The Charm and Beauty of Strong Interactions

Bruno El-Bennich
Laboratório de Física Teórica e Computacional
Universidade Cruzeiro do Sul, São Paulo

Universidade Cruzeiro do Sul
FAPESP FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO
CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

XLVII International Symposium on Multiparticle Dynamics (ISMD2017)

September 11-15, 2017, Tlaxcala City, Mexico

Hadron Physics and Flavor Physics

A twofold motivation, same headaches, a unified approach?

- Main object of study in flavor physics is the (origin of) CP-violating phase(s) in weak decays of flavored quarks confined in mesons.

  The Cabibbo-Kobayashi-Maskawa mechanism has been established as the dominant Standard Model source of CP violation in heavy meson decays. CP violation is one of the three necessary conditions for matter-antimatter asymmetry in the universe.

  ➤ Origin and Preponderance of Matter

- Main object of study in non-perturbative QCD is confinement – colored states are not observed experimentally $\Rightarrow$ theoretically not proved but good hints.

  The overwhelming bulk of visible matter is made of baryons containing light quarks. Dynamical Chiral Symmetry Breaking (DCSB) due to gluon interactions is the most important mass generating mechanism for visible matter in the Universe. Thus, for most observed matter the Higgs mechanism is almost irrelevant.

  ➤ Origin of Baryonic Matter

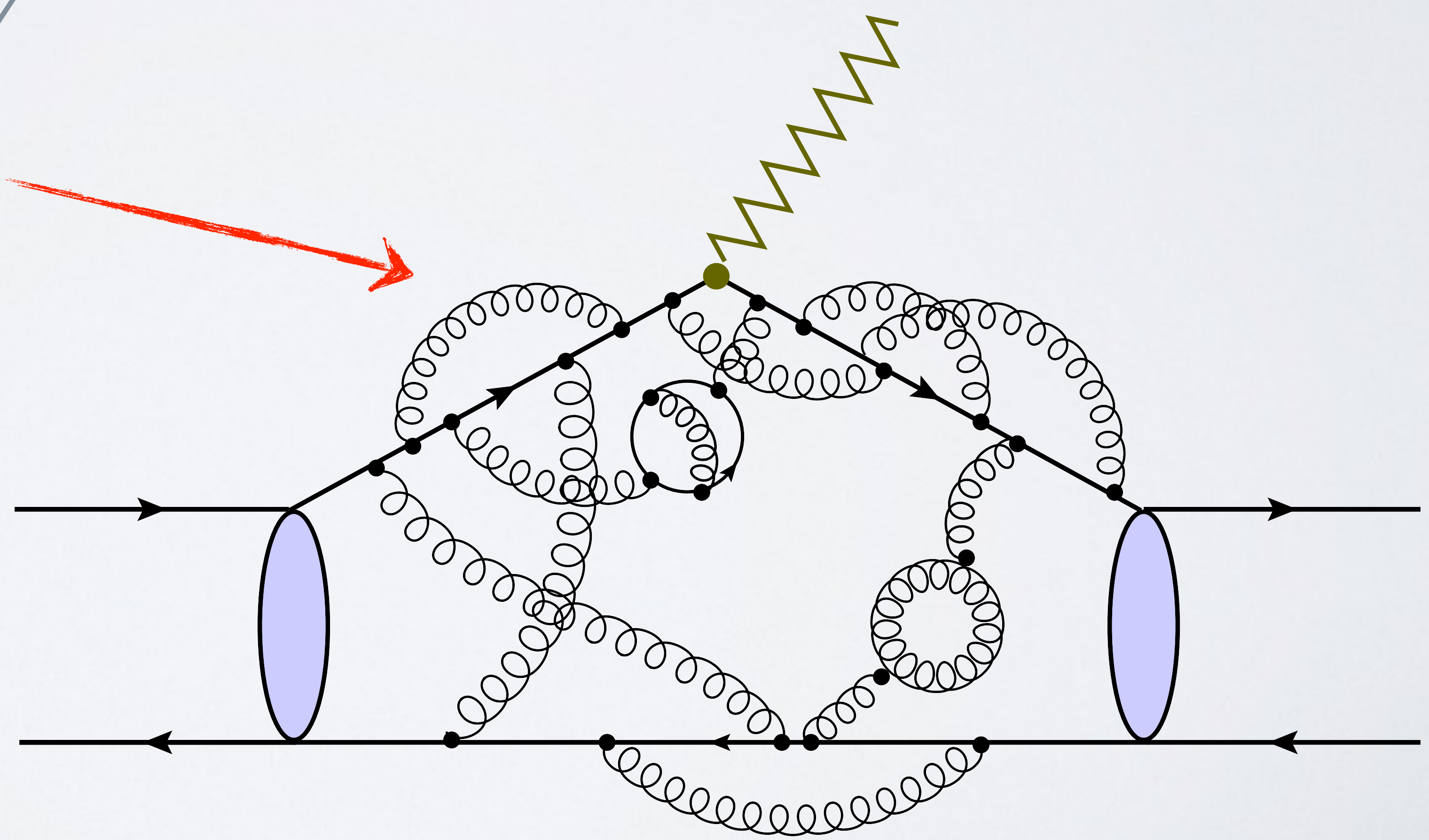
Form factors in weak heavy-meson decays

$$\langle M_1 M_2 | Q_k(\mu) | B \rangle \sim \langle M_2 | J_1 | 0 \rangle \otimes \langle M_1 | J_2 | B \rangle \times \left[1 + \sum_n r_n \alpha_s^n + \mathcal{O}(\Lambda_{\mathbf{QCD}}/m_b) \right]$$

Decay constant
(mostly known experimentally)

Radiative vertex corrections
and hard gluon exchange
with spectator quark

Hadronic transition form factor;
estimated with QCD sum rules,
lattice QCD, quark models ...



