SQM 2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

Max-Planck-Institut
für Physik

TECHNISCHE
UNIVERSITÄT
MÜNCHEN

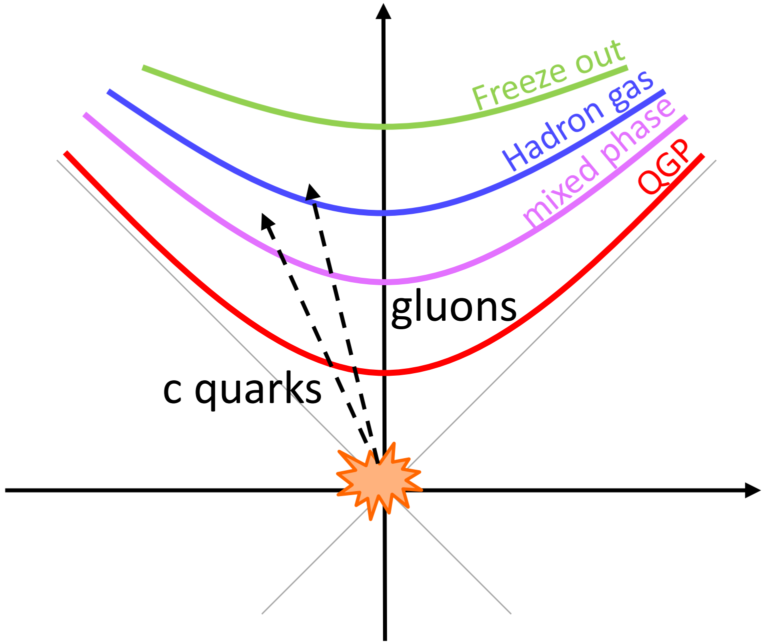
ALICE

ALICE determines the scattering parameters of D mesons with light-flavor hadrons

Emma Chizzali on behalf of the ALICE Collaboration
SQM 2022, Busan
14/06/2022

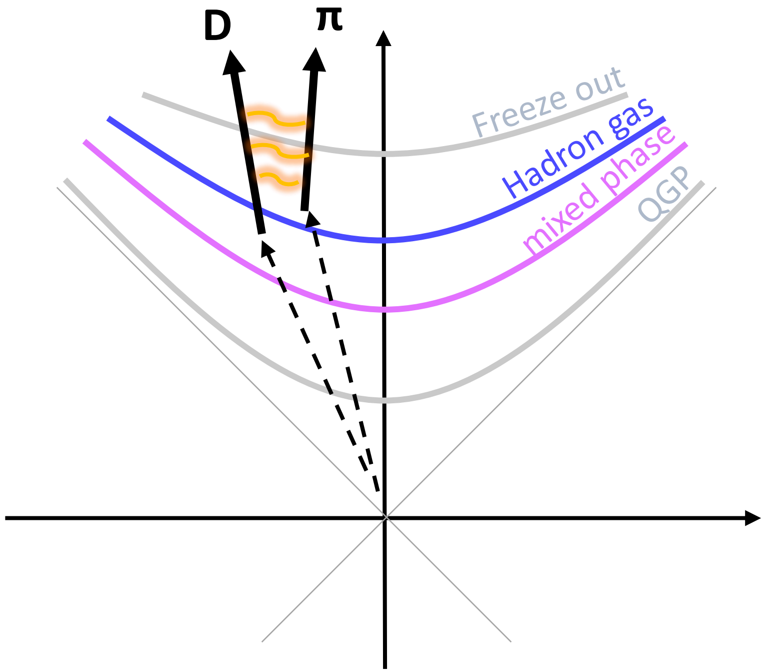
Heavy-flavor particles and the QGP

- Heavy quarks (HQ) produced right after collision
  - Thermal equilibration time of heavy quarks expected to be of the order of QGP lifetime
- Ideal probes of the QGP
  - Diffusion coefficients of HQ characterize the QGP



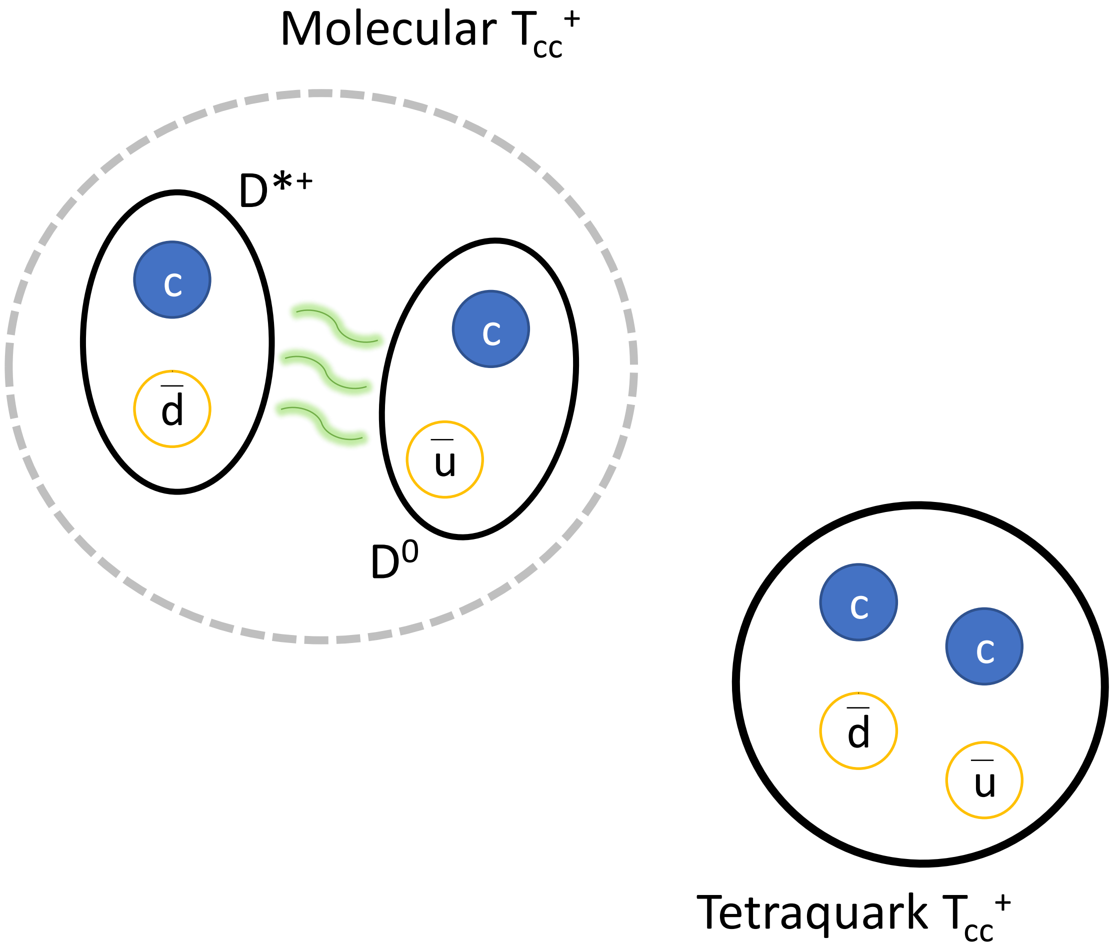
Heavy-flavor particles and the QGP

- Heavy quarks (HQ) produced right after collision
  - Thermal equilibration time of heavy quarks expected to be of the order of QGP lifetime
- Ideal probes of the QGP
  - Diffusion coefficients of HQ characterize the QGP
- During the later hadronic-phase D meson rescattering must be considered
  - Models (e.g. TAMU) depend on the scattering lengths between D meson and light hadrons
    → No experimental constraints
    Ralf Rapp et al, *Phys. Lett. B* **701** (2011) 445-450

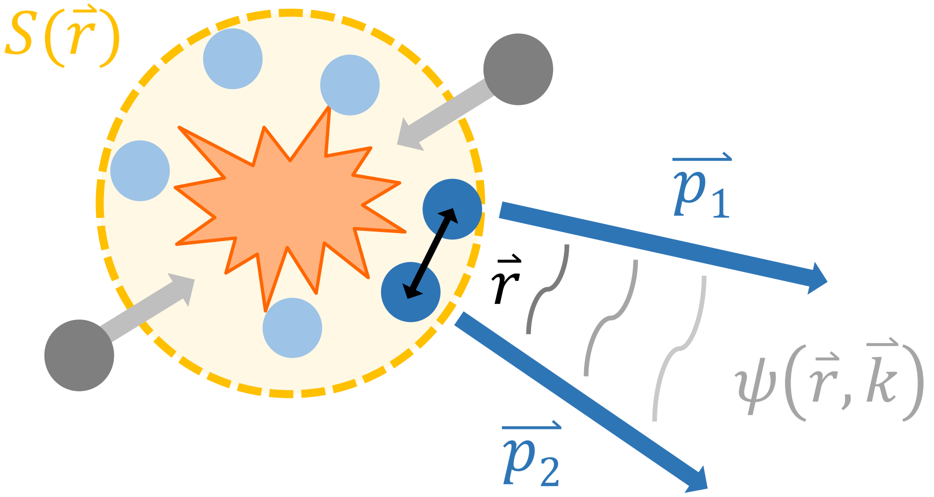


Bound states

- Strong final state interaction (FSI) can lead to formation of bound 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})
    arXiv:2109.01038
    arXiv:2109.01056v2
  - 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 whether observations are molecular states



The correlation function



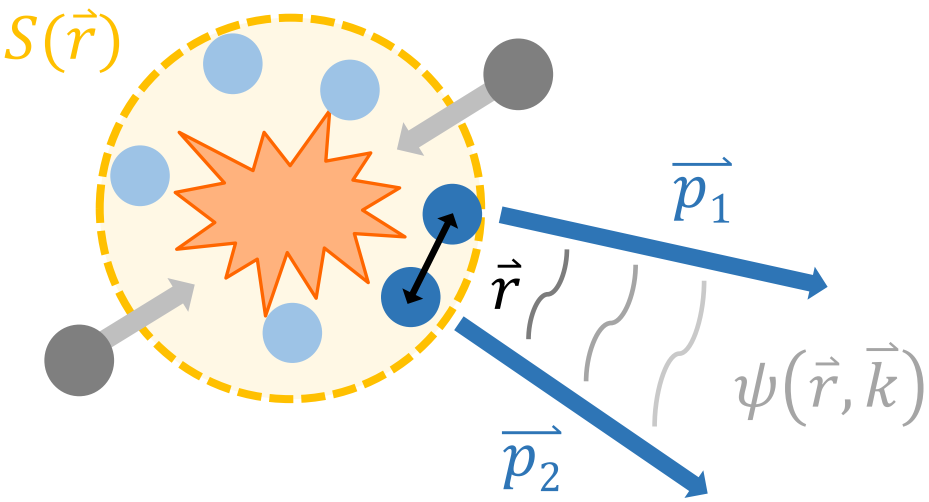
$$\underbrace{C(k^*) = \mathcal{N}\frac{\mathrm{N}_{same}(k^*)}{\mathrm{N}_{mixed}(k^*)}}_{\text{experimental definition}} = \underbrace{\int S(\vec{r}^*)\left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^*}_{\text{theoretical definition}} \xrightarrow{k^*\to\infty} 1$$

S. E. Koonin, *Physics Letters 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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Correlation function (CF) computed

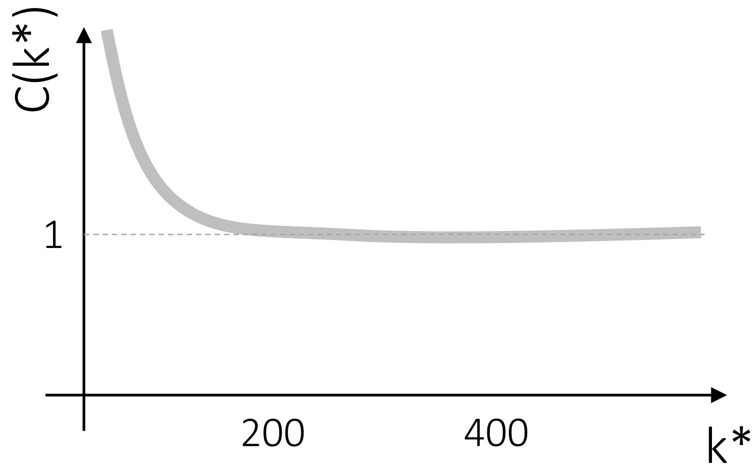
a) **numerically**, by solving Schrödinger equation for given potential employing CATS framework

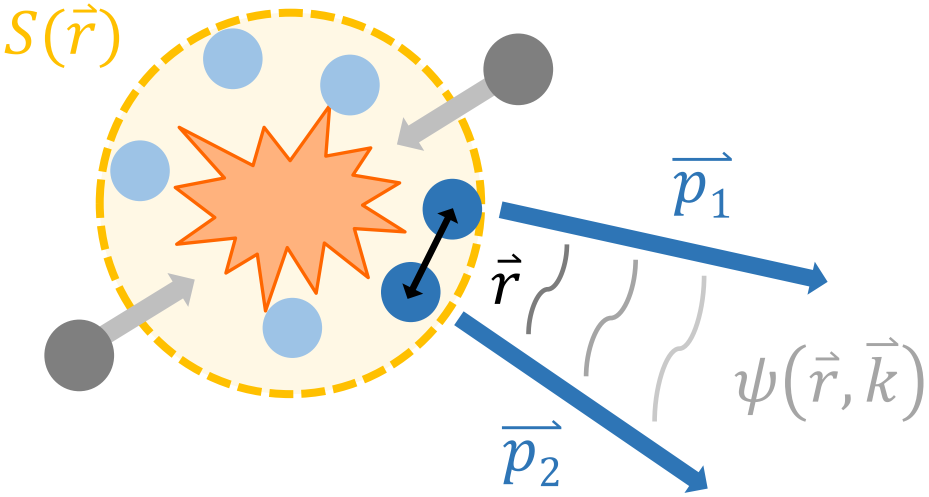
D. L. Mihaylov et al, Eur. Phys. Journal C 78 (2018) 394

b) **analytically**, by employing e.g. Lednický-Lyuboshits approach

R. Lednicky and V.L. Lyuboshits, *Sov. J. Nucl. Phys.* **53** (1982) 770

The correlation function





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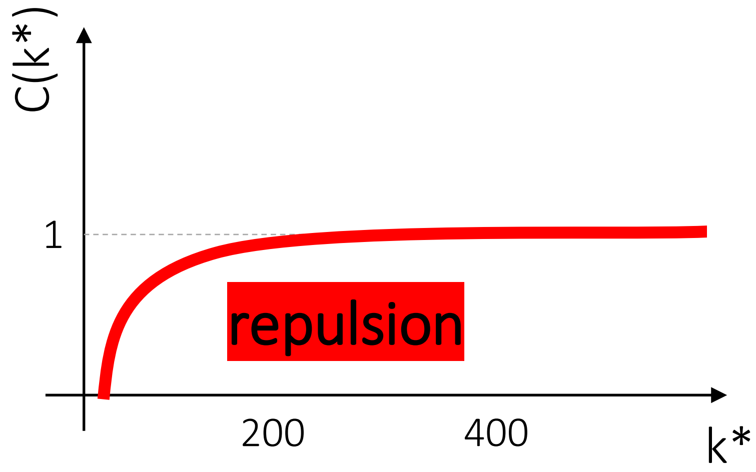

