Excited QCD 2020
Krynica Zdrój

Exotic hadrons from functional methods

Wallbott, Eichmann and CF, PRD100 (2019) 014033, [1905.02615]
Wallbott, Eichmann and CF, in preparation
CF, Huber, Sanchis-Alepuz, in preparation
1. **Glueballs in Yang-Mills theory**

   CF, Huber, Sanchis-Alepuz, in preparation

2. **Quark masses and light meson spectroscopy**

   Williams, CF, Heupel, PRD93 (2016) 034026

3. **Heavy-light tetraquarks: X(3872) and more…**

   Wallbott, Eichmann and CF, in preparation
Glueballs

Lattice:
- States in the light and heavy quark energy regions
- Most calculations quenched
- Unquenched calculations very involved

DSE:
- structural information

Morningstar and Peardon, PRD 60 (1999) 034509
Y.-Chen et al., PRD 73 (2006) 014516
Gregory et al., JHEP 1210 (2012) 170

DSE:
- structural information

Meyers, Swanson, PRD 87 (2013) 3, 036009
Sanchis-Alepuz, CF, Kellermann and von Smekal, PRD 92 (2015) 3, 034001
\[ (-\frac{1}{2}) = (-\frac{1}{2}) + \frac{1}{2} \]

Huber, in preparation
Landau gauge - 3PI truncation

\[ A^{-1} = A^{-1} - \frac{1}{2} - \frac{1}{2} \]

\[ + A^{-1} - \frac{1}{2} \]

\[ - A^{-1} - A^{-1} \]

Huber, in preparation
Huber, in preparation
Landau gauge gluon propagator

\[ D_{\mu\nu}(p) = \left( \delta_{\mu\nu} - \frac{p_{\mu}p_{\nu}}{p^2} \right) \frac{Z(p^2)}{p^2} \]

- spacelike momenta: good agreement with lattice
  - fully dressed gluon appears massive
    - Cornwall PRD 26 (1982);
    - Cucchieri, Mendes PoS Lat2007 297
    - Aguilar, Binosi, Papavassiliou, PRD 78, 025010 (2008);
    - Boucaud et al. JHEP 0806 (2008) 099;

- time-like momenta: work in progress

DSE: Huber, in preparation
Lattice: Sternbeck et al.
Glueballs from DSE/BSEs

- Mixing of two-gluon amplitudes with ghost-antighost
- Probes analytical structure of gluons and ghosts

Meyers, Swanson, PRD 87 (2013) 3, 036009
Sanchis-Alepuz, CF, Kellermann and von Smekal, PRD 92 (2015) 3, 034001
Glueballs: results

Spin 0 glueballs

Lattice: Morningstar and Peardon, PRD 60 (1999) 034509
Y. Chen et al., PRD 73 (2006) 014516
BSE: CF, Huber, Sanchis-Alepuz, in preparation

Excellent agreement lattice vs. DSE/BSE

different internal structure
1. Glueballs in Yang-Mills theory

CF, Huber, Sanchis-Alepuz, in preparation

2. Quark masses and light meson spectroscopy

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3. Heavy-light tetraquarks: X(3872) and more…

Wallbott, Eichmann and CF, in preparation
Tetraquark candidates with cqq̅c-content

Many new unexpected states found: Belle, BABAR, BES, LHCb …
Tetraquark candidates with c\bar{c}q\bar{c}-content

Many new unexpected states found: Belle, BABAR, BES, LHCb ...

Internal structure ??

Related to details of underlying QCD forces between quarks and gluons
Tetraquark candidates with $qq\bar{q}\bar{q}$-content

Light scalar mesons:

$$
\begin{array}{cccccc}
[d\bar{s}] & [u\bar{s}] & [u\bar{u}/d\bar{d}] & [s\bar{s}] & [s\bar{u}/d\bar{d}] & [u\bar{d}]
\
\kappa^0(800) & \kappa^+(800) & a_0^0(980) & f_0(980) & f_0(500) & a_0^+(980)
\
\kappa^-(800) & \bar{\kappa}^0(800) & [d\bar{u}] & [s\bar{u}] & [s\bar{d}] & [u\bar{d}]
\end{array}
$$

Wrong level ordering

Tetraquark candidates with $qqq\bar{q}$-content

Light scalar mesons:

wrong level ordering

correct level ordering

Tetraquarks from the four-body equation

Exact equation:

Two-body interactions

Three- and four-body interactions

Heupel, Eichmann, CF, PLB 718 (2012) 545-549
Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Tetraquarks from the four-body equation

Exact equation:

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Three- and four-body interactions

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Tetraquarks from the four-body equation

Exact equation:

Two-body interactions: allow for internal clustering
use rainbow-ladder approximation...

