The multiplicity of the doubly charmed state $T_{cc}^+$ in heavy-ion collisions

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Aim

- The exotics in HICs: $X(3872)$ and $T_{cc}^+$
- Molecular and tetraquark interpretations in HICs? The coalescence model
- Interactions in the hadron gas
- Rate equation and multiplicities
- System size dependence
Since 2003 [X(3872)]: about fifty states observed!

67 new hadrons at the LHC
Composition and binding mechanism?

Belle (2003): $X(3872)[J^P = 1^+]$
- Meson molecule ($\sim 10$ fm)
- Compact tetraquark ($\sim 1$ fm)

LHCb (2021): $T_{cc}^+(3875)[J^P = 1^+]$
- Hadron molecule
- Compact Tetraquark

Theoretical perspective

A compelling and unified understanding has not yet emerged

Necessity of more observables to distinguish its internal structure
Composition and binding mechanism?

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Promising alternative: exotics in HICs

Early stages of HIC’s
- Large number of $Q$’s produced
- $Q$’s coalesce to form multiquarks

Hadron gas phase
- Multiquarks: interact with other hadrons
- Absorption / production
- Ex. $X\pi \to D^{(*)}\bar{D}^{(*)} \text{ or } D^{(*)}\bar{D}^{(*)} \to X\pi$
- Properties $\to$ interpretation

(Braun-Munzinger and Donigus, Nucl. Phys. A 987 (2019) 144)
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Breaking news: first evidence of $X(3872)$ in HICs!

Evidence for $X(3872)$ in Pb-Pb Collisions and Studies of its Prompt Production at $\sqrt{s_{NN}}=5.02$ TeV

CMS Collaboration • Albert M. Sirunyan (Yerevan Phys. Inst.) et al. (Feb 25, 2021)
Published in: Phys.Rev.Lett. 128 (2022) 3, 032001 • e-Print: 2102.13048 [hep-ex]

- $X(3872) \rightarrow J/\psi \pi^+ \pi^- \rightarrow \mu^+ \mu^- \pi^+ \pi^-$
- $\rho^{(PbPb)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} = 1.08 \pm 0.9 \pm 0.52$

$\rho^{(PbPb)} \simeq 10 \rho^{(pp)}$

Unique experimental input to investigate the properties and nature of multiquark systems
Our strategy

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 size dependence of $N_{T_{cc}}$, $N_X$

$\Downarrow$

Diff. spatial configuration $\Rightarrow$ diff. hadronic interactions $\Rightarrow$ diff. final yields $N_X^{(4q)} \neq N_X^{(Mol)}$
Hadronic Interactions

\[ \mathcal{L}_{\pi DD^*} = ig_{\pi DD^*} D^*_{\mu} \bar{\tau} \cdot (\bar{D} \partial^\mu \bar{\pi} - \partial^\mu \bar{D} \bar{\pi}) + h.c., \]

\[ \mathcal{L}_{\rho DD} = ig_{\rho DD} (D \bar{\tau} \partial_\mu \bar{D} - \partial_\mu D \bar{\tau} \bar{D}) \cdot \bar{\rho}^\mu, \]

\[ \mathcal{L}_{\rho D^* D^*} = ig_{\rho D^* D^*} \left[ \left( \partial_\mu D^*_{\nu} \bar{\tau} \bar{D}^*_{\nu} - D^*_{\nu} \bar{\tau} \partial_\mu \bar{D}^*_{\nu} \right) \cdot \bar{\rho}^\mu \right. \]

\[ + \left. (D^*_{\nu} \bar{\tau} \cdot \partial_\mu \bar{\rho}_{\nu} - \partial_\mu D^*_{\nu} \bar{\tau} \cdot \bar{\rho}_{\nu}) \bar{D}^*_{\mu} \right], \]

\[ \mathcal{L}_{\pi D^* D^*} = -g_{\pi D^* D^*} \varepsilon^{\mu \nu \alpha \beta} \partial_\mu D^*_{\nu} \pi \partial_\alpha \bar{D}^*_{\beta}, \]

\[ \mathcal{L}_{\rho DD^*} = -g_{\rho DD^*} \varepsilon^{\mu \nu \alpha \beta} (D \partial_\mu \rho_{\nu} \partial_\alpha \bar{D}^*_{\beta} + \partial_\mu D^*_{\nu} \partial_\alpha \rho_{\beta} \bar{D}), \]

Ling et al. PLB (2022), 2108.00947:

\[ \mathcal{L}_{T_{cc}} = ig_{T_{cc} DD^*} T_{cc}^\mu D^*_\mu D \]

Abreu, Navarra, Nielsen, Vieira, EPJC (2022), 2110.11145 ⇒ QCD sum rules

\[ \Pi_{\alpha \mu}^{(phen)} \propto \left\langle 0| T[j^D_{\alpha} (x) j^D_\mu (y) j^+_{\mu} (0)]|0 \right\rangle; \]

\[ g_{T_{cc} DD^*} (Q^2) = g_{T_{cc} DD^*} e^{-g(Q^2 + m_D^2)}, \]

\[ g_{T_{cc} DD^*} = (1.7 \pm 0.2) \text{ GeV}. \]
Ho, Cho, Song, Lee, PRC (2018), 1702.00486: Monopole form factors

“Quasi-free” model: $\sigma_{T_{cc}\pi \rightarrow D D^* \pi} = \sigma_{D\pi \rightarrow D\pi} + \sigma_{D^*\pi \rightarrow D^*\pi} \Rightarrow$ Molecules!