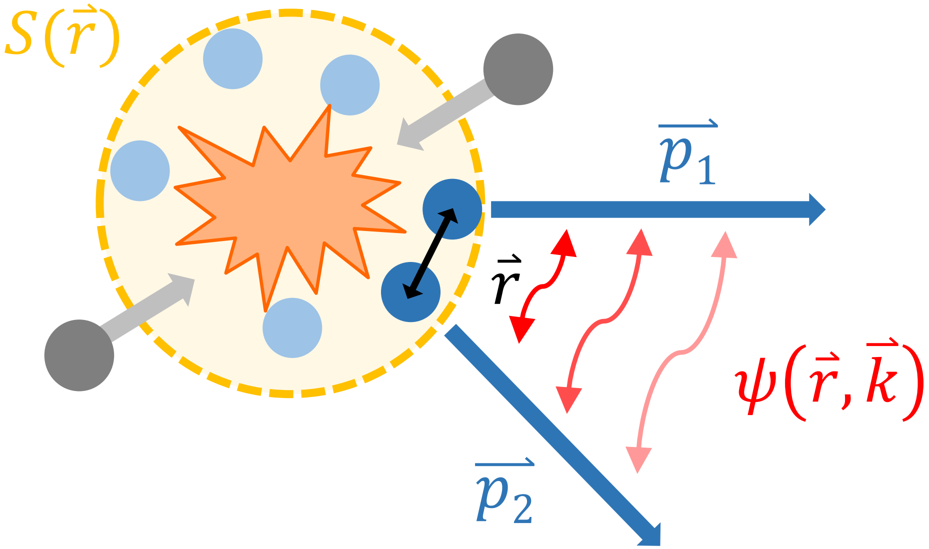

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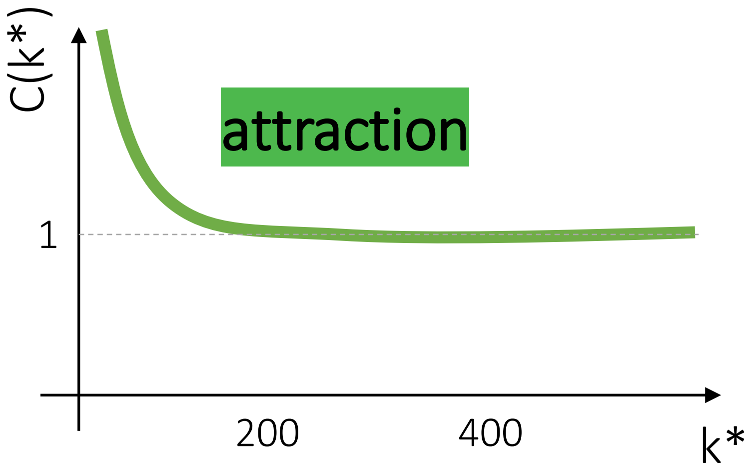

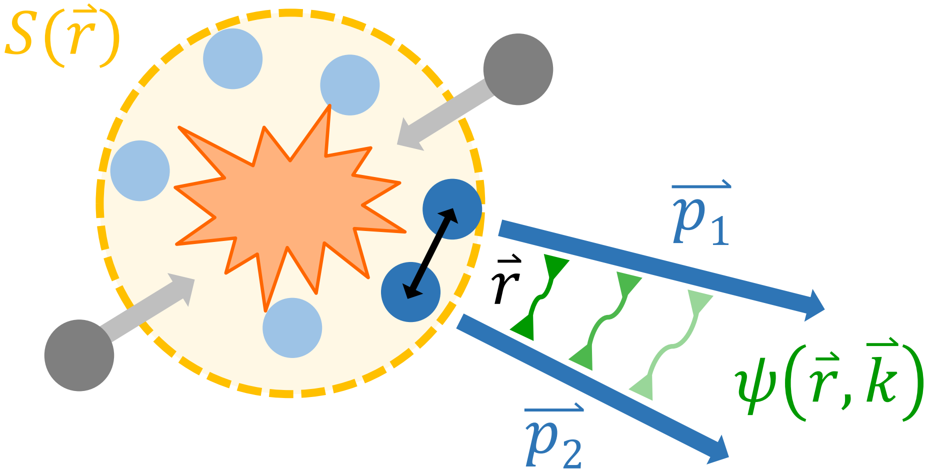

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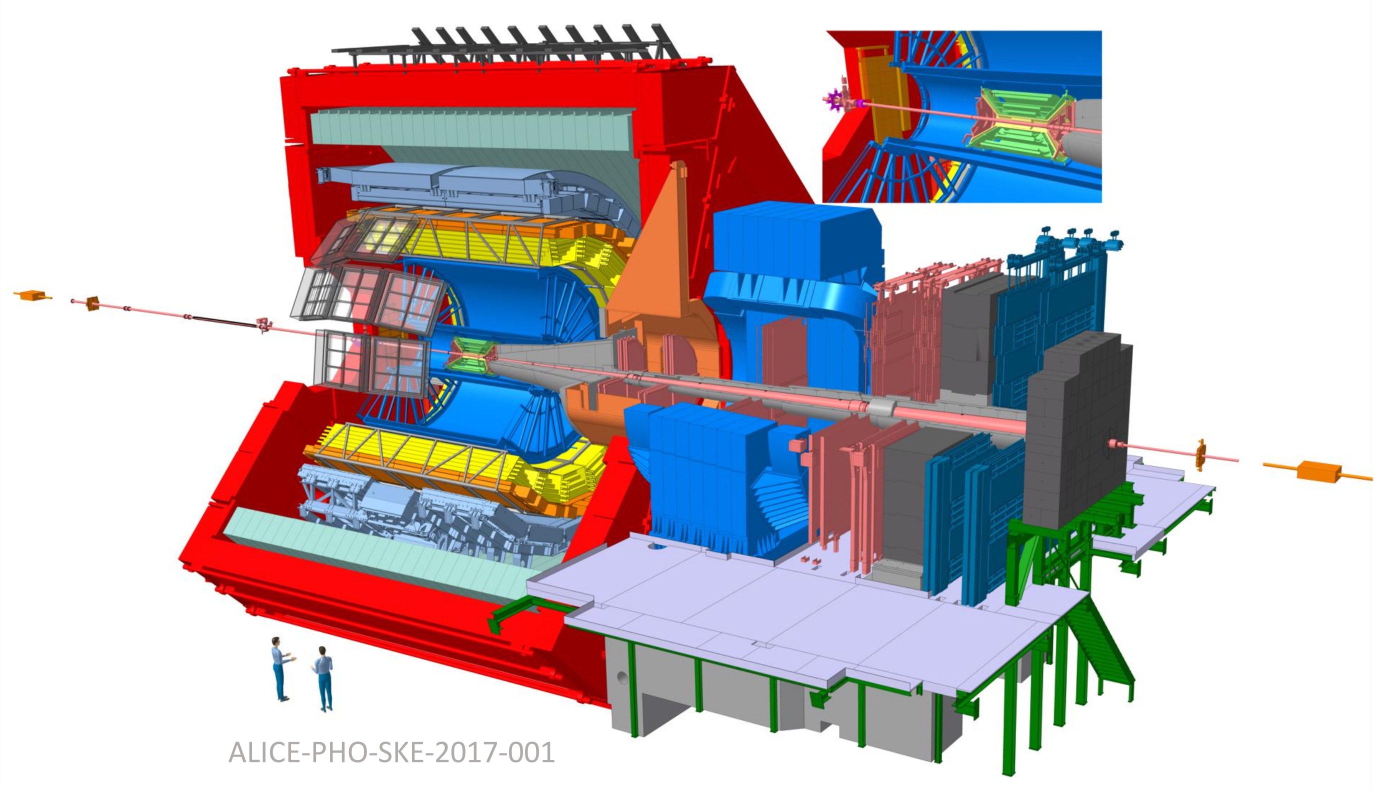
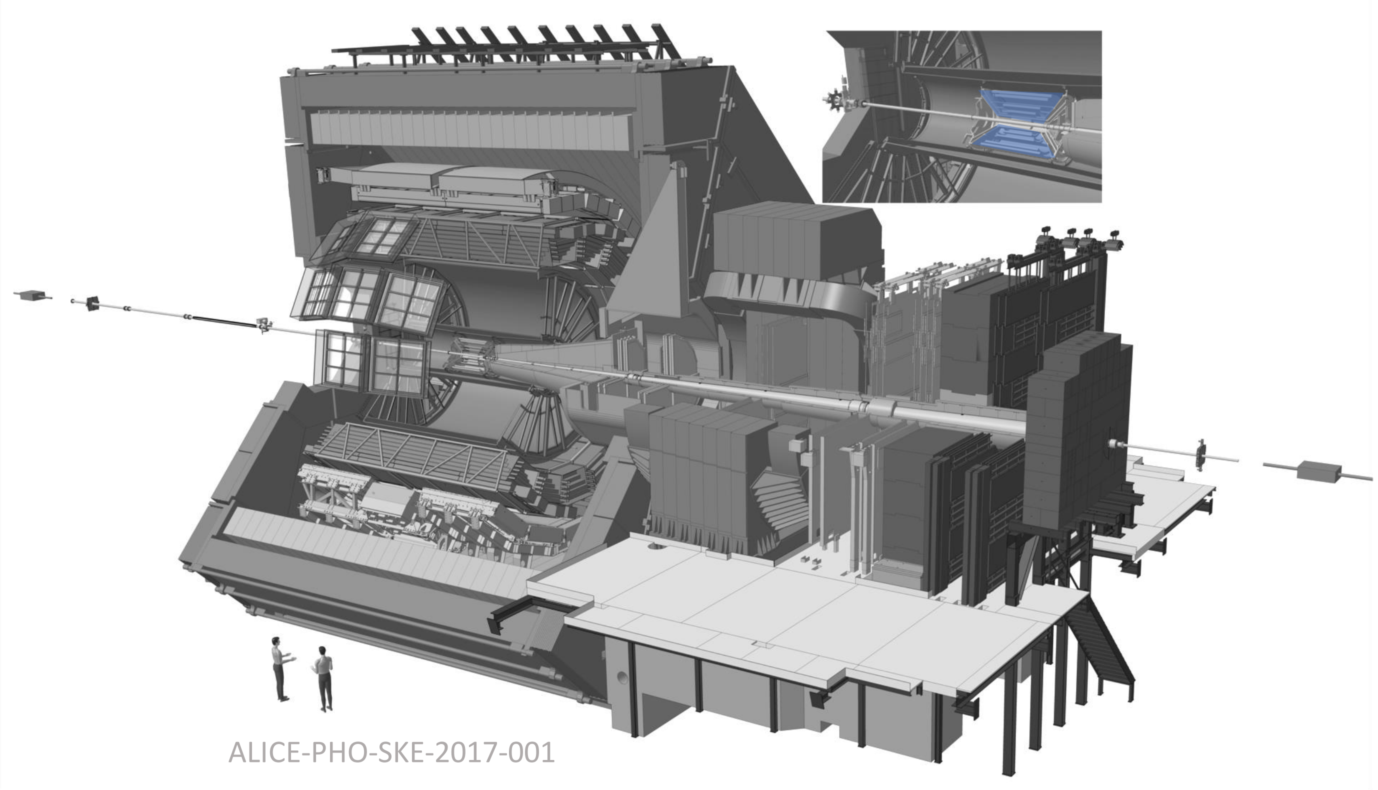


ALICE-PHO-SKE-2017-001

ALICE

ITS (Inner Tracking System)

- 6 layers of silicon detectors
- Vertex, tracking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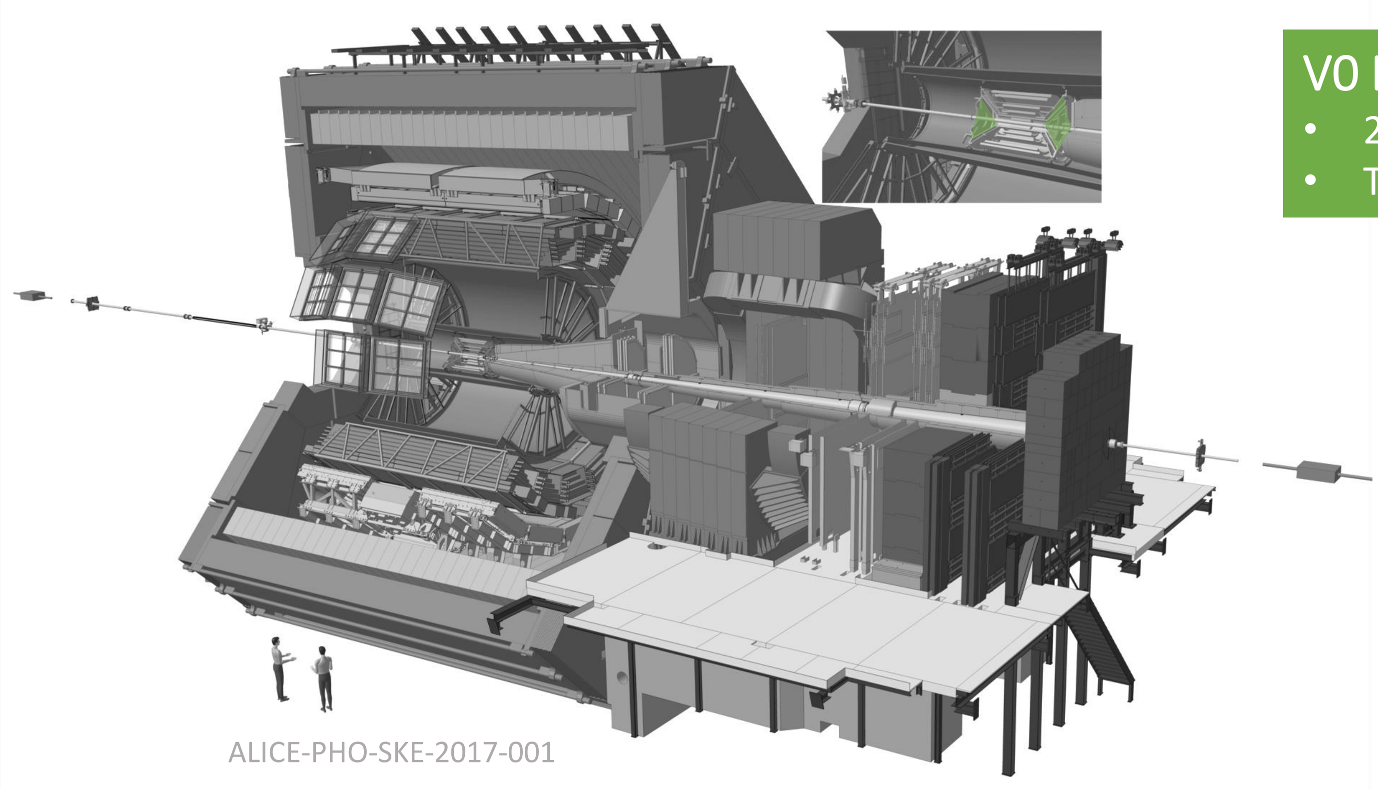
V0 Detector

- 2 scintillator arrays
- Trigger, multiplicity estimation



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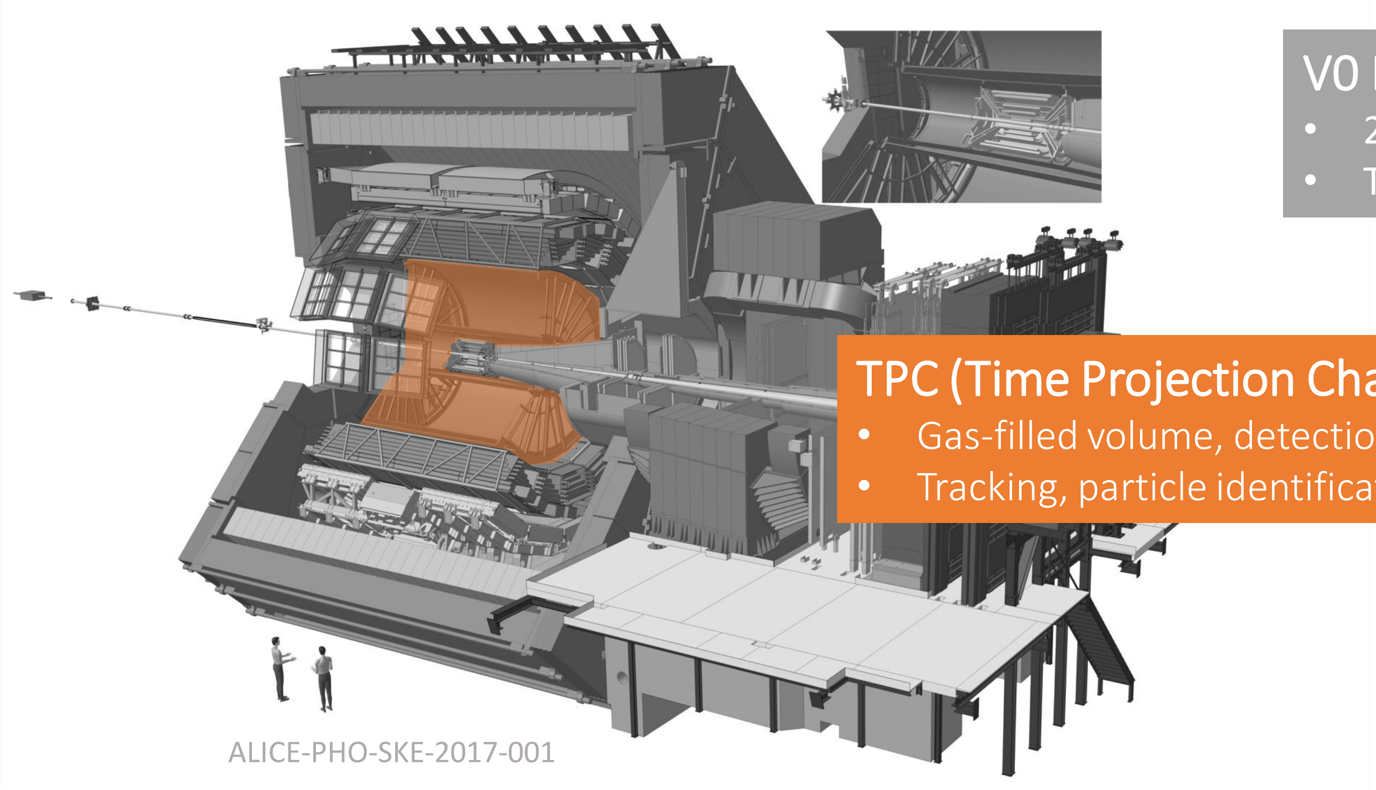
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TPC (Time Projection Chamber)
- Gas-filled volume, detection of ionization
- Tracking, particle identification (PID) (dE/dx)

