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THE STATUS OF QCD: IMPLICATIONS FOR COSMIC RAYS+

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The relationship between particle physics and cosmic ray research has been long and fruitful.
For a long period, say from 1960 to 1980, the two fields drifted apart.
Now, it seems that the relation between them has become close and that some of the most relevant questions in particle physics are possibly going to be answered by information coming from astrophysics and even specifically cosmic rays.

The purpose of my talk is to discuss problems of particle physics that are connected to the main topic of this conference, and in particular the SU(3) piece of the standard model.

It is divided into several parts:

Introduction: QCD a realization of many possible symmetries
and the fighting of anomalies.

Section 1: The hard predictions of the theory: verified.

Section 2: The soft predictions: fascinating but uncertain.

Section 3: Conclusions.

Introduction.

The daring proposal of Gell-Mann and Zweig(1, 3) that all known hadrons, are composite states of quarks has become established in a resounding way.
The idea that a physical theory would have its basic Lagrangian fields unable to have quanta as asymptotic states is now widely accepted, though no rigourous proof of its existence in the continuum has been provided (2).

The phenomenological reasons why people were led to quarks are manifold:
a): the appearence of well defined SU(3) multiplets for mesons (**1** and **8**) and baryons (**1**, **8**, **10**) and no others (3).

b): large number of sum rules and dynamical predictions that go far beyond the SU(3) symmetry and contradict SU(6), always in agreement with experiment (4).

c): the behaviour of form factors: these obey power laws that are simple functions of the number of constituents and spin structure (5), except for logarithmic corrections that depend on the interaction (6).

d): finally, deep inelastic scattering where the individual quarks are felt and many details like scaling due to the point interaction as predicted by Bjorken obtains (7). Again, small departures from scaling can pin down the dynamics.

Having established quarks, several paradoxes still remained and obvious questions had to be answered.

1. The statistics to explain the spectrum did not fit fermi like particles.
2. The quarks behaved non relativistically, raising the question of why these quarks, whose effective masses are about 300 MeV., could not be produced in the laboratory.

These questions could perhaps be answered if the quarks interact with each other via particles that carry a new conserved quantum number (colour) by means of the following Lagrangian:

$$L = -1/2 \quad G^{a}_{\mu\eta} \, G^{a\mu\eta} + \sum \Psi(\mathbf{D} - m_i)\Psi \qquad (1)$$

Where G is the gluon field, a a colour index, defined by the equation:

$$G_{\mu\eta} = \partial_\mu \mathbf{A}_\eta - \partial_\eta \mathbf{A}_\mu - ig[\, \mathbf{A}_\mu, \mathbf{A}_\eta \,]. \qquad (2)$$

Also, $\mathbf{D} = \partial^\mu \gamma_\mu$, and m^i are the masses of the quarks and g is the coupling constant. The index a is defined by the following matrix:

$$\mathbf{A}_\mu = \sum A_\mu^{\ a} \, \lambda^a/2 \qquad (3)$$

where λ are the SU(3) matrices and therefore a = 1,... 8.
This generalization of the QED lagrangian has far reaching consequences.
Let us first discuss its parameters and symmetries.
This Lagrangian has the following parameters:

a) the quark masses presumably generated by the SU(2)XU(1) part of the theory. These masses already show a vexing problem: the lightest is almost zero perhaps 1 to 5 Mev., the heaviest quark, the yet to be seen top, presumably more than 5 10^4 Mev. This is awkward and it is a manifestation of structure that we do not yet understand.

b) the gauge coupling $\alpha_s = g^2/4\pi$

Before discussing the symmetries of this most innocent looking Lagrangian, it is worth asking the question: how unique is it?. Uniqueness is a manifestation of a) prejudices, b) the scale at which one is determining the phenomena.
The general theoretical prejudices one uses are: Lorentz invariance, CPT invariance, locality and eventually renormalizability and absence of anomalies. An anomaly is, roughly speaking, a violation of a Noether conservation law by quantum effects.
The last two requirements have lately been put on firm grounds. The first, was long considered a mathematical device but has gained physical status via the renormalization group as a scale generator for the theory.
The second, via topology, has led to a deeper, though not yet complete understanding of geometrical issues that are perhaps central to string theory. They also relate to each other: renormalizability requires the absence of a certain type of anomalies.
The question of whether anomalous gauge theories exist at all has been raised by Fadeev and others (8). We will reject this possibility at this time.
Now we are ready to answer the question about uniqueness. Indeed there is a possible term that can be added to this Lagrangian without affecting the renormalization properties of the theory. It reads:

$$\vartheta\, \varepsilon_{\alpha\beta\gamma\delta}\, G_{\alpha\beta}\, G_{\gamma\delta} = \vartheta\, \tilde{G}^{\gamma\delta}\, G_{\gamma\delta} \qquad (4).$$

ϑ is a coupling parameter.
This terms looks like a total divergence. However, due to the presence of instanton solution to the equations of motion it contributes to the action. It vanishes order by order in perturbation theory. Its origin is topological.
As we shall soon see this term is central to the theory.
The term seems unavoidable, because it will anyhow appear as a counterterm for the weak interaction part of the theory. It may necessitate new types of particles, and most important at this conference, it might have profound astrophysical consequences.
In some sense this term holds the future of QCD. The structure of the QCD vacuum and the U(1) problem makes the term unavoidable.
Some of its signatures will have to be found or something unacceptable is in front of us. This is not an alarm sounding, just a friendly warning.
From the symmetry point of view this term has unwanted properties. It is originated by the strong interactions, though it violates CP. Violation of charge conjugation and parity is not large, if it exists at all for the strong interactions.

The neutron electric dipole moment sets a limit for ϑ (9):

$$\vartheta \leq 10^{-9}. \qquad (5)$$

This hits another prejudice of theorists. Elohim does not produce in the same Lagrangian two couplings so vastly different. This is the problem of naturality. More on this later. One final remark on this term: one can show that it is related to topological invariants of the theory.

So far we have discussed the local gauge invariance of the theory, and other possible interactions that we see as being of topological nature. Assume now for a second that the quarks are massive but all masses equal. Then a global (coordinate independent) symmetry obtains. The Lagrangian is invariant under the transformation:

$$\Psi^i \text{ goes into } \Psi^i + i\alpha_a(\Lambda_a)^{ij}\,\Psi^j \qquad (6)$$

where Ψ^i is the ith field and Λ the appropiate SU(N) flavour matrix.

