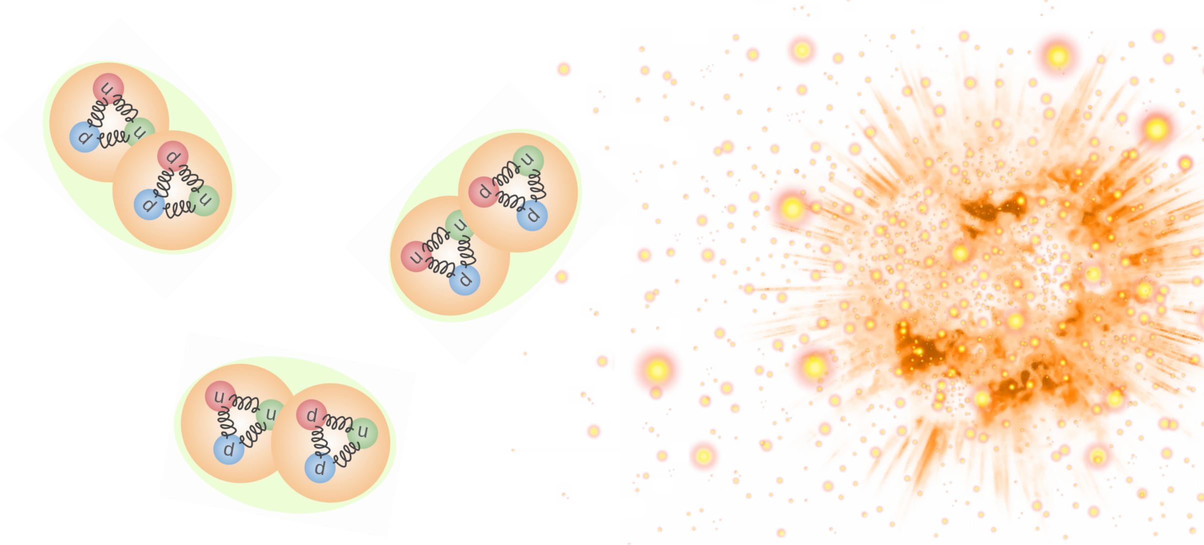
Non-identical particle femtoscopy of pairs containing (anti)deuteron in relativistic heavy-ion collisions with ALICE at the LHC

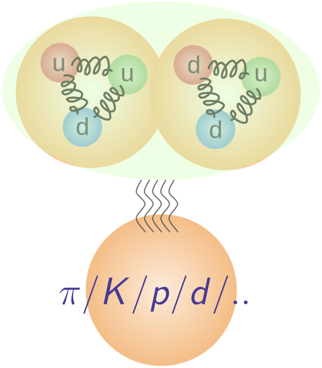
Wioleta Rzęsa (Warsaw University of Technology)
on behalf of the ALICE Collaboration

Why to study deuterons?



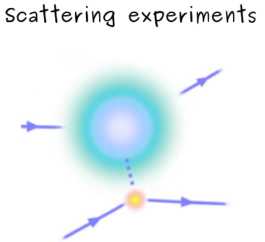
Why to study deuterons? – interactions

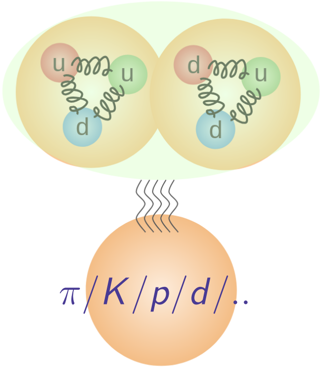
Kaon-deuteron: to determine $K^{\pm}d$ scattering parameters and obtain the full isospin dependence of the interaction, – a fundamental problem in the strangeness sector in the low-energy regime of QCD.



Why to study deuterons? – interactions

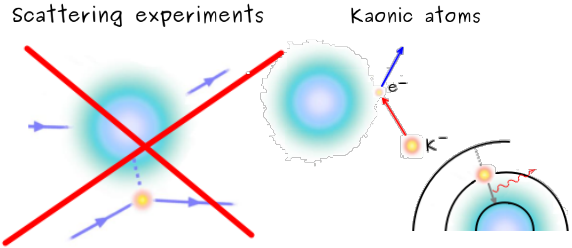
Kaon-deuteron: to determine $K^{\pm}d$ scattering parameters and obtain the full isospin dependence of the interaction, – a fundamental problem in the strangeness sector in the low-energy regime of QCD.

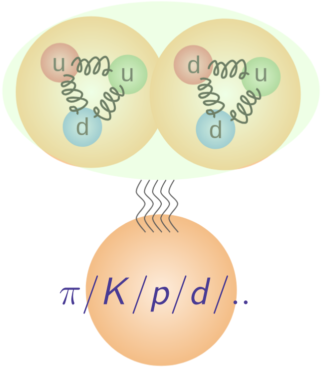




Why to study deuterons? – interactions

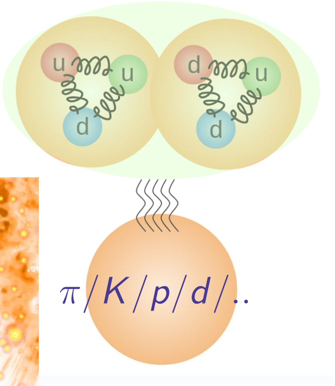
Kaon-deuteron: to determine $K^{\pm}d$ scattering parameters and obtain the full isospin dependence of the interaction, – a fundamental problem in the strangeness sector in the low-energy regime of QCD.

