UCLA Mani L. Bhaumik Institute for Theoretical Physics

50 years of Quantum Chromodynamics

11 September, 2023

Flying Penguins and Other Recollections on QCD history

Arkady Vainshtein

FTPI, U of Minnesota and KITP, UCSB

Pre QCD: Khriplovich's derivation of antiscreening in Yang-Mills, 1969

Yulik Khriplovich,

My mentor, colleague and friend

SOVIET JOURNAL OF NUCLEAR PHYSICS VOLUME 10, NUMBER 2 FEBRUARY, 1970

GREEN'S FUNCTIONS IN THEORIES WITH A NON-ABELIAN GAUGE GROUP

I. B. KHRIPLOVICH

Institute for Nuclear Physics, Siberian Section USSR Academy of Sciences

Submitted December 21, 1968

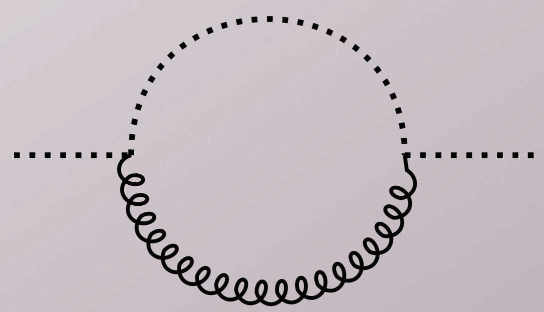
Yad. Fiz. 10, 409–424 (August, 1969)

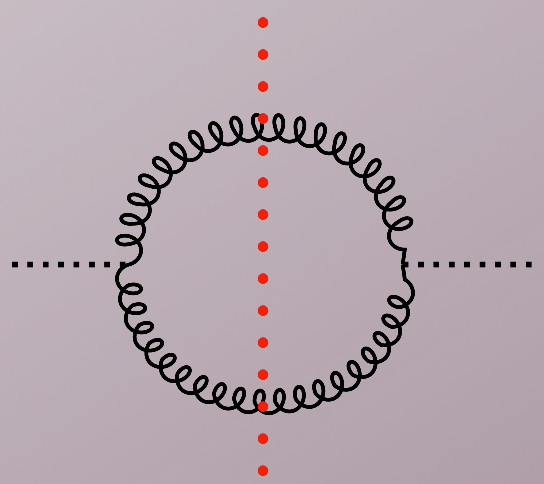
SU(2) Yang-Mills in the radiation (Coulomb) gauge.

The Green function for non-Abelian gauge field

$$\int d^4x \exp(-ipx)\langle A_\mu^\alpha(x) A_\nu^\beta(0)\rangle = i\delta^{\alpha\beta} D_{\mu\nu}(p)$$

$$D_{00} = -\frac{1}{\vec{p}^{\,2}}\left\{1 + \frac{g^2}{4\pi^2}\left[8\ln\frac{\Lambda_1^2}{\vec{p}^{\,2}} - \frac{2}{3}\ln\frac{\Lambda^2}{-p^2}\right]\right\}$$

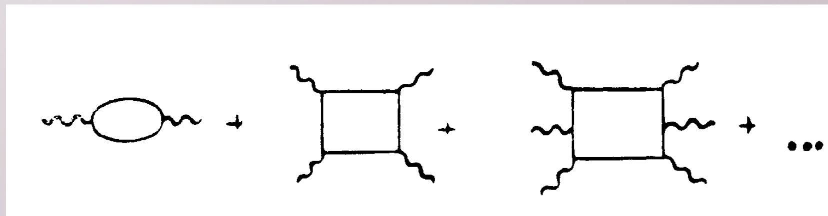




Non-dispersive part produced anti-screening and dominates numerically (12 times larger)

Earlier, in 1965, Vanyashin and Terent'ev studied electrodynamics of massive vector field. Found asymptotic freedom behavior.

