Direct Photon Production

- a status report -

J.F. Owens
Physics Department
Florida State University

RHIC Spin Physics Workshop
Brookhaven National Laboratory
March 6, 2000

Direct Photon Production

1. Why direct photons?
2. Basic theoretical input
3. Survey of data
4. Comparison of theory to experiment
5. New ideas
   - Threshold resummation
   - k_T resummation
   - Combination of the two
6. Outlook
7. Conclusions

Why Direct Photons?

- Electromagnetic probe of hard scattering

- Pointlike coupling of γ to quarks

- Simple in lowest order (!)

  - $q\overline{q} \to \gamma g$

  - $gq \to \gamma q$

- Sensitive to gluon distribution, especially if there are no valence antiquarks, e.g., pp vs. $\overline{p}p$.

- Complements information povided by other processes, e.g., jet production

- No need for jet reconstruction $\Rightarrow$ can be used at lower energies and transverse momenta

BUT...

- Large backgrounds due to neutral meson decays ($\pi^0, \eta, \omega, \ldots$)

- γ's can be generated during jet fragmentation
  - Not directly part of the short distance hard scattering
  - Requires fragmentation functions as input
  - Referred to as the bremsstrahlung or fragmentation component
  - Can be large at low values of x_T
  - Calculation requires same input as jet production

Trigger requirements and techniques change as a function of energy and transverse momentum

- If π^0 decay photons are sufficiently separated the π^0's can be reconstructed

- At higher energies the decay photons coalesce

- Separate direct and decay photons by statistical techniques

- Isolation cuts required to define the electromagnetic trigger

  – Reduces fragmentation contribution

  – Introduces some theoretical uncertainty

Direct photon production initially appears simpler than jet production, but ultimately, it has all the subprocesses of jet production plus more!

Basic Theory Input

Calculate the hard scattering at the parton level and then convolute with the appropriate parton distribution and fragmentation functions

$$E\frac{d^3\sigma}{dp^3}(AB \to \gamma + X) =$$
$$\sum_{ab}\int dx_a dx_b dz_c G_{a/A}(x_a, \mu_F^2) G_{b/B}(x_b, \mu_F^2) D_{\gamma/C}(z_c, M_F^2)$$
$$E\frac{d^3\hat{\sigma}}{dp^3}(ab \to \gamma + X)(p_\gamma, x_a, x_b, z_c, \mu_F^2, \mu_R^2, M_F^2)$$

- Parton distribution and fragmentation functions taken from fits to data for various hard scattering processes (Global Fits)

- Three scales to specify: μ_F, μ_R, M_F

- $\hat{\sigma}$ calculated perturbatively - currently up through $\mathcal{O}(\alpha\alpha_s^2)$

$\hat{\sigma}$ involves integrations over unobserved or unconstrained partons

- $\mathcal{O}(\alpha\alpha_s)$
  1. $q\bar{q} \to \gamma g$
  2. $gq \to \gamma q$
  3. $ab \to cd \otimes c \to \gamma + X$

- $\mathcal{O}(\alpha\alpha_s^2)$ add
  1. one-loop virtual contributions
  2. $q\bar{q} \to \gamma gg$
  3. $gq \to \gamma qg$
  4. $qq' \to \gamma qq'$ plus related subprocesses
  5. $\mathcal{O}(\alpha_s^3) ab \to c + X \otimes c \to \gamma + X'$

Two types of programs exist

1. Phase space integrations done symbolically so expressions for $\hat{\sigma}$ exist. Integrations over x_a, x_b, and z_c done numerically.

2. All integrations done via Monte Carlo
   - Phase space slicing method
   - Subtraction method

With Monte Carlo programs one can

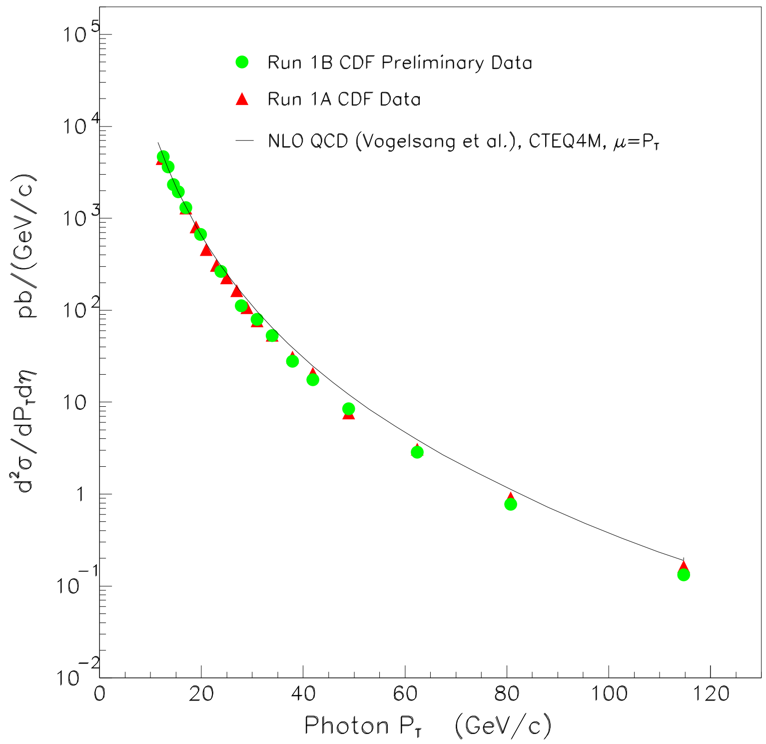
- Look at γ jet correlations
- Attempt to implement isolation cuts

Data Coverage

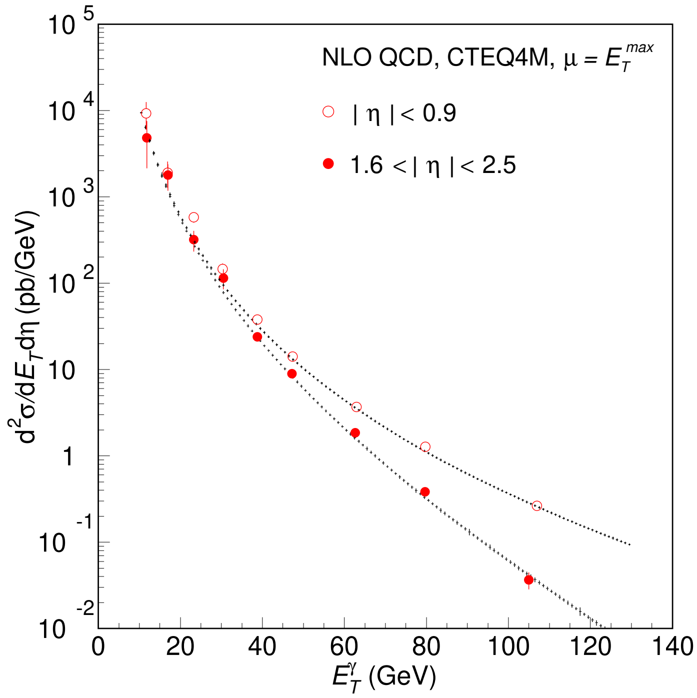
Review: W. Vogelsang and M.R. Whalley, J. Phys. G 23 (1997) A1. (see Table I)

- $\pi^{\pm}, p, \overline{p}$ on p, N targets
- $19.4 \leq \sqrt{s} \leq 1800$ GeV
- $.01 \leq x_T \leq .61, \quad x_T = 2p_T/\sqrt{s}$
- Additional new data from CDF, DØ, and E-706

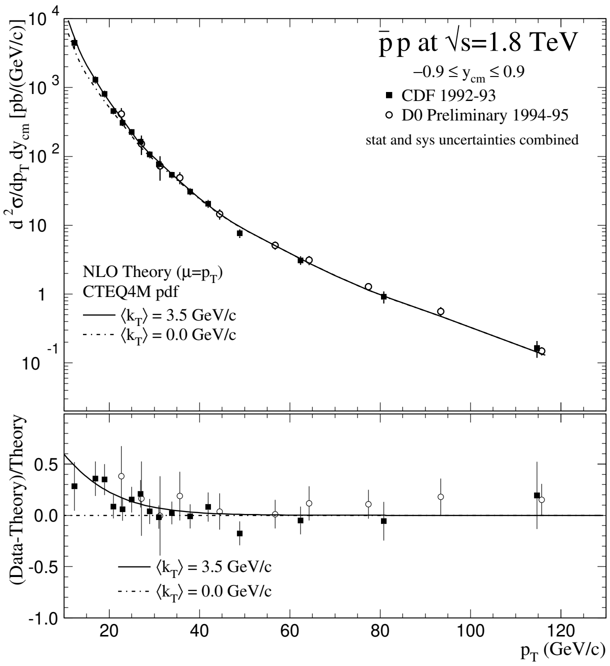
Comparison to Data



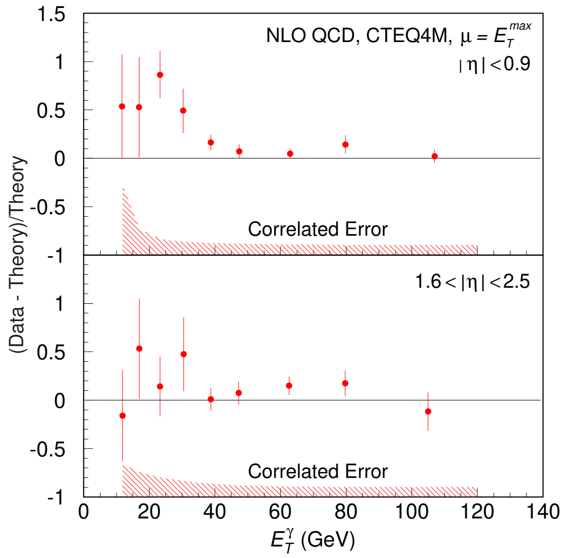
DØ Run 1b data



Agreement looks good, but what if we look on a linear scale...?