QCDSR $\Rightarrow$ Natural description for tetraquarks!

QCDSR $\Rightarrow$ Reduction of the uncertainties!
Thermally Averaged Cross Sections for tetraquarks

\[ \langle \sigma_{ab \rightarrow cd} \nu_{ab} \rangle = \frac{\int d^3 p_a d^3 p_b f_a(p_a) f_b(p_b) \sigma_{ab \rightarrow cd} \nu_{ab}}{\int d^3 p_a d^3 p_b f_a(p_a) f_b(p_b)} \]

(Inverse processes ⇒ detailed balance equation)
Time Evolution of $T_{cc}$ Multiplicity

\[
\frac{dN_{T_{cc}}(\tau)}{d\tau} = \sum_{c,c'=D,D^*; \varphi=\pi,\rho} [\langle \sigma_{cc'\rightarrow T_{cc}\varphi} n_{cc'}(\tau) N_{c'}(\tau) - \sigma_{\varphi T_{cc} \rightarrow cc' \nu_{T_{cc}\varphi}} n_{\varphi}(\tau) N_{T_{cc}}(\tau) \rangle]
\]

Bjorken picture:

\[
T(\tau) = T_C - (T_H - T_F) \left( \frac{\tau - \tau_H}{\tau_F - \tau_H} \right)^\frac{4}{5}; \quad V(\tau) = \pi \left[ R_C + v_C (\tau - \tau_C) + \frac{a_C}{2} (\tau - \tau_C)^2 \right]^2 \tau C
\]

Initial conditions $\Rightarrow$ coalescence model

\[
N_{T_{cc}}^{\text{Coal}} \approx g_T \prod_{j=1}^{n} \frac{N_j}{g_j} \prod_{i=1}^{n-1} \frac{(4\pi \sigma_i^2)^{\frac{3}{2}}}{V(1 + 2\mu_i T \sigma_i^2)} \left[ \frac{4\mu_i T \sigma_i^2}{3(1 + 2\mu_i T \sigma_i^2)} \right]^{l_i}
\]

| State      | $N^{(4q)}(\tau_C)$ | $N^{(Mol)}(\tau_H)$ |
|------------|---------------------|----------------------|
| $T^+_cc$   | $8.40 \times 10^{-5}$ | $4.10 \times 10^{-2}$ |
| $X(3872)$  | $1.81 \times 10^{-4}$ | $7.50 \times 10^{-2}$ |

- Hundred times more molecules!
- Changes in initial multiplicity due to interactions in the hadron gas?
- Different interactions for tetraquarks and molecules?
Time Evolution of $T_{cc}$ Multiplicity

Abreu, Navarra, Vieira, PRD (2022); 2202.10882

$\text{Pb - Pb at } \sqrt{s_{NN}} = 5.02 \text{ TeV}$

Difference between $N^{(4q)}$ and $N^{(Mol)}(\tau_H)$ decreases but remains large!
System size and number of charged particles

Larger size:
- Greater $\mathcal{N} = \left[ \left( \frac{dN_{ch}}{d\eta} \right) |\eta|<0.5 \right]^{1/3}$
- System lives longer
- More charm quarks
- More charmed mesons

System size and freeze-out time

Bjorken-like cooling:
$$\tau_F T_F^3 = \tau_H T_H^3$$

Evolution stops later:
$$\tau_F = \tau_H \left( \frac{T_H}{T_F^0} \right)^3 e^{3b\mathcal{N}}$$
System size and volume

- From Statistical Hadronization Model and EXHIC [Vovchenko et al. PRC (2019); 1906.03145]:
  \[ V = 2.82 N^3 \]

System size and number of quarks

- ALICE, JHEP (2015); 1505.00664: \( N_D \propto (N^3)^{1.6} \)
- \( N_c \propto N_D \propto N^{4.8} \)
- ALICE, PRC (2013): \( N_q \propto N^3 \)
- Fix the constants using EXHIC

Initial multiplicities and \( N \)

\[
N_{T_{cc}}^{(4q)} \propto \frac{N_c^2 N_c^2}{V^3} \propto N^{6.6}
\]

\[
N_{T_{cc}}^{(Mol)} \propto \frac{N_D N_D^*}{V} \propto N^{6.6}
\]

- Multiplicities grow fast with the system size!
- In the same way for molecules and tetraquarks!
Conclusions

- HICs: promising testing ground for exotics
- QCDSR: useful for tetraquarks and reduces the uncertainties
- Coalescence model: much more molecules than tetraquarks
- After the hadron gas phase: difference of multiplicities remains large!
- Difference: remains the same even for smaller systems!

Thank You!!!

Partial financial support:
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