Two-photon production in pp and $p\bar{p}$ collisions

T. Jayaraman, G. Rajasekaran,* and S. D. Rindani*
Department of Theoretical Physics, University of Madras, Guindy Campus, Madras 600 025, India
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We show that the process pp ($p\bar{p}$)$\rightarrow\gamma+\gamma+X$ is a powerful test to distinguish between gauged integer-charged-quark models (ICQM's) and fractionally-charged-quark models (FCQM's). We study the ratio of the two-photon production cross section to the lepton-pair production cross section. Below color threshold the ICQM value for this ratio ranges from 30 to 130 in pp collisions (and 10–35 in $p\bar{p}$ collisions) in the kinematic range of the CERN ISR experiment, whereas the FCQM value is 1.6. The single experimental result available so far appears to disfavor the ICQM.

Two-photon processes in e^+-e^- annihilation, leading to the production of two jets at large transverse momentum, have been considered to be good tests to distinguish between fractionally-charged-quark models (FCQM's) and integrally-charged-quark models (ICQM's). It was expected that since these processes could measure the fourth power of the quark charge, they would be able to distinguish between the two models even below a possible threshold for the production of colored hadrons. However, recent analyses[1] have shown clearly that the fact that the photons in these experiments are not completely "real" makes it somewhat more difficult to measure the color-octet part of the quark charge in the gauged ICQM, where integer-charged quarks are embedded in a spontaneously broken gauge theory. As is well known, in such models the quark charge is given by the expression[2]

$$Q=Q_0+Q_8[-m_g{}^2/(q^2-m_g{}^2)]\ , \tag{1}$$

where Q_0 is the color-singlet part of the charge, Q_8 the color-octet part, m_g the gluon mass parameter, and q the momentum transfer carried by the electromagnetic probe. Since $q^2\neq0$ over the full allowed range in two-jet production, the full octet charge cannot be seen. Hence a process with completely real photons is required to distinguish between the two models.

Two-photon production in pp and $p\bar{p}$ collisions provides a process where the full color-octet charge of the quarks can be seen. In this process the quarks and antiquarks in the two hadrons annihilate to give two real photons of large P_T, which are detected. Moreover, the charged gluons in the gauged ICQM can also contribute to two-photon production, both above and below color threshold. This effect can be significant as the gluons carry almost 50% of the momentum of the proton.

Though this process has been discussed by a number of authors,[3] its significance in distinguishing between ICQM and FCQM does not appear to have been fully realized. We calculate the contribution of quark-antiquark and gluon-antigluon annihilation to two-photon production in the gauged ICQM to the lowest order. Specifically we work with a model of spontaneously broken SU(3) $\times U(1)_{\rm EM}$ theory of strong and electromagnetic interactions (neglecting weak interactions), the details of which can be found in Ref. 4, but our results do not depend on the definite choice of Higgs structure.

It has been shown[5] that there are large higher-order (in α_s) corrections which occur in two-photon production in the FCQM, very similar to those in lepton-pair production. We therefore look only at the ratio of the cross sections for two-photon production and lepton-pair production to lowest order in the gauged ICQM and FCQM, the ratio not being expected to be very sensitive to higher-order corrections. We find that the ratio in the gauged ICQM is greatly enhanced compared to the case of the FCQM, for both pp and $p\bar{p}$ collisions.

We next present the calculation of two-photon production for gauged-ICQM quarks and gluons and that of lepton-pair production followed by the comparison of the numerical result for pp and $p\bar{p}$ collisions with the values in the gauged ICQM and FCQM.

The cross section for $q\bar{q}\rightarrow\gamma\gamma$ is standard and is given by[6]

$$\frac{d\hat{\sigma}}{d\hat{t}}=\frac{2\pi\alpha^2}{\hat{s}^2}\left[\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right]\sum_{i=1}^{3}Q_i{}^4\ , \tag{2}$$

where $\hat{s},\hat{t},\hat{u}$ are the subprocess Mandelstam variables and Q_i is the charge for a quark of definite flavor and color i. The charge factor in the FCQM is

$$\sum_{i=1}^{3}Q_i{}^4=\sum_{i=1}^{3}Q_{0i}{}^4\ , \tag{3}$$

where Q_{0i} is the color-singlet contribution to the charge. Numerically, (3) gives $\frac{16}{27}$ for u,c quarks and $\frac{1}{27}$ for d,s quarks. In the ICQM, above color threshold,

$$\sum_{i=1}^{3}Q_i{}^4=\sum_{i=1}^{3}(Q_{0i}+Q_{8i})^4\ , \tag{4}$$

and takes the value 2 for u,c quarks and 1 for d,s quarks. In Eq. (4) Q_i has been written as a sum of color-singlet and color-octet contributions Q_{0i} and Q_{8i}. Below color threshold, however, where the color singlet has to be projected in the amplitude, the charge factor is

$$\sum_{i=1}^{3} Q_i{}^4 = \left[(1/\sqrt{3}) \sum_{i=1}^{3} (Q_{0i}+Q_{8i})^2 \right]^2 . \tag{5}$$

Its value is $\frac{4}{3}$ for u,c quarks and $\frac{1}{3}$ for d,s quarks. There is no suppression of the octet charges as both photons are real.

