CTEQ Symposium 1996
Puzzles and Challenges

J.F. Owens
Florida State University

1. Welcome
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CTEQ Collaboration

CTEQ is an acronym for Collaborative Theoretical and Experimental Studies of QCD.

- Dedicated to increasing the interaction between theorists and experimentalists.
- Specific projects
  1. Summer Schools
     - Mackinac Island 1992
     - Four Winds Resort, Indiana 1993
     - Lake of the Ozarks, Missouri 1994
     - Bad Lauterburg, Germany 1995
     - Interlaken Resort, Wisconsin 1997
  2. Symposia
     - Collider Physics, MSU, 1993, 1995
     - Top Quark, Fermilab, 1995
     - Puzzles and Challenges, Fermilab, 1996
  3. Handbook on Perturbative QCD (Rev. Mod. Phys.)
  4. Global fitting subgroup

CTEQ Collaboration

Co-spokesmen

George Sterman and Wu-Ki Tung

- Argonne National Laboratory — Steve Kuhlmann
- Fermilab — Jorge Morfin
- Florida State University — J.F. Owens
- Harvard University — Sanjib Mishra
- Iowa State University — Jianwei Qiu
- Michigan State University (Host Institution) — R. Brock, J. Huston, J. Pumplin, Wu-Ki Tung, Harry Weerts, C.P. Yuan
- University of Oregon — Dave Soper
- Pennsylvania State University — John Collins, Jim Whitmore
- Southern Methodist University — Fred Olness
- SUNY Stony Brook — Jack Smith, George Sterman

1996 CTEQ Symposium

on confronting QCD with experiment

Outstanding Puzzles & Challenges

A symposium to highlight possible disagreement between experimental results and QCD predictions

Fermilab — Nov. 7-9, 1996

Partial list of topics:

- What are the outstanding controversies in pQCD?
- Is there an α_s problem?
- Can uncertainties of parton distributions be quantified? Do they obscure real, possibly new, physics?
- How well do pQCD jets match measured jets?
- NLO pQCD vs. parton showers: which approximation works best and where? Can they be reconciled?
- Multi-scale problems in QCD: does resummation help? Are renormalons relevant to phenomenology?
- Is heavy quark QCD theory really understood?
- Will we recognize BFKL physics when we see it?
- Can lattice QCD and perturbative QCD meet halfway?
- Does perturbative QCD apply to nuclear physics?

Organizing committee:

J. Huston, Michigan State University
S. Kuhlmann, Argonne National Laboratory
J. Morfin (co-chair), Fermilab
F. Olness, Southern Methodist University
J. Owens, Florida State University
D. Soper, University of Oregon
G. Sterman (co-chair), SUNY Stony Brook
Wu-Ki Tung, Michigan State University
H. Weerts, Michigan State University

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Sponsored by Fermilab and the Department of Energy

Purpose of the Symposium

- 25 years of QCD phenomenology
- Outstanding experimental progress
  - Increase in energy by about 30: ISR to Tevatron
  - Colliding beam facilities: e^+e^-, ep, and $\overline{p}p$
  - Progress in quantity and quality of data: statistics, errors, new techniques
  - Constant pressure to improve precision of theoretical predictions: need 10 % or better
- Corresponding theoretical progress
  - Next-to-leading-order calculations now exist for many processes
  - Next-to-next-to-leading-order calculations in progress
  - Progress in determination of parton distribution functions
  - Better calculations for a wider variety of observables
- Successes of QCD are legion, but...

A Different Kind of Symposium

- Don't want a series of comparisons just showing great agreement with data
- Progress is most often made when there exist contradictions or problems

So, let's focus on a limited number of areas where there appear to be problems when comparing theory and experiment. Hence we'll focus on

QCD: Puzzles and Challenges

Guiding Questions

Suppose that some phenomenon has been observed which does not appear to be described by the theory.

1. Is there a problem with applying the theory?

    - Are there approximations which have broken down?
    - Have potentially important contributions been neglected?
    - Is there some new technique, the use of which can produce predictions which more accurately reflect the true content of the theory?

2. Are the data (self) consistent?

    - Do the new data agree with interpolations and/or extrapolations based on previous data?
    - Do the new data contradict previous data?
    - Is it possible to verify or otherwise confirm the new results?

3. What new data could help resolve the discrepancy?

   - Perhaps uncertainties in parton distributions need to be reduced. What data would help?
   - If there is a deficiency in the theoretical treatment, then perhaps it would be expected to show up somewhere else. Does it?

4. What new theoretical developments are needed to improve the comparison with the data?

   - Is it possible to identify the shortcomings in the calculations?
   - If so, then can they be remedied?

Some examples selected from this symposium...

Is there an α_s problem?

Lower energy data (dominated by DIS) favor(ed) a lower value for α_s than higher energy data (dominated by LEP). Is there a problem? (fig)

- Is this a sign of new physics?
- Are there theoretical problems with the extraction of α_s?
- Can new data shed any light on this apparent difference?

