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JETS, GLUONS, QCD

by

T. F. Walsh

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JETS, GLUONS, QCD

T. F. Walsh
Deutsches Elektronen-Synchrotron DESY, Hamburg

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ABSTRACT

1. The evidence from e^+e^- collisions for QCD's gluons is considered. The criterion for a convincing experimental test is that plausible alternative scenarios fail to describe data.

2. Future experiments to establish the gauge nature of QCD are discussed.

I. INTRODUCTION

If quantum chromodynamics is really the theory of the strong interactions, we should be able to produce convincing experimental evidence that its elementary colored quarks and gluons exist. (In fact, we are obliged to do so.) This is not easy if color is confined. But it is possible - convincing evidence for quarks comes from the $q\bar{q}$ and qqq, $\overline{qqq}$ spectra, and from quark jets. Asymptotic freedom ensures perturbatively calculable rates for quanta made at short distances [1]. It is an assumption that energetic colored quanta made at short distances appear as narrow jets of colorless hadrons [2]. Data and popular myth support this. Someday it will appear as a logical consequence of the theory. But we can use this now, to produce evidence for the gluons of QCD and of the local gauge nature of the theory.

There are two aims in this talk. First, we look at the evidence

for gluons (gluon jets) and ask: how convincing is it? Scenarios are our tool. Evidence is convincing if no trivial experimental adjustments can reproduce data without QCD. Theoretical scenarios check whether data is really sensitive to the gluons' properties. They have spin one, color (and a self-interaction), but no flavor. Our second aim is to look for future experiments which will produce evidence that QCD is a local gauge theory. This means looking for the predicted three-gluon vertex in short distance reactions. (There is also a 4G vertex, which will be harder to prove real.) Strong gluon self-coupling at large distances will produce bound glue hadrons. We remark briefly on this.

II. SCENARIOS CONTRA QCD

a. Υ(9.46) DECAY

Fig. 1 recapitulates the evidence that $\Upsilon \to 3G \to$ hadrons is the Υ decay mechanism.[3] Υ thrust distributions agree with the 3G decay and not with a two jet or phase space model (the dashed lines on Figs. 1a and 1b.) P_{out} distributions (perpendicular to the event plane) also agree. So does the polar angle dependence of the thrust axis (solid line in Fig. 1c.) Everything looks satisfactory. But how convincing is it?

EXPERIMENTAL SCENARIO

One can imagine a novel "phase space" model which reproduces the T distribution in Fig. 1a. Perhaps one can come close to 1b, too. (The phase space angular distribution on Fig. 1c should, however, be flat.) Since no one has tried this, it would be unreasonable to claim that it is impossible. (The experimentalists do tell us that trivial changes, such as including meson resonances in the model, are not enough.) This scenario can be destroyed two ways

1. Find toponium,
$t\bar{t} \to 3G \to 3$ clean jets.
The decay is just positronium scaled up by a factor $M_{t\bar{t}}$ (in MeV). Unfortunately, my bookie's odds are that a scan has a probability of about 2 % per GeV of finding toponium. Maybe it will be found soon. More likely it will not be found soon.

2. Look for nontrivial Y decay angular distributions. The thrust axis distribution is of the form [4]

$$\frac{d\sigma}{d\cos\theta_T} \propto 1+\alpha(T)\cos^2\theta_T \quad (1)$$

where θ_T is the angle of the T axis to the e^+e^- beams.
We also have the decay $Y \to \gamma GG$.
The γ angular distribution is [5]

$$\frac{d\sigma}{d\cos\theta_\gamma} \propto 1+\alpha(x_\gamma)\cos^2\theta_\gamma \quad (2)$$

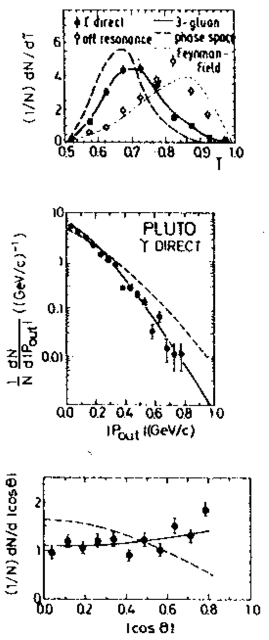

Fig. 1

Distributions in Y decay

where θ_γ is the angle between the photon and the e^+e^- beams and $x_\gamma = E_\gamma/E_B$ (E_B is the e^+ or e^- beam energy). These are shown in Fig. 2. (The average $\langle\alpha(T)\rangle = .39$[4] was used in Fig. 1c.) Angular distributions are important. Remember that the angular distribution of $e^+e^- \to q\bar{q} \to 2$ jets being $\propto 1+\cos^2\theta$ settled the question of whether or not 2 jet events were being seen at SPEAR, as well as establishing

that the jets were from spin 1/2 partons.

TWO THEORY SCENARIOS

One may wonder how much Y or toponium decay distributions depend on the essential elements of QCD. So we change them to see [6].

First, what would happen if gluons had no color? Then the decay

$$Q\bar{Q} \to g \to q\bar{q} \to 2 \text{ jets} \quad (3)$$

would dominate over $Q\bar{Q} \to 3g$. This is because (3) is allowed for colorless g but not for QCD's colored G. The two jet decay (3) is excluded by data for Y. So is the colorless gluon scenario.

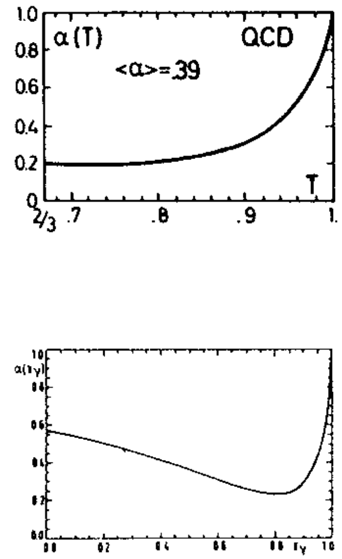

Fig. 2

$\alpha(T)$ versus T and $\alpha(x_\gamma)$ vs x_γ

Second, we ask what would happen if gluons were colored but had no spin. $Q\bar{Q} \to 3S$ (S a scalar gluon) is needed for planarity. The matrix element for $Q\bar{Q} \to 3S$ has zeros at the center of the Dalitz plot $E_1 = E_2 = E_3 = M_Y/3$ and at the midpoints of the sides $E_1 = M_Y/2$, $E_2 = E_3$ (and permutations). This is because of the symmetry of the final state. It is <u>not</u> possible to trivially reproduce the approximately constant squared matrix element of QCD. For the scalar case symmetry alone - no dynamics - enforces a kinematic configuration where one gluon is softer than the other two. Koller and Krasemann noticed that in the scalar case, there is no recoil factor suppressing soft scalar gluon emission. So the decay $Q\bar{Q} \to$ hard S + hard S + soft S dominates. The average $\alpha(T)$ from helicity is then [7]

$$\langle \alpha_{SCALAR}(T) \rangle \stackrel{\sim}{>} -1 \tag{4}$$

This is shown as a dashed line on Fig. 1c. It clearly disagrees with data, so the scalar scenario is ruled out.

From these scenarios, it's clear that $Q\bar{Q}$ decays are sensitively dependent on QCD being a theory with colored vector gluons. The observations (3) and (4) are fairly insensitive to conjectural higher order corrections to the colorless or scalar cases. Agreement of QCD with data even for Υ(9.46) is clearly nontrivial.

A remaining question is whether higher-order QCD corrections seriously modify the lowest-order predictions we have discussed. At a fixed renormalization point some of these corrections are indeed large [8]. However things may not be so bad as they seem at this first glance [9].

b. $e^+e^- \to q\bar{q} + q\bar{q}G \to$ 2 JETS + 3 JETS

The theoretical prediction for the α_s/π QCD correction to $\sigma(e^+e^- \to \text{hadrons})$ is one of the cleanest tests of the theory. It should also be possible to describe the final state at PETRA and PEP energies as due to 2 and 3 jet events [10]. This is theoretically somewhat less clean. But it may offer us convincing evidence that gluons are real.

Two jet events $e^+e^- \to q\bar{q}$ have parton thrust $T_{PARTON} = 1$. Three jet events $e^+e^- \to q\bar{q}G$ have $2/3 \le T_{PARTON} \le T_o$. (The cutoff T_o is used to distinguish three jet events - which are perturbatively small in rate at $O(\alpha_s/\pi)$ - from two jet events.) Another way of putting this is in terms of the invariant mass of a parton or pair of partons,

$$\begin{aligned} q\bar{q}:&\ p^2 = Q^2(1-T_{PARTON}) = 0 \\ q\bar{q}G:&\ p^2 = Q^2(1-T_{PARTON}) \ge p_o^2. \end{aligned} \tag{5}$$

In an appropriate gauge p^2 is the virtual $(\text{mass})^2$ of a fragmenting parton. The $q\bar{q}G$ process was chosen to be for parton masses $p^2 \ge p_o^2$, or for parton rest frame distances $\le O(1/\sqrt{p_o^2})$. A lower limit for p_o^2 is p_{NP}^2, the range of fluctuation in parton masses which can arise from the formation of two (confinement or nonperturbative) jets in $e^+e^- \to q\bar{q}$,

$$p_{NP}^2 \stackrel{\sim}{>} \langle M_{JET}^2 \rangle = \langle (\sum_i E_i)^2 - (\sum_i \vec{p}_i)^2 \rangle \approx \left[Q^2 \langle p^2 \rangle \right]^{1/2}, \tag{6}$$

where this sum is over the hadrons in the jet. (Essentially the same result comes from the requirement that the virtual parton not travel further than $\Lambda^{-1} \stackrel{\sim}{>} 1/500$ MeV in the lab before decaying to qG.)

A separation into 2 and 3 jet events is not obviously meaningful below p_{NP}^2. Higher order QCD corrections will appear. So will long-range confining forces. It also no longer makes sense to add rates rather than amplitudes. (At some very high energy, higher order effects will appear at some p_o^2 larger than the p_{NP}^2, where confinement is important. These effects will probably be hard to distinguish at PETRA and PEP.) We choose $p_o^2 \approx p_{NP}^2 \approx 20\text{-}50$ GeV^2. At $Q^2 = 50$ GeV^2 $e^+e^- \to q\bar{q} \to$ 2 jets is barely resolvable. So we expect that $q(p) \to qG \to$ 2 jets is also resolvable. One can argue about whether or not the cutoff should be placed at $p_o^2 = 50$ GeV^2 or 20 GeV^2 (i.e. $T_o = .95$ or .98 at $E_{CM} = 30$ GeV).

It is important to realize that one can calculate observables at infinite energy ignoring such a cut [11]. It is a measure of our ignorance about finite energy effects. If an observable depends sensitively on T_o at finite energy, it is a poor test of QCD.

Take the mean $\langle 1-T \rangle$ in the final state as an example. To $O(\alpha_s/\pi)$ this has the form

$$\langle 1-T_{PARTONS} \rangle = \frac{8\alpha_s}{3\pi} \int_{2/3}^{T_o} \frac{dT}{T} \ln \frac{2T-1}{1-T} + \dots . \tag{7}$$

The integrand diverges as $T \to 1$, although $\langle 1-T_{PARTONS} \rangle$ is finite. (7) therefore depends on T_o. This is a problem with many linear observables. The mean value $\langle p_\perp^n \rangle$ of hadrons relative to a jet axis depends hardly at all on T_o for $n = 2$, and does depend on T_o for $n = 1$.

If linear observables [11] depend on nonperturbative effects at present energies, quadratic variables have their own deficiency. They depend on quark and gluon fragmentation functions. See the Table

variable	linear (e.g. $\langle p_\perp \rangle$)	quadratic (e.g. $\langle p_\perp^2 \rangle$)
$D^h(z,Q^2)$ dependent?	no	yes
"infrared safe"?	yes	yes
T_o or p_{np}^2 dependent at low energy?	yes	no

(Notice that "infrared safe" merely means that an observable is finite in perturbation theory.)

Since quadratic variables can be calculated more reliably at low energy, we [12] have done so. The dependence on T_o and on quark and gluon fragmentation functions is indeed weak. Two things which can be calculated analytically are the overall $\langle p_\perp^2 \rangle$ relative to a jet axis and $\langle p_\perp^2(z) \rangle$, the mean $\langle p_\perp^2 \rangle$ of a hadron with fractional momentum $z = p/E_{BEAM}$. We also produced a Monte Carlo $e^+e^- \to q\bar{q} + q\bar{q}G$ model [12]. Fig. 3 shows the analytic and Monte Carlo results. Clearly the Monte Carlo is quantitative. It can be used to test QCD. Fig. 4 shows data [13]. The agreement is not a result of fiddling with parameters. The calculations and Monte Carlo preceeded the data by some months.

Quantitative agreement with such global QCD predictions is important. More important is the presence of three jet events [14] with the expected rates and distributions. This evidence is convincing

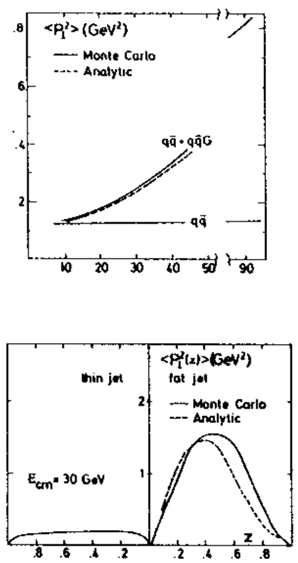

Fig. 3

Analytic Calculations and Monte Carlo Results.

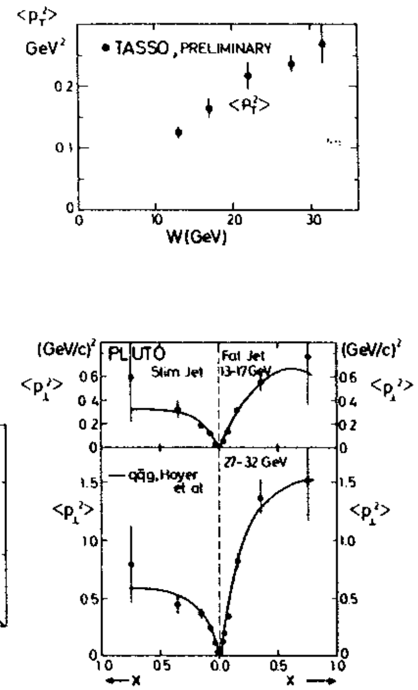

Fig. 4

TASSO data on $\langle p_\perp^2 \rangle$ and PLUTO data on $\langle p_\perp^2(z) \rangle$.

enough that we need not consider experimental scenarios as for Y(9.46).

ALTERNATIVE THEORY SCENARIOS

1. <u>It isn't QCD</u>. Maybe jet broadening and three jet events are real, but not due to QCD. We invent a scenario. But there must be ground rules. These are that a model must have plausible dimensional parameters and must be successful. Take the example in Fig. 5, [15]

where a high $p_\perp$ meson (or cluster) is radiated:
In QCD, this would be a "semi-perturbative" process. It is not so complicated as jet formation but far more model dependent than $e^+e^- \to q\bar{q}G$. The mean $\langle p_\perp^2\rangle$ of the cluster or recoil q or $\bar{q}$ has the form

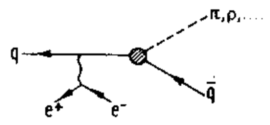

Fig. 5
A Simple Model for 3 jets

$$\langle p_\perp^2\rangle_{\substack{CLUSTER\\ \text{or } q,\bar{q}}} \approx \text{const} \int_0^{Q^2/12} \frac{dp_\perp^2}{(p_\perp^2+\mu_o^2)^n}\, p_\perp^2 \qquad (8)$$

and, choosing n = 3 as an example (your favorite model may have something different, but no matter),

$$\langle p_\perp^2\rangle_{meson} = \langle p_\perp^2\rangle_{NP} + \langle p_\perp^2\rangle_{SP}\left(1 - \frac{18\mu_o^2}{Q^2} + \ldots\right) \qquad (9)$$

The dimensional parameters are $\langle p_\perp^2\rangle_{SP}$ (the overall additive $\langle p_\perp^2\rangle$ of this process at $Q^2 \to \infty$) and the scale μ_o^2. Naively, $\langle p_\perp^2\rangle_{SP}$ ought to be much less than $\langle p_\perp^2\rangle_{NP}$ (the FF value with a Gaussian $p_\perp$ cutoff). Also, we expect the scale $\mu_o^2 \lesssim 1$ GeV^2 as for a typical hadron mass. Even if we arbitrarily set $\langle p^2\rangle_{SP} = \langle p^2\rangle_{NP}$, the Q^2 dependence of (9) cannot reproduce the data. (9) only increases by < 10 % over the PETRA range Q^2 = 200-1000 GeV^2 for μ_o^2 = 1 GeV^2. The data shows a factor ~ 2.5 increase of $\langle p_\perp^2\rangle$.

Another flaw of the model of Fig. 5 is that it does not naturally lead to the large observed jet multiplicities.

We conclude that there is no simple and plausible alternative scenario.

Remember that there is such a "higher twist" scenario for scaling violations in deep inelastic scattering [16]. That scenario depends on

the fact that higher twist effects (and QCD) lead to no scaling violations (and very tiny scaling violations) at large Q^2. Here the QCD effects <u>increase</u> with energy, e.g. $\langle p_\perp^2\rangle \sim (\alpha_s/\pi)Q^2$. Semiperturbative effects saturate. There is a qualitative distinction.

Of course, this is not to say that such semiperturbative effects are absent in data. Only that they seem small compared to $q\bar{q}G$ (and are possibly smaller than other model dependent effects such as the precise shape of jet distributions).

2. <u>Gluons are Colorless.</u> Through this order, $e^+e^- \to q\bar{q}G$ is like $e^+e^- \to 1\gamma \to \mu^+\mu^-\gamma$. The color of gluons only appears in the normalization of $q\bar{q}G$ relative to $\mu^+\mu^-\gamma$. But this is only a factor 2/3 and cannot be seen in present data. $q\bar{q}G$ is not sensitive to this feature of QCD.

3. <u>G is Spinless.</u> To exclude this and find nontrivial agreement with QCD, one has to prove that the $q\bar{q}G$ matrix element is as predicted. Another way is <u>via</u> angular distributions (Fig. 6). The angular distributions of the normal and thrust axis must be of the form

$$d\sigma/d\cos\theta_N \propto 1+\alpha_N\cos^2\theta_N;$$
$$d\sigma/d\cos\theta_T \propto 1+\alpha(T)\cos^2\theta_T \qquad (10)$$

These are shown on Fig. 7 [17]. In the table α_N for two jet events is for the case when a plane is "accidentally" fit due to fluctuations in the event.

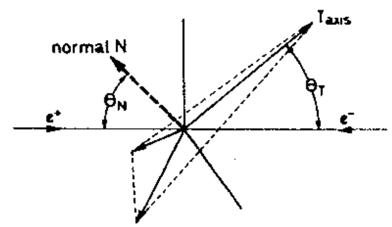

Fig. 6
The variables θ_N and θ_T

Measurement of α_N clearly proves nothing. That is why scenarios can be useful. Also, clear evidence for vector gluons from $\alpha(T)$ (or

CASE	α_N
1^- GLUON	-1/3
0^+ GLUON	-1/3
"FLAT" $q\bar{q}$	-1/3

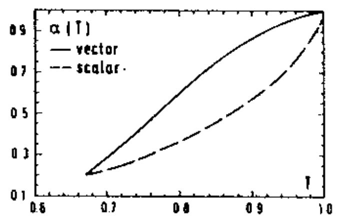

Fig. 7

α_N and $\alpha(T)$ versus thrust

other angular distributions) will need lots of data.

4. The third jet is not neutral. Rather than invent a scenario, we just show on Fig. 8 the charge correlation of the two most energetic jets [12],

$$C_{12}(T) = \langle \sum_{i\in 1} e_i \sum_{j\in 2} e_j \rangle \tag{11}$$

as a function of T. The model of Fig. 5 would not give $C_{12}(2/3)/C_{12}(1)=1/3$.

