# Investigating the properties of exotic hadrons

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(WONPAQCD 2025)

# Aim

- A brief overview on the state-of-the-art of exotic hadron spectroscopy
- Discussion about the underlying structure of exotic states and the most promising approaches
- Case study of some of the most famous exotic states
- Summary of some of our recent contributions

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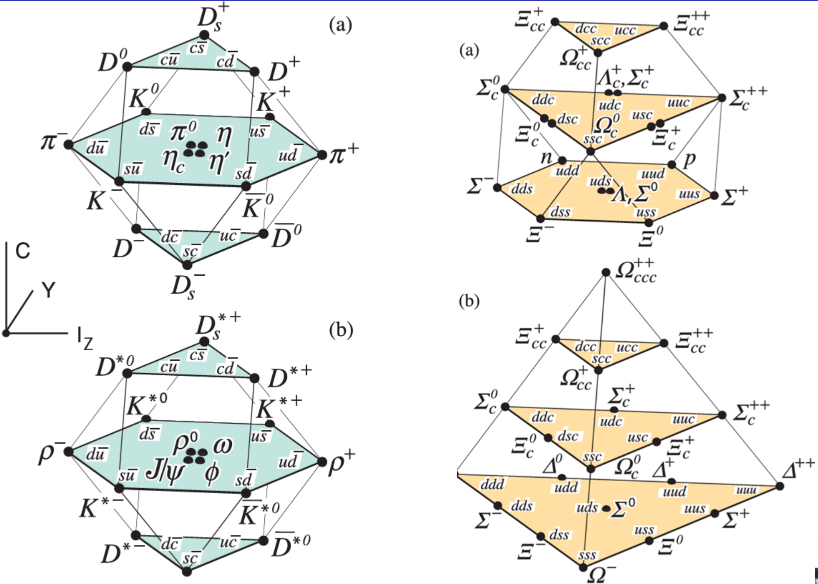
# The simple quark model (1964-1981): hadrons




(Charm: 1974; *D* mesons: 1976; Bottom: 1977; *B* mesons: 1981) [Wang, https://doi.org/10.22323/1.385.0026]

# Unconventional Hadrons?

QCD-inspired quark models: description of conventional hadrons $qqq, q\bar{q}$

What about distinct hadronic structures?

QCD does not forbid more complicated combinations!!!

$$\begin{aligned} \text{Tetraquarks} &\Rightarrow qq\bar{q}\bar{q}\ (\mathbf{3}\otimes\mathbf{3}\otimes\overline{\mathbf{3}}\otimes\overline{\mathbf{3}}=\mathbf{1}\oplus\cdots) \\ \text{Pentaquarks} &\Rightarrow qqqq\bar{q}\ (\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3}\otimes\overline{\mathbf{3}}=\mathbf{1}\oplus\cdots) \\ \text{Glueballs} &\Rightarrow gg\cdots g\ (\mathbf{8}\otimes\mathbf{8}\cdots\otimes\mathbf{8}=\mathbf{1}\oplus\cdots) \\ \text{Hybrids} &\Rightarrow q\bar{q}g\ (\mathbf{3}\otimes\overline{\mathbf{3}}\otimes\mathbf{8}=\mathbf{1}\oplus\cdots) \end{aligned}$$

If exist: new objects to study confinement mechanism;

If not exist: theory should explain why not!!!

