet Analysis



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

Calorimeter view:



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 → π

β = 0 → "near beam", β = π → "far beam"

W + Jet - Monte Carlo Samples

- **PYTHIA v5.7 Monte Carlo**
  - Full detector simulation
  - Mimic noise by overlaying pedestal data
  - 3 samples with different color coherence:

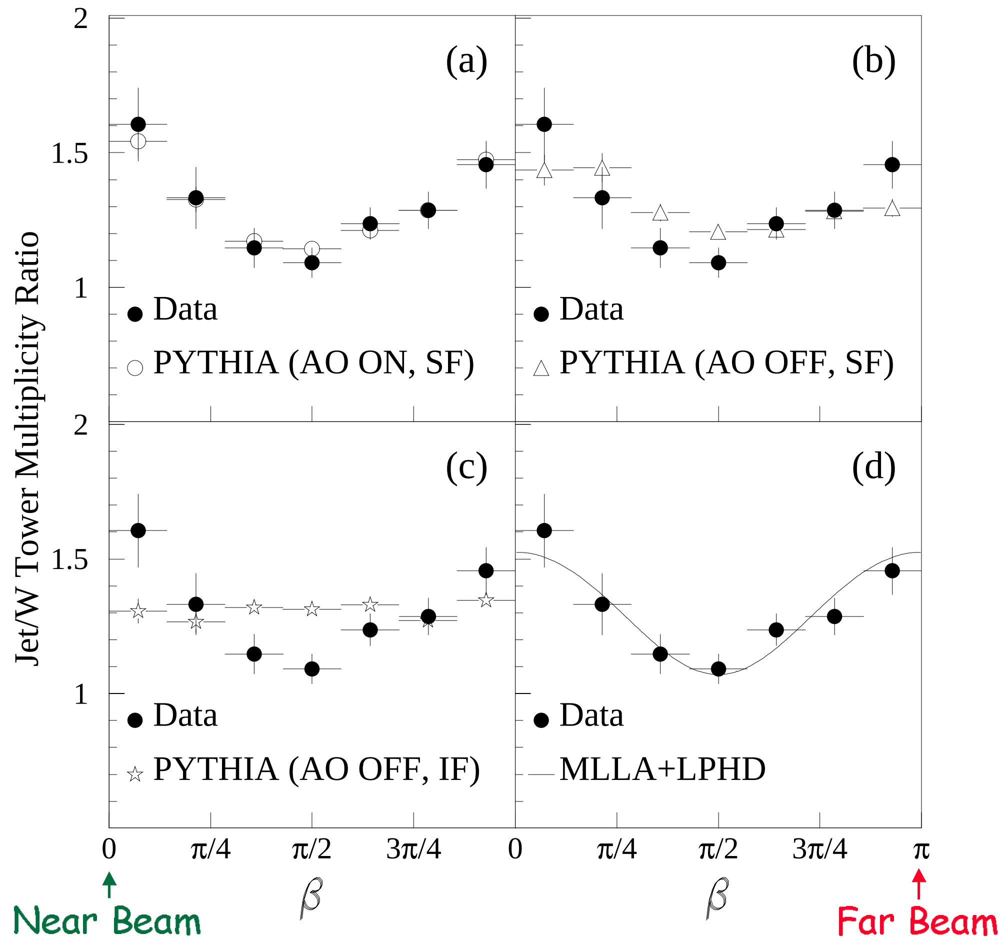
  "Full coherence": AO + String Fragmentation

  "Partial": No AO + String Fragmentation

  "No coherence": No AO + Independent Frag.

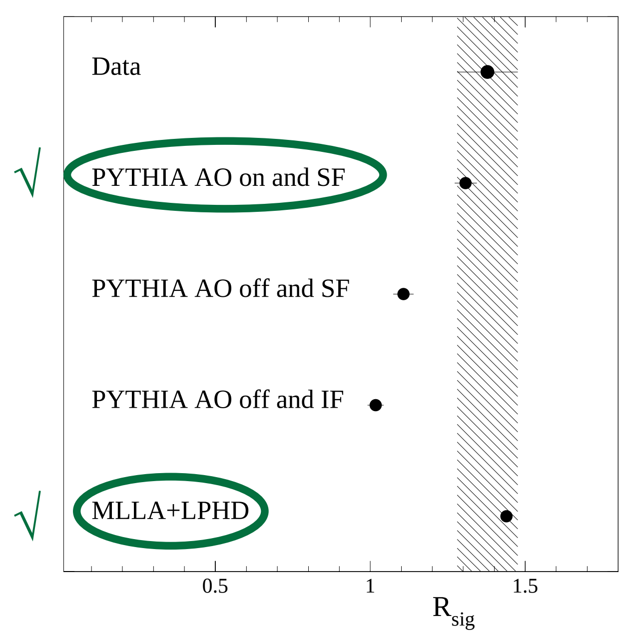
- **Analytic Predictions by Khoze and Stirling**
  - MLLA + LPHD
  - $q\bar{q}$–>Wg and qg–>Wq processes

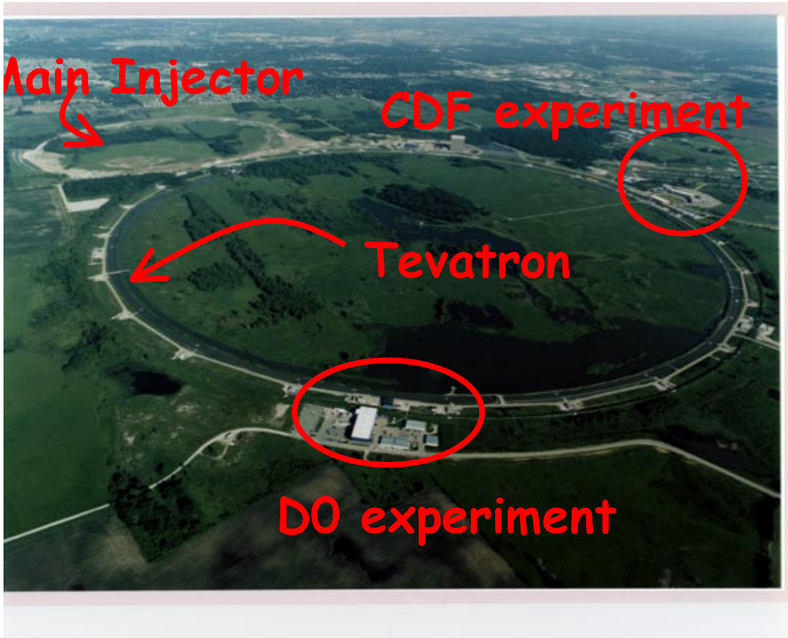
W+Jet Results



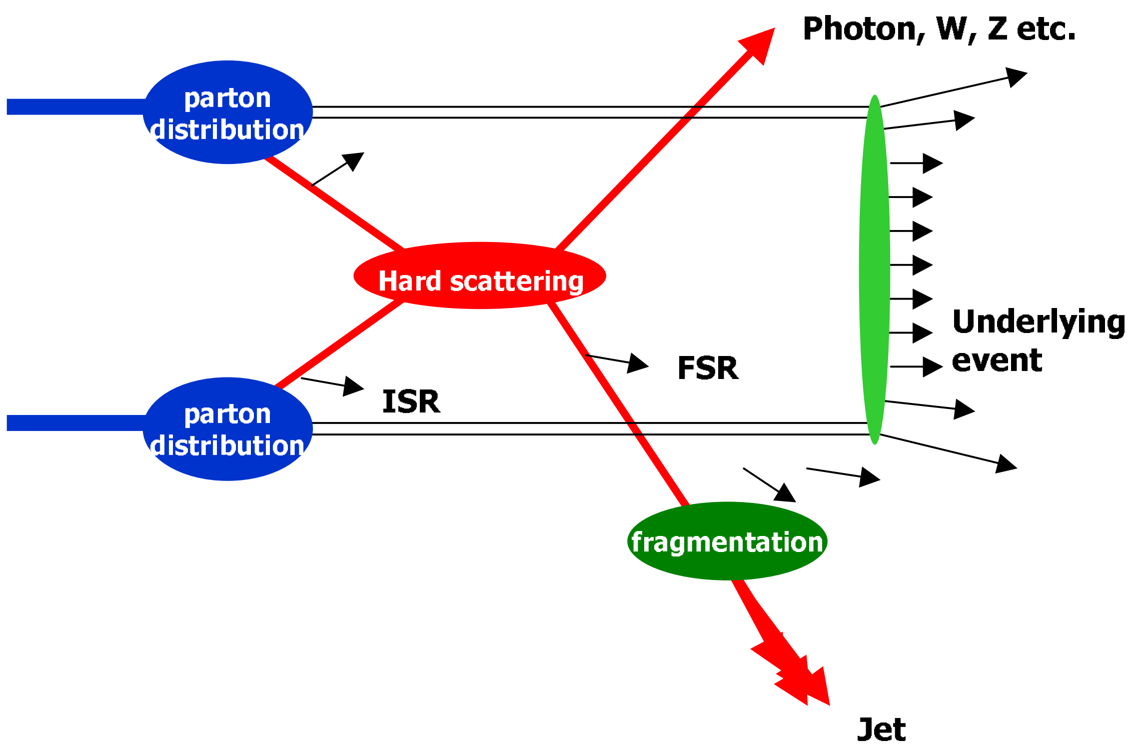
Plot the ratio or ratios

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





Jet Production



Jets at Tevatron

Motivation:

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

$$\boxed{\begin{aligned} & p_T^{\max} \sim 500\,GeV \\ & \Rightarrow \text{distance} \sim \frac{\hbar c}{p_T} \sim \frac{200\ \text{MeV}\cdot\text{fm}}{500\ \text{GeV}} \sim 10^{-19}\,m \end{aligned}}$$

- Search for new particles decaying into jet final states
- Precision studies of QCD
  - inclusive jet production
    - cross sections vs rapidity, cross sections at different CM energies, jet shapes, quark vs gluon jets...
  - dijet production
    - mass and triple differential cross sections, angular distribution, BFKL searches, diffraction...
  - multi-jets
    - cross sections, event topology, color coherence...
  - jets+vectror bosons (γ,W,Z)
    - cross sections, angular distributions, color coherence...

