Measurement of scattering parameters governing the residual strong interaction between charm and light hadrons

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What is the impact of the rescattering on the heavy-ion observables (e.g. $R_{AA}$)?

In heavy-ion collisions:
- quark–gluon plasma (QGP) formation
- system expansion and chemical freeze-out
- hadron gas $\rightarrow$ D meson rescattering

Current knowledge:
- $D^- p$: measured with femtoscopy
  $\rightarrow$ ALICE Coll., PRD 106 052010
- all other interactions: unknown

Modification of the heavy-ion observables:
- relies on theory
What is the nature of the exotic charm states?

Several non-conventional hadrons were discovered:

- slightly below the DD$^*$ thresholds → molecule candidates
- quark bags are also possible

$T_{cc}^+$: quark bag or… molecular state?

The separation between the two scenarios can be achieved with femtososcopic studies

$T_{cc}^+$ measurement → LHCb Coll, Nat. Com. 13 3351
Physics observable: correlation function (CF)

Koonin-Pratt formula

\[
C(k^*) = \xi(k^*) \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int d\mathbf{r}^* S(\mathbf{r}^*) |\Psi(\mathbf{r}^*, \mathbf{k}^*)|^2
\]

where \( k^* = |\mathbf{p}^*_1 - \mathbf{p}^*_2|/2 \) → pair rest frame

Shape of the CF → interaction:

\[
C \begin{cases} > 1 & \text{attraction} \\ < 1 & \text{repulsion} \end{cases}
\]

Strong interaction: short range → need a small source

▶ proton-proton collisions: \( r^* \sim 1 \text{ fm} \)
Experimental setup

Analyzed data:
- Run 2 data, collected by ALICE
  \[ \sqrt{s} = 13 \text{ TeV} \]
- proton-proton collisions at \( \sqrt{s} = 13 \text{ TeV} \)
- high-multiplicity trigger (V0)

Particle identification (PID) and reconstruction:
- \( \pi^\pm, K^\pm \): ITS + TPC + TOF
- \( D^+ \): via \( D^+ \to K^-\pi^+\pi^+ + \text{c.c.} \)

Selection of \( D^\pm \to \text{decay-vertex topology + PID} \)
- prompt D (from charm)
- non-prompt D (from beauty)
- combinatorial background
The correlation function: genuine interaction

$$C_{\text{raw}} = \lambda_{\text{gen}} C_{\text{gen}}$$

Primary signal particles $\rightarrow$ genuine CF

- *scattering parameters*
- formation of bound states
- ...

Source function from the universal $m_T$-scaling

$\rightarrow$ ALICE Coll., PLB 811 135849

Several corrections are necessary to obtain the genuine CF

- $B^\pm$ decays, combinatorial background etc.
The correlation function: decays from $D^{*\pm}$ mesons

\[ C_{\text{raw}} = \]

\[ \lambda_{\text{gen}} C_{\text{gen}} + \lambda_{D^*} C_{D^*} \]

About 30% of the $D^{\pm}$ are from $D^{*\pm}$ decay

Small Q-value $\Rightarrow p(D^{*\pm}) \approx p(D^{\pm})$

Modelling:

- Coulomb-only assumption for the $D^{*\pm}$-LF interaction
- compute the phase space of $D^{*\pm} \rightarrow D^{\pm} + \pi^0$
- fold interaction with phase space $\rightarrow C_{D^*}$
The correlation function: flat contributions

$$C_{\text{raw}} = \text{data}$$

\[ \lambda_{\text{gen}} C_{\text{gen}} + \lambda_{D^*} C_{D^*} + \lambda_{\text{flat}} \]

strong interaction
D from D* decays

Account for uncorrelated backgrounds:
- D mesons from beauty-hadron decays
- decay of long-living resonances
- misidentified particles e.g. $\pi \rightarrow K$

Assume no correlation \( \Rightarrow C(k^*) = 1 \)
The correlation function: hadronization

\[ C_{\text{raw}} = C_{\text{jet-like}} \left( \lambda_{\text{gen}} C_{\text{gen}} + \lambda_{D^*} C_{D^*} + \lambda_{\text{flat}} \right) \]

data \rightarrow \text{hadronization} \rightarrow \text{strong interaction} \rightarrow D \text{ from } D^* \rightarrow \text{decays}

Jet-like structures → correlation
- particles produced close in phase space

Model with MC simulations, where:
- final-state strong interaction: absent
- hadronization: present
The correlation function: combinatorial background

\[ C_{\text{raw}} = \lambda_{\text{SB}} C_{\text{SB}} + C_{\text{jet-like}} (\lambda_{\text{gen}} C_{\text{gen}} + \lambda_{D^*} C_{D^*} + \lambda_{\text{flat}}) \]

data \; \xrightarrow{} \; \text{comb. bkg} \; \xrightarrow{} \; \text{hadronization} \; \xrightarrow{} \; \text{strong interaction} \; \xrightarrow{} \; \text{D from D*} \; \xrightarrow{} \; \text{decays}

Uncorrelated \( \pi \) and K tracks \( \rightarrow \) unphysical D mesons

- about 30% of the D candidates

Modelled with sideband (SB) analysis (data-driven):

- \( 5\sigma \) away from the nominal D\( ^\pm \) mass
- CF with a pure background sample
Experimental results for DK

