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# Chiral symmetry, meson spectroscopy, and medium modifications

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Leibnitz
October 7, 2015

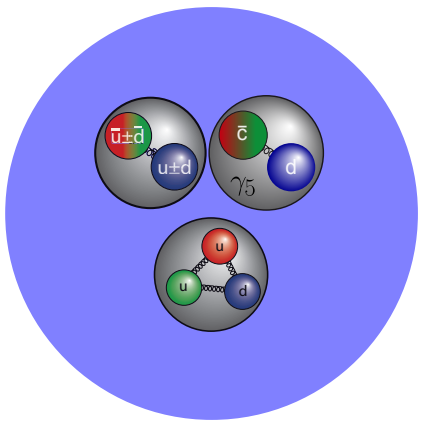
together with:

- Maria Gómez-Rocha (ECT*, Trento), Carina Popovici, Andreas Krassnigg (Univ. Graz), Wolfgang Lucha (HEPHY, Vienna)
- 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`

# Meson Spectroscopy and the Dyson-Schwinger–Bethe-Salpeter Equation Approach



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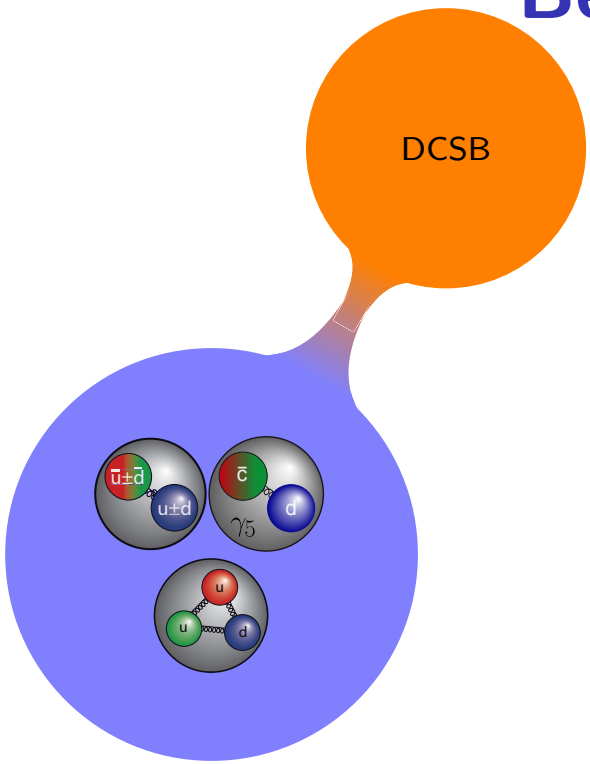

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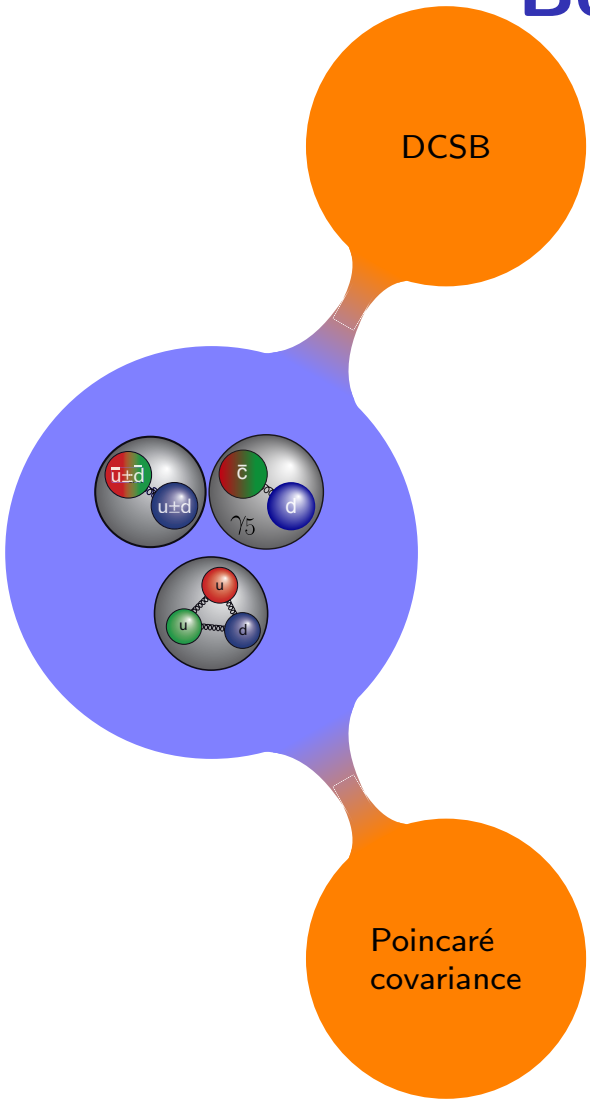

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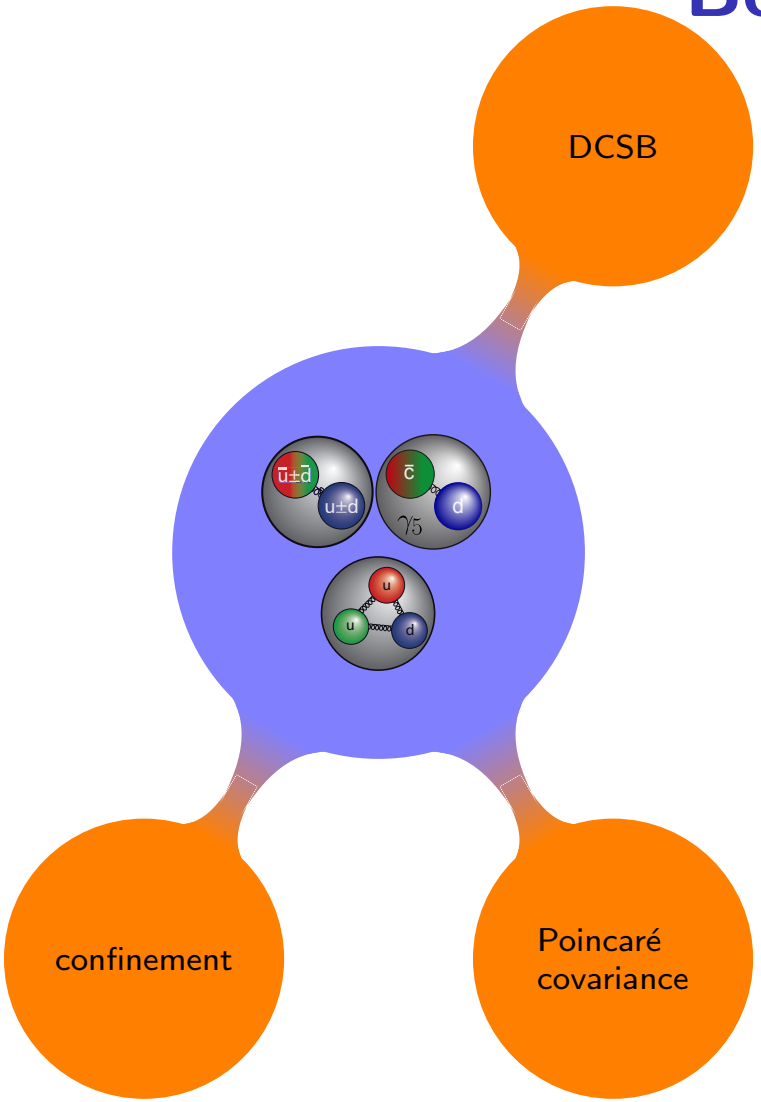

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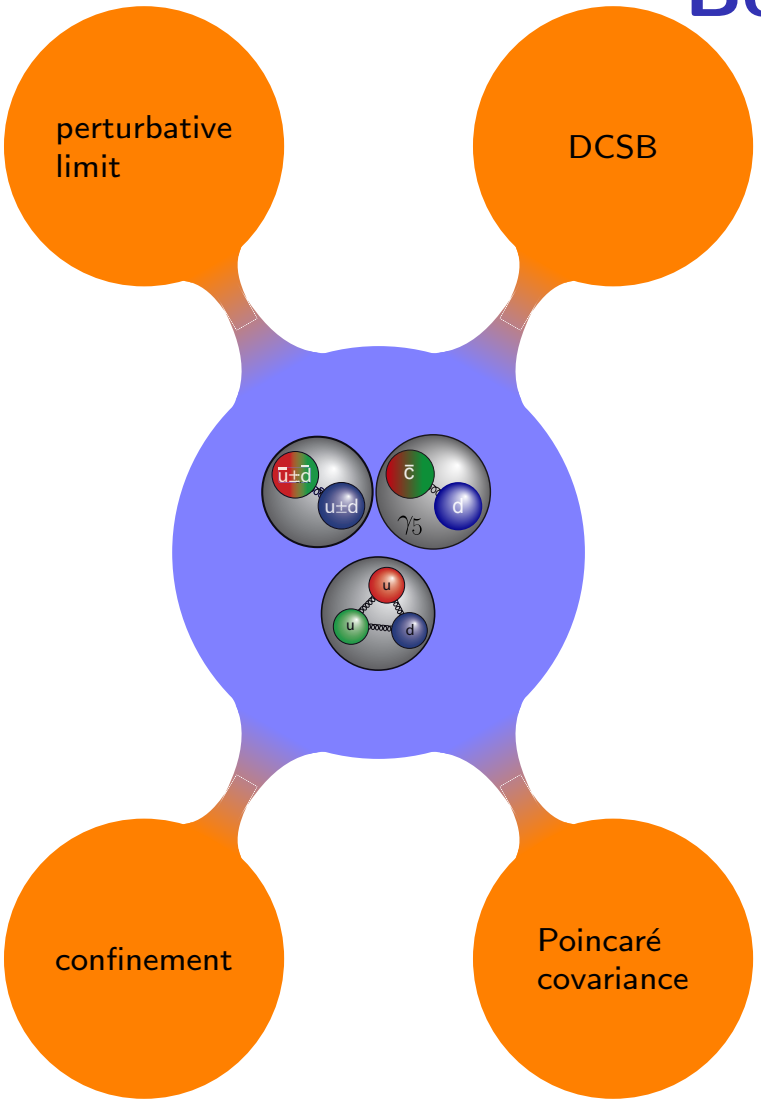

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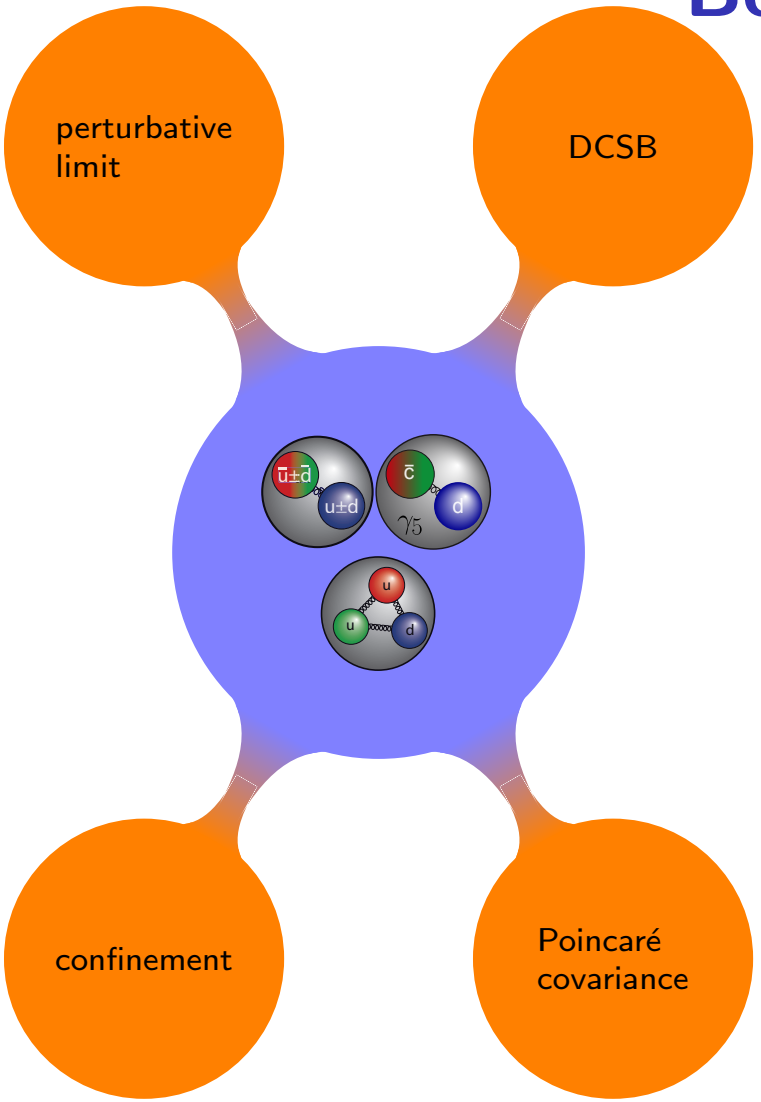


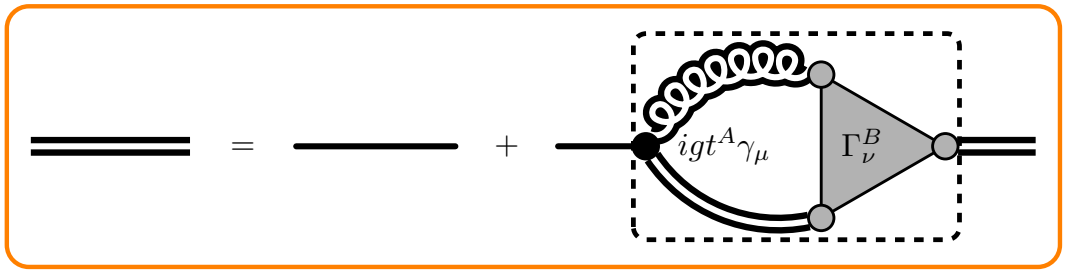

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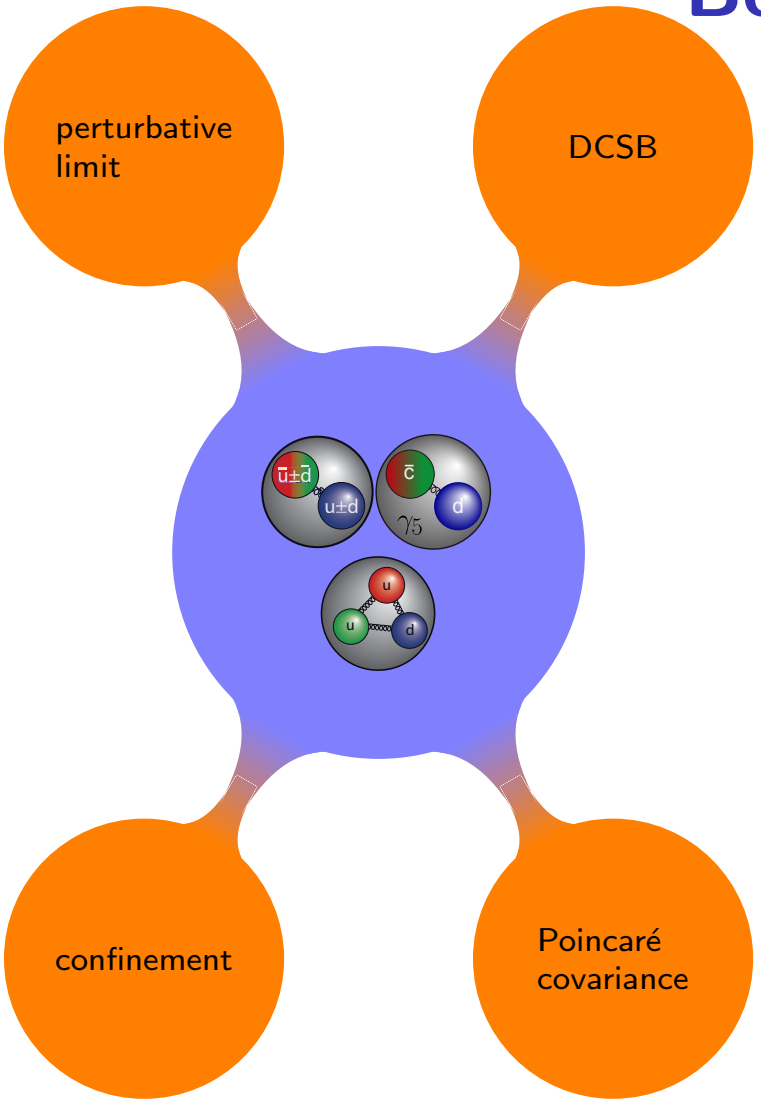


