

Studying the Interaction Between Charm and Light-Flavor Mesons

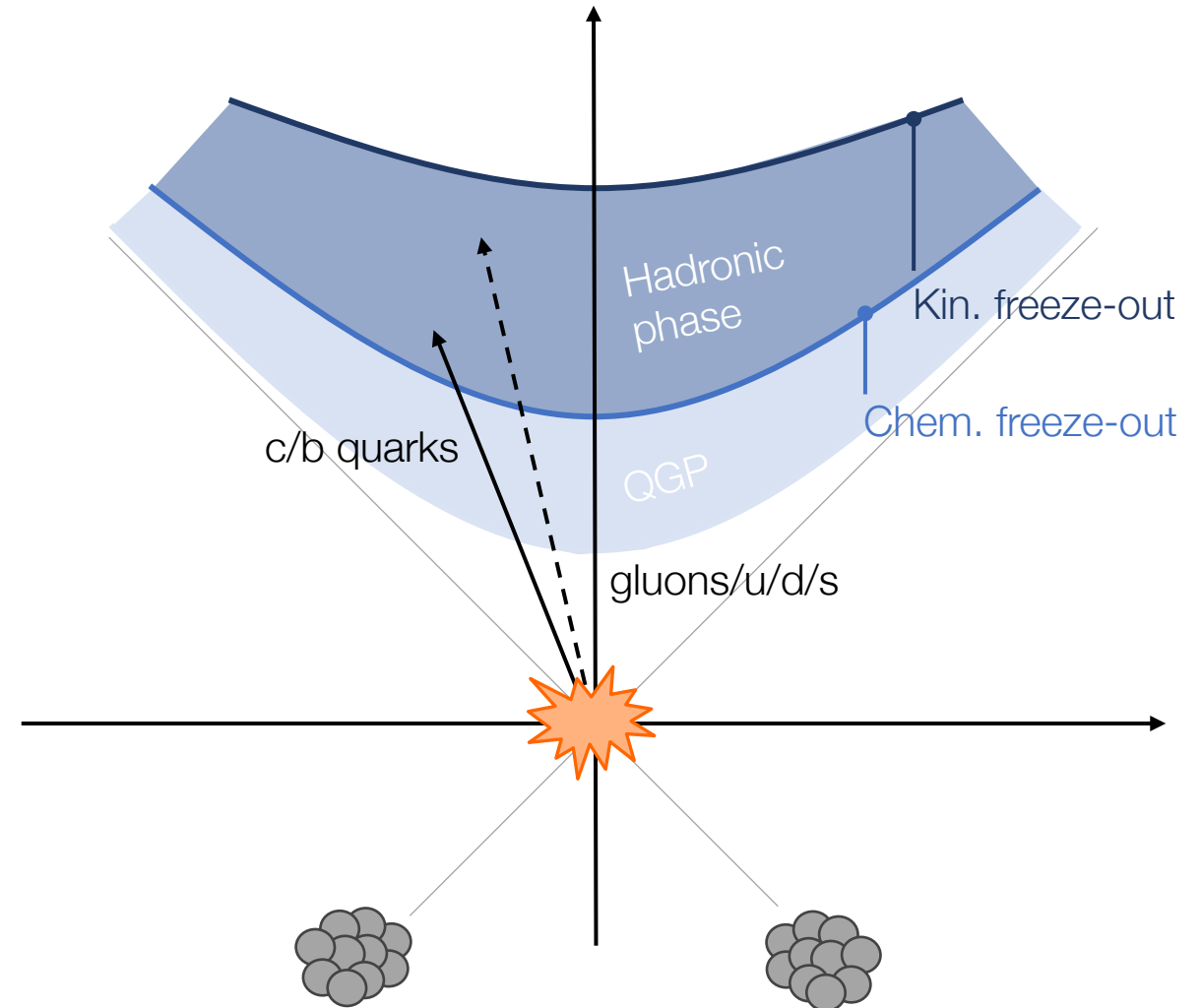
Based on arXiv:2401.13541

Emma Chizzali, Daniel Battistini, Fabrizio Grosa

QCD Seminar of the Center of Excellence in Quark Matter, May 3rd, Jyväskylä

Heavy-flavor particles and the QGP

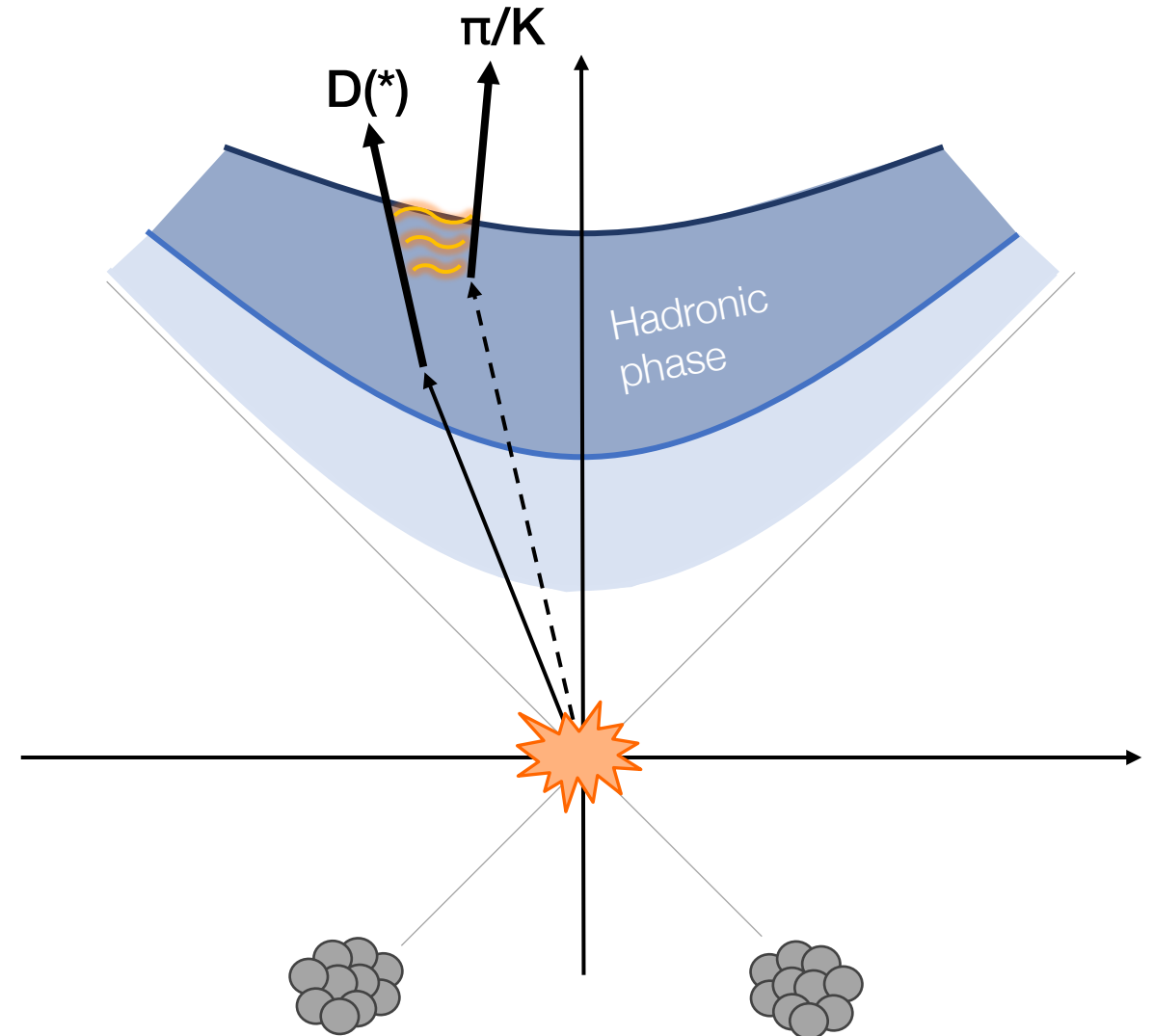
- Heavy quarks produced in heavy-ion collision
 - Thermal equilibration time expected to be of the order of QGP lifetime
 - Ideal probes of the QGP



Heavy-flavor particles and the QGP

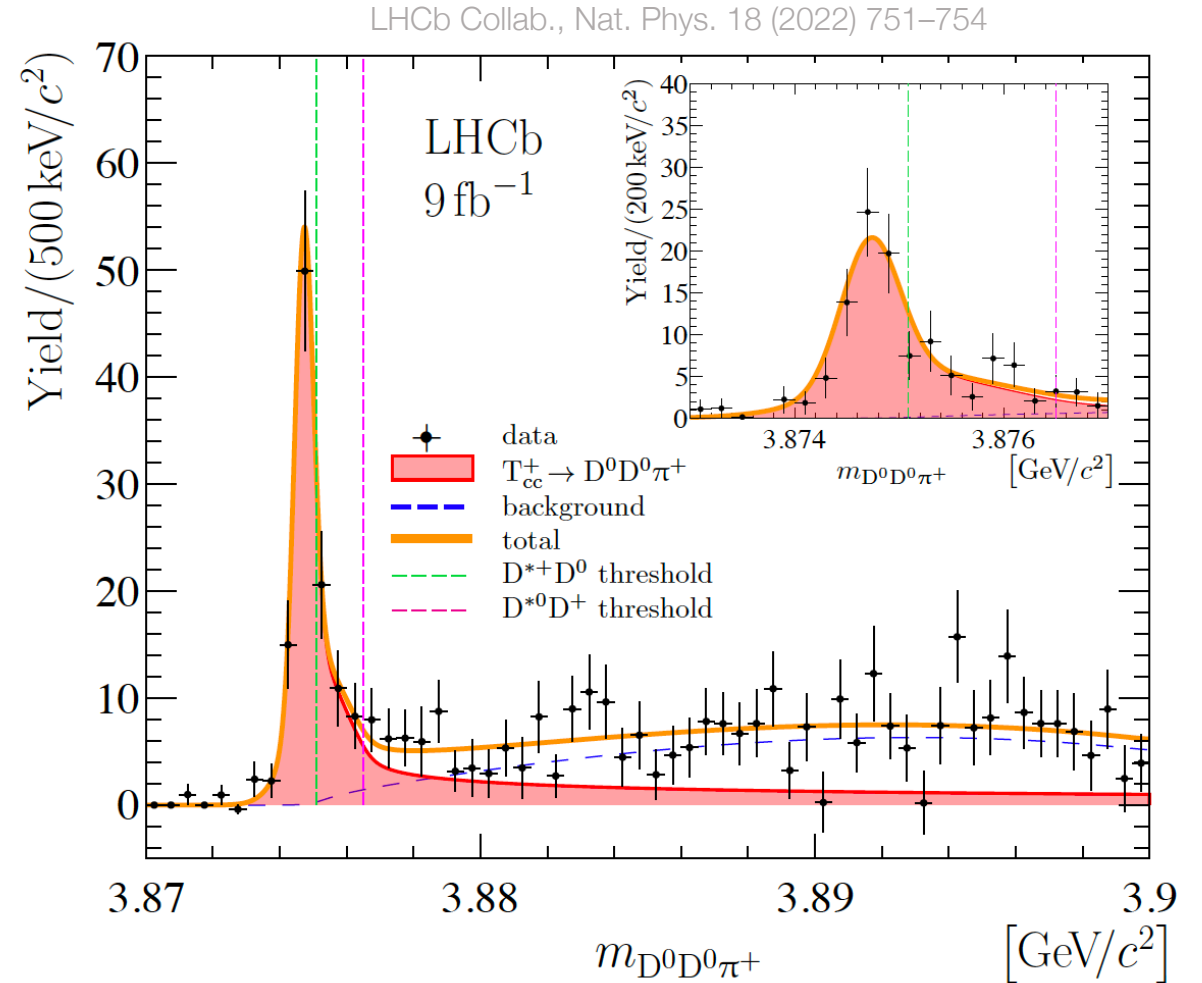
- Heavy quarks produced in heavy-ion collision
 - Thermal equilibration time expected to be of the order of QGP lifetime
 - Ideal probes of the QGP
- During hadronic phase, D meson **rescattering** has to be considered
 - Modifies heavy-ion observables
 - Transport models depend on the scattering lengths 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

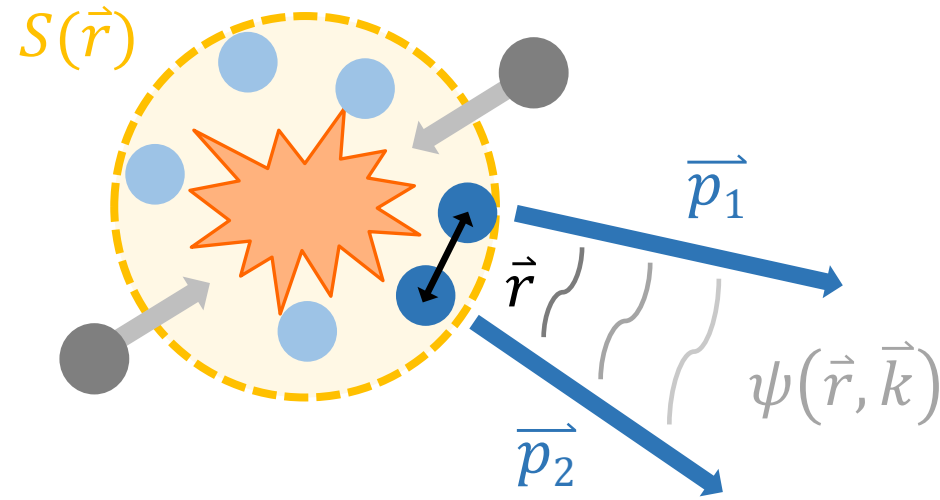


Exotic states

- 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



The correlation function



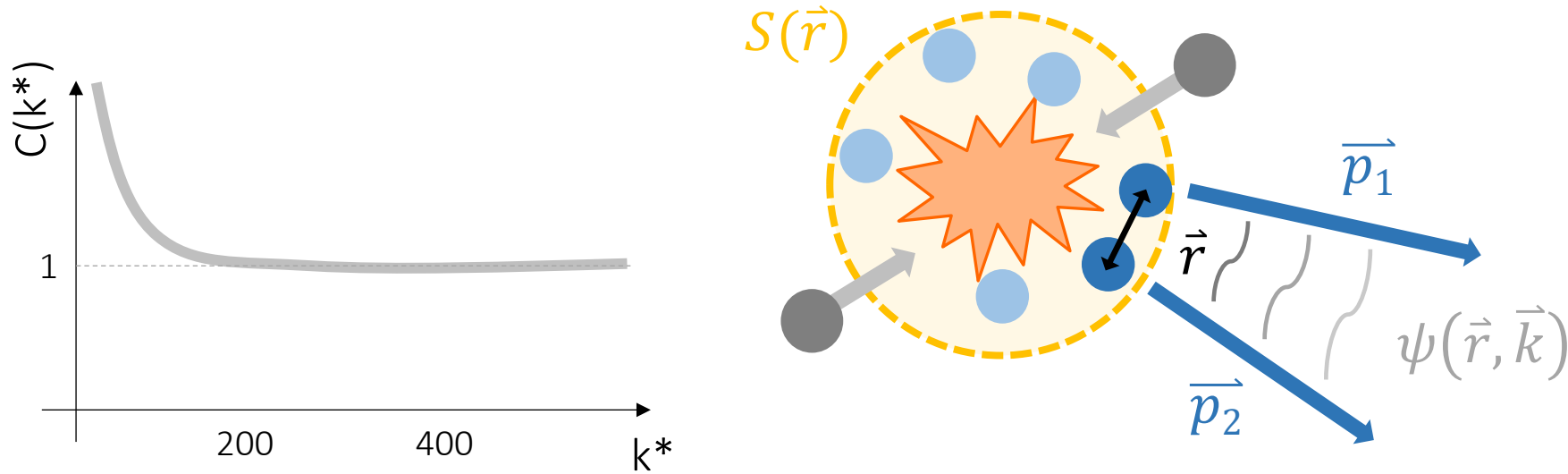
$$C(k^*) = \underbrace{\mathcal{N} \frac{N_{same}(k^*)}{N_{mixed}(k^*)}}_{\text{experimental definition}} = \underbrace{\int S(r^*) |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3 r^*}_{\text{theoretical definition}} \xrightarrow{k^* \rightarrow \infty} 1$$

