

A Pattern for the Flavor Dependent Quark-quark Interaction

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Introduction: strong interaction

Dyson-Schwinger Equation and Bethe-Salpeter Equation (DSBSE)
Approach

An Interaction Pattern & Meson Spectrum and Decay Constants

Summary

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Hadrons

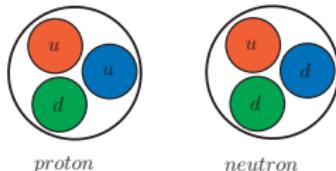


Figure 1: Proton and Neutron in quark model.

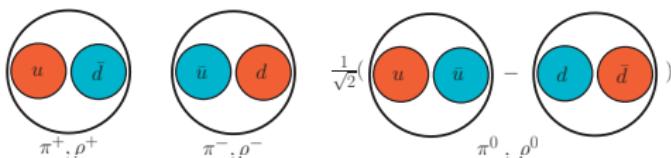


Figure 2: Mesons ($\pi^{\pm,0}, \rho^{\pm,0}$) in quark model.

- ✖ current quark mass¹:
 $m_u = 2.2_{-0.4}^{+0.6} \text{ MeV},$
 $m_d = 4.7_{-0.4}^{+0.5} \text{ MeV},$
 $\bar{m} = (m_u + m_d)/2 = 3.2 - 4.2 \text{ MeV};$
- ✖ constituent quark mass¹:
 $m_p \approx 938 \text{ MeV},$
 $m_n \approx 940 \text{ MeV},$
 $m_\rho \approx 775 \text{ MeV},$
 $\Rightarrow M_{u/d} \approx 400 \text{ MeV};$
- ✖ $m_\pi \approx 138 \text{ MeV}^1.$
- ✖ $M_{u/d} \gg \bar{m}?$ $m_\pi \ll m_\rho?$

¹C. Patrignani *et al*, Chin. Phys. C 40, 100001 (2016).

Hadrons

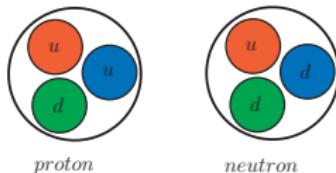


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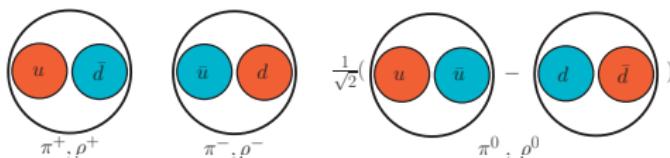


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Strong Interaction:
dynamical chiral symmetry breaking (DCSB)!

¹C. Patrignani *et al*, Chin. Phys. C 40, 100001 (2016).

Quantum Chromodynamics (QCD)

- ✚ QCD is the current theory for Strong Interaction.
- ✚ The lagrange of QCD:

$$\mathcal{L}_{\text{QCD}} = \sum_{f=1}^{N_f} \underbrace{\bar{q}_f(x)(iD - m_f)q_f(x)}_{\text{quark field}} - \underbrace{\frac{1}{4}F_{\mu\nu}^a(x)F_a^{\mu\nu}(x)}_{\text{gluon field}}, \quad (1)$$

where $D_\mu = \partial_\mu - ig\frac{\lambda^a}{2}A_\mu^a$,

$$F_{\mu\nu}^a(x) = \partial_\mu A_\nu^a(x) - \partial_\nu A_\mu^a(x) + g f^{abc} A_\mu^b(x) A_\nu^c(x),$$
$$f = u, d, s, c, b, t \text{ are different quark flavors.}$$

- ✚ Three properties of QCD:
 - ◇ DCSB,
 - ◇ confinement,
 - ◇ asymptotic freedom.

✚ Chiral rotation:

$$q_f^L \rightarrow e^{i\theta_L} q_f^L, \quad q_f^R \rightarrow e^{i\theta_R} q_f^R, \quad (2)$$

where $q^{L,R} = \mathcal{P}^{L,R} q$, $\mathcal{P}^{L,R} = \frac{1}{2}(1 \mp \gamma_5)$.

