J. Huston
CTEQ Symposium
Nov. 9,1996

How general is the

"k_T problem"?

J. Huston et al, PRD 51, 6139 (1995

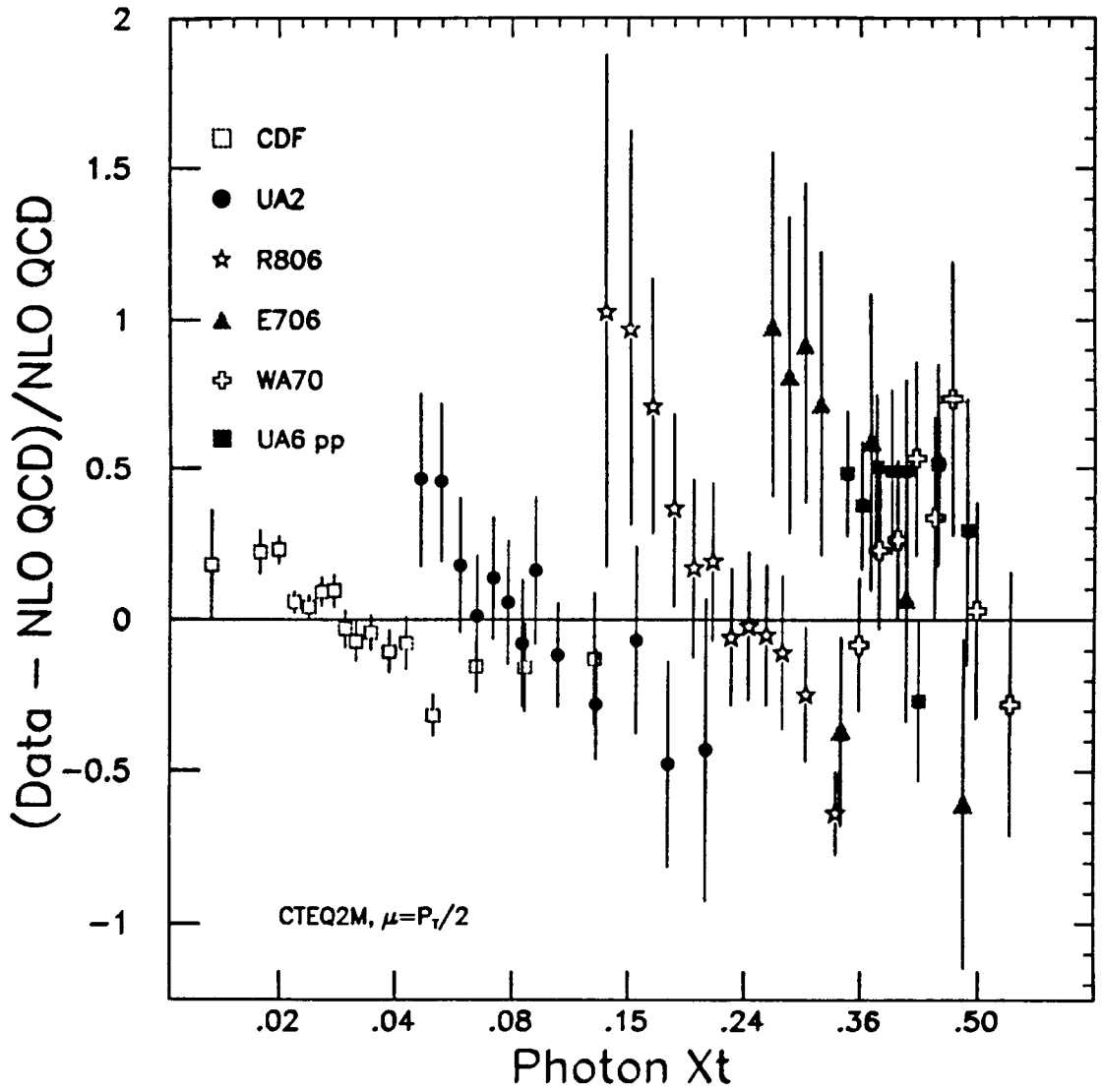
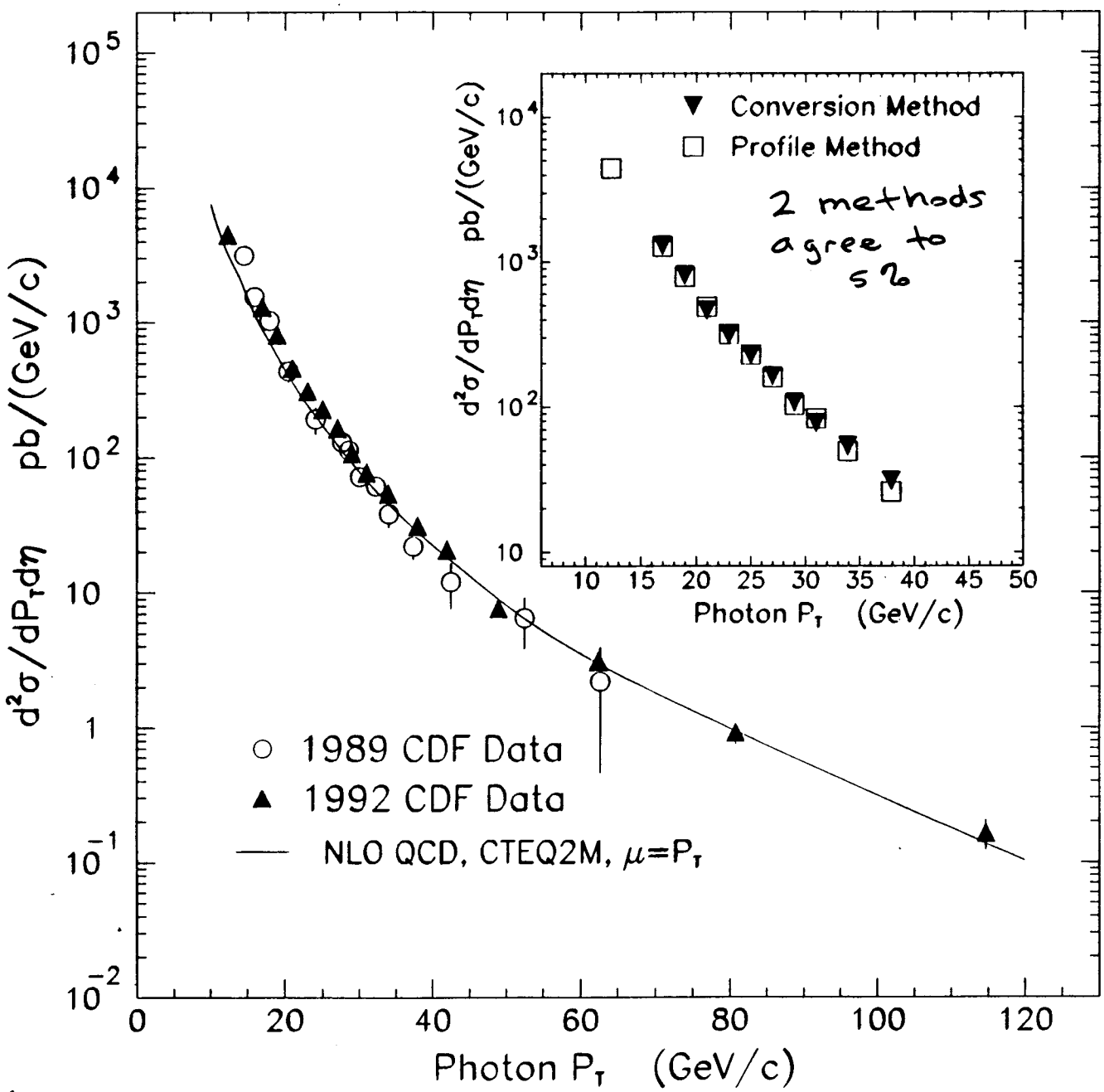
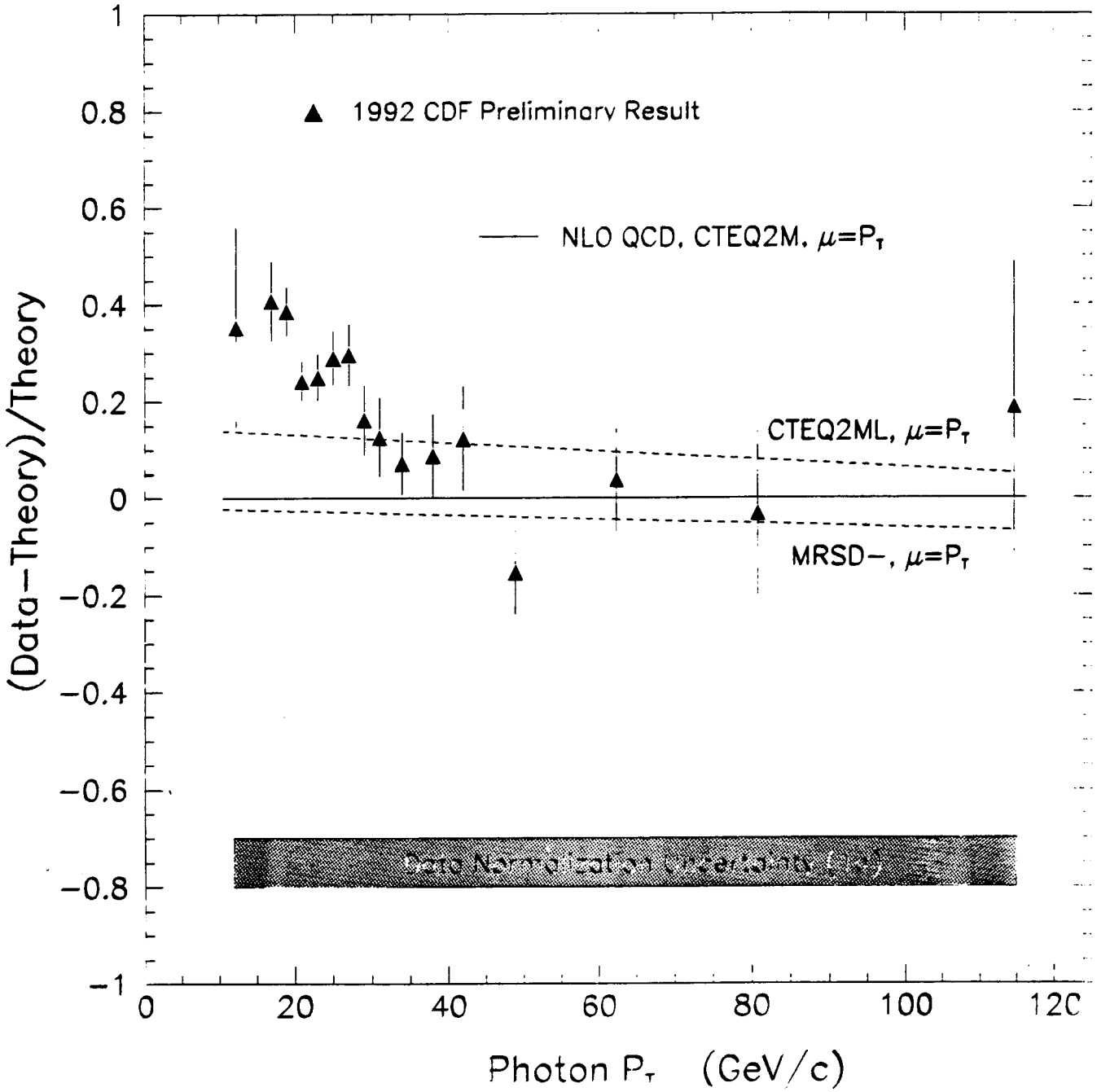


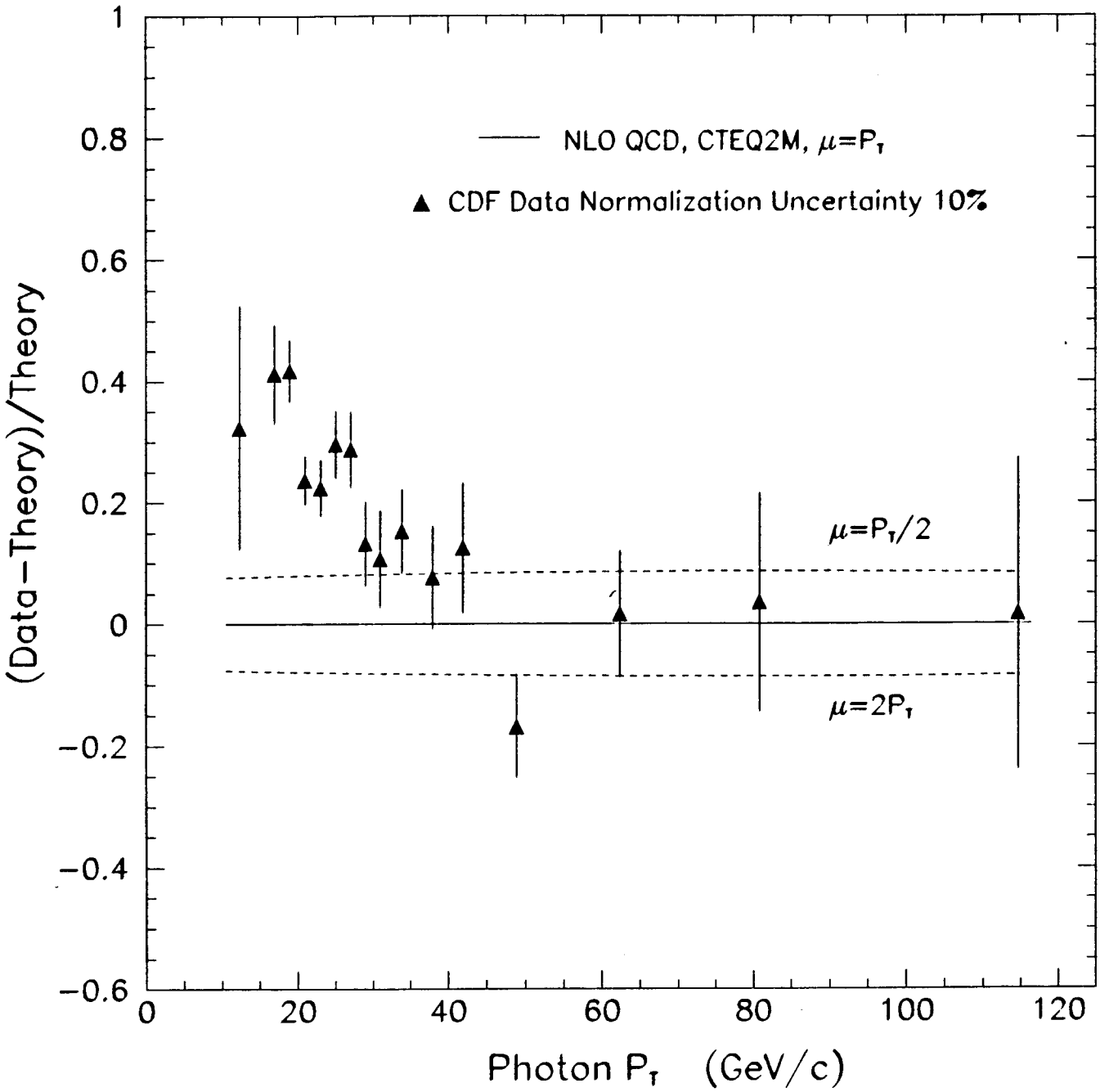
Figure 4: Compilation of direct photon experiments compared to NLO QCD predictions using CTEQ2M parton distributions. (see text)

$|\eta| < 0.9$ Run IA only

- isolation
- no charged track
- no extra photons in CES




1992 CDF Preliminary Result
NLO QCD, CTEQ2M, $\mu=P_T$
CTEQ2ML, $\mu=P_T$
MRSD−, $\mu=P_T$
Data Normalization Uncertainty (3%)
(Data−Theory)/Theory
Photon P_T (GeV/c)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
20
40
60
80
100
120


NLO QCD, CTEQ2M, $\mu=P_T$
CDF Data Normalization Uncertainty 10%
$\mu=P_T/2$
$\mu=2P_T$
(Data−Theory)/Theory
Photon P_T (GeV/c)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
0
20
40
60
80
100
120

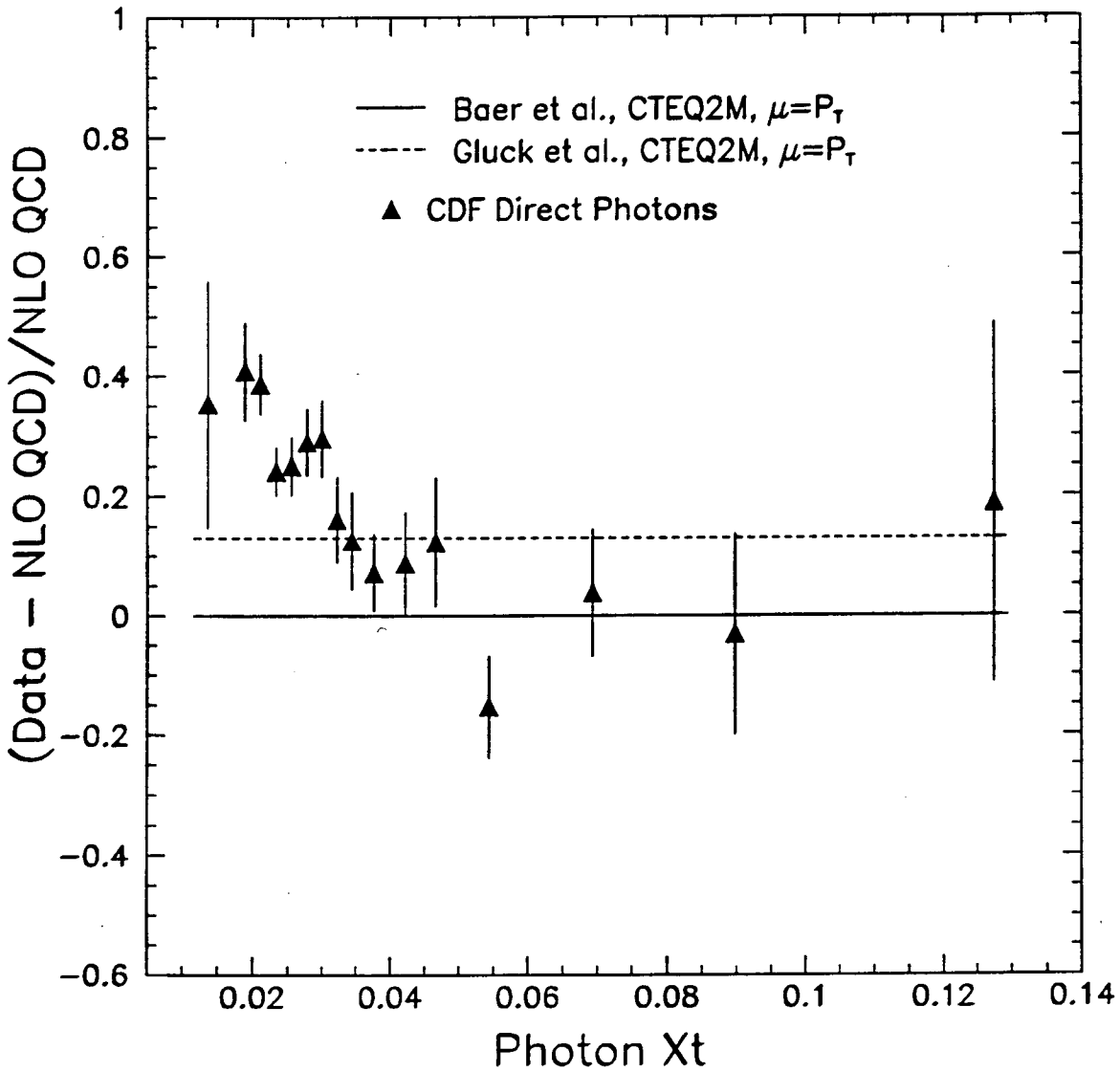
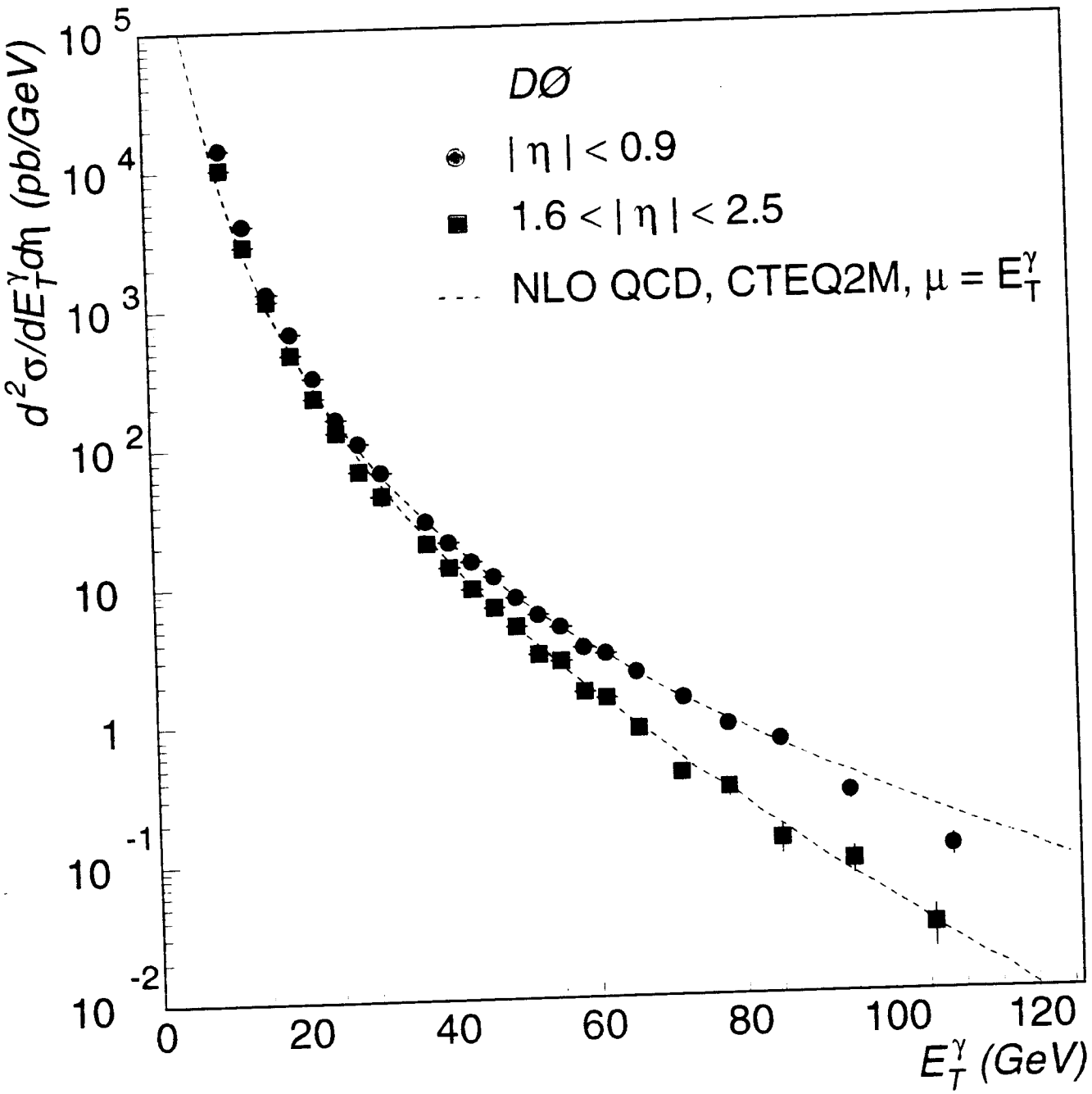
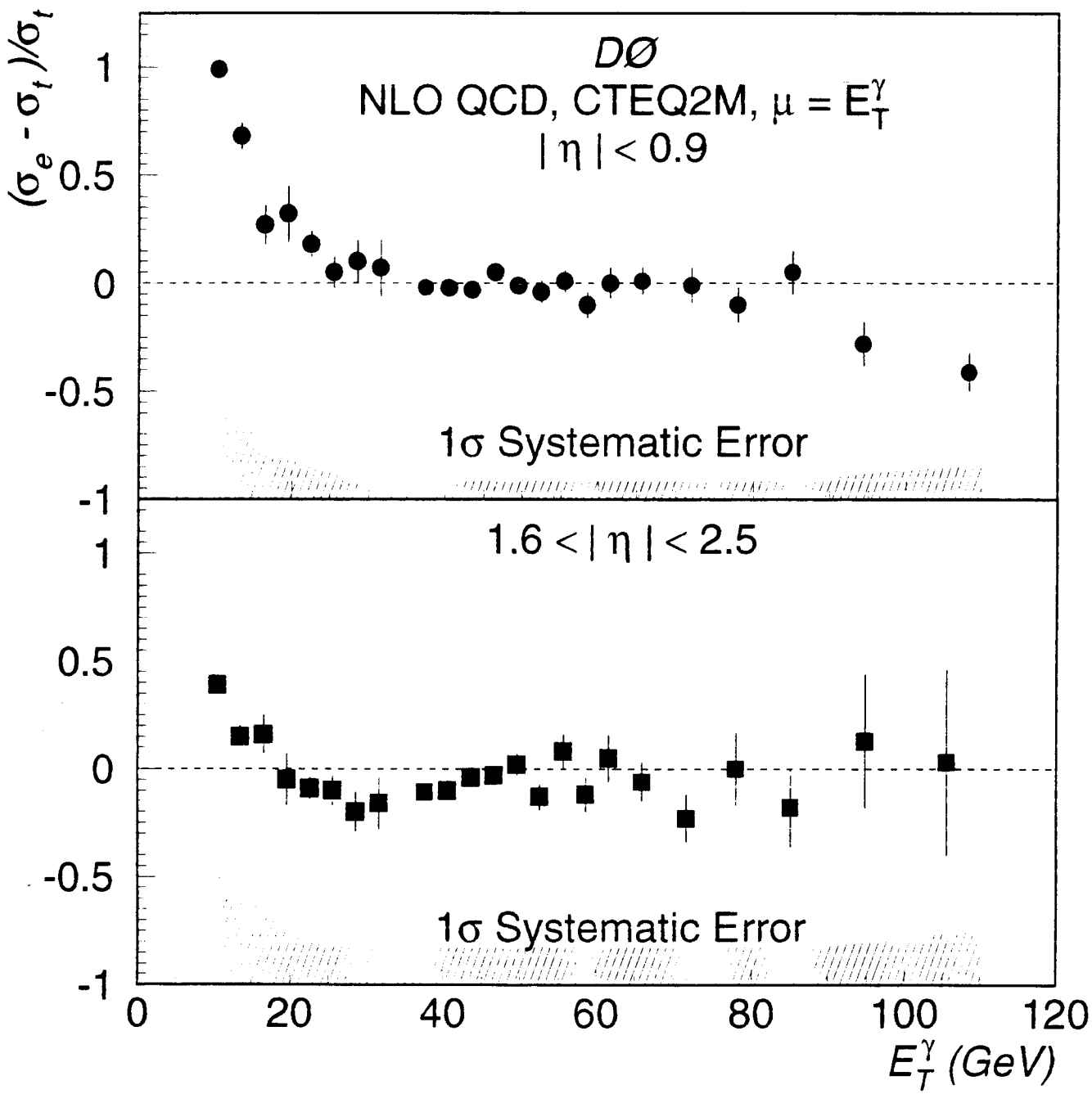