ALICE

TOF (Time Of Flight)

- Multi-gap resistive plate chambers
- PID by determining velocity

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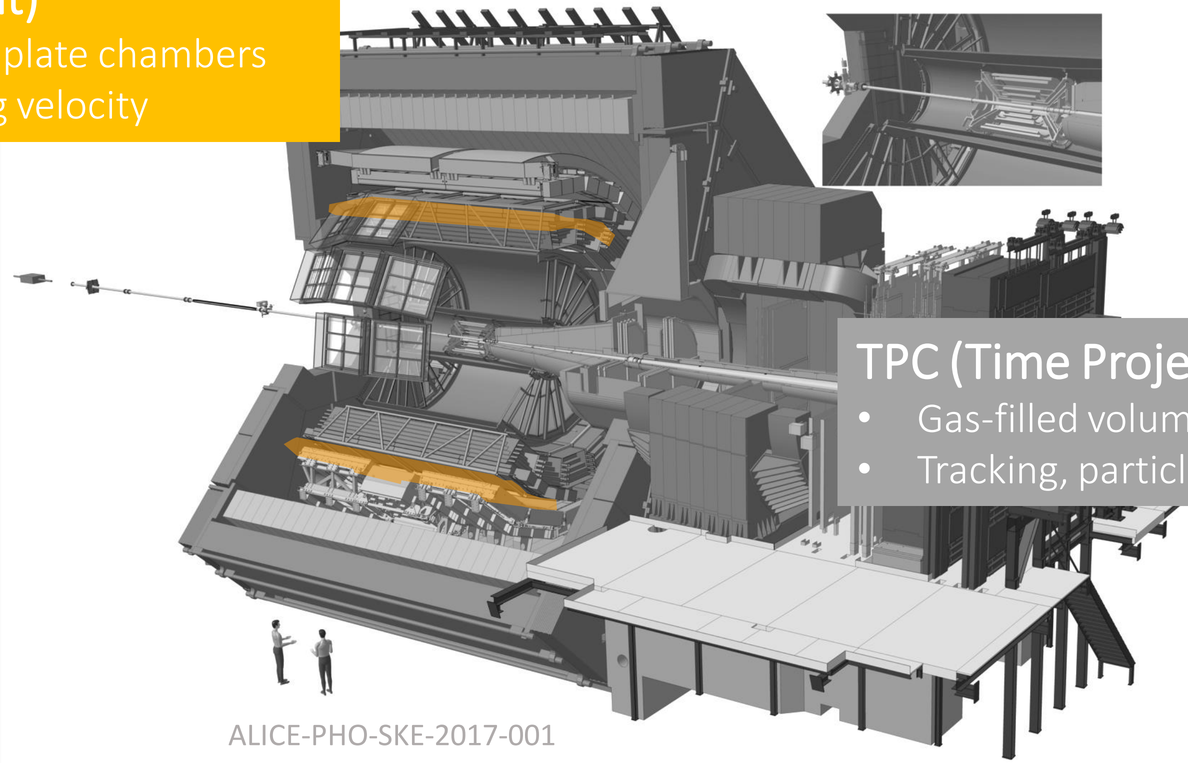
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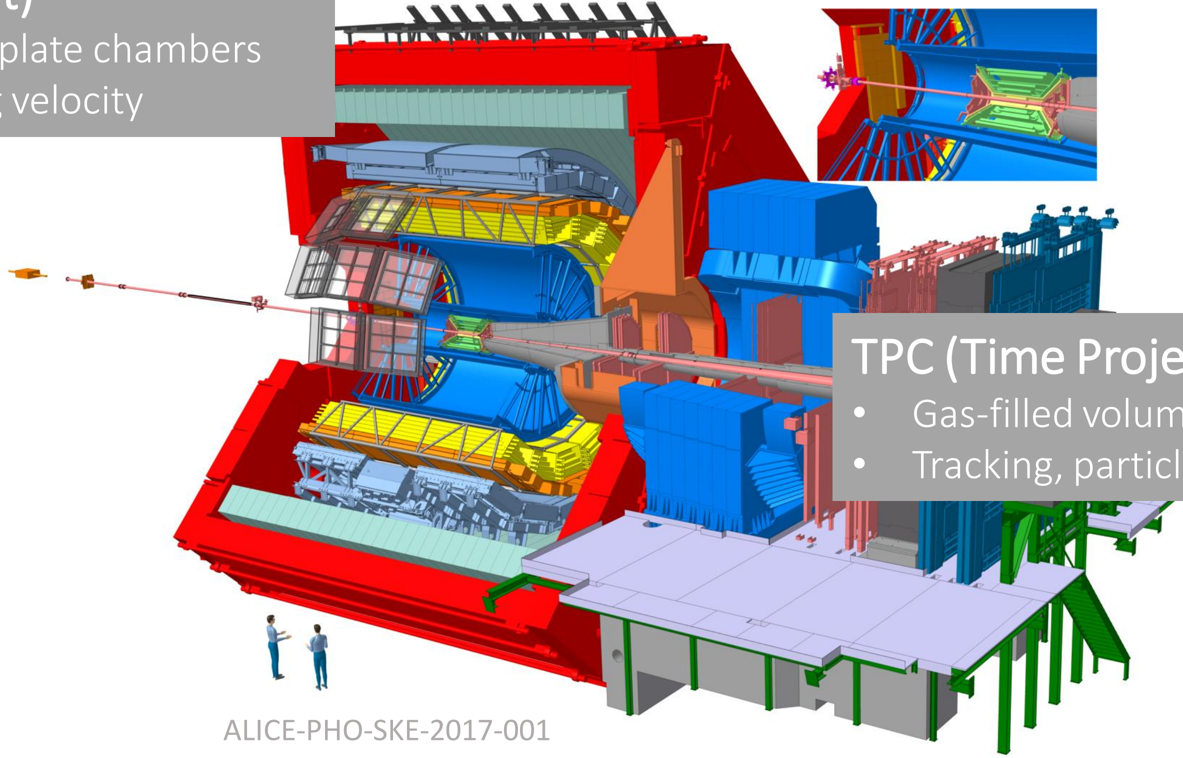

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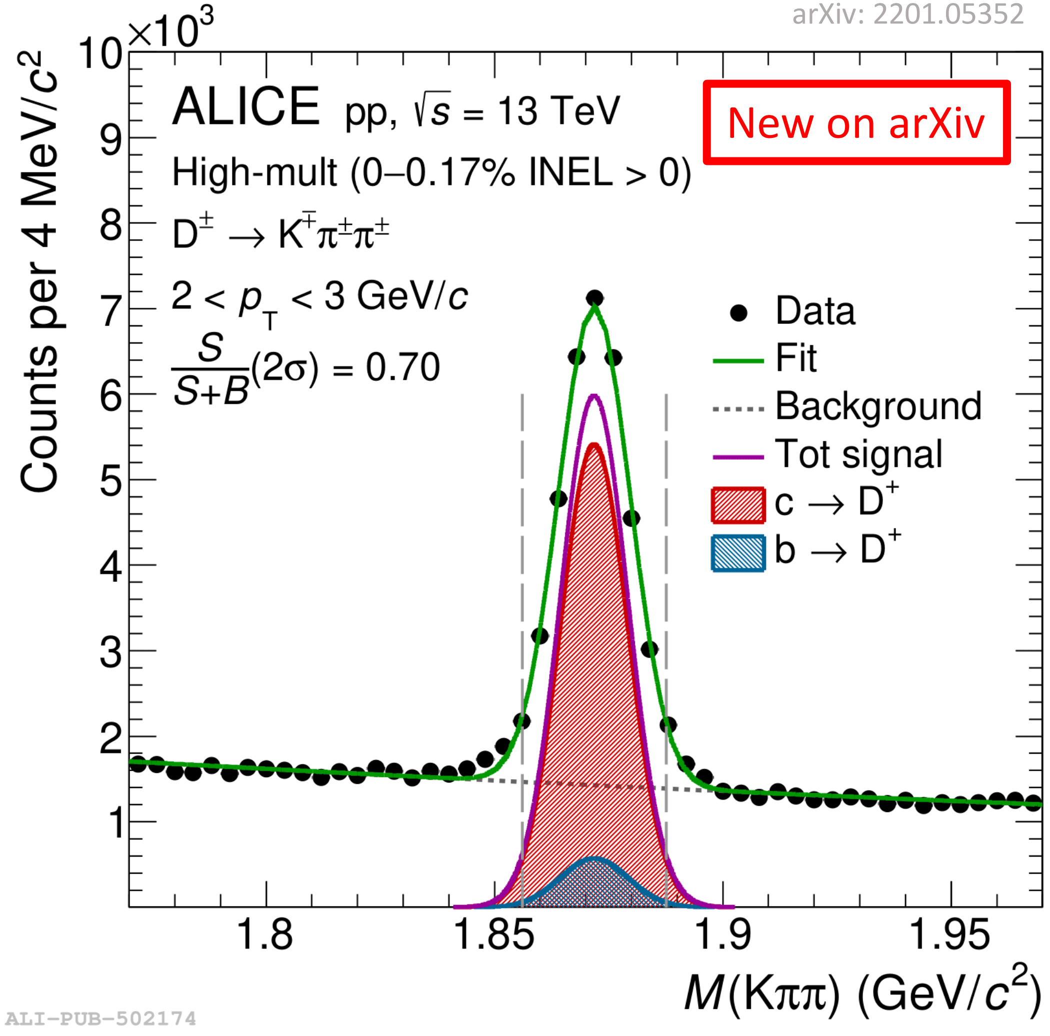
ALICE-PHO-SKE-2017-001

- LHC Run 2 dataset (2016-2018)
- High multiplicity (HM) pp collisions at $\sqrt{s}$ = 13 TeV
- Excellent PID with ALICE Detector
  - Momentum resolution $\sigma(p_T)/p_T < 0.1$
    M. Ivanov *Nuclear Physics* **A** 904–905 (2013) 162c–169c
  - Primary charged particle (p, K, π) purities up to 99%

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

arXiv: 2201.05352



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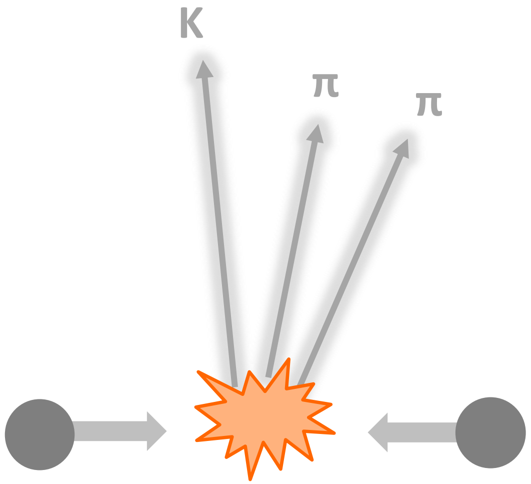

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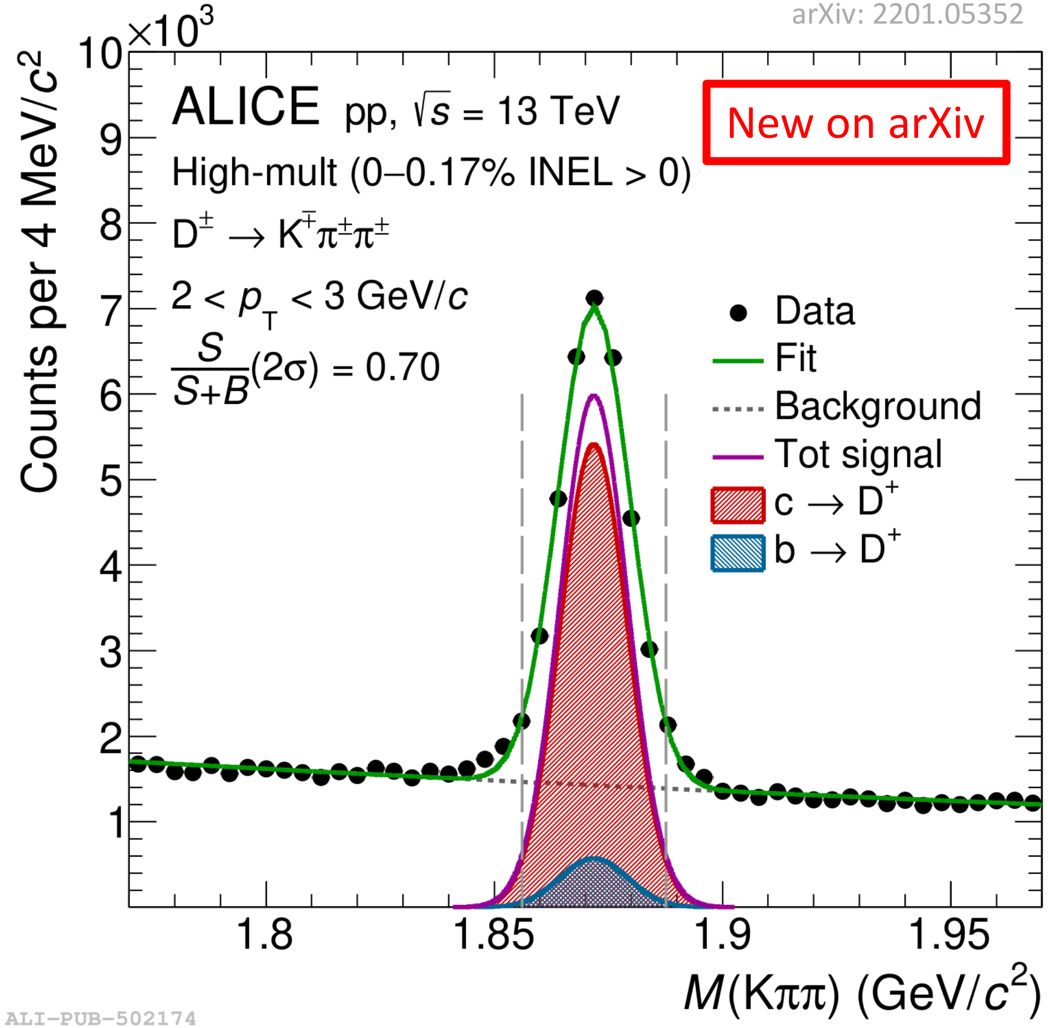

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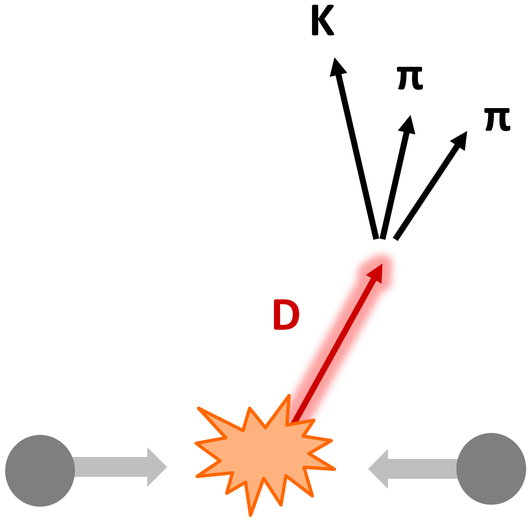

