Jet Fragmentation at CDF

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- Theoretical Introduction.
- CDF Data and MLLA – first look.
- Consistency of results within MLLA framework.
- Comparison to model-independent measurements
- Discussion & Conclusion

Jet Fragmentation=pQCD+hadronization

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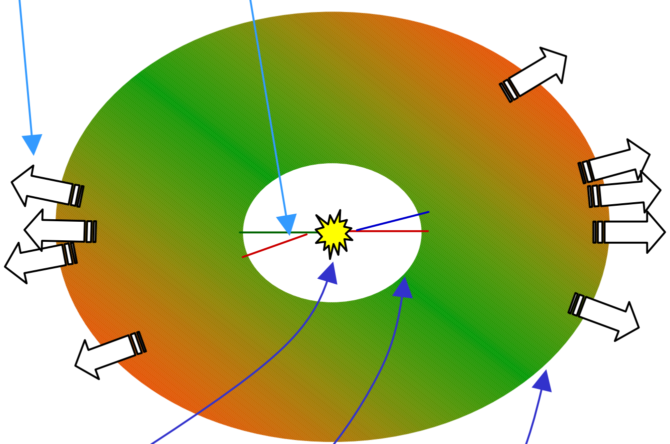

the fuzzy border between the two stages is usually associated with a k_T cut-off scale Q_{cutoff} (~1 GeV)

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

- pQCD stage that governs development of a parton shower
- Phenomenological hadronization that converts partons into hadrons

Perturbative or Non-Perturbative?

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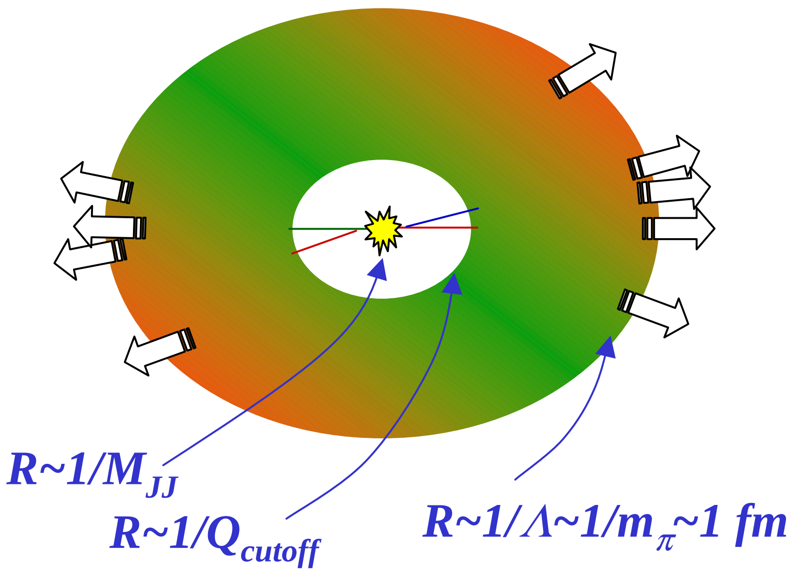
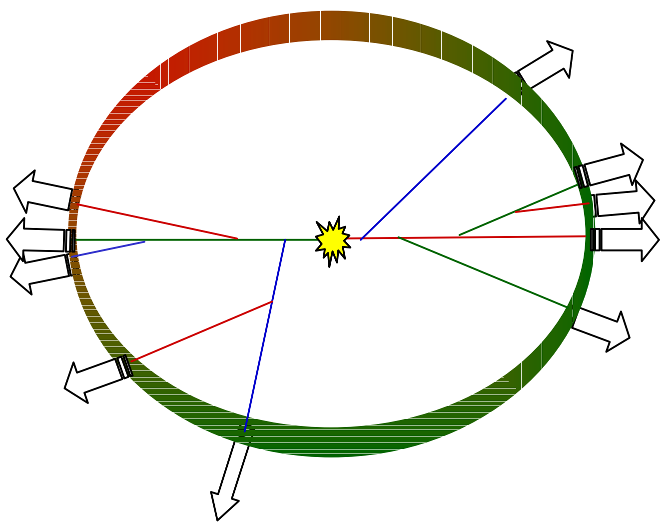


Non-Perturbative scenario:

- Properties of final hadrons are largely determined by the stage of hadronization.
- Phenomenological methods have to be used.



Perturbative scenario:

- Final hadrons "remember" properties of initial partons.
- Intra-jet characteristics can be analytically calculated in a consistent way (pQCD).

What If Perturbative?

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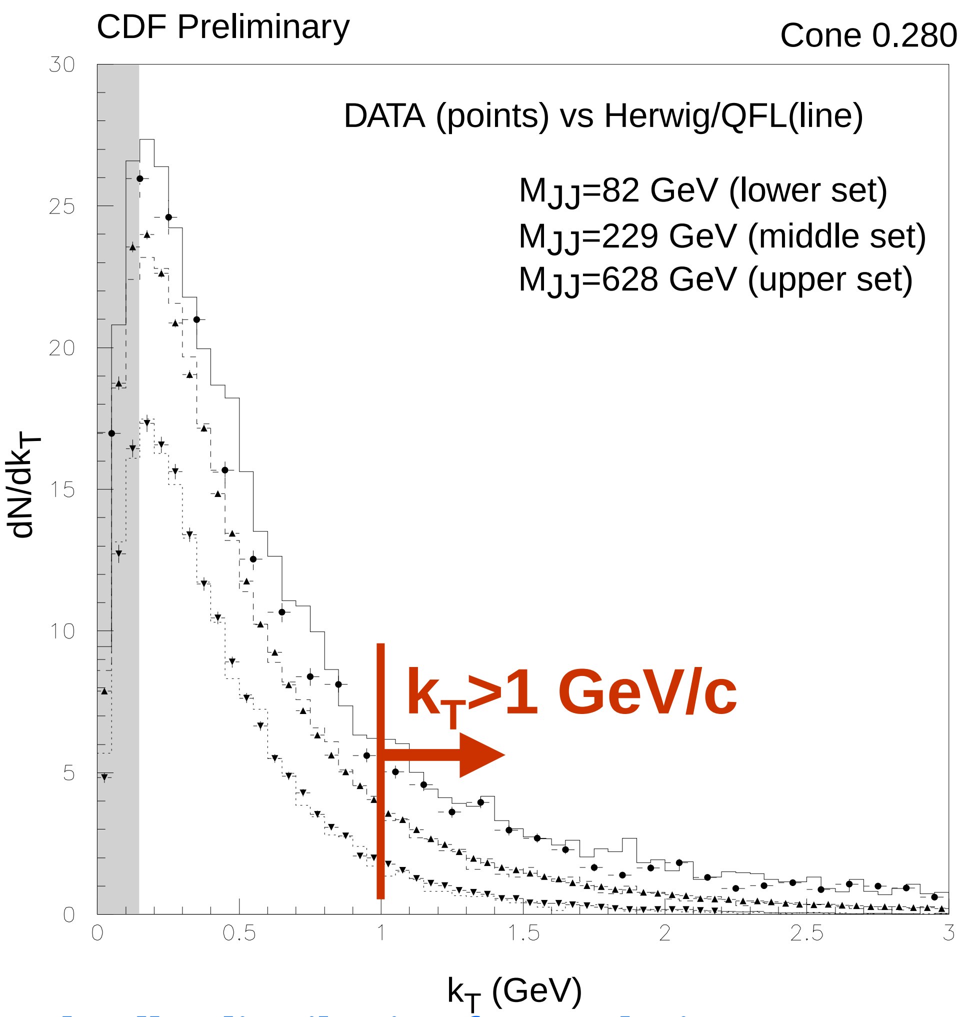

dN/dk_T distribution for tracks in cone 0.28 around the jet axis. CDF dijet events. Herwig scaled by 0.89.

