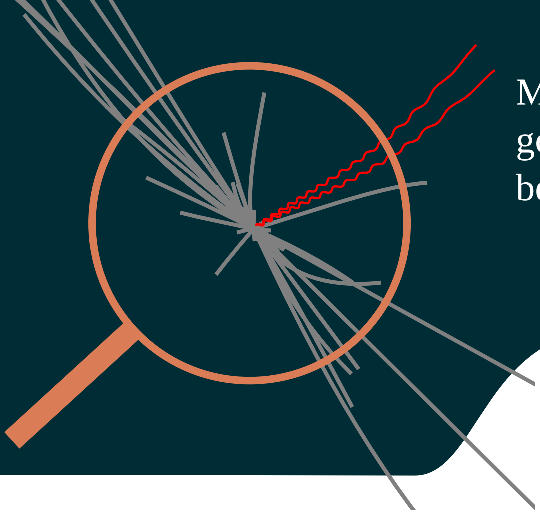

Measurement of scattering parameters governing the residual strong interaction between charm and light hadrons

Daniel Battistini, on behalf of the ALICE Collaboration

Technical University of Munich

LHCP 2023 | Belgrade, Serbia

LHCPhysics Belgrade, 22 - 26 May 2023

CERN

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ALICE

D mesons in heavy-ion collisions

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

In heavy-ion collisions:

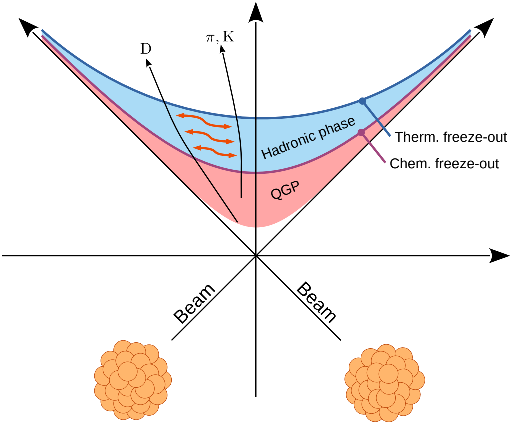
- quark–gluon plasma (QGP) formation
- system expansion and chemical freeze-out
- hadron gas $\rightarrow$ D meson rescattering

Current knowledge:

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

Modification of the heavy-ion observables:

- relies on theory

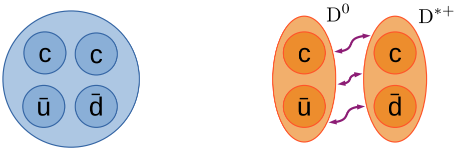


The nature of exotic charm states

What is the nature of the exotic charm states?

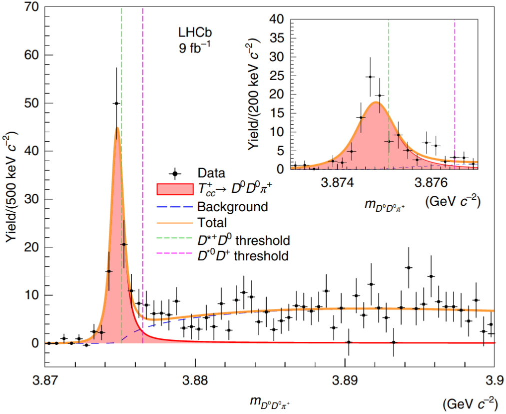
Several non-conventional hadrons were discovered:

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



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

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



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

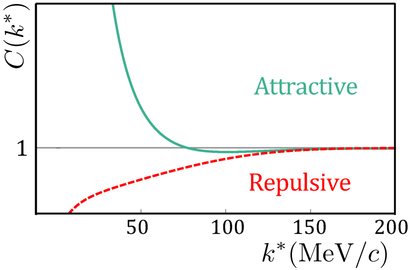
The correlation function

Physics observable: correlation function (CF)

