Study of the strong interaction between heavy flavour hadrons

Laura Fabbietti
18/10/2021
Hadron-hadron interactions studied with femtoscopy the LHC


\[
C(k^*) = \int S(r^*) |\Psi(k^*, r^*)|^2 \, d^3r^* = \xi(k^*) \bigotimes \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}
\]
Hadron-hadron interactions studied with femtoscopy the LHC

RUN 2

\( u, d, s - s \)

\[ p - p, p - \Lambda, \Lambda - \Lambda: \text{PRC 99 (2019) 024001} \]
\[ p - p, p - \Lambda, \Lambda - \Lambda: \text{arXiv:2105.05190} \]
\[ \Lambda - \Lambda: \text{Phys. Lett. B 797 (2019) 134822} \]
\[ p - \Xi^-: \text{Phys. Rev. Lett. 123 (2019) 112002} \]
\[ p - \Xi^-, p - \Omega^-: \text{Nature 588 (2020) 232-238} \]
\[ p - \Sigma^0: \text{Phys. Lett. B 805 (2020) 135419} \]
\[ p - \phi: \text{arXiv:2105.05578} \]
\[ N - \Lambda, N - \Sigma^0: \text{arXiv:2104.04427} \]

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**RUN 2**

\[ u, d, s - s \]

**RUN 3/4**

\[ u, d, s - c \]

\[
\begin{align*}
\pi, \Xi & : \text{Phys. Rev. Lett. 124 (2020) 092301} \\
p, \Xi & : \text{Phys. Rev. Lett. 123 (2019) 112002} \\
p, \Xi, p, \Omega & : \text{arXiv:2105.05578} \\
N & : \text{arXiv:2104.04427}
\end{align*}
\]

**Correlation Function**

\[
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\]
Hadron-hadron interactions studied with femtoscopy the LHC

RUN 2
\(u, d, s - s\)

RUN 3/4
\(u, d, s - c\)

ALICE 3
\(u, d, s, c, b - c, b\)

\[
p - \bar{K}: \text{Phys. Rev. Lett. 124 (2020) 092301}
\]
\[
p - p, p - \Lambda, \Lambda - \Lambda: \text{PRC 99 (2019) 024001}
\]
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p - p, p - \Lambda, \Lambda - \Lambda: \text{arXiv:2105.05190}
\]
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\Lambda - \Lambda: \text{Phys. Lett. B 797 (2019) 134822}
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p - \phi: \text{arXiv:2105.05578}
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N - \Lambda, N - \Sigma^0: \text{arXiv:2104.04427}
\]
p-D\(^-\) correlation function

- "Simplest" system: p–D\(^-\)
  - Most of the models predict repulsive interaction
  - Coulomb interaction included in all the models
  - Attraction might arise from 2-pion exchange
  - Possible pentaquark \(\Theta_c\) (c-ud-ud) resonance
    (included in the Yamaguchi model)
  - Potential calculable with lattice QCD (not yet available)

\[ \frac{\pi}{4} \sigma \]

The emitting source

\[ C(\vec{k}^\ast) = \int S(\vec{r}^\ast) \left| \psi(\vec{k}^\ast, \vec{r}^\ast) \right|^2 d^3r^\ast \]

- **Emitting source**: hypersurface at kinematic freezout of final-state particles

**\( G(\vec{r}^\ast, r_{\text{core}}, m_T) \) Universal core**

Anisotropic + pressure gradients

Radial

Different effect on different masses
The emitting source

\[ C(\vec{k}^\ast) = \int S(\vec{r}^\ast) |\psi(\vec{k}^\ast,\vec{r}^\ast)|^2 d^3r^\ast \]

- Emitting source: hypersurface at kinematic freezeout of final-state particles

\[ G(\vec{r}^\ast, r_{\text{core}}, m_T) \text{ Universal core} \quad + \quad \text{‘Tail’ Due to strong resonances} \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>Primordial fraction</th>
<th>Resonances (&lt;cT&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>33 %</td>
<td>1.6 fm</td>
</tr>
<tr>
<td>Lambda</td>
<td>34 %</td>
<td>4.7 fm</td>
</tr>
</tbody>
</table>

