DIRECT PHOTONS, MESONS, k_T, AND pQCD

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For the Fermilab E706 Collaboration

Outline:

1. Intro to k_T effects
2. About E706
   - Meson and photon signals
3. Investigating k_T in E706
   - $\gamma\gamma$, $\pi^0\pi^0$ and γ-jet distributions
   - π^0 and $D^{\pm}$ p_T distributions
4. E706 π^0s and direct photons vs pQCD
   - Cross section data for:
     ♡ π^-Be $\rightarrow \gamma, \pi^0$ X at 515 GeV/c
     ♡ pBe $\rightarrow \gamma, \pi^0$ X at 530 and 800 GeV/c
   - Varying QCD scales
   - Playing with k_T smearing
5. What are the options?

WHAT IS k_T?

- k_T refers to transverse momenta of partons in colliding particles before the hard scattering.
- Transverse motion of partons manifests itself through the kinematics of hard-scattering events ($\gamma\gamma$, γ-jet, $\pi^0\pi^0$ pairs):
  - out-of-plane momentum (P_{out})
  - transverse momentum balance ($|\vec{P}_{T_1} + \vec{P}_{T_2}|$)
  - back-to-back angle ($\Delta\Phi$).
- k_T is expected to modify
  - the magnitude (and shape) of steeply falling high-p_T cross sections
  - fragmentation distributions in jets recoiling against high p_T triggers

WA70

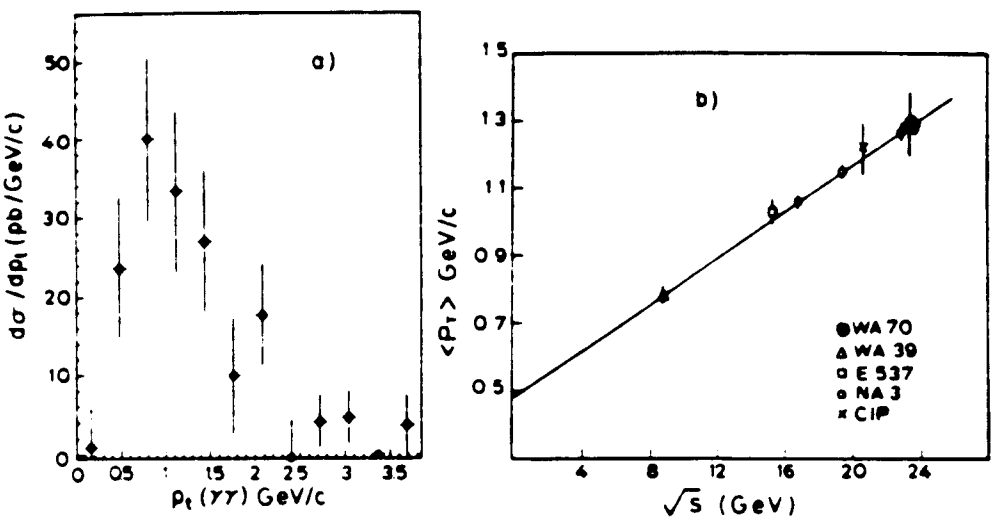


Fig. 2. (a) The differential cross section of the reaction $\pi^- p \to \gamma\gamma X$ as a function of the p_t of the $\gamma\gamma$ pair. The data are integrated over p_{t_2} from $p_{t_1} = 3.0$ GeV/c and $p_{t_2} = 2.75$ GeV/c and over the full rapidity range. The error bars include the statistical 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.

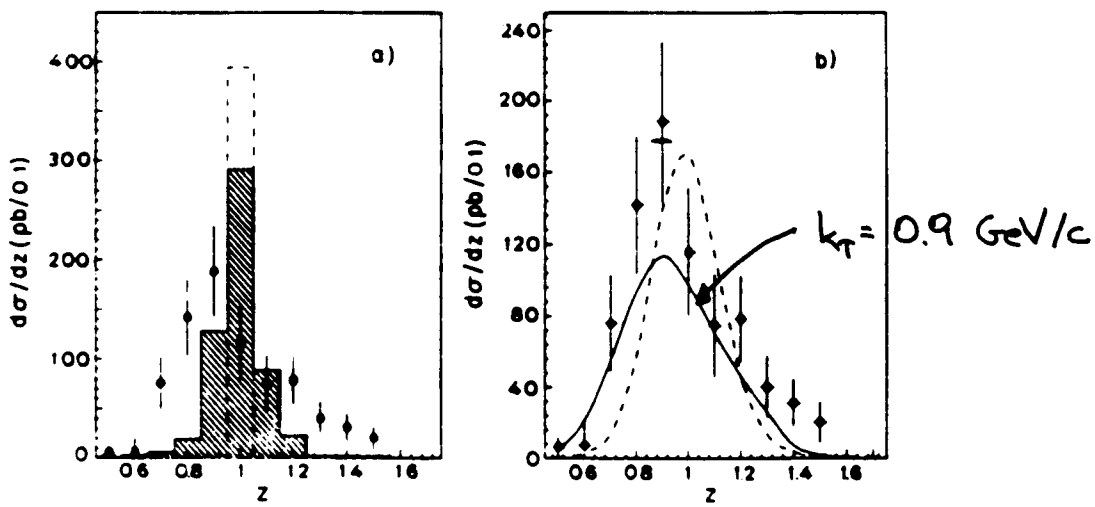
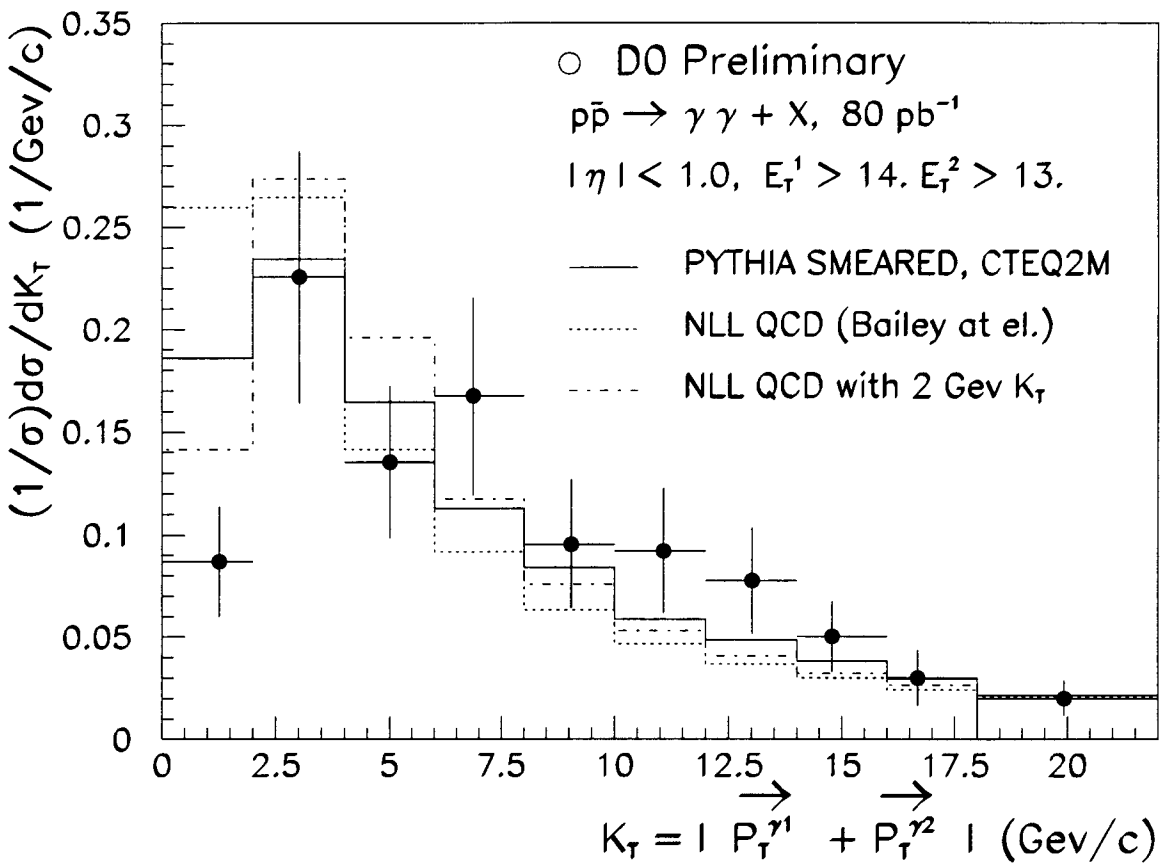
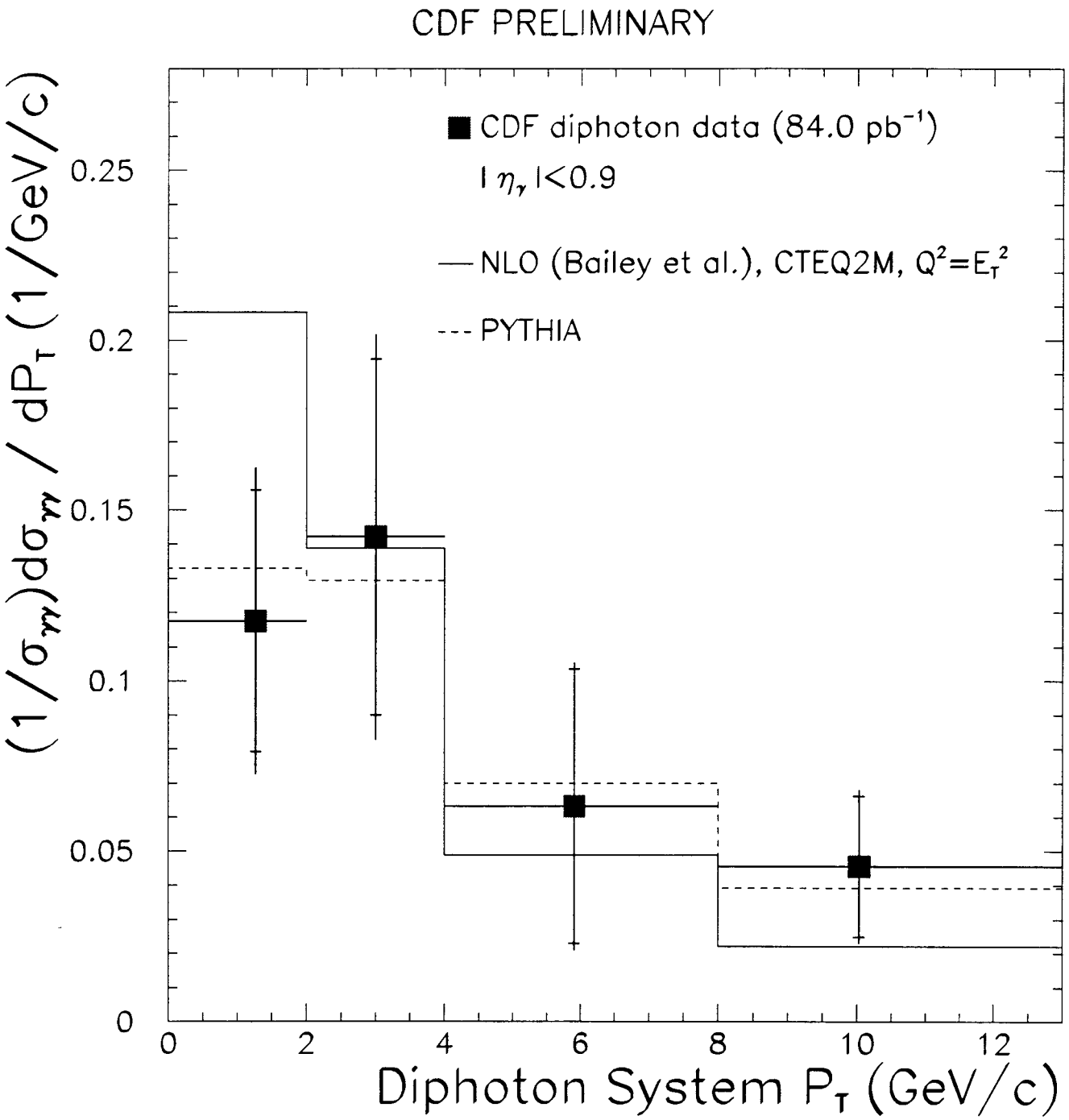
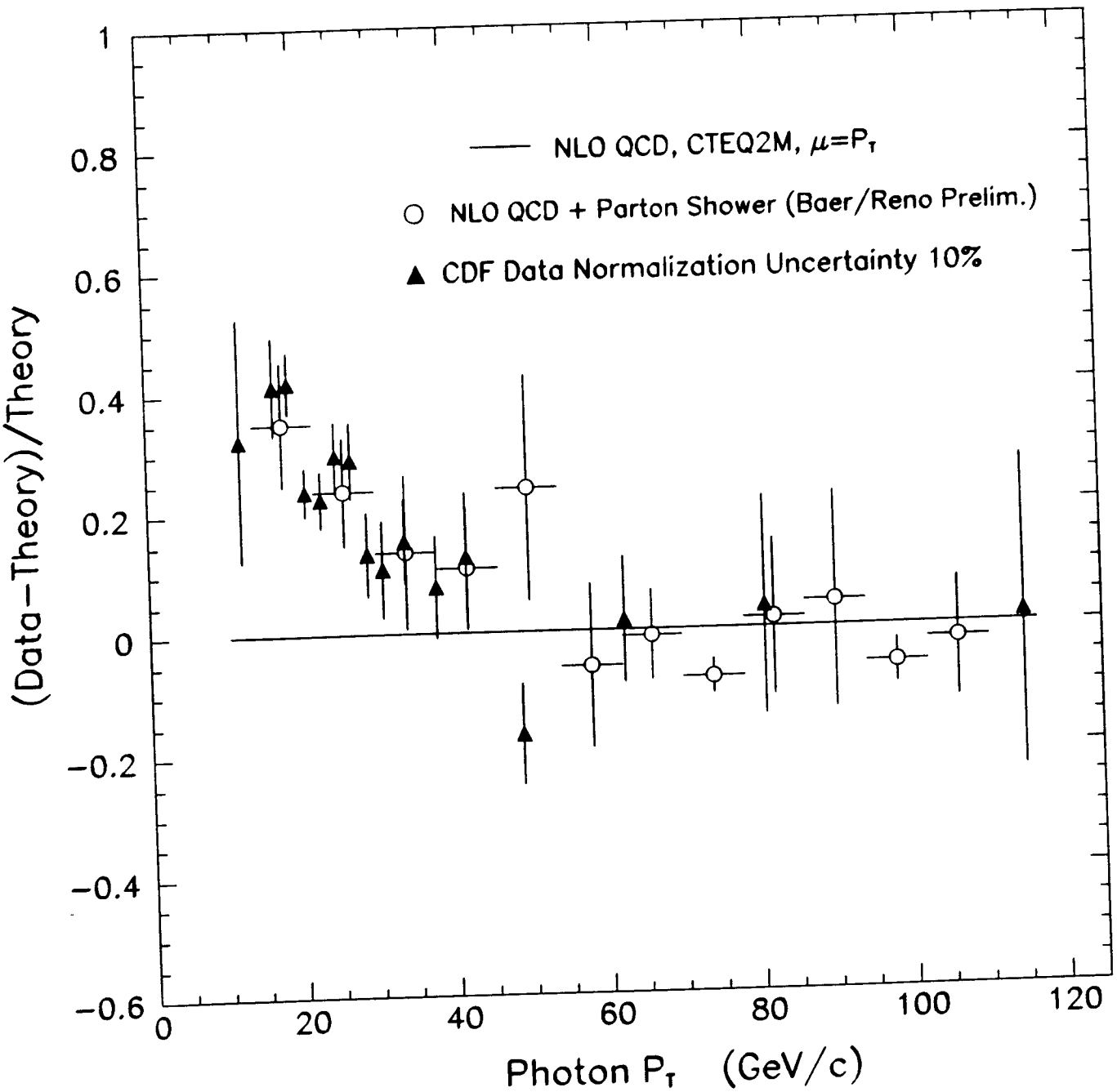