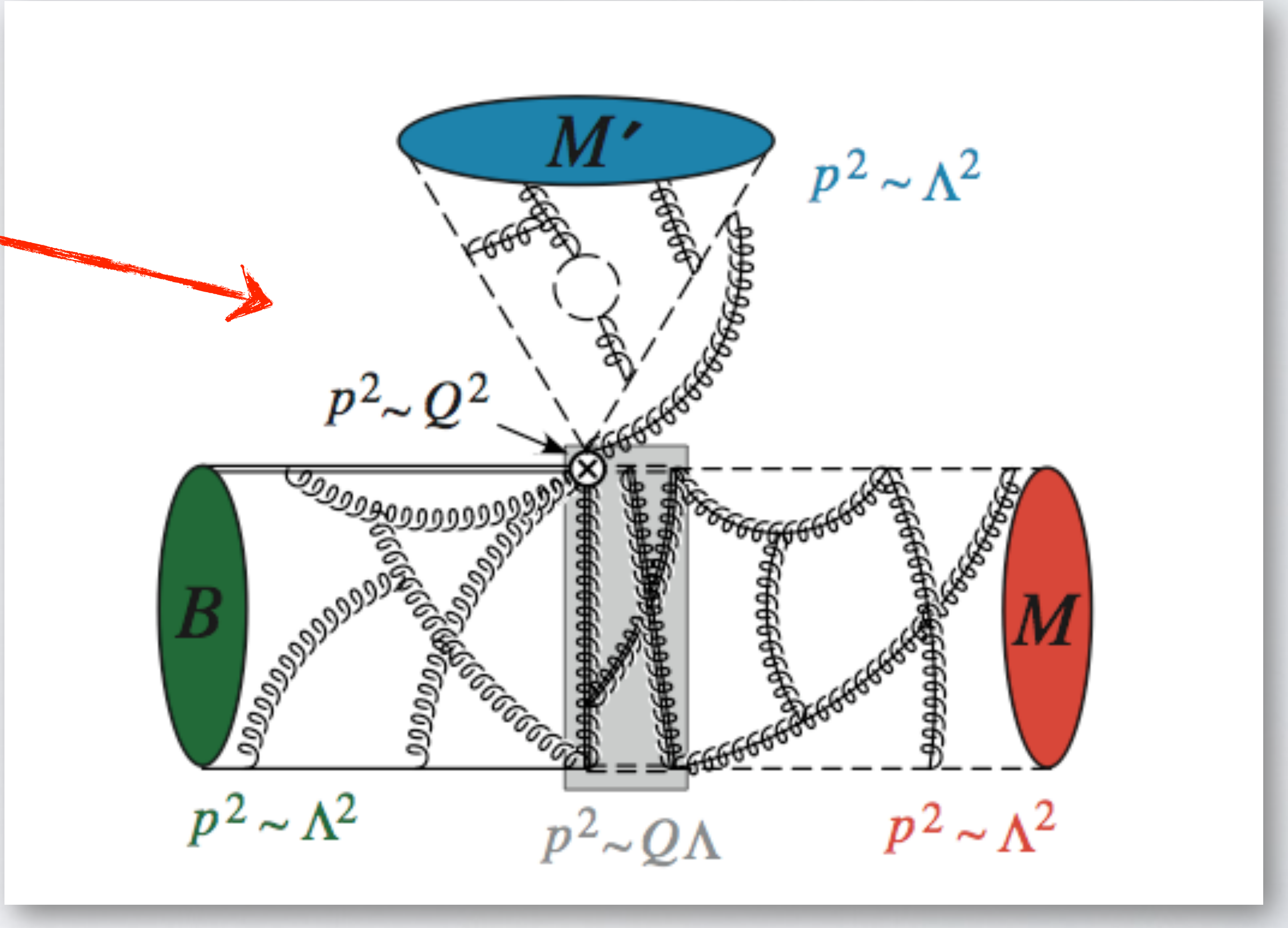
Form factors in weak heavy-meson decays

$$\langle M_1 M_2 | Q_k(\mu) | B \rangle \sim \langle M_2 | J_1 | 0 \rangle \otimes \langle M_1 | J_2 | B \rangle \times \left[1 + \sum_n r_n \alpha_s^n + \mathcal{O}(\Lambda_{\mathbf{QCD}}/m_b) \right]$$

Decay constant
(mostly known experimentally)

Radiative vertex corrections
and hard gluon exchange
with spectator quark

Hadronic transition form factor;
estimated with QCD sum rules,
lattice QCD, quark models ...



QCD factorization involves matrix elements which are convolution integrals:

$$\langle \pi^+\pi^- | (\bar{u}b)_{\mathrm{V-A}} (\bar{d}u)_{\mathrm{V-A}} | \bar{B}_d \rangle \to \int_0^1 d\xi du dv \, \Phi_B(\xi) \, \Phi_\pi(u) \, \Phi_\pi(v) \, T(\xi, u, v; m_b)$$

The integrals in the momentum fractions ξ, u and v are over a (hard) scattering kernel $T(\xi,u,v)$ and light-cone distribution amplitudes (LCDA) expanded in Gegenbauer polynomials:

$$\varphi_\pi(x;\tau) = \varphi_\pi^{\mathrm{asy}}(x) \left[1 + \sum_{j=2,4,\ldots}^{\infty} a_j^{3/2}(\tau) \, C_j^{(3/2)}(2x-1) \right]$$

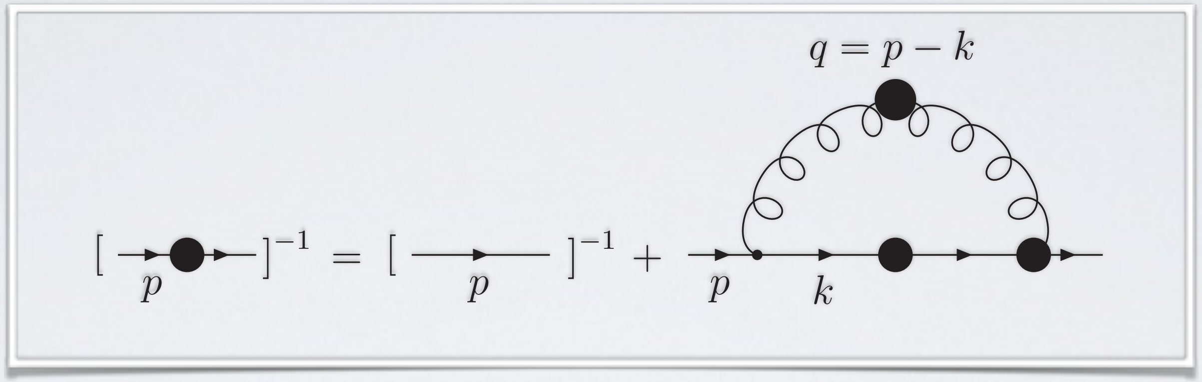
$$\varphi_\pi^{\mathrm{asy}}(x) = 6x(1-x)$$

LCDA until recently poorly known for light mesons, next to nothing is known about heavy-light mesons, mostly models and asymptotic LCDA used !

Only one available moment for pion from lattice-QCD; not better than 20%.

Nonperturbative ingredient I: Quark-Gap Equation in QCD

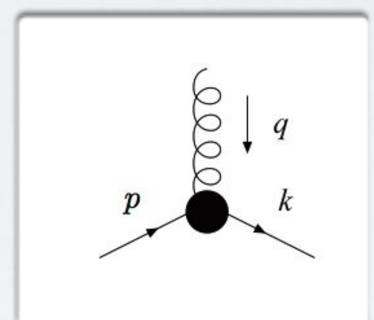
The propagator can be obtained from QCD's gap equation: the Dyson-Schwinger equation (DSE) for the dressed-fermion self-energy, which involves the set of infinitely many coupled equations.



$$S^{-1}(p) = Z_2(i\gamma \cdot p + m^{\mathrm{bm}}) + \Sigma(p) := i\gamma \cdot p\, A(p^2) + B(p^2)$$

$$\Sigma(p) = Z_1 \int^{\Lambda} \frac{d^4 q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q) \frac{\lambda^a}{2} \gamma_\mu S(q) \Gamma^a_\nu(q,p)$$

with the *running* mass function $M(p^2) = B(p^2)/A(p^2)$.