Heupel, Eichmann, CF, PLB 718 (2012) 545-549
Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Structure of the amplitude

Scalar tetraquark:

\[ \Gamma(P, p, q, k) = \sum_i f_i(s_1, \cdots, s_9) \times \tau_i(P, p, q, k) \times \text{color} \times \text{flavor} \]

- 9 Lorentz scalars (built from \( P, p, q, k \))
- 256 tensor structures (scalar tetra)

\[ 3 \otimes \bar{3}, 6 \otimes \bar{6} \text{ or } 1 \otimes 1, 8 \otimes 8 \]

Reduce \# tensor structures guided by physics:

\[ \rightarrow \sim 20 \text{ tensor structures} \]
Singlet: \[ S_0 = \frac{p^2 + q^2 + k^2}{4} \]
Doublet: \[ s \sim p^2 + q^2 - 2k^2 \]
\[ a \sim q^2 - p^2 \]

\[ p, q, k: \text{relative momenta} \]

**Four-body equation: permutations**

- **Singlet:** \[ S_0 = \frac{(p^2 + q^2 + k^2)}{4} \]
- **Doublet:** \[ s \sim p^2 + q^2 - 2k^2 \]
  \[ a \sim q^2 - p^2 \]

- **Diquark pole**
- **Meson poles**

\[ p, q, k: \text{relative momenta} \]
Singlet: \[ S_0 = \left( p^2 + q^2 + k^2 \right)/4 \]

Doublet: \[ s \sim p^2 + q^2 - 2k^2 \]
\[ a \sim q^2 - p^2 \]

\( p, q, k \): relative momenta

diquark pole

meson poles
Singlet: \[ S_0 = \frac{(p^2 + q^2 + k^2)}{4} \]

Doublet:
\[ s \sim p^2 + q^2 - 2k^2 \]
\[ a \sim q^2 - p^2 \]

$p,q,k$: relative momenta

Diquark pole

Meson poles

"hadro charmonium"

"molecule"
Bound state vs resonance: scalar tetraquarks

$\Gamma(S_0, S, a, \ldots)$

without $\Xi$-clustering

0

1200

$M_{\text{Teta}} [\text{MeV}]$

Bound state of four massive quarks

Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Bound state vs resonance: scalar tetraquarks

$\Gamma(S_0, s, a, \ldots)$

without $\pi$-clustering

0 1200

with $\pi$-clustering

400

$M_{\text{Tetra}}[\text{MeV}]$

Two-pion resonance

Bound state of four massive quarks

Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Bound state vs resonance: scalar tetraquarks

\[ \Gamma(S_0, s, a, \ldots) \]

without \( \pi \)-clustering

Bound state of four massive quarks

identify with \( f_0(500) \) (‘\( \sigma \)-meson’)

Two-pion resonance

with \( \pi \)-clustering

\[ 0 \quad 400 \quad 1200 \]

\[ M_{Tetra}[MeV] \]

Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Bound state vs resonance: scalar tetraquarks

$\Gamma(S_0, s, a, \ldots)$

without $\pi\pi$-clustering

Bound state of four massive quarks

Two-pion resonance

identify with $f_0(500)$ (‘$\sigma$-meson’)

with strange quarks: $m_\kappa \sim 750\,\text{MeV}$

$ma_0, f_0 \sim 1080\,\text{MeV}$

Eichmann, CF; Heupel, PLB 753 (2016) 282-287
\[ J^P C = 1^{++} \]

\[ \begin{align*}
\mathcal{M}_{c\bar{q}\bar{q}c} & = 3916(74) \text{ MeV} \\
\mathcal{M}_{c\bar{s}\bar{s}c} & = 4068(61) \text{ MeV}
\end{align*} \]

