Jet Fragmentation Studies at Tevatron

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Particle multiplicity and momentum distribution (CDF)
SubJet multiplicity in Quark and Gluon Jets (D0)

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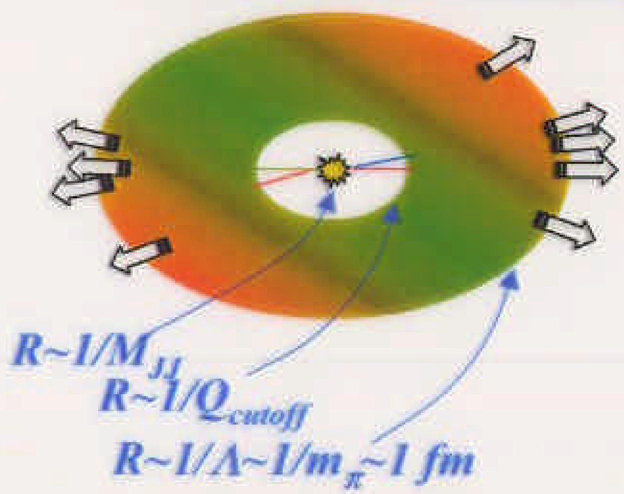
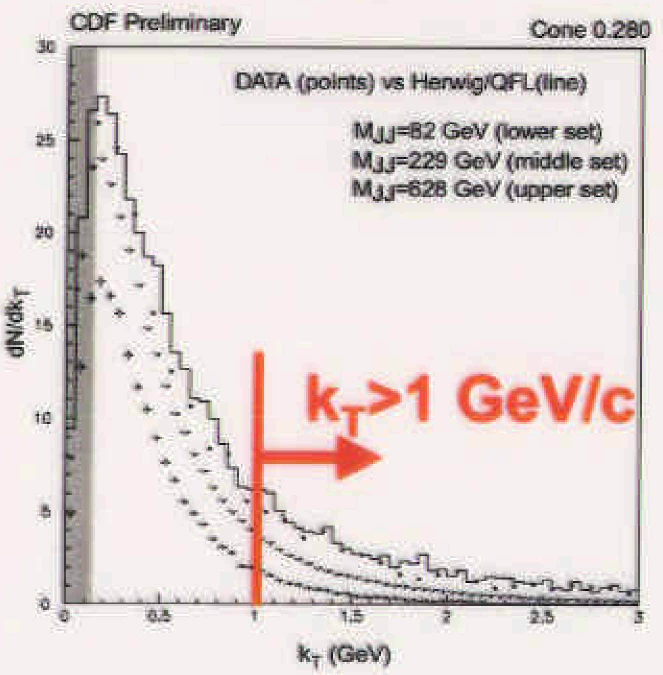
Jet Fragmentation: pQCD + hadronization



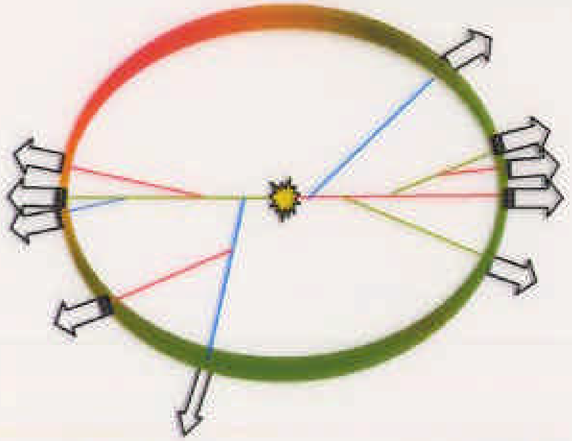


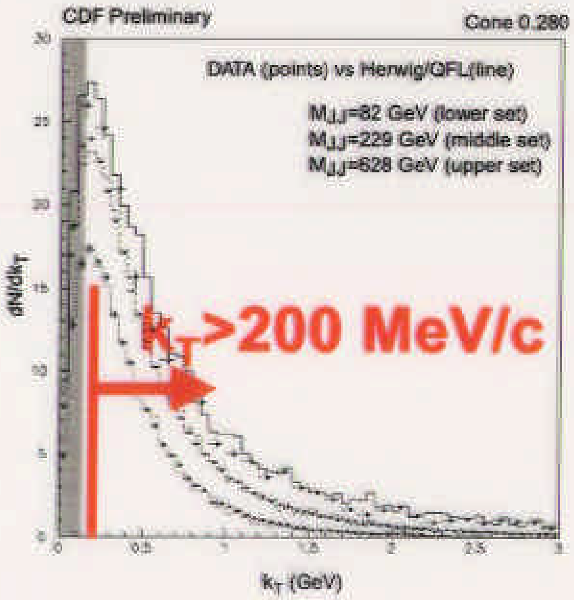
Fragmentation can be thought of as the a two-stage process:

- **pQCD stage** that governs development of a parton shower
- **phenomenological hadronization** that converts partons into hadrons
- the fuzzy border between the two stages is usually associated with a k_T cut-off scale Q_{cutoff}

pQCD with comfortably high $k_T>1$ GeV ($R<0.2$ fm) inevitably implies the dominance of the phenomenological hadronization stage.

Jet Fragmentation: pQCD dominance scenario





MLLA, Modified Leading Log Approximation, after re-summing pQCD terms in all orders, gives analytical infrared stable expressions where one can set $Q_{cutoff}=\Lambda_{QCD}=Q_{eff}$ (~200 MeV?); it explicitly accounts for soft partons $x_p=p/E_{jet}<<1$.

Mueller (1983); Dokshitzer, Troyan (1984); Malaza, Webber (1984)

LPHD, Local Parton Hadron Duality, hypothesis assumes that hadronization occurs locally at the very last moment and, therefore, hadrons "remember" parton distributions: e.g.,

$N_{hadrons}=K_{LPHD}\cdot N_{partons}$

- if all hadrons are accounted for, $K_{LPHD(all\ hadrons)} \sim 1$
- if only charged hadrons are observed, $K_{LPHD(\pm)} \sim 2/3$ (adding I=1/2 particles, e.g., K^+K^o, and particles with predominantly neutral decay modes, e.g., η, may somewhat reduce it.)

Azimov, Dokshitzer, Khoze, Troyan (1985)

MLLA: Modified Leading Log Approximation

Gluon Jets:

- **Multiplicity:**
  $N_g(Y)$, $Y=\ln(E_{jet}\sin\theta/Q_{eff})$
- **Momentum distribution:**
  $dN_g(\xi,Y)/d\xi$, $\xi=\log(1/x_p)$, $x_p=p/E_{jet}$

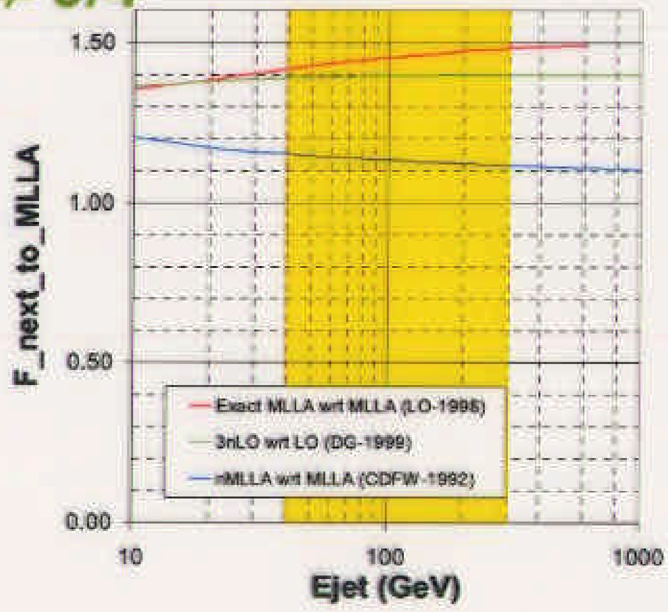
Quark Jets:

