On the screening masses for light- and heavy-hadrons

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Interdisciplinary Center for Theoretical Study
&
Peng Huanwu Center for Fundamental Theory

April 26th, 2026

第八届全国重味物理与量子色动力学研讨会

Non-Perturbative QCD:

- **Hadrons, as bound states, are dominated by non-perturbative QCD dynamics –** *Two emergent phenomena*
  - **Confinement**: Colored particles have never been seen isolated
    - ✓ Explain how quarks and gluons bind together
  - **Dynamical Chiral Symmetry Breaking (DCSB)**: Hadrons do not follow the chiral symmetry pattern
    - ✓ Explain the most important mass generating mechanism for visible matter in the Universe
  - Neither of these phenomena is apparent in QCD 's Lagrangian, HOWEVER, They play a dominant role in determining the characteristics of real-world QCD!

Non-Perturbative QCD:

- **From a quantum field theoretical point of view**, these emergent phenomena could be associated with dramatic, dynamically driven changes in the analytic structure of **QCD** 's Schwinger functions (propagators and vertices). The Schwinger functions are solutions of the quantum equations of motion (**Dyson-Schwinger equations**).
- **Dressed-quark propagator:**

  - Mass generated from the interaction of quarks with the gluon.
  - Light quarks acquire a **HUGE** constituent mass.
  - Responsible of the 98% of the mass of the proton and the large splitting between parity partners.

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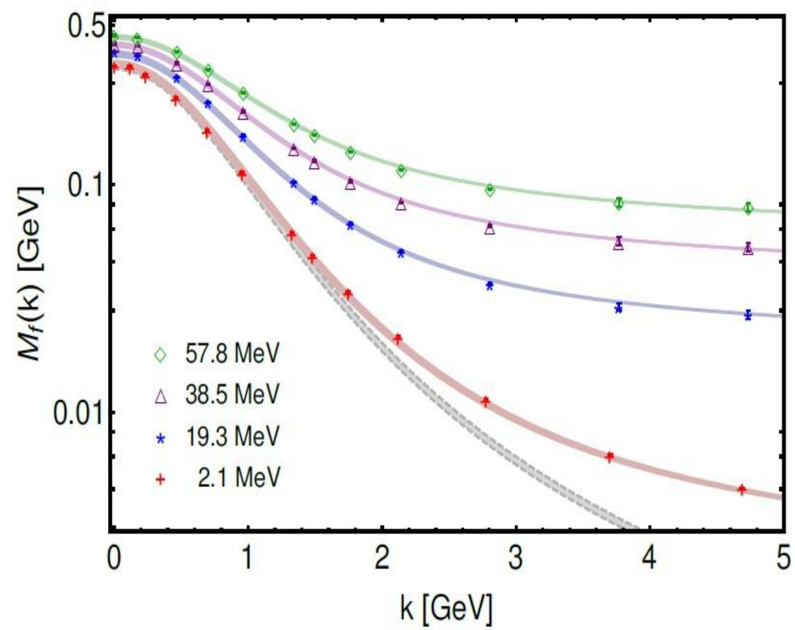
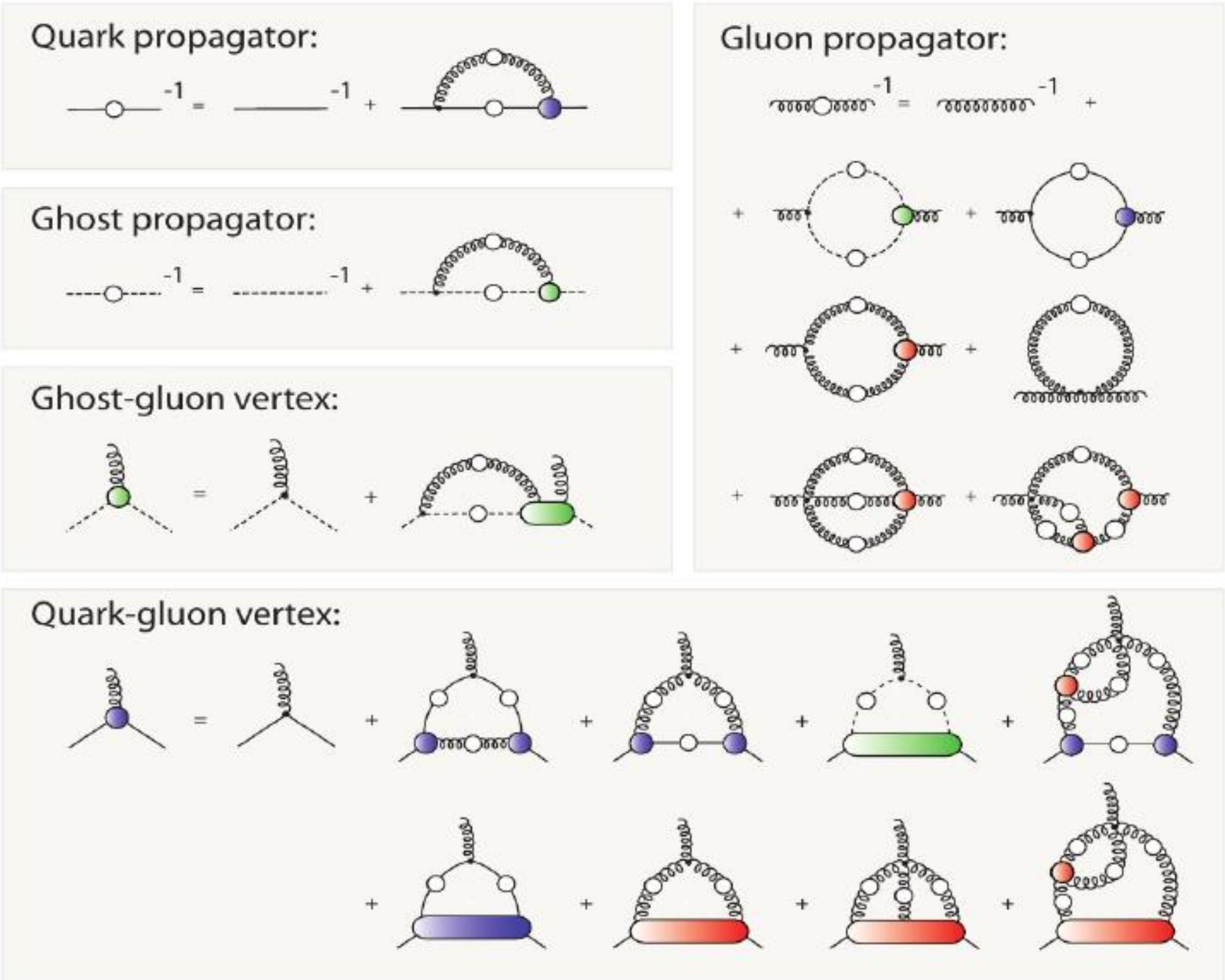


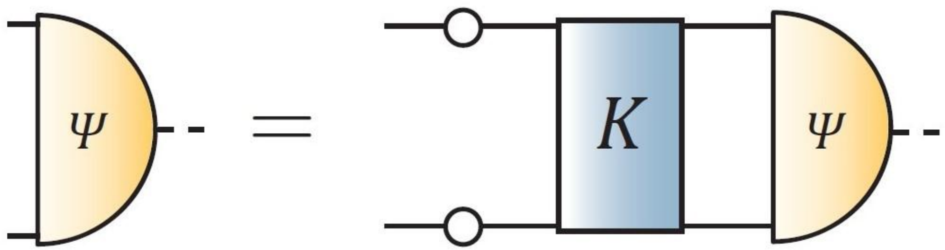
- Lei Chang, Yu-Bin Liu, Khépani Raya, J. Rodríguez-Quintero, and Yi-Bo Yang, Phys. Rev. D 104, no.9, 094509 (2021)

Continuum Schwinger function methods (CSMs)

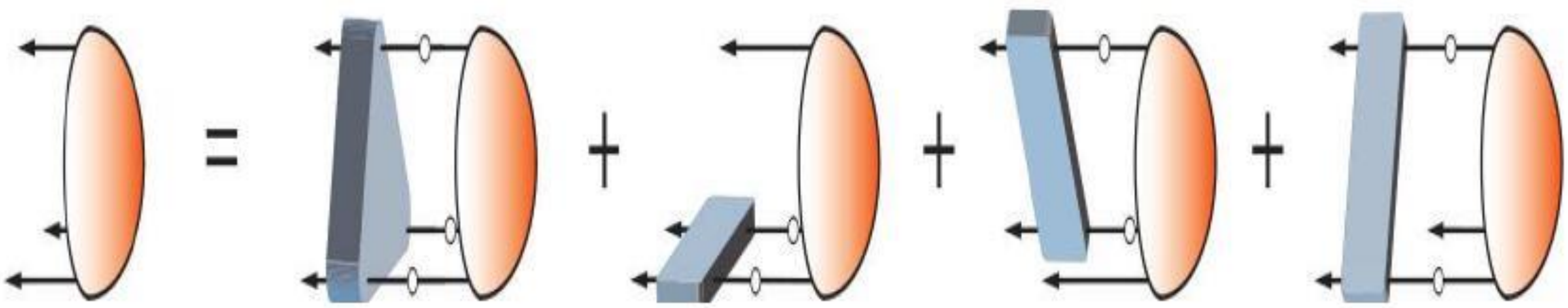


Hadrons: Bound-states in QFT

- **Mesons: a 2-body bound state problem in QFT**
  - ***Bethe-Salpeter Equation***
  - ***K*** **- fully amputated, two-particle irreducible, quark-antiquark scattering kernel**



- **Baryons: a 3-body bound state problem in QFT**
- ***Faddeev equation*****: sums all possible quantum field theoretical exchanges and interactions that can take place between the three dressed-quarks that define its valence quark content.**



2-body correlations

- **Mesons: quark-antiquark correlations -- color-singlet**
- **Diquarks: quark-quark correlations within a color-singlet baryon.**

- **Diquark correlations:**
  - In our approach: non-pointlike color-antitriplet and fully interacting.
  - Diquark correlations are soft, they possess an electromagnetic size.
  - Owing to properties of charge-conjugation, a diquark with spin-parity J^P may be viewed as a partner to the analogous J^{-P} meson.

$$\Gamma_{q\bar{q}}(p;P) = - \int \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu\, S(q+P)\Gamma_{q\bar{q}}(q;P)S(q)\,\frac{\lambda^a}{2}\,\gamma_\nu$$

$$\Gamma_{qq}(p;P)C^\dagger = -\frac{1}{2}\int \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu\, S(q+P)\Gamma_{qq}(q;P)C^\dagger S(q)\,\frac{\lambda^a}{2}\,\gamma_\nu$$

2-body correlations

- Quantum numbers:
  - $(I = 0, J^P = 0^+)$: isoscalar-scalar diquark
  - $(I = 1, J^P = 1^+)$: isovector-pseudovector diquark
  - $(I = 0, J^P = 0^-)$: isoscalar-pesudoscalar diquark
  - $(I = 0, J^P = 1^-)$: isoscalar-vector diquark
  - $(I = 1, J^P = 1^-)$: isovector-vector diquark