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\end{aligned}
$$

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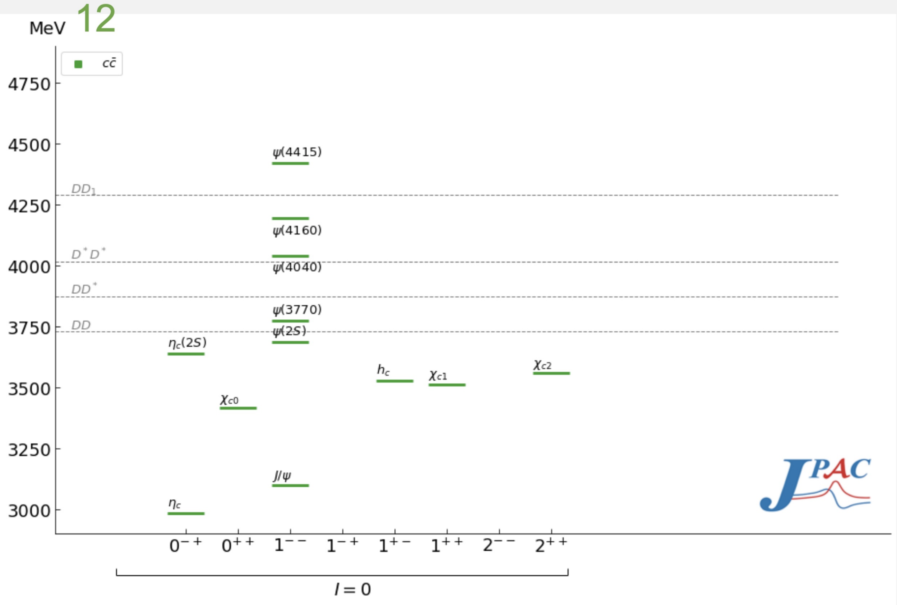
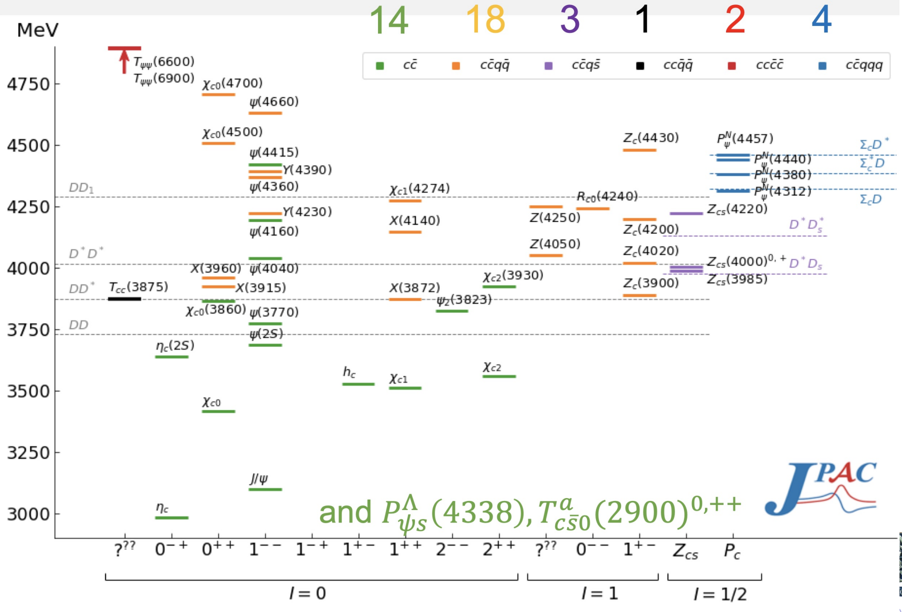
# 2003


12
MeV
$c\bar{c}$
4750
4500
4250
4000
3750
3500
3250
3000
$DD_1$
$D^*D^*$
$DD^*$
$DD$
$\psi(4415)$
$\psi(4160)$
$\psi(4040)$
$\psi(3770)$
$\psi(2S)$
$\eta_c(2S)$
$\chi_{c0}$
$h_c$
$\chi_{c1}$
$\chi_{c2}$
$J/\psi$
$\eta_c$
$0^{-+}$ $0^{++}$ $1^{--}$ $1^{-+}$ $1^{+-}$ $1^{++}$ $2^{--}$ $2^{++}$
$I = 0$
JPAC