Fig. 3. The differential cross section of the reaction $\pi^- p \to \gamma\gamma X$ as function of the z variable. The data are integrated over the full rapidity range, and over p_{t_2} from $p_{t_1} = 3$ GeV/c. For each γ entering the histogram a cut $z > 2.75/p_{t_1}$ is applied. The error bars are 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.

$$z = -\vec{p}_{T\gamma 1} \cdot \vec{p}_{T\gamma 2} / |p_{T\gamma 1}|^2$$

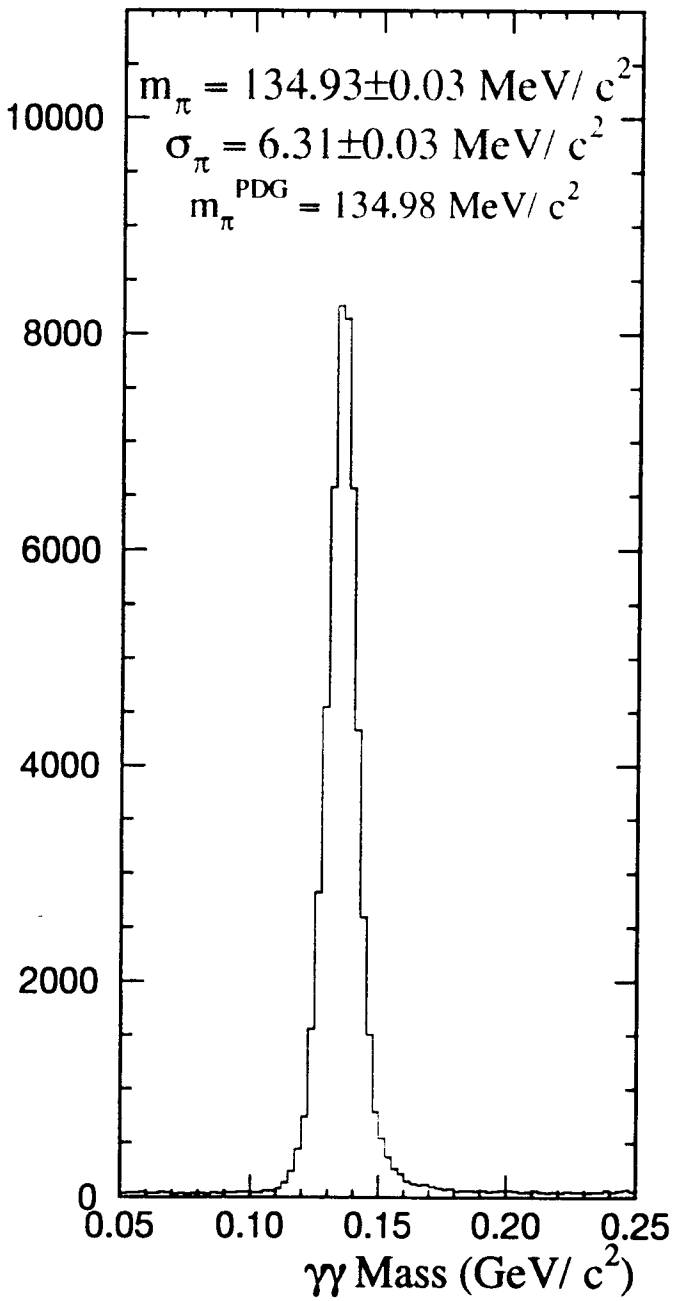

○ DØ Preliminary
$p\bar{p} \rightarrow \gamma\gamma + X$, 80 pb^{-1}
$|\eta| < 1.0$, $E_T^1 > 14.$ $E_T^2 > 13.$
PYTHIA SMEARED, CTEQ2M
NLL QCD (Bailey at el.)
NLL QCD with 2 Gev K_T
$(1/\sigma)d\sigma/dK_T$ (1/Gev/c)
$K_T = | \vec{P}_T^{\gamma 1} + \vec{P}_T^{\gamma 2} |$ (Gev/c)
0
0.05
0.1
0.15
0.2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

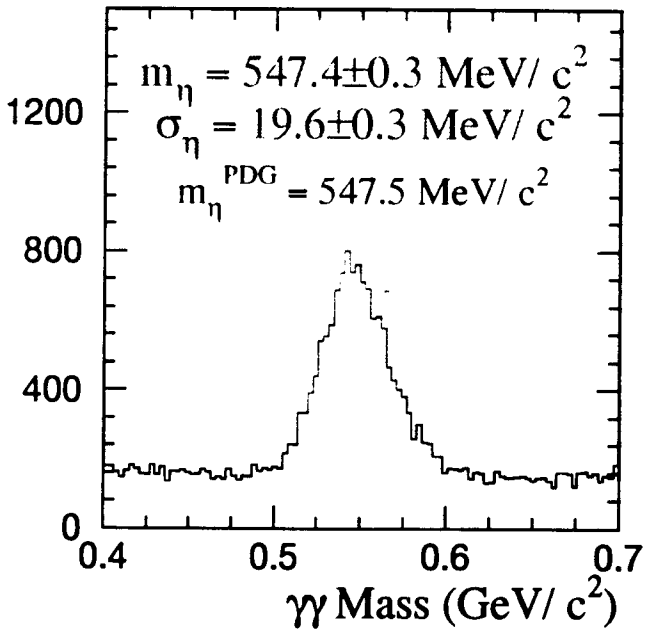

CDF PRELIMINARY
CDF diphoton data (84.0 pb^{-1})
$|\eta_\gamma|<0.9$
NLO (Bailey et al.), CTEQ2M, $Q^2=E_T^2$
PYTHIA
$(1/\sigma_{\gamma\gamma})d\sigma_{\gamma\gamma}$ / dP_T (1/GeV/c)
0
0.05
0.1
0.15
0.2
0.25
0
2
4
6
8
10
12
Diphoton System P_T (GeV/c)

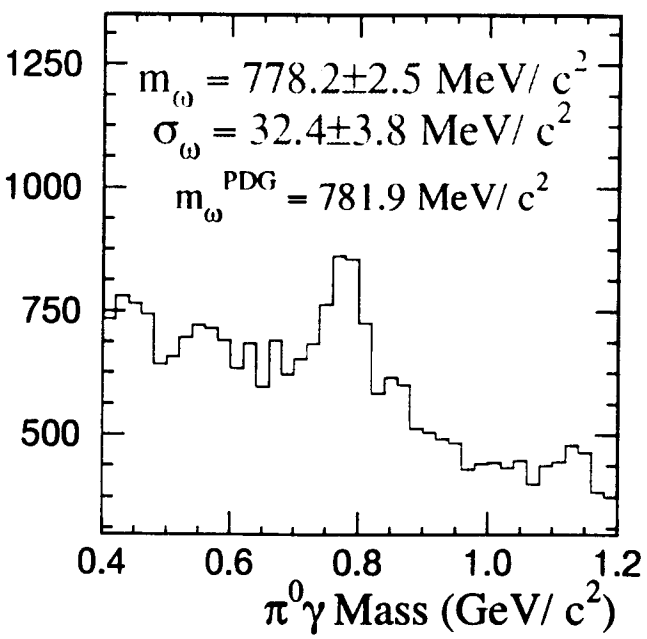

NLO QCD, CTEQ2M, $\mu=P_T$
NLO QCD + Parton Shower (Baer/Reno Prelim.)
CDF Data Normalization Uncertainty 10%
(Data−Theory)/Theory
Photon P_T (GeV/c)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
0
20
40
60
80
100
120

E706

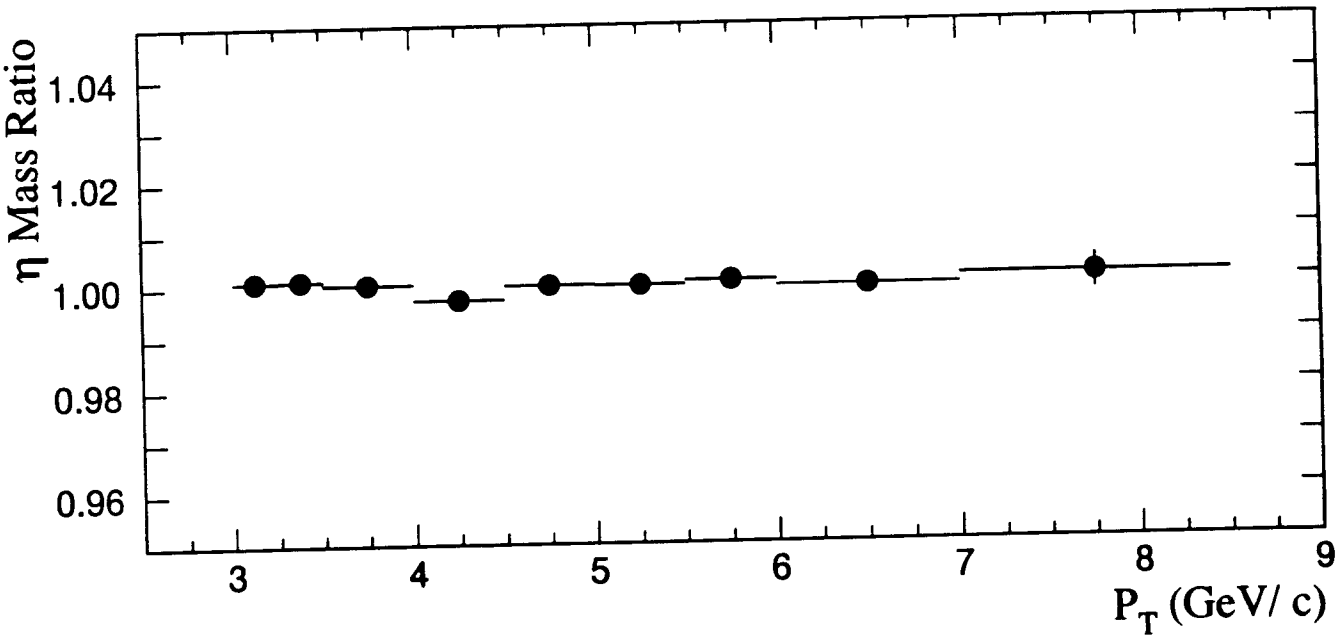
Meson Signals ($P_T > 5$ GeV/ c)

