STRONG-2020 ANNUAL MEETING (2022)

WP25-JR7
Light-and heavy-quark hadron spectroscopy (HaSP)

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Light and heavy-quark hadron spectroscopy (HaSP)

Study the spectrum of the hadrons

- A new generation of experiments is running or is in preparation at CERN, Mainz, Bonn, GSI, JLab, BESIII, Belle
- Precise and abundant data requires an adequate analysis
- A collaborative effort between experiments and theory: observables need to be interpreted using robust methods relying on 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 (EFTs) expansions

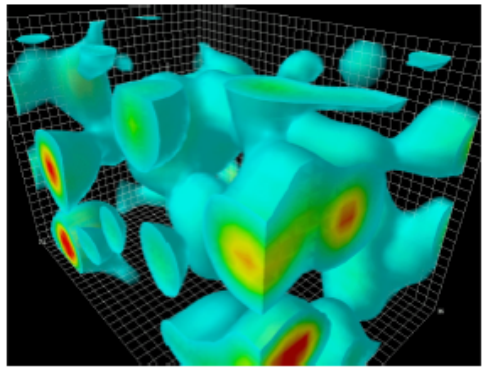
HaSP aims to coordinate the leading European institutions active in hadron spectroscopy to make progress in:

- Developing a theoretical, phenomenological, and computational foundation for scattering amplitudes
- Establishing the best practices for accessing systematic uncertainties in the analysis of hadron reaction data and interpretation of physics results

- **QCD** allows much richer hadron spectrum than **conventional** $q\bar{q}$ mesons and qqq baryons.

Exotic hadrons

glueballs	GG, GGG
multiquark states	$q\,q\,\bar{q}\,\bar{q}$, $q\,q\,q\,q\,\bar{q}$
hybrids	$q\,\bar{q}$ G, **$q\,q\,q$ G**, $q\,q\,\bar{q}\,\bar{q}$ G
molecular hadrons	$[D\bar{D}^*]$, $[\bar{D}^*\,\Sigma_c]$



Derek B. Leinweber – University of Adelaide

Discovery Exotic Mesons

Design and build detectors
Collect data
Build observables
Fit data
Extract pole position,
…

Experiments
Tools

(New and more precise) Data

Interpretation

Lattice QCD,
Constituent Models,
Effective Field Theories,
…

Theory

and temperature & density QCD phase-diagram

dispersive & analyticity techniques…

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

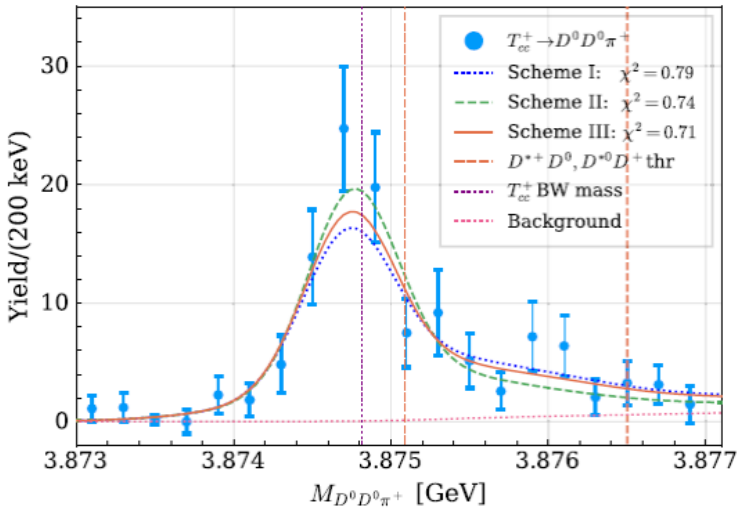
- Resonance parameter determination **(M.Ostrick – Mainz)**
- Diffractive and annihilation production and exotic baryon **(A.D'Angelo – URM-TV)**
- Di-baryon structure and parameter determination **(D. Watts – U. York)**

Progress in Tasks 1: development and application of EFTs

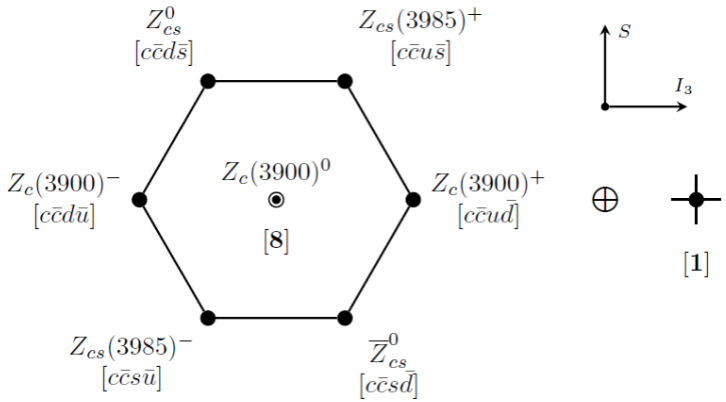
✳Refined analysis of available data and prediction of new states

ChPT, HQET or Quarkonium Non Relativistic EFTs & unitarization methods and dispersive techniques, we have made significant progress in *establishing a robust framework for studying QCD in the non-perturbative regime*. Looking for interacting hadron pairs that might produce **resonances**

- ❑ spectrum and phenomenology of (exotic) hadrons: Λ_c^*, $\Xi_{c,b}^*$, $\Xi_{cc}^{(*)}$, pentaquarks,tetraquars ($Z_{b,c}^{(*)}$, $X(3960)$, T_{cc}^+, J/ψJ/ψ) …
- ❑ scalar πK FF beyond the elastic region
- ❑ Weinberg's compositeness rule
- ❑ phenomenology of (exotic) hadrons in hot environments: $D, D^*, D_s, D_0^*, \ldots$
- ❑ Effective field theories for singular *NN* interactions



Coupled-channel approach to T_{cc}^+ including three-body effects (OPE), M.L.-Du et al., PRD 105 (20229 014024



Establishing the heavy quark spin and light flavour molecular multiplets of the X(3872), Zc(3900), and X(3960), T. Ji et al., e-Print: 2207.08563 [hep-ph] (accepted PRD)

New measurements have allowed determining the lowest-order LECs of the $D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$ EFT.

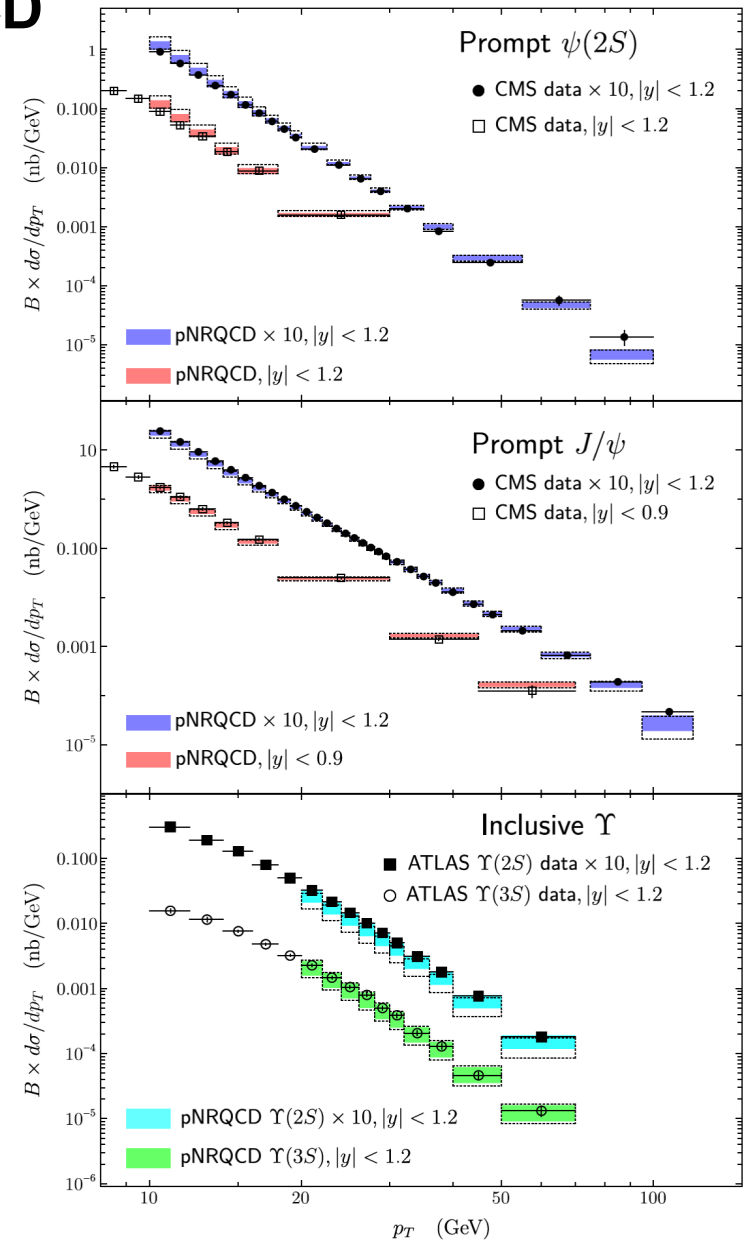
PREDICTION OF NEW EXOTIC STATES AND SU(3) CLASSIFICATION