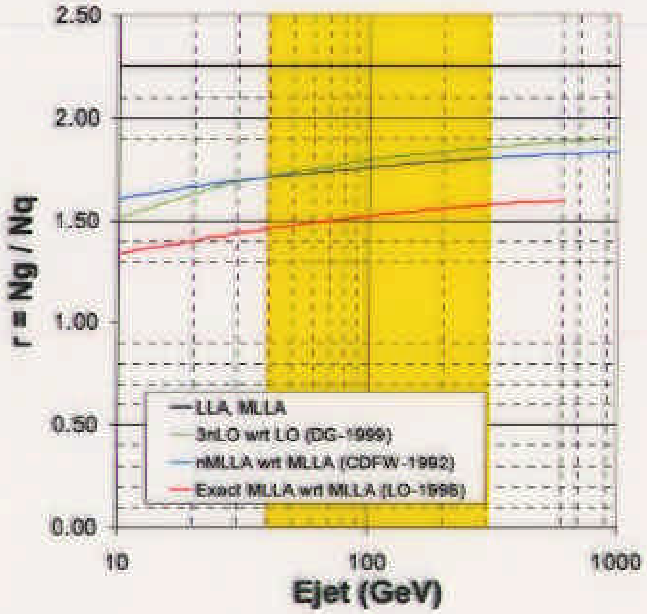
- **quark jet is different by a normalization factor 1/r,** $r = C_A/C_F=9/4$
- **Multiplicity:** $N_q(Y)=(1/r)\cdot N_g(Y)$
- **Momentum distribution:** $dN_q/d\xi=(1/r)\cdot dN_g/d\xi$

Next-to-MLLA corrections

Next-to-MLLA corrections to multiplicity of parton in gluon and quark jets:

- $N_{next\text{-}to\text{-}MLLA} = F_{next\text{-}to\text{-}MLLA} \times N_{MLLA}$ (gluon jet)
- $r \neq 9/4$

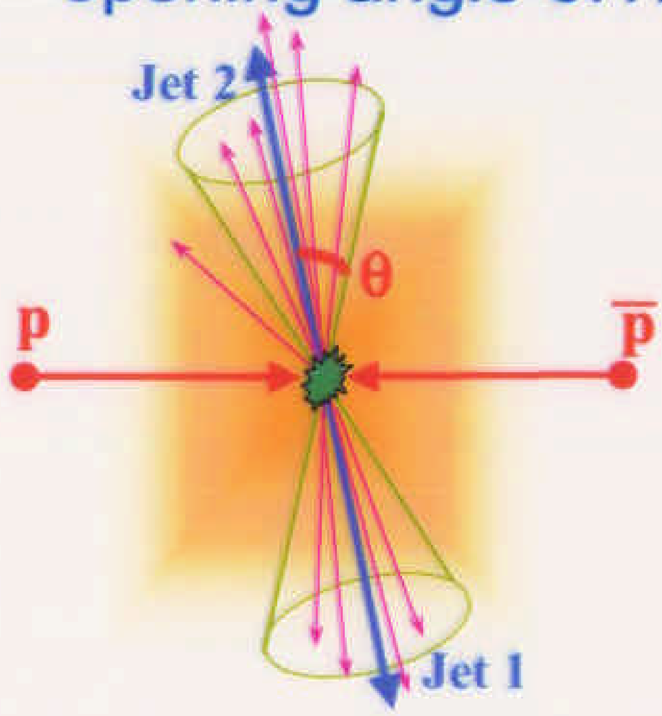


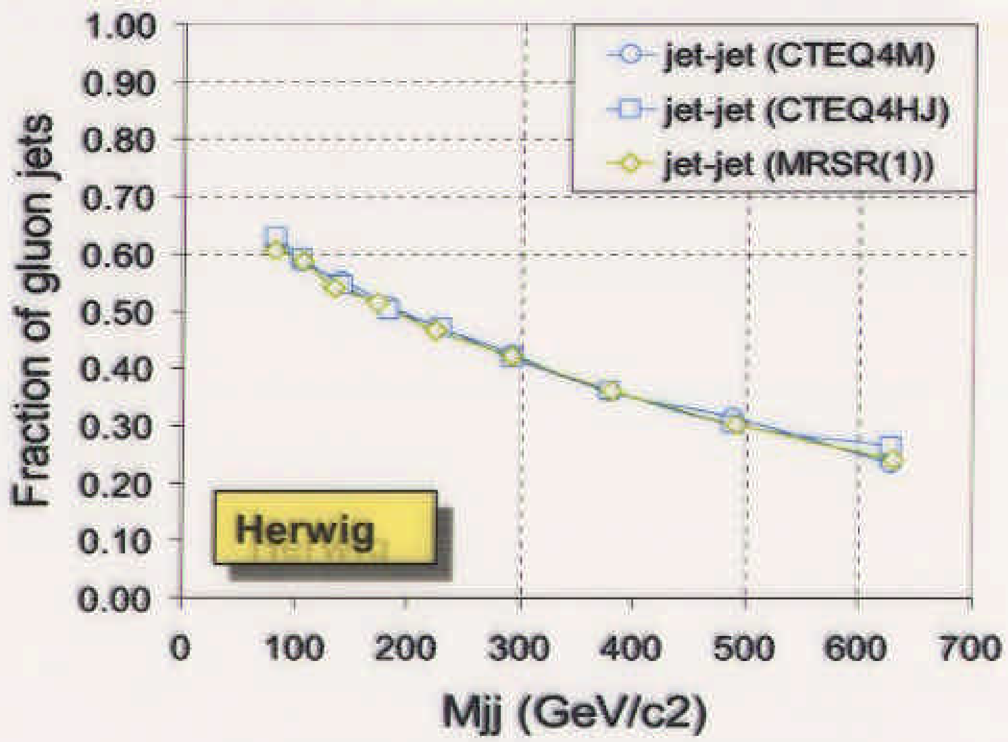


CDFW-1992 Catani, Dokshitzer, Fiorani, Webber, Nucl.Phys. B377(1992)445
LO-1998 Lupia, Ochs, Phys.Lett. B418(1998)214 and Nucl.Phys.B (Proc. Suppl.) 64(1998
DG-1999 Dremin, Gary, hep-ph/9905477v2, 3 Sep 1999

Analysis at CDF

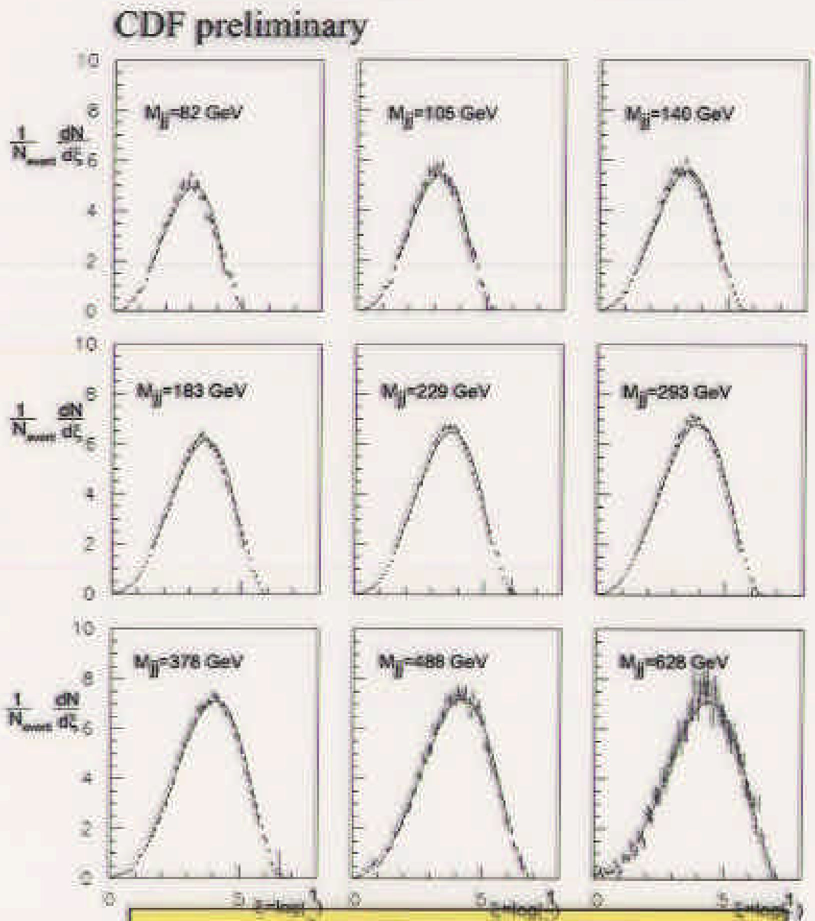
- dijet events with $80<M_{JJ}<630$ GeV/c^2
- require both jets to be in central region, well balanced $(\Delta E_T/(E^1_T+E^2_T) < 0.15, |\eta|<0.9)$
- opening angle $0.17<\theta_{cone}<0.47$





