DIS97
April 17, 1997

Jet Production at the Tevatron and Impact on the Gluon Distribution

J. Huston
Michigan State U.

... thanks to wuki

June, 1996

MSUHEP-60426
CTEQ-604

Improved Parton Distributions from Global Analysis of Recent Deep Inelastic Scattering and Inclusive Jet Data †

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Abstract

The impact of recent precision measurements of DIS structure functions and inclusive jet production at the Tevatron on the global QCD analysis of parton distribution functions is studied in detail. Particular emphasis is placed on exploring the range of variation of the gluon distribution $G(x, Q)$ allowed by these new data. The strong coupling of $G(x, Q)$ with α_s is fully taken into account. A new generation of CTEQ parton distributions, CTEQ4, is presented. It consists of the three standard sets ($\overline{\rm MS}$, DIS and leading order), a series that gives a range of parton distributions with corresponding α_s's, and a set with a low starting value of Q. Previously obtained gluon distributions that are consistent with the high E_t jet cross-section are also discussed in the context of this new global analysis.

† This work was partially supported by DOE and NSF

Global PQCD Analysis, α_S, G(x,Q), Dir. γ and Jet production

Basic Parameters of PQCD: $\alpha_S(\mu)$, $m_f(\mu)$

Non-perturbative, universal *parton distribution functions:* $q_i(x,Q_0)$, $G(x,Q_0)$

$q_i(x,Q_0)$ are well-constrained by DIS, DY data, except for some details of flavor-dep. of the sea.

α_S, $G(x,Q)$ are ***not*** well-constrained by Dir. γ data as commonly assumed/hoped, due to theo. and expt. uncertainties.

(important challenge for PQCD theory!)

Inclusive Jet production is even more sensitive to α_S and $G(x,Q)$; and the theory has less uncertainty.

⇒ Can the medium p_t inclusive jet data be used, in conjunction with new precision DIS data, to finally close-in on $G(x,Q)$ and shed light on α_S?

⇒ Can the CDF high p_t events be compatible with conventional PQCD with unconventional G(x,Q)?

Determining α_S in Global QCD Analysis of lep.-had. & had.-had. Interactions?

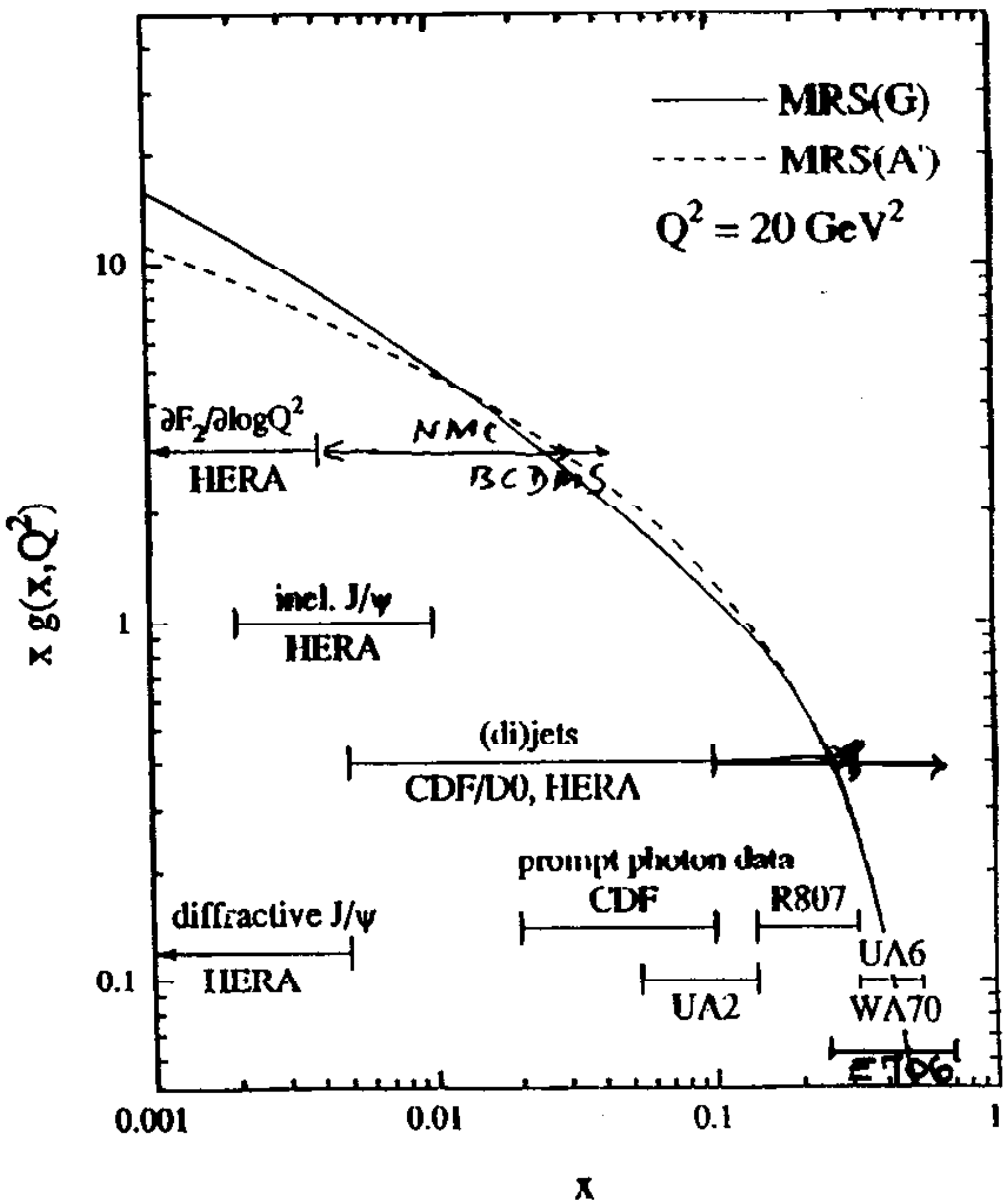
- α_S enters in all lep.-had. and had.-had. processes $\Rightarrow$ Global Analysis places important constraints on the value of α_S

- However, it is intimately coupled to $G(x,Q)$ (and $q_i(x,Q)$) $\Rightarrow$ its determination is not "clean"

♦ Determining α_S in Global Analysis is complementary to that in "dedicated experiments"

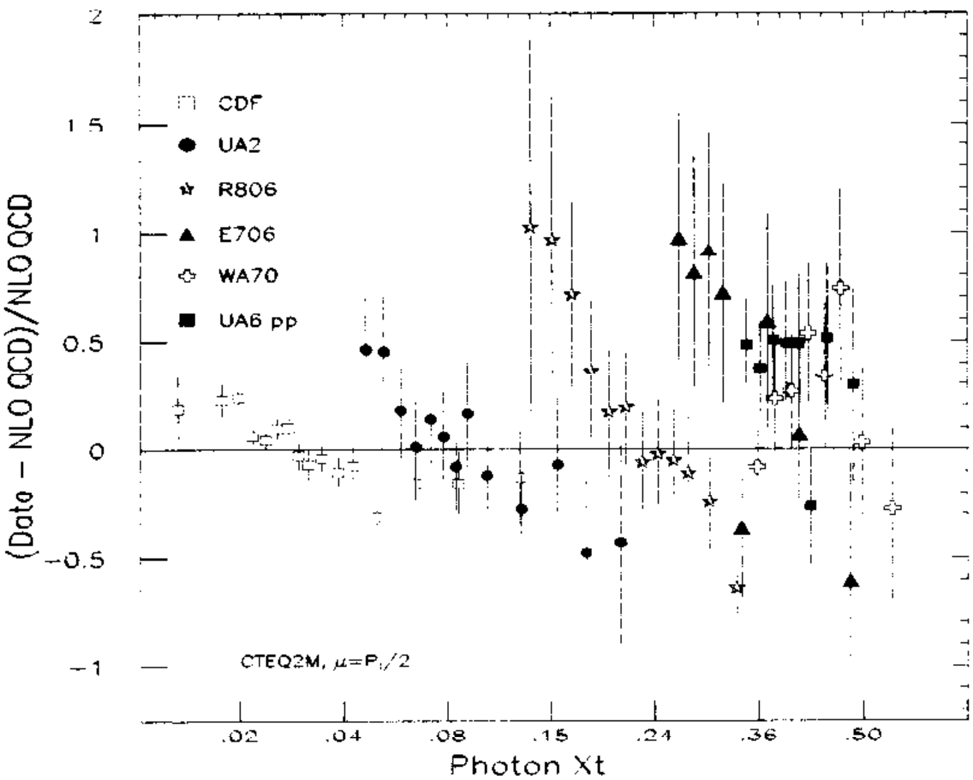
♦ It is important to study α_S in the global context to check the consistency (among different processes) required by its universal character, particularly in view of the "differences" seen in various dedicated measurements.

Sources of information on the gluon distribution



A Global Study of Inclusive Direct Photon Production Data

(Huston et.al. CTEQ-407; Phys. Rev. D51, 6139 (95))

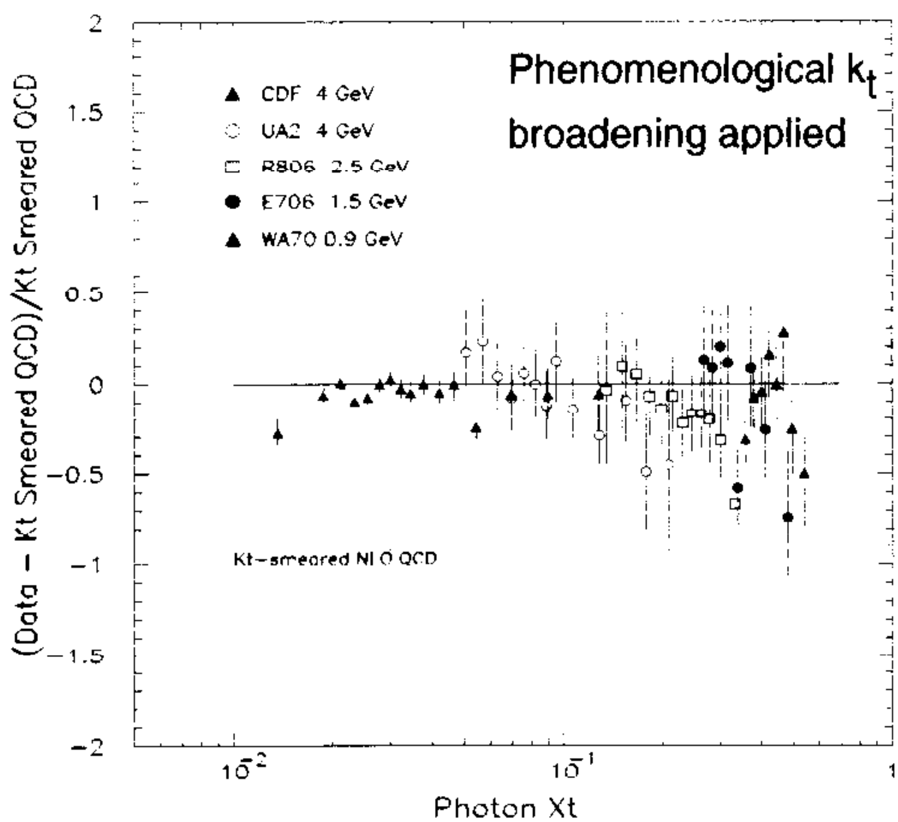


Global comparison of NLO QCD theory with fixed-target and collider data

Pattern of deviation in the shape of P_t-distr. seen for all ranges of x_t

==>

not a PDF effect.



