

The $B^{(*)}\bar{K}^{(*)}$ coupled-channel system in the hidden-gauge approach

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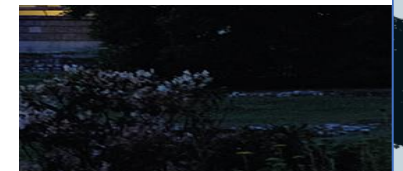
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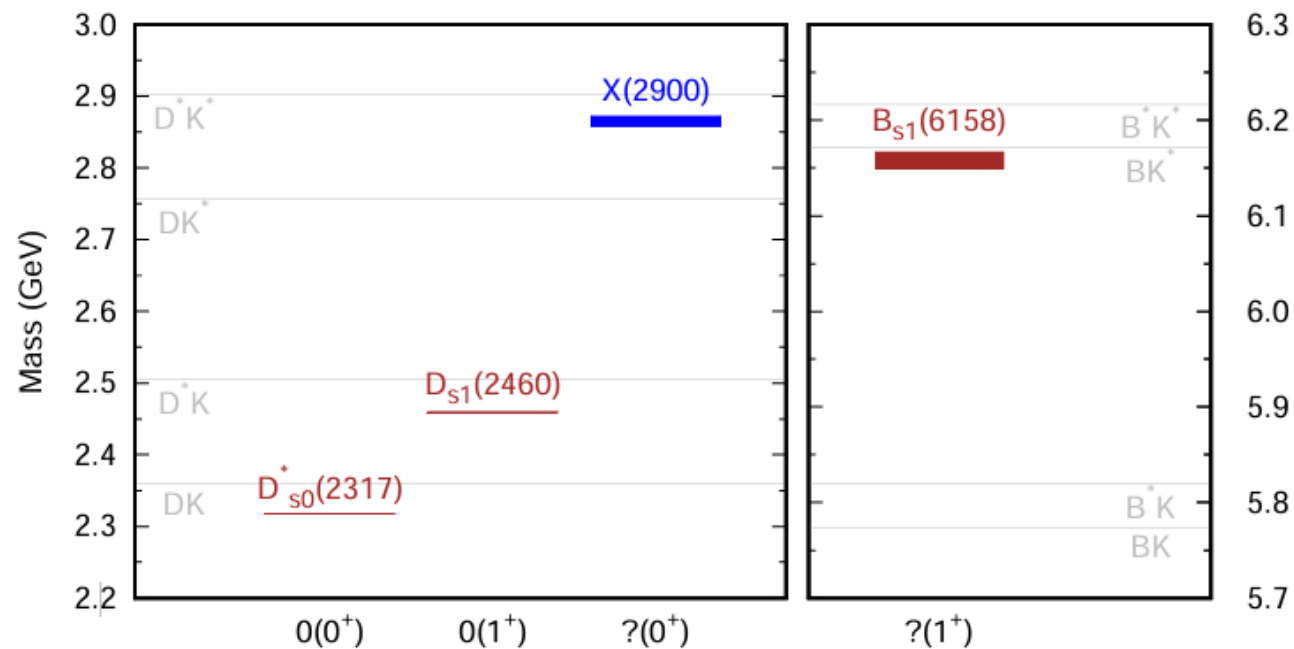
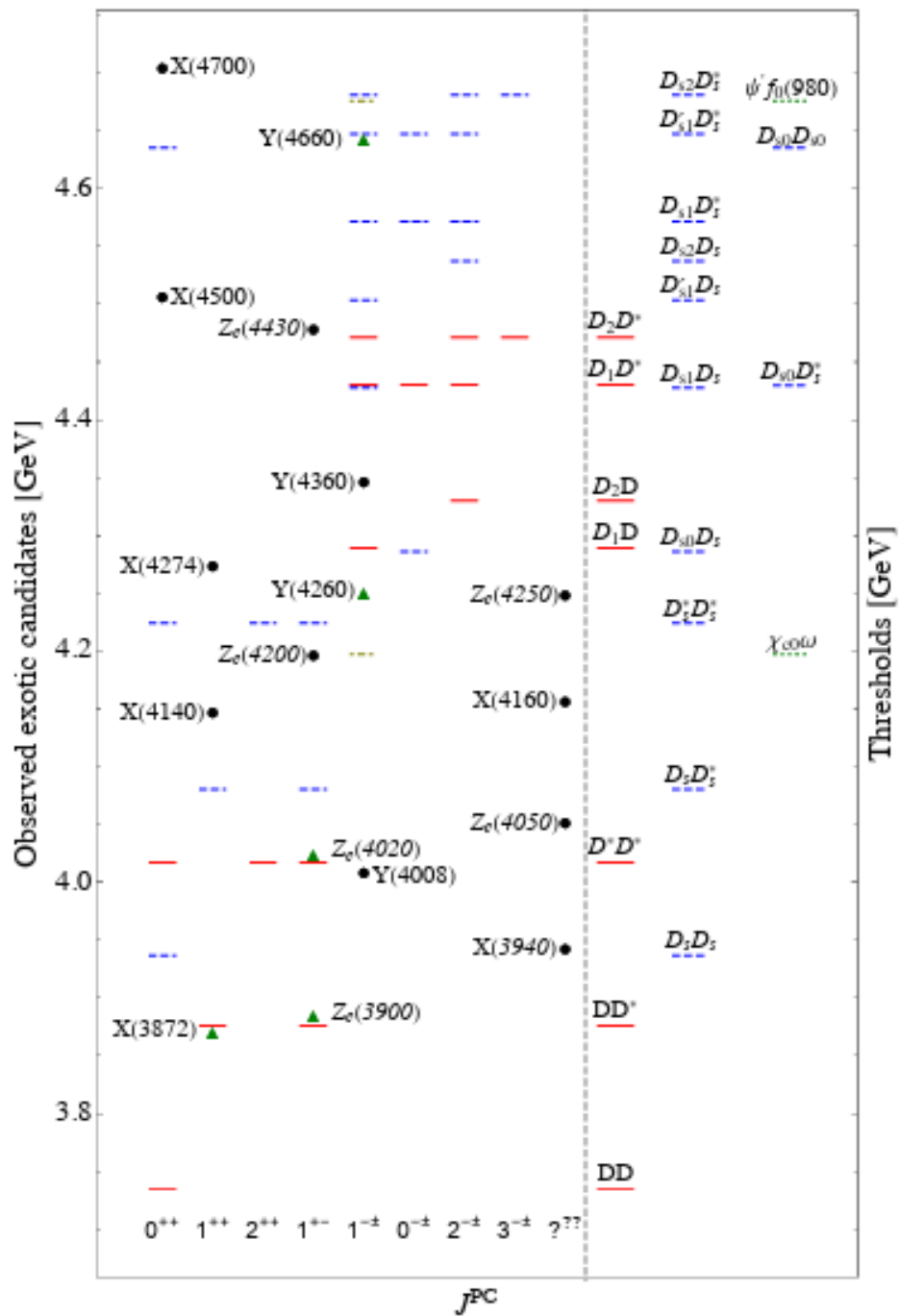
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Content

