Investigating the multiplicities and femtoscopic correlation functions of heavy-flavor and exotic hadrons

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Hadron spectroscopy and the new unexpected resonances

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Paraty

Aim

- A brief overview on the state-of-the-art of exotic hadron spectroscopy
- Discussion about the underlying structure and the most promising approaches
- Summary of some of our recent contributions (focus on femtoscopy)

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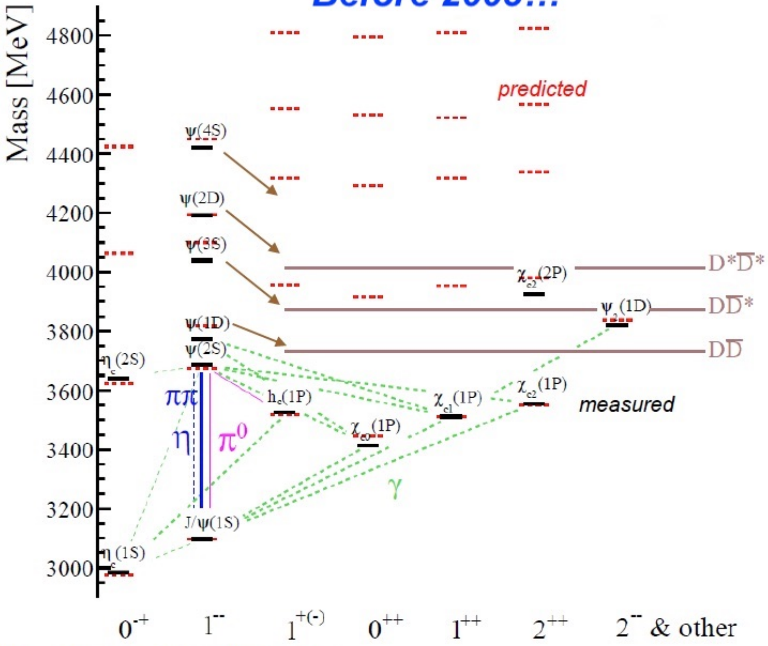
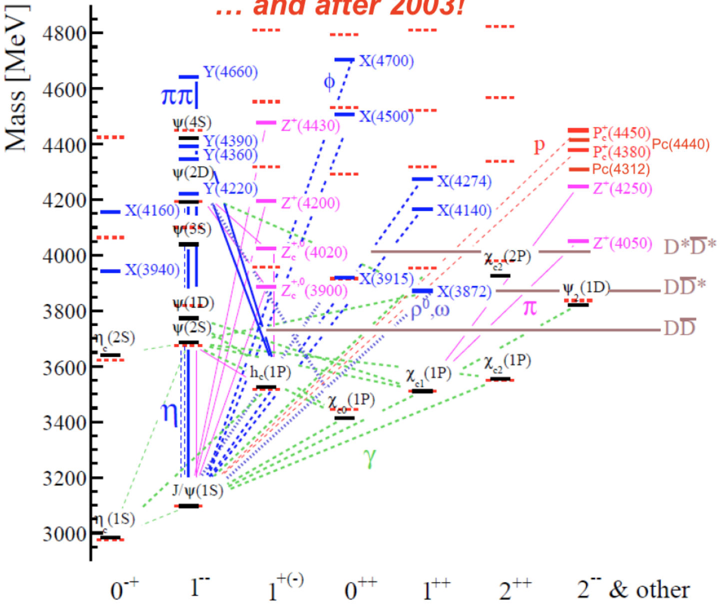
Before 2003...



