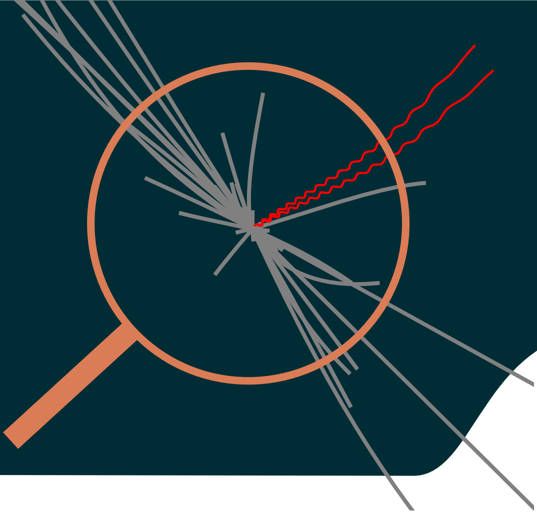


First measurement of the residual strong interaction between open-charm and light-flavor mesons

Daniel Battistini

Technical University of Munich

International school of nuclear physics | Erice, Italy

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

In heavy-ion collisions:

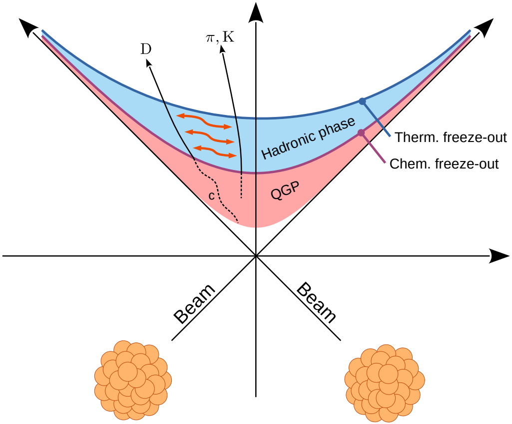
- quark–gluon plasma (QGP) formation
- system expansion and chemical freeze-out
- hadron gas $\rightarrow$ D meson rescattering

Current knowledge:

- $\mathrm{D^{-}p}$: measured with femtoscopy
  $\rightsquigarrow$ ALICE Coll., PRD 106 052010
- all other interactions: unknown

Modification of the heavy-ion observables:

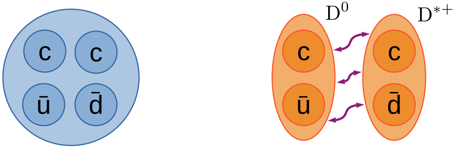
- relies on theory



What is the nature of the exotic charm states?

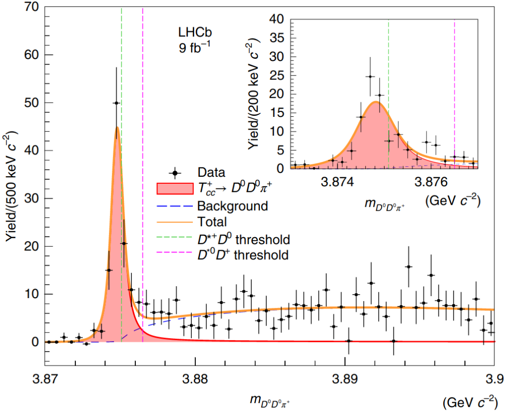
Several non-conventional hadrons were discovered:

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



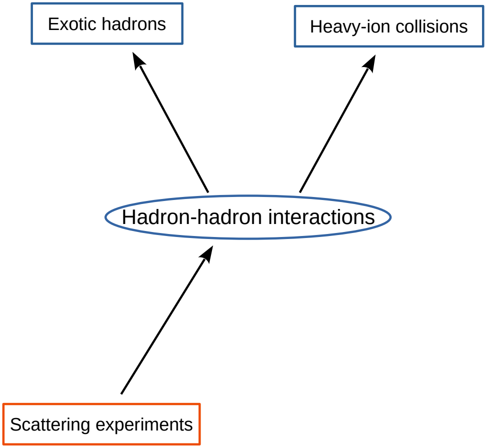
T_{cc}^{+}: quark bag or… molecular state?

