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

arXiv:2401.13541

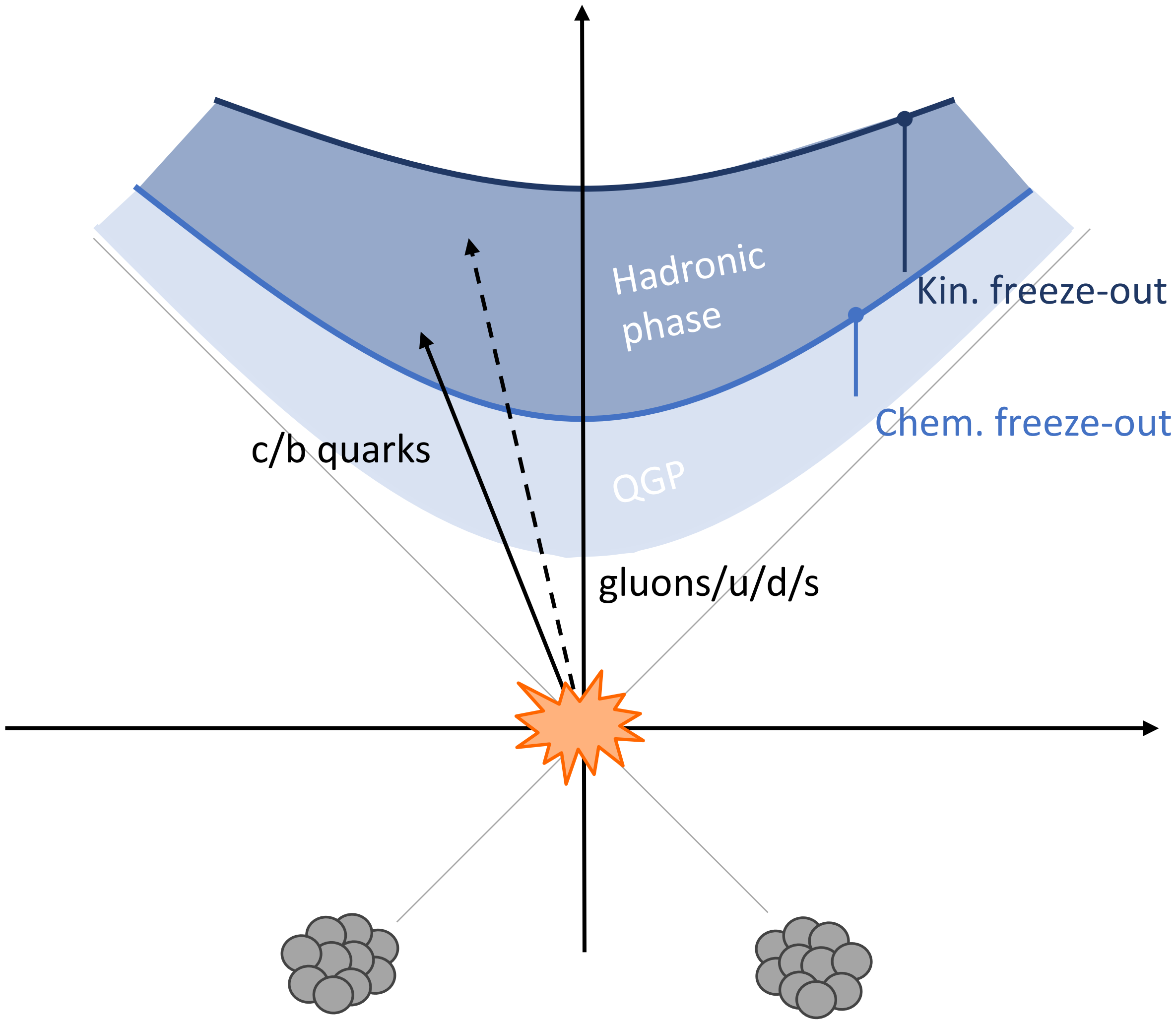
Emma Chizzali, on behalf of the ALICE Collaboration

60th International Winter Meeting on Nuclear Physics, Bormio, Italy

23/01/2024

Heavy-flavor particles and the QGP

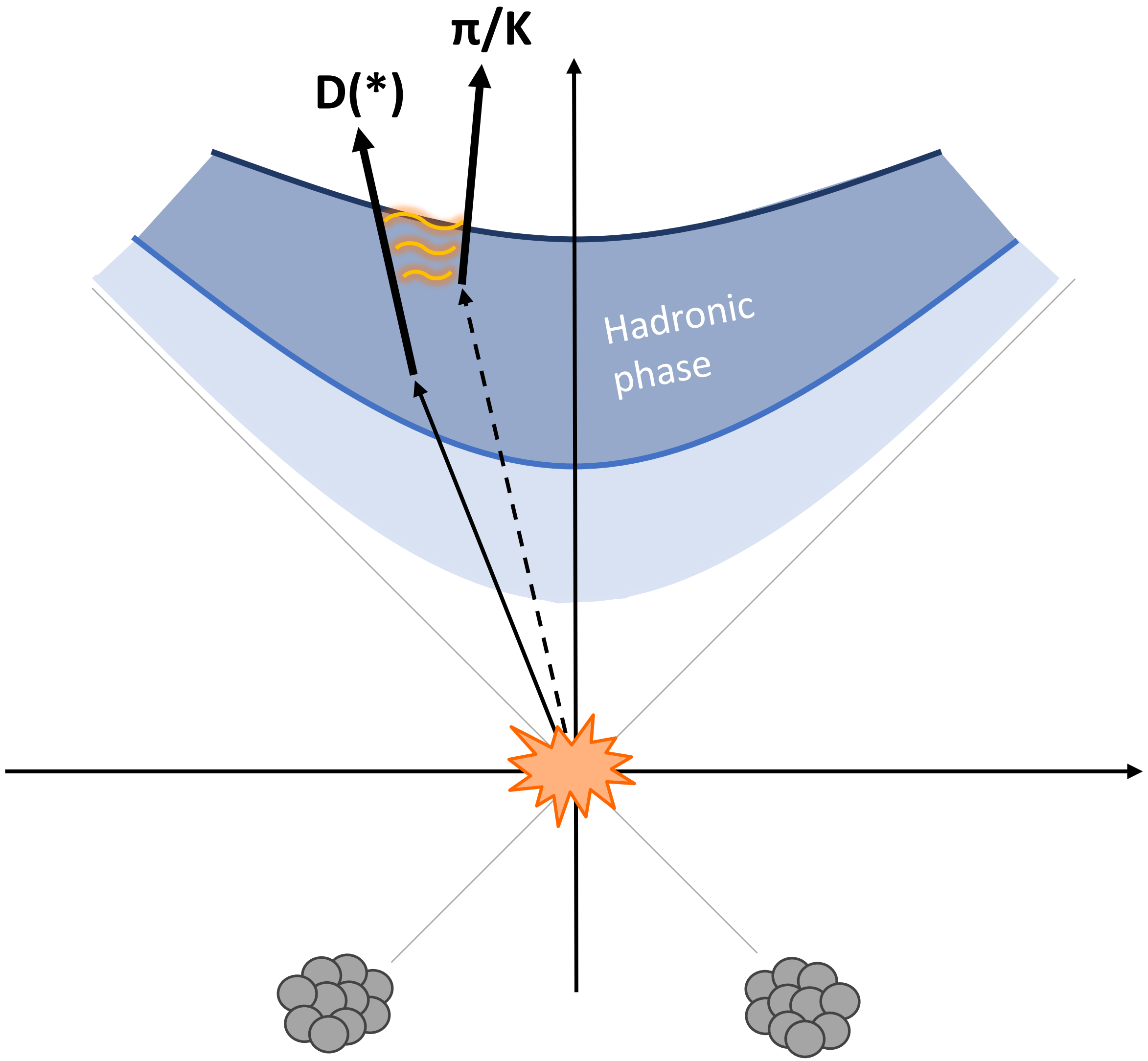
- Heavy quarks (HQ) produced in heavy-ion collision
  - Thermal equilibration time expected to be of the order of QGP lifetime
  - Ideal probes of the QGP



Heavy-flavor particles and the QGP

- Heavy quarks (HQ) produced in heavy-ion collision
  - Thermal equilibration time expected to be of the order of QGP lifetime
  - Ideal probes of the QGP
- During hadronic phase, D meson **rescattering** has to be considered
  - Modifies heavy-ion observables
  - Models depend on the scattering lengths between D meson and light hadrons
    → No experimental constraints

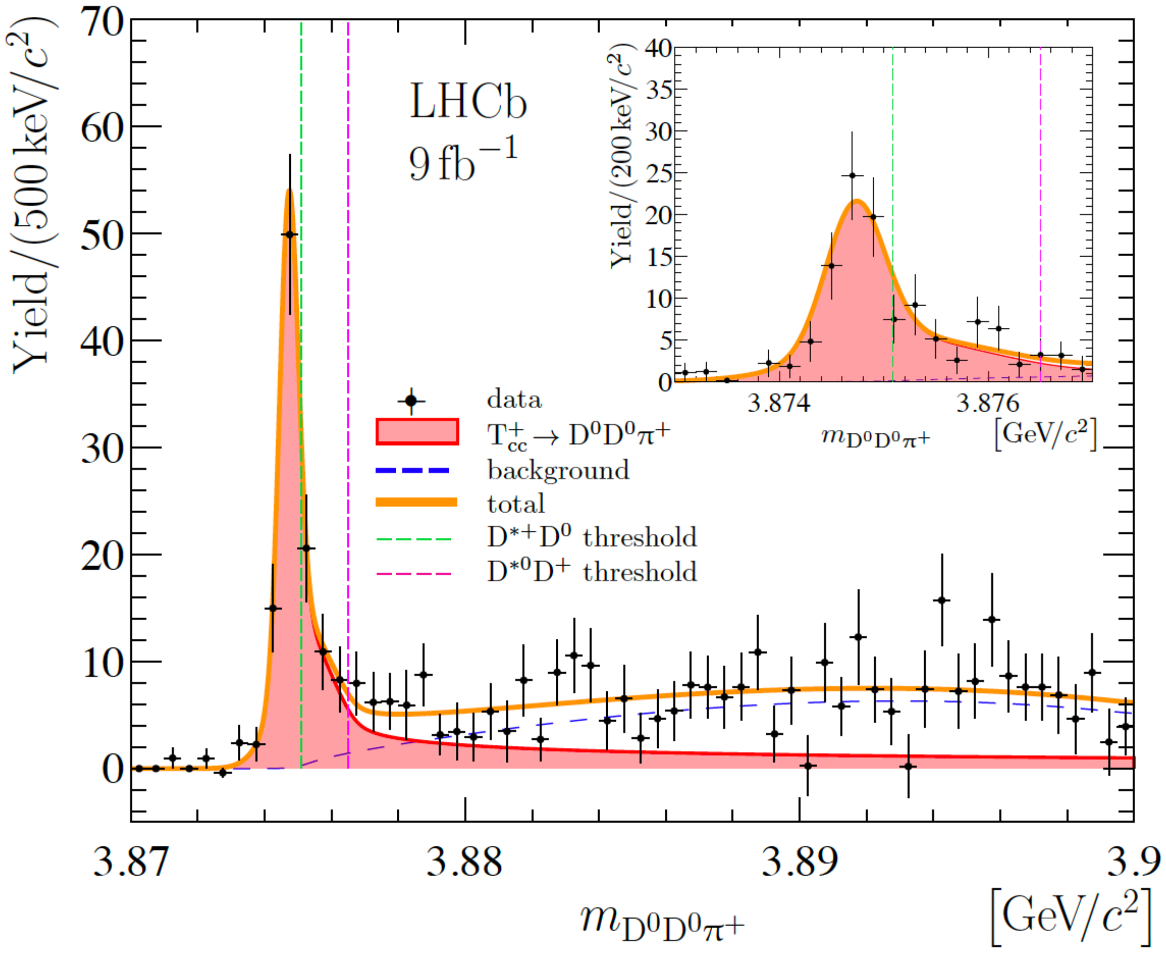
R. Rapp et al., *Phys. Lett. B* **701** (2011) 445-450
R. Rapp et al., *Phys. Lett. B* **735** (2014) 445–450
R. Rapp et al., *Phys. Rev. Lett.* **124** (2020) 042301