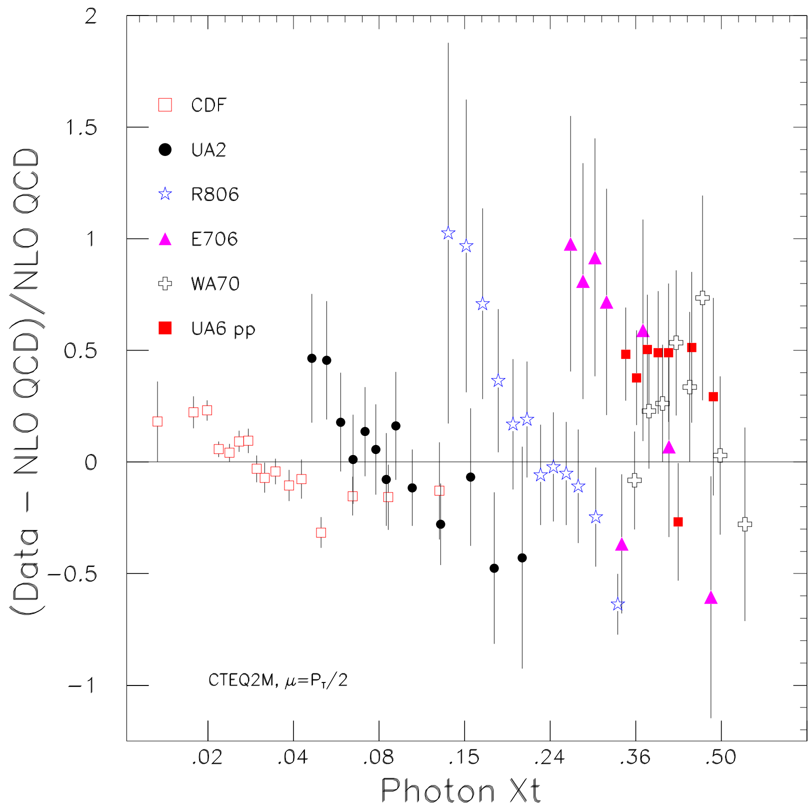


DØ Run 1b data



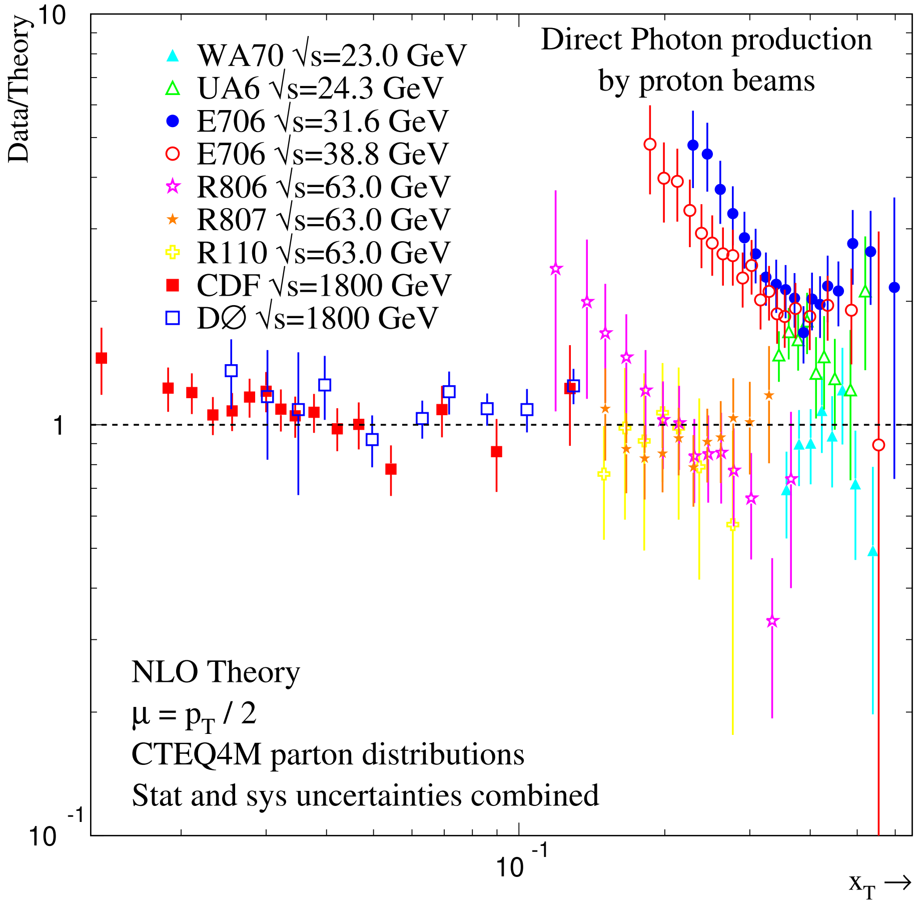
Theory underestimates the data at the low-p_T end of each plot.

What if we look at a wider range of energies? Include fixed target data and data from lower energy colliders.



See systematic pattern when plotted on a linear scale.

Situation becomes more dramatic when more recent E-706 data are included



- Data steeper than theory

- Effect appears at different x_T's $\Rightarrow$ can't be explained by pdf's.

So, is there a problem, and, if so, what can be done?

1. Examine scale dependence

   - Predictions depend on three scales

   - Examine full flexibility of the theory

2. Examine region of applicability of the theory

   - Try to estimate where the theory is reliable

   - Avoid data sets where theory uncertainties are not well controlled

3. Look for additional corrections not already included in the NLO predictions

Scale Variation

- Vary $\mu_F, \mu_R,$ and M_F to get maximum theoretical flexibility
  - Decrease $\mu_R \Rightarrow$ increase α_s
  - Decrease $\mu_F \Rightarrow$ increase σ if $x_T \geq 0.2$
  - Decrease $\mu_F \Rightarrow$ decrease σ at low-x_T
  - Fragmentation functions proportional to $\ln(M_F^2/\Lambda^2)$

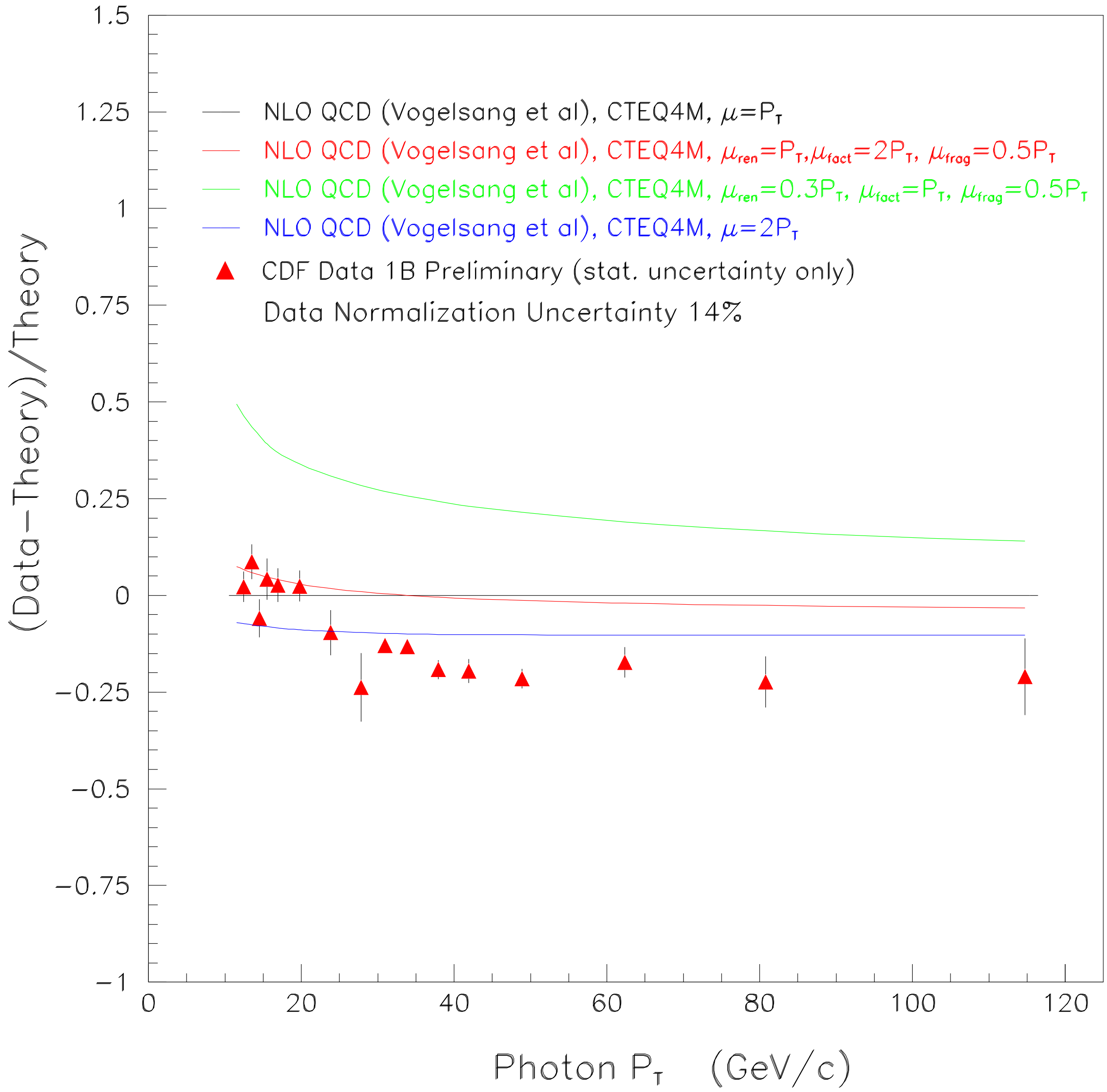
- Bottom line
  - Can change normalization
  - Can alter shape somewhat
  - Can't get correct shape and normalization simultaneously for collider data

- As always - the devil is in the details...

