MODELING PHOTON RADIATION IN SOFT HADRONIC COLLISIONS*

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Soft hadronic collisions with multiple production of (anti)quarks accompanied by soft photon radiation are described in terms of higher Fock states of the colliding hadrons, which contain a photon component as well. The Fock state distribution functions are shaped with the Quark–Gluon String Model. Photon radiation by quarks is described within the color-dipole phenomenology. The results of calculations are in good accord with available data in a wide range of transverse momenta of the photons.

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1. Introduction

It was demonstrated in [1] that the bremsstrahlung model (BM) [2], used as a reference for comparison with the production rate of small-k_T photons radiated in inelastic hadronic collisions at high energy, is incorrect, what led to the so-called soft photon puzzle (see *e.g.* in [3]). Therefore, an alternative description of soft photon radiation is required.

2. Parton model description at a hard scale

Within the parton model radiation of a heavy photon of mass M (Drell–Yan) in the target rest frame, based on the factorization theorem, has the following form:

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$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}M^2\,\mathrm{d}x_\mathrm{F}\,\mathrm{d}k_\mathrm{T}^2} = \frac{\alpha_\mathrm{em}}{3\pi M^2}\frac{x_1}{x_1+x_2}\int\limits_{x_1}^{1}\frac{\mathrm{d}\alpha}{\alpha^2}\sum_f Z_f^2\left\{q_f\left(\frac{x_1}{\alpha}\right)+\bar{q}_f\left(\frac{x_1}{\alpha}\right)\right\} \times\frac{\mathrm{d}\sigma(q_fN\to\gamma^*X)}{\mathrm{d}\ln\alpha\,\mathrm{d}^2k_\mathrm{T}}\,, \tag{1}$$

with the standard notations, $\alpha = p_+^\gamma/p_+^q$; $x_1x_2 = M^2/s$; $x_1 - x_2 = x_\mathrm{F}$.

The hard perturbative scale is imposed by the large invariant mass M of the photon (dilepton). The sum of the (anti)quark distribution function in (1) is given by the well-measured proton structure functions $F_2(x, M^2)$. The parton distribution functions in the colliding hadrons are illustrated by a parton comb in Fig. 1.

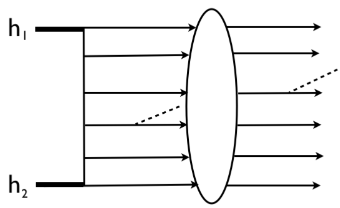

Fig. 1. Space-time pattern of particle production at high energies.

3. Parton model at a soft scale

Extrapolation of expression (1) to the soft regime is a challenge since involves unknown nonperturbative effects. That can be done only within models. For the quark distribution function, we rely on the popular and successful quark–gluon string model (QGSM) [4, 5] or a similar dual parton model [6, 7]. Both models assume the Regge behavior at the end-points $x \to 1$ or $x \to 0$ of the quark distribution functions, and a simple, but *ad hoc*, interpolation at medium x. We skip the simple, but lengthy expressions. The details can be found *e.g.* in [5].

The last factor in the radiation cross section (1) $\mathrm{d}\sigma(q_fN \to \gamma X)/\mathrm{d}\ln\alpha/\mathrm{d}^2k_\mathrm{T}$ is calculated at the soft scale within the color dipole phenomenology [8–13], adjusted to precise data on DIS from HERA,

$$\frac{\mathrm{d}\sigma(qN\to\gamma X)}{\mathrm{d}\ln\alpha\mathrm{d}^2k_\mathrm{T}} = \frac{1}{(2\pi)^2}\int \mathrm{d}^2r_1\mathrm{d}^2r_2\,\exp\left[i\vec{k}_\mathrm{T}(\vec{r}_1-\vec{r}_2)\right] \times\Psi^*_{\gamma q}(\alpha,\vec{r}_1)\Psi_{\gamma q}(\alpha,\vec{r}_2)\,\sigma_\gamma(\vec{r}_1,\vec{r}_2,\alpha)\,, \tag{2}$$

where

$$\sigma_\gamma(\vec{r}_1,\vec{r}_2,\alpha) = \frac{1}{2}\left\{\sigma_{\bar{q}q}(\alpha r_1)+\sigma_{\bar{q}q}(\alpha r_2)-\sigma_{\bar{q}q}[\alpha(\vec{r}_1-\vec{r}_2)]\right\}\,. \tag{3}$$

The quark–photon distribution function reads

$$\Psi_{\gamma q}(\alpha,\vec{r}) = \frac{\sqrt{\alpha_{\rm em}}}{2\pi}\,\chi_f \hat{O}\chi_i K_0(\alpha m_q r)\,, \tag{4}$$

and

$$\hat{O} = \vec{e}^{\,*}\left\{ i m_q \alpha^2\,[\vec{n}\times\vec{\sigma}] + \alpha\left[\vec{\sigma}\times\vec{\nabla}\right] - i(2-\alpha)\vec{\nabla}\right\}\,. \tag{5}$$

The $\bar{q}q$ dipole–nucleon cross section $\sigma_{\bar{q}q}(r)$ in (3) has been parametrized and fitted to DIS and photoproduction data from NMC and HERA. The details can be found in [10].