Figure 3: Direct photon data from the CDF experiment is compared to NLO QCD predictions. (see text)

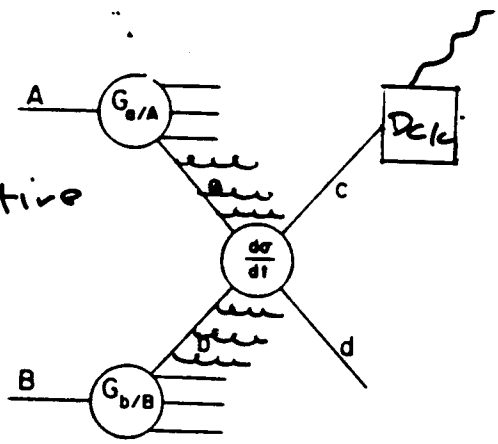

DØ
| η | < 0.9
1.6 < | η | < 2.5
NLO QCD, CTEQ2M, μ = E_T^γ
$d^2\sigma/dE_T^\gamma d\eta$ (pb/GeV)
E_T^γ (GeV)
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
0
20
40
60
80
100
120


DØ
NLO QCD, CTEQ2M, μ = E_T^γ
| η | < 0.9
1σ Systematic Error
1.6 < | η | < 2.5
1σ Systematic Error
$(\sigma_e - \sigma_t)/\sigma_t$
E_T^γ (GeV)
1
0.5
0
-0.5
-1
0
20
40
60
80
100
120

What's missing from a NLO calculation?

~~Intrinsic~~ k_T effects:

- confinement in a proton + other non-perturbative effects
- multiple soft gluon emission
  - ↳ needs resummation
    - ⇒ or run a MC like Pythia



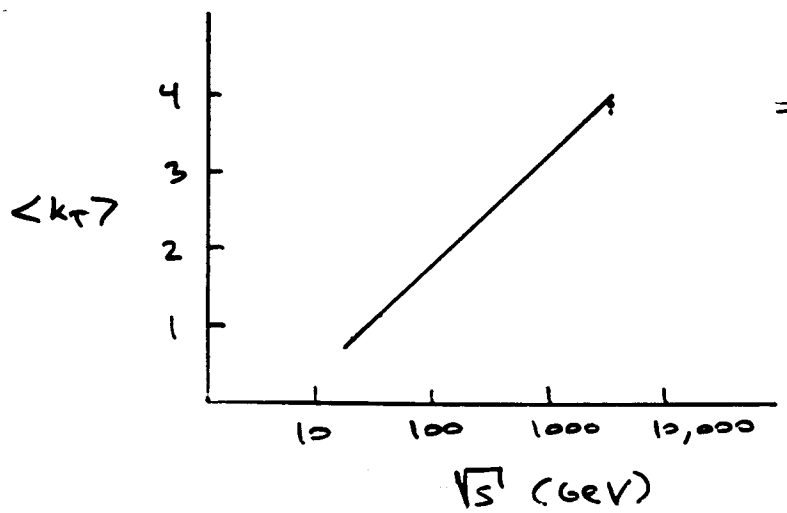
$$E_C = \frac{d\sigma}{d^3p_C}(AB \to C + X) = \sum_{abcd} \int dx_a dx_b dz_c G_{a/A}(x_a, M_d^2) G_{b/B}(x_b, M_d^2) D_{c/c}(z_c, M_f^2) \frac{\hat{s}}{z_c^2 \pi} \frac{d\sigma}{d\hat{t}}(ab \to cd)\delta(\hat{s} + \hat{t} + \hat{u})$$

$$dx_a G_{a/A}(x_a, Q^2) \to dx_a d^2k_{Ta} f(\mathbf{k}_{Ta}) G_{a/A}(x_a, Q^2), \quad (11)$$

where the distribution $f(\mathbf{k}_{Ta})$ is taken to be of the form

$$f(\mathbf{k}_{Ta}) = \frac{e^{-k_T^2/\langle k_T^2 \rangle}}{\pi \langle k_T^2 \rangle}, \quad (12)$$

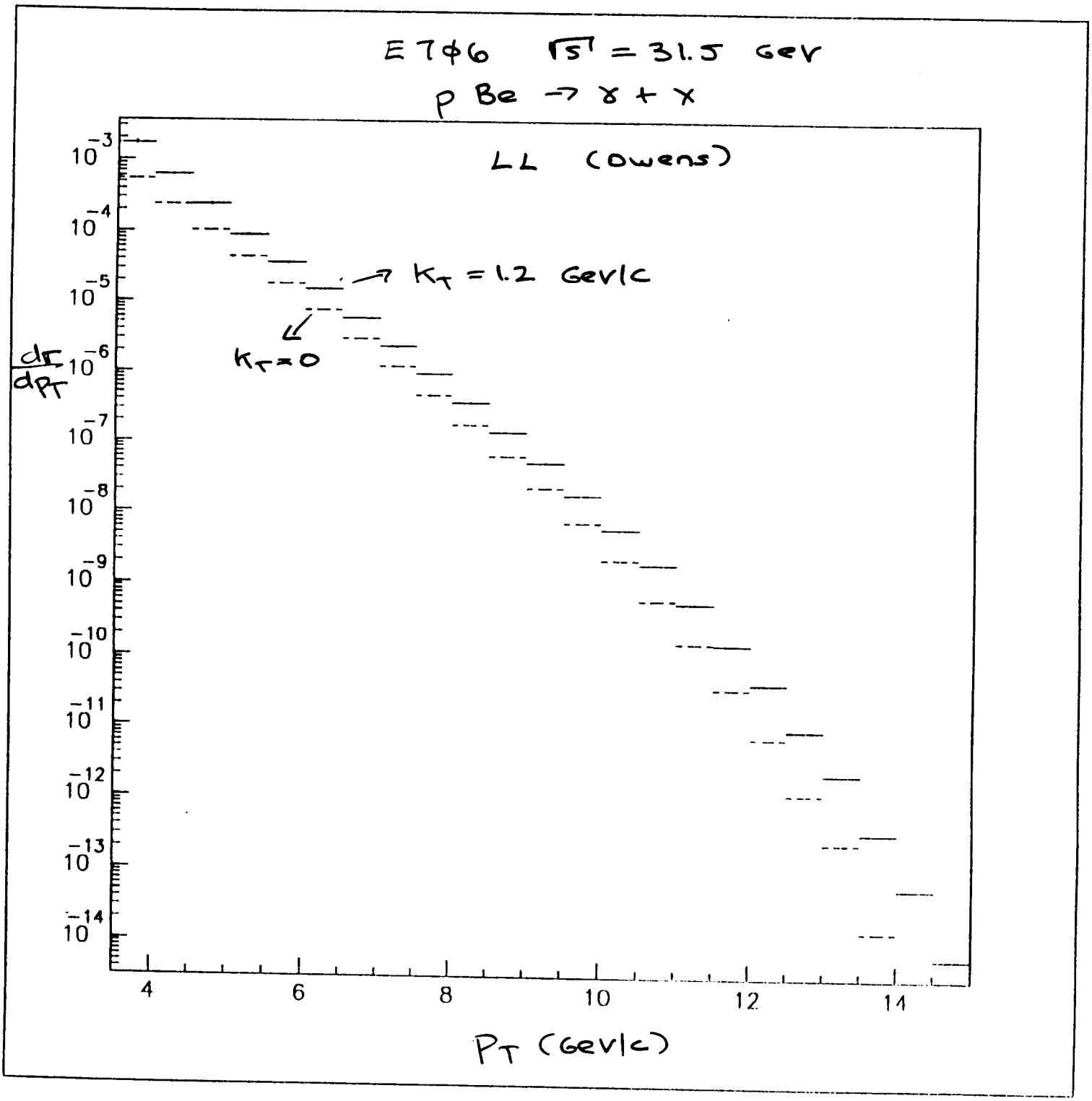
+ similar for $G_{b/B}$

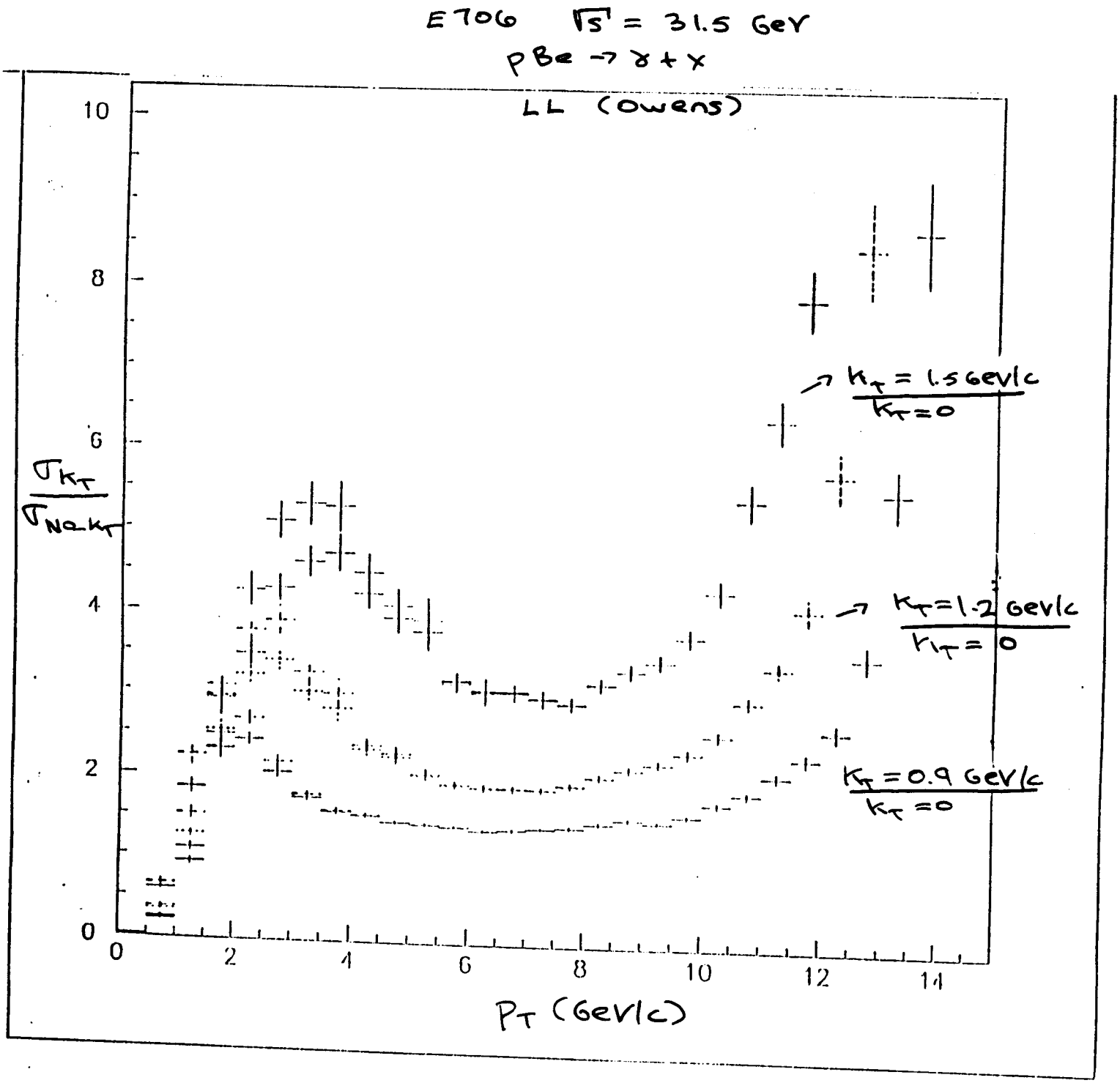


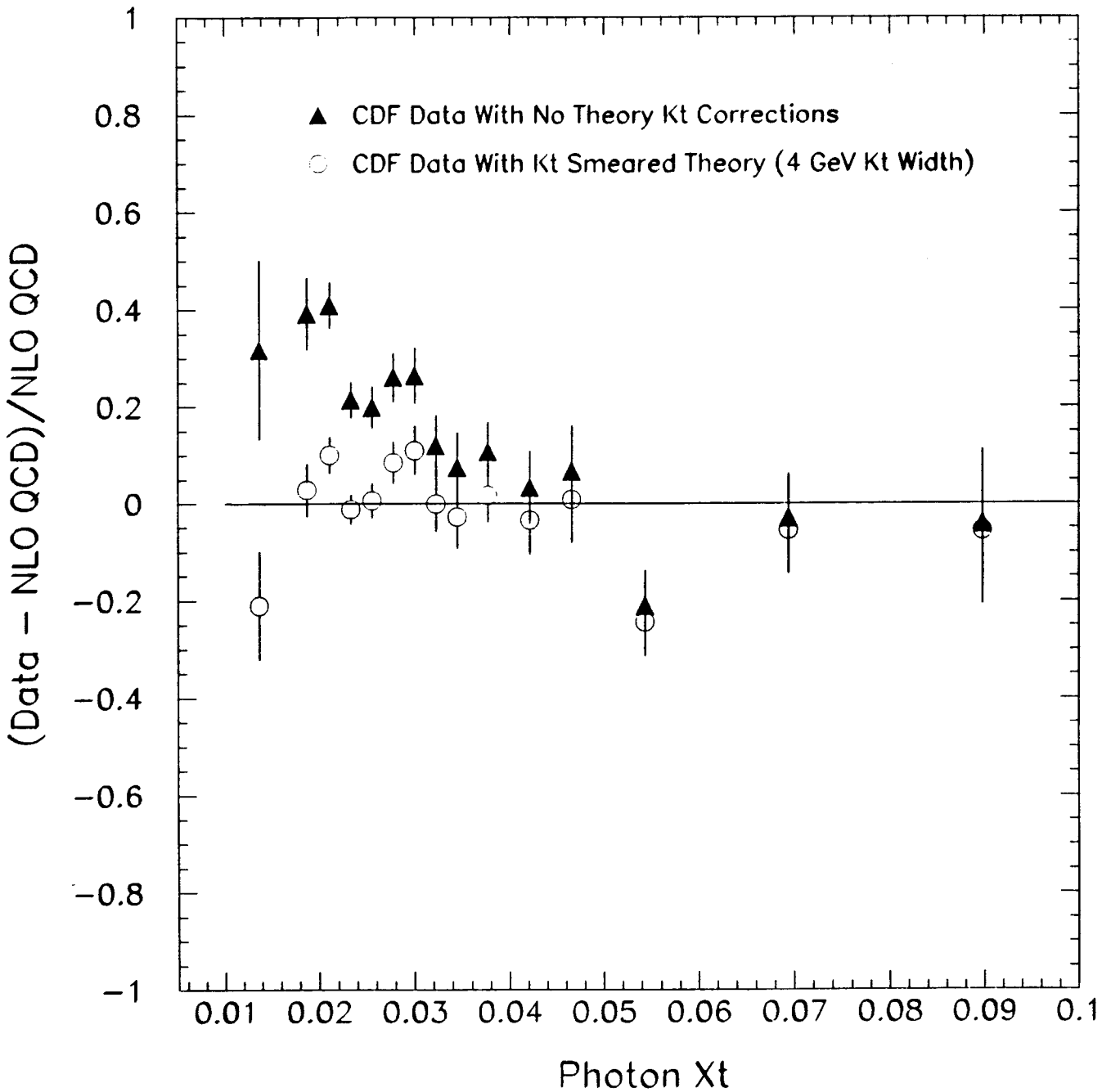
$$\Rightarrow \frac{\sigma_{k_T}}{\sigma_{NO\,k_T}} \sim 1 + \frac{\langle k_T \rangle^2 n(n+1)}{4 p_T^2}$$

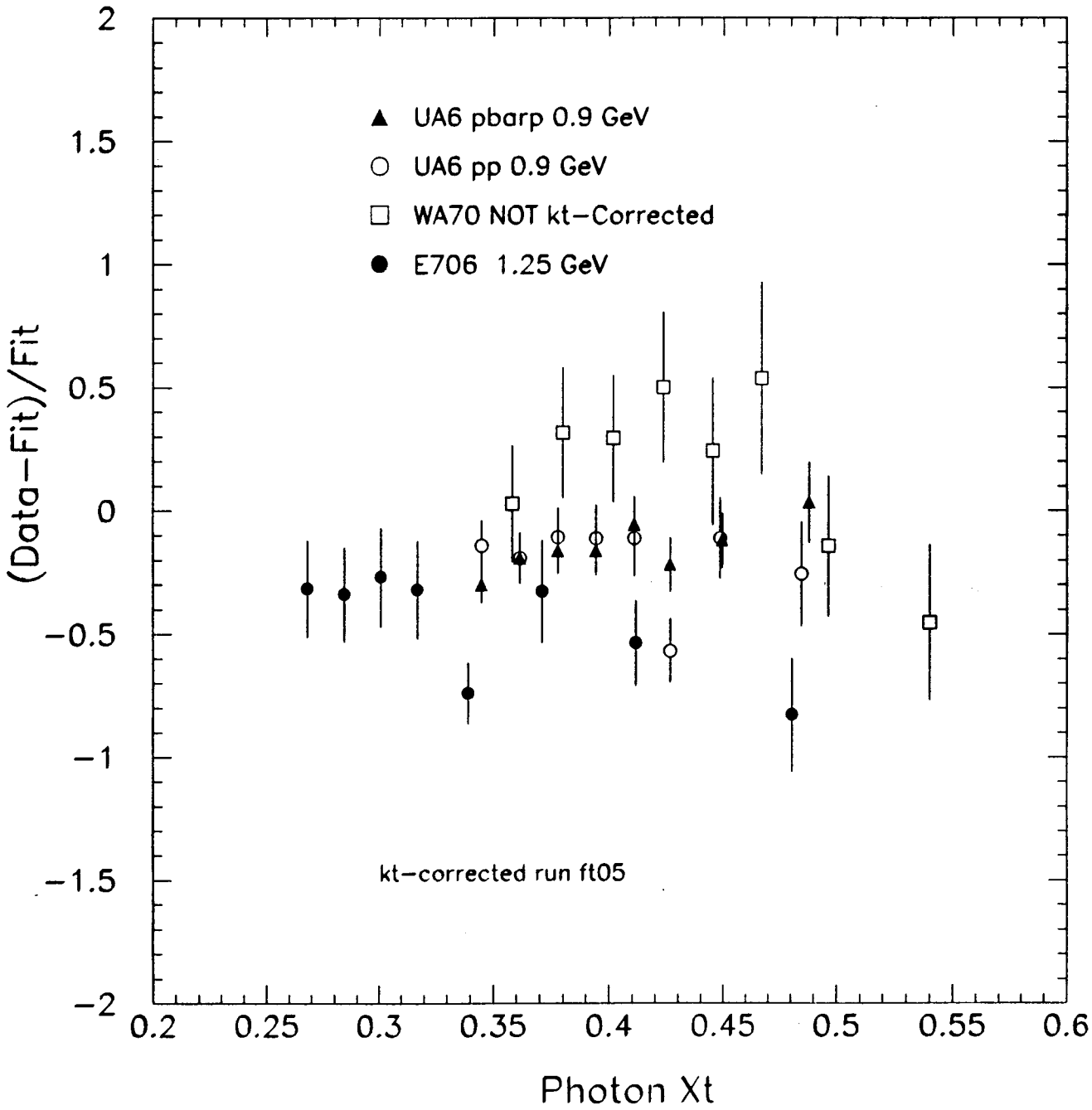
where $\frac{d\pi}{dp_T} \propto \frac{1}{p_T^n}$

