Femtoscopy and EOS at HADES and CBM

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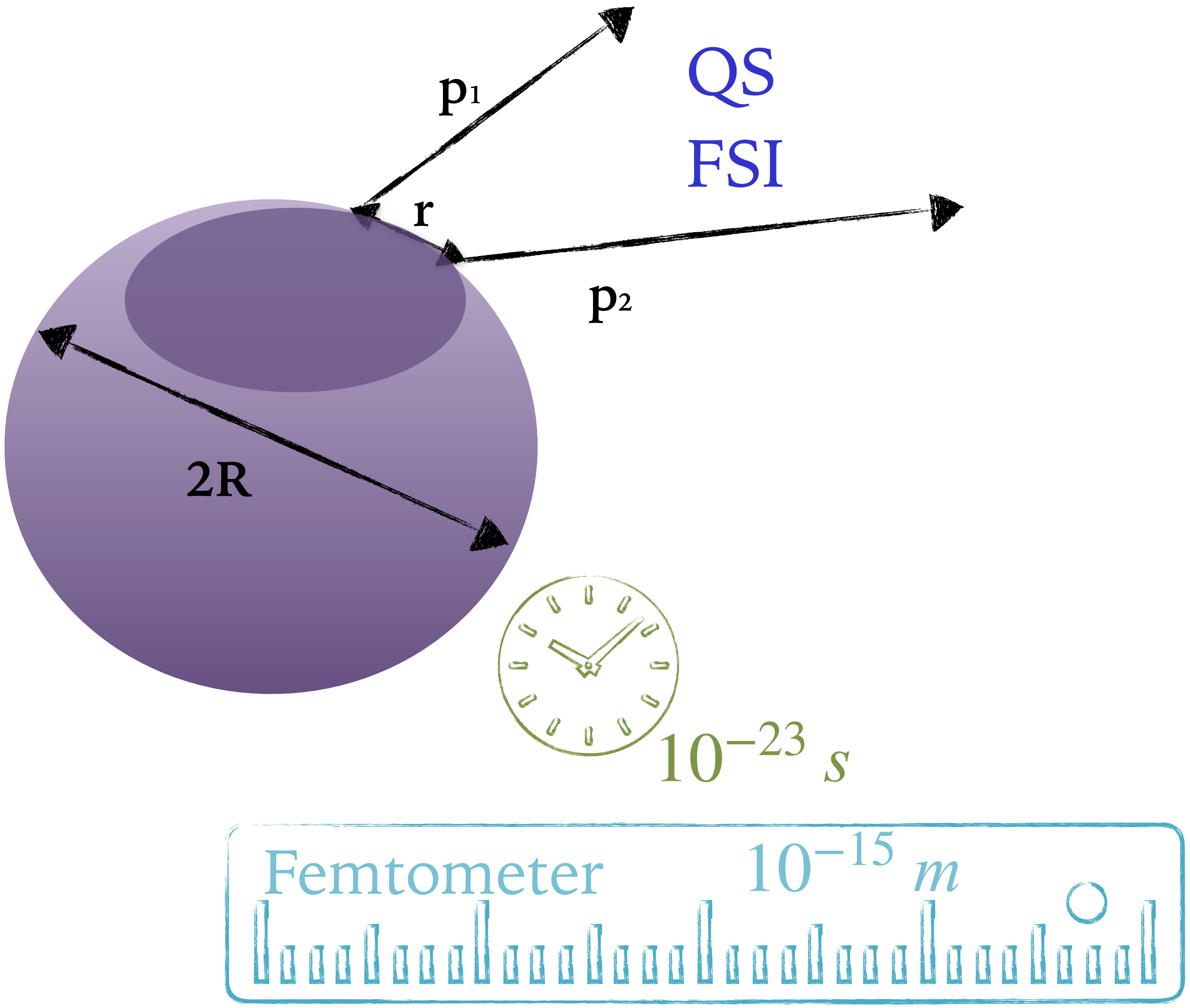
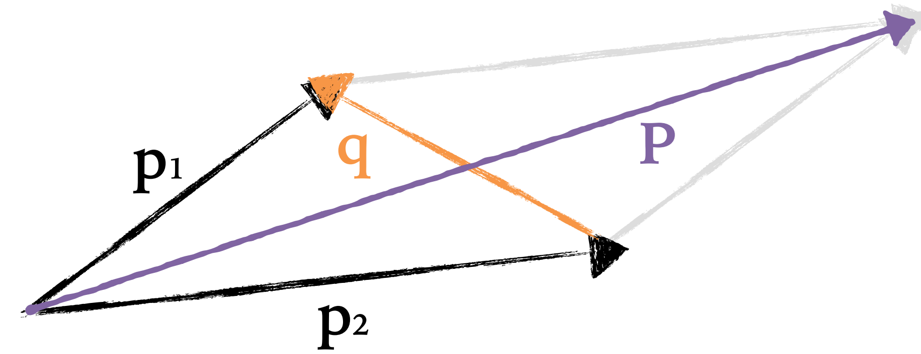
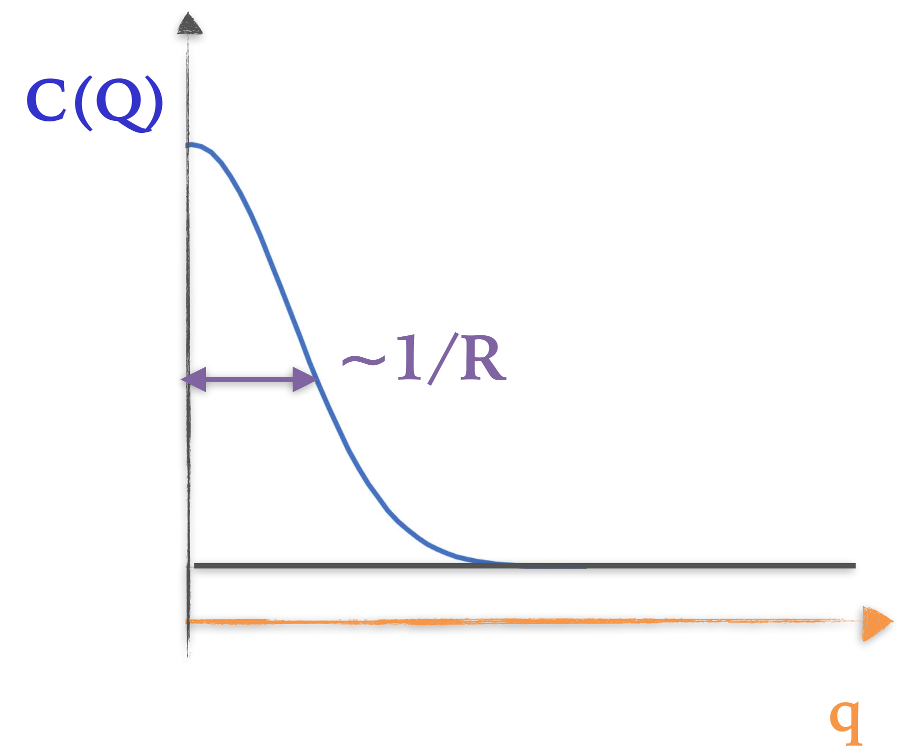
HADES
- **EoS studies**
- **NN, NY, YY**

CBM

EMMI Workshop: *Collective phenomena and the EOS of dense baryonic matter,* 10-13th November 2025, GSI







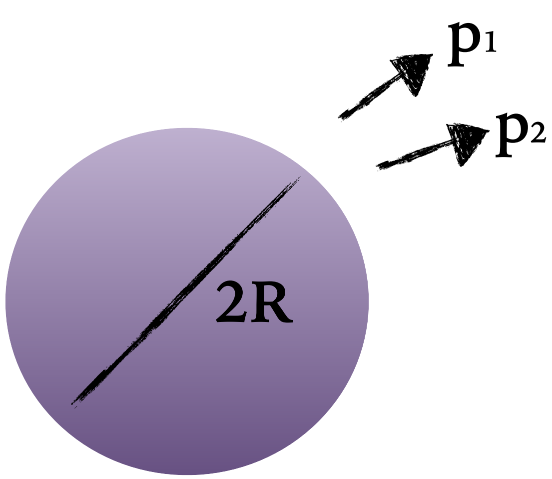
Femtoscopy

… the method to probe **geometric** and **dynamic** properties of the source (emission region, range of correlations-interactions, phase-space cloud, …)

Femtoscopy does not measure the whole source, but homogeneity length**.**

Classic femtoscopy

Femtoscopy (originating from HBT):
the method to probe **geometric** and **dynamic** properties of the source



Space-time properties ($10^{-15}m$, $10^{-23}s$) determined thanks to two-particle correlations:

Quantum Statistics (Fermi-Dirac, Bose-Einstein);

Final State Interactions (Coulomb, strong)

determined | assumed | measured

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

k^* - momentum of the first particle in the Pair Rest Frame reference

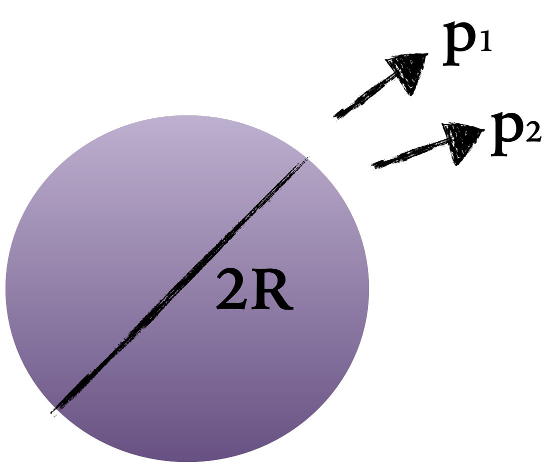
$S(r^*)$ - source function

$\Psi(k^*, r^*)$ - two-particle wave function (includes e.g. FSI interactions)

$\frac{Sgnl(k^*)}{Bckg(k^*)}$ - correlation function

Gateway to study interactions

If we assume we know the **source function**, measured **correlations** are used to determine **interactions in the final state.**



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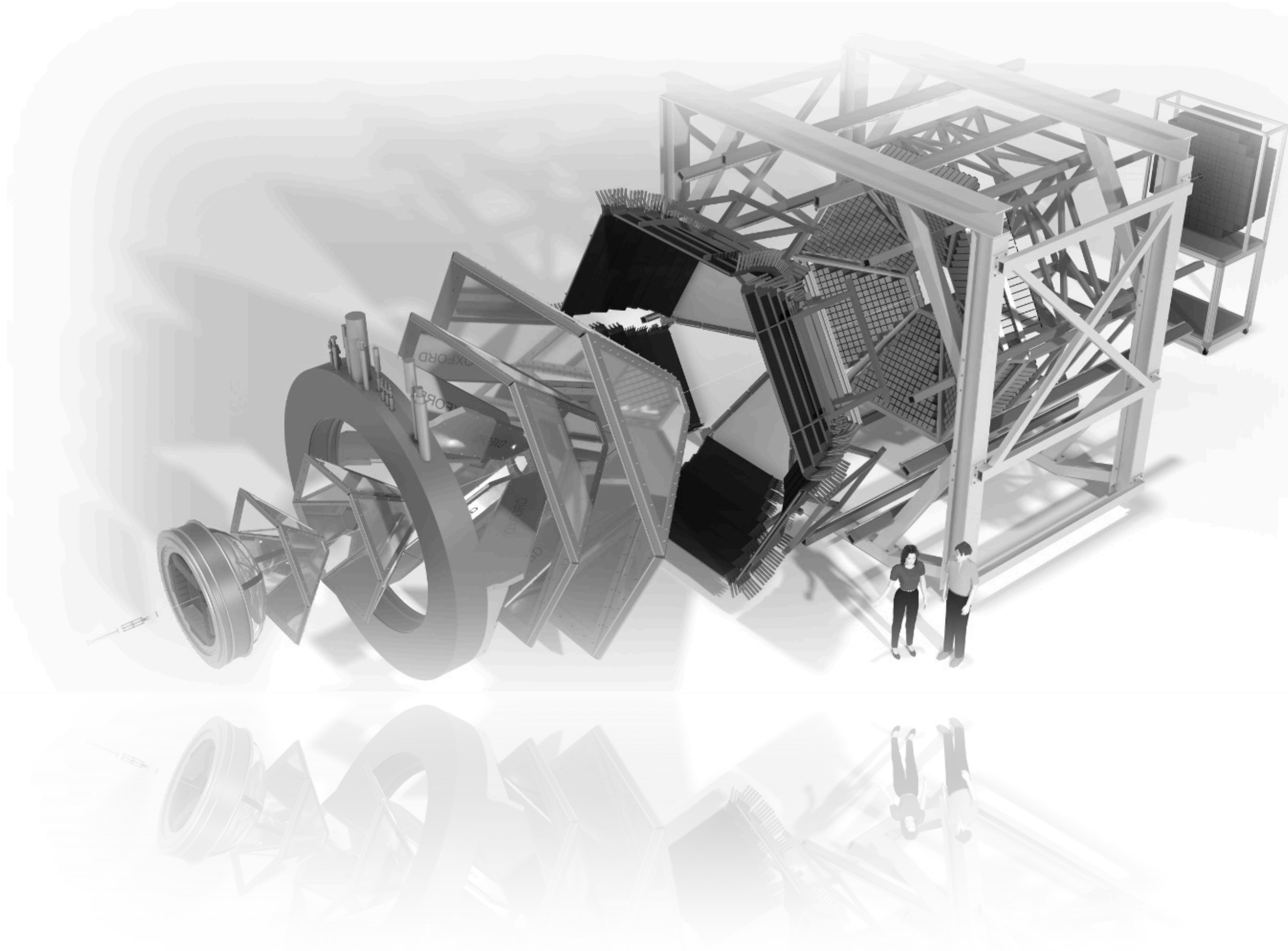
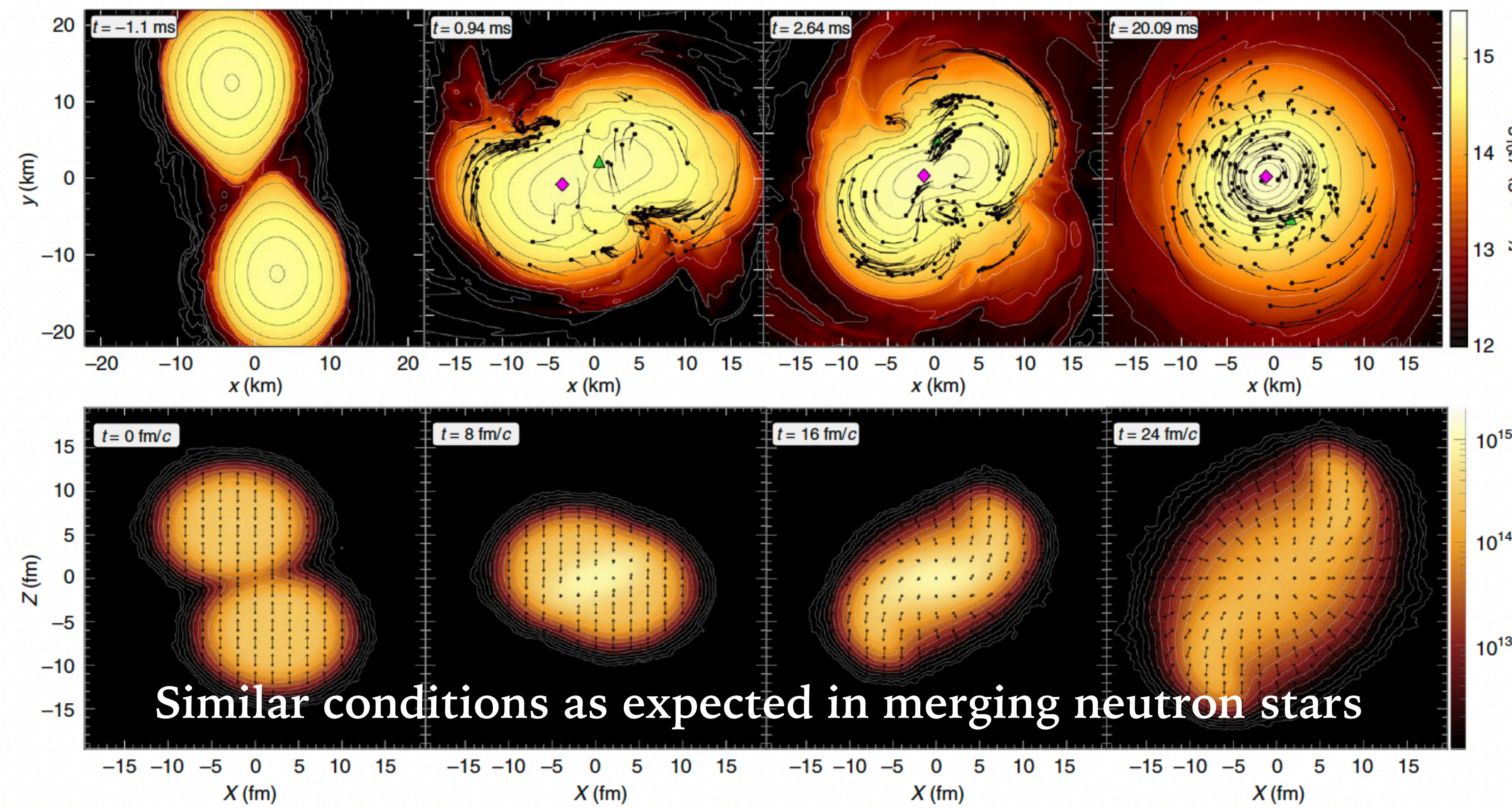


HADES

HADES physics goals



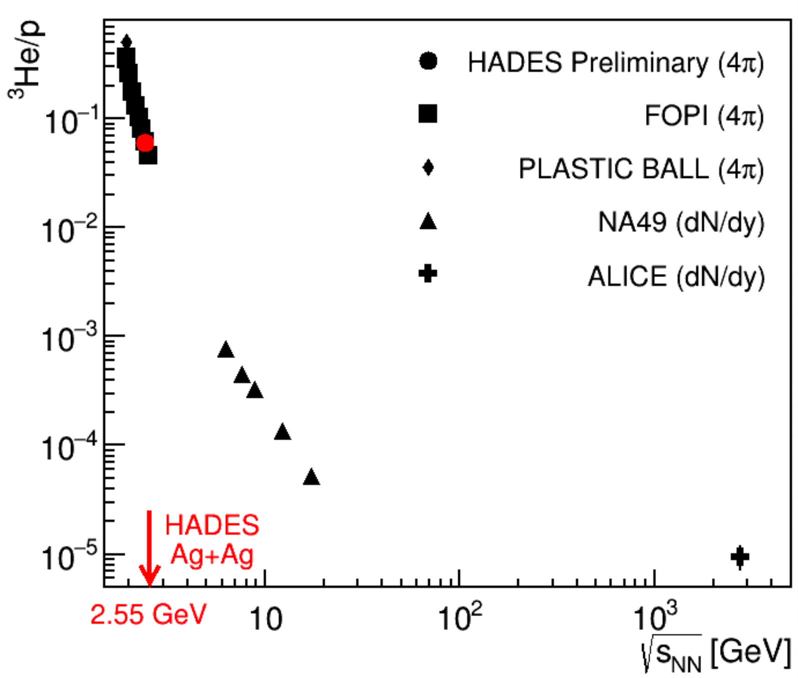
HADES, Nature Phys. 15, 1040–1045 (2019)

