Tevatron Run I QCD Results

Don Lincoln

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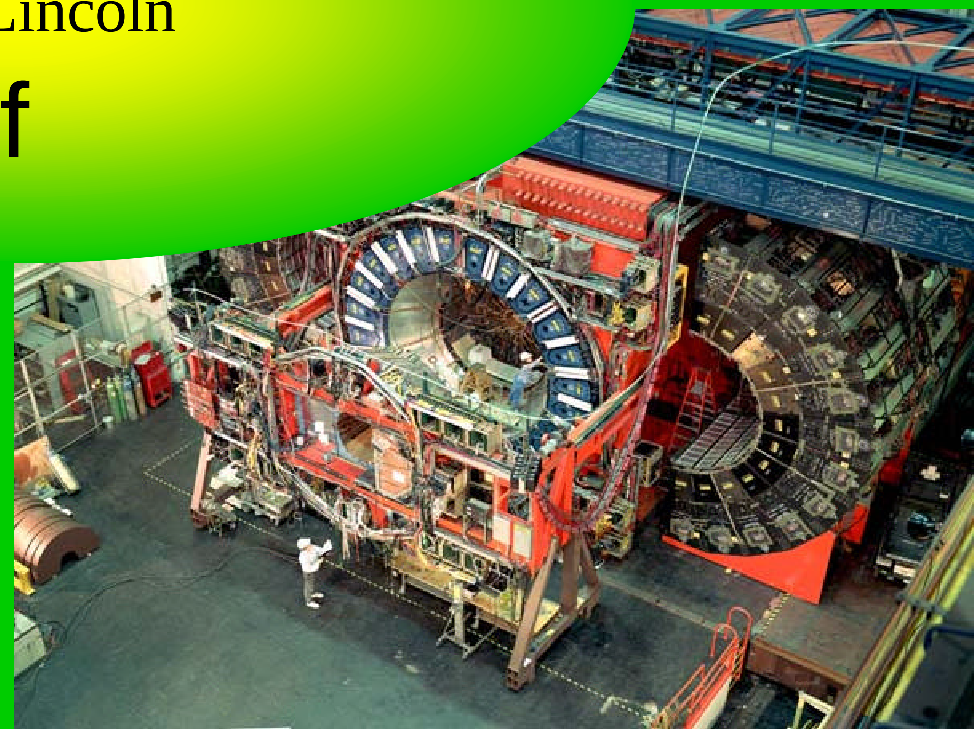


Quantum
Chromo
Dynamics

Study of the force governing the behavior of quarks and gluons

Topics Today

- Inclusive Jet Cross-Section (Cone Algorithm)
- Measurement of α_s
- Inclusive Jet Cross-Section (k_T Algorithm)
- Event shape variables New
- Jet structure/quark-gluon separation

Cone Definition of Jets

Observable remnant of parton-parton hard scatter

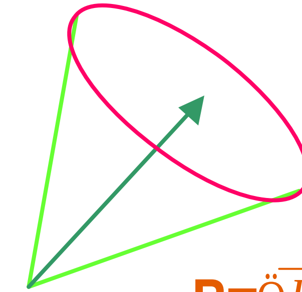
Centroid found with 4-vector addition

E_{jet} = S E_i

$E_T^{jet} = E_{jet}$ sin q_{jet}

(CDF's Definition)

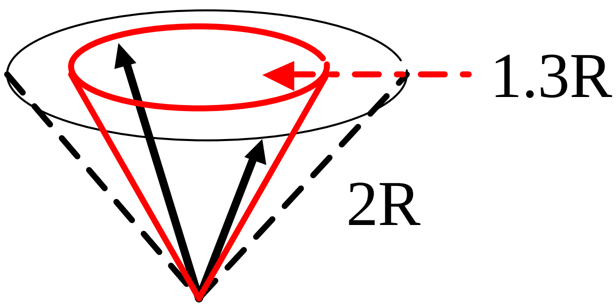
- Cone Definition R=0.7 in η–φ



R=Ö$h^2 + j^2$

h = -ln[tan(q /2)]

- Merging and splitting of jets required if they share energy



- R_{sep} required to compare theoretical predictions to data

(R_{sep} is the minimum separation of 2 partons to be considered distinct jets)

Suggests need for more robust algorithm

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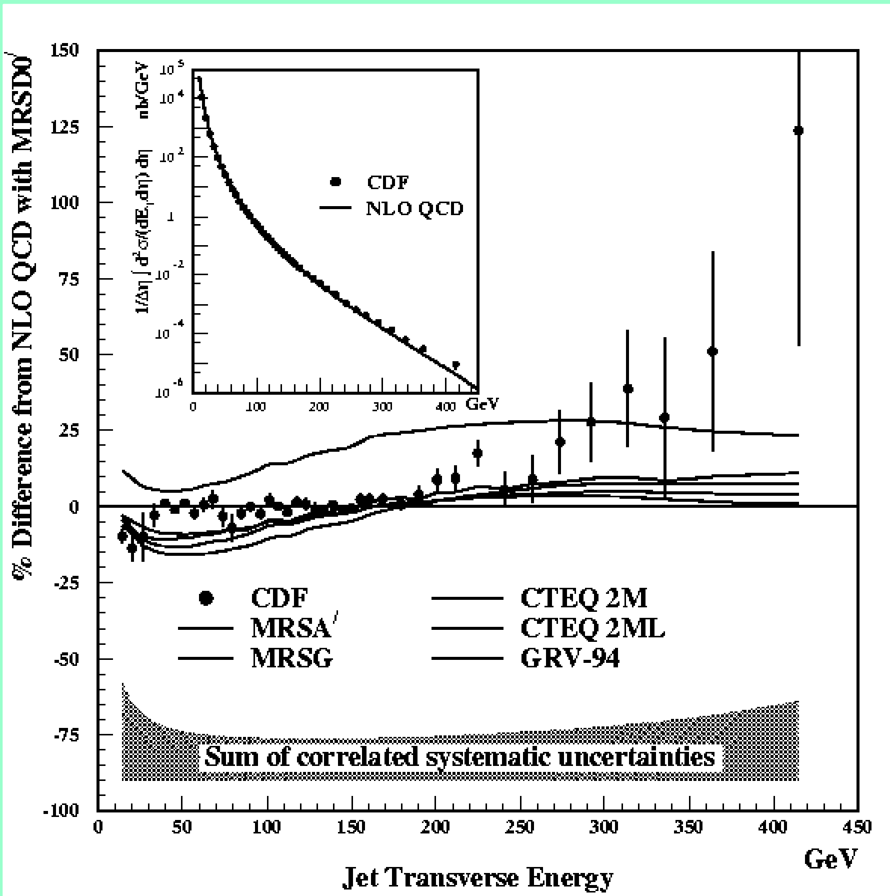
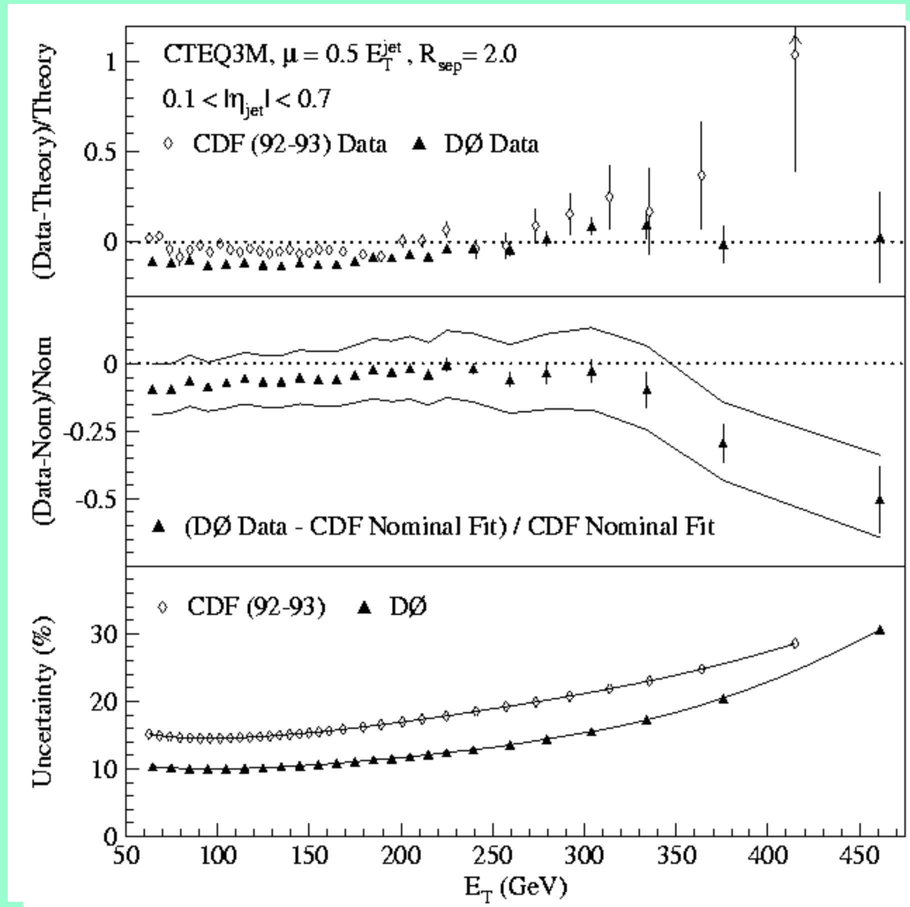
State of the Art 1995 (The Controversy)