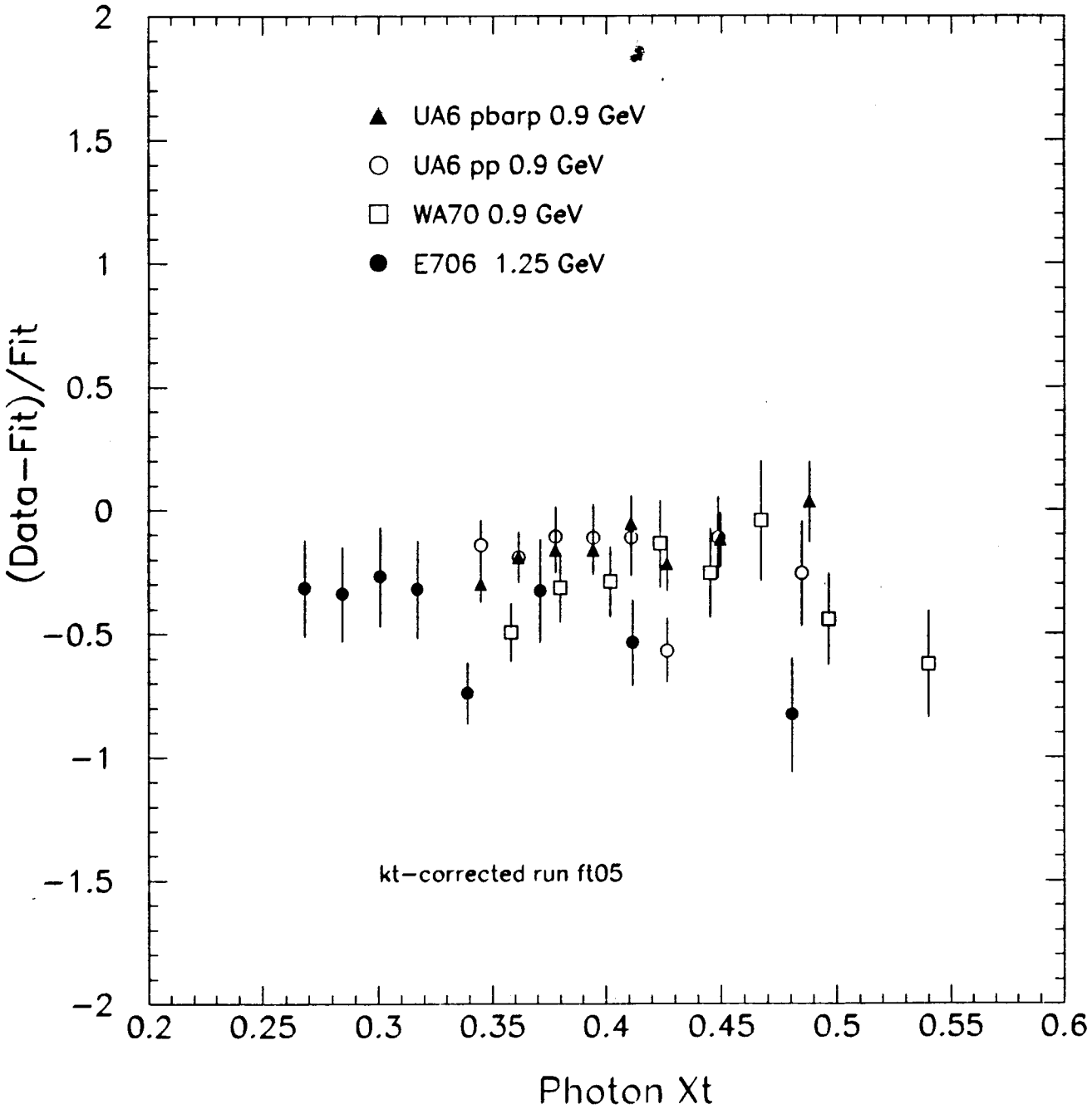
E. Kovacs
D. Soper


E706 $\sqrt{s}$ = 31.5 GeV
p Be → γ + X
LL (owens)
k_T = 1.2 GeV/c
k_T = 0
$\frac{dE}{dP_T}$
P_T (GeV/c)


E706 $\sqrt{s}$ = 31.5 GeV
pBe → γ + X
LL (Owens)
$\frac{\sigma_{k_T}}{\sigma_{NO\,k_T}}$
$k_T = 1.5$ GeV/c / $k_T = 0$
$k_T = 1.2$ GeV/c / $k_T = 0$
$k_T = 0.9$ GeV/c / $k_T = 0$
P_T (GeV/c)
0
2
4
6
8
10
12
14


CDF Data With No Theory Kt Corrections
CDF Data With Kt Smeared Theory (4 GeV Kt Width)
(Data − NLO QCD)/NLO QCD
Photon Xt
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1


UA6 pbarp 0.9 GeV
UA6 pp 0.9 GeV
WA70 NOT kt−Corrected
E706 1.25 GeV
kt−corrected run ft05
(Data−Fit)/Fit
Photon Xt
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6


UA6 pbarp 0.9 GeV
UA6 pp 0.9 GeV
WA70 0.9 GeV
E706 1.25 GeV
kt−corrected run ft05
(Data−Fit)/Fit
Photon Xt
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6

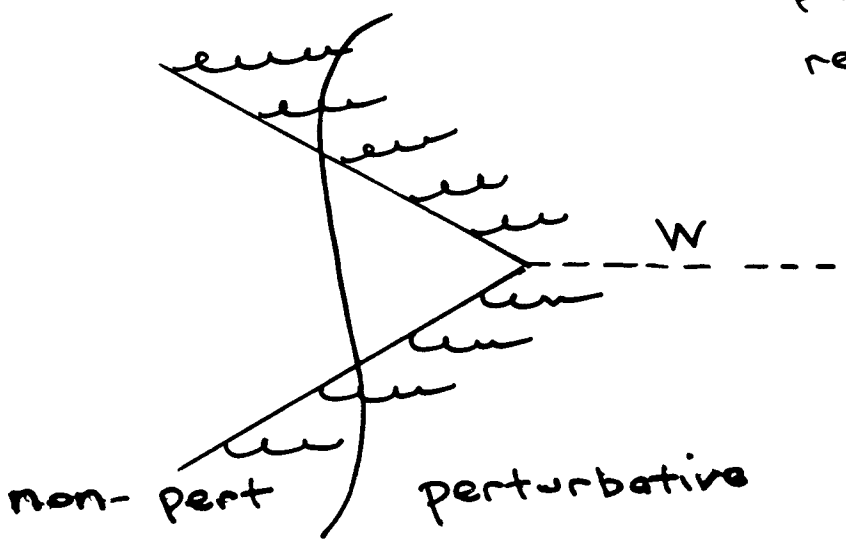
Resummation

Example : W production

$$\frac{d\sigma}{d p_T} \sim F_{q/h}(x, Q^2) \otimes e^{-S_p(Q^2, k_T^2)} \otimes e^{-S_{NP}(Q^2, k_T^2)} \otimes F_{\bar{q}/h}(x, Q^2) \otimes \sigma_{hard}$$

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

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



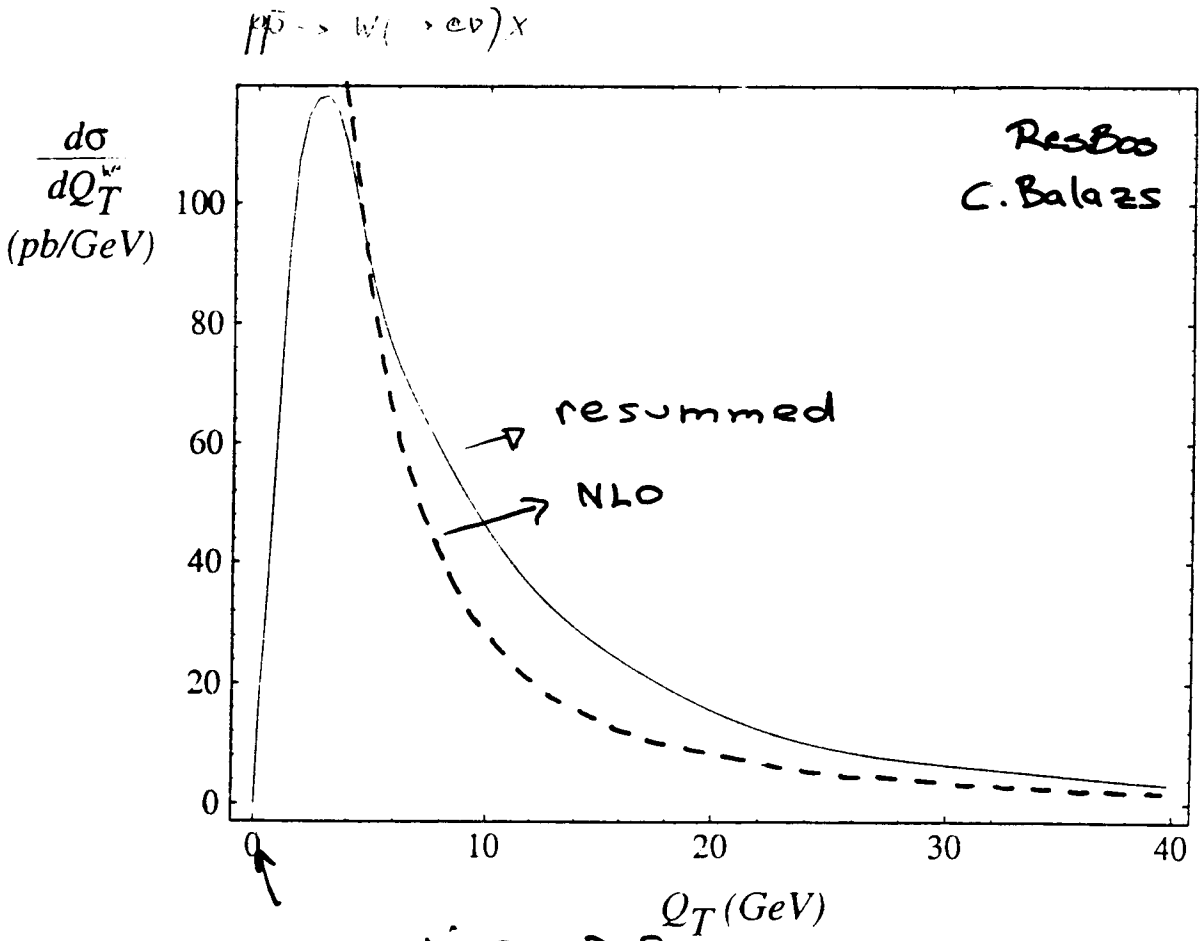
$e^{-k_T^2/\sigma^2}$

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

S_{NP} is universal can be determi from Drell-Yan Ladinsky, Yuan

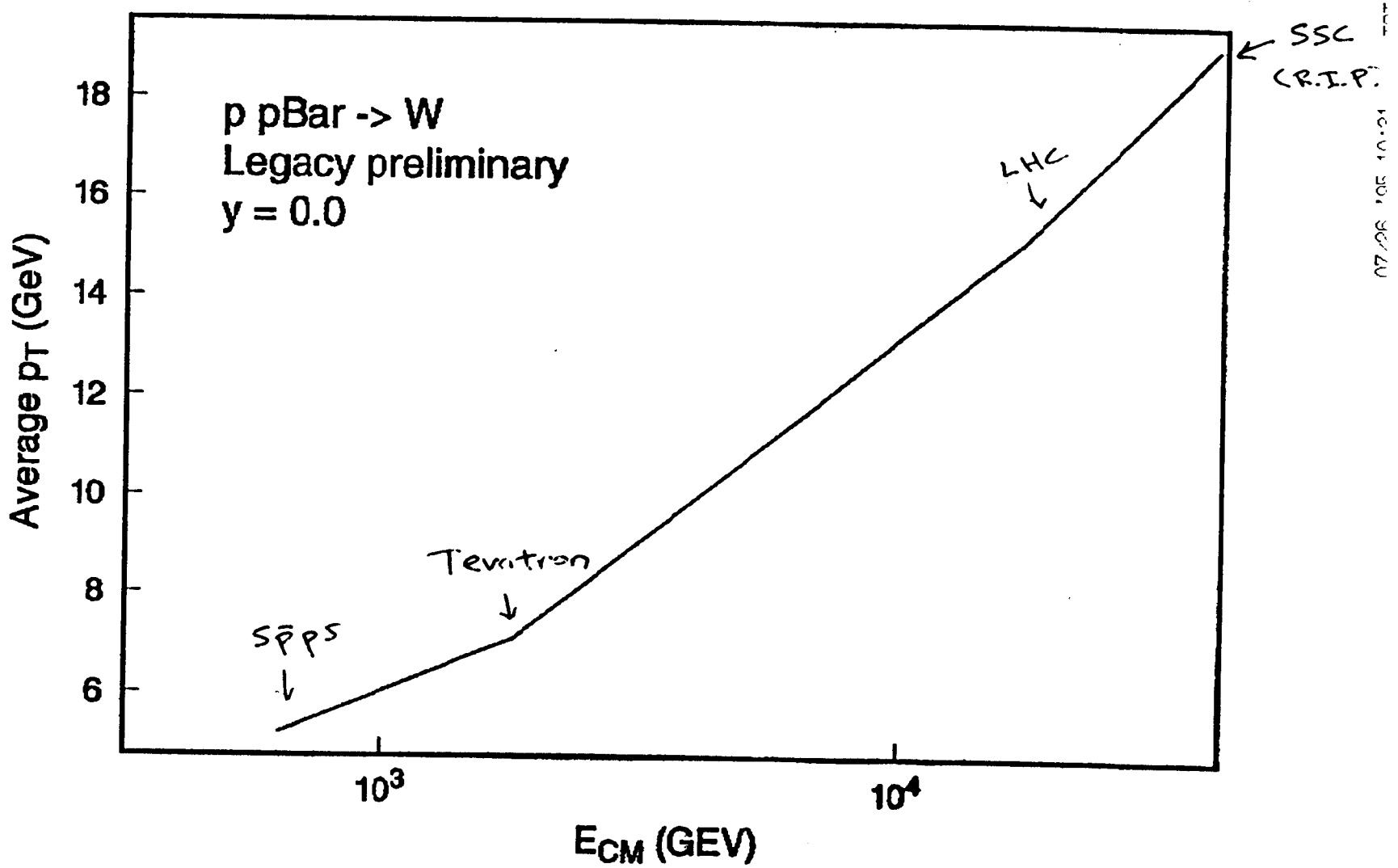
$g_1 = 0.11^{+.04}_{-.03}$ GeV

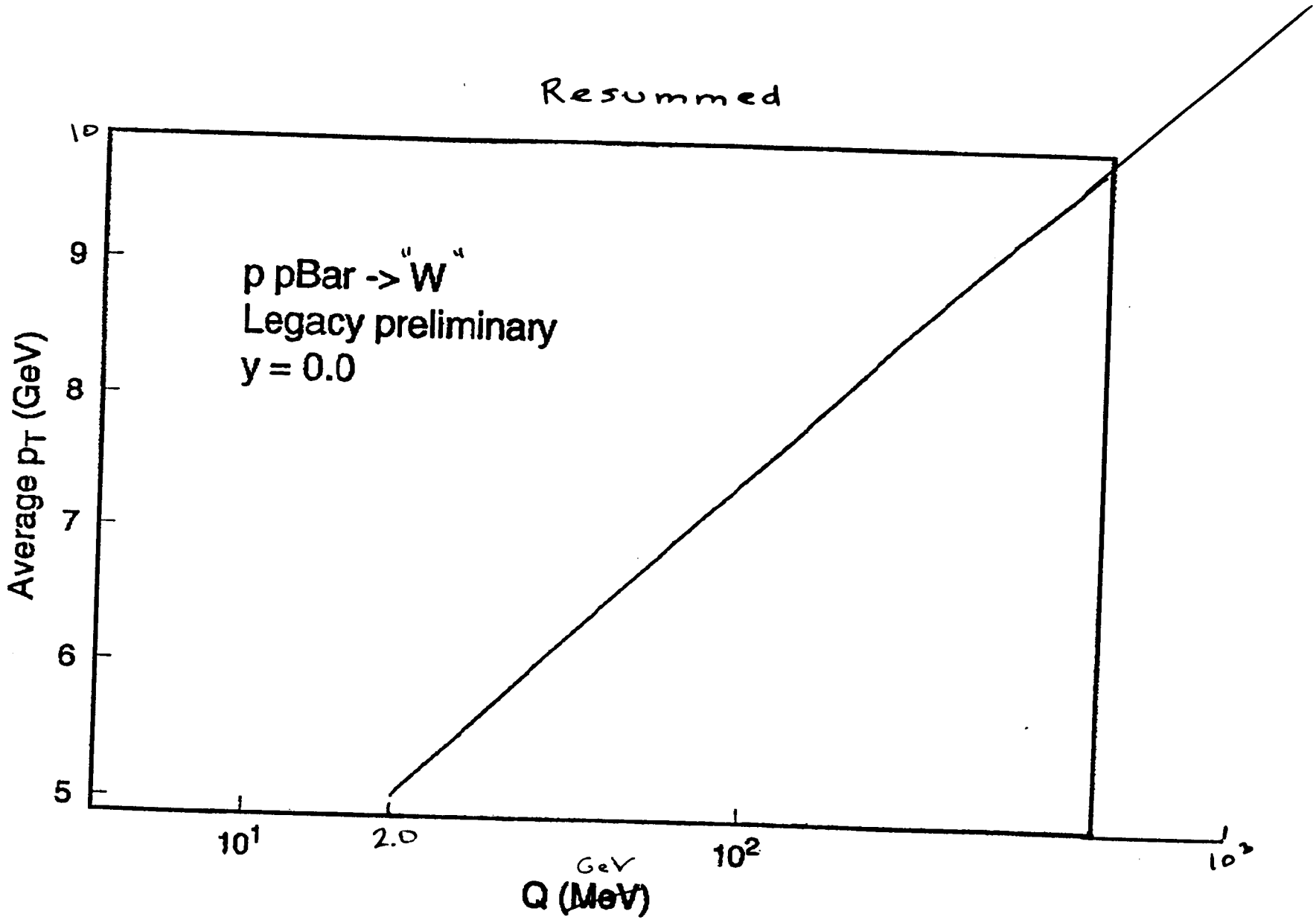
$g_2 = 0.58^{+0.1}_{-0.2}$ GeV

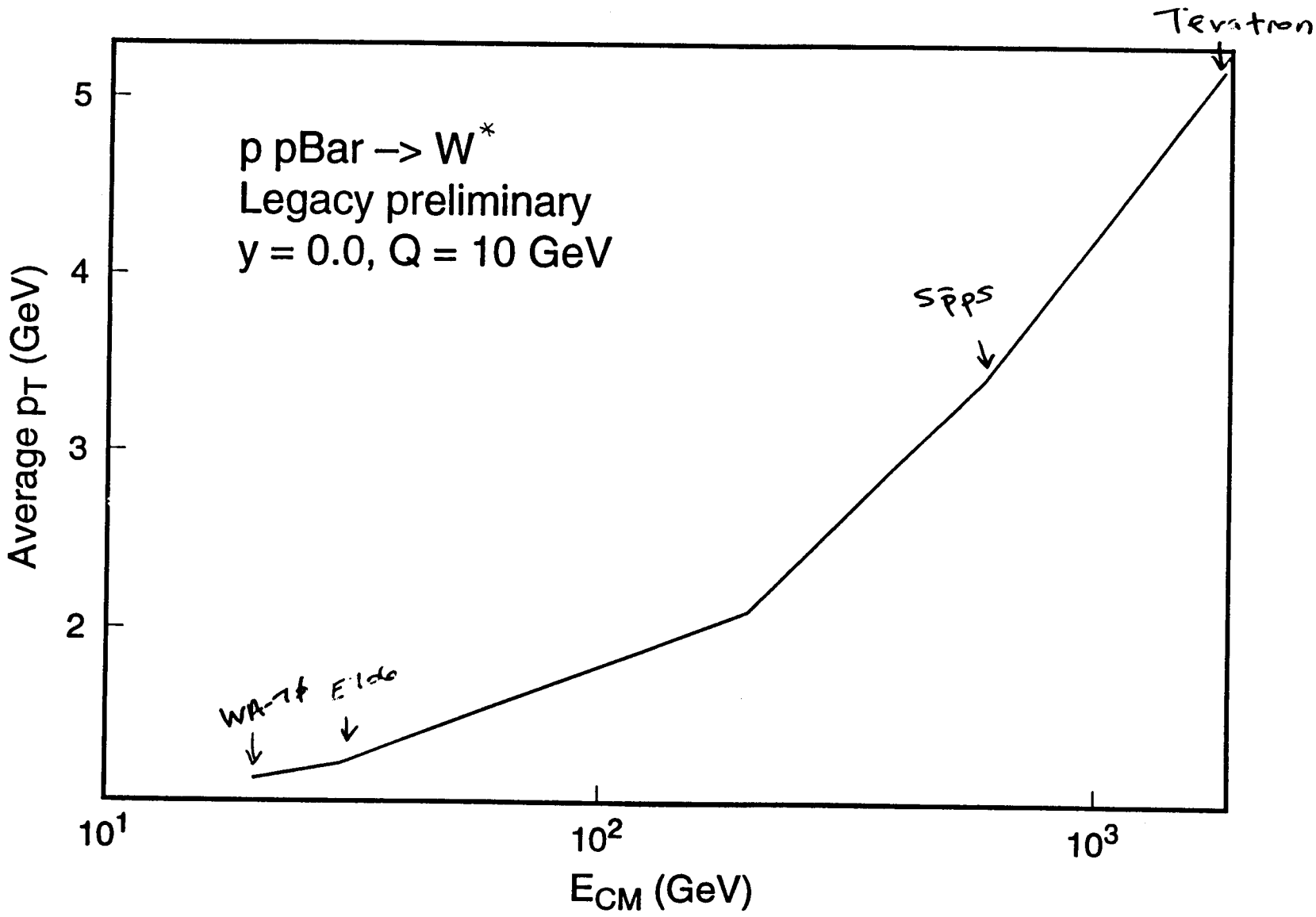


negative δ-fn
from virtual corrections
added to NLO piece

Resummed calculation (C. Balazs, C.P. Yuan)




Resummed
p pBar -> "W"
Legacy preliminary
y = 0.0
Average p_T (GeV)
10
9
8
7
6
5
10^1
2.0
GeV
10^2
10^3
Q (MeV)



p pBar –> W*
Legacy preliminary
y = 0.0, Q = 10 GeV
Average p_T (GeV)
E_{CM} (GeV)
5
4
3
2
10^1
10^2
10^3
Tevatron
$S\bar{p}pS$
WA-7
E-106

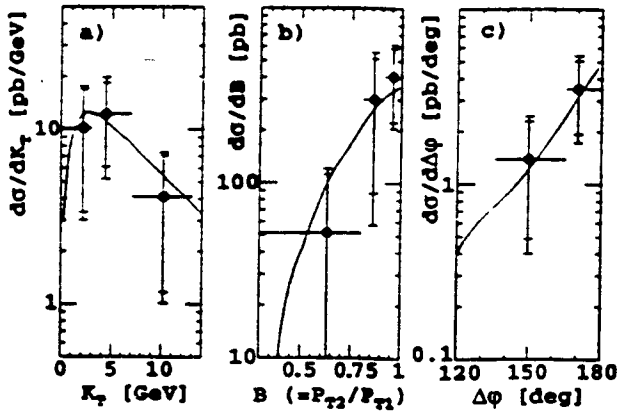


FIG. 3. The correlation of the two photons is shown by the cross section vs (a) the vector sum of the transverse momenta $K_T = |\mathbf{P}_{T1} + \mathbf{P}_{T2}|$, (b) the P_T balance $B = P_{T2}/P_{T1}$, and (c) the azimuthal angular separation $\Delta\phi = \phi_2 - \phi_1$. Our measurement is compared with a Monte Carlo prediction normalized to the data.