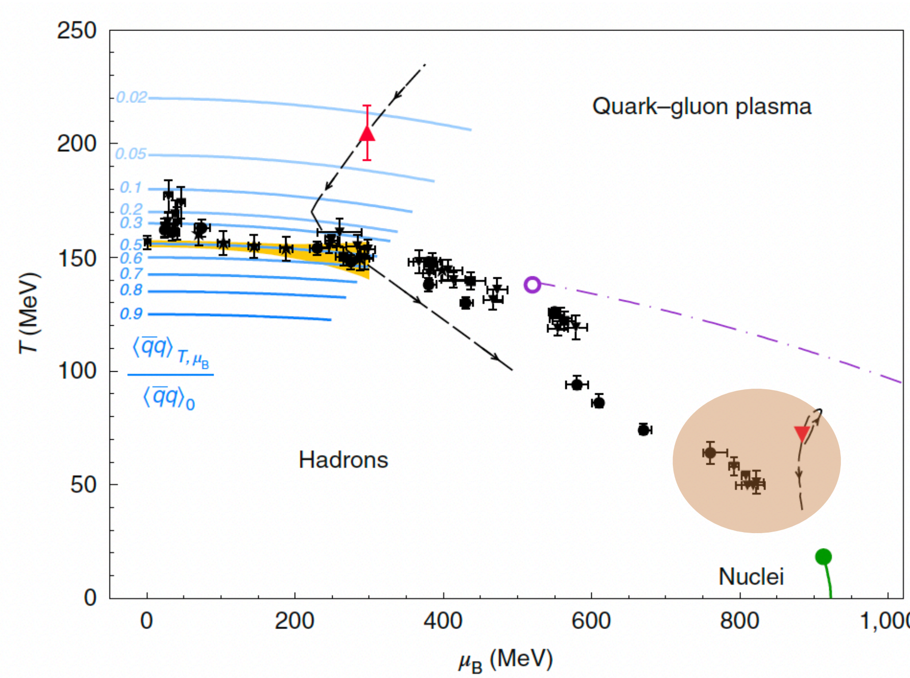
Heavy-ion collisions at $\sqrt{s_{NN}}$ up to 2.7 GeV

- Microscopic properties of baryon dominated matter
- EoS observables

π^- ($\sqrt{s}$ up to 2.35 GeV) and nucleon ($\sqrt{s}$ up to 3.46 GeV) beams:

- Reference measurements (vacuum, cold QCD matter)
- Electromagnetic structure of baryons and hyperons





High Acceptance Di-Electron Spectrometer

Fixed target experiment at **SIS-18** accelerator (**GSI**, Germany)

Magnet spectrometer

Low mass Mini-Drift-Chambers (MDCs)

Time of flight walls: RPC and TOF

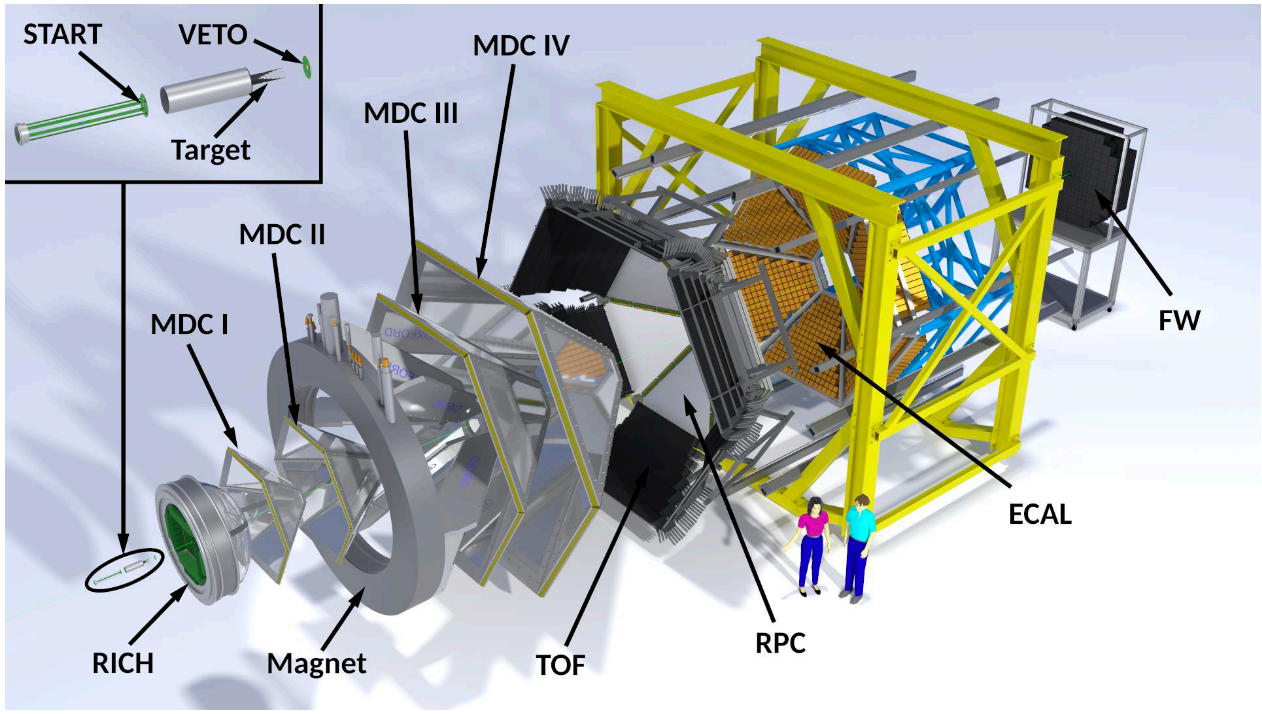
RICH and ECAL for e^+/e^- and photon identification

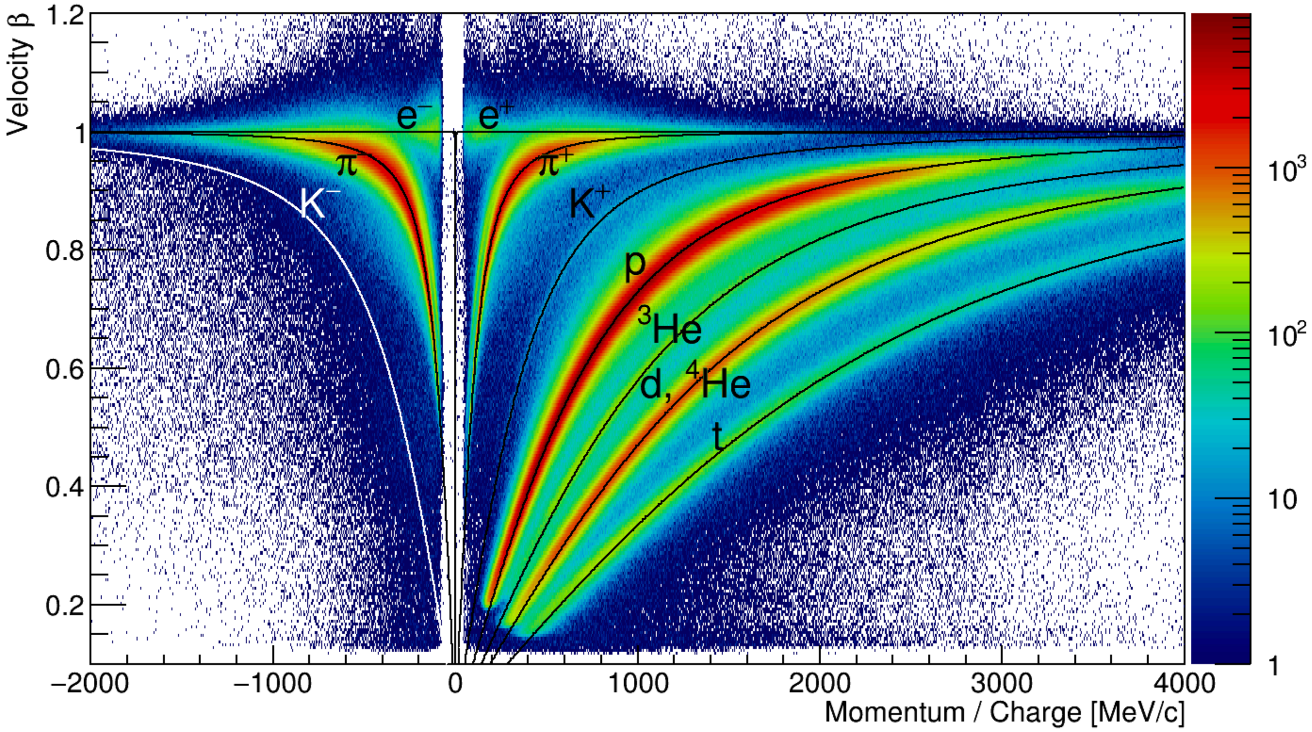
Full azimuthal angle and polar angles between 18° and 85° covered

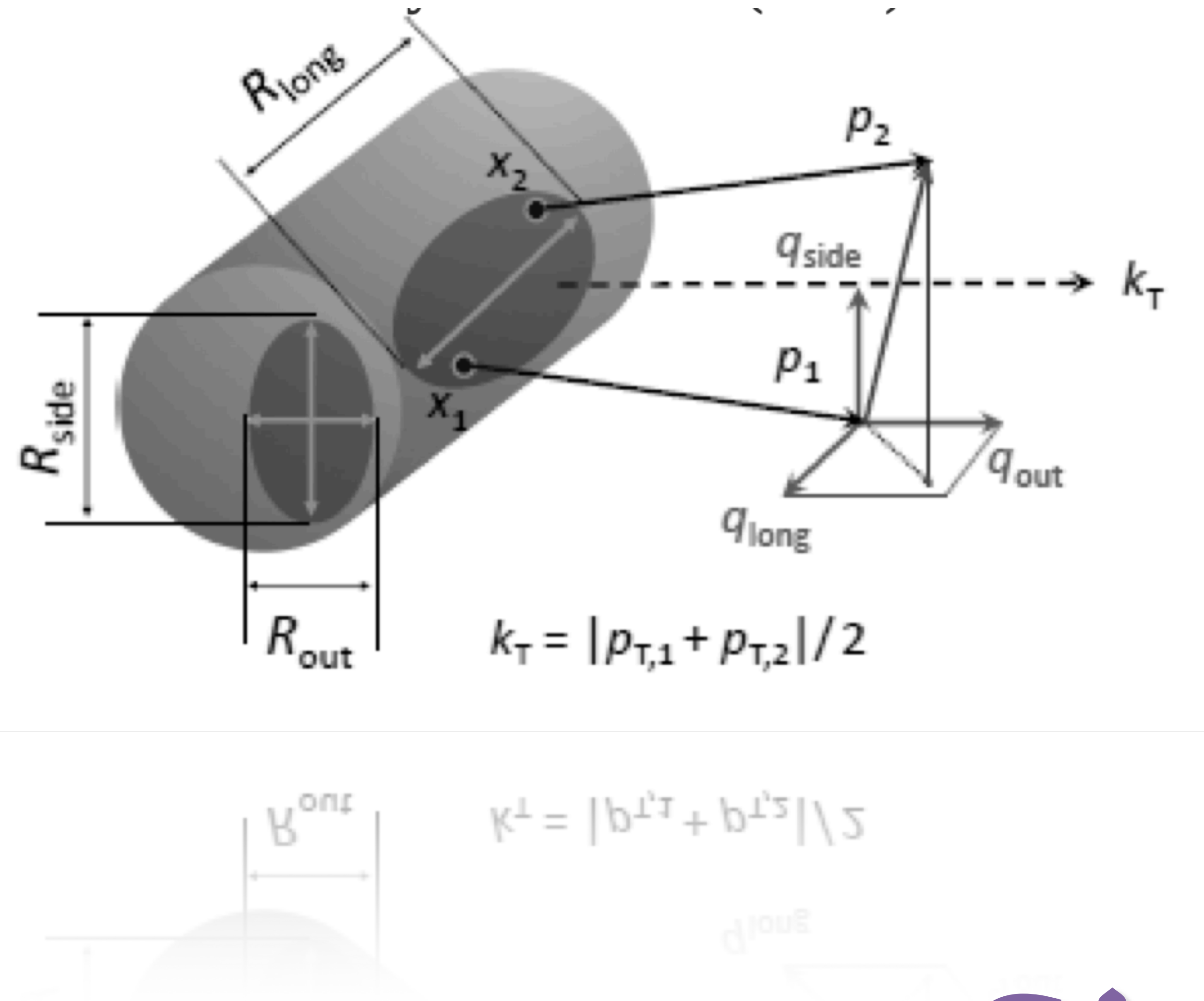
2012: Au+Au, $\sqrt{s_{NN}} = 2.42$ GeV (7 billion)

2019: Ag+Ag, $\sqrt{s_{NN}} = 2.55$ GeV
and 2.42 GeV (14 billion)

2024: Au+Au, $\sqrt{s_{NN}} = 2.24$ GeV (1.8 billion)





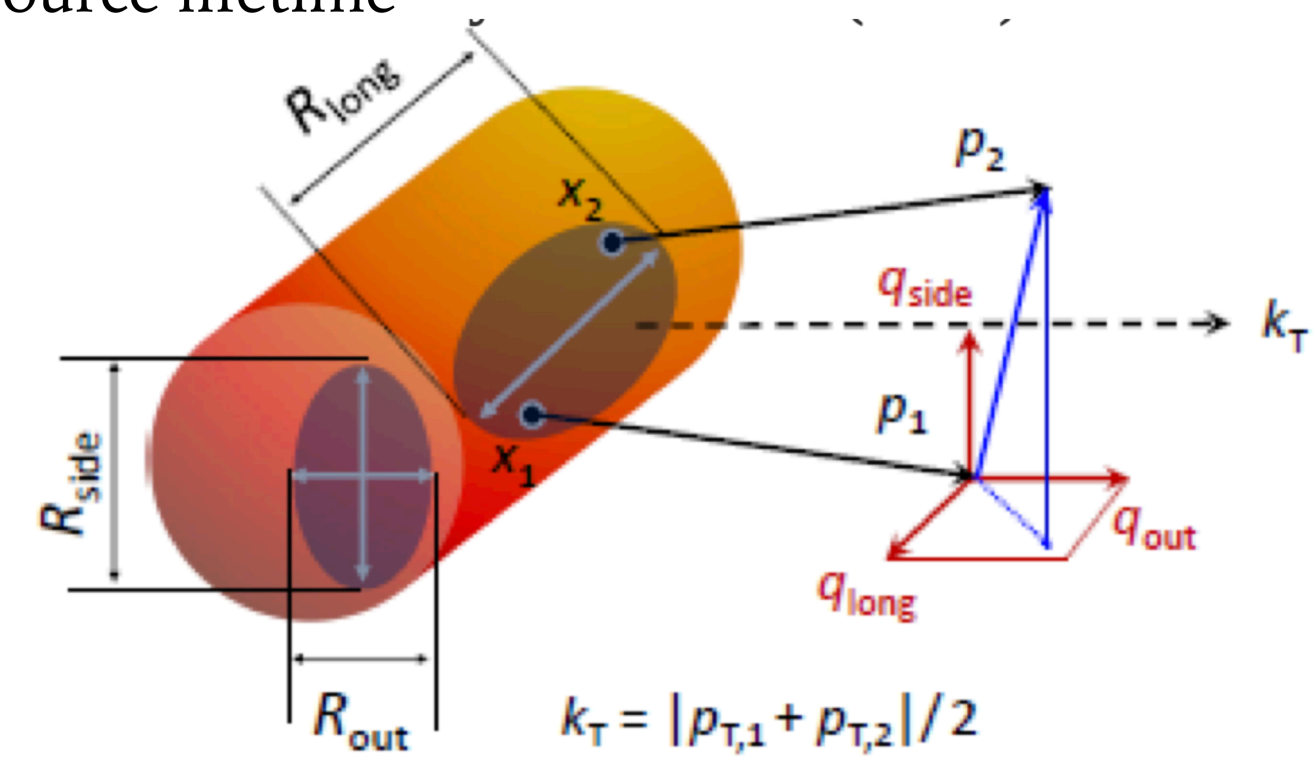


Sizes and dynamics

Bertsch-Pratt parametrization, 3D- and 1D-dimensional cases

→ R_{side} spatial source evolution in the transverse direction
→ R_{out} related to spatial and time components
→ R_{out}/R_{side} signature of phase transition
→ $R_{out}^2 - R_{side}^2 = \Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time
→ R_{long} temperature of kinetic freeze-out and source lifetime

long - determined by the beam direction
out - determined by the pair transverse momentum
side - perpendicular to *long* and *side*