High p_T excess is exciting prospect



PRL 77 438 (1996)



PRL 82 (1999) 2451

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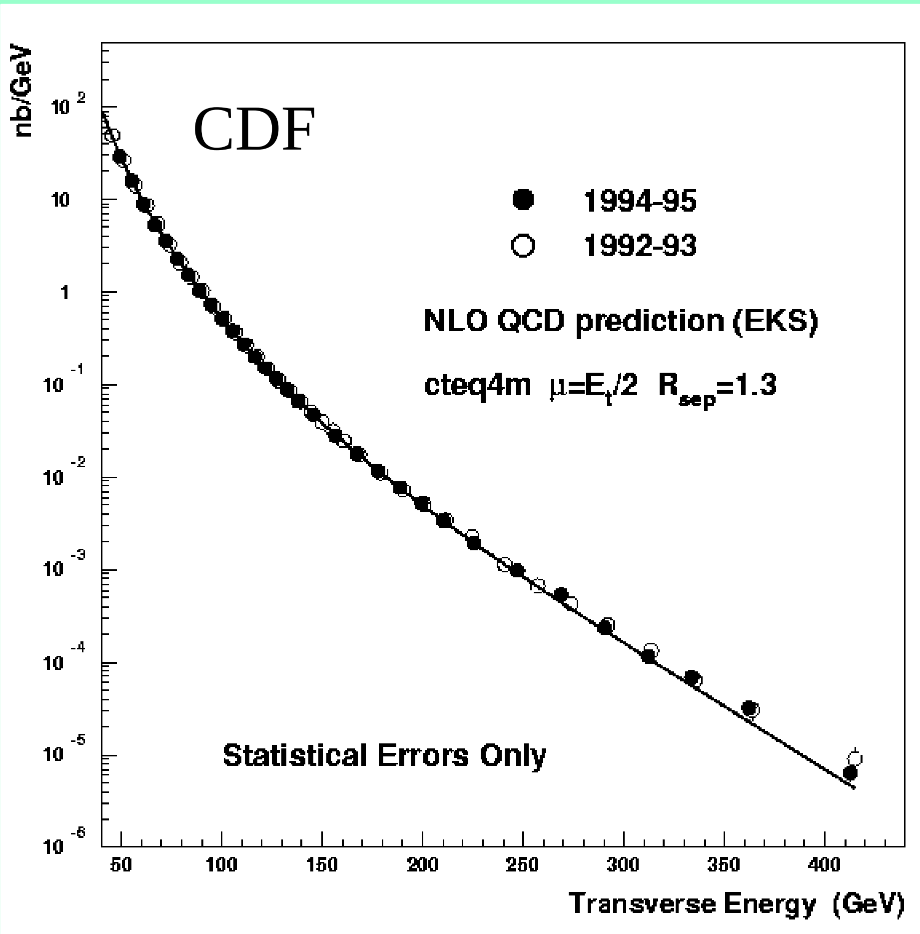
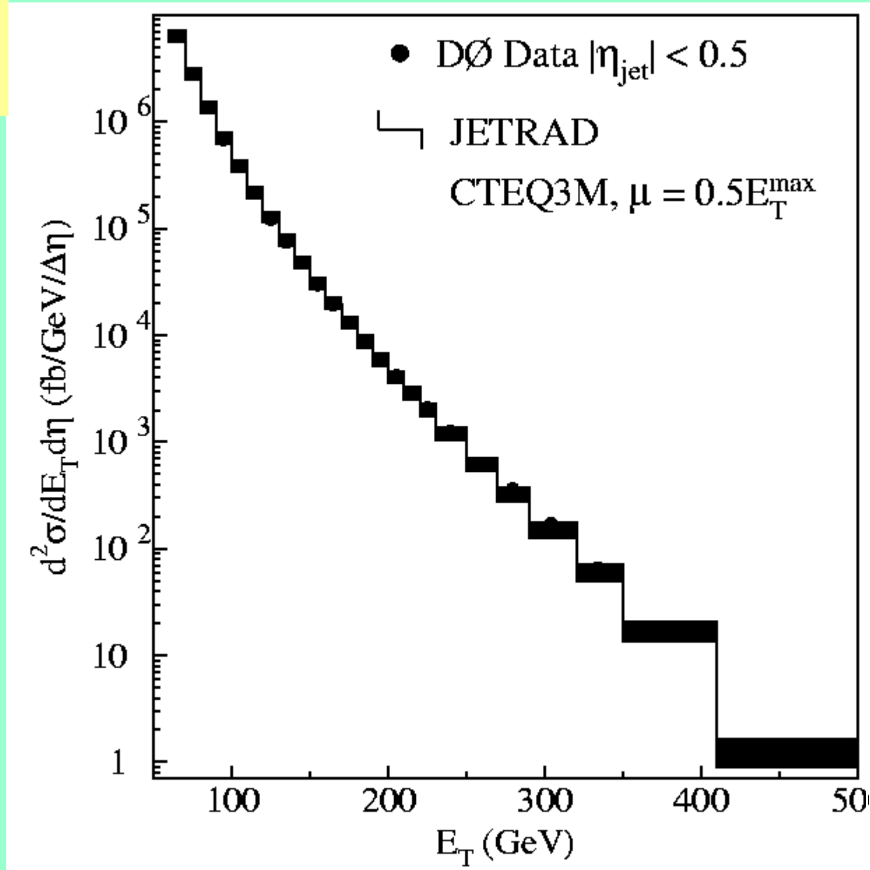
Controversy Resolved(?)

More modern pdf's (esp. CTEQ4M and CTEQ4HJ) ameliorate the disagreement

PRD 64 032001 (2001)
Erratum-ibid. D65 039903 (2002)

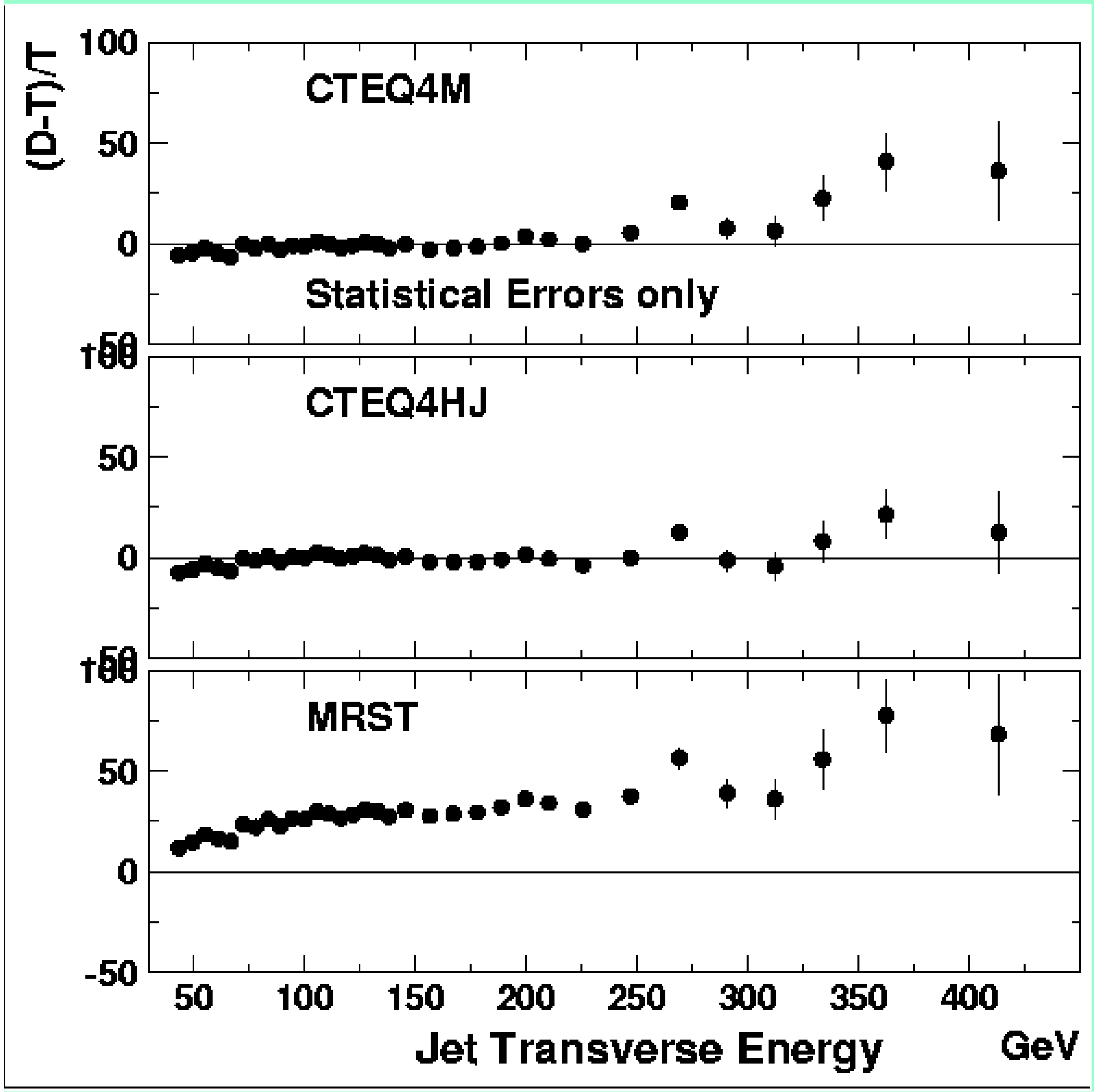




PRD 64 032003 (2001)

