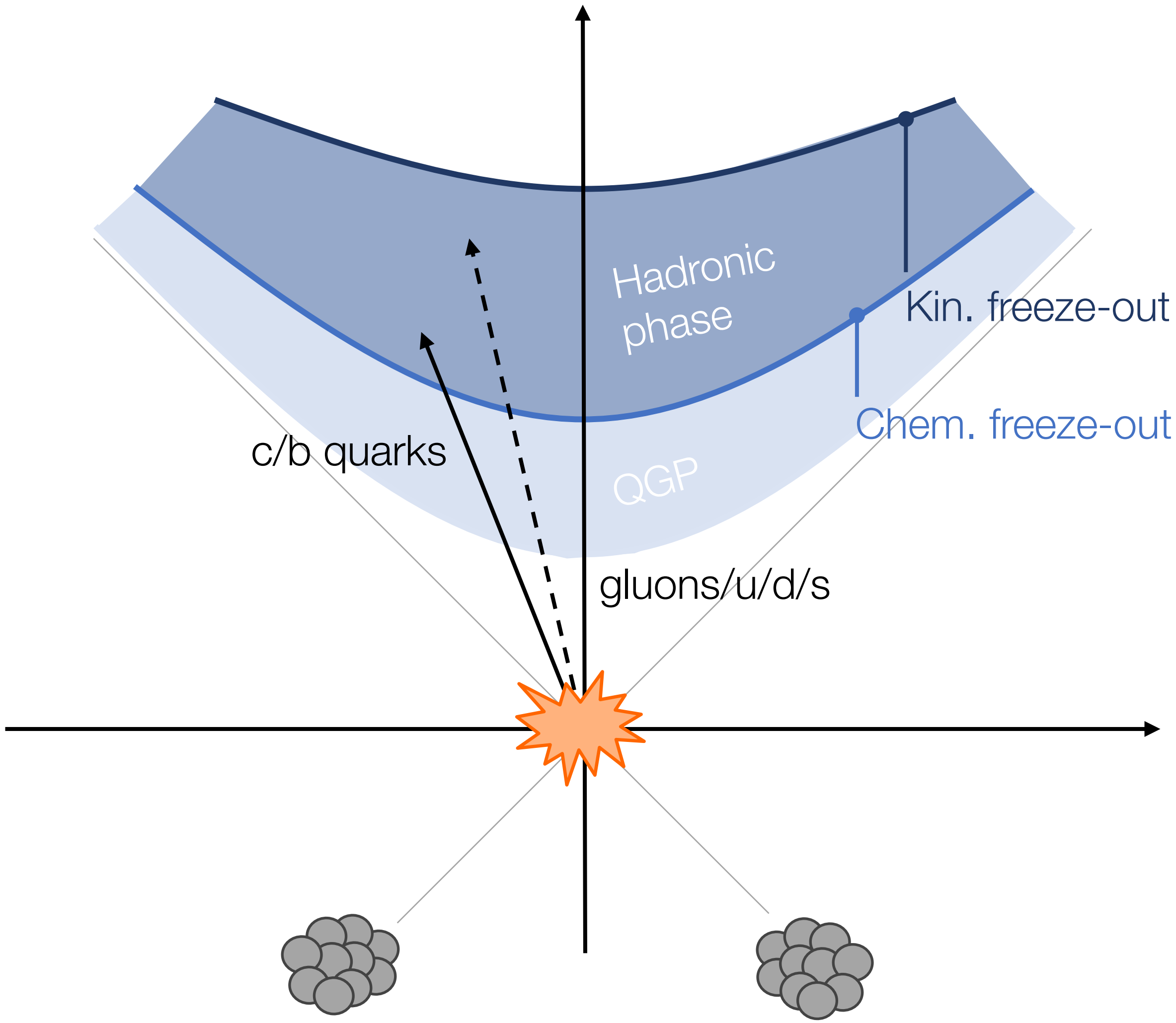
Studying the interaction between charm and light-flavor mesons with ALICE

Based on PRD 110 (2024) 032004

Emma Chizzali on behalf of the ALICE Collaboration
Hard Probes 2024, September 25th, Nagasaki

Heavy-flavor particles and the QGP

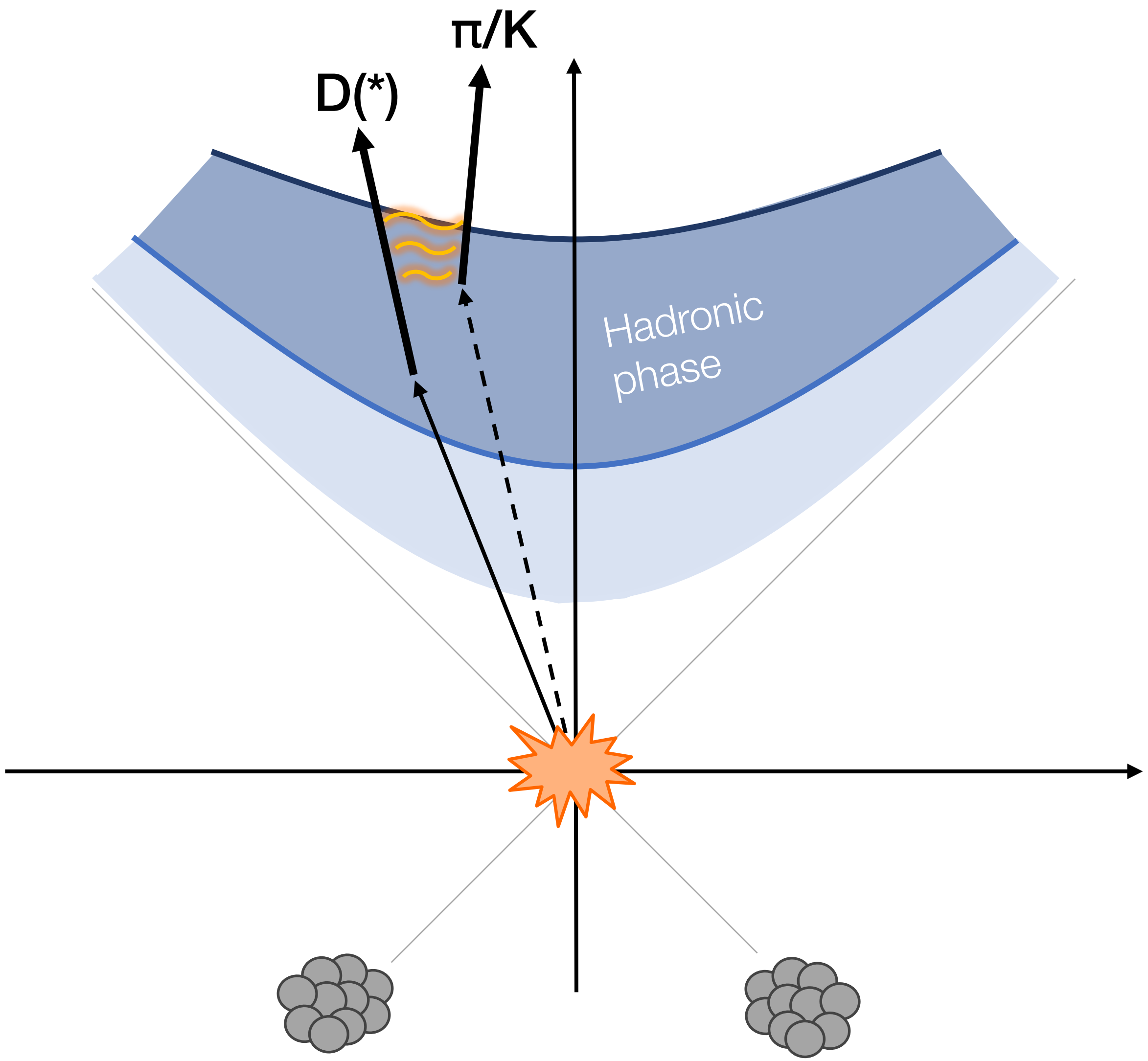
- Heavy quarks produced in heavy-ion collision
  - Thermal equilibration time expected to be of the order of QGP lifetime
  - Ideal probes of the QGP



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

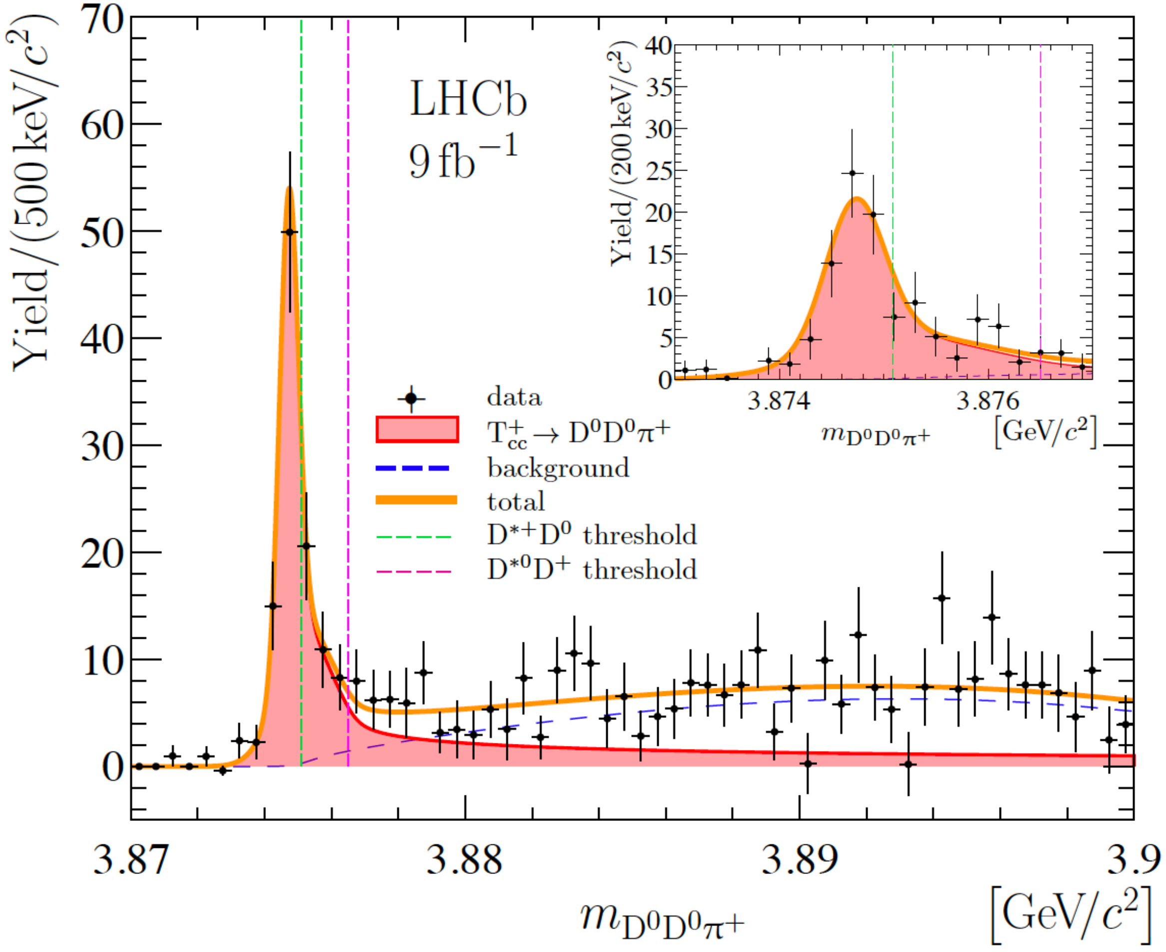
R. Rapp et al., *Phys. Lett. B* **701** (2011) 445-450
R. Rapp et al., *Phys. Lett. B* **735** (2014) 445–450
R. Rapp et al., *Phys. Rev. Lett.* **124** (2020) 042301



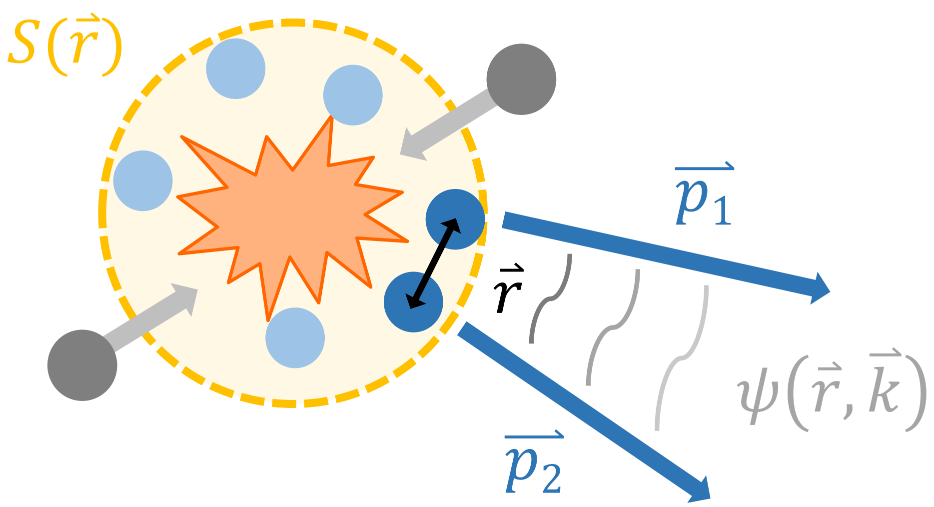
Exotic states

- 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
- Femtoscopy allows studying ithe nteraction and helps determining 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

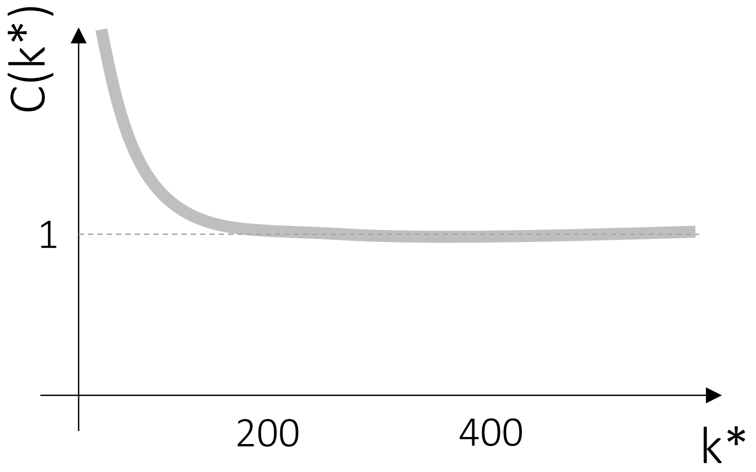
S. E. Koonin, Phys. Lett. B 70 (1977) 43-47

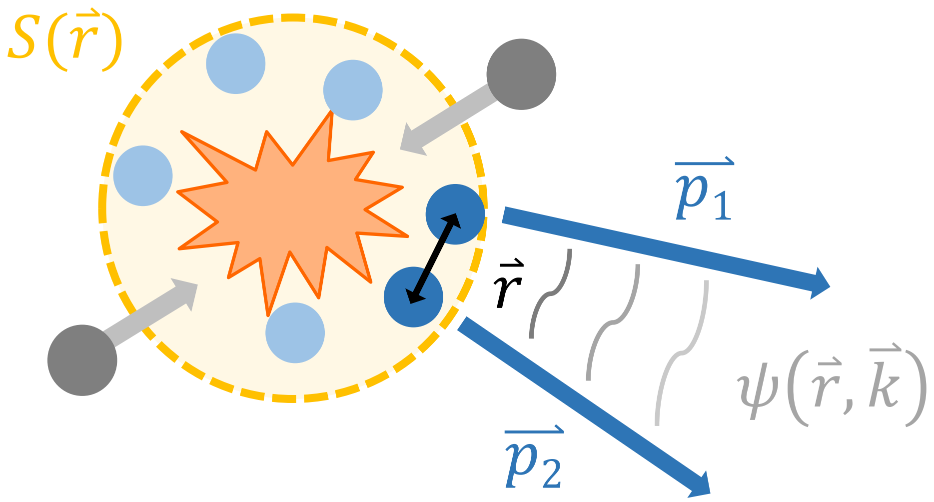
S. Pratt, Phys. Rev. C 42 (1990) 2646-2652

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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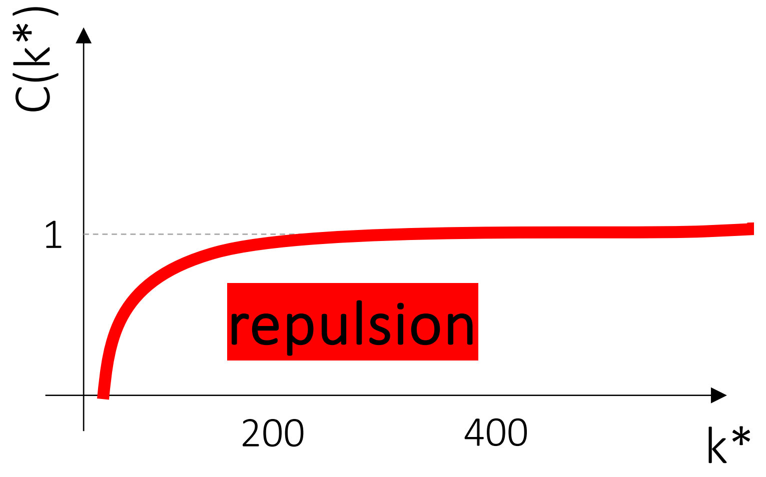

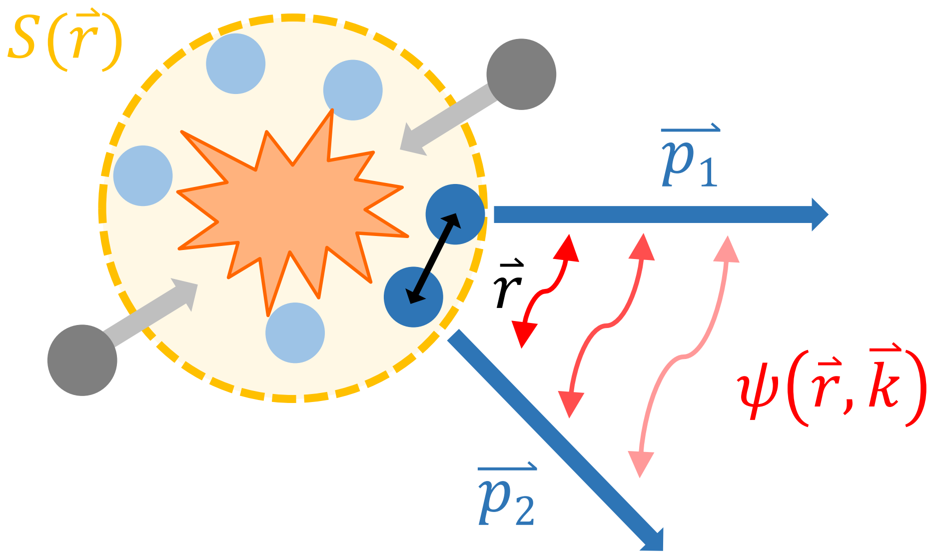

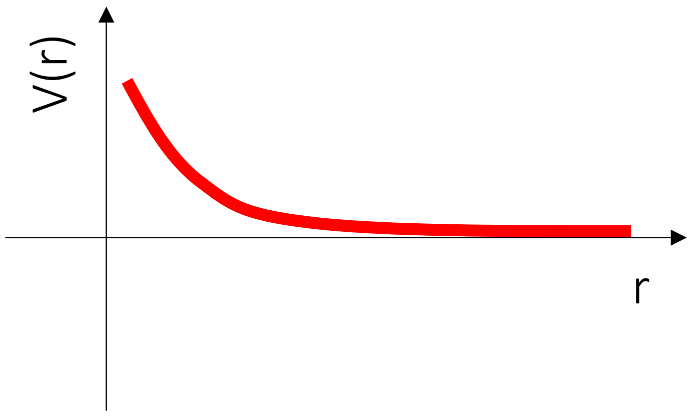

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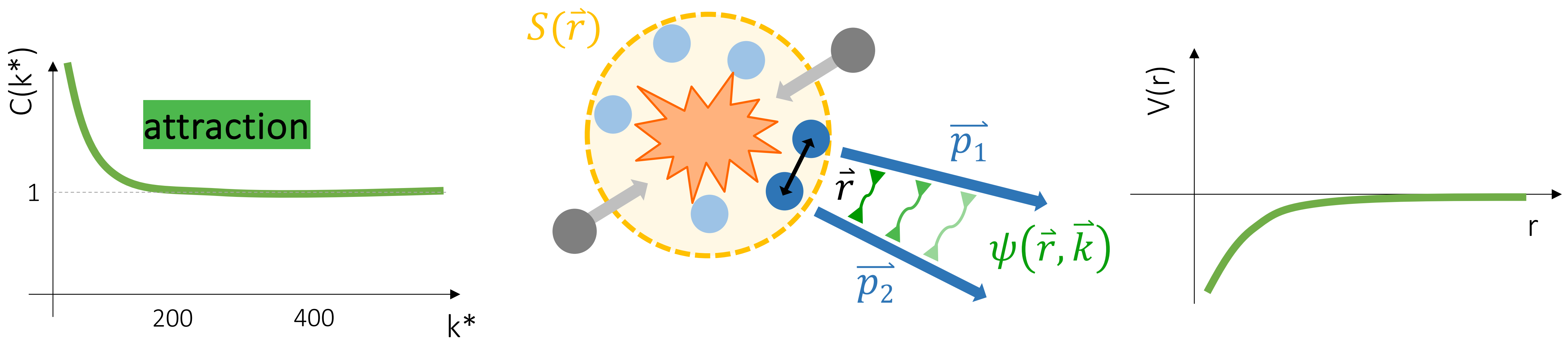

