Direct Photon Production

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Direct Photon Motivation

- Photons have a point-like coupling to the hard interaction, allowing for direct probes and precision tests of perturbative QCD
- Experimentally, the 4-vector of the photon can be measured more precisely than that of a jet, again pointing to precision tests of QCD

In these lectures, I will concentrate on photon production in hadron-hadron collisions.

- The dominance of the gluon-Compton scattering diagram allows the potential for measuring the gluon distribution in the proton (although some theoretical complications are currently making that a bit difficult).

If time allows, I may say a few words about some related processes:

- diphoton production
- photoproduction

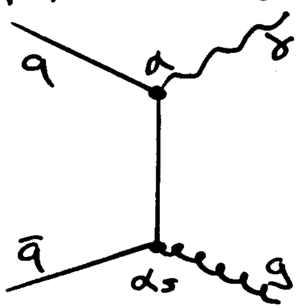
Understanding direct photon production is #2 on the CTEQ List of Top Ten Problems in QCD (http://sg1.hep.fsu.edu/~owens/QCD_list.html).

A few puzzles will be discussed along the way.

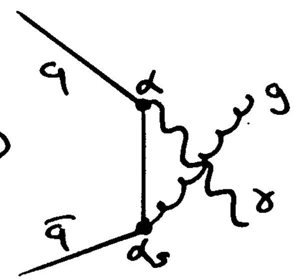
Direct Photon Production Mechanisms

The lowest order is $\alpha\alpha_s$

$q\bar{q} \to \gamma g$ annihilation

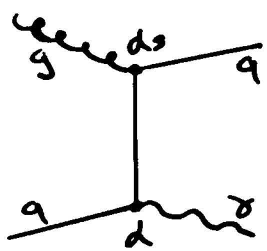


+ (crossed)



$$\frac{d\sigma}{d\hat{t}} = \frac{\pi\alpha\alpha_s}{\hat{s}^2}\,\frac{8}{9}\,e_q^2\left[\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}}\right]$$

$gq \to \gamma q$ Compton



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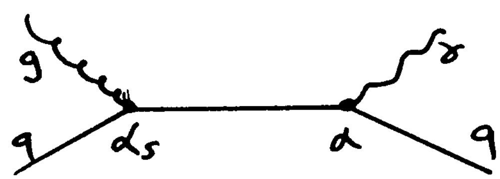
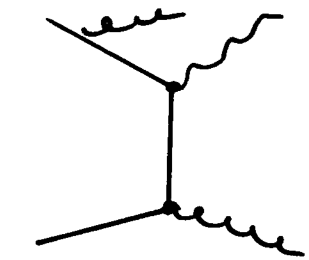


$$\frac{d\sigma}{d\hat{t}} = \frac{\pi\alpha\alpha_s}{\hat{s}^2}\,(-)\,\frac{e_q^2}{3}\left[\frac{\hat{u}}{\hat{s}} + \frac{\hat{s}}{\hat{u}}\right]$$

Leading order structure has the photon recoiling against a jet.

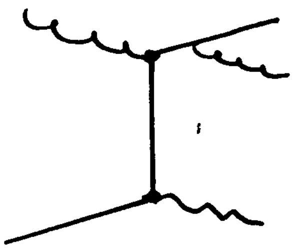
Direct Photon Production Mechanisms

Next order is $\alpha\alpha_s^2$

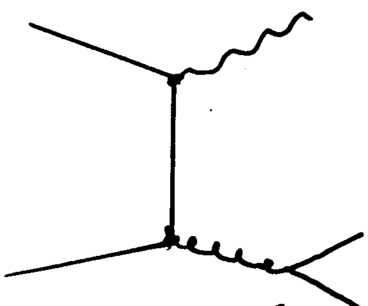


$q\bar{q} \to \gamma g g$

add extra gluon to lowest order process

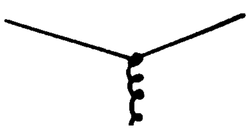


$g q \to \gamma q g$

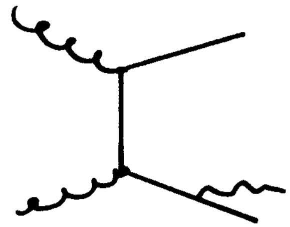


$q\bar{q} \to \gamma q'\bar{q}'$

gluon splitting into $q\bar{q}$ pair



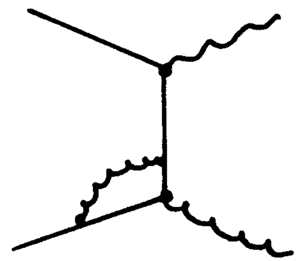
$q^{(\bar{q})} \to \gamma q^{(\bar{q})}$



$gg \to \gamma q\bar{q}$

Brems

+ virtual diagrams like

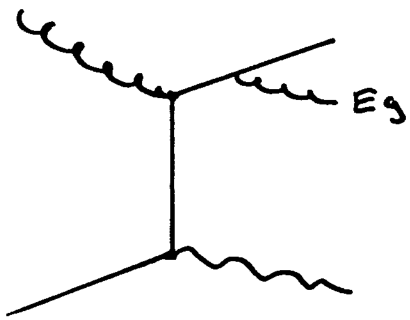


Simply related to corresponding photoproduction processes by crossing

γ is balanced by 1 or 2 jets in final state

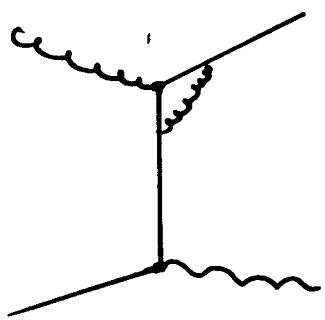
Soft and Collinear Singularities

What about singularities?



soft singularity when gluon energy goes to 0

collinear singularity when gluon is parallel to quark



singularities cancel when real+virtual diagrams are added

Net effect is an order α_s correction to the leading order process (and reduction of dependence on the renormalization scale)

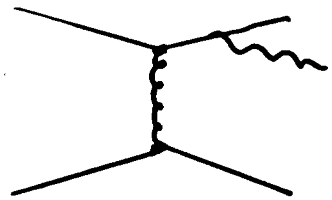
Higher Order Contributions

- We've seen that including higher order contributions beyond the leading log approximation requires the inclusion of
  - 2->3 subprocesses
  - 1 loop corrections to 2->2 subprocesses
- This means encountering various IR, UV and collinear divergences
- Can take these into account using analytic techniques (Aurenche et al), or can use a combination of analytic and Monte Carlo technolóy (Owens)
  - regularize singularities (dimensional regularization)
  - subtract UV singularities (MS scheme)
  - break 3 body contribution into 3 pieces
    - (1) soft
    - (2) collinear
    - (3) everything else (finite 3-body states with 3 well-separated energetic partons)
- use soft gluon approximation and leading pole approximation to integrate over soft and collinear contributions analytically
  - combine (1) and (2) with order $\alpha\alpha_s^2$ 2-body result
    - soft and IR singularities cancel
    - factorize collinear singularities
- Then have two types of MC events
  - finite 3 body events
  - finite 2 body events that depend logarithmically on the soft and collinear cutoffs
- The cutoff dependence cancels (mostly) when adding the two types of events

->only the total cross section has a physical meaning

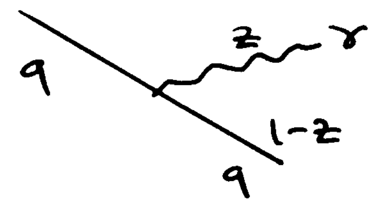
Bremsstrahlung

- Examine Bremsstrahlung diagrams in more detail



- Internal quark lines go on shell
  →long distance physics
- In this configuration, γ is accompanied by jet fragments on the same side, with a high p_T jet on the away side
- Factorize the singularity and include it a photon fragmentation function
- Sum the large logs with modified Altarelli-Parisi equations

- Bremsstrahlung diagrams are order $\alpha_s^2\alpha$
  …but one difference between γ fragmentation functions and quark/gluon fragmentation functions is that the photon fragmentation function increases logarithmically with the scale over the entire z range



$D_{\gamma/q}(z, Q^2)$
$\sim \alpha^{\gamma}(z) \ln Q^2/\Lambda^2$

-perturbative part can be calculated
-non-perturbative part usually modeled with vector dominance (and measured at LEP)

- $\sigma_{frag} \rightarrow \vartheta(\alpha_s^2) \times \vartheta(\alpha/\alpha_s) \rightarrow \vartheta(\alpha_s\alpha)$

Isolation

- Expect to see two classes of events
  - isolated (or pointlike): no hadrons accompanying the photon
  - accompanied: photon is part of a high p_T jet; part of the fragmentation is perturbatively calculable
- This is a simplistic decomposition; the situation is not so clearcut when dealing with a complete NLO calculation

Another complication: photon isolation

- Typical algorithm limits hadronic energy in a cone of radius R ($\sqrt{\Delta\eta^2+\Delta\phi^2}$) about photon direction to be less than some amount ε_γ
- Order $\alpha\alpha_s^2$ fragmentation includes $2\to3$ subprocesses
  - soft gluon singular terms cancel against IR singularities in the $2\to2$ 1-loop terms
  - ...but this requires the extra gluon to be integrated over all phase space (up to some energy cutoff); if gluon is inside the isolation cone, then the gluon phase space is limited
  - incomplete cancellation of the singular terms

Cross Section Calculation

- In order to calculate theoretical cross section, have to convolute matrix elements with parton distributions (and fragmentation functions)

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

$$E \frac{d^3\sigma}{dp^3} \equiv \frac{d^3\sigma}{dp_T^2\, dy} \to \frac{1}{2\pi E_T} \frac{d^2\sigma}{dE_T\, dm}$$

Measurement Techniques

- Have to be able to distinguish the γ signal from the backgrounds from jets fragmenting into a leading π^o (or η)

$$\sigma_\gamma \sim \vartheta\,(\alpha\alpha_s)$$
$$\sigma_{jet} \sim \vartheta\,(\alpha_s^{2})$$

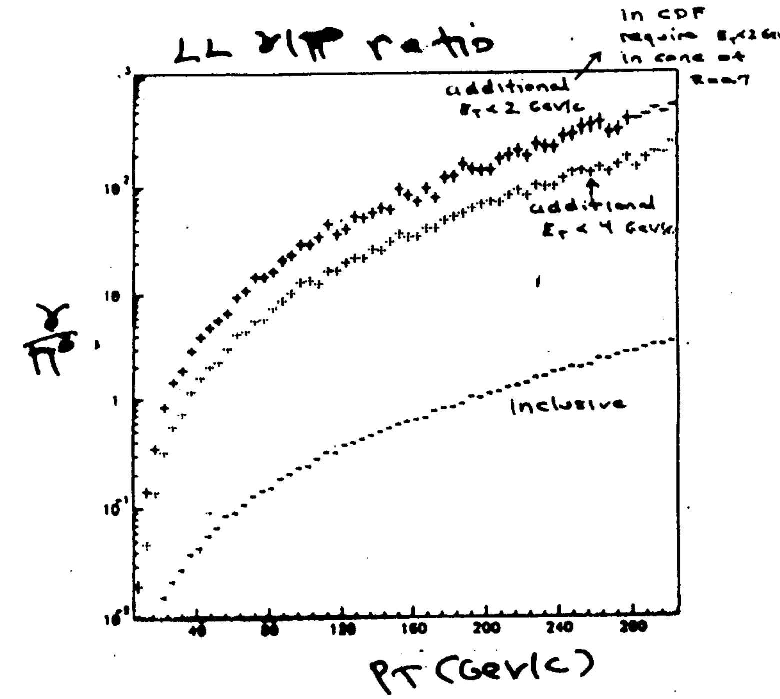
...but

- more subprocesses for jet production than for γ production
- larger color/spin factors for jet production

γ/jet ratio ~ 10^{-3} - 10^{-4}

...but interested in π^o production

->high z fragmentation of jet

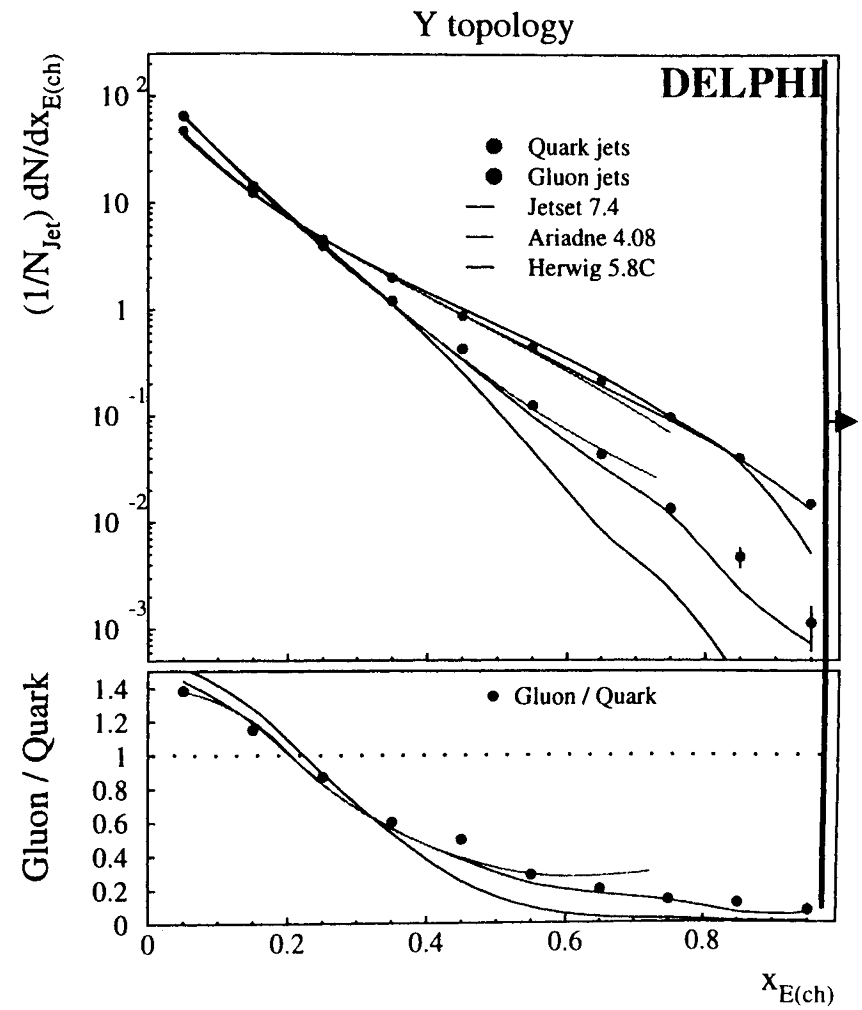


γ/π^o ratio ~ 1% (at collider)

but imposition of isolation cut (forcing the π^o to higher z) can increase the ratio by several orders of magnitude

Quark/gluon fragmentation functions

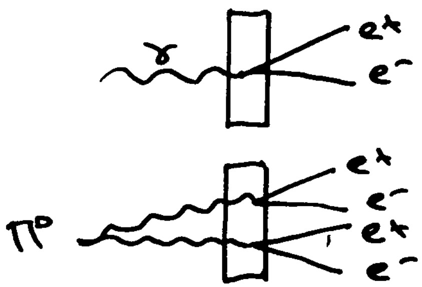
- Quark and gluon jet fragmentation functions have been studied in detail at LEP
- At the Tevatron Collider (and LHC as well) the background to direct photons comes the rare jets that fragment into a very high z ($=E_{\pi^o}/E_{jet}$) π^o, leaving little energy for the remainder of the jet
- There is little information in this region, especially for gluon jets, which are the bulk of the cross section at low E_T at the Collider



Measurement Techniques

There are a number of different techniques to distinguish photons from the π^0 background:

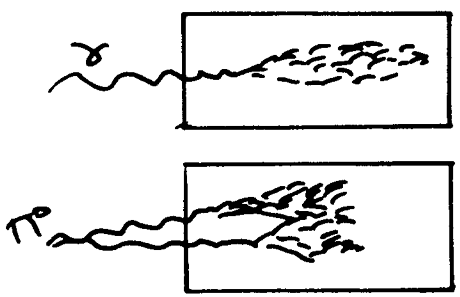
- Conversion



"Allow" γ's to convert in preconverter (typically O(1%)) of material

π° has 2× γ's

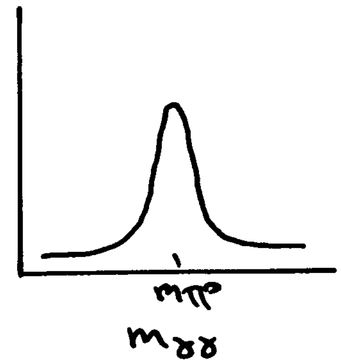
- Shower profile



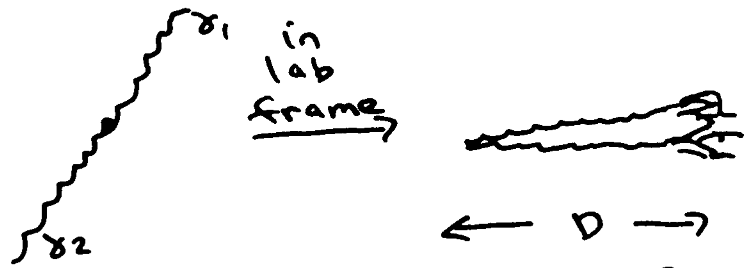
2 γ's from π° will produce EM showers with broader lateral and shallower longitudinal profiles