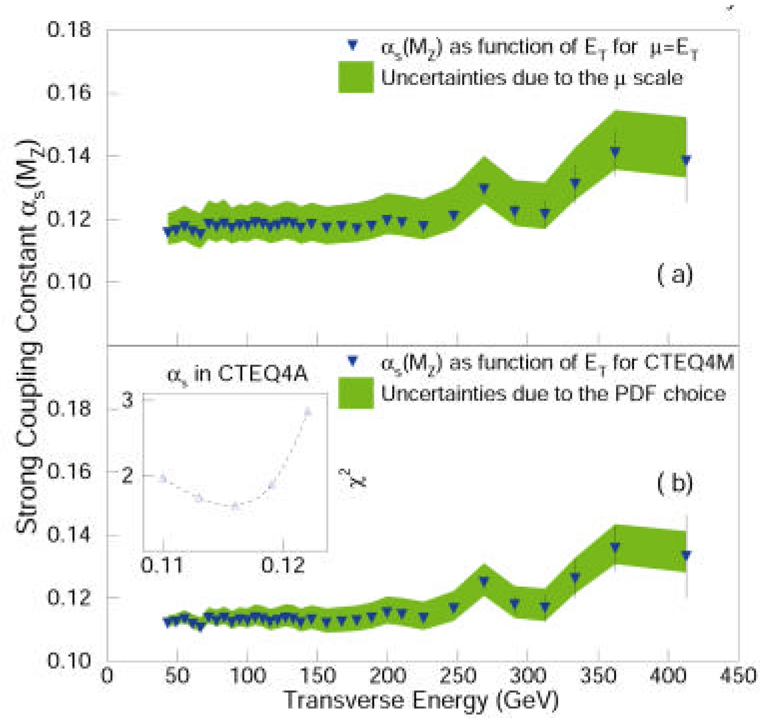
PRD 64 032003 (2001)

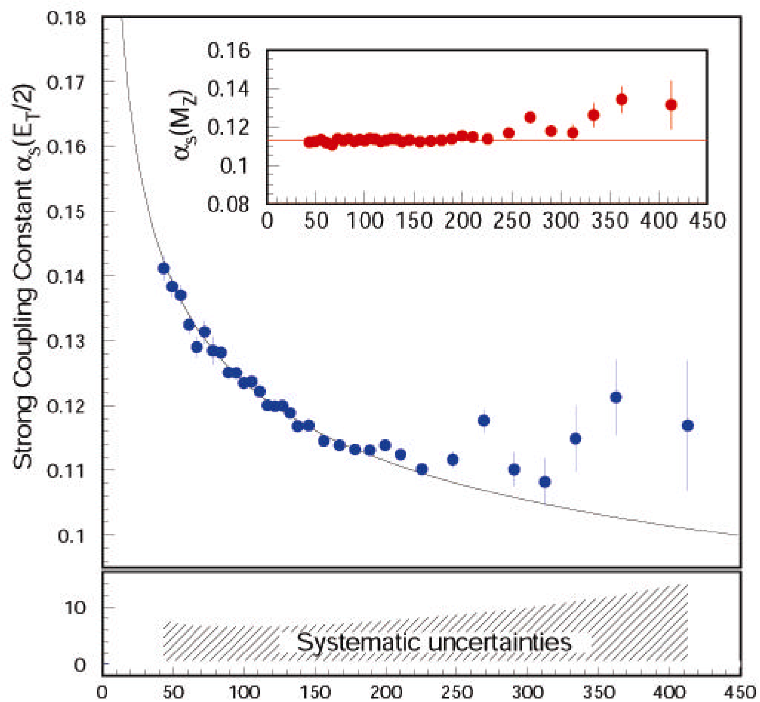
CDF 1B Result



- Plots show statistical error only
- χ^2 below include systematic error
- 33 degrees of freedom
- $R_{sep} = 1.3 \times R$ (R = 0.7)

PDF	χ^2	Confidence Level
CTEQ4M	63.1	1%
CTEQ4HJ	46.8	10.1%
MRST	49.5	7%





α_s from Inclusive Jet

$$\frac{ds}{dE_T} = a_s^2(m_R)X^{(0)}(m_R, m_F)\times$$
$$[1+a_s(m_R)k_1(m_R, m_F)]$$

- $a_s^2X^{(0)}$ is LO prediction
- $a_s^3X^{(0)}k_1$ is NLO prediction
- $X^{(0)}$ and k_1 determined from JETRAD
- $\overline{\text{MS}}$ scheme used (CTEQ4M)
- Jet cone algorithm used with $R_{sep} = 1.3$
- a_s determined in 33 E_T bins

PRL 88 042001 (2002)

α_s from Inclusive Jet

Theory errors
~ 5% (×~√2)

- α_s determined at M_Z
  - ➢ $50 < E_T < 250$ GeV

$$a_s(M_Z) = 0.1178 \pm 0.0001(\text{stat})^{+0.0081}_{-0.0095}(\text{exp.sys.})$$

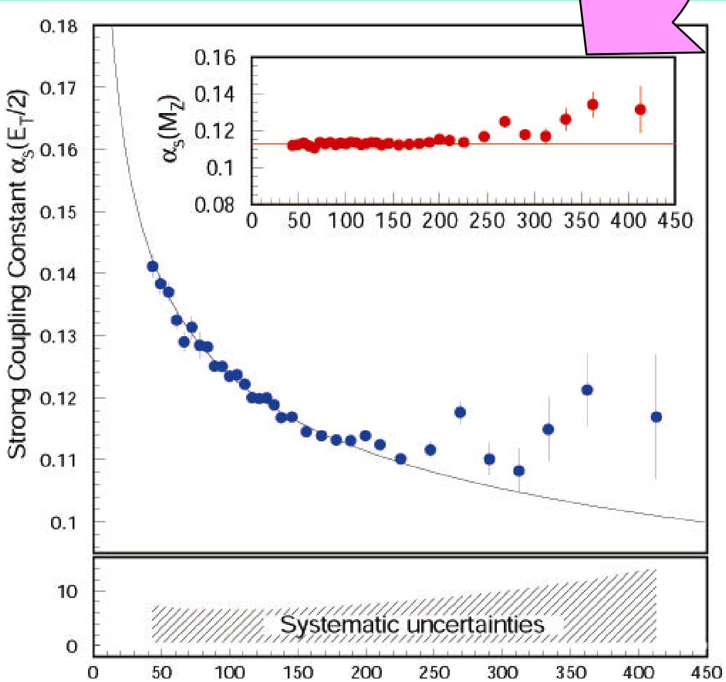
  - ➢ All E_T (CTEQ4HJ)

$$a_s(M_Z) = 0.1185 \pm 0.0001(\text{stat})$$

  - ➢ World Average

$$a_s(M_Z) = 0.1181 \pm 0.0020$$

Consequence of high E_t excess



PRL 88 042001 (2002)