Koonin-Pratt formula ⇝ M. A. Lisa, S. Pratt *et al.*, ARNPS 55 357402

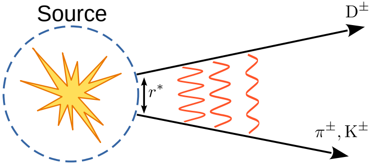
$$C(k^*) = \underbrace{\xi(k^*)\frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}}_{\text{experiment}} = \underbrace{\int \mathrm{d}\boldsymbol{r}^*\, S(\boldsymbol{r}^*)|\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2}_{\text{theory}}$$

where $k^* = |\boldsymbol{p}_1^* - \boldsymbol{p}_2^*|/2 \quad \rightarrow \quad$ pair rest frame



⇝ ALICE Coll., Nature 588, 232–238

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: $r^* \sim 1$ fm

Experimental setup

Analyzed data:

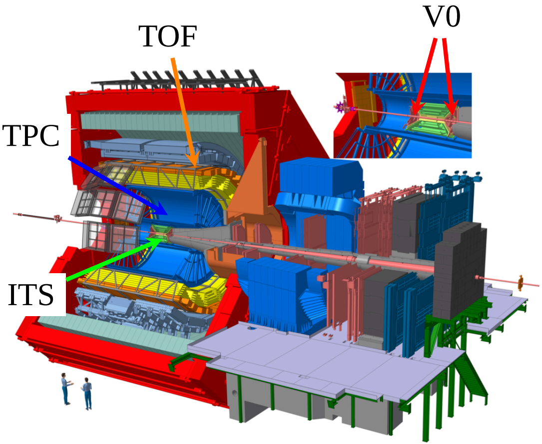
- Run 2 data, collected by ALICE
  - ⇝ ALICE Coll., IJMP A 2014 29:24
- proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$
- high-multiplicity trigger (V0)

Particle identification (PID) and reconstruction:

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

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

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



The correlation function: genuine interaction

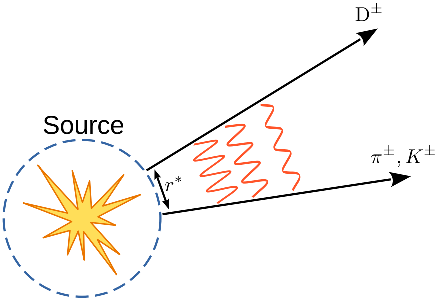
$$C_{\text{raw}} = \lambda_{\text{gen}} C_{\text{gen}}$$

C_{raw} → data

$\lambda_{\text{gen}} C_{\text{gen}}$ → strong interaction

Primary signal particles → genuine CF

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



Source function from the universal m_{T}-scaling

⇝ 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

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

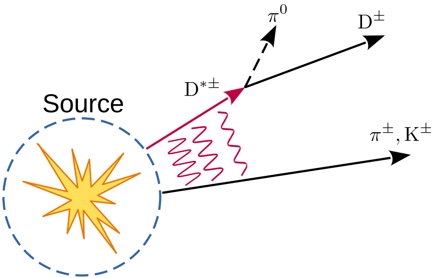
data | strong interaction | D from D*

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-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

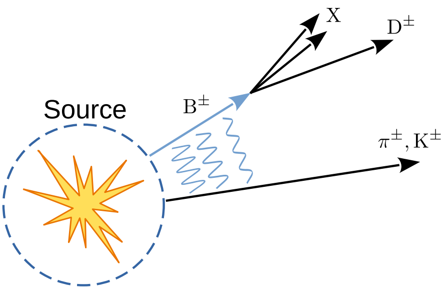
$$C_{\text{raw}} = \lambda_{\text{gen}} C_{\text{gen}} + \lambda_{\text{D}^*} C_{\text{D}^*} + \lambda_{\text{flat}}$$

data — 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. $\pi \rightarrow \text{K}$