Notice that this symmetry affects the flavour degrees of freedom and has nothing to do with colour. for N=3 this is the eightfold way of Gell-Mann and Ne'eman that paved the way to quarks. The three lightest quarks u, d, s are almost massless and called chiral. They all play important roles in astrophysical considerations.

Since the quarks are not identical in mass, (which helps solve the proton neutron mass difference sign), why is isospin symmetry so good?. As we will see later the scale of QCD, Λ_{QCD}, is believed to be between 100 and 200 MeV. Since m_d is perhaps 10 MeV., and $m_d - m_u$ about 5 MeV., one expects a large violatiuon like 5 % or more. It is amusing that the starting symmetry of hadron physics is an accidental symmetry from the modern point of view!. The little known answer to this question is that isospin symmetry has already been seen to be badly violated, and predicted to be so in many processes. These violations can be as large as 30 % (10). Isospin violation, by the way, cannot be spontaneous in QCD (11).

The light quark Lagrangian is invariant under the transformation

$$\Psi_i \text{ goes to } \Psi_i + i\,\beta^a\,(\lambda^a)_{ij}/2\;\gamma_5\Psi_j \qquad (7)$$

where we see the SU(3) group appearing again. Here again, this simple Lagrangian chooses yet a different way to realize the symmetry.

If this symmetry were to be a vacuum symmetry we should see γ_5 invariance in the spectrum. This parity degeneracy is absolutely ruled out by observation.

One must conclude that the symmetry is realized in the Goldstone mode:
The negative parity partners are absent for the lowest multiplets.
Massless pseudoscalar Goldstone bosons appear instead. Though the π and K mesons are not massless they are indeed low mass. Since we know that a tiny mass is generated by the Higgs mechanism everything seems ok: On top of the spontaneous breaking there is an explicit one induced by the SU(2)xU(1) masses.
Indeed there is good evidence that chirality can and even should be realized in this mode while other symmetries should not (11).

The realization of chiral symmetry by means of Goldstone particles is very enticing. However, it can be easily seen that the Lagrangian has too much symmetry. This is called the U(1) problem (12). The spontaneous breaking of chirality predicts another pseudoscalar particle whose mass can be bounded from above in contradiction with the available candidate: the η meson (13).
Here, it is the gauge invariance of the theory that saves the day. The Goldstone boson is pushed into the gauge dependent sector and it is not a physical state (14).
The point is that the conserved current is gauge dependent and the physical one carries an anomaly dictated by the instantons.
It is precisely the instanton term, that we see is crucial to solve the U(1) problem that characterizes the labelling of the many vacua. So, we have solved the U(1) problem but we have created a small monster: the ϑ term.

Therefore, the logic that has explained chirality and the U(1) problem forces us to enlarge the theory and add a new term to the Lagrangian.
There is a natural way to solve the problem of ϑ. This is to make this parameter a natural degree of freedom and by some mechanism force its value to relax to 0.
Such a possibility was first discussed by Peccei and Quinn (15). However, this solution is not unique.
One can introduce a new U(1) symmetry that when spontaneously broken at the SU(2)xU(1) scale will force ϑ to zero. The price to be paid is the associated Goldstone boson as pointed out by Weinberg and Wilczek (16). This particle is called the axion. If discovered, it would give the full view of QCD as an accomplished theory.

Unfortunately, the axion is not a unique prediction of the spontaneous breaking of the Peccei-Quinn symmetry. As pointed out by Kim (17), Dine, Fishler and Srednicki (18), and others (19), the couplings to quarks and leptons of the axion are relatively free.
In fact there is another possibility not completely ruled out: the lightest quark is massless (20). However, this is not easy to accomodate phenomenologically and it

would create a massless particle that also would require some explanation.

This leads to the final aspects of the theory that we will not discuss.
If we accept the axion solution, one is led to the necessity of axionic strings and domain walls. Since these ideas are due to Professor Okun and Zeldovich, I will not discuss them at all. They do represent however an integral part of the theory and one of the most promising methods to establish axions is related to cosmology.
Embedding SU(3) in a larger group is also outside the scope of my lecture. I mention that such a possibility was fully exploided in the Grand Unification Theories like SU(5) (21).
There is trouble with these theories. In the same context, the neutrino mass is also not necessarily vanishing and this is of course important in astrophysical phenomena.
Recent claims for a neutrino mass in the lab are controversial (22), and supernova experiments performed long ago and recently detected live at ease with lighter neutrinos than claimed in the experiment and are compatible with massless ones (23).

One cannot leave the subject without mentioning the possibility of embedding the theory in a string model (24) with gauge group $E_8 x E_8$. The only thing I will say about strings is that they are very appealing but it seems to require much development before workable model can have detailed predictions.
It is in this context that anomalies, local and global may show their importance.
They cancel by such variety of tricks that it looks as if the final word is not said.
Some nice string properties are: a spectrum very much as seen, unification of all interactions, axions appearing naturally, and internal consistency. This means no anomalies anywhere and a renormalizable gravitational theory.
Unfortunately no detailed predictions are possible at the present time.
There is also a possible shadow world that might be the source of Conferences for several millennia to come!.

Section 1.

I will start with the hard predictions. These ones are related to symmetries of the theory and also to processes that are at such a scale that perturbation theory is presumably valid.
Long ago, Symanzik realized that theories could exist that are simple at high energy (25), Parisi pointed out that these theories could explain the parton model, and 't Hooft first showed that nonabelian SU(3) did have such a property. It was later rediscovered by Politzer, Gross and Wilczek (25).
This most remarkable property of QCD (that for the SU(N) colour group the theory is

asymptotically free) is the basis for believing that colour is a local gauged symmetry (25). As a consequence, everything goes upside down: simplicity appears at high energy when the Lagrangian becomes free. It is nice that this possibility obtains for the nonabelian SU(N>2) groups (25). The qualitative evidence can be seen from the decay of the vector mesons that must do so via three gluons, with a factor $(\alpha_s)^3$. Since the coupling constant is already small at the ϕ, $\alpha_s(1\ \text{GeV.}) = .2$ we expect the width to be small and decreasing. There are other factors that do not permit a quantitative test. Then, the width of ϕ, Ψ/J and bottonium must decrease. The widths become indeed smaller reflecting the changing value of the coupling as a function of scale, inspite of a rapid growth of phase space.