Ellis-Soper PRD 48 3160

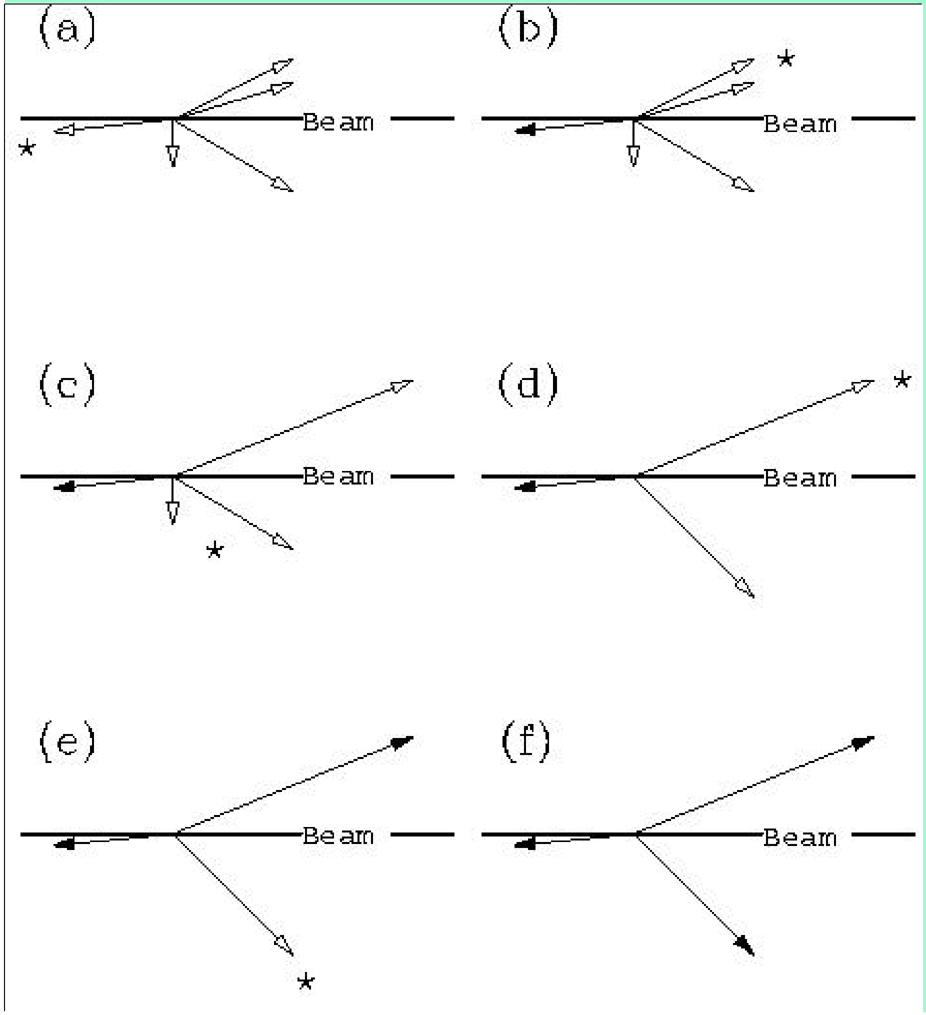
K_T Definition of Jets

$$d_{ij} = \min(E_{T,i}^2, E_{T,j}^2)\,\frac{\Delta \mathbf{R}_{ij}^2}{D^2}$$

$$d_{ii} = E_{T,i}^2$$

$\mathbf{min}(d_{ii}, d_{ij}) = d_{ij} \Rightarrow$ Merge

$\mathbf{min}(d_{ii}, d_{ij}) = d_{ii} \Rightarrow$ Jet



- K_T Definition

  cells/clusters are combined if their relative k_T^2 is "small" (relative transverse momentum) (D=1.0 or 0.5 is a scaling parameter)

  - Infrared safe
  - Same definition for partons, Monte Carlo and data
  - Allows subjet definitions

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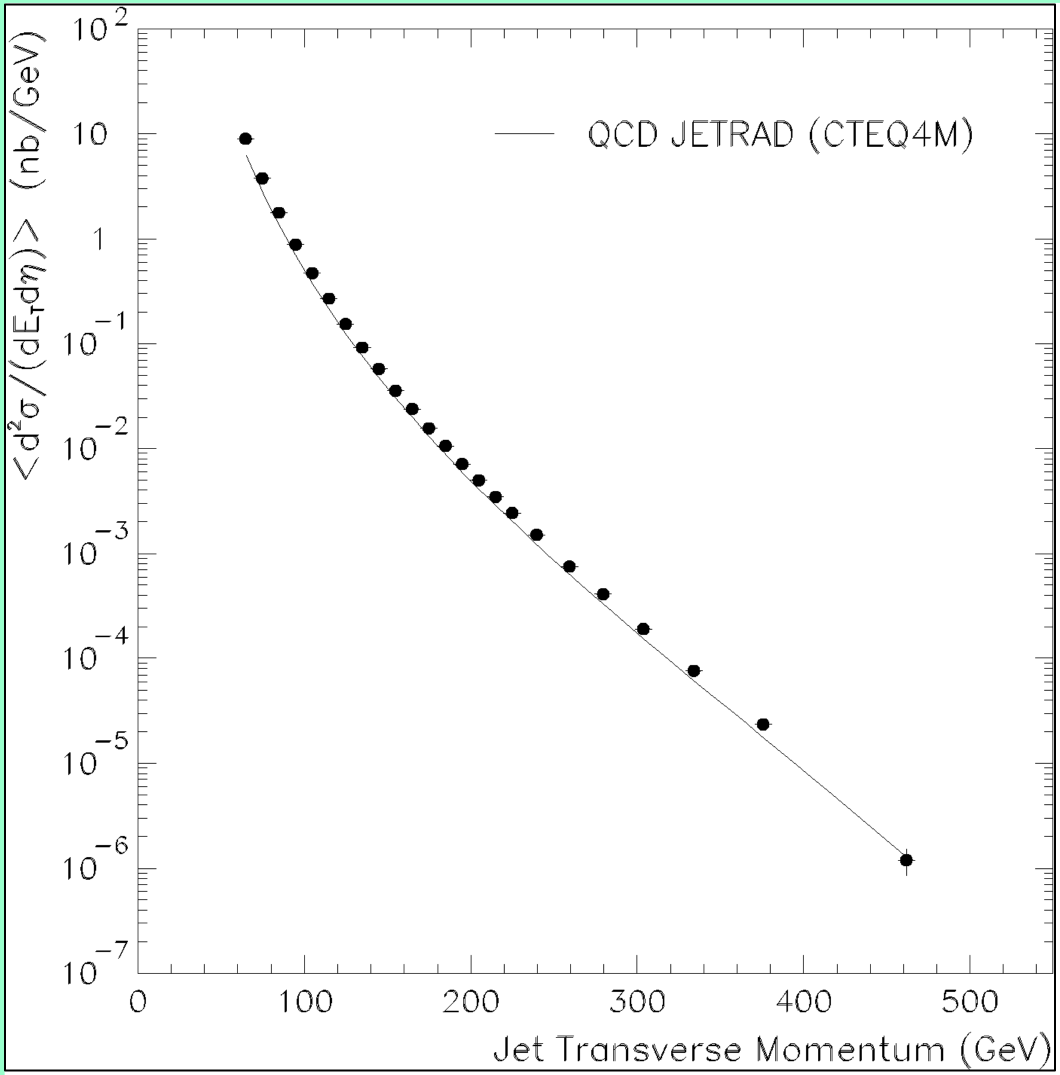
Inclusive Cross Section Using K_T Algorithm

$|\eta| < 0.5$

$D = 1.0$

- Predictions IR and UV safe
- Merging behavior well-defined for both experiment and theory

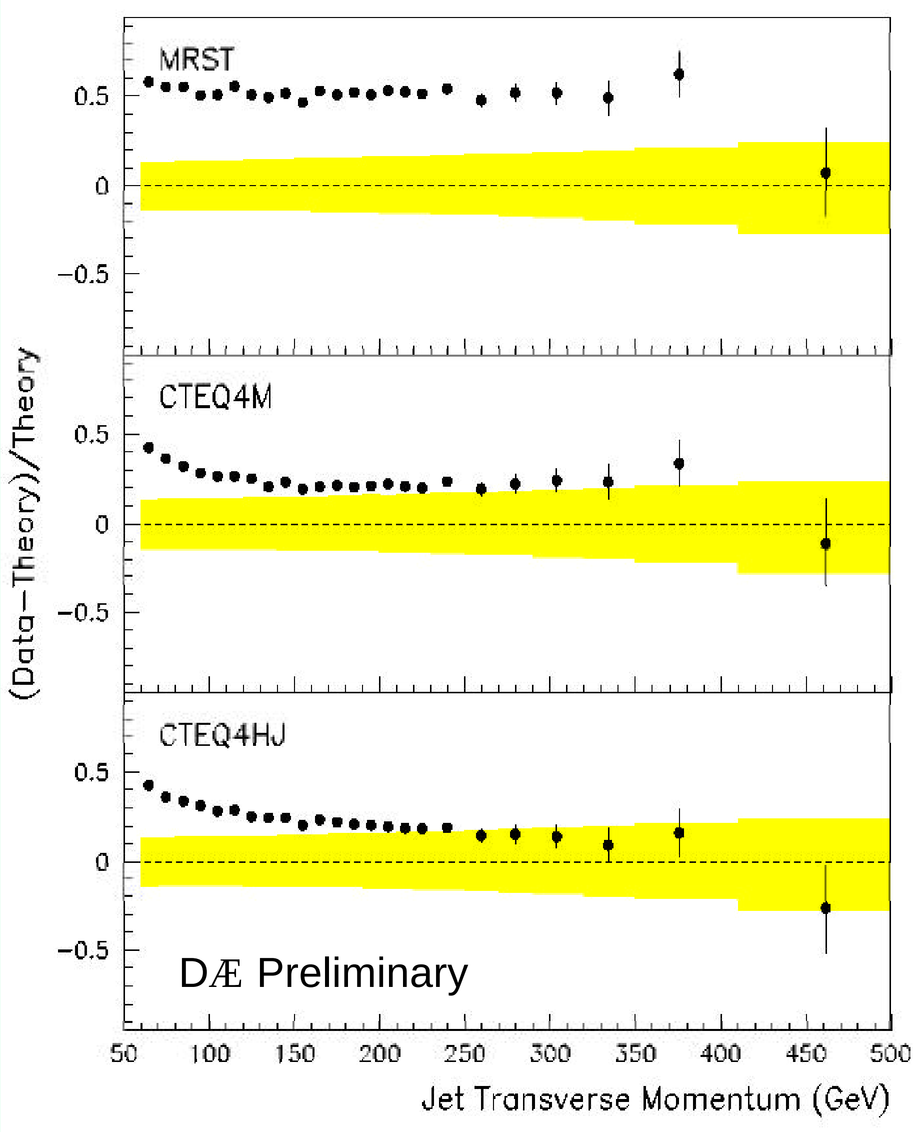


Phys. Lett. B 525 211 (2002)