Progress in Tasks 1: development and application of EFTs

✳Precise calculation of experimental observables in NRQCD

Inclusive production cross sections of heavy quarkonia based on the nonrelativistic QCD and the potential nonrelativistic QCD effective field theories: nonrelativistic QCD long- distance matrix elements for inclusive production of S-wave and P-wave heavy quarkonia

The p_T -differential cross sections for J/ψ, $\psi(2S)$, $\Upsilon(2S, 3S)$ at the LHC center of mass energy $\sqrt{s} = 7$ TeV compared with the CMS and ATLAS measurements



N. Brambilla et al., PRD 105 (2022) L111503

Progress in Tasks 1: hadron decays

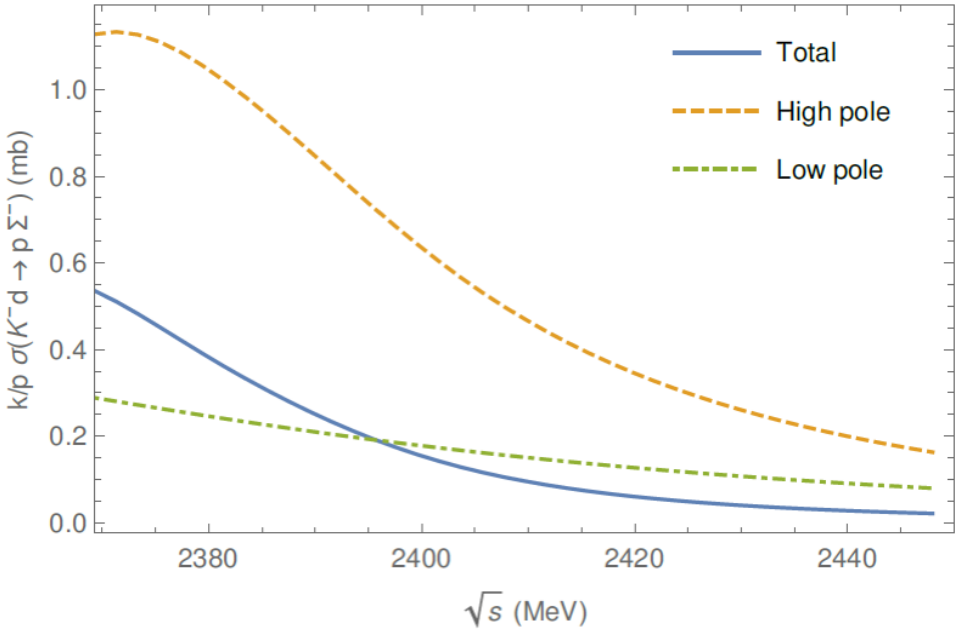
✳Sensitivity to non-perturbative effects to identify exotic quark configurations

- Study of reactions disclosing the nature of the low-lying scalar mesons: different observables for the $D_s \to \pi^+\pi^0\eta$, $D^+ \longrightarrow \pi^+\eta\eta$, $D^+ \longrightarrow \pi^+\pi^0\eta$, $D^+ \longrightarrow K^-K^+K^+$, $D^0 \longrightarrow K^-\pi^0\eta$, $J/\psi \to \gamma\pi\pi$, $\gamma\pi\eta$, $a_1(1260) \longrightarrow \pi f_0(500)$, reactions to test the nature of the scalar mesons ($f_0(500)$, $f_0(980)$, $a_0(980)\ldots$), [f.i. R. Molina, M. Döring, W.H. Liang, E. Oset, *Eur.Phys.J.C* 81 (2021) 782,...]

- Study of hadron molecules from the weak decay of heavy hadrons: double pole structure of the $K_1(1270)$ resonance, analyzed in the $\bar{B} \longrightarrow J/\psi\rho\bar{K}$, $\bar{B} \longrightarrow J/\psi\,\bar{K}^*\pi$ and $D^+ \longrightarrow \nu e^+ VP$ decays [L. Roca, W.H. Liang, E. Oset, Phys.Lett. B824 (2022) 136827

- Characteristics of some reactions in base to triangle singularities (TS) and making predictions of reactions where peaks associated to TS appear, to avert claims of discovery of new resonances when the experiments are performed

*sensitivity of the $K^-d \longrightarrow p\Sigma^-$ reaction to the properties of the $\Lambda(1405)$ resonance, which enhances the contribution of a **triangle-diagram mechanism** that dominates the reaction close to threshold*

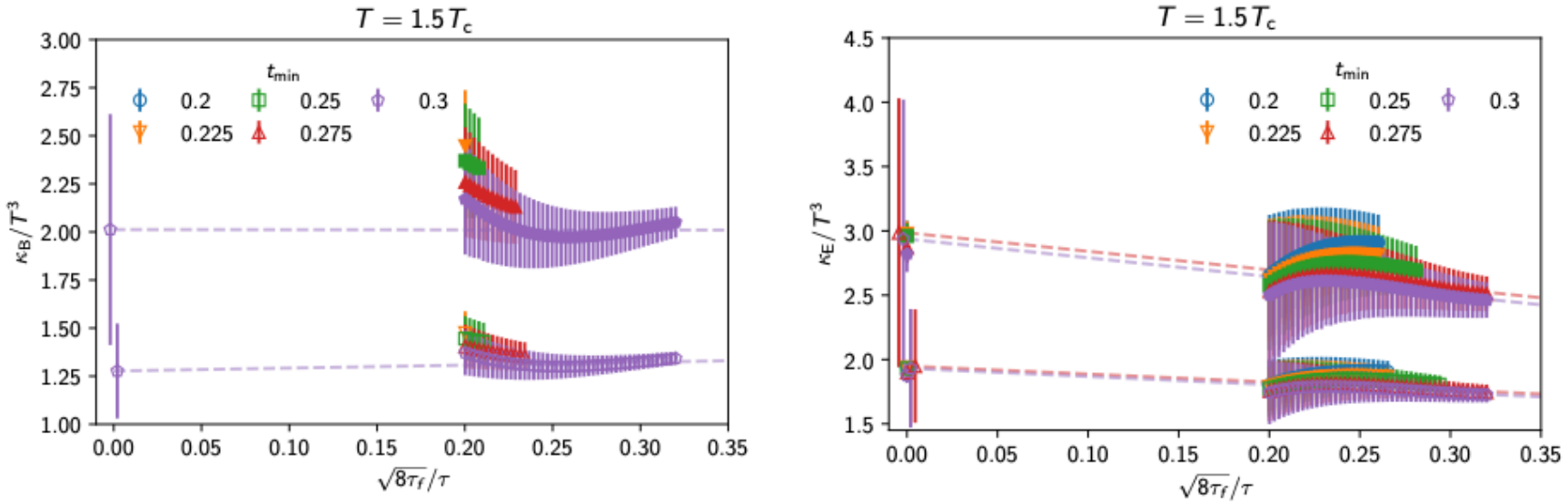


A. Feijoo, R. Molina, L.R. Dai, E. Oset e-Print: 2105.09654 [nucl-th]

Progress in Tasks 2: development and application of EFTs and Hadron Decays

✳Precise calculation of strong force at T ≠ 0 on lattice

ELECTRIC AND MAGNETIC HEAVY QUARK DIFFUSION FROM LATTICE QCD



- Goal: estimate the heavy quark diffusion coefficient at leading order in the inverse heavy quark mass expansion, κE, and the coefficient of first mass suppressed correction, κB.