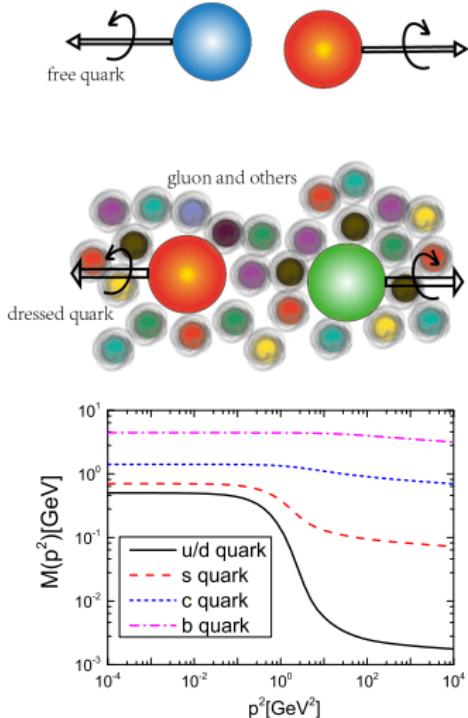
✚

$$\bar{q}_f(x) \not{D} q_f(x) = \bar{q}_f^L(x) \not{D} q_f^L(x) + \bar{q}_f^R(x) \not{D} q_f^R(x). \quad (3)$$

In the $m_f = 0$ case, the lagrange is invariant under the chiral rotation Eq. (3).

✚ However, a quark mass term destroys the chiral symmetry. Under the chiral rotaion Eq. (3),

$$m_f \bar{q} q = m_f (\bar{q}_L q_R + \bar{q}_R q_L) \rightarrow m_f (e^{i(\theta_R - \theta_L)} \bar{q}_L q_R + e^{i(\theta_L - \theta_R)} \bar{q}_R q_L). \quad (4)$$



✖ Two kinds of chiral symmetry breaking in QCD:

explicit chiral symmetry breaking (ECSB):

the explicit mass m_f in the Lagrange Eq. (1), i.e. quarks get mass due to Higgs Mechanism;

dynamical chiral symmetry breaking (DCSB): quarks get mass due to dynamics.

✖ quark mass from DCSB:

$$M_q \approx 350 - 500 \text{ MeV}^1.$$

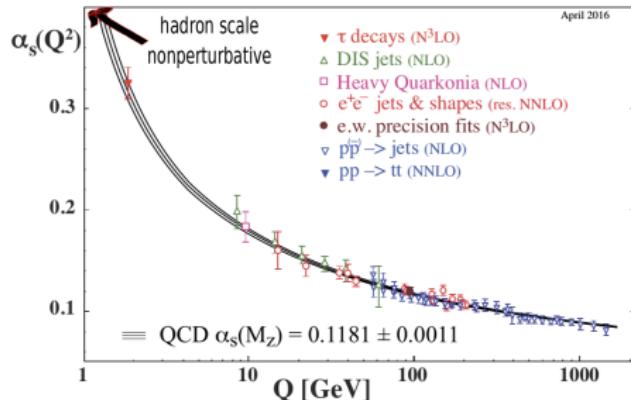
✖ gluon mass from DCSB:

$$M_g \approx 500 \text{ MeV}^2.$$

¹M. S. Bhagwat, M. A. Pichowsky, C. D. Roberts and P. C. Tandy, Phys. Rev. C 68, 015203 (2003).

²S.X. Qin, L. Chang, Y. X. Liu, C. D. Roberts and D. J. Wilson, Phys. Rev. C 84, 042202 (2011). D. Binosi, L. Chang, J. Papavassiliou and C. D. Roberts, Phys. Lett. B742, 183-188 (2015).

Asymptotic freedom



- ✚ Asymptotic freedom: coupling constant becomes weaker at larger momentum transfer.
- ✚ Only the non-Abelian gauge theories are asymptotically free, among renormalizable quantum field theories in four spacetime dimensions¹.

✚ In 1-loop perturbative QCD,

$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \ln(Q^2 / (\Lambda_{\text{QCD}}^{N_f})^2)}, \quad (5)$$

where $\beta_0 = 11 - 2N_f/3$, N_f is the quark flavor number, $\Lambda_{\text{QCD}}^{N_f}$ is the QCD scale.

¹S. Coleman and D. J. Gross, Phys. Rev. Lett. 31, 851 (1973).

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Summary

- ✖ DSEs are the motion equations of Green Functions in quantum field theory.
- ✖ DSEs can be derived from

$$0 = \frac{\delta Z[j]}{\delta \phi_k}, \quad (6)$$

where

$$Z[j] = \int D[\phi] \exp\{-S[\phi] + j_i \phi_i\} = \langle e^{j_i \phi_i} \rangle = \sum_{n=0}^{\infty} G_{i_1 \dots i_n} j_{i_1} \dots j_{i_n} \quad (7)$$

is the generating functional, and $S[\phi] = \int d^4x L(x)$ the action, $L(x)$ the Lagrangian.

