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

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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
The heavy exotics collection

- Since 2003 \([X(3872)]\): about fifty states observed!

67 new hadrons at the LHC

\begin{align*}
\Xi_b(5945)^0 & \quad \Lambda_b(5920)^0 \\
\Xi_b(5955)^- & \quad B_b(5970)^{+,-,0} \\
\Xi_b(5935)^- & \quad B_b(5840)^{+,-,0} \\
B_c(2S)^+ & \quad \Xi_b(6227)^- \\
& \quad \Xi_b(6097)^+ \\
& \quad \Lambda_b(6152)^0 \\
& \quad \Lambda_b(6146)^0 \\
B_b(6114)^0 & \quad \Xi_b(6227)^0 \\
& \quad \Xi_b(6100)^- \\
B_b(6070)^0 & \quad \Xi_b(6327)^0 \\
& \quad \Xi_b(6333)^0 \\
& \quad \Xi_b(6340)^0 \\
B_b(6227)^0 & \quad \Omega_b(6350)^- \\
& \quad \Omega_b(6340)^- \\
& \quad \Omega_b(6340)^- \\
B_b(6327)^0 & \quad \Xi_b(6070)^0 \\
& \quad \Xi_b(6100)^- \\
D_{s0}(2590) & \quad \Xi_c(2939)^0 \\
D_s(2860)^+ & \quad \Xi_c(2923)^0 \\
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\end{align*}
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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### Theoretical perspective

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The multiplicity of the $T_{cc}^+$ in HICs

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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. $X_\pi \rightarrow D(\ast)\bar{D}(\ast)$ or $D(\ast)\bar{D}(\ast) \rightarrow X_\pi$
- Properties $\rightarrow$ 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)

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

$\rho(PbPb) \approx 10 \rho(pp)$

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

$N_X^{(4q)} \neq N_X^{(Mol)}$

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Hadronic Interactions

\[ \mathcal{L}_{\pi DD^*} = ig_{\pi DD^*} D_\mu^* \vec{\tau} \cdot (\bar{D} \partial^\mu \pi - \partial^\mu \bar{D} \pi) + h.c., \]
\[ \mathcal{L}_{\rho DD} = ig_{\rho DD}(D \bar{\tau} \partial_\mu \bar{D} - \partial_\mu D \bar{\tau} \bar{D}) \cdot \bar{\rho}^\mu, \]
\[ \mathcal{L}_{\rho D^* D^*} = ig_{\rho D^* D^*} [(\partial_\mu D^{*\nu} \bar{\tau} \bar{D}_{\nu} - D^{*\nu} \bar{\tau} \partial_\mu \bar{D}_{\nu}^*) \cdot \bar{\rho}^\mu + (D^{*\nu} \bar{\tau} \cdot \partial_\mu \bar{\rho}_{\nu} - \partial_\mu D^{*\nu} \bar{\tau} \cdot \bar{\rho}_{\nu}) \bar{D}^{*\mu}] \]
\[ \mathcal{L}_{\pi D^* D^*} = -g_{\pi D^* D^*} \epsilon^{\mu \nu \alpha \beta} \partial_\mu D_{\nu}^* \pi \partial_\alpha \bar{D}_{\beta}^*, \]
\[ \mathcal{L}_{\rho DD^*} = -g_{\rho DD^*} \epsilon^{\mu \nu \alpha \beta} (D \partial_\mu \rho_{\nu} \partial_\alpha \bar{D}_{\beta}^* + \partial_\mu D_{\nu}^* \partial_\alpha \rho_{\beta} \bar{D}), \]

Ling et al. PLB (2022), 2108.00947:

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

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

\[ \Pi^{(phen)}_{\alpha \mu} \propto \langle 0 | T[j^D_{\alpha} (x) j^D_{\mu} (y) j^{+\dagger}_{\mu} (0)] | 0 \rangle; \]
\[ g_{T_{cc} DD^*}(Q^2) = g_{T_{cc} DD^*} e^{-g(Q^2 + m_D^2)}, \]
\[ g_{T_{cc} DD^*} = (1.7 \pm 0.2) \text{ GeV}. \]
Abreu, Navarra, Nielsen, Vieira, EPJC (2022), arXiv:2110.11145

Ho, Cho, Song, Lee, PRC (2018), 1702.00486: Monopole form factors

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

QCDSR ⇒ Natural description for tetraquarks!

QCDSR ⇒ Reduction of the uncertainties!

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Thermally Averaged Cross Sections for tetraquarks

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

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

$$\frac{dN_{T_{cc}}(\tau)}{d\tau} = \sum_{c,c'=D,D^*; \varphi=\pi,\rho} \left[ \langle \sigma_{cc' \to T_{cc} \varphi} v_{cc'} \rangle n_c(\tau) N_{c'}(\tau) - \langle \sigma_{T_{cc} \to cc' \varphi} v_{T_{cc} \varphi} \rangle n_{\varphi}(\tau) N_{T_{cc}}(\tau) \right]$$

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

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

<table>
<thead>
<tr>
<th>State</th>
<th>$N^{(4q)}(\tau_C)$</th>
<th>$N^{(Mol)}(\tau_H)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{cc}^+$</td>
<td>$8.40 \times 10^{-5}$</td>
<td>$4.10 \times 10^{-2}$</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>$1.81 \times 10^{-4}$</td>
<td>$7.50 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

- 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

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

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

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

System size and freeze-out time

- Bjorken-like cooling:
  \[ \tau_F T_F^3 = \tau_H T_F^3 \]
- Evolution stops later:
  \[ \tau_F = \tau_H \left( \frac{T_H}{T_{F0}} \right)^3 e^{3bN} \]
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!

\( (dN_{ch}/d\eta)^{\frac{1}{3}} \)

\( N_{T_{cc}} \)
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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