The second reassuring prediction is the 2 jet distribution as a function of angle. It is seen at the CERN collider experiments (26).

The experiment is one in which two quarks collide violently as in Rutherford scattering producing two highly excited quarks at large angles. These quarks have a colour wake that must be neutralized. This is done by bremstrhalung. One picturesque way to say it is, that because of confinement, at high energies one produces jets and not individual particles. However, these pencils of hadrons remember their parent quark and one can check Rutherford's formula:

$$d\sigma/d\cos\phi = (\alpha_s/s)(1 - \cos\phi)^{-2} \qquad (8)$$

As the figures (1,2) show it is very rewarding. At high energies it is pencils of particles (jets) the children of the quarks that are observed.

In some sonse these are the "particles" at high energies, as the π mesons are the particles at low energies.

QCD is not only in agreement with experiment, but there is no other theory that can explain this data and, for that matter, give a coherent vue of all experiments.

The next least complicated events would entail one gluon bremstrhalung. We have a three body final state. Each coloured particle leaves a wake of intense colour field behind it. The field is neutralized by pair creation. Only neutral colour hadrons are the final result. In figure 3 we see how nice is the agreement.

Of course, this simple statement is a curse for cosmic rays physics: the interesting high energy events may have a few jets but these cascade finally into pions giving enormous multiplicities. The interesting physics is then difficult to isolate.

Again, the abundance of three jets events compared to two jets events fits qualitatively the expected ratio of one extra coupling (27).

Other phenomena, like the inclusive production of vector bosons and hard γ rays is in remarkable agreement with experiment. This understanding has helped to end

speculation that new physics was present in some rare events at the CERN collider. See figure 4, 5 (23). Minicentauros are incompatible with accelerator results.
The third nice prediction is the deviations of scaling in deep inelastic scattering. With quarks alone, scaling is exact, but due to gluon emission there is a pattern of scale braking. The situation is comfortable (28).
In figure 6 we can see the BCDMS high statistics data and the very impressive agreement with QCD. As a byproduct of these measurements of the structure function F_2 one establishes that

$$\sigma_{longitudinal}/\sigma_{transverse} = R = 0.0115 \pm 0.013 \pm 0.026 \text{ (syst.)} \tag{9}$$

in agreement with the idea that the interacting partons are spin 1/2 (29).
There are still interesting dynamical problems open. Measurements of the polarized structure function are puzzling. It looks like if the polarization is not carried by the quarks. This an other polarization questions are discussed in Section 2.

Establishing the value of Λ_{MS}, the QCD scale, has proven difficult. The problem, and we will come to this again, is establishing when high energy has been achieved. The value has now been the same for a long time $\Lambda_{QCD} = 150 \pm 100$ MeV.

In the case of form factors, for example, Brodsky and Lepage (30) found a QCD formula that not only agrees with the inverse power law dictated by three quarks, but also fixes the logarithmic corrections and the absolute normalization.
Ioffe and others (31) have shown that asymptotia is far away and that this formula cannot be checked easily. The next stage is to discuss the spectrum.

The spectrum of hadrons and low energy properties has been investigated in four ways,

1. Potential models with effective hamiltonians (32)
2. QCD sum rules (33).
3. Lattice computer simulations (34).
4. The Skyrme model (35).

The spectrum itself can be divided in two parts:
1. Quark model conventional states (quark-antiquark mesons and three quark baryons).
2. States with "valence" or constituent glue. (Glueballs and exotics).

Concerning 1., all expected states of the quark model have been found. This includes the

elusive charmonium 1^{-+} state (J^{PC}). The scalar nonet is still slightly controversial. However there is no solid evidence, if any, for four quark states.
A strange dibaryon state has been conjectured on QCD arguments. This $\Lambda\Lambda$ state has been conjectured to be bound (35). It was popular at the Cygnus 3 time. The state has been predicted long ago (36) and the prognosis that it will not be stable was made at the time. It has not been found as a stable particle, though it is not final.
Anyhow, none of these states are predicted by QCD, they are not excluded either.

It should be clear from the start that the spectrum determination is a formidable problem. We are dealing with the strong coupling regime and it is difficult to make exact statements. If the mass of the quarks is very large one expects that the Coulombic gluon potential fixes the levels. How heavy is heavy has turned out to be disappointing or interesting depending on the point of view. Only at toponium the system will be truly coulombic. However if, as we will soon discuss, top is above 90 GeV. in mass (see below), it will desintegrate weakly and spectroscopy of these states will be very hard.

The potential model assumes (too optimistically) that all these nonperturbative effects can be parametrized by changes in masses and coupling constant.
One ends up with an effective Hamiltonian with masses and couplings that are not related to Lagrangian quantities.
This simple Hamiltonian can be treated a la Schroedinger, (not always!). The results are embarrassingly good, a lot of qualitative physics can be understood, but subtle, interesting effects about the vacuum get lost. Also, a plethora of relativistic and field theory effects, like annihilation or hyperfine splittings cannot be dealt with consistently.

2. The QCD sum rules, invented by Shifman, Vahinstein and Zakharov (33) is a method which in a clever way does perturbation theory on nonperturbative effects. The results of the method are quite substantial and it has the advantage over the potential model to work with the basic Lagrangian instead of effective parameters. Its problem is that it is not a basic theory and its predictive power is rather limited. Also, though the results are very impressive, the calculations are very complicated and the simple structure of linear Regge trajectories is not seen at all.

3. The lattice approach, simulating by Monte Carlo methods the two-point function on the lattice, has not been too succesful inspite of rapid advances in computer techniques. Many dedicated machines and supercomputers are now making simulations with quark loops. The results are not definitive. Extension of the technique to weak interaction three point functions has been pushed but the technical problems have not yet been overcome.

4. The Skyrme model is a very interesting theoretical model (35) in which the number of quark colours is let go to infinity. In that limit he theory is solvable. Hope that N= infinity is a good approximation for N=3 have not materialized. The results do not improve much concerning static and other properties when N^{-1} corrections are included. It does not lead to interesting phenomenology. The baryon, for N=3, does not seem to be a soliton.