Figures from Olsen,Skwarnicki,Zieminska

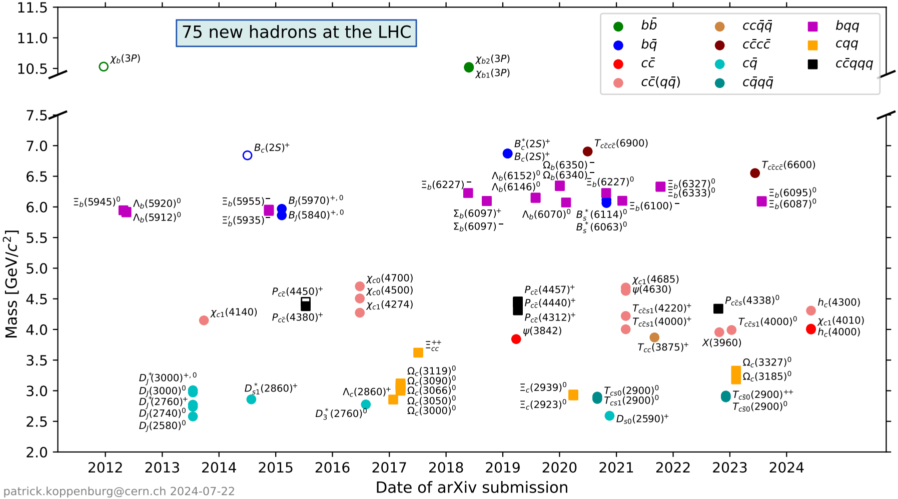
... and after 2003!



(Adapted from Skwarnicki, 2018)

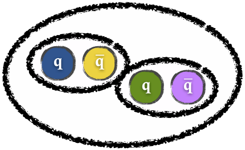
The heavy exotics collection

- Since 2003 [$X(3872)$]: about fifty candidates observed!



Intepretations for composition and binding mechanisms?

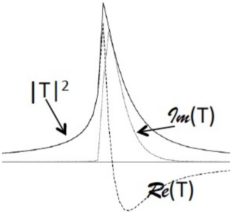
- Hadron Molecules



- Tetraquarks

- Hybrids

- Cusp effects (TS's)



- Glueballs

- . . .

Theoretical perspective

A compelling and unified understanding has not yet emerged

- No single theoretical framework explains the exotics collection
- Candidates: different interpretations (hadron molecule, diquark-antidiquark, kinematical effects, ...)
- (m, Γ) can be explained by different models or even superposition of them

- Necessity of more studies, more observables to distinguish their internal structure

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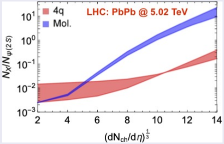
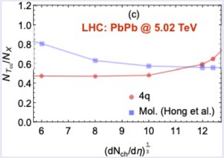
Strategy 1 $\Rightarrow$ Exotics in Heavy-Ion Collisions

$X(3872)$ $[(cq\bar{c}\bar{q}); 0(1^{++})]$



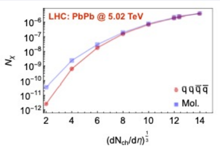
[PRD **90**, 114023 (2014); **105**, 116029 (2022); **110**, 014011 (2024); PTEP **2016**, 103B01 (2016), PLB **761**, 303 (2016); EPJC (2022); ...] (Navarra's Talk)

$T_{cc}^{+}(3875)$ $[(cc\bar{q}\bar{q}); 0(1^{+})]$



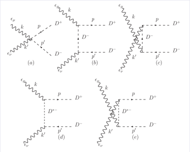
[EPJC **82**, 296 (2022); PRD **105**, 116029 (2022); NPB **985**, 115994 (2022)]

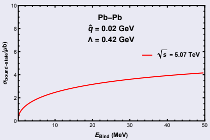
$\chi_{c1}(4274)$ $[(cs\bar{c}\bar{s}); 0^{+}(1^{++})]$



[PRD **108**, 096028 (2023); PRD **109**, 014041 (2024)]

$X(3700)^{-}$ $[(c\bar{c}q\bar{q})0^{+}(0^{++})]$



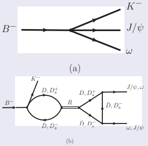


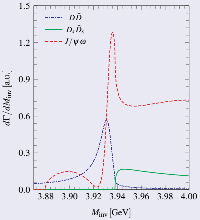
[PRD **110**, 034037 (2024)] (Sobrinho's Talk)

[Collaboration USP-UNIFESP-UFBA: Navarra, Nielsen, Torres, Kamchandani, LMA, Vieira, Britto, Magalhães ...]

