INFLUENCE OF PARTON k_T ON HIGH-p_T PARTICLE PRODUCTION AND DETERMINATION OF THE GLUON DISTRIBUTION FUNCTION

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Fixed-order perturbative QCD calculations of inclusive direct photon and meson production at high p_T, with usual choices of scales and distribution functions, fail to describe the data of Fermilab experiment E706. Effects of additional soft gluon radiation are investigated using a model that adds transverse momentum, k_T, to initial state partons. Corrected for k_T effects, the agreement of theory with E706 data is improved. A gluon distribution, obtained using deep inelastic scattering, Drell-Yan, and E706 direct photon data, is compared to recent global fits using other direct photon measurements.

1 Introduction

Not long after the partonic structure of hadrons was discovered in deep inelastic scattering (DIS), hadronic scattering experiments were proposed to search for evidence of direct photon production. Interest increased when calculations in perturbative Quantum Chromodynamics (pQCD) showed that measurements of direct photon (γ) cross sections could constrain the gluon distribution function of a nucleon [1]. In leading order (LO) pQCD, direct photons reflect the gluon distribution in *pp* scattering via the Compton process, $qg \rightarrow q\gamma$, shown in Fig. 1.

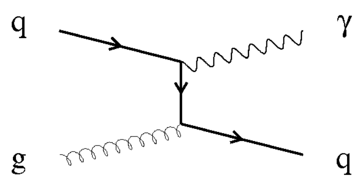

Figure 1: QCD Compton process

In principle, Drell-Yan (DY) and DIS data are sufficient to determine parton distribution functions (pdf) but, in practice, global fits [2] incorporate direct photon data to provide constraints on the gluon above $x = 0.2$. The utility of these constraints prompted pQCD calculations of the process at next-to-leading order (NLO) [3]. Direct photon data remain an important input to global pdf fits [4,5]. To further constrain the gluon at large-x, the CTEQ4M fit [5] used in the analysis below included jet production data from the CDF and D0 Tevatron collider experiments.

The results of Fermilab experiment E706 reported here represent a significant improvement in statistical and systematic precision of data on direct photon and meson production at large-x. Also, we have investigated effects of soft gluon radiation on pQCD calculations of these inclusive reactions. If these effects are incorporated into the theory, the data has the potential to improve constraints on the gluon distribution in global fits.

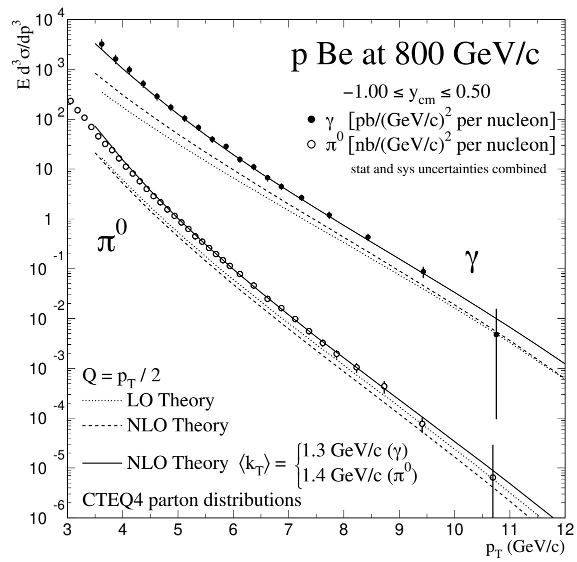

Figure 2: E706 data at $\sqrt{s}$ = 38.8 GeV compared to pQCD calculations at LO, NLO ($k_T = 0$), and NLO with k_T - corrections. The π^0 calculations use the BKK fragmentation functions [17] (ff).

