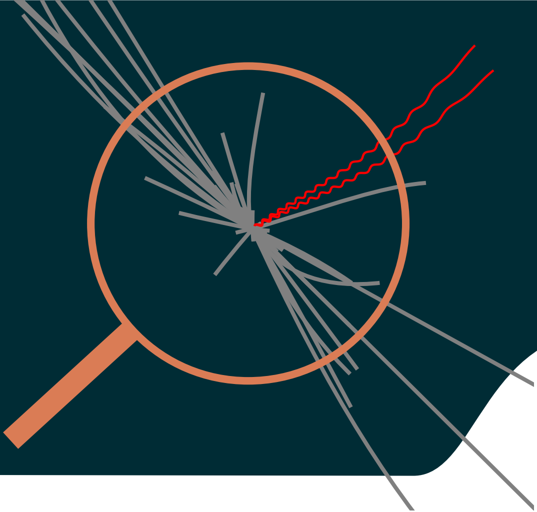


Studying the interaction between charm and light-flavor hadrons

Daniel Battistini, on behalf of the ALICE Collaboration
Technical University of Munich

BEACH 2024 | Charleston (SC), USA

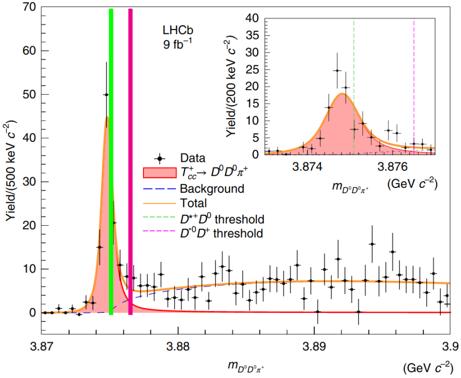
What is the nature of the exotic charm states?

Several non-conventional hadrons were discovered:

- slightly below the DD^* thresholds
  $\rightarrow$ molecule candidates
  S. Weinberg, Phys. Rev. 137, B672
  J. Song *et al.*, Eur. Phys. J. A 58, 133 (2022)
- quark bags are also possible
  Esposito *et al.*, Phys. Rev. D 105 (2022) 3, L031503

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

LHCb Coll., Nat. Com. 13 3351



Knowledge of the D meson interactions is required

Rescattering of D mesons in heavy-ion collisions

What is the impact of the rescattering on the heavy-ion observables?

In heavy-ion collisions:

- quark–gluon plasma (QGP) formation

  STAR Coll., Nucl. Phys. A 757:102-183,2005

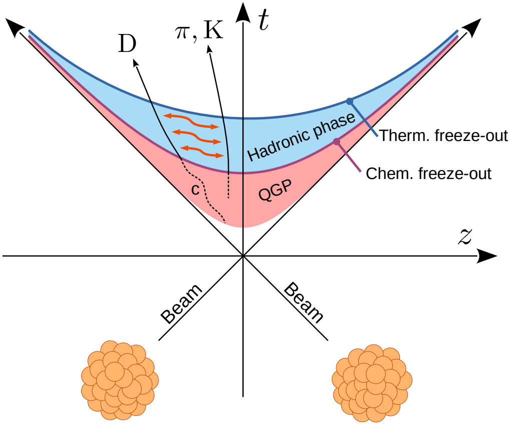
- system expansion and chemical freeze-out
- hadron gas

Charm hadrons are ideal QGP probes:

- experience the evolution of the system

D meson rescattering in the hadronic phase:

- data is scarce
- relies on theory

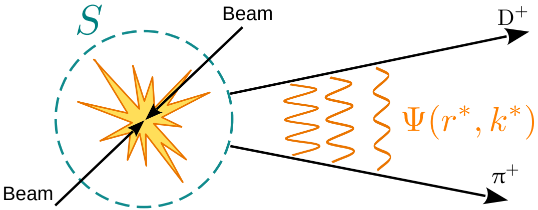


Femtoscopy as a tool to access the hadron-hadron interactions

A phase-space correlation technique

📖 L. Fabbietti *et al.* Annu. Rev. Nucl. Part. Sci. (2021) 71:377-402

Measurements performed at particle colliders (LHC)
$\rightarrow$ study the interaction at the femtometer scale



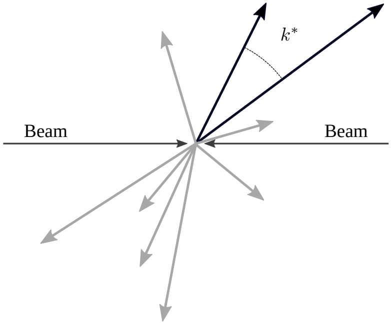
Goal: measure the interactions of D mesons with light hadrons using femtoscopy

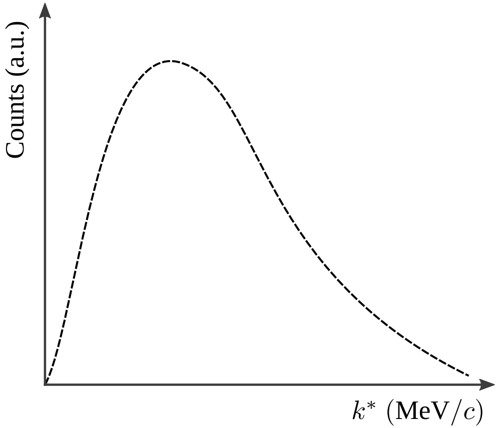
Employed in several works by ALICE:

