Annual Meeting 2024

WP25-JR7

Light-and heavy-quark hadron spectroscopy (HaSP)

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

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, Mainz, Bonn GSI, JLab, BESIII and Belle-II
- Precise and abundant data requires an adequate analysis
- Collaborative effort between experiments 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 coordinates the leading EU 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

Light and heavy-quark hadron spectroscopy (HaSP)

Task 1: Precision calculations in non-perturbative QCD (I)

- QCD Effective Field Theories: description of low energy hadronic phenomenology and properties of excited states (C.Hanhart - FZJ)
- Heavy hadrons Decay: Dalitz-plot, EFT, exotic resonances nature, isospin or CP violations (D.Rodriguez-Entem - USAL)

Task 2: Precision calculations in non-perturbative QCD (II)

- EFTs control extrapolations to physical kinematics covering regions not yet reachable in the lattice (A.Parreño – UB – A.Lovato - ANL)
- Precision spectroscopy of exotic and excited states in quarkonia using EFT combined with significant advancements in LQCD (A.Vairo - TUM)
- Heavy quarkonia in heavy-ion experiments and their suppressed production (A.Vairo - TUM)

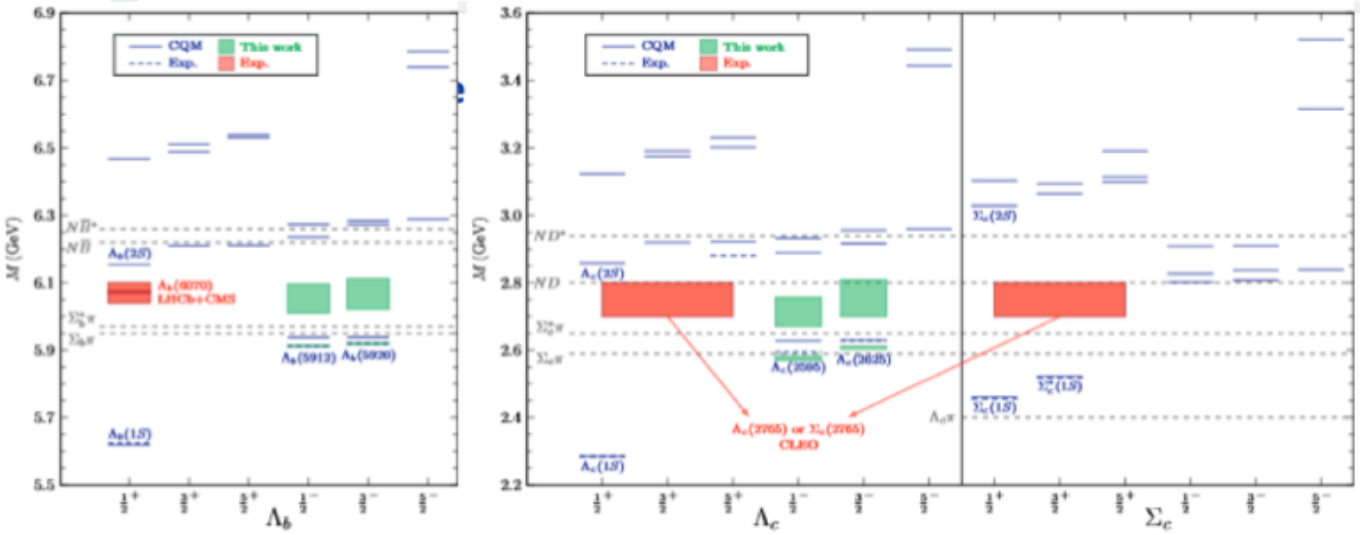
Task 3: Meson Spectroscopy analysis of new and exotic states

- Search for and study of light exotic mesons, charmonium and strangeonium (V.Mathieu -UB)
- Spectroscopy of low-lying scalars, strange mesons and strangeonia (S.Schadmand - FZJ)

Task 4: Baryon and multi-baryon spectroscopy

- Resonance parameter determination (M.Ostrick – Mainz)
- Diffractive and annihilation production and exotic baryon (A.D'Angelo – URM-TV)
- Di-baryon structure and parameter determination (D. Watts – U. York)

Task 1.1: Development and application of EFTs



✓ Best use of existing tools

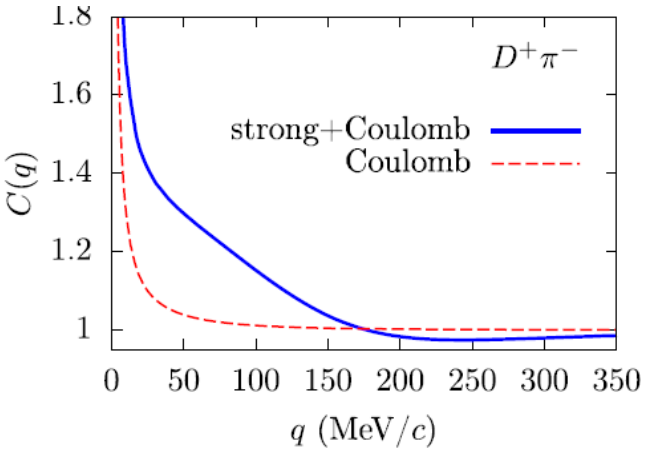
Combination of quark and hadron degrees of freedom: constituent quark-model (CQM) and chiral baryon-meson degrees of freedom to explain charm and bottom sectors.

Lowest-lying $1/2^-$ and $3/2^-$ Λ_Q resonances: rom the strange to the bottom sectors
Prog.Part.Nucl.Phys. 137 (2024) 104118

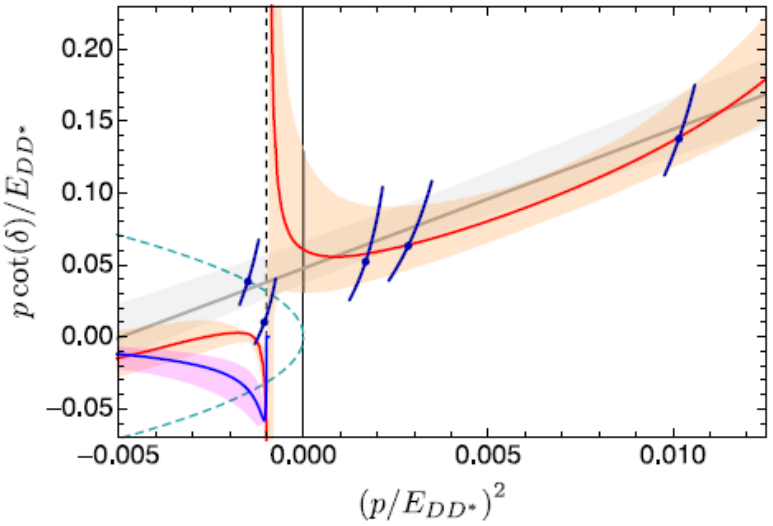
✓ New tools to study hadronic interaction

