Light-and heavy-quark hadron spectroscopy (HaSP)

WP25 – JRA7

M.Battaglieri (Jlab/INFN), J.Nieves (IFIC)

STRONG-2020 Kick-off meeting

October 23-25, 2019

Light-and heavy-quark hadron spectroscopy (HaSP)

result of merging…

- Study of the spectrum of hadrons made by light and heavy quarks (exp) presented by Marco Battaglieri

  Theoretical framework for hadron spectroscopy. Common tools for data analysis and theoretical interpretation

- Hadron Phenomenology (theor) presented by J. Nieves

  Establish joint research efforts on innovative methods in nonperturbative QCD and their applications to hadron phenomenology, including also few- and many-hadron systems, as well as to foster the interchange of ideas between groups specialized on different techniques

- Lattice QCD and effective field theories for quarkonium exotica and for Quarkonium suppression in a strongly-coupled medium (theor) presented by Antonio Vairo

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093.

Light-and heavy-quark hadron spectroscopy (HaSP)

- Study the spectrum of the hadrons
  - New generation of experiments are running or are in preparation at CERN (COMPASS, LHCb, ALICE), Mainz, Bonn, GSI, Jlab (GLUEX), BESIII, Belle, FAIR (PANDA, CBM)
  - Precise and abundant data requires an adequate analysis
  - Collaborative effort between experimental and theory: observables need to be interpreted using robust methods that rely only on the basic theoretical principles, and compared to the best solutions provided by the fundamental theory of the strong interaction via LQCD or systematic effective field theory expansions

- HaSP aims to coordinate the leading European institutions active in hadron spectroscopy to make progress in
  - Developing a theoretical, phenomenological and computational foundations for amplitudes
  - Establishment of best practices for accessing systematic uncertainties in analysis of hadron reaction data and interpretation of physics results

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Light-and heavy-quark hadron spectroscopy (HaSP)

JRA7: Hadron spectroscopy and phenomenology: Experimental and Theoretical study of hadrons made by light and heavy quarks (HaSP)							
REQUESTED EC CONTRIBUTION PER BUDGETARY ITEM AND PER BENEFICIARY							
Contr. No	Participant Acronym	Personnel (EUR)	Other costs (durables, consumables, travel, workshops) (EUR)	Total direct costs (EUR)	Indirect costs (EUR) (25%)	Total costs (EUR)	Requested EC contribution (EUR)
1	CNRS						
	CNRS/IN2P3/Paris Sud						
2	RUB						
3	FZJ						
4	UBO						
5	UMainz						
6	UHEI						
7	GSI						
8	RBI						
9	TUM						
10	INFN						
	INFN-GE						
	INFN-CT						
	INFN-FE						
	INFN-FE						
	INFN-PV						
	INFN-RM2						
	INFN-TO						
	INFN-TIFPA						
11	UBasel						
12	IFIC						
13	UCM						
14	USAL						
15	INP Krakow						
16	UEDIN						
17	UGlasgow						
	TOTAL						

France, Germany, Italy, Spain, UK, Poland, Croatia

Other involved institutions not receiving EC funds: Thomas Jefferson National Laboratory, The George Washington University

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Light-and heavy-quark hadron spectroscopy (HaSP)

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11	UBasel						
12	IFIC						
13	UCM						
14	USAL						
15	INP Krakow						
16	UEDIN						
17	UGlasgow						
	TOTAL						

Other small groups which are not beneficiaries f.i. IFIC contains groups at UB, UAB, Murcia, Granada

France, Germany, Italy, Spain, UK, Poland, Croatia

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Light-and heavy-quark hadron spectroscopy (HaSP)

