Hadron Physics: Exotic Hadrons

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Scope of this talk

- I will interpret “exotic” very loosely for this talk as hadrons that do not fit the traditional $q\bar{q}$ and qqq picture
- The focus will be on reporting progress with regard to calculations of (exotic) hadron resonances and bound states from low-energy QCD

Methods:

- Effective field theory, Lattice QCD , functional methods, data driven approaches

Locations in Germany:

- Bonn, Darmstadt/GSI, Frankfurt, Giessen, Jülich, Mainz, München, Regensburg, Wuppertal

I will cover a small selection of recent activities.
My sincere apologies for what I can not cover!

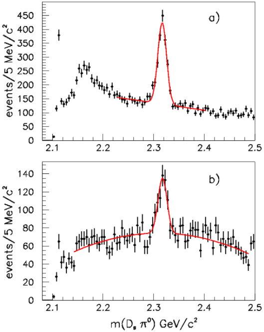
Exotic meson example: D_s and B_s

Established s and p-wave hadrons:

D_s ($J^P = 0^-$) and D_s^* (1^-)
$D_{s0}^*(2317)$ (0^+), $D_{s1}(2460)$ (1^+),
$D_{s1}(2536)$ (1^+), $D_{s2}^*(2573)$ (2^+)

B_s ($J^P = 0^-$) and B_s^* (1^-)
?
$B_{s1}(5830)$ (1^+), $B_{s2}^*(5840)$ (2^+)

$D_{s0}^*(2317)$:
PRL 90 242001 (2003)

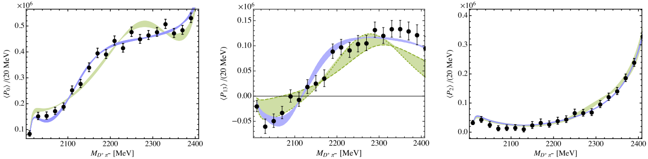


- Corresponding $D_0^*(2400)$ and $D_1(2430)$ are broad resonances
- Peculiarity: $M_{c\bar{s}} \approx M_{c\bar{d}}$ Is this really the case?
- Additional exotic states are expected (in the sextet representation)
- B_s cousins of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ not (yet) seen in experiment

The lightest $J^P = 0^+$ mesons

$D_0^*(2300)$ $I(J^P) = \frac{1}{2}(0^+)$ M.-L. Du *et al.*, PRL 126 192001 (2021)

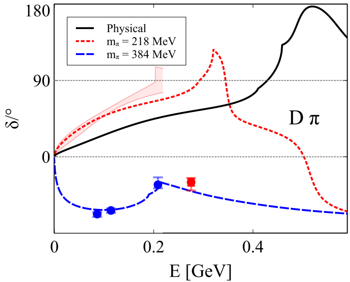
- Unitarized ChiPT leads to a much lower mass than indicated by the PDG
- Authors compare data from LHCb to PDG (Breit Wigner) and Unitarized ChiPT scenarios



- Recent Lattice QCD results from HSC also obtain a much lighter state
  HSC L. Gayer *et al.*, JHEP 07 (2021) 123

Physical predictions from EFT fits to lattice data

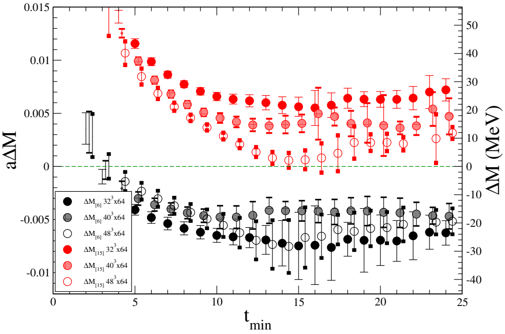
$D_0^*(2300)$ $I(J^P) = \frac{1}{2}(0^+)$ Guo, Heo, Lutz, PR**D** 98 014510 (2018)



- Low energy constants from fits to heavy-light ground-state masses and elastic phase-shift from Lattice QCD
- Chiral EFT bridges the gap between lattice data at unphysical pion masses and physical (coupled-channel) system
- Approach for future studies at GSI: Use EFT setup to arrive at predictions for physical coupled-channel scattering

An exotic state in the $D\pi$ system

Gregory, Guo, Hanhart, Krieg, Luu, arXiv:2106.15391



- Combined fits yield attraction for the [6] and repulsion for the [15]
- Authors argue this is evidence for the molecular picture
- pole position and its quark-mass dependence is left for the future

Predictions for the bottom-light and bottom-strange cousins

Fu, Grießhammer, Guo, Hanhart, Meißner, arXiv:2111.09481

- Updates and corrects previous mass estimates
- Updates the strong and radiative decays
- Shows consistency of the results with measured ratios of partial widths

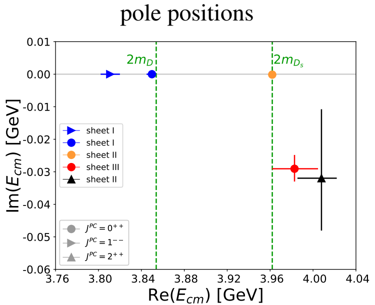
X.-Y. Guo and M.F.M. Lutz, PRD 104 054035 (2021)

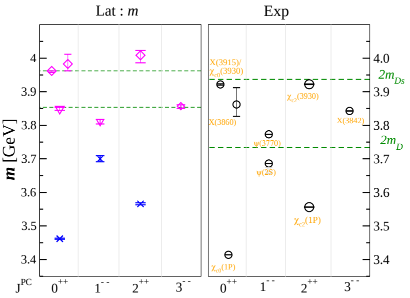
- Investigates impact of subleading-order chiral interactions
- Uses recent Lattice QCD input for masses and scattering phases in the charm sector to predict the bottom-light states

- LHCb is searching for the bottom-strange states
- $\bar{\text{P}}$ANDA should be able to determine the decay widths of the charm-strange positive parity states!

Charmonium(-like) resonances from Lattice QCD

S. Piemonte, DM *et al.* PRD 100 074505 (2019)
S. Prelovsek, DM *et al.* JHEP 06 035 (2021)

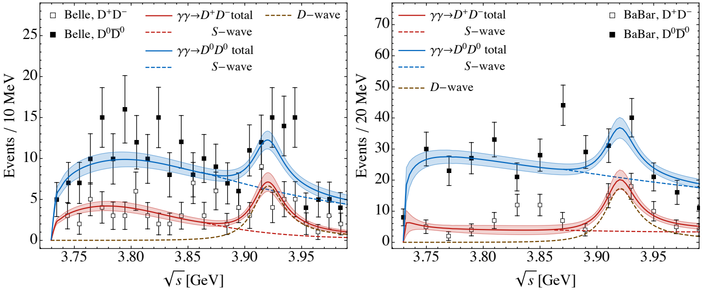




- Results suggest 3 charmonium(-like) states with $J^{PC}=0^{++}$ below ≈ 4.13 GeV (in addition to $\chi_{c0}(1P)$)
- We obtain various other states, some which previously uncertain quantum numbers
- Future studies need more physical masses / relax the assumptions that went into these results!

Dispersive analysis of $\gamma\gamma \to D\bar{D}$ data

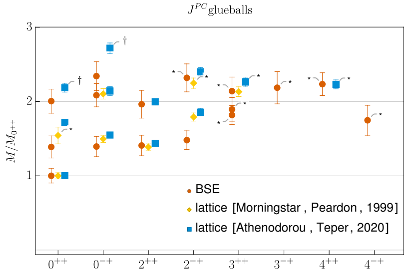
Deineka, Danilkin, Vanderhaeghen, arXiv:2111.15033



- Model-independent method based on unitarity and analyticity
- Describes published Belle data for angular distribution in $\gamma\gamma \to D\bar{D}$ and the $D\bar{D}$ invariant mass distribution in $e^+e^- \to J/\psi D\bar{D}$.
- Gives a strong indication for a $D\bar{D}$ bound state but does not need a broad resonance X(3860).
- Highlights the need for sophisticated analysis of experiment data!

