MASTER THESIS PROJECTS @ IFAE THEORY GROUP

TITLE: Applying quadratic Padé approximants to the pion vector form factor

PROJECT DESCRIPTION: The pion vector form factor function captures the strong interaction dynamics behind the coupling of a charged pion with a photon. Once Taylor expanded, the coefficients of such an expansion provide important information about the pion properties, for instance the charge radius. An improved method for obtaining theses coefficients incorporating experimental information not only al low but also at higher energies is that of Padé approximants. However, these rational approximants are meromorphic functions, while the form factor is assumed to be analytic everywhere in the complex plane except for a branch cut starting at the two-pion threshold.
The aim of this project is to use instead the so-called quadratic approximants, which by construction include a branch cut, to test whether the description of the form factor in this case is better than rational approximants, thus allowing for an improved description of the Taylor expansion coefficients.

CONTACT PERSON: Rafel Escribano (rescriba@ifae.es)

TITLE: A first prediction of the radiative decays $\eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$

PROJECT DESCRIPTION: Very recently, the BES-III Collaboration has measured for the first time the doubly radiative decay $\eta' \to \pi^0\gamma\gamma$ with a result that seems to be two times bigger than naïve theoretical expectations existing so far.
Given the importance of these decays for testing effective theories of QCD at low energy, the aim of this project is to perform a detailed computation of this process taking into account the contribution of intermediate vector and scalar resonances. Special emphasis will be devoted to the calculation of the dominant ω-exchange in a very simple framework named Vector Meson Dominance.

CONTACT PERSON: Rafel Escribano (rescriba@ifae.es)

TITLE: The Born-Infeld Theory

PROJECT DESCRIPTION:

Several of the most notorious open questions in particle physics deal with photons and photon-matter interactions. It is well stablished that the relativistic theory behind such interactions is the Quantum Electrodynamics (QED) and then such open questions are explored within QED. What would happen, however, if QED would not be the final answer? What if QED would be only the low-energy realization of a more fundamental theory yet to be discovered?

In this Bachelor project, we will explore a modification of QED to introduce non-linearities. Such extension is known as the Born-Infeld Theory, an example of what is known as nonlinear electrodynamics. Of special relevance will be the comparison between this theory and QED at low energies, the Heisenberg-Euler Theory. This project is rather formal and only for those wishing to learn the techniques of field theory.

This project requires knowledge about electrodynamics and quantum mechanics. Aspects of effective field theories will be learnt and calculations for photon-photon scattering will be performed, calculations partially based on published results. The last part will require simulations of the obtained results and comparison with experimental data.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Electric dipole moments: a small window to the future

PROJECT DESCRIPTION:

Electric dipole moments (EdMs) of constituent particles such as protons and neutrons violate both parity and time-reversal symmetries. As such, the measurement of these EdMs yield a model-independent measure of CP violation, a clue ingredient to understand the matter-antimatter asymmetry in the universe. The Large Hadron Collider has not discovered new particles yet. Precise EdM measurements can fill the gap towards a complete new scenario in understanding the basic of our universe.

The project will consist on understanding EdMs, explore what is known and what not, their role in understanding our universe and make a first calculation within the context of electrodynamics and quantum mechanics of a neutron EdM. In a second part, using the language of effective Lagrangians, a potential relation between CP violating hadronic decays such as eta and eta-prime to two pions and the proton and neutron EdMs will be studied.

This is a formal project for those interested in the most mathematic aspects of particle interactions.

The methodology will consist in reading published articles about the subject, understanding present experimental bounds after searching in specialised databases, and a first glance toward the calculation of the neutron and proton EdM using quantum field theory techniques.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Photon-photon scattering at the Large Hadron Collider

PROJECT DESCRIPTION:

Photon-photon scattering, also called light-by-light $\gamma\gamma\rightarrow\gamma\gamma$ scattering, is a purely quantum-mechanical process forbidden in classical electrodynamics. However, and thanks to the polarisation of the vacuum, quantum electrodynamics allows such a reaction via virtual one-loop box diagrams which, at leading order in the fine structure constant, is still a very suppressed process.

With enough precision, contributions of the Standard Model of particle physics will also show up by yielding the light-by-light scattering with electrically charged fermions and W bosons as mediators of the interaction. At some point, then, hadronic matter will enter into the game, in the form of quark-loop diagrams of particular flavour Nf.

In this project, we shall understand the light-by-light scattering process, specified by each energy region, and focus on the role of the quark loops. We shall attempt for a leading order calculation of the hadronic calculations and a first glance towards the non-perturbative contribution (which is, when quarks hadronize to form bound states) to such process.