- ✓ G. Eichmann, H. Sanchis-Alepuz, R. Williams, R. Alkofer, C. S. Fischer, Prog.Part.Nucl.Phys. 91 (2016) 1-100
- ✓ Chen Chen, B. El-Bennich, C. D. Roberts, S. M. Schmidt, J. Segovia, S-L. Wan, Phys.Rev. D97 (2018) no.3, 034016

Quark-diquark Faddeev equation

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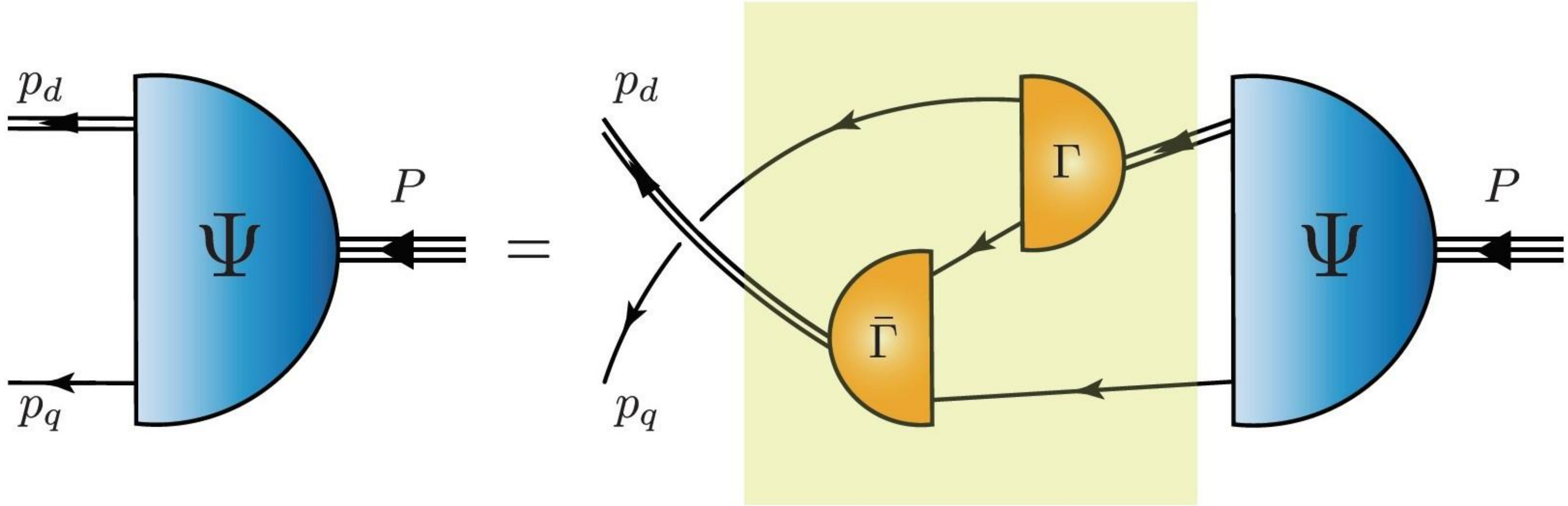
- ✓ Chen Chen, B. El-Bennich, C. D. Roberts, S. M. Schmidt, J. Segovia, S-L. Wan, Phys.Rev. D97 (2018) no.3, 034016

- Three-body bound states → Quark-diquark two-body bound states

- ✓ R.T. Cahill, Craig D. Roberts, J. Praschifka, Phys. Rev. D 36 (1987) 2804
- ✓ R.T. Cahill, Craig D. Roberts, J. Praschifka, Austral.J.Phys. 42 (1989) 129-145



Quark-diquark Faddeev equation

ELSEVIER

Progress in Particle and Nuclear Physics

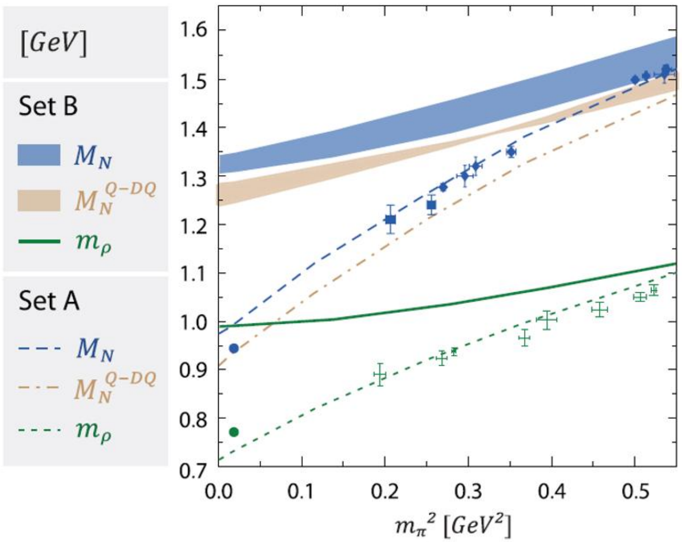
Volume 116, January 2021, 103835

Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6, 7], E. Cisbani [8], M. Ding [9], G. Eichmann [10, 11], R. Ent [12], J. Ferretti [13] ✉, R.W. Gothe [14], T. Horn [15, 12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18, 19] ✉ … B.B. Wojtsekhowski [12] ✉

Quark-diquark Faddeev equation



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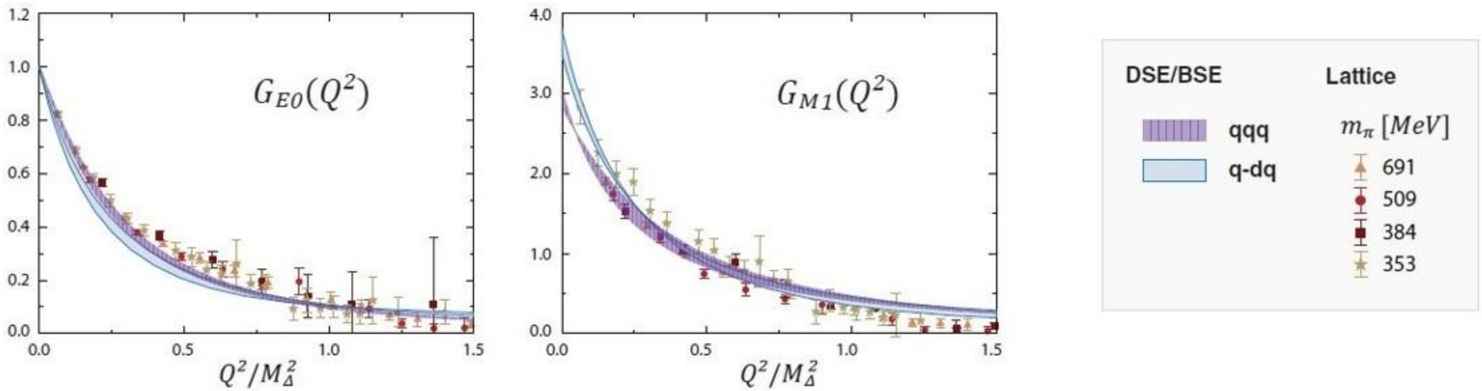

QCD-kindred model

- **Solution to the 60 year puzzle -- Roper resonance: Discovered in 1963, the Roper resonance appears to be an exact copy of the proton except that its mass is *50%* greater and it is unstable…**

PRL 115, 171801 (2015) PHYSICAL REVIEW LETTERS week ending 23 OCTOBER 2015

Completing the Picture of the Roper Resonance

Jorge Segovia,[1] Bruno El-Bennich,[2,3] Eduardo Rojas,[2,4] Ian C. Cloët,[5] Craig D. Roberts,[5] Shu-Sheng Xu,[6] and Hong-Shi Zong[6]

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[2]*Laboratório de Física Teórica e Computacional, Universidade Cruzeiro do Sul, 01506-000 São Paulo, SP, Brazil*
[3]*Instituto de Física Teórica, Universidade Estadual Paulista, 01140-070 São Paulo, SP, Brazil*
[4]*Instituto de Física, Universidad de Antioquia, Calle 70 No. 52-21, Medellín, Colombia*
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(Received 16 April 2015; revised manuscript received 29 July 2015; published 21 October 2015)

We employ a continuum approach to the three valence-quark bound-state problem in relativistic quantum field theory to predict a range of properties of the proton's radial excitation and thereby unify them with those of numerous other hadrons. Our analysis indicates that the nucleon's first radial excitation is the Roper resonance. It consists of a core of three dressed quarks, which expresses its valence-quark content and whose charge radius is 80% larger than the proton analogue. That core is complemented by a meson cloud, which reduces the observed Roper mass by roughly 20%. The meson cloud materially affects long-wavelength characteristics of the Roper electroproduction amplitudes but the quark core is revealed to probes with $Q^2 \gtrsim 3m_N^2$.

DOI: 10.1103/PhysRevLett.115.171801 PACS numbers: 13.40.Gp, 14.20.Dh, 14.20.Gk, 11.15.Tk

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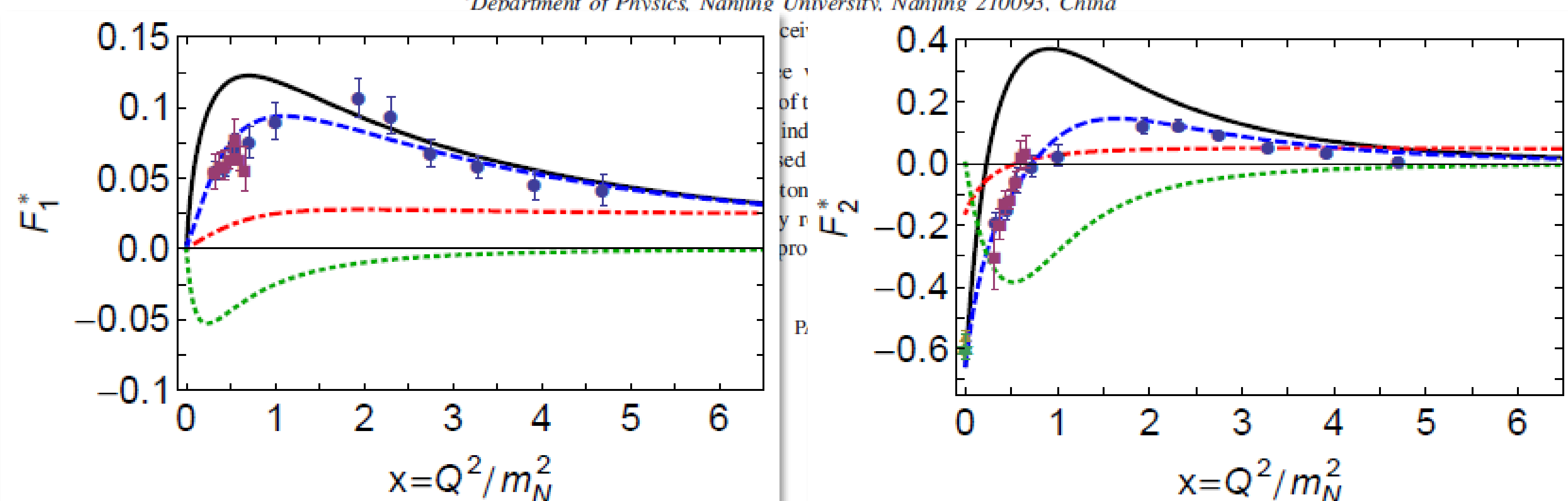