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

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

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

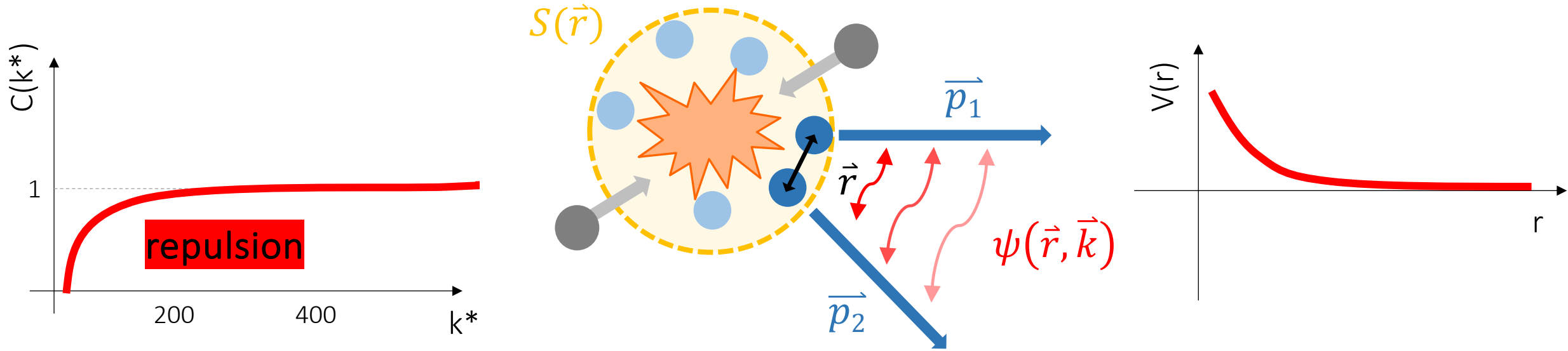
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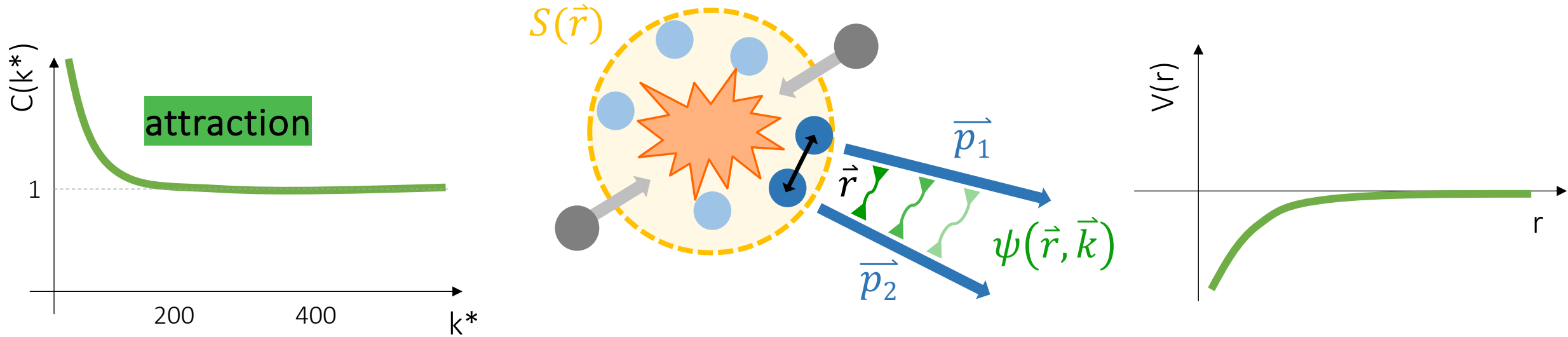
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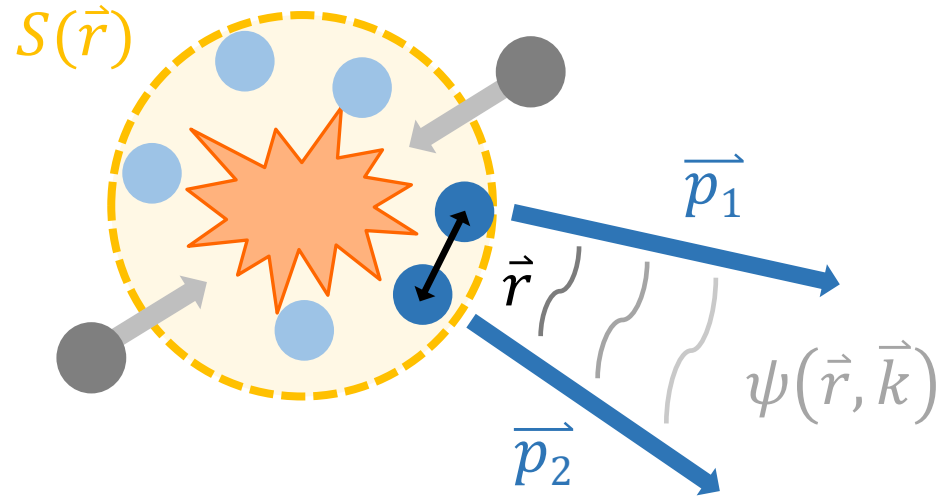
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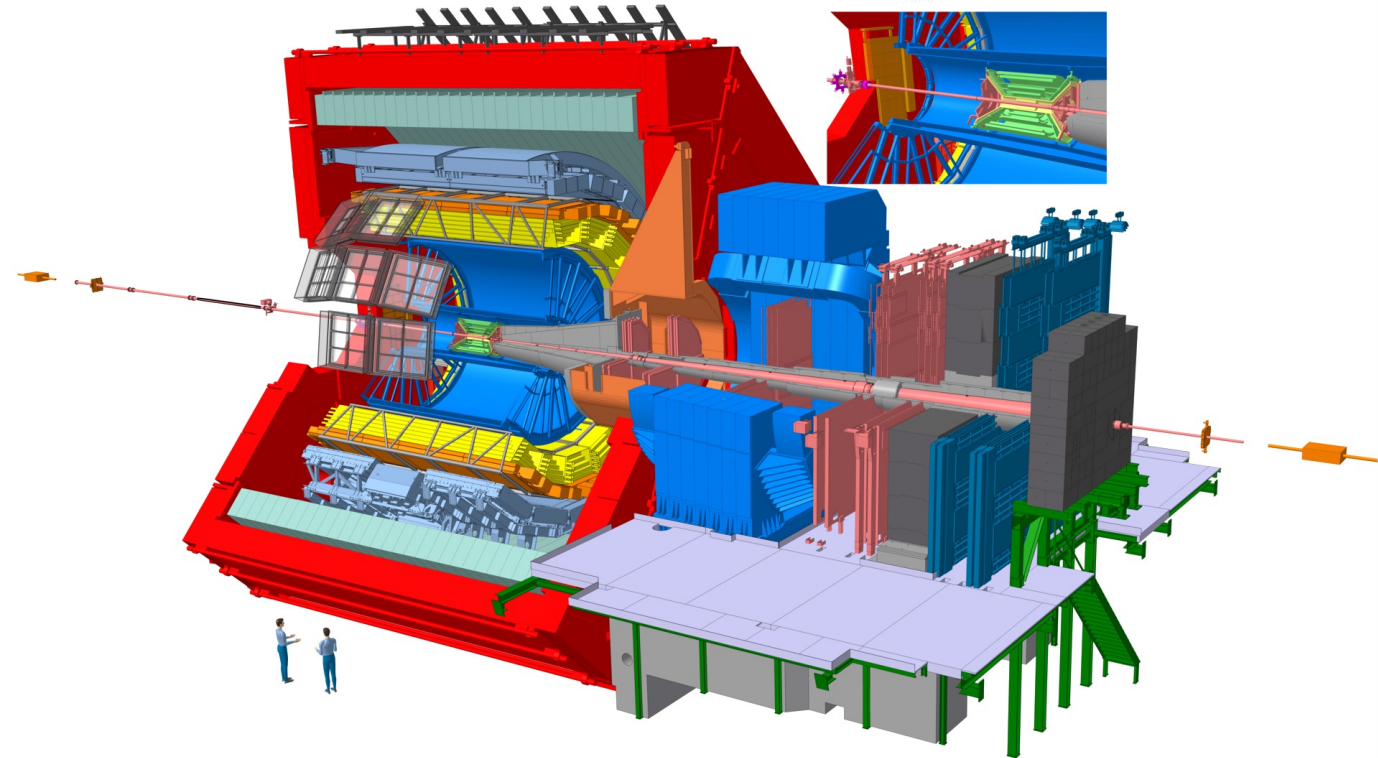
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Source constrained from pp pairs (av18, well known interaction)

ALICE Collab., Physics Letters B, 811 (2020) 135849, arXiv:2311.14527

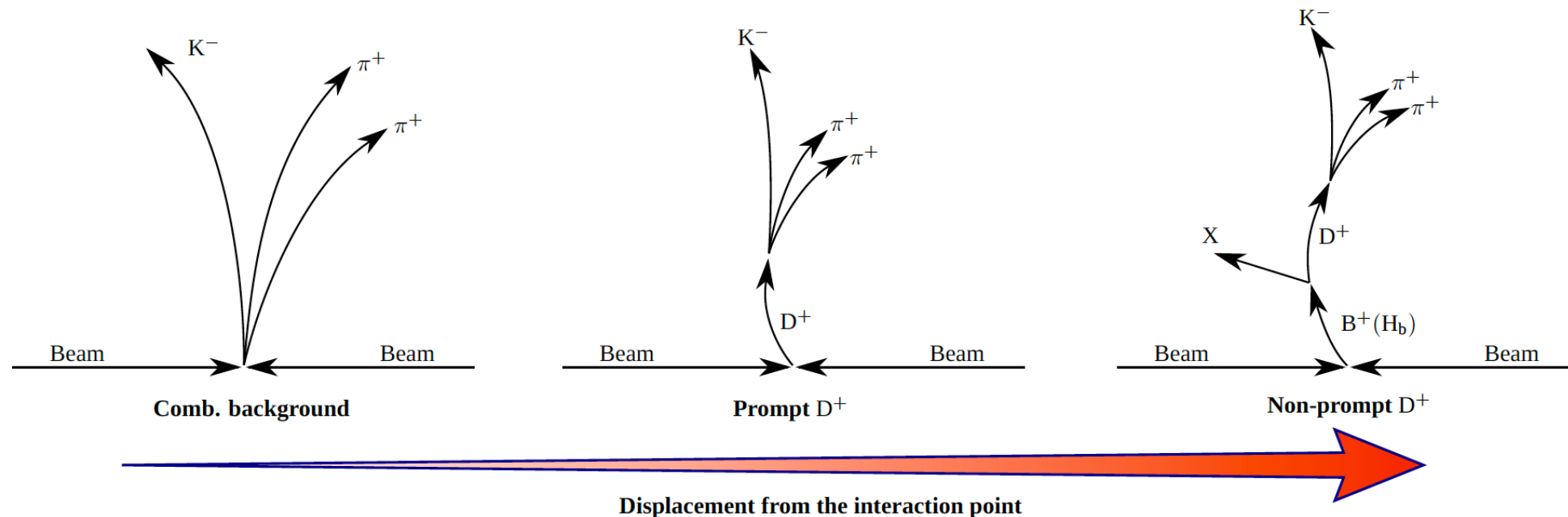
- LHC Run 2 dataset (2016-2018)
- High multiplicity (HM) pp collisions at $\sqrt{s} = 13$ TeV
- Excellent PID with ALICE detector
 - Momentum resolution $\sigma(p_T)/p_T \sim O(1\%)$
M. Ivanov Nuclear Physics A 904–905 (2013) 162c–169c
 - Charged particle (K, π) purities up to 99%
 - Primary fractions of $\sim 90(95)\%$ for K(π)



ALICE-PHO-SKE-2017-001

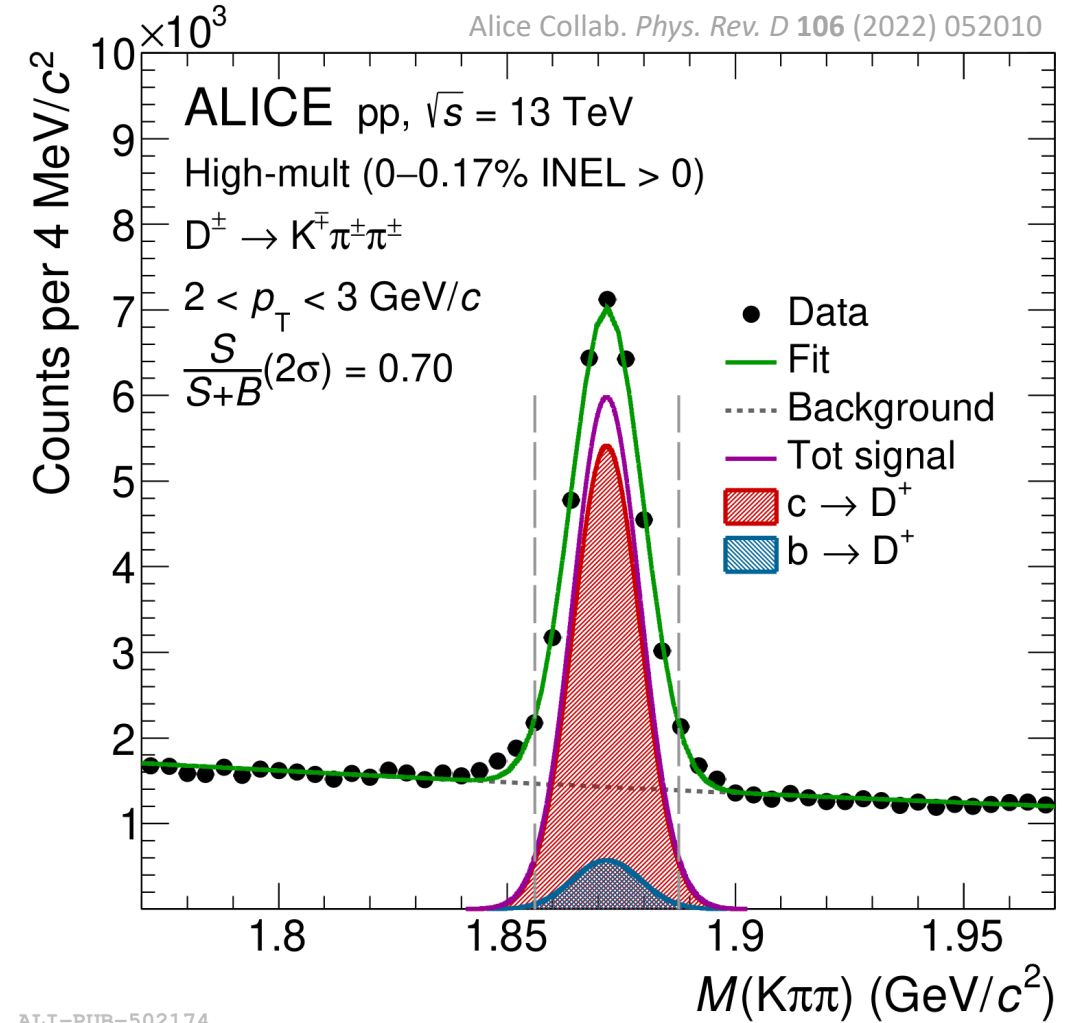
D meson reconstruction

- Reconstructed from hadronic decay channels into π and K \rightarrow small BR
- Candidates consist of
 - **Combinatorial background** \rightarrow random combination of uncorrelated π and K
 - **Prompt D** \rightarrow hadronization of the charm quark or strong decay of excited states
 - **Non-prompt D** (feed-down) \rightarrow decay products of beauty hadrons
- Different decay topologies ($\langle c\tau_D \rangle \sim 100\mu\text{m}$, $\langle c\tau_B \rangle \sim 500\mu\text{m}$) exploited to maximise prompt contribution
- Multi-class machine learning algorithm based on Boosted Decision Trees



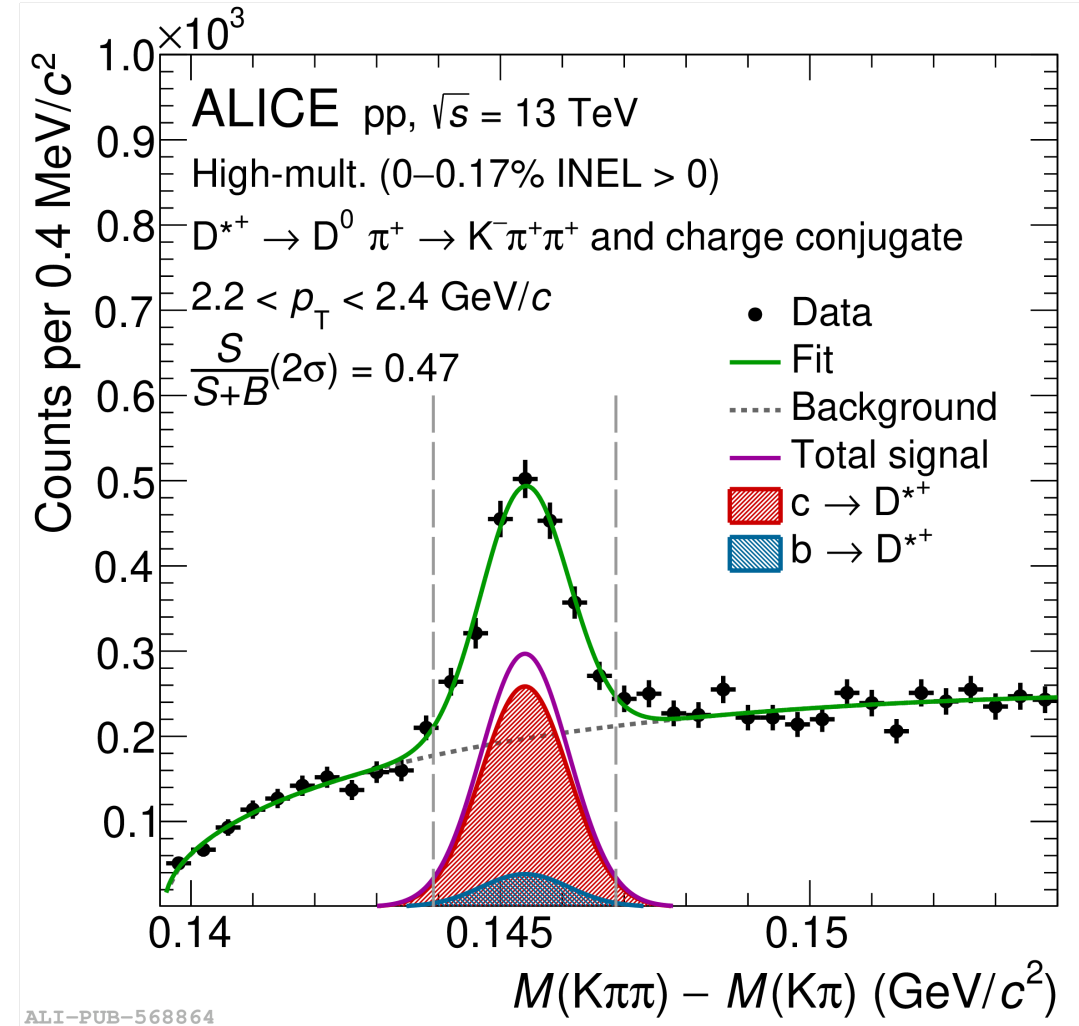
D meson reconstruction

- Decay channel $D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$
 - BR=(9.38±0.16)%
PDG, Prog. Theo. Exp. Phys. (2020) 083C01
 - Purity of D meson candidates ~70%
 - Fraction of D from b ~8% (**non-prompt contribution**)
Measured with a data-driven method, which relies on displacement of the D candidates
 - Fraction of D from D* ~30% (**part of prompt contribution**)
Estimated via MC simulation with Pythia anchored to the D⁺ and D* cross section in pp collisions at $\sqrt{s} = 5.02$ TeV



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Estimated via MC simulation with Pythia anchored to the D⁺ and D* cross section in pp collisions at $\sqrt{s} = 5.02$ TeV
- Similar purity and secondaries from b for D* candidates
 - Decay channel $D^{\pm*} \rightarrow D^0 \pi^\pm \rightarrow (K^\mp \pi^\pm) \pi^\pm$ with BR=(67.7±0.5)% and BR=(3.95±0.03)%

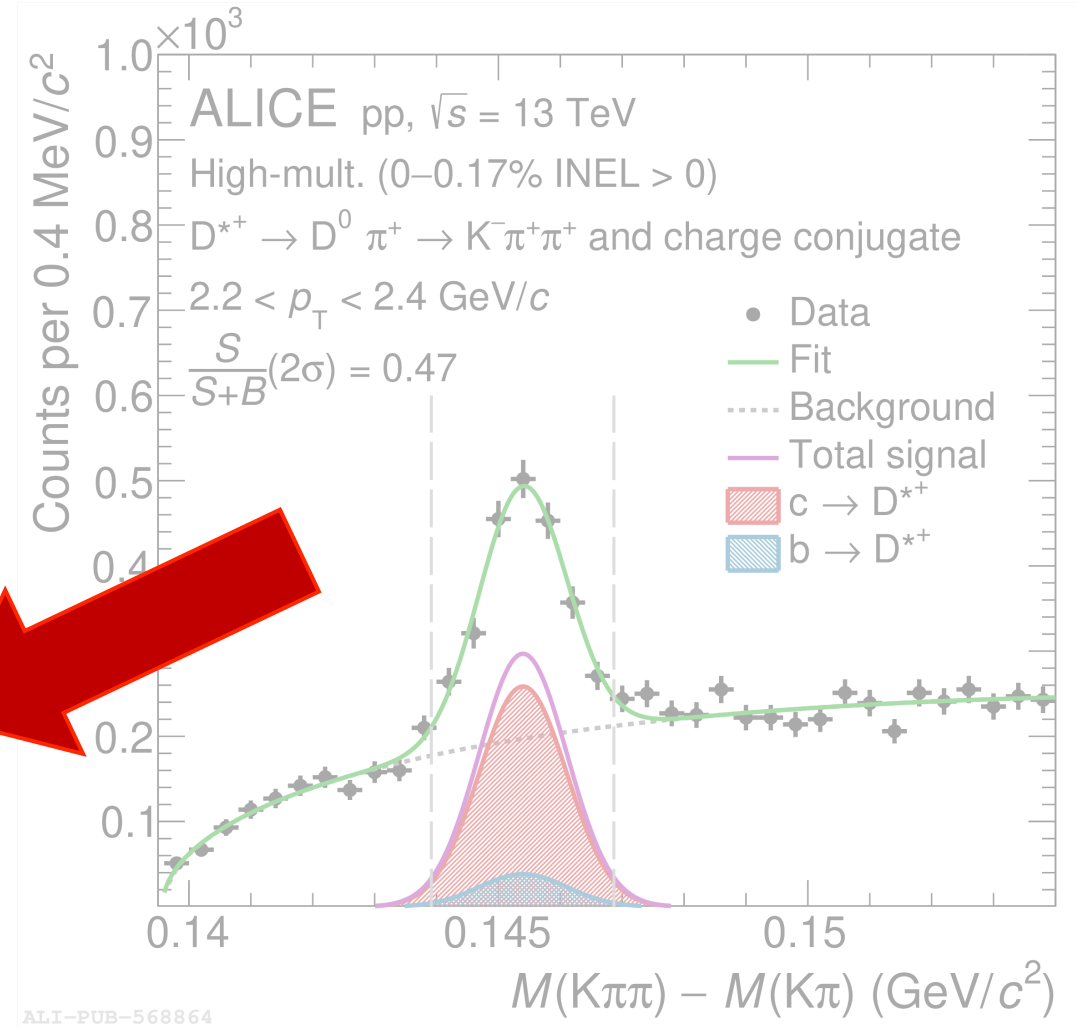


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Estimated via MC simulation with Pythia based on the D+ and D* cross sections
- Similar purity
 - Decay channel $D^0 \rightarrow K^- \pi^+ \pi^+$
BR=(67.7±0.4)%