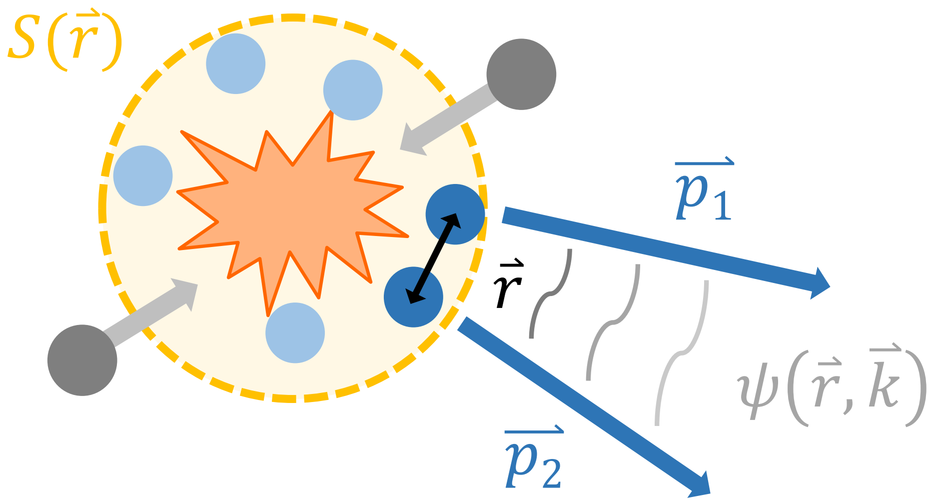
Exotic states

- Strong final-state interaction (FSI) can lead to formation of bound or molecular states
- Several new states observed
  - Hidden charm and/or beauty (XYZ states)
    A. Hosaka et al., *PTEP* **2016 no. 6** (2016) 062C01
    LHCb Collab, *JHEP* **07** (2019) 035
  - Open charm (T_{cc})
    LHCb Collab., *Nat. Phys.* **18** (2022) 751–754
  - Pentaquark states (e.g., $P_c(4380)$, $P_c(4450)$)
    LHCb Collab., *Phys. Rev. Lett.* **115** (2015) 072001
    LHCb Collab., *Phys. Rev. Lett.* **122 no. 22**, (2019) 222001
- Measurement of the strong FSI needed to determine nature of states

LHCb Collab., *Nat. Phys.* **18** (2022) 751–754



The correlation function



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

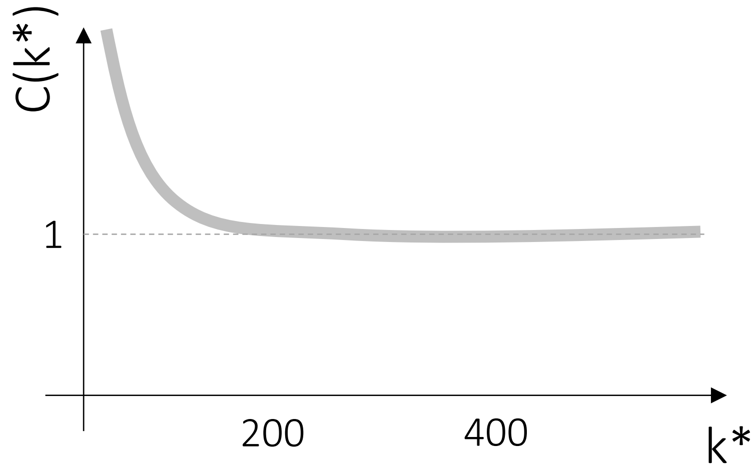
experimental definition — theoretical definition

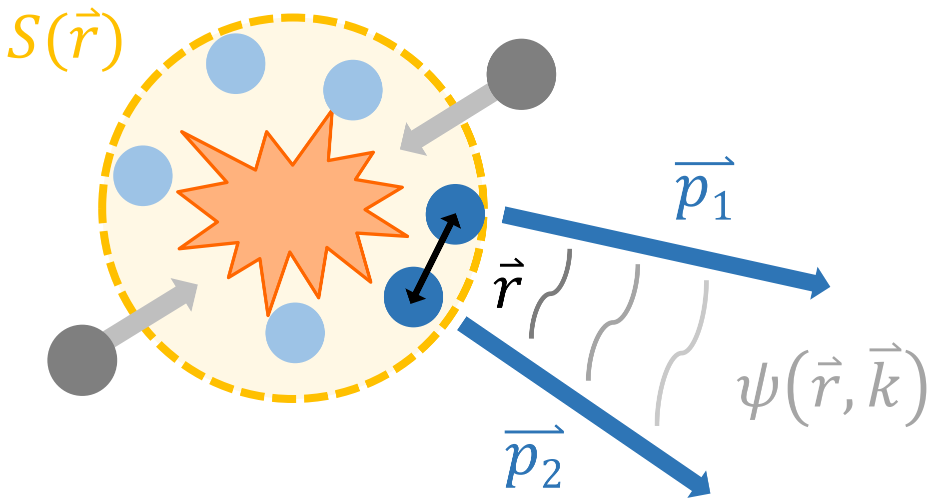
S. E. Koonin, *Phys. Lett. B* **70** (1977) 43-47
S. Pratt, *Phys. Rev. C* **42** (1990) 2646-2652

Relative momentum $\vec{k}^* = \frac{1}{2} \mid \vec{p}_1^* - \vec{p}_2^* \mid$ and $\vec{p}_1^* + \vec{p}_2^* = 0$

Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

The correlation function





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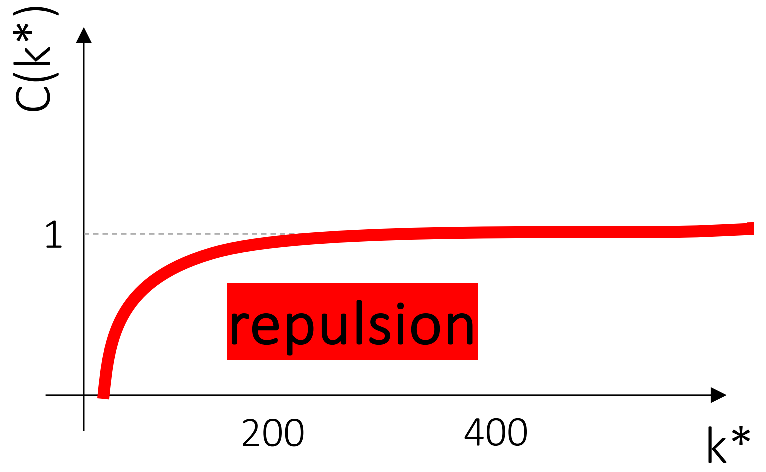

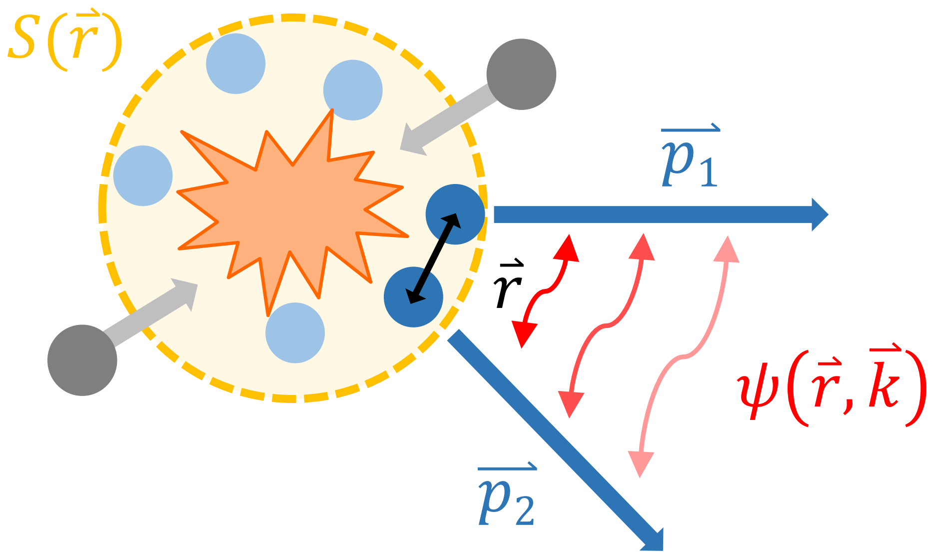

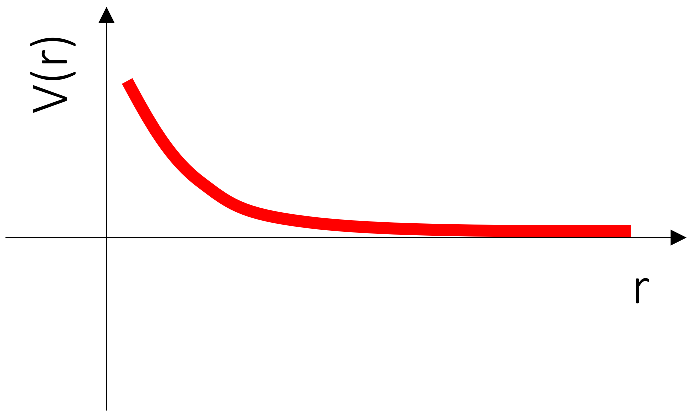

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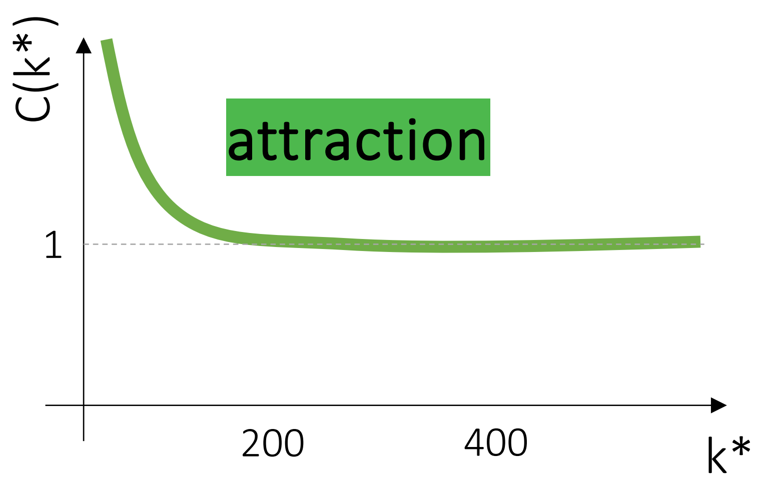