- **Ordinary Perturbative QCD (k_T >1 GeV) ≡ dominance of the phenomenological hadronization** (too few particles with such high k_T). Any predictions would rely heavily on hadronization model.
- One needs to handle particles in the **region of k_T well below 1 GeV**.
- **"Improved" perturbative model needed !**

Perturbative Dominance Scenario.

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MLLA + LPHD

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

(Modified Leading Log Approximation)

- Analytical results are infrared stable ⇒ cut-off scale parameter Q_{eff} can be pushed down to Λ_{QCD}~250 MeV.

- **Soft partons are accounted for!**

Azimov, Dokshitzer, Khoze, Troyan (1985)

(Local Parton-Hadron Duality)

- Hadronization occurs locally at the last moment ⇒ hadrons "remember" features of parton distributions.

$$N_{hadrons}/N_{partons}=K_{LPHD}$$

- **Hadron distributions are related to Parton ones!**

Result = Perturbative Model, which potentially may coherently describe jet fragmentation!

Two parameters only - Q_{eff} and K_{LPHD}

MLLA Parameters.

What is the most favorable scenario?

- ***Q_{eff}*** **-** as low as possible (to include soft particles which constitute the majority of all). Preferably down to $\Lambda_{\mathbf{QCD}}$.
- ***K_{LPHD}*~1** - **"One parton becomes one hadron".** In our case (charged particles) $K_{LPHD}^{charged}$ **~ 1/2 - 2/3.**
- It would be nice to have something model-independent to compare the MLLA parameters to.

MLLA Predictions

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 Calculations.

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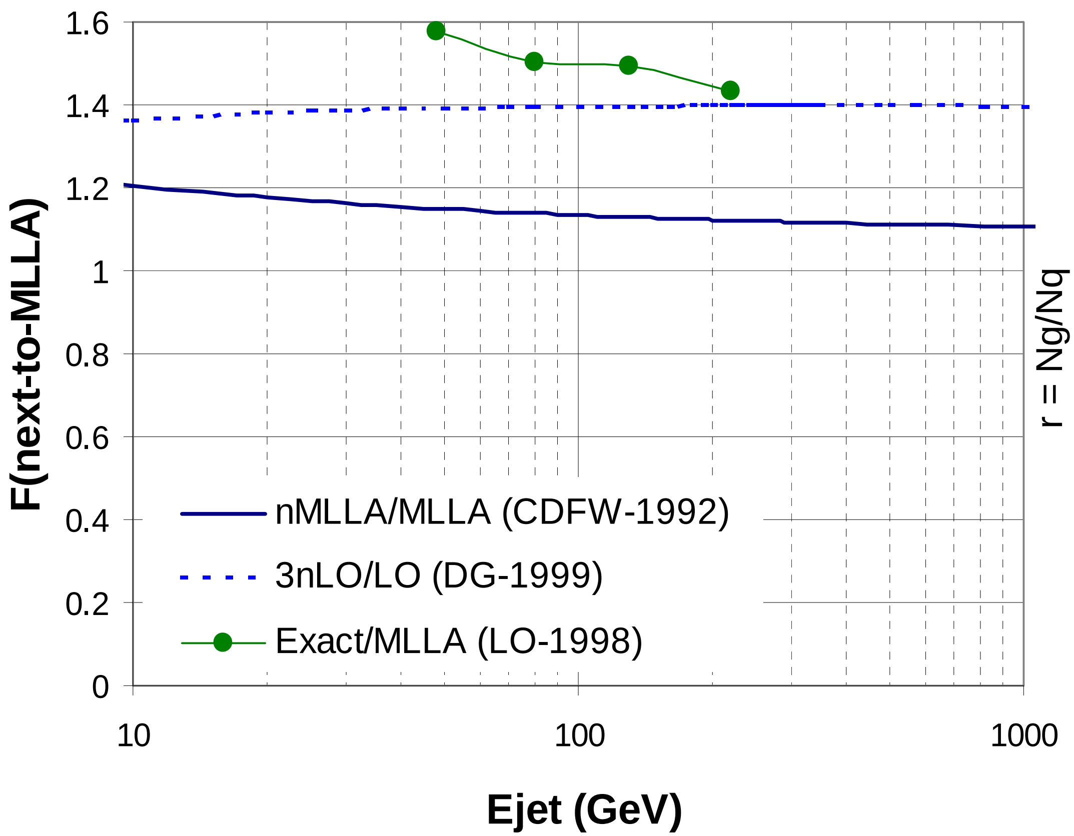
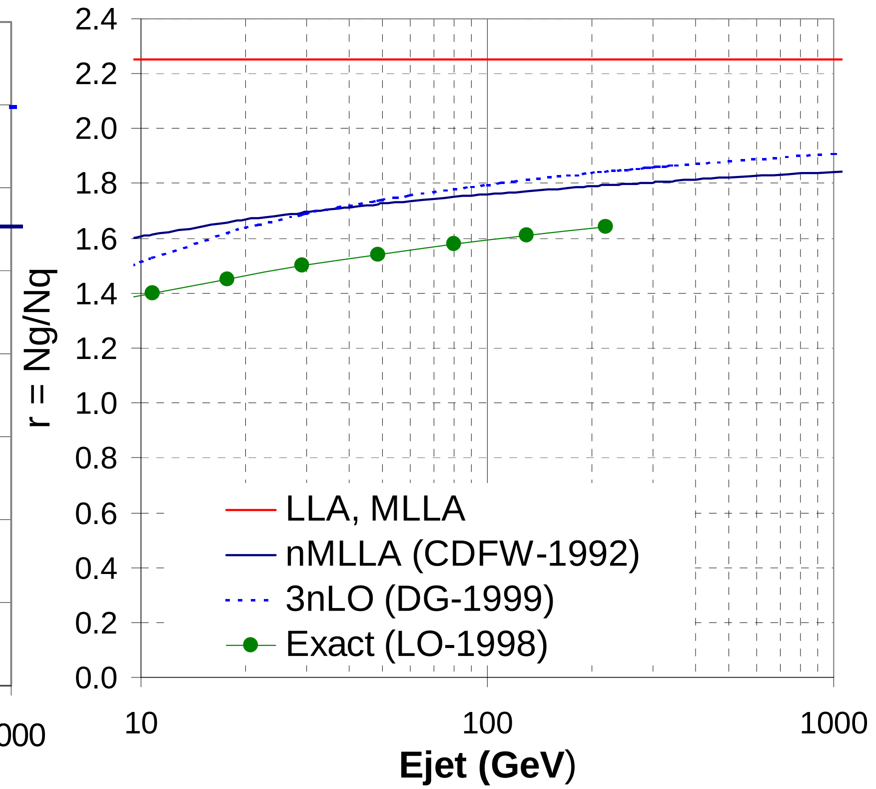
Change in gluon spectrum:

$$N_g^{\,next\text{-}to\text{-}MLLA}(Y,\xi) = F^{next\text{-}to\text{-}MLLA}\, N_g(Y,\xi)^{MLLA}$$



Change in ratio of multiplicities:

$r = 9/4 \rightarrow 1.6\text{-}1.8$



Analysis at CDF.