$D_{\mu\nu}$: dressed-gluon propagator

$\Gamma^a_\nu(q,p)$: dressed quark-gluon vertex

Z_2 : quark wave function renormalization constant

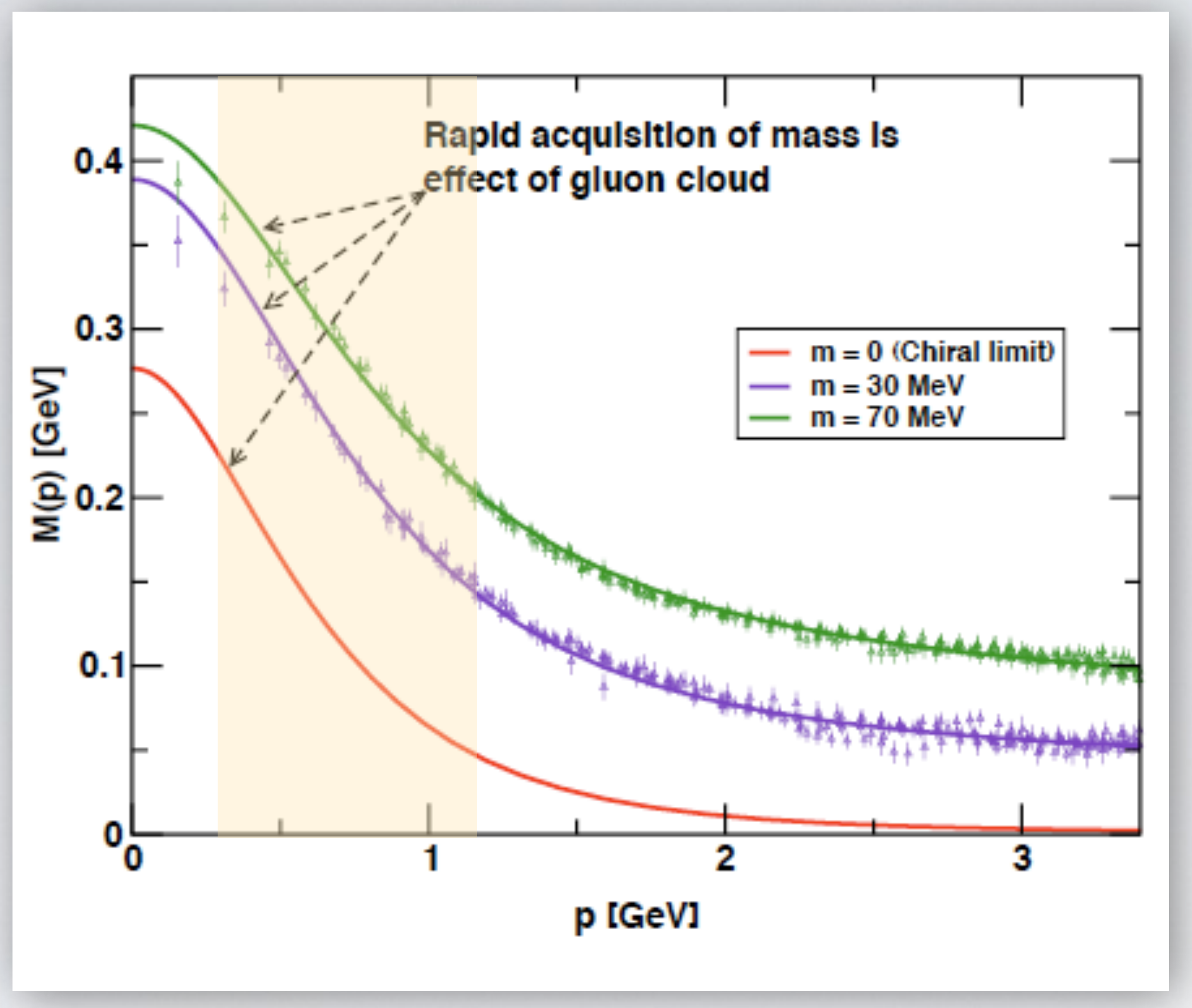
Z_1 : quark-gluon vertex renormalization constant

Each satisfies it's own DSE !

$$S^{-1}(p)|_{p^2=\zeta^2} = i\gamma \cdot p + m(\zeta)$$

where ζ is the renormalization point.

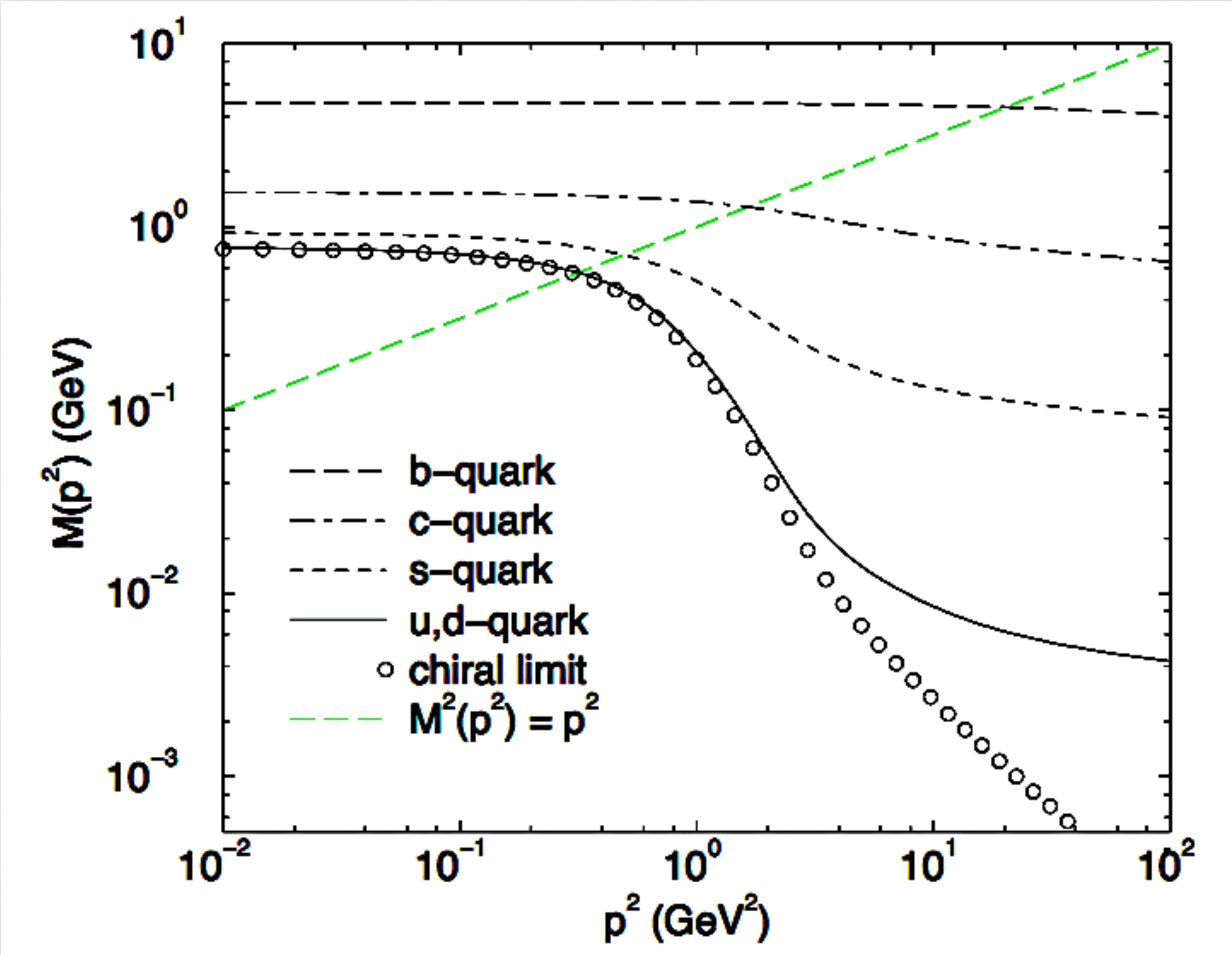
Running mass functions $M(p^2) = \frac{B(p^2)}{A(p^2)}$



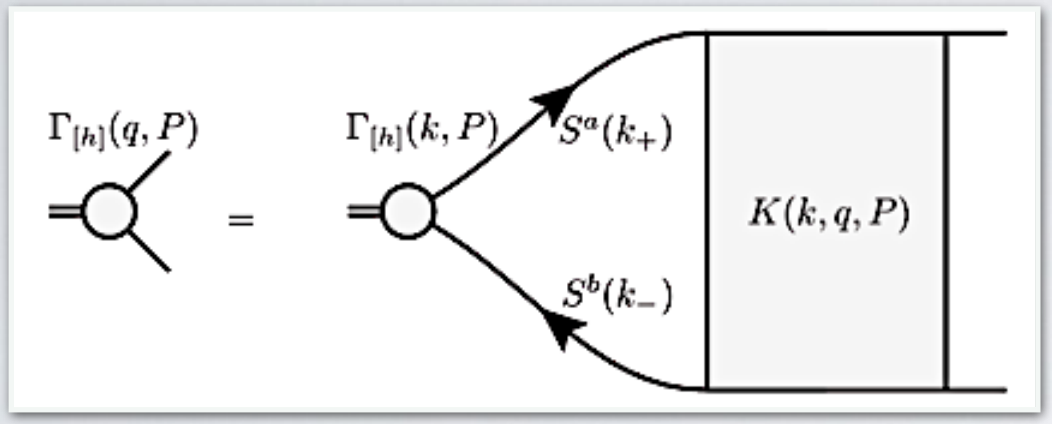
➪ For light quarks the Higgs mechanism is almost irrelevant!