- Clues in the charm sector
- Formalism
- Results
- Conclusions

Clues in the charm sector



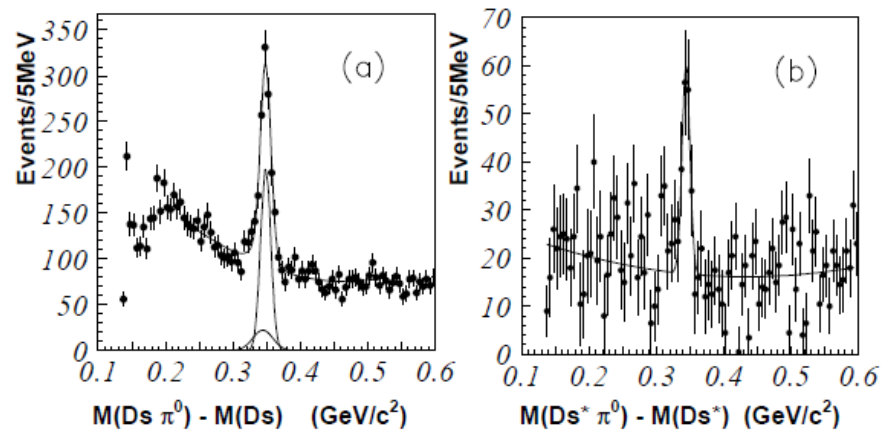
S. Y. Kong, J. T. Zhu, D. Song, and J. He, Phys. Rev. D 104, 094012 (2021).

→ Lots of data

↓ Little data

F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, and B.-S. Zou, Rev. Mod. Phys. 90, 015004 (2018).