# 2022


14 18 3 1 2 4
$c\bar{c}$ $c\bar{c}q\bar{q}$ $c\bar{c}q\bar{s}$ $cc\bar{q}\bar{q}$ $cc\bar{c}\bar{c}$ $c\bar{c}qqq$
MeV
4750
4500
4250
4000
3750
3500
3250
3000
$T_{\psi\psi}(6600)$
$T_{\psi\psi}(6900)$
$\chi_{c0}(4700)$
$\psi(4660)$
$\chi_{c0}(4500)$
$\psi(4415)$
$Y(4390)$
$\psi(4360)$
$Y(4230)$
$\psi(4160)$
$X(3960)$
$\psi(4040)$
$X(3915)$
$\chi_{c0}(3860)$
$\psi(3770)$
$\psi(2S)$
$J/\psi$
$\eta_c(2S)$
$\eta_c$
$\chi_{c0}$
$h_c$
$\chi_{c1}$
$\chi_{c1}(4274)$
$X(4140)$
$X(3872)$
$\psi_2(3823)$
$\chi_{c2}(3930)$
$\chi_{c2}$
$T_{cc}(3875)$
$Z(4250)$
$Z(4050)$
$R_{c0}(4240)$
$Z_c(4430)$
$Z_c(4200)$
$Z_c(4020)$
$Z_c(3900)$
$Z_{cs}(4220)$
$Z_{cs}(4000)^{0,+}$
$Z_{cs}(3985)$
$P_\psi^N(4457)$
$P_\psi^N(4440)$
$P_\psi^N(4380)$
$P_\psi^N(4312)$
$DD_1$
$D^*D^*$
$DD^*$
$DD$
$\Sigma_c D^*$
$\Sigma_c^* D$
$\Sigma_c D$
$D^*D_s^*$
$D^*D_s$
$?^{??}$ $0^{-+}$ $0^{++}$ $1^{--}$ $1^{-+}$ $1^{+-}$ $1^{++}$ $2^{--}$ $2^{++}$ $?^{??}$ $0^{--}$ $1^{+-}$ $Z_{cs}$ $P_c$
$I = 0$
$I = 1$
$I = 1/2$
and $P_{\psi s}^{\Lambda}(4338), T_{c\bar{s}0}^{a}(2900)^{0,++}$
JPAC

# Why exotic hadron states?

- Properties do not match standard quark-model predictions
- Decays require $> 3$ valence quarks
- Production/decay properties incompatible with mesons/baryons

## Ex.1: Unconventional quantum numbers

- $Z$'s: manifestly 4-quark states:

$$Z_c^+(3900) \to J/\psi\pi^+$$

- $T^*_{cs0}(2900)$: $Q = +2, S = 1$ $(c\bar{s}u\bar{d})$

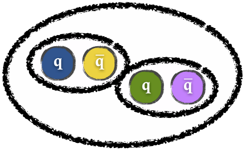
## Ex.2: Production/decay properties incompatible with mesons/baryons

- isospin violation (if $X(3872) \sim c\bar{c}$: decay highly suppressed)

$$X(3872) \to \rho^0 J/\psi \to \pi^+\pi^- J/\psi$$

# Theory: composition and binding mechanisms?

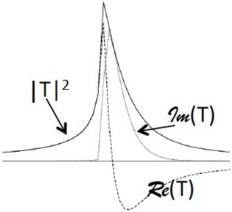
- Hadron Molecules




- Tetraquarks


- Hybrids


- Cusp effects (TS's)




- Glueballs


- . . .

