



Multiquark states with functional methods

Gernot Eichmann

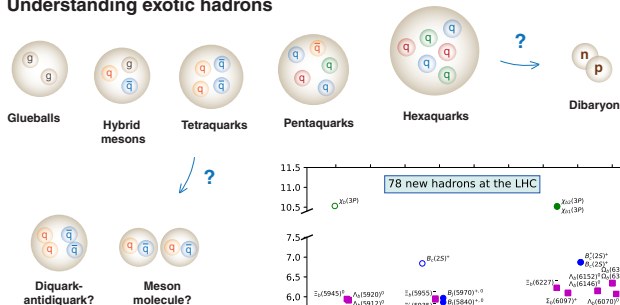
University of Graz

**ACHT 2025: Non-perturbative methods in
strongly interacting quantum many-body systems**

Budapest, Hungary, May 6, 2025

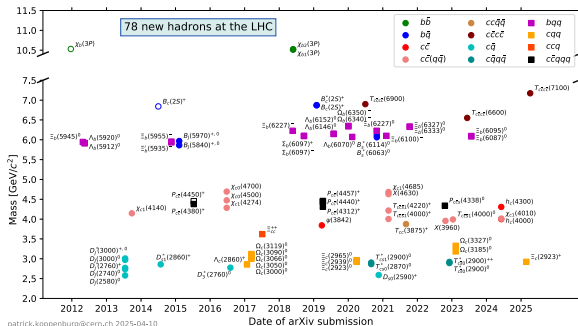
Motivation

• Understanding exotic hadrons



• New four-quark states:

Open-charm T_{cc}^+ (3875),
all-charm $T_{cc\bar{c}\bar{c}}$ (6600),
hidden-charm & open-strange, ...

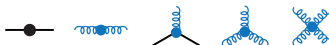


patrick.koppenburg@cern.ch 2025-04-10

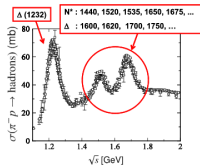
<https://www.nikhef.nl/~pkoppenburg/particles.html>
<https://qwgh.ph.nat.tum.de/exoticschub>

Theory tools

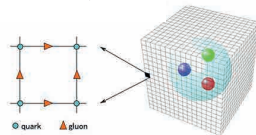
Functional methods (DSEs & BSEs, FRG, ...)



Amplitude analyses



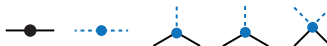
Lattice QCD



Phenomenological models

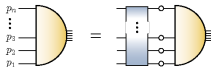


Effective theories (ChPT, ...)



Functional methods

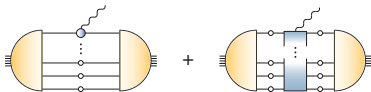
- Hadronic **bound-state equations**
(Bethe-Salpeter & Faddeev eqs)



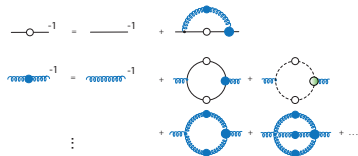
“QFT analogue of Schrödinger eq.”

- hadron masses & “wave functions”
- **spectroscopy calculations**

- **Structure calculations:**
form factors, PDFs, GPDs, TMDs,
two-photon processes, ...

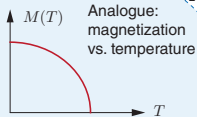


- Ingredients: **QCD's n-point functions**,
computed from DSEs (quantum eqs. of motion)
or FRG (functional renormalization group)



- Dynamical mass generation,
gluon mass gap, confinement,
QCD phase diagram, ...

Functional methods



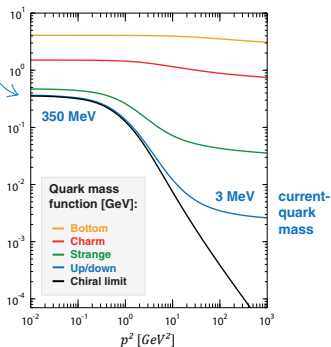
- Ingredients: **QCD's n-point functions**,
Satisfy quantum eqs. of motion (DSEs)

Quark mass

$$\begin{aligned}
 \text{---} \circ^{-1} &= \text{---}^{-1} + \text{---} \circ \text{---} \\
 \text{---} \bullet \text{---}^{-1} &= \text{---} \bullet \text{---}^{-1} + \text{---} \circ \text{---} + \text{---} \bullet \text{---} \\
 &\vdots
 \end{aligned}$$

The diagrams represent quark self-energy corrections. The first equation shows a bare quark line with a self-energy loop. The second equation shows a quark line with a self-energy loop and a gluon exchange loop. The third equation shows a quark line with a self-energy loop and a gluon exchange loop, plus a quark line with a self-energy loop and a gluon exchange loop, plus a quark line with a self-energy loop and a gluon exchange loop, plus ...

"constituent-quark mass"



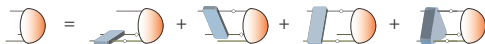
→ Dynamical mass generation,
gluon mass gap, confinement, ...



Baryons

Three-quark BSE (Faddeev equation) for baryons:

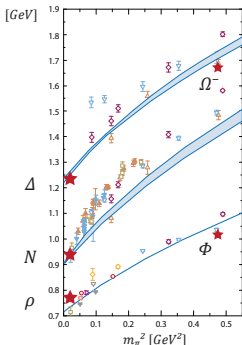
GE, Alkofer, Nicmorus, Krassnigg, PRL 104 (2010)



2-body kernel:
fixed in meson sector

3-body kernel:

Leading diagram (3-gluon vertex)
vanishes by color trace,
higher-order diagrams small (?)
2-quark correlations dominant?