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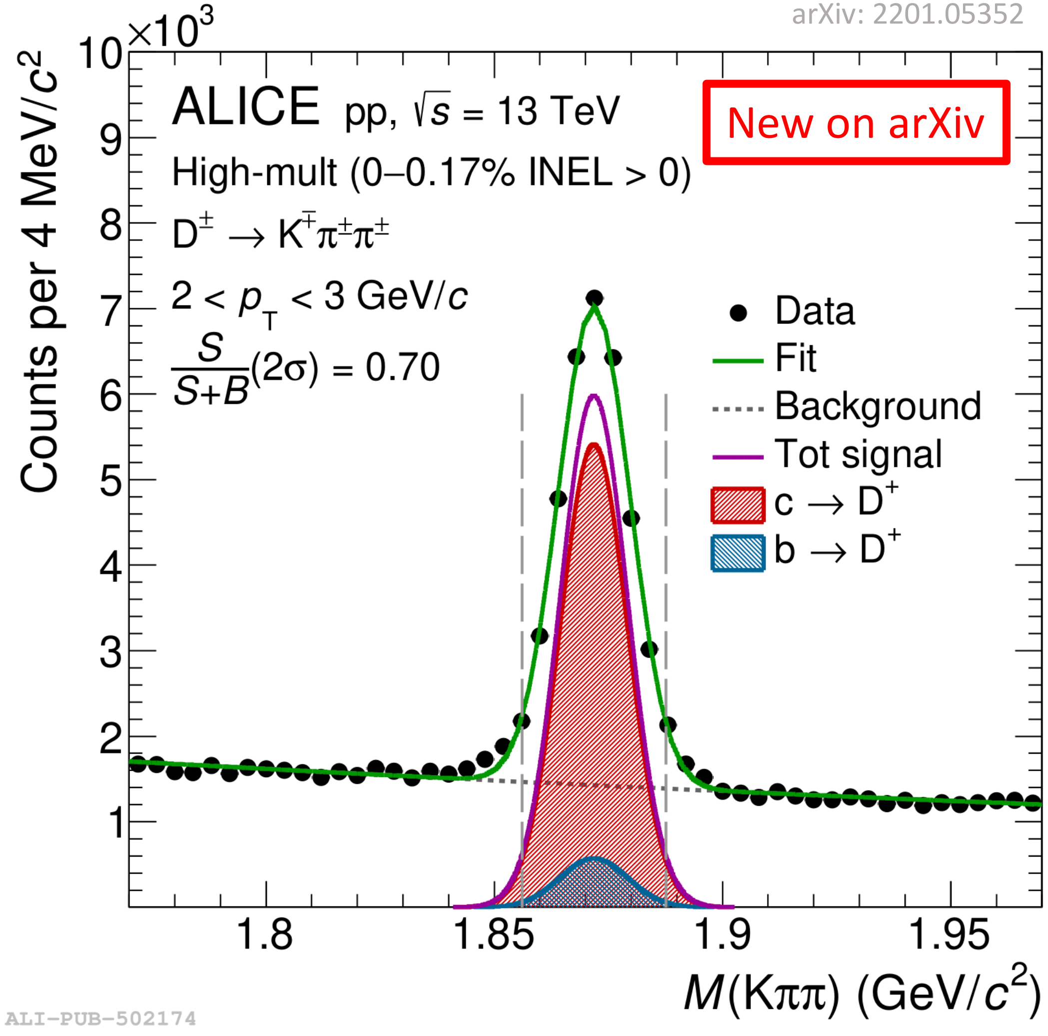

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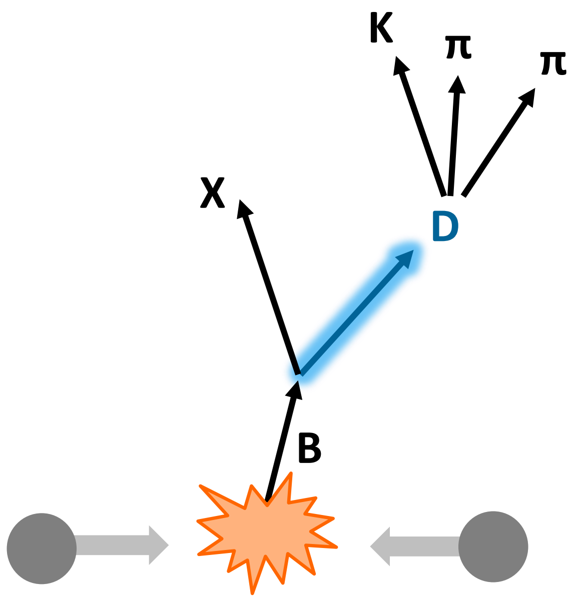

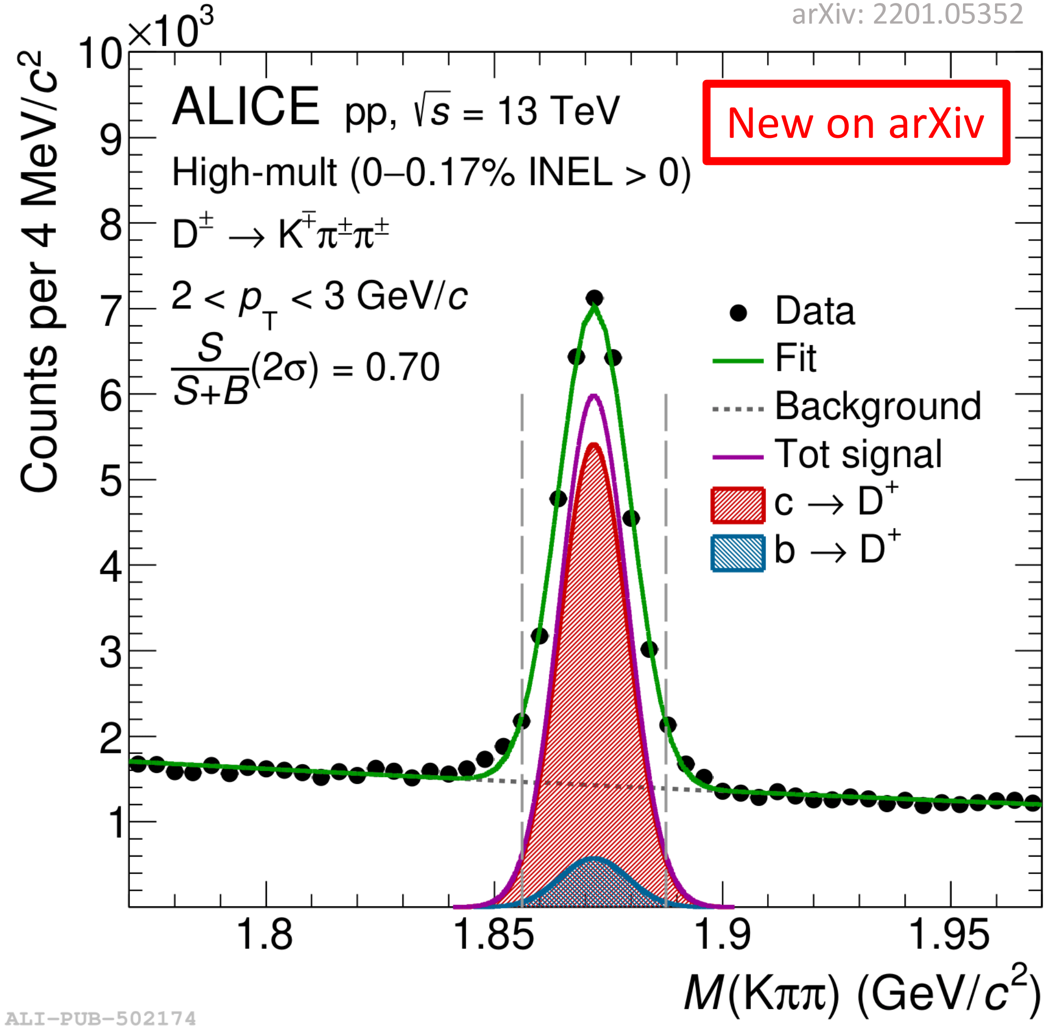

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  - Prompt D → hadronization of the charm quark or strong decay from excited states
  - Non-prompt D (feed-down) → decay products of beauty hadrons
- Purity of D meson candidates ∼70%

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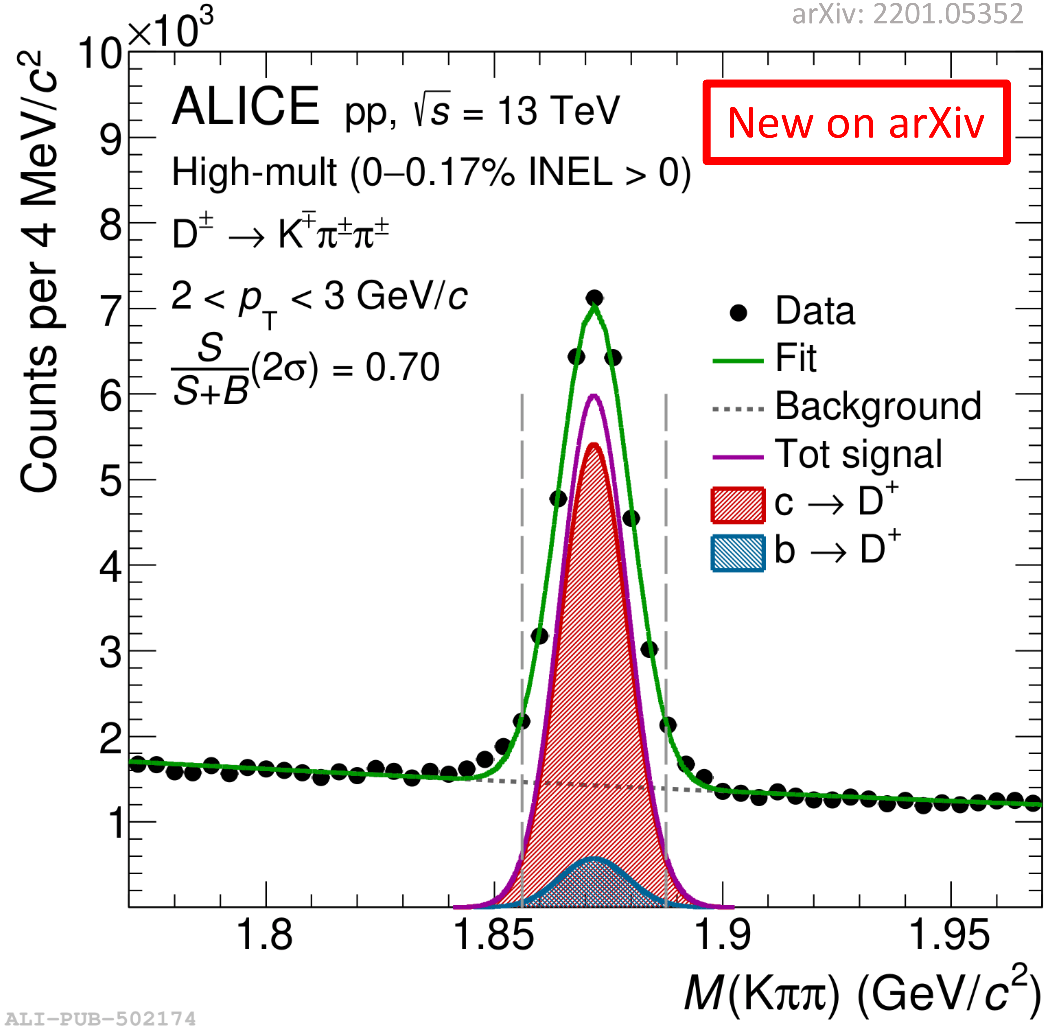
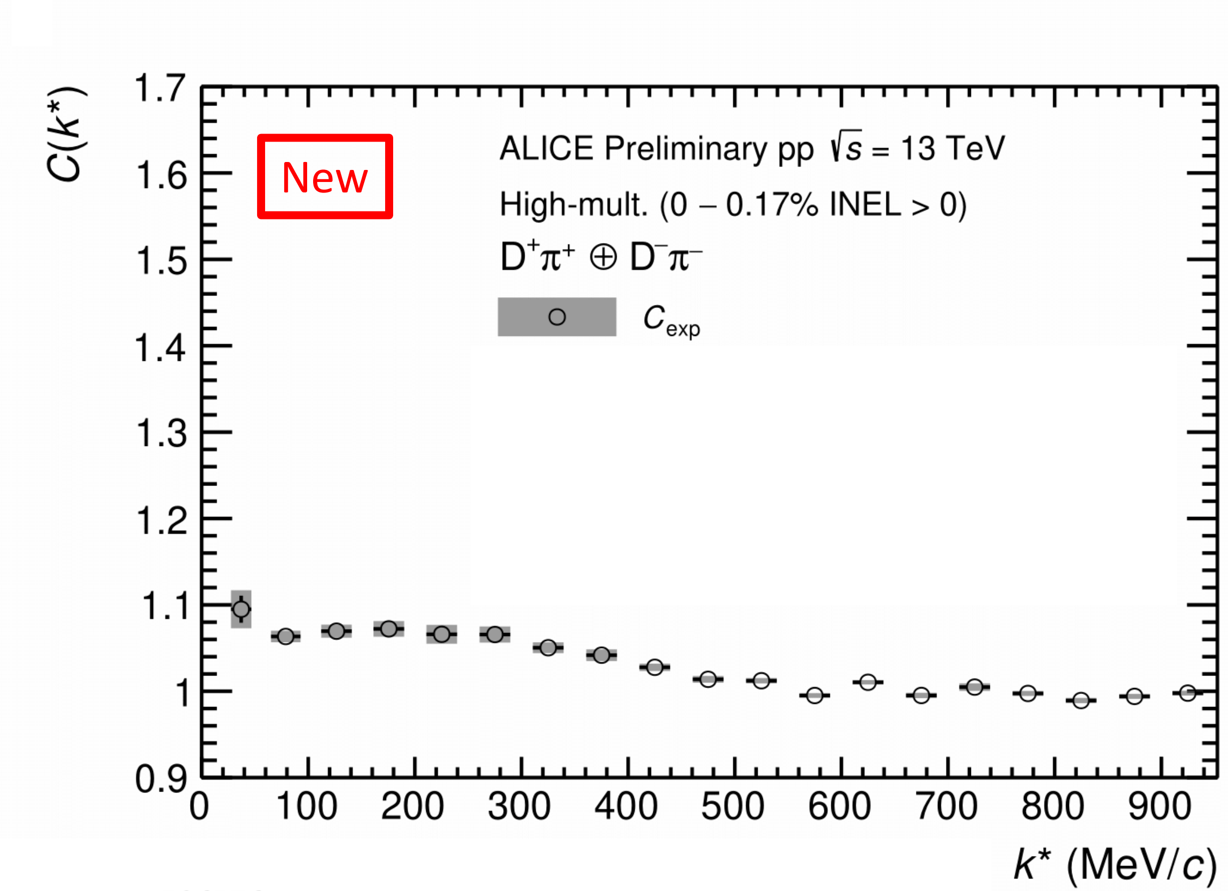


Raw correlation function

Includes additional background contributions besides the one arising from genuine FSI interaction