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# $X(3872)$: features

**2020 Review of Particle Physics.**
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

**BELLE: PRL 91, 262001 (2003)**

**$c\bar{c}$ MESONS**
**(including possibly non-$q\bar{q}$ states)**

INSPIRE search

$\chi_{c1}(3872)$ $I^G(J^{PC}) = 0^+(1^{++})$ ← **BELLE,CLEO, CDF, BABAR, LHCb (2003-2015)**

also known as $X(3872)$

$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE — $3871.69 \pm 0.17$ MeV

$\chi_{c1}(3872)$ MASS FROM $\overline{D}^{*0} D^0$ MODE

$m_{\chi_{c1}(3872)} - m_{J/\psi}$

$m_{\chi_{c1}(3872)} - m_{J/\psi}$ — $775 \pm 4$ MeV

$m_{\chi_{c1}(3872)} - m_{\psi(2S)}$

$\chi_{c1}(3872)$ WIDTH — $< 1.2$ MeV CL=90.0%

$\chi_{c1}(3872)$ WIDTH FROM $\overline{D}^{*0} D^0$ MODE

**Impressive fine tuning**
$M_X - M_{D^0} - M_{D^{*0}} = 44 \pm 116$ keV
**(LHCb 2005.13422):**

**Very narrow width!**

**Decay Modes**

Expand all decays

**Isospin violation for strong decays**

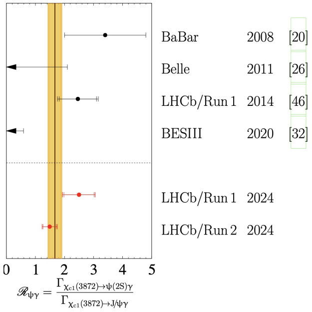
| | Mode | Fraction ($\Gamma_i/\Gamma$) | Scale Factor/ Conf. Level | P (MeV/c) |
|---|---|---|---|---|
| $\Gamma_1$ | $e^+e^-$ | | | 1936 |
| $\Gamma_2$ | $\pi^+\pi^- J/\psi(1S)$ | $> 3.2\%$ | | 650 |
| $\Gamma_3$ | $\rho^0 J/\psi(1S)$ | | | -1 |
| $\Gamma_4$ | $\omega J/\psi(1S)$ | $> 2.3\%$ | | -1 |
| $\Gamma_5$ | $D^0\overline{D}^0\pi^0$ | $> 40\%$ | | 117 |
| $\Gamma_6$ | $\overline{D}^{*0} D^0$ | $> 30\%$ | | 4 |
| $\Gamma_7$ | $\gamma\gamma$ | | | 1936 |
| $\Gamma_8$ | $D^0\overline{D}^0$ | | | 520 |
| $\Gamma_9$ | $D^+D^-$ | | | 502 |
| $\Gamma_{10}$ | $\gamma\chi_{c1}$ | | | 344 |

**Large fraction for this channel, despite the tiny phase space**

# Debate on the $X(3872)$ : $|c\bar{c}\rangle, |c\bar{c}q\bar{q}\rangle$ or $|D\bar{D}^*\rangle$?

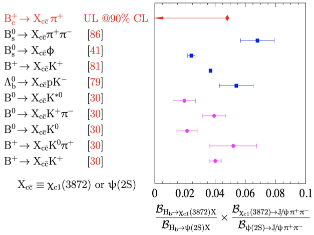
## LHCb: JHEP **11**, 121 (2024)

- Run 1 + Run 2: $\mathcal{R}_{\psi(2S)\gamma/\psi\gamma}$ non-compatible with the pure $|D\bar{D}^*\rangle$
- It agrees with $|c\bar{c}\rangle(X_{c1}(2^3P_1))$, $|c\bar{c}q\bar{q}\rangle, |D\bar{D}^*\rangle + |c\bar{c}q\bar{q}\rangle$




## LHCb: JHEP **06**, 013 (2025)

- LHCb: No enhancement for $X(3872)$ production in $B_c \to X(3872)\pi$
- Maiani et al., PRD **94**, 3 (2016): $B_c \to X(3872)\pi$ as a source with the $|c\bar{c}q\bar{q}\rangle$

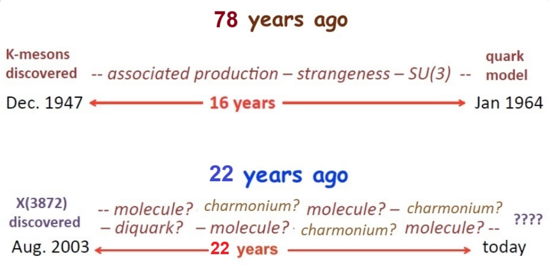


# $X(3872)$ story

A superposition $|X(3872)\rangle \propto |c\bar{c}\rangle, |c\bar{c}q\bar{q}\rangle, |D\bar{D}^*\rangle$ ?

## Brambilla el al. PRL **135**, 13 (2025)

“The $X(3872)$ and $T_{cc}^{+}(3875)$ are neither simple molecules nor compact tetraquarks but result from a conspiracy between the short- and long-range behavior of potentials–constrained by symmetry and by lattice QCD near the string-breaking region."