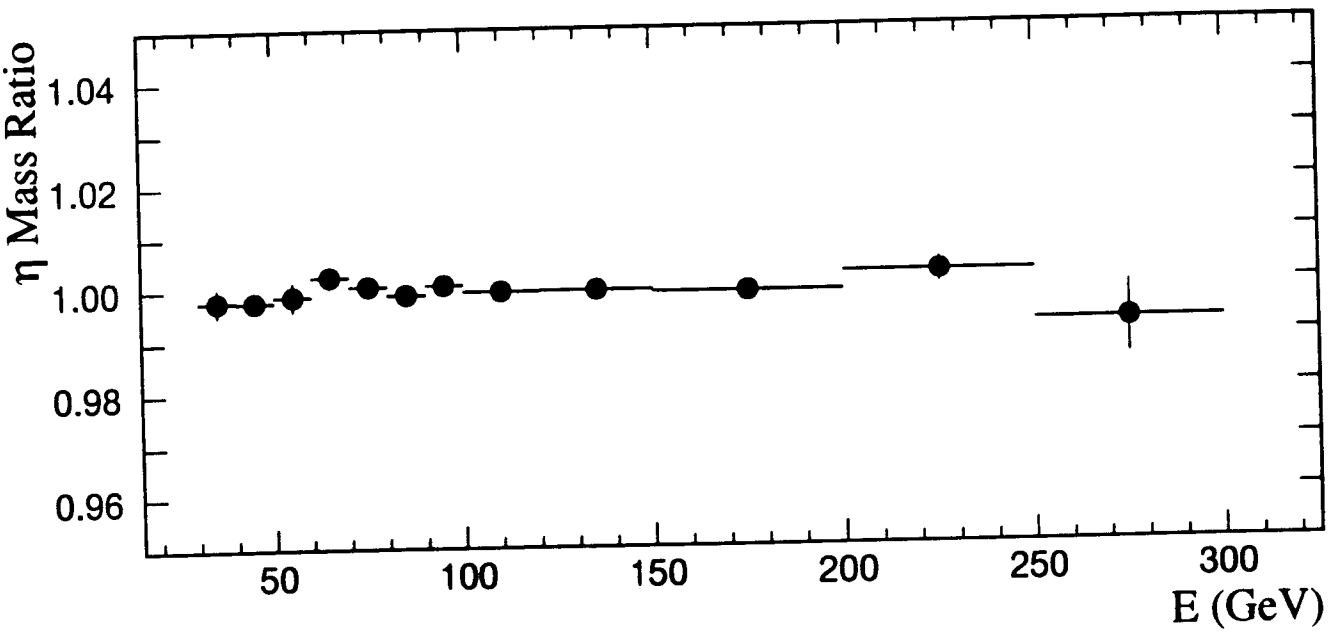


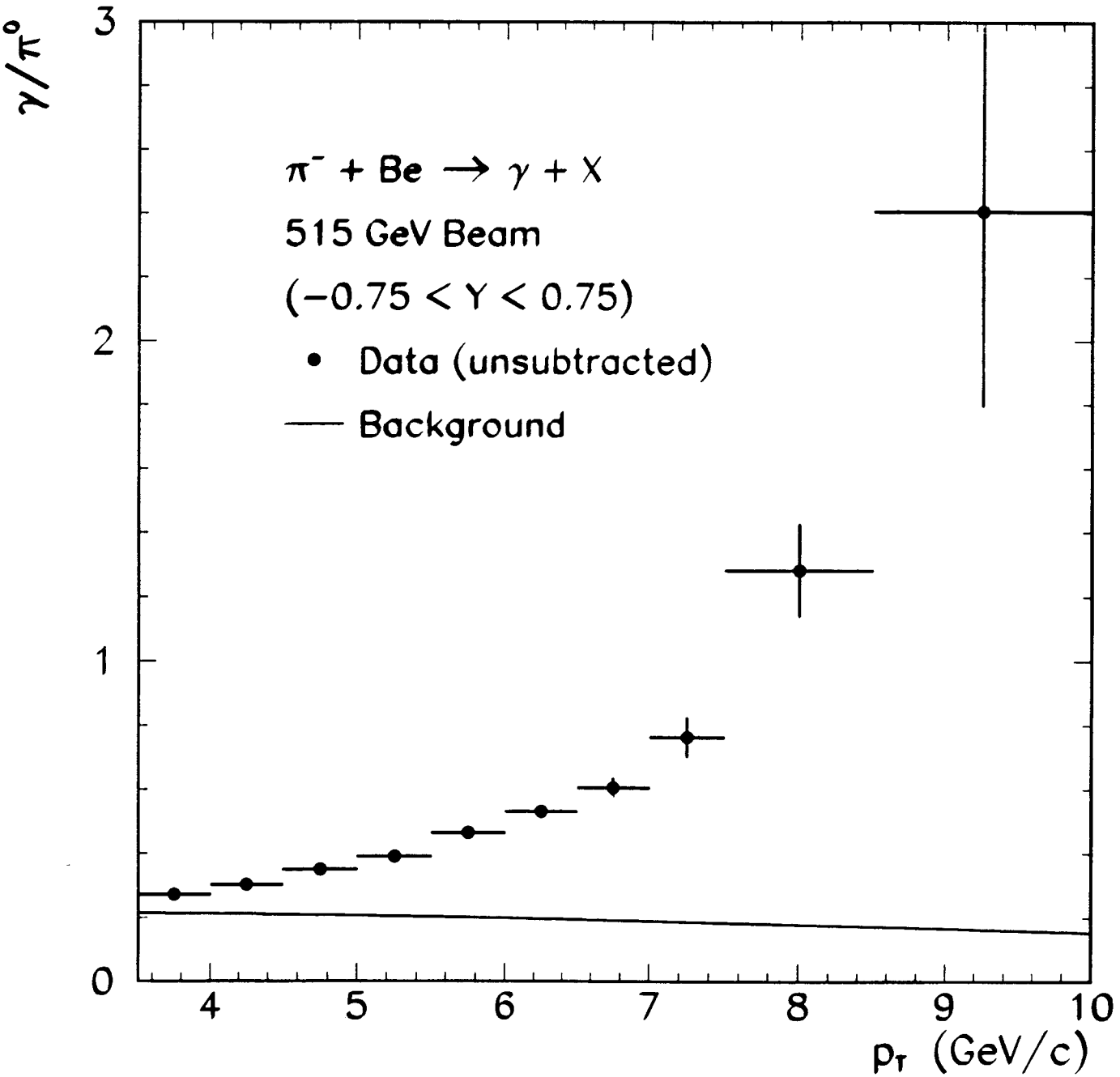




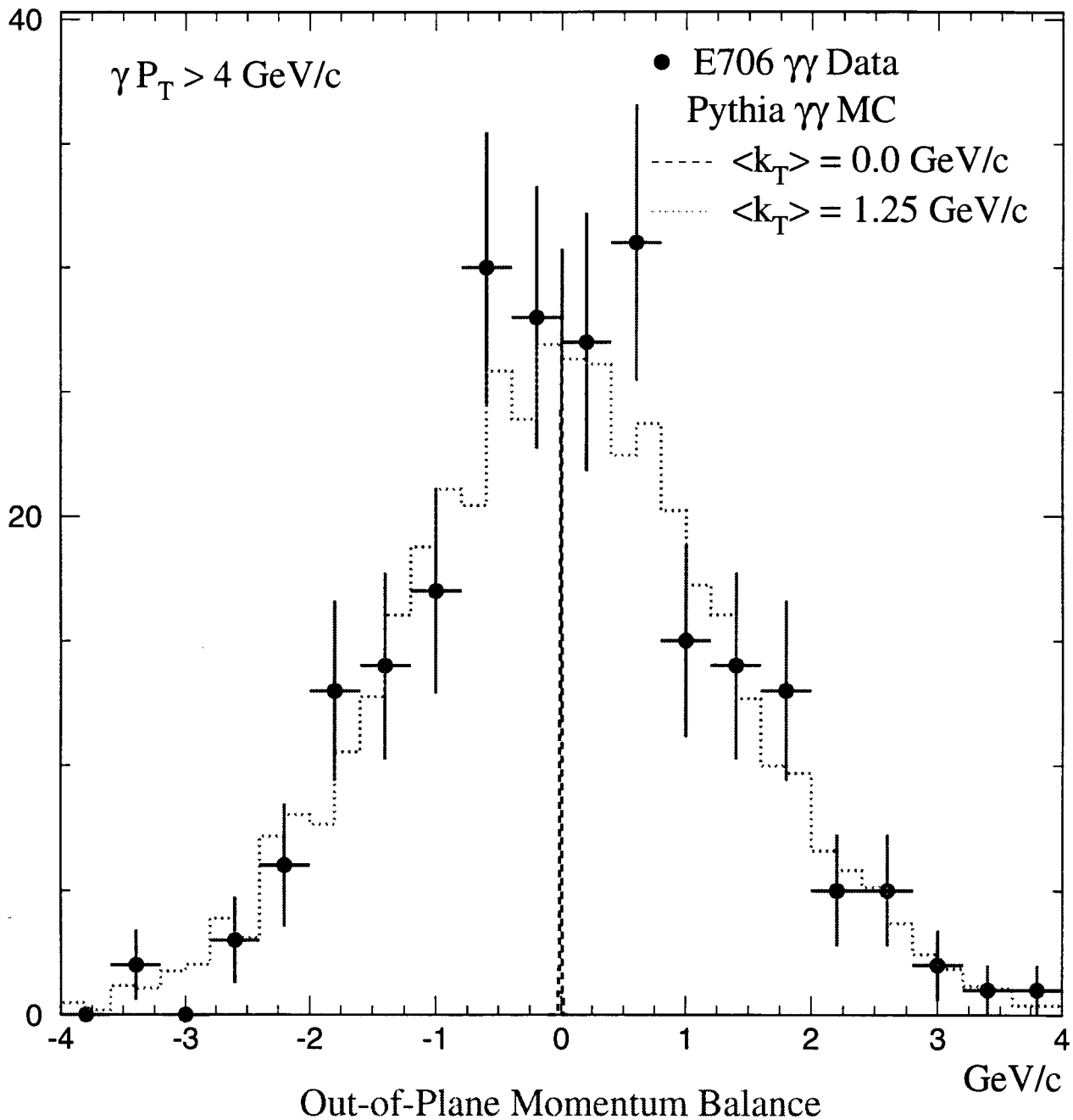
Energy Scale Linearity



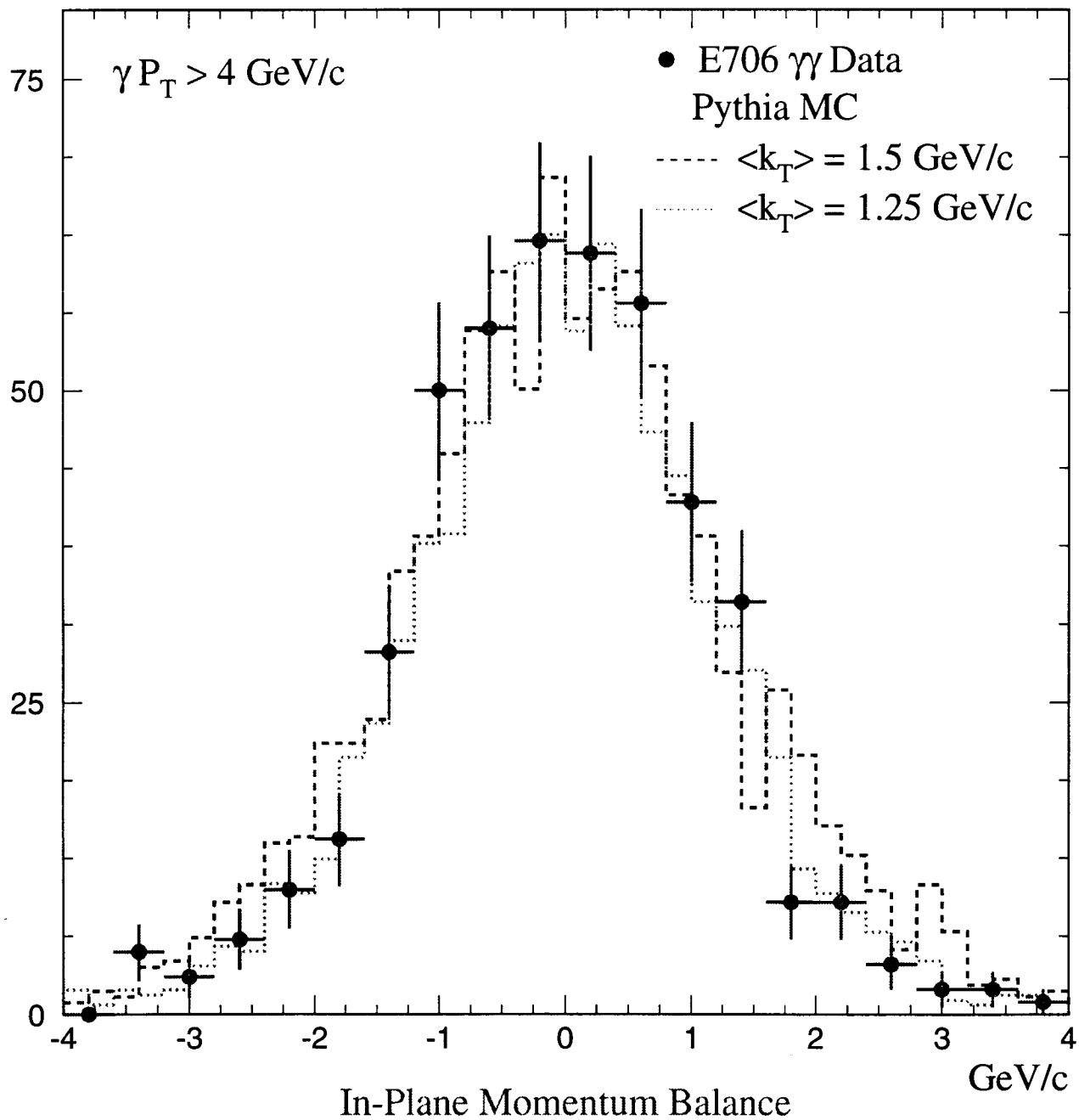



γ/π°
3
2
1
0
π⁻ + Be → γ + X
515 GeV Beam
(−0.75 < Y < 0.75)
• Data (unsubtracted)
— Background
4
5
6
7
8
9
10
p_T (GeV/c)

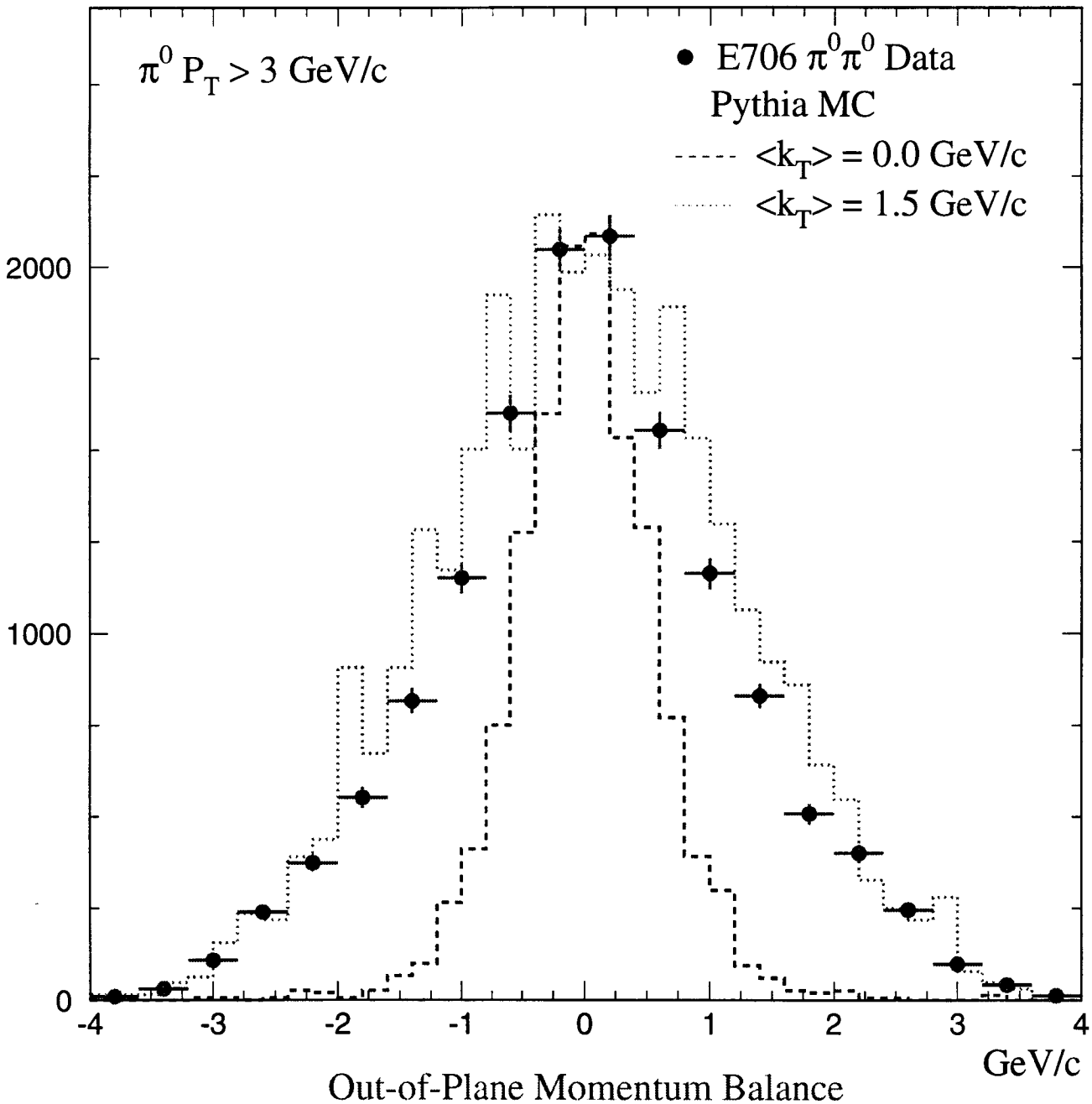
Diphoton Production (Unsubtracted)



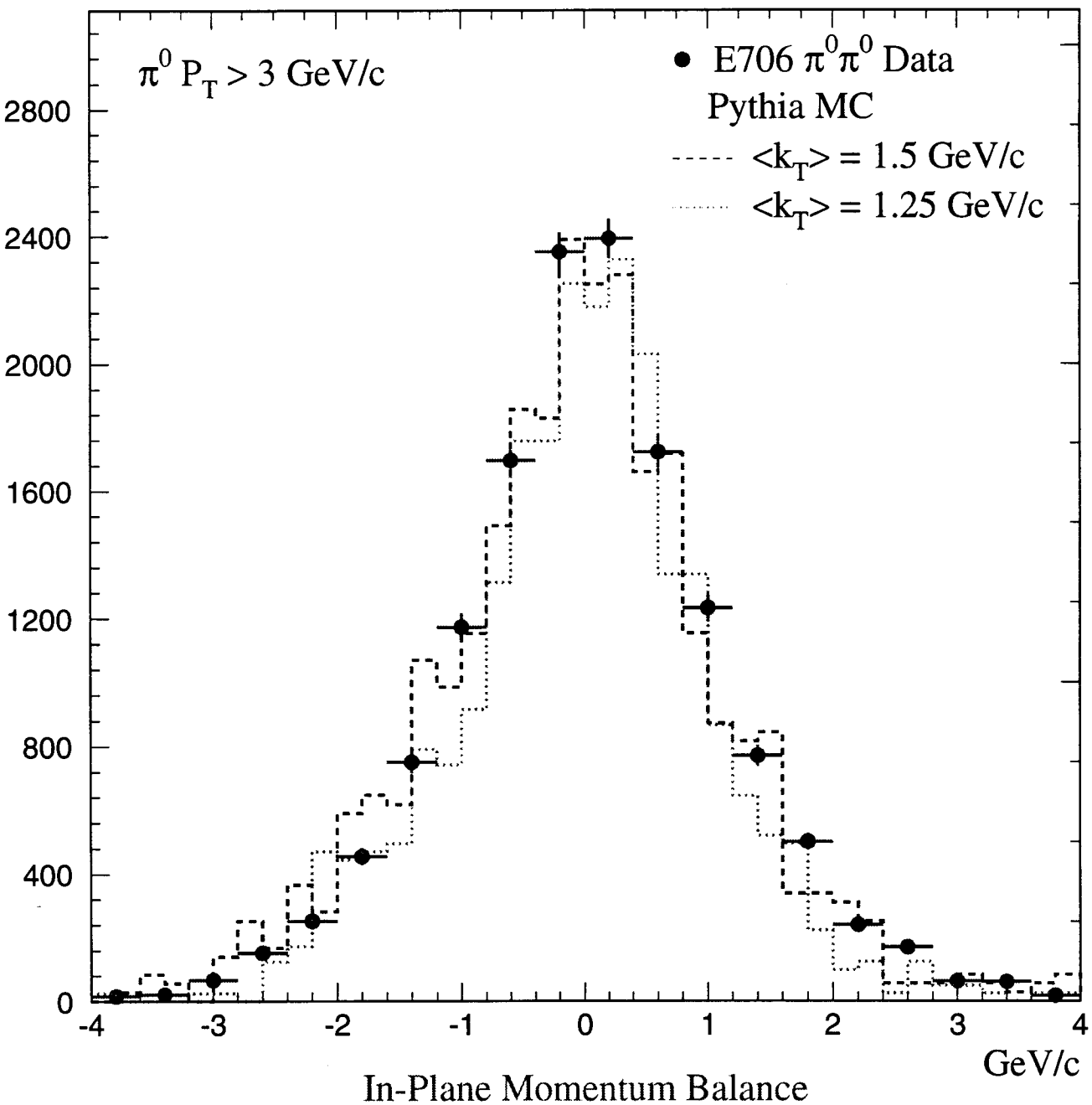
Diphoton Production (Unsubtracted)