At collider, use isolation to improve the signal/background

- Reconstruction



Requires
- good EM resol
- large accepta
- good angular resolution for EM calorimet



$\Delta r_{\gamma\gamma} \propto \frac{2 m_{\pi^0}}{E_{\pi^0}}$ r

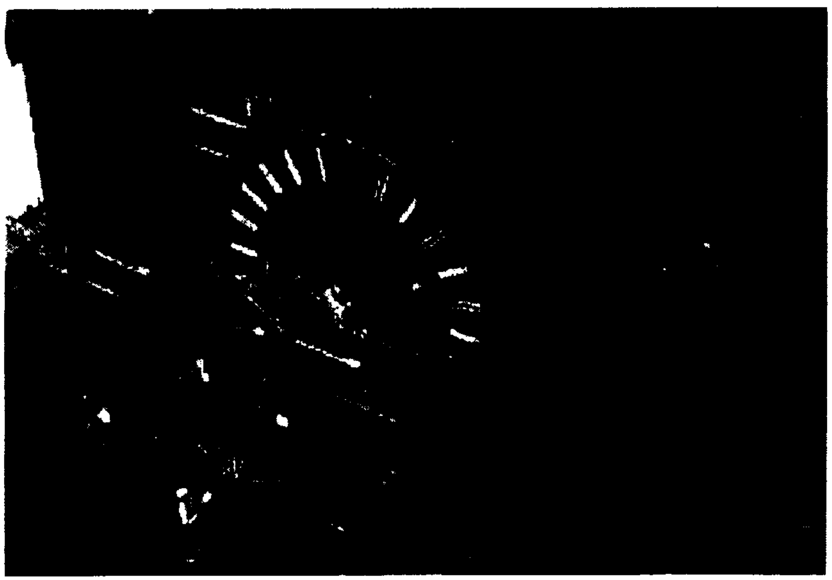
for E_{π^0} = 200 Ge

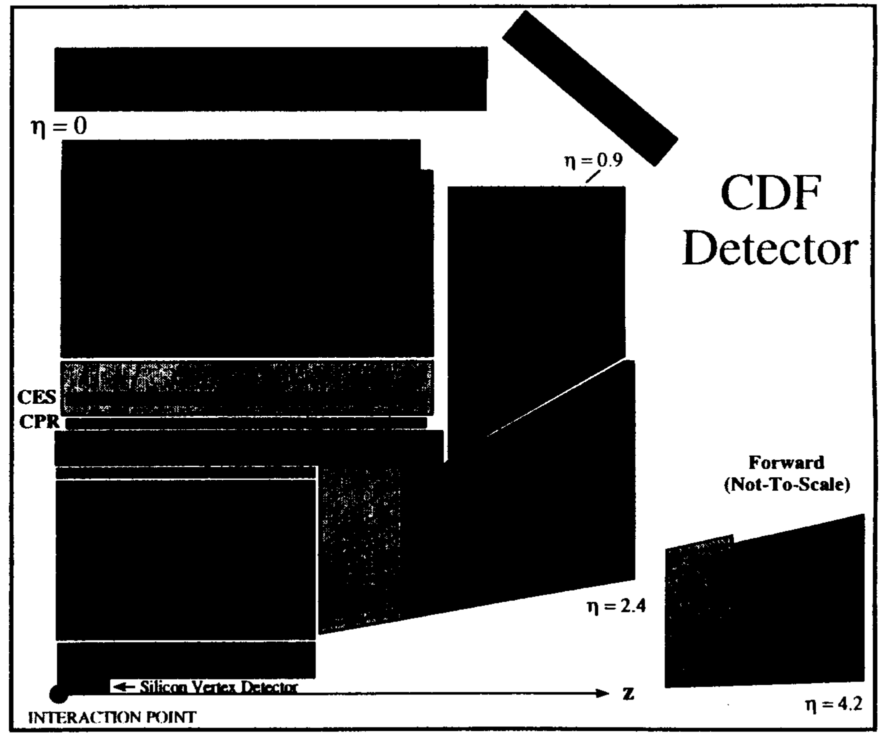
$\Delta r_{\gamma\gamma}$ ~ 1 cm @

Used in fixed target experiments

Direct Photons at CDF

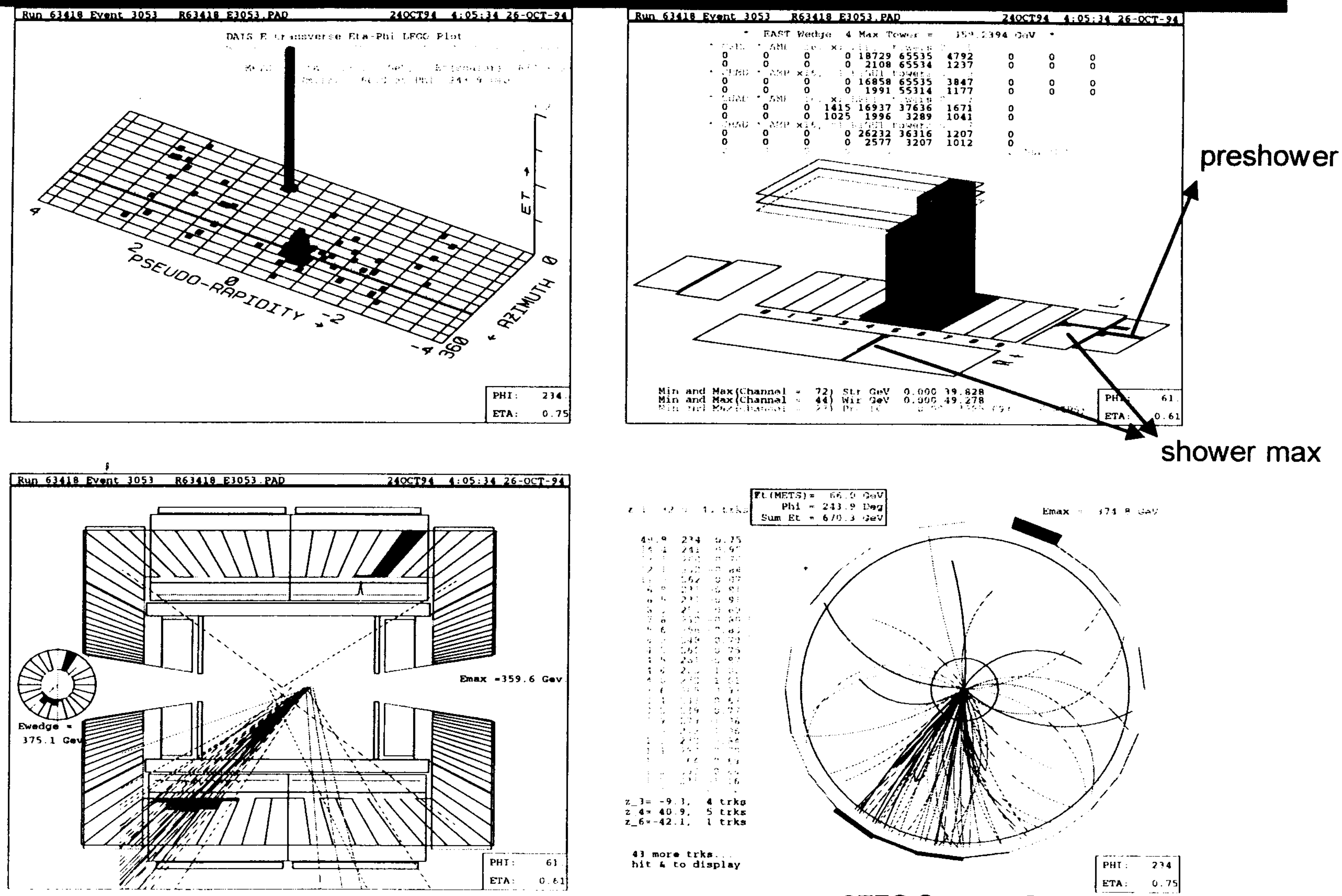
- Two techniques utilized for determination of photon signal
  - EM shower width
  - Photon conversion probability
- Use of techniques feasible because of isolation cuts applied to boost signal/background





Define a photon as:

- 1, 2 or 3 continguous EM towers
- No track pointing at photon
- Small fraction of energy in hadron calorimeter



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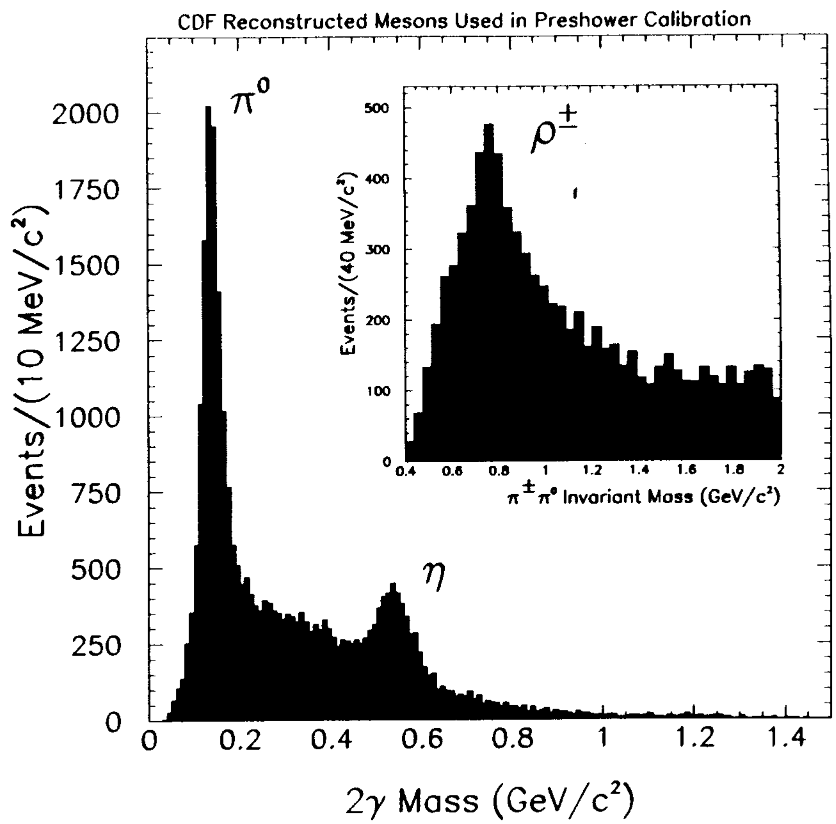
Preshower Calibration

- For some limited number of events (where the two photons straddle towers), it is possible to reconstruct the diphoton mass.
- These events can be used to calibrate the conversion probabilities, and thus the amount of material.



Discrimination variables

- Make use of tighter shower profiles (in general) for single photons as compared to π^0's

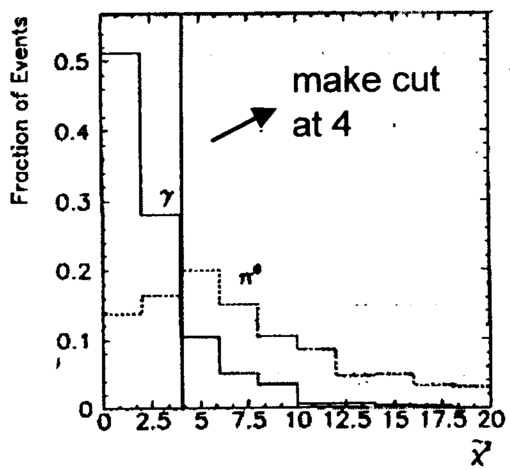
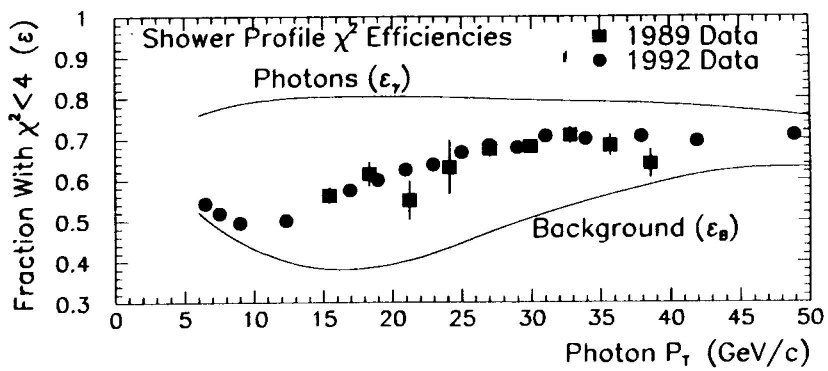
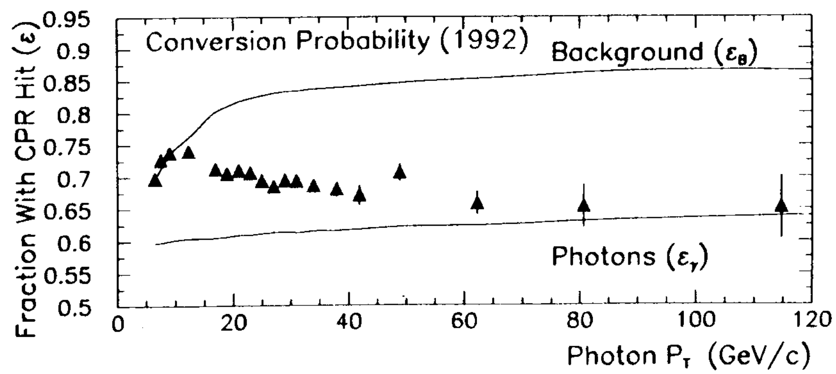


FIG. 3. Simulated $\tilde{\chi}^2$ distributions for 15 GeV/c photons (solid) and π^0's (dashed).

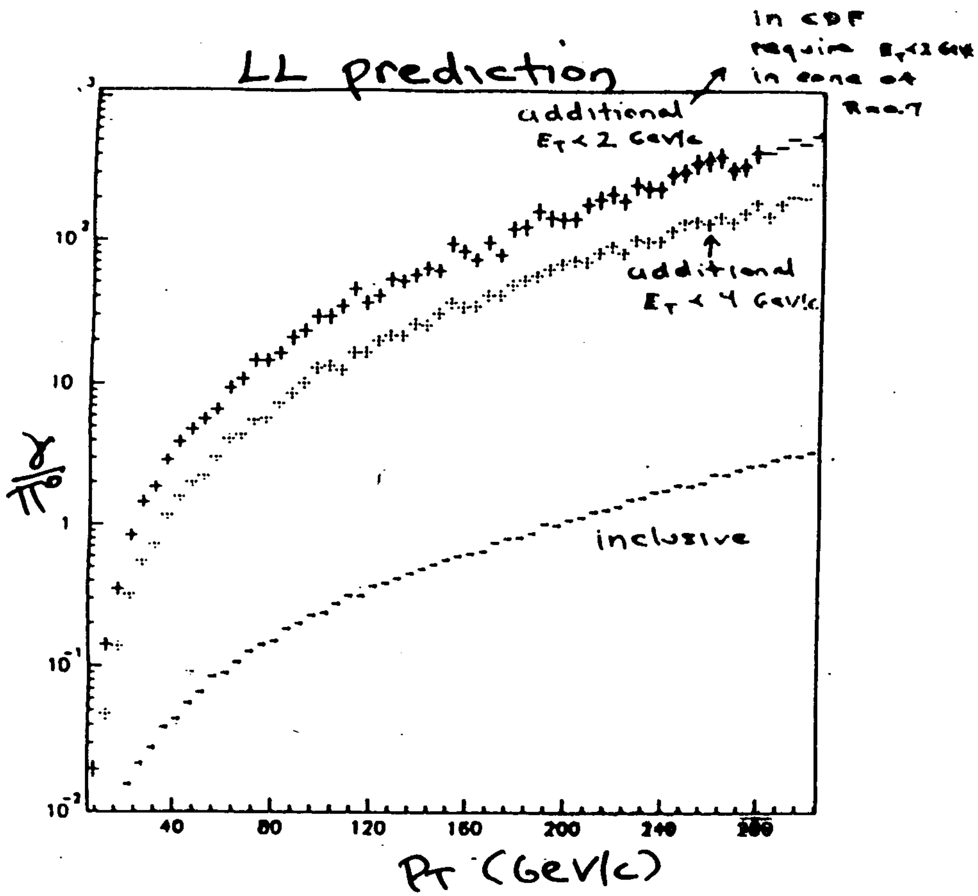
- Make use of greater conversion probability for π^0 than for single photon
  - Probability for 1 photon not converting is $P\gamma = e^{-7/9t}$ (t is # of radiation lengths)
  - Probability of 2 photons not converting is $P\gamma^2$