- pp, pΛ, $\Lambda\Lambda$: 📖 ALICE Coll., Phys.Rev.C 99 (2019) 2, 024001
- p$\bar{\text{p}}$, p$\bar{\Lambda}$, $\Lambda\bar{\Lambda}$: 📖 ALICE Coll., Phys. Lett. B 829 (2022) 137060
- ppp, ppΛ: 📖 ALICE Coll., Eur. Phys. J. A 59 (2023) 7, 145
- pp$\text{K}^{\pm}$: 📖 ALICE Coll., Eur. Phys. J. A 59 (2023) 12, 298
- pϕ: 📖 ALICE Coll., Phys. Rev. Lett. 127 (2021) 17, 172301
- $\Lambda\text{K}^{\pm}$: 📖 ALICE Coll., Phys. Lett. B 845 (2023) 138145
- pΣ^0: 📖 ALICE Coll., Phys. Lett. B 805 (2020) 135419
- pK^-: 📖 ALICE Coll., Phys. Rev. Lett. 124 (2020) 9, 092301
- pΩ: 📖 ALICE Coll., Nature 588 (2020) 232-238
- $\Lambda\Xi$: 📖 ALICE Coll.,Phys. Lett. B 844 (2023) 137223
- pΞ: 📖 ALICE Coll., Phys. Rev. Lett. 123 (2019) 11, 112002
- pD: 📖 ALICE Coll., arXiv:2201.05352
- pd, K^+d: 📖 ALICE Coll., arXiv:2308.16120
- $\pi\pi$, pK^+: 📖 ALICE Coll., arXiv:2311.14527

The same-event distribution

Study the relative momentum in the pair rest frame: $k^* = |\boldsymbol{p}_\mathrm{A}^* - \boldsymbol{p}_\mathrm{B}^*|/2$





k^* is modified depending on the interaction between the particles

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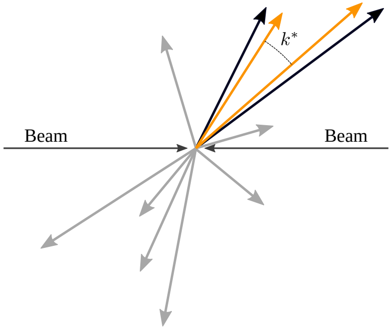

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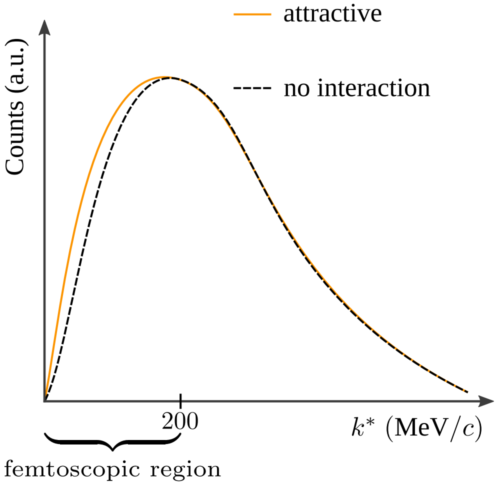

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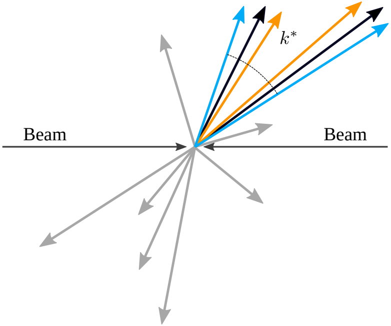

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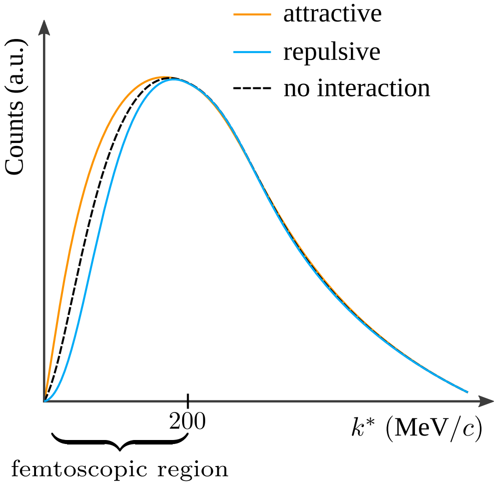
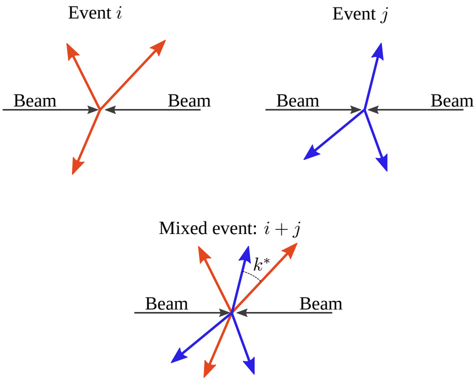
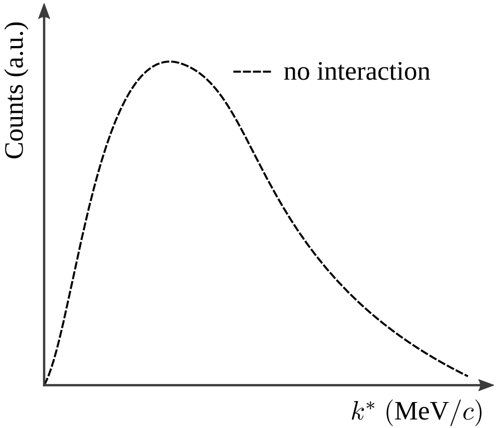