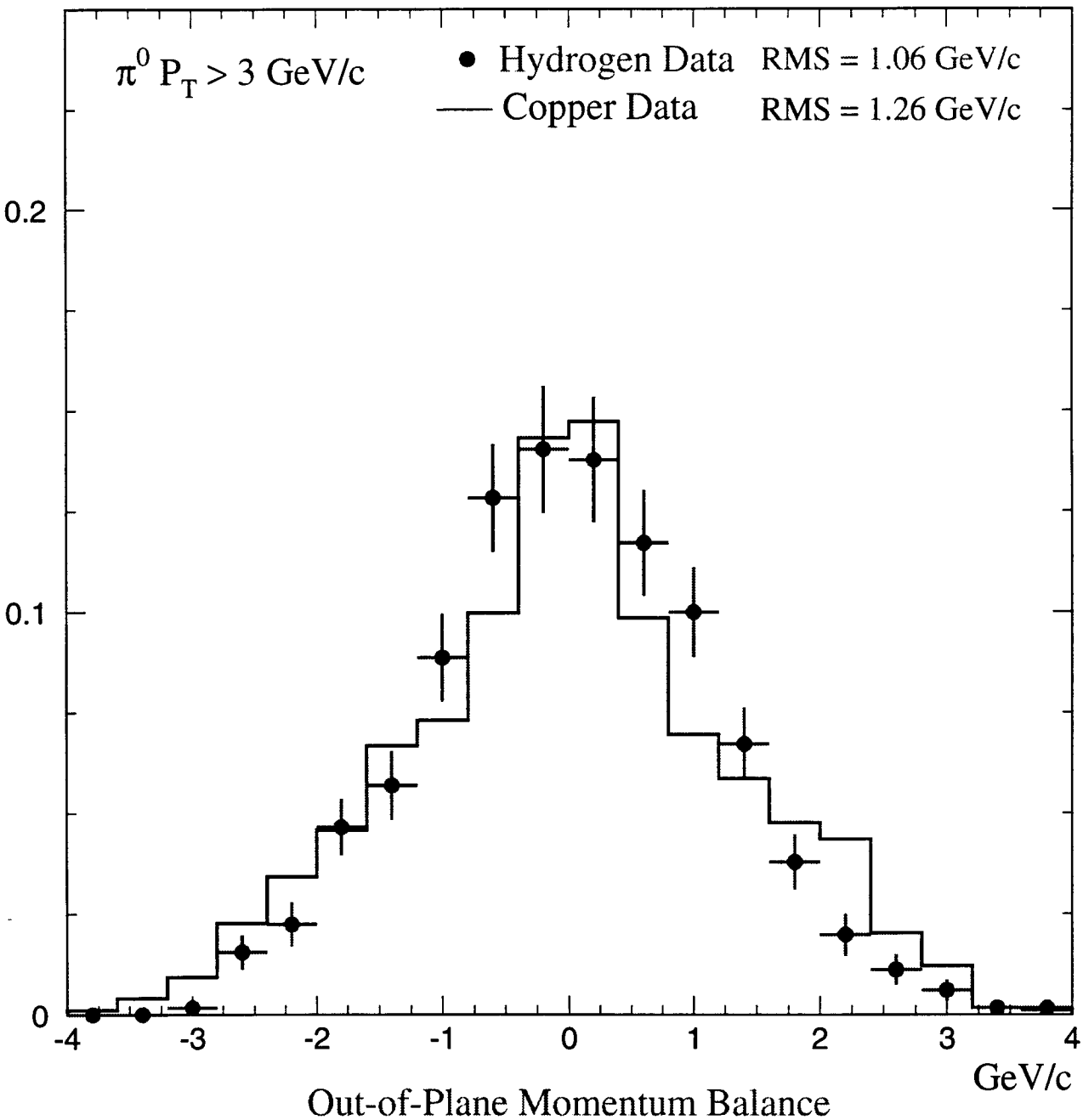
$\pi^0\pi^0$ Production

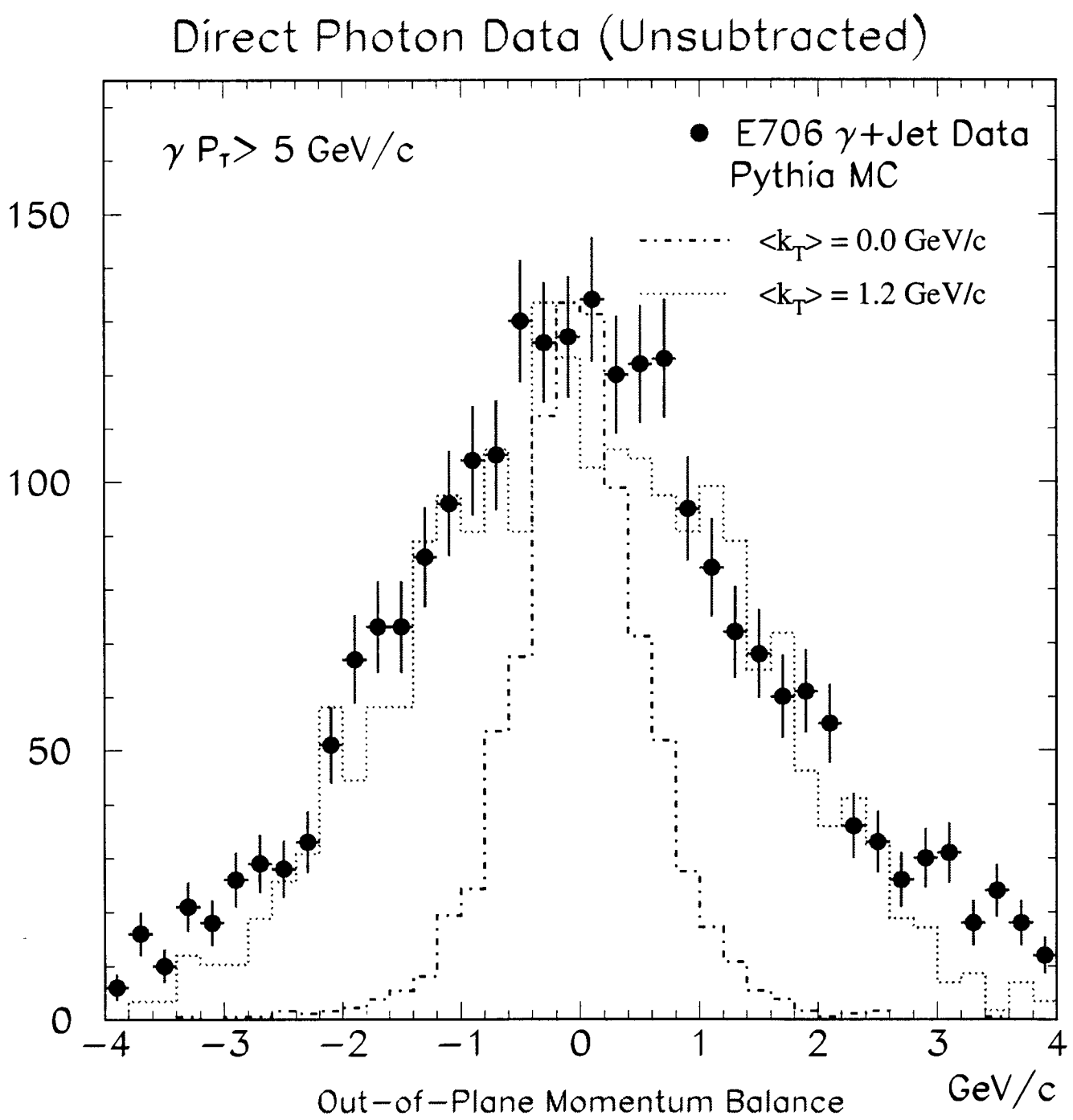


$\pi^0\pi^0$ Production

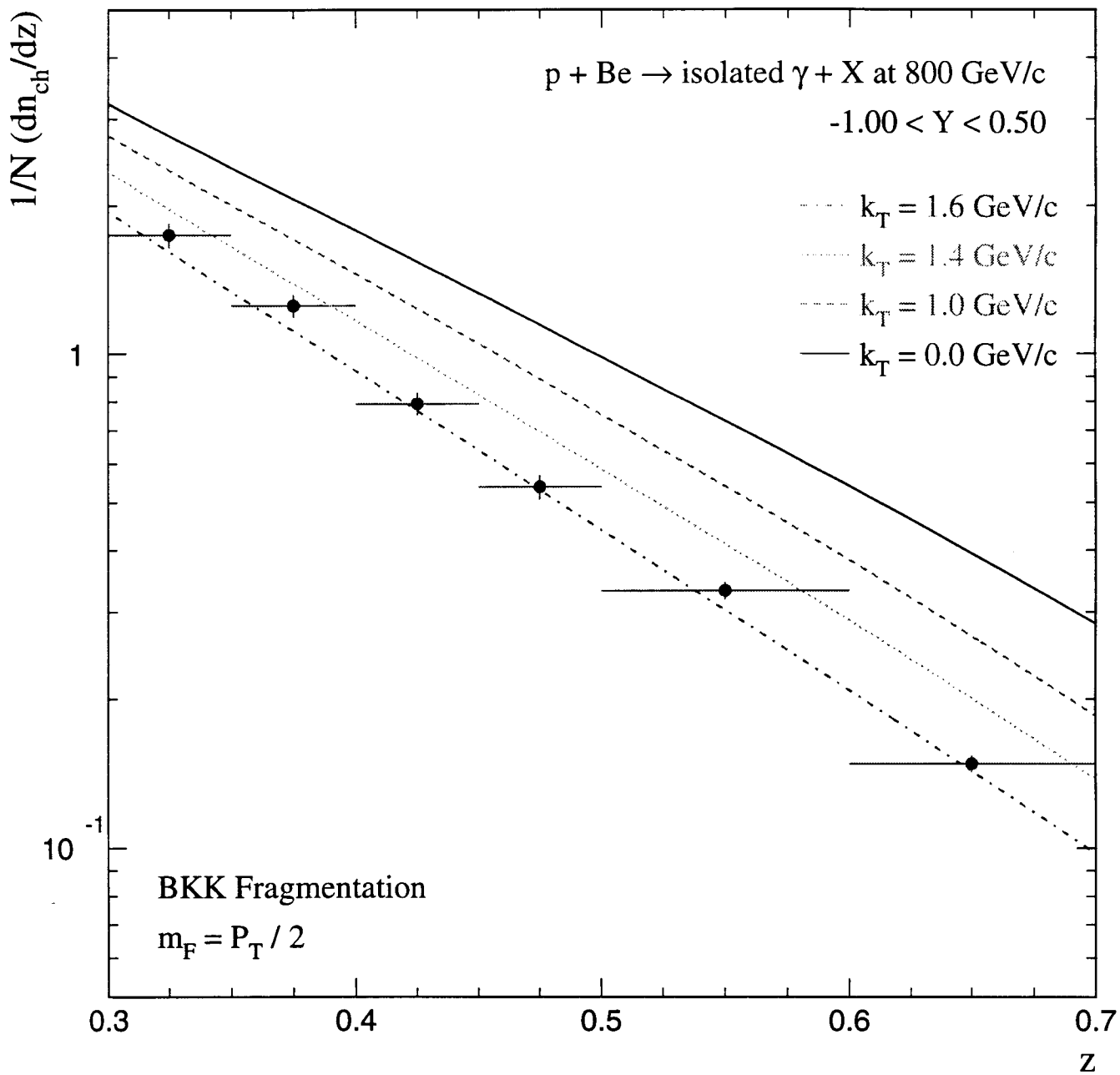


$\pi^0\pi^0$ Production

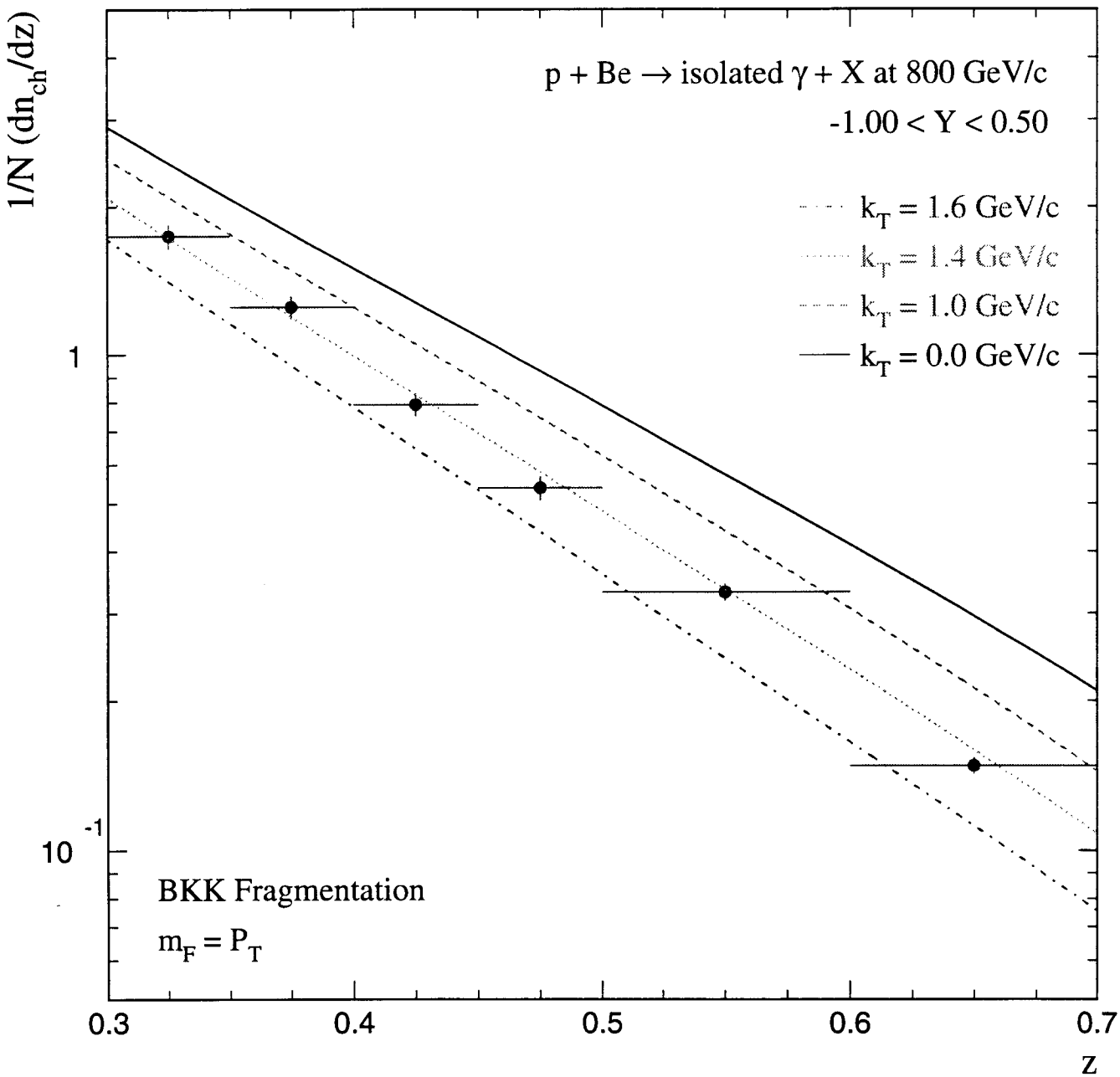


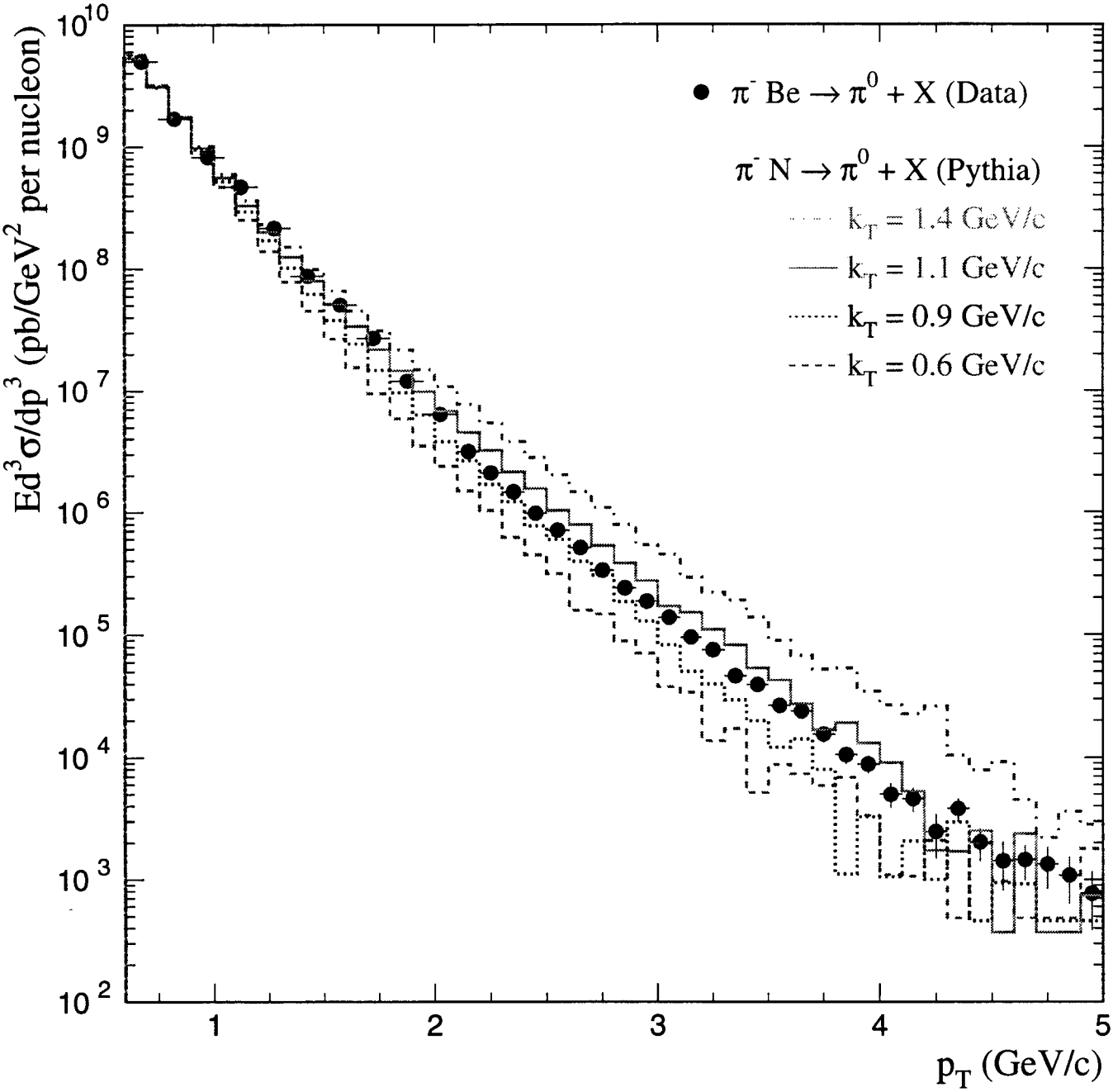

Direct Photon Data (Unsubtracted)
γ P_T> 5 GeV/c
E706 γ+Jet Data
Pythia MC
<k_T> = 0.0 GeV/c