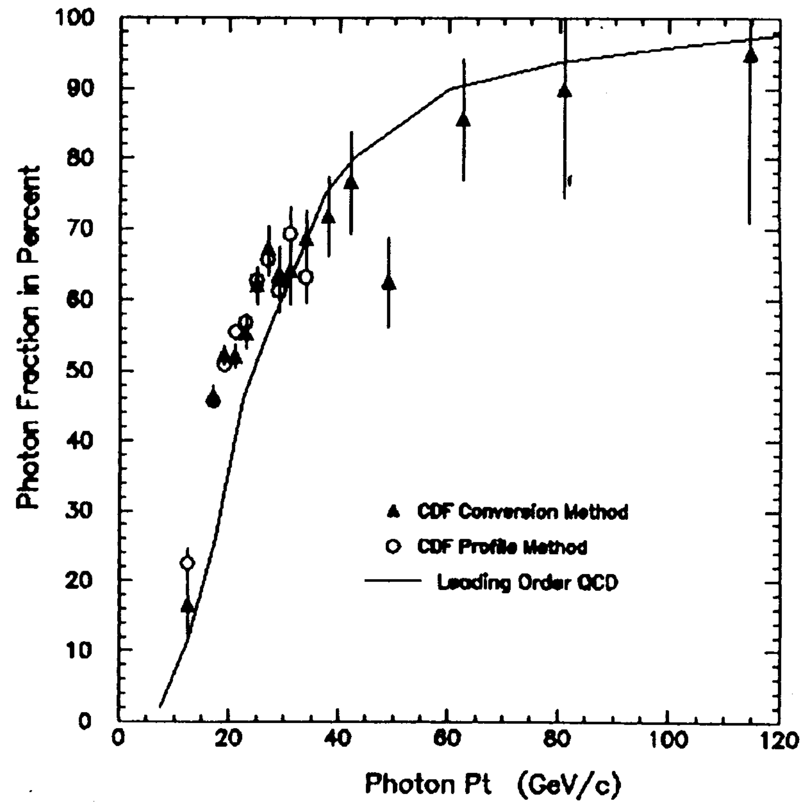
Run 1A results (~19 pb^{-1})





Photon Fraction





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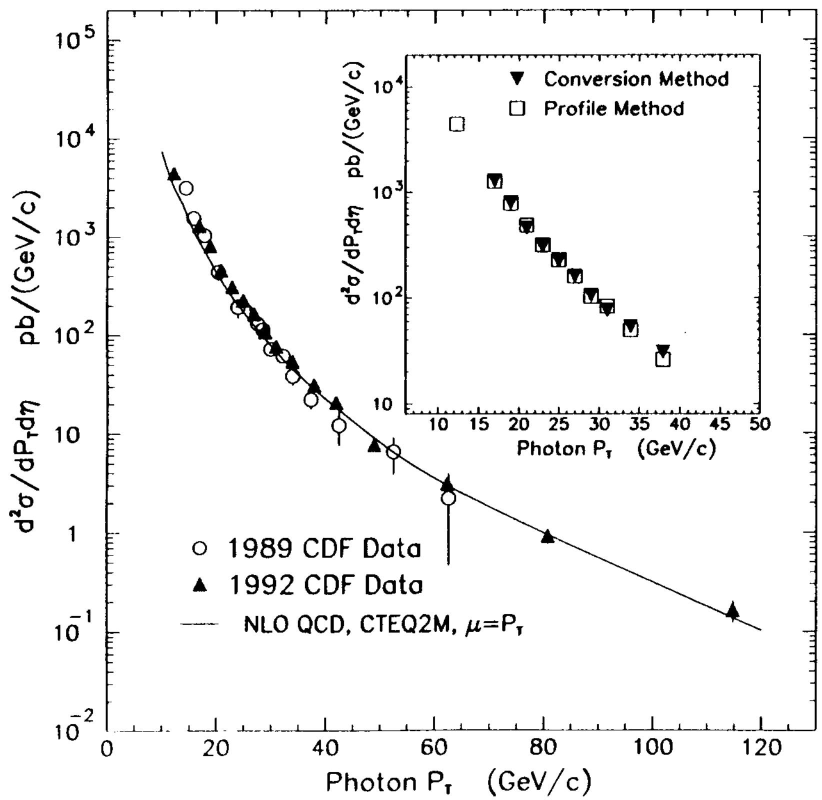
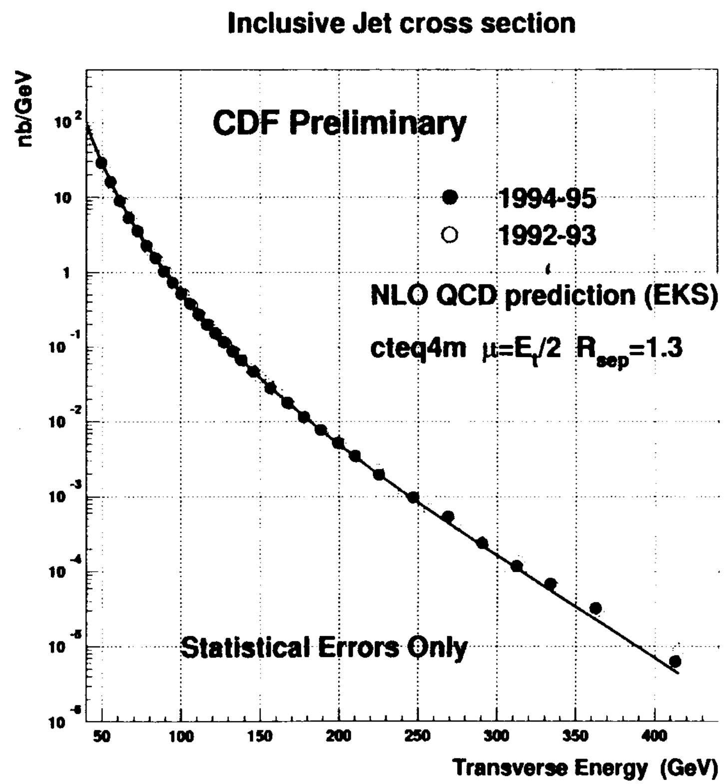
Photon/Jet Cross Sections

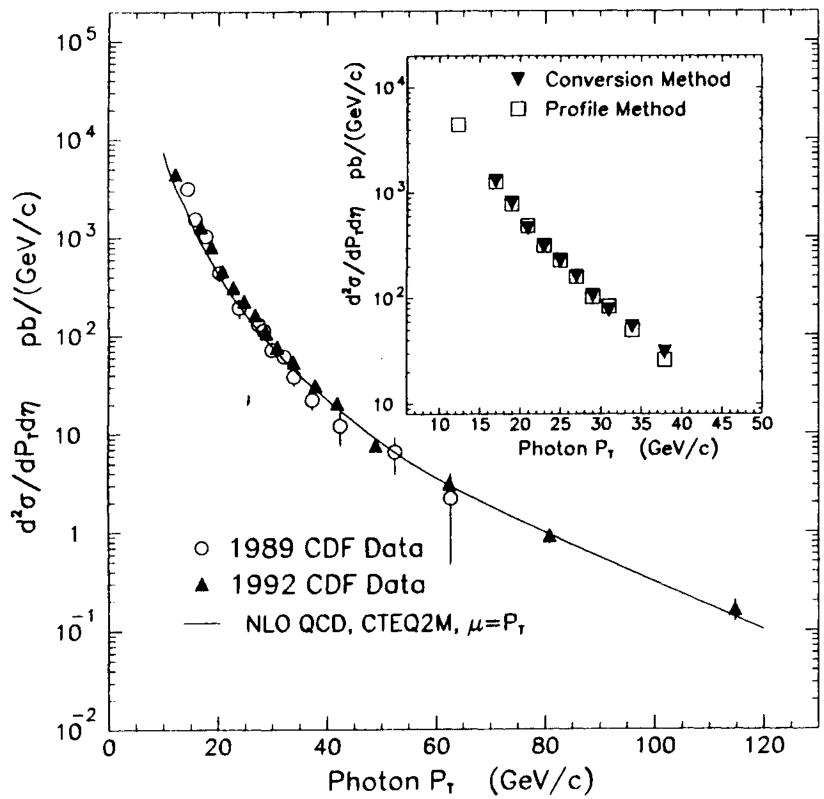
- Note that it's easier to measure low E_T photons than low E_T jets
- Note difference in scale of cross sections

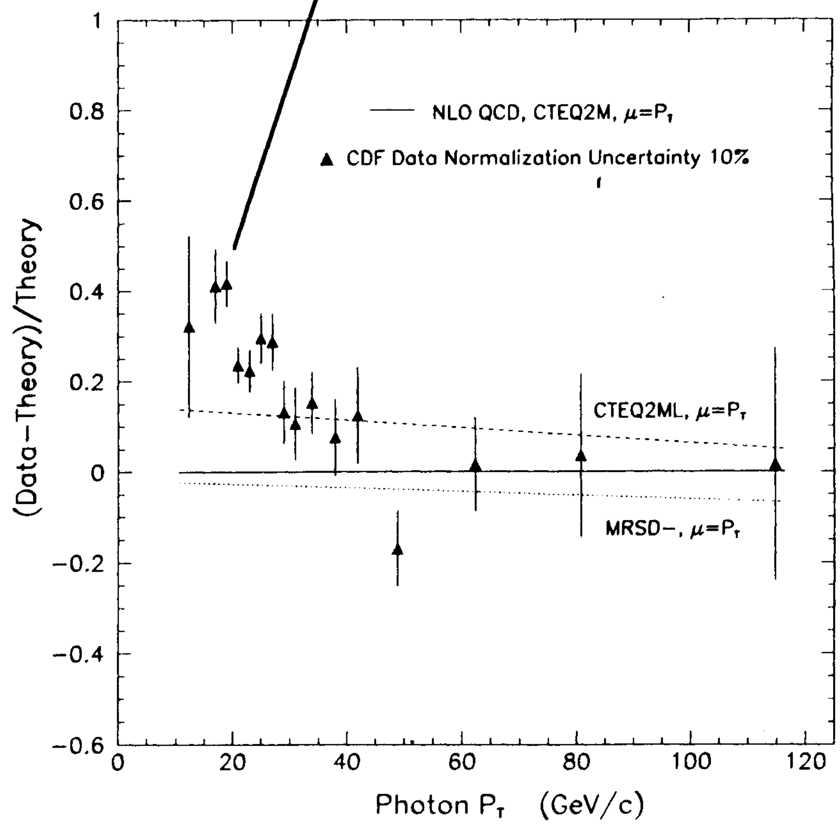




Situation at end of Run 1A

Puzzle #1: possible excess at low p_T





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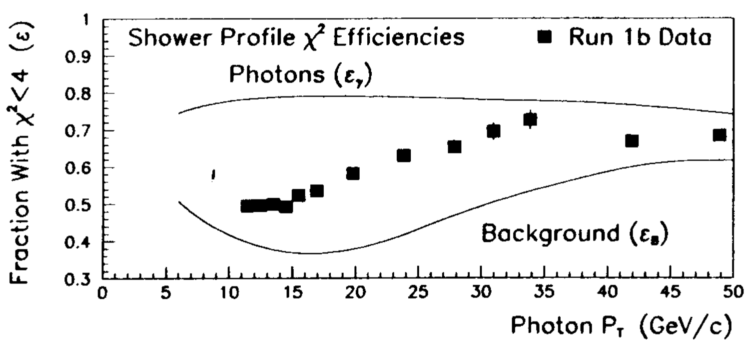
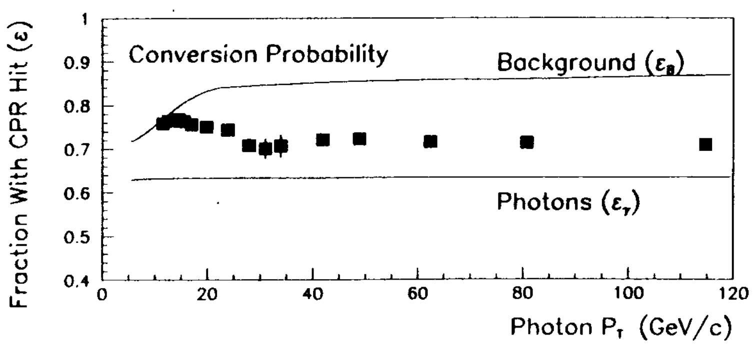
Puzzle # 2

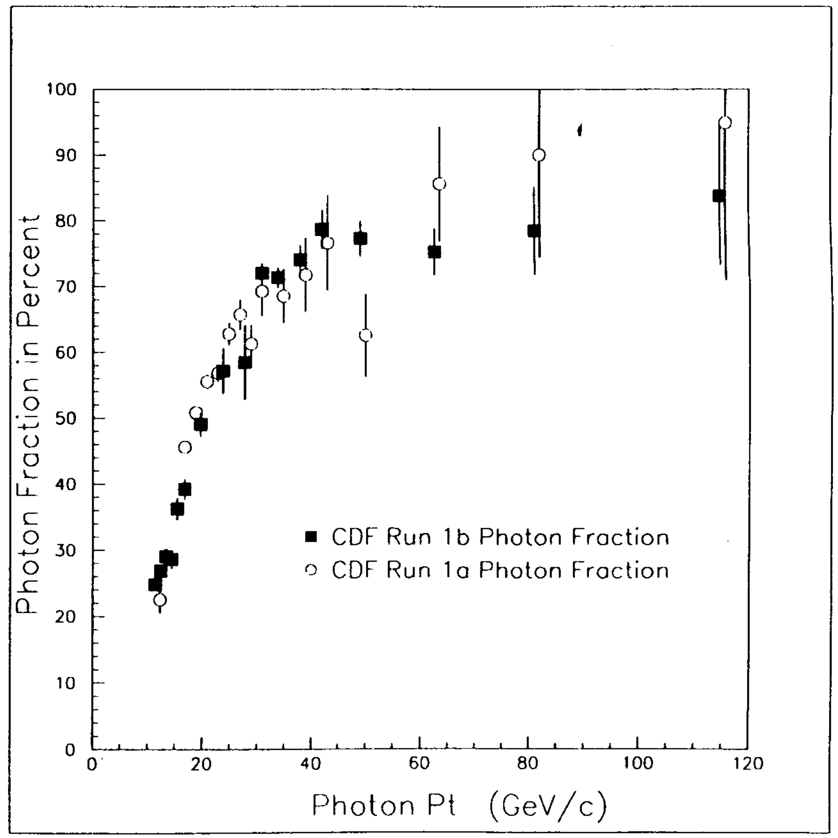
- Higher statistics in Run 1B (~87 pb^{-1})
- Is it possible that the photon fraction does NOT go to 100% at high p_T for isolated photons?

Fraction of Photons = $(\varepsilon_B-\varepsilon)/(\varepsilon_B-\varepsilon_T)$





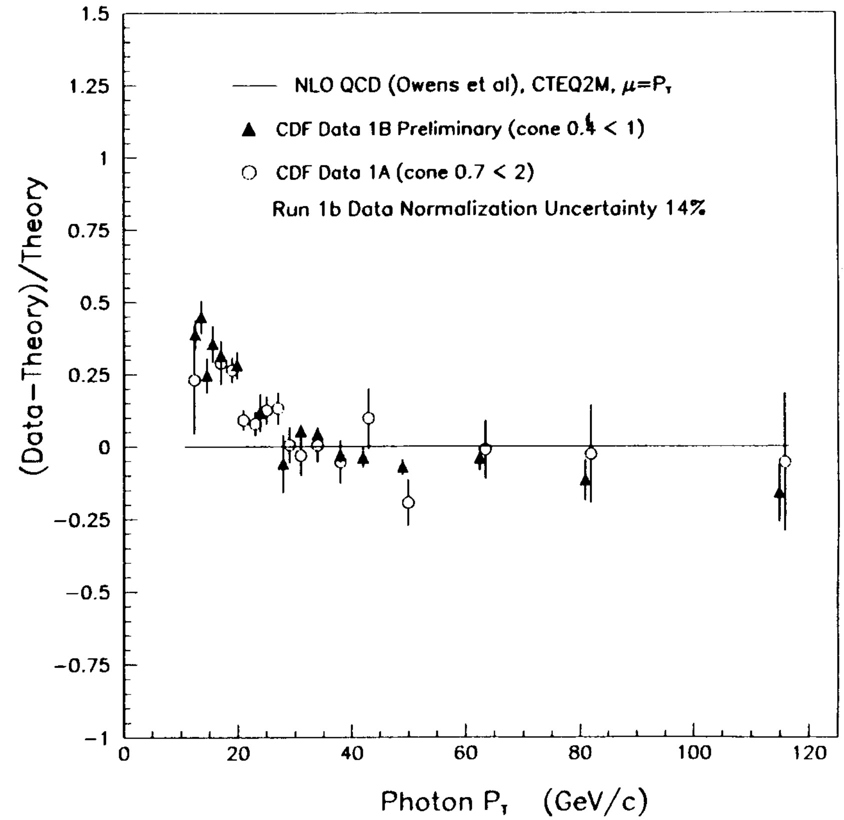
Photon fraction requiring:
- Run 1A: <2 GeV/c in cone of 0.7
- Run 1B: <1 GeV/c in cone of 0.4



1b vs 1a

- CDF data from Run 1B agrees with that from 1A and probes both low E_T and high E_T regions in more detail