- Analogous results for many **form factors**

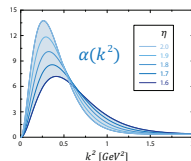
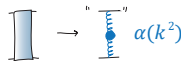
Review: GE, Sanchis-Alepuz, Williams, Alkofer, Fischer,
Prog. Part. Nucl. Phys. 91 (2016)

- Relativistically, nucleon also has **p waves!**

L = 0

L = 1

Rainbow-ladder



Scale set by f_π ,
shape parameter $\rightarrow$ bands

Maris, Tandy, PRC 60 (1999)

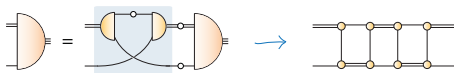
see also:

Qin, Roberts, Schmidt,
PRD 97 (2018)

Diquark correlations

- Quark-diquark** (two-body) equation

Oettel et al., PRC 58 (1998), GE et al., Ann. Phys. 323 (2008), Cloet et al., FBS 46 (2009), Segovia et al., PRL 115 (2015)



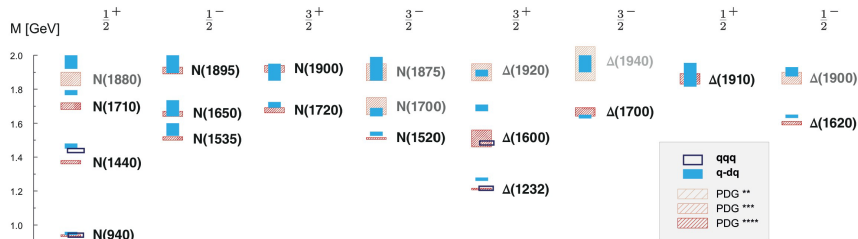
Diquark clustering in baryons?

Barabanov et al., Prog. Part. Nucl. Phys. 116 (2021)



- Three-quark** and **quark-diquark** results very similar

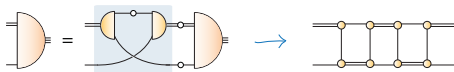
GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)



Diquark correlations

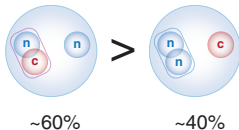
- Quark-diquark** (two-body) equation

Oettel et al., PRC 58 (1998), GE et al., Ann. Phys. 323 (2008), ...



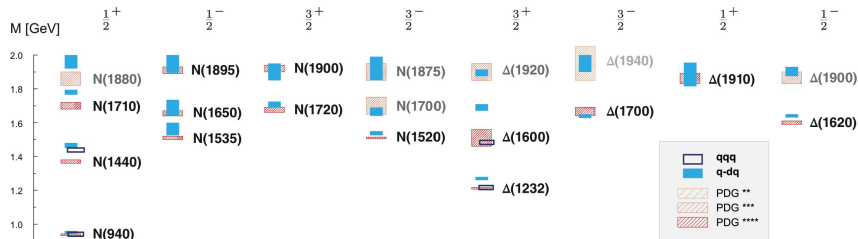
Heavy baryons

Torcato, Arriaga, GE, Peña, FBS 64 (2023)



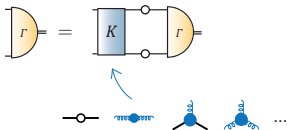
- Three-quark** and **quark-diquark** results very similar

GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)



Towards ab-initio

- **Goal:** go towards ab-initio calculations by calculating **higher n-point functions**



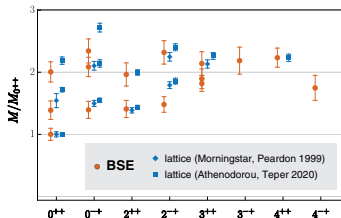
...
 Williams, Fischer, Heupel, PRD 93 (2016),
 Cyrol et al., PRD 97 (2018),
 Oliveira, Silva, Skullerud, Sternbeck, PRD 99 (2019),
 Aguilar et al., EPJ C 80 (2020),
 Huber, PRD 101 (2020),
 Qin, Roberts, Chin. Phys. Lett. 38 (2021),
 GE, Pawłowski, Silva, PRD 104 (2021),
 ...

truncation error:

1 60% **2** 10% **3** 4%

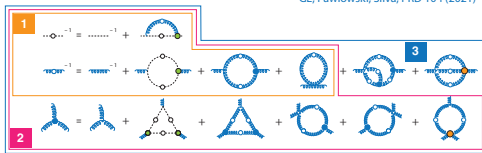
- **Glueball spectrum** agrees with lattice QCD

Huber, Fischer, Sanchis-Alepuz, EPJ C 80 (2020), EPJ C 81 (2021)



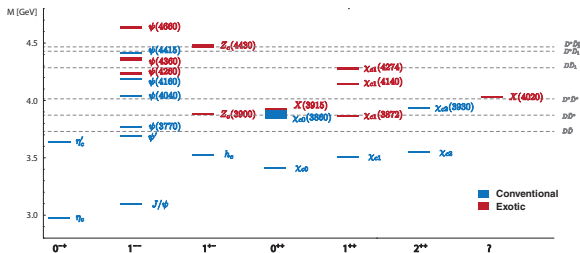
- **Coupled Yang-Mills DSEs**

Huber, PRD 101 (2020),
 GE, Pawłowski, Silva, PRD 104 (2021)



→ see seminar by Markus Huber

Exotic mesons



Reviews:

Chen, Chen, Liu, Zhu,
Phys. Rept. 639 (2016), 1601.02092

Lebed, Mitchell, Swanson
PPNP 93 (2017), 1610.04528

Esposito, Pilloni, Polosa,
Phys. Rept. 668 (2017), 1611.07920

Guo, Hanhart, Meißner et al.,
Rev. Mod. Phys. 90 (2018), 1705.00141

Ali, Lange, Stone,
PPNP 97 (2017), 1706.00610

Olsen, Skwarnicki, Zieminska,
Rev. Mod. Phys. 90 (2019), 1708.04012

Liu, Chen, Chen, Liu, Zhu,
PPNP 107 (2019), 1903.11976

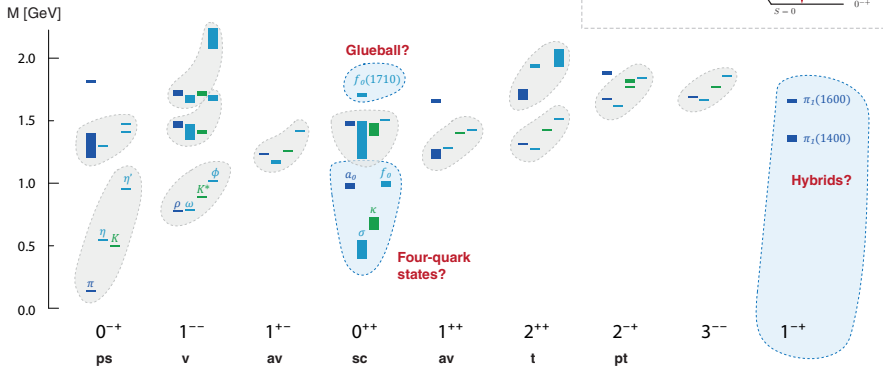
Brambilla, Eidelman, Hanhart et al.,
Phys. Rept. 873 (2020)

...

