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On the recent observation of the hadroproduction of prompt photons

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The recent observations of prompt photons in hadron collisions are confronted with the predictions of perturbative quantum chromodynamics, with very encouraging results. We discuss the data, and comment on their experimental and theoretical implications.

I. INTRODUCTION AND REVIEW

The observation of high-transverse-momentum (p_T) prompt photons in high-energy pBe (Ref. 1) and pp (Ref. 2) collisions has recently been reported. The existence of prompt photons populating the high-p_T region is required by quantum chromodynamics (QCD): the photon couples to the electric charge of quarks in a pointlike manner; therefore the fast quarks responsible for the abundant production of hadrons with large p_T will radiate and be the origin of prompt photons in the same kinematic range. The prompt-photon cross sections have been calculated in perturbative QCD,[3-8] and the measured cross sections are of the predicted order of magnitude. Here we wish to make a detailed comparison between data and theoretical calculations.

In lowest-order QCD the diagrams responsible for the production of high-transverse-momentum real photons are those shown in Figs. 1(a) and 1(b). The cross sections for these parton subprocesses are given, respectively, by

$$\frac{d\sigma^{gq}}{dt}=\frac{\pi\alpha\alpha_s}{3}\frac{s^2+u^2}{s^3(-u)}, \tag{1a}$$

$$\frac{d\sigma^{q\bar{q}}}{dt}=\frac{\pi\alpha\alpha_s}{9}\frac{t^2+u^2}{s^2tu}. \tag{1b}$$

Here g (q) stands for gluon (quark), s, t, u are the usual Mandelstam invariants for the subprocess, and $\alpha_s=1.51/\ln(p_T{}^2/0.25\ \text{GeV}^2)$ is the strong fine-structure constant. The convolution over initial parton densities giving the cross section $E\,d\sigma/d^3p$ to be compared to data is described in detail in Ref. 3, including a particular choice of parton densities.

The data[1,2] for γ/π^0 are shown in Fig. 2, plotted as a function of p_T for various energies. The calculated γ/π^0 ratio is shown for comparison. This quantity has been obtained from the QCD prompt-photon spectrum divided by a parametrization of the *measured* π^0 cross section[9-14] [we take $(\pi^+ + \pi^-)/2$ for $p_T \gtrsim 4$ GeV, for $\sqrt{s}=19.4$, 23.8 GeV (Ref. 15)]. We note that this simple QCD calculation predicted[3] prompt-photon cross sections in very good agreement with the CERN ISR data, and consistent with the highest-p_T Fermilab data. Notice, however, that for p_T values in the range 1.5–3.5 GeV the calculation falls well below the Fermilab measurements. We note, however, that the calculations of γ/π^0 are actually for production at 90°. The Fermilab experiment has a wide acceptance, $160°<\theta<90°$, and finds some increase of γ/π^0 with increasing x_F. This would indicate that γ/π^0 at 90° for $\sqrt{s}=19.4$, 23.8 GeV would be somewhat lower than shown in Fig. 2. The effect is less than a factor of 2. The statistical level of the data sample did not allow the detailed study of γ/π^0 versus p_T in bands of x_F which would be needed in order to clearly separate the p_T and x_F behavior. Further discussion is given by Cox.[1]

A useful way to study the energy dependence of the data is to plot it in the form

$$\frac{\gamma}{\pi}=(p_T)^n f(x_T=2p_T/\sqrt{s}), \tag{2}$$

with

$$n=n_\pi-n_\gamma.$$

Indeed, up to logarithms, QCD implies that both the γ and π cross sections exhibit the scaling of Eq. (2) with $n_\pi=n_\gamma=4$ and therefore $n=0$. The logarithms and soft (small-x_T) effects modify n so that it is no longer a constant. We may still consider effective values, valid locally, and it is well known that $n_\pi^{\text{eff}}\simeq 8$ instead of 4 in order to recover agreement with the data. Because of the absence of a fragmentation function in the final state and its associated scaling violations we expect $n_\gamma^{\text{eff}}<n_\pi^{\text{eff}}$. In conclusion

$$0<n^{\text{eff}}<4.$$

Note that the constituent-interchange-model (CIM) calculation, which we will discuss further on, predicts $n=2$ ($n_\gamma=6, n_\pi=8$). The data indicates $n=1$–2; see Figs. 3(a), 3(b).

