6th Workshop on Future Directions in Spectroscopy Analysis (FDSA2025)

Tuesday 9 December 2025 - Thursday 11 December 2025

Facultat de Física, Universitat de Barcelona

Book of Abstracts

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Hyperfine splittings of heavy quarkonium hybrids

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In the framework of the Born-Oppenheimer Effective Field Theory, the hyperfine structure of heavy quarkonium hybrids at leading order in the $1/m_Q$ expansion is determined by two potentials. We estimate those potentials by interpolating between the known short distance behavior and the long distance behavior calculated in the QCD Effective String Theory. The long distance behavior depends, at leading order, on two parameters which can be obtained from the long distance behavior of the heavy quarkonium potentials (up to sign ambiguities). The short distance behavior depends, at leading order, on two extra paramentes, which are obtained from a lattice calculation of the lower lying charmonium hybrid multiplets. This allows us to predict the hyperfine splitting both of bottomonium hybrids and of higher multiplets of charmonium hybrids. We carry out a careful error analysis and compare with other approaches.

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Studying the Glueball Spectrum within Constituent Models

Author: Cyrille Chevalier[1]

[1] *University of Mons*

Glueballs are elusive states. These unique particles, arising directly from the non-Abelian nature of the QCD gauge symmetry, were theoretically predicted in the early 1970s. Yet, their experimental observation remains a matter of debate within the community. The existing signals are difficult to interpret, partly due to the lack of theoretical consensus on their expected properties.

Various approaches have been employed to determine these properties, including calculations based on lattice QCD, Bethe-Salpeter equations, QCD sum rules, the bag model, and the Coulomb-gauge Hamiltonian. The present talk analyses the glueball spectrum from a different perspective, that of constituent models. In this framework, glueballs are treated as bound states of several constituent gluons. The focus is placed on the two-gluon sector, illustrating how a glueball mass spectrum can be obtained at relatively low numerical cost within this model. The issue of the constituent gluon mass is discussed in this context. The resulting masses are finally compared with those from lattice QCD and show notable agreement.

GlueX/CLAS: Moments / 6

2Pi0 Moment and Partial Wave Analysis

Author: Alexandra Berger[1]

[1] *University of Glasgow*

Quantum Chromodynamics (QCD) is the theory of the strong force and gives rise to a spectrum of hadrons. Hadrons such as qq773; and qqq states have been observed but others, such as the gg (glueball) or the qq773;g (hybrid) state are not forbidden. A gg pair can share the same quantum numbers as a qq773; meson, resulting in the 'mixing'of their respective states; the observed physical particle is a superposition of pure glueball and pure meson states.
The pi;8304; pi;8304; channel provides a window into these states, and others, due to a high level of statistics and quantum number restraints ensuring the even spin number of the intermediate particle. Through this channel an analysis sensitive to quantum number of the lowest lying glueball at J^{PC} = 0⁽⁺⁺⁾ and possible 'mixed'J^{PC} = 2⁽⁺⁺⁾ state become possible, as well as an analysis of other states which require clearer branching fractions and differential cross sections to compare with theoretical predictions.
Using data obtained as part of the GlueX collaboration at the Thomas Jefferson National Accelerator Facility, alongside sPlot analysis techniques, encouraging preliminary moment and partial wave analysis results have been obtained using a combination of parametric and non-parametric moment models. Future work will study the systematics of different fit methods in detail.

CLAS / EIC / **7**

Moments of Angular Distribution of the K+K- System with CLAS12

Author: Charlie Velasquez[1]

[1] *University of York*

Since the prediction of the meson in 1935, facilities and institutions across the world have contributed to the discovery of over 200 distinct types, some of those being the well-known pions, kaons and J/Ψ. Understanding the properties of the mesons, including their spin, lifetime and mass, allows for the classification of this vast family of hadrons to be improved. This is particularly important in the case of the discovery of new or exotic mesons. In this endeavour, determining the spin is vitally important. A set of quantities known as moments of angular distributions relate the spin of a meson to the angular distributions of its decay products; furthermore, these quantities can be extracted unambiguously and directly from experimental data. The Thomas Jefferson National Accelerator Facility, also known as Jefferson Lab, located in Virginia, is home to the Continuous Electron Beam Accelerator Facility (CEBAF), which is capable of producing a high-luminosity 12 GeV electron beam. When this beam impinges on a supercooled liquid hydrogen target, electron-proton interactions result in the production of various mesons, which are then detected by the CEBAF Large Acceptance Spectrometer at 12 GeV (CLAS12). The purpose of this research is to use CLAS12 at Jefferson Lab to obtain the moments of angular distributions of mesons that decay into pairs of oppositely charged kaons.