The methodology will consist in working out the relevant Feynman diagrams at the loop level, and attempt their calculations. Few results can be found in published articles but there are still missing pieces to calculate. We shall then compare our results with published ones and try our own contribution.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Sum rules within the large-Nc limit of Quantum Chromodynamics

PROJECT DESCRIPTION:

Quantum Chromodynamics (QCD) is believed to be the gauge theory describing the interactions between gluons and quarks as degrees of freedom, being the gluons the force carriers of the theory, such as is the photon for quantum electrodynamics. Within QCD, the role of the electric charge is play by the colour charge. In fact, QCD is a non-abelian gauge theory with a symmetry group of SU(3). Nevertheless, neither gluons nor quarks are observed isolated in nature due to the confinement phenomenon. In practice, quarks form hadrons and only the properties of these hadrons and their decays is what we can observe and measure.

Symmetries play a key role toward understanding the physics behind hadronic interactions. In particular, sum rules understood as relations among integrals over given cross sections of particular quantum numbers yield important information on the way quarks form hadrons. Since the confinement mechanism is not well understood yet, the aforementioned cross sections cannot be calculated and the usefulness of sum rules cannot be put under scrutiny. Still, there is a framework where such calculations can be performed which is the limit where the number of colour charges goes to infinity.

The goal of this project is to calculate certain *photon-photon to hadron* cross sections within the large-Nc limit of Quantum Chromodynamics and check whether the sum rules work. An immediate application of these results will be related to the hadronic contribution to the anomalous magnetic moment of the muon for which a state-of-the-art discrepancy at the level of 3 to 4 standard deviations between theory and experiment is observed.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Veneziano amplitudes for the light-by-light scattering

PROJECT DESCRIPTION:

The anomalous magnetic moment of a particle is a quantum mechanics effect induced by loop diagrams on top of the classical magnetic moment. For elementary particles with spin ½ , the classic Dirac theory predicts a value which deviates from the measured one precisely by the anomalous magnetic moment. Being a loop contribution, the knowledge of the whole Standard Model of particle physics is required. It is so that the anomalous magnetic moment has been recognise as the particle physics in a nutshell.

State-of-the-art measurement and calculations deviate by about 4 standard deviations, not enough to claim that the Standard Model is not complete, but large enough to sound the alarms. From the theory side, the largest source of error comes from a class of diagrams called hadronic light-by-light scattering contributions. They are purely quantum-mechanical objects and represent an unsolvable multi-scale problem.

In this project, we would like to approach the hadronic light-by-light scattering contributions using string theory insights condensed in the form of Veneziano amplitudes. With such amplitudes, we will attempt to explore the whole light-by-light and discuss the role of the different quantum numbers entering into the process.

This is an innovative project which will require a state-of-the-art reading to get the required background as well as formal developments giving raise to the formulation of the desired amplitudes. Fortunately, part of the calculates required are already available in the literature, calculations which will have to crosschecked in detail.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: The proton radius puzzle from a new perspective: modifying quantum electrodynamics.

PROJECT DESCRIPTION:

The proton, one of the fundamental constituents of matter -which was discovered almost hundred years ago- has lost weight. No one knows exactly how big a proton is, and that's a problem.

Protons are particles found inside the nucleus of atoms. For years, the proton's radius seemed pinned down at about 0.877 femtometer. But in 2010, a new measurement technique yielded a different answer which leads to what is known as the “proton radius puzzle”. Experimentally, one does not directly measure the physical size of the proton, but rather its effective volume via scattering experiments and from that infer its radius.
The measurement of the Lamb Shift was a clue point to establish Quantum Electrodynamics

as the theory of light-matter interaction. Yet, a recent measurement of the Lamb Shift in a muon hydrogen has shaken our understanding of the basics of our universe since yielded a proton's radius quite different from the one obtained using well-stablished scattering experiments.

The different among the measurements is such that to solve it one is starting to doubt about the validity of the Standard Model of particle physics. Most of the theoretical attempts then speculate about physics beyond the Standard Model as a way to closing in the gap. The standard path of these new theories requires the inclusion of extra particles heavy enough not to be detected at the Large Hadron Collider. Nowadays, this path could not solve the puzzle yet.

