Exotic molecular meson states of open bottom and strange flavors

E.Oset and L.R. arXiv:2207.08538 [hep-ph], submitted to EPJC

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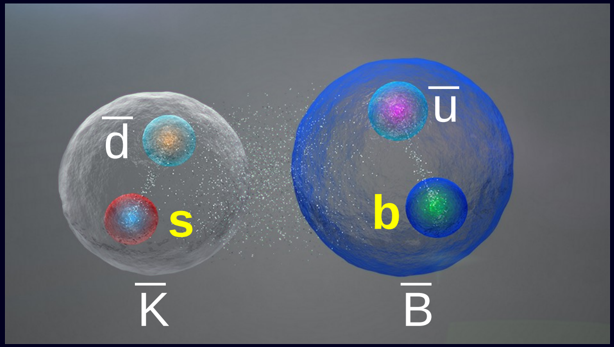


QNP2022 – September 7, 2022

Introduction

✓ Exotic (non $\bar{q}q$) open heavy flavors recently discovered, $X_0(2900)$ (c, s) LHCb 2020

Explanations as:
- tetraquark (Wang, He, Zhang,...)
- $D^*\bar{K}^*$ molecule Geng, Molina, Oset, Liu, Xie, Xue, Huang , ...
  (R. Molina plenary talk yesterday)
- triangular singularity Liu, Xie, Burns,...

(Also recently exp. $T_{cs}(2900)$ (c,$\bar{s}$) LHCb 2022)

✓ c, c open flavors: exp. $T^+_{cc}(3875)$ LHCb 2020

molecular D^*D (1^+): Li, sun, Liu,Xhu ('21); Meng, Wang, '21; Ling, Liu, Geng, Wang, Xie '22; Feijoo, Liang, Oset '21, ...
(R. Molina plenary talk yesterday)

✓ b, b open flavors: (no exp.)

Predicted molecular B^*B, B^*B^*, $B^*_sB^*$ (1^+) states: Dai,Oset,Feijoo,Molina, L.R.,Torres,Khemchandani, PRD105 (2022)

✓ c, b open flavors: (no exp.)

Predicted $\bar{B}D(0^+)$, $\bar{B}^*D(1^+)$, $\bar{B}D^*(1^+)$ and $\bar{B}^*D^*(0^+, 1^+, 2^+)$ states in Sakai, L.R., Oset PRD96 (2017) 5, 054023

Aim of **this work**: Extend the molecular picture to the **b**, **s** flavors from BK, B*K,BK*,B*K* interaction

Idea: Meson-meson interaction from suitable Lagrangians plus implementation of unitarity → UChPT

Basic idea of UChPT:

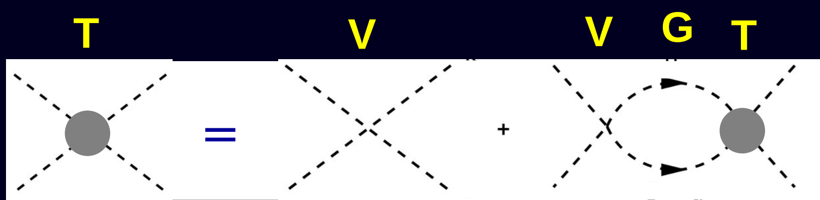
Oller, Oset, Dobado, Pelaez, Meissner, Kaiser, Weise, Ramos, Vicente-Vacas, Nieves, Ruiz-Arriola, Lutz,...

Input:

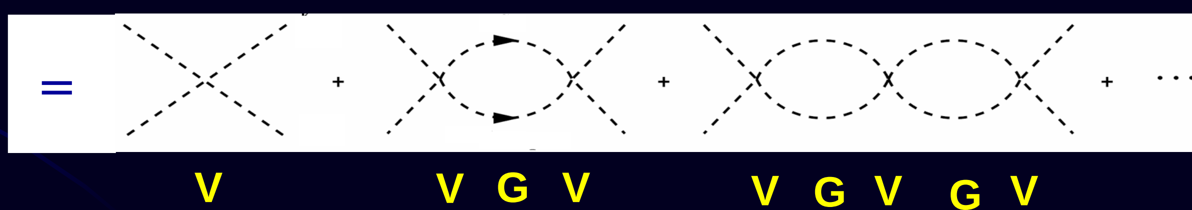
lowest order chiral Lagrangian
+ implementation of **unitarity** in coupled channels
+ exploitation of analytic properties

} Extended range of applicability of ChPT to higher energies

Unitarity of the S-matrix implies:



$$T = \frac{V}{1 - VG}$$



(Bethe-Salpeter eq.)