- Several tetraquark candidates in **charmonium spectrum**: $X(3872)$, $X(3915)$, $Z_c(3900)$,
- Z states cannot be $c\bar{c}$ since they carry charge
- Recent additions: all-charm $X(6900)$, open-charm T_{cc}^+ , ...
- Oldest tetraquark candidates: **light scalar mesons**

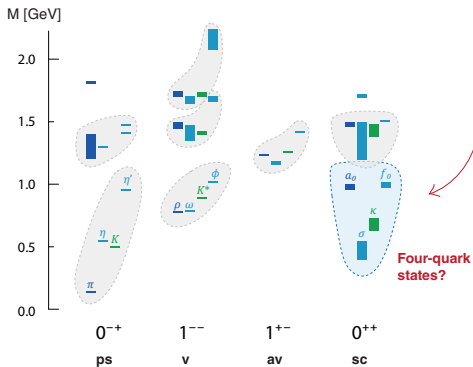
Light exotic mesons

Light meson spectrum
(PDG 2020)



Light exotic mesons

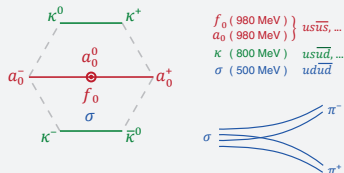
Light meson spectrum (PDG 2020)



• Diquark-antidiquark?

Explains mass ordering & decay widths

Jaffe 1977, Close, Tornqvist 2002,
Maiani, Polosa, Riquer 2004



• Meson molecules?

Weinstein, Isgur 1982, 1990; Close, Isgur, Kumano 1993

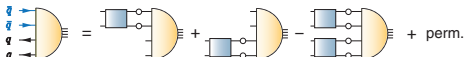
• Non- $q\bar{q}$ nature supported by various approaches

Pelaez, Phys. Rept. 658 (2016)

Four-quark states

- Light scalar mesons (σ , κ , a_0 , f_0) as **four-quark states**:

GE, Fischer, Heupel, PLB 753 (2016)



$$\Gamma(p, q, k, P) = \sum_i f_i(p^2, q^2, k^2, \{\omega_j\}, \{\eta_j\}) \tau_i(p, q, k, P) \otimes \text{Color} \otimes \text{Flavor}$$

9 Lorentz invariants:

$$p^2, \quad q^2, \quad k^2, \quad P^2 = -M^2$$

$$\omega_1 = q \cdot k \quad \eta_1 = p \cdot P$$

$$\omega_2 = p \cdot k \quad \eta_2 = q \cdot P$$

$$\omega_3 = p \cdot q \quad \eta_3 = k \cdot P$$

256 Dirac-Lorentz tensors

2 Color tensors:

$$3 \otimes \bar{3}, \quad 6 \otimes \bar{6} \quad \text{or}$$

$$1 \otimes 1, \quad 8 \otimes 8$$

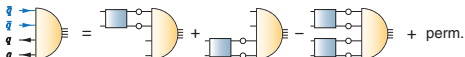
(Fierz-equivalent)

		dim K	memory
$K \psi_i = \lambda_i \psi_i$	Mesons	10^3	20 MB
	Baryons	10^8	10^7 GB
	Tetraquarks	10^{13}	10^{18} GB

Four-quark states

- Light scalar mesons (σ , κ , a_0 , f_0) as **four-quark states**:

GE, Fischer, Heupel, PLB 753 (2016)



$$\Gamma(p, q, k, P) = \sum_i f_i(p^2, q^2, k^2, \{\omega_j\}, \{\eta_j\}) \tau_i(p, q, k, P) \otimes \text{Color} \otimes \text{Flavor}$$

9 Lorentz invariants:

$$p^2, \quad q^2, \quad k^2, \quad P^2 = -M^2$$

$$\omega_1 = q \cdot k \quad \eta_1 = p \cdot P$$

$$\omega_2 = p \cdot k \quad \eta_2 = q \cdot P$$

$$\omega_3 = p \cdot q \quad \eta_3 = k \cdot P$$

256 Dirac-Lorentz tensors

2 Color tensors:

$$3 \otimes \bar{3}, \quad 6 \otimes \bar{6} \quad \text{or}$$

$$1 \otimes 1, \quad 8 \otimes 8$$

(Fierz-equivalent)

- Group momentum variables into multiplets of **permutation group S4**:
can switch off groups of variables without destroying symmetries

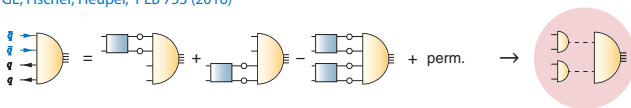
GE, Fischer, Heupel, PRD 92 (2015)

$$f_i(\mathcal{S}_0, \nabla, \triangle, \circ)$$

Four-quark states

- Light scalar mesons (σ , κ , a_0 , f_0) as **four-quark states**:

GE, Fischer, Heupel, PLB 753 (2016)



