Faculty of Physics
Warsaw University of Technology

Femtoscopy measurements of the $\mathrm{p}-\Lambda$ and $\mathrm{d}-\Lambda$ systems as a tool for studying the strong interaction parameters

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XVII Polish Workshop on Relativistic Heavy-Ion Collisions
14-15.12.2024, Warsaw, Poland

National Science Centre Poland
Research University Excellence Initiative

Motivation

1. Hyperons are expected to appear **in the core of Neutron Stars** (NS)
2. Hyperons **soften the Equation of State** (EoS) - reduction of maximum NS mass

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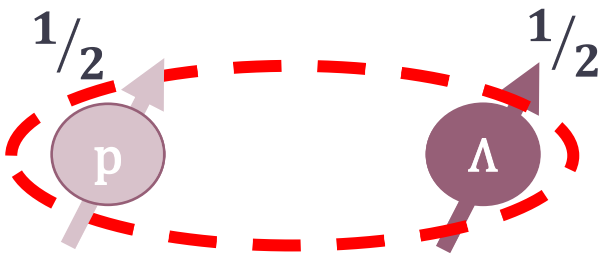
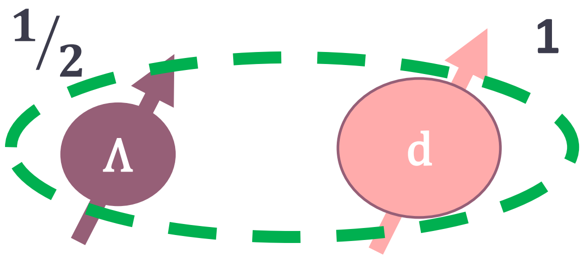
2. Hyperons **soften the Equation of State** (EoS) - reduction of maximum NS mass
3. Unique information on **spin and state, source size, potential type, interaction lenght…**



Spin states:
singlet (S) $^1S_0$
triplet (T) $^3S_1$

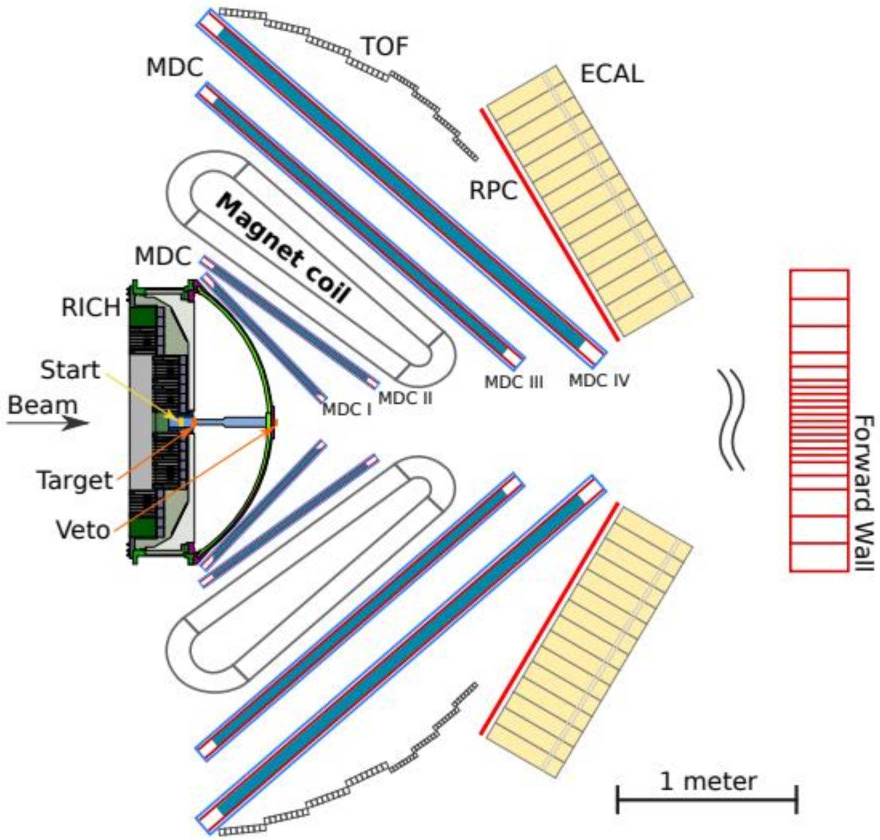


Spin states:
doublet (D) $^2S_{1/2}$
quartet (Q) $^4S_{3/2}$

1. d-Λ CF offers additional insights into **the structure of the hypertriton** $^3_\Lambda H$ and **the nature of 3-body interactions**

$$^3_\Lambda H \rightarrow p + \pi^- + d \text{ decay}$$

The HADES experiment



Dataset

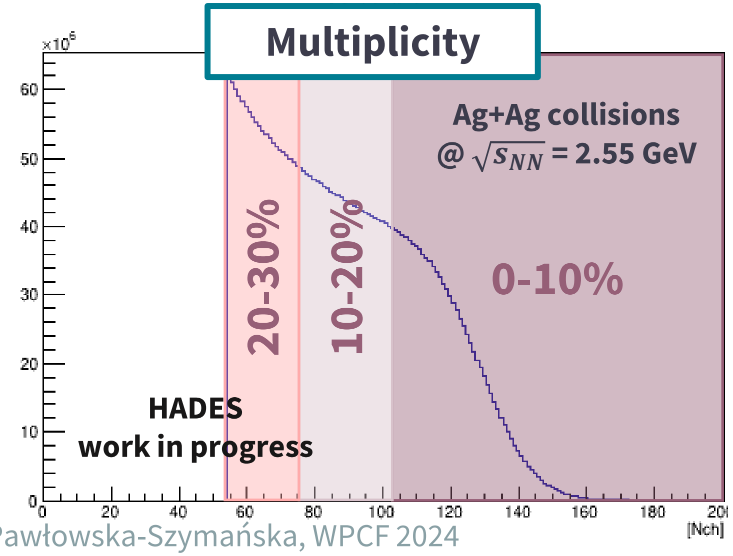
Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.55 GeV
No. of events 6.7 x 10^9

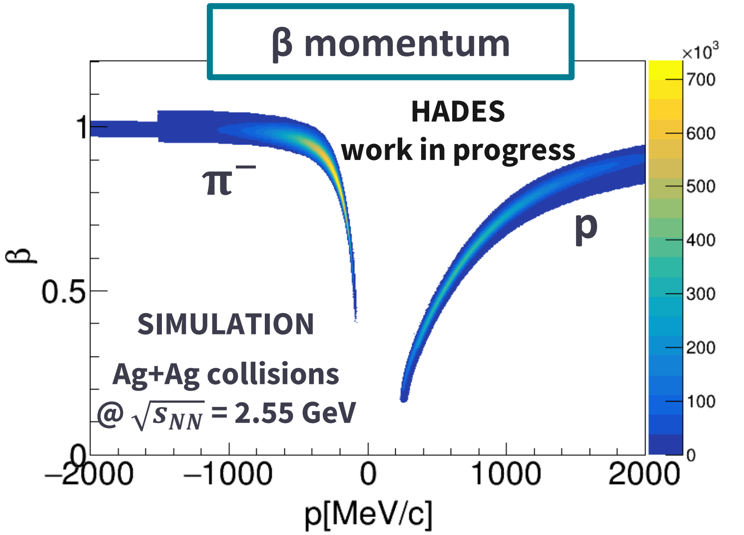
Events

Target plate selection (segmented target)
Centrality 0-10%, 10-20%, 20-30% and 0-30%

Track

β momentum cuts for daughter particles (2σ)
dE/dx cut for deuteron (2σ)