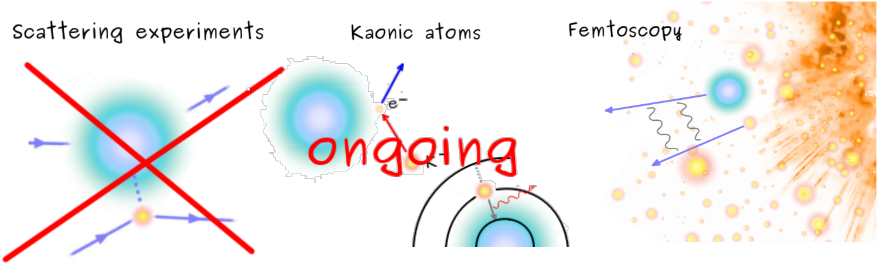




Why to study deuterons? – interactions

Kaon-deuteron: to determine $K^{\pm}d$ scattering parameters and obtain the full isospin dependence of the interaction, – a fundamental problem in the strangeness sector in the low-energy regime of QCD.





Not measured so far!

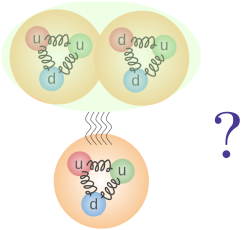
Why to study deuterons? – interactions

Proton-deuteron: deuteron is a composite object consisting of a proton and a neutron. What is the dynamic of the interaction?

?

Why to study deuterons? – interactions

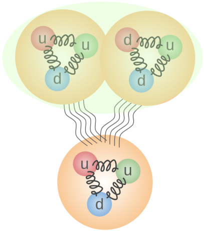
Proton-deuteron: deuteron is a composite object consisting of a proton and a neutron. What is the dynamic of the interaction?



Why to study deuterons? – interactions

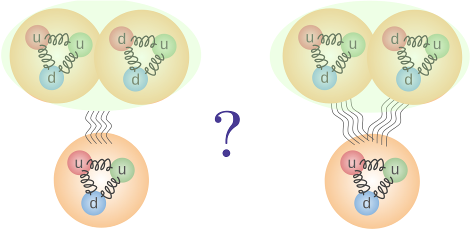
Proton-deuteron: deuteron is a composite object consisting of a proton and a neutron. What is the dynamic of the interaction?

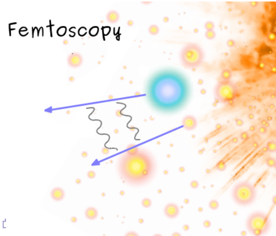
?



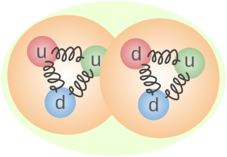
Why to study deuterons? – interactions

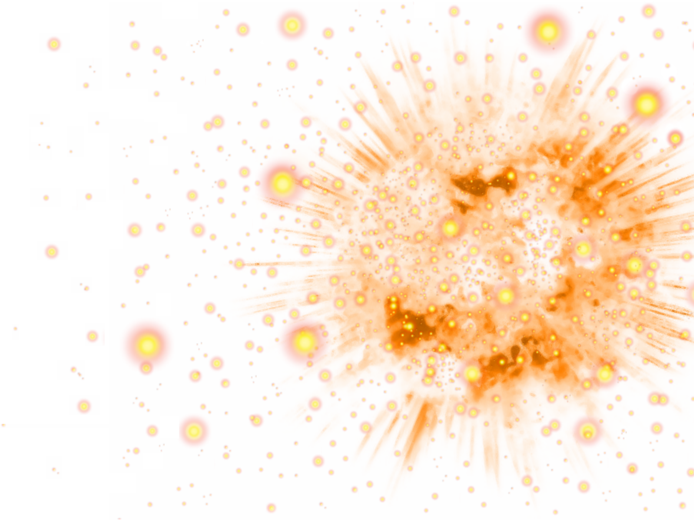
Proton-deuteron: deuteron is a composite object consisting of a proton and a neutron. What is the dynamic of the interaction?





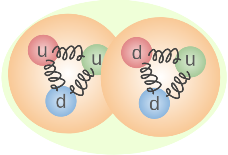
Why to study deuterons? – production mechanism



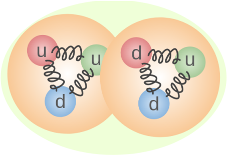


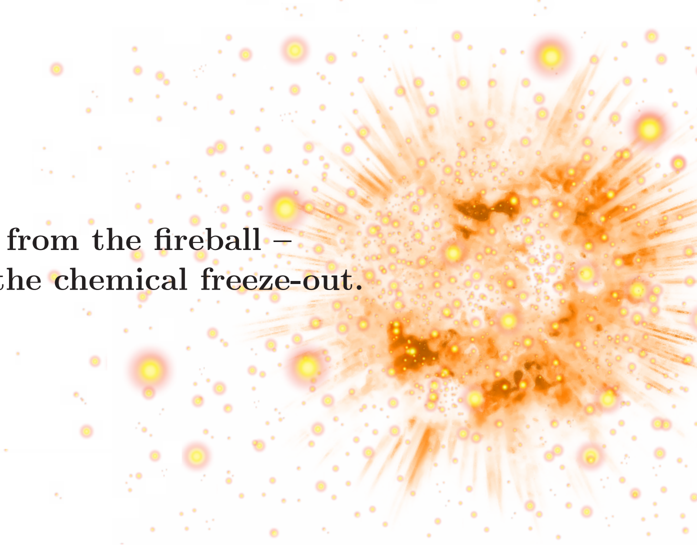
Why to study deuterons? – production mechanism

"Thermal"



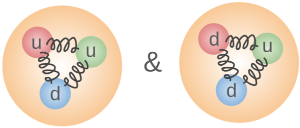
Emission directly from the fireball –
creation before the chemical freeze-out.