Fit with the Lednický-Lyuboshits (LL) model $\rightarrow$ scattering parameters

\[ a_{KD}(I = 1) = -0.08 \pm 0.16 \text{(stat)} \pm 0.06 \text{(syst)}^{+0.02}_{-0.02} \text{(source syst.)} \text{ fm} \]

\[ a_{KD}(I = 0, 1) = -0.16 \pm 0.14 \text{(stat)} \pm 0.04 \text{(syst)}^{+0.04}_{-0.05} \text{(source syst.)} \text{ fm} \]
Comparisons with theoretical models: DK

DK scattering parameters from theoretical models

⇝ L. Liu et al, PRD 87 014508,
⇝ X.-Y. Guo et al, PRD 98 014510
⇝ Huang et al, PRD 15 036016,
⇝ Z.-H. Guo et al, EPJC 79 13

CFs: gaussian potential + Koonin-Pratt formula

Results:

► compatible with all theoretical models
► improve precision with Run 3 data
Experimental results for $D\pi$

Combined fit with the LL model $\rightarrow$ scattering parameters


$\triangleright a_{D\pi} \left( I = \frac{1}{2} \right) = -0.03 \pm 0.04 \text{(stat)} \pm 0.02 \text{(syst)}_{-0.01}^{+0.01} \text{(source)} \text{ fm}$

$\triangleright a_{D\pi} \left( I = \frac{3}{2} \right) = -0.06 \pm 0.03 \text{(stat)} \pm 0.02 \text{(syst)}_{-0.03}^{+0.01} \text{(source)} \text{ fm}$
Comparisons with theoretical models: $D\pi$

$D\pi$ scattering parameters from theoretical models

⇝ L. Liu et al, PRD 87 014508, ⇝ X.-Y. Guo et al, PRD 98 014510
⇝ Huang et al, PRD 15 036016, ⇝ Z.-H. Guo et al, EPJC 79 13

CFs: gaussian potential + Koonin-Pratt formula

Same charge: agreement

Opposite charge: discrepancy
Charm hadron femtoscopy with ALICE 3

ALICE 3: a next generation experiment
→ for details: R. Münzer, PIS5, ALICE upgrades

The study of exotic charm states will be possible
⇝ ALICE Coll., arXiv:2211.02491

Test the formation of DD* and D¯¯D* bound states:
▶ T_{cc}^+ could be a D^0 D* molecule
▶ χ_{c1}(3872) could be a D¯¯D* molecule

Upgrade projection:
▶ assume a gaussian potential
▶ scan different source radii

Bound state → depletion in the CF
Conclusions

Femtoscopy with charm hadrons? It’s possible!

- first measurement of $D\pi$, $DK$ scattering parameters

$D\pi$ interaction, comparison with theory:

- $I = 3/2$: compatible
- $I = 1/2$: not compatible

Shallow interaction in all cases:

- small impact on heavy-ion observables

Outlook

- Run 3 $\rightarrow$ improvement on statistics and precision
- ALICE 3 $\rightarrow$ $DD^*$ bound states studies
Selection of $D^\pm$ mesons

Exploit the decay-vertex topology of the candidates
Machine learning algorithm based on boosted decision trees

Displacement from the interaction point
D$^\pm$ reconstruction performance

Fit to the invariant mass of the D$^\pm$ candidates:

- signal → gaussian
- background → exponential
- purity ~70%

Data-driven separation between prompt and non-prompt
### Scattering parameters from theoretical models

<table>
<thead>
<tr>
<th>Channel</th>
<th>(Spin, Isospin)</th>
<th>Scattering parameters for different models (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D\pi$</td>
<td>(0, 3/2)</td>
<td>-0.10</td>
</tr>
<tr>
<td></td>
<td>(0, 1/2)</td>
<td>0.37</td>
</tr>
<tr>
<td>$DK$</td>
<td>(1, 1)</td>
<td>0.07 + 0.17i</td>
</tr>
<tr>
<td>$DK$</td>
<td>(-1, 0)</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>(-1, 1)</td>
<td>-0.20</td>
</tr>
</tbody>
</table>

### References:

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- Z.-H. Guo et al, EPJC 79 13
The Lednický-Lyuboshits model

To fit the correlation function:

\[
C(k^*) = A_C(k^*) \left[ 1 + \frac{1}{2} \left| \frac{f(k^*)}{r_0} \right|^2 \left( 1 - \frac{d_0}{2\sqrt{\pi}r_0} + \frac{1}{2}(A_C(k^*) - 1)^2(1 - e^{-(2k^*r_0)^2}) \right) 
+ \frac{2\Re(f(k^*))}{\sqrt{\pi}r_0} F_1(2k^*r_0) 
- \Im(f(k^*)) \left( \frac{F_2(2k^*r_0)}{r_0} + (A_C(k^*) - 1)2k^* \cos(r_0k^*)e^{-(k^*r_0)^2} \right) \right] 
\]

where \( f(k^*) = \left( \frac{1}{a_0} + \frac{1}{2}d_0k^* - ik^* \right)^{-1} \)

Reference:

\[ \Rightarrow \quad \text{M. Gmitro, J. Kvasil, R. Lednický and V. L. Lyuboshitz, Czech. J. Phys. B 36 1281 1287} \]