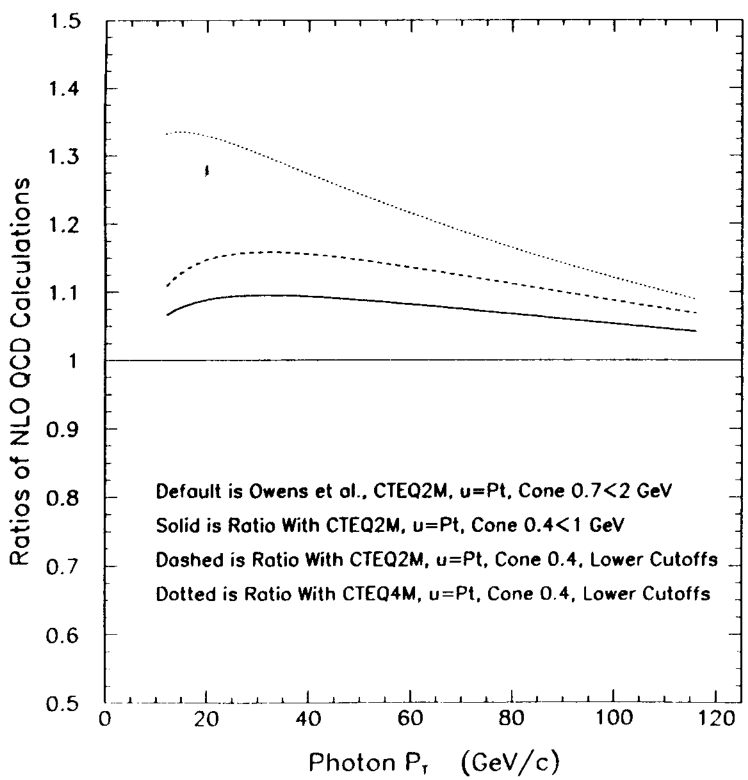
Data vs. 1a Theory
(1b theory rescaled by ratio of 1a/1b)



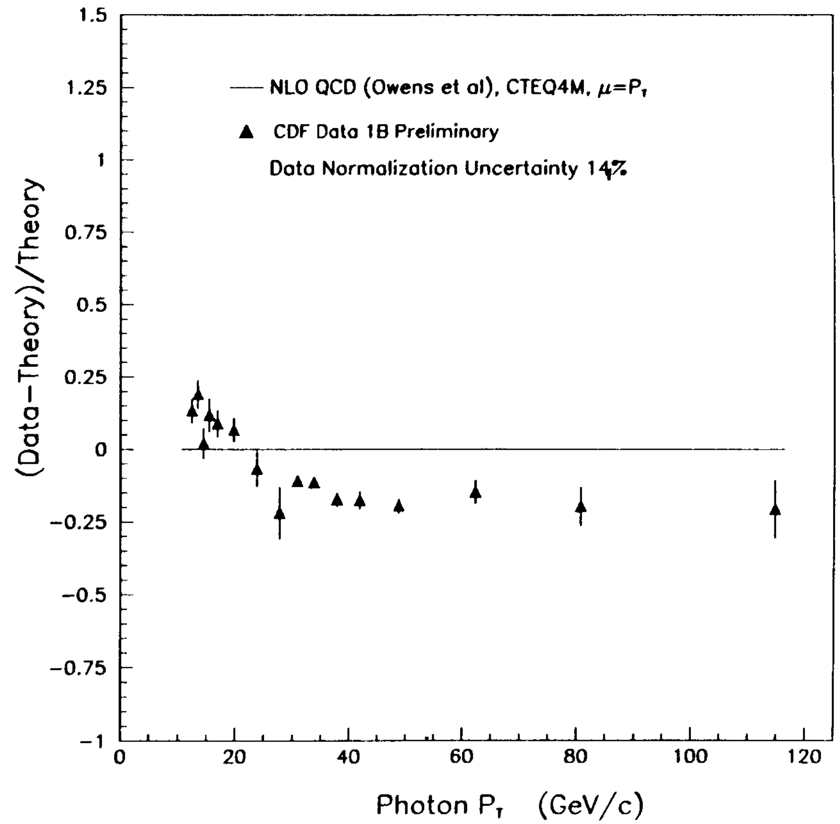
Theory Evolution

- Changing the pdf (CTEQ4M should be used in place of CTEQ2M), isolation cut, and 2->3 body NLO cutoff changes theory prediction

Theory Evolution Using Owens et al Calculations



Data still shows shape problem at low p_T but now there may be a deficit at high p_T

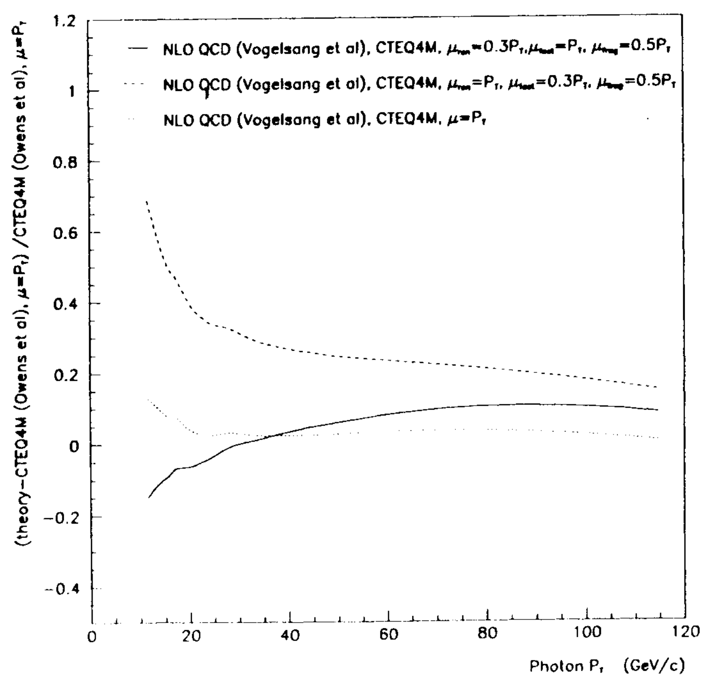


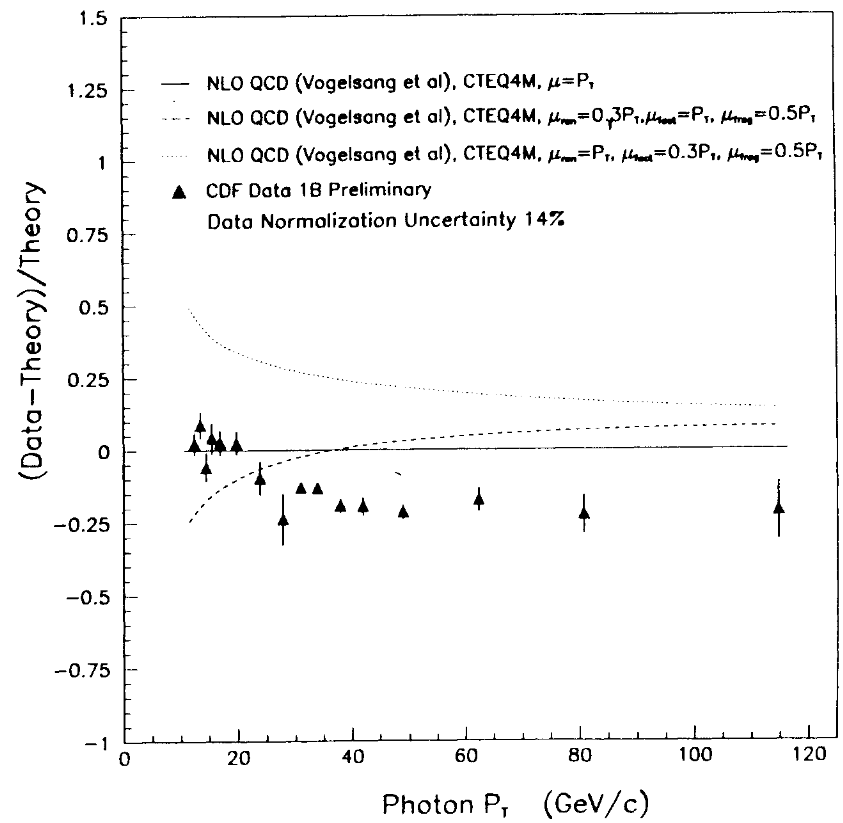
Theory Wiggle Room

- Vogelsang prediction has improved treatment of Bremsstrahlung (effect at lowest p_T)
- Show flexibility of QCD by varying renormalization, factorization and fragmentation scales independently

Can add some shape to the prediction but hard to get good agreement with data ...and it's "not natural" to change the scales so arbitrarily → editorial opinion

Comparison of Vogelsang et al with Owens et al

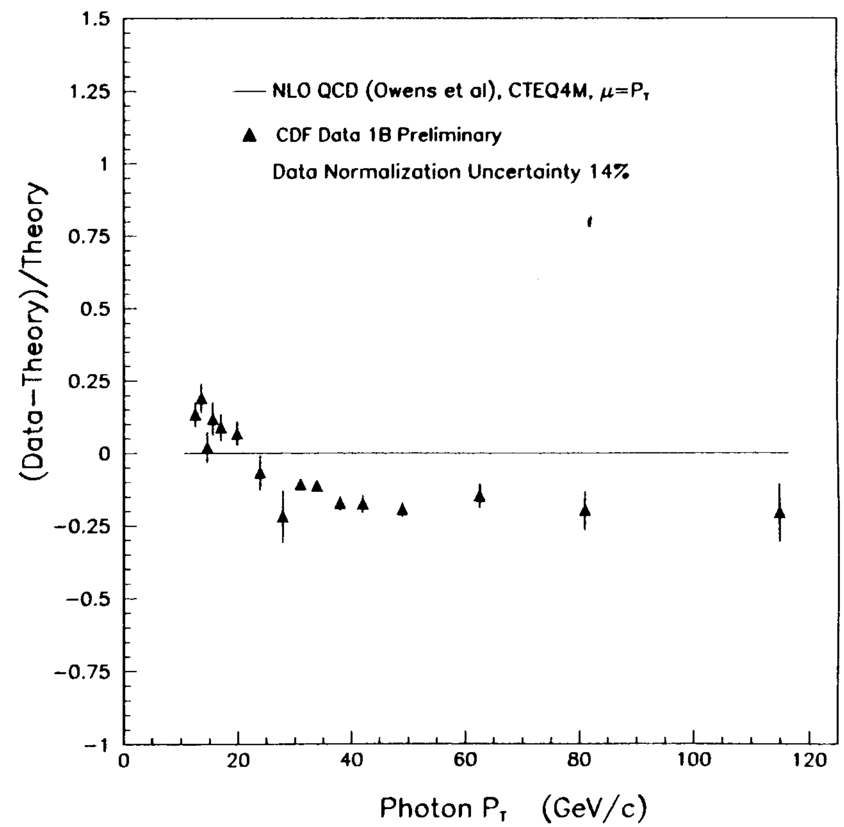




Puzzle # 3

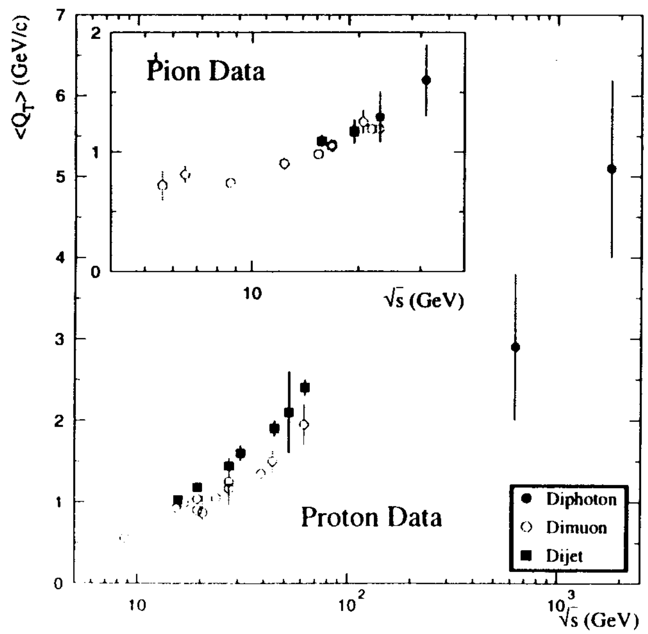
- Why is theory larger than data at high p_T?
- Could soft gluon radiation from initial state by spoiling isolation cut?

CTEQ List of Top 10 Measurements would like to see:
Isolation energy distribution as a function of photon E_T

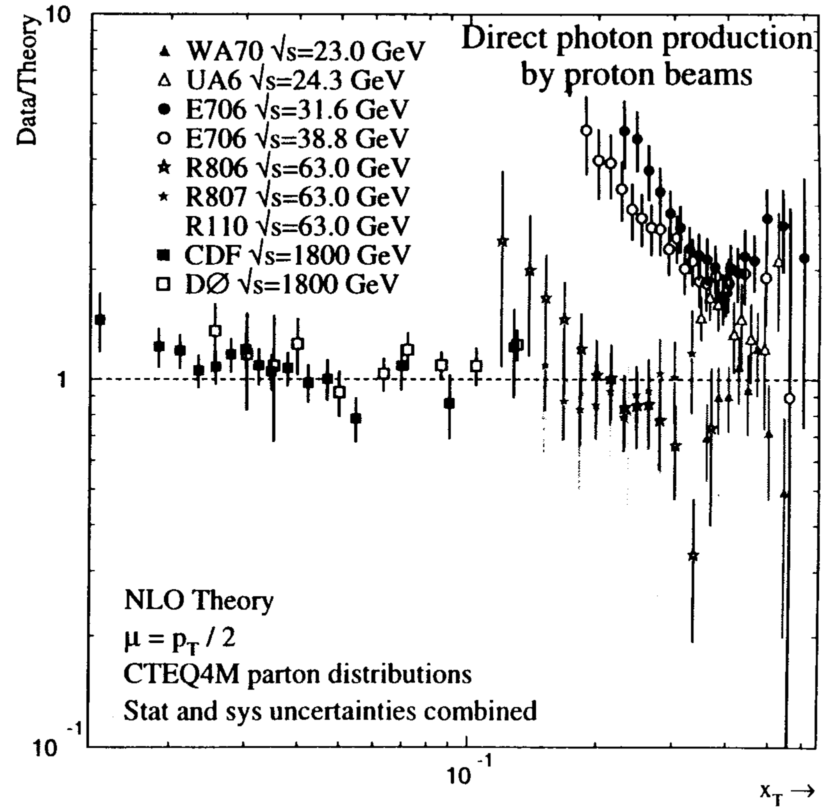


Back to Puzzle #1:Direct Photons and k_T

- NLO QCD inadequate to explain size of observed k_T in DY, W/Z, and diphoton distributions; full resummation calculations needed
- May be similar effect in direct γ; no rigorous resummation calculation available for direct γ
  - complicated by color flow from initial to final state

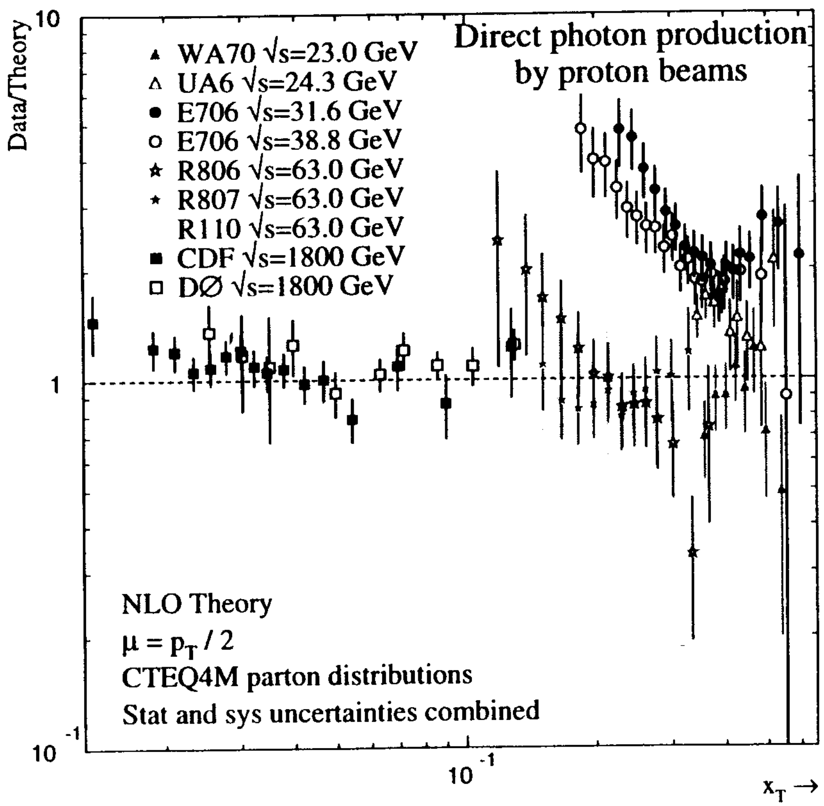


- But yet there is a pattern of deviations of data from NLO QCD predictions, both at the collider and for fixed target experiments



Back to Puzzle #1:Direct Photons and k_T

- ...but yet there is a pattern of deviations of data from NLO QCD predictions, both at the collider and for fixed target experiments



<u>Hypothesis:</u>

•Soft gluon radiation causes deviations from NLO QCD at low E_T

•$<k_T>$ increases as log of s

- •1 GeV/c for fixed target
- •3-4 GeV/c for Tevatron collider
- •6-7 GeV/c for LHC (low mass states)

...yet the brilliance of this hypothesis is not universally accepted (especially in Europe). Why?

