The Joint Physics Analysis Center: Recent results

César Fernández-Ramírez
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México 04510, Mexico
E-mail: cesar.fernandez@nucleares.unam.mx

Abstract. We review some of the recent achievements of the Joint Physics Analysis Center, a theoretical collaboration with ties to experimental collaborations, that aims to provide amplitudes suitable for the analysis of the current and forthcoming experimental data on hadron physics. Since its foundation in 2013, the group is focused on hadron spectroscopy in preparation for the forthcoming high statistics and high precision experimental data from BELLEII, BESIII, CLAS12, COMPASS, GlueX, LHCb and (hopefully) PANDA collaborations. So far, we have developed amplitudes for $\pi N$ scattering, $KN$ scattering, pion and $J/\psi$ photoproduction, two kaon photoproduction and three-body decays of light mesons ($\eta$, $\omega$, $\phi$). The codes for the amplitudes are available to download from the group web page and can be straightforwardly incorporated to the analysis of the experimental data.

1. Introduction
One of the many challenges of physics is to achieve a comprehensive understanding of the phenomena produced by strong coupling Quantum Chromodynamics (QCD), responsible for the binding of quarks inside hadrons and for more than 95% of the mass of the visible Universe. Hadrons are color singlets due to color confinement. Hence, the simplest structures are $q\bar{q}$ (quark-antiquark) for mesons and $qqq$ (3-quarks) for baryons. However, there are many other ways we could build color neutral hadrons, for example: glueballs made out of a number of gluons, multi-quark states such as tetraquarks ($qq\bar{q}\bar{q}$) or pentaquarks ($qqqq\bar{q}$), hybrid mesons and baryons with gluonic components ($q\bar{q}g$ and $qqqg$) and so on. For a recent, brief and pedagogical summary of the current status of hadron physics we refer the reader to [1].

In the last years we have witnessed a dramatic advancement in detection techniques and accelerator technologies from the experimental side and algorithms for first principle QCD analyses on the theoretical side [2]. Consequently, many experimental facilities throughout the world have research programs on hadron spectroscopy, among them: LHCb [3], CMS [4] and COMPASS [5] at CERN (Geneve, Switzerland), CLAS12 [6] and GlueX [7] at Jefferson Lab (Newport News VA, USA), BESIII [8] at the Beijing Electron Positron Collider (Beijing, China), KLOE2 [9] at Laboratori Nazionali di Frascati (Frascati, Italy), BELLEII [10] at KEK (Tsukuba, Japan), the Hadron Experimental Facility [11] at J-PARC (Tokai, Japan), and (hopefully) the future PANDA [12] at FAIR (Darmstadt, Germany). As a result, several candidates for exotic hadrons beyond the $q\bar{q}$ and $qqq$ picture have been discovered both in the meson [13] and baryon [14] sectors.

Given the experimental and theoretical interest on hadron spectroscopy, the Joint Physics Analysis Center (JPAC) [15] was set up to develop theoretical and phenomenological analysis...
methods to support hadron physics experiments. It started out in 2013 with 8 researchers, as a joint venture between Indiana University, George Washington University and Jefferson Lab. Currently it has expanded to 20 researchers distributed among the three founding institutions plus Rheinischen Friedrich-Wilhelms Universität Bonn and Johannes Gutenberg Universität Mainz in Germany, IFIC/CSIC-Universidad de Valencia in Spain, and Universidad Nacional Autónoma de México in Mexico.

The JPAC researchers are using S-matrix theory principles, \textit{i.e.} analyticity, crossing symmetry and unitarity \cite{16}– to develop scattering amplitudes for several hadron reactions of theoretical and experimental interest. In doing so, we work closely with experimentalists to implement the amplitudes in the existing data-analysis software.

The methods to write the amplitudes include the K-matrix \cite{17} and N/D parametrizations \cite{18}. These can be complemented with chiral symmetry constraints at low-energies \cite{19} or Regge asymptotics \cite{20} if needed. The amplitudes can be analytically continued from the real axis where the experimental data live to the complex-\(s\) plane and to the unphysical Riemann sheets, which allows us to unravel the existing resonances contributing to the physical reactions. It is important to note that the amplitudes developed by JPAC and the analytical continuation to the complex plane are also necessary to extract the resonances and their properties from first principle lattice gauge QCD \cite{21}.

In the next section we briefly summarize some of the results obtained by the group during the last two years.