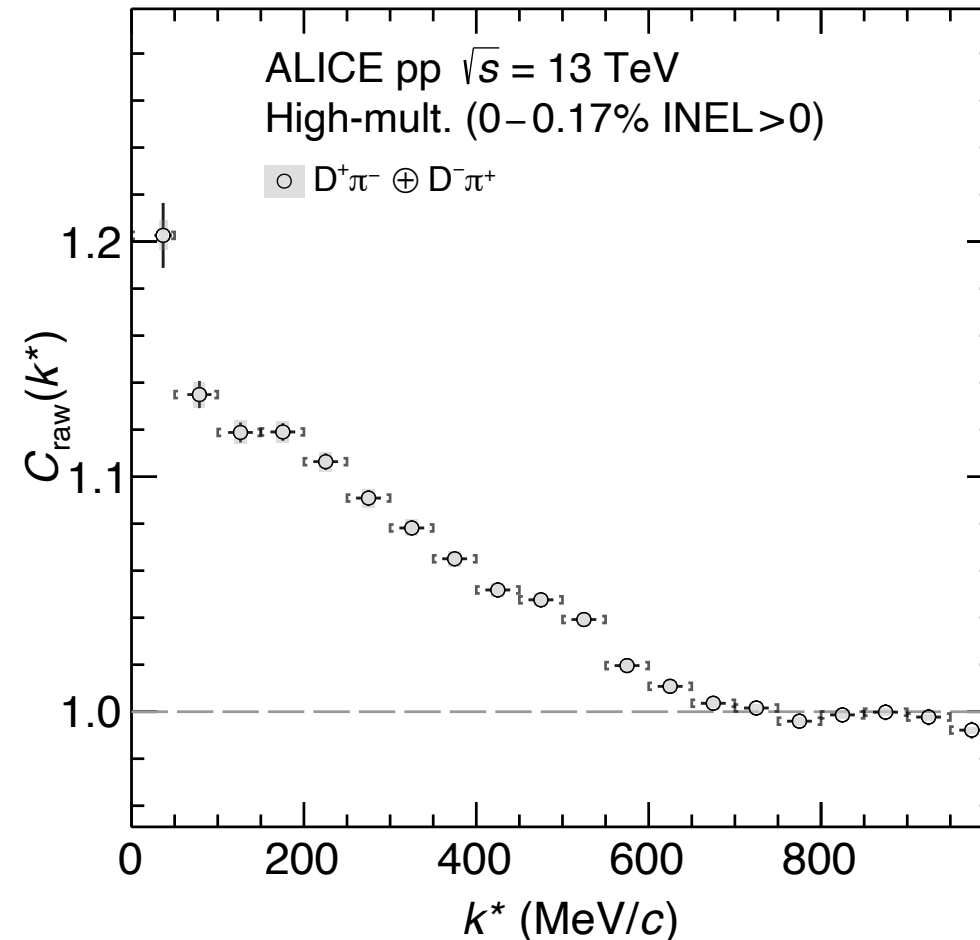
Use correlation data to study residual final state interaction among D-K, D-π, D*-K, D*-π

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



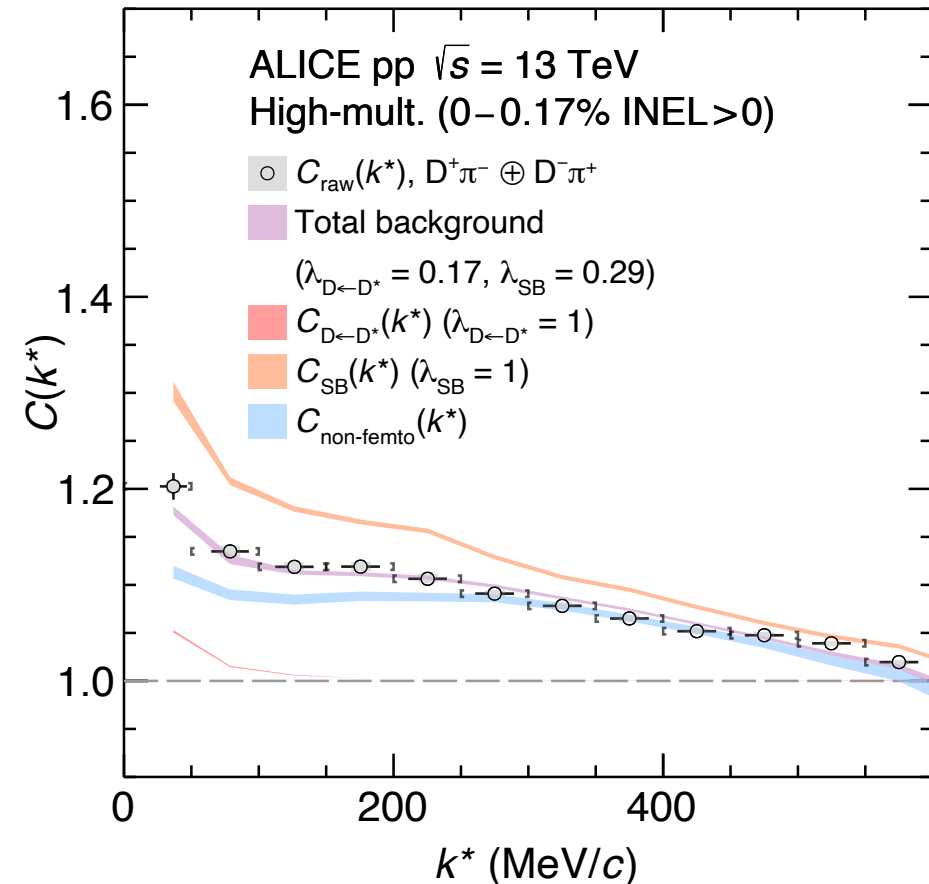
Modelling of the raw correlation function

$$C_{raw}(k^*) = C_{non-femto}(k^*) \times C_{femto}(k^*)$$

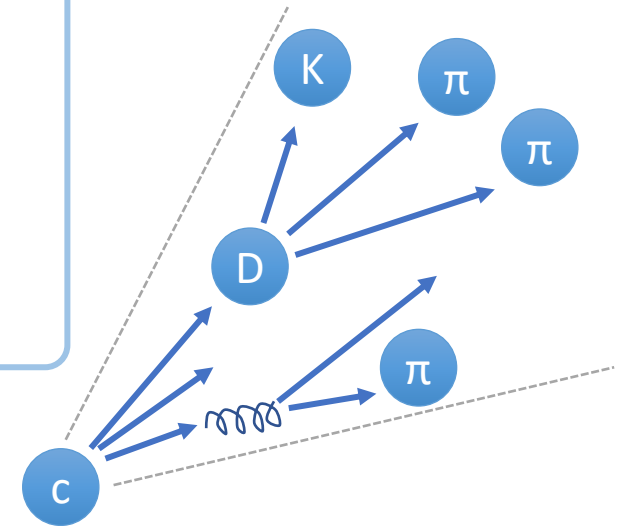


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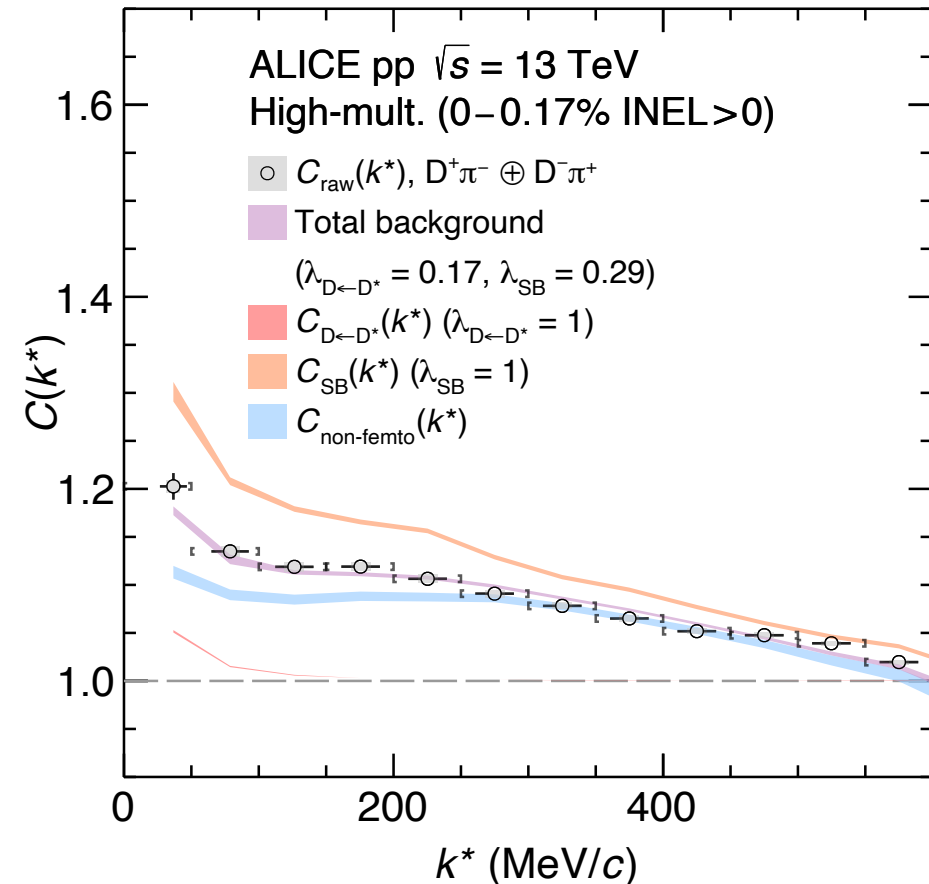


- Not related to final state interaction between particles
 - Energy-momentum conservation effects
 - Mini-jets
- Modeled using MC simulations



Modelling of the raw correlation function

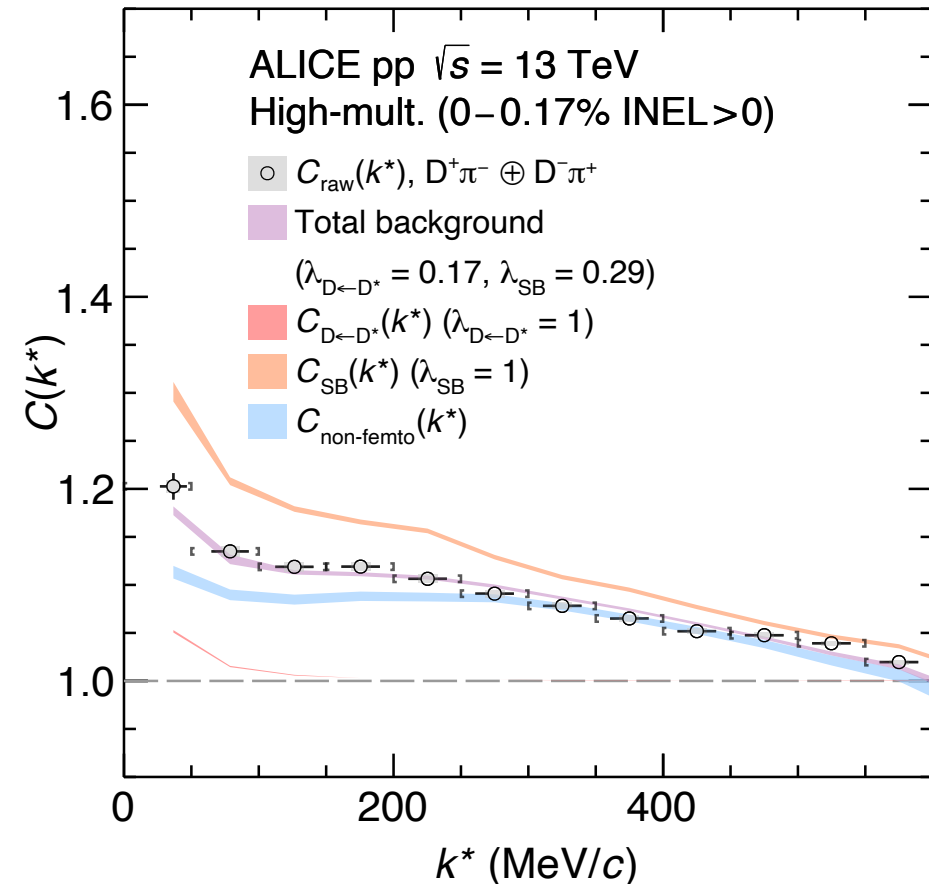
$$C_{raw}(k^*) = C_{non-femto}(k^*) \times C_{femto}(k^*)$$



- Includes contributions related to final state interaction
- Considers feed-down contribution to single-particle yields and misidentifications
 - **Genuine contribution** from primary particle interaction
 - **Combinatorial background** from misidentified D/D* mesons
 - **Feed-down contribution** from excited charm states $D^* \rightarrow D$
 - **Flat contribution**, includes all the remaining negligible contributions

Modelling of the raw correlation function

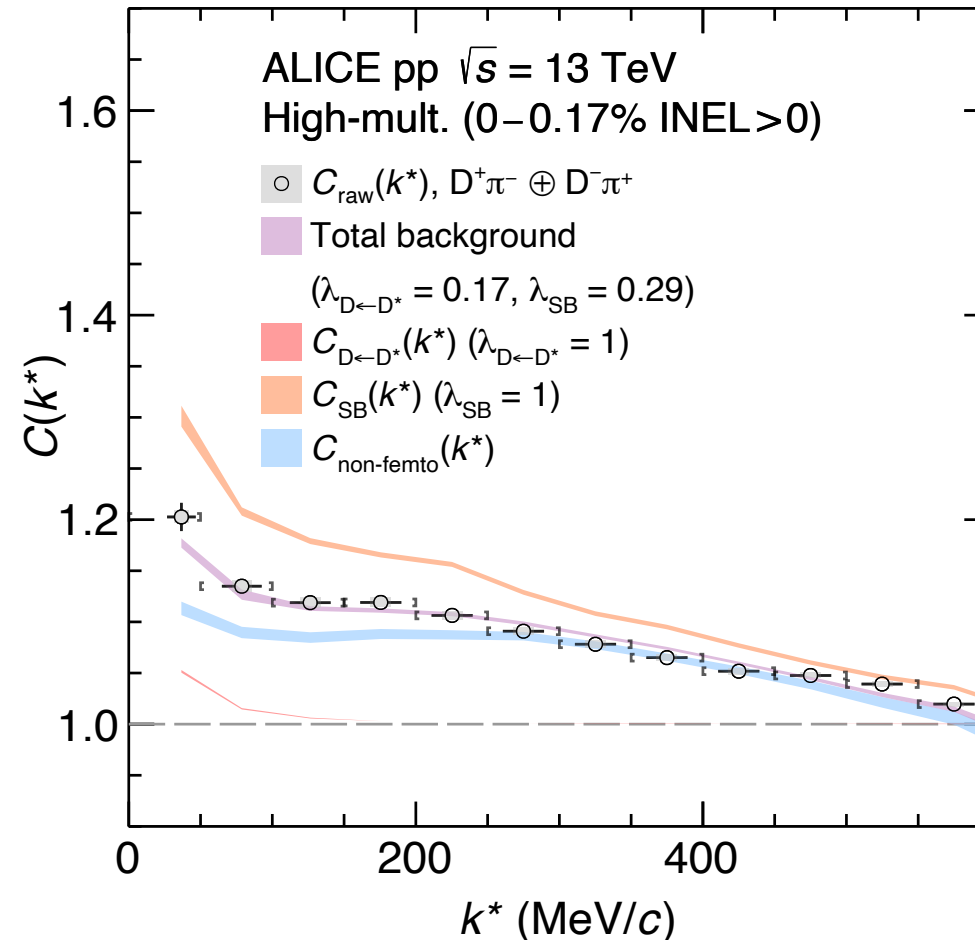
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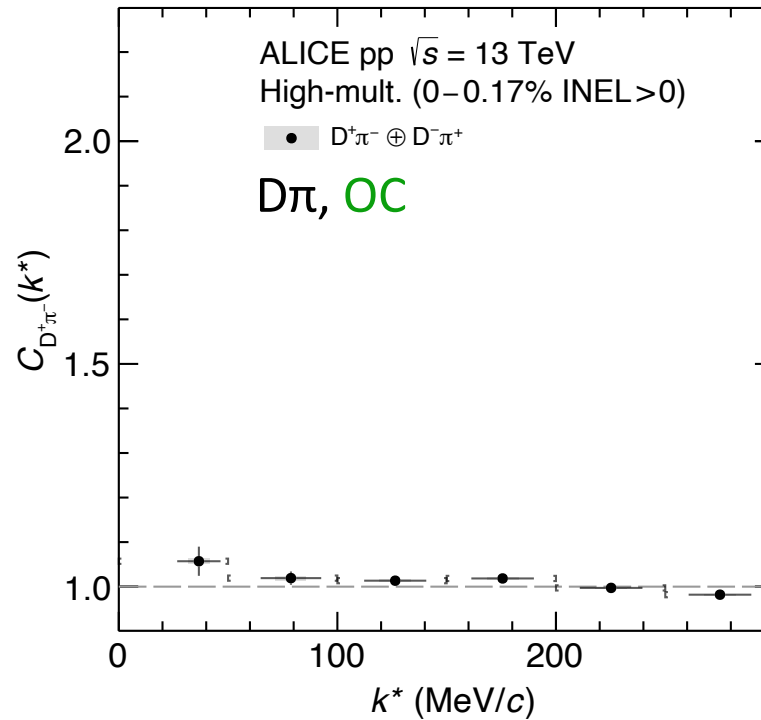
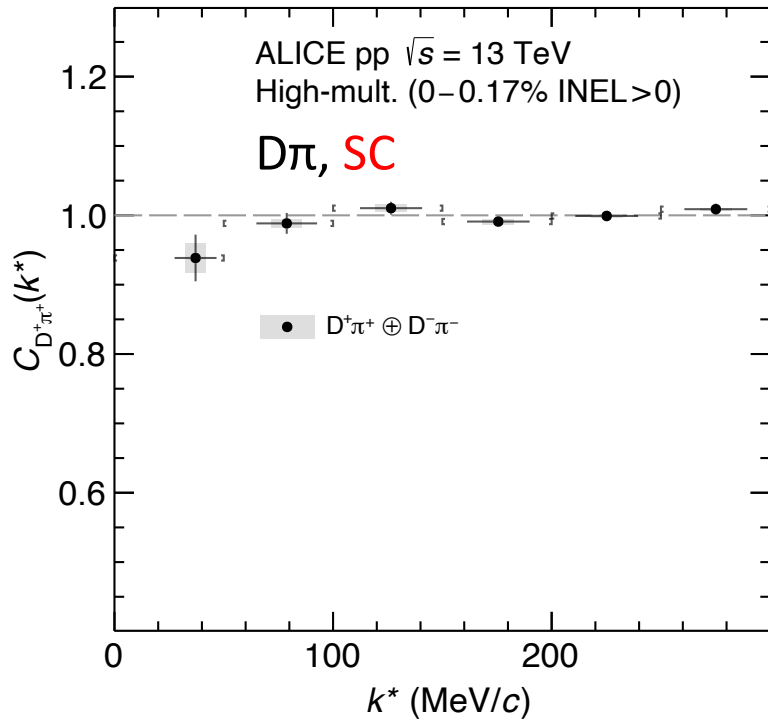
$$C_{raw}(k^*) = C_{non-femto}(k^*) \times C_{femto}(k^*)$$



Genuine correlation function

- Measurement of $D^{(*)}$ -K and $D^{(*)}$ - π correlation functions for same charge (SC) and opposite charge (OC) configuration
- Correction for feed-down, misidentifications etc. (Total Background) to extract **genuine CF** from data
- Sensitive to **Coulomb** and **strong** interaction