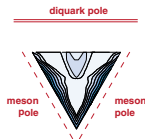
- BSE dynamically generates **meson poles** in BS amplitude:

$$f_i(S_0, \nabla, \triangle, \circ) \rightarrow 1500 \text{ MeV}$$

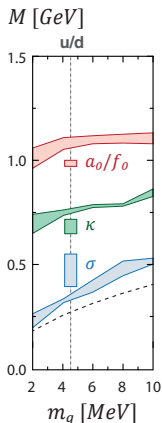
$$f_i(S_0, \nabla, \triangle, \circ) \rightarrow 1500 \text{ MeV}$$

$$f_i(S_0, \nabla, \triangle, \circ) \rightarrow 1200 \text{ MeV}$$

$$f_i(S_0, \nabla, \triangle, \circ) \rightarrow \mathbf{350 \text{ MeV !}}$$



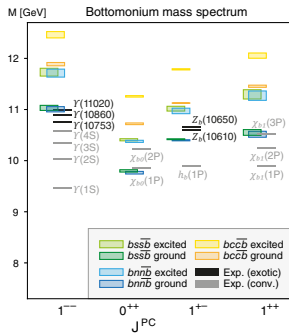
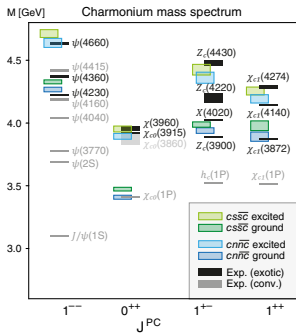
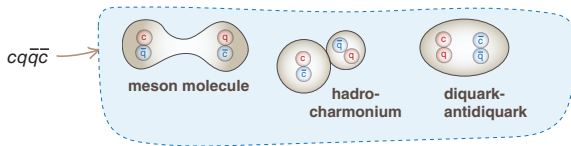
- "Light scalar mesons" look like **meson molecules**, diquark-antidiquark components almost negligible. Lightness is inherited from pseudoscalar Goldstone bosons!



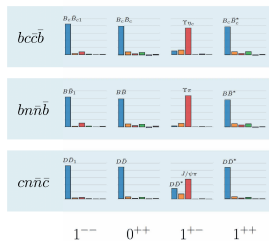
Four-quark states

Hidden charm, hidden bottom

Hoffer, GE, Fischer,
PRD 109 (2024)



Wave-function components:



Four-quark states

Open-flavor states

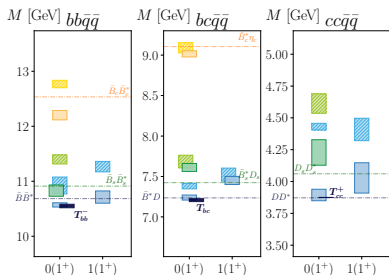
Hoffer, GE, Fischer,
PRD 111 (2025)



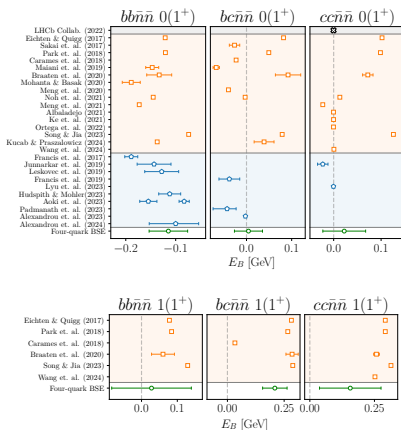
meson molecule



diquark-antidiquark



Binding energies (ground states):



Four-quark states

Open-flavor states

Hoffer, GE, Fischer,
PRD 111 (2025)

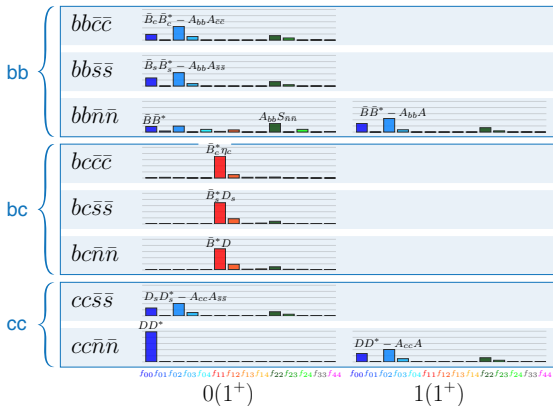


meson molecule



diquark-antidiquark

Wave-function components:



$I(J^P)$	Physical components					
	$1 \otimes 1$		$\bar{3} \otimes 3$	$8 \otimes 8$		$\bar{6} \otimes 6$
	f_0	f_1	f_2	f_3	f_4	f_5
$0(1^+) b\bar{b}n\bar{n}$	$B\bar{B}^*$	$B^* \bar{B}^*$	$A_{bb}S$	$B\bar{B}^*$	$B^* \bar{B}^*$	$S_{bb}A$
$b\bar{c}n\bar{n}$	$B\bar{D}^*$	$B^* \bar{D}^*$	$A_{bc}S$	$B\bar{D}^*$	$B^* \bar{D}^*$	$S_{bc}A$
$c\bar{c}n\bar{n}$	$D\bar{D}^*$	$D^* \bar{D}^*$	$A_{cc}S$	$D\bar{D}^*$	$D^* \bar{D}^*$	$S_{cc}A$
$b\bar{b}s\bar{s}$	$B_s\bar{B}_s^*$	—	$A_{bb}A_{ss}$	$B_s\bar{B}_s^*$	—	—
$b\bar{c}s\bar{s}$	$B_s\bar{D}_s^*$	$B_s^* \bar{D}_s^*$	$S_{bc}A_{ss}$	$B_s\bar{D}_s^*$	$B_s^* \bar{D}_s^*$	$A_{bc}S_{ss}$
$c\bar{c}s\bar{s}$	$D_s\bar{D}_s^*$	—	$A_{cc}A_{ss}$	$D_s\bar{D}_s^*$	—	—
$1(1^+) b\bar{b}q\bar{q}$	$B\bar{B}^*$	—	$A_{bb}A$	$B\bar{B}^*$	—	—
$c\bar{c}q\bar{q}$	$D\bar{D}^*$	—	$A_{cc}A$	$D\bar{D}^*$	—	—