TASKS/Subtasks																
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Precision calculations in non-perturbative QCD (I)																
1.1 Development and application of EFTs			**M1**							**M3**			**M4**			
1.2 Hadron decays			**M1**							**M3**			**M4**			
2. Precision calculations in non-perturbative QCD (II)																
2.1 Study of hadron resonances, form factors, LECs, etc			**M1**							**M3**			**M4**			
2.2 Computation of heavy-quark, hybrid and tetraquark potentials			**M1**							**M3**			**M4**			
2.3 Computation of m.e. for in medium quarkonium evolution			**M1**							**M3**			**M4**			
3. Meson Spectroscopy analysis of new and exotic states																
3.1 Search for and study of light exotic mesons, charmonium and strangeonium						**M2**				**M3**			**M4**			
3.2 Spectroscopy of low-lying scalars, strange mesons and strangeonia						**M2**				**M3**			**M4**			
4. Baryon and multi-baryon Spectroscopy																
4.1 Resonance parameter determination						**M2**				**M3**			**M4**			
4.2 Diffractive and annihilation production and exotic baryons						**M2**				**M3**			**M4**			
4.3 Dibaryon structure and parameter determination						**M2**				**M3**			**M4**			

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Light-and heavy-quark hadron spectroscopy (HaSP)

- Task 1: Precision calculations in non-perturbative QCD (I)
  - QCD Effective Field Theories (EFT's) combined with analyticity and dispersion relations: description of low energy hadronic phenomenology, including properties of excited states.
  - Decays of heavy hadrons, looking for particular interacting hadron pairs in the final state that might produce resonant states: Dalitz-plot based methods, EFT and dispersive techniques, we shall also explore issues such as the exotic nature of resonances, isospin or CP violations.
- 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.
  - Precision spectroscopy of exotic and excited states in quarkonia using EFT combined with significant advancements in LQCD, treatment of states above thresholds in coupled-channel scattering analyses
  - Heavy quarkonia in heavy-ion experiments and their suppressed production

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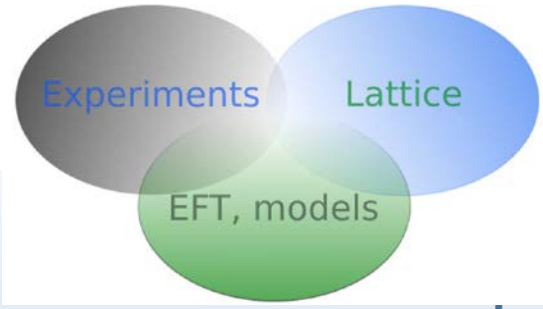
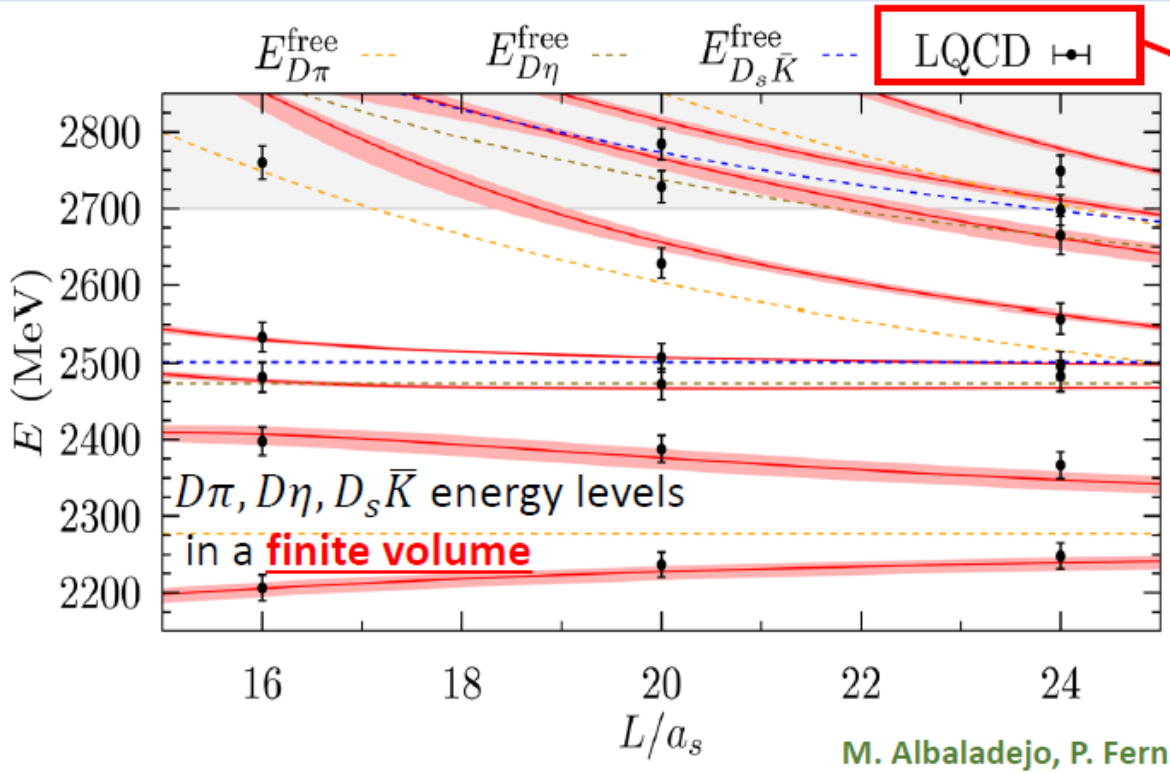
Light-and heavy-quark hadron spectroscopy (HaSP)