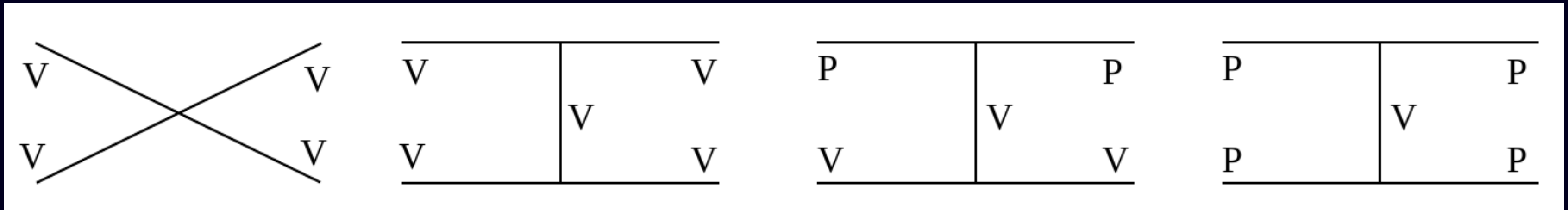
The kernel of the BS equation, **V**, is the lowest order ChPT Lagrangian

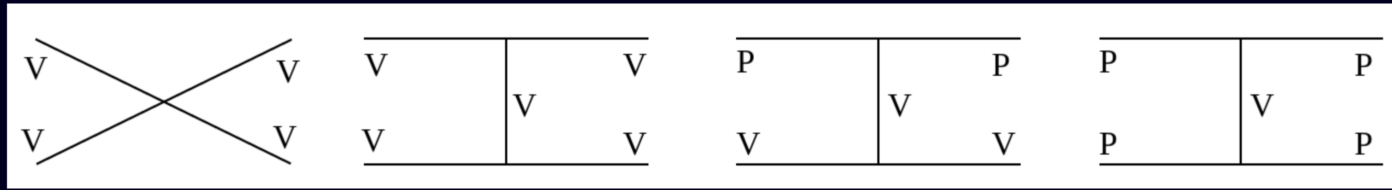
Effectively, one is summing this infinite series of diagrams

$$G = \frac{1}{16\pi^2}\left(\alpha + Log\frac{m_1^2}{\mu^2} + \frac{m_2^2 - m_1^2 + s}{2s} Log\frac{m_2^2}{m_1^2} + \frac{p}{\sqrt{s}}\left(Log\frac{s - m_2^2 + m_1^2 + 2p\sqrt{s}}{-s + m_2^2 - m_1^2 + 2p\sqrt{s}} + Log\frac{s + m_2^2 - m_1^2 + 2p\sqrt{s}}{-s - m_2^2 + m_1^2 + 2p\sqrt{s}}\right)\right)$$

$$G = \int_0^{q_{max}} \frac{q^2 dq}{(2\pi)^2} \frac{\omega_1 + \omega_2}{\omega_1\omega_2[(P^0)^2 - (\omega_1 + \omega_2)^2 + i\epsilon]}$$

In the present case, for the kernel of the Bethe-Salpeter equation for
BK,B*K*,BK*,B*K, we need





Interaction kernel provided by the hidden gauge symmetry Lagrangians:

Bando, Kugo, Yamawaki '84, '88

$$\mathcal{L} = -\frac{1}{4}\langle \bar{V}_{\mu\nu}\bar{V}^{\mu\nu}\rangle + \frac{1}{2}M_v^2\langle[V_\mu - (i/g)\Gamma_\mu]^2\rangle$$

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

$$\Phi = \begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

$$\bar{V}_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

$$\Gamma_\mu = \frac{1}{2}\left\{u^\dagger[\partial_\mu - i(v_\mu + a_\mu)]u + u[\partial_\mu - i(v_\mu - a_\mu)]u^\dagger\right\}$$

$$u^2 = U = \exp\left(\frac{i\sqrt{2}\Phi}{f}\right)$$

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

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

$$\mathcal{L}_{VVVV} = \frac{g^2}{2}\langle V^\mu V^\nu V^\mu V^\nu - V^\nu V^\mu V^\mu V^\nu\rangle$$