The cross section for $g^+g^- \to \gamma\gamma$ in the ICQM is given by

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{16\pi\alpha^2 C}{9\hat{s}^2} \left[\frac{\hat{s}^2}{\hat{t}^2} + \frac{\hat{s}^2}{\hat{u}^2} + \frac{3}{2} \right] \tag{6}$$

in the limit of small gluon masses. C is the gluon charge factor due to the four integrally charged gluons of the ICQM. Equation (6) is calculated in terms of the electromagnetic interactions of the color eigenstates of the charged gluons which are given by[2]

$$\langle G^n(p') \,|\, j_\mu^{\mathrm{EM}}(k) \,|\, G^m(p) \rangle = i f_{lmn} \left[\delta_{l3} + \frac{1}{\sqrt{3}} \delta_{l8} \right] \epsilon^\alpha \epsilon'^\beta V_{\mu\alpha\beta} [m_g{}^2/(k^2 - m_g{}^2)] , \tag{7}$$

where G^m is a color eigenstate of the gluon, ϵ^α its polarization vector, $V_{\mu\alpha\beta}$ the Yang-Mills vertex, and f_{lmn} the structure constants of SU(3) of color. The gluon charge factor C may be obtained by summing over the structure constants appropriately in the matrix element squared. Thus we find that $C=2$ below color threshold and $C=4$ above color threshold.

We can now write down the full hadron-hadron differential cross section. The quark contribution obtained from Eq. (2) is given by

$$\frac{d^3\sigma}{dM\,dy\,d\cos\theta} = \frac{4\pi\alpha^2}{9Ms} \frac{1+\cos^2\theta}{\sin^2\theta} \sum_q \left[\sum_i Q_i{}^4 \right] [q_A(x_1)\bar{q}_B(x_2) + \bar{q}_A(x_1) q_B(x_2)] , \tag{8}$$

where $q_A(x)$ and $\bar{q}_A(x)$ are the distribution functions of a quark and antiquark of definite flavor q in hadron A, y the rapidity and M the invariant mass of the photon pair, and $\sum_q$ indicates a summation over all flavors relevant at the energies concerned. θ is the polar angle of the photon in the quark-antiquark center-of-mass frame (which coincides with the laboratory frame when $y=0$). The kinematics are considerably simplified when $y=0$. Then $x_1 = x_2 = \sqrt{\tau}$ where $\tau = M^2/s$. If further the two photons are detected at 90° in the laboratory frame, then

$$\left. \frac{d^3\sigma}{dM\,dy\,d\cos\theta} \right|_{\substack{y=0 \\ \theta=90^\circ}} = \frac{4\pi\alpha^2}{9Ms} \sum_q \left[\sum_i Q_i{}^4 \right] [q_A(\sqrt{\tau})\bar{q}_B(\sqrt{\tau}) + \bar{q}_A(\sqrt{\tau}) q_B(\sqrt{\tau})] . \tag{9}$$

Similarly the gluon contribution is

$$\left. \frac{d^3\sigma}{dM\,dy\,d\cos\theta} \right|_{\substack{y=0 \\ \theta=90^\circ}} = \frac{152\pi\alpha^2 C}{9Ms} g_A(\sqrt{\tau}) g_B(\sqrt{\tau}) , \tag{10}$$

where $g_A(x)$ is the gluon distribution function in the hadron A and we have summed over the charged gluons in each hadron.

For lepton-pair production we use the well-known Drell-Yan mechanism in the lowest order,[7] in which a quark and an antiquark from either hadron annihilate to give a virtual photon which then produces a lepton pair. It is immediately obvious that if the k^2 of the virtual photon is such that $k^2 \gg m_g{}^2$ (as is true in the experimental situation), then the color-octet part of the charge is completely suppressed in the ICQM. Hence the quarks in the ICQM and FCQM give the same cross section for lepton-pair production, both above and below color threshold.

In the ICQM, the charged gluons can also contribute to this process in the lowest order. However, if we are below color threshold the charged gluons cannot contribute. The two charged gluons couple only to the color-octet part of the electromagnetic current. Hence the two jets formed by the spectator partons in the colliding hadrons must together be in a color-octet state. If the energy is below color threshold this will not happen. Hence the charged gluons do not contribute to lepton-pair production below color threshold.