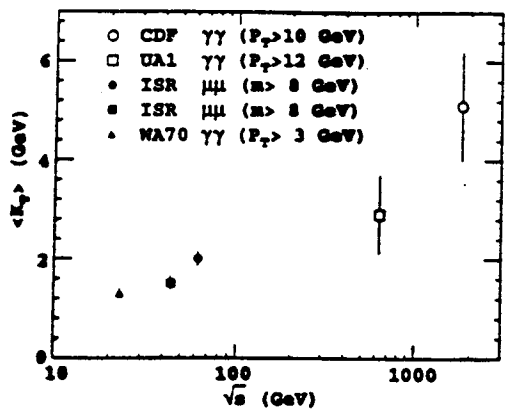


FIG. 4. The mean value of K_T vs collision energy measured in diphoton events at CDF, UA1 [9], and WA70 [1] and in high mass dimuon events at the CERN ISR [10].

may be caused by the roughly increasing P_T of the measurements, also shown in Fig. 4. We have measured $\langle K_T \rangle$ for diphotons with $10 < P_T < 19$ GeV and $0 < K_T < 13$ GeV; measurements with data samples that have enough events to find diphotons at higher P_T and K_T should also find a larger $\langle K_T \rangle$. Significant K_T, which is often not adequately included in QCD calculations, can affect P_T distributions in hadronic collisions.

In summary, we have measured the diphoton cross section to be $86 \pm 27(\text{stat}) {}^{+33}_{-23}(\text{syst})$ pb for photons with P_T in the range 10–19 GeV in events containing two isolated photons with pseudorapidity $|\eta| < 0.9$. We have measured the mean transverse momentum of the diphoton system to be $\langle K_T \rangle = 5.1 \pm 1.1$ GeV. The diphoton differential cross section is roughly 3 times what QCD calculations predict, and may be a larger background to Higgs boson detection than was previously anticipated.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation, the Italian Istituto Nazionale di Fisica Nucleare, the Ministry of Science, Culture and Education of Japan, the Natural Sciences and Engineering Research Council of Canada, and the Alfred P. Sloan Foundation. We also wish to thank B. Bailey, J. F. Owens, and J. Ohnemus for the results of their calculation.

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[a]Visitor.

[1] E Bonvin *et al.*, Phys. Lett. B 236, 523 (1990).
[2] F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 271, 387 (1988).
[3] F. Abe *et al.*, Phys. Rev. D 43, 2070 (1991).
[4] F. Abe *et al.*, Phys. Rev. Lett. 68, 2734 (1992); Fermilab-PUB-92/01-E, 1992 (unpublished).
[5] PYTHIA 5.4 described in H. Bengtsson and T. Sjostrand, Comput. Phys. Commun. 46, 43 (1987), was used to generate events which we passed through a detector simulation when necessary.
[6] B. Bailey, J. F. Owens, and J. Ohnemus, Phys. Rev. D 46, 2018 (1992).
[7] Set B with $\Lambda_{\overline{\text{MS}}} = 190$ MeV in P. N. Harriman *et al.*, Phys. Rev. D 42, 798 (1990).
[8] Set D_0 in A. D. Martin, W. J. Stirling, and R. G. Roberts, Phys. Rev. D 47, 867 (1993).
[9] The K_T was calculated from the data in UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. B 209, 385 (1988).
[10] D. Antreasyan *et al.*, Phys. Rev. Lett. 47, 12 (1981).

Incorporation of soft gluon effects in a NLO calculation

$g\,q \to \gamma\,q$

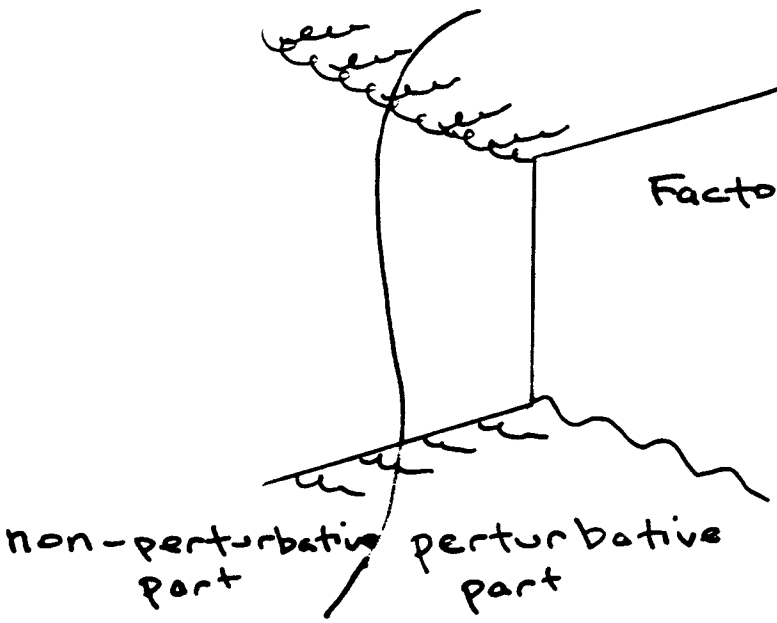
$$\frac{d\sigma}{dp_T} \sim F_{g/h}(x, Q^2) \otimes e^{-S_P(Q^2, k_T^2)} \otimes e^{-S_{NP}(Q^2, k_T^2}$$

S_P: perturbative part of resummation

S_{NP}: non-pert part

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

$S_{NP} \to e^{-k_T^2/\sigma^2}$



$\sigma^2 = g_1 + g_2 \log \frac{Q}{Q_0}$

S_{NP} is universal can be determined from Drell-Yan

Ladinsky, Yuan

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

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

Baer + Reno have incorporated soft gluon radiation into a NLO γ calculation

$S_P \to$ initial state gluon radiation a la Pythia

$S_{NP} \to$ thru Gaussian smearing shown above

$\Rightarrow$ k_T effects + NLO normalization

similar to work on W production

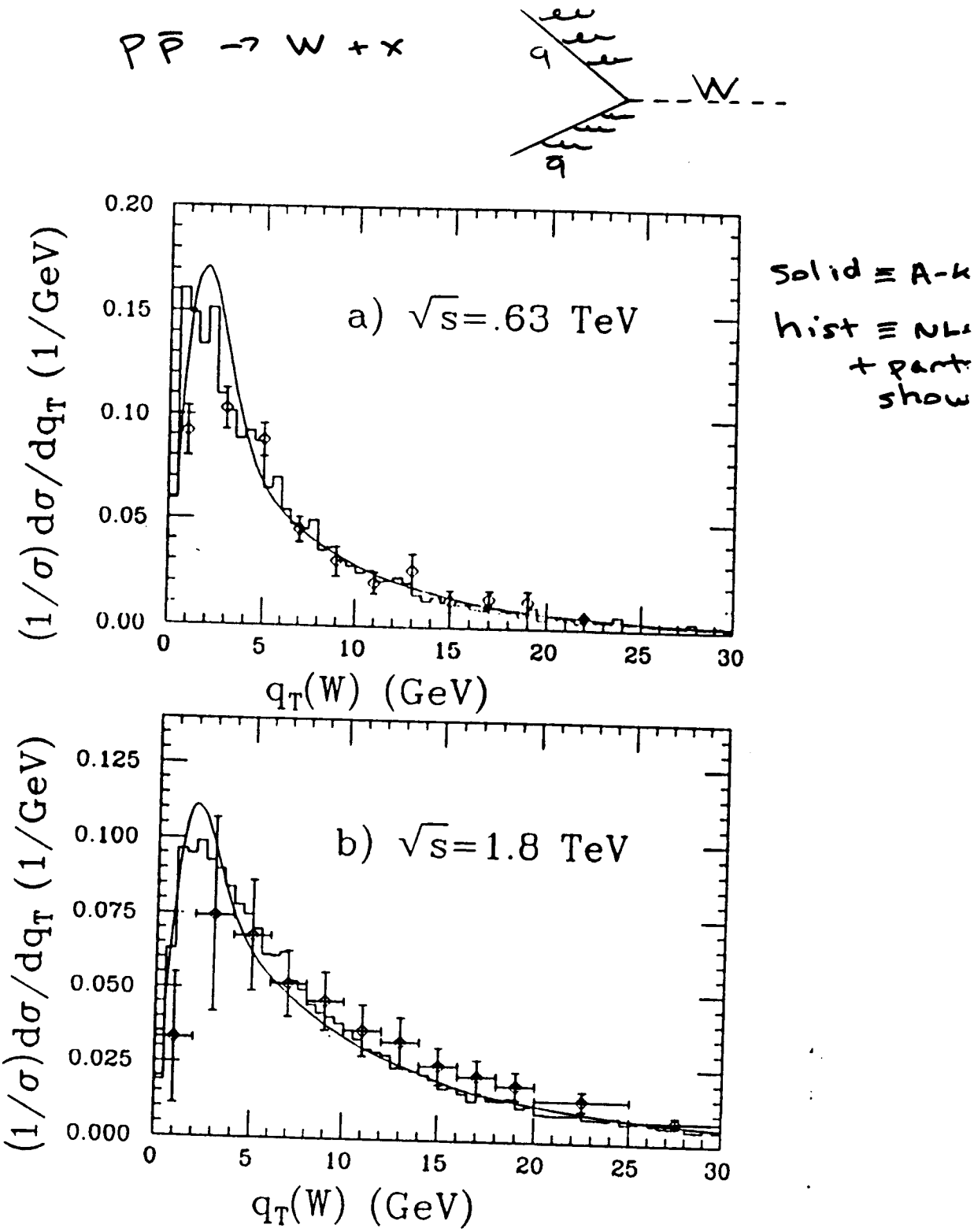
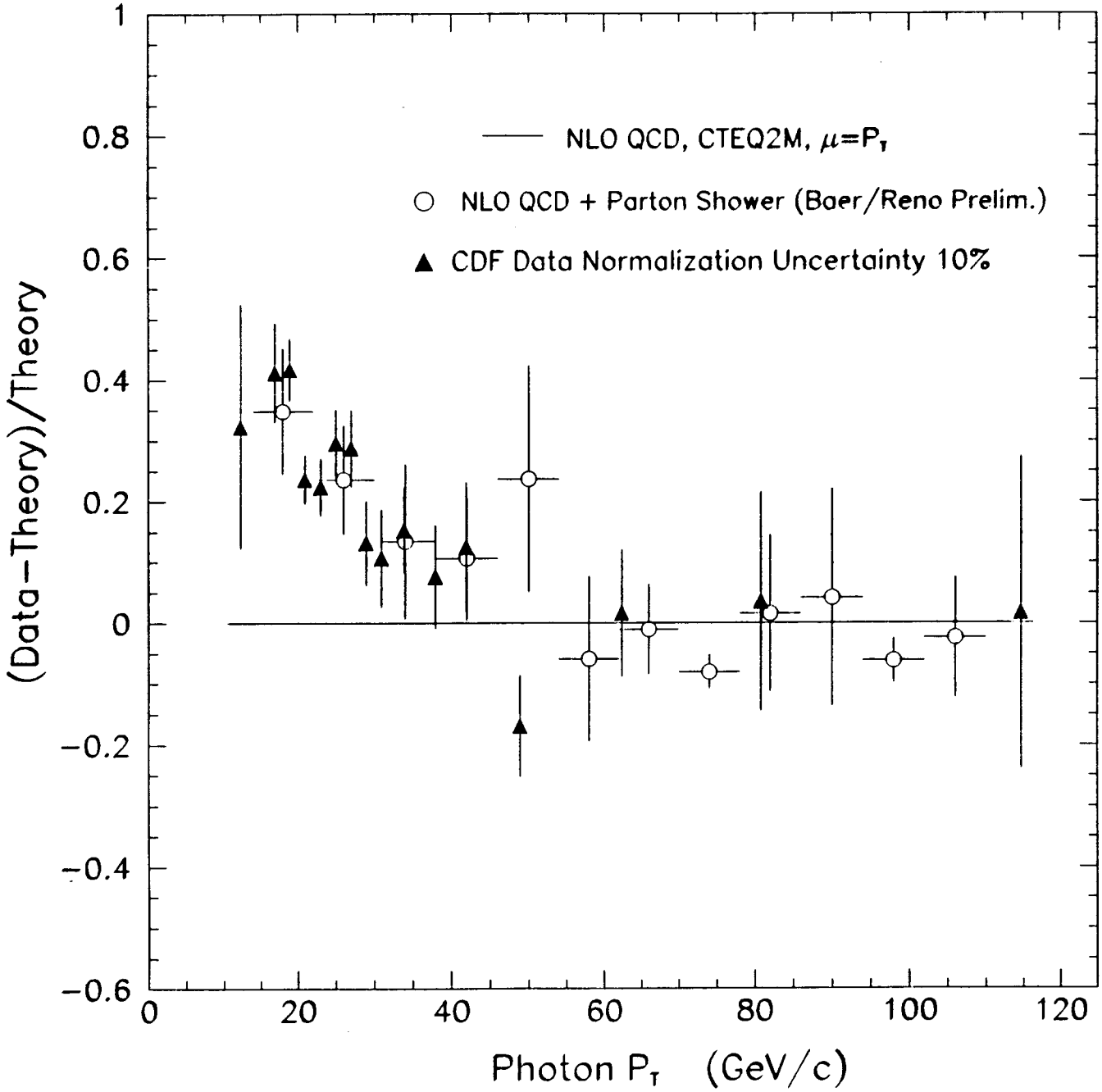
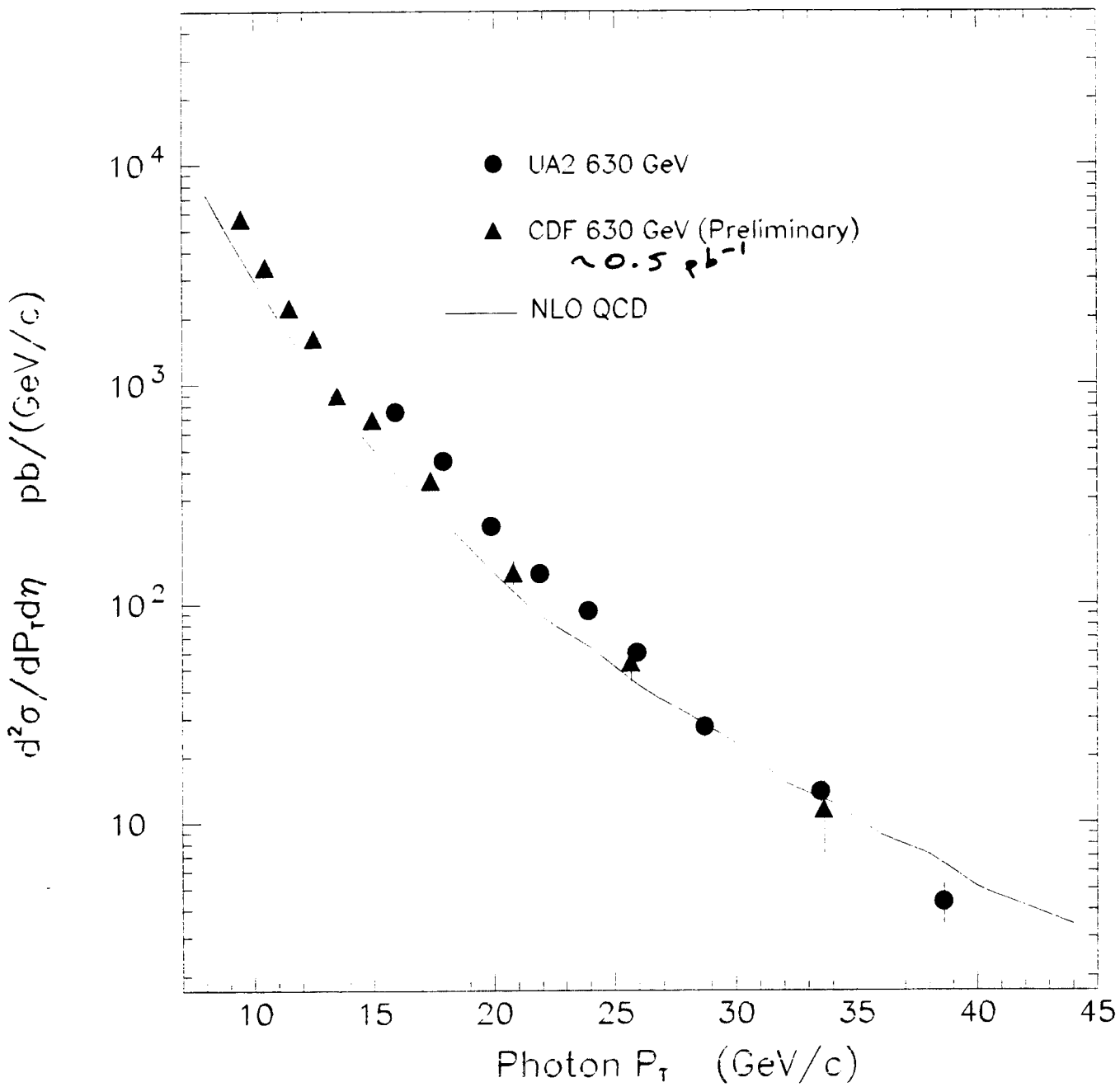
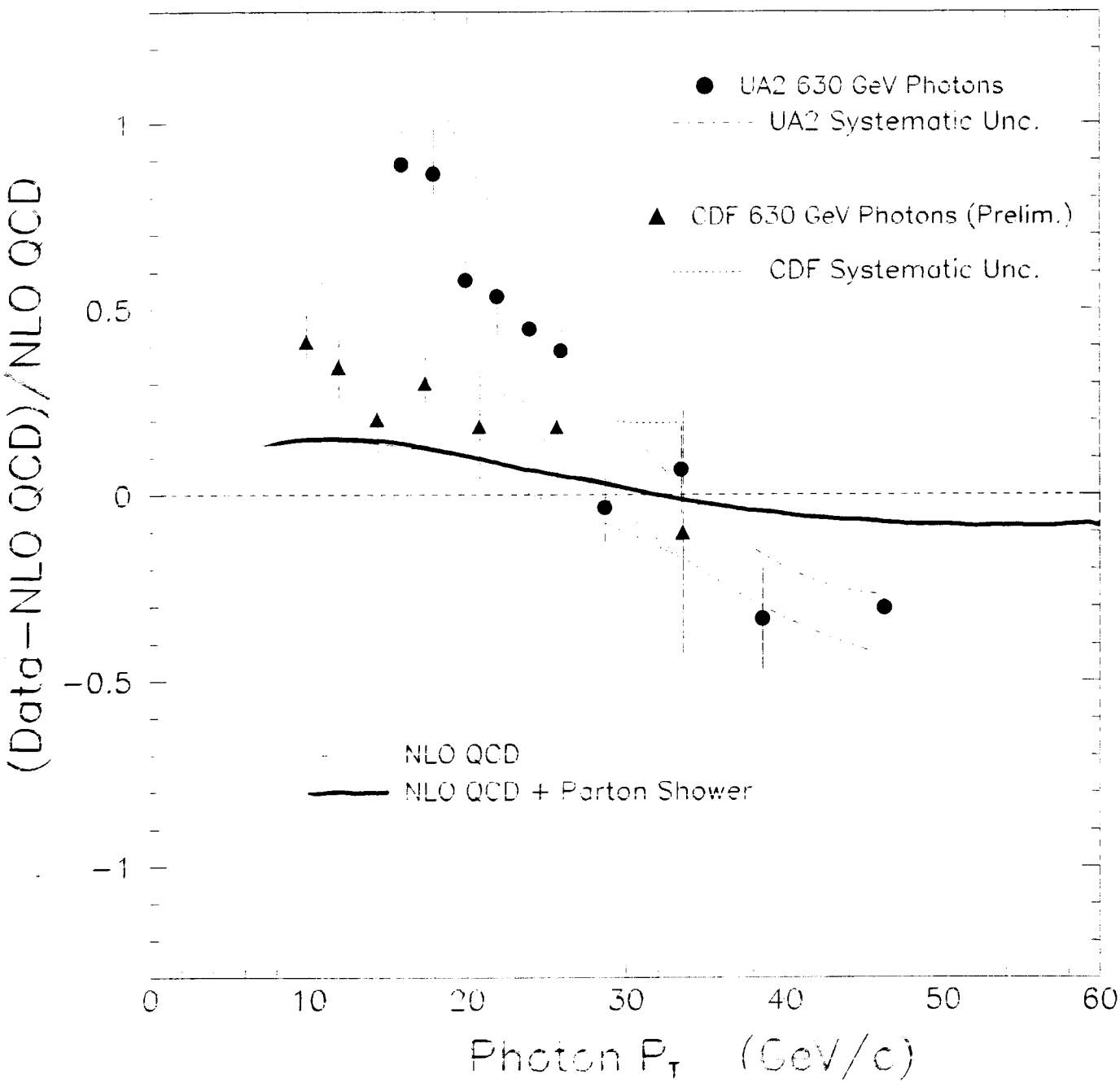


FIG. 3. The AK [18] central values (solid curves) are compared with the $O(\alpha_s)$ plus shower result (solid histogram) and the data for (a) $\sqrt{s}=0.63$ TeV and (b) $\sqrt{s}=1.8$ TeV. The data are taken from Refs. [19,20] for (a) and (b), respectively.