✓ Free energy leve $+\,\omega_i'\left(\frac{2\pi}{L}\vec{n}\right)$ **Unitarized Heavy Meson ChPT in finite volume**

✓ Interacting energy levels $E_n(L)$ such that: $\boxed{\mathcal{T}^{-1}(E_n^2(L),L)=0}$ **[poles of the $\mathcal{T}$ matrix]**

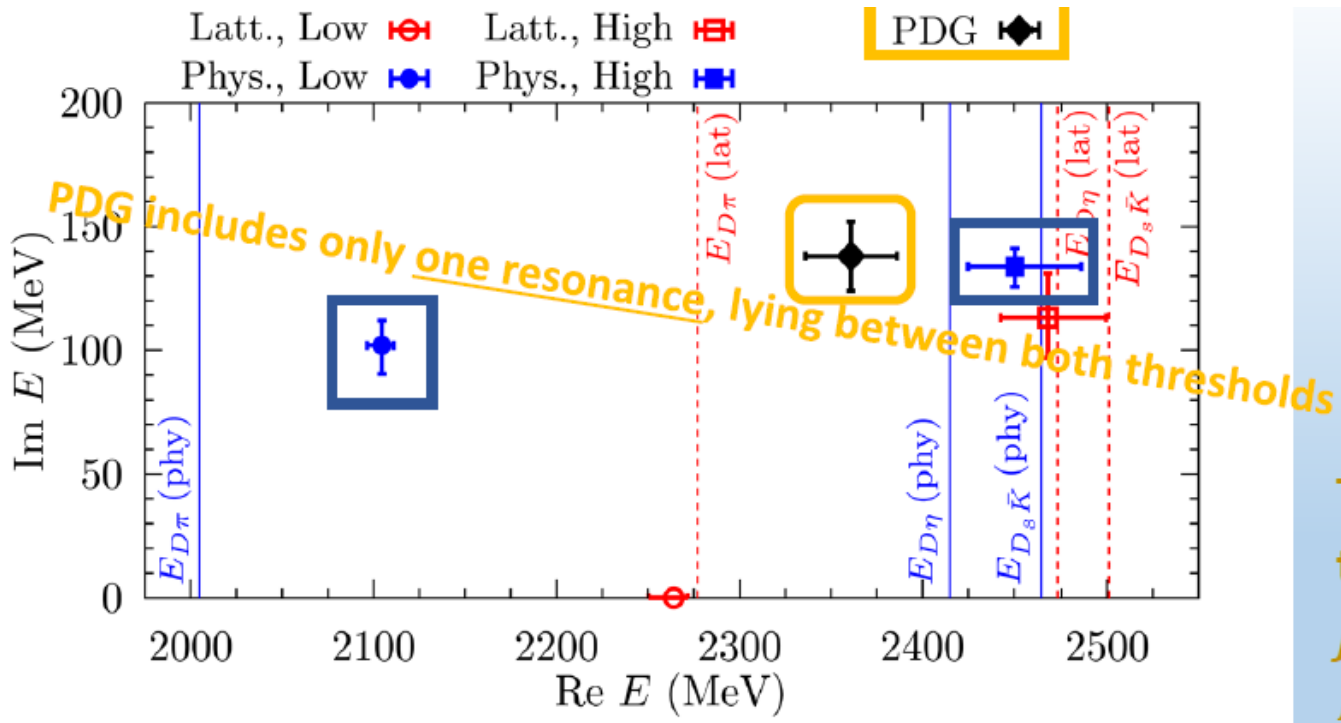


LQCD: G. Moir et al., JHEP 1610 (2016) 011 (Hadron Spectrum Collaboration). $D\pi, D\eta, D_s\bar{K}$ coupled-channes

M (MeV)	Latt.	Phys.
π	391	138
K	550	496
η	588	548
D	1886	1867
D_s	1952	1968

M. Albaladejo, P. Fernández, F.-K. Guo, J. Nieves PLB 767 (2017) 465

Light-and heavy-quark hadron spectroscopy (HaSP)



- ✓ The $D_0^*(2400)$ structure is actually produced by two different states (poles), together with complicated interferences with thresholds
- ✓ **LQCD analysis: only one** bound-state pole, relevant for the $D_0^*(2400)$, was found just below the $D\pi$ threshold

Two pole structure for the PDG $D_0^*(2400)$, $J^P = 0^+$ [partner of $D_s(2317)$]

Masses	M (MeV)	$\Gamma/2$ (MeV)	RS	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