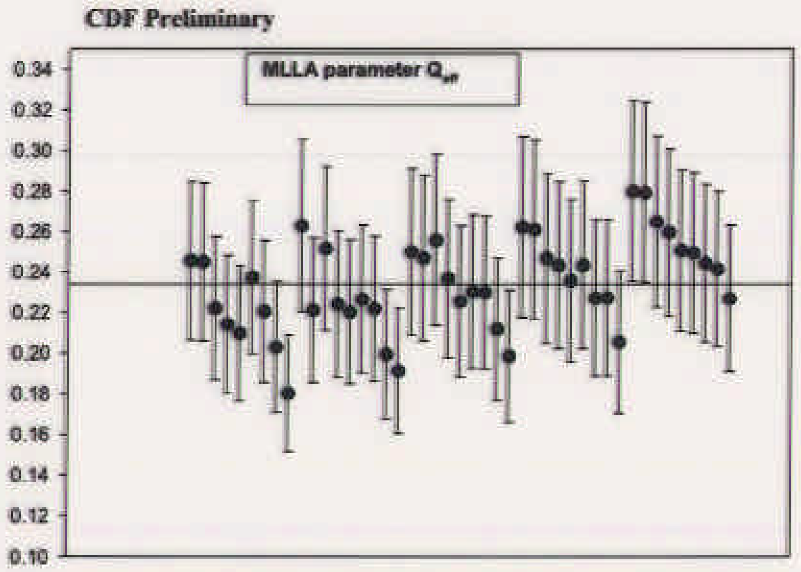
Momentum distribution of tracks

M_{jj}-scan (θ_{cone}=0.47), MLLA fit



ξ=log(1/x)

Q_{eff} for all 9 M_{jj}'s and 5 opening angles θ_{cone}'s



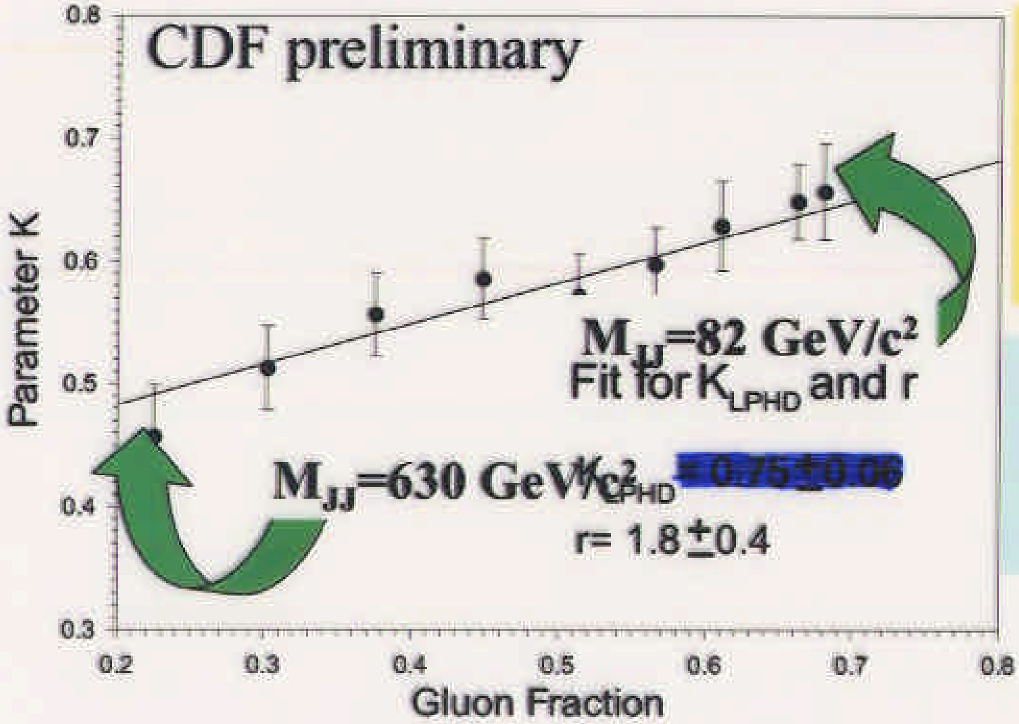
Fitted values for Q_{eff} corresponding to 45 (5 cones x 9 dijet mass cuts) possible combinations. Five series of data points correspond to five cone sizes, 9 data points within every cone size correspond to different dijet masses (lowest at left). Qeff=240 ±40 MeV.

MLLA fit dN(ξ,Y)/dξ

Q_{eff}≈constant=240±40 MeV

Momentum distribution of tracks

$$N_{hadrons}(M_{jj},\xi) = K_{LPHD}\, N_{partons} = K_{LPHD}\, (\varepsilon_g\, N^{g\text{-}jet}(\xi) + \varepsilon_q\, N^{q\text{-}jet}(\xi))$$
$$= K_{LPHD}\, (\varepsilon_{g(M_{jj})} + (1-\varepsilon_{g(M_{jj})})/r)\, N^{g\text{-}jet}(\xi)$$
$$= K_{LPHD}\, (\varepsilon_{g(M_{jj})} + (1-\varepsilon_{g(M_{jj})})/r)\, F_{next\text{-}to\text{-}MLLA}\, N^{g\text{-}jet}(\xi)$$
$$= K(Mjj)\, N^{g\text{-}jet}(\xi)$$



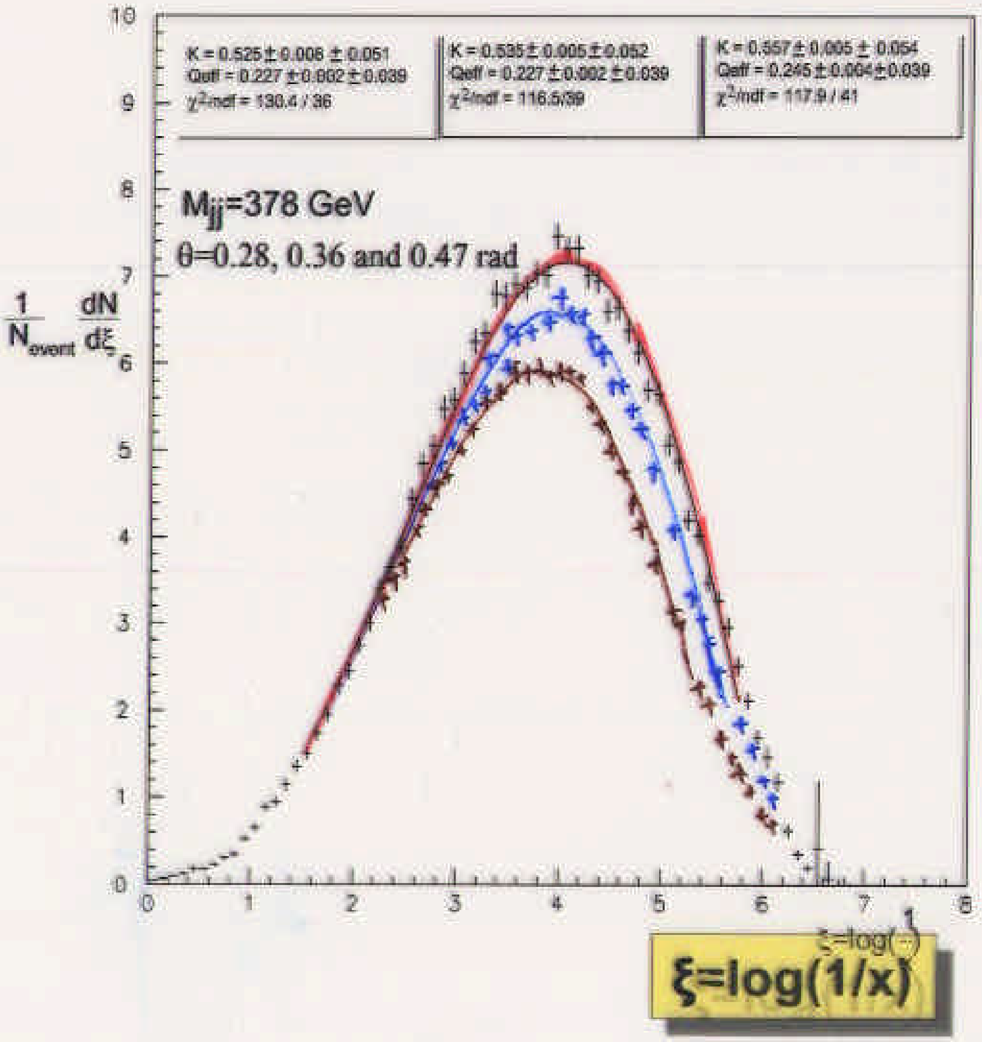
K vs. gluon jet fraction

- $r=1.8\pm0.4$ (indirect)
- $K_{LPHD}=0.58\pm0.05\pm0.08$

the measurement is "indirect":
the result relies on MLLA-predicted $dN_g(\xi,M_{jj})/d\xi$