Method: Gradient flow for noise reduction, showing how to control the distortions due to non-zero flow time

Results: At 1.5Tc we obtain: $1.70 \le \kappa_E/T^3 \le 3.12$ and $1.23 < \kappa_B/T^3 < 2.74$

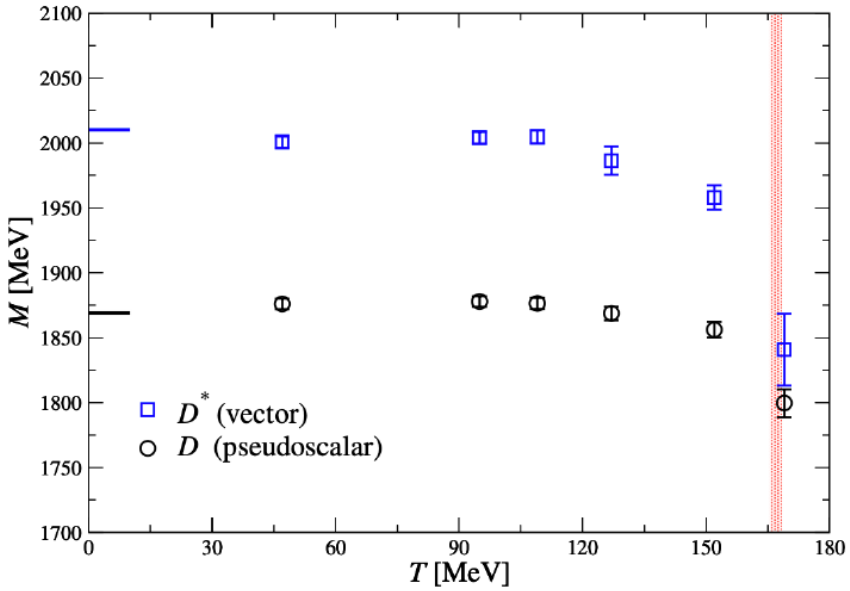
  hep-lat/2206.02861

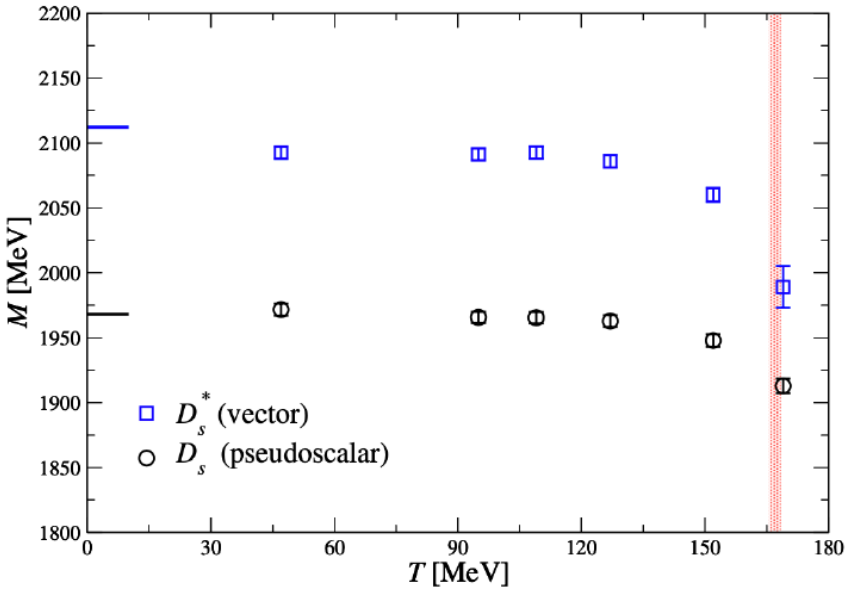
Progress in Tasks 2: heavy-quark, hybrid and tetraquark potentials

✳Thermal modification of hadrons on lattice

SPECTROSCOPY AT T>0 WITH HEAVY QUARKS

- 2+1 dynamic fermions (full QCD) @ $m_\pi = 239$ MeV
- $T < T_c$ (~150 MeV)





- D and D_S mesons in the hadronic phase
- Approaching thermal crossover : thermal modification of hadrons (as expected in QGP)

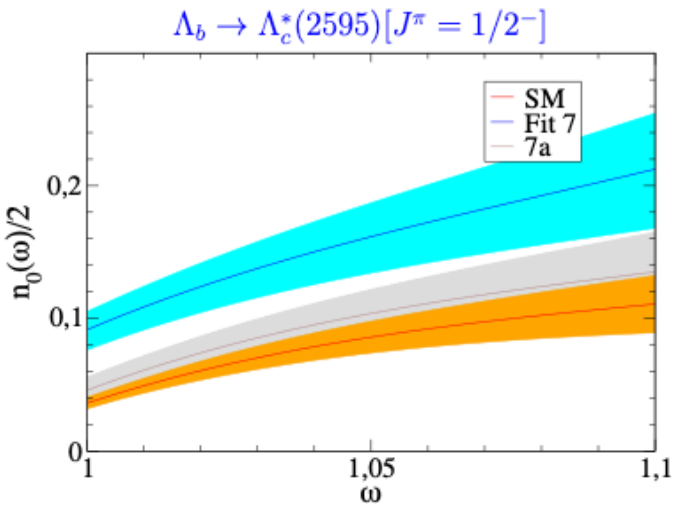
	J^P	PDG	T[MeV]= 47	95	109	127	152	169
D	0^-	1869.65(5)	1876(4)	1878(4)	1876(4)	1869(5)	1856(6)	1800(11)
D^*	1^-	2010.26(5)	2001(4)	2004(4)	2005(5)	1986(11)	1958(9)	1841(28)
D_s	0^-	1968.34(7)	1972(5)	1966(4)	1965(4)	1963(4)	1948(5)	1913(6)
D_s^*	1^-	2112.2(4)	2092(4)	2091(5)	2092(5)	2086(5)	2060(6)	1989(16)

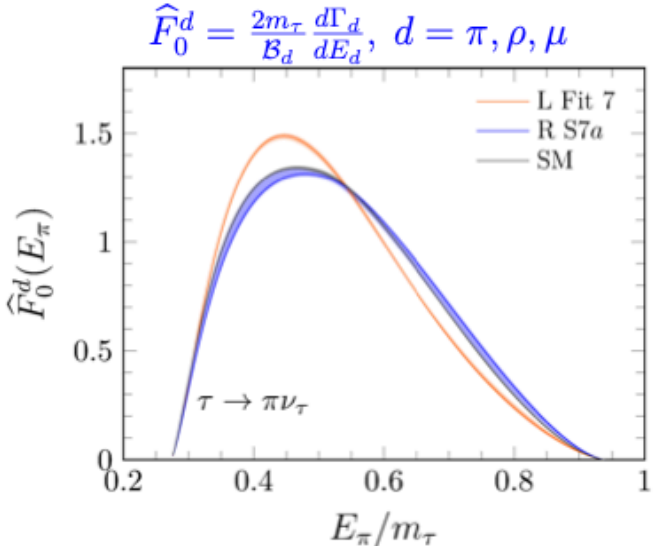
G. Aarts, C. Allton, R. Bignell, T. J. Burns, S. C. García-Mascaraque, S. Hands, B. Jäger, S. Kim, , S. M. Ryan, J.-I. Skullerud – arXiv:2209.14681 [hep-lat]

Progress in Tasks 2: development and application of EFTs and Hadron Decays

✳Sensitivity to BSM physics

LEPTON FLAVOUR UNIVERSALITY VIOLATION AND NEW PHYSICS IN $b \to c\ell\bar{\nu}_\ell$ SEMILEPTONIC TRANSITIONS





- Goal: Understand discrepancies between Standard Model predictions and experimental data on Lepton flavor universality and gauge the need for new Physics

  Method: Model-independent approach: combine effective field-theory and Lattice-QCD

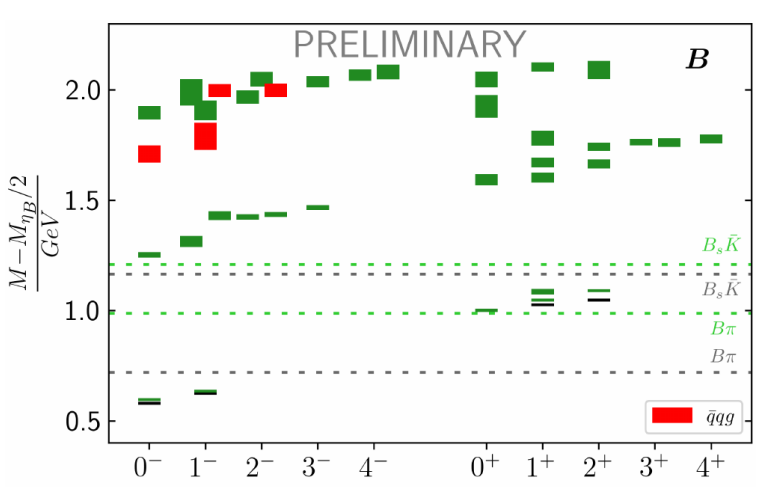
  Results: Different extensions of the SM can explain the data; statistically enhanced distributions like $d\Gamma_d/d\cos\theta_d$ or $d\Gamma_d/dE_d$ can help in distinguishing them

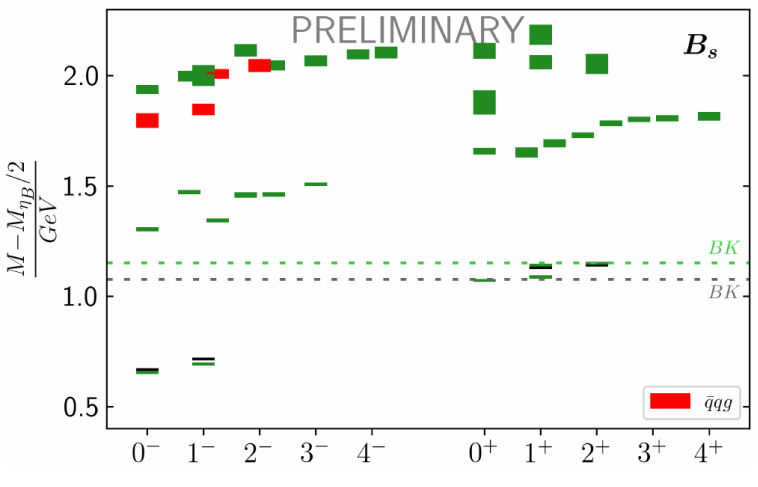
Progress in Tasks 2: heavy-quark, hybrid and tetraquark potentials