COMPASS/GlueX: Double Regge / **8**

Double-regge amplitudes

Authors: Adam Szczepaniak[1]; César Fernández Ramírez[2]

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We will review the theory behind Double-Regge amplitudes that describe the high energy regime of diffractive eta-pi production.

Machine Learning / **9**

Machine Learning aided pole localization for the resonance $a_0(980)$ - status of the project.

Author: Łukasz Bibrzycki[1]

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Using several amplitude parametrizations like explicitly unitary amplitudes in the scattering length approximation and the separable potentials we describe the coupled channel $\pi\eta$, $K\overline{K}$ scattering in the vicinity of the $a_0(980)$ resonance.

Then we train the neural network to localize the poles corresponding to the $a_0(980)$ resonance across several decay reactions. We aim for a global analysis that evaluates the pole determinations by different experiments and checks the consistency of various model approaches. Status of this project will be presented.

COMPASS/GlueX: Double Regge / **10**

Welcome

Author: Vincent Mathieu[1]

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Welcome

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Probing $\eta\pi$ Production with Finite-Energy Sum Rules

Author: Nadine Hammoud[1]

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The study of hadronic scattering processes remains fundamental for understanding the dynamics of strong interactions across energy scales. Finite-Energy Sum Rules (FESR) provide a powerful framework for connecting low-energy resonance behavior with the high-energy regime described by Regge theory, offering valuable constraints on phenomenological amplitudes. Motivated by the COMPASS measurements of ($\eta\pi$) production, the reaction ($\pi p \rightarrow \pi\eta p$) is examined within this framework. This channel is particularly well suited for probing the transition between resonance-dominated and Regge-dominated dynamics, and for exploring possible contributions from exotic mesons. The analysis sheds light on the consistency of amplitude descriptions across energies and enhances our understanding of the mechanisms governing ($\eta\pi$) production.

GlueX/CLAS: Moments / 12

A double-Regge exchange model for high-energy $\eta^{(\prime)}\pi$ photoproduction

Author: Gloria Montana[1]

[1] *Universitat de Barcelona & ICCUB*

The study of $\eta^{(\prime)}\pi$ photoproduction is particularly interesting for the search for the lowest lying hybrid meson with exotic quantum numbers, the $\pi_1(1600)$, at the GlueX experiment at Jefferson Lab. In this talk, I will present a model based on a double-Regge exchange of vector trajectories for $\eta^{(\prime)}\pi$ photoproduction at high energies. The model successfully describes CLAS data at large $\eta\pi$ invariant mass and predicts a sizable forward-backward angular asymmetry at GlueX energies, larger in $\eta'\pi$ than in $\eta\pi$, indicating the presence of strong exotic partial waves in the resonance region, particularly in the $\eta'\pi$ channel.

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The Quark-Diquark Structure of Baryons

Author: Clara Tourbez[1]

[1] *UMONS*

Baryons can be described within several theoretical frameworks. Among them, the constituent approach is widely used. In this context, we aim to evaluate the accuracy of an approached model of baryons: the quark-diquark approximation. It consists in separating the three-body system into two subsequent two-body ones: a pair of two quarks (the diquark) and a subsystem consisting of the diquark and the remaining quark. This approximation is widely employed, but its accuracy is rarely evaluated. The goal of this work is to perform this evaluation by comparison with a three-body model. The baryon masses and characteristic distances are computed and analysed within both approaches. Additionally, an original procedure to establish the quark-diquark potential will be presented with the aim to increase the precision of this approximation.