A completely different and speculative alternative would modify the rules of Quantum Electrodynamics. This is the avenue proposed within this project. For more information, please do not hesitate to contact me.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Dispersive approach to the electron and muon anomalous magnetic moment the meaning of the alpha/2pi correction

PROJECT DESCRIPTION:

Understanding Quantum Electrodynamics calls for having more insight and physical intuition behind QED calculations. As Feynman once said, we have no way to get a general idea of the result of a calculation to be expected. For example, for the first QED correction to the anomalous electron magnetic moment, the famous alpha/2pi correction, we do not have a physical picture by which we can easily see that the correction is indeed alpha/2pi, we do not even know why the sign is positive (other than computing it). This consideration of course translates as well to the second-order calculation, and so on.

Is there any general idea of what is contained in each correction? Along these lines, is there any physical intuition on how a calculation for the anomalous electron moment would translate into the muonic or tauonic counterpart?

In this project, we will explore the role of dispersion relations for the electromagnetic interaction vertex calculated using the analytic properties of Feynman graphs in perturbation theory together with the exact Thomson limit of the Compton scattering of photons by electrons.

In this case, an intuitive view of the result, modulus and sign, can be easily gained and the relation between different lepton moments explored.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Unitary constraints on Dalitz plot distributions: separating the wheat from the chaff.

Resonance contributions versus non-resonance backgrounds

PROJECT DESCRIPTION:

The Dalitz-plot distributions (DP) characterises the physics region of a particular 3-body decay in terms of the invariant masses of its final state. The distribution of the population of experimental events on the Dalitz region given raise to the DP reveals the presence of 2-particle resonances formed in any of the three pairs of particles. The analysis of DP in B decays is difficult because involves the presence of many structures in a large range of available energy. The large mass of the B meson in contrast to the low mass of the particle in the final state (pion, kaon, eta) allow the intermediate states to undertake rescattering and eventually yield resonance states.

One of the most used technics in experimental studies for B decays is the isobar model understood as a superposition of Breit-Wigner (BW) resonances. BWs, however, when superposed, break unitary and modify the phase motion of the distribution with potential errors obviated in practice.

In this project, we shall explore the constraints imposed by unitary, analyticity, and crossing symmetry in 3-body decays with important rescattering effects. In this respect, we foresee to produce a model-independent method for analysing DP and test the viability of the recent discovered resonances in DPs. This methodology will be important as well for studying CP asymmetries already observed in in 3-body decays.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Regge trajectories in the baryon sector. A test of the diquark content on baryon spectroscopy

PROJECT DESCRIPTION:

Baryons are composite subatomic particles made up of three quarks, which participate in the strong interactions of the Standard Model. The most familiar baryons are the protons and neutrons that make up most of the mass of the visible matter in the universe. The way how the quarks inside baryons interact among themselves to give raise to their mass is still an open question. Any model explaining this process has to face the proliferation of baryon resonances in the light-quark sector observed in spectroscopy.

One of the most successful scenarios based on old String Theory ideas considers the baryon made up of a diquark system interacting with the third split-apart quark.

In this project, we propose to explore the spectroscopy induced by such ideas making use of Regge trajectories, a classification of particles in terms of internal quantum numbers and mass, and contrast it with the state-of-the-art spectroscopy studies collected in the Particle Data Tables.

This study should allow us to conclude whether the diquark model explored recently in the context of AdS/QCD theories holds and whether the standard quark model is enough for describing the zoo of baryon resonances.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Violations of the Landau-Yang theorem and implications for gamma gamma physics

PROJECT DESCRIPTION:

The Landau-Yang theorem states that due to the conservation of C-parity (charge conjugation) a stationary state with spin-1 cannot decay into two photons. Its application to the recently measured 125GeV mass particle decaying into two photons ruled out the possibility that such particle is a spin-1 state. The Landau-Yang theorem, however, requires explicit and implicit assumptions. When they are avoided, the possibility of a spin-1 particle decaying into two photons will not be prohibited and this may have implications for calculations of observables for which high precision is required.

In particular, when either the spin-1 particle or the photons are off-shell, are virtual, the transition is possible. This can have implications in phenomenological studies of photon photon scattering cross sections at low and high energies.

In this project, we shall explore the assumptions given raise to the Landau-Yang theorem, consider the cases where such result can be avoided and study the implications for the e+e- to e+e- pi+ pi- amplitude.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Bootstrap method as a noise filtering for experimental data how unitary constraints improve the determination of fundamental constants

PROJECT DESCRIPTION:

It is a common practice in particle physics to extract the value of fundamental constants of nature after a fit to a given set of experimental data. The experimental uncertainty induces an error on the determination of the constant. The same happens when studying structure functions, form factors, or scattering amplitudes using a particular parameterization which coefficients must be fitted to experimental results.

Physical amplitudes respect basic properties such as unitary, analyticity, and crossing symmetry, and one can wonder whether the experimental data one should use do as well respect such fundamental constraints.