QCD-kindred model

- The electromagnetic nucleon-to-Δ(1600) transition form factors

PHYSICAL REVIEW D **100**, 034001 (2019)

Transition form factors: $\gamma^* + p \to \Delta(1232)$, $\Delta(1600)$

Y. Lu,[1,*] C. Chen,[2,†] Z.-F. Cui,[1,‡] C. D. Roberts,[3,§] S. M. Schmidt,[4,∥] J. Segovia,[5,¶] and H.-S. Zong[1,6,**]
[1]*Department of Physics, Nanjing University, Nanjing, Jiangsu 210093, China*
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[3]*Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
[4]*Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, D-52425 Jülich, Germany*
[5]*Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, E-41013 Sevilla, Spain*
[6]*Joint Center for Particle, Nuclear Physics and Cosmology, Nanjing, Jiangsu 210093, China*

- In 2023, those (parameter-free) predictions were confirmed in an analysis of data obtained using the CLAS detector at JLab

PHYSICAL REVIEW C **108**, 025204 (2023)

First results on nucleon resonance electroexcitation amplitudes from $ep \to e'\pi^+\pi^-p'$ cross sections at $W = 1.4$–1.7 GeV and $Q^2 = 2.0$–$5.0\,\mathrm{GeV}^2$

V. I. Mokeev,[1,*] P. Achenbach,[1] V. D. Burkert,[1] D. S. Carman,[1] R. W. Gothe,[2] A. N. Hiller Blin,[3] E. L. Isupov,[4] K. Joo,[5] K. Neupane,[2] and A. Trivedi[2]
[1]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[2]*University of South Carolina, Columbia, South Carolina 29208, USA*
[3]*Institute for Theoretical Physics, Tübingen University, D-72076 Tübingen, Germany*
[4]*Skobeltsyn Institute of Nuclear Physics and Physics Department, Lomonosov Moscow State University, 119234 Moscow, Russia*
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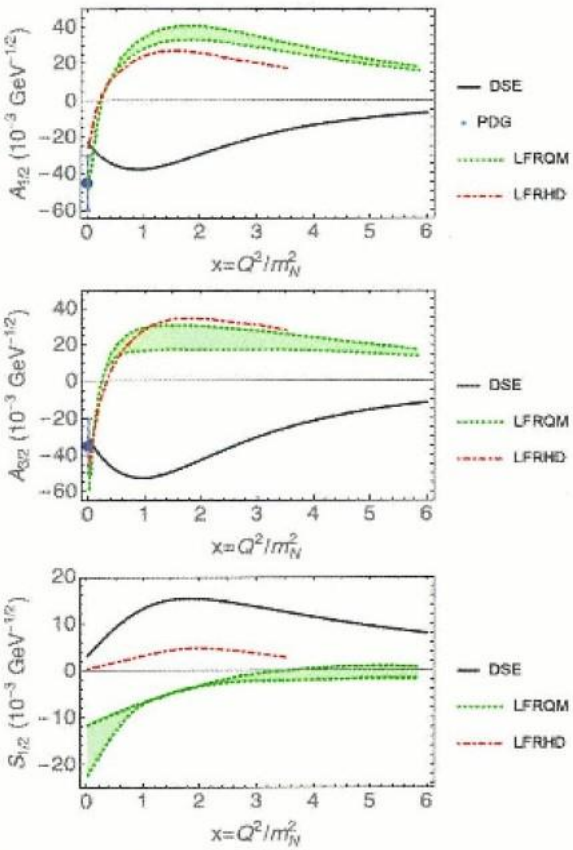
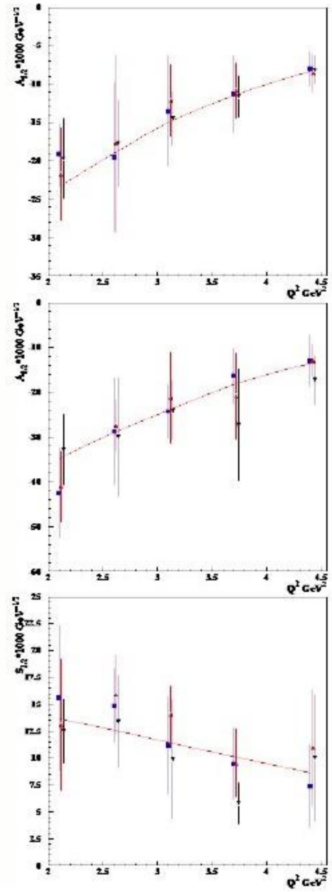
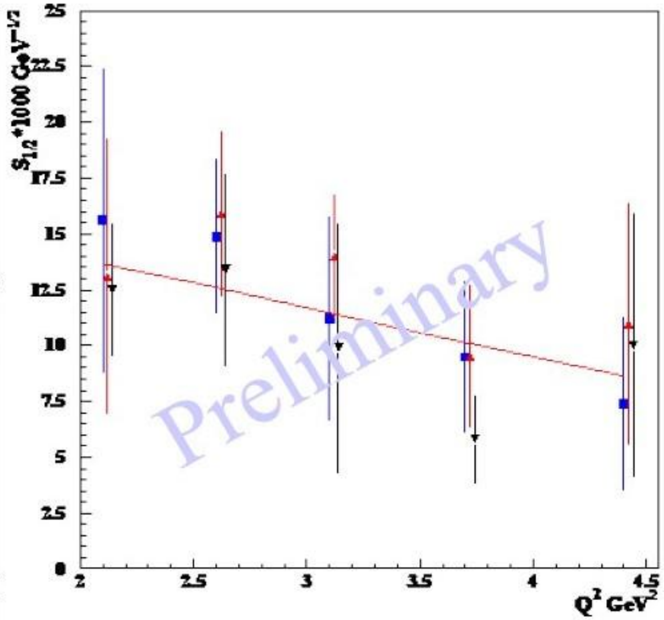
Δ(1600)3/2+ Form Factors in CSM Approach

Viktor Mokeev

CSM predictions of the Δ(1600)3/2+ electrocouplings







Spring 2022 analysis of Arjun's $\pi^+\pi^-p$ differential cross sections for $2.0GeV^2<Q^2<5.0GeV^2$ within three W-intervals, 1.46GeV<W<1.56GeV, 1.51GeV<W<1.61GeV, and 1.56GeV<W<1.66GeV.

Ya Lu et al., PRD 100, 034001 (2019)

QCD-kindred model

PHYSICAL REVIEW LETTERS **133,** 131901 (2024)

Nucleon-to-Δ Axial and Pseudoscalar Transition Form Factors

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[1]Interdisciplinary Center for Theoretical Study, University of Science and Technology of China, Hefei, Anhui 230026, China
[2]Peng Huanwu Center for Fundamental Theory, Hefei, Anhui 230026, China
[3]Institut für Theoretische Physik, Justus-Liebig-Universität Gießen, D-35392 Gießen, Germany
[4]Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung, Campus Gießen, 35392 Gießen, Germany
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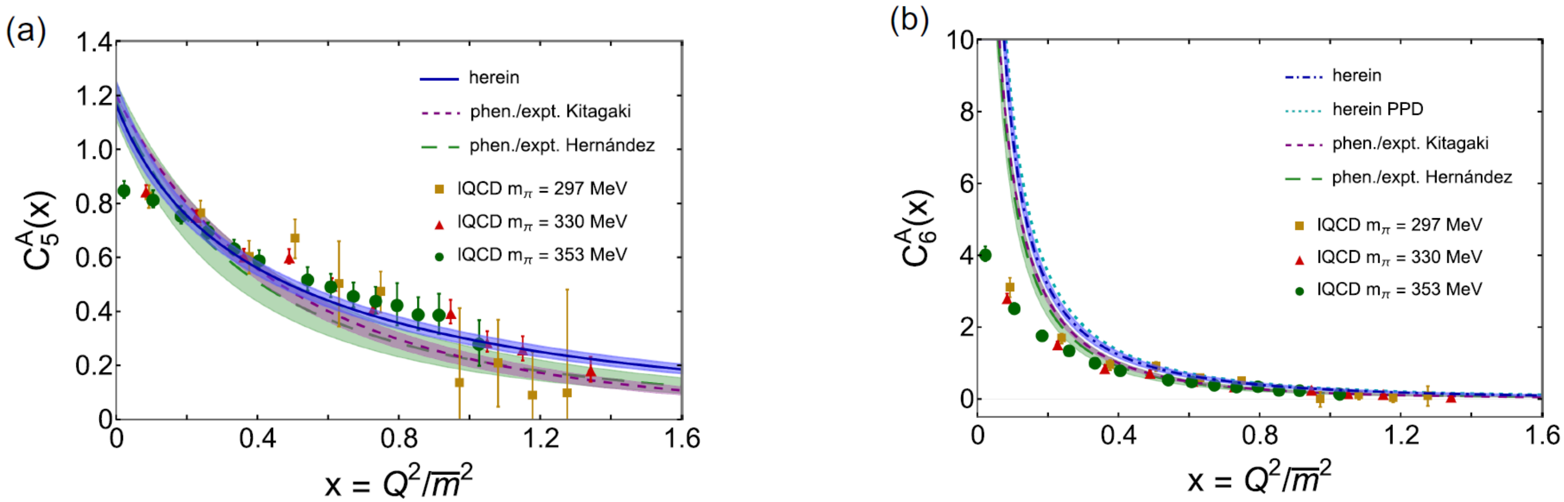
[6]Institute for Nonperturbative Physics, Nanjing University, Nanjing, Jiangsu 210093, China

(Received 21 December 2023; revised 19 July 2024; accepted 21 August 2024; published 25 September 2024)



DSEs at finite temperature & density

PERGAMON

Progress in Particle and Nuclear Physics 45 (2000) S1–S103

Progress in Particle and Nuclear Physics

http://www.elsevier.nl/locate/npe

Dyson-Schwinger Equations: Density, Temperature and Continuum Strong QCD

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Progress in Particle and Nuclear Physics 105 (2019) 1–60

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/ppnp

Review

QCD at finite temperature and chemical potential from Dyson–Schwinger equations

Check for updates

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DSEs at finite temperature

- Currently, it is widely accepted that strongly interacting matter transitions from hadronic excitations to quark-gluon plasma (QGP) at high temperatures, where quarks and gluons become deconfined and chiral symmetry is restored.

- For strongly interacting matter, one key aspect of studying is the behavior of screening masses, which are defined by the exponential decay of the spatial correlation functions.

