Scientific and personal recollections of Roberto Petronzio

Giorgio Parisi

Roberto Petronzio was born in 1949. He graduated with Nicola Cabibbo in 1972 in Rome University *La Sapienza*.

He was a researcher in Rome University *La Sapienza* up to 1979.

At that time he went to CERN as staff member from 1979 to 1986.

In 1987 he came back to Rome and he became a full professor of the newly founded University of *Tor Vergata*.

From 2004 to 2011 he was president of the INFN, the Italian Institute of Nuclear Physics.

He was very successful in this enterprise. He managed to lead the institute through a very turbulent period, maintaining independence from political power, with the same calm and determination with which he was able to lead a sailboat in a stormy sea.

I will try to divide his works into different overlapping categories

- Perturbative QCD

- Weak interaction

- Lattice QCD, the exploratory age.

- Weak interactions on the lattice

- Lattice QCD, the mature age.

The fist paper of Roberto was *The nucleon as a bound state of three quarks and deep inelastic phenomena*. It appeared in August 1973.

It was based on a very nice idea of describing the quarks wave function inside the nucleon in the $p = \infty$ frame using information coming from internal symmetries like $SU(6)$. The paper was extended to get predictions for other processes like electron-proton annihilation, neutrino scattering and lepton production in proton-proton predictions.

It was a very interesting paper:

- Good models of parton distribution were quite rare at that time. It one of the first reasonable model for the gluonic structure function.

- It stress the importance of the $p = \infty$ frame, that will play a very important role in understanding scaling violations in a parton model framework.

In the complex of the 56, $\ell = 0$ and 70, $\ell = 1$ states there are three spin $\frac{1}{2}$ octets which, according to this rule, have the explicit expression (for $J_z = +\frac{1}{2}$):

$$|A\rangle = |8, \tfrac{1}{2}, \tfrac{1}{2}, 0, 0\rangle_{56}$$

$$|B\rangle = -\frac{1}{\sqrt{3}} |8, \tfrac{1}{2}, \tfrac{1}{2}, 1, 0\rangle_{70} - \sqrt{\tfrac{2}{3}} |8, \tfrac{1}{2}, -\tfrac{1}{2}, 1, 1\rangle_{70} \qquad (25)$$

$$|C\rangle = \frac{1}{\sqrt{2}} |8, \tfrac{3}{2}, \tfrac{3}{2}, 1, -1\rangle_{70} + \frac{1}{\sqrt{3}} |8, \tfrac{3}{2}, \tfrac{1}{2}, 1, 0\rangle_{70} + \frac{1}{\sqrt{6}} |8, \tfrac{3}{2}, -\tfrac{1}{2}, 1, 1\rangle_{70}$$

The physical baryon octet will be a linear superposition of these states.

On the basis of Eqs. (16), (21), (22), and (25) we can explicitly compute the distribution functions $p_0(x)$ and $n_0(x)$, i.e. the average number of p and n constituents inside a proton, with a fraction x of total momentum. In the case of a pure 56, $\ell = 0$, the wave function factorizes into a space part and SU(6)$_W$ tensor [see Eqs. (15) and (21)] so that

$$P_0(x) = 2 n_0(x) \qquad (\text{unmixed } 56, \ell = 0) \qquad (26)$$

As mentioned in the Introduction, this leads in our scheme to the bound:

$$\frac{3}{2} \geqslant \frac{F_2^{eN}}{F_2^{eP}} \geqslant \frac{2}{3} \qquad (\text{unmixed } 56, \ell = 0)$$

which is contradicted by experimental data in the region $x \sim 1$.

I started to work with Roberto in 1974. Maybe our best paper of the Roman period was *On the breaking of Bjorken scaling*, which was the first computation were scaling violations were computed in QCD taking care of the presence of Gluons.

The paper was built on Roberto's great experience on parton wave functions inside the nucleon, especially on the gluonic contribution.

