

Light- and heavy-quark hadron spectroscopy (HaSP)

STRONG2020, WP25-JR7

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I. JRA7-HASP: LIGHT- AND HEAVY-QUARK HADRON SPECTROSCOPY

A. Project objectives

The light- and heavy-quark hadron spectroscopy (HaSP) network coordinated the leading European institutions participating to STRONG2020 and active in the field of hadron spectroscopy with the objective of making progress in the development of theoretical, phenomenological, and computational foundations for amplitude, and establishing best practices for accessing systematic uncertainties in the analysis of hadron reaction data, and interpretation of physics results.

B. Introduction

Fundamental interactions of components of matter are not yet fully understood. Some basic questions such as: how the mass of the visible world is generated? How do the quarks, light constituents of the proton and neutron (and the other hadrons) sum up to provide the visible mass of nucleons (and therefore the visible mass of universe)? Why does the mediator of the strong interaction (the so called gluon) not show up in the spectrum of hadrons? Are the three quarks (that make baryons) and quark-antiquarks configurations (that make mesons) the only possible ones (see the recent claim from LHCb about a penta-quark baryon)? The answer to these (simple!) questions requires a sophisticated procedure that involves both experiments and theories necessary to interpret data.

To face the challenge presented by new experiments in which a huge amount of high-quality data are available, we need to develop a set of tools to optimize each step in the analysis. Data need to be collected, analyzed, transferred, accessed and stored in a convenient and accessible repository. Reconstructed four-momenta need to be feed to sophisticated partial-wave analyses that, making use of experimental and theoretical constraints, provide reliable results. Observables need to be compared to the best existing solution of the fundamental theory of the strong interaction provided by the Lattice-QCD and interpreted by using effective models that pick out the underlying dominant mechanisms of the theory. This complex analysis chain requires that the different skills and competences that are present in the hadron physics community be shared among groups and collaborations. Parallel computing, algorithmic optimization, cloud technology, massive data management, together with a thorough and well-founded theoretical framework that can be used to analyze data require that experts share information and techniques to produce reliable results. The goal of HaSP networking was to address this problem supporting exchanges and establishing links among these different communities. The theoretical community needs to establish a contact with experimental collaborations that are performing the experiments and event-based analyses. Sophisticated computing techniques need to be merged with the specific requirements of a well-motivated and solid phenomenological scheme to perform high-level analysis necessary for physics interpretation. Senior scientists need to transfer their competences and their background to the new generation of researchers that will be the resource of the future. In the five years of the project it was not possible to address all these issues but HaSP represented a first, and we believe successful, attempt to organize the hadron spectroscopy community setting up a network of competences and people as a base for further progress in the field.

C. Achievements

The project included a large fraction of the research community working on hadron physics in Europe and the US. The networking activity linked together hadron physics laboratories in Europe (CERN, Mainz, Bonn, GSI), the US (JLab and the BNL) and Asia (BESIII and Belle-II). It strengthened the existing contacts between experimental collaborations (e.g. CLAS at JLab and LHCb at CERN), institutions (e.g. GWU, Mainz and Bonn) and theory groups (e.g. JPAC at JLab/GWU/IU). Discovery of new states of hadronic matter beyond the Standard Quark Model requires checks and confirmation by different experiments and analysis techniques. HaSP promoted a global network of Labs and Insti-

tutions committed in present and future data analysis to cross check any possible findings, providing a robust and theoretically sound analysis framework.

1. On existing Research Infrastructures

Data collected in recent years by laboratories involved in hadron physics (CERN, Mainz, Bonn, JLab, and BESIII) have been used as benchmarks of the new tools developed by the HaSP networking activity. The complementary nature of different facilities is a key feature of the field; HaSP represented a forum to enhance this through the exchange of ideas, sharing preliminary results, coordinating future experiments and analysis at different labs. Exchange of data, cross checks of different analysis methods as well as tests of the new analysis algorithms and optimization of the theoretical framework had a significant impact on the knowledge and understanding of the existing hadronic states, providing accurate predictions and indications for the experiments running in the near future. Exchange of personnel between different institutions, experimental collaborations and theoretical groups led to a mutual benefit in sharing expertise and competences.

2. On future Research Infrastructures

Experiments planned at EU and international laboratories, as well as the theory community that support them, benefit from common analysis tools development. HaSP deployed a web portal (<http://web.ge.infn.it/jstrong2020/>), where information, news, pre-prints, preliminary data analyses, analysis tools, were made available to experimental and theoretical groups of the network.

3. On the development of advanced theoretical methods

In parallel to advances in theoretical studies of QCD, e.g. using lattice-gauge techniques, HaSP developed methods to describe hadronic reactions. With the new high-quality data provided by experimental project's partners, and the development of adequate theoretical methods provided by the theoretical counterparts, HaSP made significant progress in description and interpretation of the current hadron phenomenology.

4. On new opportunities for synergies

The HaSP networking activity provided a way to exchange data, tools and researchers between the different experiments, institutions and groups. Sharing expertise and specific skills stimulated new synergies between groups and individuals. In particular, the interaction between the experimental and theoretical community provided a bi-directional communication channel resulting in a significant mutual benefit. Exchange with other communities such as Information Technology and Computer Science provided a mutual exchange of techniques and skills. Reciprocal visits of researchers in hosting institutions and laboratories led to a network of contacts and reference that strongly enhanced the productivity and knowledge of individual groups.

5. On partnership between non-European and European institutes

Collaboration between institutions and Laboratories from EU and abroad has been part of the core of the whole HaSP working package. EU partners of HaSP with leading roles in non-EU laboratories provided a natural link between Collaborations and Institutions. HaSP strengthened a network already in place that connects CERN, GSI, MAINZ, and BONN laboratories to Jefferson Lab (US) and BESIII (China). Partnership between US and EU groups benefit by the direct involvement in HaSP of leading

oversea institution such as The George Washington University, Indiana University and the JLab Physics Analysis Center at JLab, leveraging investment of US agencies such as DOE and NSF.

D. Organization

The networking activity of HaSP was organized in four main tasks, which are, in turn, split into a total of 10 sub-tasks. Sub-tasks have not functioned as isolated units since they have shared common physical interests and objectives. Thus, there has been a constant flow of communication between them, greatly favored by the collaboration established within the joint research activity. Each of these sub-tasks has been coordinated by one or two leading researchers in the field, who have also prepared materials for all reports of the working group activity in the STRONG-2020 Annual Meetings, collaborated to shape the scientific programs of the joint theory-experimental workshop organized by HaSP in Valencia (Spain) (<https://indico.ice.csic.es/event/24/>), the München STRONG-2020 Hadron Spectroscopy General Workshop (<https://indico.ph.tum.de/event/6977/>) (Germany), the York (<https://agenda.infn.it/event/27658/>) topical Workshop (United Kingdom), and the STRONG-2020 HaSP School organized in Salamanca (Spain) (<https://diarium.usal.es/strong2020/>). The list of tasks/sub-tasks and coordinators are reported below:

- Task 1: Precision calculations in non-perturbative QCD (I); Effective Field Theories (EFT's), analyticity and dispersion relations
 - T1.1: *Development and application of Effective Field Theories*, C. Hanhart (Institute for Advanced Simulation, Institut für Kernphysik and Jülich Center for Hadron Physics, Forschungszentrum Jülich, Germany).
 - T1.2: *Heavy hadrons decays: Dalitz-plot, EFT, exotic resonances nature, isospin or CP violations*, D. R. Entem (Departamento de Física Fundamental, Universidad de Salamanca, Spain).
- Task 2: Precision calculations in non-perturbative QCD (II)
 - T2.1: *Hadron resonances, form factors, LECs, fundamental parameters of QCD and light nuclei spectroscopy*, A. Lovato (Physics Division, Argonne National Laboratory) and A. Parreño (Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Spain).
 - T2.2: *Computation of heavy-quark, hybrid and tetraquark potentials*, A. Vairo (Physik-Department, Technical University Munich, Germany).
 - T2.3: *Computation of matrix elements for in medium quarkonium evolution*, A. Vairo (Physik-Department, Technical University Munich, Germany).
- Task 3: Meson Spectroscopy analysis of new and exotic states
 - T3.1: *Search for and study of light exotic mesons, charmonium and strangeonium*, V. Mathieu (Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Spain).
 - T3.2: *Spectroscopy of low-lying scalars, strange mesons and strangeonia*, S. Schadmand (GSI Helmholtzzentrum für Schwerionenforschung GmbH), Germany.
- Task 4: Baryon Spectroscopy
 - T4.1: *Resonance parameter determination*, M. Ostrick (Institut für Kernphysik, University of Mainz, Germany).
 - T4.2: *Diffraction and annihilation production and exotic baryon*, A. D'Angelo (Università di Roma Tor Vergata, Italy).

– T4.3: *Dibaryon structure and parameter determination* , D.P. Watts (University of York, United Kingdom).