Momentum distribution of tracks

CDF preliminary



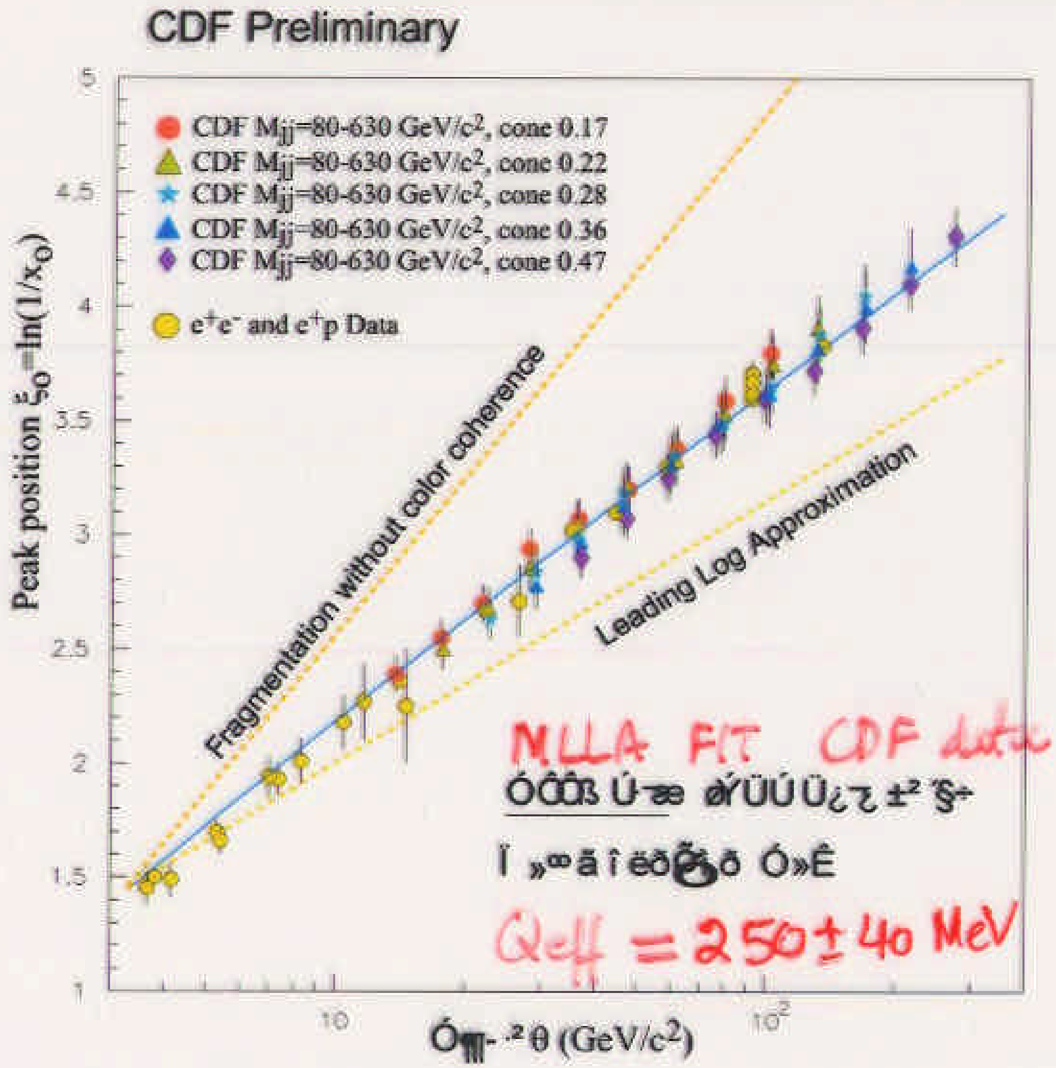
For fixed M_{jj},

K should be angle independent

MLLA-fitted values of K:

- θ_{cone}=0.47 K=0.56 ±0.05
- θ_{cone}=0.36 K=0.54± 0.05
- θ_{cone}=0.28 K=0.53 ±0.05

Peak of momentum distribution of tracks



$$\xi_0 = \frac{1}{2}Y + (cY)^{1/2} - c$$
$$Y = \ln(E_{jet}\sin\theta / Q_{eff})$$

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Peak position ξ_0 vs M_{JJ}

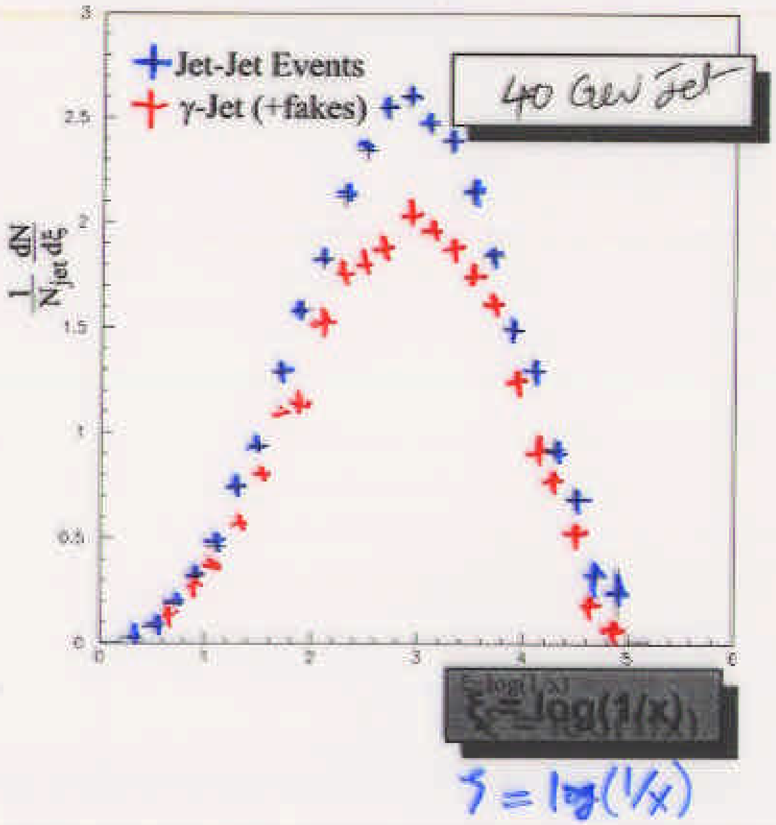
$Q_{eff} = 250 \pm 40$ MeV

Model-independent measurement of r

Jet-jet $N_{hadrons}(\xi) = K_{LPHD}(\varepsilon_{g(Mjj)} + (1-\varepsilon_{g(Mjj)})/r) F_{next\text{-}to\text{-}MLLA} N^{g\text{-}jet}(\xi)$

γ-jet $N'_{hadrons}(\xi) = K_{LPHD}(\varepsilon'_{g(Mjj)} + (1-\varepsilon'_{g(Mjj)})/r) F_{next\text{-}to\text{-}MLLA} N^{g\text{-}jet}(\xi)$