Extension to *b* quark mesons:

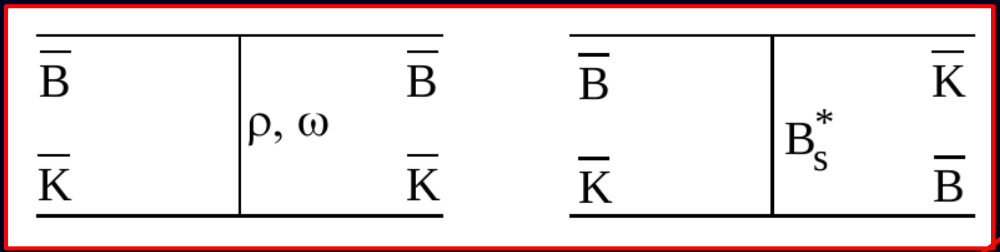
R. Molina, T. Branz and E. Oset, PRD82 (2010) 014010.

L. R. Dai, E. Oset, A. Feijoo, R. Molina, L.R., A. M. Torres and K. P. Khemchandani, PRD105 (2022) no.7, 074017

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

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

$\bar{B}\bar{K}$ system



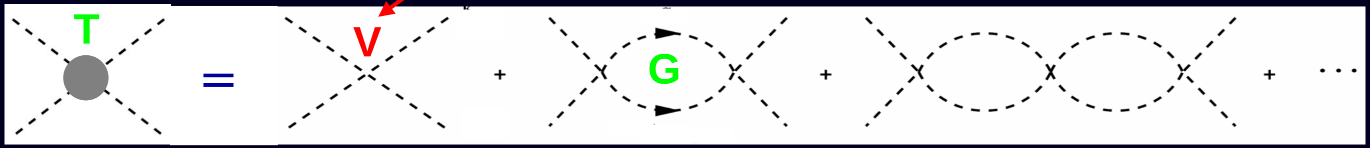
$$\mathcal{L}_{VPP} = -ig\,\langle [P, \partial_\mu P] V^\mu \rangle$$

$$V_{\bar{B}\bar{K}\to\bar{B}\bar{K}} = -\frac{g^2}{m^2_{B_s^*}}(p_1+p_4)(p_2+p_3) + \frac{1}{2}g^2\left(\frac{1}{m^2_\omega} - \frac{3}{m^2_\rho}\right)(p_1+p_3)(p_2+p_4)$$

V

$-18.7g^2$ @ threshold (**attraction**)

Kernel of Bethe-Salpeter



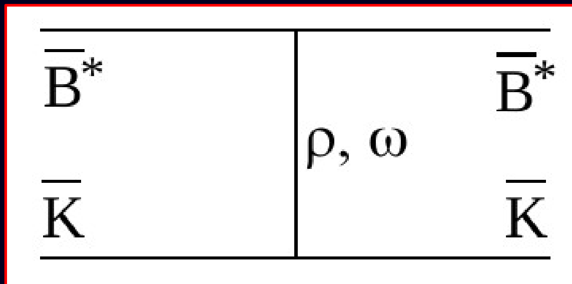
$$T = \frac{V}{1 - VG}$$

G is regularized with the same cutoff as to get the experimental mass of the $X_0(2866)$ in $D^*\bar{K}^*$

Main source of uncertainty

$$G = \int_0^{q_{\max}} \frac{d^3q}{(2\pi)^3}\,\frac{\omega_B + \omega_K}{2\omega_B\omega_K}\,\frac{1}{s - (\omega_B + \omega_K)^2 + i\epsilon}$$