lattice	2264^{+8}_{-14}	0	(000)	$7.7^{+1.2}_{-1.1}$	$0.3^{+0.5}_{-0.3}$	$4.2^{+1.1}_{-1.0}$
	2468^{+32}_{-25}	113^{+18}_{-16}	(110)	$5.2^{+0.6}_{-0.4}$	$6.7^{+0.6}_{-0.4}$	$13.2^{+0.6}_{-0.5}$
physical	2105^{+6}_{-8}	102^{+10}_{-12}	(100)	$9.4^{+0.2}_{-0.2}$	$1.8^{+0.7}_{-0.7}$	$4.4^{+0.5}_{-0.5}$
	2451^{+36}_{-26}	134^{+7}_{-8}	(110)	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

M. Albaladejo, P. Fernández, F.-K. Guo, J. Nieves. PLB 767 (2017) 465

Light-and heavy-quark hadron spectroscopy (HaSP)

Chiral $D_{(s)}^{(*)}\phi$ molecular structure natural solution to three (experimental) puzzles:

- ✓ Why are the $M_{D_{s0}^*(2317)}$ & $M_{D_{s1}(2460)} \ll$ CQM $c\bar{s}$ 0^+ and 1^+ mass predictions
- ✓ Why $(M_{D_{s1}(2460)} - M_{D_{s0}^*(2317)}) \sim (M_{D^*} - M_D)$ within 1 MeV.
- ✓ Why are the $D_0^*(2400)$ $[0^+]$ and $D_1(2430)$ $[1^+]$ masses (higher members of the two-pole structure) almost equal to or even higher than their strange siblings despite of $\frac{m_s}{m_d} \sim 20$