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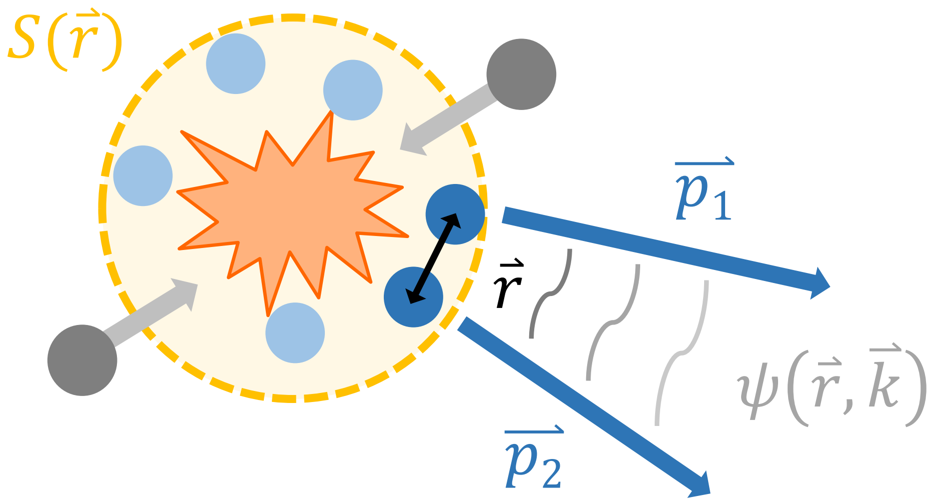

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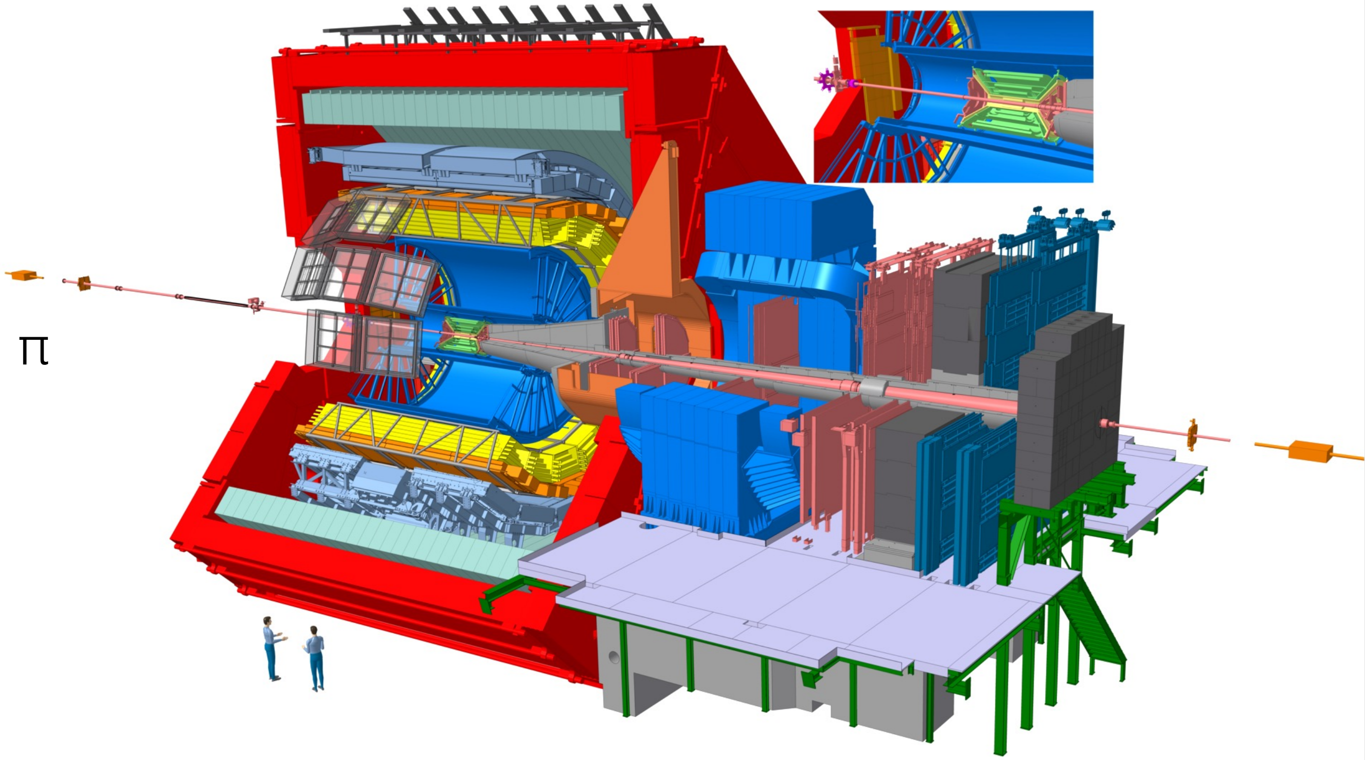
S. E. Koonin, Phys. Lett. B 70 (1977) 43-47
S. Pratt, Phys. Rev. C 42 (1990) 2646-2652

Source constrained from pp pairs (Argonne v18, well known potential)
ALICE Collab., Physics Letters B, 811 (2020) 135849, arXiv:2311.14527

ALICE

- LHC Run 2 dataset from 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 ~90(95)% for K(π)
- D(*) mesons reconstructed from decay to K and π (BR<10%) using machine-learning algorithm
  - Purity ~70%, primary fraction ~65%



ALICE-PHO-SKE-2017-001

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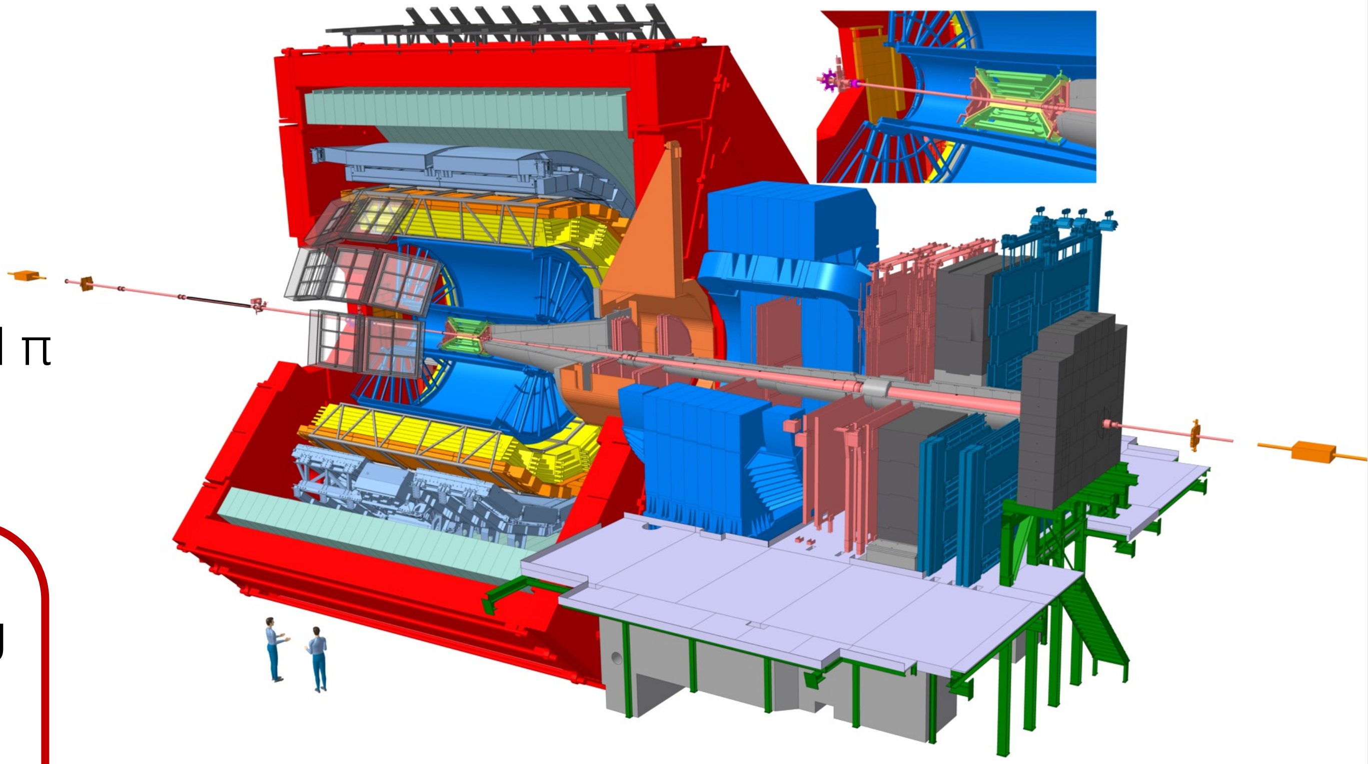
Use correlation data to study residual final-state interaction among D–K, D–π, D*–K, D*–π

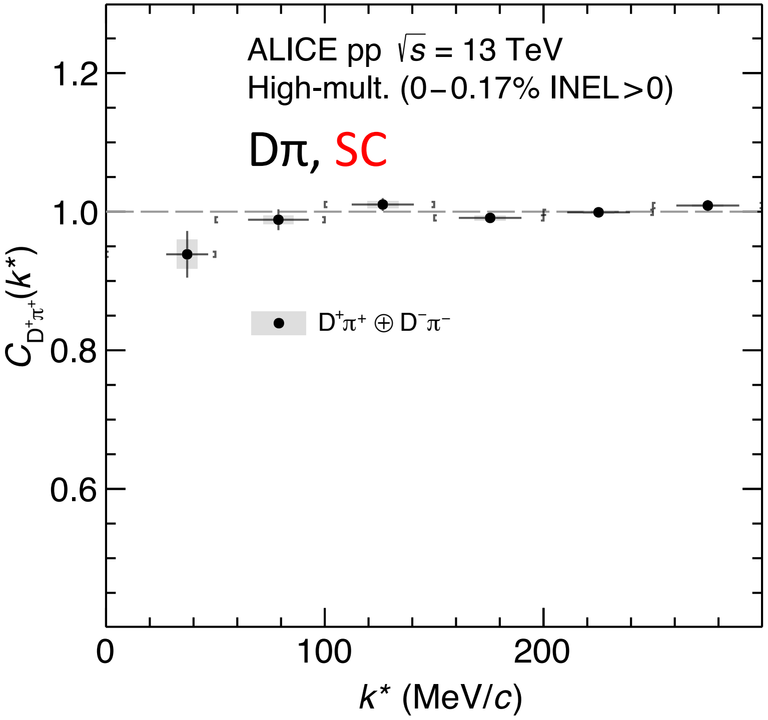
Approach already successfully applied to study D-p system
ALICE Collab. Phys. Rev. D 106 (2022) 052010

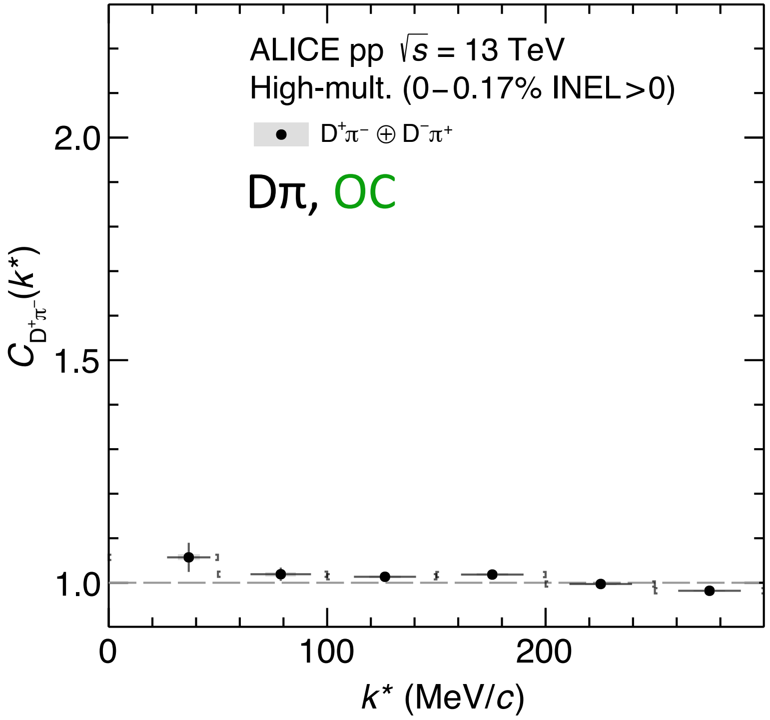


ALICE-PHO-SKE-2017-001

Genuine correlation function

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





new publication

PRD **110** (2024) 032004

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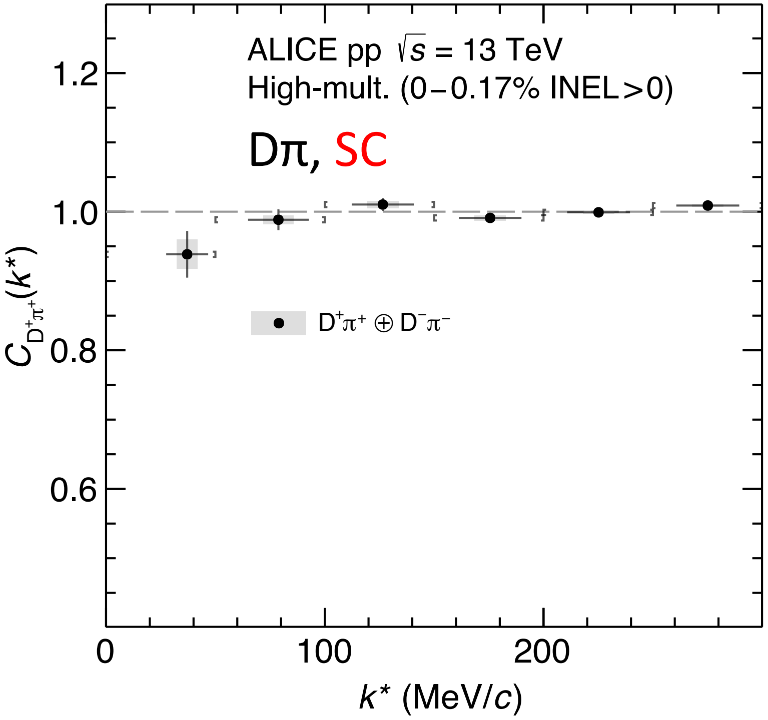
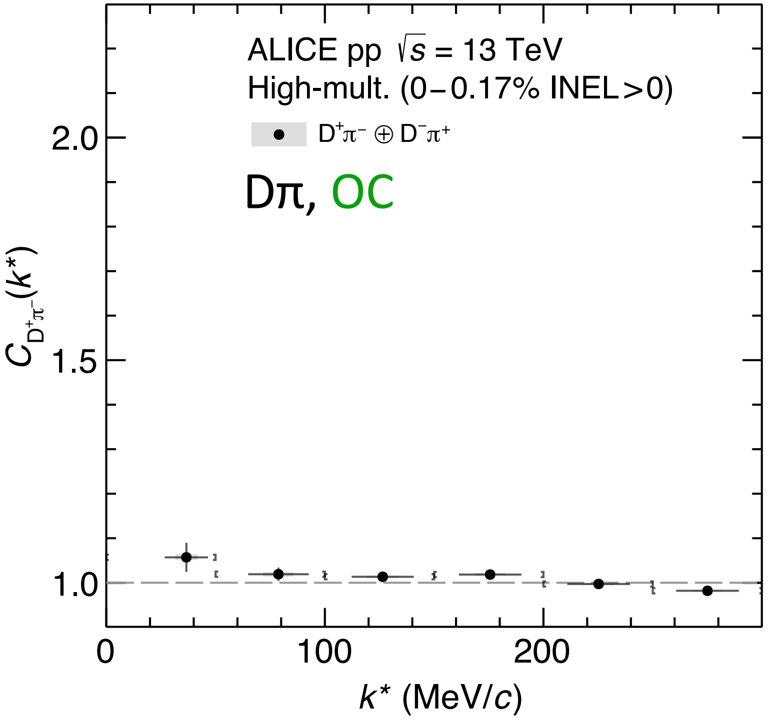


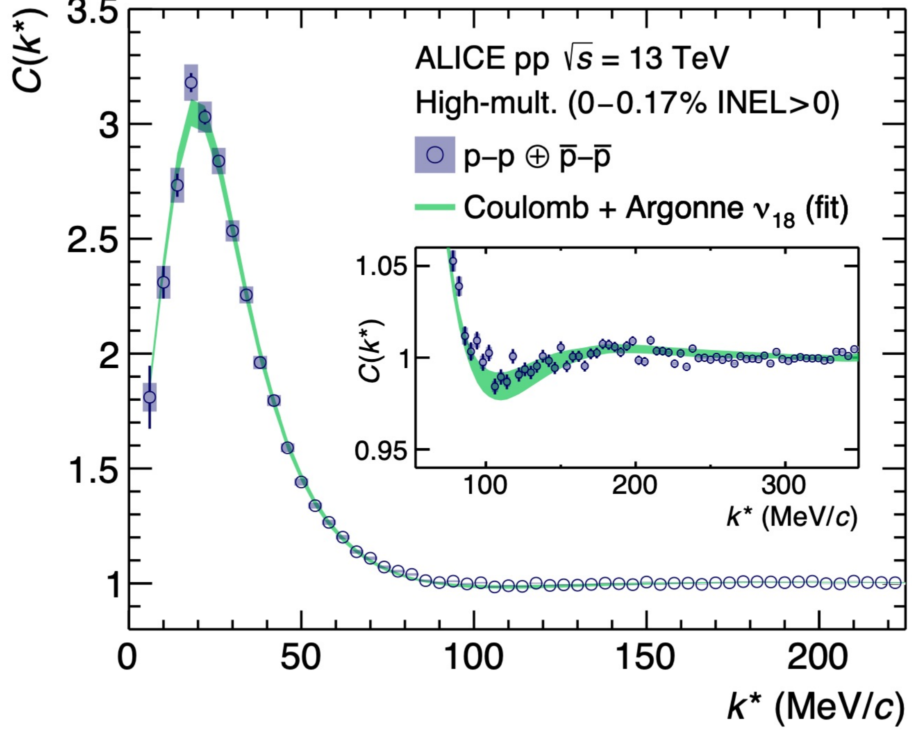


new publication

PRD 110 (2024) 032004

Comparison to NN system

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



D-light meson scattering lengths

Pair	(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.	Z.-W. Liu et al.
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
D(*)K	(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

D-mesons (L. Liu et al. through J. M. Torres-Rincon et al.)