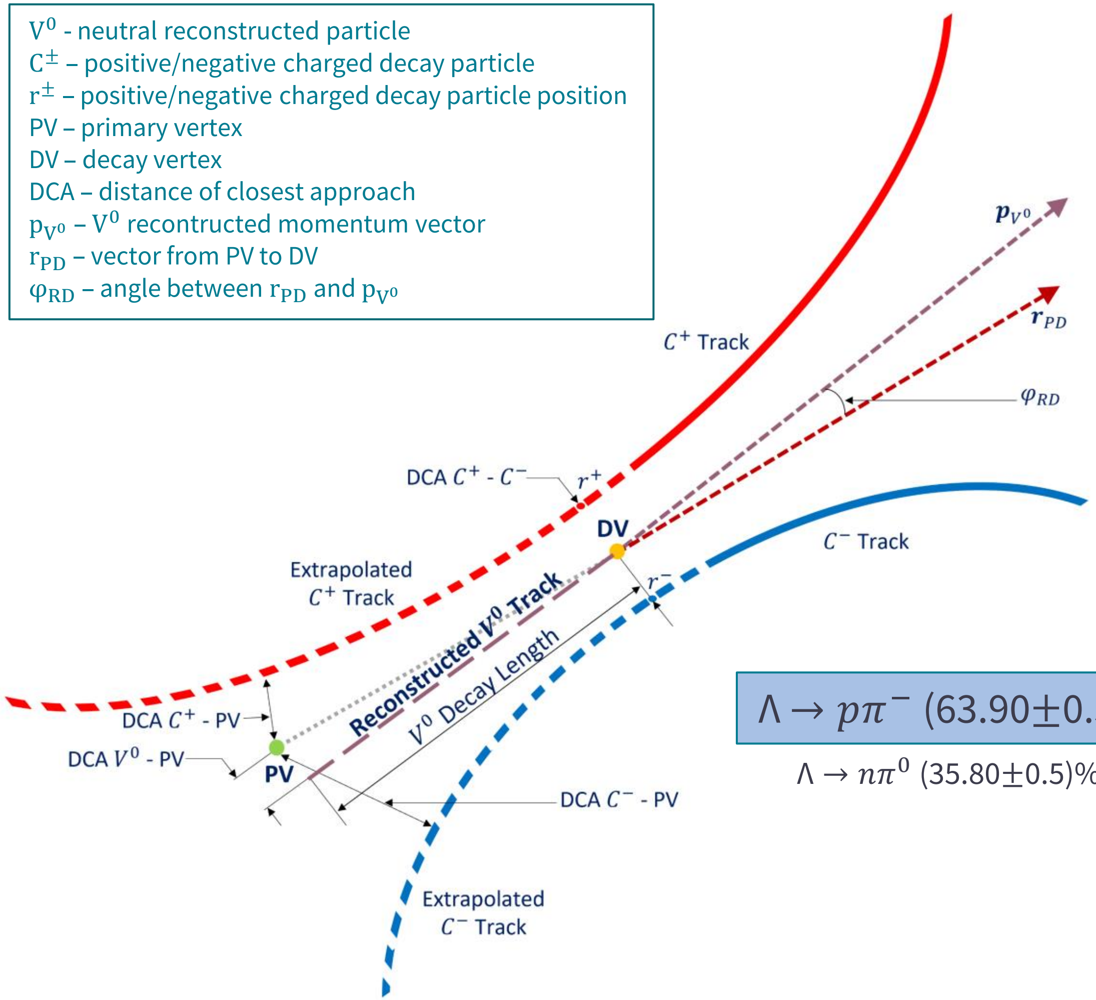




HADES

Lambda reconstruction

V^0 - neutral reconstructed particle
$C^{\pm}$ – positive/negative charged decay particle
$r^{\pm}$ – positive/negative charged decay particle position
PV – primary vertex
DV – decay vertex
DCA – distance of closest approach
p_{V^0} – V^0 recontructed momentum vector
r_{PD} – vector from PV to DV
φ_{RD} – angle between r_{PD} and p_{V^0}

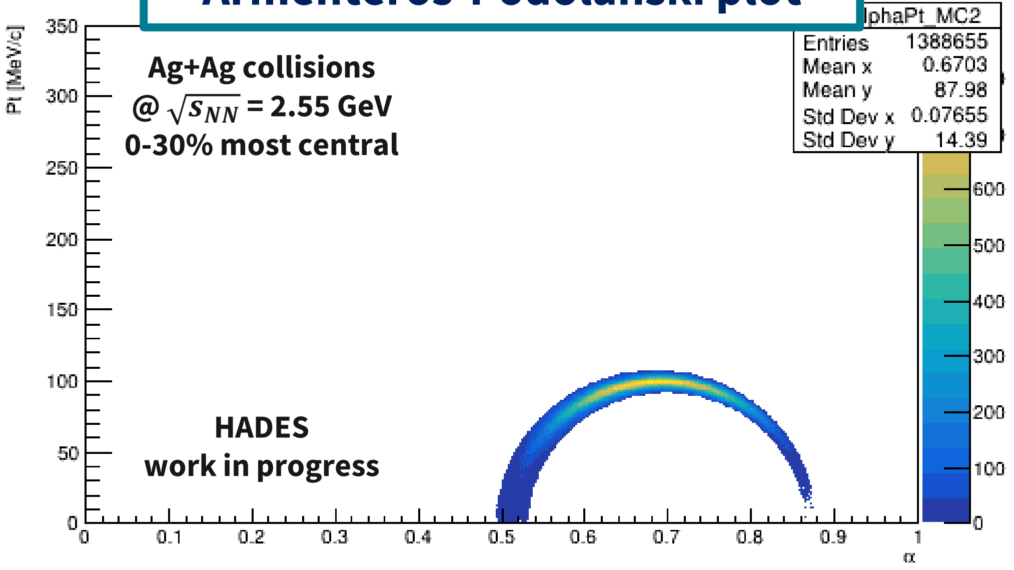


$\Lambda \to p\pi^-$ (63.90±0.5)%

$\Lambda \to n\pi^0$ (35.80±0.5)%

DCA between daughter to PV	$>$ **0.8 cm** for p $>$ **2.4 cm** for π^-
DCA between daughters	$<$ **0.6 cm**
DCA between V^0 and PV	$<$ **0.5 cm**
Decay lenght	$>$ **6.5 cm**

Armenteros-Podolański plot



Femtoscopy - introduction

Femtoscopy (originating from Hanbury-Brown and Twiss interferometry): a method to probe **geometric** and **dynamic** properties of the source.

statistical | model | exp

$$CF(k^*) = \frac{P_{12}(\overrightarrow{p_1},\overrightarrow{p_2})}{P_1(\overrightarrow{p_1})P_2(\overrightarrow{p_2})} = \int d^3r\, S(\vec{r})|\Psi(k^*,\vec{r})|^2 = \frac{A(k^*)}{B(k^*)}$$

$\overrightarrow{p_1}, \overrightarrow{p_2}$ - single particle momentum

$S(\vec{r})$ – source function
$\Psi(k^*,\vec{r})$ – pair wave function
k^*– center-of- mass momentum
$\vec{r}$ – relative distance between two particles

$A(\vec{q})$ - correlated
$B(\vec{q})$ - uncorrelated

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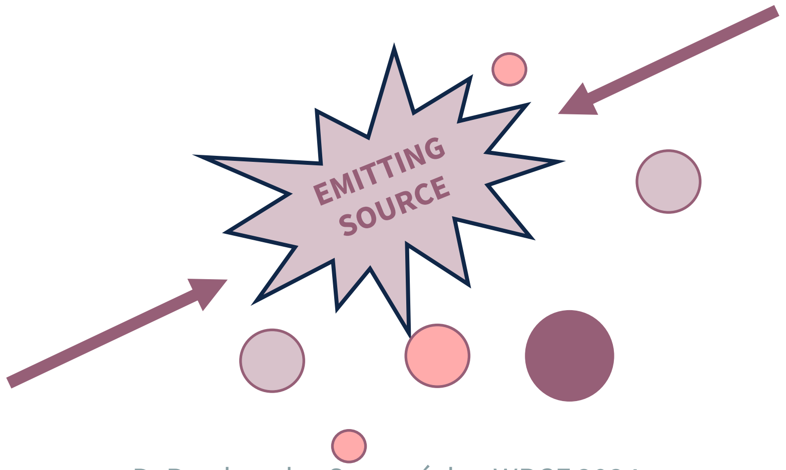
Characteristics of the particle-emitting source:
size – R
correlation strength - λ