It is remarkable that the computation was done 1976 *before Altarelli Parisi evolution equations*.
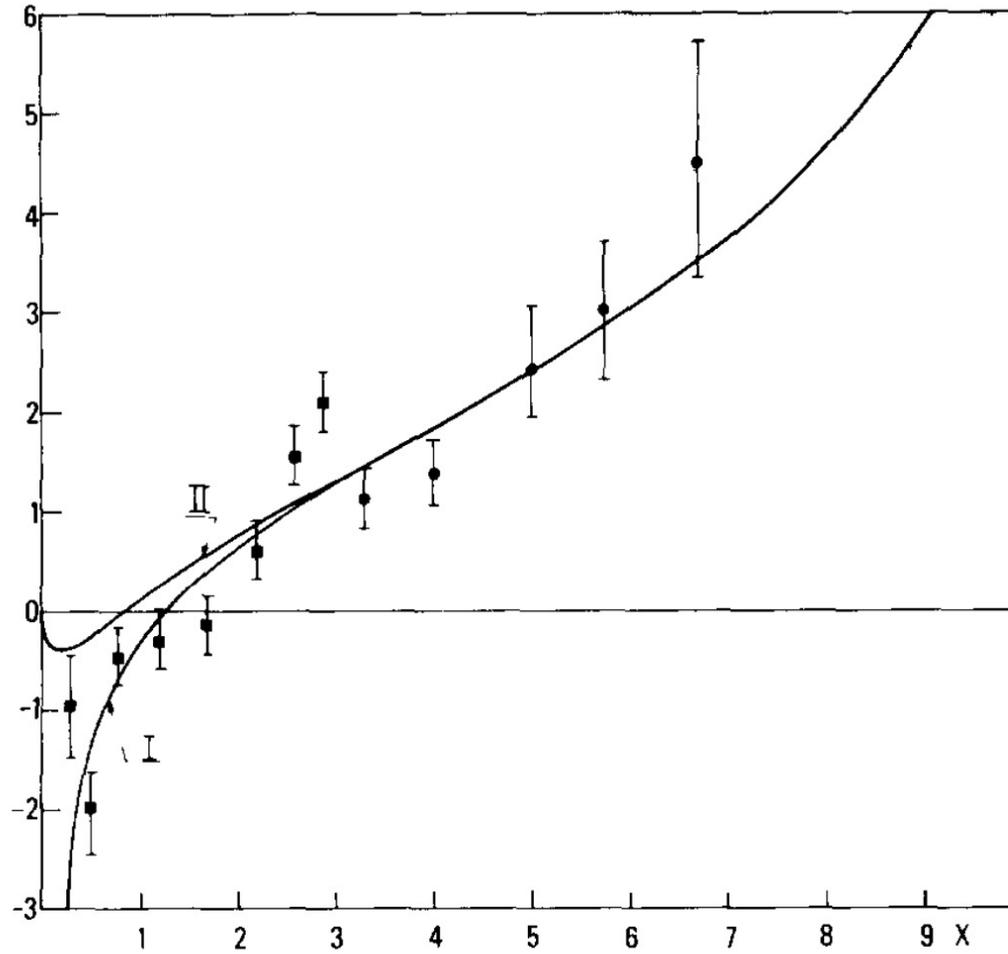
Fig. 3 Curve I is our prediction for $d \ln F_2^p(x, q^2)/d \ln q^2$ compared with experimental data taken from ref. [15] (●) and ref. [16] (■): the points taken from ref. [15] are $[d \ln W_1/d \ln q^2 + d \ln W_2/d \ln q^2]/2$ which correspond to $(c_1 + c_2)/2$ of their table 1. Curve II is obtained retaining only the octet operators in the operator expansion.

Roberto went to CERN in 1977. Most of his works of the fist years were on QCD and weak interactions.

A seminal work with deep theoretical consequences was *Relating hard QCD processes through the universality of mass singularities* with Amati and Veneziano (1978).

"We obtain at all orders the factorization of mass singularities for every hard QCD process. These appear in a universal factor that can be reabsorbed into the standard parton density. Thus suitable ratios of cross sections can be computed by a perturbative expansion in the running coupling constant. "

This paper proved the correctness of the perturbative expansion for hard processes.

At the end of the seventies, the first QCD pertubative contributions were computed.

Two crucial seminal contributions were given by Roberto in 1978 with the papers *Transverse momentum of muon pairs produced in hadronic collisions* and *Transverse momentum in Drell-Yan processes* by Altarelli, myself and Roberto. A careful job was done in studying the increase of the average squared momentum transverse as function of Q^2 as functions of the various parameters.

A problem that we had to face was the separation of the two contributions: one coming from the intrinsic spread of the quark wave function and one coming from hard processes.