D*-mesons (J. M. Torres-Rincon et al. and Z.-W. Liu 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 (2023) 096008
Z.-W. Liu et al., Phys. Rev. D 84 (2011) 034002

- 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

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D-mesons

D*-mesons

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
Z.-H. Guo et al., Eur. Phys. J. C 79 (2019) 13
B.-L. Huang et al., Phys. Rev. D 105 (2022) 036016
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Z.-W. Liu et al., Phys. Rev. D 84 (2011) 034002

Dπ and DK interaction

PRD 110 (2024) 032004
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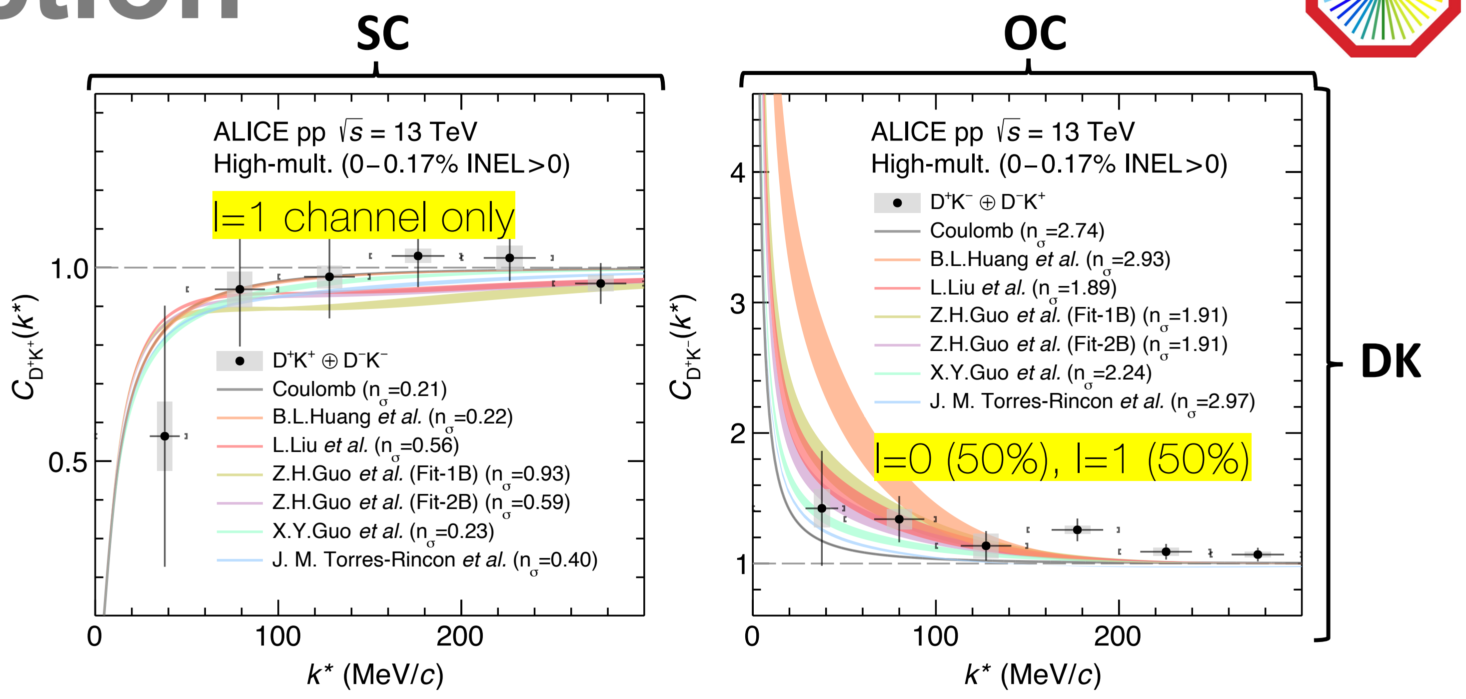
- DK
  - Limited by statistics → LHC Run 3 data needed
  - Compatible with models



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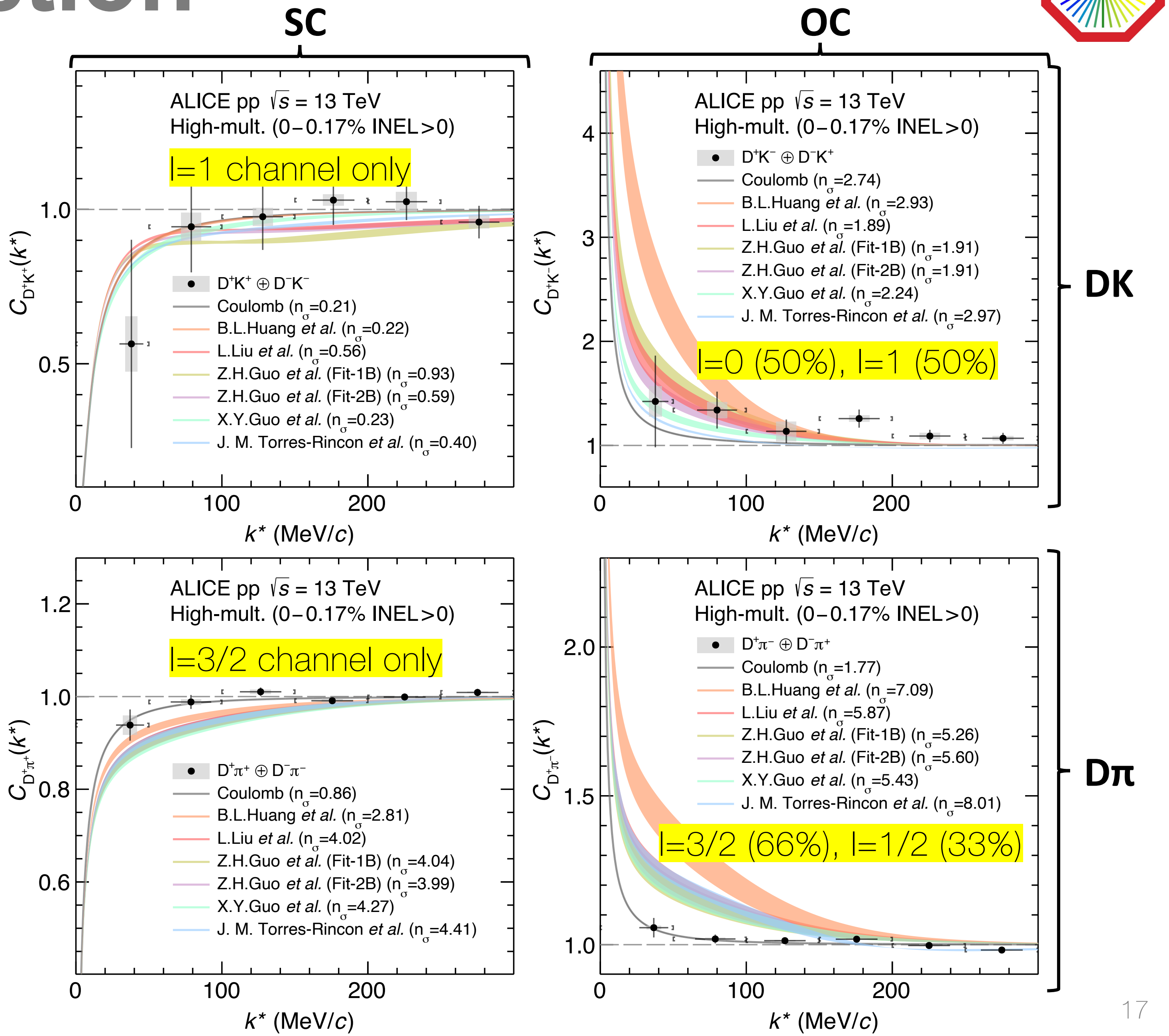
- DK
  - Limited by statistics → LHC Run 3 data needed
  - Compatible with models
- Dπ
  - Coulomb-only interaction favoured
  - Tension with theoretical models



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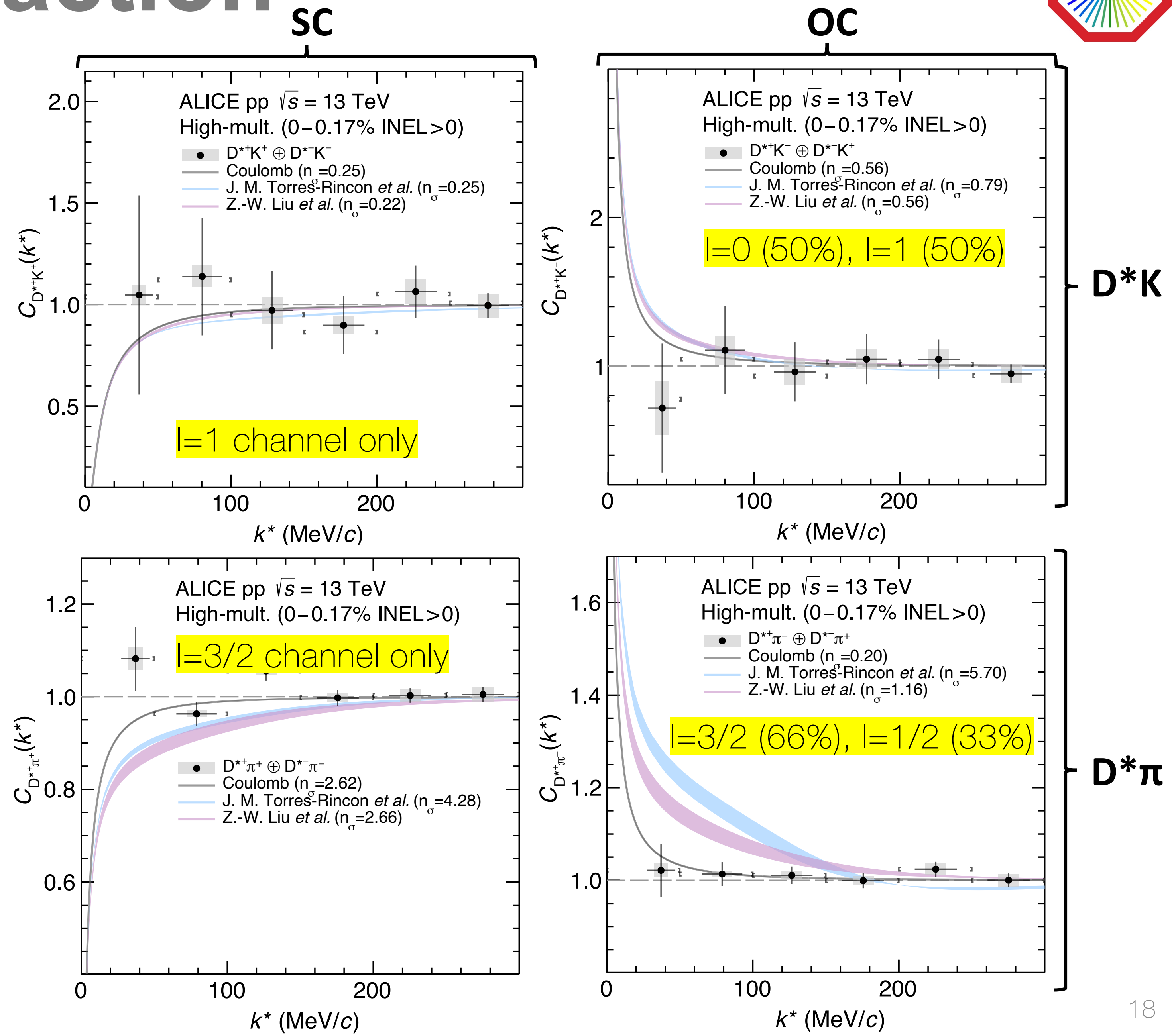
J. M. Torres-Rincon et al., Phys. Rev. D 108 (2023) 096008

D*π and D*K interaction

PRD 110 (2024) 032004
new publication

- 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 theoretical model



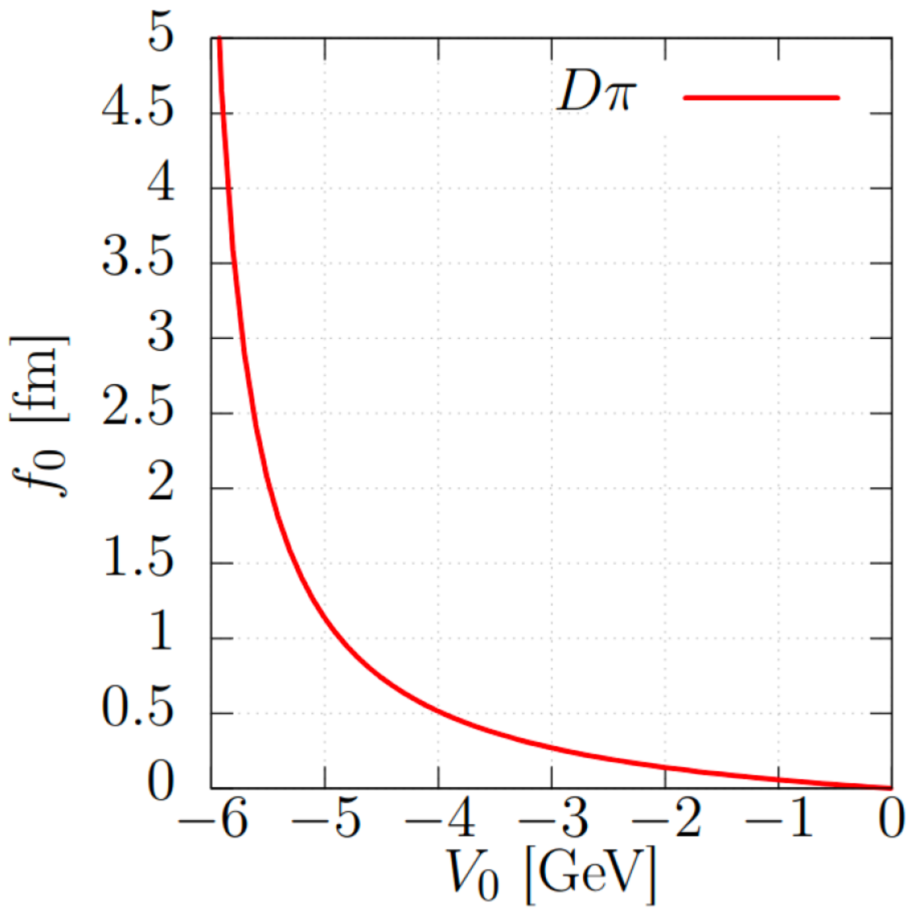
J. M. Torres-Rincon et al., Phys. Rev. D 108 (2023) 096008
Z.-W. Liu et al., Phys. Rev. D 84 (2011) 034002

D(*)π scattering parameters from fit

- $D^{(*)+}\pi^+$ and $D^{(*)+}\pi^-$ share I=3/2 channel
  → simultaneous fit
- Correlation function obtained using Gaussian potential

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

  - Strength adjustable
  - Range: mass of the ρ meson
- Scattering length then obtained from effective range expansion



Thx to Dr. Yuki Kamiya

Dπ correlation function fit

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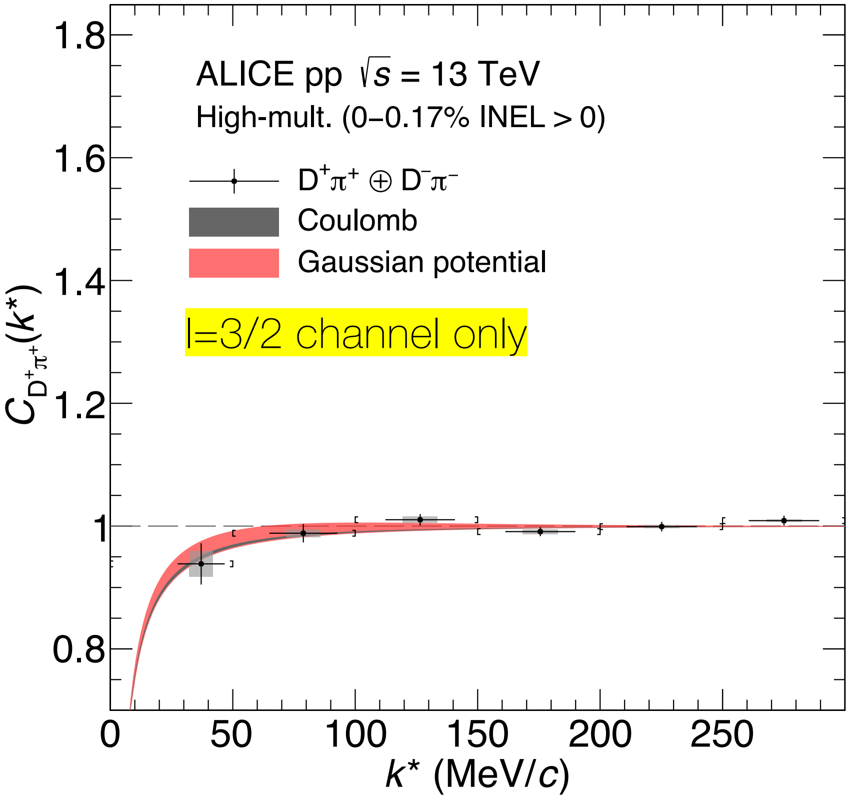
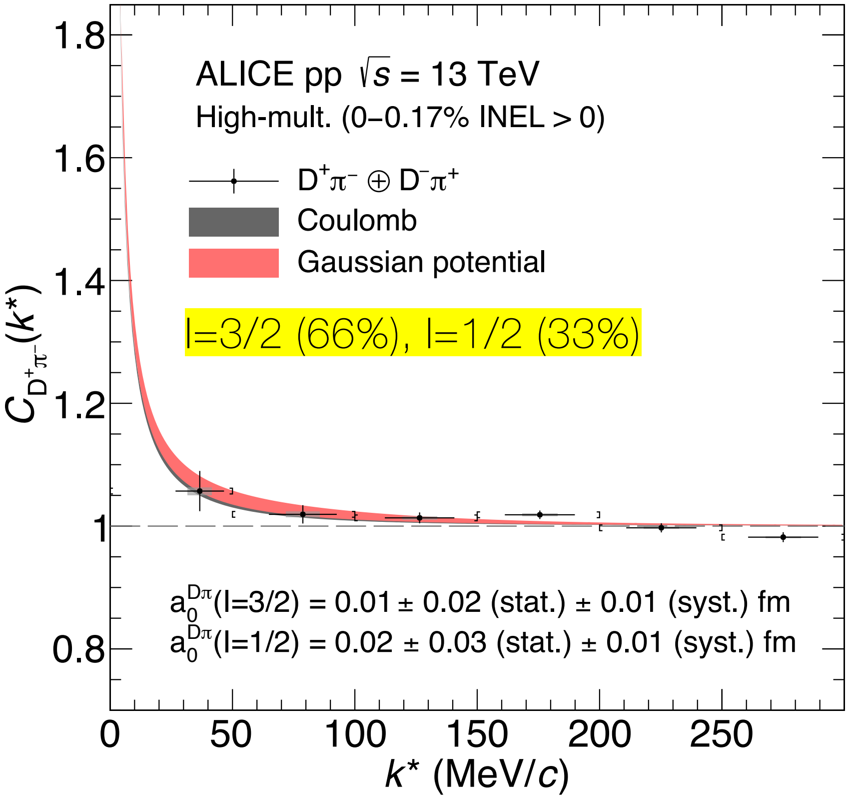
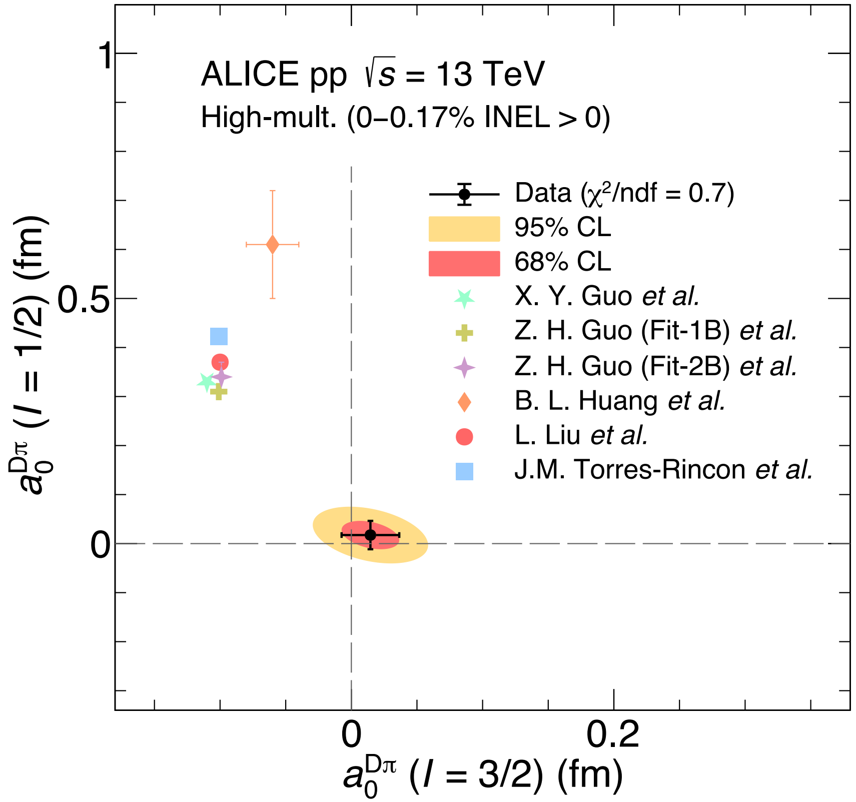
PRD **110** (2024) 032004