- **CDF – Collider Detector at Tevatron, a $p\bar{p}$ - collider with $\sqrt{s}$ =1800 GeV**

Explicit Advantages :

- Dijet masses available at CDF significantly expand potential area of study.
- $\mathbf{E_{jet}}$ $\theta/\mathbf{Q_{eff}}$ scaling can be checked on a wide range of energies. (has never been done).
- Possibility to analyze data samples enriched either by quark or gluon jets.

Complications:

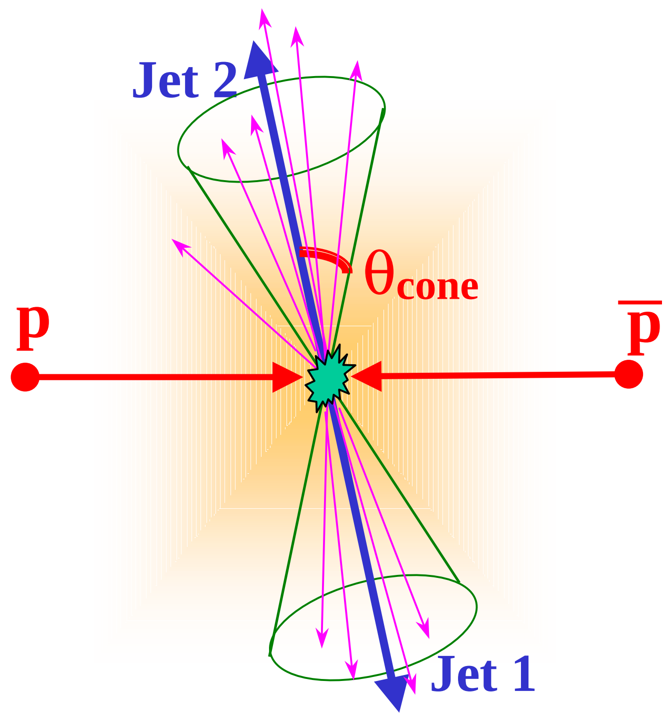
- Background environment is less trivial.
- Secondary events in the same bunch crossing.
- Underlying event debris.
- Tracker inefficiency, calorimeter response corrections and many others

Major Detector elements used:

- Vertex Chamber
- Central Tracker
- Calorimeters

Analysis at CDF.

- **CDF Run 1B Data.**
- **100,000 Dijet Events : M_{jj}=80 - 630 GeV**
- **Jets - Cone Algorithm**
- **both jets are in central region, well balanced (E_{jet}~E_{Tjet}~M_{jj}/2)**
- **Particles counted in 3 cone-sizes 0.28<θ_{cone}<0.47 around the jet axis**
- **Mixture of quark and gluon jets**



Data Analysis and Fits:

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- Hadron momentum distribution:

$$N_{hadron}(\xi) = \underbrace{K_{LPHD}^{charged}\left[\varepsilon_g(E_{jet}) + \frac{1}{r}(1-\varepsilon_g(E_{jet}))\right]F^{next-to-MLLA}}_{K} N_g(\xi, Q_{eff}, E_{jet})$$

- Data was fitted with classic MLLA gluon spectrum, parameter $K \neq \mathbf{K_{LPHD}^{charged}}$ and depends on E_{jet}:

$$K = K_{LPHD}^{charged} F^{next-to-MLLA}\left[\varepsilon_g(E_{jet}) + \frac{1}{r}(1-\varepsilon_g(E_{jet}))\right]$$

Parameters: $K_{LPHD}^{charged}$, r, Q_{eff}

Momentum Distribution of Particles

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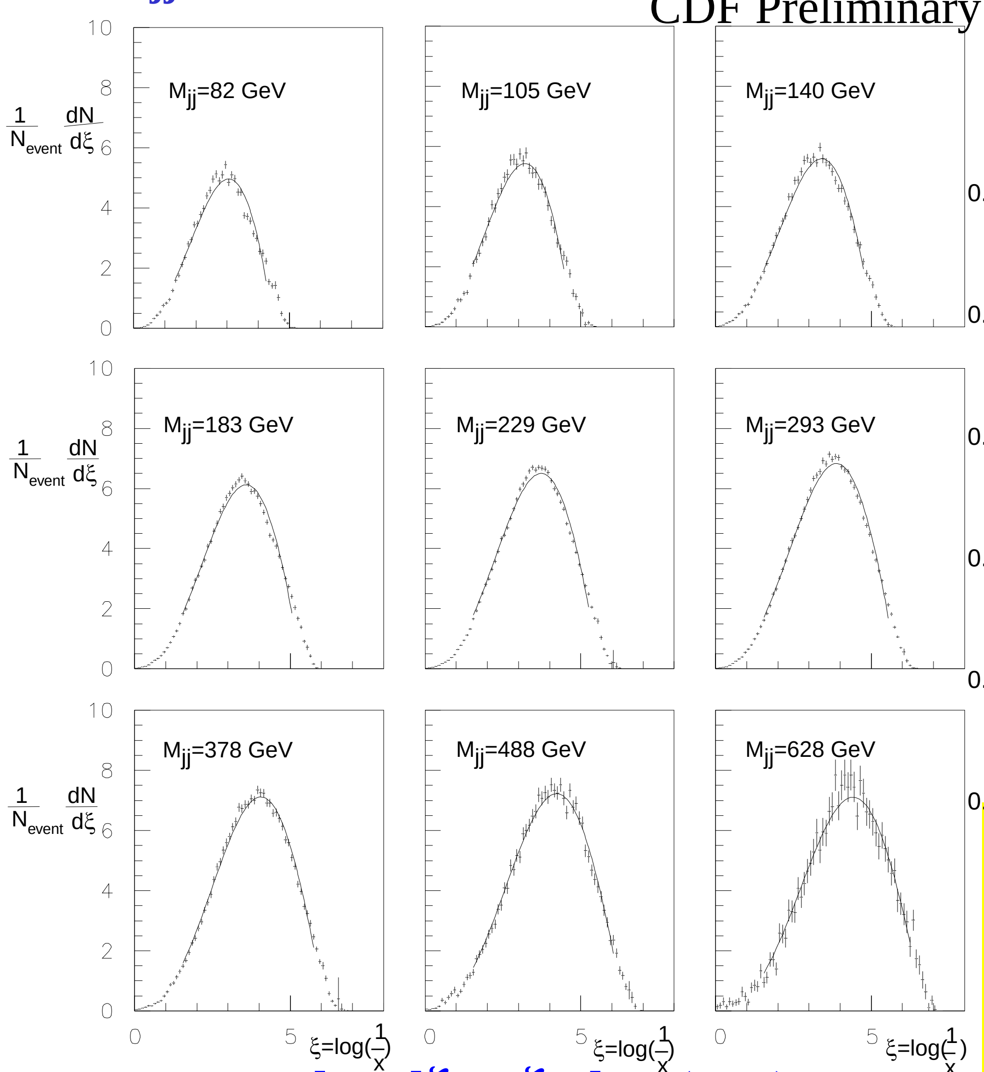
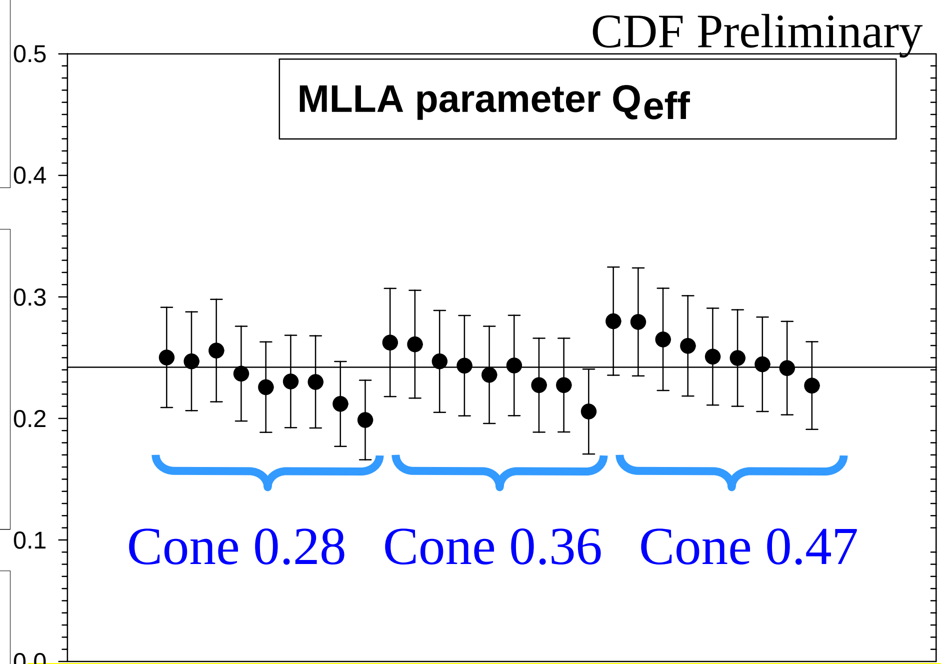
M_{jj}-scan (θ_{cone}=0.47), MLLA fit