A paper that had a long influence was Small transverse momentum distributions in hard processes by Roberto and myself (1979). The problem was the find the *small* transverse momentum behaviour of the transverse momentum distribution of hard produced pairs as the effect of multiple gluon productions. Many ingredients entered in the cocktail.

- The leading logs approximation for multiple soft gluon bremsstrahlung.
- The exponential dumping of the elastic form factors.
- The different behaviour of the cross sections in momentum and in impact parameter space.

An other paper that had a long and may be larger influence was Singlet parton densities beyond leading order by Curci, Furmanski, and Roberto (1980).

This was the manifesto for next to the leading order computation in QCD. The importance of the paper was not only in the detailed computations, that were highly non-trivial, but in proving for the first time that those computations were possible

The technical tool that the invented was based on the explicitly on the factorization properties of mass singularities. In this way *"within our scheme the predictions for a particular process are obtained by convoluting a universal parton density with a short-distance cross section specific to the process."*

It was the triumph for the marriage of the parton model with QCD.

The same technology allowed the computation of next to the leading order results in other processes, as it was done in the paper by *Lepton pair production at large transverse momentum in second order QCD* Ellis, Martinelli and Roberto (1983).

Roberto was always very interested in weak interaction. There were two remarkable papers Bounds on the Number and Masses of Quarks and Leptons by Maiani, myself and Roberto (1978) and Bounds on the fermions and Higgs boson masses in grand unified theories by Cabibbo, Maiani, myself and Roberto (1979).

"In the framework of grand unifying theories, the requirement that no interaction becomes strong and no vacuum instability develops up to the unification energy is shown to imply upper bounds to the fermion masses as well as upper and lower bounds to the Higgs boson mass."
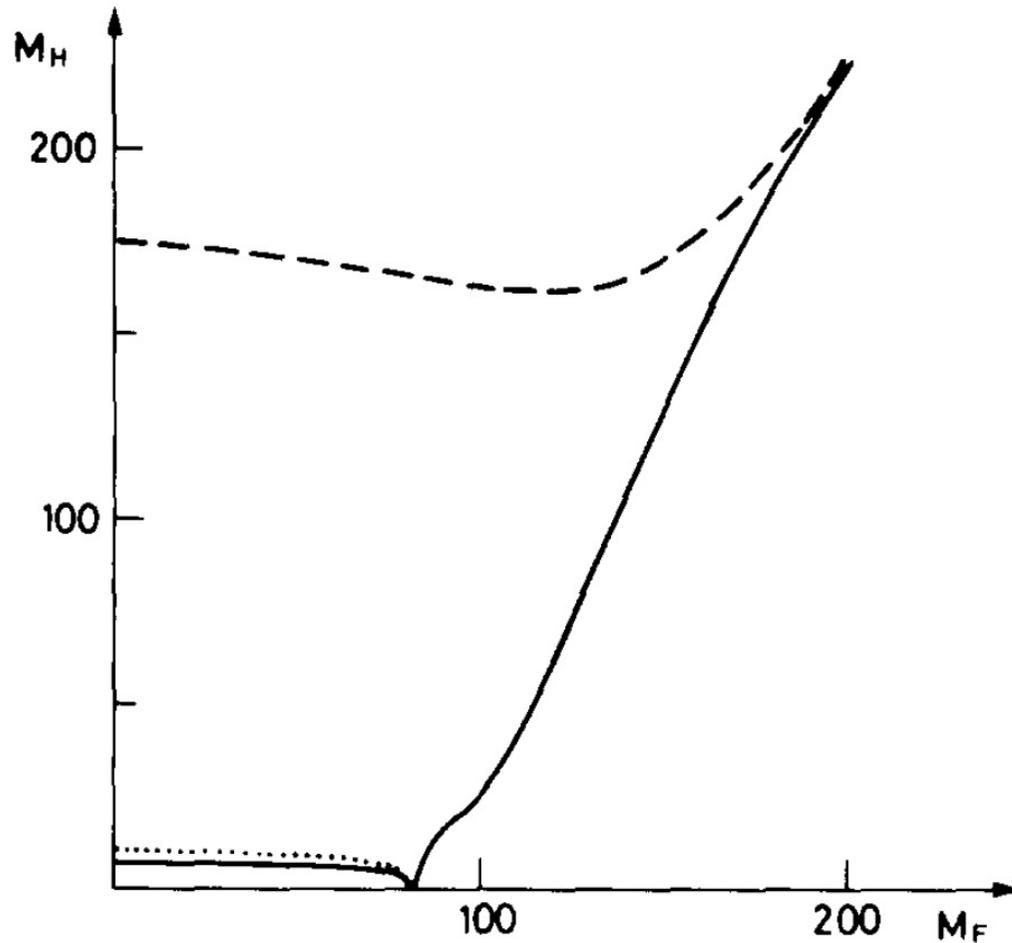
Fig. 1. Bounds on the mass of the Higgs boson (m_H) as a function of the top quark mass (M_f) in the case of three generations. We have taken $\sin^2 \theta_W = 0.2$. The dashed line and the full line represent the upper and the lower bound, respectively. The dotted line is the prediction of the massless theory. The curves end in correspondence to the upper bound on M_f, eq. (4.2).