Combining the QGSM distribution functions with the cross section (2) results in the radiation cross section, which is parameter-free (we do not fit the data to be explained), either in the shape of $k_{\rm T}$ distribution or in the absolute values. We assumed a primordial transverse momentum distribution of the incoming quarks to have a Gaussian shape with $\sqrt{\langle q_{\rm T}^2\rangle} = 0.35$ GeV. Correspondingly, the radiated photon acquires additional transverse momentum $\vec{k}'_{\rm T} = \alpha\vec{q}_{\rm T}$.

4. Comparison with data

The results of calculations are compared with data on the radiative cross section of $\pi^+ p \to \gamma + X$ from the NA22 experiment at $E_{\rm lab} = 250$ GeV in Fig. 2, and from WA91/WA83 experiments at $E_{\rm lab} = 280$ GeV in Fig. 3.

We see no sizable deviation from data at small $k_{\rm T}$, *i.e.* no anomalous enhancement of soft photons.

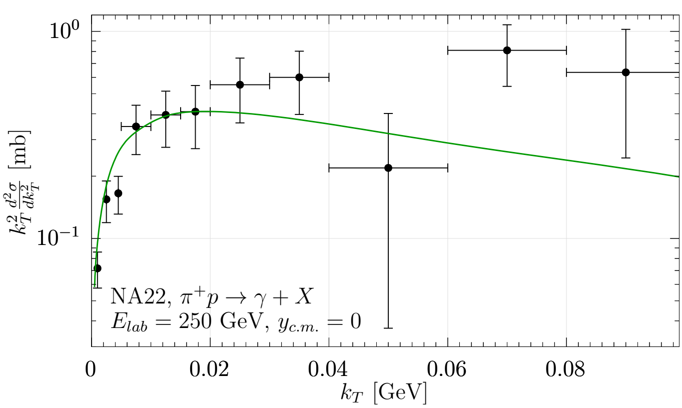

Fig. 2. Comparison with data of the NA22 experiment [14] for $\pi^+ p \to \gamma X$ at $E_{\rm lab} = 250$ GeV.

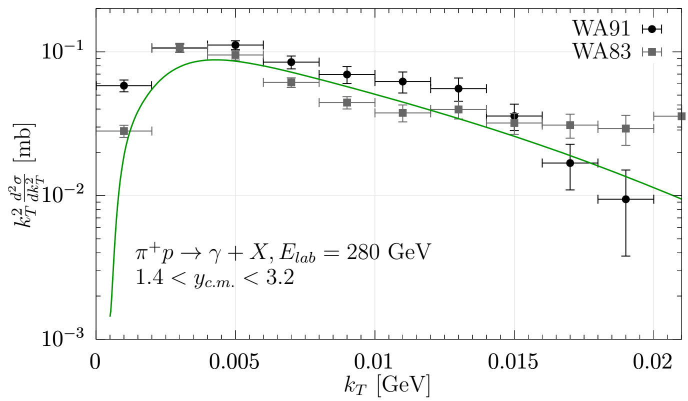

Fig. 3. Comparison with data of the WA83 [15] and WA91 [16] experiments for $\pi^+ p \to \gamma X$ at $E_{\rm lab} = 280$ GeV.

At somewhat higher energy $E_{\rm lab} = 450$ GeV [17], our calculations depicted by the solid curve in Fig. 4 apparently overestimate the data of the WA102 experiment. However, the experiment had specific cuts, namely, events with a number of charge tracks $N_{\rm ch} > 8$ were excluded. To calculate the multiplicity distribution, we assume the Poisson distribution of a number of unitary cut Pomerons and employed the result of QGSM [18]. Thus, we obtained a suppression factor

$$\delta = \frac{\sum_{N_{\rm ch}=0}^{8}}{\sum_{N_{\rm ch}=0}^{\infty}} = 0.39\,. \tag{6}$$

The dashed curve, which incorporates this factor, agrees well with the data.

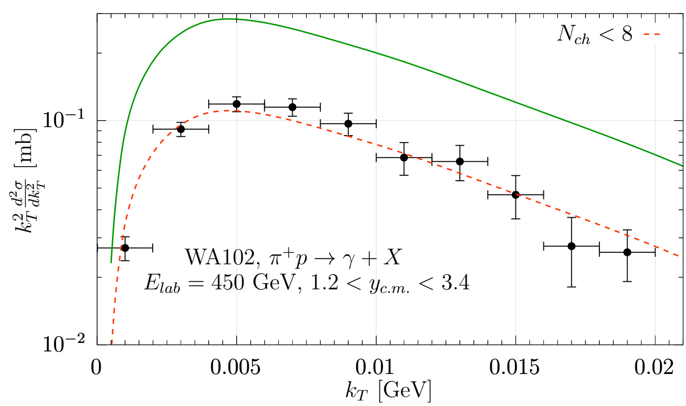

Fig. 4. Comparison with data of the WA102 [17] experiment for $\pi^+{\rm Be} \to \gamma X$ at $E_{\rm lab} = 450$ GeV.

5. Conclusions

— The observed enhancement of low-k_{T} photons in comparison with incorrect calculations should not be treated as a puzzle.

— The parton model description of photon radiation is extrapolated to the soft scale regime. The (anti)quark distribution functions are evaluated within the popular quark–gluon string model, based on the Regge phenomenology.

— Soft photon bremsstrahlung by projectile quarks is calculated within the color–dipole model. The quark–antiquark dipole cross section is fitted to DIS and soft photoproduction data in a wide range of transverse dipole separations and energies.

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