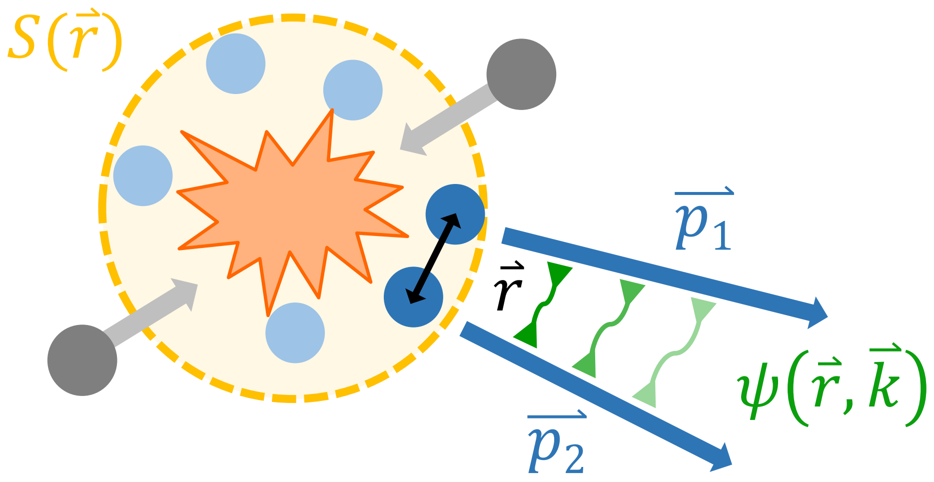

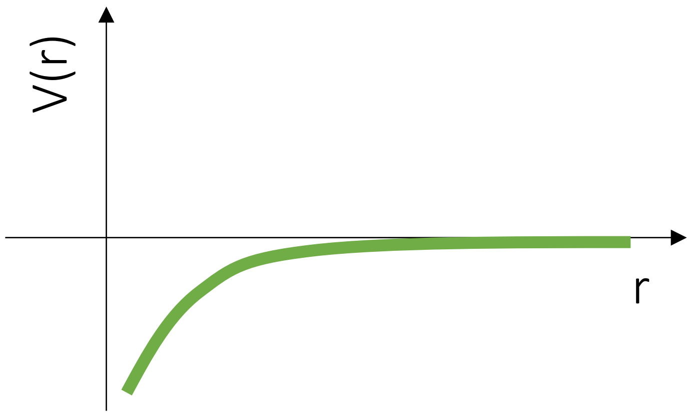

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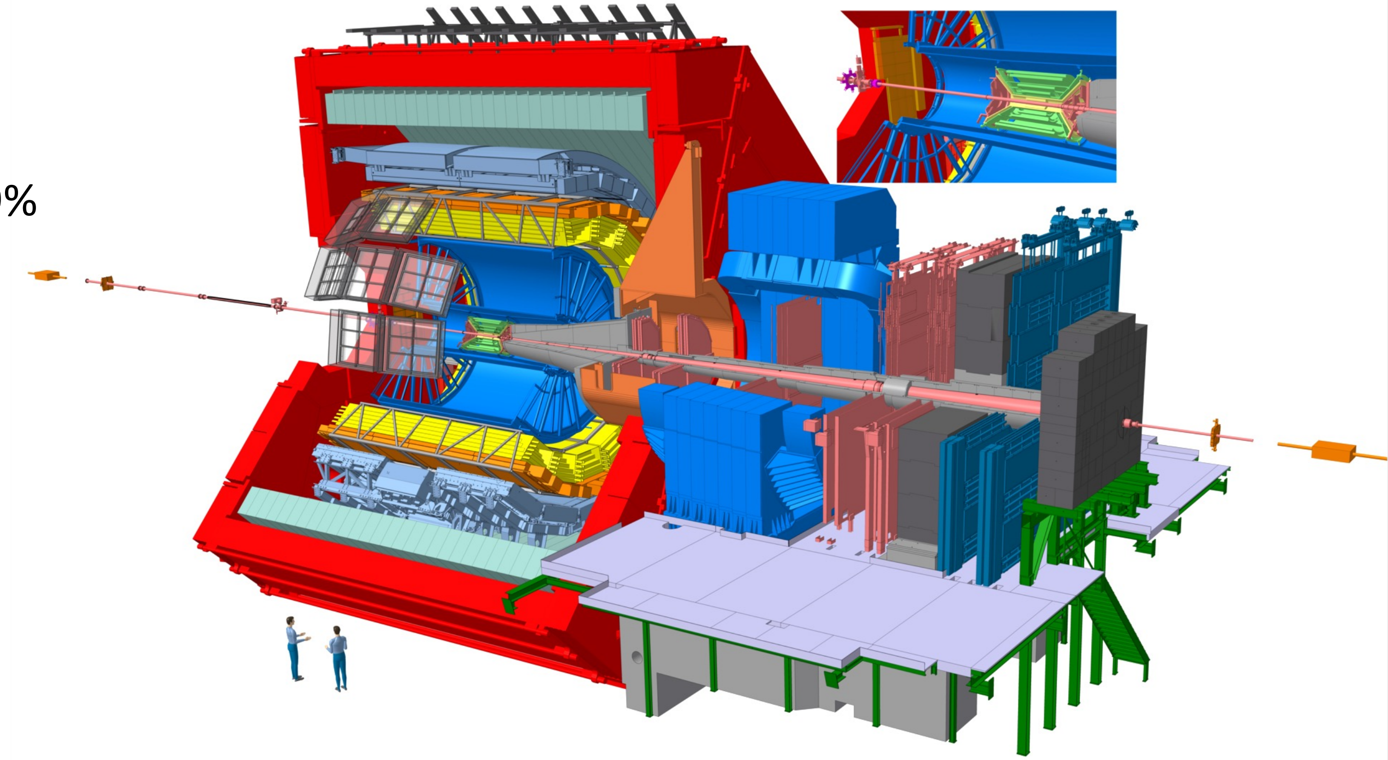
ALICE

- LHC Run 2 dataset (2016-2018)
- High multiplicity (HM) pp collisions at $\sqrt{s}$ = 13 TeV
- Excellent PID with ALICE detector
  - Momentum resolution $\sigma(p_T)/p_T \sim O(1\%)$
    M. Ivanov *Nuclear Physics* **A** 904–905 (2013) 162c–169c
  - Primary charged particle (p, K, π) purities up to 99%
  - D and D* mesons reconstructed using machine learning → purities ~70%



ALICE-PHO-SKE-2017-001

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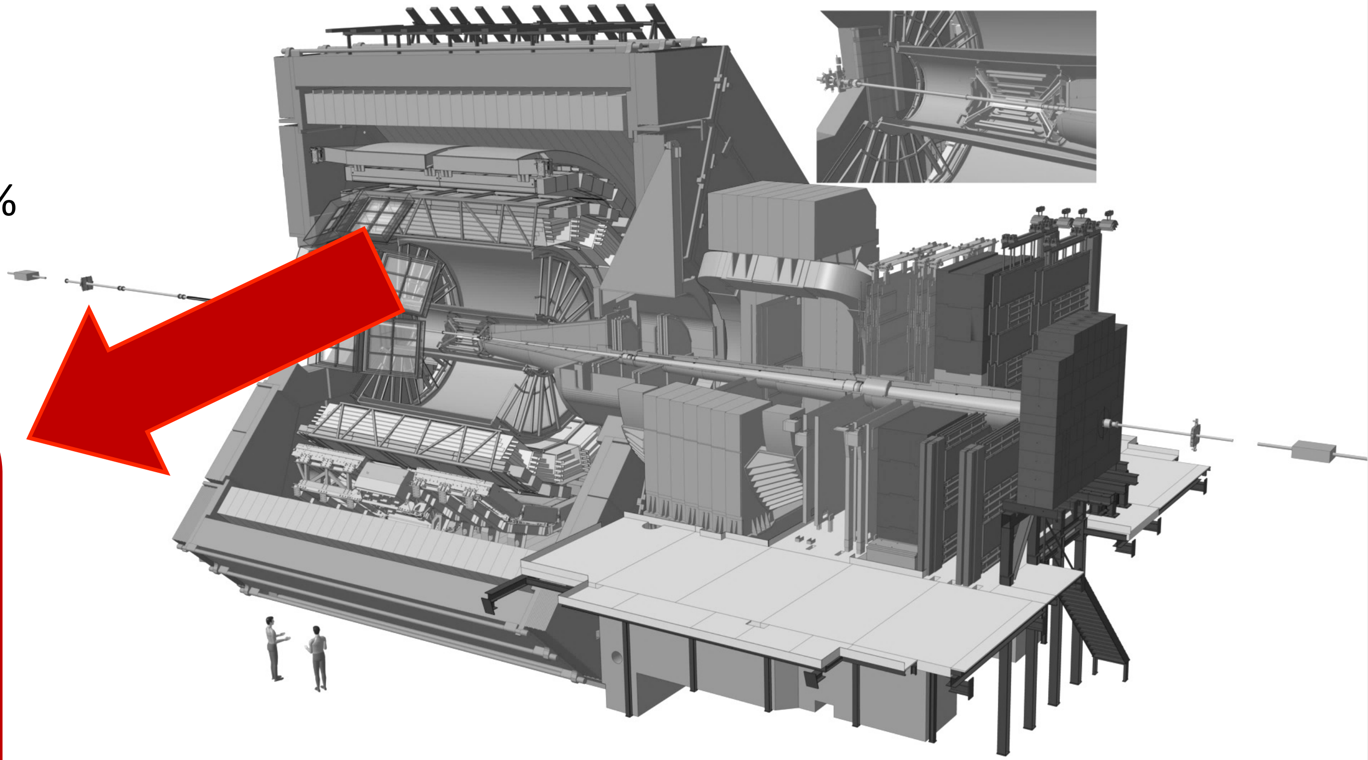
Use correlation data to study residual final state interaction among
D−K, D−π, D*−K, D*−π

Approach already successfully applied to study D-p system
Alice Collab. *Phys. Rev. D* **106** (2022) 052010



ALICE-PHO-SKE-2017-001

Genuine correlation function

- Measurement of D(*)-K and D(*)-π correlation functions for same charge (SC) and opposite charge (OC) configuration
- Sensitive to **Coulomb** and **strong** interaction

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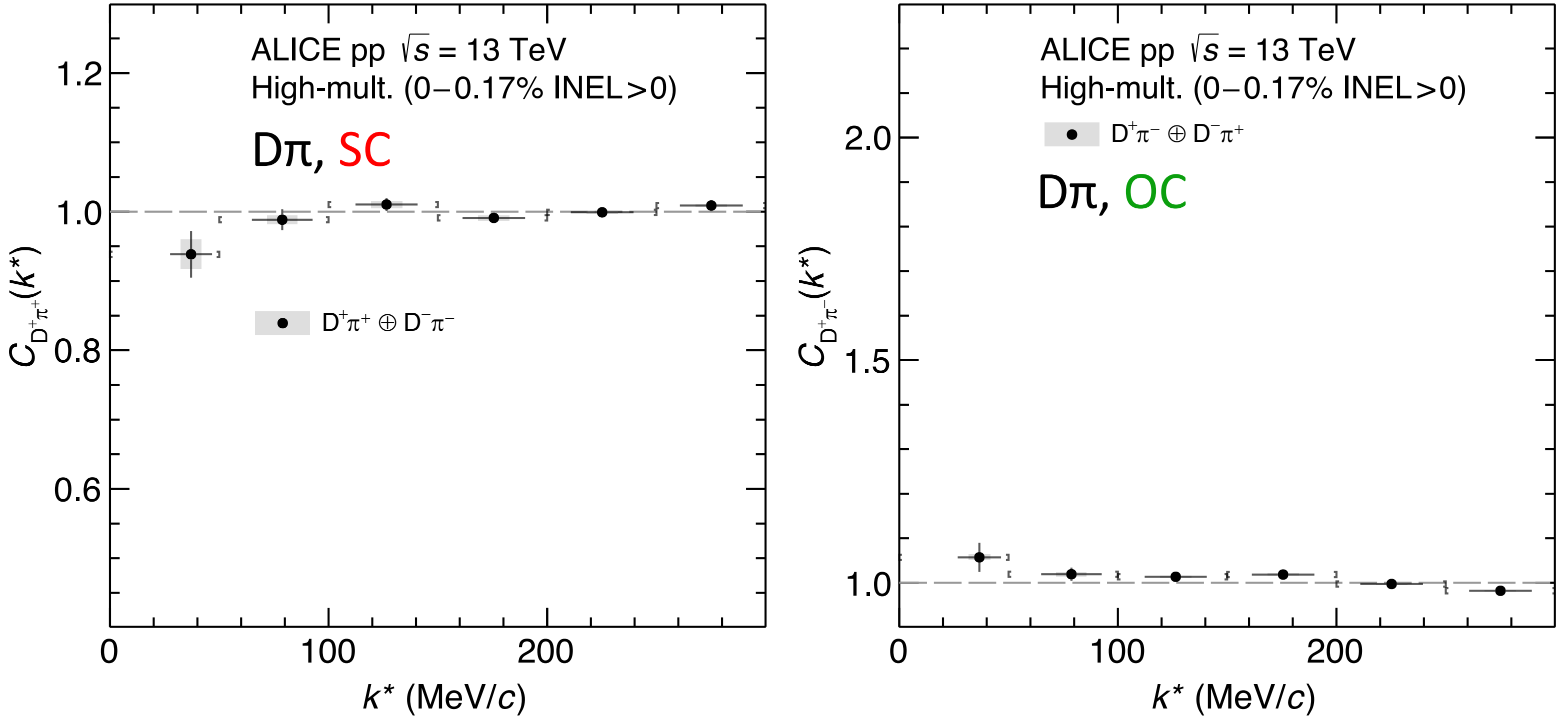