$\bar{B}^*\bar{K}$



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

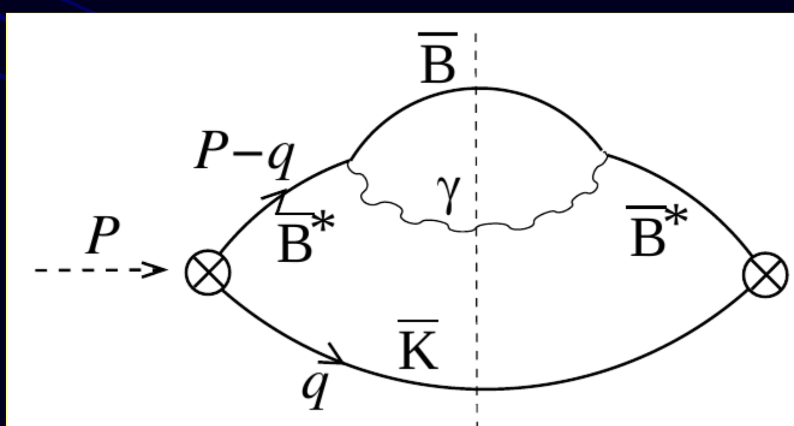
$$\mathcal{L}_{VVV} = ig\,\langle (V^\mu \partial_\nu V_\mu - \partial_\nu V^\mu V_\mu) V^\nu \rangle$$

V

$$V_{\bar{B}^*\bar{K}\to\bar{B}^*\bar{K}} = \frac{1}{2} g^2 \left(\frac{1}{m_\omega^2} - \frac{3}{m_\rho^2} \right) (p_1 + p_3)(p_2 + p_4)\, \vec{\epsilon}_{\bar{B}^*} \cdot \vec{\epsilon}_{\bar{B}^*}{}'$$

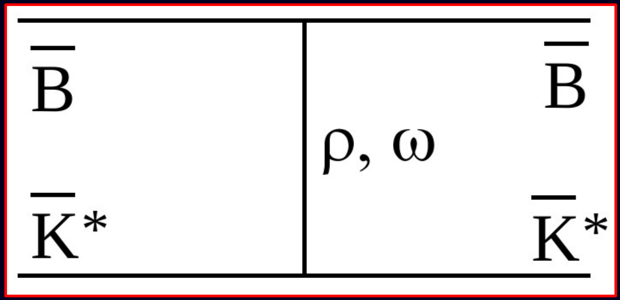
$-17.7 g^2$ @ threshold (**attraction**)

Source of the **width** of the generated state:



(electromagnetic scale)

$\bar{B}\bar{K}^*$



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

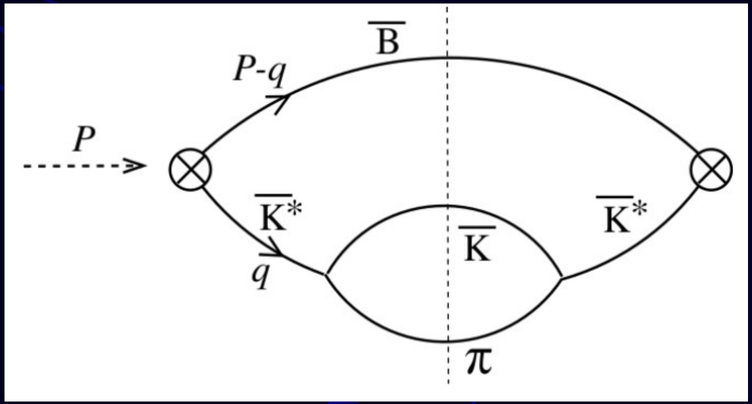
$$\mathcal{L}_{VVV} = ig \langle (V^\mu \partial_\nu V_\mu - \partial_\nu V^\mu V_\mu) V^\nu \rangle$$

V

$$V_{\bar{B}\bar{K}^* \to \bar{B}\bar{K}^*} = \frac{1}{2} g^2 \left(\frac{1}{m_\omega^2} - \frac{3}{m_\rho^2} \right) (p_1 + p_3)(p_2 + p_4)\, \vec{\epsilon}_{\bar{K}^*} \cdot \vec{\epsilon}_{\bar{K}^*}{}'$$

