The Charm and Beauty of Strong Interactions

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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 ⇒ 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

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

- 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 ...
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Hadronic transition form factor; estimated with QCD sum rules, lattice QCD, quark models ...
QCD factorization involves matrix elements which are convolution integrals:

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

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

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

\[
\varphi_\pi^{asy}(x) = 6x(1 - x).
\]

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.

\[
S^{-1}(p) = Z_2(i\gamma \cdot p + m^{\text{bm}}) + \Sigma(p) := i\gamma \cdot p A(p^2) + B(p^2)
\]

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

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

- For light quarks the Higgs mechanism is almost irrelevant!
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\textendash 40\%
Nonperturbative QCD based ansatz for interaction kernel

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

Rainbow-Ladder truncation:

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

Rainbow-ladder truncation (leading symmetry-preserving approximation)

\[ S(p) = \quad + \quad + \quad + \quad + \quad + \ldots \]

\[ G^4(k, q, P) = \quad + \quad + \quad + \quad + \quad + \ldots \]

Model gluon propagator, solve quark propagator and 4-point Green function.
Nonperturbative QCD based ansatz for interaction kernel

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

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

\[ \Gamma_{P_n}(p, P) = \gamma_5 \left[ i \mathbb{I} D E_{P_n}(p, P) + \gamma \cdot P F_{P_n}(p, P) \right. \\
+ \gamma \cdot p (p \cdot P) G_{P_n}(p, P) + \sigma_{\mu\nu} p_\mu p_\nu H_{P_n}(p, P) \left. \right] \]
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.

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

Bogolubsky et al. (2009)
Pseudoscalar- and Vector-Meson Spectroscopy

<table>
<thead>
<tr>
<th>$J^{PC} = 0^{-+}$</th>
<th>DSE-BSE</th>
<th>PDG</th>
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<tbody>
<tr>
<td>$m_{\pi}$</td>
<td>0.136</td>
<td>0.139</td>
</tr>
<tr>
<td>$f_{\pi}$</td>
<td>0.139</td>
<td>0.1304</td>
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<tr>
<td>$m_{\pi(1300)}$</td>
<td>1.414</td>
<td>1.30 ± 0.10</td>
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<tr>
<td>$f_{\pi(1300)}$</td>
<td>$8.3 \times 10^{-4}$</td>
<td>—</td>
</tr>
<tr>
<td>$m_{K}$</td>
<td>0.493</td>
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<tr>
<td>$f_{K}$</td>
<td>0.164</td>
<td>0.156</td>
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<tr>
<td>$m_{K(1460)}$</td>
<td>1.580</td>
<td>1.460</td>
</tr>
<tr>
<td>$f_{K(1460)}$</td>
<td>0.017</td>
<td>—</td>
</tr>
<tr>
<td>$m_{\eta_c(1S)}$</td>
<td>3.065</td>
<td>2.984</td>
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<tr>
<td>$f_{\eta_c(1S)}$</td>
<td>0.389</td>
<td>0.395</td>
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<tr>
<td>$m_{\eta_c(2S)}$</td>
<td>3.784</td>
<td>3.639</td>
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<tr>
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<td>0.105</td>
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<table>
<thead>
<tr>
<th>$J^{PC} = 1^{--}$</th>
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<th>PDG</th>
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<tbody>
<tr>
<td>$m_{\rho^0(770)}$</td>
<td>0.742</td>
<td>0.775</td>
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<tr>
<td>$f_{\rho^0(770)}$</td>
<td>0.231</td>
<td>0.221</td>
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<tr>
<td>$m_{\rho^0(1450)}$</td>
<td>1.284</td>
<td>1.465</td>
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<tr>
<td>$f_{\rho^0(1450)}$</td>
<td>0.150</td>
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<tr>
<td>$m_{K^*(892)}$</td>
<td>0.951</td>
<td>0.896</td>
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<tr>
<td>$f_{K^*(892)}$</td>
<td>0.287</td>
<td>0.217</td>
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<tr>
<td>$m_{K^*(1410)}$</td>
<td>1.217</td>
<td>1.414</td>
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<tr>
<td>$f_{K^*(1410)}$</td>
<td>0.127</td>
<td>—</td>
</tr>
<tr>
<td>$m_{\phi(1020)}$</td>
<td>1.087</td>
<td>1.019</td>
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<tr>
<td>$f_{\phi(1020)}$</td>
<td>0.305</td>
<td>0.322</td>
</tr>
<tr>
<td>$m_{\phi(1680)}$</td>
<td>1.650</td>
<td>1.659</td>
</tr>
<tr>
<td>$f_{\phi(1680)}$</td>
<td>0.138</td>
<td>—</td>
</tr>
<tr>
<td>$m_{J/\psi}$</td>
<td>3.114</td>
<td>3.097</td>
</tr>
<tr>
<td>$f_{J/\psi}$</td>
<td>0.433</td>
<td>0.416</td>
</tr>
<tr>
<td>$m_{\psi(2S)}$</td>
<td>3.760</td>
<td>3.689</td>
</tr>
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<td>$f_{\psi(2S)}$</td>
<td>0.176</td>
<td>0.295</td>
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<tr>
<td>$m_{\Upsilon(1S)}$</td>
<td>9.634</td>
<td>9.460</td>
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<tr>
<td>$f_{\Upsilon(1S)}$</td>
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<td>0.715</td>
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<tr>
<td>$m_{\Upsilon(2S)}$</td>
<td>10.140</td>
<td>10.023</td>
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<tr>
<td>$f_{\Upsilon(2S)}$</td>
<td>0.564</td>
<td>0.497</td>
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Weak decay constant for radially excited states vanish — only strong decays possible:

\[ f_{P_n}^0 \equiv 0, \ n \geq 1 \]
So far, we have first results for the heavy-light systems: $D$ mesons

<table>
<thead>
<tr>
<th>Model</th>
<th>Experiment [63]</th>
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<tr>
<td>$m_D$</td>
<td>2.115</td>
</tr>
<tr>
<td>$f_D$</td>
<td>0.204</td>
</tr>
<tr>
<td>$m_{D_s}$</td>
<td>2.130</td>
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<tr>
<td>$f_{D_s}$</td>
<td>0.249</td>
</tr>
</tbody>
</table>


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

\[ D \text{-meson interactions with nucleons} \]

Meson exchange — effective Lagrangians

Diagram a):
- Symbol: \( \bar{D} \)
- Symbol: \( D \)
- Labels: \( \rho, \omega \)

Diagram b):
- Symbol: \( \pi, \rho \)
- Symbol: \( \pi, \rho \)
- Symbol: \( \rho \)
- Symbol: \( \Delta \)

Symbols:
- \( \bar{D} \): anti-D meson
- \( D \): D meson
- \( N \): nucleon
- \( \rho \): rho meson
- \( \omega \): omega meson
- \( \pi \): pion
- \( \sigma \): sigma meson
- \( a_0 \): a0 meson
- \( \Delta \): delta baryon
- \( \Lambda_c \): lambda_c baryon
- \( \Sigma_c \): sigma_c baryon
SU(4) symmetry used ....

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

Jülich model:
A. Müller-Groeling et al. NPA 513, 557 (1990)
M. Hoffmann et al. NPA 593, 341 (1995)
Flavor SU(3), SU(4) … sensible symmetries?

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

- Ratio measures the effect of SU(4) breaking \( \approx 300\% \)
- SU(3) breaking \( \approx 20-30\% \)

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

B. E., G. Krein, L. Chang, C.D. Roberts and D. Wilson, PRD (2012)
Consequences for DN cross sections?

The integrated $DqD$ 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 bottomonium 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.