- The screening mass is physically connected to the response of the medium inserted into the probe hadron. On the chiral symmetry restoration domain, for any hadronic parity-partner-pair, i.e., a hadron and its parity partner, the associated screening masses are expected to degenerate.

DSEs at finite temperature

- arXiv:2412.15045 [hep-ph]

PHYSICAL REVIEW D **112,** 014022 (2025)

Screening masses of positive- and negative-parity hadron ground states, including those with strangeness

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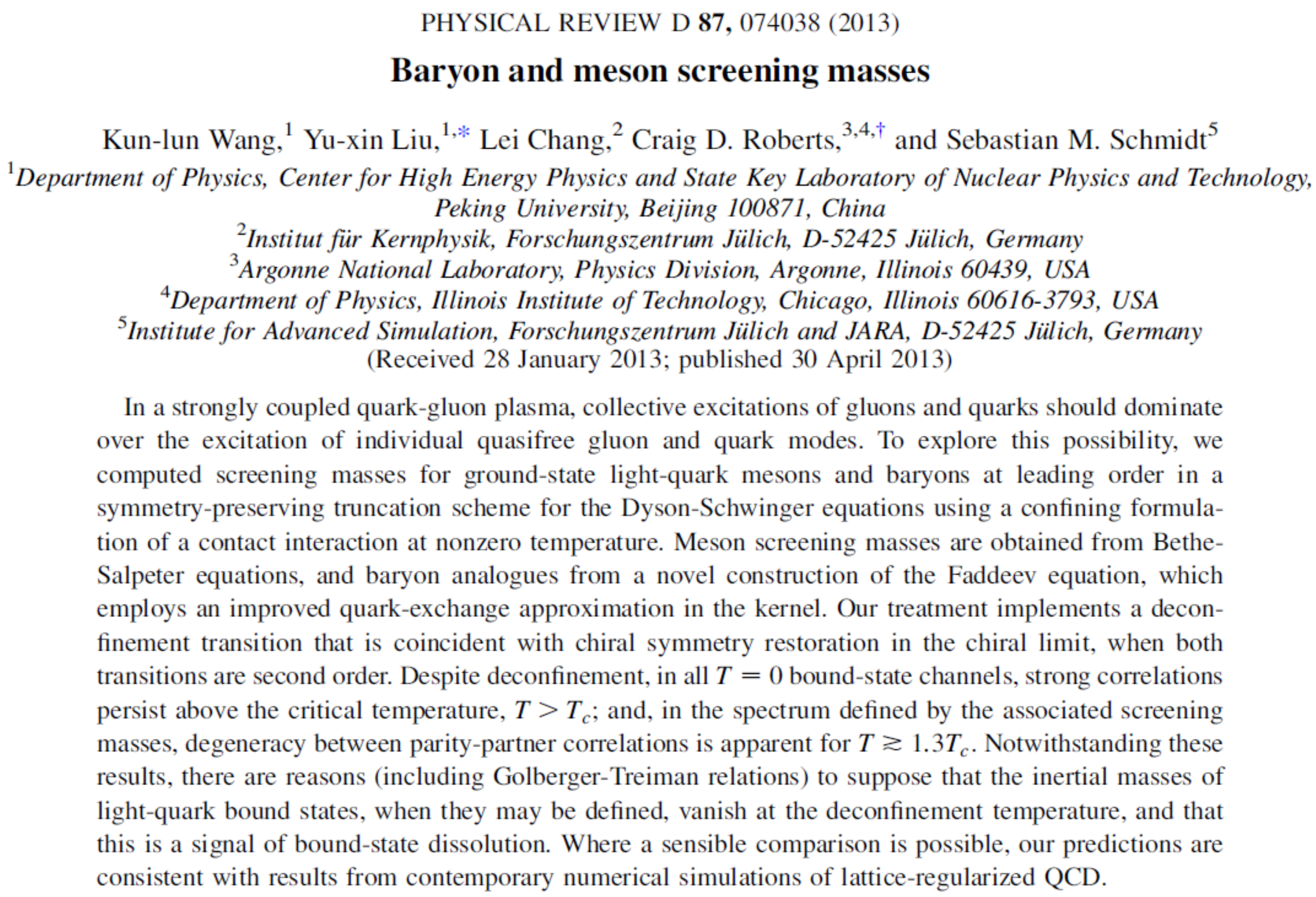
(Received 27 December 2024; accepted 12 June 2025; published 9 July 2025)

Using a symmetry-preserving treatment of a vector × vector contact interaction at nonzero temperature, we compute the screening masses of flavor-SU(3) ground-state $J^P = 0^\pm$, $1^\pm$ mesons, and $J^P = 1/2^\pm$, $3/2^\pm$ baryons. We find that all correlation channels allowed at $T = 0$ persist when the temperature increases, even above the QCD phase transition temperature. The results for mesons qualitatively agree with those obtained from the contemporary lattice-regularized quantum chromodynamics simulations. One of the most remarkable features is that each parity-partner-pair degenerates when $T > T_c$, with T_c being the critical temperature. For each pair, the screening mass of the negative parity meson increases monotonously with temperature. In contrast, the screening mass of the meson with positive parity is almost invariant on the domain $T \lesssim T_c/2$; when T gets close to T_c, it decreases but soon increases again and finally degenerates with its parity partner, which signals the restoration of chiral symmetry. We also find that the T-dependent behaviors of baryon screening masses are quite similar to those of the mesons. For baryons, the dynamical, nonpointlike diquark correlations play a crucial role in the screening mass evolution. We further calculate the evolution of the fraction of each kind of diquark within baryons respective to temperature. We observe that, at high temperatures, only $J = 0$ scalar and pseudoscalar diquark correlations can survive within $J^P = 1/2^\pm$ baryons.

DSEs at finite temperature

- Phys.Rev.D 87 (2013) 7, 074038


PHYSICAL REVIEW D **87**, 074038 (2013)

Baryon and meson screening masses

Kun-lun Wang,[1] Yu-xin Liu,[1,*] Lei Chang,[2] Craig D. Roberts,[3,4,†] and Sebastian M. Schmidt[5]

[1]*Department of Physics, Center for High Energy Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

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(Received 28 January 2013; published 30 April 2013)

In a strongly coupled quark-gluon plasma, collective excitations of gluons and quarks should dominate over the excitation of individual quasifree gluon and quark modes. To explore this possibility, we computed screening masses for ground-state light-quark mesons and baryons at leading order in a symmetry-preserving truncation scheme for the Dyson-Schwinger equations using a confining formulation of a contact interaction at nonzero temperature. Meson screening masses are obtained from Bethe-Salpeter equations, and baryon analogues from a novel construction of the Faddeev equation, which employs an improved quark-exchange approximation in the kernel. Our treatment implements a deconfinement transition that is coincident with chiral symmetry restoration in the chiral limit, when both transitions are second order. Despite deconfinement, in all $T = 0$ bound-state channels, strong correlations persist above the critical temperature, $T > T_c$; and, in the spectrum defined by the associated screening masses, degeneracy between parity-partner correlations is apparent for $T \gtrsim 1.3T_c$. Notwithstanding these results, there are reasons (including Golberger-Treiman relations) to suppose that the inertial masses of light-quark bound states, when they may be defined, vanish at the deconfinement temperature, and that this is a signal of bound-state dissolution. Where a sensible comparison is possible, our predictions are consistent with results from contemporary numerical simulations of lattice-regularized QCD.

DSEs at finite temperature

- **A symmetry-preserving treatment of a vector × vector contact interaction (SCI) at nonzero temperature:**

$$\mathcal{K}_{\alpha\beta,\gamma\delta} = g^2 D_{\mu\nu}(k)[i\gamma_\mu]_{\alpha\beta}[i\gamma_\nu]_{\gamma\delta} \,, \tag{1}$$

where $D_{\mu\nu}$ is the gluon propagator. Furthermore, in this work, we use the following SCI *Ansätz*

$$g^2 D_{\mu\nu}(k) = \delta_{\mu\nu}\frac{4\pi\alpha_{\rm IR}}{m_G^2} \,, \tag{2}$$

- **Dressed-quark propagator**

$$S_f^{-1}(p;T) = i\vec{\gamma}\cdot\vec{p} + i\gamma_4\omega_n + m_f + \frac{16\pi\alpha_{\rm IR}}{3m_G^2}\int_{l,dq}\gamma_\mu S_f(q;T)\gamma_\mu$$

- **Dressed-quark mass**

$$M_f(T) = m_f + \frac{16\pi\alpha_{\rm IR}}{3m_G^2}\int_{l,dq}\frac{4M_f(T)}{s_l + M_f(T)^2}$$

DSEs at finite temperature

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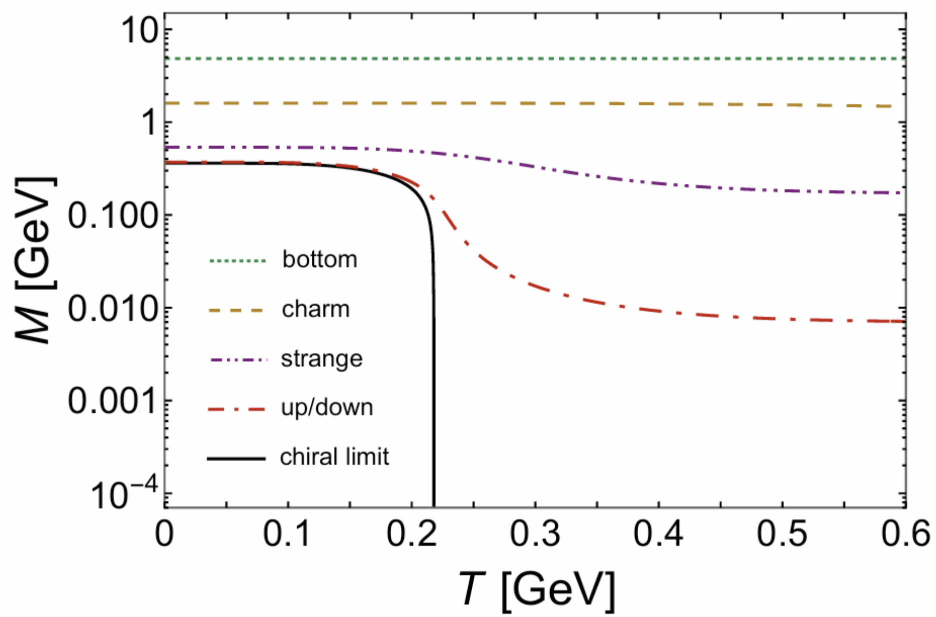