$dN/d\xi$, $\xi=\log(1/x)$

Q_{eff} for all 9 M_{jj}'s and 3 opening cone-sizes



MLLA fit $dN(\xi,Y)/d\xi$

$Q_{eff}\approx$constant=240±40 MeV

Momentum Distribution of Particles

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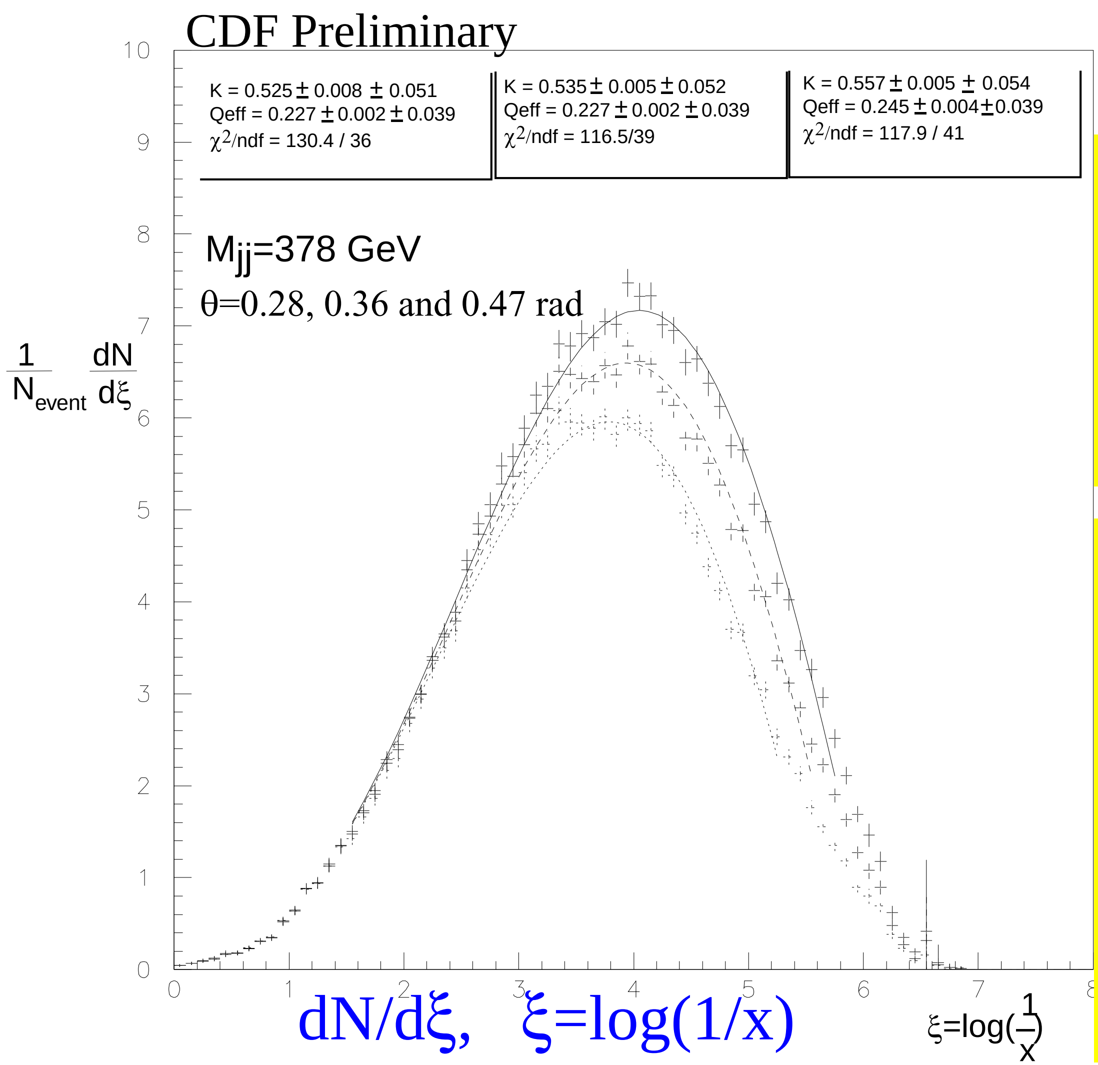
$$K = K_{LPHD}^{charged} F^{next-to-MLLA}\left[\varepsilon_g(E_{jet}) + \frac{1}{r}(1-\varepsilon_g(E_{jet}))\right]$$



dN/dξ, ξ=log(1/x)

For fixed M_{jj}, *K* should be cone-size independent

MLLA-fitted values of *K*:

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

Fit of all three distributions with a single Q_{eff}

- θ_{cone}=0.47 K=0.53 ±0.05 (syst)
- θ_{cone}=0.36 K=0.52± 0.05 (syst)
- θ_{cone}=0.28 K=0.52 ±0.05 (syst)