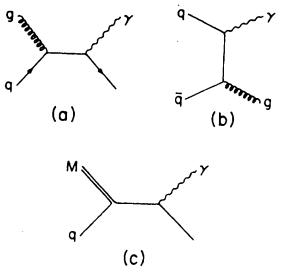

FIG. 1. Diagrams for the hadroproduction of high-p_T photons: (a) QCD gluon-quark "Compton" scattering; (b) QCD quark-antiquark annihilation; (c) CIM meson-quark scattering.

II. A CRITIQUE OF QCD COMPUTATIONS AND ALTERNATIVE SOURCES OF DIRECT PHOTONS

Our inability to accommodate the low-p_T, low-$\sqrt{s}$ data raises the possibility of alternative sources of direct photons, such as the meson-quark scattering graph of Fig. 1(c). Alternatively it could just reflect our inability to do quantitative QCD calculations when venturing into the small-p_T kinematic range. We first ask how unambiguous the QCD predictions are, and will subsequently address the question of alternative sources. The calculations shown in Fig. 2 are in the context of

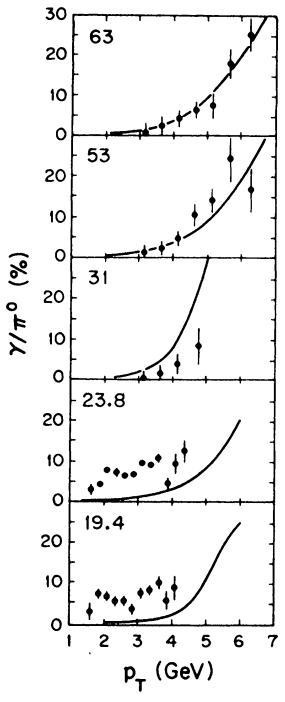

FIG. 2. The QCD calculation of γ/π^0 of Ref. 3 is compared to data at various energies. The data at $\sqrt{s}$ = 19.4 and 23.8 GeV come from Ref. 1, and those at $\sqrt{s}$ = 31, 53, and 63 GeV come from Ref. 2.

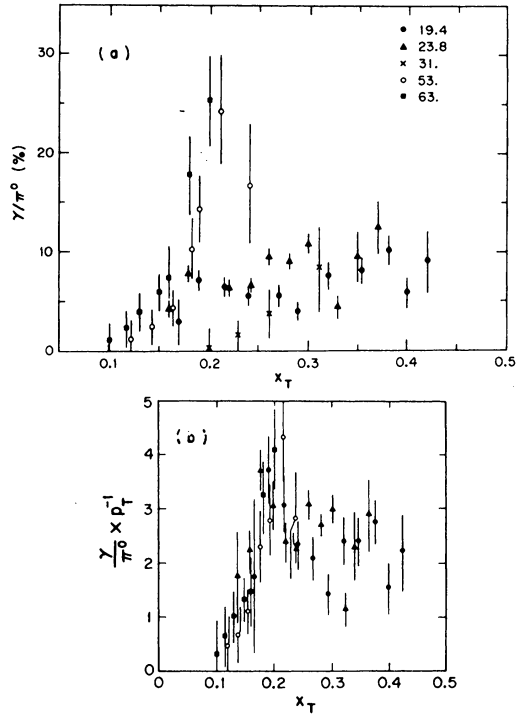

FIG. 3. (a) Data on γ/π^0 plotted as a function of $x_T = 2p_T/\sqrt{s}$. (b) Data on γ/π^0 (in percent) divided by p_T (in GeV) and plotted as a function of x_T.

a straightforward hard-scattering formalism, and no parton transverse momentum or logarithmic corrections have been considered. These are known to be important in order to quantitatively explain π^0 production at intermediate p_T values in terms of lowest-order QCD graphs. The fact that we agree with the ISR prompt-photon data for $p_T < 6$ GeV might then be surprising. However, we note that the calculation of prompt photons is cleaner than that of mesons, in that the photons are produced directly via a pointlike coupling, whereas the mesons are produced via parton fragmentation. We now systematically discuss various sources of uncertainty in the calculation.