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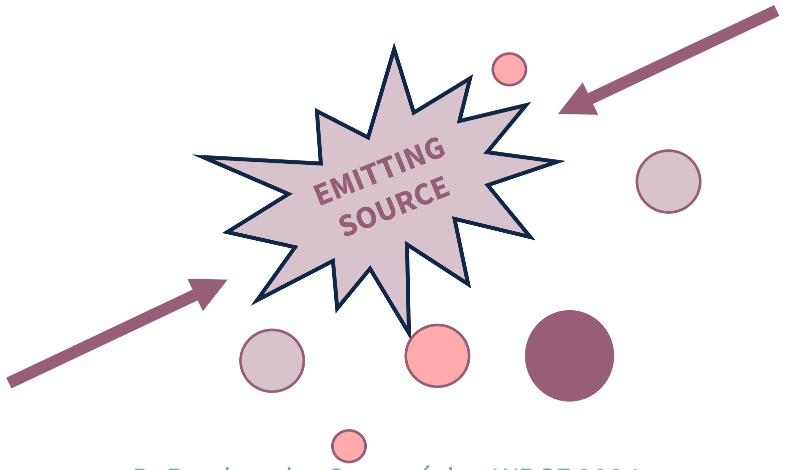

Strong interactions between particles:
scattering length – f_0
effective range – d_0

Lednicky-Lyuboshitz formalism

R. Lednicky, et al. Sov.J.Nucl.Phys. 35 (1982) 770
J. Haidenbauer, Phys.Rev.C 102 (2020) 3, 034001

Assumptions:

1. Smoothness approximation for source function.
2. Effective range expansion for pair wave function.
3. Static and spherical Gaussian source.
4. Approximate the wave function by its asymptotic form.

$$CF(k^*) \approx 1 + \frac{|f(k^*)|^2}{2R^2} F(d_0) + \frac{2\Re f(k^*)}{\sqrt{\pi}R} F_1(2k^*R) - \frac{\Im f(k^*)}{R} F_2(2k^*R)$$

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Scattering amplitude (effective range expansion)

$$f(k^*) \approx \frac{1}{-\frac{1}{f_0} + \frac{d_0 k^{*2}}{2} - ik}$$

f_0 - scattering length
d_0 - effective range

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Correction that accounts for the deviation of the true wave function from the asymptotic form

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$$F_1(x) = \int_0^x dt \frac{e^{t^2} - x^2}{x}$$

$$F_2(x) = \frac{1 - e^{-x^2}}{x}$$

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4. Approxima

C ... R)

SPIN AVERAGED

works reasonably well for source sizes larger than the range of interaction

Scattering amplitude (efective range expansion)

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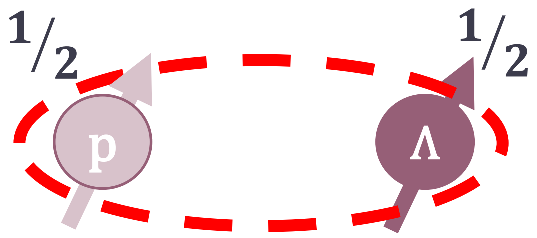
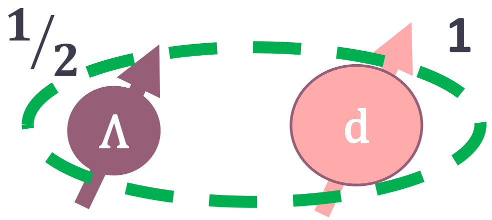
SPIN SEPARATED



singlet (S) $^1S_0$
triplet (T) $^3S_1$



doublet (D) $^2S_{1/2}$
quartet (Q) $^4S_{3/2}$

Pair wave function:

$$|\Psi(k^*,\vec{r})|^2 \rightarrow f_{S1}\left|\Psi_{1/2}(k^*,\vec{r})\right|^2 + f_{S2}\left|\Psi_{3/2}(k^*,\vec{r})\right|^2$$

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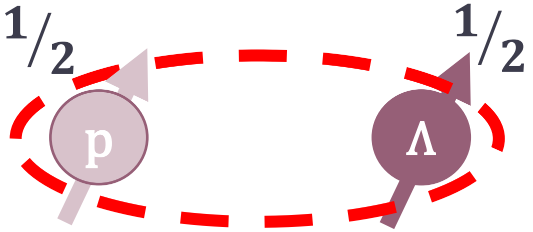

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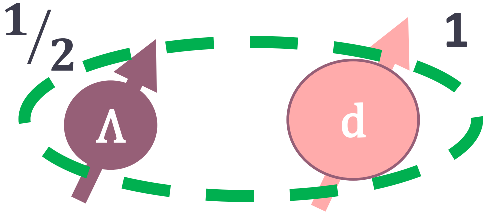


doublet (D) $^2S_{1/2}$
quartet (Q) $^4S_{3/2}$

p-Λ = 1/4 S + 3/4 T
d-Λ = 1/3 D + 2/3 Q

Pair wave function:

$$|\Psi(k^*,\vec{r})|^2 \to f_{S1}\left|\Psi_{1/2}(k^*,\vec{r})\right|^2 + f_{S2}\left|\Psi_{3/2}(k^*,\vec{r})\right|^2$$

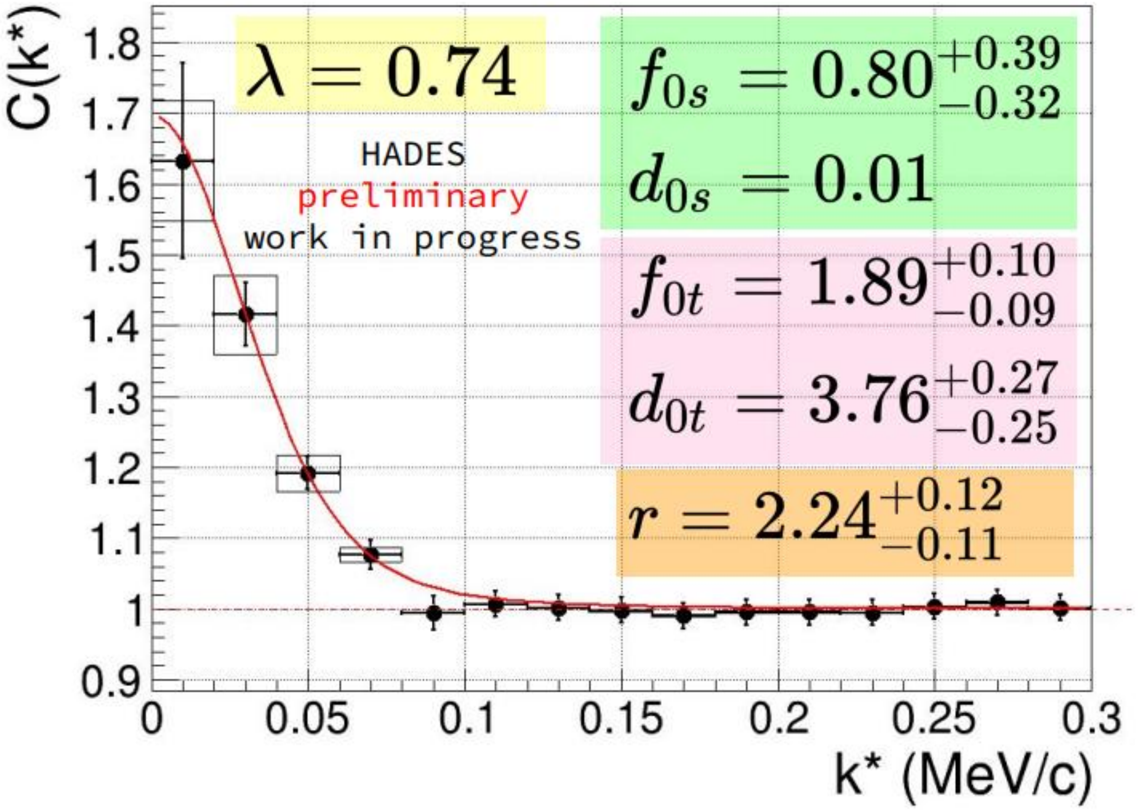
$$CF(k^*) \approx 1 + \frac{|f(k^*)|^2}{2R^2}F(d_{01}) + \frac{2\Re f(k^*)}{\sqrt{\pi}R}F_1(2k^*R) - \frac{\Im f(k^*)}{R}F_2(2k^*R) + \frac{|f(k^*)|^2}{2R^2}F(d_{02}) + \frac{2\Re f(k^*)}{\sqrt{\pi}R}F_1(2k^*R) - \frac{\Im f(k^*)}{R}F_2(2k^*R)$$