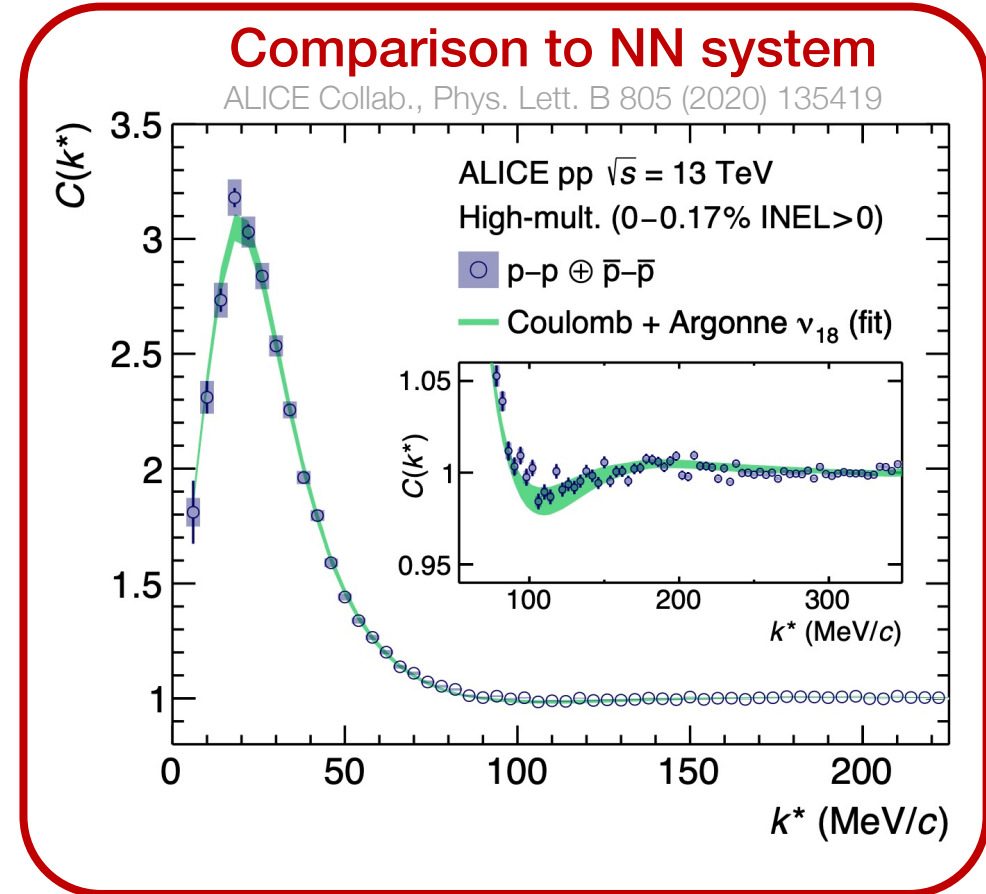
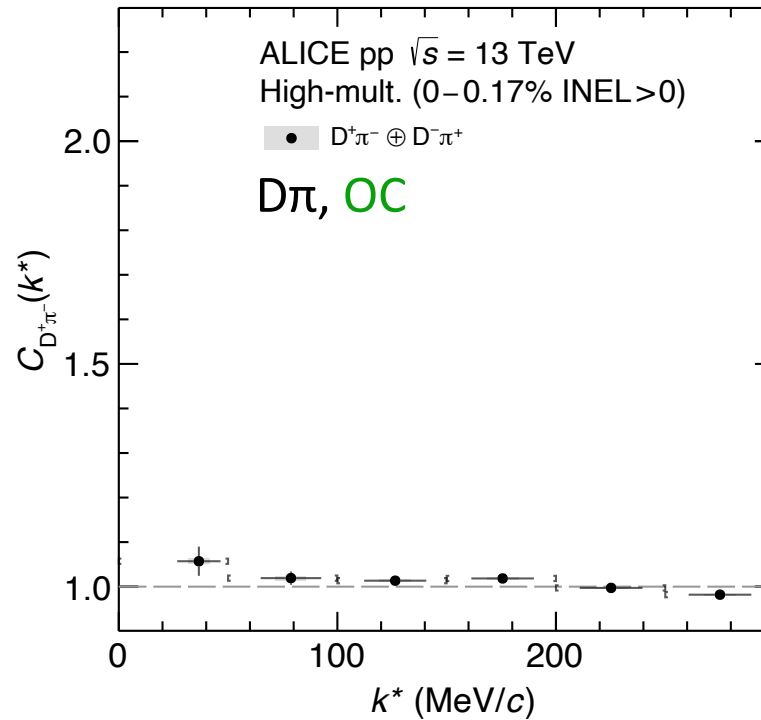
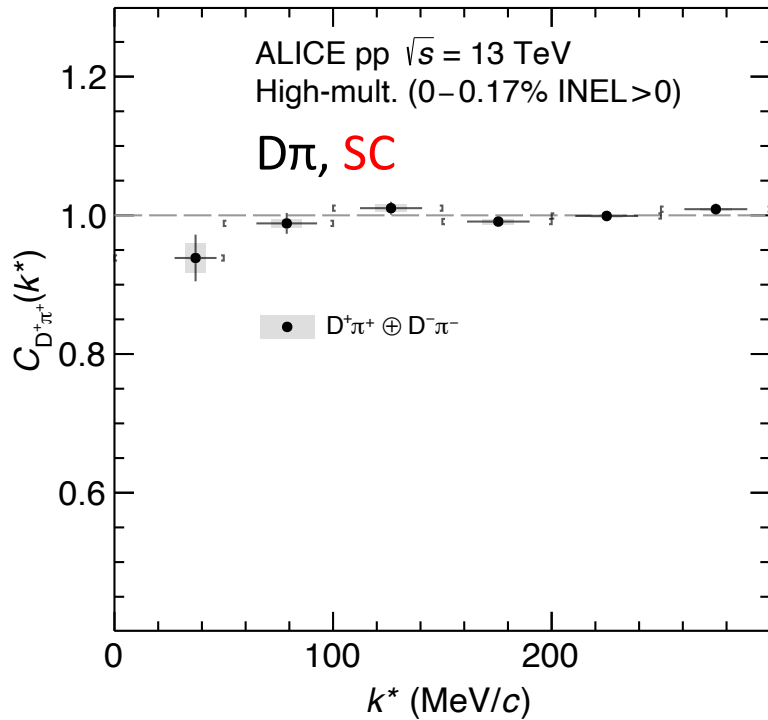
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D-light meson scattering lengths

Pair	(S,I)	L. Liu et al.	X.-Y. Guo et al.	Z.-H. Guo et al.		B.-L. Huang et al.	J. M. Torres-Rincon et al.	Z.-W. Liu et al.
				Fit-1B	Fit-2B			
D π	(0,3/2)	-0.10 fm	-0.11 fm	-0.101 fm	-0.099 fm	-0.06 fm	-0.101 fm	-0.12-i0.00036 fm
	(0,1/2)	0.37 fm	0.33 fm	0.31 fm	0.34 fm	0.61 fm	0.423 fm	0.27-i0.00036i 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	-0.22+i0.18 fm
D \bar{K}	(-1,0)	0.84 fm	0.46 fm	0.96 fm	0.68 fm	1.81 fm	0.399 fm	-0.19-i1.7*10 ⁻⁶ fm
	(-1,1)	-0.20 fm	-0.22 fm	-0.18 fm	-0.19 fm	-0.24 fm	-0.233 fm	0.29+i5.2*10 ⁻⁶ fm

L. Liu et al, *Phys. Rev. D* 87 (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 (2023) 096008

Z.-W. Liu et al, *Phys. Rev. D* 84 (2011) 034002

- Very small ($\sim 0.1 - 0.5$ fm) scattering parameters compared to other interactions
 - Light-flavor–light-flavor $\sim 7-8$ fm
 - Light-flavor–strange $\sim 1-2$ fm

D-light meson scattering lengths

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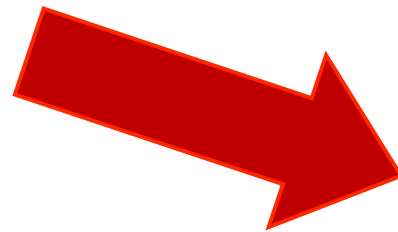
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J. M. Torres-Rincon et al, Phys. Rev. D 108 (2023) 096008

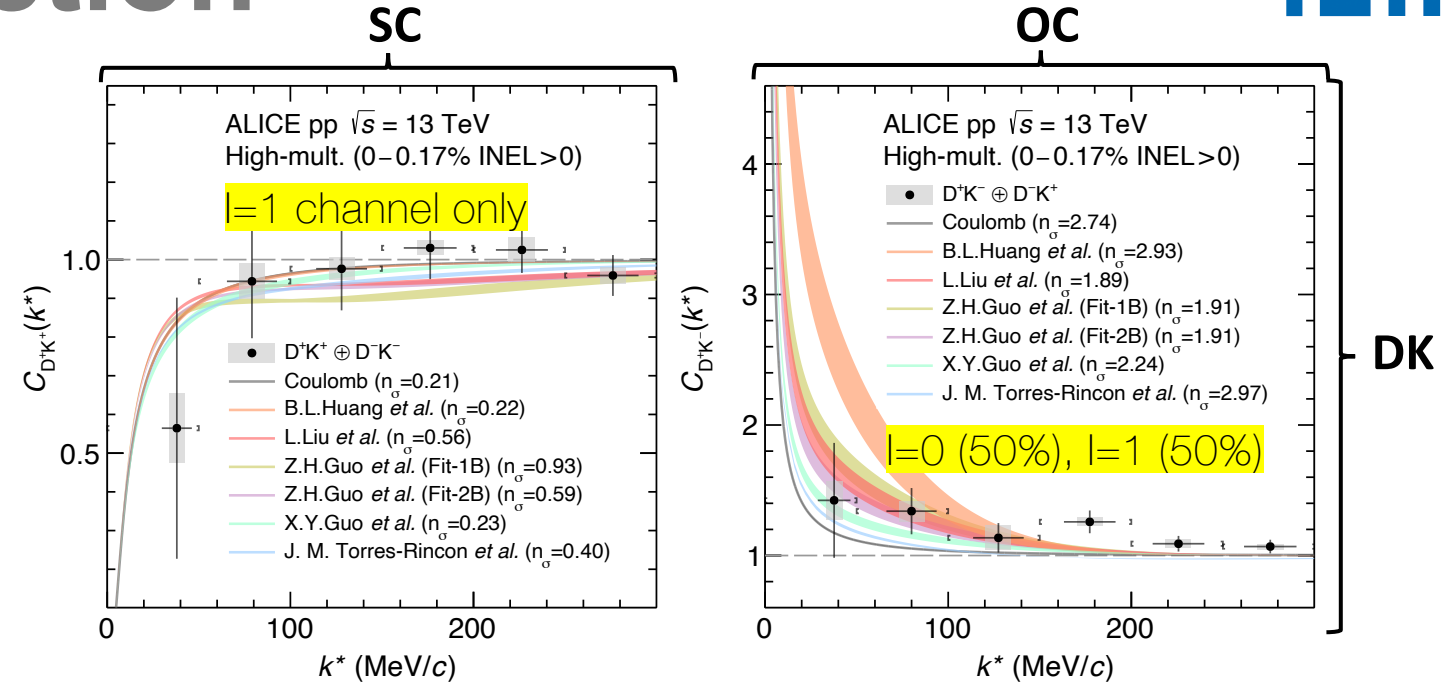
Z.-W. Liu et al, Phys. Rev. D 84 (2011) 034002



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

D π and DK interaction

- DK
 - Limited by statistics \rightarrow LHC Run 3 data needed
 - Compatible with models



L. Liu *et al.*, Phys. Rev. D **87** (2013) 014508

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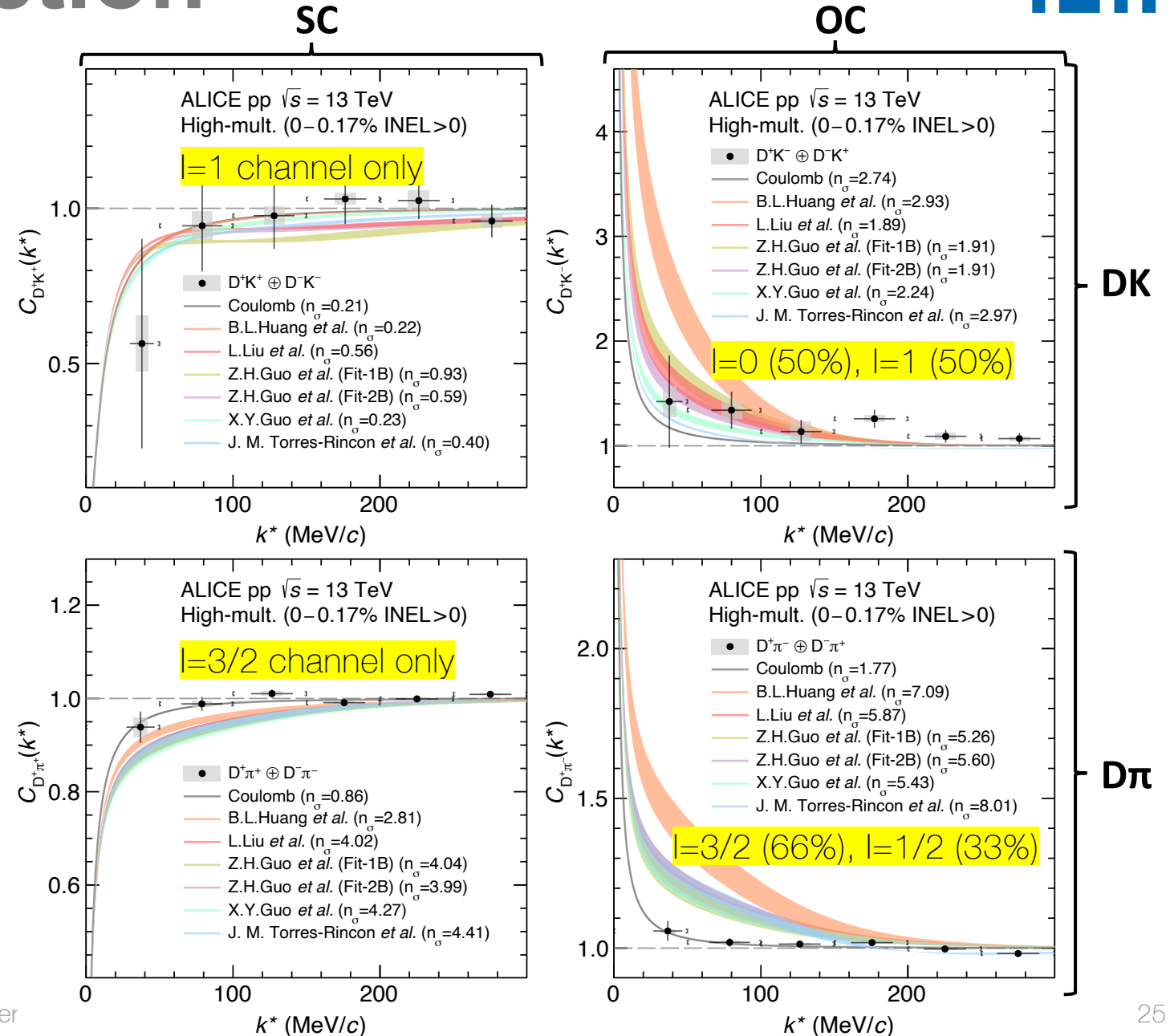
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B.-L. Huang *et al.*, Phys. Rev. D **105** (2022) 036016

J. M. Torres-Rincon *et al.*, Phys. Rev. D **108** (2023) 096008

D π and DK interaction

- DK
 - Limited by statistics \rightarrow LHC Run 3 data needed
 - Compatible with models
- D π
 - Coulomb-only interaction favoured
 - Tension with theory models



L. Liu *et al.*, Phys. Rev. D87 (2013) 014508

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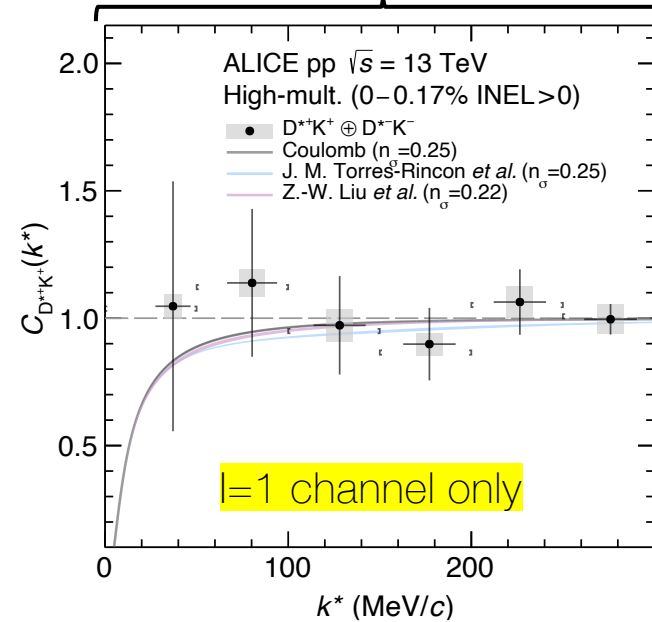
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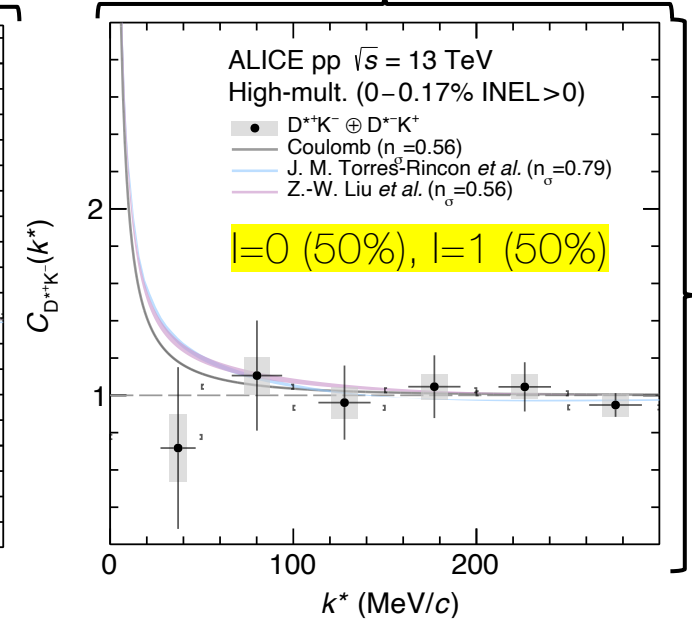
D* π and D*K interaction

- 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

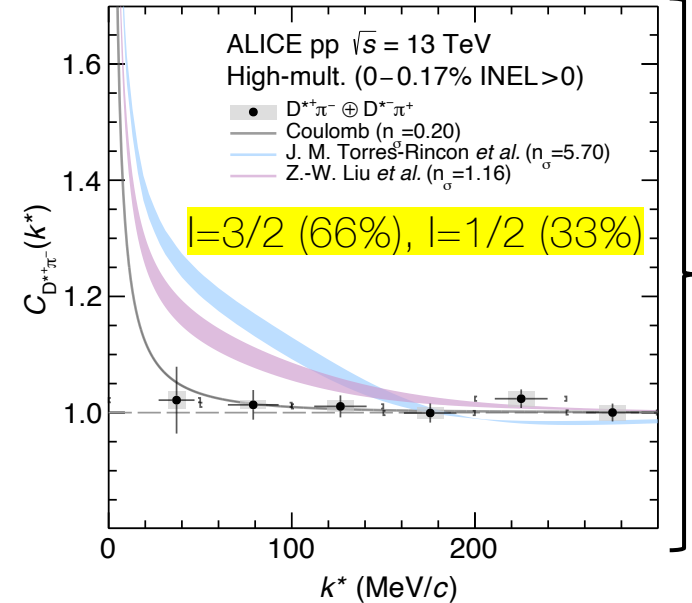
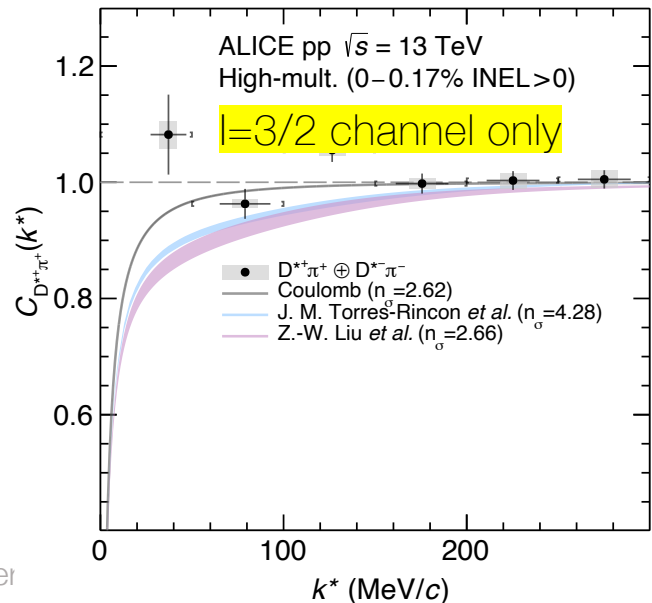
SC