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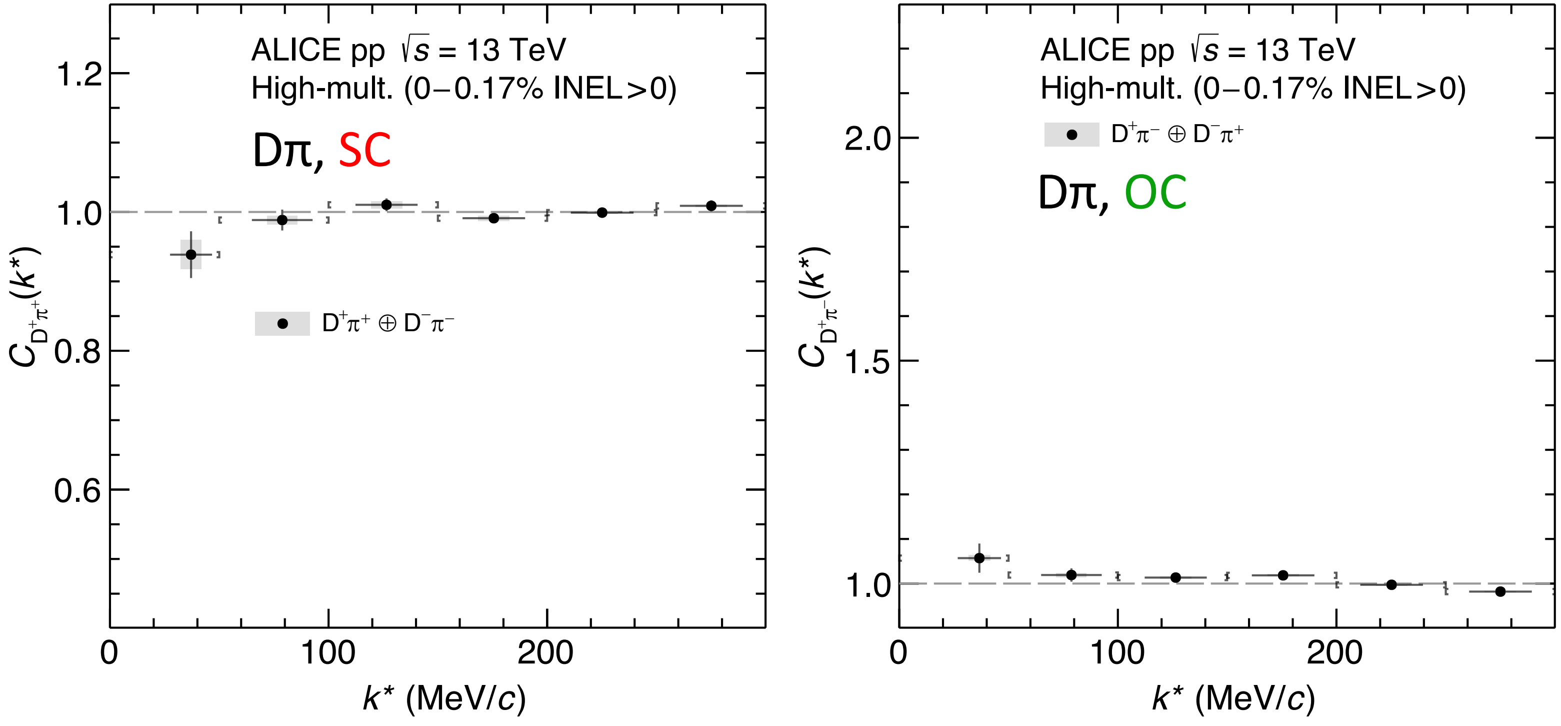
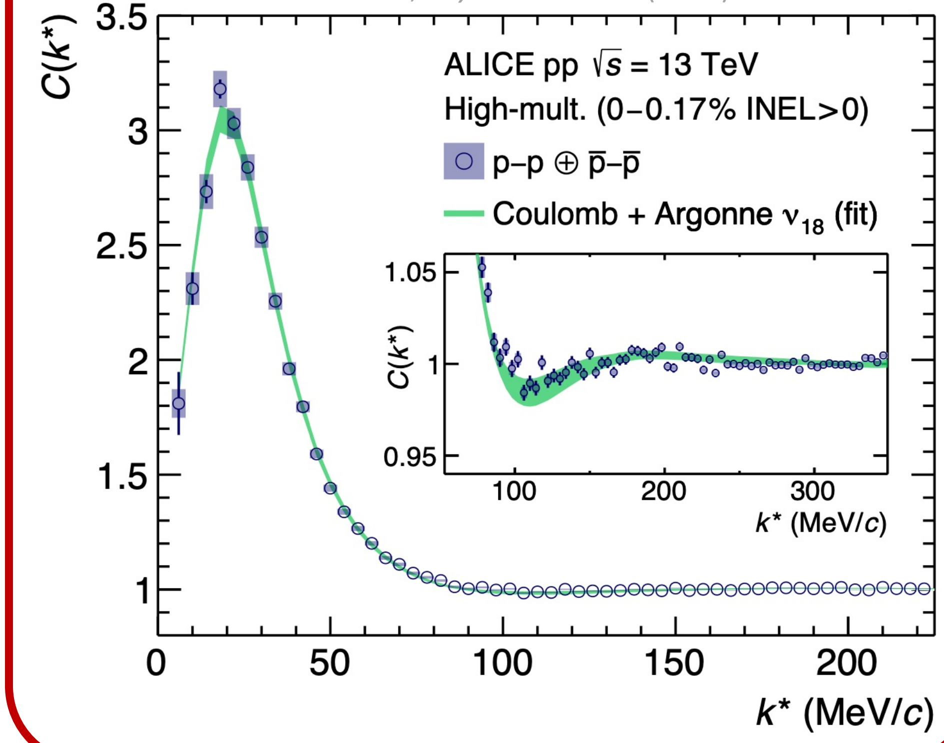


Comparison to NN system

ALICE Collab., *Phys. Lett. B* **805** (2020) 135419



D-light meson scattering lengths

ALICE

Channel	(S,I)	L. Liu *et al.*	X.-Y. Guo *et al.*	Z.-H. Guo *et al.* Fit-1B	Z.-H. Guo *et al.* Fit-2B	B.-L. Huang *et al.*	J. M. Torres-Rincon *et al.*
Dπ	(0,3/2)	-0.10 fm	-0.11 fm	-0.101 fm	-0.099 fm	-0.06 fm	-0.101 fm
	(0,1/2)	0.37 fm	0.33 fm	0.31 fm	0.34 fm	0.61 fm	0.423 fm
DK	(1,1)	0.07+i0.17 fm	-0.05 fm	0.06+i0.30 fm	0.05+i0.17 fm	-0.01 fm	-0.027+i0.083 fm
$D\bar{K}$	(-1,0)	0.84 fm	0.46 fm	0.96 fm	0.68 fm	1.81 fm	0.399 fm
	(-1,1)	-0.20 fm	-0.22 fm	-0.18 fm	-0.19 fm	-0.24 fm	-0.233 fm

Lattice QCD + chiral extrapolation (L. Liu *et al.*, X.-Y. Guo *et al.*, Z.-H. Guo *et al.*)

Lattice QCD + chiral perturbation theory (B.-L. Huang *et al.*)

Lattice QCD[1] + Unitarized effective field theory (J. M. Torres-Rincon *et al.*)

[1]Values of LECs of NLO contribution from of the Fit-2B to LQCD from Z.-H. Guo et al.

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
J. M. Torres-Rincon et al, *Phys. Rev. D* **108**, 096008

- Very **small** (~0.1 – 0.5 fm) scattering parameters compared to other interactions
  - Light-flavor−light-flavor~7-8 fm
  - Light-flavor−strange~1-2 fm

D-light meson scattering lengths

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Go from isospin (theory) to charge (data) basis using Clebsch-Gordan coefficients

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
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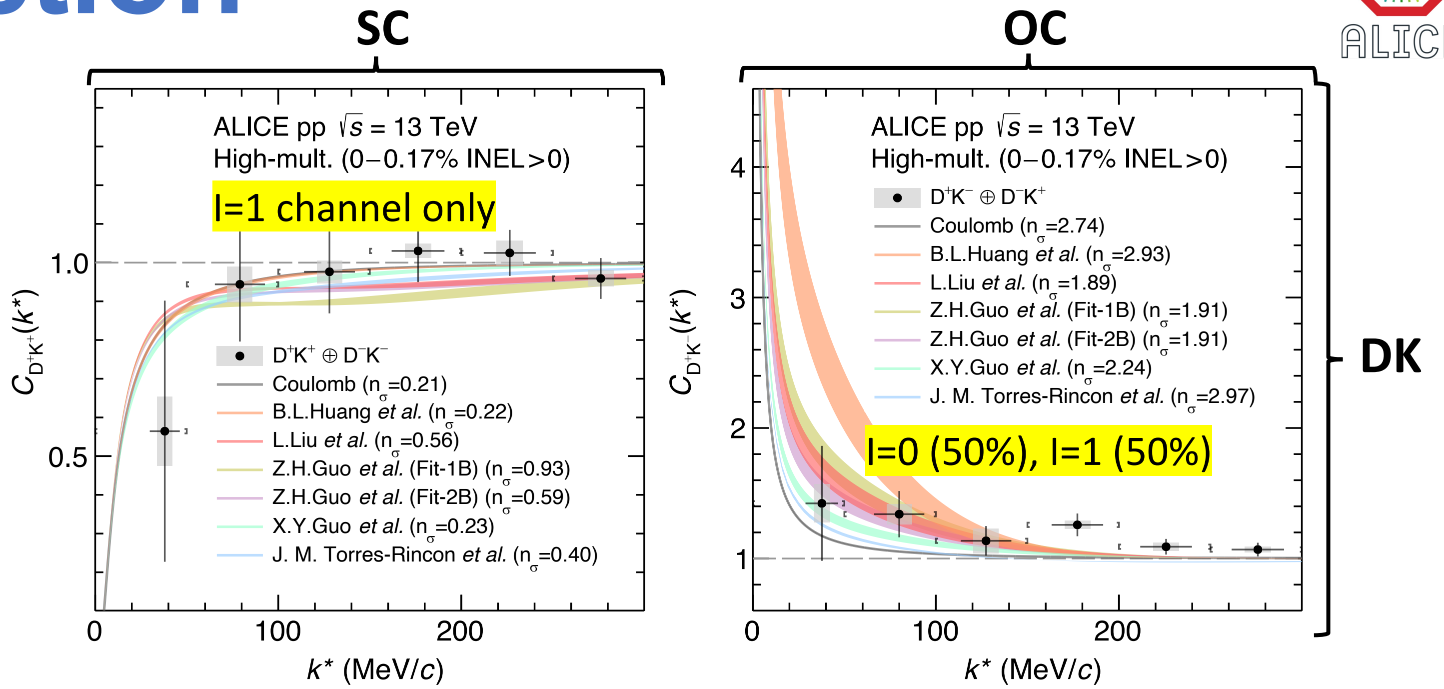
Dπ and DK interaction