Equation of the fields

$$L_{\text{QCD}} = -\frac{1}{4}F_a^{\mu\nu}F_a^{\mu\nu} + \frac{1}{2}[\bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi + h.c.], \quad (8)$$

where $F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_a^{rs} A_r^\mu A_s^\nu$ is the color-electro-magnetic field tensor, A_a^μ is the color vector potential, $D_\mu = \partial_\mu + igA_\mu$, $A_\mu = A_{a,\mu}\lambda^a/2$, λ^a the Gell-Mann matrices. The Euler equations,

$$\frac{\delta \int d^4x L(x)}{\delta \phi} = 0 \implies \frac{\partial}{\partial x_\nu} \left[\frac{\delta L}{\delta(\partial_\nu \phi)} \right] - \frac{\delta L}{\delta \phi} = 0. \quad (9)$$

With $\phi = A_\mu^a$, $\frac{\delta L}{\delta(\partial_\nu A_\mu^a)} = -F_a^{\nu\mu}$, $\frac{\delta L}{\delta A_\mu^a} = -gJ_a^\mu$, $J_a^\mu = \bar{\Psi}\gamma^\mu \frac{\lambda_a}{2}\Psi + f_a^{rs}F_r^{\mu\nu}A_{s,\nu}$, get the **color-Maxwell equations**:

$$\partial_\nu F_a^{\mu\nu} = gJ_a^\mu. \quad (10)$$

With $\phi = \bar{\Psi}_\alpha$, $\frac{\delta L}{\delta(\partial_\nu \bar{\Psi}_\alpha)} = -\frac{i}{2}\gamma_\alpha^\nu \Psi_\beta$,

$\frac{\delta L}{\delta \bar{\Psi}_\alpha} = (\frac{i}{2}\gamma^\mu \partial_\mu - g\gamma^\mu A_\mu \frac{\lambda^a}{2})_{\alpha\beta} \Psi_\beta - m\Psi_\alpha$, get the **color-Dirac equations**:

$$(i\gamma^\mu D_\mu - m)\Psi = 0. \quad (11)$$

Equation of the propagator and bound states

$$0 = \frac{\delta}{\delta\eta(y)} \left\langle \frac{\delta}{\delta\bar{q}(x)} S[A, q, \bar{q}, \bar{c}, c] - \eta(x) \right\rangle. \quad (12)$$

✖ Quark Gap equation:

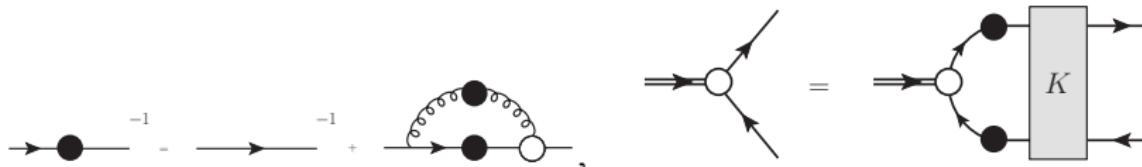
$$S^{-1}(k) = Z_2(i\cancel{k} + Z_m m) + g^2 Z_{1F} \int \frac{d^4 q}{(2\pi)^4} t^a \gamma_\mu S(q) \Gamma_\nu^b(q, k) D_{\mu\nu}^{ab}(k - q), \quad (13)$$

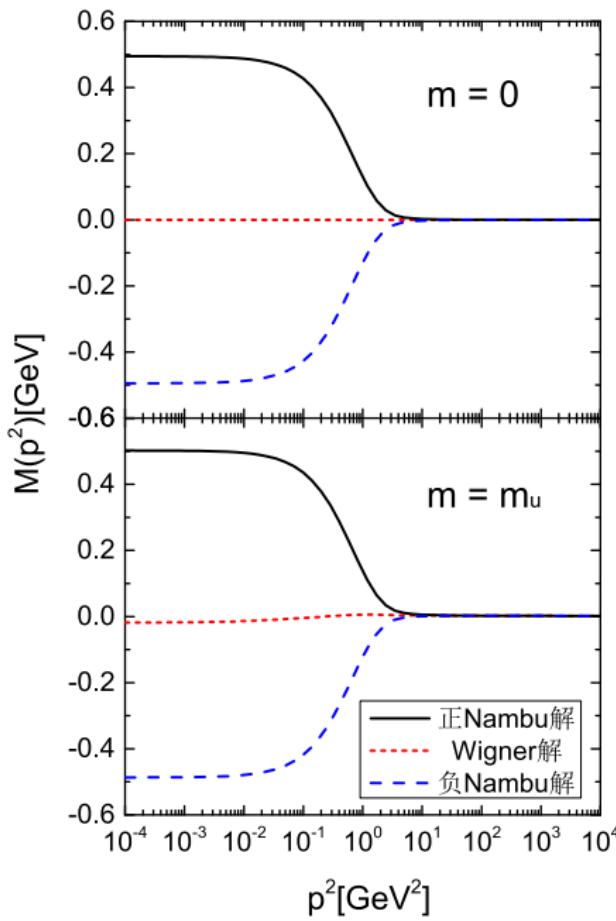
where $S(k)$ is the quark propagator, $D_{\mu\nu}^{ab}(k - q)$ is the gluon propagator, $\Gamma_\nu^b(q, k)$ is the proper quark-gluon vertex.