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Three-body decays with Khuri-Treiman equations

Author: Sergi Gonzalez-Solis[1]

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One of the main issues posed by the presence of hadrons in any reaction is their final-state interactions, which are formally expressed in terms of the unitarity of the amplitude. In two-body scattering, unitarity is usually imposed in the direct channel only, as one is not sensitive to the details of the crossed channels. This is certainly not the case for a three-body decay, where the three possible two-hadron channels are physical, and one ideally wants to impose unitarity in all channels at once. The Khuri-Treiman formalism is a dispersive approach which indeed allows one to do so. In this talk, I will review the contributions made by the JPAC Collaboration to this field with focus on various important applications, e.g. $V \to 3\pi$ ($V = \omega, \phi, J/\psi$) or the exotic $\pi_1(1600) \to 3\pi$ decay.

CLAS / EIC / 15

Meson Spectroscopy with Electron Scattering

Author: Derek Glazier[1]

[1] *University of Glasgow*

Experiments at CLAS12 and the Electron Ion Collider facilitate production of meson resonances dominantly through low Q2 virtual photoproduction (or quasi-real photoproduction). This provides an effectively elliptically polarised photon beam which provides stringent constraints on the underlying partial wave amplitudes. We will consider the prospects for analysing exotic mesons at the EIC with such a process. We will review the tools available for such studies and discuss what is required to develop a rigorous spectroscopy programme at the EIC.

CLAS / EIC / 16

Measurement of exclusive J/ψ photoproduction with the CLAS12 experiment: unpolarized cross section and perspectives for polarization observables

Author: Pierre Chatagnon[1]

[1] *CEA Saclay*

The photo-production of vector mesons off the nucleon has long been established as an important tool to access the gluon content of the nucleon. In particular, the photo-production of J/ψ near the threshold energy has been related to the Gluons Gravitational Form Factors of the nucleon. However, the validity of this interpretation must be tested and additional contributions such as open charm loop diagrams or possible pentaquarks have to be fully understood. In this talk, I will present results on the unpolarized cross-section of the near-threshold photoproduction of J/ψ, using data taken by the CLAS12 detector at Jefferson Lab, on proton and deuterium targets. Perspectives to measure beam and target polarization observables will also be discussed.

Machine Learning / 17

A variational approach to quantum field theory

Author: Martí Rovira i Pons[1]

Co-authors: Assumpta Parreño [2]; Robert Perry [3]

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[3] *University of Barcelona*

In strongly coupled field theories, perturbation theory cannot be employed to study the low-energy spectrum. Thus, non-perturbative techniques are required. One possibility is the Lagrangian approach, where energies are extracted from the Euclidean-time dependence of correlation functions. This method suffers from excited-state contamination at shorter times and rapidly growing statistical noise at larger times, leaving only a narrow time window to extract the energy of the system. An alternative is the variational approach in the Hamiltonian formalism, which does not present such signal-to-noise problem. However, it recquires the choice of a trial wave function. In this work, we study the viability of employing a neural network as a variational ansatz. As a first step towards

more phenomenologically interesting strongly coupled theories, like quantum chromodynamics, we study scalar field theories with quartic couplings.

COMPASS/GlueX: Double Regge / 18

A double-Regge exchange model for high-energy $\eta^{(\prime)}\pi$ photoproduction

Author: Gloria Montana[1]

[1] *Universitat de Barcelona & ICCUB*

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GlueX/CLAS: Moments / 19

Moments of Angular Distribution of the K+K- System with CLAS12

Author: Charlie Velasquez[1]

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Since the prediction of the meson in 1935, facilities and institutions across the world have contributed to the discovery of over 200 distinct types, some of those being the well-known pions, kaons and J/Ψ. Understanding the properties of the mesons, including their spin, lifetime and mass, allows for the classification of this vast family of hadrons to be improved. This is particularly important in the case of the discovery of new or exotic mesons. In this endeavour, determining the spin is vitally important. A set of quantities known as moments of angular distributions relate the spin of a meson to the angular distributions of its decay products; furthermore, these quantities can be extracted unambiguously and directly from experimental data. The Thomas Jefferson National Accelerator Facility, also known as Jefferson Lab, located in Virginia, is home to the Continuous Electron Beam Accelerator Facility (CEBAF), which is capable of producing a high-luminosity 12 GeV electron beam. When this beam impinges on a supercooled liquid hydrogen target, electron-proton interactions result in the production of various mesons, which are then detected by the CEBAF Large Acceptance Spectrometer at 12 GeV (CLAS12). The purpose of this research is to use CLAS12 at Jefferson Lab to obtain the moments of angular distributions of mesons that decay into pairs of oppositely charged kaons.

