

Exotic and non-exotic meson spectroscopy, chiral symmetry, and medium modifications

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Erice
September 22, 2015

together with:

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- Sergey Dorkin (JINR, Dubna & Univ. Dubna), Leonid Kaptari (JINR, Dubna & HZDR, Dresden), Burkhard Kämpfer (HZDR, Dresden & TU Dresden)
- Stefan Leupold (Univ. Uppsala)

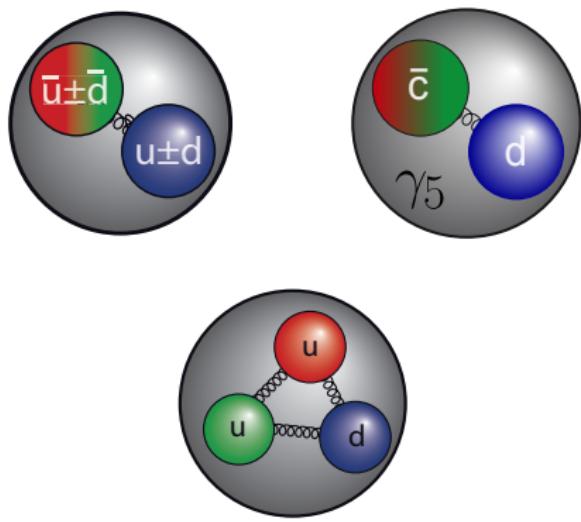
supported by:

Austrian Science Fund (FWF) project no. P25121-N27,
Heisenberg-Landau program of the JINR-FRG collaboration,
GSI-FE, BMBF

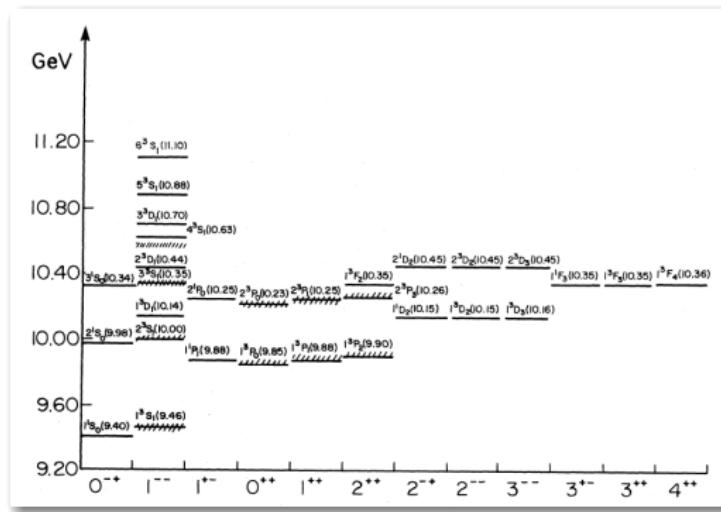
Covariant.ModelsOfHadrons.com

The Problem

- study hadrons as composites of quarks and gluons
 - issues
 - chiral symmetry and $D\chi SB$
 - Poincaré covariance
 - confinement
 - perturbative limit
- calculate observables
- comprehensive phenomenology



Incitement



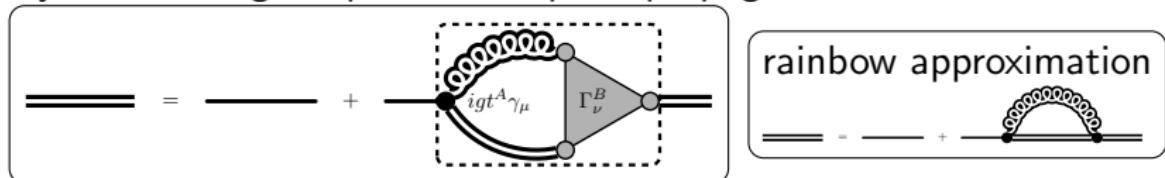
[Bottomonium by Godfrey, Isgur, 1985]

The Tool

- Dyson-Schwinger equations can be used to solve QCD
- Bethe-Salpeter and Faddeev-type equations allow covariant and symmetry-preserving study of bound-state problems
- Infinite set of coupled (and nonlinear) integral equations
- Numerical studies: Truncation \leftrightarrow numerical effort
- Make the truncation respect symmetries
- Construct sophisticated models
- Perform reliable calculations of hadron properties

Dyson-Schwinger and Bethe-Salpeter Equations

Dyson-Schwinger equation for quark propagator

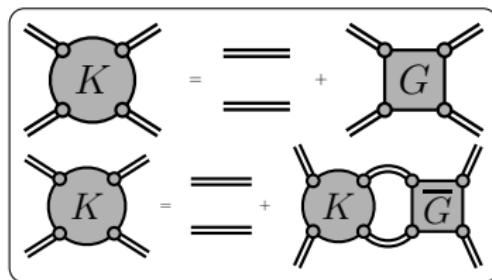


rainbow approximation

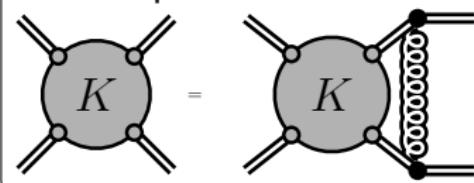


$$S^{-1}(p) = S^{(0)-1} + \int dq G_{\mu\nu}(p-q)\gamma_\mu S(q)\gamma_\nu$$

Bethe-Salpeter equation



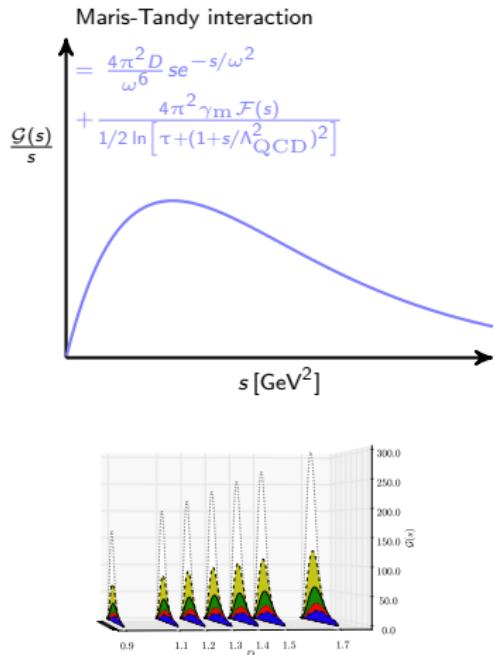
homogeneous, rainbow-ladder approximation



$$\Gamma(p; P) = \Gamma^{(0)}(p) - \int dq G_{\mu\nu}(p-q)\gamma_\mu S(q_+) \Gamma(q; P) S(q_-) \gamma_\nu$$

Model and Strategy

... so far no comprehensive attempt at RL meson phenomenology

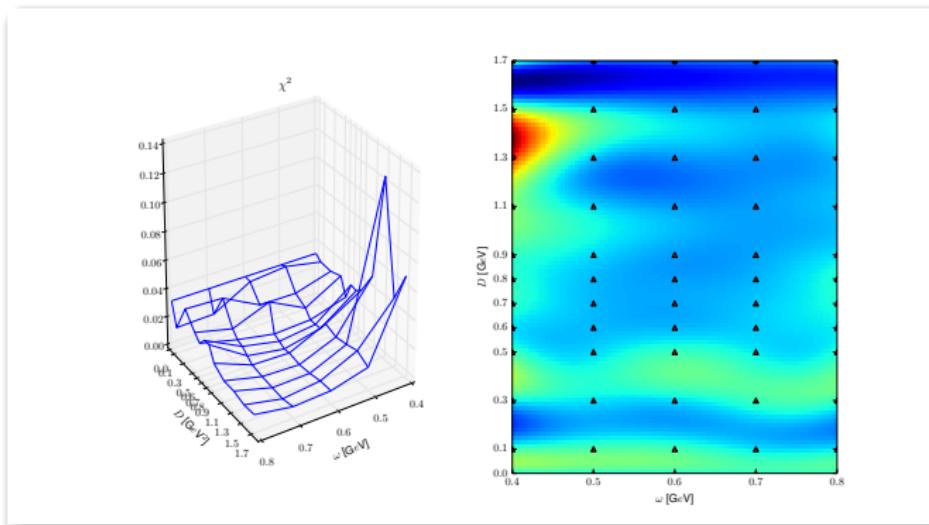


- application to systems where corrections to RL are expected to be least important → bottomonium
- leave functional and UV form unchanged
- allow for more freedom in the effective interaction → quark mass dependence, vary ω and D independently
- include lowest radial excitations
- $J = 0, 1, 2, \dots$

... is that good enough?