✖ Bethe-Salpeter equation:

$$\Gamma(k; P) = \int \frac{d^4 q}{(2\pi)^4} S(q_+) \Gamma(q; P) S(q_-) K(k, q; P), \quad (14)$$

where $\Gamma(k; P)$ is the BS amplitude.





$$\begin{aligned}
 S(k) &= \frac{1}{i\cancel{k}A(k^2) + B(k^2)} \\
 &= \frac{Z(k^2)}{i\cancel{k} + M(k^2)} \\
 &= -i\cancel{k}\sigma_v(k^2) + \sigma_s(k^2)
 \end{aligned} \tag{15}$$

A toy model:

$$\Gamma_\nu^b(q, k) \rightarrow \gamma_\nu \frac{\lambda^b}{2}, \\
 g^2 D_{\mu\nu}^{ab}(k - q) \rightarrow \delta^{ab} \delta_{\mu\nu} \frac{\alpha_{IR}}{m_G^2},$$

$$\begin{aligned}
 S^{-1}(k) &= (i\cancel{k} + m) + \\
 &\quad \frac{16\pi\alpha_{IR}}{3m_G^2} \int \frac{d^4q}{(2\pi)^4} \gamma_\mu S(q) \gamma_\mu.
 \end{aligned}$$

The axial-vector-Ward-Takahashi-Identity (AVWTI)

$$-iP_\mu \Gamma_{5\mu}^j(k; P) = S^{-1}(k_+) \gamma_5 \frac{\tau^j}{2} + \gamma_5 \frac{\tau^j}{2} S^{-1}(k_-) - 2m(\zeta) \Gamma_5^j(k; P), \quad (16)$$

where τ^j is the Pauli matrix, $\Gamma_{5\mu}^j$ is the axial vector vertex

$$\Gamma_{5\mu}^j(k; P) = \frac{f_\pi P_\mu}{P^2 + m_\pi^2} \Gamma_\pi^j(k; P) + \text{regular terms}, \quad (17)$$

f_π is the leptonic decay constant, Γ_π^j the Bethe-Salpeter amplitude.

$$\Gamma_\pi^j(k; P) = \tau^j \gamma_5 [iE_\pi(k; P) + \not{P}F_\pi(k; P) + \not{k}k \cdot P G_\pi(k; P) + \sigma^{k,P} H_\pi(k; P)]. \quad (18)$$

In the chiral limit, $m(\zeta) = 0$, $m_\pi = 0$, put Eq.(15), Eq.(17) and Eq.(18) into Eq.(16), get

$$f_\pi E_\pi(k; 0) = B(k^2). \quad (19)$$

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Gap equation:

$$\begin{aligned} S_f^{-1}(k) &= Z_2(i\gamma \cdot k + Z_m m_f) \\ &+ \frac{4}{3}Z_1 \int_{dq}^{\Lambda} \gamma_\mu S_f(q) \bar{g}^2 D_{\mu\nu}(l) \Gamma_\nu^f(k, q). \end{aligned} \quad (20)$$

Bethe-Salpeter equation:

$$[\Gamma^{fg}(k; P)]_\beta^\alpha = \int_{dq}^{\Lambda} [\mathcal{K}^{fg}(k, q; P)]_{\sigma\beta}^{\alpha\delta} [\chi^{fg}(q; P)]_\delta^\sigma, \quad (21)$$

where $\chi^{fg}(q; P) = S_f(q_+) \Gamma^{fg}(q; P) S_g(q_-)$ is the wave function, with $q_+ = q + \iota P/2$, $q_- = q - (1 - \iota)P/2$, $\iota \in [0, 1]$.