Generally speaking, one can't describe *all* the data by just varying the scales.

For a detailed discussion as applied to earlier data see W. Vogelsang and A. Vogt, hep-ph/9505404, Nucl. Phys. B453, 334 (1995).

Example scale variations for CDF data



Critically examine both the data sets and the properties of the theoretical calculations

- P. Aurenche *et al.*, hep-ph/9811382, Eur. Phys. J. C9, 107 (1999) for direct photons

Exclude data sets where theoretical uncertainties in the predictions may be large

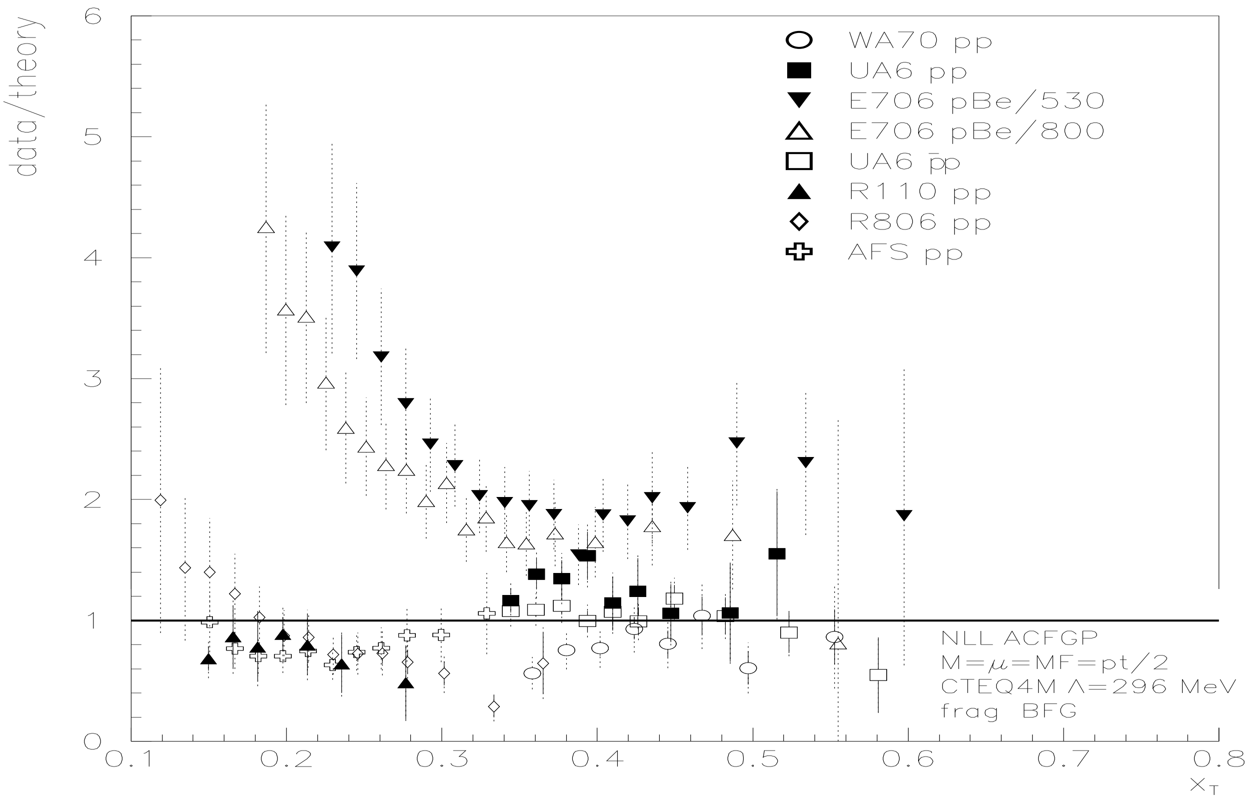
- remove data on nuclear targets (no E-706)

- remove data taken with photon isolation cuts (no collider data except from ISR)

- use only $p, \overline{p}$ beams (remove pion beam data)

- Essentially leaves only WA-70, UA-6, and some ISR experiments

- Agreement between theory and data is good



CTEQ4M pdf's used, all scales set to $p_T/2$

Require $p_T/2 \geq 2.56$ GeV (input scale for pdf's)

What about the other experiments?

- Examine the stability of the theory to changes in scale (PMS criterion for optimized s-cales)

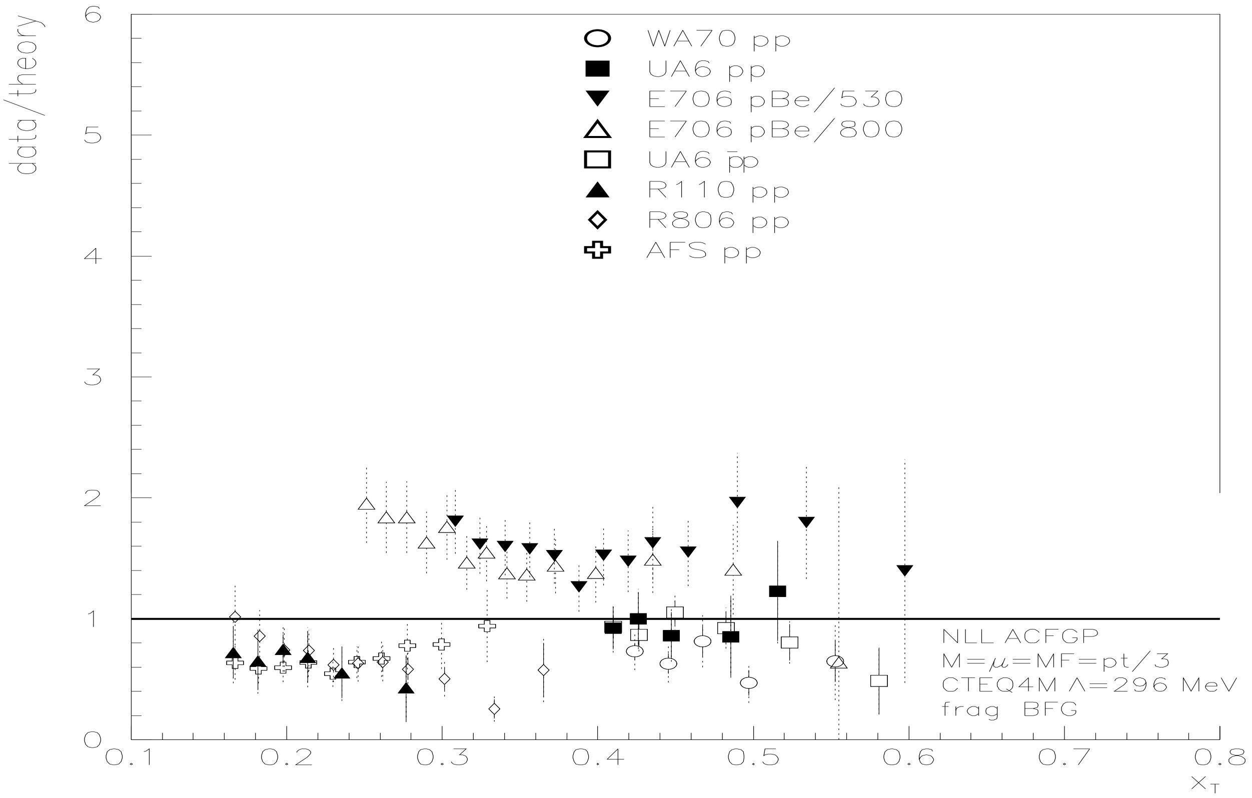
- Exclude some low-x_T data where the optimized scale is below the input scale used by the pdf's

- Exclude fixed target points below p_T of 5 GeV due to lack of stablility in the predictions

- Rationale is that one should exclude regions where large higher order corrections are expected

- Final result is that the E706 data appear to be shifted by an overall normalization factor

Reference contains good discussions of theoretical issues related to scale dependence, isolation cuts, consistency between data sets.



Points below p_T=5 GeV excluded

Appears that data sets can be related by over-all normalization factors

Is that the end of the story?

What about π^0 production?