- DK
  - Limited by statistics → LHC Run3 data needed
  - Compatible with models



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Dπ and DK interaction

arXiv:2401.13541

- DK
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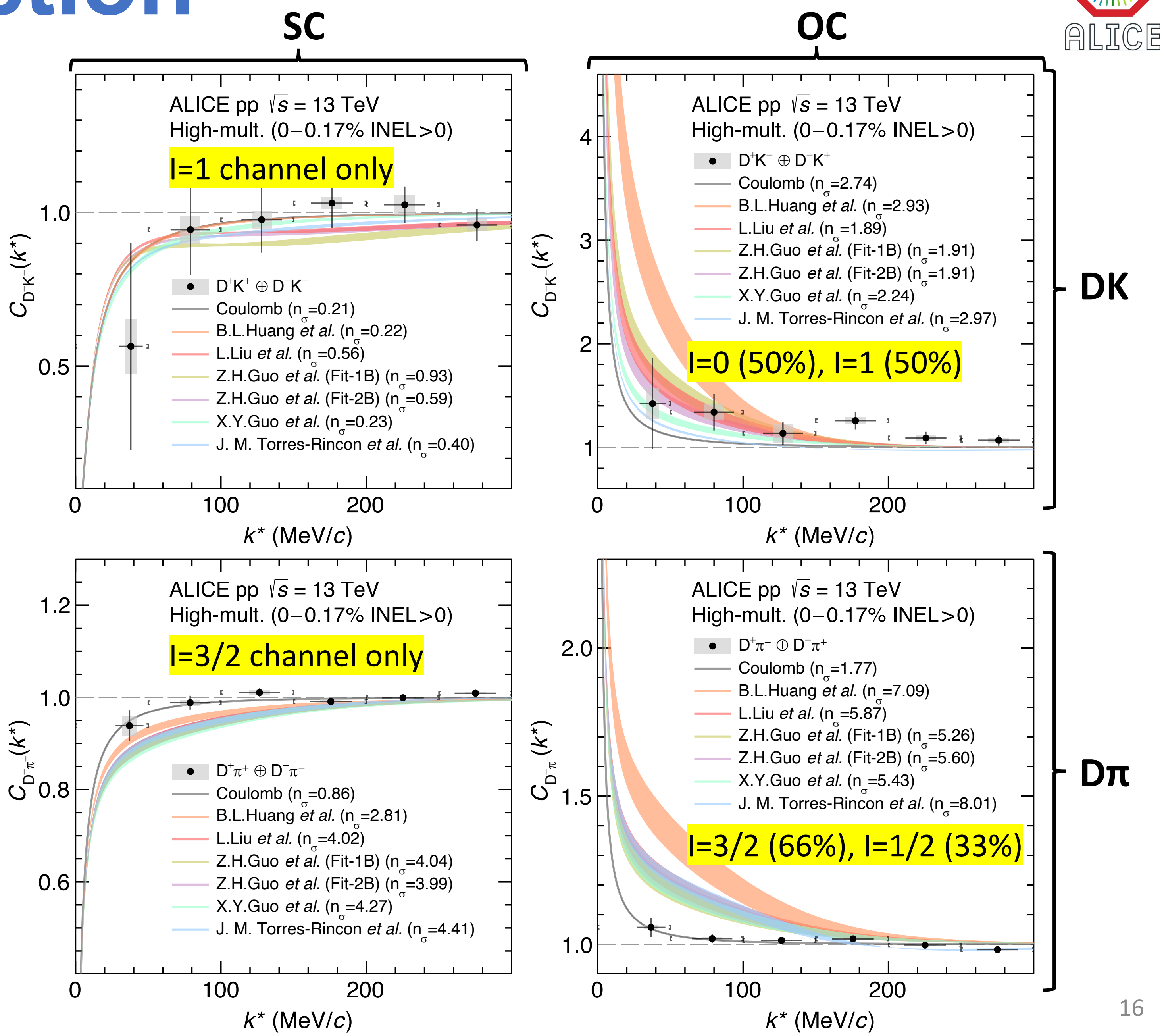
  - Compatible with models
- Dπ
  - Coulomb-only interaction favoured
  - Tension with theory models



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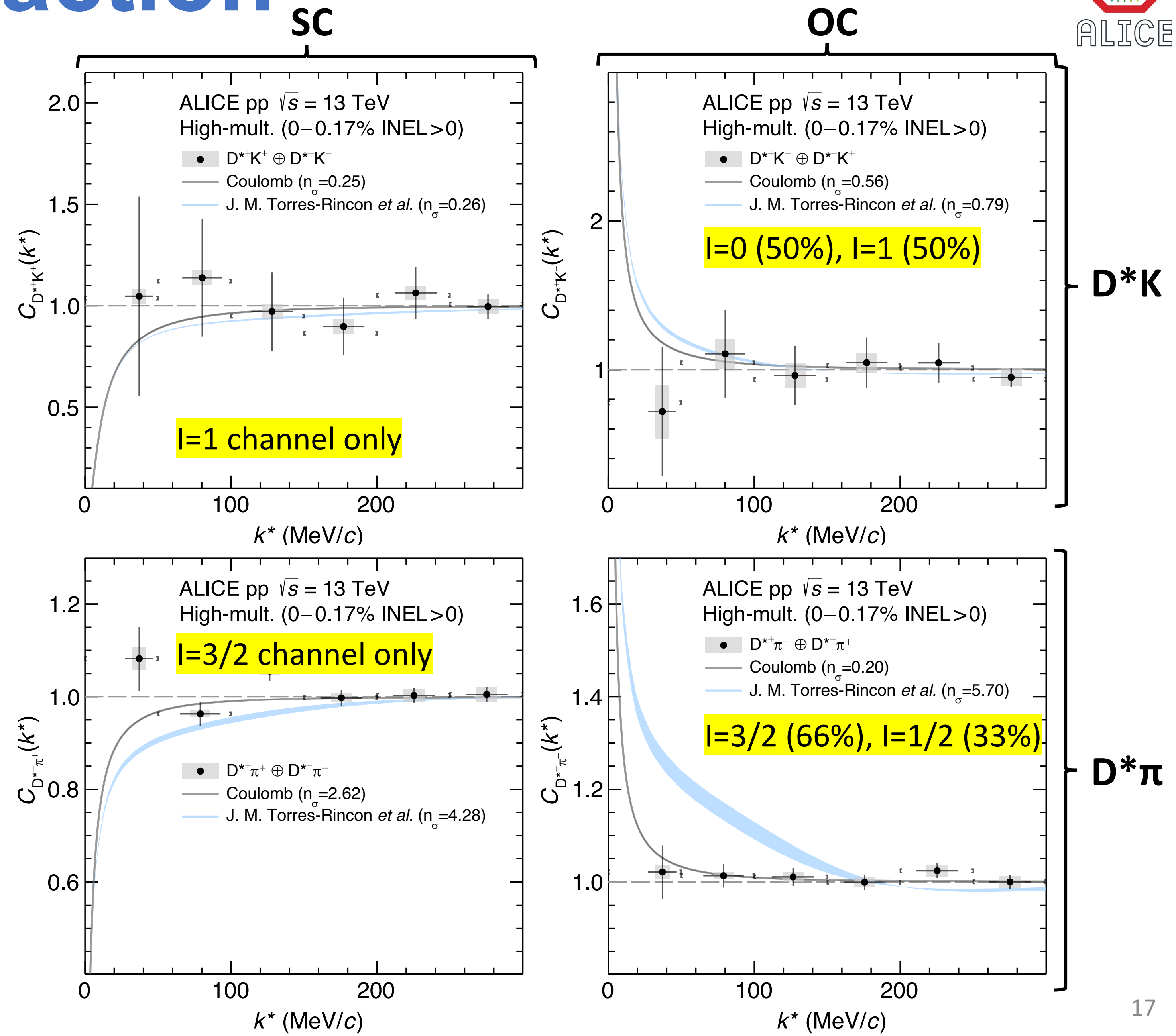
J. M. Torres-Rincon et al, *Phys. Rev. D* **108**, 096008

D*π and D*K interaction

arXiv:2401.13541

- Similar results as for D-K/π
  → heavy-quark spin symmetry
- D*K
  - Limited by statistics → LHC Run 3 data needed
  - Compatible with model
- D*π
  - Coulomb-only interaction favoured
  - Tension with theory model