OC

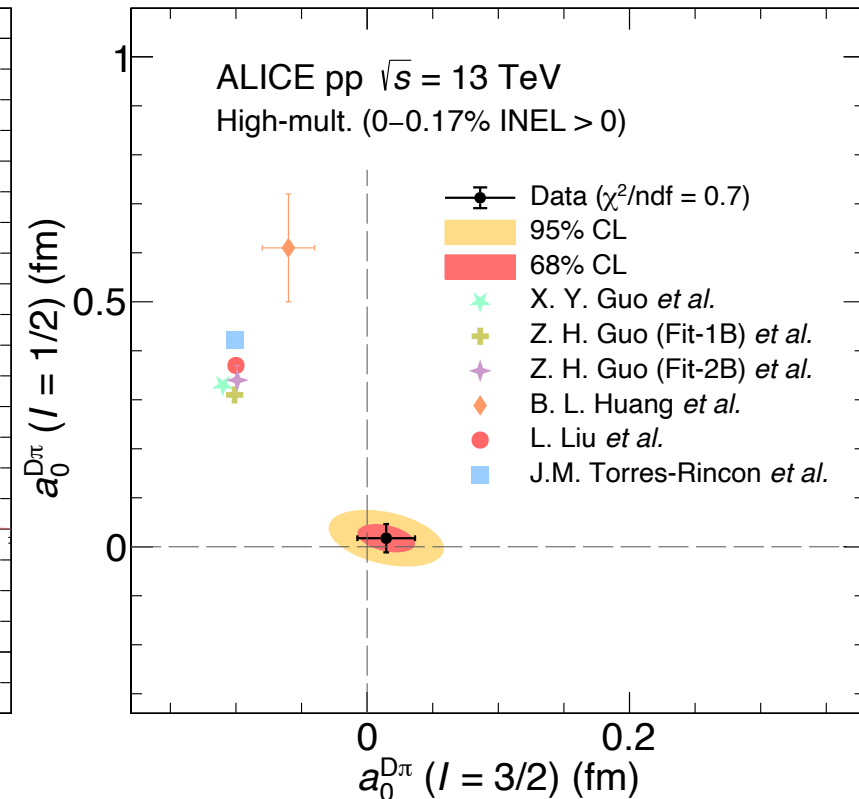
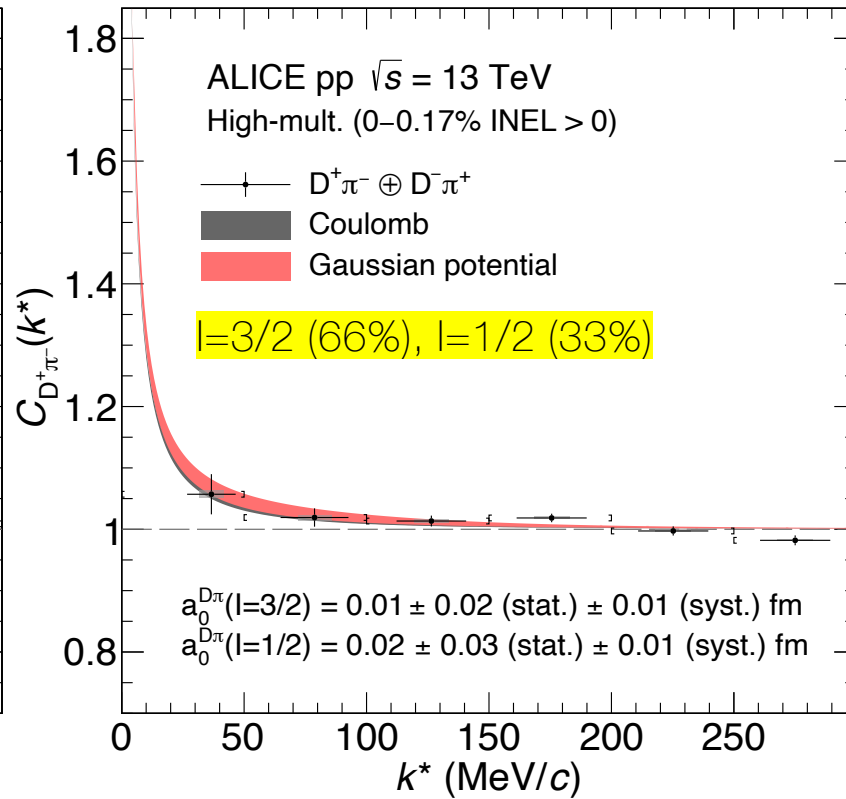
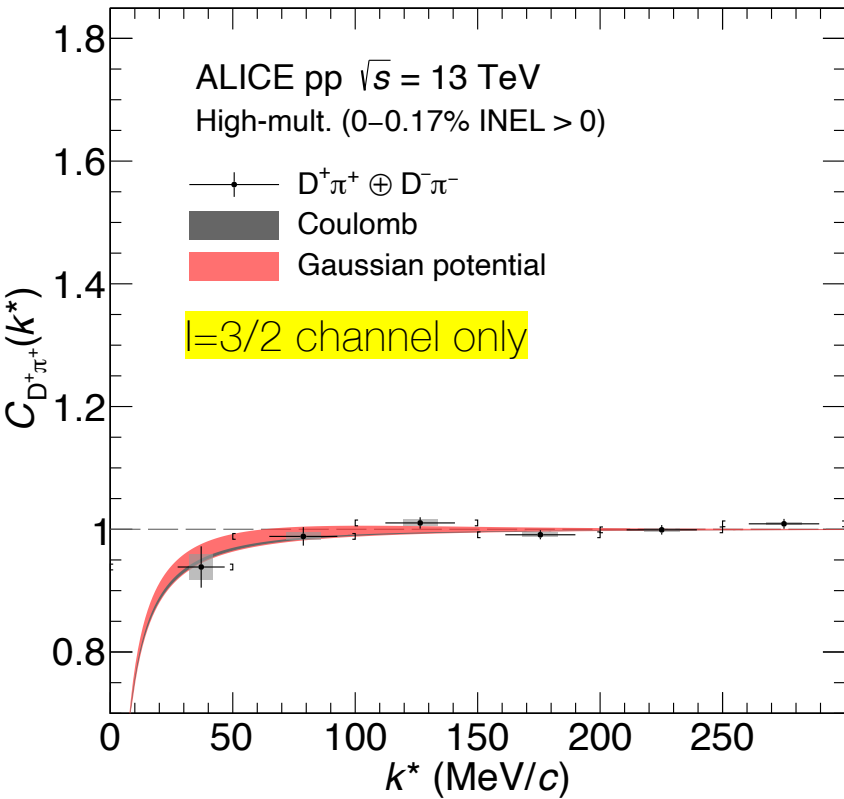


D*K



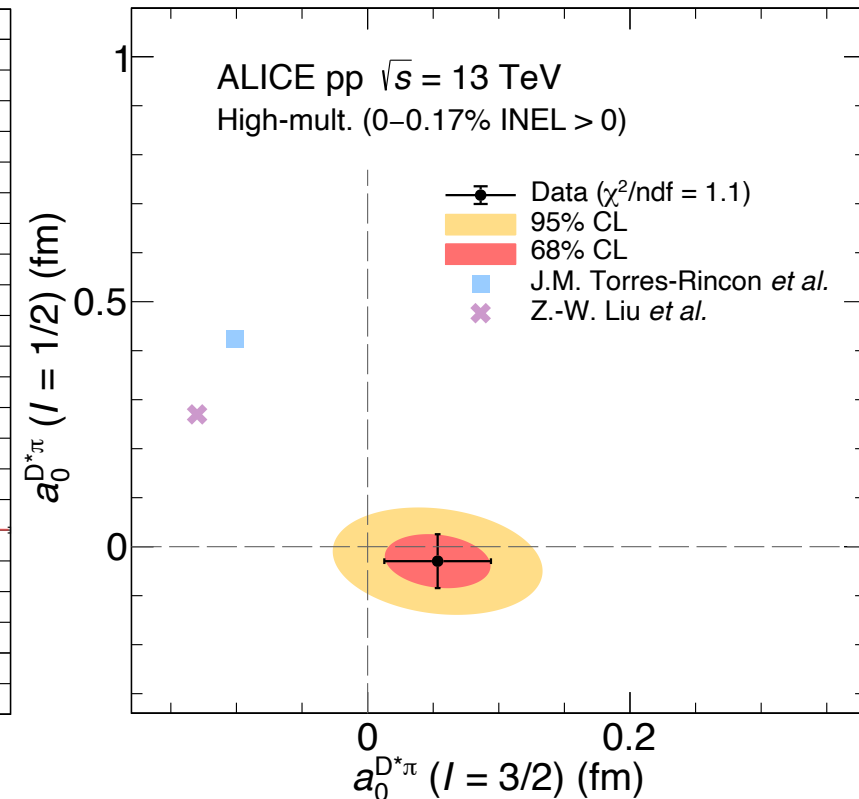
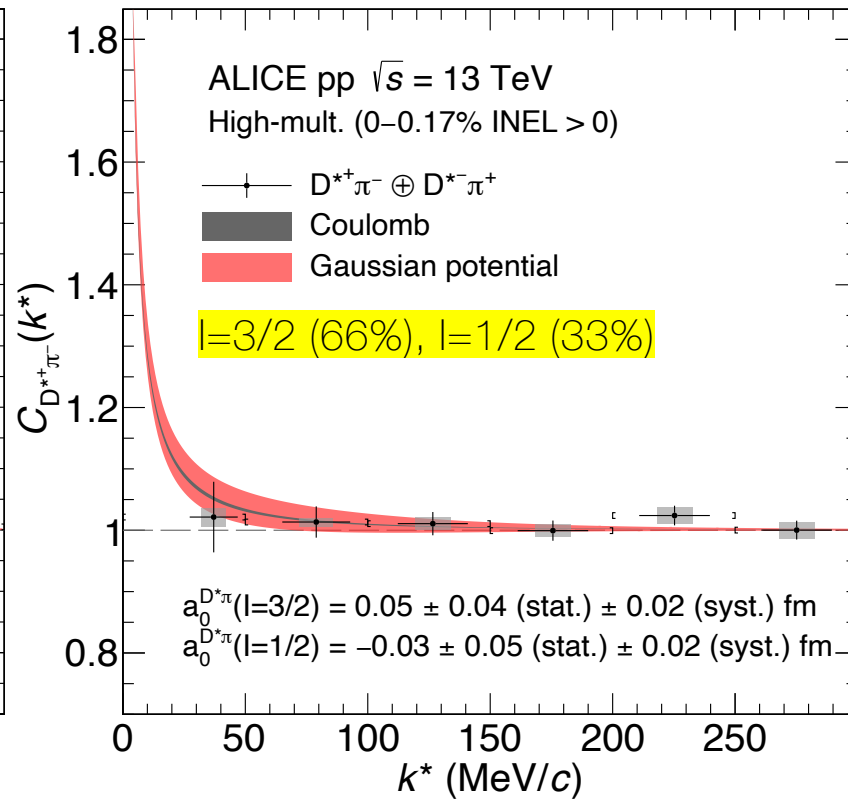
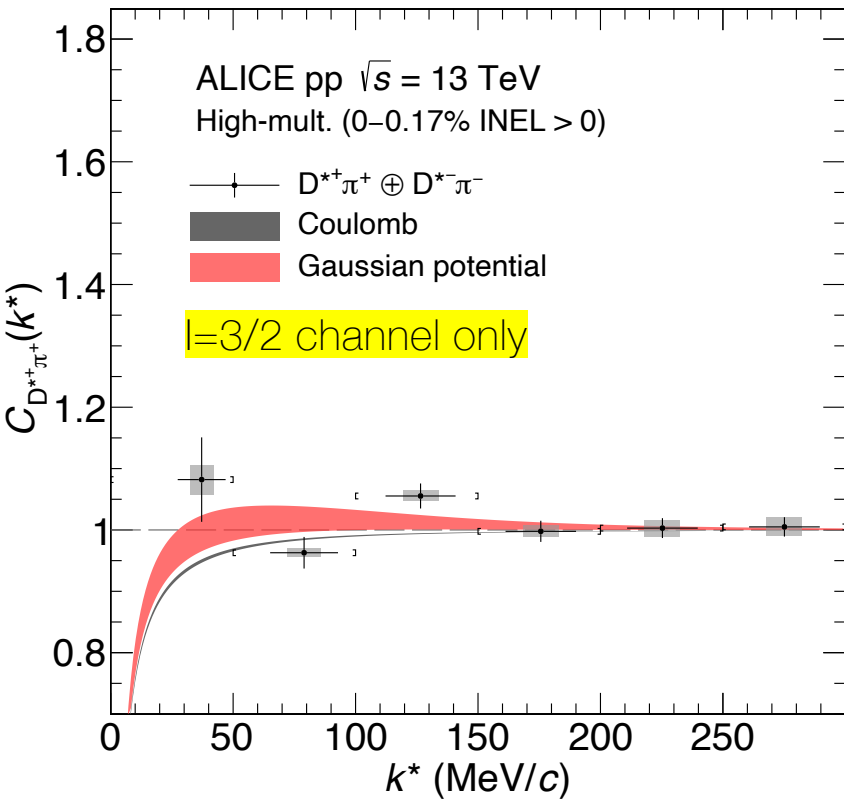
D*\mathpi

D π correlation function fit



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

D* π correlation function fit

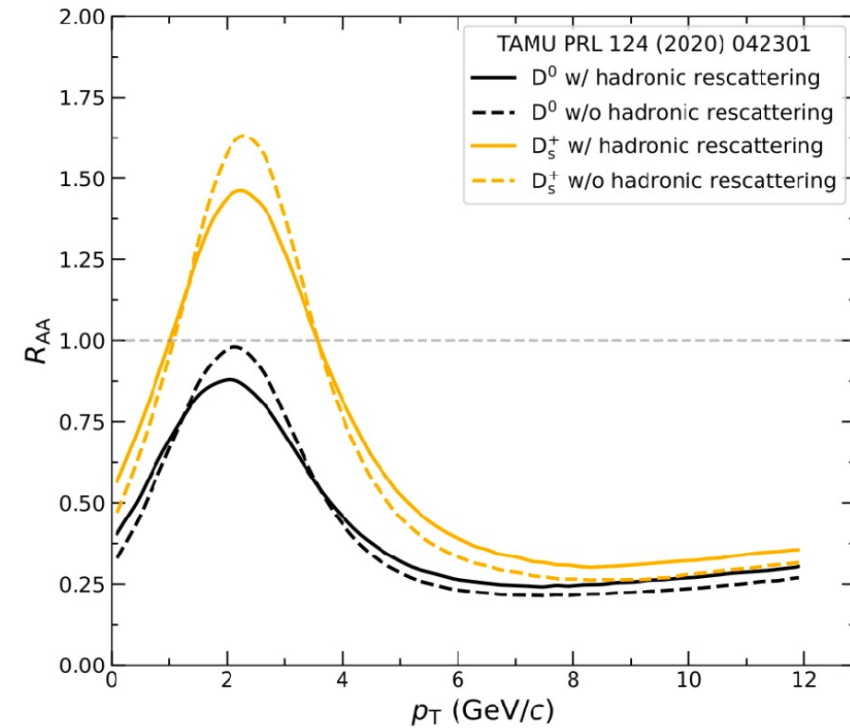
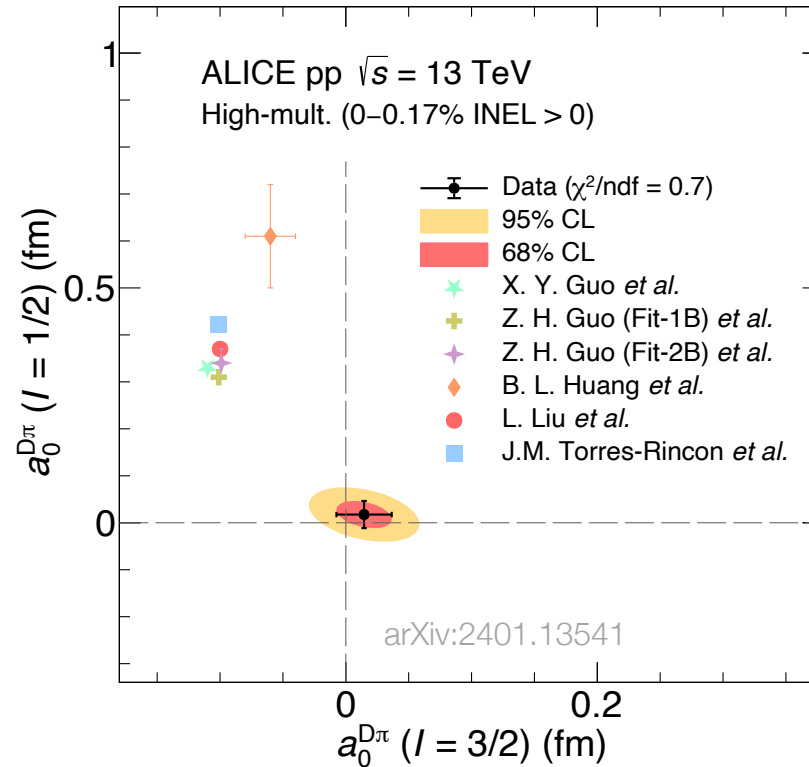


- Shared $l=3/2$ channel \rightarrow simultaneous fit
- Vanishing scattering parameters within uncertainties
- Scattering parameters compatible with $D\pi$ results \rightarrow Heavy-quark spin symmetry

Nuclear modification factor

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

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

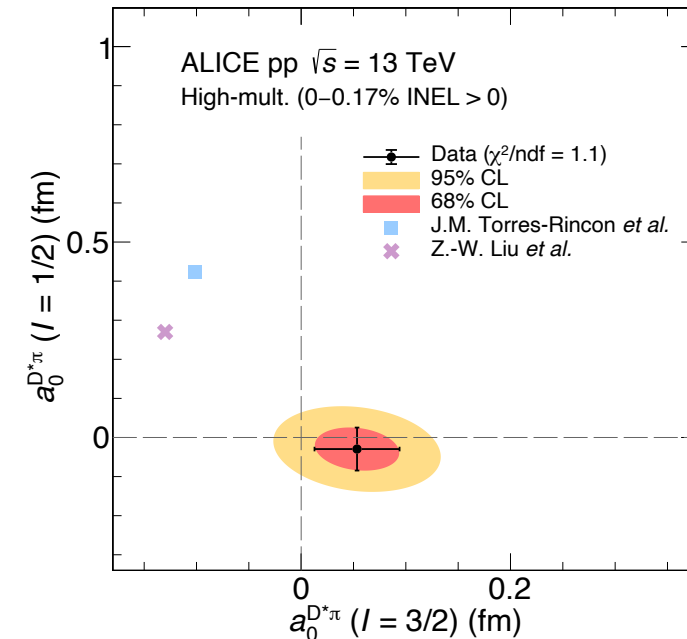
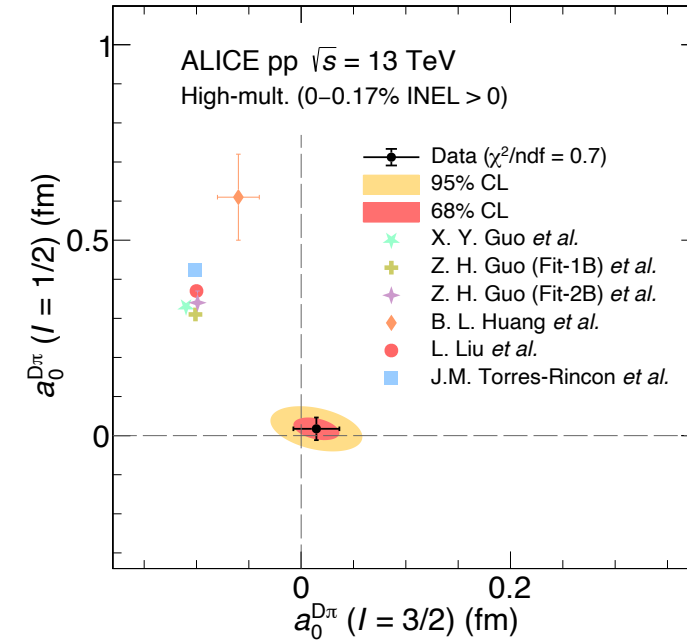