Pattern of observed behavior suggests energy-dependent broadening of transverse momentum of initial state partons, perhaps due to multi-gluon radiation
-- confirmed by shower MC calculations.

Resummation

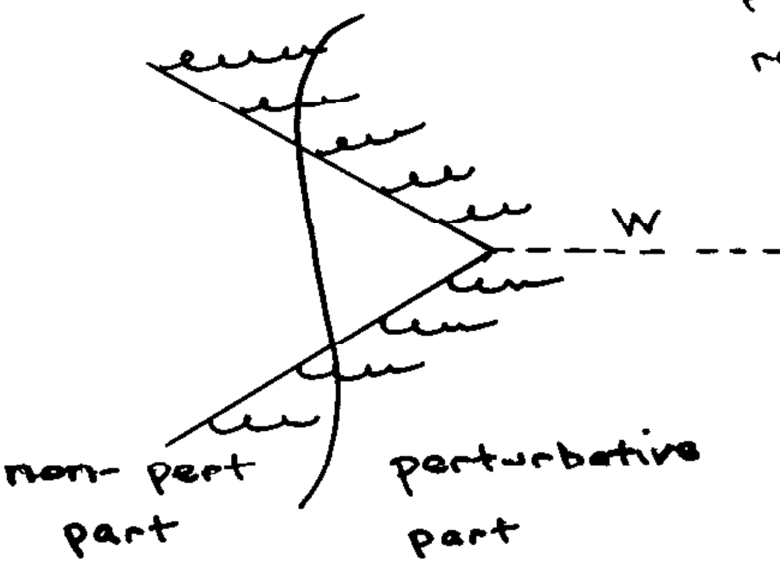
Example : W production

$$\frac{d\sigma}{dp_T} \sim F_{q/h}(x,Q^2) \otimes e^{-S_P(Q^2,k_T^2)} \otimes e^{-S_{NP}(Q^2,k_T^2)}$$

$$\otimes F_{\bar{q}/h}(x,Q^2) \otimes \sigma_{hard}$$

$e^{-S_P(Q^2,k_T^2)}$ → perturbative part of resummation

$e^{-S_{NP}(Q^2,k_T^2)}$ → non-perturbative part → $e^{-k_T^2/\sigma^2}$



$\sigma^2 = g_1 + g_2 \log Q/Q_0$

S_{NP} is universal

can be determine

from Drell-Yan

Ladinsky, Yuan

$g_1 = 0.11^{+.04}_{-.03}$ GeV^2

$g_2 = 0.58^{+0.1}_{-0.2}$ GeV^2

Inclusive Jet Cross-section in PQCD

LO X-section: $\sim \alpha_S^2 \cdot G^2(x,Q) + \alpha_s^2\, G(x,Q)\, Q(x,Q)$
$+ \alpha_s^2\, Q(x,Q)\, Q(x,Q)$

NLO X-section:

Jet algorithm dependent, but, by now, well developed. (Aversa *etal*, Ellis *etal*, Giele *etal*..)

Uncertainties – large p_t

Threshold Resummation effects °

($x \to 1$, cf. DY & Top production)

Uncertainties – small p_t

Scale dependence (only for very small p_t)*

Initial-state multi-gluon radiation corrections *

("k_t broadening" in DY, Dir. γ, ...)

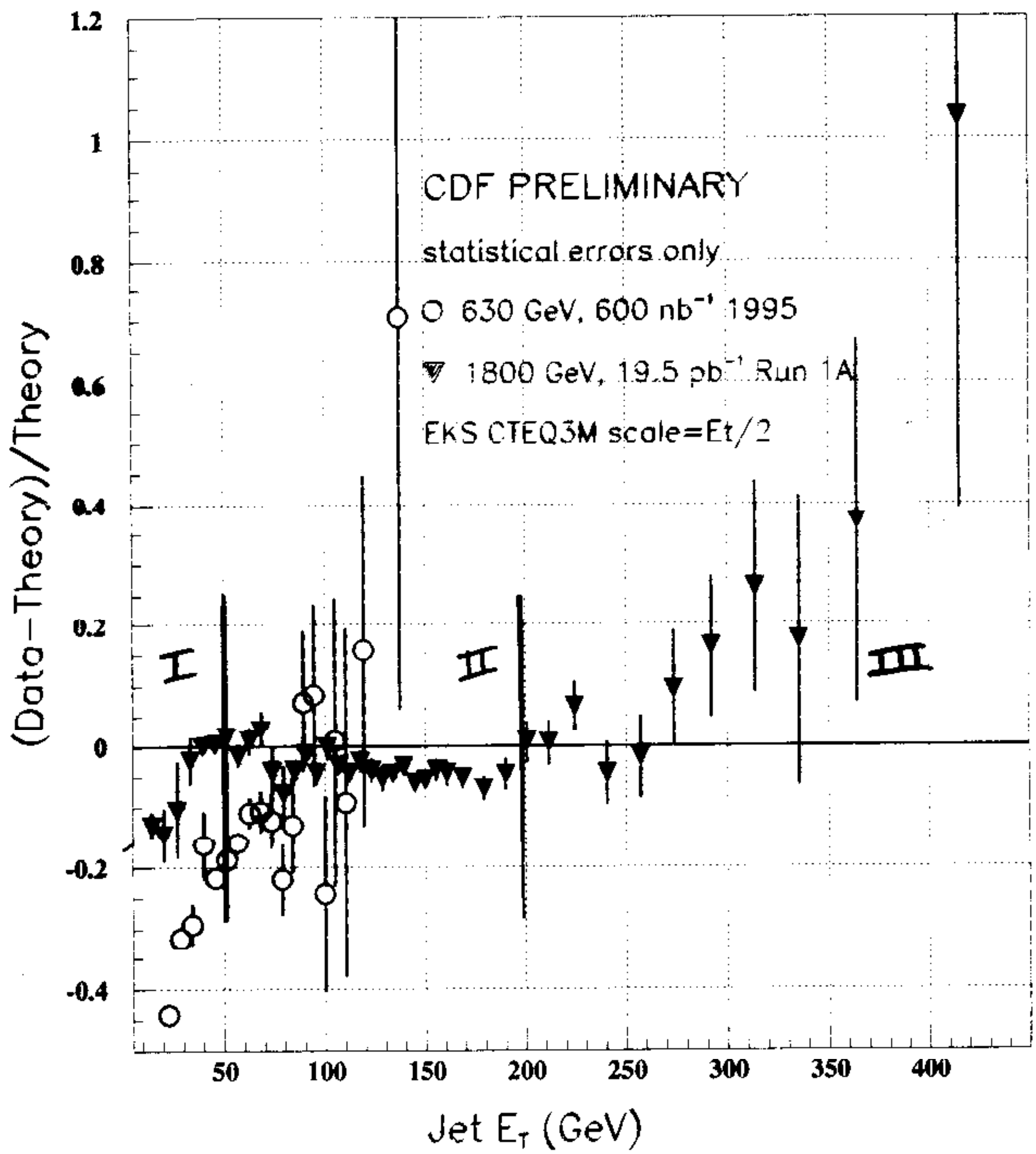
Non-perturbative corrections ($\sim O(1/p_t)$?)

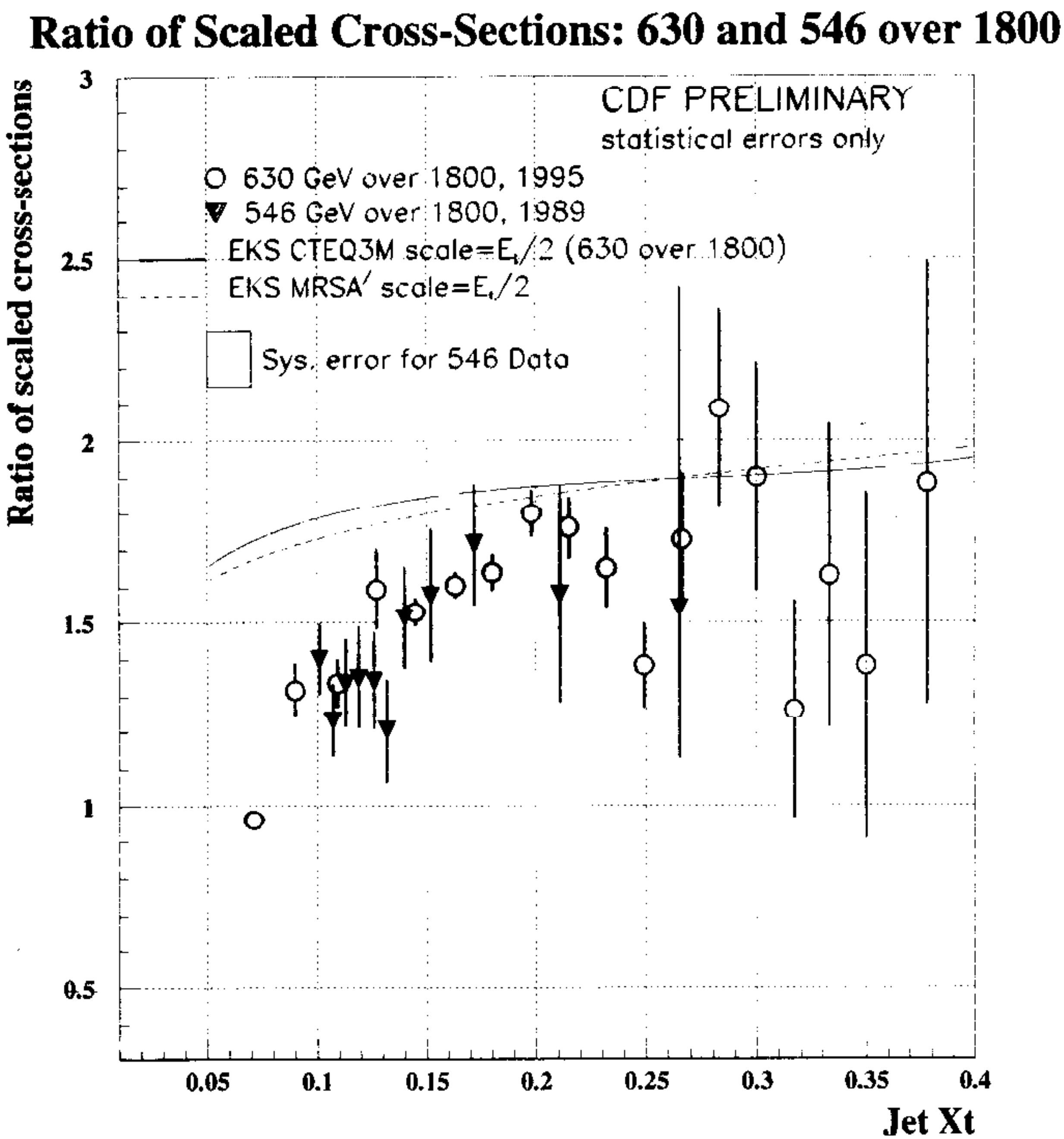
Jet Definition: fragmentation prod. outside jet cone*;