Parameters of strong interaction
scattering length: f_0(S), f_0(T) | f_0(D), f_0(Q)
effective range: d_0(S), d_0(T) | d_0(D), d_0(Q)

p-Λ correlation functions

p-Λ CF - Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 GeV

0-30% central events



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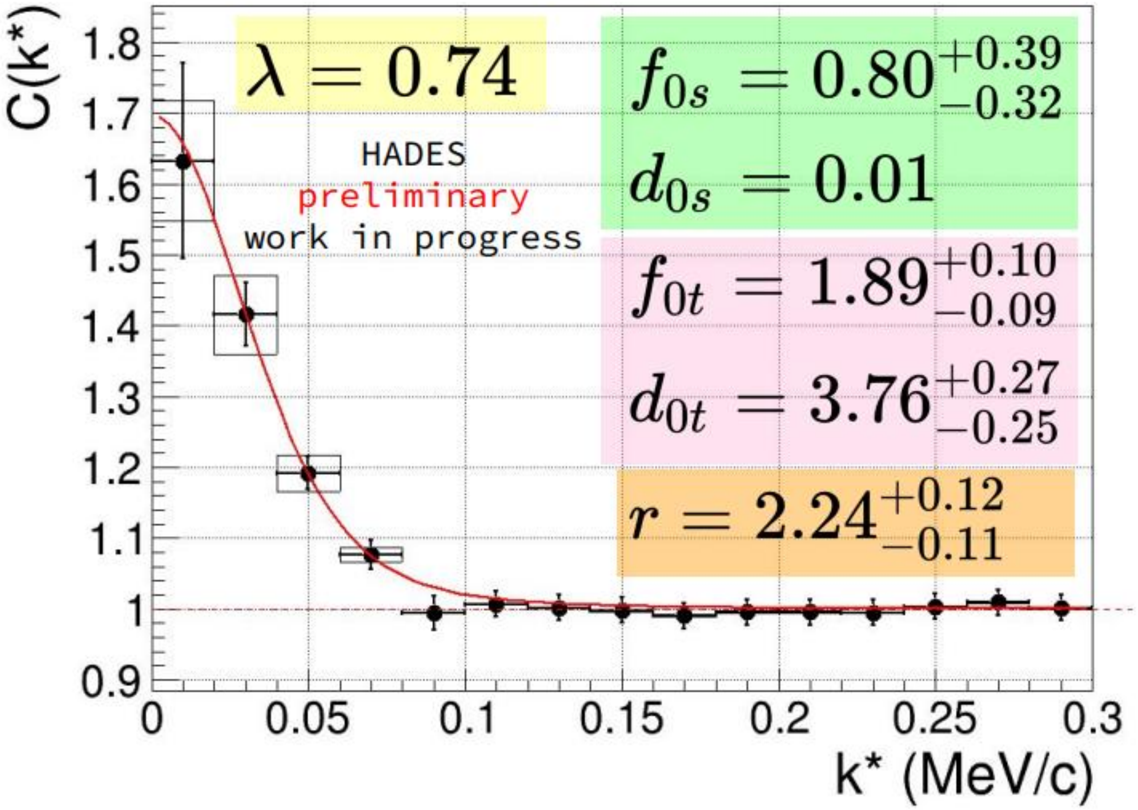

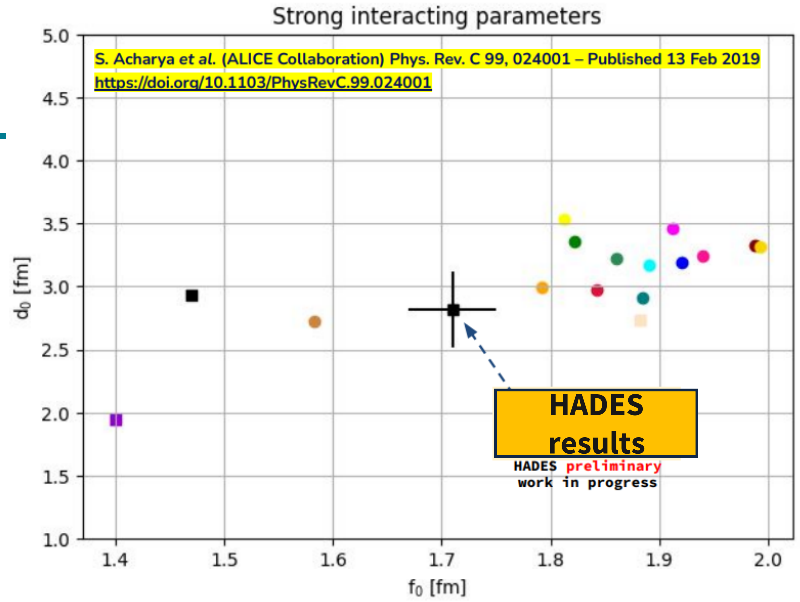

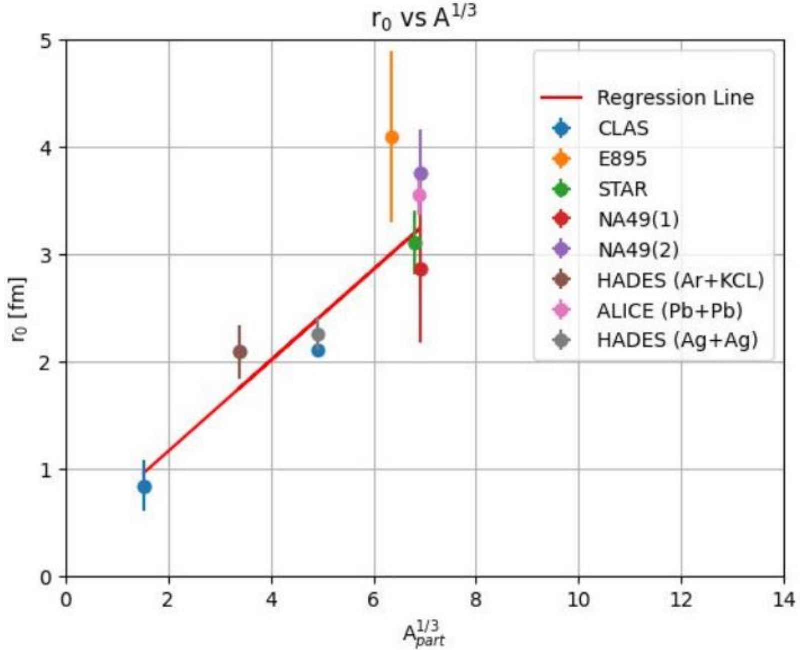

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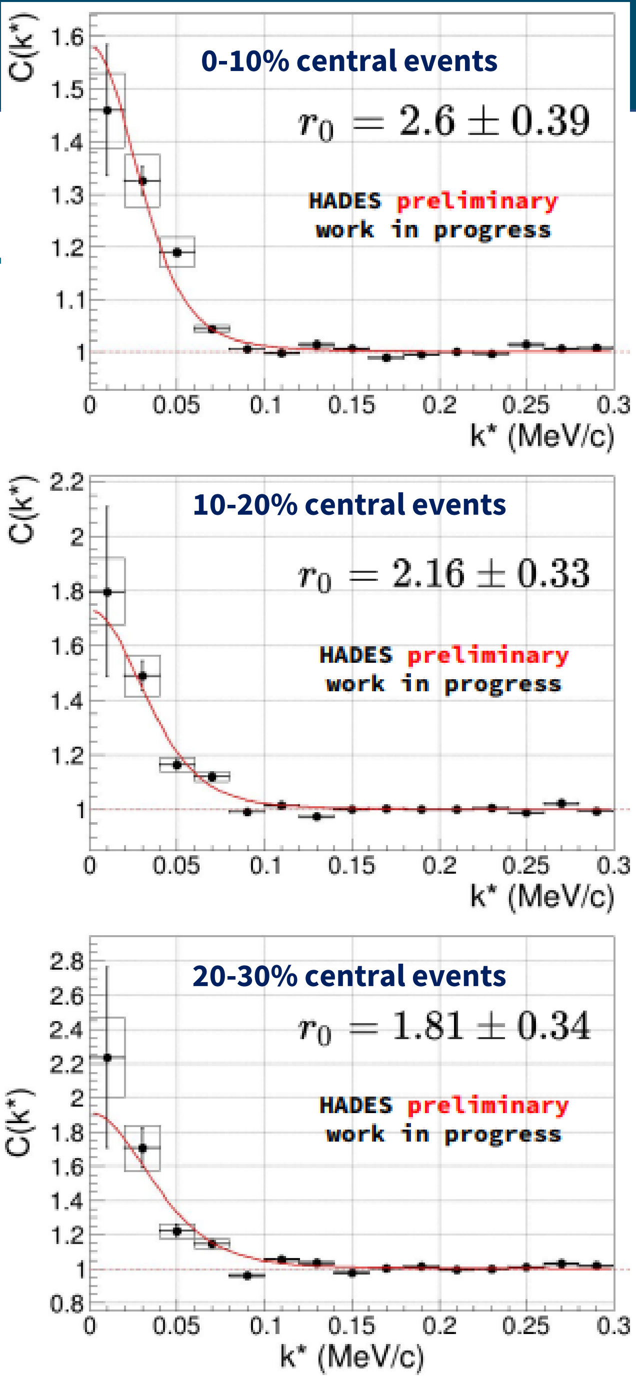
centrality dependence