GlueX/CLAS: Moments / 20

Measurement of exclusive J/ψ photoproduction with the CLAS12 experiment: unpolarized cross section and perspectives for polarization observables

Author: Pierre Chatagnon[1]

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The photo-production of vector mesons off the nucleon has long been established as an important tool to access the gluon content of the nucleon. In particular, the photo-production of J/ψ near the threshold energy has been related to the Gluons Gravitational Form Factors of the nucleon. However, the validity of this interpretation must be tested and additional contributions such as open charm loop diagrams or possible pentaquarks have to be fully understood. In this talk, I will present results on the unpolarized cross-section of the near-threshold photoproduction of J/ψ, using data taken by the CLAS12 detector at Jefferson Lab, on proton and deuterium targets. Perspectives to measure beam and target polarization observables will also be discussed.

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Addressing the pΩ femtoscopy correlation function using baryon-baryon effective potentials

Authors: Assumpta Parreño[1]; Juan Torres-Rincon[2]; Marc Piquer i Méndez[1]

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[2] *ICCUB*

We have generated an updated version of the pΩ potential for low-energy interactions based on an effective field theory approach. This potential, together with other potentials based either on different parametrizations or lattice QCD, have been used to solve the Schrödinger equation, obtaining the scattering wave functions. Using these wave functions, we have computed the pΩ femtoscopic correlation functions, comparing the results with those published by the ALICE collaboration. Building on this work on the direct problem in femtoscopy, we are starting to work on the inverse problem of computing the potential parameters from the correlation function values using neural networks.

Machine Learning / 22

Learning the spectrum with Neural Quantum States

Authors: Javi Rozalén Sarmiento[1]; James Keeble[2]; Mehdi Drissi[3]; Arnau Rios Huguet[4]

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The quantum many-body problem lies at the heart of a wide spectrum of physical phenomena, ranging from interacting quarks to molecular dynamics, yet it poses a great computational challenge that remains unsolved. Traditional approaches often face a trade-off between accuracy and tractability, due to an underlying issue commonly known as the "curse of dimensionality". In this context, the method of Neural Quantum States (NQS) [1] offers a promising way around these difficulties. The Variational Monte Carlo framework tames the exponentially growing number of states, while the use of neural network ansätze equips it with great representation power. In this talk, I will introduce

the core ideas behind NQS and highlight some of their most successful applications, ranging from Quantum Chemistry [2, 3] to ab-initio Nuclear Structure [4-6]. I will also discuss current challenges in the field and outline major research directions shaping the development of NQS methods.

[1] G. Carleo and M. Troyer, Science 355 602-606 (2017)
[2] D. Pfau, J. Spencer et al., Phys. Rev. Research 2, 033429 (2020)
[3] D. Pfau, S. Axelrod et al., Science 385 (2024)
[4] J. Keeble and A. Rios, Phys. Lett. B 135743 (2020)
[5] A. Gnech, B. Fore et al., Phys. Rev. Lett.133, 142501 (2024)
[6] M. Rigo, B. Hall et al., Phys. Rev. E 107, 025310 (2023)

Phenomenology / **23**

A search for molecular-type hidden charm pentaquarks with an improved unitarization method

Authors: Angels Ramos[1]; Erick Einar Garcia Gonzales[None]; Volodymyr Magas[2]

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[2] *University of Barcelona & ICC, Spain*

The existence of the nucleonic pentaquark resonances $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$, $P_{c\bar{c}s}(4338)^0$ and $P_{c\bar{c}s}(4459)^0$, established by the LHCb collaboration, has been one of the major discoveries in hadron physics in the latest years. Most of these states (5 out of 6) can be understood as hadronic molecules, namely bound states of a sufficiently attractive meson-baryon interaction.