Anisotropic + pressure gradients
Radial

Different effect on different masses

U. Wiedemann, U. Heinz (PRC56 R610, 1997)
Data-driven modelling of the emitting source

Fit correlation functions of $p-p$ and $p-\Lambda$ pairs

- Interaction precisely described
- Gaussian source with radius as free parameter

Source size $\sim 1\text{fm}$ makes the high-multiplicity $pp$ system suitable for the study of hadron–hadron interactions
### D- in Run 2

**PDG2020, Prog. Theor. Exp. Phys. (2020) 083C01**

<table>
<thead>
<tr>
<th>hadron</th>
<th>decay channel</th>
<th>$c\tau (\mu m)$</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^-$</td>
<td>$K^+ \pi^- \pi^-$</td>
<td>312</td>
<td>9.38</td>
</tr>
</tbody>
</table>

- **Excellent identification of D and D***
- **Relevant sources of background**
  1. Uncorrelated ($K^+ \pi^- \pi^-$) background candidates
     - Parametrised from the measured $C(k^*)$ computed with $D^-$ candidates in the sidebands
  2. $D^-$ from $D^{*-}$ decays ($\sim 30\%$ of $D^-$)
     - $p-$ $D^{*-}$ strong interaction not known, only Coulomb considered

- **All contributions to the correlation function under control**
- **Statistically at the limit for Run 2 but feasibility demonstrated**
- **Paper in preparation!!**
In Run 3 we will test with precision the interactions among charm and non charmed hadrons.

Model | $f_0 (I = 0)$ | $f_0 (I = 1)$
--- | --- | ---
Coulomb | | |
Haidenbauer et al. [13] | $- \frac{g_0^2}{4\pi} = 1$ | 0.14 | -0.28 |
| $- \frac{g_0^2}{4\pi} = 2.25$ | 0.67 | 0.04 |
Hofmann and Lutz [14] | | |
Yamaguchi et al. [16] | | -0.16 | -0.26 |
Fontoura et al. [15] | | 0.03 | -0.25 |

Yamaguchi et al, Phys. Rev. D84 (2011) 014032
Which correlations could be of interest?

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>X(3872) [14]</td>
<td>3872 ± 0.17</td>
<td>1.19 ± 0.21</td>
<td>D^0\bar{D}^0(-0.04), D^{*+}\bar{D}^0(-8.11)</td>
<td>π^+π^-J/ψ, π^+π^-π^0J/ψ</td>
</tr>
<tr>
<td>X(3940) [14]</td>
<td>3942 ± 9</td>
<td>37</td>
<td>D^*\bar{D}^+(-75 ± 9)</td>
<td>D^*D</td>
</tr>
<tr>
<td>X(4140) [14]</td>
<td>4147 ± 4.5</td>
<td>83 ± 21</td>
<td>D_s\bar{D}<em>s^0(-66^{+9}</em>{-3.2})</td>
<td>φJ/ψ</td>
</tr>
<tr>
<td>X(4274) [14]</td>
<td>4273 ± 8.3</td>
<td>56 ± 11</td>
<td>D_s\bar{D}<em>s^+(-49.1^{+19.1}</em>{-1})</td>
<td>φJ/ψ</td>
</tr>
<tr>
<td>Z_b(10610) [14]</td>
<td>10607 ± 2.0</td>
<td>18.4 ± 2.4</td>
<td>BB^*(4±3.2)</td>
<td>π±γ(nS)</td>
</tr>
<tr>
<td>Z_b^+(10650) [14]</td>
<td>10652.2 ± 1.5</td>
<td>11.5 ± 2.2</td>
<td>B^+\bar{B}^*(+2.9)</td>
<td>π±γ(nS)</td>
</tr>
<tr>
<td>P_c^+(4312) [15]</td>
<td>4311.9 ± 0.7</td>
<td>9.8 ± 2.7 ±3.7</td>
<td>Σ_c\bar{D}(-9.7)</td>
<td>π±γ(nS)</td>
</tr>
<tr>
<td>P_c^+(4440) [15]</td>
<td>4440.3 ± 1.3</td>
<td>20.6 ± 4.9 ±8.7</td>
<td>Σ_c\bar{D}^*(21.8)</td>
<td>π±γ(nS)</td>
</tr>
<tr>
<td>P_c^+(4457) [15]</td>
<td>4457.3 ± 1.3</td>
<td>6.4 ± 2.0 ±5.7</td>
<td>Σ_c\bar{D}^*(-4.8)</td>
<td>pJ/ψ, pJ/ψ</td>
</tr>
<tr>
<td>T_{cc}^+ [16]</td>
<td>3874.827</td>
<td>0.410</td>
<td>D^{*+}D^0(-0.273), D^{*0}D^+(−1.523)</td>
<td>D^0D^0π^+</td>
</tr>
</tbody>
</table>