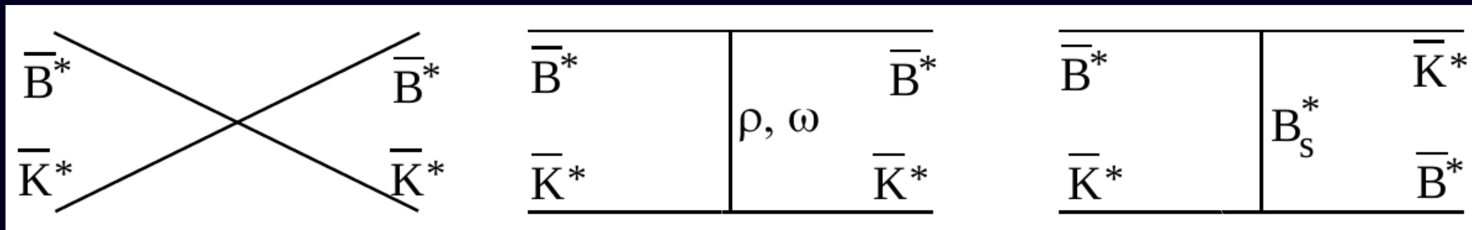
$-31.6 g^2$ @ threshold (**attraction**)

Source of the **width** of the generated state:



(strong scale)

$\bar{B}^*\bar{K}^*$ system



$\mathcal{L}_{VVVV} = \frac{g^2}{2}\langle V^\mu V^\nu V^\mu V^\nu - V^\nu V^\mu V^\mu V^\nu \rangle$

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

$$V_{\text{contact}} = \begin{cases} 4g^2 & \text{for } J = 0, \\ 0 & \text{for } J = 1, \\ -2g^2 & \text{for } J = 2. \end{cases}$$

$$\frac{1}{2}g^2\left(\frac{1}{m_\omega^2} - \frac{3}{m_\rho^2}\right)(p_1+p_3)(p_2+p_4)$$

$$\frac{1}{2}g^2\left(\frac{1}{m_\omega^2} - \frac{3}{m_\rho^2}\right)(p_1+p_3)(p_2+p_4)$$

$$-\frac{g^2}{m_{B_s^*}^2}(p_1+p_4)(p_2+p_3)$$

$$\frac{g^2}{m_{B_s^*}^2}(p_1+p_4)(p_2+p_3)$$

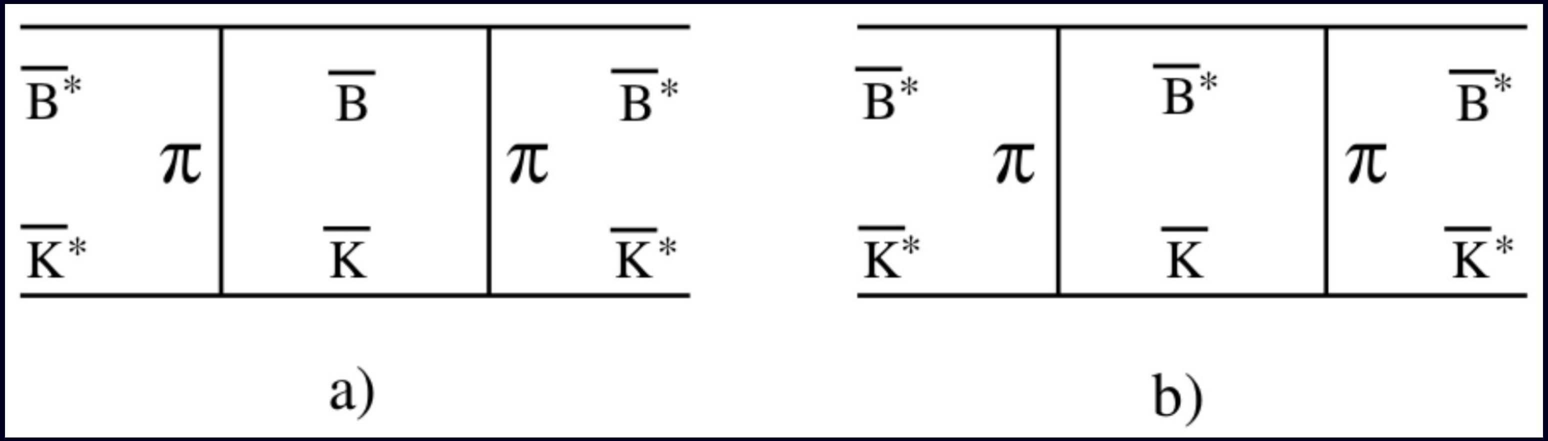
for $J = 0,\ 2$ (

for $J = 1$

@ threshold: $-29g^2$ (J=0), $-30g^2$ (J=1), $-35g^2$ (J=2) → **attraction**

The potentials are attractive for all the channels! (in s-wave)