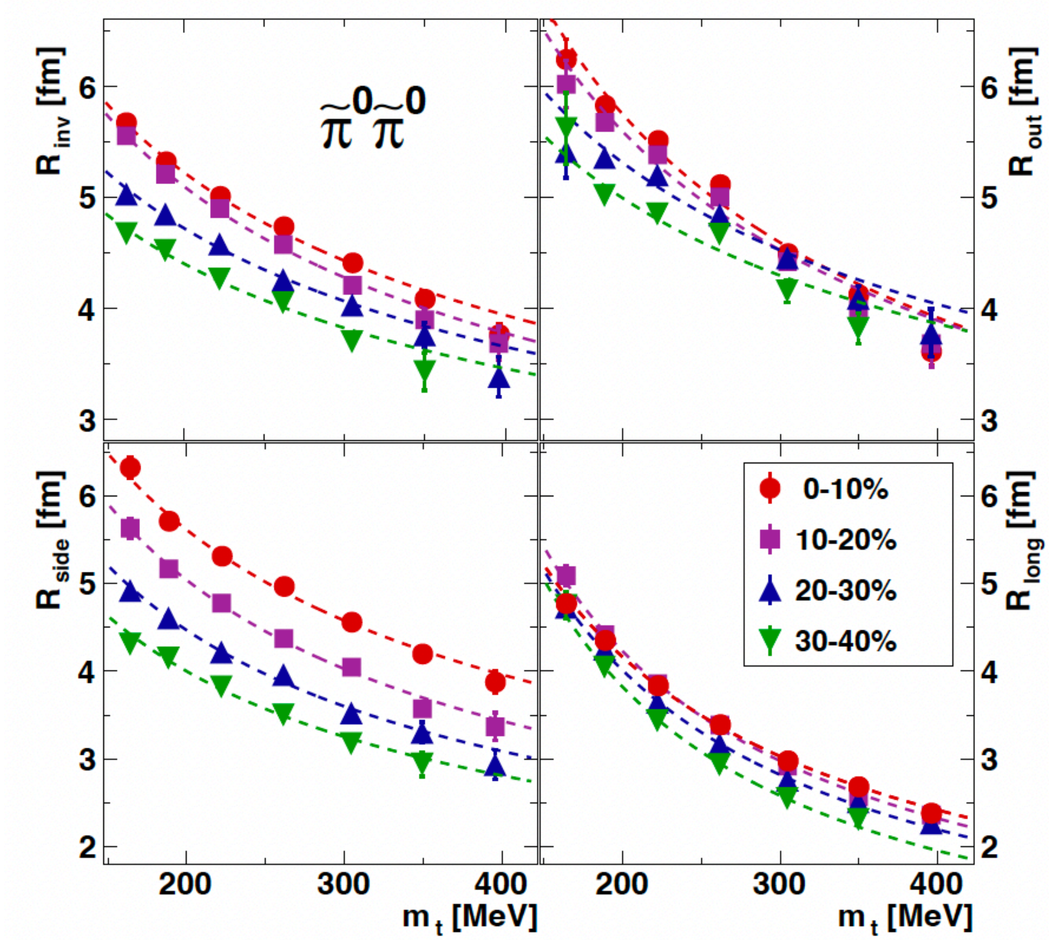


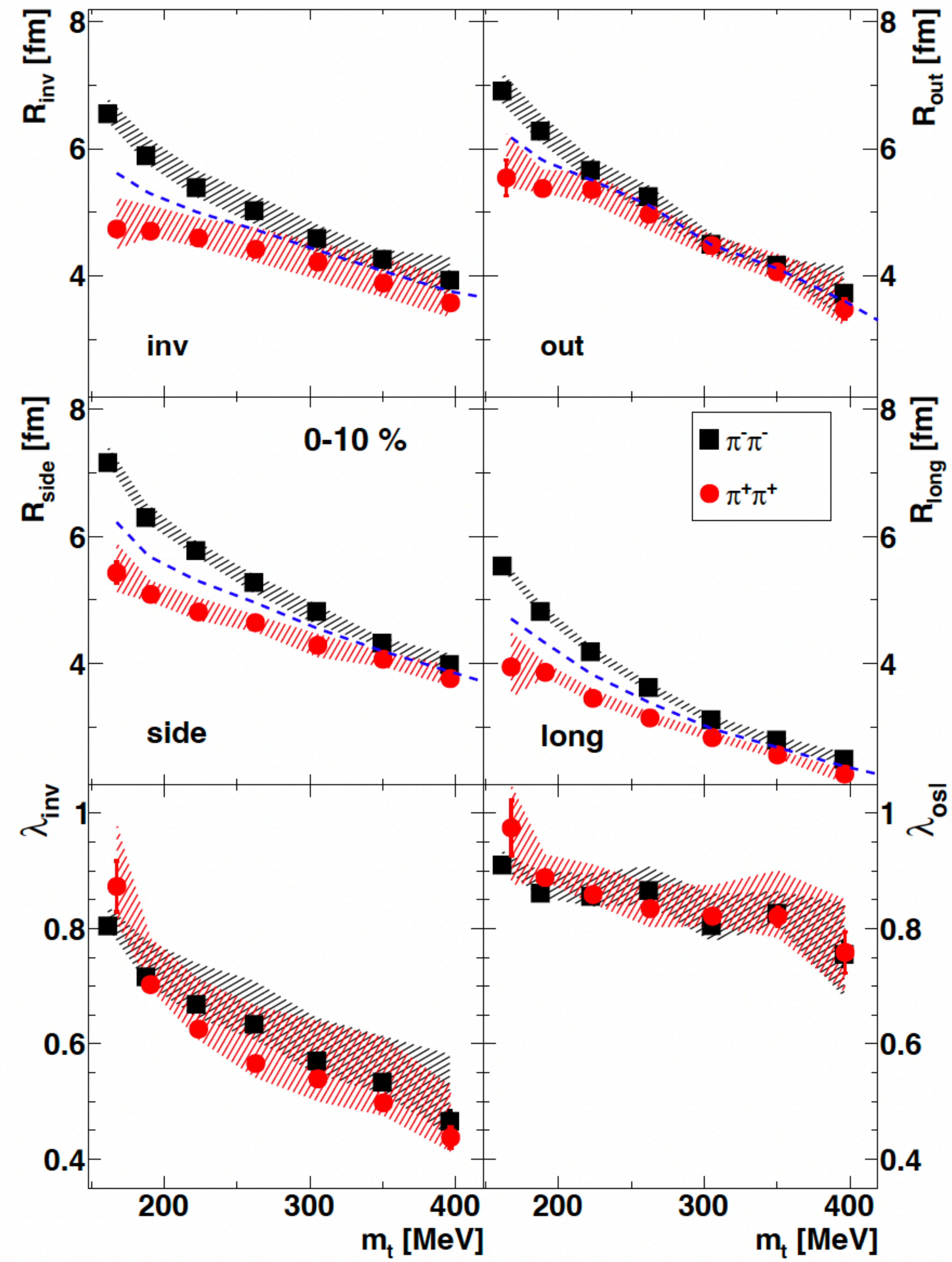
3D case is considered if statistics is enough and two-particle correlations are easy to describe (Quantum Statistics and Coulomb FSI).

$$C(\vec{q}) = (1-\lambda) + K_{\mathrm{Coul}}(q_{\mathrm{inv}})\lambda$$
$$\times \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2q_o q_s R_{os}^2 - 2q_o q_l R_{ol}^2\right)$$

Identical pion correlations

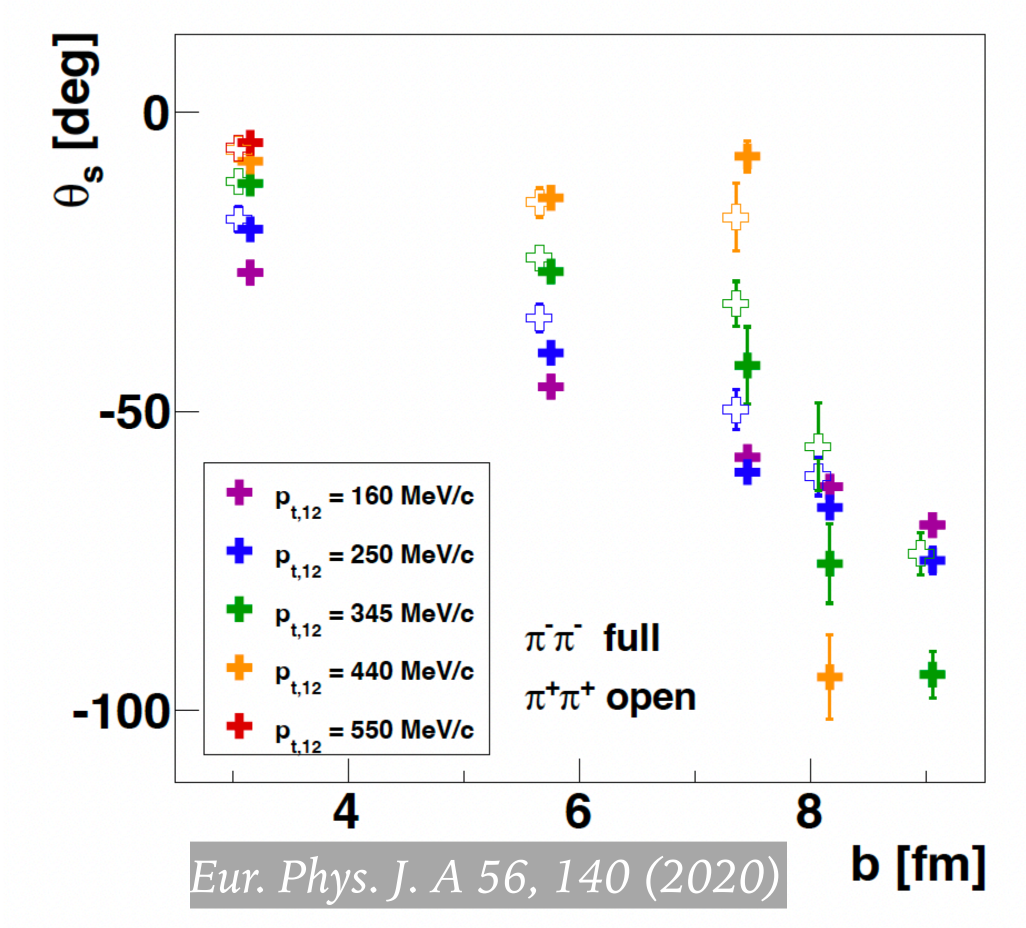
- 10% of most central collisions.
- 7 k_T intervals.
- Differences in HBT parameters for π^- and π^+ (especially low p_T) due to Coulomb effect.
- Neutral π deduced from interpolations of the charged π data.



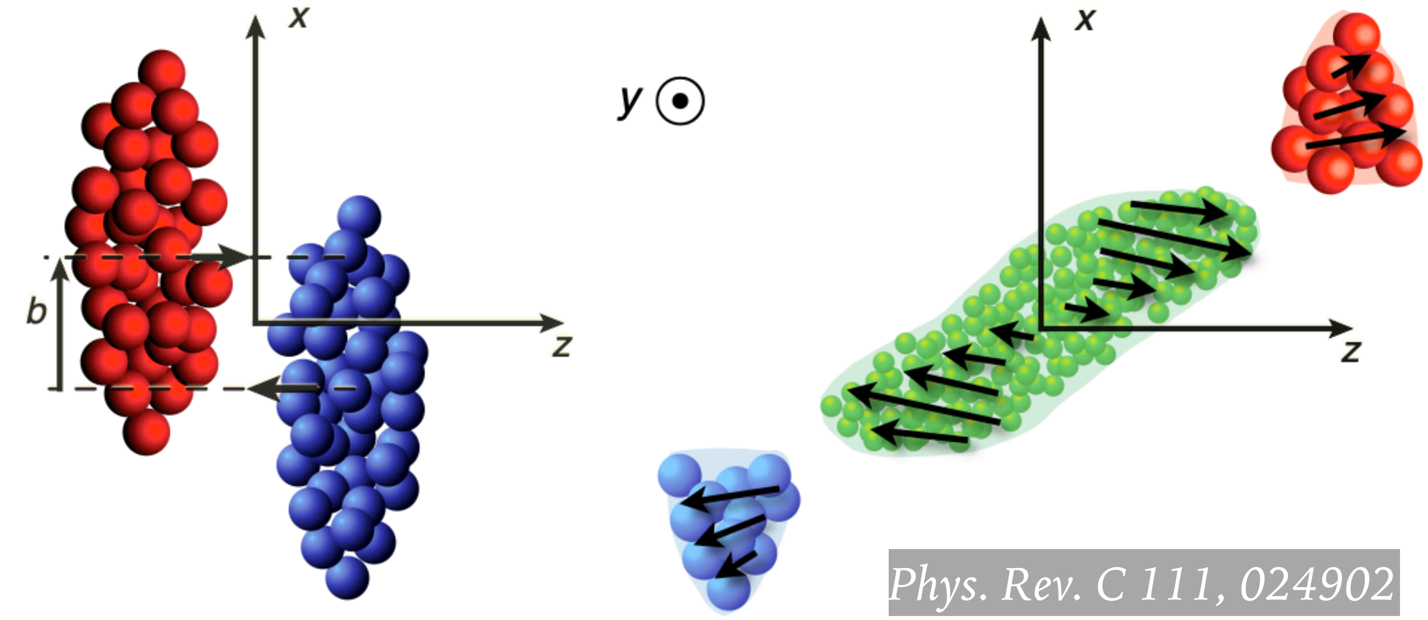


Eur. Phys. J. A 56, 140 (2020)

Identical pion correlations - the tilt angle



Eur. Phys. J. A 56, 140 (2020)



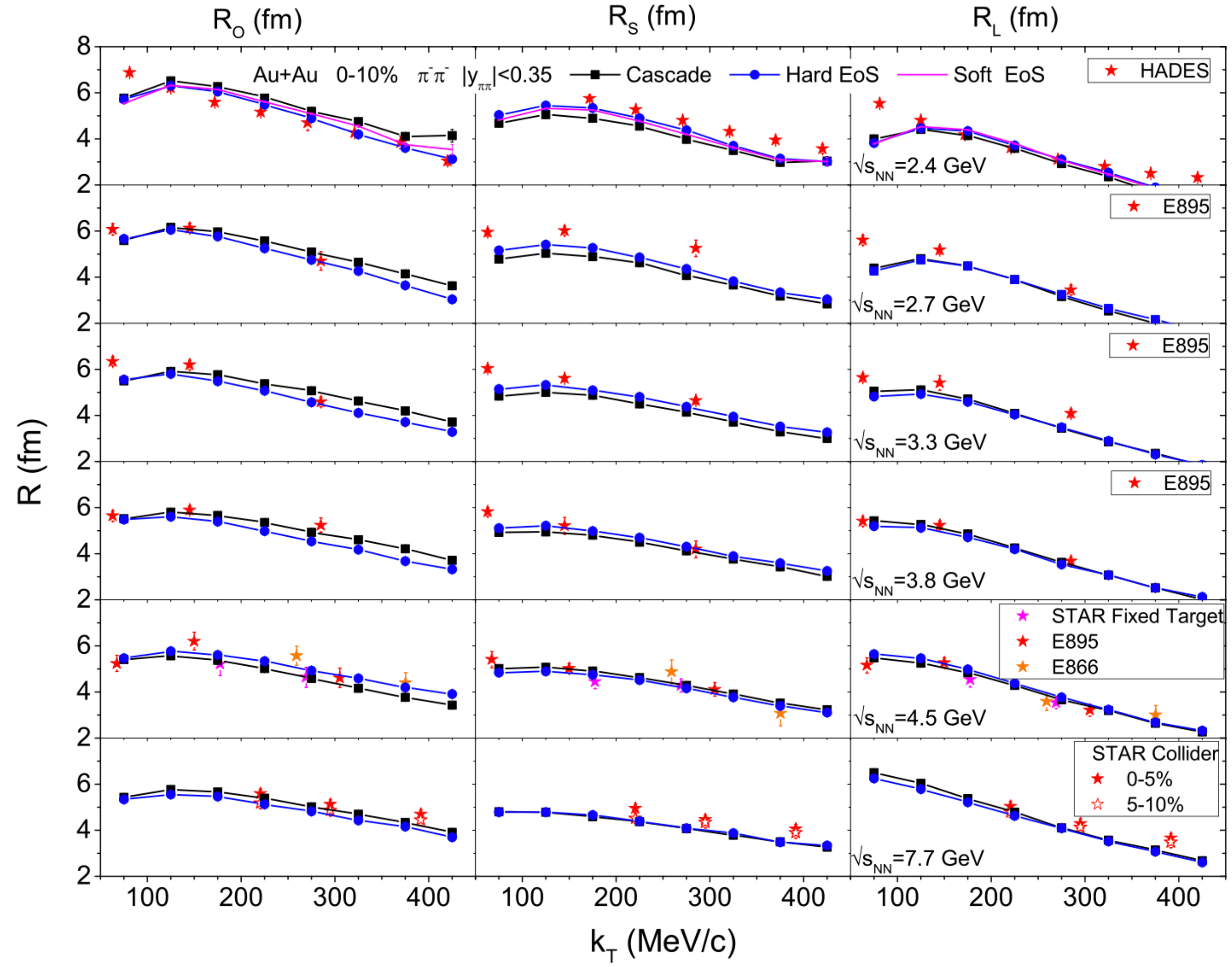
Phys. Rev. C 111, 024902

- Directed flow is attributed to the tilted source (from forward-backward asymmetry of the initial geometry).
- Tilt angle of the source describes the azimuthal distribution of the particles.

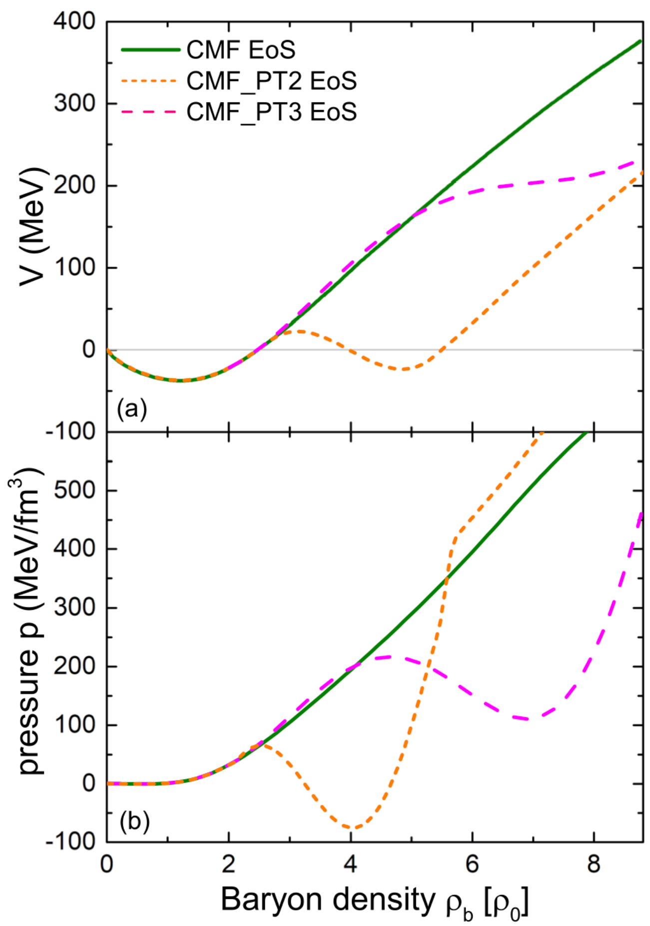
$$\theta_{out-long} = \frac{1}{2}tan^{-1}(\frac{4R^2_{out-long,1}}{R^2_{long,0} - R^2_{side,0} + 2R^2_{side,2}}) \qquad \theta_{side-long} = \frac{1}{2}tan^{-1}(\frac{4R^2_{side-long,1}}{R^2_{long,0} - R^2_{side,0} + 2R^2_{side,2}})$$

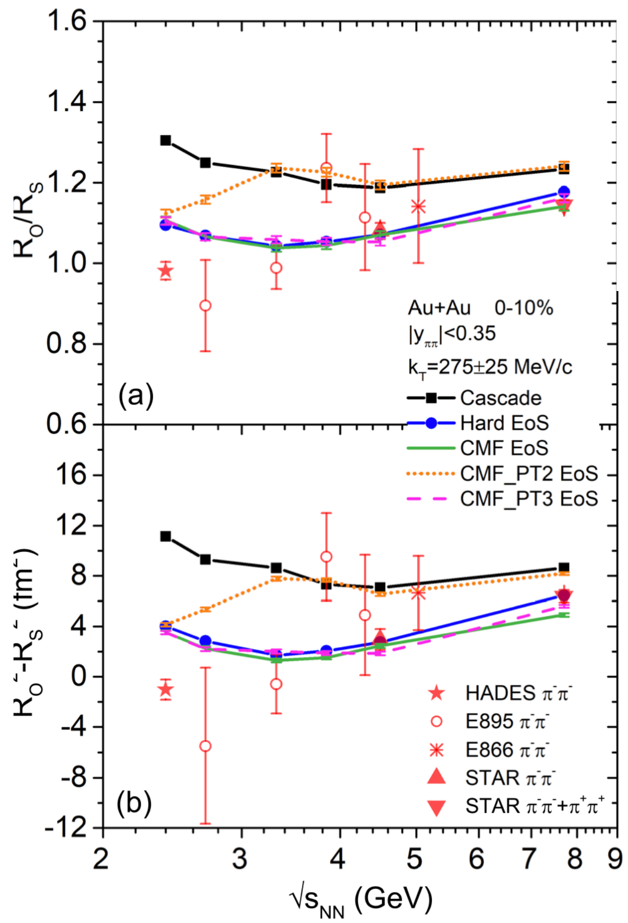
Sensitivity of the HBT to the EoS with UrQMD

- HBT parameters sensitive to the stiffness of the EoS, can be used to constrain and understand the QCD EoS.
- PT with a significant softening of the EoS below 4 times nuclear saturation density can be excluded.