There are large logs that need to be resummed when there is a restriction of phase space for soft gluon emission.

- •as for example at high x
- •or at low system k_T
  - •Drell-Yan production
  - •diphoton production
  - • γ + jet production

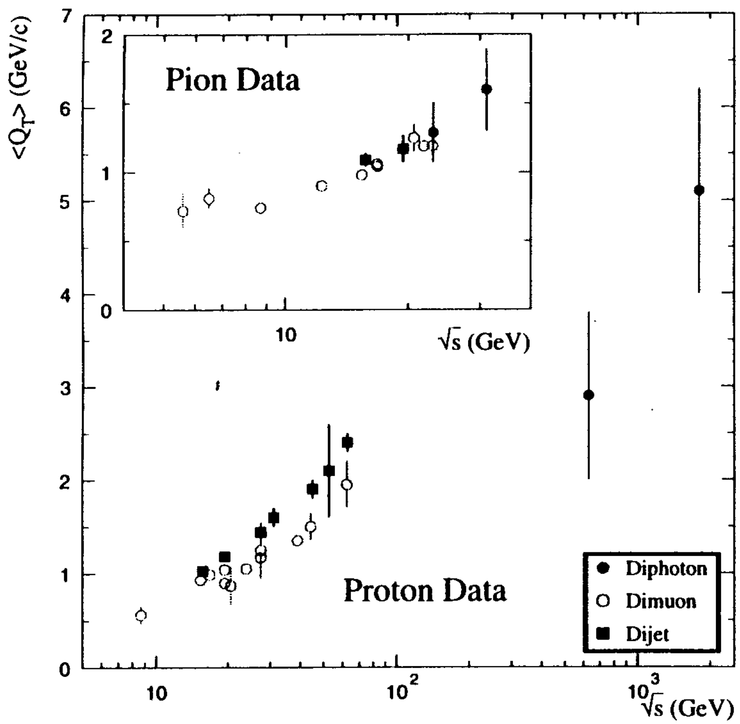
...but for single photon production (ignoring away-side jet) there are no explicit restrictions (except at high x)

Direct Photons and k_T

- Yet intuition tells you that these gluons are emitted and they should have an effect on a steeply falling p_T spectrum (like in direct photon production)
  - Can observe these effects, for example, by running HERWIG, PYTHIA
- Implement the effects of soft gluon radiation by incorporating Gaussian k_T distributions for the incoming partons in the proton-proton collision
  - Take the values of k_T to be used either from the plot on the previous transparency or directly from experimental observables

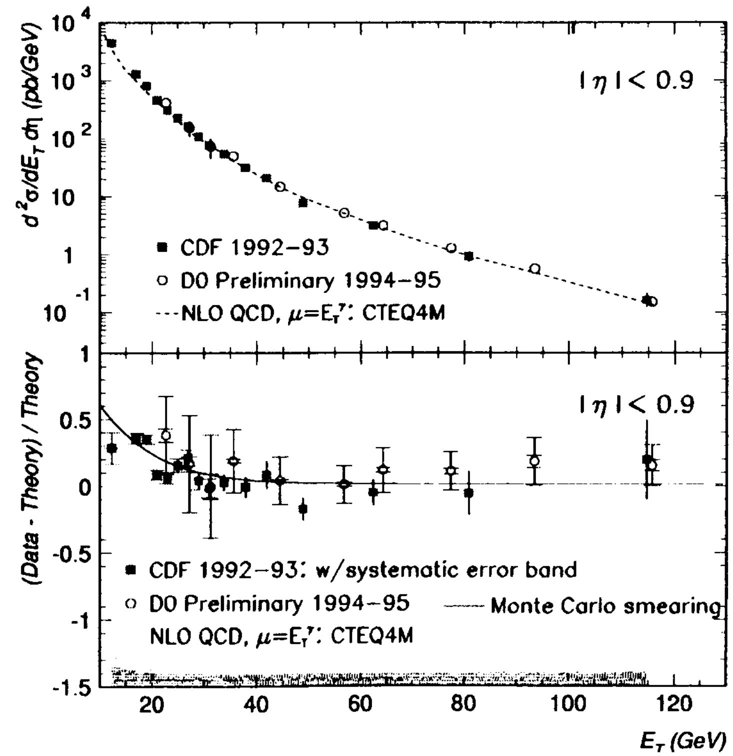
CDF/D0 and k_T

- Implement k_T smearing using $\langle k_T \rangle$ of 3.5 GeV/c per parton



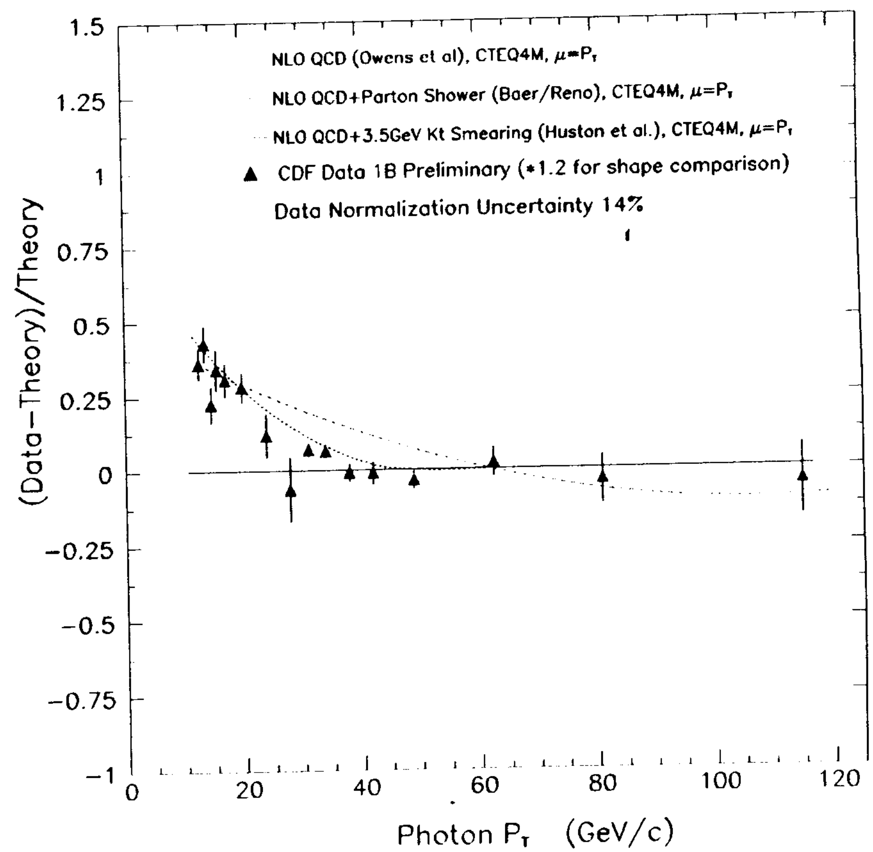
•The alert student may ask why aren't the same effects observed with jets.
•Other (larger) power corrections are masking the effects.

- Effect falls off as $1/p_T^2$

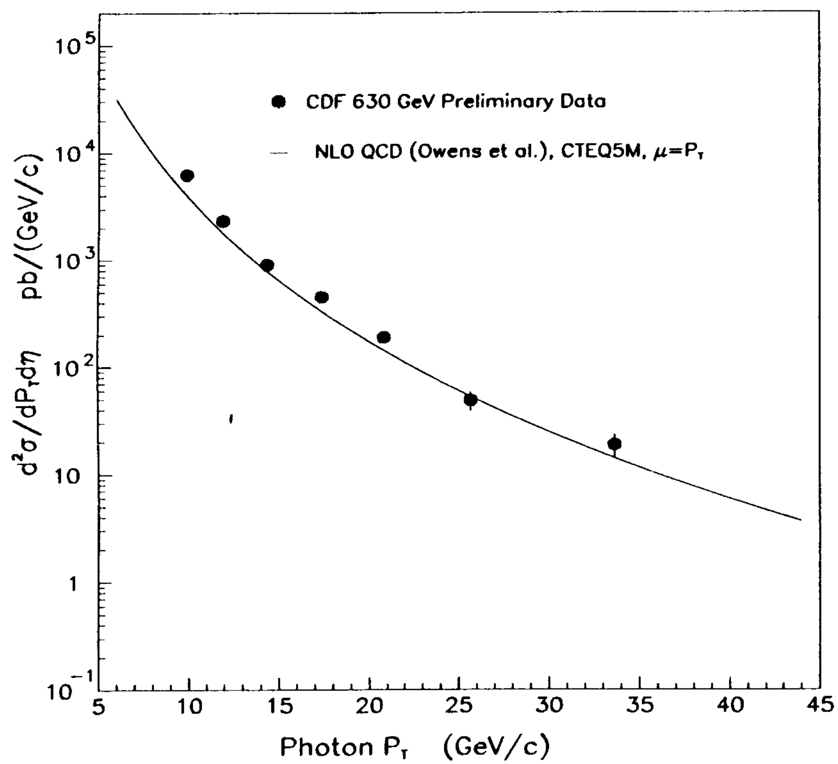


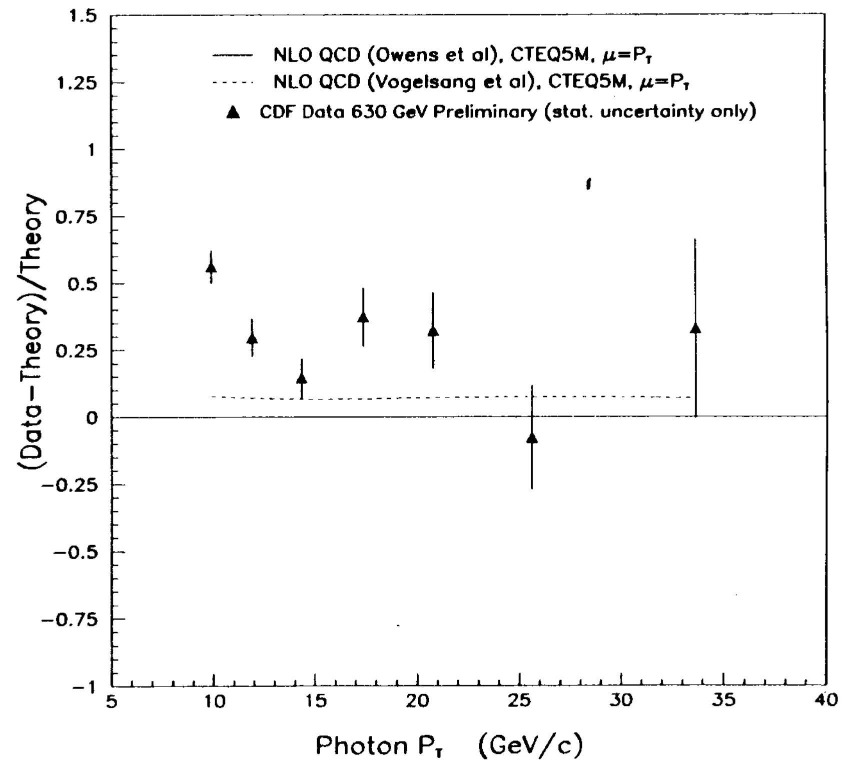
k_T Implementations

- Can try to implement k_T smearing through added parton showering
  - effects tend to fall off as $1/p_T$ rather than $1/p_T^2$
  - produces a deficit at high p_T



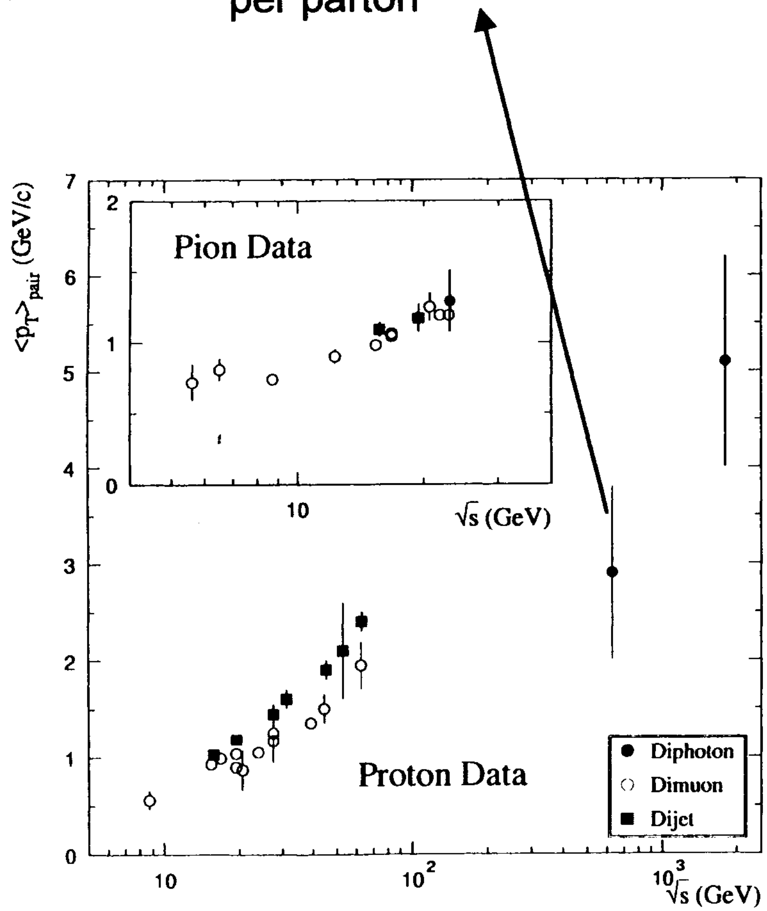
Photons at 630 GeV

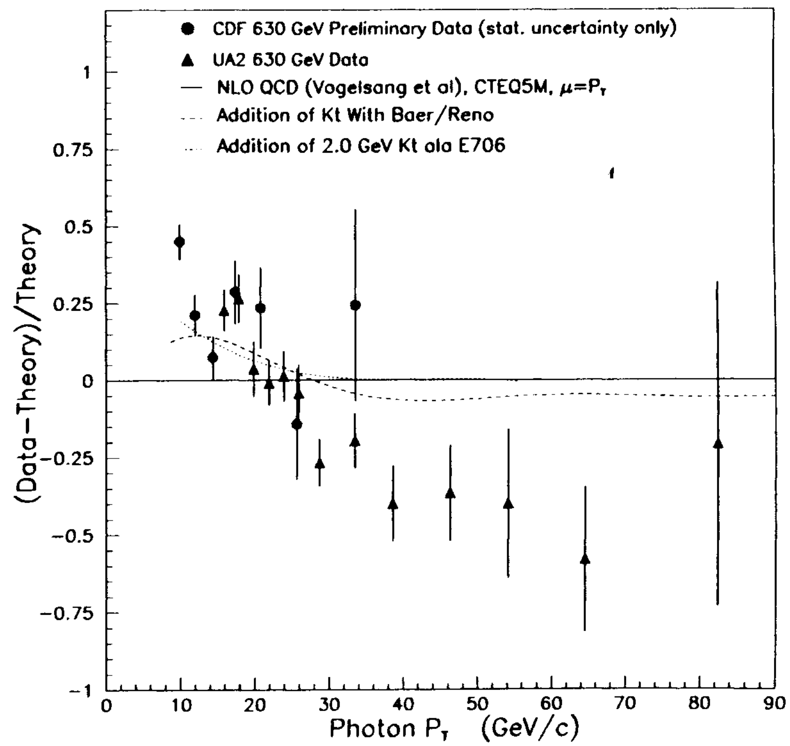




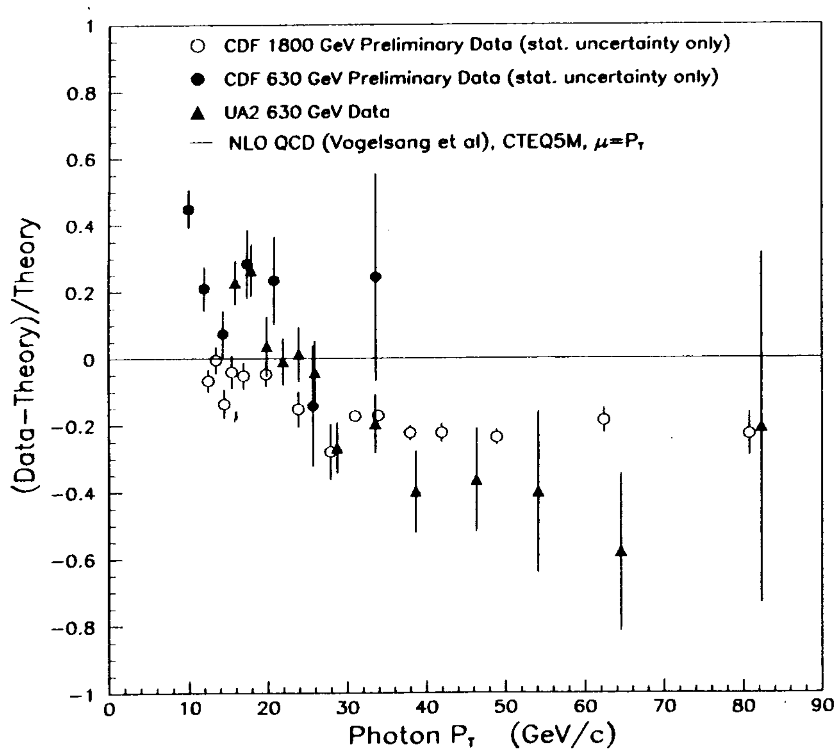
Low p_T shape problems at 630 too?