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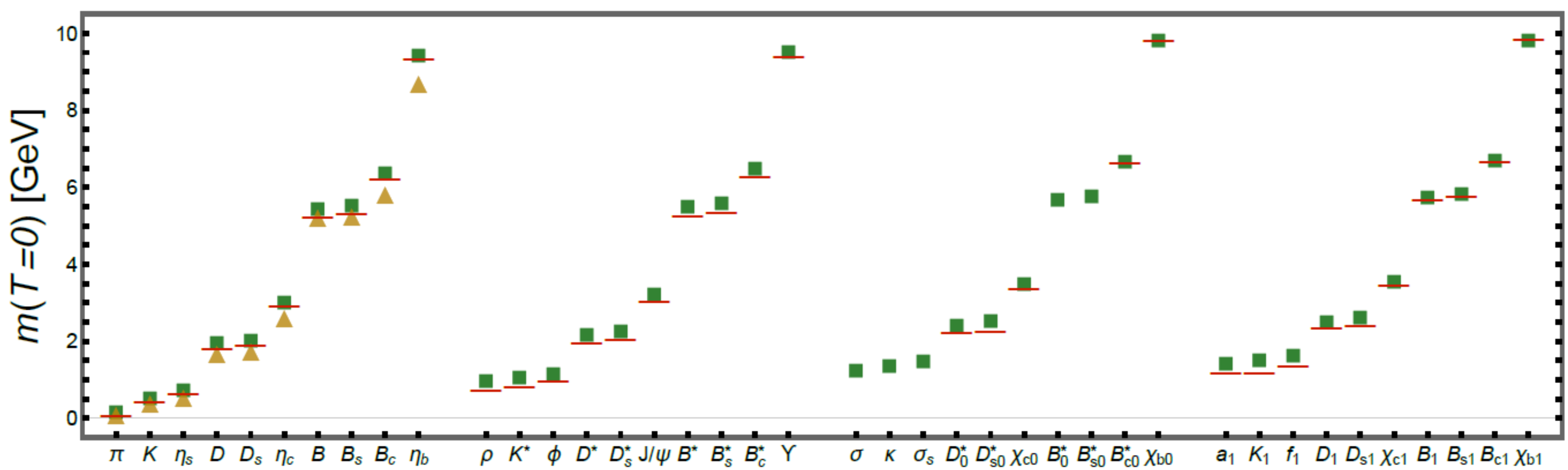

Screening masses: mesons

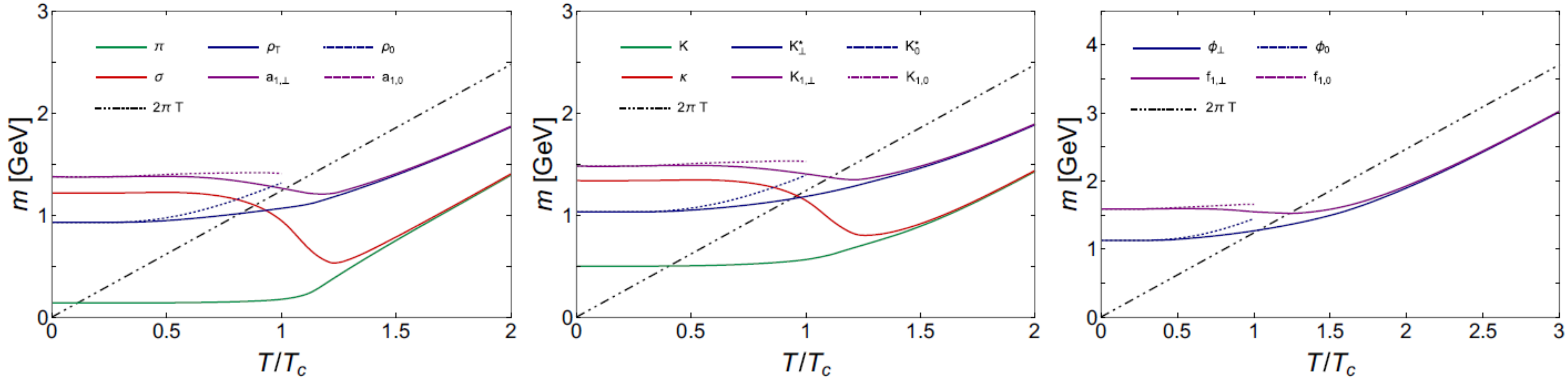

FIG. 3. (Left to right) Screening masses of mesons, for the light-light, light-strange, and strange-strange ($\bar{s}s$) sectors. In each figure: *green curve*: pseudoscalar meson; *red curve*: scalar meson; *blue curves*: vector meson; *purple curves*: axial-vector meson; and *black dot-dot-dashed curve*: free theory limit of $m = 2\pi T$. For the $J = 1$ vector and axial-vector mesons, transverse modes are traced with solid lines and longitudinal modes with dotted lines.

Screening masses: mesons

Meson screening masses in (2+1)-flavor QCD #1

Alexei Bazavov (Michigan State U.), Simon Dentinger (Bielefeld U.), Heng-Tong Ding (Hua-Zhong Normal U.), Prasad Hegde (Bangalore, Indian Inst. Sci.), Olaf Kaczmarek (Bielefeld U. and Hua-Zhong Normal U.) et al. (Aug 26, 2019)

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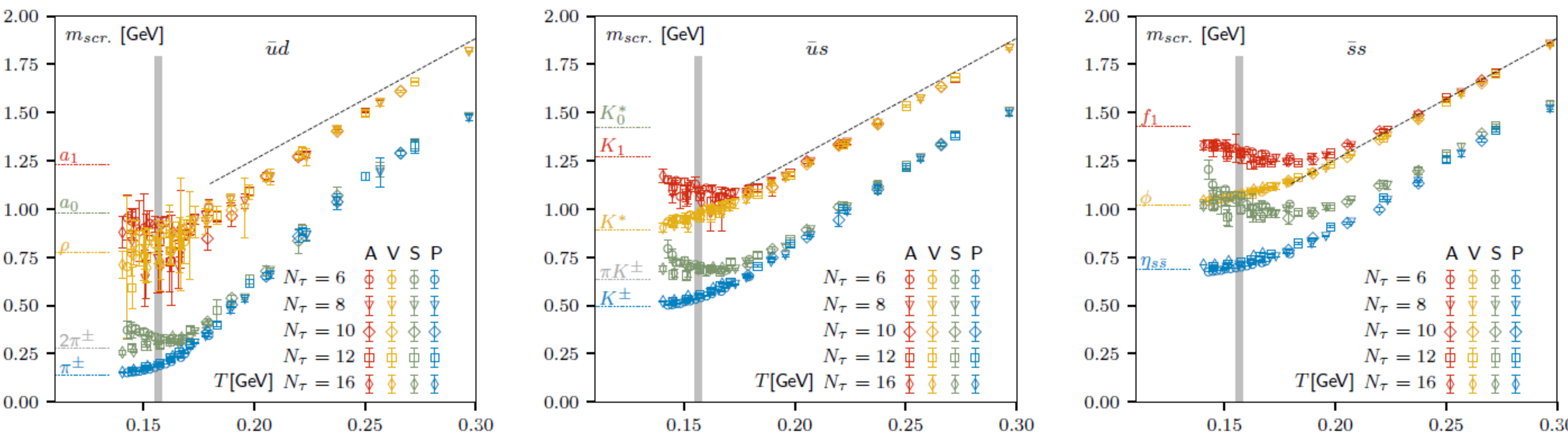
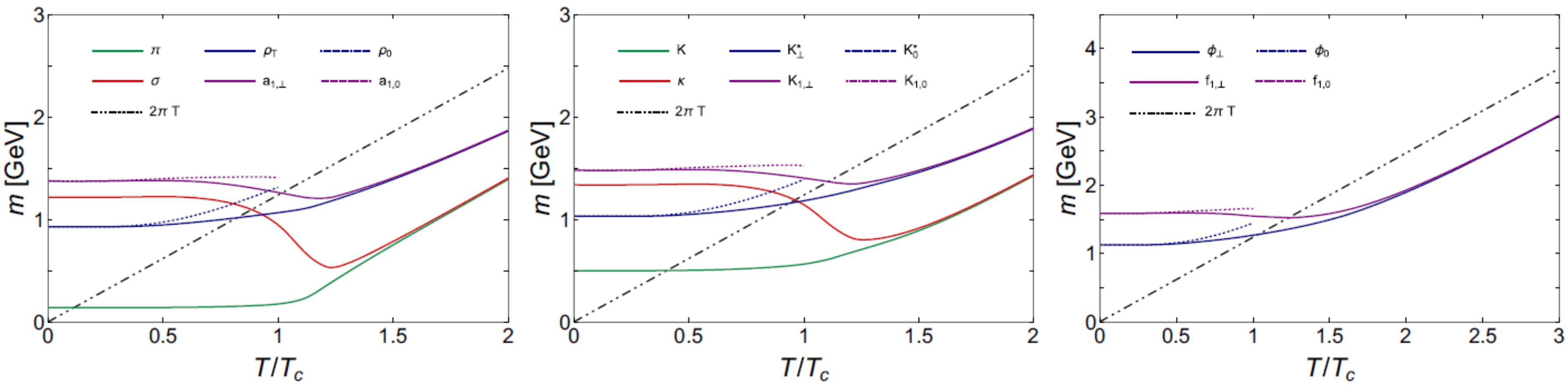
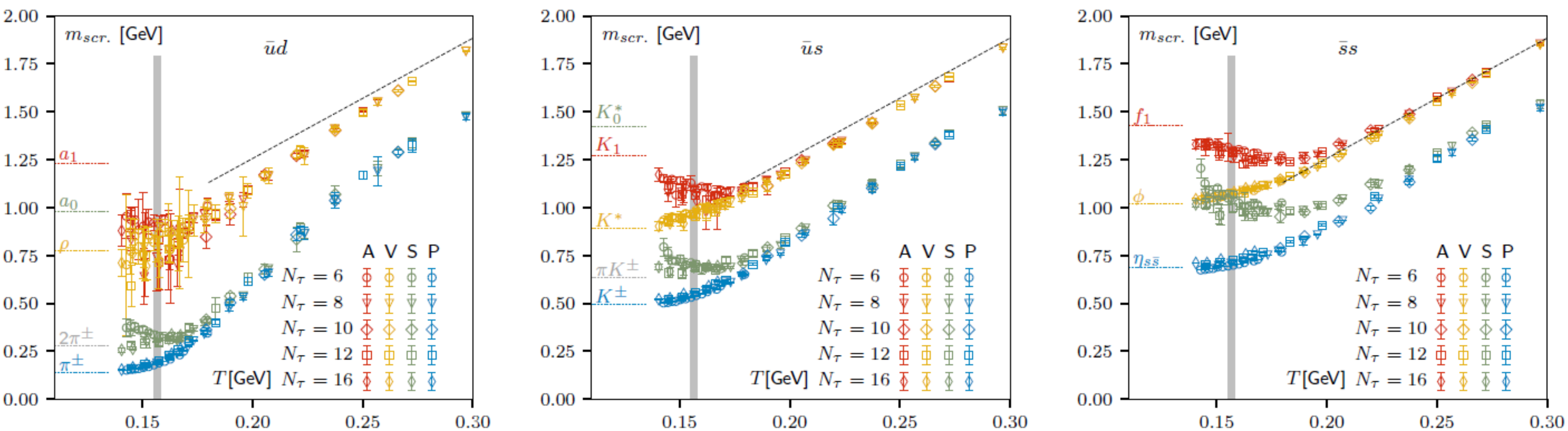


Figure 5. (Left to right) Results for all four screening masses for the $\bar{u}d$, $\bar{u}s$ and $\bar{s}s$ flavor combinations. The gray vertical band in all the figures represents the pseudo-critical temperature, $T_{pc} = 156.5(1.5)$ MeV [6]. The dashed lines corresponds to the free theory limit of $m = 2\pi T$.