Peak of the Momentum Distribution

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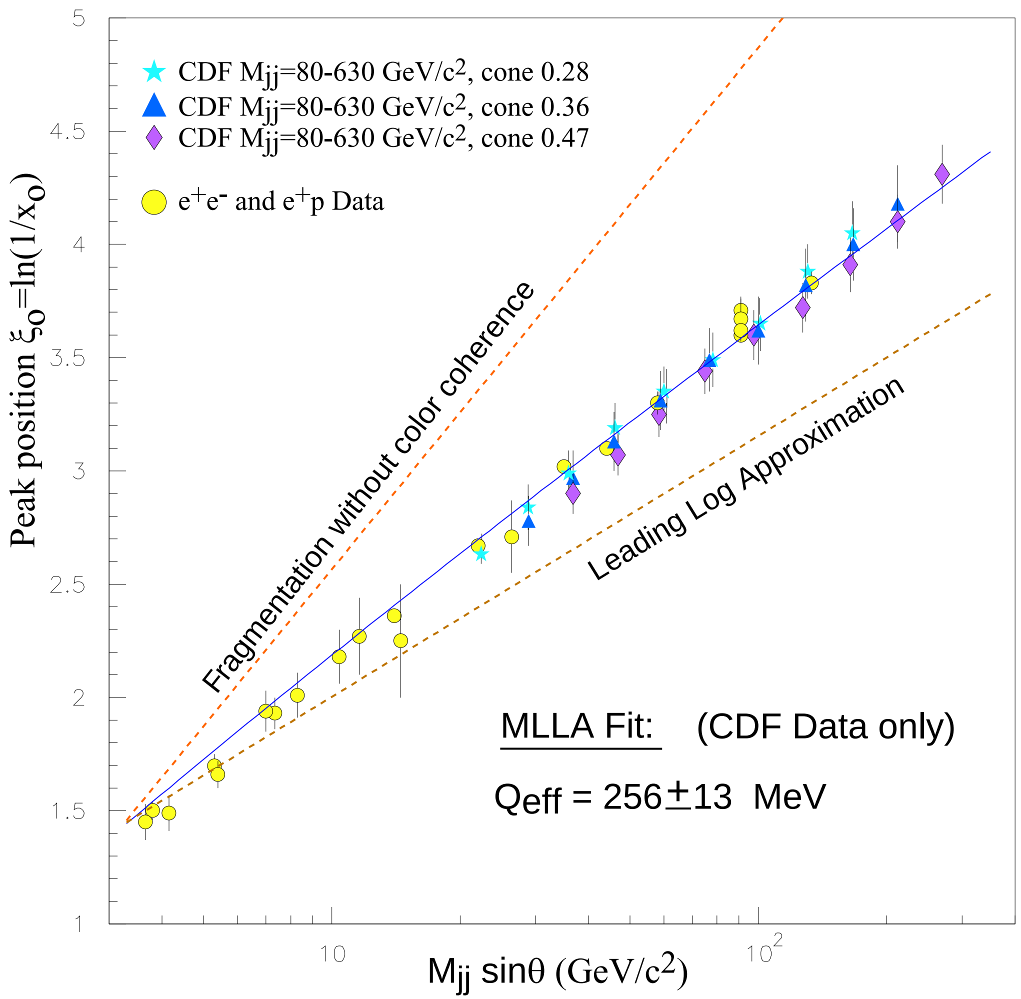
In MLLA peak ξ_o vs. M_{JJ}: $\xi_0 = 1/2\, Y + (cY)^{1/2} - c$,

$Y = \ln(E_{jet} \sin\theta / Q_{eff})$, c = 0.29 for $n_f = 3$

CDF Preliminary



Peak ξ_o vs. $M_{JJ}\sin\theta$ fit:

Q_{eff}=256±13 MeV

Intermediate Summary

Based on the momentum distribution:

- Q_{eff} is not constant but "reasonably universal" and has a plausible value (~240 MeV).
- K shows some unexpected (but very moderate) trends, such as a slight fall for smaller angles.
- $(E_{jet}\theta/Q_{eff})$ scaling is evident (peak evolution)

Conclusion:

- Data supports the perturbative dominance scenario.
- Moderate deviations from the theory may indicate presence of higher order and hadronization effects.

Momentum Distribution of Particles

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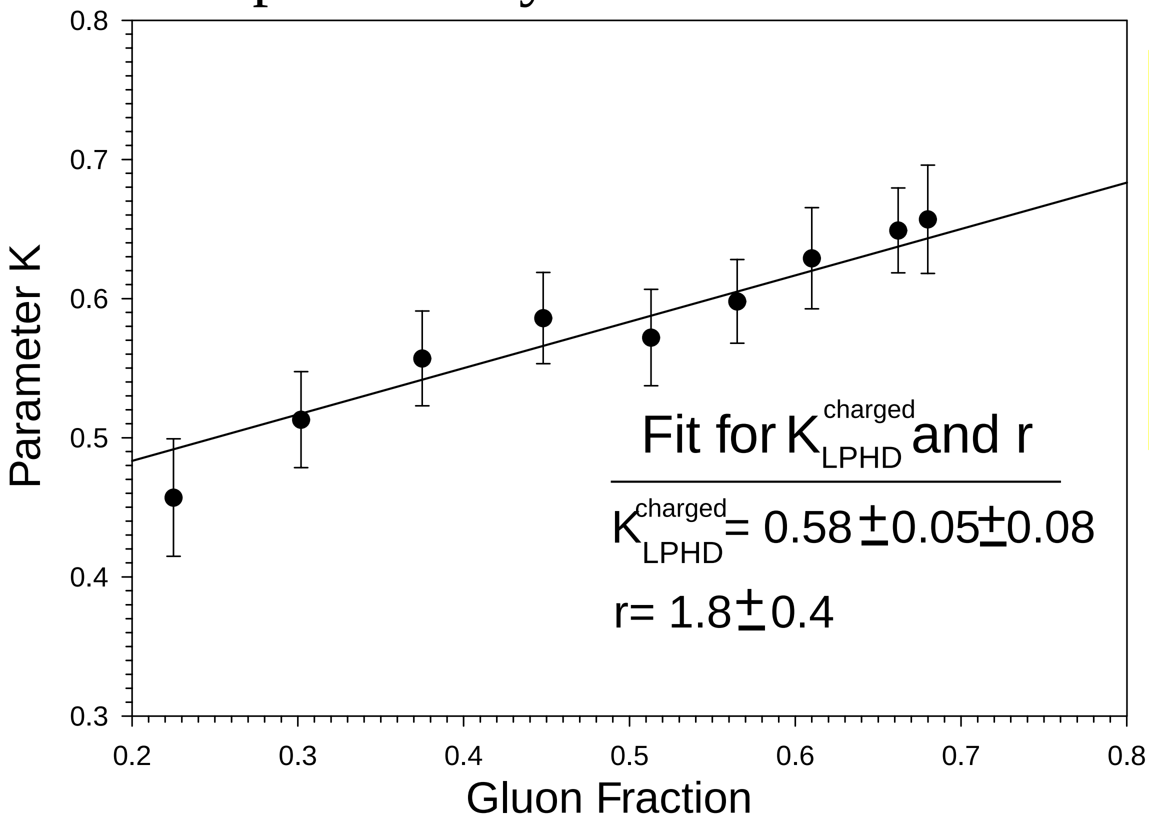
$$K = K_{LPHD}^{charged} F^{next-to-MLLA} \left[\varepsilon_g (E_{jet}) + \frac{1}{r}(1 - \varepsilon_g (E_{jet})) \right]$$