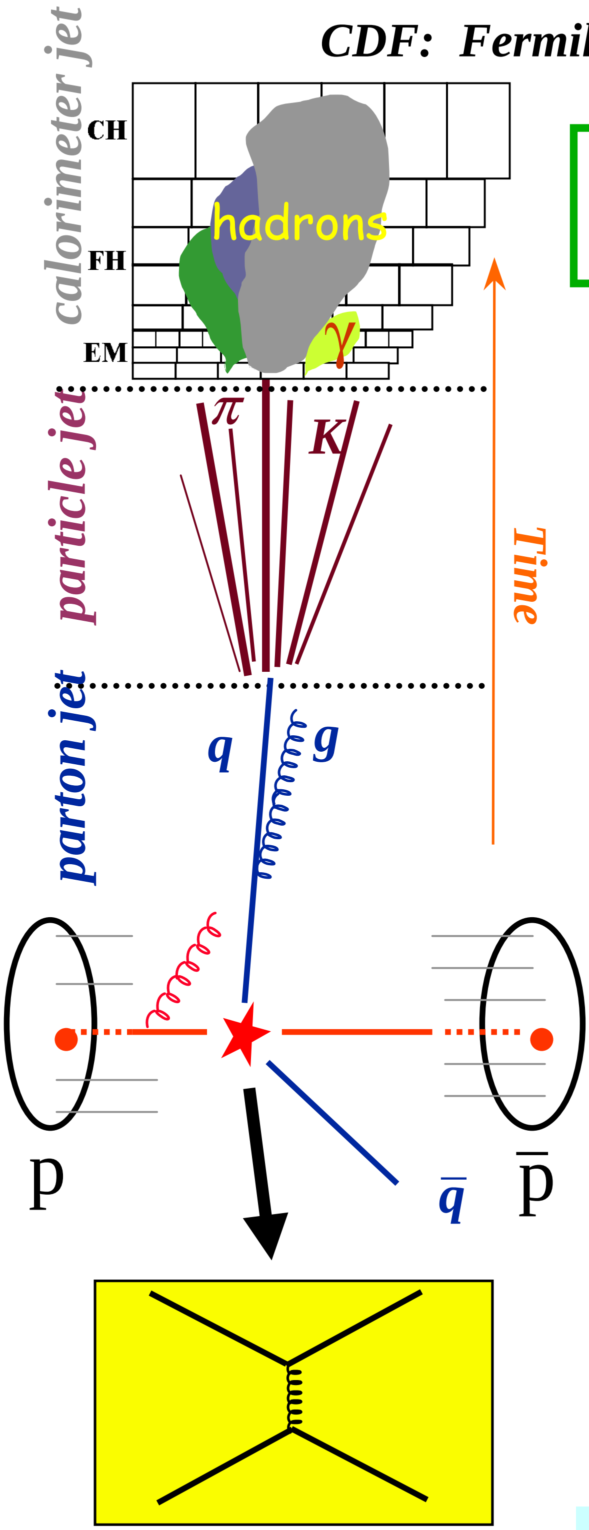
Challenges with Jets

- 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/Biases
- Jet Calibration
  - vs E, η
  - underlying event definition
- 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
  - simulation of underlying event
  - hadronization models
  - ...

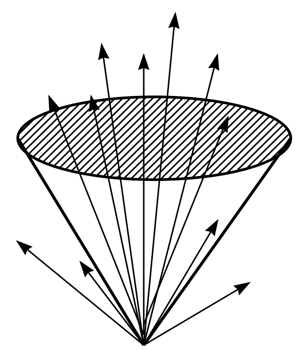
Jet Energy Scale

D0: NIM A424 352-392 (1999) (hep-ex/9805009)

CDF: Fermilab-Pub-01-008-E



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**

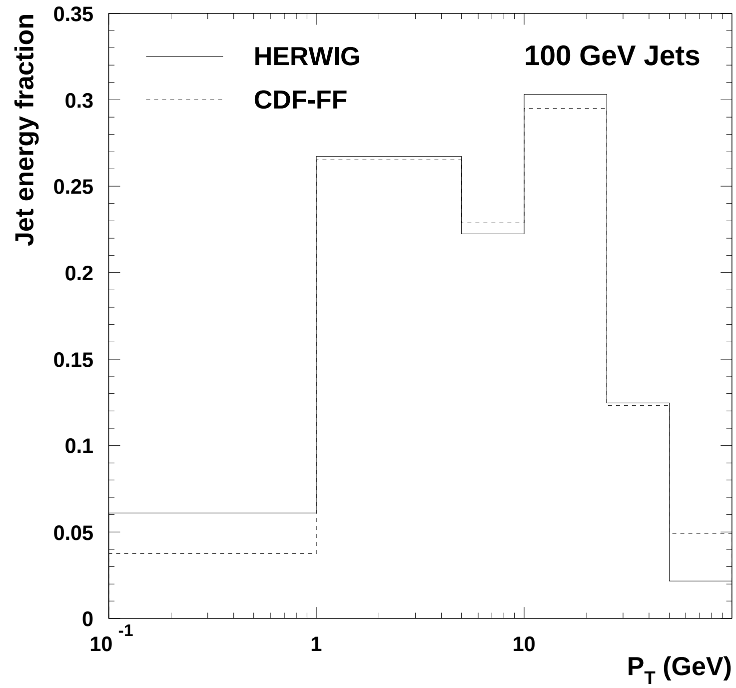
E_O **Offset (Ur noise, Mult. Int., pile-up, UE)**

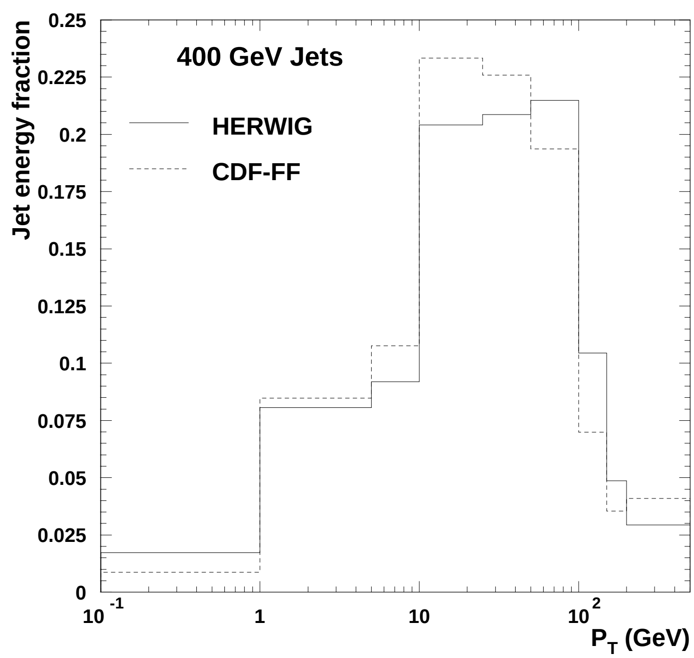
R_{jet} **Calorimeter Jet Response**

Measured in situ using γ – Jet P_T balance

R_{OOC} **Out of Cone Calorimeter Showering**

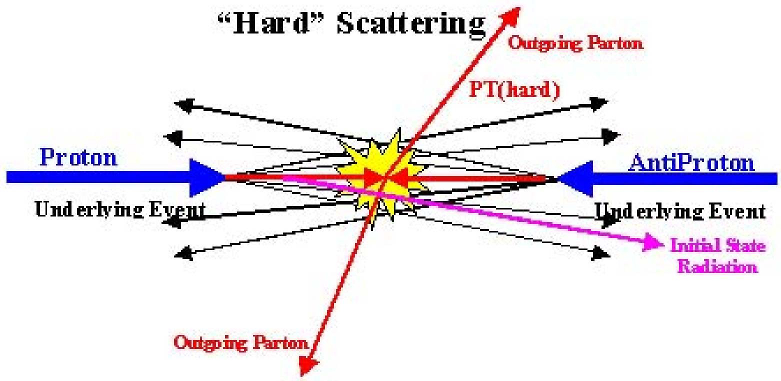
Particle p_T distribution in Jets





- 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)



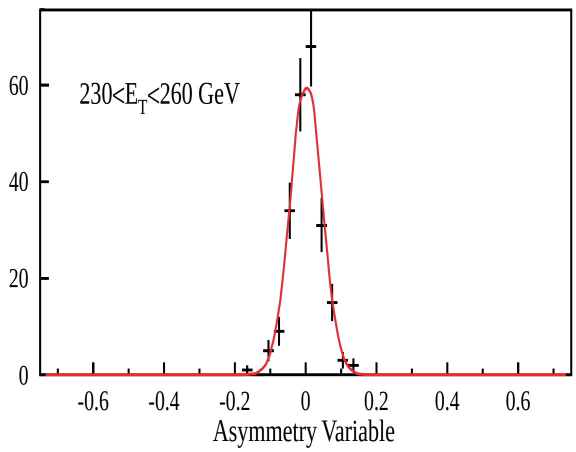
- The UE event is the ambient energy from fragmentation of partons not associated with the hard scattering
  - not well defined theoretically
- CDF:
  - measures underlying energy (UE+multiple interactions) under the jet cone from MB events as a function of number of vertices
  - comparison of underlying energy from MB events (scaled to the number of vertices in hard scatter data) to energy deposited $\pm$ 90^0 from leading jet in dijet events showed consistent result: 2.2 $\pm$ 0.7 GeV under central 0.7 cone jets
- DØ:
  - measures underlying event from MB events
  - underlying energy for central 0.7 cone jets: ~1-2 GeV (depending on luminosity)

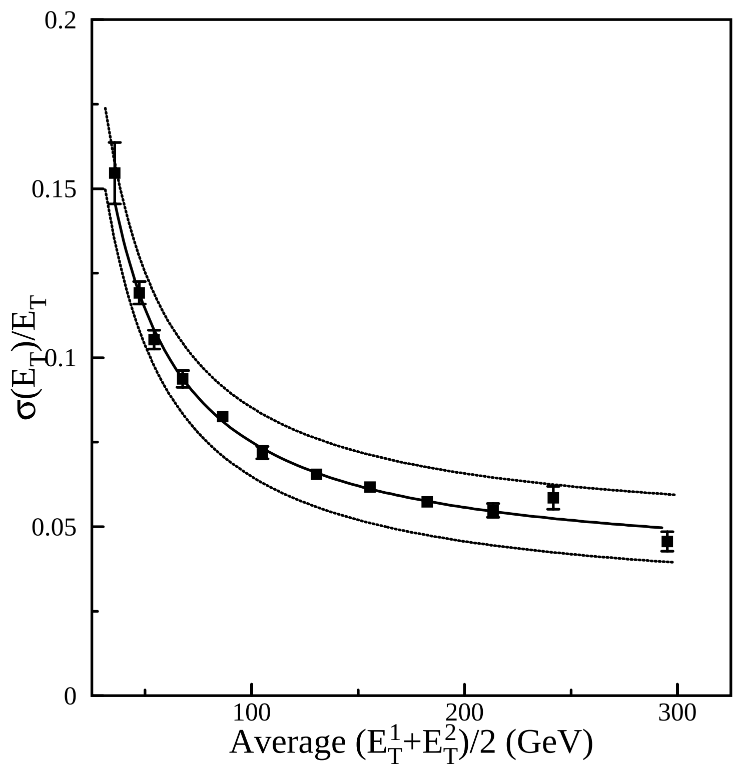
Jet Energy Resolution

- Measured from dijet collider data using E_T balance:

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

In the limit of no soft radiation



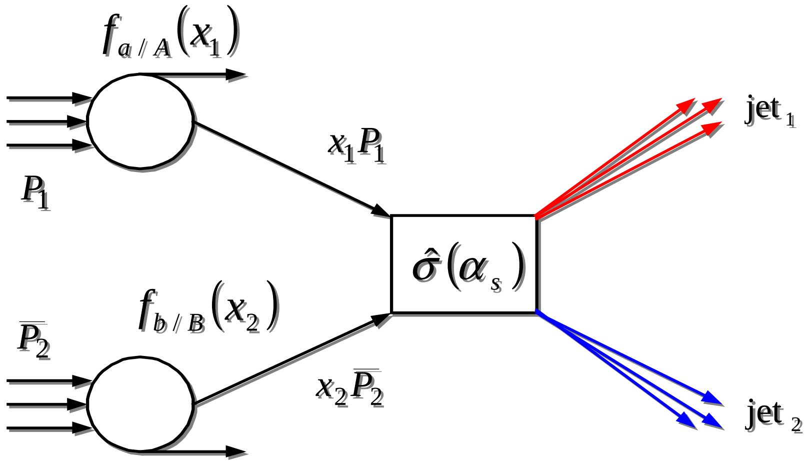


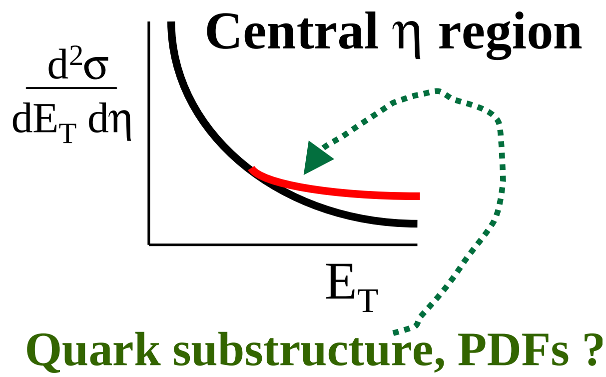
- Unsmearing procedure:
  - convolute "true cross section" $f(E_T)$ with a Gaussian smearing

$$\boxed{F(E_T) = \int \frac{1}{\sqrt{2\pi\sigma}} e^{\frac{-(E'_T - E_T)^2}{2\sigma^2}} \cdot f(E'_T)\, dE'_T} \quad \boxed{f(E'_T) = AE'^{-B}_T\left(1 - \frac{2E'_T}{\sqrt{s}}\right)^C}$$

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

Inclusive Jet Cross Section



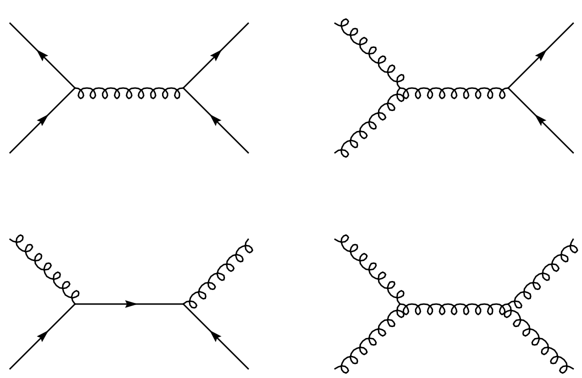


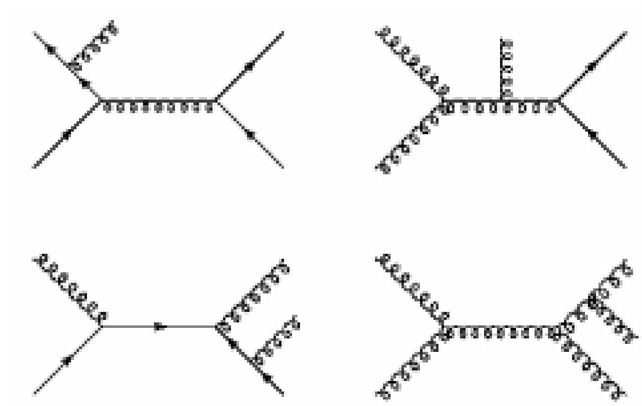
$$\frac{d\sigma}{dP_T} \approx \sum_{a,b} \int dx_a\, f_{a/A}(x_a,\mu) \int dx_b\, f_{b/B}(x_b,\mu)\, \frac{d\hat{\sigma}}{dP_T}$$

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

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

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





$\boxed{\text{Test of pQCD}}$

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

Jets from thrust / coarse clustering

1982-3:AFS - Direct Evidence… $\sqrt{s}$ = 63 GeV, Jet CS @ y=0
qualitative comparison w/ gluon models in pdf's
" " - Further Evidence…
UA2 - Observation of… $\sqrt{s}$ = 540 GeV, Jet CS @ h=0
qualitative comparison w/ QCD calc. (Horgan&Jacob)
AFS - Jet CS at $\sqrt{s}$ = 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 @ $\sqrt{s}$ = 1.8 & 0.63 TeV, NLO QCD

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

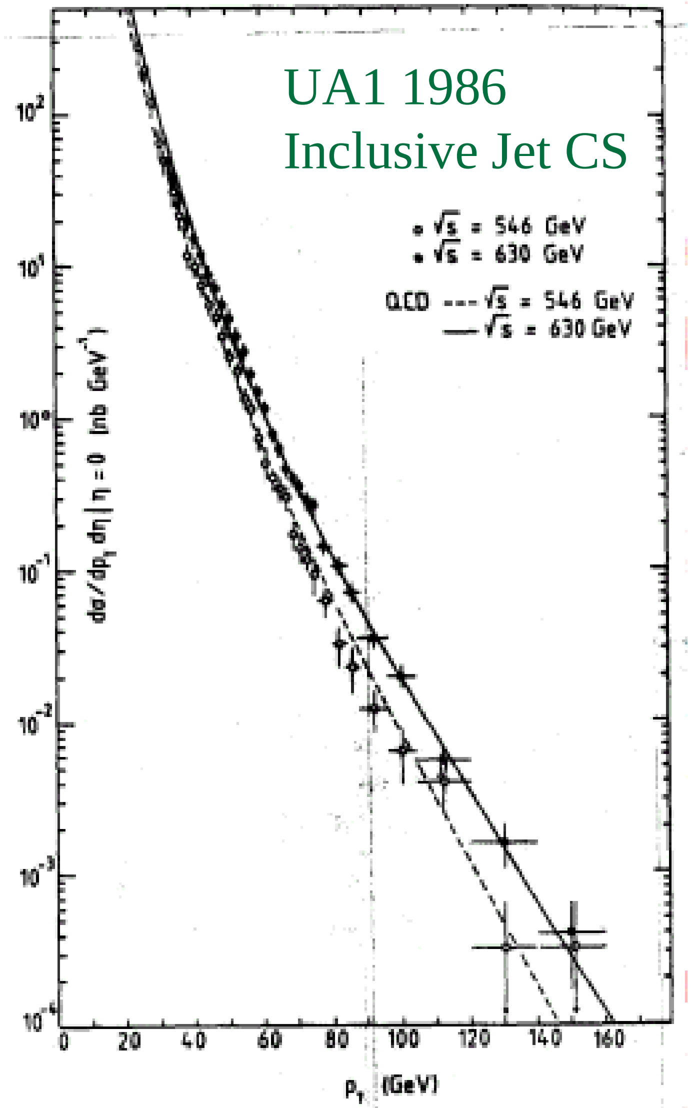
$\Delta E_T \rightarrow E_T$ **bin size** $\quad \varepsilon \rightarrow$ **selection efficiency**

$\Delta\eta \rightarrow \eta$ **bin size** $\quad L \rightarrow$ **inst. Luminosity**

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

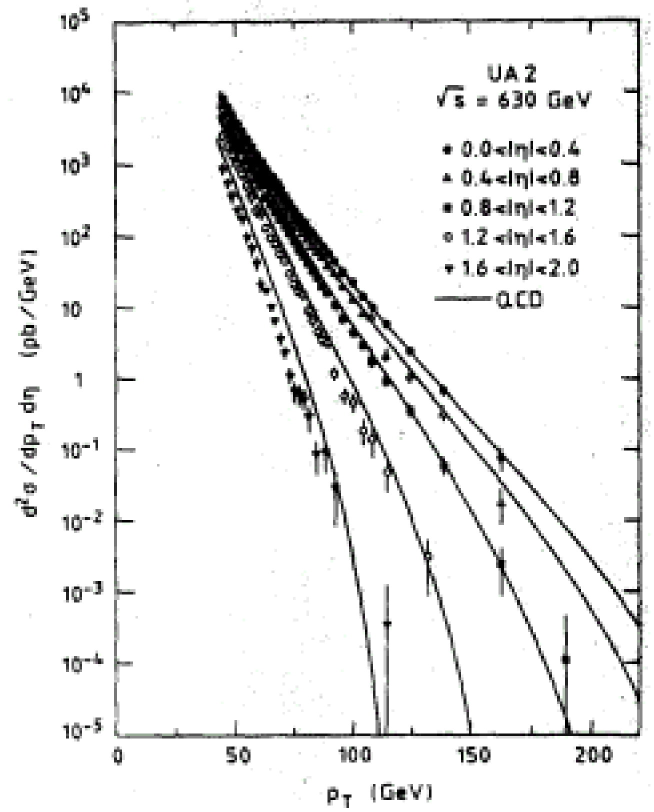
The old days…

UA1 1986
Inclusive Jet CS



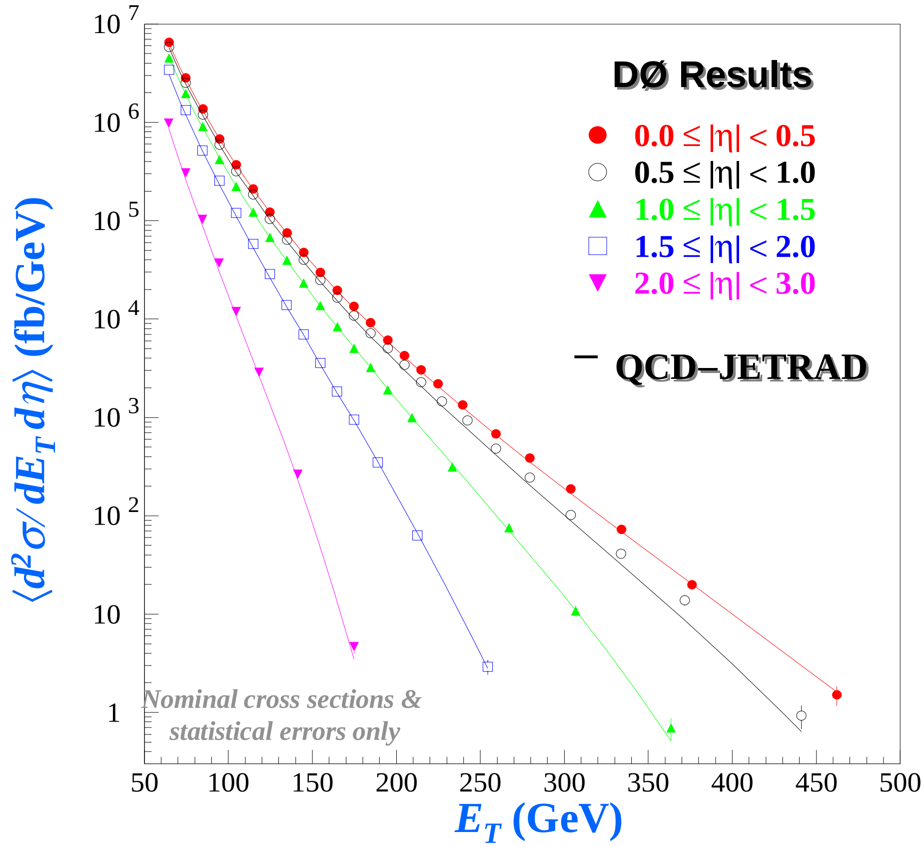
Uncertainties ~ 70% on CS:
 ±50% accept./jet corr (smearing)
 ±40% calib ±10% aging ±15% Lum
Λ_C > 400 GeV *"Exp and theo. Uncerts. taken in to account"*