Vladimir Vanyashin



Mikhail Terent'ev
1935-1996

SOVIET PHYSICS JETP VOLUME 21, NUMBER 2 AUGUST, 1965

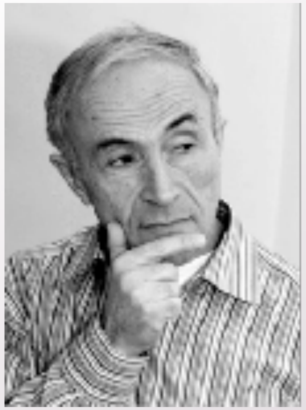
THE VACUUM POLARIZATION OF A CHARGED VECTOR FIELD

V. S. VANYASHIN and M. V. TERENT'EV

Submitted to JETP editor June 13, 1964; resubmitted October 10, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) 48, 565-573 (February, 1965)

The nonlinear additions to the Lagrangian of a constant electromagnetic field, caused by the vacuum polarization of a charged vector field, are calculated in the special case in which the gyromagnetic ratio of the vector boson is equal to 2. The result is exact for an arbritrarily strong electromagnetic field, but does not take into account radiative corrections, which can play an important part in the unrenormalized electrodynamics of a vector boson. The anomalous character of the charge renormalization is pointed out.



Zero Mass Limit and Renormalizability in the Theory of Massive Yang-Mills Field

A.I. Vainshtein and I.B. Khriplovich
Soviet Jour. of Nucl. Phys., 13(1971)111

Our study was initiated by the paper by Tini Veltman who suggested that the massive theory could be renormalizable, based on his computations of one-loop graphs.

Nuclear Physics B7(1968) 637-650. North-Holland Publ. Comp., Amsterdam

PERTURBATION THEORY OF MASSIVE YANG-MILLS FIELDS

M. VELTMAN

Abstract: Perturbation theory of massive Yang-Mills fields is investigated with the help of the Bell-Treiman transformation. Primitive diagrams containing one closed loop are shown to be convergent if there are more than four external vector boson lines. The investigation presented does not exclude the possibility that the theory is renormalizable.

We considered the three level amplitude M of fermion-antifermion annihilation into n massive vector particles. The singular at large energies/small mass behavior comes from longitudinal polarizations.

$$\epsilon^L_\mu = \left(\frac{|\vec{k}|}{\mu}, 0, 0, \frac{\omega}{\mu}\right) = \frac{k_\mu}{\mu} - \frac{\mu}{\omega + |\vec{k}|} n_\mu \qquad n_\mu = (1, 0, 0, -1)$$

The amplitude

$$M = \epsilon_{\mu_1}(k_1)\epsilon_{\mu_2}(k_1)...\epsilon_{\mu_n}(k_n)M^{\mu_1\mu_2...\mu_n}$$

is nonsingular at $\mu \to 0$ limit in case of neutral vector field interacting with conserved current, because

$$k_{\mu_i}M^{\mu_1...\mu_i...\mu_n} = 0$$

and the longitudinal polarizations decouple.
It does not happen in the non-Abelian case, starting with two quanta. It corresponds to the finite discontinuity at $\mu \to 0$ in the imaginary part for the one-loop and singular behavior for higher loops.

A convenient way to present dynamics of the longitudinal quanta is to use the Stückelberg gauge substitution for the Proca field, $B_\mu = B_\mu^a t^a$

$$B_\mu = S^\dagger \left(A_\mu + \frac{i}{g}\,\partial_\mu S S^\dagger \right) S$$

where the the field A_μ is taken in radiation gauge, $\partial_m A_m = 0$, i.e. refers to transversal quanta, and the unitary unimodular matrix S describes the longitudinal ones. Then the mass term of B_μ field leads to

$$\frac{1}{4(g/\mu)^2}\,\mathrm{Tr}\,\partial_\mu S \partial_\mu S^\dagger \qquad\qquad S = \frac{1 - i\phi/2}{1 + i\phi/2}$$

It is recognizable SU(2)xSU(2) chiral Lagrangian with coupling g/μ, evidently nonrenormalizable.