In Secs. II-V, we collect some results and references which illustrate the most important activities of the groups coordinated by the STRONG-2020 HaSP working package. This material has been taken from the reports prepared by the coordinators of each of the sub-tasks for the STRONG-2020 Annual meetings celebrated in Nantes (October 2019, <https://indico.in2p3.fr/event/19715/> and November 2021, <https://indico.in2p3.fr/event/25163/>), on-line (October 2020, <https://indico.in2p3.fr/event/20784/>), in Paris (October 2022, <https://indico.in2p3.fr/event/27767/>), at CERN (November 2023, <https://indico.cern.ch/event/1264833/>) and in Frascati (June 2024, <https://indico.in2p3.fr/event/32198/>).

II. TASK 1: PRECISION CALCULATIONS IN NON-PERTURBATIVE QCD (I)

QCD symmetries at the hadron level can be used to construct Effective Field Theories (EFT's) able to describe the low energy hadronic phenomenology. Dispersion relations provide rigorous constraints to theoretical predictions that can be used to obtain accurate properties of excited states. Especially when combined with EFT's, they provide a very powerful connection between the Hadronic and QCD realms.

A. T1.1 Development and application of Effective Field Theories (EFTs)

Chiral perturbation theory, Heavy Quark, Effective Theory or Quarkonium, Non Relativistic EFTs and the newly developed Born Oppenheimer EFT are exploited. If appropriate tailor made unitarization methods and dispersive techniques are employed in addition, to set up a robust framework to study QCD in the non-perturbative regime. These studies provide access to the spectrum, and in general the phenomenology of hadrons both in the free space and in extreme environments. In addition, the possible role of kinematic singularities, the so-called triangle singularities, in generating experimental signals, is investigated. List of achievements:

1. Effective field theories for exotic hadrons: Results are classified attending to the employed degrees of freedom: quarks or hadrons. As we will see, different groups (Salamanca, Jülich, Bochum, Valencia, Beijing) have actively worked in these topics, joining efforts to provide a robust description of the exciting discoveries by LHCb and BESIII of exotic states.
 - *Studies on tetraquarks with strangeness using hadronic degrees of freedom*. The observation of structures in the $D_s\bar{D}^*$ triggered theoretical studies employing hadronic EFTs.
 - (a) In Refs. [1, 2] the question was addressed, if the lower state could be close relative of the well-established $Z_c(3900)$ and $Z_c(4020)$ states (isovector states containing hidden charm). As a very non-trivial finding, the role of triangle singularities in the mentioned transition was stressed. The work was extended in its energy range of applicability in Ref. [3] by the inclusion of more intermediate states with their interactions constrained by heavy-quark spin symmetry. It turns out that also for the higher thresholds the triangle singularities contribute significantly
 - (b) The strange partners of the Z_c tetraquark states have been also studied using a constituent quark model [4]. This latter one and the previous EFT approaches can fit the $J/\psi K^-$ invariant mass distribution measured by BESIII and LHCb. In both type of schemes the $Z_{cs}(3985)$ is the SU(3) partner of the $Z_c(3900)$, and a partner of the $Z_c(4020)$ is predicted in the 4110 MeV energy region. Within the ETF schemes, it is compatible with a resonance or virtual state, while in the constituent quark model approach is obtained as a virtual state.
 - *Hidden charm states*. the LHCb Collaboration reported a near-threshold enhancement $X(3960)$ in the $D_s^+ D_s^-$ invariant mass distribution. In the analyses carried out in Refs. [5, 6] it was established the heavy quark spin and light flavour molecular multiplets of the $X(3872)$, $Z_c(3900)$ and the $X(3960)$. In addition, the effect of triangle singularities on experimental signatures is employed in [7] to propose a high accuracy determination of the mass of the $X(3872)$.
 - *Studies of low lying, negative parity isoscalar hyperons*. Lattice QCD (LQCD) spectra are analyzed for low-lying, negative parity Λ states (Ref. [8]). It is found that the lattice data are consistent with the proposed two-pole structure of the $\Lambda(1405)$. A further study [9], where recent LQCD results [10, 11] are analyzed using next-to-leading order unitarized ChPT give further support to these findings. The work of Ref. [12] provides an excellent review on two-pole structures in QCD. Other molecular states among the excited nucleon and hyperon resonances were discussed in [13, 14], odd-parity resonances with open charm and/or bottom

[15–19], strange SU(3) partners of the LHCb pentaquarks [20–22] or double-strangeness molecular-type pentaquarks from coupled-channel dynamics [23] have been considered. Also in this context, an EFT constructed analogous to the one now routinely used for few nucleon systems is employed to analyse the pentaquark data by LHCb [24, 25].

- *Studies of the $T_{cc}(3875)^+$.* The studies performed [26–29] investigated the recently found $T_{cc}(3875)^+$ state, the three first ones without, the latter with non-perturbative one pion-exchange in the binding potential. While all these works agree that the properties of this state are consistent with a molecular nature, the extracted pole locations vary significantly. Further in Ref. [30], it was demonstrated that lattice data with unphysical pion masses for the T_{cc} cannot be analysed with the standard Lüscher method, since the left-hand cut is too close by. This work inspired Ref. [31] which proposes a solution to the problem.

We also mention Ref. [32], where a double beauty tetraquark with quantum numbers $J^P = 1^+$ is predicted. It is below the strong and electromagnetic thresholds, while the semileptonic and non-leptonic weak decays have been evaluated giving a lifetime of 7.6 ps.

- *Studies of the $J/\psi - J/\psi$.* The structures observed recently at LHCb in the $J/\psi - J/\psi$ channel were analyzed in a coupled-channel framework including the relevant double-vector channels. An additional state near $J/\psi - J/\psi$ threshold is predicted [33] and further discussions can be found in [34].
- *Effective range expansion for narrow near-threshold resonances.* The role of isospin violating terms as well as strong correlations in the Flatté parameters that emerge in data fitting for very near threshold resonance states was investigated in Ref. [35]. In particular, it was argued that isospin violating contributions need to be subtracted prior to applying the Weinberg criterion to understand the structure of the wave function and an improved Flatté parametrization was suggested that is free of the mentioned correlations. Within the research on exotic states in terms of hadron degrees of freedom, we refer to the findings in Refs. [36–38], where a criterion to quantify the two hadron component of weakly bound and virtual states are provided.

2. Effective field theories for conventional states. Within the Born-Oppenheimer EFT (BOEFT), we model the potentials relevant for the hyperfine splitting of doubly heavy baryons using perturbative non-relativistic QCD (pNRQCD) for the short distances, an effective string theory for the long distances and lattice data for the charm case to fix the unknown parameters. Predictions for double bottom baryons are also given [39, 40]. In addition, the spin structure of heavy-quark hybrids has been discussed within the non-relativistic BOEFT approach up to next-to-leading order in the heavy-quark mass expansion [41].

3. Heavy and light quarks in the medium or at finite temperature

- *In-medium kinetic theory of D mesons and heavy-flavor transport coefficients.* The kinetic theory of D -mesons has been extended to accommodate thermal and off-shell effects due to the medium modification of the heavy-meson spectral functions [42]. The thermal width of D mesons due to their scattering off light mesons is analyzed, focusing on new in-medium effects: off-shell corrections, inelastic channels, and the contribution of the Landau cut. The latter effect, which is absent for vacuum scattering amplitudes, brings sizable corrections at moderate temperatures. It is found that the D -meson spatial diffusion coefficient matches smoothly to the latest results of lattice-QCD calculations and Bayesian analyses at higher temperatures.
- *Degeneracy patterns of chiral companions at finite temperature.* We have done work focusing on the chiral symmetry restoration of chiral hadronic partners expected at high temperatures. The cases where the chiral states are either fundamental degrees of freedom or (dynamically-generated) composed states are addressed. In particular, the intriguing case in which chiral symmetry restoration involves more than two chiral partners, as the double-pole structure of the $D_0^*(2300)$ meson, is discussed in Ref. [43]. This latter work used the results on pseudoscalar and vector open-charm mesons at finite temperature obtained in

[44, 45], which are also employed in Ref. [46] to analyze the properties of the $X(3872)$ and $X(4014)$ hidden-charm states at finite temperature. The open-charm Euclidean correlators have been also computed for the first time in [47] using the thermal spectral functions extracted from a finite-temperature self-consistent unitarized approach based on a chiral EFT that implements (HQSS). The results compare well with those from LQCD.