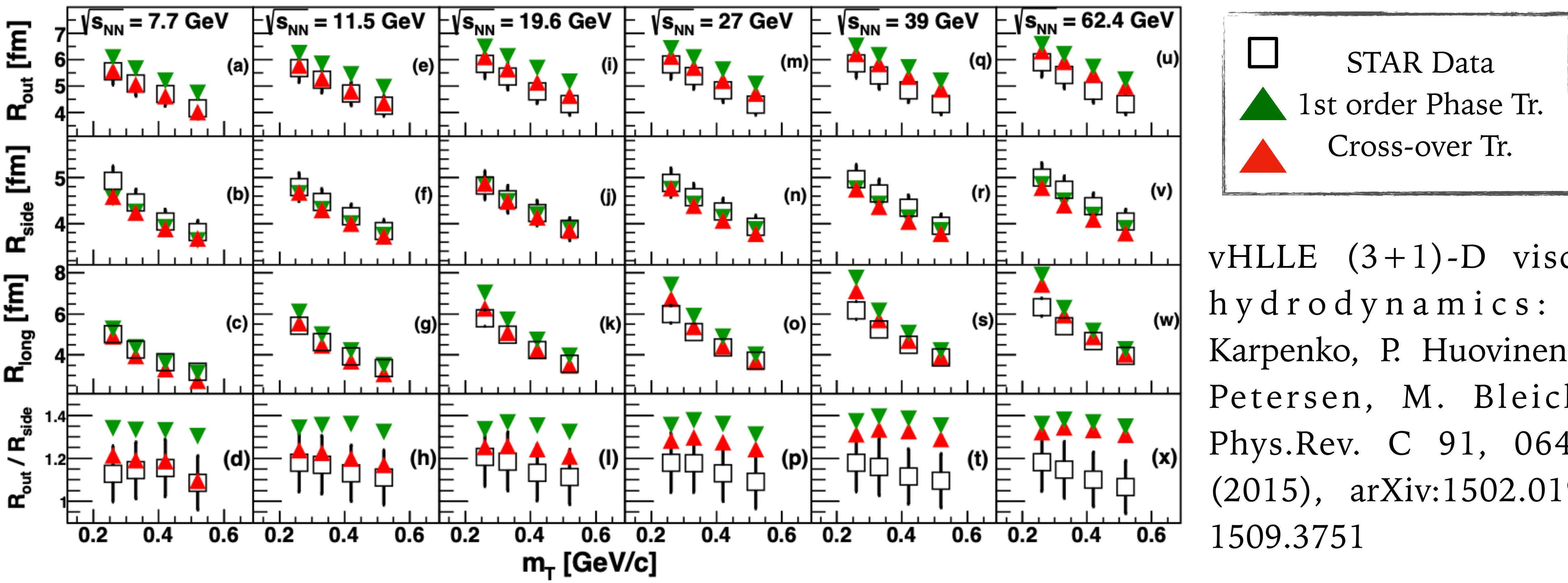


Sci. China-Phys. Mech. Astron. 66, 232011 (2023)





How to measure phase transition?



vHLLE (3+1)-D viscous hydrodynamics: Iu. Karpenko, P. Huovinen, H. Petersen, M. Bleicher; Phys.Rev. C 91, 064901 (2015), arXiv:1502.01978, 1509.3751

Pre-thermal → Hydrodynamical phase → Hydronic cascades

UrQMD — vHLEE — UrQMD

HadronGas + Bag Model → 1st order PT ; P.F. Kolb, et al, PR C 62, 054909 (2000)

Chiral EoS → crossover PT (XPT); J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

vHLEE+UrQMD model verify **sensitivity of HBT measurements to the first-order phase transi**tion

Phys. Rev. C 96 (2017) no.2, 024911

3D / asHBT to be studied for p-p correlations

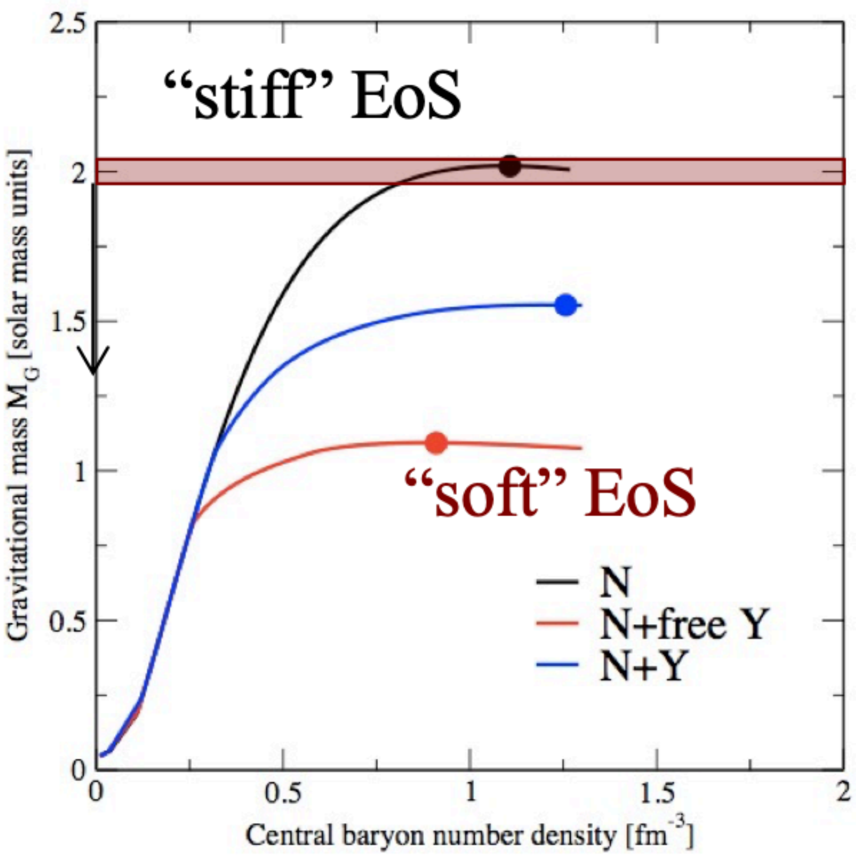
NN, NY interactions

Neutron star puzzle

- **Hyperons**: expected in the core of neutron stars; **conversion of N into Y energetically favorable.**
- Appearance of Y: The relieve of Fermi pressure → **softer EoS → mass reduction (incompatible with observation).**

$M_{NS} \approx 1 \div 2\ M_{\odot}$
$R \approx$ 10-12 km
$\rho \approx 3 \div 5\ \rho_0$

The solution requires a mechanism that could provide the **additional pressure** at high densities needed to make the EoS stiffer.



$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3

A few possible mechanisms, one of them:

Two- (and more) body YN, YY, NNY, NYY, … interactions.

The existence of **hypernuclei** (confirmed by attractive YN interaction) → indicates the possibility to bind Y to N. The measurement of the YN and YY interactions leads to important implications for the possible formation of **YN, YY, NNY, NYY, … bound states**.

Lednicky-Lyuboshitz model

The correlation function can be calculated analytically by averaging **Ψ** over the total spin S and the distribution of the relative distances **S(r*)**

Ref : Lednicky, Richard & Lyuboshits, V.L.. (1982). Sov. J. Nucl. Phys. (Engl. Transl.); (United States). 35:5.

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

The normalized pair separation distribution (source function) **S(r*)** is assumed to be Gaussian,

$$S(r^*) = (2\sqrt{\pi} r_0)^{-3} e^{-\frac{r^{*2}}{4r_0^2}},$$

$$\Psi^S(r^*,k^*) = e^{-ik^*r^*} + f^S(k^*)\frac{e^{ik^*r^*}}{r^*} \qquad f^S(k^*) = \left(\frac{1}{f_0^S} + \frac{1}{2}d_0^S k^{*2} - ik^*\right)^{-1}$$ Strong

$$|\Psi^C(r^*,k^*)| = \sqrt{A_C}\,e^{-ik^*r^*}F(-i\eta,1,i\zeta) \qquad A_C(\eta) = \frac{2\pi}{k^* a_c}\left(exp\left(\pm\frac{2\pi}{k^* a_c}\right) - 1\right)^{-1}$$ Coulomb

F- confluent hypergeometric function

f_0 and d_0 - parameters of strong interaction.

Theoretical correlation function (k*) depends on: R, f_0 and d_0.

f_0 - the scattering length, determines low-energy scattering.

The elastic cross section, σ_e, (at low energies) determined by the scattering length, $\lim_{k\to 0}\sigma_e = 4\pi f_0^2$

d_0 - the effective range, corresponds to the range of the potential (simplified scenario - the square well potential.

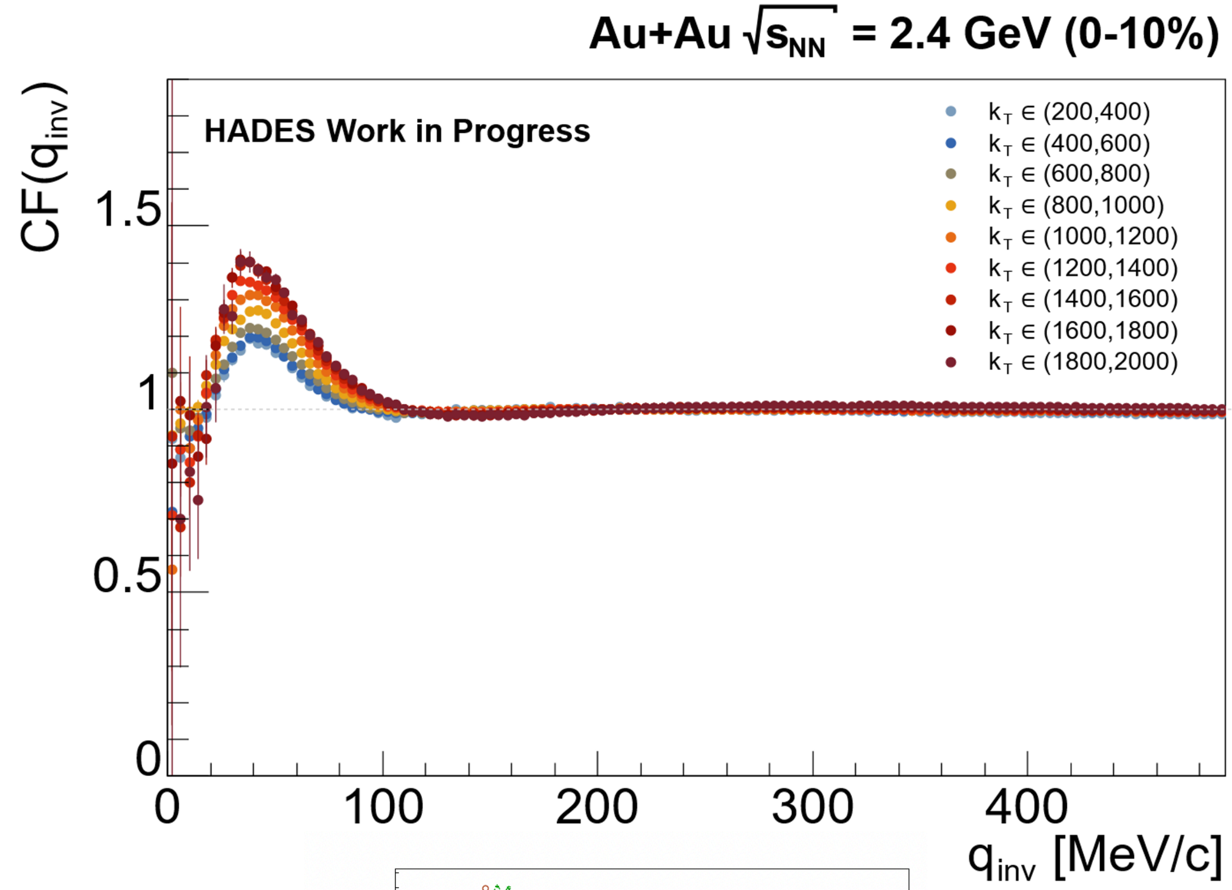
For identical systems one has to include QS (Fermi-Dirac / Bose-Einstein) as well.

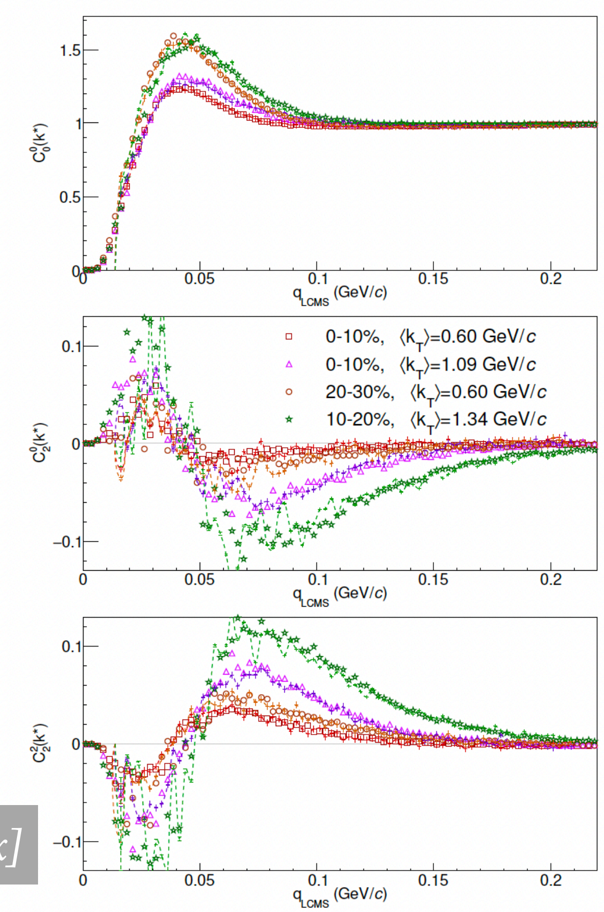
Proton - proton correlations

- High stopping in HADES implies large abundance of protons
- Protons expected to be more sensitive to the EOS
- So far only 1D analysis done, 3D analysis coming soon, BP parameters from protons to compare to pions
- Plan to use SH decompositions

$$C_l^m(k*) = \int C(\overrightarrow{k*})Y_l^m(\theta_k, \phi_k)dcos(\theta)d\phi_k$$

- SMASH predictions for 3D p-p correlations for HADES (and CBM / STAR FXT) for various EoS in progress





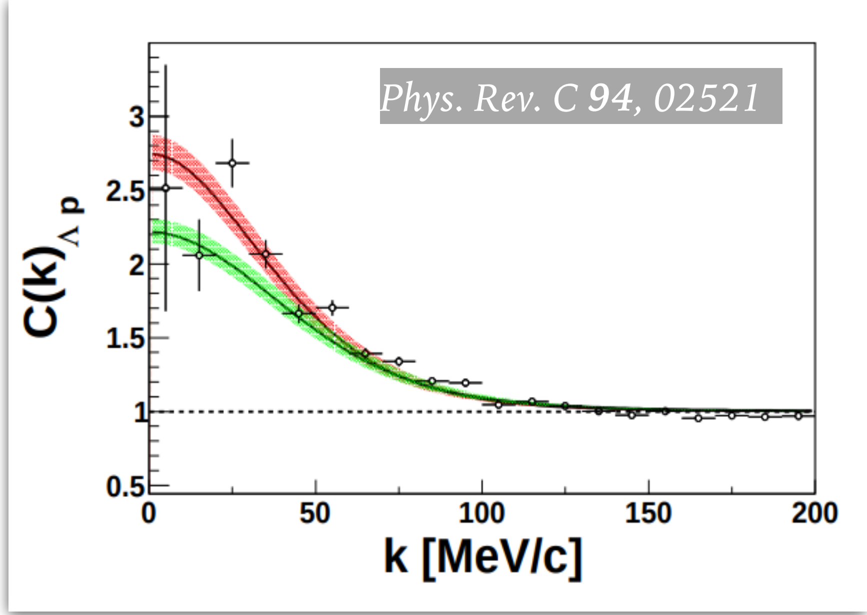
e-Print: 2505.05276 [hep-ex]

Proton - lambda correlations

Model		$f_0^{S=0}$ (fm)	$f_0^{S=1}$ (fm)	$d_0^{S=0}$ (fm)	$d_0^{S=1}$ (fm)	n_σ
ND [77]		1.77	2.06	3.78	3.18	1.1
NF [78]		2.18	1.93	3.19	3.358	1.1
NSC89 [79]		2.73	1.48	2.87	3.04	0.9
NSC97 [80]	a	0.71	2.18	5.86	2.76	1.0
	b	0.9	2.13	4.92	2.84	1.0
	c	1.2	2.08	4.11	2.92	1.0
	d	1.71	1.95	3.46	3.08	1.0
	e	2.1	1.86	3.19	3.19	1.1
	f	2.51	1.75	3.03	3.32	1.0
ESC08 [81]		2.7	1.65	2.97	3.63	0.9
χEFT	LO [25]	1.91	1.23	1.4	2.13	1.8
	NLO [26]	2.91	1.54	2.78	2.72	1.5
Jülich	A [82]	1.56	1.59	1.43	3.16	1.0
	J04 [83]	2.56	1.66	2.75	2.93	1.4
	J04c [83]	2.66	1.57	2.67	3.08	1.1

S. Acharya *et al.* Phys. Rev. C 99, 024001 – Published 13 Feb 2019
https://doi.org/10.1103/PhysRevC.99.024001

parameter scan boundaries : f_0 [0.01, 5.0], d_{0s} [0.01, 2.0] and d_{0t} [0.01, 5.0]