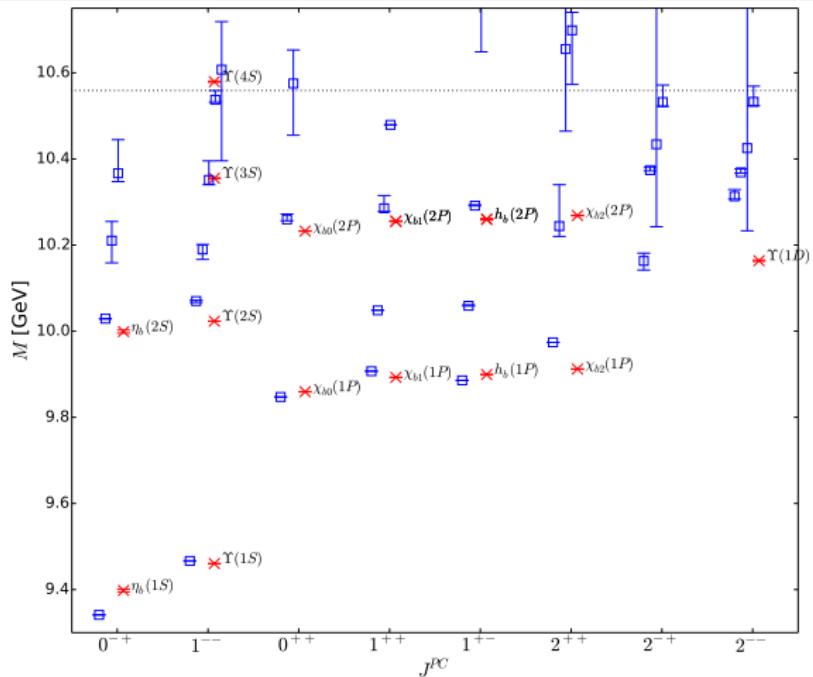
Bottomonium

- evaluate splittings at $(\omega - D)$ -grid
- find minimal $\chi^2(\omega, D) = \sum_{\text{splittings}} (\Delta M_{\text{exp}} - \Delta M_{\text{th}})^2$
- find minimal $\bar{\chi}^2(m_q) = \sum_{\text{groundstates}} (M_{\text{exp}} - M_{\text{th}})^2$ for optimal (ω, D)



[C. Popovici, T. Hilger, M. Gómez-Rocha, A. Krassnigg, Few Body Syst. **56**: 481, 2015.]

Bottomonium



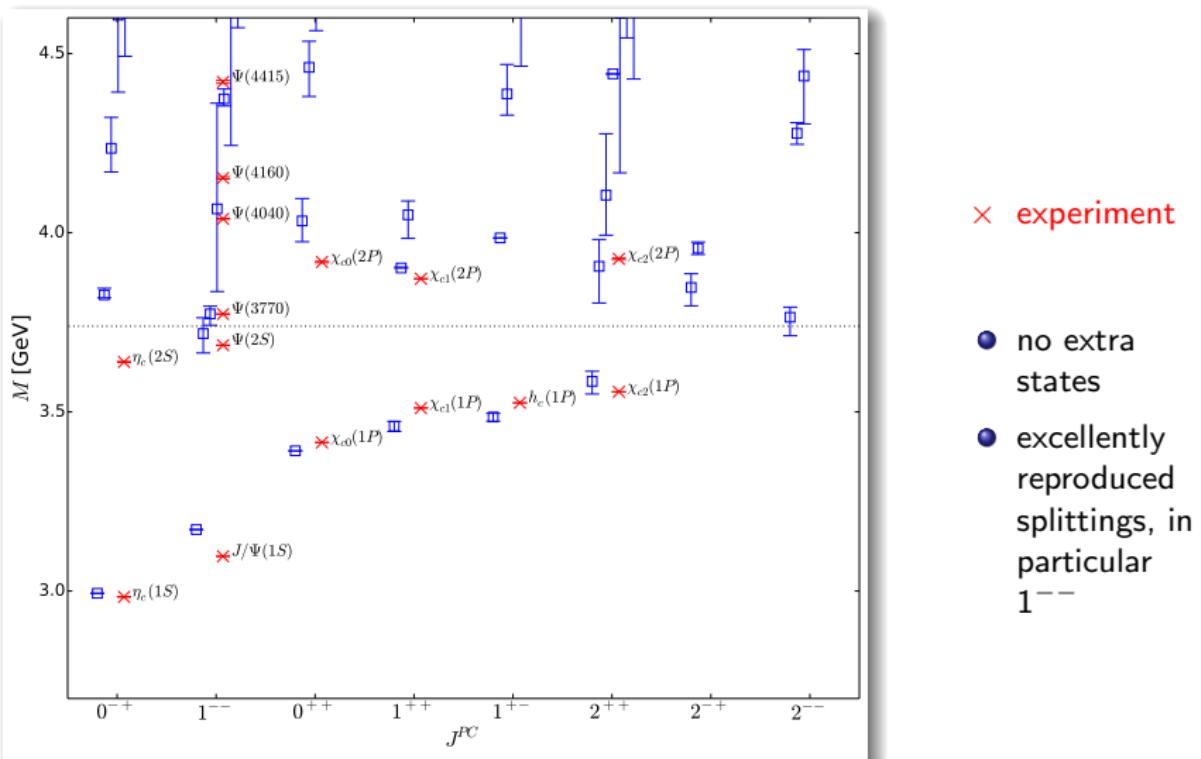
× experiment

- good identification of states
- well reproduced splittings (excitations, level orderings)

[T. Hilger, C. Popovici, M. Gómez-Rocha, A. Krassnigg, Phys. Rev. D 91: 034013, 2015.]

- $m_b = 3.635 \text{ GeV}$ at $\mu = 19 \text{ GeV}$, $\omega = 0.7 \text{ GeV}$, $D = 1.3 \text{ GeV}^2$

Charmonium

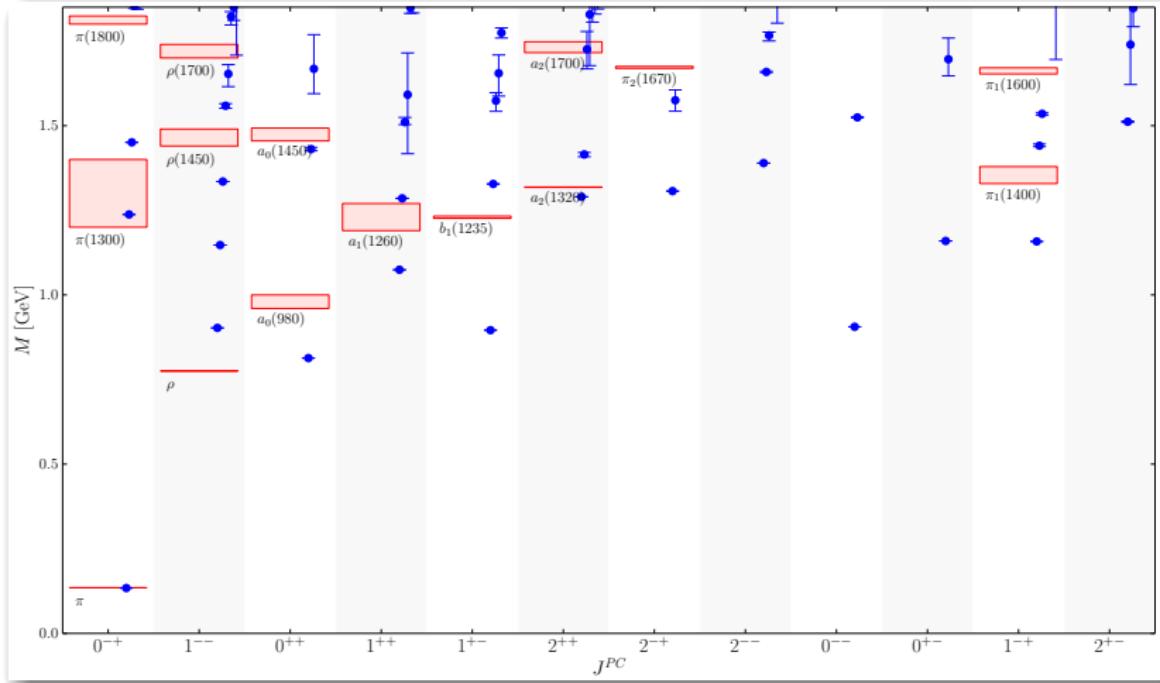


- no extra states
- excellently reproduced splittings, in particular 1^{--}

[T. Hilger, C. Popovici, M. Gómez-Rocha, A. Krassnigg, Phys. Rev. D **91**: 034013, 2015.]