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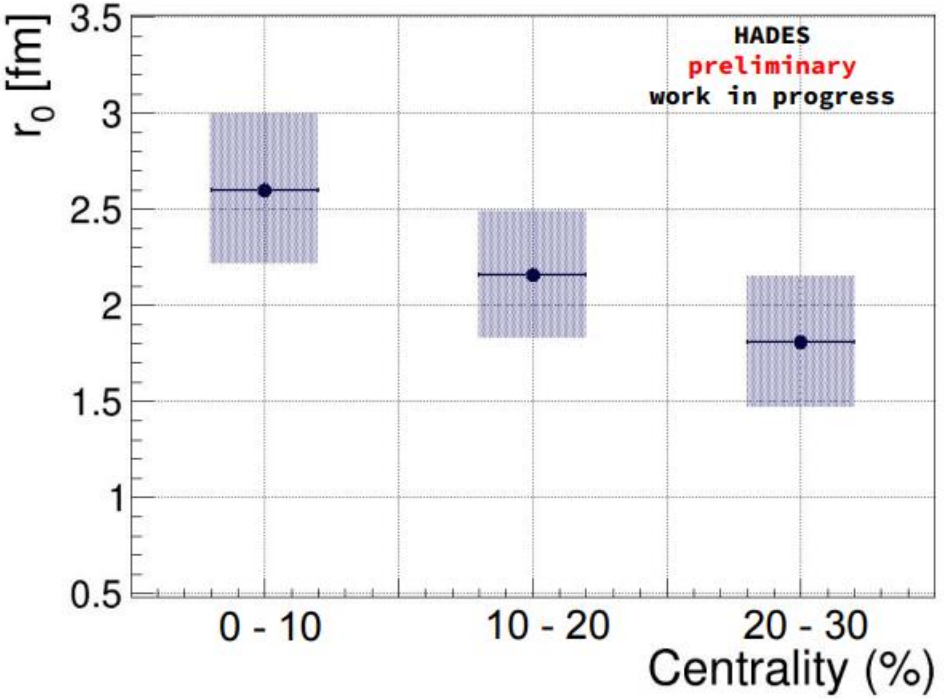
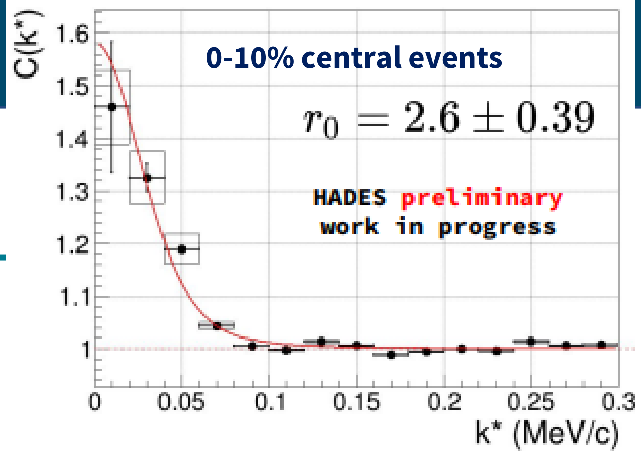
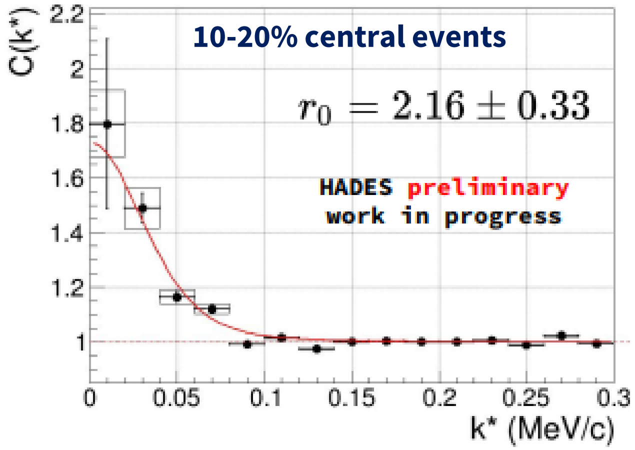
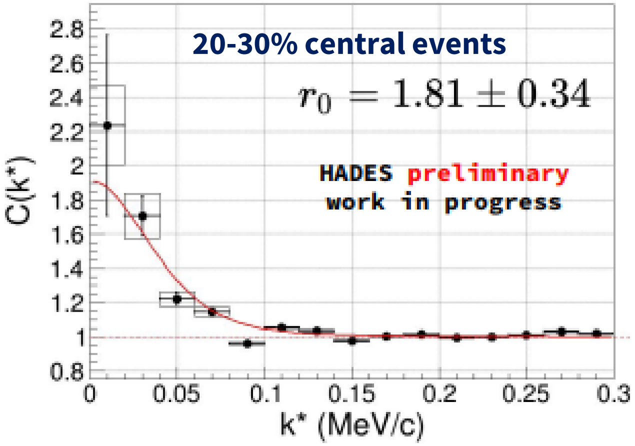