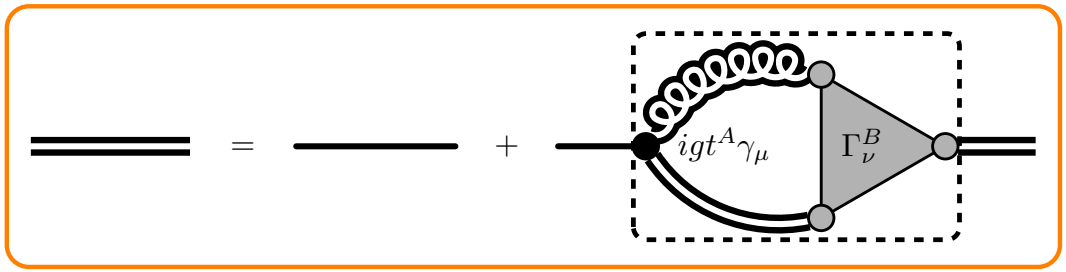


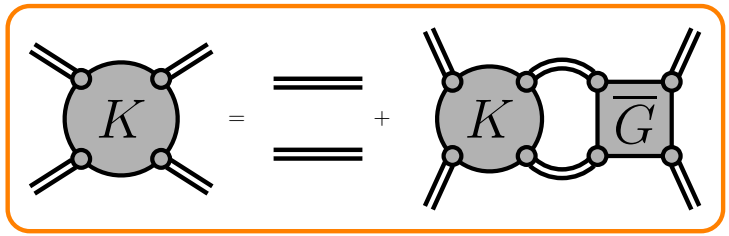

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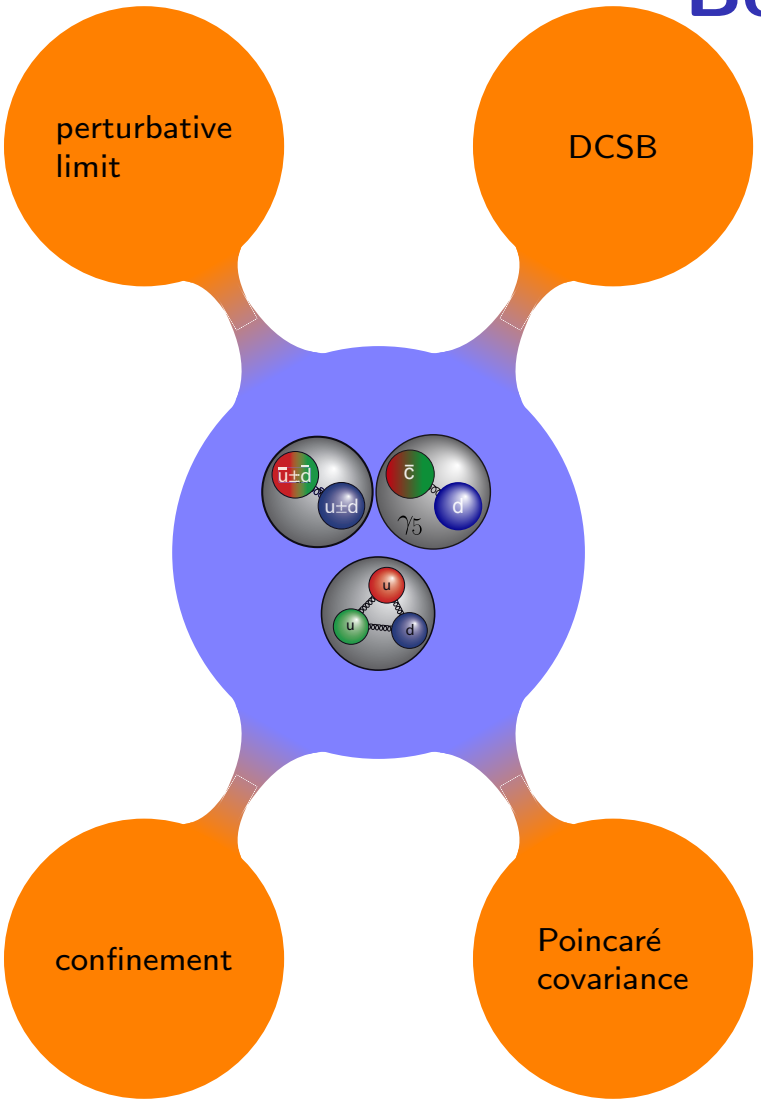


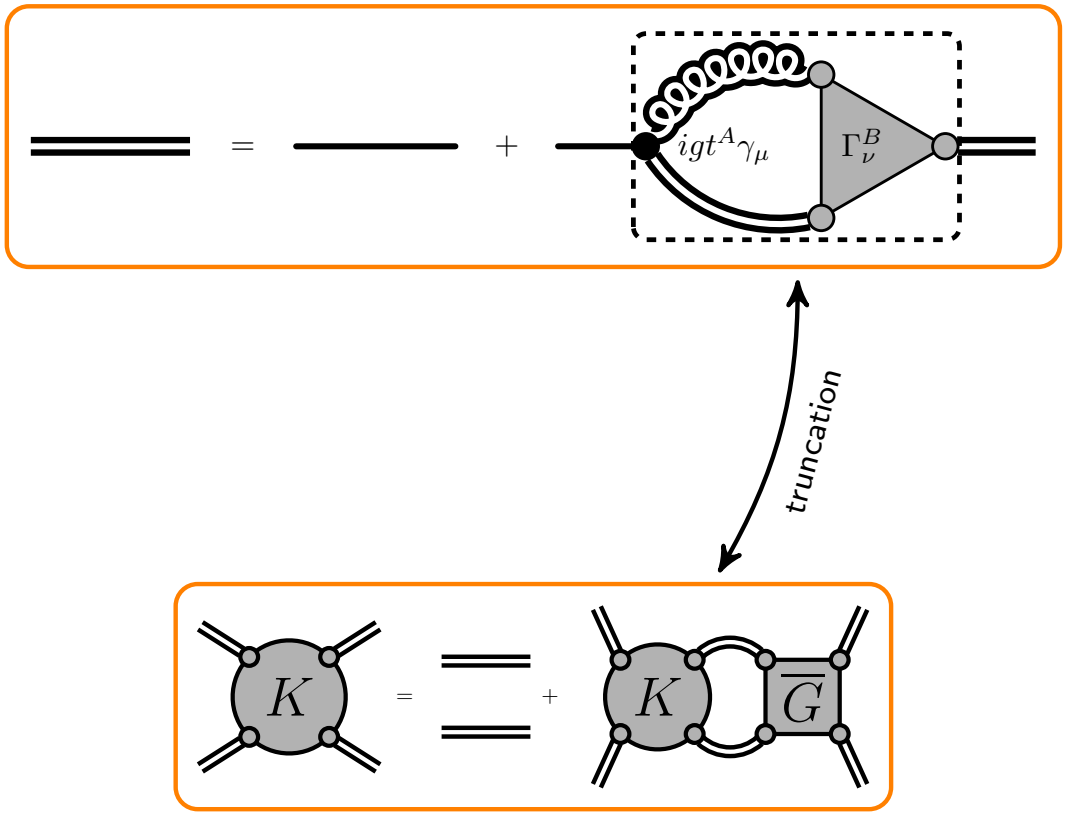

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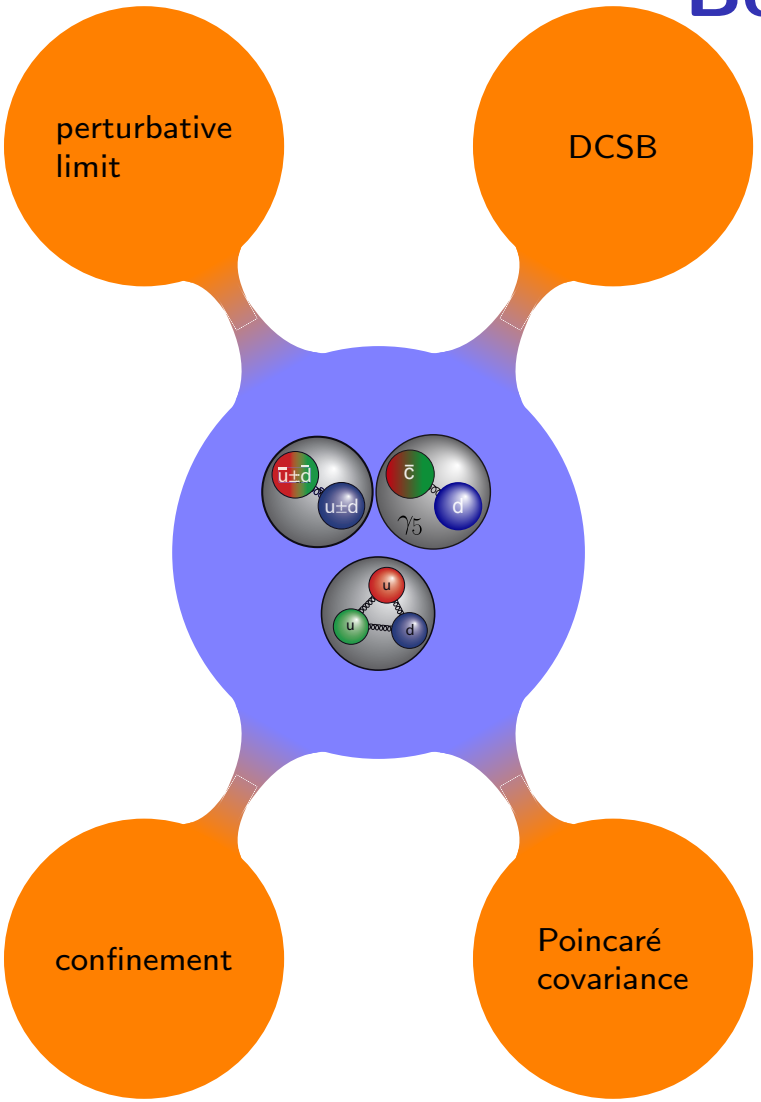


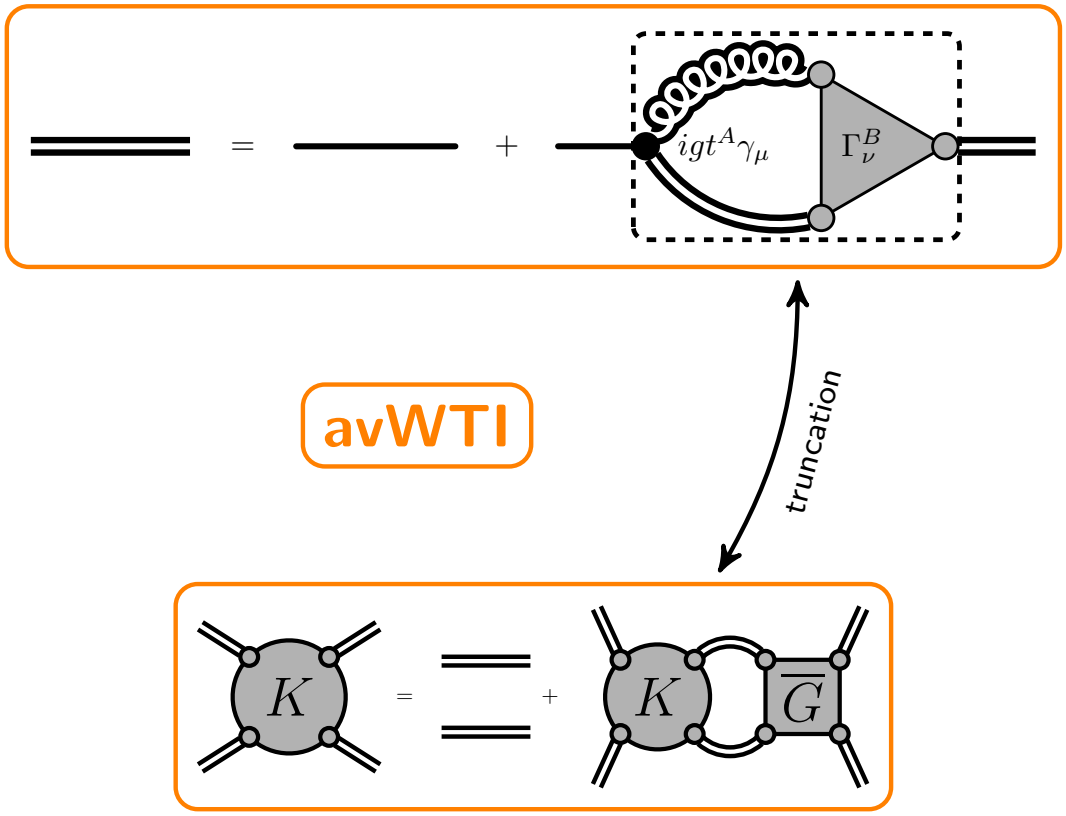

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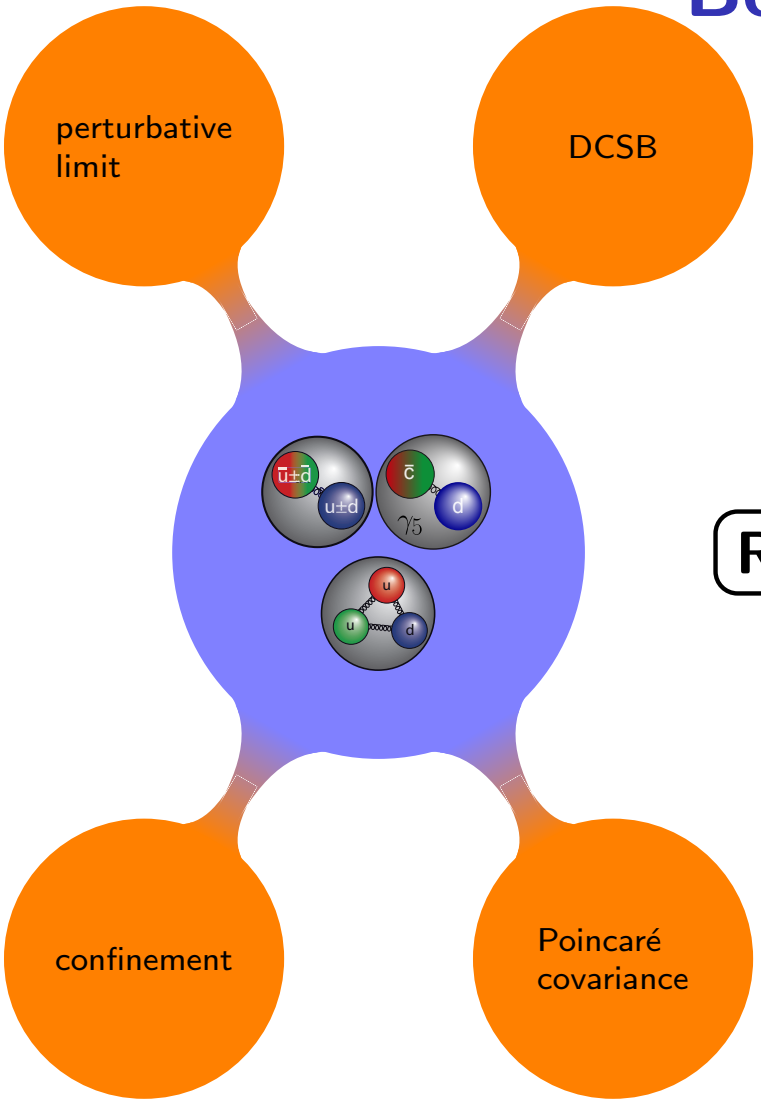
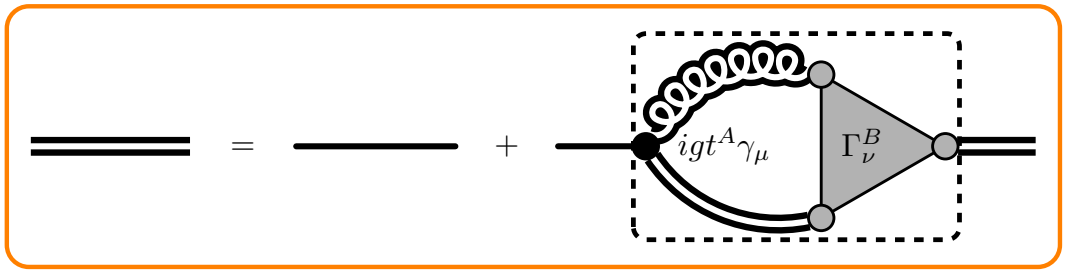
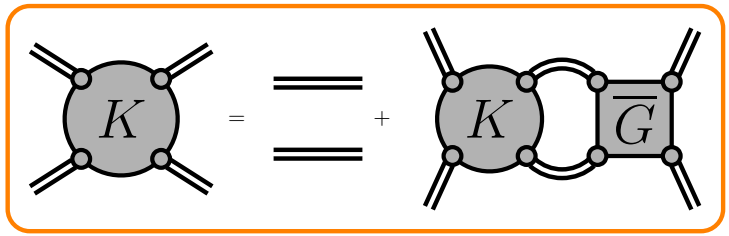