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Raw correlation function

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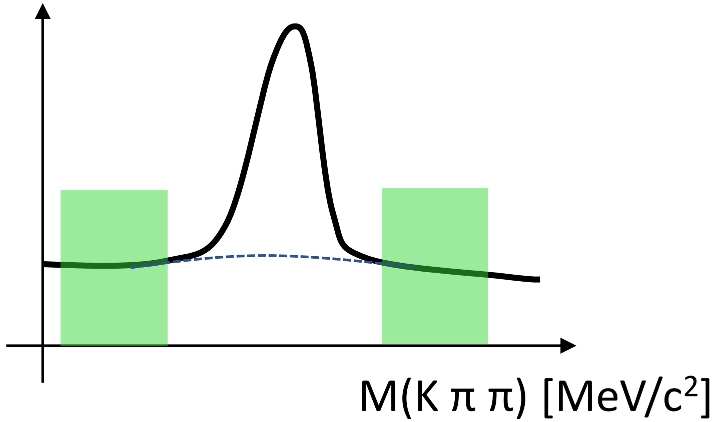
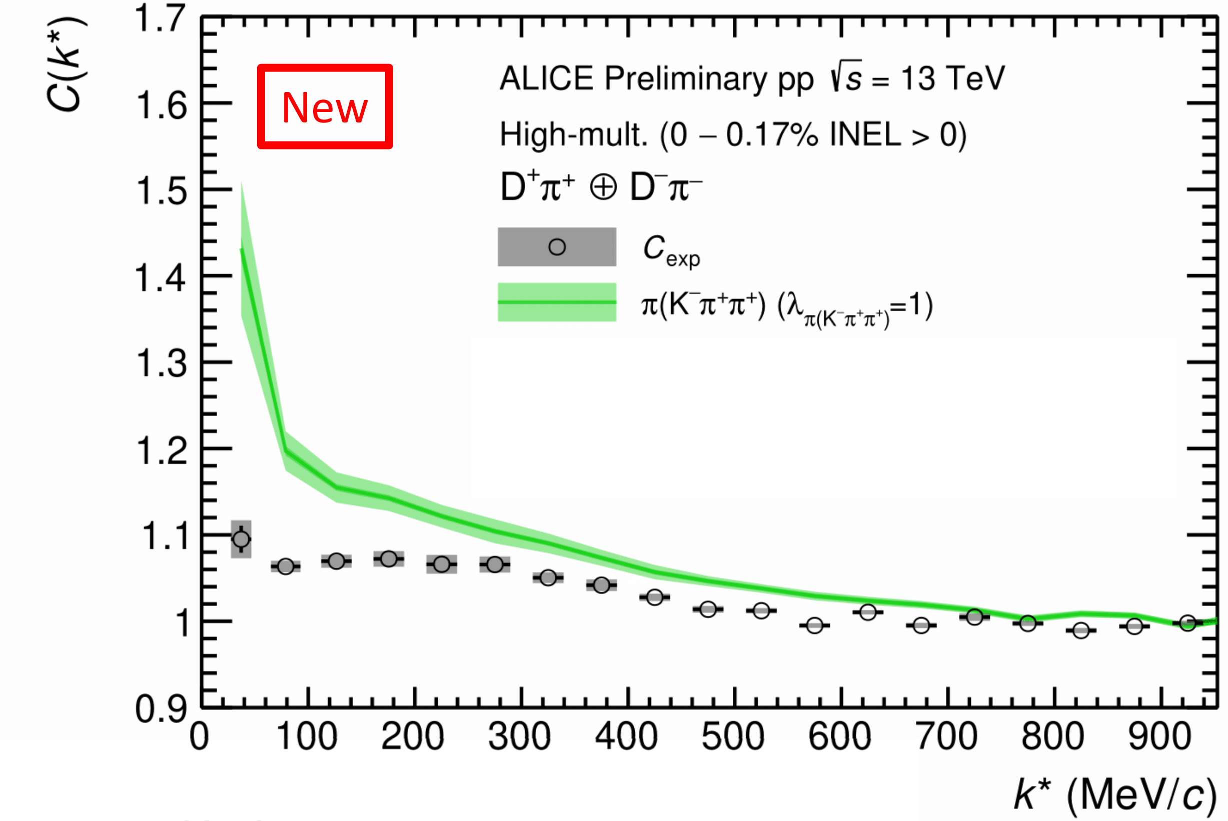
- Combinatorial background
  obtained from sidebands of D meson invariant mass spectrum





ALI-PREL-506576

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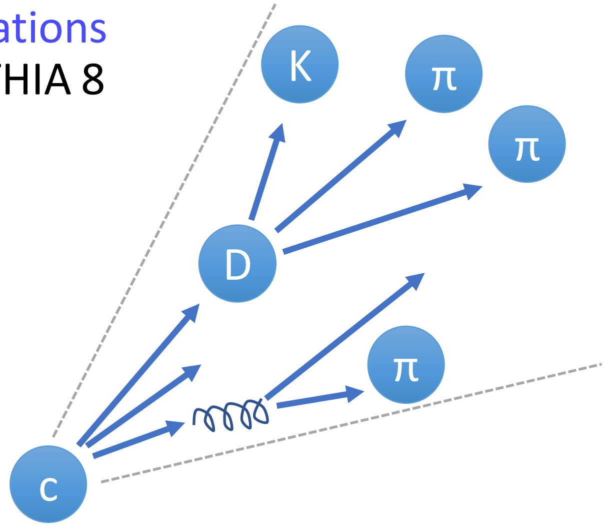
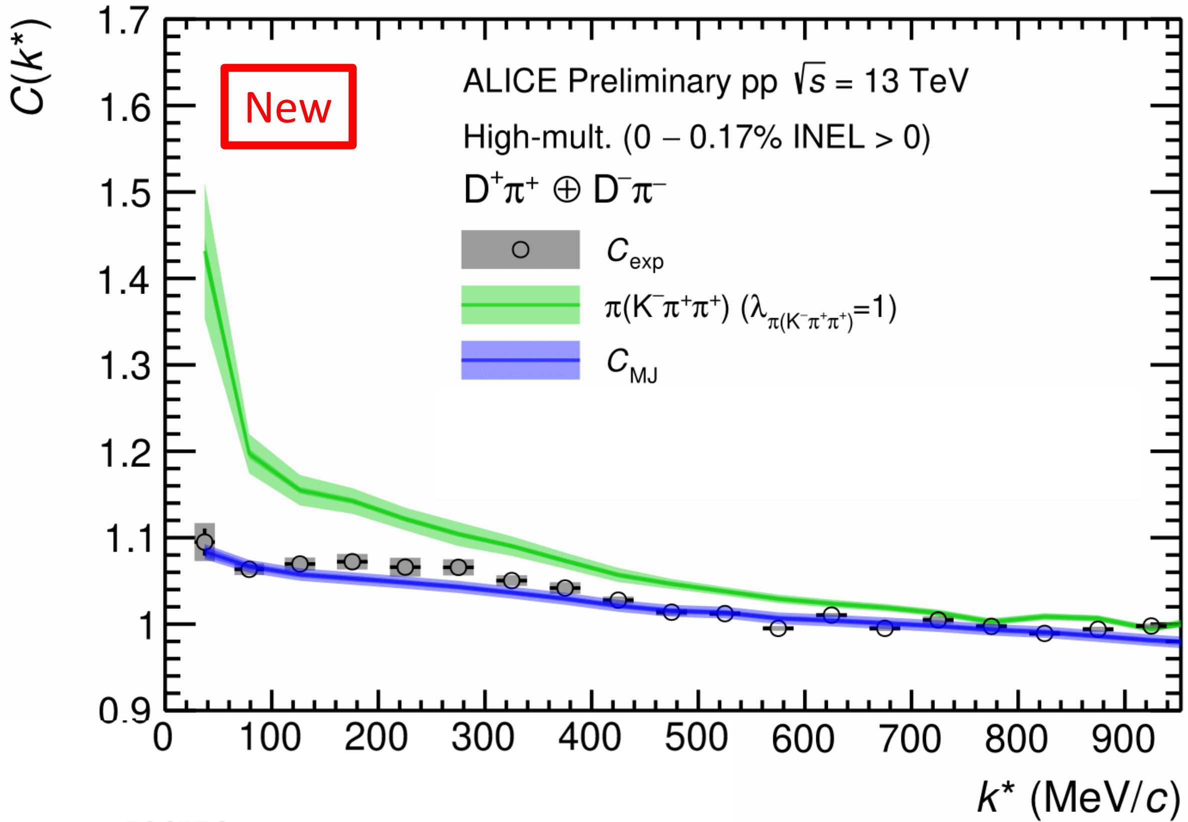
- Jet-like auto-correlations
  estimated with PYTHIA 8





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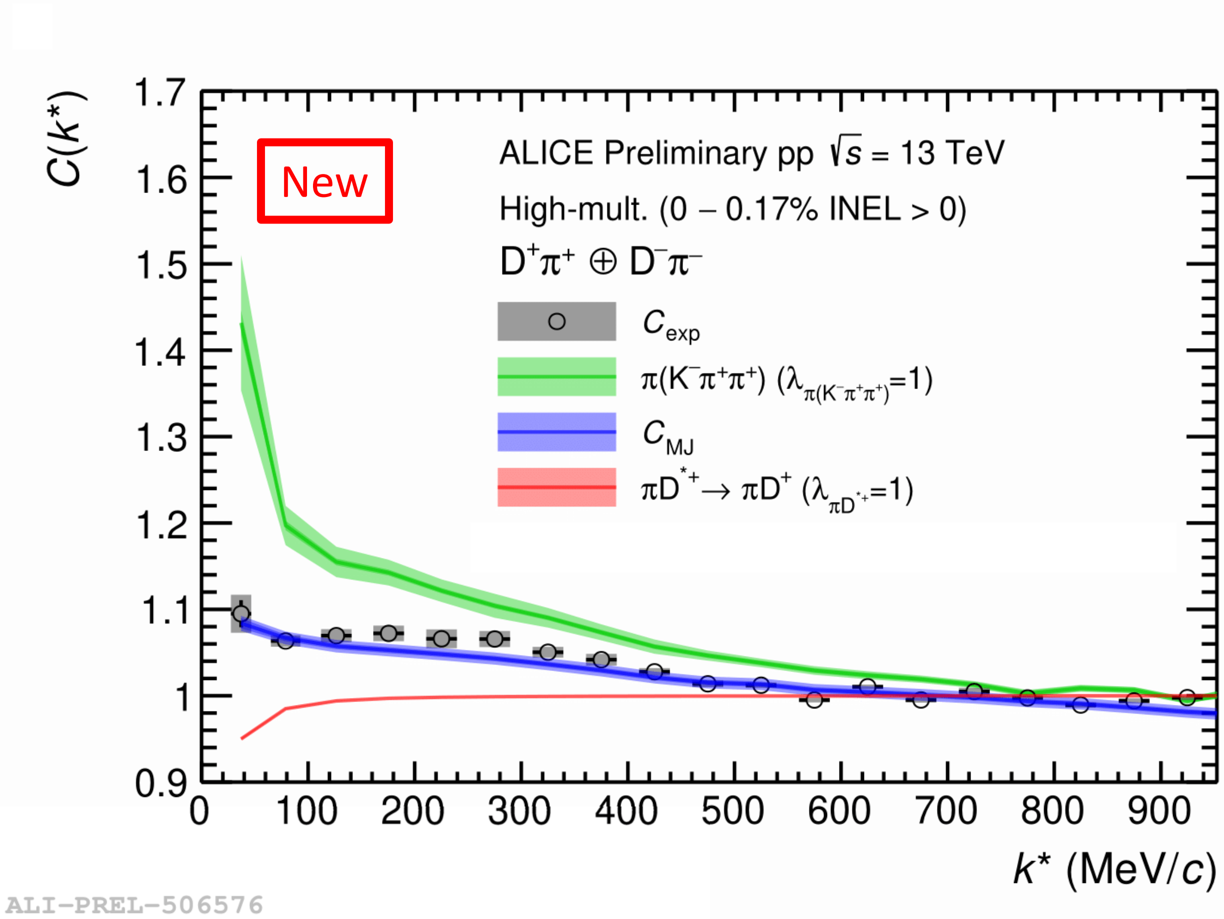

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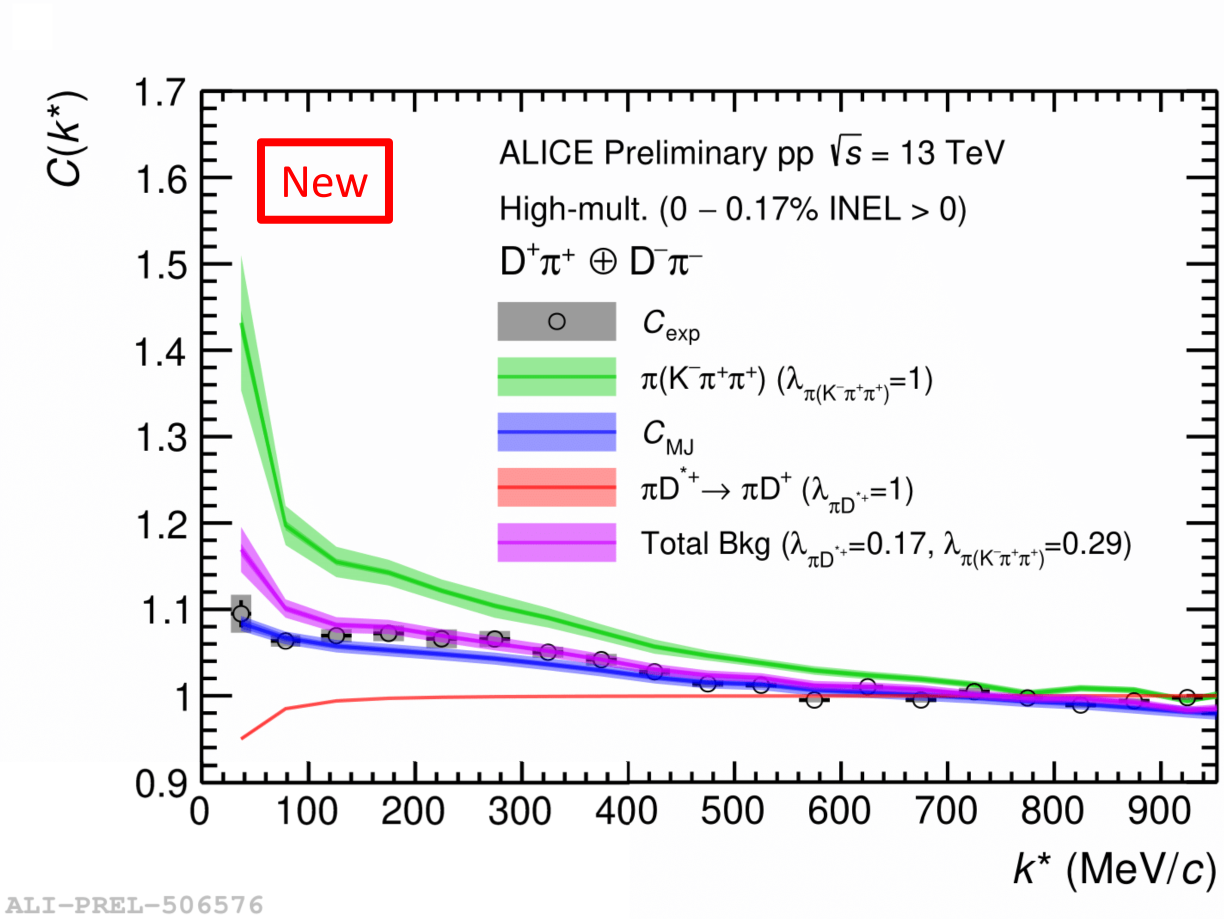
→ Combined to total background used to extract genuine correlation function from data

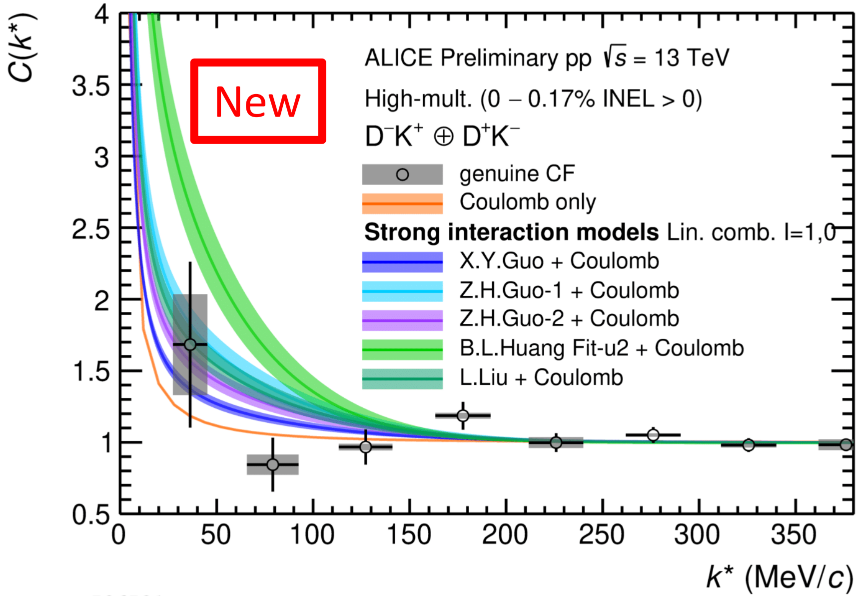


ALI-PREL-506576

Dπ and DK interaction

- Predictions of scattering lengths derived from lattice QCD calculations
    - Very small (~0.1-0.5 fm) compared to other interactions (eg. light-light ~7-8 fm, light-strange ~1 fm)
- Model correlation functions obtained from Gaussian-type potential, tuned to reproduce scattering lengths