Tetraquarks with cc  
Tetraquarks with bb  
Pentaquarks with cc  
Tetraquarks with bb  
Or all molecular states?
Correlation functions and bound states

- Correlation functions can be used to study the existence of bound states.
- Interplay between system size and scattering length can lead to a size-dependent modification of the correlation function in presence of a bound state.

\[ x = qR \quad y = \frac{R}{a_0} \]

\[ C(q) = 1 + \frac{1}{x^2 + y^2} \left[ \frac{1}{2} - \frac{2y}{\sqrt{\pi}} \int_0^{2x} dt \frac{e^{t^2-4x^2}}{x} - \frac{(1 - e^{-4x^2})}{2} \right] \]

R = source size
q = invariant relative momentum
a₀ = scattering length

- A single measurement at fixed R does not suffice.
- A systematic measurements of different sizes is necessary:
  - pp (R = 1 fm), p-Pb (R = 1.5 fm), Pb-Pb (R = 2.6 fm)

![Correlation function graph](image)
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Example: \( a_0 = 5 \) fm

Interaction only attractive
Existence of a bound state

Recent measurement of a tetraquark candidate by LHCb

- Just below $D^0D^{*+}$ and $D^+D^*$ thresholds → candidate to be a molecular state

Its nature can be assessed via the measurement of $DD^*$ correlations

- In case of a bound state ($T_{cc}^+$) the correlation function is expected to change from smaller to larger than unity for different source sizes

Scan from pp to AA collisions needed

ALICE3 is the ideal detector for acceptance and purity for the heavy flavour signal

E. S. Swanson, Phys. Rept. 429 (2006) 243-305
ALICE 3 projections for the $D^*+D^0$

Projection according to 6 years of data taking
- Enough sensitivity to verify/exclude formation of bound state
- Although scan over wide range of source size needed
  - Necessity to perform measurement from pp to Pb–Pb

Reminder:
A comprehensive measurement of the correlations among proton, hyperons and kaons is necessary to pin down the source properties
Summary of the strong interaction studies between heavy flavour hadrons

Femtoscopy at the LHC has been established as a solid technique to study the residual strong interaction among hadrons.

Run 2: the (almost) complete set of interaction $u,d,s,s$ has been measured!

Run 3: all the interactions among $u,d,s,c,s$ will be accessed with high precision.

ALICE3: $c,c$, $b,b$ correlations will be measured in different colliding system to test residual strong interaction and study molecular state.

ALICE3 unique detector for its large geometrical acceptance and vertexing resolution for charm and beauty hadron and strange weak decays.
$C(\vec{k}^*) = \mathcal{N} \frac{N_{\text{pairs}}^{\text{same}}(k^*)}{N_{\text{pairs}}^{\text{mixed}}(k^*)}$

- 500M Pythia8 (CR mode2) events simulated
- NB: $D^0$ from $D^{*+}$ decays are excluded because would probe $D^{*+} D^{*+}$ interaction instead
- Flat at unity also for low $k^* \rightarrow D^0$ and $D^{*+}$ cannot come from same jet
Calibrating the p-D⁻ source

Source size not necessarily the same for charm hadrons (depends on hadronisation)

- Study performed with PYTHIA8.3 indicates that the source might be 25% lower than the p–p source for the corresponding $<m_T>$
- Added as systematic uncertainty
$C(\vec{k}^*) = \mathcal{N} \frac{N_{\text{pairs}}(k^*)_{\text{same}}}{N_{\text{pairs}}(k^*)_{\text{mixed}}}$

- Rising trend because charm and anti-charm quarks mostly come from same hard scattering