2 E706 results on π^0 and direct photon production

E706 is a Fermilab fixed-target experiment using 530 and 800 GeV/c beams to study pN collisions at $\sqrt{s} = 31.6$ and 38.8 GeV. In a recent publication [6] the collaboration showed that NLO pQCD calculations, using conventional choices of scale and parton distribution functions, fail to predict the shape and magnitude of the direct photon and π^0 cross sections. In Figure 2, the E706 data at $\sqrt{s} = 38.8$ GeV is compared to LO and NLO pQCD calculations. The typical uncertainties of about 30% from the choice of scale are too small to account for the large deviations (factors of 2 to 3) of theory from the data. Also shown are NLO calculations corrected for smearing effects of an assumed gaussian distributed transverse momentum, k_T, of the incident partons. These corrections, using $\langle k_T \rangle$/parton = 1.3 GeV/c and 1.4 GeV/c, in direct photon and π^0

production respectively, increase the calculated cross sections into close agreement with the data.

3 Multiple soft gluon radiation

In high–p_T hadronic scattering a resummation of high-order perturbative processes is required to incorporate the transverse effects of soft gluon radiation [8]. This has been achieved for some hadronic reactions, such as W/Z, DY and double direct photon production, where the large-q^2 parton scattering results in a colorless final state [9]. It is more difficult to extend these calculations to reactions, such as direct photon production, that involve a parton jet in the final state. Also, at the energies of the E706 experiment, non-perturbative components may be significant and must, therefore, be added to a resummed calculation.

In lieu of a formal calculation, we simulate the effects of soft gluon radiation in a model implemented in a leading order pQCD Monte Carlo [10], adding to each colliding parton an effective initial state transverse momentum, k_T, with a gaussian variance. A parameter serving a similar function can be found in most MC event generators [11]. The resulting growth of the LO cross section is characterized by a k_T-enhancement factor, $K(p_T)$. Multiplying NLO calculations by $K(p_T)$ corrects for soft gluon radiation effects. This procedure ignores the double counting of single gluon emission. However, at the energies of the E706 experiment the single gluon process generates a minimal k_T ($<k_T> \sim 0.4$ GeV/c) in NLO calculations.

The values for $<k_T>$ per parton used in the calculations of direct photon production at $\sqrt{s}$ = 31.6 and 38.8 GeV, were suggested by a number of related features of multiparticle production observed in the E706 experiment [6]. Data from other experiments on pair production reactions, shown in Fig. 3, also exhibit large $<k_T>$/parton ($<p_T>_{\mathrm{pair}}/\sqrt{2}$) values that rise slowly with increasing collision energy [12,13]. The $\gamma\gamma$ and $\mu\mu$ reactions are dominated by $q\bar{q}$ annihilation. In reactions such as direct photon and (to a lesser extent) di-jet production that involve incident gluons which radiate with a higher probability than quarks, it is reasonable to expect that $<k_T>$ could be somewhat larger. This is observed in the E706 direct photon data and, perhaps, can be seen in the *pp* di-jet data shown in Fig. 3.

In contrast to effects from changes in the scale in pQCD calculations, k_T corrections affect both the shape and the magnitude of cross sections. The data at $\sqrt{s}$ = 31.6 GeV, are shown in Fig. 4 overlaid with the NLO calculations ($<k_T> = 0$), and calculations corrected for three values of $<k_T>$. The lower portion of the figure displays the fractional deviations of theory from direct photon data.

Reasonable agreement is achieved with E706 direct photon cross sections at $\sqrt{s}$ = 31.6 GeV/c for $<k_T>$ = 1.2 GeV/c. Multiplying the calculations by $K(p_T)$ has