Running mass functions

The large current-quark mass of the *b* quark almost entirely suppresses momentum-dependent dressing, so that $M_b(p^2)$ is nearly constant on a substantial domain. This is true to a lesser extent for the *c* quark where there still is a difference of about 30–40%



Nonperturbative ingredient II: Bethe-Salpeter Equations for QCD Bound States



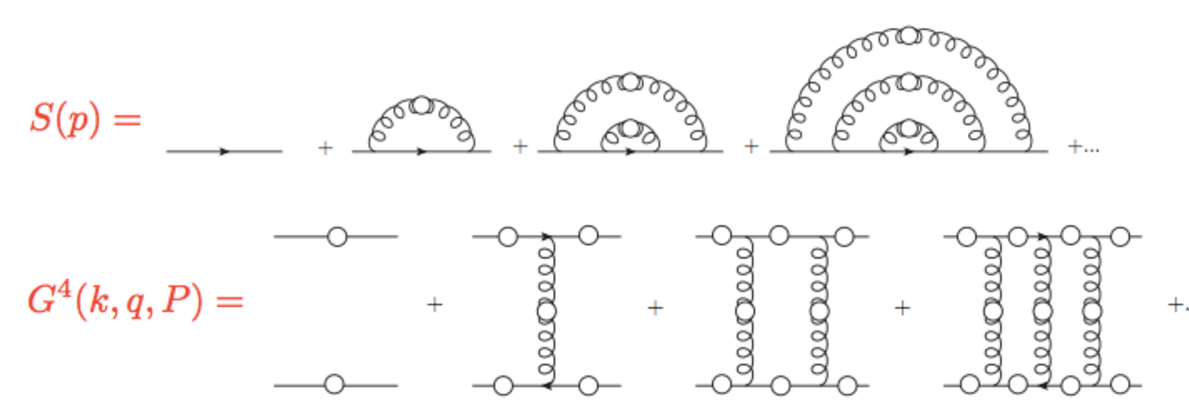
Nonperturbative QCD based ansatz for interaction kernel

$$\Gamma(P,p) = \int \frac{d^4k}{(2\pi)^4} K(P,p,k)\, S(k-\tfrac{P}{2})\, \Gamma(P,k)\, S(k+\tfrac{P}{2})$$

Rainbow-Ladder truncation:

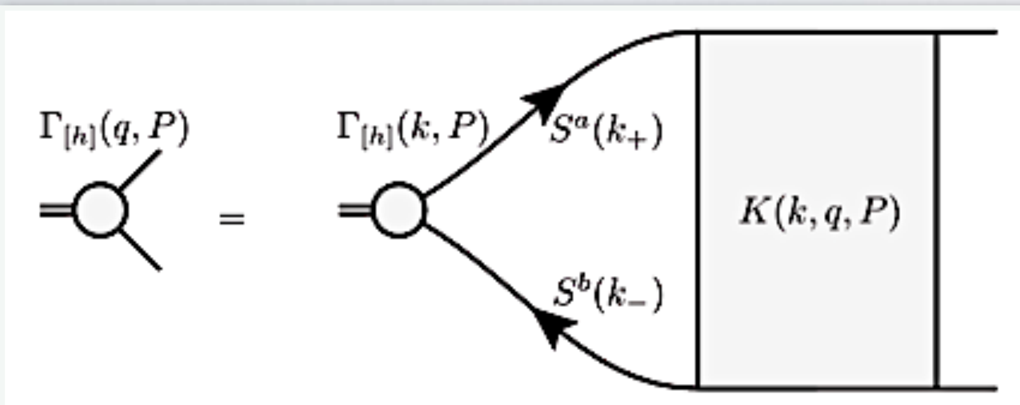
$$K(P,p,k) = -\frac{Z_2^2\, \mathcal{G}(q^2)}{q^2} \left(\frac{\lambda^a}{2}\gamma_\mu\right) T_{\mu\nu}(q) \left(\frac{\lambda^a}{2}\gamma_\nu\right)$$

Rainbow-ladder truncation (leading symmetry-preserving approximation)



Model gluon propagator, solve quark propagator and 4-point Green function.

Nonperturbative ingredient II:
Bethe-Salpeter Equations for QCD Bound States



Nonperturbative QCD based ansatz for interaction kernel

$$\Gamma(P,p) = \int \frac{d^4k}{(2\pi)^4}\, K(P,p,k)\, S(k-\tfrac{P}{2})\,\Gamma(P,k)\,S(k+\tfrac{P}{2})$$

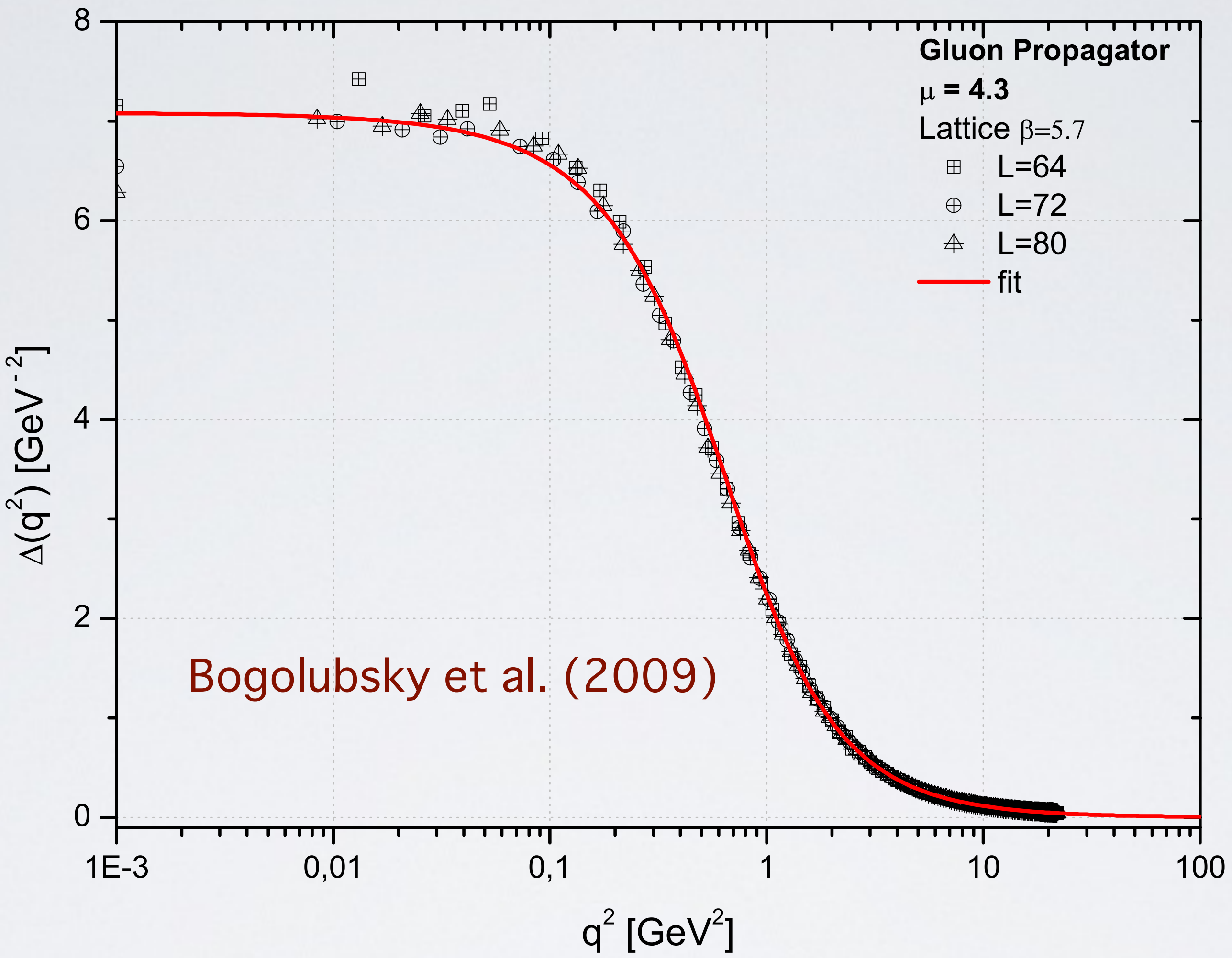
Rainbow-Ladder truncation:

$$K(P,p,k) = -\frac{Z_2^2\,\mathcal{G}(q^2)}{q^2}\left(\frac{\lambda^a}{2}\gamma_\mu\right) T_{\mu\nu}(q)\left(\frac{\lambda^a}{2}\gamma_\nu\right)$$

General solution for Poincaré invariant ground- and excited-state amplitudes

$$\Gamma_{P_n}(p,P) = \gamma_5\big[\, i\,\mathbb{I}_D E_{P_n}(p,P) + \gamma\cdot P\, F_{P_n}(p,P) \\ + \gamma\cdot p\,(p\cdot P) G_{P_n}(p,P) + \sigma_{\mu\nu}p_\mu P_\nu\, H_{P_n}(p,P)\big]$$

Gluon dressing function: QCD based interaction



Use effective interaction which reproduces Lattice QCD and DSE results for gluon-dressing function: infrared massive fixed point; ultraviolet massless propagator.