The differential cross section for the quark contribution to lepton-pair production is a standard result[5] and we write it down directly, with the variables defined in the same way as for photons in the previous section,

$$\left. \frac{d^3\sigma}{dM\,dy\,d\cos\theta} \right|_{\substack{y=0 \\ \theta=90^\circ}} = \frac{\pi\alpha^2}{3Ms} \sum_q Q^2 [q_A(\sqrt{\tau})\bar{q}_B(\sqrt{\tau}) + \bar{q}_A(\sqrt{\tau}) q_B(\sqrt{\tau})] , \tag{11}$$

where Q^2 is the square of the charge of the quark of definite flavor (or the square of the color-singlet part of the charge in the ICQM) and $\sum_q$ is a summation over the relevant flavors.

The differential cross section for $g^+g^- \to e^+e^-$ above color threshold is found[8] to be

$$\frac{d\hat{\sigma}}{d\cos\theta} = \frac{\pi\alpha^2 C'}{36\hat{s}} (1-\cos^2\theta) , \tag{12}$$

where C' is the charge factor for the gluons. C' is, of course, 4, since it includes a summation over all gluons. Then the gluon contribution to lepton-pair production is given by

$$\left.\frac{d^3\sigma}{dM\,dy\,d\cos\theta}\right|_{\substack{y=0\\ \theta=90^\circ}}=\frac{\pi\alpha^2 c'}{18Ms}g_A(\sqrt{\tau})g_B(\sqrt{\tau})\ . \tag{13}$$

We now compare the numerical values of the ratios of two-photon production to lepton-pair production in the ICQM and in FCQM. For the quark and gluon distributions in the proton we use a number of Q^2-independent distributions. As the purpose is merely to obtain an idea of the numbers involved, the quark and gluon distributions we use are those that are obtained from fitting deep-inelastic lepton-hadron scattering data by FCQM theoretical considerations ignoring Q^2-dependent contributions. A complete analysis would require however the extraction of the distributions from data in the framework of the ICQM. This would be a difficult exercise, especially if we were to consider $O(\alpha_s)$, corrections in the framework of the ICQM.

We define a ratio R by

$$R=\left.\frac{d^3\sigma(AB\to\gamma\gamma+X)/dM\,dy\,d\cos\theta}{d^3\sigma(AB\to e^+e^-+X)/dM\,dy\,d\cos\theta}\right|_{\substack{y=0\\ \theta=90^\circ}}, \tag{14}$$

where A and B denote the colliding hadrons. We calculate R in the FCQM and both above and below color threshold in the ICQM for pp as well as $p\bar{p}$ collisions. We have calculated R for the quark distributions of Refs. 9, 10, and 11, which we call, respectively, model (a), model (b), and model (c). In all three cases we parametrize the gluon distribution in the form

$$g(x)=0.0625(n+1)(1-x)^n x^{-1}$$

and vary n from 3 to 8. In the calculations we have chosen the τ values in the same range as the CERN ISR experiment.[12]

The results for pp collisions are shown in Fig. 1 and the results for $p\bar{p}$ collisions in Fig. 2. We find that the ICQM values for R are at least an order of magnitude above those for the FCQM, for pp collisions. We have shown only the two extreme cases of the gluon distributions for the ICQM values below color threshold. The values of R for model (c) show the same variations as those of model (b) though the curves are shifted slightly upwards by 10% and therefore have not been shown separately. Above color threshold the ICQM values are even higher; for instance, for $M=7$ GeV in the case of model (a) with $n=3$ in the gluon distribution, $R=100.7$ for the ICQM above color threshold. The general variation of R follows the same pattern as the values below color threshold. Though not shown in Fig. 1 for convenience, R is 1.6 and 4.0 (for $7<M<12$ GeV) for FCQM and ICQM quarks, respectively, in pp collisions.

In the case of $p\bar{p}$ collisions (in Fig. 2) the ICQM values for R are not as high as in the case of pp collisions. We have shown again only the values below color threshold, those above color threshold being even higher. We have also plotted R separately for the quark contribution alone in the ICQM and FCQM. In this case R is insensitive to changes in the quark distribution and hence only a single curve [for model (a) distributions] is shown.