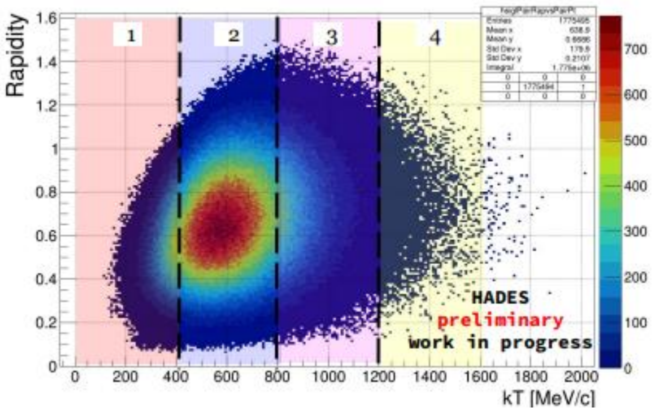


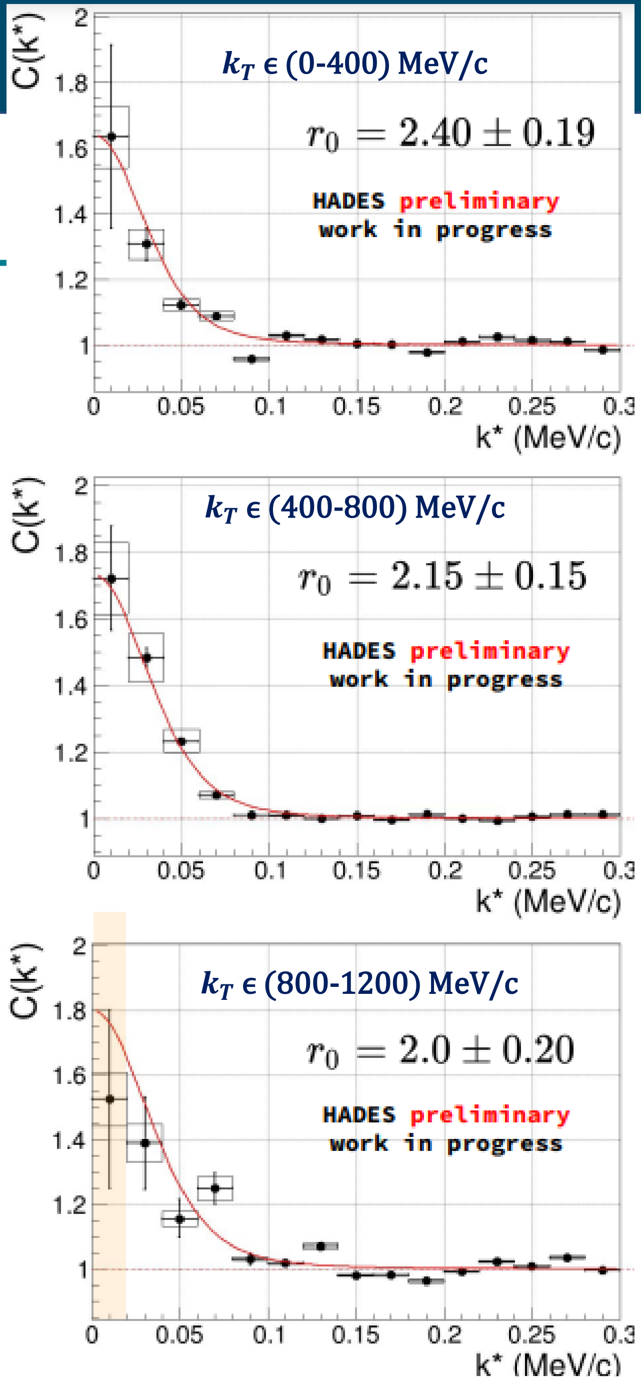
Expected centrality dependence

$r_0(0-10\%) > r_0(10-20\%) > r_0(20-30\%)$

p-Λ CF - Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 GeV

pair transverse mass dependence





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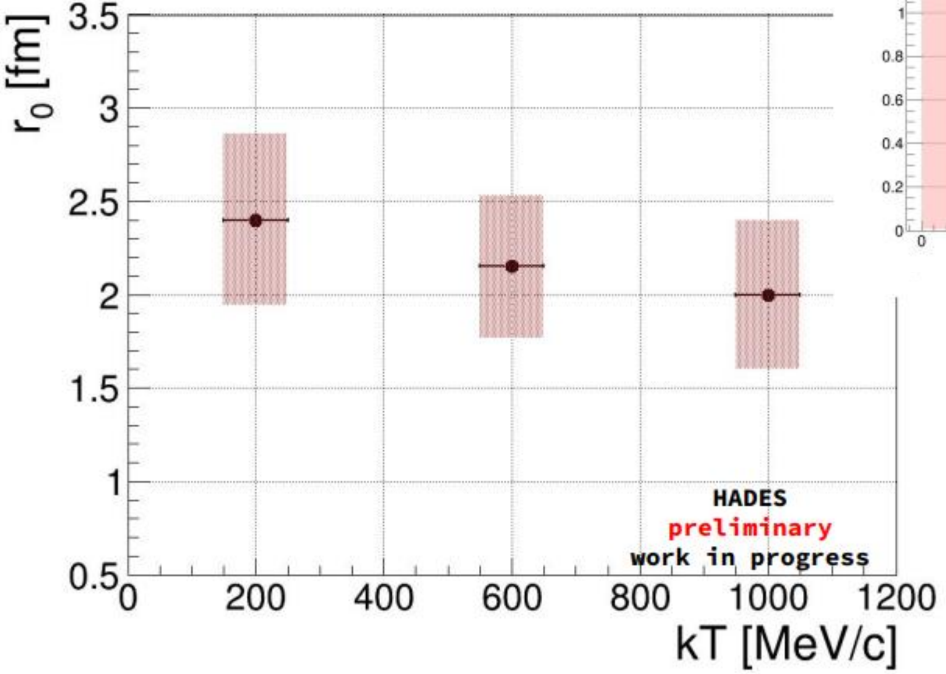
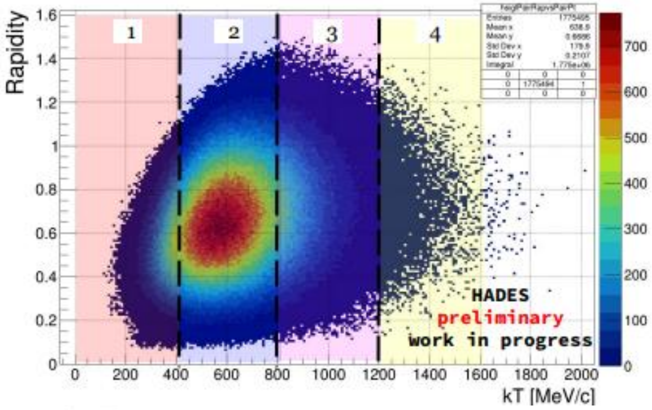
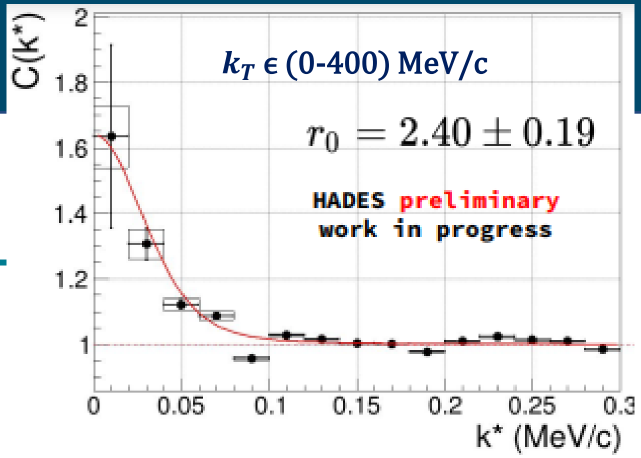
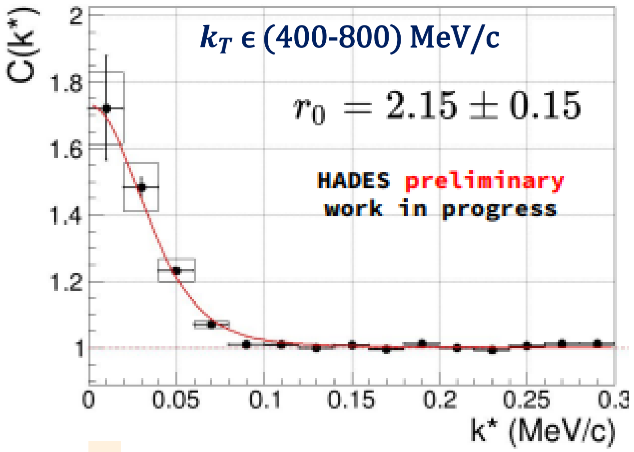
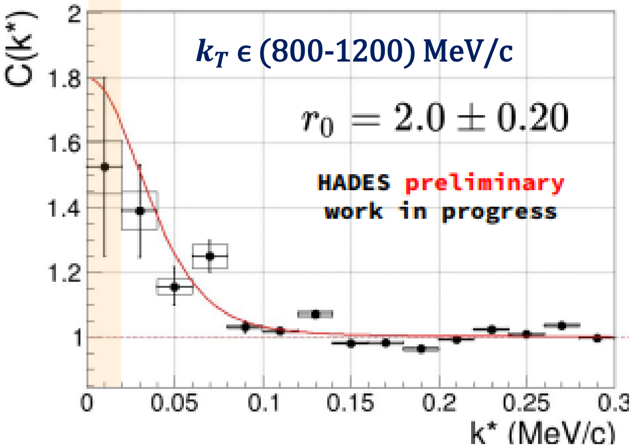