Assume no correlation $\Rightarrow \quad C(k^*) = 1$



The correlation function: hadronization

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

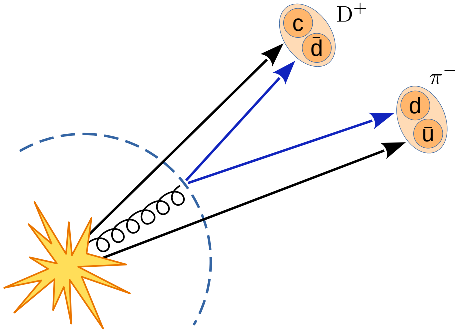
- C_{raw} → data
- $C_{\text{jet-like}}$ → hadronization
- $\lambda_{\text{gen}} C_{\text{gen}}$ → strong interaction
- $\lambda_{\text{D}^*} C_{\text{D}^*}$ → D from D*
- λ_{flat} → decays

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

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

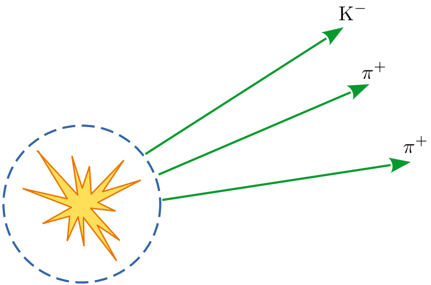
- C_{raw} → data
- $\lambda_{\text{SB}} C_{\text{SB}}$ → comb. bkg
- $C_{\text{jet-like}}$ → hadronization
- $\lambda_{\text{gen}} C_{\text{gen}}$ → strong interaction
- $\lambda_{\text{D}^*} C_{\text{D}^*}$ → D from D*
- λ_{flat} → decays

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

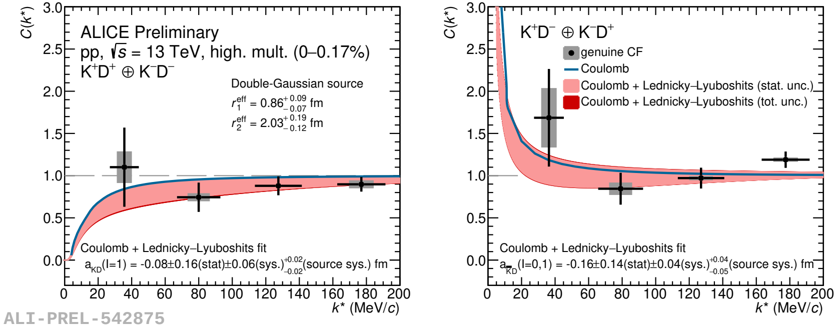
- about 30% of the D candidates

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

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



Experimental results for DK



Fit with the Lednický-Lyuboshits (LL) model → scattering parameters

⇝ M. Gmitro, J. Kvasil, R. Lednický and V. L. Lyuboshitz, Czech. J. Phys. B 36 1281 1287

- $a_{\text{KD}}(I = 1) = -0.08 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})^{+0.02}_{-0.02}(\text{source})$ fm
- $a_{\bar{\text{K}}\text{D}}(I = 0, 1) = -0.16 \pm 0.14(\text{stat}) \pm 0.04(\text{syst})^{+0.04}_{-0.05}(\text{source})$ fm

Comparisons with theoretical models: DK

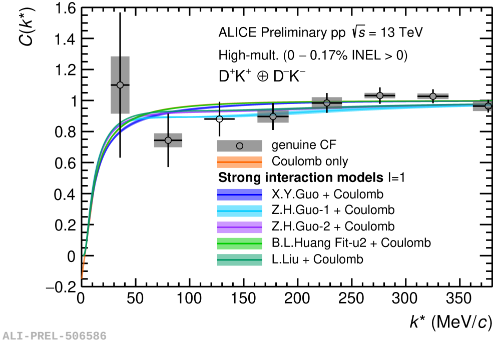
DK scattering parameters from theoretical models

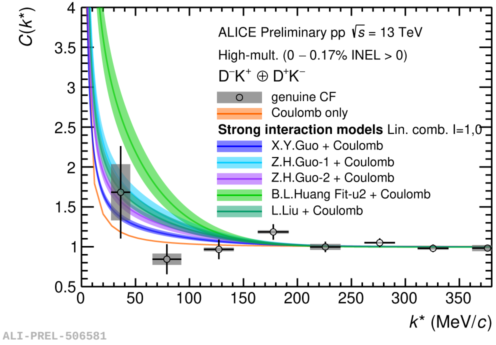
- ⇝ L. Liu et al, PRD 87 014508,
- ⇝ X.-Y. Guo et al, PRD 98 014510
- ⇝ Huang et al, PRD 15 036016,
- ⇝ Z.-H. Guo et al, EPJC 79 13

CFs: gaussian potential + Koonin-Pratt formula

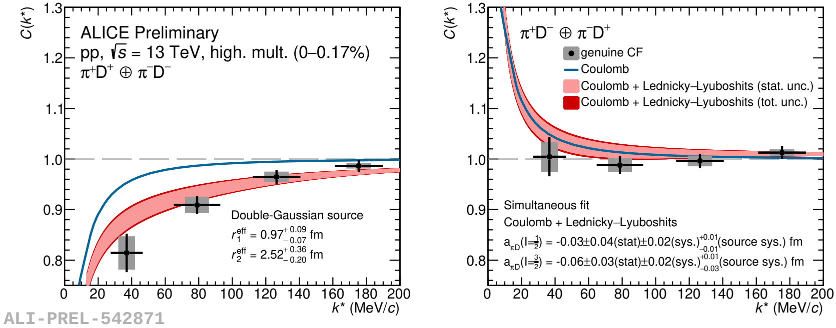
Results:

- compatible with all theoretical models
- improve precision with Run 3 data





Experimental results for Dπ



Combined fit with the LL model → scattering parameters

⇝ M. Gmitro, J. Kvasil, R. Lednický and V. L. Lyuboshitz, Czech. J. Phys. B 36 1281 1287

- $a_{\pi\mathrm{D}}\left(I=\frac{1}{2}\right) = -0.03 \pm 0.04(\mathrm{stat}) \pm 0.02(\mathrm{syst})^{+0.01}_{-0.01}(\mathrm{source})$ fm
- $a_{\pi\mathrm{D}}\left(I=\frac{3}{2}\right) = -0.06 \pm 0.03(\mathrm{stat}) \pm 0.02(\mathrm{syst})^{+0.01}_{-0.03}(\mathrm{source})$ fm

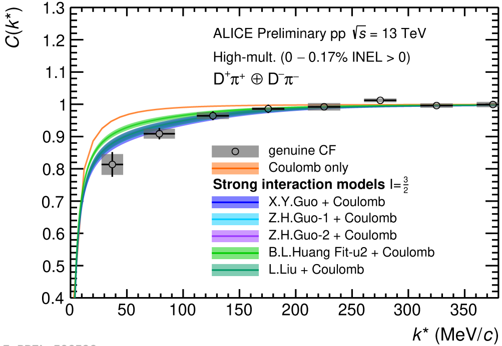
Comparisons with theoretical models: $D\pi$

$D\pi$ 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

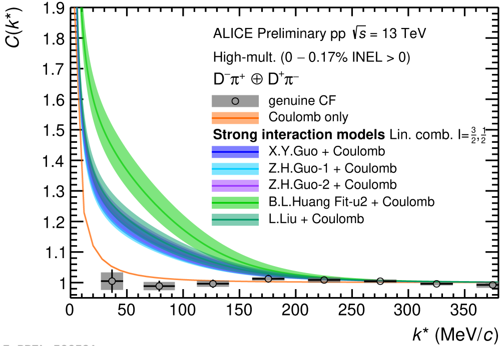
CFs: gaussian potential + Koonin-Pratt formula