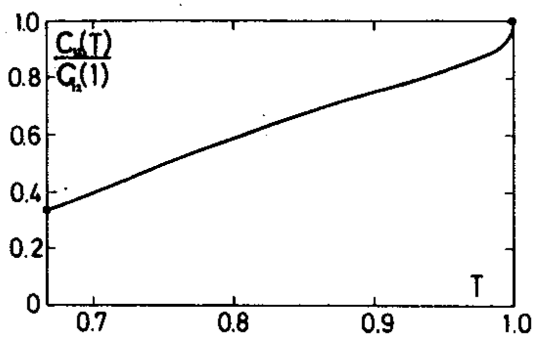

Fig. 8

The charge correlation

This check will also require a lot of data.

III. THE GAUGE NATURE OF QCD

1. TOPONIUM DECAYS

One nice way to find evidence for the 3G vertex of QCD, and therefore its gauge nature, is analogous to $e^+e^- \to q\bar{q} + q\bar{q}G$. Namely the $C = +Q\bar{Q}$ decay

$$Q\bar{Q} \to GG + GGG \tag{12}$$

(plus $Gq\bar{q}$, which is tiny). Figure 9 shows $d\sigma/dT$ for the 3G decay of the ^3P_o $Q\bar{Q}$ state [18]. Because of the 3G vertex the 3 jet rate should be about 9/4 times that in $e^+e^- \to q\bar{q}+q\bar{q}G$ at the same energy [19]. (This can be large.) The ^3P_J states have to be reached via the radiative decay of a ^3S state produced by e^+e^-. The decay

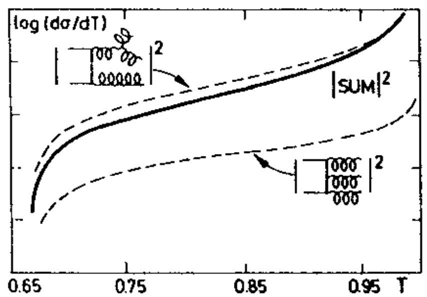

Fig. 9

Thrust distribution for $Q\bar{Q} \to 3G$

$$1^3S_1 \; Q\bar{Q} \to GGG + GGGG \tag{13}$$

(plus a small $GGq\bar{q}$ rate) will be easier to see but harder to analyze. (There is also a $Q\bar{Q} \to 1\gamma \to q\bar{q} + q\bar{q}G$ background, absent in (12), and at really large $Q\bar{Q}$ mass the weak decay background of the heavy bound quarks, $Q \to qq\bar{q}$ and $\bar{Q} \to \bar{q}\bar{q}q$).

2. Z^o DECAYS

There is another chance to see the 3G vertex in decays

$$Z^o \to q\bar{q}GG \to 4 \text{ jets} \quad (14)$$

where the 3G vertex appears (although it is not leading for large M_Z). This will require some angular gymnastics. There is also a "back-ground" from $Z^o \to t\bar{t} \to 3q+3\bar{q} \to 6$ jets if M_t is large.

Angular asymmetries for $e^+e^- \to q\bar{q}GG$ have been calculated [20] and appear large enough to measure. (14) would then be an easy related experiment for the SLAC single-pass collider.

3. G JET SPLITTING

A virtual gluon produced at very high $p_\perp$ can radiate a brems-strahlung gluon itself (because of its color charge). Namely

$$p\bar{p} \text{ or } pp \longrightarrow (\text{high } p_\perp \text{ virtual G}) + \text{other stuff}, \quad \text{virtual G} \to GG \to 2 \text{ jets} \quad (15)$$

One would then see a gluon jet often "resolved" into a hard gluon subjet and a nearby soft gluon subjet. The energy and angle distribution of the soft subjet would be $\propto dE/E\, d\theta/\theta$ - just as for the photon in $e \to e\gamma$ or the gluon in $q \to qG$. However, (15) should happen 9/4 times as often as for $q \to qG$. This is about the most elegant way to see that QCD is a local gauge theory. The problem is that jets in $p\bar{p}$ do not come labelled as to whether they are from gluon or quark ancestors at short distance.