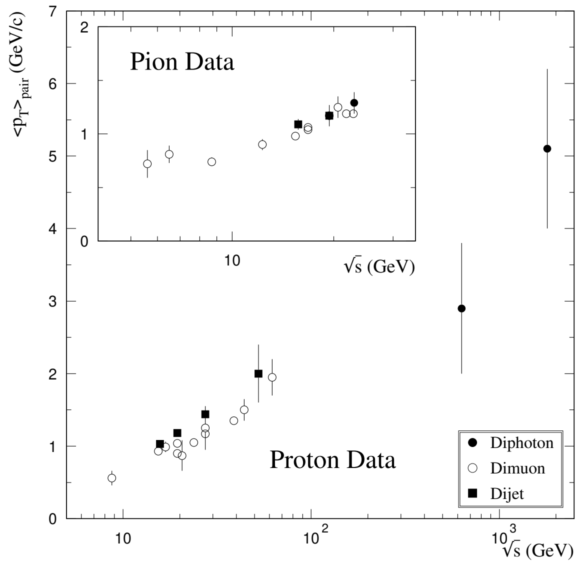

Figure 3: The energy dependence of the mean transverse momentum of particle pairs, $<p_T>_{\mathrm{pair}}$ observed in other experiments.

non-linear effects on the shape and magnitude of the cross sections and theory approaches data only for values of $<k_T>$ above 1.0 GeV/c. Also, π^0 cross sections above p_T = 5 GeV/c are reproduced well using a $<k_T>$ = 1.4 GeV/c, although for p_T < 5 GeV/c , the π^0 data fall slightly below the calculation.

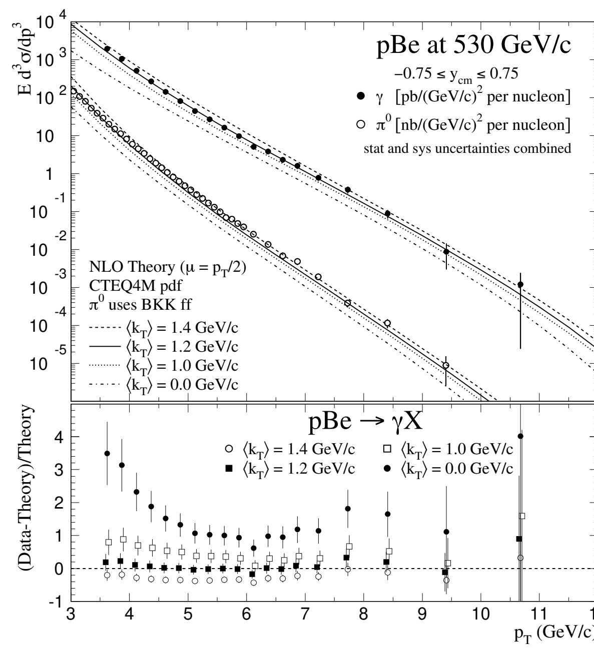

Figure 4: E706 data at $\sqrt{s}$ = 31.6 GeV compared to NLO pQCD calculations with corrections for various $<k_T>$ values (π^0 uses BKK fragmentation functions), and in the lower portion, the fractional deviations of the theory from the data.

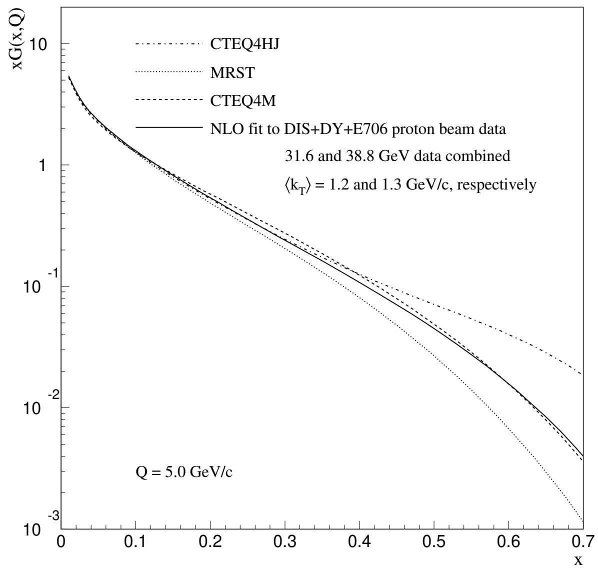

Figure 5: A comparison of published gluon distribution functions with the gluon determined with DIS, DY, and E706 data in the CTEQ fitting package modified to incorporate k_T corrected NLO calculations.