(i) Soft effects. The QCD calculation diverges as $p_T \to 0$ so that further regularization of the calculation could alter the results. This divergence also occurs in the closely related context of highly virtual photon (lepton pair) production with $p_T \approx 0$. (For a recent review and references, see Ref. 16. Calculation details are given in Ref. 3, and regularization details in Ref. 17.) Here the diagrams of Figs. 1(a) and 1(b) are again calculated, but with the outgoing photon off-shell. The real-photon calculation can therefore be directly normalized[3] using data on high-transverse-momentum lepton pairs. Indeed, the diagrams of Fig. 1(a), 1(b) are the source of both of them. The

resulting γ/π yield is shown as a dashed line in Fig. 4.

(ii) Scaling violations. Our parton densities are "effective" densities, which in principle should exhibit scaling violations, which are surely relevant. However, in practice, the uncertainty provided by scaling violations is complemented by uncertainty in the initial (at the renormalization point) shape of the gluon density. Because these two aspects of scaling violations tend to compensate, the net result of their inclusion can either enhance or decrease the γ/π ratio. Because our scaling parton densities are in agreement with data on lepton-pair p_T spectra and p_T integrated cross sections,[18] we believe they represent correct effective densities. The calculations using three different choices of parton densities are shown in Fig. 5, compared to the measured π^0 cross section, at $\sqrt{s}=53$ GeV and 90° in the center of mass. The solid curve is the prediction of Ref. 3; the dashed curve uses the scaling violating densities of Ref. 6; the dotted curve is a different implementation of scaling violations.[5,19] Note that at high p_T the two photons from the decay $\pi^0 \to \gamma\gamma$ are not resolved, and consequently the measured cross section is actually for π^0 *plus* prompt photon.

The level of uncertainty provided by (i) and (ii) above is further demonstrated in Fig. 4, where data at $p_{1ab}=200$ GeV is compared to four different calculational possibilities.

(iii) Angular dependence. The Fermilab data[1] is taken over a wide range of x_F, in the center-of-mass angular range $90°<\theta<160°$. The ISR data is taken over an angular range about 90° in the center of mass. In order to measure γ/π^0 it is important to know

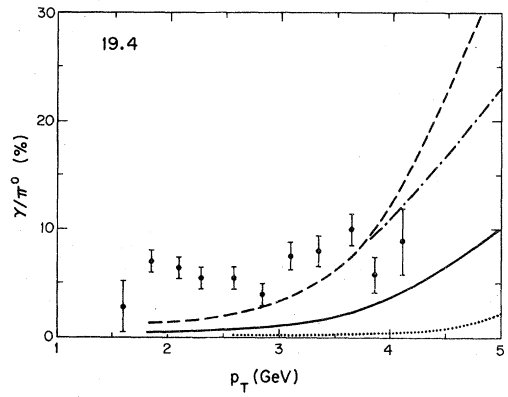

FIG. 4. Data (Ref. 1) on γ/π^0 at $\sqrt{s}=19.4$ GeV are compared with QCD calculations using the parton densities of Ref. 3 (solid line), Ref. 6 (dashed-dotted line), and Ref. 19 (dotted line). The dashed line is the QCD calculation normalized directly to the lepton pair data. The dramatic rise of the curves at $p_T \simeq 4$ GeV comes from the rapid falloff of the measured π cross sections.