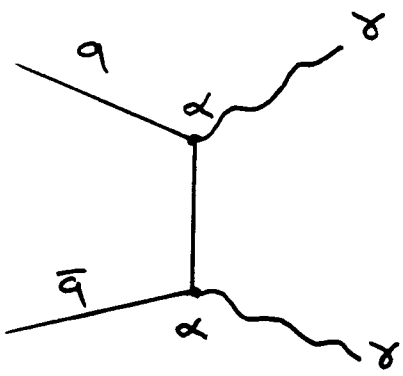

NLO QCD, CTEQ2M, $\mu=P_T$
NLO QCD + Parton Shower (Baer/Reno Prelim.)
CDF Data Normalization Uncertainty 10%
(Data−Theory)/Theory
Photon P_T (GeV/c)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
0
20
40
60
80
100
120


UA2 630 GeV
CDF 630 GeV (Preliminary)
~0.5 pb⁻¹
NLO QCD
$d^2\sigma/dP_T d\eta$ pb/(GeV/c)
10^4
10^3
10^2
10
10
15
20
25
30
35
40
45
Photon P_T (GeV/c)


UA2 630 GeV Photons
UA2 Systematic Unc.
CDF 630 GeV Photons (Prelim.)
CDF Systematic Unc.
NLO QCD
NLO QCD + Parton Shower
(Data−NLO QCD)/NLO QCD
Photon P_T (GeV/c)
1
0.5
0
−0.5
−1
0
10
20
30
40
50
60

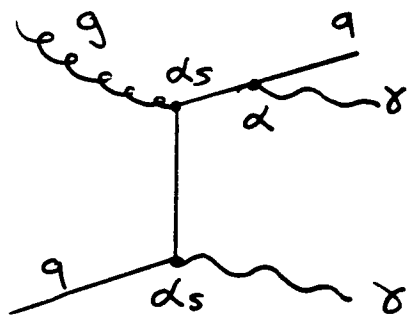
Two Photon Production

$q\bar{q}$ annihilation



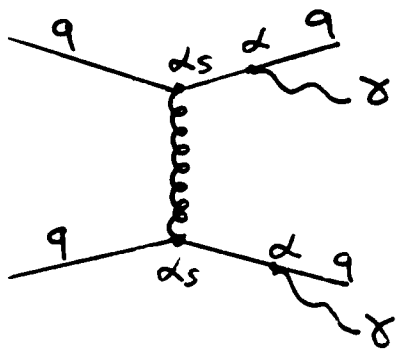
$\Theta(\alpha^2)$

single bremsstrahlung



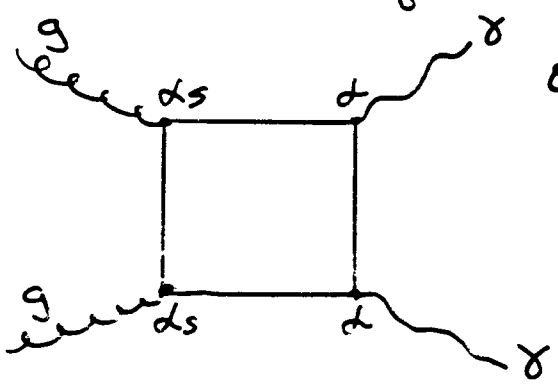
$\Theta(\alpha^2)$ but suppressed by isolation cut

double bremsstrahlung



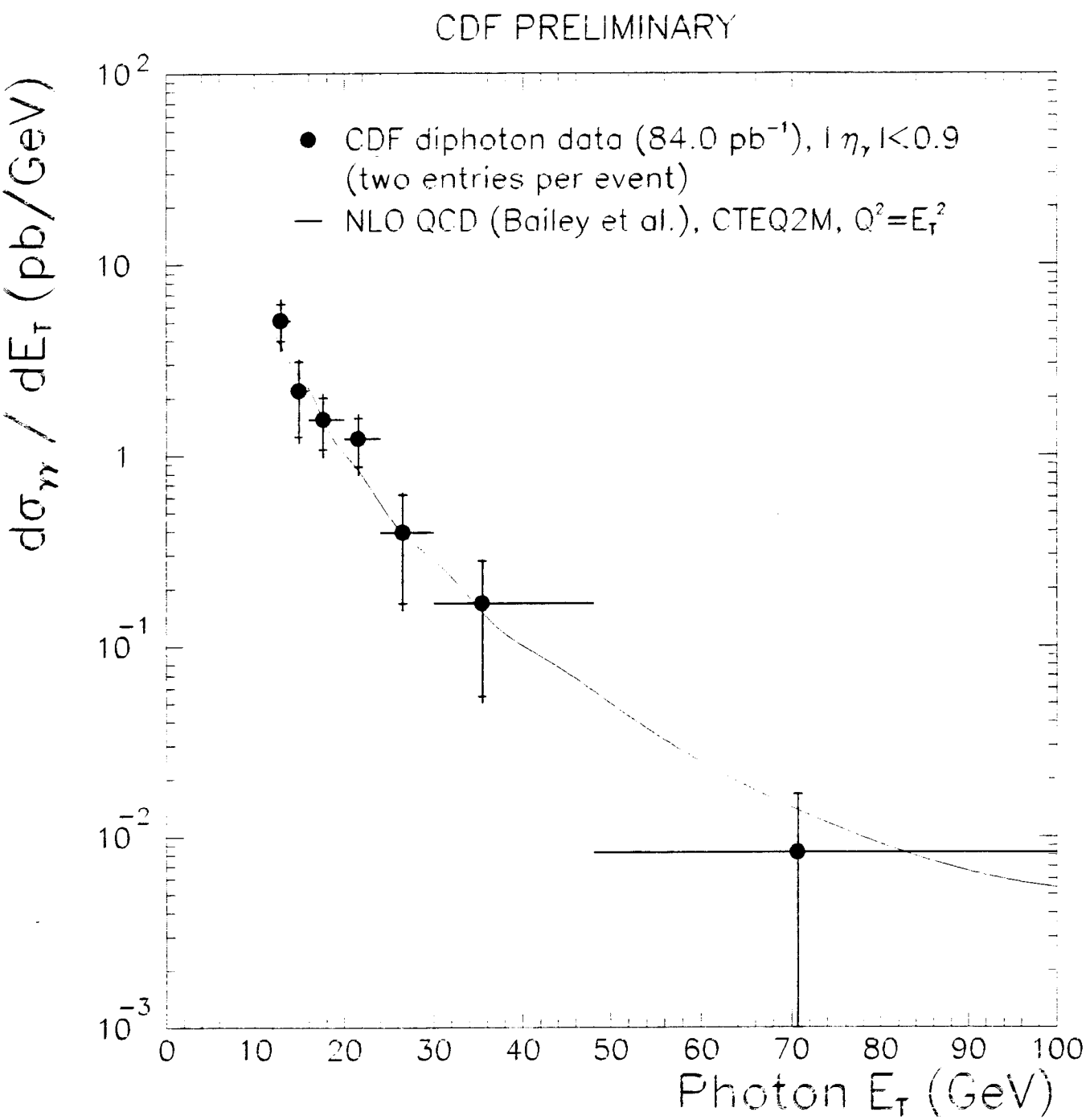
$\Theta(\alpha^2)$ but greatly suppress by isolation

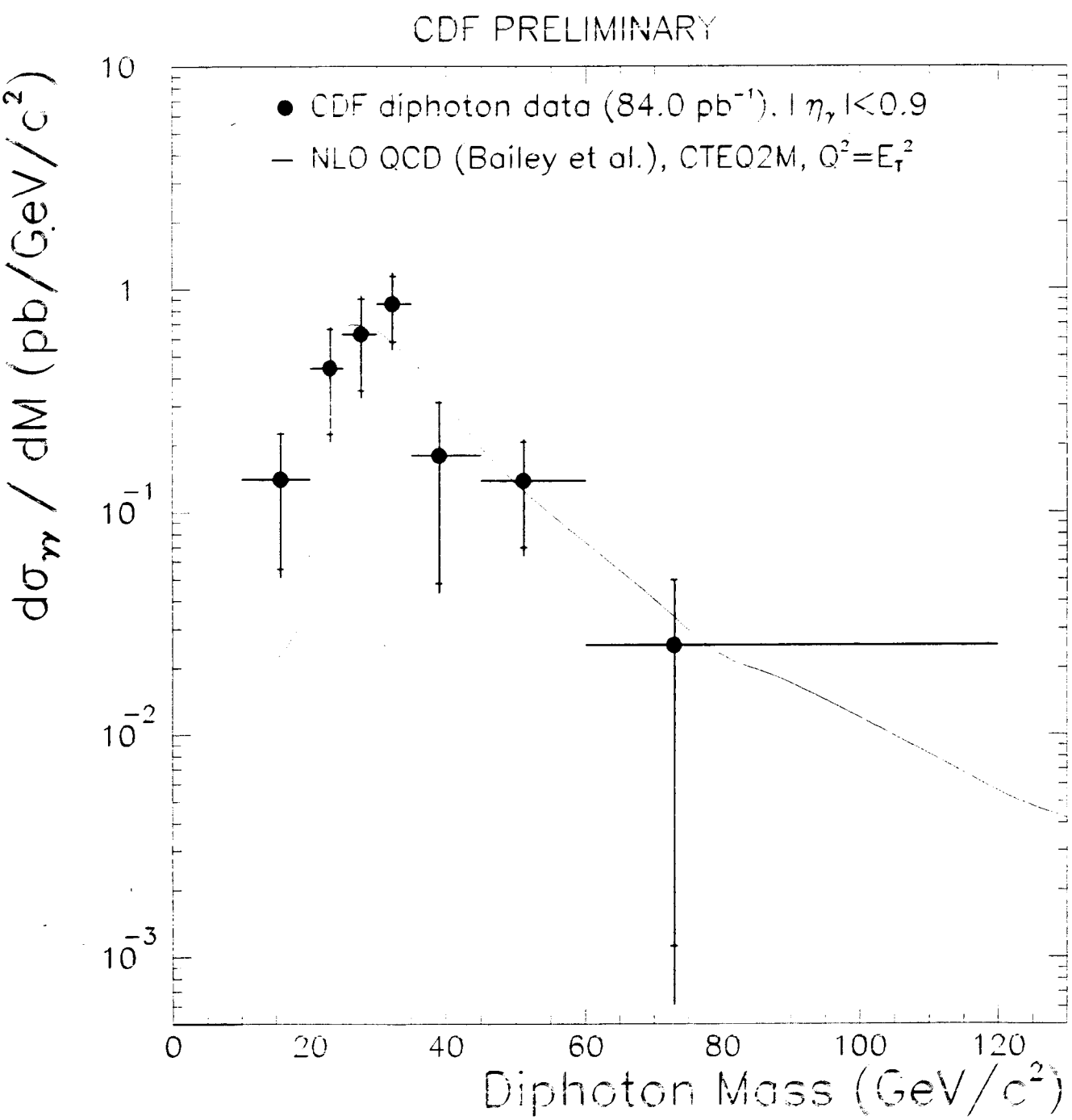
box

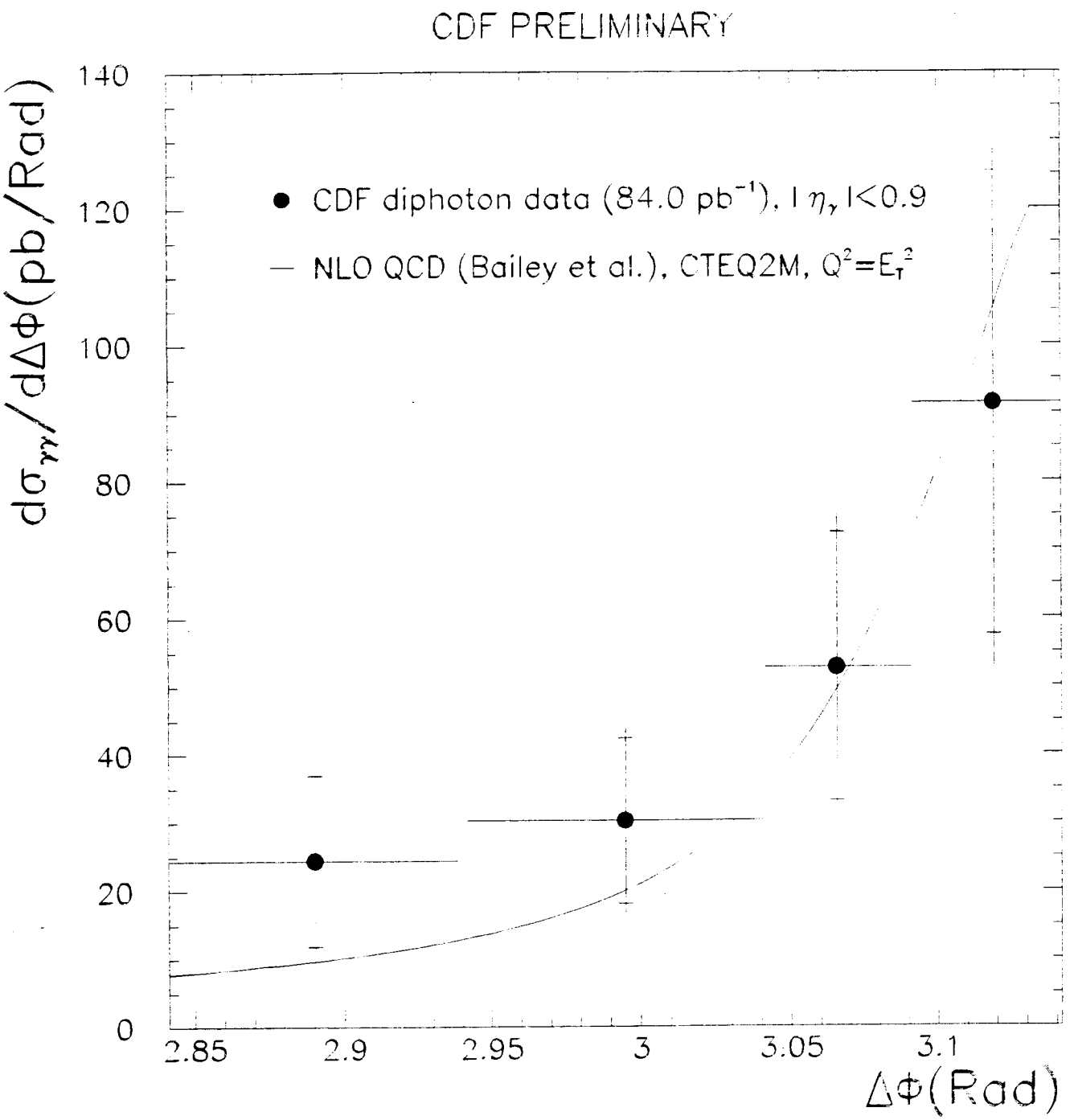


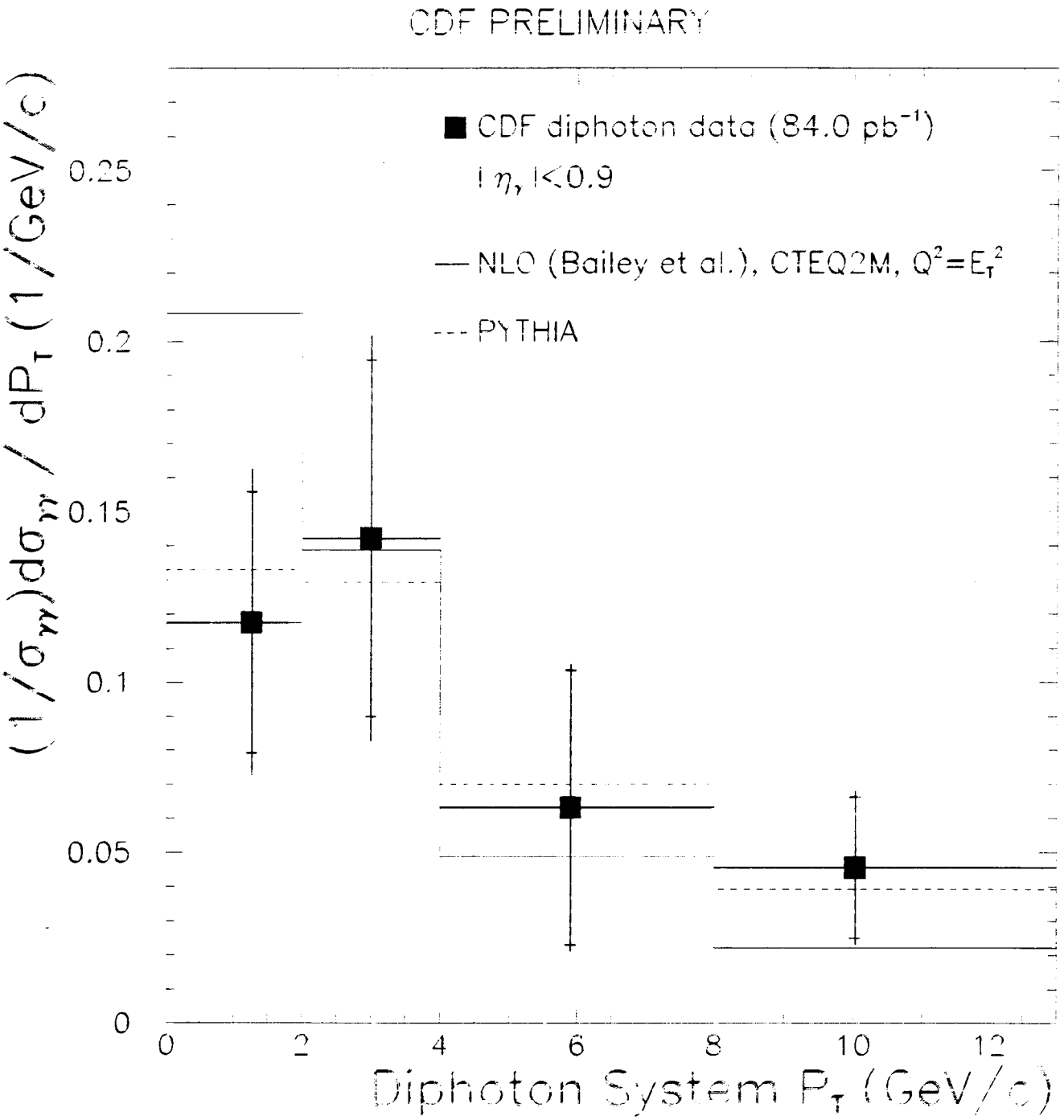
$\Theta(\alpha_s^2\alpha^2)$

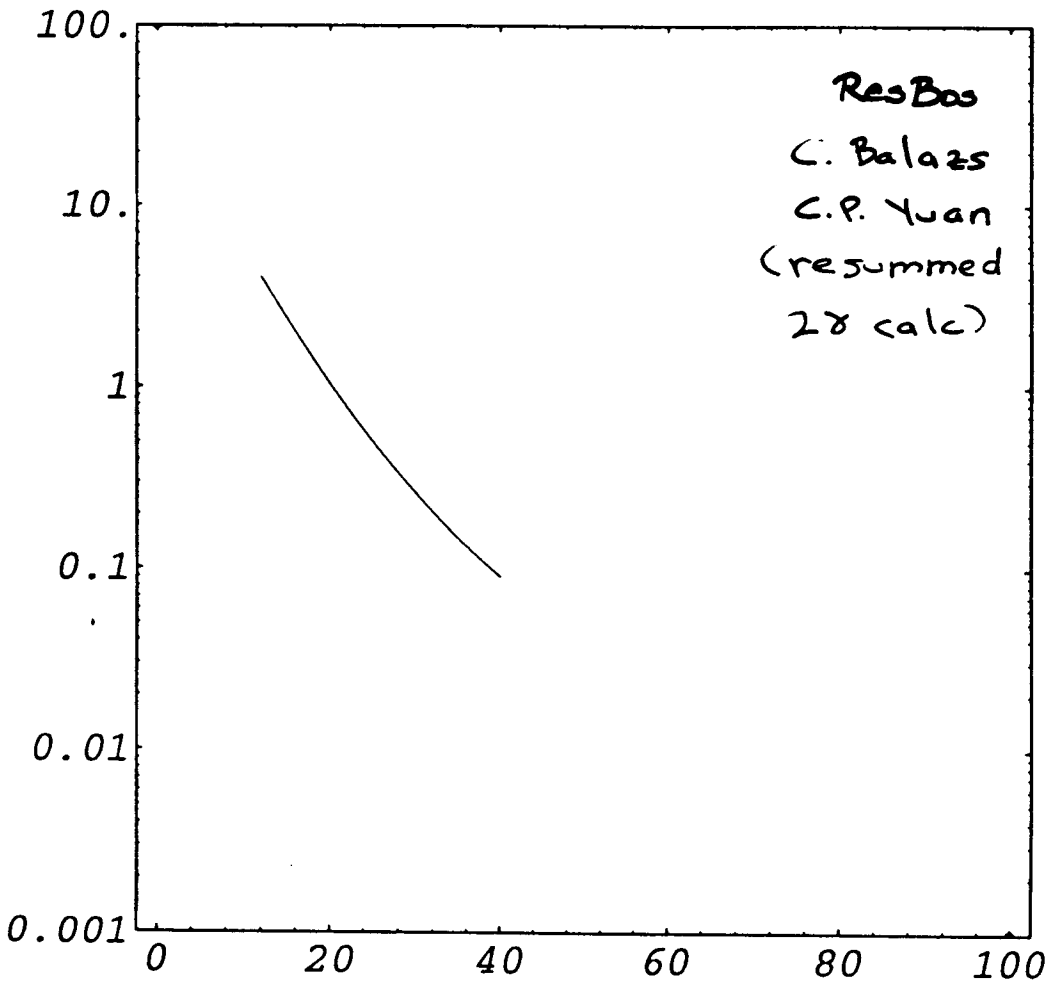
Interesting QCD process...
and also forms background to processes like $H^0 \to \gamma\gamma$
Same measurement techniques apply.