(Adapted from S. Olsen, SCGP Workshop on Exotic Hadrons and Flavor Physics, May 2018 )

## 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, kinematic effects, ...)
- $(m, \Gamma)$ can be explained by different models or even superposition of them

- Necessity of more observables to distinguish their internal structure

- Let us focus on some of our contributions

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

Hadronic Interactions $\Rightarrow$ Effective Lagrangians

$\Downarrow$

Amplitudes $\Rightarrow$ Cross Sections $\Rightarrow$ Therm. Av. Cross Sections

$\Downarrow$

Coalescence Model, Bjorken picture $\Rightarrow$ Kinetic (rate) equation

$\Downarrow$

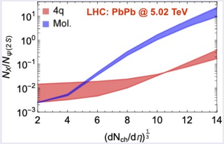
Time Evolution and system size dependence of $N^{(4q)}$ and $N^{(Mol)}$

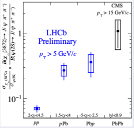
$\Downarrow$

Diff. spatial conf. $\Rightarrow$ diff. hadron interactions $\Rightarrow$ $N^{(4q)} \neq N^{(Mol)}$

# Strategy 1 ⇒ Exotics in Heavy-Ion Collisions

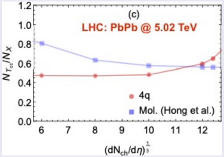
## $X(3872)\ \ [(cq\bar{c}\bar{q}); 0(1^{++})]$



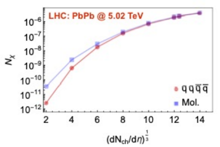

[PRD **90**, 114023 (2014); **105**, 116029 (2022); **110**, 014011 (2024); PTEP **2016**, 103B01 (2016), PLB **761**, 303 (2016); EPJC (2022); ...] $(N^{(4q)} << N^{(Mol)}\ ;\quad R \sim \mathrm{Data})$

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



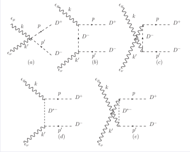

[EPJC **82**, 296 (2022); PRD **105**, 116029 (2022); NPB **985**, 115994 (2022)]

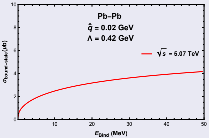
## $\chi_{c1}(4274)\ \ [(cs\bar{c}\bar{s});\ \ 0^{+}(1^{++})]$




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

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

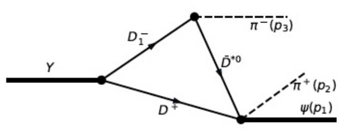





[PRD **110**, 034037 (2024)]

[Collaboration USP-UNIFESP-UFBA: Navarra, Nielsen, Torres, Kamchandani, LMA, Bertunlani (Texas), Britto (UFRB), ...]

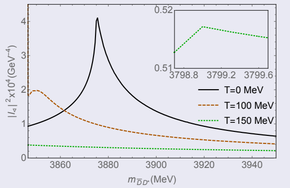
# Strategy 2 → exotic states as kinematical effects



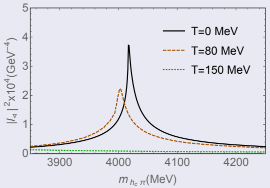

- $Z_c(3900)$: triangle singularity or new hadron?
- Can HICs help discern the correct interpretation?

[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)]

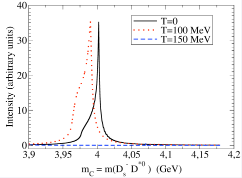
### $Z_c(3900)$ $[(cq\bar{c}\bar{q}); 1(1^-)]$




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



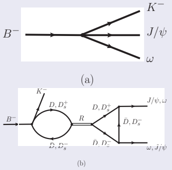

### $Z_{cs}(3985)^-$ $[(cs\bar{c}\bar{u})\frac{1}{2}(1^+)]$

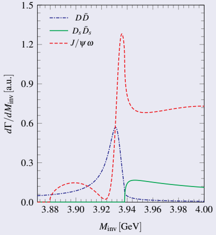



- Singularity disappears at temperatures just below $T_H$
- Medium: spectroscopic filter to distinguish actual hadrons from TSs

# Strategy 3 → Production of exotics in hadron decays

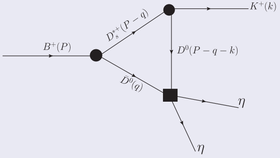
## $X(3930, 3960)$ in $B \to KJ/\psi\omega$