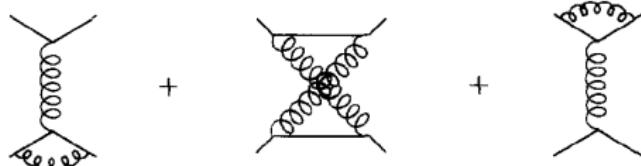
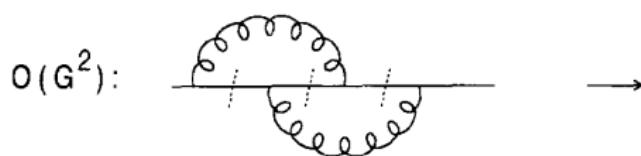
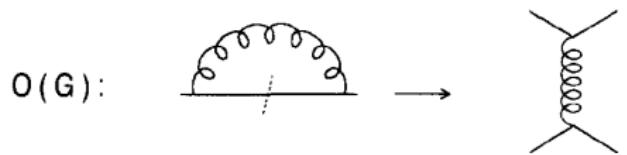
$\Gamma_\mu(k, q)$ is composed of 12 Lorentz covariants:

$$\{\gamma_\mu, k_\mu, q_\mu\} \times \{\mathbf{1}, \not{k}, \not{q}, [\not{k}, \not{q}]\} \quad (22)$$

Rainbow approximation: $\Gamma_\mu(\not{k}, \not{q}) = \gamma_\mu$.

avWTI constraint on the quark-antiquark scattering kernel:

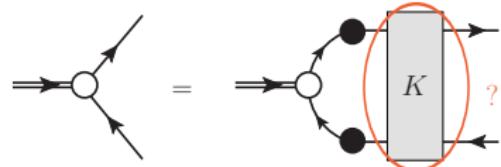
$$\text{DSE: } \gamma_\mu S(k) \gamma_\nu \longrightarrow \text{BSE: } \gamma_\mu \chi(k; P) \gamma_\nu,$$



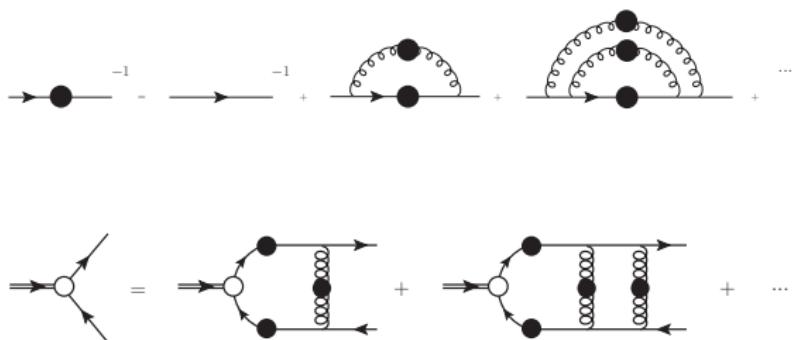
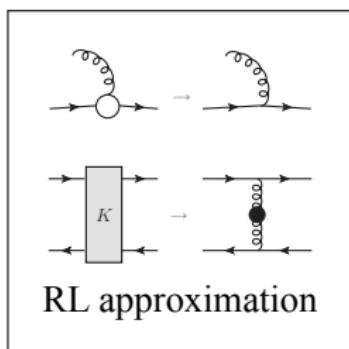
Rainbow-Ladder(RL) approximation

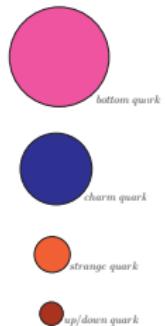


Gap Equation



Bethe-Salpeter Equation





$$\bar{g}^2 Z_1 D_{\mu\nu}(l) \Gamma_\nu^f(k, q) \rightarrow [Z_2]^2 \tilde{D}_{\mu\nu}^f(l) \gamma_\nu,$$

$$[K^{fg}(k, q; P)]_{\sigma\beta}^{\alpha\delta} \rightarrow -\frac{4}{3} [Z_2]^2 \tilde{D}_{\mu\nu}^{fg}(l) [\gamma_\mu]_\sigma^\alpha [\gamma_\nu]_\beta^\delta.$$

RL Gap equation:

$$S_f^{-1}(k) = Z_2(i\gamma \cdot k + Z_m m_f) + \frac{4}{3} [Z_2]^2 \int_{dq}^\Lambda \tilde{D}_{\mu\nu}^f(l) \gamma_\mu S_f(q) \gamma_\nu. \quad (23)$$