Source on imaginary part (width) in B*K* system:



(only for J=0,2)

(only for J=1,2)

$$V_{\mathrm{boxA}} = i36g^4 \int \frac{d^4q}{(2\pi)^4} \frac{\vec{\epsilon}_1\cdot\vec{q}\,\vec{\epsilon}_2\cdot\vec{q}\,\vec{\epsilon}_3\cdot\vec{q}\,\vec{\epsilon}_4\cdot\vec{q}}{[q^2-m_\pi^2]^2[(p_1-q)^2-m_B^2+i\epsilon][(p_2+q)^2-m_K^2+i\epsilon]}$$

$$\mathrm{Im}\,V_{\mathrm{boxA}} = -3g^4\frac{1}{10\pi\sqrt{s}}q^5\frac{1}{[(\omega_K-p_2^0)^2-\vec{q}^{\,2}-m_\pi^2]^2}F_J F^4(q)\left(\frac{m_{B^*}}{m_{K^*}}\right)^2$$

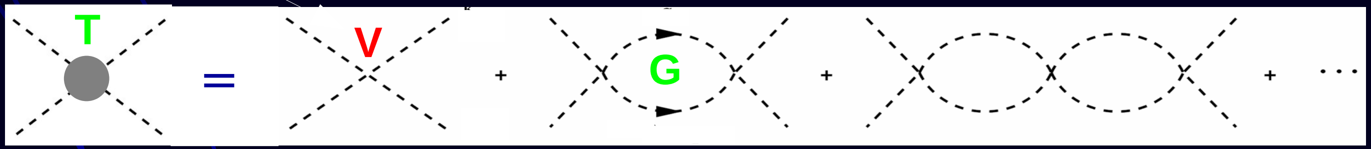
$$F(q) = \exp[-q^2/\Lambda^2]$$

$$ImV_{\mathrm{boxB}} = -\frac{1}{8\pi\sqrt{s}}q^5\,(G'gm_{B^*})^2\,\frac{1}{((\omega_K-p_2^0)^2-\vec{q}^{\,2}-m_\pi^2)^2}F'_J F^4(q)$$

Total kernel:

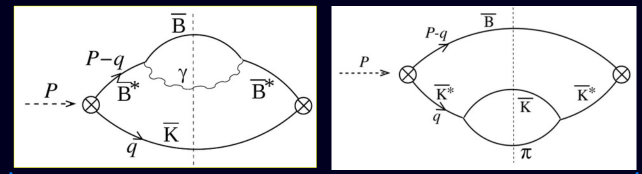
$$V = V_{\mathrm{contact}} + V_{\mathrm{exch.}} + i\mathrm{Im}\,V_{\mathrm{boxA}} + i\mathrm{Im}\,V_{\mathrm{boxB}}$$

$$T = \frac{V}{1-VG}$$



Results

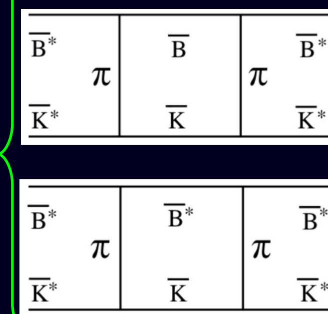
$$T \simeq \frac{g_R^2}{s - s_R}$$



threshold — Binding energy — coupling

channel	$I(J^P)$	E_B (MeV)	g_R (GeV)	width without box diagrams (MeV)	full width (MeV)
$\bar{B}\bar{K}(5774.7)$	$0(0^+)$	7–22	17–22	–	–
$\bar{B}^*\bar{K}(5820.4)$	$0(1^+)$	3–15	14–20	(117-10) eV	(117-10) eV
$\bar{B}\bar{K}^*(6172.9)$	$0(1^+)$	70–117	34–38	6.5–1.9	6.5–1.9
$\bar{B}^*\bar{K}^*(6218.6)$	$0(0^+)$	54-94	31–35	9.0–3.1	115–160
	$0(1^+)$	62–106	33–37	7.6–2.4	13–10
	$0(2^+)$	90–145	38–42	4.2–0.9	55–80

\+



- ✓ We find **bound states** for all the channels studied
- ✓ Binding energies bigger than for D*K̄* in R. Molina and E. Oset, Phys. Lett. B 811 (2020), 135870.