- \( m_c \) fixed
- \( m_q \) varied

**DD* components dominate!**

\[ M_{1^{++}}^{c\bar{q}\bar{q}c} = 3916(74) \text{ MeV} \quad \rightarrow \quad X(3872) \]

Wallbott, Eichmann and CF, PRD100 (2019) 014033, [1905.02615]
$J^P_C = 1^{--}$ and $0^{++}$

$1(1^{+-}) \, cqq\bar{c}$

$M_{cq\bar{q}c}^{1^{+-}} = 3741(91) \rightarrow Z(3900)$

$M_{cq\bar{q}c}^{0^{++}} = 3195(107) \rightarrow \, ?$

mass pattern matches molecule picture of Cleven et al. PRD 92 (2015) 014005:
Open charm four-quark states

$0(1^+)\: cc\bar{q}\bar{q}$

- $m_D + m_{D^*}$
- $DD^*$
- $DD^* + AS$
- $DD^* + AS + D^*D^*$

$1(1^+)\: cc\bar{q}\bar{q}$

- $m_D + m_{D^*}$
- $DD^*$
- $DD^* + AA$

$1(0^+)\: cc\bar{q}\bar{q}$

- $m_D + m_{D^*}$
- $DD^* + D^*D^* + AA$

- DD(*) and diquarks important!
Internal dynamics very important!!

Glueballs:
- First quantitatively reliable results using very involved truncation
  (Wallbott, Eichmann and CF, PRD100 (2019) 014033, [1905.02615])
  First results in open charm channels

Four-quark states:
- Closed flavor states dominated by meson-meson clusters
  (diquarks are almost irrelevant!)
- Dynamical description of $\sigma$: $\pi\pi$ resonance
  (Eichmann, CF, Heupel, PLB 753 (2016) 282-287)
- Dynamical description of $X(3872)$ and $Z(3900)$: $DD^*$ dominated

Glueballs:
- First quantitatively reliable results using very involved truncation
  (Wallbott, Eichmann and CF, PRD100 (2019) 014033, [1905.02615])

Summary

First results in open charm channels
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
42nd Course

QCD under extreme conditions

- from heavy-ion collisions to the phase diagram

Erice-Sicily: September 16-24, 2020

Directors of the school
Michael Buballa, Amand Faessler, and Christian Fischer

- Phase diagram and equation of state of strong interaction matter
- Phenomenology and size dependence of high-energy nuclear collisions
- Lattice and continuum approaches to hot and dense QCD
- Search for the QCD critical end point
- Electromagnetic probes and spectral functions of hadrons in nuclear matter
- Quarkonia and open heavy flavors
- Particle correlations and fluctuations
- Nuclei, hyper-nuclei and exotica in heavy ion collisions
- Jets, parton energy loss, and parton-medium interactions
- QCD in large external magnetic fields and in rotating systems
- Phase transitions in binary star mergers
- Future hadron and lepton colliders
Structure of the amplitude

Scalar tetraquark:

\[\Gamma(P, p, q, k) = \sum_i f_i(s_1, \cdots, s_9) \times \tau_i(P, p, q, k) \times \text{color} \times \text{flavor}\]

- 9 Lorentz scalars (built from $P, p, q, k$)
- 256 tensor structures (scalar tetra)
- Reasonable approximation: keep s-waves only; $\rightarrow 16$ tensor structures
- $\Gamma(P, p, q, k) \rightarrow \Gamma(S_0, s, a, \ldots)$
1. Glueballs in Yang-Mills theory

CF, Huber, Sanchis-Alepuz, in preparation

2. Quark masses and light meson spectroscopy

Williams, CF, Heupel, PRD93 (2016) 034026

3. Heavy-light tetraquarks: X(3872) and more...

Wallbott, Eichmann and CF, in preparation
Properties of QCD: Dynamical mass generation

\[ m_{\text{proton}} = 938 \text{ MeV} \]