2. Recent results

2.1. Three-body meson decays

Three-body decays play an essential role studying hadron dynamics and hadron spectroscopy. The extraction of CP violation phases often requires the amplitude analysis of three-body \(B\) and \(D\) decays \cite{22} and several candidates for non-quark model states have been observed in heavy mesons decaying into three particles \cite{14, 23, 24}. Heavy-meson decays have complicated phase spaces and their analysis can be cumbersome, hence, it is better to test our ideas on amplitude-building with simpler cases, like the decay of light mesons, \textit{i.e.} \(\eta, \omega, \phi \to 3\pi\). Besides, these decays are interesting \textit{per se} given the current and forthcoming precision data from various collaborations \cite{25}. For these reasons, at JPAC we have developed an intensive work on dispersive approaches for three-particle final state interaction based on the Khuri-Treiman equations \cite{26} and generalized Veneziano amplitudes \cite{27}, —this last work for \(J/\psi \to 3\pi\) decay, although it can also be used for light-meson decays. Based on the dispersive approach we have developed amplitudes for \(\eta\) \cite{28, 29}, \(\omega\) \cite{30}, and \(\phi\) \cite{30} decays to \(3\pi\).

The \(\eta \to 3\pi\) decay is of particular interest because it is isospin-breaking and provides insight on the light-quark mass difference

\[
\frac{1}{Q^2} = \frac{m_q^2 - m_u^2}{m_s^2 - \bar{m}^2}, \quad \bar{m} = \frac{(m_u + m_d)}{2},
\]

where \(m_u, m_d\) and \(m_s\) are the masses of \(u, d\) and \(s\) quarks respectively. In \cite{29} we performed a simultaneous global fit to the KLOE-2 \cite{31} and WASA-at-COSY data \cite{32} with two real parameters and we determined \(Q = 21.6 \pm 0.4\) \cite{29} by matching our dispersive approach to next-to-leading order Chiral Perturbation Theory (\(\chi PT\)) near the Adler zero \cite{33}.

2.2. Meson-baryon scattering

Meson-baryon scattering is one of the main resources to study the baryon spectrum. At JPAC, we have focused on \(\pi N\) \cite{34} and \(K N\) \cite{35} scattering because these are common final states detected in hadron experiments. In \cite{34} we developed high-energy \(\pi N\) amplitudes using Regge
physics [20] and connected them to the low-energy amplitudes (resonance region) from [36] using dispersion relations and Finite-Energy Sum Rules (FESRs). Consequently, we built a new set of πN amplitudes that cover the whole energy range for forward scattering.

In [35] we built a coupled-channel ¯KN scattering model in the resonance region that incorporates up to 13 channels per partial wave and fulfills unitarity, has the correct analytical properties for the amplitudes in the resonance region and has the right threshold behavior for the partial waves. We also imposed analyticity of partial waves in the complex angular momentum plane [37]. The model was fitted to the Kent State University single-energy partial waves [38] using a genetic algorithm [39] and MINUIT [40]. We estimated the uncertainties in the parameters using bootstrap technique [41]. Once the model was fitted to the single-energy partial waves and the parameters established, we analytically continued the partial waves to the unphysical Riemann sheets and found the Λ∗ and Σ∗ poles (resonances) that constitute the low-lying hyperon spectrum [35, 42]. We expect to develop forward-scattering ¯KN amplitudes [43] that cover the whole energy range combining high-energy ¯KN Regge amplitudes with the low-energy amplitudes in [35] using FESR as was done in [34] for πN scattering.

The identification of baryons beyond the constituent quark model (either hybrids with glue as an essential constituent, molecules or pentaquarks) requires the identification of a whole flavor family, and not only the detailed study of one particular state [1]. Resonances of different angular momenta share the same Regge trajectory, what gives the spectrum an organized structure [20, 44]. The structure of the spectrum and the shape of the trajectories provide information on the composition of the states [35, 42, 45, 46, 48]. In [46] we combined Regge phenomenology [20, 37], the information on the hyperon spectrum from [35], and the Λ(1405) pole positions from [47] to gain insight on the nature of the two Λ(1405) states. We found that the higher-mass pole appears to be (mostly) a three-quark hyperon and the lower-mass pole either a molecule or a pentaquark [46, 48].

2.3. Meson photoproduction

Another front where JPAC is producing results is meson photoproduction. In particular, we have worked on two kaon photoproduction [49], high-energy pion photoproduction [50] and J/ψ photoproduction [51].