(Linear if plotted K vs ε_g)

CDF preliminary



(assuming $F^{next-to-MLLA}$=1.35±0.15)

K vs. gluon jet fraction fit:

- indirect r=1.8±0.4
- $K_{LPHD}^{charged}$=0.58 ±0.10

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

Multiplicity in Dijet Events

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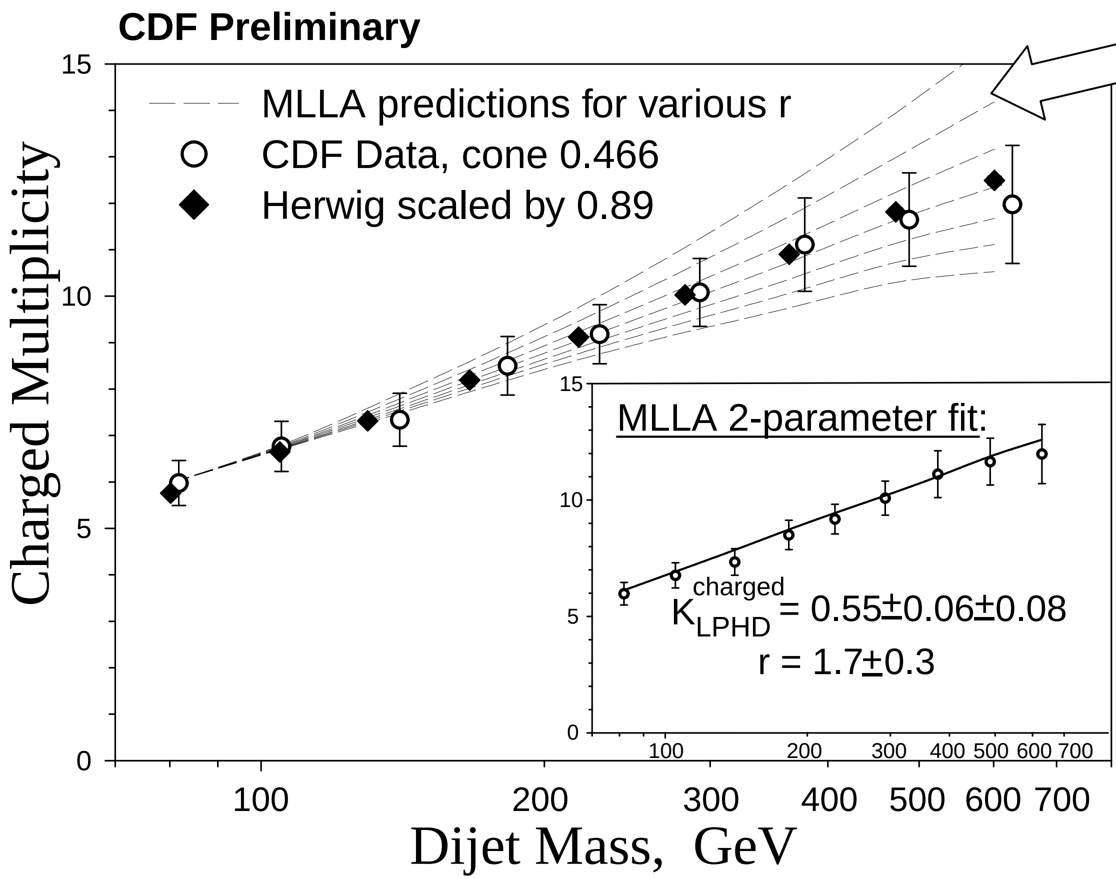

dashed curves from top to bottom
r=1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.25

(assuming $F^{\text{next-to-MLLA}}=1.35\pm0.15$)

<u>MLLA fit of N_{jet} vs. M_{JJ}:</u>

– indirect $r=1.7\pm0.3$

– $K_{LPHD}^{charged}=0.55\pm0.10$

The measurement is "indirect": result relies on MLLA-governed dependence $N_g(E_{Jet})$

Another Intermediate Summary

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Analysis in the framework of MLLA:

Assuming next-to-MLLA correction $F^{\text{next-to-MLLA}}=1.35 \pm 0.15$:

Momentum spectrum:

$K^{charged}_{LPHD} = 0.58 \pm 0.10$

$r = 1.8 \pm 0.4$

Multiplicity:

$K^{charged}_{LPHD} = 0.55 \pm 0.10$

$r = 1.7 \pm 0.3$

- Self-consistent, even though multiplicity measurement does not rely on the shape of the spectrum!
- r was treated as a free parameter, but still indirect!

Does it all make sense? Is it consistent with everything else?

Ratio of Gluon/Quark Jet Multiplicities.

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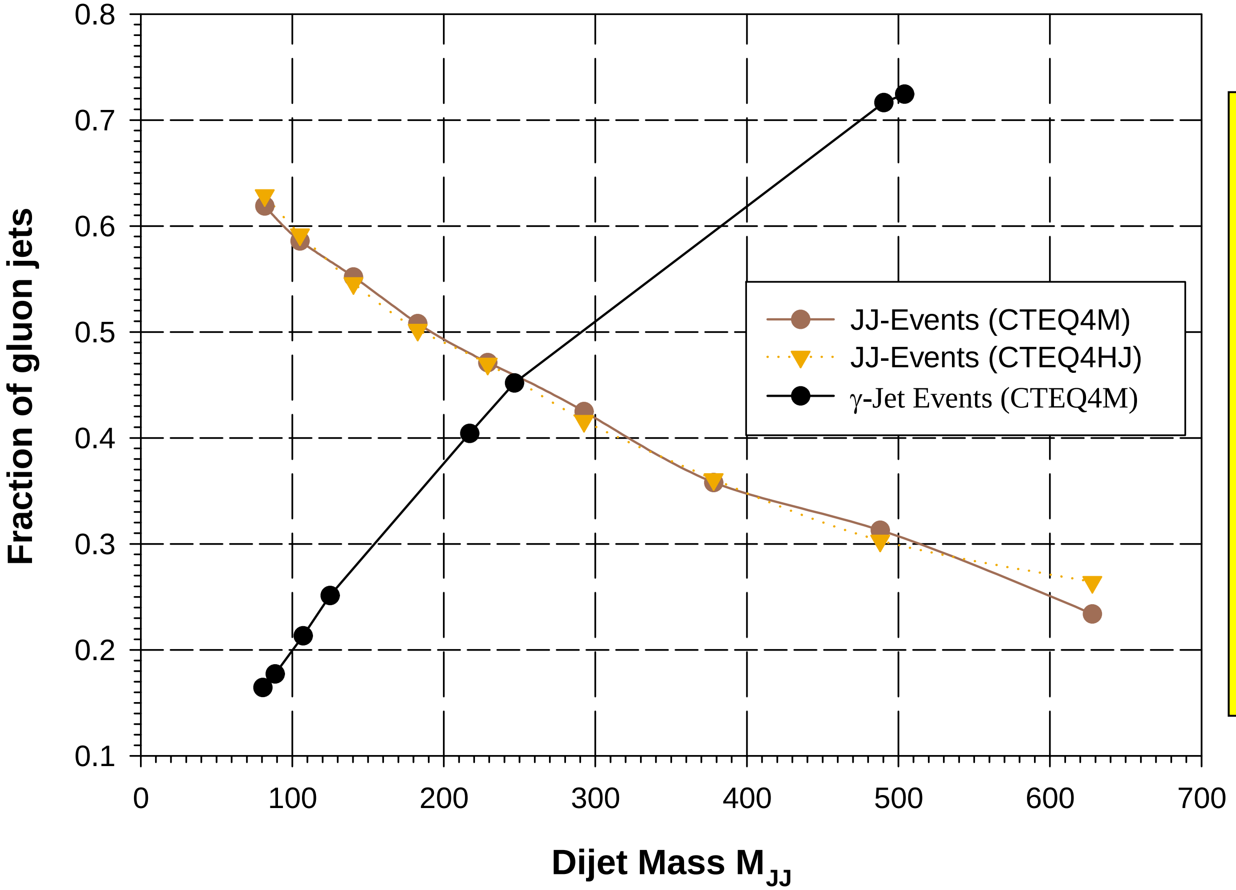
To measure ratio r in a model-independent way, one may compare two samples with different gluon/quark jet fractions.