Femtoscopy of D mesons and light mesons upon unitarized effective field theories

Correlation function measured by ALICE at LHC
Phys. Rev. D 108 (2023) 9, 096008



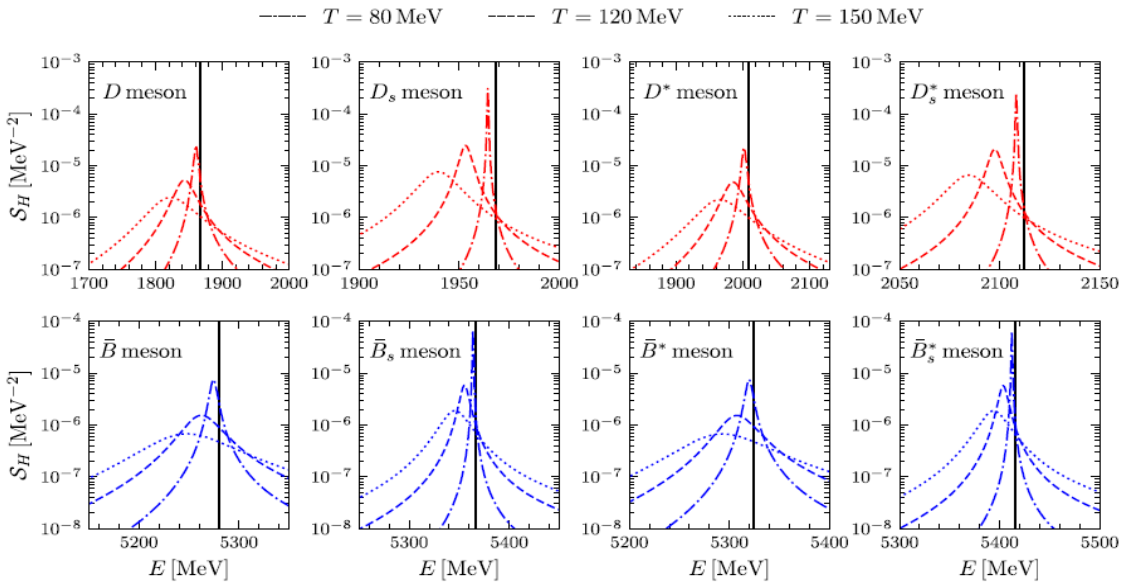
Task 1.1: Development and application of EFTs



✓ Development of precision methods

Lattice data with unphysical pion masses for the T_{cc} cannot be analyzedwith the standard Lüscher method, since the left-hand cut is too close by

Role of Left-Hand Cut Contributions on Pole Extractions from Lattice Data: Case Study for $T_{cc}(3875)^+$, Phys. Rev. Lett. 131 (2023) 131903; Phys. Rev. D109 (2024) L071506

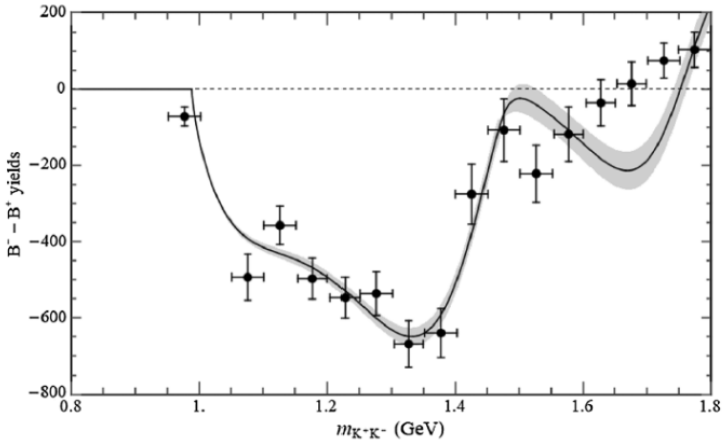


meson spectral functions at finite temperature

✓ Engagement of young researchers

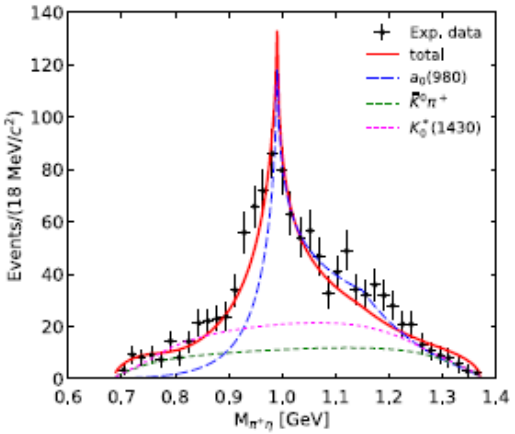
Gloria Montaña (PhD U. Barcelona) was the 2023 recipient of the APS PhD dissertation award in Hadronic Physics *"For outstanding progress in understanding the properties of heavy mesons in hot matter with the combination of non-perturbative hadronic theories and finite-temperature field theories"*
https://www.aps.org/funding-recognition/award/dissertation-award-hadronic-physics

Task 2.1: Heavy hadrons decays: Dalitz-plot, EFT, exotic resonances nature, isospin or CP violations



✓ Explanation of the reach phenomenology

Dispersive $\pi\pi \to K\bar{K}$ Amplitude and Giant CP Violation in B to Three Light-Meson Decays at LHCb, Phys. Rev. Lett. (2023) 130 (2023) 201901



$P_{\psi s}^{\Lambda}$ strange hidden-charm pentaquarks

Table 7
Predicted $P_{\psi ss}^{N}$ and $P_{\Upsilon ss}^{N}$ meson-baryon molecules. The main decay channels of each candidate is shown, with the partial width (in MeV) in parenthesis.