Comparison with Theory

- Normalization differs by 20% or more
- No significant deviations of predictions from data, when correlated systematic errors are included
- When first 4 data points ignored, probabilities are 60-80%

PDF	c /dof	Prob
MRST	1.12	31
MRSTg↑	1.38	10
MRSTg↓	1.17	25
CTEQ3M	1.56	4
CTEQ4M	1.30	15
CTEQ4HJ	1.13	29



Phys. Lett. B 525 211 (2002)

Transverse 'Thrust' at DÆ Using K_T jets

Traditional variable (thrust) not suitable for hadron-collider environment. (Lorentz boost invariance)

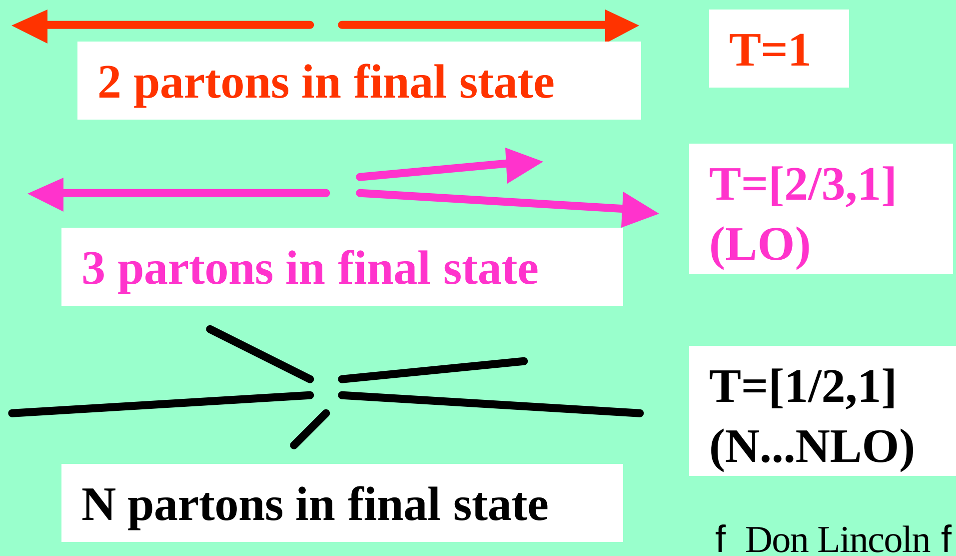
Transverse Thrust:

$$T_2^T = \max_{\hat{n}} \frac{\sum_i \left| \vec{p}_{ti} \cdot \hat{n} \right|}{\sum_i \left| \vec{p}_{ti} \right|}$$

Event shapes used at e^+e^- and ep to test QCD developments like resummation calculations and non-perturbative corrections

Non-perturbative corrections: of the order of 1/Q. Related to hadronization effects.

Resummations: needed at small values of the shape variable where fixed-order perturbative calculations are expected to fail.



Dijet Transverse Thrust cross section

Run Ib (1994-1996), $\sqrt{s} = 1.8\,TeV$, $\int \mathbf{L} = 88\ pb^{-1}$

K_T algorithm (parameter D = 1)

Event Selection:

- Vertex cut (| z | < 50 cm, *e* ~ 90 %)
- Jet quality cuts (*e* ~ 99.5 %)
  (0.05 < *EMF* < 0.95, *CHF* < 0.4)
- Trigger-specific leading jet p_T cuts
- Cut on missing E_T ($\not{E}_T / p_T^{lj} < 0.7$)
- $|\eta_1| < 1$, $|\eta_2| < 1$, $|\eta_3| < 3$ (if present)
- Bin in $$HT_3 = \sum_{j=1}^{3} E_{T,i}^{\text{jet}}$$

Non-Traditional Aspects

Use only leading two jets to calculate T_2^T

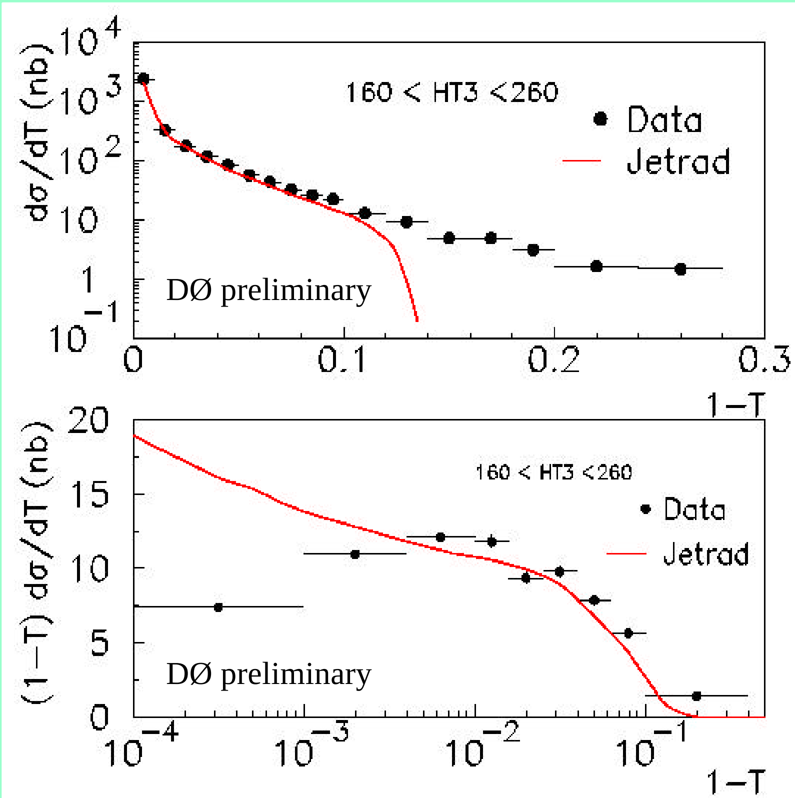
Bin in HT_3

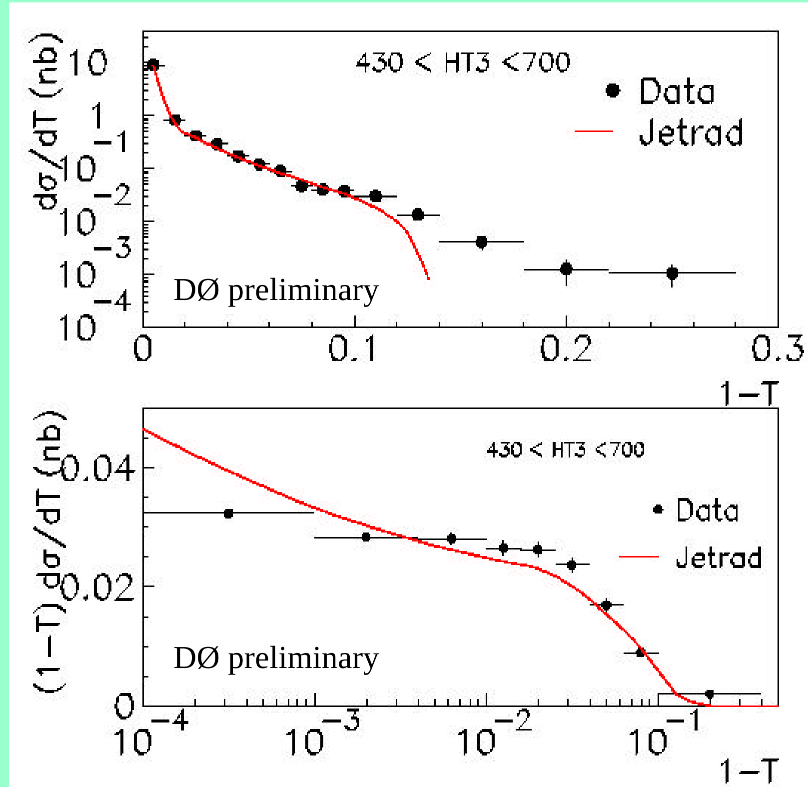
Compromise on measuring hard scale and insensitivity to noise.