- Vanishing scattering parameters in both isospin channels
- Tension with theory especially in I=1/2 channel

D*π correlation function fit

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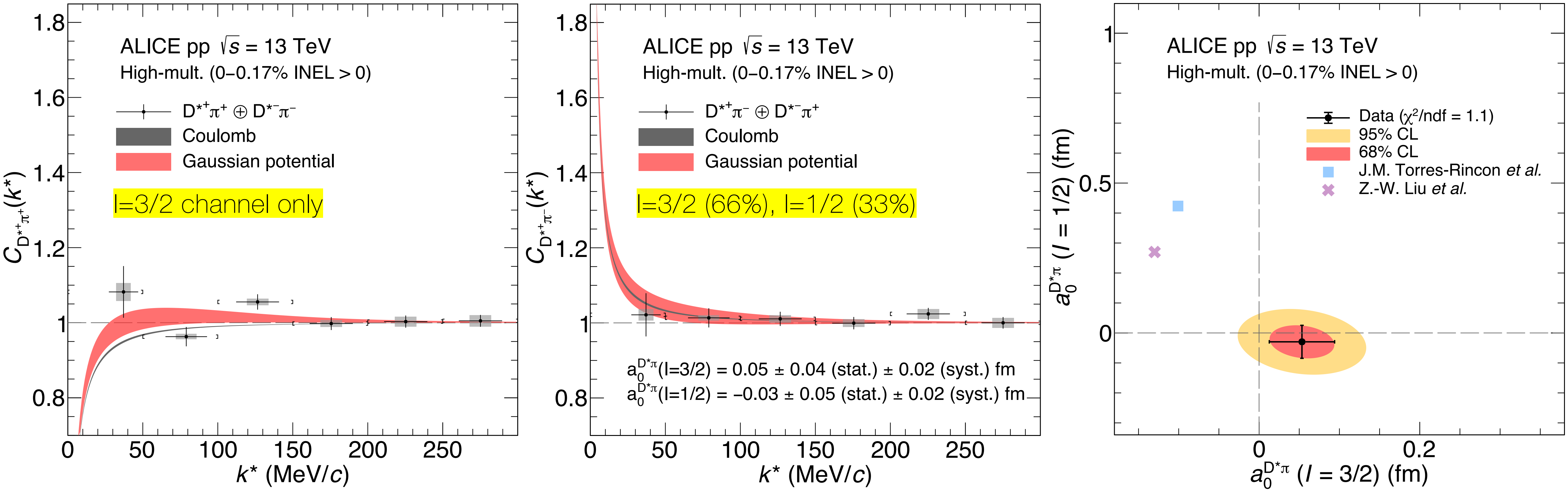
PRD 110 (2024) 032004

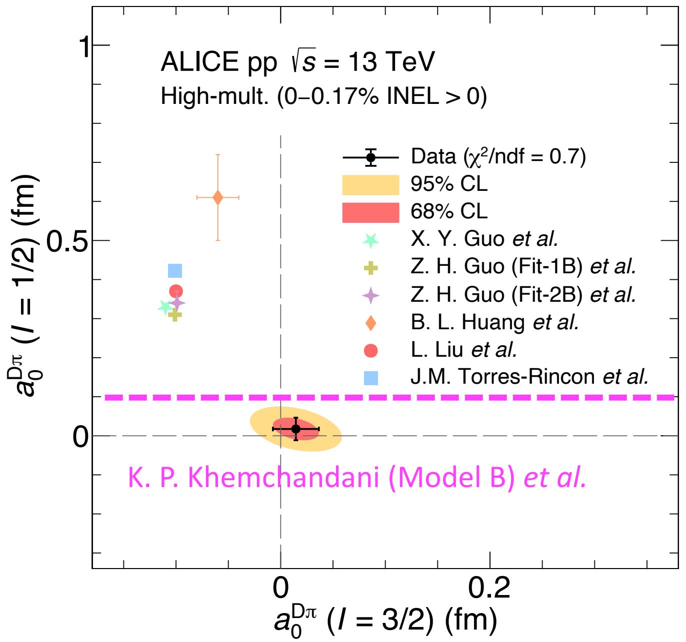


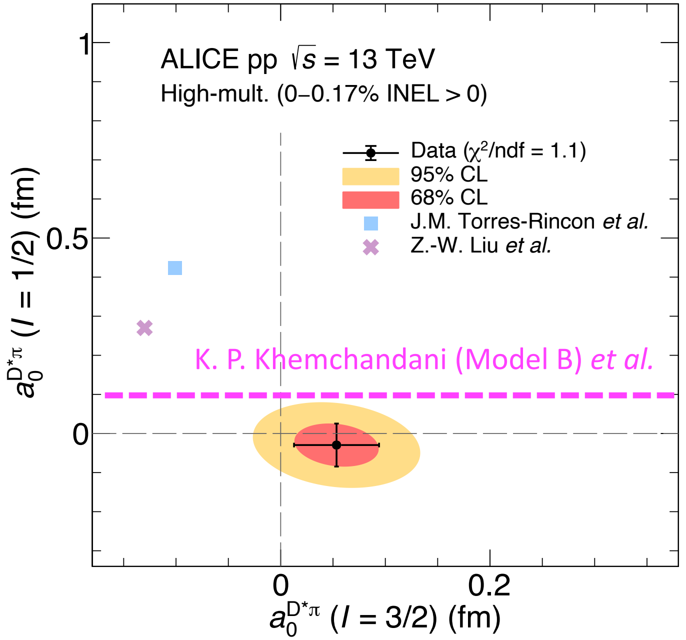
- Vanishing scattering parameters within uncertainties
- Scattering parameters compatible with Dπ results → Heavy-quark spin symmetry

New theoretical approaches

- Data inspired new theoretical calculations
- Smaller scattering length obtained $a_{D^*\pi}(I=1/2)=0.1$ fm, 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
    Belle Collaboration, Phys. Rev. D 69 (2004) 112002
    LHCb Collaboration Phys. Rev. D 92 (2015) 012012
- Heavy-quark symmetry → also smaller value for $a_{D\pi}(I=1/2)$ expected

new publication PRD 110 (2024) 032004





Conclusion

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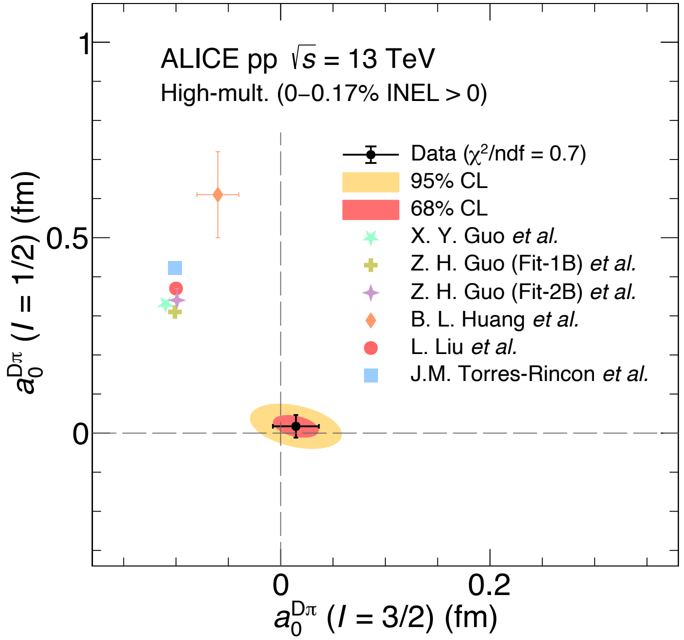
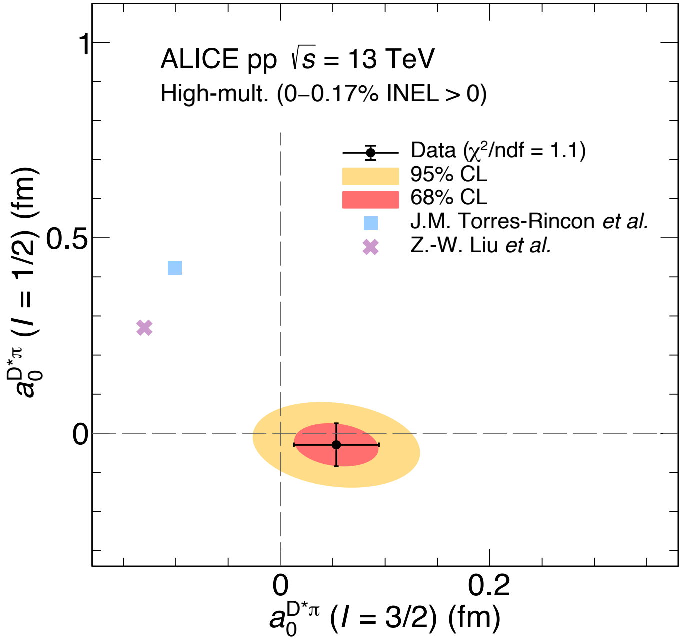
- First measurement of interaction between charm and light-flavor mesons in pp collisions at $\sqrt{s}$ = 13 TeV
  PRD 110 (2024) 032004
- Strong interaction found to be shallow
  → Data compatible with Coulomb-only hypothesis
- D(*)-light-flavor meson interactions are similar
  → heavy-quark spin symmetry
- Tension with theory in the case of Dπ and D*π
- Significant improvement of statistics foreseen with LHC Run 3 data





Additional material

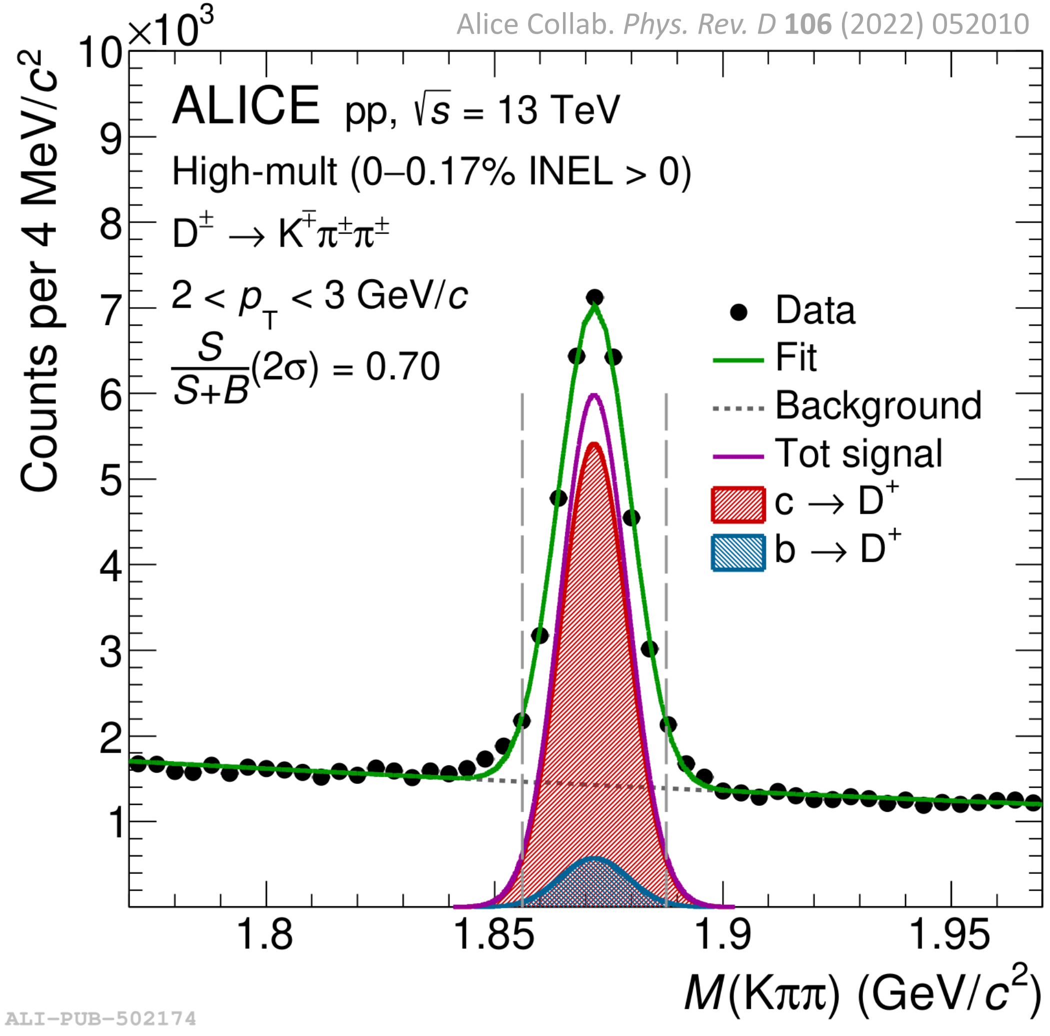
D meson reconstruction

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

D meson reconstruction

- Decay channel $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$
  - 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

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



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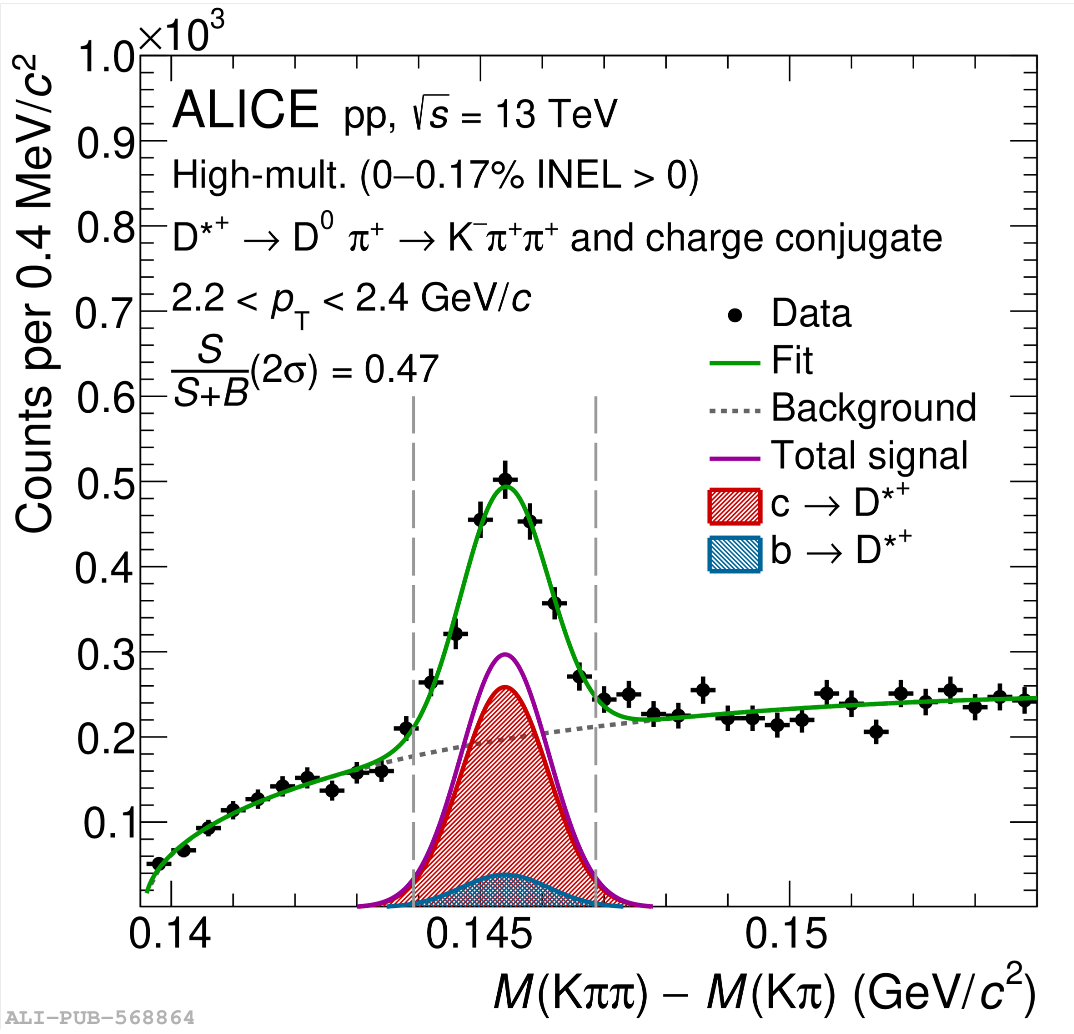
    Estimated via MC simulation with Pythia anchored to the D+ and D* cross section in pp collisions at $\sqrt{s}$ = 5.02 TeV
- Similar purity and secondaries from b for D* candidates
  - Decay channel $D^{\pm *} \rightarrow D^{0}\pi^{\pm} \rightarrow (K^{\mp}\pi^{\pm})\pi^{\pm}$ with BR=(67.7±0.5)% and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