- *Temperature dependence of the pole position of the $K_0^*(700)$ and $K^*(892)$ resonances.* In Ref. [48], the pion-kaon scattering amplitude and the properties of these resonances were studied in a finite temperature (T) scenario, with T increasing from 0 to 200 MeV.
 - *Properties of the $T_{cc}(3875)$ and $D_{s0}^*(2317)$ in nuclear matter.* In Refs. [49, 50], these exotic states, and their anti-particles, were studied embedded in a nuclear medium. The nuclear environment modifies the spectral functions of these exotic states. Moreover, for those states with not well defined C -parity, it breaks charge-conjugation symmetry, and induces different particle-antiparticle line-shapes. If these distinctive density dependencies were experimentally confirmed, it would give support to the presence of important molecular components in these exotic states. These two works are based on Ref. [51] where a study of the properties of the $X(3872)$ embedded in a nuclear medium is performed, in terms of the $D^{(*)}$ and $\bar{D}^{(*)}$ spectral functions. This is of interest for the future detector PANDA at FAIR (GSI, Germany).
4. Inclusive production cross sections of heavy quarkonia. We develop a formalism for computing inclusive production cross sections of heavy quarkonia based on the nonrelativistic QCD and the potential nonrelativistic QCD effective field theories. Based on this formalism, we compute the nonrelativistic QCD long- distance matrix elements (LDMEs) for inclusive production of S-wave and P-wave heavy quarkonia. This greatly reduces the number of nonperturbative unknowns and brings in a substantial enhancement in the predictive power of the NRQCD factorization formalism. We obtain improved determinations of the LDMEs and find cross sections and polarizations that agree well with LHC data. Our results may have important implications in pinning down the heavy quarkonium production mechanism [52–55].
5. Phenomenological studies of hadronic reactions in the light sector.
- *Meson sector.* A dispersive model-independent analysis of πK and $\pi\pi \rightarrow K\bar{K}$ partial-waves in the low energy region below 1.6 GeV is performed in [56–58], using coupled forward, fixed- t and hyperbolic dispersion relations. The results consist of precise and ready-to-use partial wave parameterizations for further final-state interaction studies, as well as a model independent determination of the lightest strange meson $K_0^*(700)$ and $f_0(1370)$. We have also provided in a simple and easy-to-use description of $\pi\pi$ S and P partial-wave data up to 2 GeV, which reproduces as well accurately the hadron resonance poles in these processes. This description is consistent with forward and crossing-symmetric dispersion relations (Roy). The dispersive $\pi\pi \rightarrow K\bar{K}$ amplitude was used in [59] to describe the giant CP violation in B to three light-meson decays ($B^\pm \rightarrow K^\pm\pi^+\pi^-$ and $B^\pm \rightarrow K^\pm K^+K^-$) at LHCb. We also mention the development in [60] of a new parametrization for πK S-wave scattering and the corresponding form factor valid up to 2.3 GeV, beyond the elastic region, and that includes inelastic effects via resonance exchange. The obtained form-factor fulfills all constraints from πK scattering and maintains the correct analytic structure. It is applied to study the $\tau \rightarrow K_S\pi\nu_\tau$ and to extract the pole parameters of the $K_0^*(1430)$ and $K_0^*(1950)$.
 - *Baryon sector.* A chiral $\bar{K}N$ interaction model that includes the partial wave amplitudes emerging from the chiral SU(3) meson-baryon Lagrangian up to the D-waves and next-to-leading order in the chiral expansion is presented in Ref. [61]. The model parameters are fitted to a large pool of experimental data in the relevant energy range where these new contributions are expected to be important. It is found that the chiral higher partial waves permit extending the description of the scattering data to higher energies, as well as accounting for structures in the reaction cross-sections that cannot be accommodated by theoretical models limited to the S-waves.

6. Femtoscopia studies. Femtoscopy techniques were developed as tools to study the possible creation and properties of the quark-gluon plasma in relativistic heavy-ion collisions. Experiments are designed to be sensitive to correlations in momentum space for any hadron-hadron pair, and in particular to measure two-particle correlation functions (CFs). These latter observables are obtained as the quotient of the number of pairs of combined particles with the same relative momentum produced in the same collision event over the reference distribution of pairs from mixed events. In high-multiplicity events of pp , pA and AA collisions, the hadron production yields are well described by statistical models, which makes clearer the connection between CFs and two-hadron interactions and scattering parameters. In this context, Goldstone boson- D meson CFs have been evaluated in [62, 63] and they turn out to be in sharp disagreement with recent determinations reported by the ALICE experiment. This is an intriguing problem which needs to be further studied and understood. CFs related to signatures of the $T_{cc}(3875)$ or $N^*(1535)$ were computed in [64] and [65], respectively, while the low-energy $S = -2$ meson-baryon interaction was constrained with two-particle correlations in Ref. [66].

7. Effective field theories for singular NN interactions

- *Non-perturbative methods for singular NN interactions.* Different approaches for the renormalization of singular interactions in the context of EFT have been compared, including renormalization with boundary conditions, renormalization with one (or none) counter term and the exact N/D method. Using one or no subtractions, the three methods have been shown to give the same results. However, the exact N/D method allows one to do more than one subtraction. In particular it is possible to renormalize the singular repulsive case which is not possible in the other methods [67].
- *NN interactions with Δ degrees of freedom.* The nucleon-nucleon potentials from Δ -full chiral effective-field-theory have been analyzed in Ref. [68]. The χ^2/dof of different potentials have been shown to be bigger than the expected due to truncation errors in the EFT. A refit of the potentials to NN data have been done and the consequences for nuclear matter calculations have been analyzed.

8. New methods to handle problems in hadron physics. In Ref. [69], it was developed a symbolic manipulation program to calculate matching coefficients in non-relativistic EFTs.

B. T1.2 Hadron decays

We investigate decays of heavy hadrons, looking for particular interacting hadron pairs in the final state that might produce resonant states. Using Dalitz-plot based methods, EFT and dispersive techniques, we have also explored issues such as the exotic nature of resonances, isospin or CP violations. Hadron decays and hadron reactions are essential in hadron physics. Heavy hadrons are produced in colliders and they are observed through their decay products in different reactions. Their decay properties due to the electromagnetic, weak and strong interactions are deeply related with their nature so the analysis of hadron decays give us important hints to understand hadron states. There are different pictures to understand hadrons as conventional quark model states, dynamically generated resonances, unconventional quark model states as tetraquarks or pentaquarks, etc. Many hadrons can be accommodated in several pictures but its decay properties are usually the best tool to discriminate between them. Also the deviations from well known conservation laws, as for example isospin conservation, is a way to get signatures on new physics.

The study of hadron decays (T1.2) relies on and nicely complements the activities of subtasks T1.1 and T2 below, because it is usually needed to employ the EFTs or non-perturbative methods developed in the latter to describe the reactions discussed in T1.2. Actually, one can frequently see research teams involved in both type of projects. Moreover, we also benefit from the collaboration with the experimental groups, many of them part of HaSP, engaged in the measurements of the reactions studied in T1.2.

1. Electromagnetic interaction.

- *Quarkonium decays.* The theoretical description of charmonium transitions is analyzed in [70] using an elementary emission model to build the most general electromagnetic transition operator. Accurate results for the widths are obtained from a simple quark potential model reasonably fitting the spectroscopy if the complete form of the operator is used. Using an EFT approach we computed in [71] the electromagnetic and inclusive decay widths into light hadrons for P-wave quarkonia. There, the decay widths of 2S and 3S bottomonium states into lepton pairs and their ratios with the inclusive widths into light hadrons at relative order v^2 (v is the relative velocity of the heavy quark and antiquark) in the perturbative expansion are computed. The mass distribution of the decay $\psi(3770) \rightarrow \gamma D\bar{D}$ was analyzed in [72]. Since the $D\bar{D}$ scattering amplitude is involved, using a model that generates a bound state, it has been shown to have a mass distribution which could easily be measured in BESIII, very different from phase-space.

How the $X(3872)$ and its spin-two HQSS partner show up in e^+e^- collisions were discussed in Refs. [73, 74]. The decays of vector charmonia in pairs of baryons and anti-baryons belonging to the spin-1/2 flavor SU(3) octet was studied in Refs [75–77]. In the framework of a model, which is based on an effective strong Lagrangian density, we have identified the purely strong, purely electromagnetic and mixed strong-electromagnetic contributions to the total branching ratios of these decays. Of particular interest is the mixed strong-electromagnetic contribution that is proven to be crucial for the correct description of the decay mechanism. As a byproduct, the purely electromagnetic branching ratio can be also exploited to obtain the Born non-resonant cross section of the annihilation processes e^+e^- into baryon-anti-baryon at the vector charmonium mass.

- *Light meson decays.* An improved phenomenological model that describes $V \rightarrow P\gamma$ and $P \rightarrow V\gamma$ decays including isospin-symmetry breaking is presented in [78]. Statistical fits to the most recent experimental data for the radiative transitions and estimations for the mixing angles amongst the three pseudoscalar states $\pi^0 - \eta - \eta'$ with vanishing third-component of isospin are obtained. The current experimental uncertainties allow for isospin-symmetry violations with a confidence level of approximately 2.5σ . Further studies of the $\eta'\pi^0\gamma\gamma$ and $\eta' \rightarrow \eta\gamma\gamma$ [79] and $\eta'\pi^0\ell^+\ell^-$ and $\eta' \rightarrow \eta\ell^+\ell^-$ [80, 81] decays have been studied searching for new physics signatures. We also mention a dispersive analysis of $\eta' \rightarrow \pi^+\pi^-\gamma$ and $\eta' \rightarrow \ell^+\ell^-\gamma$ reactions, which accounts, in a consistent way, for the effects of $\rho-\omega$ mixing.