Knowledge of the D meson interactions is required

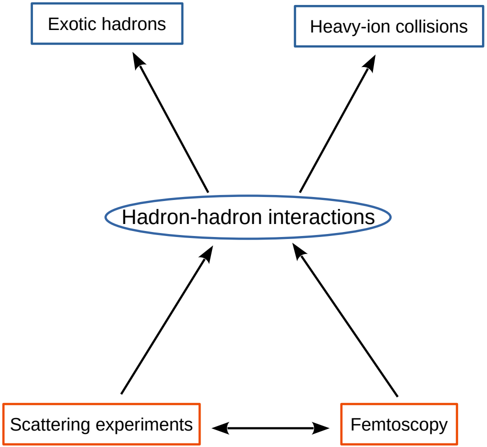


T_{cc}^{+} measurement $\rightsquigarrow$ LHCb Coll, Nat. Com. 13 3351

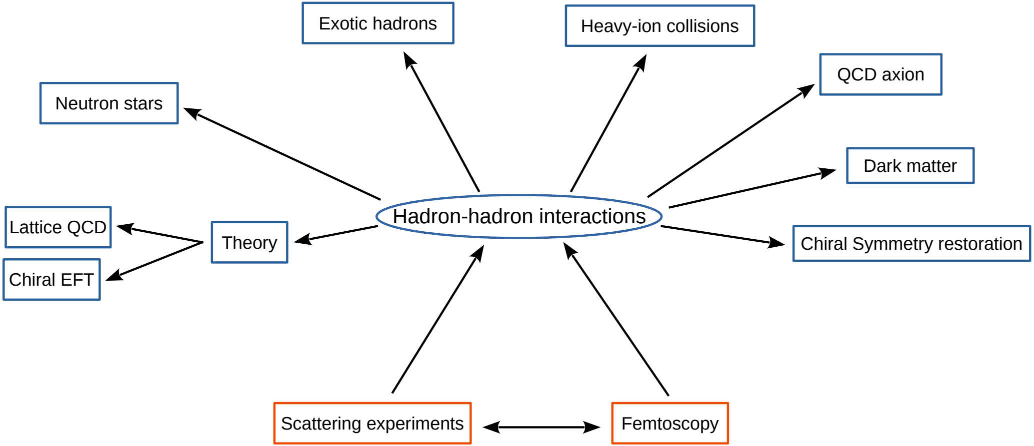
The study of hadron-hadron interactions



The study of hadron-hadron interactions

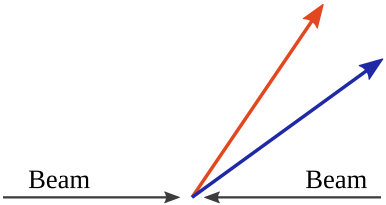


The study of hadron-hadron interactions



Goal: study the interaction between hadrons

The idea: the relative-momentum $k^* = \frac{|\boldsymbol{p}_1^* - \boldsymbol{p}_2^*|}{2}$ is modified by the interaction



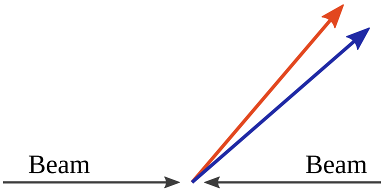
The Idea of femtoscopy

Goal: study the interaction between hadrons

The idea: the relative-momentum $k^* = \frac{|\boldsymbol{p}_1^* - \boldsymbol{p}_2^*|}{2}$ is modified by the interaction

If the interaction is

- attractive $\rightarrow$ smaller relative momentum



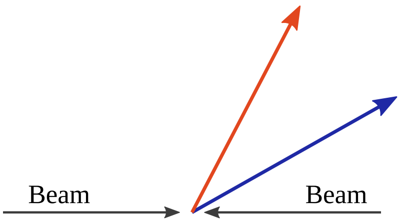
The Idea of femtoscopy

Goal: study the interaction between hadrons

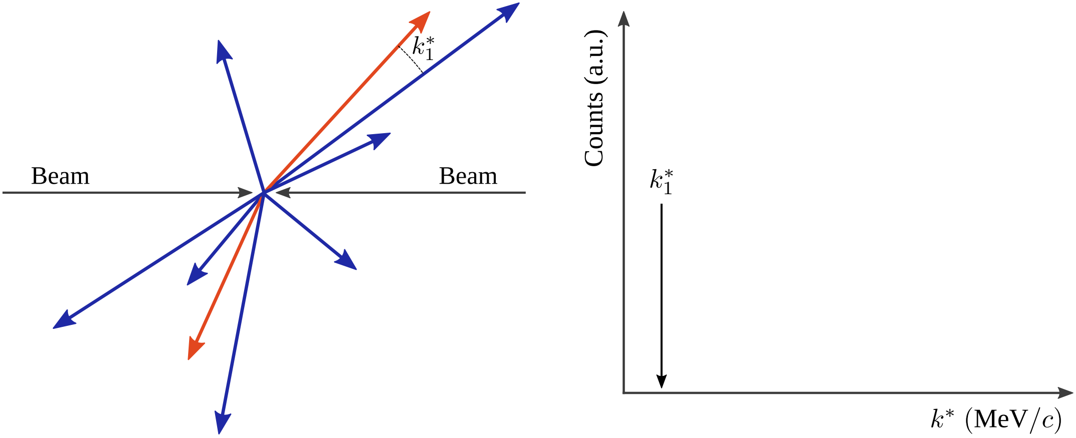
The idea: the relative-momentum $k^* = \frac{|\boldsymbol{p}_1^* - \boldsymbol{p}_2^*|}{2}$ is modified by the interaction