→ T_{bb} is complicated mixture of molecule and diquark-antidiquark

Can **quantify** meson-meson and diquark-antidiquark contributions

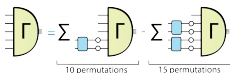
→ T_{cc} sits on top of threshold, pure molecule

Other recent developments

- Five-body equations**

GE, Torres, PRD xx (2025)

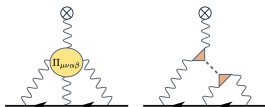
GE, Peña, Torres, PLB xx (2025)



→ see talk by Raúl Torres

- Axial & scalar $\rightarrow \gamma\gamma$ contributions to muon g-2**

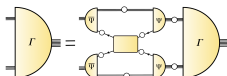
GE, Fischer, Häuser, Regenfelder, EPJ C 85 (2025)



- Structure of the deuteron**

Arriaga, GE, Nunes, Peña, Stadler,

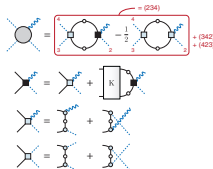
in preparation



- Timelike form factor**

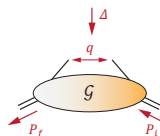
$\gamma^* \pi \rightarrow \pi \pi$

Miramontes, GE, Alkofer, 2504.20899



- Hadron structure: PDFs & TMDs**

GE, Ferreira, Stadler, in preparation



$$\mathcal{G}(z, P, \Delta) = \langle P_f | T \Phi(z) \mathcal{O} \Phi(0) | P_i \rangle$$

→ see talk by Eduardo Ferreira

840. Wilhelm and Else Heraeus Seminar on Real-Time and Non-Equilibrium QFT

Oberwölz, Austria, Sep 1 - 5, 2025

<https://indico.global/event/11677>

Key speakers:

Jürgen Berges (University of Heidelberg)
David Blaschke (University of Wrocław)
Kirill Boguslavski (TU Vienna)
Stefan Flörchinger (University of Jena)
Tobias Frederico (ITA, Sao Paulo)
Jana Günther (University of Wuppertal)
Julia Harz (Johannes Gutenberg University of Mainz)
Andreas Ipp (TU Vienna)
Karl Jansen (DESY Zeuthen)
Sonia Kabana (University of Tarapacá)
Maria Lombardo (INFN Florence)
Jan Pawłowski (University of Heidelberg)
Lorenz von Smekal (University of Gießen)

Registration open until June 15, 2025

Organizers: Gernot Eichmann, Reinhard Alkofer,
Markus Huber, Willibald Plessas, Dénes Sexty



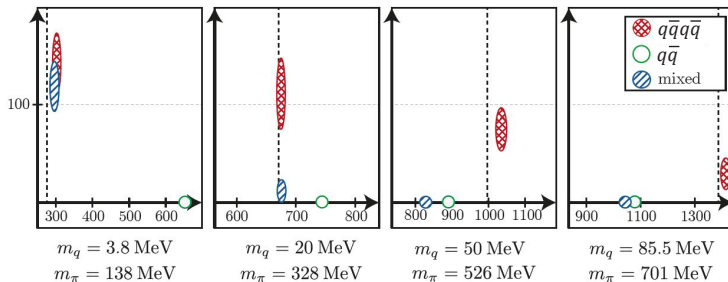
Thank you!

Backup slides

Four-quark states

Four-quark vs. $q\bar{q}$ dominance

Santowsky, Fischer, PRD 105 (2022)

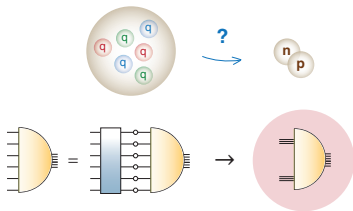


Light quarks:
 $\pi\pi$ dominant

Strange quarks:
 $q\bar{q}$ dominant

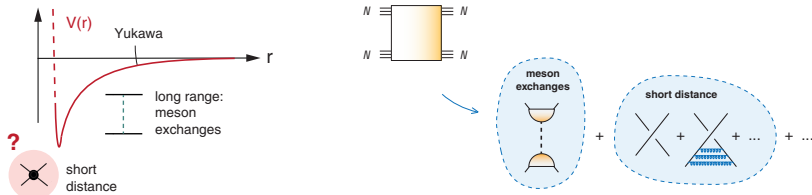
Nucleons in nuclei?

Transition from quarks & gluons to **light nuclei**:

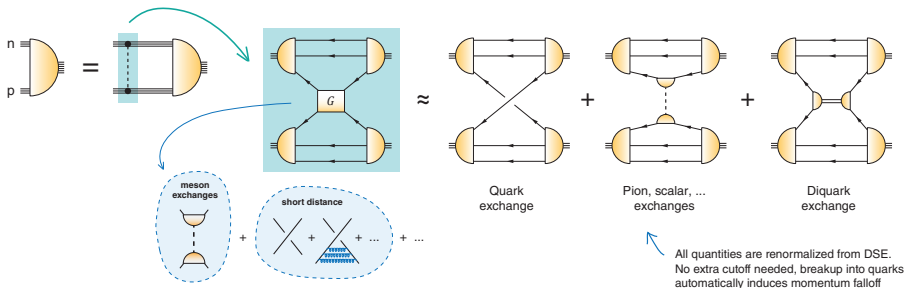


- Relativistic structure of **deuteron**?
- Exotic dibaryons, hypernuclei, short-range correlations, EMC effect ...

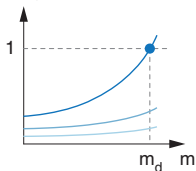
Microscopic origins of **short-range nuclear force**?



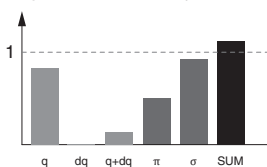
Deuteron



Eigenvalue (sketch)



Eigenvalue at $m = m_d$



Diquark exchange is repulsive, almost cancels quark exchange!

preliminary

Arriaga, GE, Nunes, Peña, in preparation

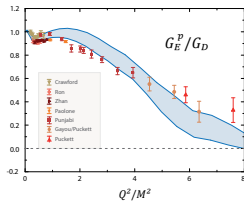
OAM composition:



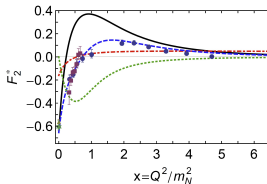
The deuteron is relativistic!