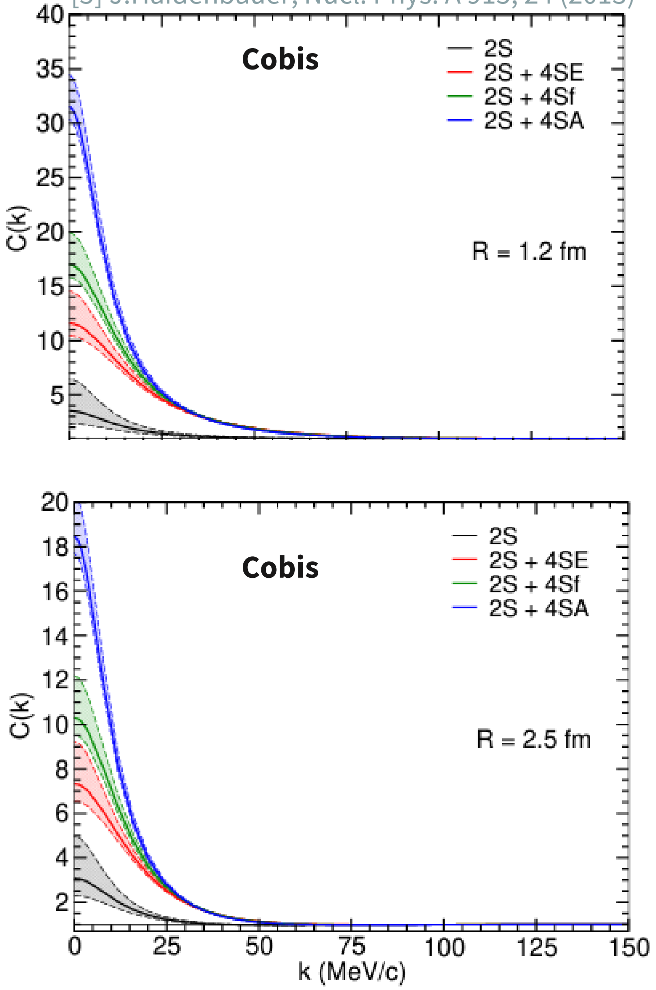
Expected k_T dependence

$$r_0(\mathrm{k_{T1}}) > r_0\mathrm{k_{T2}} > r_0(\mathrm{k_{T3}})$$

d-Λ correlation functions

d-Λ CF – theoretical predictions

[5] J.Haidenbauer, Nucl. Phys. A 915, 24 (2013)



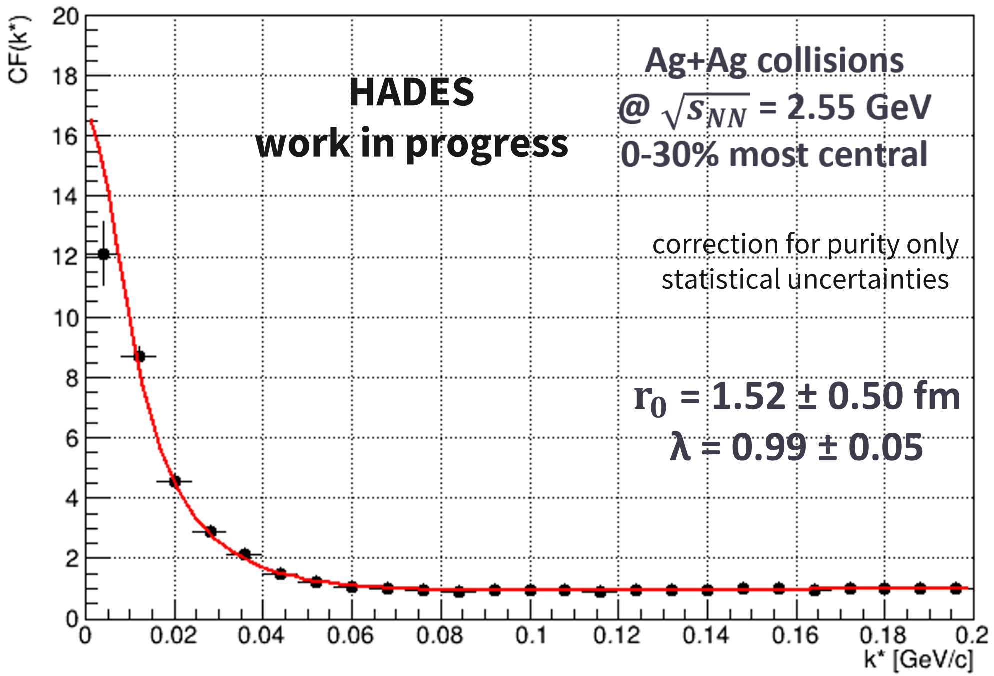
2S – spin averaged results where in doublet state the effective range expansion (ERE) parameters of Cobis
4S – quartet state results building on ΛN scattering lengths from Alexander (A), Rijken(f) and Haidenbauer (E)

		Cobis[1]	Hammer[2]	Alexander[3]	Rijken[4]	Haidenbauer[5]
D	f_0 [fm]	$-16.3^{+2.1}_{-4.0}$	$-16.8^{+2.4}_{-4.4}$			
	d_0 [fm]	3.2	2.3			
Q	f_0 [fm]			7.6	10.8	17.3
	d_0 [fm]			3.6	3.8	3.6

[1] A.Cobis, J.Phys. G 23, 401 (1997)
[2] H.W.Hammer, Nucl. Phys. A 705, 173 (2002)
[3] G.Alexander, Phys. Rev. 173, 1452 (1968)
[4] T.A.Rijken, Prog. Theor. Phys. Suppl. 185, 14 (2010)

d-Λ CF - Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 GeV

0-30% central events



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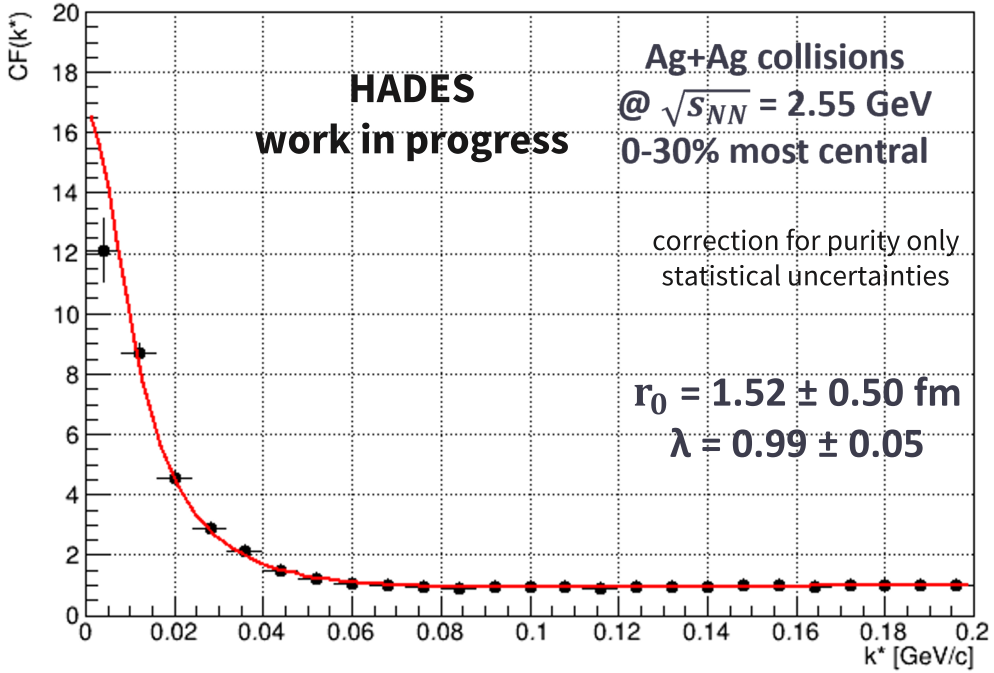
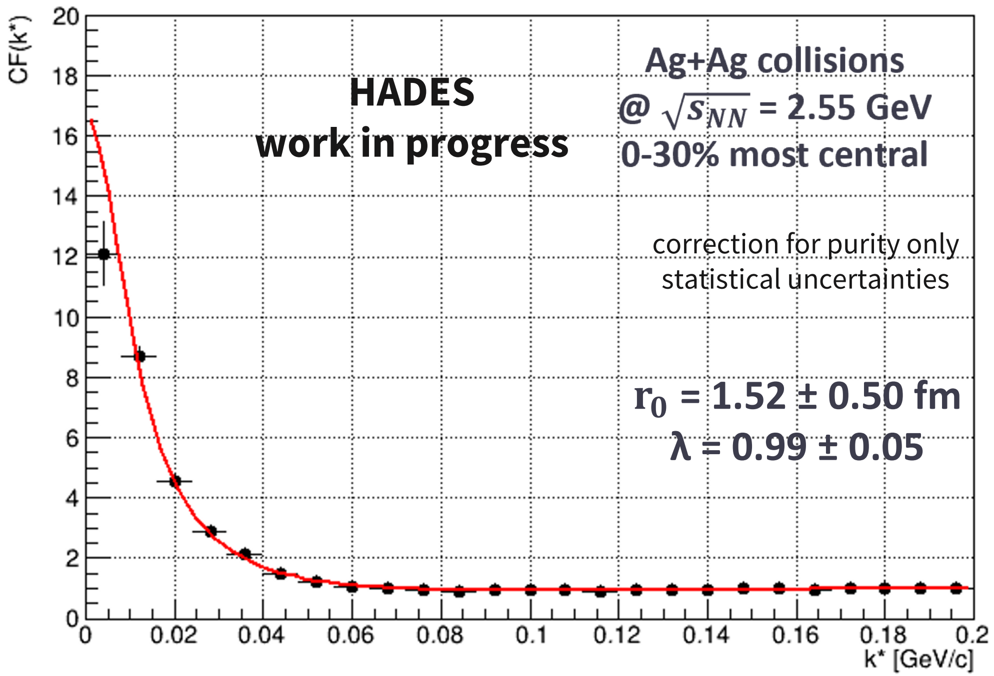