Screening masses: mesons





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Screening masses: diquarks

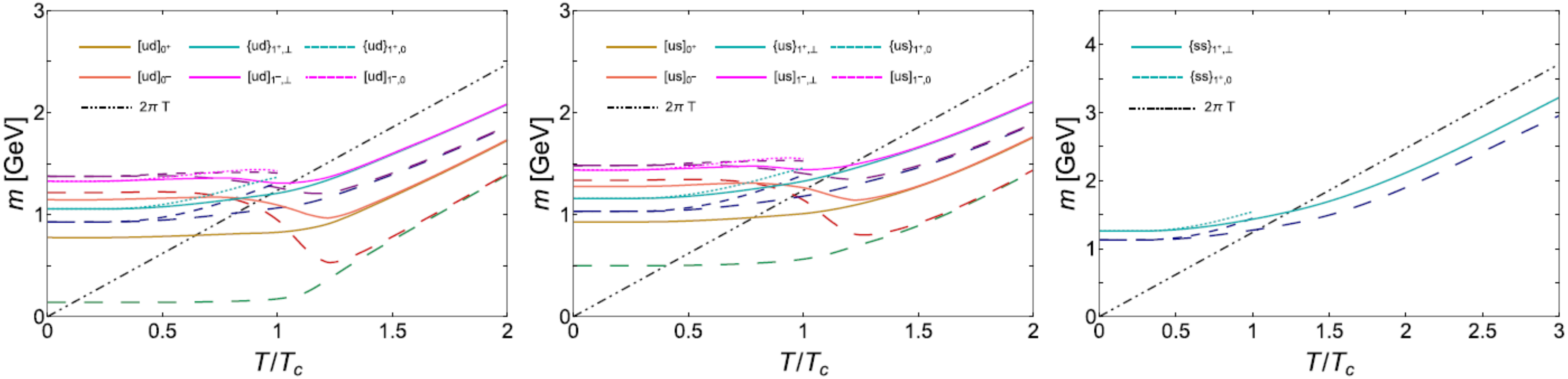


FIG. 5. (Left to right) Screening masses of diquarks with strangeness $S = 0, 1, 2$, in comparison with the results of their meson partners from Fig. 3. In each figure: *gold curve*: scalar diquark; *coral curve*: pseudoscalar diquark; *cyan curves*: axial-vector diquark; *magenta curves*: vector diquark; and *black dot-dot-dashed curve*: free theory limit of $m = 2\pi T$. For the $J = 1$ axial-vector and vector diquarks, transverse modes are traced with solid lines and longitudinal modes with dotted lines. For the legends of mesons the colors are the same as those in Fig. 3, except that the *long dashed curves* represent the $J = 0$ and the transverse modes of the $J = 1$ mesons, and the *short dashed curves* are for the longitudinal modes of the $J = 1$ mesons.

Screening masses: $J^P = 1/2^{\pm}$ baryons

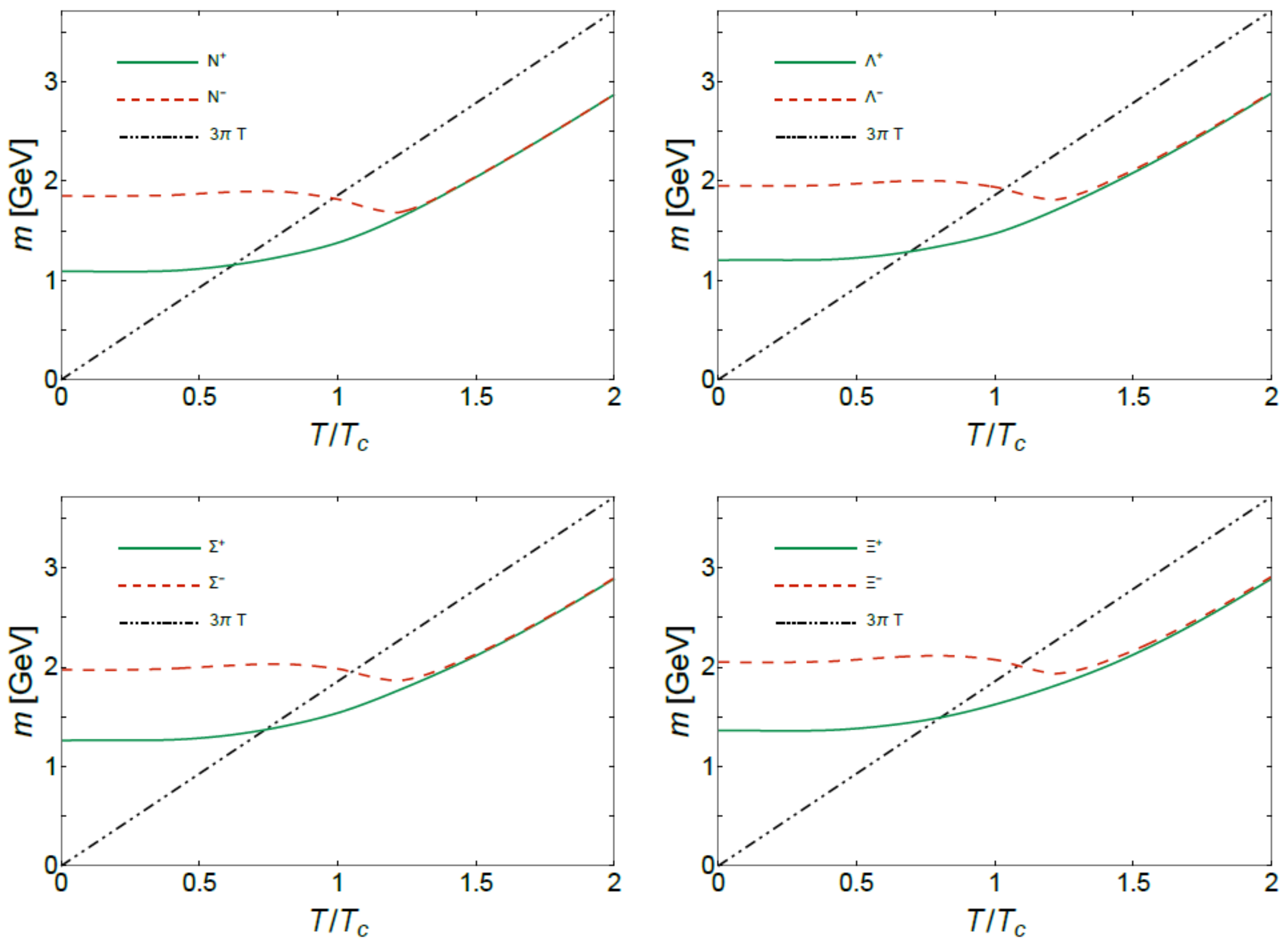
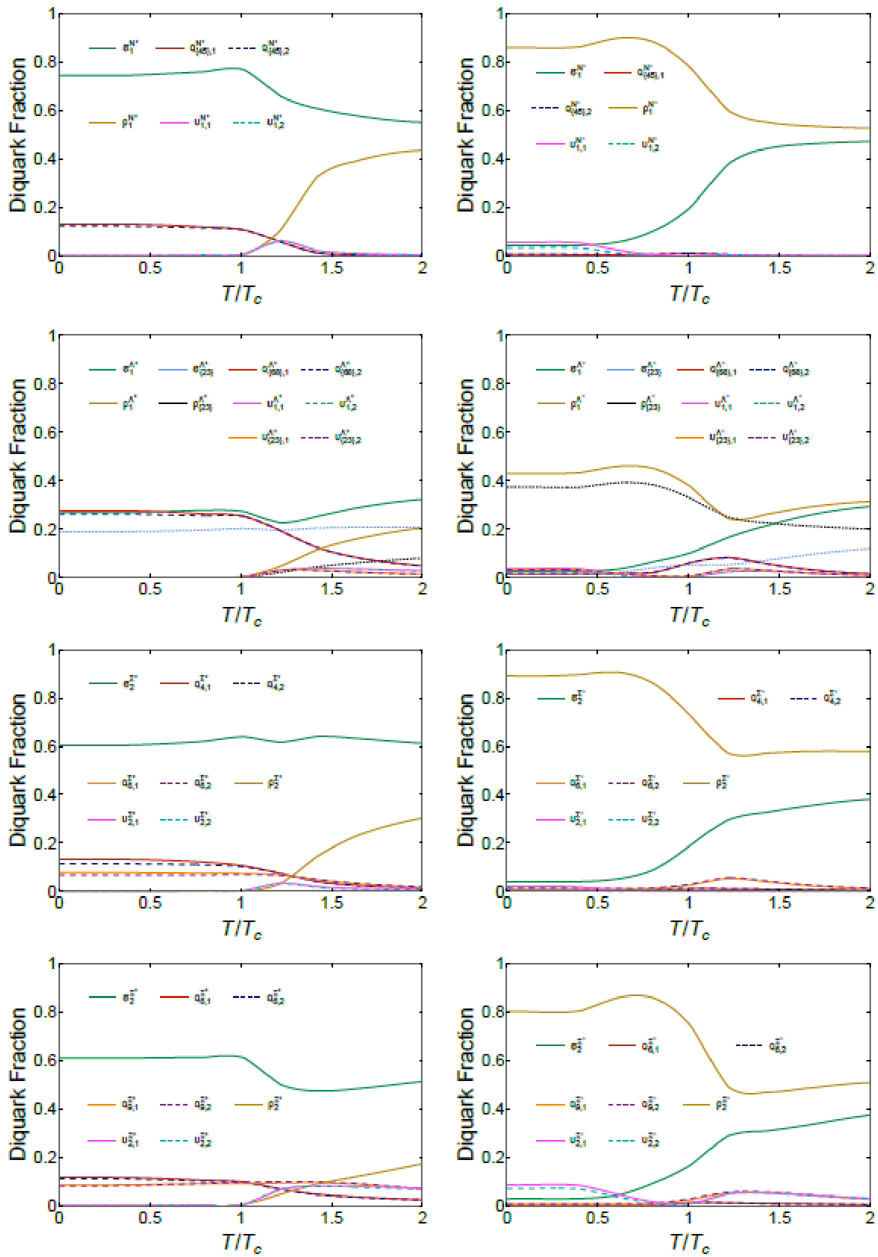


FIG. 6. Screening masses of $J^P = 1/2^{\pm}$ baryon ground states. In each figure: *solid green curve*: positive-parity baryon; *dashed red curve*: negative-parity baryon; and *black dot-dot-dashed curve*: free theory limit of $m = 3\pi T$.