	J^P	Channel	Mass [MeV]	Main Decay channels
$P_{\psi ss}^{N}$	$\frac{1}{2}^-$	$\bar{D}_s\Xi_c$	4436.8	$J/\psi\Xi$ (9.9), $\eta_c\Xi$ (1.4)
		$\bar{D}_s\Xi_c'$	4544.0	$J/\psi\Xi$ (1.0), $\eta_c\Xi$ (0.7)
		$\bar{D}_s^*\Xi_c$	4580.8	$J/\psi\Xi$ (0.9), $\eta_c\Xi$ (1.0)
	$\frac{3}{2}^-$	$\bar{D}_s^*\Xi_c$	4581.1	$J/\psi\Xi$ (1.2)
		$\bar{D}_s\Xi_c^*$	4613.0	$J/\psi\Xi$ (0.8), $\eta_c\Xi^*$ (1.3)
		$\bar{D}_s^*\Xi_c'$	4684.9	$\bar{D}_s^*\Xi_c^*$ (3.1), $J/\psi\Xi^*$ (7.7)
		$\bar{D}_s^*\Xi_c^*$	4758.1	$\eta_c\Xi^*$ (0.03)
	$\frac{5}{2}^-$	$\bar{D}_s^*\Xi_c^*$	4751.7	$J/\psi\Xi^*$ (4.6)
$P_{\Upsilon ss}^{N}$	$\frac{1}{2}^-$	$B_s\Xi_b$	11142.6	$\Upsilon\Xi$ (1.3), $\eta_b\Xi$ (0.2)
		$B_s\Xi_b'$	11281.4	$\Upsilon\Xi^*$ (2.0)
		$B_s^*\Xi_b'$	11348.5	$B_s\Xi_b'$ (22.4)
		$B_s^*\Xi_b$	11191.9	$\Upsilon\Xi$ (0.2), $\eta_b\Xi$ (0.4)
	$\frac{3}{2}^-$	$B_s^*\Xi_b$	11194.2	$\Upsilon\Xi$ (0.3)
		$B_s\Xi_b^*$	11304.0	$\Upsilon\Xi*$ (0.5), $\eta_b\Xi^*$ (0.1)
		$B_s^*\Xi_b'$	11321.8	$B_s^*\Xi_b^*$ (5.7), $\Upsilon\Xi^*$ (0.6)
		$B_s^*\Xi_b^*$	11361.9	$B_s\Xi_c^*$ (0.4)
	$\frac{5}{2}^-$	$B_s^*\Xi_b^*$	11337.6	$\Upsilon\Xi^*$ (0.5)

Phys.Lett.B 838 (2023) 137747: Strange hidden-charm pentaquarks are anaylized in a couple channel formalism within the chiral quark model. Partial widths to different decay channels are analyzed.

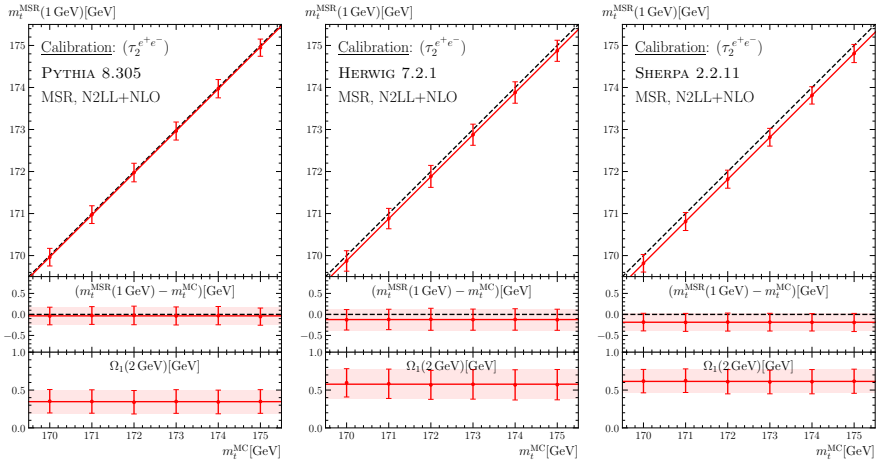
✓ Predicting exotic states from light/heavy q decays

The nature of $T_{\psi\psi}$ tetraquarks are studied within a Chiral Quark model and decays to the different channels are analyzed, Phys. Rev. D 108 (2023) 094023

Task 2.1: Heavy hadrons decays: Dalitz-plot, EFT, exotic resonances nature, isospin or CP violations

✓ Development of new tools

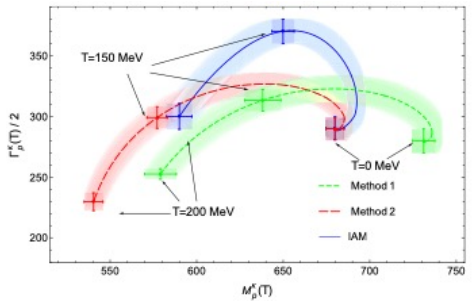
Important progress on calibrating the top quark mass. A precise relation is found between the parameter entering Monte Carlo simulations (determined in experimental analysis) with the mass defined in QFT at next-to-next-to leading logarithm. [JHEP 12 (2023), 065]

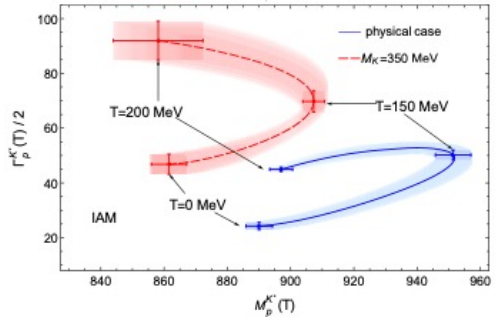


Dependence of the fit result for the MSR mass $m_t^{MSR}(R = 1GeV)$ and Ω_1 (2 GeV) on the input m_t^{MC} for Pythia, Herwig and Sherpa

"Revolver", a public c++ library (with Python and Mathematica wrappers) to calculate the evolution and the matching of the strong coupling constant and quark masses. [JHEP 03 (2020) 094]ç