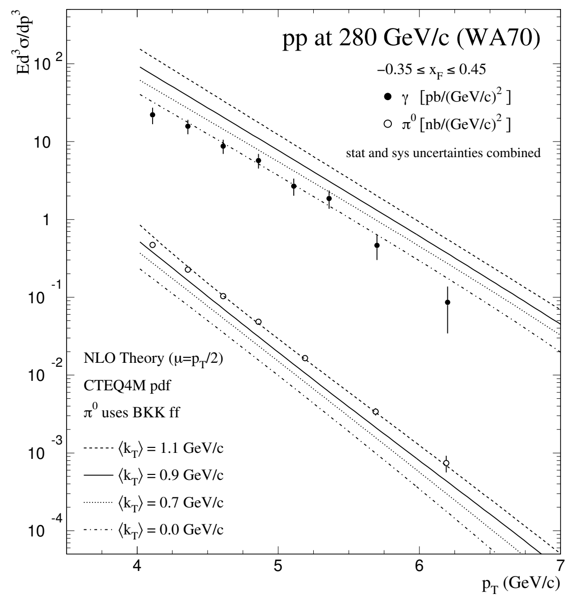

Figure 6: WA70 data at $\sqrt{s}$ = 23.0 GeV compared with NLO pQCD calculations with corrections for various $<k_T>$ values (π^0 uses BKK [17] fragmentation. functions).

4 Impact of k_T on the gluon distribution

Three recent gluon fits (not using E706 data) are compared in Fig. 5, to the gluon determined using DIS, Drell-Yan, and only E706 direct photon data as input to the CTEQ pdf fitting program [14], modified to incorporate the k_T-corrections discussed in the previous section. Only the CTEQ4M gluon agrees well with our result, while the gluon determined by emphasizing the CDF high–E_T jet data points, CTEQ4HJ [15], is much larger at high x. Also shown is the gluon determined by MRST [4], using direct photon data only from the WA70 experiment [16]. This distribution function is below that of the E706 fit over the full range of x. Treatment of k_T that leads to this behavior of the gluon fit using the WA70 data is discussed in the next section.

5 The model applied to the data of WA70

The direct photon data of the WA70 experiment have strongly influenced gluon distribution function fits from the time of the first NLO pQCD calculations [2,3]. Acceptable fits for the gluon distribution function were obtained using the WA70 data without introducing k_T corrections of the type discussed above, i.e., $<k_T> = 0$. This implies a strong energy dependence of $<k_T>$ in direct photon production, not expected in this hard scattering reaction.

The predictions of our model are compared in Fig. 6 to direct photon and π^0 production data of WA70 at $\sqrt{s}$ = 23.0 GeV/c. The WA70 direct photon data were used in the CTEQ4M pdf fits (with $<k_T> = 0$), and that value is favored in our model as well. However, a reasonable match to WA70 π^0 data is achieved by our model with a $<k_T>$ =1.1 GeV/c, and this value is consistent with a slow rise in $<k_T>$ with increasing collision energy. The WA70 measurement of $<k_T>$ = 0.9 GeV/c for di-photon production in pion collisions [18] is also consistent with this trend.

The discrepancy in the level of $<k_T>$ required by the direct photon data of the two experiments was observed during a recent update of pdf fits by MRST [4]. To investigate the effects of $<k_T>$ on the p_T spectrum, MRST use a gaussian smearing of the predictions, with a mean value $<k_T>_{\mathrm{MRST}}$. Their definition, and the $<k_T>$/parton used in this report, we believe [19], are related by $<k_T>$/parton = $\sqrt{2}$ $<k_T>_{\mathrm{MRST}}$, although differences in the techniques used to correct the theory may also affect this relationship.