Jet production rate α_s^3 is NLO

Event shape observables α_s^3 is LO

Dijet Transverse Thrust cross section





CTEQ4HJ, $\mu_F = \mu_R = P_T^{\max}/2$

Only statistical errors included

Deviations at

High (1-T) $\rightarrow$ higher order

Low (1-T) $\rightarrow$ resummation

$$\frac{ds}{dT_2^T} = \frac{N}{\Delta T_2^T L e}$$

Systematic error work underway

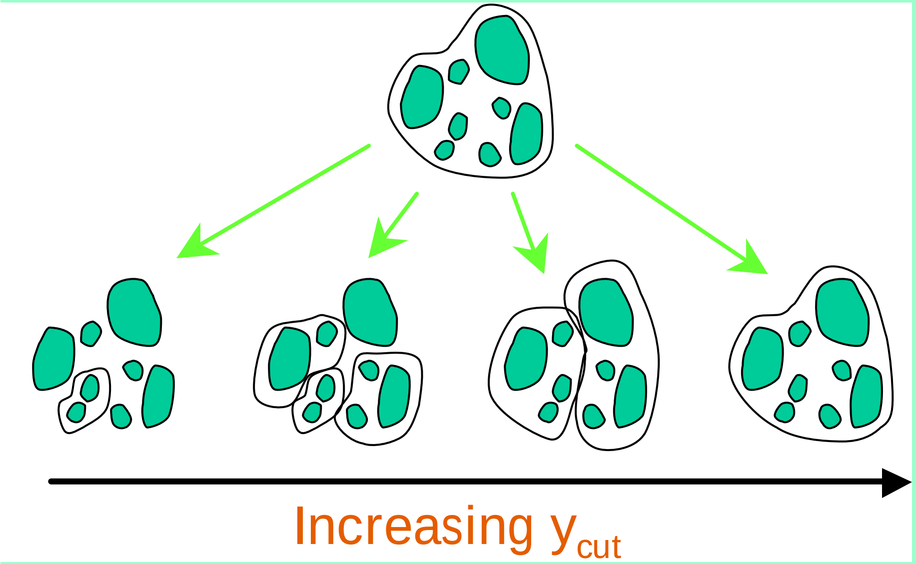
Preprint forthcoming

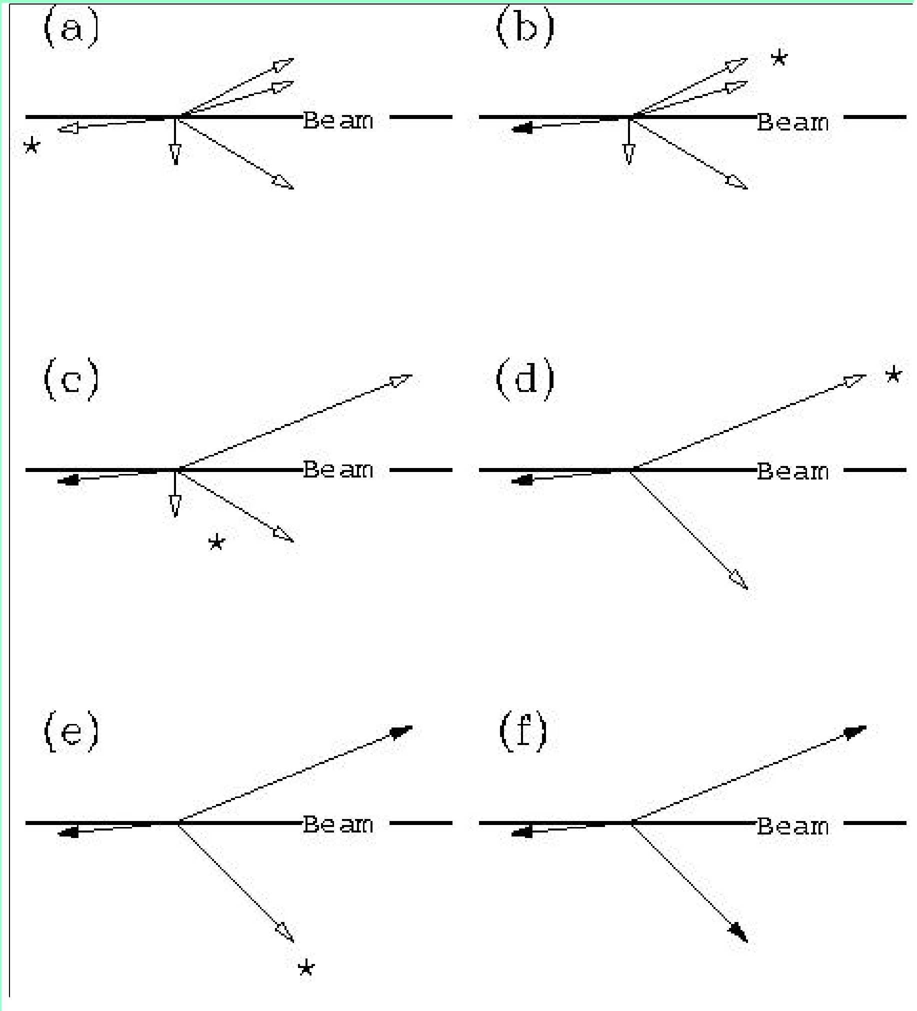
K_T Algorithm and Subjets

For subjets, define "large" K_T

$$\frac{\min(E_{T,i}^2, E_{T,j}^2)}{E_T^2(\text{jet})} \frac{\Delta \mathbf{R}_{ij}^2}{D^2} > y_{\text{cut}}$$

($y_{cut} = 10^{-3}$, D = 0.5)

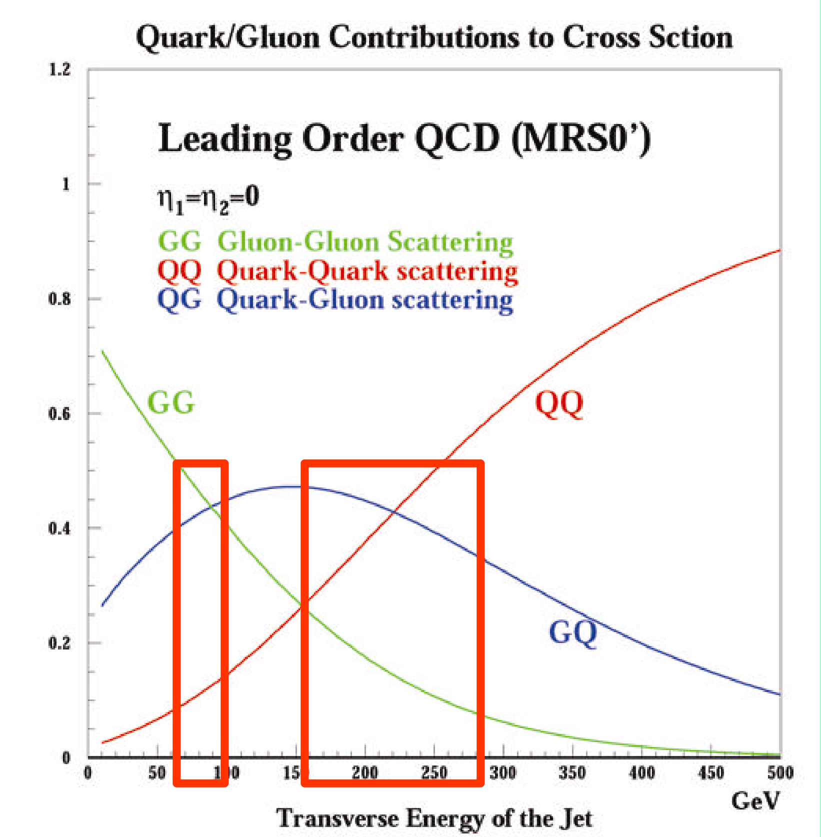




PRD 65 052008 (2002)

Quark/Gluon Separation

- Quark/gluon separation interesting
  - QCD/fragmentation studies
  - Useful for enhancing quark-only final states (c.f. tt $\rightarrow$ all jets)
  - Find quark (gluon) enhanced samples.



Use 55 < pt < 100 GeV

$x_{630} \sim 0.09 - 0.16$

$x_{1800} \sim 0.03 - 0.055$

$$f_g^{630} \sim 0.46$$

$$f_g^{1800} \sim 0.66$$

Parton Level

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DÆ Subjet Multiplicity Using K_T Algorithm

- Assume M_g, M_Q independent of Ö *s*

Mean Jet Multiplicity

$$\langle M \rangle = f_g M_g + (1-f_g)\, M_Q$$

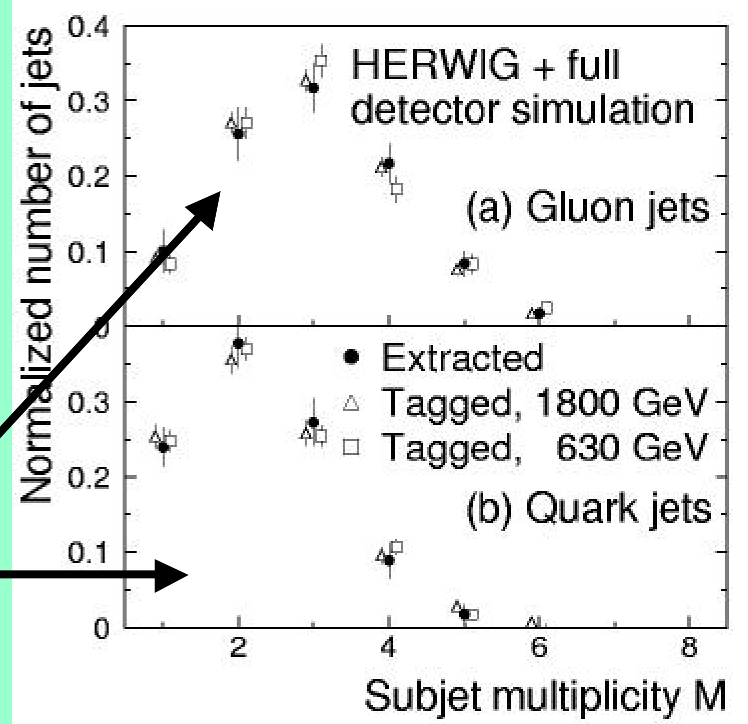
Gluon Jet Fraction ***Quark Jet Fraction***