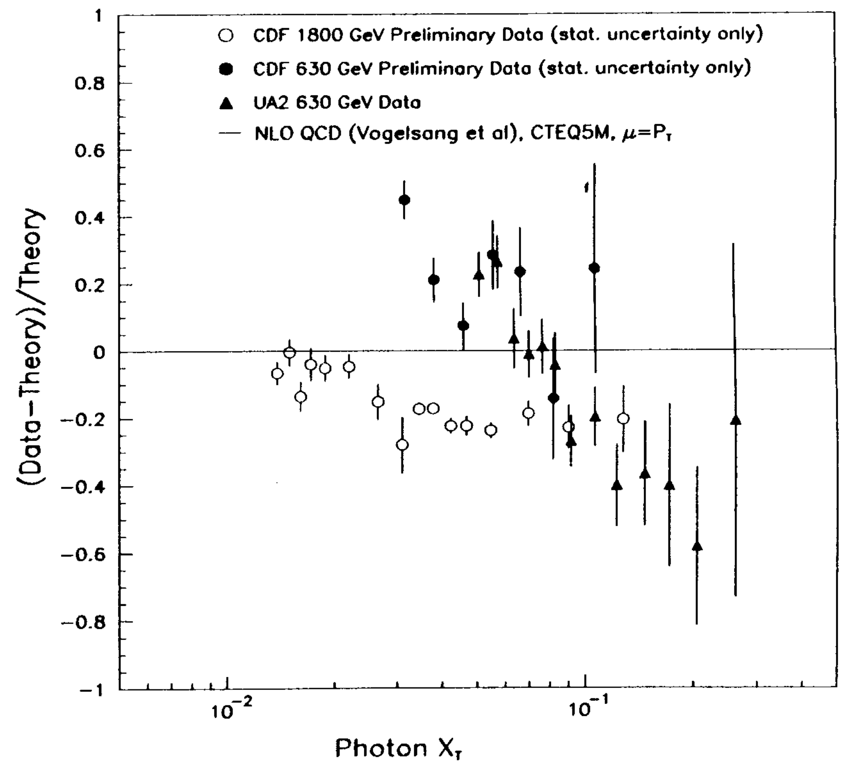
expect about 2-2.5 GeV/c
per parton





Universal Problems at high p_T?





Diphoton Measurements at CDF

2 aspects:

•QCD measurements of $\gamma\gamma$

•exotic searches with diphotons, e.g. Higgs->$\gamma\gamma$: looser cuts to maximize efficiency

Require:

•$E_T^{\gamma1,\gamma2} > 12$ GeV/c

•Isolation energy in cone of 0.4 < 1 GeV/c

saturated by MB energy for $\gamma\gamma$

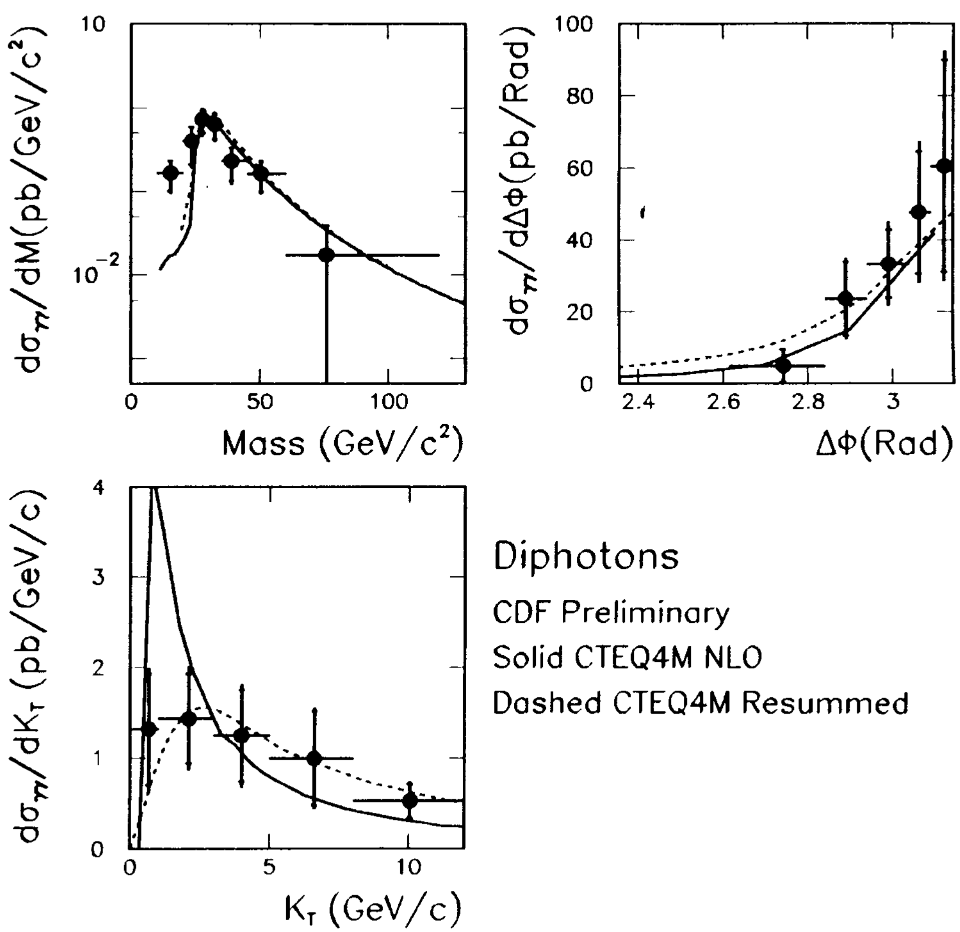
N.B. backgrounds come from jets with z_{π^o} (=E_{π^o}/E_{jet}) > $E_{\pi^o}/(E_{\pi^o}+1)$

•z_{min}~0.95 for E_T^{π}=20 GeV/c

•fragmentation functions not well determined here, especially not with gluons and especially not in Monte Carlos

Note that distributions that are δ functions at LO are not well-described at NLO

->need resummed predictions



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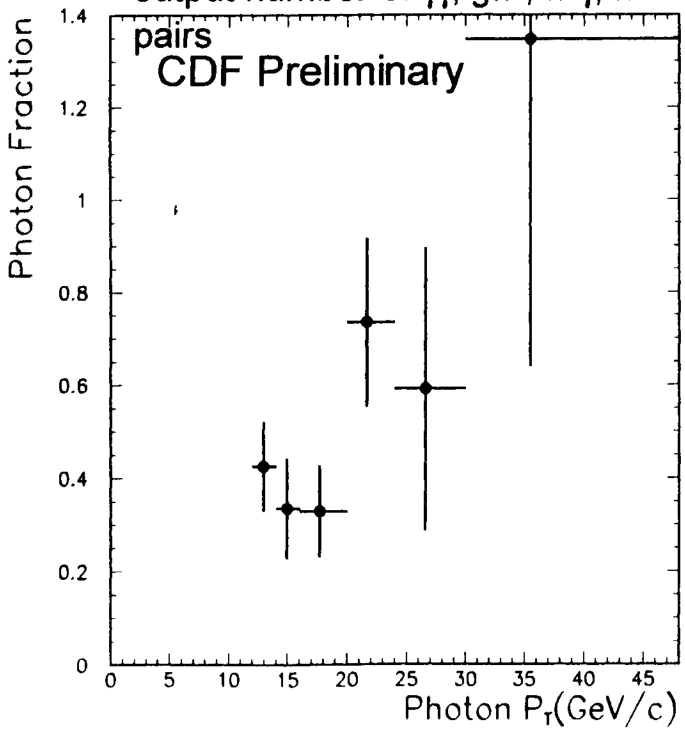
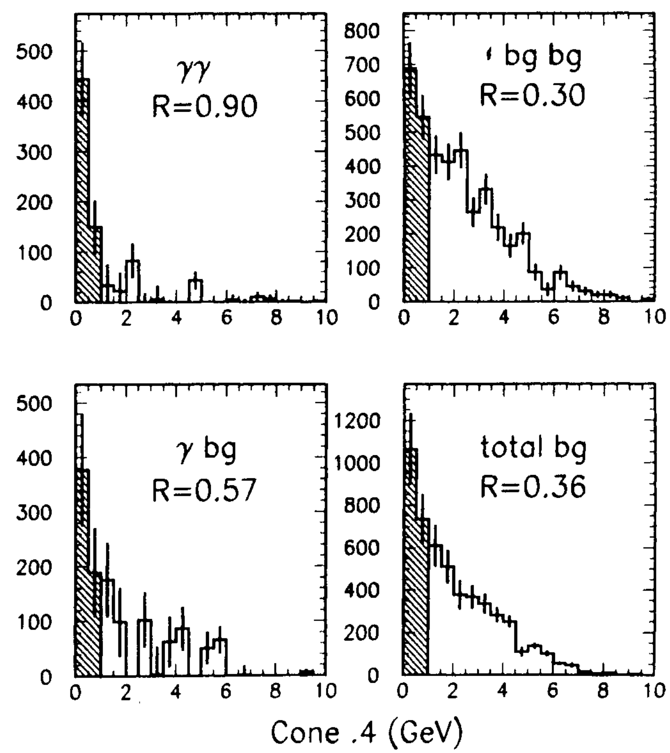
Diphoton Fractions

- Background subtraction more complicated for diphoton case
  - both photons can fail CES/CPR test, both can pass, or one can pass and one fail;
  - end up with 4X4 matrix to invert with output number of $\gamma\gamma$, $g\pi^o$, $\pi^o\gamma$, $\pi^o\pi^o$ pairs



•As expected diphoton events are more isolated than background

•consistent with min bias energy



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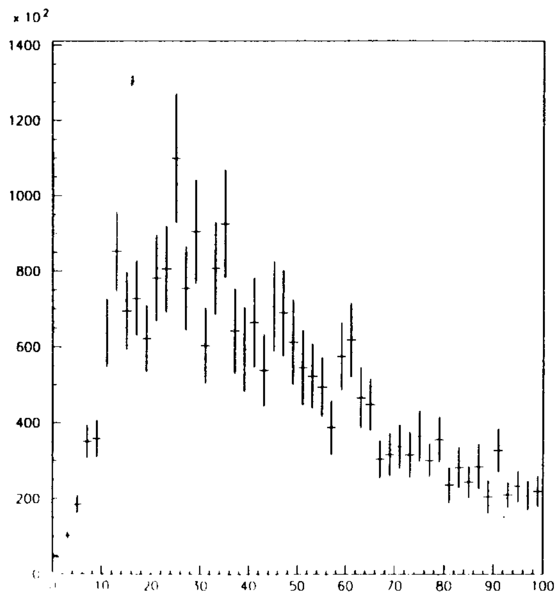
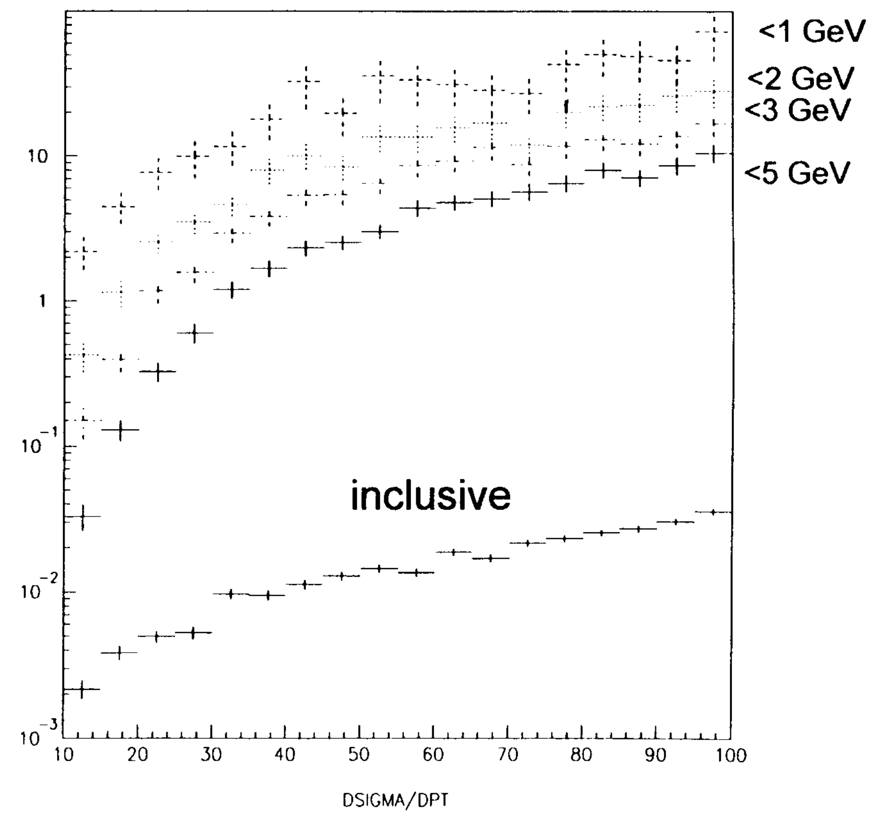
γ/π^o ratio at the LHC

- Use same leading order program as was used at the Tevatron to look at the γ/π^o ratio as a function of the isolation cut
- Inclusive γ/π^o ratio is extremely small but the imposition of a reasonable isolation cut brings the ratio to the order of 1 or larger in the range of interest
  - expect γ/π^o to be of same order as $\pi^o\pi^o$
- Picking out the tail of the isolation energy distribution



isolation energy for π^o's with E_T>25 GeV

• γ/π^o as a function of isolation energy;
uses a collinear approximation to fragmentation
•no explicit isolation cut in ATLAS; would be very interesting to study effective isolation cut

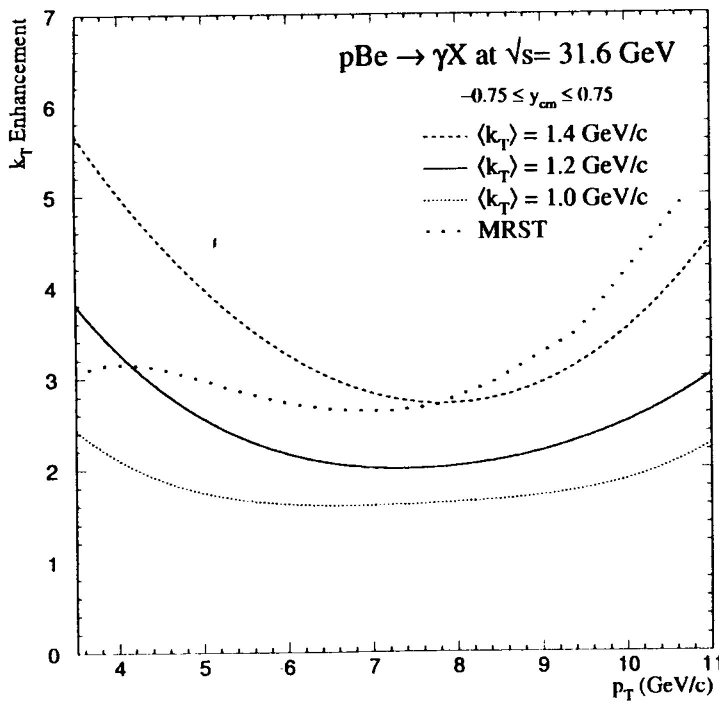


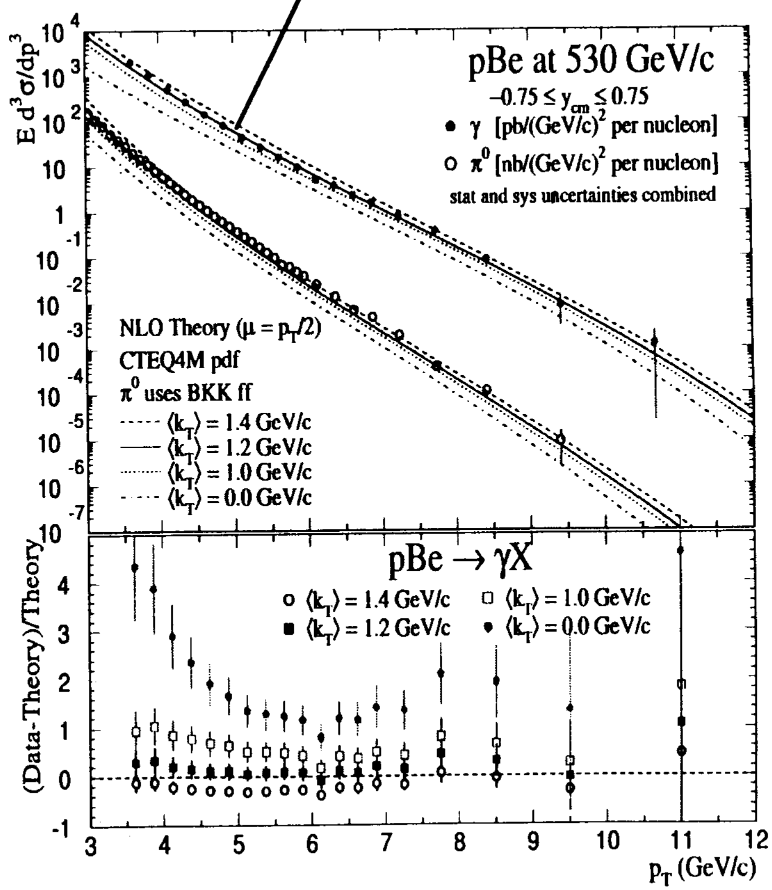
Direct Photons and k_T

- Effects of k_T more severe at fixed target energies
- Theoretical uncertainties too large to use direct photons for determination of gluon distribution