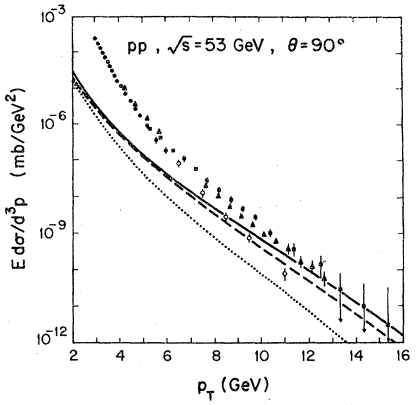

FIG. 5. QCD calculations of direct photons are compared to π^0 data. The solid, dashed, and dotted lines use the parton densities of Refs. 3, 6, and 19, respectively. The data are from Refs. 20, 11, 12, and 21.

the angular dependence of the photon cross section. Our results for this are shown in Figs. 6(a) and 6(b), where the cross sections at $\sqrt{s}=19.4$ and 53 GeV are plotted as a function of center-of-mass angle $\theta_{c.m.}$ for various fixed p_T values. The Fermilab group also analyzed the x_F dependence of the data. The excess of observed photons for large values of x_F is difficult to accommodate using any type of hard-scattering mechanism. The excess may be connected to the fact that the fixed angular acceptance forces p_T to become large as x_F becomes large, and large p_T is where γ/π^0 increases.

(iv) Atomic-number dependence. A further complication is that the Fermilab experiment is carried out on beryllium. If one writes the π cross section as varying as $A^{\alpha_\pi(p_T)}$ with atomic number A, then for $p_T \lesssim 6$ GeV $\alpha_\pi(p_T)$ is an increasing function of p_T.[15] Presumably the same is true for the corresponding $\alpha_\gamma(p_T)$, but because of the electromagnetic, as opposed to strong, coupling of the photons to hadrons $\alpha_\gamma(p_T) < \alpha_\pi(p_T)$. Consequently, γ/π^0 should be smaller in pBe collisions than in pp collisions. This makes a possible discrepancy between calculation and data for the lower-p_T 200-GeV data even greater.

The ambiguities in calculating γ spectra at intermediate p_T are further clouded by the possibility of additional sources, such as constituent-interchange-model (CIM) mechanisms.[4,7,22] In the CIM the dominant mechanism for producing high-p_T prompt photons is $q_1 M \to q_2 \gamma$, where M is a meson; the diagram is shown in Fig. 1(c). The subprocess cross section is

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha\alpha_M}{s^2}\frac{s^2+u^2}{(-t)}\left(\frac{e_{q_1}}{u}+\frac{e_{q_2}}{s}\right)^2, \tag{3}$$