$$f_g^{630} = 0.33$$

$$f_g^{1800} = 0.59$$

After fragmentation

Uncorrected



$$M_g = \frac{(1-f_{630})M_{1800} - (1-f_{1800})M_{630}}{f_{1800} - f_{630}}$$

$$M_Q = \frac{f_{1800}M_{630} - f_{630}M_{1800}}{f_{1800} - f_{630}}$$

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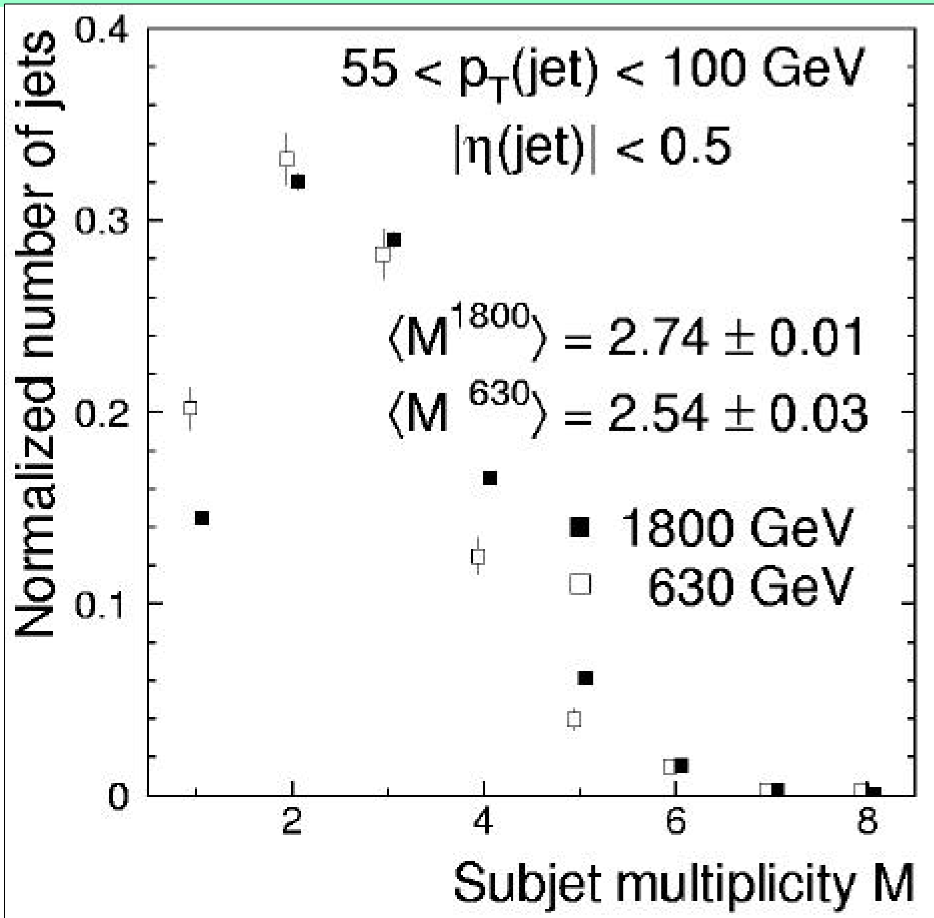
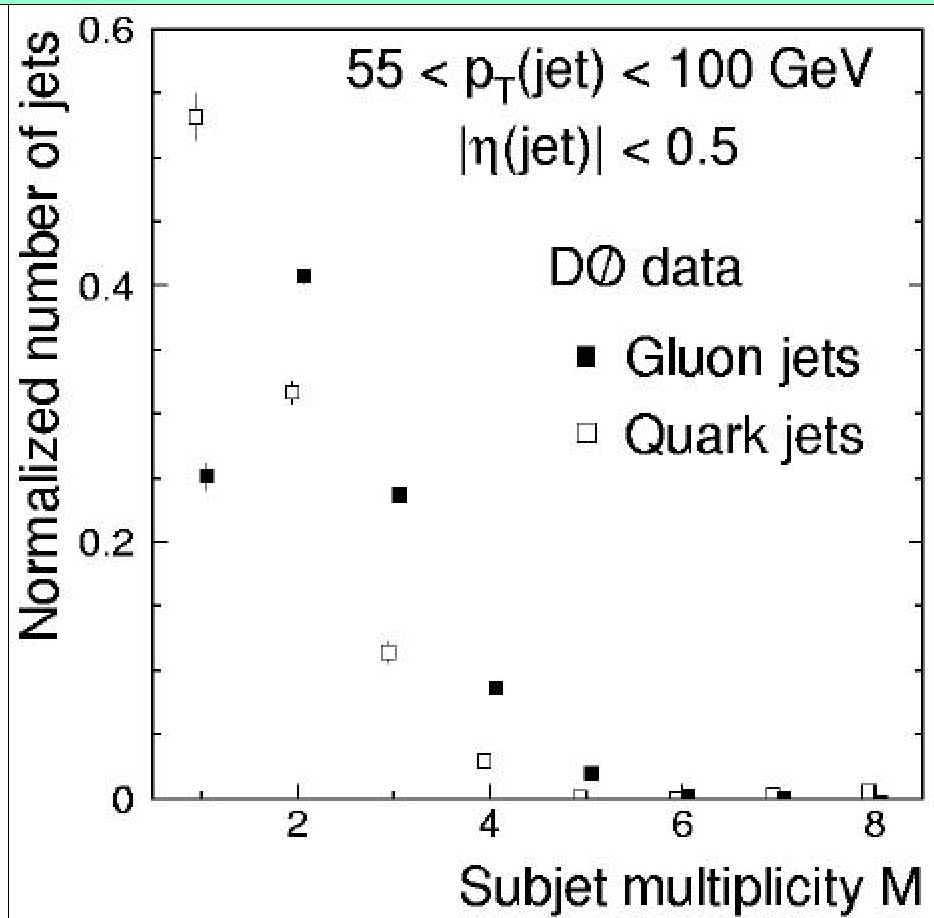
DÆ Subjet Multiplicity Using K_T Algorithm

Raw Subjet Multiplicities



Extracted Quark and Gluon Multiplicities



Higher M ⇒ more gluon jets at 1800 GeV

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DÆ Subjet Multiplicity Using K_T Algorithm

$$R \equiv \frac{\langle M_g \rangle - 1}{\langle M_Q \rangle - 1}$$

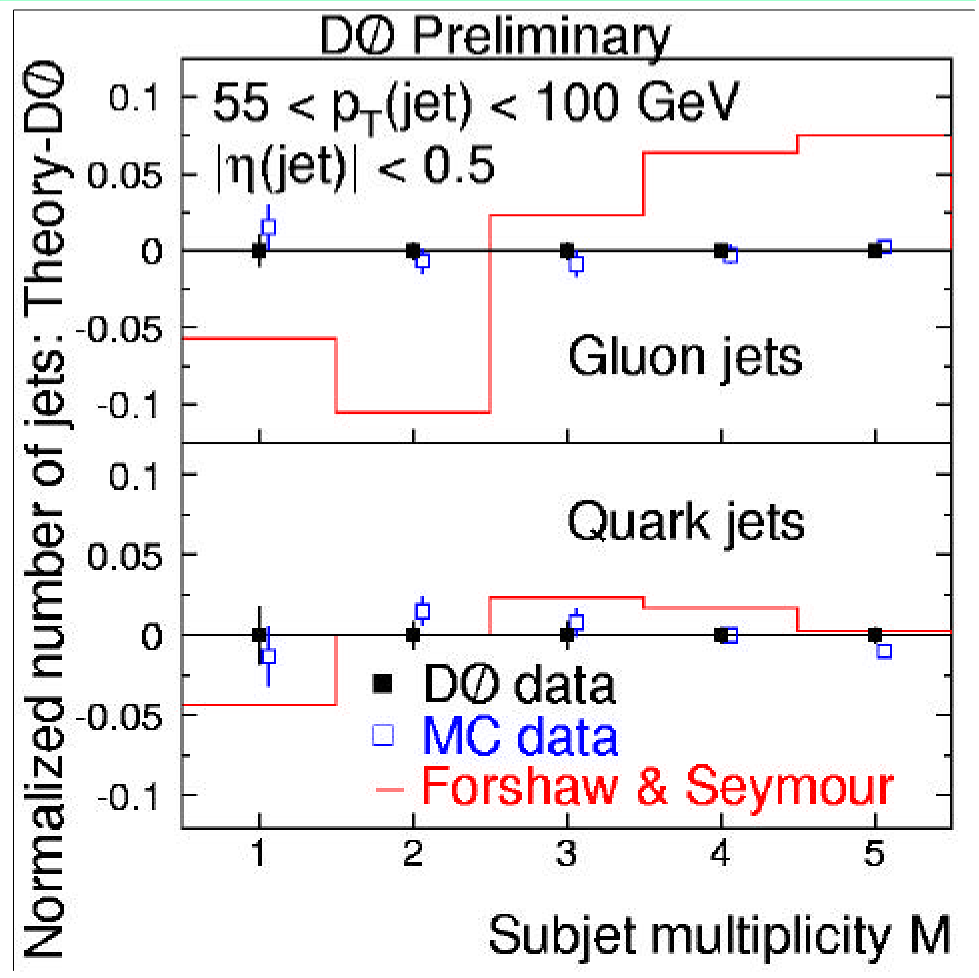
Amount of radiation

$$R = 1.84 \pm 0.15\,(\text{stat})\ {}^{+0.22}_{-0.16}\,(\text{syst})$$

HERWIG prediction

$= 1.91 \pm 0.16$ (stat)