	Process	Ref.	Q [GeV]	$\alpha_s(Q)$	$\alpha_s(M_{Z^0})$	$\Delta\alpha_s(M_{Z^0})$ exp.	theor.	order of perturb.
1	R_τ [LEP]	[7-10]	1.78	$0.318 \pm^{0.048}_{0.039}$	$0.117 \pm^{0.006}_{0.005}$	$\pm^{0.003}_{0.004}$	$\pm^{0.005}_{0.004}$	NNLO
2	R_τ [world]	[2]	1.78	0.32 ± 0.04	$0.118 \pm^{0.004}_{0.006}$	–	–	NNLO
3	DIS [ν]	[3]	5.0	$0.193 \pm^{0.019}_{0.018}$	$0.111 \pm^{0.006}_{0.007}$	$+^{0.004}_{-0.006}$	0.004	NLO
4	DIS [μ]	[12]	7.1	0.180 ± 0.014	0.113 ± 0.005	0.003	0.004	NLO
5	$J/\Psi, \Upsilon$ decay	[4]	10.0	$0.167 \pm^{0.015}_{0.011}$	$0.113 \pm^{0.007}_{0.005}$	–	–	NLO
6	e^+e^- [σ_{had}]	[14]	34.0	0.163 ± 0.022	0.135 ± 0.015	–	–	NNLO
7	e^+e^- [shapes]	[15]	35.0	0.14 ± 0.02	0.119 ± 0.014	–	–	NLO
8	$p\bar{p} \to b\bar{b}X$	[11]	20.0	$0.136 \pm^{0.025}_{0.024}$	$0.108 \pm^{0.015}_{0.014}$	0.006	$\pm^{0.014}_{0.013}$	NLO
9	$p\bar{p} \to W$ *jets*	[13]	80.6	0.123 ± 0.027	0.121 ± 0.026	0.018	0.020	NLO
10	$\Gamma(Z^0 \to$ had.)	[5]	91.2	0.133 ± 0.012	0.133 ± 0.012	0.012	$\pm^{0.003}_{0.001}$	NNLO
11	Z^0 ev. shapes							
	ALEPH	[7]	91.2	$0.119 \pm^{0.008}_{0.010}$		–	–	NLO
	DELPHI	[8]	91.2	0.113 ± 0.007		0.002	0.007	NLO
	L3	[9]	91.2	0.118 ± 0.010		–	–	NLO
	OPAL	[10]	91.2	$0.122 \pm^{0.006}_{0.005}$		0.001	$\pm^{0.006}_{0.005}$	NLO
	SLD	[6]	91.2	$0.120 \pm^{0.015}_{0.013}$		0.009	$+^{0.012}_{-0.009}$	NLO
	Average	[6-10]	91.2		0.119 ± 0.006	0.001	0.006	NLO
12	Z^0 ev. shapes							
	ALEPH	[7]	91.2	0.125 ± 0.005		0.002	0.004	resum.
	DELPHI	[8]	91.2	0.122 ± 0.006		0.002	0.006	resum.
	L3	[9]	91.2	0.126 ± 0.009		0.003	0.008	resum.
	OPAL	[10]	91.2	$0.122 \pm^{0.003}_{0.006}$		0.001	$\pm^{0.003}_{0.006}$	resum.
	Average	[7-10]	91.2		0.123 ± 0.005	0.001	0.005	resum.

Table 1: Summary of measurements of α_s. For details see text.

Processes	Q [GeV]	$\Lambda^{(5)}_{\overline{MS}}$ [MeV]	$\alpha_s(M_{Z^0})$	χ^2/d.o.f.
2,3,4,5,8	1.78 - 20.0	157^{+27}_{-25}	0.113	0.6/4
6,7,9,10,11,12	34.0 - 91.2	271^{+51}_{-45}	0.123	1.8/5
2 - 12	1.78 - 91.2	193^{+23}_{-21}	0.117	7.5/10
2 - 12	1.78 - 91.2	α_s = const. = 0.133 ± 0.003		62.4/10

Table 2: Results of QCD fits to the experimental data on $\alpha_s(Q)$ as listed in Table 1. See text for the interpretation of errors and other details.

From S. Bethke + S. Catani
Moriond '92

Measurement	μ/GeV	$\alpha_s(\mu)$	$\alpha_s(M_Z)$
BJSR [7]	1.58	$0.375 \pm {}^{0.062}_{0.081}$	$0.122 \pm {}^{0.005}_{0.009}$
GLSR [8]	1.732	0.240 ± 0.047	$0.107 \pm {}^{0.007}_{0.009}$
R_Z [9, 10, 11]	91.2	0.128 ± 0.006	0.128 ± 0.006
R_τ [12]	31.6	0.153 ± 0.017	0.127 ± 0.012
R_τ [13]	34.0	0.165 ± 0.022	0.136 ± 0.015
R_τ [14]	1.777	0.375 ± 0.032	0.123 ± 0.003
R_τ [15]	1.777	0.302 ± 0.035	0.124 ± 0.004
R_τ, Moments [16]	1.777	0.355 ± 0.021	0.121 ± 0.003
R_τ(PDG), Moments [17]	1.777	$0.302 \pm {}^{0.024}_{0.025}$	0.114 ± 0.003
$\eta_c \to \gamma\gamma$ [17]	2.98	0.187 ± 0.029	0.101 ± 0.010
$\Gamma(\Upsilon \to gg\gamma)/\Gamma(\Upsilon \to ggg)$ [17]	9.46	0.164 ± 0.013	0.111 ± 0.006
$\Gamma(J/\Psi, \Upsilon \to ggg)/\Gamma(J/Psi, \Upsilon \to e^+e^-)$ [18]	10.0	$0.167 \pm {}^{0.015}_{0.011}$	$0.113 \pm {}^{0.007}_{0.005}$
Lattice Gauge Theory (Υ level splitting) [19]	5.0	0.203 ± 0.010	0.115 ± 0.002
Deep Inelastic Scattering	7.1	0.177 ± 0.012	0.113 ± 0.005
scaling violation in e^+e^--annihilation [20]	56.5		0.118 ± 0.005
scaling violation in e^+e^--annihilation [21]	44.7		0.127 ± 0.011
$ep \to$ Jets [22]	17.3		0.123 ± 0.018
$ep \to$ Jets [23]	20.4	$0.150 \pm {}^{0.014}_{0.013}$	0.126 ± 0.008
$p\bar{p} \to$ W+Jets [24]	80.2	0.123 ± 0.025	0.121 ± 0.024
$p\bar{p} \to$ W+Jets [25]	80.2	$0.123 \pm {}^{0.015}_{0.014}$	$0.120 \pm {}^{0.014}_{0.012}$
$pp, p\bar{p} \to \gamma$ +Jets [26]	4.0	$0.206 \pm {}^{0.042}_{0.033}$	$0.112 \pm {}^{0.012}_{0.010}$
$p\bar{p} - > b\bar{b}$+Jets [27]	20.0	$0.138 \pm {}^{0.028}_{0.019}$	$0.109 \pm {}^{0.016}_{0.012}$
e^+e^- — hadrons (event shapes) [28]	10.53	0.164 ± 0.015	0.113 ± 0.006
e^+e^- — hadrons (event shapes) [29]	29.0	0.160 ± 0.012	0.129 ± 0.008
e^+e^- — hadrons (event shapes) [30]	29.0	0.149 ± 0.007	0.122 ± 0.005
$e^+e^- \to$ hadrons (event shapes) [31]	34.0	0.140 ± 0.020	0.119 ± 0.014
$e^+e^- \to$ hadrons (event shapes) [32]	53.3	0.129 ± 0.012	0.119 ± 0.010
$e^+e^- \to$ hadrons (event shapes) [33]	57.9	0.134 ± 0.006	0.124 ± 0.005
$e^+e^- \to$ hadrons (event shapes) [34]	58.0	0.132 ± 0.005	0.123 ± 0.004
$e^+e^- \to$ hadrons (event shapes) [35]	58.0	0.139 ± 0.008	0.129 ± 0.007
$e^+e^- \to$ hadrons (event shapes) [36]	58.5	0.129 ± 0.006	0.120 ± 0.005
$e^+e^- \to$ hadrons (event shapes) [32]	59.5	0.122 ± 0.013	0.114 ± 0.012
$e^+e^- \to$ hadrons (event shapes) [30]	91.2	0.123 ± 0.010	0.123 ± 0.010
$e^+e^- \to$ hadrons (event shapes) [37]	91.2	0.120 ± 0.008	0.120 ± 0.008
$e^+e^- \to$ hadrons (event shapes) [38]	91.2	0.125 ± 0.005	0.125 ± 0.005
$e^+e^- \to$ hadrons (event shapes) [39]	91.2	0.123 ± 0.006	0.123 ± 0.006
$e^+e^- \to$ hadrons (event shapes) [40]	91.2	0.124 ± 0.007	0.124 ± 0.007
$e^+e^- \to$ hadrons (event shapes) [41]	91.2	0.120 ± 0.006	0.120 ± 0.006