✓ Progress in extracting resonance parameter at different T





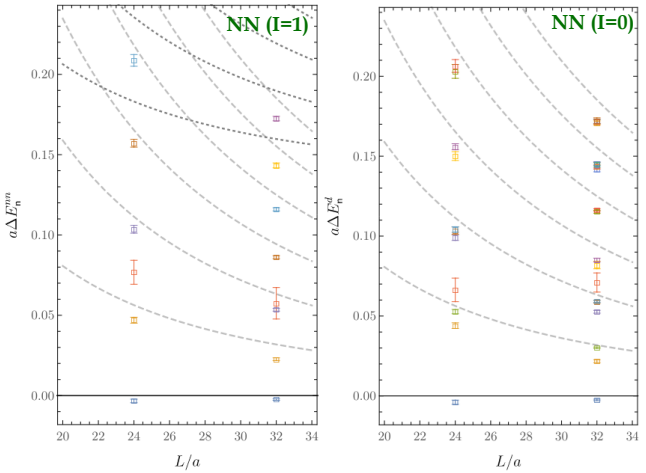
- Light scalars review [Eur. Phys. J. C 83 (2023) 1125]
- Branching ratios of overlapping resonances [Phys. Lett. B 844 (2023) 138070].
- Reliable determination of the pole parameters and residues of nucleon resonances [Phys. Lett. B 853 (2024) 138698]
- Isospin Breaking in Hadronic Vacuum Polarization [Phys. Rev. Lett. 131 (2023)]
- Isospin violation in the pion–nucleon σ-term [Phys. Lett. B 843 (2023) 138001];
- Role of a light quark-antiquark pair with zero total angular momentum from Landau-gauge Green's functions [Phys. Rev. D 109 (2024)];
- Pion form factor with dispersion relations[2405.09517 [hep-ph]];
- Seacrh of BSM physics: $\bar{B}_s \to D_s^{(*)}\tau^-\bar{\nu}_\tau$ semileptonic decays using lattice QCD form factors and heavy quark effective theory [JHEP 01 (2024) 163]
- Pion-Kaon scattering amplitude and the $K^0(700)$ and $K^*(892)$ resonances at finite temperature [JHEP 08 (2023)]

Task 2.1: Heavy hadrons decays: Dalitz-plot, EFT, exotic resonances nature, isospin or CP violations

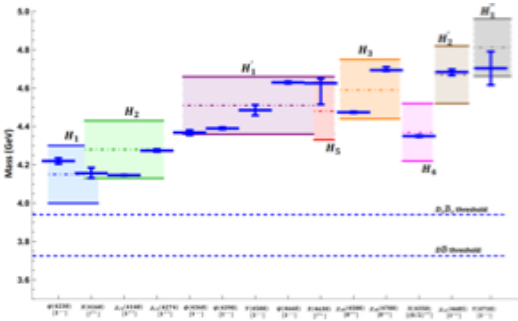
✓ Tools for discovery exotic multi-q configurations

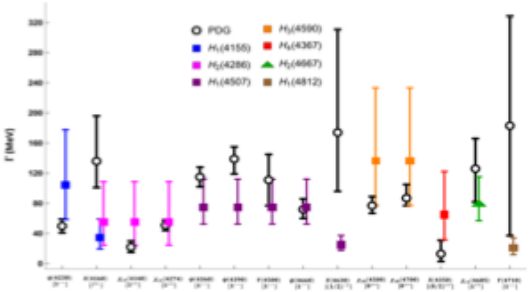
$m_\pi \sim 800\text{MeV},\ b = 0.1453\ \text{fm}$
$L_S^3 \times L_T = 32^3 \times 48 \quad \text{and} \quad 24^3 \times 48$

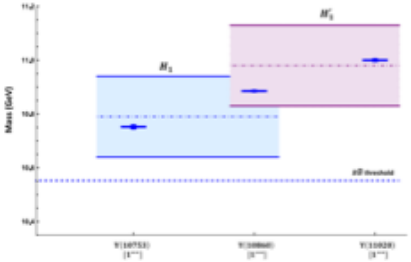
- We extended our Lattice-QCD variational study of nucleon-nucleon interactions (PRD 107 (2023) 9, 094508) by considering an additional volume and a complete basis of local nucleon-nucleon hexaquark operator (e-Print: 2404.12039 [hep-lat])
- The combination of dibaryon and hexaquark operators provides 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_π = 170 MeV and controlling lattice artifacts.

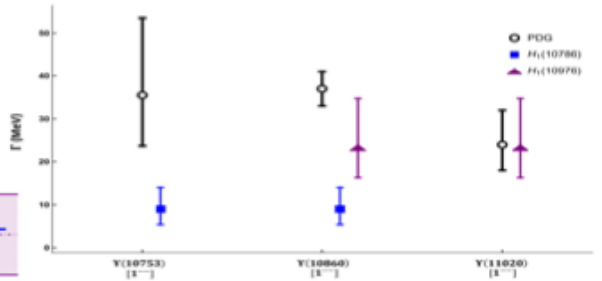


- Hybrid spectrum and widths vs observed exotics in the charmonium and bottomonium sector









Brambilla, Lai, Mohapatra, Vairo
Phys. Rev. D. 107, 054034 (2023)

STRONG-2020

Task 2.2: Heavy-quark, hybrid and tetraquark potentials

✓ Hadron & BSM physics (DM)

Progress Achieved in Last Year:

- Born-Oppenheimer EFT framework (BOEFT): Address exotic states with at-least 2 heavy quarks (hybrids, tetraquarks, pentaquarks etc.) based on BO-approximation and lattice QCD inputs.
- Obtained general coupled channel Schrodinger equation for any exotic states with two heavy quarks: heavy quark-heavy-antiquark or heavy quark-quark exotic states.
- Obtained results on predicted multiplets of tetraquark and pentaquark states
- Results on relevant lattice operators for computing static energies for tetraquark & pentaquark
- New results on behavior of tetraquark & pentaquark static energies based on BOEFT
- ERC Advanced Grant 2023: Nora Brambilla (Technical University of Munich)
  "Effective Field Theories to understand and predict the Nature of the XYZ Exotic Hadrons"

Plans:

- Describing hybrid-quarkonium mixing in BOEFT framework. Computing the mixing potential using lattice QCD
- Phenomenological applications to $X(3872), T_{cc}(3875)^+, Z_c, Z_b$ & $P_c(4312)^+$ states and decays to quarkonium and heavy-light threshold states

Achievements beyond the initial work programme:

- results obtained in pNREFTs have been extended to the study of heavy Dark Matter: Effective field theories for dark matter pairs in the early universe: cross sections and widths & center-of-mass recoil effects. JHEP 07 (2023) 006 & e-Print: 2402.12787
- 2nd Edition of the Workshop 'Quarkonia meet Dark Matter' (QMDM) Mar 18-22, 2024, Garching https://indico.ph.tum.de/event/7422/

