Unquenching and unitarising mesons in quark models and on the lattice

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I. Introduction: concepts of unitarisation and unquenching

- Most mesons are more or less broad resonances, originally generated in elastic scattering off baryons, but nowadays usually created in production processes.
- Modern quark models include these features, by accounting for strong decay and the dynamical effects thereof, via full-fledged unitarisation or calculating mass shifts from coupled channels.
- Strong mesonic decay is dominated by the creation of one or more new light $q\bar{q}$ pairs respecting the OZI (alias Zweig) rule.
- Often such models are sloppily called "unquenched".
- The term "unquenching" stems from the lattice, which implies accounting for virtual quark loops.
- In recent years, also the lattice has started to describe mesonic resonances, employing Lüscher's finite-volume method in the elastic case or generalisations thereof for inelastic resonances.
- In the following some old and new model predictions will be briefly reviewed, and compared to very recent lattice results.

II. Unitarised and coupled-channel quark models

- The pioneering coupled-channel/unitarised models were developed about four decades ago by the following groups:
  Cornell, Phys. Rev. Lett. **36** (1976) 500 (charmonium);
  Helsinki, Ann. Phys. **123** (1979) 1 (pseudoscalar, vector states);
  Nijmegen, Phys. Rev. D **21** (1980) 772 (vector $c\bar{c}$, $b\bar{b}$ states).
- Only the Nijmegen model amounted to a full S-matrix unitarisation of a complete bare confinement spectrum, with several open and closed two-meson channels.
- A very significant further advance was the chiral quark model by Bicudo & Ribeiro, Phys. Rev. D **42** (1990) 1611; 1625; 1635 (π, ρ, ϕ). This model was the first to combine dynamical chiral symmetry breaking, the full Dirac spin structure in a relativistic wave equation, and coupled-channel mass shifts via the RGM.
- More recent unitarised/coupled-channel models were due to e.g. Simonov, Kalashnikova (Moscow), Barnes (Tennessee), Swanson (Pittsburgh), Santopinto (Genova).
- Next some selected results will be shown.

G. Rupp and E. van Beveren, Chin. Phys. C **41** (2017) 053104

Table 1. Negative real mass shifts from unquenching. Abbreviations: P, V, S=pseudoscalar, vector, scalar mesons, respectively; q=light quark. See text and Ref. [20] for further details.

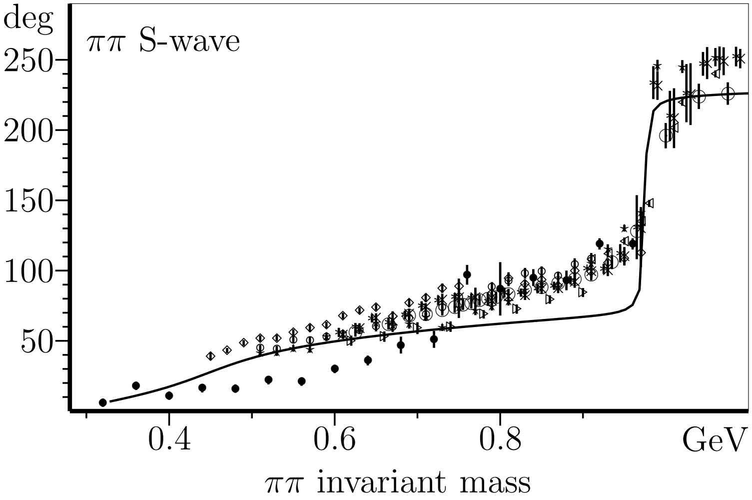
Refs.	mesons	$-\Delta M/\text{MeV}$
[21]	charmonium	48–180
[22, 27]	light P, V	530–780, 320–500
[23, 28]	$q\bar{q}$, $c\bar{q}$, $c\bar{s}$, $c\bar{c}$, $b\bar{b}$; P, V	$\approx$ 30–350
[29]	σ, κ, $f_0(980)$, $a_0(980)$	510–830
[29]	standard S (1.3–1.5 GeV)	~ 0
[30]	$\rho(770)$, $\phi(1020)$	328, 94
[24]	$D^\star_{s0}(2317)$, $D^\star_0(2400)$	260, 410
[31]	$D^\star_{s0}(2317)$, $D^\star_s(2632)$	173, 51
[32]	charmonium	165–228
[33]	charmonium	416–521
[34]	X(3872)	$\approx$100
[35]	$c\bar{q}$, $c\bar{s}$; $J^P = 1^+$	4–13, 5–93

E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, T. M. Yan, Phys. Rev. D **21** (1980) 203

TABLE VII. Mass shifts in the coupled-channel calculation of charmonium states; see the text for the parameters used.

State	Bare mass (MeV)	Mass shift (MeV)	Renormalized mass (MeV)
1^3S_1	3143	−48	3095
2^3S_1	3802	−118	3684
3^3S_1	4280	−55	4225
4^3S_1	4687	−62	4625
1^3P_2	3615	−92	3523
1^3P_1	3615	−98	3517
1^1P_0	3615	−96	3519
1^3D_1	3935	−180	3755
2^3D_1	4372	−142	4230

E. van Beveren, T. A. Rijken, K. Metzger, C. Dullemond, G. Rupp, and J. E. Ribeiro, Z. Phys. C **30** (1986) 615



Poles predicted at **(470 − *i*208)** MeV and **(990 − *i*20)** MeV.

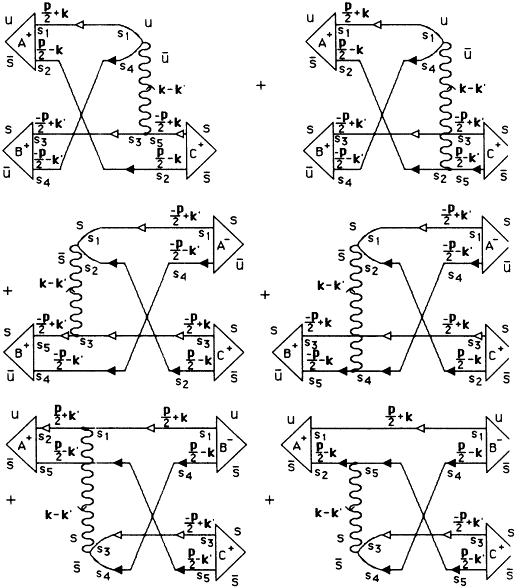


FIG. 9. Diagrams responsible for the formation (and destruction) of resonance C in the scattering of two meson: A and B. The diagrams displaying the contribution of the negative-energy components of the mesonic wave functions are also presented.

P. Bicudo and J. E. Ribeiro, Phys. Rev. D **42** (1990) 1635

III. Lattice and model results from unquenching/unitarisation

- In recent years, two major lattice collaborations have been very successful in obtaining exciting results for mesonic resonances:

  (i) The Graz–Ljubljana–Vancouver–Fermilab–Mainz collaboration: e.g. $D^{\star}_{s0}(2317)$, $D_{s1}(2460)$, $X(3872)$, $K^{\star}(892)$, $K^{\star}(1410)$.

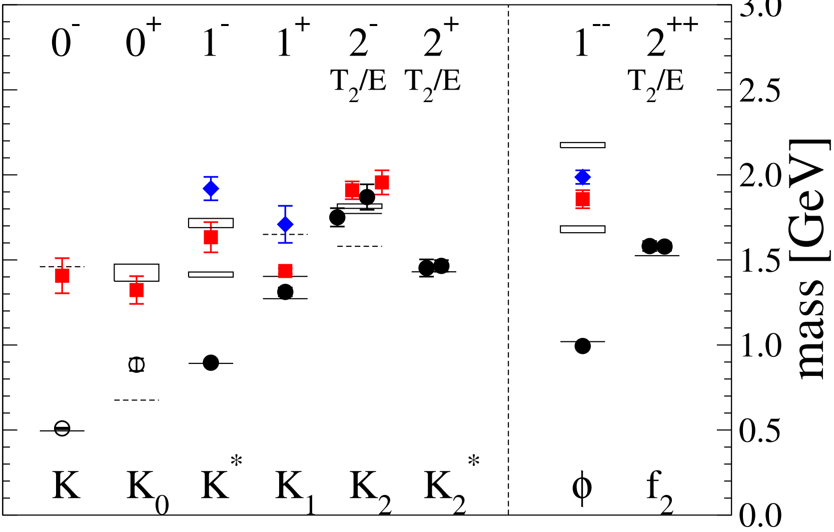
  This group has so far limited its resonance descriptions to single-channel meson-meson scattering, using Lüscher's original finite-volume method.

  (ii) The JLab, Hadron Spectrum Collaboration: e.g. $\rho(770)$, $K^{\star}(892)$, $K^{\star}_0(800)$, $a_0(980)$, $f_0(500)$.

  This collaboration has already studied inelastic resonances with two coupled meson-meson channels.