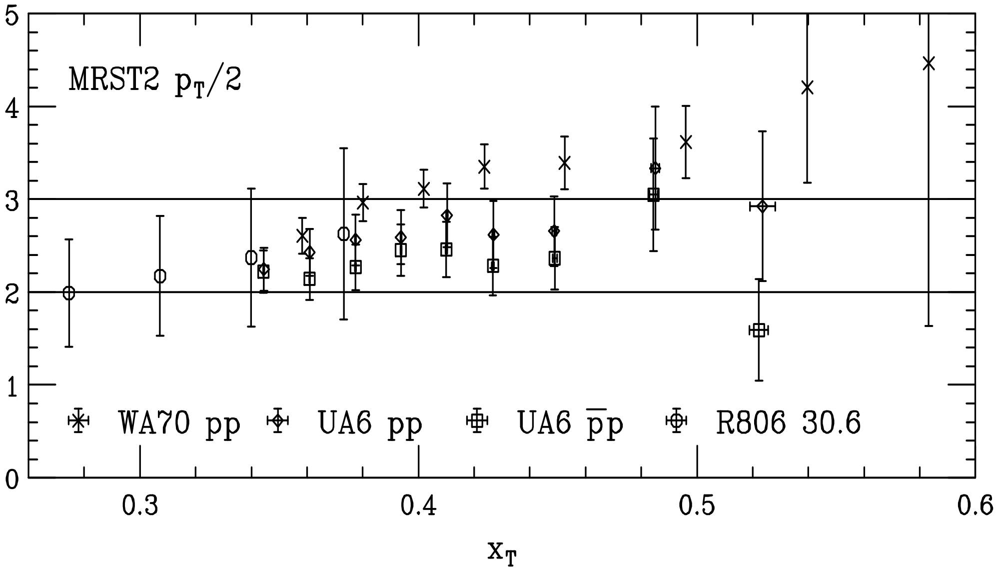
- P. Aurenche *et al.*, hep-ph/9910252 for π^0 production

Critical examination of the comparison between theory and experiment

- NLO theory underestimates data for all experiments

- Basically looks like an overall normalization problem

So, there is agreement that NLO calculations underestimate *all* of the π^0 data and *some* of the γ data. Clearly, the final answer is not in.



8: *Comparison of WA70 [12], UA6 [11] and ISR [21] π^0 data with NLO predictions* *n the MRST2 [5] parton densities. All scales are set equal to $p_T/2$ with $p_T = 2x_T\sqrt{s}$.* *rizontal lines drawn at 2 and 3 illustrate the mutual agreement of all data sets to* $\pm 20\%$.

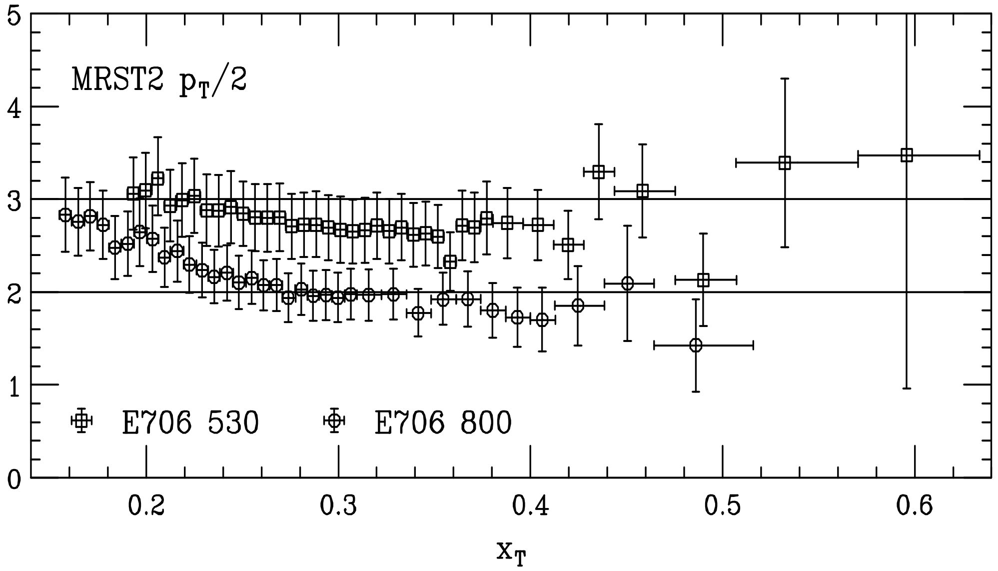


Figure 9: *Same as Fig. 8, but for E706 [10] π^0 data.*

New Theoretical Ideas

1. Threshold Resummation

2. k_T Resummation

3. Combination of the two

Threshold Resummation

Basic Physics -

- in inclusive calculations singularities from soft real gluon emission cancel against infrared singularities from virtual gluon emission.

- Limitations on real gluon emission imposed by phase space constraints can upset this cancelation.

- Singular terms still cancel, but there can be large logarithmic remainders.

- Classic example is thrust distribution in $e^+e^- \to jets$

High-p_T/high-mass particle production

- Phase space for gluon emission is limited near threshold in the parton-parton scattering subprocess

- Steeply falling pdf's constrain real gluon emission when high-mass or high-p_T is required

Define $v = 1 + t/s$ and $w = -u/(s+t)$.

Threshold occurs at $w = 1$ $(s + t + u = 0)$

$\frac{d\sigma}{dvdw}$ contains terms like $\alpha_s^m \left(\frac{\ln^n(1-w)}{1-w}\right)_+$

Can sum leading logs $(n = 2m - 1)$,

next-to-leading-logs $(n = 2m - 2)$, etc.

Technicalities:

- Take Mellin transform of cross section
- Corrections exponentiate in transform space
- Take inverse transform to get the corrected cross section
- Can expand the exponential and then transform in order to predict singular terms from higher orders, e.g., two-loops

Results

- Corrections large as $x_T \to 1$
- Variations with respect to scale(s) reduced
- Corrections with $\mu = p_T/2$ small at intermediate x_T

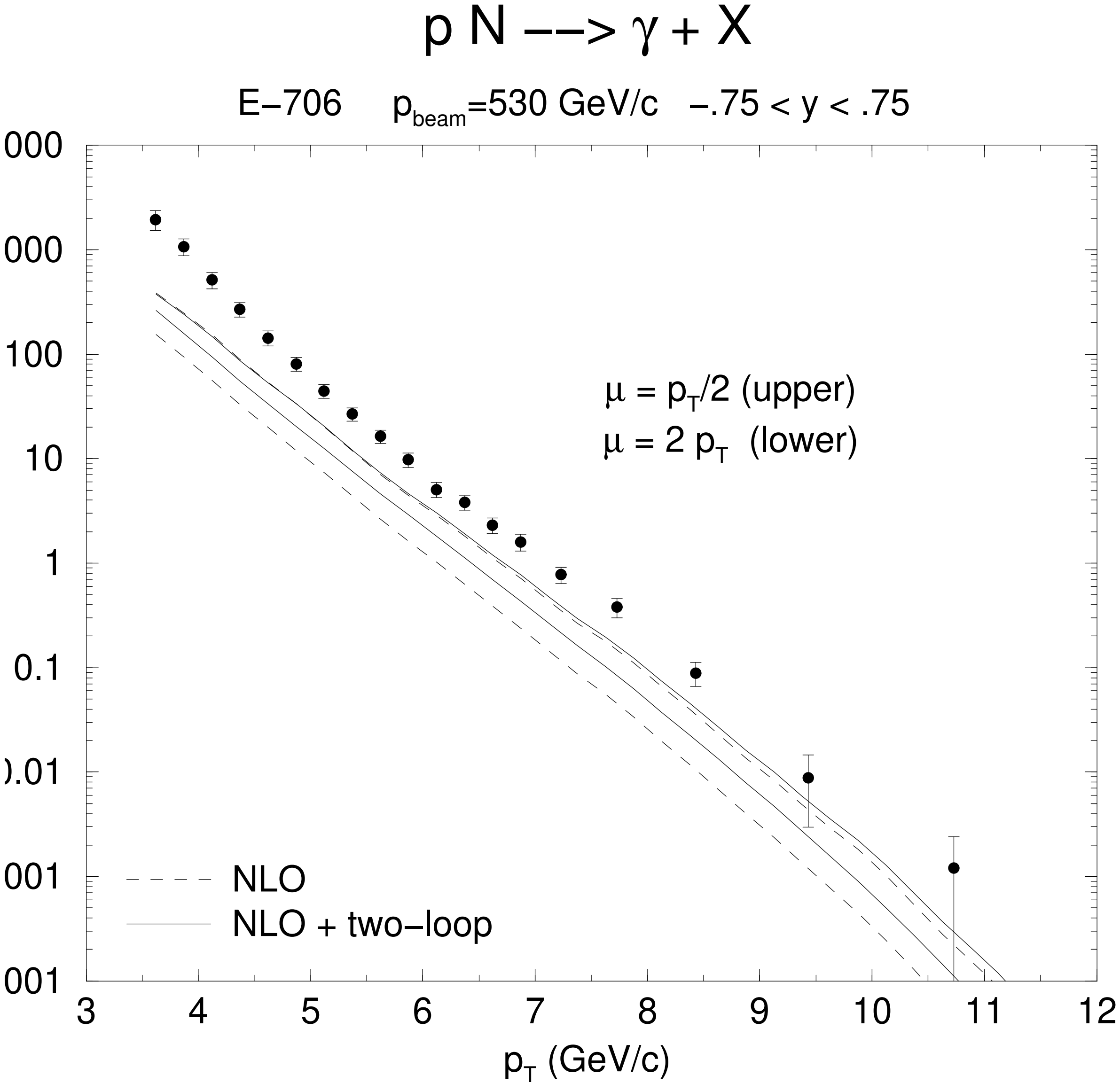
Threshold resummation can't solve the current dilemma, but the results are interesting nonetheless.

For more details see:

1. E. Laenen, G. Oderda, and G. Sterman, hep-ph/9806467, Phys. Lett. B438, 173 (1998)

2. S. Catani, M.L. Mangano, and P. Nason, hep-ph/9806484, JHEP 9807 (1998) 024; S. Catani, *et al.*, hep-ph/9903436, JHEP 9903 (1999) 025.