Table 1: Compilation of measurements of the strong coupling constant. The errors are the total uncertainties, which in most cases are dominated by the theoretical uncertainties.

From M. Schmelling
Physics in Collision 15 (1995)

Phys Rev. D 50, 1299 (1994)

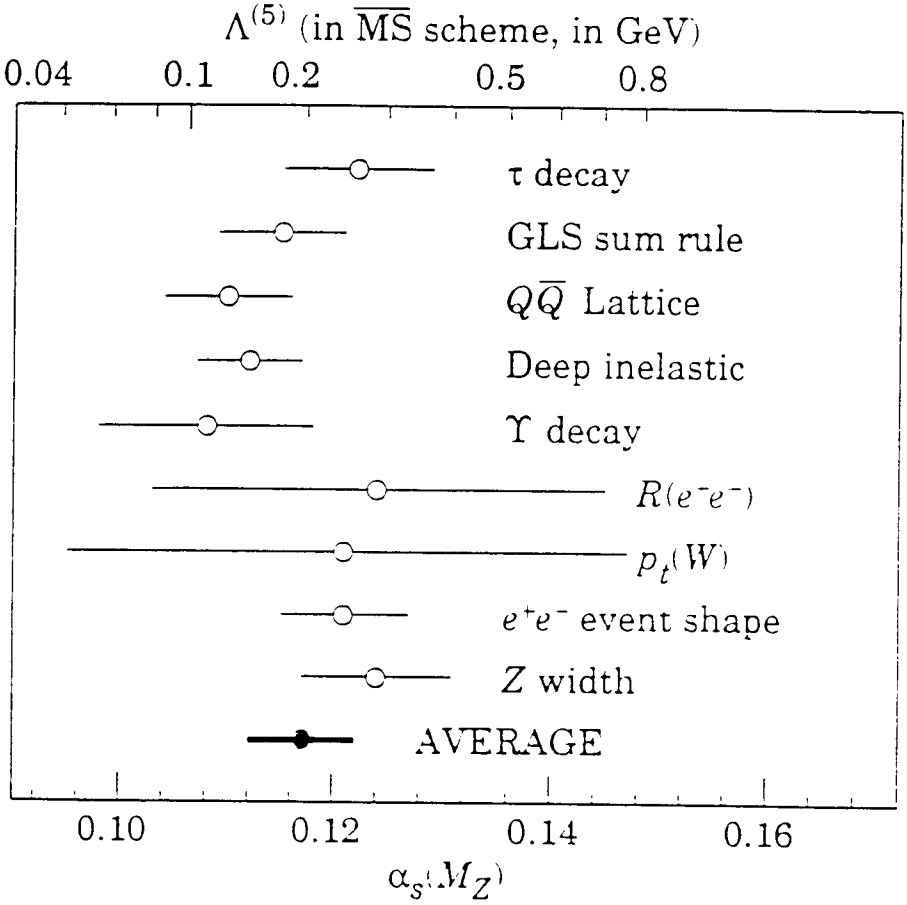

Figure 25.1: Summary of the values of $\alpha_s(M_Z)$ and $\Lambda^{(5)}$ from various processes ordered from top to bottom by increasing energy scale of the measurements. The values shown indicate the process and the measured value of α_s extrapolated up to $\mu = M_Z$. The error shown is the *total* error including theoretical uncertainties. The weighted average is obtained from the above values using the method discussed in the text.

Parton Distributions Functions

- What are the sources of uncertainty in the distributions?
- Can these uncertainties be quantified?
- How well do we really know the various distributions? (Different groups using the same methods and the same data get about the same results. But this doesn't mean that the errors on the distributions are accurately estimated by the small differences between different sets.)
- There is a danger of missing new physics if discrepancies are removed by simply refitting PDF's.
- What new data could be used to better refine the PDF's?
- When significant changes occur in one or more distributions, what are the effects (if any) on other types of data?

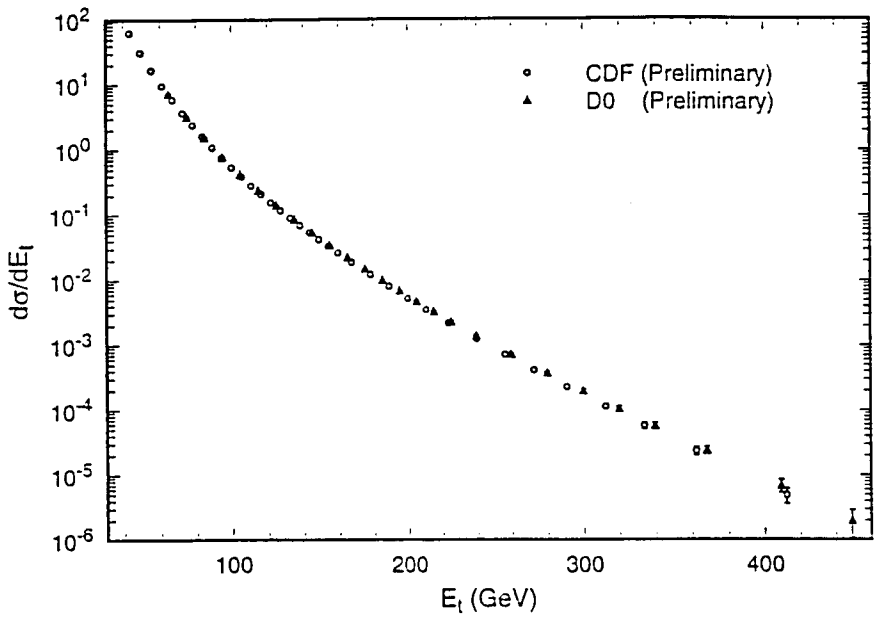

Figure 6: Inclusive jet cross-section measured by the CDF and D0 collaborations in Run-IB at the Tevatron.