J. M. Torres-Rincon et al, *Phys. Rev. D* **108**, 096008

Dπ correlation function fit

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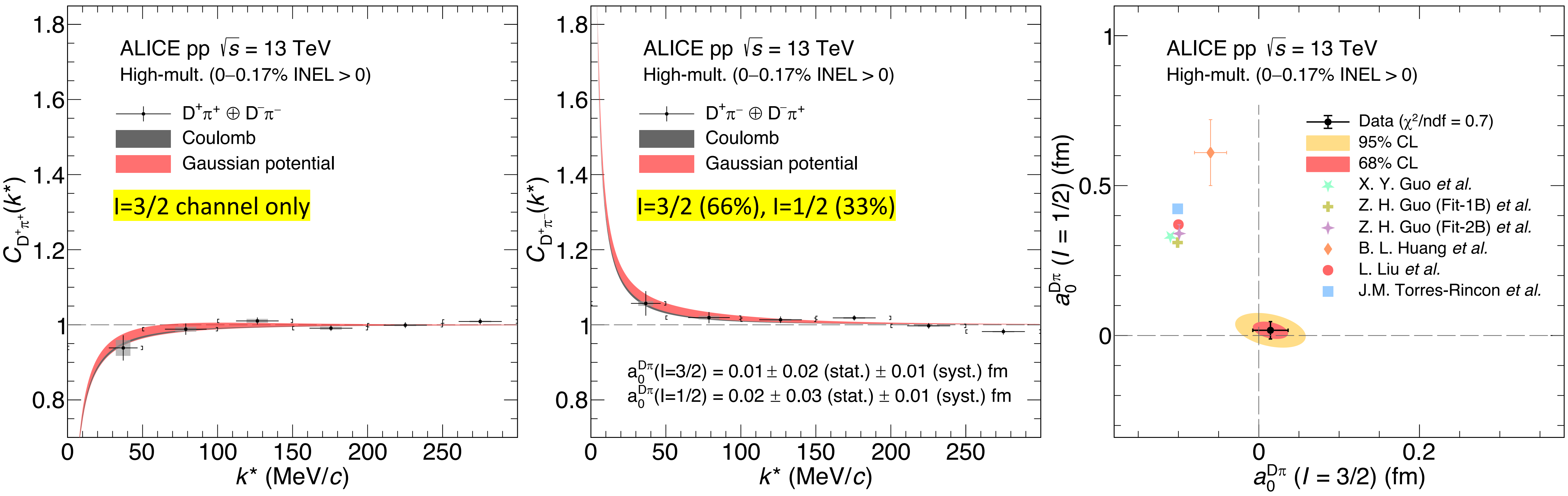
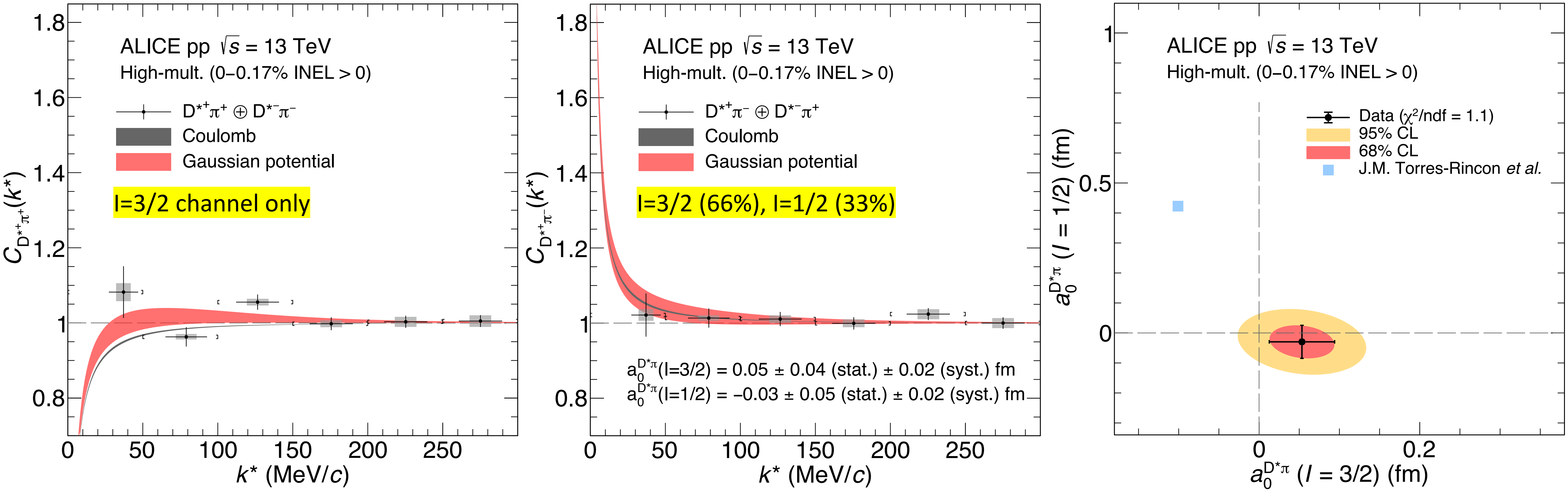


- $D^+\pi^+$ and $D^+\pi^-$ share I=3/2 channel→ simultaneous fit
- Vanishing scattering parameters in both isospin channels
- Tension with theory especially in I=1/2 channel

D*π correlation function fit

arXiv:2401.13541

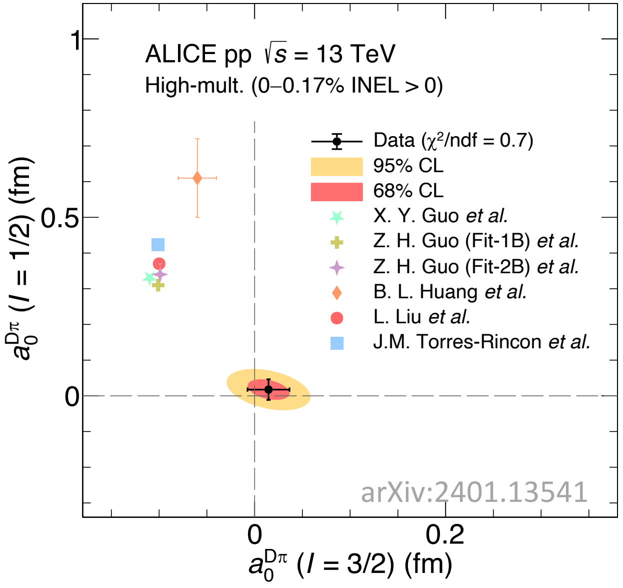


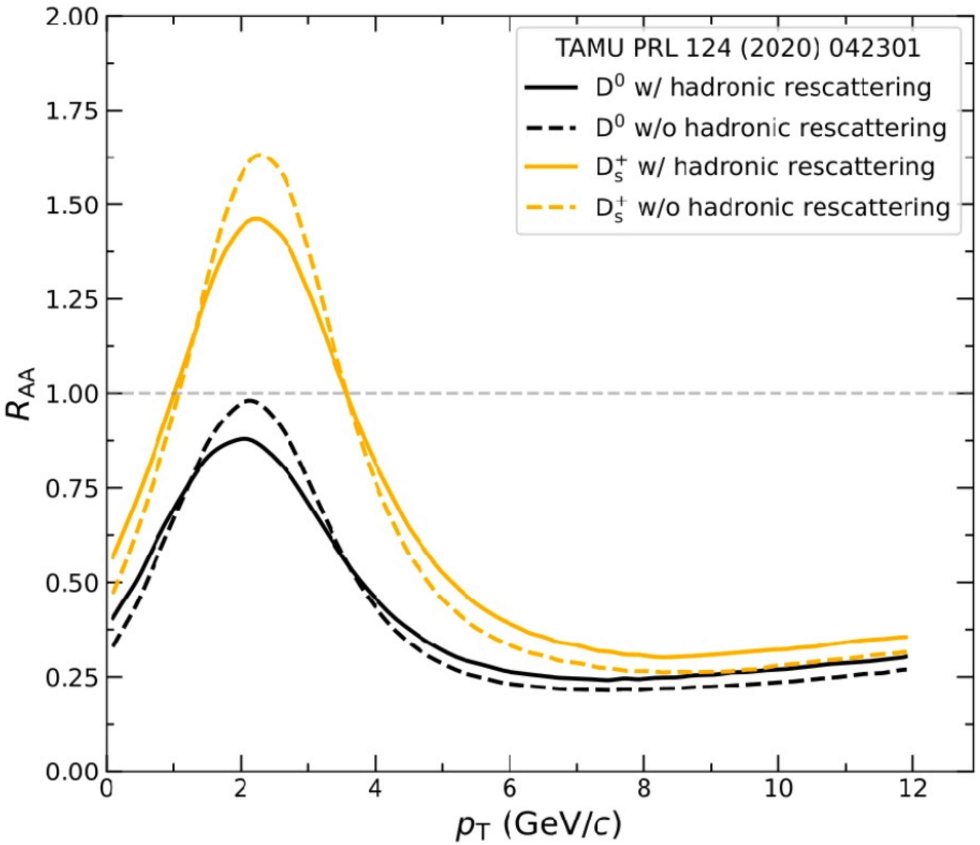
- Shared I=3/2 channel → simultaneous fit
- Vanishing scattering parameters within uncertainties
- Scattering parameters compatible with Dπ results → Heavy-quark spin symmetry

Nuclear modification factor

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- Heavy-ion observable
- Modified by rescattering and sensitive to energy loss of c quark
- Effect of rescattering might be much smaller, as models employ larger theory values for now





Conclusion

- First measurement of interaction between charm and light-flavor mesons in pp collisions at √s = 13 TeV
  arXiv:2401.13541
- Strong interaction found to be shallow
  → Data compatible with Coulomb-only hypothesis
- D(*)-light-flavor meson interactions are similar
  → heavy-quark spin symmetry
- Tension with theory in the case of Dπ and D∗π
- Smaller effect on heavy-ion observables, as rescattering models employ larger theory values for now
- Significant improvement of statistics foreseen with LHC Run 3 data

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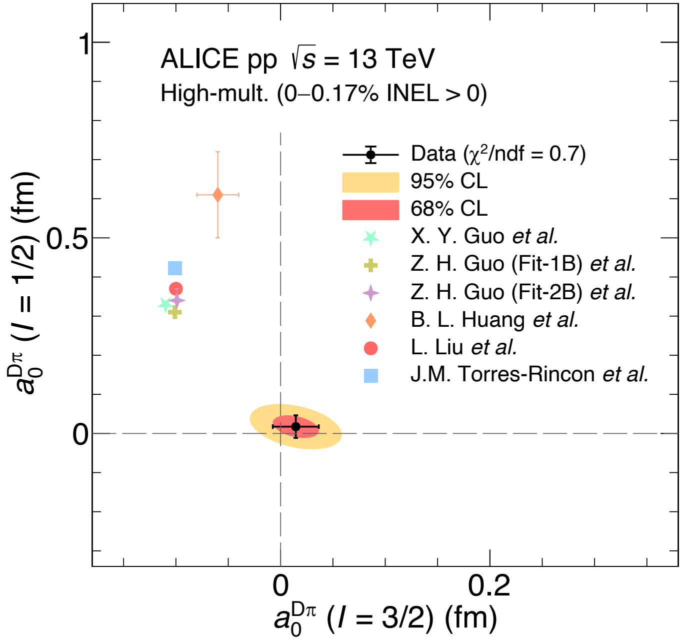
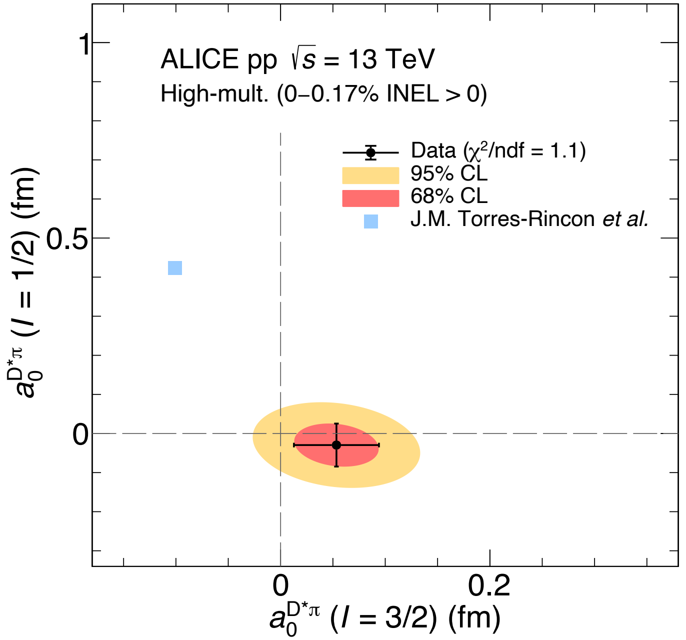