If the interaction is

- attractive $\rightarrow$ smaller relative momentum
- repulsive $\rightarrow$ larger relative momentum

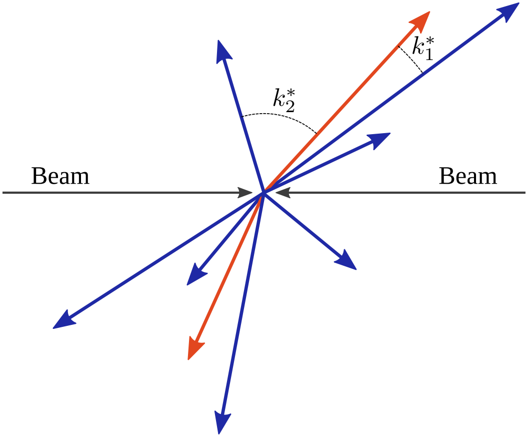


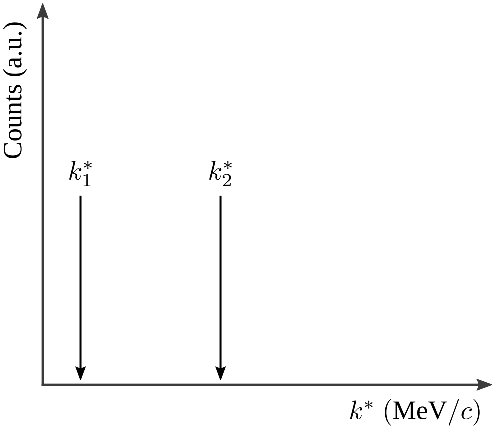
Building the correlation function



Compute k^* for all pairs in all events

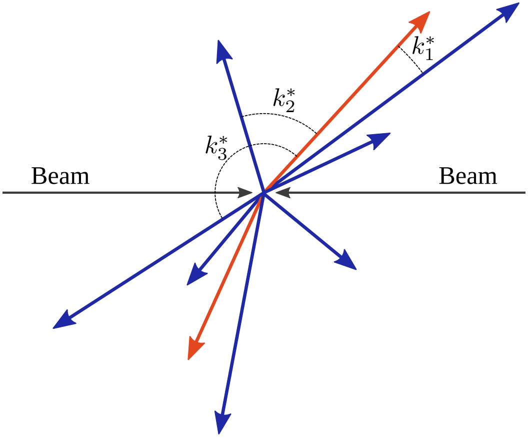
Building the correlation function

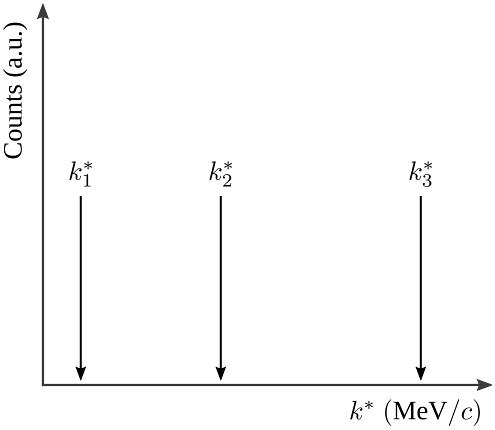




Compute k^* for all pairs in all events

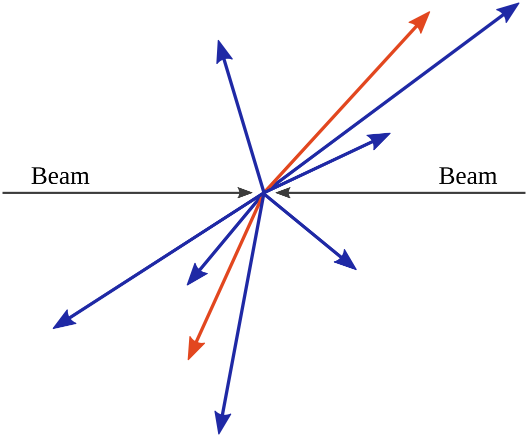
Building the correlation function

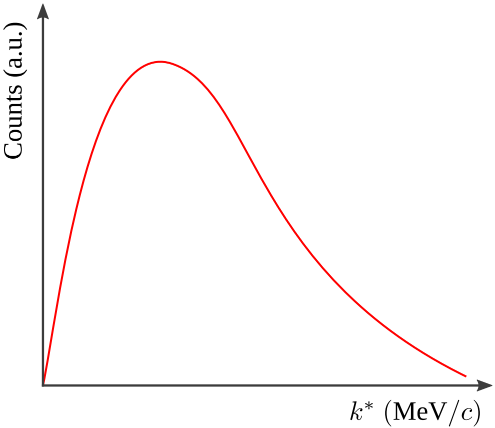




Compute k^* for all pairs in all events

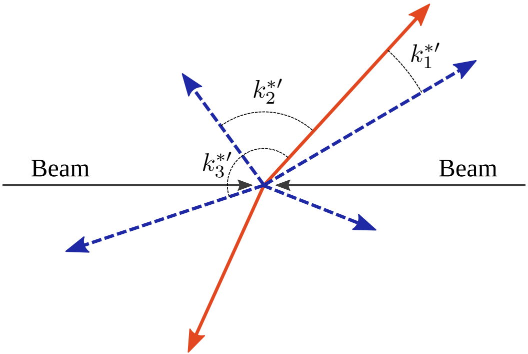