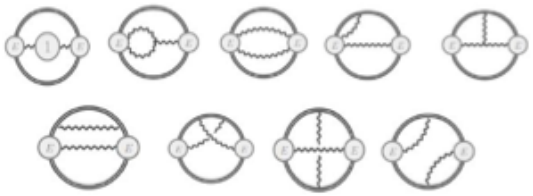
Task 2.3: Computation of matrix elements for in medium quarkonium evolution

✓ AI-supported methods applied to hadron physics

Progress Achieved in the Last Year *(in collaboration with N. Brambilla, P. Panayiotou, S. Sappi)*:

- Computed analytically chromo-electric correlator in different representations in a general gauge to NLO
- Direct evaluation of the correlator itself using Integration by parts

Diagrams in HTL perturbation theory



Machine Learning approaches in Lattice QCD - an interdisciplinary exchange, February 27 - March 3, 2023, Garching https://indico.ph.tum.de/event/7116/

Plans:

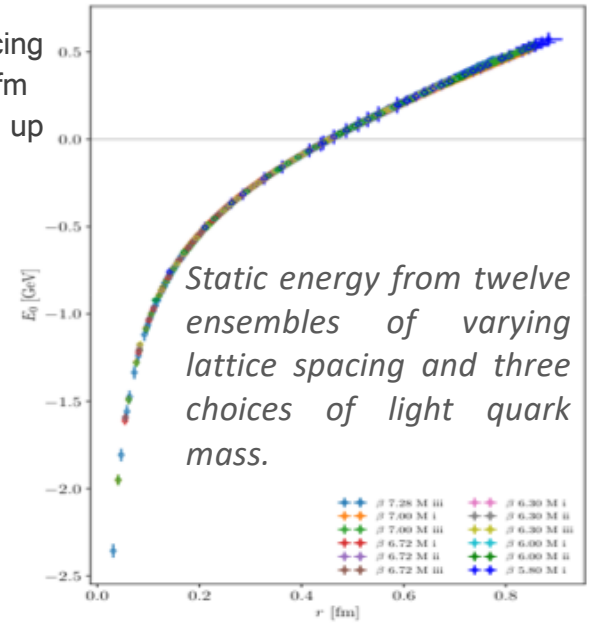
- Compare and use in Euclidean space in conjunction with lattice QCD
- Derive transport coefficient κ from an Euclidean correlator

✓ LQCD achievements

Precise extraction of α_s using a Lattice-QCD calculation of the QCD static energy and comparing it to a perturbative calculation of the same quantity in QCD at NNNLL [TUMQCD Phys. Rev. D 107 (2023) 7, 074503].

Static energy from (2+1+1)-Flavor lattice QCD

Lattice spacing up to 0.032 fm
Pion mass up to 210 MeV



Static energy from twelve ensembles of varying lattice spacing and three choices of light quark mass.

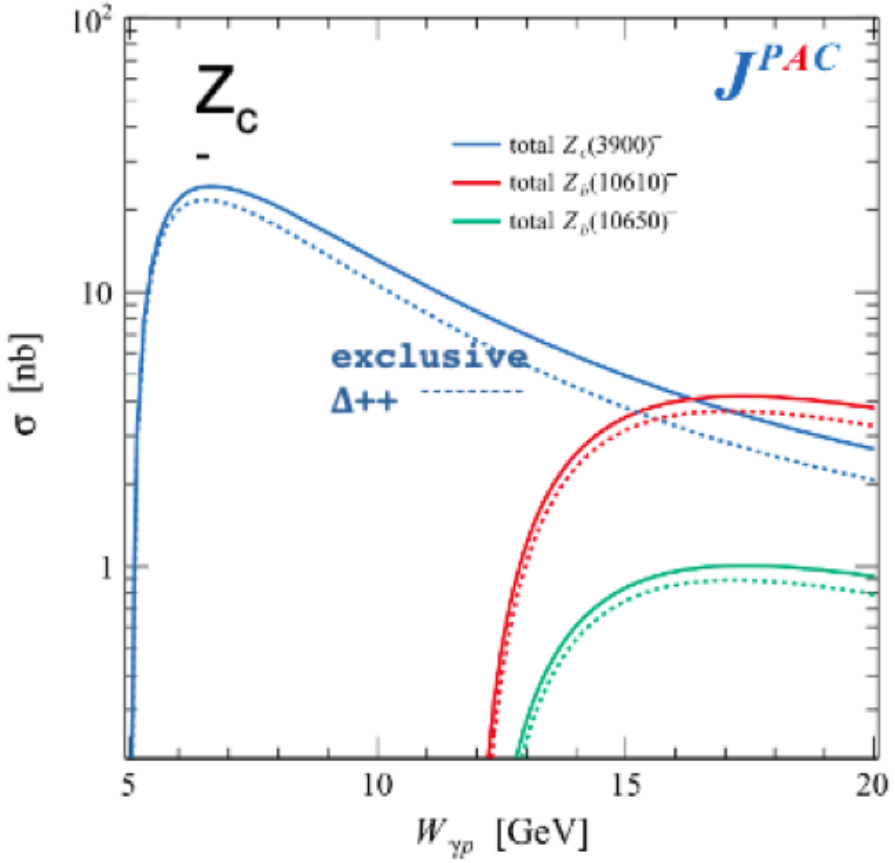
Task 3.1: Light Exotic Meson, Strangeonium and Charmonium

✓ Support to phenomenological analysis (PWA)

Progress achieved and highlights during 2023:

We proved that there are no mathematical ambiguities in partial-wave analysis of two mesons produced with a linearly polarized photon beam. We present Monte Carlo simulations to illustrate our results. JPAC (Smith et al), *Phys.Rev.D* 108 (2023) 7, 076001

The previous results on Z production has been included in the ElSpectro MC generator.
JPAC collaboration with the Glasgow group (D. Glazier et al)