MRST confirm that a gluon distribution determined using only WA70 direct photon data, cannot describe the E706 data if $<k_T> = 0$ is assumed for both experiments. MRST provide three solutions for the gluon taking values of $<k_T> = 0$, 0.6 and 0.9 GeV/c, and using only the WA70 direct photon data in the fit. Predictions, using the gluon determined with $<k_T> = 0$, must be smeared with a $<k_T>$/parton ≈ 1.3 GeV/c to match the E706 data at $\sqrt{s}$ = 31.6 GeV. This large change in $<k_T>$, over a relatively small $\sqrt{s}$ interval, is noted by MRST. Nevertheless, that result is retained as their upper limit for the gluon distribution function. In spite of the substantial difference in the $<k_T>$ values required to accommodate the data from the two experiments, this gluon distribution is very close to the CTEQ4M fit, and the k_T smearing required to match the E706 data is consistent with the results of our model shown earlier in Fig. 4.

A second fit, again using only the WA70 direct photon data, but with a more realistic value for $<k_T>$/parton = 0.6 GeV/c, yields the gluon distribution function, shown in Fig. 5 with the label MRST [20]; it is lower than the CTEQ4M solution by about a factor of two at large-x (>0.5). Using in the fit a $<k_T>$/parton = 0.9 GeV/c, the maximum value MRST consider compatible with the WA70 data, results in a gluon that is lower by another factor of two. It is clear, therefore, that attempts to reconcile the WA70 and E706 results can have substantive effects on the gluon distribution function. Nevertheless, the phenomenological nature of the k_T corrections employed make it difficult to categorically exclude some mitigating explanation.

6 Conclusions

The values of $<k_T>$/parton used in our model are chosen consistent with well established trends in large-q^2 hadronic reactions that have been interpreted as originating in the transverse momentum of initial state partons. The phenomenological procedure used here merges, across an arbitrary dividing line, effects of high-order terms in pQCD and non-perturbative contributions, to obtain useful cross section calculations.

A $<k_T>$/parton in the range 1.2-1.4 GeV/c, as indicated by other di-muon and di-photon experimental observations, brings NLO pQCD calculations of direct photon and π^0 cross sections into reasonable agreement with the E706 data at two collision energies, $\sqrt{s}$ = 31.6 and 38.8 GeV. Using DIS, Drell-Yan, and the E706 direct photon data in a pdf fitting program that incorporates k_T effects into the NLO calculations, results in a gluon distribution similar to the CTEQ4M fit.

The model described above does not produce a consistent picture of k_T effects in the WA70 data for incident protons; the value $<k_T>$ = 0, preferred by the direct photon data does not reproduce the corresponding π^0 data. Using higher values of $<k_T>$/parton, consistent with results our model and with established trends, MRST find gluon distribution functions much lower than the E706 or CTEQ4M fits at large-x.

To assess the impact of E706 direct photon cross sections on global pdf fits, we assign an uncertainty of about ±0.2 GeV/c in the value of $<k_T>$/parton used to correct NLO calculations at our energies. This estimate, based on the behavior of pair production reactions, leads to an uncertainty contribution of about ±25%, in the gluon distribution function in the range x = 0.4 to 0.6. Scale uncertainties in NLO pQCD calculations at these energies are also of this order. Of course, knowledge of the gluon distribution is subject to other uncertainties, common to all inputs, such as those introduced by the large-x parameterization used in the fitting programs.

Jet cross section calculations at collider energies are relatively insensitive to effects of k_T and scale. However, normalization uncertainties (~10%) in these experiments have an effect on global fits for the gluon that is magnified by the small contribution (~20%) of incident gluons in jet production at high-E_T. Comparable uncertainties are obtained for the gluon at large-x when E706 direct photon data and a k_T corrected theory are used in global fits. The two data sets are therefore complementary, and using both in global fits should reduce the overall uncertainties in the gluon distribution function at large-x.

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20. Of the three solutions for the gluon presented in Ref. [4], using <k_T>/parton = 0, 0.6 and 0.9 GeV/c, only the solution labeled MRST, with <k_T>/parton = 0.6 GeV/c is shown in Fig. 5.