Building the correlation function

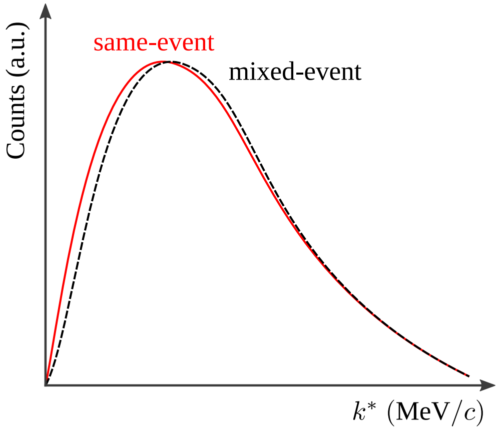




Obtain a k^* distribution $\rightarrow$ is it possible to extract some physics?

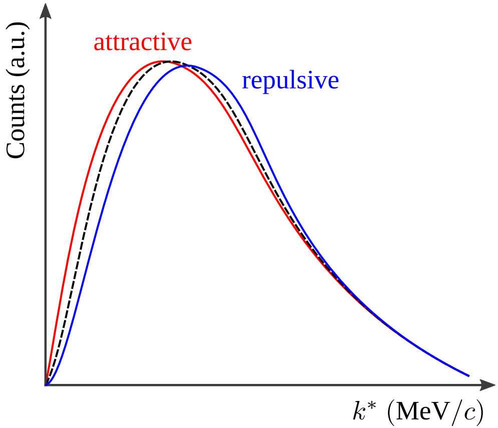
Building the correlation function

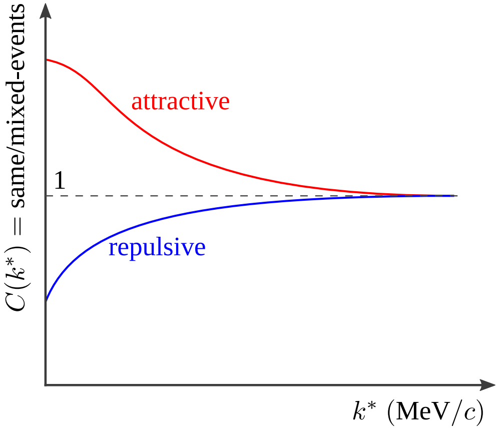




Not yet: a reference distribution is needed → event mixing to “switch off” the interaction

Building the correlation function





If the correlation function = 1 $\Rightarrow$ no interaction

The master formula of femtoscopy

Shape of the correlation function $\rightarrow$ attractive/repulsive interaction

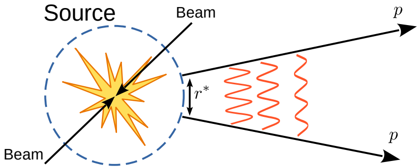
How to quantify? How to compare with theory?