In [49] the double-Regge limit for the γp → K+K−p reaction was computed. This reaction has been measured by CLAS collaboration (currently under analysis) and is of interest to study mesons with hidden strangeness that decay into two kaons. The double-Regge production mechanism constitutes a background to the reaction that contributes to the whole Dalitz plot and needs to be removed in order to isolate the mesons of interest.

There are many pion photoproduction models in the literature that describe the resonance region [52] but not recent ones for the high-energy regime. Considering that CLAS and GlueX collaborations will collect pion photoproduction data in the $E_\gamma \simeq 3-10$ GeV region we developed a high-energy neutral pion photoproduction [50] that covers the $E_\gamma > 4$ GeV region where the Regge poles dominate the amplitudes.

LHCb collaboration reported two possible candidates for pentaquarks in the J/ψp channel [14], however, the existence of these states is still to be confirmed. One of the most interesting proposals to detect the narrow P_c(4450) pentaquark was made by Karliner and Rosner in [53]. They proposed to measure J/ψ photoproduction from the proton. If there is a pentaquark resonance that strongly couples to the J/ψp channel, it should be possible to detect it in the γp → J/ψp reaction. In [51] we built up a full model for this reaction and analyzed the available experimental data on J/ψp photoproduction from the proton. The resonance was introduced as a Breit–Wigner amplitude and the background was modeled with a Pomeron exchange. We found that data allow for the existence of a pentaquark whose J/ψp branching ratio has to be below 30% for spin-parity assignment $J^P = 3/2^−$ and below 17% for $J^P = 5/2^+$ at a 95%
confidence level. Jefferson Lab has just approved an experiment to measure this reaction [54].

3. Web page
We created an interactive website to make the exchange of information between JPAC and other theorists and experimentalist easier [55]. The JPAC web page at Indiana University [15] hosts downloadable versions of the codes to compute the $\eta \rightarrow 3\pi$ amplitude from [28, 29], the $\omega/\phi \rightarrow 3\pi$ amplitudes from [30], the $\pi N$ amplitudes employing FESRs from [34], the $KN$ partial waves and observables in the resonance region from [35] and the high-energy pion photoproduction observables from [50]. The codes can also be run on the web page and the outputs downloaded. Codes to compute the generalized Veneziano amplitude from [27] and the double-Regge limit for the $\gamma p \rightarrow K^+K^-p$ reaction using the model in [49] are available upon request. The codes for pentaquark photoproduction [51] will be available in the near future. We are currently in the process of building up a mirror of the JPAC web page with additional functionalities at Universidad Nacional Autónoma de México, hosted at the web servers of Instituto de Ciencias Nucleares [56].

4. Final remarks
The JPAC is a theoretical collaboration oriented to work with experimental collaborations and willing to cooperate with other theory groups. At present we have standing collaborations with BESIII, COMPASS, CLAS, GlueX, KLOE and LHCb. We are focused on hadron spectroscopy delivering amplitudes for three-body meson decays [26, 27, 28, 29, 30], meson-baryon scattering [34, 35, 42, 43], Regge phenomenology to gain insight on the internal structure of hadrons [46, 48] and meson photoproduction [49, 50, 51]. Codes for the amplitudes are available either from the JPAC web page [15, 55, 56] or upon request. We invite the hadron physics community to visit the website and send their comments and suggestions to the JPAC members.

Acknowledgments
We thank the Division of Particles and Fields of the Mexican Physical Society for their kind invitation to write this brief report on JPAC purpose and recent activities.