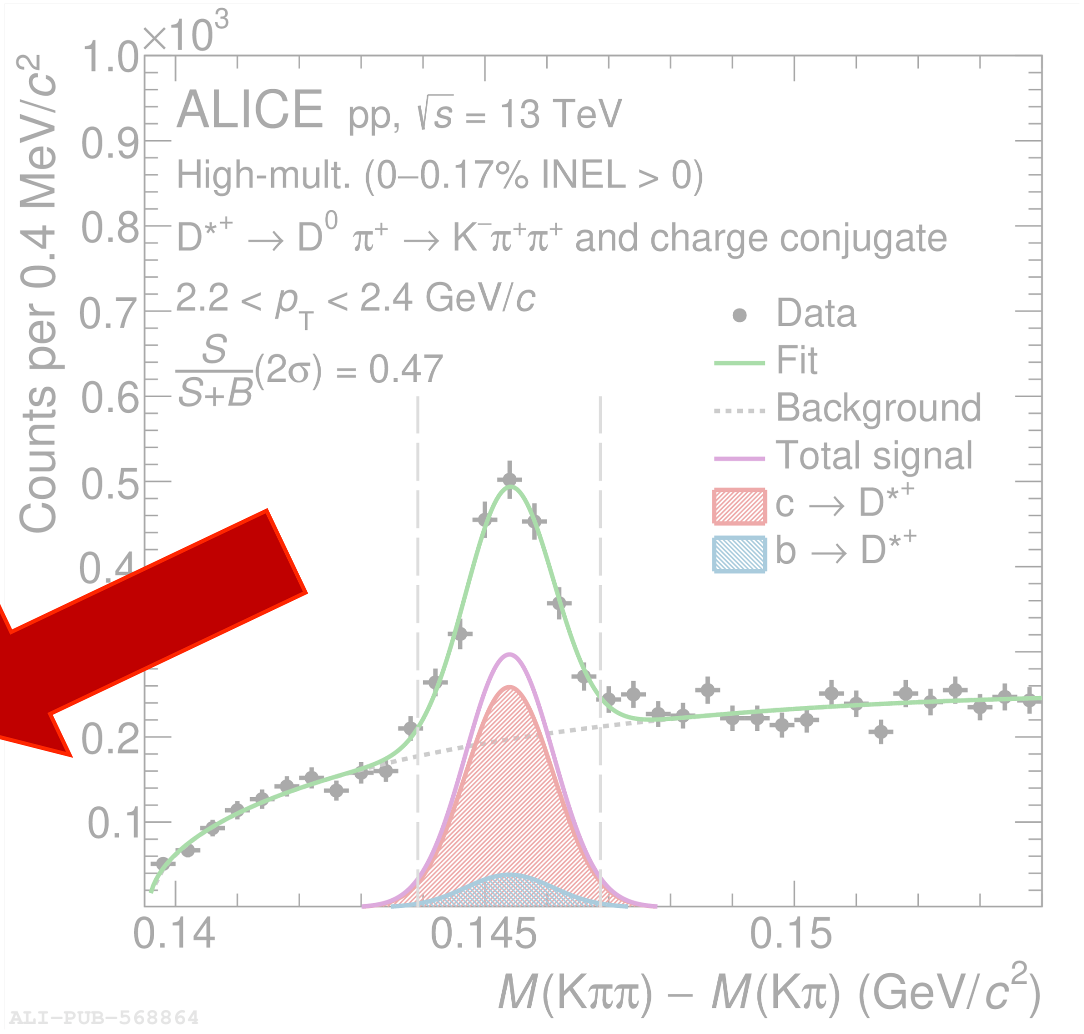


D meson reconstruction

- 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 based on the D+ and D* cro
- Similar purity s
  - Decay cha
    BR=(67.7±

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

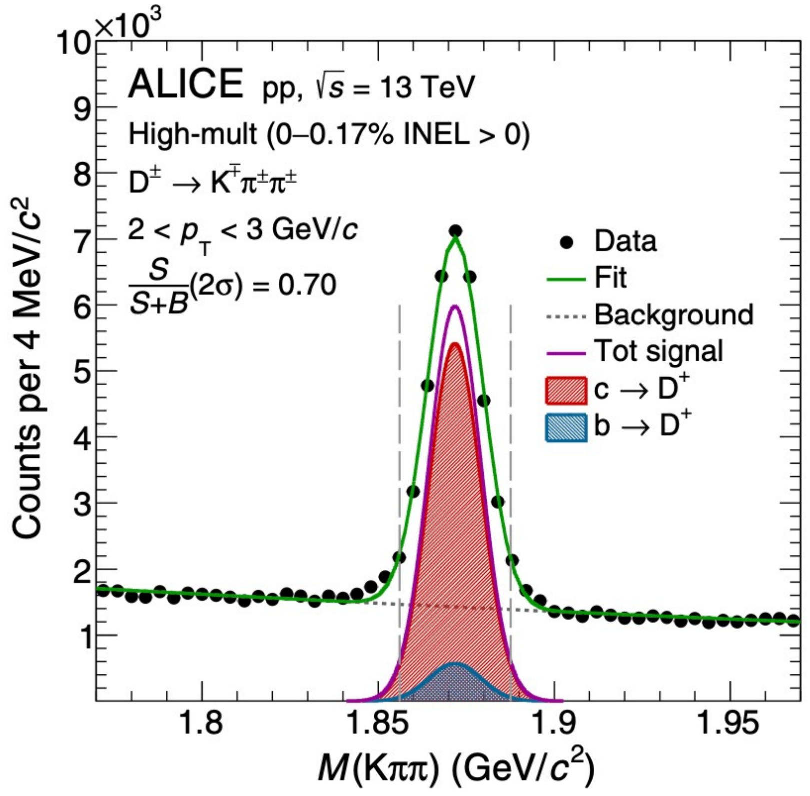
Approach already successfully applied to study D-p system
Alice Collab. Phys. Rev. D 106 (2022) 052010

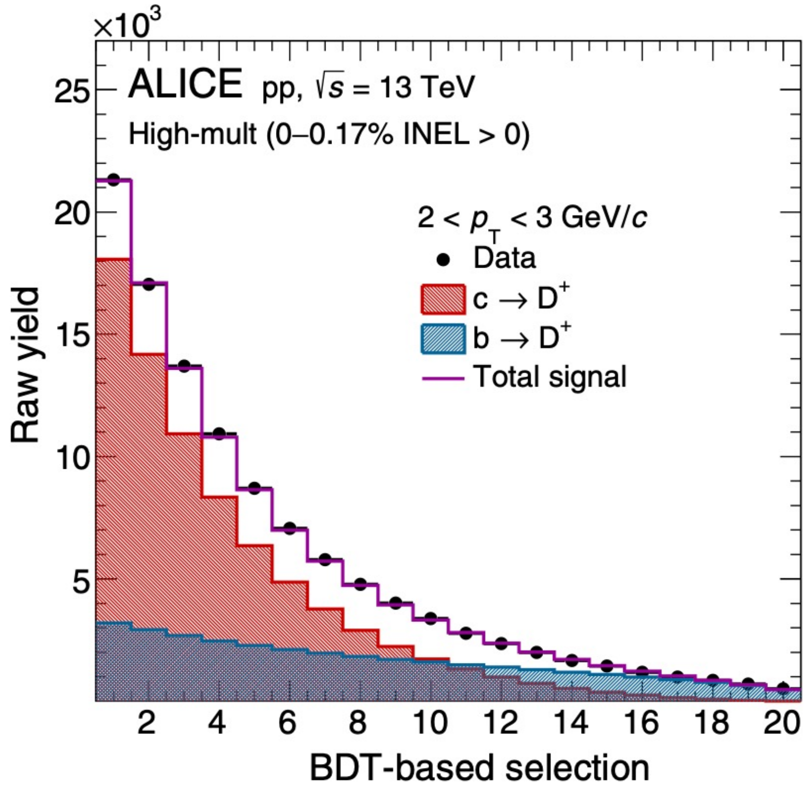


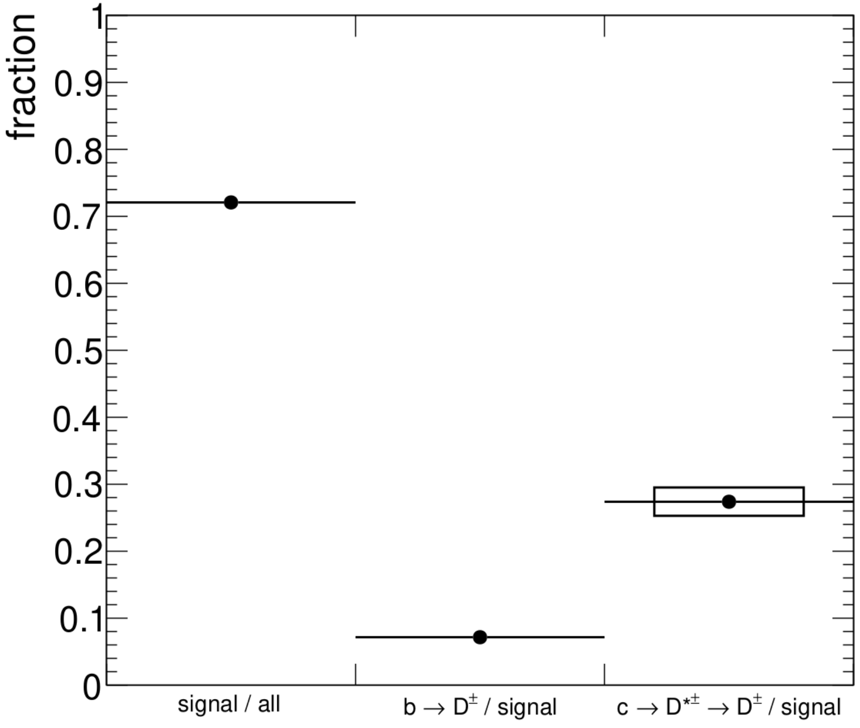
D meson reconstruction

- 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%

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

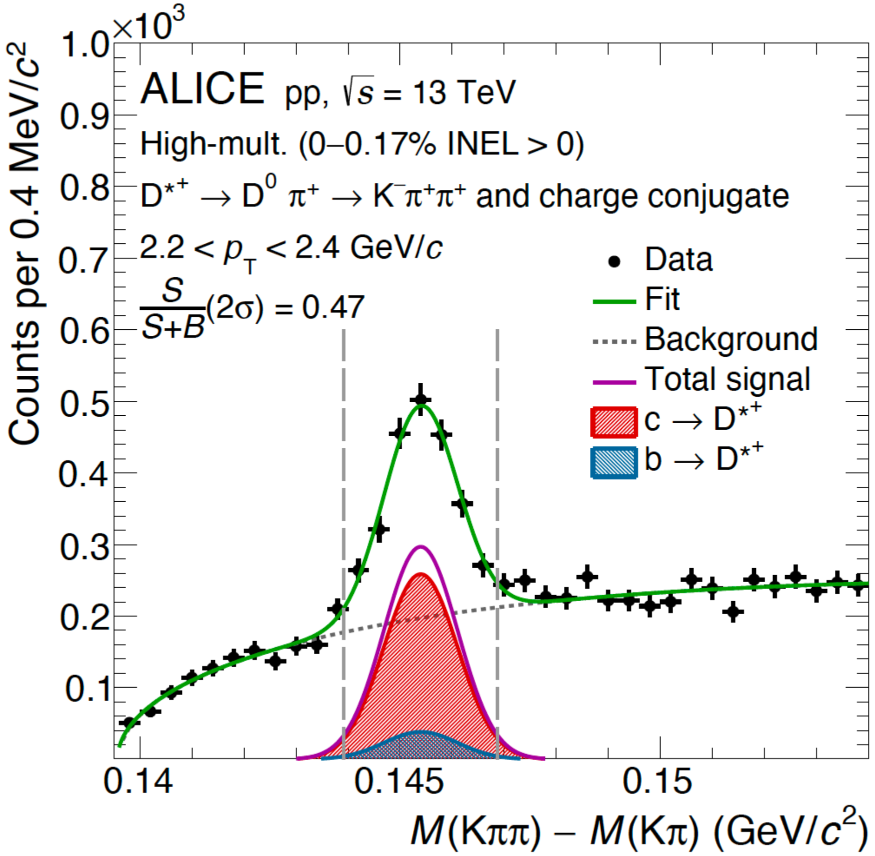


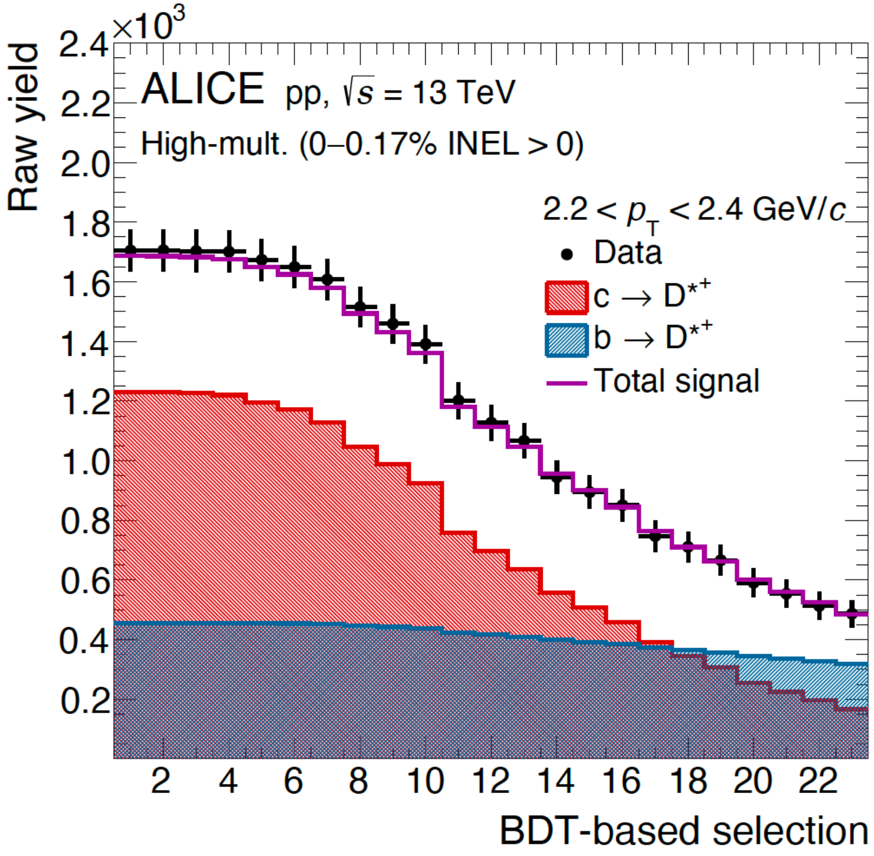




D* meson reconstruction

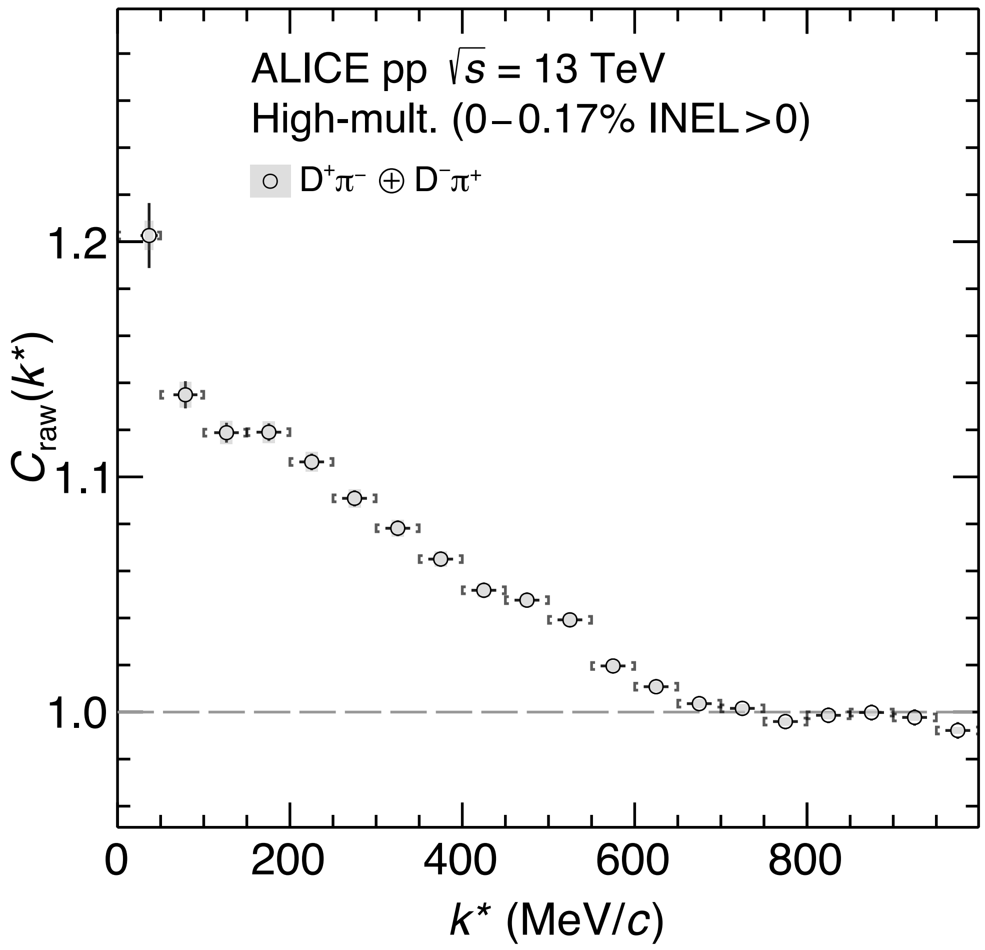
- Decay channel $D^{\pm *} \rightarrow D^0 \pi^{\pm}$ with BR=(67.7±0.5)%





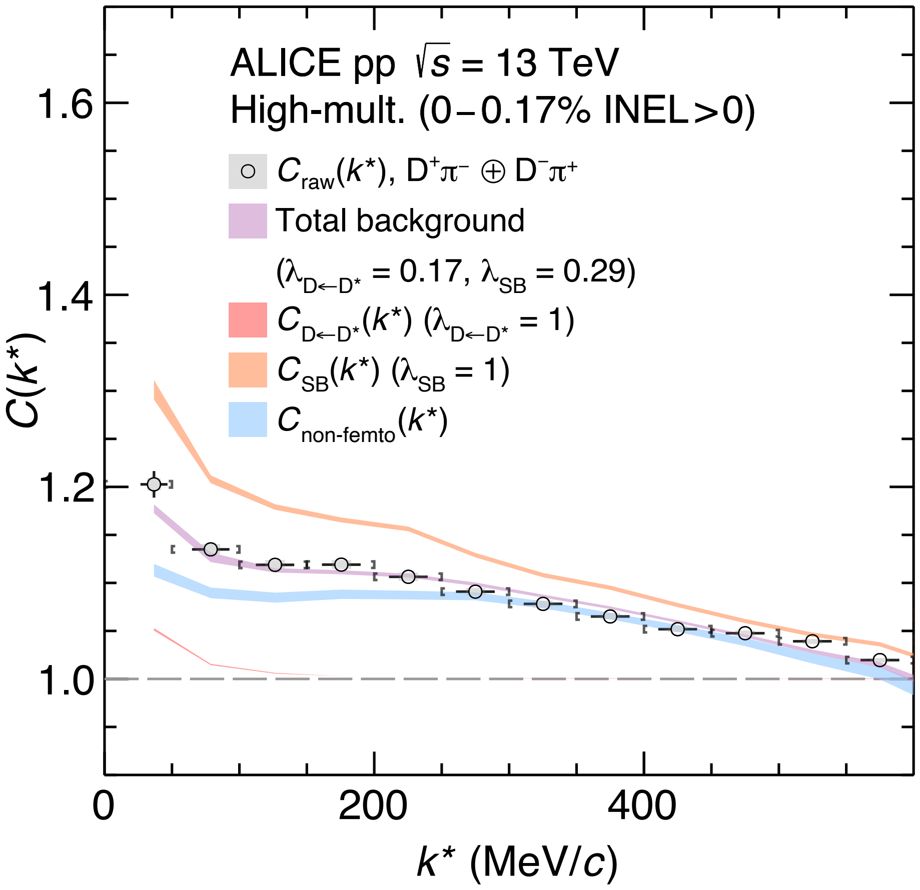
Modelling of the raw correlation function