Dijet events vs photon+jet events is one of the choices.



•Fractions of gluon jets in dijet and photon+jet events (Herwig5.6)

Momentum Spectrum

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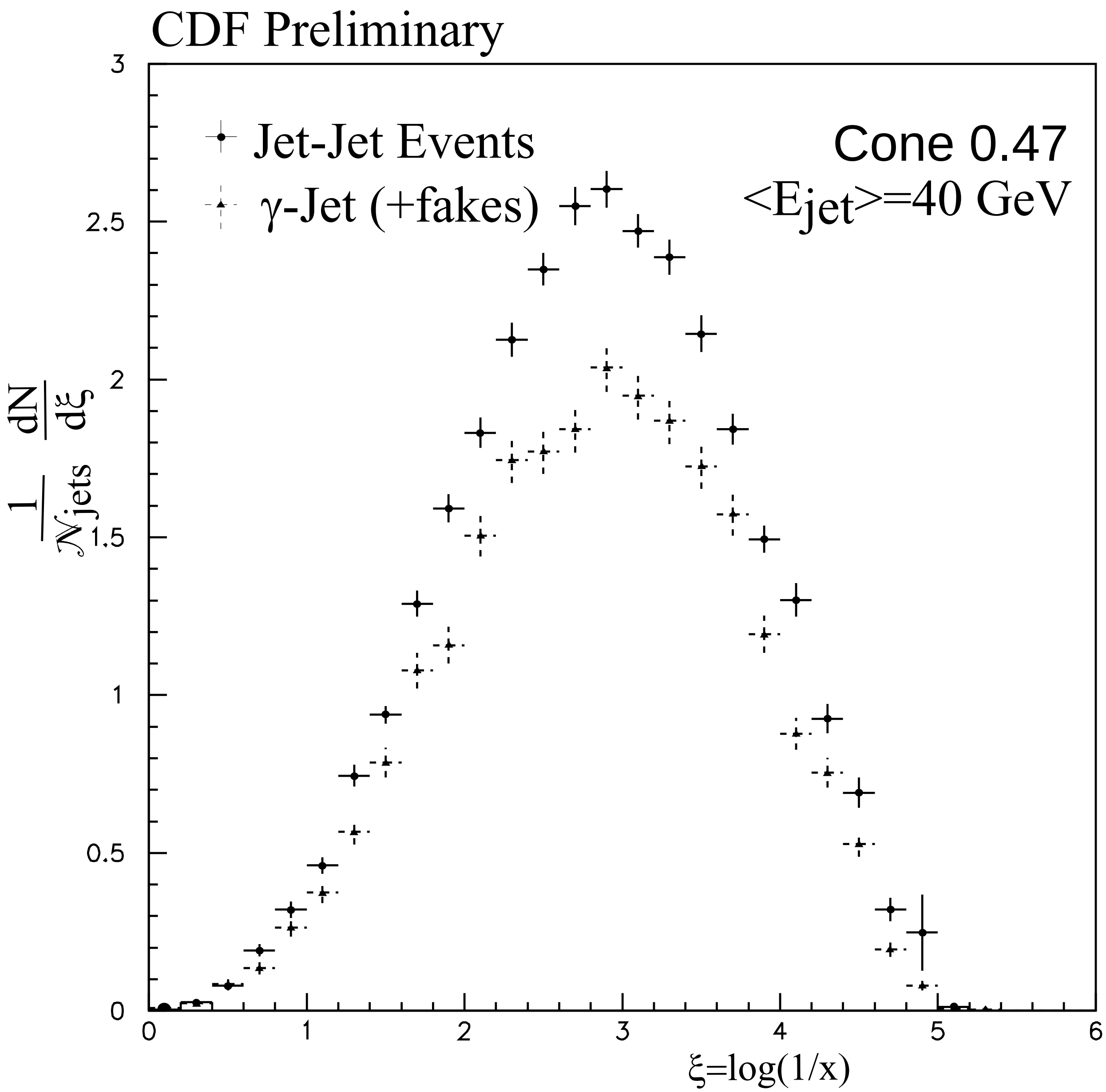
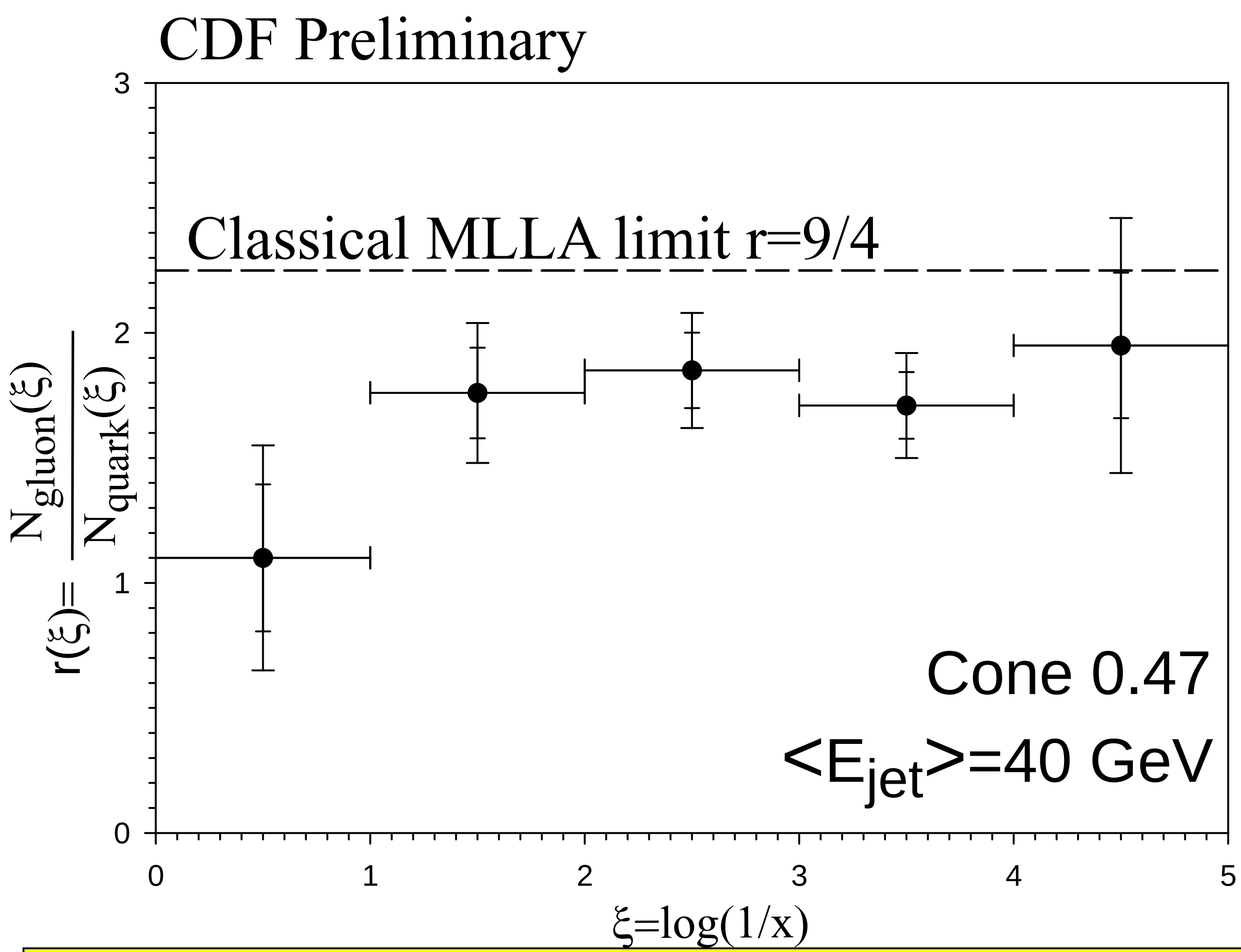