Flavour changing top decays in supersymmetric extensions of the standard model de Divitiis, Roberto, and Silvestrini (1997)

The flavour changing top decays $t \rightarrow charm + Z_0$, $t \rightarrow charm + g$, $t \rightarrow charm + \gamma$, are predicted with invisible rates within the standard model and may represent a window on new physics. We consider these processes in supersymmetric extensions of the standard model and we show that observable rates can be obtained only if the SUSY breaking is non-universal and flavour dependent.

Probing new physics through $\mu - e$ universality in $K \rightarrow l + \nu$ Masiero, Roberto and Paradisi (2006)

"Supersymmetric (SUSY) extensions of the Standard Model can exhibit $\mu - e$ nonuniversal contributions(...) They are quite effective in constraining relevant regions of SUSY models with lepton flavour violating currents."

However, starting from the eights, the central interests of Roberto were related to lattice theories.

Roberto started to work on lattice theories with Guido Martinelli and myself on the two-dimensional $O(3)$ spin model in (1981).

In this framework we presented the *first explicit computation of the improved action on the lattice* where $O(a^2)$ corrections were absent (1982).

Roberto (with Martinelli and Virasoro) presented the first computations topological charge for the two-dimensional $O(3)$ spin model.

Most of the fun was with lattice QCD. It was a new world that we started to explore with excitement. All the low-energy strong interaction parameters were computable.
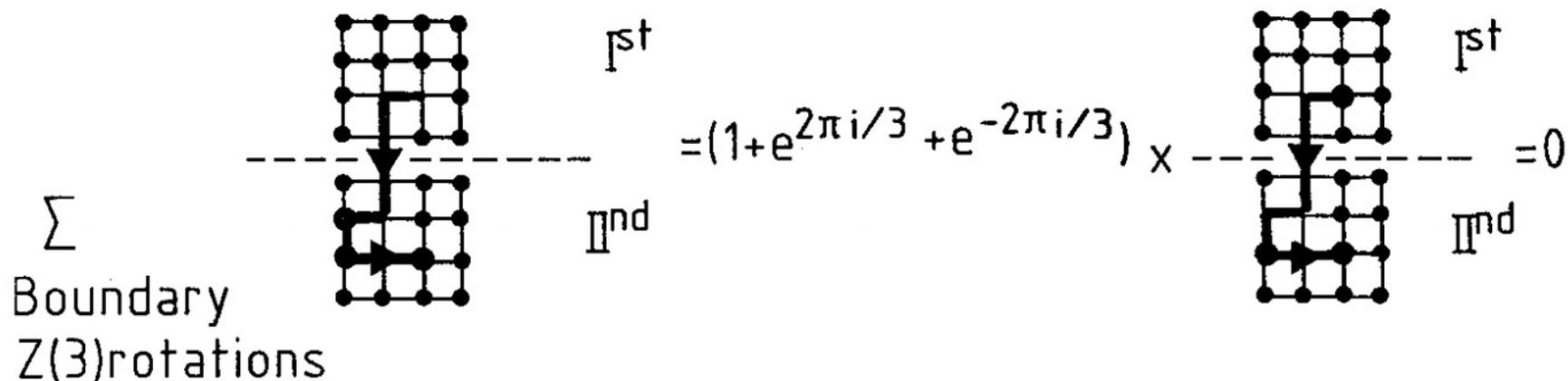
We computed the proton and neutron magnetic moments in lattice QCD by measuring the mass splitting in presence of a magnetic field (with Martinelli and Rapuano).