Strategy 2 → Exotics in hadron decays

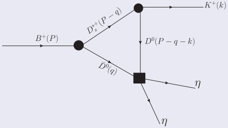
$X(3930, 3960)$ in $B \to KJ/\psi\omega$

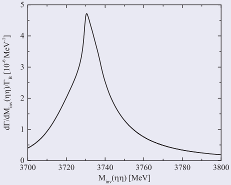




[Collaboration Valencia-UFBA (Abreu, Albaladejo, Feijoo, Oset, Nieves); EPJC **83**, 309 (2023)]

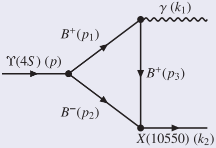
$D\bar{D}(3720)$ in $B^+ \to K^+\eta\eta$





[Collaboration Valencia-Beihang-UFBA (Brandão, Song, Abreu, Oset); PRD **108**, 054004 (2023)] (Brandão's talk)

$B\bar{B}(10550)$ in $\Upsilon(4S) \to \gamma X(10550)$



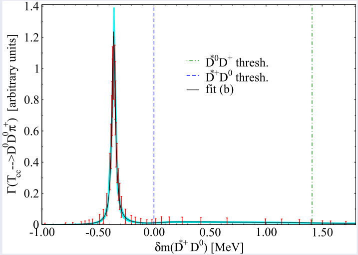
E_B [MeV]	$g_{XB\bar{B}}$ [GeV]	$\Gamma_{\Upsilon(4S)\to\gamma X(10550)}$ [keV]	$\mathcal{B}_{\Upsilon(4S)\to\gamma X(10550)}$
5	28.50	1.55	7.55×10^{-5}
10	33.96	2.59	1.25×10^{-4}
25	47.94	6.90	3.37×10^{-4}
50	67.87	19.87	9.70×10^{-4}
75	85.85	42.34	2.06×10^{-3}
100	102.73	76.79	3.75×10^{-3}

$\Gamma_{\Upsilon(\mathbf{4}S)\to\gamma X(\mathbf{10550})} \sim 0.5 - 192\ keV$

[Collaboration UFRB-UFBA (Britto, Abreu); PRD **110**, 056008 (2024)]

Strategy 3 → Compositeness of exotic states

Weinberg criterion + Bethe-Salpeter form. + fit

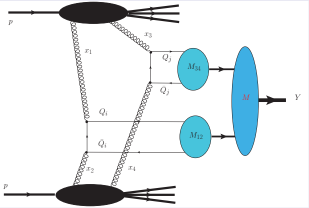


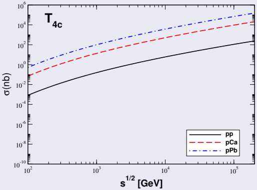
	a_i [fm]	$r_{0,i}$ [fm]
$i = 1$ $(D^{*+}D^0)$	$(7.60 \pm 0.14) - i\,(1.73 \pm 0.09)$	-2.94 ± 0.04
$i = 2$ $(D^{*0}D^+)$	$(1.99 \pm 0.07) - i\,(1.25 \pm 0.23)$	$(0.11 \pm 0.17) - i\,(2.74 \pm 0.22)$

B [KeV]	Γ [KeV]	g_1 [MeV]	g_2 [MeV]	P_1	P_2
360 ± 2	38 ± 1	3875 ± 51	-4077 ± 72	0.697 ± 0.017	0.301 ± 0.009

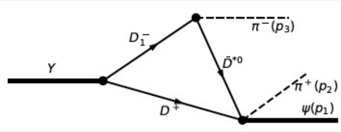
[Collaboration Valencia-Huzhou-UFBA: Dai, LMA, Feijoo, Oset, EPJC **83**, 983 (2023)]

Strategy 4 → T_{4Q} through DPS



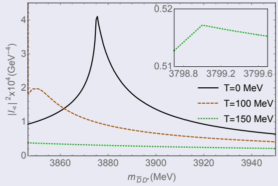


[Coll. UNIFESP-UFPEL-UFBA: LMA, Cerqueira, Carvalho, Gonçalves; EPJC **84**, 470 (2024)] (Carvalho's talk)

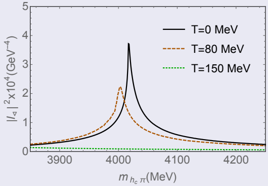


- $Z_c(3900)$: triangle singularity or new hadron?
- Can HICs help to discern the correct interpretation?