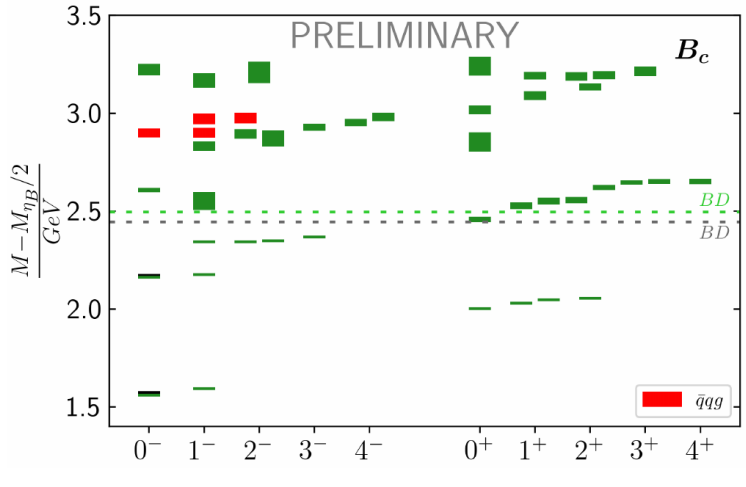
✳Precise calculation of hadron spectrum on lattice

LATTICE SPECTRA OF B, B_S, B_C MESONS

- Preliminary results for the heavy meson spectroscopy extended to heavy-light sector







- 2+1 dynamic fermions (full QCD) @ $m_\pi = 400$ MeV
- qqg hybrids states in red

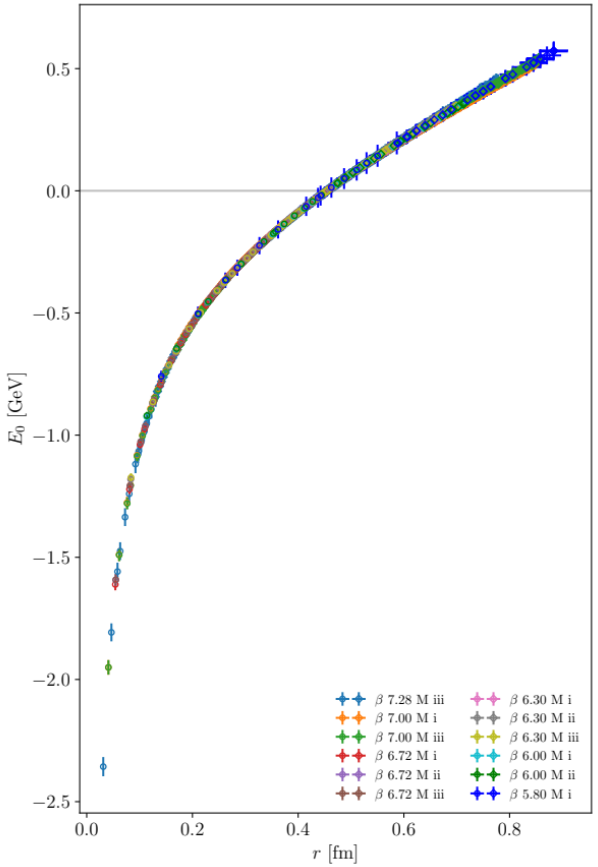
Luke Gayer & Sinéad M. Ryan – In preparation

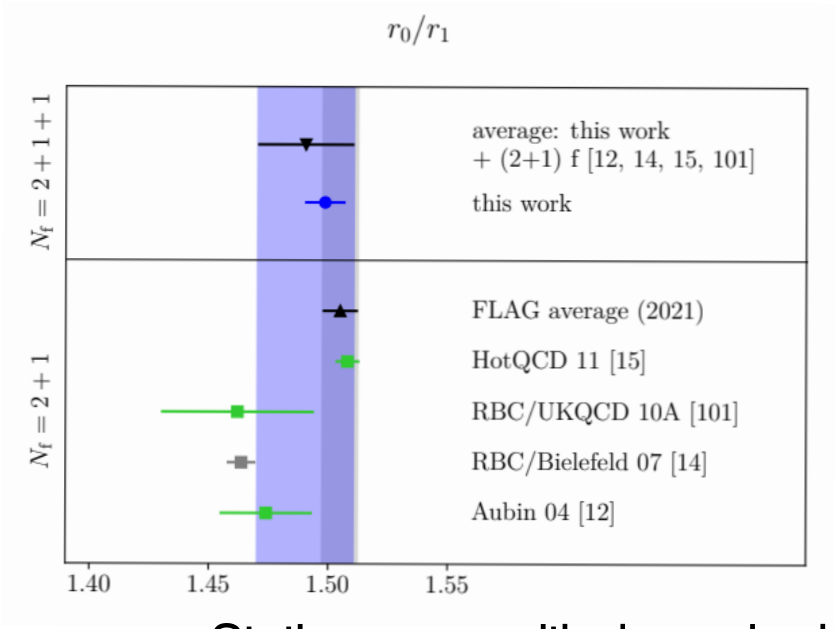
Progress in Tasks 2: heavy-quark, hybrid and tetraquark potentials

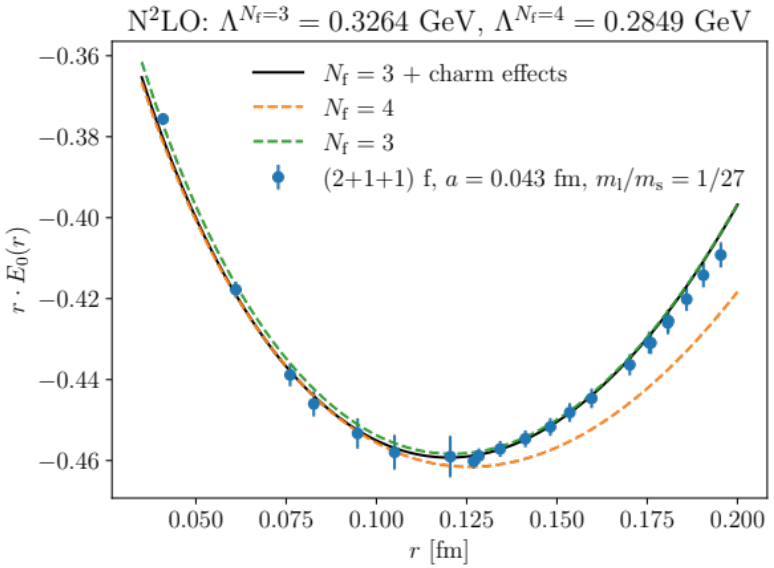
✳Precise calculation of strong force on lattice

STATIC ENERGY IN 2+1+1 FLAVOR LATTICE QCD

- Computed the static energy in 2+1+1 flavour lattice with several quark masses, including the physical one







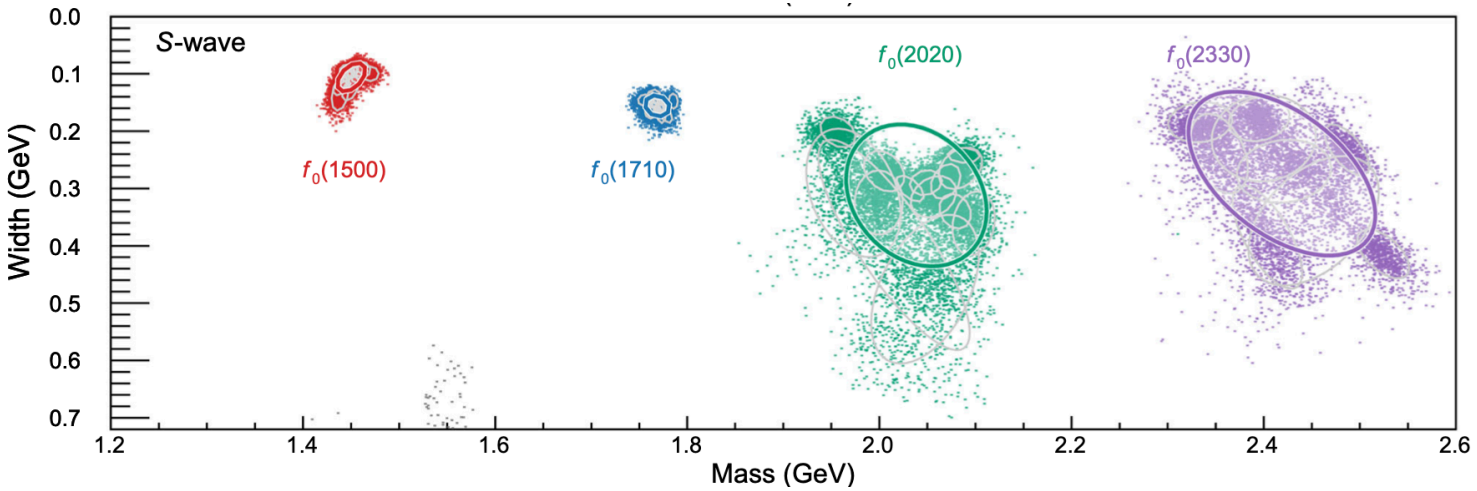
- Static energy with dynamic charm measured from lattice QCD
- Can observe charm effects
- Precise determination of the lattice scales