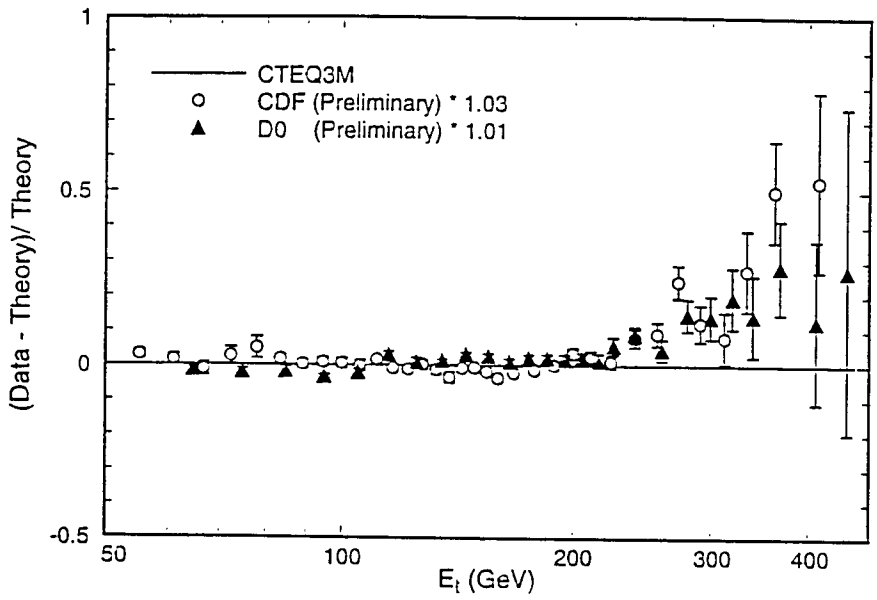

Figure 8: Inclusive jet cross-section measured by the CDF and D0 collaborations in Run-IB at the Tevatron normalized to NLO QCD calculations based on CTEQ3M PDF's. The difference in rapidity coverage of the two experiments are taken into account.

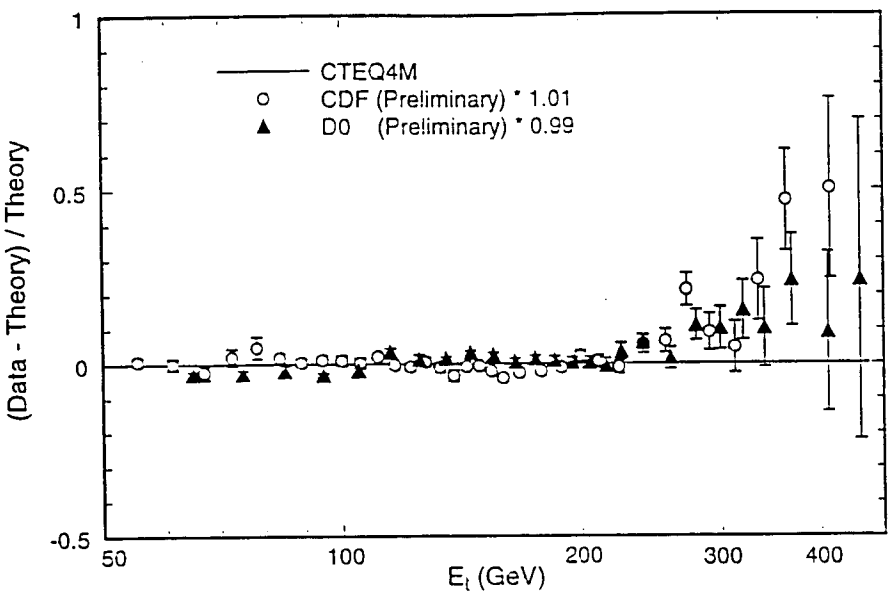

Figure 12: Inclusive jet cross-section of CDF and D0 compared to NLO QCD calculations based on the new CTEQ4M parton distributions.

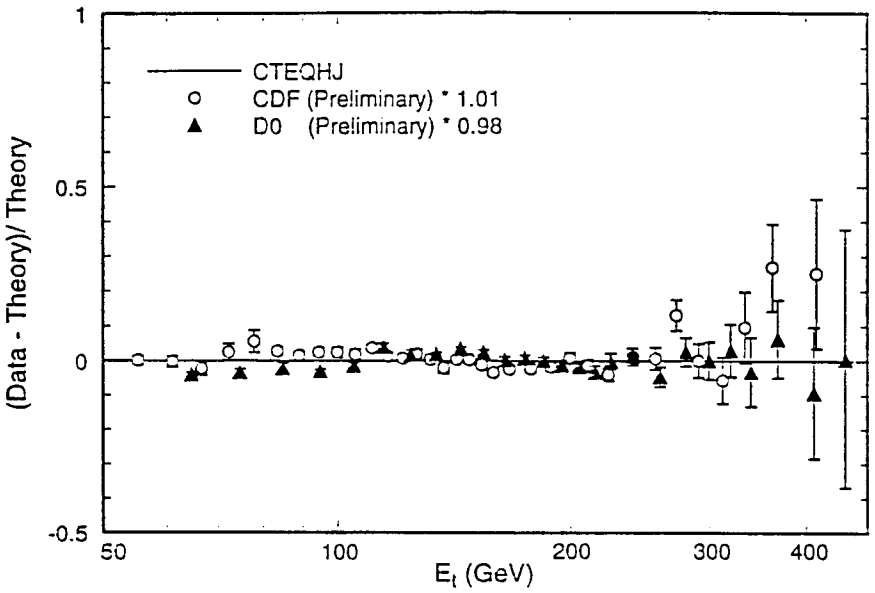

Figure 18: Inclusive jet cross-section of CDF and D0 compared to NLO QCD calculations based on the CTEQ4HJ parton distributions.