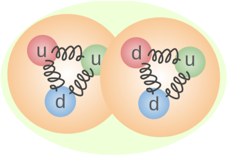


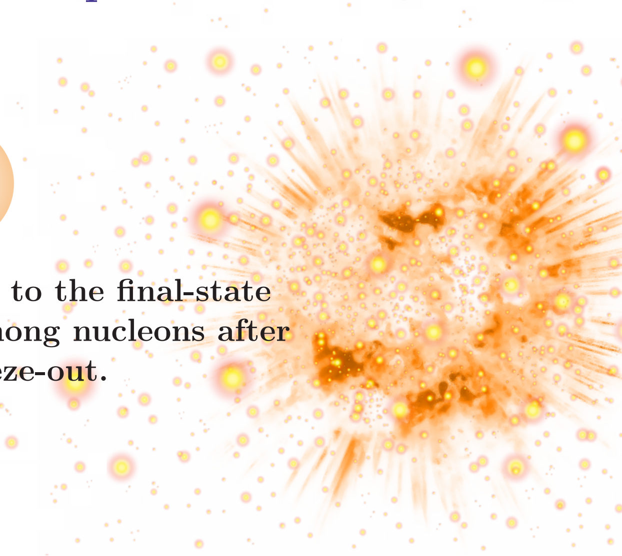
Why to study deuterons? – production mechanism

"Coalescence"

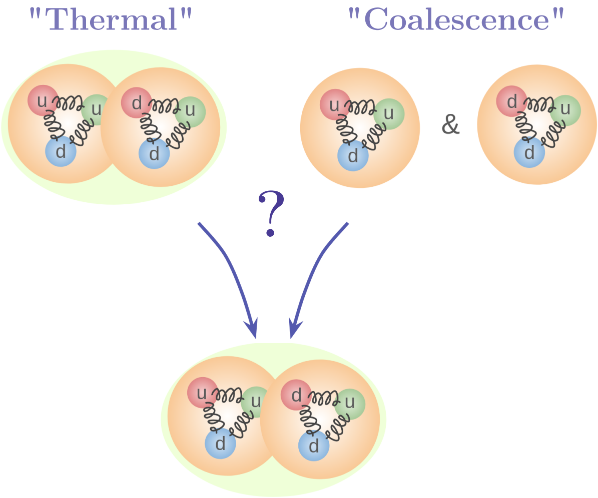


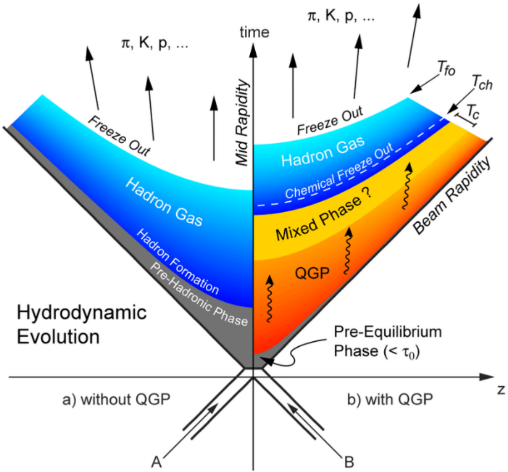
Creation due to the final-state interactions among nucleons after the chemical freeze-out.





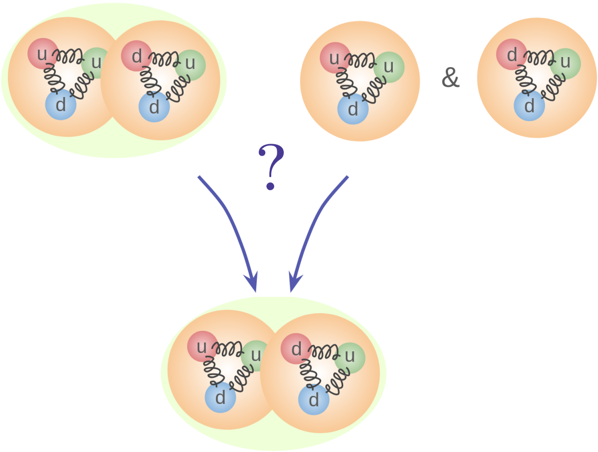
Why to study deuterons? – production mechanism