Clues in the charm sector



$D_{s0}(2317), D_{s1}(2460)$

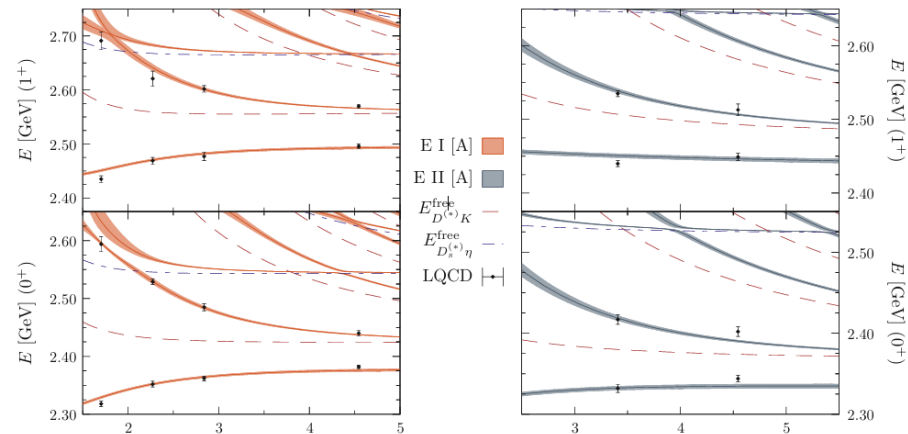
$c\bar{s}$ state

Molecular DK, D*K state

Compact tetraquark

Mixed state

Y. Mikami, et al., Phys. Rev. Lett. 92 (2004) 012002.



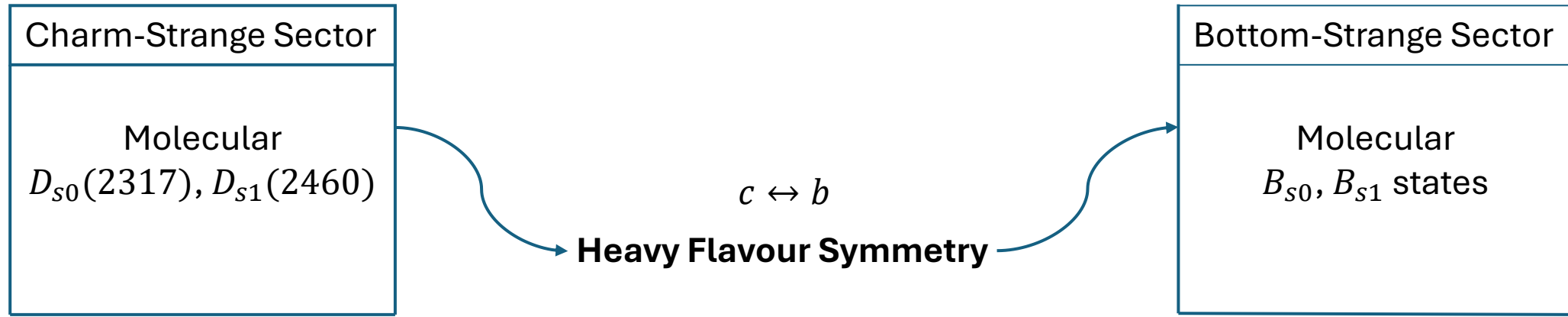
- $D_{s0}(2317) \sim 72\% \pm 18\%$ molecular component.

- $D_{s1}(2460) \sim 57\% \pm 27\%$ molecular component.

M. Albaladejo, P. Fernandez-Soler, J. Nieves, and P. G. Ortega, Eur. Phys. J. C 78, 722 (2018).

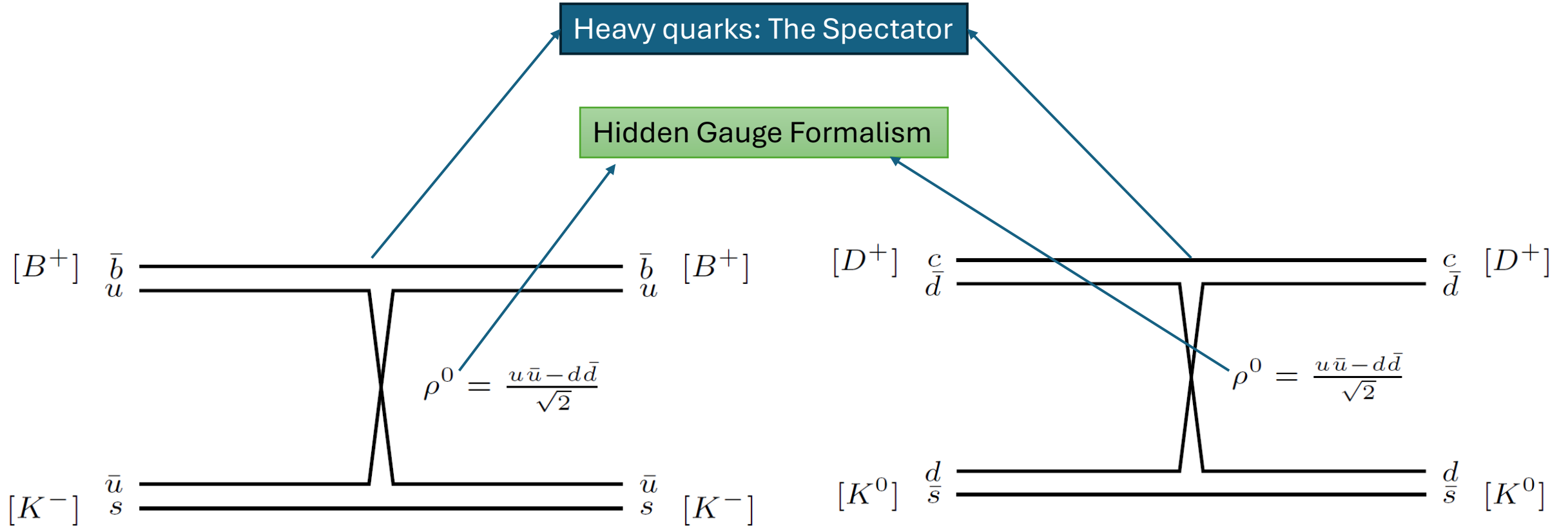
A. Martínez Torres, E. Oset, S. Prelovsek, and A. Ramos, Reanalysis of lattice QCD spectra leading to the $D^* s_0(2317)$ and $D^* s_1(2460)$, JHEP 05, 153, arXiv:1412.1706 [hep-lat].