Baryon structure

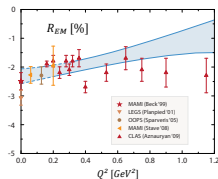
Nucleon electromagnetic FFs
GE, PRD 84 (2011)



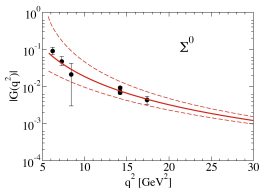
Roper em. transition FFs
Segovia et al., PRL 115 (2015)



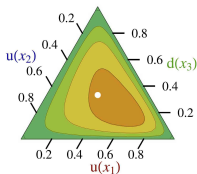
Δ em. transition FFs
GE, Nicmorus, PRD 85 (2012)



Timelike em. strangeness FFs
Ramalho, Peña, PRD 101 (2020)



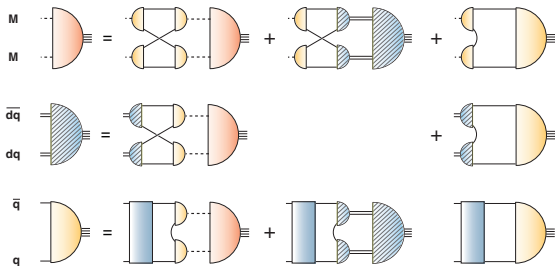
Distribution amplitudes
Mezrag, Segovia, Chang, Roberts, PLB 783 (2018)



Four-quark states

Two-body formulation: **meson-meson / diquark-antidiquark**, follows from four-quark eq. (analogue of quark-diquark for baryons)

Heupel, GE, Fischer, PLB 718 (2012)

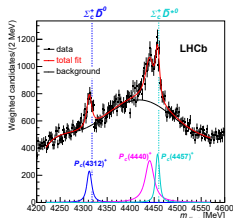


Include **mixing with $q\bar{q}$** :
 $\pi\pi$ still dominant

Santowsky, GE, Fischer, Wallbott,
 Williams, PRD 102 (2020)

[MeV]	ground state mass	first excitation
$\pi\pi$	416 ± 26	970 ± 130
$\pi\pi + 0^+0^+$	416 ± 26	970 ± 130
$q\bar{q}$	667 ± 2	1036 ± 8
$\pi\pi + q\bar{q}$	472 ± 22	1080 ± 280
$\pi\pi + 0^+0^+ + q\bar{q}$	456 ± 24	1110 ± 110

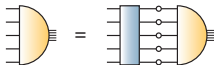
Pentaquarks?



Aaij et al., PRL 112 (2019)

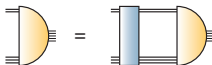
- 5-body equation:** in progress

GE, Peña, Torres, in preparation

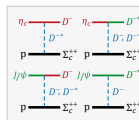
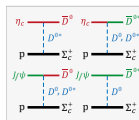
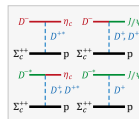
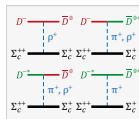
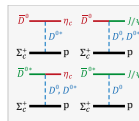
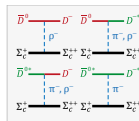
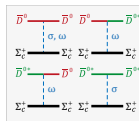


- Meson-baryon equation with hadronic exchanges**

GE, Lourenco, Peña, Stadler, Torres, in preparation



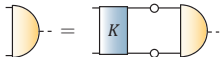
... all couplings calculated dynamically



Diquark correlations

Mesons and diquarks closely related through BSE

Maris, FBS 32 (2002)

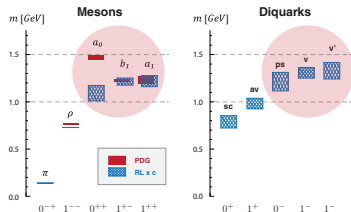


Lowest-lying diquarks are dominant for ground-state octet & decuplet baryons

pseudoscalar mesons $\Leftrightarrow$ **scalar diquarks** (~ 0.8 GeV)
vector mesons $\Leftrightarrow$ **axialvector diquarks** (~ 1 GeV)

Higher-lying diquarks are subleading, but contribute to excited states & remaining channels

scalar mesons $\Leftrightarrow$ **pseudoscalar diquarks** (~ 1.2 GeV)
axialvector mesons $\Leftrightarrow$ **vector diquarks** (~ 1.3 GeV)



In RL, these are too strongly bound; simulate beyond-RL effects by (one) strength parameter c

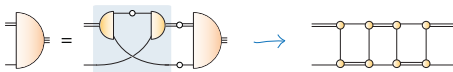
Roberts, Chang, Cloet, Roberts, FBS 51 (2011)

GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)

Diquark correlations

- Quark-diquark (two-body) equation**

Oettel et al., PRC 58 (1998), GE et al., Ann. Phys. 323 (2008), Cloet et al., FBS 46 (2009), Segovia et al., PRL 115 (2015), Chen et al., PRD 97 (2018)



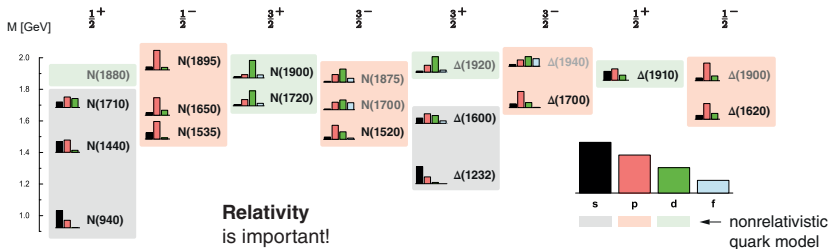
Diquark clustering in baryons?