CDF Preliminary

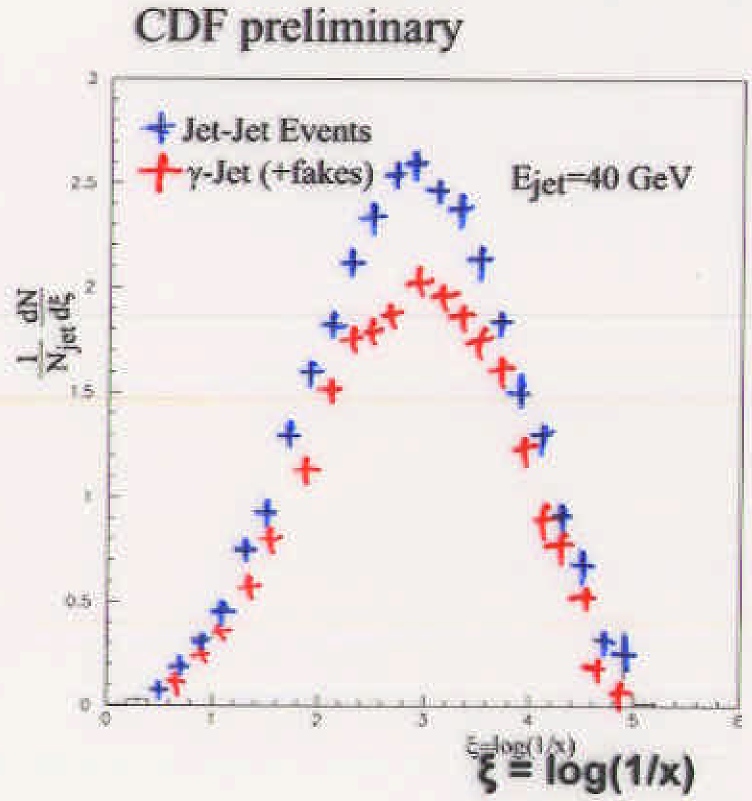


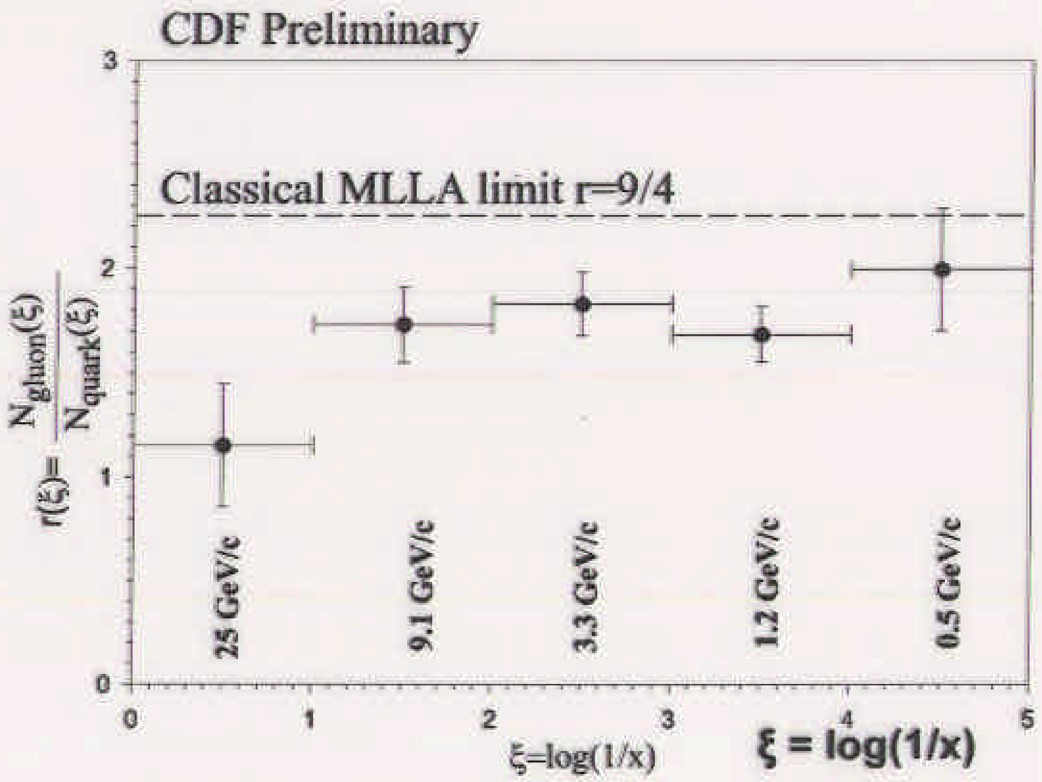
- Dijets with M_{jj}=80 GeV/c^2:
  N = 5.77±0.03 tracks/jet
- Photon-jets with $M_{\gamma j}$=80 GeV/c^2:
  N'_{jet} = 4.83 ±0.05 tracks/jet
  (Photon-jet sample has ~70% of true photon-jets and ~30% of fakes--dijets)

<u>direct measurement of r</u>

r = 1.74 ± 0.11 ± 0.07

Does r depend on particle momenta?





r may depend on particle momentum, being larger for soft particles, but errors are too large.

Does $K_{LPHD(+/-)}$ make sense?

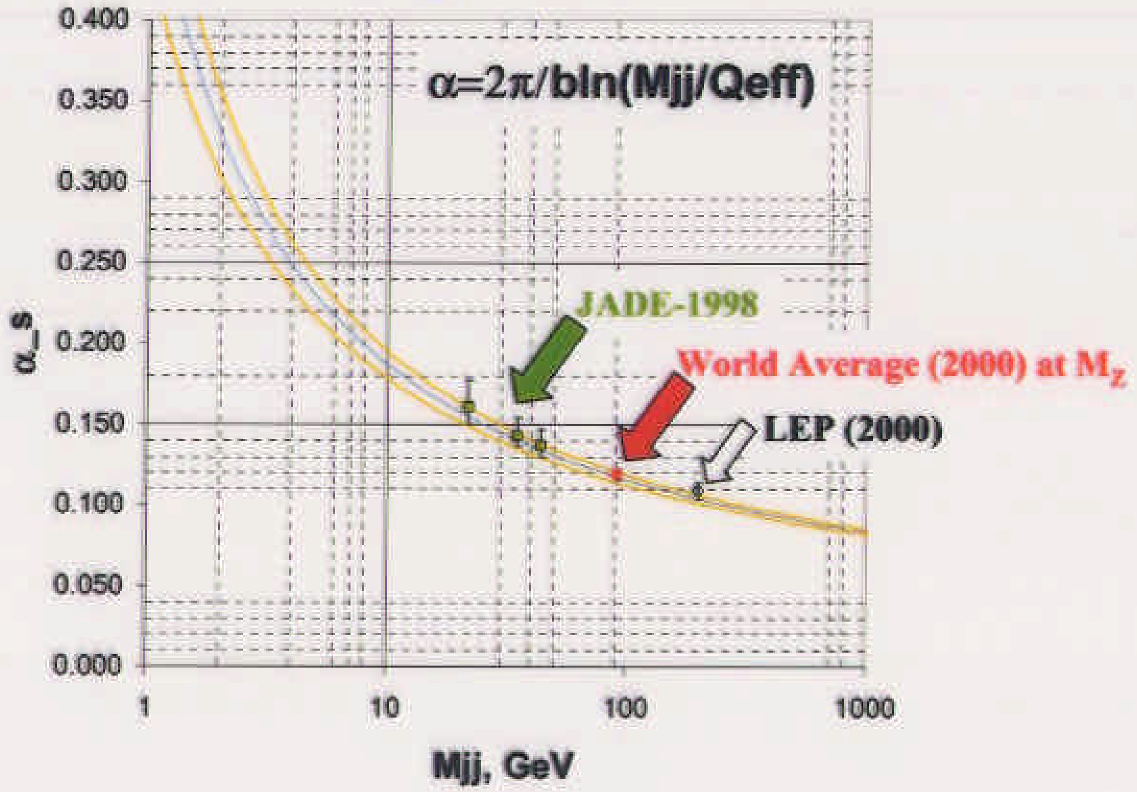
LPHD:

- We measured $K_{LPHD\,(+/-)} = N_{hadrons(+/-)} / N_{partons} = 0.56 \pm 0.10$
- Energy fraction carried by charged particles:
  TASSO: 0.59 ± 0.01 for $Q=12\text{-}42$ GeV -- Z.Phys.C22(1984)307

Does Q_{eff} make sense?

MLLA Q_{eff}:

- MLLA $\alpha_s = 2\pi/(b \cdot \ln(k_T/\Lambda_{QCD}))$
- $Q_{cutoff} = \Lambda_{QCD} = Q_{eff}$
- Measured Q_{eff} = 240±40 MeV



Jet Fragmentation at CDF: conclusions

Momentum distribution of tracks at $80<M_{jj}<630$ GeV/c^2:

- Qeff = 240 ± 40 MeV
- r = 1.8 ± 0.4 (in the framework of MLLA)
- K_{LPHD} = 0.58 ± 0.10 (assuming next-to-MLLA corrections)

Peak position vs M_{jj}:

- Qeff = 250 ± 40 MeV

Multiplicity in dijet events vs. M_{jj} ($80<M_{jj}<630$ GeV/c^2):

- r = 1.7 ± 0.3 (in the framework of MLLA)
- K_{LPHD} = 0.55 ± 0.10 (assuming next-to-MLLA corrections)

Multiplicity in dijet events vs. photon-jet events at M_{jj} =82 GeV/c^2:

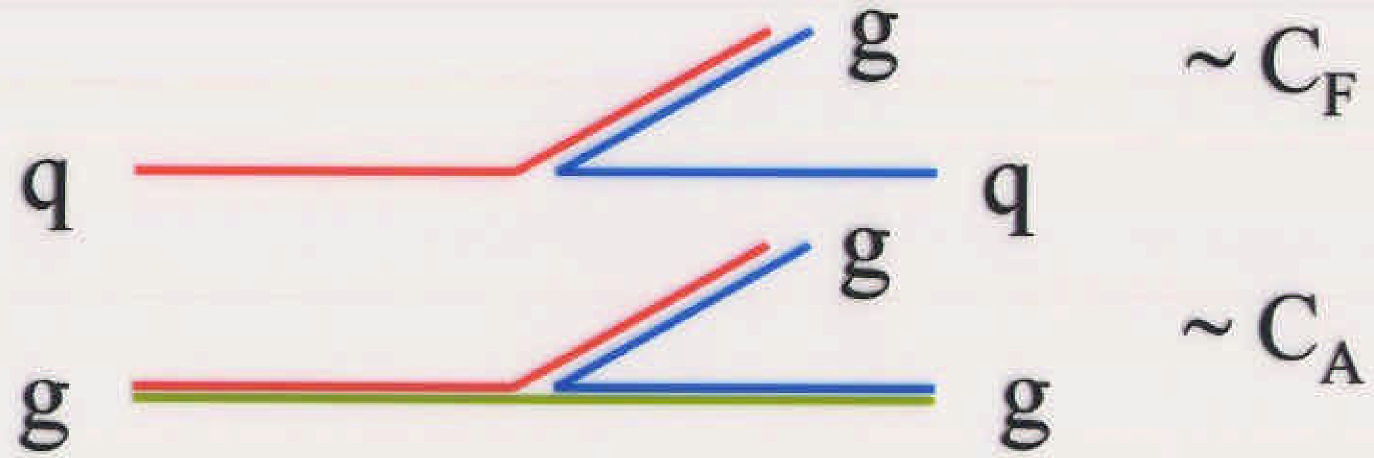
- r = 1.74 ± 0.11 ± 0.07 (model independent)

Subjet Structure Using the k_T Algorithm

- k_T Jet Algorithm
  - Subjets
- Method
  - Quark and Gluon Jet Extraction
  - Gluon Jet Fraction
- Raw Measurement
- Corrections
- Systematic Errors
- Conclusions

Motivation & Goals

- Tevatron = jet factory
- QCD: jets come from quarks and gluons
- Quark & Gluon jets different



Ratio: $C_A/C_F = 9/4$

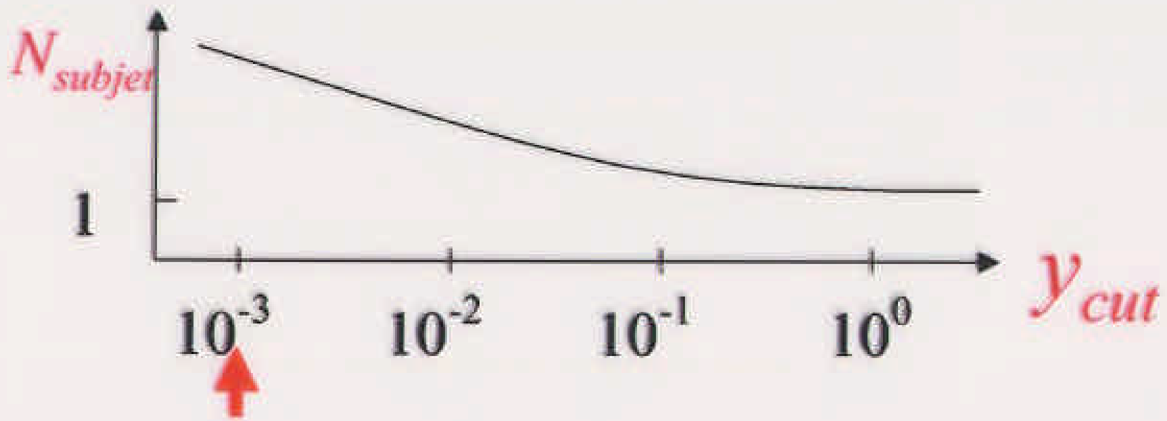
- Measure it (statistically)!

Structure in k_T Jets:Subjets

- Unravel jets until all subjets separated by y_{cut}

$$\left(\frac{p_T^{rel}}{E_T^{jet}}\right)^2 > y_{cut}$$

- Resolution parameter y_{cut}
  - $y_{cut} \to 1$ Single subjet per jet
  - $y_{cut} \to 0$ Infinite resolution
- Subjet Multiplicity



Quark and Gluon SubJet Extraction

- **Linear combination:**

Jet Observable → M; Gluon Jet Fraction → f_g; Quark Jet Fraction → $(1-f_g)$

$$M = f_g M_g + \underbrace{(1-f_g)}_{\text{Quark Jet Fraction}} M_q$$

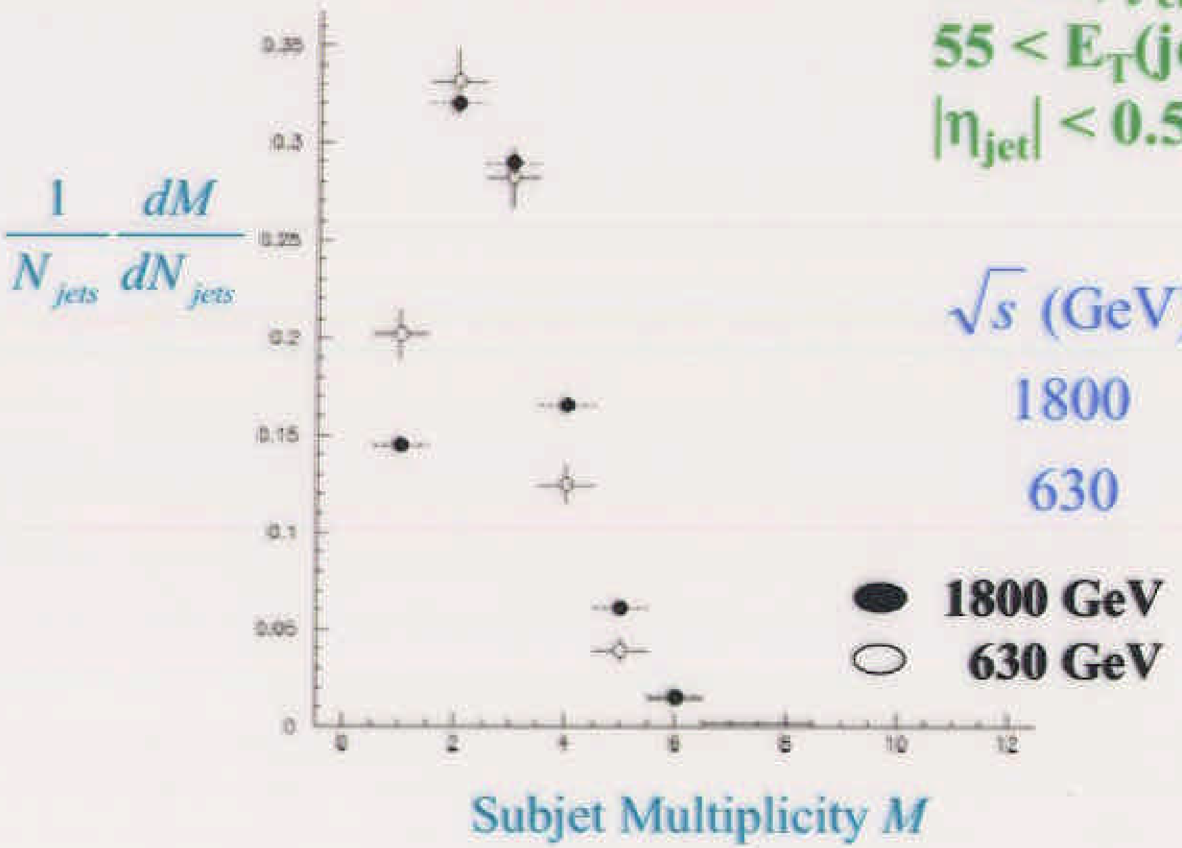
- **Assume M_g, M_q independent of cms energy**
- **Solve for q/g jet observables**

$$M_q = \frac{f^{1800} M^{630} - f^{630} M^{1800}}{f^{1800} - f^{630}}$$

$$M_g = \frac{(1 - f^{630}) M^{1800} - (1 - f^{1800}) M^{630}}{f^{1800} - f^{630}}$$