Jet Physics

- primary tool in collider physics
- test of QCD/EW physics
- search for new physics
- how well do various treatments of jets describe observations?

Heavy Quark Production

- What constitutes a heavy quark depends on the center-of-mass energy
- Recent b-quark measurements agree with theory, but the theoretical uncertainties are still large
- Some problems are indicated by recent data for ψ' production as compared to theory

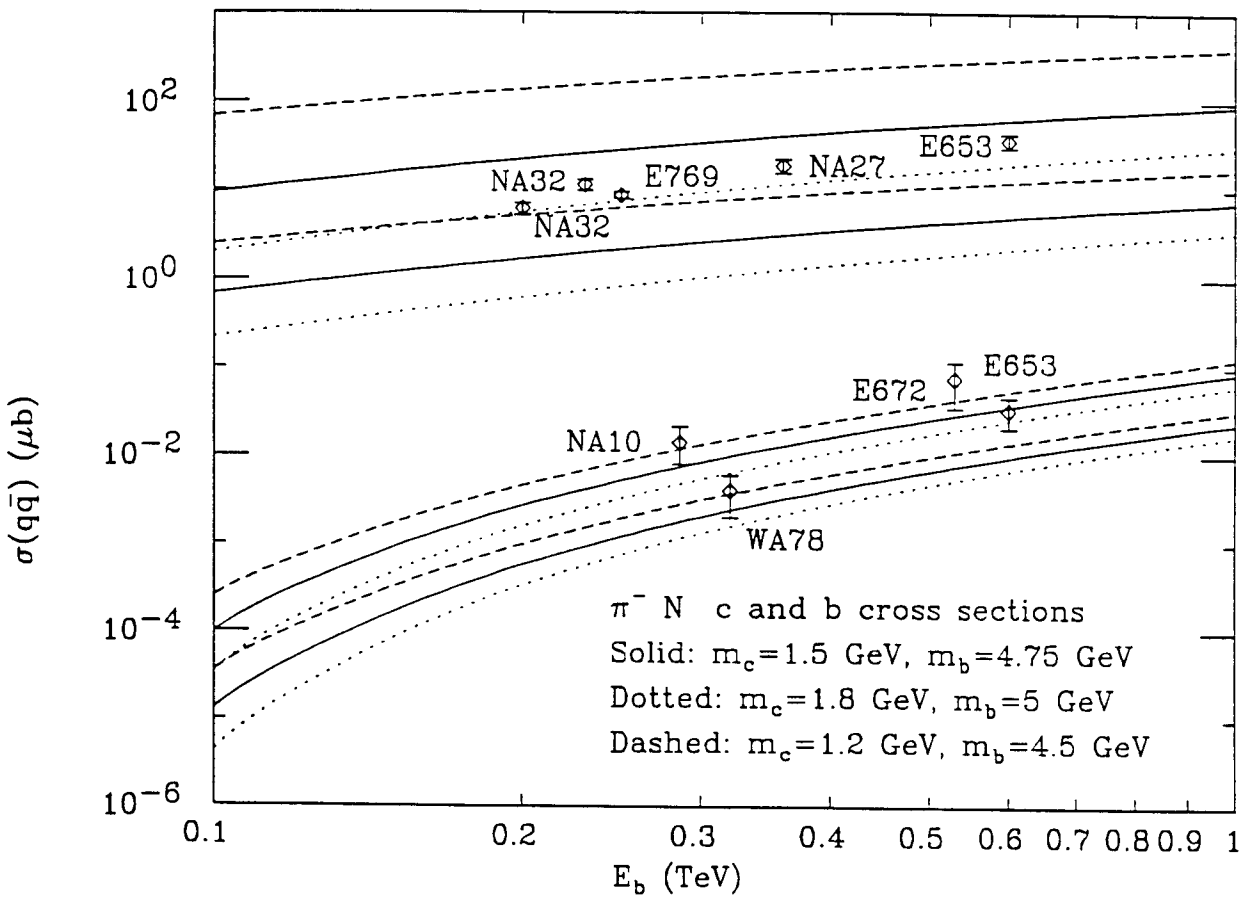

Figure 2: Cross sections for b and c production in πN collisions. For details see text (from ref. [8]).

G. Schuler CERN-TH/95-75

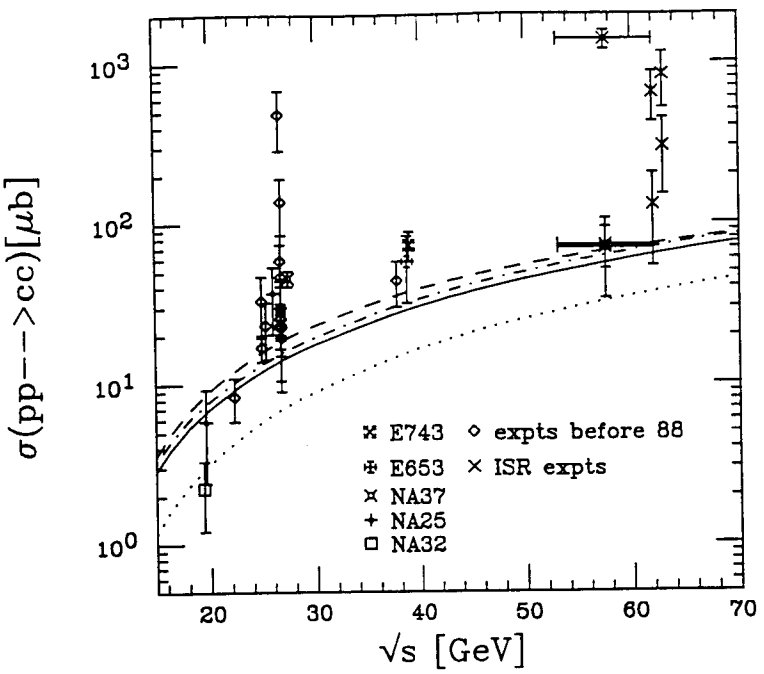

Figure 3: Total charm production cross sections from pp and pA measurements compared to calculations. The curves are: MRS D$-'$ $m_c = 1.2$ GeV, $\mu = 2m_c$ (solid); MRS D0$'$ $m_c = 1.2$ GeV, $\mu = 2m_c$ (dashed); GRV HO $m_c = 1.3$ GeV, $\mu = m_c$ (dot-dashed); GRV HO $m_c = 1.5$ GeV, $\mu = m_c$ (dotted) (from ref. [10]).