- $m_c = 0.855 \text{ GeV}$ at $\mu = 19 \text{ GeV}$, $\omega = 0.7 \text{ GeV}$, $D = 0.5 \text{ GeV}^2$

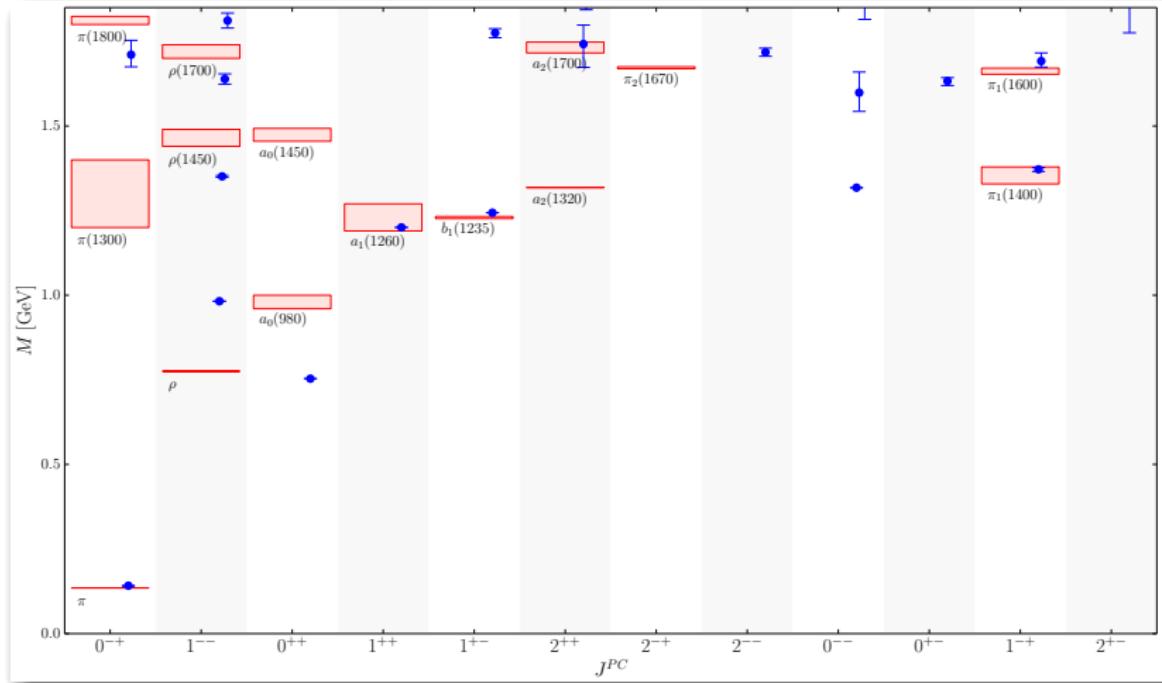
Light Isovector Quarkonium



[T. Hilger, M. Gómez-Rocha, A. Krassnigg, arXiv:1508.07183]

- $m_q = 0.003 \text{ GeV}$ at $\mu = 19 \text{ GeV}$, $\omega = 0.4 \text{ GeV}$, $D = 1.7 \text{ GeV}^2$

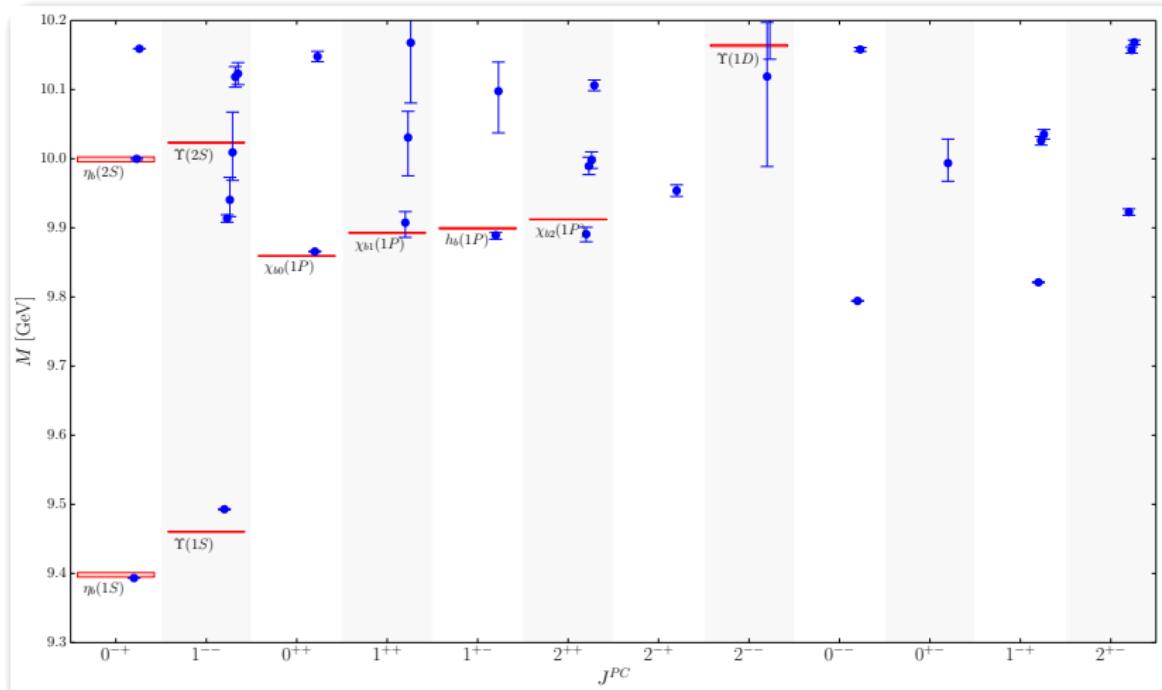
Exotics: Light Isovector Quarkonium



[T. Hilger, M. Gómez-Rocha, A. Krassnigg, Phys. Rev. D **91**: 114004, 2015.]

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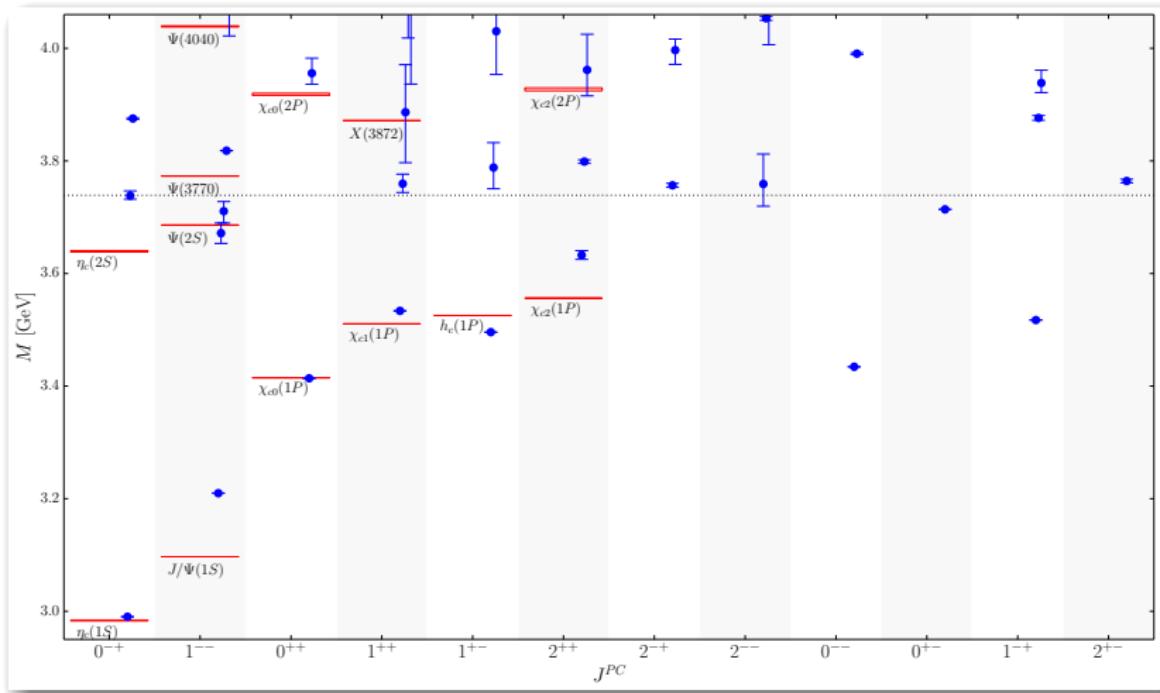
Exotics: Bottomonium



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- $m_b = 3.635$ GeV at $\mu = 19$ GeV, $\omega = 0.7$ GeV, $D = 0.8$ GeV 2

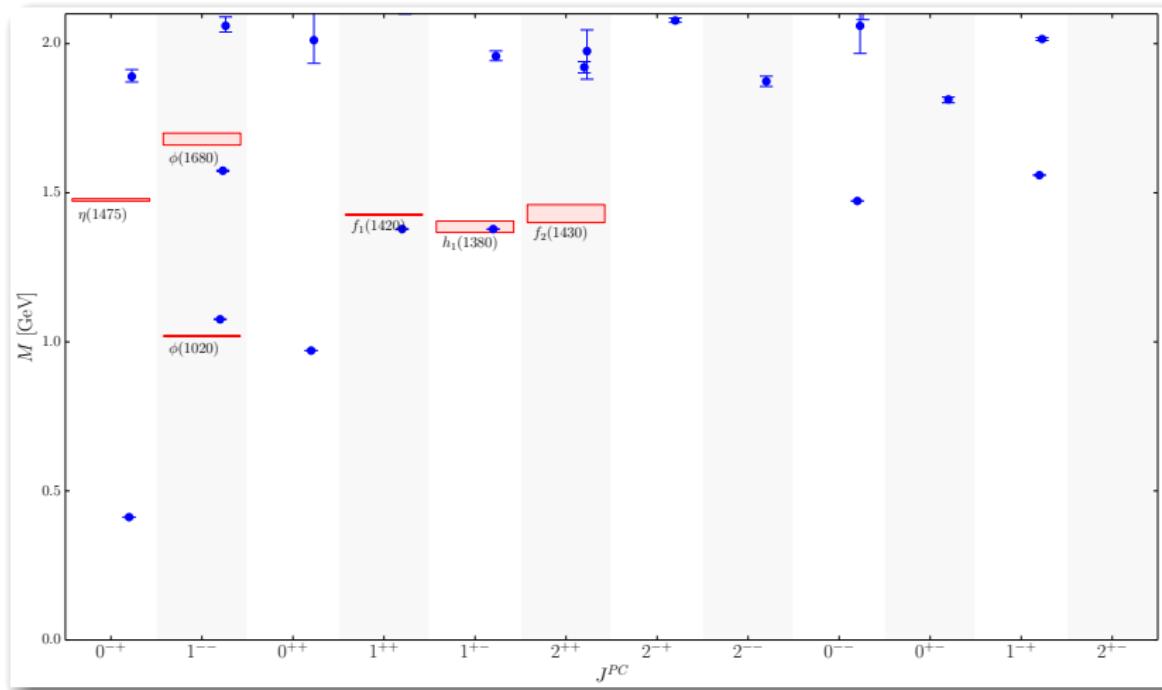
Exotics: Charmonium



[T. Hilger, M. Gómez-Rocha, A. Krassnigg, Phys. Rev. D **91**: 114004, 2015.]