The mixed-event distribution

Select the particles from different events:

- the interaction is absent
- underlying phase space is described



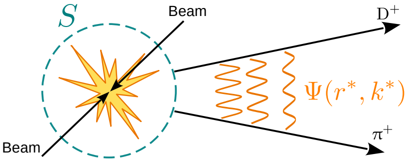


The femtoscopic correlation function

The Koonin-Pratt formula:

M. A. Lisa and S. Pratt *et al.*, ARNPS 55 357402

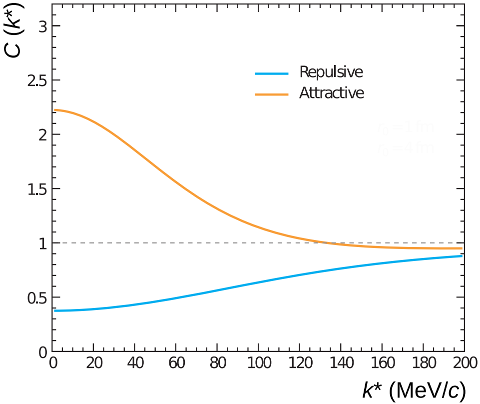
$$C(k^*) = \underbrace{\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}}_{\text{experiment}} = \underbrace{\int \mathrm{d}\boldsymbol{r}^*\, S(\boldsymbol{r}^*)\, |\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2}_{\text{Koonin-Pratt}}$$



where:

- S is the source function
- Ψ is the wave function

Ann. Rev. Nucl. Part. Sci. 71 (2021) 377-402

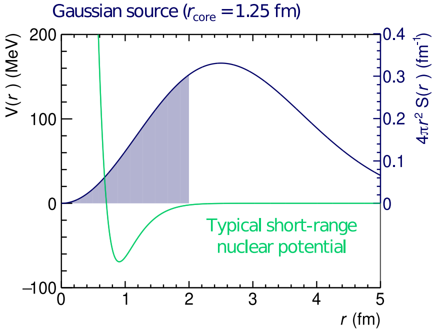


Shape influenced by the nature of the interaction

The source function

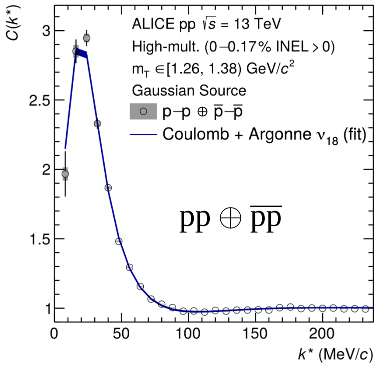
$S(r^*)$ = probability density function of r^*
$\rightarrow$ a property of the collision system

In proton-proton collisions at the LHC:
$r_{\text{core}} = 1 - 2$ fm (corrected for resonances)



To determine the source size:

- fix the pp interactions from scattering data
- compute C with the Koonin-Pratt formula
- fit the pp correlation function



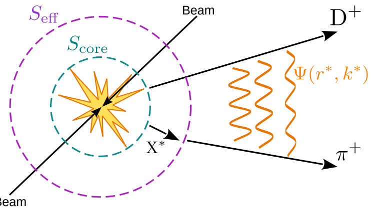
The source function

Measurement of the source in pp collisions:

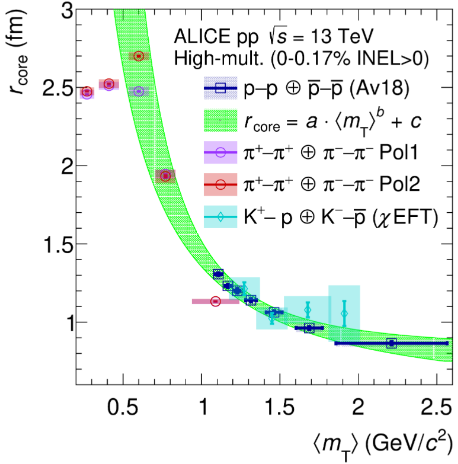
- assume a gaussian profile
- differential in the transverse mass m_{T}
- for different particle pairs

Corrected for short-living resonances ($c\tau < 5$ fm):

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



ALICE Coll., arXiv:2311.14527



$$m_{\mathrm{T}} = \sqrt{k_{\mathrm{T}}^2 + \langle m \rangle^2}, \quad k_{\mathrm{T}} = |\boldsymbol{p}_{\mathrm{T},1} + \boldsymbol{p}_{\mathrm{T},2}|/2$$