We were thinking about regularizing it by passing to the renormalizable linear sigma-model but did not manage to realize that the extra sigma field is just the Higgs field of the Weinberg model published 2 years before.

We turned to the Weinberg model in 1973 when its renormalizibility was already proven by Gerard ’t Hooft.

LIMITATION ON THE MASSES OF SUPERCHARGED HADRONS IN THE WEINBERG MODEL

A. I. Vainshtein and I. B. Khriplovich

Pisma Zh.Eksp.Teor.Fiz. 18 (1973) 141-145

$$\frac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{G^2 m_{p'}^4 \cos^2\theta}{2\pi^4}$$

$$m_{p'} \lesssim 9 \text{ GeV}$$

$$m_L - m_S = \frac{2(m_{p'} - m_{p})^2}{m_\mu^2}\Gamma(K^+ \to \mu^+\nu)$$

$$m_{p'} - m_p \sim 1 \text{ GeV}$$

More known reference is

Rare Decay Modes of the K-Mesons in Gauge Theories

- Mary K. Gailard and Benjamin W. Lee

Phys.Rev.D 10 (1974) 897

SVZ

Misha Shifman
Arkady Vainshtein
Valya Zakharov

The picture is taken in 1999 when we received the APS Sakurai prize. Three lectures where we divided our topics. I was talking on the penguin mechanism of $\Delta I = 1/2$ enhancement in K-decays.

How Penguins Started to Fly

It was an exciting period, with Quantum Chromodynamics (QCD) emerging as the theory of strong interactions, when three of us – Valya Zakharov, Misha Shifman and I – started in 1973 to work on QCD effects in weak processes. The most dramatic signature of strong interactions in these processes is the so called ΔI = 1/2 rule in nonleptonic weak decays of strange particles.

$$\frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K^+ \to \pi^+\pi^0)} = 450$$

The dominance of $\Delta I = 1/2$ is evident.

The weak interactions are carried by W bosons, so the characteristic distances are $\sim\ 1/m_W$ with $m_W\ =\ 80\ \mathrm{GeV}$. The QCD analysis at these distances in the effective Hamiltonian was done in 1974 by Mary K. Gaillard with Ben Lee, and by Guido Altarelli with Luciano Miani. Summing up $\log(m_W/\Lambda_{\rm QCD})$ they found some enhancement but short of the explanation.

Besides $1/m_W$ and $1/\Lambda_{QCD}$ there are scales provided by masses of heavy quarks t, b and c. In 1975 the object of our study was distances of order $1/m_c$ – the top and bottom quarks were not yet discovered.

At first sight, the c quark loops looked to be unimportant for nonleptonic decays of strange particles in view of the famous Glashow-Illiopoulos-Miani cancellation (GIM) with corresponding up quark loops. In 1975 the universal belief that this cancellation produced the suppression factor

$$\frac{m_c^2 - m_u^2}{m_W^2}$$

We found instead that:

(i) The cancellation is distance dependent. Denoting $r = 1/\mu$, we have

$$\frac{m_c^2 - m_u^2}{\mu^2}, \qquad \text{for } m_c \ll \mu \leq m_W;$$

$$\log \frac{m_c^2}{\mu^2}, \qquad \text{for } \mu \ll m_c.$$

No suppression below m_c!

(ii) Moreover, new operators appearing in the effective Hamiltonian at distances larger than $1/m_c$ are qualitatively different - they contain right- handed light quark fields in contrast to the purely left-handed structures at distances much smaller than $1/m_c$. The right-handed quarks are coupled via gluons which carry no isospin; for this reason new operators contribute to $\Delta I = 1/2$ transitions only.

(iii) For the mechanism we suggested it was crucial that the matrix elements of novel operators were much larger than those for purely left-handed operators. The enhancement appears via the ratio

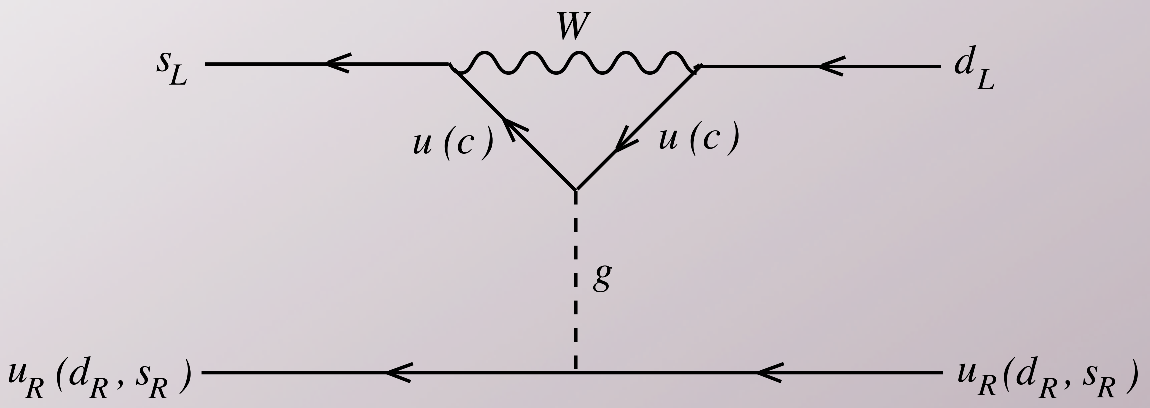
$$\frac{m_\pi^2}{m_u + m_d} \sim 2\,\mathrm{GeV}\,,$$

which is large due to the small light quark masses. The small values of these masses was a new idea at the time, advocated in 1974 by Heiri Leutwyler and Murray Gell-Mann.

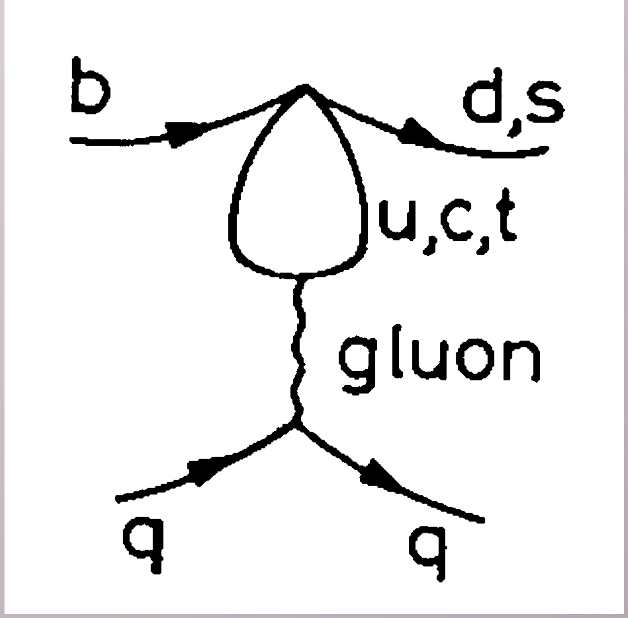
We had a hard time communicating our idea to the world. Our first publication was a short letter published on July 20, 1975 in the Letters to the Journal of Theoretical and Experimental Physics. Although an English translation of JETP Letters was available in the West we sent a more detailed version to Nuclear Physics shortly after. The process took more than a year and a half! Eventually the paper was published in the March 1977 issue of Nuclear Physics without any revision, but only after we appealed to David Gross who was then on the editorial board.

I think, that in recognition of our work in the world at large it was Mary K. Gaillard who first broke the ice – she mentioned the idea in one of her review talks. Moreover, she collaborated with John Ellis, Dimitri Nanopoulos, and Serge Rudaz in the work in which they applied a similar mechanism to B physics. It is in this work that the mechanism was christened the penguin.

How come? Figure shows the key Feynman diagram for the new operators in the form we drew it in our original publications,



It does not look at all penguin-like, right? Now look how a similar diagram is drawn in the paper of the four authors mentioned above. And even better in John Ellis' blackboard drawing. He has the whole story to tell about it.



We were so exhausted by the fight with Nuclear Physics that we decided to send our next publication containing a detailed theory of nonleptonic decays to Soviet Physics JETP instead of an international journal. It was published in 1977.

CAN CONFINEMENT ENSURE NATURAL CP INVARIANCE OF STRONG INTERACTIONS?

M.A. SHIFMAN, A.I. VAINSHTEIN and V.I. ZAKHAROV

Nucl. Phys. B166 (1980) 493

P- and T-invariance violation in quantum chromodynamics due to the so-called θ-term is discussed. It is shown that irrespectively of how the confinement works there emerge observable P- and T-odd effects. The proof is based on the assumption that QCD resolves the U(1) problem, i.e., the mass of the singlet pseudoscalar meson does not vanish in the chiral limit. We suggest a modification of the axion scheme which restores the natural P and T invariance of the theory and cannot be ruled out experimentally.

$$\Delta\mathscr{L} = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\widetilde{G^a_{\mu\nu}}$$

$$G^a_{\mu\nu}\widetilde{G^a_{\mu\nu}} = \partial_\mu \mathscr{K}_\mu ,$$

$$\mathscr{K}_\mu = 2\epsilon_{\mu\nu\lambda\sigma}(A^a_\nu \partial_\lambda A^a_\sigma + \tfrac{1}{3} g_s f^{abc} A^a_\nu A^b_\lambda A^c_\sigma)$$

Instanton produces dependence on θ but confinement deletes long-range. Sasha Polyakov and Peter Minkowski expressed their doubts giving certain arguments. We tried to check this. As we wrote:

> Our final result complies with the conclusion on CP violation so that most readers can, justifiably, loose interest in the paper at this point.

$$\left\langle 0 \left| \frac{\alpha_s}{\pi} G^a_{\mu\nu}\widetilde{G^a_{\mu\nu}} \right| 0 \right\rangle \simeq -\theta f_\pi^2 m_\pi^2 \frac{4 m_u m_d}{(m_u + m_d)^2}$$

$$A(\eta \to \pi^+\pi^-) \simeq \theta \frac{m_\pi^2}{\sqrt{6} f_\pi} \frac{4 m_u m_d}{(m_u + m_d)^2} ,$$

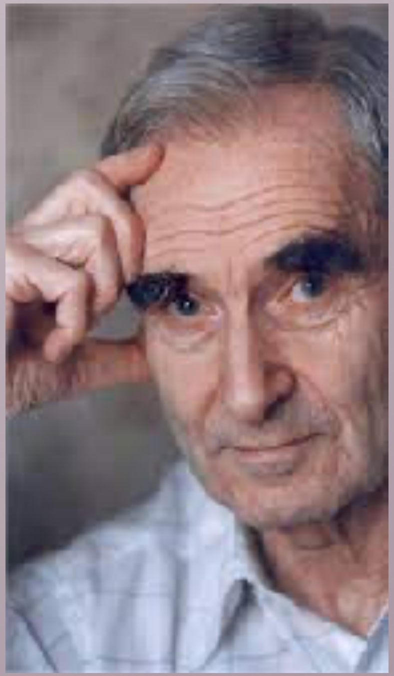
Also we suggested a variant of invisible axion dubbed later as KSVZ.

Conclusions

I am thankful to the Organizers for the opportunity to share these recollections. I'd like to finish by expressing my gratitude to Yulik, Valya and Misha for the long-term collaboration.

I am grateful to my advisers.
My first adviser in the Budker Institute was Victor Galitskii.
He defined my career in physics sending me to ITEP where my PhD adviser was Boris Ioffe.

Victor Galitskii
1924-1981



Boris Ioffe
1926-2022