In this project, we will explore the statistical method of bootstrapping to design a method which should yield a noise filtering for experimental data. In cases where experimental uncertainties overpass the unitary constraints, after applying the noise filtering method, one should expect smaller final uncertainties in the determination of constants and structure functions.

We will then explore the method of noise filtering using the bootstrapping technic to study the hadronic vacuum polarization function of a heavy quark and the pseudoscalar meson transition form factor.

CONTACT PERSON: Pere Masjuan (masjuan@ifae.es)

TITLE: Axion-like particles at low energies

PROJECT DESCRIPTION:

Axion-like particles (ALPs) appear in many well-motivated extensions of the Standard Model and are very attractive both for their simplicity and as well for being an economic proposal, able to explain if they exist, several of the current open questions in particle physics. They are believed to be very light relative to the scale of new physics from which they stem, since they are pseudo-Goldstone bosons of an underlying broken symmetry. Still, their mass and coupling to other particles are arbitrary parameters to be determined or bounded by experiment.

In this project, using the language of Effective Field Theories, we shall describe the interactions of ALPs with the Standard Model fields with special emphasis on hadronic particles at low energies. This exercise should provide information on both mass of the ALP and information about its coupling to the fermions of the Standard Model. Beyond that, by supplementing the effective Lagrangian with the QCD Lagrangian, we will observe how the QCD dynamics generates a mass for the ALPs. This is an interesting feature of the interaction that allow to discuss the origin of the required new physics scenario. By looking in particular to the decay of the ALP into 3 pions, aspects of mixing with the neutral pion and final state interactions via pion rescattering, will also be considered, discussing for the first time the potential role of the ALPs at the precision low-energy frontier of the Standard Model. Finally, including coupling to photons and leptons, the role of ALPs to solve the long-standing discrepancy of the muon anomalous magnetic moment of the muon will we pursuit.

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TITLE: On the Electromagnetic Line-shapes of Heavy Quarkonia

PROJECT DESCRIPTION:

Electromagnetic transitions below open-flavor thresholds are often one of the largest decay modes for charmonium and bottomonium states, making them a suitable experimental tool to access the lowest spectra of heavy quarkonia. In the last years, an experimental controversy had arisen in the electromagnetic line-shape of the $J/\psi \to \gamma\ \eta_c$, transition challenging the theoretical determinations of the η_c Breit-Wigner parameters (mass and width), but also the determination of the decay's branching ratio.

We analysed the reaction in a non-relativistic effective field theory (EFT) framework of quantum chromodynamics (QCD), and observed that the photon spectrum line-shape is divergent at large energies due to polynomially and logarithmically divergent terms, that upon integration over the photon energies in Dimensional Regularization (DR) produce no contribution or can be renormalized. We proposed to subtract these divergences at the line-shape level in a manner consistent with the calculation of the width in DR and MS-scheme. We analysed CLEO's data with the proposed subtracted line-shape and find good agreement between the theoretical prediction and the experimental result.

New data has become available for the photon spectrum line-shape of the $\psi(2S) \to \gamma\ \eta_c$ and $\Upsilon(1S) \to \gamma\ \eta_b$ decay processes for which similar issues have been already seen by experimentalists. We propose to study these reactions within the same formalism, taking into account the finite width of the hidden charm and hidden bottom eta-meson and including v^2 corrections.

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TITLE: Towards an understanding of double-heavy quark baryon spectroscopy

PROJECT DESCRIPTION:

Up to 2016 only baryons made entirely of light quarks (up, down, strange) or with one heavy quark (charm, bottom) had been observed. This has changed with the recent discovery by the LHCb Collaboration of a new particle called Ξ_{cc}^{++} containing two charm quarks. Its mass, 3621 MeV, is almost four times heavier than the most familiar baryon, the proton, a property that arises from its doubly charmed quark content. The first unambiguously detection of the Ξ_{cc}^{++} raises the expectations that the LHC observes in the near future other representatives of the family of doubly-heavy baryons.

Double-charmed or -bottom baryons can be studied within a non-relativistic effective field theory (EFT) formalism of quantum chromodynamics (QCD). The system is characterized by the very different dynamical time scales of the heavy and light quark components which allows a description of the system inspired by the Born-Oppenheimer approximation familiar in molecular physics. This approach has already been developed to study heavy quark-gluon hybrids.

We propose to explore this approach for double-heavy baryons and test it against experiment. The study will answer some important questions such as what kind of quark-quark interactions are active in heavy baryons that contain light quarks.

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