Qin, Chang, Liu, Roberts and Wilson 2011

$$\mathcal{G}(s) = \frac{8\pi^2}{\omega^4} D e^{-s/\omega^2} + \frac{8\pi^2 \gamma_m}{\ln\left[\tau + (1 + s/\Lambda_{QCD}^2)\right]} \mathcal{F}(s)$$

Pseudoscalar- and Vector-Meson Spectroscopy

$J^{PC}=0^{-+}$	DSE-BSE	PDG
m_π	0.136	0.139
f_π	0.139	0.1304
$m_{\pi(1300)}$	1.414	1.30 ± 0.10
$f_{\pi(1300)}$	8.3×10^{-4}	—
m_K	0.493	0.493
f_K	0.164	0.156
$m_{K(1460)}$	1.580	1.460
$f_{K(1460)}$	0.017	—
$m_{\eta_c(1S)}$	3.065	2.984
$f_{\eta_c(1S)}$	0.389	0.395
$m_{\eta_c(2S)}$	3.784	3.639
$f_{\eta_c(2S)}$	0.105	—

E. Rojas, B. E. & J. P. B. C. de Melo, PRD (2014)
F. Mojica, C. Vera, E. Rojas & B. E., PRD (2017)

Weak decay constant for radially excited states vanish — only strong decays possible:

$$f^0_{P_n} \equiv 0\,,\ n \geq 1$$

$J^{PC}=1^{--}$	DSE-BSE	PDG
$m_{\rho^0(770)}$	0.742	0.775
$f_{\rho^0(770)}$	0.231	0.221
$m_{\rho^0(1450)}$	1.284	1.465
$f_{\rho^0(1450)}$	0.150	—
$m_{K^*(892)}$	0.951	0.896
$f_{K^*(892)}$	0.287	0.217
$m_{K^*(1410)}$	1.217	1.414
$f_{K^*(1410)}$	0.127	—
$m_{\phi(1020)}$	1.087	1.019
$f_{\phi(1020)}$	0.305	0.322
$m_{\phi(1680)}$	1.650	1.659
$f_{\phi(1680)}$	0.138	—
$m_{J/\psi}$	3.114	3.097
$f_{J/\psi}$	0.433	0.416
$m_{\psi(2S)}$	3.760	3.689
$f_{\psi(2S)}$	0.176	0.295
$m_{\Upsilon(1S)}$	9.634	9.460
$f_{\Upsilon(1S)}$	—	0.715
$m_{\Upsilon(2S)}$	10.140	10.023
$f_{\Upsilon(2S)}$	0.564	0.497

Open-flavor mesons

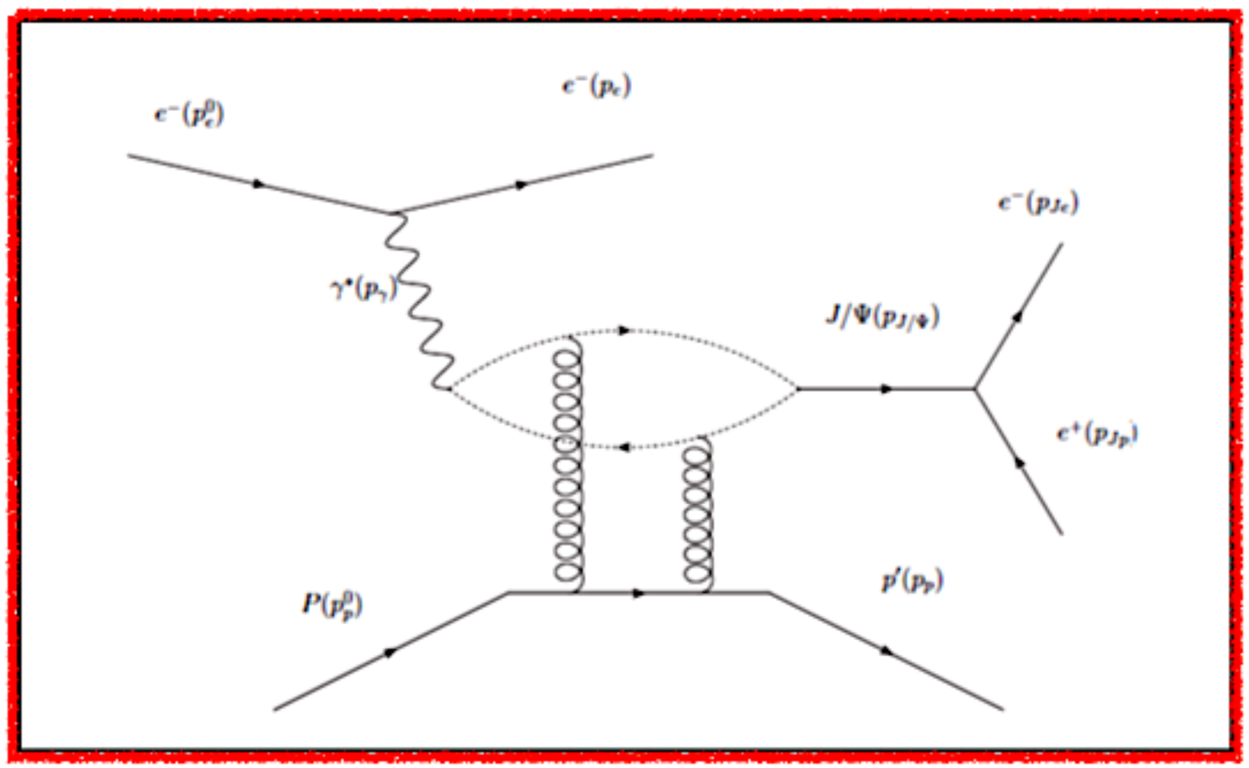
- So far, we have first results for the heavy-light systems: *D* mesons

	Model	Experiment [63]
m_D	2.115	1.869
f_D	0.204	$0.2067 \pm 0.0085 \pm 0.0025$
m_{D_s}	2.130	1.968
f_{D_s}	0.249	0.260 ± 0.004

E. Rojas, B. E. & J. P. B. C. de Melo, PRD (2014)

- However, masses too large and mass difference too small.
- This was expected, strong mass asymmetry doesn't allow for simple quark-gluon vertex and rainbow-ladder truncation.