Effect of "underlying event" fr target-beam remnants*;

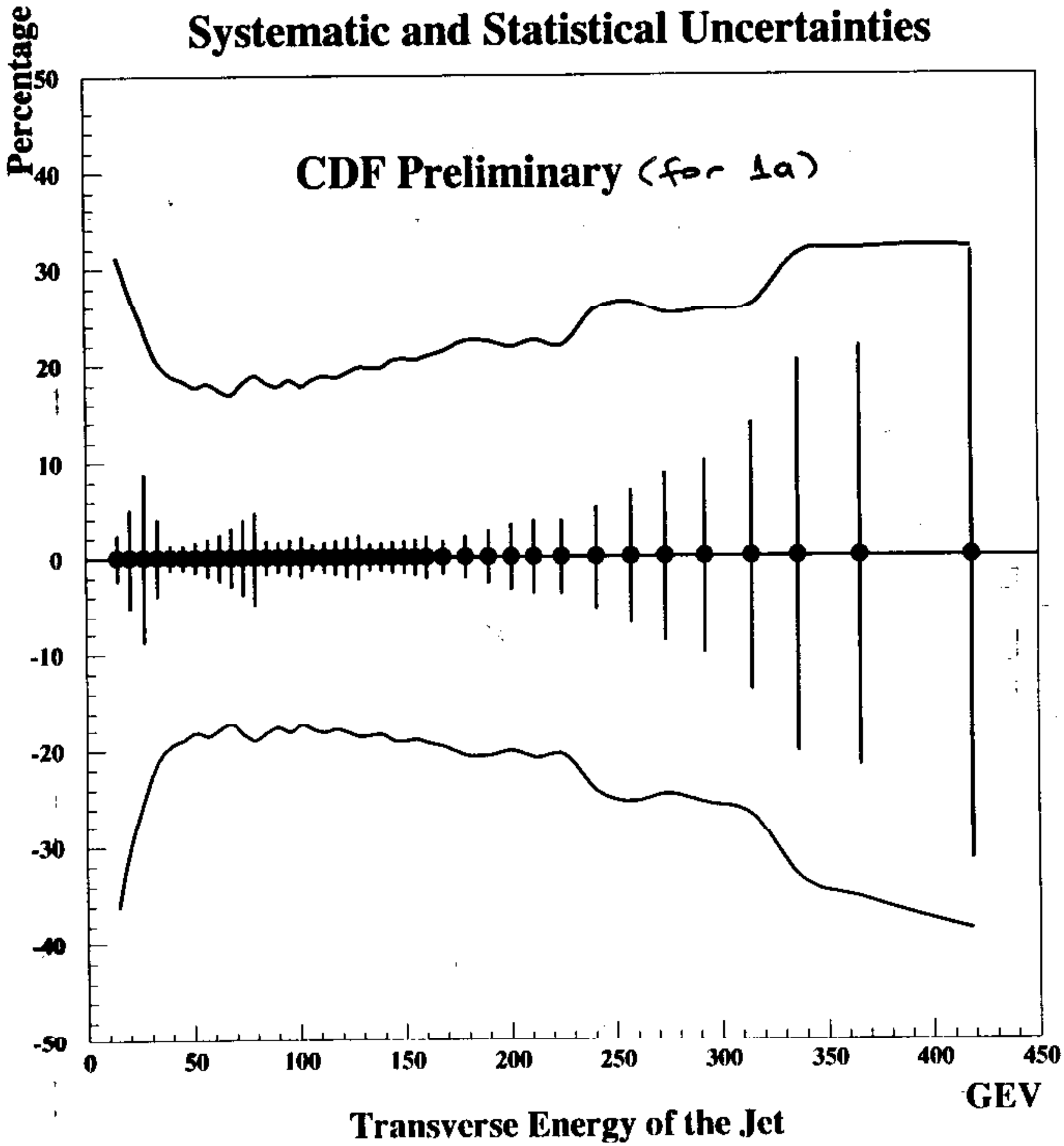
Observed lack of "x_t scaling" in CDF 630/900 X-sec ratio*

CDF: 630 GeV vs 1800 GeV



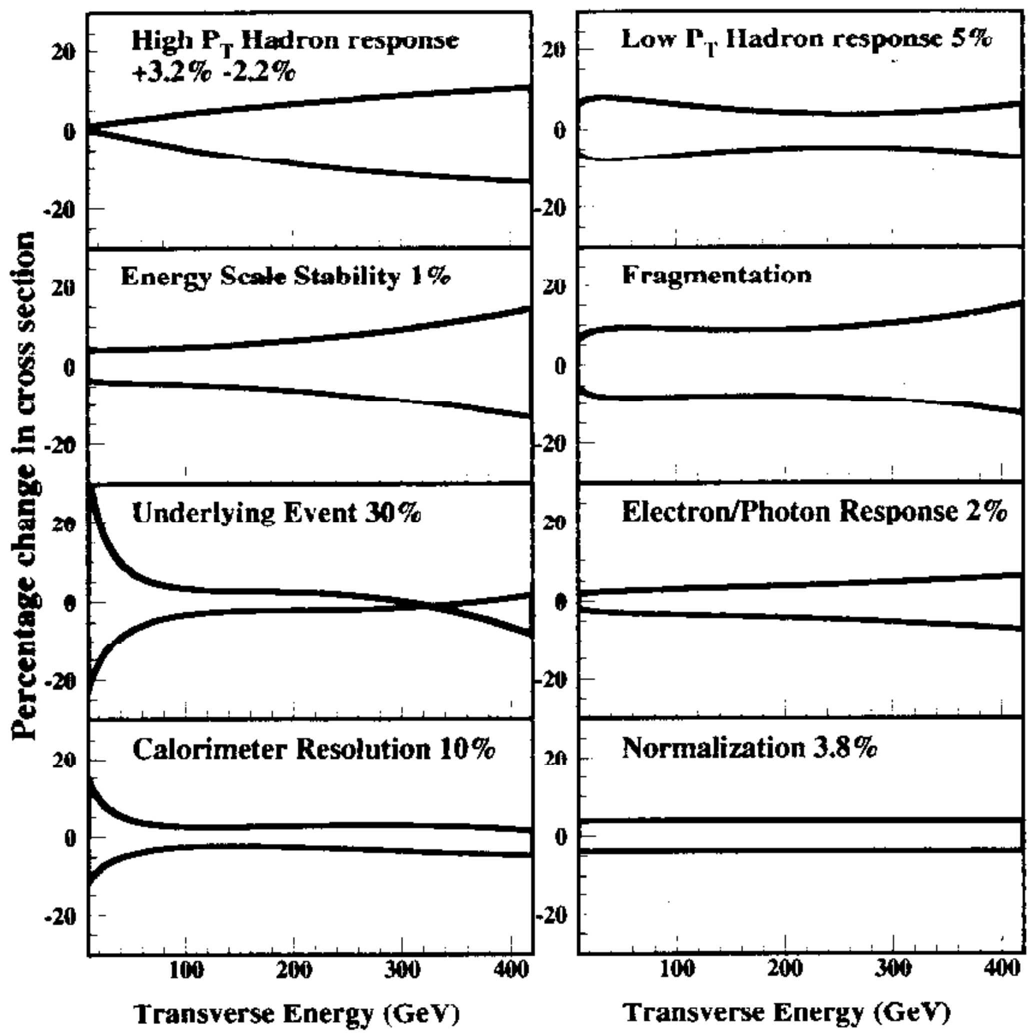


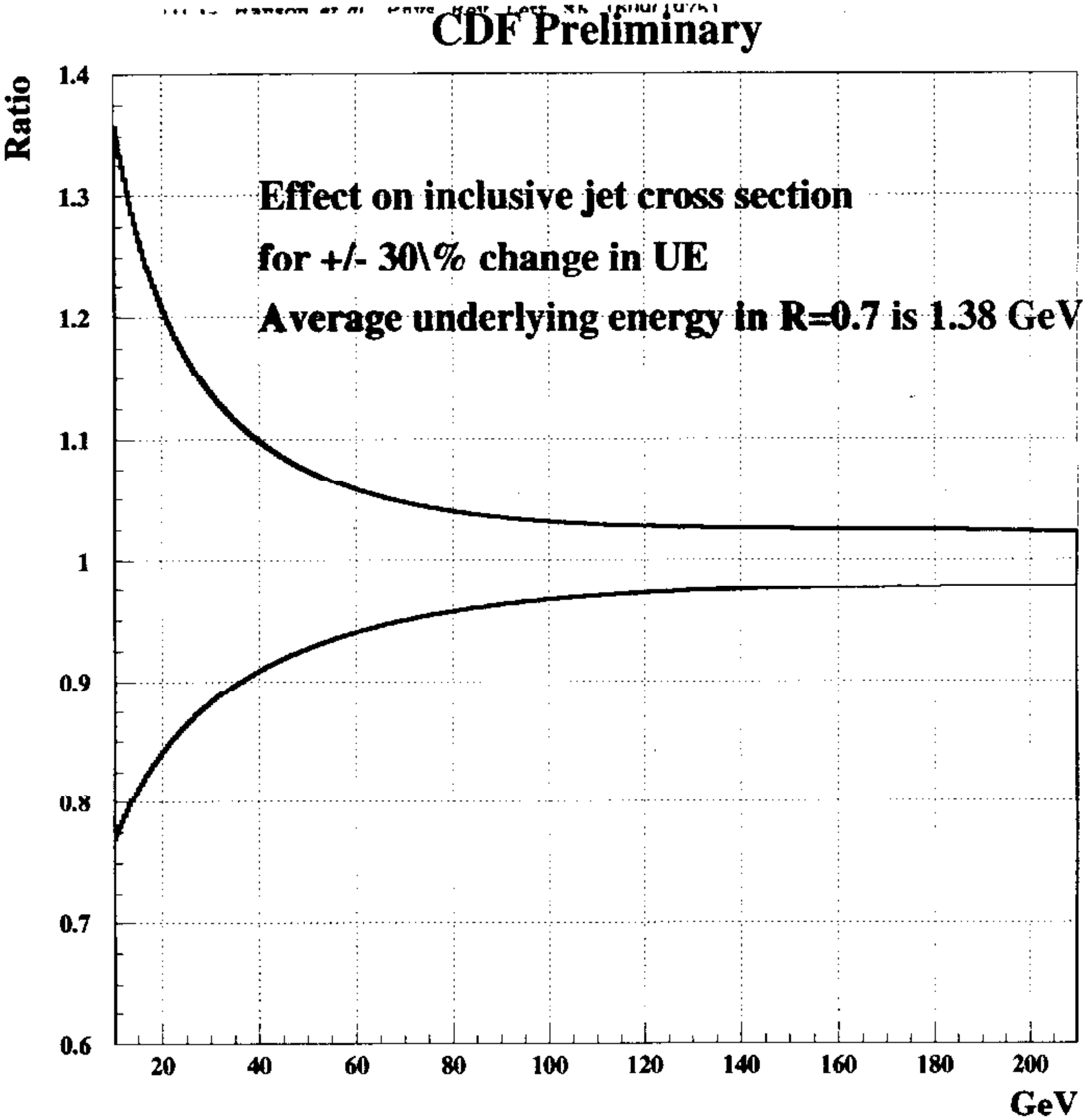
Ratio of Scaled Cross-Sections: 630 and 546 over 1800
CDF PRELIMINARY
statistical errors only
630 GeV over 1800, 1995
546 GeV over 1800, 1989
EKS CTEQ3M scale=$E_t/2$ (630 over 1800)
EKS MRSA′ scale=$E_t/2$
Sys. error for 546 Data
Ratio of scaled cross-sections
Jet Xt
3
2.5
2
1.5
1
0.5
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4