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

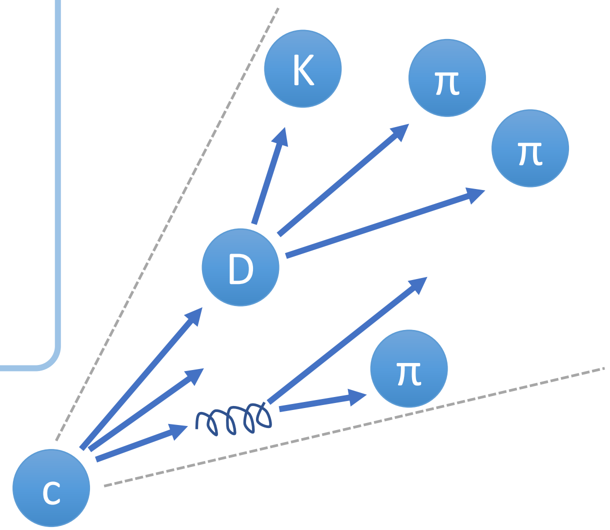


Modelling of the raw correlation function

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

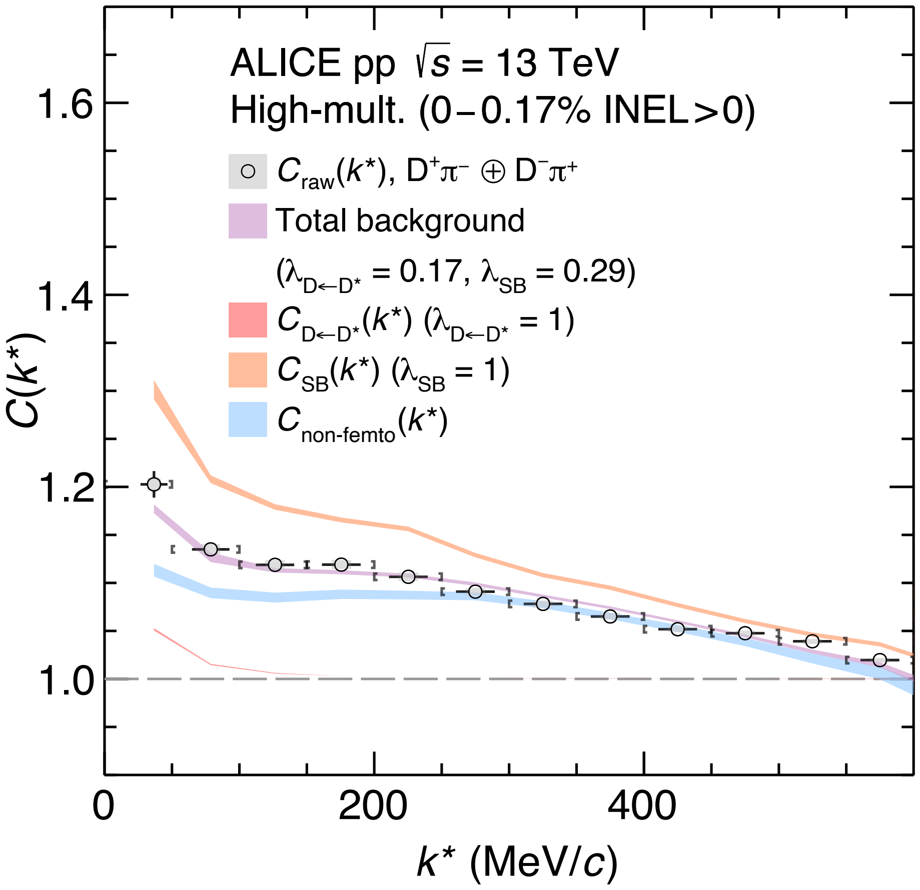


- Not related to final state interaction between particles
  - Energy-momentum conservation effects
  - Mini-jets
- Modeled using MC simulations



Modelling of the raw correlation function

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



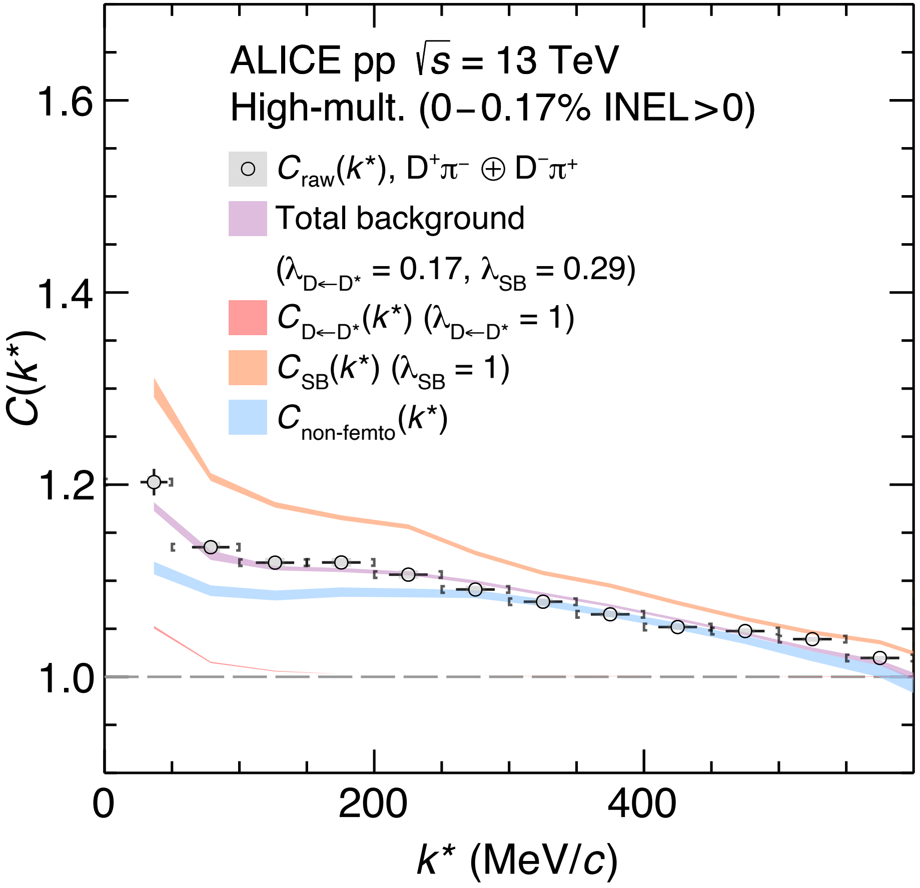
$C_{femto}(k^*) = \sum_{i,j} \lambda_{ij} \times C_{ij}(k^*)$

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

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

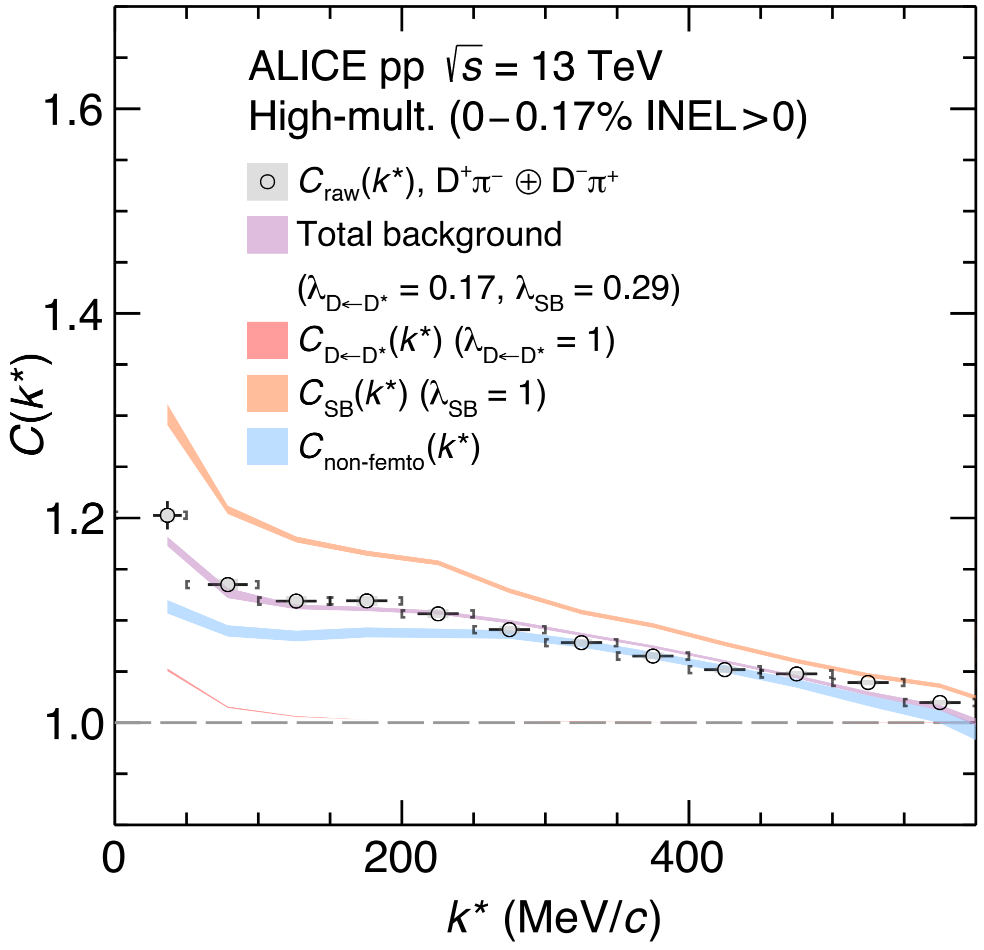


In this case

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

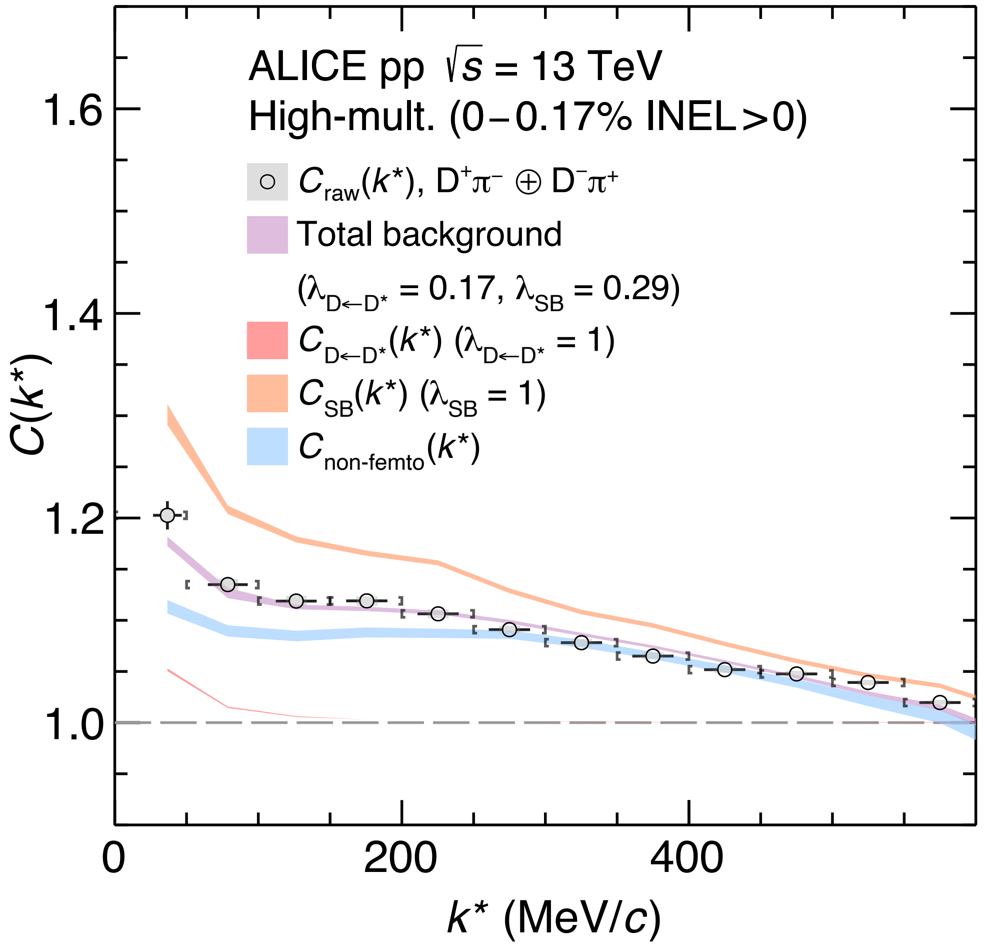
Modelling of the raw correlation function

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



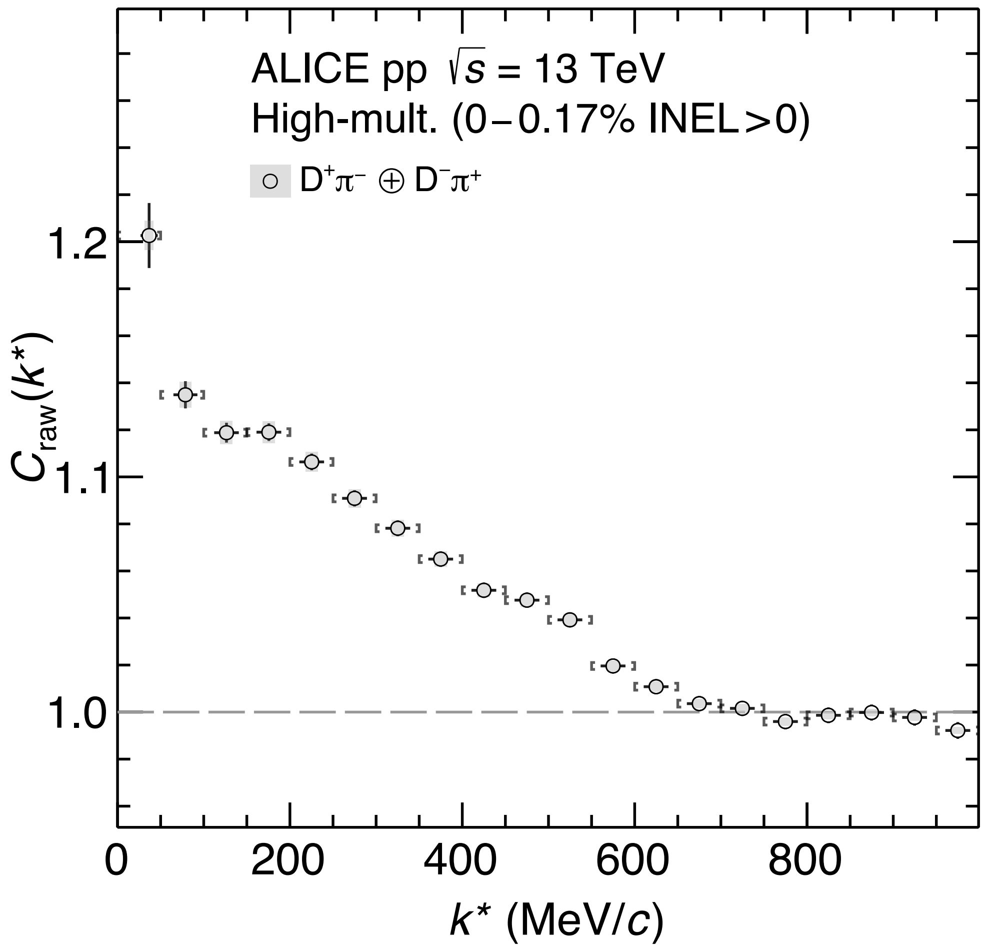
Modelling of the raw correlation function

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



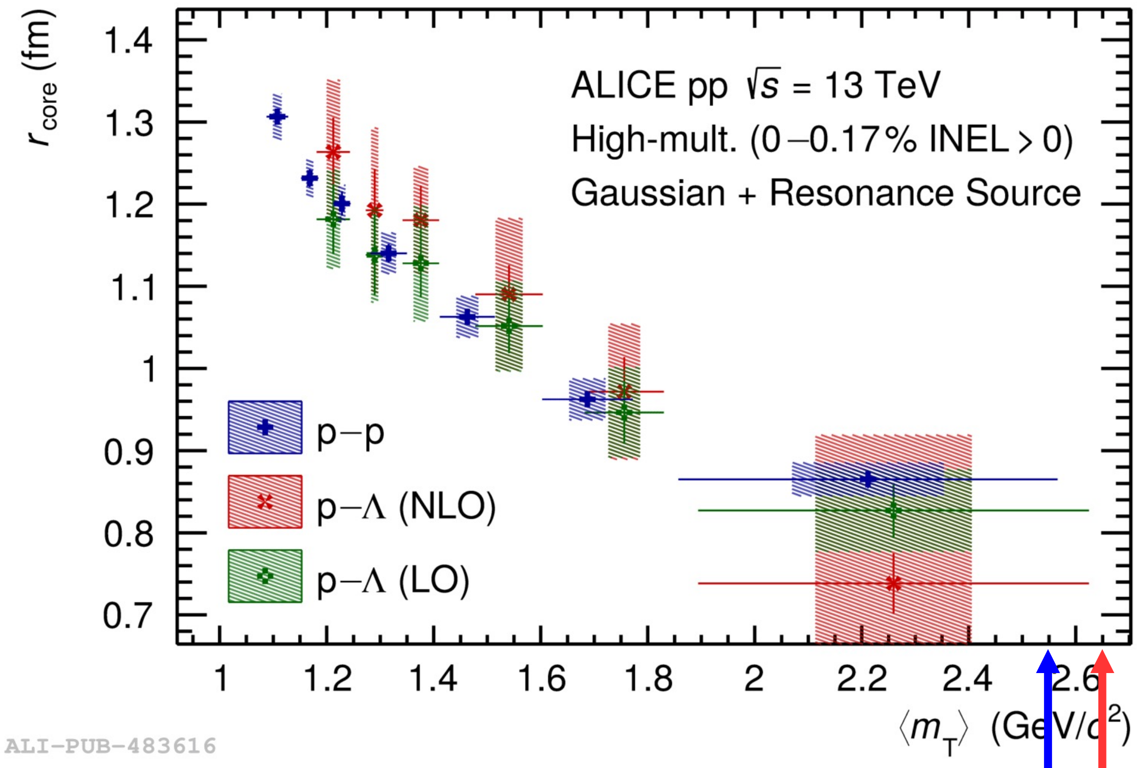
Modelling of the raw correlation function