Experimental setup: the ALICE detector in Run 2

Dataset: high-multiplicity proton-proton collisions at $\sqrt{s} = 13$ TeV

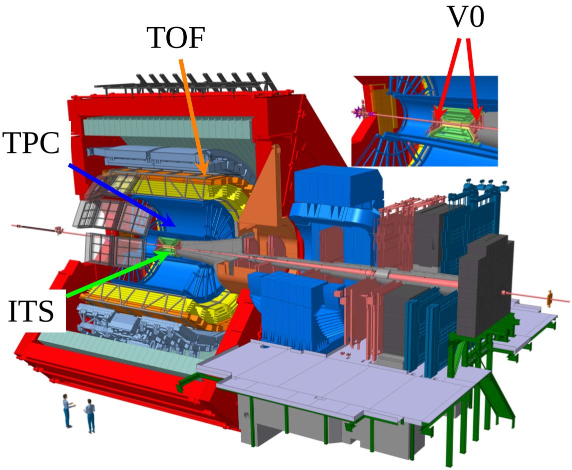
The particles in the final state (p, K and π) are measured with the ALICE detector using:

- ITS: tracking and vertex reconstruction
- TPC: tracking and particle identification
- TOF: particle identification
- V0: multiplicity estimation

Decay channels used for reconstruction:

- $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ BR ≈ 2.7 %
- $D^+ \to K^-\pi^+\pi^+$ BR ≈ 9.4 %

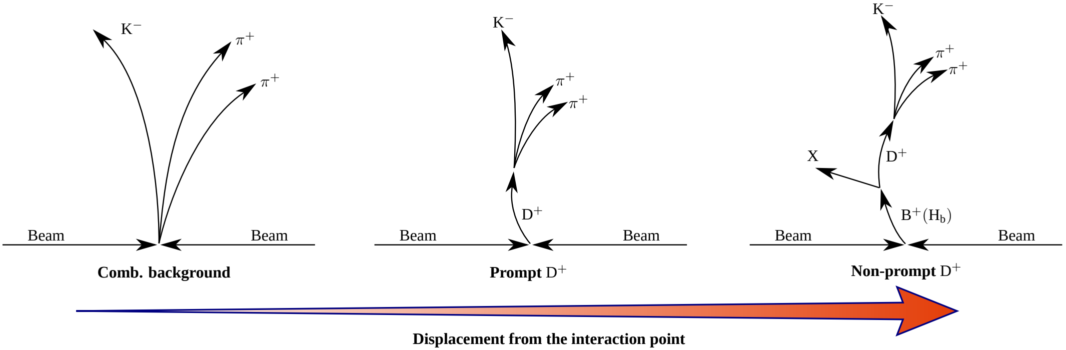
ALICE Coll., Int. J. Mod. Phys. A 29 (2014) 1430044 ALICE Coll., JINST 3 (2008) S08002



Selection of D mesons

Exploit the decay-vertex topology of the candidates

- $c\tau(\mathrm{D}) \approx 100$ µm
- $c\tau(\mathrm{B}) \approx 500$ µm



D meson reconstruction performance

Machine learning algorithm based on boosted decision trees

ALICE Coll., JHEP 05 (2021) 220

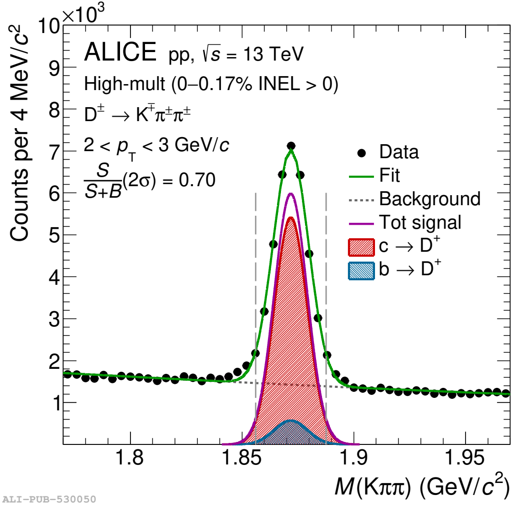
Selection of $D^{\pm} \to$ decay-vertex topology + PID

- from c quark hadronization (prompt)
- from beauty hadron decays (non-prompt)
- combinatorial background

Data-driven separation between signal/background and prompt/non-prompt

- purity ~70%
- non-prompt fraction ~7%

ALICE Coll., Phys. Rev. D 106 (2022) 5, 052010



The correlation function: genuine interaction

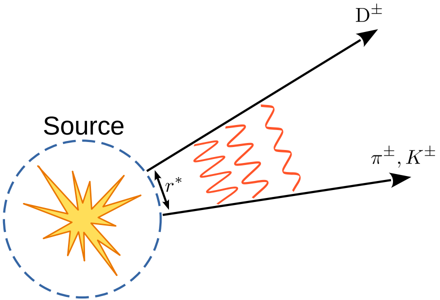
$$\boxed{C_{\text{raw}}} = \boxed{\lambda_{\text{gen}} C_{\text{gen}}}$$

data — strong interaction

Primary signal particles → genuine CF
- **scattering parameters**
- formation of bound states