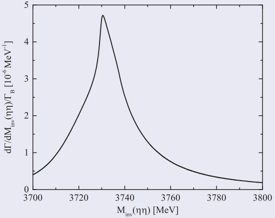



[Collaboration Valencia-UFBA (Abreu, Albaladejo, Feijoo, Oset, Nieves); EPJC **83**, 309 (2023)]

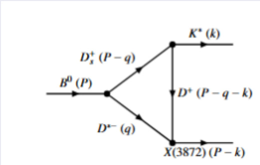
## $D\bar{D}(3720)$ in $B^+ \to K^+\eta\eta$

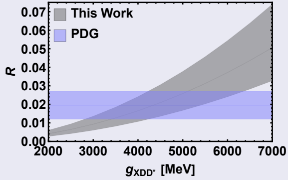



[Collaboration Valencia-Beihang-UFBA (Brandão, Song, Abreu, Oset); PRD **108**, 054004 (2023)]

## $X(3872)$ in $B^0 \to K^{*0}X(3872)$

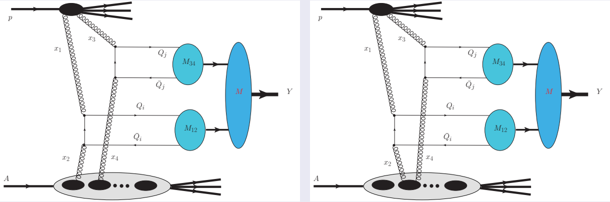


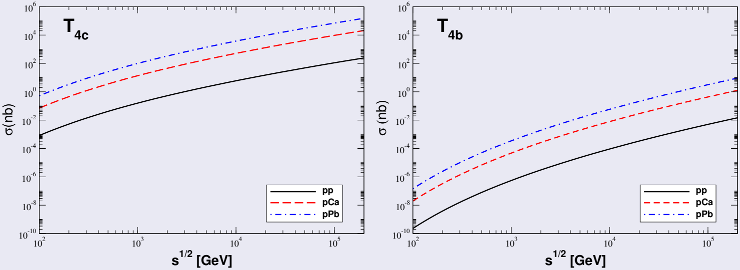




$$R = \frac{\mathcal{B}(X(3872))}{\mathcal{B}(\psi(2S))} \sim 1.5 \times 10^{-2}.$$

[Abreu; PRD **112**, 096002 (2025)]

# Strategy 4 → Production of $T_{4c}$ and $T_{4b}$ states through DPS in pp and pA collisions




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

# Strategy 5 → Femtoscopy

## Generalized coupled-channel CF for a specific channel $i$

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

$\vec{k}$: 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;

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

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

# Searching for the $X(3700)$ signature

- Controversy: $X(3700)$ not yet listed in the RPP
- Femtoscopic $D\bar{D}$ correlations can carry the signature of $X(3700)$
- $X(3700)$: bound state dynamically generated by solving the BSE

$$|D\bar{D}, I=0\rangle = \sqrt{\frac{1}{2}}\left[\left|D^0\bar{D}^0\right\rangle + \left|D^+D^-\right\rangle\right]$$

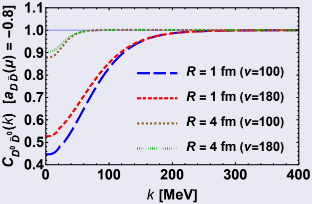
Experimentally accessible CFs:

$$C_{D^0\bar{D}^0}(k) = C^{(S)}_{D^0\bar{D}^0}(k),$$
$$C_{D^+D^-}(k) = C^{(S)}_{D^+D^-}(k) + C^{(C)}_{D^+D^-}(k),$$

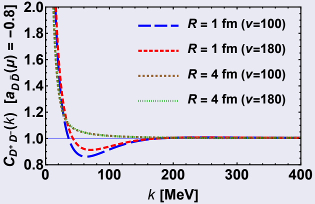
$C^{(S)}_i(k)$: the pure strong contribution
$C^{(C)}_{D^+D^-}(k)$: Coulomb contribution
(Calculated with the complete Coulomb wavefunction: $\Phi^{\mathrm{C}}(r,z;k) = e^{-\pi\gamma/2}\Gamma(1+i\gamma)e^{ikz}\ {}_1F_1(-i\gamma;1;ik(r-z))$,