CDF PRELIMINARY
CDF diphoton data (84.0 pb^{-1}), $|\eta_\gamma|<0.9$
(two entries per event)
NLO QCD (Bailey et al.), CTEQ2M, $Q^2=E_T^2$
$d\sigma_{\gamma\gamma}$ / dE_T (pb/GeV)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
0
10
20
30
40
50
60
70
80
90
100
Photon E_T (GeV)


CDF PRELIMINARY
CDF diphoton data (84.0 pb^{-1}), $|\eta_\gamma|<0.9$
NLO QCD (Bailey et al.), CTEQ2M, $Q^2=E_T^2$
$d\sigma_{\gamma\gamma}$ / dM (pb/GeV/c^2)
10
1
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100
120
Diphoton Mass (GeV/c^2)


CDF PRELIMINARY
CDF diphoton data (84.0 pb^{-1}), $|\eta_\gamma|<0.9$
NLO QCD (Bailey et al.), CTEQ2M, $Q^2=E_T^2$
$d\sigma_{\gamma\gamma}/d\Delta\Phi$(pb/Rad)
$\Delta\Phi$(Rad)
0
20
40
60
80
100
120
140
2.85
2.9
2.95
3
3.05
3.1


CDF PRELIMINARY
CDF diphoton data (84.0 pb^{-1})
$|\eta_\gamma|<0.9$
NLO (Bailey et al.), CTEQ2M, $Q^2=E_T^2$
PYTHIA
$(1/\sigma_{\gamma\gamma})d\sigma_{\gamma\gamma}/dP_T$ (1/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)


100.
10.
1
0.1
0.01
0.001
0
20
40
60
80
100
ResBos
C. Balazs
C.P. Yuan
(resummed
2γ calc)

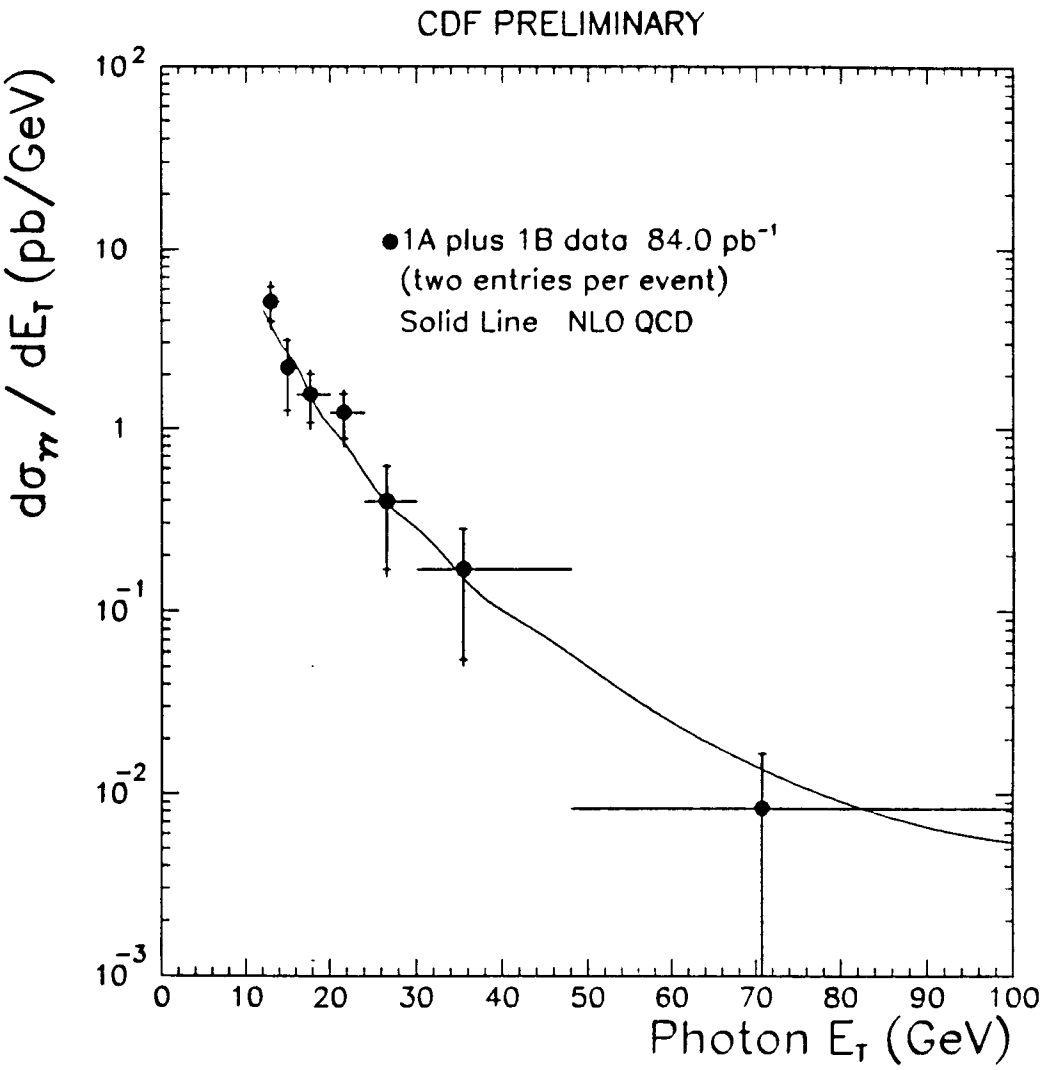
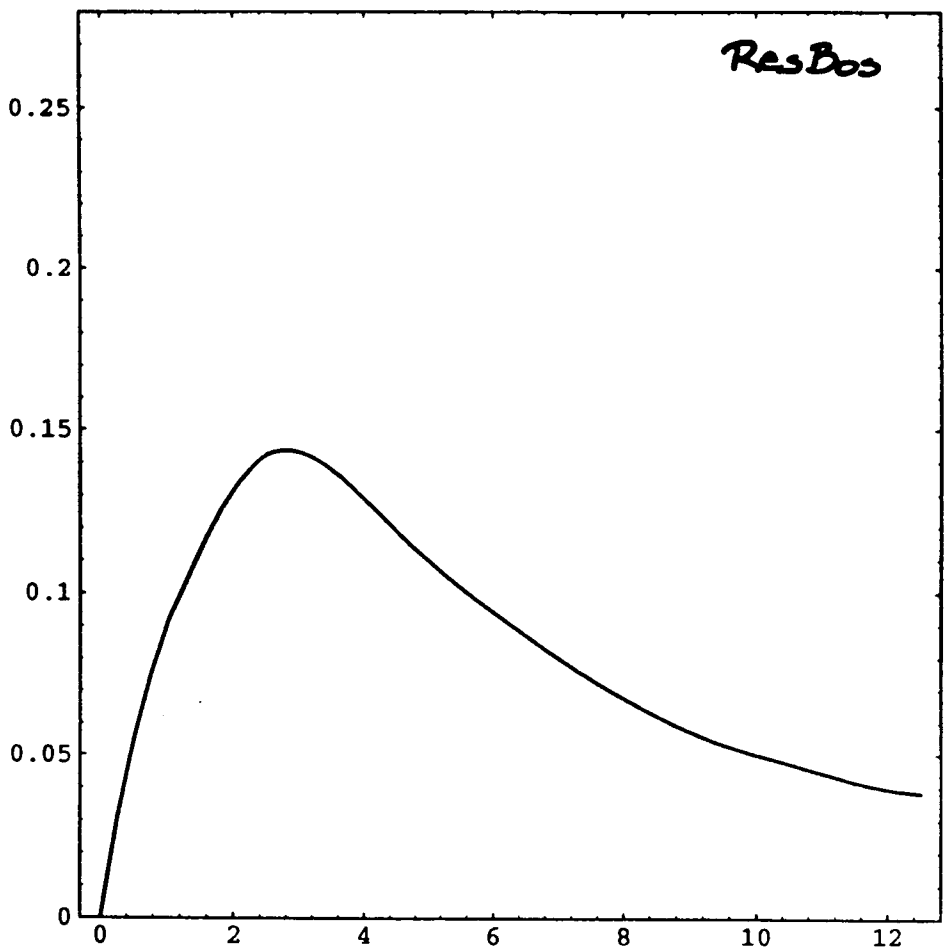


Figure 10: The diphoton cross section as a function of photon E_T from 1A plus 1B data. Solid line shows the NLO QCD calculation.


ResBos
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12

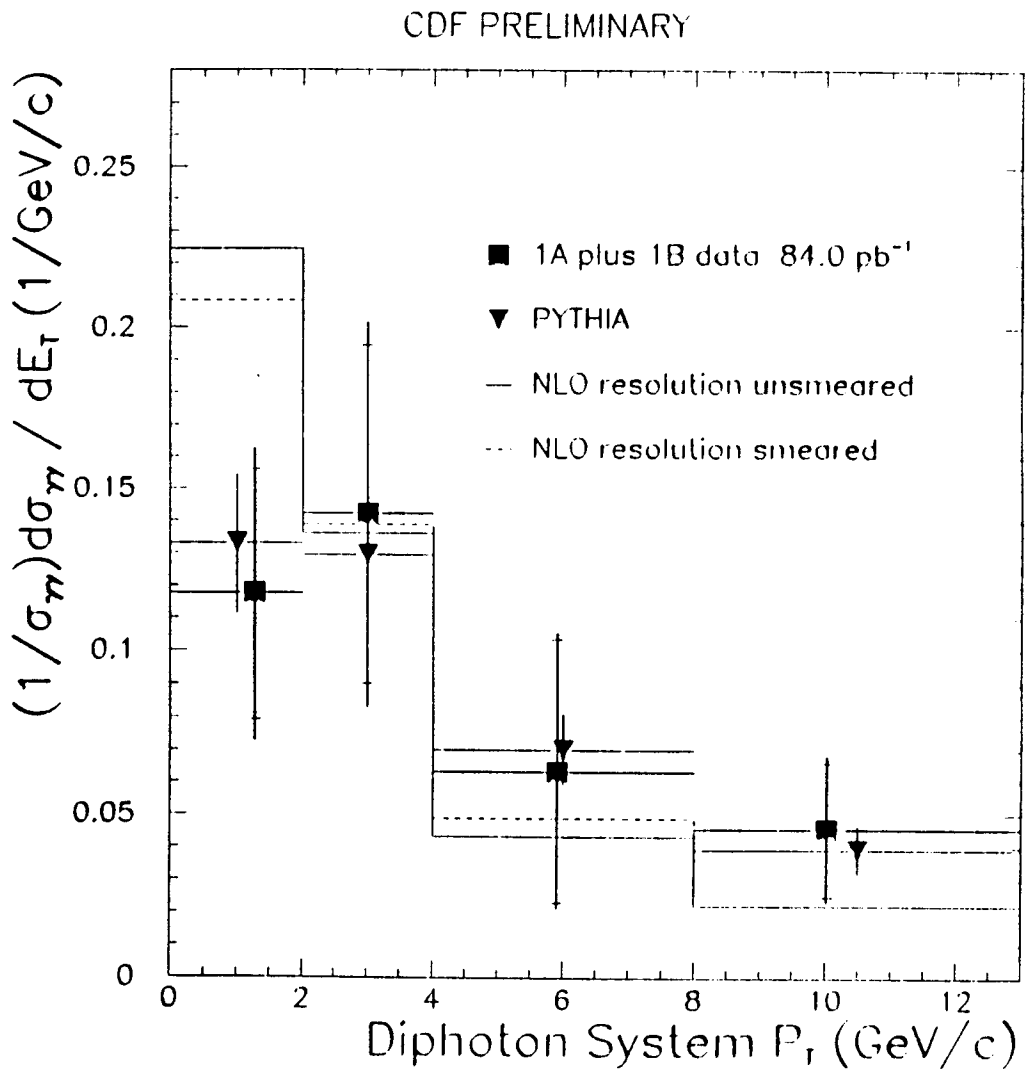
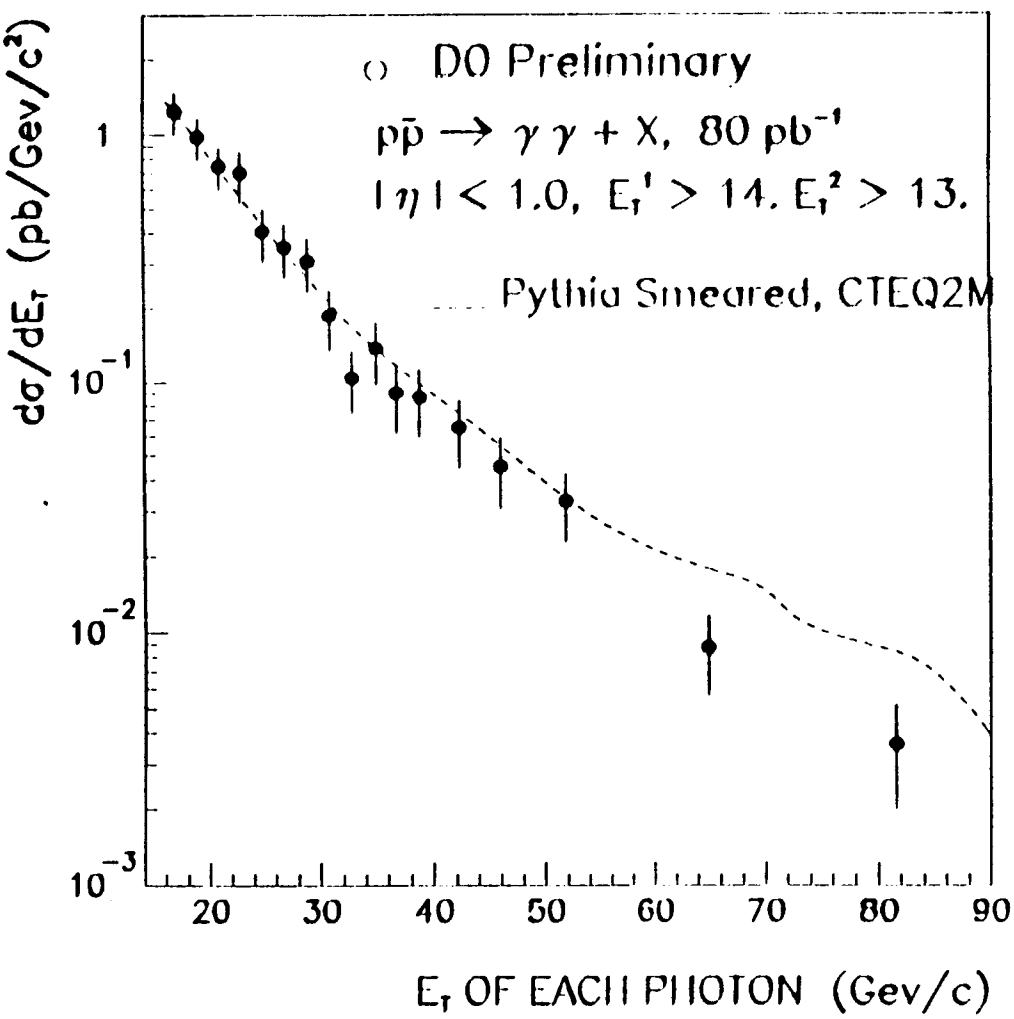
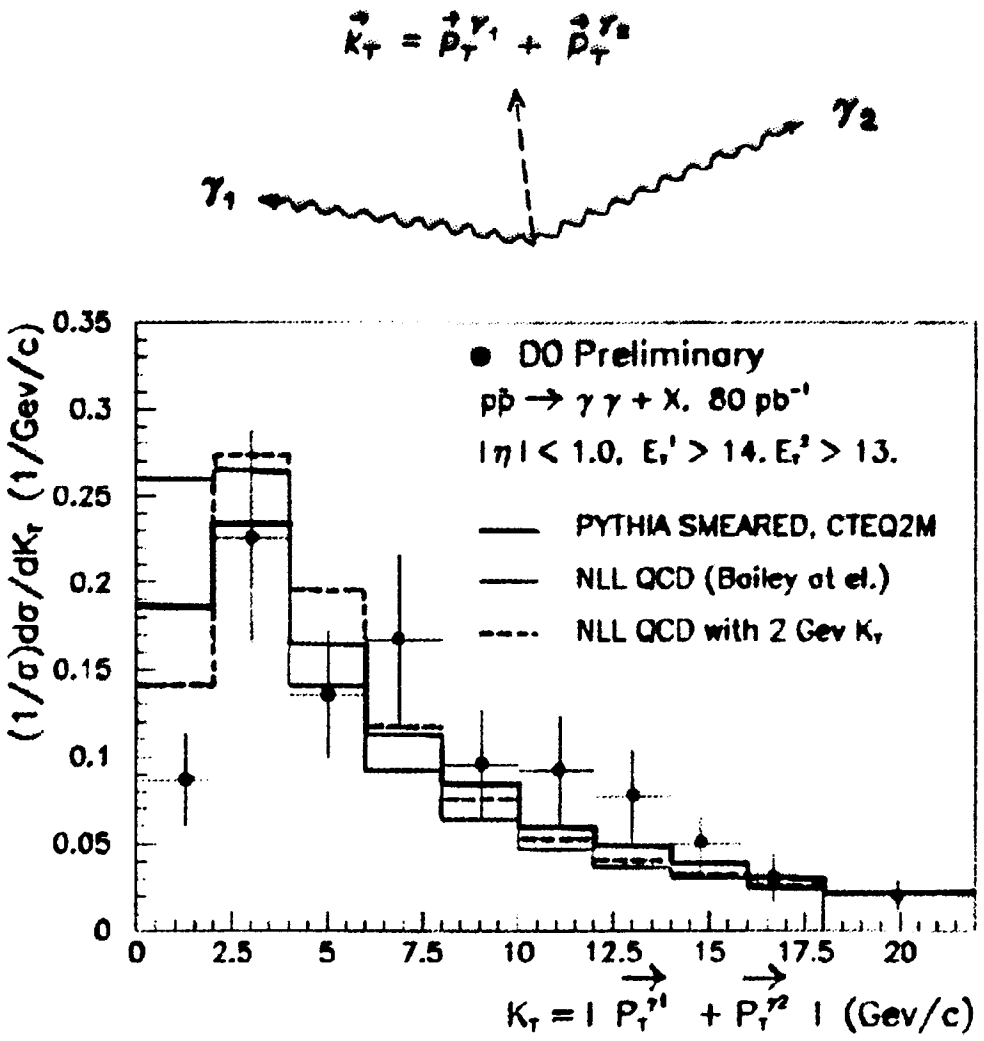
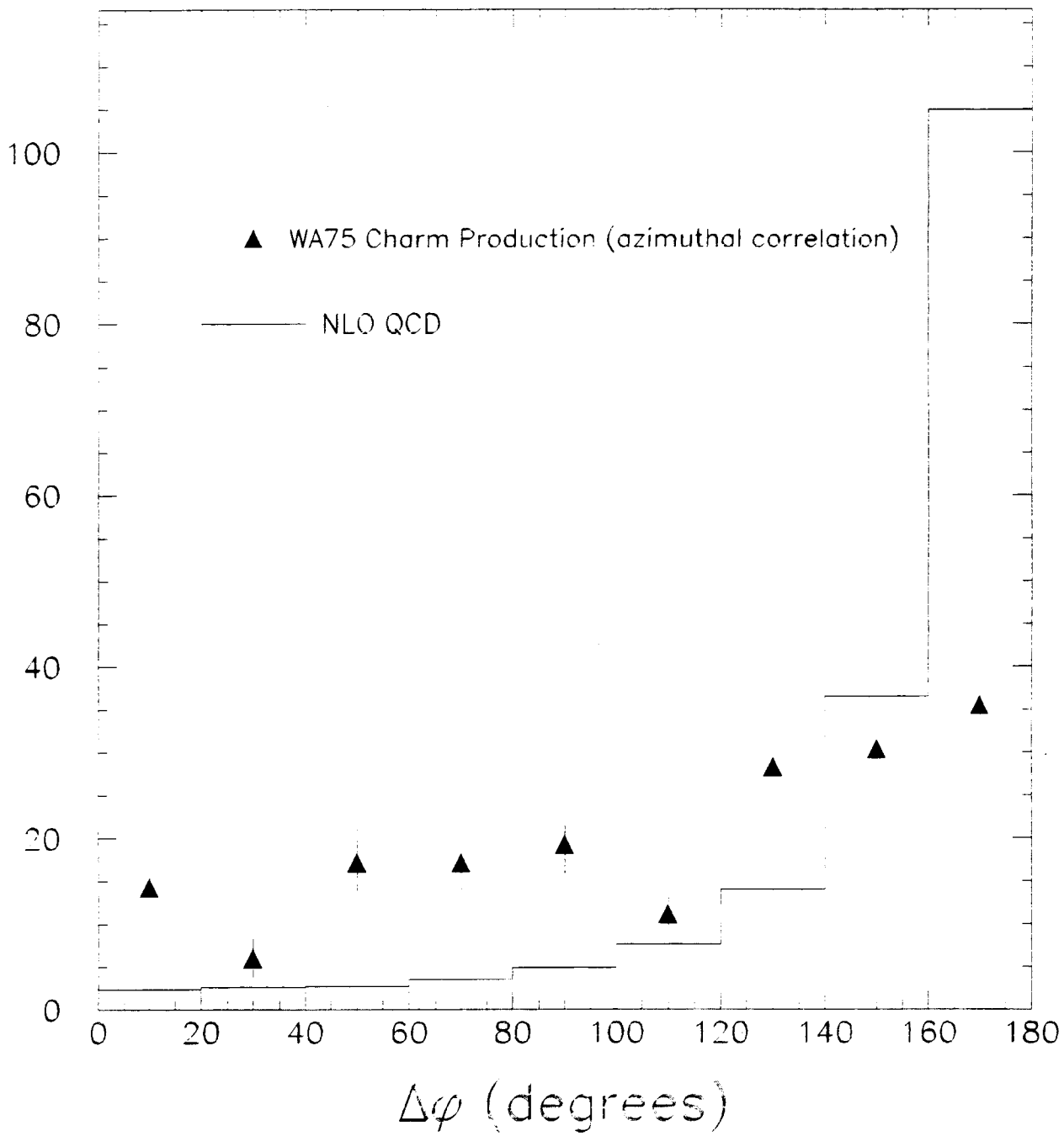
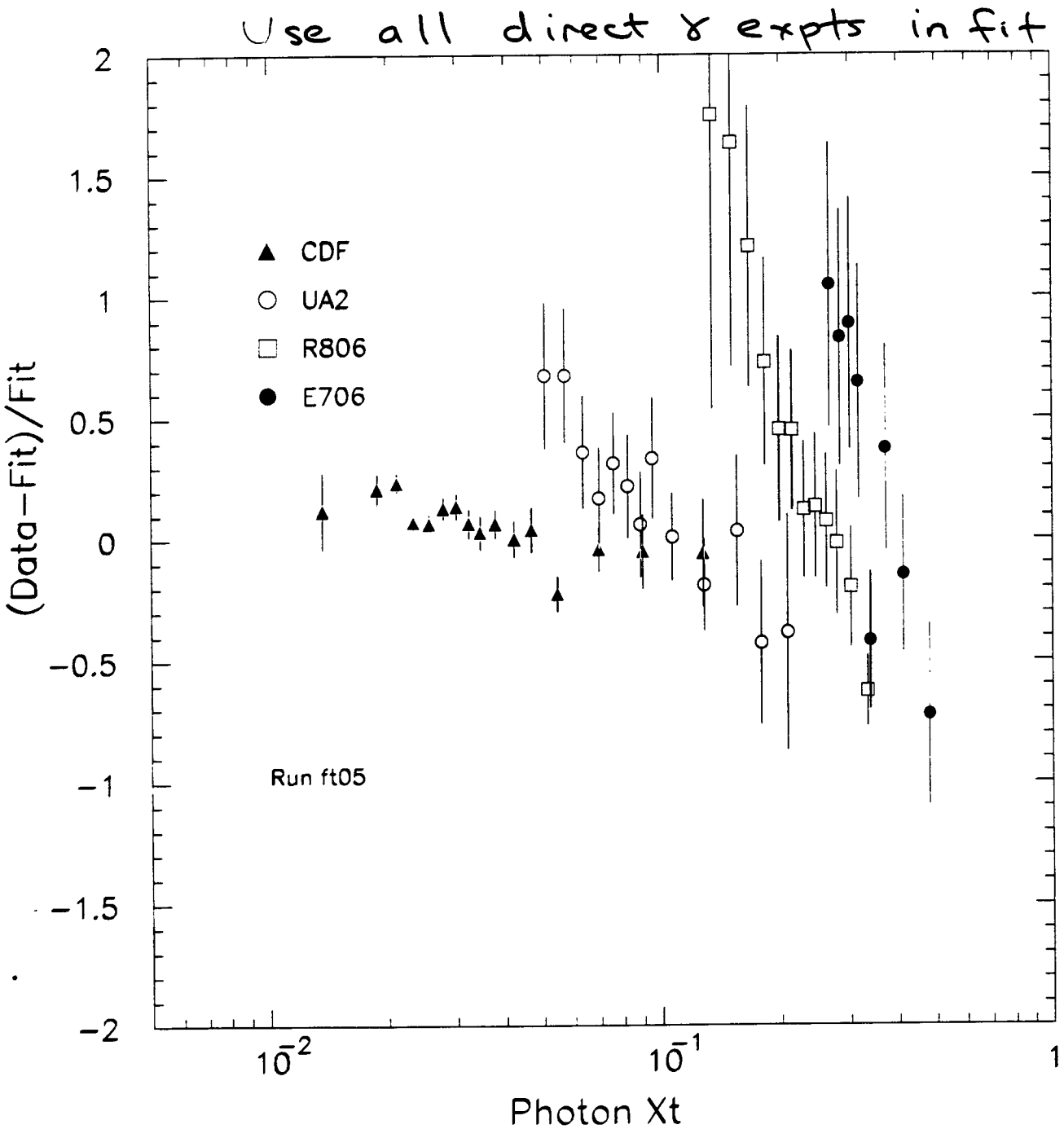