...confirmed by LHCb data for the $B^- \to D^+\pi^-\pi^-$ reaction

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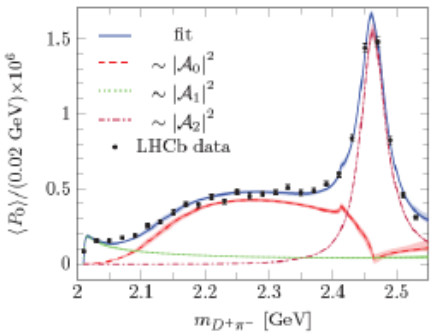
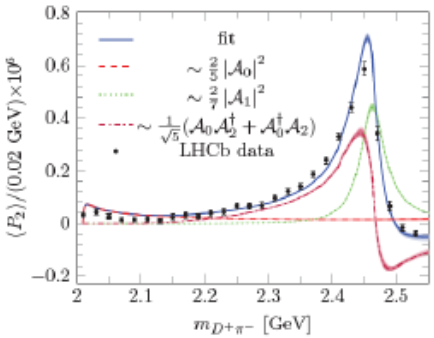
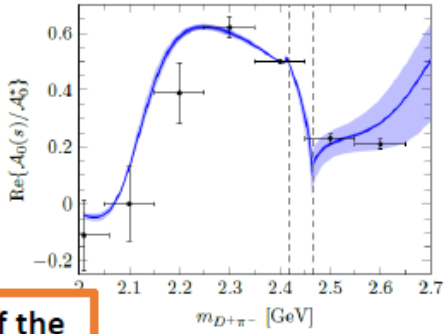
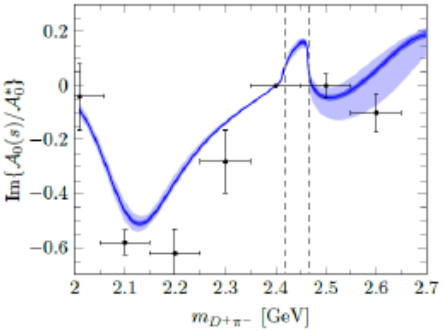


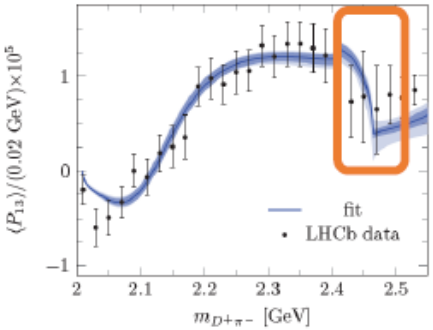


$\mathcal{A}_0$ (S-wave)

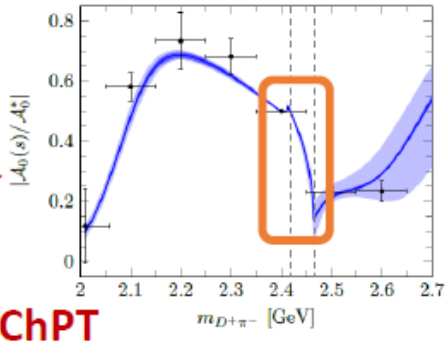




$\langle P_0 \rangle$
$\langle P_2 \rangle$
$\langle P_{13} \rangle$



cusps: opening of the $D^0\eta$ and $D_s^+K^-$ thresholds enhanced by the higher $D_0^*(2400)$ pole



$$\langle P_0 \rangle \propto \boxed{|\mathcal{A}_0|^2} + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2,$$

$$\langle P_2 \rangle \propto \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}\boxed{|\mathcal{A}_0|}|\mathcal{A}_2|\cos(\Delta\delta_2),$$