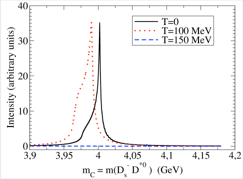
$Z_c(3900)$ $[(cq\bar{c}\bar{q}); 1(1^-)]$



$Z_c(4020)$ $[(cq\bar{c}\bar{q}); 1(?^?)]$



$Z_{cs}(3985)^-$ $[(cs\bar{c}\bar{u})\frac{1}{2}(1^+)]$



- Singularity disappears at temperatures just below T_H
- Medium: spectroscopic filter to distinguish actual hadrons from TSs

[Collaboration U.Complutense Madrid-UFBA (F. Llanes-Estrada, ...); EPJ C 81, 430 (2021); PoS EPS-HEP2021 (2022) 278]; Nucl.Part.Phys.Proc. 318, 32 (2022)]

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Generalized coupled-channel CF for a specific channel i

$$C_i(k) = \frac{N_i(\vec{k}_1, \vec{k}_2)}{N(\vec{k}_1)N(\vec{k}_2)} \simeq \int d^3\vec{r} S_{12}(\vec{r})|\Psi_i(\vec{r}, \vec{k})|^2$$
$$= 1 + 4\pi \int_0^\infty dr r^2 S_{12}(\vec{r}) \left(\sum_j w_j |j_0(kr)\delta_{ji} + T_{ji}(\sqrt{s})\widetilde{G}_j(r;s)|^2 - j_0^2(kr) \right),$$

$\vec{k}$: relative momentum;
w_j: weight of the observed channel j (common choice: $w_j = 1$);
$E = \sqrt{s}$: 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 (larger R : larger system size $pp \to pA \to AA$ collisions)

Lednicky-Lyuboshits (LL) approximation (asymptotic Ψ $(r \to \infty)$)

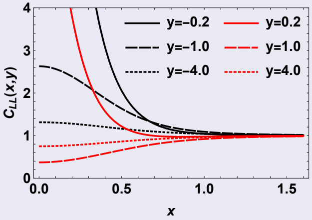
Using

$$-\frac{T}{8\pi\sqrt{s}} = f(k) \equiv \frac{1}{k\cot\delta(k) - ik} = \frac{R}{-R/a - ikR},$$

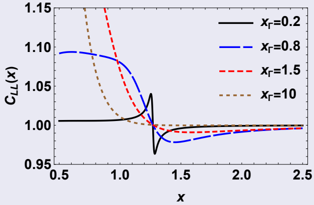
then

$$C_{LL}(x,y) = 1 + \frac{1}{x^2+y^2}\left[\frac{1}{2} - \frac{2y}{\sqrt{\pi}}F_2(2x) - xF_3(2x)\right],$$

$x = kR$; $y = R/a$ (a: scattering length); $F_2(z) = \int dt \frac{e^{t^2-z^2}}{z}$, $F_3(z) = \frac{1-e^{-z^2}}{z}$



- $a < 0$: attractive interaction
- $a > 0$: with a bound state



- Resonance at $k_R(\delta = \pi/2)$:

  $C_{LL}(x_R) = 1 + \frac{e^{-4x_R^2}}{2x_R^2}$

  $x_\Gamma = \sqrt{\mu\Gamma R^2}$ (μ: reduced mass)

Dependence on $R, a \to$ bound or quasi-bound state; resonance

Predictions for the T_{bb}^{+} state

$B^{*+}B^{0}$; $B^{*0}B^{+}$ interactions

Bethe-Salpeter formalism:

$$T = [1 - VG]^{-1}\, V \ ,$$

V: interaction potential
(Use of local hidden gauge approach);

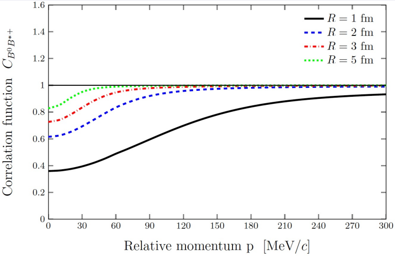
G: loop function ($q_{max} = 420$ MeV).