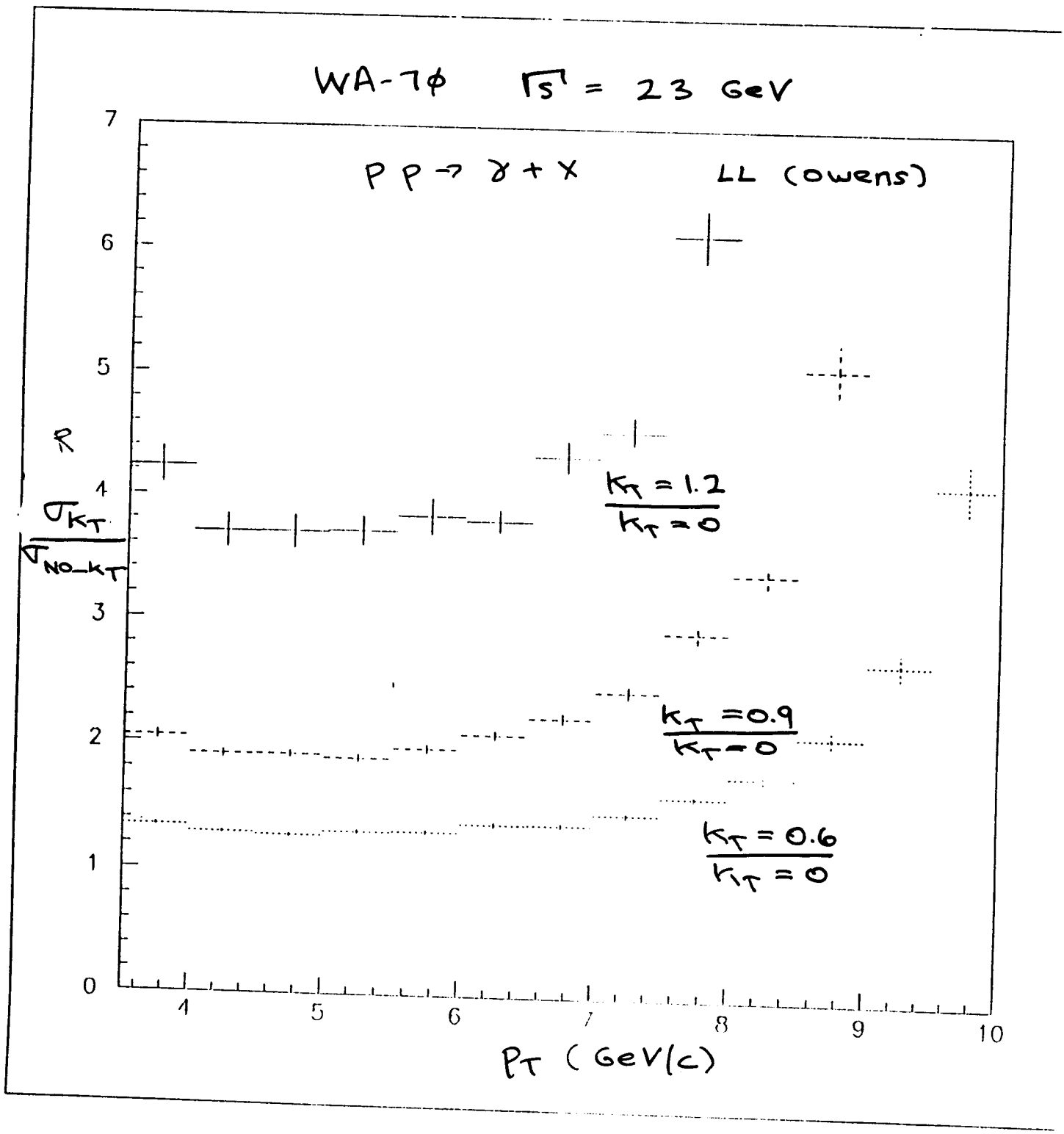
Figure 16: Normalized diphoton cross section as a function of diphoton system P_T. Error bars show statistical uncertainties only. Rectanglar plots show the result of this analysis from 1A plus 1B data. Triangle plots are results from PYTHIA. Solid histogram shows the NLO QCD calculation without smearing of the resolution of the electromagnetic calorimeter. Dashed histogram shows the NLO QCD calculation with the resolution smearing.


DO Preliminary
$p\bar{p} \rightarrow \gamma\gamma + X$, 80 pb^{-1}
$|\eta| < 1.0$, $E_T^1 > 14$. $E_T^2 > 13$.
Pythia Smeared, CTEQ2M
$d\sigma/dE_T$ (pb/Gev/c^2)
1
10^{-1}
10^{-2}
10^{-3}
20
30
40
50
60
70
80
90
E_T OF EACH PHOTON (Gev/c)


$\vec{k}_T = \vec{p}_T^{\gamma_1} + \vec{p}_T^{\gamma_2}$
γ_1
γ_2
DO Preliminary
$p\bar{p} \rightarrow \gamma\gamma + X$, 80 pb^{-1}
$|\eta| < 1.0$, $E_T^1 > 14$, $E_T^2 > 13$.
PYTHIA SMEARED, CTEQ2M
NLL QCD (Bailey et el.)
NLL QCD with 2 Gev K_T
$(1/\sigma)d\sigma/dK_T$ (1/Gev/c)
$K_T = | \vec{P}_T^{\gamma 1} + \vec{P}_T^{\gamma 2} |$ (Gev/c)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
2.5
5
7.5
10
12.5
15
17.5
20


WA75 Charm Production (azimuthal correlation)
NLO QCD
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
Δφ (degrees)


Use all direct γ expts in fit
(Data−Fit)/Fit
Photon Xt
CDF
UA2
R806
E706
Run ft05
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
10^{-2}
10^{-1}
1


WA-7φ √s = 23 GeV
P P → γ + X
LL (owens)
R
σ_kT / σ_NO_kT
k_T = 1.2 / k_T = 0
k_T = 0.9 / k_T = 0
k_T = 0.6 / k_T = 0
P_T (GeV/c)
0
1
2
3
4
5
6
7
1
5
6
7
8
9
10

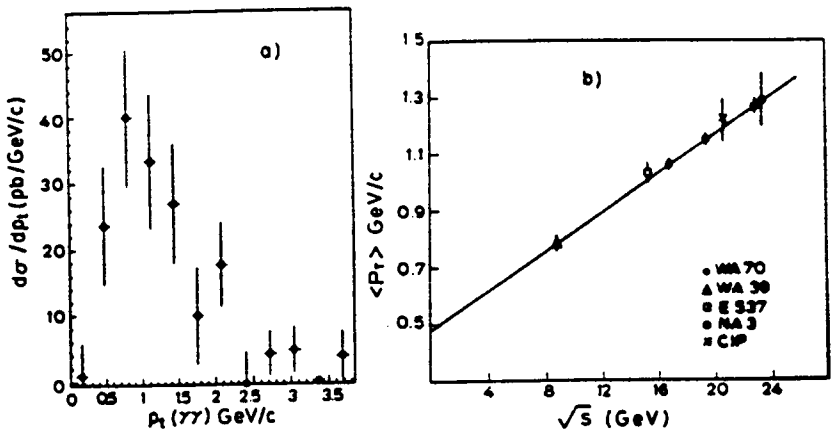


Fig. 2. (a) The differential cross section of the reaction $\pi^- p \to \gamma\gamma X$ as a function of the p_t of the $\gamma\gamma$ pair. The data are integrated over p_u from $p_{u1} = 3.0$ GeV/c and $p_{u2} = 2.75$ GeV/c and over the full rapidity range. The error bars include the statistical uncertainties of the data and of the Monte Carlo's. (b) The mean p_t of the $\gamma\gamma$ pair compared to the mean p_t of the lepton pair measured in the reaction $\pi^- N \to \mu^+\mu^- X$ by various Drell–Yan experiments. The line is the fit from ref. [7] described in the text.

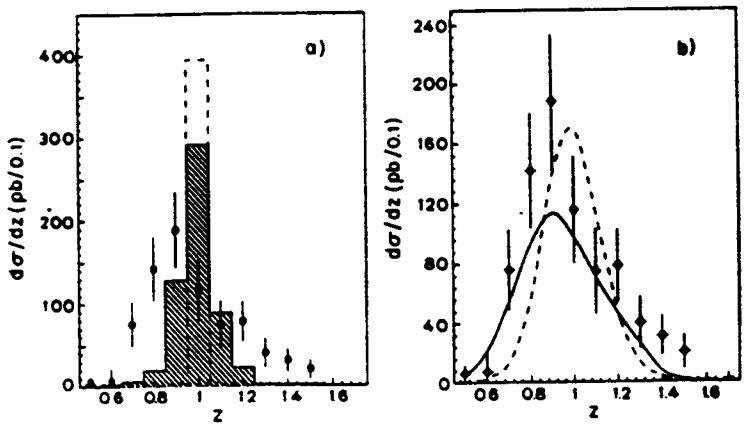


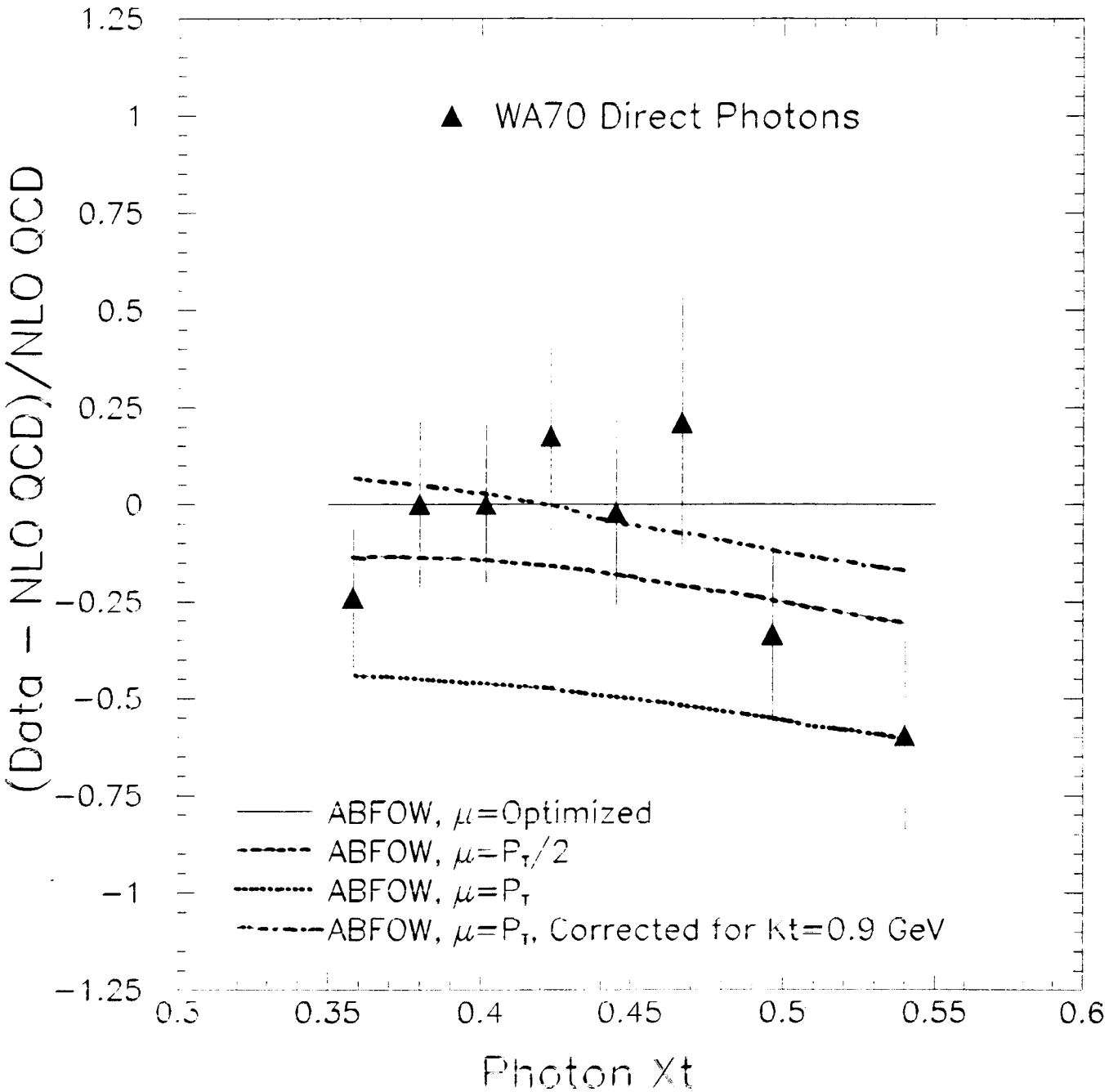
Fig. 3. The differential cross section of the reaction $\pi^- p \to \gamma\gamma X$ as function of the z variable. The data are integrated over the full rapidity range, and over p_u from $p_u = 3$ GeV/c. For each γ entering the histogram a cut $z > 2.75/p_u$ is applied. The error bars are the statistical uncertainties of the data and of the Monte Carlo's. (a) The leading order $q\bar{q} \to \gamma\gamma$ prediction (broken line) and the BLL QCD calculations [2] (shaded area) are indicated. (b) The BLL calculations widened by an intrinsic transverse momentum $\langle k_t \rangle = 0.34$ GeV/c (broken line) and by $\langle k_t \rangle = 0.9$ GeV/c (continuous line) are superimposed on the data.

the primordial k_t has a value of $\langle k_t \rangle \simeq 0.48/\sqrt{2} = 0.34$ GeV/c and the experimentally observed higher values are due to dynamical effects. The value obtained in the present experiment is consistent with the Drell–Yan results at a similar energy (fig. 2b).

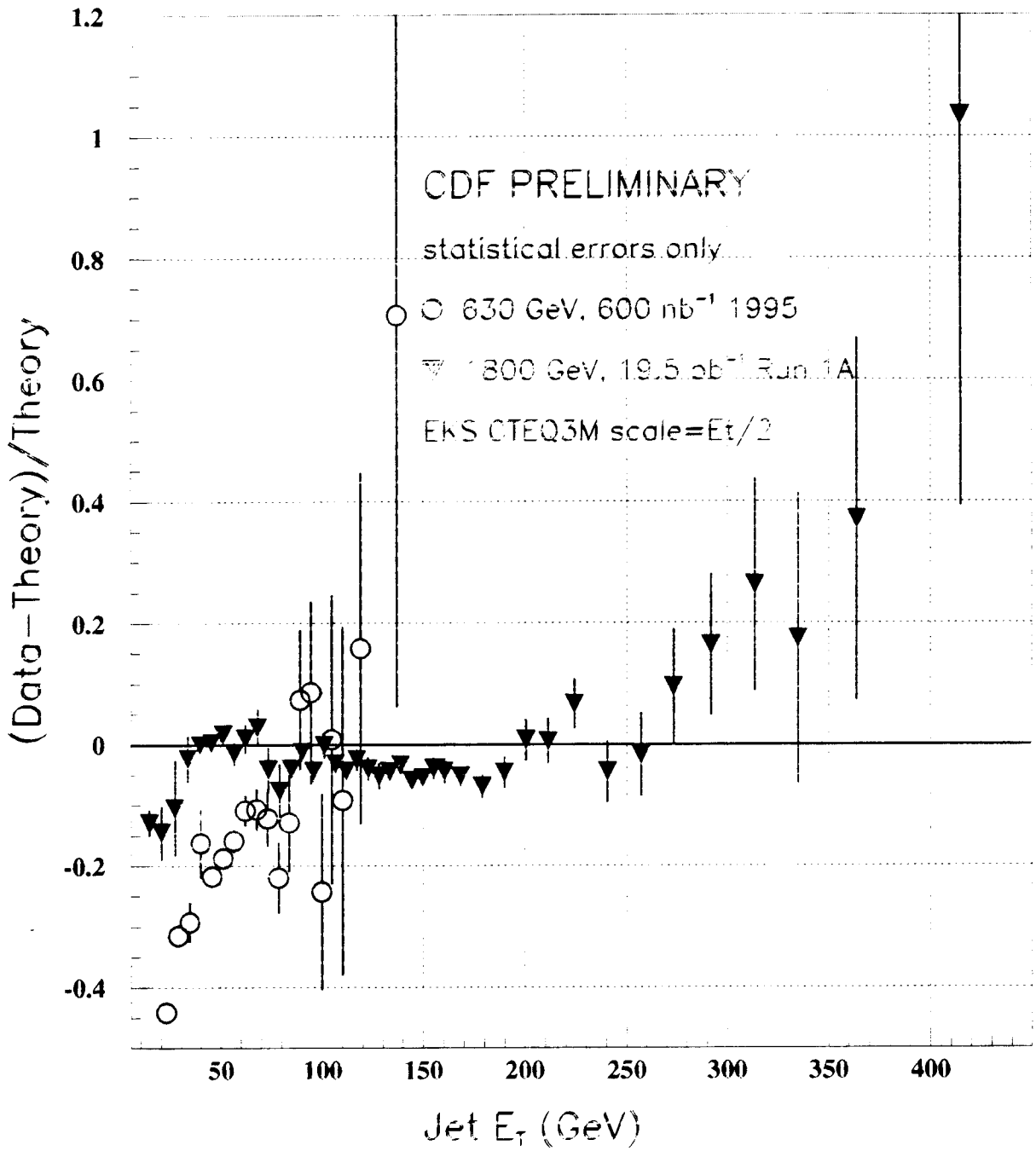
Fig. 3 shows the differential cross section $d\sigma/dz$. In order to compare with the analytical QCD program, a binning wider than twice the experimental resolution ($\sigma_z = 0.037$) was chosen and a cut $z > 2.75/p_u$ was applied for each photon entering the histogram. The BLL predictions [2], without folding in the experimental resolution and intrinsic k_t effects, are shown in fig. 3a. The distribution $d\sigma/dz \sim \delta(1-z)$, characteristic of the leading order calculation (broken line in fig. 3a), is widened by the presence of BLL QCD diagrams (shaded histogram), which also produce

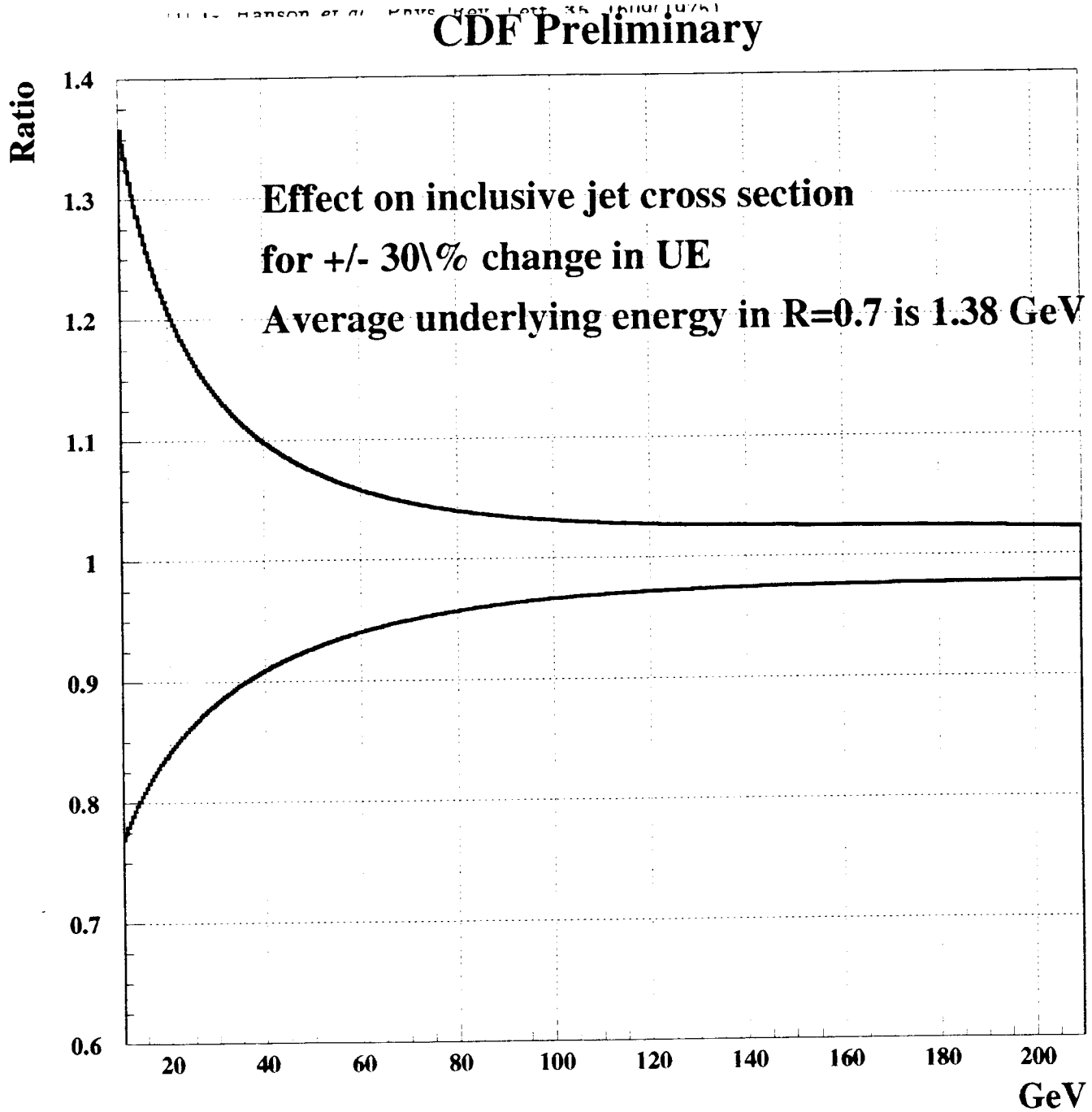
ABFOW first pdf to use direct photon (WA70)