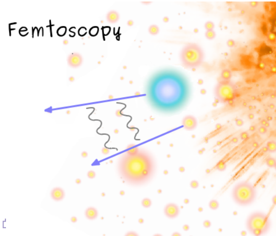


Why to study deuterons? – production mechanism

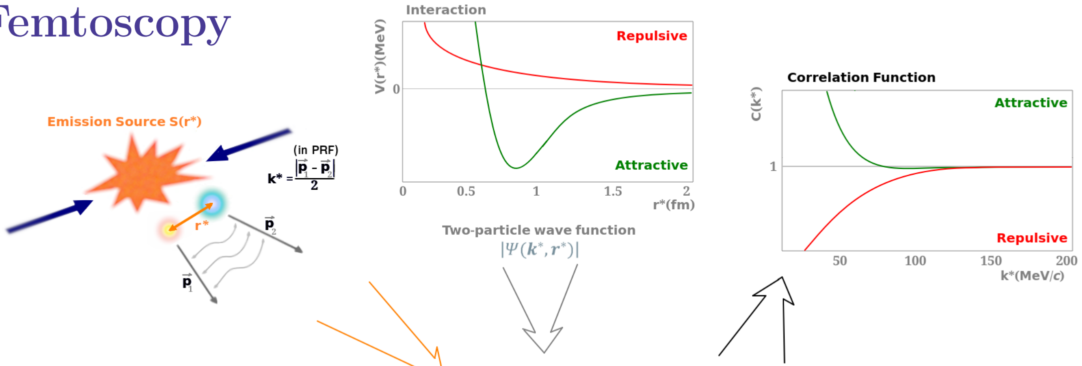
"Thermal" "Coalescence"



Pion-deuteron, proton-deuteron: to constrain the space–time characteristic of emission of deuterons.



Femtoscopy



$$C(k^*) = \int S(r^*) \, |\Psi(k^*, r^*)|^2 \, d^3r^* = \xi(k^*) \cdot \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

- **Femtoscopy**: determination of the space–time characteristics of the particle-emitting source using correlation function (CF) in momentum space.
- **CF**: convolution of the source function and wave function (the latter can combine quantum statistics, as well as strong and Coulomb forces).

Correlation function

$$C(k^*) = \int S(r^*)|\Psi(k^*, r^*)|^2 d^3 r^*$$

Correlation function

$$C(k^*) = \int S(r^*)|\Psi(k^*, r^*)|^2 d^3 r^*$$

- What shape is it?
- What size?
- (Anti-)deuterons' production mechanism?

$$S(r^*) \sim r^{*2} exp\left(\frac{r^{*2}}{2R_{AB}^2}\right)$$

Correlation function

$$C(k^*) = \int S(r^*)|\Psi(k^*, r^*)|^2 d^3r^*$$

- What shape is it?
- What size?
- (Anti-)deuterons' production mechanism?

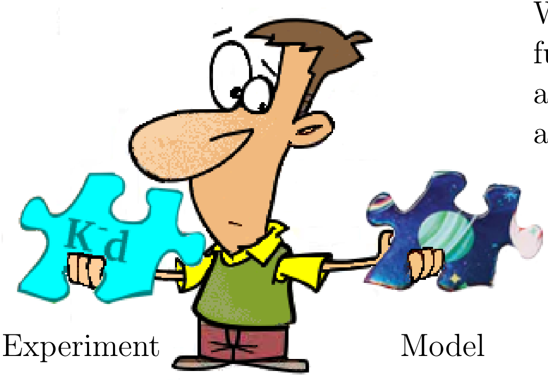
- How to calculate this?
- f_0 - scattering length?
- d_0 - zero effective-range?

$$S(r^*) \sim r^{*2} exp\left(\frac{r^{*2}}{2R_{AB}^2}\right)$$

$$\Psi = exp\left(-ik^*r\right) + f\frac{exp(ik^*r)}{r}$$

$$f^{-1}(k^*) = \frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - ik^*$$

A magic power of femtoscopy

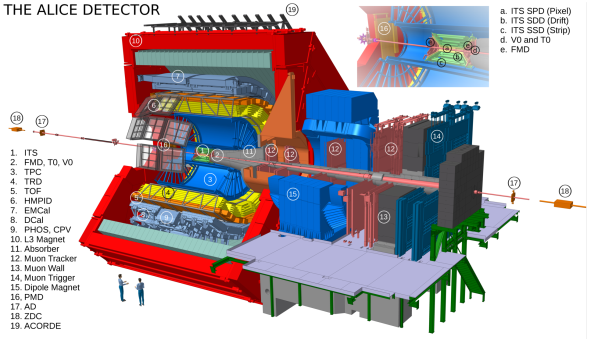


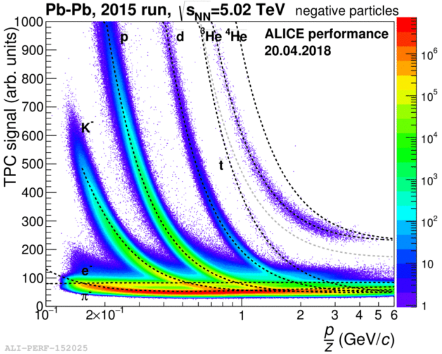
We can compare experimental correlation functions with available models and conclude about their parameterisation, i.e: source and/or interaction parameters.

We need: experimental data and models.

Data

- $K^{\pm}d/K^{\pm};\overline{d}$ $\pi^{\pm}d/\pi^{\pm}\overline{d}$ CF – Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (3 centrality intervals: $0-10\%, 10-30\%, 30-50\%$)
- pd CF – pp collisions at $\sqrt{s} = 13$ TeV.





