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Scaling of single photon production in hadronic collisions

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Abstract. Scaling of single photon production in pp and $p\overline{p}$ collisions is studied. It is empirically observed that the available data scales $\sim s^{1/2}/p_{\mathrm{T}}^5$ for $x_{\mathrm{T}} = 2p_{\mathrm{T}}/s^{1/2} \leq 0.1$ and $\sim (s^{1/2})^{3.3}/p_{\mathrm{T}}^9$ for larger x_{T}. The NLO pQCD predictions for pp collisions at an $s^{1/2}$ of 200 and 5500 GeV, relevant for RHIC and LHC energies are seen to closely follow this scaling behavior. Implications for single photon production in heavy ion collisions are discussed.

Radiation of single photons in pp and $p\overline{p}$ collisions has been studied for a long time, in order to get information about the partonic distributions of nucleons and to test the applicability of pQCD. A similar expectation is also associated with the study of the Drell–Yan process. In this connection the so-called Craigie fit [1] to the Drell–Yan data, showing a scaling

$$M^3 \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}M\mathrm{d}y}\right)_{y=0} = 3\times10^{-32}\mathrm{e}^{-15M/(s^{1/2})}\,\mathrm{cm}^2\,\mathrm{GeV}^2, \quad (1)$$

has remained a very useful tool for identifying the source of dileptons in hadronic collisions. Scaling relations are also useful in estimating the strength of "corrections" which cause a deviation from the expected behavior.

Owens [2] has discussed the possible scaling of the production of single photons in hadronic collisions. To leading order in α_{s}, single photons originate from Compton ($qg \to q\gamma$) and annihilation ($q\overline{q} \to g\gamma$) processes, whose cross-sections, $\mathrm{d}\sigma/\mathrm{d}t$, have dimensions of $1/\mathrm{GeV}^4$. This follows from the fact that the strong and electromagnetic coupling constants are dimensionless and for massless partons no other (mass) scale enters into the problem. This, Owens argued, can be used to construct a scaling relationship for the invariant cross-section, $E\mathrm{d}^3\sigma/\mathrm{d}^3p$, by combining the kinematic variable, p_{T}, s, and θ (or the rapidity y), or equivalently, p_{T}, $x_{\mathrm{T}} = 2p_{\mathrm{T}}/(s^{1/2})$, and θ, etc., so that one could write

$$E\frac{\mathrm{d}^\sigma}{\mathrm{d}^3p}(A + B \to \gamma + X) = \frac{F(x_{\mathrm{T}},\theta)}{p_{\mathrm{T}}^n}, \quad (2)$$

with $n = 4$ and $F(x_{\mathrm{T}},\theta)$ a dimensionless function. This argument needs to be refined to accommodate the fact that the strong coupling constant α_{s} depends on the QCD scale parameter Λ which has dimensions of momentum, and the structure functions depend on the Q^2 at which they are sampled. This, along with higher order terms, would admit a more complicated dependence on the momentum parameter p_{T}. It has been argued that such scaling violations, depending on the kinematic region, could increase n to 6.

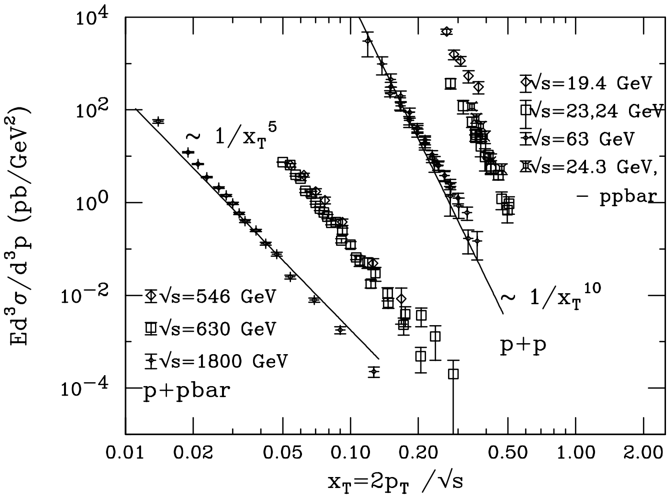

Fig. 1. The available single photon data for pp and $p\overline{p}$ taken from the compilation of Vogelsang and Whalley [3]. The large x_{T} data are taken from the E704 experiment (19.4 GeV) [5], the WA70 experiment (22.96 GeV) [6], the NA24 experiment (23.75 GeV) [7], the UA6 experiment (24.30 GeV) [8], the R110, R806, and R807 experiments (63 GeV) [9,11,10] and the UA6 experiment at 24.30 GeV for $p\overline{p}$. The small x_{T} data are limited to $p\overline{p}$ and are taken from the UA1 and UA2 experiments (540 and 630 GeV) [12,13] and the CDF and D0 experiments at 1800 GeV [14,15]