Source function from the universal m_{T}-scaling

ALICE Coll., Phys. Lett. B 811 135849



The correlation function: decays from $D^{*\pm}$ mesons

$$\boxed{C_{\rm raw}} = \boxed{\lambda_{\rm gen} C_{\rm gen}} + \boxed{\lambda_{\rm D^*} C_{\rm D^*}}$$

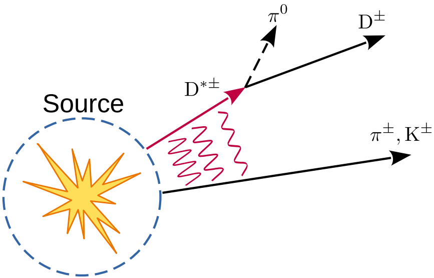
data — strong interaction — D from D*

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

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

Modelling:

- Coulomb interaction between $D^{*\pm}$ and π,K
- compute the phase space of $D^{*\pm} \rightarrow D^{\pm} + \pi^0$
- fold interaction with phase space $\rightarrow C_{\rm D^*}$



The correlation function: flat contributions

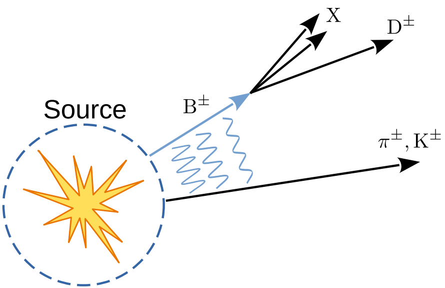
$$C_{\mathrm{raw}} = \lambda_{\mathrm{gen}} C_{\mathrm{gen}} + \lambda_{\mathrm{D}^*} C_{\mathrm{D}^*} + \lambda_{\mathrm{flat}}$$

- C_{raw} → data
- $\lambda_{\mathrm{gen}} C_{\mathrm{gen}}$ → strong interaction
- $\lambda_{\mathrm{D}^*} C_{\mathrm{D}^*}$ → D from D*
- λ_{flat} → decays

Account for uncorrelated backgrounds:

- D mesons from beauty-hadron decays
- decay of long-living resonances
- misidentified particles

Assume no correlation



The correlation function: hadronization

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

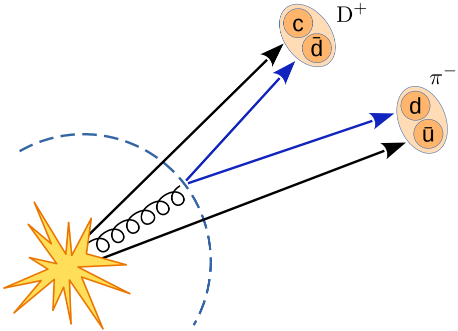
data — hadronization — strong interaction — D from D* — decays

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

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

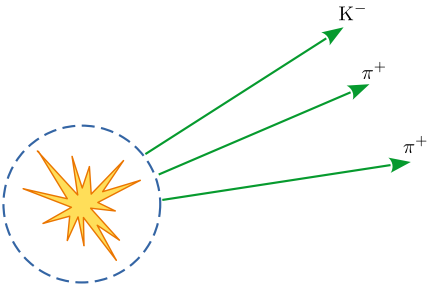
- C_{raw} → data
- $\lambda_{\text{SB}} C_{\text{SB}}$ → comb. bkg
- $C_{\text{jet-like}}$ → hadronization
- $\lambda_{\text{gen}} C_{\text{gen}}$ → strong interaction
- $\lambda_{\text{D}^*} C_{\text{D}^*}$ → D from D*
- λ_{flat} → decays

Uncorrelated π and K tracks $\rightarrow$ unphysical D mesons

- about 30% of the D candidates

Modelled with sideband (SB) invariant mass analysis:

- data-driven
- 5σ away from the nominal $\text{D}^{\pm}$ mass
- C with a pure background sample



The study of D$^{(*)}\pi$ interactions

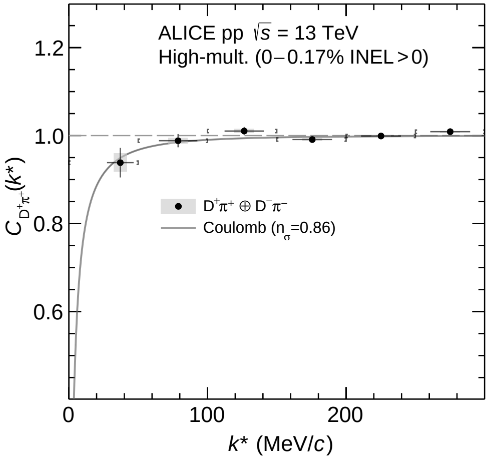
Theoretical predictions:

- lattice QCD calculations + chiral extrapolation
  - L. Liu *et al.*, Phys. Rev. D 87 014508
  - X.-Y. Guo *et al.*, Phys. Rev. D 98 014510
  - Z.-H. Guo *et al.*, Eur. Phys. J. C 79 13
- effective field theories
  - Huang *et al.*, Phys. Rev. D 15 036016
  - J. M. Torres-Rincon *et al.*, arXiv 2307.02102