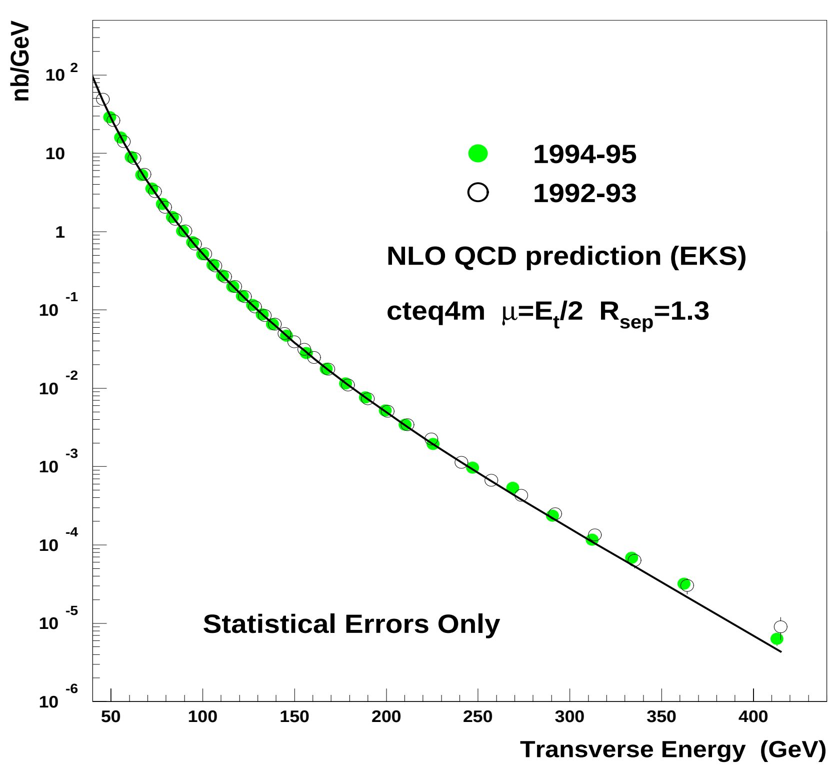
UA2 1991
Inclusive Jet CS



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"*

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





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

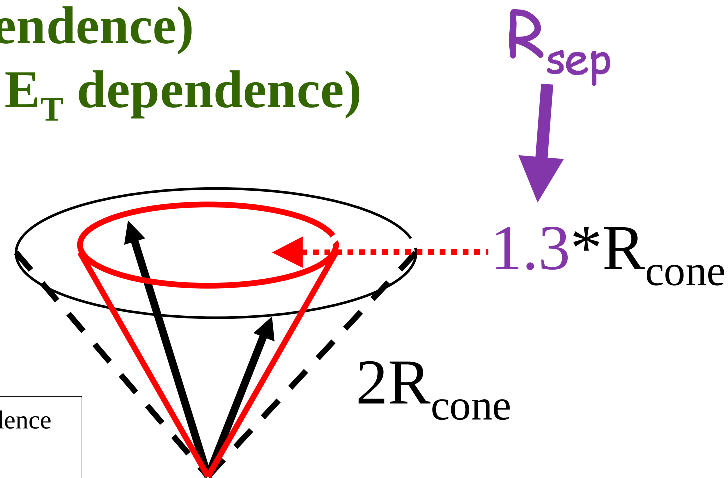
- **Choices (hep-ph/9801285, Eur. Phys. J. C. 5, 687 1998):**

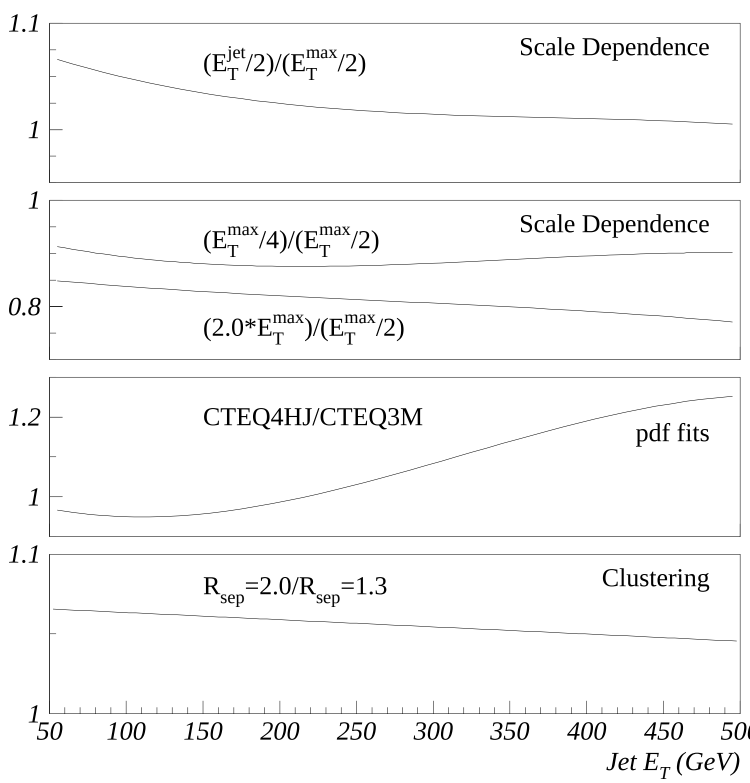
  Renormalization Scale (10%)

  PDFs (~20% with E_T dependence)

  Clustering Alg. (5% with E_T dependence)

Jet Clustering Algorithm at NLO



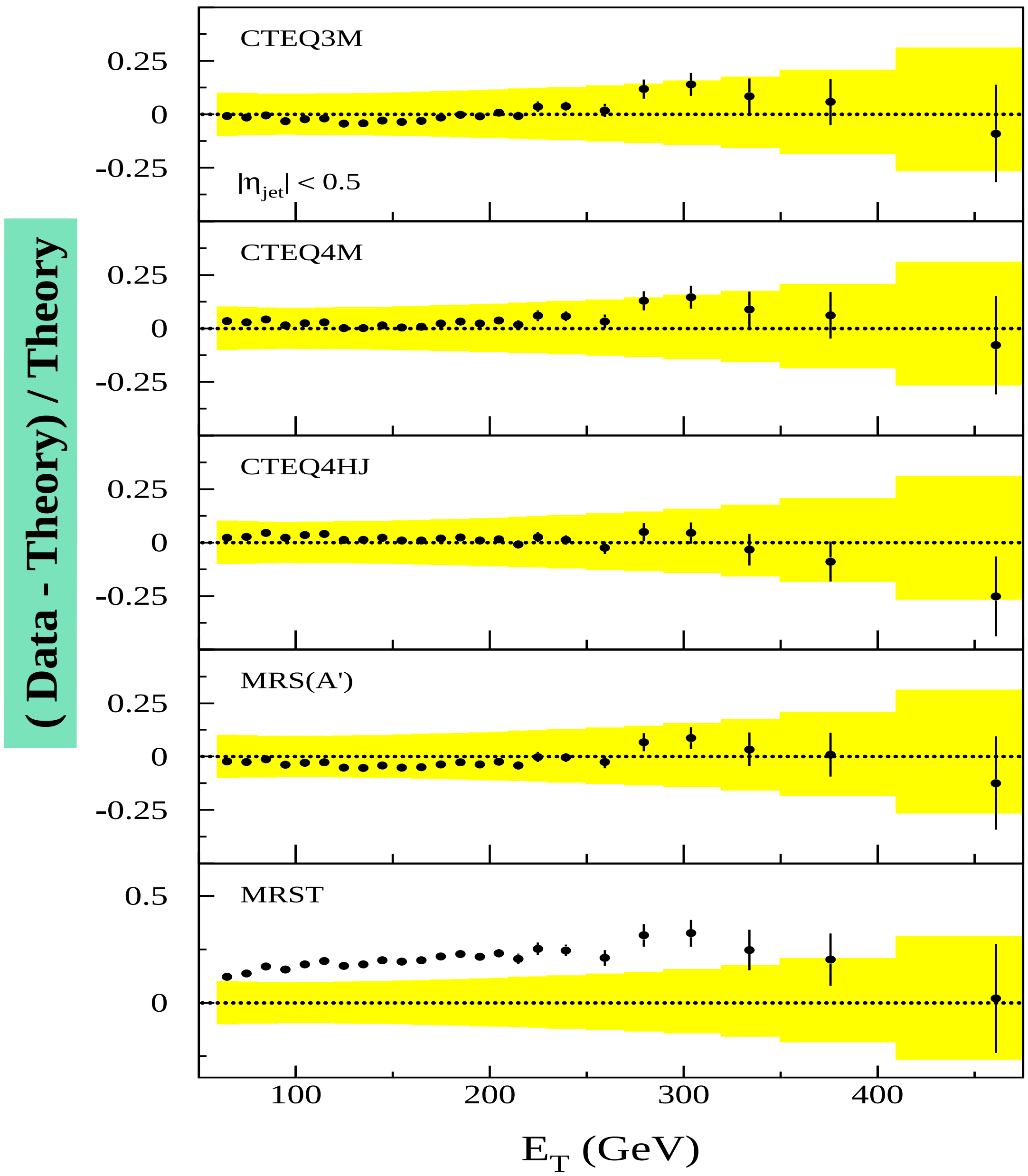


DØ uses: JETRAD
$\mu = 0.5E_T^{Max}$, $R_{sep}=1.3$

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

Data vs Theory

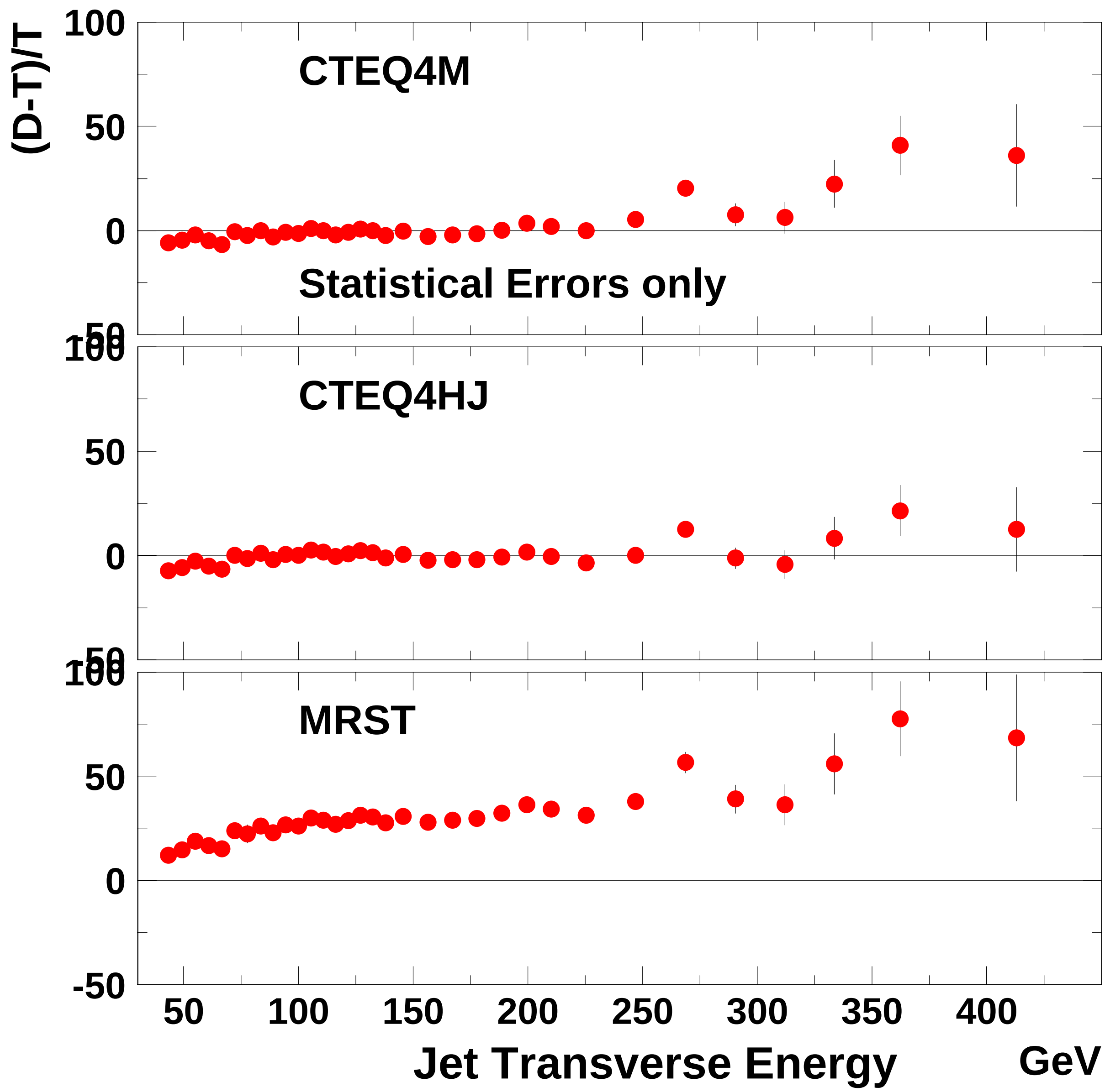
JETRAD : $\mu = 0.5E_T^{Max}$, R_{sep}=1.3



QCD prediction agrees excellently with data for jets out to 450 GeV (half of beam energy), over 7 orders of magnitude !

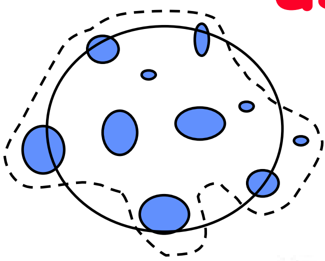
Data vs Theory

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

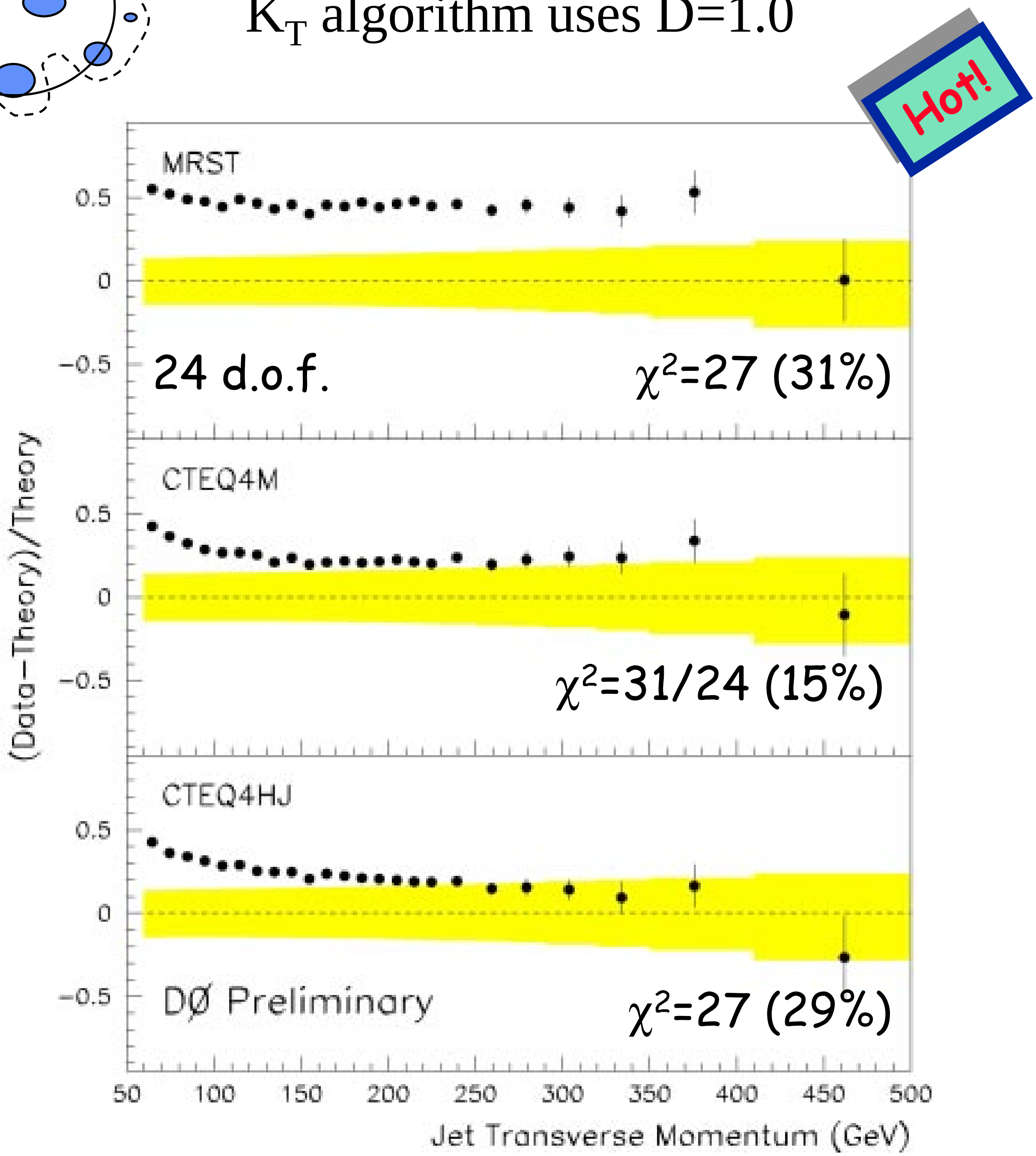


Result is sensitive to high-x gluon density

Inclusive Jet Cross Section using the K_T algorithm

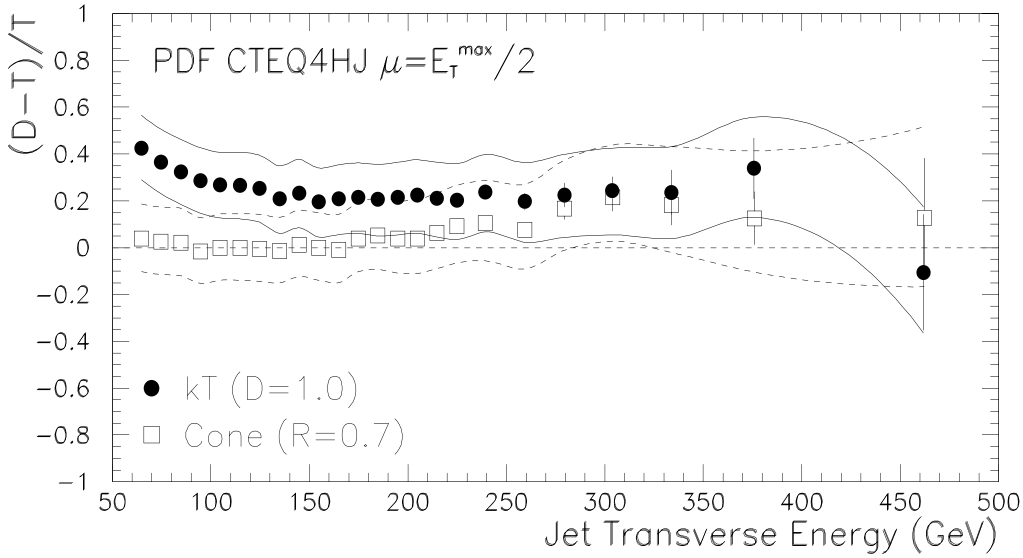


K_T algorithm uses D=1.0



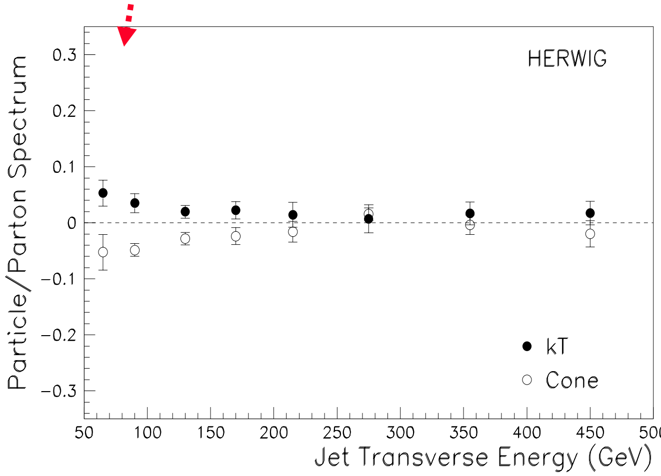
Differences with NLO theory mostly at low E_T

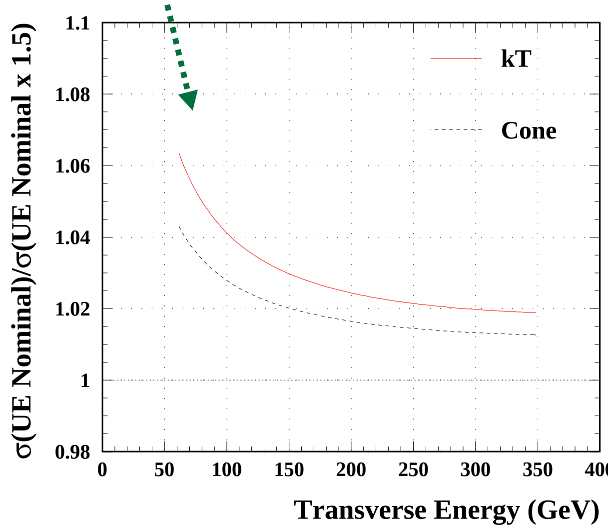
More on K_T Jet Cross Section



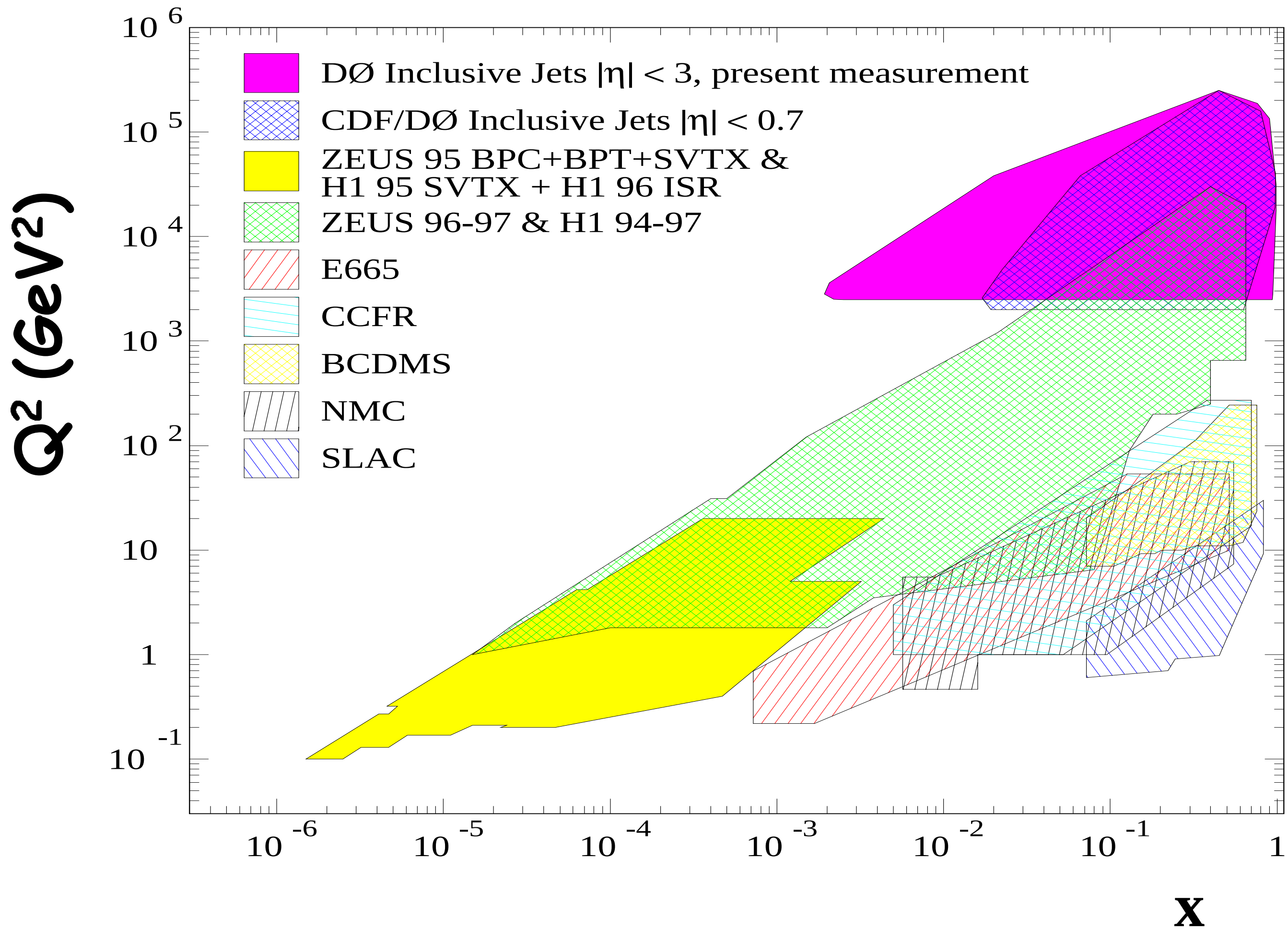
NLO cross sections with K_T (D=1) and Cone (R=0.7, R_{sep}=1.3) jets agree!

- K_T jets cluster more energy than cone
- The difference between NLO (or cone) and K_T jet cross sections is partly due to:
  - hadronic showering effects (parton to particle)
  - potential uncertainties in the definition of underlying event





Tevatron X-Q^2 Reach

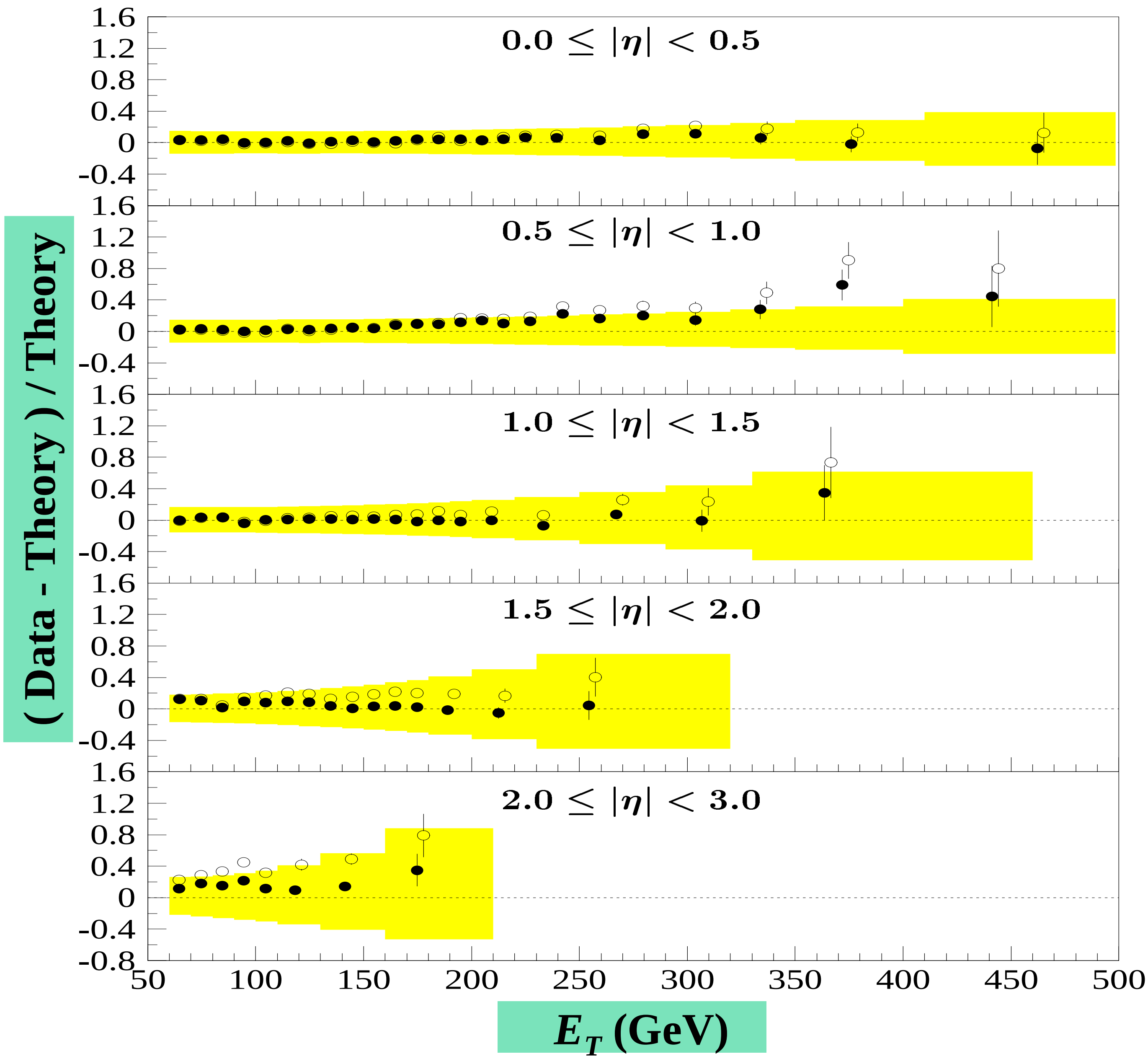


Tevatron data overlaps and extends reach of DIS

Rapidity Dependence of Inclusive Jet Cross Section

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

$R_{sep} = 1.3$



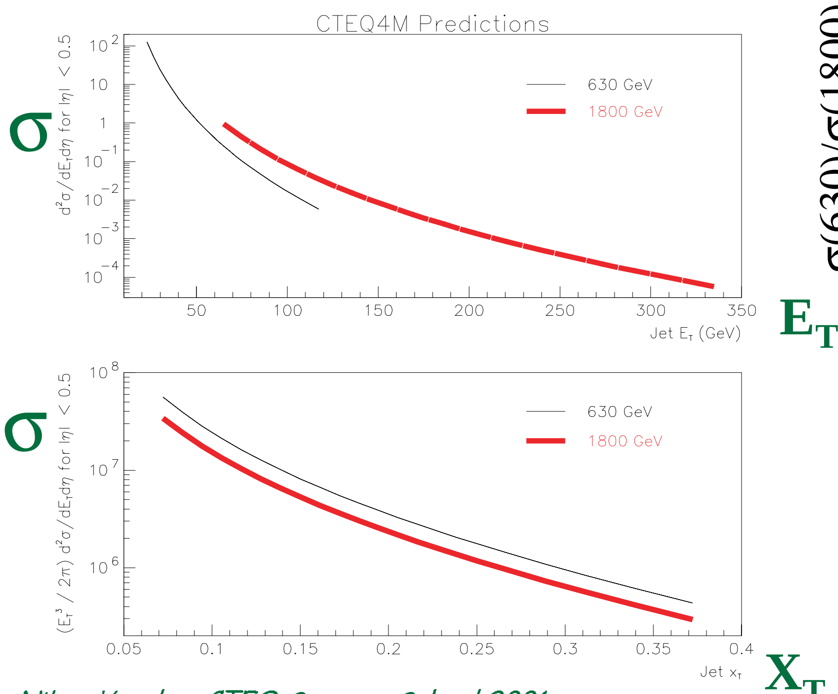
Good agreement with NLO QCD

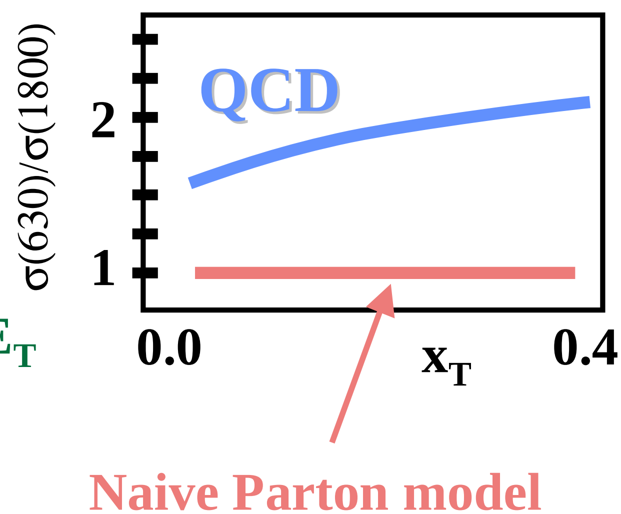
Inclusive Jet Cross Section Ratio: σ(630)/σ(1800) vs X_T