2. Weak interaction.

- *Semileptonic decays.*
 - (a) We proposed a model independent parametrization for the form factors in the semileptonic $\bar{B} \rightarrow D\ell\bar{\nu}_\ell$ decay [82]. Using recent experimental and LQCD data, we determine precisely the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ and the ratio of decays between the τ and μ/e channels. Strong hints about the existence of at least one bound and one virtual $\bar{B}\bar{D}$ S-wave 0^+ states are given.
 - (b) The decays $D^+ \rightarrow \nu_e e^+ \rho\bar{K}$, $D^+ \rightarrow \nu_e e^+ \pi\bar{K}^*$, have been analyzed in [83]. The goal is to check the double pole nature of the $K_1(1270)$ predicted by unitary extensions of chiral perturbation theory. The analysis shows that these decays are suitable to distinguish experimentally the predicted double pole. Recent studies on the $K_1(1270)$ produced in the non-leptonic reactions $\bar{B} \rightarrow J/\psi\rho\bar{K}$, $J/\psi\bar{K}^*\pi$ have been carried out in Refs. [84, 85].
- *Study of reactions disclosing the nature of the low-lying scalar mesons.* We have studied [86–90] different observables for the $D_s \rightarrow \pi^+\pi_0\eta$, $D^+ \rightarrow \pi^+\eta\eta$, $D^+ \rightarrow \pi^+\pi^0\eta$, $D^+ \rightarrow K^+K^+K^-$, $D^0 \rightarrow K^-\pi^+\eta$, $J/\psi \rightarrow \gamma\pi\pi$, $\gamma\pi\eta$, $a_1(1260) \rightarrow \pi f_0(500)$, reactions to test the nature of the scalar mesons $f_0(500)$, $f_0(980)$, $a_0(980)$, \dots , which could be dynamically produced in these decays. If the particle is dynamically generated from the interaction of other two, the production mode proceeds in two steps: the first one produces the constituents, and in a second part these two constituents propagate (interact among

themselves) producing the dynamically generated state. The features of this mechanism are quite different from those of a direct particle production in the reaction, and the study of different observables gives finally support to one or another picture.

- *The weak decay $\Lambda_b \rightarrow J/\psi \Lambda \phi$* . This reaction is studied in [21]. This process may present signatures for exotic hadrons in all three final two-body channels. In the $J/\psi \phi$ invariant mass spectrum the interplay between the $X(4140)$ and the $X(4160)$ states is investigated. In the $J/\psi \Lambda$ mass spectrum we conclude that a strange partner of the hidden-charm pentaquark may be identified if it is present in the range between 4450-4500 MeV. Finally, we find that a resonance at around 2160 MeV, predicted by some coupled-channels dynamical models, has very little chance to be experimentally detected in the $\phi \Lambda$ spectrum.
3. Exotics. The nature of the exotic states in the heavy quark sector (XYZ mesons) are still unknown. Several of the exotic states have been discovered in experiments from their decays to quarkonium. Therefore, a theoretical understanding of the decays of the XYZ states might be another avenue in understanding their structure. However there are other decay effects that can be give a similar signal to hadrons, being one of the most important the triangular singularities in the decay processes.
- *Inclusive and semi-inclusive decays of heavy-quark hybrids*. We have investigated the inclusive and semi-inclusive decays of heavy-quark hybrids in the framework of the BOEFT. In the semi-inclusive decays, we compute the decays of heavy quarkonium hybrids into traditional quarkonium in the EFT framework. We start with the weakly coupled potential NRQCD effective theory that describes systems with two heavy quarks and incorporates multipole expansions and use it to develop a BOEFT to describe the hybrids and evaluate the decay rates. We computed both the spin-conserving and spin-flipping decay rates and find that our numerical results of the decay rates are different from the previous studies ([91, 92]).
 - *Triangle singularities*. Some works have been done to explain experimental characteristics of some reactions in base to triangle singularities (TS) and making predictions of reactions where peaks associated to TS appear, to avert claims of discovery of new resonances when the experiments are performed. We highlight three publications [93–95]. In the two latter ones, we have examined a TS mechanism for the $pp \rightarrow \pi^+ d$ fusion reaction, and its relation to the dibaryon " $d^*(2380)$ " peak, whose existence is challenged by our findings. Finally, in the most recent work [93], we have studied the sensitivity of the $K^- d \rightarrow p \Sigma^-$ reaction to the properties of the $\Lambda(1405)$ resonance, which enhances the contribution of a triangle-diagram mechanism that dominates the reaction close to threshold.
 - *Tetraquarks*. The possible existence of the $J^{PC} = 1^{+-}$ partner of the $X(3872)$ has been analysed in a constituent quark model [96]. The state have been only seen by the COMPASS Collaboration and needs confirmation. The model predicts two candidates that differs in the strong and radiative decays, which could help to distinguish between them.

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III. TASK 2. PRECISION CALCULATIONS IN NON-PERTURBATIVE QCD (II)

EFT techniques complement very efficiently LQCD simulations, allowing to better control the needed extrapolations to physical kinematics and covering regions of parameter space not yet reachable in the lattice. Concerning systems made of two heavy quarks (generically called quarkonia) their study has witnessed an enormous theoretical progress due to the use of EFTs (non-relativistic QCD, NRQCD, potential NRQCD, pNRQCD, Born-Oppenheimer EFT, BOEFT, ...) combined with significant advancements in LQCD calculations of hadronic observables allowing precision spectroscopy of exotic and excited states and the treatment of states above thresholds in coupled channel scattering analyses. Heavy quarkonia provide also a clear signature in heavy-ion experiments and their suppressed production is a hard-probe of the medium formed therein (e.g. bottomonium suppression has been already observed in heavy-ion collisions at the LHC).

A. T2.1 Hadron resonances, form factors, LECs, fundamental parameters of QCD and light nuclei spectroscopy

We aim at studying Lattice-QCD (LQCD) simulations in finite volumes. Methods have been developed to deal with the extraction of the properties of hadrons from the simulations. Lattice and Green's function MC simulations, combining chiral NN and $3N$ forces, will be also performed to study light and medium-heavy nuclei.

1. Nuclear structure and electroweak responses.

- *Neutron matter.* Comprehensive set of neutron matter calculations using as input nucleon-nucleon chiral-EFT interactions that explicitly include the excitation of the Δ resonance was carried out in [1]. We benchmarked the predictions of the auxiliary-field diffusion Monte Carlo (AFDMC), the Fermi-hypernetted chain (FHNC), and the Brueckner-Hartree-Fock (BHF) many-body methods. We removed the bias affecting previous AFDMC calculations by performing unconstrained-path imaginary-time propagations, finding a much better agreement with FHNC and BHF. In a synergistic effort with experimentalists, we study nuclear electromagnetic transitions [2, 3] and the evolution of magic numbers in neutron-rich nuclei [4, 5]. Ab initio calculations of medium-mass and heavy nuclei based on chiral EFTNN+ $3N$ forces have been carried out in [6] and neutrinoless double- β decay matrix elements evaluated in Ref. [7].

In Ref. [8] we studied the equation of state of infinite neutron matter as obtained from highly-realistic Hamiltonians that include nucleon-nucleon and three-nucleon coordinate-space potentials. As before, we benchmark three independent many-body methods: Brueckner-Bethe-Goldstone (BBG), Fermi hypernetted chain/single-operator chain (FHNC/SOC), and AFDMC. We find them to provide similar equations of state when the Argonne nucleon-nucleon potentials are used in combination with the Urbana IX three-body force. Only at densities larger than about 1.5 the nuclear saturation density, the FHNC/SOC energies are appreciably lower than the other two approaches. The AFDMC calculations carried out with all of the Norfolk potentials fitted to reproduce the experimental trinucleon ground-state energies and nd doublet scattering length yield unphysically bound neutron matter, associated with the formation of neutron droplets. Including tritium beta-decay in the fitting procedure, as in the second family of Norfolk potentials, mitigates but does not completely resolve this problem. An excellent agreement between the BBG and AFDMC results is found for the subset of Norfolk interactions that do not make neutron-matter collapse, while the FHNC/SOC equations of state are moderately softer.

- *Artificial neural networks.* Solving the nuclear many-body Schrödinger equation involves non-trivial difficulties, due to the non-perturbative nature and strong spin-isospin dependence of nuclear interactions. Artificial neural networks have proven to be able to compactly represent the wave functions of nuclei with up to $A = 4$ nucleons. In Ref. [9], we extend this

approach to ${}^6\text{Li}$ and ${}^6\text{He}$ nuclei, using as input a leading-order pionless effective field theory Hamiltonian. We successfully benchmark their binding energies, point-nucleon densities, and radii with the highly-accurate hyperspherical harmonics method. Recently, inclusive electron-nucleus scattering with Bayesian artificial neural networks was discussed in [10].