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Exotics: Strangeonium



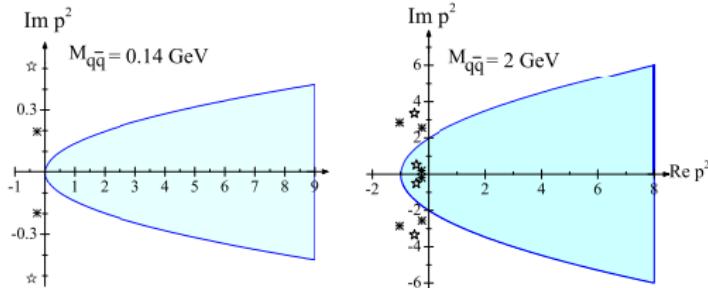
[T. Hilger, M. Gómez-Rocha, A. Krassnigg, arXiv:1508.07183]

- $m_q = 0.070$ GeV at $\mu = 19$ GeV, $\omega = 0.8$ GeV, $D = 1.7$ GeV 2

Outlook: Decay Constants

state	J^{PC}	radial excitations							
		ground states		1st		2nd			
		f calc.	f exp.	f calc.	f exp.	f calc.	f exp.		
η_c	0^{-+}	401	338	244(12)	243()	145(145)	—		
J/Ψ	1^{--}	450	416	30(3)	296()	118(91)	100()		
η_b	0^{-+}	773	—	419(8)	—	534(57)	—		
Υ	1^{--}	768	701	467(17)	497()	41(7)	430()		

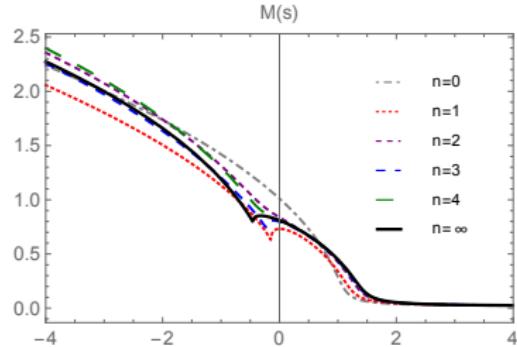
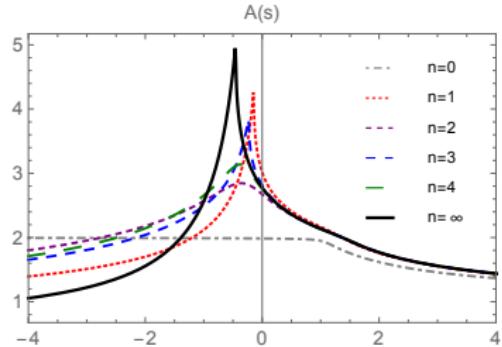
A Path to Open Flavor Meson Spectroscopy



[S. Dorkin, L. Kaptari, T. Hilger, B. Kämpfer, Phys. Rev. C **89**: 034005, 2014.]

- numerics technically involved
- Outlook: AVWTI construction
- estimate BRL corrections
- Munczek-Nemirovsky model: $\mathcal{G}(s) \propto s \delta^{(4)}(s)$
- integral equations reduce to algebraic equations
- infinite dressing of quark-gluon vertex with gluon loops possible

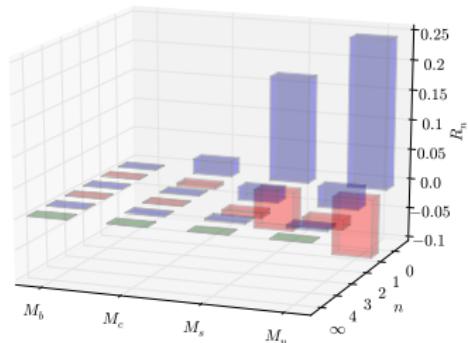
Quark-Gluon Vertex and Quark Propagator



[M. Gómez-Rocha, T. Hilger, A. Krassnigg, accepted by PRD,

arXiv:1506.03686] [M. Gómez-Rocha, T. Hilger, A. Krassnigg, Few
Body Syst. **56**: 475, 2015.]

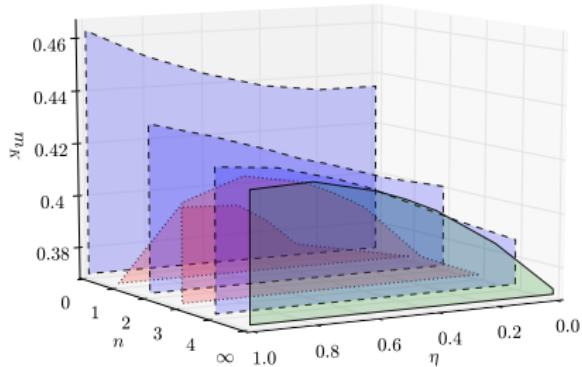
$$R_n := \frac{M_n(s=0) - M_\infty(s=0)}{M_\infty(s=0)}$$



- qualitative differences on timelike domain
- weaker effect for heavier quarks

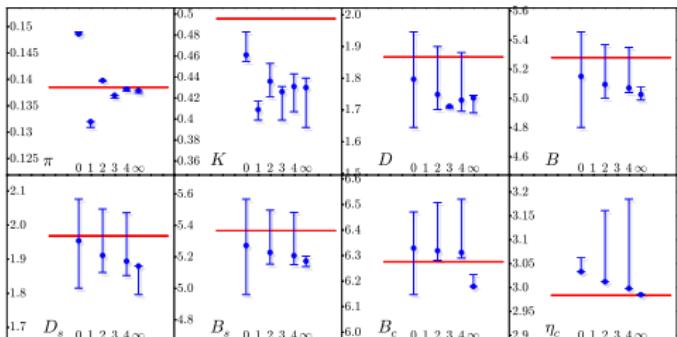
Quark-Gluon Vertex Dressing and Meson Masses

[M. Gómez-Rocha, T. Hilger, A. Krassnigg, accepted by PRD, arXiv:1506.03686]



- momentum partitioning dependence
- minimize dressing correction
- error estimate

- sizeable but not overwhelming dressing effects
- careful, comprehensive RL phenomenology worthwhile



Reminder: Chiral Symmetry

two flavor Lagrangian:

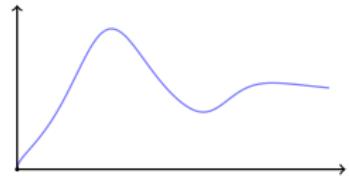
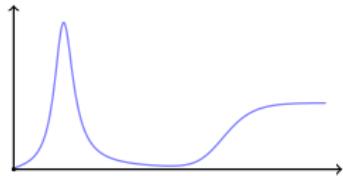
$$\mathcal{L} = \begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix}^T \left(i\gamma_\mu \partial^\mu - \begin{bmatrix} m_u & 0 \\ 0 & m_d \end{bmatrix} \right) \begin{pmatrix} u \\ d \end{pmatrix}$$

$P = -1$ meson current:
 $j_\mu^{V,\tau}(x) = \bar{\psi} \gamma_\mu \tau \psi$

$P = +1$ meson current:
 $j_\mu^{A,\tau}(x) = \bar{\psi} \gamma_5 \gamma_\mu \tau \psi$

current-current correlator:

$$\Pi_{\mu\nu}^X(q) = i \int d^4x e^{-iqx} \langle 0 | T \left[j_\mu^{X,\tau}(x) \left(j_\nu^{X,\tau}(0) \right)^\dagger \right] | 0 \rangle$$



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chiral transformations:

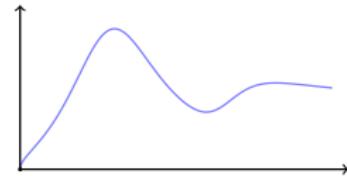
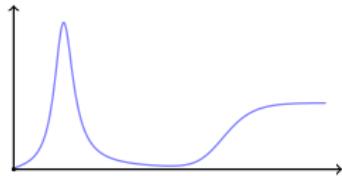
$$\mathcal{T} : \psi_{R,L} \equiv \frac{1 \pm \gamma_5}{2} \begin{pmatrix} u \\ d \end{pmatrix} \rightarrow e^{-i \frac{\vec{\lambda}}{2} \vec{\Theta}_{R,L}} \psi_{R,L}$$