Kd correlation functions

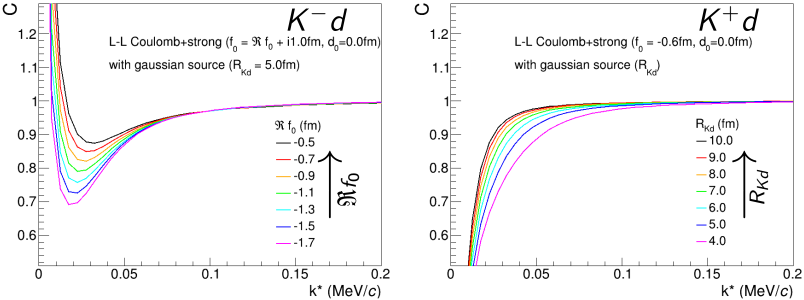
Modeling correlation functions

- Theoretical CFs modeled with Lednický-Lyuboshits approach [1] with the assumptions:
  - gaussian source,
  - zero effective-range approximation of the interaction, $d_0 = 0.0$ fm.
- Numerical calculation of theoretical CFs for different fit parameters.

Fit parameters:

- source radii (R_{Kd})
- scattering lengths (f_0):
  - K^-d ($\Re$, $\Im$)
  - K^+d ($\Re$)

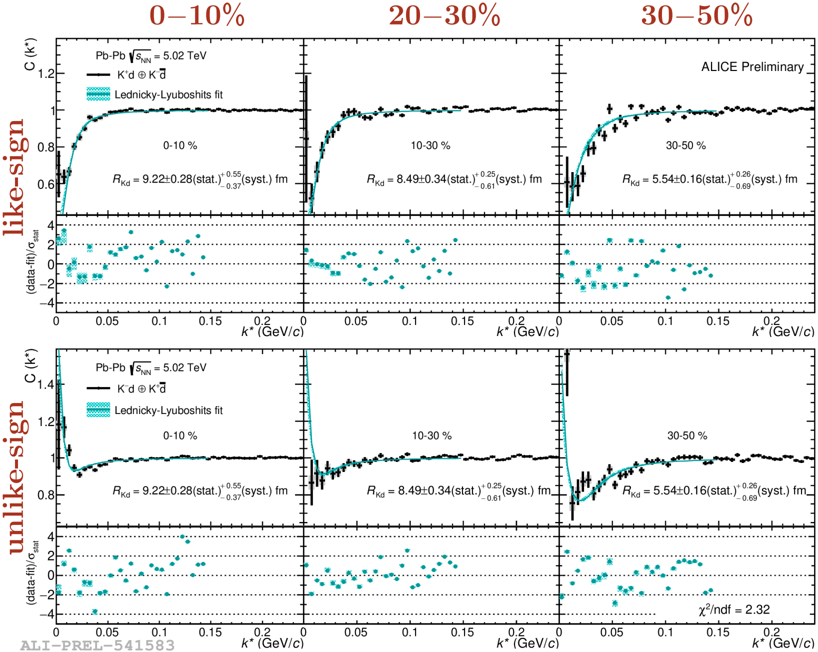
Examples of modeled CFs for different values of fit parameters



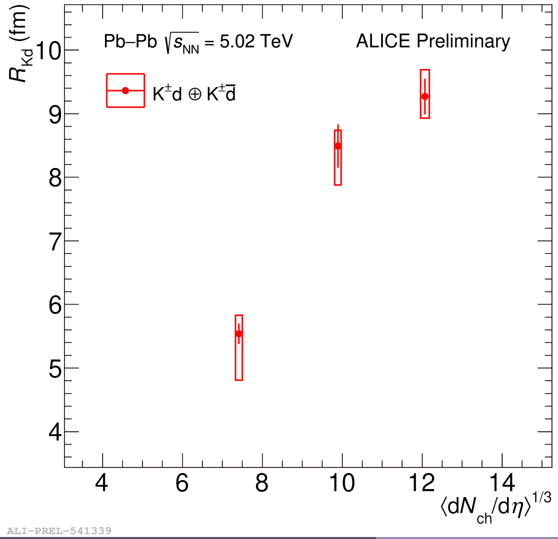
[1] Lednický, R. and Lyuboshits, V. L., Final state interaction effect on pairing correlations between particles with small relative momenta, Yad. Fiz. 35 (1981).

Kd in Pb–Pb with L-L fit

- Simultaneous fit to 6 CFs.
- Source radii from like- and unlike-sign pairs:
  - one R_{Kd} per centrality.
- Scattering lengths from three centralites:
  - one $f_0(\Re,\Im)$ for unlike-sign pairs,
  - one $f_0(\Re)$ for like-sign pairs.



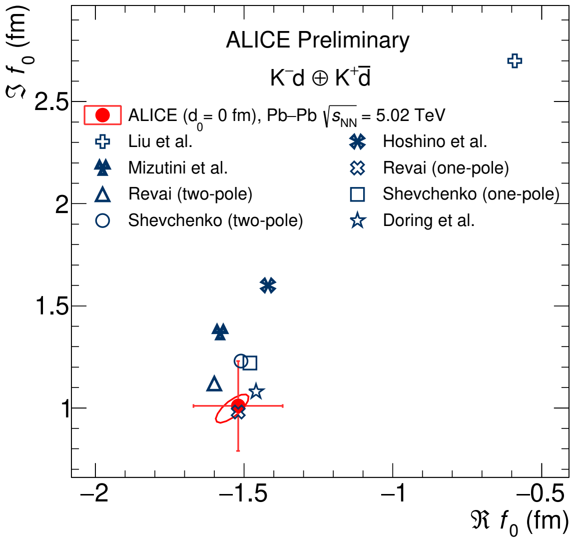
Kd radii



- 3 radii for 3 centralities (the same radius for all particle pairs).
- Source size increases with multiplicity.

