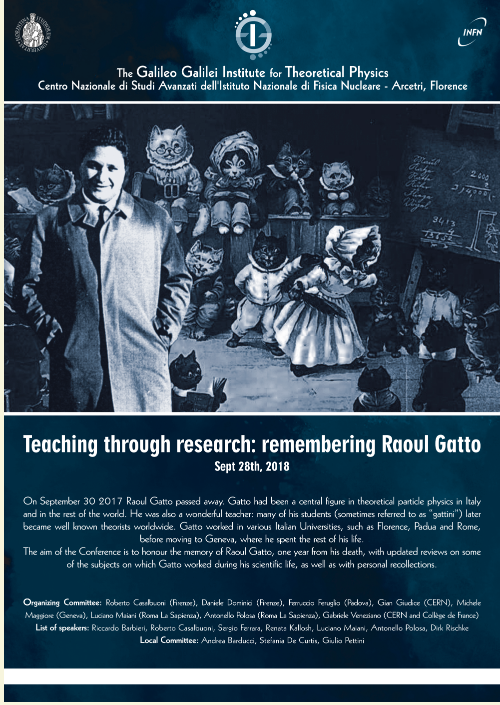

30 years with Raoul

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- Gatto arrived in Florence, from Cagliari in 1962-63
- In 1966 the group of the “gattini” in Florence was dissolving, since some of them were going to the States and others to Rome, so Gatto decided to recruit new students from Florence.

Gatto and the “kitten” school, elaborated from *Mrs Tabitha's Cats' Academy*, (1895) a Louis Wain painting, gift of Veneziano to Raoul in the occasion of his 60th birthsday.

- In november 1966, I first met Gatto, a few days after the flood in Florence, in the occasion of my exam in Quantum Mechanics. Ademollo was in charge of the course but Gatto replaced him.

Raoul in the early 60s

- After the exam Gatto asked me which kind of physics I was interested in, I said:

“particle physics”

and him:

“Experimental or theoretical?”

I answered that I did not know yet, then he replied:

“Well, experiments require a deep preparation both in experimental and theoretical physics, whereas for a theoretician only theory is necessary.”

That was enough to convince me.

- As my first impression about Gatto, this is best expressed by what Guido Altarelli said in the occasion of Raoul's 60th birthday:

«When, as a student, you first met Gatto, there was no doubt that he was a great man, a great person, the master, though, in the eqrly sixties the age difference between him and us (his students) was no more than 10-12 years.»

- On the other hand Gatto was always very kind with his students, also if he did not agree with you. If you expressed some idea in physics that he was not convinced about, he said, with his typical tone of voice:

«This is very interesting, I never heard before what you are saying»

or

«This is very interesting, I have never seen this thing in the literature.».

This meant that he was in disagreement

- During the fall of 1967, Gatto assigned me a thesis about the Gell-mann problem of "**saturating current algebra with an infinite set of resonances**".
- Problem complicated due to the covariance properties of the currents. But Gatto provided me with a way out handing me a preprint by Leutwyler et al. (Phys.Rev. **177**, 2133, 1969) about the use of infinite component wave equations to obtain covariant currents. The idea was to use unitary reps. of the Lorentz group. This went back to a Majorana paper (N.C. 9, **335**, 1932) devised to avoid the negative energy solutions present in the Dirac equation.

- In the thesis work (discussed in March 69) I presented an equation giving a linear mass spectrum (in 68 Veneziano amplitude) but also with complex space-like solutions, that we thougt to be avoidable.
- I wrote a few papers on this subject with Gatto and Longhi, but at the end of the game we discovered that the space-like solutions are unavoidable since they are necessary for the completeness of the solutions of the wave equation.

- Gatto went on live to CERN in 1967-68 and moved to Padua in 1968.
- I graduated in March 1969 and Gatto found for me an INFN temporary position in Padua, where I remained also in 1970 with a fellowship. I went back to Florence in 1971, since Gatto at the end of the same year would move to Rome.
- Eventually he moved to Geneva in 1975 to occupy the chair previously held by Stuckelberg

- When in Geneva, Raoul had many collaborations with visiting people as, for instance, Barbieri, Menotti, Morchio and Strocchi from Pisa; Paccanoni, Sartori and Vendramin from Padua; Caffo and Remiddi from Bologna and, with Savoy who, coming from Padua, had a temporary position in Geneva, and with Abud a PhD student.
- A partial list of his collaborators is given in the following slide, ordered according to the number of the joint papers:

Collaborators of Raoul (> 2 joint papers)

R.Casalbuoni.1 (127)
D.Dominici.1 (60)
S.De.Curtis.1 (60)
G.Nardulli.1 (45)
F.Feruglio.1 (44)
A.Deandrea.1 (38)
M.Ruggieri.1 (26)
N.Di.Bartolomeo.1 (24)
A.Barducci.1 (23)
G.Pettini.1 (21)
G.Sartori.1 (18)
P.Chiappetta.1 (17)
S.Ferrara.1 (16)
A.F.Grillo.1 (15)
Riccardo.Barbieri.1 (14)
G.Altarelli.1 (12)
P.Menotti.1 (12)
E.Remiddi.1 (10)
G.Preparata.1 (10)
I.Vendramin.1 (10)

M.Mannarelli.1 (9)
M.Caffo.1 (8)
M.Ciminale.1 (8)
M.Modugno.1 (8)
C.A.Savoy.1 (7)
F.Strocchi.1 (7)
M.Abud.2 (7)
A.D.Polosa.1 (6)
H.Abuki.1 (6)
J.F.Gunion.1 (6)
M.Grazzini.1 (6)
N.Cabibbo.1 (6)

B.Mele.1 (5)
F.Bordi.1 (5)
G.Parisi.1 (5)
M.Ademollo.1 (5)
Z.Kunszt.1 (5)
G.Longhi.1 (4)
J.Terron.1 (4)
L.Casetti.1 (4)
M.Pettini.1 (4)
M.Tonin.1 (4)
R.Anglani.1 (4)
R.Kogerler.1 (4)
F.Buccella.1 (3)
G.Morchio.1 (3)
L.Maiani.1 (3)
M.C.Cousinou.1 (3)
M.L.Mangano.1 (3)
N.D.Ippolito.1 (3)
Pietro.Colangelo.1 (3)
U.Baur.1 (3)

- After the collaboration in the infinite component wave equations, I had no more occasion to see Raoul since 1979, when I visited CERN for 3 months.
- We were together at a seminar of Harari about the “rishon” model, and at the end we discussed the possibility of doing something in that subject. From that moment we started a collaboration that went along since 2006.

COMPOSITE MODELS

- We began to work on composite models with a first paper (Phys. Lett. **93B**, 47, 1980) where we proposed a very simple model based on constituents belonging to a representation (**3**,**N**) 0f SU(3)scxSU(N) (eventually we took N = 5). The model suffered of two problems: it did not satisfy the ‘t Hooft anomaly conditions, and it required a very high scale of compositness to cope with proton decay.
- As a matter of fact, we learned about the anomaly conditions from a ‘t Hooft seminar at CERN when we were completing our paper.

- The ‘t Hooft anomaly conditions, that are necessary in order to get massless composite states, require the equality of the anomalies at the level of composite and constituent states. The requirement of having massless (or almost massless) quarks and leptons is related to the supposedly high scale of compositness compared with the QCD scale. The idea was to start with a massless theory and introduce the masses later as perturbative terms.
- However, ‘t Hooft conditions were very hard to be satisfied. In fact, many of the models on composite quarks and leptons appearing in that period did not satisfy it

- A way to satisfy the anomaly conditions was to use the constituents-composite duality (complementarity) which was based on the one-to-one correspondence of the spectra in the two sectors. A prototype was the Fahri-Susskind model which is the Higgs model in the broken phase for the components, but when the interaction becomes strong, the spectrum of the composites corresponds one-to-one to to the spectrum of the constituents. We considered also a supersymmetric model. Collaborators of that period were Francesco Bordi (a student of mine) ad Daniele Dominici (thesis with Longhi).

- But this line of research ended when the interest shifted to the indirect effects of composite models in a model independent way.

Raoul in 1981

DYNAMICAL SYMMETRY BREAKING

- In 1982 I assigned a thesis work to Stefania De Curtis and Elena Castellani (now Professor in Phylosophy of Science) based on the effective action of Cornwall, Jackiw and Tomboulis (CJT) which allows to deal with dynamical symmetry breaking.

- In the summer of 1983 Stefania and I went to Geneva and she presented her results to Raoul. He was impressed and proposed to apply the method to QCD. We wrote various papers on the argument, with a final result in 1988 (Phys. Rev. 38, **238**, 1988) obtained in collaboration with Andrea Barducci (thesis with Ademollo), Stefania and Daniele. This paper was quoted for several years by the PDG as an example of a theoretical calculation of quark masses.

HIGGS BOSON

- A break in the QCD line of research occurred in 1985. The Standard Model was now fully accepted. The missing element (in addition to the top quark) was the Higgs boson, on which the mechanism of electro-weak symmetry breaking rested. Given the lack of experimental informations on the matter, the idea began to circulate that the breaking could be dynamical and due to a strong interaction at the TeV scale, similar to QCD, called technicolor.

- Raoul had a particular intuition in choosing interesting problems that could be solved, and he was reading every day the new preprints and he handed us the most interesting ones with the important points underlined.
- He learned that the japanese group of Bando and Yamawaki was using a method called “hidden gauge symmetries” to obtain the chiral lagrangian for QCD. So he suggested to use the same method to obtain a low-energy description of the electroweak symmetry breaking. The idea was that the Higgs was very heavy, whatever his origin could have been.

- We started this line of research in an independent way, Raoul amd Daniele in Geneva (Daniele was there for a two years period) and Stefania and I in Florence. The resulting model (Phys. Lett. **155B**, 95, 1986), originated by these efforts, was named, years later, BESS (Brealing Electroweak Symmetry Strongly) following the proposal by Ferruccio Feruglio who contributed a lot to the study of the phenomenology of the model, particularly in relation to the precision physics at LEP (see later).

INTERLUDE

- In 1987, I went to Lecce where I got a chair in Theoretical Physics. Since my teaching duty involved only one semester, I used to spend the rest of my time as a visitor in Geneva. At that time the group was working at full capacity, supported by regular visitors from Florence, Ferruccio from Padua and by other Italian PhD students (see later).

- Ferruccio has described how Gatto was leading the group in the following way:

"…When I arrived in Geneva I was rather surprised at the way Gatto interacted with the rest of the group. We, his collaborators, had our offices in a building which was detached from the School of Physics at the University of Geneva, where Gatto had his office. Despite the short distance, Gatto never came to our building. He preferred to talk to us over the phone on a daily basis.

Every afternoon (or almost) at around five o'clock, he called one of us to discuss the latest developments in the project we were working on.

He would spend a hour or more bringing himself up to date but also making comments, asking questions and giving advices…..Generally, once a week, the whole group migrated to Gatto's room for a discussion at the blackboard, in which even some of the younger members dared to present some points and some new ideas.”

- To this memory, I would like to add the following remark:

"When the conceptual aspects of a problem were solved and there were only calculations to be done, Raoul disappeared. But, incredibly, as soon as we had finished the calculations, the phone started to ring, it was him.".

SUSY

- The scattering of the longitudinal componemts of vector resonances wich are present in the BESS model (analogue of the rho-meson) could have a phenomenological role at the LHC and the SSC.
- In order to calculate these amplitudes we made use of the equivalence theorem by Cornwall, Levine and Tiktopoulos (Phys. Rev. **D10**, 1145, 1974) stating the equality of the scattering amplitude among the longitudinal components of the vector bosons and the amplitudes for the corresponding Goldstones.

- This suggested to Raoul to investigate, in the supergravity context, the relation between the amplitudes of the spin 3/2 gravitinos and the ones for the Goldstinos. This led us to the formulation of an equivalence theorem for supergravity (R.C. De Curtis, Dominici, Feruglio, Gatto, Phys. Lett. 215B, 313, 1988).

- The excursus in the SUSY world lead us to another interesting problem: the non-linear version of the Higgs model can be obtained sending the masse or the self-coupling of the Higgs to infinity. Then, what would happen to a scalar superfield in an arbitrary Kaler manifold sending the curvature to infinity?

- It turns out that in this limit one obtains a non-linear version of SUSY which can be expressed via a constraint on the superfield:

$$\Phi^2 = 0$$

- which is analogous to the constraint on the Higgs field in the same limit

$$\Phi_H^2 = < \Phi_H^2 >$$

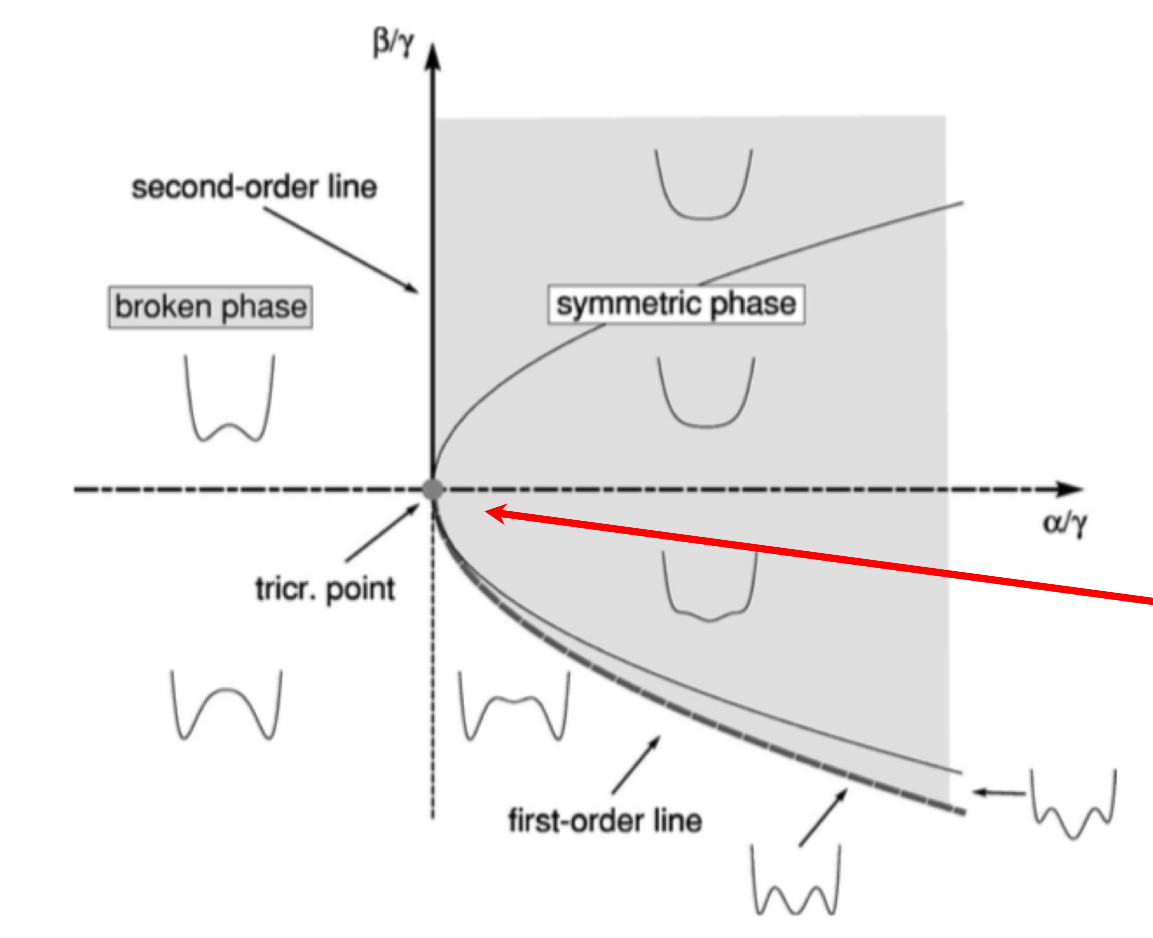
- This paper (R.C., De Curtis, Dominici, Feruglio, Gatto. Phys. Lett. **220B**, 569, 1989), except for a couple of scattered quotations, was never cited until 2010, after more than 20 years, by Antoniadis, Dudas et al… But then it became quite popular among people interested in supergravity.

QCD AT FINITE TEMPERATURE AND DENSITY

- At more or less the same time, Raoul's collaboration with Barducci, De Curtis, Giulio Pettini (a student of mine), and myself went back to QCD, but this time at finite temperature and density, using again the CJT method. The most important result, found in this research, was that the phase diagram of QCD, in temperature and chemical potential, shows up a tricritical point, that is a point where a first order phase transition line meets a line of second order (Phys. Lett. **231B**, 463, 1989).

- What we had found out was completely unexpected, and we did not know any paper mentioning such a possibility. At first, we thought it was an effect due to the approximations used. We then decided to look at the Gross-Neveu model, a two-dimensional model which has many of the characteristics of QCD. We found that also in that case the tricritical point is present. (U. Wolff, Phys. Lett. **157B**, 303, 1985)
- I have to confess that, at the beginning, we did not quite understand the origin of such a result.

- I presented this paper to the Aachen Conference in September 1989. I remember that Karsch found our result particularly hard to believe. It must be said that the calculations on the lattice were made at zero density, due to technical problems, while the tricritical point is an effect of finite temperature and density.
- Only later we understood our finding, expanding: the grand potential as a series in the order parameter, when close to the second order phase transition



$$\Omega = \frac{1}{2}\alpha\Delta^2 + \frac{1}{4}\beta\Delta^4 + \frac{1}{6}\gamma\Delta^6.$$

$$\alpha(T_{tc}, \mu_{tc}) = \beta(T_{tc}, \mu_{tc}) = 0$$

When moving close to α = 0 and β > 0, one approaches negative values of β, the phase transition goes from second to first order. The tricricritical point is defined by α = β = 0. This translates in the plane (T,μ) since both α and β are functions of the temperature and of the chemical potential.

- We later discovered that two japanese, Asakawa and Yazaki (Nucl. Phys. **A504**, 668, 1989), had achieved the same result using a Nambu-Jona Lasinio approximation to QCD.

- Thr possible existence of the tricritical point in QCD is also supported by some lattice calculation at finite density (Z. Fodor and S. D. Katz, Phys. Lett. **B 534** (2002) 87)

LEP PERIOD

- Between the end of 1989 and the beginning of 1990, the LEP at CERN and its competitor, SLC at SLAC, came into operation and we started with a more phenomenological work. Peskin and Takeushi before, Altarelli, Barbieri and Caravaglios after, had shown that the characteristics of the Z, which were to be measured with great precision at the two machines, could be summarised in three parameters, whose deviations from their SM value represented a measure of the effects of possible new physics beyond the Standard Model.

- The group focussed on the deviations of these parameters arising from the BESS model. Part of these works and also the study of the heavy vector bosons were carried out not only by the group made up by Raoul, Stefania, Daniele, Ferruccio and myself, but we got contributions also from Guido Altarelli and Pierre Chiappetta.

- The parameters defining the BESS model were the gauge coupling of the new vector resonances and their direct couopling to the fermions. I remember that the region allowed by the data was becoming smaller and smaller as the new data were arriving, and, at some point, Guido, with his typical sense of humor, defined that region as the

“**strip of Gaza**”.

HEAVYY QUARKS AND MESONS

- In 1992, Aldo Deandrea and Nicola di Bartolomeo arrived in Geneva, as Raoul's PhD students, and they were involved both in some BESS extension and into a collaboration started the year before with Giuseppe Nardulli (Bari) in a line of research on effective models for heavy quarks and mesons, for which many experimental results were arriving. This line of research ended with a review, published in Physics Report **281,** 1455, 1997, which is still receiving great attention from the experts. This work continued until 2000 as a collaboration of Raoul with Beppe, Deandrea and Polosa

Raoul in 1996

QCD AT T = 0 AND HIGH DENSITY

- In 1998, there was a renewd interest in QCD at high density. In this problem color symmetry is broken in a way similar to the breaking of the U(1) in superconductivity with the formation of diquark condensates analogous to the Cooper pairs.

- Since we had been interested in QCD at finite temperature and density, Raoul immediately saw the possibility of a new line of research. I went to CERN in July 1999, and we started to work on this subject formulating the effective lagrangian describing the Goldstone fields originating from the breaking of $SU(3)_c$ (Phys. Lett. **464B**, 111, 1999).
- In the summer of 2000, I met Beppe Nardulli in DESY, and together with Raoul and several students of Beppe in Bari (Mannarelli, Ruggieri et al.), we started a deeper study of this subject.

- Many aspects of high density QCD, with various possible phases, were studied in this project. The most interesting results were the discovery of an instability in the phase which was thought to be the most energetically favourable (Phys. Lett. **605B**, 162, 2005), and in a subsequent work (Phys. Lett. **627B**, 89, 2005), where it was shown that such instability would not occur in a non-homogeneous phase: the so-called LOFF (Larkin-Ovchinnikov-Fulde-Ferrel) phase, extensively studied by the condensed matter physicists.

Raoul in 1998

THE END OF THE COLLABORATION

- Starting from 2005 I was involned with the foundation of the GGI and then as deputy coordinator from 2006 to 2012. As a consequence, with my great regret, I was unable to continue the collaboration with Rapul and the other members of the group.

- After 2006 Raoul continued to work in QCD at high density with Beppe and his Bari students. Beppe passed away in 2008 and Raoul continued on the subject with Ruggieri, Anglani, Ciminale, Ippolito, Pellicoro (all Beppe students) and Abuki an INFN vistor in Bari
- His last paper was in 2014 (Phys.Lett. **B734,** 255, 2014) with Ruggieri and Castorina, Oliva and Greco from Catania.

- I met Raoul for the last time at CERN in 2006. Since then we were exchanging e-mails and very few telephone calls. Last e-mail I got from him was on Dece,mber 22, 2015 in answer to my wishes for the incoming Xmas and said:
- "….. My illness obliges me to stay, for most of my time, at the hospital with a slow but continuous worsening, I am trying to adapt myself to this situation…."

- In fact, since 2014 it had been increasingly difficult to communicate with Raoul. The fact that he could no longer continue his activity had a profound effect on him, considering his passion for physics.

- An example of this, I remember that once he had to go through total anestesia for a surgery. he told me that the first thing he did, as soon as he was awake, was to try to remember the Schrodinger and the Dirac equations

1973 – The prize of the President of the Italian Republic

2003 – The Fermi prize from the Italian Society of Physics

- Althought I was prepared, when I learned that Raoul was passed away, I was deeply shocked and moved. I had lost a great master and a friend