We computed (1982) the strange hadron masses, in particular the $\Lambda - \Sigma_0$ splitting (with Martinelli and Omero)

We also computed (1982) the string tension (Rapuano, Roberto and myself). The computation was possible due to a clever trick (multihit).

Boundary effects and hadron masses in lattice QCD (Martinelli, Roberto, Rapuano and myself 1983)

A relevant contribution to the large fluctuations of hadron masses present in lattice calculations with periodic boundary conditions is due to unphysical quark paths which are absent in the infinite volume limit. We show that these contributions can be eliminated by averaging over possible rotations of the boundary links by the elements of the Z(3) subgroup. In this way, the "effective" volume for these paths is triplicated.

$$\sum_{\text{Boundary Z(3)rotations}} \quad \boxed{\text{I}^{st}, \text{II}^{nd}} \quad = (1+e^{2\pi i/3} + e^{-2\pi i/3}) \times \boxed{\text{I}^{st}, \text{II}^{nd}} = 0$$

A very remarkable paper was *Hadron spectrum in quenched QCD on a $10^3 \times 20$ lattice* by Lipps, Martinelli, Roberto and Rapuano (1983). ($5^3 \times 10$, $6^3 \times 12$, $8^3 \times 16$)

Having used $m_{\eta s}$ and m_ϕ as inputs, we get the following results: [for the "strange proton", the "experimental" value has been obtained by standard SU(3) mass formulae]

$$a^{-1} = (2.2 \pm 0.1)\,\text{GeV}, \quad K_s = 0.1548 \pm 0.0002\,,$$

$$m_{ps} = (1.55 \pm 0.15)\,\text{GeV} \quad (\text{"exp"} = 1.51\,\text{GeV})\,,$$

$$m_{\Omega^-} = (1.65 \pm 0.15)\,\text{GeV} \quad (\text{exp} = 1.67\,\text{GeV})\,. \quad (4)$$

Having the pion mass as an extra input to fix the value of K_u we get

$$K_u = 0.1566 \pm 0.0002$$

$$m_\rho = (0.82 \pm 0.03)\,\text{GeV}; \quad m_K = (0.50 \pm 0.03)\,\text{GeV},$$

$$m_{K^*} = (0.93 \pm 0.04)\,\text{GeV}; \quad m_p = (1.25 \pm 0.15)\,\text{GeV};$$

$$m_\Delta = (1.35 \pm 0.20)\,\text{GeV}\,.$$

Roberto was also among the proponents of the first APE project (1984) ($12^3 \times 24$).

Weak interactions on the lattice Cabibbo, Martinelli, Petronzio (1984)

We show that lattice QCD can be used to evaluate the matrix elements of four-fermion operators which are relevant for weak decays.

The notation for these operators is that used in ref. [3]. Our results are

$$\frac{\langle \pi^+|(\bar{u}\gamma_L^\mu u)(\bar{s}\gamma_\mu^L d)|K^+\rangle}{m^2} = (4a^2)(3.7 \pm 0.3)10^{-3} \quad [2.4 \times 10^{-3}],$$

$$\frac{\langle \pi^+|(\bar{s}\gamma_L^\mu u)(\bar{u}\gamma_\mu^L d)|K^+\rangle}{m^2} = (4a^2)(8.8 \pm 0.7)10^{-3} \quad [7.2 \times 10^{-3}],$$

$$\langle \pi^+|(\bar{s}\gamma_L^\mu d)(\bar{u}\gamma_\mu^R u)|K^+\rangle = (16a^4)(-4.2 \pm 0.9)10^{-2} \quad [-1.20 \times 10^{-2}],$$

$$\langle \pi^+|(\bar{s}t^A\gamma_L^\mu d)(\bar{u}t^A\gamma_\mu^R u)|K^+\rangle = (16a^4)(-6.8 \pm 0.8)10^{-2} \quad [-1.63 \times 10^{-2}],$$

where the values in brackets are those given in ref. [10] on the basis of vacuum saturation. There is a general agreement between our results and those of ref. [10].