$K^{-}d$ scattering length

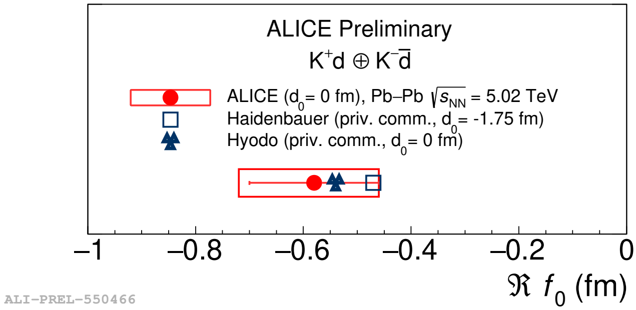
- $\Re f_0$ and $\Im f_0$ are in agreement with most of the available calculations.



ALI−PREL−550469

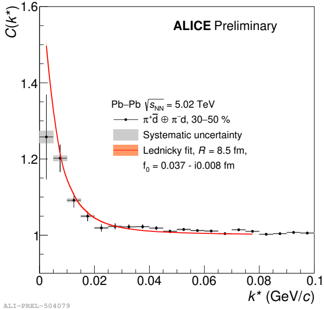
K^+d scattering length

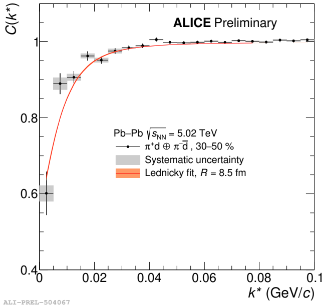
- $\Re f_0$ is in agreement with available calculations.



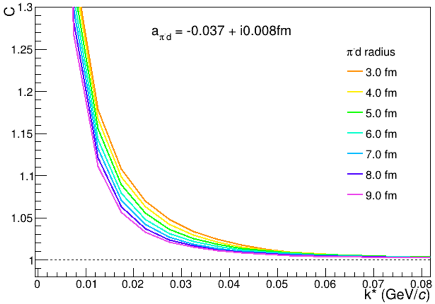
πd correlation functions

πd correlation functions

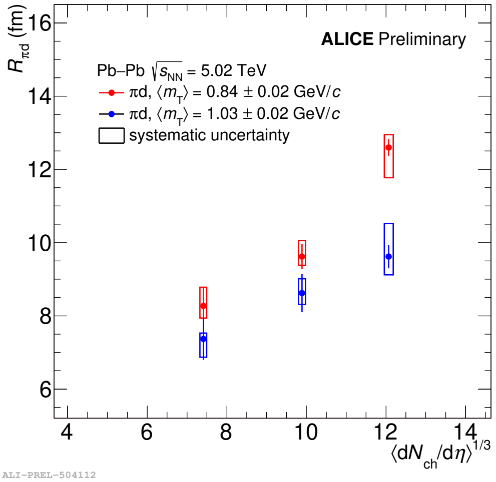




- Lednický-Lyuboshits simultaneous fit to opposite (Coulomb & strong) and same (Coulomb) charges particle pairs.
- Zero effective-range approximation ($d_0 = 0$).



πd radii



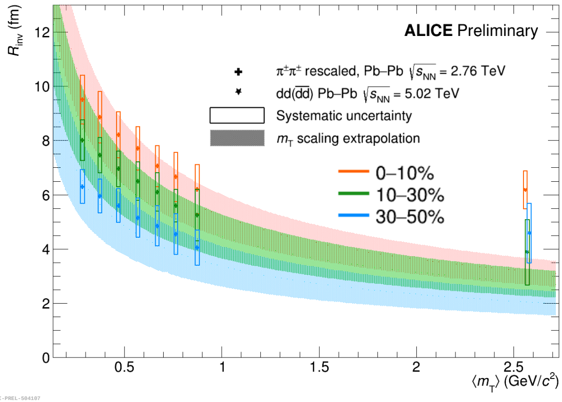
- 6 πd radii: 3 centralities, 2 m_T of πd particle pairs.
- πd radii depend on $< m_T >$ and multiplicity.

Comparisons with other hadrons

$$R_{\pi \mathrm{d}} = \sqrt{R_{\pi}^2 + R_{\mathrm{d}}^2}$$

$$R_{\mathrm{d}} = \sqrt{R_{\pi \mathrm{d}}^2 - R_{\pi}^2}$$

- $d(\overline{d})$ source sizes estimated from measured πd radii and single pion radii (measured in Pb–Pb at 2.76 TeV [2] rescaled to 5.02 TeV) are larger than radii expected from m_{T} scaling.