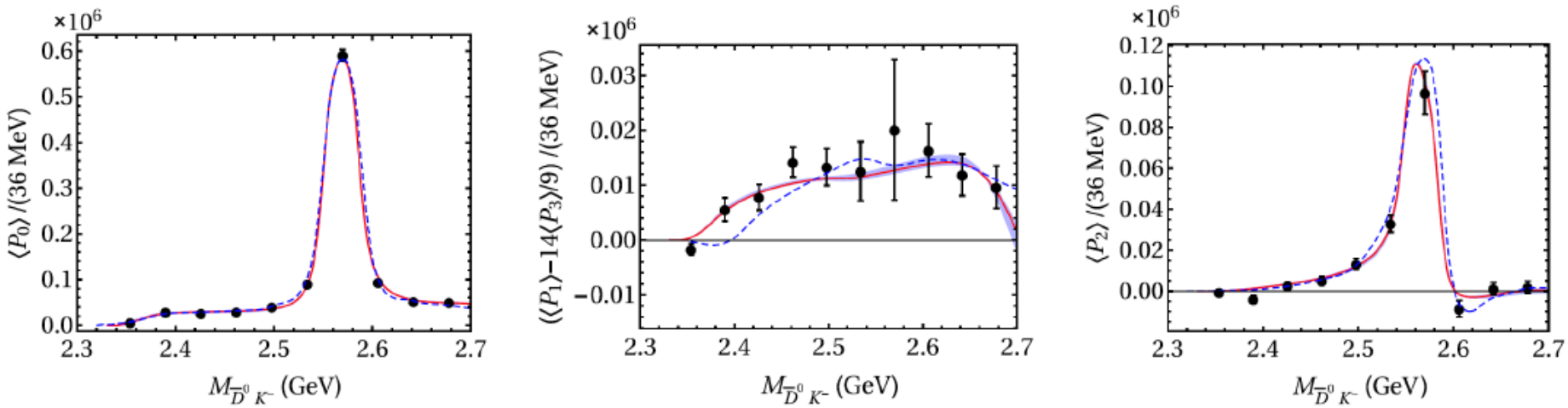
$$\langle P_{13} \rangle \equiv \langle P_1 \rangle - \frac{14}{9}\langle P_3 \rangle \propto \frac{2}{\sqrt{3}}\boxed{|\mathcal{A}_0|}|\mathcal{A}_1|\cos(\Delta\delta_1),$$

$\mathcal{A}_0$ (S-wave) from UHMChPT

...confirmed by LHCb data [R. Aaij et al. (LHCb Collaboration) PRD 94 (2016) 072001] for the $B^- \to D^+\pi^-\pi^-$ reaction

Juan Nieves, IFIC (CSIC & UV)

Light-and heavy-quark hadron spectroscopy (HaSP)



the LHCb data [R. Aaij et al. PRD 90 (2014) 072003] for the angular moments for $B_s^0 \longrightarrow \bar{D}^0 K^- \pi^+$ can be easily reproduced in the same framework with the untarized chiral $\bar{D}\bar{K}$ coupled-channels S-wave amplitude

$\mathbf{D_s(2317)}$

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Light-and heavy-quark hadron spectroscopy (HaSP)

Precise determinations of form factors, low-energy constants and fundamental parameters of QCD, as α_s or the quark masses etc..

- ✓ **Theoretical control of hadronic inputs in low-energy electroweak transitions: for instance hadron corrections induced by resonance dynamics to form factors for $b \longrightarrow s l \bar{l}$ and $B \longrightarrow D^{(*)}$ transitions (SM anomalies)**

- ✓ **Determination of LECs, quark masses, or fundamental parameters as α_s [f.i. QCD static energy: LQCD vs N3LO pNRQCD**, A. Bazavov, N. Brambilla, X. Garcia i Tormo, P. Petreczky, J. Soto, A. Vairo **PRD 90 (2014) 074038.]**

FSI driven by chiral symmetry

- ✓ **Three-body hadronic *B* and *D* weak decay amplitudes: $B \longrightarrow \boxed{3\pi}$, $B \longrightarrow \boxed{K\,2\pi}$, ...**
  fundamental for interpretation of CP asymmetries in the Dalitz plots (see for instance D. Boito, J. -P. Dedonder, B. El-Bennich, R. Escribano, R. Kaminski, L. Lesniak, B. Loiseau, arXiv:1709.09739)

PHYSICAL REVIEW D **96**, 072001 (2017)

Evidence for *CP* violation in $B^+ \to K^*(892)^+\pi^0$ from a Dalitz plot analysis of $B^+ \to K_S^0\pi^+\pi^0$ decays

BaBaR

- Task 3: Meson Spectroscopy analysis of new and exotic states
  - Exotic experimental discoveries by COMPASS, LHCb, BESIII, Belle using different probes, in different kinematic regimes
  - Combined Partial Wave Analyses (PWAs) of the same final state measured in different experiments
- Task 4: Baryon and multi-baryon spectroscopy
  - Extract baryon resonance parameters (mass, width, pole position)
  - Extend to 4q, 5q and 6q configurations the analysis framework