Largest uncertainty comes from the gluon fractions in the PDFs



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Summary #1

- CDF's new inclusive jet analysis does not show the dramatic high p_T excess of earlier analyses and highlights need for better high-*x* gluon pdfs

- CDF has recently published a nice analysis measuring α_s from 50-250 GeV and evolved it to M_z, where it agrees nicely with the world average
  – Analysis does show sensitivity to the high $p_\perp$ excess described above

Summary #2

- DØ has recently completed an extensive program using the k_T jet-finding algorithm
  - Inclusive jet cross-section
    - Reasonable agreement with NLO calculations
    - Prefers CTEQ4HJ and MRST pdfs
    - $k_\perp$ jets contain more energy than similar cone jets
  - Event shape analysis (using transverse thrust)
    - Very preliminary results shown here. Preprint available soon.
  - Jet structure analysis
    - Good agreement with HERWIG
    - Approximately twice as much radiation from gluon jets as from quark jets.

www-d0.fnal.gov/~lucifer/PowerPoint/LaThuile2002.ppt

DÆ Subjet Multiplicity Using K_T Algorithm

- Perturbative and resummed calculations predict that gluon jets have higher subjet multiplicity than quark jets, on average.

- Linear Combination:

Mean Jet Multiplicity

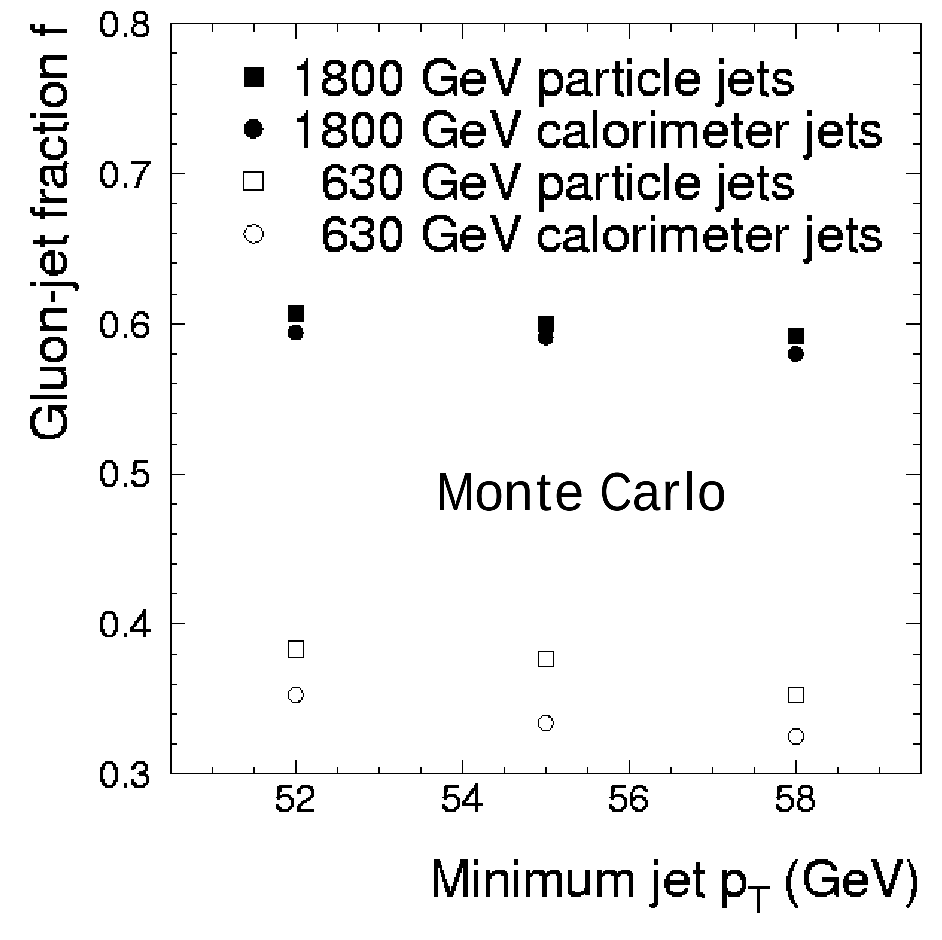
$$\langle M \rangle = f_g M_g + (1-f_g)\, M_Q$$

Gluon Jet Fraction *Quark Jet Fraction*

$$f_g^{630} = 0.33$$

$$f_g^{1800} = 0.59$$

After fragmentation



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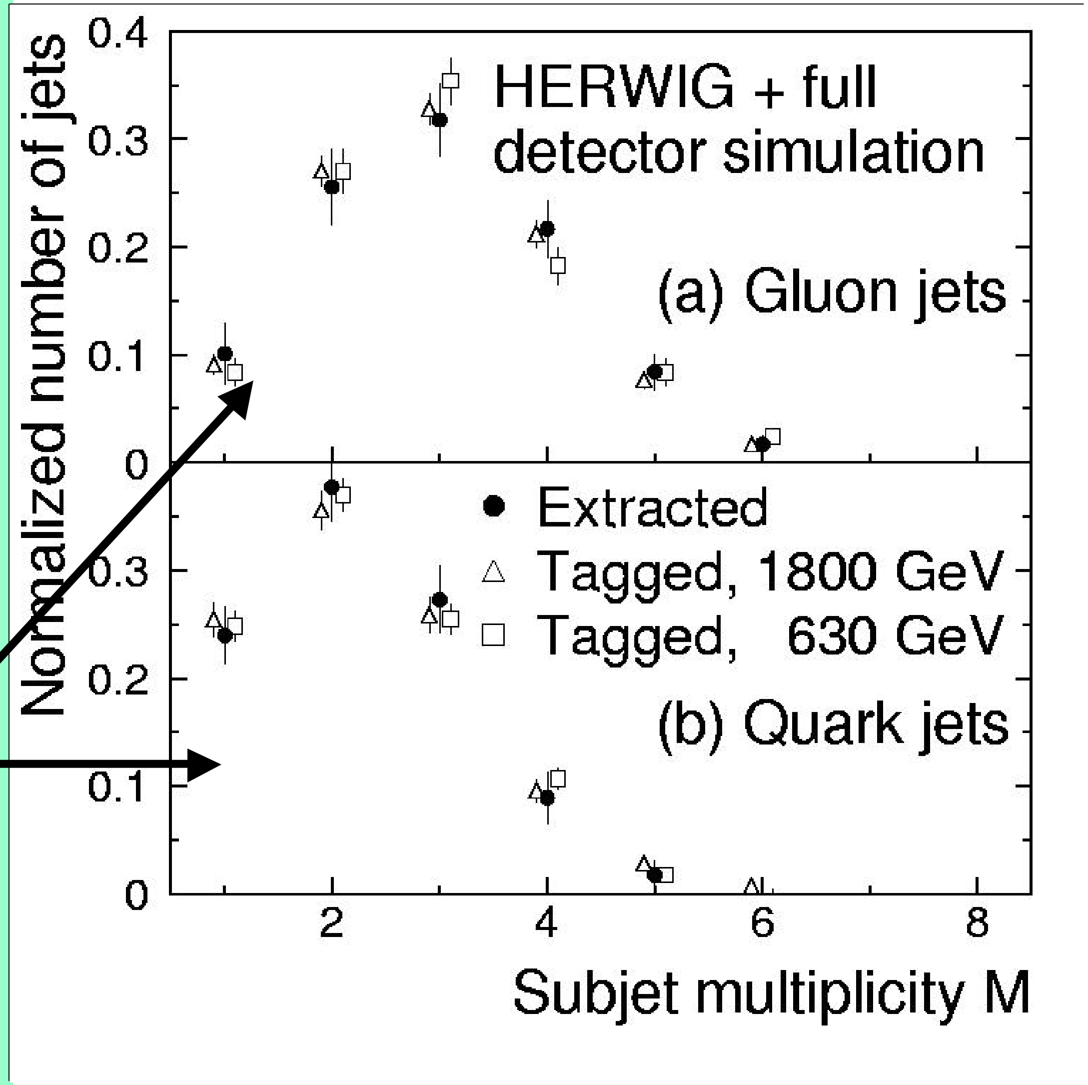
DÆ Subjet Multiplicity Using K_T Algorithm

- Assume M_g, M_Q independent of Ö *s*

$$M_g = \frac{(1-f_{630})M_{1800} - (1-f_{1800})M_{630}}{f_{1800} - f_{630}}$$

$$M_q = \frac{f_{1800}M_{630} - f_{630}M_{1800}}{f_{1800} - f_{630}}$$

Uncorrected



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