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



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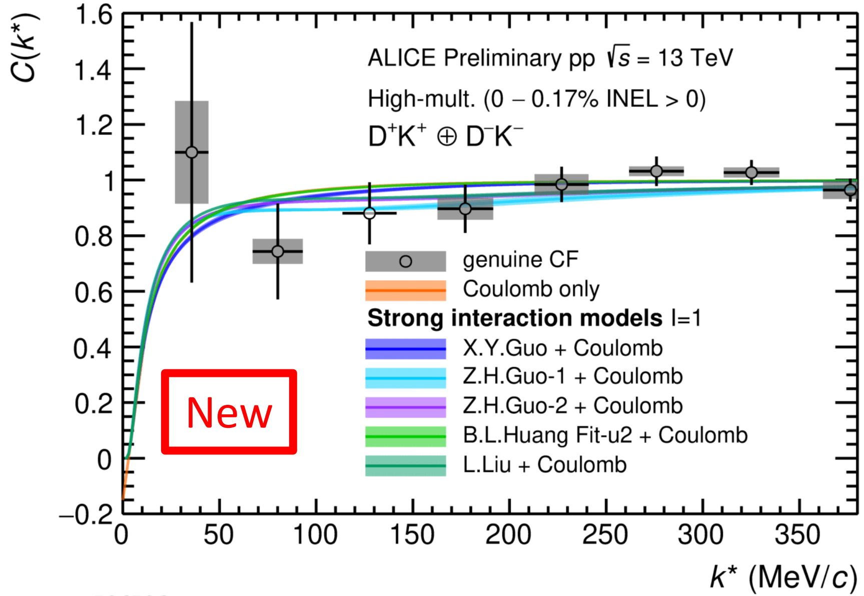

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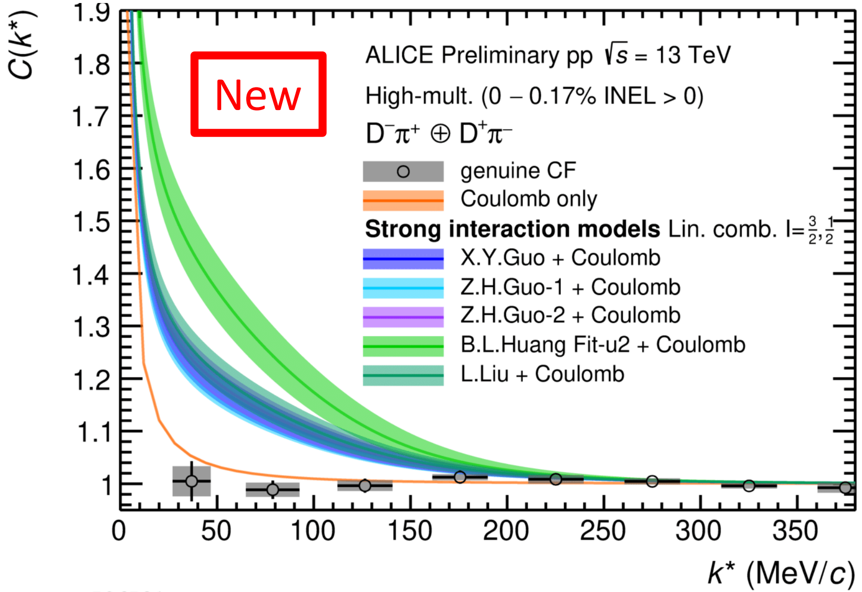

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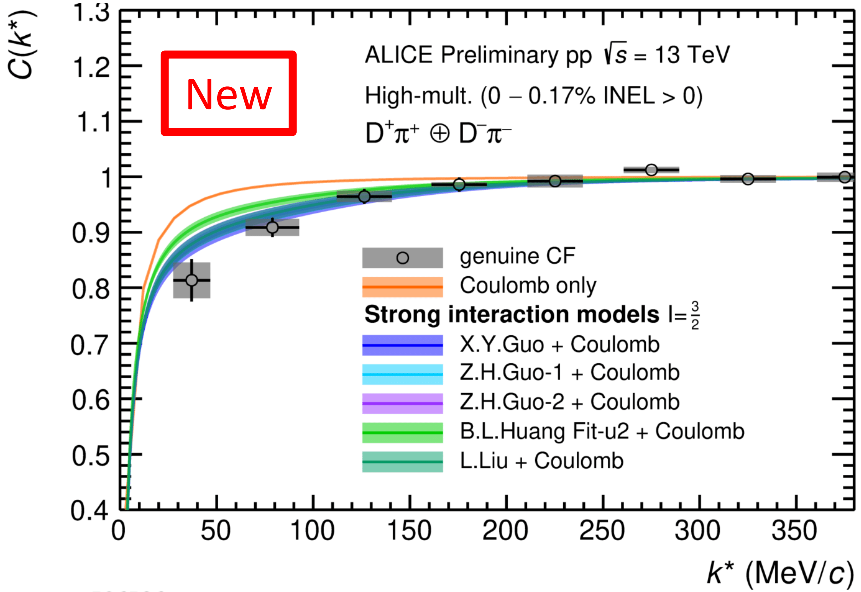

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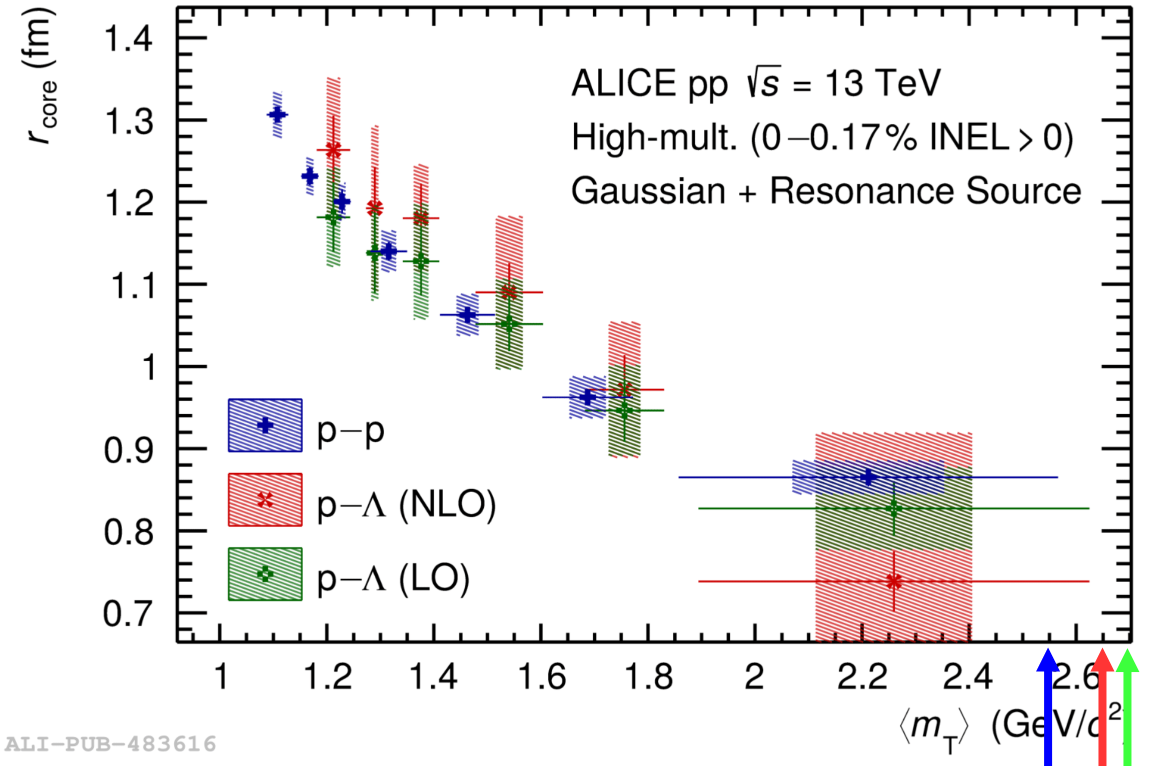
Source

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

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



$<m_{T,\,Dp}> = 2.7$ GeV/c^2

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

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

Source

- Particle emission from Gaussian core source
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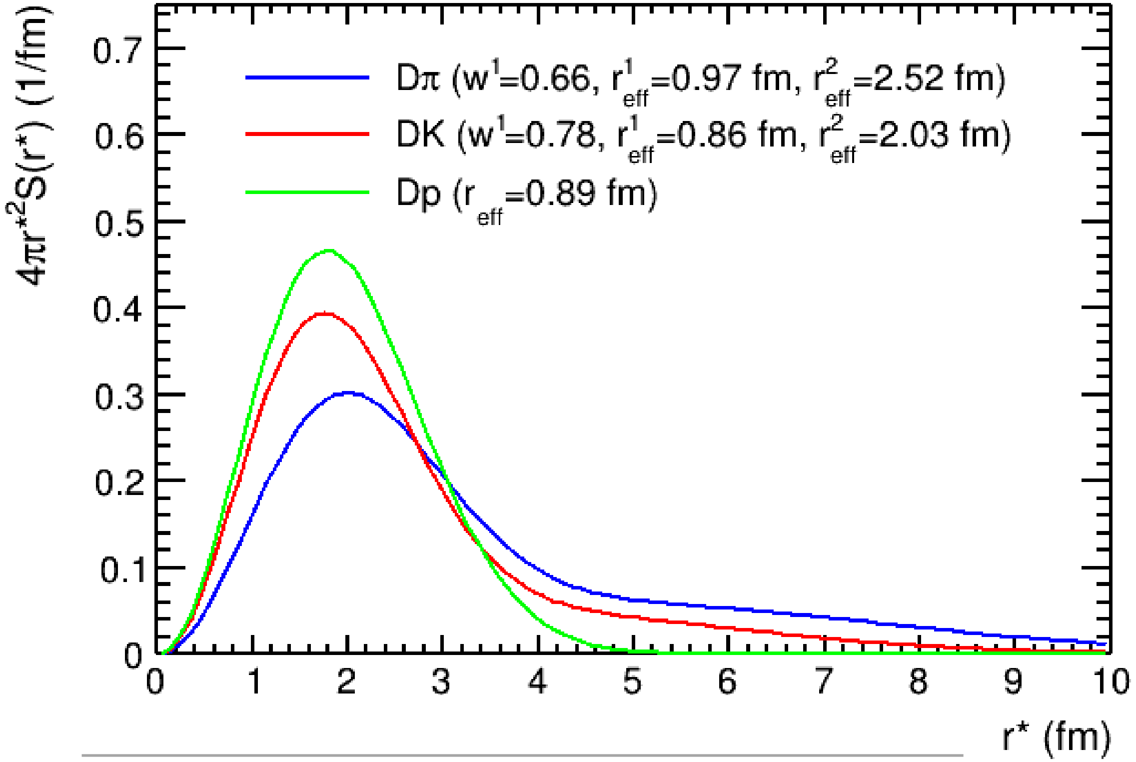
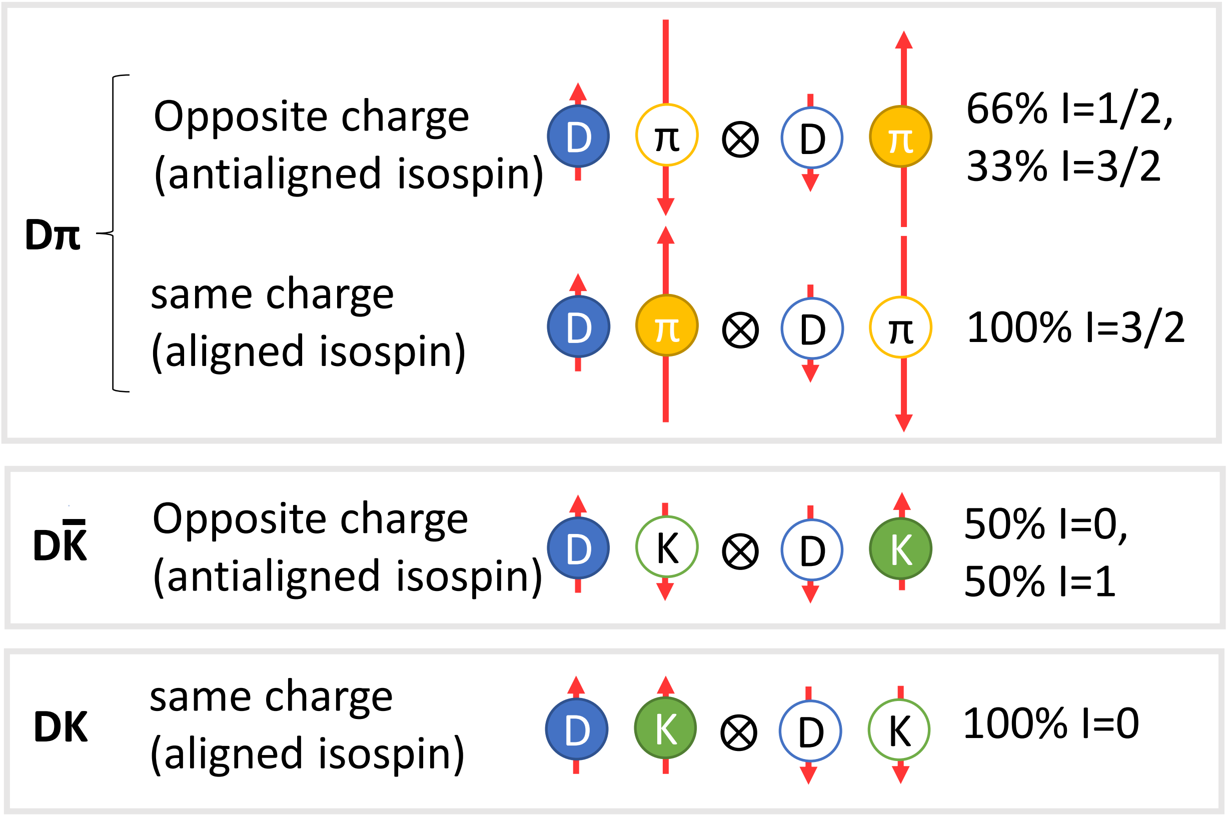
    ALICE Collab., Physics Letters B, 811 (2020) 135849
- Core radius effectively increased by short-lived strongly decaying resonances (cτ ≈ r_{core})
  - Gaussian profile Dp source
    - $r_{eff} = 0.89^{+0.08}_{-0.22}\ fm$
  - DK and Dπ source described by weighted (w^1) sum of two Gaussian sources, to 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

- Depending on charge combination different isospin states contribute to total correlation function



Dπ

Opposite charge
(antialigned isospin)

66% I=1/2,
33% I=3/2

same charge
(aligned isospin)

100% I=3/2

D$\bar{K}$

Opposite charge
(antialigned isospin)