- *Electroweak responses.* An accurate understanding of neutrino interactions with nuclei is fundamental for the success of the world-wide neutrino-oscillation program. Within our effective model of nuclear dynamics, we study exclusive final state hadron observables from neutrino-nucleus multi-nucleon knockout [11], charged-current quasielastic-like processes with not pions in the final state [12] and the polarization of τ in quasielastic (anti-)neutrino scattering [13, 14].

2. LQCD calculations of nuclear systems. In Ref. [15] tests of interpolating-operator dependence in lattice simulations of two-nucleon systems were performed using a variational approach, where a wide range of interpolating operators was considered (dibaryon operators built from products of plane-wave nucleons, hexaquark operators built from six localized quarks, and quasi-local operators). This work investigates the reliability of the energy spectra obtained in LQCD calculations and highlights both the strengths and weaknesses of variational methods. Finite-volume pionless effective field theory at next-to-leading order (NLO) is used to analyze in [16], the two-nucleon lattice QCD spectrum of Ref. [15]. As a result, different low energy constants (LECs) are constrained, relativistic corrections are incorporated, allowing for the extractions of NLO LECs, as well as the leading S-D wave mixing term in the deuteron channel.

Refs. [17, 18] show LQCD results of nuclear interactions at a pion mass of 450 MeV. The axial charge of the triton has been investigated in [17]. The axial current matrix elements were computed using background field techniques, and finite-volume pionless effective field theory is used to extrapolate the results to infinite volume. Accounting for previous results at heavier pion mass, a simple quark mass extrapolation leads to a value of the ratio of the triton to proton axial charges at the physical quark masses consistent with the ratio determined from experiment, smaller than (but close to) 1, showing that QCD can explain the modification of the axial charge of the triton from that of the proton. Ref. [18] focuses on the interactions between two octet baryons in systems with strangeness from 0 to -4 . The S-wave scattering phase shifts, low-energy scattering parameters, and binding energies (when applicable) are extracted using Lüscher’s formalism, and the low-energy coefficients in pionless EFT relevant for two-baryon interactions, including those responsible for SU(3) flavor-symmetry breaking, are constrained. In [19], the progress of LQCD studies of nuclear matrix elements of electroweak currents and beyond SM operators is summarized, and connections with effective field theories and nuclear models are outlined.

Lattice-QCD variational study of nucleon nucleon interactions of Ref. [15] is extended by considering a additional volume and a complete basis of dibaryon and local hexaquark operators in [16]. The combination of dibaryon and hexaquark operators provides strong evidence for the presence of an additional energy level in both the deuteron and dineutron channels. Ongoing work focuses on studying octet baryon-octet baryon scattering at $m_\pi = 170$ MeV and controlling lattice artifacts.

3. The proton radius puzzle. In Ref. [20] the authors review determinations of the electric proton charge radius from a diverse set of low-energy observables. After exploring under which conditions it can be related to Wilson coefficients of appropriate effective field theories, the discussion is generalized to other low-energy constants, providing us with a unified framework to deal with a set of low-energy constants of the proton associated with its electromagnetic interactions.
4. Determination of the strong coupling constant. Refs. [21–23] analyzed for the first time the static energy in $2 + 1 + 1$ -flavor QCD. The free energy is also discussed in [21]. The static energy was obtained by measuring Wilson line correlators in Coulomb gauge using the HISQ action, yielding the scales $r_0/a, r_1/a, r_2/a$, their ratios, and the string tension σr_t^2 . For the first time the effects due to the dynamical charm-quark could be explored by comparing the lattice results to

continuum results of the static energy with and without a massive flavor at three-loop accuracy. Gauge-field ensembles from the HotQCD and MILC Collaborations were used for the singlet free energy at finite temperature up to distances as small as 0.0081 fm.

A one loop calculation of the QCD static force using gradient flow was performed in [24], useful to guide the continuum extrapolation of the lattice calculation of the force. The calculation represents a direct extraction of the static force (Refs. [25, 26] and [27]) in contrast to traditional calculations where the static potential is computed first and then the derivative is taken. The approach is based on expectation values of Wilson loops or Polyakov loops with chromoelectric field insertions. The method allows for a novel precise extraction of α_s .

The matching coefficients in SCET and bHQET have been obtained giving the series coefficients for the full theory up to α_s^4 . Using the Borel-transform variable the convergence of the series have been quantified and estimate the size of the non-perturbative corrections [28]. In addition, Ref. [29] presents a C++ library for renormalization group evolution and automatic flavor matching of the QCD coupling and quark masses, as well as precise conversion between various quark mass renormalization schemes. The numerical code is public and may be accessed through Mathematica and Python interfaces. The code is being used by experimental collaborations at LHC that measure the top quark mass, as well as in theoretical studies. The low momentum expansion of vector, axial-vector, scalar and pseudo-scalar heavy quark current correlators have been determined in the large- β_0 limit of QCD. The results have been used to study the higher order behavior of dimensionless ratios of vector and pseudo-scalar moments in order to determine a precise value of the strong coupling constant α_s from relativistic quarkonium sum rules and lattice data [30, 31]. These ratios benefit from a partial cancellation of the leading renormalon singularities. The results of Ref. [32] can guide the design of combinations of moments with improved perturbative behavior.

5. Jets. The 2-jettiness differential distribution for boosted top quark pairs produced in e^+e^- collisions have been studied. It was found that the top MSR mass may be determined with perturbative uncertainties well below 100 MeV from the peak position [33].
6. Signatures of Beyond the Standard Model (BSM) physics.
 - *Heavy baryon decays*. The $\Lambda_b \rightarrow \Lambda_c \tau \bar{\nu}_\tau$ decay has been analyzed to identify observables that can be measured by LHCb and can give hints of new physics beyond the Standard Model. The most promising observables are those that involve the polarization of the τ lepton, and seven observables have been identified [34–36]. The same analysis have been extended to other $b \rightarrow c \tau \bar{\nu}_\tau$ semileptonic decays.
 - *B-meson decays*. A model-independent global fit to $b \rightarrow s \ell^+ \ell^-$ observables to confirm existing new physics patterns and to identify new ones emerging from the inclusion of the updated LHCb and Belle measurements of R_K and R_{K^*} , respectively, was performed in Ref. [37]. The analysis suggests the presence of right-handed couplings encoded in some of the Wilson coefficients. It is discussed a scenario that provides a simple and model-independent connection to the $b \rightarrow c \tau \bar{\nu}_\tau$ anomalies, which provides a preference of $\sim 7\sigma$ with respect to the Standard Model.

B. T2.2 Computation of heavy-quark, hybrid and tetraquark potentials

The long-term aim of this subtask is to compute on the lattice the relativistic corrections to the heavy quark potential, and hybrid and tetraquark potentials as defined in the non-relativistic effective field theories pNRQCD and BOEFT using unquenched lattice QCD.

We have computed the QCD static force and potential using gradient flow at next-to-leading order in the strong coupling [24]. The static force is the spatial derivative of the static potential: it encodes the QCD interaction at both short and long distances. While on the one side the static force has the advantage of being free of the $\mathcal{O}(\Lambda_{\text{QCD}})$ renormalon affecting the static potential when computed in

perturbation theory, on the other side its direct lattice QCD computation suffers from poor convergence [27]. The convergence can be improved by using gradient flow, where the gauge fields in the operator definition of a given quantity are replaced by flowed fields at flow time t , which effectively smear the gauge fields over a distance of order square root of t , while they reduce to the QCD fields in the limit $t \rightarrow 0$. Based on a next-to-leading order calculation, we have explored the properties of the static force for arbitrary values of flow time, which may be useful for lattice QCD studies. A lattice study can be found in [25, 26]. This is an important result that open the possibility to calculate on the lattice all correlators emerging in the nonrelativistic effective field theory, including pNRQCD and BOEFT. We have also carried out a lattice study of the QCD static energy with 2+1+1 flavors (lattice spacing up to 0.032 fm and pion mass up to 210 MeV) that shows decoupling when moving from short to large distances of the static sources. Results were reported in Refs. [22, 23]. As mentioned above, this work allowed a precise extraction of α_s comparing to a perturbative calculation of the static energy in QCD at N³LO.

There has been noteworthy progress in heavy Quarkonium spectroscopy with the computation on unquenched lattices (2+1 flavors) of the excited and exotic bottomonium spectrum (including hybrids) in [38]. This has been the first fully relativistic and unquenched lattice calculation in the bottomonium sector and it was carried out by the Hadron Spectrum collaboration. Related to this calculation is the study of QCD thermodynamics with 2+1 flavors of Wilson fermions of Ref. [39]. It set the groundwork for further studies of spectroscopy, including for heavy quarks. The present status of the art of hadron spectroscopy with lattice QCD has been summarized in [40].

Finally in this research line we highlight three recent important developments. First, a step forward in the understanding how to establish a systematic approach for calculating the matching from the gradient-flow scheme to the $\overline{\text{MS}}$ scheme in the limit of small flow time for off-light cone Wilson-line operators [41]. This will be crucial to use the lattice gradient flow calculations of the low energy correlators in the nonrelativistic effective field theories for quarkonium and exotics.