Quenched glueballs from functional equations

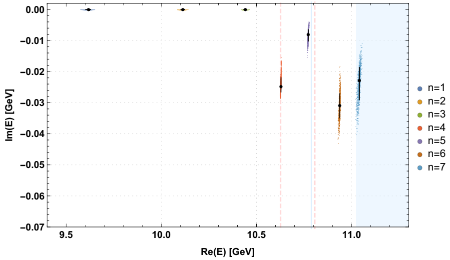
M.Q.Huber, C.S. Fischer, H. Sanchis-Alepuz, arXiv:2110.09180
and arXiv:2111.10197



- Results from self-consistently calculated two- and three-point functions
- The only free parameter is the gauge coupling
- Fully self-consistent calculation for the pseudoscalar glueball
- Neither the lattice nor the DS results account for decays
- High spin states interesting for searches at $\bar{\text{P}}$ANDA

Spectrum and composition of the $Y(nS)$ states

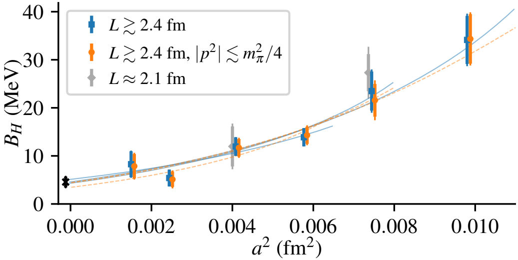
Bicudo, Cardoso, Müller, Wagner, PRD 103 074507 (2021)



- Uses Lattice QCD string-breaking potentials as input to a coupled-channel Schroedinger equation
- Results are for static b-quarks
- Qualitative pattern agrees with experiment and suggests four-quark nature of the $Y(10753)$ observed by Belle
- Can be extended to further quantum numbers and by calculating additional $N_f = 2 + 1$ Lattice QCD potentials

The H-Dibaryon: Progress and a word of caution

Green, Hanlon, Junnarkar, Wittig, arXiv:2103.01054



- First study of baryon-baryon scattering in the continuum limit
- Strategy: Global fits to the energy levels with parameterizations that account for discretization effects
- Binding energy at $SU(3)$ point with $m_\pi = 420$ MeV

$$B_H^{SU(3)_f} = 4.56 \pm 1.13 \pm 0.63 \text{ MeV}$$

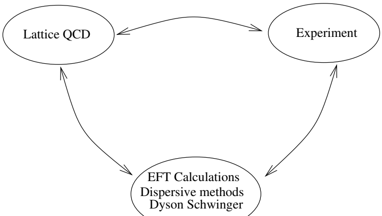
- Very large discretization effects in the binding energy!

Strategy and perspective – my own point of view

- Considerable experimental effort on hadron spectroscopy and interactions
- Examples covered highlight the need for a tight connection between theory and experiment
- Theory should strive to make predictions for new facilities.
- Spectroscopy input also needed for precision physics

How to arrive at emerging description from QCD?

- Direct lattice calculations for simple observables
- Use EFT, dispersion theory, functional methods to extent reach
- Test physical models



Backup slides

χ'_{c0}, $X(3915)$ and $X(3860)$: A bit of history

$X(3915)$ $I^G(J^{PC}) = 0^+(0 \text{ or } 2^{++})$

was $\chi_{c0}(3915)$

$\chi_{c0}(3860)$ $I^G(J^{PC}) = 0^+(0^{++})$

- The PDG used to interpret $X(3915)$ as a regular charmonium (χ'_{c0})
- The χ'_{c0} is expected to be broad, decaying into $D\bar{D}$

Guo, Meissner PRD 86, 091501 (2012)
Olsen, PRD 91 057501 (2015)

- The $X(3915)$ may instead be the already known spin-2 state

Zhou *et al.*, PRL 115 022001(2015)

- Observation of an alternative $\chi_{c0}(2P)$ by Belle:

Chilikin *et al.* PRD 95 112003 (2017)

$$M = 3862^{+26+40}_{-32-13}\ \text{MeV} \qquad \Gamma = 201^{+154+88}_{-067-82}\ \text{MeV}$$

- New observation by LHCb($\chi_{c0}(3930)$):

Aaij *et al.*, PRD 102 112003 (2020)

$$M = 3923.8 \pm 1.5 \pm 0.4\ \text{MeV} \qquad \Gamma = 17.4 \pm 5.1 \pm 0.8\ \text{MeV}$$