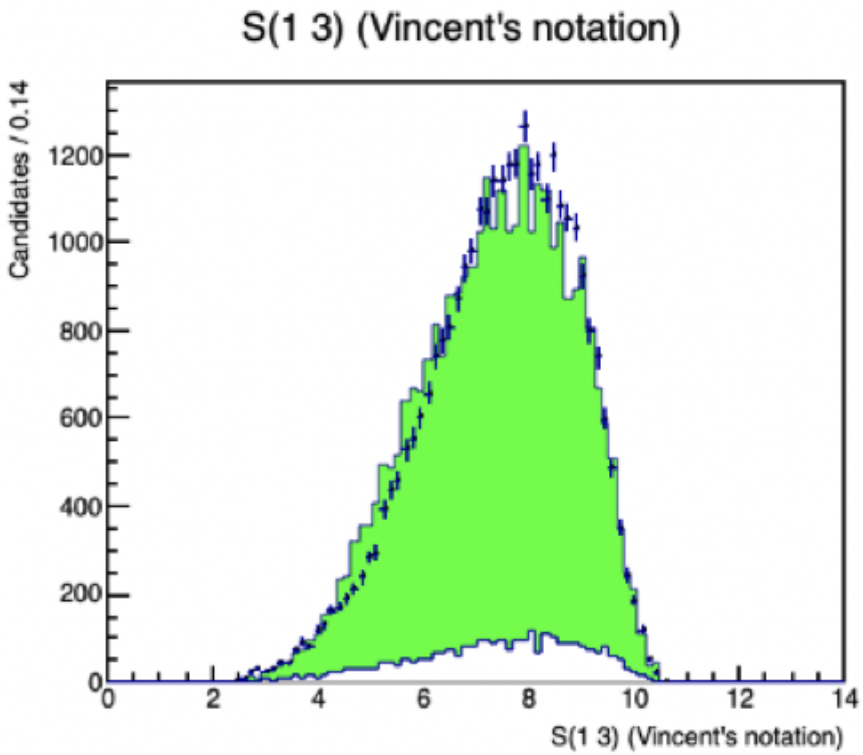
Task 3.1: Light Exotic Meson, Strangeonium and Charmonium

✓ Data-driven analysis tools development

Plans and remaining tasks until the end of the project

In the last year we explored the effect of the heavy light meson thresholds on the quarkonium energy level, for charmonium and bottomonium.
We have developed an EFT to describe the quarkonium far from the threshold and we have used a Born Oppenheimer EFT To describe the quarkonia close to threshold.
A paper is in preparation on this (N. Brambilla, A. Mohapatra, T. Scirpa A. Vairo).

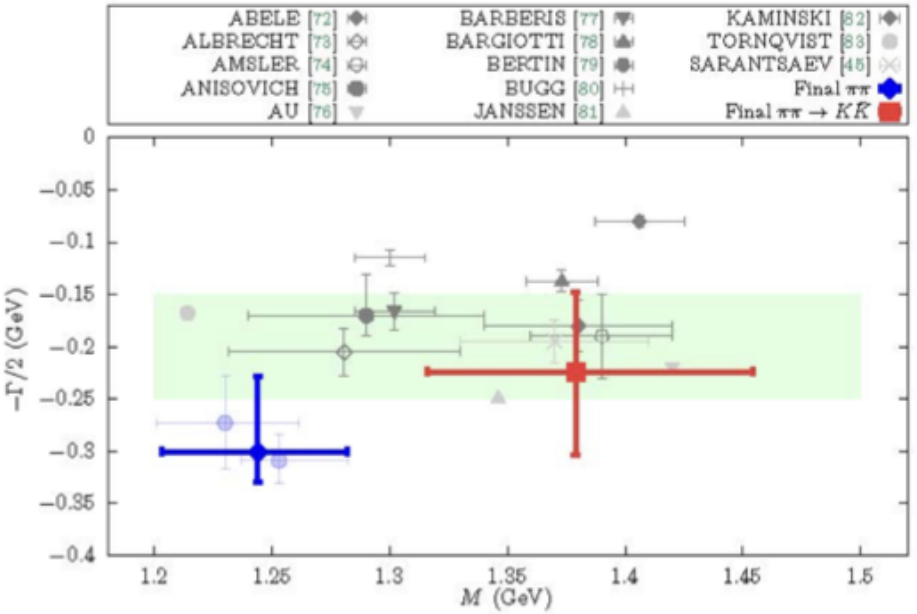
We will continue our collaborative work with the GlueX collaboration on the eta-pi channel (search for light exotic).
We are currently investigating the GlueX data in the double Regge region, comparing the data with the expected dependence on Mandelstam variables, predicted by Regge theory.



Task 3.2: Dispersive and analytic methods to determine the f0(1370) from scattering data

✓ Resonance parameters extraction from data

J. R. Peláez, A.Rodas, J.Ruiz de Elvira e-Print:2206.14822 [hep-ph]
- f0(1370) candidate to complete the controversial scalar nonet above 1 GeV
- Interesting for studies of lightest glueball and its mixing scheme..
- Challenge: Strong model dependence



Resonance poles can be determined from data with forward Dispersion Relations and analytic continuation methods

Remaining model dependence be due to inconsistencies between ππ→ππ and ππ→KK data sets

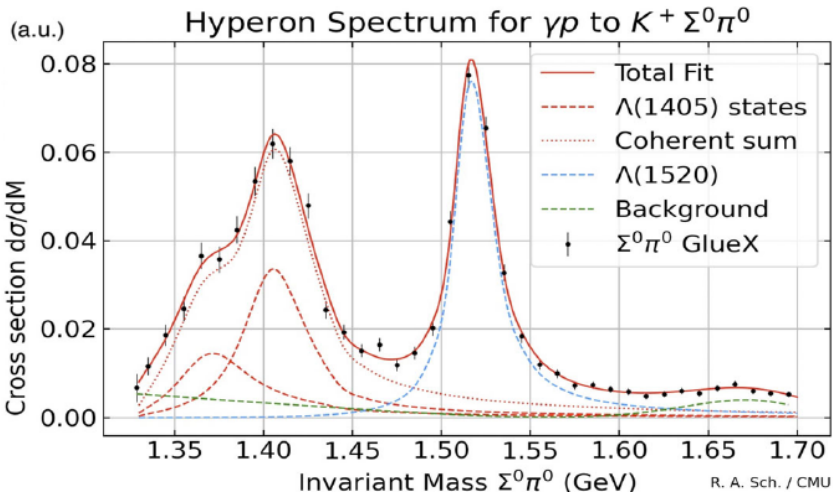
Task 4.1: Baryon Resonance parameter determination

✓ Further observables (spin, line-shape, …) to constraint resonance models

New experimental data:

Light Baryons

- Polarisation transfer to neutrons in π+ photoproduction at **MAMI**; PLB 847 (2023) 138283
- Spin observables T, P, and H in quasi-free π^0 and η porduction at **ELSA**; EPJ A (2023) 59:232
- Preliminary data on L(1405) and L(1520) from **GlueX**
- Preliminary data on $K^0\Sigma^+$ from **CLAS**



Heavy Baryons:

- 2 W_c and 2 X_b baryons discovered at **LHCb**
- PRL 131 (2023) 17, 171901 and PRL 131 (2023) 13, 131902

Task 4.1: Baryon Resonance parameter determination

New PWA and theory results:

✓ Theory/experiment collaboration to extend PWA

- Jülich-Bonn-WashingtonDC:
  - Composition of N* and Δ resonances via coupled-channel dynamics, arXiv:2307.06799
  - Inclusion of KΛ electroproduction data, arXiv:2307.10051
  - Heavy meson–heavy baryon coupled-channel interactions, EPJC(2022) 82:497
  - New interactive Webpage: https://jbw.phys.gwu.edu/

- Laurent+Pietarinen PWA of kaon photoproduction
  - PRC 108 (2023) 1, 014615
- Meson photoproduction interpreted by Regge phenomenology
  - Phys.Rev.C 107 (2023) 1, 015203
- Truncated PWA for η-photoproduction via Bayesian Statistics;
  - arXiv:2305.10367

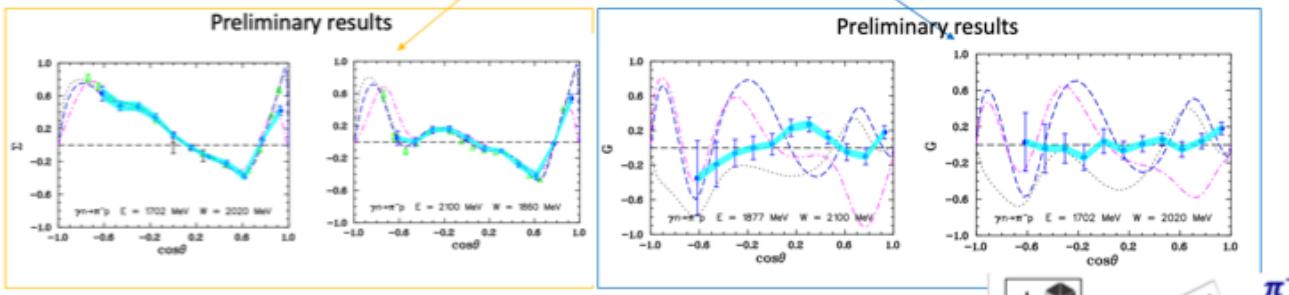
Task 4.2: Baryon Spectroscopy: Diffractive and annihilation production and exotic baryons

$\vec{\gamma}\vec{n}(p) \rightarrow \pi^- p(p)$ – photoproduction on a polarized HD target

Measurements of Σ and G polarization observables

$$\frac{d\sigma(P_\gamma, P_D)}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left(1 - P_\gamma^L \Sigma(\theta;W)\cos(2\phi_\gamma) + P_\gamma^L P_D^V G(\theta;W)\sin(2\phi_\gamma)\right)$$

HD-ice frozen-spin polarized target
polarized n



SAID SM22 — · — · PION-MAID 2021 ····· B

Preliminary results by: Haiyun Lu for the g14 analysis group

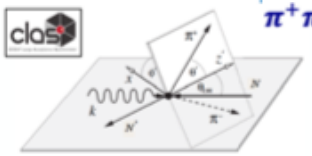
✓ Spin observables in baryon sector

$\pi^+\pi^-$ photoproduction – polarized p target

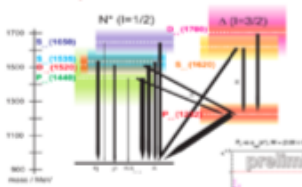
Measurements of polarization observables

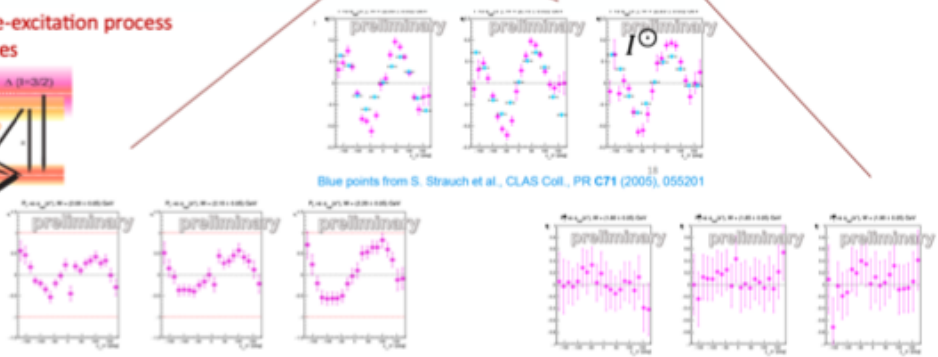
$$\frac{d\sigma}{dx_i} = \sigma_0\{(1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_\odot(\mathbf{I^\odot} + \Lambda_z \cdot \mathbf{P_z^\odot})\}$$

HD-ice frozen-spin polarized target
polarized p



Possible two-steps de-excitation process of baryonic resonances



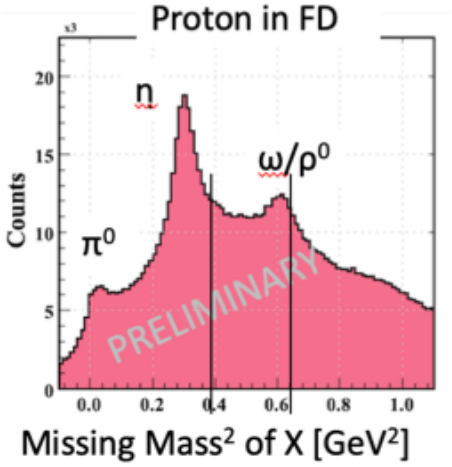


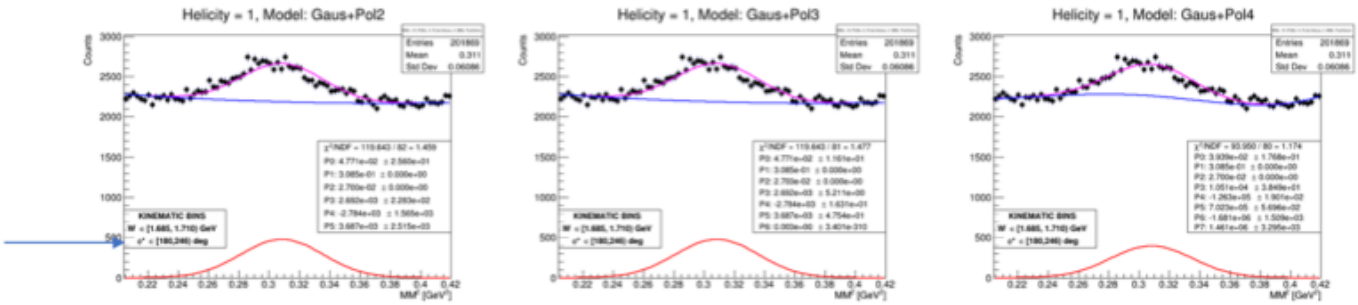
Preliminary results by: Alessandra Filippi for the g14 analysis group