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



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

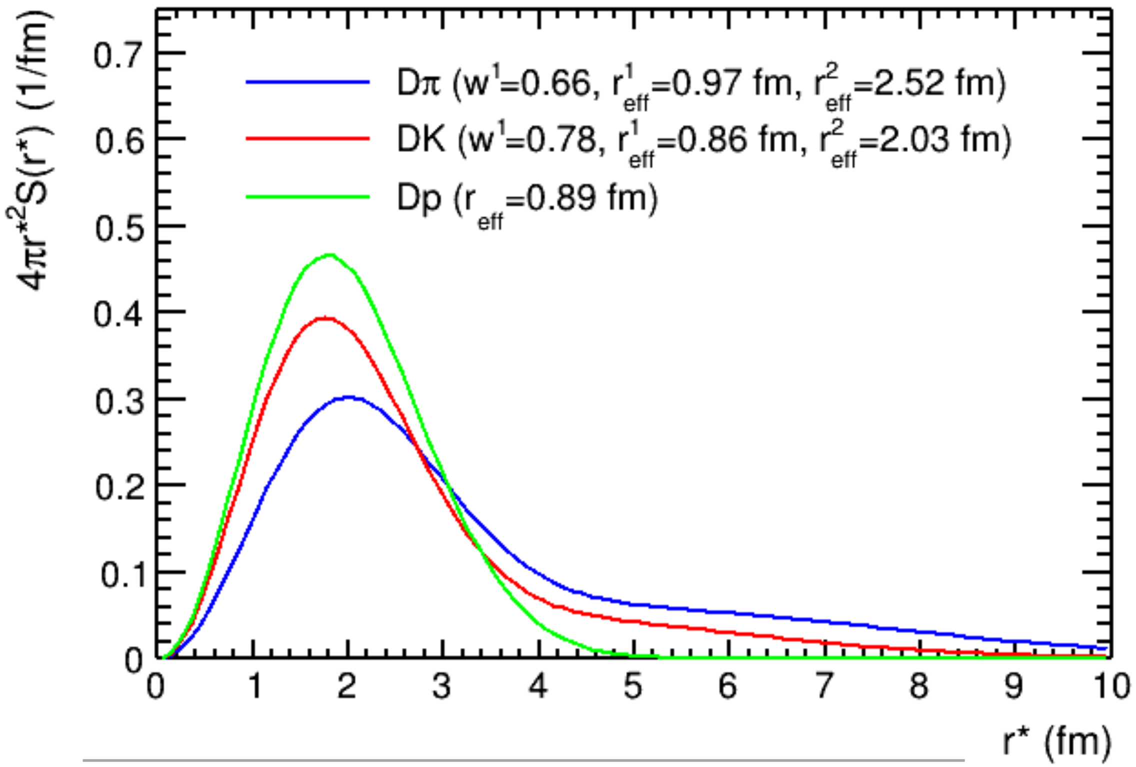


<$m_{T,DK}$> = 2.65 GeV/c^2

<$m_{T,D\pi}$> = 2.55 GeV/c^2

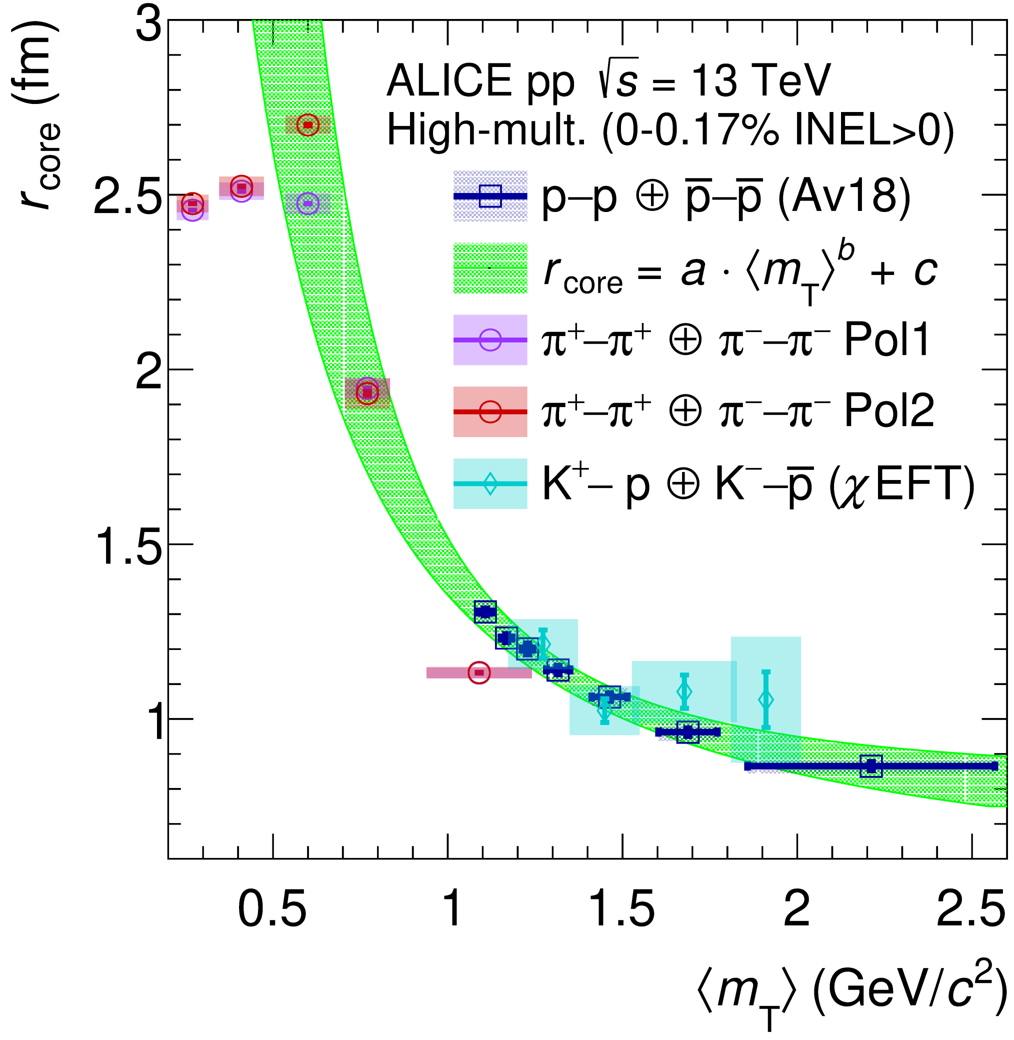
Source

- 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 ($c\tau \approx r_{core}$)
  - DK and Dπ source described by weighted (w^1) sum of two Gaussian sources, to describe tail from longer-lived resonances:
    - DK: $r_{eff}^1 = 0.86^{+0.09}_{-0.07} fm, r_{eff}^2 = 2.03^{+0.19}_{-0.12} fm$
    - Dπ: $r_{eff}^1 = 0.97^{+0.09}_{-0.08} fm, r_{eff}^2 = 2.52^{+0.36}_{-0.20} fm$



	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

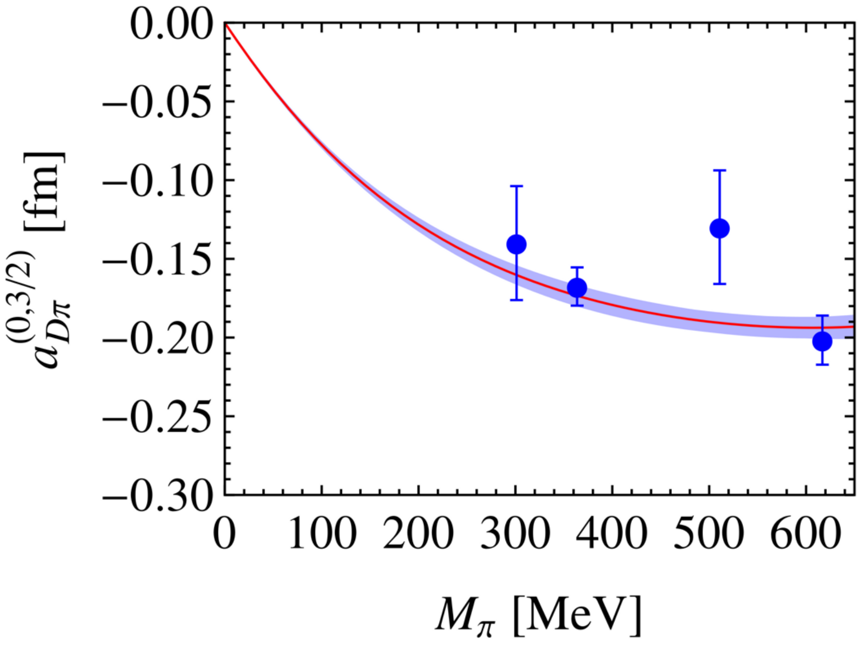
Source extended to mesons



ALI-PUB-566229

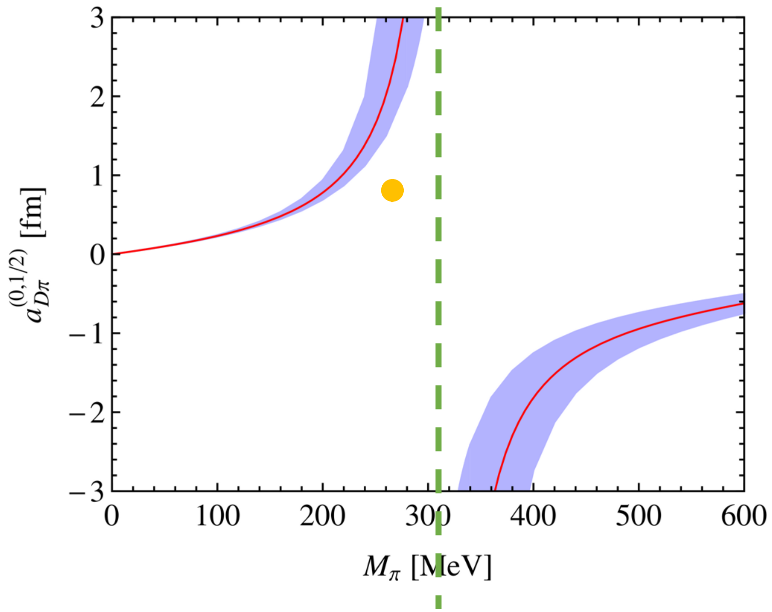
Dπ and DK interaction

- 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 $D_s0^*(2317)$

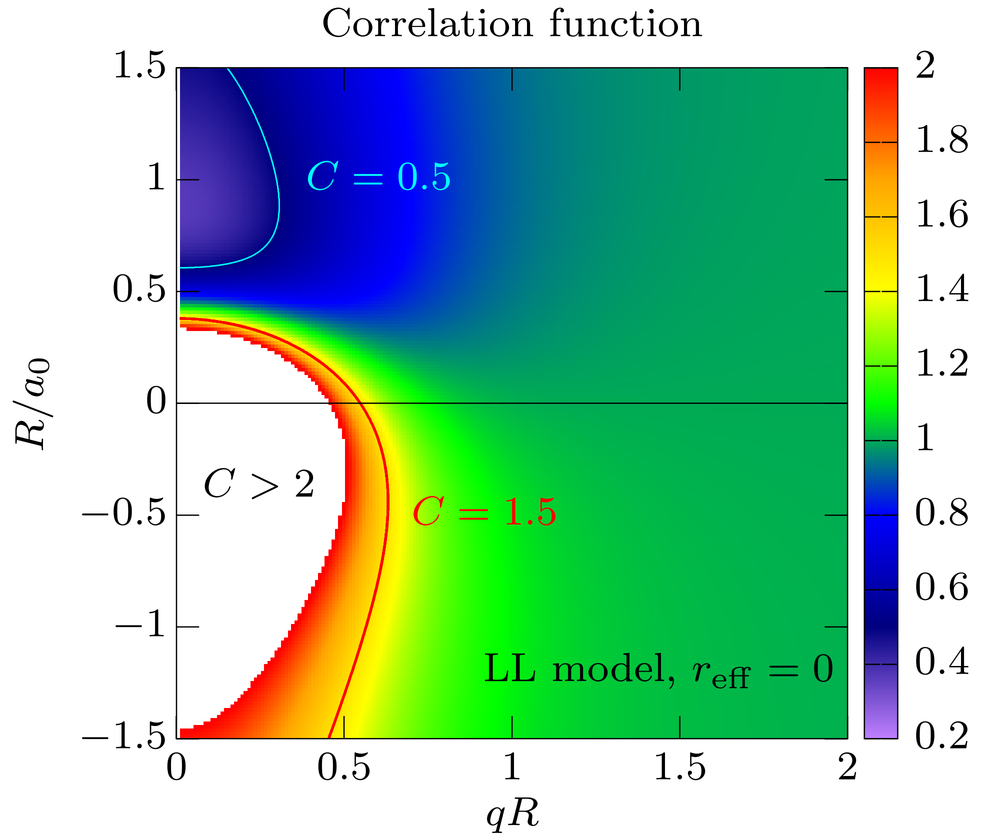
Correlation function and bound states

- 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 problem

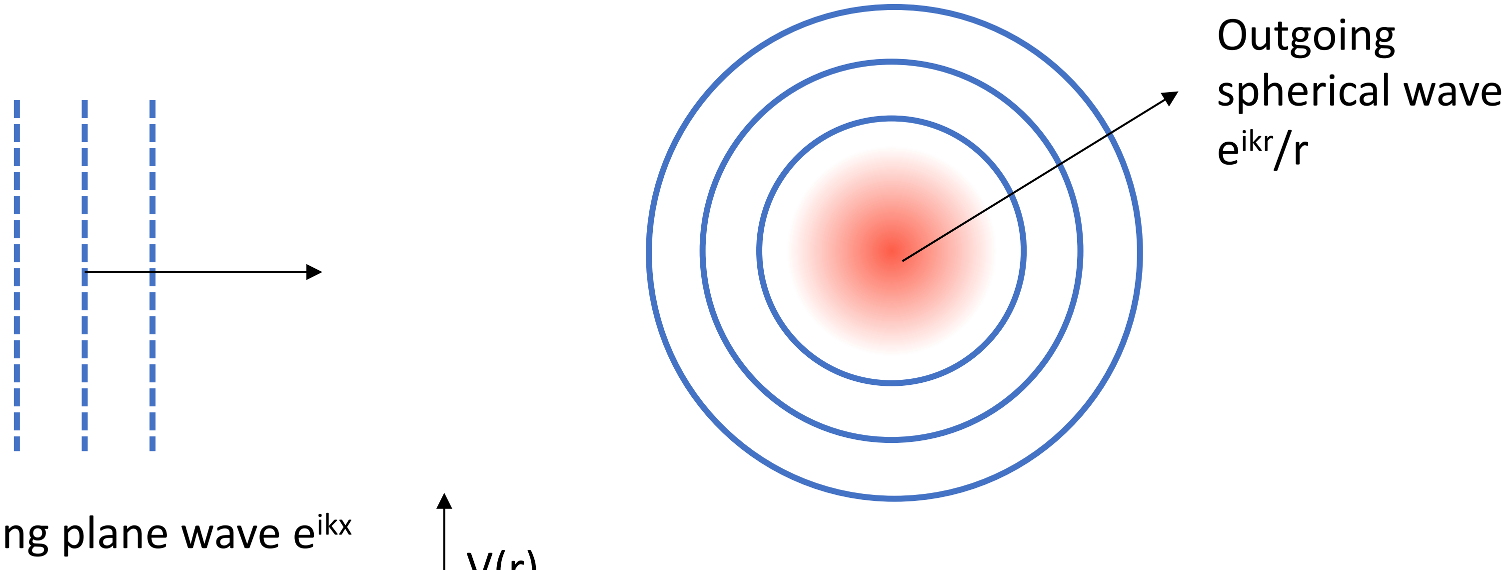
Scattering length a_0 related to phase shift of outgoing wave via

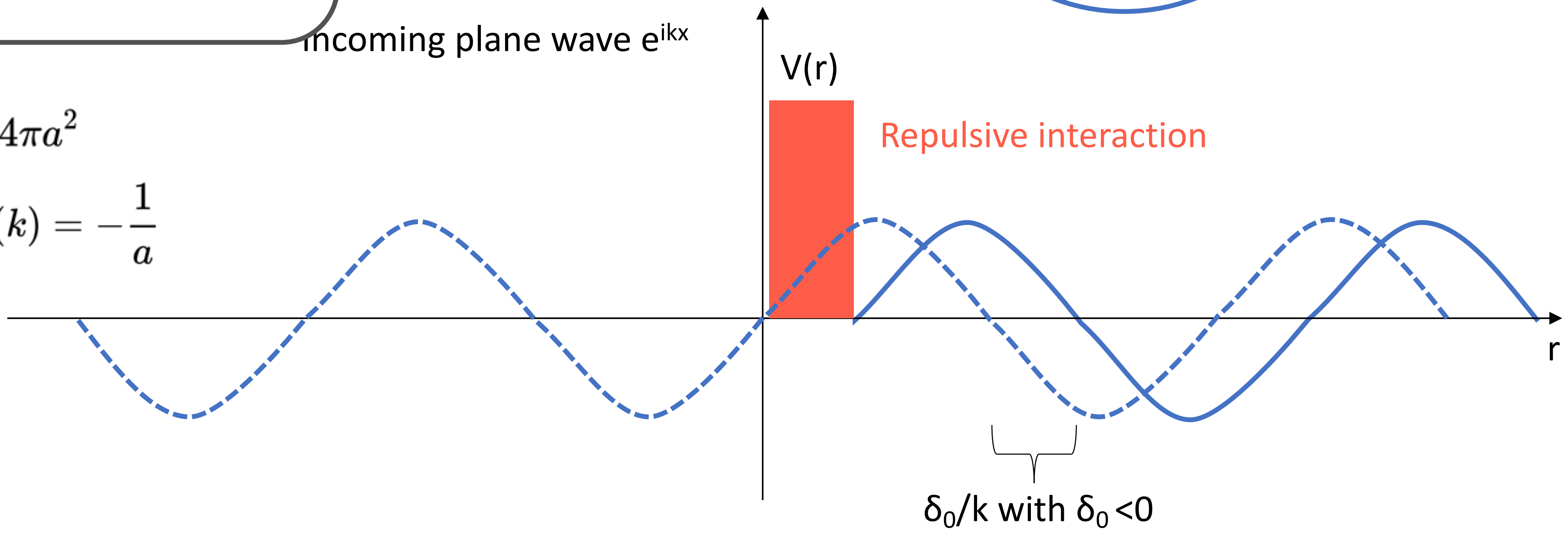
$$\lim_{k\to 0} k \cot\delta_0(k) = \frac{1}{a_0}$$