- Koonin-Pratt equation

$$C(k^*) = \underbrace{\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}}_{\text{experiment}} = \underbrace{\int \mathrm{d}\boldsymbol{r}^*\, S(\boldsymbol{r}^*)|\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2}_{\text{theory}}$$

Where:

- S: source function
- r^*: relative distance of particles at production
- Ψ: 2-particle wave function



The source function

$$C(k^*) = \int \mathrm{d}\boldsymbol{r}^*\, S(\boldsymbol{r}^*) |\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$$

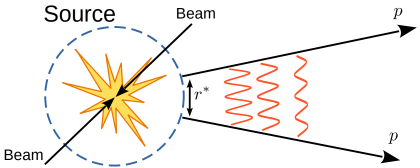
source ⇄ interaction

Two uses:

- known **interaction** → measure the **source**
- known **source** → measure the **interaction**

To “calibrate” the framework:

- assume a gaussian source
- pairs with known interaction → source size



The study of the hadron-hadron interactions: scattering theory

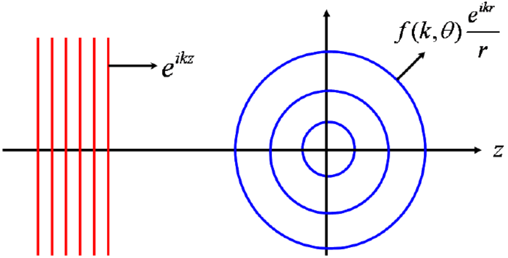
The wave function is expressed as:

$$\psi(\mathbf{r}) = e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$$

with $f(\theta)$: scattering amplitude

The cross section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = |f(\theta)|^2$$



The study of the interaction

In general: solve numerically

$$C(k^*) = \int \mathrm{d}\boldsymbol{r}^* \, S(\boldsymbol{r}^*) |\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$$

Write the wave function as:

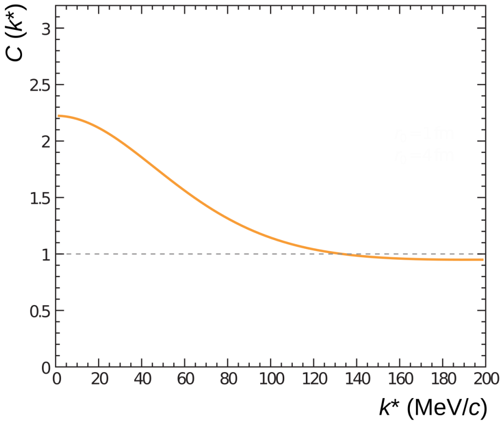
$$\Psi(\boldsymbol{k}^*, \boldsymbol{r}^*) \approx e^{i\boldsymbol{k}^*\boldsymbol{r}^*} + f(k^*)\frac{e^{ik^*r^*}}{r^*}$$

and the effective range expansion

$$f(k^*) \approx \left(\frac{1}{a_0} + \frac{1}{2}d_0 k^{*2} - ik^*\right)^{-1}$$

The scattering parameters are:

- a_0: scattering length
- d_0: effective range

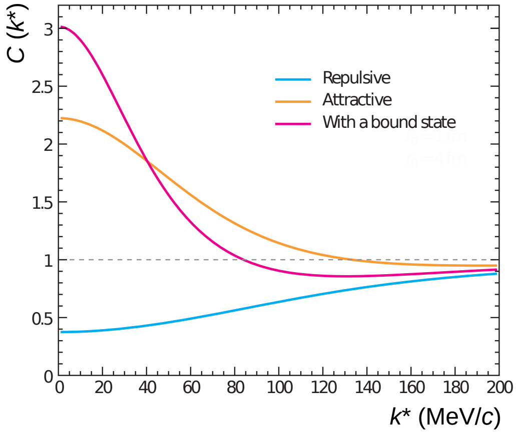


Correlation function for an attractive potential

The shape of the correlation function

Shape of the CF $\rightarrow$ interaction:

$$C \begin{cases} > 1 & \text{attraction: } a_0 > 0 \\ < 1 & \text{repulsion: } a_0 < 0 \\ \lessgtr 1 & \text{bound state: } a_0 < 0 \end{cases}$$



The CF allows us to determine the nature of the interaction

The typical observables:

- scattering length
- effective range

Bound states

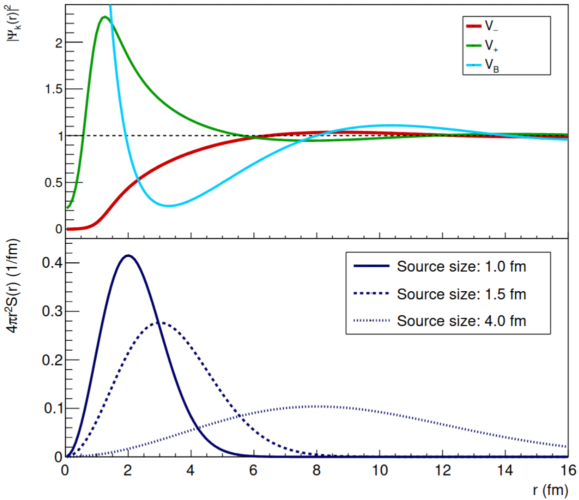
Formation of a bound state:

- non-trivial solution of the Schröd. eq.
- the wave function is depleted at intermediate r

Different sources probe different regions of the wavefunctions, according to

$$C(k^*) = \int \mathrm{d}\boldsymbol{r}^* \, S(\boldsymbol{r}^*) |\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$$

For large sources → CF < 1



Experimental setup

Analyzed data:

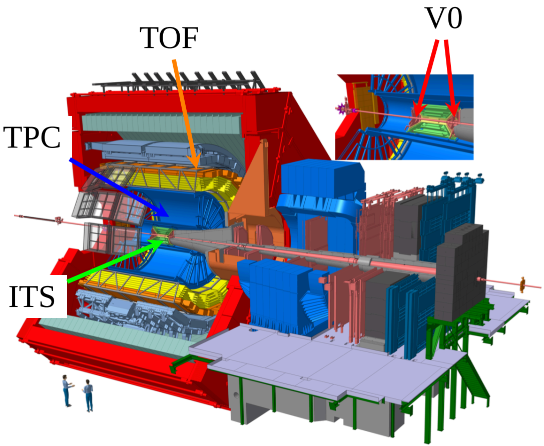
- Run 2 data, collected by ALICE
  - ⇝ ALICE Coll., IJMP A 2014 29:24
- proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$
- high-multiplicity trigger (V0)

Particle identification (PID) and reconstruction:

- $\pi^{\pm}, \text{K}^{\pm}$: ITS + TPC + TOF
- D^{+}: via $\text{D}^{+} \rightarrow \text{K}^{-}\pi^{+}\pi^{+} + \text{c.c.}$
- D^{*+}: via $\text{D}^{*+} \rightarrow \text{D}^{0}(\rightarrow \text{K}^{-}\pi^{+})\pi^{+} + \text{c.c.}$

Selection of $\text{D}^{\pm} \rightarrow$ decay-vertex topology + PID

- prompt D (from charm)
- non-prompt D (from beauty)
- combinatorial background



Modeling the correlation function

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

data | comb. bkg | hadronization | strong interaction | D from D* | decays

Physics: extracted from C_{gen}

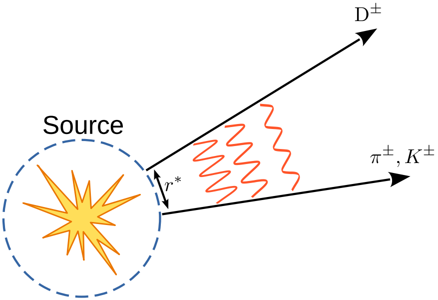
Other terms $\rightarrow$ background contributions

- estimated with various techniques

λ-parameters $\rightarrow$ weight each term based on

- purity
- fraction

$$\lambda_i^{\text{D}\pi} = p_i^{\text{D}} f_i^{\text{D}} p_i^{\pi} f_i^{\pi}$$



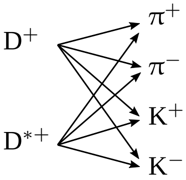
Results

Available theoretical models:

- ⇝ Huang *et al*, PRD 15 036016
- ⇝ L. Liu *et al*, PRD 87 014508
- ⇝ Z.-H. Guo *et al*, EPJC 79 13
- ⇝ X.-Y. Guo *et al*, PRD 98 014510
- ⇝ J. M. Torres-Rincon *et al*, arXiv 2307.02102

(Plot not public)

Correlation functions of



+ charge-conjugates

Deviation from Coulomb $\rightarrow$ strong interaction

Results for Dπ

(Plot not public)

Results for $D^*\pi$

(Plot not public)

Extraction of the scattering parameters

(Plot not public)

Use the Lednický-Lyuboshits model

⇝ R. Lednický *et al*, Czech. J. Phys. B 36 1281 1287

- effective range approximation
- use effective range $d_0 = 0$

Isospin channels:

- $D^+ \pi^+$: pure ($I = 3/2$)
- $D^+ \pi^-$: mixed ($I = 3/2 \oplus I = 1/2$)

Use a combined fit procedure where the scattering parameter $a_0^{D\pi}(I = 3/2)$ is shared

Extraction of the Dπ scattering length

(Plot not public)

Extraction of the $D^*\pi$ scattering length

(Plot not public)

Scattering lenghts

(Plot not public)

Tension with the theoretical models for both isospin channels

Conclusions

Femtoscopy $\rightarrow$ hadron-hadron interactions

- complementary tool to scattering experiments
- works also for charm hadrons!