Task 4.2: Baryon Spectroscopy: Diffractive and annihilation production and exotic baryons

η electro – production – Beam Spin Asymmetry

✓ New, high-stats electroproduction data

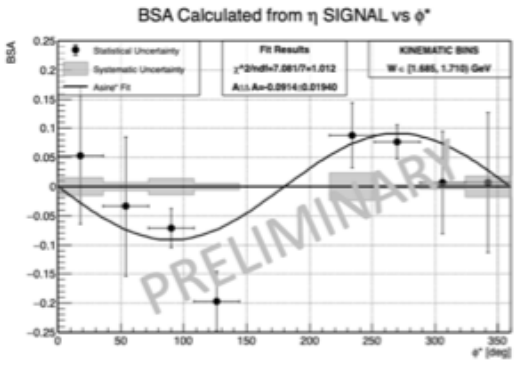


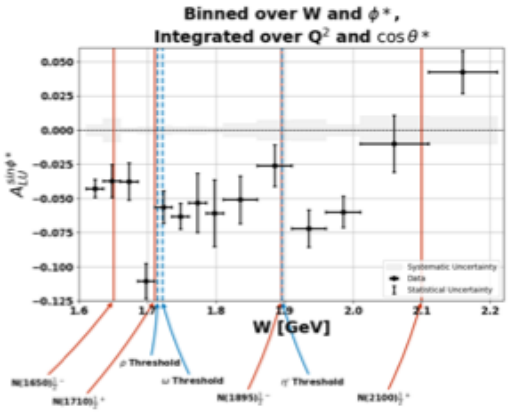


Events extraction through peak vs background fitting

$$\mathrm{BSA} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

$$\mathrm{BSA} \approx A_{LU}^{\sin\phi*} \sin\phi*$$





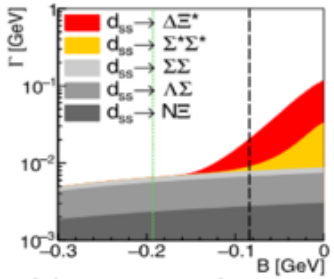
Preliminary results by: Isabel Illari for the RG-K analysis group

Task 4.3: Di-baryon structure and parameter determination

✓ Exotic nuclear phenomena and impact in other fields (astrophysics)

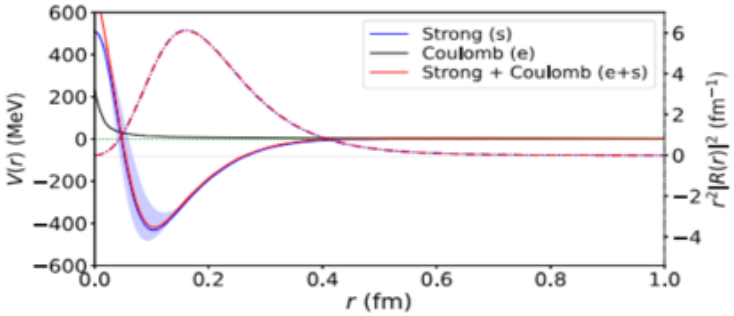
Dibaryons

Dibaryons and where to find them



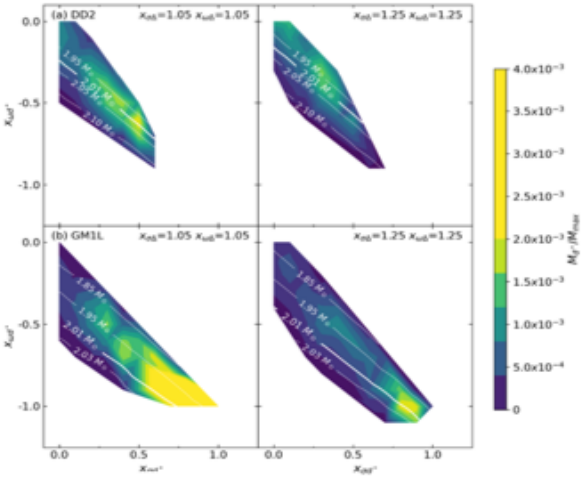
M Bashkanov *et al* 2024 *J. Phys. G: Nucl. Part. Phys.* **51** 045106

Strongly Bound Dibaryon with Maximal Beauty Flavor from Lattice QCD



N. Mathur, M. Padmanath, and D. Chakraborty, Phys. Rev. Lett. **130**, 111901

Destabilization of high-mass neutron stars by the emergence of d^*-hexaquarks



Marcos O. Celi *et al* Phys. Rev. D **109**, 023004

- Dibaryons session at NStar24: https://indico.jlab.org/event/729/
- A lot of progress with dibaryons in Lattice QCD
- A lot of progress with dibaryons in Functional methods

Summary

- STRONG2020-HaSp made progress in hadron interaction theory, phenomenology and data analysis
- Development of new theoretical tools and applications to the vast hadron phenomenology
- Progress in theoretical tools for discovery: multi-q, exotic configurations , BSM, …
- Development of AI-supported tools for hadron spectroscopy analysis
- Development of phenomenological analysis framework to extract resonance parameters from data
- Established a strong connection between experimental and theoretical groups in Europe (and beyond)
- Significant progress but many interesting problems remain opened requiring further investigation
- Hadron spectroscopy: a vibrant field that involves a large community in Europe (and beyond!)
- Schools and meeting engaged a large number of young researchers (students, postdocs)
- The hadron spectroscopy community is ready to engage a new project beyond STRONG2020