Second, the celebration of the 2nd Edition of the Workshop 'Quarkonia meet Dark Matter' (March 2024 Garching, Germany) <https://indico.ph.tum.de/event/7422/>. The aim of the meeting was to provide to particle physicists a platform for exchanging knowledge and methodologies at the intersection of both fields. And third, the celebration of the workshop 'Machine Learning approaches in Lattice QCD - an interdisciplinary exchange' (February 2023, Garching, Germany) <https://indico.ph.tum.de/event/7116/>. The objective of this event was an interdisciplinary exchange for accelerating developments of machine learning techniques in Lattice QCD with experts in Machine learning, LQCD, and other related fields.

Future plans of research include the description of the hybrid-quarkonium mixing in BOEFT framework, computing the mixing potential using LQCD, and phenomenological applications to $X(3872)$, $T_{cc}^+(3875)$, $Z_c(3900)$, $Z_b(10610)$, $Z_b(10650)$ and $P_c(4312)$ states and decays to quarkonium and heavy-light threshold states.

C. T2.3 Computation of matrix elements for in medium quarkonium evolution

This subtask deals with quarkonium propagation and suppression in the medium formed in heavy-ion collisions. The quarkonium low-energy out of equilibrium dynamics is governed by in-medium correlators, which we aim to compute in LQCD.

The bottomonium spectral function at nonzero temperature and density has been investigated by the FASTSUM collaboration with a variety of methods in [42–45] and [46]. The properties of the thermal transition in QCD, using anisotropic, fixed-scale lattice simulations with $N_f=2+1$ flavors of Wilson fermion have been studied in [39]. Observables have been compared for two values of the pion mass, focusing on chiral properties. Results have been obtained for the Polyakov loop, various susceptibilities, the chiral condensate and its susceptibility, and the onset of parity doubling in the light and strange baryonic sector.

On the other hand, the properties of D , D_s , D^* and D_s^* open-charm mesons at nonzero temperature have been analyzed in Ref. [47], where results in the hadronic phase from LQCD are reported. This is a full QCD 2+1 simulation using dynamical fermions with $m_\pi \sim 240$ MeV. LQCD data are obtained

approaching thermal crossover (~ 150 MeV), and the observed thermal modification of hadrons are as expected in quark-gluon plasma (QGP) scenario. In addition, the behavior of spin 1/2 charmed baryons as the temperature increases is discussed in [48] from anisotropic lattice QCD simulations with $N_F = 2 + 1$ dynamical flavors. Temperature effects are found to be prominent throughout the hadronic phase for all negative parity channels considered and for some positive parity channels. Subsequently and where possible, the masses of the ground states as a function of temperature are determined. The effect of chiral symmetry restoration is considered and an estimate of the pseudo-critical temperature from singly charmed baryonic correlators is also extracted.

The Lindblad equation describes the heavy quarkonium evolution in the hot medium created at the early stages of high-energy heavy-ion collisions. We have solved the Lindblad equation to calculate experimental observables including the nuclear modification factor R_{AA} and the elliptic flow ν_2 . The equation depends on only two diffusion coefficients, which have been determined in LQCD [49].

The heavy quark and quarkonium behavior in a QGP is governed by transport coefficients that can be computed non-perturbatively on LQCD. The heavy quark diffusion coefficient was computed in quenched QCD over a wide range of temperatures (from 1.1 to 10000 times the critical temperature) in [50]. It was found that within errors the lattice results are remarkably compatible with the next-to-leading order perturbative result.

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IV. TASK 3. MESON SPECTROSCOPY ANALYSIS OF NEW AND EXOTIC STATES

A large number of “exotic” experimental discoveries, which did not fit the expectations of the quark model, as well as the unprecedented statistical precision have been obtained by COMPASS, LHCb, BESIII, Belle and other experiments. These discoveries occur in the open and hidden charm and bottom sectors, but some of them also correspond to the light quark sector. HaSP performed combined Partial Wave Analyses (PWAs) of the same final state measured in different experiments, making use of the theoretical tools developed in Task1 and Task2.

A. T3.1 Search for and study of light exotic mesons, charmonium and strangeonium

In the recent years, high-energy physics experiments have delivered a lot of unexpected exotic hadron resonances, which challenge the quark model of mesons with a quark-antiquark pair. Candidates for tetraquarks, molecules, and hadrons with gluonic degrees of freedom have been found. In the heavy quark sector, their unknown nature has led to the denomination of “XYZ states”. In fixed target experiments, these possible resonances are often produced in association with baryon resonances. In this case, the desired meson final states need to be either separated from the meson signal by kinematical cuts or parameterized jointly with the baryonic structures. With the meson final states single out, establishing the existence of isolated resonances that go beyond the minimal quark model require performing coupled-channels partial-wave analysis at a level never achieved before and comparing these measurements to modern theoretical predictions. To achieve these goal the research activity performed in T3.1 required a strict coordination with Task 4.1. In fact, in light quark spectroscopy, the separation between baryon and meson resonances created in the interaction of a real or virtual photon with the nucleon, is not enough to decouple the two. A combined analysis that describes the reaction amplitude as a function of all degrees of freedom is therefore necessary. Moreover, a joint effort between theorists and experimentalists is therefore needed to embed theoretical calculation into Monte-Carlo simulations and developing new models to analyze experimental data. The GlueX and CLAS collaborations at the Jefferson Lab have an ongoing program to detect light exotic meson in electro- and photoproduction. Their programs complement the COMPASS effort at CERN who recently observed the lightest hybrid meson $\pi 1$ decaying in both $\eta\pi^-$ and $\eta'\pi^-$ final states. These channels, as well as their neutral partners $\eta^{(\prime)}\pi^0$, are currently under investigation by the GlueX collaboration to confirm the production of exotic meson in photoproduction. The forthcoming data obtained in electro-production by the CLAS detector should provide further inside on the gluonic degrees of freedom of the $\pi 1$ wave function. The BESIII collaboration collected a total of 10 billion of J/ψ in 2019, which can be used to improve previous analyses and to study more in detail and with an unprecedented accuracy the light hadron spectrum. The new scan data collected between 4.29 and 4.42 GeV in the center of mass energy, together with the new data set between 4.6 and 4.7 GeV, will be helpful to better investigate the “XYZ states”. LHCb is also actively studying the properties of “XYZ states” produced diffractively and in B meson decays.

In Ref. [1], the formalism to extract polarized observables in two-meson photoproduction has been developed. A new observable, sensitive to exotic meson, has been proposed. This formalism is currently implemented in several GlueX and CLAS12 analyses. Most of XYZ candidates are observed in three-body final states. In Ref. [2], the general formalism to analyze any three-body is presented. A code, ready for direct implementation in data analysis, is available online on the JPAC website (<https://ceem.indiana.edu/jpac>). Theoretical cross sections of exclusive XYZ production at the future EIC has been calculated in Ref. [3]. The code available from this article has in addition been incorporated into an event generator for electroproduction of XYZ which will be used to plan for an EIC spectroscopy program [4]. Using a non relativistic effective field theory description the spin structure of hybrids has been investigated [5]. In Ref. [6], the wave function of the X(3872) and other charmonium are obtained from Coulomb-gauge model of QCD. The properties of several heavy quarkonia have been investigated using nonrelativistic QCD and nonrelativistic field theories (EFT) in Refs. [7–14]. EFT were also used to study the properties of the light exotic nonet in Refs. [15, 16]. The members of the LHCb collaboration have reported the production of strange mesons and strangeonia

in pp interaction in a series of publications [17–23]. The production of strange and charmed mesons in the medium have been studied within an effective field theory approach in Refs. [24–28]. The influence of the medium on triangle singularities has been investigated in Ref. [29]. An extraction of the exotic meson π_1 has been reported by the COMPASS collaboration in Ref. [30]. The same data set has been analysed in the high mass region in Ref. [31]. In particular, extraction of the forward- backward asymmetry (related to the amount of exotic meson produced) is presented. A review about glueballs has been published [32]. Several exotic candidates have been reported recently by the BESIII and LHCb collaborations [33–36]. In particular the η_1 , the iso-partner of the π_1 , has been reported by the BESIII collaboration in Ref. [37]. Determination of resonance parameters were performed in Ref. [38] and Ref. [39], where scalar and tensor pole positions were studied using innovative and dispersion relation methods, respectively. Further exotic new states were observed by the BESIII Collaboration performing sophisticated partial wave analyses on final states $\eta(\prime)$ -rich and reported in Ref. [37, 40–42]. In the *charm* sector, the same Collaboration reported about a possible charm-strange tetraquark state $Z_{cs}(3985)$ in ref [43]. Experimental observations led to a significant activity by theory groups aiming to predict spin partners of the new states. Some examples in the B sector, concerning the DK final state, are reported in Refs. [44, 45]. Further studies performed by JPAC proved that there are no mathematical ambiguities in partial-wave analysis of two mesons produced with a linearly polarized photon beam. Results were illustrated by Monte Carlo simulations [46]. A collaborative effort of the theory groups with experimental collaborations operating the GlueX, CLAS12 and BESIII detectors is foreseen for the next few years.