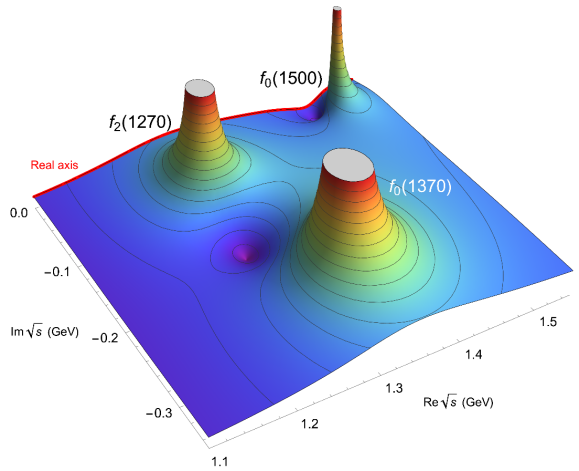
N. Brambilla, R. L. Delgado, A. S. Kronfeld, Viljami Leino, P. Petreczky, S. Steinbeißer, A. Vairo and J. H. Weber – arXiv:2206.03156 [hep-lat]

Progress in Task 3: Search for and study of light exotic mesons, charmonium and strangeonium

✳Development and application of new analysis tools

Determination of the scalar and tensor pole positions from J/psi radiative decays by JPAC, **Rodas et al EPJ82 (2022), 1**





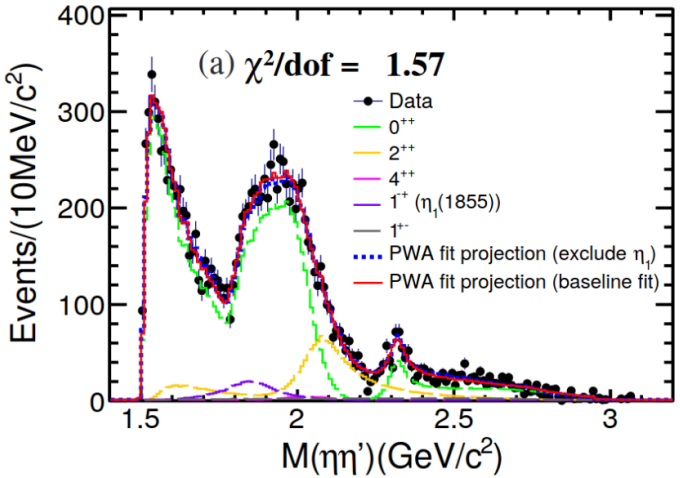
Determination of the f0(1370) pole position from dispersion relation by **Pelaez, Rodas and de Elvira in arXiv:2206.14822**

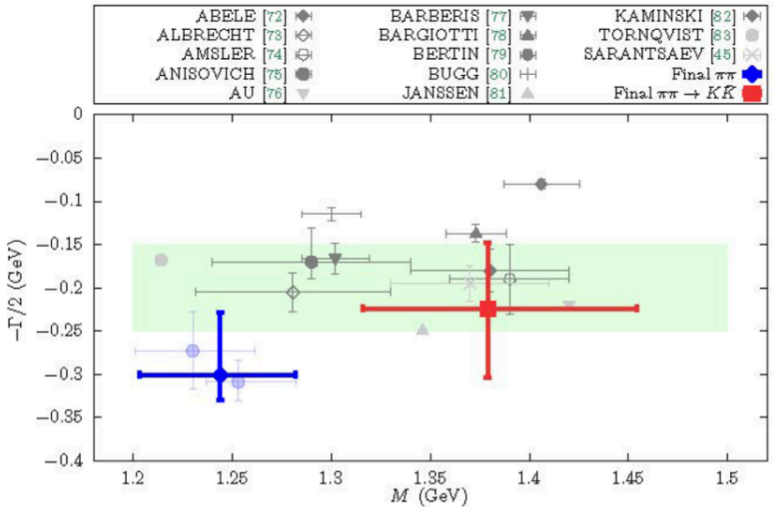
Observation of new exotic candidates by **INFN Ferrara group from BESIII collaboration**

$\eta_1(1855)$ in $\eta'\eta$ arXiv:2202.00621 & 2202.00623

$f_0(2480)$ in $\eta'\eta'$ PRD105(2022) 072002

$X(2600)$ in $\pi\pi\eta'$ PRL129 (2022) 042001

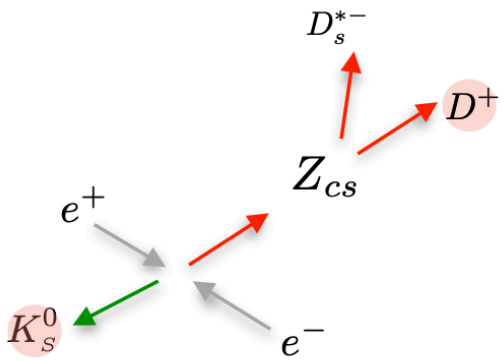


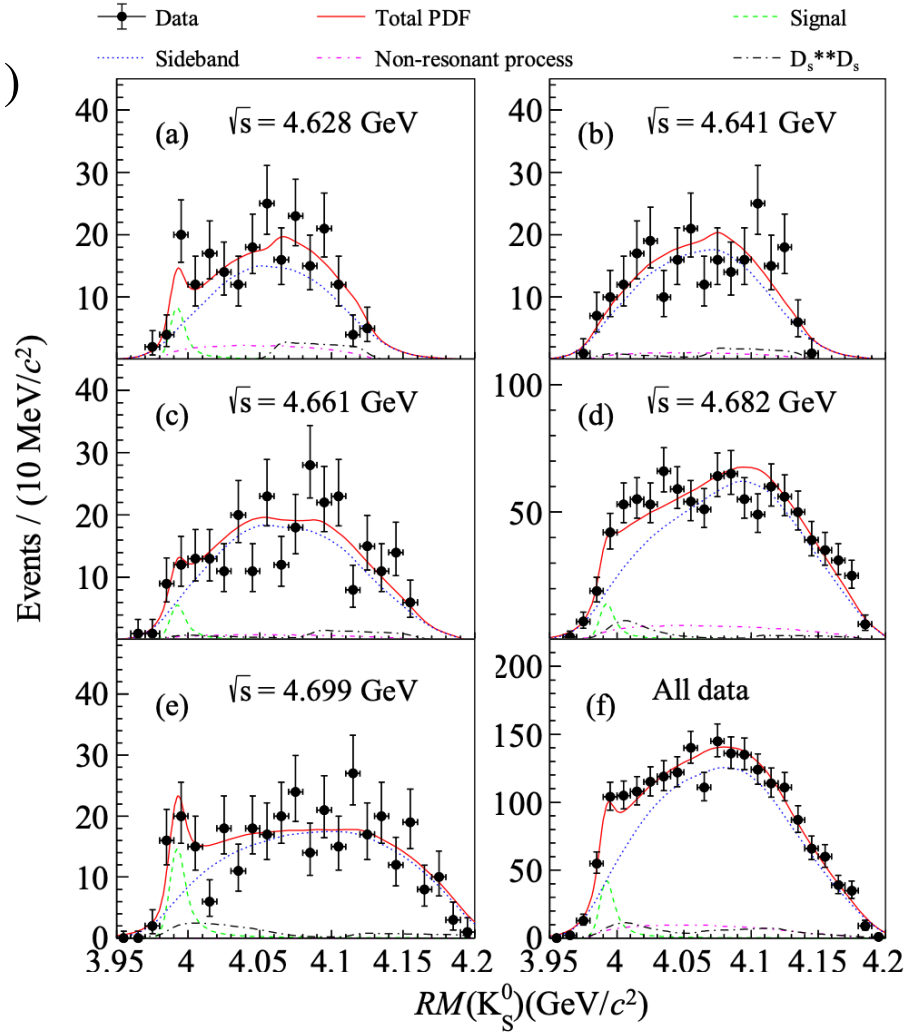


Progress in Task 3: Search for and study of light exotic mesons, charmonium and strangeonium

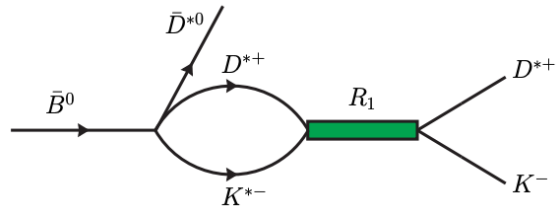
✳New exotic states observations and predictions