Systematic and Statistical Uncertainties
Percentage
CDF Preliminary (for 1a)
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
50
100
150
200
250
300
350
400
450
GEV
Transverse Energy of the Jet

Systematic Errors

1)Evaluate change in Response Functions
2)Use new Response Functions to derive New Physics curve
3)Compare to "Standard Curve"




CDF Preliminary
Ratio
Effect on inclusive jet cross section
for +/- 30\% change in UE
Average underlying energy in R=0.7 is 1.38 GeV
GeV
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
20
40
60
80
100
120
140
160
180
200

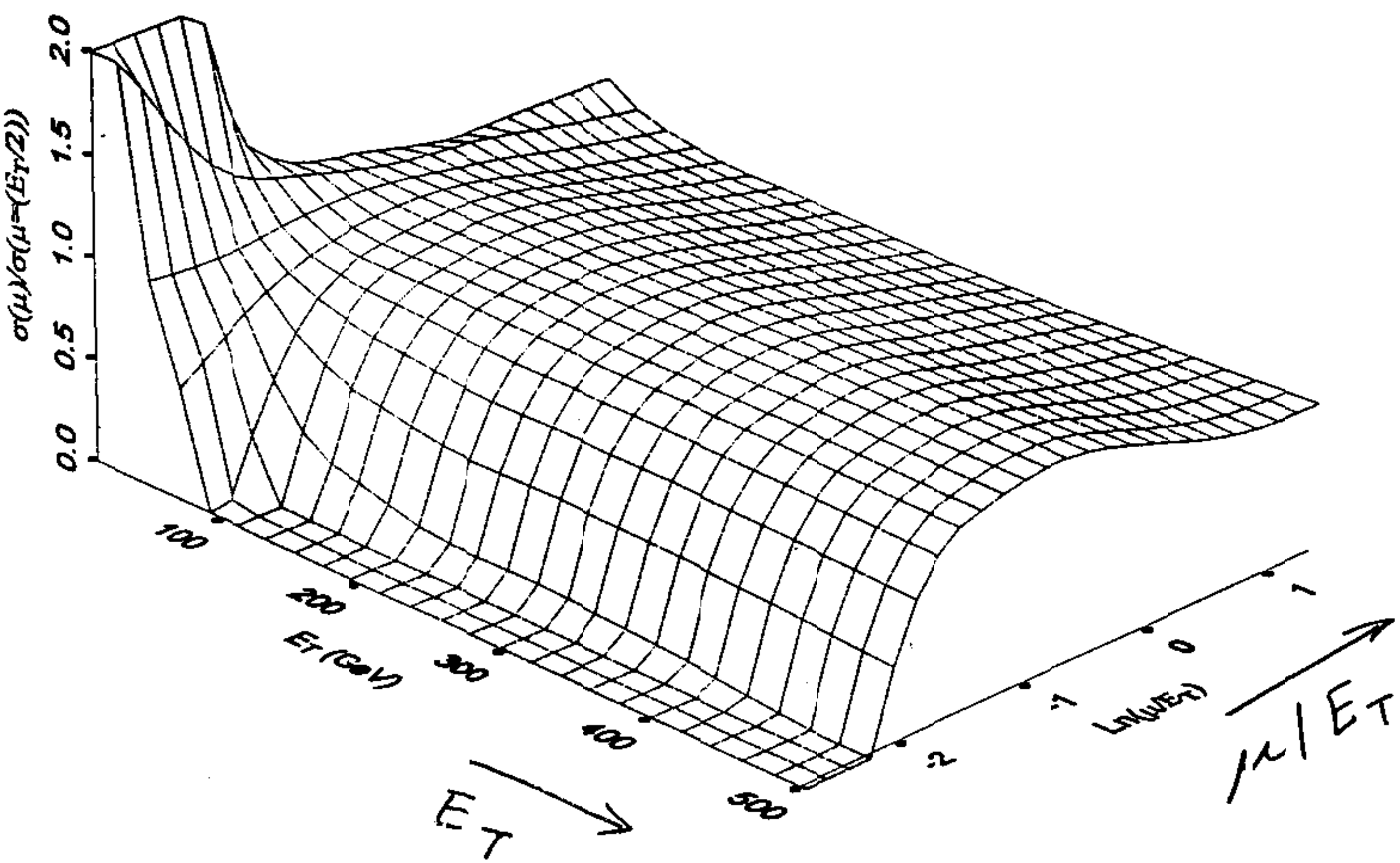
SDEcdfmuf Dec. 1, 1995 7:30:50 AM

NLO

μ Dependence of Inclusive Jet Cross Section

$\sqrt{s}$ = 1800 GeV, 0.1 < η < 0.7, HMRS(B),ppbar

R=0.7



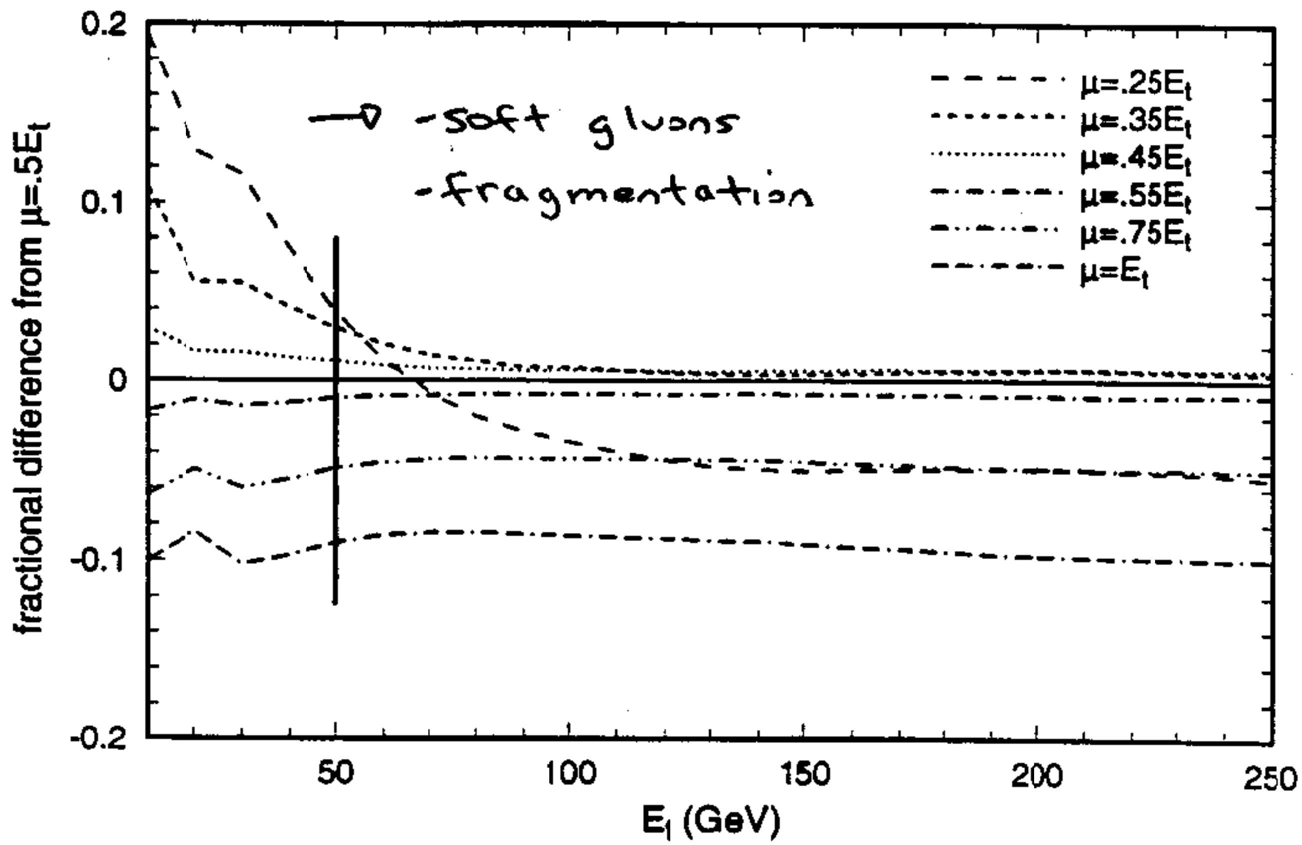


Figure 8: Fractional difference between $\frac{d\sigma}{dE_t}(E_t, \mu)$ and $\frac{d\sigma}{dE_t}(E_t, \mu = E_t/2)$ as a function of E_t for a variety values of μ calculated in NLO QCD.

Lai, Tung
MSU-HEP-60508

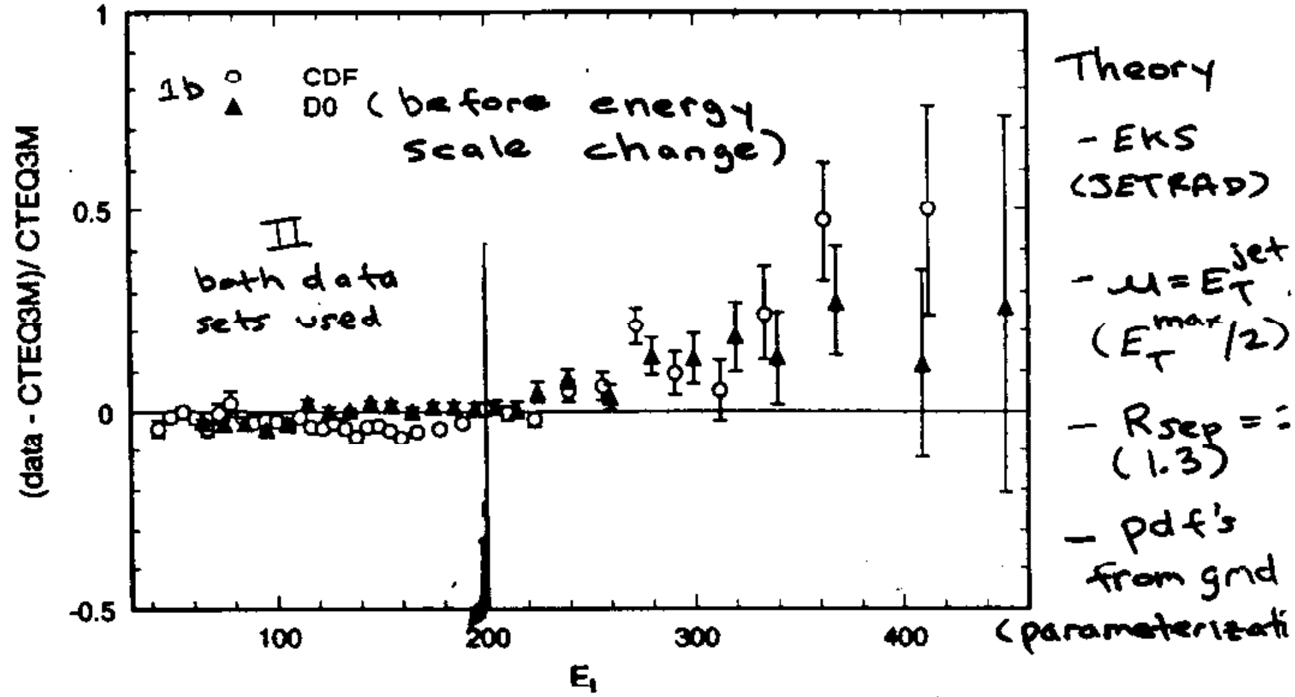


FIG. 1. The CDF and D0 Run Ib data compared to NLO QCD using CTEQ3M parton distributions.