<k_T> = 1.2 GeV/c
150
100
50
0
−4
−3
−2
−1
0
1
2
3
4
Out−of−Plane Momentum Balance
GeV/c

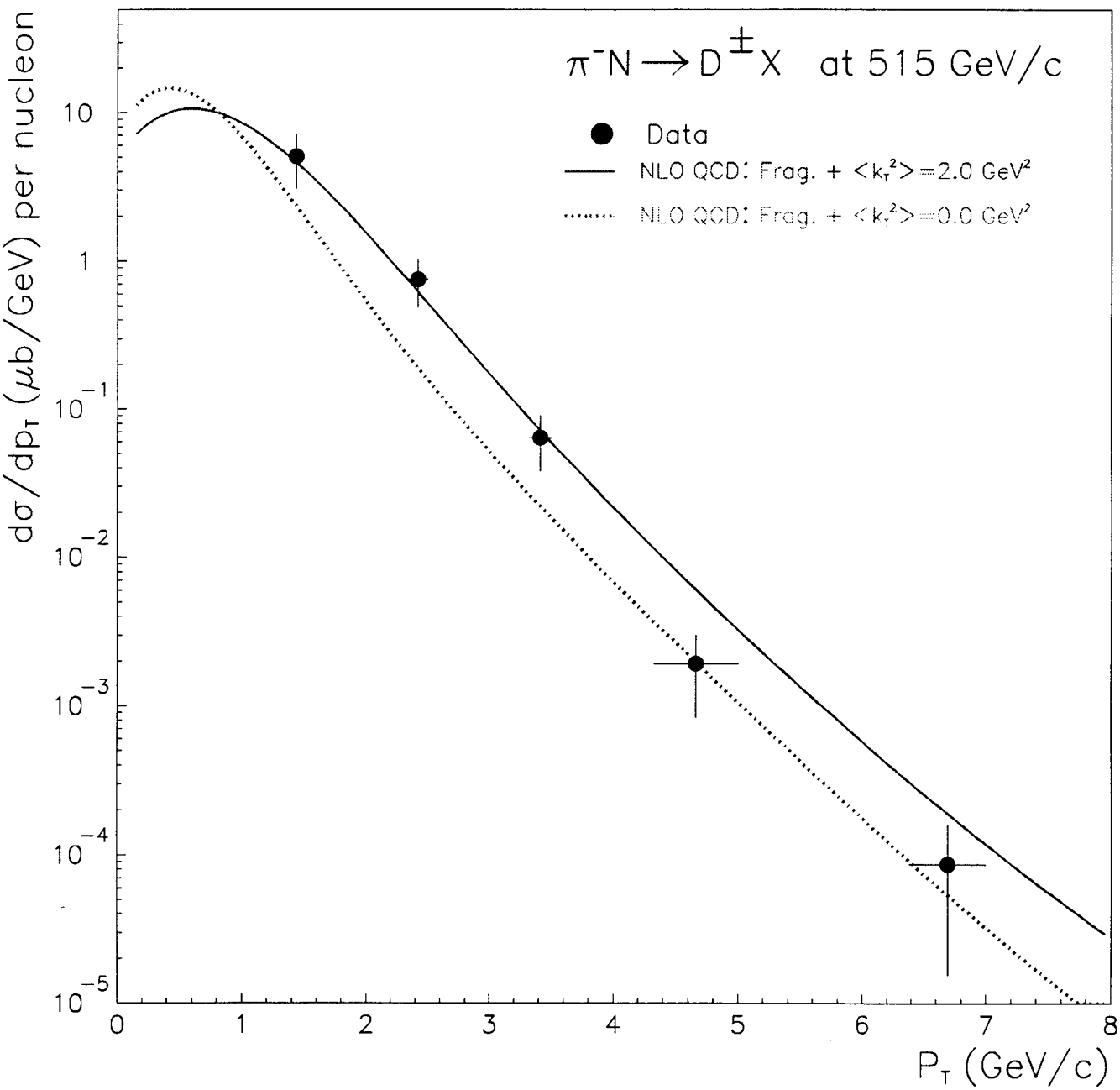
Away Side

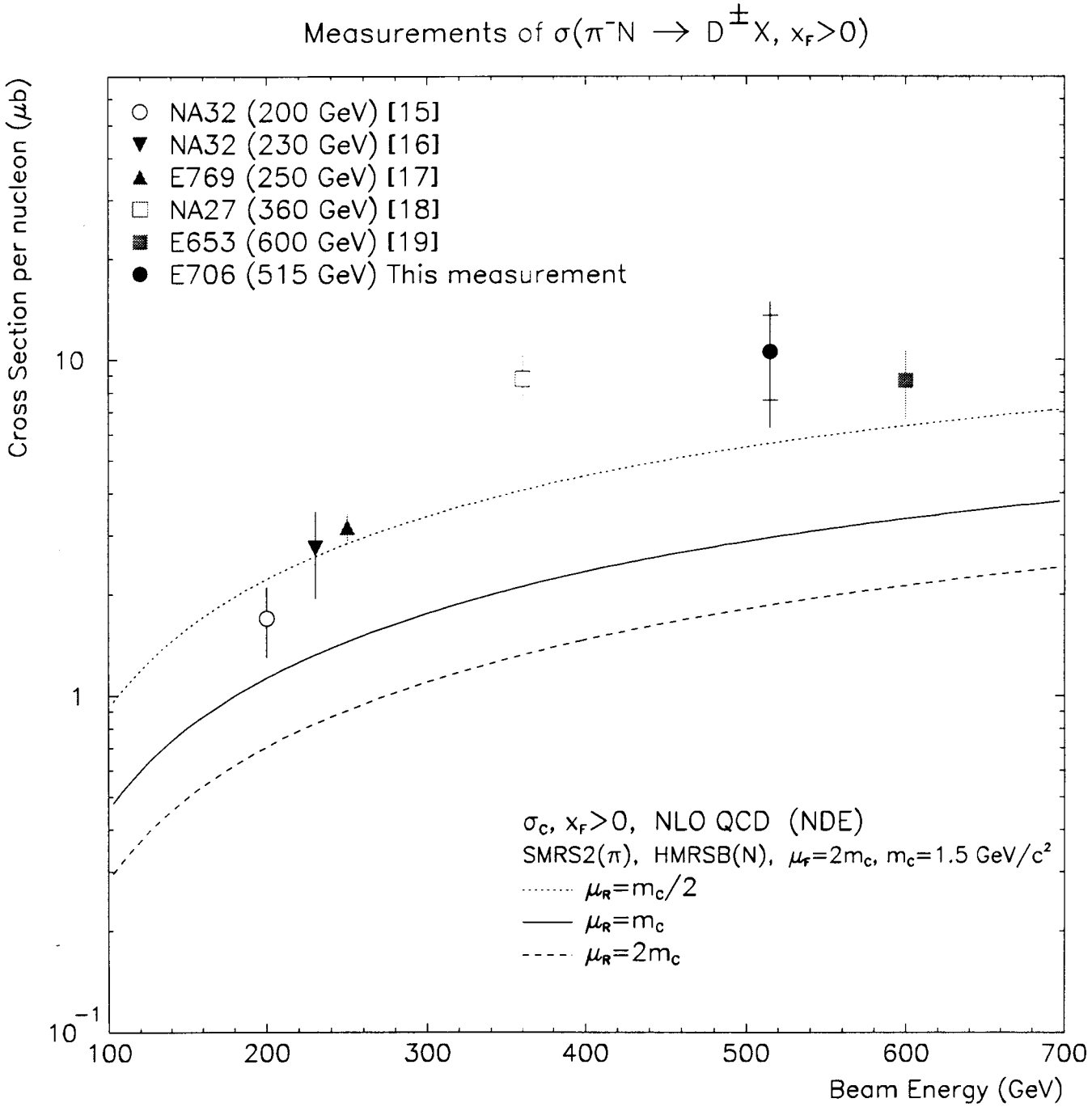

1/N (dn_ch/dz)
p + Be → isolated γ + X at 800 GeV/c
-1.00 < Y < 0.50
k_T = 1.6 GeV/c
k_T = 1.4 GeV/c
k_T = 1.0 GeV/c
k_T = 0.0 GeV/c
1
10^-1
BKK Fragmentation
m_F = P_T / 2
0.3
0.4
0.5
0.6
0.7
z