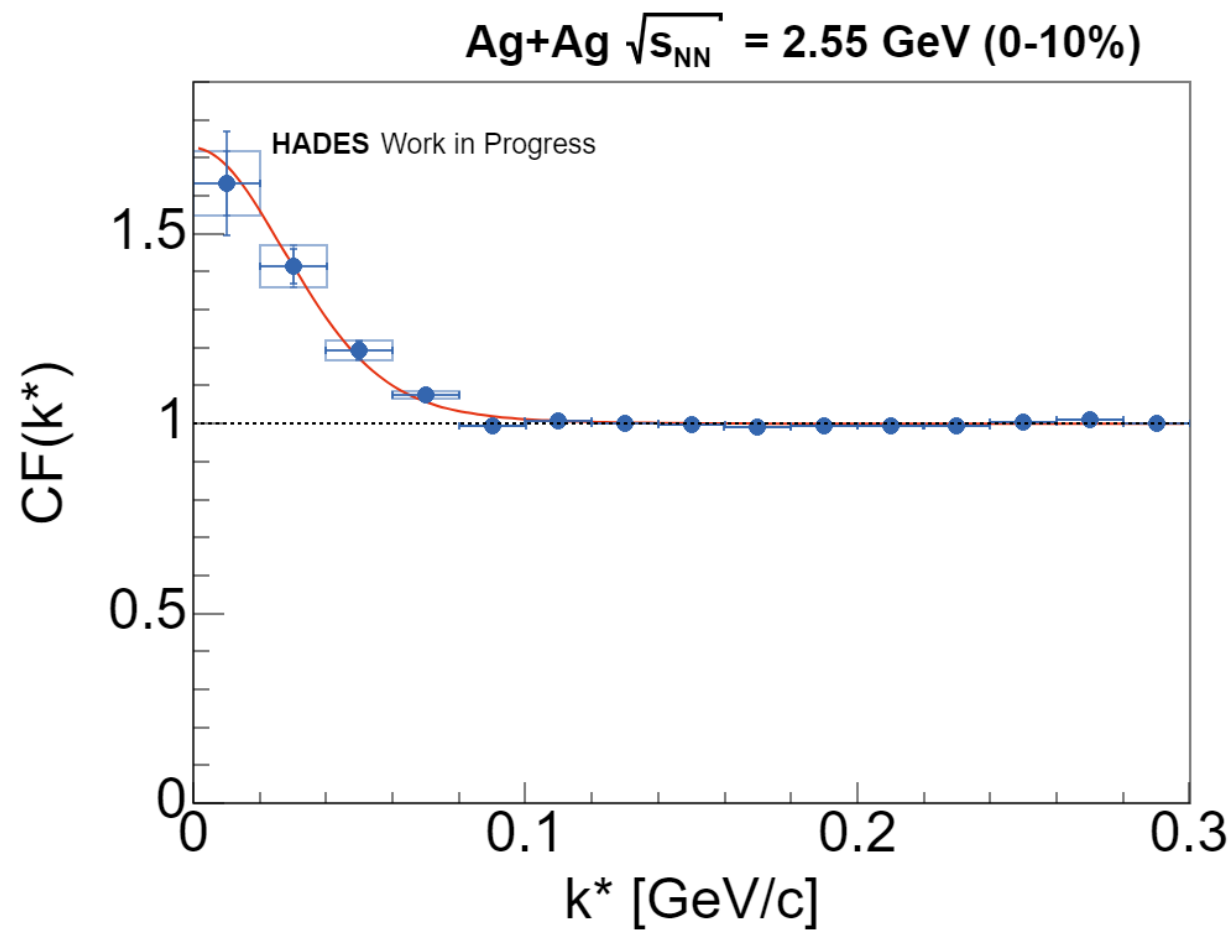
Parame-ters	p-Nb (LO)	p-Nb (NLO)
f_{0s}	1.91 fm	2.91 fm
d_{0s}	1.40 fm	2.78 fm
f_{0t}	1.23 fm	1.54fm
d_{0t}	2.13 fm	2.72fm
r_0	1.71± 0.10	1.62± 0.02

Proton - lambda correlations

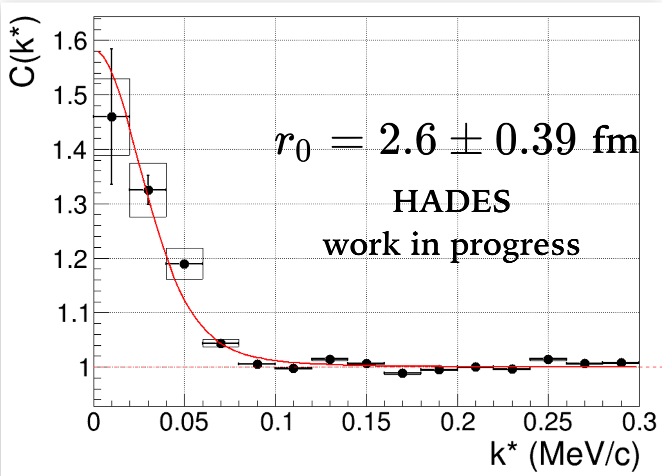
- $p - \Lambda$ correlations – first step to study N-Y interactions in HIC
- Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV fitted using L-L parametrisation
- First spin separated measurements of strong interaction parameters of the $p - \Lambda$ interaction obtained from HIC:

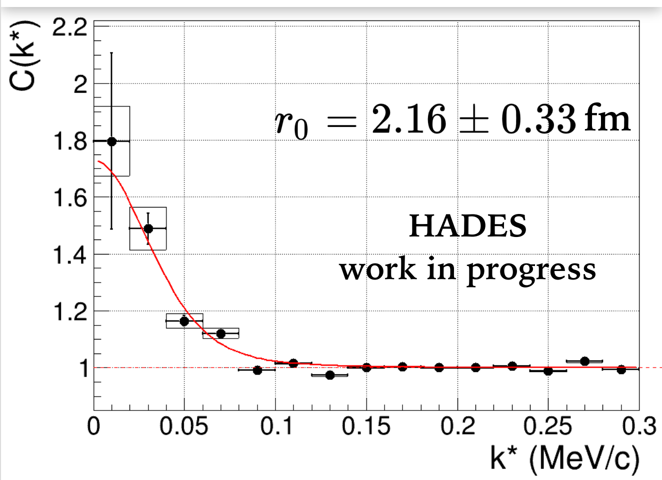
$f_0 = 1.93^{+0.48}_{-0.42}$ $d_0 = 0.01$ for S=0

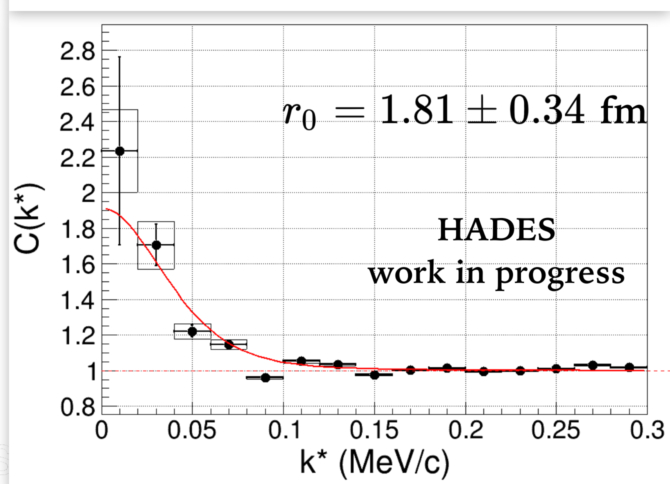
$f_0 = 1.76^{0.14}_{-0.49}$ $d_0 = 3.44^{+0.36}_{-0.49}$ for S=1



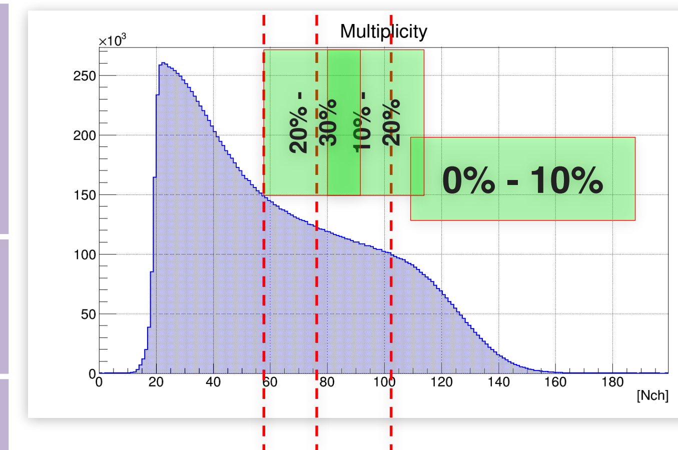
Proton - lambda correlations: centrality dependence

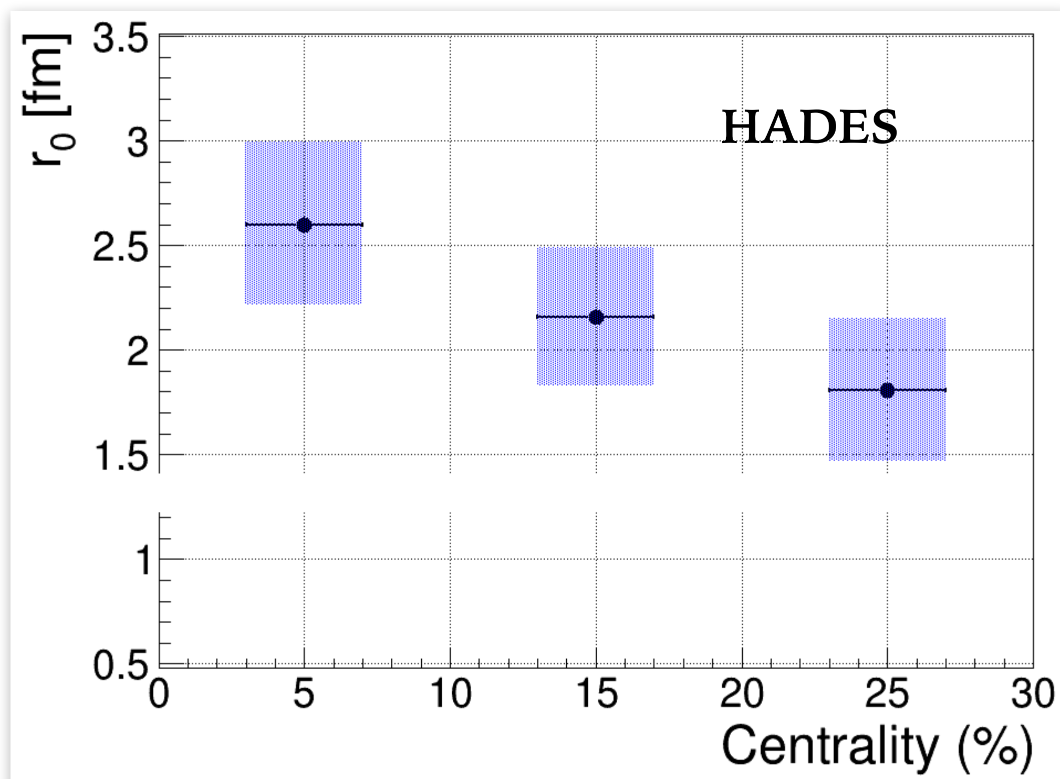




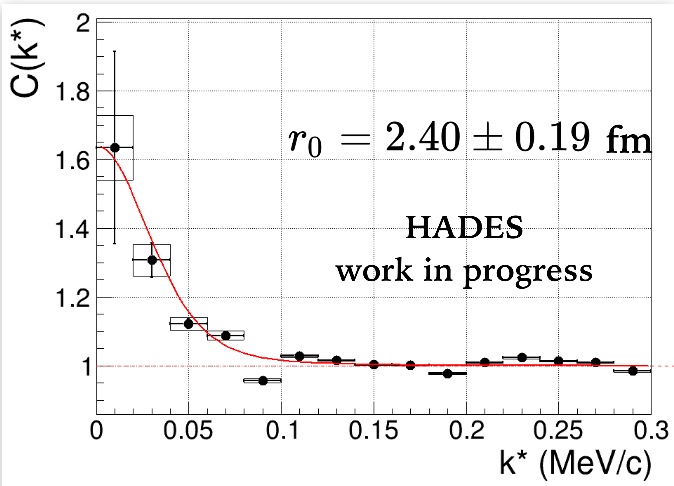


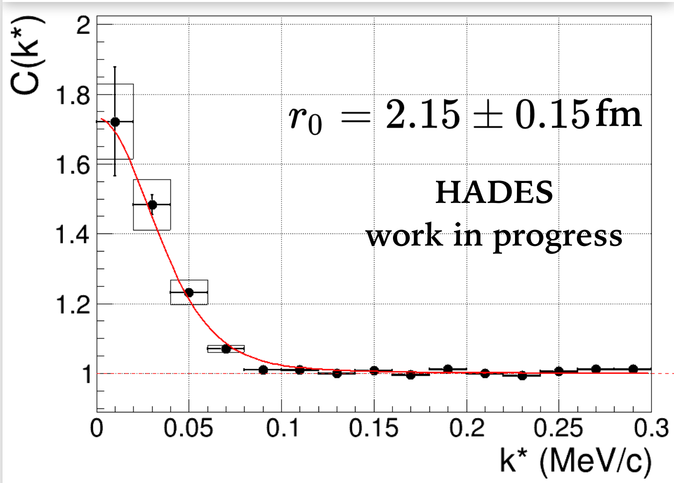
Centrality	Systematic Uncertainty
0 - 10 %	15.30 %
10 - 20 %	15.49 %
20 - 30 %	19.00 %

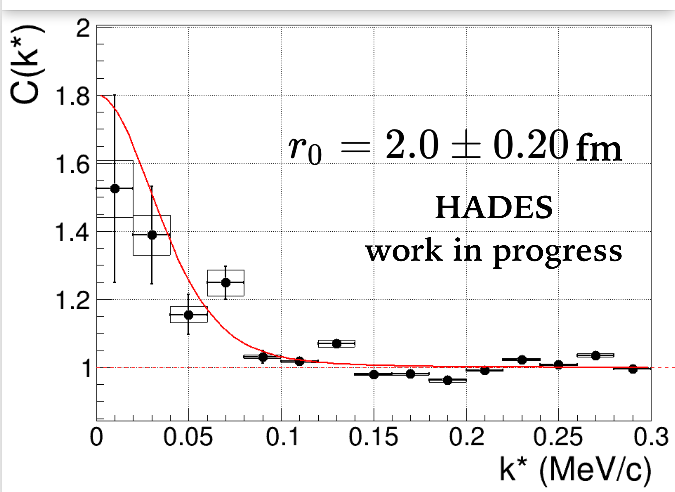




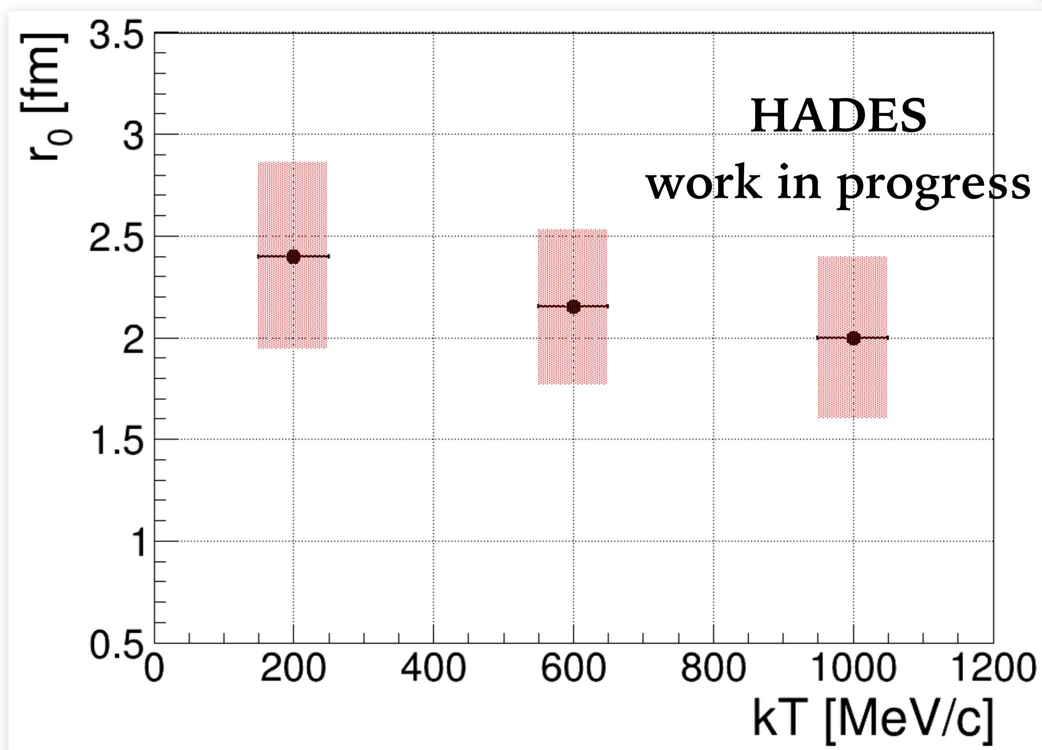
Proton - lambda correlations: k_T dependence