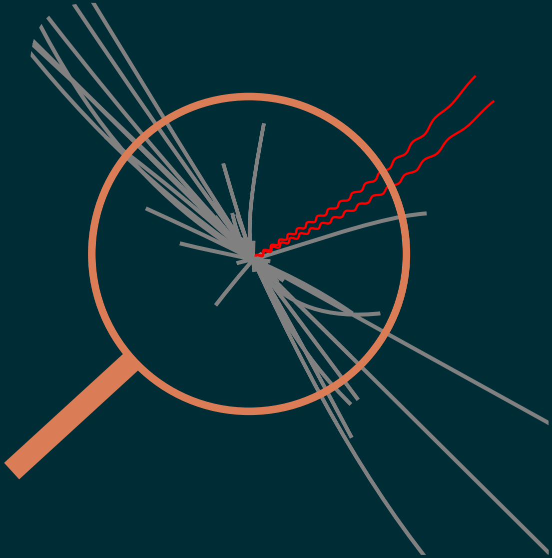
Results of charm femtoscopy:

- shallow interactions
- Dπ and D$^{*}\pi$ interactions are similar
  $\rightarrow$ heavy-quark spin symmetry
- tension with theory

Conclusions:

- small effect on heavy-ion observables
- is the source larger for charm?

(Plot not public)



Additional material

The source function

To determine the source size:

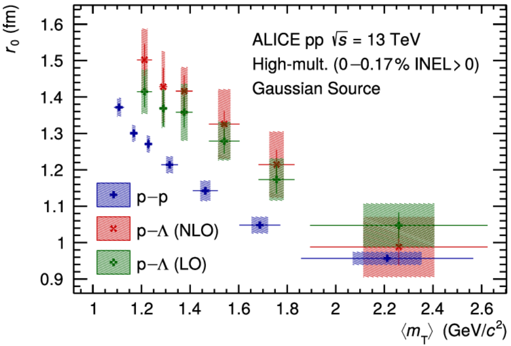
- use a potential for the pp interaction
- solve the Schrödinger equation $\rightarrow \Psi$
- fold with the source $\rightarrow C(k^*; r^*)$
- fix the source size with a fit

Differentially in trasnverse mass m_{T}

Depends on the collision system:

- proton-proton $\rightarrow$ small source: $\langle r^* \rangle \approx 1$ fm
- lead-lead $\rightarrow$ large source: $\langle r^* \rangle \approx 8$ fm

It's different for pp and pΛ...
... or is it?



$$m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + m^2}, \quad k_{\mathrm{T}} = |p_{\mathrm{T},1} + p_{\mathrm{T},2}|/2$$

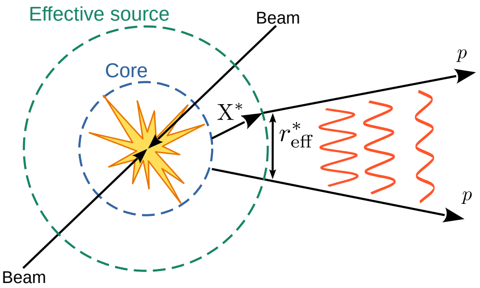
The contribution of resonances

Not all particles are primary

short-living resonances → enlargment of the source

To describe the effective source size r^*_{eff}:

- angular distributions from EPOS
- yields from the statistical hadronization model



The contribution of resonances

Not all particles are primary

short-living resonances $\rightarrow$ enlargment of the source

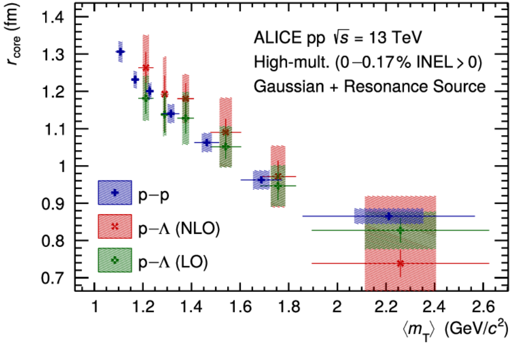
To describe the effective source size r^*_{eff}:

- angular distributions from EPOS
- yields from the statistical hadronization model

The source core is the same for pp and pΛ

- Assume a universal source

The framework is calibrated: new particle pairs can be studied



Determination of the source

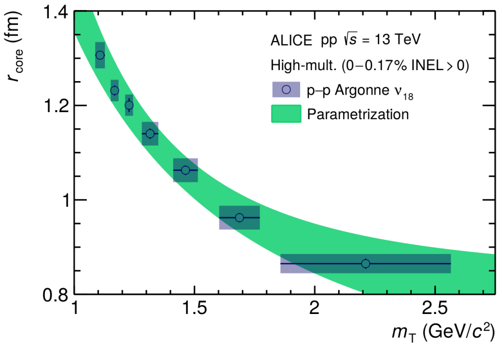
To determine r^*_{eff} for a new pair of particles:

- use the pp data (most precise)

The procedure:

- compute the average m_{T} for the pair of interest
- compute the r_{core} corresponding to that m_{T}
- include the resonances
- compute the effective size r^*_{eff} of the source

Once the effective source is known, the interaction can be accessed



Results for DK

(Plot not public)

Results for D^*K

(Plot not public)

Charm hadron femtoscopy with ALICE 3

ALICE 3: a next generation experiment

⇝ ALICE Coll., arXiv:2211.02491

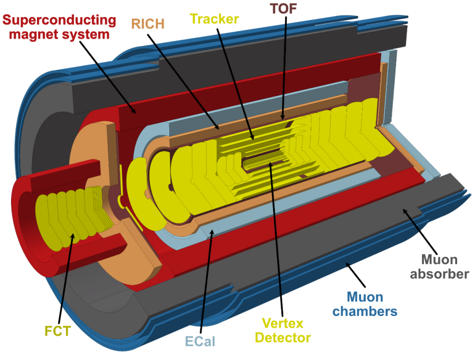
Planned for the Run 5 and Run 6

The study of exotic charm states will be possible
Test the formation of DD^* and $D\bar{D}^*$ bound states:

- T_{cc}^{+} could be a D^0D^* molecule
- $\chi_{c1}(3872)$ could be a $D\bar{D}^*$ molecule

Upgrade projection:

- pythia 8 event generator
- proton-proton collisions at $\sqrt{s} = 14$ TeV
- assume a gaussian potential (with bound state)
- scan different source radii



Charm hadron femtoscopy with ALICE 3

The T_{cc}^{+}: a DD^{*} molecule candidate

- Binding energy ≈ 360 keV
- scattering length = $-7.16 + i1.85$ fm

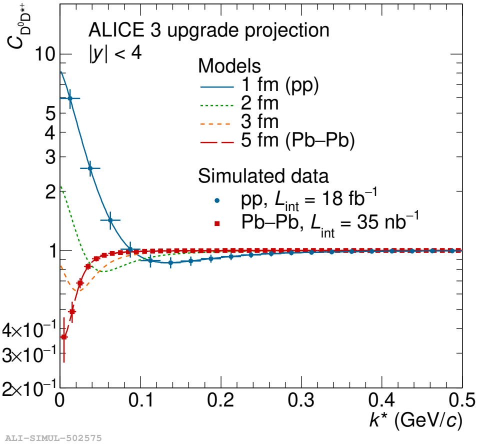
  $\rightsquigarrow$ LHCb Coll, Nat. Com. 13 3351

Tune the potential $\rightarrow$ mass and width of T_{cc}^{+}

Test 4 different source sizes

- proton-proton: $r^{*} \approx 1$ fm
- lead-lead: $r^{*} \approx 5$ fm

Bound state $\rightarrow$ flip of the CF below 1



Charm hadron femtoscopy with ALICE 3

The $\chi_{c1}(3872)$: molecule candidates

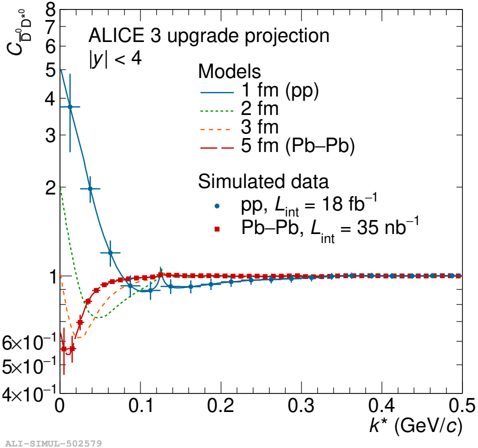
- $D^0\,\bar{D}^{*0}$ (dominant)
- $D^+\,\bar{D}^{*-}$

Assume a $D^0\,\bar{D}^{*0}$ molecule

- Binding energy $\approx$ 40 keV

Features of the CF:

- cusp at 120 MeV/c (due to $D^+\,\bar{D}^{*-}$ coupling)
- inversion of the CF for large systems
- source size dependence



Charm hadron femtoscopy with ALICE 3

The $\chi_{c1}(3872)$: molecule candidates

- $D^0\,\bar{D}^{*0}$ (dominant)
- $D^+\,\bar{D}^{*-}$

Assume a $D^+\,\bar{D}^{*-}$ molecule (subdominant)

- Binding energy $\approx$ 8 MeV

Features of the CF:

- no cusp ($D^0\,\bar{D}^{*0}$ coupling below threshold)
- no inversion of the CF for large systems
  $\approx$ no bound state
- almost no source size dependence