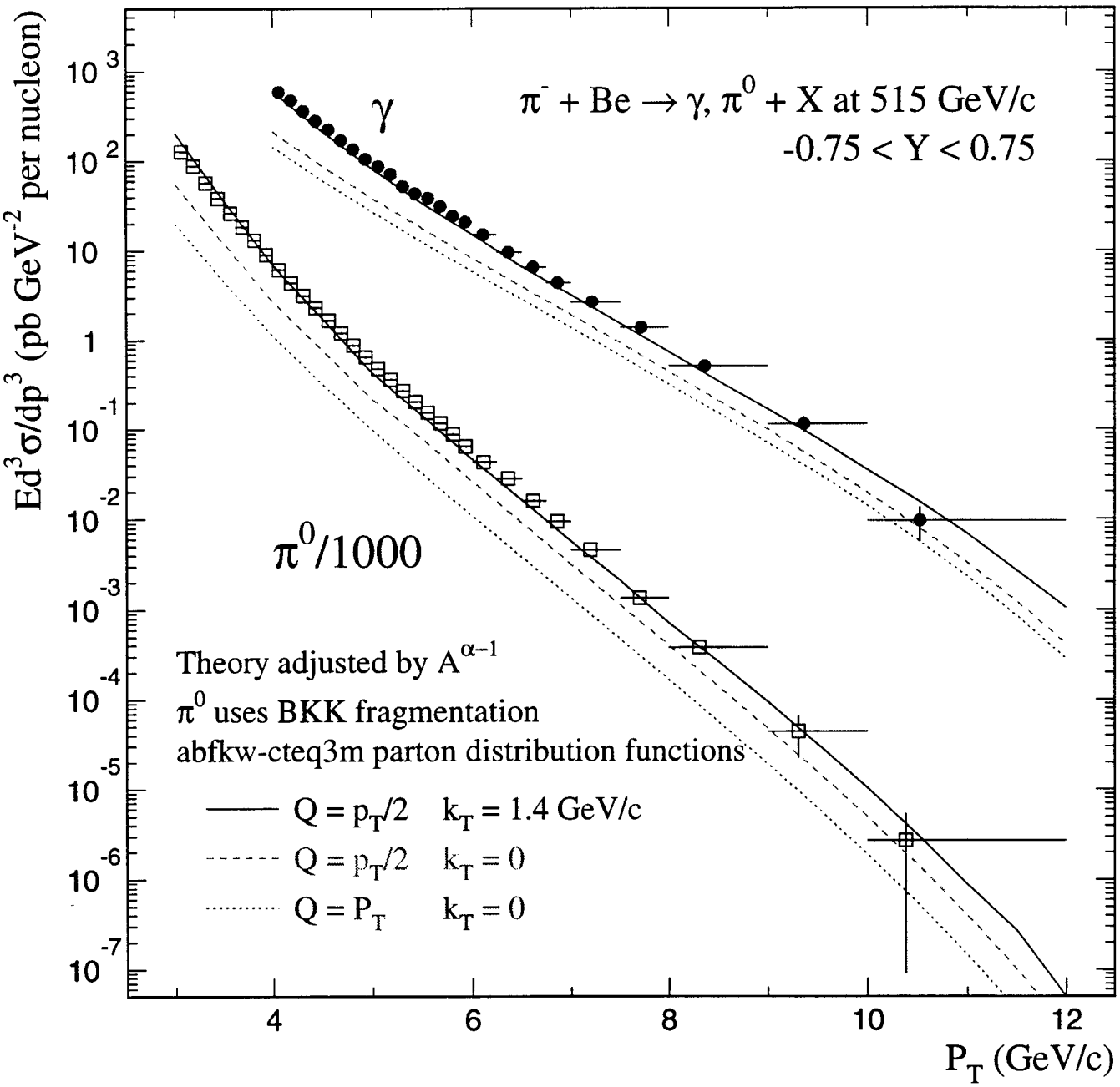
Away Side

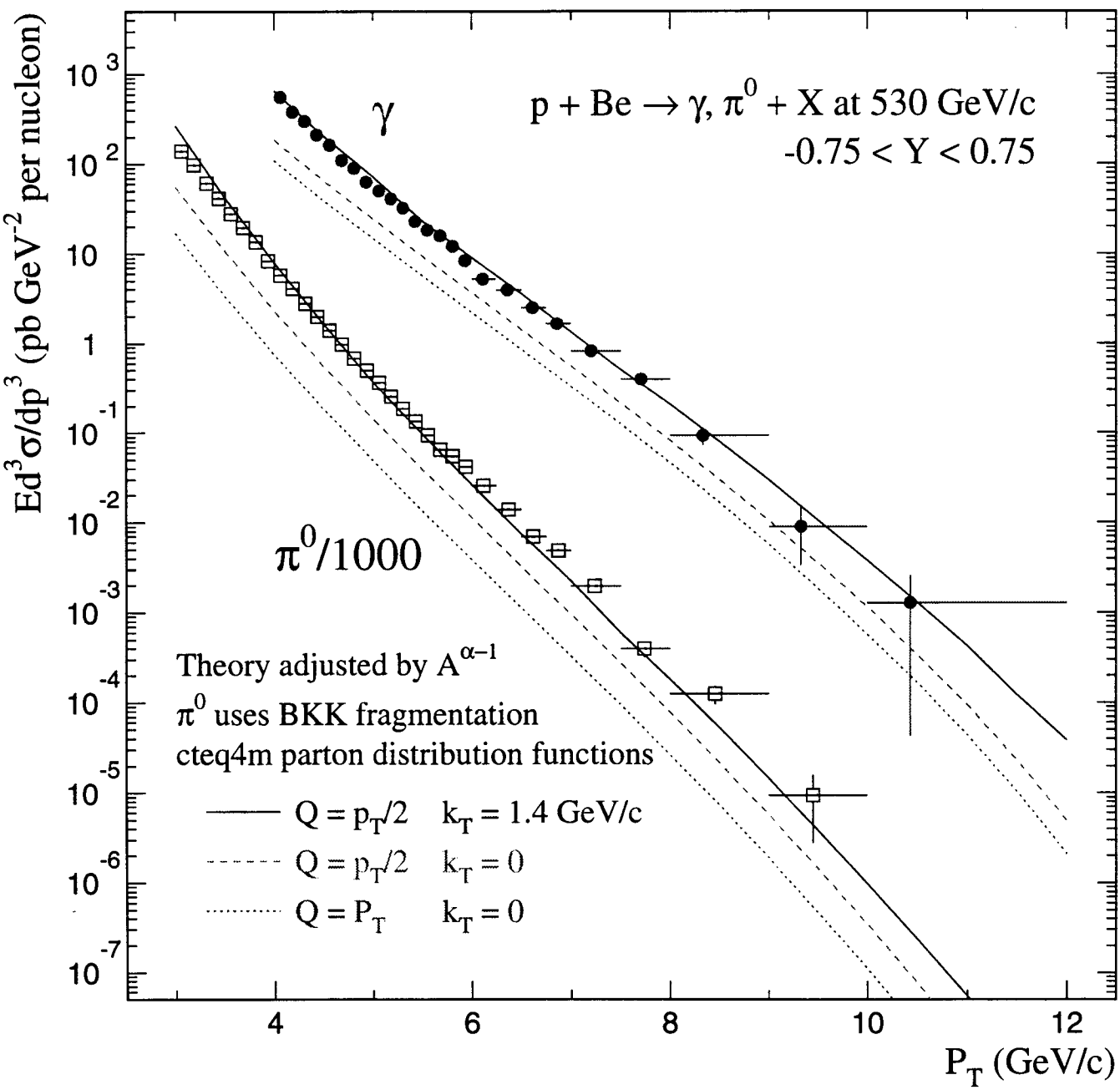

1/N (dn_ch/dz)
p + Be → isolated γ + X at 800 GeV/c
-1.00 < Y < 0.50
k_T = 1.6 GeV/c
k_T = 1.4 GeV/c
k_T = 1.0 GeV/c
k_T = 0.0 GeV/c
1
10^-1
BKK Fragmentation
m_F = P_T
0.3
0.4
0.5
0.6
0.7
z

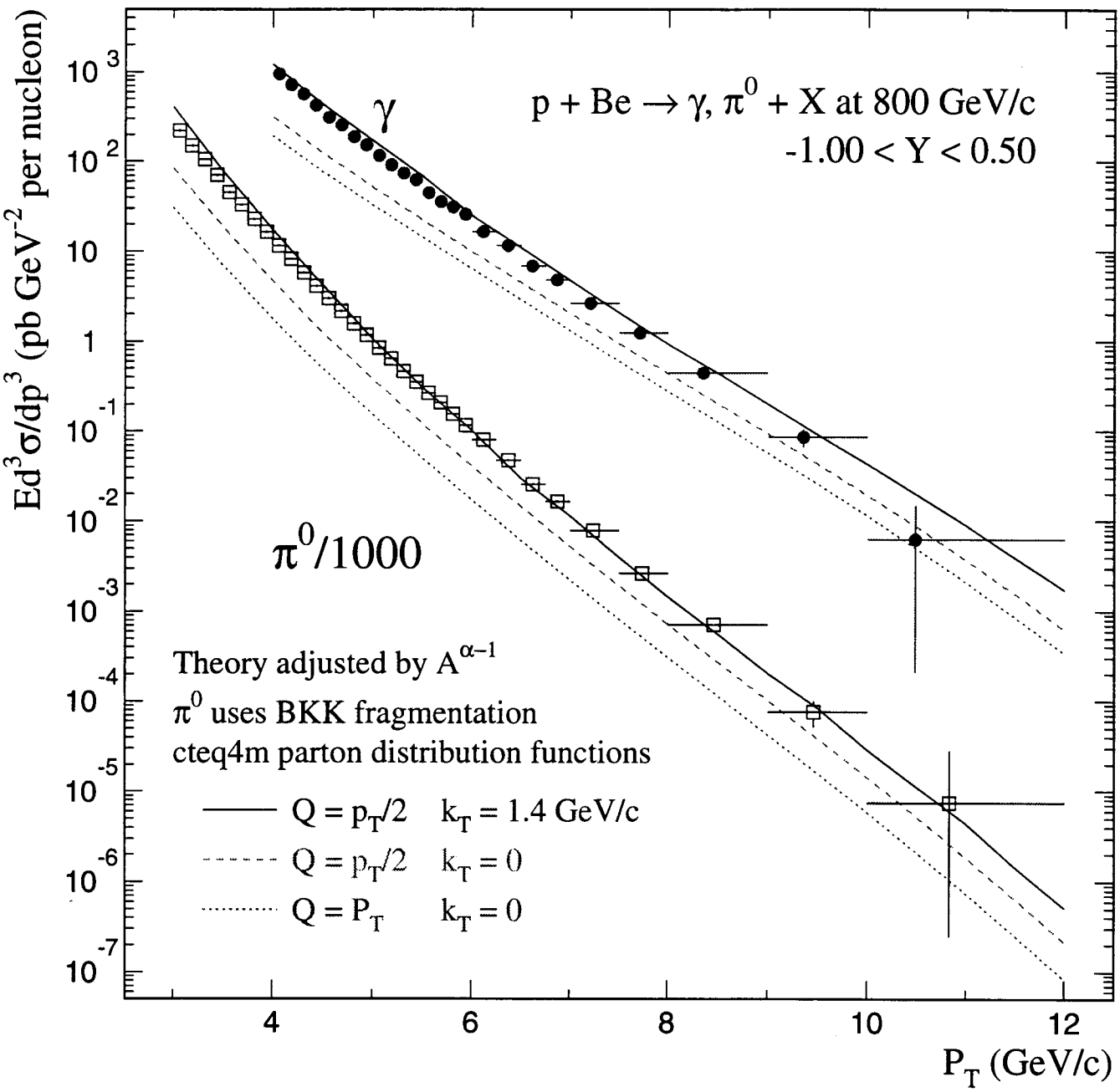

$Ed^3\sigma/dp^3$ (pb/GeV^2 per nucleon)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
1
2
3
4
5
p_T (GeV/c)
π^- Be $\rightarrow \pi^0$ + X (Data)
π^- N $\rightarrow \pi^0$ + X (Pythia)
k_T = 1.4 GeV/c
k_T = 1.1 GeV/c
k_T = 0.9 GeV/c
k_T = 0.6 GeV/c


$\pi^- N \rightarrow D^{\pm} X$ at 515 GeV/c
Data
NLO QCD: Frag. + $<k_T^2>$=2.0 GeV^2
NLO QCD: Frag. + $<k_T^2>$=0.0 GeV^2
$d\sigma/dp_T$ (μb/GeV) per nucleon
P_T (GeV/c)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
1
2
3
4
5
6
7
8


Measurements of σ(π⁻N → D±X, x_F>0)
Cross Section per nucleon (μb)
NA32 (200 GeV) [15]
NA32 (230 GeV) [16]
E769 (250 GeV) [17]
NA27 (360 GeV) [18]
E653 (600 GeV) [19]
E706 (515 GeV) This measurement
10
1
10⁻¹
100
200
300
400
500
600
700
Beam Energy (GeV)
σ_c, x_F>0, NLO QCD (NDE)
SMRS2(π), HMRSB(N), μ_F=2m_c, m_c=1.5 GeV/c²
μ_R=m_c/2
μ_R=m_c
μ_R=2m_c


$\pi^- + Be \rightarrow \gamma, \pi^0 + X$ at 515 GeV/c
$-0.75 < Y < 0.75$
γ
$\pi^0/1000$
Theory adjusted by $A^{\alpha-1}$
π^0 uses BKK fragmentation
abfkw-cteq3m parton distribution functions
$Q = p_T/2$ $k_T = 1.4$ GeV/c
$Q = p_T/2$ $k_T = 0$
$Q = P_T$ $k_T = 0$
$Ed^3\sigma/dp^3$ (pb GeV^{-2} per nucleon)
P_T (GeV/c)

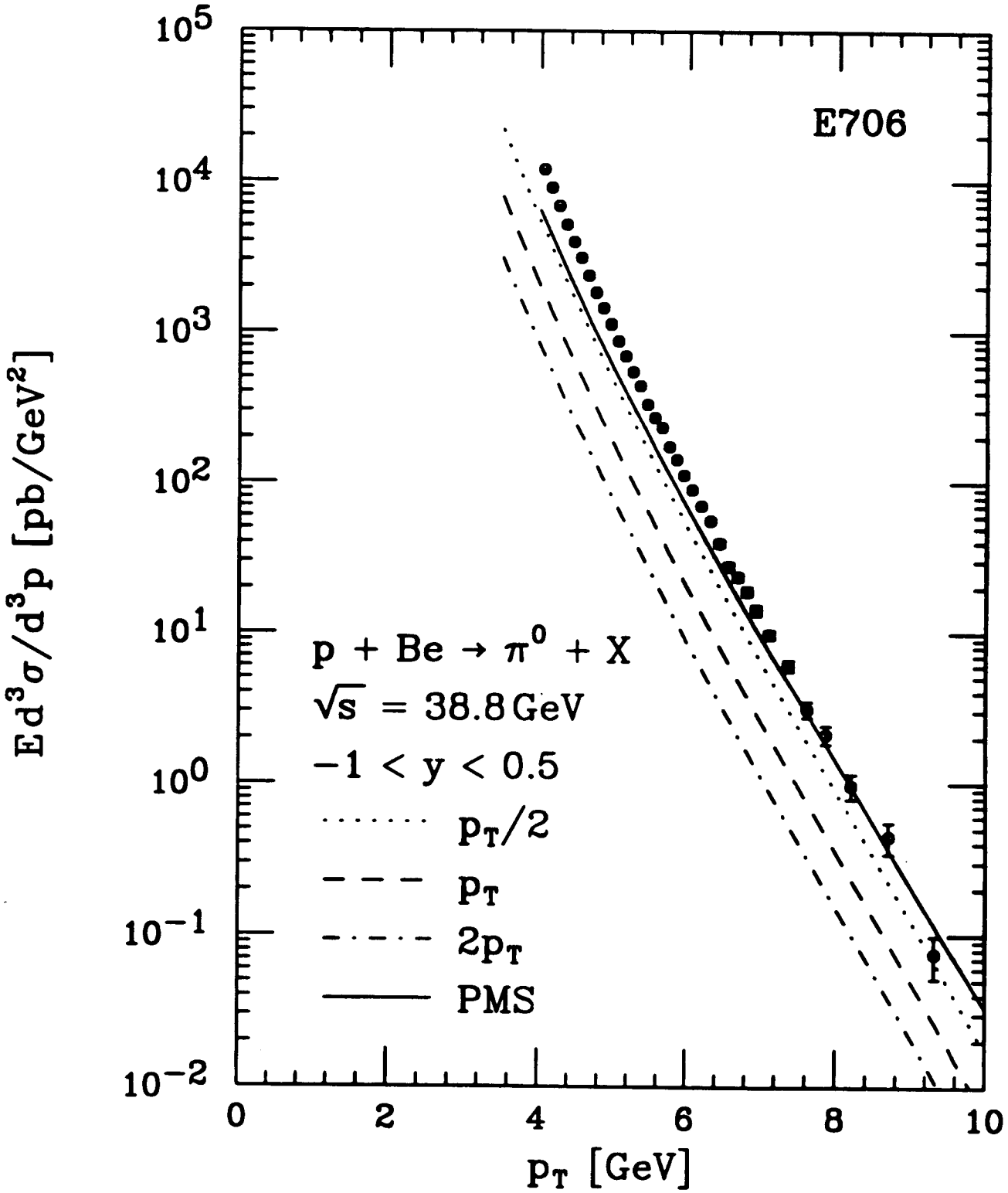

$Ed^3\sigma/dp^3$ (pb GeV^{-2} per nucleon)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
4
6
8
10
12
P_T (GeV/c)
γ
$p + Be \rightarrow \gamma, \pi^0 + X$ at 530 GeV/c
$-0.75 < Y < 0.75$
$\pi^0/1000$
Theory adjusted by $A^{\alpha-1}$
π^0 uses BKK fragmentation
cteq4m parton distribution functions
$Q = p_T/2$ $k_T = 1.4$ GeV/c
$Q = p_T/2$ $k_T = 0$
$Q = P_T$ $k_T = 0$


$Ed^3\sigma/dp^3$ (pb GeV^{-2} per nucleon)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
γ
p + Be $\rightarrow \gamma, \pi^0$ + X at 800 GeV/c
-1.00 < Y < 0.50
π^0/1000
Theory adjusted by $A^{\alpha-1}$
π^0 uses BKK fragmentation
cteq4m parton distribution functions
$Q = p_T/2$ $k_T = 1.4$ GeV/c
$Q = p_T/2$ $k_T = 0$
$Q = P_T$ $k_T = 0$
4
6
8
10
12
P_T (GeV/c)