There were many remarkable papers on weak interactions in lattice theories. Among them:

The Kaon B-parameter and $K - \pi$ and $K - \pi\pi$ transition amplitudes on the lattice. Gavela, Maiani, Petrarca, Roberto, Rapuano.... (1988)

We find $\langle K^+|H_w|\pi + \pi_0\rangle/m_K = (7 \pm 2) \times 10^{-8}$ to be compared with the experimental value of 3.7×10^{-8}

Quenched lattice calculation of the $B \to D\,l\,\nu$ decay rate

de Divitiis, Molinaro, Roberto and Tantalo (2009)

Non-perturbative determination of the running coupling constant in quenched SU (2) (1993)

de Divitiis, Frezzotti, Guagnelli and Roberto

Through a finite-size renormalization group technique we calculate the running coupling constant for quenched SU(2) with a few percent error over a range of energy varying by a factor thirty. The definition is based on the ratio of correlations of Polyakov loops with twisted boundary conditions. The extrapolation to the continuum limit is governed by corrections due to lattice artifacts which appear to be rather smooth and proportional to the square of the lattice spacing.
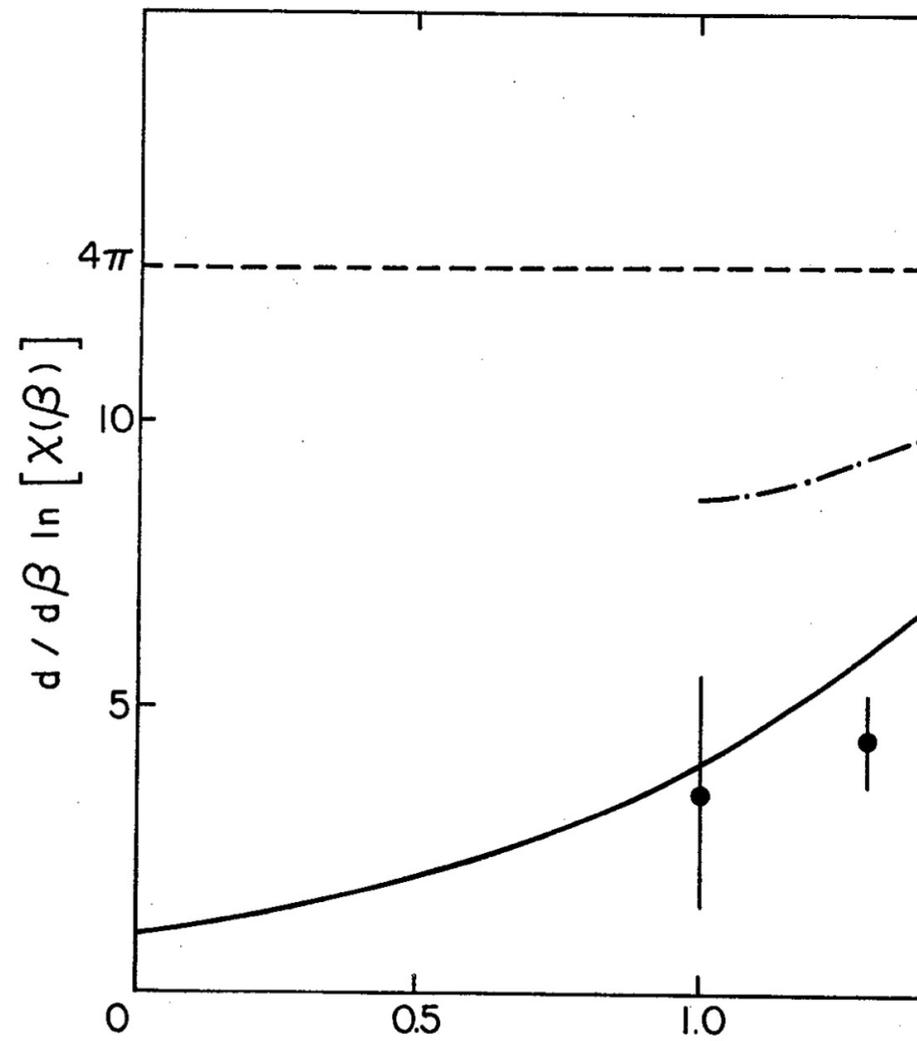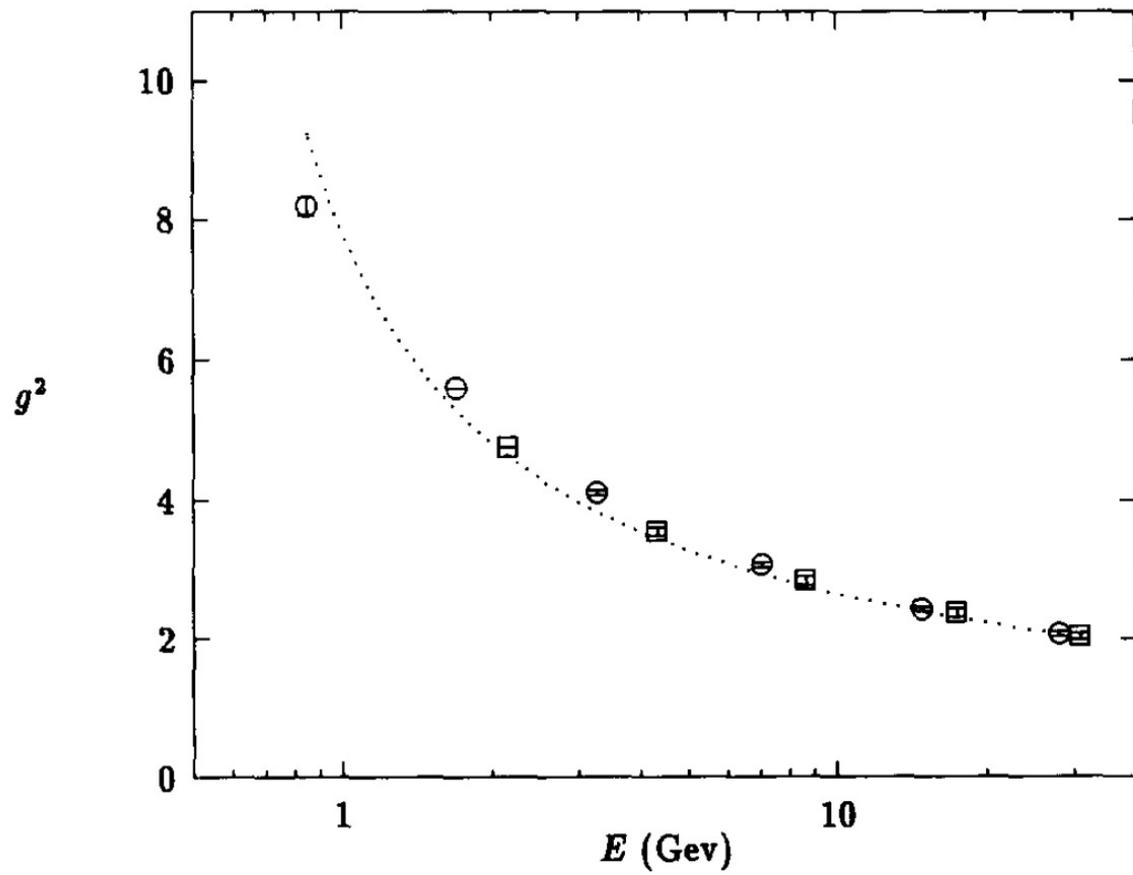
On the discretization of physical momenta in lattice QCD