${}_1F_1(x,y;z)$ confluent hypergeometrical function ; $\gamma$: Sommerfeld factor: $\gamma = Z_1 Z_2 \frac{\mu\alpha}{k}$ )

# CFs of the $D^0\bar{D}^0$, $D^+D^-$ pairs




- Low $k$: dip and increase with the augmentation of $R \rightarrow$ bound state (Bound state: $\tilde{a}_{D\bar{D}}/R \sim 1$: CF with a stronger dip at $k \sim 0$; )
- Measurements in $pp$, $pA$, and $AA$: help us to elucidate if is a bound state
- Larger width (larger $v$) $\rightarrow$ weaker dip
- Pole nearer the $D\bar{D}$ threshold (higher $a_{D\bar{D}}(\mu)$) $\rightarrow$ more intense correlations

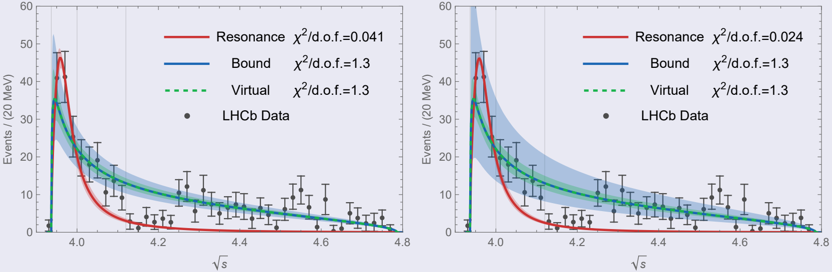



- Low $k$ $\rightarrow$ the attractive Coulomb interaction yields a sizable enhancement
- Strong contribution $\rightarrow$ appears only at moderate values of $k$ by means of a dip only for smaller sources
- $D^+D^-$ CF $\rightarrow$ more sensitive to the signature of the $X(3700)$ if it is a narrow and weakly bound structure, produced in a smaller source environment

[Collaboration Barcelona-UFBA (Torres-Rincón, LMA); PRD **112**, 016003 (2025)]

# Traces of the $X(3960)$ state

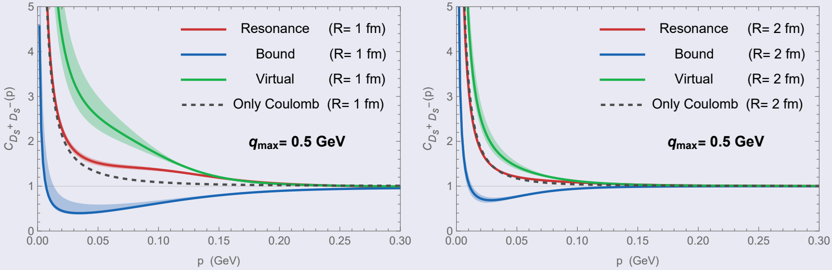
- LHCb (2022):
  $m_{X(3960)} = 3956 \pm 5 \pm 10$ MeV, $\Gamma_{X(3960)} = 43 \pm 13 \pm 8$ MeV
- Controversy: resonance? Enhancement due to the $X(3930)$?
- Amplitudes encoding the distinct interpretations of the $X(3960)$ state calculated using Bethe-Salpeter formalism




- IMD: insufficient to distinguish between these interpretations
- Femtoscopic $D_s^+ D_s^-$ correlations can carry the signature of $X(3960)$

# CFs of the $D_s^+ D_s^-$ pair

[Collaboration Beihang (China)-UFBA (H.N. Liu, Z.W. Liu, L.S. Geng, LMA); arXiv:2511.19098]




- Virtual-state scenario: strong enhancement
- Bound-state: clear suppression
- Resonant configuration: moderate augmentation relative to the pure Coulomb CF
- Measurements in small collision systems: the contrast between the interpretations is most pronounced

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# Summary

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

**Can we develop a comprehensive understanding of hadron structure?**

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

## Thank You!!!

Financial support: