Lectures on Jet Physics

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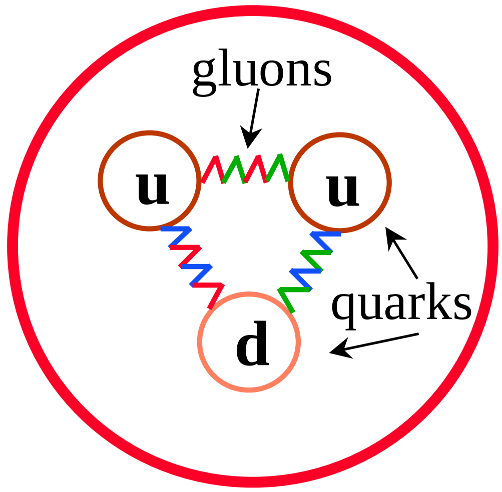
Outline

- Introduction
  - QCD
  - Processes under study
  - Kinematics
  - Event generators
  - What is a Jet
- Review of Jet Algorithms
- Jet Characteristics
  - Jet energy profile
  - Differences between Quark and Gluon jets
  - Color coherence
- Jet Production
  - Jets at Tevatron
  - Jets at HERA
- Final Remarks

Quantum ChromoDynamics (QCD)

QCD : Theory of Strong Interactions

Proton



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
- Gluons carry color and can interact to each other - very important difference from QED - from Abelian to non-Abelian theory
- At large distances: quark-quark interactions are large (quark confinement)

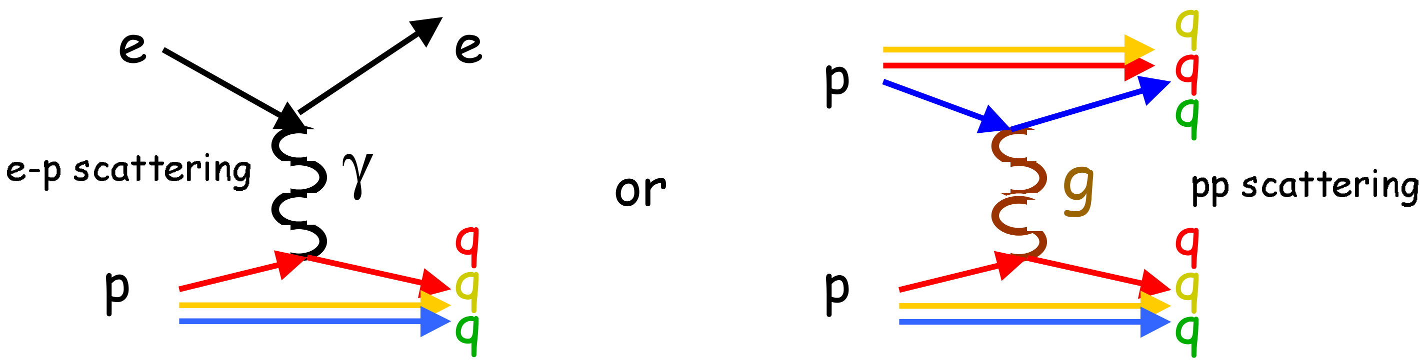
  At small distances: quark-quark interactions are small (asymptotic freedom)

Coupling constant ~ α_s (analogous to α in QED)

Free particles do not carry color

Dynamical Evidence for Quarks in Hadrons

Scattering processes involving the proton reveal pointlike particles with quark properties (spin 1/2; charges 2/3 or -1/3) (Friedman, Kendall, Taylor et al.)



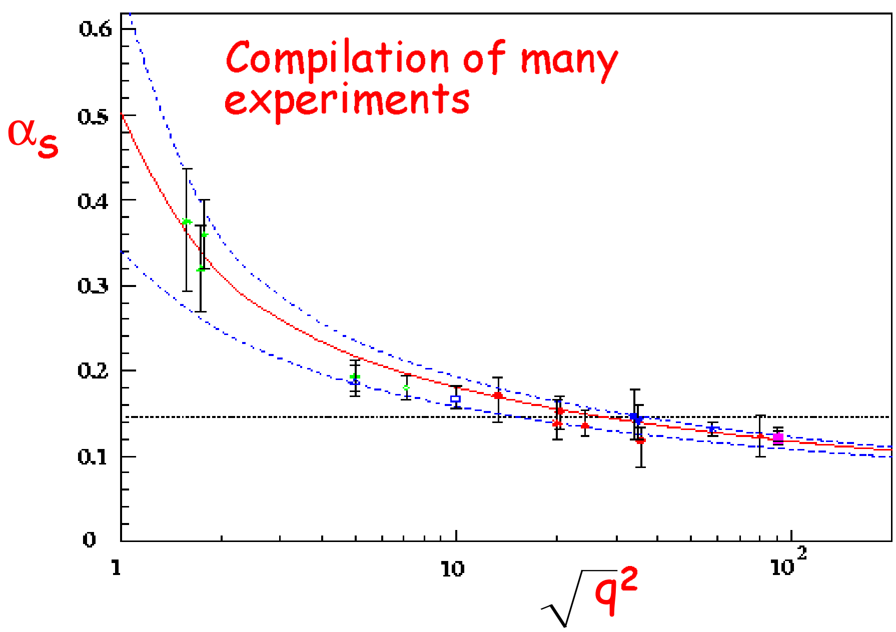
Experiments similar to Rutherford scattering showing pointlike nucleus! see pointlike constituents with essentially $1/\sin^4(\theta/2)$ behavior: (with spectator quarks not participating)

The "Running" α_s

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

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

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: **jets**

Historic Perspective of QCD

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)

← Discovery of the b-quark (FNAL)

PETRA

← 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

← Next to Leading Order pQCD predictions for jet
production

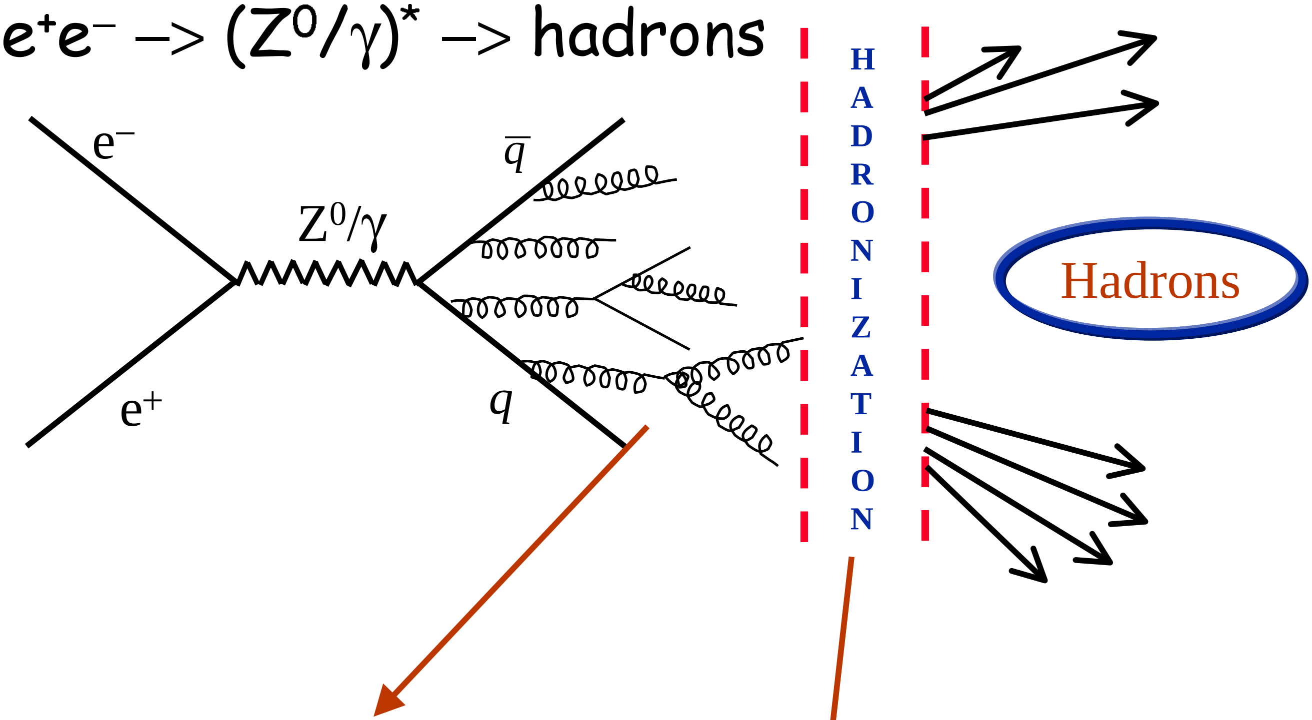
D0

← Discovery of the t-quark (FNAL)

e^+e^- Annihilations

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

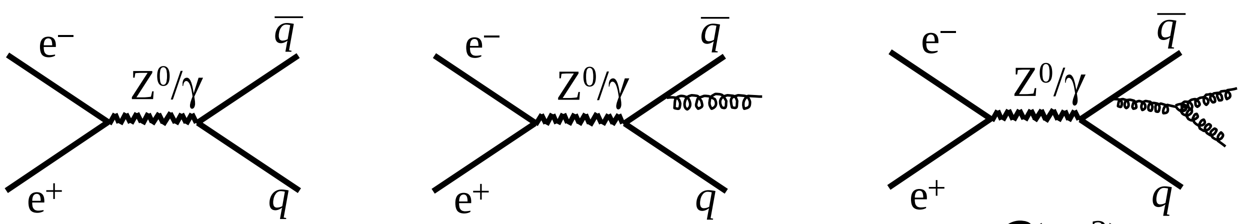
$e^+e^- \rightarrow (Z^0/\gamma)^* \rightarrow$ hadrons



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

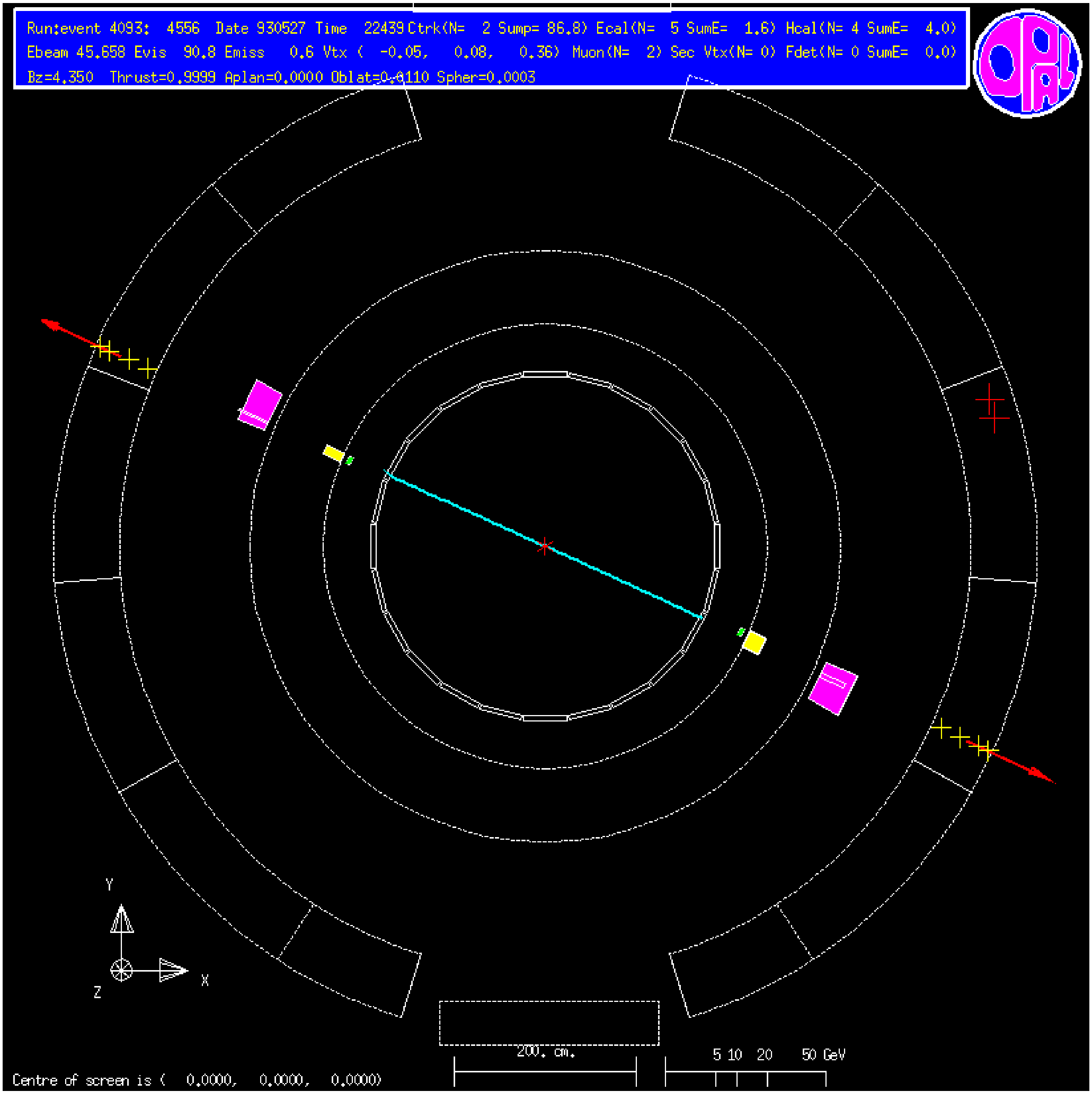
Non-perturbative phase
$\alpha_s\geq 1$

Fixed Order QCD

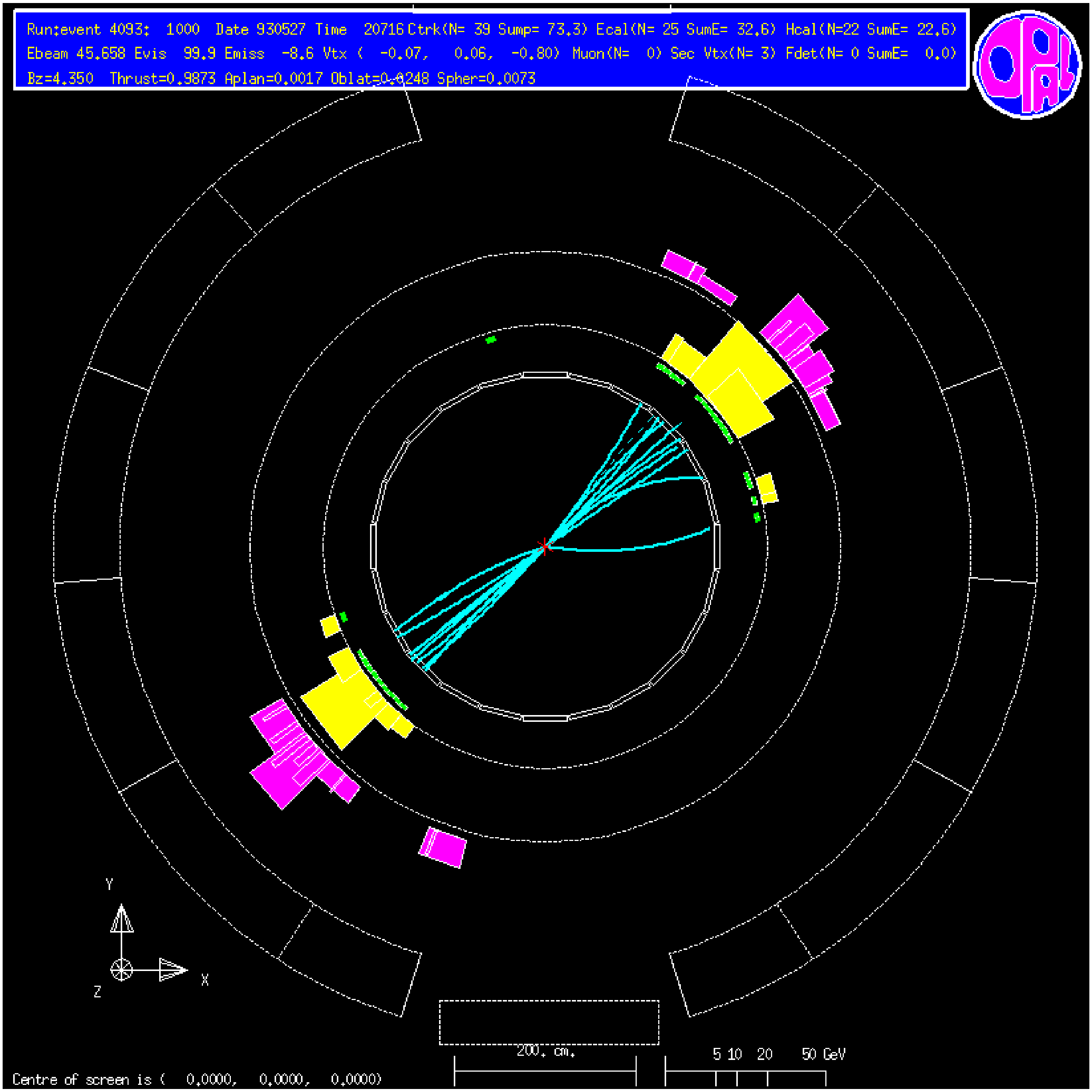


$\mathcal{O}(\alpha_s^0)$ $\mathcal{O}(\alpha_s^1)$ $\mathcal{O}(\alpha_s^2)$

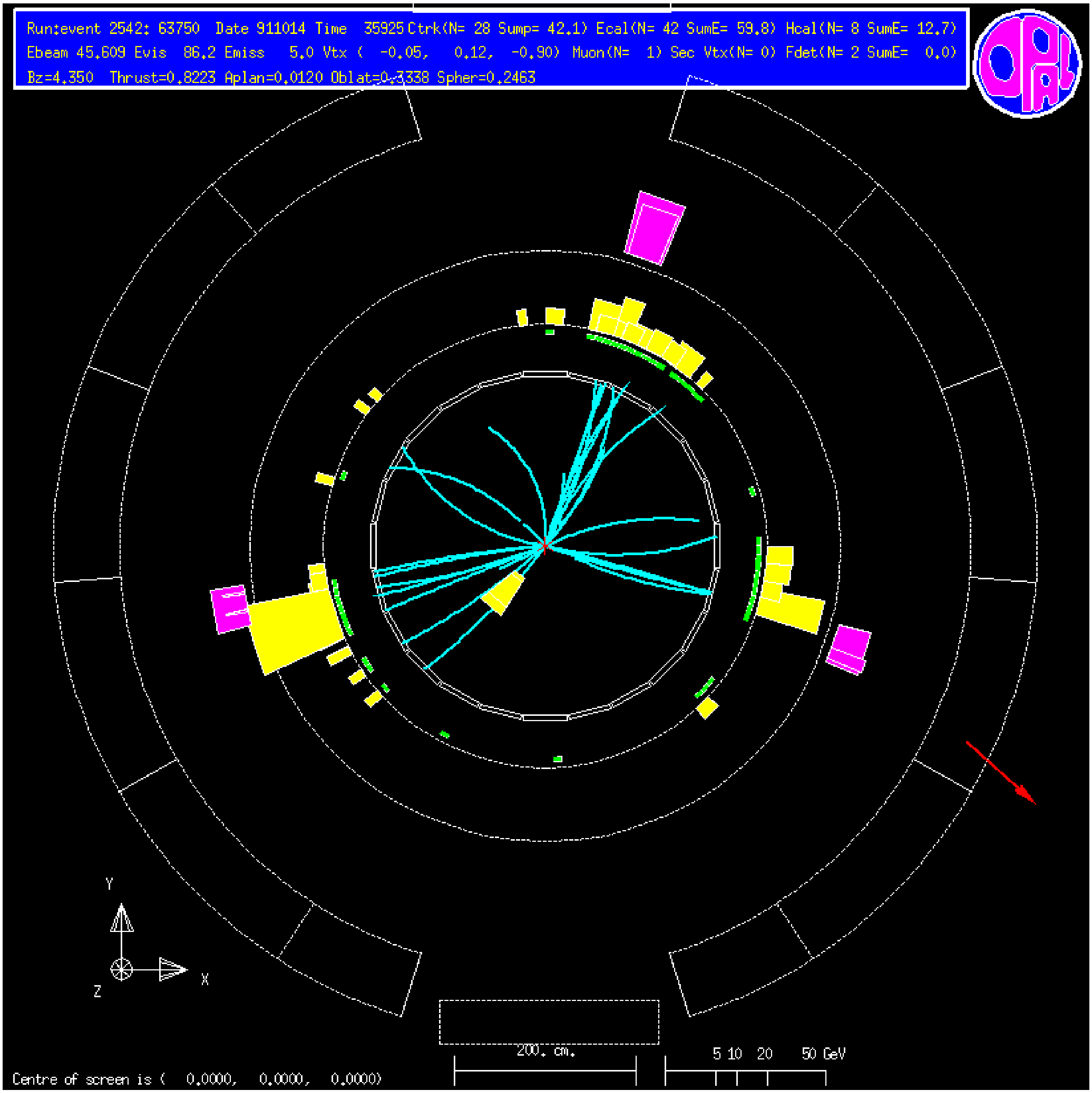
$e^+e^- \rightarrow \mu^+\mu^-$



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

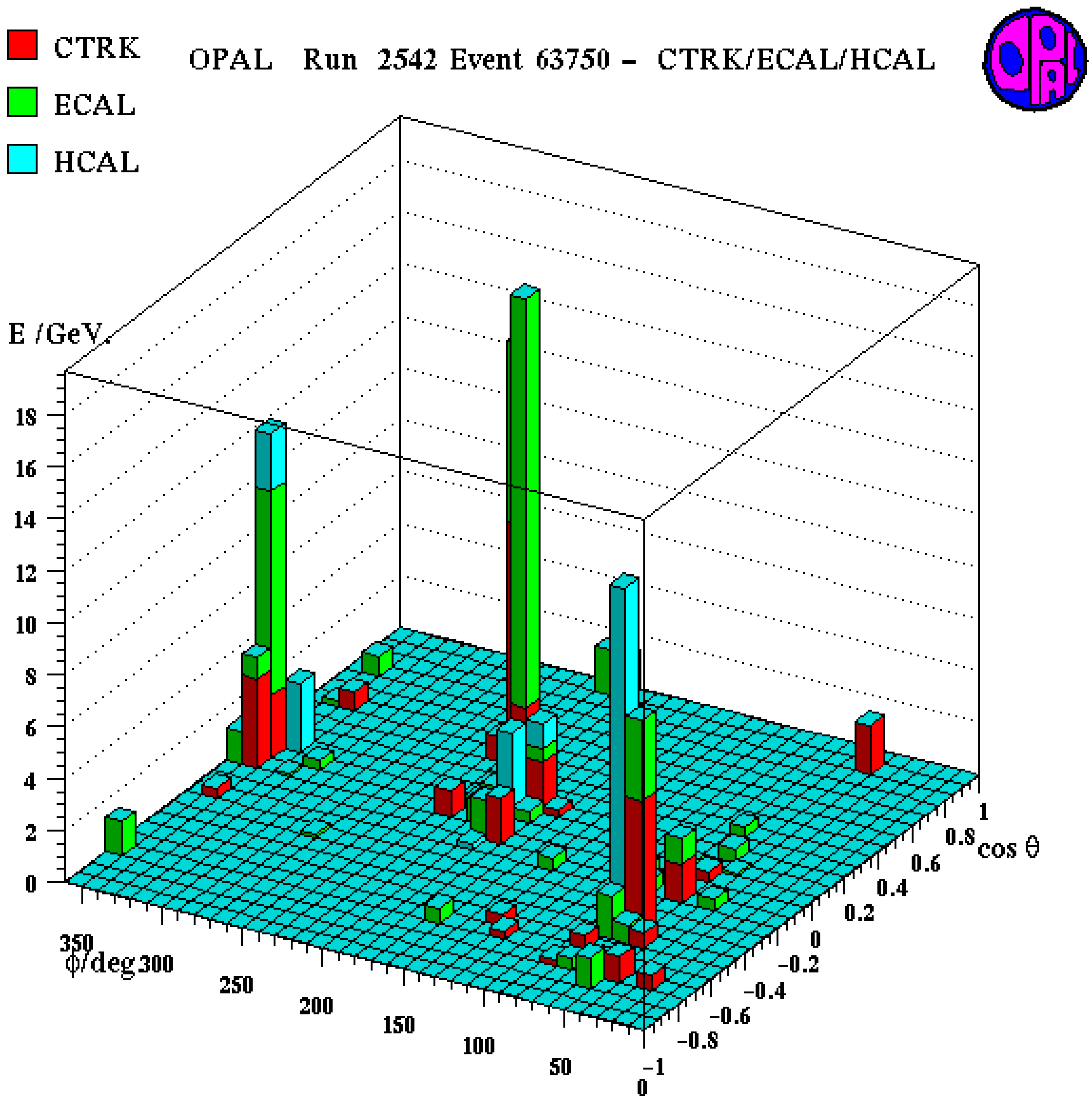


e^+e^- –> $q\bar{q}g$



Run:event 2542: 63750 Date 911014 Time 35925 Ctrk(N= 28 Sump= 42.1) Ecal(N= 42 SumE= 59.8) Hcal(N= 8 SumE= 12.7)
Ebeam 45.609 Evis 86.2 Emiss 5.0 Vtx (-0.05, 0.12, -0.90) Muon(N= 1) Sec Vtx(N= 0) Fdet(N= 2 SumE= 0.0)
Bz=4.350 Thrust=0.8223 Aplan=0.0120 Oblat=0.3338 Spher=0.2463
Y
Z
X
200. cm.
5 10 20 50 GeV
Centre of screen is (0.0000, 0.0000, 0.0000)

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


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
-1
-0.8
-0.6
-0.4
-0.2
0
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0.6
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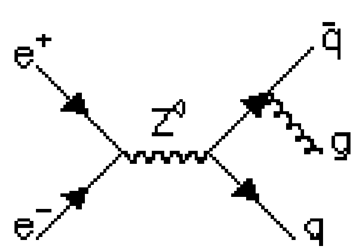
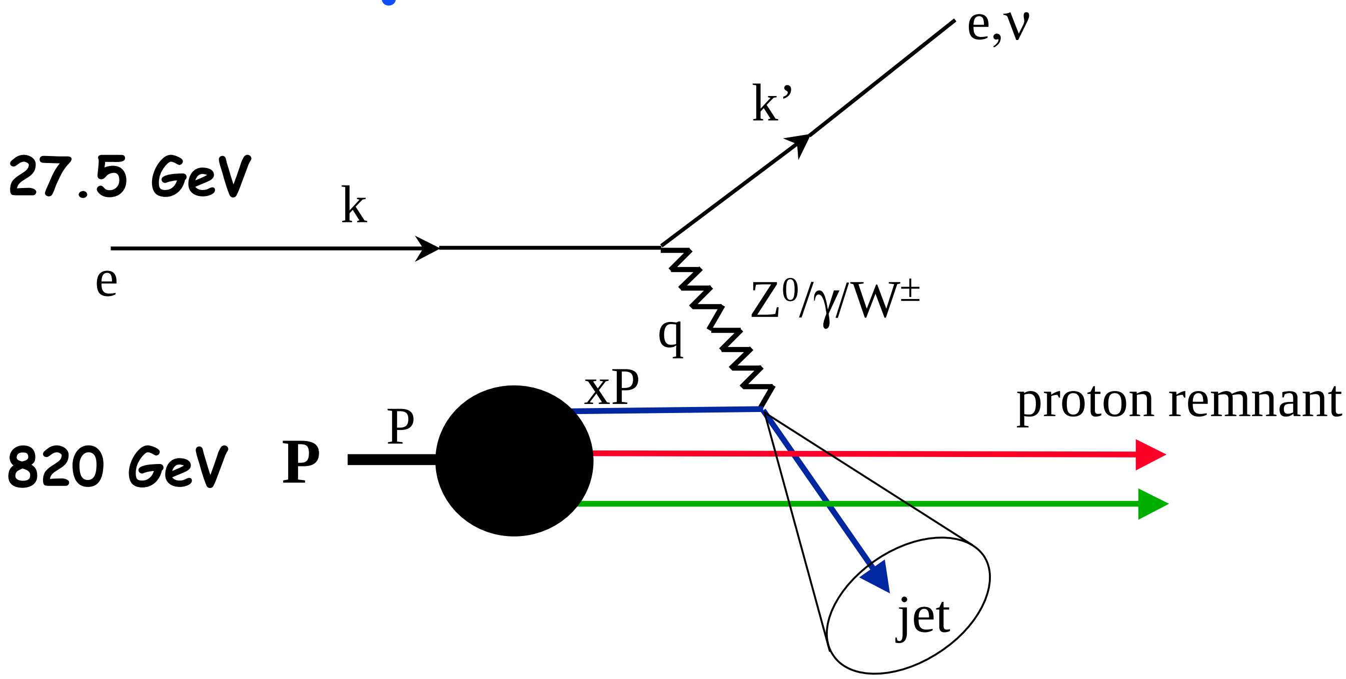
1
cos θ


e+
e−
Z0
q̄
g
q

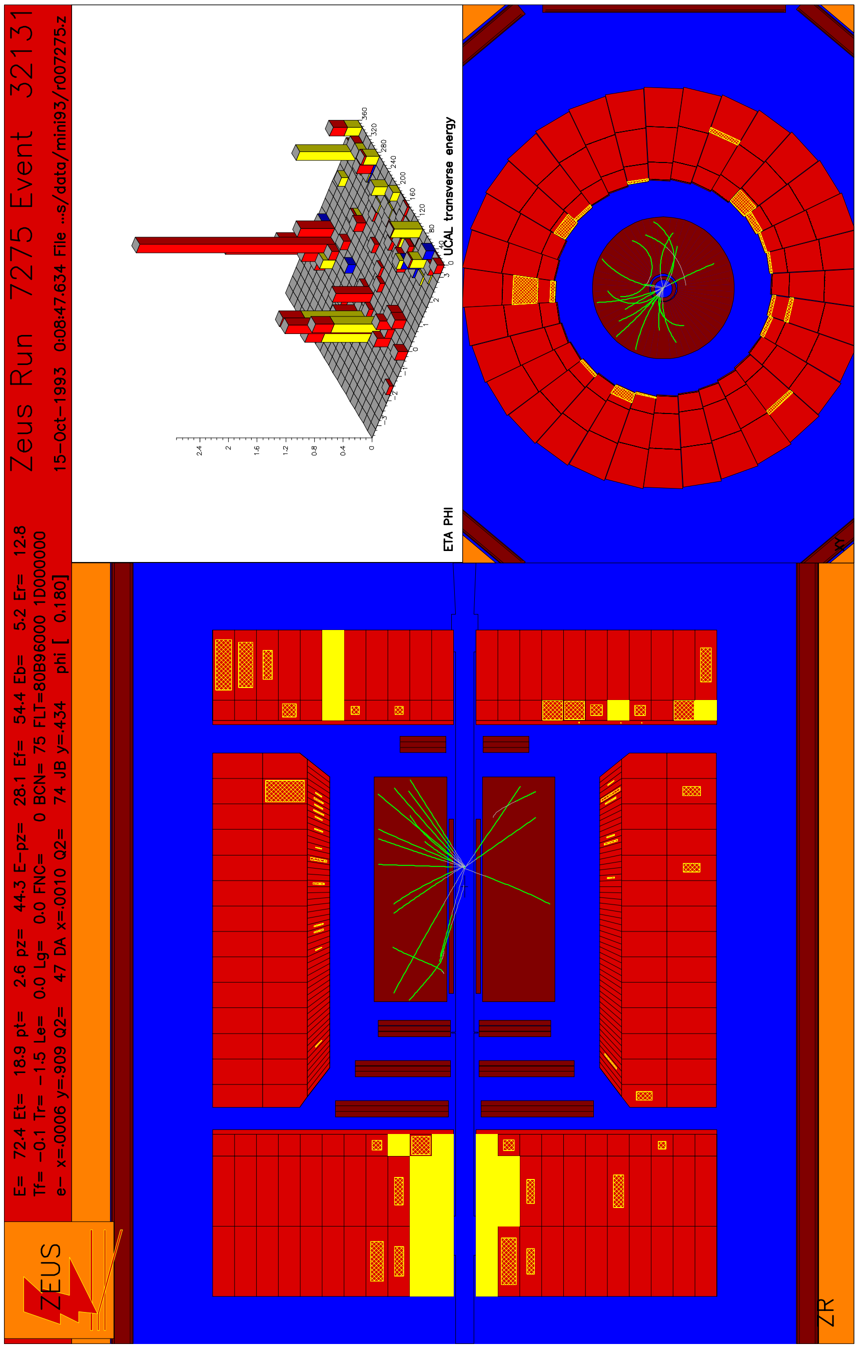
ep Interactions

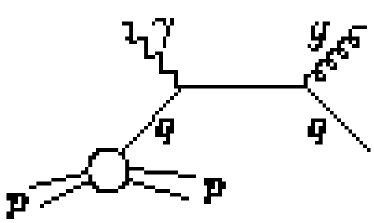


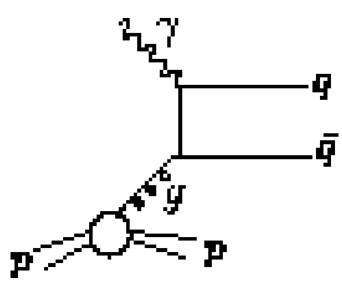
$k = (E, \boldsymbol{k})$	4-momentum for incoming e^-
$k' = (E, \boldsymbol{k}')$	4-momentum for outgoing e^-
$Q^2 = -q^2 = -(k - k')^2$	4-momentum transfer
$x = \dfrac{Q^2}{2P \cdot q}$	parton momentum fraction
$y = \dfrac{P \cdot q}{P \cdot k} = \dfrac{E - E'}{E}$	fractional energy transfer
$s = (P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

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

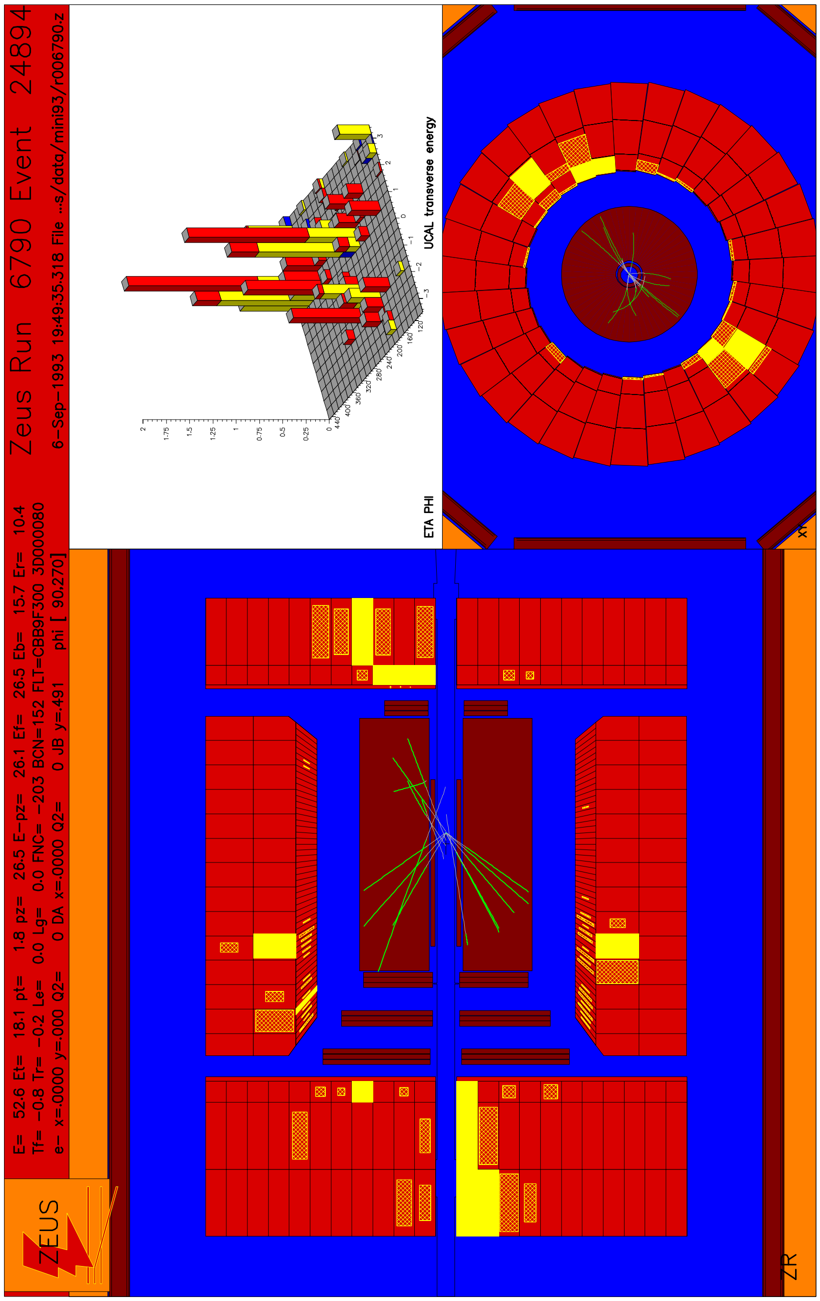
"Direct" Photon Process

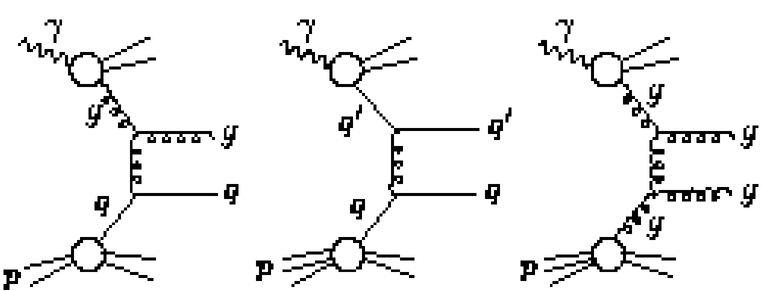




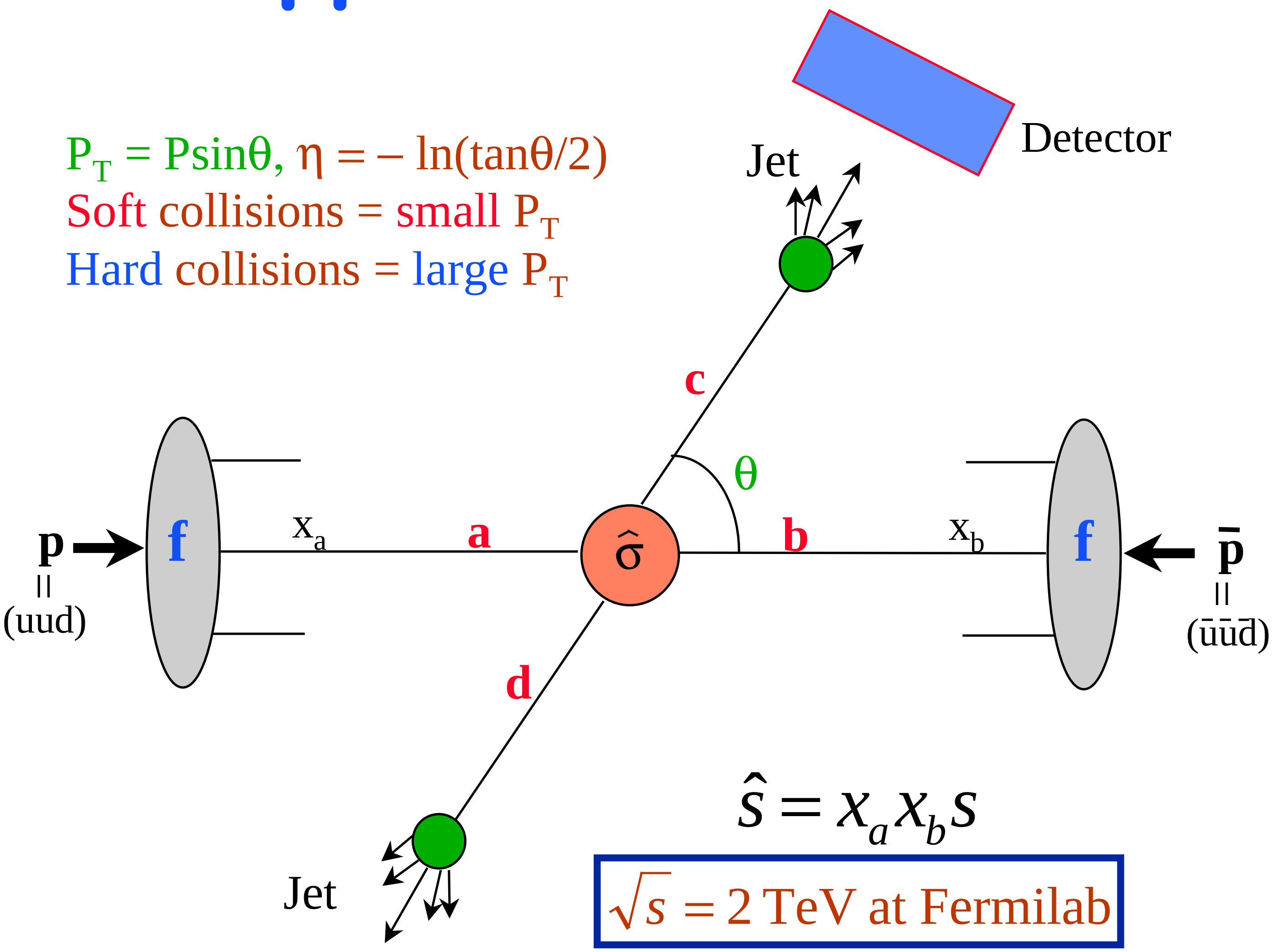


"Resolved" Photon Process





$p\bar{p}$ Interactions



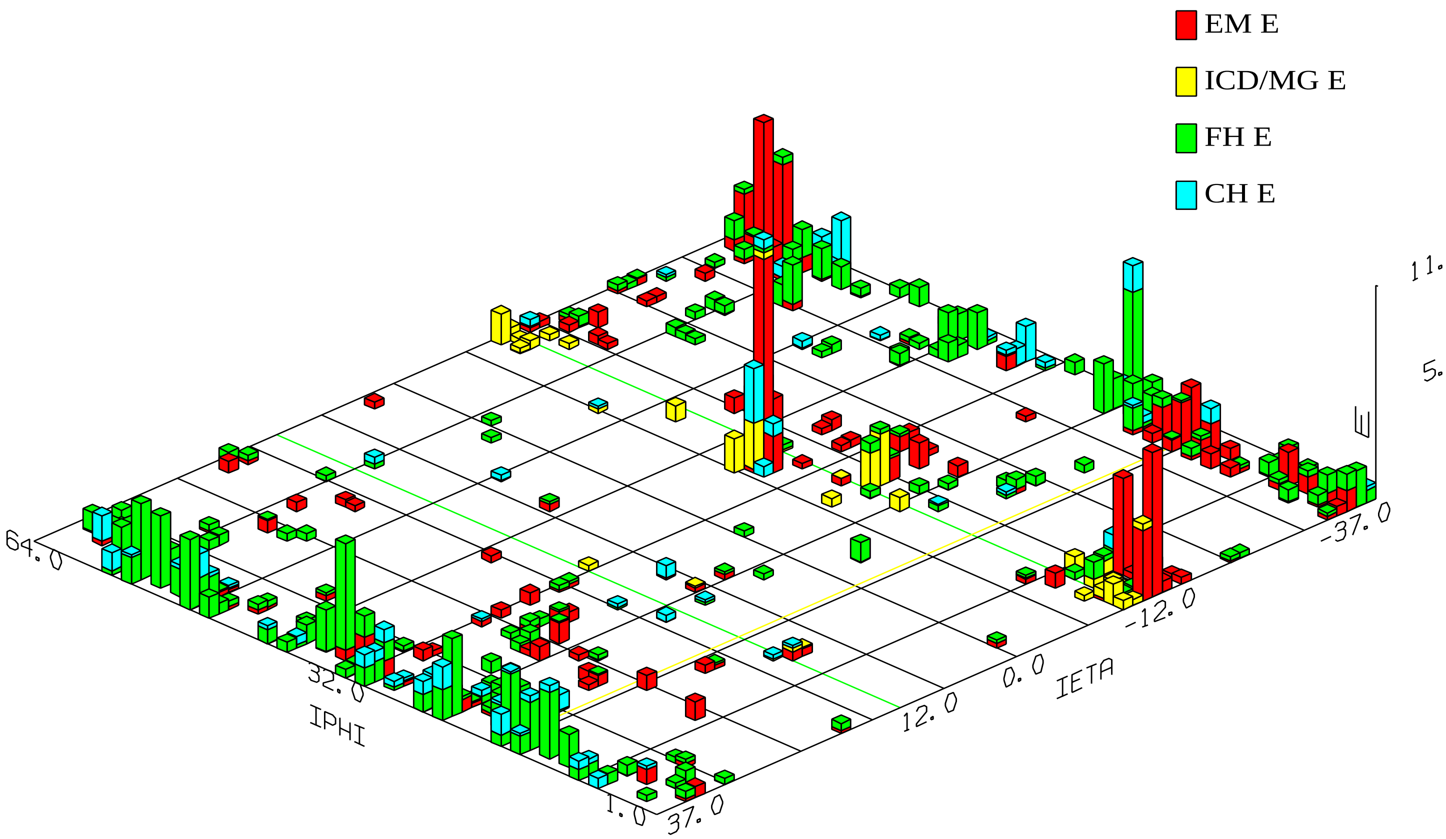
- $f_{a/A}(x_a,\mu)$: Probability function to find a parton of type **a** inside hadron **A** with momentum fraction x_a - ***Parton Distribution Functions***

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

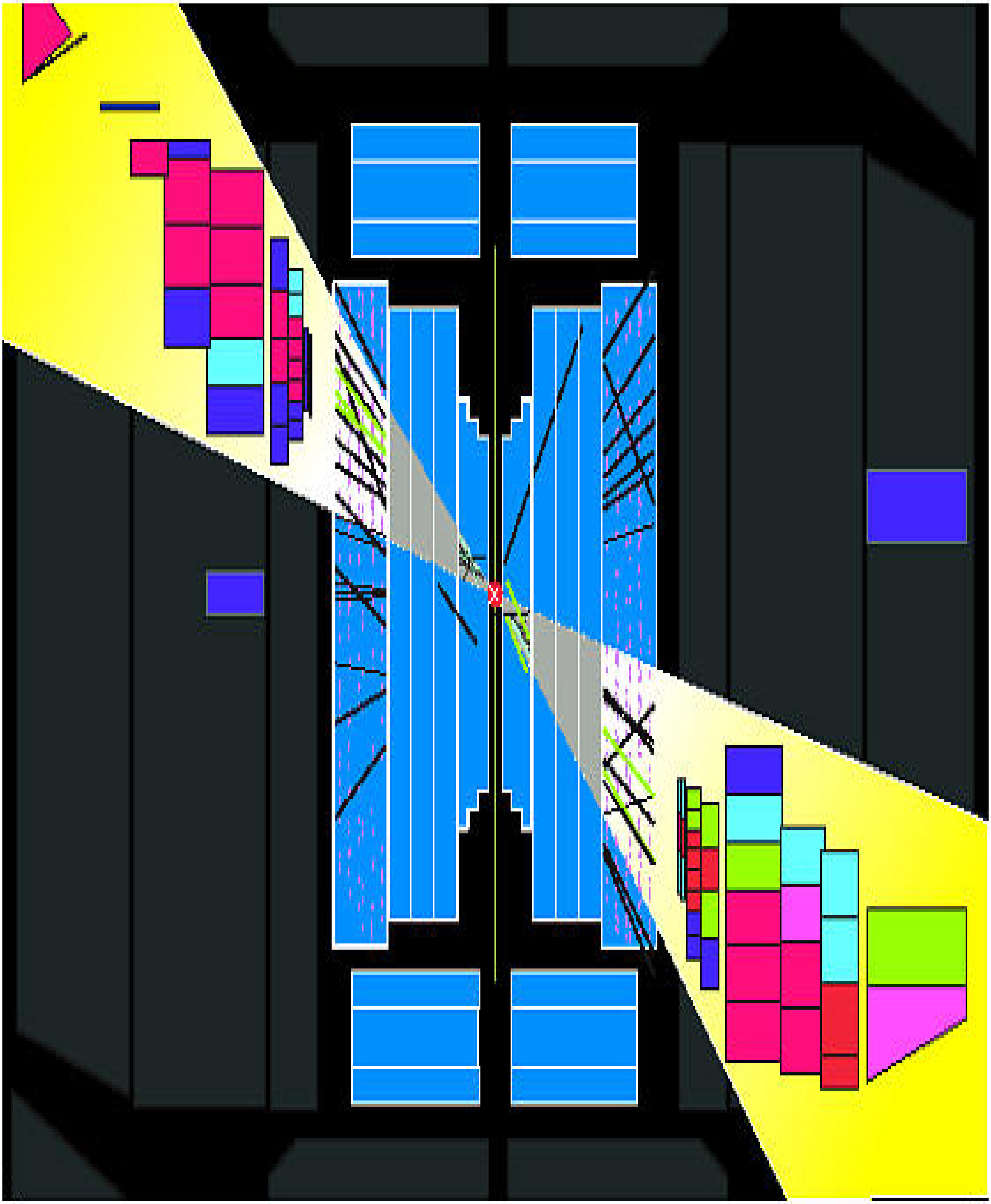
  μ: 4-momentum transfer related to the "scale" of the interaction

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

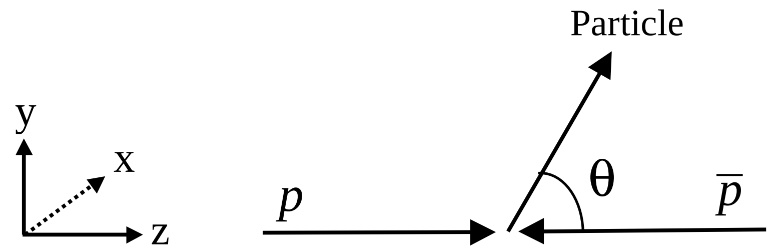
$p\bar{p}$ Interactions cont'd



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



Kinematics in Hadronic Collisions



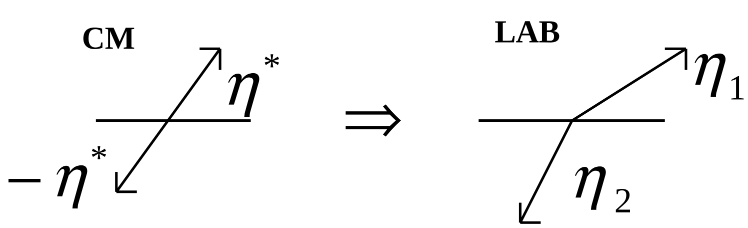
Rapidity (y) and Pseudo-rapidity (η)

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

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

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

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

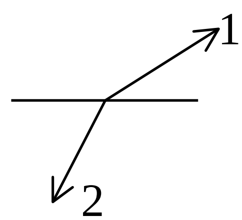
$$p_T \equiv p \sin\theta$$

$$p_z = E \tanh y$$

$$E = E_T \cosh y$$

$$p_z = E_T \sinh y$$

Invariant Mass

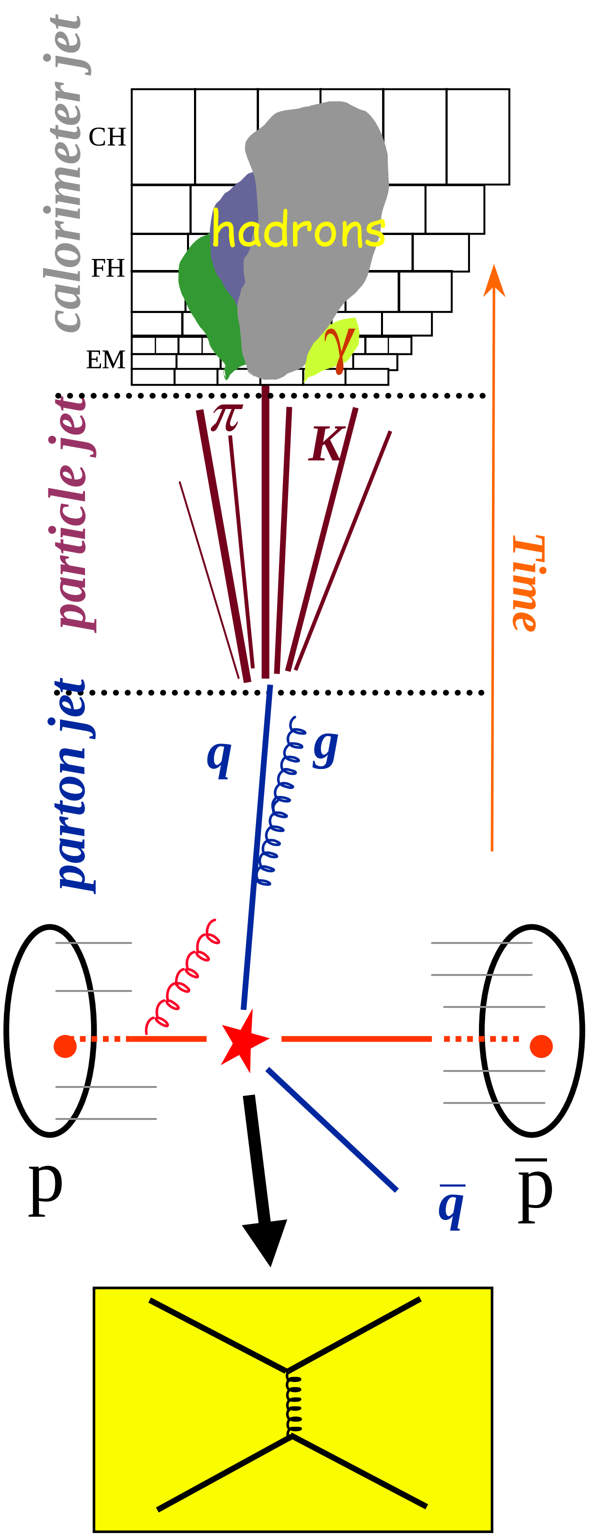


$$M_{12}^2 \equiv (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu})$$

$$= m_1^2 + m_2^2 + 2(E_1 E_2 - \boldsymbol{p}_1 \cdot \boldsymbol{p}_2)$$

$$\xrightarrow[m_1, m_2 \to 0]{} 2E_{T1}E_{T2}(\cosh\Delta\eta - \cos\Delta\phi)$$

What is an Event Generator ?

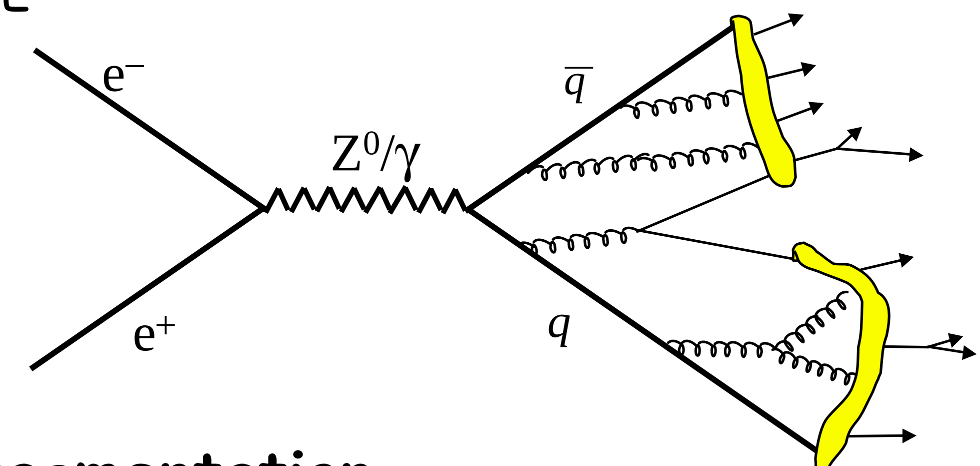


- A "Fortran" program (typically 1-50k lines of code) that generates events, trying to simulate Nature!
- Events vary from one to the next (random numbers)
- Expect to reproduce average behavior and fluctuations of real data
- Event Generators include:
  - Parton Distribution functions
  - Initial state 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

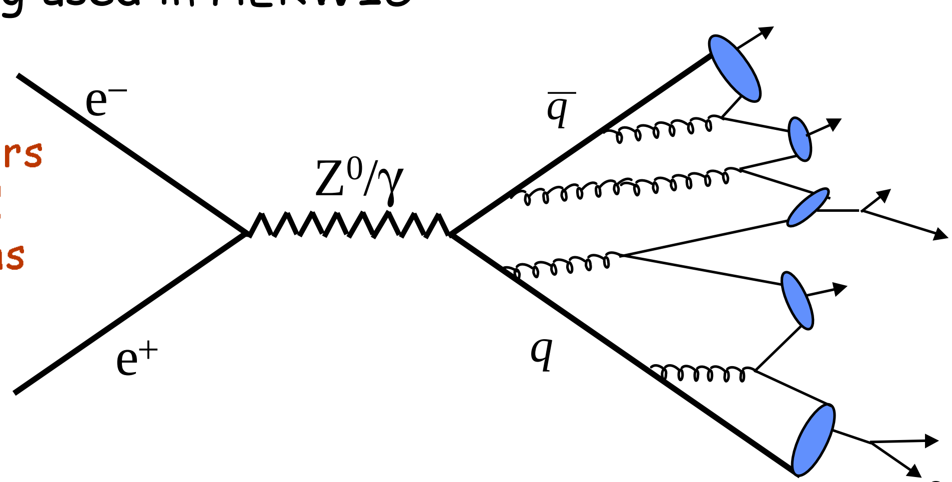
- **Independent fragmentation**
  - it is being used in ISAJET and COJETS
  - simplest scheme - each parton fragments independently following the approach of Fied and Feynman
- **String fragmentation**
  - it is being used in JETSET, PYTHIA, LEPTO, ARIADNE

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

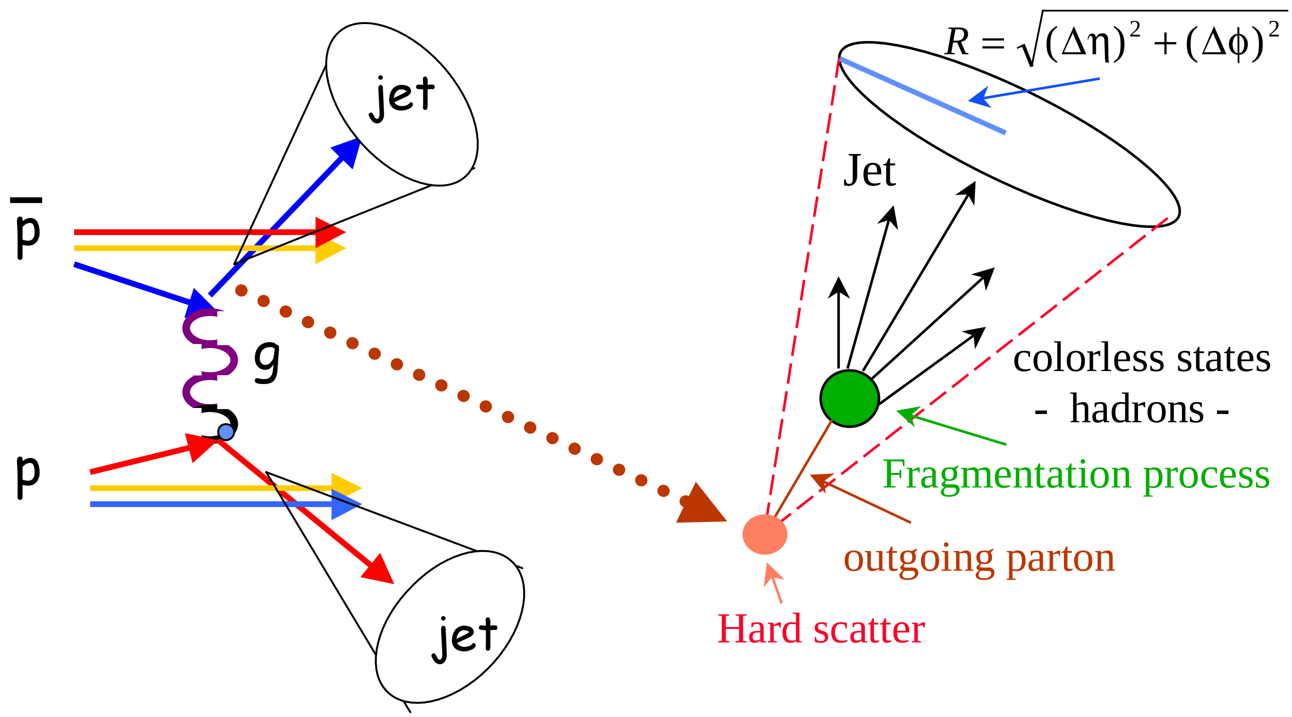


- **Cluster fragmentation**
  - it is being used in HERWIG

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



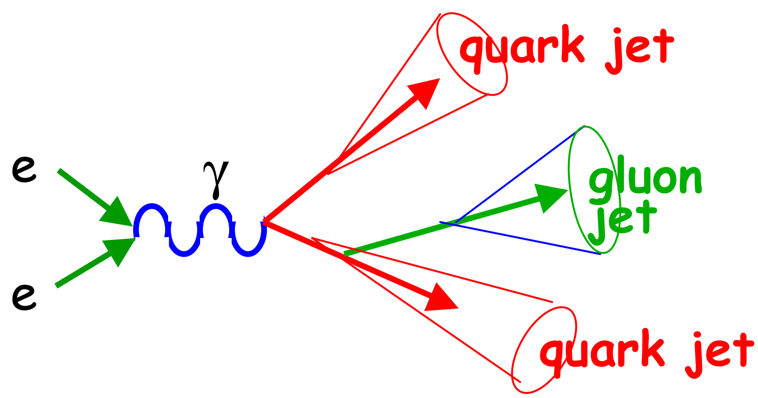
What are Jets ?



- 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

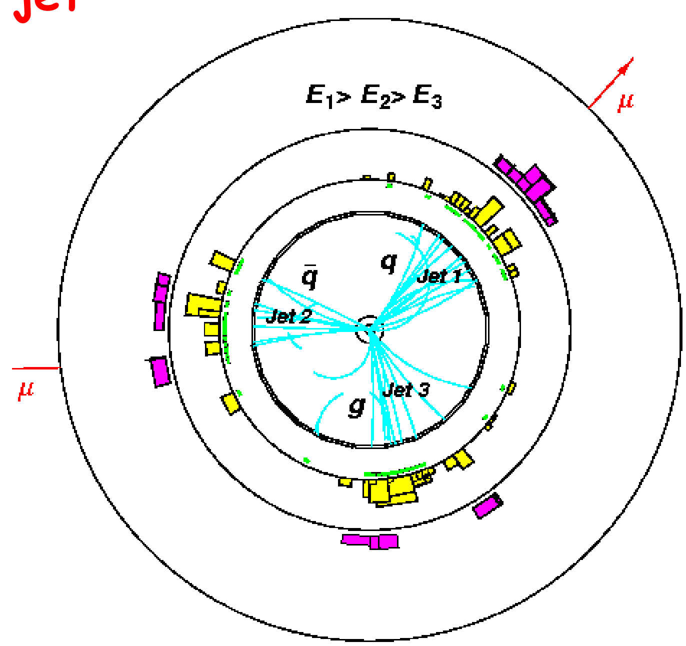
Evidence for Jets

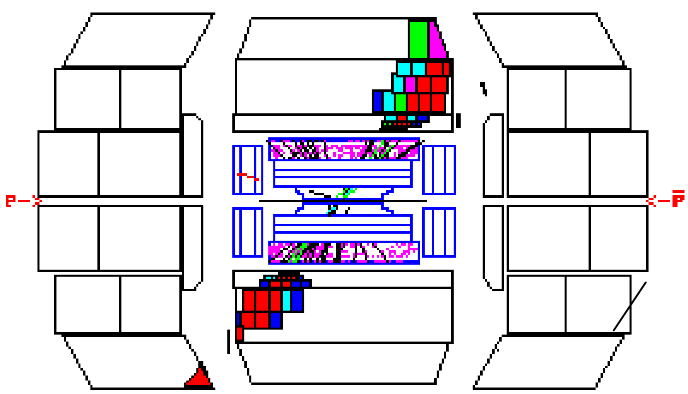
e^+e^- collisions proceed through an intermediate state of a photon (or Z); such collisions lead to quark antiquark. Presence of 3rd jet signals gluon radiation



(gluon jets are broader than quark jets)

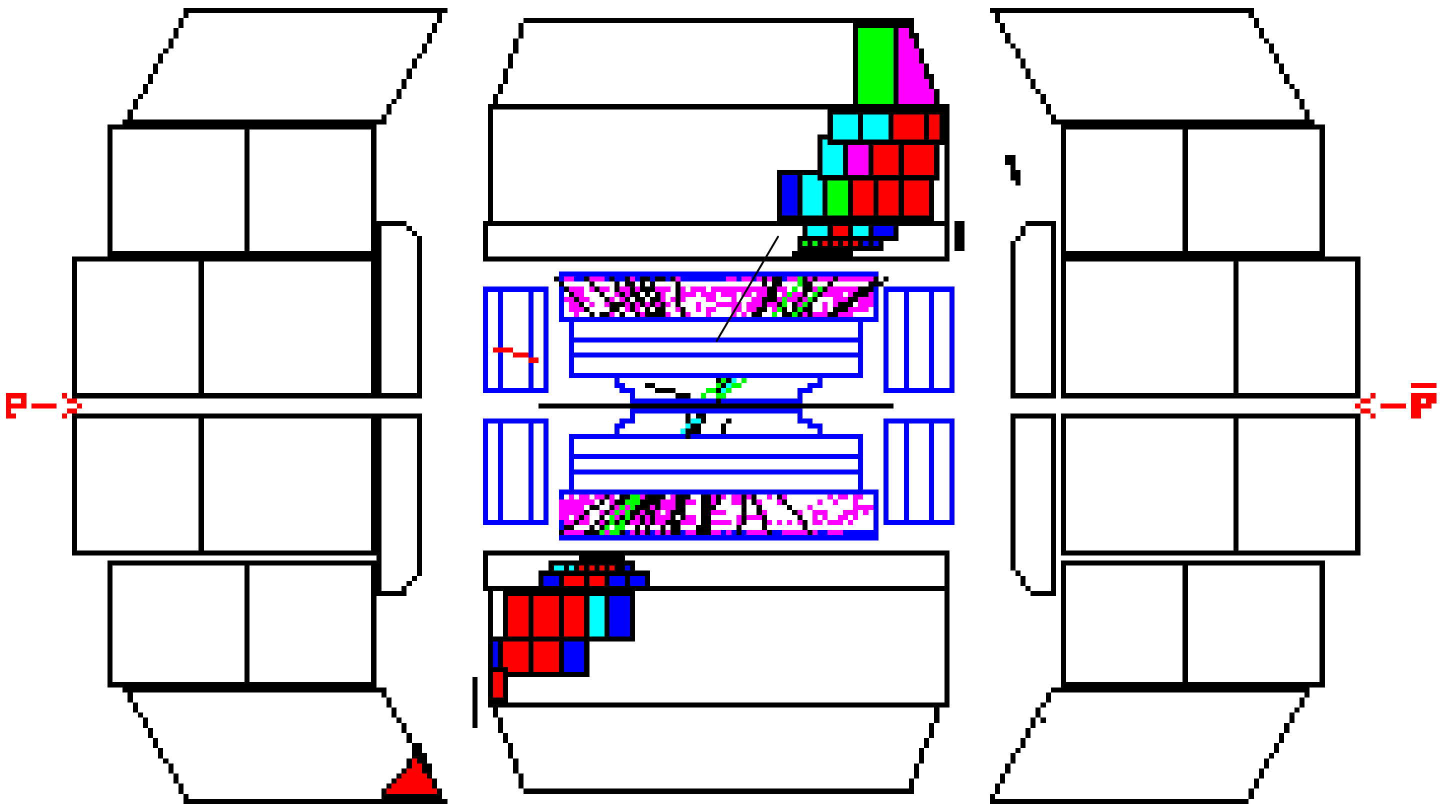
Typical ee event with 2 quarks and one gluon. (**Gluons exist** and are manifested as jets).





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)

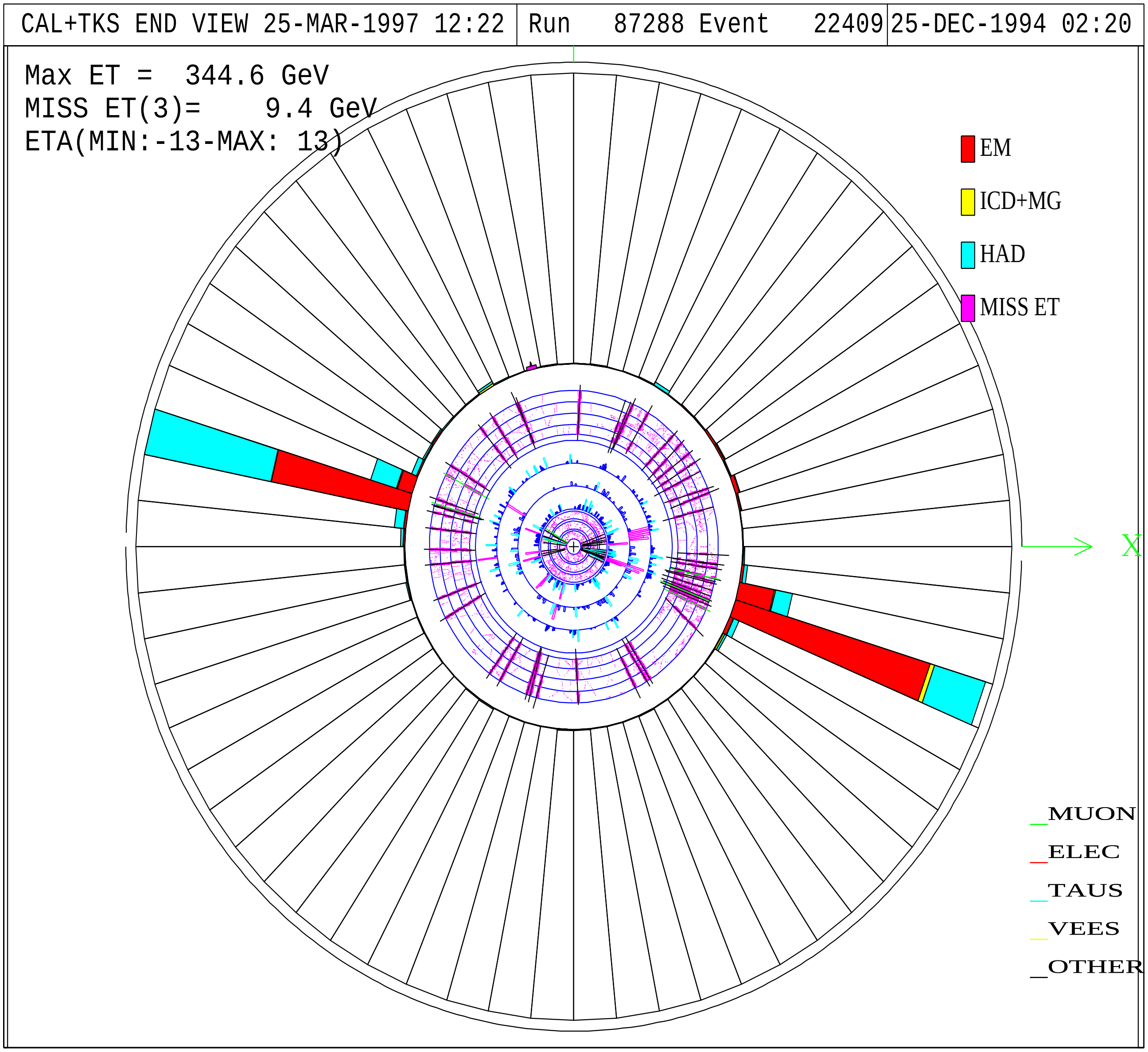
High-E_T DØ Event



$E_{T,1}$ = 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

High-E_T DØ Event



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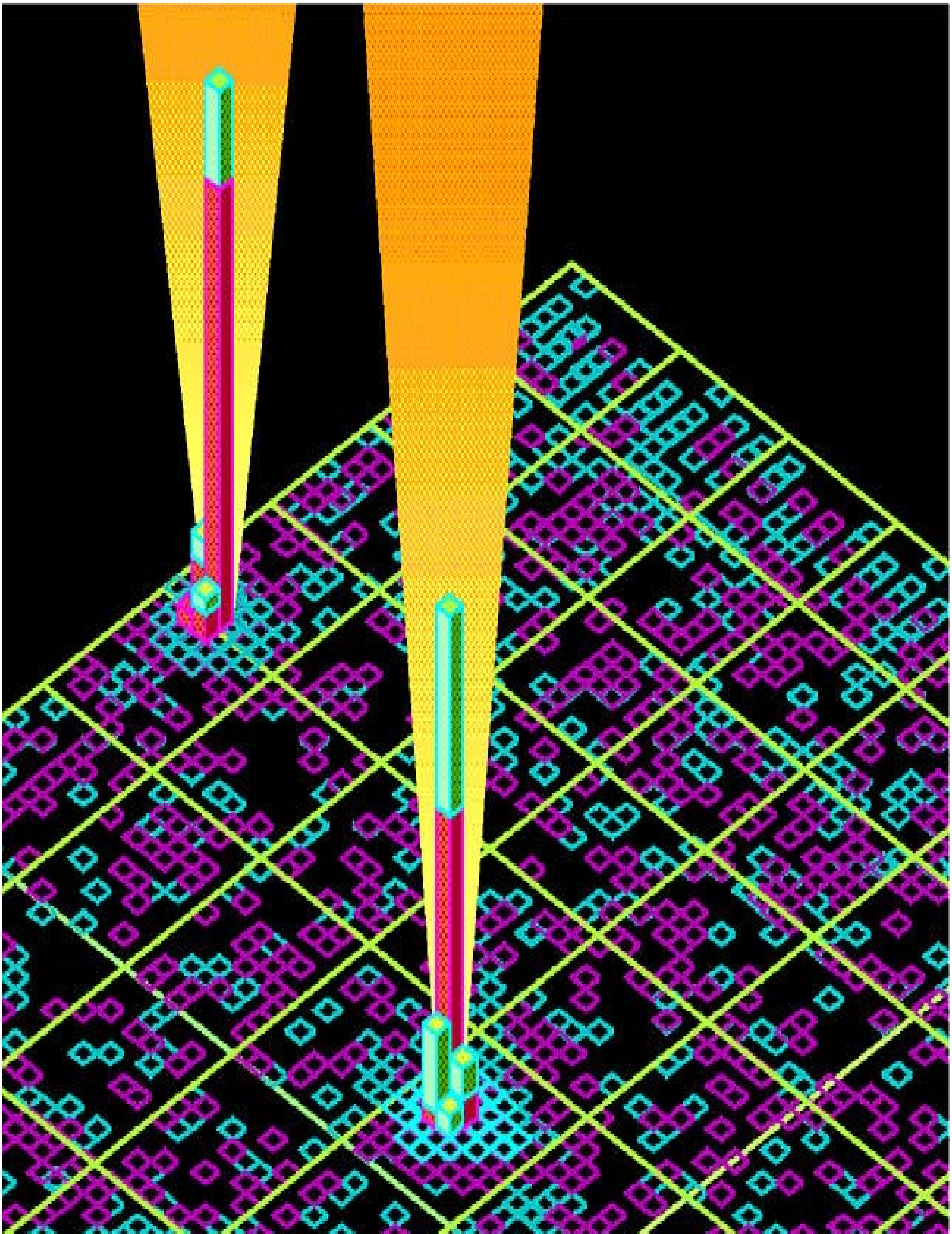
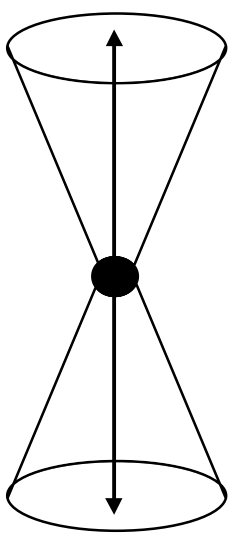


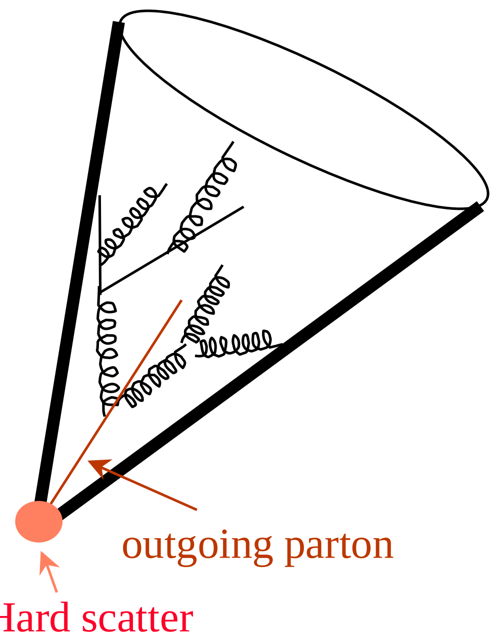
Jet Algorithms

- **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

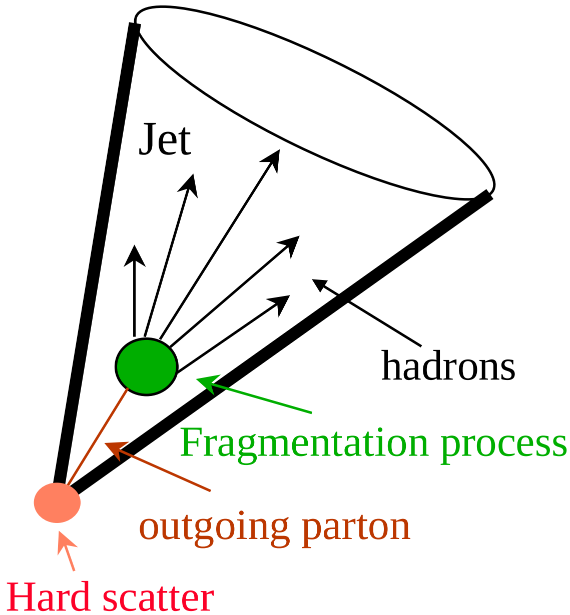
Leading Order





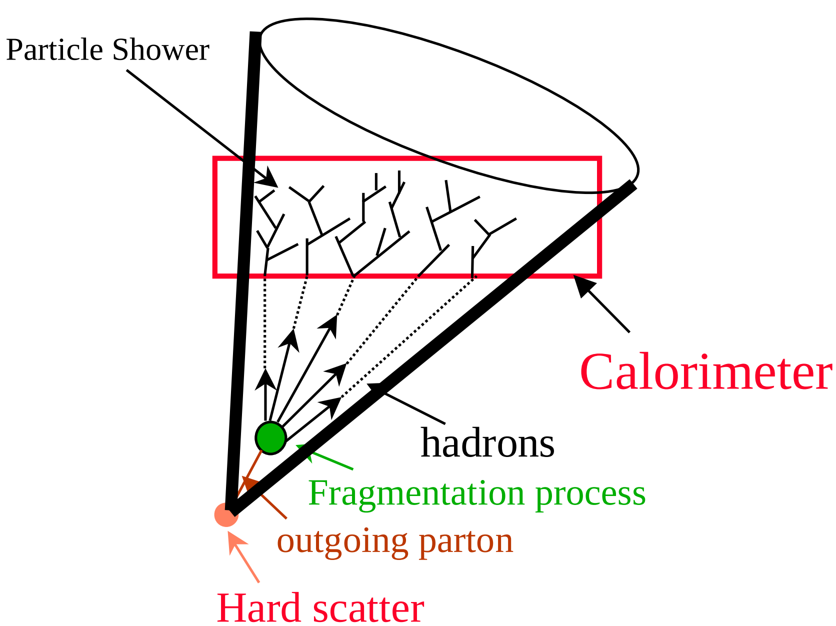
Jet Algorithms cont'd

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



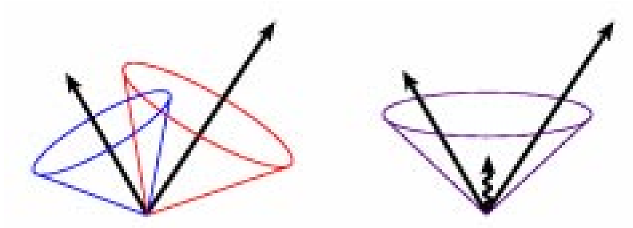
The idea is to come up with a jet algorithm which minimizes the non-perturbative hadronization effects

- **Jets at the "Detector Level"**

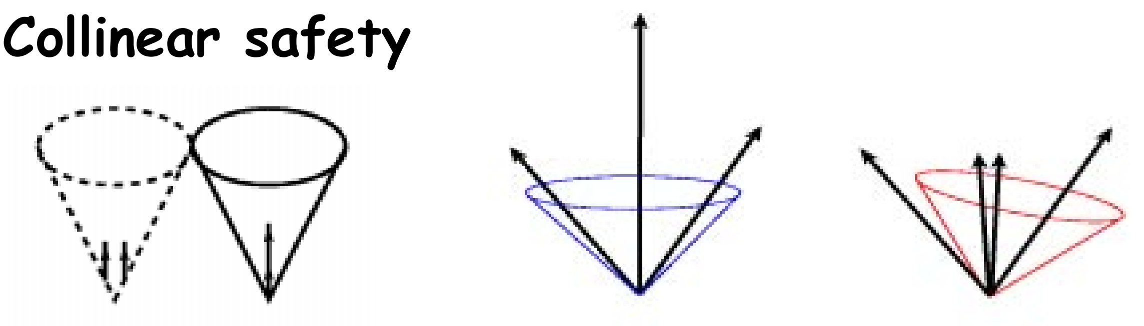


Jet Algorithms - Requirements

- **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

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

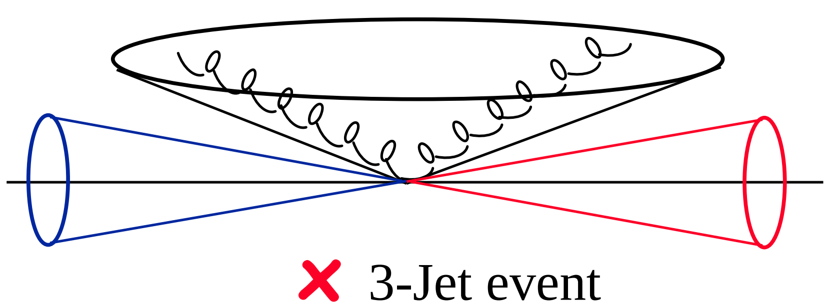
$$\min(y_{ij}) = \min(\frac{M_{ij}^2}{E_{vis}^2}) < y_{cut}$$

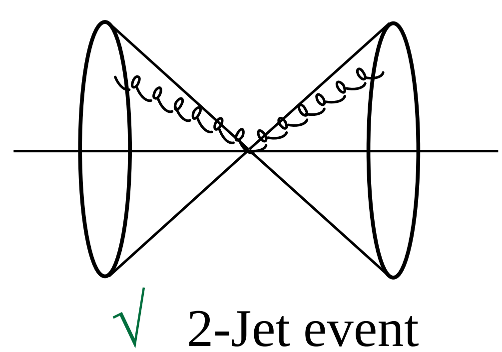
(E_{vis} is the sum of all particle energies)

- 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





The Durham or "K_T" Algorithm

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

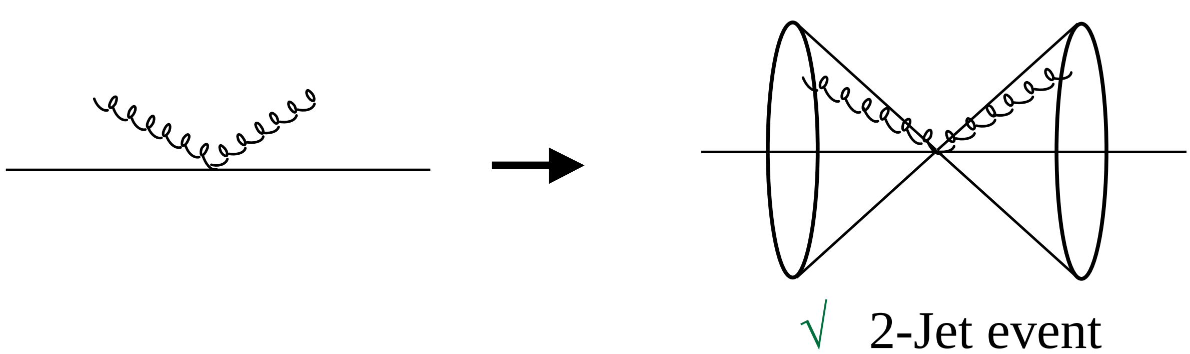
$$\min(y_{ij}) = \frac{M_{ij}^2}{E_{vis}^2} < y_{cut}$$

For small θ_{ij}

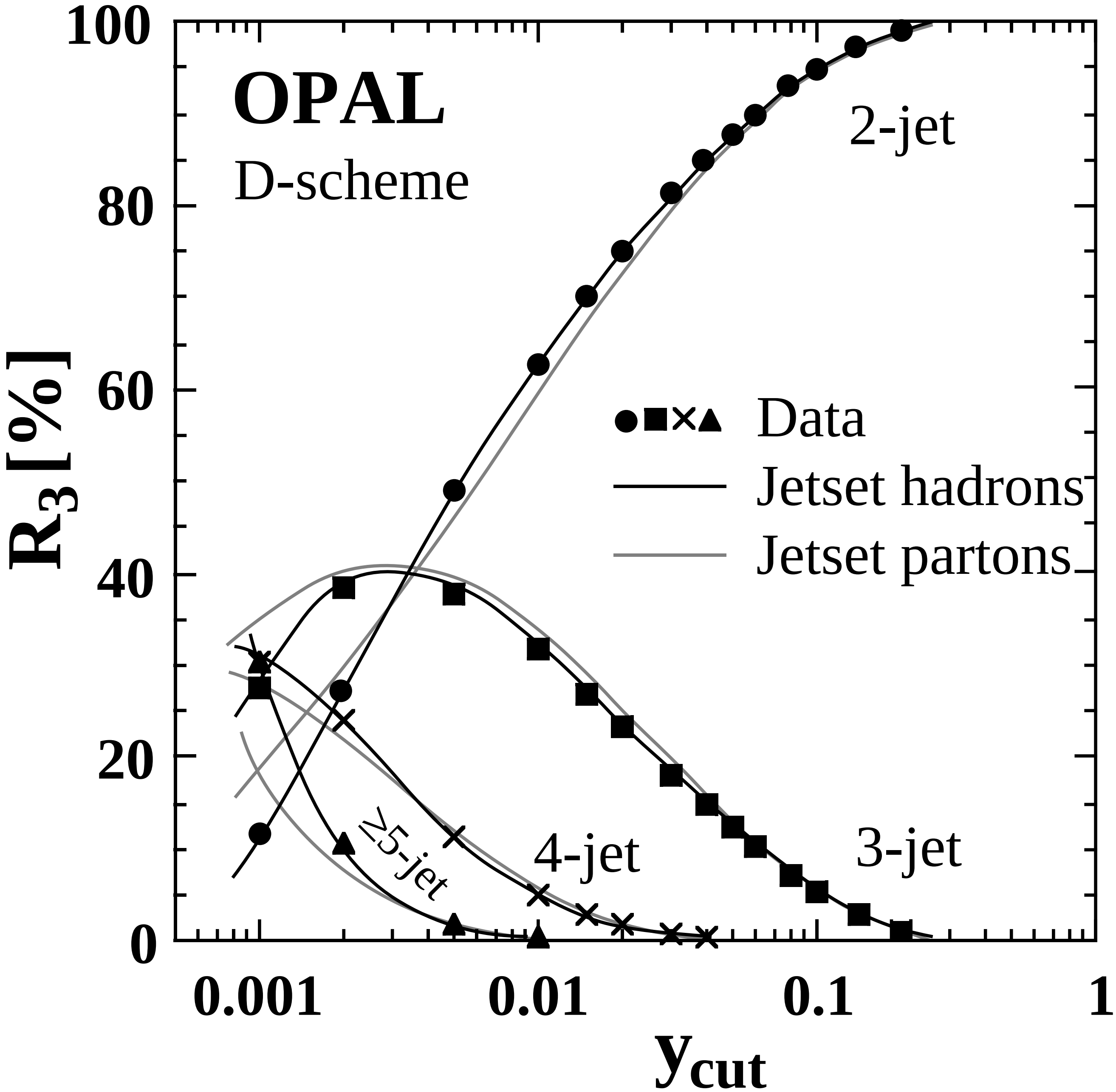
$$M_{ij}^2 \approx 2\min(E_i^2, E_j^2)\left(1-(1-\frac{\theta_{ij}^2}{2}+\cdots)\right)$$

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

- 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}

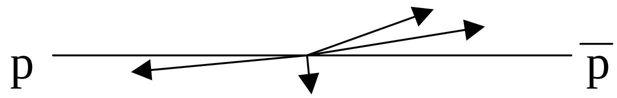


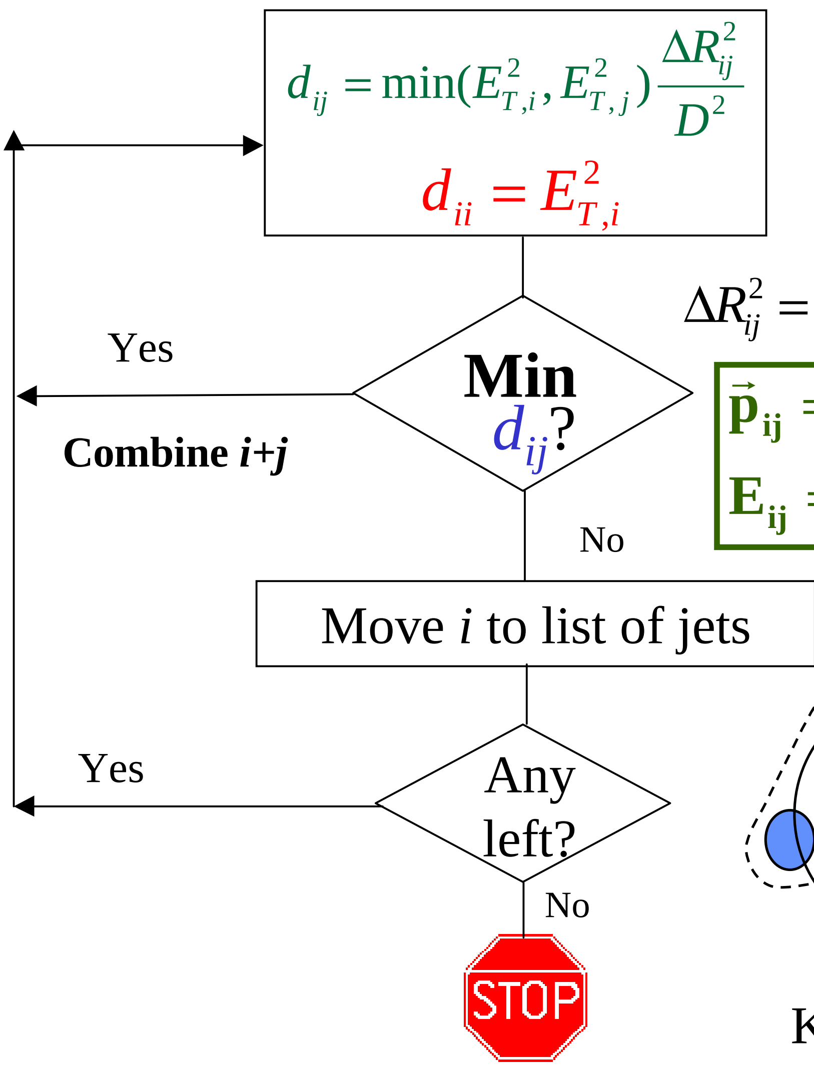
Jet Rates vs y_{cut}



A "K_T" Algorithm for hadron colliders

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



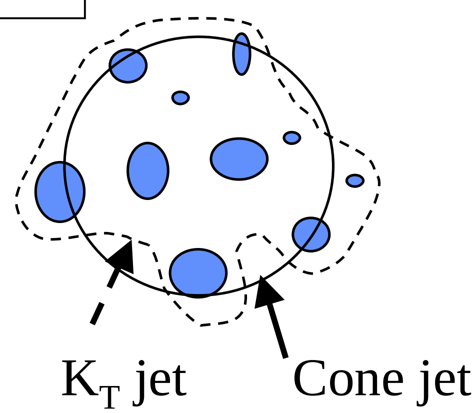


D~1

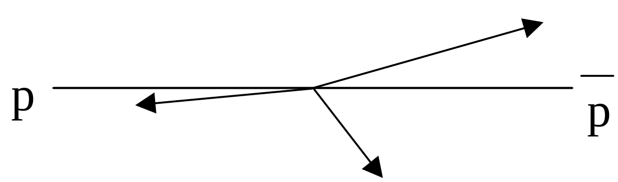
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$\vec{\mathbf{p}}_{\mathbf{ij}} = \vec{\mathbf{p}}_{\mathbf{i}} + \vec{\mathbf{p}}_{\mathbf{j}}$$

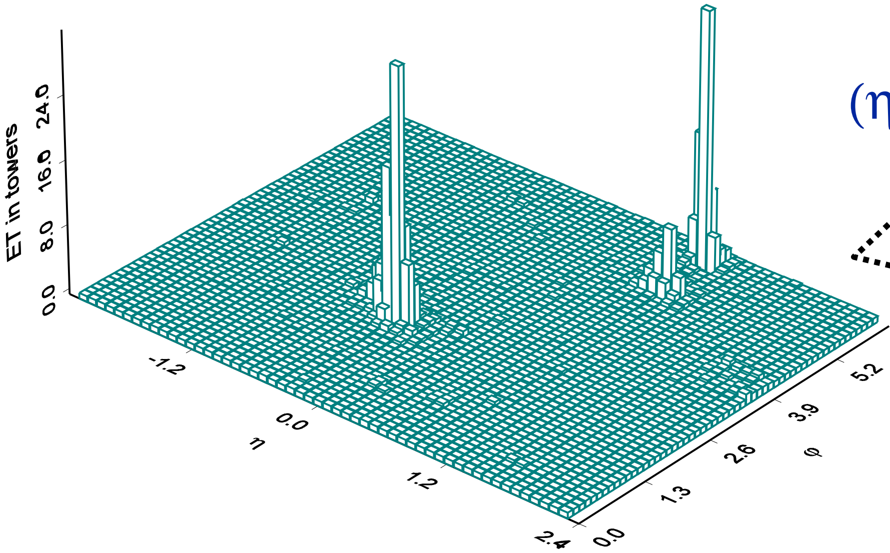
$$\mathbf{E}_{\mathbf{ij}} = \mathbf{E}_{\mathbf{i}} + \mathbf{E}_{\mathbf{j}}$$

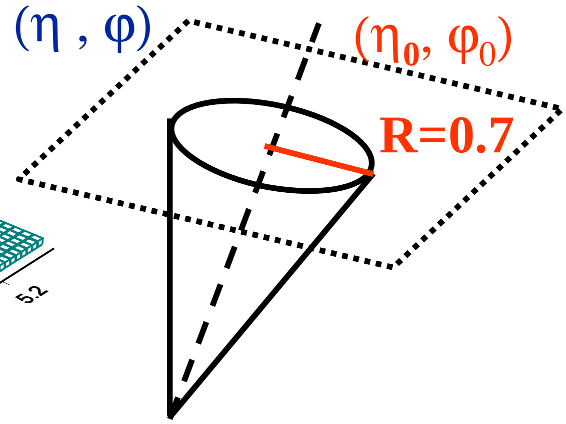


Output: List of jets $(\Delta R \geq D)$

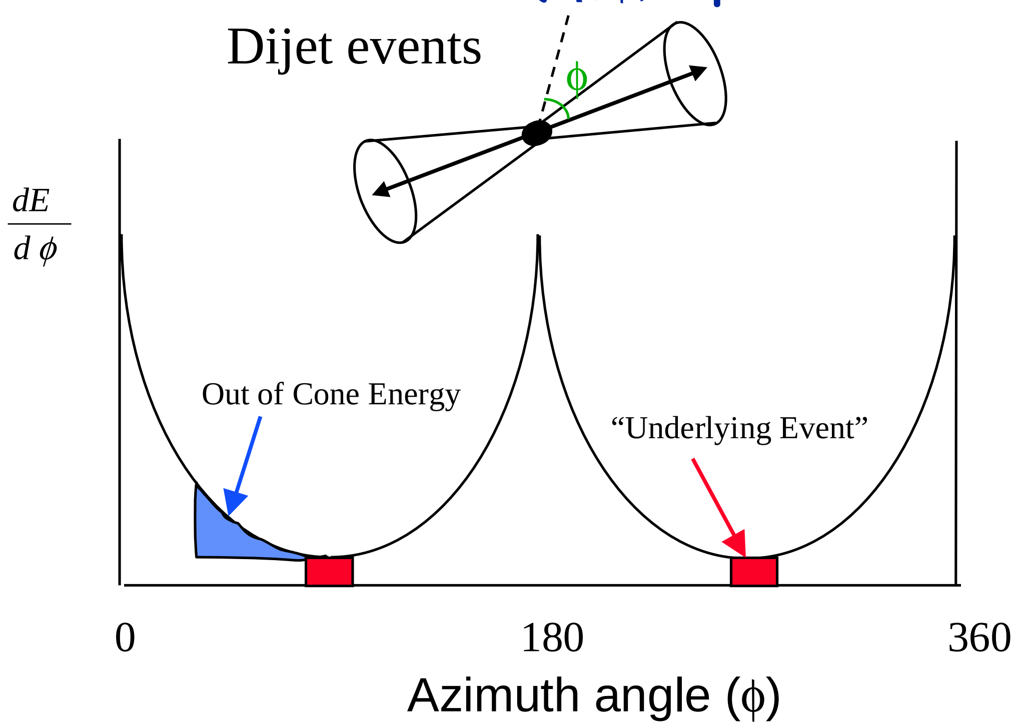


The "Cone" Algorithm



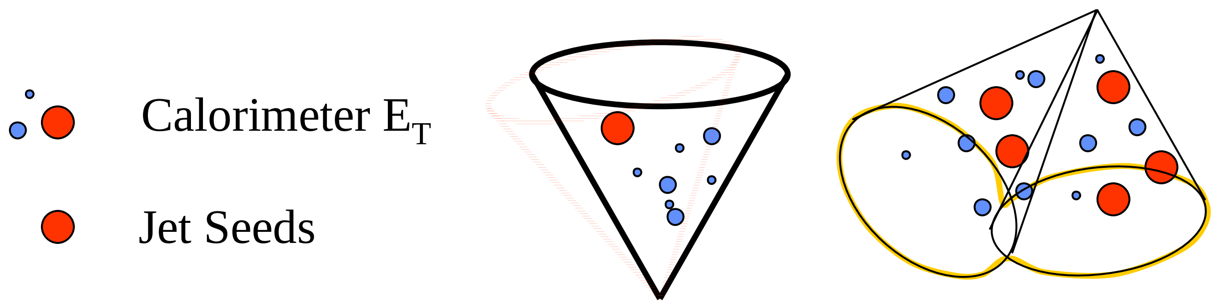


- A more intuitive representation of a jet that that given by recombination jet finders
- It clusters particles whose trajectories lie in an area $A=\pi R^2$ of (η,ϕ) space



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

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

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

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:

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

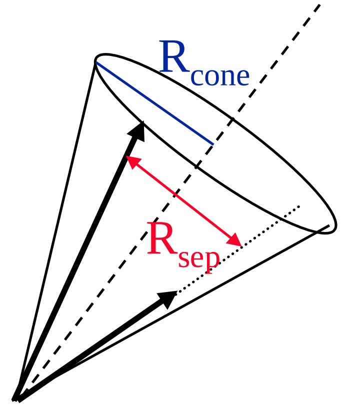
CDF's E_T:

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

D0's E_T:

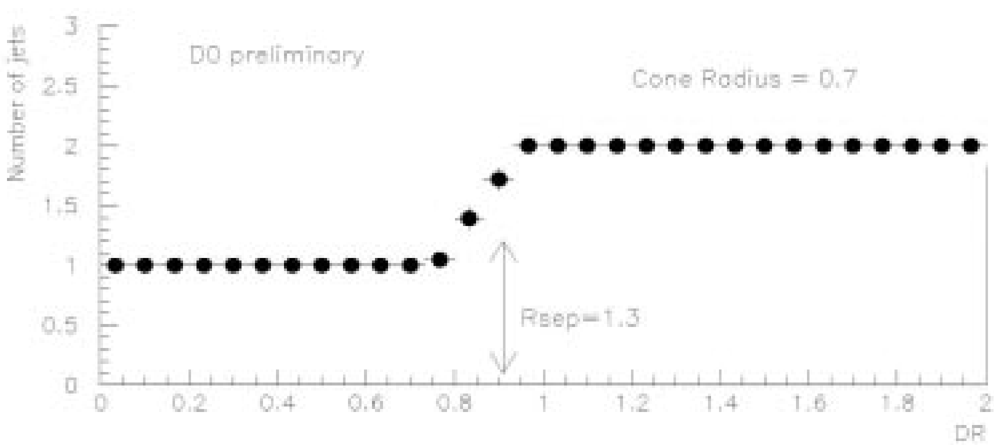
$$E_T^J = \sum_{i \subset J} E_T^i$$

The "Cone" Algorithm at the NLO Parton Level



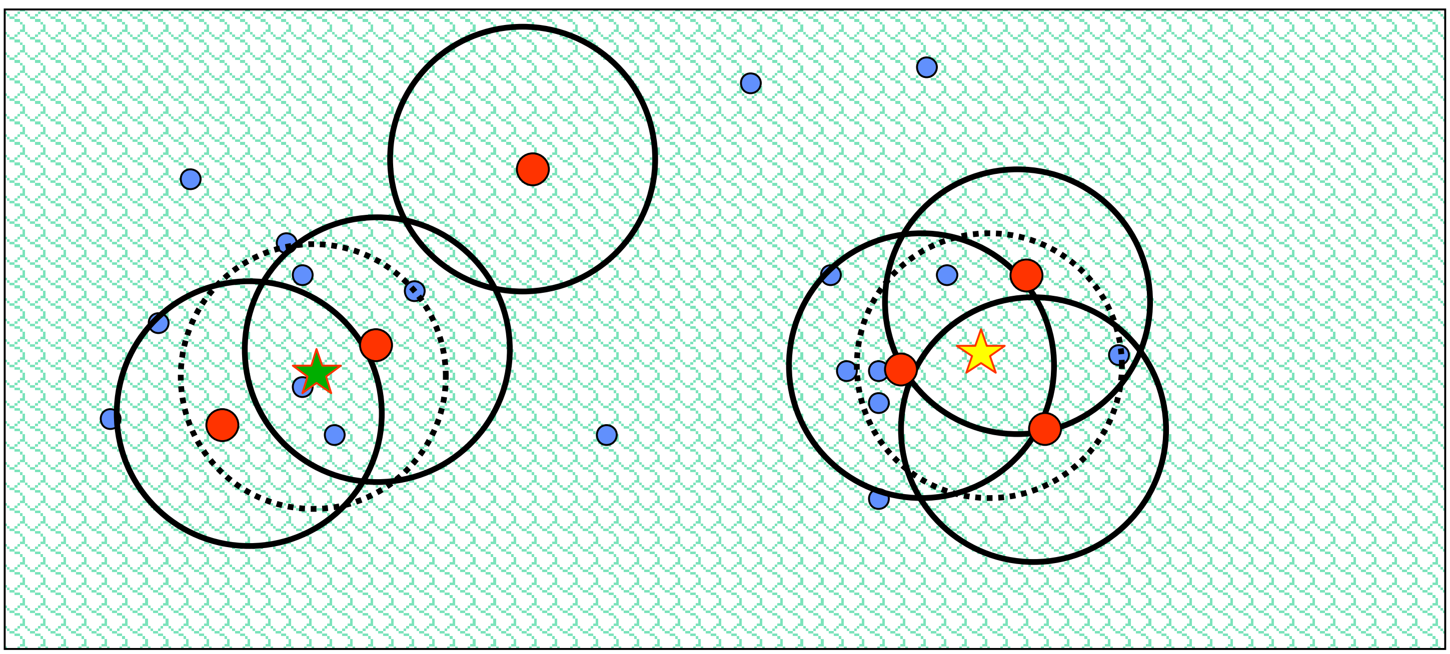
- Apply Snowmass recipe
  - Each parton must be within R_c (=0.7) of centroid
- The two partons must be within R_{sep}*R_c of one another, where Rsep varies from 1 - 2 (R_{sep}=1.3 for D0)
  - Introduce ad-hoc parameter R_{sep} to control parton recombination in the theoretical jet algorithm

If jets from separate events are overlayed then they can be distinguished at (1.2-1.3)R_c or R_{sep} = 0.9 for 0.7 cones:



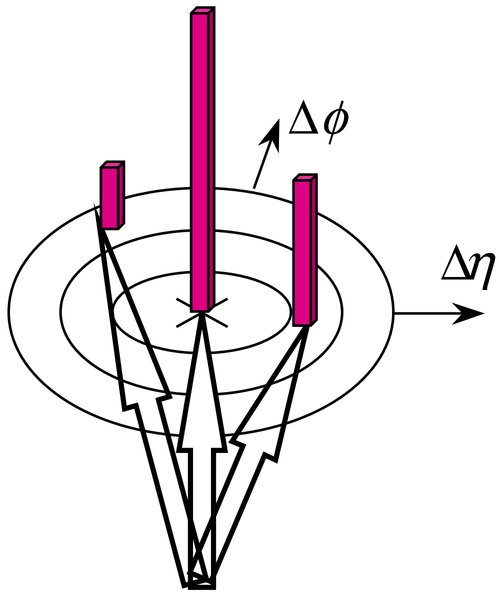
"Midpoint" or Improved Legacy Cone Algorithm

- A product of the Tevatron QCD Workshop for Run II
  - Define algorithms to remove ad-hoc R_{sep} parameter in NLO cone jet clustering
- Use 4-vectors to cluster in y and ϕ, find all stable cones around seeds/preclusters
- Then find stable cones around 'midpoints'
  - The Mid Point algorithm adds new 'pseudo seeds' between each pair of jets satisfying the distance (ΔR) requirement: $R_{cone} < \Delta R < 2 \times R_{cone}$



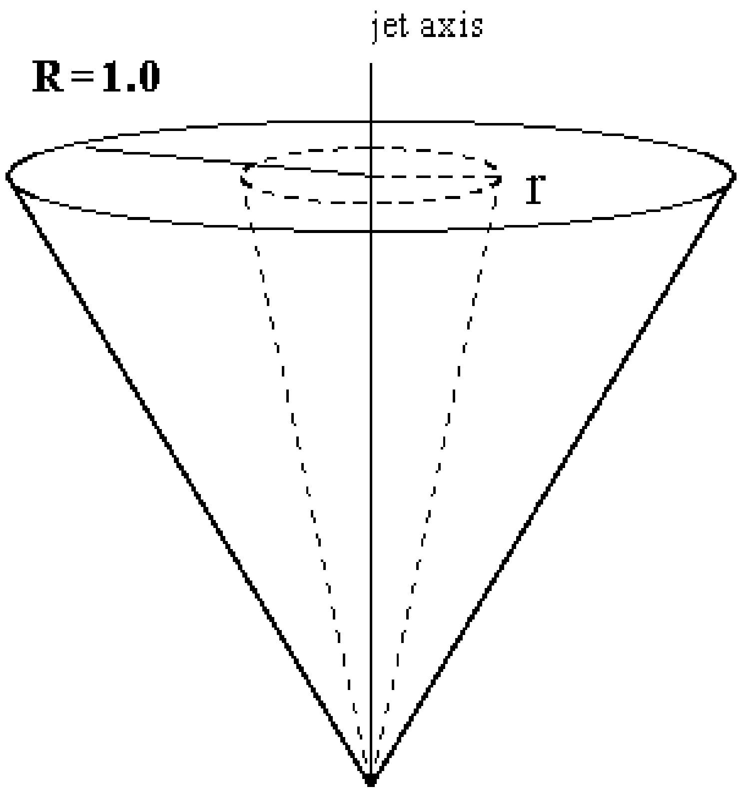
● **Seed > ~1 GeV** ★ ☆ **ILCA added seeds placed at ET-weighted midpoints**

- Do a P_T-ordered splitting/merging only after all stable cones are found

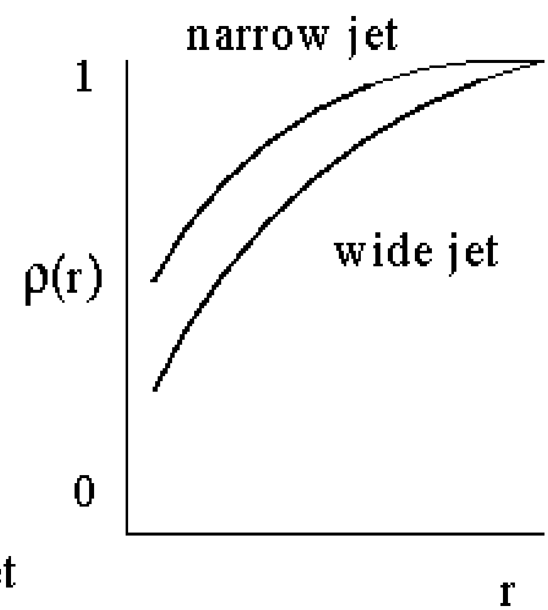


Jet Characteristics

Jet Shape Measurement



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



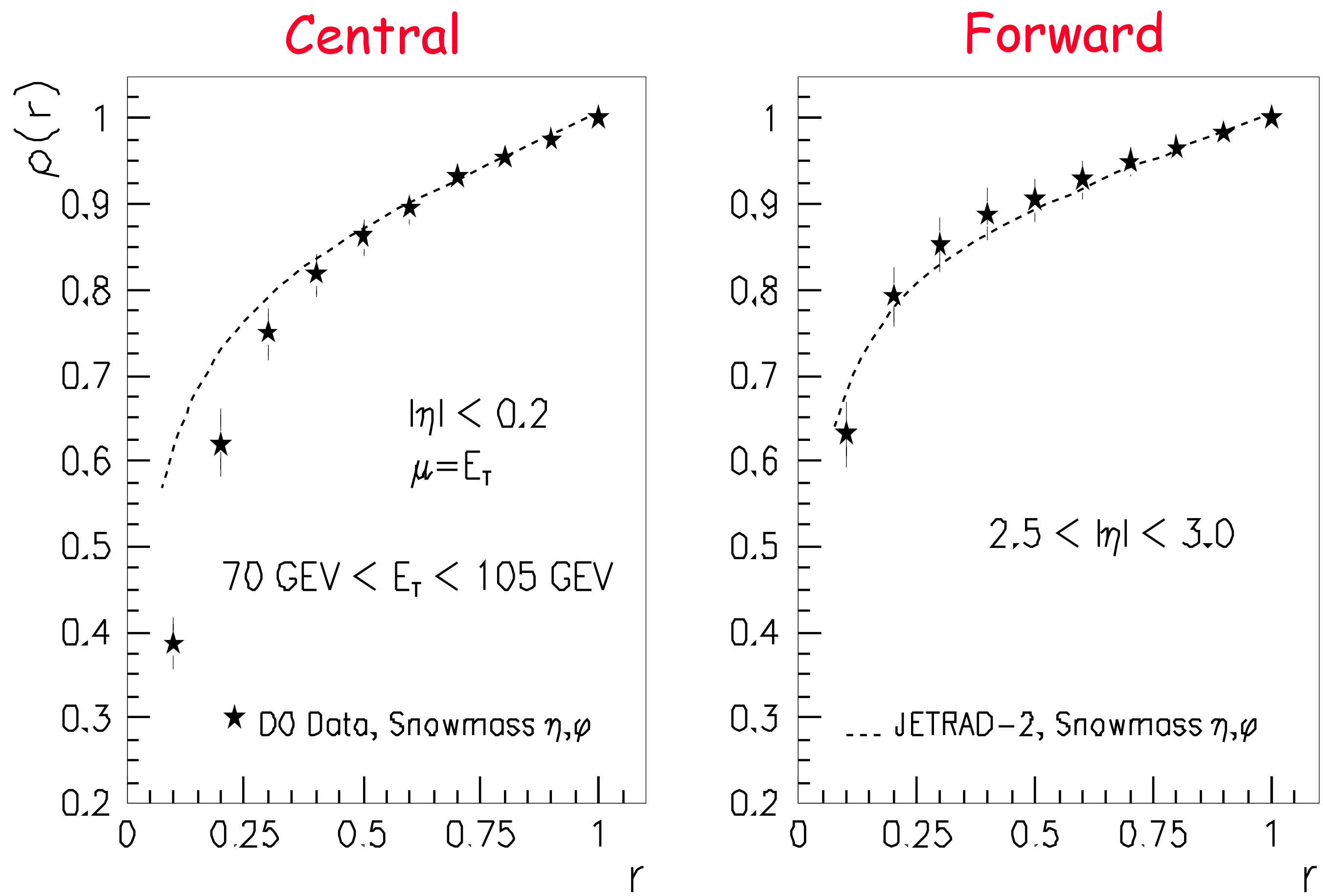
Calculate average integrated jet E_T fraction as a function of radial distance from jet axis:

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

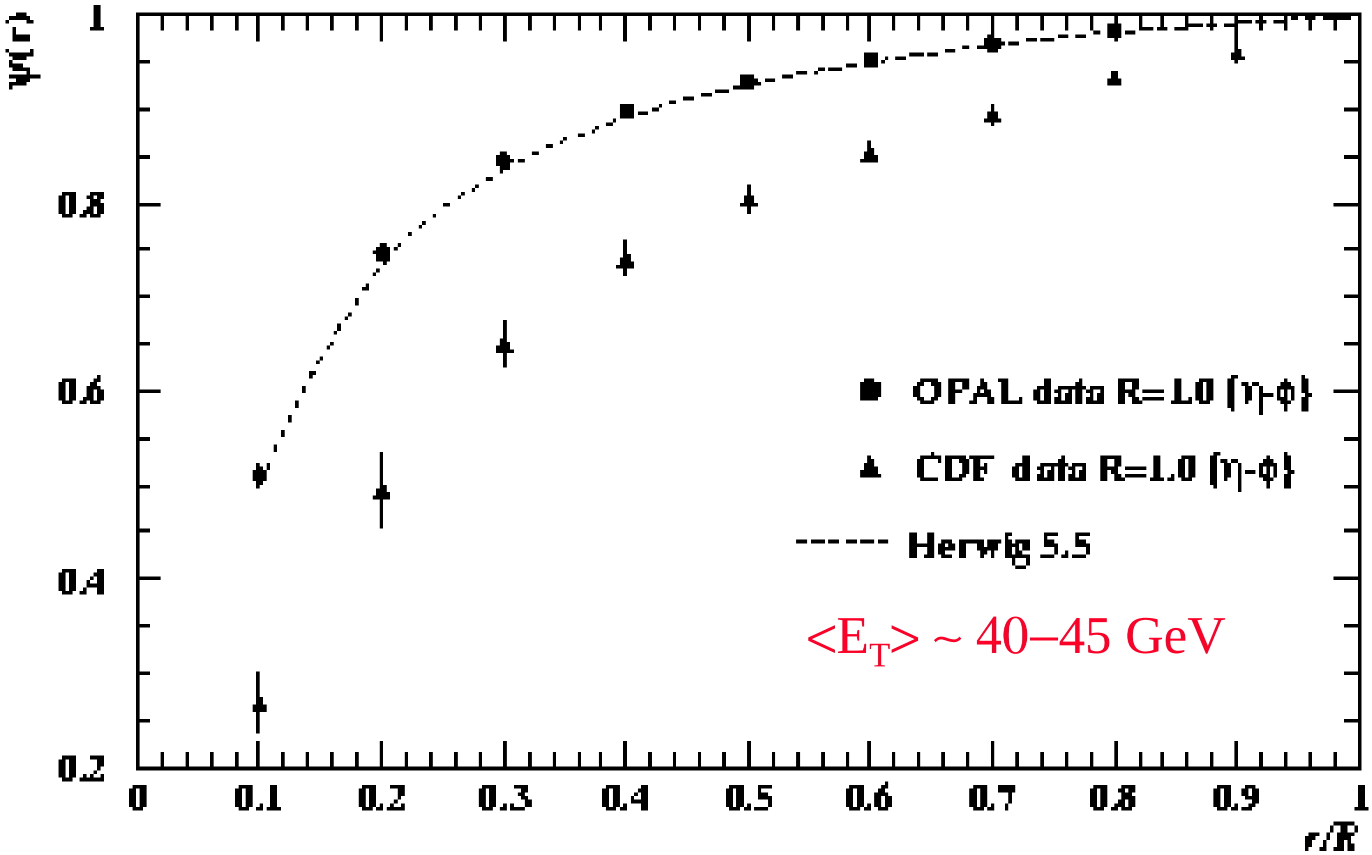
The investigation of jet profiles gives insights into the transition between the parton produced in the hard process and the observed spray of hadrons

Niko:

Jet energy profiles at Tevatron



- Forward jets are narrower than jets in the central region for similar E_T
  - forward jets have higher energy for similar E_T
  - forward jets are quark enriched whereas central jets are mostly gluons
- 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
- HERWIG jets (not shown) are narrower that the data

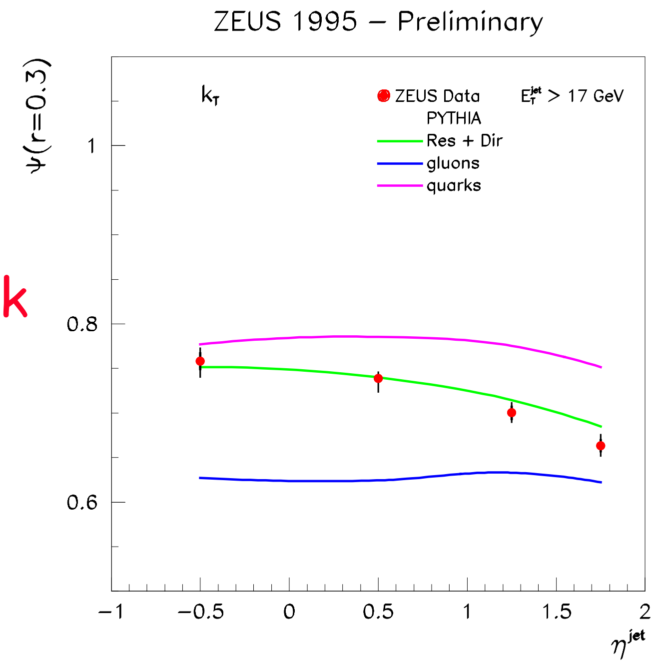


Jet Energy Profiles at e^+e^-

- 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

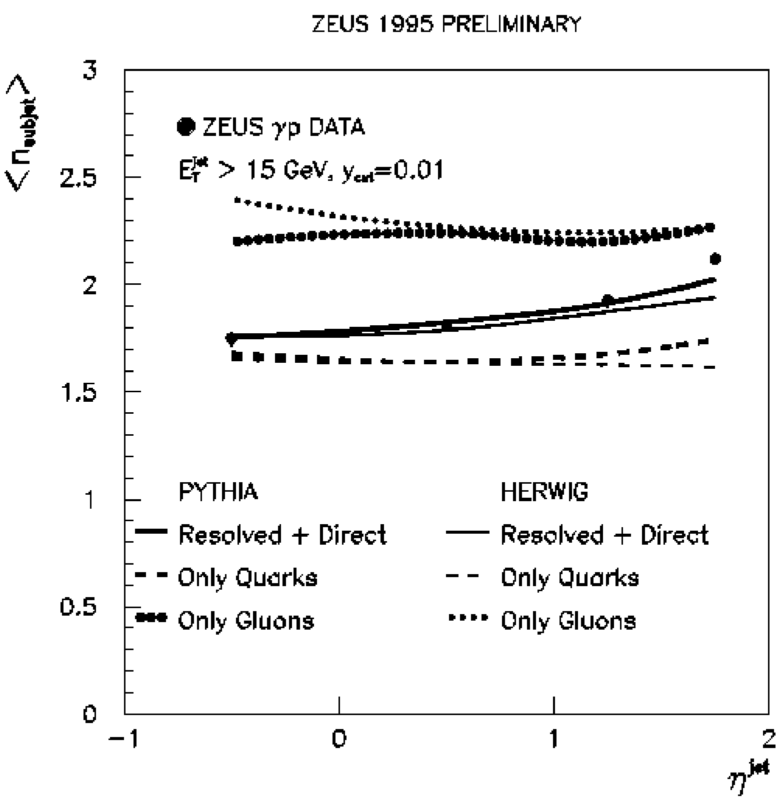
Jet Energy Profiles at ep

- **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:

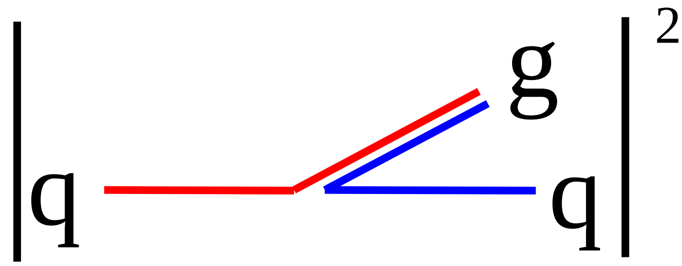
$$\gamma g \rightarrow q\bar{q}$$

$$q_\gamma g_p \rightarrow qg$$

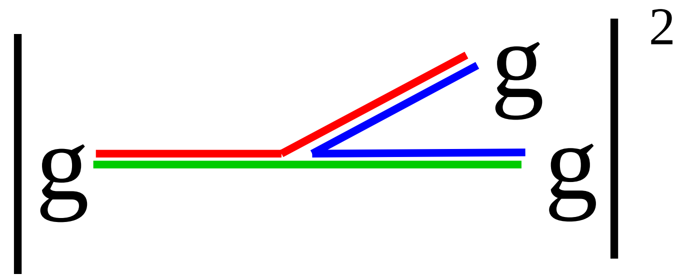
Quark vs Gluon Jets

Deepen understanding of jet substructure

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



$\sim C_F = 4/3$



$\sim C_A = 3$

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

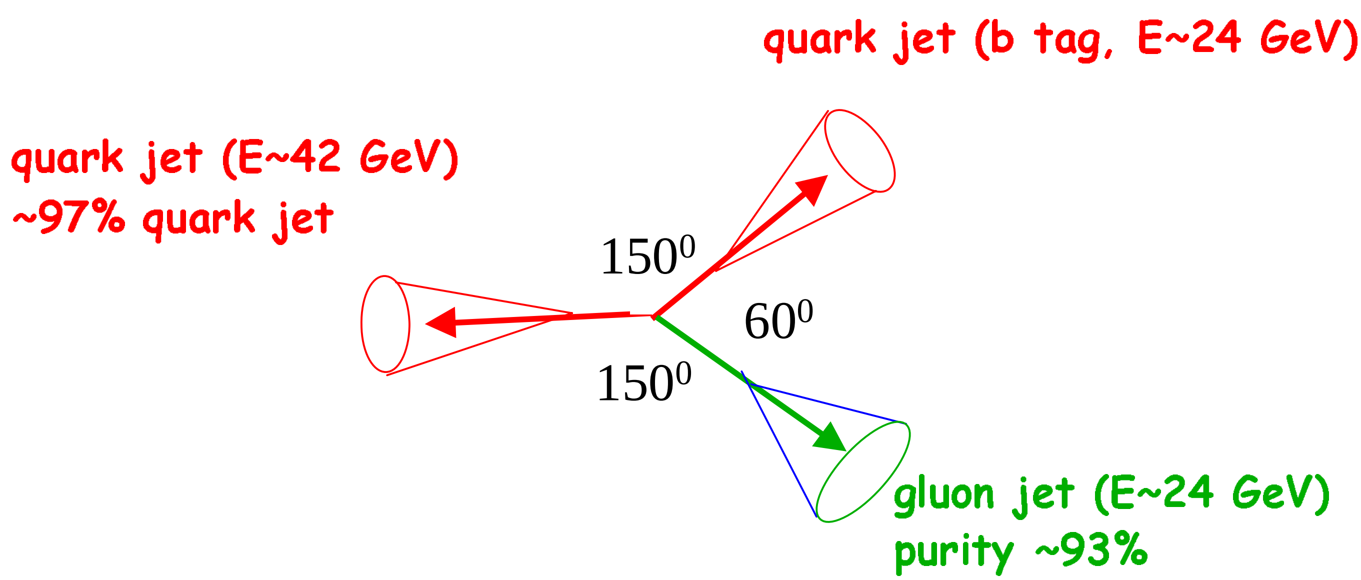
At Leading Order: $\quad r \sim \frac{C_A}{C_F} = \frac{9}{4}$

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

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

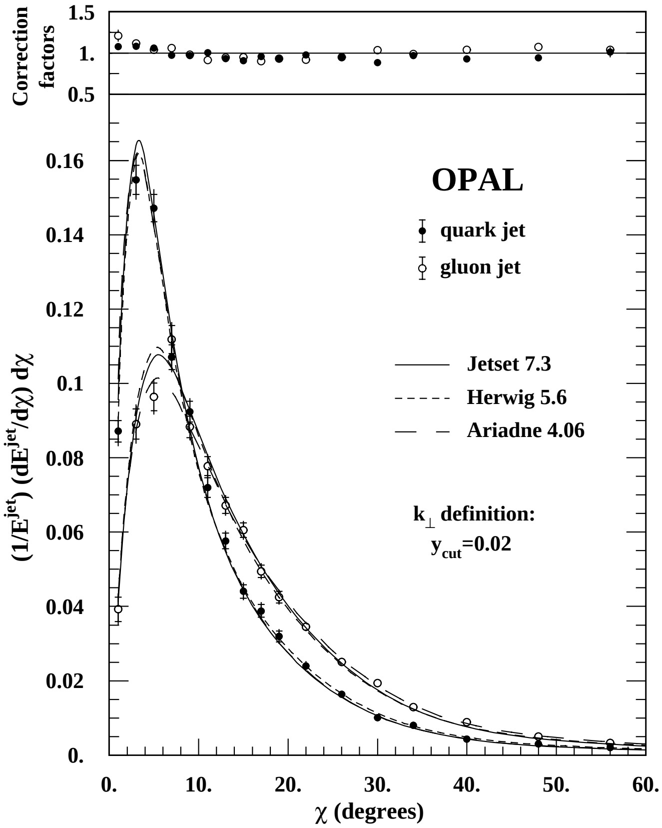
Quark vs Gluon Jets (LEP1)

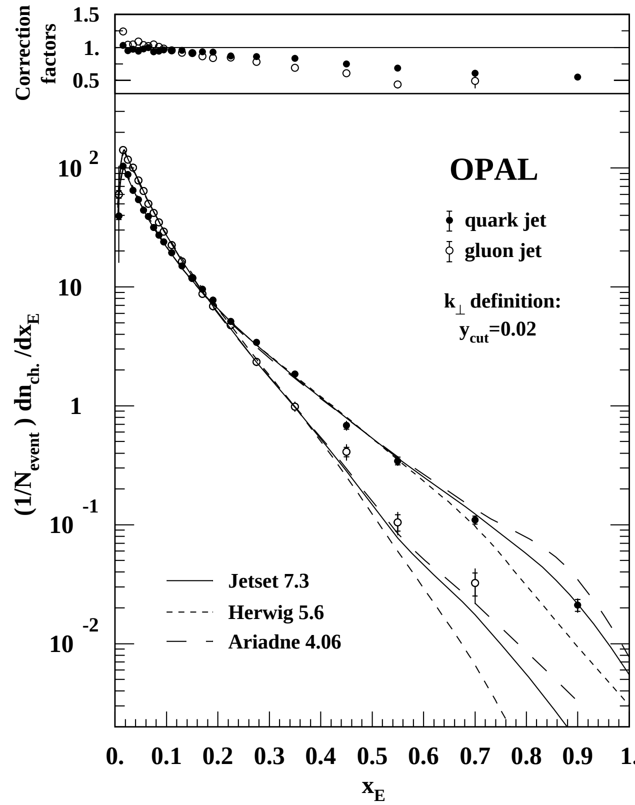
- Expectation:
  - Gluon jets are broader than quark jets
  - Gluon jets have softer fragmentation function than quark jets
- LEP1 measurement (OPAL)
  - Select three jet events

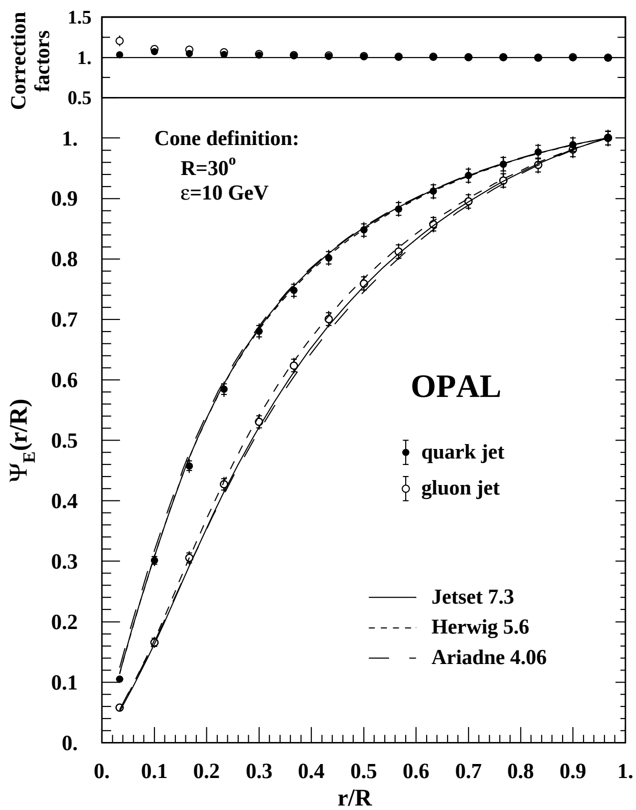


  - Repeat analysis with a "KT" (Durham) and "cone" jet algorithm in order to compare with Tevatron results

Quark vs Gluon Jets (LEP1)







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 a new analysis on gluon vs quark jets which is almost entirely independent of the choice of the jet finding algorithm used

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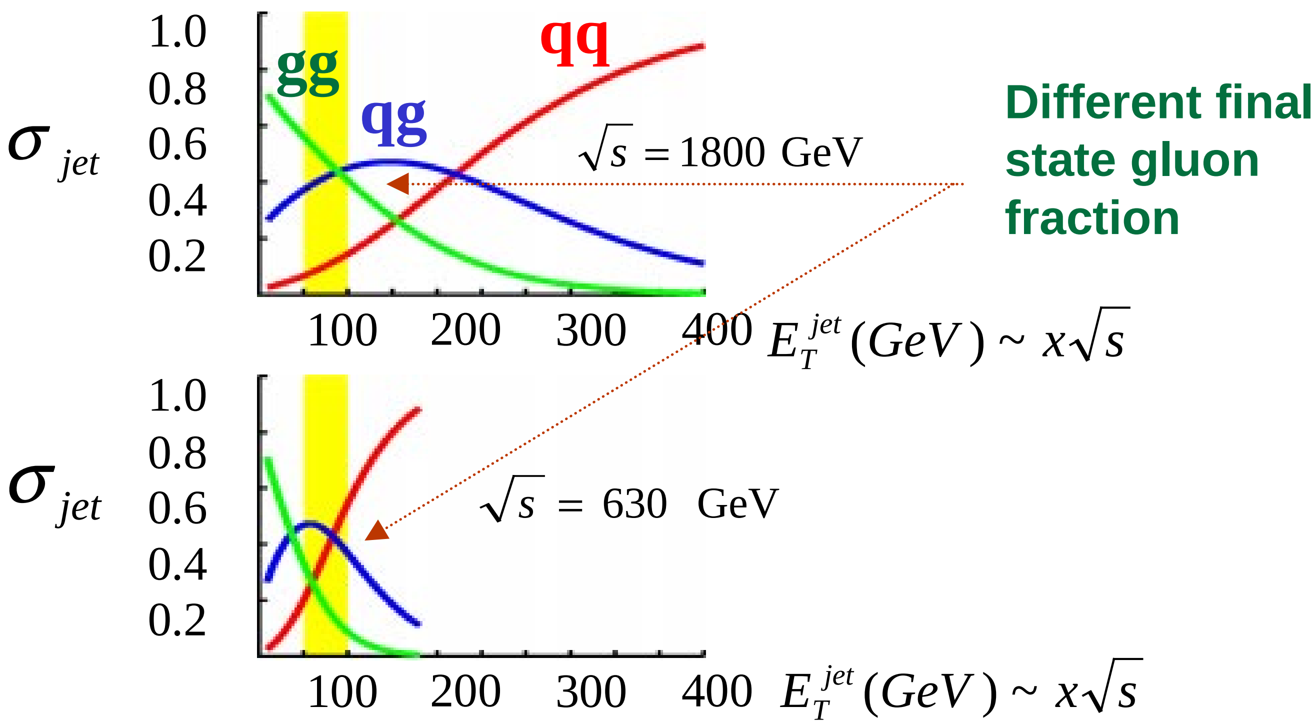
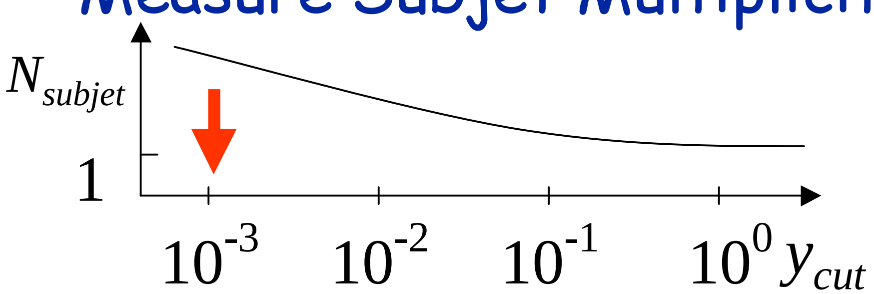
Quark vs Gluon Jets (Tevatron/D0)

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

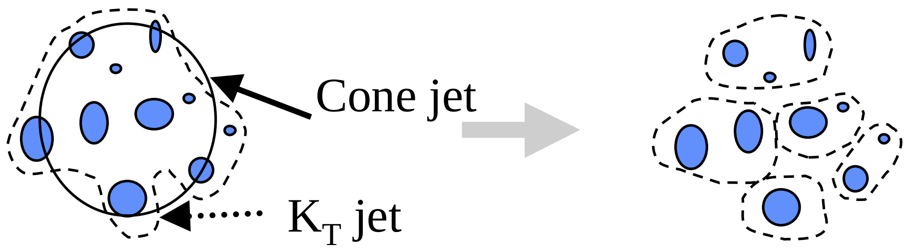


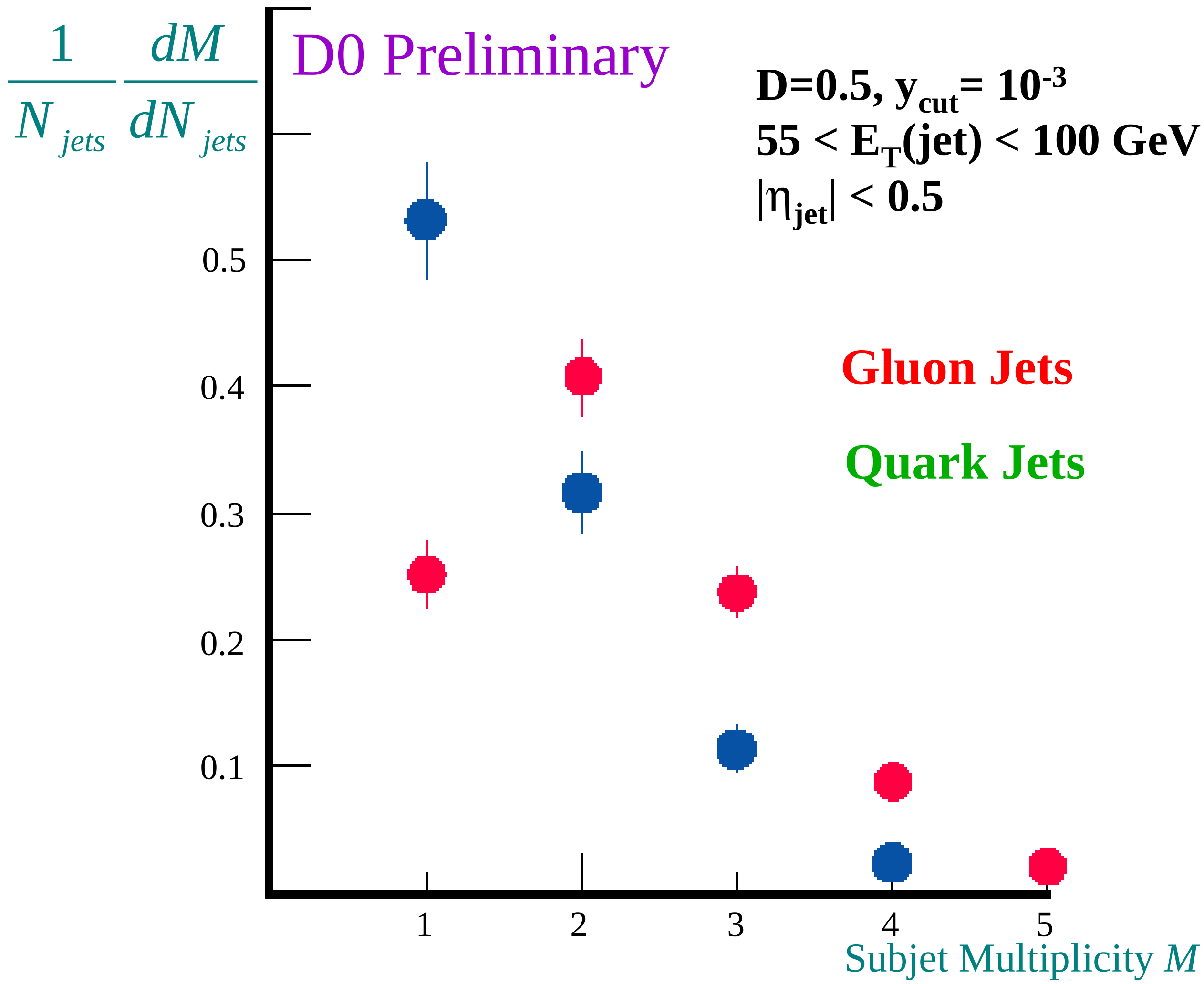
- Rerun k_T algorithm on all 4-vectors merged into jet:
  - Recombine energy clusters into subjets separated by y_{CUT} (a resolution parameter)
- Measure Subjet Multiplicity: $\left(\frac{\approx p_T^{rel}}{E_T^{jet}}\right)^2 > y_{cut},$



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

Subjet Multiplicity



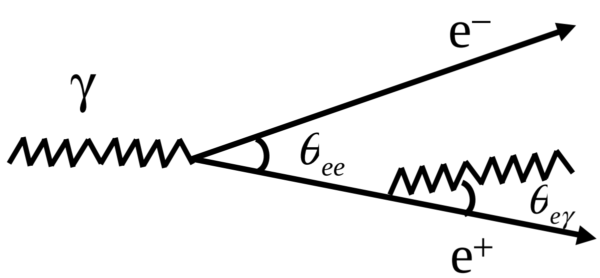


$$R = \frac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1} = 1.91 \pm 0.04$$ **(D0 Data)**

$$R = 1.86 \pm 0.04$$ **(HERWIG 5.9)**

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

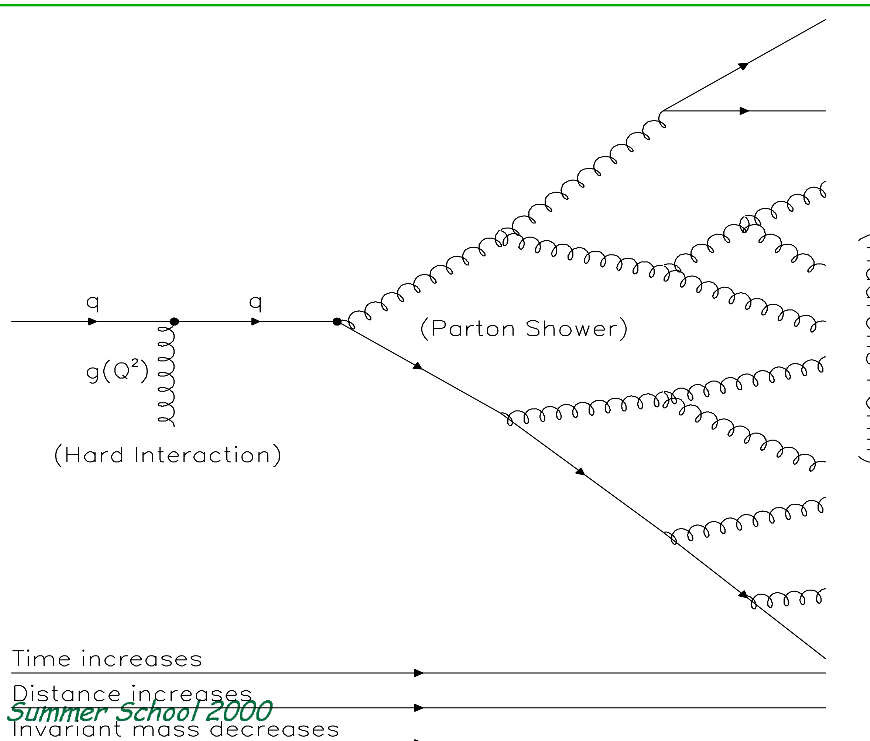
Shower Development

"Traditional Approach"

- Shower develops according to pQCD into jets of partons until a scale of $Q_0 \sim 1$ 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 $Q_0 \sim 250$ MeV.
- No hadronization process.
  Hadron spectra = Parton spectra
- Simplicity. Only two essential parameters (Λ_{QCD} and Q_0) and an overall normalization factor

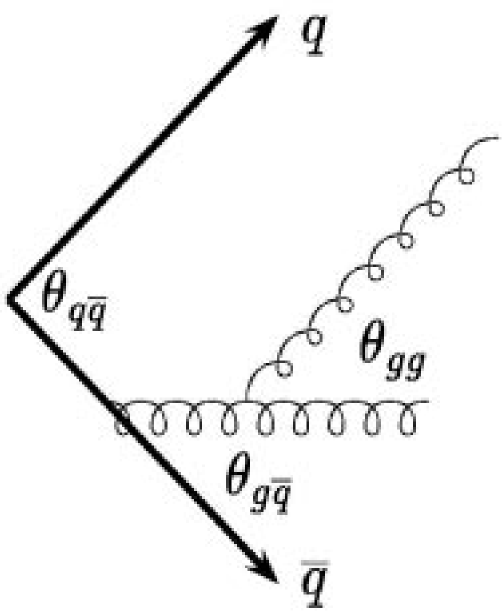


Intrajet Coherence

- 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

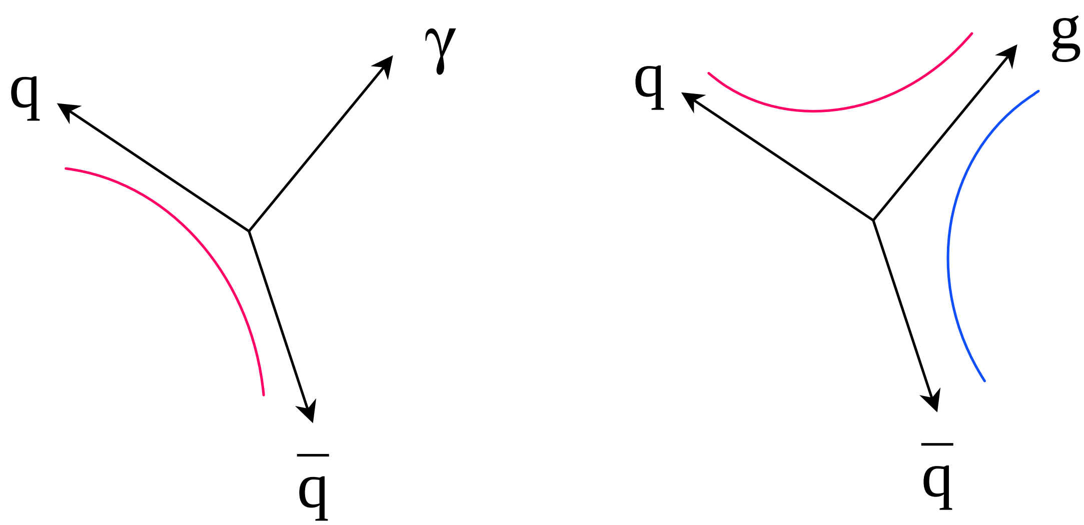
Non-Perturbative: Use phenomenological models to simulate the non-perturbative hadronization stage, e.g. the LUND string model or the cluster fragmentation model.

Interjet Coherence

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

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

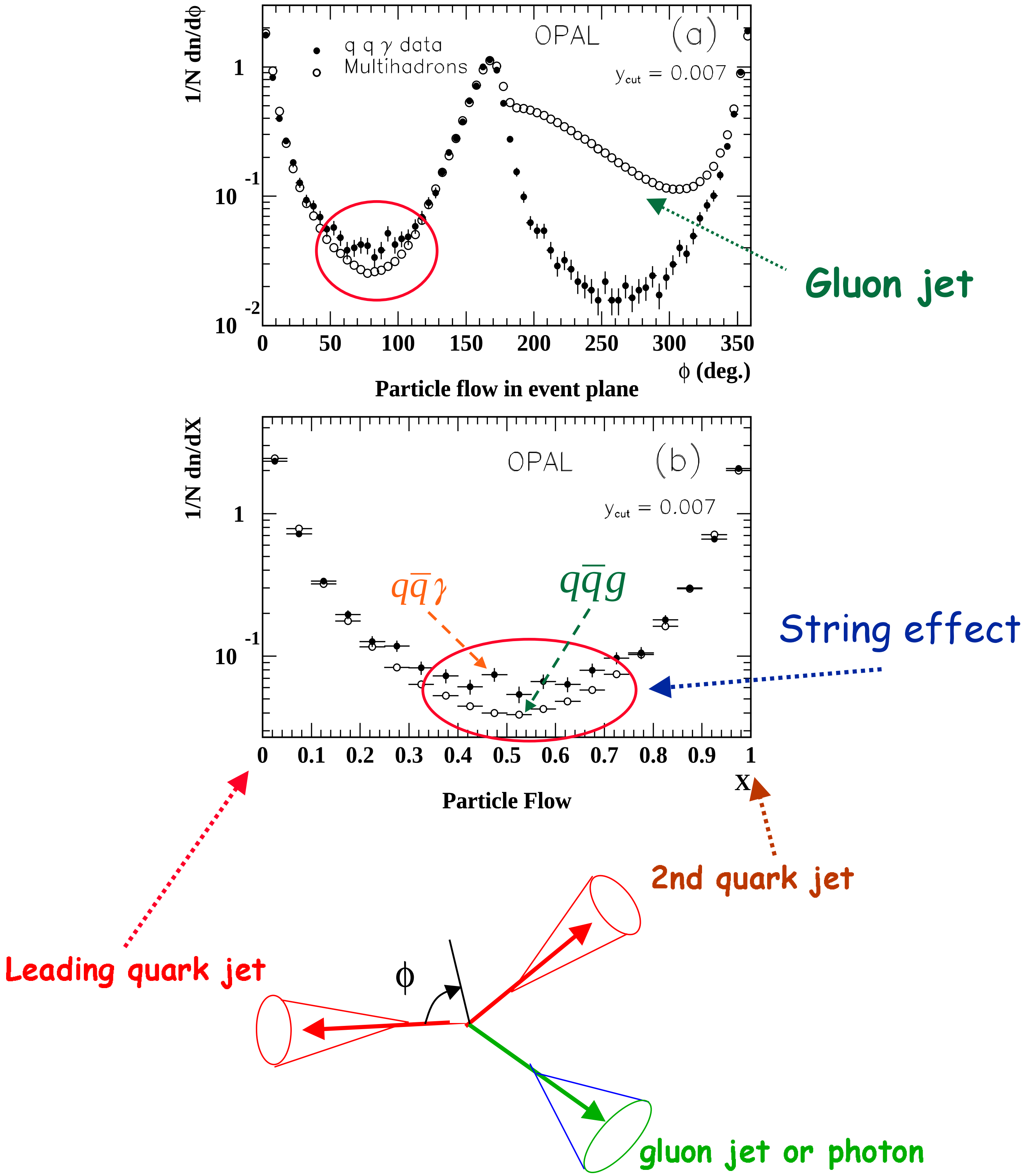
First observations of final state color coherence effects in the early '80's (JADE, TPC/2γ, TASSO, MARK II Collaborations) (**"string"** or **"drag"** effect)



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

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

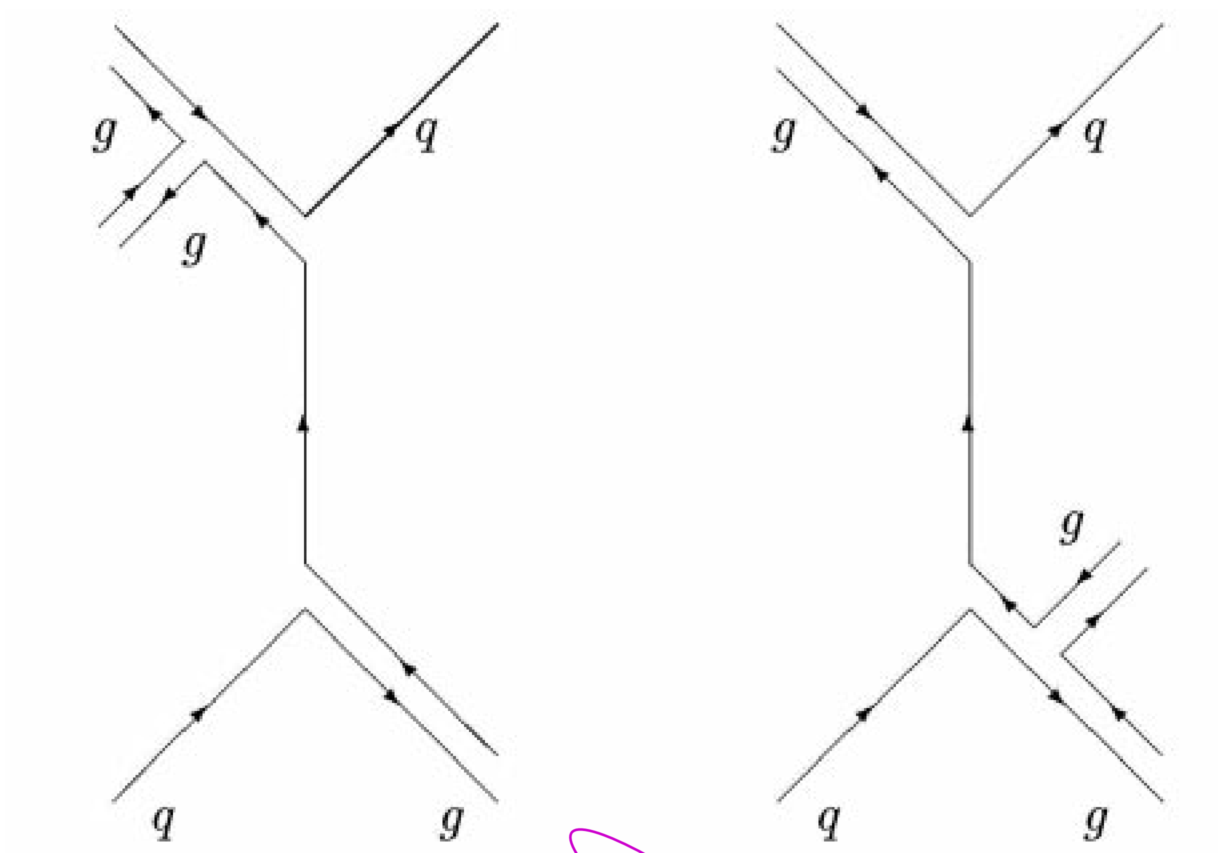


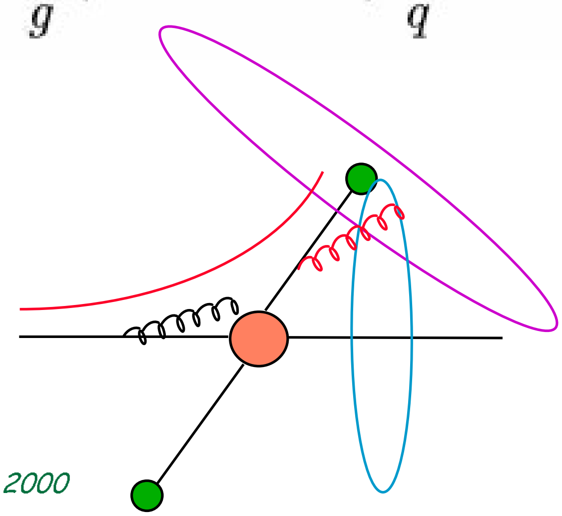
Interjet Coherence

$p\bar{p}$ interactions:

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

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





Results on Coherence

Intrajer Coherence

☞ Hump-backed plateau

Interjer Coherence

☞ Multijets

☞ Particle flow in W+Jets events

☞ String Effect in e^+e^-

• Experimental issues:

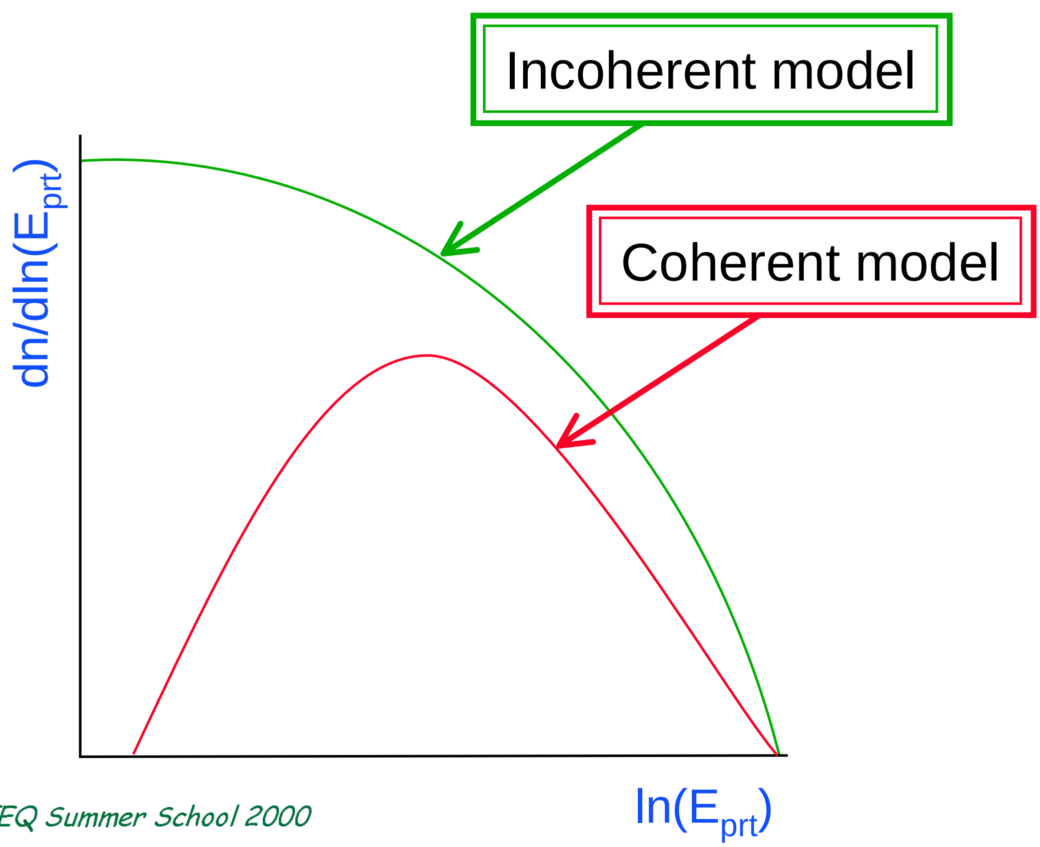
➨ Can Color Coherence effects survive hadronization process?

➨ What is relative importance of perturbative vs. non-perturbative contributions?

Hump-backed plateau

- Direct consequence of CC+LPHD
- Depletion of soft particle production within jets
- Approximately Gaussian shape of inclusive distribution in the variable $\xi=\ln(E_{jet}/E_{prt})=\ln(1/x)$
- The height of the *hump* is increasing with energy and peaks at $E_{prt} \sim E_{jet}^{0.5}$
- Analytic calculations: MLLA+LPHD

$$\frac{1}{\sigma}\frac{d\sigma}{d\xi_p} = K_{LPHD} \bullet f\left(\xi_p, Y, \lambda\right) \qquad Y = \log\frac{\sqrt{s}}{Q_0} \; ; \; \lambda = \log\frac{Q_0}{\Lambda}$$

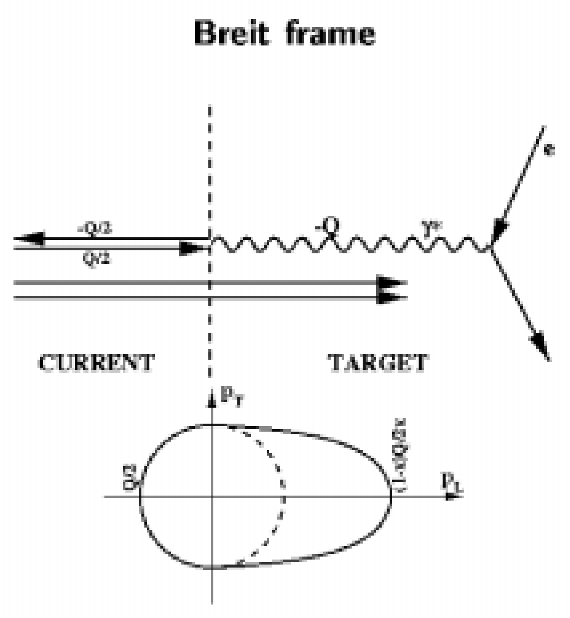


Hump-backed plateau

Results

Charged hadron inclusive fragmentation functions

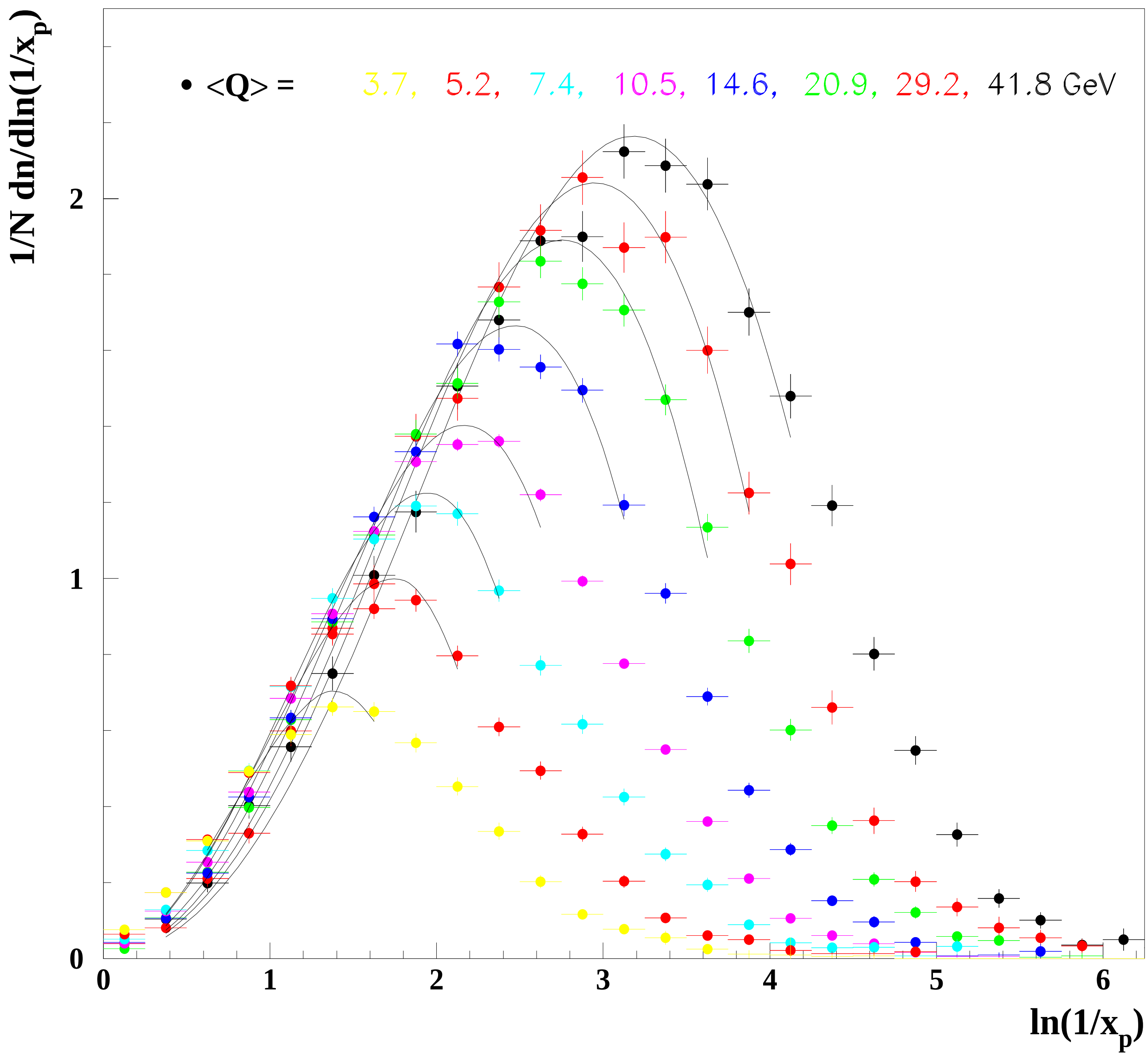
HERA



- P_T of tracks > 150 MeV/c
- Studies performed at the Breit Frame of Reference
- Concentrate on the "current" hemisphere of the interaction (fragmentation products of the outgoing quark)
- The DIS "current" fragmentation (CF) functions at a momentum transfer Q are analogous to the e^+e^- fragmentation functions at center of mass energy equal to Q
- Test of the universality of fragmentation functions

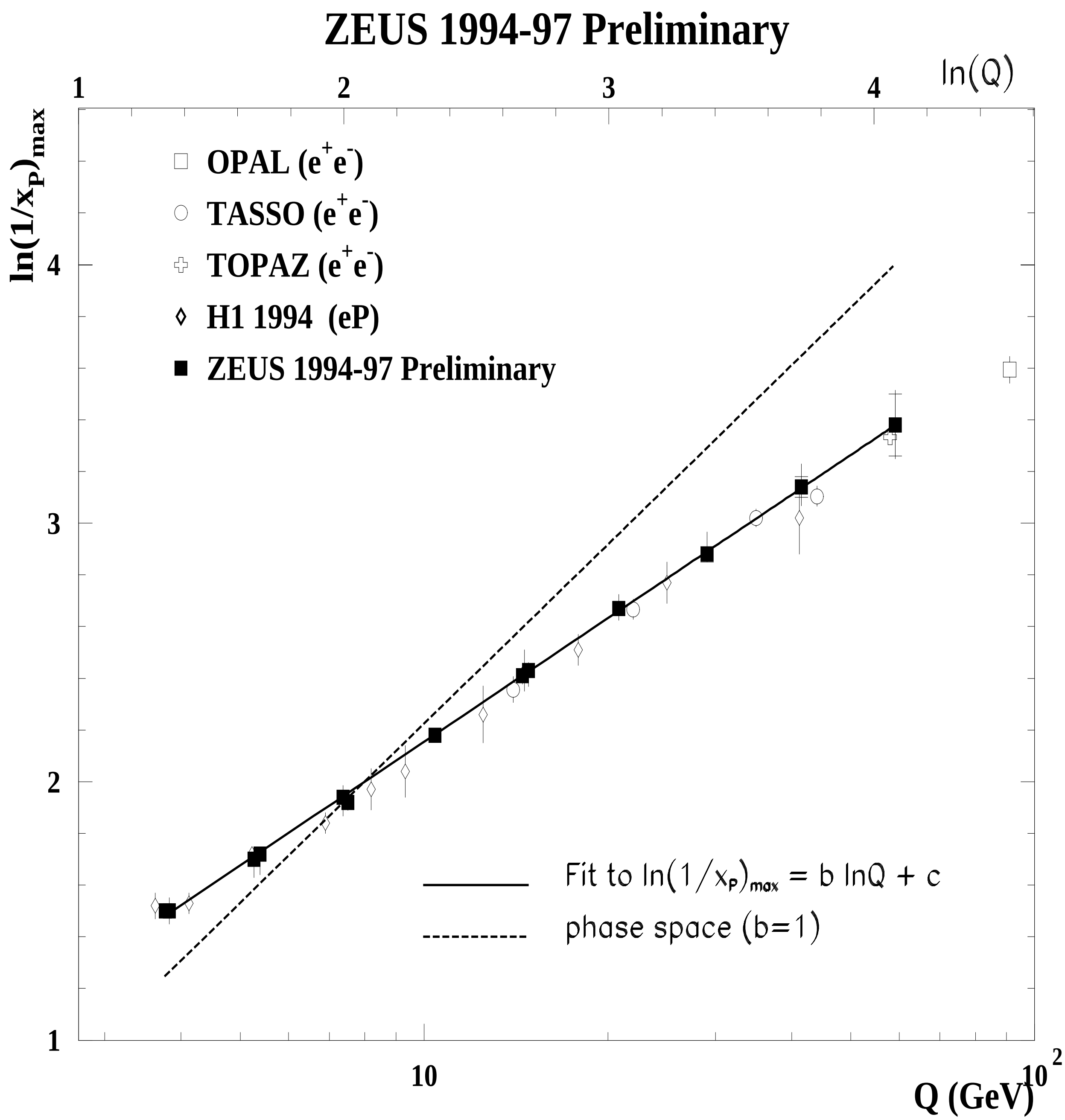
$\log(1/x_p)$ evolution

ZEUS 1994-97 Preliminary



- MLLA curves fit data well
- clear increase of $\ln(1/x_p)_{max}$ and multiplicity with Q

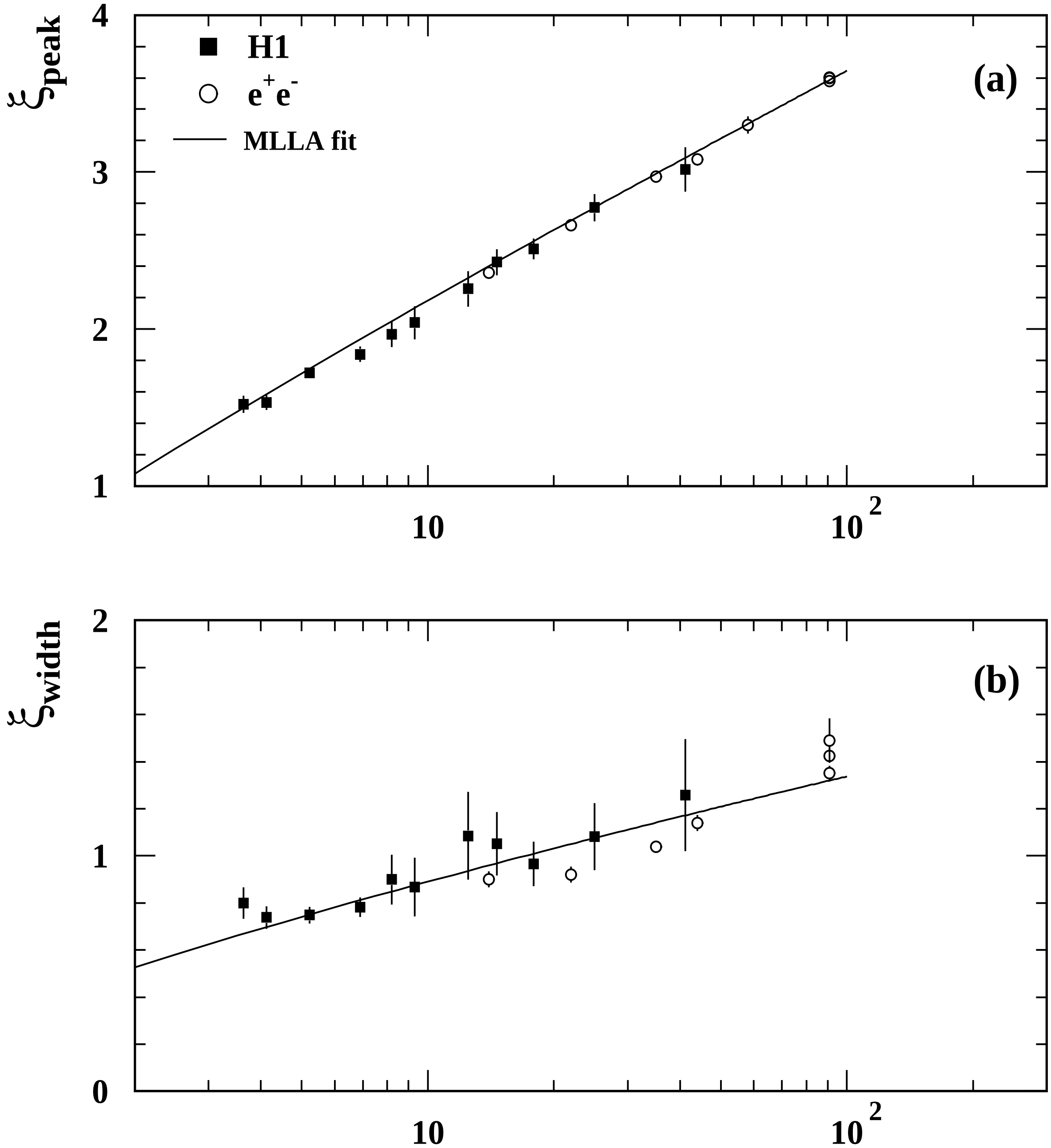
$\xi^* \ (\xi_{peak}) \equiv \log(1/x_p)_{max}$ evolution



- Incoherent fragmentation (phase space) excluded by both DIS & e^+e^-
- MLLA fit (not shown) with Y=log(Q/2Λ):

$$\log(1/x_p)_{\max} = 0.5Y + c\sqrt{Y} - c^2 \Rightarrow \Lambda_{eff} \approx 245\text{MeV}$$

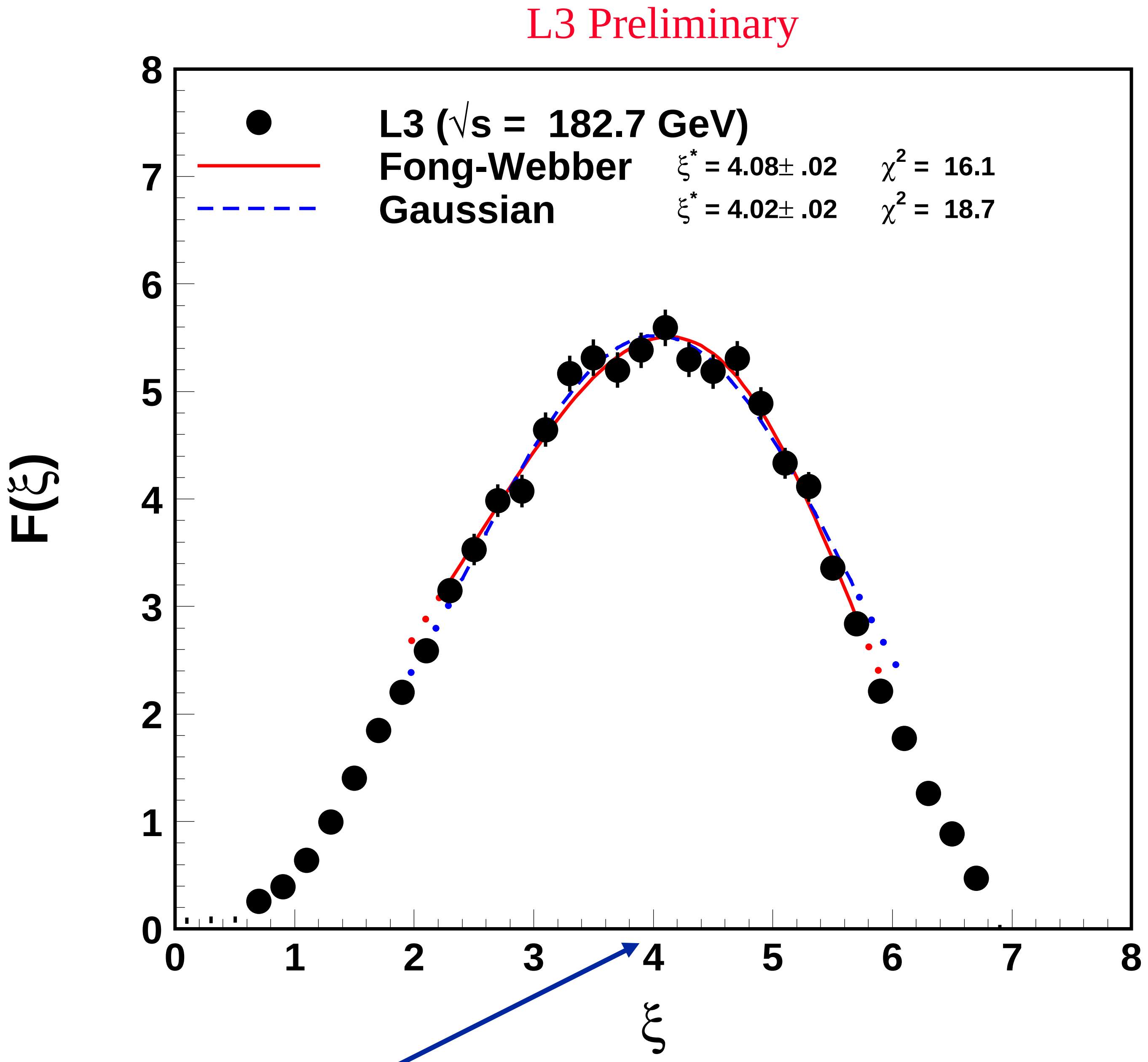
ξ_{peak} and ξ_{width} evolution



- MLLA predictions fit data well
- A simultaneous fit to the peak and width values of H1 data, yields a value of Λ_{eff}=0.21 ± 0.02 GeV, in agreement with LEP

Results from LEP

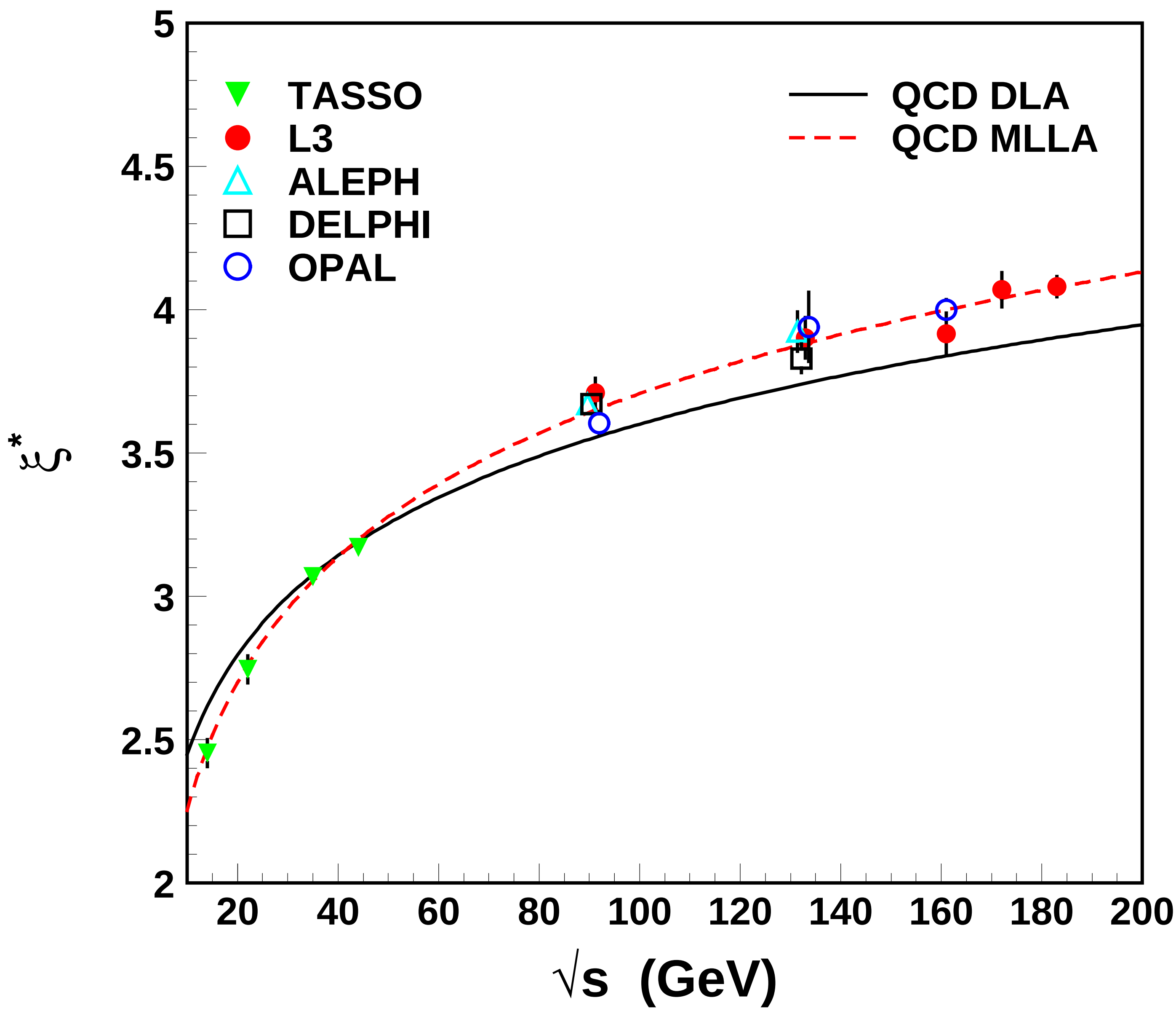
$\log(1/x_p)$ evolution



ξ^*(183 GeV) = 4.08 ± 0.02 ± 0.03

$\log(1/x_p)_{max}$ evolution

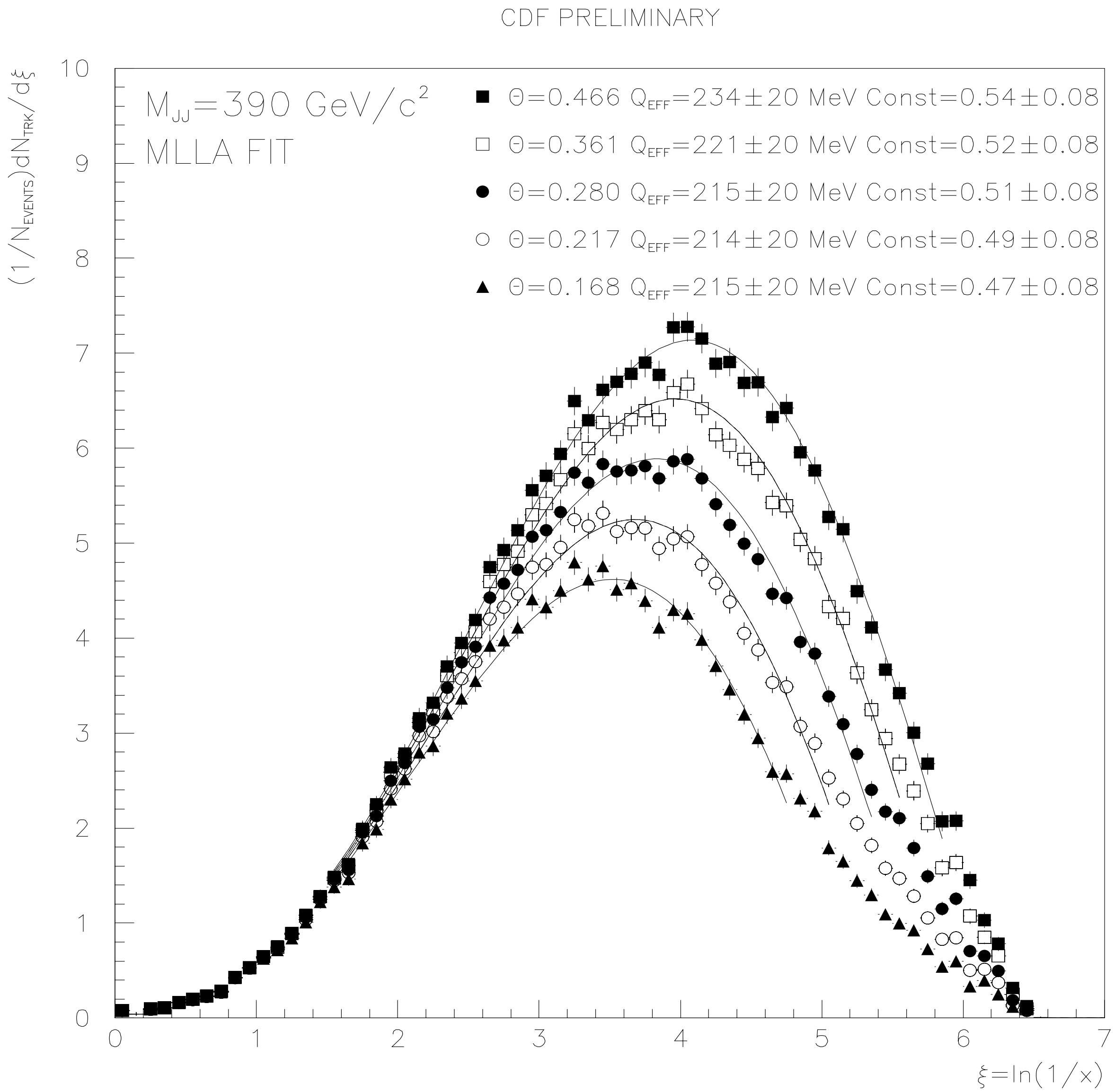
L3 Preliminary



MLLA prediction fits the data better than DLA

Results from TEVATRON

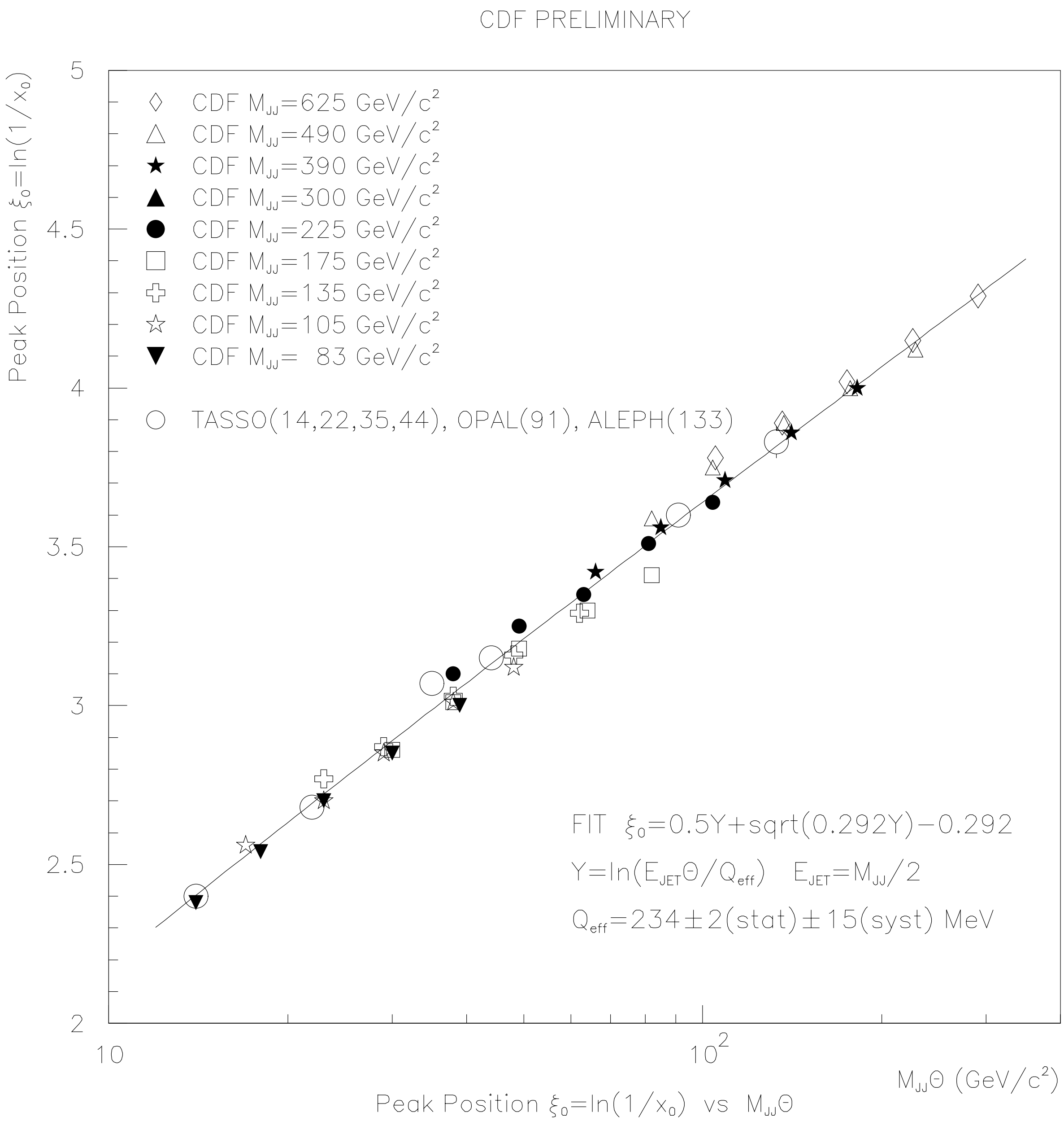
log(1/x_p) evolution



Dijet events: $E_{jet} = M_{jj}/2,\ Y = \ln\left(\frac{E_{jet}\cdot\theta_{cone}}{Q_{eff}}\right),\ \xi = \ln\frac{E_{jet}}{p_{trk}}$

$$Q_{eff} \equiv Q_0 = \Lambda_{QCD}$$

$\log(1/x_p)_{max}$ evolution

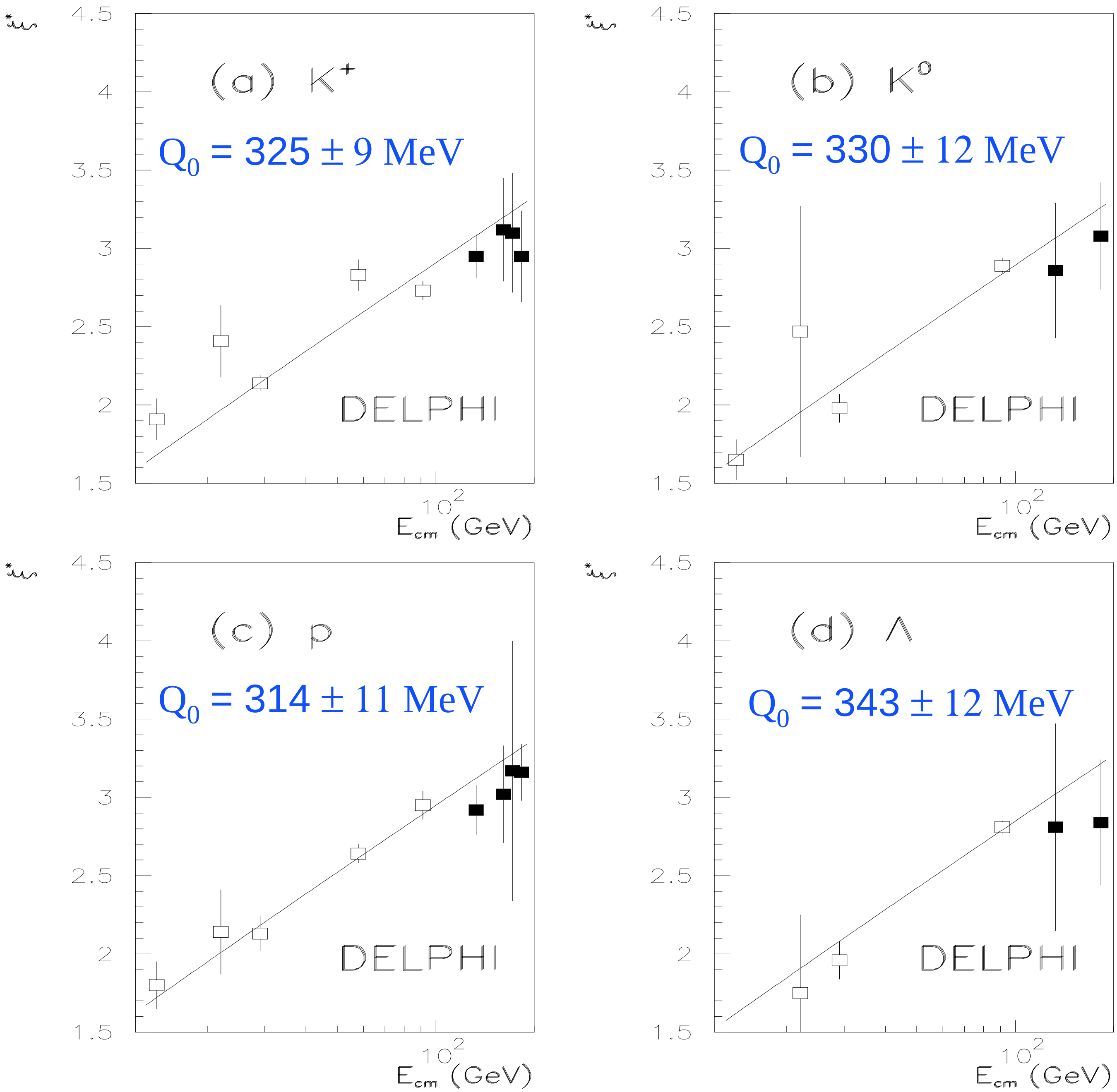


Excellent agreement with MLLA prediction

Production of identified particles

ξ^* evolution

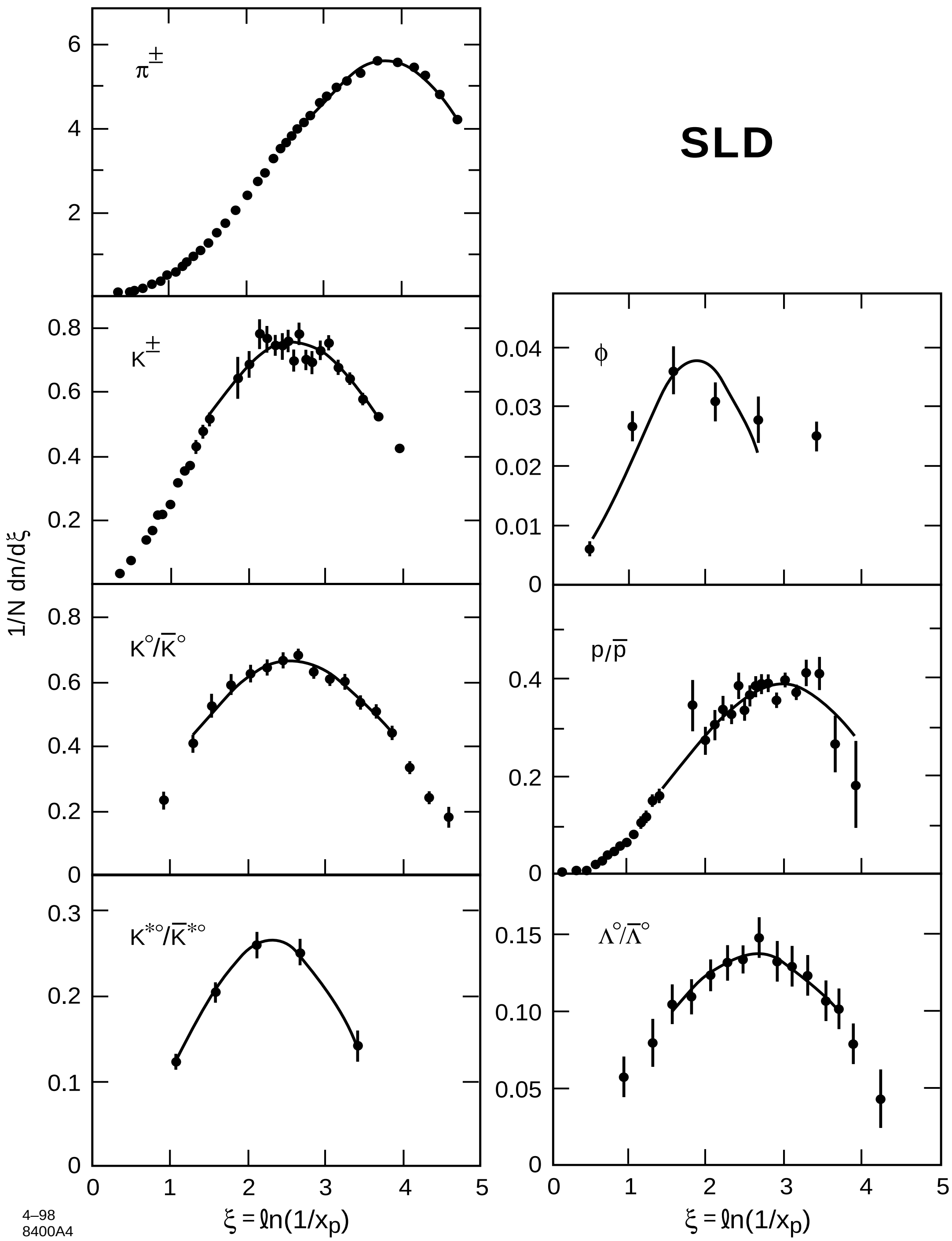
DELPHI Preliminary



- MLLA+LPHD fits the data well (Λ=150 MeV)
- Momentum cut-off parameter Q_0 ~ 330 MeV

Production of identified particles

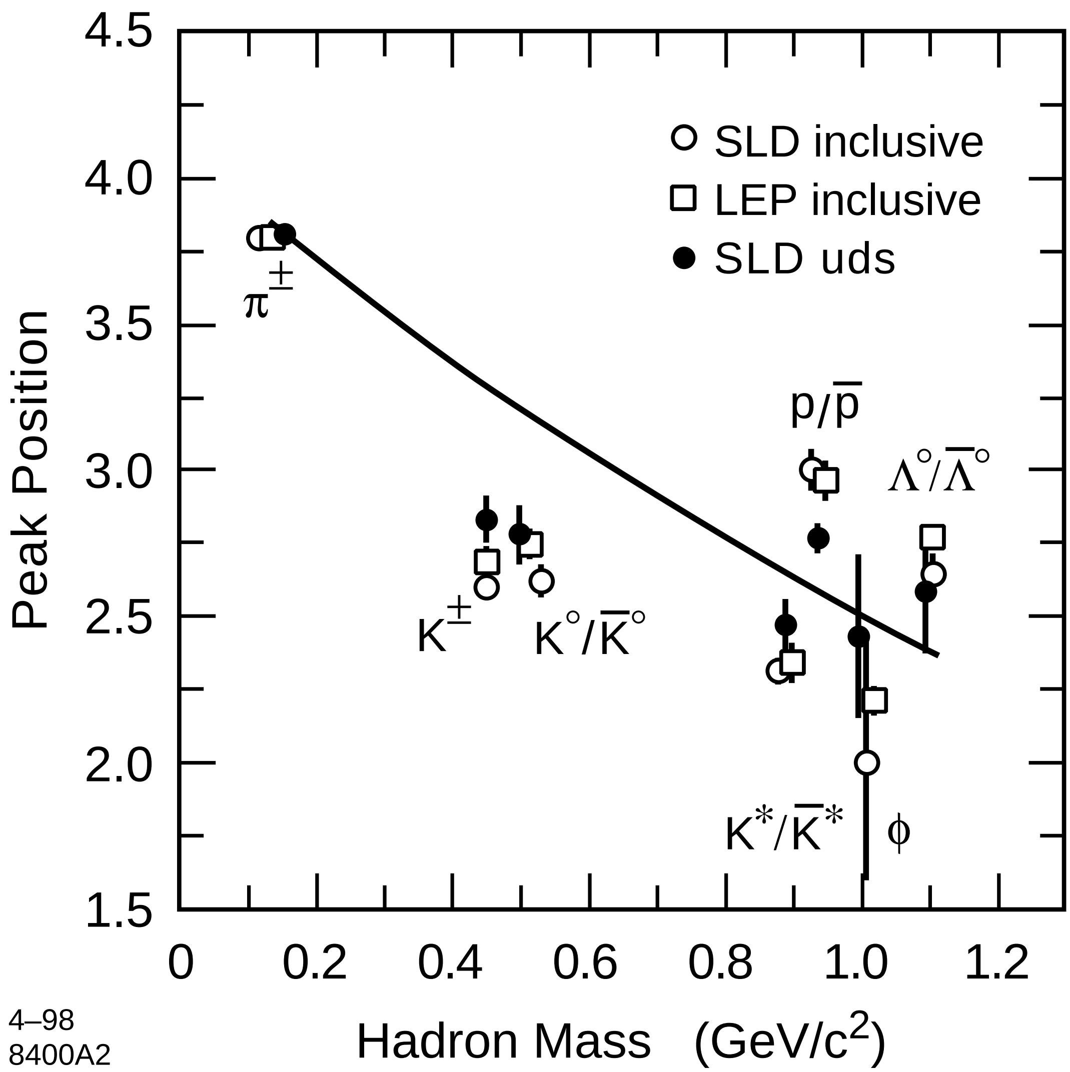
ξ distribution



Production of identified particles

ξ^* vs Hadron Mass

SLD



Except for pions, there is no monotonic mass-dependence of the peak position ξ^*

or

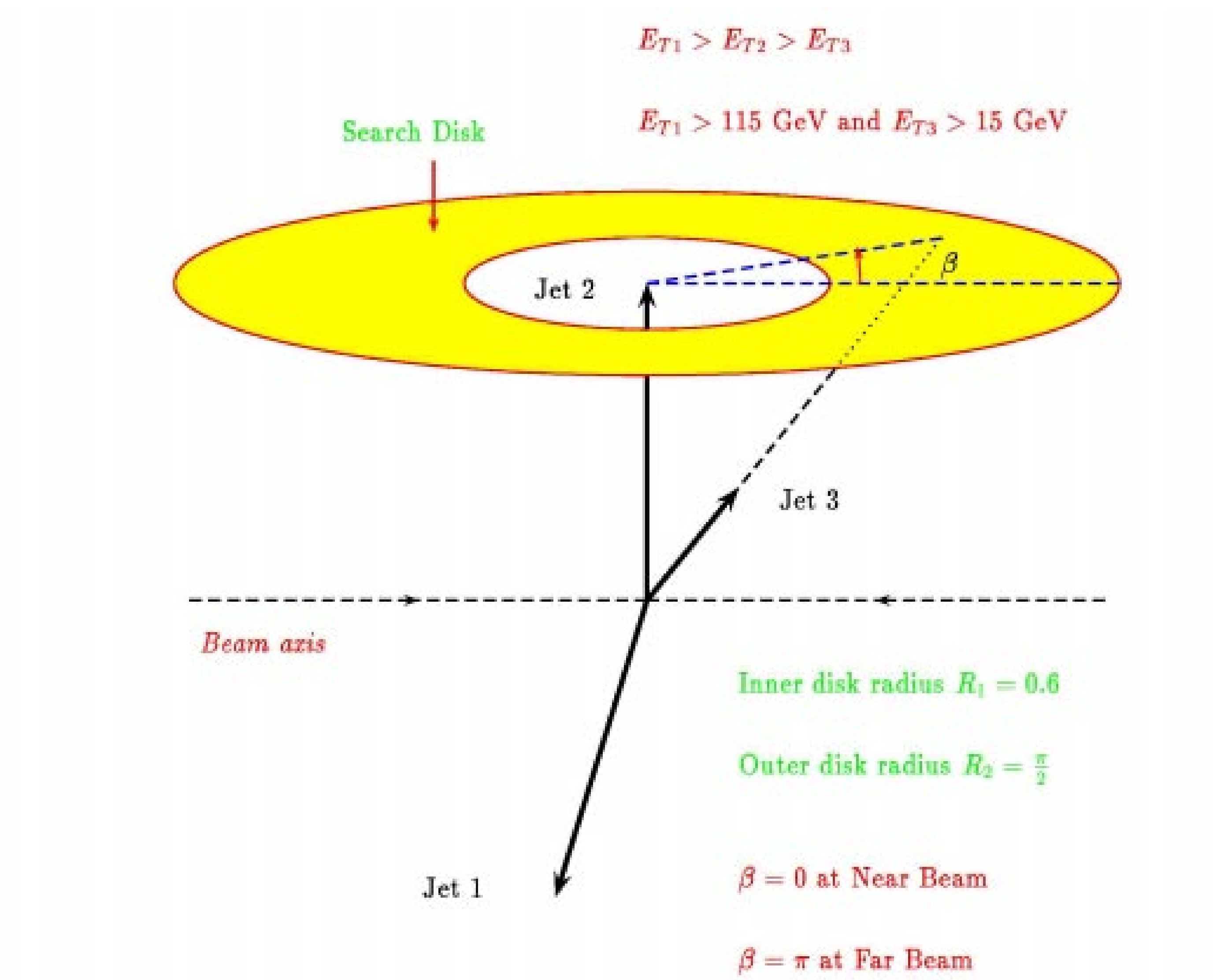
the peak position decreases vs mass differently for mesons and baryons (why? LPHD?)

Multijets Results

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

- 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



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

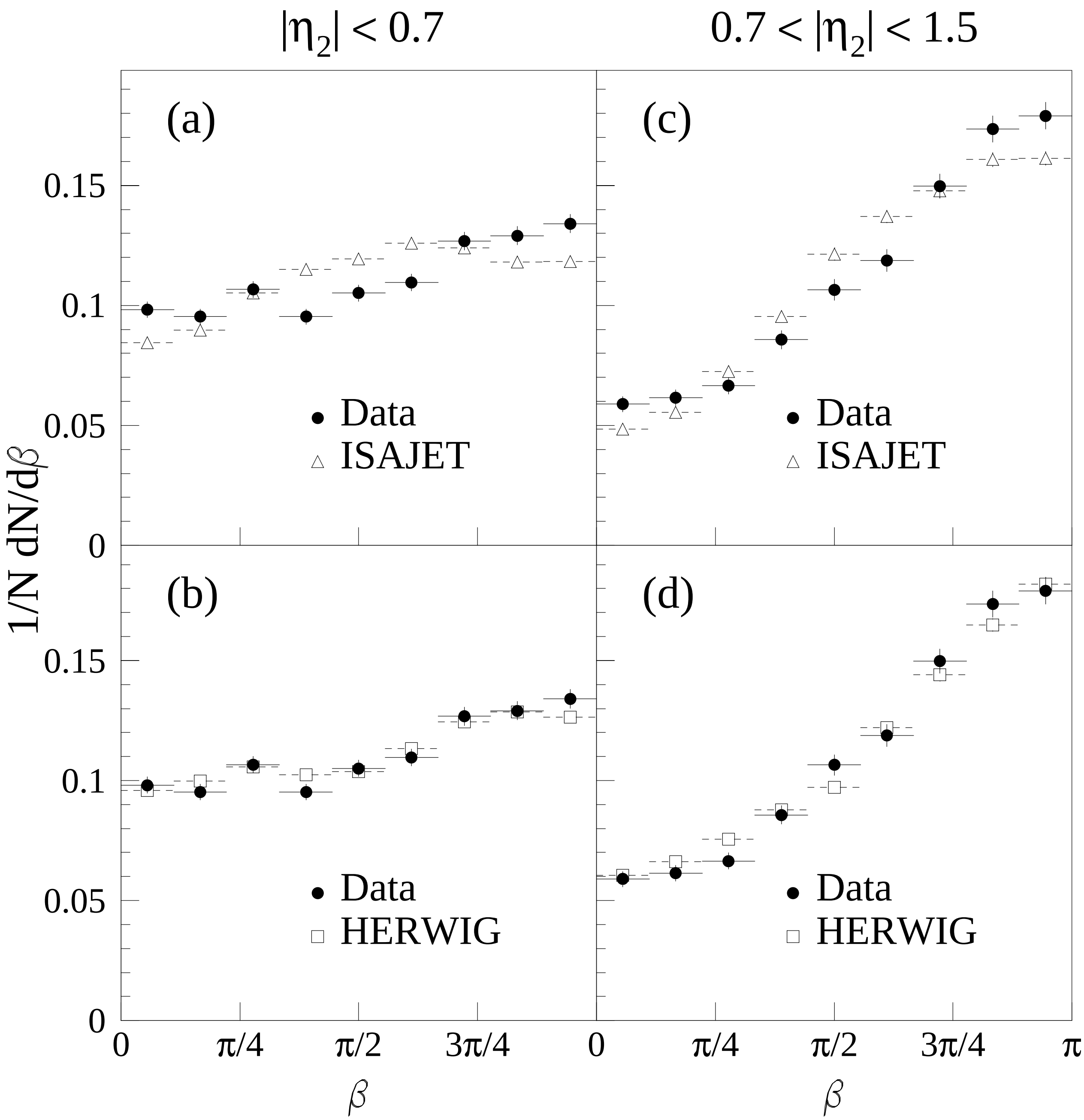
Monte Carlo Simulations

- 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

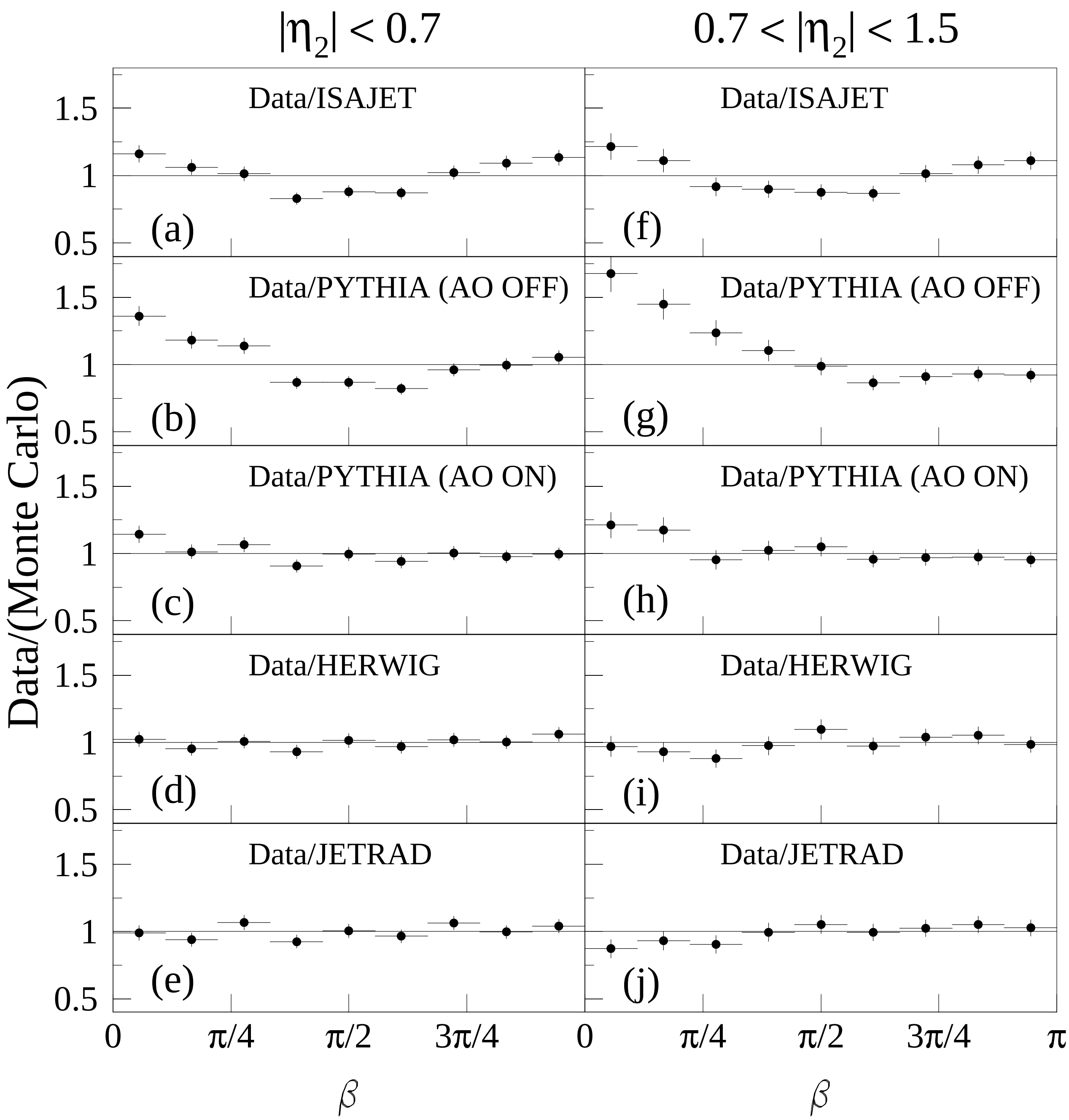
- **Parton-level pQCD calculation**:
  - JETRAD v1.1
    - $O(\alpha_s^3)$ parton level, one loop $2 \to 2$, tree level $2 \to 3$ scattering amplitudes
    - No fragmentation

3–jet β distributions



HERWIG agrees with the data distributions

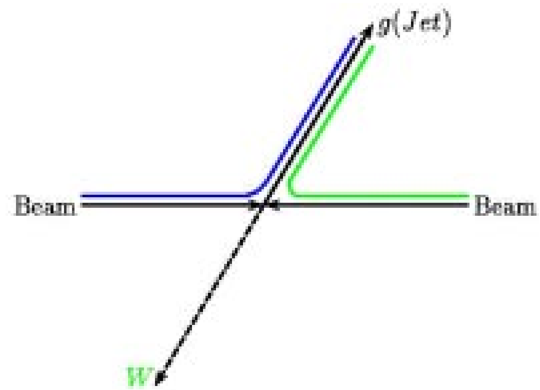
3–jet Data/Monte Carlo



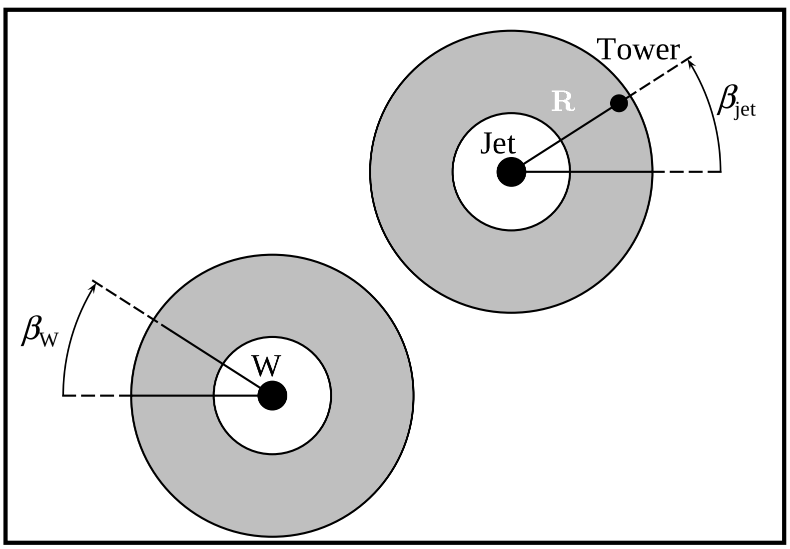
- HERWIG and JETRAD agree best with the data
- MC models w/o CC effects disagree with the data

W+Jet Analysis

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



Calorimeter view:



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

β range: $0 \rightarrow \pi$ (to improve statistics)

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

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

$$\beta = \tan^{-1}(\mathrm{sign}(\eta_{W,Jet})\, \Delta\phi / \Delta\eta)$$

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:

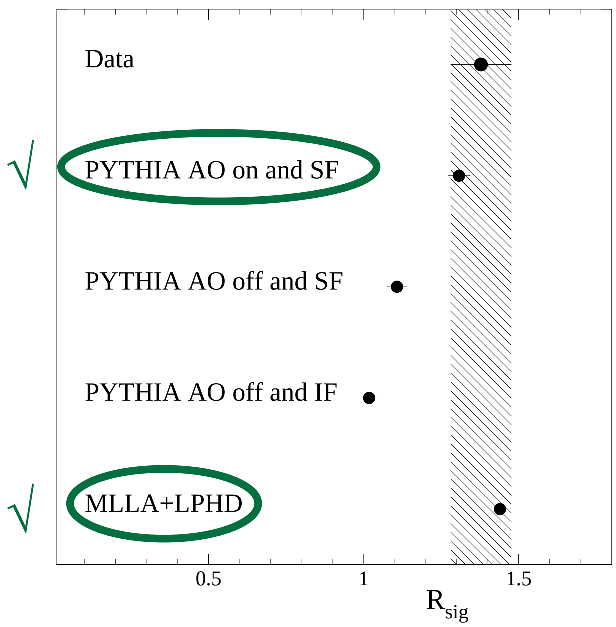
  "Full coherence": AO + String Fragmentation

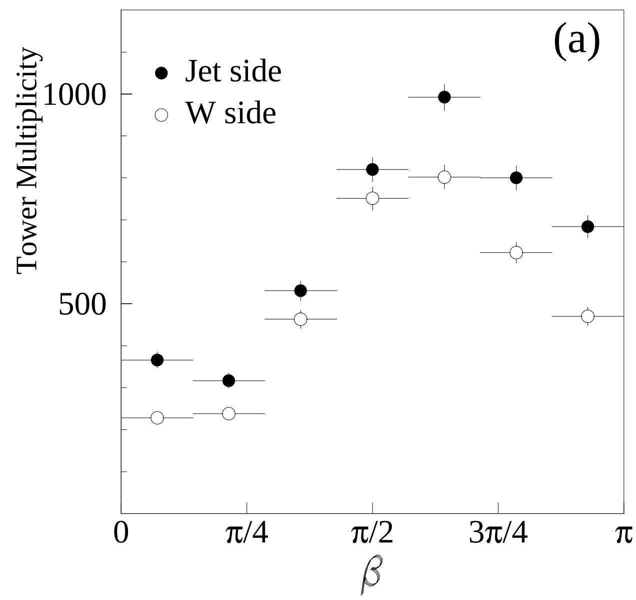
  "Partial": No AO + String Fragmentation

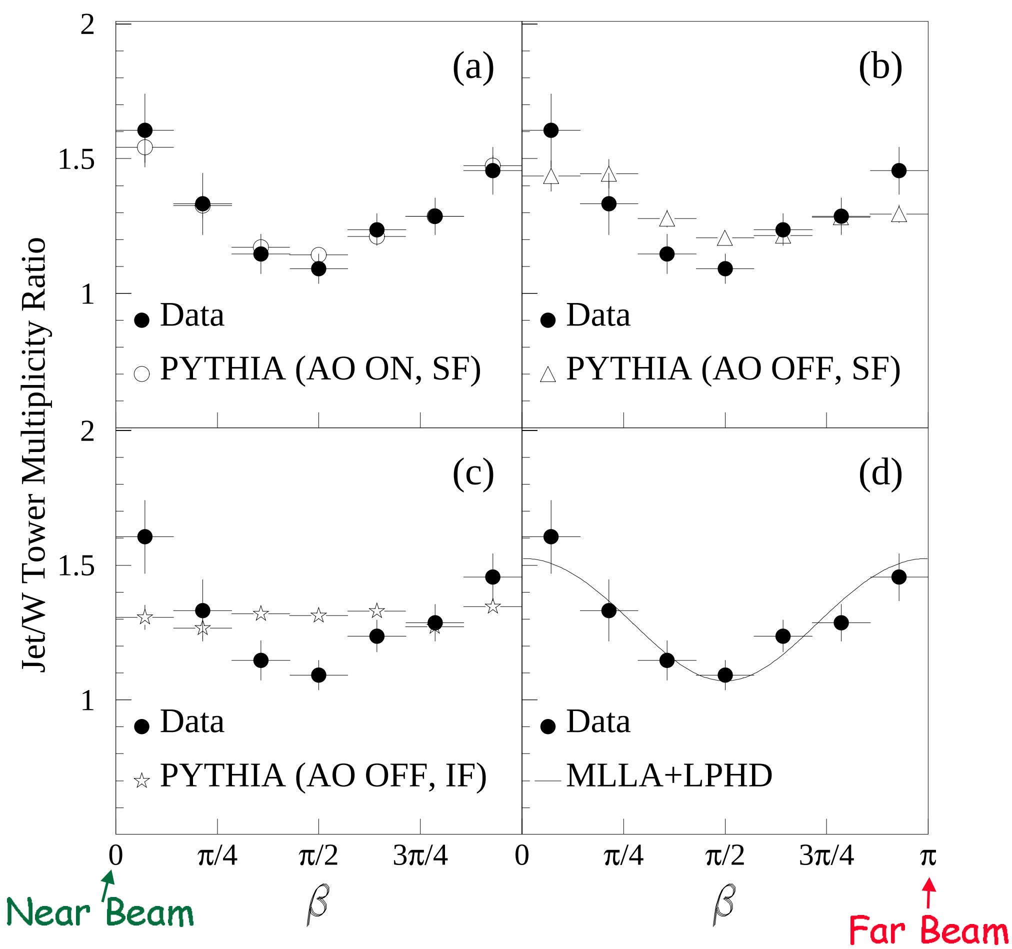
  "No coherence": No AO + Independent Frag.

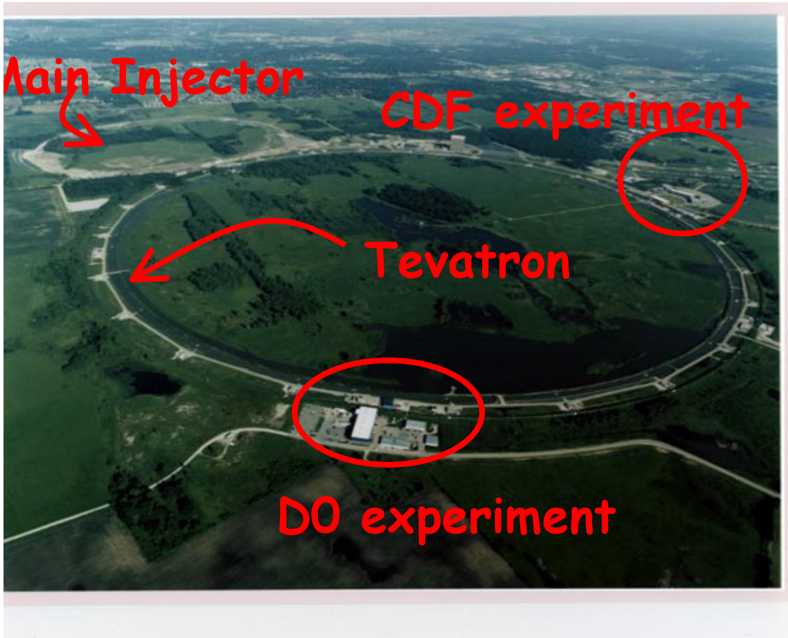
- **Analytic Predictions by Khoze and Stirling**
  - MLLA + LPHD
  - $q\bar{q}$–>Wg and qg–>Wq processes
  - hep-ph/9612351

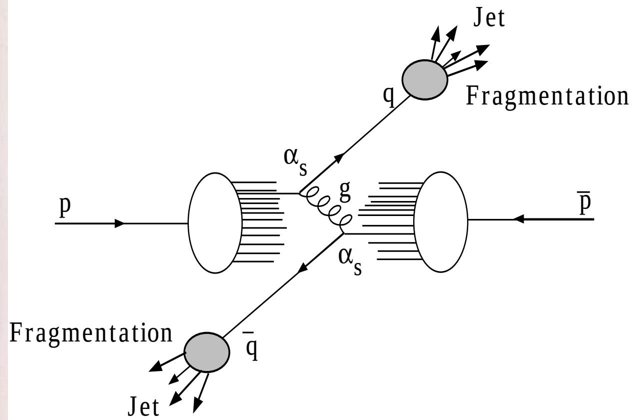
W+Jet Results



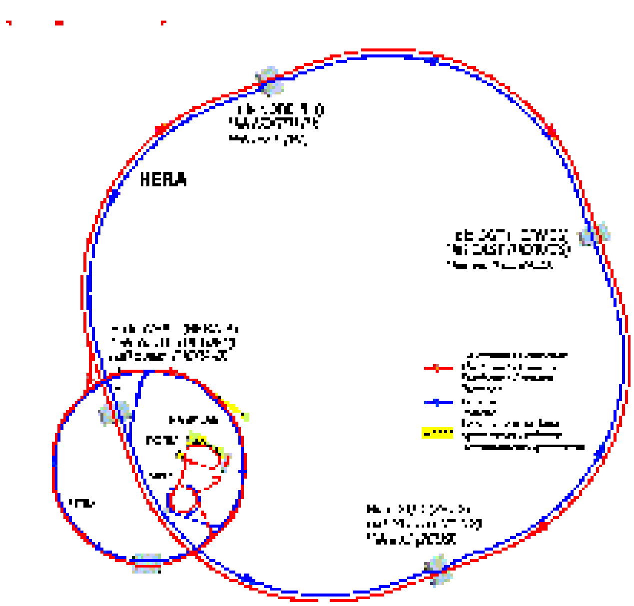


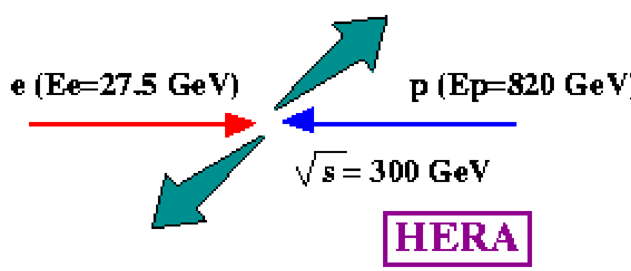






Jet Production





Jets at Tevatron

Motivation:

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

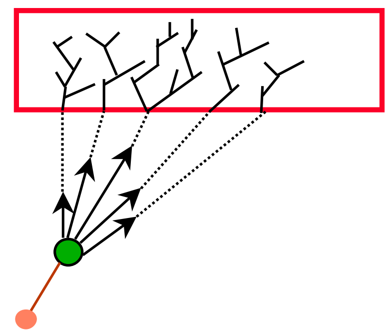
$$p_T^{\max} \sim 500\,GeV$$
$$\Rightarrow \text{distance} \sim \frac{\hbar c}{p_T} \sim \frac{200\,\text{MeV}\cdot\text{fm}}{500\,\text{GeV}} \sim 10^{-19}\,m$$

- Search for new particles decaying into jet final states
- Test of QCD in glory detail
  - inclusive jet production
    - cross sections vs rapidity, cross sections at different CM energies, jet shapes...
  - 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...

Jets:
From Detector to Hadron Level

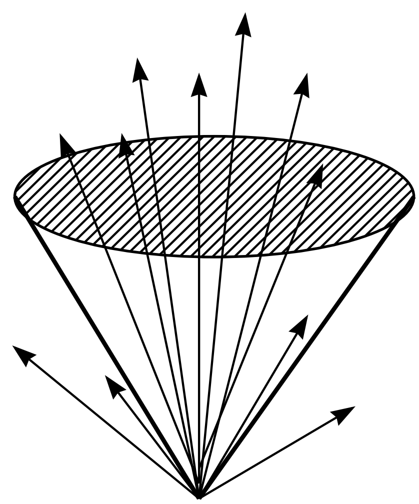
» Energy Scale

Detector



$E^{Jet}_{measured} < E^{Jet}_{particles}$

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



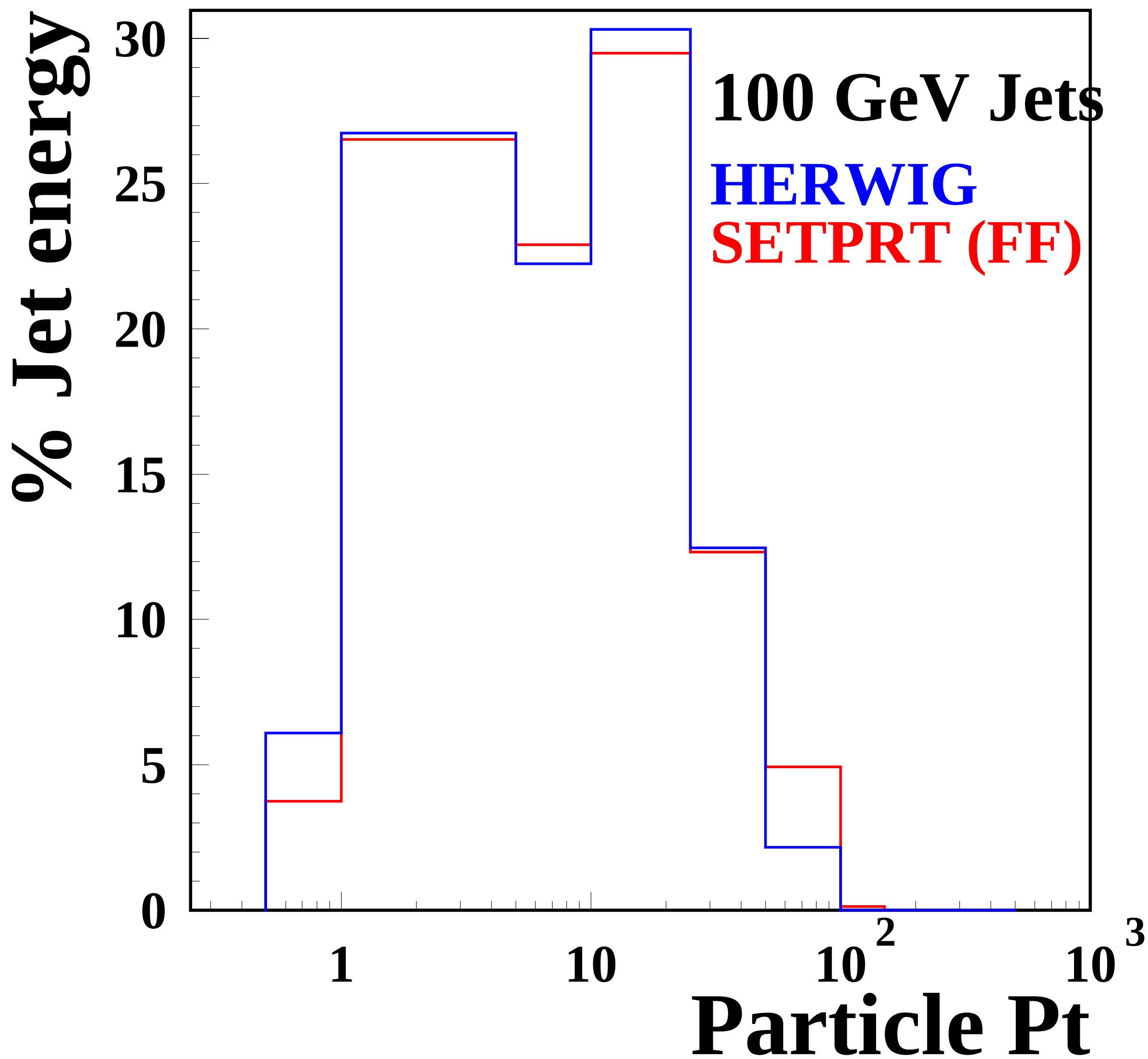
E^{ptcl} **"True" Jet Energy**

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

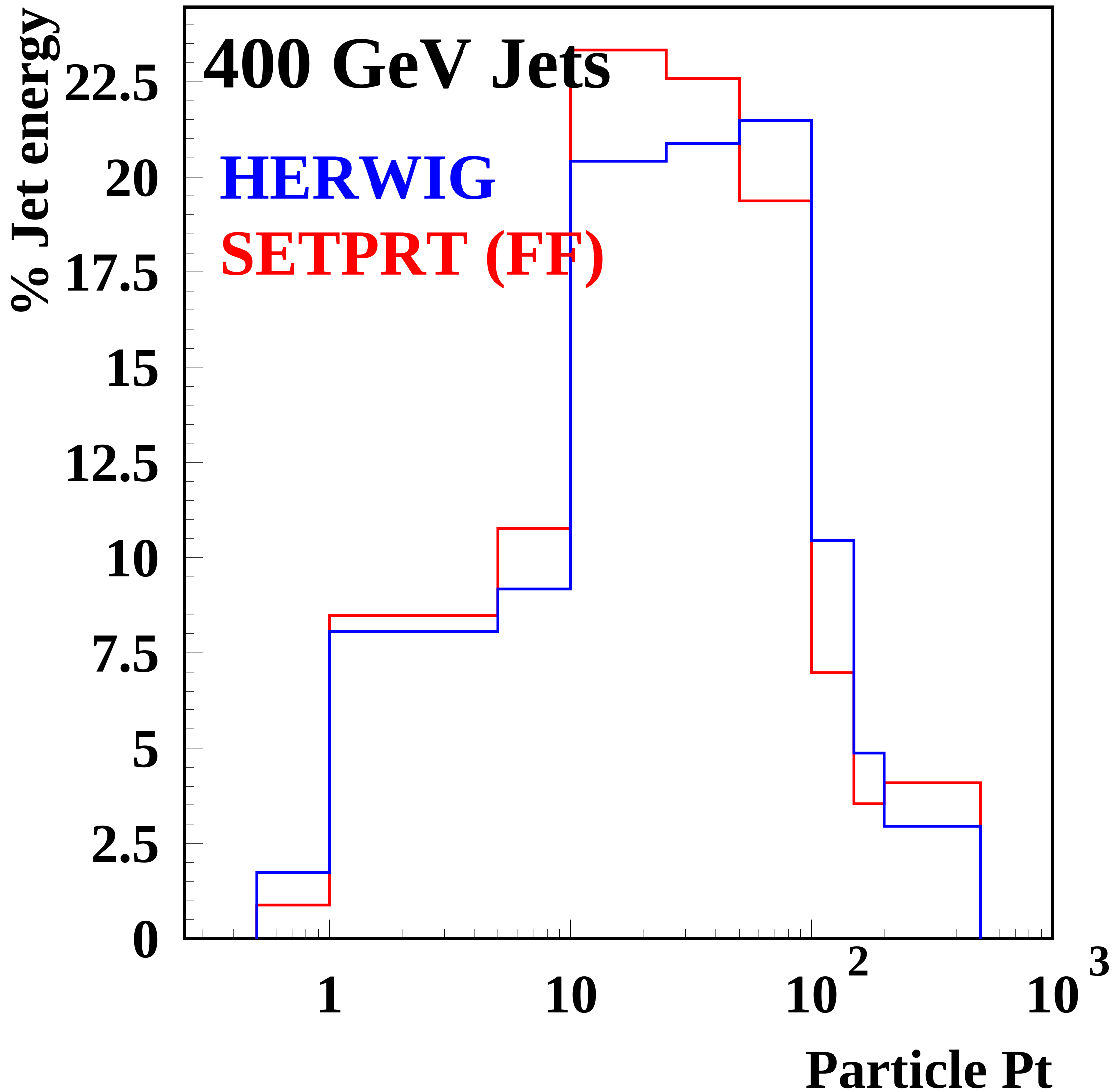
E_O **Offset (noise, Mult. Int., pile-up, UE)**

R_{jet} **Calorimeter Jet Response**

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



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

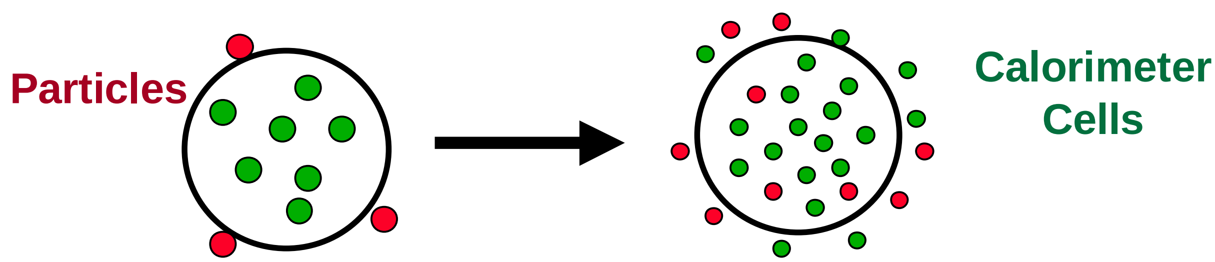


400 GeV Jets are primarily (80%) particles with $P_T < 100$ GeV.

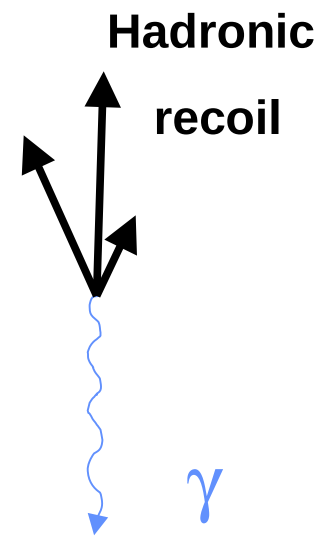
Only 3-4% of the jet E_T is carried by particles with $P_T \geq 200$ GeV.

Jets:
From Detector to Hadron Level cont'd

- **Offset**
  - Underlying event (UE):
    - At 1800 GeV, UE ~ 700 MeV/unit $\eta x \phi$, which corresponds to E~1GeV under a R=0.7 jet cone
    - At 630 GeV, UE ~ 500 MeV/unit $\eta x \phi$, which corresponds to E~0.8GeV under a R=0.7 jet cone
  - Noise, pileup, additional $p\bar{p}$ interactions
- **Response**
  - D0: hadronic response is determined from the missing transverse energy of photon+Jet events
  - CDF: jet response is determined using measured jet fragmentation and test beam/in situ calorimeter response information
- **Out of Cone Showering**
  - Correction increases as a function of η
  - It is measured from MC simulations



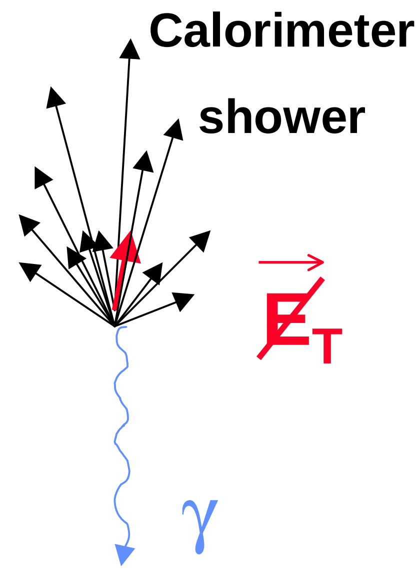
The MPF Method



Missing E_T Projection Fraction

$$\vec{P}_{T\gamma} = -\vec{P}_T^{had}$$

After calorimeter showering :



Missing E_T:

$$\vec{\not{E}}_T = -\sum_{i=1}^{n} \vec{P}_{Ti}$$

$$\vec{\not{E}}_T = -\left(\vec{P}_{T\gamma} + R_{had}\ \vec{P}_T^{had}\right)$$

$$\vec{\not{E}}_T = \vec{P}_{T\gamma}\left(R_{had} - 1\right)$$

$$R_{had} = 1 + \frac{\vec{\not{E}}_T \cdot \hat{n}_\gamma}{P_{T\gamma}} = 1 + MPF$$

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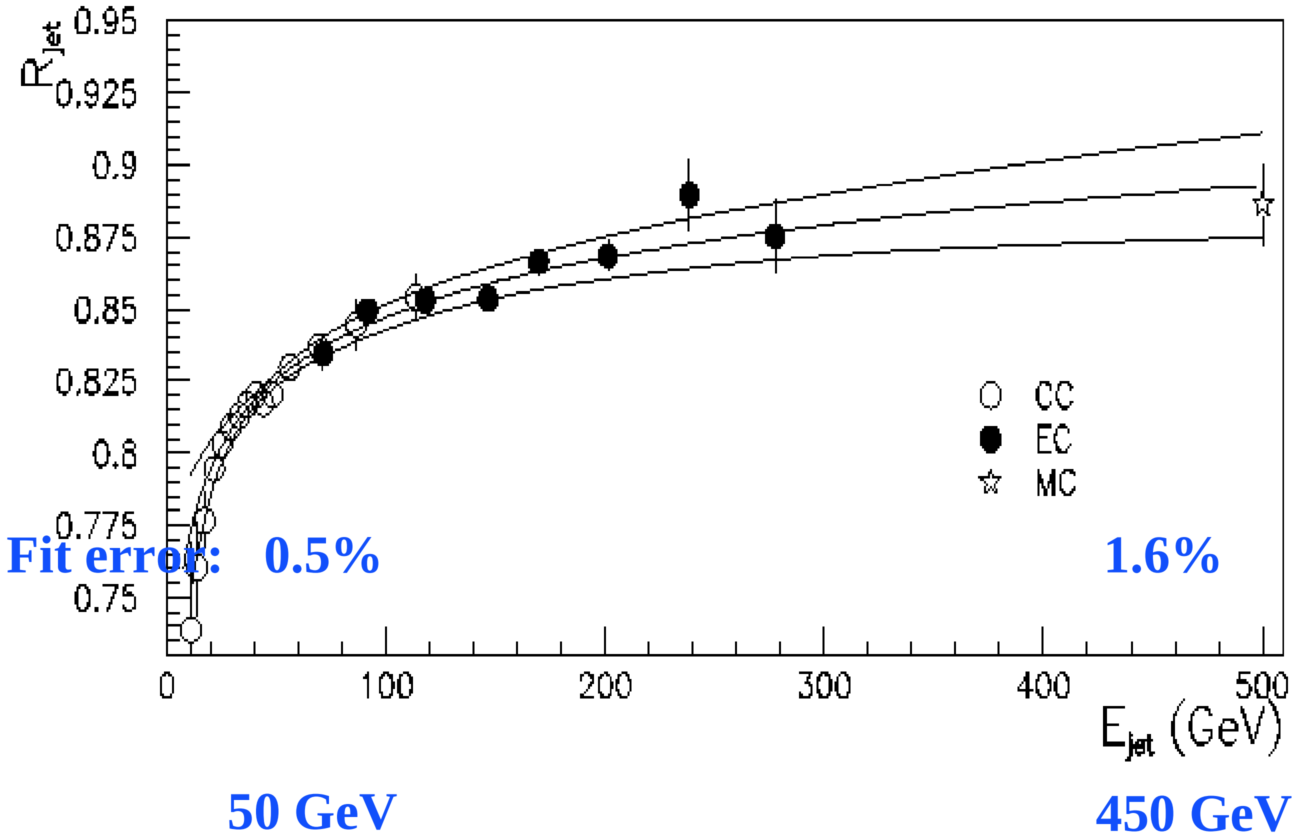
Jet Response vs E_{jet}

Non-linearities ⟶ $R_\pi \sim \ln(E)$

$$R_{jet} = A + B \ln(E_{jet}) + C [\ln(E_{jet})]2$$



Largest source of uncertainty at large E_{jet}

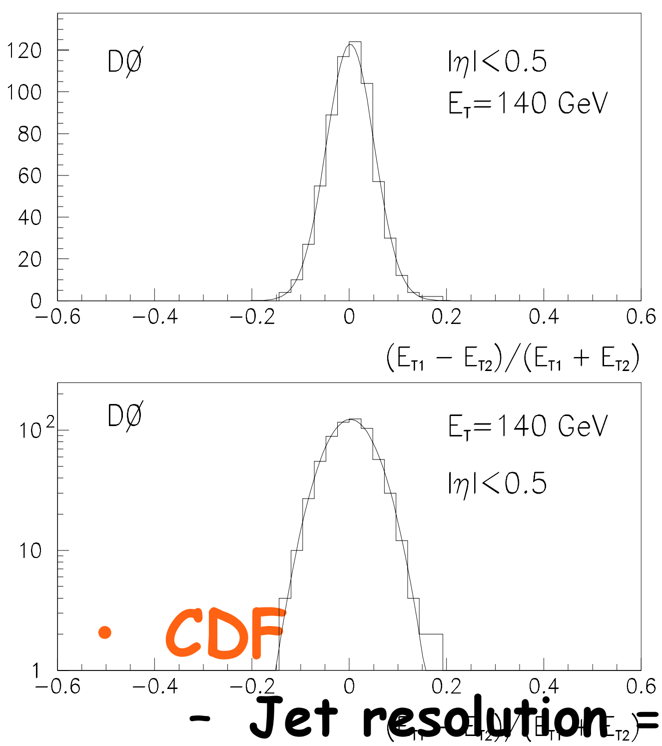
Jets:
From Detector to Hadron Level cont'd

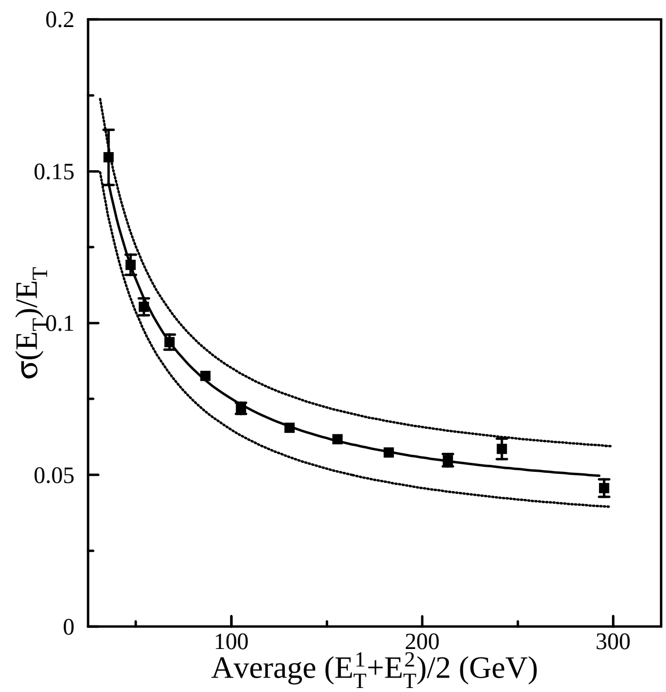
» Energy/Position Resolution

- DO
  - Measured from dijet collider data using E_T balance:

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

In the limit of no soft radiation

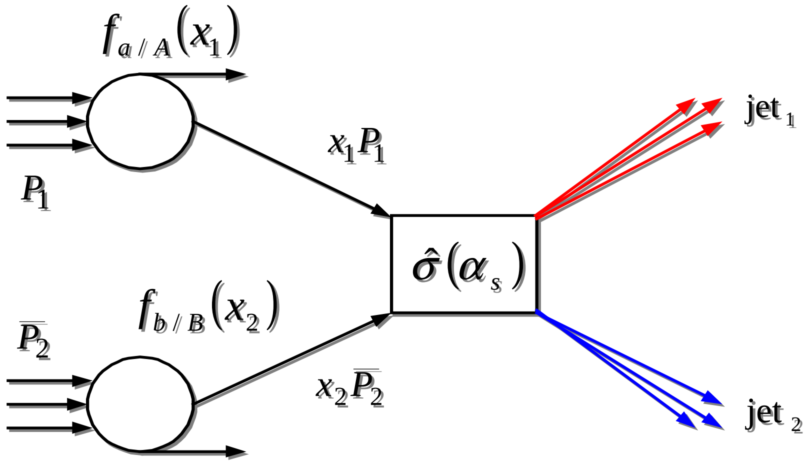


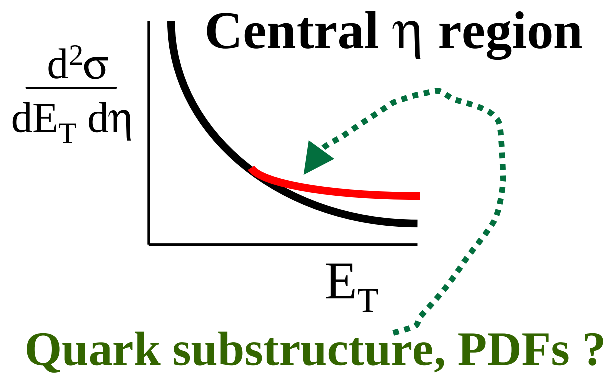


- CDF
  - Jet resolution = width of response function

$\sigma_{RMS} \sim 0.1E_T + 1$ GeV for $35<E_T<450$ GeV

Inclusive Jet Cross Section

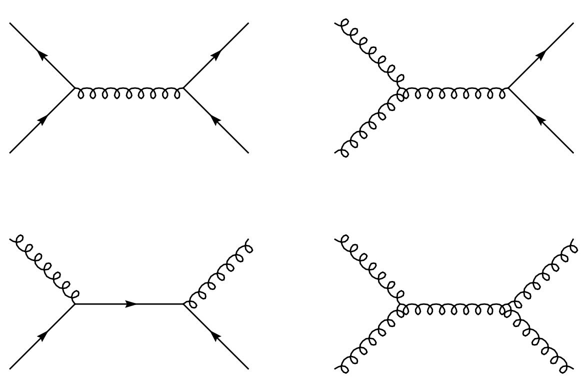




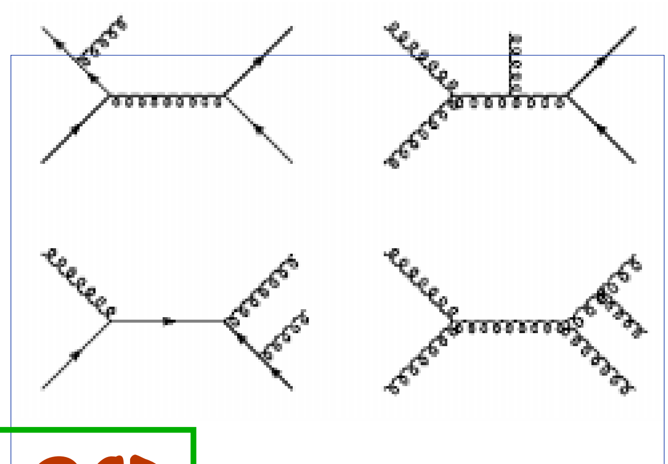
$$\frac{d\sigma}{dP_T} \approx \sum_{a,b} \int dx_a\, f_{a/A}(x_a,\mu) \int dx_b\, f_{b/B}(x_b,\mu)\, \frac{d\hat{\sigma}}{dP_T}$$

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

LO $= O(\alpha_s^2)$



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



Test of QCD

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 @ h=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

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

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

$\Delta E_T \rightarrow$ ***E_T bin size***

$\Delta\eta \rightarrow$ ***η bin size***

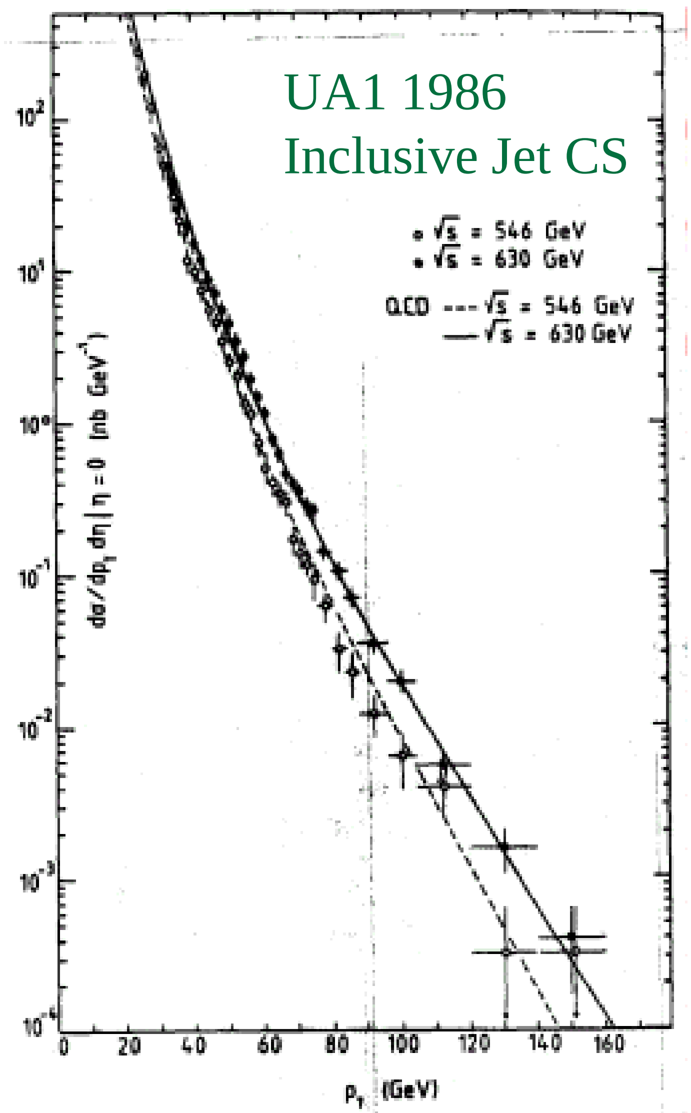
$N_{jet} \rightarrow$ ***# of jets in the bin***

$\varepsilon \rightarrow$ ***selection efficiency***

$L \rightarrow$ ***inst. Luminosity***

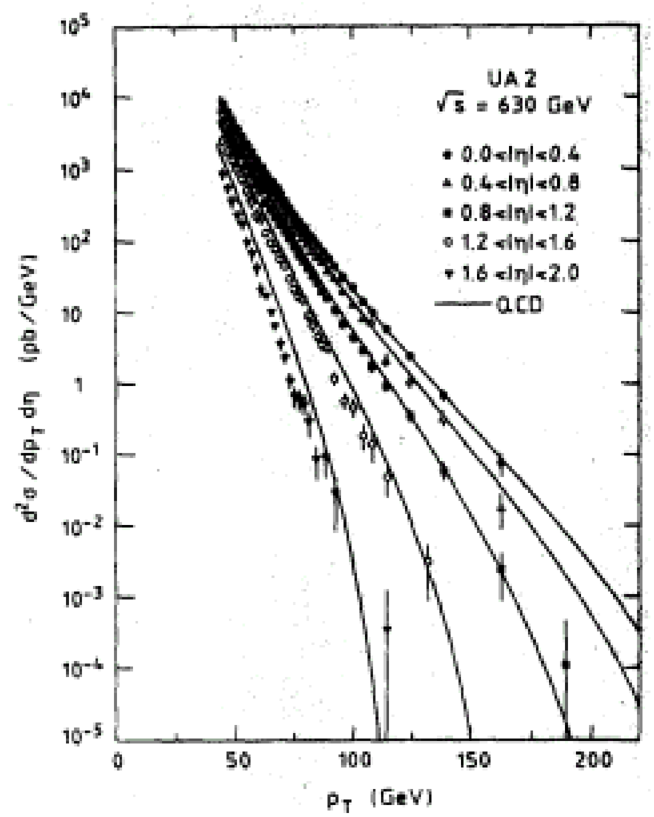
The old days…

UA1 1986
Inclusive Jet CS



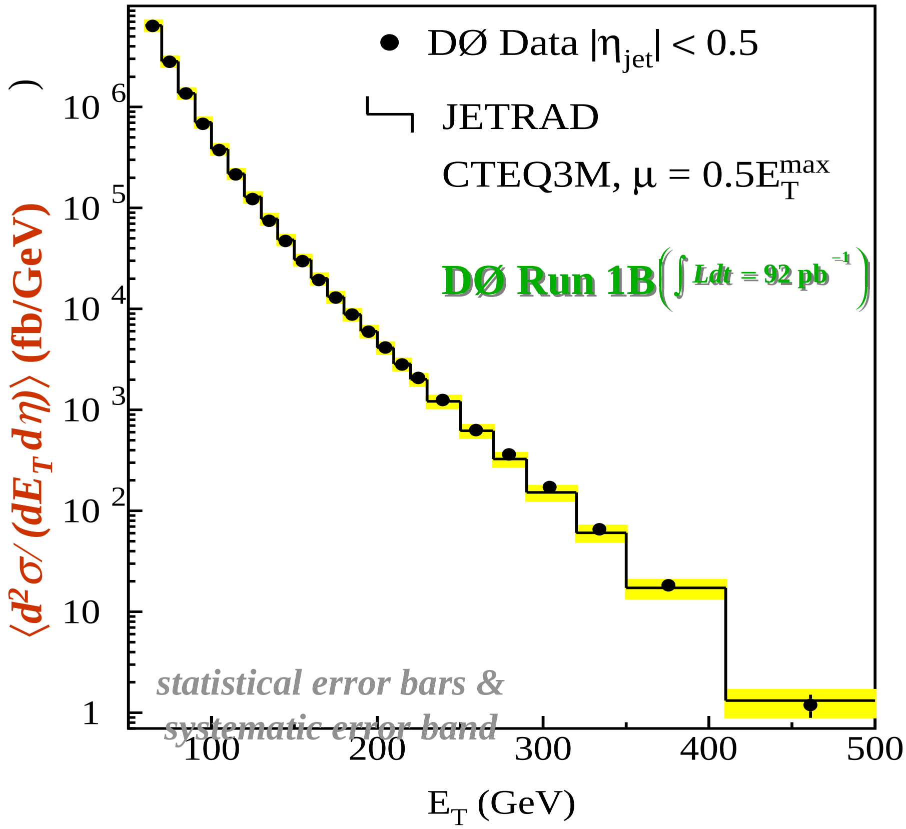
Uncertainties ~ 70% on CS:
±50% accept./jet corr (smearing)
±40% calib ±10% aging ±15% Lum
Λ_C > 400 GeV *"Exp and theo. Uncerts. taken in to account"*

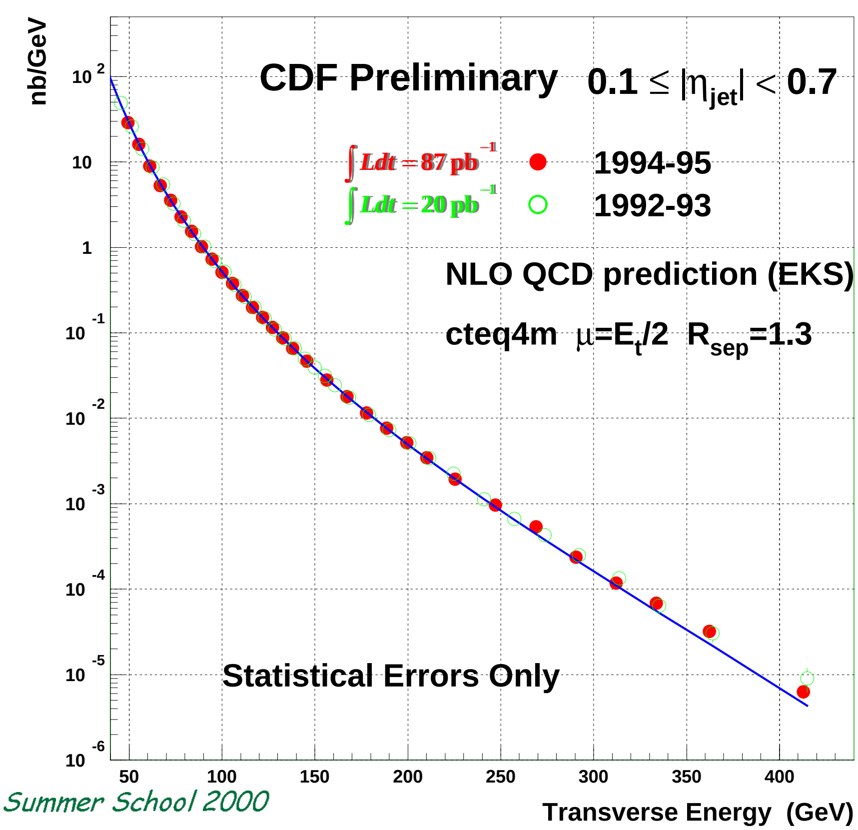
UA2 1991
Inclusive Jet CS



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"*

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





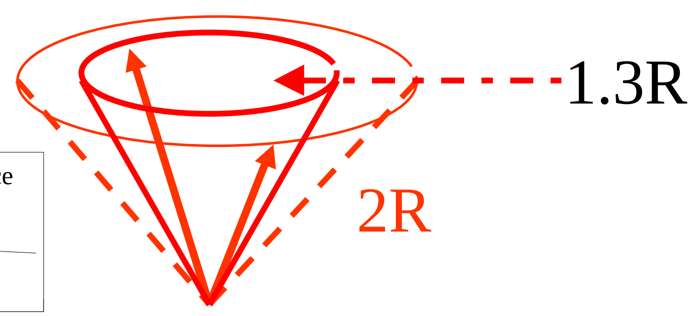
Theory Predictions

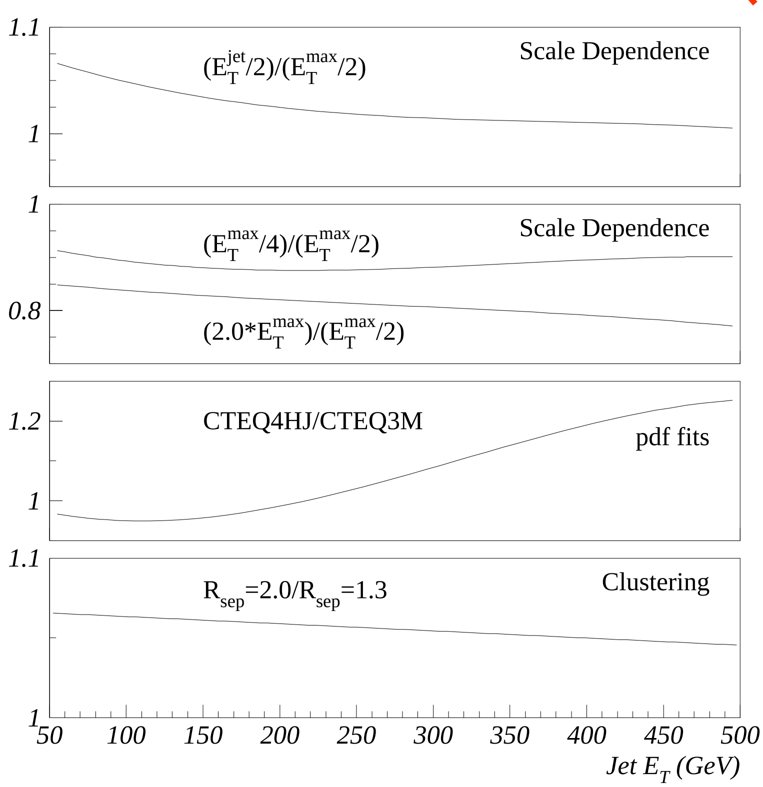
- **NLO QCD predictions** (α_s^3) :

Ellis, Kunszt, Soper, Phys. Rev. D, 64, (1990)
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)



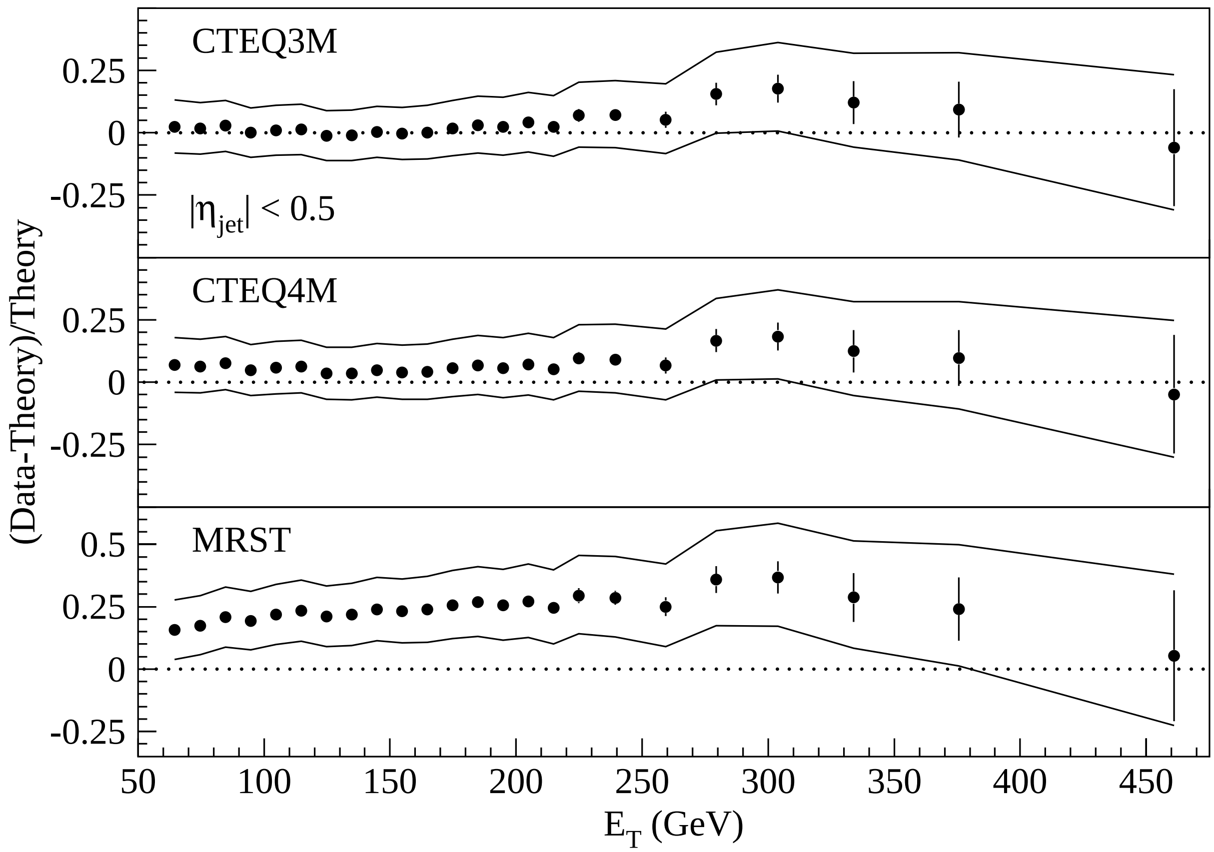


D0 uses: JETRAD
$\mu = 0.5E_T^{Max}$, $R_{sep}=1.3$

CDF uses: EKS
$\mu=0.5E_T^{Jet}$, $R_{sep}=2.0$

Data vs Theory

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



Energy (GeV)	E scale (%)	Res. (%)	Lum. (%)	Total (%)
100	+7.7 / -7.0	+2 / -2	6.1	10
400	+20 / -19	+3.5 / -4.5	6.1	22