The data for single photon production has been compiled and carefully analyzed using the NLO pQCD treatment by Vogelsang and Whalley [3] and Aurenche et al. [4]. Our goal here is much more modest; we analyze them empirically to look for scaling if any. We see (Fig. 1) that, indeed, the data show a different scaling behavior for the regions $x_{\mathrm{T}} < 0.1$ and $x_{\mathrm{T}} > 0.1$, as is evident from the two

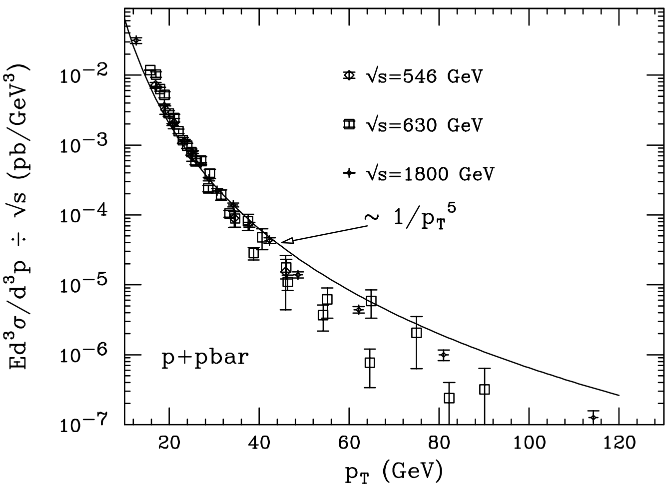

Fig. 2. Fit to single photon data at small x_T using the scaling (3) obtained in the present work

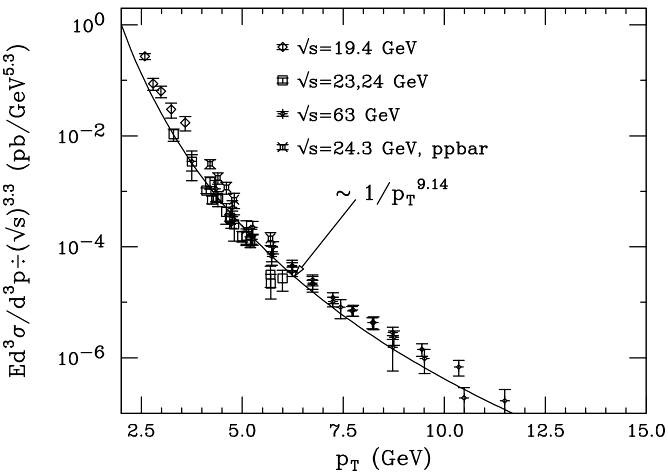

Fig. 3. Fit to single photon data at large x_T using the scaling (4) obtained in the present work

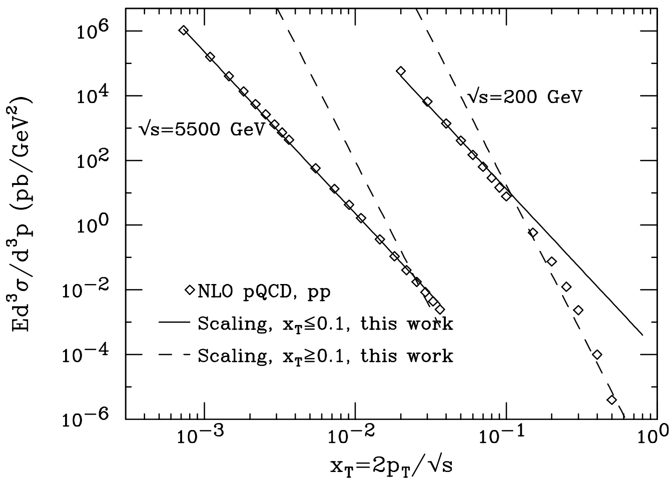

Fig. 4. Test of the scaling observed in the present work against NLO pQCD predictions [17] for single photons at RHIC and LHC energies in pp collisions

lines drawn through them to guide the eye and to indicate the slope (i.e. the power of p_T) for a given $s^{1/2}$.