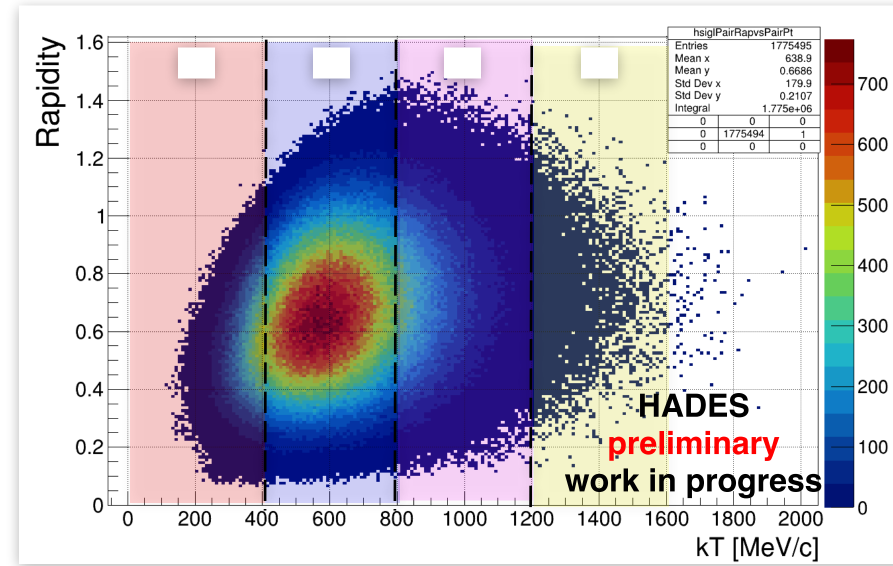






k_T [GeV/c]	Systematic Uncertainty
0 - 400	19 %
400 - 800	15 %
800 - 1200	22 %





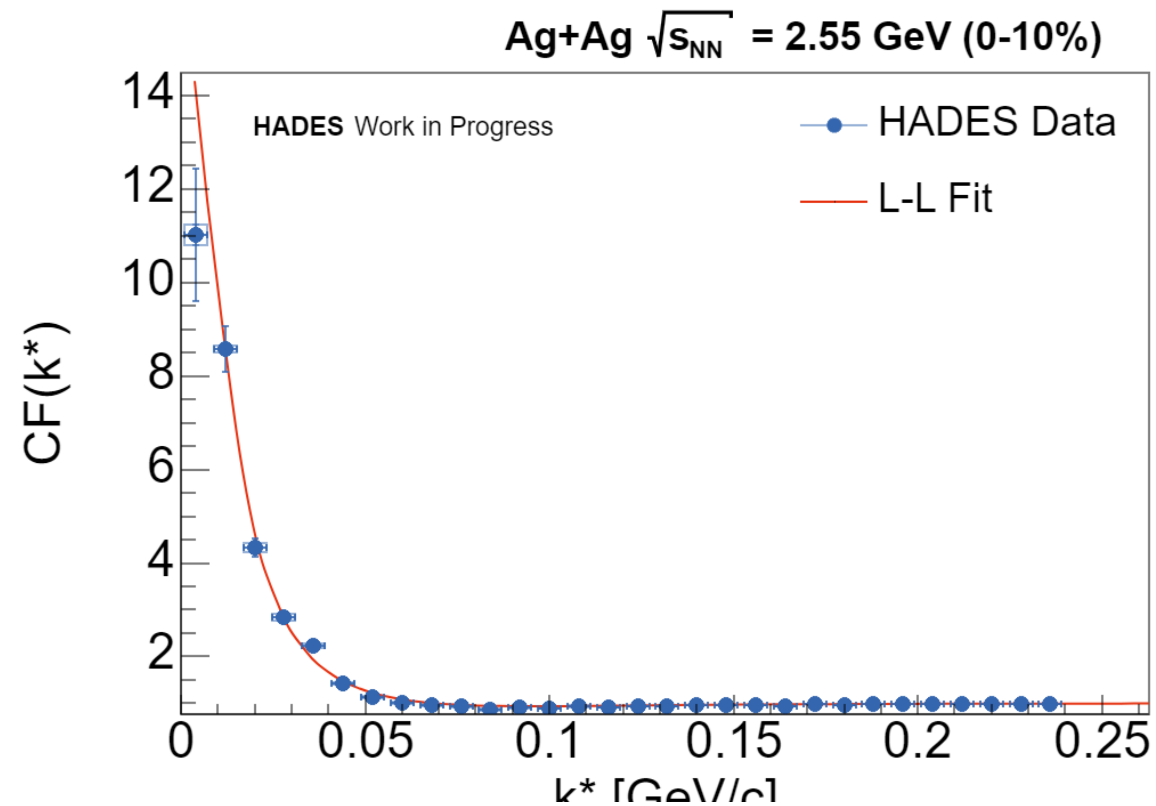
$$k_T = \frac{p_{T_1} + p_{T_2}}{2}$$

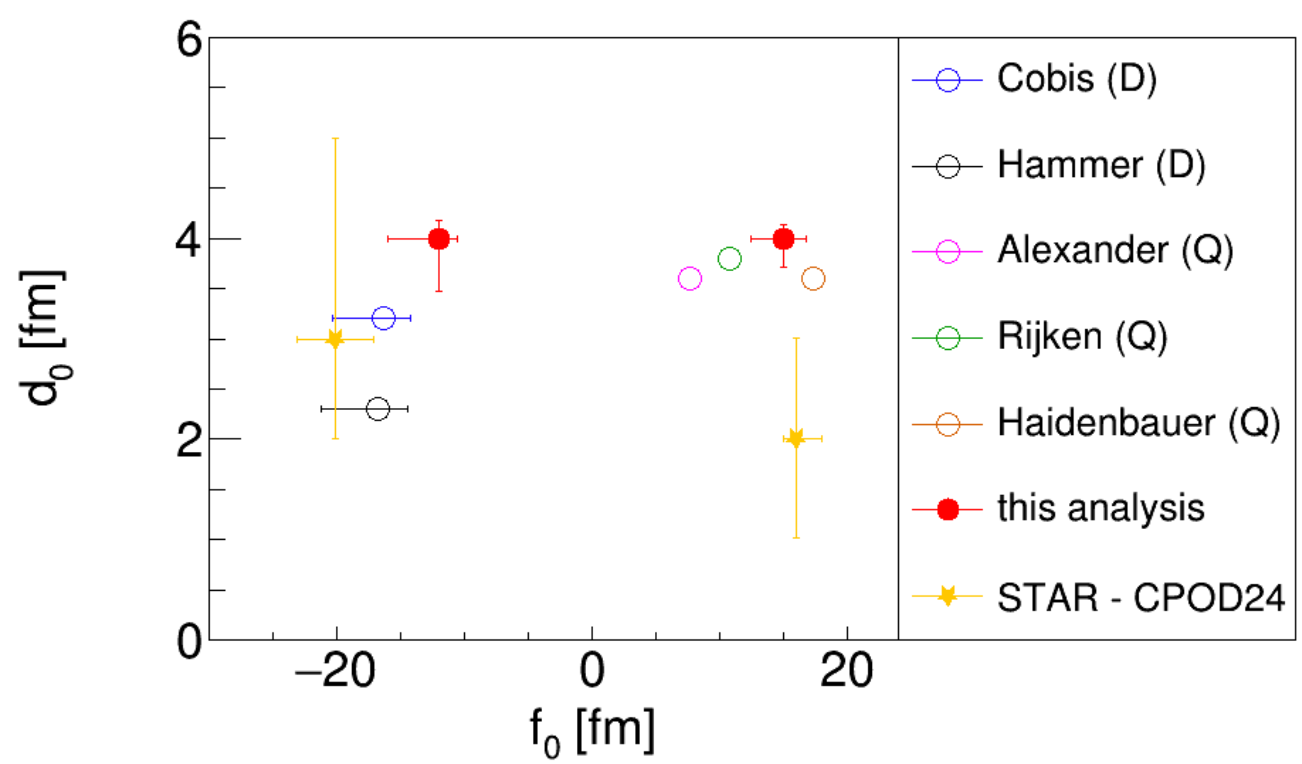
Deuteron - lambda correlations

- $d - \Lambda$ correlations – next step to study N-Y interactions in HIC
- Insight to study production of hypertriton
- Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV fitted using L-L parametrisation
- First look at spin separated measurements of strong interaction parameters of the $d - \Lambda$ interaction obtained from HIC:

$f_0 = -12^{+1.44}_{-3.92}$ $\quad d_0 = 4^{+0.18}_{-0.53}$ $\quad$ Doublet

$f_0 = 15^{+1.73}_{-2.58}$ $\quad d_0 = 4^{+0.13}_{-0.28}$ $\quad$ Quartet





Deuteron - lambda correlations

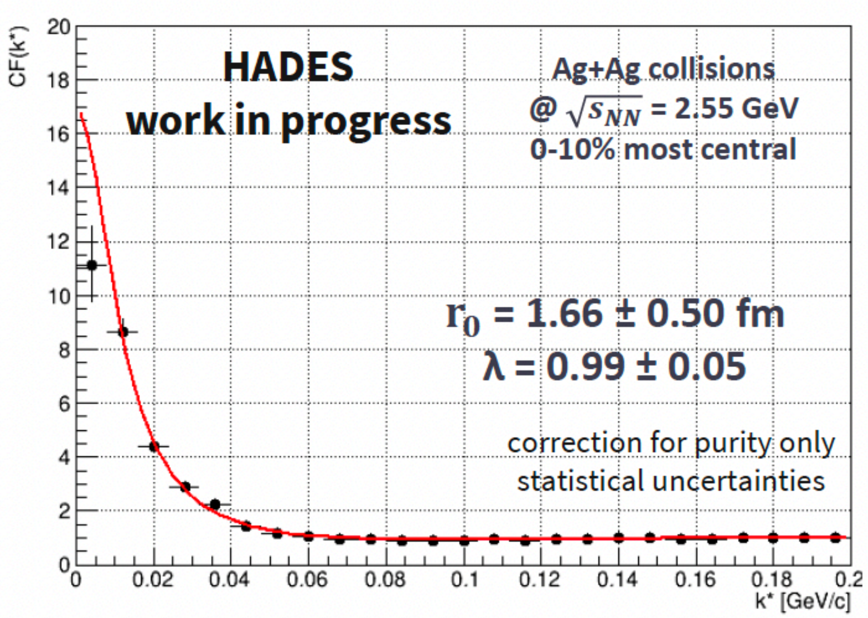
Expected centrality dependence:

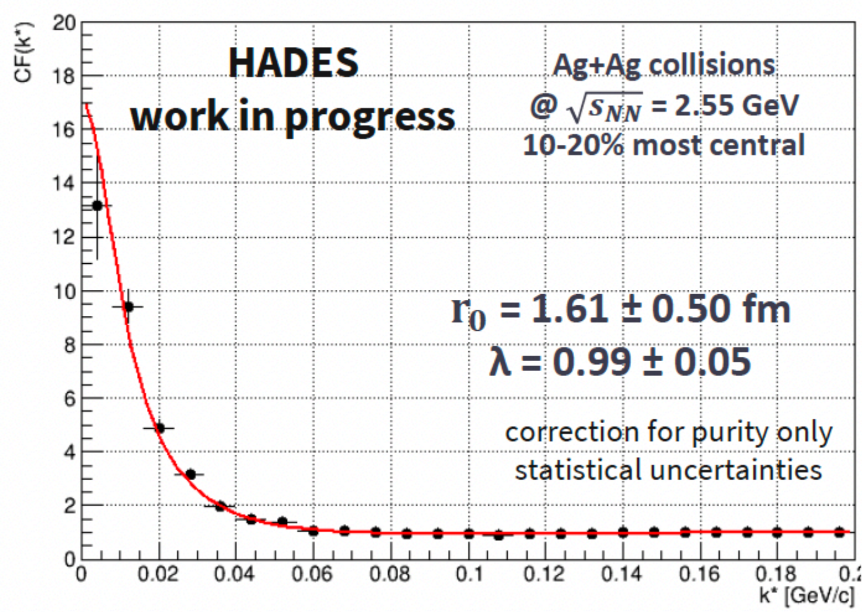
$R_{0-10\%} > R_{10-20\%} > R_{20-30\%}$

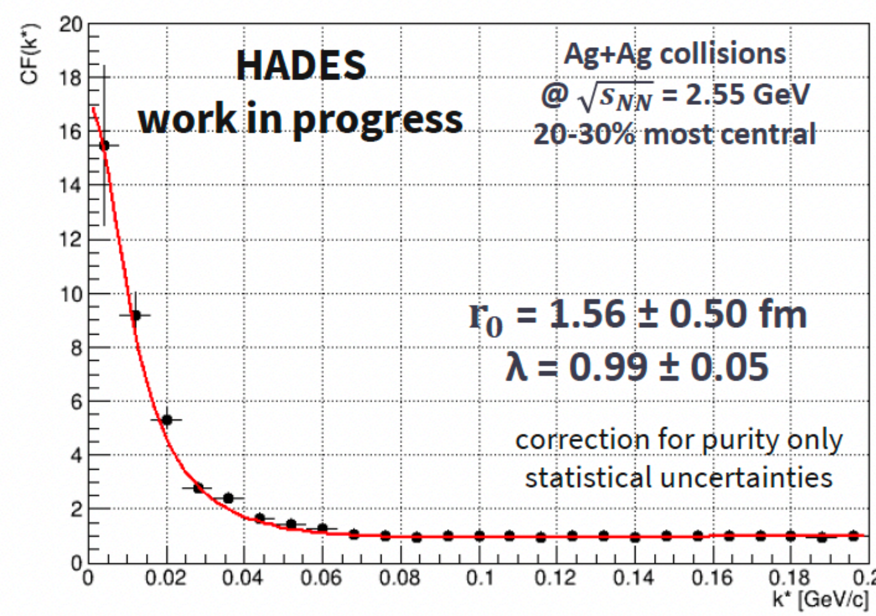
- First look at spin separated measurements of strong interaction parameters of the $d-\Lambda$ interaction obtained from HIC:

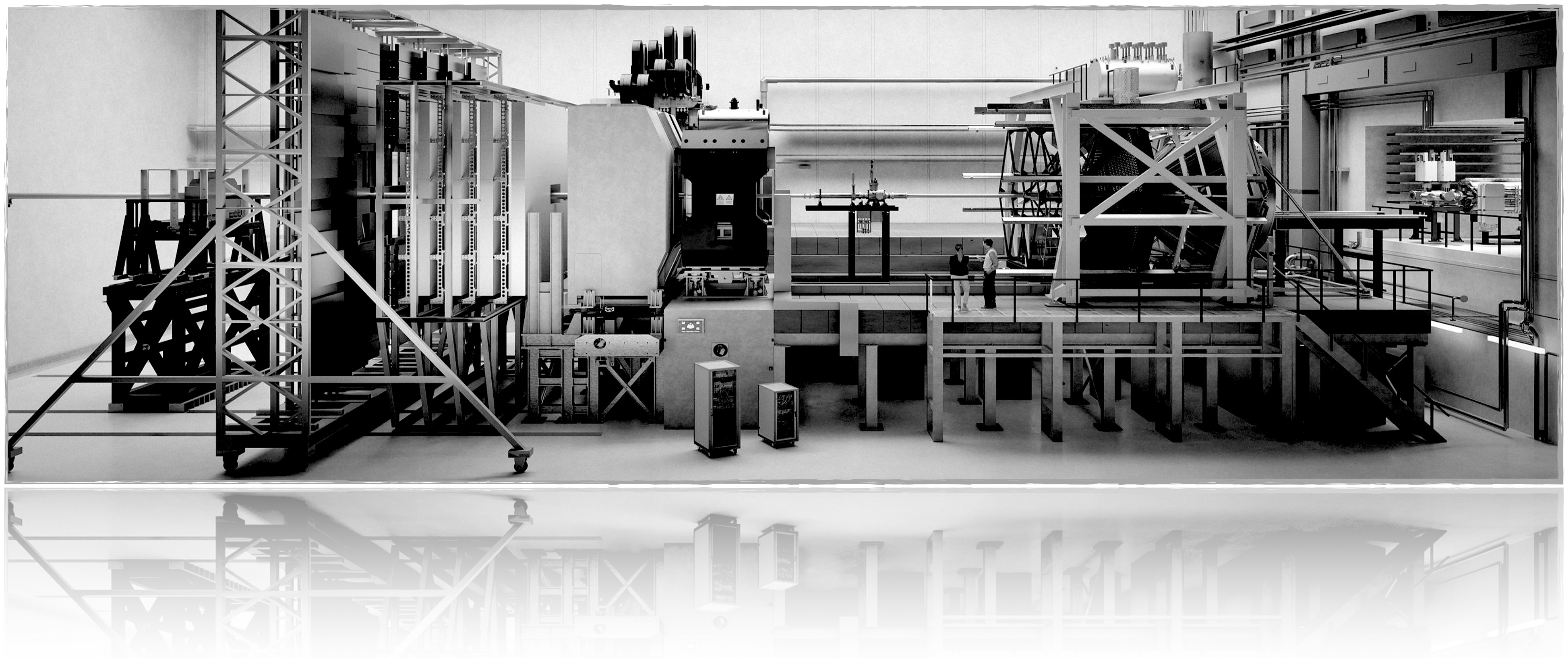
$f_0 = -12^{+1.44}_{-3.92}$ $d_0 = 4^{+0.18}_{-0.53}$ Doublet