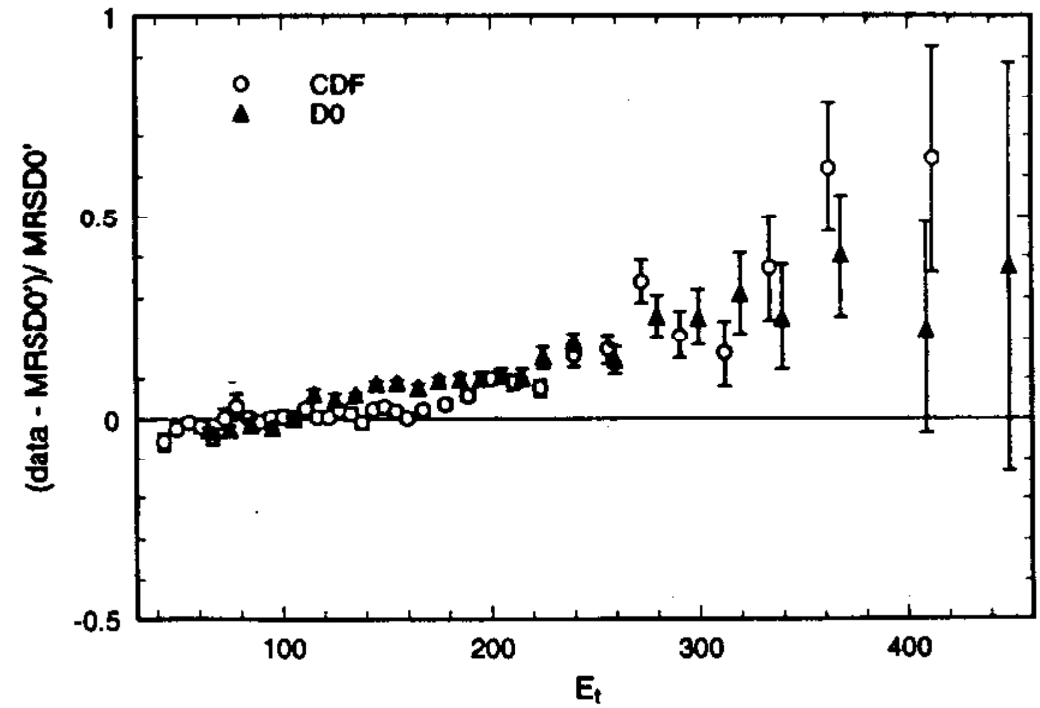
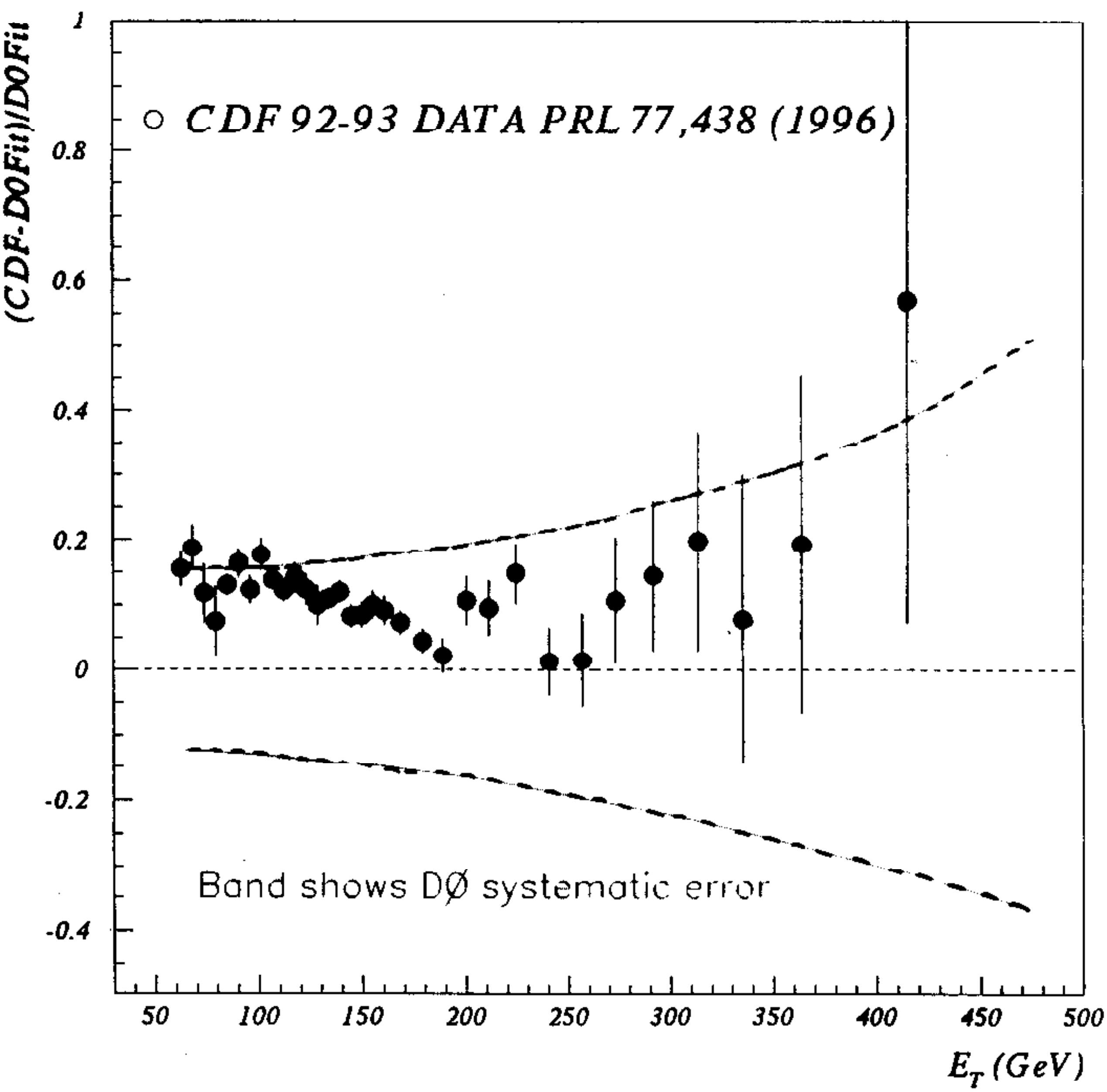
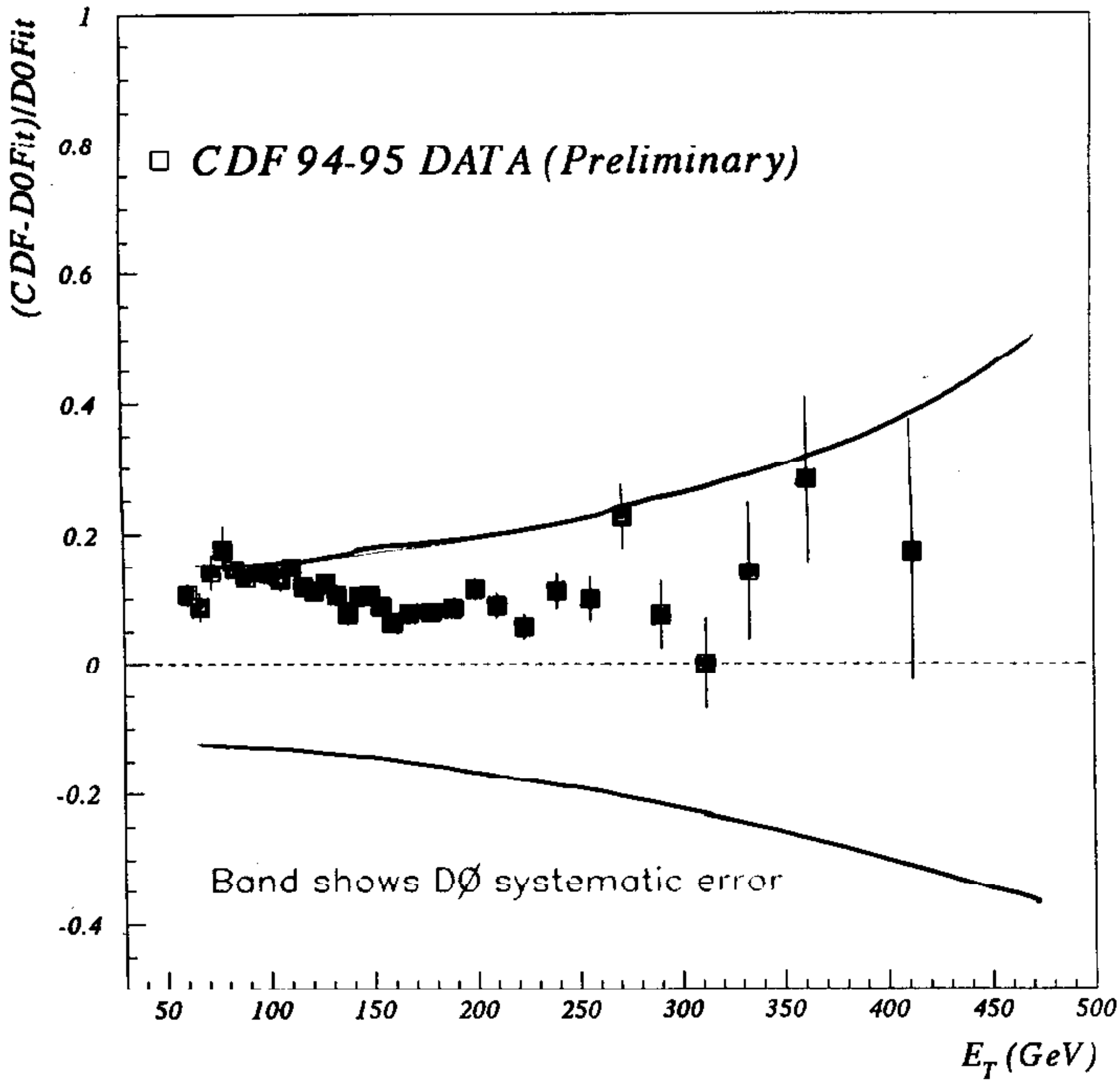


FIG. 2. The CDF and D0 Run Ib data compared to NLO QCD using MRSD0' parton distributions.