These comments referred to quark model states. I repeat, postdiction has been quite successful. What about the genuine degrees of freedom of QCD, the gluons?. Here the situation is quite embarrassing both theoretically and experimentally. In spite of enormous work, predictions concerning pure glue states are not firm, and no firm evidence on the experimental side has been forthcoming. Candidates are born and die but nothing has entered the books. The same can be said about mixed states like $\bar{q}qg$.
Again, though it is not endangering the validity of QCD insofar as there is no blatant contradiction between hard predictions and measurement, it is annoying that these states are absent. Perhaps patience is necessary. LEAR, the CERN facility might solve this problem. I insist, the trouble is the inability of theorists to tackle soft gluon problems.

There is another hard prediction: the theory must cope with the ϑ vacuum. It is a hard prediction because ϑ vacuum is an integral and necessary part of the theory and crucial to solve the U(1) problem. It is a soft one, because it is not possible to pin down the solution uniquely. We will discuss it in the next section.

Another hard prediction is the phase transition to quark and gluons. Here again it is not in doubt that baryons and mesons will dissolve into something else. However, the details of the phase transition, its dependence on quark masses, the temperature at which it occurs, the connection with chiral restoration and other mayor issues are soft problems (37).
Recently however, one of the disputes has been settled. The transition is first order (37) and there is now universal agreement that the temperature for deconfinement and chiral restoration is about the same. It is around T = 200 MeV.
I will not discuss finite temperature QCD further here, except for its potential bearing on a most fascinating problem: the ground state at zero temperature of a large collection of quarks. Which is the most probable configuration?, normal baryons?.
Witten (38), made the following appealing scenario. We do believe that quark matter is the appropiate phase at some high enough pressure. One may assume that instead of N nucleons we have a confined system of 3N wandering quarks. Therefore each quark

wave function overlaps significantly with all others. The chemical potential of the quarks is of the order of the transition pressure which is believed to be a few hundred MeV. If the strange quark mass is low, (and some people believe it might be as low as 80 MeV. at the appropiate scale (39), then the weak interactions will establish a new equilibrium between u, d and s quarks. The Gibbs potential minimization will favour equal population for all species.

In plain language it is favorable to fill three Fermi seas: the mass term of the strange quark can compete with the top of the u and d Fermi sea.

The remarkable possibility exists that, even at zero pressure, this state will be the most stable, and therefore QCD's ground state.

Besides being an intriguing possibility, our inability to decide whether this is or is not the case, shows the difficulties in solving QCD.

It has been thought that strange matter could have been a component of the dark matter, though it seems unlikely it could survive the first second after the big bang.

Strange stars, however are not ruled out (40).

It seems that if nuggets of negatively charged strange matter arrival to earth, it might be catastrophic (40).

It is amusing to think that some of the reported cosmic ray events in which only baryons are seen in the final state might be the debris of the collision of a nugget in the upper atmosphere.

Section 2.

What about quark masses?. The effect on the quarks of the gluon interactions is to dress the SU(2)xU(1) masses to make them constitutent masses.

One is interested in going backwards and establishing these basic parameters.

The traditional method is to try chiral perturbation theory. I cannot go into the details here (41) but it is not clear that we have completely understood the problem. Masses of light quarks are not known to within a factor of two, and the thorny problem of the possible vanishing of the u quark mass is not settled.

Some ratios are known quite well from current algebra but these relations are not enough to get a definite answer.

How about the non chiral quarks? The c and b quarks masses are well known (33).

The top must exist, but in the last few months evidence claimed about its existence has vanished and the present lower bound on its mass is 50 GeV. and perhaps more like 70 GeV (23). A recent measurement of isospin violation presented at the 1987 DESY meeting suggests that m_t is larger than 100 GeV.

What about condensates? When a symmetry is spontaneously broken the order parameter in field theory appears as a condensate. For chirality it is $\bar{\Psi}\Psi$. Its value is also not too well known and the SU(3) flavour breaking is still an open problem (33). Other condensates not being protected by a symmetry are more model dependent, we will not discuss them here (42).

There is very little at low scales that unequivocally tests the theory. This is particularly troublesome because the bulk of the data is not amenable to description in simple terms. The most critical aspect of the difficulty is hadronization. This is the process by which the quarks reorganize themselves into colour singlets in nonperturbative ways. This leaves the problems of nuclear interactions and related processes outside the scope of QCD. It is therefore important to do some modelling. Even the simplest problems like proton-proton scattering are complicated. This simple scattering problem is a six body problem. With modern algebraic computer techniques, thousands of diagrams have been calculated, but only the perturbative pieces. This makes the results unreliable (43).

Interesting attempts have been made to understand soft processes (44), and there has been some penomenological success, but it is difficult to be sure of their relevance.

Polarization phenomena are still puzzling. The simplest large angle ratio prediction in QCD to leading order, fails completely (45). QCD to leading order predicts helicity conservation which in turns predicts a vanishing analyzing power parameter A. This is because it is proportional to the helicity flip amplitude that should vanish. Experimentally it is 30 per cent (which is large) and there is no obvious way out of this problem.
As stated in the first section the deep inelastic scattering results on polarized targets are troublesome.
The results show that the asymmetry A_1 is very small at small x. Assuming that the strange sea is vanishing in the proton and carries no spin, there is a sum rule that is badly disobeyed by the data (28). It looks as if the spin of the proton is carried by gluons. We have not heard the last on this (46). Remember, however that polarizations are most sensitive quantities.
Anyhow, none of the aforementioned problems is very serious.
All of these results are dependent on assumptions. Failure indicates that some assumption about scales, or absence of power corrections is not valid. I recall the example of the form factor that shows this problem precisely.

The next crucial problem is the structure of the vacuum. As we explained before the instanton vacuum solves the U(1) axial problem in the theory at the expense of creating a related one, strong CP violation.

There are several ways to get out of the riddle:

1. To make the u quark massless. Contrary to common belief this is not ruled out. However, it will be then necessary to explain why this situation occurs.
2. To make ϑ vanish as a relaxing dynamic variable. Then, the associated Goldstone boson, the axion, must exist.
3. Same as 2, but making the axion invisible.
4. Other solutions.