$f_0 = 15^{+1.73}_{-2.58}$ $d_0 = 4^{+0.13}_{-0.28}$ Quartet







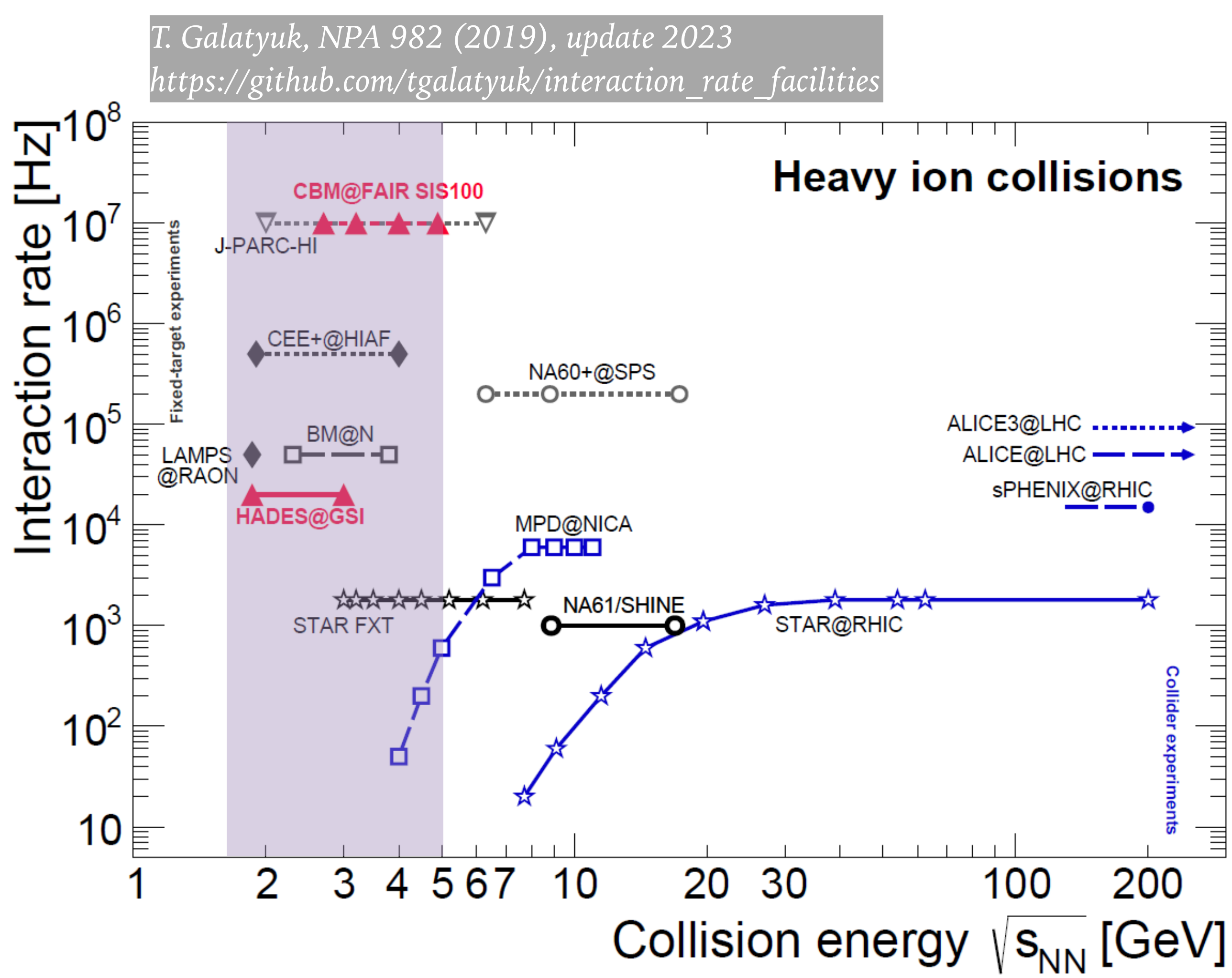


CBM

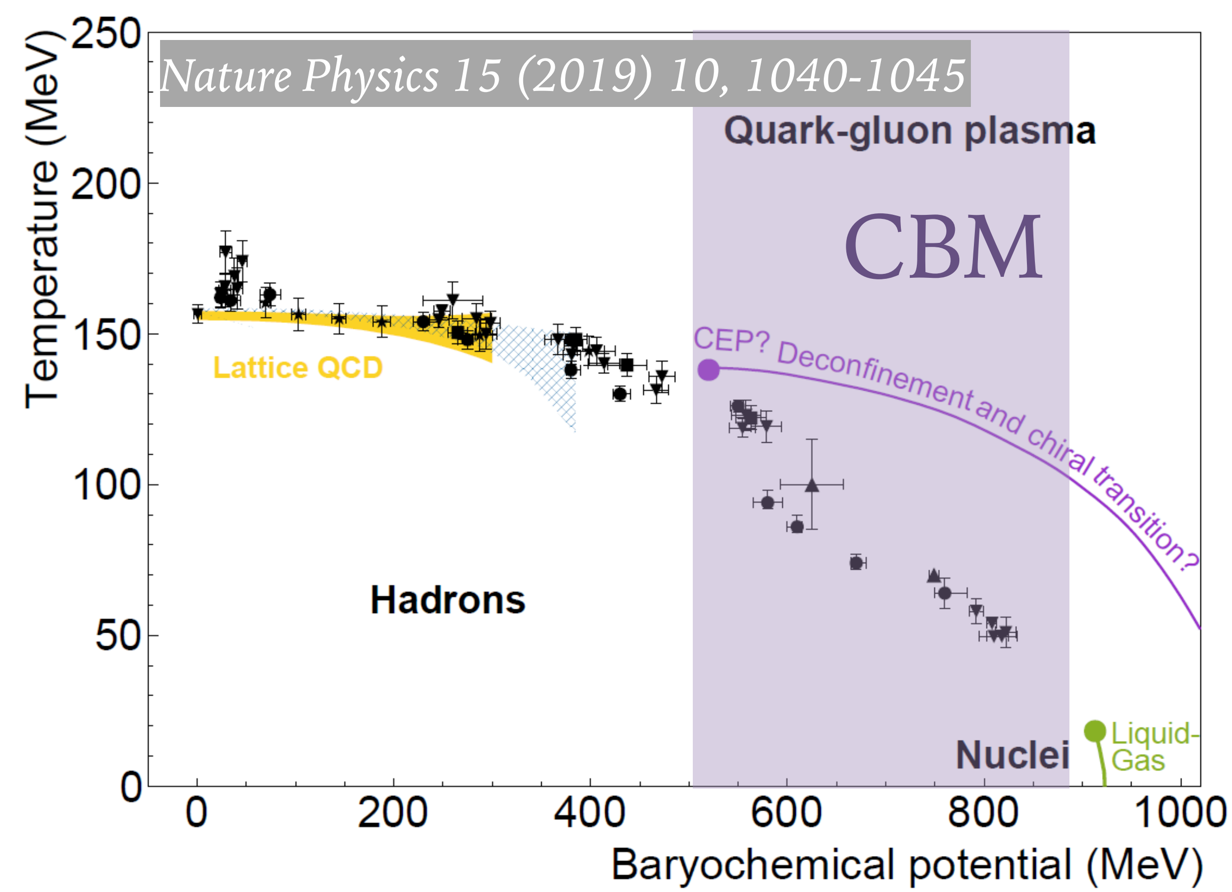
Compressed Baryonic Matter experiment

Key observables – systematic measurements!

- **Fluctuations**: System transition via first order phase transition line, Critical Point;
- **Hadrons, Strangeness, Charm**: System in equilibrium, Hypernuclei, Vorticity, Flow, EOS;
- **Dileptons** : Emissivity of dense baryonic matter: lifetime, temperature, density, in-medium properties;
- **Correlations**: Flow, Vorticity, YN, YNN, … interactions and 3D studies possible **(femtoscopy)**.



Experimental investigation of the region of the $500 < \mu_B < 850$ **(MeV)**



Summary

Wrap -up

Femtoscopy is sensitive to different EoS

Depending on the available statistics one can focus on 1D- or 3D studies

It is possible to use traditional HBT technique to deduce 3D HBT parameters

One can determine parameters of interactions, search for possible bound states and look for an evidence to make the EoS softer

HADES has already measured many systems

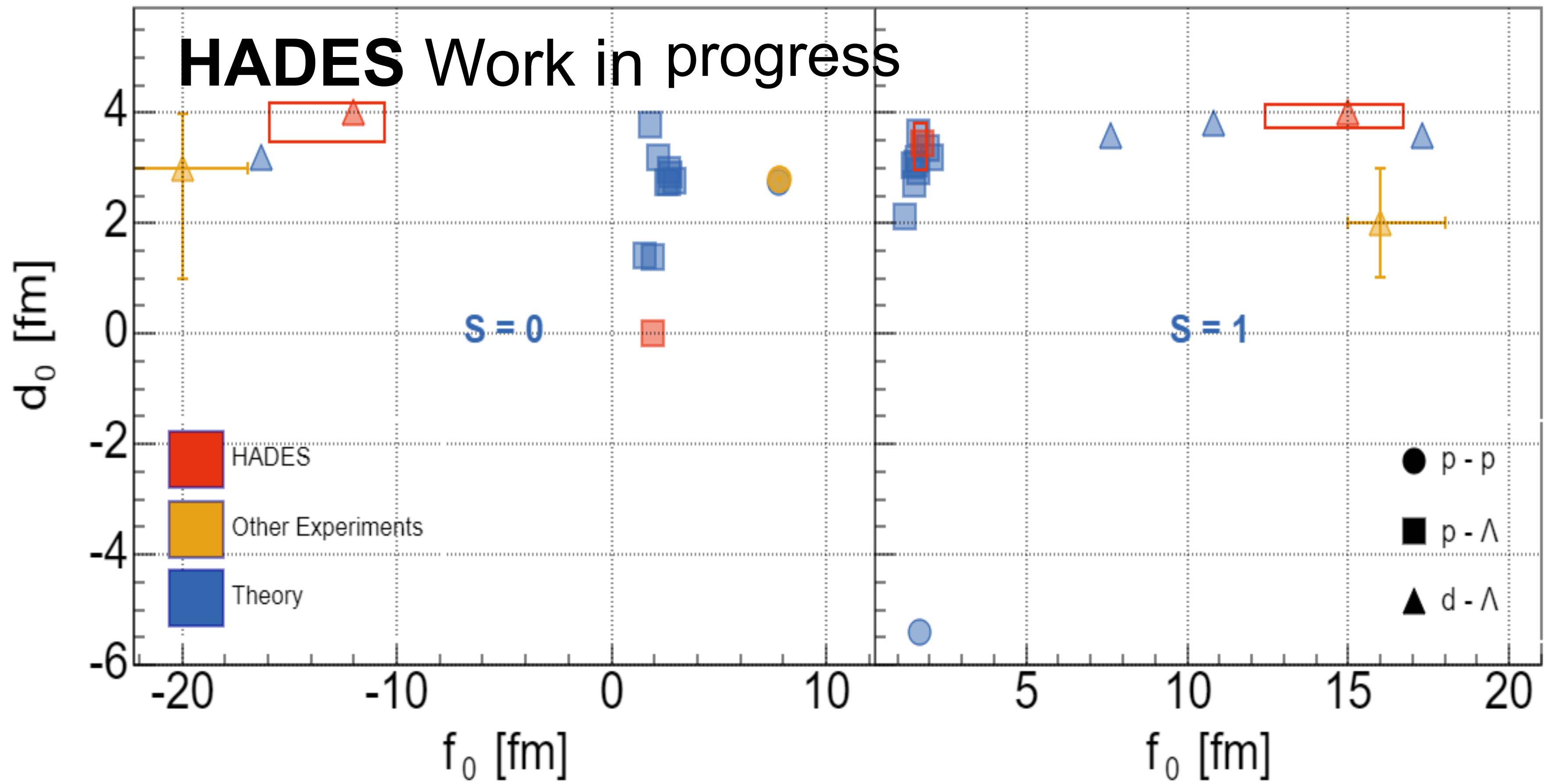
Future CBM (and HADES) will use higher statistics

Thank you!

Supporting slides

FSI parameters

- Clear separation of FSI



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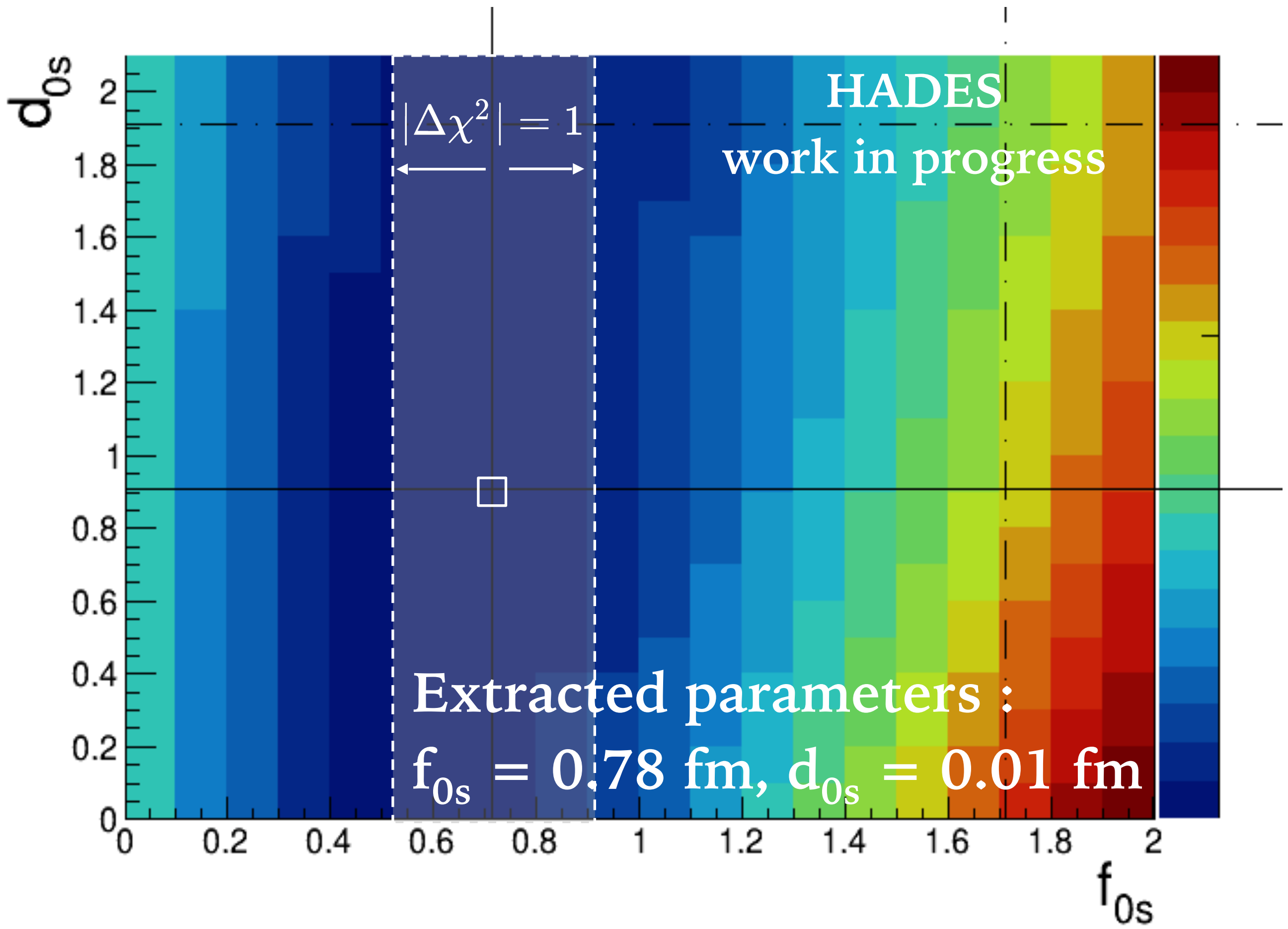
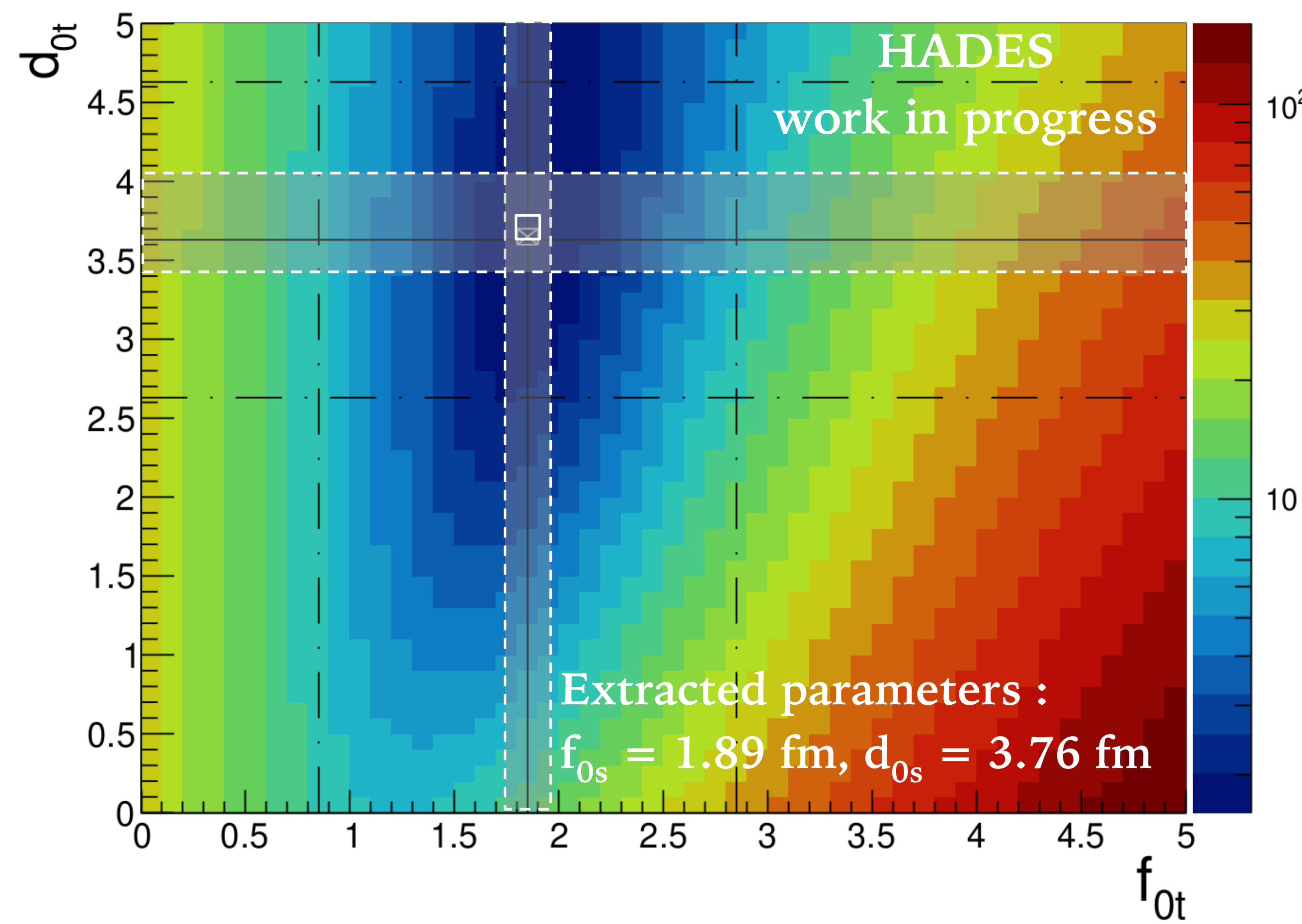
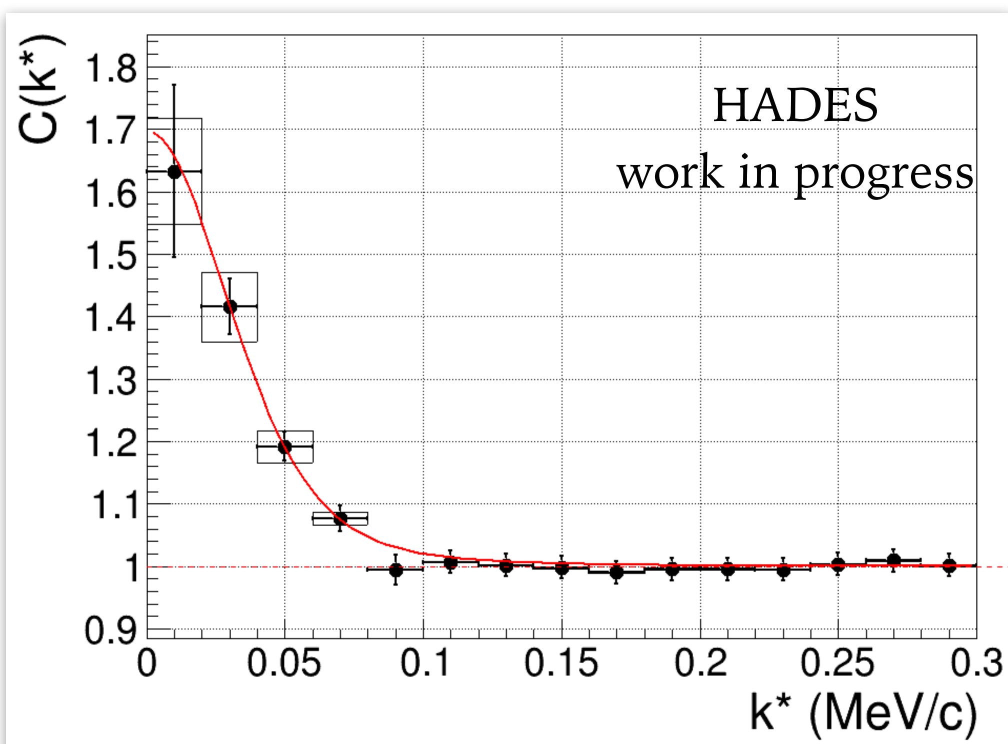
YN ($p\Lambda$) correlations at HADES