3. N. Kidonakis and J.F. Owens, hep-ph/9912388, Phys. Rev. D (in press)


p N --> γ + X
E−706 p_beam=530 GeV/c −.75 < y < .75
μ = p_T/2 (upper)
μ = 2 p_T (lower)
NLO
NLO + two−loop
p_T (GeV/c)
3
4
5
6
7
8
9
10
11
12
000
000
100
10
1
0.1
).01
001
001

k_T or Recoil Effects

History

- Well-known since the 70's (ISR experiments)
- high-p_T events show deviations from planar structure expected from $2 \to 2$ hard scattering, e.g., p_{out}, p_T imbalance
- Correlations observed between high-p_T hadrons and opposite side beam fragments
- Early QCD calculations used $2 \to 2$ QCD scattering subprocesses with gaussian k_T smearing (Feynman, Field, and Fox)
- Largely forgotten as new data from colliders at large values of p_T became available
- Effects largest at the low end of the p_T spectrum
- Effects fall off as an inverse power of P_T relative to the leading terms
- "Rediscovered " when precise fixed target data and low-x_T collider data became available

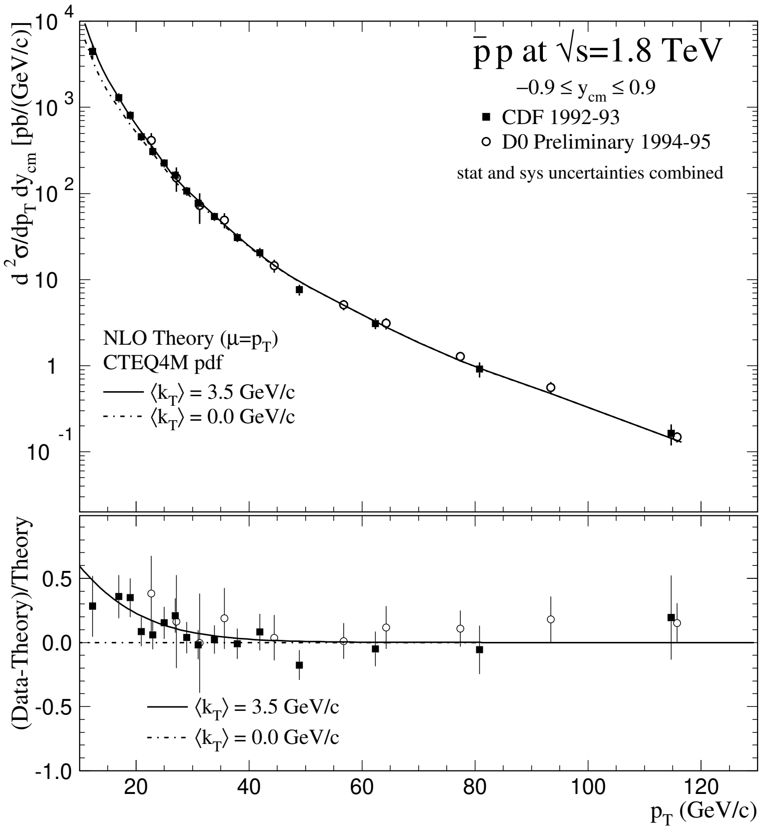
Phenomenological Approach

- Use gaussian (on shell) k_T smearing
- Adjust amount of k_T to fit data on p_T imbalance ($\gamma\pi^0$, etc.) at each energy
- k_T due to
  1. nonperturbative contribution
  2. perturbative initial state shower contribution
- can describe E-706, CDF, DØ data
- Relatively smaller smearing at lower energies (Wa-70, UA-6)

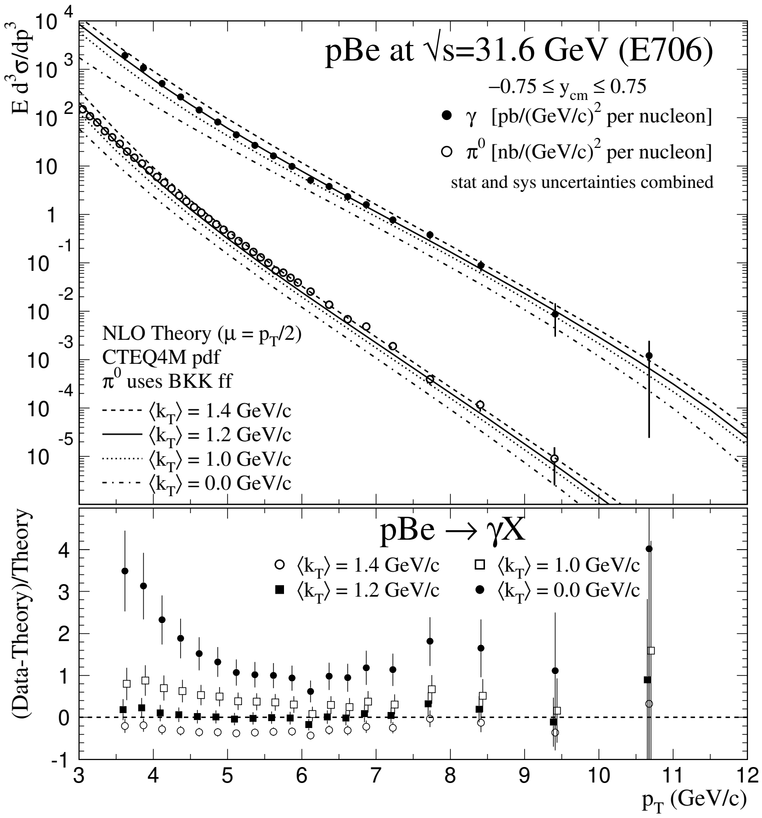
For further details see L. Apanasevich *et al.*, hep-ph/9808467, Phys. Rev. D59, 074007 (1999)

Does this model have have a basis in theory?

Yes!



$\bar{p}p$ at $\sqrt{s}$=1.8 TeV
$-0.9 \le y_{cm} \le 0.9$
CDF 1992-93
D0 Preliminary 1994-95
stat and sys uncertainties combined
NLO Theory (μ=p_T)
CTEQ4M pdf
$\langle k_T \rangle$ = 3.5 GeV/c
$\langle k_T \rangle$ = 0.0 GeV/c
$d^2\sigma/dp_T dy_{cm}$ [pb/(GeV/c)]
(Data-Theory)/Theory
p_T (GeV/c)



pBe at $\sqrt{s}$=31.6 GeV (E706)
$-0.75 \le y_{cm} \le 0.75$
γ [pb/(GeV/c)^2 per nucleon]
π^0 [nb/(GeV/c)^2 per nucleon]
stat and sys uncertainties combined
NLO Theory ($\mu = p_T/2$)
CTEQ4M pdf
π^0 uses BKK ff
$\langle k_T \rangle$ = 1.4 GeV/c
$\langle k_T \rangle$ = 1.2 GeV/c
$\langle k_T \rangle$ = 1.0 GeV/c
$\langle k_T \rangle$ = 0.0 GeV/c
$E\, d^3\sigma/dp^3$
pBe $\rightarrow \gamma$X
(Data-Theory)/Theory
p_T (GeV/c)

Basic Idea

Consider the production of a γ-jet system

- γ and jet balance in p_T at lowest order

- $\mathcal{O}(\alpha_s)$ corrections give γ-jet system a p_T kick but it diverges at $p_T = 0$

- Analogous to vector boson production at low p_T

- Can calculate γ-jet k_T distribution using k_T resummation techniques

  1. Collins-Soper-Sterman: resum in impact parameter space

  2. Dokshitzer-Dyakonov-Troyan: resum in k_T space

- Two methods compared for vector boson production (Ellis and Veseli)

Basic Idea (continued)

Usual hard scattering formalism relies on factorization of collinear singularities associated with the initial state partons.

Parton tranverse degrees of freedom are integrated out

Recoil effects are not retained – “collinear approximation”

γ-jet system recoils due to initial state parton emission

γ transverse momentum can get a contribution form this recoil

Effect is included in higher order calculations, but NLO only has one gluon treated exaclty – insufficient to describe data

Recent Applications

Kimber-Martin-Ryskin apply DDT formalism - colliding partons have a net k_T

$$E\frac{d^3\sigma}{dp^3} = \int \mathcal{L}(x_1, x_2, q_t)\frac{dx_1}{x_1}\frac{dx_2}{x_2}dq_t^2 \times\frac{d\hat{\sigma}}{d\hat{t}}d\hat{t}\frac{d\phi}{2\pi}\delta(\eta_\gamma - ...)\delta(p_{t\gamma}^2 - ...)\theta(\mu^2 - q_t^2)\theta(|\hat{t}| - q_t^2)$$

where $\mathcal{L}$ is a q_t dependent parton-parton luminosity given by

$$\mathcal{L}_{ab}(x_1, x_2, q_t) = \frac{\partial}{\partial\lambda^2}\left[a(x_1, \lambda^2)T_a(\lambda,\mu)b(x_2,\lambda^2)T_b(\lambda,\mu)\right]|_{\lambda=q_t}.$$

Here a and b represent pdf's, either xq, $x\overline{q}$, or xg.

The *survival probability* T is given by

$$T_a(\lambda,\mu) = \exp\left(-\int_{\lambda^2}^{\mu^2}\frac{\alpha_s(p_t)}{2\pi}\frac{dp_t^2}{p_t^2}\int_0^{1-\Delta}\frac{dz'}{1-z'}2C_a\right)$$

with $C_q = C_F$ and $Cg = C_A$.

The parton luminosity function can also be written as

$$\mathcal{L}_{ab}(x_1, x_2, q_t) = \int f_a(x_1, k_1^2, \mu^2) f_b(x_2, k_2^2, \mu^2) \delta^2(\vec{k}_1 + \vec{k}_2 - \vec{q}_t) \frac{d^2k_1 d^2k_2}{\pi k_1^2 k_2^2}$$

In this form it is clear that the parton transverse momenta are taken into account to produce an overall net $\vec{q}_T$ for the colliding pair.