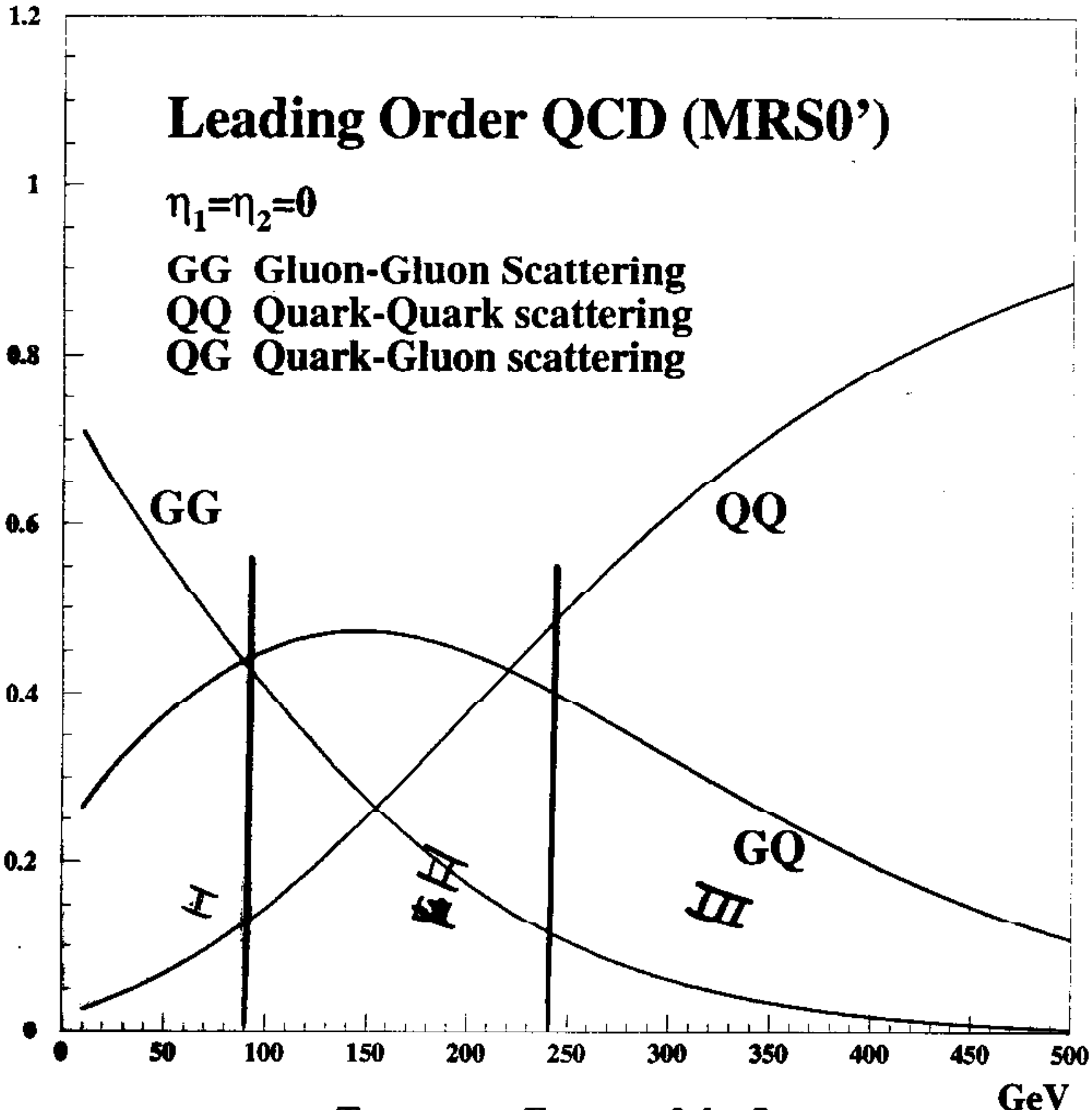


(CDF-D0Fit)/D0Fit
○ CDF 92-93 DATA PRL 77,438 (1996)
Band shows DØ systematic error
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
50
100
150
200
250
300
350
400
450
500
E_T (GeV)



(CDF-D0Fit)/D0Fit
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
□ CDF 94-95 DATA (Preliminary)
Band shows DØ systematic error
50
100
150
200
250
300
350
400
450
500
E_T (GeV)

Quark/Gluon Contributions to Cross Sction



Transverse Energy of the Jet

Recent Experimental Developments

More DIS Data:

HERA – "1994 Run"

More extensive, from x 10^{-6} to 0.3

and More precise (2-3%)

First data on charged-current cross-sections

First measurements of F_L

First measurements of F_2^{charm}

NMC –Analysis of small angle data

Extends to lower x and Q^2, R (L/T),

bridges HERA and BCDMS

E665 –New

New Process:

Tevatron Inclusive Jets – CDF/D0

$15\ \text{GeV} < E_t < 450\ \text{GeV}$

Processes and Experiments used in CTEQ Global QCD Analysis

Process	Experiment	Measurable	# Points	Note
DIS	BCDMS	$F^{\mu}_{2\ H}, F^{\mu}_{2\ D}$	324	PL **B223** '89
	NMC	$F^{\mu}_{2\ H}, F^{\mu}_{2\ D}, F^{\mu}_{2\ n/p}$	297	PL **B364** '95
	E665	$F^{\mu}_{2\ H}, F^{\mu}_{2\ D}$	70	FNAL-95/396
	H1	$F^{e}_{2\ H}$	172	DESY 96-039
	ZEUS	$F^{e}_{2\ H}$	179	DESY 96-076
	CCFR	$F^{\nu}_{2\ Fe}, x\ F^{\nu}_{3\ Fe}$	126	'93 (Pri. Com.)
Drell-Yan	E605	$sd\sigma/d\sqrt{\tau}dy$	119	PR **D43** '91
	NA-51	A_{DY}	1	PL **B332** '94
W-prod.	CDF	Lepton asym.	9	PRL **74** '95
Direct γ	WA70	$Ed^3\sigma/d^3p$	8	Z.Phys.**C38** '88
	UA6	$Ed^3\sigma/d^3p$	16	PL **B317** '93
Incl. Jet	CDF	$d\sigma/dE_t$	36	PRL **77** '96, APS '96
	D0	$d\sigma/dE_t$	26	Moriond '96

New CTEQ Global Analysis:

How Well do we know G(x,Q)?

at low to moderate x?

Will study in two steps:

Impact of New and More Precise DIS data (1995):

HERA, NMC, E665 — significant

Impact of Inclusive CDF/D0 Jet data:

CDF (excluding low and high P_t regions) — 1st time

Phenomenological Sources of Uncertainties on G(x,Q):

Value of α_s

Will explore the range: $0.105 < \alpha_s(m_Z) < 0.125$

Parametrization of $G(x,Q_0)$

$$G(x,Q_0) = A\, x^B\, (1-x)^C\, P(x; D, ...)$$

P(x; D, ...): functional form? $B_{gluon} = B_{sea\ quarks}$?

How many parameters?

Will compare:

(i) "minimal": $B_g = B_{s.q.}$; A - D (CTEQ3)

(ii) "2 + min" : $B_g \neq B_{s.q.}$; A - E (CTEQ2, MRSG, ..)

Data Selection: in particular, choice of "Q_{cut}"

$Q > Q_{cut}$ so that perturbative NLO QCD ("twist-two") theory will be applicable.

Will explore: $Q_{cut} = 2, 3, 4, 5$ GeV

Six Series of Global Fits to explore Range Variation of PDF's

	Data			Para-meters	Varying
	<1995	NewDIS	Jet		
A	x			m.	α_S
B	x	x		m.	α_S
C	x	x		2+m.	α_S
D	x	x	x	m.	α_S
E	x	x	x	2+m.	α_S
F	x	x	x	2+m.	Q_{cut}

m parameterization

$G(x, Q_0) =$

$A_0 x^{A_1} (1-x)^{A_2} (1+A_3 x)$

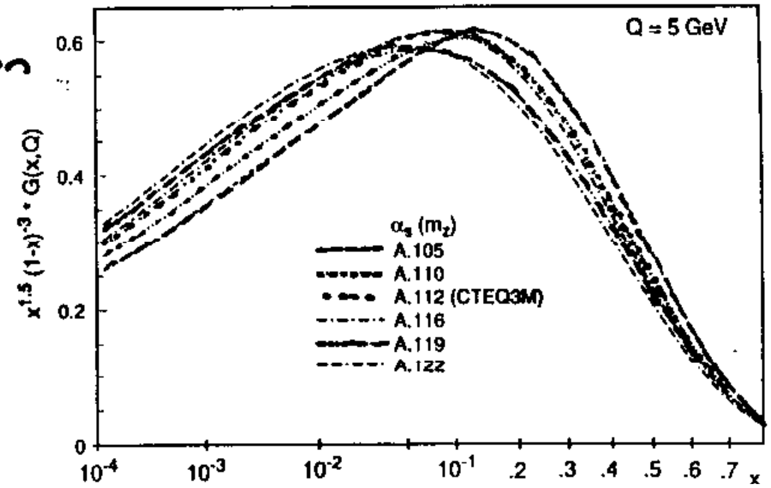


Figure 3: Series-A gluon distributions normalized by the function $x^{-1.5}(1-x)^3$ in order to display clearly the behavior of $G(x, Q)$ over the entire x-range. For the same purpose, the horizontal x-axis is drawn with a scale which smoothly changes from log- to linear behavior.