Summary

✓ Exotic mesons with open heavy flavor are poorly studied experimentally but increasingly widely studied theoretically

✓ We study open b + s flavors from BK, B*K,BK*,B*K* interaction using UChPT.

✓ Potentials obtained from lowest order hidden gauge local symmetry Lagrangians with tree level contact terms and vector meson exchange

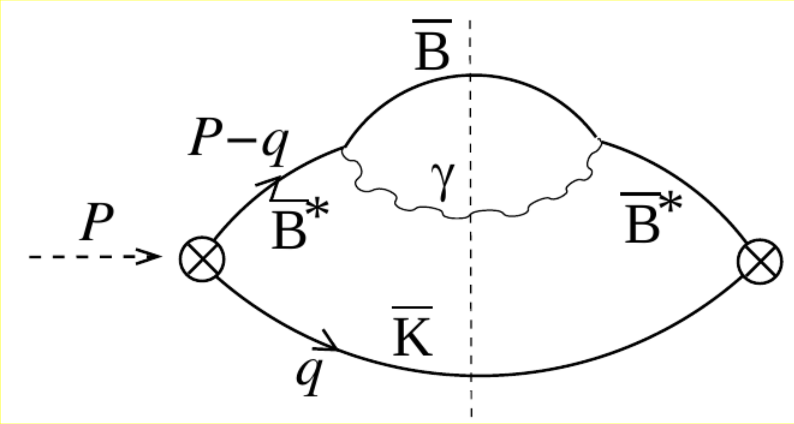
✓ Main source of uncertainty: regulator (cutoff) of the meson-meson loop function (obtained to get $X_0(2866)$ mass in $D^*\bar{K}^*$ interaction)

✓ We evaluate widths by identifying the main sources of imaginary parts:
decay of unstable components + box diagrams

✓ We find **bound states** for all the channels studied

✓Despite the uncertainty obtained, it is a grounded and sound conclusion of the present study that these exotic states must exist