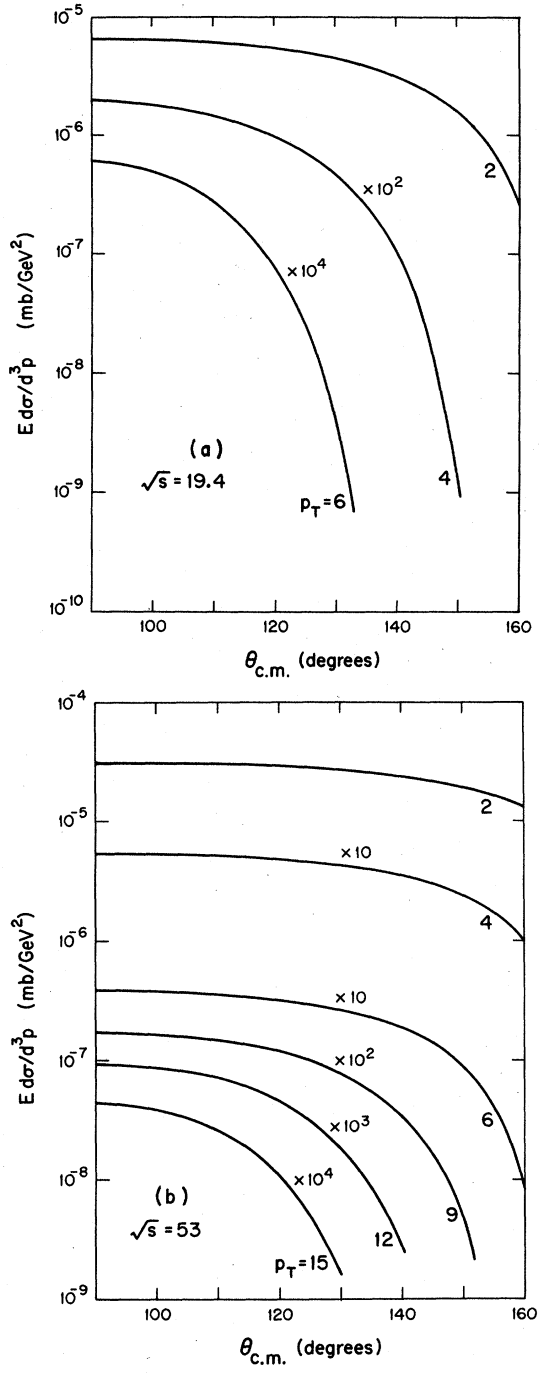

FIG. 6. Angular dependence of prompt-photon cross sections calculated in QCD. Some of the curves have been multiplied by powers of 10, as indicated.

where $\alpha_M \simeq 2$ GeV is the coupling of a meson to $q\bar{q}$, and e_{q_i} is the charge of quark q_i. The calculation, including quark and meson densities is described in detail in Ref. 4. Our results are in good agreement with the approximate methods

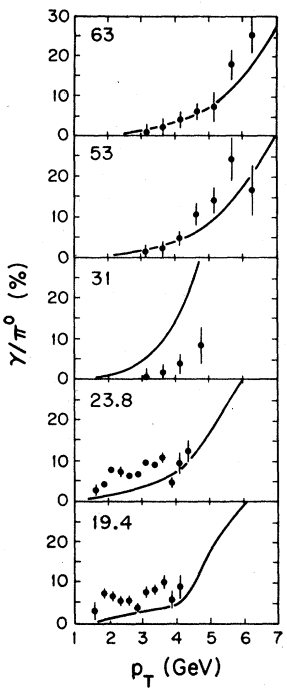

FIG. 7. The CIM calculation of γ/π^0 is compared to data at various energies.

used in Ref. 4.

Again normalizing the calculated γ yield to the measured π spectrum, we show γ/π calculated in the CIM compared to the data in Fig. 7. We have two comments. First, the calculated curves are very similar, both qualitatively and quantitatively, with those calculated from QCD. Second, the CIM cannot explain the lower p_T γ/π^0 measured at Fermilab—if one increases the CIM result by a factor of 2, it would be inconsistent with the ISR result. Adding together the QCD and CIM results leads to similar conclusions. We note, however, that over the presently measured kinematic range, the CIM results are very similar to those from QCD.

Explicit consideration of parton transverse form factors and additional CIM-type contributions have been advocated to carry perturbative QCD calculations into the intermediate p_T range. To accommodate the γ/π data over the full energy range seems to challenge the quantitative aspects of both approaches.

III. FURTHER EXPERIMENTAL AND THEORETICAL IMPLICATIONS

As we have already discussed, the measured high-p_T π^0 cross section, where the two photons from the decay $\pi^0 \to \gamma\gamma$ cannot be resolved, is actually the cross section for π^0 plus prompt

photon. It may be possible to exploit this fact to make an experimental estimate of the direct photon yield in an experiment[13] where both charged and neutral pions are detected. If a high-transverse-momentum pion is produced from the fragmentation of a high-transverse-momentum quark or gluon, then using isospin symmetry we find for the high-p_T yields,

$$\pi^0 = \tfrac{1}{2}(\pi^+ + \pi^-) . \tag{4}$$

An excess of the π^0 yield above this value, when known sources of photons such as η have been subtracted,[13] may be attributed to direct photons. Applying this procedure to the results of the CERN-Columbia-Rockefeller-Saclay experiment[13] gives $\gamma/\pi \sim 20\%$ in the range $3 \lesssim p_T \lesssim 6$ GeV, at $\sqrt{s} = 63$ GeV, consistent with the measurements of Ref. 2.