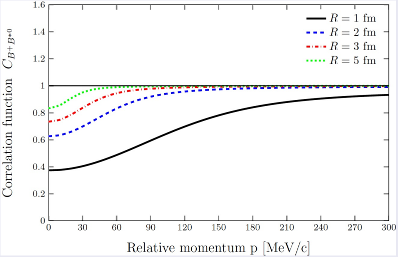
$I = 0$ state:

$$|BB, I = 0\rangle = -\frac{1}{\sqrt{2}}(B^{*+}B^{0} - B^{*0}B^{+}).$$

[Collaboration Valencia-Huzhou-UFBA (Dai, LMA, Feijoo, Molina, Oset); PRD **109**, 016014 (2024)]

$C_{B^{*+}B^{0}}$ and $C_{B^{*0}B^{+}}$





T_{bb}^{+} as a molecular state → the only interpretation from these CF's?

Inverse Problem

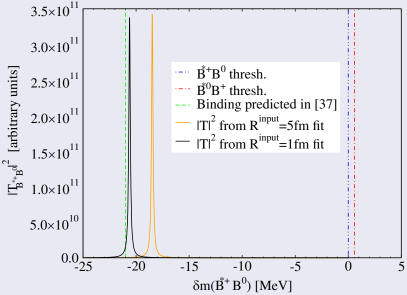
- Extraction of relevant observables from the CFs
- Assumption: isospin symmetry, $\langle I=0|V|I=0\rangle = 1 \rightarrow V_{11} = V_{22}$
- No a priori choice: freedom is left for nonmolecular components
- Contribution from nonmolecular states: energy-dependent terms,

$$V_{11} = V'_{11} + \frac{\alpha}{m_V^2}(s - s_0)$$
$$V_{12} = V'_{12} + \frac{\beta}{m_V^2}(s - s_0)$$

Fit to the synthetic data

- Parameter space: $\{q_{max}, V'_{11}, V'_{12}, \alpha, \beta, R\}$
- CFs are used to produce synthetic data
- Fit for the CFs ($R^{(input)} = 1$ fm):

$$\begin{aligned} q_{max} &= 445 \pm 29 \text{ MeV}, \\ V'_{11} &= 70 \pm 360, \\ V'_{12} &= 3463 \pm 1272, \\ \alpha &= -170 \pm 336, \\ \beta &= 290 \pm 346, \\ R &= 0.98 \pm 0.02\text{fm} \end{aligned}$$



- From CFs: Bound state with $I = 0$!
- $E_b = 20.62$ MeV ($R^{(input)} = 1$ fm)
- $E_b = 18.48$ MeV ($R^{(input)} = 5$ fm)
- In Dai et al. PRD 105, **074017** (2022): $E_b = 21$ MeV

R^{input} (fm)	a_1 (fm)	$r_{0,1}$ (fm)	a_2 (fm)	$r_{0,2}$ (fm)
1	0.85 ± 0.18	-0.11 ± 0.51	$(0.81 \pm 0.13) - i(0.03 \pm 0.03)$	$(0.43 \pm 0.11) - i(0.38 \pm 0.29)$
5	0.85 ± 0.19	-0.92 ± 1.78	$(0.77 \pm 0.13) - i(0.05 \pm 0.06)$	$(0.26 \pm 0.40) - i(0.87 \pm 1.13)$

R^{input} (fm)	g_1 (MeV)	g_2 (MeV)	P_1	P_2	Z
1	33039 ± 14744	-32031 ± 17367	0.44 ± 0.06	0.43 ± 0.05	0.13 ± 0.11
5	30970 ± 19666	-31181 ± 19718	0.41 ± 0.11	0.39 ± 0.11	0.19 ± 0.22

- Molecular probability: $P_1 + P_2 = 0.87 \pm 0.11$ (compatible with 1)
- Nonmolecular probability: $Z = 1 - (P_1 + P_2) = 0.13 \pm 0.11$
- A clear molecular nature for the T_{bb}^{+} state!

Can CFs shed light on the nature of the D_1 states?