References
[1] Pennington MR 2016 J. Phys. G: Nucl. Part. Phys. 43 054001
[2] Battaglieri M et al 2015 Acta Phys. Polon. B 46 257
Briceno RA et al 2016 Chin. Phys. C 40 042001
Dudek JJ, Shepherd MR and Mitchell RE 2016 Nature 534 487
[3] http://lhcb-public.web.cern.ch/lhcb-public/
[4] http://cms.web.cern.ch
[5] https://wwwcompass.cern.ch
[6] https://www.jlab.org/Hall-B/
[7] http://www.gluex.org/GlueX/
[8] http://www.ihep.ac.cn/english/E-Bepc/
[9] http://www.lnf.infn.it/kloe2/
[10] https://www.belle2.org
[11] http://j-parc.jp/Hadron/en/
[12] http://www.fair-center.eu/public/experiment-program/antiproton-physics/
[13] Choi S et al (Belle collaboration) 2008 Phys. Rev. Lett. 100, 142001
Aaij R et al (LHCb collaboration) 2014 Phys. Rev. Lett. 112 222002
[14] Aaij R et al (LHCb collaboration) 2015 Phys. Rev. Lett. 115 072001
Aaij R et al (LHCb collaboration) 2016 Preprint 1604.05708 [hep-ex]
[15] http://www.indiana.edu/~jpac/
[16] Eden RJ, Landschoff PV, Olive DI and Polkinghorne JC 2003 The Analytic S-Matrix (Cambridge: Cambridge University Press)
[17] Wigner EP 1946 Phys. Rev. 70 15
| Reference                                                                 | Year   | Journal/Book                                                                 | Authors                                                                 |
|--------------------------------------------------------------------------|--------|------------------------------------------------------------------------------|------------------------------------------------------------------------|
| [18] Chew GF and Mandelegam S 1960 Phys. Rev. 119 467                     | 1960   |                                                                              |                                                                        |
| [19] Donoghue JF, Golowich E and Holstein BR 1992 Cambridge Monographs in | 1992   | Particle Physics, Nuclear Physics and Cosmology Vol. 2: Dynamics of the      |                                                                        |
|                                                                       |        | Standard Model (Cambridge: Cambridge University Press)                       |                                                                        |
| [20] Collins PDB 1977 An Introduction to Regge Theory and High-Energy     | 1977   | Physics (Cambridge: Cambridge University Press)                              |                                                                        |
| [21] Dudek JJ, Edwards RG, Thomas CE and Wilson DJ 2014 Phys. Rev. Lett. | 2014   | 113 182001                                                                   |                                                                        |
| [22] Dudek JJ, Edwards RG and Wilson DJ 2015 Phys. Rev. D 92 094502       | 2015   |                                                                              |                                                                        |
| [23] Swanson ES 2006 Phys. Rep. 429 243                                   | 2006   |                                                                              |                                                                        |
| [24] Ablikim M et al (BESIII collaboration) 2013 Phys. Rev. Lett. 110 252001 | 2013   |                                                                              |                                                                        |
| [25] Eugenio P et al (CLAS collaboration) 2003 Search for new forms of    | 2003   | hadronic matter in photoproduction,                                         |                                                                        |
|                                                                       |        | Jefferson Lab experiment E04-005                                              |                                                                        |
| [26] Guo P, Danilkin IV and Szczepaniak AP 2015 Eur. Phys. J. A 51 135    | 2015   |                                                                              |                                                                        |
| [27] Szczepaniak AP and Pennington MR 2014 Phys. Lett. B 737 283           | 2014   |                                                                              |                                                                        |
| [28] Guo P et al (Particle Data Group) 2014 Chin. Phys. C 38 090001       | 2014   |                                                                              |                                                                        |
| [29] Guo P, Danilkin IV, Fernández-Ramírez C, Mathieu V and Szczepaniak   | 2015   | AP 2016 Preprint 1608.01447 [hep-ph]                                         |                                                                        |
| [30] Danilkin IV, Fernández-Ramírez C, Guo P, Mathieu V, Shi M, Schott D | 2015   | and Szczepaniak AP 2015 Phys. Rev. D 91 040920                                |                                                                        |
| [31] Adlarson P et al (WASA-at-COSY collaboration) 2014 Phys. Rev. C 90 045207 | 2014   |                                                                              |                                                                        |
| [32] Anastasi A et al (KLOE2 collaboration) 2016 JHEP 1605 019              | 2016   |                                                                              |                                                                        |
| [33] Colangelo G, Lanz S and Passemar E 2009 PoS CD09 047                 | 2009   |                                                                              |                                                                        |
| [34] Mathieu V, Danilkin IV, Fernández-Ramírez C, Pennington MR, Schott D | 2015   | Phys. Rev. D 92 074004                                                        |                                                                        |
| [35] Fernández-Ramírez C, Danilkin IV, Manley DM, Mathieu V and Szczepaniak | 2016   | Phys. Rev. D 93 034029                                                        |                                                                        |
| [36] Workman RL, Arndt RA, Briscoe WI, Paris MW and Strakovsky II 2012    | 2012   | Phys. Rev. C 86 035202                                                        |                                                                        |
| [37] Gribov VN 2003 The Theory of Complex Angular Momenta (Cambridge:     | 2003   |                                                                              |                                                                        |
|                                                                       |        | Cambridge University Press)                                                  |                                                                        |
| [38] Zhang H, Tupsan J, Shrestha M and Manley DM 2013 Phys. Rev. C 88 035204 | 2013   |                                                                              |                                                                        |
| [39] Fernández-Ramírez C, Moya de Guerra E, Udías A and Udías JM 2008     | 2008   | Phys. Rev. C 77 065212                                                        |                                                                        |
| [40] James F and Roos M 1975 Comput. Phys. Commun. 10 343                 | 1975   |                                                                              |                                                                        |
| [41] Press WH, Teukolsky SA, Vetterling WT and Flannery BP 1992 Numerical | 1992   | Recipes: The Art of Scientific Computing (Cambridge: Cambridge University     |                                                                        |
|                                                                       |        | Press)                                                                       |                                                                        |
| [42] Fernández-Ramírez C and Szczepaniak AP 2016 in Hyperon Studies at    | 2016   |                                                                              |                                                                        |
|                                                                       |        | JLab ——Mini-Proceedings of the Workshop on Physics with Neutral Kaon Beam   |                                                                        |
|                                                                       |        | at JLab (KL2016), ed. M. Amarian et al Preprint 1604.02141 [hep-ph], p. 95 |                                                                        |
[43] Mathieu V 2016 in Opportunities in the Hyperon Spectrum with Neutral Kaon Beam —Mini-Proceedings of the Workshop on Physics with Neutral Kaon Beam at JLab (KL2016), ed. M. Amaryan et al Preprint 1604.02141 [hep-ph], p. 152