**Rainbow-Ladder truncation $\Longrightarrow$ avWTI**



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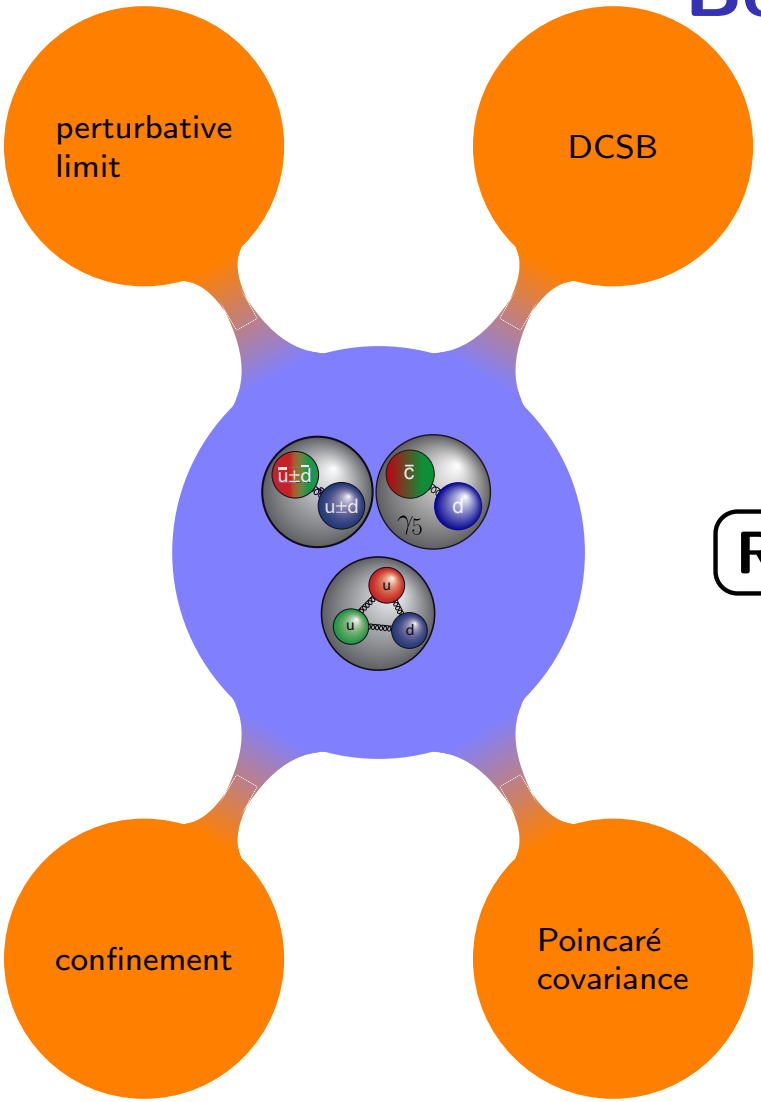


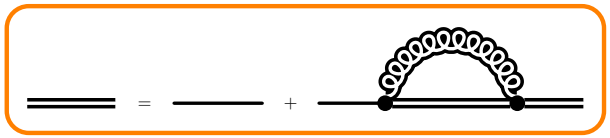

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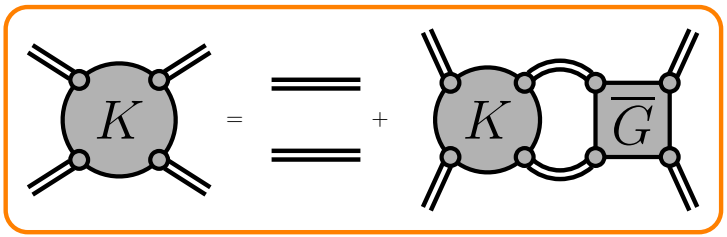

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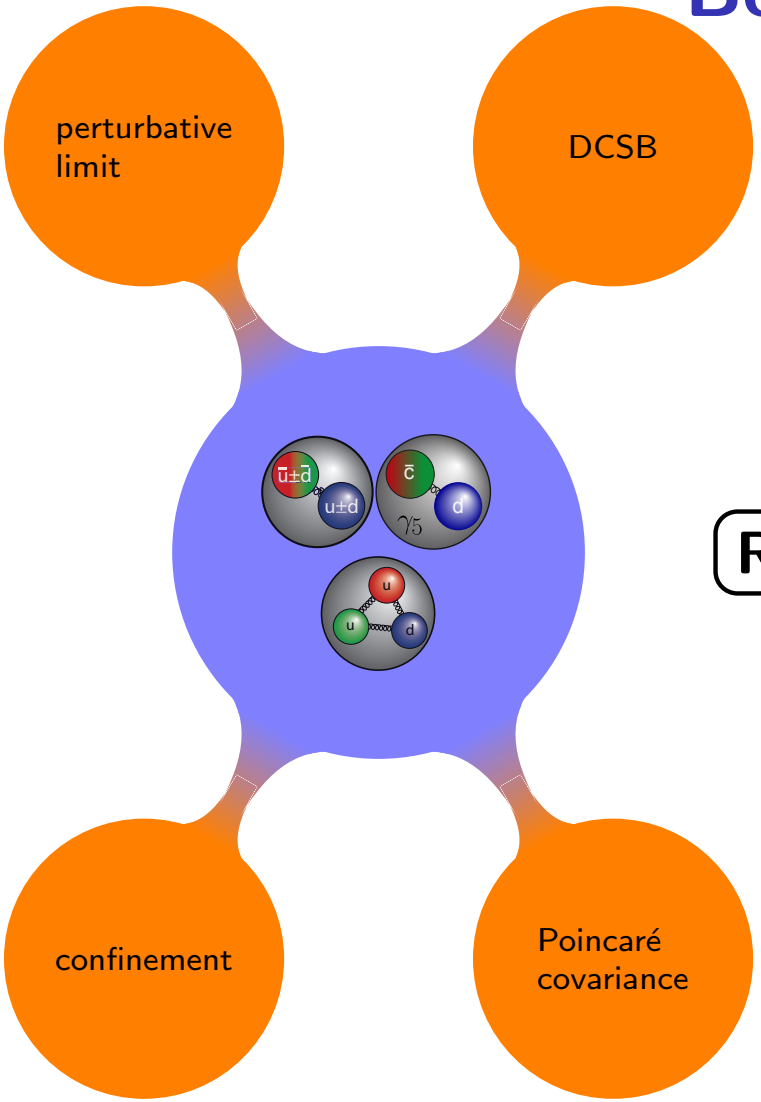
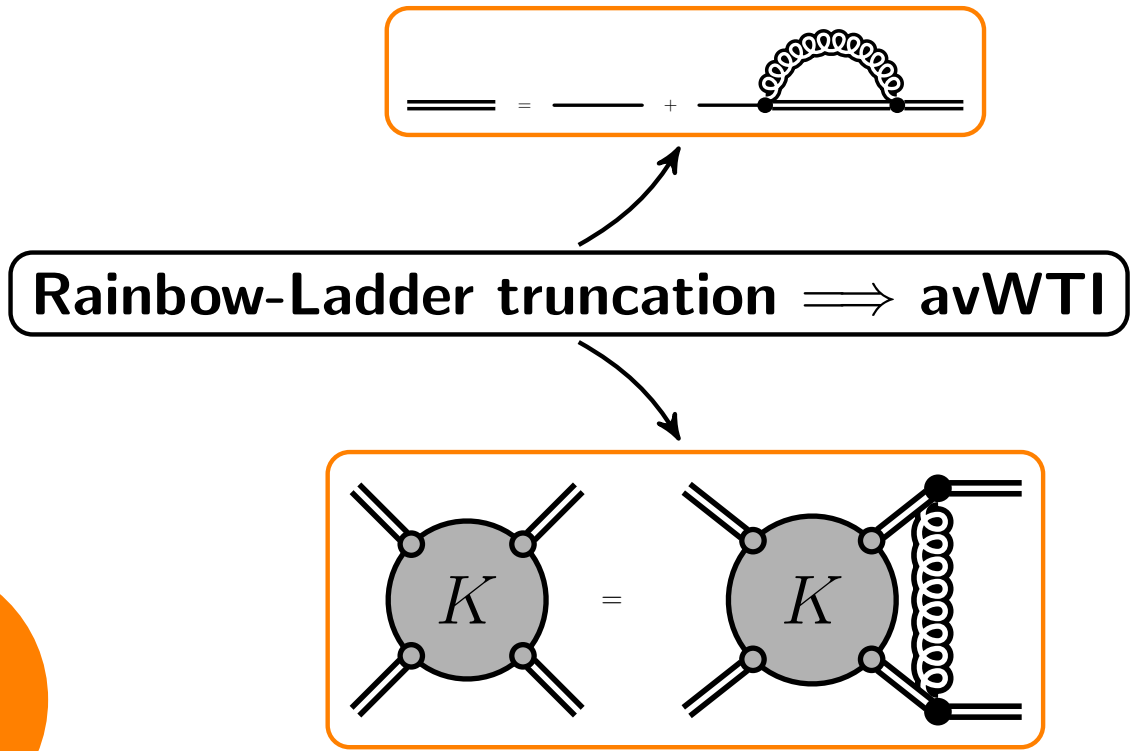
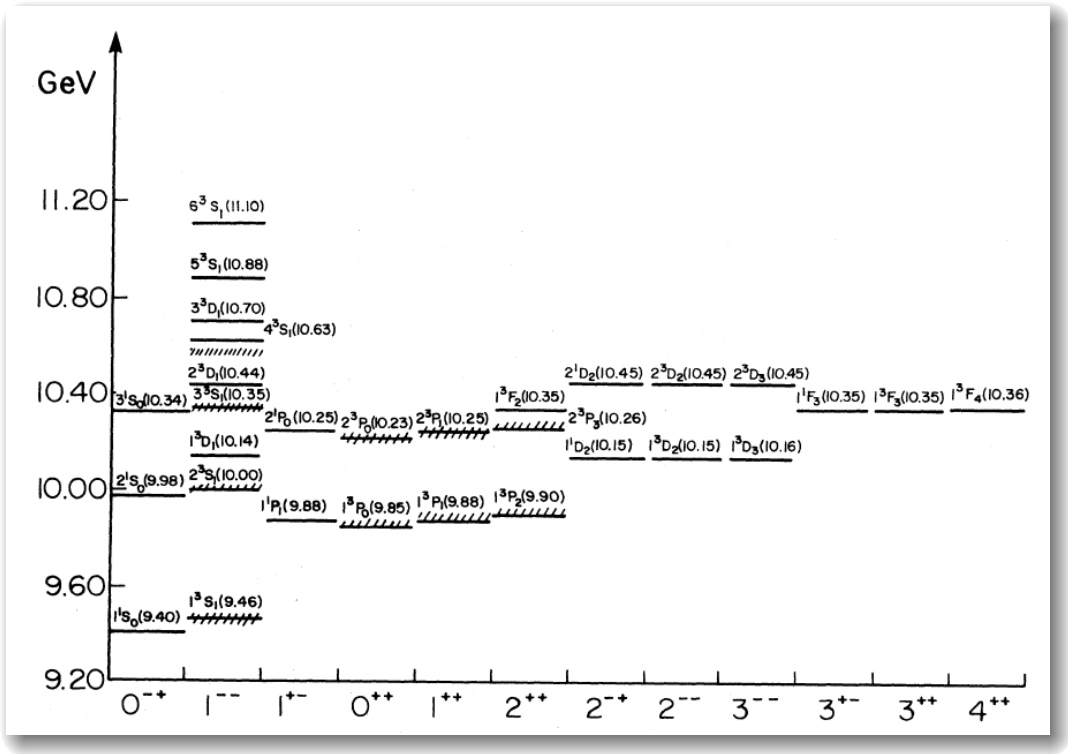


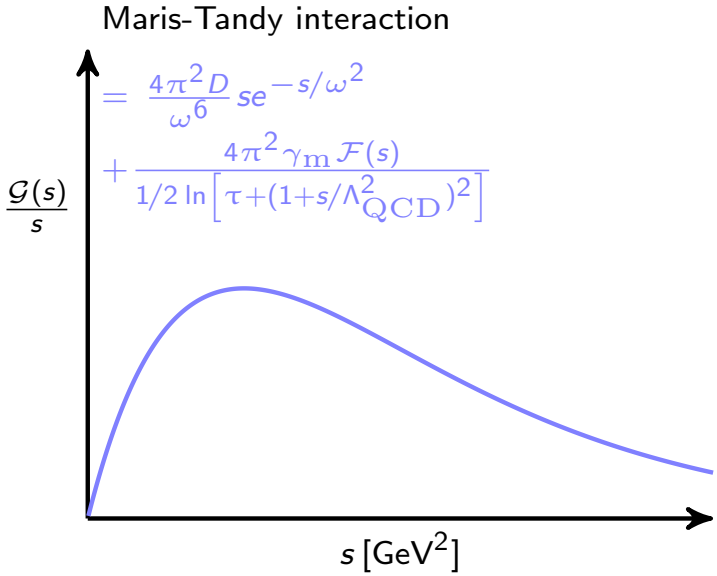
# Incitement

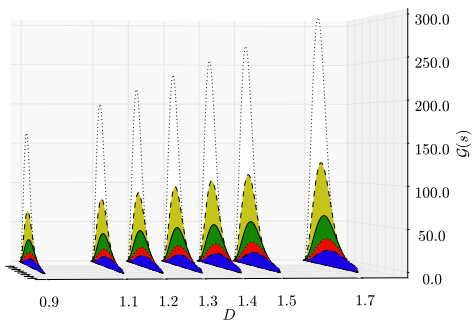



[Bottomonium by Godfrey, Isgur, 1985]

# Model and Strategy

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



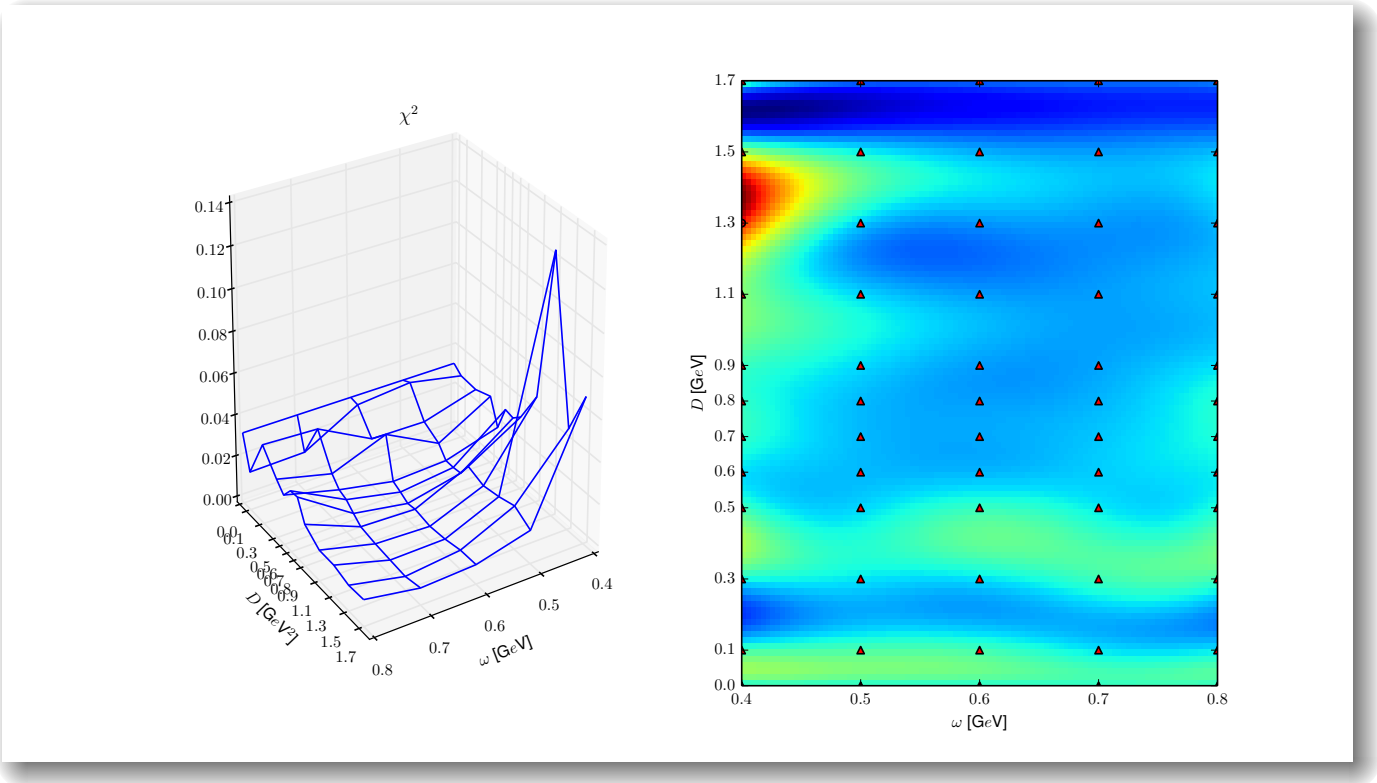




. . . is that good enough?