- Purity of the photon+jet sample ~ 70%
- Distributions are clearly different.
- Ratio r is greater than one!

Ratio of Gluon/Quark Momentum Distributions



$$r(\xi) = \frac{N_{gluon}(\xi)}{N_{quark}(\xi)}$$

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

Dependence of r on Jet Energy

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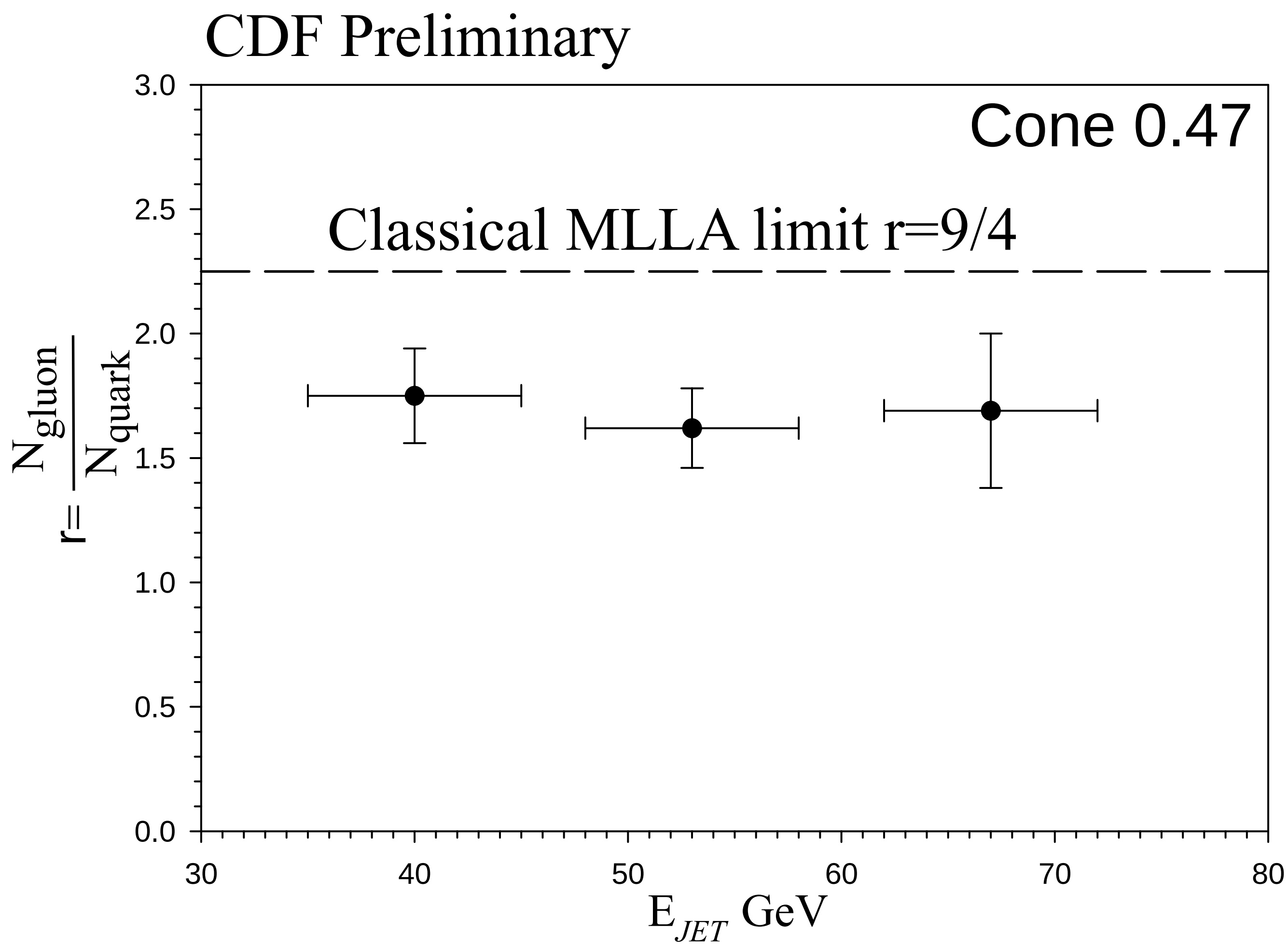

$$r = \frac{N_{gluon}}{N_{quark}}$$

For E_{jet}= 40 GeV, r= 1.76 ± 0.1

Consistency Checks

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Measurement in MLLA context	Model-independent measurement/expectation
r, ratio of particle multiplicities in gluon and quark jets:	
r=1.7±0.3 (shape)	r=1.76±0.11±0.15 (comparison of dijet and γ-jet events)
r=1.8±0.4 (total multiplicity)	
Parton-to-hadron Conversion rate $K_{LPHD}^{charged}$:	
$K_{LPHD}^{charged}$=0.58±0.10 (shape)	isotopic invariance → 1/2 -2/3
$K_{LPHD}^{charged}$=0.55±0.10 (multiplicity)	fraction of jet energy carried by charged particles f=0.55±0.01 [TASSO]

MLLA cut-off scale Qeff :

$Qeff$ = 240 ± 40 MeV(shape)

$Qeff$ = 256 ± 13 MeV(peak position)

Conclusions

- This study is the first detailed and comprehensive wide-range experimental comparison of the MLLA predictions to the data.
- Our results show reasonable and consistent agreement with the predictions of the MLLA, supporting the applicability of perturbative methods for jet fragmentation.
- Observed moderate deviations from the theory may indicate presence of higher order and hadronization effects.
- Run II of the Tevatron (2001) with significantly improved CDF detector and higher luminosity will present a perfect opportunity to continue these studies.