[44] Chew GF and Frautschi SC 1962 Phys. Rev. Lett. 8 41

[45] Londergan JT, Nebreda J, Peláez JR and Szczepaniak AP 2014 Phys. Lett. B 729 9

Carrasco JA, Nebreda J, Peláez JR and Szczepaniak AP 2015 Phys. Lett. B 749 399

Peláez JR and Rodas A 2016 Preprint 1607.03750 [hep-ph]

[46] Fernández-Ramírez C, Danilkin IV, Mathieu V and Szczepaniak AP 2016 Phys. Rev. D 93 074015

[47] Roca L and Oset E 2013 Phys. Rev. C 87 055201

Mai M and Meißner U-G 2015 Eur. Phys. J. A 51 30

[48] Shi M, Danilkin IV, Fernández-Ramírez C, Mathieu V, Pennington MR, Schott D and Szczepaniak AP 2015 Phys. Rev. D 91 034007

[49] Mathieu V, Fox G and Szczepaniak AP 2015 Phys. Rev. D 92 074013

[50] Hiller Blin AN, Fernández-Ramírez C, Jackura A, Mathieu V, Mokeev VI, Pilloni A and Szczepaniak AP 2016 Phys. Rev. D 94 034002

[51] Drechsel D, Hanstein O, Kamalov SS and Tiator L 1999 Nucl. Phys. A 645 145

Fernández-Ramírez C, Moya de Guerra E and Udías JM 2006 Ann. Phys., NY 321 1408

Drechsel D, Kamalov SS and Tiator L 2007 Eur. Phys. J. A 34 69

Mariano A 2007 Phys. Lett. B 647 253

Mariano A 2007 J. Phys. G: Nucl. Phys. 34 1627

Juliá-Díaz B, Lee T-SH, Matsuyama A, Sato T and Smith LC 2008 Phys. Rev. C 77 04520

Fernández-Ramírez C, Moya de Guerra E and Udías JM 2008 Phys. Lett. B 660 188

Gasparian A and Lutz MFM 2010 Nucl. Phys. A 848 126

Workman RL, Briscoe WJ, Paris MW and Strakovsky II 2012 Phys. Rev. C 85 025201

Anisovich AV, Beck R, Klempt E, Nikonov VA, Sarantsev AV and Thoma U 2012 Eur. Phys. J. A 48 88

Kamano H, Nakamura SX, Lee T-SH and Sato T 2013 Phys. Rev. C 88 035209

Röhrchen D, Döring M, Huang F, Haberzettl H, Haidenbauer J, Hanhart C, Krewald S, Meißner U-G and Nakayama K 2014 Eur. Phys. J. A 50 101

[52] Karliner M and Rosner JI 2016 Phys. Lett. B 752 329

[53] Mezziani Z-E et al (Hall C collaboration) 2016 A Search for the LHCb Charmed “Pentaquark” using Photoproduction of J/ψ at Threshold in Hall C at Jefferson Lab, PAC44 approved experimental proposal PR12-16-007 at Jefferson Lab

[54] Mathieu V 2016 AIP Conf. Proc. 1735 070004

[55] http://nucleares.unam.mx/