Can femtoscopic correlation function shed light on the nature of the lightest, charm, axial mesons?

Luciano Melo Abreu

Universidade Federal da Bahia (Brazil)

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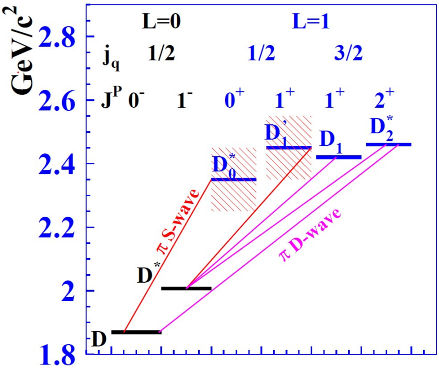
Outline

- A brief overview on the two lightest axial mesons with charm: $D_1(2430)$ and $D_1(2420)$
- Description based on the dynamics at the quark level as well as among hadrons
- Use of two approaches resulting in different scattering lengths: one in agreement with lattice QCD and the other with data of ALICE
- Investigation if the correlation function for channels dominated by strong interactions are sensitive to two scenarios

- D-meson excitations:



[Belle, PRD 69, 112002 (2004)]

- PDG:

$D_1(2420)$:

$M = 2422.1 \pm 0.6$ MeV,

$\Gamma = 31.3 \pm 1.9$ MeV.

$D_1(2430)$:

$M = 2412 \pm 9$ MeV,

$\Gamma = 314 \pm 29$ MeV.

- Belle (2004) and LHCb (2020): fit from the $D^*\pi$ invariant mass distribution of $B^- \to D^{*+}\pi^-\pi^-$ decay

Explanation of the masses and widths ($R = \Gamma_{D_1(2430)}/\Gamma_{D_1(2420)} \sim 10$) from the same dynamics: controversies

- Models based purely on hadron dynamics: existence of two low-lying D_1's, but predictions do not coincide with experiments
- Heavy quark symmetry: decay rates lead $R \sim 10$ once the states are assumed with 1^1P_1 and 1^3P_1 (Manohar-Wise book)
- Quark model states with mixing: R far from data (e.g. Ferretti and Santopinto, PRD 97, 114020 (2018))
- Mixing of the two states through the consideration of hadron loops can describe R (Zhou and Xiao, PRD 84, 034023 (2011))
- Different types of mixing of the 1^1P_1 and 1^3P_1 states lead to similar masses but different values of the R
- Hadron loops or meson clouds are useful in better describing the properties of $D_1(2420)$ and $D_1(2430)$

Scattering length $a_{D^{(*)}\pi}$ ($D^*\pi$: main decay of the D_1 states):

Femtoscopy (ALICE, arXiv:2401.13541)
Lattice QCD (Mohler et al. PRD 87, 034501 (2013)) → DISAGREEMENT
EFT predictions(Torres-Rincon et al. PRD 108, 096008 (2023))

Purposes of this work

- Obtention of a model that can describe the mass and width of the two lowest-lying D_1 states
  Our attempt shows that an interplay of quark-hadron degrees of freedom can be useful
- Investigation if femtoscopic correlation functions can be useful in resolving the situation
  Focus on channels $D^{*+(0)}\pi^{0(+)}$, dominated by strong interactions, not needing Coulomb interactions
  (different of those in PRD 108, 096008 (2023) [unitarized ChPT with heavy quark symmetry]);
  They can be used to settle the value of the $D^*\pi$ scattering length

Scattering amplitudes

Our approach

Meson-meson coupled channel + Bare quark-model pole

- Interactions between vector and pseudoscalar mesons based on SU(4) symmetry: Gamermann and Oset, EPJA 33, 119 (2007); Malabarba et al., PRD 107, 036016 (2023)

Lowest-order amplitude ($I = 1/2$):

$$V_{ij} = \frac{C_{ij}}{4f^2}(s-u)\,\vec{\epsilon}\cdot\vec{\epsilon}',$$

	πD^*	$D\rho$	$\bar{K}D_s^*$	$D_s\bar{K}^*$
πD^*	-2	$\gamma/2$	$-\sqrt{\frac{3}{2}}$	0
$D\rho$		-2	0	$\sqrt{\frac{3}{2}}$
$\bar{K}D_s^*$			-1	0
$D_s\bar{K}^*$				-1

C_{ij} for the most relevant channels to study the D_1 states

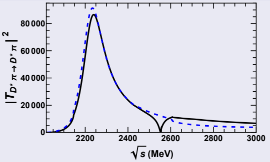
$\gamma = \left(\frac{m_L}{m_H}\right)^2$; $m_L = 800$ MeV and $m_H = 2050$ MeV