Add new DIS data

E665, NMC, HERA

still "m"

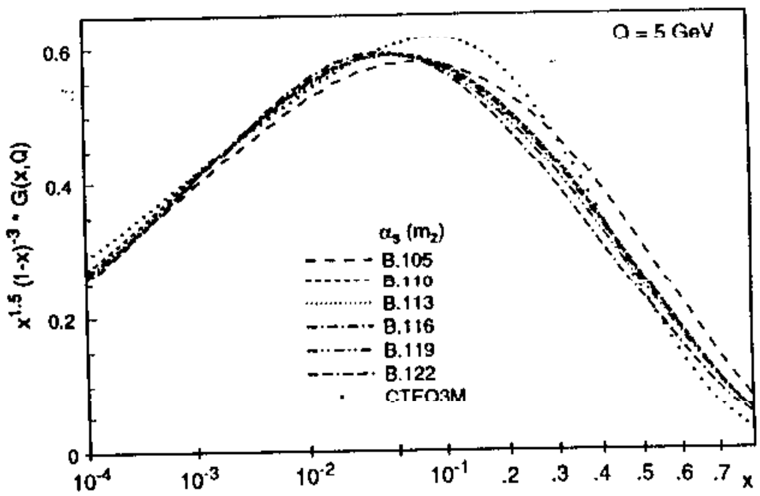


Figure 4: Series-B gluon distributions normalized by the function $x^{-1.5}(1-x)^3$ (cf. caption of previous figure.)

new DIS data

but

"m+z"

$G(x, Q_0) =$

$A_0 x^{A_1} (1-x)^{A_2} (1+A_3 x^{A_4})$

$A_1^g \neq A_1^{sea}$

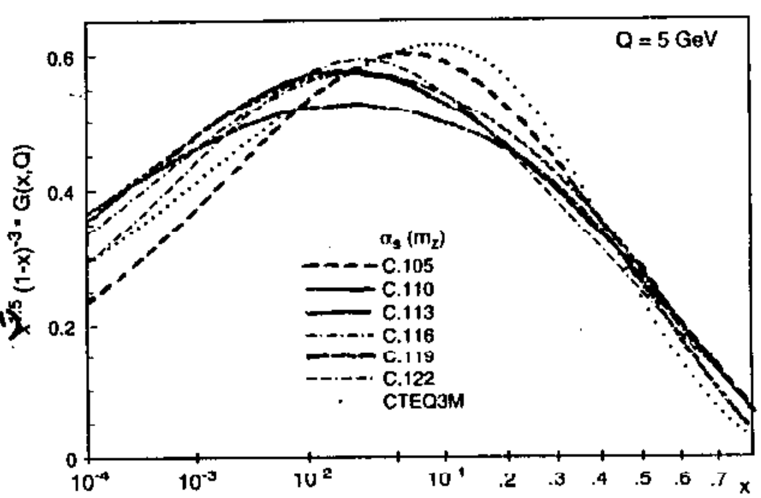


Figure 5: Series-C gluon distributions normalized by the function $x^{-1.5}(1-x)^3$

	α_s series		
CTEQ4A1	1	0.110	2.56
CTEQ4A2	2	0.113	2.56
CTEQ4A3	Same as CTEQ4M	0.116	2.56
CTEQ4A4	4	0.119	2.56
CTEQ4A5	5	0.122	2.56

new DIS data + TeV jets

2+m

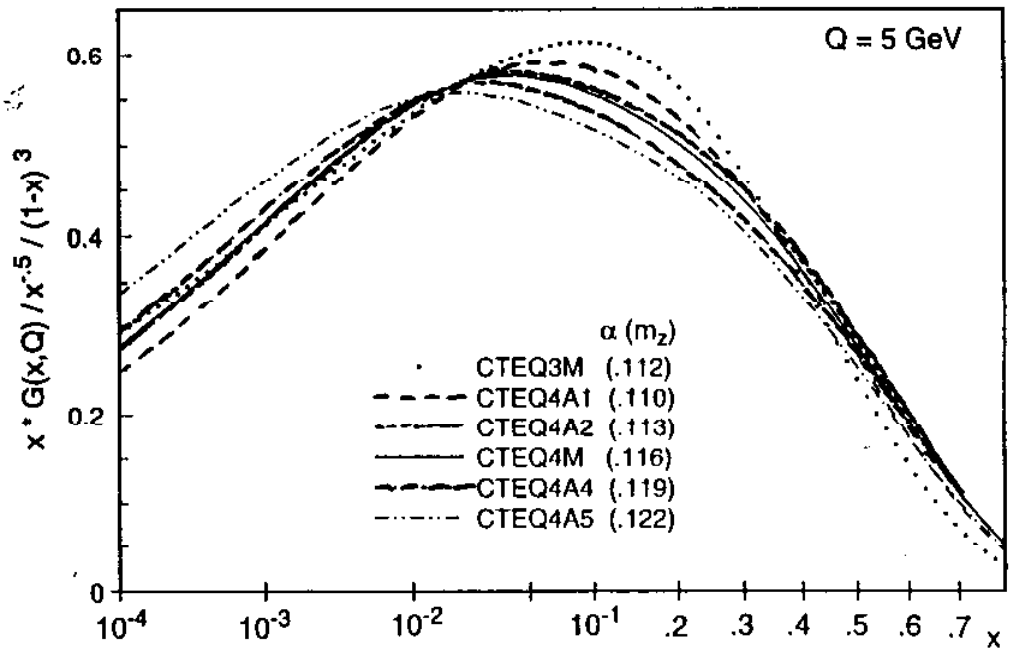


Figure 15: Series-CTEQ4A gluon distributions normalized by the function $x^{-1.5}(1-x)^3$.

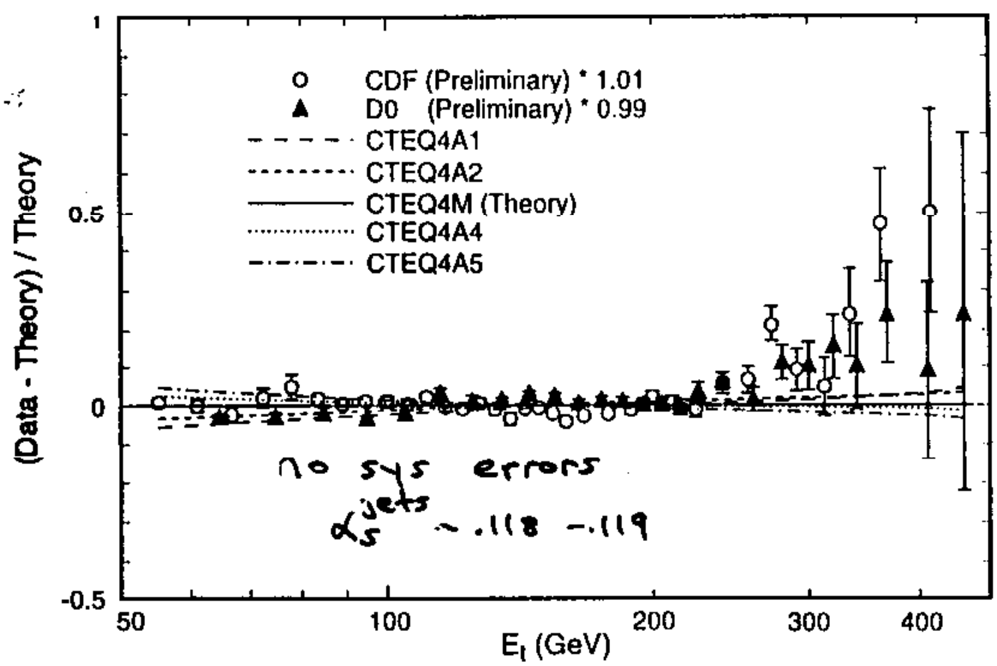


Figure 14: Inclusive jet cross-section of CDF and D0 compared to NLO QCD calculations based on the new CTEQ4A series of parton distributions.

Collisions Hint That Quarks Might Not Be Indivisible

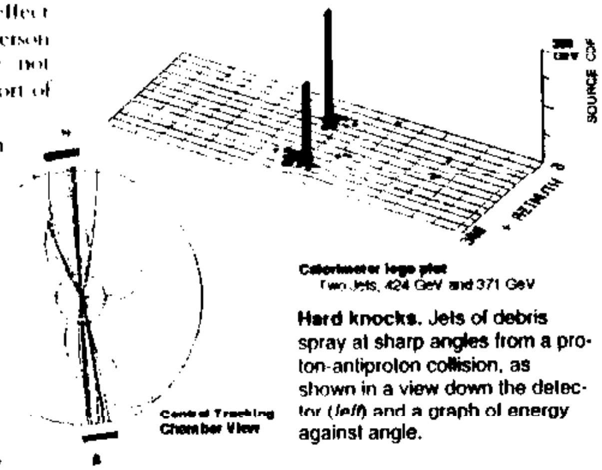
BATAVIA, ILLINOIS—When two groups of particle physicists at the Fermi National Accelerator Laboratory announced last March that they had found the top quark, they put the capstone on the current theory of the fundamental structure of matter, called the Standard Model. Now, just short of a year later, *Science* has learned that one of those groups has evidence that could challenge the model. During a yearlong run on Fermilab's Tevatron particle accelerator, the CDF collaboration—for Collider Detector at Fermilab—observed an unexpectedly large number of "hard," or violent, collisions between quarks, which the Standard Model identifies as a fundamental building block of matter. "This is just the sort of effect you would see," says CDF co-spokesperson William Carithers, "if quarks were not fundamental particles but had some sort of internal structure."

"If [quark substructure] was true, then its relevance would be very, very large," says Guido Altarelli of CERN, the European particle physics laboratory in Geneva. But he and Carithers, who is based at Lawrence Berkeley National Laboratory, quickly add that it's too soon to conclude that the Standard Model is in serious danger. Physicists both inside and outside the 444-member CDF collaboration are furiously sorting through other, less earth-shaking explanations for the data, which the CDF group describes in a paper submitted 2 weeks ago to *Physical Review Letters*. They range from the creation of an unknown particle during the collisions—the explanation Altarelli favors—to minor errors in Standard Model predictions about the behavior of quarks. Neither alternative would require a major refurbishing of theory.

But if quarks do turn out to have a substructure, the discovery would be something of a reprise of Sir Ernest Rutherford's discovery of the atomic nucleus at the turn of the century. Rutherford and his co-workers smashed positively charged alpha particles into gold foil and noticed that there were too many hard collisions—those from which the particles caromed at nearly right angles—to be explained by a structureless "plum pudding" model of the atom. Instead, Rutherford concluded, the particles must be running into a small, hard kernel he called the nucleus.

Physicists now know that the nucleus itself has structure: first the protons and neutrons making up the nucleus and, inside each of them, three quarks immersed in short-lived "virtual" quarks and their antimatter counterparts, antiquarks. The whole quantum-mechanical stew is held together by particles called gluons. Just as Rutherford tested his understanding of atomic structure by probing atoms with alpha particles, the CDF team tested its picture of this structural hierarchy by colliding protons with antiprotons in the Tevatron, the world's most powerful accelerator.

Most of the collisions were glancing. But every so often a quark from one proton collided head on with a quark or gluon from the other, sending debris flying at a sharp angle to the beams. In the world of particle physics, the more powerful a collision, the smaller the distances it can probe. And at the energy of the Tevatron—1.8 trillion electron volts—the debris from these hard collisions gave information about the smallest distance scales ever explored.



Hard knocks. Jets of debris spray at sharp angles from a proton-antiproton collision, as shown in a view down the detector (*left*) and a graph of energy against angle.

The collaborators compared the frequency of the sideways "jets" of debris (see graphic) that spewed from the collisions with the predictions of quantum chromodynamics (QCD), the mathematical apparatus for calculating quark interactions in the Standard Model. Down to energies corresponding to scales of about a thousandth the size of the proton, says Carithers, the agreement with QCD was "right bang on." But then the frequency of high-angle jets began to diverge from theory, and at scales 10 times smaller the frequency of these jets was at least 50% higher than the prediction.

As these events began to accumulate, says CDF co-spokesperson Giorgio Bellettini of the Istituto Nazionale di Fisica Nucleare an[d] the University of Pisa in Italy, "a fierce figh[t] broke out within the collaboration over how to gauge the small chance that systemati[c] experimental errors could explain the re[-]sults. The researchers made exhaustive test[s] of the possibility that a "conspiracy" of ra[n]dom or systematic errors might be foolin[g] them, says Bellettini. Finally, he says, th[e] collaboration reached a consensus that th[e] excess had to be real.