Clues in the charm sector



WHAT EFT's HAVE TO SAY ABOUT THIS?

Formalism



Formalism

- We have

$$\mathcal{L}_{VVV} = ig \langle (V^\nu \partial_\mu V_\nu - \partial_\mu V^\nu V_\nu) V^\mu \rangle,$$

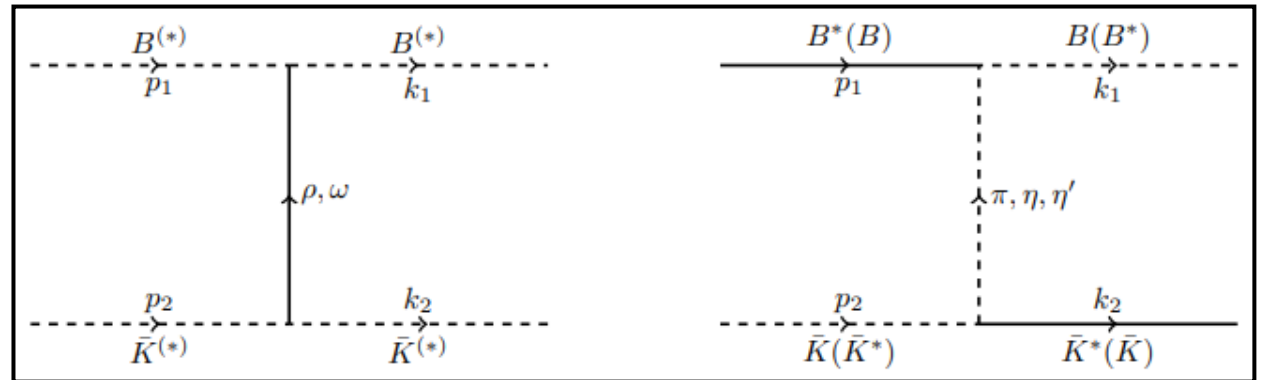
$$\mathcal{L}_{VPP} = -ig \langle [P, \partial_\mu P] V^\mu \rangle.$$

where

$$g = \frac{M_V}{2f}.$$

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ & B^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} & K^0 & B^0 \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & B_s^0 \\ B^- & \bar{B}^0 & \bar{B}_s^0 & \eta_b \end{pmatrix}$$

$$V_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} & B^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} & B^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi & B_s^{*0} \\ B^{*-} & \bar{B}^{*0} & \bar{B}_s^{*0} & \Upsilon \end{pmatrix}_\mu$$



Formalism

TABLE I. Potential of the $B^{(*)}\bar{K}^{(*)}$ channels and $B^*\bar{K} - B\bar{K}^*$ coupled channel.

| Channel (J^P) | Potential |
|---------------------------------|---|
| $B\bar{K} (0^+)$ | $\frac{g^2}{2} (3D_{su}(m_\rho) + D_{su}(m_\omega))$ |
| $B^*\bar{K} - B\bar{K}^* (1^+)$ | $V_{11} = -\frac{g^2}{2} (3D_{su}(m_\rho) + D_{su}(m_\omega)) \varepsilon(p_1) \cdot \varepsilon^*(k_1)$ $V_{12} = \frac{2g^2}{3} (-4D_t(m_\eta) + D_t(m_{\eta'}) - 9D_\pi) k_1 \cdot \varepsilon(p_1) p_2 \cdot \varepsilon^*(k_2)$ $V_{21} = \frac{2g^2}{3} (-4D_t(m_\eta) + D_t(m_{\eta'}) - 9D_\pi) k_2 \cdot \varepsilon(p_2) p_1 \cdot \varepsilon^*(k_1)$ $V_{22} = -\frac{g^2}{2} (3D_{su}(m_\rho) + D_{su}(m_\omega)) \varepsilon(p_2) \cdot \varepsilon^*(k_2)$ |
| $B^*\bar{K}^* (0^+/1^+/2^+)$ | $\frac{g^2}{2} (3D_{su}(m_\rho) + D_{su}(m_\omega)) \varepsilon(p_1) \cdot \varepsilon^*(k_1) \varepsilon(p_2) \cdot \varepsilon^*(k_2)$ |

