Paolo-Fest, Nordita, 15-16/05/2023

QCDing with Paolo:
a break from the string

Gabriele Veneziano

A life-long story of friendship & collaboration

Paolo followed a professional path quite parallel to mine and this gave rise to various periods of active interaction and collaboration

- DRM/hadronic string @ MIT, CERN, Nordita (=> F. Gliozzi's talk)
- QFT (QCD) intermezzo (this talk)
- Strings/branes after the GS revolution (=> R. Russo's talk)
- Gravitational scattering/radiation (=> C. Heissenberg's talk)

DRM/String days @ MIT*

for Paolo: end 1969-end 1971

(second year by turning down
a permanent job in Italy)

for me: Sept. 1968-June 1972

*see F. Gliozzi for the physics

A common mentor: Sergio Fubini.

A common friend: Emilio Del Giudice.

Lots of discussions (and not only about physics) but did not get to work together. Somewhat out of phase...

In the summer of 1970 I wrote a paper with Sergio et al. on DRM unitarization. In the fall I went to the IAS for a term. By then my interests had moved in different directions (topological unitarization of DRM, later understood as 1/N...)

Paolo and Emilio instead worked closer to Sergio and wrote their celebrated DDF paper opening the way to the no-ghost theorem by Goddard & Thorn and by Brower.

In 1972 Paolo moved to CERN for two years before taking a job at Nordita. In those years a big (by theory standards) collaboration that became known as Ademollo et al. started. It pioneered the idea of quantizing strings in non-trivial backgrounds.

Nando, who was part of it, will also cover that period.

I had moved back to the Weizmann Institute but with an agreement with CERN/TH to spend there extended summers

Paolo and I did regularly meet and discuss in those occasions but did not get to work together…yet.

I remember instead an amusing episode concerning…housing.

AT CERN 1979/80

(Paolo as visitor after Nordita, myself on the staff since 1976)

By then a revolution had taken place and QFT had made a remarkable comeback: the standard model of electroweak and strong interactions had been formulated by 1973.

The attention of the community went into working out the predictions of the SM and testing it (according to Paolo also a matter of survival for non-tenured theorists!)

For those like Paolo and myself who had played with DRM's as a theory of strong interaction the obvious choice was to work on QCD.

Two properties of QCD attracted our attention:

1. Dimensional transmutation: i.e. the emergence of a scale in a theory that started without any scale. This is how the fundamental length/mass scale of string theory would magically come out of QCD.

2. The topological organization of Feynman diagrams via large-N expansions ('tHooft, GV, Witten) in close analogy with the topology of DRM/string diagrams.

In the summer and fall of 1978 Paolo had written a couple of remarkable papers with D'Adda and Luescher about large-n expansions in two-dimensional CP^n models (sharing many properties with QCD, like asymptotic freedom, dimensional transmutation, and spont. chiral symmetry breaking).

The neutron's EDM story

Volume 88B, number 1, 2 PHYSICS LETTERS 3 December 1979

CHIRAL ESTIMATE OF THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON IN QUANTUM CHROMODYNAMICS

R.J. CREWTHER, P. DI VECCHIA and G. VENEZIANO
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and

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Received 7 September 1979

Current algebra for *CP* violating strong interactions is investigated. In particular, the neutron electric dipole moment D_n is shown to behave as $\theta m_\pi^2 \ln m_\pi^2$ for small pion mass m_π and *CP* violating parameter θ. This logarithm is explicitly calculable: it contributes $5.2 \times 10^{-16}\theta$ cm to D_n. This result is somewhat larger than a previous $O(m_\pi^2)$ estimate based on the bag model.

In April 1979 Witten (then at Harvard) had proposed a large-N_c solution to the U(1)-problem (absence of a 9^{th} light pseudoscalar, $m_\eta >> m_\pi$, small singlet-octet mixing angle, ..). I had met Witten at Harvard earlier that year and had discussed the problem with him (I had my own way to argue that there should be a 1/N solution).

A bit later (also in April-'79) I wrote my paper on the U(1)-problem and its large-N resolution a la Witten. Some of Crewther's early objections to an instanton-based solution could be answered.

In the summer of 1979 Witten was visiting the theory division at CERN. Paolo was there and so was Crewther (possibly as a fellow?). We also took advantage of many conversations with Coleman.