Barabanov et al., Prog. Part. Nucl. Phys. 116 (2021)



- Three-quark and quark-diquark results very similar**

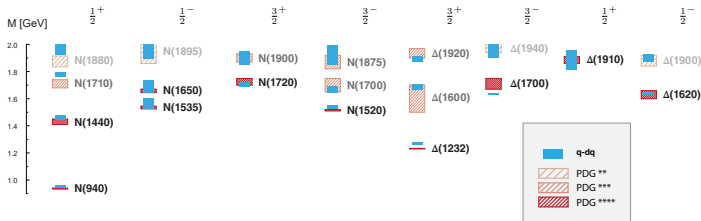
GE, Fischer, Sanchis-Alepuz, PRD 94 (2016), GE, FBS 63 (2022)



Diquark correlations

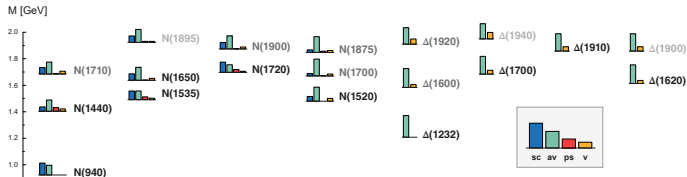
Light baryon spectrum

GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)



Diquark content:

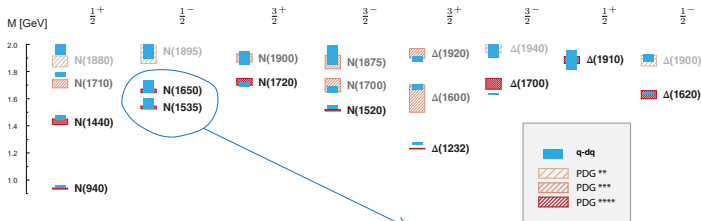
Barabanov et al., PNP 116 (2021)



Diquark correlations

Light baryon spectrum

GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)



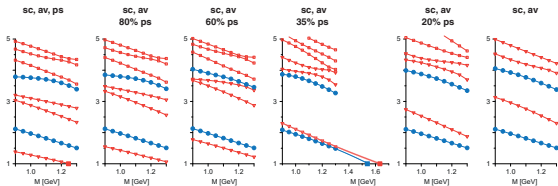
RL, all diquarks:
"N(1535)" too low

"Beyond RL":
N(1535), N(1650)

RL, sc+av only:
"N(1650)" too high

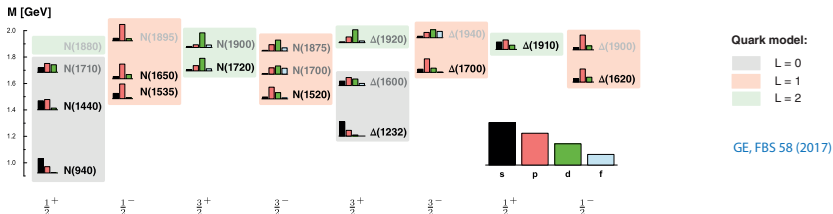
- **Level ordering** determined by diquark dynamics
- Diquarks are not pointlike, also here **rich spectrum!**

Barabanov et al., PNP 116 (2021)



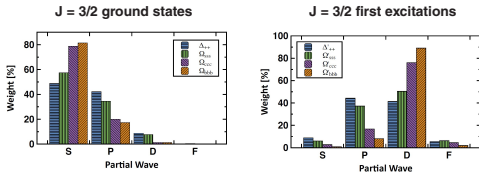
Relativistic effects

Orbital angular momentum: clear traces of nonrelativistic quark model, but strong relativistic effects (in some cases even dominant)



Relativistic contributions
even up to bottom baryons!

[Qin, Roberts, Schmidt, PRD 97 \(2018\)](#)

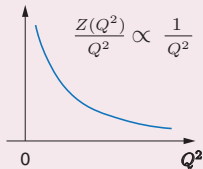


Towards ab-initio

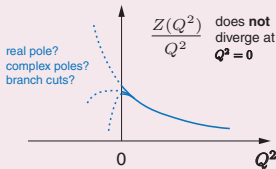
Gluon propagator:

$$D^{\mu\nu}(Q) = \underbrace{\frac{Z(Q^2)}{Q^2}}_{\text{transverse dressing}} \left(\delta^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2} \right) + \xi \underbrace{\frac{L(Q^2)}{Q^2}}_{\text{longitudinal dressing} = 1} \frac{Q^\mu Q^\nu}{Q^2}$$

- **Perturbation theory:**
Massless gluon pole



- **Nonperturbative calculations:**
Massless pole disappears!



Family of “**decoupling**” solutions, also seen in lattice QCD

Cucchieri, Maas, Mendes, PRD 77 (2008)
Boucaud et al., JHEP 06 (2008)
Bogolubsky et al., PLB 676 (2009)
Fischer, Maas, Pawłowski, Ann. Phys. 324 (2009)
Duarte, Oliveira, Silva, PRD 94 (2016)
Aguilar et al., EPJ C 80 (2020)

Endpoint is “**scaling**” solution, confinement manifest

Lerche, Smekal, PRD 65 (2002)
Fischer, Alkofer, PLB 536 (2002)
Alkofer, Fischer, Llanes-Estrada, MPLA 23 (2008)

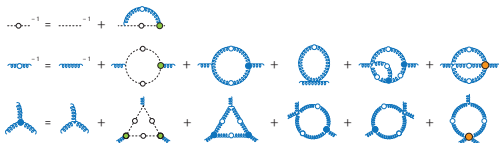
All solutions show **gluon mass gap**

$$\lim_{r \rightarrow \infty} \int \frac{d^3 Q}{(2\pi)^3} \frac{Z(Q^2)}{Q^2} e^{i \mathbf{x} \cdot \mathbf{Q}} \propto e^{-m_{\text{gap}} r}$$

Coupled Yang-Mills DSEs

GE, Pawłowski, Silva, PRD 104 (2021)

→ Test confinement
in hadron observables!