The values of R in $p\bar{p}$ collisions for the ICQM above color threshold are also higher as in pp collisions; for instance for model (a) distributions, $M=7$ GeV and $n=3$ in the gluon distribution, $R=38.5$. The R values above

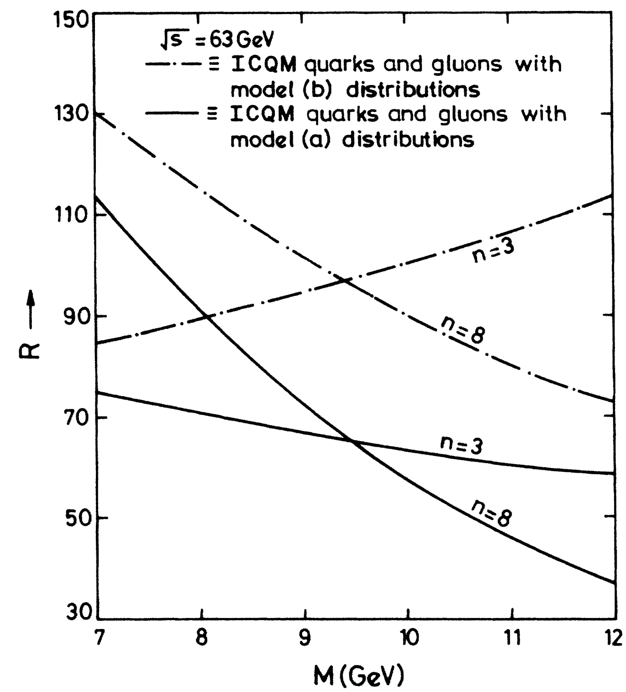

FIG. 1. R [defined in Eq. (14) in the text] in pp collisions for ICQM quarks and gluons with different gluon and quark distributions, below color threshold.

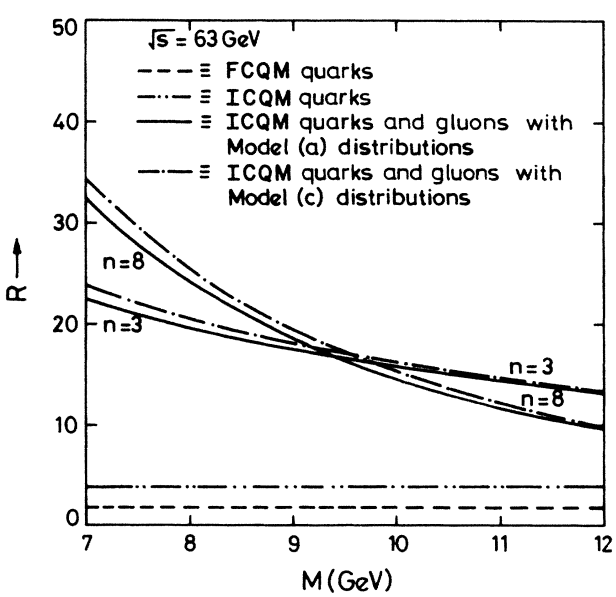

FIG. 2. R [defined in Eq. (14) in the text] in $p\bar{p}$ collisions for ICQM quarks and gluons with different gluon and quark distributions and also for ICQM quarks and FCQM quarks alone with model (a) quark distributions. All the curves are for energies below color threshold.

color threshold show the same general behavior with M as in the case of the ICQM below color threshold.

Two points may be noted before we conclude. First, there can be contributions to two-photon production from the gluons of the FCQM (Ref. 5). This higher-order (in α_s) contribution is, however, in the case of pp and $p\bar{p}$ collisions less than 50% of the quark contribution. The gluons in the ICQM, in contrast, give a huge contribution even in the lowest order.

Second, we must exercise some caution in understanding these large numbers in the case of the ICQM. In contrast with deep-inelastic scattering and other similar situations where the gluon contribution is lower than that of the quarks, the gluon contribution here is considerably enhanced. We must emphasize, however, the fact that contrary to our assumptions above, the transverse and longitudinal gluon modes could have different distributions. This may then bring down (or increase?) the total gluon contribution to the cross section. Nevertheless, quarks in the ICQM provide a larger ratio R than in the FCQM by about a factor of 2.5 in both pp and $p\bar{p}$ collisions. This process should therefore provide a good distinguishing test between the ICQM and FCQM irrespective of the location of the color threshold and of the ambiguities in the extraction of the gluon distributions.

The ISR experiments[12] have measured the ratio of the number of photon pairs produced to the number of lepton pairs to be 1.7 ± 1 where the transverse momentum of the photons or leptons is greater than 3 GeV/c and the invariant mass of the photon and lepton pairs is between 8 and 11 GeV. This is in good agreement with the value expected from the FCQM. Though we are unable to make a detailed comparison of the data with the results expected from the ICQM for want of sufficient details about the experimental cuts, the ICQM does appear strongly disfavored by the data.

We note finally that we have ignored the problem of color oscillations pointed out by Lipkin.[13] If true, this would wipe out the contribution of the color-octet part of the electromagnetic current in this process below color threshold. Then the ISR experimental results would still be compatible with the ICQM if we assumed that color had not been excited at those energies.

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*Present address: Institute of Mathematical Sciences, Madras 600 113, India.

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