Next we perform a fit and find that to a very good accuracy, the data show a scaling, such that

$$\left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p}\right)_{y=0} = 6495 \times \frac{\sqrt{s}}{p_\mathrm{T}^5}\ \mathrm{pb/GeV}^2, \quad x_\mathrm{T} < 0.1, \quad (3)$$

which varies as $F(x_\mathrm{T})/p_\mathrm{T}^4$ and corresponds to $n = 4$, suggesting that the scaling violations are small in this kinematic region (see Fig. 2). Numbers varying by a few percent are obtained in an unrestricted fit when the powers of $s^{1/2}$ and p_T were used as free parameters.

For the kinematic region $x_\mathrm{T} > 0.1$ we find (see Fig. 3)

$$\left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p}\right)_{y=0} = 574.6 \times \frac{(\sqrt{s})^{3.3}}{p_\mathrm{T}^{9.14}}\ \mathrm{pb/GeV}^2, \quad x_\mathrm{T} > 0.1, \quad (4)$$

which varies as $F(x_\mathrm{T})/p_\mathrm{T}^{5.8}$ and corresponds to $n = 5.8$ in the notation of Owens (2). This indicates a large contribution of higher order processes and associated deviation from the simple scaling at smaller x_T.

We digress a little to indicate that even though the E704 data [5] at $s^{1/2} = 19.4$ GeV have been included in Fig. 3, they were not included in the fitting procedure, which became unstable when this was done. We also add that in the analysis of Vogelsang and Whalley [3] only these data show a large deviation from the NLO pQCD results obtained there.

A comparison of the E704 data at $s^{1/2} = 19.4$ GeV with the NA24 [7] data at $s^{1/2} = 23.75$ GeV further shows that the former has a result which is about 50% larger at $p_\mathrm{T} \approx 3.2$ GeV which is very curious. The scaling seen here predicts that for a given p_T, the production at 19.4 GeV should be a factor of two smaller, compared to its value at 23.75 GeV.

Even though it is preposterous to argue about experimental data, it is tempting to note that the data at 19.4 GeV are a factor of 3.5 larger than "expected" on the basis of this scaling. If this were indeed so, then the NLO pQCD results in Fig. 4 of Vogelsang and Whalley would provide a perfect description to the "correct data", without any need of inclusion of the so-called intrinsic k_T effects [16]. The inconsistency of these data as well as the absence of the requirement to include intrinsic k_T effects has been discussed in great detail by Aurenche et al. [4].

We have already noted that the NLO pQCD analysis by Vogelsang and Whalley and Aurenche et al has provided a reasonably accurate description of the data included in the analysis here. Thus it would be fair to say that the scaling behavior observed in the present work is a fair representation of the NLO pQCD predictions for single photons from pp collisions. (The slight difference between the results for pp and $p\overline{p}$ is neglected here. In any case, the Compton term would dominate the contributions for not too large values of p_T.)

In Fig. 4 we have plotted the NLO pQCD predictions of pp scattering at 200 and 5500 GeV obtained in [17], which are relevant for the experiments to be performed at RHIC and LHC. For the higher energies the range of p_{T} considered limits x_{T} to only smaller values and the scaling (3) provides a very good description to the predictions. The range of p_{T} considered at 200 GeV is such that it spans both the low x_{T} as well as the high x_{T} regions considered in the scalings seen here. It is gratifying to note that the NLO pQCD results change over from the scaling (3) to that of (4) as x_{T} increases beyond 0.1.

What do these results mean for the recently measured single photon data by the WA98 group for the Pb + Pb collisions at the CERN SPS?

We recall an interesting observation made some time ago by the authors of [20]. Assuming that such heavy ion collisions lead to the formation of quark–gluon plasma and assuming that the system thus formed undergoes a boost-invariant expansion [21], one can relate the particle rapidity density ($\mathrm{d}N/\mathrm{d}y$) to the initial time (τ_0) and the temperature (T_0):

$$\frac{2\pi^4}{45\zeta(3)}\frac{1}{A_{\mathrm{T}}}\frac{\mathrm{d}N}{\mathrm{d}y} = 4aT_0^3\tau_0, \qquad (5)$$

where A_{T} is the transverse dimension of the system and a is decided by the number of degrees in the plasma.

It was pointed out [20] that as the quantity

$$\frac{1}{A_{\mathrm{T}}}\frac{\mathrm{d}N}{\mathrm{d}y} \approx 5\,\mathrm{fm}^{-2} \qquad (6)$$

for both the S + Au and the Pb + Pb systems in the WA80 [19] and the WA98 [18] experiments at the CERN SPS, we are offered a unique opportunity of comparing two systems of different volumes which may have identical initial conditions! It is seen that if the transverse expansion of the system does not play a significant role, then for a given τ_0, the only scale in the system is provided by the temperature, for a baryon-free plasma.