The depth of the potential is tuned to reproduce the scattering lengths

Shared scattering parameters:

$$\begin{cases} a_0^{\mathrm{D}^+\pi^+} = a_0^{I=3/2} \\ a_0^{\mathrm{D}^+\pi^-} = \frac{1}{3}a_0^{I=3/2} + \frac{2}{3}a_0^{I=1/2} \end{cases}$$



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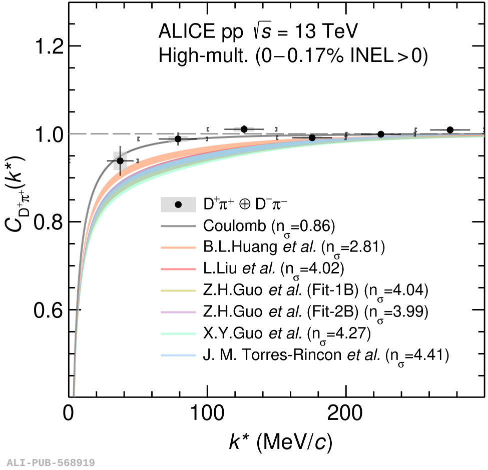
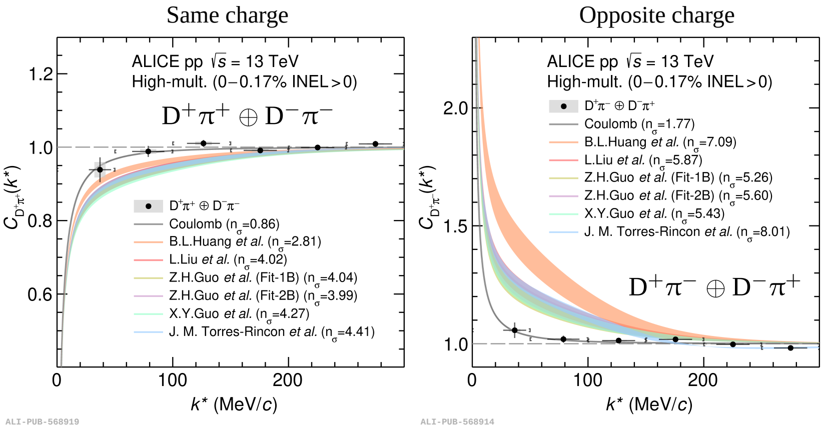


Comparisons with theoretical models: Dπ

ALICE Coll., arXiv:2401.13541



Dπ theoretical models:

- J. M. Torres-Rincon *et al.*, arXiv 2307.02102
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- Z.-H. Guo *et al.*, Eur. Phys. J. C 79 13
- L. Liu *et al.*, Phys. Rev. D 87 014508,

Results:

- tension with models
- compatible with Coulomb-only interaction

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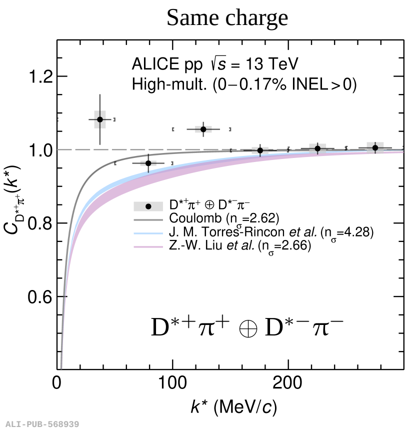

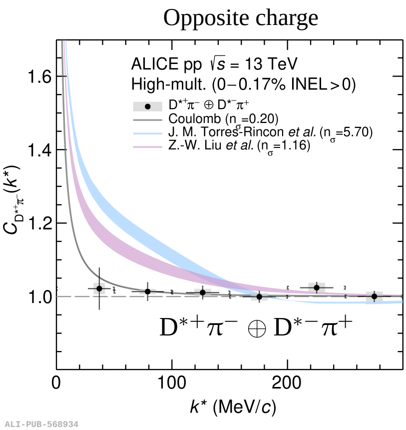

$D^*\pi$ theoretical models:

- J. M. Torres-Rincon *et al.*, arXiv 2307.02102
- Z.-W. Liu *et al.*, Phys. Rev. D 84, 034002

Results:

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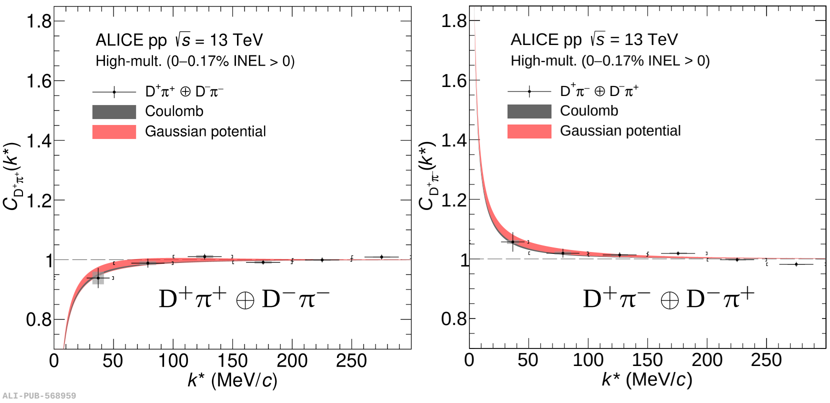
- compatible with Coulomb-only interaction