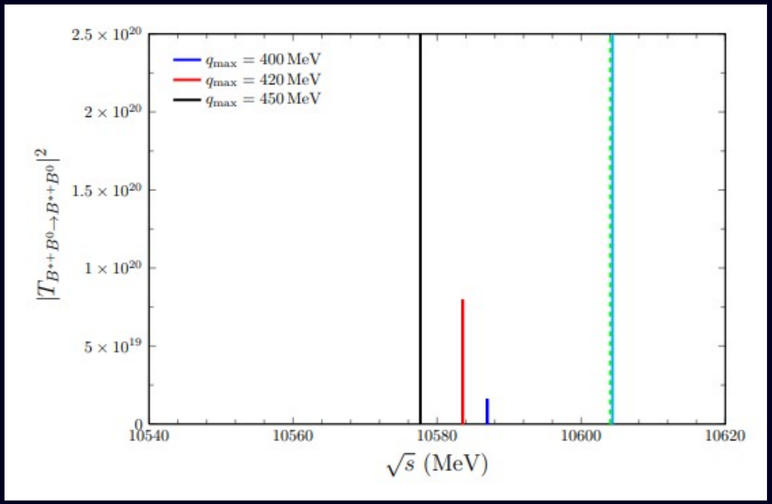
BACKUP SLIDES



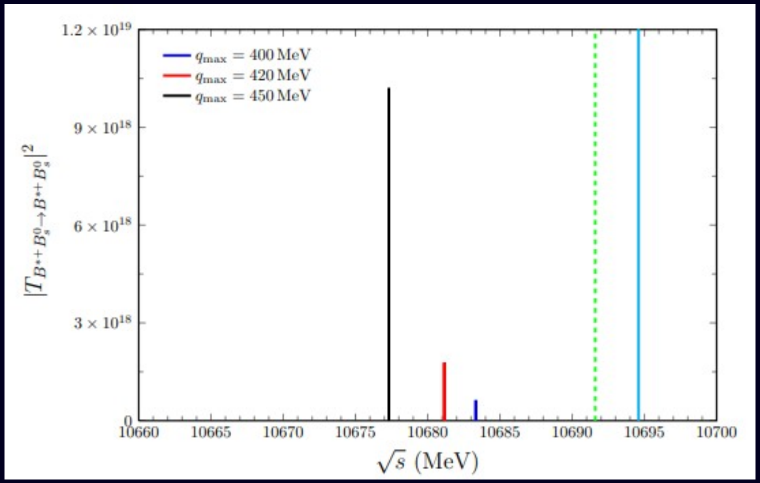
$$G(s) \simeq \int_0^{q_{\max}} dq \frac{q^2}{4\pi^2} \frac{\omega_B + \omega_{K^*}}{\omega_B \omega_{K^*}} \frac{1}{\sqrt{s} + \omega_B + \omega_{K^*}} \frac{1}{\sqrt{s} - \omega_{K^*} - \omega_B + i \frac{\sqrt{s'}}{2\omega_{K^*}} \Gamma_{K^*}(s')},$$

with $s' = (\sqrt{s} - \omega_B)^2 - \vec{q}^{\,2}$, and

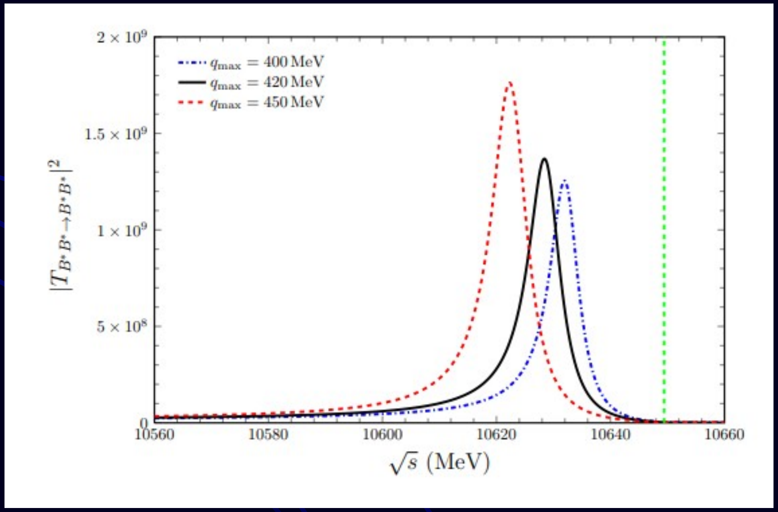
$$\Gamma_{K^*}(s') = \Gamma_{K^*}(m_{K^*}^2) \frac{m_{K^*}^2}{s'} \left(\frac{p_\pi(s')}{p_\pi(m_{K^*}^2)} \right)^3 \Theta(\sqrt{s'} - m_K - m_\pi),$$



q_{max} = 400 MeV
q_{max} = 420 MeV
q_{max} = 450 MeV
$|T_{B^{*+}B^0 \to B^{*+}B^0}|^2$
2.5×10^{20}
2×10^{20}
1.5×10^{20}
1×10^{20}
5×10^{19}
0
10540
10560
10580
10600
10620
$\sqrt{s}$ (MeV)



q_{max} = 400 MeV
q_{max} = 420 MeV
q_{max} = 450 MeV
$|T_{B^{*+}B_s^0 \to B^{*+}B_s^0}|^2$
1.2×10^{19}
9×10^{18}
6×10^{18}
3×10^{18}
0
10660
10665
10670
10675
10680
10685
10690
10695
10700
$\sqrt{s}$ (MeV)



q_{max} = 400 MeV
q_{max} = 420 MeV
q_{max} = 450 MeV
$|T_{B^*B^* \to B^*B^*}|^2$
2×10^{9}
1.5×10^{9}
1×10^{9}
5×10^{8}
0
10560
10580
10600
10620
10640
10660
$\sqrt{s}$ (MeV)

UChPT (unitary extensions of chiral perturbation theory)

ChPT very sucessful to describe a large amount of phenomenology at low energies

Problems (limitations) of ChPT:

- The number of parameters increases a lot with the order of the expansion
- The energy range of applicability is restricted to low energies

Typically till the energies where the first resonances appear

A resonance implies a pole, which a perturbative expansion can never produce

ChPT cannot be applied to the region of intermediate energies where the hadronic spectrum is very rich