Diquark fractions: $J^P = 1/2^{\pm}$ baryons



Diquark fractions: $J^P = 1/2^{\pm}$ baryons

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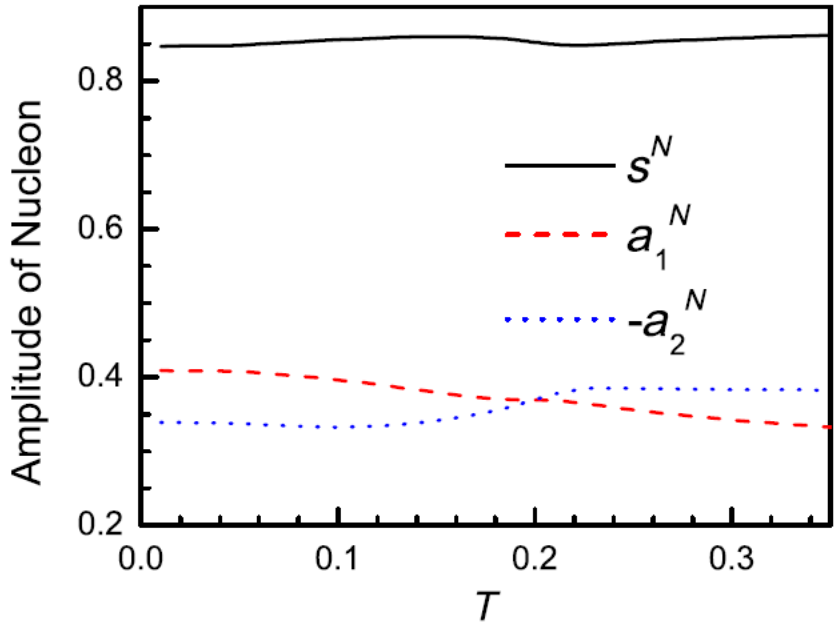


FIG. 11 (color online). Evolution of the nucleon's Faddeev amplitude with temperature: *solid curve*: scalar diquark component; and *dashed, dotted curves*: the two distinct axial-vector diquark structures. [See Eqs. (C1) and (C2).]

Screening masses: $J^P = 3/2^{\pm}$ baryons

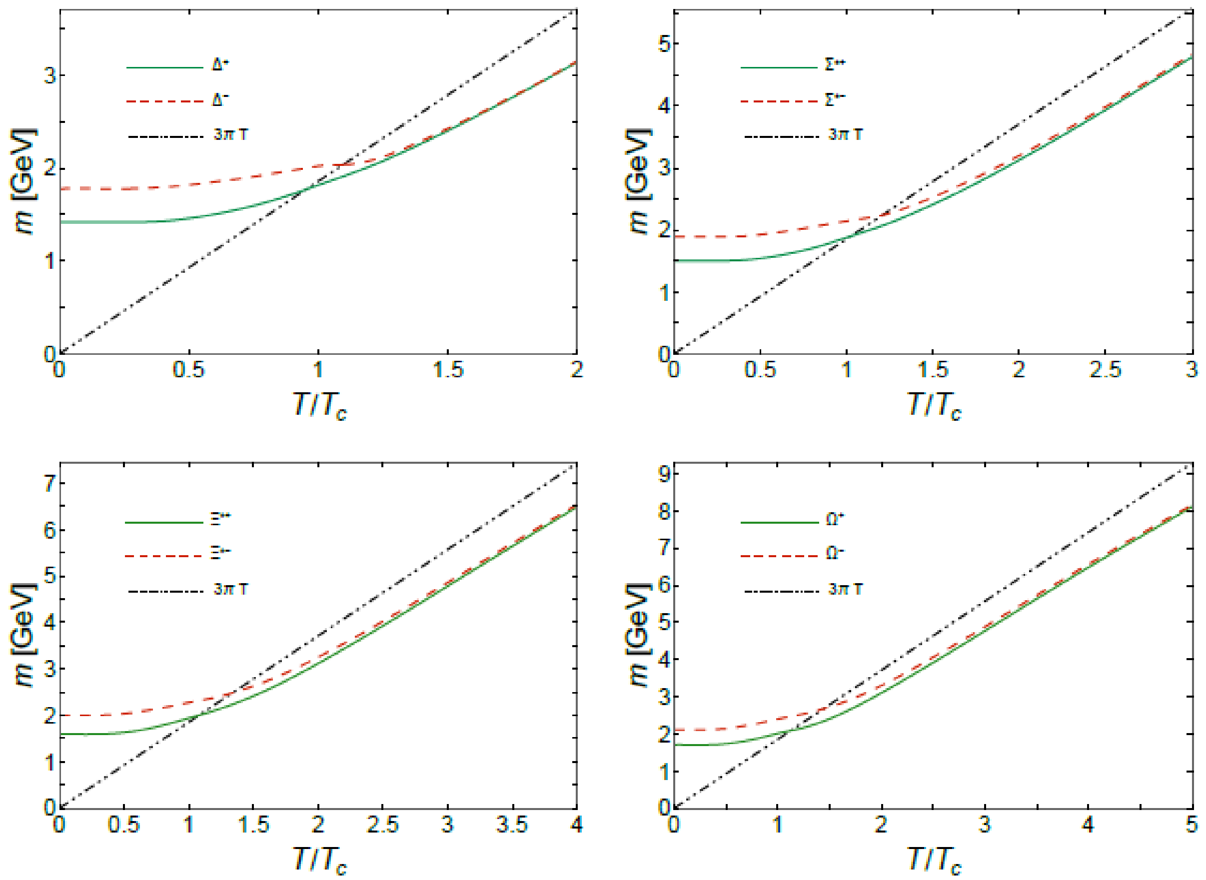
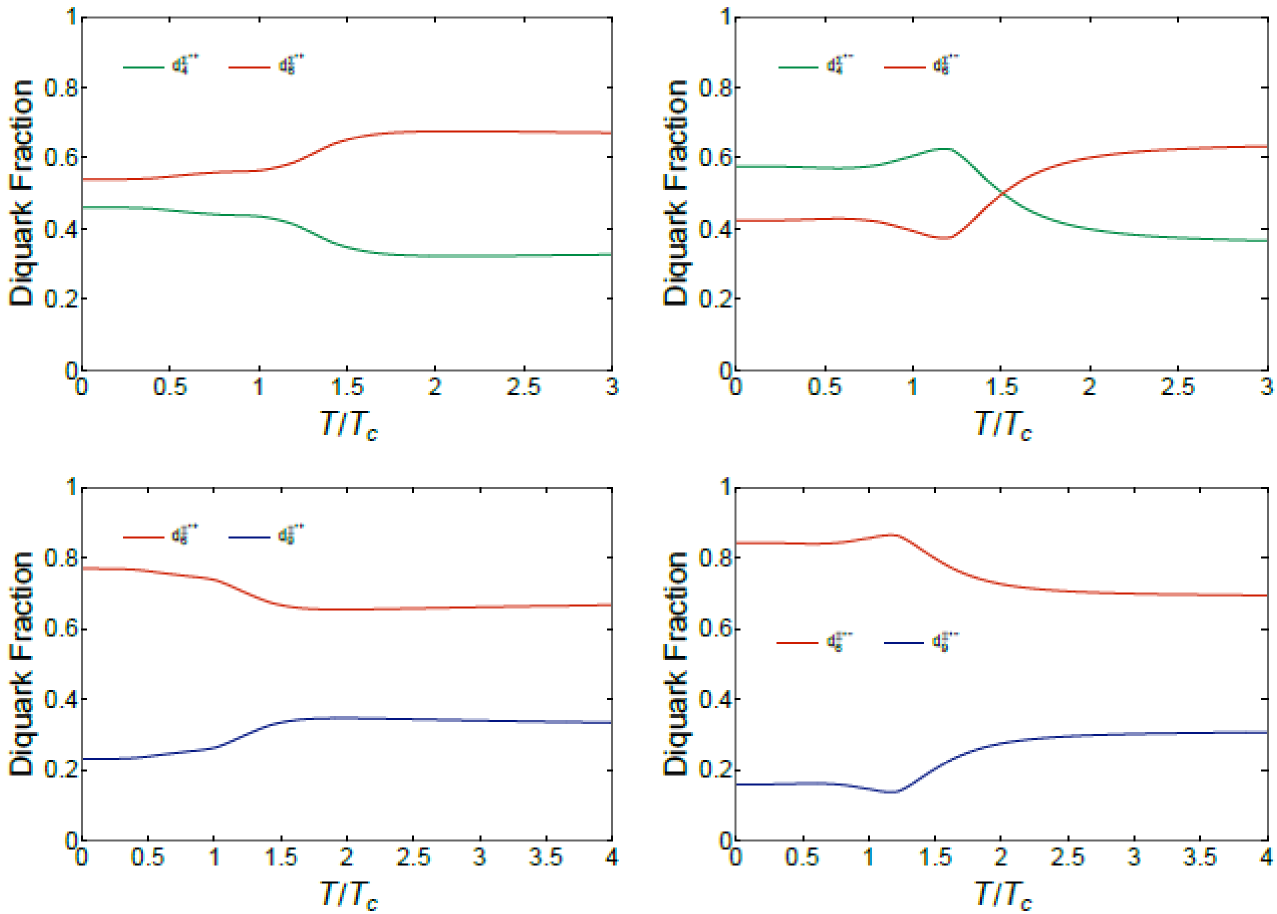
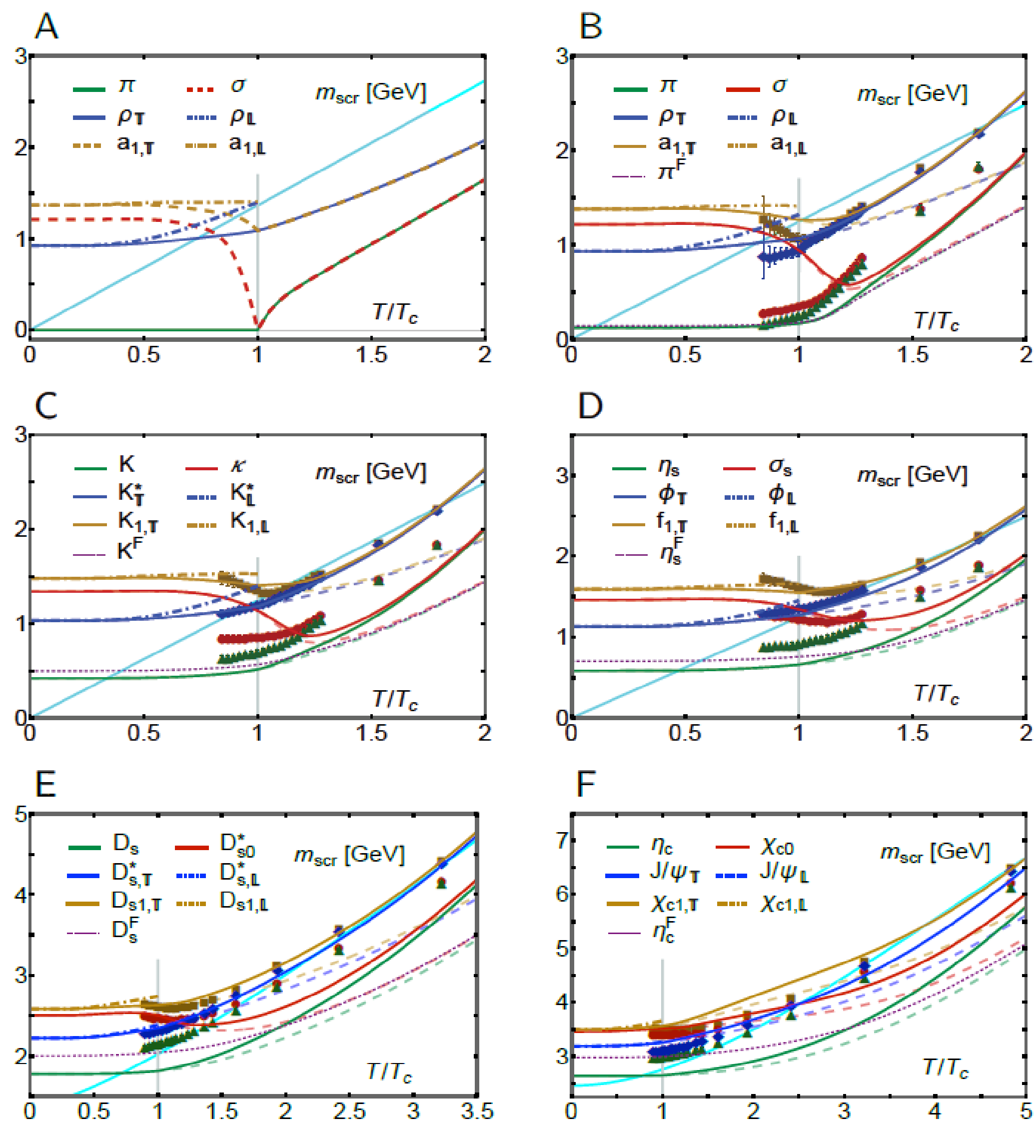