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

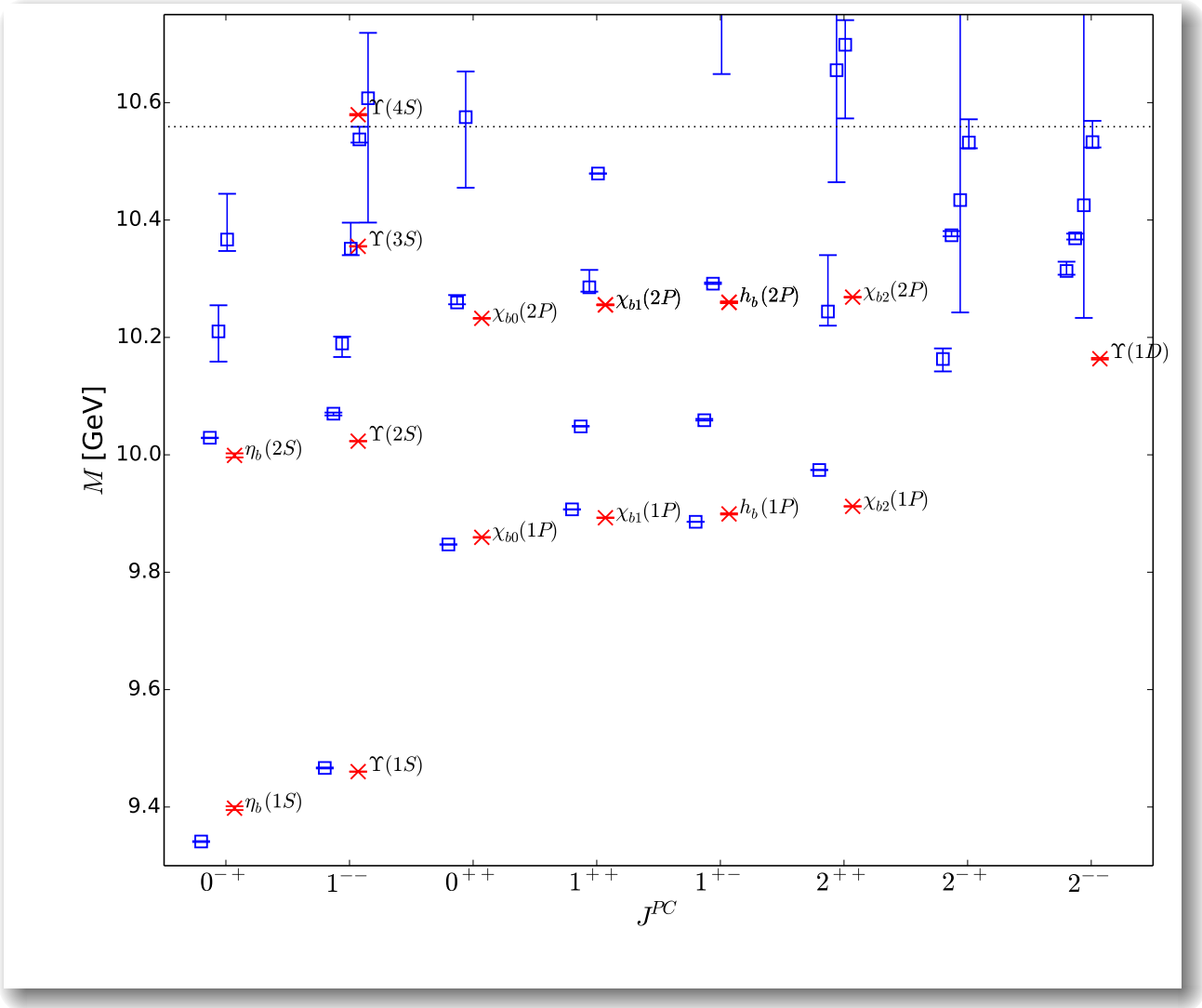
# Bottomonium

- 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 $(\omega, D)$




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

# Bottomonium



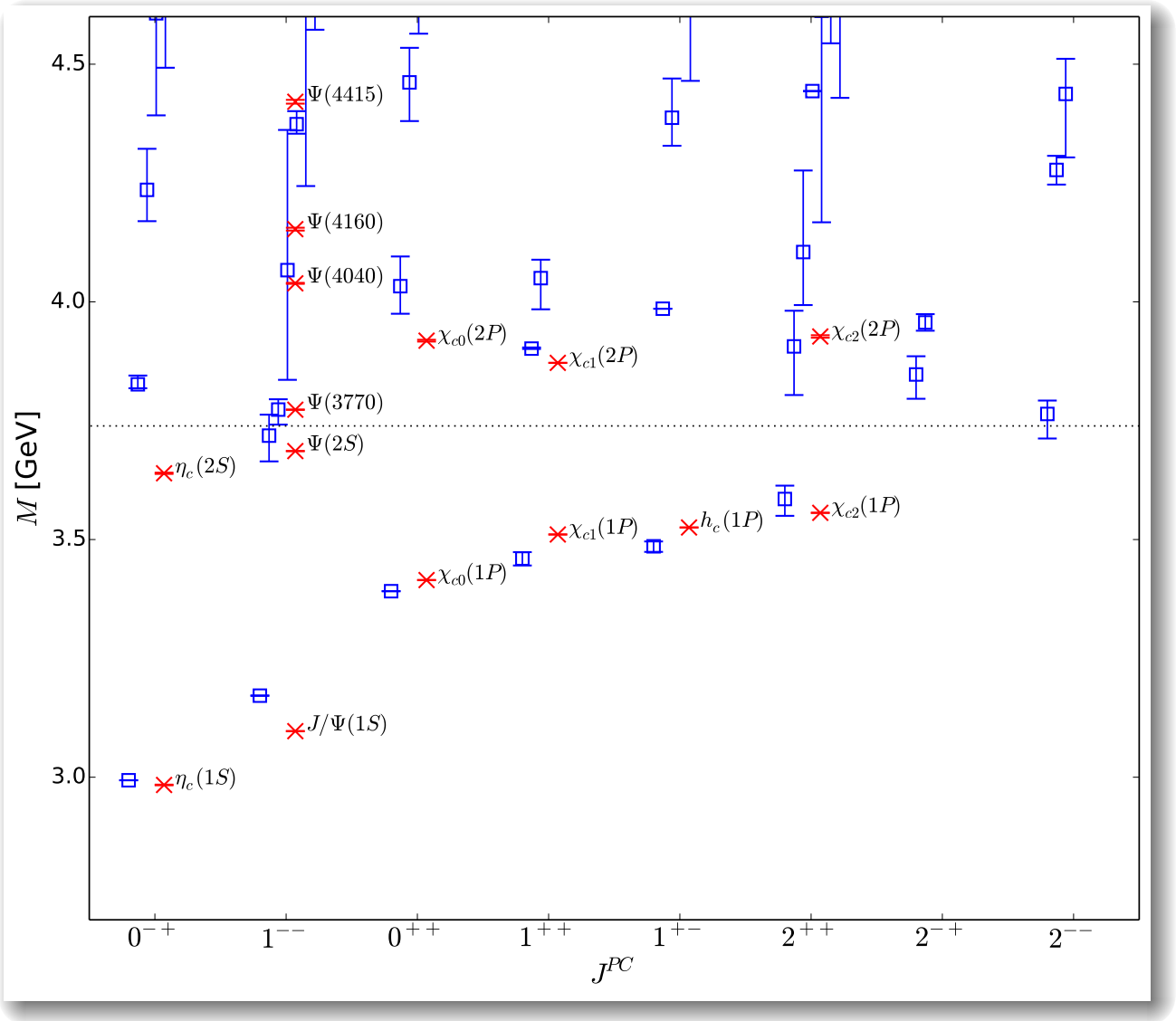

× experiment

- 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.]

- $m_{\mathrm{b}} = 3.635\,\mathrm{GeV}$ at $\mu = 19\,\mathrm{GeV}$, $\omega = 0.7\,\mathrm{GeV}$, $D = 1.3\,\mathrm{GeV}^2$

