ALICE determines the scattering parameters of D mesons with light-flavor hadrons

Emma Chizzali on behalf of the ALICE Collaboration

SQM 2022, Busan
14/06/2022
Heavy-flavor particles and the QGP

• Heavy quarks (HQ) produced right after collision
  • Thermal equilibration time of heavy quarks expected to be of the order of QGP lifetime

• Ideal probes of the QGP
  • Diffusion coefficients of HQ characterize the QGP
Heavy-flavor particles and the QGP

• Heavy quarks (HQ) produced right after collision
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• Ideal probes of the QGP
  • Diffusion coefficients of HQ characterize the QGP

• During the later hadronic-phase D meson rescattering must be considered
  • Models (e.g. TAMU) depend on the scattering lengths between D meson and light hadrons
    → No experimental constraints

Bound states

- Strong final state interaction (FSI) can lead to formation of bound states
- Several new states observed
  - Hidden charm and/or beauty (XYZ states)
    A. Hosaka et al., *PTEP* 2016 no. 6 (2016) 062C01
  - Open charm ($T_{cc}$)
    arXiv:2109.01038
    arXiv:2109.01056v2
  - Pentaquark states (e.g., $P_c(4380)$, $P_c(4450)$)
- Measurement of the strong FSI needed to determine whether observations are molecular states
The correlation function

\[ C(k^*) = \mathcal{N} \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* \xrightarrow{k^* \to \infty} 1 \]

experimental definition

theoretical definition

S. E. Koonin, Physics Letters B 70 (1977) 43-47
S. Pratt, Phys. Rev. C 42 (1990) 2646-2652

Relative momentum \( \vec{k}^* = \frac{1}{2} | \vec{p}_1^* - \vec{p}_2^* | \) and \( \vec{p}_1^* + \vec{p}_2^* = 0 \)
Relative distance \( \vec{r}^* = \vec{r}_1^* - \vec{r}_2^* \)
The correlation function

\[ C(k^*) = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} = \int S(\vec{r}^*) |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3\vec{r}^* \xrightarrow{k^* \to \infty} 1 \]

Correlation function (CF) computed

**a)** **numerically**, by solving Schrödinger equation for given potential employing CATS framework


**b)** **analytically**, by employing e.g. Lednický-Lyuboshits approach

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- **Experimental definition**
- **Theoretical definition**

The correlation function

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**Experimental definition**

**Theoretical definition**

ITS (Inner Tracking System)
- 6 layers of silicon detectors
- Vertex, tracking
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V0 Detector
- 2 scintillator arrays
- Trigger, multiplicity estimation
TPC (Time Projection Chamber)
- Gas-filled volume, detection of ionization
- Tracking, particle identification (PID) (dE/dx)

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- Multi-gap resistive plate chambers
- PID by determining velocity

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ALICE

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LHC Run 2 dataset (2016-2018)
High multiplicity (HM) pp collisions at $\sqrt{s} = 13$ TeV
Excellent PID with ALICE Detector
• Momentum resolution $\sigma(p_T)/p_T < 0.1$
  M. Ivanov Nuclear Physics A 904–905 (2013) 162c–169c
• Primary charged particle ($p$, $K$, $\pi$) purities up to 99%
D meson reconstruction

- Decay channel $D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$
  - $\text{BR} = (9.38 \pm 0.16)\%$

PDG, Prog. Theo. Exp. Phys. (2020) 083C01

New on arXiv: 2201.05352
D meson reconstruction

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- Candidates consist of
  - Combinatorial background $\rightarrow$ random combination of uncorrelated pions and kaons

\[\text{Counts per 4 MeV/c}^2\]

**ALICE** pp, $\sqrt{s} = 13$ TeV
High-mult (0–0.17% INEL > 0)

\[\frac{S}{S+B(2\sigma)} = 0.70\]

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  - Non-prompt D (feed-down) $\rightarrow$ decay products of beauty hadrons

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ALICE pp, $\sqrt{s} = 13$ TeV
High-multiplicity (0–0.17% INEL > 0)
$D^\pm \rightarrow K^{\mp}\pi^\pm\pi^\pm$
$2 < p_T < 3$ GeV/c
$S/S+B(2\sigma) = 0.70$

Data
Fit
Background
Total signal
$c \rightarrow D^+$
$b \rightarrow D^+$
D meson reconstruction

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• Purity of D meson candidates $\sim 70\%$
Raw correlation function

Includes additional background contributions besides the one arising from genuine FSI interaction
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- Combinatorial background obtained from sidebands of D meson invariant mass spectrum
Raw correlation function

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- **Combinatorial background** obtained from sidebands of D meson invariant mass spectrum

- **Jet-like auto-correlations** estimated with PYTHIA 8

![Graph showing correlation function](ALICE-PREL-506576)
Raw correlation function

Includes additional background contributions besides the one arising from genuine FSI interaction

- Combinatorial background obtained from sidebands of D meson invariant mass spectrum
- Jet-like auto-correlations estimated with PYTHIA 8
- Feed-down from D* modelled assuming Coulomb-only interaction
Raw correlation function

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- Combinatorial background obtained from sidebands of D meson invariant mass spectrum
- Jet-like auto-correlations estimated with PYTHIA 8
- Feed-down from D* modelled assuming Coulomb-only interaction

→ Combined to total background used to extract genuine correlation function from data
Dπ and DK interaction

• Predictions of scattering lengths derived from lattice QCD calculations
  • Very small (~0.1-0.5 fm) compared to other interactions (e.g. light-light ~7-8 fm, light-strange ~1 fm)

• Model correlation functions obtained from Gaussian-type potential, tuned to reproduce scattering lengths

B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Source

- Particle emission from Gaussian core source
  - Universal source model constrained from pp pairs (well known interaction)


\[
\langle m_T^{p-p} \rangle = 2.7 \text{ GeV}/c^2
\]

\[
\langle m_T^{p-\Lambda \text{ (NLO)}} \rangle = 2.65 \text{ GeV}/c^2
\]

\[
\langle m_T^{p-\Lambda \text{ (LO)}} \rangle = 2.55 \text{ GeV}/c^2
\]

ALICE pp $\sqrt{s} = 13$ TeV
High-mult. (0–0.17% INEL > 0)
Gaussian + Resonance Source
Source

- Particle emission from Gaussian core source
  - Universal source model constrained from pp pairs (well known interaction)

- Core radius effectively increased by short-lived strongly decaying resonances ($c\tau \approx r_{\text{core}}$)
  - Gaussian profile $D_p$ source
    - $r_{\text{eff}} = 0.89^{+0.08}_{-0.22} \text{ fm}$
  - DK and $D\pi$ source described by weighted ($w^2$) sum of two Gaussian sources, to describe tail from longer-lived resonances:
    - DK: $r_{\text{eff}}^1 = 0.86^{+0.09}_{-0.07} \text{ fm}, r_{\text{eff}}^2 = 2.03^{+0.19}_{-0.12} \text{ fm}
    - $D\pi$: $r_{\text{eff}}^1 = 0.97^{+0.09}_{-0.08} \text{ fm}, r_{\text{eff}}^2 = 2.52^{+0.36}_{-0.20} \text{ fm}$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$&lt;c\tau&gt;$ [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>-</td>
</tr>
<tr>
<td>$p$</td>
<td>$\Delta$</td>
</tr>
<tr>
<td>$K$</td>
<td>$K^0, K^\pm$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>$\rho^0, \rho^\pm, K^0, K^\pm, \omega(782)$</td>
</tr>
</tbody>
</table>
Dπ and DK interaction

- Depending on charge combination different isospin states contribute to total correlation function

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Opposite Charge (Antialigned Isospin)</th>
<th>Same Charge (Aligned Isospin)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dπ</td>
<td>D ( \times ) π ( \times ) D ( \times ) π</td>
<td>66% ( I=1/2 ), 33% ( I=3/2 )</td>
<td></td>
</tr>
<tr>
<td>D( \bar{K} )</td>
<td>D ( \times ) K ( \times ) D ( \times ) K</td>
<td>50% ( I=0 ), 50% ( I=1 )</td>
<td></td>
</tr>
<tr>
<td>DK</td>
<td>D ( \times ) K ( \times ) D ( \times ) K</td>
<td>100% ( I=0 )</td>
<td></td>
</tr>
</tbody>
</table>
Dπ correlation function fit

- D⁺π⁺ and D⁺π⁻ share l=3/2 scattering length \( \rightarrow \) simultaneous fit with Lednický-Lyuboshits formula
  - Values indicate small rescattering in hadronic phase of HIC
  - Scattering length for l=3/2 in agreement with models, while significantly smaller for l=1/2

ALICE Preliminary
pp, \( \sqrt{s} = 13 \text{ TeV} \), high mult. (0–0.17%)
π⁺D⁻ + π⁻D⁺

l=3/2 channel only

New

\( a_{0,l}(l=2) \) fm

\( r_1^{l=2} = 0.97_{-0.37}^{+0.21} \text{ fm} \)
\( r_2^{l=2} = 2.52_{-0.20}^{+0.36} \text{ fm} \)
Dp interaction

- Model CF obtained from Gaussian-type of potential tuned to reproduce the scattering parameters predicted by theory
  - Scattering lengths very small in comparison to interactions involving light hadrons
  - Most models predict repulsive interaction
  - Possible formation of bound state (Y. Yamaguchi et al.)
- Data compatible with Coulomb interaction

### References

Dp interaction

- Confidence interval of scattering length of I=0 channel evaluated by varying the Gaussian potential strength and effective source radius
  - I=1 contribution assumed to be negligible
Dp interaction

- Confidence interval of scattering length of $l=0$ channel evaluated by varying the Gaussian potential strength and effective source radius
  - $l=1$ contribution assumed to be negligible
- Interaction is either **shallow attractive** or strongly attractive with formation of bound state
Dp interaction

- Confidence interval of scattering length of $I=0$ channel evaluated by varying the Gaussian potential strength and effective source radius
  - $I=1$ contribution assumed to be negligible
- Interaction is either shallow attractive or strongly attractive with formation of bound state
Conclusion

• First experimental measurement of the interaction between D mesons and light-flavor hadrons
• Interactions found to be shallow in comparison to the ones including only light hadrons
• Possible formation of a ND bound state not excluded by data
• Significant improvement of statistics foreseen with LHC Run 3 data
Additional material
## $D\pi$ and $DK$ scattering length

<table>
<thead>
<tr>
<th>Channel</th>
<th>$(S,I)$</th>
<th>$L.\ Liu$</th>
<th>$X.-Y.\ Guo$</th>
<th>$B.-L.\ Huang$</th>
<th>$Z.-H.\ Guo\ -\ 1$</th>
<th>$Z.-H.\ Guo\ -\ 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D\pi$</td>
<td>$(0,3/2)$</td>
<td>-0.10 fm</td>
<td>-0.11 fm</td>
<td>-0.06 fm</td>
<td>-0.101 fm</td>
<td>-0.099 fm</td>
</tr>
<tr>
<td></td>
<td>$(0,1/2)$</td>
<td>0.37 fm</td>
<td>0.33 fm</td>
<td>0.61 fm</td>
<td>0.31 fm</td>
<td>0.34 fm</td>
</tr>
<tr>
<td>$DK$</td>
<td>$(1,1)$</td>
<td>0.07+i0.17 fm</td>
<td>-0.05 fm</td>
<td>-0.01 fm</td>
<td>0.06+i0.30 fm</td>
<td>0.05+i0.17 fm</td>
</tr>
<tr>
<td>$D\bar{K}$</td>
<td>$(-1,0)$</td>
<td>0.84 fm</td>
<td>0.46 fm</td>
<td>1.81 fm</td>
<td>0.96 fm</td>
<td>0.68 fm</td>
</tr>
<tr>
<td></td>
<td>$(-1,1)$</td>
<td>-0.20 fm</td>
<td>-0.22 fm</td>
<td>-0.24 fm</td>
<td>-0.18 fm</td>
<td>-0.19 fm</td>
</tr>
</tbody>
</table>

### Diagrams

1. **Opposite charge (antialigned isospin)**
   - $D\pi \otimes D\pi$
   - $66\% I=1/2$, $33\% I=3/2$

2. **Same charge (aligned isospin)**
   - $D\pi \otimes D\pi$
   - $100\% I=3/2$

3. **Opposite charge (antialigned isospin)**
   - $D\bar{K} \otimes D\bar{K}$
   - $50\% I=0$, $50\% I=1$

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B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
# Dp scattering length

<table>
<thead>
<tr>
<th>Model</th>
<th>$l=0$ [fm]</th>
<th>$l=1$ [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. Haidenbauer $g_\sigma^2/4\pi = 1$ meson-exchange</td>
<td>0.14</td>
<td>-0.28</td>
</tr>
<tr>
<td>J. Haidenbauer $g_\sigma^2/4\pi = 2.25$ meson-exchange</td>
<td>0.67</td>
<td>0.04</td>
</tr>
<tr>
<td>J. Hofmann and M. Lutz SU(4) Contact interaction</td>
<td>-0.16</td>
<td>-0.26</td>
</tr>
<tr>
<td>Fontura Chiral-quark model</td>
<td>0.16</td>
<td>-0.25</td>
</tr>
<tr>
<td>Yamaguchi Meson-exchange on HQ symmetry</td>
<td>-4.38</td>
<td>-0.07</td>
</tr>
</tbody>
</table>

Opposite charge (antialigned isospin) $\bar{D}p \otimes Dp$ $50\% l=0$, $50\% l=1$

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Yamaguchi et al, Phys. Rev. D84 (2011) 014032
Dπ and DK interaction

- Lattice data only available for Dπ(I=3/2) and D⁺K⁻ (I=0,1)
  - Scattering parameters at physical quark masses obtained from chiral extrapolation
- Dπ(I=1/2) and D⁺K⁺ (I=0,1) rely on predictions from fitting the available lattice data


Bound-state pole formation corresponding to D₂⁰⁺(2317)
DK correlation function fit

\[ C(k^*) \]

- **\( D^+K^+ \) and \( D^+K^- \) fitted individually with Lednický-Lyuboshits formula**


**Double-Gaussian source**

- \( I = 1 \) channel only

**Results:**

- \( r_1^{\text{eff}} = 0.86 \pm 0.09 \) fm
- \( r_2^{\text{eff}} = 2.03 \pm 0.19 \) fm

**Graphs:**

- **Left graph:** ALICE Preliminary
  - pp, \( \sqrt{s} = 13 \) TeV, high mult. (0–0.17%)
  - \( K^0D^+ \oplus K^-D^+ \)

- **Right graph:**
  - \( K^0D^- \oplus K^+D^+ \)
  - Coulomb + Lednický–Lyuboshits (stat. unc.)
  - Coulomb + Lednický–Lyuboshits (tot. unc.)

**Graph Details:**

- \( I = 0 \) (50%), \( I = 1 \) (50%)

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**ALICE PRELIMINARY**

**SQM 2022 | Emma Chizzali**
Different sign convention $f_0, a_0 = -a$ !

**Figure 2.6:** Reduced wave-function $u(r)$ for zero-energy ($k^* \approx 0$) as function of $r$ for a repulsive potential (a), an attractive potential (b) and increased attractive potential (c). The intercept of the outside $u(r)$ with the $r$-axis gives the scattering length $a$. Figures taken from [113].
Lednický-Lyuboshits model

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

Analytical approach to model CF for strong final state interaction within effective range expansion


- isotropic source of Gaussian profile \( S(r^*) \)
- scattering amplitude: \( f(k^*) = \left( \frac{1}{a_0} + \frac{1}{2}d_0k^2 - ik^* \right)^{-1} \)
  - Effective range \( d_0 \) and scattering length \( a_0 \)
- spin averaged scattering parameters