ATHENNA* collaboration JLab @ 12 GeV

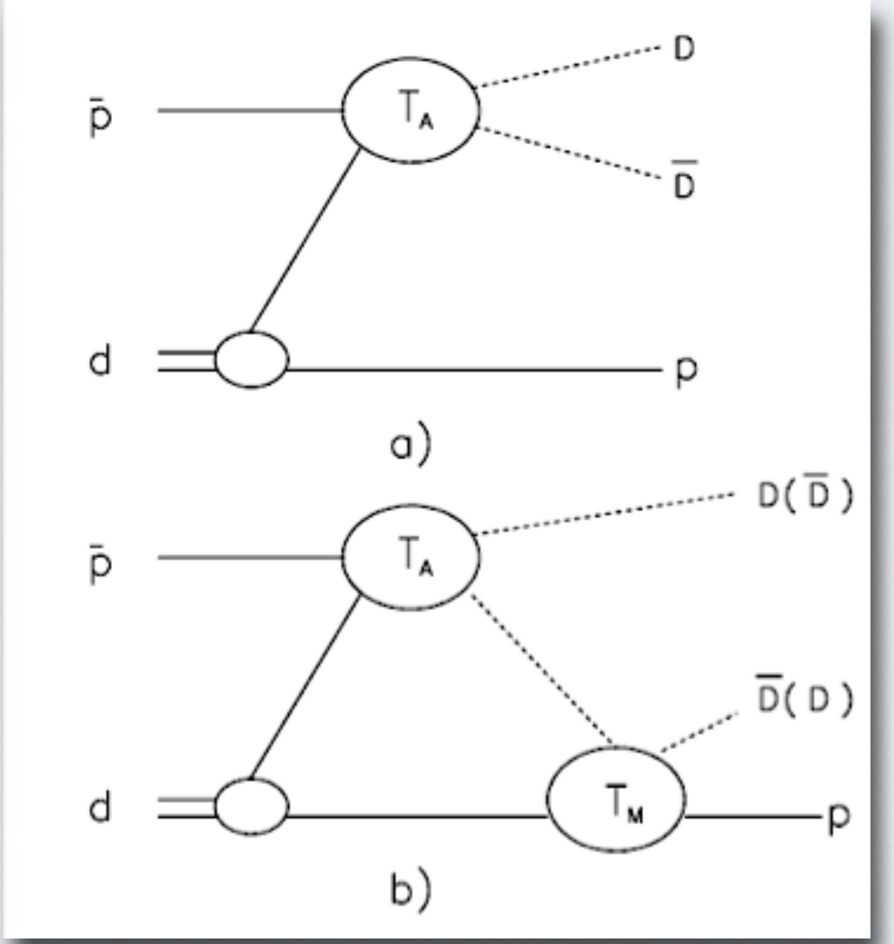


Z.-E. Meziani (Co-spokesperson/Contact)
N. Sparveris (Co-spokesperson)
Z.W. Zhao (Co-spokesperson)

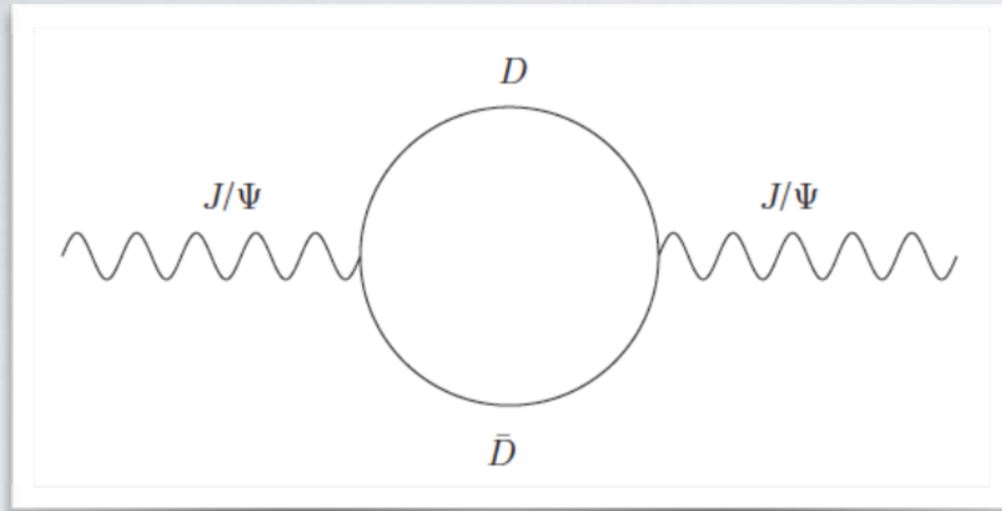
*A J/Ψ THreshold Electroproduction on the Nucleon and Nuclei Analysis

Antiproton annihilation on the deuteron

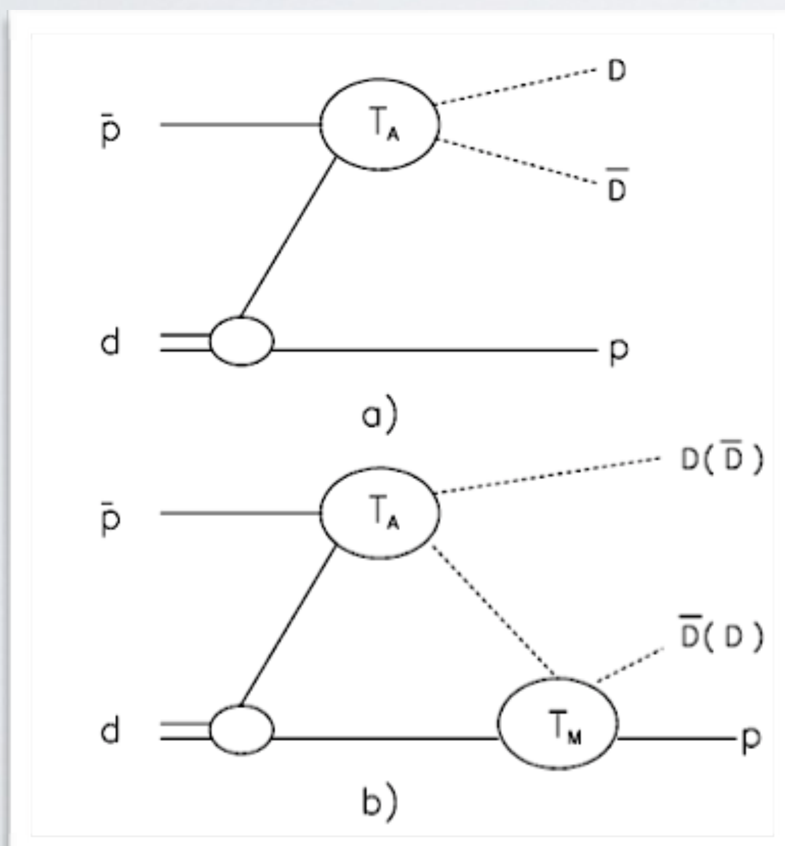
PANDA @ Facility for Antiproton and Ion Research (FAIR)