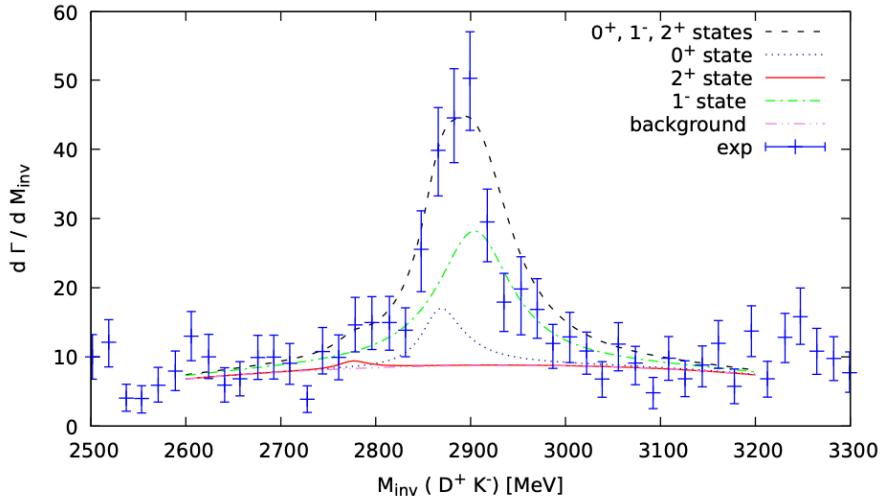
Observation of a new strange $c\bar{c}$-like state $Z_{cs}(3985)$ in e+ e- →KDD*
by the Bochum group
from BESII collaboration
BESIII PRL129 (2022) 112003





Theoretical prediction of R1, the X(2866) partner, and development of a method to find the spin-2 partner of the X(2866), both in DK final states in B meson decays
by the Valencia group
Dai, Molina and Oset PLB832 (2022) 137219
Bayar and Oset PLB833 (2022) 137364



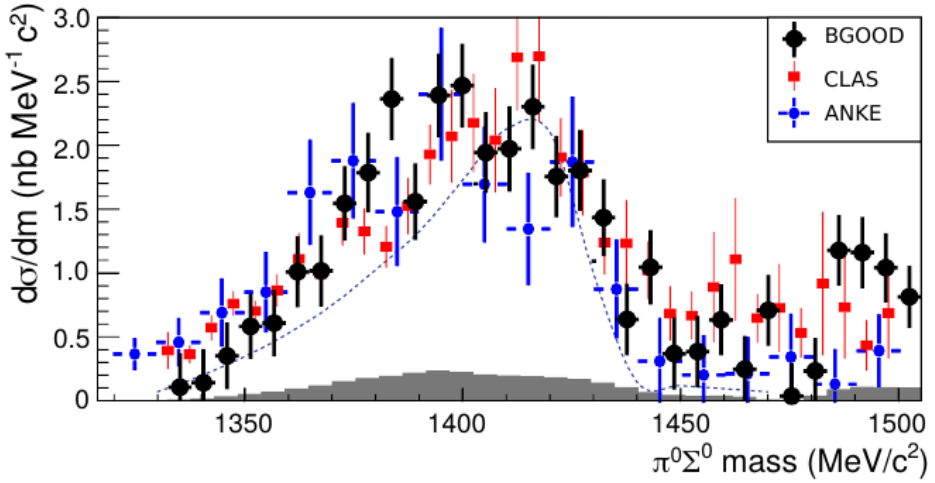


Progress in Task 4: Resonance parameter determination

✳Precise resonance parameter extraction

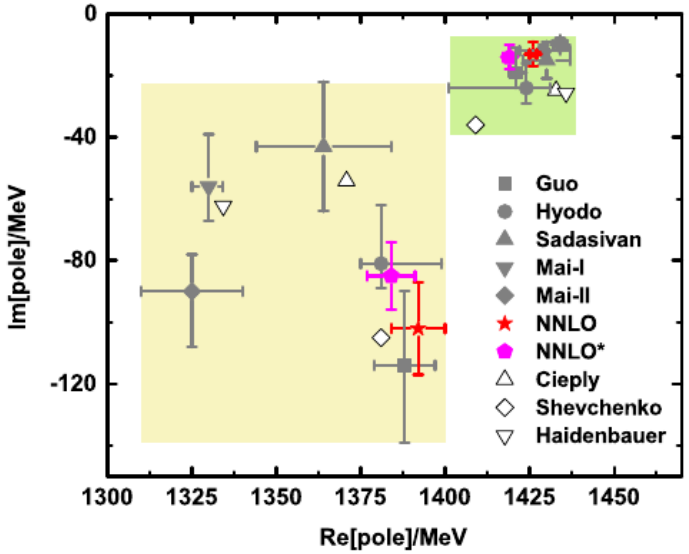
Results on the Λ(1405)

- New data from BGO-OD at ELSA Phys.Lett.B 833 (2022) 13737
- New data from GlueX arXiv:2209.06230
- Two pole structures confirmed arXiv:2209.02471



Strangeness photoproduction

- BGO-OD: γn→ K0Σ0 arXiv:2108.13319
- Jülich-Bonn coupled-channel approach for KΣ arXiv:2208.00089
- Laurent+Pietarinnen analysis of multipoles arXiv:2206.05979



Progress in Task 4: Resonance parameter determination

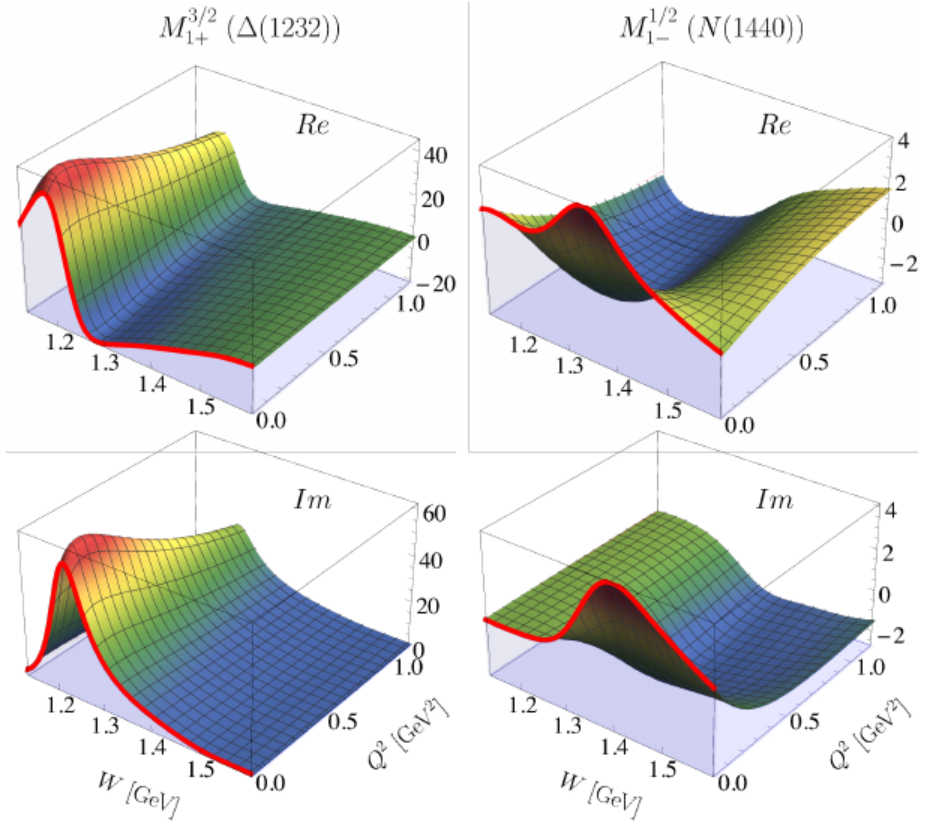
✳New observables interpretation

π and η production

- Spin dependence of π^0 and $\pi^0\pi^{+/-}$ photoproduction off nucleons (A2-MAMI Eur.Phys.J.A 58 (2022) 6, 113, Eur.Phys.J.A 57 (2021) 6, 205)
- Polarization observables in double neutral pion photoproduction (CBELSA/TAPS arXiv:2207.01981)
- Jü-Bo-GWU coupled channel analysis of π and η electroproduction Phys. Rev. C 106, 01520 (2022)