If 1 was true, the problems would be solved in a most elegant way. It is not considered probable and it will be necessary to understand why it happens.

Let us discuss 2 and 3, mainly because of their relevance in cosmic ray and astropyhsics.

Let me first summarize the theoretical situation.

In the introduction we pointed out that a new renormalizable term can be added to the Lagrangian. Then we showed that indeed these terms must exist.

Define the ϑ vacuum as a linear combination of al possible vacua that differ by topological Pontryagin index and are therefore generated by gauge transformations that cannot be deformed to unity.

it then reads:

$$|\vartheta\rangle = \sum e^{in\vartheta}|n\rangle \tag{10}$$

where n characterizes a state with this topological number in appropiate units. After some manipulation one obtains

$$\langle\vartheta'|e^{-Ht}|\vartheta\rangle = \delta(\vartheta' - \vartheta) \int dA^{\mu}\exp(-\int d^4x\ (L + L_{\vartheta}) \tag{11}$$

where $L_{\vartheta} = i\vartheta q$ and in Minkowski space it becomes

$$L_M(\vartheta) = \vartheta/32\pi^2\ F^a{}_{\mu\eta}\tilde{F}^a{}_{\mu\eta} \tag{12}.$$

If a quark is massless $\vartheta = 0$ is a stable solution because the instanton term does not couple in that case different topological sectors. In the general case the Lagrangian reads:

$$L = -1/4g^2\, F^i_{\mu\eta}\, F^{i\mu\eta} + 1/2\, \partial a_\mu \partial a_\mu + \sum \bar{q}(iD - m)q + L_M(\vartheta) + L^1 \qquad (13)$$

where L^1 has a the axion field instead of ϑ.

ϑ here is the combined value of ϑ given by QCD and the electroweak theory.

We can eliminate the L term by shifting the a field. Vafa and Witten (11) have given a nice proof that this Lagrangian leads to a vacuum energy that minimizes the potential energy for $\vartheta = 0$. However the price has been the a dynamical massless Goldstone field.

Having taken into account the gluonic interactions we must include other effects as well. These corrections give tiny values for ϑ that we can ignore. The Peccei Quinn mechanism has the beauty of showing that different ϑ's do not lead to different theories, but just different vacua of the same theory and that $\vartheta = 0$ is preferred.

The details about the axion field are model dependent.

The simplest original model is to construct a global symmetry that couples to he gluon via aFF. This is achieved by enlarging the standard model to two Higgs doublets and using as a dynamical field the phase not used to create longitudinal degrees of freedom for the W and Z. One must avoid also having a potential. This is achieved by having the symmetry spontaneously broken at a given scale.

The mass of the particle is (19)

$$m_a = 73.6\ (x + x^{-1})\ \text{kev.}, \qquad (14)$$

where $x = \Gamma^1/\Gamma^2$ and reflects the different couplings of u and d quarks.

I do not enter into details but the choice is dictated by the need to avoid neutral flavour changing processes.

The analysis of possible axions is therefore a function of the parameter x.

As it turns out the hadronic couplings are completely fixed.

The width into an $e_+ e_-$ pair is

$$\Gamma(a \to e_+e_-) = (x^2,\ x^{-2},\ 0).2.56\ x10^8\ \sec^{-1} x(m_a/\text{MeV})x(1 - 4m_e{}^2/m_a{}^2)^{1/2} \qquad (15)$$

the three options in the first parenthesis depending on the model one chooses for the leptonic interaction of the axion, which is model dependent.

Similarly, the axion hadron interactions below the symmetry breaking scale can be calculated as a low energy theorem and one can show that

$$K^+ \text{ to } \pi + a \;/\; K^+ \text{ to all } \sim 3.3\ 10^{-6}\ (x + x^{-1})^2 \geq 1.3\ 10^{-5} \qquad (16)$$

which contradicts experiment by several orders of magnitude. However this derivation assumes a long lived axion. In this case the scale v becomes larger than 10^4 GeV. From other decays, nuclear transitions, and reactor experiments, it seems that a particle of mass like as seen in Darmstadt with mass 1.8 MeV. is ruled out. See figure 6.

I have no time to discuss in detail the situation. Suppose that there is an axion of m_a = 1.8 MeV.
One then sees that many experiments seems to rule out a particle that can couple both to electrons and light quarks, because some unobserved rates become intolerable.
One can allow flavour changing couplings but a Pandora box gets open. Details can be seen in the Kim review (19).
There are also astronomical bounds. See figure 7.

Nevertheless a cautionary word seems necessary. There is a large number of puzzling experiments getting a 1.8 MeV. resonance. Darmstadt (47), Los Alamos (48), Stuttgart (49) Tokyo (50) and Stockholm (51) see "something" in positron thorium scattering.
Others, Argonne (52) do not.
Since the situation is complicated, and it might be, if exists, a different physical phenomenon, we stick to the third possibility: the invisible axion.
This is the accepted explanation, mainly because it cannot be ruled out!.
Sikivie (53), has proposed an astrophysical experiment. Because of their properties, these actions are good candidates to explain dark matter. The expected density of 300 MeV./cm^3 would produce a signal into 2 γ that can be detected in a resonant cavity. This experiment has been performed (54). Unfortunately, the sensitivity is still 300 times less than needed (see figure 8). Nevertheless it seems that improvements to reach the expected level are within reach.
The situation is not hopeless but slightly discouraging. However, there might be even other ways out of the problem.

4. Kim (19) discusses the many possible models. None has the elegance of the axion model. However the problem is still open.

3. Conclusions

QCD is fine and dandy. It is part of the standard model that fits all known phenomena in a simple and accurate way. There are no serious failures. Sometimes calculations are too hard but there is nothing that invalidates the theory.
Most serious is that a) some degrees of freedom (gluons) are not fully seen, and b) the ϑ vacuum is not fully established.
It is not a complete theory. Its embedding in grand unified models and or string models is not yet accomplished. However is providing astrophysics with plenty of new tools, unexpected particles, that will keep us busy for years to come.

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Figure Captions

Figure 1. 2 jet angular distribution from UA1.

Figure 2. 3 jet events.