Same charge: agreement



ALI-PREL-506596

Opposite charge: discrepancy



ALI-PREL-506591

Charm hadron femtoscopy with ALICE 3

ALICE 3: a next generation experiment

$\longrightarrow$ for details: R. Münzer, PlS5, ALICE upgrades

The study of exotic charm states will be possible

$\rightsquigarrow$ ALICE Coll., arXiv:2211.02491

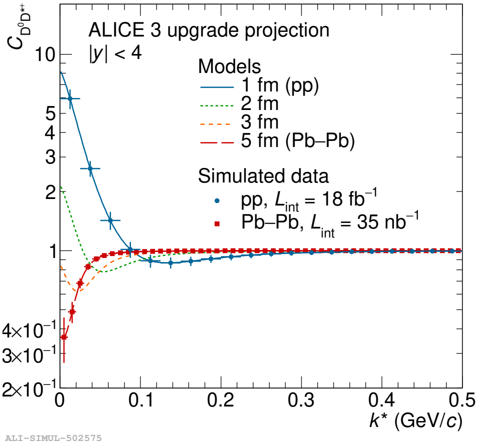
Test the formation of DD^* and $\mathrm{D\bar{D}}^*$ bound states:

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

Upgrade projection:

- assume a gaussian potential
- scan different source radii

Bound state $\rightarrow$ depletion in the CF



Conclusions

Femtoscopy with charm hadrons? It's possible!

- first measurement of Dπ, DK scattering parameters

Dπ interaction, comparison with theory:

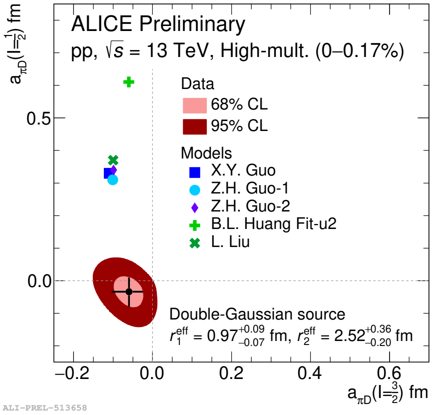
- $I = 3/2$: compatible
- $I = 1/2$: not compatible

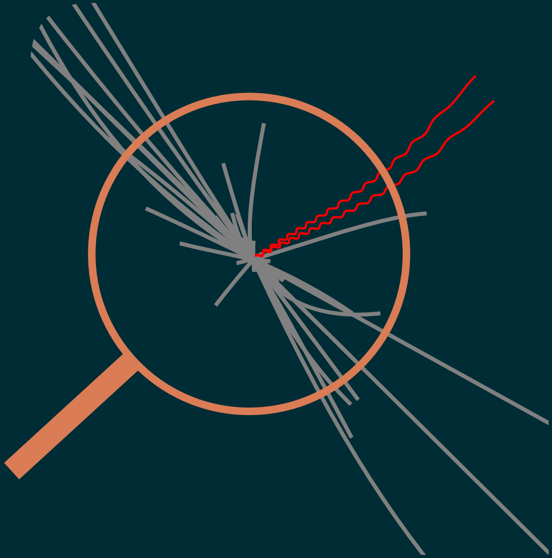
Shallow interaction in all cases:

- small impact on heavy-ion observables

Outlook

- Run 3 $\rightarrow$ improvement on statistics and precision
- ALICE 3 $\rightarrow$ DD* bound states studies