Formalism

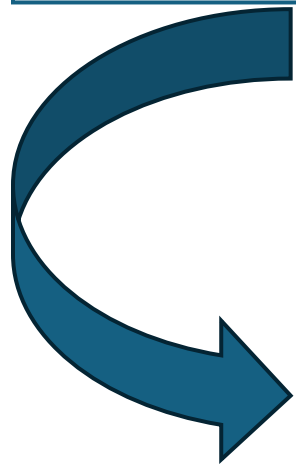
Lippmann-Schwinger equation:

$$T_{ij}(E, p, k) = V_{ij}(E, p, k) + \sum_k \int_{\Lambda} \frac{d^3 \vec{q}}{(2\pi)^3} V_{ik}(E, p, q) I_k(E, q) T_{kj}(E, q, k),$$

where

$$I_k(E, q) = \frac{\omega_1(q) + \omega_2(q)}{2\omega_1\omega_2} \cdot \frac{1}{E^2 - (\omega_1(q) + \omega_2(q))^2 + i\epsilon}, \quad I(E, q) = \frac{1}{4\omega_{\bar{K}^*}\omega_{B^{(*)}}} \cdot \frac{1}{P^0 - \omega_{\bar{K}^*} - \omega_{B^{(*)}} + i\frac{\Gamma}{2}}.$$

Three-body cut



$$T = \frac{V}{I - VG}$$



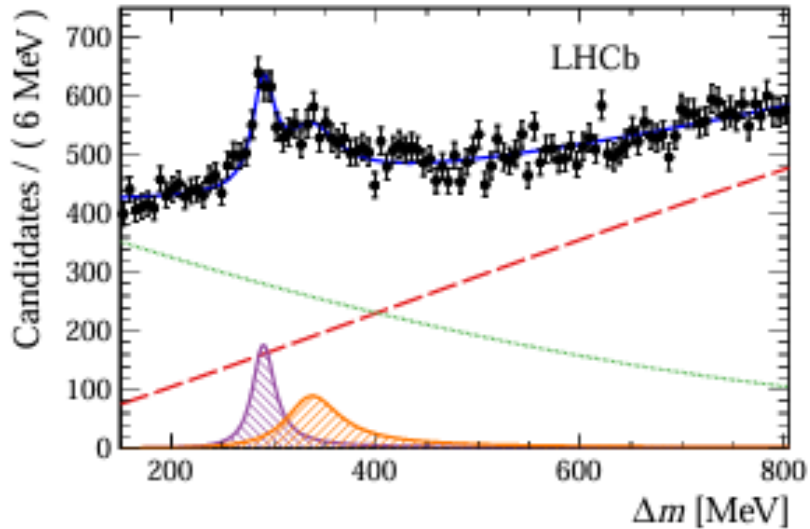
$$\det(I - VG) = 0$$

Bound state.

Virtual state.

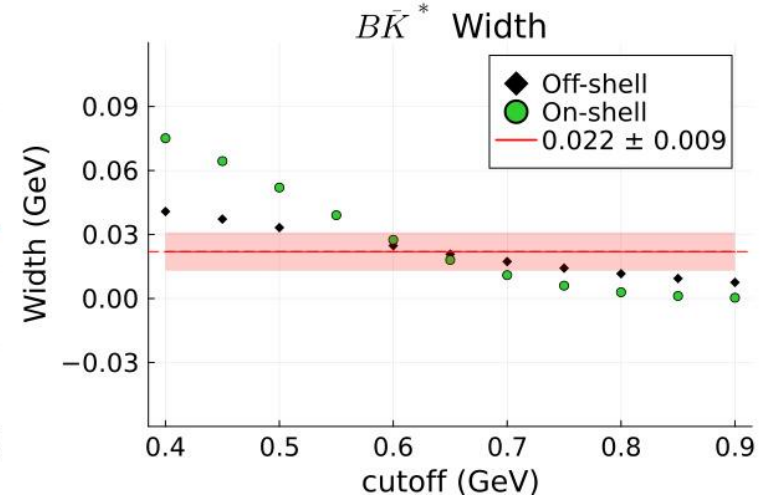
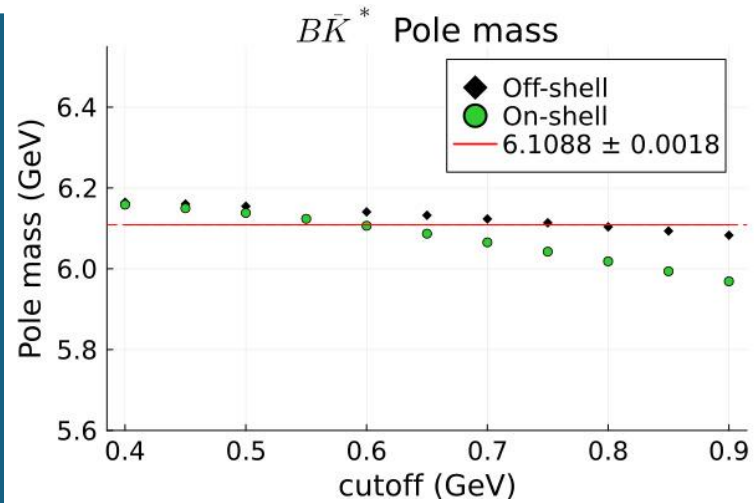
Resonance.