The four of us had a few discussions and concluded that one should look for strong-CP violations in hadronic physics as a result of a non-vanishing θ angle.

[BTW: the old argument by Weinberg that strong-interactions would automatically respect CP is invalidated by instantons: can't have the cake (solve U(1) prob.) and eat it (solve strong-CP prob.)]

We wanted to make sure that such effects would be unavoidable and (at least in principle) observable.

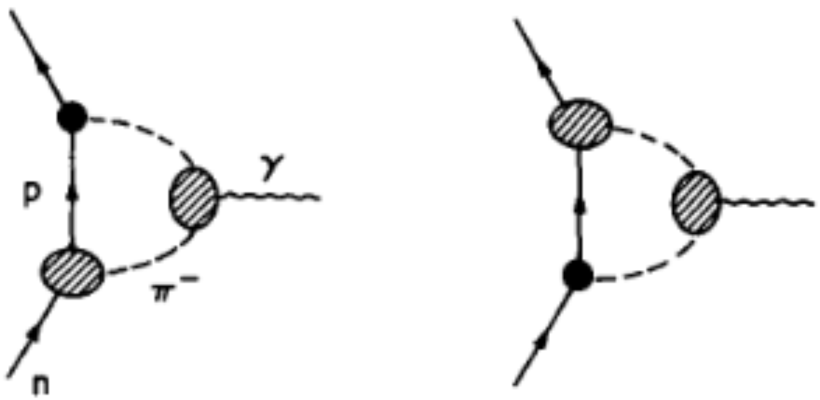
We first computed the contribution of θ to $\eta \to 2\pi$. That was theoretically simple to work out from Current Algebra, but could hardly put strong bounds on θ.

We knew that a much more sensitive quantity was the neutron's EDM, D_n and that there was a computation by Baluni giving an estimate on the proportionality constant between D_n and θ.

There was still a fudge factor to be fixed and no proof that it could not be zero by some unknown reason.

We started working on this. The first thing to do was to find a CP violating pion nucleon coupling (without γ_5). Again a straightforward Current Algebra calculation.

The crucial point, however, was the realization that coupling a photon to the neutron through a pion loop would produce (thanks to the above coupling) a distinctive logarithmically enhanced (~ log m_π) contribution to D_n.



That term could not be canceled by non-enhanced terms (except perhaps at a fine-tuned value of the pion mass) and therefore we had a proof that the effect was there.

Cutting off the log at a typical UV QCD scale also gave a more reliable estimate of Baluni's fudge factor. The present experimental upper bound on θ still uses, I believe, our estimate.

The large-N Lagrangian story

Nuclear Physics B171 (1980) 253--272

CHIRAL DYNAMICS IN THE LARGE N LIMIT

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Received 25 February 1980

We construct an effective lagrangian describing the low-energy spectrum and dynamics of the pseudoscalar nonet in the large N_{colour} limit of QCD. Effects of the axial anomaly and of a possible non-zero vacuum angle are incorporated together with corrections of order $m_q N_c/\Lambda$.

Paolo and I kept discussing with Witten about finding a compact way to represent the joint effects of SSB, of the explicit breaking due to quark masses, and of the one due to the U(1) anomaly, all at once in the large-N_c limit.

But Witten left to Cargèse and then went back directly to Harvard. Paolo and I (probably with inputs from Witten) managed to write down an effective action that incorporated the U(1) anomaly (also inspired by some explicit calculations by Franco Riva in CP^n). We wrote draft with all three authors in the first page and sent it to Witten.

Witten, however, did not like the presence of a heavy glueball field (the topological change density) in the action and, after a while, sent us back his own version of the paper (in which the heavy field had been integrated out) still with all three names on it.

Discussions followed about how to combine in a single paper either one or both formulations with all three authors.

We finally opted for two separate papers: one by Paolo and myself, one by Witten alone. This delayed submission to NPB…

Reading again Witten's paper I realized how much credit he gives to us as if his paper was just a follow-up to ours (and to parallel papers by Rosenzweig, Schechter & Trahern, and by Nath & Arnowitt).