# Charmonium



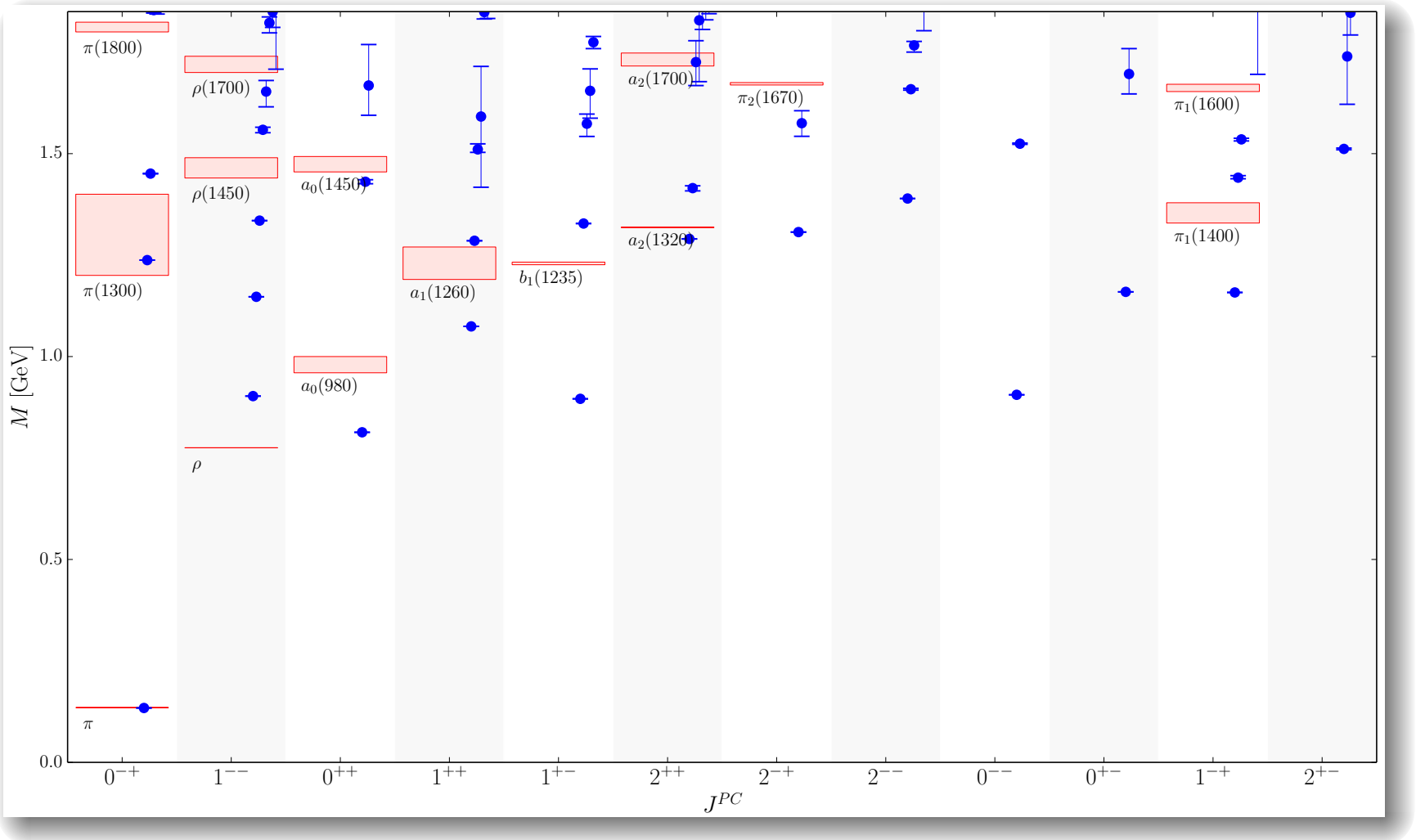

× experiment

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

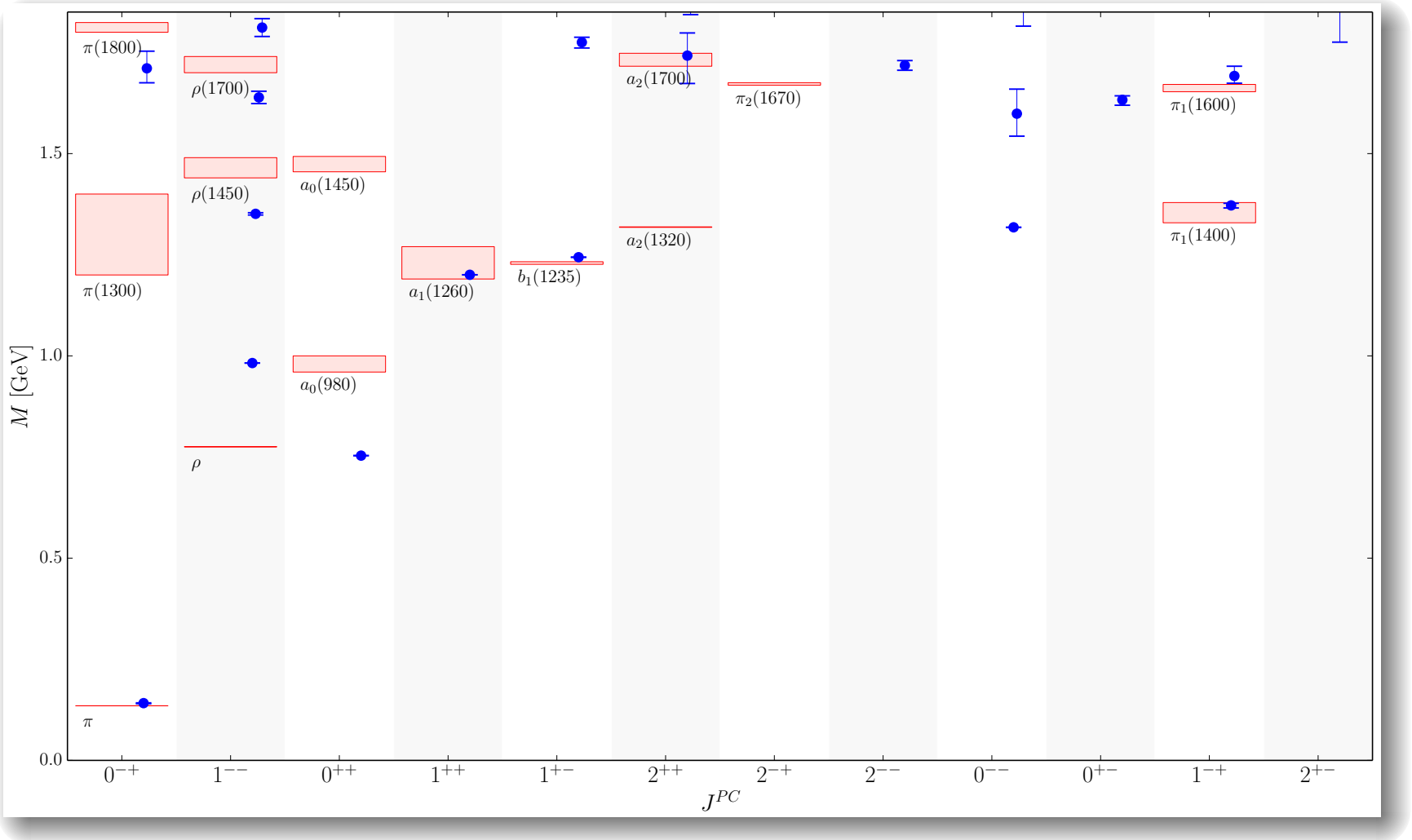
# Light Isovector Quarkonium




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

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

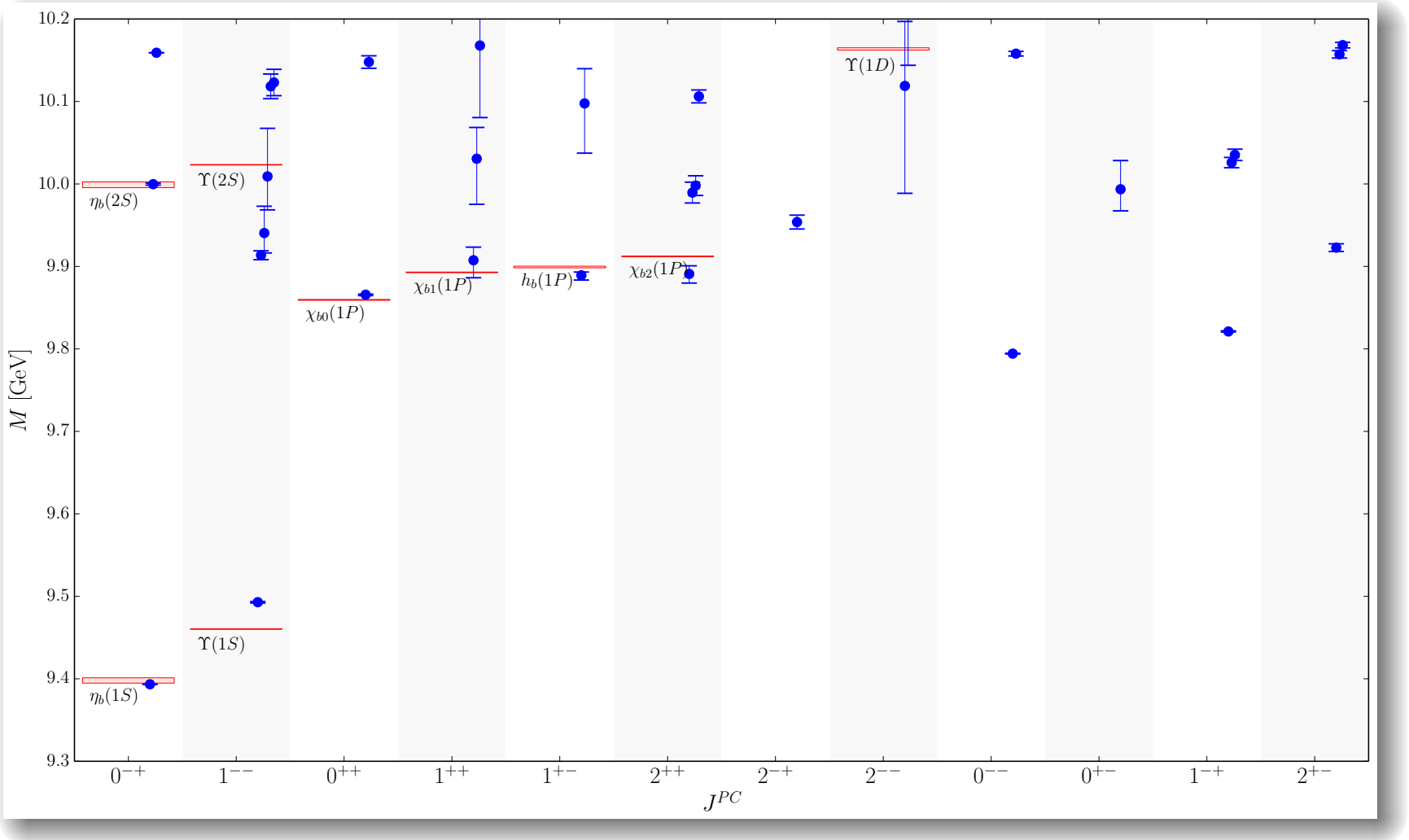
# Exotics: Light Isovector Quarkonium




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

- $m_{\mathrm{q}} = 0.003\,\mathrm{GeV}$ at $\mu = 19\,\mathrm{GeV}$, $\omega = 0.7\,\mathrm{GeV}$, $D = 1.4\,\mathrm{GeV}^2$

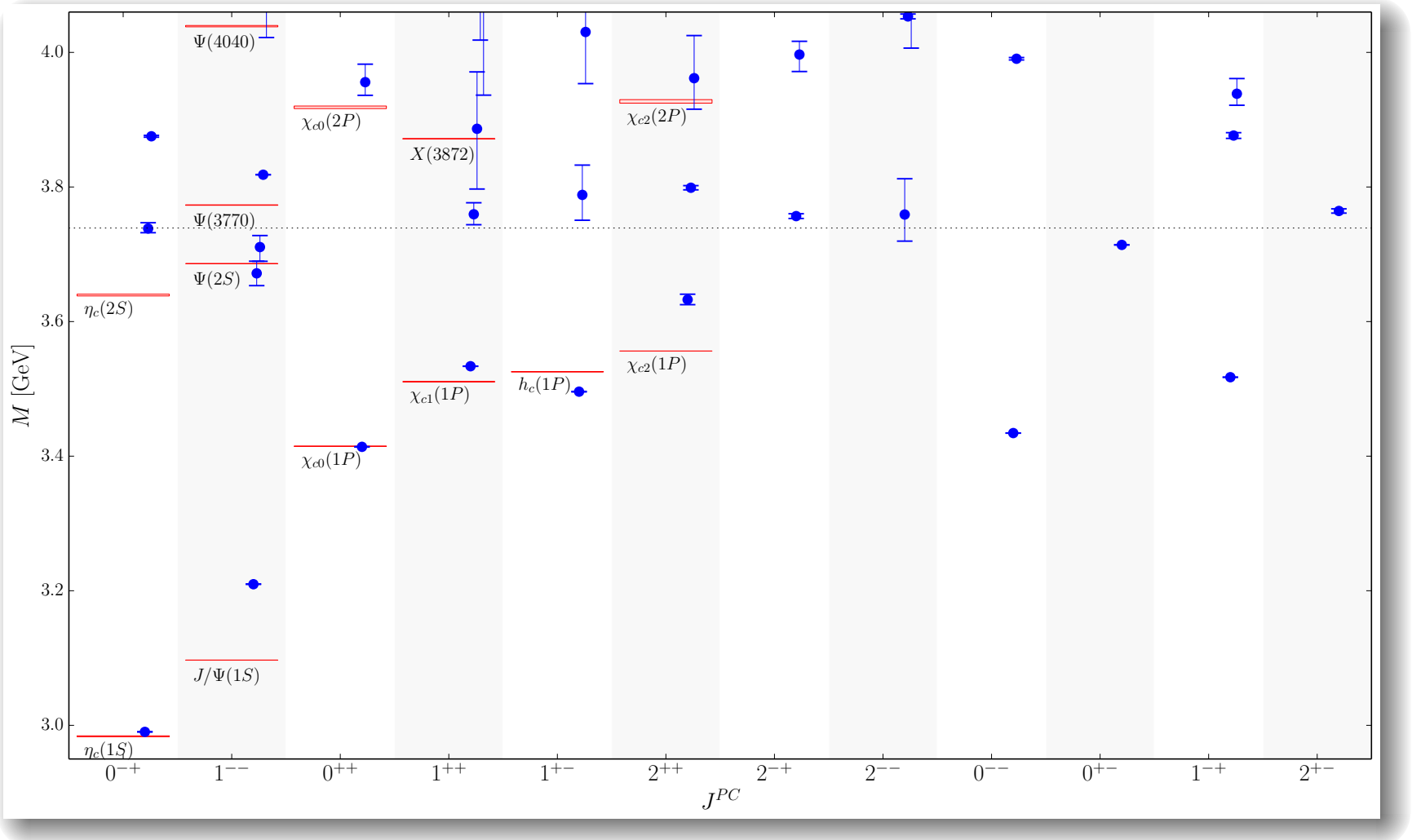
# Exotics: Bottomonium




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

- $m_{\mathrm{b}} = 3.635\,\mathrm{GeV}$ at $\mu = 19\,\mathrm{GeV}$, $\omega = 0.7\,\mathrm{GeV}$, $D = 0.8\,\mathrm{GeV}^2$

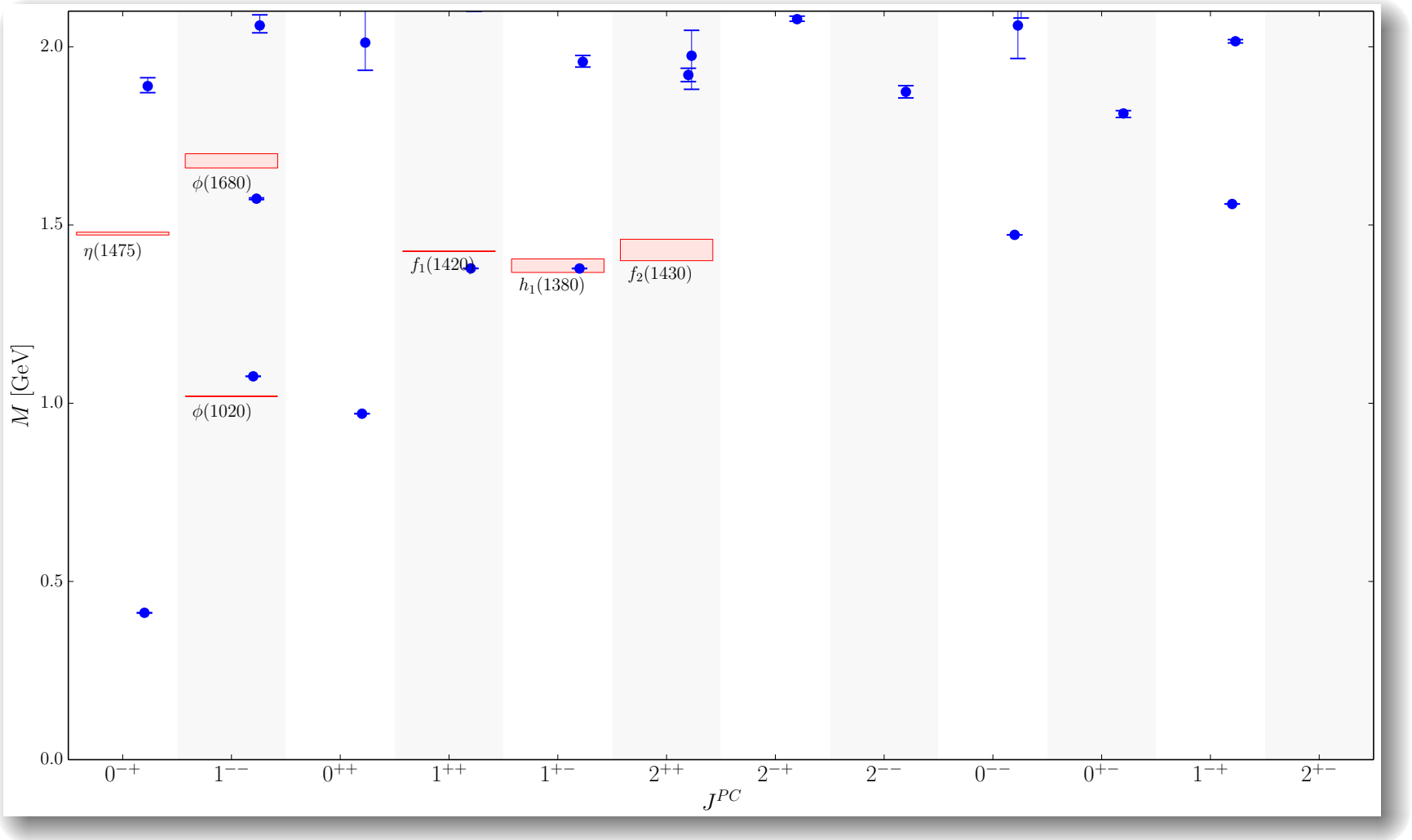
# Exotics: Charmonium




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

- $m_c = 0.855\,\text{GeV}$ at $\mu = 19\,\text{GeV}$, $\omega = 0.6\,\text{GeV}$, $D = 0.9\,\text{GeV}^2$

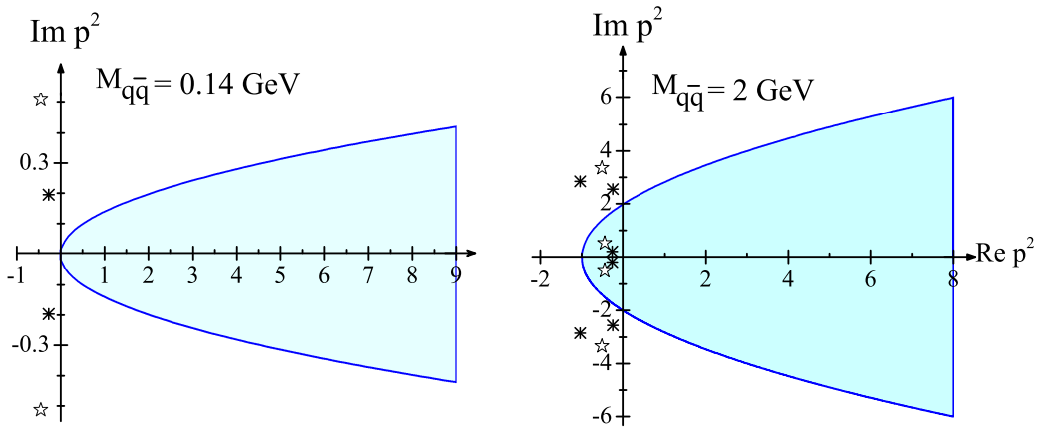
# Exotics: Strangeonium




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

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

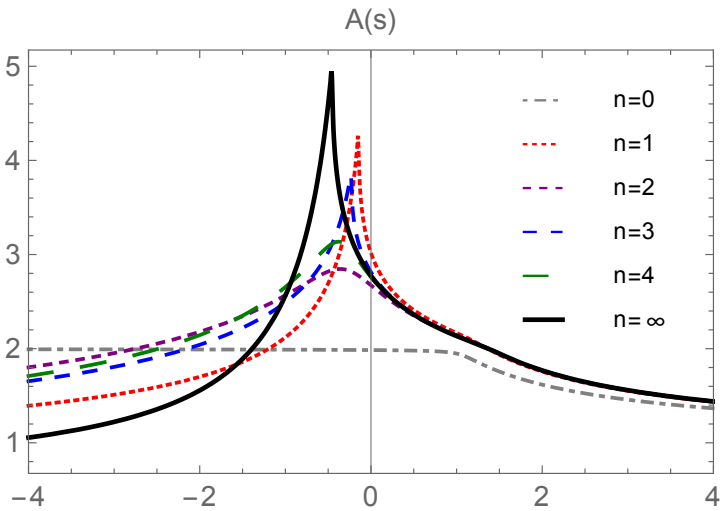
# A Path to Open Flavor Meson Spectroscopy