Further information may be obtained through studying the jet on the away side from a high-p_T direct photon. Indeed such measurements may help in their detection. The cross section for the production of a high-p_T photon of momentum p and rapidity y, together with an away-side jet (parton) of rapidity y_J is

$$\frac{Ed\sigma}{d^3p\,dy_J} = \frac{1}{\pi}\frac{d\sigma^{\mathrm{SP}}}{dt} x_1 f^B(x_1) x_2 f^T(x_2) , \tag{5}$$

where

$$x_{1,2} = \tfrac{1}{2} x_T (e^{\pm y} + e^{\pm y_J}) ,$$

$$x_T = \frac{2p_T}{\sqrt{s}} , \tag{6}$$

and where f^B (f^T) is the parton density in the beam (target). σ^{SP} is the subprocess cross section.

In pp collision, the dominant mechanism in QCD for producing high-p_T direct photons is quark-gluon scattering.[3] So a measurement of the cross section in Eq. (5) would give a direct determination of the gluon density in the proton, as the quark density is already known from lepto-production experiments. Further, the away-side jet will dominantly be a quark, and then specializing to $y = y_J = 0$ we have for the distribution of a hadron h in the away-side jet in terms of its fractional momentum $z = p_T^h/p_T^\gamma$,

$$\frac{dN^h}{dz} = \frac{\sum e_q^2 q(x_T) D_q^h(z)}{\sum e_q^2 q(x_T)} , \tag{7}$$

where e_q is the charge of quark q, $q(x)$ is its distribution in a proton, and D_q^h describes the fragmentation $q \to h$. Note that this is the same distribution as for hadrons produced in the parton fragmentation region in deep inelastic lepton scattering from a proton target. The resulting hadron distribution may be noticeable in that (i) the production of positive particles is enhanced, and (ii) the spectrum is harder, compared to away-side hadrons produced opposite a high-p_T π^0 trigger.

We comment that in $\bar{p}p$ collisions, the dominant mechanism for high-p_T direct photon production is $q\bar{q} \to \gamma g$. The away-side jet comes from gluon fragmentation.

The production of prompt photons at high p_T necessarily leads to the production of prompt leptons, which come in pairs.[16,23] The photons undergo internal conversion, producing an important source of prompt leptons. The lepton spectrum can be easily calculated[23] from the prompt-photon spectrum, using a bremsstrahlung approximation, and the result, at $\sqrt{s} = 53$ GeV and 90° in the center of mass, is shown in Fig. 8, normalized to π data and compared to available data.[24] Note that the once mystical lepton-pion ratio $l/\pi \simeq 10^{-4}$ is now seen as a transient value for p_T values in the resonance region $m_\rho/2 \lesssim p_T \lesssim m_\psi/2$. Prompt photons produced from bremsstrahlung by (a) charged hadrons[25] for $p_T \lesssim m_\rho/2$; (b) quarks for $p_T \gtrsim m_\psi/2$, provide sources of direct leptons in excess of the $l/\pi \simeq 10^{-4}$ ratio. Because of the bremsstrahlung origin of the l/π ratio, we clearly expect that $e/\pi > \mu/\pi$, both at small ($p_T \lesssim 1$) and large ($p_T \gtrsim m_\psi/2$) transverse momentum. We need not list again the uncertainties involved in the calculation. We simply note that this mechanism, along with others calculable in QCD,[26,27] leads to copious prompt lepton production at high transverse momentum.

The increased γ/π and l/π ratio with decreasing transverse momentum due to the enhanced bremsstrahlung of charged secondaries draws our attention to the fact that the problem of prompt photons is potentially interesting, whatever the kinematic range of p_T. Although we escaped to the large-p_T region to recover simple perturbative

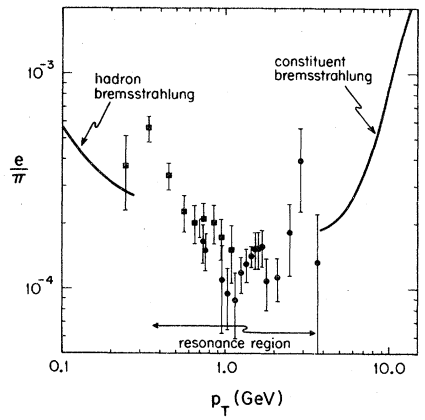

FIG. 8. Calculations of e/π are compared to data at $\sqrt{s} = 53$ GeV, 90°.