By unitarizing the scattering amplitude in the t-channel vector-meson exchange interaction model one can investigate the dynamically generated resonances. We revisited the procedure of the unitarized coupled-channel hidden gauge formalism, which has been a very successful approach in explaining many exotic hadrons in the charm and hidden charm sectors. The unitarization procedure requires the regularization of the meson-baryon loop function, commonly done using either a cut-off ($G^{\rm CO}$) or dimensional regularization ($G^{\rm DR}$). Although both schemes should yield similar results, some unphysical structures in the T-matrix were found that could not be associated to any resonance or bound state. We introduce a novel hybrid loop function ($G^{\rm HY}$), which combines both dimensional and cut-off regularizations. This approach enables a cleaner analysis of the scattering amplitude by avoiding the generation of unphysical poles, while keeping the properties of the dynamically generated states unaltered. In particular, this improved procedure allows us to predict two new pentaquark states in the $S = -1$, $I = 1$ sector. These states are dynamically generated in a very specific way, via a strong non-diagonal attraction between the two heaviest meson-baryon channels. This mechanism is also related to the generation of the two predicted pentaquark states in the $S = -2$, $I = 1/2$ sector reported in PRL 130, 091903 (2023) and PRD 111, 054020 (2025). This effect was overlooked before, because other research groups were discouraged by the repulsive character of the diagonal kernel coefficients, and because the complex structure of the scattering amplitudes obtained with both $G^{\rm DR}$ and $G^{\rm CO}$ - with unphysical structures - has obscured these physical states.

We hope that our work would stimulate experiments looking for these new pentaquark states, the discovery of which would enrich the family of observed exotic baryons.

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Spectroscopy at BESIII: Overview of most recent results

Author: Marco Scodeggio[1]

[1] *INFN - Sezione di Ferrara*

Over the past two decades, a new class of exotic states, commonly referred to as XYZ states, has been identified. These states are incompatible with the conventional quark–antiquark picture and are therefore considered candidates for tetraquarks, mesonic molecules, or hybrids. Since the BESIII experiment began colliding e^+e^- beams in the center-of-mass energy range between 2.0 and 4.9 GeV, it has made major contributions to our understanding of this new family of states, which still lack a clear theoretical interpretation. BESIII data sets have allowed us to deepen our knowledge of the properties of charmonia, to investigate the light-hadron spectra, and to search for exotic XYZ hadrons and shed light on their nature. In this talk, I will present some of the most recent and noteworthy results from the BESIII collaboration, together with possible interpretations and their implications for the spectroscopy of non-ordinary hadrons.

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The KLong Facility in Hall D at Jefferson Lab

Author: Stuart Fegan[1]

[1] *University of York*

The KLong Experiment in Jefferson Lab Hall D will use a secondary beam of neutral kaons and the GlueX experimental setup to perform strange hadron spectroscopy. By achieving a flux on the order of 1×10^4 K_L/sec, KLF will allow a broad range of measurements that improve the statistics of previous world data by several orders of magnitude.

The experiment will measure both differential cross sections and self-analysed polarisations of the produced Λ, Σ, Ξ and Ω hyperons spanning the mass range W = 1490 MeV to 2500 MeV. KLF data will significantly constrain partial wave analyses and reduce model-dependent uncertainties in the extraction of the properties and pole positions of the strange hyperon resonances, as well as establish the orbitally excited multiplets in the spectra of the Ξ and Ω hyperons. The proposed facility will also explore the strange meson sector through measurements of the final state $K\pi$ system up to 2 GeV invariant mass, and with the addition of nuclear emulsion detectors for high-resolution tracking, contribute to studies of hypernuclei.

This talk will give an overview of the KLong Facility design, current status, and prospects for its impact in strangeness spectroscopy.

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A 3-body formalism for determining the nature of X(3872)

Author: Giorgio Foti[1]

[1] *University of Messina & INFN Catania*

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S-matrix theory is one of the most powerful framework to study the unstable states
that populate QCD spectrum. In particular, it is very useful to extract physical properties
of the “exotics” candidates - particles that cannot be described by ordinary quark model -
in a non perturbative, phenomenological way. In this talk, I will introduce some 3-body formalisms
we are developing to determine the nature of the tetraquark candidate X(3872) in the S-matrix context: are the long-range interaction mediated by pions enough strong to bind it?