In the form previously given, it becomes clear that the evolved partons are sampled at a scale given by q_t, and not some scale proportional to the photon p_T.

Comments

1. Parton luminosity function $\mathcal{L}$ has a q_T width that grows with energy (fig)

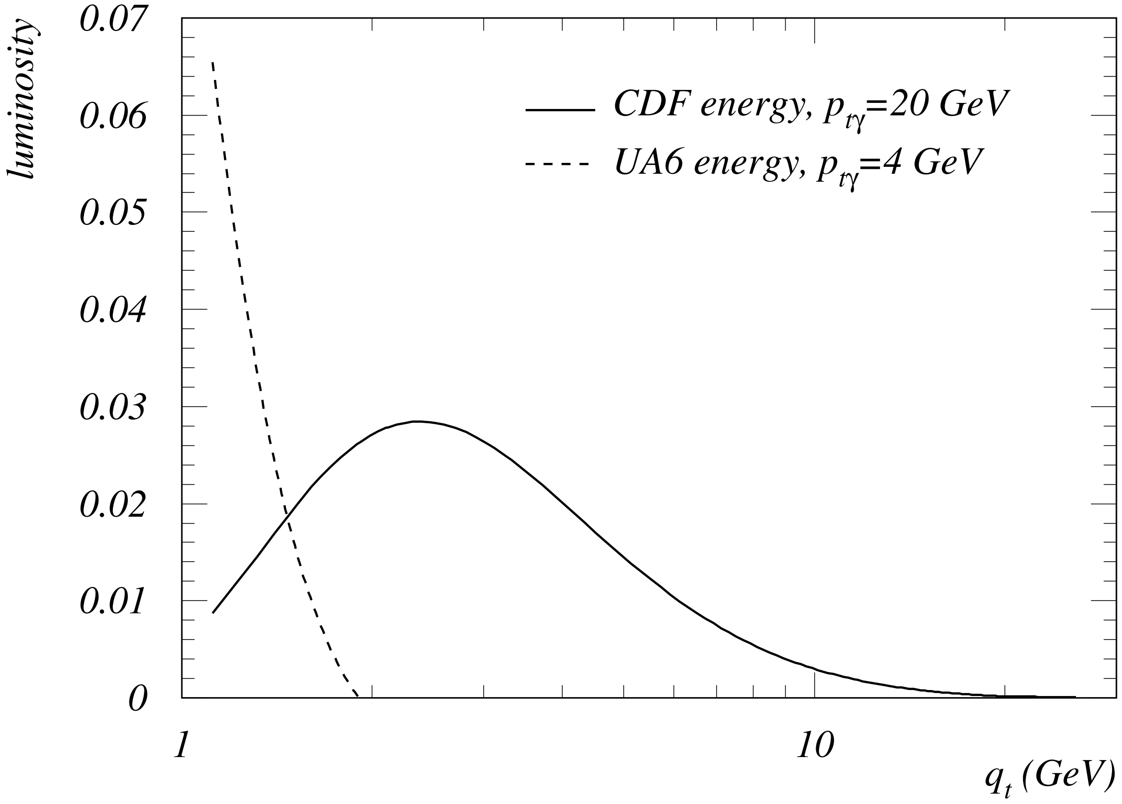
2. Results are somewhat counterintuitive...

   - q_t effect is not large at the low-p_T end

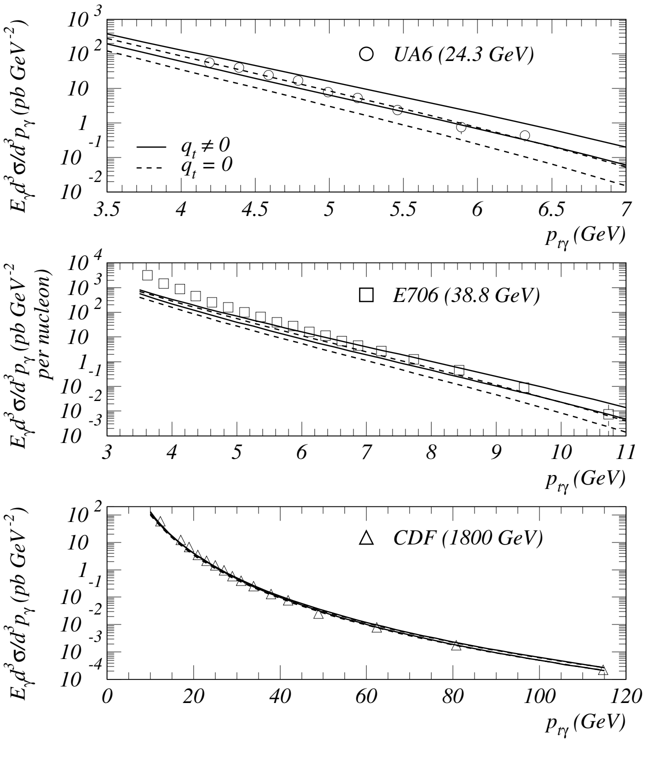
   - Smearing gets larger as p_T grows

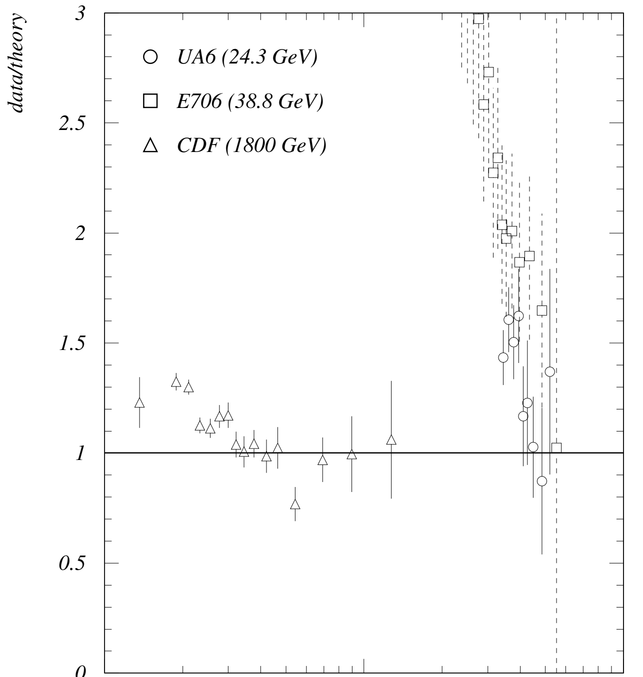
3. First point is due to the fact that for small p_T the parton evolution has not generated much gluon emission

4. The second is due to two effects: the evolution at higher values of p_T generates a wider q_T distribution and the cuts which enforce the strong ordering constraints are less restrictive at higher p_T



luminosity
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1
10
q_t (GeV)
CDF energy, $p_{t\gamma}$=20 GeV
UA6 energy, $p_{t\gamma}$=4 GeV


UA6 (24.3 GeV)
$q_t \neq 0$
$q_t = 0$
$E_\gamma d^3\sigma/d^3p_\gamma$ (pb GeV^{-2})
$p_{T\gamma}$ (GeV)
E706 (38.8 GeV)
$E_\gamma d^3\sigma/d^3p_\gamma$ (pb GeV^{-2} per nucleon)
$p_{T\gamma}$ (GeV)
CDF (1800 GeV)
$E_\gamma d^3\sigma/d^3p_\gamma$ (pb GeV^{-2})
$p_{T\gamma}$ (GeV)


data/theory
UA6 (24.3 GeV)
E706 (38.8 GeV)
CDF (1800 GeV)
x_T

Nonperturbative Effects

- KMR normalize their result such that the integral over q_t up to q_0, the pdf input scale, reproduces the perturbative result

- Equivalent to keeping only the perturbatively generated q_t

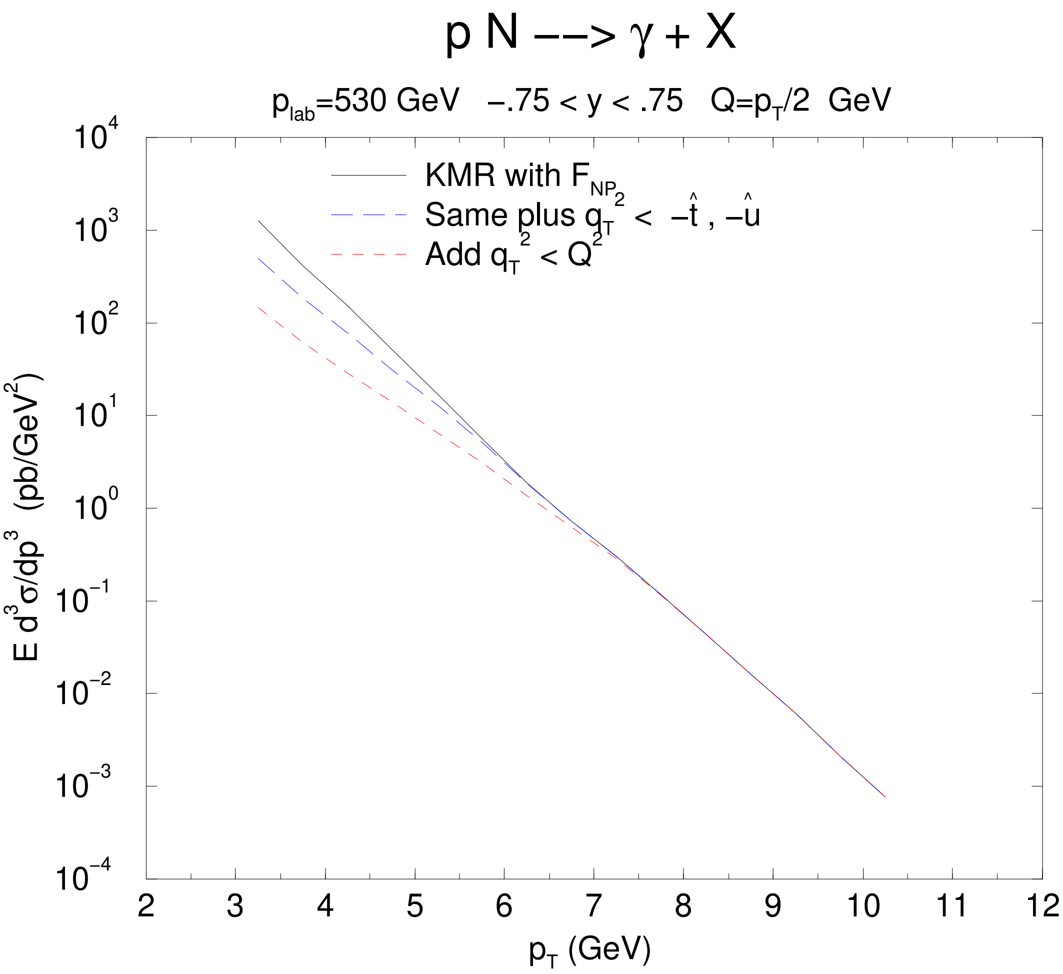
- Can add a nonperturbative contribution to $\mathcal{L}$ following the treatment of Ellis and Veseli for vector boson production