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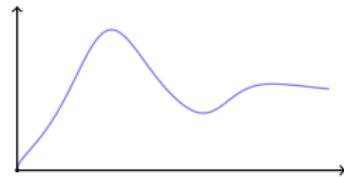
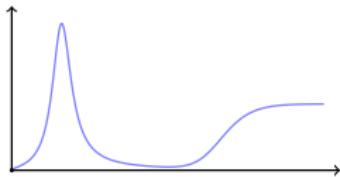
invariant for $m_{u,d} = 0$

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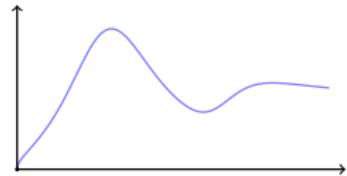
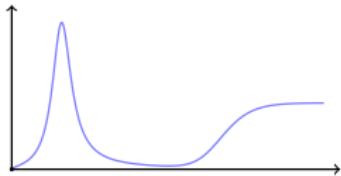
conversion by set of finite $\{\Theta_{R,L}\}$

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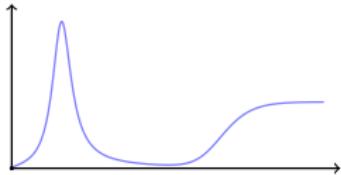
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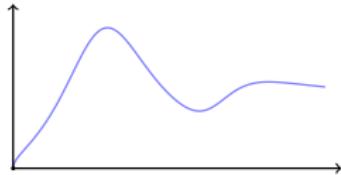
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chirally symmetric $|0\rangle$
parity blind correlators
degenerate spectra



Reminder: Chiral Symmetry and Open Flavor Mesons

three flavor Lagrangian:

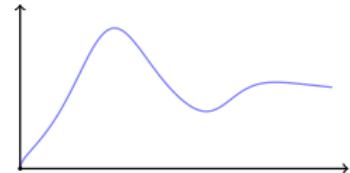
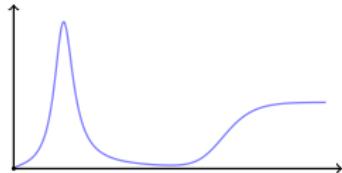
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Reminder: Chiral Symmetry and Open Flavor Mesons

three flavor Lagrangian:

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chiral transformations:

$$\mathcal{T} : \psi_{R,L} \equiv \frac{1 \pm \gamma_5}{2} \begin{pmatrix} u \\ d \\ h \end{pmatrix}$$

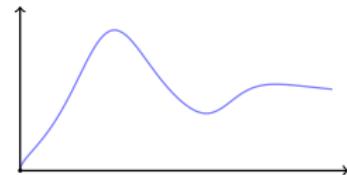
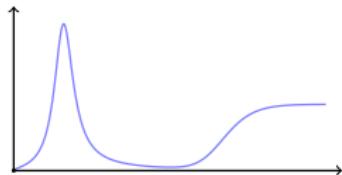
$$\rightarrow \exp \left\{ -\frac{i}{2} \begin{bmatrix} \Theta_3 & \Theta_1 - i\Theta_2 & 0 \\ \Theta_1 + i\Theta_2 & -\Theta_3 & 0 \\ 0 & 0 & 0 \end{bmatrix}_{R,L} \right\} \psi_{R,L}$$

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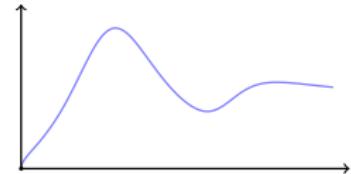
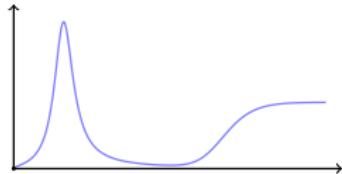
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$$\rightarrow \exp \left\{ -\frac{i}{2} \begin{bmatrix} \Theta_3 & \Theta_1 - i\Theta_2 & 0 \\ \Theta_1 + i\Theta_2 & -\Theta_3 & 0 \\ 0 & 0 & 0 \end{bmatrix}_{R,L} \right\} \psi_{R,L}$$

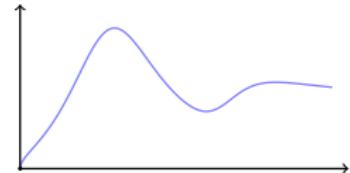
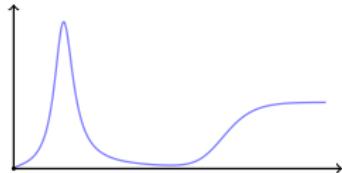
$P = -1$ meson current:
 $j_\mu^{V,\tau}(x) = \bar{\psi} \gamma_\mu \tau \psi$

conversion by set of finite $\{\Theta_{R,L}\}$

$P = +1$ meson current:
 $j_\mu^{A,\tau}(x) = \bar{\psi} \gamma_5 \gamma_\mu \tau \psi$

current-current correlator:

$$\Pi_{\mu\nu}^X(q) = i \int d^4x e^{-iqx} \langle 0 | T \left[j_\mu^{X,\tau}(x) \left(j_\nu^{X,\tau}(0) \right)^\dagger \right] | 0 \rangle$$



Reminder: Chiral Symmetry and Open Flavor Mesons

three flavor Lagrangian:

$$\mathcal{L} = \begin{pmatrix} \bar{u} \\ \bar{d} \\ \bar{h} \end{pmatrix}^T \left(i\gamma_\mu \partial^\mu - \begin{bmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_h \end{bmatrix} \right) \begin{pmatrix} u \\ d \\ h \end{pmatrix}$$



invariant for $m_{u,d} = 0$

chiral transformations:

$$\mathcal{T} : \psi_{R,L} \equiv \frac{1 \pm \gamma_5}{2} \begin{pmatrix} u \\ d \\ h \end{pmatrix}$$

$$\rightarrow \exp \left\{ -\frac{i}{2} \begin{bmatrix} \Theta_3 & \Theta_1 - i\Theta_2 & 0 \\ \Theta_1 + i\Theta_2 & -\Theta_3 & 0 \\ 0 & 0 & 0 \end{bmatrix}_{R,L} \right\} \psi_{R,L}$$

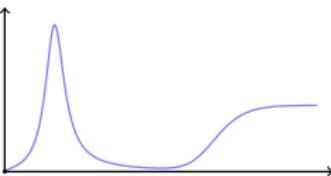
$P = -1$ meson current:
 $j_\mu^{V,\tau}(x) = \bar{\psi} \gamma_\mu \tau \psi$

conversion by set of finite $\{\Theta_{R,L}\}$

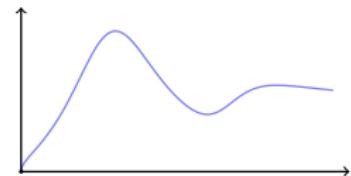
$P = +1$ meson current:
 $j_\mu^{A,\tau}(x) = \bar{\psi} \gamma_5 \gamma_\mu \tau \psi$

current-current correlator:

$$\Pi_{\mu\nu}^X(q) = i \int d^4x e^{-iqx} \langle 0 | T \left[j_\mu^{X,\tau}(x) \left(j_\nu^{X,\tau}(0) \right)^\dagger \right] | 0 \rangle$$