Conclusion

- First measurement of interaction between charm and light-flavor mesons in pp collisions at $\sqrt{s} = 13$ 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 $D\pi$ and $D^*\pi$
- Smaller effect of rescattering on heavy-ion observables, as models employ larger theory values for now
- Significant improvement of statistics foreseen with LHC Run 3 data



Additional material

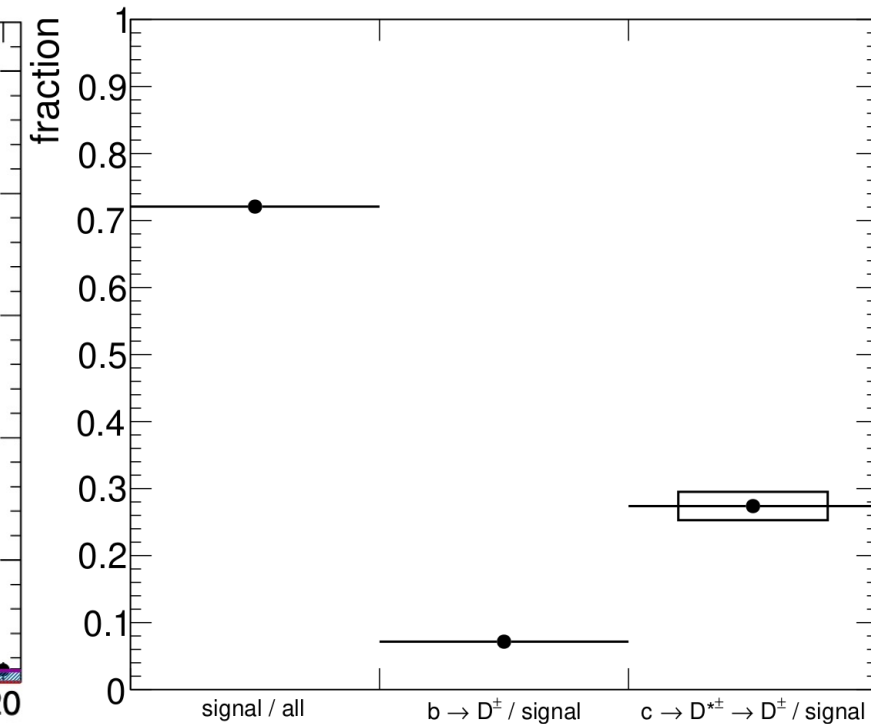
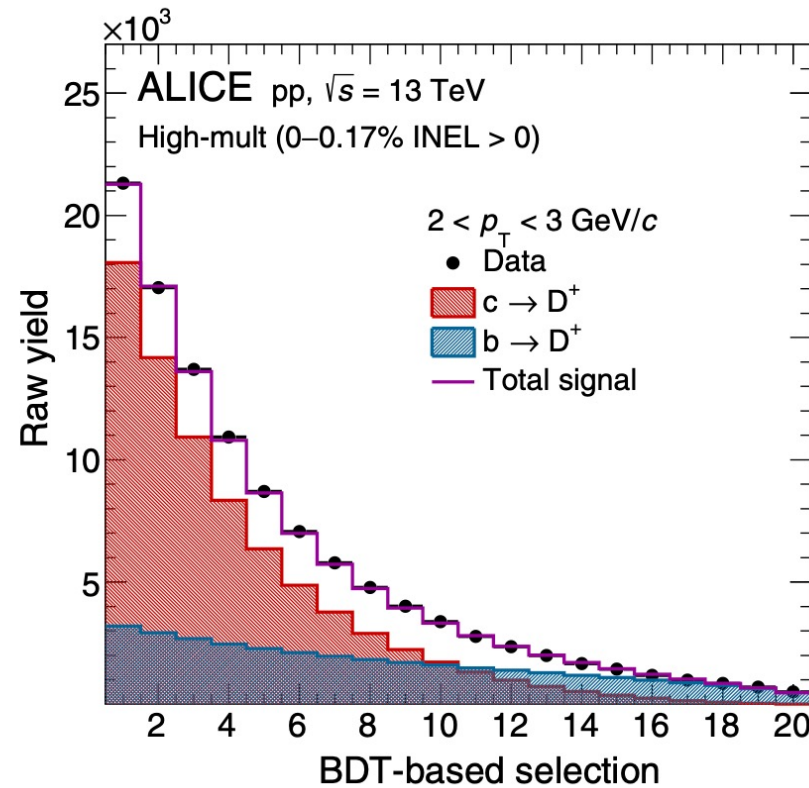
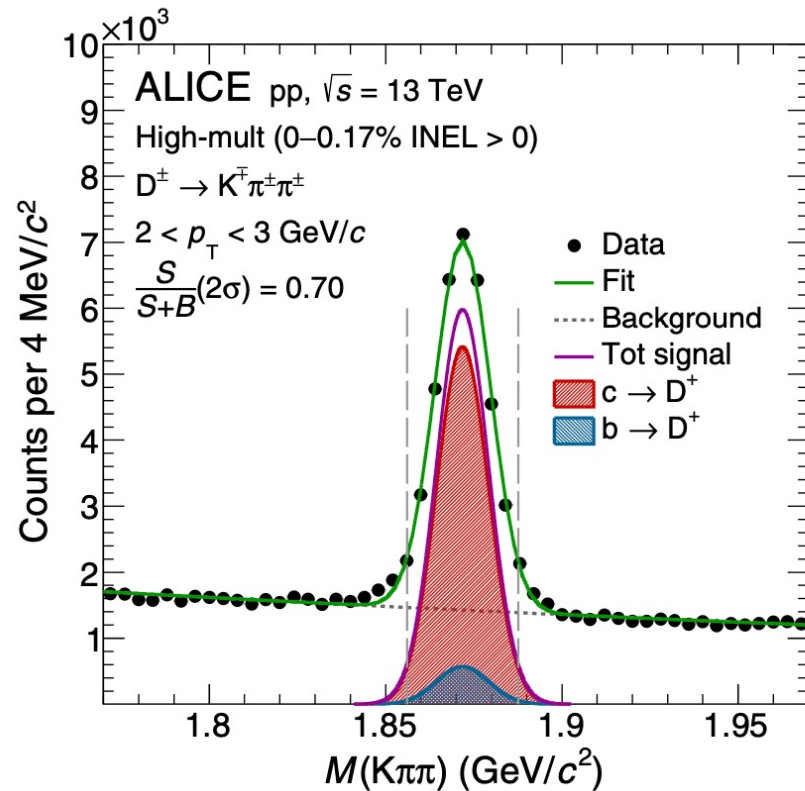
D meson reconstruction

- Decay channel $D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$
 - BR=(9.38±0.16)%

PDG, *Prog. Theo. Exp. Phys.* (2020) 083C01

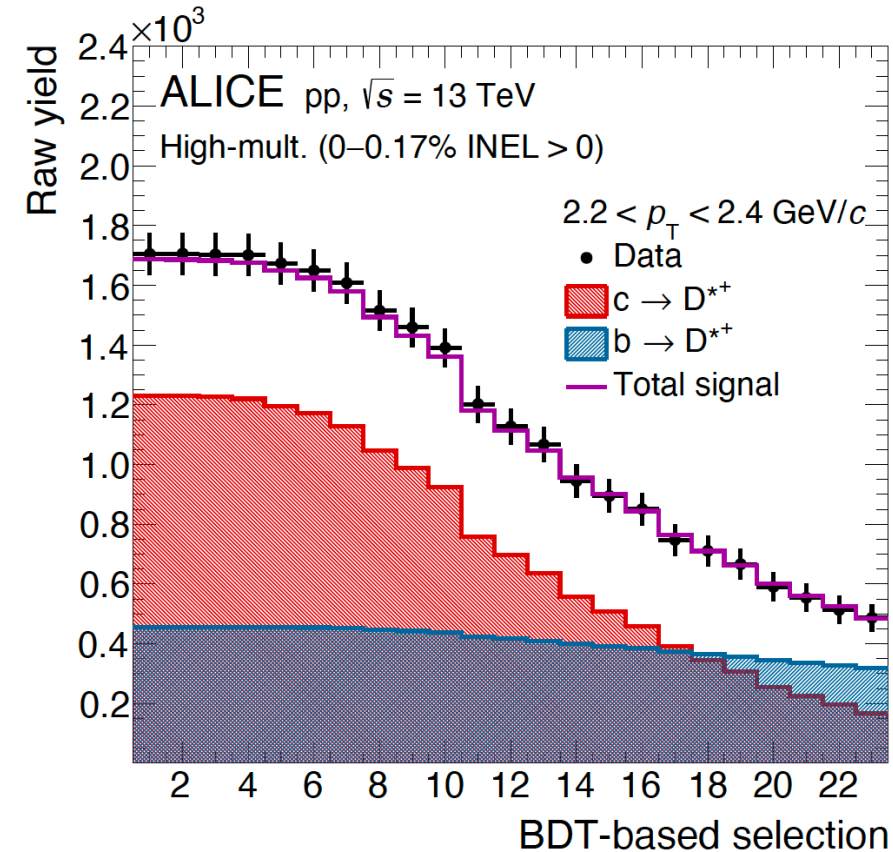
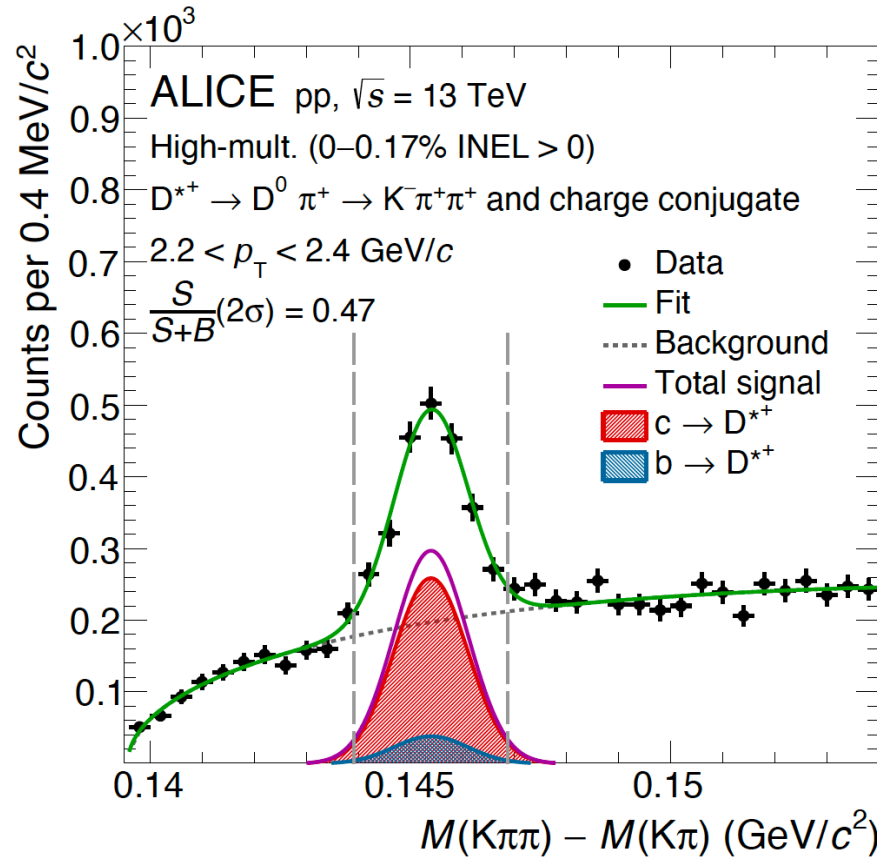
Alice Collab. *Phys. Rev. D* **106** (2022) 052010

- Purity of D meson candidates ~70%



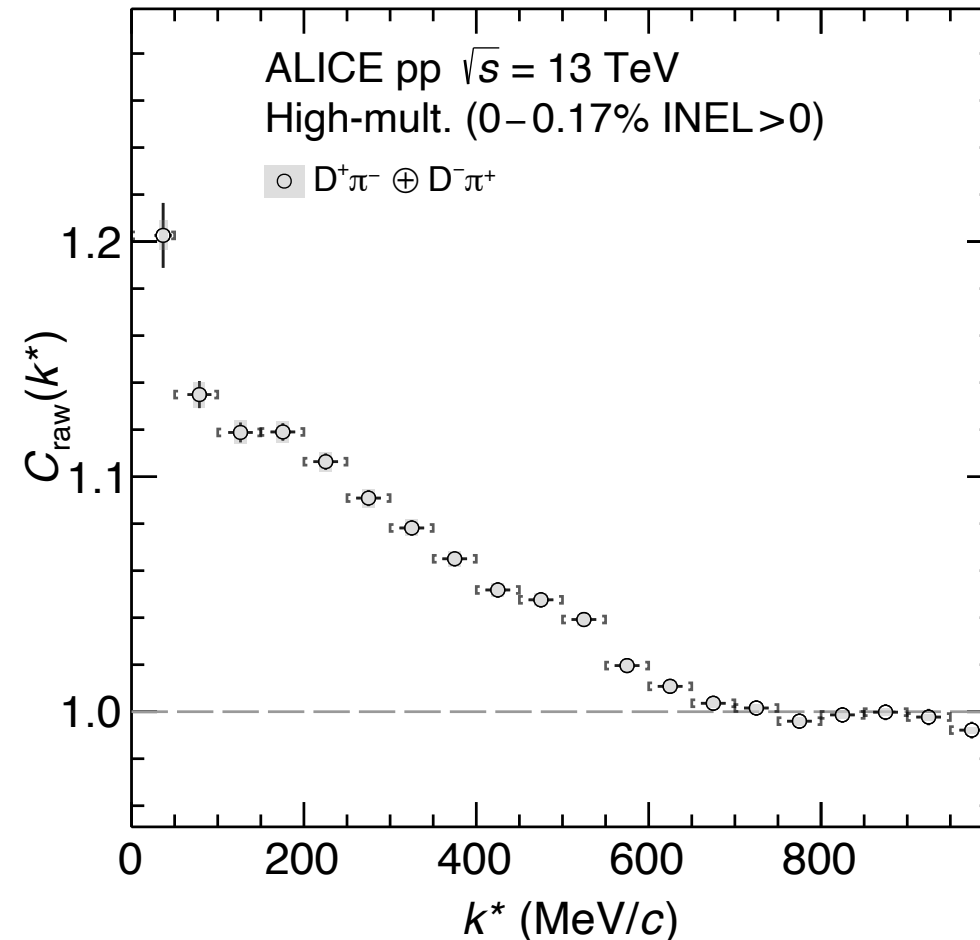
D* meson reconstruction

- Decay channel $D^{\pm*} \rightarrow D^0 \pi^{\pm}$ with $\text{BR}=(67.7 \pm 0.5)\%$



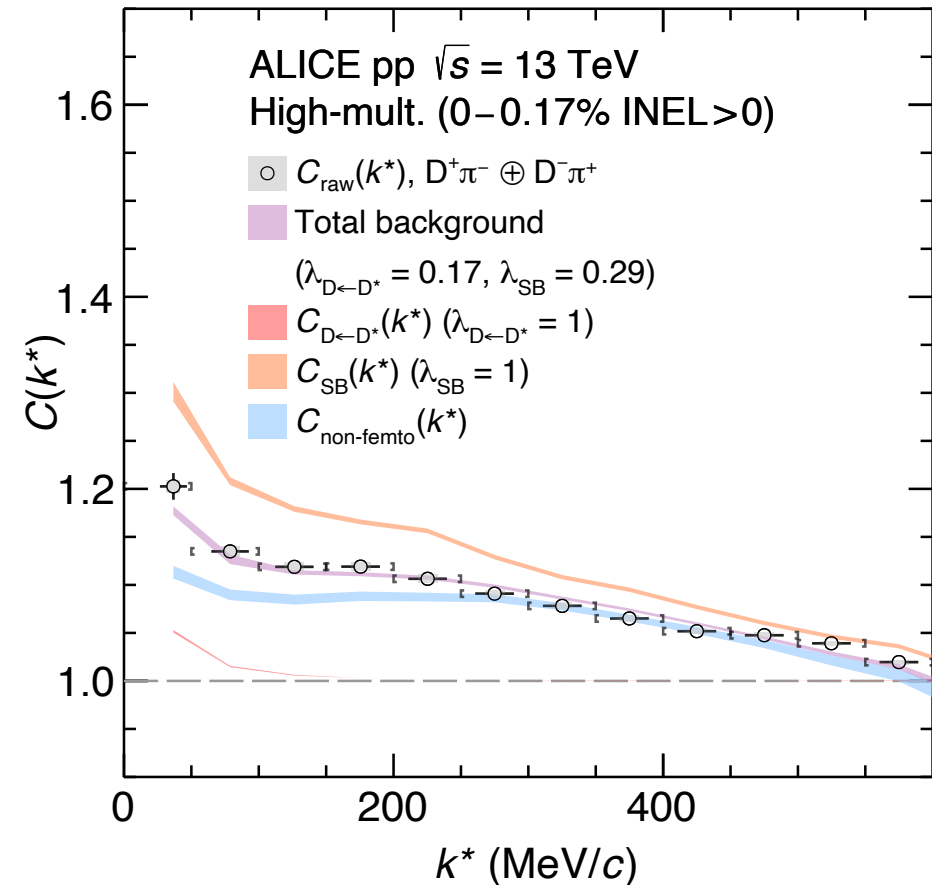
Modelling of the raw correlation function

$$C_{raw}(k^*) = C_{non-femto}(k^*) \times C_{femto}(k^*)$$

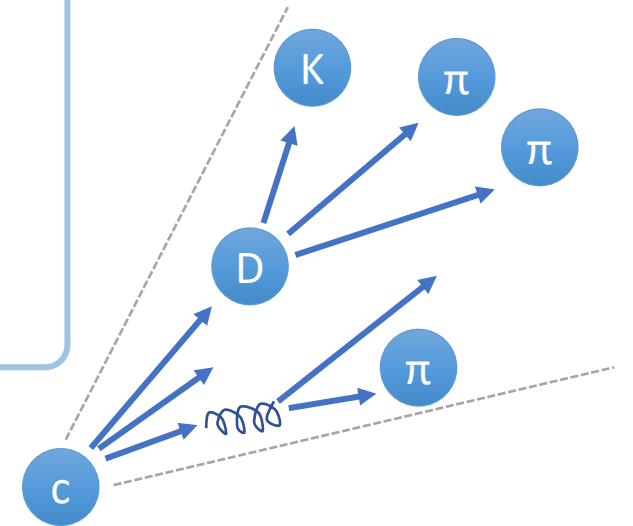


Modelling of the raw correlation function

$$C_{raw}(k^*) = C_{non-femto}(k^*) \times C_{femto}(k^*)$$

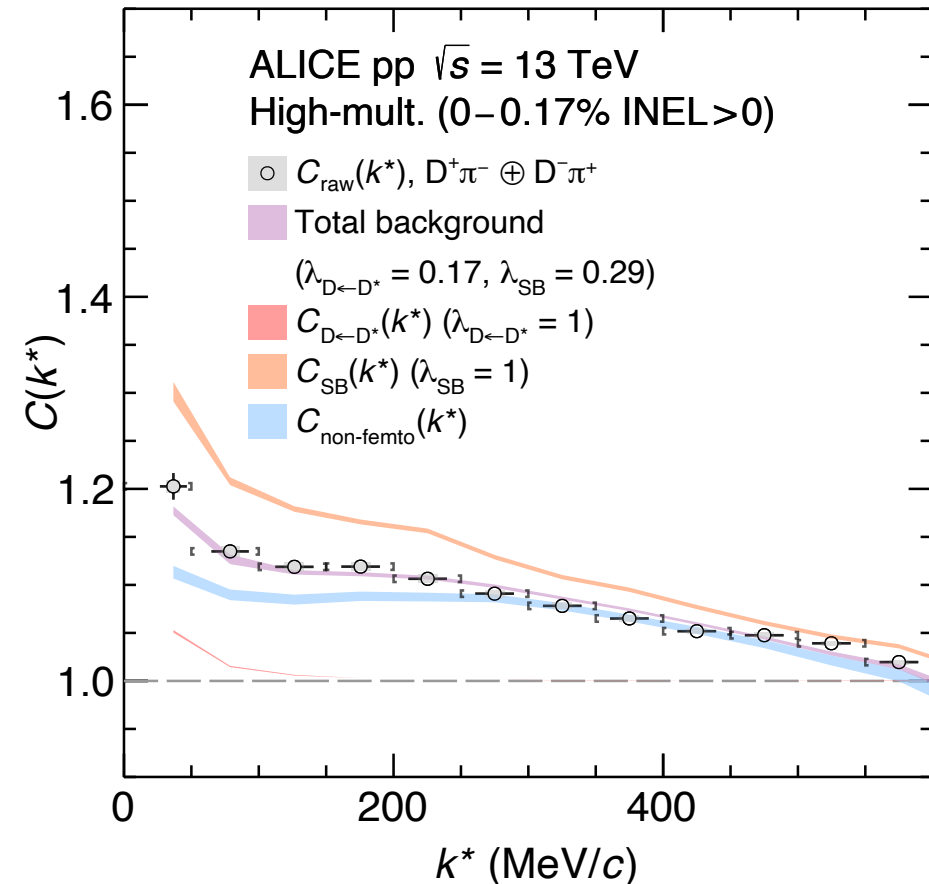


- Not related to final state interaction between particles
 - Energy-momentum conservation effects
 - Mini-jets
- Modeled using MC simulations