And to el. Cross section via

$$\lim_{k\to 0} \sigma_e = 4\pi a^2$$

$$\lim_{k\to 0} k \cot\delta(k) = -\frac{1}{a}$$

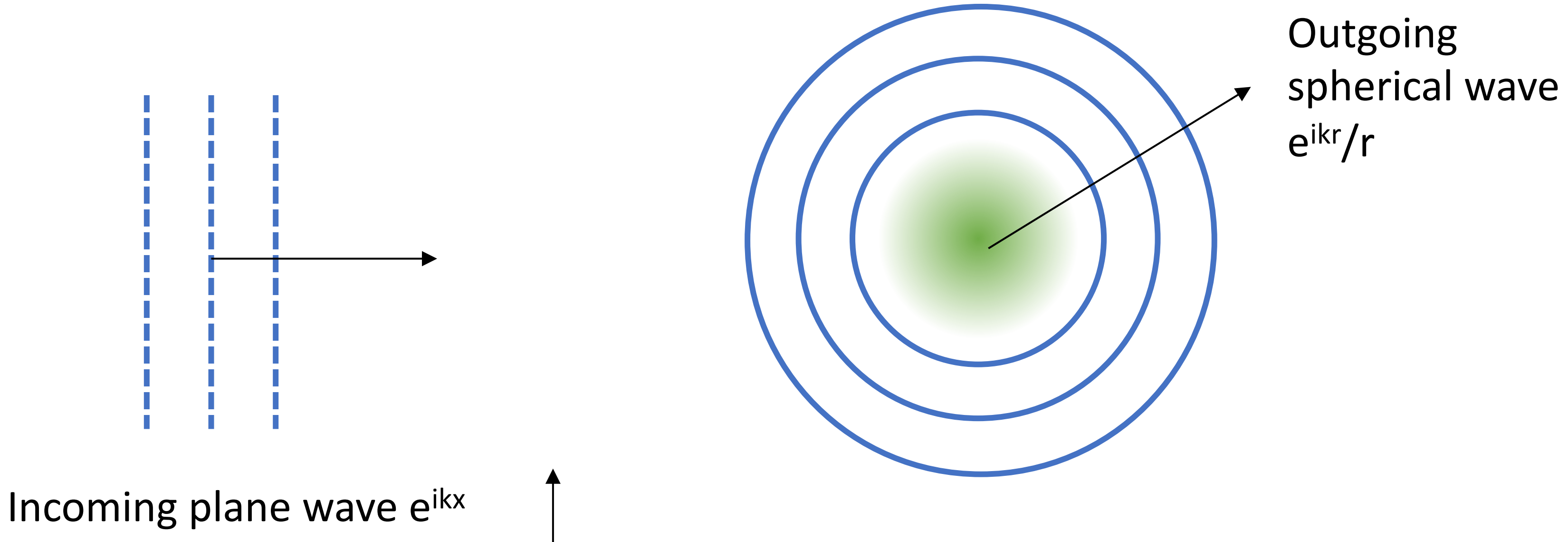


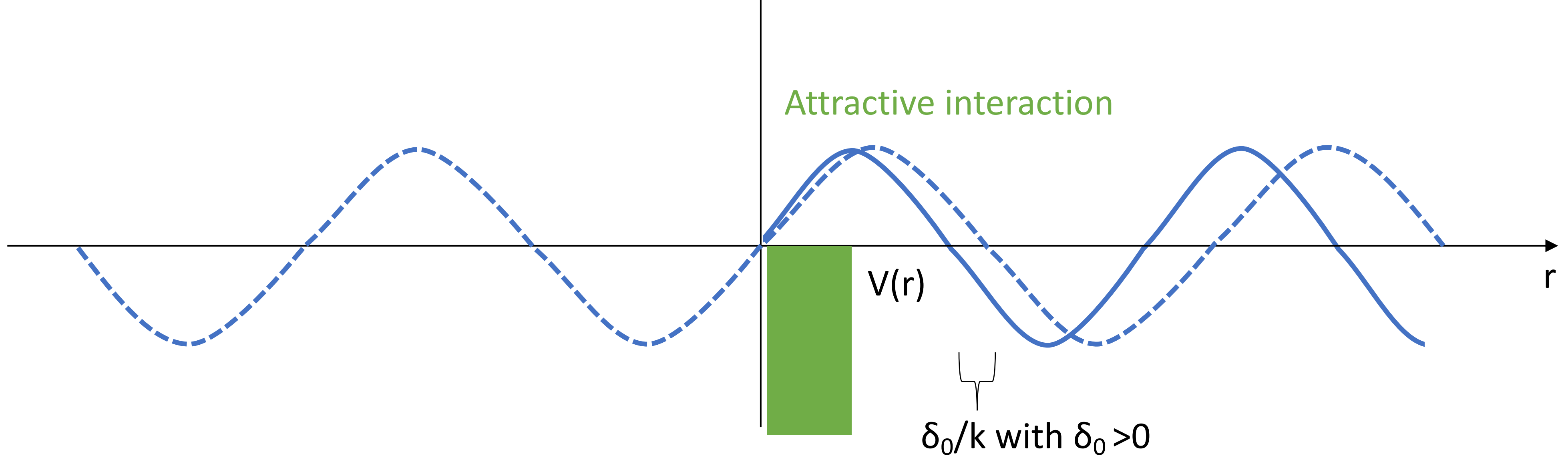


Scattering problem

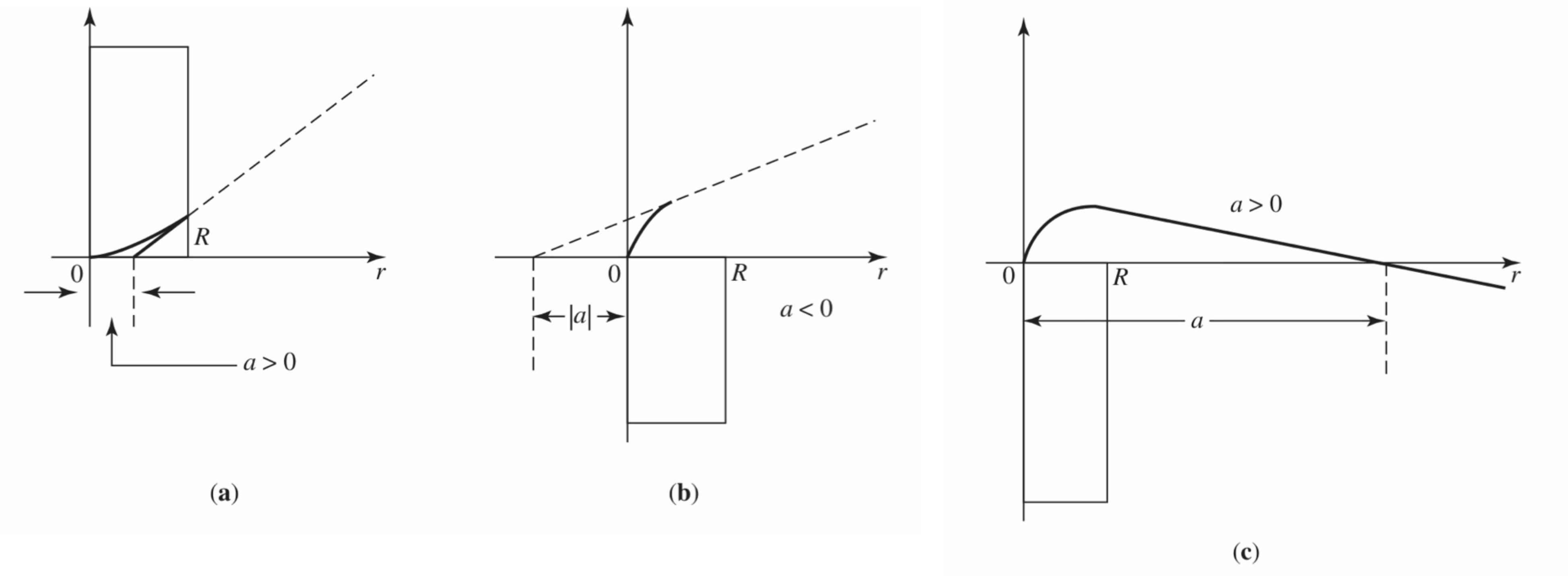
$$\lim_{k \to 0} k \cot \delta(k) = -\frac{1}{a}$$

$$\lim_{k \to 0} \sigma_e = 4\pi a^2$$



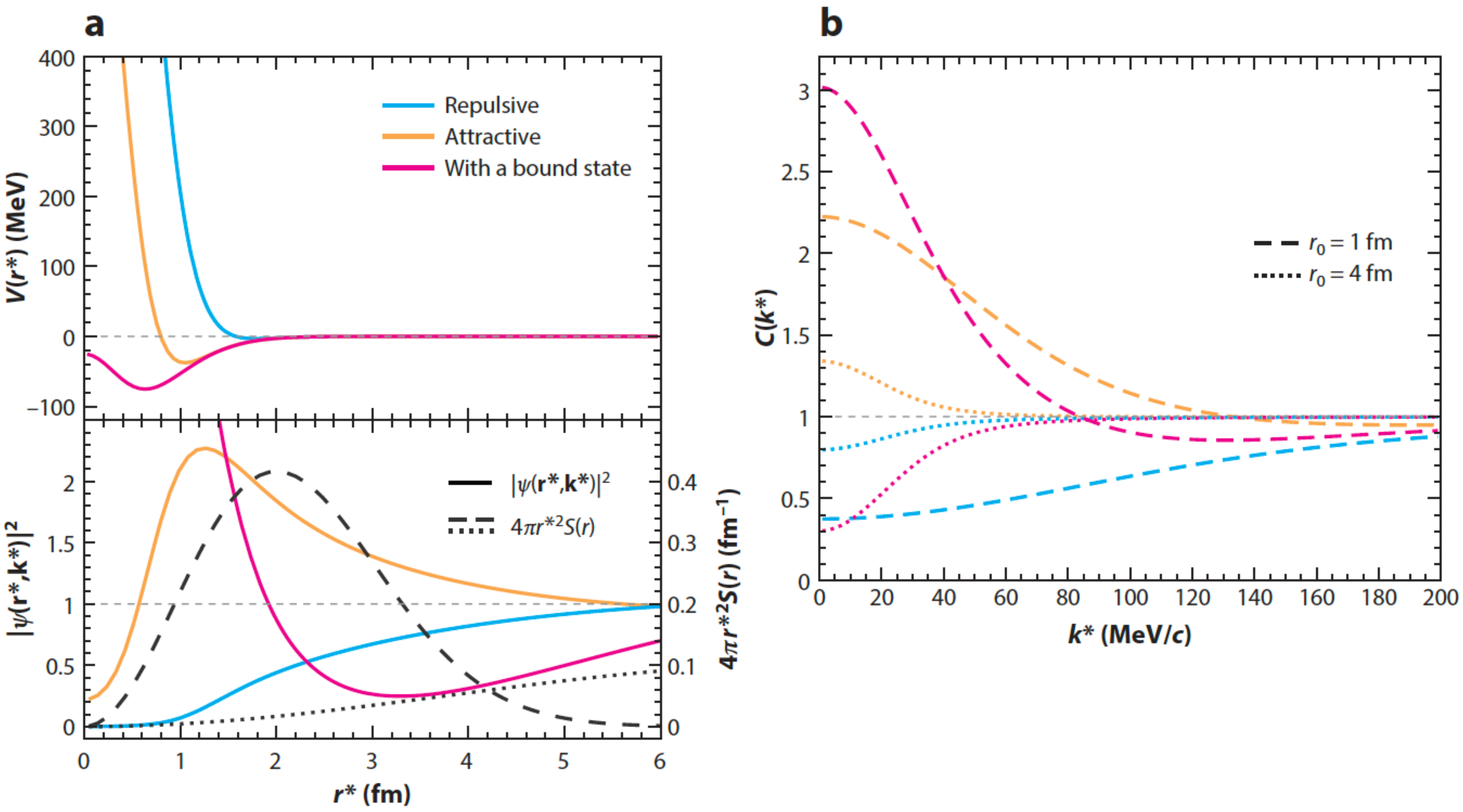


Sign of the scattering length



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].

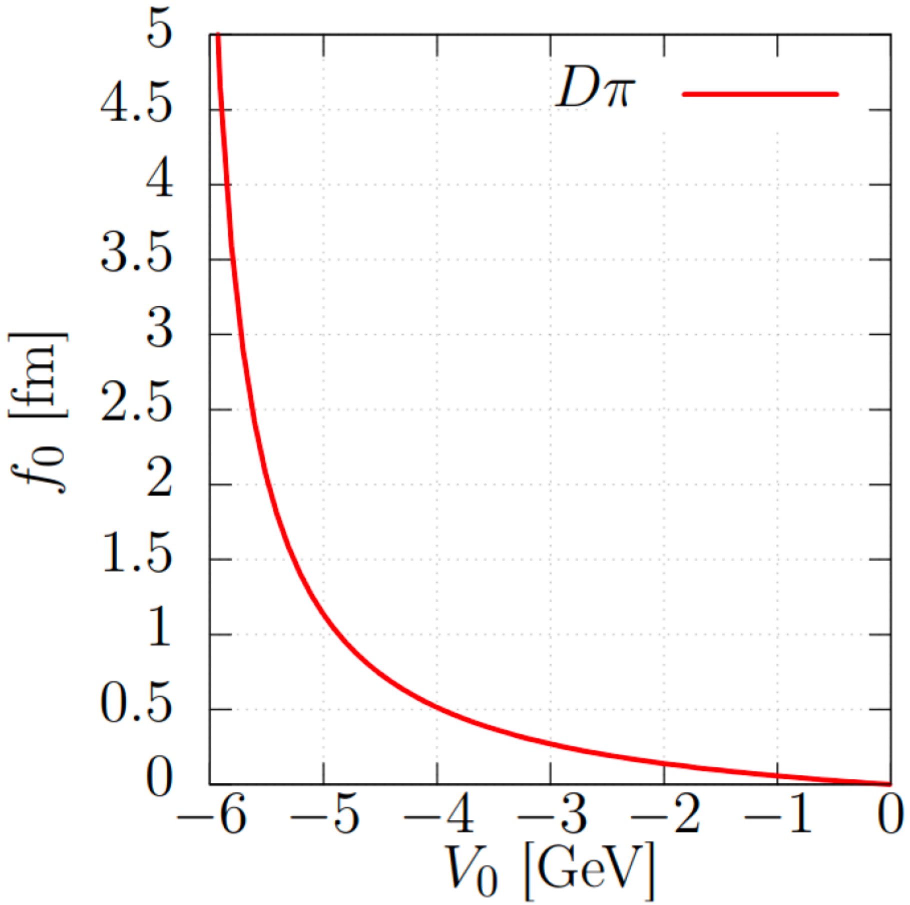


a
400
300
200
100
0
−100
V(r*) (MeV)
Repulsive
Attractive
With a bound state
2
1.5
1
0.5
0
|ψ(r*,k*)|²
|ψ(r*,k*)|²
4πr*²S(r)
0.4
0.3
0.2
0.1
0
4πr*²S(r) (fm⁻¹)
0
1
2
3
4
5
6
r* (fm)
b
3
2.5
2
1.5
1
0.5
0
C(k*)
r₀ = 1 fm
r₀ = 4 fm
0
20
40
60
80
100
120
140
160
180
200
k* (MeV/c)

Gaussian Potential

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

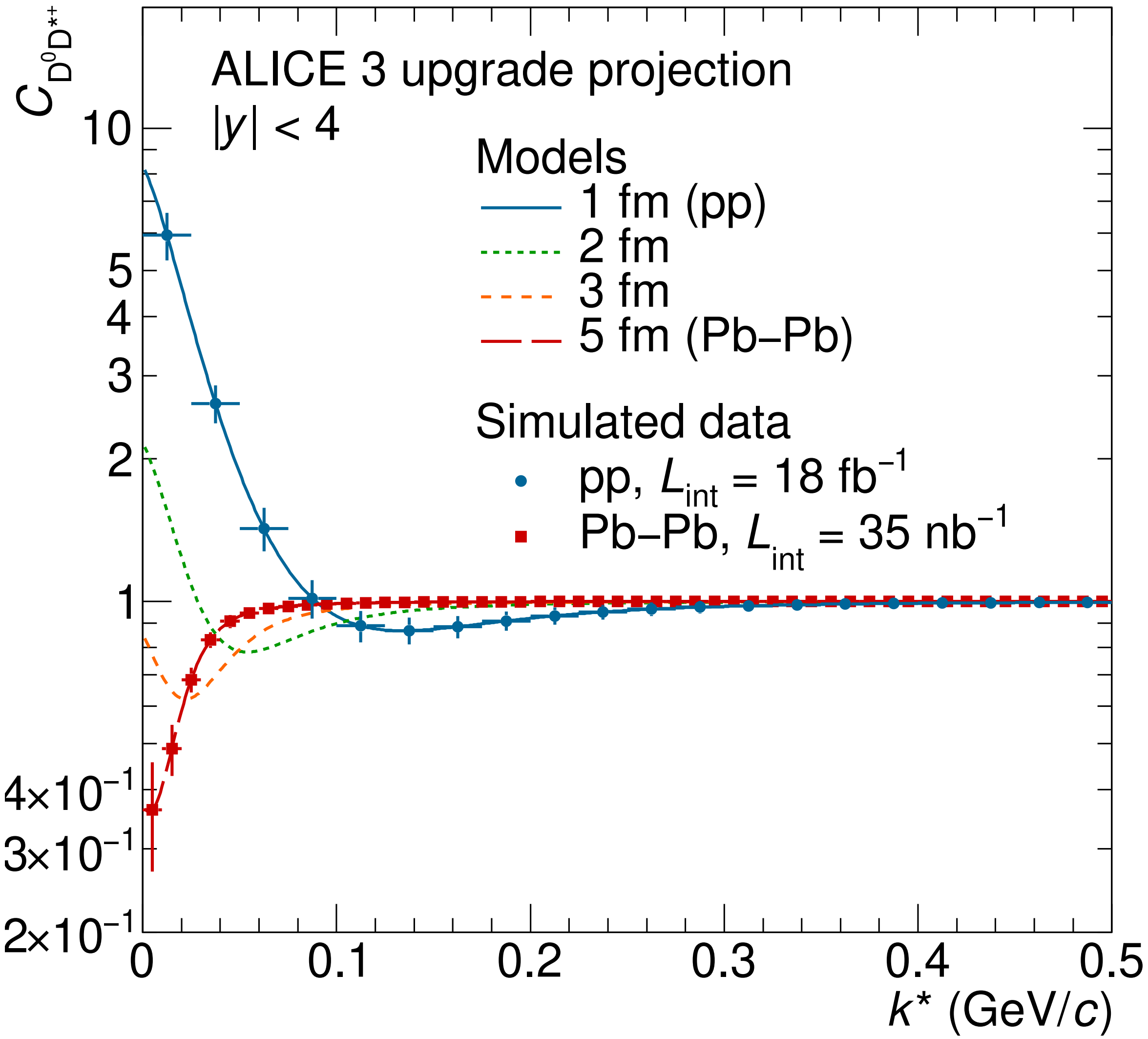
- Strength adjustable
- Range: mass of the ρ meson



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

Charm femtoscopy with ALICE 3

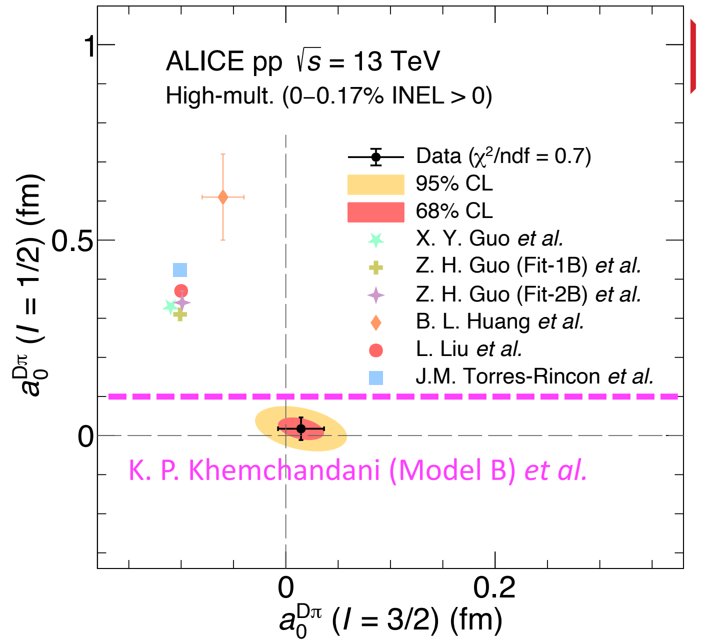
- ALICE 3: a next generation experiment
  arXiv:2211.02491v1
- Possible to study exotic charm states
- Test formation of DD^* and $\bar{D}D^*$ bound states
  - T_{CC}^+ could be D^0D^* molecule
  - $X_{c1}(3872)$ could be a $\bar{D}D^*$ molecule
- Upgrade projection
  - Gaussian potential
  - Different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

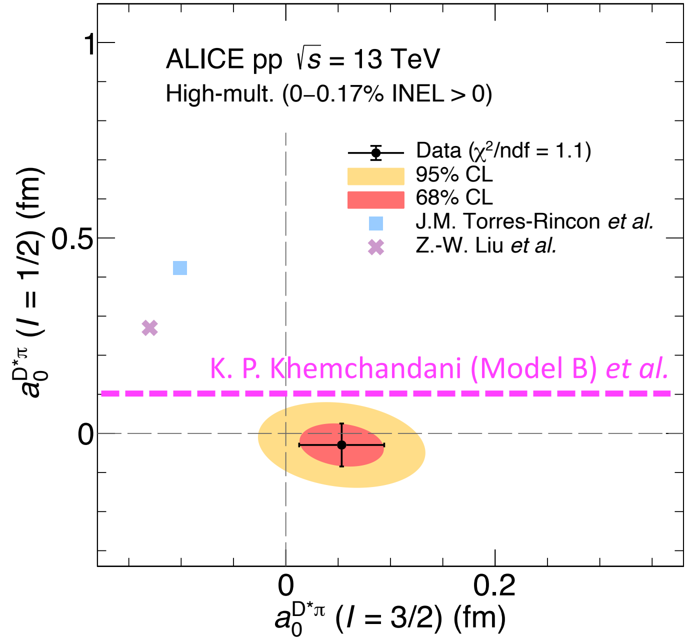


ALI-SIMUL-502575

Deviation with theory

- Larger source of r_{eff}~3 fm could accommodate the theroy predicitons 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 $a^{D^*\pi}(I=1/2)=0.1$ 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
    Belle Collaboration, Phys. Rev. D 69 (2004) 112002
    LHCb Collaboration Phys. Rev. D 92 (2015) 012012
  - Heavy-quark symmetry → also smaller value for $a^{D\pi}(I=1/2)$ expected





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 transport models employ larger theory values for now