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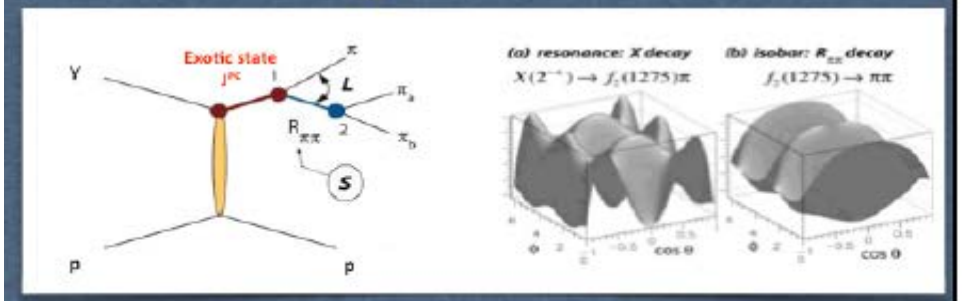
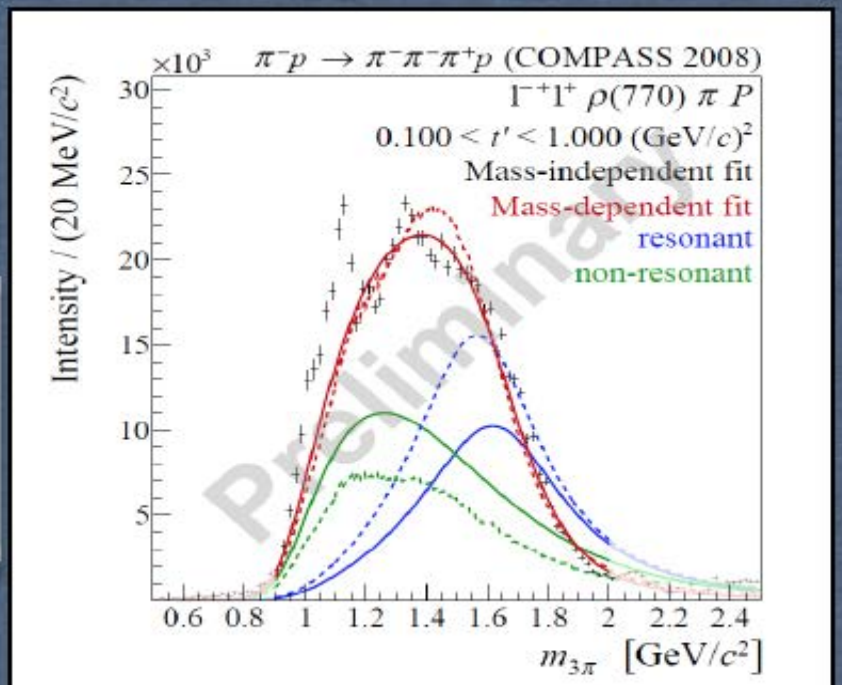
Light-and heavy-quark hadron spectroscopy (HaSP)

Hadron spectroscopy ingredients

- Experiment
- Theory
- Analysis tools





Resonance parameters for $\pi_1(1600)$

$M_0 = 1600^{+100}_{-50}$ MeV/c^2

$\Gamma_0 = 610^{+70}_{-240}$ MeV/c^2

- Data preservation

Deliverables

- Deliverables due for Reporting Period 1 (18 months, June 2019-November 2020): D25.1 is due M18 (November 2020)

Deliverable Number[14]	Deliverable Title	Lead beneficiary	Type[15]	Dissemination level[16]	Due Date (in months)[17]
D25.1	HaSP Combined Analysis framework	30 - INFN	Websites, patents filling, etc.	Public	18

- D25.1 'HaSP Combined Analysis framework'.