Results



R. Aaij et al. (LHCb), Eur. Phys. J. C 81, 601 (2021),
arXiv:2010.15931 [hep-ex]

If decays in $B^{*+}K^{-}$,
 $m_1 = (6108.8 \pm 1.8) \text{ MeV}$,
 $\Gamma_1 = (22 \pm 9) \text{ MeV}$,
 $m_2 = (6158 \pm 9) \text{ MeV}$,
 $\Gamma_2 = (72 \pm 43) \text{ MeV}$.



OFF-SHELL $\xrightarrow{\chi^2/d.o.f = 1.15}$ $\Lambda = 775 \text{ MeV}$

ON-SHELL $\xrightarrow{\chi^2/d.o.f = 0.72}$ $\Lambda = 593 \text{ MeV}$

Results

$$\begin{aligned}
 m_1 &= (6108.8 \pm 1.8) \text{ MeV}, \\
 \Gamma_1 &= (22 \pm 9) \text{ MeV}, \\
 m_2 &= (6158 \pm 9) \text{ MeV}, \\
 \Gamma_2 &= (72 \pm 43) \text{ MeV}.
 \end{aligned}$$

TABLE II. Predicted pole positions of the $B^{(*)}\bar{K}^{(*)}$ systems with the on-shell potentials. In the fourth column, “+” and “-” indicate that the poles lie on the physical and unphysical RS relative to the corresponding two-body threshold, respectively. The quantity g_i in the fifth column denotes the S -wave effective coupling. The sixth column, labeled “Thr.,” represents the relevant threshold. The binding energy E_b is defined as the difference between the real part of the pole position and the relevant threshold.

| J^P | Channel | Pole [MeV] | RS | g_i [GeV] | Thr. [MeV] | E_b [MeV] |
|---------------|----------------|-----------------|-----|---------------|------------|-------------|
| 0^+ | $B\bar{K}$ | 5758.9 | (+) | 23.0 | 5775.0 | -16.1 |
| 1^+ | $B^*\bar{K}$ | 5804.0 | (+) | 23.0 | 5820.0 | -16.0 |
| 1^+ | $B\bar{K}^*$ | $6109.0 - 7.2i$ | (+) | $39.5 - 2.5i$ | 6173.0 | -64.0 |
| $0^+/1^+/2^+$ | $B^*\bar{K}^*$ | $6154.1 - 7.2i$ | (+) | $38.8 - 2.8i$ | 6218.0 | -63.9 |

TABLE III. Predicted pole positions of the $B^{(*)}\bar{K}^{(*)}$ systems with the off-shell potentials.

| J^P | Channel | Pole [MeV] | RS | g_i [GeV] | Thr. [MeV] | E_b [MeV] |
|---------------|-------------------------|-----------------|--------|----------------|------------|-------------|
| 0^+ | $B\bar{K}$ | 5757.2 | (+) | 24.8 | 5775.0 | -17.8 |
| 1^+ | $B^*\bar{K}-B\bar{K}^*$ | 5802.4 | (+, +) | 25.0 | 5820.0 | -17.6 |
| | | $6108.8 - 6.4i$ | (-, +) | $0.2 + 0.5i$ | 6173.0 | -64.2 |
| | | | | $-28.7 + 1.6i$ | | |
| $0^+/1^+/2^+$ | $B^*\bar{K}^*$ | $6155.8 - 6.4i$ | (+) | $45.1 - 2.2i$ | 6218.0 | -62.2 |

Results

Three-body effect

TABLE II. Predicted pole positions of the $B^{(*)}\bar{K}^{(*)}$ systems with the on-shell potentials. In the fourth column, “+” and “-” indicate that the poles lie on the physical and unphysical RS relative to the corresponding two-body threshold, respectively. The quantity g_i in the fifth column denotes the S -wave effective coupling. The sixth column, labeled “Thr.,” represents the relevant threshold. The binding energy E_b is defined as the difference between the real part of the pole position and the relevant threshold.

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| 1^+ | $B\bar{K}^*$ | 6109.0 - 7.2 <i>i</i> | (+) | 39.5 - 2.5 <i>i</i> | 6173.0 | -64.0 |
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TABLE III. Predicted pole positions of the $B^{(*)}\bar{K}^{(*)}$ systems with the off-shell potentials.