- **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**
  - Ratio allows subrtantial reduction in uncertainties (in theory and experiment)

$$\boxed{E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^4} f(x_T) \quad \text{where } x_T = \frac{2p_T}{\sqrt{s}}}$$

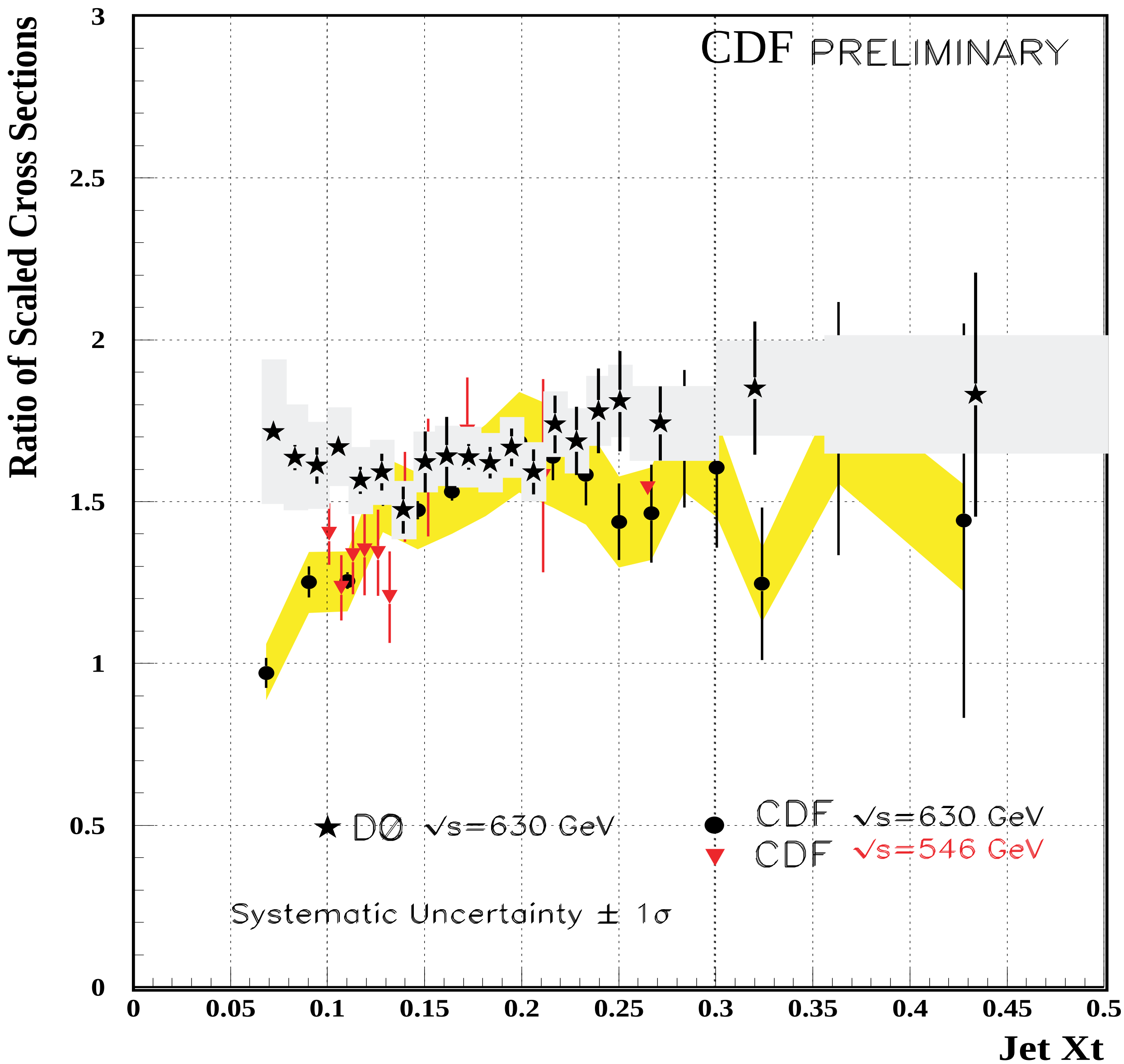
$$R(x_T) \equiv \frac{p_T^4 \cdot E\dfrac{d^3\sigma}{dp^3}(\sqrt{s} = 630\text{ GeV})}{p_T^4 \cdot E\dfrac{d^3\sigma}{dp^3}(\sqrt{s} = 1800\text{ GeV})} \sim 1 + \text{scaling violating terms}$$





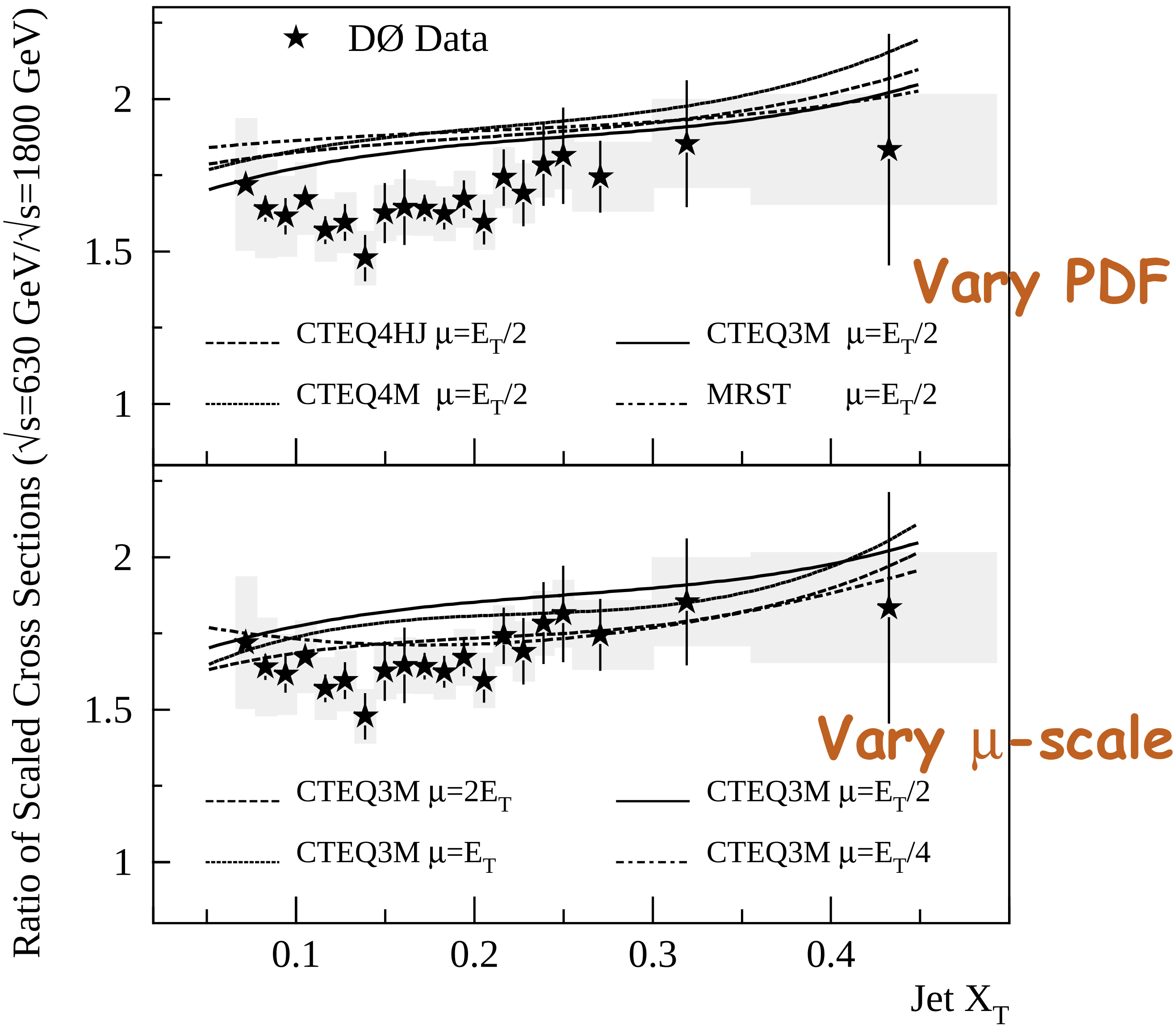
$\sigma(630)/\sigma(1800)$ vs X_T

- DØ and CDF both measure the ratio of cross sections 630/1800 GeV



- **Consistent at high x_T, possible discrepancy at low values**

$\sigma(630)/\sigma(1800)$ vs X_T



- Uncertainties due to PDF's are significantly reduced in the ratio
- Better agreement with NLO QCD in shape than in normalization

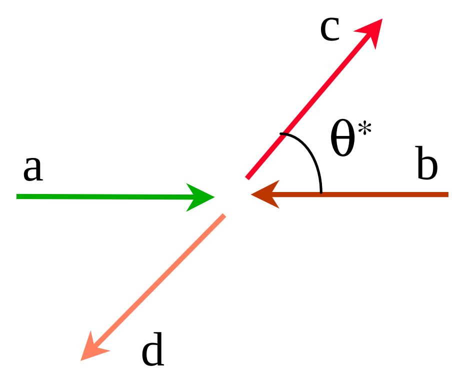
PDF	χ^2 (20 dof)	Prob(%)
CTEQ3M	20.5	42.5
CTEQ4M	22.4	31.9
CTEQ4HJ	21.0	40.0
MRST	22.2	33.0

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)



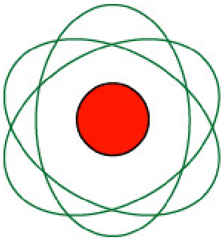
$$\frac{d\hat{\sigma}}{d\cos\theta^*} \approx \frac{1}{\left(1-\cos\theta^*\right)^2}$$

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

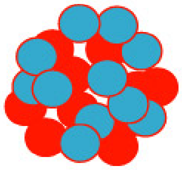
- **Dominant subprocesses have very similar shape for $d\hat{\sigma}/d\cos\theta^*$ with different weights:**

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

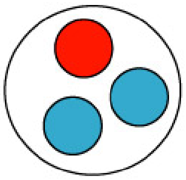
Angular Distributions –> Sensitive to Hard Scatter Dynamics