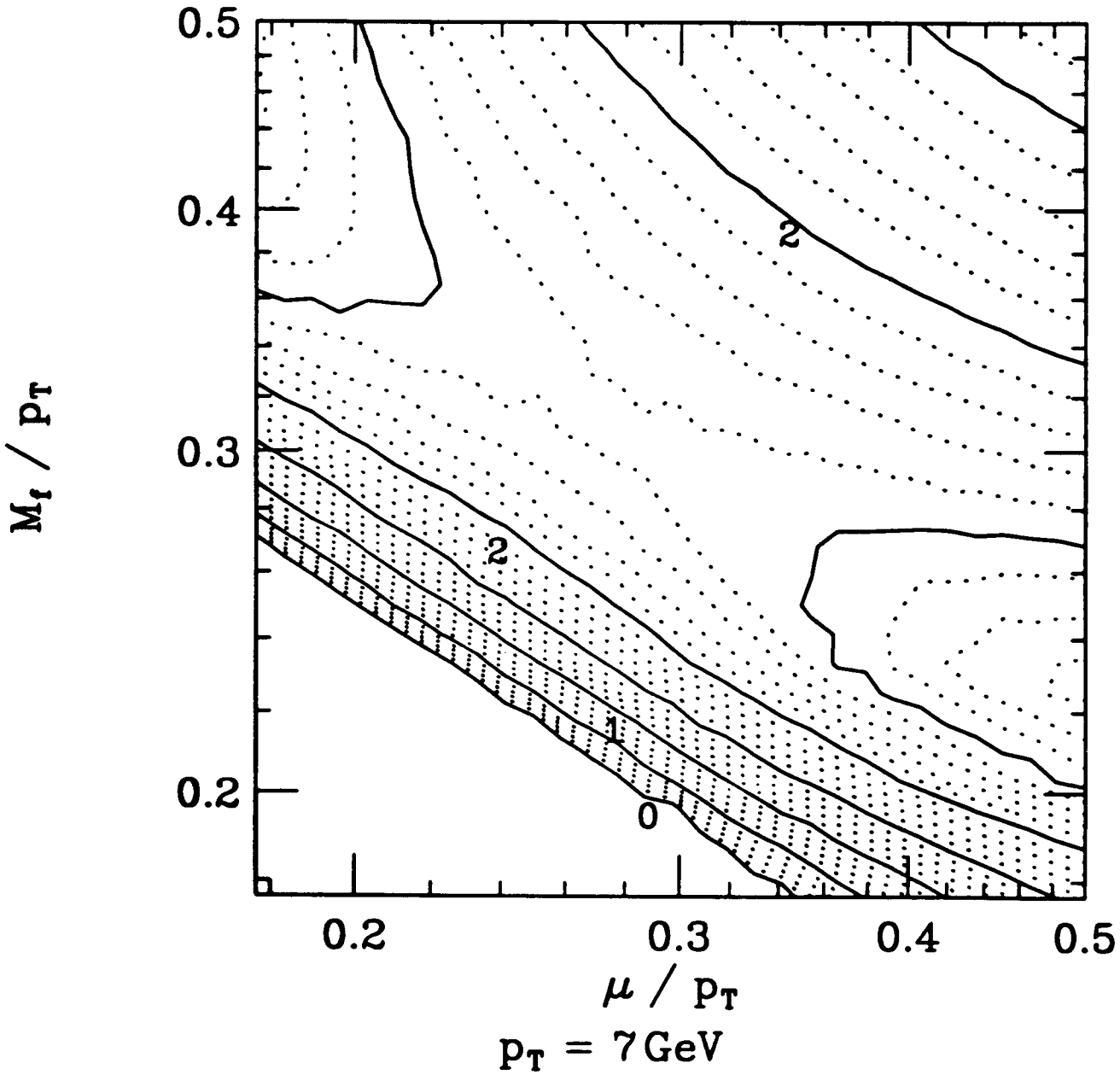
WHAT ARE THE OPTIONS?

1. k_T smearing:
   - CTEQ said so.
   - George Sterman proved it.
   - Data has it.
   - It works.
   - Nothing else seems to work (so far).
2. Other choices of QCD scales:
   - Optimized scales. (Aurenche, Kniehl)
   - Other scale setting methods?
   - Arbitrary small and/or unequal scales to match the data.
3. Resummation of soft gluon emissions:
   - Is resummation expected to change inclusive cross sections *à la* DY K-factors?
   - Is resummation acting like an effective k_T smearing? (cf $\gamma\gamma$)
4. Partial explanations:
   - Modified PDFs.
   - NLL treatment of brems contribution. (Gordon, Chiapetta et al)
   - Resummation of $\log(1-z)$ in $D_{q\to\gamma}$? (Glover, Morgan)
   - New fits to meson fragmentation functions, with LEP data as constraints for the gluon fragmentation. (Greco, Kniehl, et al)
5. **Ideas from participants of this meeting!**

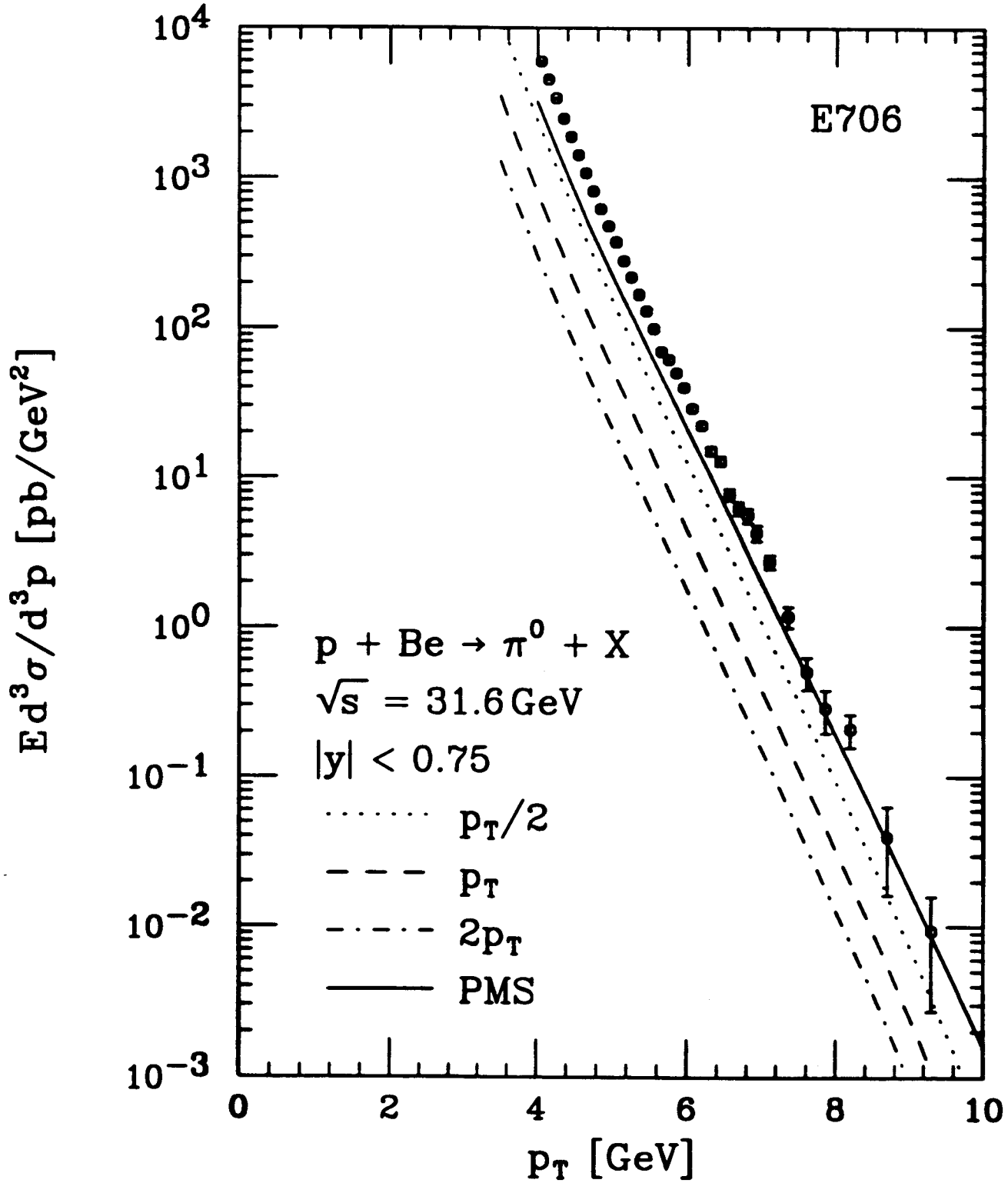
COURTESY OF B. KNIEHL

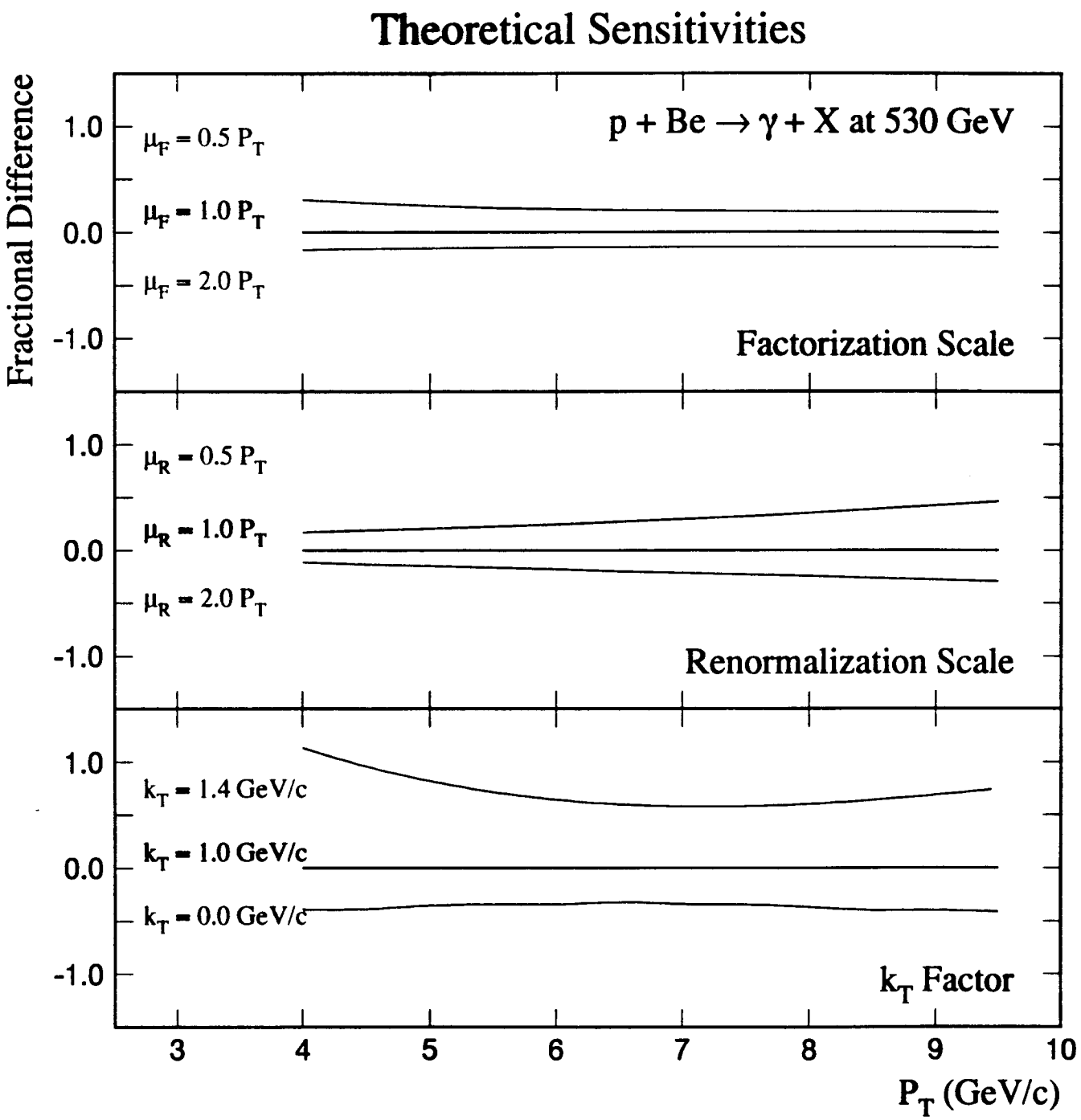


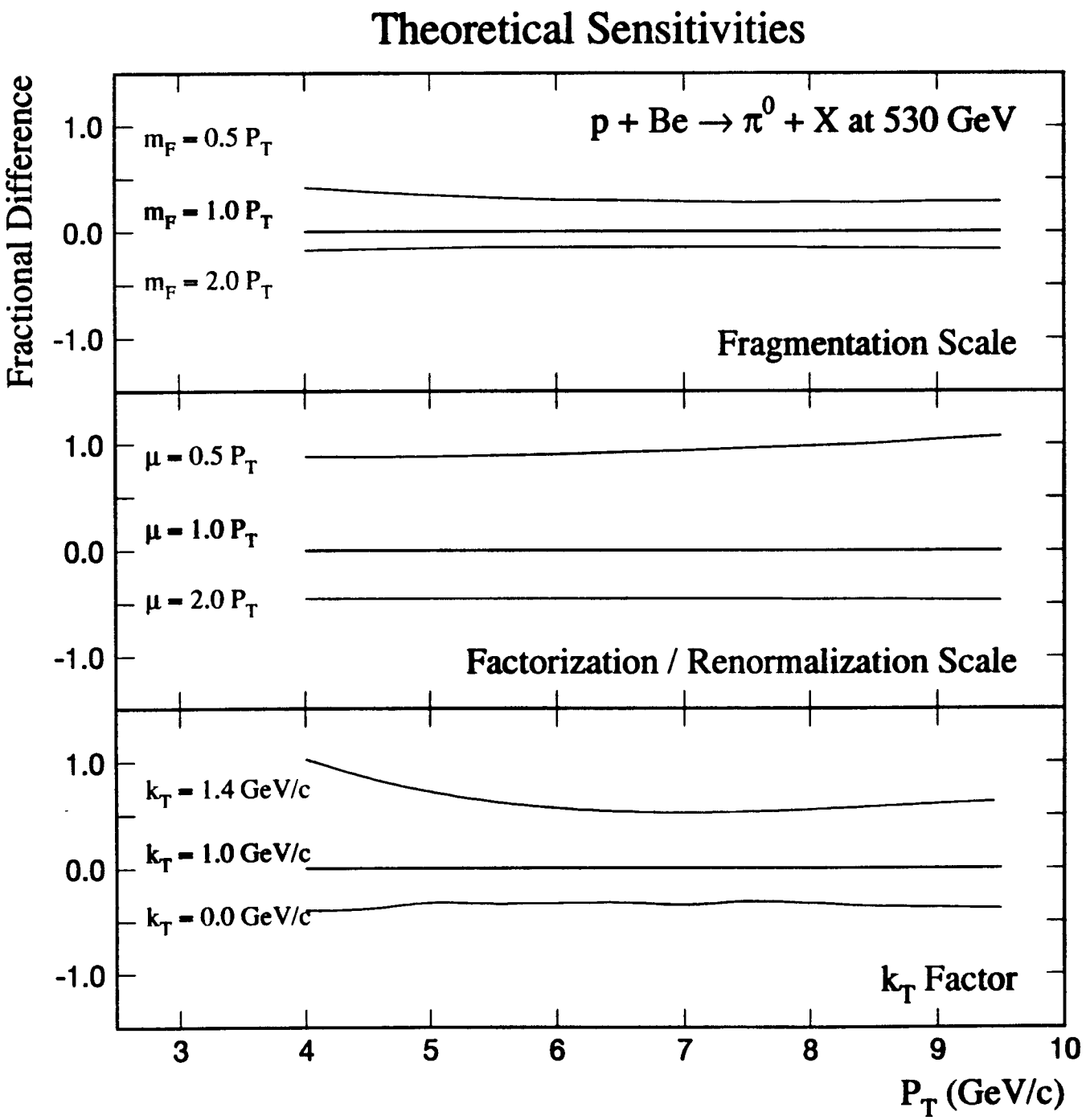
COURTESY OF B. KNIEHI



COURTESY OF B. KNIEHL




Theoretical Sensitivities
Fractional Difference
p + Be → γ + X at 530 GeV
μF = 0.5 PT
μF = 1.0 PT
μF = 2.0 PT
Factorization Scale
μR = 0.5 PT
μR = 1.0 PT
μR = 2.0 PT
Renormalization Scale
kT = 1.4 GeV/c
kT = 1.0 GeV/c
kT = 0.0 GeV/c
kT Factor
1.0
0.0
-1.0
3
4
5
6
7
8
9
10
PT (GeV/c)