MRS also uses WA70

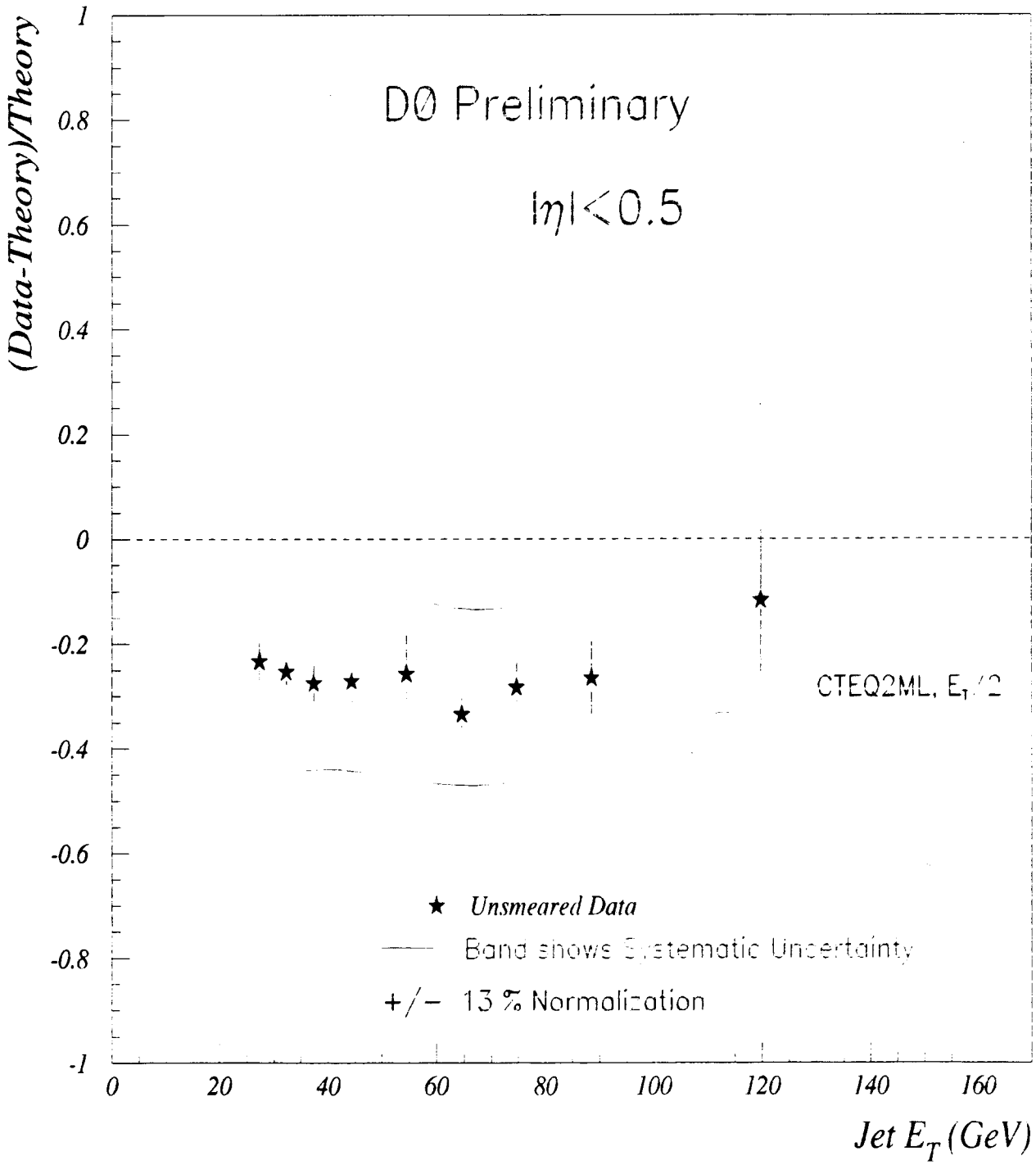


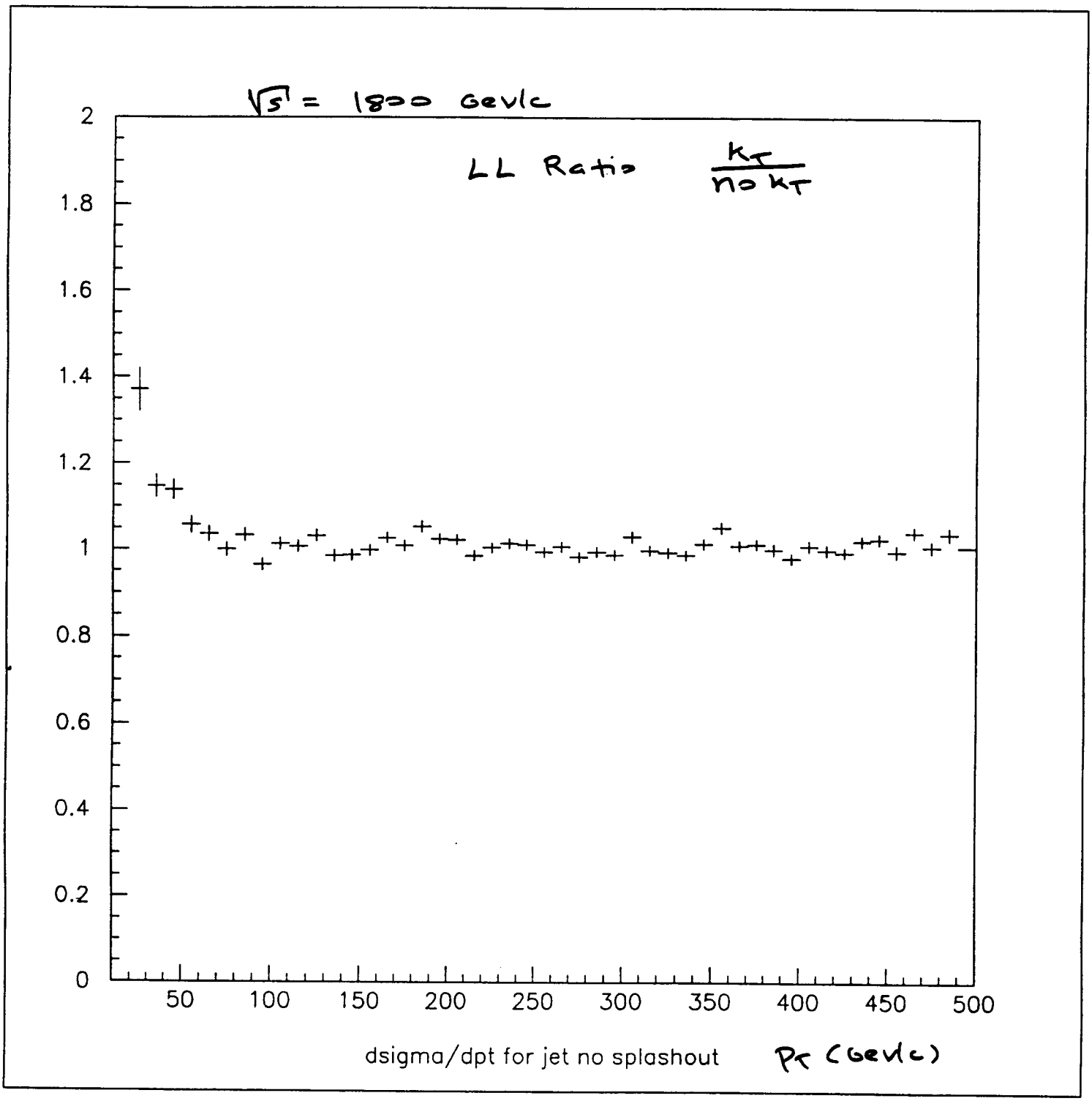
CDF: 630 GeV vs 1800 GeV



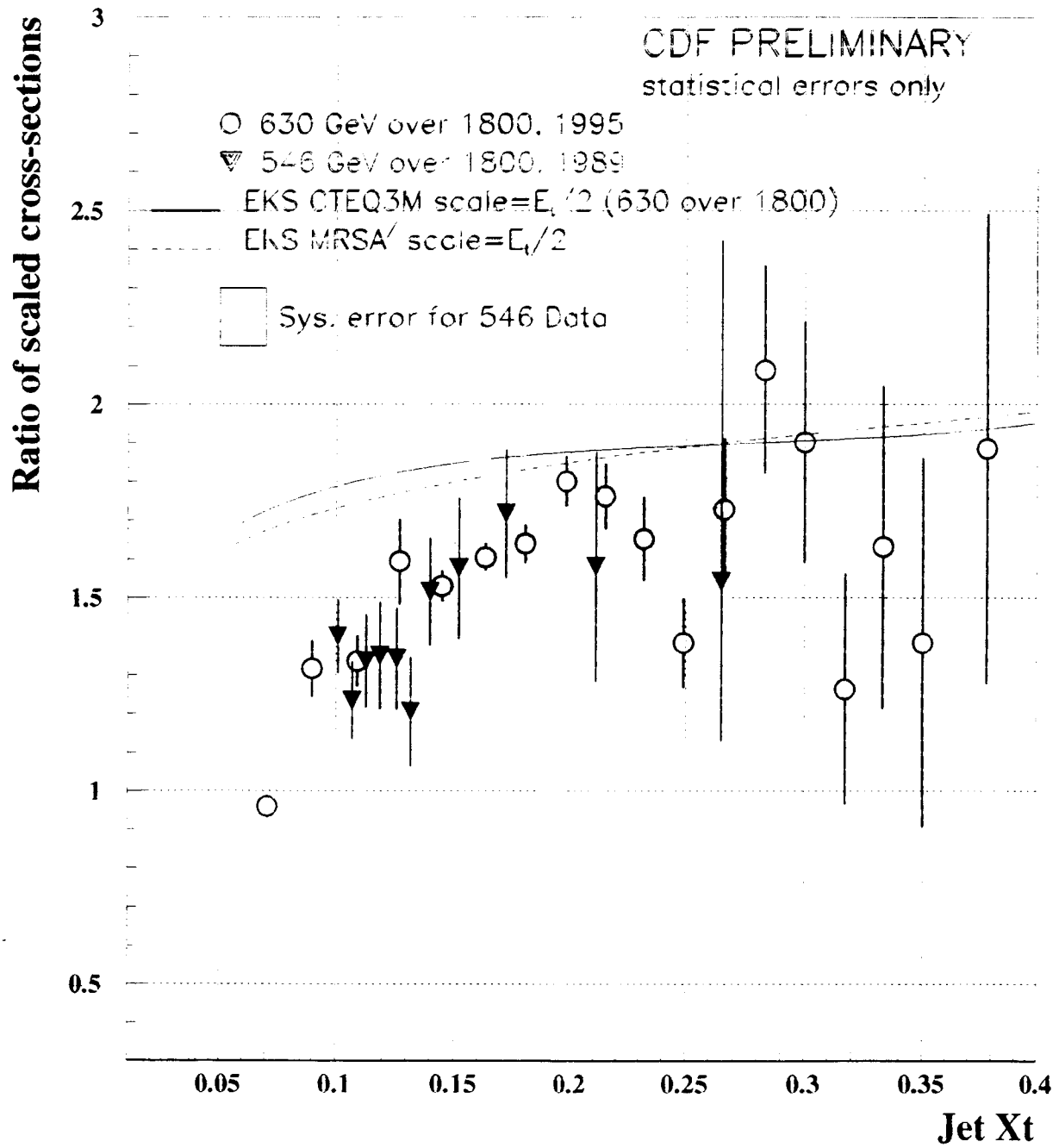

CDF Preliminary
Ratio
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
Effect on inclusive jet cross section
for +/- 30\% change in UE
Average underlying energy in R=0.7 is 1.38 GeV
20
40
60
80
100
120
140
160
180
200
GeV

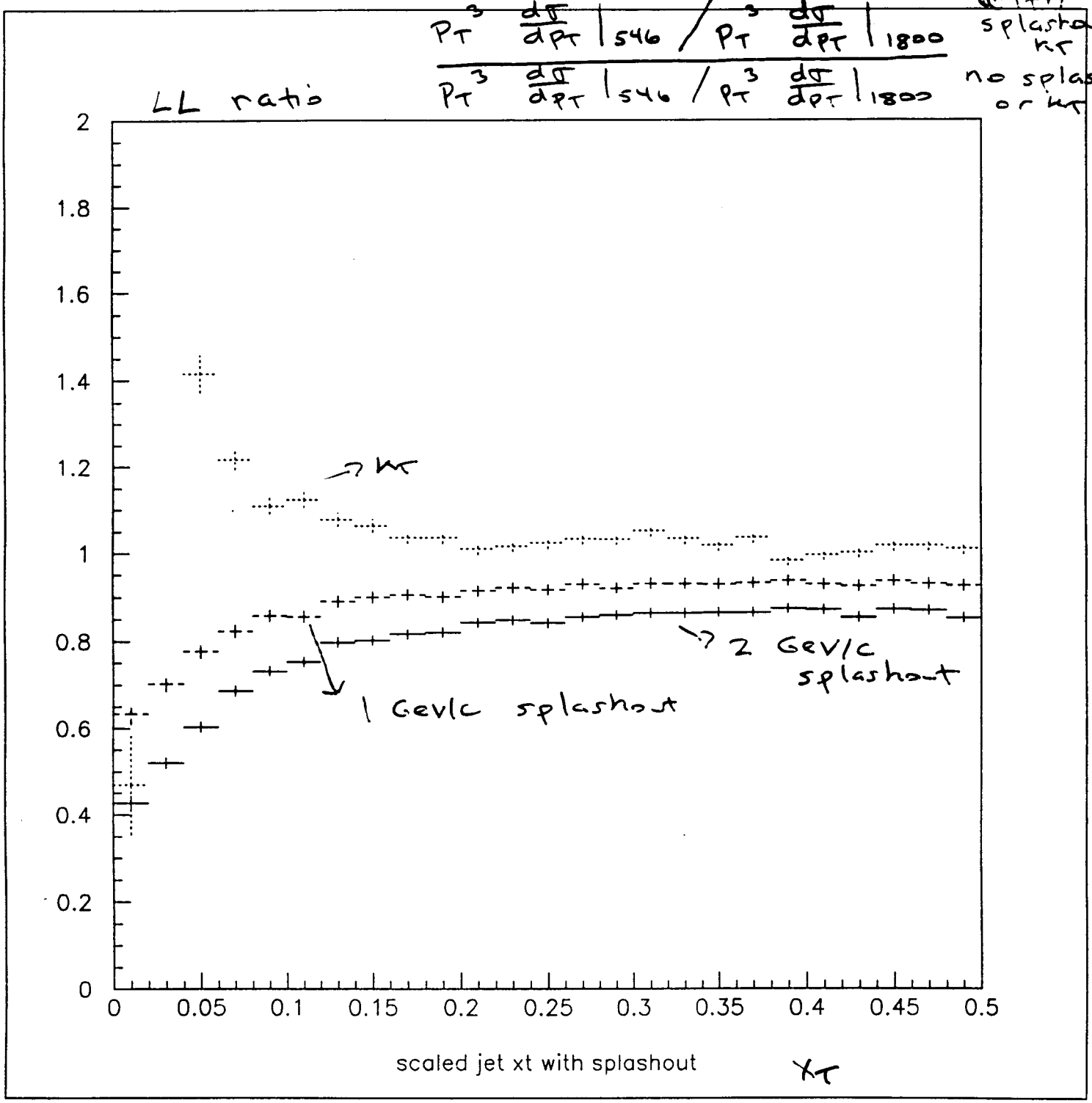
Data (630 GeV CM Energy) and NLO QCD

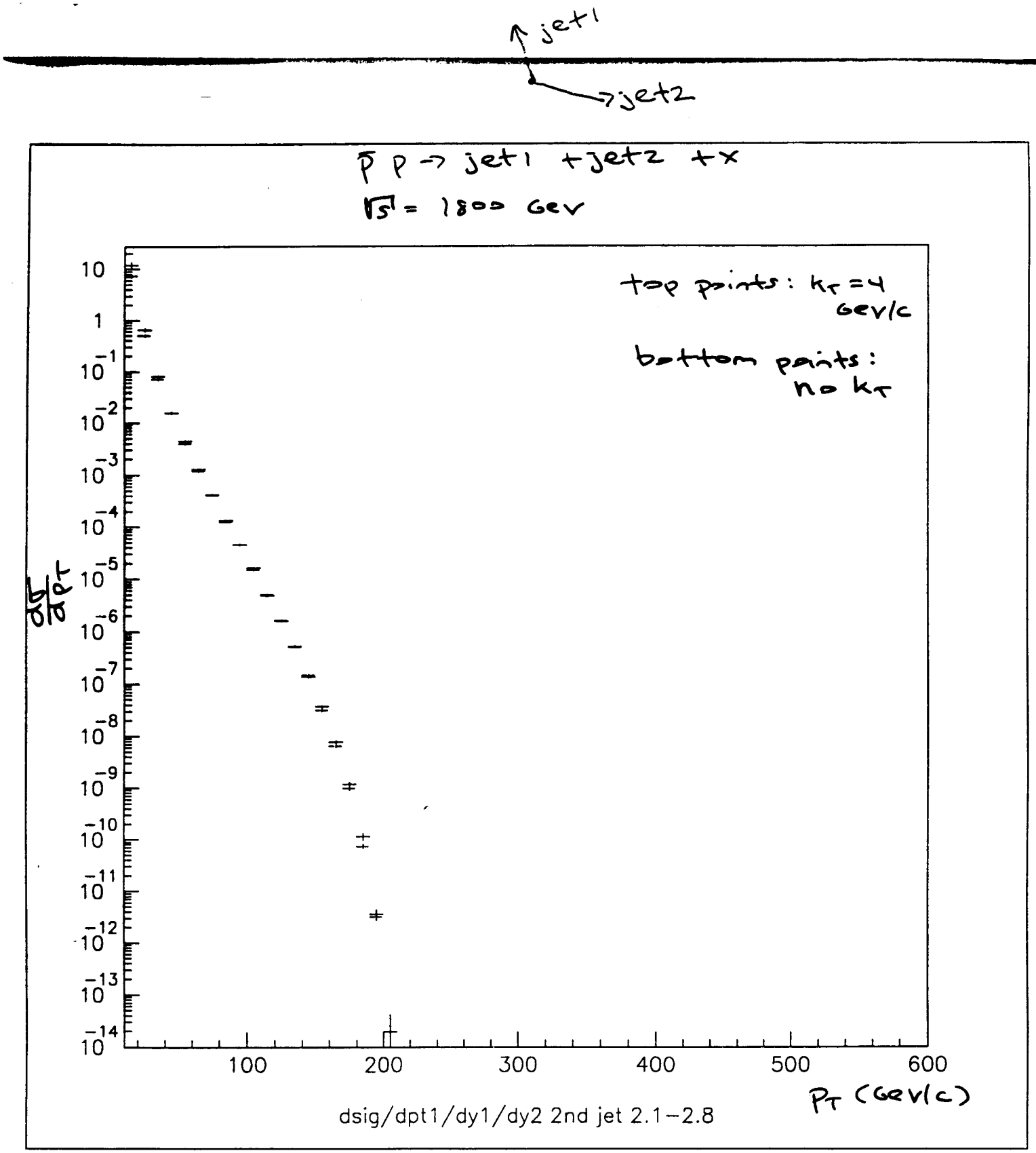


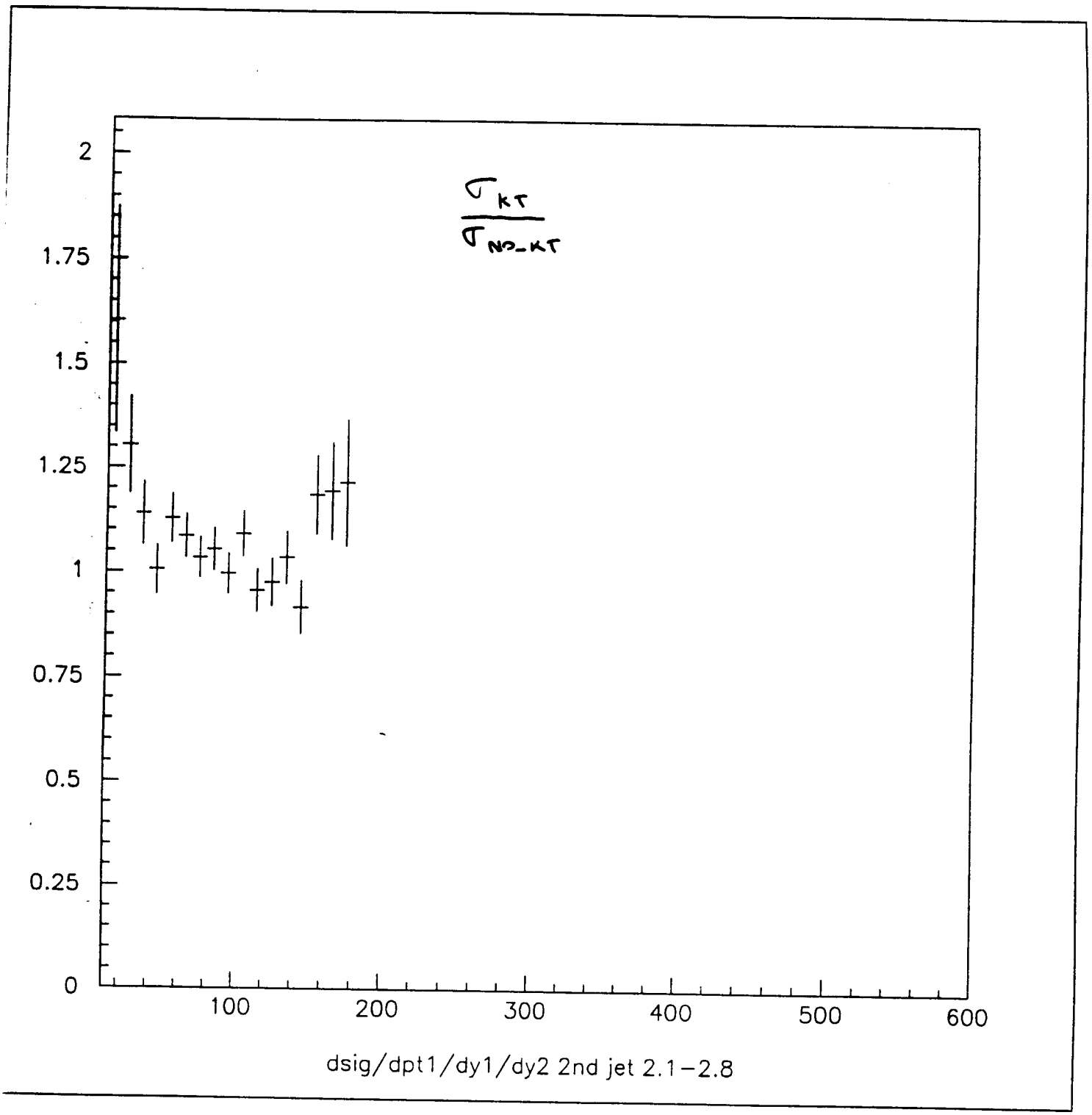

√s = 1800 GeV/c
LL Ratio kT / no kT
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
50
100
150
200
250
300
350
400
450
500
dsigma/dpt for jet no splashout
Pt (GeV/c)

Ratio of Scaled Cross-Sections: 630 and 546 over 1800




LL ratio
$\frac{P_T^3 \frac{d\sigma}{dp_T}|_{546} / P_T^3 \frac{d\sigma}{dp_T}|_{1800}}{P_T^3 \frac{d\sigma}{dp_T}|_{546} / P_T^3 \frac{d\sigma}{dp_T}|_{1800}}$
with splash. kT
no splash or kT
kT
2 GeV/c splashout
1 GeV/c splashout
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
scaled jet xt with splashout
xT


jet1
jet2
$\bar{p}\,p \to$ jet1 + jet2 + X
$\sqrt{s}$ = 1800 GeV
top points: k_T = 4 GeV/c
bottom points: no k_T
$\frac{d\sigma}{dp_T}$
10^{1}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
100
200
300
400
500
600
P_T (GeV/c)
dsig/dpt1/dy1/dy2 2nd jet 2.1−2.8


$\frac{\sigma_{KT}}{\sigma_{NO\_KT}}$
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
100
200
300
400
500
600
dsig/dpt1/dy1/dy2 2nd jet 2.1−2.8

Conclusions

1. Universality of soft gluon effects in hard scattering processes

-->jet physics

2. More formal theory for soft gluon effects in hard scattering processes

-->resummation

Where is the second scale for direct photons, or for jets...

non-perturbative part => renormalons?

3. Resummation for 2γ production

(C. Balazs, C.P. Yuan)

addition of parton showers to NLO 2γ production

(C. Balazs, J. Huston)