# Pietro Giudice
# Research Statement

**Theoretical background**:

My research is focused on the study of non-perturbative aspects of gauge theories by computer simulations. Quantum field theories, in particular gauge theories, have been remarkably successful in predicting physical observables related to the world of elementary particles. Particularly noteworthy is the theoretical framework which describes the strong interactions of quarks and gluons (the constituents of hadrons, *e.g.* protons and neutrons): the gauge theory of quantum chromodynamics (QCD). Unfortunately, even though these theories are simple in form and we can write down the equations of motion of the fields, solving them is still a challenge, as well as determining simple properties of the particles. The formulation of QCD on a space-time lattice, introduced in the seventies, gave an important boost to tackle many unsolved problems: the lattice approach provides us with the tool to do direct simulations of the theory on a computer; it is based on a Monte Carlo evaluation of the Euclidean path integral.

Quarks and gluons are permanently confined; this means that it is not possible to separate an isolated quark at a macroscopic distance from a bound state. On the other hand, we know that confinement property of hadronic matter can disappear when the matter is under "extreme" conditions of temperature and/or (baryon) density.

Understanding the behaviour of hadronic matter under extreme conditions of temperature and density has attracted much attention in the last decades. At very high temperatures hadrons melt, and their constituents form a new phase of matter, the so-called quark-gluon plasma (QGP). The deconfinement phase transition from hadronic matter to quark-gluon matter takes place at a temperature that is 100 thousand times hotter than the interior of the sun. Such conditions did exist in the early universe a few microseconds after the big bang and can be created in heavy ion collisions at ultra-relativistic energies as provided by the accelerators RHIC (Relativistic Heavy Ion Collider) at Brookhaven (USA), and LHC (Large Hadron Collider) at CERN (European Organisation for Nuclear Research) – Geneva (Switzerland).

In highly compressed cold nuclear matter, as it may exist in the interior of neutron stars, the hadrons also lose their identity and dissolve into quarks and gluons. The expectation is that a rich structure appears in the phase diagram (including the so-called color superconductive phase).

To understand the QCD phase diagram in the region of high baryon densities new particle accelerators and detectors are going to be built in the next years: FAIR (Facility for Antiproton and Ion Research) at the GSI site in Germany with the Compressed Baryonic Matter (CBM) experiment; the Nuclotron-based Ion Collider fAcility (NICA) at Joint Institute for Nuclear Research (JINR), Dubna; there is also a plan for using heavy-ion beam at J-PARC, the Japan Proton Accelerator Research Complex.

A quantitative determination of the QCD phase diagram in the temperature-density plane is therefore of both great theoretical and experimental interest.

To study QCD at nonzero baryon density we need to introduce a nonzero baryon chemical potential ($\mu_b$) in the theory; unfortunately, the term which contain this parameter becomes a complex number and, as a consequence, the probabilistic interpretation, underlying the possibility of performing Monte Carlo simulations is lost: this is the so-called *sign problem*.

**Track record**:

There are different methods which attempt to circumvent the sign problem and during my career, I have now ten years of experience working on the sign problem, I have contributed to developing new ways to deal with this issue.

One possibility is the analytic continuation method; in this approach one simulates the theory using an imaginary $\mu_b$, which has no sign problem. The results are later analytically continuated to the real one. I have tested, for the first time [1], the method in the case of a non-Abelian gauge theory, with two colors, where actually there is no sign problem. It was therefore possible to study the limits of the method and its range of applicability.

Recently, an alternative to Monte Carlo simulations has been proposed: in this case the (stochastic) evolution of the gauge fields is governed by complexified Langevin equations, which can be integrated even at non-zero $\mu_b$. The problem in this case is that even if it is always possible to obtain an answer from the Langevin algorithm, sometimes it is wrong. I have tried to shed light on this problem studying a simple model [2]. I have clarified the relevance of taking under control the distribution, which is effectively sampled during the stochastic process, to justify the procedure. If the distribution has support in a strip in the complexified configuration space only, correct results are expected.

Other interesting developments come from theories which share important features with QCD and where simulations at non-zero $\mu_b$ are possible. The most interesting case is "2-color QCD" where a variety of distinct physical regimes appear at low temperature as $\mu_b$ is increased. I have used lattice simulations to study the phase diagram of this theory and interesting properties have already been observed [3]. This work, which is conducted by different members of a collaboration which involve Swansea University (UK) and University of Maynooth (Ireland), is still underway.

In all three cases the impact has been significant: 1) the method of analytic continuation is now used with confidence also in "3-color QCD"; 2) the Langevin method has been recently started to be tested in 3-color QCD with interesting results and my work shows how to check the correctness of the results; 3) the phase diagram of 2-color QCD is of large interest for people who work with "effective models" because they can use the lattice results to improve their models.

Moreover, it is worth mentioning here my contributions to study the properties of the phase diagram in the opposite regime, high temperature and low/zero baryon density, where the QGP is formed. In a recent paper [4], which is the fruit of a collaboration involving four universities, we have measured two transport coefficients, the electrical conductivity and the charge diffusion, which characterise the QGP.