Modelling of the raw correlation function

$$C_{raw}(k^*) = C_{non-femto}(k^*) \times C_{femto}(k^*)$$



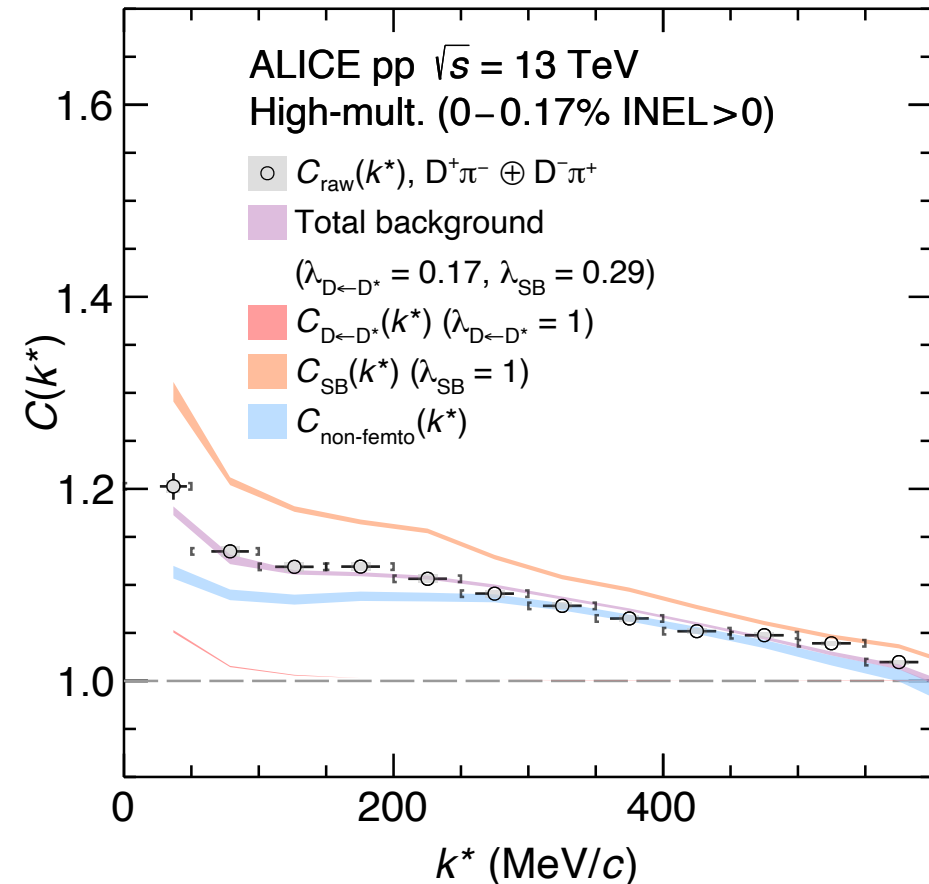
$$C_{femto}(k^*) = \sum_{i,j} \lambda_{ij} \times C_{ij}(k^*)$$

with $\lambda_{ij} = p_i f_i p_j f_j$, the purities and fractions of specific contribution

- Includes contributions related to final state interaction
- Considers feed-down contribution to single-particle yields and misidentifications

Modelling of the raw correlation function

$$C_{raw}(k^*) = C_{non-femto}(k^*) \times C_{femto}(k^*)$$

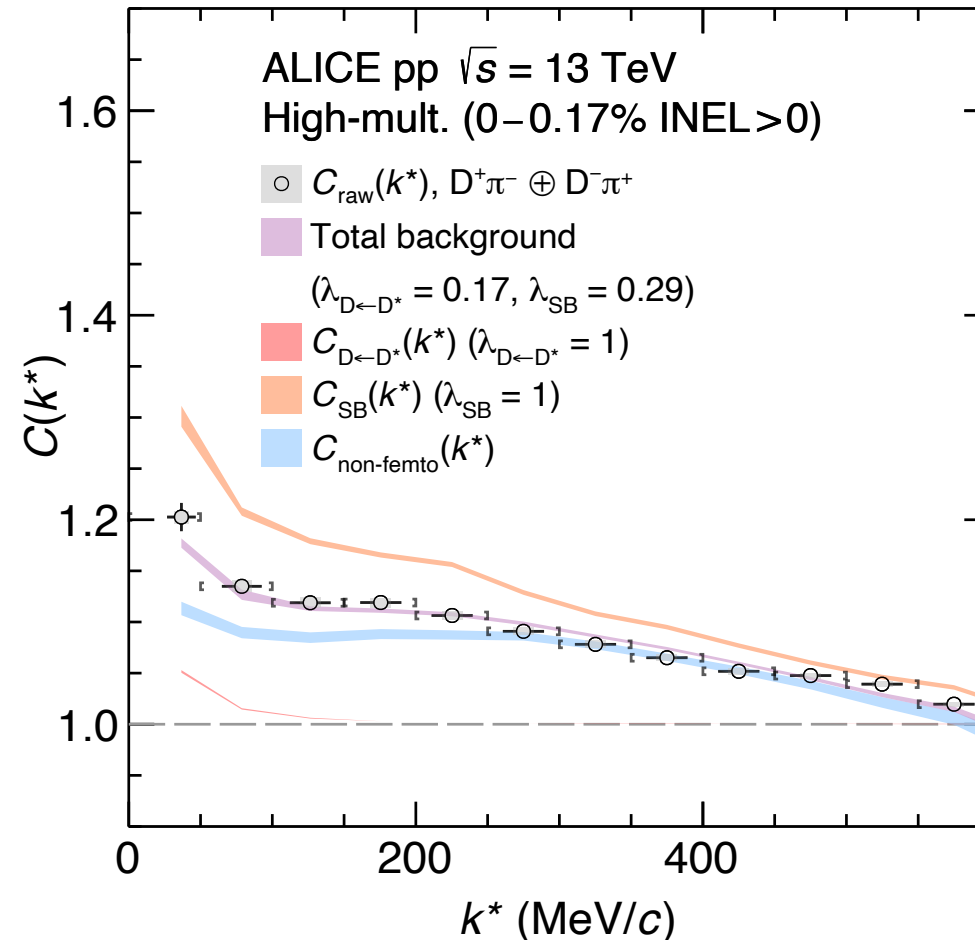


In this case

- **Genuine contribution** from primary particle interaction \rightarrow of interest
- **Combinatorial background** from misidentified D/D* mesons \rightarrow Sideband analysis
- **Feed-down contribution** from excited charm states $D^* \rightarrow D$
- **Flat contribution**, including misidentifications and feed-down to light mesons \rightarrow negligible, therefore $C(k^*)=1$

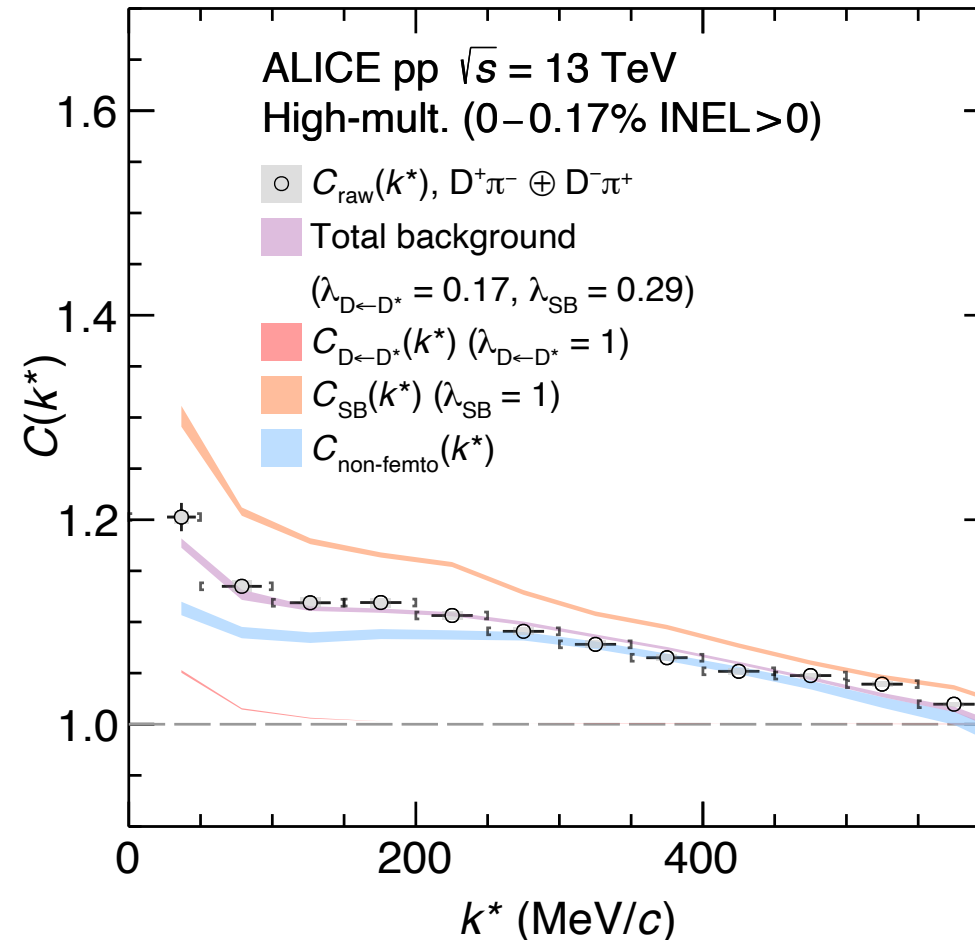
Modelling of the raw correlation function

$$C_{raw}(k^*) = \lambda_{SB} C_{SB}(k^*) + C_{non-femto}(k^*) \times [\lambda_{gen} C_{gen}(k^*) + \lambda_{D^* \rightarrow D} C_{D^* \rightarrow D}(k^*) + \lambda_{flat}]$$



Modelling of the raw correlation function

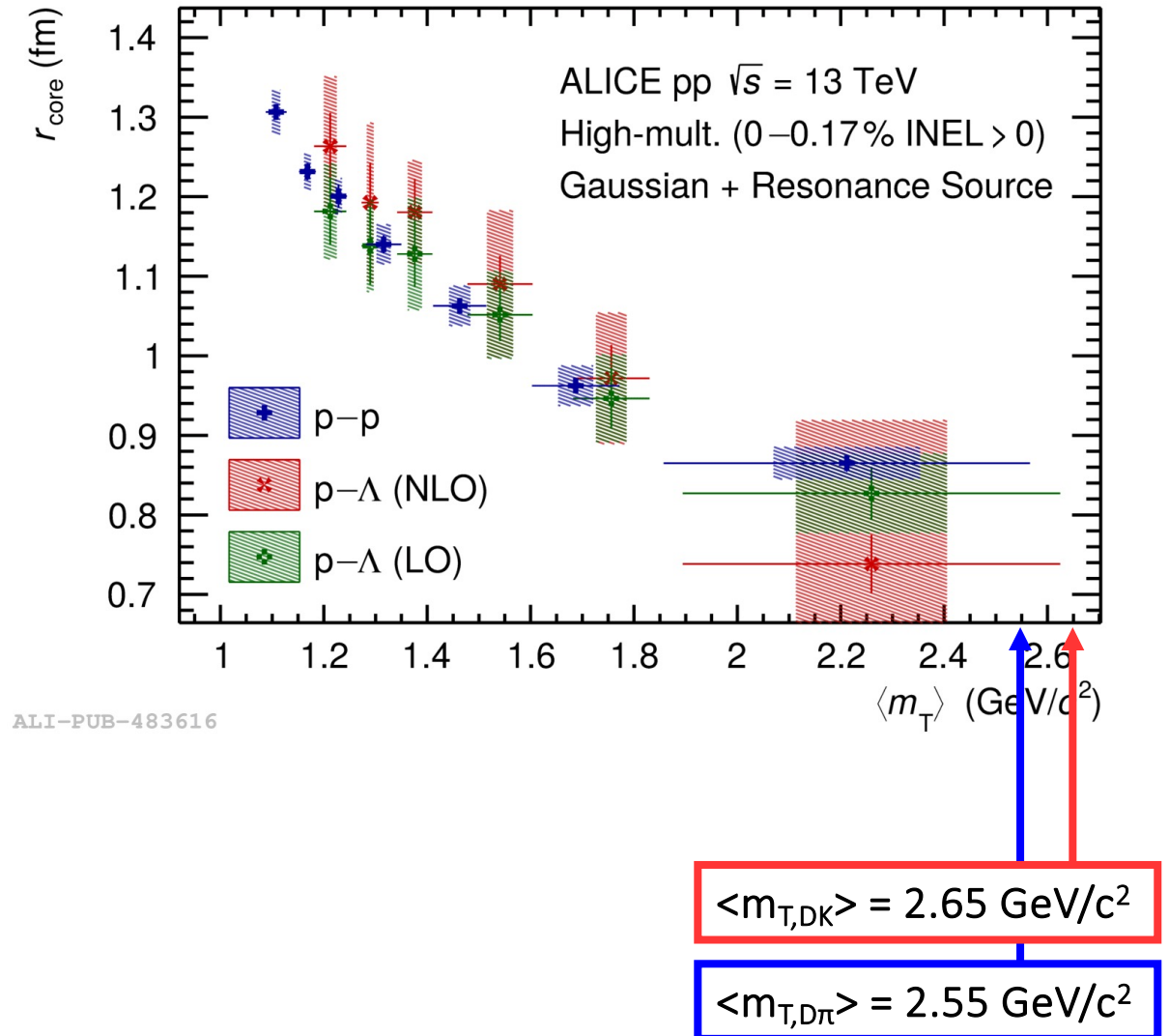
$$C_{bkg}(k^*) = \lambda_{SB} C_{SB}(k^*) + C_{non-femto}(k^*) \times [\lambda_{gen} \cdot \mathbf{1} + \lambda_{D^* \rightarrow D} C_{D^* \rightarrow D}(k^*) + \lambda_{flat}]$$



Source

- Particle emission from Gaussian core source
 - Universal source model constrained from pp pairs (well known interaction)

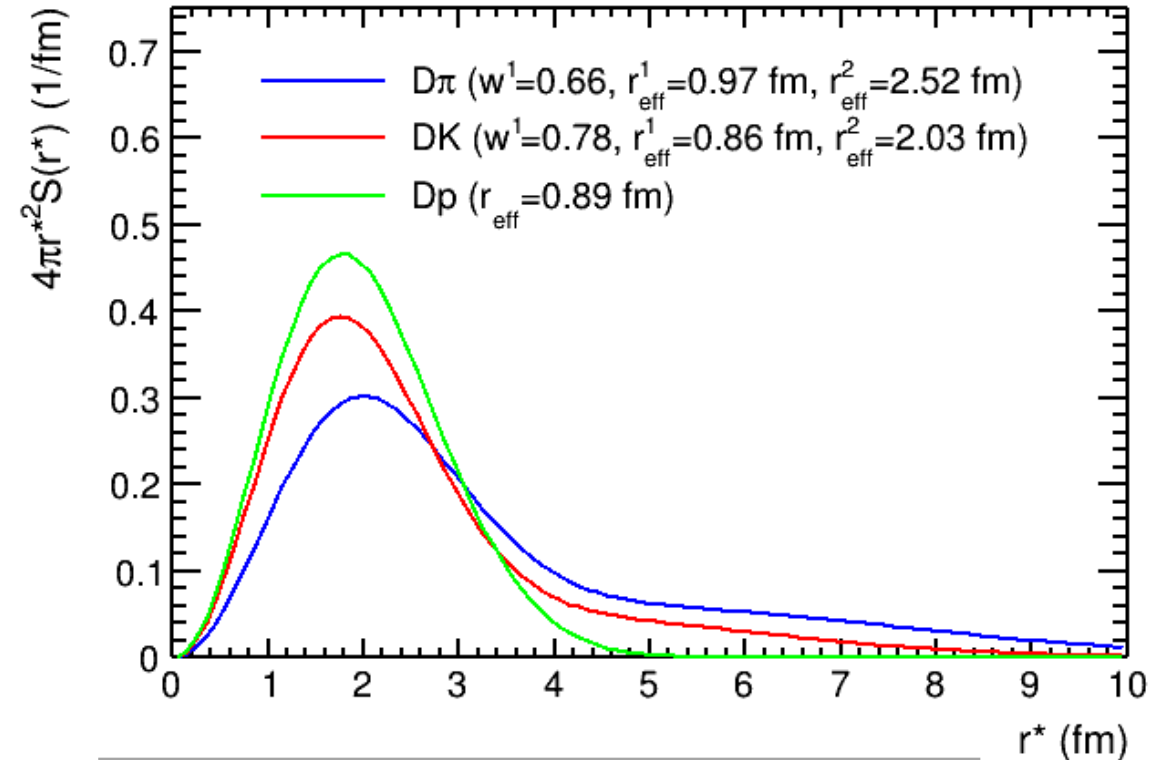
ALICE Collab., Physics Letters B, 811 (2020) 135849