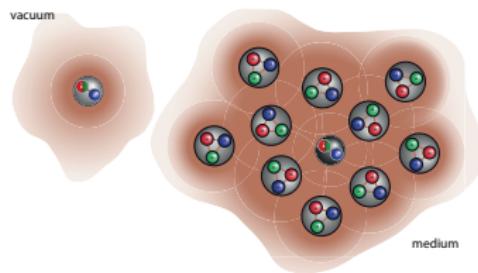


chirally symmetric $|0\rangle$
 parity blind correlators
 degenerate spectra



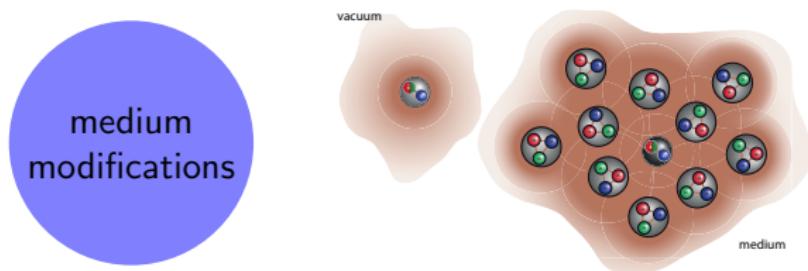
Open Flavor Mesons in the Medium

- A Window to DCSB



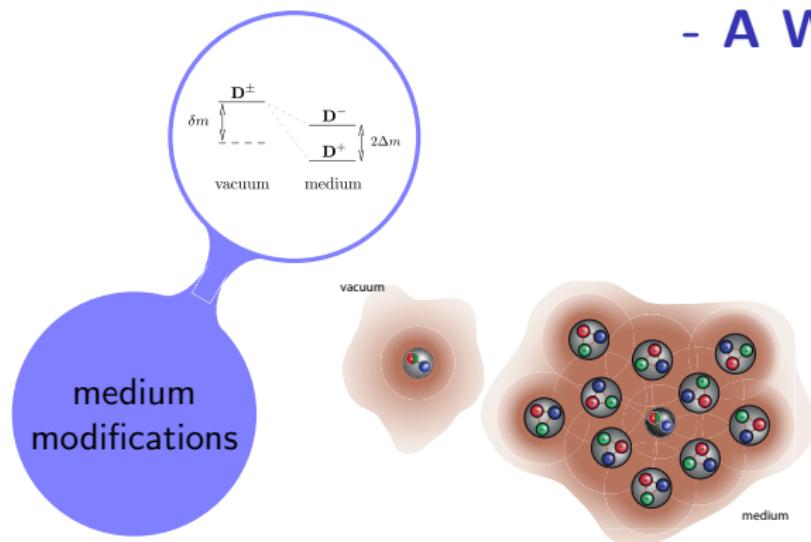
Open Flavor Mesons in the Medium

- A Window to DCSB



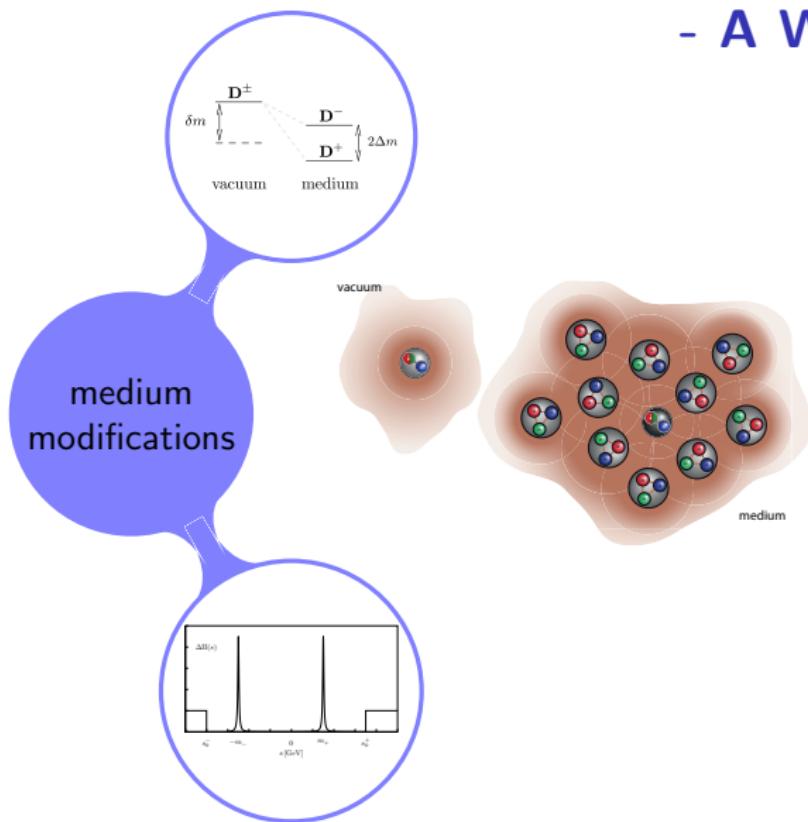
Open Flavor Mesons in the Medium

- A Window to DCSB



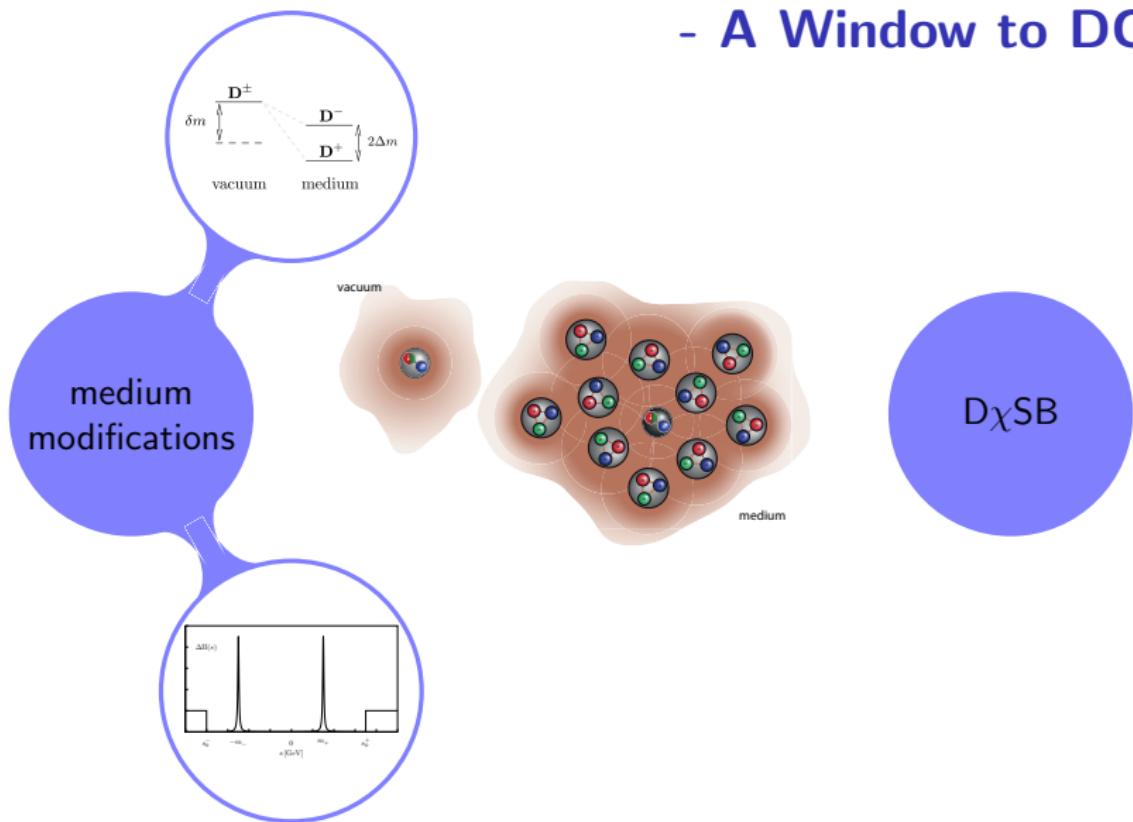
Open Flavor Mesons in the Medium

- A Window to DCSB



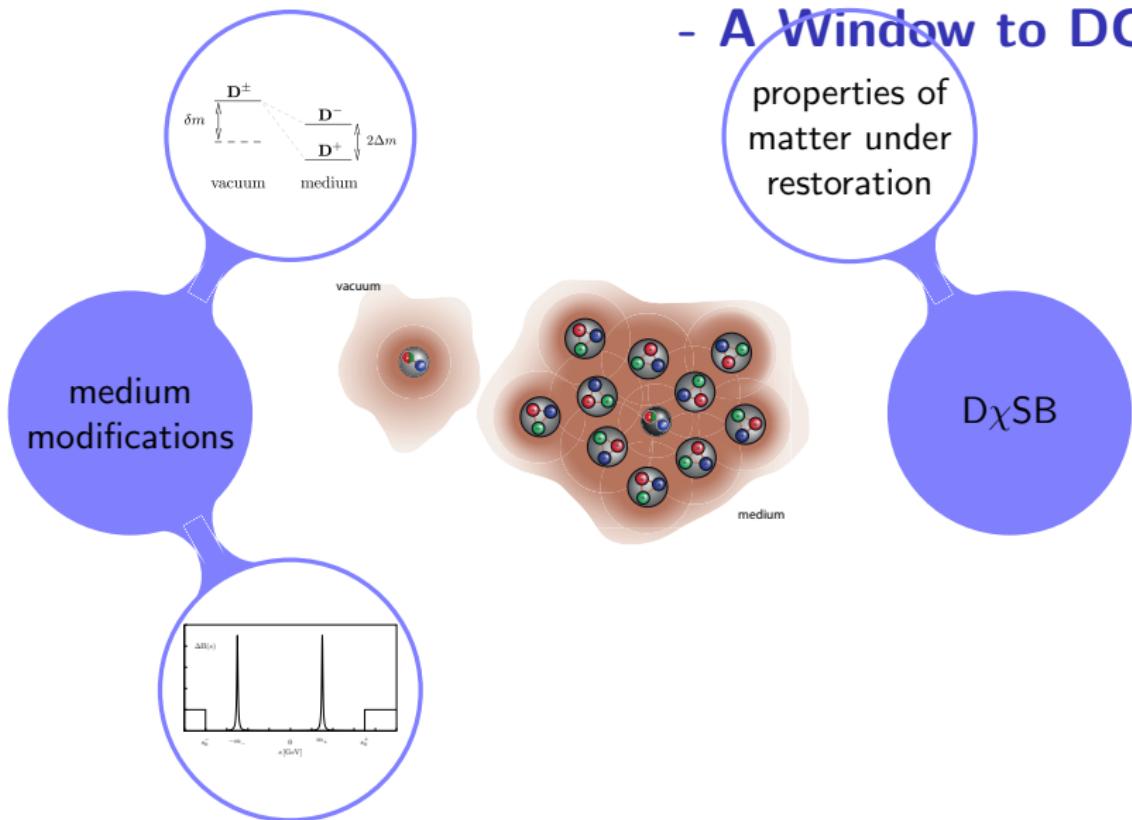
Open Flavor Mesons in the Medium

- A Window to DCSB



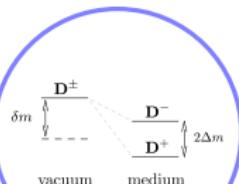
Open Flavor Mesons in the Medium

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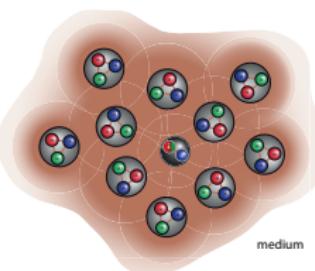
Open Flavor Mesons in the Medium