Dynamical quark masses via weak force

<table>
<thead>
<tr>
<th>quarks</th>
<th>u</th>
<th>d</th>
<th>s</th>
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</tr>
</thead>
<tbody>
<tr>
<td>( M_{\text{weak}} ) [MeV]</td>
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Properties of QCD: Dynamical mass generation

Dynamical quark masses via weak force and strong force:

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Yoichiro Nambu, Nobel prize 2008
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Yoichiro Nambu, Nobel prize 2008
Dyson-Schwinger equations - “3PI vs RL”

\[
Z_{QCD} = \int \mathcal{D}[\Psi, A] \exp \left\{ \frac{1}{4} \left( F_{\mu\nu}^a \right)^2 \right\}
\]

propagators

\[
\begin{align*}
\begin{array}{c}
\begin{array}{c}
-1 \\
\end{array}
\end{array}
\end{align*}
\quad = \quad
\begin{align*}
\begin{array}{c}
\begin{array}{c}
-1 \\
\end{array}
\end{array}
\end{align*}

\quad - \quad
\begin{align*}
\begin{array}{c}
\begin{array}{c}
\text{vertex}
\end{array}
\end{array}
\end{align*}
\]

CF, Alkofer, PRD67 (2003) 094020
Williams, CF, Heupel, PRD93 (2016) 034026
Huber, EPJ C77 (2017) no.11, 733
Dyson-Schwinger equations - “3PI vs RL”

\[
Z_{QCD} = \int D[\Psi, A] \exp \left\{ - \int d^4x \left( \bar{\Psi} i\gamma^\mu - m \right) \Psi - \frac{1}{4} (F_{\mu\nu}^a)^2 \right\}
\]

propagators

\begin{align*}
-1 & = -1 \\
\frac{1}{2} & = \frac{1}{2} \\
-\frac{1}{6} & = -\frac{1}{2}
\end{align*}

CF, Alkofer, PRD 67 (2003) 094020
Williams, CF, Heupel, PRD 93 (2016) 034026
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\[ Z_{QCD} = \int \mathcal{D}[\Psi, A] \exp \left\{ -\int d^4x \left( \bar{\Psi} (i\not{D} - m) \Psi - \frac{1}{4} (F_{\mu\nu}^a)^2 \right) \right\} \]

propagators

\[ = \quad = \quad = \]

vertices

\[ = + \quad = -2 \]

\[ = + \quad = \text{perm.} \]

CF, Alkofer, PRD67 (2003) 094020
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propagators

\[
\begin{align*}
\frac{1}{\pi} & = \frac{1}{\pi} - \frac{1}{\pi} \\
\frac{1}{6} & = \frac{1}{6} - \frac{1}{2} \\
\frac{1}{2} & = \frac{1}{2} - \frac{1}{2} \\
\frac{1}{2} & = \frac{1}{2} - \frac{1}{2} \\
\end{align*}
\]

vertices

\[
\begin{align*}
\frac{1}{2} & = \frac{1}{2} + \frac{1}{2} \\
\frac{1}{2} & = \frac{1}{2} + \frac{1}{2} \\
\frac{1}{2} & = \frac{1}{2} + \frac{1}{2} \\
\frac{1}{2} & = \frac{1}{2} + \frac{1}{2} \\
\end{align*}
\]

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Dyson-Schwinger equations - “3PI vs RL”

\[
\mathcal{Z}_{QCD} = \int \mathcal{D}[\Psi, A] \exp \left\{ -\int d^4x \left( \bar{\Psi} (i\gamma^\mu D_\mu - m) \Psi - \frac{1}{4} (F_{\mu\nu}^a)^2 \right) \right\}
\]

propagators

\[
\begin{align*}
-1 & = -1 \\
\text{vertices} & = -1 \\
\text{vertices} & = 1 - \frac{1}{2} \\
\text{vertices} & = -\frac{1}{6} \\
\text{vertices} & = -\frac{1}{2} \\
\text{vertices} & = -1
\end{align*}
\]