Figure 3. Inclusive vector boson production, from Ref.23.
Inclusive γ production from Ref. 23.

Figure 4. Deep inelastic BCDMS data, CERN preprint.

Figure 5. Axion bounds, from Ref. 19.

Figure 6. The axion 2 γ limit, Ref. 54.

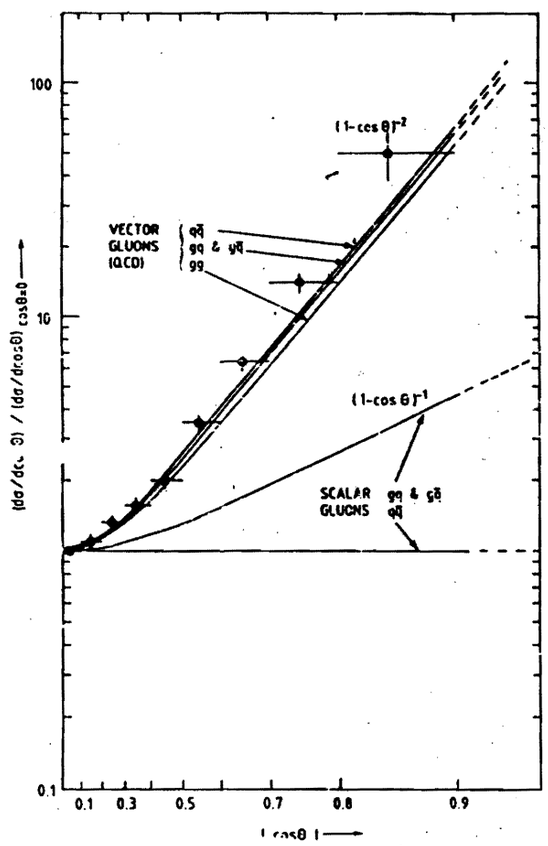

100
10
0.1
0.1
0.3
0.5
0.7
0.8
0.9
(1-cos θ)⁻²
VECTOR
GLUONS
(QCD)
qq̄
gq & gq̄
gg
(1-cos θ)⁻¹
SCALAR
GLUONS
gq & gq̄
qq̄

Figure 1

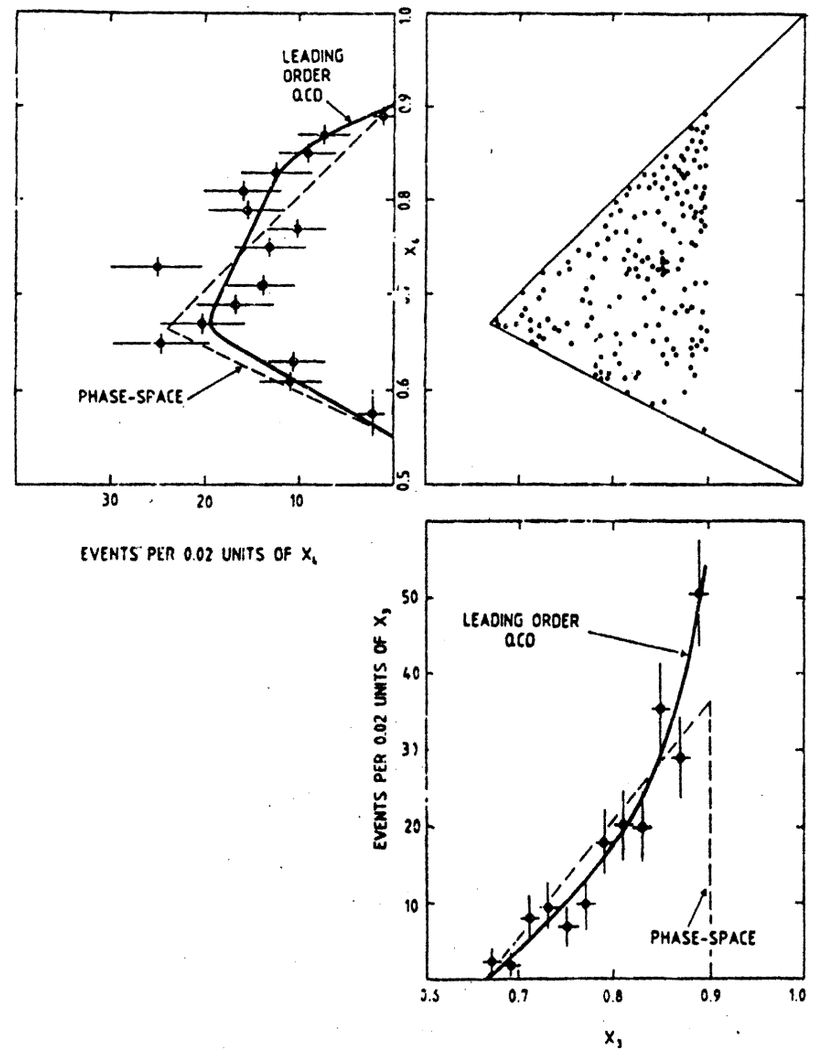


Fig. 4. The Dalitz plot (x_3 versus x_4) for the three-jet sample. The solid curves represent the predictions of the leading-order QCD bremsstrahlung formulae [6].

Figure 2

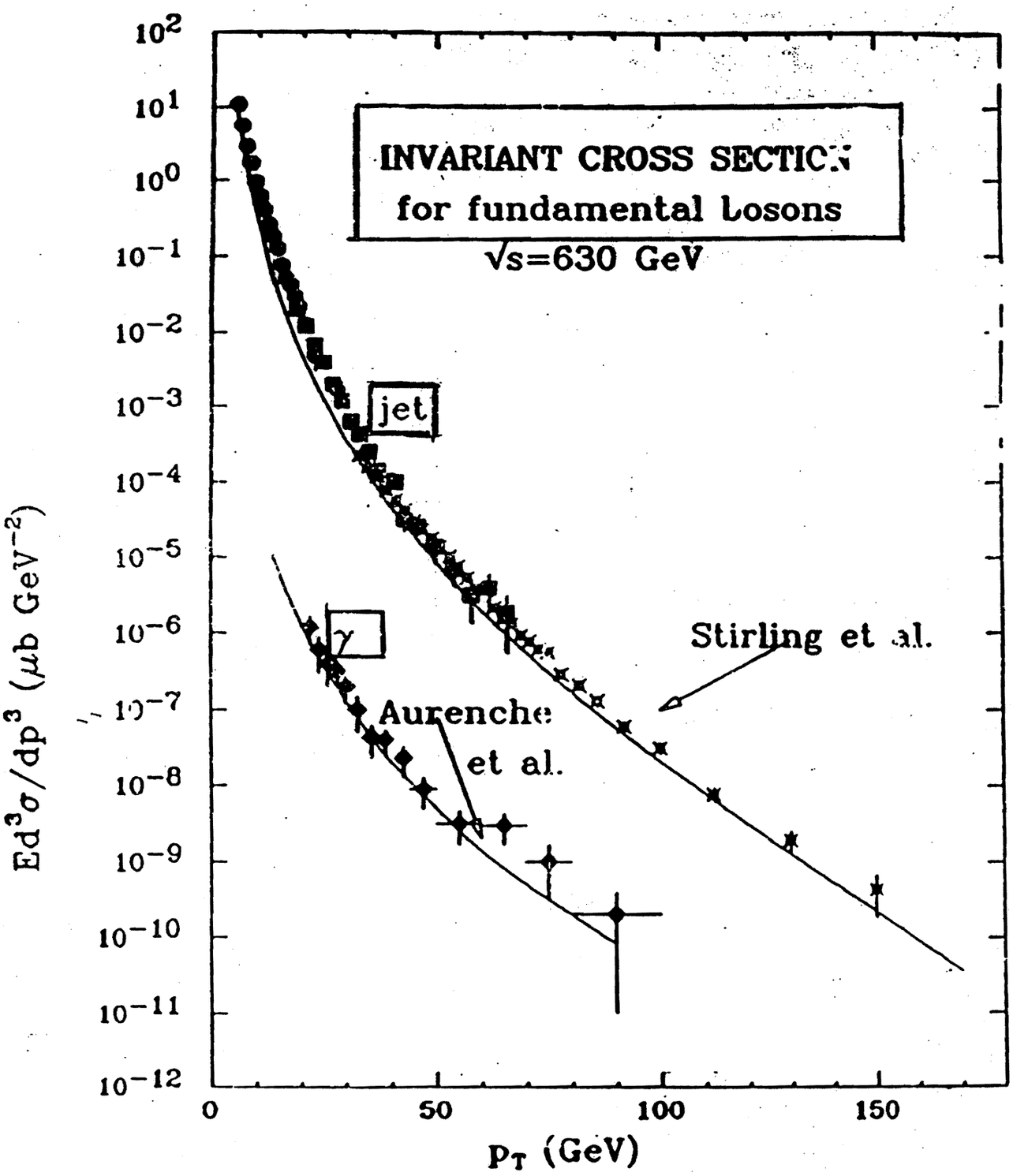
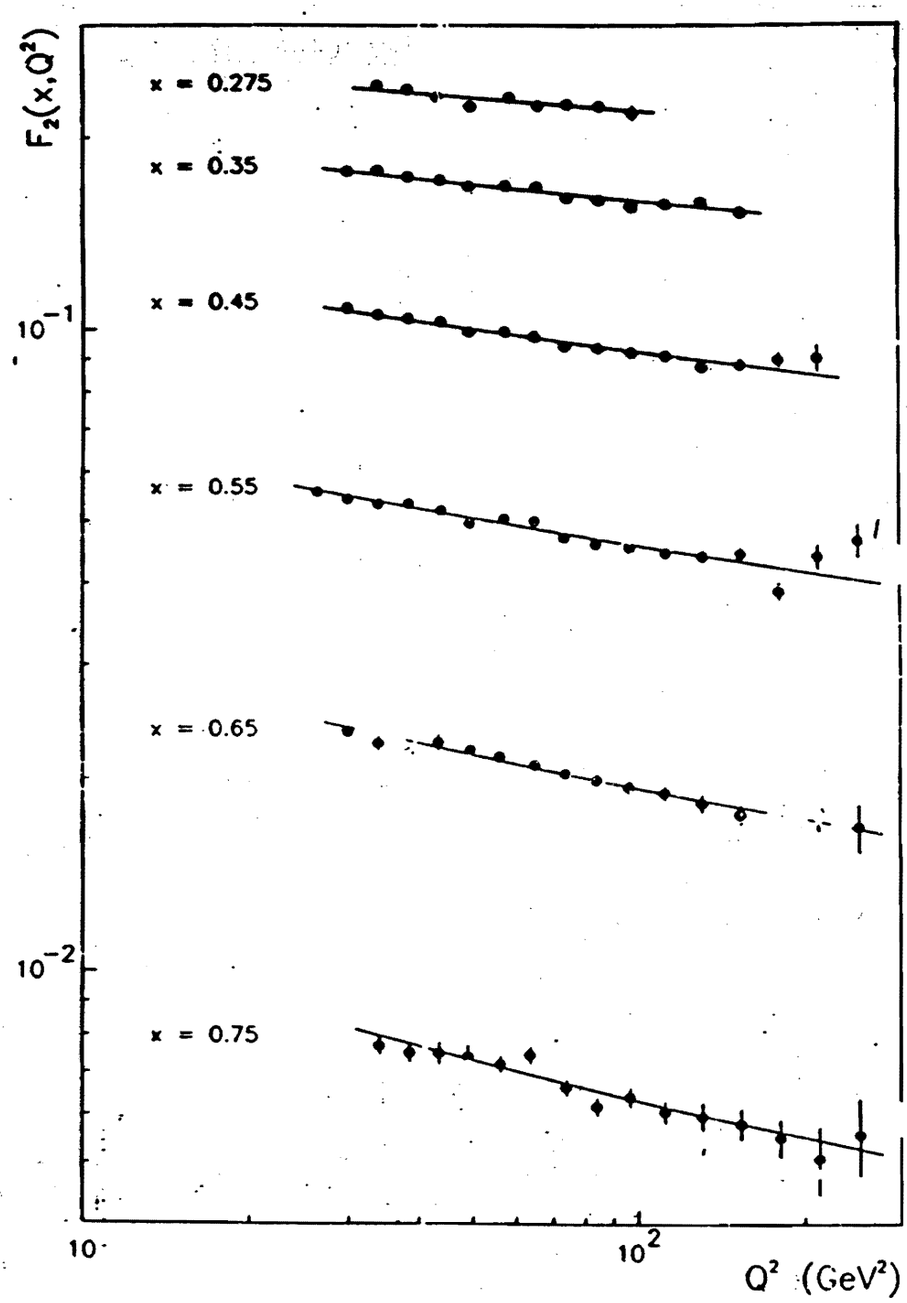