- A Window to DCSB



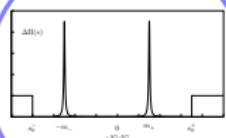
medium
modifications

vacuum



$D\chi_{SB}$

properties of
matter under
restoration



order
parameters
 $\langle \bar{q}q \rangle \rightarrow \times \leftarrow$

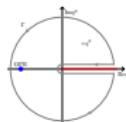
Hadron physics and QCD sum rules

current-current correlator

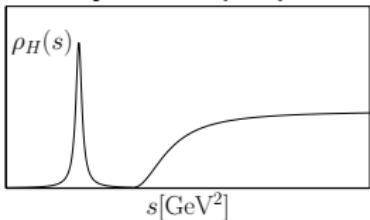
$$\Pi_{\mu\nu}(q) = i \int d^4x e^{iqx} \langle T [j_\mu(x) (j_\nu(0))^\dagger] \rangle$$

dispersion relation

$$\Pi(q^2) = \frac{1}{\pi} \int_0^\infty ds \frac{\Delta\Pi(s)}{s - q^2}$$



spectral density \leftrightarrow hadronic properties



operator product expansion

$$= C_1(q) + C_2(q) \langle \bar{q}q \rangle + C_3(q) \langle \bar{q}g\sigma\mathcal{G}q \rangle + \dots$$

$$= \text{---○---} + \text{---○---×---} + \text{---○---×---○---} + \dots$$

QCD condensates:

- encode medium dependence
- order parameters of chiral symmetry phase transition



$$\int_0^\infty \left[\rho_H(s) \right] = \text{---○---} + \text{---○---×---} + \text{---○---×---○---} + \dots$$

Order Parameters and Light Quark Currents

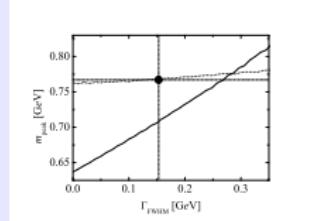
- $\langle \bar{q}q \rangle$ suppression in light-quark meson operator product expansion (e.g. ρ meson sum rules): $m_q \langle \bar{q}q \rangle$
- $\langle \bar{q}q \rangle$ influence via assumptions/models: e.g.
 - $\langle \bar{q}\Gamma q\bar{q}\Gamma q \rangle \propto \langle \bar{q}q \rangle^2$
→ fragile transition to medium
 - continuum threshold $s_0 \leftrightarrow f_\pi \leftrightarrow \langle \bar{q}q \rangle$
- determination of other order parameters (e.g. four-quark condensates $\langle \bar{q}\Gamma q\bar{q}\Gamma q \rangle$) is model dependent

Properties of the ρ Meson under Chiral Symmetry Restoration

impact of D χ SB order parameters on
the ρ meson and implications of chirally
symmetric sum rules

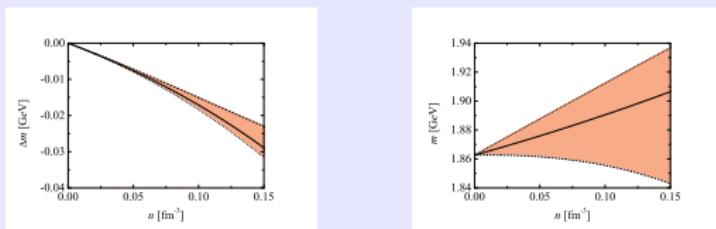
[TH, R. Thomas, B. Kämpfer, S. Leupold, Phys. Lett. B 709 (2012)

200]



Spin-0 Open Flavor Mesons at Finite Density

- particle-antiparticle splitting + shift



- $\langle \bar{q}q \rangle$ amplification due to heavy charm quark mass: $m_c \langle \bar{q}q \rangle$

[TH, R. Thomas, B. Kämpfer, Phys. Rev. C **79** (2009) 025202]

[S. Zschocke, TH, B. Kämpfer, Eur. Phys. J. A **47** (2011) 151]

[TH, B. Kämpfer, Nucl. Phys. B Proc. Suppl. **207-208** (2010) 025202]

[TH, B. Kämpfer, Conf. Proc. Italian Phys. Soc. **99** (2010)]

[B. Kämpfer, TH, H. Schade, R. Schulze, G. Wolf, PoSBormio **2010**]

[R. Rapp et al., *In-medium excitations*, Lect. Notes Phys. **814** 335 (2011)]

Chiral QCD Sum Rules for Open Flavor Spin-0 and -1 Mesons at Finite Density

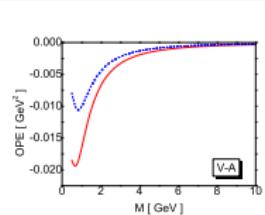
- Weinberg-Kapusta-Shuryak sum rules: $\langle \bar{q}q \rangle$ -suppression by light quark mass
- open flavor chiral partner sum rules: spectral differences driven by order parameters only
- amplification of order parameters due to heavy charm quark mass
- hierarchy of order parameters

[TH, B. Kämpfer, S. Leupold, Phys. Rev. C **84** (2011) 045202]

[TH, T. Buchheim, B. Kämpfer, S. Leupold, Prog. Part. Nucl. Phys. **67** (2012) 188]

[TH, R. Schulze, B. Kämpfer, J. Phys. G: Nucl. Part. Phys. **37** (2010) 094054]

[TH, B. Kämpfer, Nucl. Phys. Proc. Suppl. **207-208** (2010) 277]



Four-Quark Condensates and Open Flavor Mesons

[T. Buchheim, TH, B. Kämpfer,

Phys. Rev. C **91** (2015)] [T. Buchheim,

TH, B. Kämpfer, arXiv:1509.06144]

- order parameters
- spin-0 and -1
- in-medium
- chiral sum rules

Four-Quark Condensates and Open Flavor Mesons

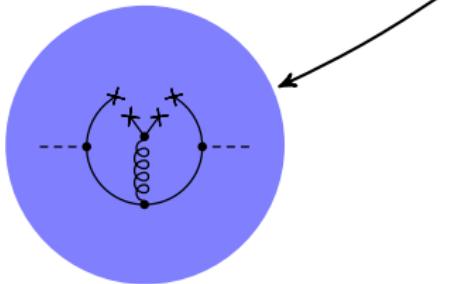
[T. Buchheim, TH, B. Kämpfer,

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$$\langle \bar{\psi} \sigma \tau \Gamma \psi \bar{\psi} \sigma' \tau' \Gamma' \psi \rangle$$