Raw Data: 1800 & 630

D0 Preliminary



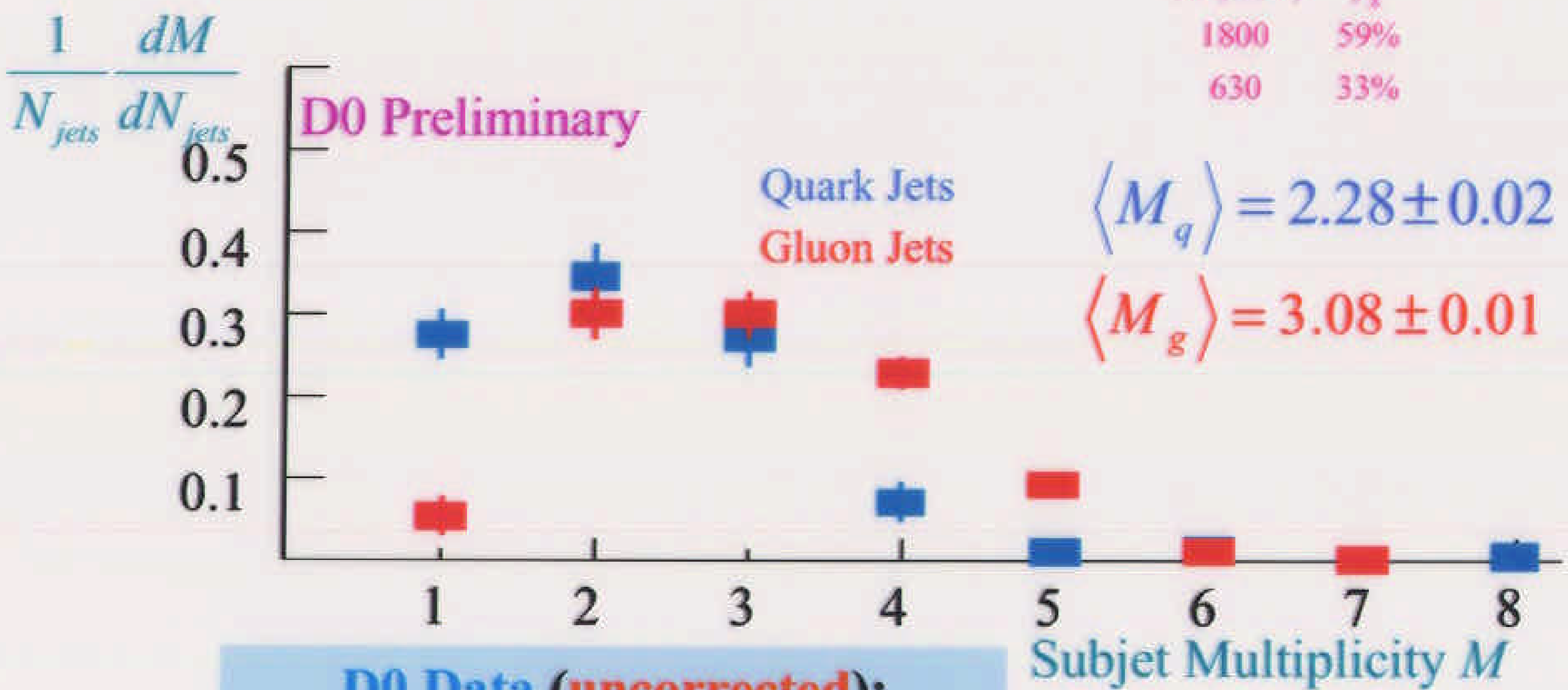
D=0.5, $y_{cut} = 10^{-3}$
$55 < E_T(jet) < 100$ GeV
$|\eta_{jet}| < 0.5$

$\sqrt{s}$ (GeV)	$\langle M \rangle$
1800	2.74 ± 0.01
630	2.54 ± 0.03

More subjets at $\sqrt{s}$ = *1800* GeV

Quark & Gluon Jets From Raw Data

$\sqrt{s}$ (GeV)	f_g
1800	59%
630	33%



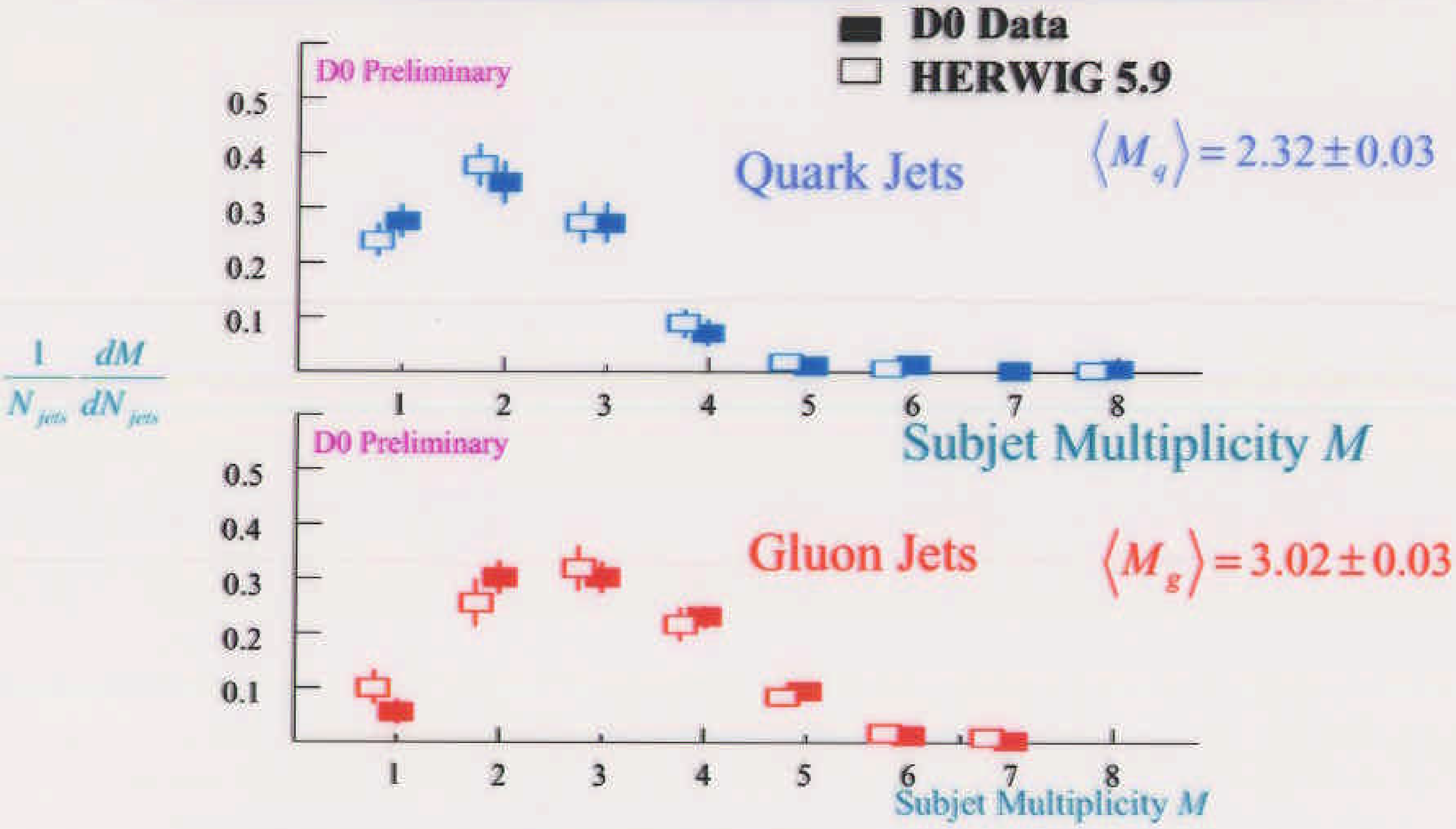
$$\langle M_q \rangle = 2.28 \pm 0.02$$

$$\langle M_g \rangle = 3.08 \pm 0.01$$

D0 Data (uncorrected):

$$R \equiv \frac{\langle M_g \rangle - 1}{\langle M_q \rangle - 1} = 1.63 \pm 0.02$$