Extraction of the scattering parameters

ALICE Coll., arXiv:2401.13541

Same charge

Opposite charge



Effective gaussian potential model:

$V(V_0, r) = V_0 e^{-(m_\rho r)^2}$

Y. Kamiya, Phys. Rev. Lett. 124, 132501 (2020)

- V0: adjustable parameter
- m_ρ: range of the interaction

Simultaneous fit of the two scattering lengths

Extraction of the scattering parameters

ALICE Coll., arXiv:2401.13541

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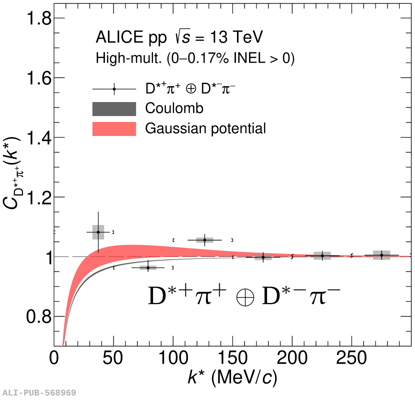
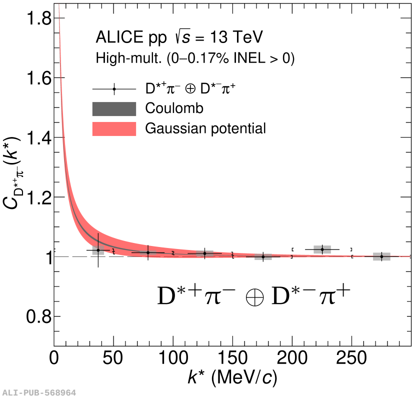


Opposite charge



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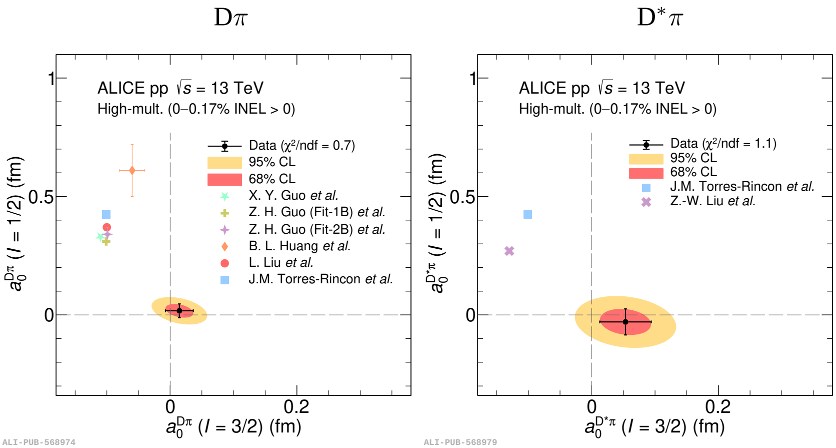
ALICE Coll., arXiv:2401.13541



Small scattering lengths:

- compatible with Coulomb-only assumption
- theoretical models overestimate the strength of the interaction

Scattering lengths are similar for Dπ and D$^*\pi$:

- heavy-quark spin symmetry

Charm hadron femtoscopy in Run 3

Run 3 data-taking period (2022-ongoing):

- upgraded ITS $\rightarrow$ better pointing resolution
- upgraded TPC $\rightarrow$ continuous readout
- larger luminosity

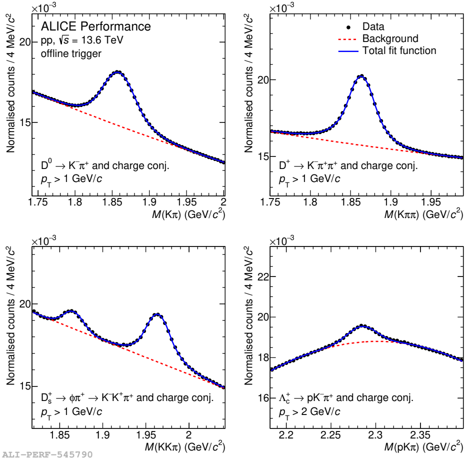
Offline software triggers with machine learning for:

- D^0p and $\overline{D}^0p$
- $D^{\pm}p$, $D_s^{\pm}p$, and $\Lambda_c^{\pm}p$

The study of charm-hadrons interactions will be refined and extended to other systems

- $\Lambda_c^+ p \rightarrow$ charm nuclei

S. Maeda *et al.*, PTEP 2016 (2016) 2, 023D02



ALICE 3: a next generation heavy-ion experiment

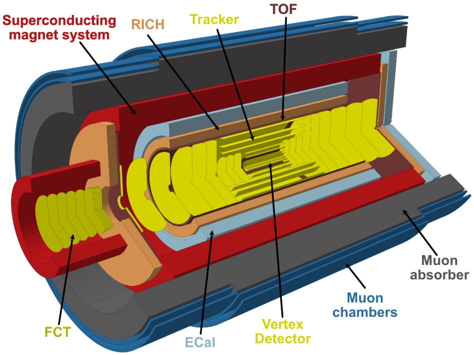
Planned for the Run 5 and Run 6 (2035–2040)