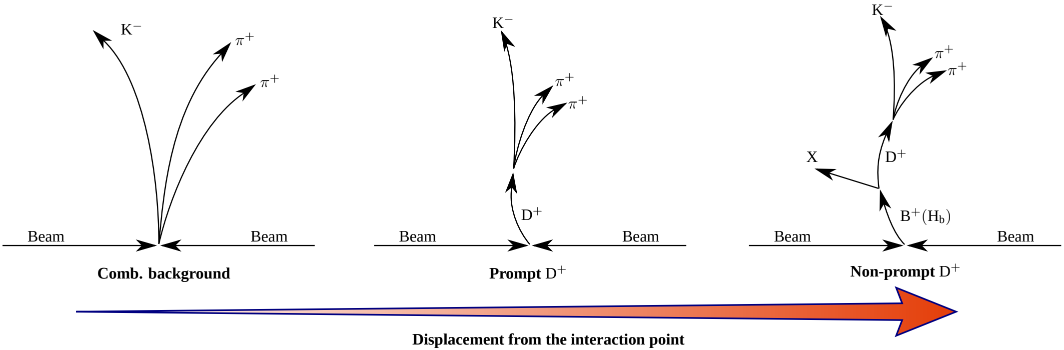




Additional material

Selection of $D^{\pm}$ mesons

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

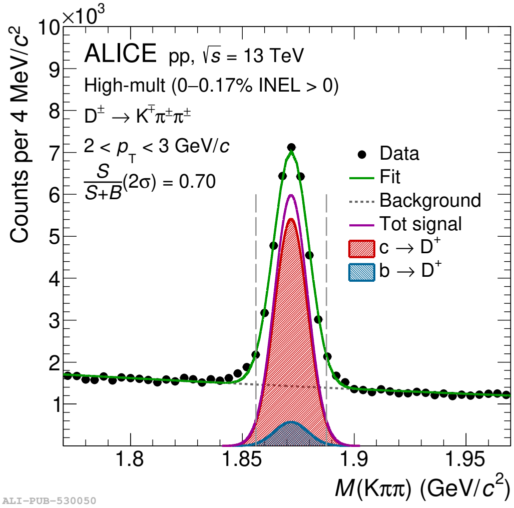


$D^{\pm}$ reconstruction performance

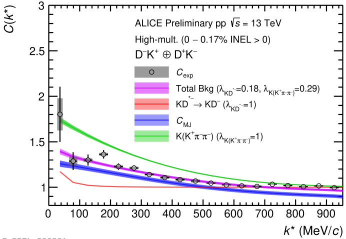
Fit to the invariant mass of the $D^{\pm}$ candidates:

- signal $\rightarrow$ gaussian
- background $\rightarrow$ exponential
- purity ~70%

Data-driven separation between prompt and non-prompt



Corrections to the CF



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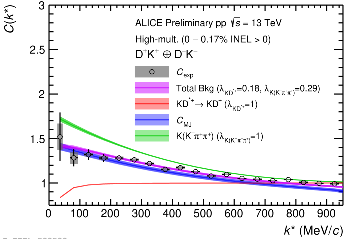
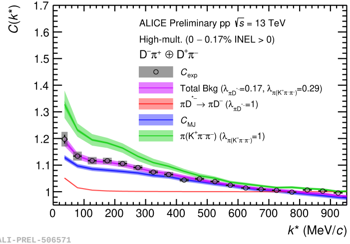


ALI-PREL-506566



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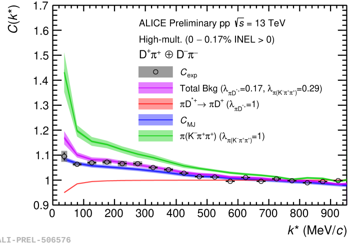

ALI-PREL-506576

Scattering parameters - theoretical predictions

Scattering parameters from theoretical models

Channel	(Spin, Isospin)	Scattering parameters for different models (fm)				
		L. Liu et al	X.-Y. Guo et al	B.-L. Huang et al	Z.-H. Guo 1 et al	Z.-H. Guo 2 et al
Dπ	(0, 3/2)	-0.10	-0.11	-0.06	-0.101	-0.099
	(0, 1/2)	0.37	0.33	0.61	0.31	0.34
DK	(1, 1)	0.07 + 0.17i	-0.05	-0.01	0.06 + 0.30i	0.05 + 0.17i
DK	(-1, 0)	0.84	0.46	1.81	0.96	0.68
	(-1, 1)	-0.20	-0.22	-0.24	-0.18	-0.19

References:

- 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

The Lednický-Lyuboshits model

To fit the correlation function:

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

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

Reference:

⇝ M. Gmitro, J. Kvasil, R. Lednický and V. L. Lyuboshitz, Czech. J. Phys. B 36 1281 1287