**Research plan**:

My research plan for the next years is mainly focused on investigate the properties of cold dense matter. The sign problem will be tackled exploring the most promising methods:

1. The first method is the Langevin approach. It is a powerful method which could give us the capability to simulate dense matter; unfortunately, the most general conditions to characterise its reliability have not been formulated. My task is therefore to understand, both from a purely theoretical point of view and by numerical simulations on different models, the fundamental reason of the failure of the method in some cases. A way to shed light on the problem seems to be linked with the properties of the distribution which is sampled during the stochastic process: my plan is to explore this connection. Having a trustworthy Langevin method could be a real breakthrough, paving the way to understand the behavior of dense strongly interacting matter from first principles.

2. I want to understand better the phase diagram of gauge theories at low temperature and non-zero baryonic density studying 2-color QCD. It is a theory where it is possible to do simulations at $\mu_b$ different from zero; this means that it is possible to explore its phase diagram. This has a few important consequences: first of all, we will see what kind of phases, maybe new and unexpected, are present in a gauge theory; we will understand the role of the lattice discretisation effects at high values of $\mu_b$; we will have well defined results against which results of effective theories can be compared. All these results will have a clear and immediate application in the study and comprehension of similar effects in QCD. Many interesting properties have been discovered studying the theory with two Wilson fermions, but complete understanding is still far away. My task, therefore, consists in extending the simulations done so far, to unexplored regions of the parameter space. Moreover, so far the theory has been simulated on very coarse lattices; it is timely to go closer to the continuum limit. This can be done by simulations of the theory with smaller lattice spacings just changing the parameters and/or studying it with improved actions, e.g. introducing a clover term. Finally, an interesting topic I will cover during this study, in the context of 2-color QCD, are the conjectured inhomogeneous states of QCD, in particular the so-called LOFF phase (where Cooper pair have nonzero total momentum).

3. The third method I will explore is based on the idea to look at the problem using the so called "canonical ensemble" (CE). All the methods described above are based on the "grand canonical ensemble" (GCE) where the system is characterised by having a fixed $\mu_b$; in the CE instead the total quark number is fixed. In this case there is no sign problem because the simulations are done using pure imaginary $\mu_b$. Of course also the CE approach has some difficulties which have to

be tackled, but in contrast to the sign problem, they do not undermine the foundations of Monte Carlo simulations because they are not conceptual problems, but just numerical problems.

This research plan will require simulations on modern massively parallel supercomputers. As discussed in details in my CV, I have much experience with High Performance Computing: I have worked with cluster of computers and different Blue Gene machines (series P and Q). I will apply for computer time provided by national and international computer centers.

**Conclusions**:

New experimental results, which will appear in the next years, need a solid theoretical background to be correctly interpreted. Therefore it is timely for this a systematic study of the different approaches which have the potentiality to circumvent the "sign problem" and finally gives us access to the exploration of the phase diagram of QCD.

Finally, I want to mention that the sign problem is of concern not only to the community of particle physics: on the contrary, it is an obstacle to progress in many areas, from condensed matter physics (Hubbard model) to nuclear physics (study of neutron matter including explicit pionic degree of freedom in the effective Lagrangian) and common to all situations in which researchers, trying to simulate a system or a class of phenomena, are faced with complex actions. This means that giving a contribution to the solution of this problem could have important impact in different disciplines, and could lead to unexpected advances.

**Alternative projects**:

During my academic career I have worked on different problems which can be studied using the lattice field approach and Monte Carlo simulations and which could have further developments in the next years.

I tested on the lattice the effective string picture which describes the thin flux tube connecting a quark pair in the confining phase. This has been done studying 3D $Z_4$ gauge model [5] and the percolation gauge theory [6] at finite temperature.

Moreover, I investigated the properties of QED in three dimensions with dynamical fermions [7]; the effect of a strong magnetic field has been considered in [8] with its implications in understanding the properties of graphene under the same conditions.

The most recent interest is instead connected with the study of the effect of supersymmetry in the non-perturbative properties of a gauge theory at zero and nonzero temperature [9].

# References


[1] P. Giudice and A. Papa, Phys. Rev. D **69** (2004) 094509 [arXiv:hep-lat/0401024].

[2] G. Aarts, P. Giudice and E. Seiler, Annals Phys. **337** (2013) 238 [arXiv:1306.3075 [hep-lat]].

[3] S. Cotter, P. Giudice, S. Hands and J. I. Skullerud, Phys. Rev. D **87** (2013) 3, 034507 [arXiv:1210.4496 [hep-lat]].

[4] G. Aarts, C. Allton, A. Amato, P. Giudice, S. Hands and J. I. Skullerud, JHEP **1502** (2015) 186 [arXiv:1412.6411 [hep-lat]].

[5] P. Giudice, F. Gliozzi and S. Lottini, JHEP **0701** (2007) 084 [hep-th/0612131].

[6] P. Giudice, F. Gliozzi and S. Lottini, JHEP **0903** (2009) 104 [arXiv:0901.0748 [hep-lat]].

[7] R. Fiore, P. Giudice, D. Giuliano, D. Marmottini, A. Papa and P. Sodano, Phys. Rev. D **72** (2005) 094508 [Phys. Rev. D **72** (2005) 119902] [hep-lat/0506020].

[8] P. Cea, L. Cosmai, P. Giudice and A. Papa, Phys. Rev. D **85** (2012) 094505 [arXiv:1204.6112 [hep-lat]].

[9] G. Bergner, P. Giudice, G. Münster, S. Piemonte and D. Sandbrink, JHEP **1411** (2014) 049 [arXiv:1405.3180 [hep-lat]].