- Additional contribution: Box diagrams for the $D\rho \to D^*\pi \to D\rho$ with pseudoscalar exchange (PPV and PVV vertices)
- Solution of the Bethe-Salpeter equation (G: loop function):

$$T = V + VGT$$

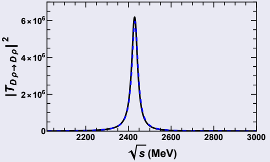
First state

- $M \sim 2428$ MeV, $\Gamma \sim 33$ MeV
- Strong (weak) coupling to $D\rho$ ($D^*\pi$)
- Good agreement with $D_1(2420)$



Second state

- $M \sim 2220$ MeV, $\Gamma \sim 131$ MeV
- Strong coupling to $D^*\pi$
- Discrepancy with $D_1(2430)$



Better description: addition of a bare quark-model pole for $D^*\pi$

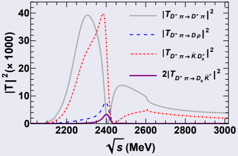
$$V_{QM} = \pm \frac{g_{QM}^2}{s - M_{QM}^2};$$

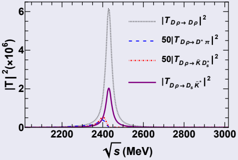
M_{QM}, g_{QM}: adjusted to describe the $D_1(2430)$ as well as the $D^*\pi$ scattering lengths

Model A

$$V_{QM} = -\frac{6000^2}{s - 2440^2}$$

(Godfrey and Isgur, PRD 32, 189 (1985))





- $D^*\pi$: $M \sim 2304$ MeV, $\Gamma \sim 160$ MeV

  (Lower limit for $D_1(2430)$ from Babar (2006))

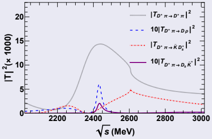
- $a^{(1/2)}_{D^*\pi} = -0.20$ fm

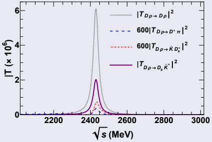
  (In accordance with lattice results for $a^{(1/2)}_{D\pi}$ (Liu et al. PRD 87, 014508 (2013)))

Model B

$$V_{QM} = \frac{10000^2}{s - 2370^2}$$

(g_{QM}, M_{QM} considered as free parameters)





- $D^*\pi$: $M \sim 2436$ MeV, $\Gamma \sim 311$ MeV

  (Agreement with LHCb and Belle data)

- $a^{(1/2)}_{D^*\pi} = 0.1$ fm

  (In accordance with recent Alice results for $a^{(1/2)}_{D^*\pi}$ (e-Print: 2401.13541 [nucl-ex]))

Correlation Functions

Generalized coupled-channel CF for a specific channel i

$$C_i(k) \simeq \int d^3\vec{r} S_{12}(\vec{r}) |\Psi(\vec{r},\vec{k})|^2$$

$$= 1 + 4\pi\theta(\Lambda - k) \int_0^\infty dr r^2 S_{12}(\vec{r}) \left(\sum_j |j_0(kr)\delta_{ji} + T_{ji}(\sqrt{s})\widetilde{G}_j(r;s)|^2 - j_0^2(kr) \right),$$

$\vec{k}$: relative momentum;
$E = \sqrt{s}$: the CM energy;
T_{ji}: elements of the scattering matrix encoding the meson–meson interactions;

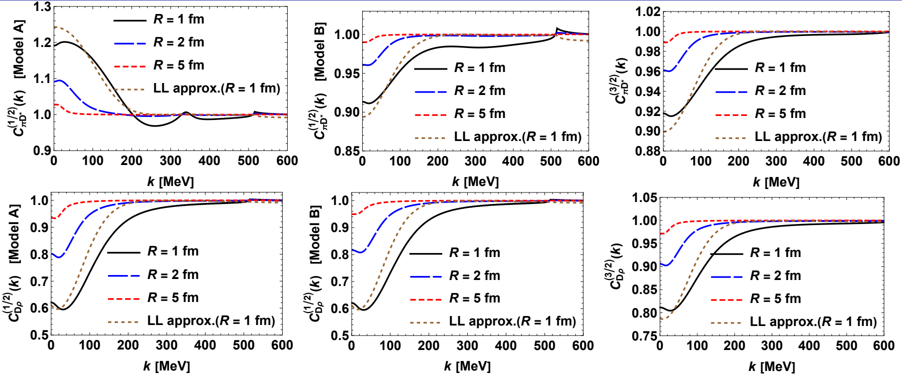
$$\widetilde{G}_j(r;s) = \int_{|\vec{q}|<\Lambda} \frac{d^3q}{(2\pi)^3} \frac{\omega_1^{(j)} + \omega_2^{(j)}}{2\omega_1^{(j)}\omega_2^{(j)}} \frac{j_0(qr)}{s - \left(\omega_1^{(j)} + \omega_2^{(j)}\right)^2 + i\varepsilon},$$