RL Bethe-Salpeter equation:

$$\Gamma^{fg}(k; P) = -\frac{4}{3} [Z_2]^2 \int_{dq}^\Lambda \tilde{D}_{\mu\nu}^{fg}(l) \gamma_\mu \chi^{fg}(q; P) \gamma_\nu. \quad (24)$$

$$\mathcal{G}^f(s) = \mathcal{G}^{ff}(s), \quad \mathcal{G}^{fg}(s) = \mathcal{G}_{IR}^{fg}(s) + \mathcal{G}_{UV}(s), \quad (25)$$

$$\mathcal{G}_{IR}^{fg}(s) = 8\pi^2 \frac{D^2}{\omega^4} e^{-s/\omega^2} \rightarrow \mathcal{G}_{IR}^{fg}(s) = 8\pi^2 \frac{D_f D_g}{\omega_f^2 \omega_g^2} e^{-s/(\omega_f \omega_g)}, \quad (26)$$

$$\mathcal{G}_{UV}(s) = \frac{8\pi^2 \gamma_m \mathcal{F}(s)}{\ln[\tau + (1 + s/\Lambda_{QCD}^2)^2]}. \quad (27)$$

	herein	lQCD	expt.		herein	lQCD
M_π	<u>0.138</u>	*	0.138(1)	f_π	<u>0.0093</u>	0.0093(1)
M_K	<u>0.496</u>	*	0.496(1)	f_K	<u>0.111</u>	0.111(1)
M_D	<u>1.867</u>	1.865(3)	1.867(1)	f_D	0.151(1)	0.150(1)
$M_{D_s^\pm}$	<u>1.968</u>	1.968(3)	1.968(1)	$f_{D_s^\pm}$	0.181(1)	0.177(1)
M_{η_c}	<u>2.984</u>	*	2.984(1)	f_{η_c}	<u>0.278</u>	0.278(2)
M_B	<u>5.279</u>	5.283(8)	5.279(1)	f_B	0.141(2)	0.134(1)
$M_{B_s^\pm}$	5.377(1)	5.366(8)	5.367(1)	$f_{B_s^\pm}$	0.168(2)	0.163(1)
M_{B_c}	6.290(3)	6.276(7)	6.275(1)	f_{B_c}	0.312(1)	0.307(10)
M_{η_b}	<u>9.399</u>	*	9.399(2)	f_{η_b}	<u>0.472</u>	0.472(5)

Parameters:

$$\{\omega_f, D_f, m_f\},$$

$$f \in \{u/d, s, c, b\}.$$

$$\omega_u \in [0.45, 0.55] \text{ GeV}.$$

✚ Decay constants errors are less than 6%.

$$\blacksquare f_{D_s^\pm}^{\text{expt.}} = 179(4) \text{ GeV}^1.$$

✚ original RL²:

$$M_{B_c} = 6.39 \text{ GeV}, f_{B_c} = 0.43 \text{ GeV}.$$

¹Phys.Rev.Lett.122,071802(2019).

²Phys.Rev.,D97,114017(2018).

avWTI \Leftrightarrow the Gell-Mann--Oakes--Renner(GMOR) relation:

$$\tilde{f}_{0^-} := (m_f + m_g) \rho_{0^-} / M_{0^-}^2 = f_{0^-}.$$

$$f_{0^-} P_\mu := Z_2 N_c \operatorname{tr} \int_{dk}^\Lambda \gamma_5 \gamma_\mu S_f(k_+) \Gamma_{0^-}^{fg}(k; P) S_g(k_-),$$

$$\rho_{0^-} := Z_4 N_c \operatorname{tr} \int_{dk}^\Lambda \gamma_5 S_f(k_+) \Gamma_{0^-}^{fg}(k; P) S_g(k_-),$$

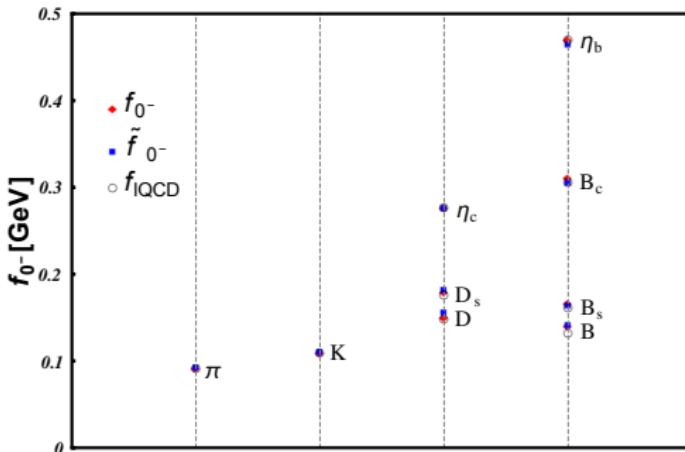


Figure 3: f_{0^-} and \tilde{f}_{0^-} deviate by no more than 3%.