de Divitiis, Roberto and Tantalo (2004)

"We have argued that the limitation represented by the finite volume momentum quantization rule can be overcome by using different boundary conditions for different fermion species."

"The method proposed can be applied to study all the quantities of phenomenological interest that would benefit from the introduction of continuous physical momenta like, for example, weak matrix elements."

QCD with light Wilson quarks on fine lattices : first experiences and physics results

Del Debbio, Giusti, Lüscher, Petronzio and Tantalo (2007)

The universality of the continuum limit and the applicability of renormalized perturbation theory are tested in the SU(2) lattice gauge theory by computing two different non-perturbatively defined running couplings over a large range of energies.

The lattice data (which were generated on the powerful APE computers at Rome II and DESY) are extrapolated to the continuum limit by simulating sequences of lattices with decreasing spacings. Our results confirm the expected universality at all energies to a precision of a few percent. We find, however, that perturbation theory must be used with care when matching different renormalized couplings at high energies.

Not only week but also full electromagnetic interactions

Leading isospin breaking effects on the lattice

de Divitiis, Frezzotti, Lubicz, Martinelli, Roberto, Rossi, Sanfilippo, Simula, and Tantalo (2013)

We present a method to evaluate on the lattice the leading isospin breaking effects due to both the small mass difference between the up and down quarks and the QED interaction. (...) We treated the dynamical quarks as electrically neutral particles (electroquenched approximation) and neglected a disconnected diagram in the charged and neutral pion mass splitting.

Why should we work on this problem if we do not have fun?

Nicola Cabibbo