Anomalous soft photons in hadron-hadron collisions: synchrotron radiation from the QCD vacuum?

In the late 1970's theoretical views were developed where the QCD vacuum state was supposed to be full of gluon fields.

Shifman, Vainshtein and Zakharov introduced the gluon condensate

$$G_2 = \langle 0 | \frac{g^2}{4\pi^2} G^a_{\mu\nu}(x)\, G^{a\mu\nu}(x) | 0 \rangle$$

$$= \frac{1}{4\pi^2} (0.95 \pm 0.45) \text{ GeV}^4. \qquad (D1)$$

(numerical value from H. G. Dosch, Progr. in Part. and Nucl. Phys. (1994))

For the uncontracted gluon tensors this gives

$$\langle 0 | \frac{g^2}{4\pi^2} G^a_{\mu\nu}(x)\, G^b_{\rho\sigma}(x) | 0 \rangle$$

$$= \frac{1}{96} \delta^{ab} \left(g_{\mu\rho} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\rho} \right) G_2 \; , \qquad (D2)$$

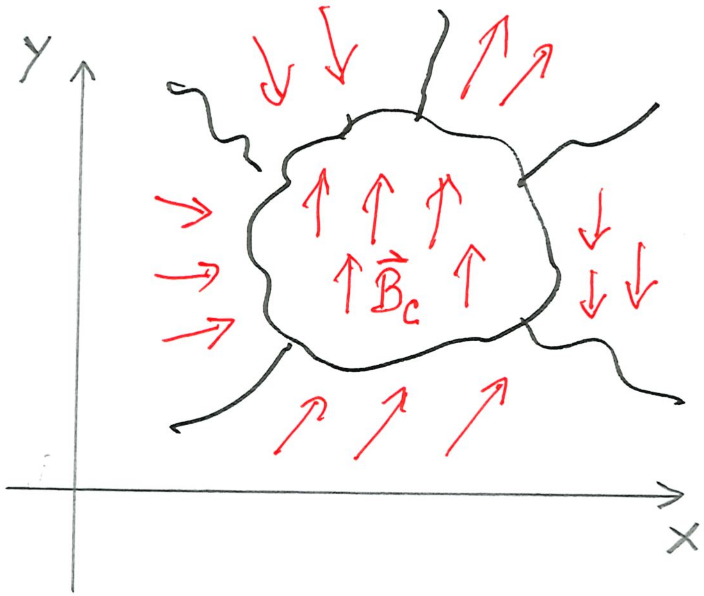
$$\langle 0 | g^2 \vec{B}^a(x)\, \vec{B}^a(x) | 0 \rangle = - \langle 0 | g^2 \vec{E}^a(x)\, \vec{E}^a(x) | 0 \rangle$$

$$= \pi^2 G_2 \cong (700\ \text{MeV})^4 . \qquad (D3)$$

Here it is assumed that the products of field strengths are normal ordered with respect to the "perturbative vacuum". Then (D3) tells us that in the QCD vacuum the chromomagnetic field has bigger fluctuations, the chromoelectric field smaller fluctuations than in the perturbative vacuum.

Of course, there are no constant color fields in the vacuum. But there may be fluctuating domains of nearly constant color fields.

An instantanous picture of the QCD vacuum in Euclidean space could look as follows:



The typical size of such fluctuating domains is estimated to be

$$a \cong 0.35 \text{ fm} \tag{D4}$$

Translating this naively to Minkowski space we expect fluctuating domains of typical size for a domain centered at the origin $x^\mu = 0$:

$$|x_\mu x^\mu| \lesssim a^2 . \tag{D5}$$

In the following we are interested in light hadrons where the radius $R \simeq 1$ fm is substantially larger than a.

A fast quark can spend a relatively long time in such a domain.

D5

and using Lorentz and parity invariance

$$ {}^{b}_{\rho\sigma}(x)\Big|0\Big\rangle = \frac{1}{96}\delta^{ab}(g_{\mu\rho}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\rho})G_2. \tag{2.2}$$

ɔelectric and chromomagnetic fields this

$$ |0\rangle = \pi^2 G_2 \simeq (700\ \text{MeV})^4, $$

$$ |0\rangle = -\pi^2 G_2. \tag{2.3}$$

ʼs assumes that the product of the field mal ordered with respect to the "pertur-ʼ. Thus (2.3) should be interpreted in nse: in the physical vacuum the chromo-ıuctuates with bigger, the chromoelectric er amplitude than in the "perturbative

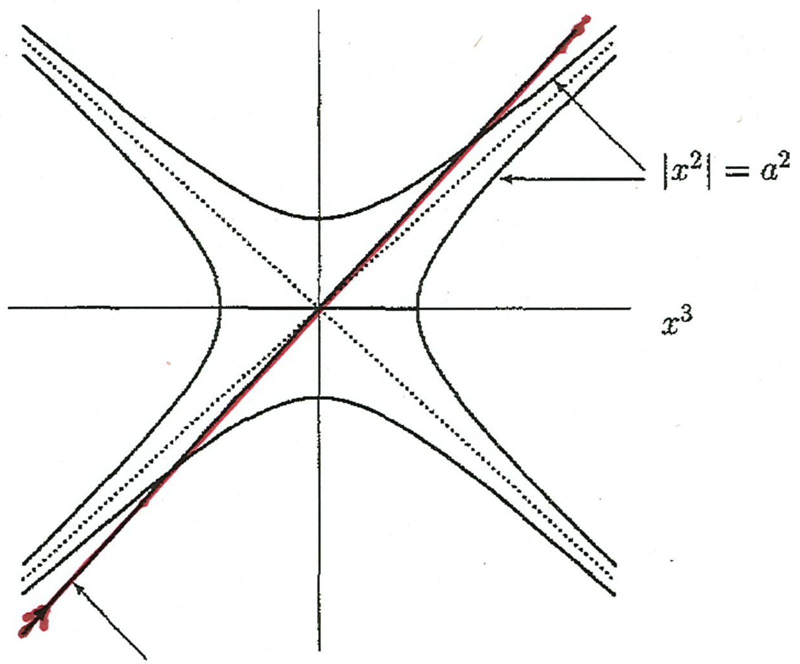


Fig. 1. Sketch of a "colour domain" in Minkowski space and of a quark from a fast hadron moving through it

Now what will happen if a fast, nearly massless, u or d quark moves through a nearly constant chromomagnetic field?

- deflection of the quark,
- gluon synchrotron radiation,
- photon synchrotron radiation.

For a light hadron the $u, d, \bar{u}, \bar{d}$ quarks forming it will typically feel different vacuum domains due to $R \gg a$.

For an isolated hadron travelling with velocity nearly light velocity past the observer these gluons and photons are part of the cloud of virtual particles around the hadron (cf. Weizsäcker–Williams!). In a hadronic collision these particles can become real.

In the paper "Soft photons in hadron-hadron collisions: synchrotron radiation from the QCD vacuum" by G.W. Botz, P. Haberl and O.N., Z. Phys. C 67, 143 (1995), we gave an estimate of such emissions in the inelastic reaction

$$p(p_1) + N(p_2) \longrightarrow \text{hadrons} + \gamma(k), \quad (N = p, n).$$

We obtained, using standard synchrotron formulas, for the emission in the overall c.m. system

$$\omega \frac{d^3 n_\gamma^{(syn)}}{d^3 k} = \frac{\alpha}{\omega^{4/3}} \left(l_{eff} \right)^{2/3} \Sigma(\cos\vartheta^*),$$

$$\cos\vartheta^* = \hat{p}_1 \cdot \hat{k}, \qquad l_{eff} = \frac{\sigma}{g B_c},$$

$\sigma \cong 300$ MeV = mean transverse momentum of a quark in a hadron.

$$\Sigma(\cos\vartheta^*) \propto (\sin\vartheta^*)^{-2/3}$$ except for ϑ^* near 0° and 180°.

Note that we have

$$\frac{\omega\, d^3 n_\gamma^{(syn)}}{d^3 k} \Bigg/ \frac{\omega\, d^3 n_\gamma^{(bremsstr.)}}{d^3 k} \propto \omega^{2/3} \quad \text{for } \omega \to 0.$$

Weinberg's soft-photon theorem is respected.

We have compared our theory with the experimental results from p - Be collisions at 450 GeV incident proton momentum from J. Antos et al., Z. Phys. C59, 547 (1993).

D9

The final hadronic state contains in most of the cases two nucleons plus pions. We will neglect other particle compositions of the final state in the following.

In Fig. 4 we reproduce Fig. 5 of [3] with the normalization provided to us by H.J. Specht. Here we use the variables in the overall c.m. system:

$$k_T = (\mathbf{k}^2 - (\hat{\mathbf{p}}_1 \cdot \mathbf{k})^2)^{1/2},$$

$$y = -\ln\tan(\vartheta^*/2),$$

$$\vartheta^* = \sphericalangle(\mathbf{k}, \mathbf{p}_1). \tag{3.3}$$

Expressed in these variables our prediction for synchrotron photons (2.39), (2.40) reads

$$\frac{d^2 n_\gamma^{(\mathrm{syn})}}{dk_T dy} = \frac{2\pi\alpha(l_{\mathrm{eff}})^{2/3}}{k_T^{1/3}}(\sin\vartheta^*)^{4/3}\,\Sigma(\cos\vartheta^*). \tag{3.4}$$

In the sum over the final state hadrons h in (2.40) we include 2 nucleons plus pions, as mentioned above. Consider first the two nucleons. These are "leading" particles and carry away a substantial fraction of the available energy in forward and backward direction, respectively (cf. [37]). We estimate their contribution to Σ to be approximately the same as for the initial state nucleons. Next we consider the contribution to Σ from π^+, π^-, π^0. Due to isospin and charge conjugation invariance the structure functions F_2 for π^+, π^- and π^0 are equal. At least approximately also the inclusive cross sections for π^+, π^- and π^0 are equal [37]. Making this assumption, we obtain from (2.40) for the reaction (3.1)

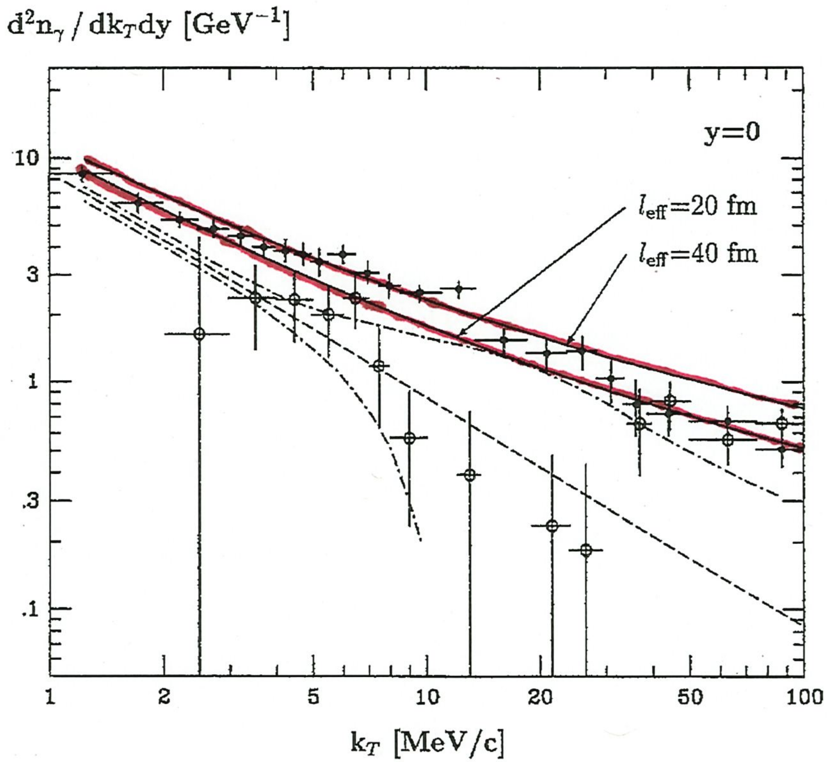


Fig. 4. The $|\mathbf{k}_T|$ distribution for direct photons emitted at c.m. rapidity $y = 0$ in p–Be collisions at 450 GeV incident proton momentum from [3]. The normalization is according to a private communication by H.J. Specht. The background of decay photons is subtracted. The dashed line gives the expected yield of photons from hadronic bremsstrahlung, the dash-dotted lines show the upper and lower limits including the systematic errors in the shape of the decay background and the bremsstrahlung calculation (cf. [3]). The lower (upper) solid line is the result of our calculation for synchrotron photons ((3.4) ff.) with $l_{\mathrm{eff}} = 20$ fm ($l_{\mathrm{eff}} = 40$ fm) added to the spectrum of hadronic bremsstrahlung

We have

$$\ell_{eff} = \frac{\sigma}{g B_c}, \quad g B_c = \frac{\sigma}{\ell_{eff}}, \quad \sigma \cong 300 \text{ MeV},$$

This gives

$$g B_c = (54 \text{ MeV})^2 \text{ for } \ell_{eff} = 20 \text{ fm},$$

$$= (38 \text{ MeV})^2 \text{ for } \ell_{eff} = 40 \text{ fm}.$$

The vacuum fields must be shielded inside the hadrons since these values for $g B_c$ are much smaller than in (D3). Maybe this shielding is done by the synchrotron gluons.