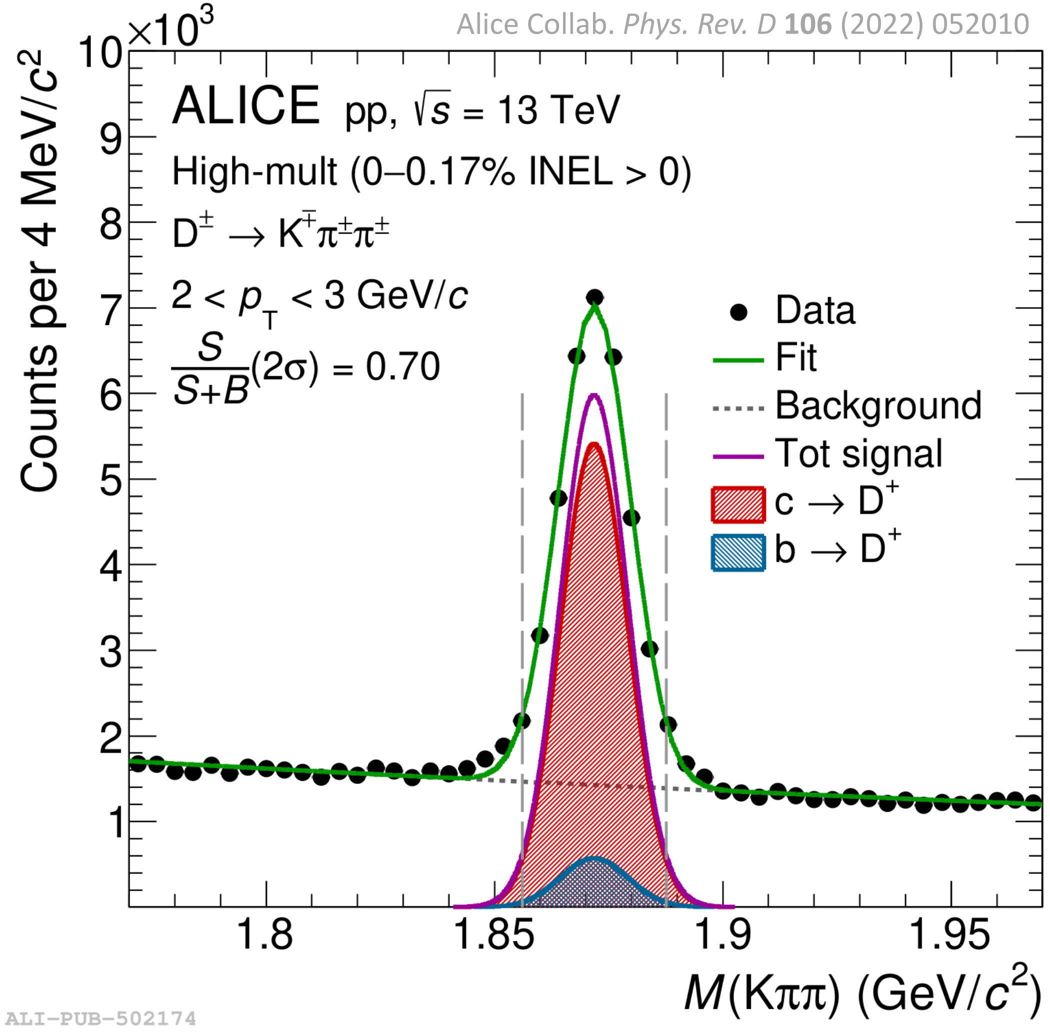


Additional material

D meson reconstruction

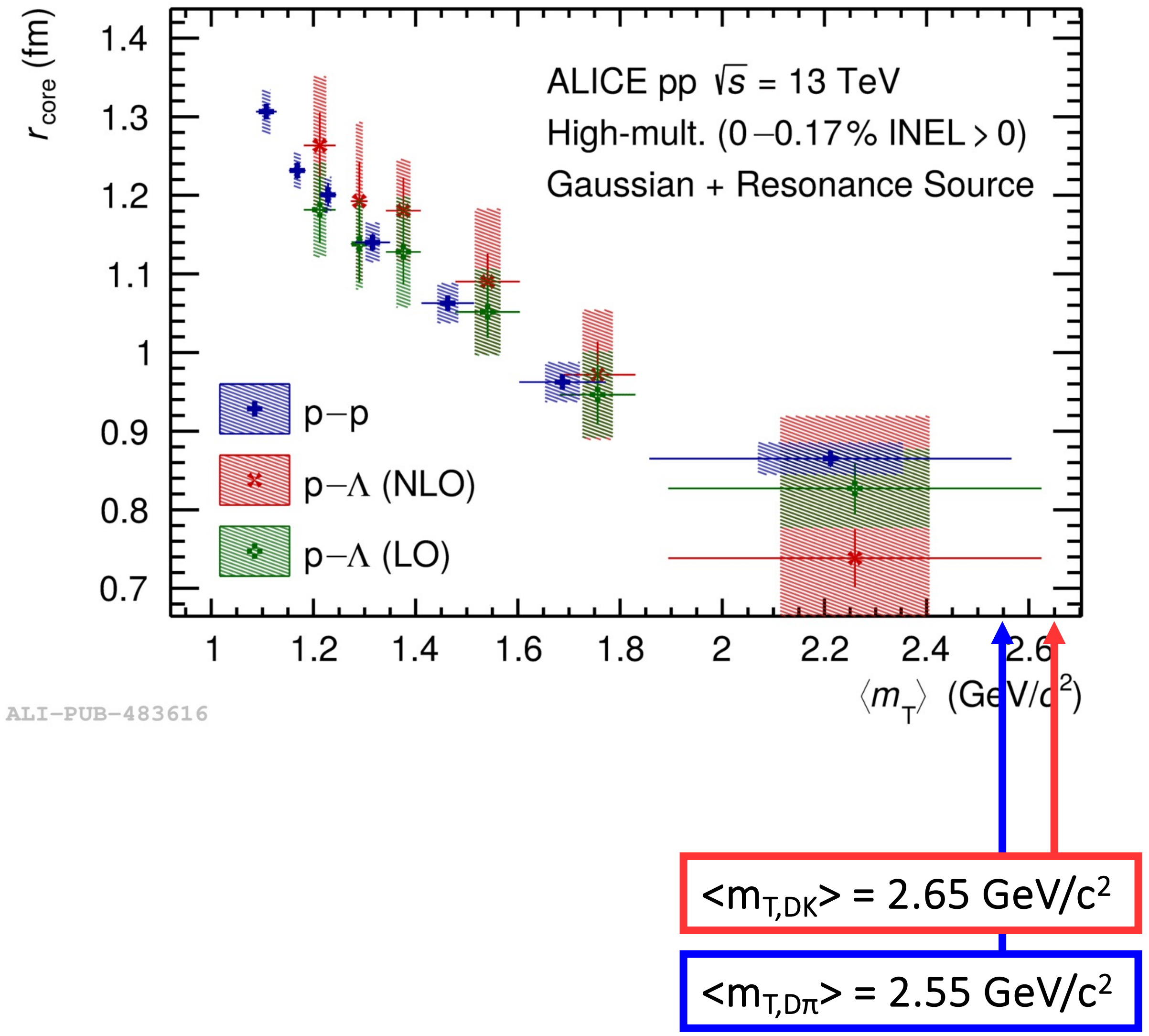
- Decay channel $D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$
  - BR=(9.38±0.16)%
    PDG, *Prog. Theo. Exp. Phys.* (2020) 083C01
- Candidates consist of
  - Combinatorial background → random combination of uncorrelated pions and kaons
  - Prompt D → hadronization of the charm quark or strong decay from excited states
  - Non-prompt D (feed-down) → decay products of beauty hadrons
- Purity of D meson candidates ~70%
- Similar purity for D* candidates
  - Decay channel $D^{\pm *} \rightarrow D^0\pi^{\pm}$ with BR=(67.7±0.5)%

Alice Collab. *Phys. Rev. D* **106** (2022) 052010



Source

- Particle emission from Gaussian core source
  - Universal source model constrained from pp pairs (well known interaction)
    ALICE Collab., Physics Letters B, 811 (2020) 135849



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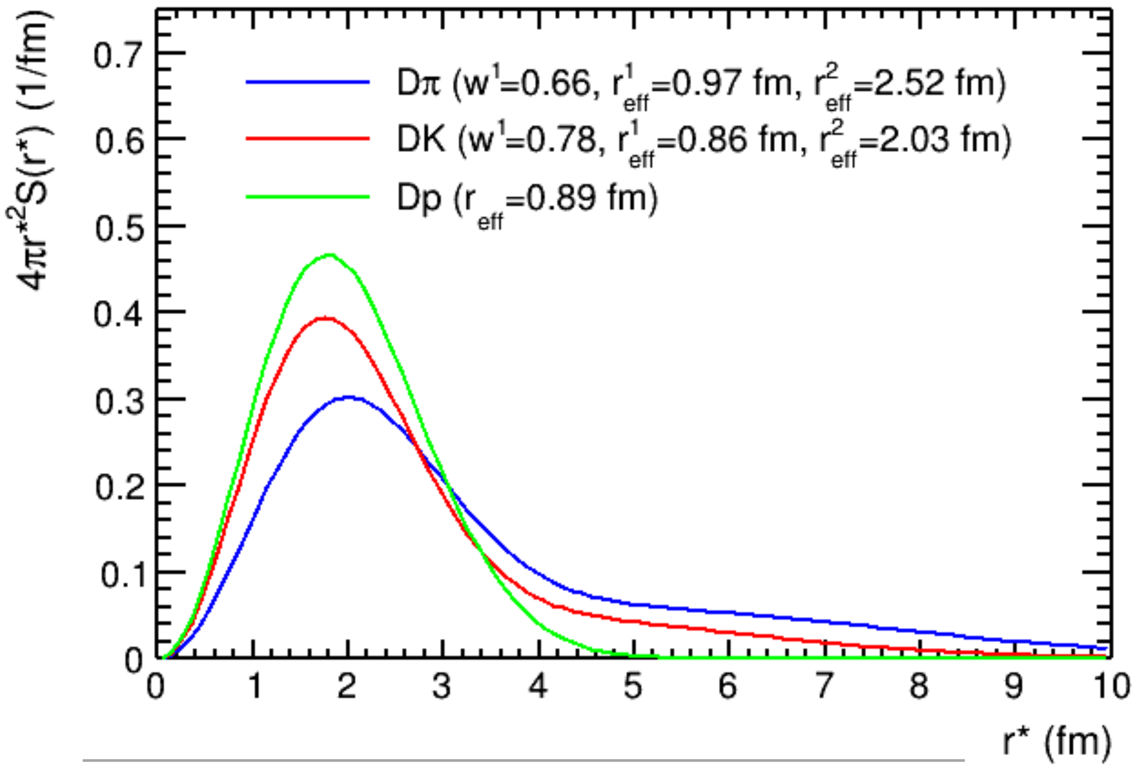
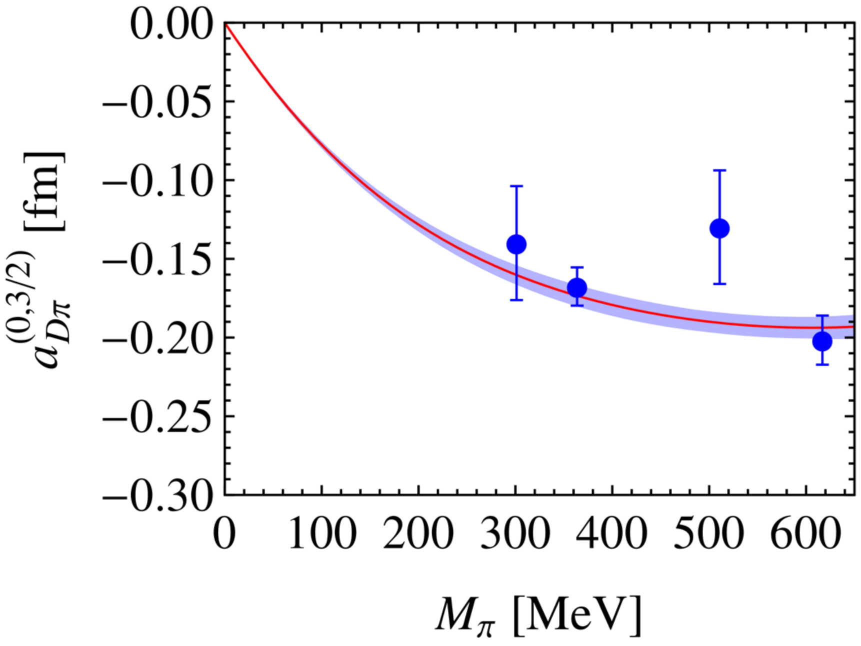
    ALICE Collab., Physics Letters B, 811 (2020) 135849
- Core radius effectively increased by short-lived strongly decaying resonances ($c\tau \approx r_{core}$)
  - Gaussian profile Dp source
    - $r_{eff} = 0.89^{+0.08}_{-0.22}\ fm$
  - DK and Dπ source described by weighted (w^1) sum of two Gaussian sources, to describe tail from longer-lived resonances:
    - DK: $r^1_{eff} = 0.86^{+0.09}_{-0.07} fm, r^2_{eff} = 2.03^{+0.19}_{-0.12} fm$
    - Dπ: $r^1_{eff} = 0.97^{+0.09}_{-0.08} fm, r^2_{eff} = 2.52^{+0.36}_{-0.20} fm$



	main reso. contributions	<cτ > [fm]
D	-	
p	Δ	1.7
K	K^{*0}, $K^{*\pm}$	4.2
π	ρ^0, $\rho^\pm$, K^{*0}, $K^{*\pm}$,ω(782)	1.3-23.4