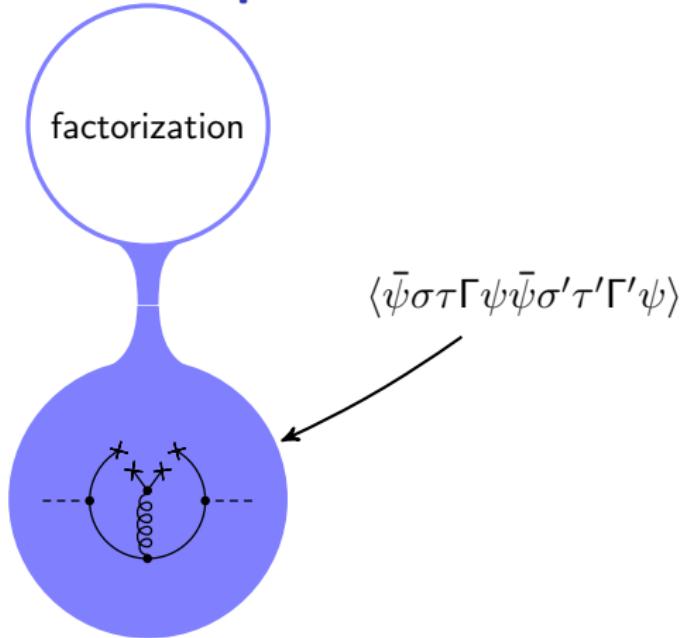
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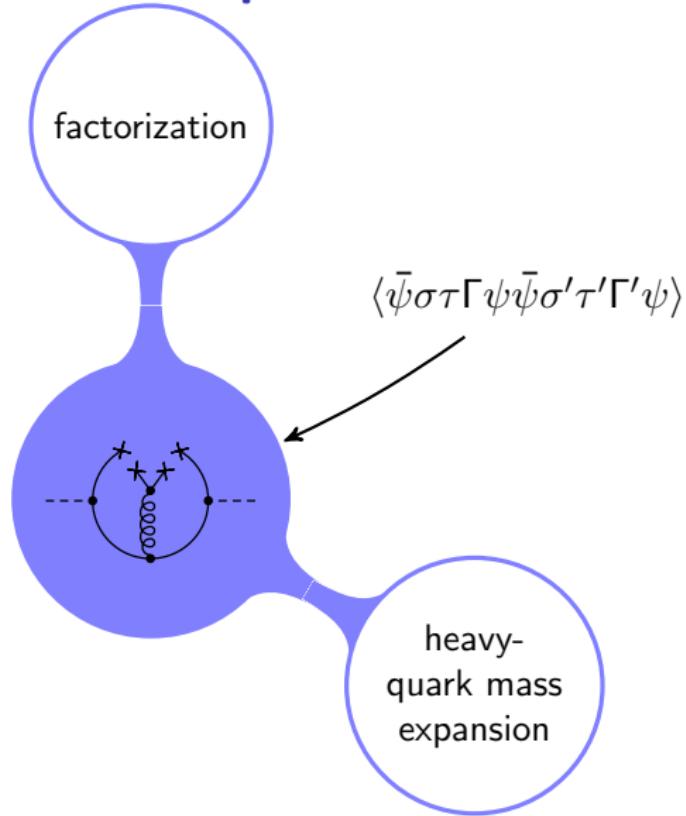
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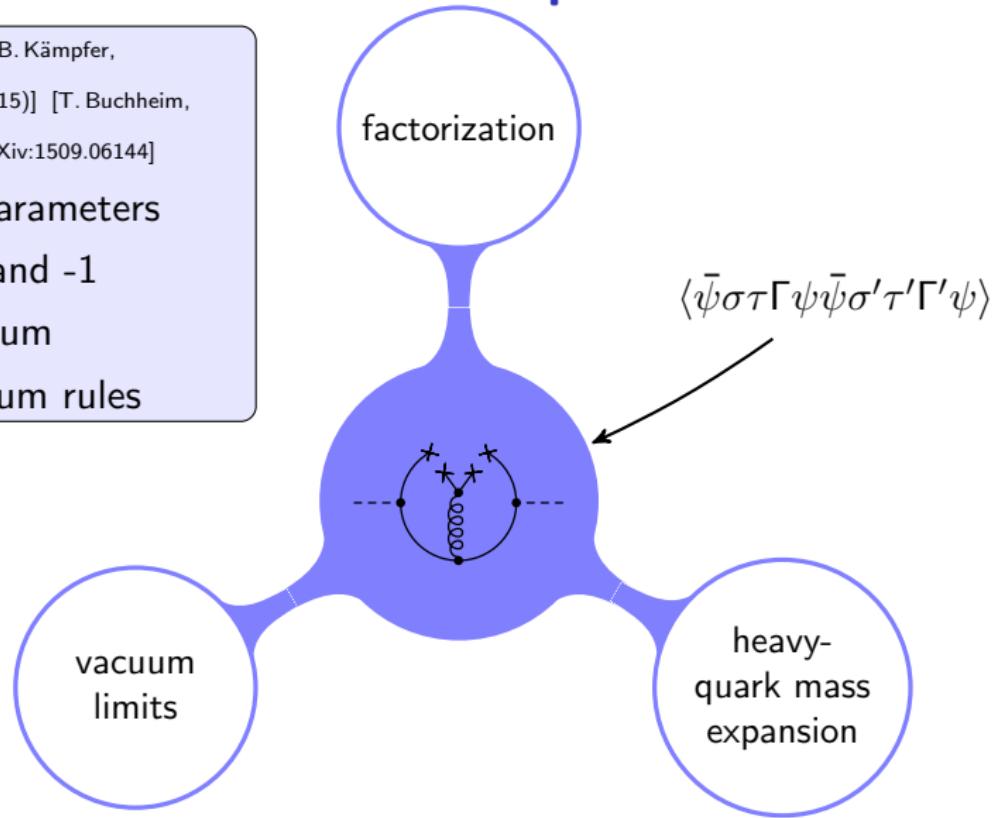
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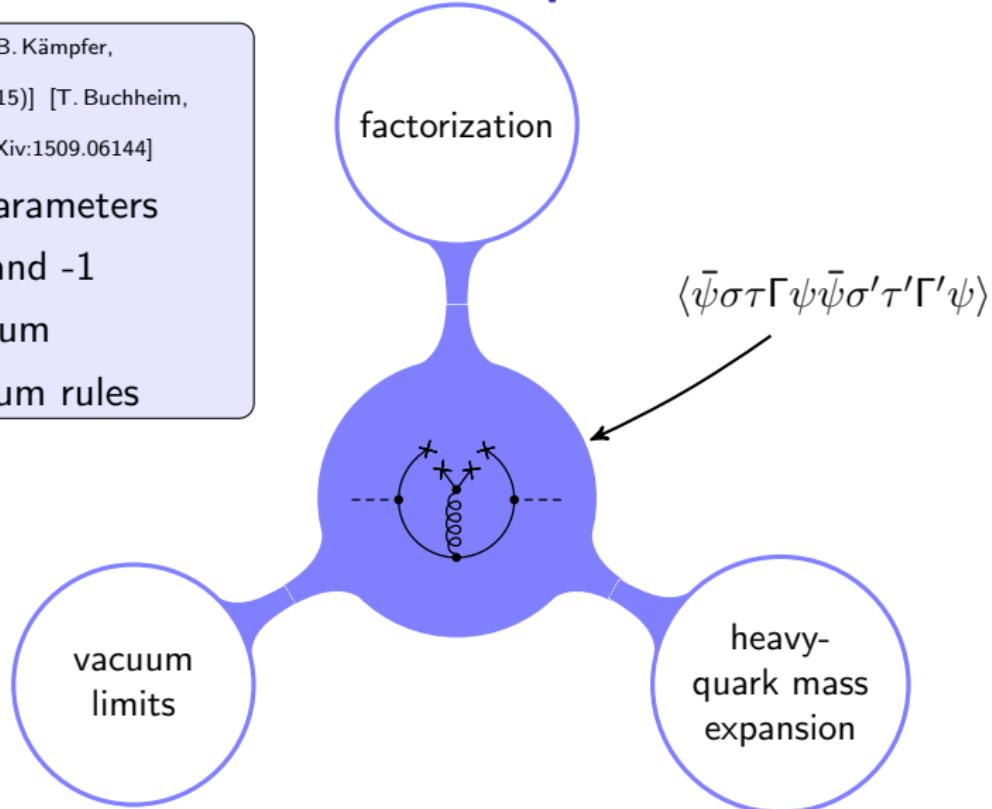


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Phys. Rev. C **91** (2015)] [T. Buchheim,
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- order parameters
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- in-medium
- chiral sum rules



[T. Buchheim, TH, B. Kämpfer, J. Phys. Conf. Ser. **503** (2014)]
[T. Buchheim, TH, B. Kämpfer, E.P.J. WoC **81** (2014)]

[T. Buchheim, TH, B. Kämpfer, Nucl. Phys. Proc. Suppl. **258-259** (2015)]

Summary I

- quark mass dependence of effective interaction
- optimized rainbow-ladder DS-BS study describes ground states and lowest radial excitations
- extra states in vector- and axial-vector channel for bottomonium
- *exotic* charmonium, bottomonium (and light isovector) spectrum
- 1st BRL study of open flavor mesons in Munczek-Nemirovsky model
- stay tuned: ... decay constants ... open flavor mesons ...

[M. Gómez-Rocha, T. Hilger, A. Krassnigg, accepted by PRD, arXiv:1506.03686]

[T. Hilger, M. Gómez-Rocha, A. Krassnigg, arXiv:1508.07183]

[T. Hilger, M. Gómez-Rocha, A. Krassnigg, Phys. Rev. D **91**: 114004, 2015.]

[T. Hilger, C. Popovici, M. Gómez-Rocha, A. Krassnigg, Phys. Rev. D **91**: 034013, 2015.]

[M. Gómez-Rocha, T. Hilger, A. Krassnigg, Few Body Syst. **56**: 475, 2015.]

[C. Popovici, T. Hilger, M. Gómez-Rocha, A. Krassnigg, Few Body Syst. **56**: 481, 2015.]

Summary II

light four-quark condensates for D mesons in medium

[T. Buchheim, TH, B. Kämpfer, Phys. Rev. C **91** (2015)]

- heavy-quark mass expansion and factorization of four-quark condensates in the medium
- continuous transition from medium to vacuum → algebraic vacuum limits

[T. Buchheim, TH, B. Kämpfer, J. Phys. Conf. Ser. **503** (2014)]

[T. Buchheim, TH, B. Kämpfer, Nucl. Phys. Proc. Suppl. **258-259** (2015)]

[T. Buchheim, TH, B. Kämpfer, E. P. J. WoC **81** (2014)]



Der Wissenschaftsfonds.

KARL-FRANZENS-UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



Thank You!

Your funding
agency
could be here!

T. Hilger