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| | | 6108.8 - 6.4 <i>i</i> | (-, +) | -1.7 | 6173.0 | -64.2 |
| | | | | 0.2 + 0.5 <i>i</i> | | |
| $0^+/1^+/2^+$ | $B^*\bar{K}^*$ | 6155.8 - 6.4 <i>i</i> | (+) | -28.7 + 1.6 <i>i</i> | 6218.0 | -62.2 |

Results

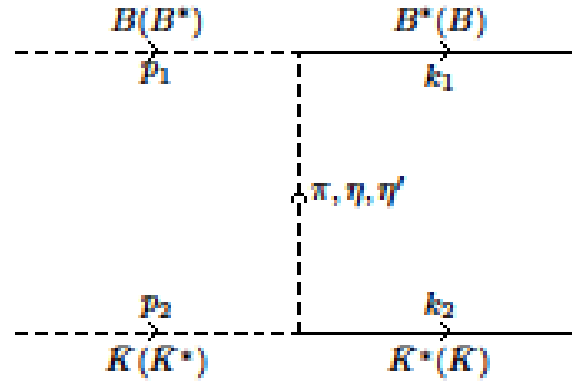
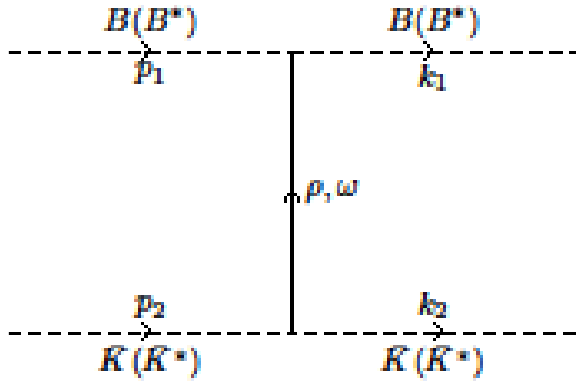
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TABLE III. Predicted pole positions of the $B^{(*)}\bar{K}^{(*)}$ systems with the off-shell potentials

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| $0^+/1^+/2^+$ | $B^*\bar{K}^*$ | $6155.8 - 6.4i$ | (+) | $45.1 - 2.2i$ | 6218.0 | -62.2 |

Results



For $J = 0$:

$$V = \begin{pmatrix} V_{11}^{SS} & 0 & V_{12}^{SS} & V_{12}^{SD} \\ 0 & 0 & 0 & 0 \\ V_{21}^{SS} & 0 & V_{22}^{SS} & V_{22}^{SD} \\ V_{21}^{DS} & 0 & V_{22}^{DS} & V_{22}^{DD} \end{pmatrix}$$

For $J = 1$:

$$V = \begin{pmatrix} V_{22}^{SS} & V_{22}^{SD} \\ V_{22}^{DS} & V_{22}^{DD} \end{pmatrix}$$

For $J = 2$:

$$V = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & V_{11}^{DD} & V_{12}^{DS} & V_{12}^{DD} \\ 0 & V_{21}^{SD} & V_{22}^{SS} & V_{22}^{SD} \\ 0 & V_{21}^{DD} & V_{22}^{DS} & V_{22}^{DD} \end{pmatrix}$$

$$V_{11} = \frac{g^2}{2} \left(3D_{su}(m_\rho) + D_{su}(m_\omega) \right),$$

$$V_{12} = 4g^2 \left(-\frac{2}{3}D_t(m_\eta) + \frac{1}{6}D_t(m_{\eta'}) - \frac{3}{2}D_\pi \right) p_1 \varepsilon(k_1) p_2 \varepsilon^*(k_2),$$

$$V_{21} = 4g^2 \left(-\frac{2}{3}D_t(m_\eta) + \frac{1}{6}D_t(m_{\eta'}) - \frac{3}{2}D_\pi \right) k_1 \varepsilon(p_1) k_2 \varepsilon^*(p_2),$$

$$V_{22} = \frac{g^2}{2} \left(3D_{su}(m_\rho) + D_{su}(m_\omega) \right) \varepsilon(p_1) \cdot \varepsilon^*(k_1) \varepsilon(p_2) \cdot \varepsilon^*(k_2).$$

F. Gil-Domínguez, A. Giachino y R. Molina,
 “Quark mass dependence of the $T_{cc}(3875)^+$ ”,
 Physical Review D 111, 016029, 2025.

$$g_{B^*BP} \approx 6.3$$

Conclusions

Using HGF, taking into account the three-body effect when \bar{K}^* is involved, we have solved the LS equation in the on-shell and off-shell approach.

The cutoff is determined by reproducing the pole position of $B_{sJ}(6063)^0$, interpreting it as a $B\bar{K}^*$ molecule.

Our results support the existence of six $B^{(*)}\bar{K}^{(*)}$ molecules:

1. Two poles near $B\bar{K}$ and $B^*\bar{K}$ thresholds.
2. A pole close to the $B\bar{K}^*$. Possibly corresponds to $B_{sJ}(6063)^0$.
3. Three poles in the $B^*\bar{K}^*$ system with $J^P = 0^+, 1^+, 2^+$. The $J^P = 1^+$ molecule may be related to the $B_{sJ}(6114)^0$ state.