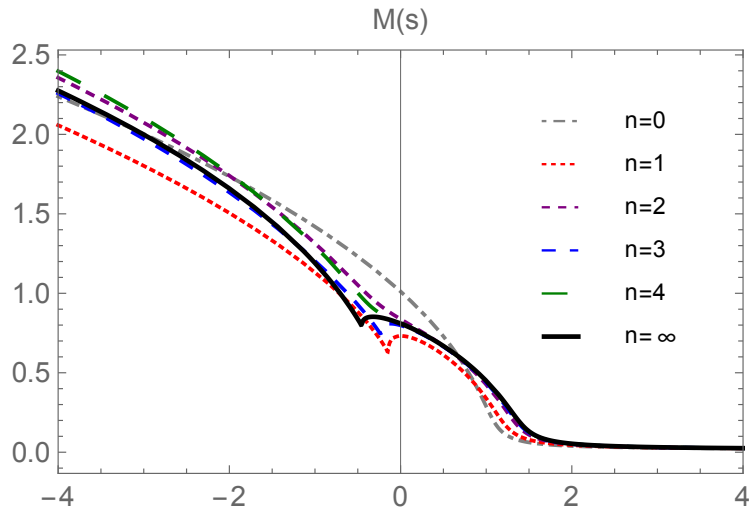


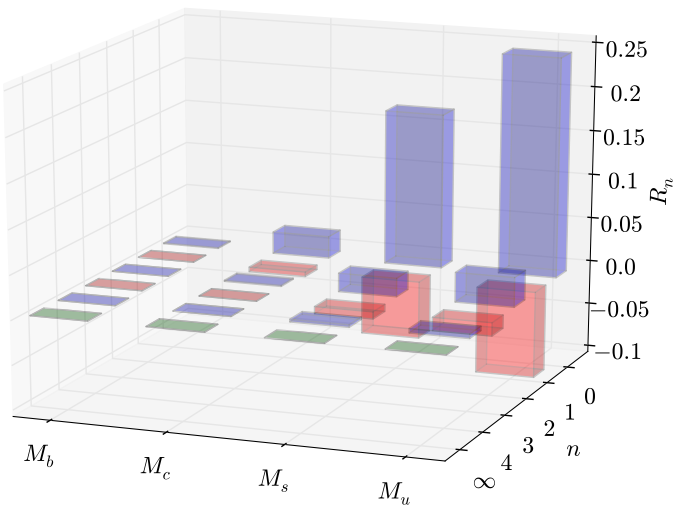

[S. Dorkin, L. Kaptari, T. Hilger, B. Kämpfer, Phys. Rev. C **89**: 034005, 2014.]

- 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



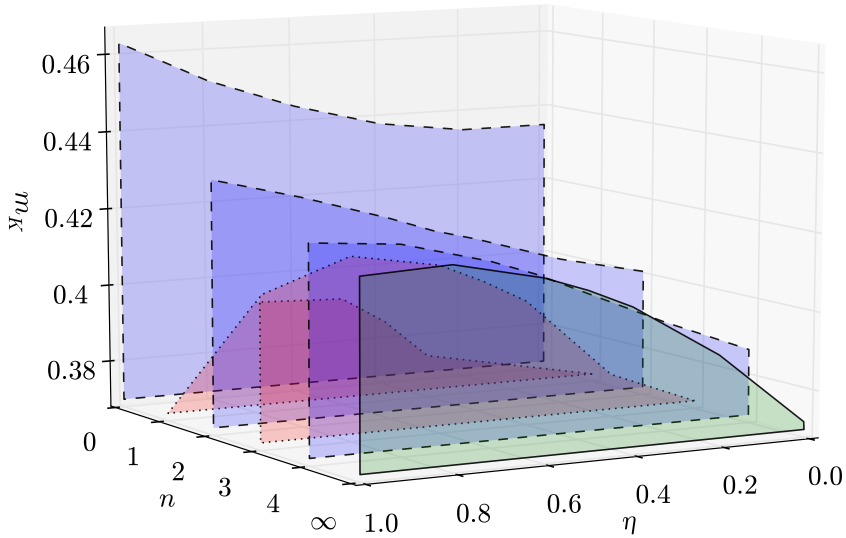

[M. Gómez-Rocha, T. Hilger, A. Krassnigg, accepted by PRD, arXiv:1506.03686] [M. Gómez-Rocha, T. Hilger, A. Krassnigg, Few Body Syst. **56**: 475, 2015.]

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

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

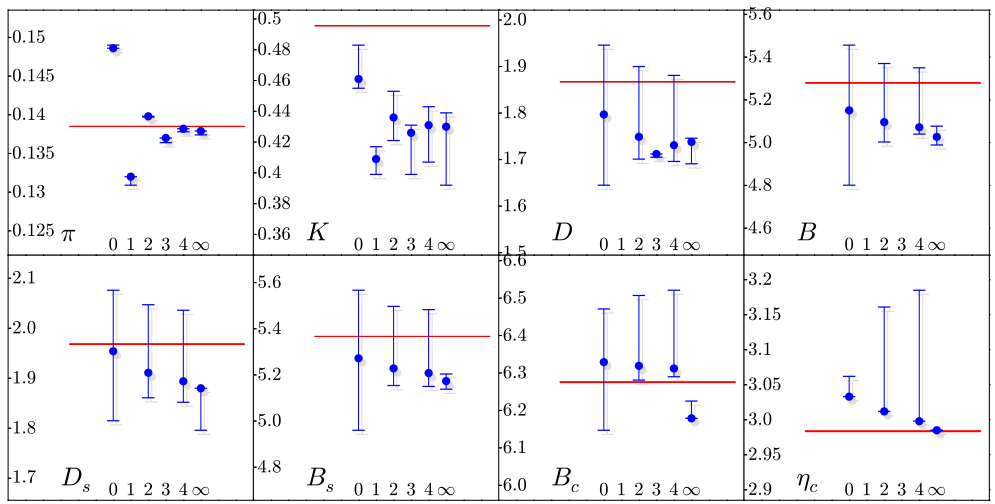
# Quark-Gluon Vertex Dressing and Meson Masses

[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:

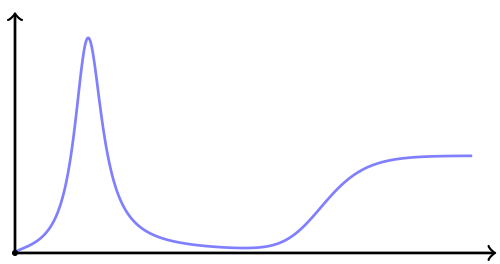
$$j_\mu^{\mathrm{V},\tau}(x) = \bar{\psi}\gamma_\mu \tau \psi$$

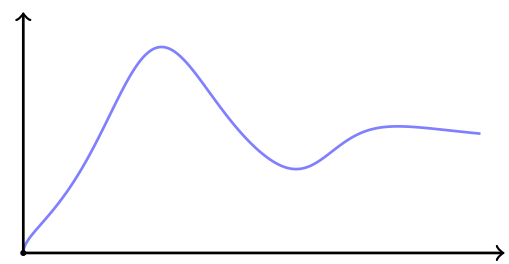
$P = +1$ meson current:

$$j_\mu^{\mathrm{A},\tau}(x) = \bar{\psi}\gamma_5\gamma_\mu \tau \psi$$

current-current correlator:

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





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chiral transformations:

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

$P = -1$ meson current:

$$j_\mu^{\mathrm{V},\tau}(x) = \bar{\psi} \gamma_\mu \tau \psi$$

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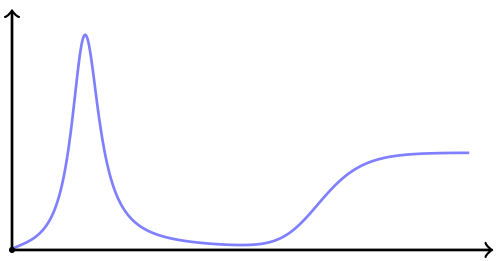

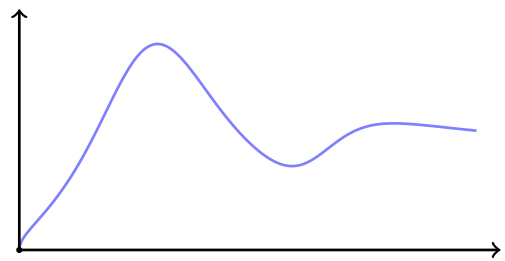

# Reminder: Chiral Symmetry

two flavor Lagrangian:

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

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

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

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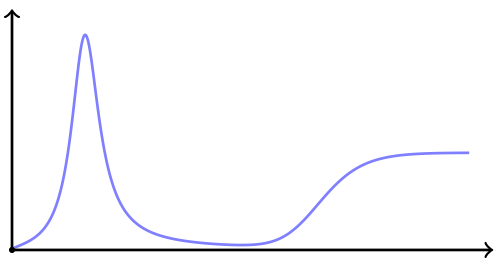

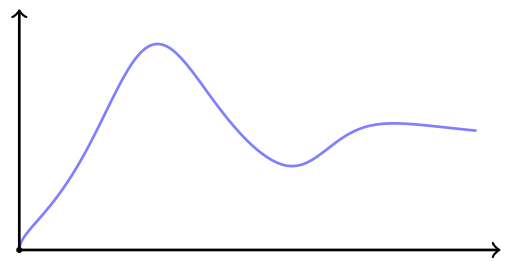

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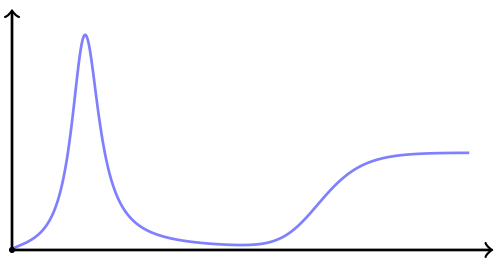

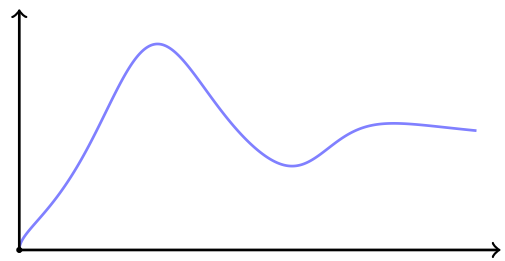

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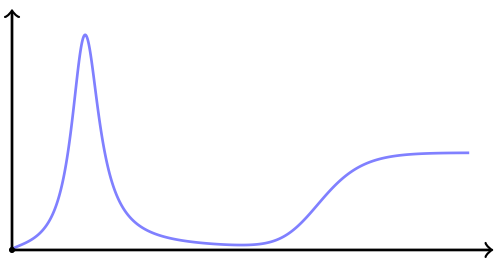

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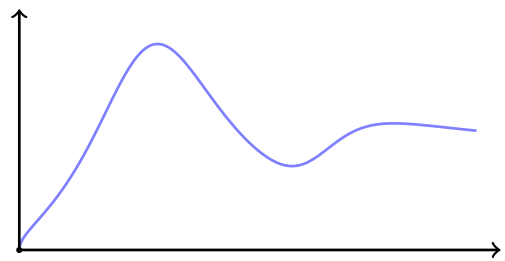

# Reminder: Chiral Symmetry and Open Flavor Mesons

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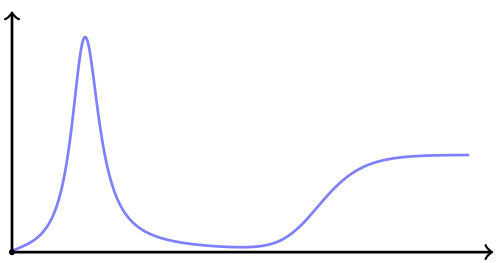

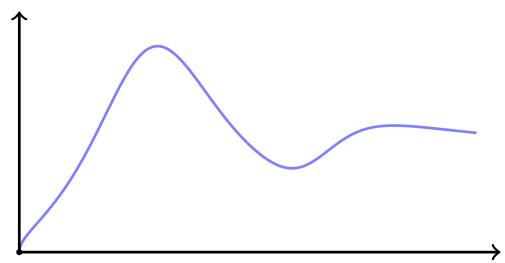

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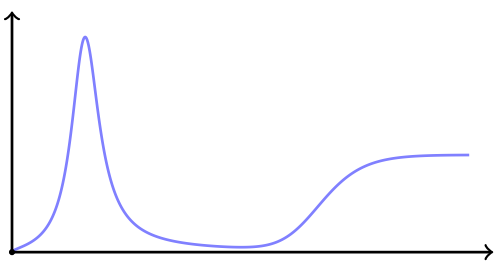

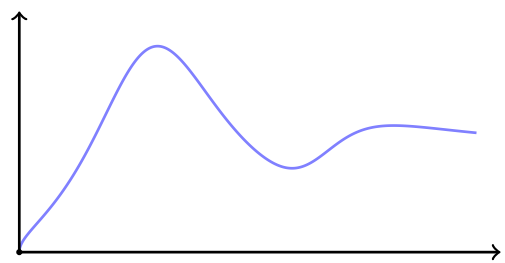

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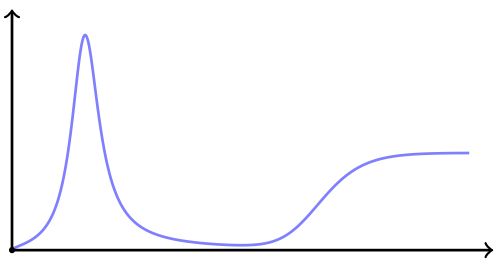

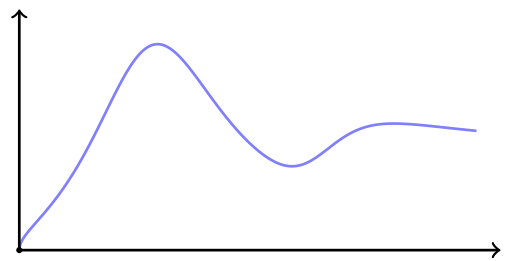

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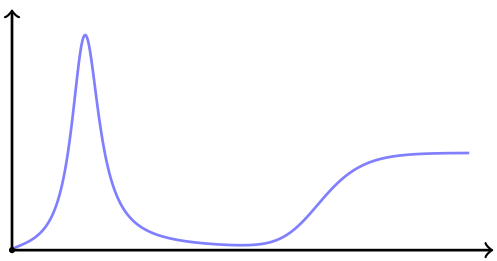

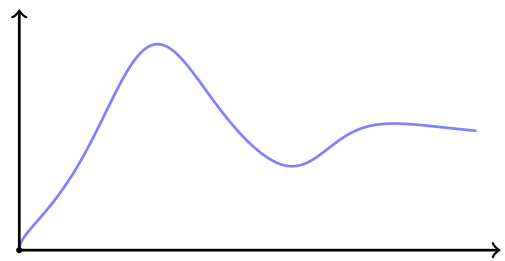

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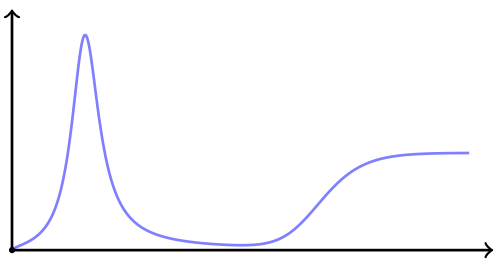