D	f_0 [fm]	$-12^{+1.44}_{-3.92}$
	d_0 [fm]	$4^{+0.18}_{-0.53}$
Q	f_0 [fm]	$15^{+1.73}_{-2.58}$
	d_0 [fm]	$4^{+0.13}_{-0.28}$

d-Λ CF - Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 GeV

0-30% central events



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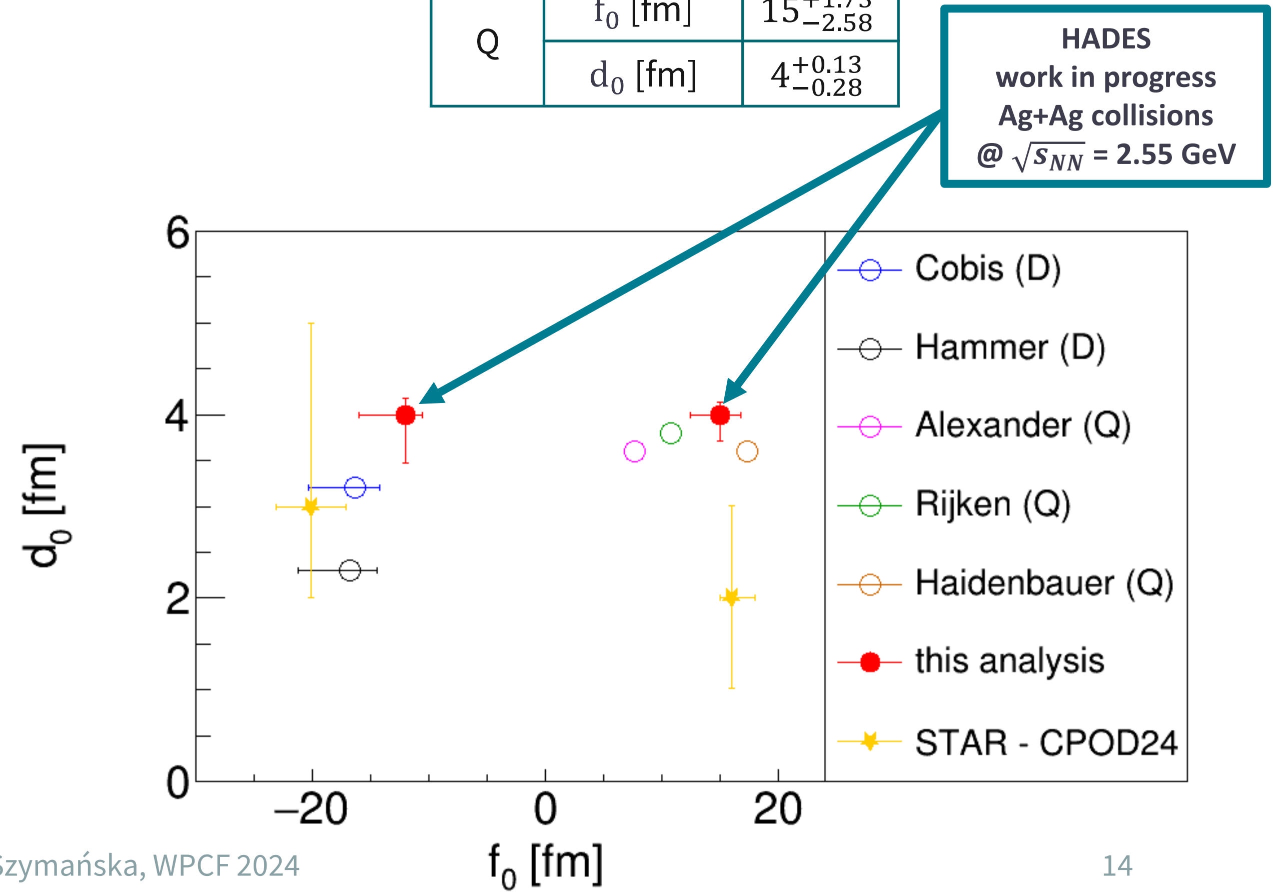
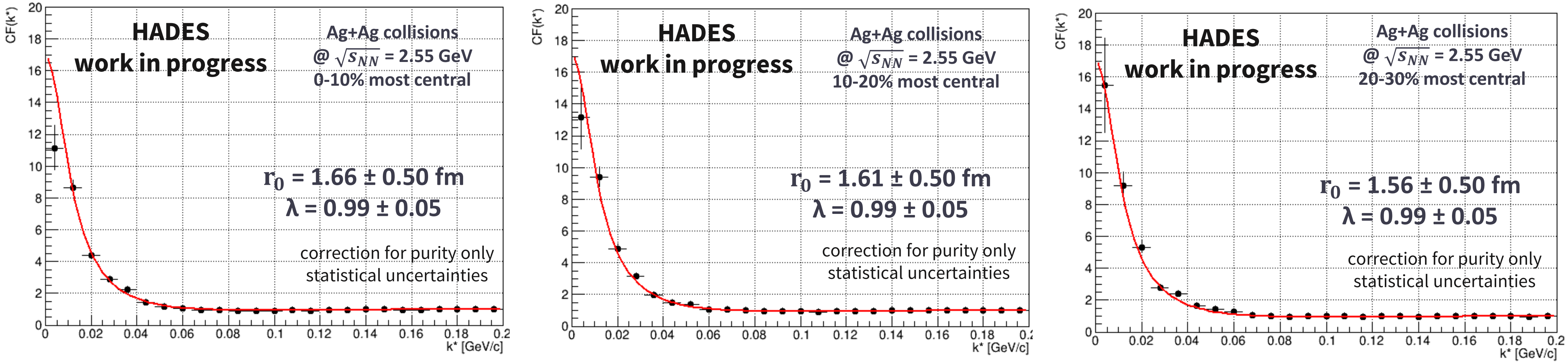


d-Λ CF - Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 GeV

centrality dependence



Expected centrality dependence

$$r_0(0-10\%) > r_0(10-20\%) > r_0(20-30\%)$$

Summary

The correlation signals in Ag+Ag collision were extracted : p–Λ and d-Λ

p–Λ correlation function

1. Resolution effects (θ, φ, p) studies are performed
2. Systematics studies are performed
3. Detector effects, purity determination and model interference are studied
4. Parameters of strong interaction:

Singlet state	$f_0 = 0.80^{+0.39}_{-0.32}\text{fm}$	$d_0 = 0.01\text{fm}$
Triplet state	$f_0 = 1.89^{+0.10}_{-0.09}\text{fm}$	$d_0 = 3.76^{+0.27}_{-0.25}\text{fm}$

d–Λ correlation function

1. First results using data collected by HADES are presented
2. Preliminary parameters of strong interaction:

Doublet state	$f_0 = -12^{+1.44}_{-3.92}\text{fm}$	$d_0 = 4^{+0.18}_{-0.53}\text{fm}$
Quartet state	$f_0 = 15^{+1.73}_{-2.58}\text{fm}$	$d_0 = 4^{+0.13}_{-0.28}\text{fm}$

Momentum resolution correction and systematic uncertainties are still work in progress

Thank you for your attention!

Uncertainties of strong parameters in d-Λ

10% difference in χ^2 test