Review articles

- Mai, Meißner Urbach, Towards a theory of hadron resonances, arXiv:2206.01477
- Thiel, Afzal, Wunderlich, Light Baryon Spectroscopy, PPNP 125 (2022) 103949



selected multipoles obtained by Jü-Bo-GWU coupled channel analysis

Progress in Task 4: Baryon spectroscopy

✳ **New (polarisation) observables**

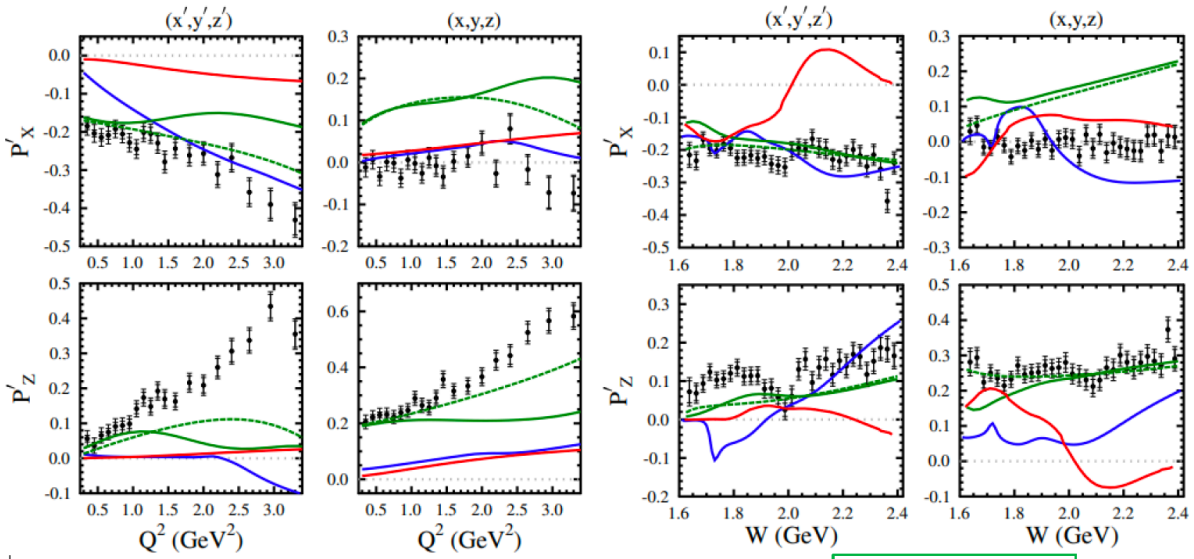
KY electro – production – Transfer polarization Asymmetry

$$A = \frac{N^+ - N^-}{N^+ + N^-} = \nu_Y \alpha_\Lambda P_b \mathcal{P}'_Y \cos\theta_p^{RF}$$

PHYSICAL REVIEW C **105**, 065201 (2022)

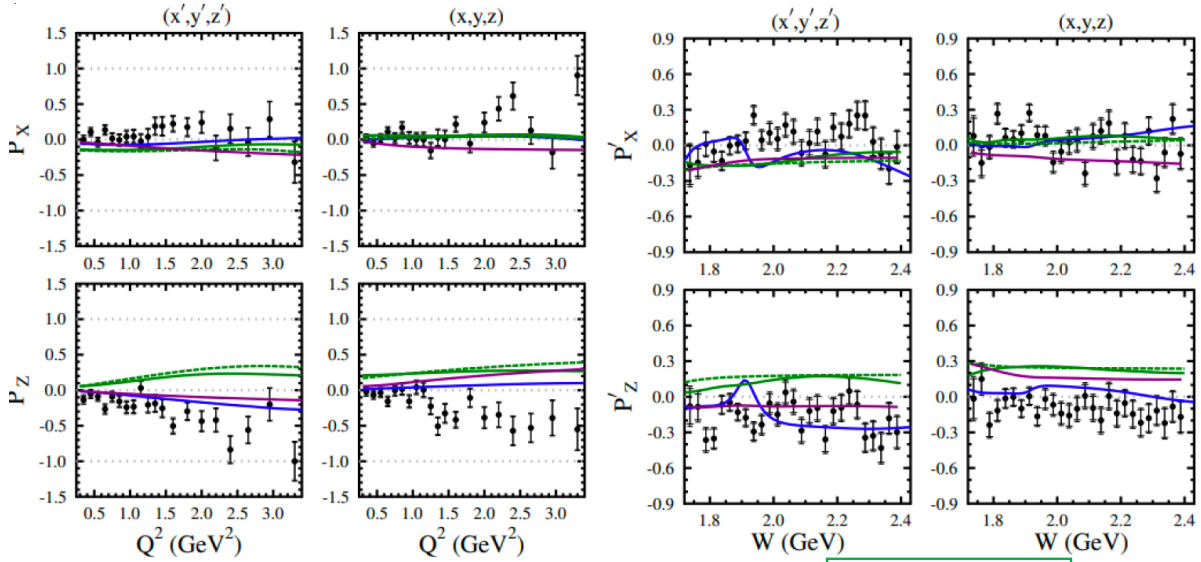
Beam-recoil transferred polarization in K^+Y electroproduction in the nucleon resonance region with CLAS12

Λ Polarization Asymmetry



6.535 GeV

Σ^0 Polarization Asymmetry

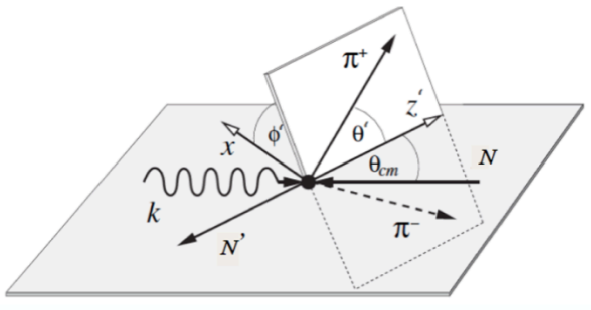


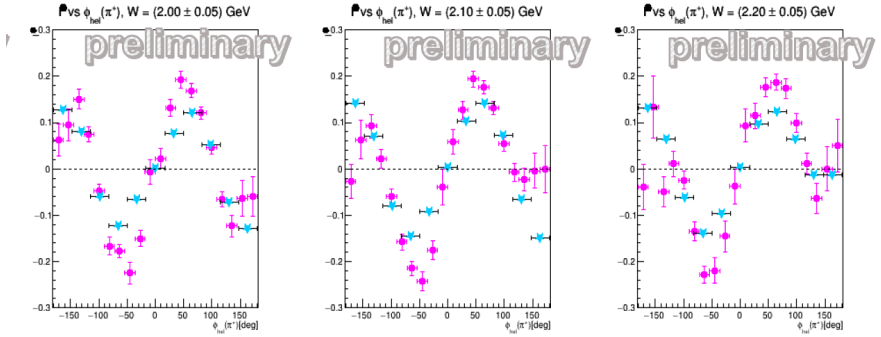
6.535 GeV

Lucilla Lanza & Dan Carman for the RG-K analysis group

Progress in Task 4: Baryon spectroscopy

✳ New (polarisation) observables

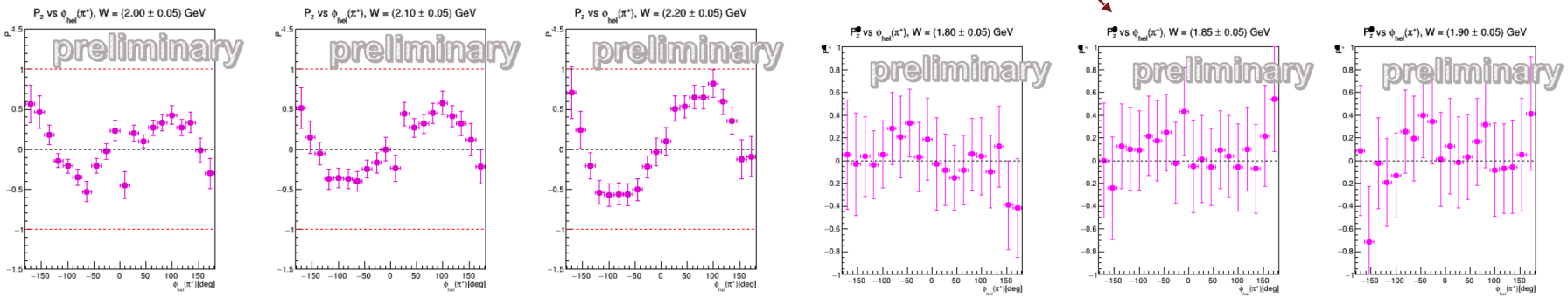




Blue points from S. Strauch et al., CLAS Coll., PR **C71** (2005), 055201

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

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



Preliminary results by: Alessandra Filippi for the g14 analysis group

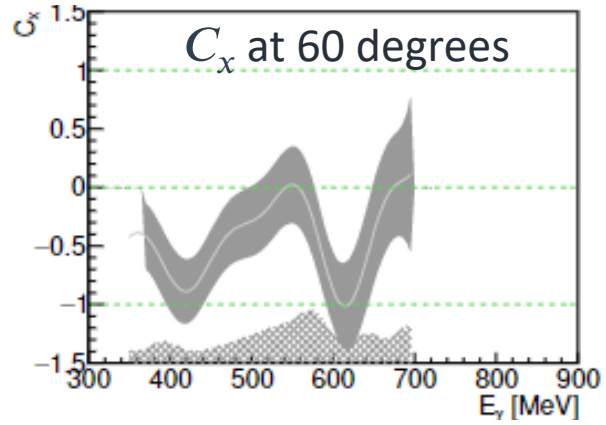
Progress in Task 4: Di-baryon structure and parameter determination