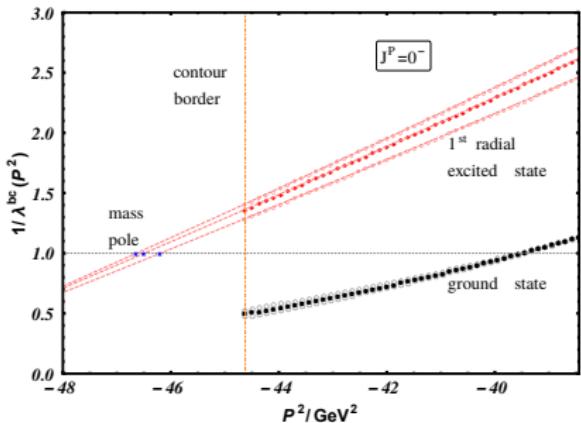
	herein	lQCD	expt.		herein	lQCD
M_ρ	0.724(2)	0.780(16)	0.775(1)	f_ρ	0.149(1)	--
M_{K^*}	0.924(2)	0.933(1)	0.896(1)	f_{K^*}	0.160(2)	--
M_ϕ	1.070(1)	1.032(16)	1.019(1)	f_ϕ	0.191(1)	0.170(13)
M_{D^*}	2.108(4)	2.013(14)	2.009(1)	f_{D^*}	0.174(4)	0.158(6)
$M_{D_s^{*+}}$	2.166(7)	2.116(11)	2.112(1)	$f_{D_s^{*+}}$	0.206(2)	0.190(5)
$M_{J/\psi}$	3.132(2)	3.098(3)	3.097(1)	$f_{J/\psi}$	0.304(1)	0.286(4)
M_{B^*}	5.369(5)	5.321(8)	5.325(1)	f_{B^*}	0.132(3)	0.131(5)
$M_{B_s^{*+}}$	5.440(1)	5.411(5)	5.415(2)	$f_{B_s^{*+}}$	0.152(2)	0.158(4)
$M_{B_c^*}$	6.357(3)	6.331(7)	--	$f_{B_c^*}$	0.305(5)	0.298(9)
M_Υ	9.454(1)	*	9.460(1)	f_Υ	0.442(3)	0.459(22)

errors	light	heavy
masses	6%	1%
decay constants	12%	7%

original RL¹:
 $M_{B_c^*} = 6.54 \text{ GeV}, f_{B_c^*} = 0.43 \text{ GeV}.$

¹Phys.Rev.,D97,114017(2018).

Radial Excited B_c

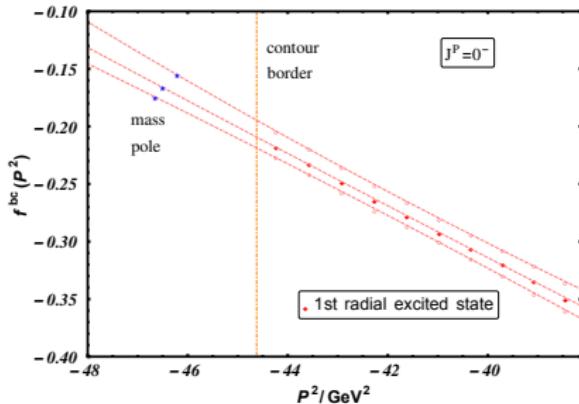


	$M_{\eta_c(2S)}$	$M_{\psi(2S)}$	$M_{\psi(2S)} - M_{\eta_c(2S)}$
here	3.606(18)	3.645(18)	0.039
expt.	3.638(1)	3.686(1)	0.048
	$M_{B_c^+(2S)}$	$M_{B_c^{*+}(2S)}$	$M_{B_c^+(2S)} - M_{B_c^{*+}(2S)}^{\text{rec}}$
here	6.813(16)	6.841(18)	0.039
expt.	6.872(2)	--	0.031
	$M_{\eta_b(2S)}$	$M_{\Upsilon(2S)}$	$M_{\Upsilon(2S)} - M_{\eta_b(2S)}$
here	9.915(15)	9.941(15)	0.026
expt.	9.999(4)	10.023(1)	0.024

$$\frac{1}{\lambda^{fg}(P^2)} = \frac{1 + \sum_{n=1}^{N_o} a_n (P^2 + s)^n}{1 + \sum_{n=1}^{N_o} b_n (P^2 + s)^n},$$

$$M_{B_c^{*+}(2S)}^{\text{rec}} = M_{B_c^{*+}(2S)} - (M_{B_c^{*+}(1S)} - M_{B_c^+(1S)}).$$

Mass errors in RL approximation : 1%.