  - Ensures proper normalization after integrating over q_t

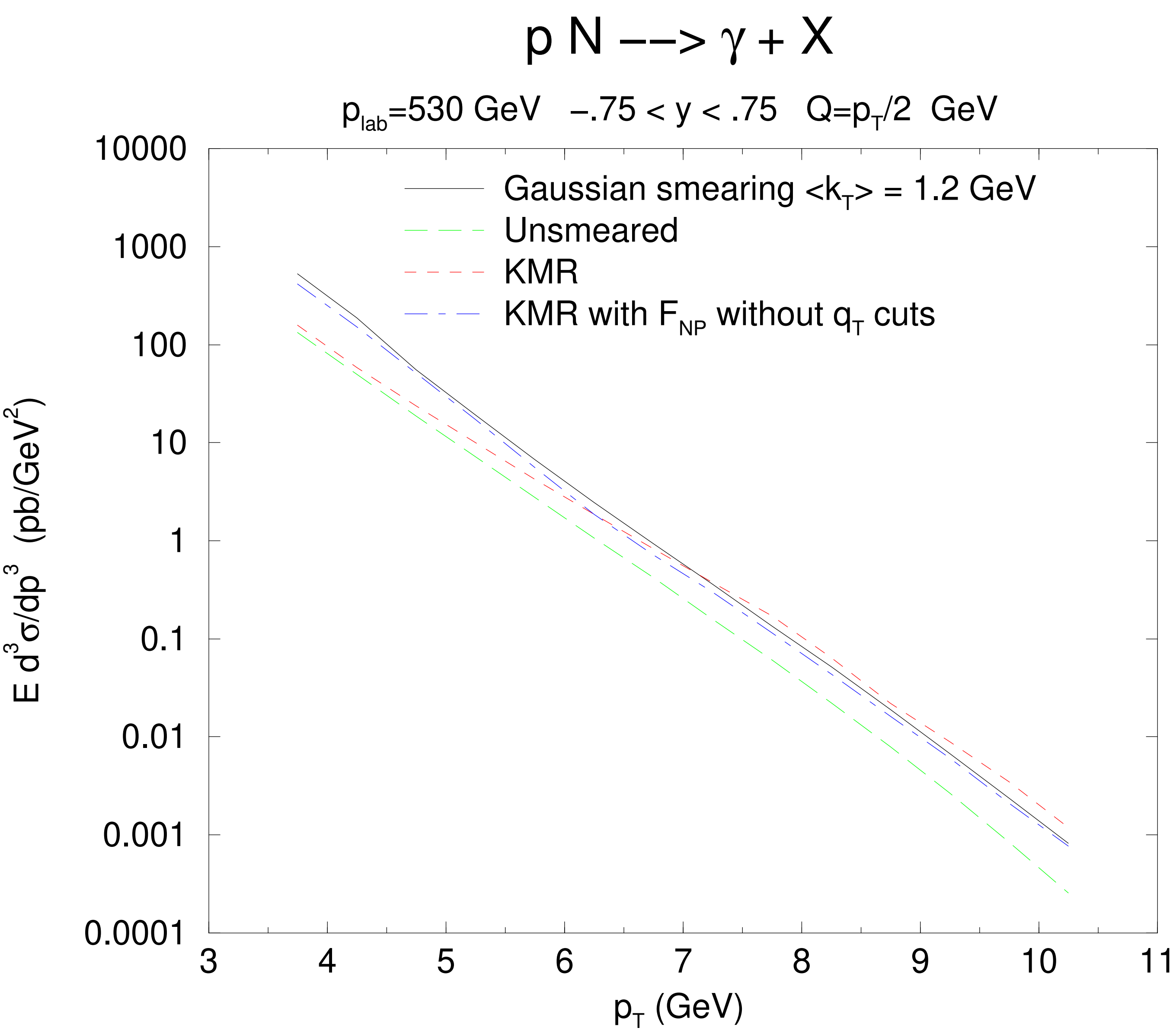
  - Avoids Landau pole in α_s as q_t goes to zero

- Can adjust nonperturbative parameter to give the observed $\gamma\pi^0$ p_T imbalance once a full calculation is done

- Low-p_T enhancement dependent on precise cuts placed on q_t distribution and choice of scale



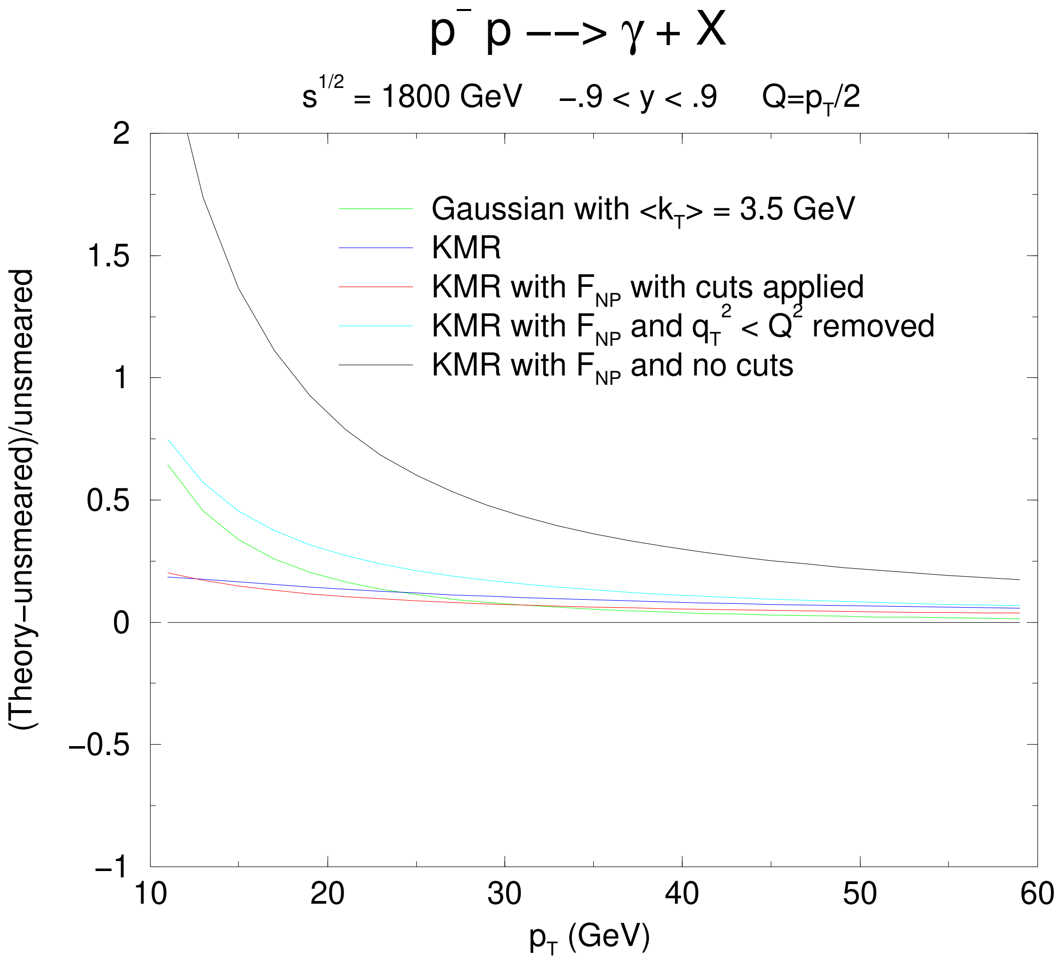
- Conclude that it is possible to reproduce the trend of the phenomenological k_T approach if the nonperturbative contribution is included


p N --> γ + X
p_lab=530 GeV   -.75 < y < .75   Q=p_T/2 GeV
Gaussian smearing <k_T> = 1.2 GeV
Unsmeared
KMR
KMR with F_NP without q_T cuts
E d^3σ/dp^3 (pb/GeV^2)
p_T (GeV)
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
3
4
5
6
7
8
9
10
11

But, all is not well when one goes to the collider regime....