✳New observables in baryon spectroscopy

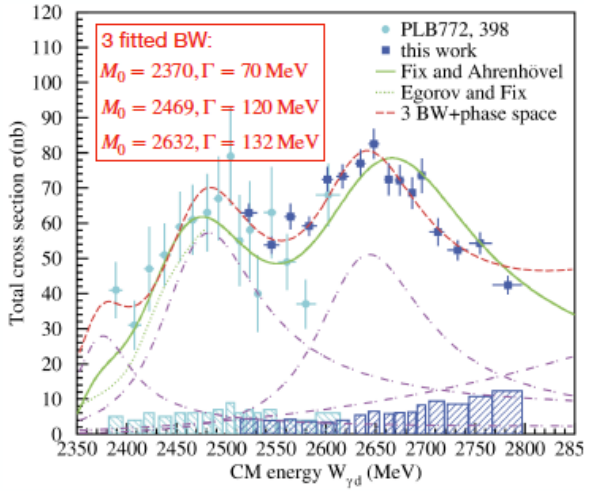
The d*(2380)

- Six-quark state evidenced in pn scattering at WASA – $J^P=3^+$
- New evidence – induced/transferred nucleon polarisation observables with EM probes

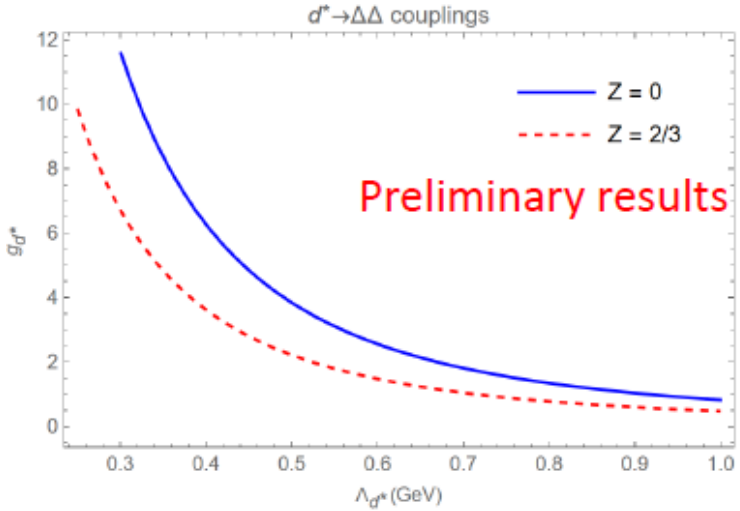
Bashkanov, DPW; arXiv: 2206.12299 (2022)

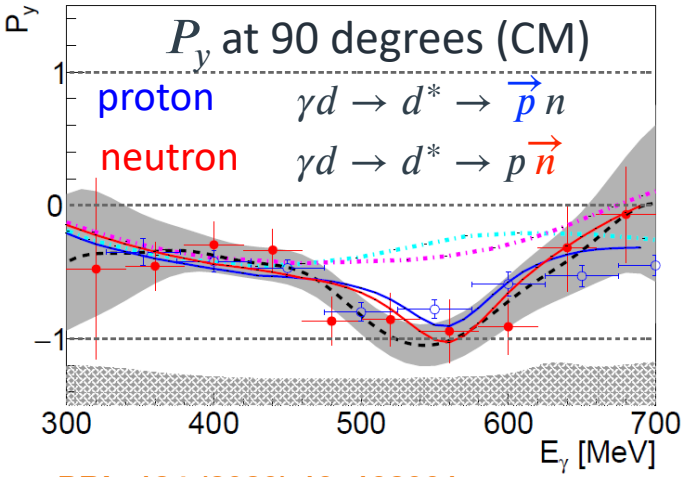


- New measurements : dππ photoproductions BGOOD@ELSA (forward deuteron angles)



- New effective Lagrangian calculations of d*->ΔΔ decay(Samart – Khon kaen)





PRL. 124 (2020) 13, 132001

Progress in Task 4: Di-baryon structure and parameter determination

✳Baryon spectroscopy extension to charm and beauty sector

Theory progress in beauty and charm quark sectors

- One Boson exchange models extended to include exchange of charmonia –> bound systems

  Liu. Geng (Beijing/Zhengzou); CHIN. PHYS. LETT. Vol. 38, No. 10 (2021) 101201

- First lattice QCD – deeply bound beauty dibaryon

  Mathur, Padmanath, Chakraborty (Mumbai/Mainz) e-Print: 2205.02862 (2022)

- Effective SU(3) Lagrangian -> predicts bound systems of many charmed hyperons

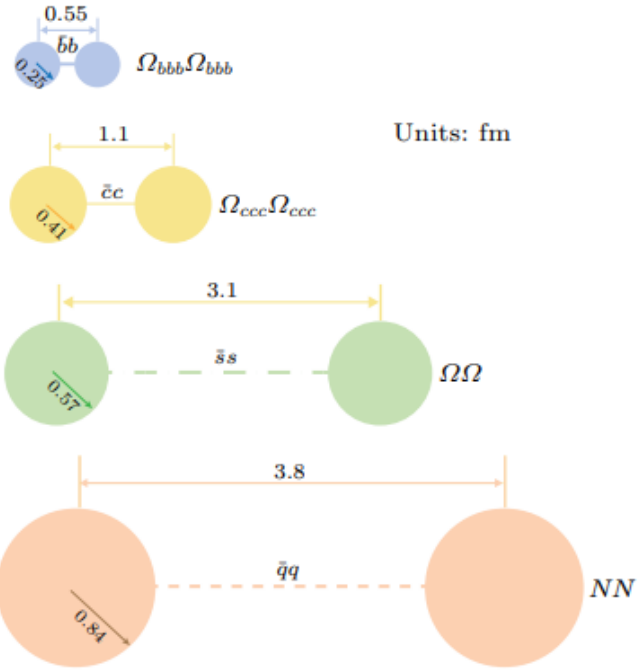
  Shu-Yi Kong , Jun-Tao Zhu , Jun He (Nanjing, Lanzouh), arXiv:2208.11962

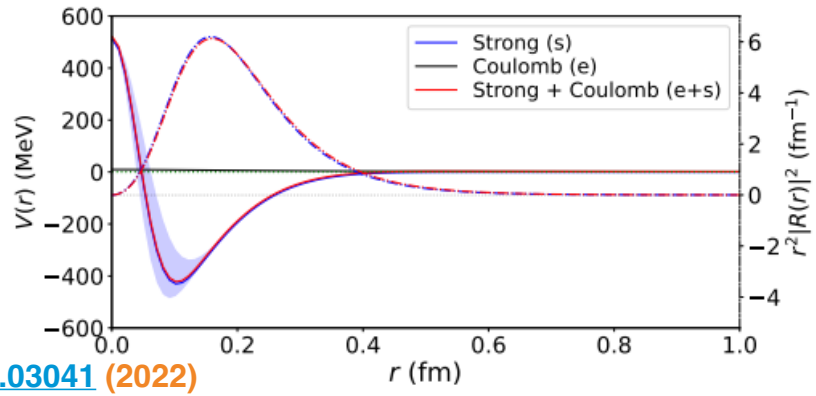
- BUT.. Some approaches do not predict bound states in bottom, charm sector

  Lyu et. al (Peking/Riken,Kyoto) PRL 127, 072003 (2021)

- HAL QCD

- Constituent quark model





Qi-Fang Lu , Dian-Yong Chen, Yu-Bing Dong (Beijing, Lanzhou, Osaka, Nanjing, Changsha) : e-Print: 2208.03041 (2022)

Summary

- EU: Hadron spectroscopy keeps attracting contributions from the EU experimental and theoretical communities, well represented in JR7-WP25
- PROGRESS: Significant progress in 2022 in all Tasks:
  - exploring exotic hadronic configurations (theory and exp)
  - predicting hadron spectrum using pNRQCD, EFT, and LQCD
  - exploring strong force modification in the hot hadronic matter and BSM physics in hadronic systems
  - developing tools to distinguish genuine exotic configurations from other non-perturbative effects
  - interpreting new data to confirm exotic configurations (meson and baryon sectors, including c and b sectors)
  - interpreting old data with new analysis tools
  - studying new polarisation observables to gain insight into internal hadron structures
- GLOBAL: Significant exchange and coordination (workshops, common analysis, and actions, …) with non-EU institutions/labs
- STATUS: JR7-WP25 milestones and plans are well on-time
- EXTENSION: No modifications wrt the original plan are needed and an extension beyond Nov ’23 is not strictly needed
- PRESENT: Seeking a recommendation about hadron spectroscopy in NuPECC LRP (and NSAC LRP in the US)
- FUTURE: The whole hadron spectroscopy community is eager to present a new proposal for a future EU-funded initiative!