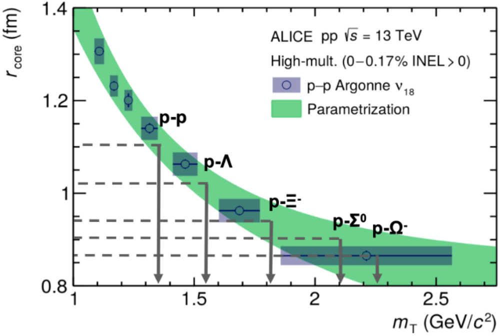


[2] ALICE Collaboration, One-dimensional pion, kaon, and proton femtoscopy in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

pd correlation functions

Modeling correlation functions

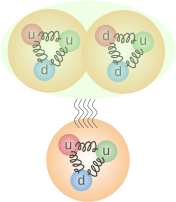
ALICE Collab, PLB 811, 135849 (2020)



pd source size R $= 1.08^{+0.06}_{-0.06} fm$

$$C(k^*) = \int S(\vec{r}^*)|\Psi(\vec{k}^*, \vec{r}^*)|^2 d^3\vec{r}^*$$

Modeling correlation functions – two body

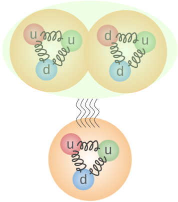


p–d as an effective two body Lednický-Lyuboshits approach with Strong interaction constrained from the scattering measurements [3].

$$C(k^*) = \int S(\vec{r}^*)|\Psi(\vec{k}^*, \vec{r}^*)|^2 d^3\vec{r}^*$$

[3] In the backup.

Modeling correlation functions – two body

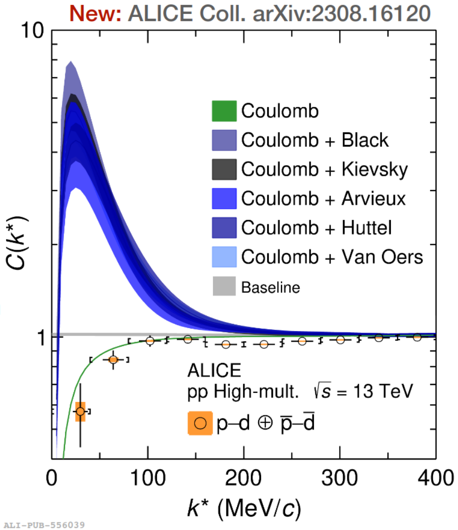


p–d as an effective two body Lednický-Lyuboshits approach with Strong interaction constrained from the scattering measurements [3].

pd source size R $= 1.08^{+0.06}_{-0.06} fm$

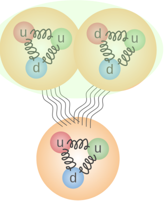
Failed to reproduce experimental data.

- Asymptotic strong interaction: not sufficient for distances ∼1 fm?
- Pauli blocking at short distances?



[3] In the backup.

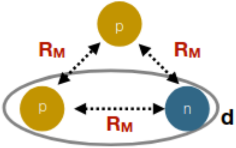
Modeling correlation functions – three body

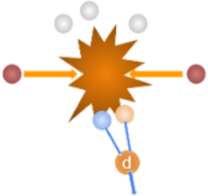


A three-nucleon dynamics of p-(pn)[4]

$R_M = 1.43 \pm 0.16\ fm$, nucleon-nucleon source size in pd

Assumption: coalescence production, A_d - formation probability of d

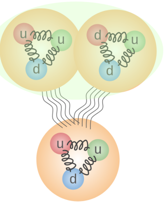




$$C(k^*) = \frac{1}{16A_d} \sum_{m_2,m_1} \int \rho^5 d\rho d\Omega |\Psi_{m_2,m_1 \vec{k}^*}|^2 \frac{e^{-\rho/4R_M^2}}{(4\pi R_M^2)^3}$$

[4] M. Viviani, et al. Role of three-body dynamics in nucleon-deuteron correlation functions

Modeling correlation functions – three body

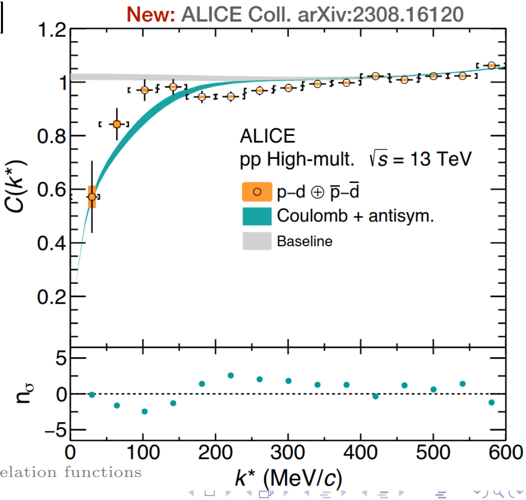


A three-nucleon dynamics of p-(pn)[4]

$R_M = 1.43 \pm 0.16\ fm$,
nucleon-nucleon source size in pd

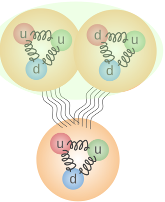
Assumption: coalescence production,
A_d - formation probability of d

Coulomb only cannot reproduce the experimental data.



[4] M. Viviani, et al. Role of three-body dynamics in nucleon-deuteron correlation functions

Modeling correlation functions – three body

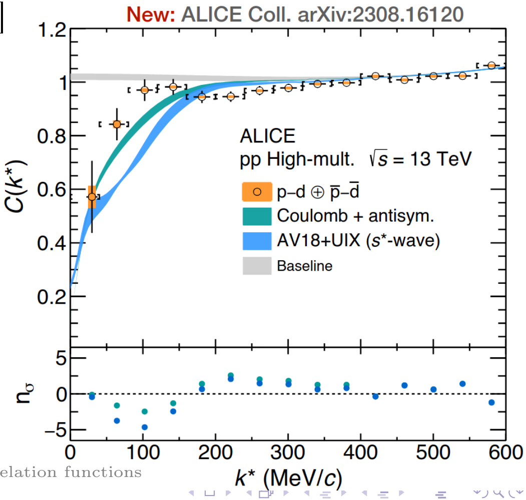


A three-nucleon dynamics of p-(pn)[4]

$R_M = 1.43 \pm 0.16\ fm$,
nucleon-nucleon source size in pd

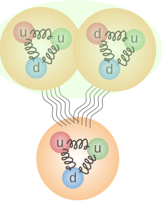
Assumption: coalescence production,
A_d - formation probability of d

EFT NLO (s-wave) cannot describe the experimental data.