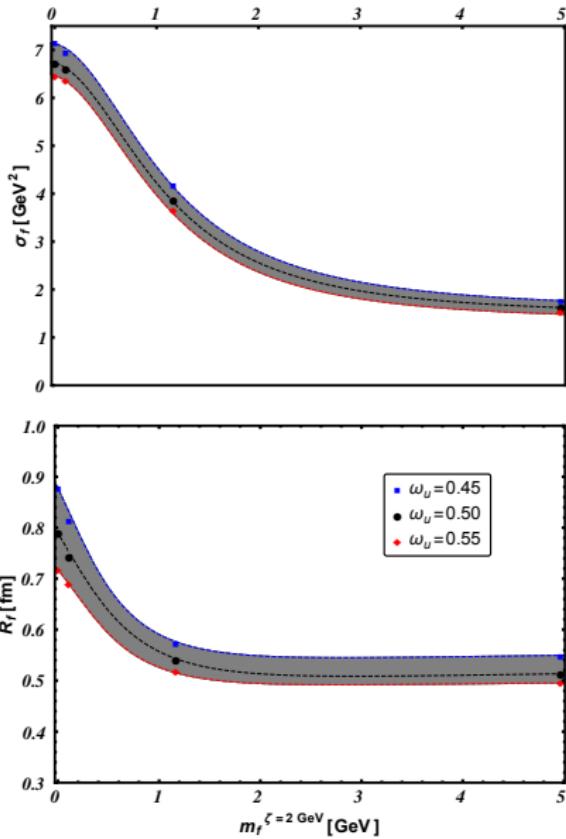
$$f^{fg}(P^2) = \frac{f_0 + \sum_{n=1}^{N_o} c_n (P^2 + s)^n}{1 + \sum_{n=1}^{N_o} d_n (P^2 + s)^n},$$

$f_{\eta_c(2S)}$	$f_{\psi(2S)}$	$f_{B_c^+(2S)}$	$f_{B_c^{*+}(2S)}$	$f_{\eta_b(2S)}$	$f_{\Upsilon(2S)}$
-0.097(2)	-0.119(6)	-0.165(10)	-0.161(7)	-0.310(5)	-0.320(6)

	$f_{\psi(2S)}$	$f_{B_c^{*+}(2S)}$	$f_{\Upsilon(2S)}$
RL-DSE	-0.119(6)	-0.161(7)	-0.320(6)
expt.	-0.208(2)	--	-0.352(2)
$\eta_{expt.}^{RL}$	42%	27%	12%

$$\Gamma_{V \rightarrow e^+ e^-} = \frac{8\pi e_f^2 \alpha_{em}^2 f_{1-}}{3M_{1-}}$$

$$\eta_{expt.}^{RL} = |(f^{RL} - f^{expt.})/f^{expt.}|.$$



flavor	$\bar{m}_f^{\zeta=2 \text{ GeV}}$	w_f	D_f^2	w_f	D_f^2	w_f	D_f^2
u	0.0049	0.450	1.133	0.500	1.060	0.550	1.014
s	0.112	0.490	1.090	0.530	1.040	0.570	0.998
c	1.17	0.690	0.645	0.730	0.599	0.760	0.570
b	4.97	0.722	0.258	0.766	0.241	0.792	0.231

$$\mathcal{V}_{\text{IR}}^{ff}(\vec{r}) = \int d^3l \mathcal{G}_{\text{IR}}^{ff}(l^2) e^{-\vec{l} \cdot \vec{r}/\omega_f^2} \propto e^{-\vec{r}^2/R_f^2}$$

The interaction radius: $R_f = 2/\omega_f$.

The interaction strength:

$$\sigma_f = \frac{1}{4\pi} \int_{\Lambda_{\text{QCD}}^2}^{(10\Lambda_{\text{QCD}})^2} ds \mathcal{G}^{ff}(s) * s.$$

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Summary

- ✖ DSBSE approach is an relativistic covariant nonperturbative QCD approach.
- ✖ This approach expresses DCSB and the Goldstone boson properties of the pion.
- ✖ The flavor dependence of the full quark-antiquark interaction is an intrinsic property of QCD, and crucial for an unified description of light, heavy-light and heavy hadrons.
- ✖ The strength and radius of the quark-quark interaction reduce as quark mass raises.