($\omega_a^{(j)} \equiv \omega_a^{(j)}(k) = \sqrt{k^2 + m_a^2}$; $\Lambda = 700$ MeV);
$S_{12}(\vec{r})$: source function,

$$S_{12}(\vec{r}) = \frac{1}{(4\pi)^{\frac{3}{2}} R^3} \exp\left(-\frac{r^2}{4R^2}\right),$$

(R: source size parameter)

Results: Correlation Functions in isospin basis



Lednicky-Lyuboshits: $C_{LL} = 1 + \frac{1}{(kR)^2 + (\frac{R}{a})^2}\left[\frac{1}{2} - \frac{2R}{a\sqrt{\pi}}F_2(2kR) - kRF_3(2kR)\right]$; $F_2 = \int dt \frac{e^{t^2 - z^2}}{z}$, $F_3 = \frac{1 - e^{-z^2}}{z}$

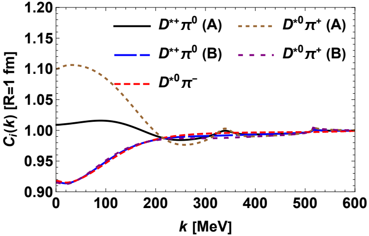
- Model A: $C^{(1/2)}_{D^*\pi}(k=0)|_{R=1\text{fm}} > 1$, because of the attractive character and $a^{(1/2)}_{D^*\pi} < 0$
- Model B: $C^{(1/2)}_{D^*\pi}(k=0)|_{R=1\text{fm}} < 1$, because of $a^{(1/2)}_{D^*\pi} = 0.1$ fm $< 2.3R$ (same in $C^{(3/2)}_{D^*\pi}$)
- Both models: $C^{(1/2)}_{D^*\pi}(k>0)$ reflects the behavior of $T^{(1/2)}_{D^*\pi,D^*\pi}$ (same in $C^{(3/2)}_{D^*\pi}$)
- Dip in $C^{(1/2)}_{D\rho}(k=0)$: influence of the narrow state in $T^{(1/2)}_{D\rho,D\rho}$ below the $D\rho$ threshold

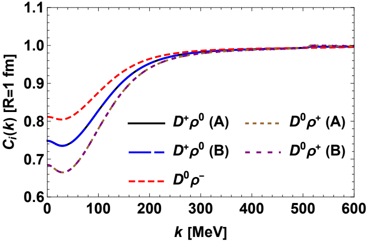
Results: Correlation Functions in physical basis

$$C_{D^{*0}\pi^+} \equiv C_{D^{*0}\pi^+ \to D^{*0}\pi^+} + C_{D^{*+}\pi^0 \to D^{*0}\pi^+} = \frac{2}{3} C^{(\frac{1}{2})}_{D^*\pi} + \frac{1}{3} C^{(\frac{3}{2})}_{D^*\pi};$$

$$C_{D^{*+}\pi^0} \equiv C_{D^{*0}\pi^+ \to D^{*+}\pi^0} + C_{D^{*+}\pi^0 \to D^{*+}\pi^0} = \frac{1}{3} C^{(\frac{1}{2})}_{D^*\pi} + \frac{2}{3} C^{(\frac{3}{2})}_{D^*\pi}; \quad C_{D^{*0}\pi^-} \equiv C^{(\frac{3}{2})}_{D^*\pi};$$

($D\rho$: analogous)





- Model A: features of $T^{(1/2)}_{D^*\pi, D^*\pi}$ are more notable in the channel $D^{*0}\pi^+$, because of the bigger weight of the $I = 1/2$
- Model B: there is no sizable difference between $D^{*0}\pi^+$, $D^{*+}\pi^0$ and $D^{*0}\pi^-$ (similarity between $C^{(1/2)}_{D^*\pi}(k)$ and $C^{(3/2)}_{D^*\pi}(k)$)
- $C_{D^+\rho^0}(k)$ closer to one at threshold than $C_{D^0\rho^+}(k)$ (difference from isospin weights)
- $D^{*0}\pi^+$ and $D^0\rho^+$: more appropriate to test both models

Summary

Properties of the two lightest D_1 states

- Description of their different widths once their masses are assumed: possible via heavy quark symmetry
- Explanation of masses and widths from the same dynamics: not trivial
- $a^{(1/2)}_{D^{(*)}\pi}$ from femtoscopy based on Alice data: disagreement with lattice QCD calculations and EFT predictions

Our work

- Comprehension of the D_1 states and characterization of $a^{(1/2)}_{D^*\pi}$
- Approach: meson-meson interactions + bare quark model pole used as kernels to solve the Bethe-Salpeter equation
- Good description for the $D_1(2420)$ and $D_1(2430)$, with two different scenarios for bare quark-model pole giving distinct $a^{(1/2)}_{D^*\pi}$
- Correlation functions of the $D^{*0}\pi^+$ and $D^{*0}\rho^+$ channels for smaller source sizes: can bring useful information