[4] M. Viviani, et al. Role of three-body dynamics in nucleon-deuteron correlation functions

Modeling correlation functions – three body



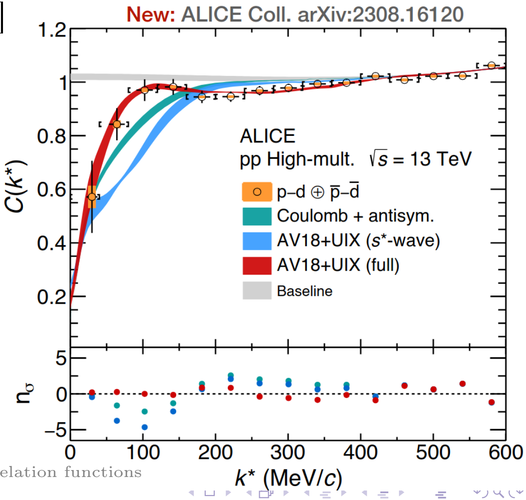
A three-nucleon dynamics of p-(pn)[4]

$R_M = 1.43 \pm 0.16\ fm$,
nucleon-nucleon source size in pd

Assumption: coalescence production,
A_d - formation probability of d

EFT NLO (s+p+d waves) can describe the experimental data.

- Three-body dynamics at short distances
- Higher partial wave up to d-waves are necessary (s-wave only is not sufficient)



[4] M. Viviani, et al. Role of three-body dynamics in nucleon-deuteron correlation functions

Summary

- First ever measurements of:

  → femtoscopic correlations with deuterons in relativistic heavy-ion collisions,
  → the scattering parameters of the strong interaction,
  of $\mathrm{K}^{\pm}d$ pairs,
  → d source sizes,
  → πd and Kd source sizes.

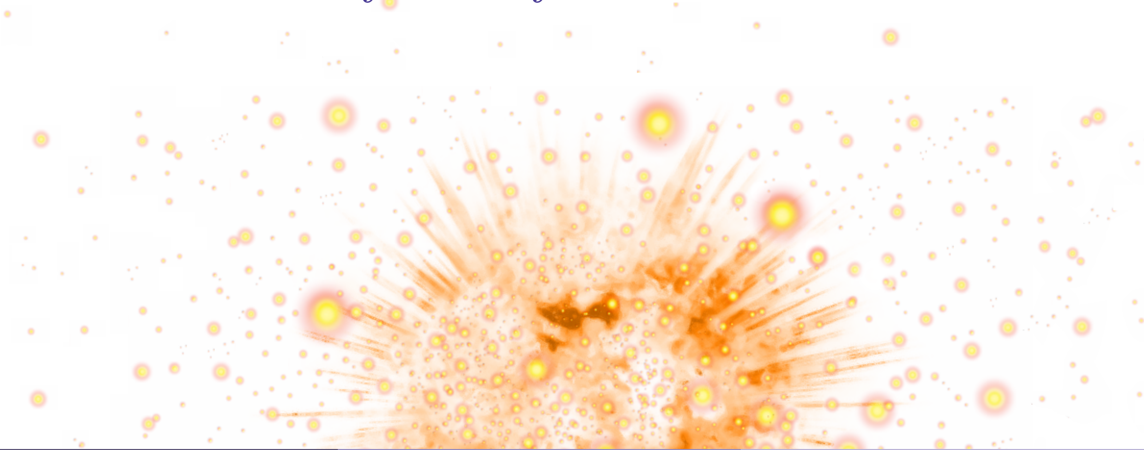
Summary

- First ever measurements of:

$\rightarrow$ femtoscopic correlations with deuterons in relativistic heavy-ion collisions,
$\rightarrow$ the scattering parameters of the strong interaction,
of $K^{\pm}d$ pairs,
$\rightarrow$ d source sizes,
$\rightarrow$ πd and Kd source sizes,

$\rightarrow$ femtoscopic correlations with deuterons in pp collisions,
$\rightarrow$ Revealing the importance of three-body interactions and higher order partial waves at small distances.

Thank you for your attention!



[3]

$S = 1/2$		$S = 3/2$		
a_0(fm)	d_0(fm)	a_0(fm)	d_0(fm)	
$1.30^{+0.20}_{-0.20}$	—	$11.40^{+1.80}_{-1.20}$	$2.05^{+0.25}_{-0.25}$	Van Oers,Brockmann et al. Nucl. Phys. A 561-583 (196
$2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$11.88^{-0.10}_{+0.40}$	$2.63^{+0.01}_{-0.02}$	J.Arvieux et al. Nucl. Phys. A 221 253-268 (1973)
4.0	—	11.1	—	E.Huttel et al. Nucl. Phys. A 406 443-455 (1983)
0.024	—	13.8	—	A.Kievsky et al. PLB 406 292-296 (1997)
$-0.13^{+0.04}_{-0.04}$	—	$14.70^{+2.30}_{-2.30}$	—	T.C.Black et al. PLB 471 103-107 (1999)