Monte Carlo calculations of jet evolution indicate that the sub-jet structure in (15) will be easily visible for jets with $p_{\perp,JET} \sim 300$ GeV at the FNAL 2 TeV $p\bar{p}$ collider, if it reaches a luminosity of 10^{30} cm^{-2} sec^{-1}.[21] The same applies to Isabelle. De-monstrating $G \to GG$ breakup at the CERN $p\bar{p}$ collider is harder because $p_{\perp,JET}$ is much less.

4. LOOKING FOR BOUND GLUE

QCD should have hadrons made of bound glue (glueballs, gluonia or glue bacteria depending on individual fantasy). These mesonic glue states will be made in gluon jets, but the rates are surely quite model dependent. (Υ(9.46) decays will be a good place to look.)[22]

A hopefully model independent source of bound glue is

$$Q\bar{Q} \to \gamma + \text{bound glue state}$$

(Fig. 10). $Q\bar{Q} \to \gamma GG$ is a short-distance source of colorless GG pairs. At long distances, $GG \to$ glue bound glue or $GG \to q\bar{q}$ meson. The latter should be Zweig suppressed. Naive duality suggests that the former produce oscillations about the Born cross section for γGG (Fig. 11)[5].

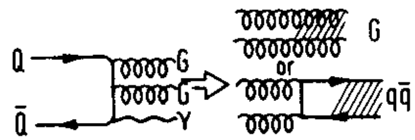

Fig. 10

$Q\bar{Q}$ Radiative Decay

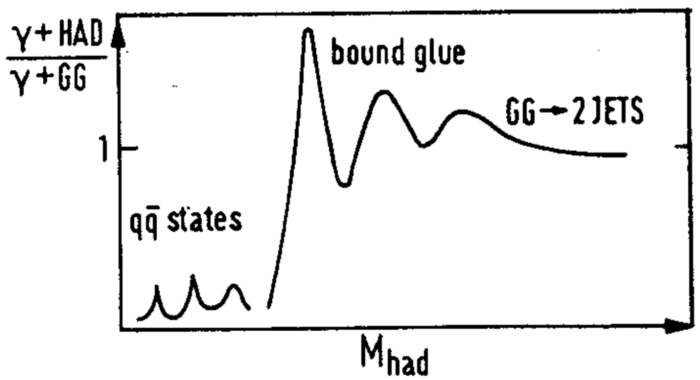

Fig. 11

Naive duality gives rates. Approximate the Born γ spectrum by $(1/\Gamma_{\gamma GG})d\Gamma/dx_\gamma \cong 2x_\gamma$. Then the single γ branching ratio is the same as the fractional rate of γGG in a GG mass slice of width $\Delta m_{\mathcal{G}}$,

$$\frac{\Gamma(\gamma\mathcal{G})}{\Gamma_{\gamma GG}} \cong \frac{4m_{\mathcal{G}}\,\Delta m_{\mathcal{G}}}{M^2}\left(1 - \frac{m_{\mathcal{G}}^2}{M^2}\right) \tag{16}$$

or, for J/ψ, $B(\gamma\mathcal{G}) \sim 2\ \%\ \ \Delta m_{\mathcal{G}}/(1/2\ \mathrm{GeV})$. Zweig's rule would then imply a $\gamma f^0(1260)$ rate perhaps $\sim 10^{-1}$ this or ~ 0.2 %. This is roughly correct. (Of course, (16) could easily be wrong by a factor 2.)

It is interesting that activity is seen in $J/\Psi \to \gamma$ + hadrons by MARK II and the Crystal Ball [23]. Rates fall below the lowest order QCD expectation at low recoil mass. Then a resonance (E(1420)?) appears and at higher GG masses the rates are large. This resembles Fig. 11 - perhaps accidentally. If it is no accident, then some of the activity seen at higher masses might be due to overlapping resonances, not resolved in the Crystal Ball γ spectrum. The E(1420) might also have a nonstandard J^P, perhaps 0^-.

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