FIG. 8. Screening masses of $J^P = 3/2^{\pm}$ baryon ground states. In each figure: *solid green curve*: positive-parity baryon; *dashed red curve*: negative-parity baryon; and *black dot-dot-dashed curve*: free theory limit of $m = 3\pi T$.

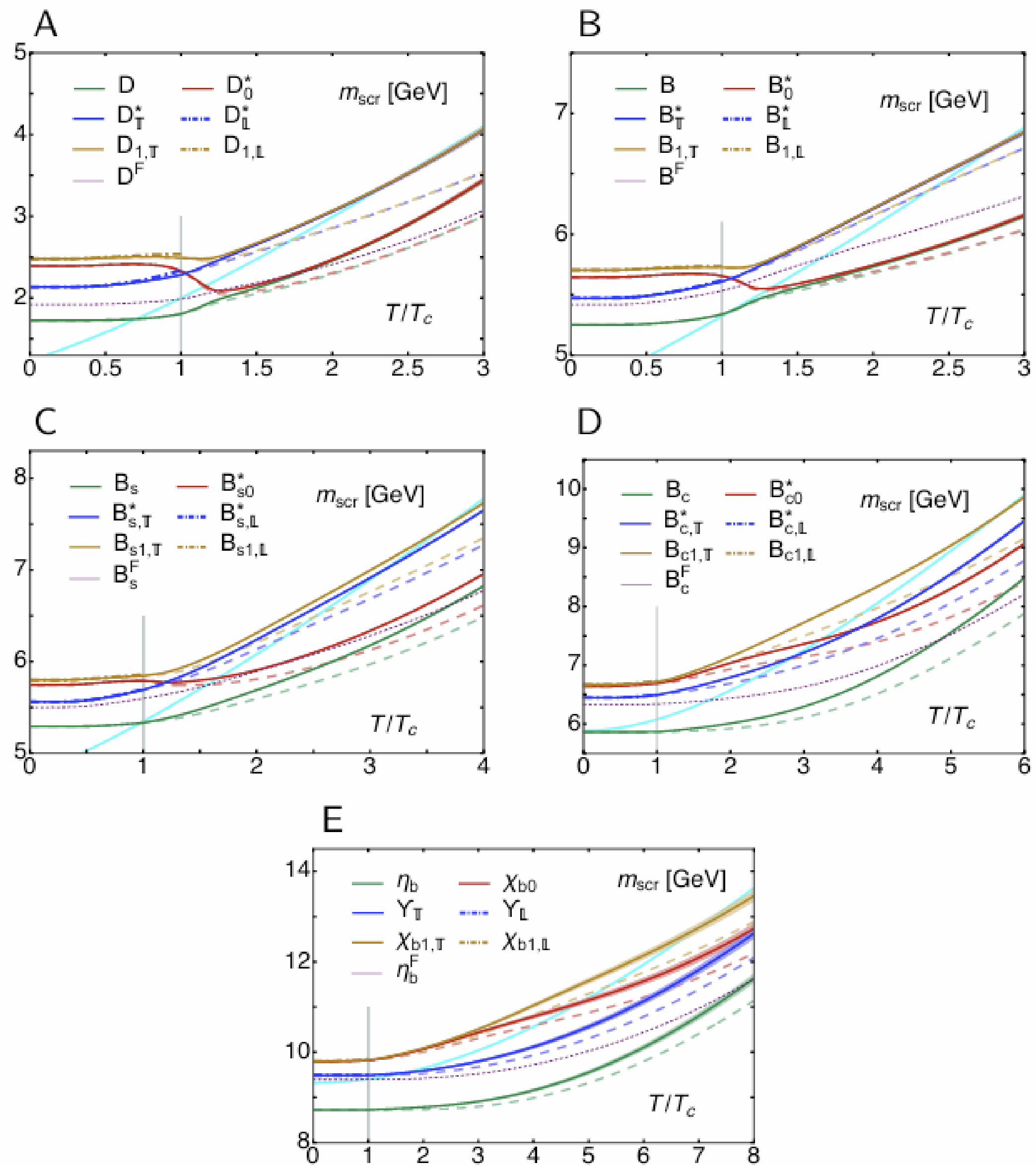
Diquark fractions: $J^P = 3/2^{\pm}$ baryons



Screening masses for light- and heavy-hadrons



Screening masses for light- and heavy-hadrons



Summary & Perspective

- Dyson-Schwinger equations, Bethe-Salpeter equations, Faddeev equation
- Diquark correlations in baryons
- A symmetry-preserving treatment of a vector $\times$ vector contact interaction (SCI) at nonzero temperature
- Screening masses of positive- and negative-parity hadron ground states, for light- and heavy-hadrons
- Large T: the scalar and pseudoscalar diquarks are dominant
- A long-term goal is to compute the hadron screening masses using a realistic QCD-connected interaction kernel (quark+diquark & three-body approaches).
- Finite density, magnetic field…

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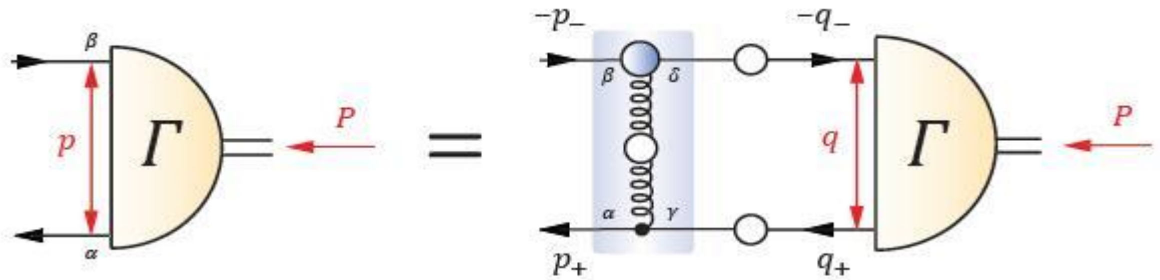
Thank you!

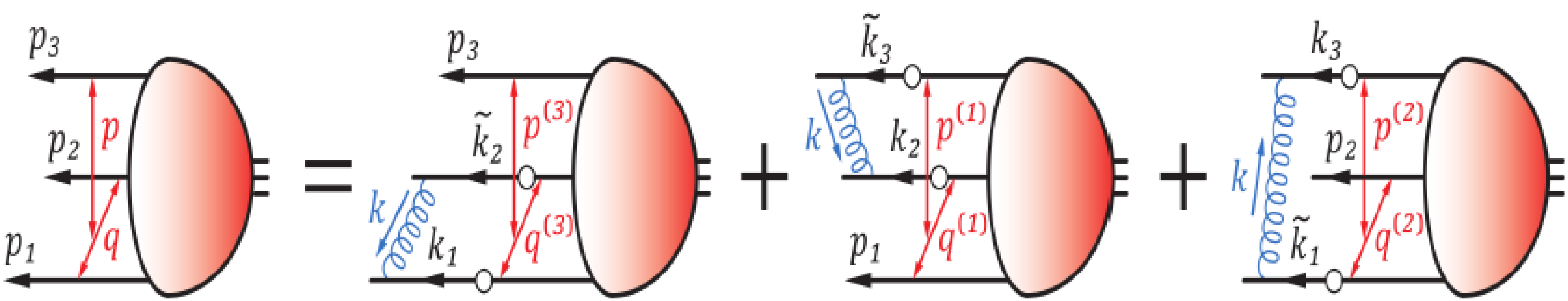
Hadrons: Bound-states in QFT

- **Mesons: a 2-body bound state problem in QFT**
  - ***Bethe-Salpeter Equation***
  - ***K* - fully amputated, two-particle irreducible, quark-antiquark scattering kernel**



- **Baryons: a 3-body bound state problem in QFT**
- ***Faddeev equation*: sums all possible quantum field theoretical exchanges and interactions that can take place between the three dressed-quarks that define its valence quark content.**

Faddeev equation in rainbow-ladder truncation



2-body correlations

- Quantum numbers:
  - $(I = 0, J^P = 0^+)$: isoscalar-scalar diquark
  - $(I = 1, J^P = 1^+)$: isovector-pseudovector diquark
  - $(I = 0, J^P = 0^-)$: isoscalar-pesudoscalar diquark
  - $(I = 0, J^P = 1^-)$: isoscalar-vector diquark
  - $(I = 1, J^P = 1^-)$: isovector-vector diquark

- ✓ G. Eichmann, H. Sanchis-Alepuz, R. Williams, R. Alkofer, C. S. Fischer, Prog.Part.Nucl.Phys. 91 (2016) 1-100
- ✓ Chen Chen, B. El-Bennich, C. D. Roberts, S. M. Schmidt, J. Segovia, S-L. Wan, Phys.Rev. D97 (2018) no.3, 034016

- Three-body bound states
  - **The diquark *Ansatz* for the 4-point Green's function of the quark-quark correlations:**