  (CTEQ conclusion)

note agreement of π^o's with similar k_T corrections

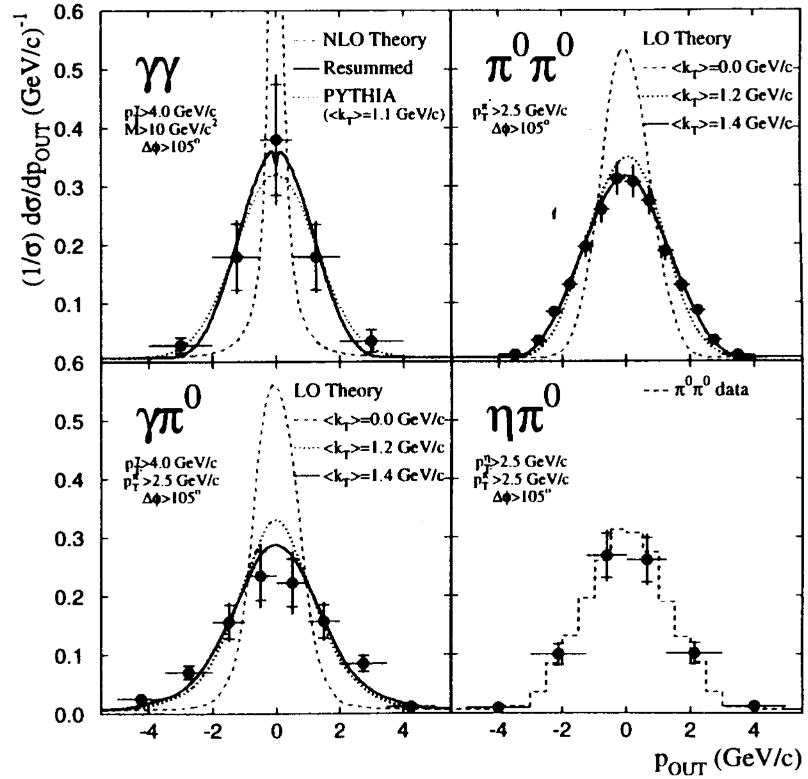




MRST k_T correction for E706; both MRST and CTEQ4 pdf's describe E706 data, so MRST gluon is < CTEQ4 at high x

Measurement of k_T in E706

- Can directly determine the level of k_T in E706 physics by measuring the pout distributions for $\gamma\gamma$, $\pi^o\pi^o$, $\gamma\pi^o$ pairs
  - consistent with the 1 GeV/c level



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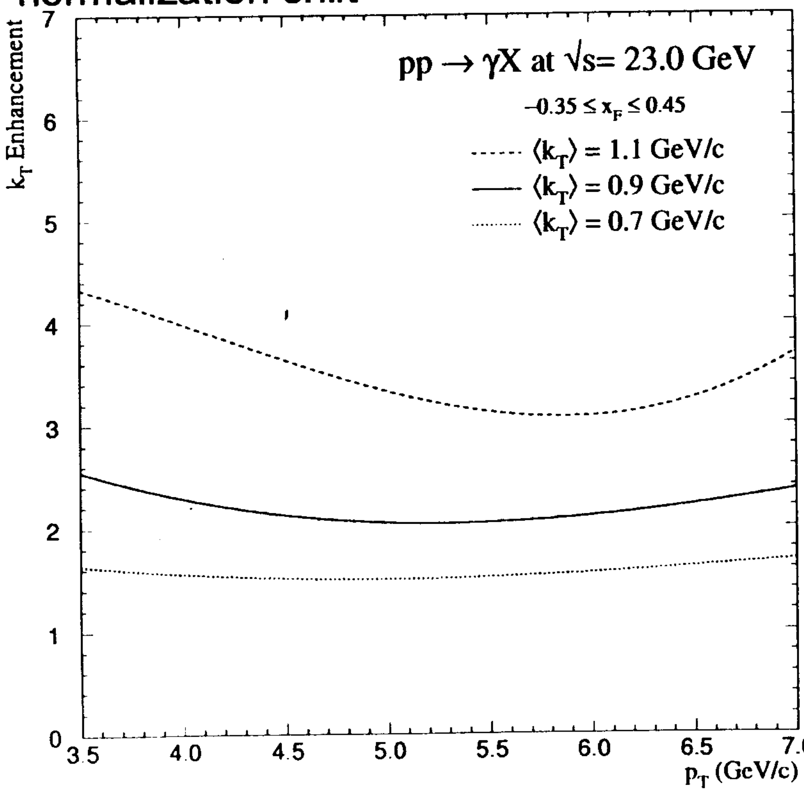
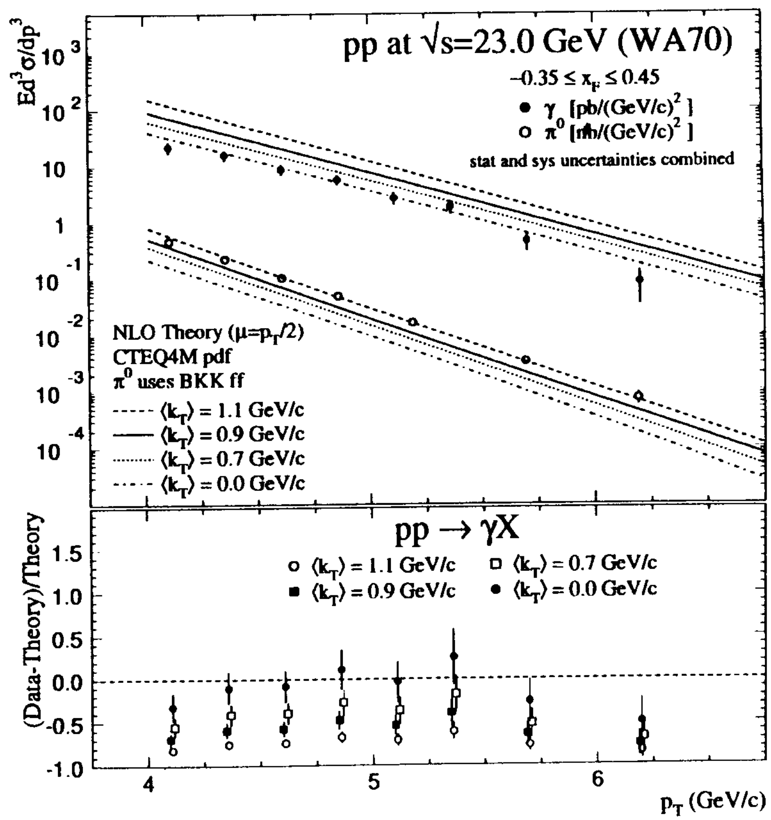
k_T for WA70 (pp)

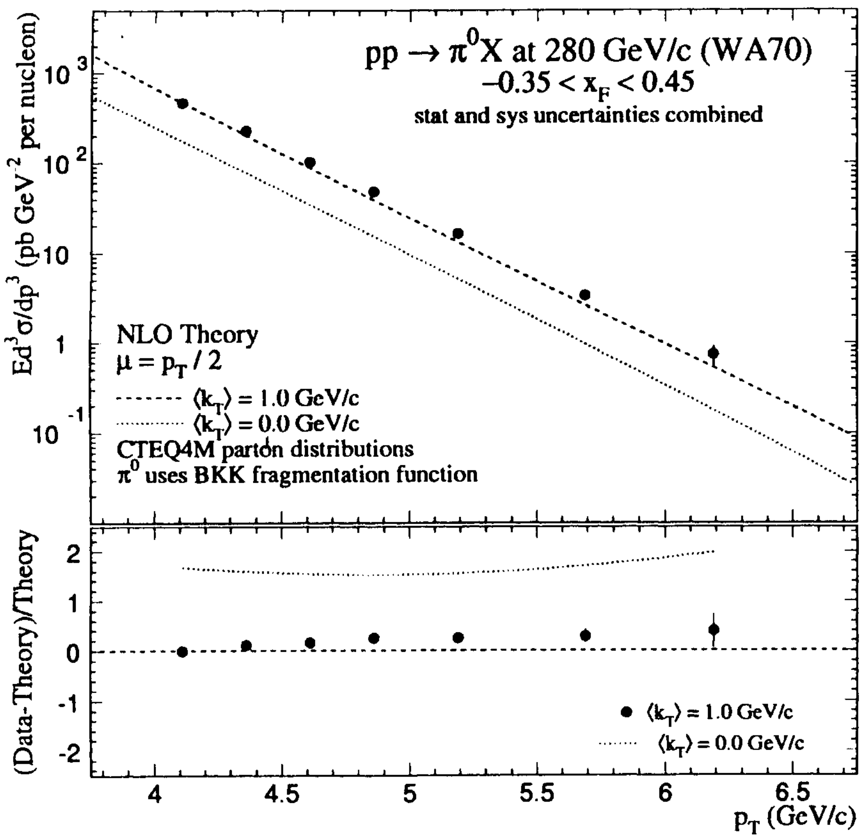
Use an average k_T of 0.9 GeV/c for WA70 (measured by them in $\gamma\gamma$ production in $\pi^- p$ collisions); see factor of 2 enhancement expected; note that effect is primarily a normalization shift

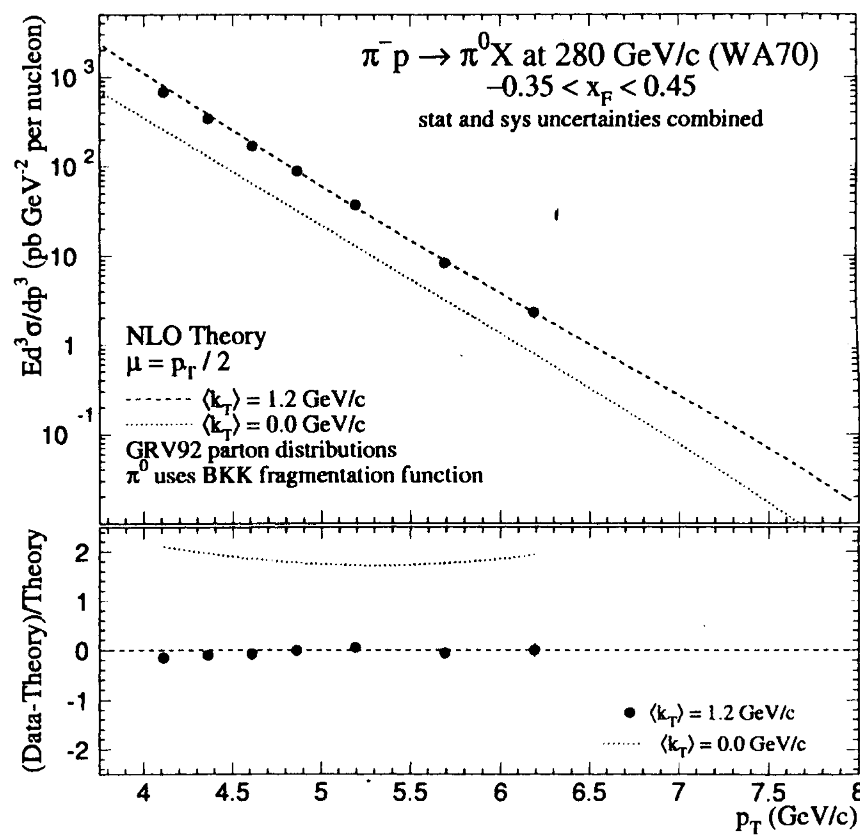


γ data are happiest with no k_T; π^0 data require on order of a GeV/c



WA70 π^o data

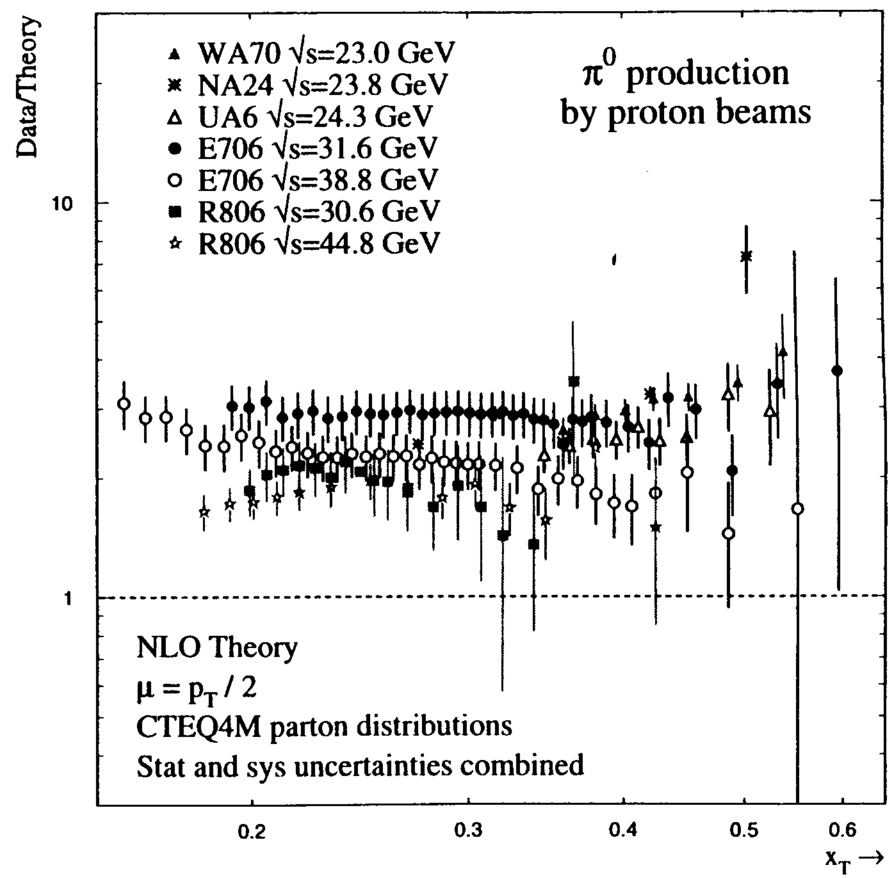




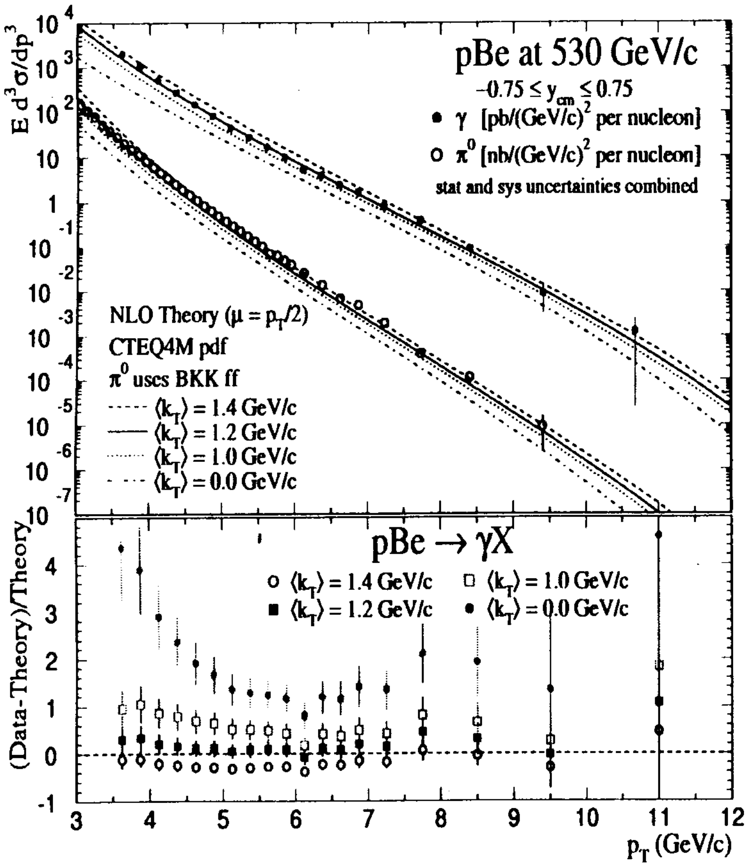
Problems with π^o's

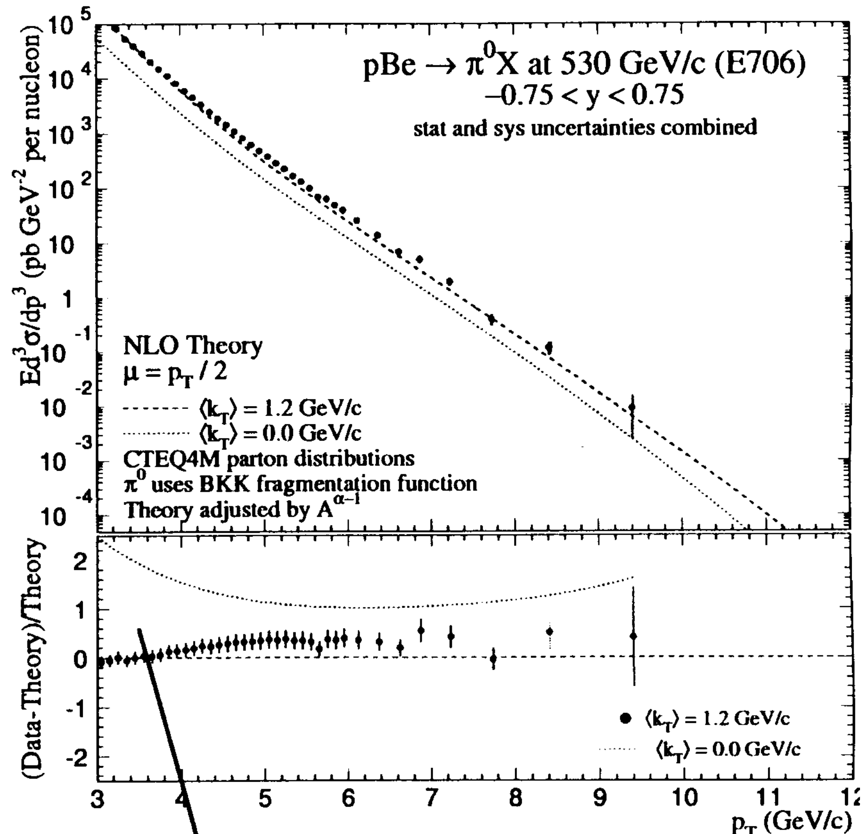
- Recent paper by Aurenche et al (hep-ph/9910252) comparing cross sections for π^o's to NLO predictions
- Data cross sections universally larger than NLO predictions (by a constant factor?)
- What's the cause? Is it related to the problems with inclusive photon production? Or different (higher order corrections, uncertainties in fragmentation functions).

