The CLAS12-PANDA Physics Analysis Program

One of the primary goals of JLab and PANDA physics programs is to identify and extract hadron resonance parameters. When a resonance couples strongly to an open channel by it decays before being detected and establishing its existence requires a search for poles in the complex energy or angular momentum planes. To do this conclusively, from experimental data, requires development of theoretical reaction amplitudes, which can be analytically continued outside the physical region of the kinematical variables: energies, momenta, and angular momenta.

# Principles of Reaction Theory

The first appearance of hadronic physics at the forefront of high-energy research occurred 40 years ago. At that time, experimental datasets were sparse (with many orders of magnitude less precision than permitted by 21st century technology), computational resources were scarce, and the real degrees of freedom of the strong interaction along with its unique properties were just being identified. In spite of these limitations, a great deal of understanding of hadron reaction theory was achieved and various methods for data analysis and interpretation were proposed. The methodology is based on exploration of the analytical properties of the reaction amplitude (S-matrix). By itself it does not provide a unique set of rules for writing amplitudes to fit and interpret data. However, it suggests which effects should be included in amplitude analyses. The methodology of imposing S-matrix constraints on amplitude phenomenology has proven very successful in the past. Its implementation in modern amplitude analysis toolkits can take advantage of results from lattice gauge theory simulations and effective field theory approaches.

## Physics Analysis Program

A conventional description of a decay of a state with well defined spin and parity to a multi-particle final state is based on the isobar model. In proton-anti-proton annihilation (PANDA) such initial states are obtained when the center of mass energy matches that of a narrow resonance, e.g. one of the charmonium states or when a narrow resonance is produced down the decay chain, e.g. a D-meson from proton-anti-proton -> D-anti-D. At CLAS photons are scattered at high energy and a multi-particle system with meson (baryon) quantum numbers emerges from the “top” (“bottom”) vertex representing photon (target) fragmentation. In this case the following discussion applies to individual partial waves of the meson or baryon system separately. The factorization between the two is predicted by the Regge theory at asymptotically large center of mass energies. At finite energies of the CLAS experiment corrections, which in general violate this factorization, may need to be studied.

In the isobar model the decay amplitude is written as a sum of products of amplitudes, with each term in the sum describing a sequential two-body decay where the decay products are either the stable final state particles or other isobars. An individual isobar is often parameterized by a Breit-Wigner amplitude. Other parameterizations, which retain the two-body factorization are applied when a single isobar cannot be well identified and involve, for example the K-matrix, Omnes, or Chew-Mandelstam amplitudes. The isobar model can be derived from a particular representation of the full reaction amplitude (Mandelstam representation) using certain approximations, which include truncating the partial wave expansion and neglecting re-scattering between particles/isobars emerging from distinct two-body channels. The importance of the neglected effects needs to be investigated on the case-by-case basis. In general, however, the isobar model is expected to be a good approximation when particles emerging from isobars in distinct channels do not overlap in phase space. When phase space opens up due to a large mass of the decaying particle, e.g. in charmonium decay to light hadrons, ’s , K’s, ’s etc. (PANDA) or when light hadrons are from a decay of large mass excitations of the photon (or target) in the photon-proton collisions (JLab), several partial waves are expected to contribute. In this case, instead of summing over a large number of individual isobars it becomes necessary to invoke Regge theory, which can describe the cumulative effect of many (infinite) exchanges of isobars in one channel on another one. The peripheral production characteristic to high-energy photon-proton reactions is also present in proton-anti-proton annihilations at PANDA. These processes will provide important tests of Regge factorization hypothesis. In hadronic reactions Regge theory enables to relate amplitudes describing reactions related by crossing. It for example, implies relationships between parameters of directly produced resonances and properties of Regge exchanges aka. reggeons. This duality enables to impose constrains on resonance parameters through so the called finite energy sum rules (FESR’s) that so far have not been implemented in modern amplitude analyses. Implementation of resonance-reggeon duality and FESR’s will be a key novel feature of the combined JLab/PANDA development of amplitude analysis toolkit.

## Implementation and tools

In order to experimentally extract observables connected to the aspects discussed above, several requirements have to be met in terms of software environment.

Since amplitude analyses usually require high statistic samples with very low background level, excellent reconstruction efficiency for charged and neutral particles is required. This goes together with the need for good particle identification and effective pre-selection of reactions. In particular for PANDA the latter requirement plays a special role since the expected ratio of background to signal cross section is of the order of O(104) – O(107). This will be realized with a complete online reconstruction approach to filter events based on a high level of reconstructed information that include invariant masses, particle multiplicities and even vertex quality. In the PANDA environment a framework based on *FairRoot* [http://fairroot.gsi.de] will be used and is currently being used for detector simulation and reconstruction.

For the high-level amplitude analysis certain software implementations with varying degree of physics input already exist. For example *ComPWA* is currently being developed by the PANDA collaboration as a framework that in addition to handing data and simulations builds in several dynamical models e.g. Breit-Wigner, K-Matrix parameterizations in multiple kinematical settings e.g. helicity formalism, covariant tensor formalism etc. An alternative is to use a package, which is optimized for handing intensive calculations over large data sets, but is otherwise physics-blind. This allows the user to supply their own amplitudes for physics analysis. A package of this type, called *AmpTools* has been develop at Indiana University and been used in CLAS12 simulations.