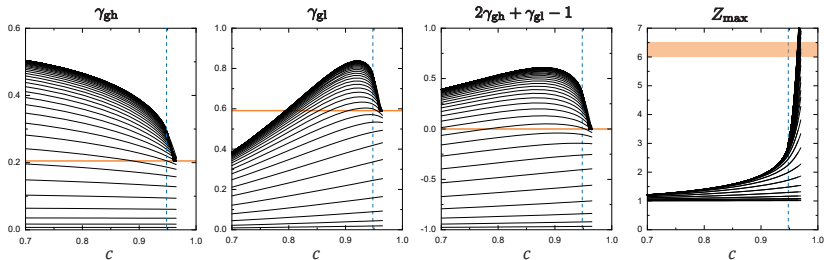


Truncation error

- Set $Z_{3g} \rightarrow c Z_{3g}$... quantifies deviation from STI (without truncation: $c = 1$), same effect from “over-renormalizing” 3-gluon vertex
- YM system only converges up to $c_{\max} < 1$
- Anomalous dimensions reproduced for

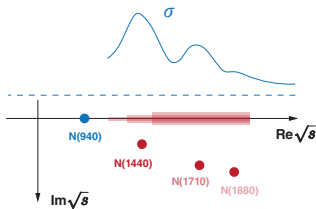
1	$c \sim 0.4$
2	$c \sim 0.9$
3	$c \sim 0.96$

 } $\Rightarrow$ identifies “physical point” for each truncation
 GE, Pawłowski, Silva, PRD 104 (2021)



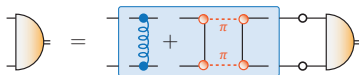
Resonances

- Most hadrons are **resonances** and decay $\Leftrightarrow$ poles in complex momentum plane



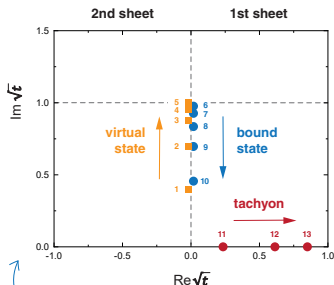
- BSE kernel must include decay channels:
 ρ meson becomes resonance

Williams, PLB 798 (2019), Miramontes, Sanchis-Alepuz, EPJA 55 (2019), Santowsky, GE, Fischer, Wallbott, PRD 102 (2020), Miramontes, Sanchis-Alepuz, Alkofer, PRD 103 (2021)



- Contour deformations** as tool to go beyond thresholds

GE, Duarte, Peña, Stadler, PRD 100 (2019)

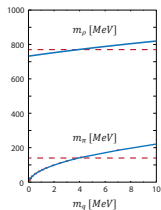


Scattering equation for 4-point function

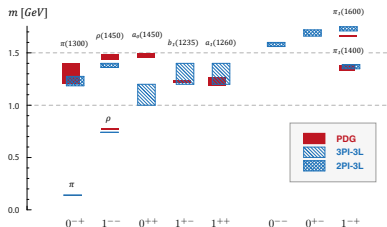
$$\text{Diagram} = \text{Diagram} + \text{Diagram} + \text{Diagram} + \text{Diagram}$$

Mesons

- Pion is **Goldstone boson**: $m_\pi^2 \sim m_q$



- Light meson spectrum** beyond rainbow-ladder

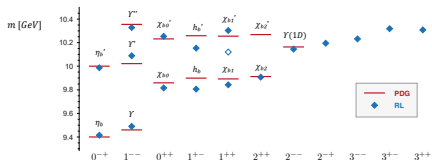


Williams, Fischer, Heupel,
PRD 93 (2016)

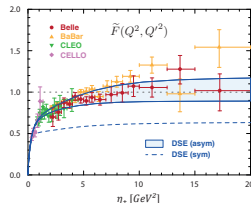
GE, Sanchis-Alepuz, Williams,
Alkofer, Fischer, PPNP 91 (2016)

- Bottomonium spectrum**

Fischer, Kubrak, Williams, EPJ A 51 (2015)

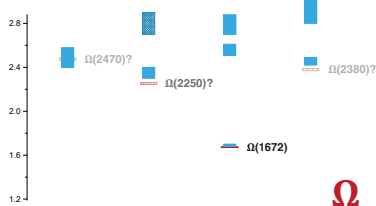
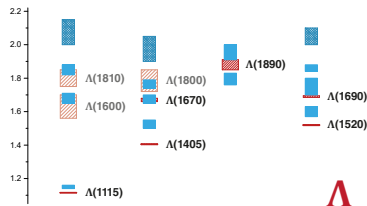
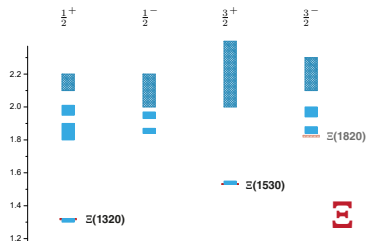
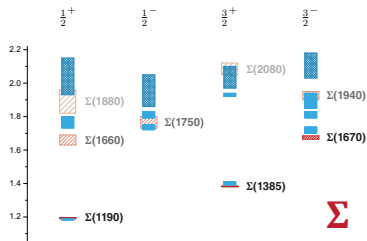


- Pion transition form factor**



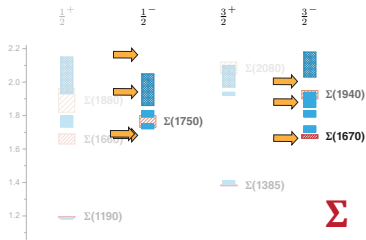
GE, Fischer, Weil, Williams,
PLB 774 (2017)

Strange baryons



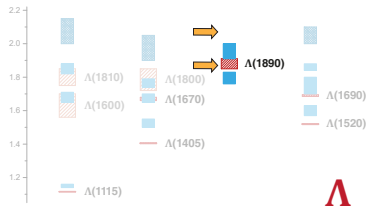
GE, Fischer, FBS 60 (2019), Fischer, GE, PoS Hadron 2017

Strange baryons



New states from Bonn-Gatchina

[Sarantsev et al., 1907.13387 \[nucl-ex\]](#)



GE, Fischer, FBS 60 (2019), Fischer, GE, PoS Hadron 2017