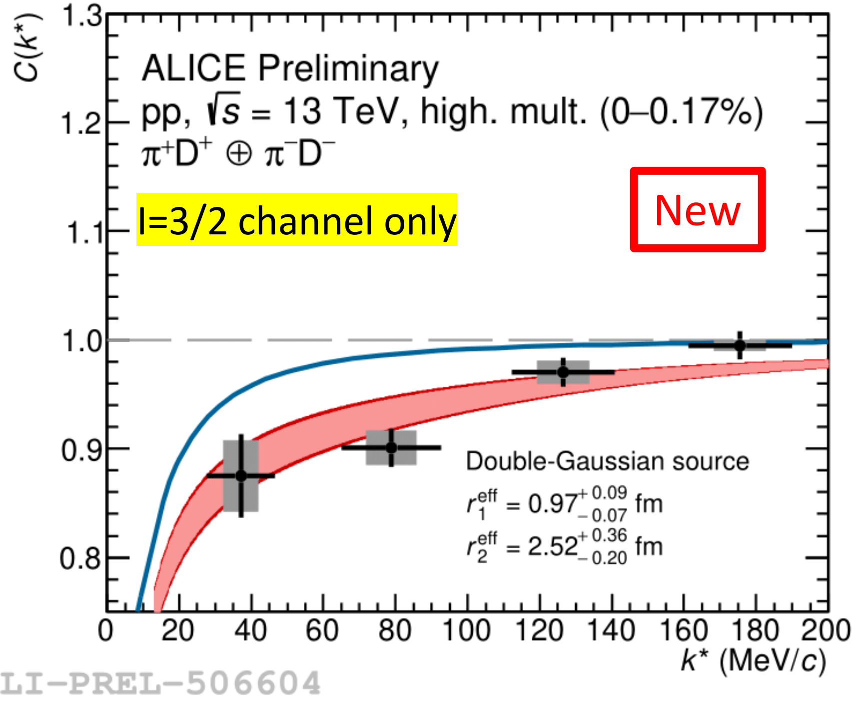
50% I=0,
50% I=1

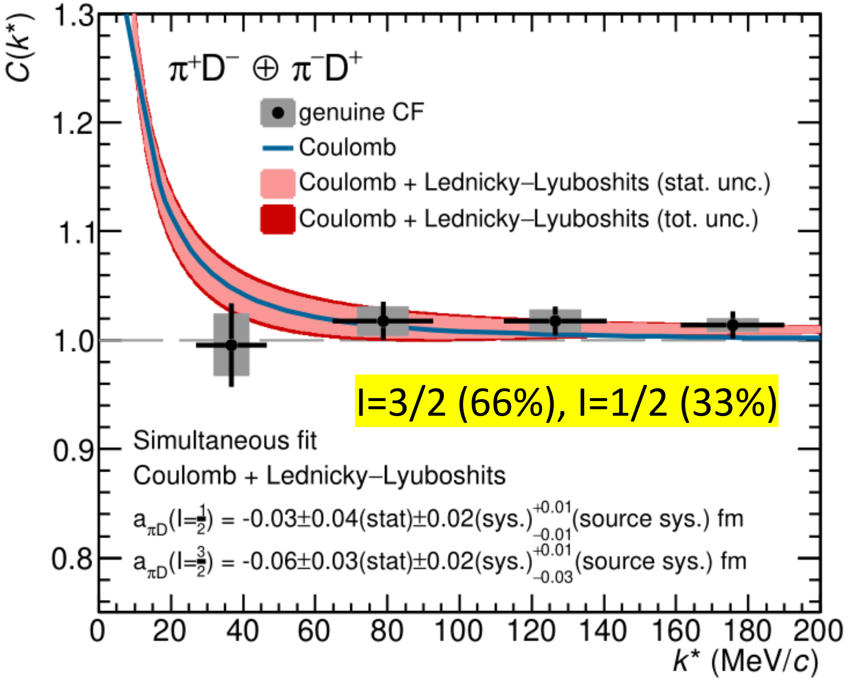
DK

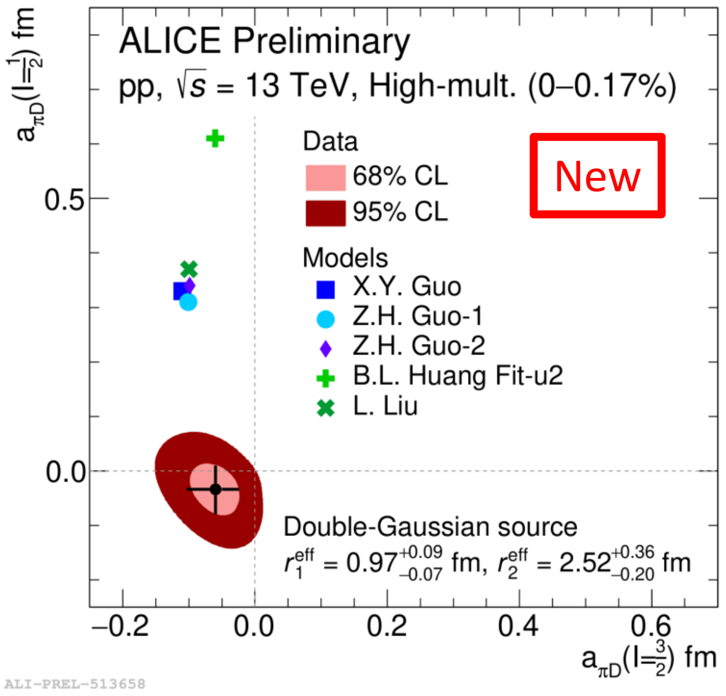
same charge
(aligned isospin)

100% I=0

Dπ correlation function fit







- $D^+\pi^+$ and $D^+\pi^-$ share I=3/2 scattering length → simultaneous fit with Lednický-Lyuboshits formula

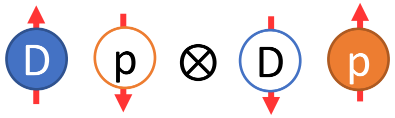
  R. Lednicky and V.L. Lyuboshits, *Sov. J. Nucl. Phys*. **53** (1982) 770

  - Values indicate small rescattering in hadronic phase of HIC
  - Scattering length for I=3/2 in agreement with models, while significantly smaller for I=1/2

Dp interaction

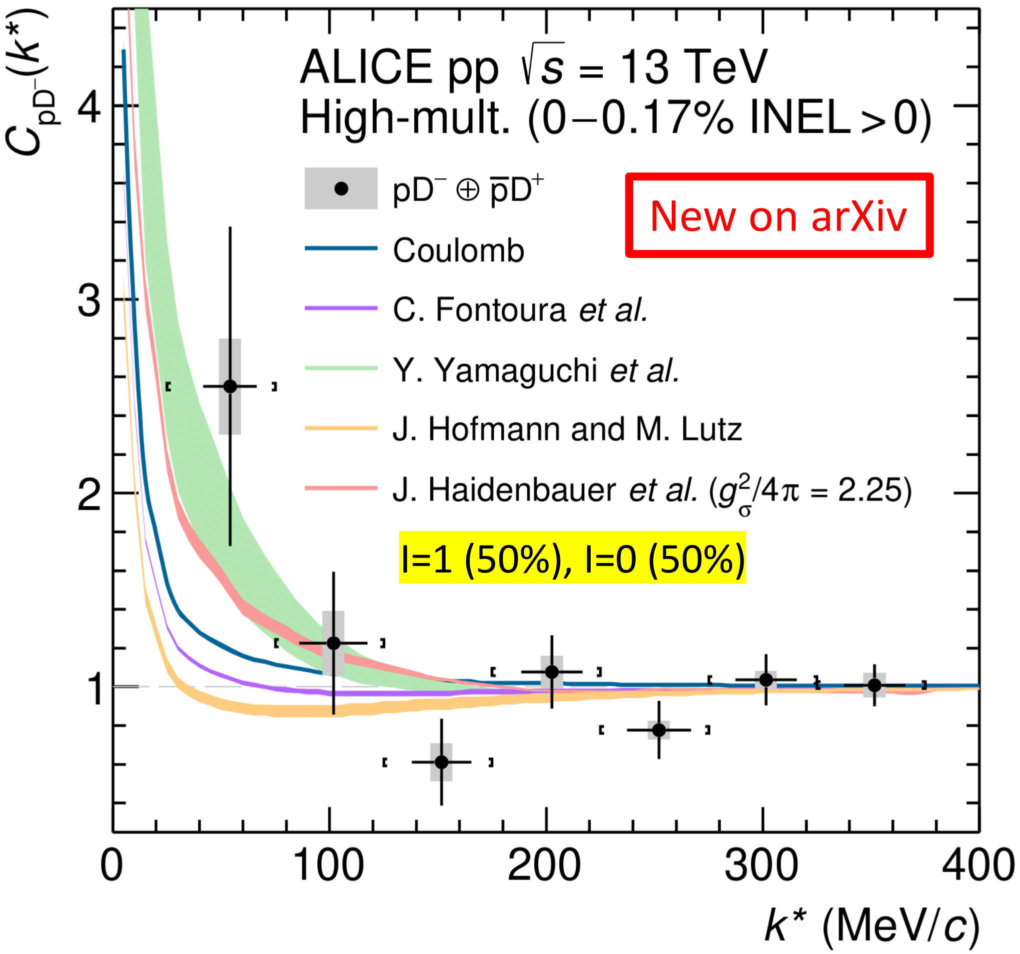
- Model CF obtained from Gaussian-type of potential tuned to reproduce the scattering parameters predicted by theory
  - Scattering lengths very small in comparison to interactions involving light hadrons
  - Most models predict repulsive interaction
  - Possible formation of bound state (Y. Yamaguchi et al.)
- Data compatible with Coulomb interaction

Opposite charge (antialigned isospin)



50% I=0, 50% I=1

arXiv: 2201.05352



New on arXiv

I=1 (50%), I=0 (50%)

ALI-PUB-502166

J. Haidenbauer et al, Eur. Phys. J. A33 (2007) 107—117

J. Hofmann and M. Lutz, Nucl. Phys. A 763 (2005) 90—139

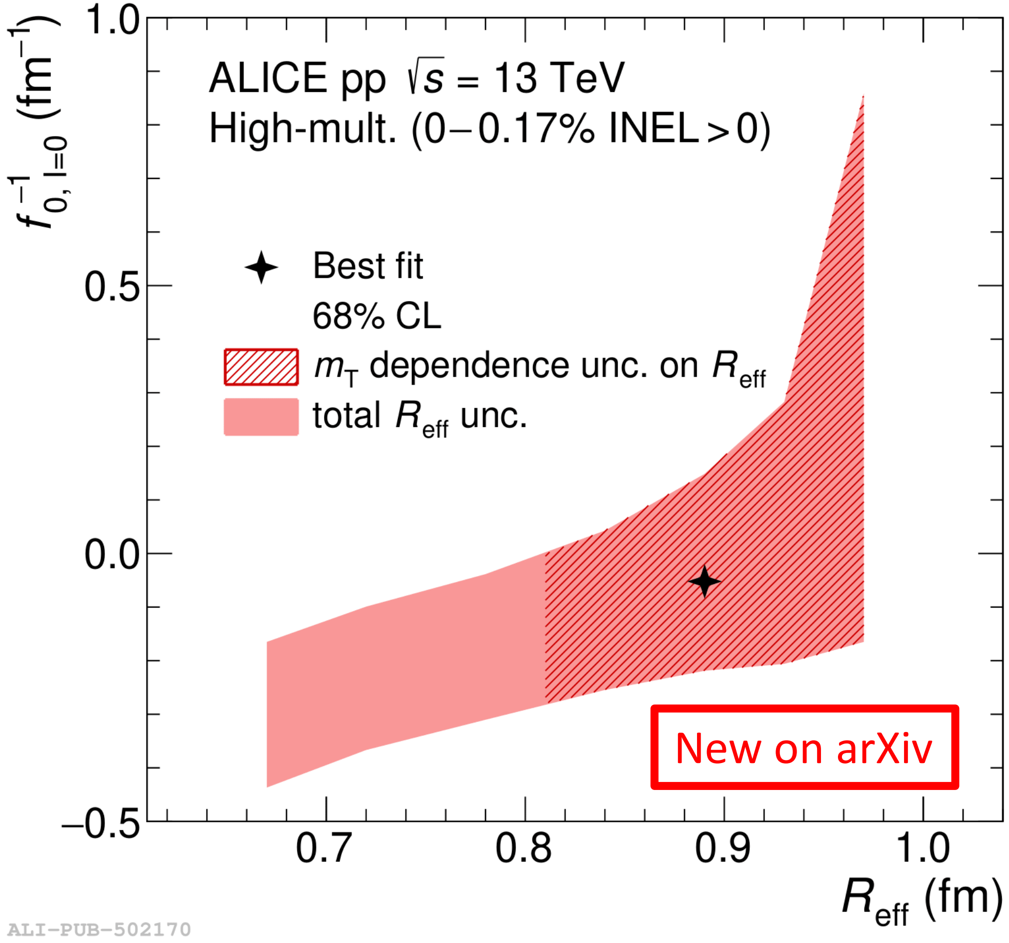
Fontura et al, Phys. Rev. C 87 (2013) 025206

Yamaguchi et al, Phys. Rev. D84 (2011) 014032

Dp interaction

- Confidence interval of scattering length of I=0 channel evaluated by varying the Gaussian potential strength and effective source radius
    - I=1 contribution assumed to be negligible

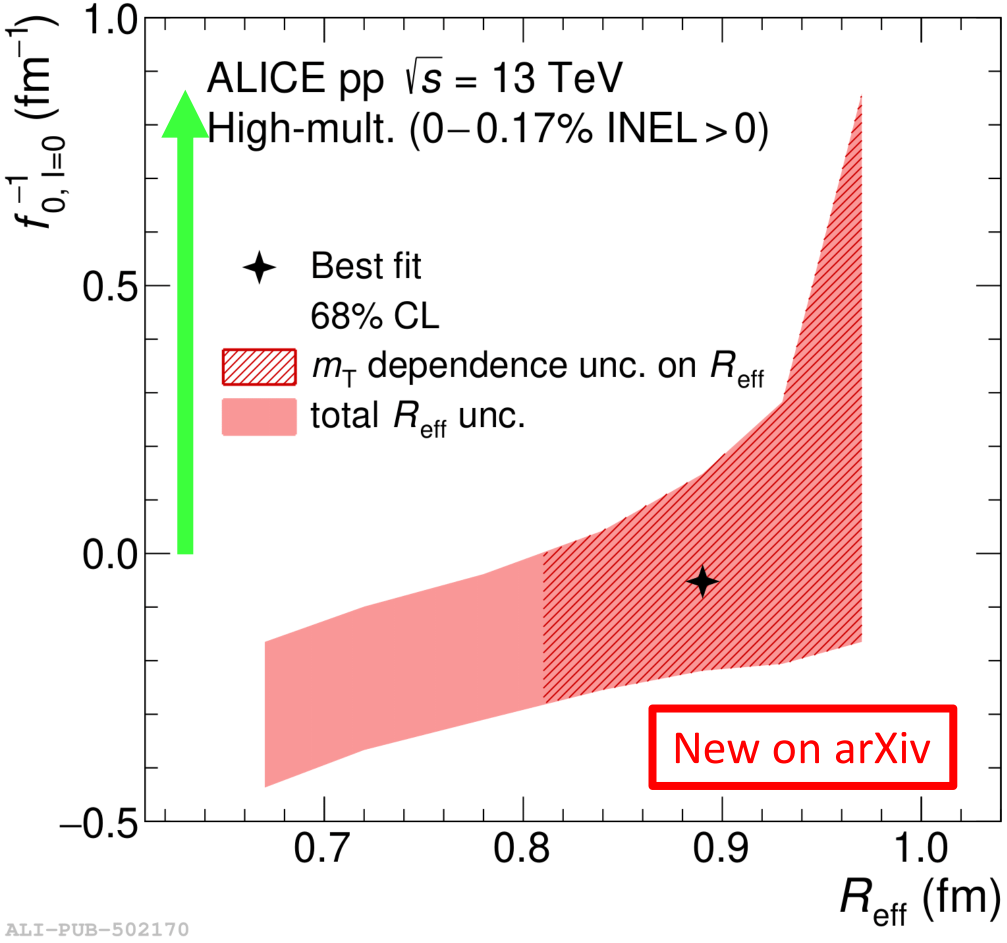
arXiv: 2201.05352



Dp interaction

- Confidence interval of scattering length of I=0 channel evaluated by varying the Gaussian potential strength and effective source radius
    - I=1 contribution assumed to be negligible
- Interaction is either shallow attractive or strongly attractive with formation of bound state