PDG: evidence of two D_1 states with $J^P = 1^+$

$$D_1(2420): \quad M = 2422.1 \pm 0.6 \text{ MeV}, \quad \Gamma = 31.3 \pm 1.9 \text{ MeV}.$$
$$D_1(2430): \quad M = 2412 \pm 9 \text{ MeV}, \quad \Gamma = 314 \pm 29 \text{ MeV}.$$

Description of M's and $R = \Gamma_{D_1(2420)}/\Gamma_{D_1(2430)} \sim 10$ from the same dynamics: controversies (see Kamchandani et al. PRD **110**, 036008 (2024))

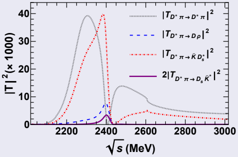
Our purpose [Collaboration USP-UNIFESP-UFBA: Navarra, Torres, Kamchandani, LMA]

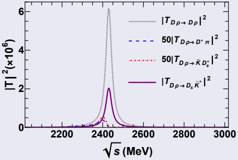
- Model: Meson-meson coupled channel + Bare quark-model pole
  (Interplay of quark-hadron degrees of freedom)
- Investigation if CFs can be useful
  Focus: channels $D^{*+(0)}\pi^{0(+)}$, dominated by strong interactions

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))

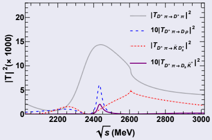
- $a^{(1/2)}_{D^*\pi} = -0.20$ fm

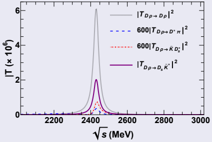
  (In accordance with lattice results for $a^{(1/2)}_{D\pi}$ (Liu et al. PRD 87, 014508 (2013)))

Model B

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

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





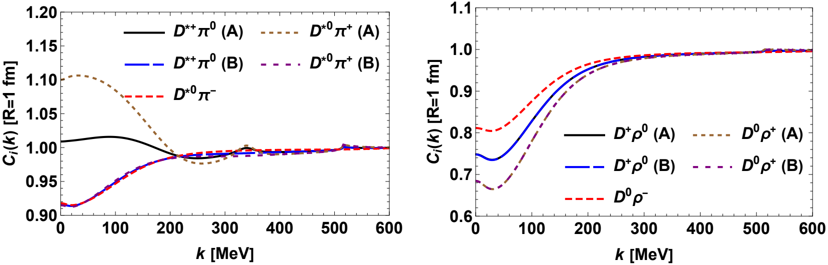
- $D^*\pi$: $M \sim 2436$ MeV, $\Gamma \sim 311$ MeV

  (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]))

Results [Kamchandani, LMA, Torres, Navarra; PRD **110**, 036008 (2024)]:



- Model A: $C_{D^{*0}\pi^+}(k=0)|_{R=1\mathrm{fm}} > 1$ (attractive character)
- Model B: $C_{D^{*0}\pi^+}(k=0)|_{R=1\mathrm{fm}} < 1$ ($a^{(1/2)}_{D^*\pi} = 0.1\ \mathrm{fm} < 2.3R$)
- Both models: $C_{D^{*0}\pi^+}(k>0)$ reflects the behavior of $T_{D^{*0}\pi^+}$
- Dip in $C_{^0\rho^+}(k=0)$: influence of the narrow state in $T^{(1/2)}_{D\rho,D\rho}$ below the $D\rho$ threshold
- $D^{*0}\pi^+$ and $D^0\rho^+$: more appropriate to test both models

[ϕN CF: LMA, Gubler, Khemchandani, Torres, Hosaka, arXiv:2409.05170]

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Summary

- Hadron Spectrum: richer than what we expected
- New particle zoo near $D^{(*)}\bar{D}^{*}$, $B^{(*)}\bar{B}^{*}$ thresholds: not $(\bar{q}q, qqq)$

General description of exotic states?

- It remains a great challenge!!!
- More experimental and theoretical investigations are necessary to shed light on their dynamics

Thank You!!!

Financial support:

CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

INCT-FNA Instituto Nacional de Ciência e Tecnologia Física Nuclear e Aplicações

fapesb Fundação de Amparo à Pesquisa do Estado da Bahia

FAPESP Fundação de Amparo à Pesquisa do Estado de São Paulo

Virtute Spiritus 1808