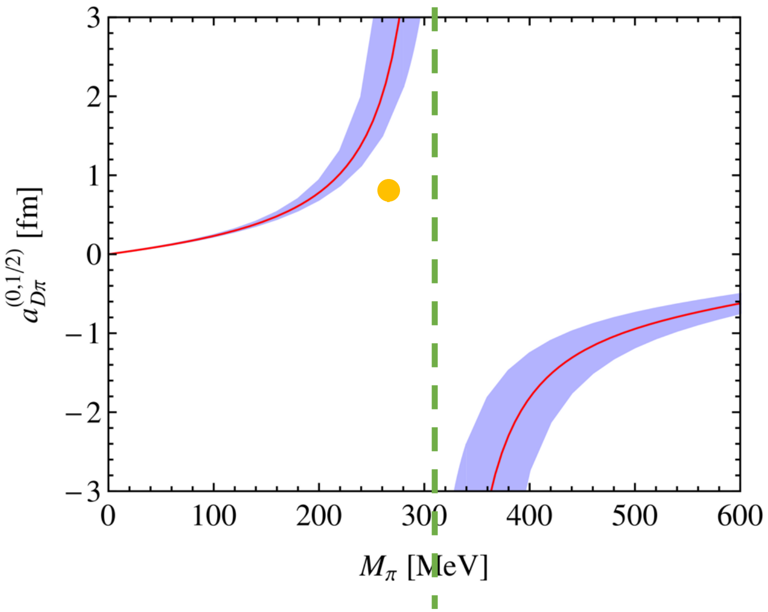
Dπ and DK interaction

- 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



D. Mohler et al., *Phys. Rev. D* **87** (2013) 034501

X.-Y. Guo et al, *Phys. Rev. D* **98** (2018) 014510



Bound-state pole formation corresponding to $D_s0^*(2317)$

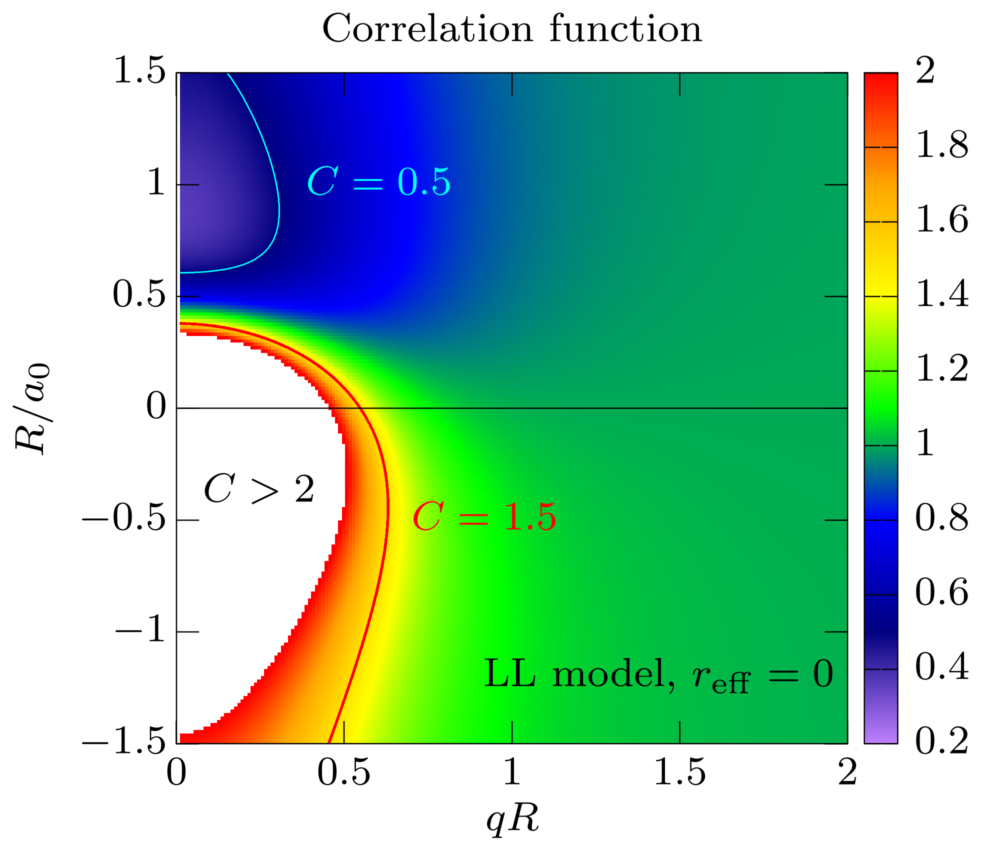
Correlation function and bound states

- 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

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

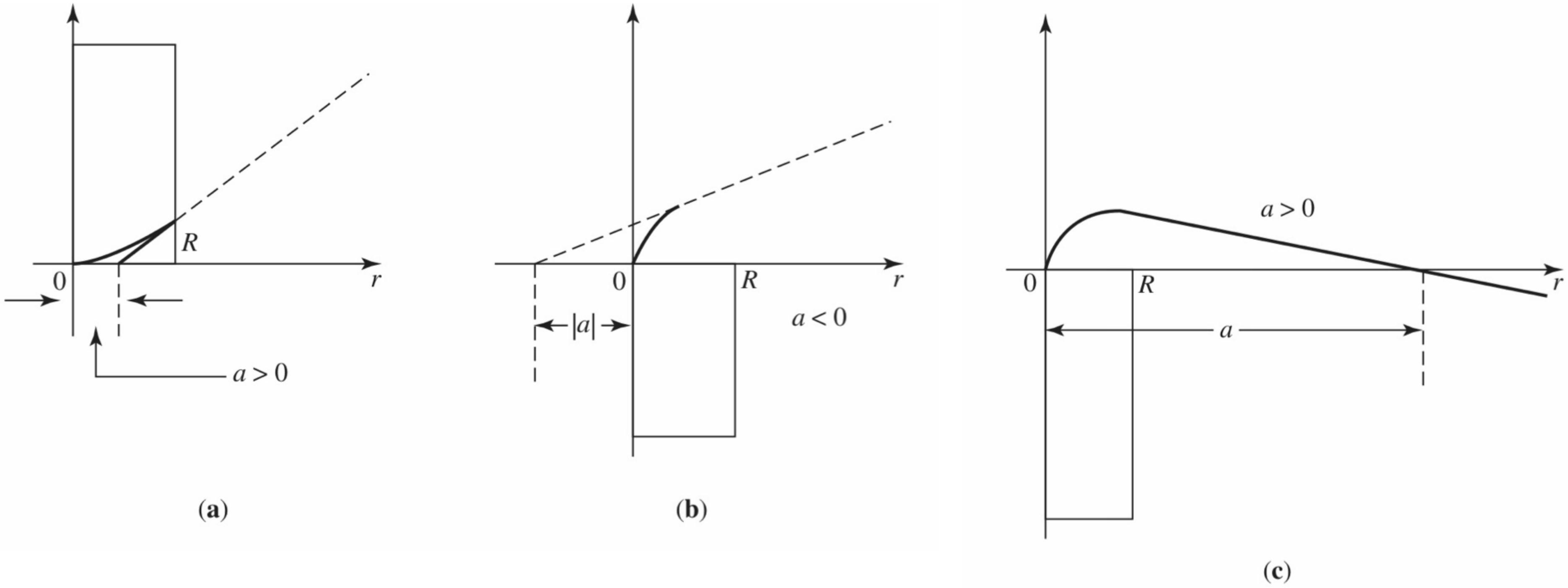
$$x = qR \quad y = \frac{R}{a_0}$$

R= source size
q= invariant relative momentum
a_0= scattering length



Y. Kamiya et al. arXiv:2108.09644v1

Scattering length



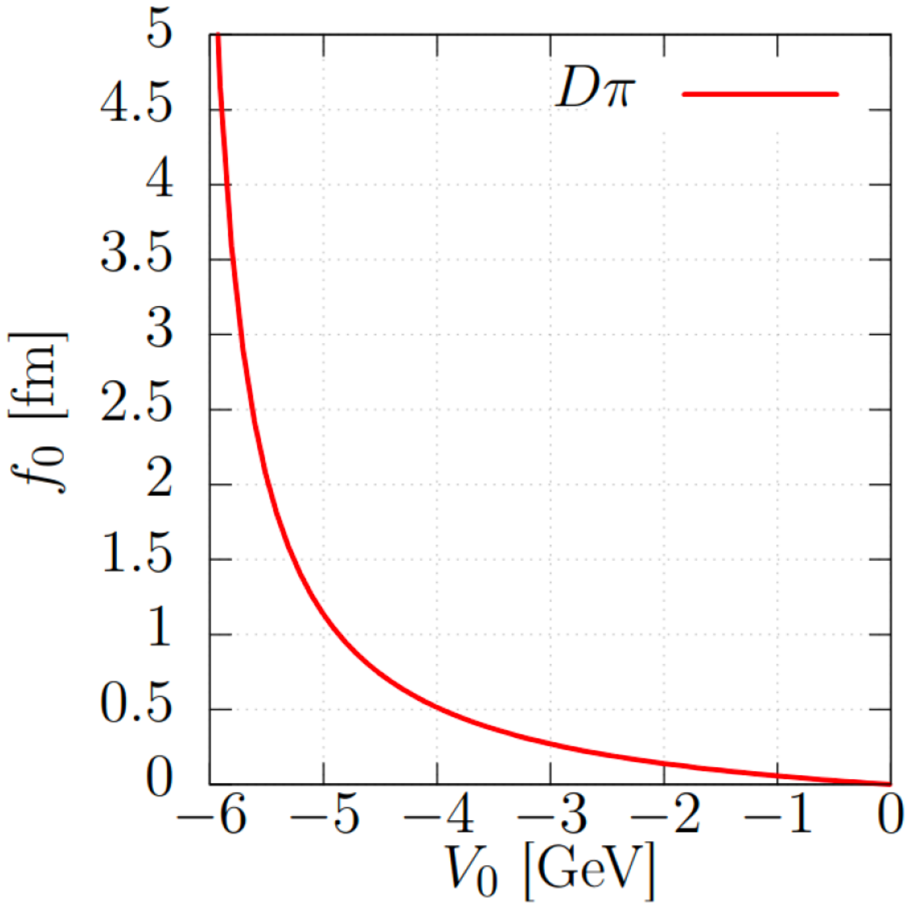
Different sign convention f0, a0 = -a !

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].

Gaussian Potential

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

- Strength adjustable
- Range: mass of the ρ meson



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Charm femtoscopy with ALICE 3

- ALICE 3: a next generation experiment
  arXiv:2211.02491v1
- Possible to study exotic charm states
- Test formation of DD^* and $D\bar{D}^*$ bound states
  - T_{cc}^+ could be D^0D^* molecule
  - $X_{c1}(3872)$ could be a $D\bar{D}^*$ molecule
- Upgrade projection
  - Gaussian potential
  - Different source radii