- Find including F_{NP} with cuts $\simeq$ KMR without F_{NP}

- In this energy regime removing the cuts gives too large an effect!



Why?

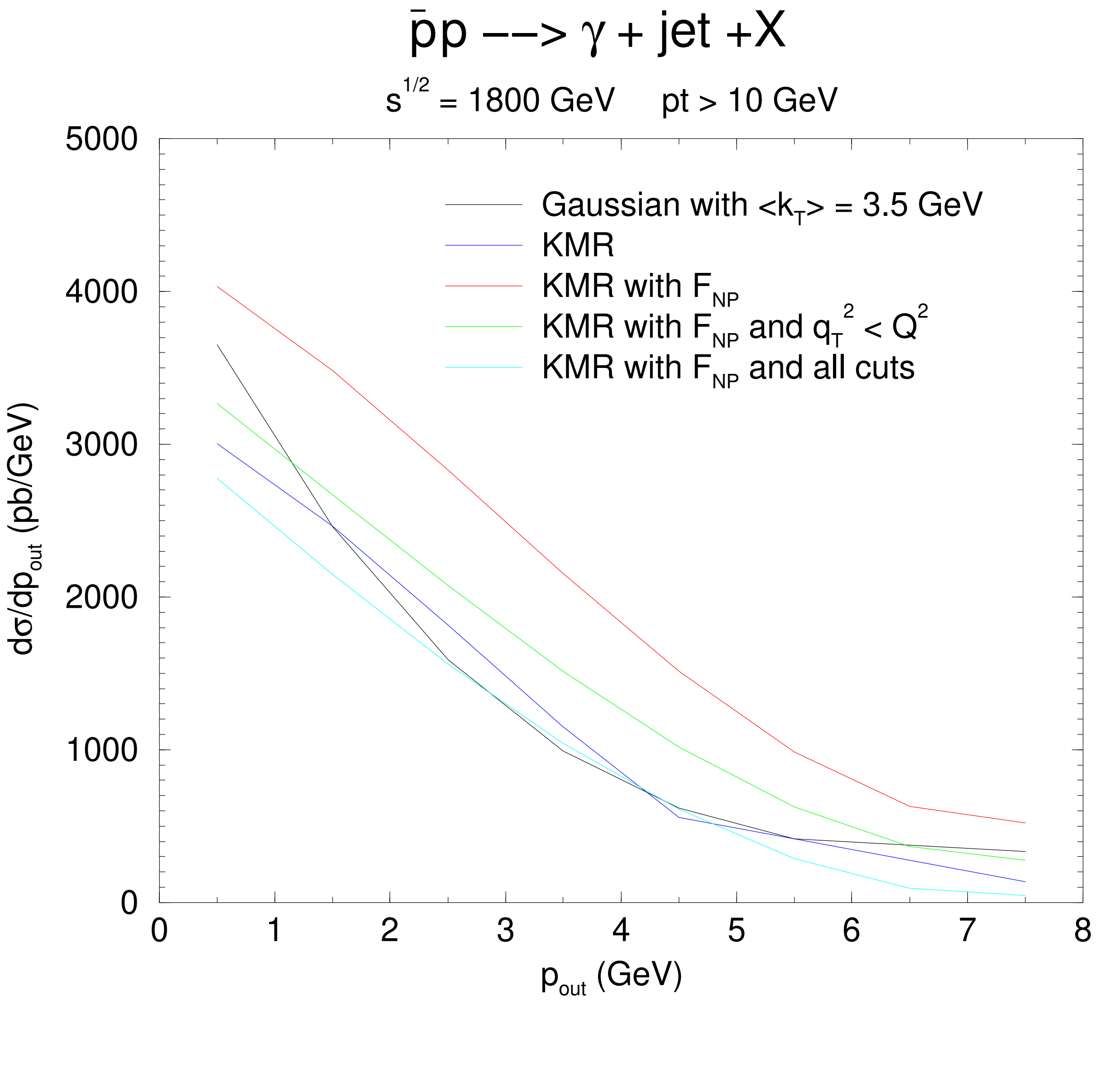
1. Perturbatively generated distribution has non-gaussian tail

2. Wider than gaussian form with $< k_T >$=3.5 GeV

3. Distribution is so wide that cuts are needed to retain the hard scattering picture

4. Note that the p_{out} distribution shape is not too sensitive to F_{NP} or to cuts!

Conclude: KMR/DDT approach with strong ordering can not explain collider and fixed target data simultaneously, even if a nonperturbative contribution is added.



p̄p --> γ + jet +X
s^1/2 = 1800 GeV pt > 10 GeV
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
dσ/dp_out (pb/GeV)
p_out (GeV)
Gaussian with <k_T> = 3.5 GeV
KMR
KMR with F_NP
KMR with F_NP and q_T^2 < Q^2
KMR with F_NP and all cuts

Recent Result - Combine threshold and recoil resummation formalisms

E. Laenen, G. Sterman, and W. Vogelsang, hep-ph/0002078

New formalism

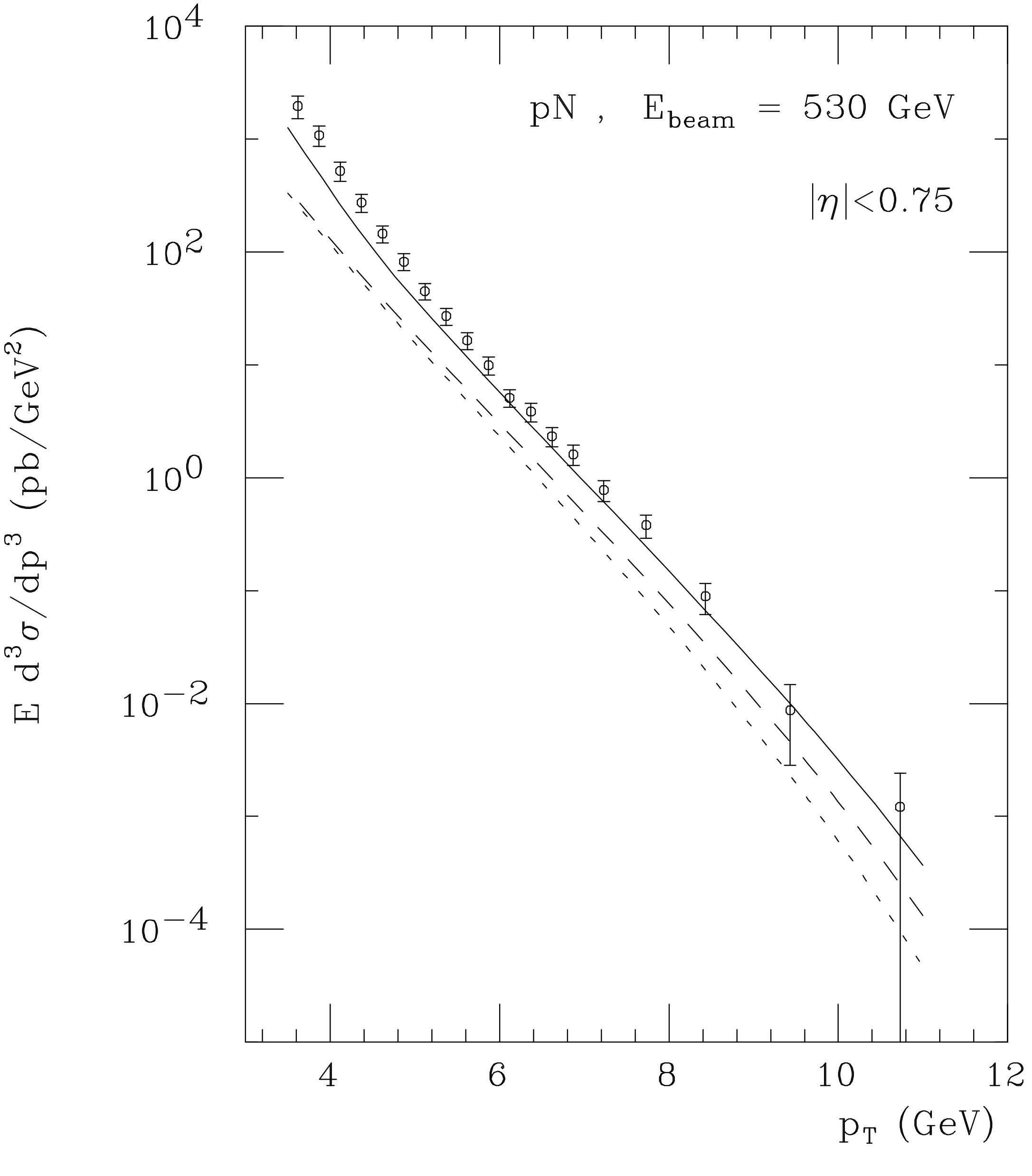
- Use double moments (Mellin and Fourier transforms)

- Retain the physics of the threshold resummation *and* include recoil effects of initial state gluon emission

- Conserve both energy and momentum (logitudinal and transverse)

- Preliminary results are encouraging (fig)

- Full study of parameter dependence and properties of the formalism underway



pN , E_beam = 530 GeV
|η|<0.75
E d³σ/dp³ (pb/GeV²)
10^4
10^2
10^0
10^-2
10^-4
4
6
8
10
12
p_T (GeV)

Conclusions

1. Despite many years of study, there is still work needed in the study of direct photons
2. Can not describe *all* the data with a single NLO QCD calculation
3. Still room for additional experimental work to resolve possible discrepancies between data sets
4. Recent progress in understanding threshold and k_T resummation corrections
5. Fully understanding direct photon production may force us to revise the methods used to calculate hard scattering processes
6. The times are still interesting...!