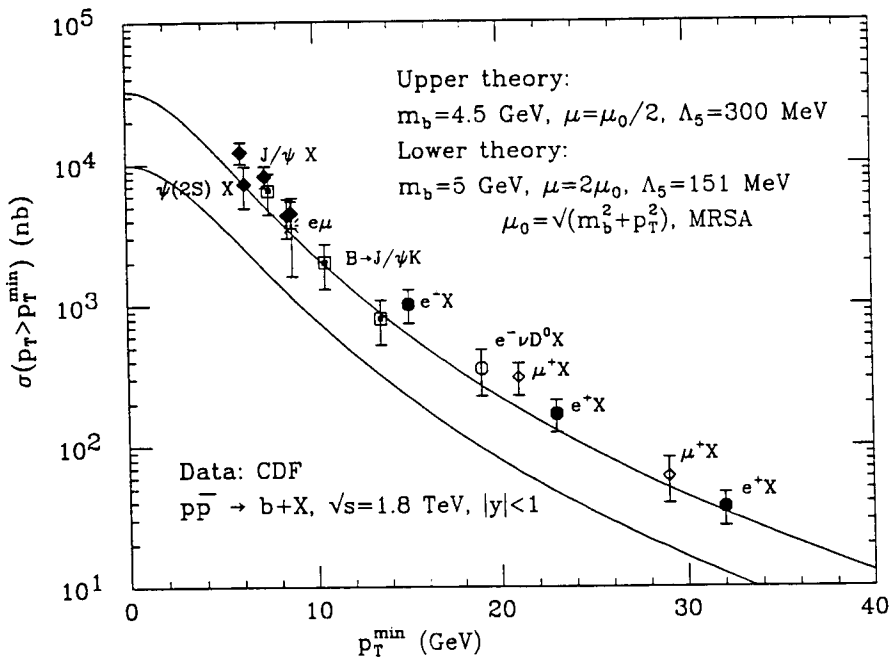

Figure 4: The b-quark cross sections at CDF. For details see text (from ref. [8]).

G. Schuler
CERN-TH/95-75

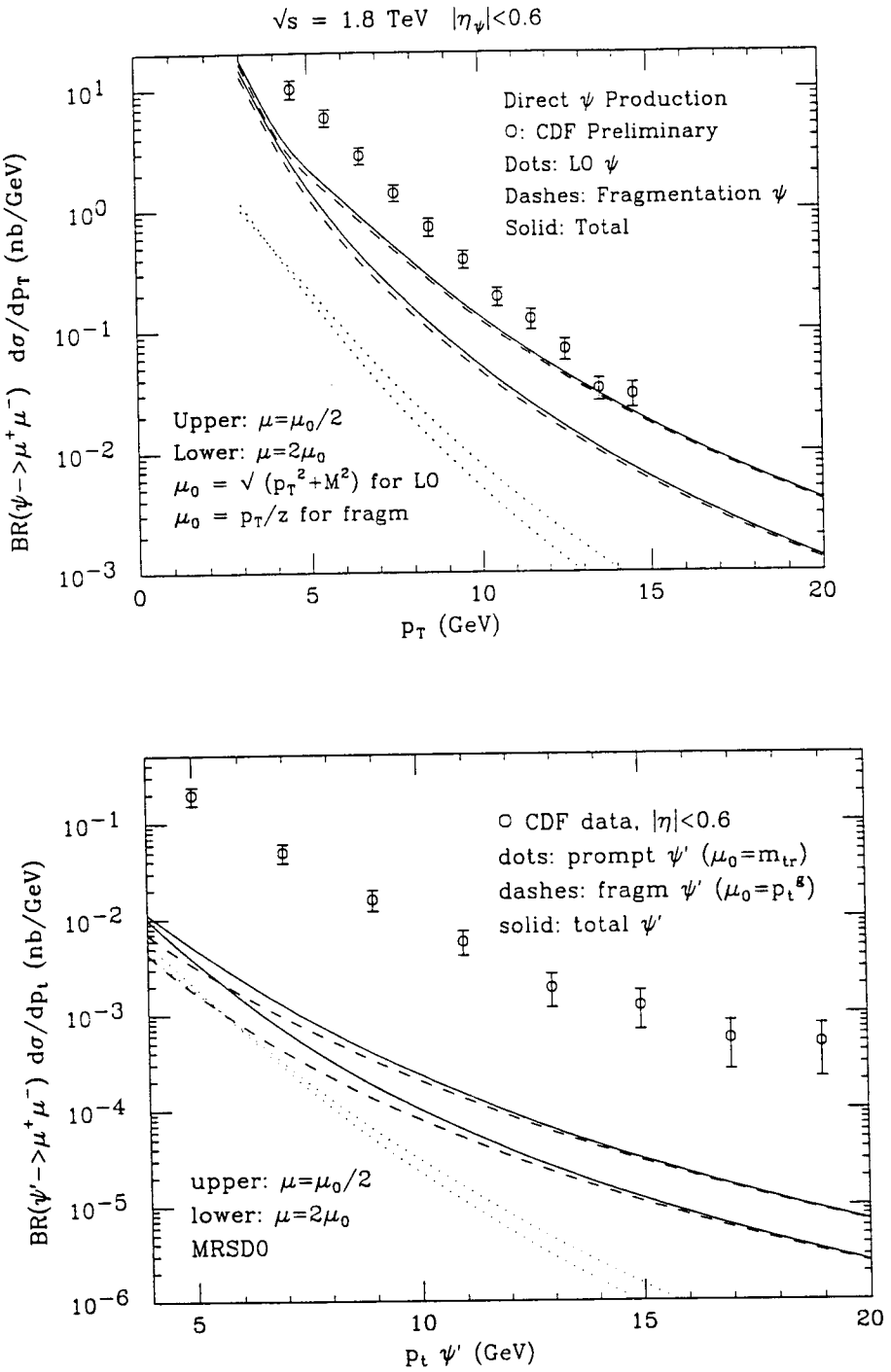

Figure 5: Preliminary CDF data for prompt J/ψ and ψ' production compared with theoretical predictions of the total fragmentation contribution (solid curves) and the total leading-order contribution (dashed curves) (from ref. [26]).