- k_T corrections similar to those used for single photon production provide a reasonably good description of the experimental π^o cross sections



Look in detail at π^o agreement



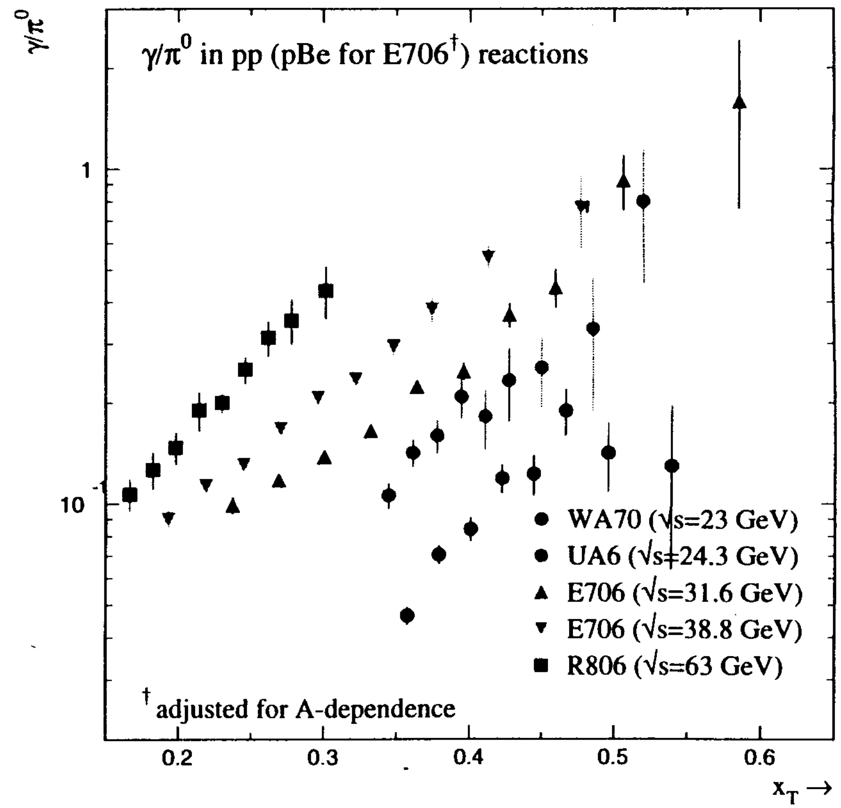


Note that k_T correction slope is not as great as for single photons; π^o only takes a fraction z of the jet momentum and k_T; fraction decreases as p_T decrease

γ/π^o ratios

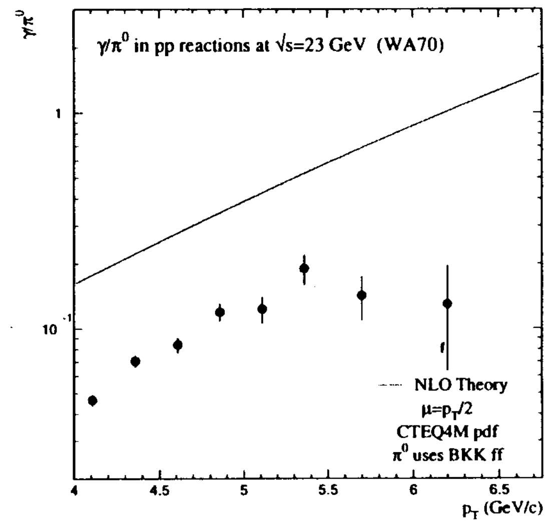
- World's π^o data are consistently different from NLO predictions
- World's γ data are inconsistently different from NLO predictions
- Look at γ/π^o ratio to see if problem may be "signal-to-background" (hope that many systematic errors (both theory and experiment) will cancel

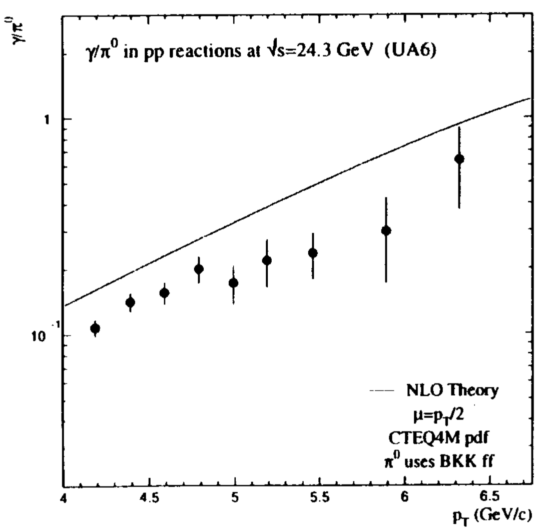
- Investigation in progress

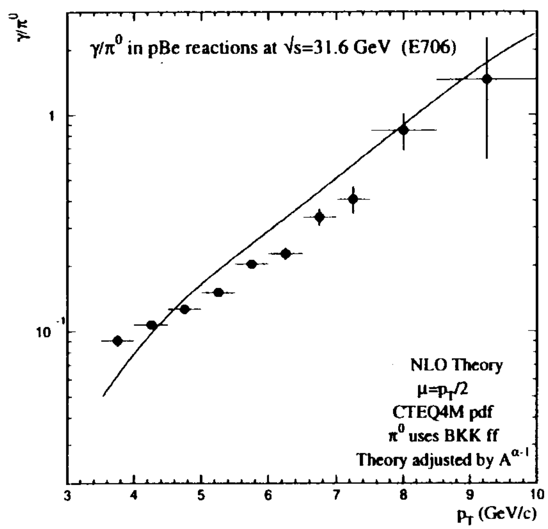


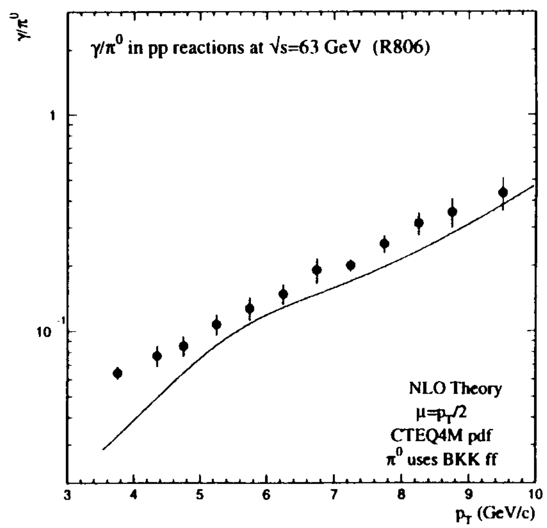
γ/π^o ratios

- Tendency for γ/π^o ratio to agree better with theory at higher center-of-mass energies
- Discrepancy between WA70 and UA6? (similar energies)









Direct Photons and resummation

- Threshold resummation for direct photon production has been performed by two groups with similar results: scale dependence of cross section is reduced with some enhancement at high p_T/x. E706 cross section is still larger than the theory.
- Can k_T and threshold resummation approaches be combined, a la George Sterman's approach?

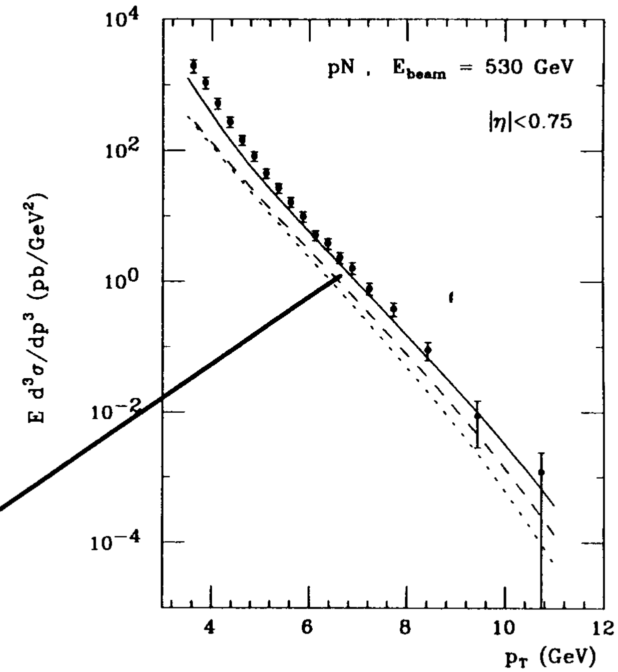
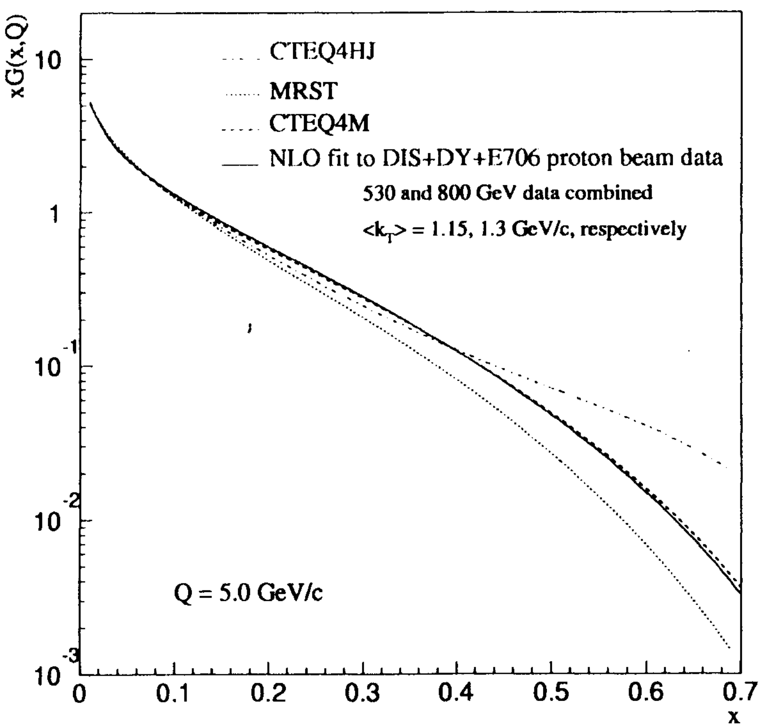


Figure 2: Prompt photon cross section $Ed^3\sigma_{pN\to\gamma X}/dp^3$ for pN collisions at $\sqrt{s}$ = 31.5
The dotted line represents the full NLO calculation, while the dashed and solid lines respect
incorporate pure threshold resummation [5] and the joint resummation described in this p
Data have been taken from [2].

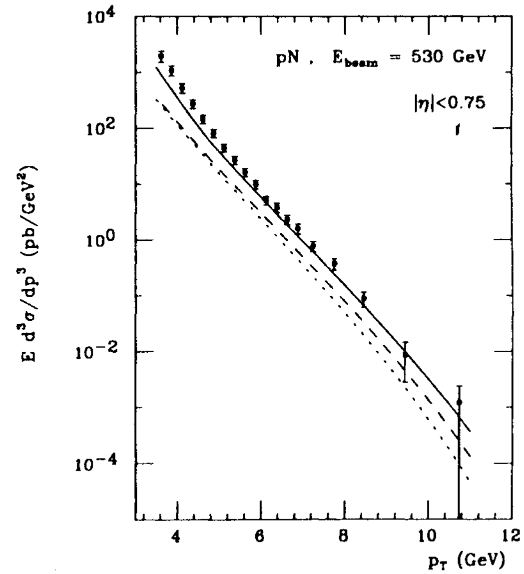
Note that effect (from this preliminary result) is not so different from Gaussian k_T smearing.

Key Question

What does the gluon distribution do at high x?



Does George's calculation saturate the high x cross section using CTEQ4M(5M)?



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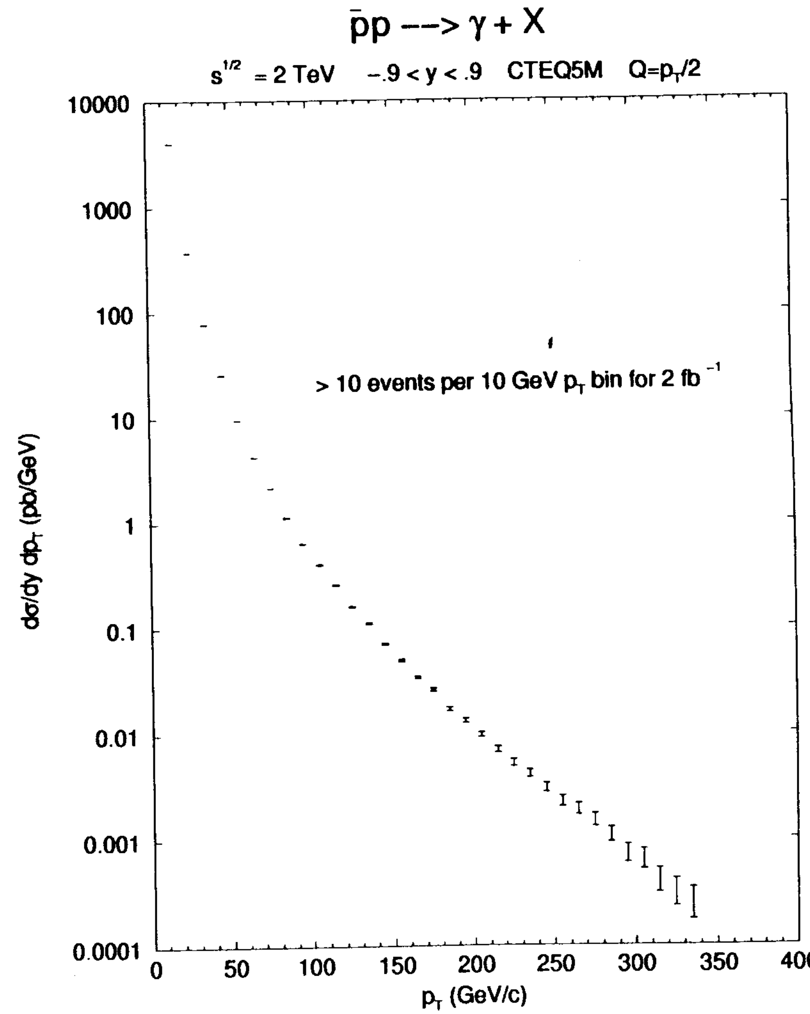
Future Tevatron Plans

- Run II: Spring of '00 to '02(3?)
  - Upgrade to 2.0 TeV
  - 2-4 fb^{-1} of data
    - ~2-4 X 10^6 W events
    - ~6-12 X 10^3 jets events with E_T > 300 GeV/c; jet σ measured precisely to 500 GeV/c
    - ~1.4-2.8 X 10^4 $\gamma\gamma$ events (p_T> 12 GeV/c)
  - Both CDF and D0 have plans for extensive hard diffraction physics measurements in Run II with Roman pots and high rapidity calorimeter coverage (D0's proposal has PAC approval; CDF proposal will be presented soon)
- Run III: 2003-2007
  - Order of 30 fb^{-1}

Run 2: inclusive photon production

- Inclusive photon reach for 2 fb^{-1}



Run 2: inclusive photon production