Members of the Strong2020 networks have participated to the elaboration of the Yellow book [47] in the perspective of the future Electron-Ion Collider (EIC).

B. T3.2 Spectroscopy of low-lying scalars, strange mesons and strangeonia

The task T3.2 is dedicated to spectroscopy of low-lying scalars, strange mesons and strangeonia. A new generation of dedicated experiments in hadron physics has started with the aim of uncovering properties of strong interactions and specifically the mysteries of confinement. ELSA, MAMI, CERN, and Jefferson Lab are providing precise and abundant data on poorly known and understood scalar and strange-rich mesons. Complementary information from experiments that make use of nuclear target can be used to constrain the sophisticated PWA in meson spectroscopy. A significant progress in spectroscopy of low-lying scalars and strange mesons include: realization of a KLong facility at Jefferson Lab (KLF); analyses of JLab CLAS6 and GlueX data, and multi-channel analysis of existing data by the Bonn-Gatchina PWA Group, and first results from ALICE experiment at CERN.

Approval of a KLong beam Facility (KLF), hosted by Hall-D at Jefferson Lab. A substantial part of its scientific program foresees an extensive study of strange baryonic excitations and of mesons with strange content. Among the latter, focus will be put on the search and characterization of the $\kappa/K_0^*(700)$ scalar, in its overlap with the $a_0/f_0(500)$ and the $f_0(980)$, and of other strange excited resonances belonging to heavier nonets and decaying sizably in $K\pi$, about which the available information is still considerably scarce. In this respect, the KLF program will be thoroughly complementary to the investigations by CLAS12.

The CLAS6 experiment at Jefferson Lab collected a sizable amount of high resolution data with a real photon beam on a proton target at beam energies up to 5 GeV. The data were used for first exploratory searches for light mesons production with open and hidden strangeness, selecting channels with kaons in the final state. These investigations are deeply intertwined with the search of the lightest exotics of the meson spectrum (glueballs and hybrids). Identification and disentanglement of the states call for large statistics and sophisticated analysis methods. Similar analyses are being carried out with the data collected by the upgraded CLAS12 experiment. Important first outcomes about scalars and their features will be provided by the study of the $\pi^+\pi^-$, K^+K^- and $K_S^0K_S^0$ decay channels through partial wave analyses.

The primary goal of the GlueX Experiment at Jefferson Lab is to identify and study the spectrum of light quark hybrid mesons through photoproduction. A large and unique data set with great prospect for establishing the light-quark hybrid meson is being acquired. The current hybrid searches are fo-

cused on several "golden channels" with sufficiently large cross sections and clean signals, including $\eta\pi$, $\eta'\pi$, $\eta\pi\pi$, $\omega\pi\pi$, and K^*K . The current focus is on the development and validation of the reaction models needed to reproduce the amplitude. The models are developed in collaboration with several groups of theorists, including the The Joint Physics Analysis Center (JPAC).

A multi-channel analysis of existing data has been performed by the BnGa-PWA group where older published data (GAMS, CERN-Munich, Crystal Barrel $\bar{p}N$, and some BES-data) are used. Presently, there are mainly results on baryons.

ALICE completed a measurement of $f_0(980)$ spectra in different multiplicity class in pp collisions at 13 TeV. $f_0(980)$ is identified by its decay $\pi^+\pi^-$. Hadronic resonances identification was performed using machine learning techniques.

From the theory side, a dispersive model-independent analysis of pion-kaon and pion-pion->kaon-antikaon partial-wave scattering data in the low energy region below 1.6 GeV, has been provided by means of coupled forward, fixed-t and hyperbolic dispersion relations. The respective group has delivered precise and ready-to-use partial-wave parameterizations for further final-state interaction studies, as well as a model-independent determination of the lightest strange meson, the controversial kappa or $K_0^*(700)$, which should remove its "Needs Confirmation" status in the Review of Particle Physics. Several theoreticians in HadSpec have also helped in writing the KLong beam Facility (KLF) proposal to measure K-pi scattering at low energies and a more precise determination of the kappa.

Further progress includes a comparison between results for the light scalar mesons, including the lightest strange resonance, obtained either from unitarization methods for Effective Field Theory scattering amplitudes or from purely dispersive approaches [48]. For several decades, the $\sigma/f_0(500)$ and $\kappa/K_0^*(700)$ resonances have been subject to long-standing debate. Both their existence and properties were controversial until very recently. We compared model-independent dispersive and analytic techniques versus unitarized Chiral Perturbation Theory, when applied to the lightest scalar mesons $\sigma/f_0(500)$ and $\kappa/K_0^*(700)$. Generically, the former have settled the long-standing controversy about the existence of these states, providing a precise determination of their parameters, whereas unitarization of chiral effective theories allows us to understand their nature, spectroscopic classification and dependence on QCD parameters. Here we review in a pedagogical way their uses, advantages and caveats. Some of these studies were performed in collaboration with the JPAC Group (see Task T3.1) leading to a proposal for a new experimental facility with a secondary kaon beam to be built at Jefferson Lab. The pole position of the scalar (and tensor) mesons in the range 1-2 GeV was derived from J/ψ radiative decays [38]. A systematic analysis of J/ψ radiative decays in conjunction with neutral pions and kaons using partial waves measured by BESIII was performed. A large set of amplitude parametrizations was used to reduce the model bias determining the physical properties of seven scalar and tensor resonances in the 1–2.5 GeV mass range. These include the well known $f_0(1500)$ and $f_0(1710)$, that are considered to be the primary glueball candidates. The hierarchy of resonance couplings determined from this analysis favors the latter as the one with the largest glueball component.

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V. TASK 4. BARYON SPECTROSCOPY

Baryon resonance parameters (e.g. mass, width, pole position) have been extracted so far by partial-wave analyses of scattering data. An intense effort has started to add information from photon-induced meson production at ELSA, TJNAF and MAMI, from charmonium decays at BESIII and diffractive pp reactions at COMPASS. The recent strong indications for a resonance around 2.4GeV in the 6-quark system are an important advance in the quest for a deeper understanding of QCD and bound quark systems beyond the usual $3q$ and $2q$ systems. Other experiments are providing evidence for the existence of $4q$ (Belle, BaBar, BESIII, LHCb) and $5q$ (LHCb) systems. The same analysis framework developed for Task 3 could be used to extract resonance parameters adopting the state-of-the-art calculations developed in Task 1.

A. T4.1 Resonance parameter determination

The formation of light-quark baryon resonances is studied in meson nucleon scattering and photon-induced meson production. Due to the huge experimental effort at several photon-beam facilities, in particular ELSA, GRAAL, TJNAF, and MAMI, precision data for many spin-dependent observables in photo- and electroproduction of light mesons are available or are expected in the near future. The activity of HaSP groups focused on publishing new experimental data and refining partial wave analyses. New experimental data on photo- and electro-induced meson production on protons and deuterons measured by the CB-ELSA, BGOOD, CLAS, CLAS12, GlueX and A2-MAMI collaborations were published with a significant contribution from institutions participating in STRONG2020-HaSP [1–12]. The results cover helicity dependent pion production, kaon hyperon production and pi eta production in an energy range which is crucial for the extraction of light baryon resonance parameters. The new data are presently studied within several partial wave analyses. A new unitary MAID model is almost final and a publication is under preparation. An extension of the latest Jülich-Bonn model to pion and eta electroproduction has been published incorporating constraints from pion-induced and photoproduction data [9]. A single-energy partial-wave analysis method based on a simultaneous use of amplitude and partial-wave analyses was applied to $K^+\Lambda$ photoproduction [13]. New studies on so called complete experiments in single and double meson photo- and electroproduction were published [14, 15]. Strangeness photoproduction studies benefit by recent measurements performed in Bonn on neutral channels [7] and couple-channels analysis performed by Jülich-Bonn groups [16] and theoretical development in Partial Wave Analysis [17]. Further studies on $\Lambda(1405)$ were published by the GlueX Collaboration in Ref [18] and phenomenological analysis in Ref. [19]. A tight collaboration between experimental and theory groups in Jülich, Bonn and Washington led to the publications of significant results on pi-eta electroproduction [20] couple-channels analysis and other related subjects [21, 22]. New experimental data on heavy quark baryons were published by the LHCb collaboration including new evidence for pentaquark configurations [23–26]. Deep Neural Networks were applied for the first time to LHCb data by the JPAC collaboration in order to study exotic baryons [27]. We want to stress that a combined analysis, coordinated with the activity of T3.1 is necessary to extract resonance parameters and describe the electro/photoproduction in a consistent way. In particular, the amplitude analysis (Regge Theory inspired and polarization formalism) developed for light quark meson spectroscopy in T3.1 has been extensively used to study the nucleon resonances and determine their parameters. Experimental and theoretical reviews of the field were published in the two papers [28, 29].