If this reasoning is correct, then the radiation of single photons per unit transverse area would be identical. This leads to a simple geometrical factor of ~ 3.5 by which the data for the S + Au system can be scaled to get the results for the Pb + Pb system.

What about the contribution of prompt photons for the two cases? The scaling behavior of the prompt photons seen here suggests that we may obtain the prompt photon yield for the WA98 experiment as

$$\left(\frac{\mathrm{d}N_{\mathrm{prompt}}}{\mathrm{d}^2p_{\mathrm{T}}\mathrm{d}y}\right)_{\mathrm{PbPb}} = \left(\frac{17.4}{20}\right)^{3.3} \times \left(\frac{T_{\mathrm{PbPb}}(b=0)}{T_{\mathrm{SAu}}(b=0)}\right) \times \left(\frac{\mathrm{d}N_{\mathrm{prompt}}}{\mathrm{d}^2p_{\mathrm{T}}\mathrm{d}y}\right)_{\mathrm{SAu}}, \qquad (7)$$

where $s_{NN}^{1/2} = 17.4$ and 20 GeV for the WA98 and the WA80 experiments. This suggests that the prompt photon production for the WA98 experiment can be obtained by multiplying the corresponding contribution for the WA80 experiment by a numerical factor of ~ 3.43. This is quite close to the factor of 3.5 obtained earlier for the thermal photon yield! In view of the above it is felt that the sum

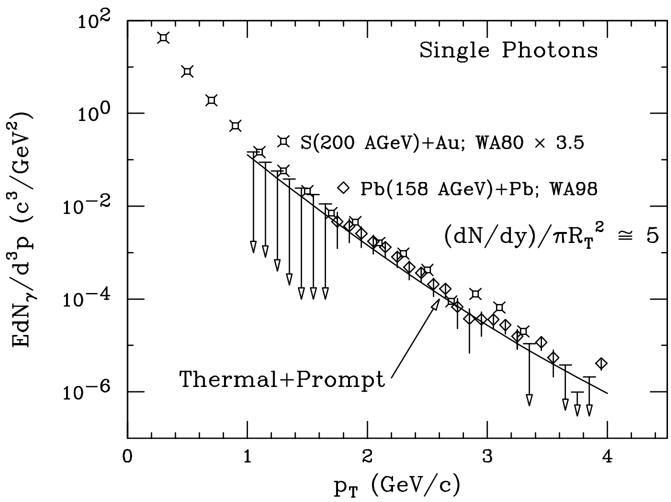

Fig. 5. Single photon production observed in S + Au collisions (only upper limits) in the WA80 experiment [19] and in Pb + Pb collisions in the WA98 experiment [18]. The WA80 "data" have been rescaled using the scaling relation suggested in [20] and implied by the relations (5) and (6) given in the text. The solid curve gives the predictions of [22] suggesting a thermal source for these photons, while the dashed curve gives the predictions based on the scaling observed in this work for prompt photons

of thermal and prompt photon productions for the two experiments should differ by a factor of about 3.5!

In Fig. 5 we show the upper limit of the S + Au multiplied by this factor against the (upper limit and) the data for the Pb + Pb system reported by the WA98 experiment. It is a pity that the weakness of this signal, which is buried into the huge background of decay photons, has resulted in the identification of only the upper limit of the single photon production for the S + Au system. Still, it is interesting to note that the upper limit measured in the WA80 experiment is consistent with the excess of single photon production obtained by the WA98 experiment.

We have also shown a recent explanation of the data data [22] using (corrected) two loop rates for photon production from the QGP along with the contribution of hadronic reactions, as well the prompt photons estimated by Wong and Wang [16] within a pQCD with inclusion of effects of the intrinsic p_{T} of the partons.

In brief, we have seen that the data for single photon production in nucleon–nucleon collisions can be broadly divided into two regions, $x_{\mathrm{T}} < 0.1$ and $x_{\mathrm{T}} > 0.1$. A scaling behavior $\sim F(x_{\mathrm{T}})/p_{\mathrm{T}}^4$ is seen for low x_{T} data, as expected from leading order pQCD, while for larger x_{T} a behavior $\sim F(x_{\mathrm{T}})/p_{\mathrm{T}}^{5.8}$ is observed, which indicates large corrections to the lowest order QCD results. It is hoped that these observations may provide a useful guideline for identification of the source of single photons as well as the extent of corrections over the lowest order pQCD for these processes.

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