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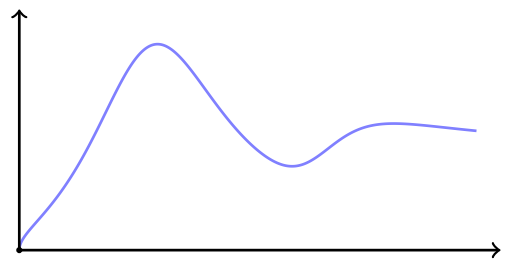
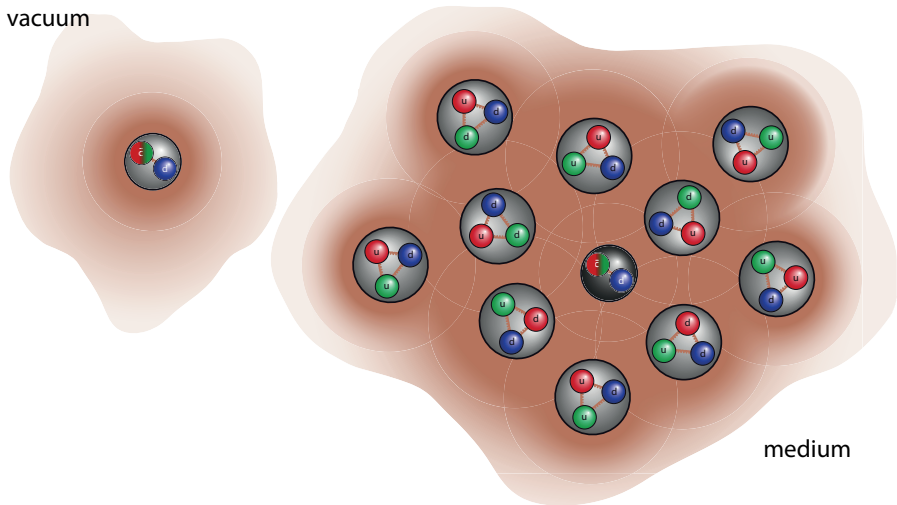


# Open Flavor Mesons in the Medium
## - A Window to DCSB



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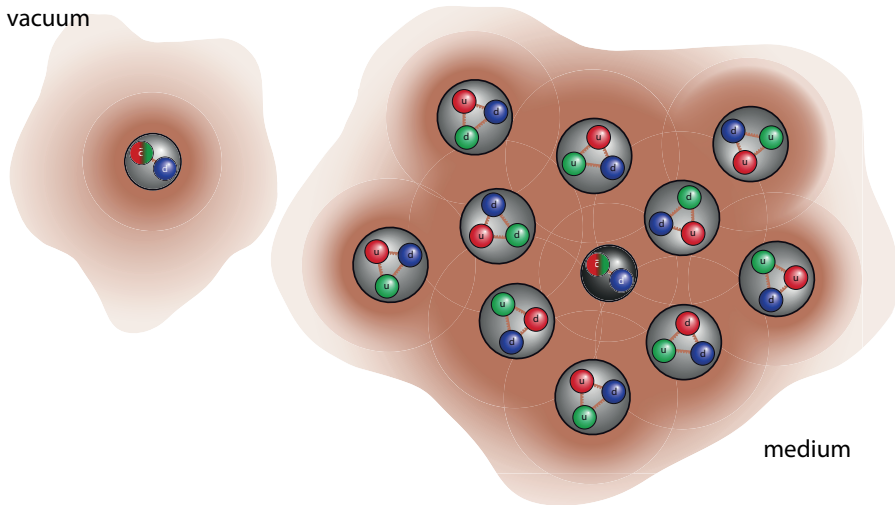
medium
modifications



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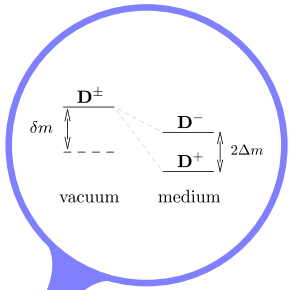
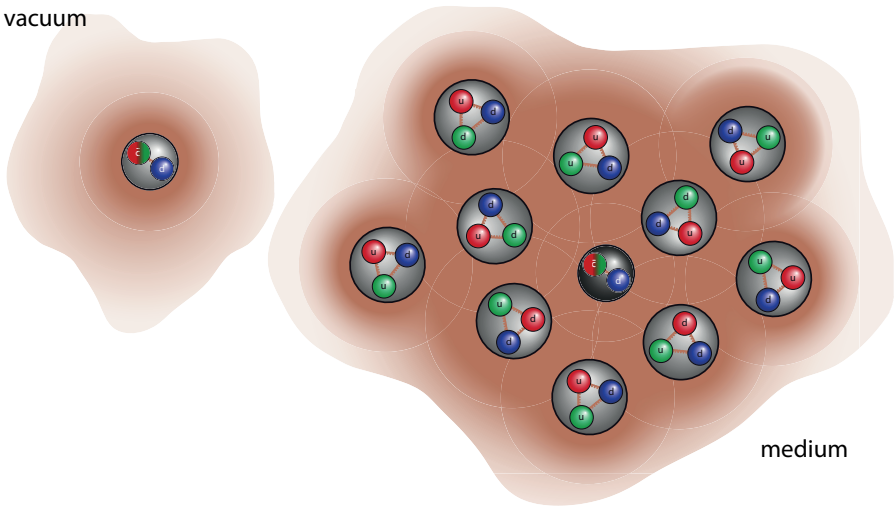



medium modifications

vacuum



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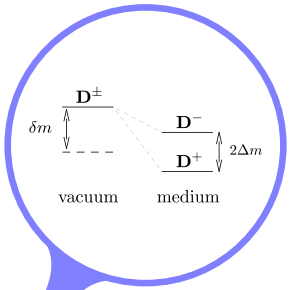


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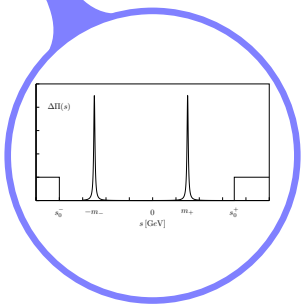


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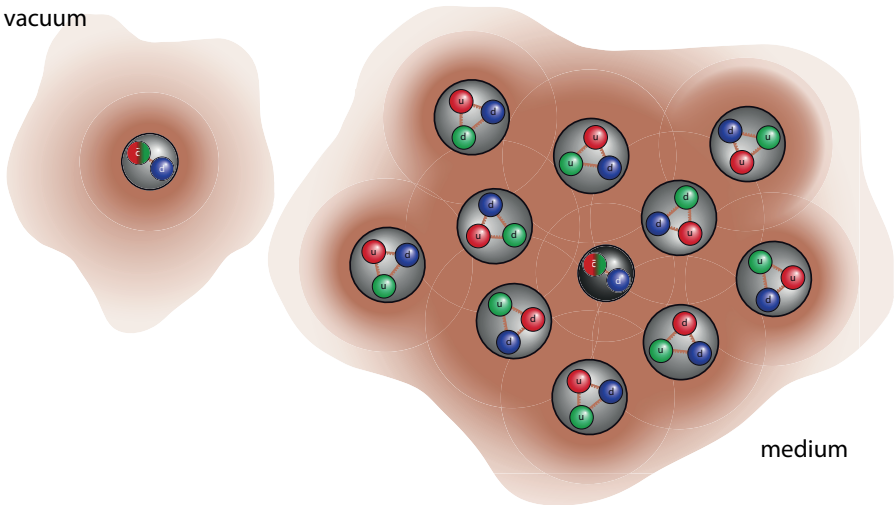

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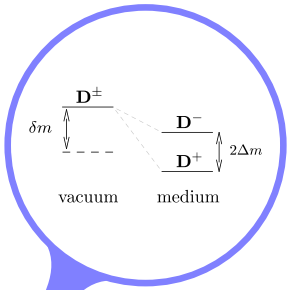


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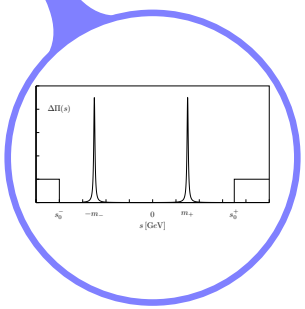


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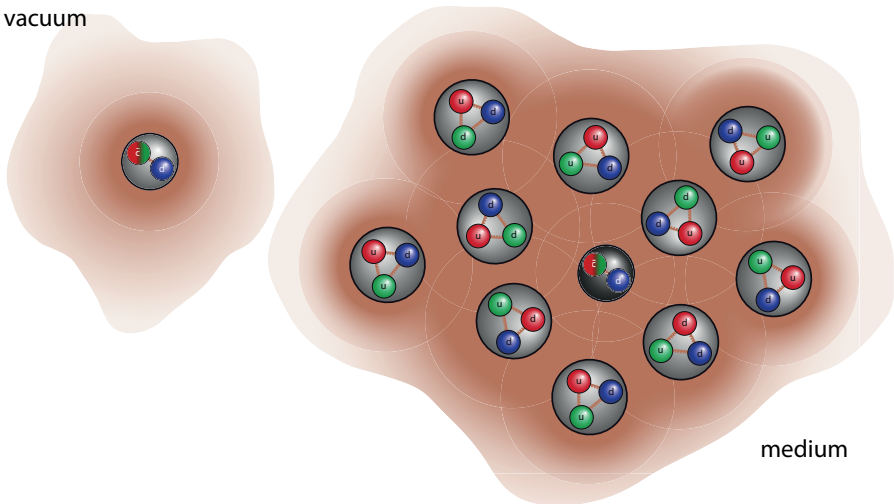


D$\chi$SB

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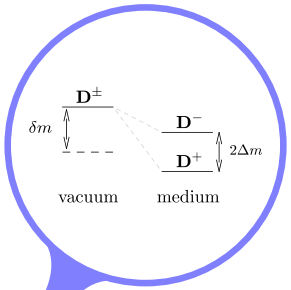


properties of matter under restoration

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D$\chi$SB

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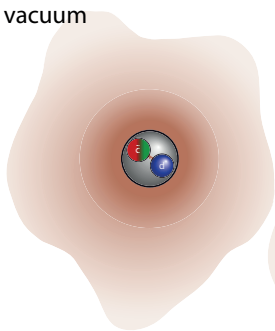

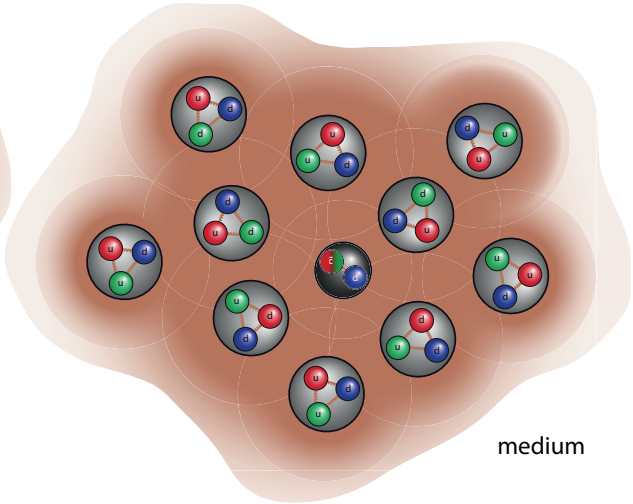

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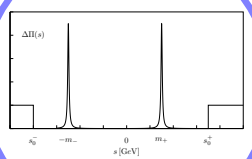

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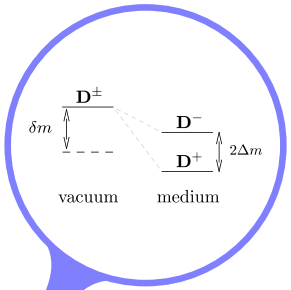


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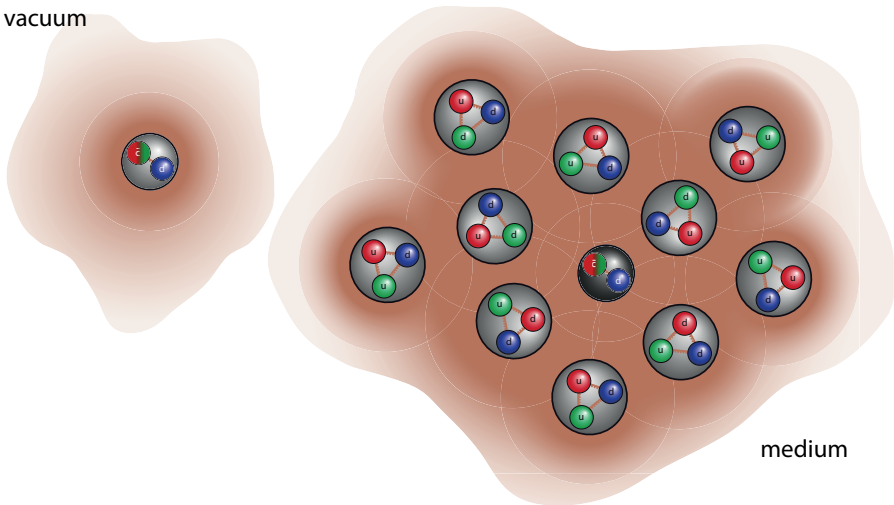


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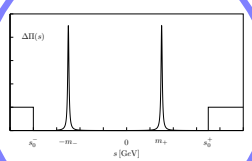


order parameters

$\langle \bar{q}q \rangle$

# Hadron physics and QCD sum rules

current-current correlator

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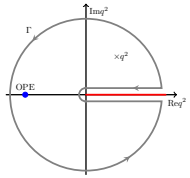
separation of scales

dispersion relation

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



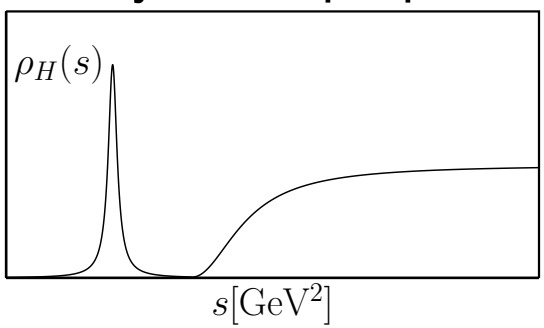

operator product expansion

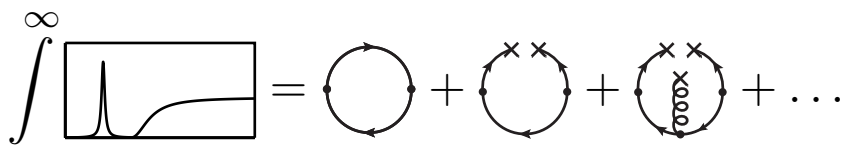
$$= C_1(q) + C_2(q)\langle\bar{q}q\rangle + C_3(q)\langle\bar{q}g\sigma\mathcal{G}q\rangle + \dots$$

QCD condensates:

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

spectral density $\leftrightarrow$ hadronic properties



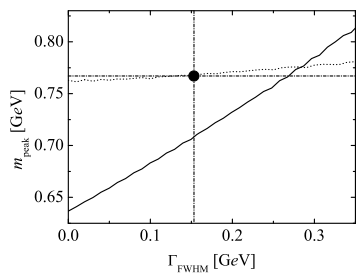
# Order Parameters and Light Quark Currents

- $\langle \bar{q}q \rangle$ 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.
  - $\langle \bar{q}\Gamma q \bar{q}\Gamma q \rangle \propto \langle \bar{q}q \rangle^2$
    $\rightarrow$ 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

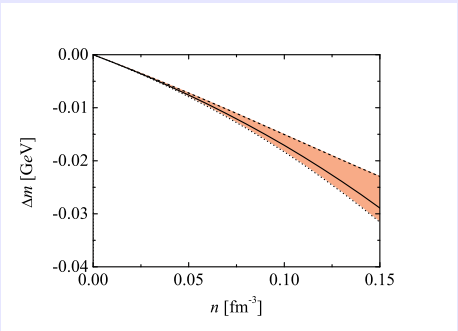
impact of D$\chi$SB order parameters on the ρ meson and implications of chirally symmetric sum rules

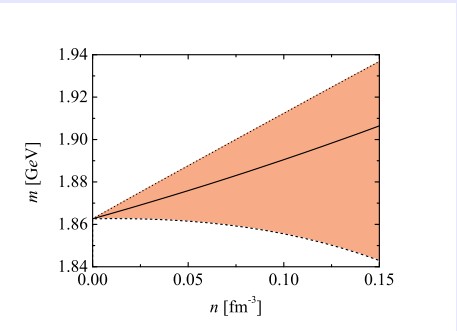
[TH, R. Thomas, B. Kämpfer, S. Leupold, Phys. Lett. B **709** (2012) 200]