Our paper was followed by a more detailed study of pseudoscalar masses, mixings and decays in collaboration with F. Nicodemi and R. Pettorino.

$$\mathcal{L}(U,U^{+},q)=\mathcal{L}_0(U,U^{+})+\tfrac{1}{2}iq(x)\mathrm{Tr}\left[\log U-\log U^{+}\right]$$
$$+\frac{N}{aF_\pi^2}q^2(x)-\theta q(x)+\frac{F_\pi}{2\sqrt{2}}\mathrm{Tr}(MU+M^{+}U^{+})$$

The large-N effective Lagrangian neatly summarizes all the basic properties that follow from SSB, the explicit breaking due to quark masses, the effect of the strong anomaly, and those of the θ angle.

It gives immediately the WV formula for the η' mass. It shows how different quantities depend on θ and how θ-dependence disappears if one quark is massless. It also connects (in a non-trivial way) the topological susceptibilities of pure YM theory to the one in QCD. It shows how periodicity in θ is recovered thanks to some level crossing at $\theta = \pi$ (thereby answering earlier objections by Crewther)

[Many times we (but more particularly Crewther) unsuccessfully tried to convince convince 't Hooft that his determinant action did not satisfy the anomalous WI's and that the U(1) problem can be solved in the large-N limit where diluted instantons are exp.ally suppressed.]

Topological susceptibility on the lattice

Nuclear Physics B192 (1981) 392–408

Nucl.Phys.B 192 (1981) 392, Phys.Lett.B 108 (1982) 323

PRELIMINARY EVIDENCE FOR $U_A(1)$ BREAKING IN QCD FROM LATTICE CALCULATIONS

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Received 15 June 1981

We suggest a simple definition of the topological charge density $Q(x)$ in the lattice Yang-Mills theory and evaluate $A \equiv \int d^4x \langle Q(x)Q(0)\rangle$ in SU(2) by Monte Carlo simulation. The "data" interpolate well between the strong and weak coupling expansions, which we compute to order g^{-12} and g^6, respectively. After subtraction of the perturbative tail, our points exhibit the expected asymptotic freedom behaviour giving $A^{1/4} \simeq (0.11 \pm 0.02)K^{1/2}$, K being the SU(2) quarkless string tension. Although a larger value for $A^{1/4}K^{-1/2}$ would be preferable, we are led to conclude (at least tentatively) that the $U_A(1)$ problem of QCD is indeed solved perturbatively in the quark loop expansion.

After a brief period in Berlin, Paolo got a job at Wuppertal U. He met there K. Fabricius, an expert in lattice QCD.

Together with G.C. Rossi we decided to test the idea of a non-vanishing topological susceptibility χ_{YM} in Yang-Mills theory (this is the basic quantity for solving the U(1) problem in the large-N_c limit. One needs $\chi_{YM} \sim (180 \text{ MeV})^4$ in order to fit the data.)

Although by now there are more sophisticated definition for the topological change on the lattice (e.g. using overlap fermions satisfying the Ginsparg-Wilson relation) our def. of the topological change is still much used for its simplicity.

It gave the first evidence for a non-vanishing χ_{YM} (now known to be in the right ball-park range and NOT falling down with N_c!)

Variations on the large-N effective action

Minimal composite Higgs models

Volume 95B, number 2 PHYSICS LETTERS 22 September 1980

MINIMAL COMPOSITE HIGGS SYSTEMS

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Received 10 June 1980

Extending to technicolour models recent results on the chiral, large N_c limit of QCD, we argue that minimal composite Higgs systems must contain an η like Higgs particle, whose peculiar properties follow from current algebra and large N arguments only. By contrast, the usual scalar Higgs is a model-independent entity without clear experimental signature.

An amusing variation is to apply the scheme to technicolour (TC) as a model for a composite Higgs (now exp.^{lly} disfavored…)

Since techicolour is a QCD-like gauge theory one can apply the same techniques provided N_{tc} is large enough. Furthermore, in order to construct a minimal model, we took TC with two (massless) techni-flavours forming an SU(2)xU(1) standard doublet.

Because of χSB & the U(1) tc-anomaly the spectrum before electroweak gauging has three massless tc-pions and a massive tc-η. After EW-gauging, the former are eaten up and give mass to the W's and the Z. No light scalar Higgs is left… except at large N_{tc} .