Monte Carlo Prediction

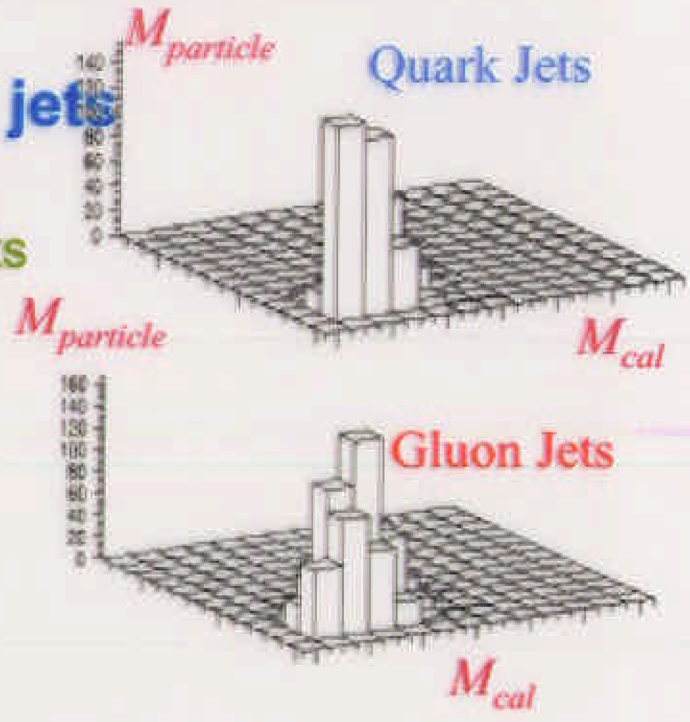


HERWIG 5.9 (uncorrected): R=1.53 ± 0.04

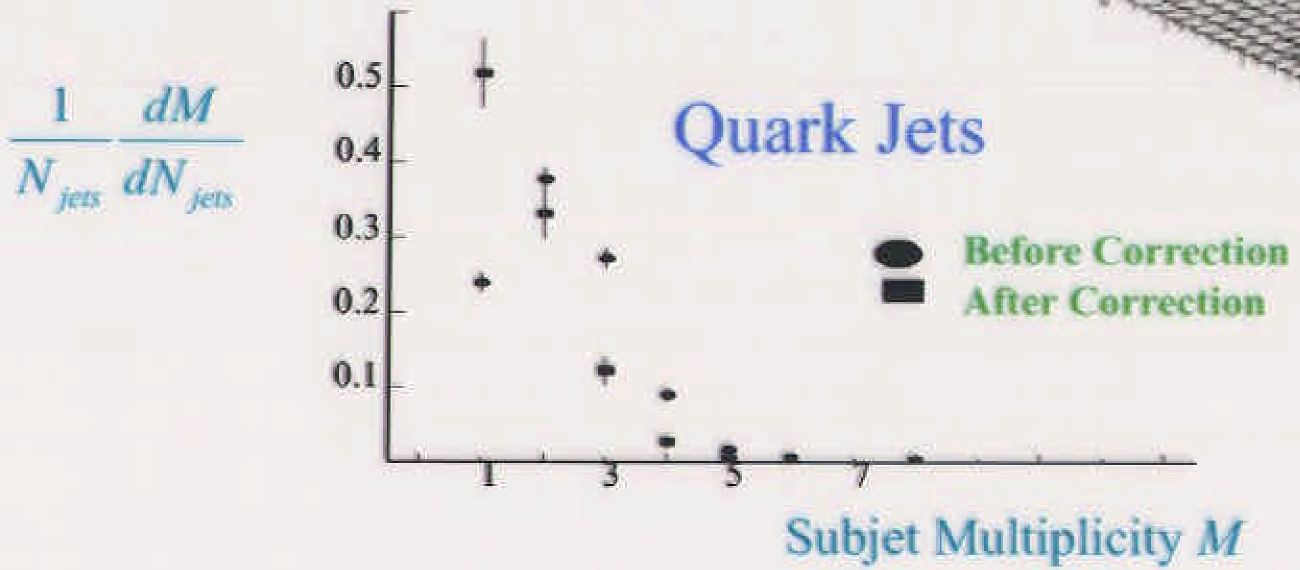
Unsmearing the Subjet Multiplicity

Measure MC subjet multiplicity in particle level jets vs calorimeter level jets

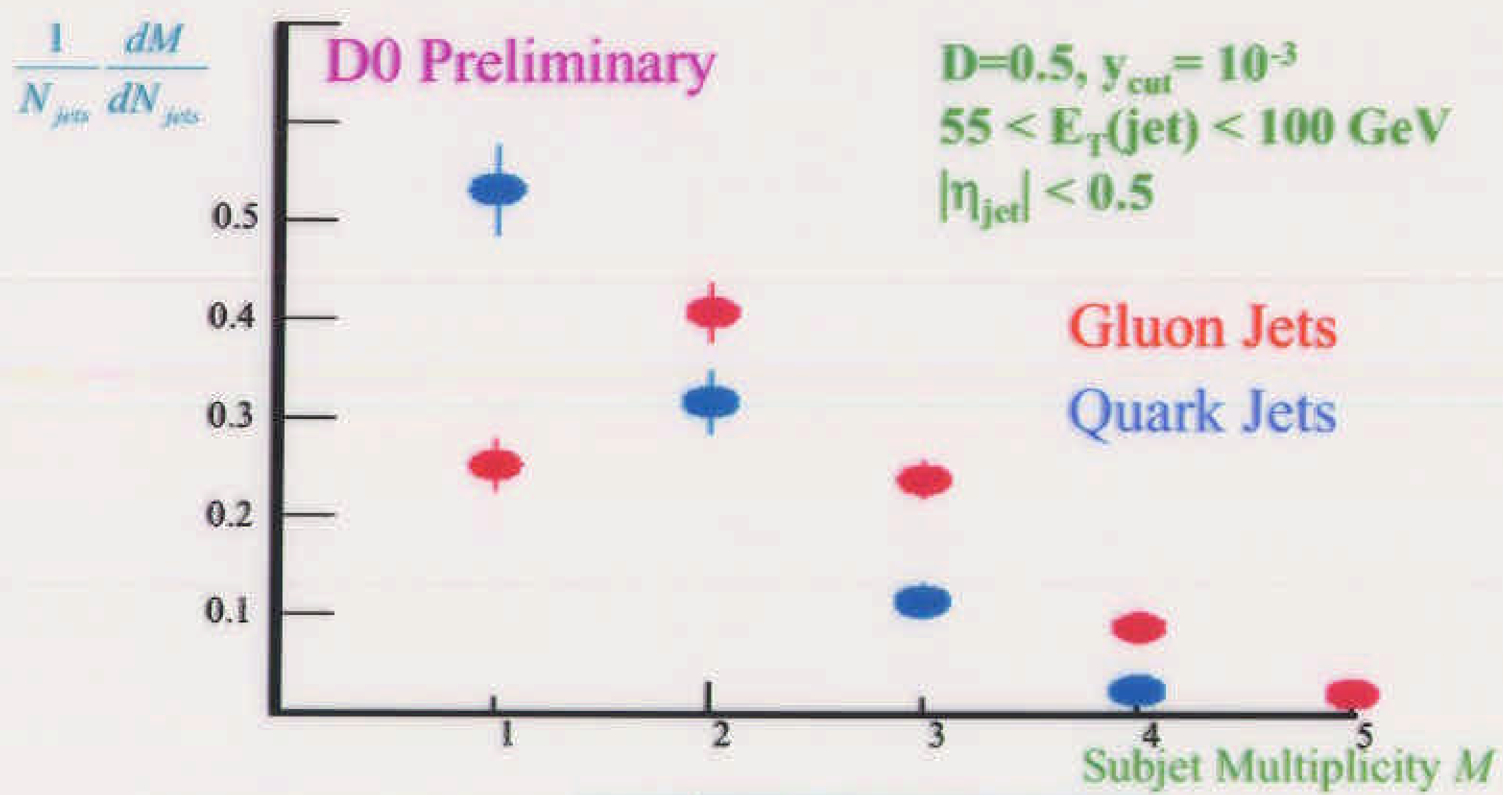
- Use 2D histogram to correct cal level jets
- Separate corrections for quark & gluon jets



Measurement of M_{cal} replaced with a *distribution* in $M_{particle}$



Corrected Subjet Multiplicity



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

HERWIG 5.9 $R = 1.86 \pm 0.04$

Conclusions of SubJet Analysis

- More subjets at 1800 GeV compared to 630 GeV
- Using gluon fraction from Herwig at two cms energies, we extract subjet multiplicities in quark and gluon jets.
- More subjets in gluon jets than in quark jets

$$R \equiv \frac{\langle M_G \rangle - 1}{\langle M_q \rangle - 1}$$

$$= 1.91 \pm 0.04\ (\text{stat})\ \pm^{0.23}_{0.19}\ (\text{sys})$$