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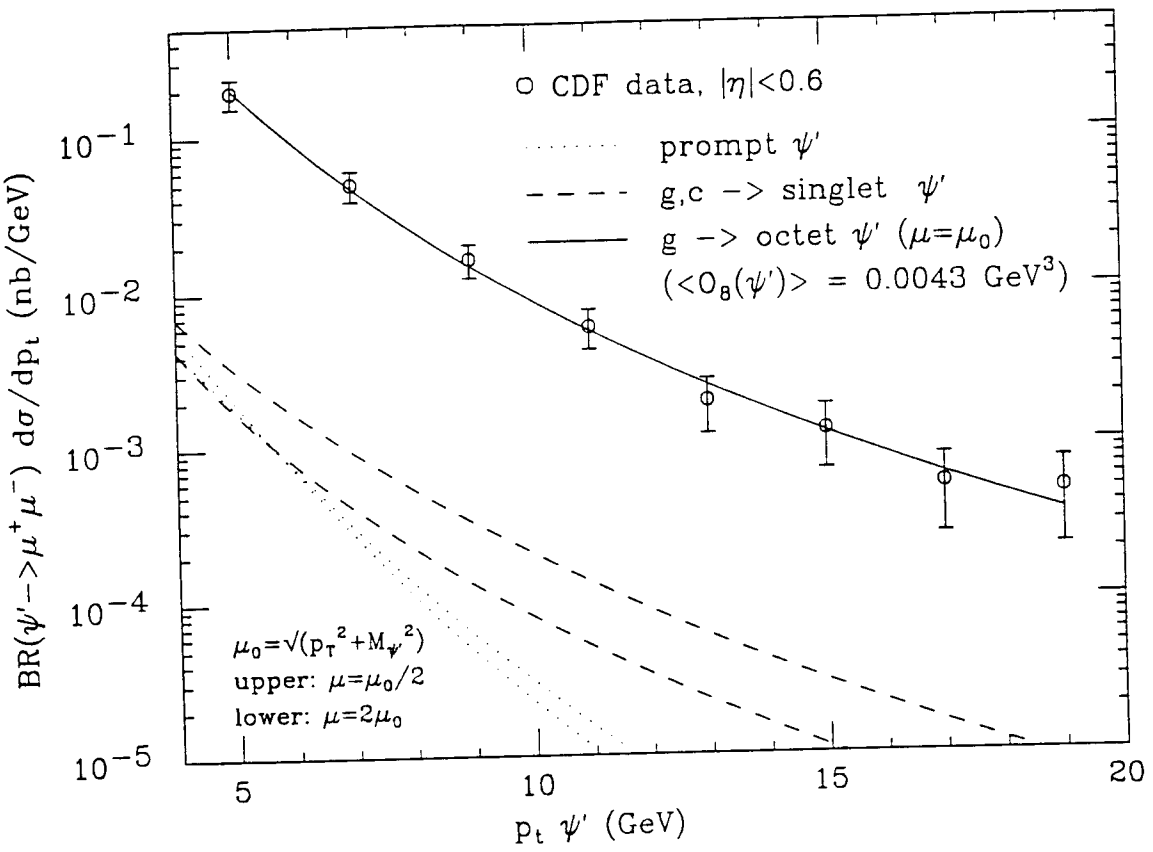

Figure 3: Inclusive prompt ψ' p_T distribution. CDF data versus theory. We show the contribution of the different sources. Dotted lines: LO production in the CSM; dashed lines: gluon and charm fragmentation in the CSM; solid line: gluon fragmentation in the colour octet mechanism.

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Beyond NLO Calculations

- NLO calculations constitute the current standard for most QCD/EW comparisons with data
- Are they sufficient? (It depends on the observable!)
- What effects are missing and how can they be included?
- Resummation