# Spin-0 Open Flavor Mesons at Finite Density

- particle-antiparticle splitting + shift



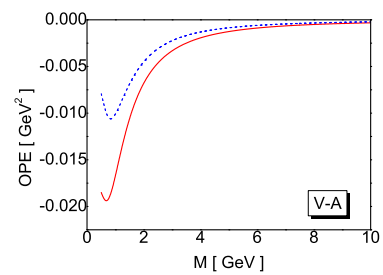

- $\langle \bar{q}q \rangle$ amplification due to heavy charm quark mass: $m_c \langle \bar{q}q \rangle$


[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

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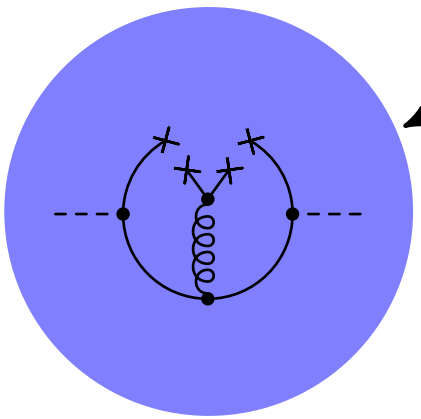
$$\langle \bar{\psi} \sigma \tau \Gamma \psi \bar{\psi} \sigma' \tau' \Gamma' \psi \rangle$$



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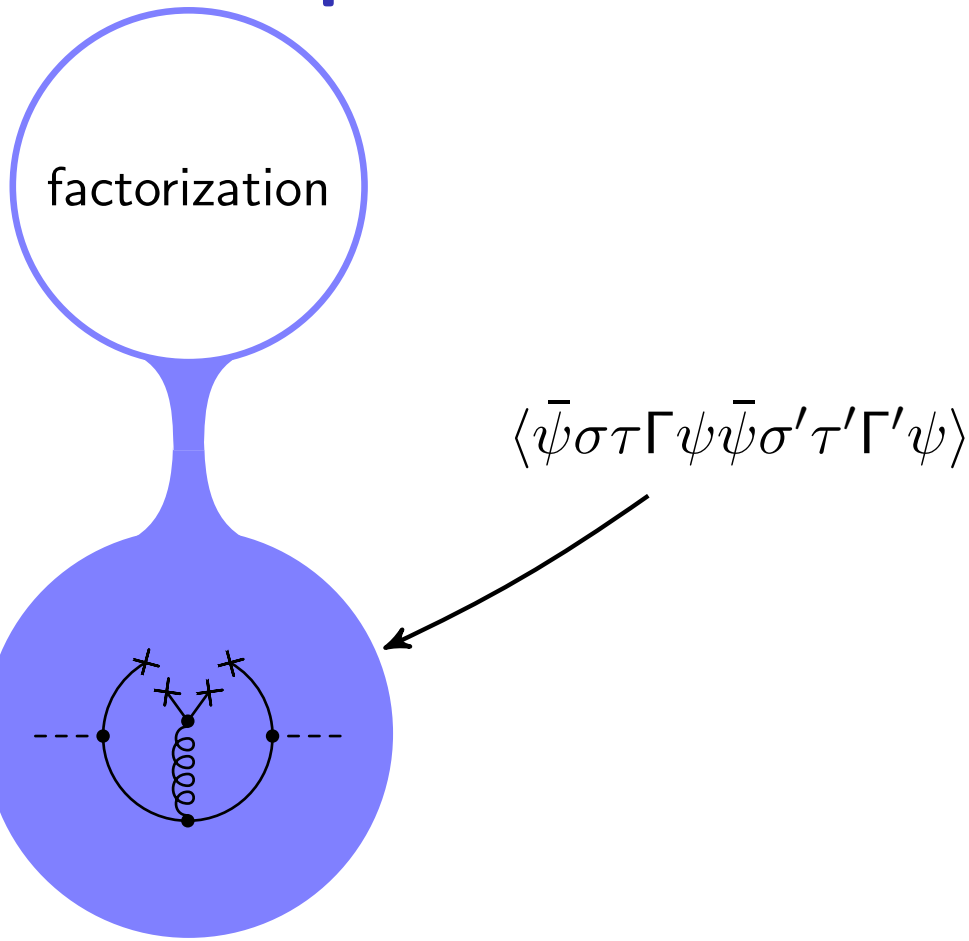

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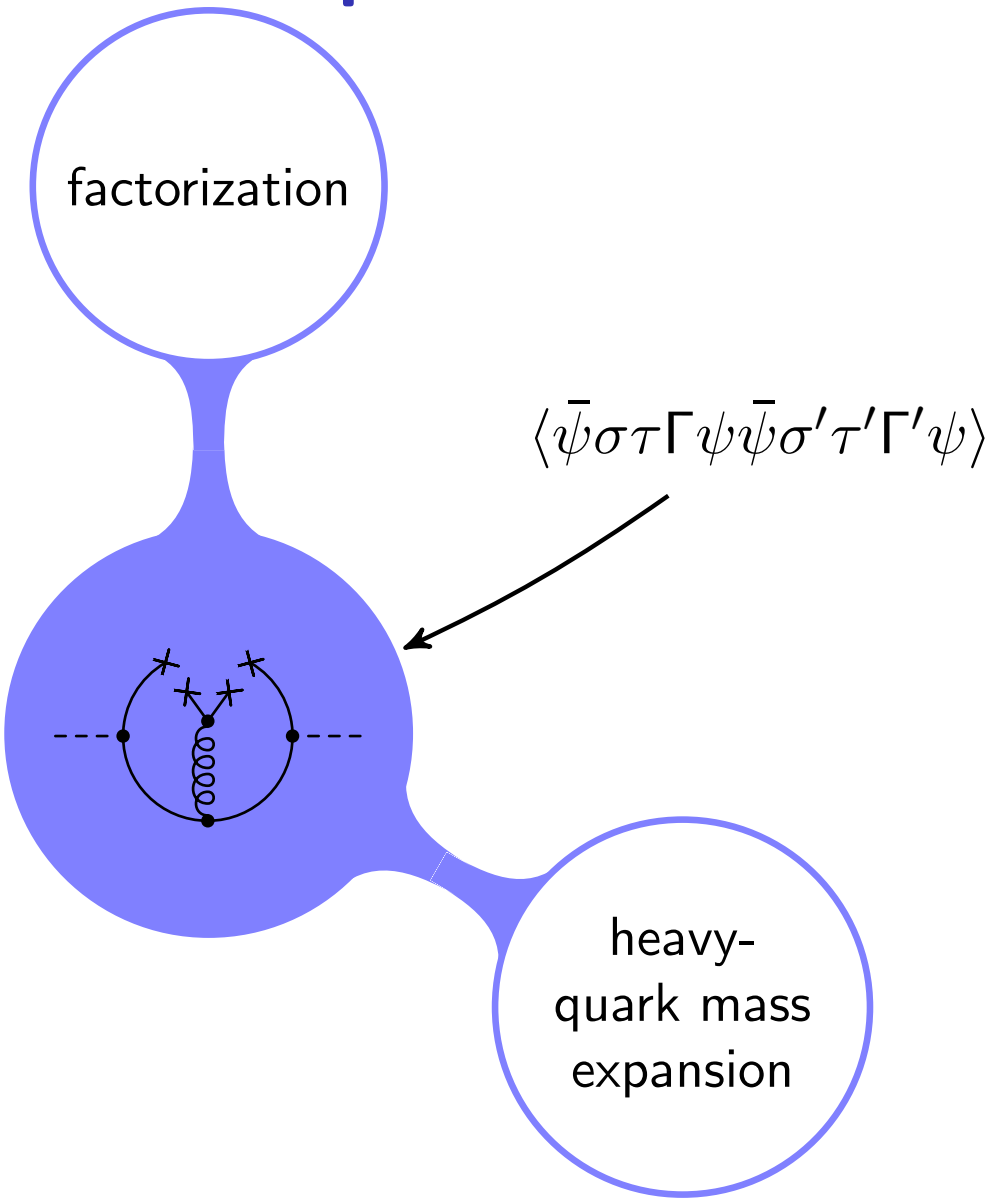

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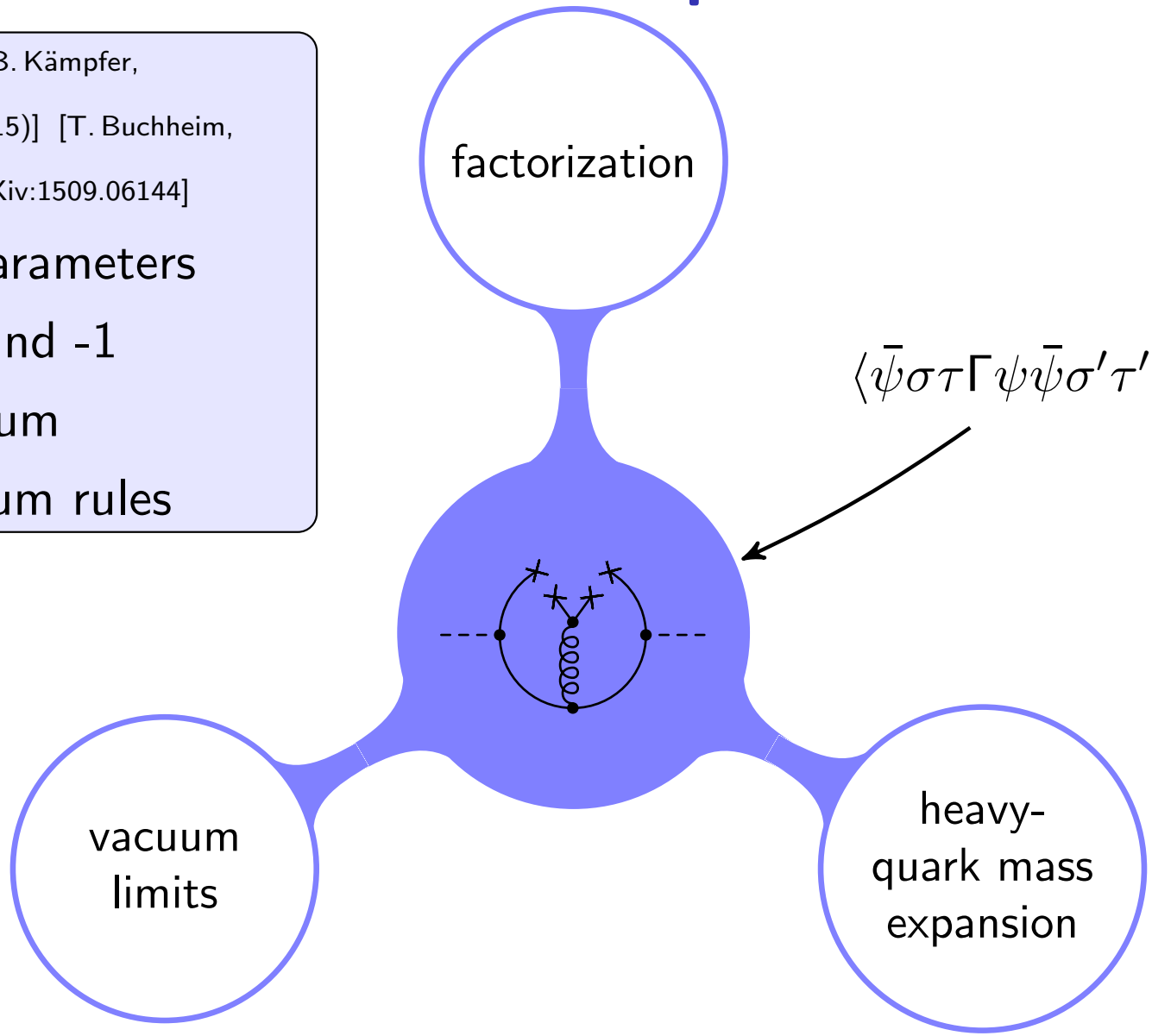

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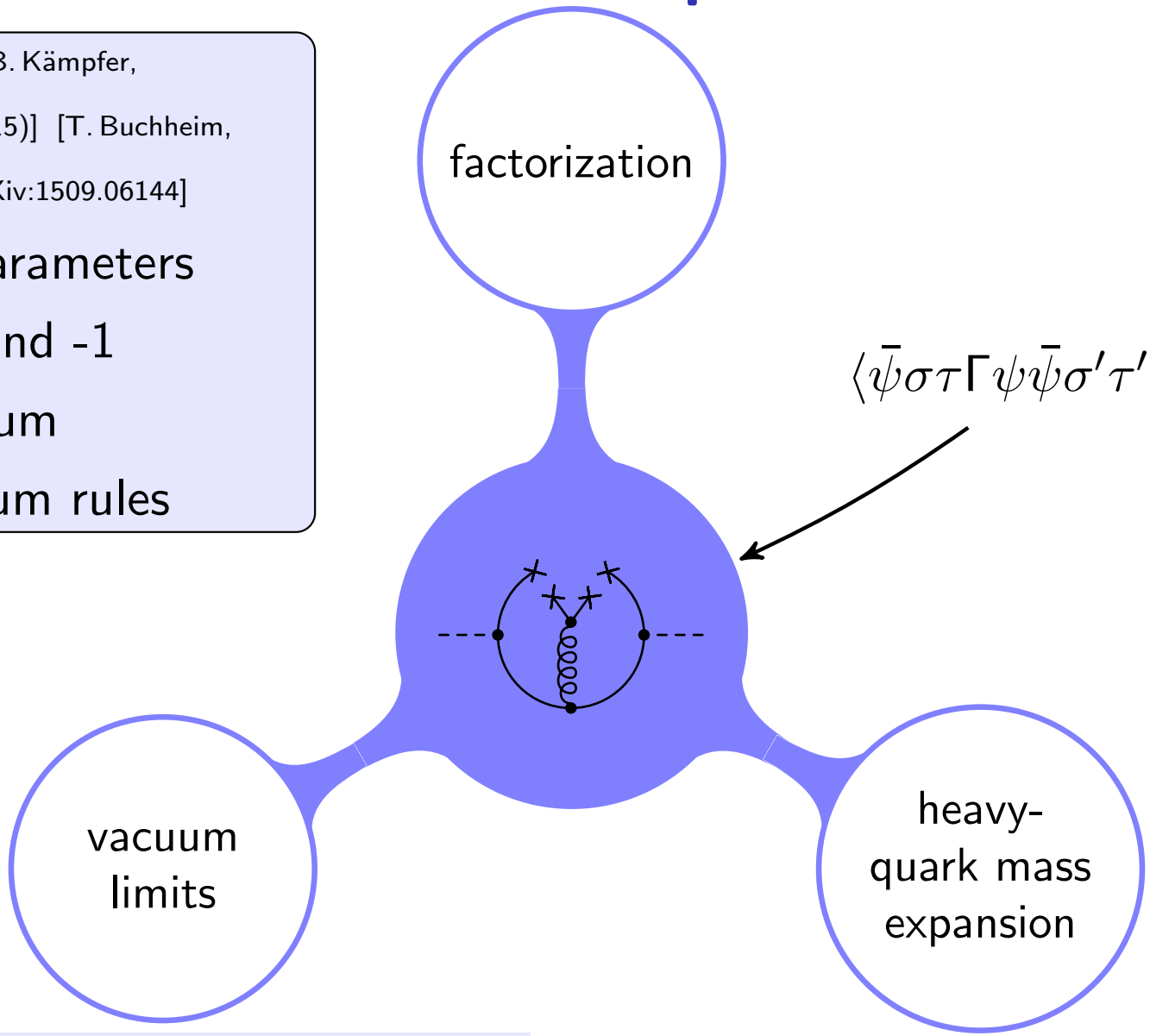


[T. Buchheim, TH, B. Kämpfer, J. Phys. Conf. Ser. **503** (2014)]
[T. Buchheim, TH, B. Kämpfer, E.P.J. WoC **81** (2014)]

[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)]
[T. Buchheim, TH, B. Kämpfer, arXiv:1509.06144]

- heavy-quark mass expansion and factorization of four-quark condensates in the medium
- continuous transition from medium to vacuum $\rightarrow$ 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.

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# Thank You!

Your funding agency could be here!

T. Hilger