QCD prediction agrees excellently 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

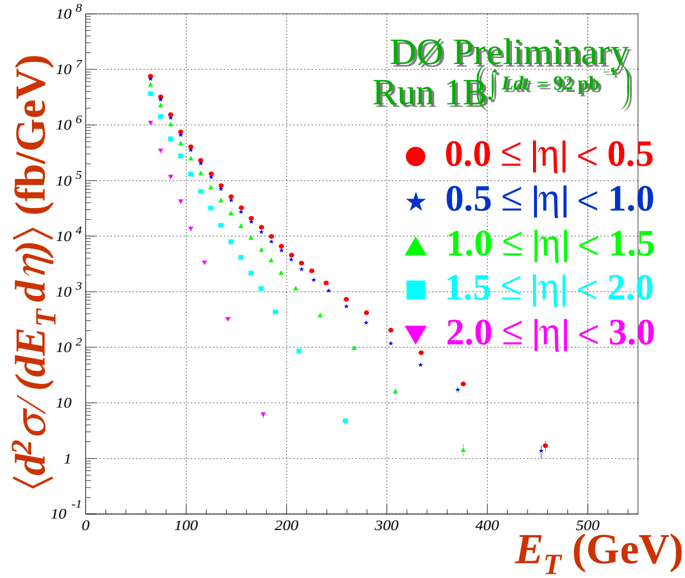
Rapidity Dependence of Inclusive Jet Cross Section

Comparisons to JETRAD with:

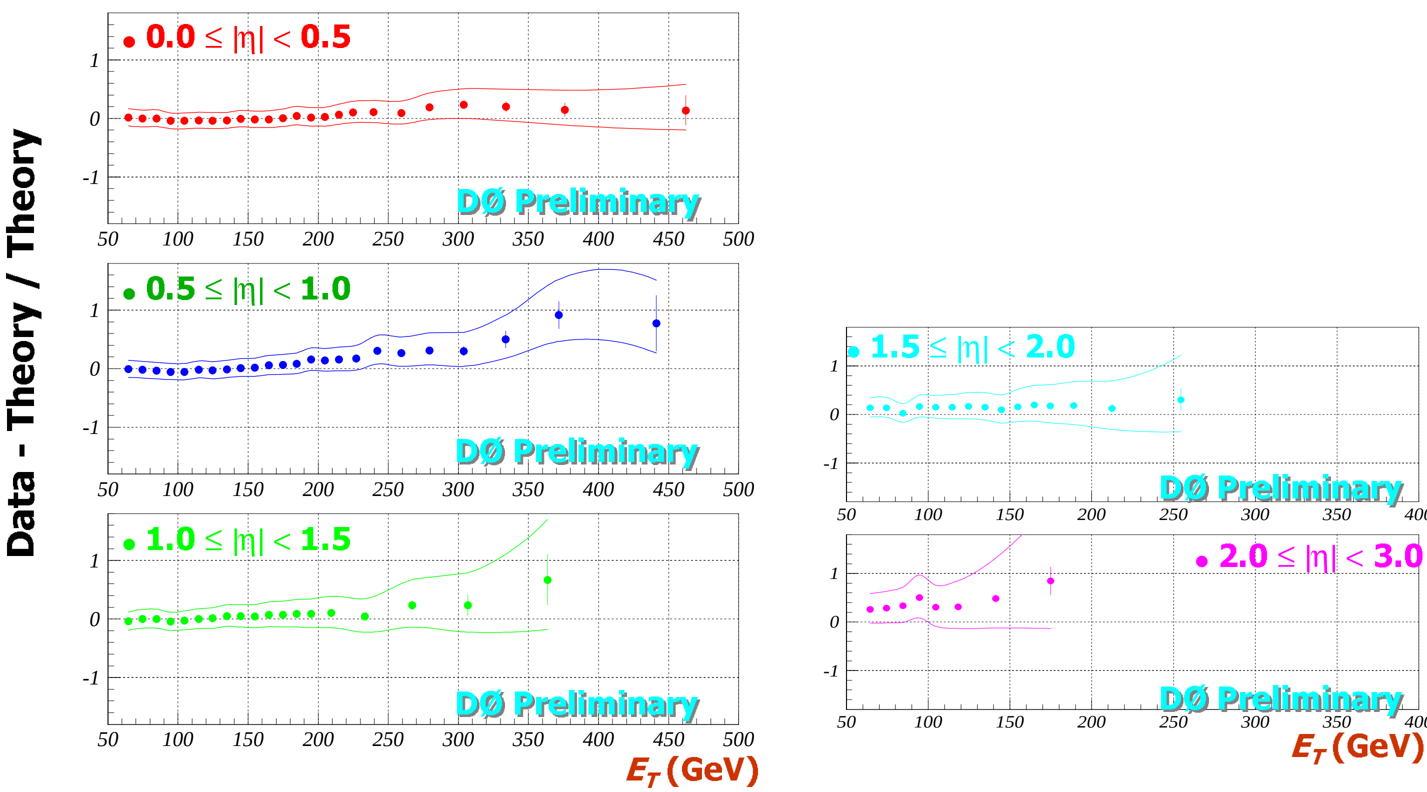
PDF: CTEQ3M

$$\mu = E_T^{\max}/2$$

$R_{sep} = 1.3$



DØ inclusive cross sections up to |η| = 3.0



Good agreement with NLO QCD

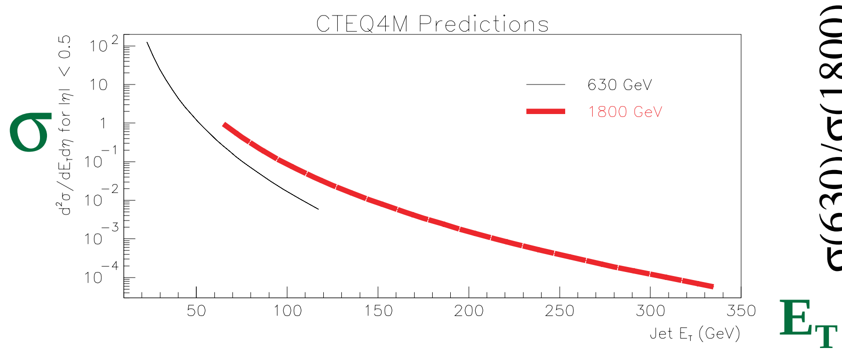
Inclusive Jet Cross Section Ratio: σ(630)/σ(1800) vs X_T

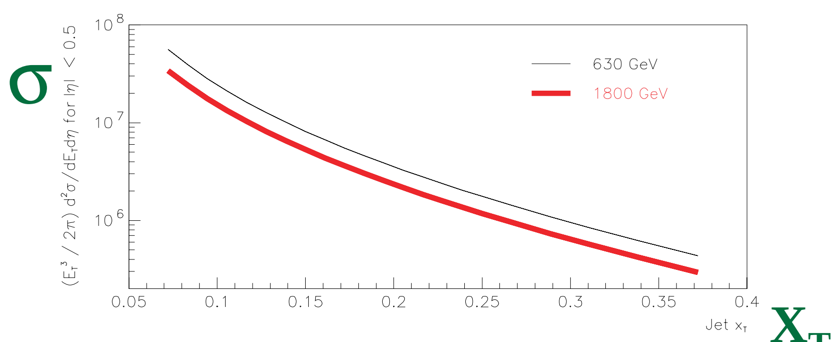
- **Cross Section Scaling**
  - At Born level ($\mathcal{O}(\alpha_s^2)$) :
- **Scaling violations**
  - PDFs, $\alpha_s(Q^2)$
- **Ratio of the scale invariant cross sections at different CM energies**
  - Ratio allows subrtantial reduction in uncertainties (in theory and experiment)

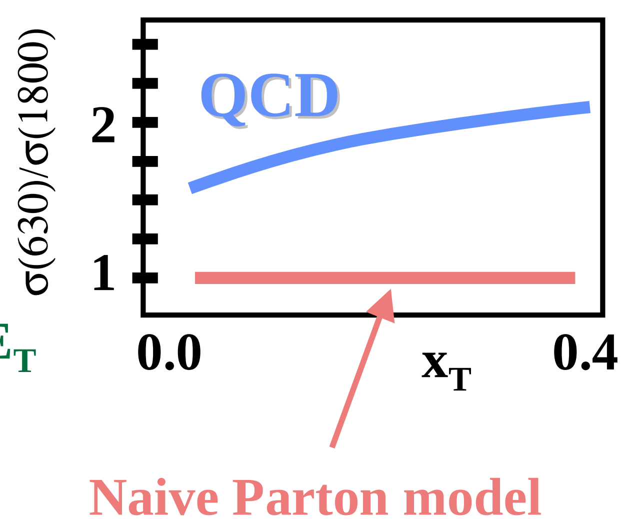
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^4} f(x_T)$$

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

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

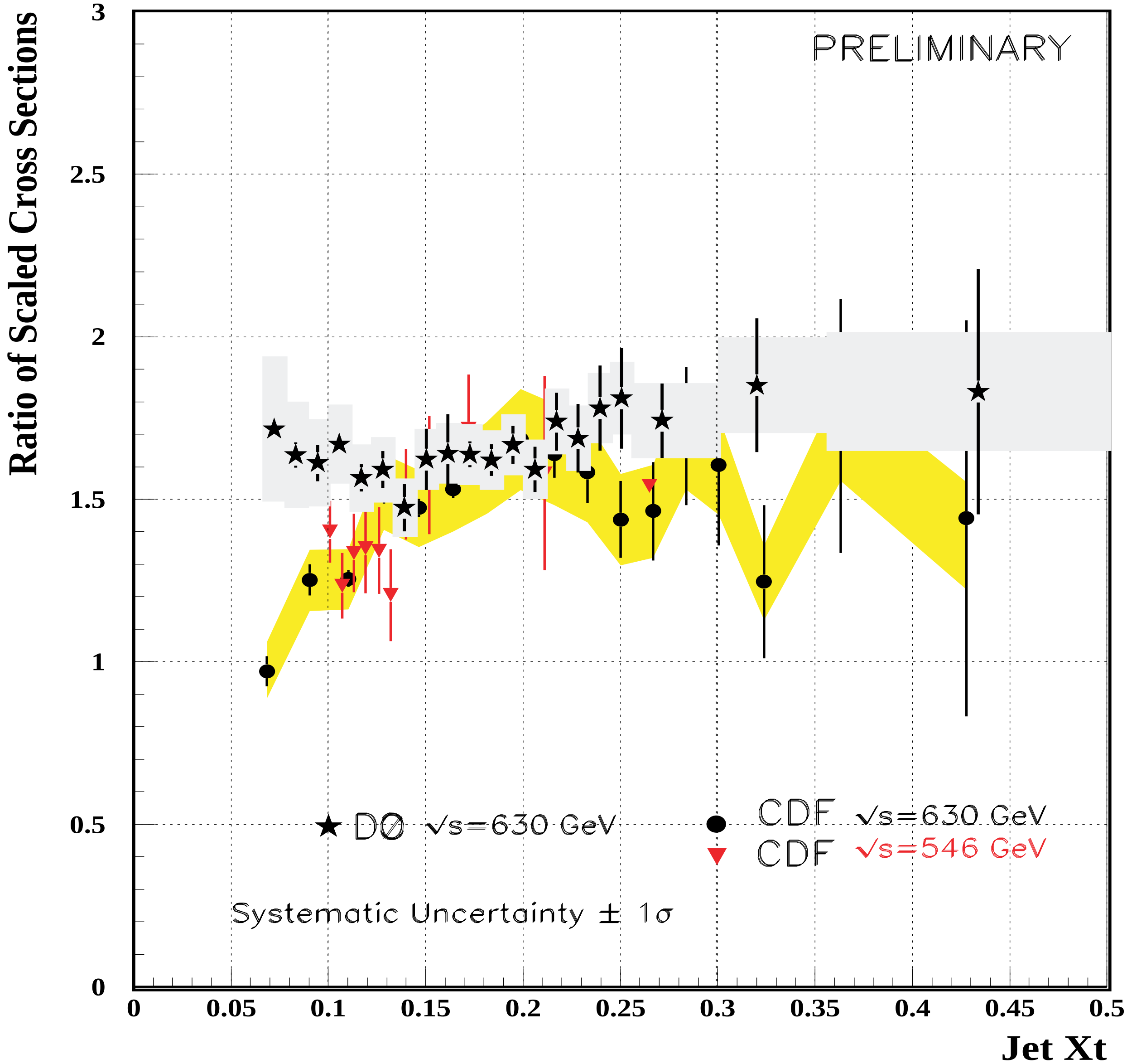






$\sigma(630)/\sigma(1800)$ vs X_T

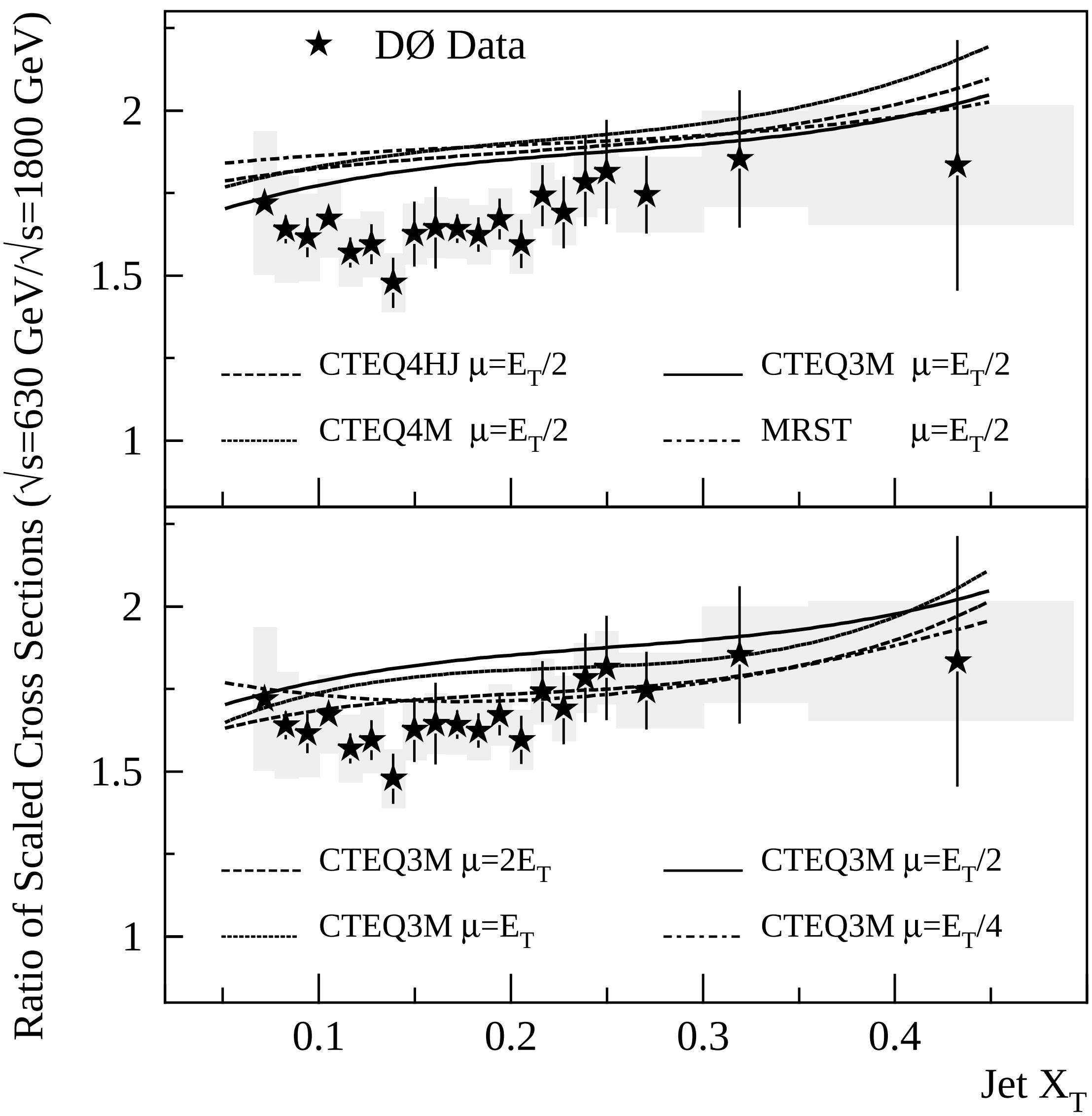
- DØ and CDF both measure a preliminary ratio of cross sections 630/1800 GeV



- Not obviously consistent with each other (especially at low x_T)

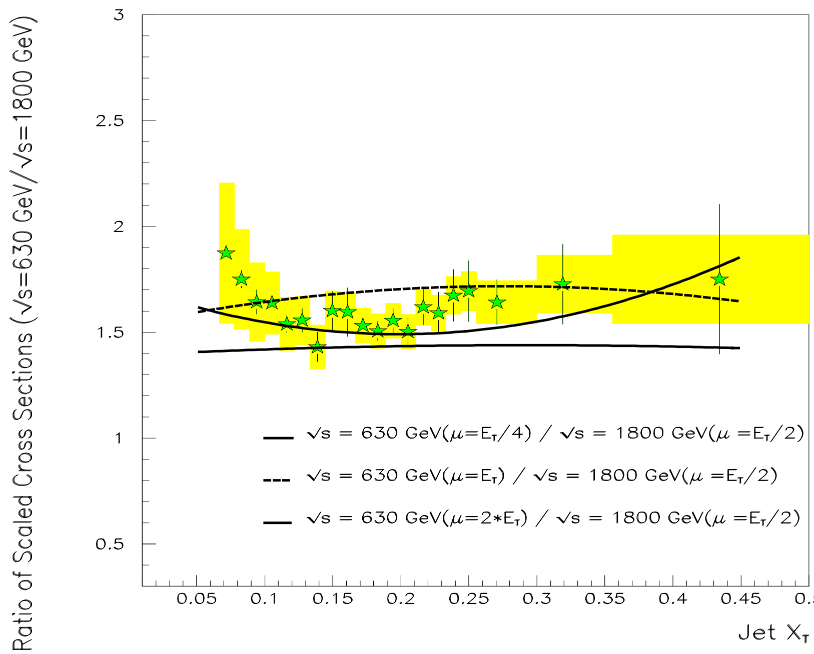
$\sigma(630)/\sigma(1800)$ vs X_T

- Uncertainties due to PDF's are significantly reduced in the ratio
- Good agreement with NLO QCD in shape and normalization within 1-2σ
- Work is underway for obtaining quantitative measure of agreement, such as χ^2

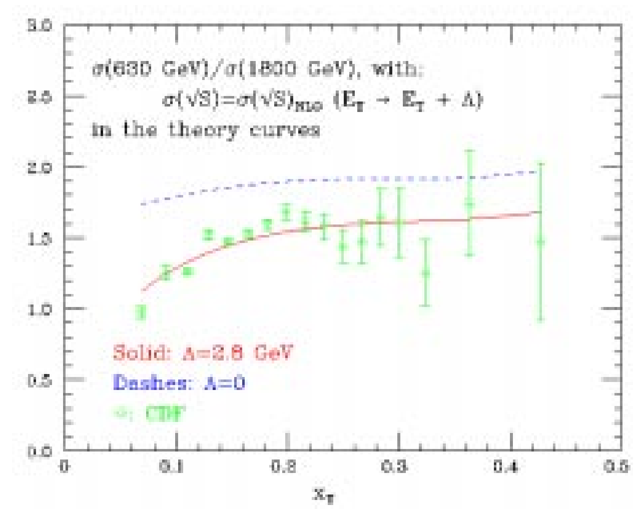


Suggested Explanations:

- **Different renormalization scales at the two CM energies**
  - OK, so it's allowed, but...



- **Mangano proposes an O(3GeV) non-perturbative shift in jet energy**
  - losses out of cone
  - underlying event
  - intrinsic K_T
  - could be under or overcorrecting the data (or even different between the experiments?)

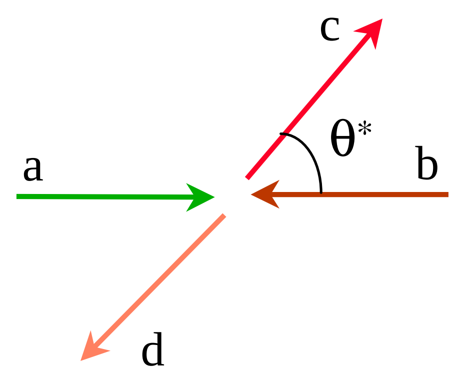


Dijet Production

- 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)



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

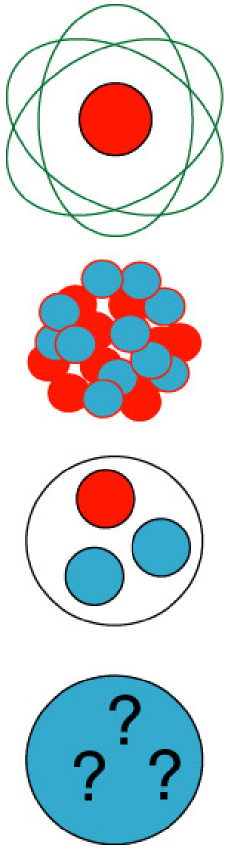
characteristic of the exchange of a vector boson
– gluons have spin = 1 –

- 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



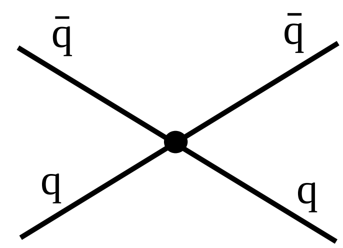
Hypothesis: Quarks are bound states of preons
Preons interact by means of a new strong interaction - metacolor -

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



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

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

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

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

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

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

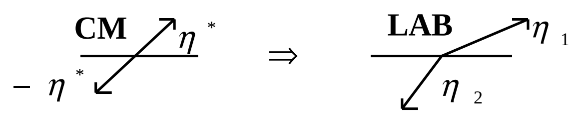
Angular Distributions –> Quark Substructure

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

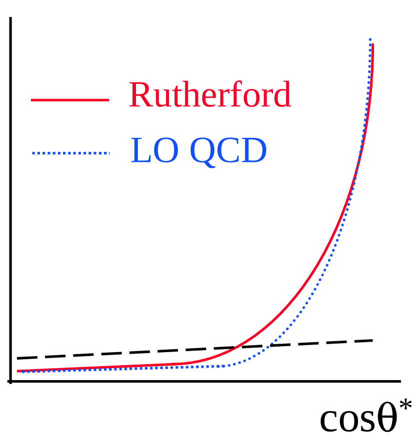
⟶ From $\cos\theta^{*}$ variable to χ

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

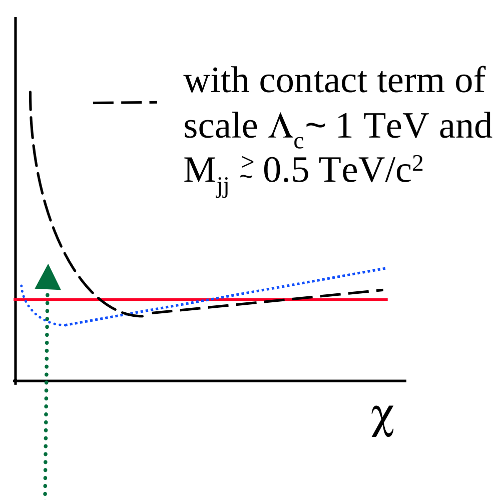
$$\chi = e^{2|\eta^{*}|} = \frac{1+\cos\theta^{*}}{1-\cos\theta^{*}}$$



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



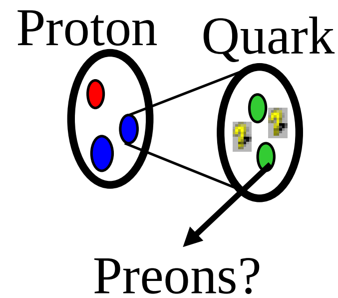
⇒

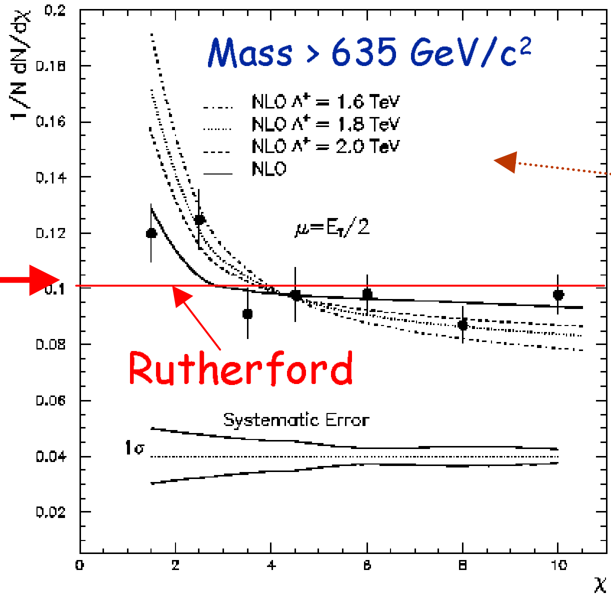


$dN/d\chi$ sensitive to contact interactions

Limits of Quark Substructure

Angular Distributions



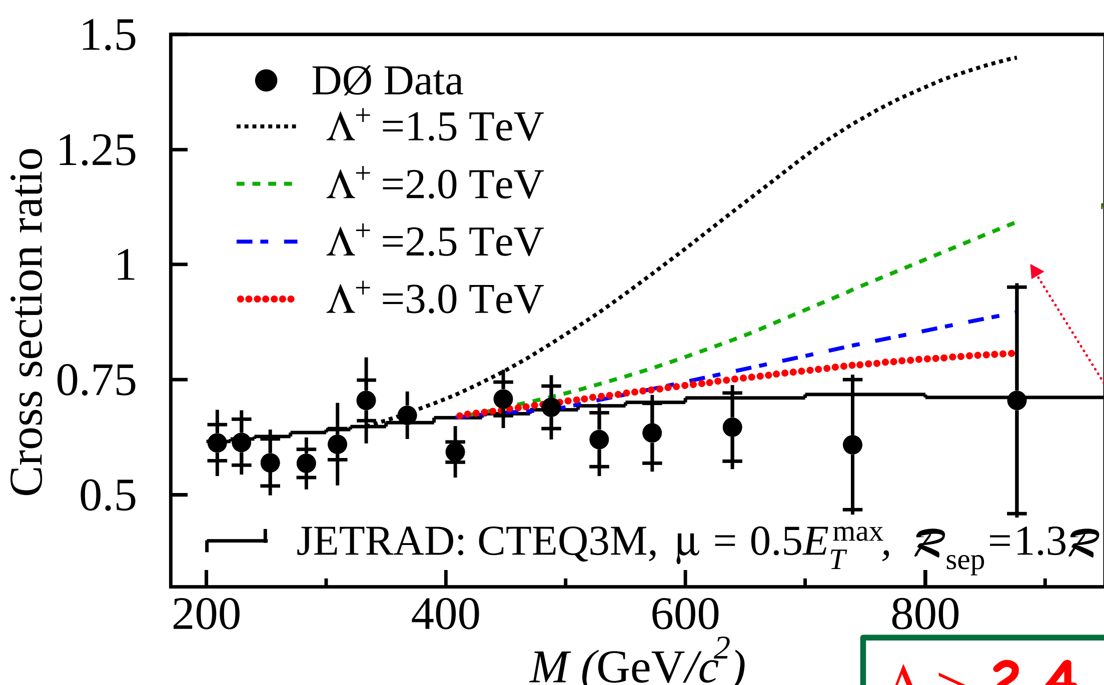


95% CL Compositeness Limit:

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

Dijet Mass Cross Section Ratio

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

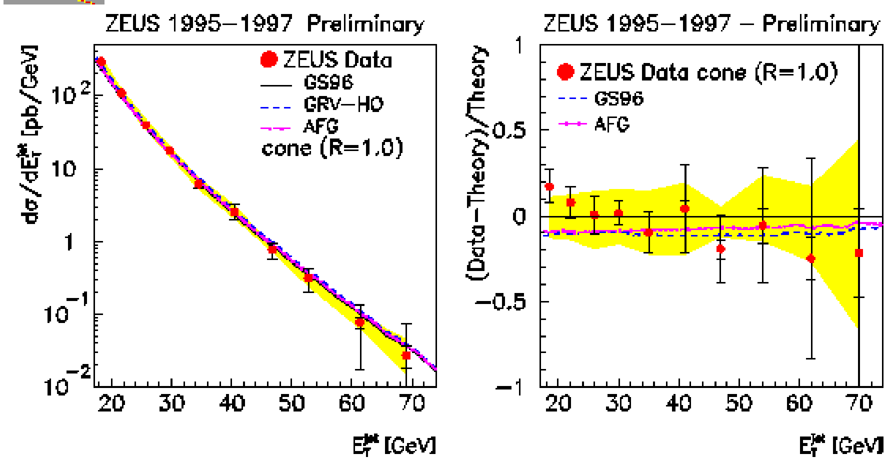
Jets at HERA

Measurement of $\frac{d\sigma}{dE_T^{jet}}$ in inclusive jet production

- Jets searched using an iterative cone algorithm
- Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 4$ GeV^2
- $\frac{d\sigma}{dE_T^{jet}}$ for E_T^{jet} between 17 and 74 GeV

  integrated over $-0.75 < \eta^{jet} < 2.5$

$R = 1.0$



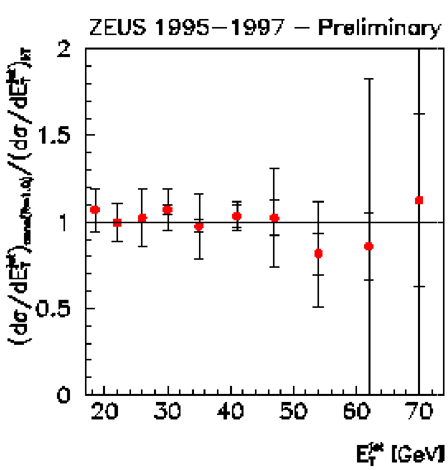
- The NLO calculations give a reasonable description of the measured differential cross section in magnitude and shape

- cone vs. k_T algorithm:

$\rightarrow$ measured

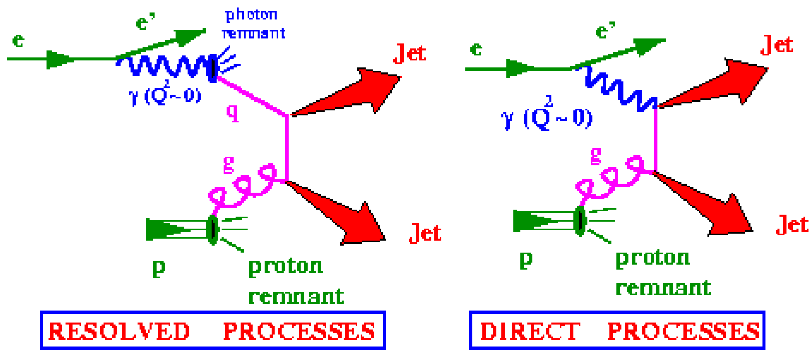
$$\frac{d\sigma/dE_T^{jet}|_{cone}}{d\sigma/dE_T^{jet}|_{k_T}} \approx 1$$

typically within $\pm 10\%$



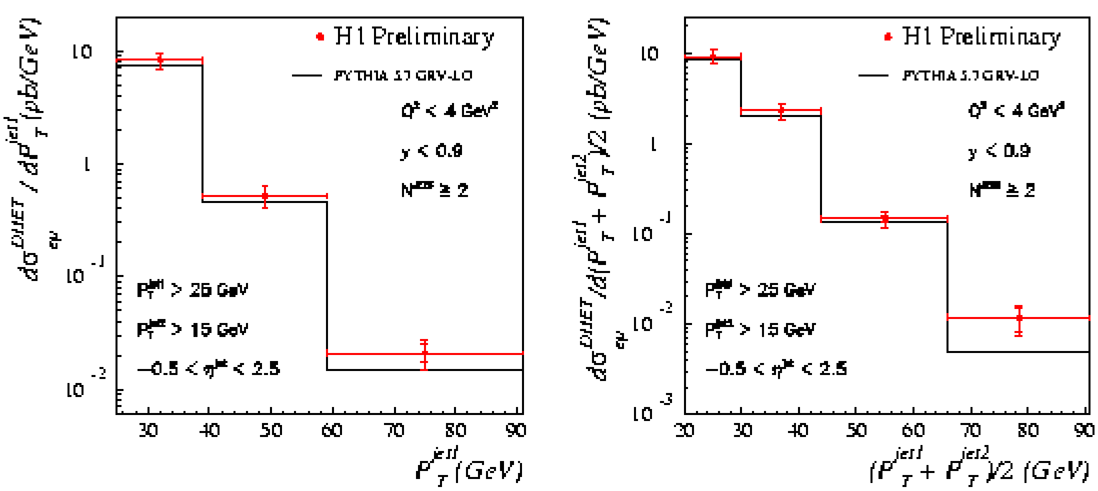
Dijet Production

$$ep \rightarrow e + \text{jet} + \text{jet} + X$$



- Tests of QCD in dijet photoproduction
- Jets searched using the k_T cluster algorithm
- Kinematic region: $y < 0.9$ and $Q^2 < 4$ GeV^2
- $\frac{d\sigma}{dp_T^{jet1}}$ for p_T^{jet1} between 25 and 90 GeV and $\frac{d\sigma}{d(p_T^{jet1}+p_T^{jet2})/2}$ for $(p_T^{jet1} + p_T^{jet2})/2$ between 20 and 90 GeV integrated over $-0.5 < \eta^{jet} < 2.5$

$$\frac{d\sigma}{dp_T^{jet}}$$



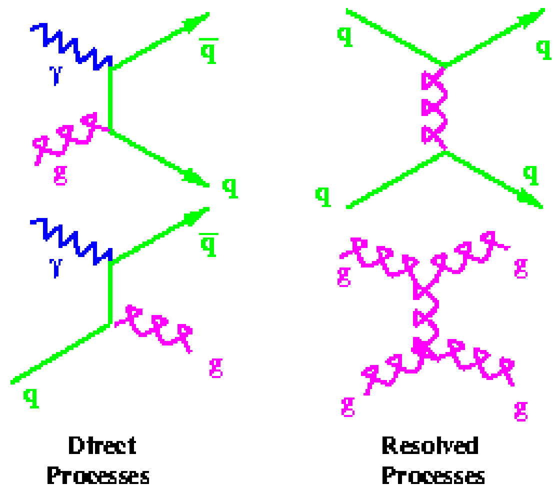
- The leading-logarithm parton shower Monte Carlo gives a good description of the data in shape

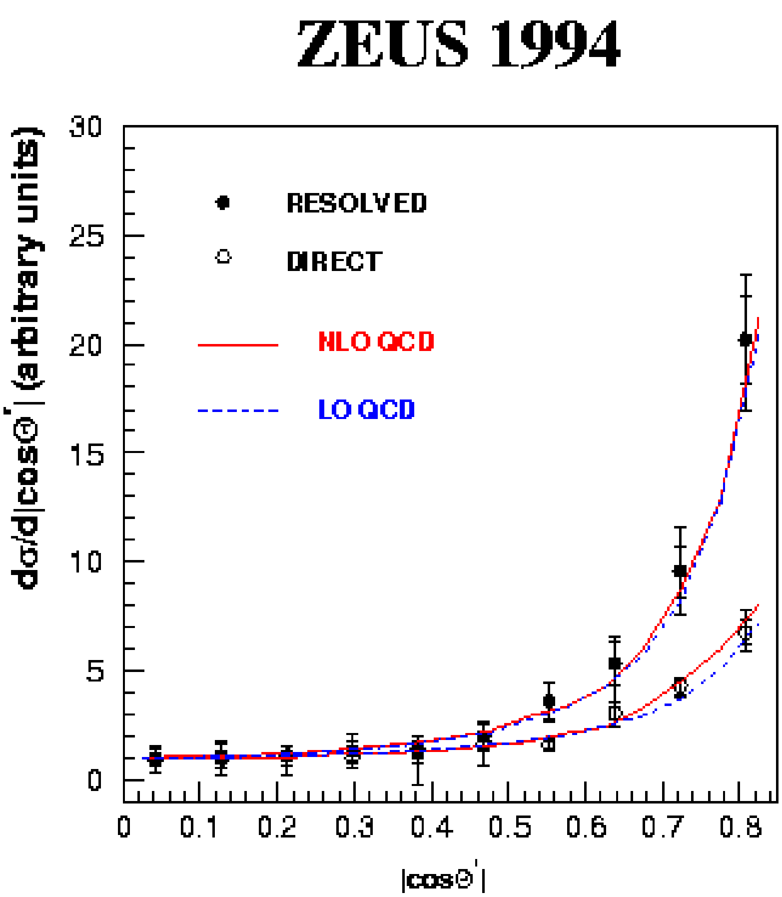
Dijet Angular Distributions

→ sensitive to the spin of the exchanged particle in two-body processes:

resolved: gluon exchange
$$\sim (1 - |\cos\theta^*|)^{-2}$$

direct: quark exchange
$$\sim (1 - |\cos\theta^*|)^{-1}$$





Collab., Phys. Lett. B384 (1996) 401

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
- Lately there has been a lot of progress on jet algorithm development
- We need more theoretical and experimental effort to understand the underlying event
  - don't subtract it out from jet energies?
- Shall we be correcting the jets for hadronization effects?
  - how to deal with model dependence?
- Finally, there are many other topics on jets which I didn't cover:
  - α_s measurements
  - heavy quarks
  - BFKL, Diffractive studies
  - jets with vector bosons
  - jet final states at LEP
  - ...