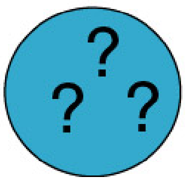
Search for Quark Substructure



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



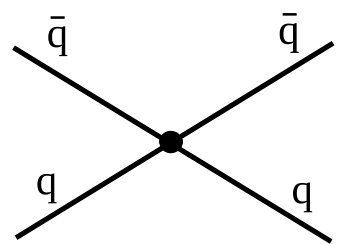
Compositeness Scale: Λ_c



$\Lambda_c = \infty$ –> 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]

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

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

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

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

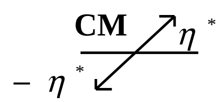
Angular Distributions –> Quark Substructure

- QCD is dominated by ~ $1/(1-\cos\theta^*)^2$
- Contact interactions by ~ $(1+\cos\theta^*)^2$

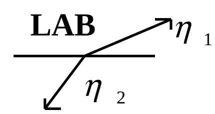
⟶ From $\cos\theta^*$ variable to χ

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

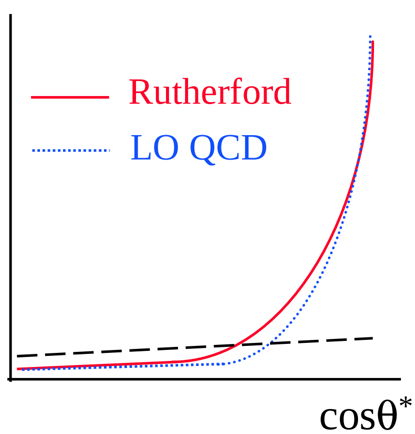
$$\chi = e^{2|\eta^*|} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



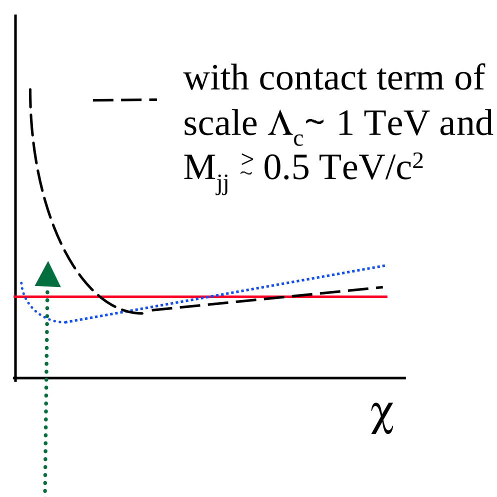
$\Rightarrow$



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



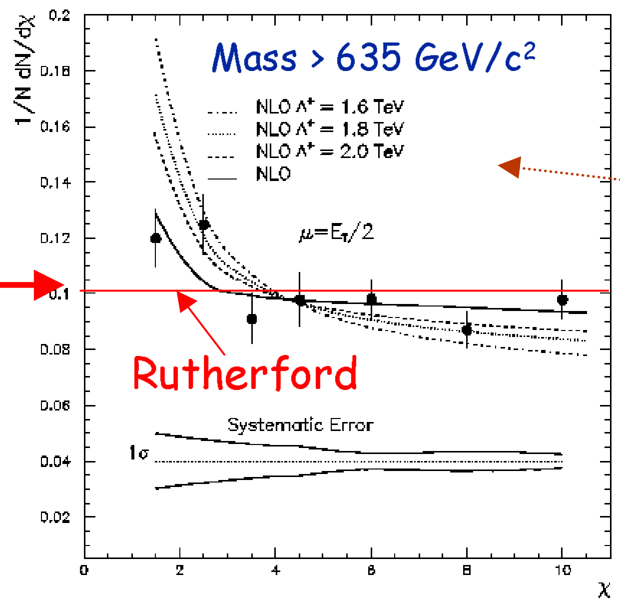
$\Rightarrow$

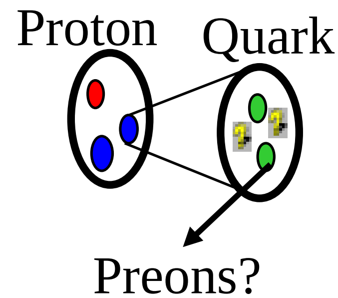


$dN/d\chi$ sensitive to contact interactions

Limits of Quark Substructure

Dijet Angular Distributions



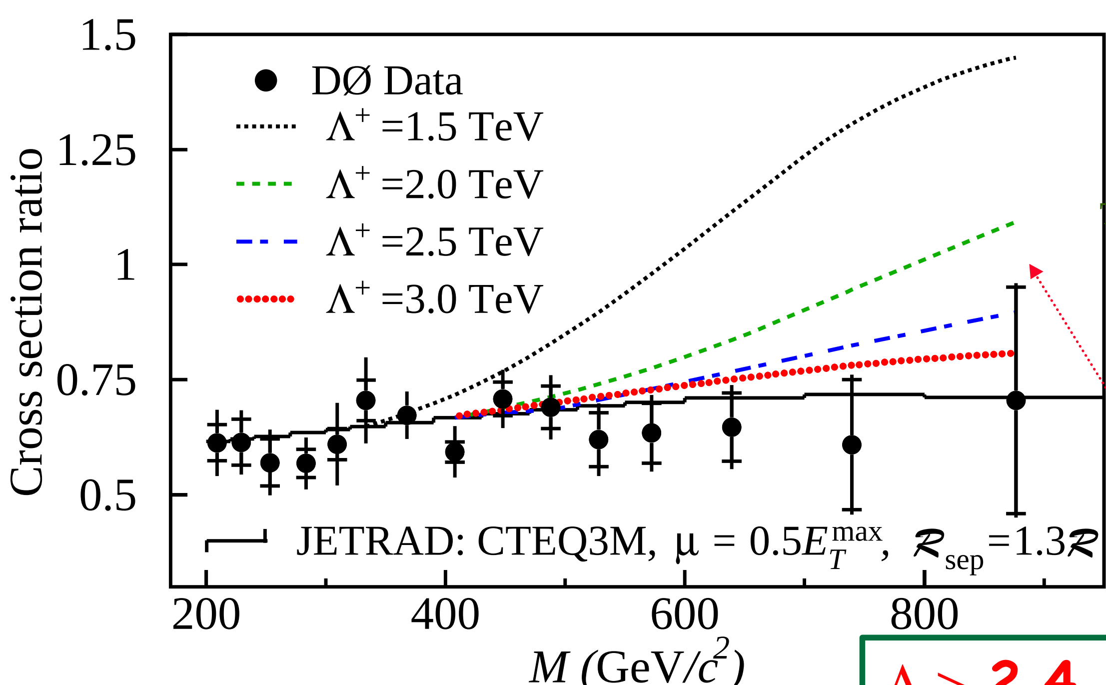


95% CL Compositeness Limit:

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

Dijet Mass Cross Section Ratio

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



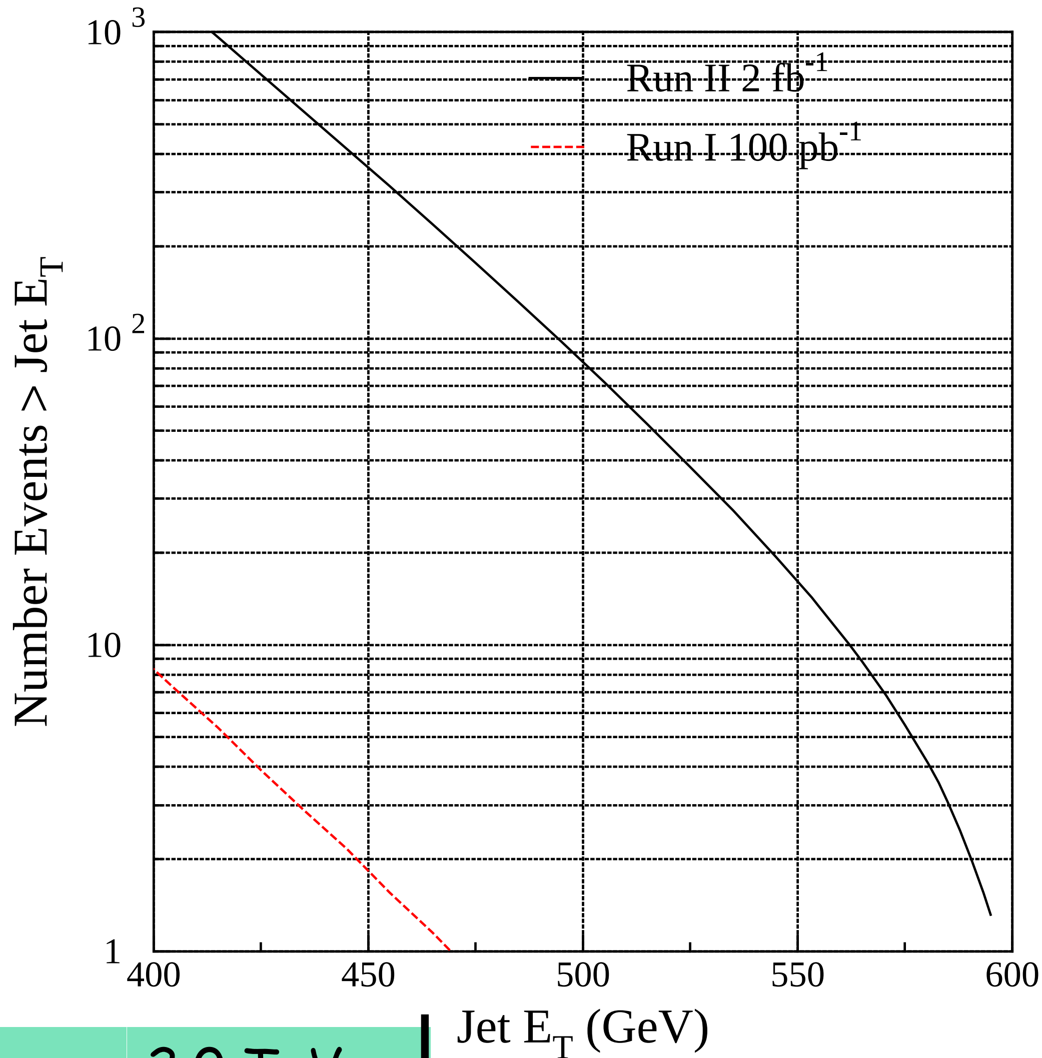
Systematic Uncertainty ~ 8%

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

NLO QCD in good agreement with data

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

Looking Ahead: Tevatron Run II



$\sqrt{s}$	2.0 TeV
Luminosity	2×10^{32}
$\int Ldt$	2-30fb^{-1}

Run commenced March 2001

Detector Commissioning taking place!

Physics data in autumn

First results in early 2002

Run II:

~100 events ET > 490 GeV

~1K events ET > 400 GeV

Run I:

16 Events E_T> 410 GeV

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

Final Remarks

- Testing QCD typically means testing our ability to calculate within QCD
  - Our perturbative tools are working well, especially at moderate to high scales
- Experimental results have recently reached or exceeded the accuracy of theoretical predictions
  - need for NNLO calculations for jet production
- We need more theoretical and experimental effort to understand the underlying event & hadronization effects
  - don't subtract UE out from jet energies?
  - how to deal with haronization?
- Tevatron Run II has started:

  BIG Opportunity for QCD