COMPASS/GlueX: Double Regge / **27**

Pseudoscalar meson-pair production beyond the resonance region at COMPASS

Author: Henri Pekeler[None]

The COMPASS experiment at CERN's SPS provides a very large data set to study the light-meson spectrum in diffractive production reactions of 190 GeV/c beam pions with protons. Among the many different final states accessible, $\eta\pi^-$ and $\eta'\pi^-$ are clean channels to investigate the lightest hybrid-meson candidate, the $\pi_1(1600)$. One challenge in the extraction of resonance parameters, like pole positions, is the separation of resonant and non-resonant processes.

To better constrain the non-resonant production mechanism of these final states, we analyze the high-mass region, i.e. $4\,\mathrm{GeV/c^2} < m_{\eta^{(\prime)}\pi^-} < 6\,\mathrm{GeV/c^2}$, using the double-Regge exchange model by Shimada er al., [Nucl. Phys. B 142 (1978)]. The model describes the dependence of the amplitude of a given double-Regge exchange on the invariant variables in terms of Regge trajectories. In addition, form factors are introduced at every vertex to parameterize the t-dependence of the coupling. We perform an event-based likelihood fit to the full COMPASS data set and show that the high-mass data can be described by only 13 parameters.

CLAS / EIC / **28**

Generalising Moments Analysis for Electroproduction

Author: Dillon Leahy[1]

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The Electron Ion Collider (EIC) is a proposed future collider in which the next generation of hadron spectroscopy experiments are set to take place. During electroproduction, resonances are produced through the exchange of a virtual photon, which gives greater detail on different production mechanisms compared to that of a real photon. The EIC will also have access to polarised electron and proton beams, providing the opportunity to investigate the physics of resonances by using the polarisation information to access otherwise inaccessible observables, such as cross-sections. To accommodate this, we will have to update the current electroproduction formalism to include a generalised moments analysis. In this presentation, first I will review the current electroproduction formalism and the moments analysis for photoproduction, then the derivation of this new generalisation for electroproduction, finally I shall provide an outline of the future of this project.

GlueX/CLAS: Moments / **29**

Angular analysis of 2π and 3π systems recoiling against Δ^{++} at GlueX

Author: Ilia Belov[None]

The GlueX experiment in Hall D at Jefferson Lab is designed for studies of light meson spectroscopy with a focus on searches for hybrid mesons that have exotic quantum numbers and therefore cannot be classified among conventional hadrons. The experimental facility exploits a tagged photon beam with energies from 3 GeV to 12 GeV incident on a liquid hydrogen fixed target. A significant part of the GlueX physics program is dedicated to comprehensive studies of the t-channel exchange mechanism between baryonic and mesonic systems, which is made possible by operating with a linearly polarized photon beam in the energy range from 8.2 GeV to 8.8 GeV. The photoproduction

mechanisms are probed by measurements of Spin Density Matrix Elements (SDMEs). Furthermore, advanced searches for spin-exotic mesons are performed through the application of Partial Wave Analysis (PWA) techniques.

In this talk, I present two ongoing physics analyses of the data collected in 2017-2018. First physics analysis is aimed at measurement of the SDMEs in the $\gamma p \to \Delta^{++}(\to p\pi^+)\rho^-(\to \pi^-\pi^0)$ reaction. A fit model is constructed for a simultaneous fit of angular distributions in both baryonic and mesonic systems. Second physics analysis is aimed at the PWA of a $\pi^+\pi^-\pi^-$ system produced in the $\gamma p \to \pi^+\pi^-\pi^-\Delta^{++}(\to p\pi^+)$ reaction. In the approximation of an Isobar decay, data with the selected three-pion final states will be fitted as a superposition of partial waves contributing to the total intensity. The PWA techniques will be applied to angle fits in certain bins of $m_{3\pi}$ and $-t$. Particular interest lies in establishing of a resonant spin-exotic 1^{-+} contribution coming from the P-wave $\rho\,\pi^-$ configuration.