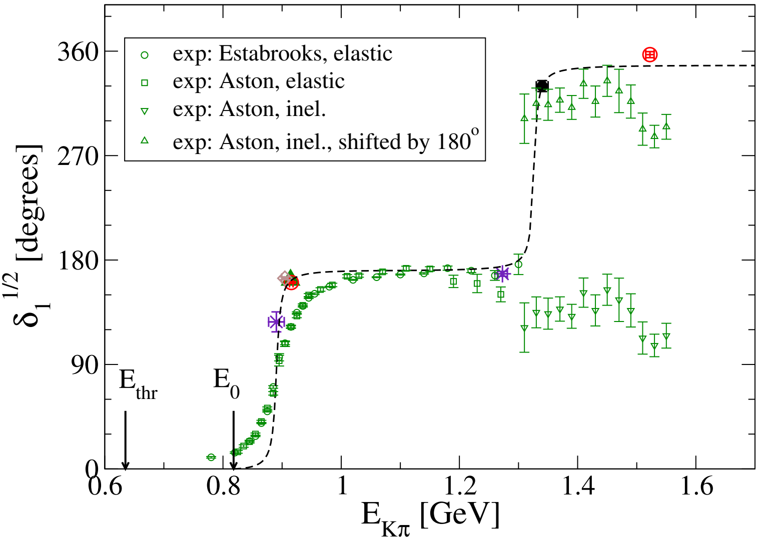
- In the following slides several recent results and remarks by these two groups will be shown, also in comparison with some model results by e.g. E. van Beveren, S. Coito, G. Rupp.

G. Engel, C. Lang, D. Mohler, A. Schäfer, PoS Hadron2013 (2013) 118 [arXiv:1311.6579 [hep-ph]: $K^{\star\prime}$ level above 1.6 GeV:



- However, $K^{\star\prime}$ resonance at (1.33 ± 0.02) GeV (Exp. 1.41):

S. Prelovsek, L. Leskovec, C. Lang, D. Mohler, Phys. Rev. D **88** (2013) 054508



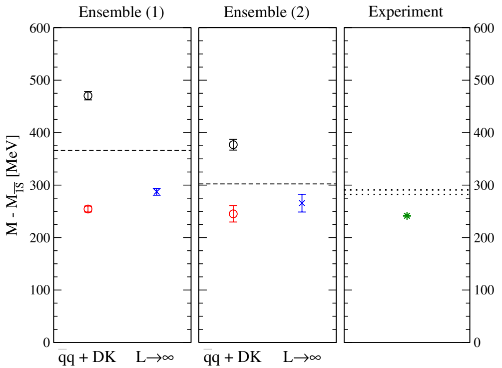


FIG. 3 (color online). The final result for the $D_{s0}^*(2317)$ mass is given by the crosses in the left and middle panels, while the experimental value is given in the right panel. Instead of the mass itself, we compare the values of $M_{L\to\infty}^{D_0^*(2317)} - M_{\overline{1S}}$, where $M_{\overline{1S}}^{\rm exp} = \frac{1}{4}(m_{D_s} + 3m_{D_s^*}) \simeq 2076$ MeV. The value of the bound state position in the infinite volume limit $M_{L\to\infty}^{D_0^*(2317)}$ is obtained from the pole condition $\cot\delta = i$. The two lowest energy levels from our simulation in the finite volume are given by the circles in the left and middle panels. Dashed lines represent the threshold for DK in our simulation ($m_u = m_d$), and dotted lines the thresholds for D^0K^+, K^0D^+ in experiment.

D. Mohler, C. B. Lang, L. Leskovec, S. Prelovsek, R. M. Woloshyn, Phys. Rev. Lett. **111** (2013) 222001

Confirmed early model description:

E. van Beveren, G. Rupp, Phys. Rev. Lett. **91** (2003) 012003

M. Padmanath, C. B.Lang, and S. Prelovsek Phys. Rev. D **92** (2015) 034501

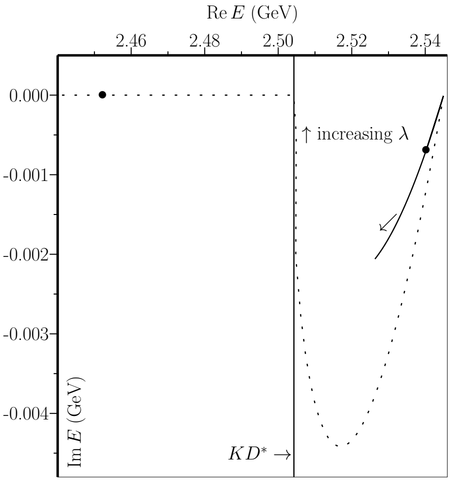
We perform a lattice study of charmonium-like mesons with $J^{PC} = 1^{++}$ and three quark contents $\bar{c}c\bar{d}u$, $\bar{c}c(\bar{u}u + \bar{d}d)$ and $\bar{c}c\bar{s}s$, where the later two can mix with $\bar{c}c$. This simulation with $N_f = 2$ and $m_\pi \simeq 266$ MeV aims at the possible signatures of four-quark exotic states. We utilize a large basis of $\bar{c}c$, two-meson and diquark-antidiquark interpolating fields, with diquarks in both antitriplet and sextet color representations. A lattice candidate for $X(3872)$ with $I = 0$ is observed very close to the experimental state only if both $\bar{c}c$ and $D\bar{D}^*$ interpolators are included; the candidate is not found if diquark-antidiquark and $D\bar{D}^*$ are used in the absence of $\bar{c}c$. No candidate for neutral or charged $X(3872)$, or any other exotic candidates are found in the $I = 1$ channel. We also do not find signatures of exotic $\bar{c}c\bar{s}s$ candidates below 4.2 GeV, such as $Y(4140)$. Possible physics and methodology related reasons for that are discussed. Along the way, we present the diquark-antidiquark operators as linear combinations of the two-meson operators via the Fierz transformations.

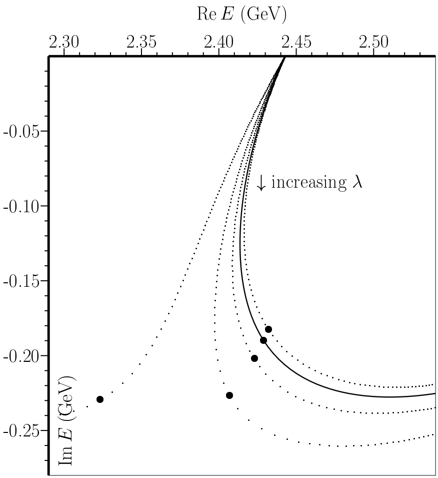
> *. . . "In the physical world with $N_c = 3$, it is argued that tetraquarks could exist at subleading orders [46] of large N_c QCD. However, in the presence of the leading order two-meson terms, one should take caution in interpreting the nature of the levels purely based on their overlap factors onto various four-quark interpolators." . . .*

Correlation functions and the finite-volume spectrum.— The discrete spectrum of hadronic eigenstates of QCD in a finite volume is extracted from two-point correlation functions $C_{ab}(t,t';\vec{P}) = \langle 0|\mathcal{O}_a(t,\vec{P})\mathcal{O}_b^\dagger(t',\vec{P})|0\rangle$, with spatial momentum $\vec{P} = (2\pi/L)[n_x,n_y,n_z]$, where $n_i \in \mathbb{Z}$ in an $L \times L \times L$ box. We use a large basis of interpolating fields $\mathcal{O}_a$ from two classes. The first are single-meson-like operators [13,14,17] which resemble a $q\bar{q}$ construction of definite momentum $(\bar{\psi}\mathbf{\Gamma}\psi)_{\vec{P}}$, where $\mathbf{\Gamma}$ are operators acting in spin, color, and position space [11]. Both $u\bar{u}+d\bar{d}$ and $s\bar{s}$ flavor constructions are included [16,23]. The second class of operators are those resembling a pair of pions $\pi\pi$ with definite relative and total momentum $\sum_{\hat{p}_1,\hat{p}_2} w_{\vec{p}_1,\vec{p}_2;\vec{P}}(\bar{\psi}\mathbf{\Gamma_1}\psi)_{\vec{p}_1}(\bar{\psi}\mathbf{\Gamma_2}\psi)_{\vec{p}_2}$ [18], projected into isospin $=0$. Each isovector pionlike operator is constructed as the particular linear superposition, in a large basis of single-meson operators, that maximally overlaps with the pseudoscalar ground state [17,18].

R. A. Briceño, J. J. Dudek, R. G. Edwards, and D. J. Wilson, Phys. Rev. Lett. **118** (2017) 022002

S. Coito, G. Rupp, and E. van Beveren, Phys. Rev. D **84** (2011) 094020





$D_{s1}(2460)$ and $D_{s1}(2536)$

$D_1(2430)$

IV. Conclusions

- In recent years lattice approaches have made enormous progress in describing mesonic ground-state resonances and even a few excitations.
- In view of the persisting controversies about the nature of several enigmatic mesonic enhancements observed in experiment, this is of vital importance to work as a filter on the avalanche of experimental and model claims about the alleged discovery of exotic states.
- Of particular significance is the lattice observation that a very narrow meson may owe its tiny width to a large negative mass shift due to coupled-channel unitarisation, pushing the state's mass below its lowest strong decay threshold.
- This confirms our old as well as recent model results indicating that the argument of a meson's small width as a justification to ignore coupled-channel effects is fallacious.