INVARIANT CROSS SECTION
for fundamental bosons
√s=630 GeV
jet
γ
Stirling et al.
Aurenche
et al.
Ed³σ/dp³ (μb GeV⁻²)
p_T (GeV)
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
0
50
100
150

Figure 3



F.G. 1

Figure 4

Astrophysical constraints on light pseudoscalars. The constraints on Yukawa couplings apply to all light pseudoscalars

Stellar object	Yukawa coupling	Hadronic axion ($c_{a\gamma\gamma} = -1.92$)	DFSZ axion ($c_{a\gamma\gamma} = 0.75$)
Sun		$F_a > 0.59 \times 10^7$ GeV or $m_a < 1.1$ eV	$F_a > 2.3 \times 10^6$ GeV or $m_a < 2.7$ eV
Red giants	$f_e < 0.9 \times 10^{-12}$	no useful bound	($F_a > 0.9 \times 1$[illegible] for $X_e = 1$)
White dwarfs	($f_e < 0.4 \times 10^{-12}$)	$F_a > 1.0 \times 10^7$ GeV or $m_a < 0.59$ eV	$F_a > 4.1 \times 10^6$ GeV or $m_a < 1.5$ eV ($F_a > 2 \times 10^8$ GeV for $X_e = 1$)
Supernovae	no bound	no bound	no bound
Neutron star core without superfluidity	$f_n < (0.5 \sim 0.7) \times 10^{-10}$	unknown	unknown
Neutron star crust	$f_e < (2.8 \sim 3.4) \times 10^{-12}$	no bound	($F_a > (1.8 \sim 1.5) \times 10^8$ GeV or $m_a < 0.03$–0.04 eV for $X_e = 1$)

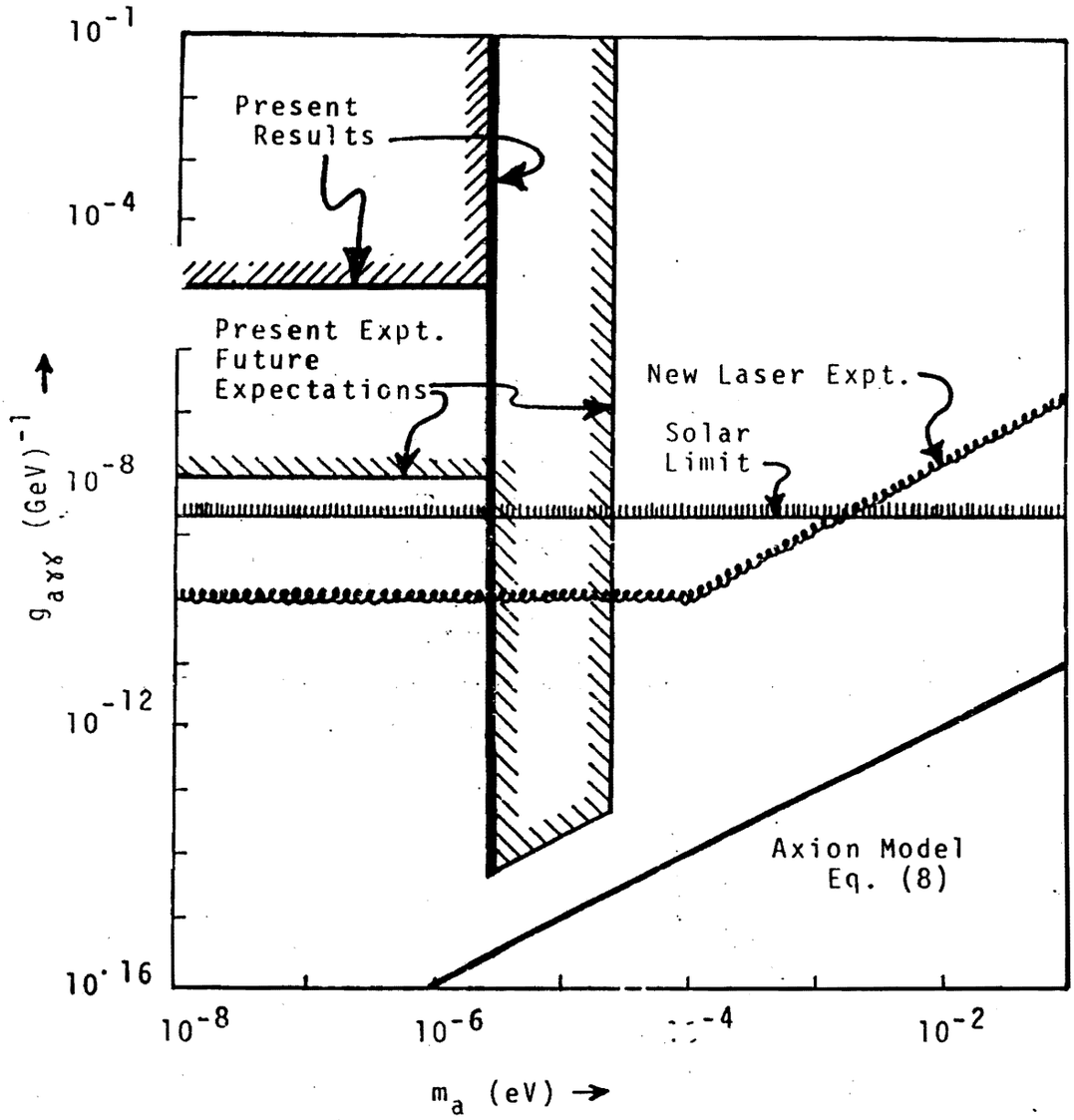


Fig. 7. Limits on the coupling constant for axion decay into two photons as a function of axion mass for present and future experiments. The axion model, Eq. (8), is also shown.

Figure 6