We will develop **a data common analysis framework** that making use of the theory progress of Tasks 1 and 2 will allow to determine (exotic) meson and baryon resonance parameters (Tasks 3 and 4). Data provided by different experimental collaborations (LHCb, COMPASS, MAINZ, TJNAF, BES, ALICE) filtered by the same final state will be analyzed in a combined analysis to constraint parameters and provide a reliable extraction. The framework will be made available to all HaSP institutions during the development phase and deployed to the whole hadron spectroscopy community at the end of the term.

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Update on progress

- T1: Precision calculations in non-perturbative QCD (I)
- T2: Precision calculations in non-perturbative QCD (II)
  - *Global parameterization of $\pi\pi$ scattering up to 2 GeV.* J.R. Pelaez, A. Rodas (Madrid U.), and J. Ruiz De Elvira (U. Bern, AEC);arXiv:1907.13162
  - *Mixing and $m_q$dependence of axial vector mesons in the Coulomb gauge QCD model*. L.M. Abreu, A.G. Favero (Bahia, U), F. Llanes-Estrada and A. García-Sánchez (U. Madrid); arXiv: 1908.11154
  - *Further tests of lepton flavour universality from the charged lepton energy distribution in $b \to c$ semileptonic decays: The case of $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$.* N.Penalva (IFIC), E. Hernández (Salamanca U.) and J. Nieves (IFIC); arXiv:1908.02328
  - *On the nature of the lowest-lying odd parity charmed baryon $\Lambda_c(2595)$ and $\Lambda_c(2625)$ resonances.* J. Nieves and R. Pavao (IFIC); arXiv: 1907.05747
  - *Prediction of hidden charm strange molecular baryon states with heavy quark spin symmetry.* C.-W. Xiao (Centrat South U.), J. Nieves and E. Oset (IFIC); arXiv:1906.09010 (PLB in print)
  - *Heavy quark spin symmetric molecular states from $\bar{D}^{(*)}\Sigma_c^{(*)}$and other coupled channels in the light of the recent LHCb pentaquark .* C.-W. Xiao (Centrat South U.), J. Nieves and E. Oset (IFIC); Phys. Rev. D100 (2019) 014021
  - …….
  - Open-and hidden-charm meson spectroscopy energies, J. Nieves talk at 'Implications of LHCb measurements and future prospects', CERN, October 2019
  - ……

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Update on progress

Deciphering Strong-Interaction Phenomenology through Precision Hadron-Spectroscopy 7 - 31 October 2019, Munich (MIAPP)
Stephan Paul, Nora Brambilla, Simon Eidelman, Christoph Hanhart, Luciano Maiani

- T3: Meson Spectroscopy analysis of new and exotic states
- T4: Baryon and multi-baryon spectroscopy
  - Defining best collaborative tools and analysis framework distribution
  - Setting up a common analysis framework: data format, analysis strategy, analysis tools, golden channels, MC simulations
  - Working on the definition of a web site to collect different data and make them available to all HaSP WP
  - Setting up regular meetings among collaborators

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Milestones

- MS52 has to be achieved M9 (Feb 2020)
- MS53 has to be achieved M18 (November 2020)

Milestone number[18]	Milestone title	Lead beneficiary	Due Date (in months)	Means of verification
MS52	Topical Workshop on Theoretical aspects of Hadron Spectroscopy and	30 - INFN	9	Web site
	Phenomenology (IFIC). Tasks 1 and 2			
MS53	Topical Workshop on Experimental Aspects of Hadron Spectroscopy and Phenomenology (UEdin). Tasks 3 and 4	30 - INFN	18	Web site

- Advancement?
- Expected delivery date?

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Milestone	Due Date (in months)	Means of verification
Topical Workshop on Theoretical aspects of Hadron Spectroscopy and Phenomenology **(IFIC)**	9 ***Feb-March 2020***	Web site
Topical Workshop on Experimental Aspects of Hadron Spectroscopy and Phenomenology (UEdin).	18	Web site
General Workshop on Hadron Spectroscopy and Phenomenology (TUM)	28	Workshop Proceedings
School on Hadron Spectroscopy and Phenomenology (Salamanca)	38	School Proceedings