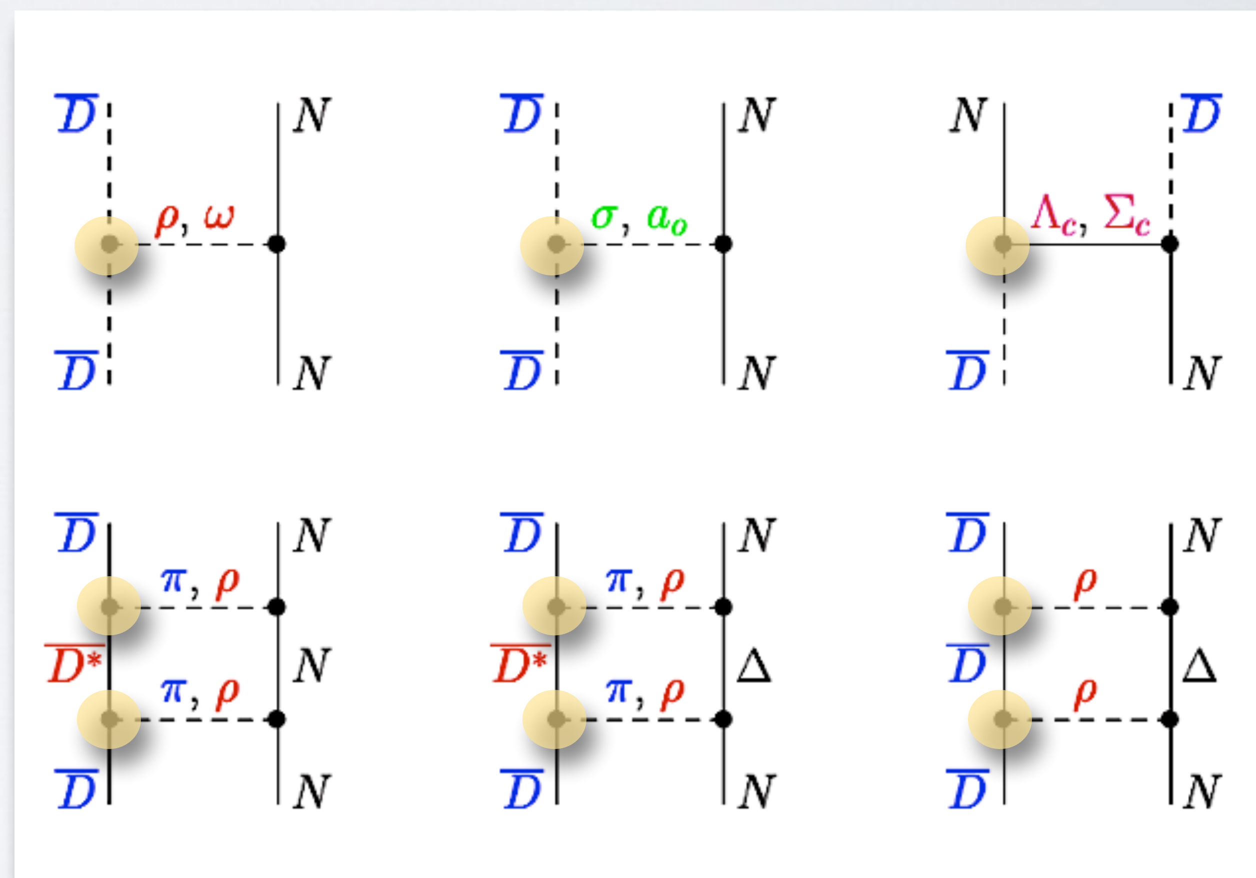
Phenomenological Heavy-Meson Lagrangians



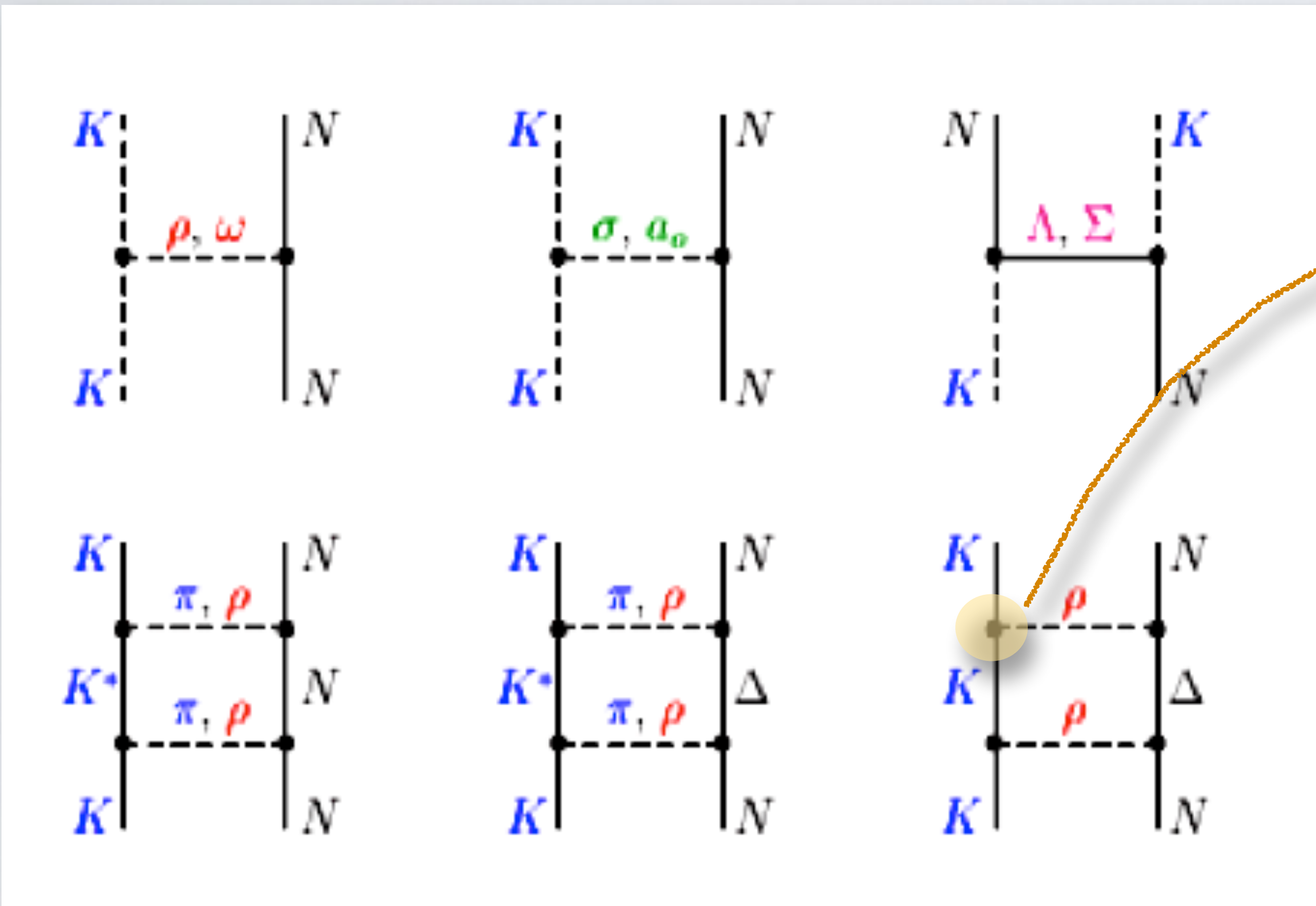
D-meson interactions with nucleons

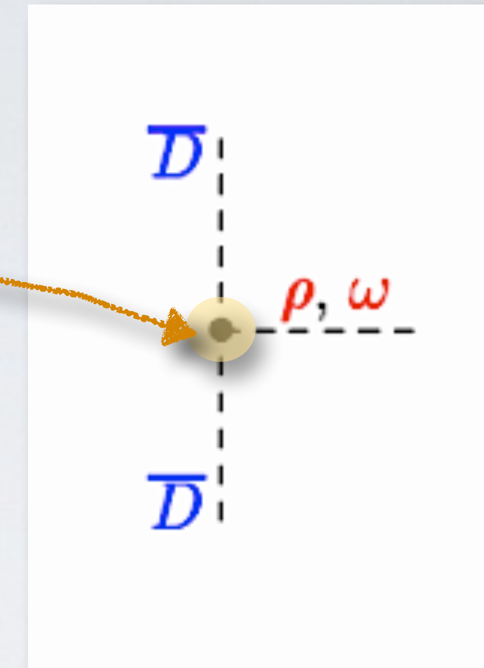


Meson exchange — effective Lagrangians



SU(4) symmetry used ....





Jülich model:

A. Müller-Groeling et al. NPA 513, 557 (1990)

M. Hoffmann et al. NPA 593, 341 (1995)

D. Hadjimichef, J. Haidenbauer and G. Krein, PRC 66 (2002)

$$SU(4)\ \text{symmetry:}\ g_{D\rho D} = g_{D\omega D} = g_{KK\rho} = \frac{1}{2} g_{\pi\pi\rho}$$

Flavor SU(3), SU(4) … sensible symmetries?