Theoretical Sensitivities
Fractional Difference
p + Be → π0 + X at 530 GeV
mF = 0.5 PT
mF = 1.0 PT
mF = 2.0 PT
Fragmentation Scale
μ = 0.5 PT
μ = 1.0 PT
μ = 2.0 PT
Factorization / Renormalization Scale
kT = 1.4 GeV/c
kT = 1.0 GeV/c
kT = 0.0 GeV/c
kT Factor
1.0
0.0
-1.0
3
4
5
6
7
8
9
10
PT (GeV/c)

WA70 88 DATA

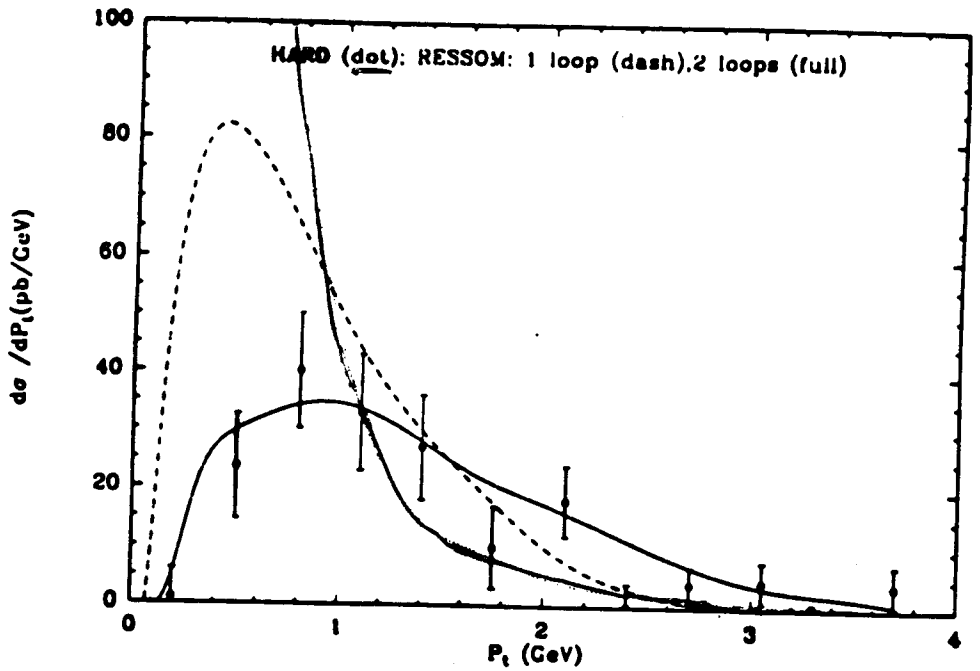
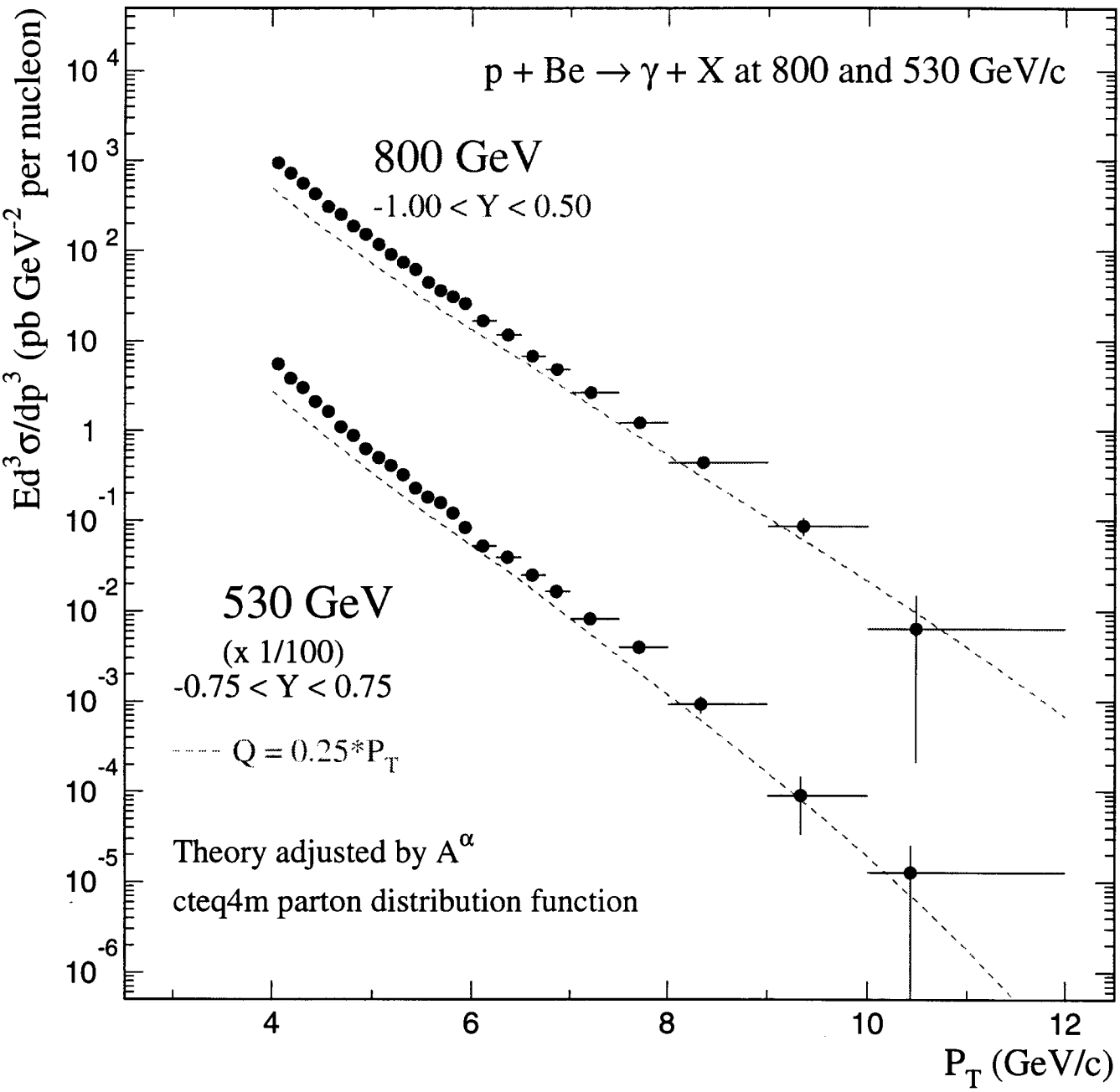
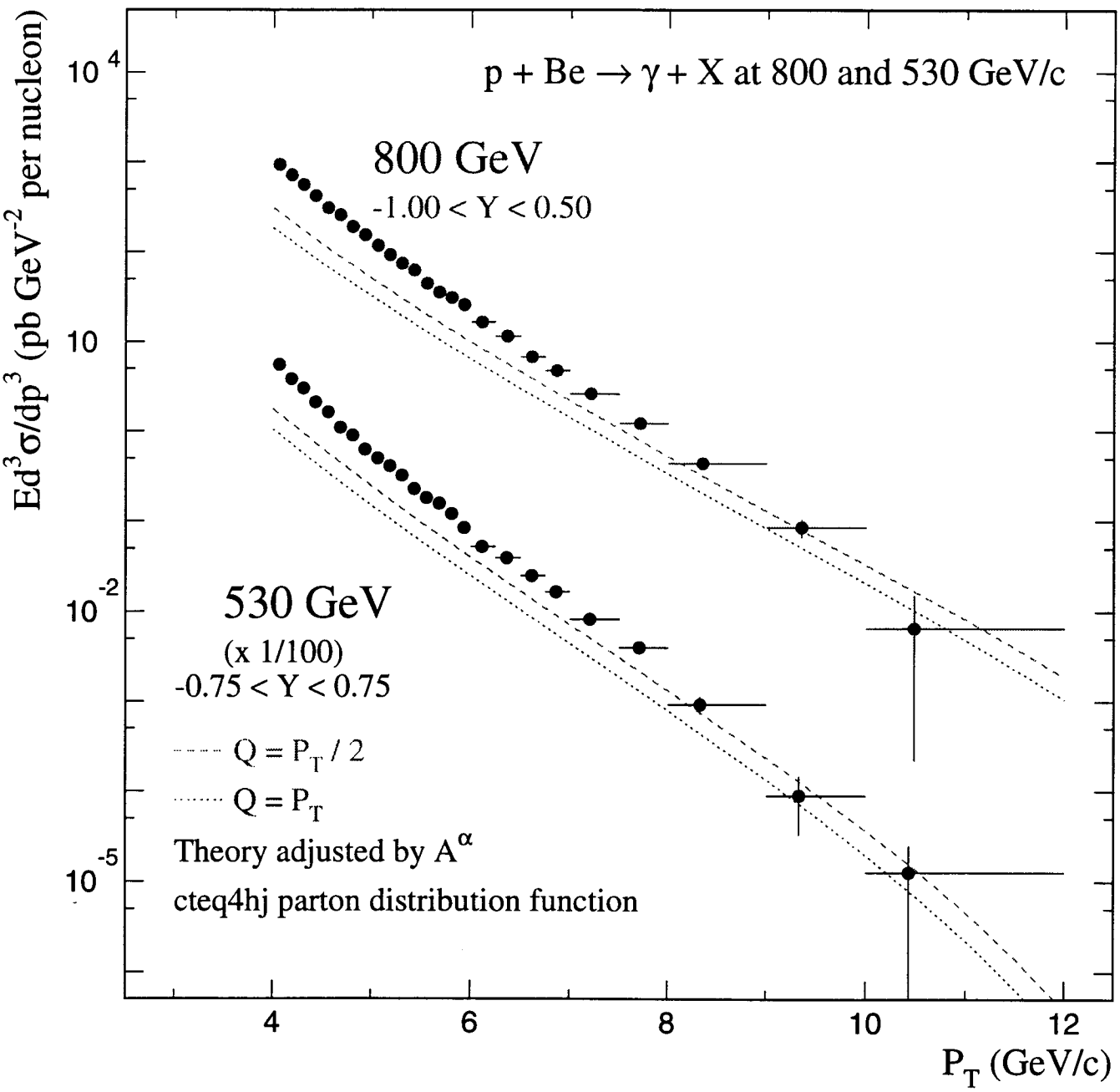
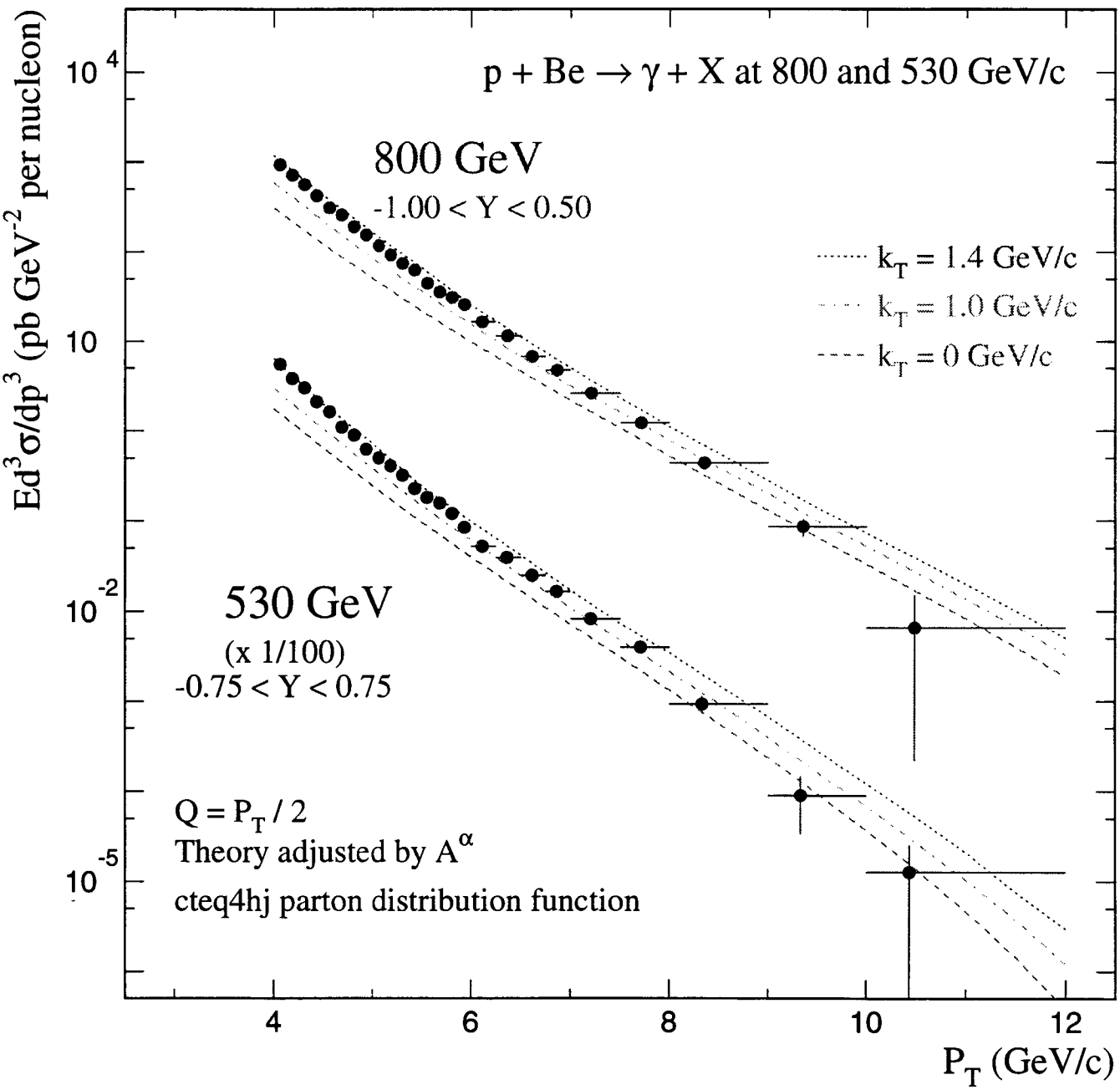


Fig. 1. The transverse momentum spectrum of the photon pair from WA70 experiment. Full curve: two-loop resummed formula. Dashed curve: one-loop resummed formula. Dotted curve: hard perturbative contribution.


p + Be → γ + X at 800 and 530 GeV/c
800 GeV
-1.00 < Y < 0.50
530 GeV
(x 1/100)
-0.75 < Y < 0.75
Q = 0.25*P_T
Theory adjusted by A^α
cteq4m parton distribution function
Ed^3σ/dp^3 (pb GeV^-2 per nucleon)
P_T (GeV/c)
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
4
6
8
10
12


p + Be → γ + X at 800 and 530 GeV/c
800 GeV
-1.00 < Y < 0.50
530 GeV
(x 1/100)
-0.75 < Y < 0.75
Q = P_T / 2
Q = P_T
Theory adjusted by A^α
cteq4hj parton distribution function
Ed³σ/dp³ (pb GeV⁻² per nucleon)
P_T (GeV/c)
10⁴
10
10⁻²
10⁻⁵
4
6
8
10
12


p + Be → γ + X at 800 and 530 GeV/c
800 GeV
-1.00 < Y < 0.50
k_T = 1.4 GeV/c
k_T = 1.0 GeV/c
k_T = 0 GeV/c
530 GeV
(x 1/100)
-0.75 < Y < 0.75
Q = P_T / 2
Theory adjusted by A^{α}
cteq4hj parton distribution function
$Ed^3\sigma/dp^3$ (pb GeV^{-2} per nucleon)
P_T (GeV/c)
10^4
10
10^{-2}
10^{-5}
4
6
8
10
12