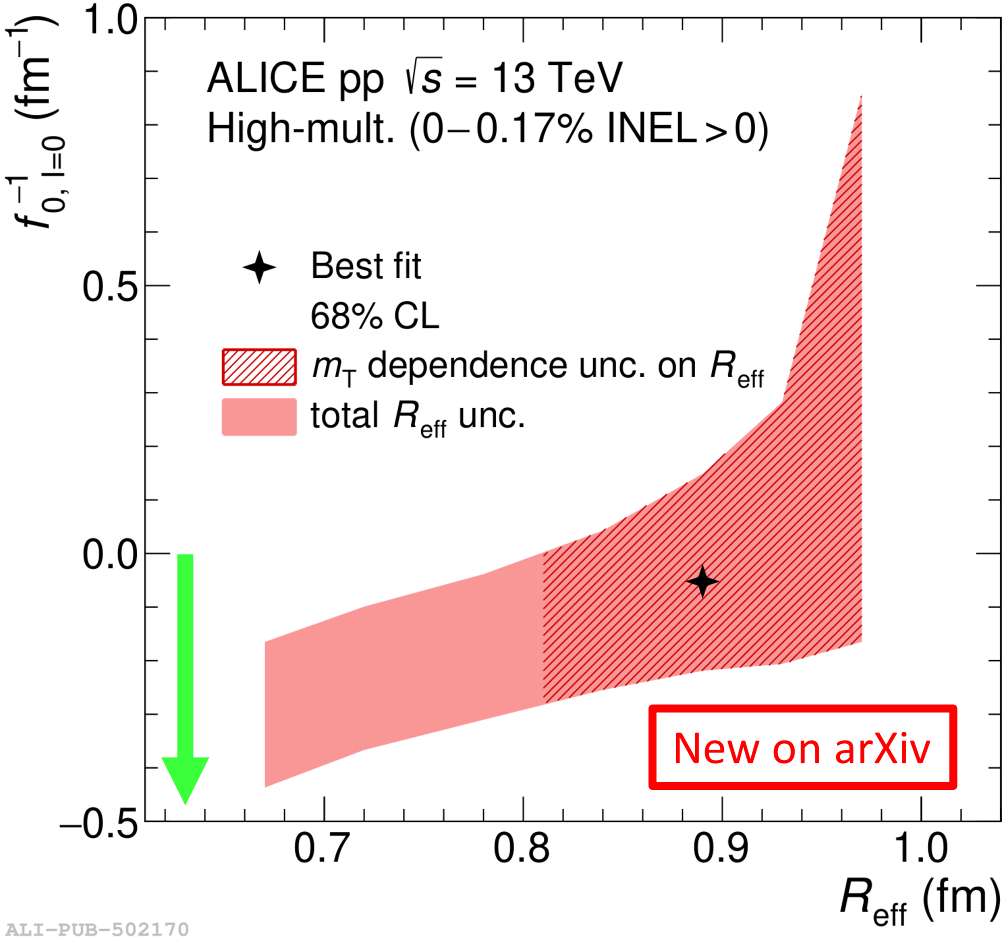
arXiv: 2201.05352



Dp interaction

- Confidence interval of scattering length of I=0 channel evaluated by varying the Gaussian potential strength and effective source radius
  - I=1 contribution assumed to be negligible
- Interaction is either shallow attractive or strongly attractive with formation of bound state

arXiv: 2201.05352



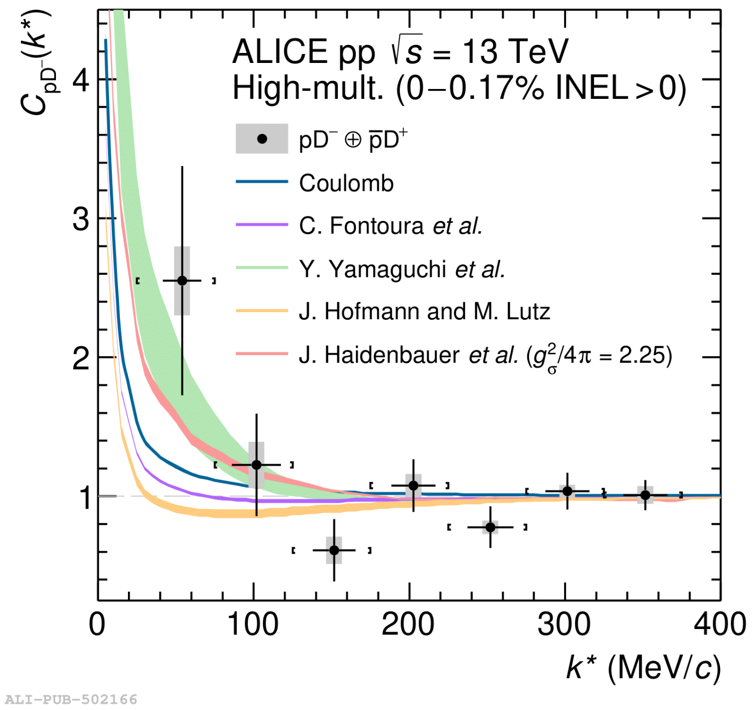
New on arXiv

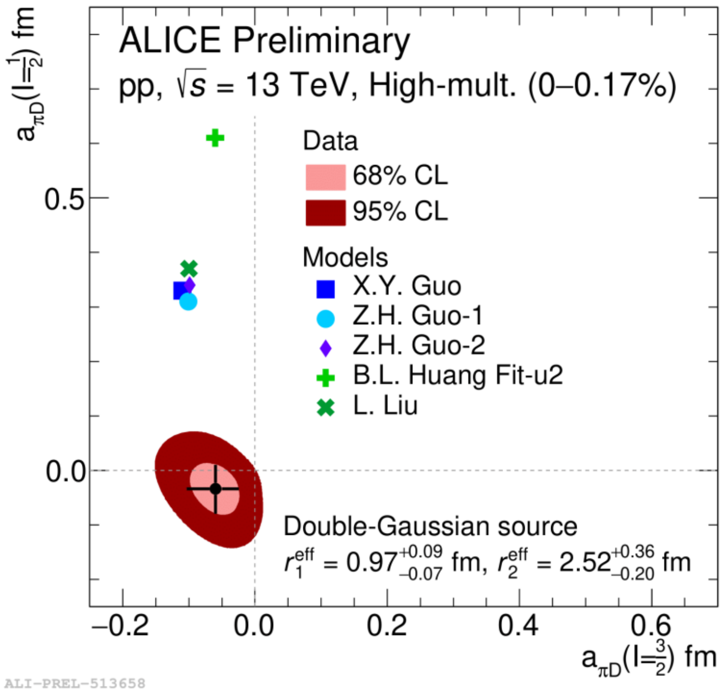
ALI-PUB-502170

Conclusion

- First experimental measurement of the interaction between D mesons and light-flavor hadrons
- Interactions found to be shallow in comparison to the ones including only light hadrons
- Possible formation of a ND bound state not excluded by data
- Significant improvement of statistics foreseen with LHC Run 3 data

arXiv: 2201.05352





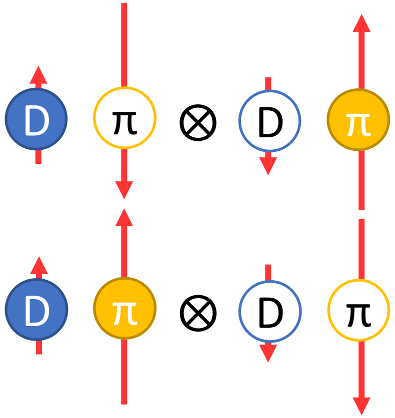
Additional material

Dπ and DK scattering length

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

①

Opposite charge
(antialigned isospin)

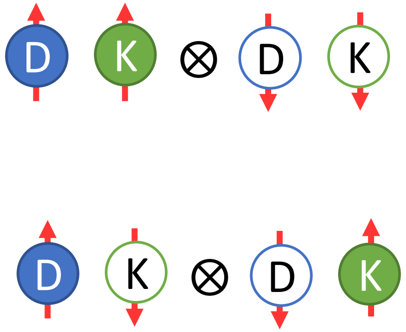


66% I=1/2,
33% I=3/2

same charge
(aligned isospin)

100% I=3/2

② same charge
(aligned isospin)



100% I=0

③ Opposite charge
(antialigned isospin)

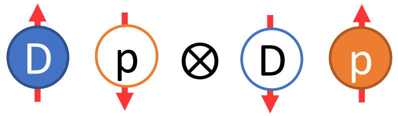
50% I=0,
50% I=1

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

Dp scattering length

Model	I=0 [fm]	I=1 [fm]
J. Haidenbauer $g_\sigma^2/4\pi = 1$ meson-exchange	0.14	-0.28
J. Haidenbauer $g_\sigma^2/4\pi = 2.25$ meson-exchange	0.67	0.04
J. Hofmann and M. Lutz SU(4) Contact interaction	-0.16	-0.26
Fontura Chiral-quark model	0.16	-0.25
Yamaguchi Meson-exchange on HQ symmetry	-4.38	-0.07

Opposite charge
(antialigned isospin)



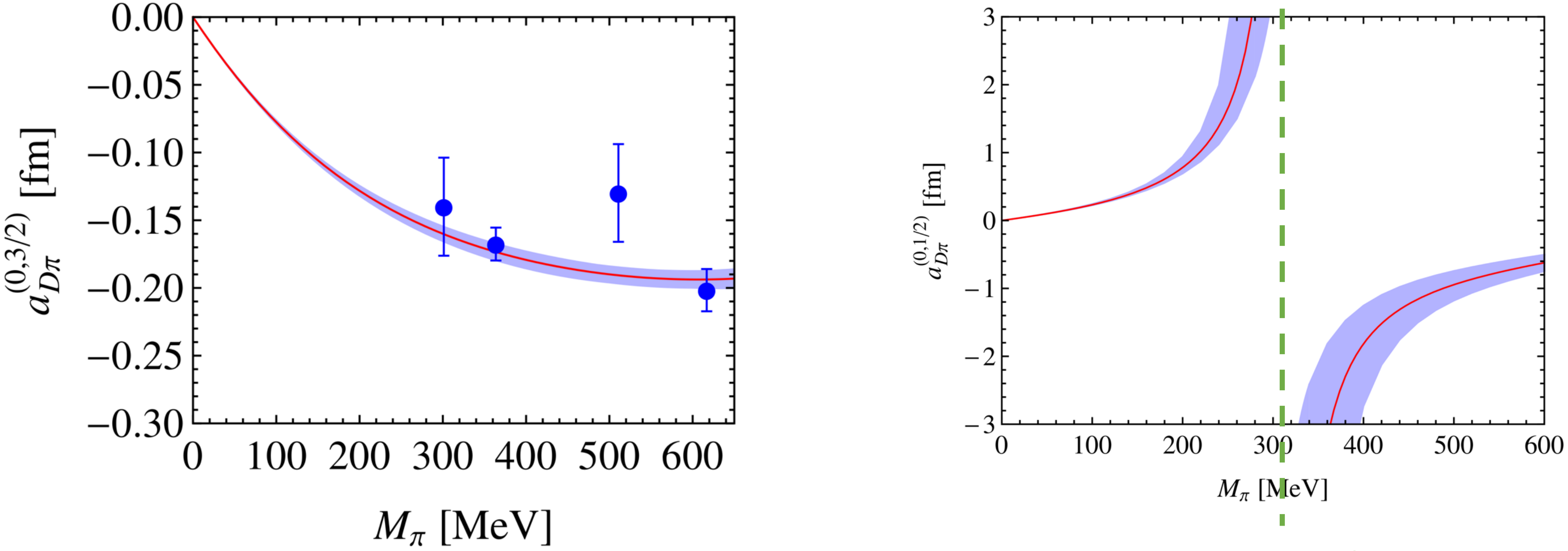
50% I=0,
50% I=1

J. Haidenbauer et al, Eur. Phys. J. A33 (2007) 107—117
J. Hofmann and M. Lutz, Nucl. Phys. A 763 (2005) 90—139
Fontura et al, Phys. Rev. C 87 (2013) 025206
Yamaguchi et al, Phys. Rev. D84 (2011) 014032

Dπ and DK interaction

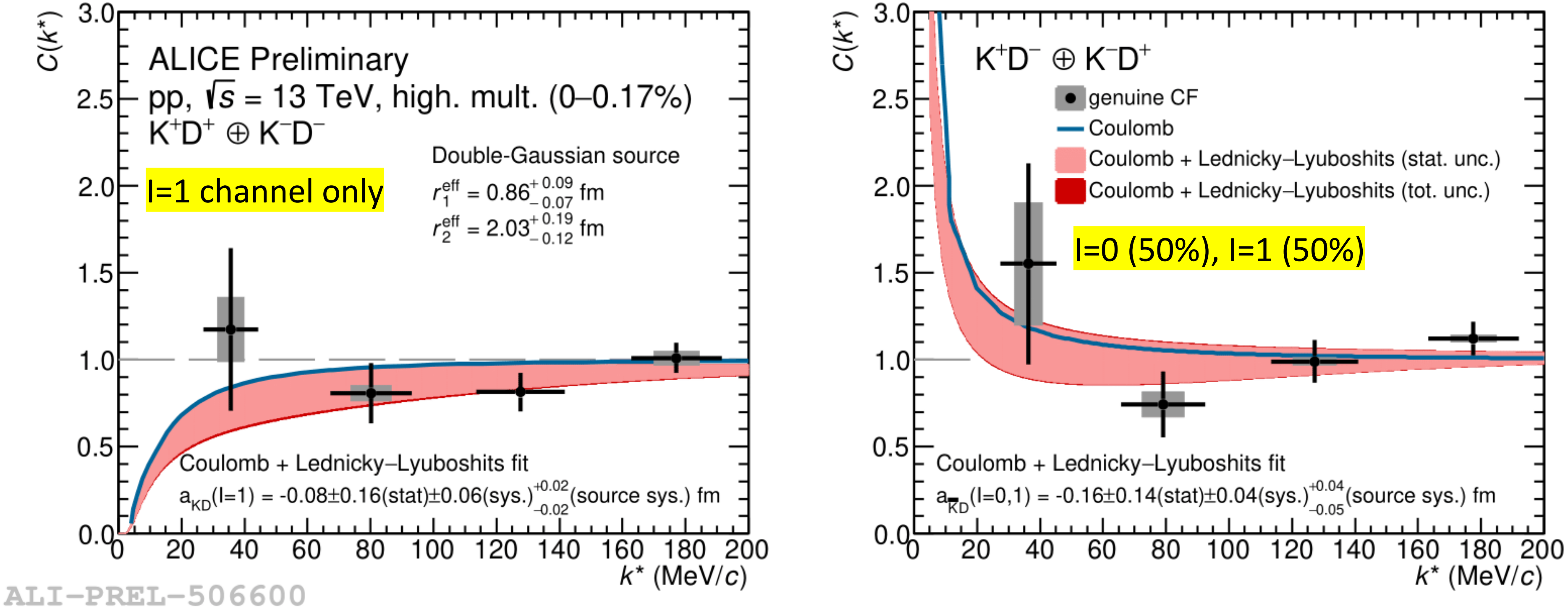
- Lattice data only available for Dπ(I=3/2) and D^+K^- (I=0,1)
  - Scattering parameters at physical quark masses obtained from chiral extrapolation
- Dπ(I=1/2) and D^+K^+ (I=0,1) rely on predictions from fitting the available lattice data

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



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

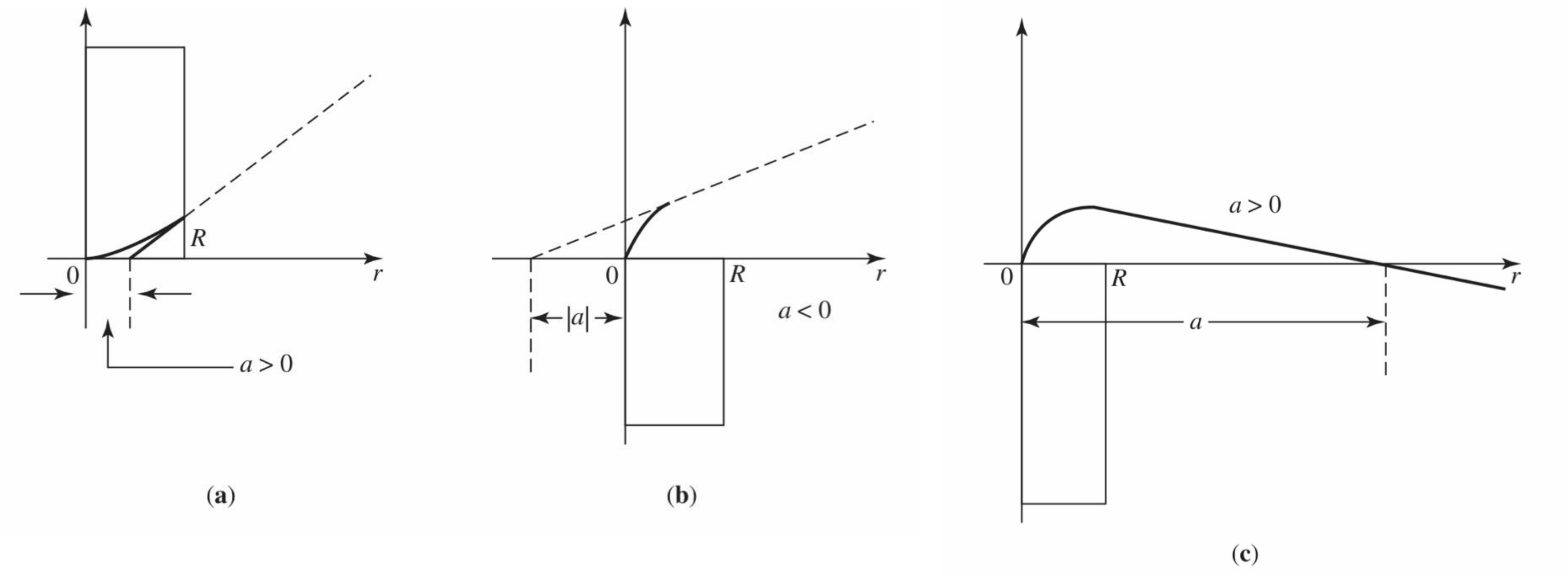
DK correlation function fit



- D⁺K⁺ and D⁺K⁻ fited individually with Lednický-Lyuboshits formula

R. Lednickyand V.L. Lyuboshits,*Sov. J. Nucl. Phys*. **53** (1982) 770

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].

Lednický-Lyuboshits model

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

Analytical approach to model CF for strong final state interaction within effective range expansion

R. Lednicky and V.L. Lyuboshits, *Sov. J. Nucl. Phys.* **53** (1982) 770

- isotropic source of Gaussian profile $S(r^*)$
- scattering amplitude: $f(k^*) = \left(\frac{1}{a_0} + \frac{1}{2} d_0 k^{*2} - ik^*\right)^{-1}$
  - Effective range d_0 and scattering length a_0
- spin averaged scattering parameters