- large-area silicon detector
- stronger magnetic field: 2 T (0.5 T in ALICE 2)

Main improvements:

- vertex resolution ≈ 2 µm (in Run 2 ≈ 100 µm)
- large acceptance: $|\eta| < 4$
- large luminosity $\mathcal{L}_{\text{int}} = 18\ \text{fb}^{-1}$

ALICE Coll., arXiv:2211.02491



Charm hadron femtoscopy with ALICE 3: T_{cc}^{+}

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

- binding energy $\approx$ 360 keV
- scattering length = $(-7.16 + i1.85)$ fm

LHCb Coll., Nat. Com. 13 3351

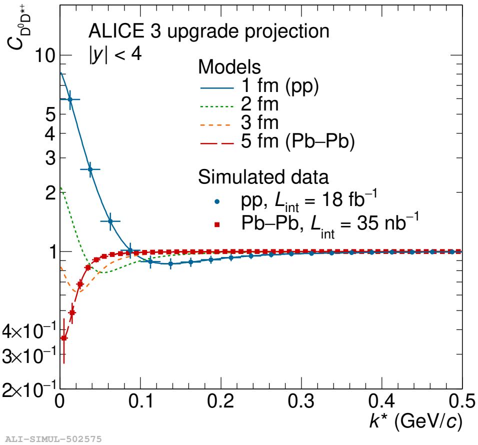
Prediction for the D D^{*} interaction:

Y. Kamiya *et al.*, Eur. Phys. J. A 58 (2022) 7, 131

- assume that T_{cc}^{+} is a molecule
- effective gaussian potential model
- coupled channel dynamics

Pythia simulation scaled to the expected luminosity

ALICE Coll., arXiv:2211.02491

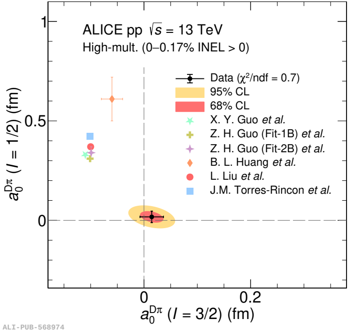


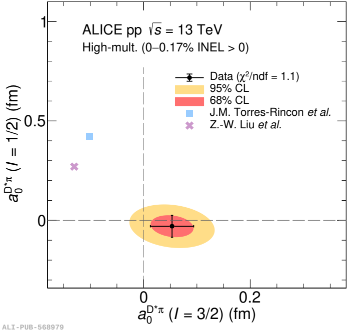
Conclusions

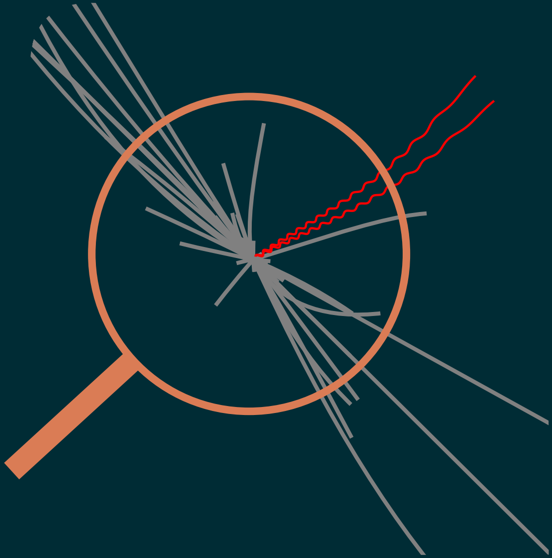
Results of charm femtoscopy:

- small scattering length $\rightarrow$ shallow interactions
- Dπ and D$^*\pi$ interactions are similar $\rightarrow$ heavy-quark spin symmetry

Rescattering in heavy-ion collisions $\rightarrow$ expected to be very small







Additional material

Rescattering of D mesons in heavy-ion collisions

What is the impact of the rescattering on the heavy-ion observables?

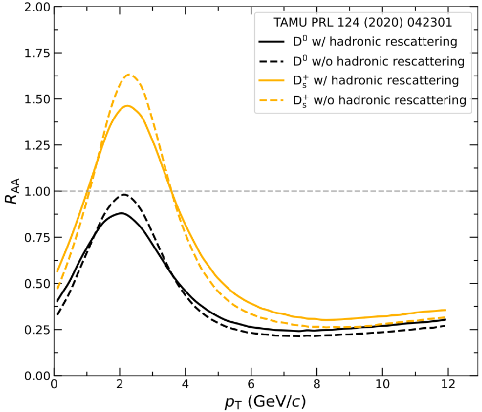
In heavy-ion collisions:

- quark–gluon plasma (QGP) formation
- system expansion and chemical freeze-out
- hadron gas

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- sensitive to the energy loss of the c quark
- modified by the rescattering



M. He and R. Rapp, Phys. Rev. Lett. 124 042301