B. T4.2 Diffractive and annihilation production and exotic baryon

One of the still open problems in the description of the baryon spectrum by Quark Models or lattice QCD is the missing observation of a sizable number of nucleonic resonances. Significant progress has been made in recent years and is evident in several new entries of N^* and Δ^* states in the latest editions of the Review of Particle Properties (PDG), as well as the inclusion of the transition form factor measurement for several excited states. Most of the newly discovered states have masses in the

range 1.85 GeV to 2.1 GeV where precise photoproduction data were driving the new observations, however the mass region above 2.1 GeV has hardly been studied. This is the region where the gluonic excitations are expected to occur, representing the focus of the task in the search of exotic baryons. The existence of "exotic baryons" whose structure is more complex than a simple three-quark state not only is compatible with QCD predictions, but it has been experimentally observed at LHCb, where evidence of penta-quark states has been obtained. In the search for "missing resonances", with the scope of a better understanding the nucleon dynamics, new important information can be provided by precision electromagnetic machines operating polarized beams. The availability of polarized photon beams impinging on polarized targets provide access to single and double polarization observables of meson photoproduction processes, which strongly constrain the reaction amplitudes and proved to be the new key information in the discovery of the new resonances. Electro-production of the same mesons-baryon final states produced in photo-reactions allows for the extraction of the resonance electro-couplings and the study of their evolution as a function of the Q^2 photon virtuality. This additional information allows to picture the evolution of the effective-degrees N^* freedom as a function of the distance scale and to assess the possible hybrid nature of new resonances. New results for CLAS and CLAS12 data have been obtained on photo and electro-production of mesons, where KY final states have been investigated.

Single pion photoproduction on proton target. The double-polarization observable G has been measured for single pion photoproduction (π^+ and π^0), using a longitudinally spin-polarized proton target and an energy tagged (0.73-2.3 GeV) and linearly polarized photon beam [12]. The large data set has provided an important constraint on the properties and spectrum of excited nucleon states decaying to $N\pi$ in the mass range from 1.4 to 2.2 GeV, as well as for background (non-resonant) photoproduction processes. The considerable improvement achieved in the description of the observable within the SAID and Bonn-Gatchina approaches after implementation of the data, illustrates that the partial-wave analyses now significantly extend the knowledge on $N\pi$ photoproduction amplitudes at GeV.

Photo induced KY production. A new measurement of the beam-spin asymmetry has been obtained for the reaction $\bar{\gamma} + n \rightarrow K^+ + \Sigma^-$ on quasi-free neutrons in a liquid-deuterium target, for photon beam energies in the range 1.1 to 2.3 GeV [30]. The new dataset includes data at previously unmeasured photon energy and angular ranges, thereby providing new constraints on partial wave analyses used to extract properties of the excited nucleon states. Predictions from an isobar model indicate strong sensitivity to $N(1720)_{3/2^+}$ and incorporating the new data shows significant changes in $\gamma - n$ couplings of resonances which have small branching ratios to the πN channel. The reaction $\gamma p \rightarrow K^+ \Lambda(1520)$ has also been studied using photoproduction data from the CLAS g12 dataset and identifying the $\Lambda(1520)$ via the exclusive detection of the two decay channels [11]. The differential cross sections, as a function of center-of-mass angle, have been extended to higher photon energies, comparing to previously published CLAS results. Comparison with theoretical models show that no new N^* resonances decaying into the K^+ are necessary to describe the $\Lambda(1520)$ production. Some of these results have been shared with T3.2 to shape the physics program of the future kaon-beam facility at Jefferson Lab. Electro-induced KY production. First results from CLAS12 RG-K data have been obtained for beam-recoil transferred polarizations for the exclusive electroproduction of and final states from an unpolarized proton target [3]. The measurements at beam energies of 6.535 GeV and 7.546 GeV span the range of four-momentum transfer Q^2 from 0.3 to 4.5 GeV² and invariant energy W from 1.6 to 2.4 GeV, while covering the full center-of-mass angular range of the K^+ . These new data extend the existing hyperon polarization data from CLAS in a similar kinematic range but from a significantly larger dataset. They represent an important addition to the world data, allowing for better exploration of the reaction mechanism in strangeness production processes, for further understanding of the spectrum and structure of excited nucleon states, and for improved insight into the strong interaction in the regime of non-perturbative dynamics. A combined analysis that includes results of T4.1 concerning the KA photoproduction is currently undergoing.

Data Analysis and Interpretation: The first model independent analysis of experimental data on the hidden-charm pentaquark-like $P_c(4312)$ resonance, observed by the LHCb Collaboration, has been performed using Deep Neural Networks to determine the nature of the exotic hadron [27]. It is found that its most likely interpretation is that of a virtual state. The interest of the method is that it can be applied to other near-threshold resonance candidates. In coordination with T3.1, a combined anal-

ysis of J/ψ production at threshold studied with the GLUEX detector led to JPAC group to propose $P_c(4312)$ as a possible virtual state in $\Sigma^+ D^0$ channel.

C. T4.3 Dibaryon structure and parameter determination

Task 4.3 focused on study and searches for non-standard (hexaquark) configurations for hadronic matter. The task primarily focused on the light quark sector (u, d and s quarks), exploiting polarization observables and beam facilities at the frontiers of intensity to provide new levels of precision in searching for and establishing hexaquark states.

A first data set on the photoproduction of dibaryons containing strange quarks was obtained from deuterium target at Jefferson Lab with CLAS12. Analysis is ongoing. Preliminary results show first determination of Lambda polarization in photoproduction from deuterium targets. This will be compared to benchmark data set from proton targets. The ratio will provide new sensitivities to molecular and hexaquark states. Final states with strangeness 2 and 3 can be extracted from both hydrogen and deuterium targets. The scaling behavior of such production processes for protons and deuterons will provide new sensitivities, both in the 5- and 6-quark sector. The approved beam time at MAMI on polarized deuterium targets has been delayed due to loss of polarized target expertise following the boycott of Russian scientists. The analysis of the transferred polarization (Cx') in deuterium photodisintegration has been completed published in Ref. [31]. The measure Cx' shows structure in the region of the d^* hexaquark and also shows complementary behavior to the, recently published, induced polarization (Py). The Cx' analysis employed a cross-verification with this well-established quantity for the $n\pi^+$ reaction. This extends the data set and provides new information also for nucleon resonance studies. Results obtained in meson (see Task T3.1) and baryon (see T4.1) spectroscopy are the building block for a comprehensive understanding of resonances in multi-nucleons systems. The scientific activity of T4.2 largely benefit from the input provided by the phenomenological models (single nucleon production amplitudes) developed by the other Tasks. The network has been expanded to include the theoretical physics group at Khon Kaen University, Thailand. Initial theoretical studies of the internal structure of the $d^*(2380)$ based on Weinberg compositeness criteria support a hexaquark nature for the $d^*(2380)$. In Ref. [32] we have developed a novel technique to extract hyperon nucleon interaction strength over a large energy range. Its validity was tested for the Lambda-proton scattering, which is of a highest importance for the physics of neutron stars and solution of the so-called "hyperon puzzle". Other theoretical explorations included strongly bound dibaryons from Lattice QCD [33] and effect of destabilization of high mass neutron stars by the emergence of d^* -hexaquarks [34]. A review of the current status of the field can be found in Ref. [35].

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VI. HASP LEGACY

To make the best and most efficient use of knowledge, HaSP set-up a web-based portal for hadron spectroscopy <http://web.ge.infn.it/jstrong2020/>. The portal, open to the whole hadron spectroscopy community, is intended as a living tool to collect and organize information and procedures developed by the networking activity. The portal will remain accessible beyond the end of the project preserving the outcomes of the networking activity in the future. The most part of the activity of this networking is done using open-source and open-access tools. The whole networking outreach has been public and available for free.

The science addressed in this network includes the investigation of the origin of mass of the visible universe around us. Over 90% of this "mass" is in fact energy produced by the physical phenomena that we are attempting to elucidate. This energy manifests itself as mass through Einstein's relation $E = mc^2$. Establishing the detailed nature of such mass-generating mechanisms regularly make the lists of the major unsolved problems in physics. Outreach information, which is accessible to the general public, has been produced and presented at science festivals and outreach talks in schools and universities. The learning/teaching process among the HaSP participants and other researchers interested in hadron spectroscopy represented an important aspect of the network. One of the main outreach of HaSP has been to teach and train young researchers responsible for the next-generation experiments on the amplitude analysis, transferring skills and expertise that are presently in the hands of senior collaborators. Dedicated visits and mid to long-term stays in hosting Institutions/Laboratories represented a significant fraction of the received funding. Senior collaborators tutored young researchers and students interested in hadron spectroscopy. HaSP organized a school (<https://diarium.usal.es/strong2020/>) to teach the basis of data analysis, amplitude analysis and show in realistic case studies the tools developed by the network's activity. The HaSP workshops represented a valuable occasion for young researchers, not only to learn from their senior colleagues, but also to present their original work in a stimulating environment with sizable time allocated for discussions. The HaSP web portal has been used to collect supporting material for offline classes and as a forum to discuss hot topics among the whole network.