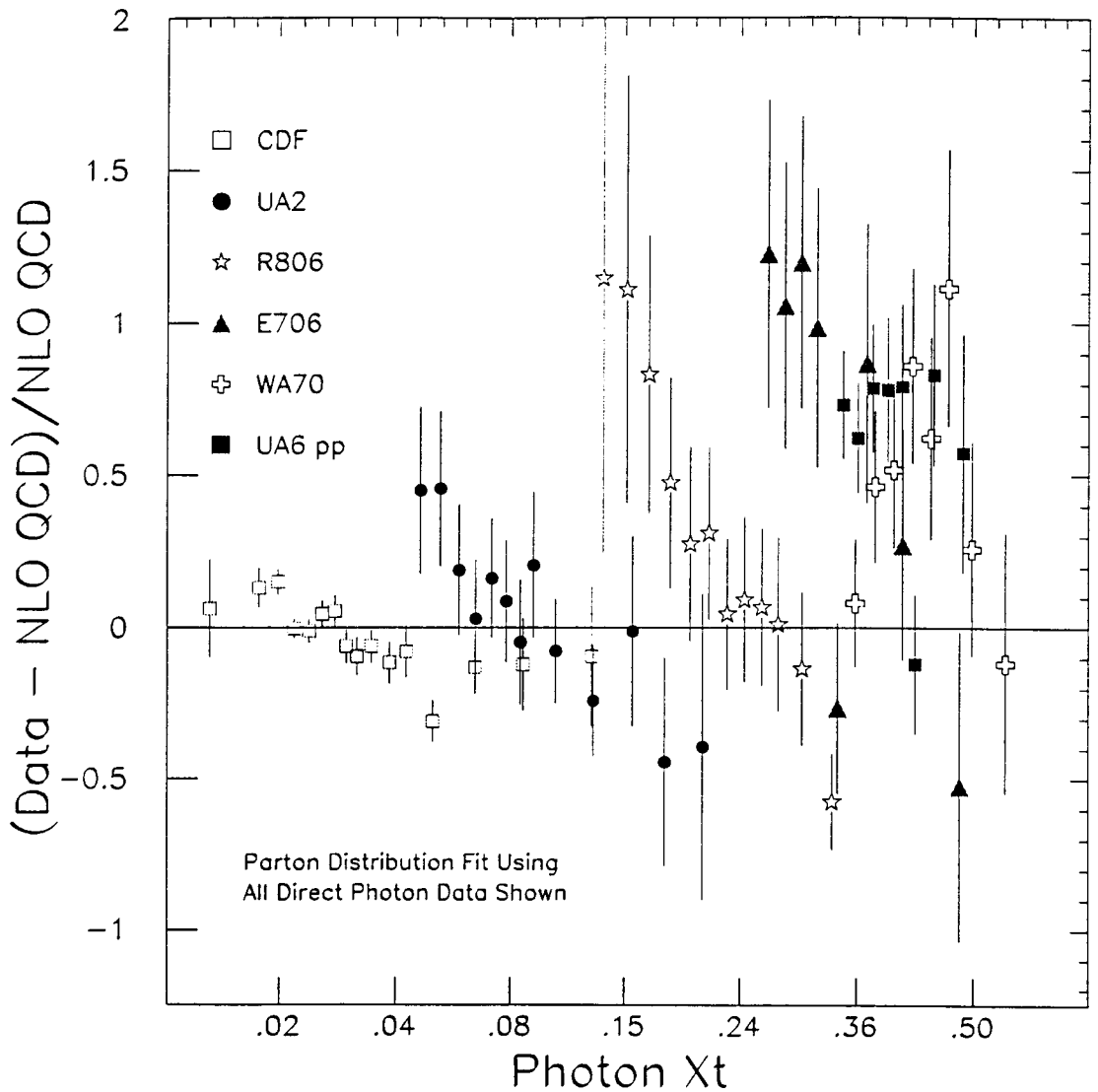
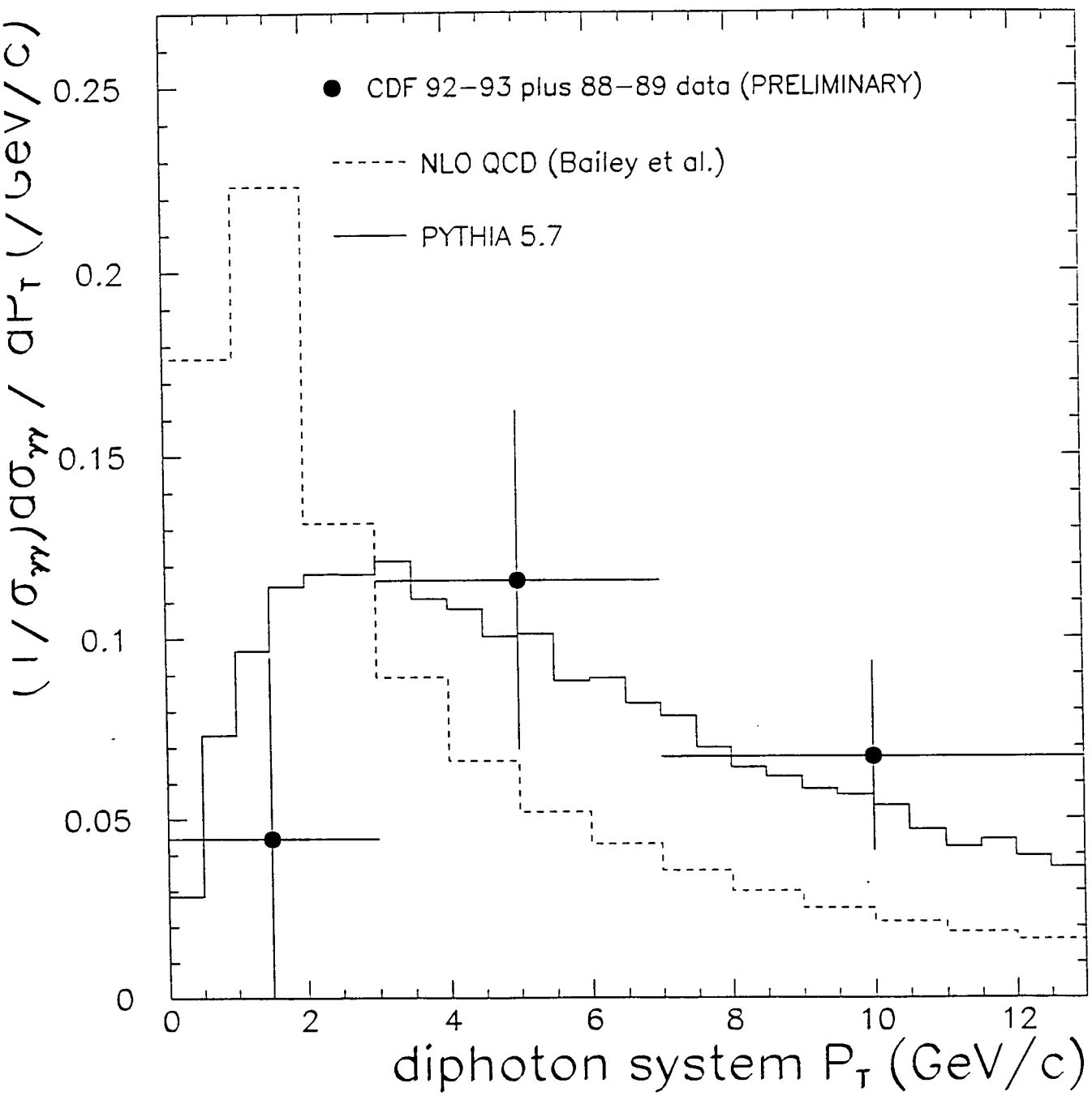


Figure 5: Compilation of direct photon experiments compared to a NLO QCD prediction using parton distributions fit using all the data shown. (see text)


CDF 92–93 plus 88–89 data (PRELIMINARY)
NLO QCD (Bailey et al.)
PYTHIA 5.7
$(1/\sigma_{\gamma\gamma})d\sigma_{\gamma\gamma}/dP_T$ (/GeV/c)
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12
diphoton system P_T (GeV/c)

Perturbative - Nonperturbative Interface

- Double parton scattering?
- QCD in nucleus-nucleus collisions
- Why is BFKL interesting?
- Perturbative and lattice QCD

Guiding Questions

- Is the theoretical treatment adequate?
- Are the data (self) consistent?
- What new data could help resolve the discrepancy?
- What new theoretical developments are needed to improve the comparison with the data?