We dubbed this particle the η-Higgs since it shared some properties of a SM Higgs and some of the η' of QCD and computed a few of its properties (such as $\eta_H \to 2\gamma$) as a function of N_{tc}

Adding the axion I

The Physics of the θ-angle

for

Composite Extensions of the Standard Model

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We analyse the θ-angle physics associated to extensions of the standard model of particle interactions featuring new strongly coupled sectors. We start by providing a pedagogical review of the θ-angle physics for Quantum Chromodynamics (QCD) including also the axion properties. We then move to analyse composite extensions of the standard model elucidating the interplay between the new θ-angle with the QCD one. We consider first QCD-like dynamics and then generalise it to consider several kinds of new strongly coupled gauge theories with fermions transforming according to different matter representations. Our analysis is of immediate use for different models of composite Higgs dynamics, composite dark matter and inflation.

- *Eur.Phys.J.Plus* 129 (2014) 26 1310.0954 *[hep-ph]*

Another amusing variation is to add an axion to the Lagrangian…so that the strong-CP problem is automatically solved.

In general an axion is a pseudo-NG boson whose mass is entirely produced by the anomaly (Cf. QCD with a single massless quark). So adding the axion is like adding an extra massless quark but with a much larger condensate ($f_a \gg f_\pi$ implying $m_a \ll m_\pi$).

All the details are beautifully worked out in that paper by Paolo and F. Sannino.

Adding the axion II

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Spontaneous CP breaking in QCD and the axion potential: an effective Lagrangian approach

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JHEP12(2017)

In that paper we studied the possible spontaneous breaking of CP near $\theta = \pi$ and its implications on the axion potential. There are two competing small scales and the physics depends on their ratio:

$$\epsilon = \frac{m_q \langle \bar{q} q \rangle}{\chi_{YM}} \sim \frac{m_\pi^2}{a} \sim \frac{m_q N_c}{\Lambda_{QCD}}$$

At zero temperature with $N_c = 3$, $\epsilon < 1$ but near the QCD phase transition it can be much larger and this would imply interesting new features of the axion potential near its periodicity value.

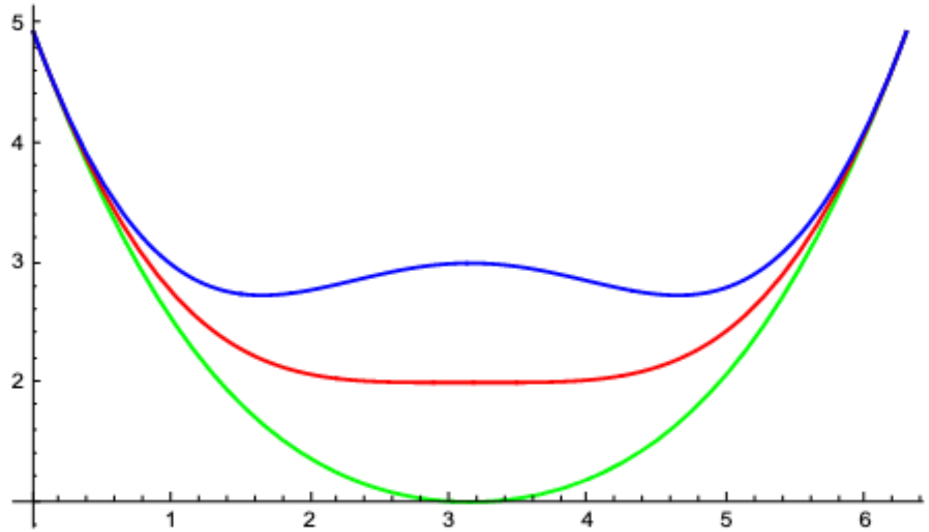

Figure 2: $V(\phi)$ of Eq. (3.1) at $\theta = \pi$, and $\epsilon = 0.5$ (green curve), $\epsilon = 1.0$ (red) and $\epsilon = 2.0$ (blue).

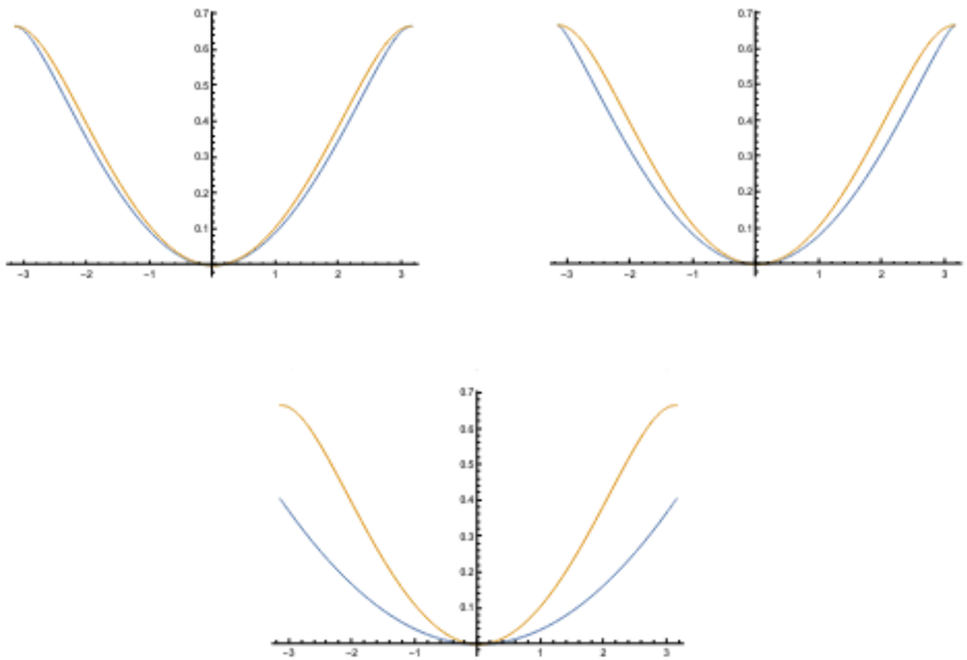

Figure 9: Comparing the conventional axion potential (yellow curves) with the "exact" one (blue curves) for $N_f = 2, \mu_d^2 = 2\mu_u^2$ and at three values of μ_u^2/a: $0.25, 0.5$ (critical value), 2.5. In the first two cases the two potentials (but not necessarily their derivatives) agree at $\zeta = \pm\pi$ while in the third (overcritical) case even the values of the potentials disagree at the boundary of the periodicity interval.

Back to strings and branes!

(see Rodolfo Russo)

Shortly after the GS 1984 revolution both Paolo and myself went back to strings, although in somewhat different directions.

Our world-lines crossed again about ten years ago because of Paolo's work on D-branes and the boundary-state formalism and my own work (with Amati and Ciafaloni) on Planckian energy collisions of strings.

The natural overlap in our interests was the study of high-energy collisions of strings off a stack of D-branes.

This was the start of another fruitful collaboration involving also G. D'Appollonio and R. Russo.

…and now moving on to black holes and gravitational waves!

(see Carlo Heissenberg)

Both string-string and string-brane collisions were thought of as theoretical laboratories for understanding quantum gravity in a string theory context. They were some kind of gedanken experiments in the spirit of the early days of quantum mechanics

To our (or at least to my) surprise the methods used in that context (e.g. the gravitational eikonal approximation) turned out to be relevant for the study of the collision of very massive -rather than very energetic- objects, such as astrophysical black holes.

This shift of interest was of course much motivated by the 2015-16 LIGO-VIRGO detection of GW from coalescing black holes.

This is how Paolo and I ended up working on the subject and getting stuck with a long overdue Phys. Rep. on it...

Concluding remarks

Paolo has kept his style in work intact over these many decades and throughout the diverse subjects he has worked on.

No matter what topic he is on, it has to be supported by solid calculations of which he keeps detailed Tex records.

Since the invention of Latex I don't remember him sending me copy of a hand-written calculation. I know that I should do the same …

His ability to interact with other people, to guide younger colleagues, and to integrate easily in new groups is exceptional. And so is his acquaintance with the literature.

Modesty and understatements are also among Paolo's virtues in a world where selling (sometimes smoke) is the key to get recognition.

I was lucky having you as friend and collaborator for so long. Let's try to continue for many years to come...

...AND HAPPY BIRTHDAY!