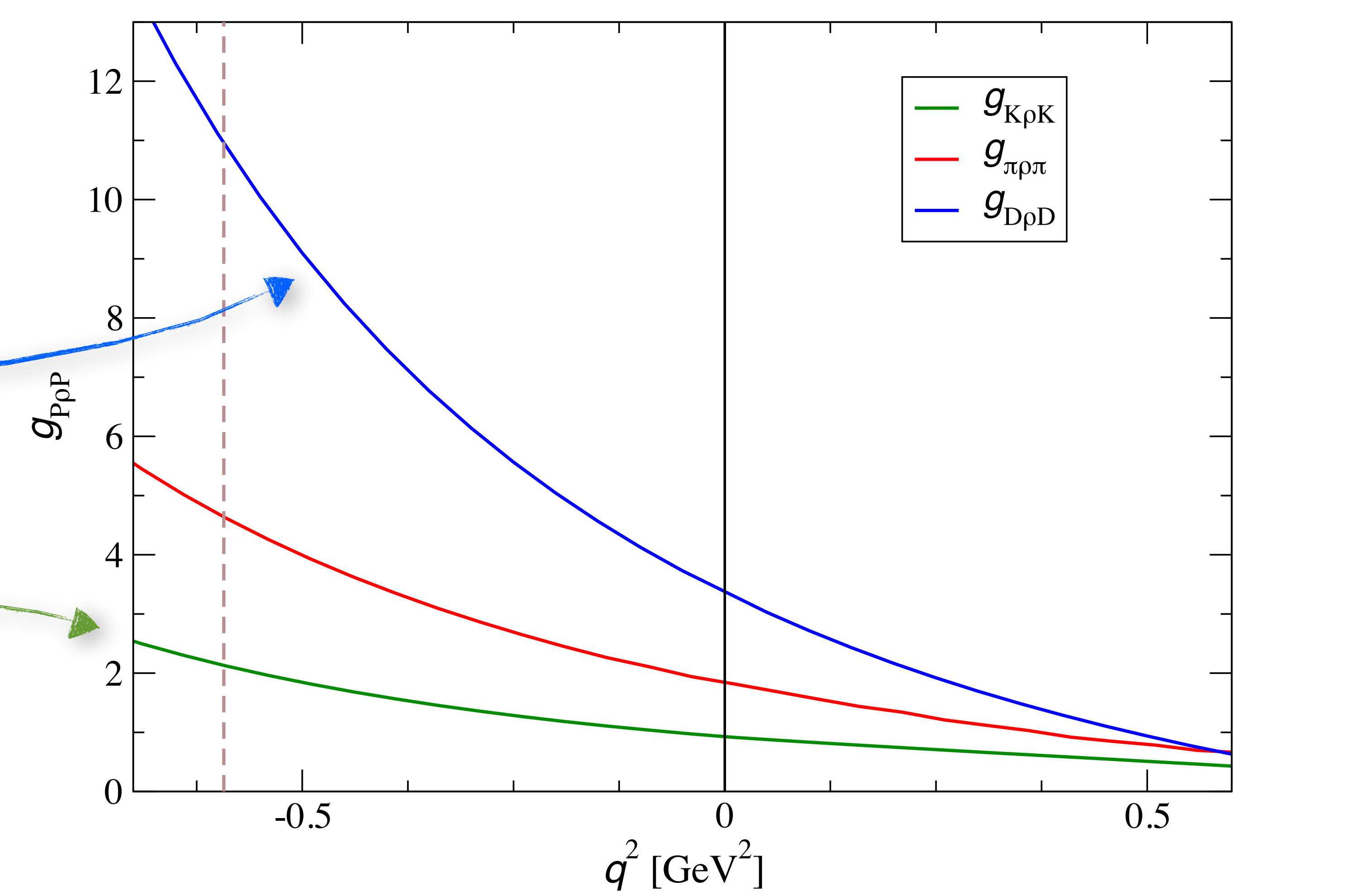
Define $\zeta_\rho := \dfrac{g_{D\rho D}(q^2)}{g_{K\rho K}(q^2)}$

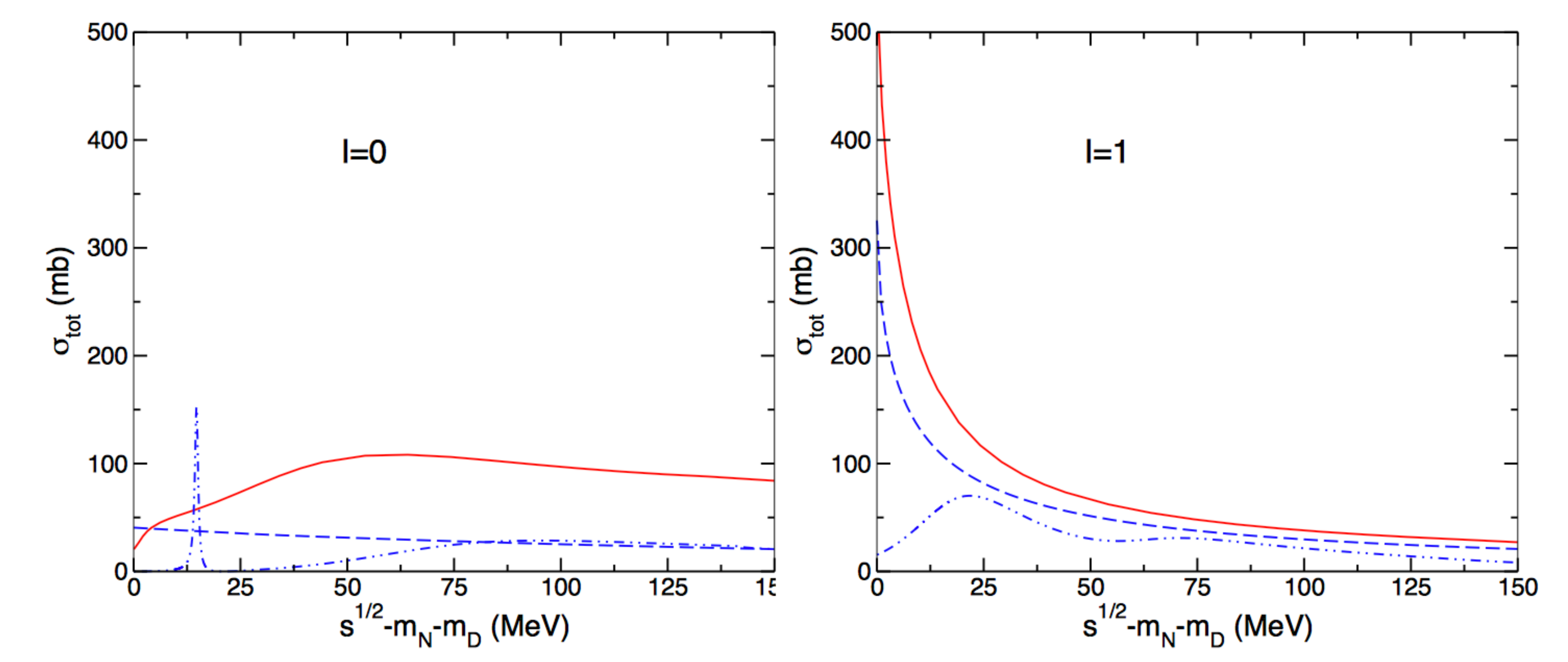
Ratio measures the effect of SU(4) breaking ≈ 300%

SU(3) breaking ≈ 20−30%

$$g_{D\rho D} \neq g_{K\rho K} \neq \frac{1}{2} g_{\pi\rho\pi}$$

B. E., G. Krein, L. Chang, C.D. Roberts and D. Wilson, PRD (2012)





L. Tolos, J. Haidenbauer and G. Krein, Eur. Phys. J. (2011)

Consequences for DN cross sections?

The integrated $D\rho D$ interaction is enhanced by about 40% compared with an *SU*(4) prediction for the coupling/form factor.

Large value value for the interaction strength entails an enhanced cross section in *DN* scattering (I = 1 cross section inflated by a factor 4–5).

Possible novel charmed resonances or bound states in nuclei?

Conclusions

- Long path from QCD based modeling toward nonperturbative numerical solutions of quark propagators and quark-antiquark bound states for flavored mesons respecting *chiral symmetry* and *Poincaré covariance*.
- Simplest truncation so far results in a good reproduction of charmonium and bottonium mass spectrum and their weak decay constants. Complicated disparate scales in heavy-light mesons require a more sophisticated treatment beyond leading truncation.
- Work on gap equation with real lattice QCD data for gluon propagator and full nonperturbative quark-gluon structure is ambitious program but under work.