**THANK YOU FOR YOUR
ATTENTION**

SS wave expansion for $B^* \bar{K}^*$

$$V_0(p, k) = \int_{-1}^1 dz D(s, t, u) \left[\frac{1}{2} - \frac{pkz}{6m_{p_1} m_{k_1}} - \frac{pkz}{6m_{p_2} m_{k_2}} + \frac{p^2 k^2}{6m_{p_1} m_{k_1} m_{p_2} m_{k_2}} \right],$$

$$V_1(p, k) = \int_{-1}^1 dz D(s, t, u) \left[\frac{1}{2} - \frac{pkz}{6m_{p_1} m_{k_1}} - \frac{pkz}{6m_{p_2} m_{k_2}} \right],$$

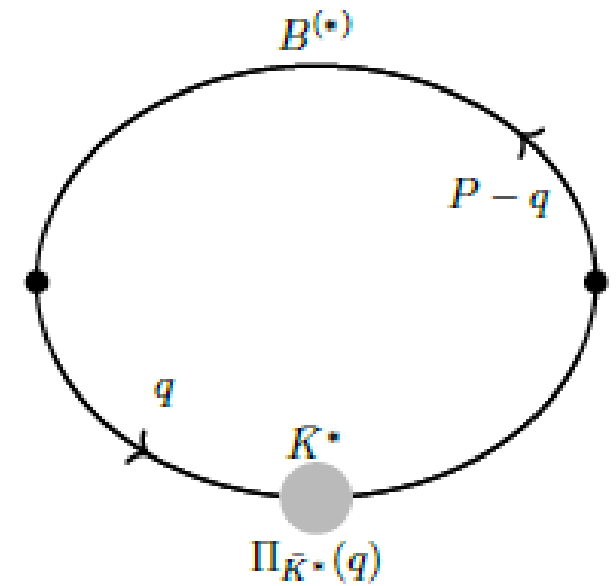
$$V_2(p, k) = \int_{-1}^1 dz D(s, t, u) \left[\frac{1}{2} - \frac{pkz}{6m_{p_1} m_{k_1}} - \frac{pkz}{6m_{p_2} m_{k_2}} + \frac{p^2 k^2}{30m_{p_1} m_{k_1} m_{p_2} m_{k_2}} (3z^2 - 1) \right],$$

Loop

$$G(P^0) \approx \int \frac{d^4 p}{(2\pi)^4} \frac{1}{4\omega_{\bar{K}^*} \omega_{B^*}} \cdot \frac{1}{q^0 - \omega_{\bar{K}^*} + i\frac{\Gamma}{2}} \cdot \frac{1}{P^0 - q^0 - \omega_{B^*} + i\varepsilon}.$$

We integrate the q^0 component,

$$G(P^0) = \int \frac{dq}{8\pi^2 \omega_{\bar{K}^*} \omega_{B^*}} \cdot \frac{\vec{q}^2}{P^0 - \omega_{\bar{K}^*} - \omega_{B^*} + i\frac{\Gamma}{2}}.$$



Riemann Sheets

The on-Shell momentum p_k^{on} is determined by the zeros of the denominator of the Green's function.

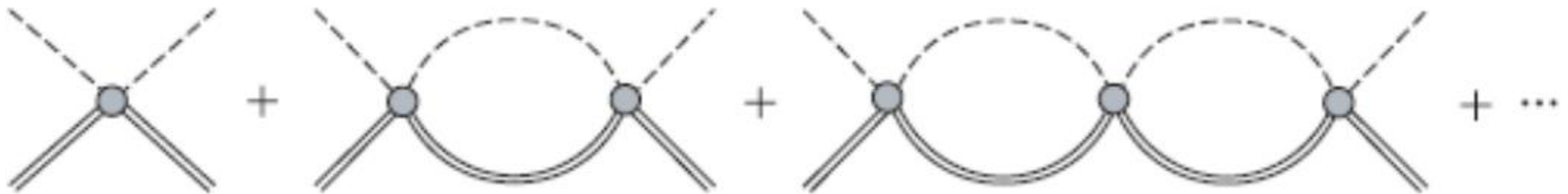
$$G_k^{on,-}(E) = G_k^{on,+}(E) + \frac{ip_k^{on}}{4\pi E},$$
$$G_k^{on,-}(E) = \int \frac{d^3q}{(2\pi)^3} I_k(E, q).$$

Considering the second RS of the $B^{(*)}K\pi$ three-body cut, the momentum-dependent partial width can be replaced by

$$\Gamma_i(M) \rightarrow -\Gamma_i(M) \text{ for } \Im(M) < 0.$$

Lippmann-Schwinger unitarization

$$T = V + VGV + VG^2V + \dots = V + VGT$$



Nagahiro H. et al., "Hidden gauge formalism for the radiative decays of axial-vector mesons", Phys. Rev. D 79, 014015(2009); arXiv:0809.0943[hep-ph].