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propagators

-1 = \ \ \ \ \ -1

vertices

“rainbow-ladder” (RL) : model for gluon+vertex

\[ \begin{array}{c}
-1 \\
\text{\begin{array}{c}
-1 \text{ (3PI)} \\
\quad\quad \text{=} \\
\quad\quad \text{=}
\end{array}}
\end{array} \]

\[ \text{\begin{array}{c}
-2 \quad + \\
\text{\begin{array}{c}
\quad + \\
\quad + \\
\quad +
\end{array}}
\end{array}} \quad + \text{perm.} \]

CF, Alkofer, PRD67 (2003) 094020
Williams, CF, Heupel, PRD93 (2016) 034026
Huber, EPJ C77 (2017) no.11, 733
Quarks: mass from interaction

\[ S(p) = Z_f(p^2) \frac{-i\mathbf{p}^2 + M(p^2)}{p^2 + M^2(p^2)} \]

‘constituent quark’: large mass; very composite

‘current quark’: - small mass; non-composite
‘constituent quark’:
large mass; very composite

‘current quark’:
- small mass; non-composite

\[ Z_f(p^2) \frac{-i\gamma + M(p^2)}{p^2 + M^2(p^2)} \]

Quark Mass Function: \( M(p^2) \) [GeV]

- Bottom quark
- Charm quark
- Strange quark
- Up/Down quark
- Chiral limit

\( M(p^2) = Z_f(p^2) \frac{-i\gamma + M(p^2)}{p^2 + M^2(p^2)} \)

Williams, EPJ C 60 (2009) 47
Heupel, PRD 93 (2016) 034026
Theoretical Tools: DSEs and BSEs

Kernel K uniquely related to quark-DSE via axWTI

→ Pion is bound state and Goldstone boson

Maris, Roberts, Tandy, PLB 420 (1998) 267

- Determine gauge invariant spectrum from underlying, gauge dependent quark/gluon dynamics
**Light meson spectrum - full 3PI-calculation**

- **m [GeV]**

- **π(1300)**
  - **ρ(1450)**
  - **a_0(1450)**
  - **b_1(1235)**
  - **a_1(1260)**

- **π_1(1600)**
- **π_1(1400)**

- **ρ**
- **π**

- **J^{PC}**

- **0−+**
- **1−−**
- **0++**
- **1++**
- **0−−**
- **0++**
- **1−+**

- **good agreement with experiment in most channels**
- **special channels:**
  - **pseudoscalar** 0−+: (pseudo-) Goldstone bosons
  - **scalar** 0++: complicated channel…

*Experiment our results*

*PDG*
*3PI-3L*
*2PI-3L*

*Williams, CF, Heupel, PRD93 (2016) 034026*
spectrum in one to one agreement with experiment
• correct level ordering (without coupled channel effects...)

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
spectrum in one to one agreement with experiment
correct level ordering (without coupled channel effects...)
three-body agrees with diquark-quark-quark where applicable
zero crossing of wave function: 2s-state

every state is mixture of several partial waves!
different internal structure of radial excitations

tension with simpler calculations ('contact interaction', 'quark-diquark model'):
Wilson, Cloet, Chang and Roberts, PRC 85 (2012) 025205,
Segovia, El-Bennich, Rojas, Cloet, Roberts, Xu and Zong, PRL 115 (2015) 17
Lu, Chen, Roberts et al., PRC 96 (2017) 015208
Strange baryon spectrum: DSE-RL (preliminary !)
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\[ \begin{array}{c}
\Lambda(1115) \\
\Lambda(1810) \\
\Lambda(1800) \\
\Lambda(1600) \\
\Lambda(1670) \\
\Lambda(1405) \\
\Lambda(1890) \\
\Lambda(1690) \\
\Lambda(1520) \\
\frac{3}{2}^+ \\
\frac{3}{2}^- \\
\frac{3}{2}^+ \\
\frac{3}{2}^- \\
\frac{3}{2}^+ \\
\frac{3}{2}^- \\
\Omega(2470)? \\
\Omega(2250)? \\
\Omega(2380)? \\
\end{array} \]
Strange baryon spectrum: DSE-RL (preliminary !)

New states: Bonn-Gatchina (talk of M. Matveev)
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Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
CF, Eichmann PoS Hadron 2017 (2018) 007
Sanchis-Alepuz, CF, PRD 90 (2014) 096001
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