ALI-PUB-483616

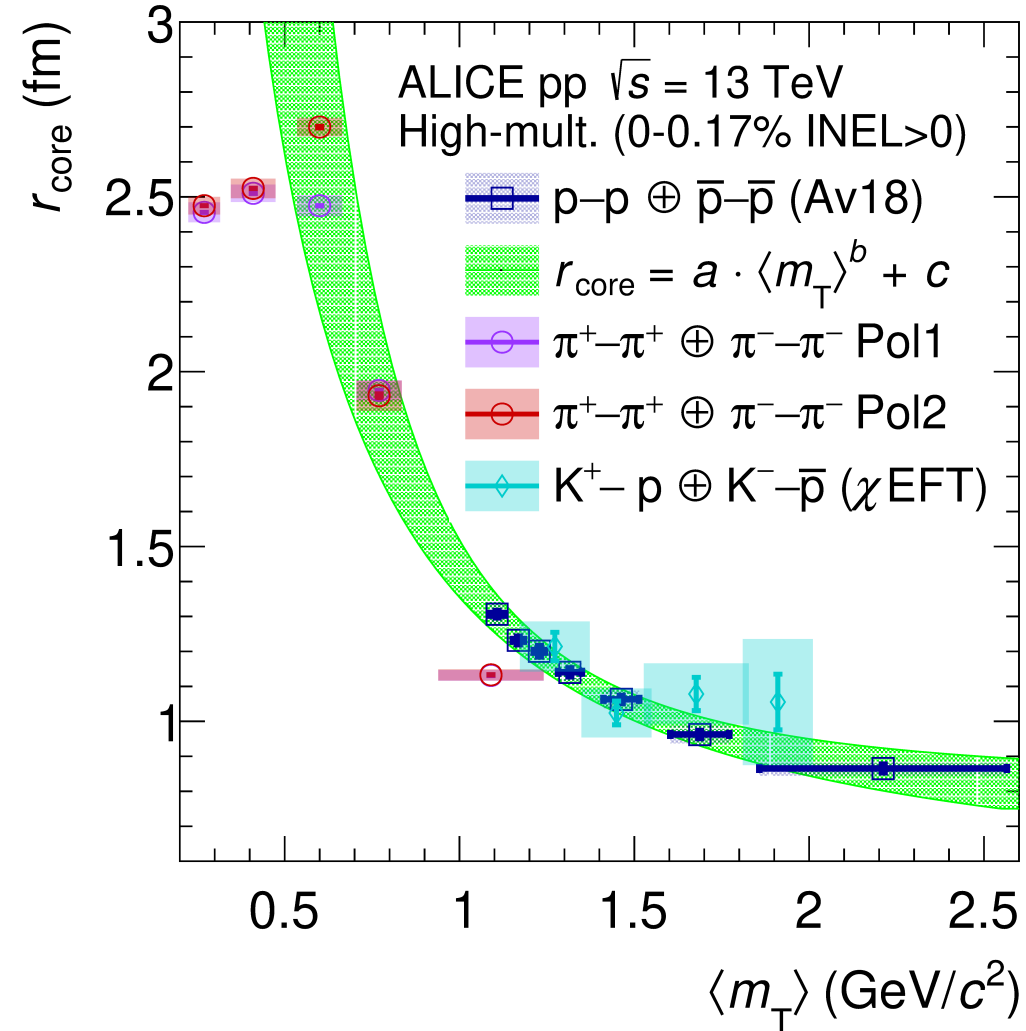
Source

- Particle emission from Gaussian core source
 - Universal source model constrained from pp pairs (well known interaction)
ALICE Collab., Physics Letters B, 811 (2020) 135849
- Core radius effectively increased by short-lived strongly decaying resonances ($\langle \tau \rangle \approx r_{\text{core}}$)
 - DK and D π source described by weighted (w^1) sum of two Gaussian sources, to describe tail from longer-lived resonances:
 - DK: $r_{\text{eff}}^1 = 0.86^{+0.09}_{-0.07} \text{ fm}, r_{\text{eff}}^2 = 2.03^{+0.19}_{-0.12} \text{ fm}$
 - D π : $r_{\text{eff}}^1 = 0.97^{+0.09}_{-0.08} \text{ fm}, r_{\text{eff}}^2 = 2.52^{+0.36}_{-0.20} \text{ fm}$



	main reso. contributions	$\langle \tau \rangle$ [fm]
D	-	
p	Δ	1.7
K	$K^{*0}, K^{*\pm}$	4.2
π	$\rho^0, \rho^\pm, K^{*0}, K^{*\pm}, \omega(782)$	1.3-23.4

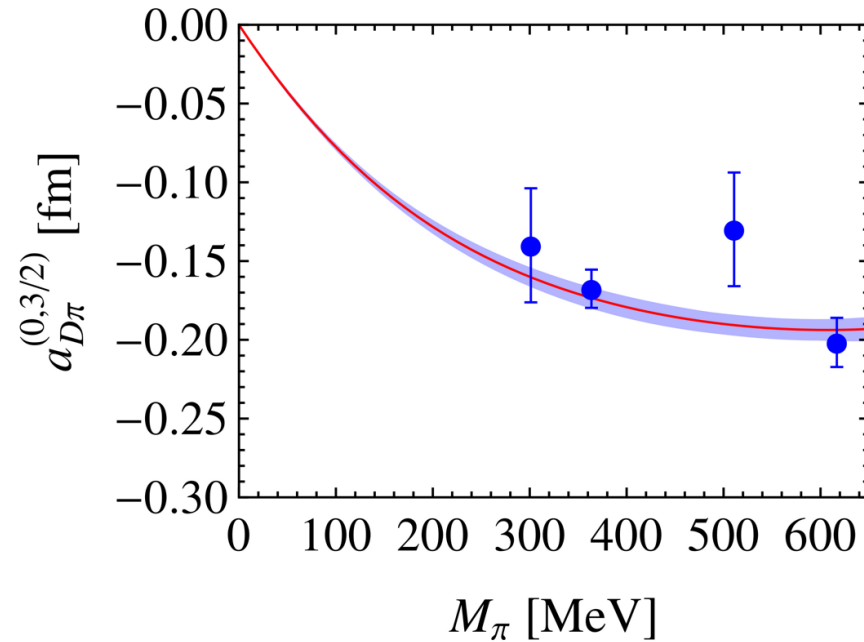
Source extended to mesons



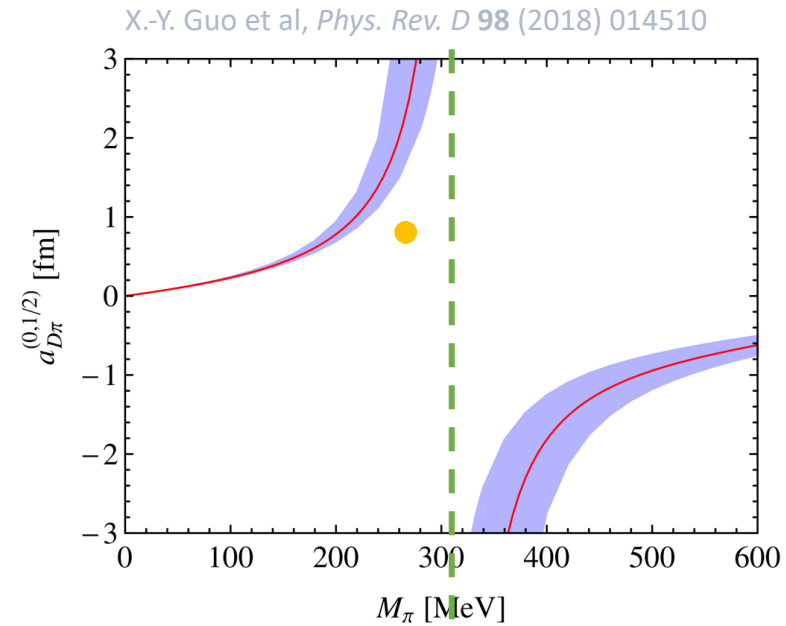
ALI-PUB-566229

$D\pi$ and DK interaction

- Lattice data only available for $D\pi(l=3/2)$ and $D^+K^- (l=0,1)$
 - Scattering parameters at physical quark masses obtained from chiral extrapolation
- $D\pi(l=1/2)$ and $D^+K^+ (l=0,1)$ rely on predictions from fitting the available lattice data



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



Bound-state pole formation corresponding to $D_s 0^*(2317)$

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

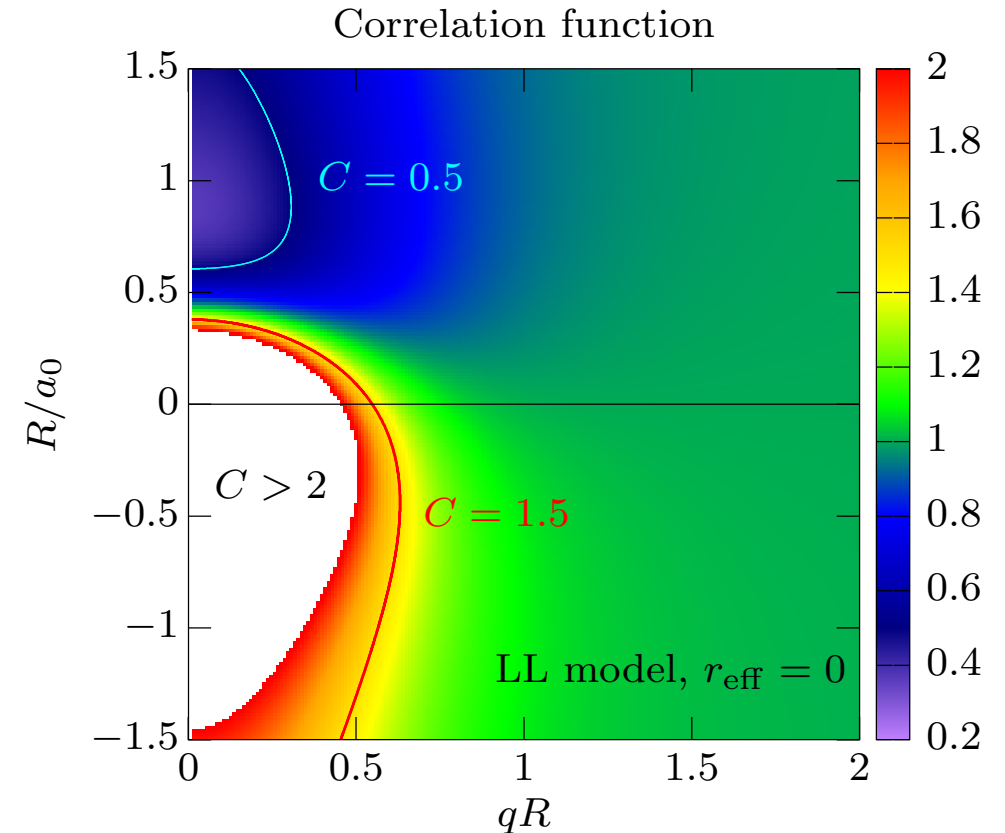
$$C(q) = 1 + \frac{1}{x^2 + y^2} \left[\frac{1}{2} - \frac{2y}{\sqrt{\pi}} \int_0^{2x} dt \frac{e^{t^2 - 4x^2}}{x} - \frac{(1 - e^{-4x^2})}{2} \right]$$

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

R= source size

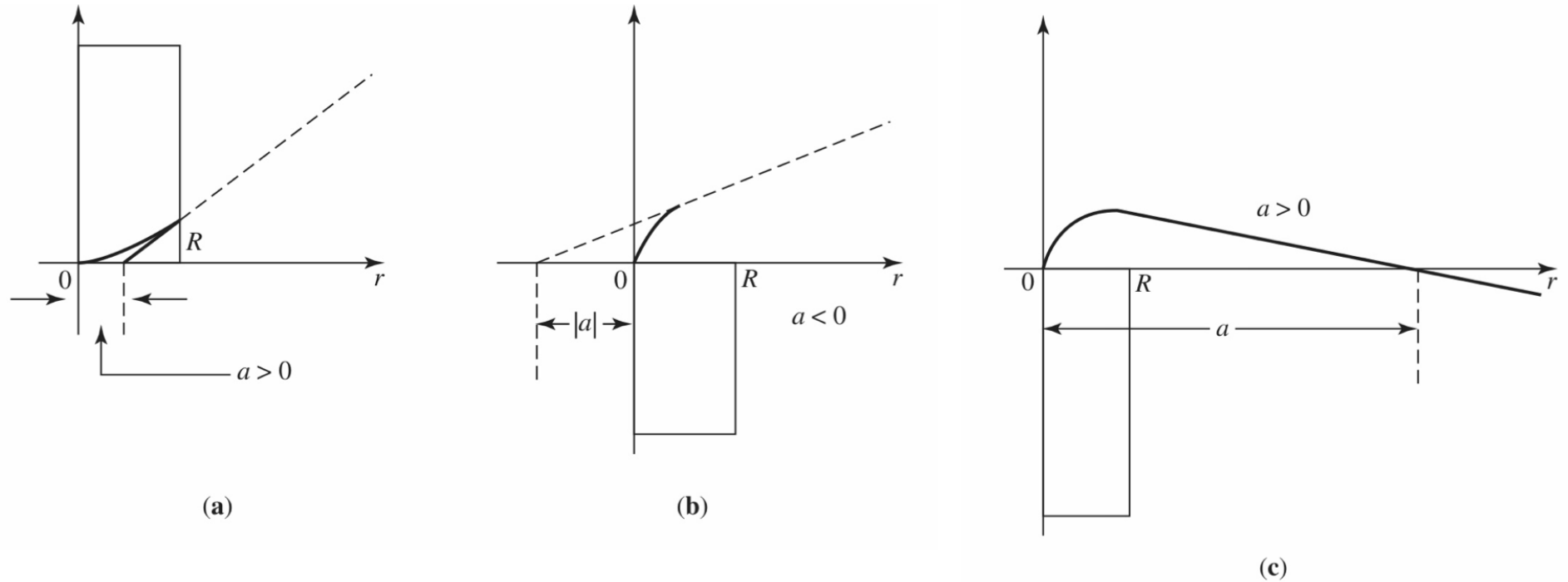
q= invariant relative momentum

a₀= scattering length



Y. Kamiya et al. arXiv:2108.09644v1

Scattering length



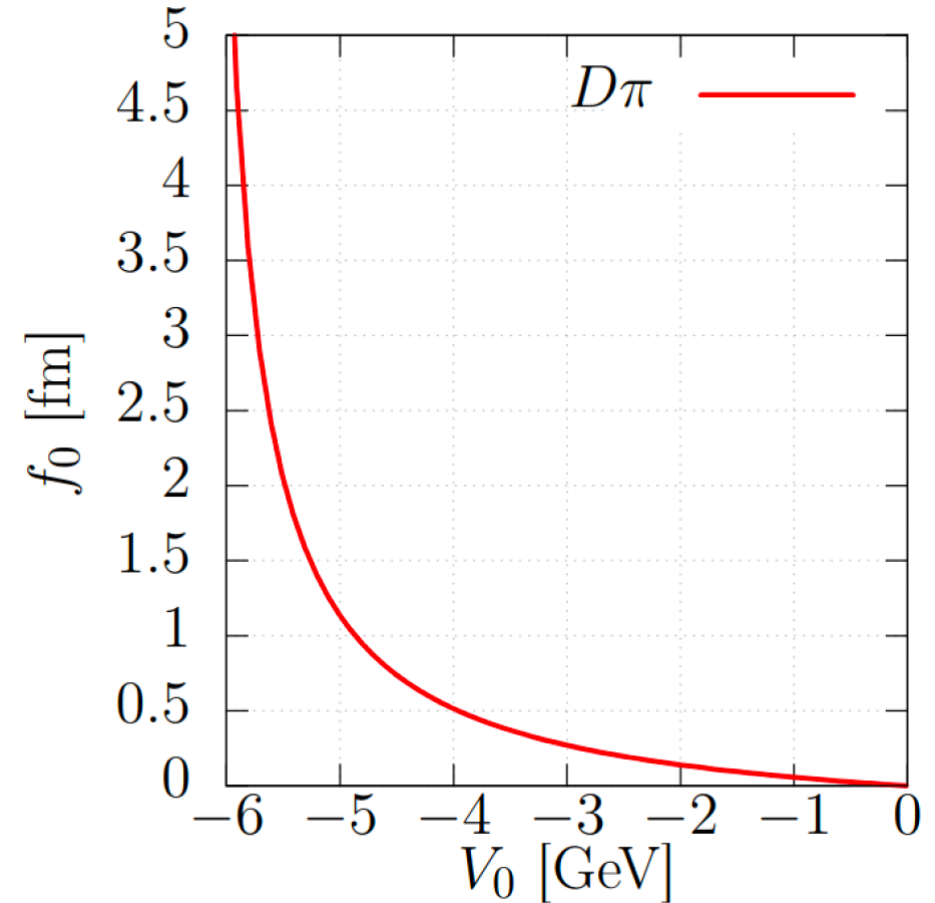
Different sign convention
 $a_0 = -a$!

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

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

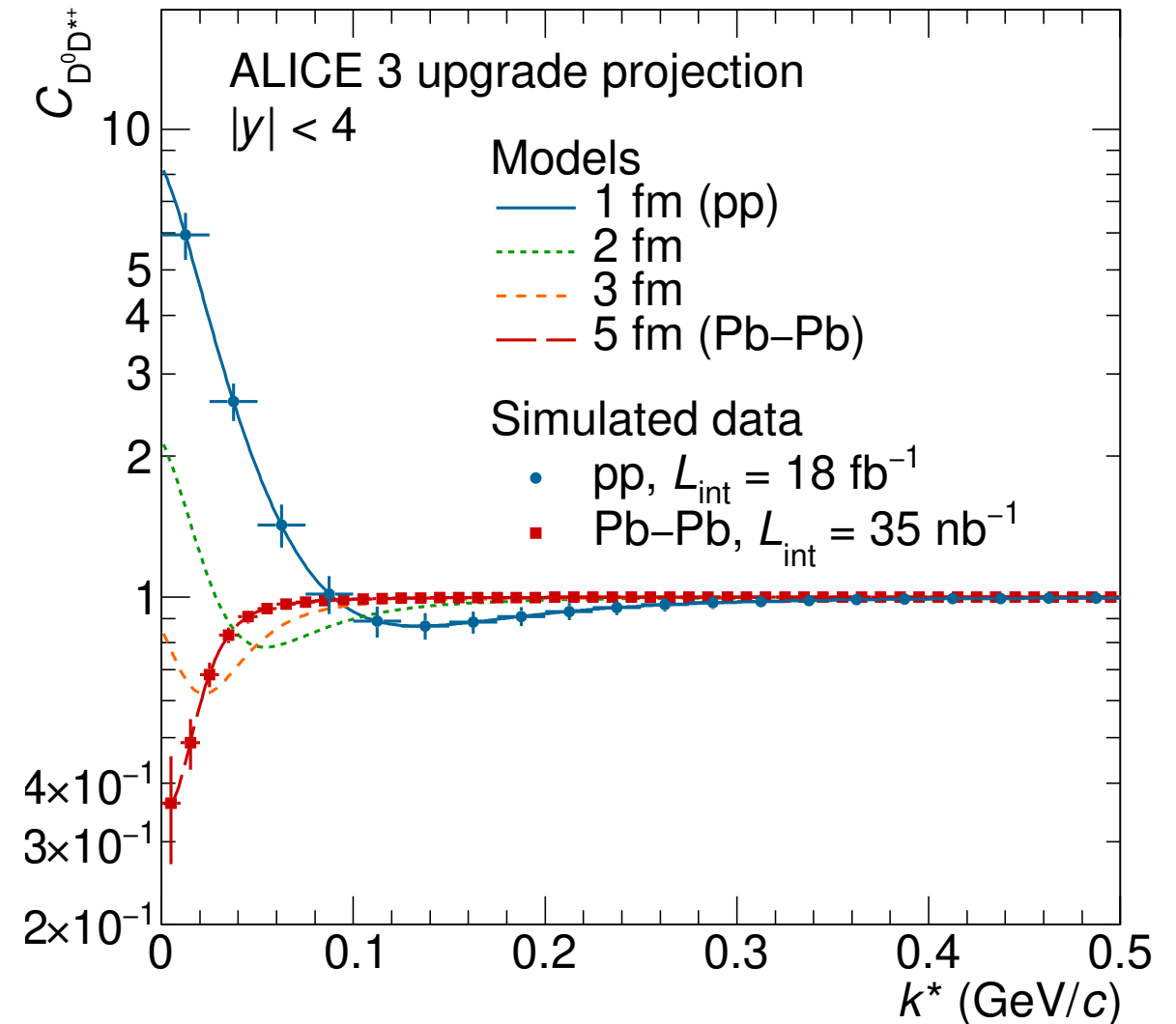
- Strength adjustable
- Range: mass of the ρ meson



Y. Kamiya et al., EPJA 58 (2022) 7, 131

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 $\bar{D}D^*$ bound states
 - T_{CC^+} could be D^0D^* molecule
 - $X_{c1}(3872)$ could be a $\bar{D}D^*$ molecule
- Upgrade projection
 - Gaussian potential
 - Different source radii



ALI-SIMUL-502575

Deviation with theory

- Larger source of $r_{\text{eff}} \sim 3$ fm could accommodate the theory predictions of L.Liu etc
 - Not well motivated, as unphysically large for pp collisions (~ 1 fm)
 - Source model worked well for pD femtoscopic study

ALICE Collaboration, Phys. Rev. D 106 (2022) 052010

- Smaller scattering length obtained $a_0^{D^*\pi}(l=1/2) = 0.1$ fm (Model B), when considering molecular nature of D1 states (D1(2420) and D1(2430))

K. P. Khemchandani, L. M. Abreu, A. Martinez Torres, and F. S. Navarra, arXiv:2312.11811

- Hidden gauge formalism with unitarization in coupled channels
- D1(2430) explicitly added as bare quark-model pole structure to better accommodate it within experimental observations
- Heavy-quark symmetry \rightarrow also smaller value for $a_0^{D^*\pi}(l=1/2)$ expected

Belle Collaboration, Phys. Rev. D 69 (2004) 112002
LHCb Collaboration Phys. Rev. D 92 (2015) 012012