QCD dynamics, the "gammaization" of hadron collisions was predicted[28] in 1962 by E. L. Feinberg, with no restriction on the transverse momentum of the secondaries. His proposal essentially consists in calculating the "background radiation" from a hadron collision. We reproduce it below, to illustrate its importance and the unusual and exciting possibilities that could be revealed in studies of γ/π ratios in the small-p_T regime. Colliding hadrons swiftly pump their energy in a limited volume of hadronic matter. After expansion it reaches freeze-out and produces hadrons. Before cooling down, however, charge fluctuations result in the radiation of photons. If we model the charge fluctuations in terms of n_π π mesons interacting (i.e., colliding or annihilating) ν times, then (t is time here)

$$\frac{dn_\gamma}{dt} \cong n_\pi \nu \alpha . \tag{8}$$

This goes on for a characteristic time

$$t \cong V^{1/3} \cong (n_\pi / m_\pi^{\,3})^{1/3} . \tag{9}$$

This is the time it takes to form physical hadrons (every π meson is assumed to occupy one Compton wavelength and therefore occupy a volume $V \cong n_\pi / m_\pi^{\,3}$). From Eqs. (4), (5) we obtain

$$\frac{n_\gamma}{n_\pi} = C \alpha n_\pi^{\,1/3} \tag{10}$$

with $C \simeq 10$. Therefore, $n_\gamma/n_\pi \simeq 15\%$ at $\sqrt{s} = 50$ GeV where $n_\pi \simeq 12$; notice, however, that n_γ/n_π will exceed unity at energies in the 10^2–10^3 TeV range (in this type of model $n_\pi \propto \sqrt{s}$).

If indeed a large fraction of the produced hadrons, and not just the high-transverse-momentum secondaries, are photons at energies above typically 100 TeV, their signature should be dramatic even in the most routine cosmic-ray experiments above that energy. They have most likely been observed. In extensive-air-shower experiments one observes the production of charged and neutral π mesons in a cosmic-ray interaction via the development through the atmosphere of an electromagnetic shower with two components, a muon and an electron-photon component, originating respectively from charged- and neutral-π decays. The energy deposited into the components is in the ratio

$$\frac{E_\gamma}{E_\mu} = \frac{\pi^0}{\pi^0 + \pi^+ + \pi^-} = \frac{1}{3} .$$

It is clear that if photons become a major part of the secondaries this ratio will increase and reach a value of

$$\frac{2\gamma + \pi^0}{2\gamma + \pi^0 + \pi^+ + \pi^-} = \frac{3}{5}$$

when $\gamma/\pi = 1$. Here we took into account the two polarization states of the γ. There is a wealth of literature corroborating this trend.[29] Anomalous development of the e-γ component of air showers has been observed. The anomaly appears around 10 TeV and becomes dramatic above 100 TeV. Anomalous development of air showers in calorimeter experiments has been interpreted as an increase in E_γ/E_μ by about a factor of 2 as required by gammaization. Direct evidence for production of photons in isolated events above 100 TeV has recently been presented.

To conclude, the observation of prompt photons at the present levels is very encouraging for QCD. Their existence is predicted by QCD, and a detailed comparison of calculation and data at high p_T and energy can give important information about quark densities and scaling violations. In particular, the dominant $O(\alpha_s)$ QCD subprocess for high-p_T prompt-photon production in pp collisions is $gq \to \gamma q$, the "Compton scattering" subprocess. The cross section here, as for high-p_T lepton pairs, will give direct information about the gluon density. We look forward to more detailed measurements of prompt photons and leptons with high p_T, and to a renewed interest in the problem of γ/π ratios at all values of p_T.

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