Now they are left to explain it. Steve Gee[r], a CDF team member at Fermilab, describe[s] the most dramatic possibility: "It migh[t] mean that, just as in Rutherford's atom there's a hard center" lurking inside th[e] quarks, as some speculative theories sugges[t].

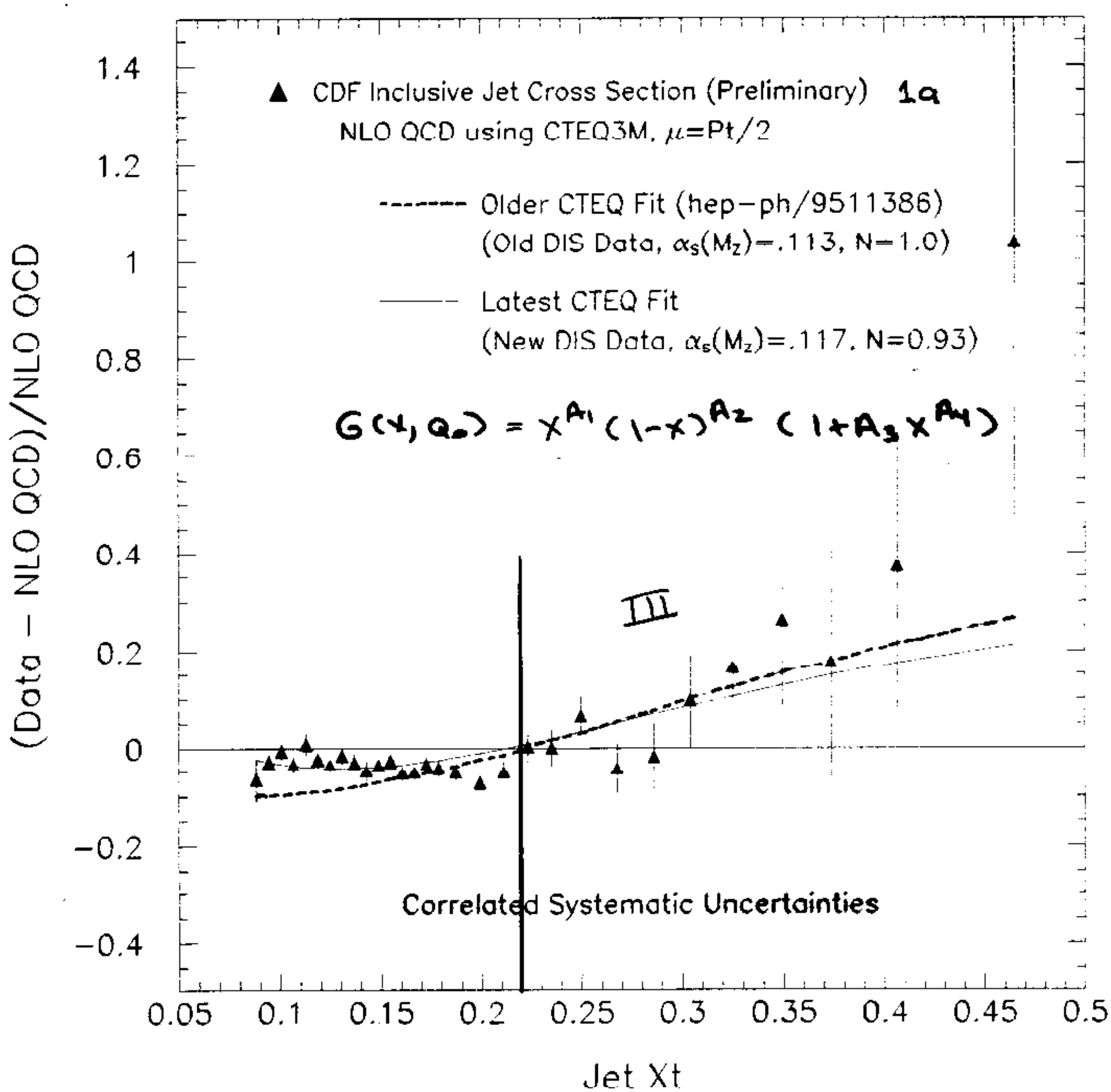
But Geer points out that several othe[r] explanations might account for the measure[-]ments. The more mundane possibility, he says, has to do with how momentum is par[-]celed out among the components of a speed[-]ing proton. The hardest collisions occu[r] when two quarks that happen to carry a hig[h] fraction of each proton's momentum meet head on. But the massless glu[-]ons can carry momentum as well. S[o] if, say, QCD underestimates how of[-]ten gluons carry a high fraction of th[e] momentum, then the quarks they en[-]counter could suffer an unexpecte[d] number of violent collisions, and "w[e] could end up with more energetic je[ts] than expected," Geer says.

A more radical suggestion [b]y Altarelli and Pierre Chiapetta [of] CERN posits that the energetic quar[k] collisions occasionally generate a ne[w] heavy particle—a cousin of the Z^0, [a] known massive particle that appear[s] briefly in high-energy collisions. Th[e] creation of the particle would give th[e] quarks another way to interact, boosting th[e] collision frequency. And when it decays, th[e] particle would spray jets of debris to the sid[e] of the collisions, mimicking an excess of har[d] collisions. The new particle might also ex[-]plain a nagging observation made at CERN. Researchers there have noted that the rate [at] which the Z^0 decays into bottom and cha[rm] quarks doesn't match theory. The Z^0 migh[t] "mix" with, or transform into, its heavi[er] cousin, which would alter its lifetime an[d] might explain the decay rates.

The CDF team is already grindin[g] through new data to see if it can find any wa[y] to distinguish among these possibilities—f[or] example, by studying the detailed angul[ar] distribution of the jets. But for now, the team is glad that the data are on their way to pub[-]lication and a wider group of particle theo[-]rists around the world will be trying to mak[e] sense of them. Says Brenna Flaugher, a CD[F] team member at Fermilab, "This is where th[e] fun begins, I guess."

–James Gla[nz]

Gluons at high x



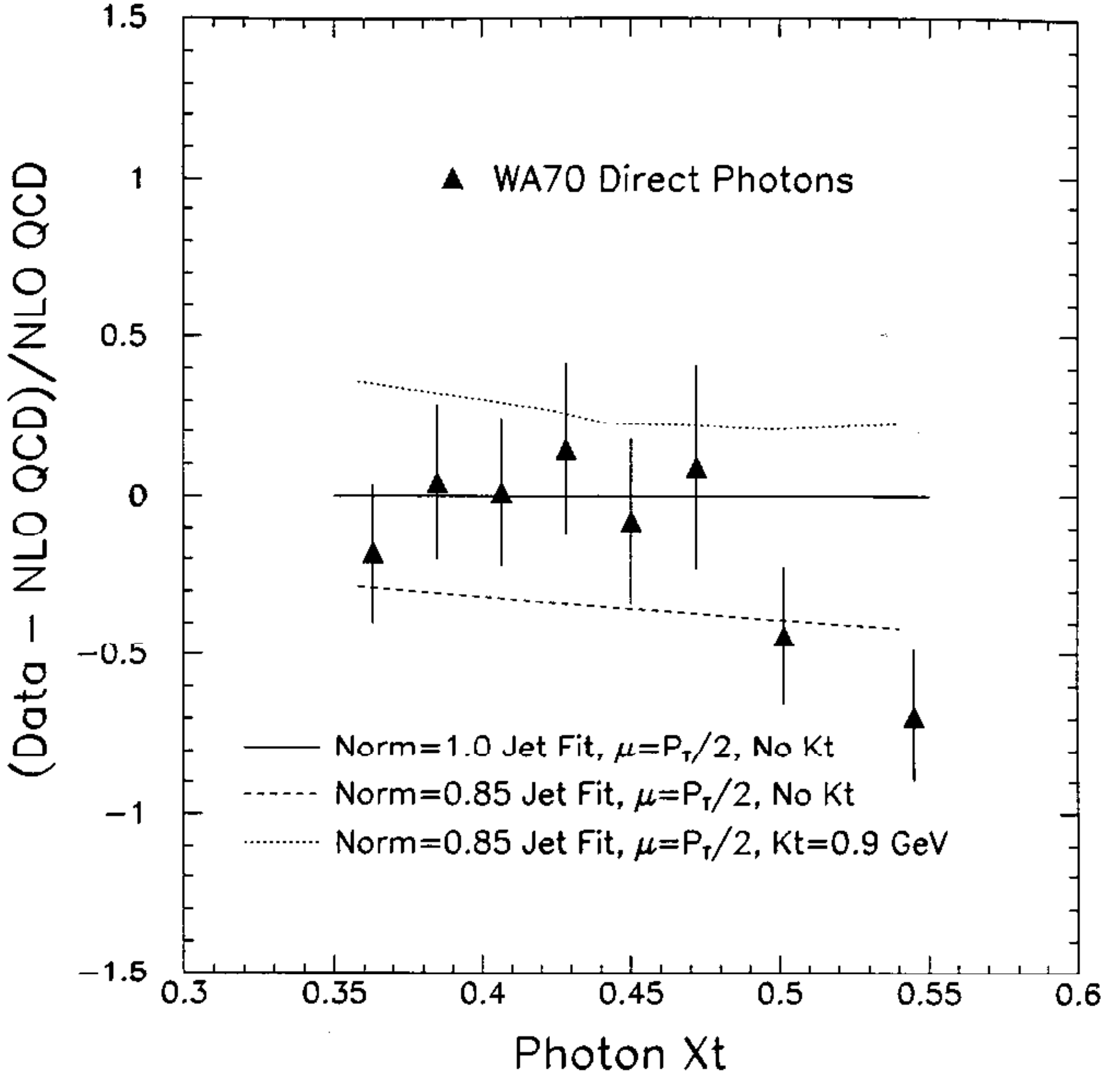


Figure 4: The WA70 direct photon data is compared to NLO QCD calculations using the two sets of jet-fit gluons. (see text)

Summary of New Global Analysis of PDF's

Considerable progress has been made in determining the hither-to-fore elusive $G(x,Q)$ and its uncertainties

New and more precise DIS data (HERA, NMC, E665) help narrow down the PDF's, including $G(x,Q)$, using the "minimal" parametrization

Inclusive Jet data in the medium p_t range have significant impact in narrowing down $G(x,Q)$ over a wide range of x, even with a more general parametrization

The range of uncertainty in $G(x,Q)$ at Q=5 GeV due to variations in α_S, parametrization, and choice of Q_{cut} in data selection are all ≤ 10 % for x < 0.3
(This is within the range of the dedicated studies of HERA, BCDMS, ...; but over the much wider kinematic region.)

The uncertainty in $G(x,Q)$ above x = 0.3 is still not well established. More experimental input from jet measurements (inclusive and semi-inclusive) at several different energies will be crucial. Better theoretical understanding of the direct photon cross-section will be important to provide independent constraints on $G(x,Q)$.