$\lambda = 0.74$

$f_{0s} = 0.80^{+0.39}_{-0.32}$

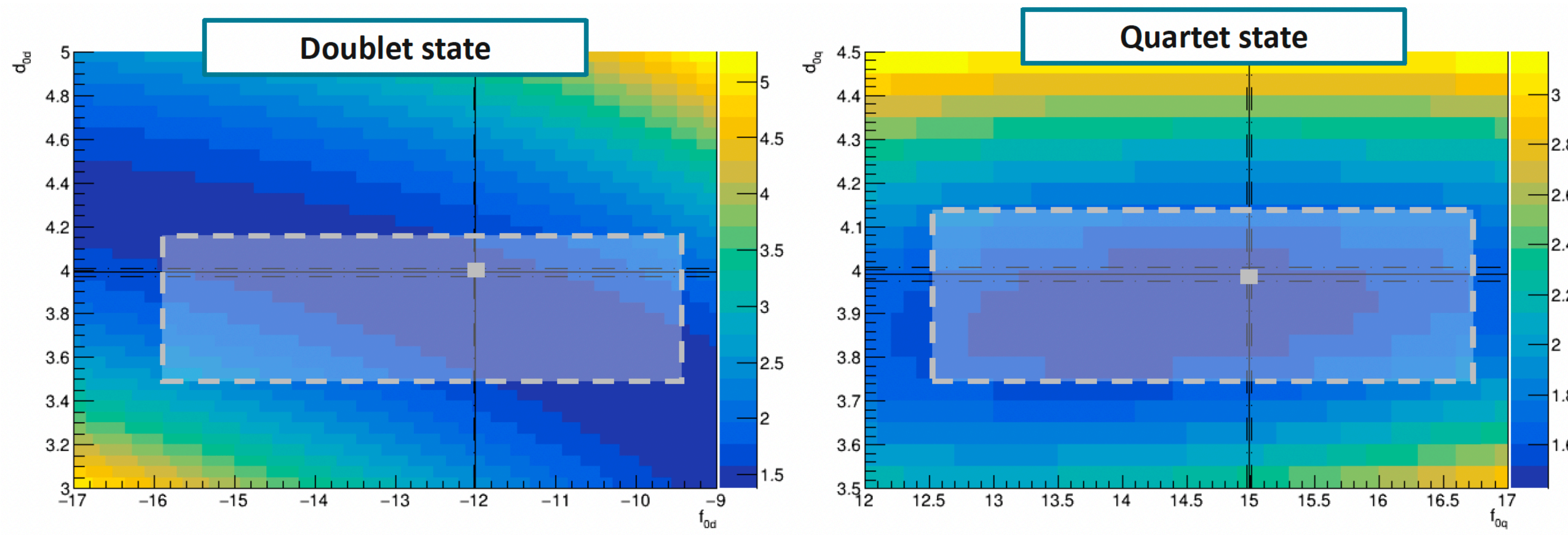
$d_{0s} = 0.01$

$f_{0t} = 1.89^{+0.10}_{-0.09}$

$d_{0t} = 3.76^{+0.27}_{-0.25}$

$r = 2.24^{+0.12}_{-0.11}$

YN ($d\Lambda$) correlations at HADES



Strange hadronic matter in the inner core

The inner core of the neutron star is totally unknown. One of the most probable scenarios is that hyperons (baryons with strange quarks) appear at a density larger than (2–3) ρ_0

Λ hyperons, being free from Pauli exclusion principle by neutrons, are allowed to stay at the bottom of the attractive nuclear potential made by neutrons. When the kinetic energy of a neutron on the Fermi surface of the degenerate neutron matter exceeds the Λ-n mass difference of 176 MeV, it converts into a Λ hyperon via weak interaction.

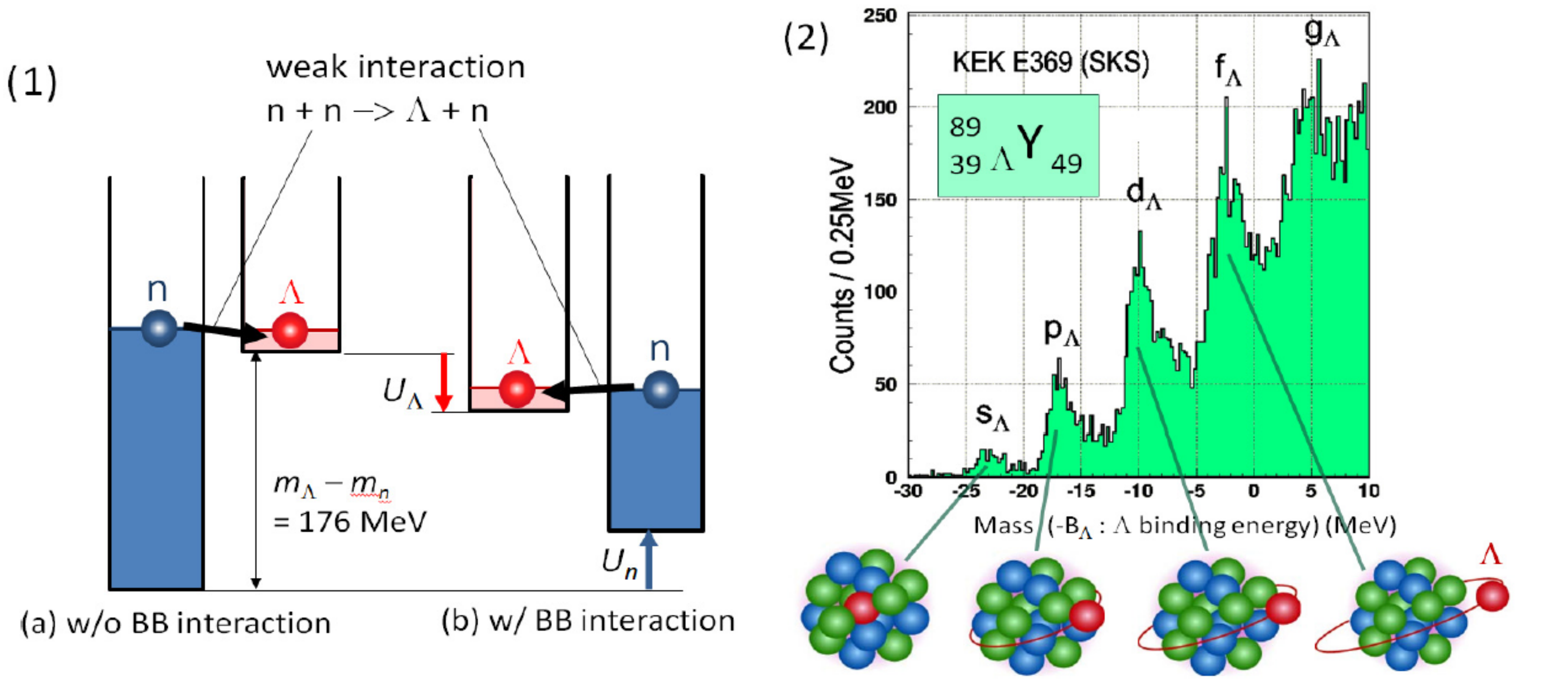
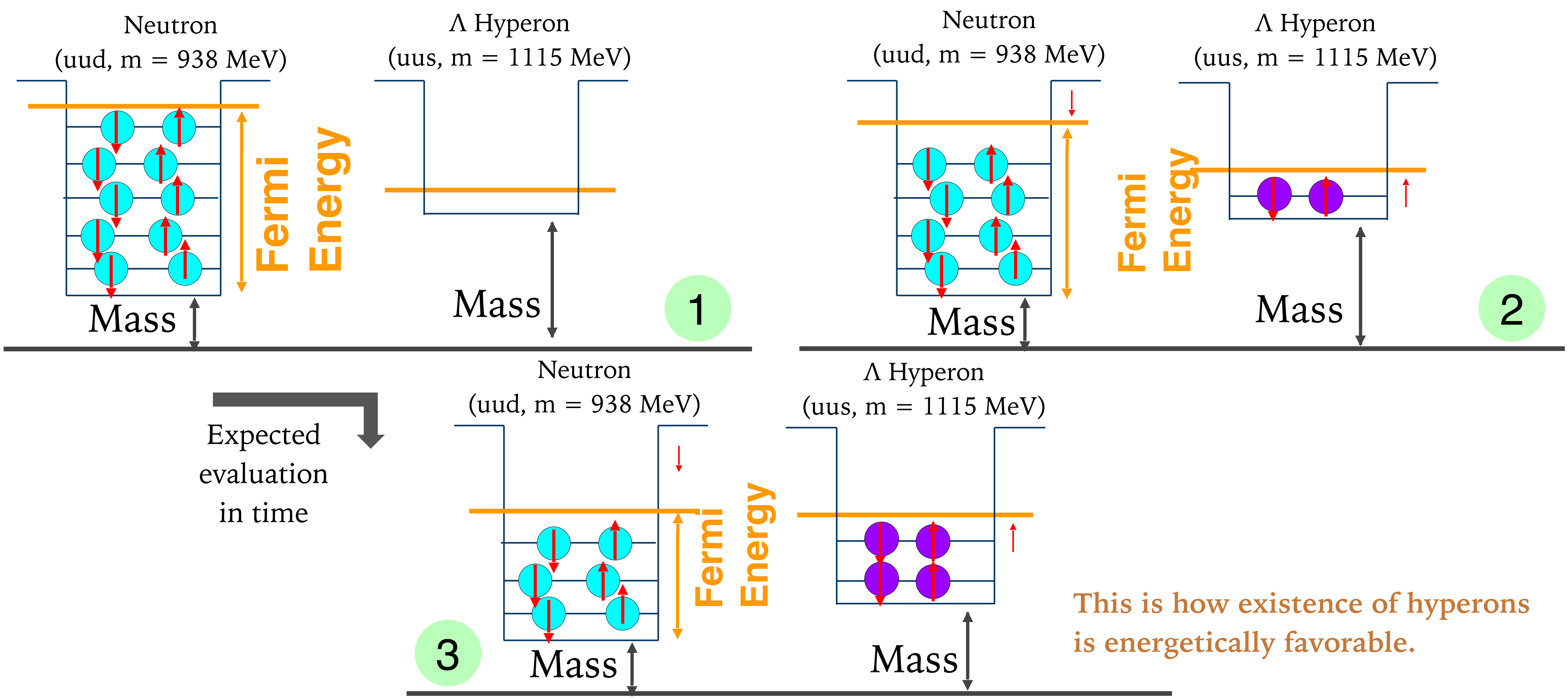


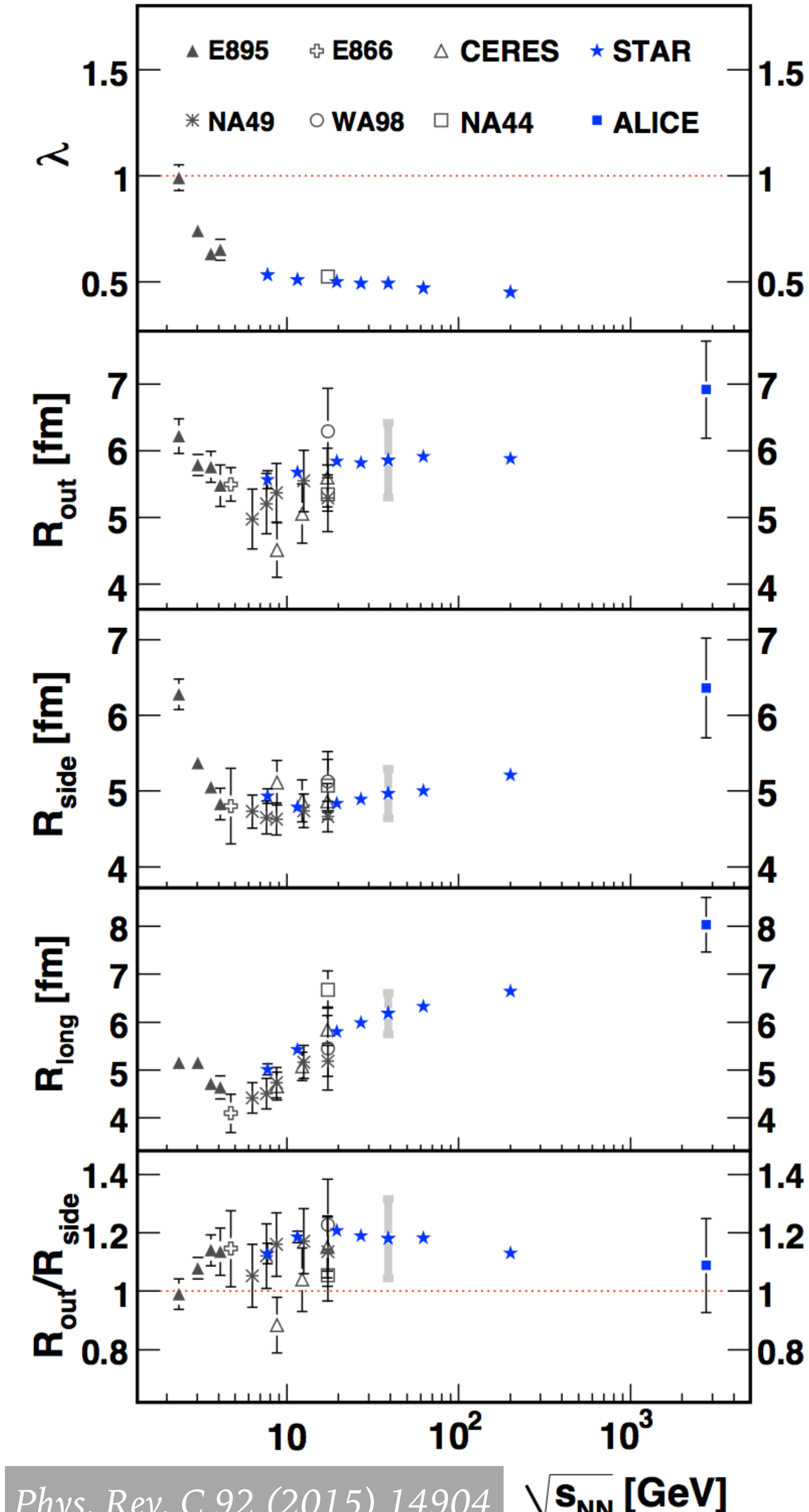
Fig. 3. (1) Energies of neutrons and Λ hyperons in high density neutron matter confined in the potential made by gravity. See text for details. (2) Excitation spectrum of a Λ hypernucleus ${}^{89}_{\Lambda}$Y via the (π^+, K^+) reaction on ^{89}Y target [6].

Hyperon production



This is how existence of hyperons is energetically favorable.

Identical pion femtoscopy at STAR



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→ R_{side} spatial source evolution in the transverse direction

→ R_{out} related to spatial and time components

→ R_{out}/R_{side} signature of phase transition

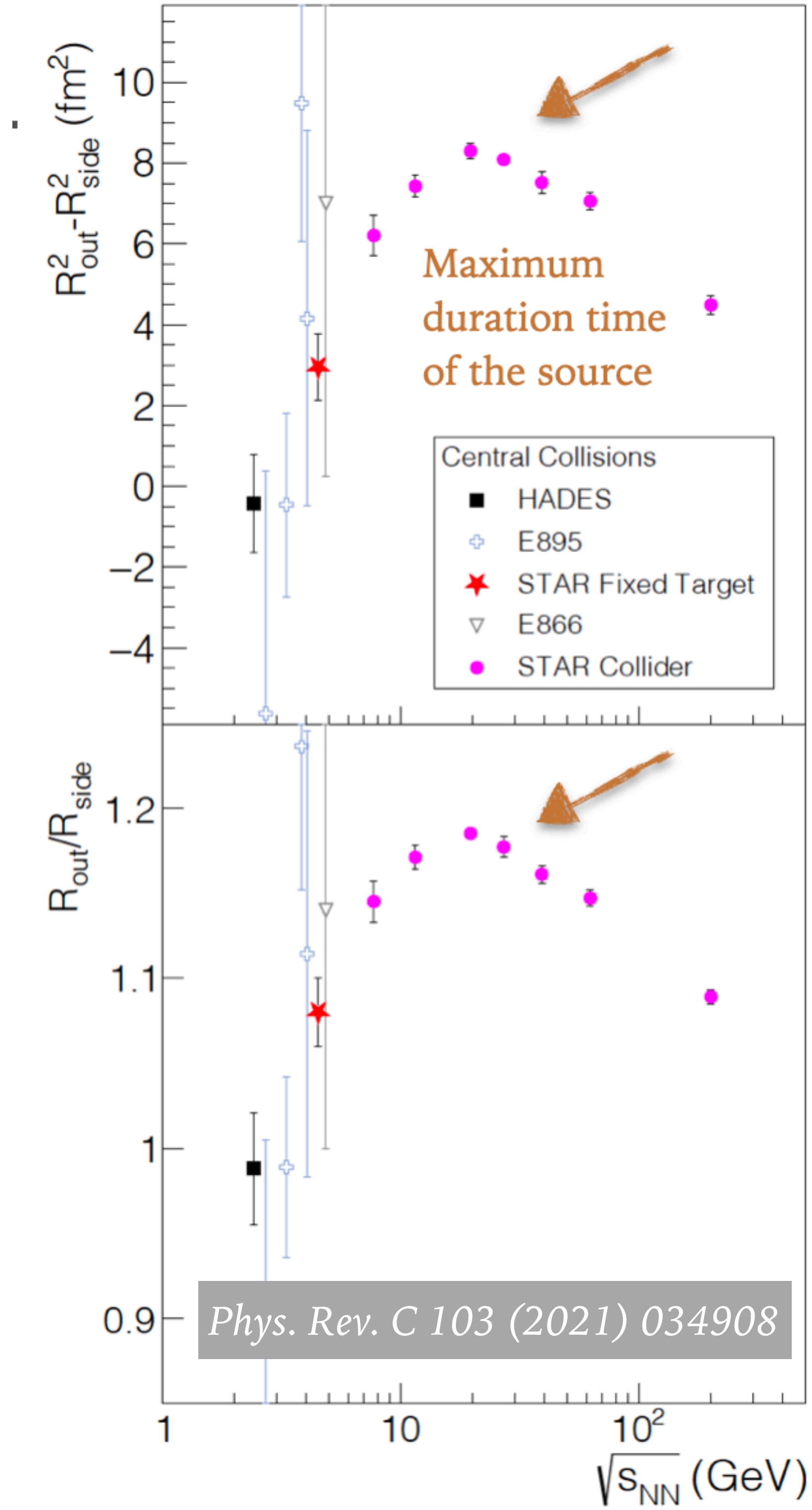
→ R_{out}^{2}- R_{side}^{2} = $\Delta\tau^2 \beta_t^2$; $\Delta\tau$ – emission time

→ R_{long} temperature of kinetic freeze-out and source lifetime

$$C(\vec{q}) = (1-\lambda) + K_{\mathrm{Coul}}(q_{\mathrm{inv}})\lambda$$
$$\times \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2q_o q_s R_{os}^2 - 2q_o q_l R_{ol}^2\right)$$

HBT source sizes determined for wide range of collision energy;
Non-monotonic behavior seen in three directions

Looking for phase transition at STAR



Phys. Rev. C 103 (2021) 034908

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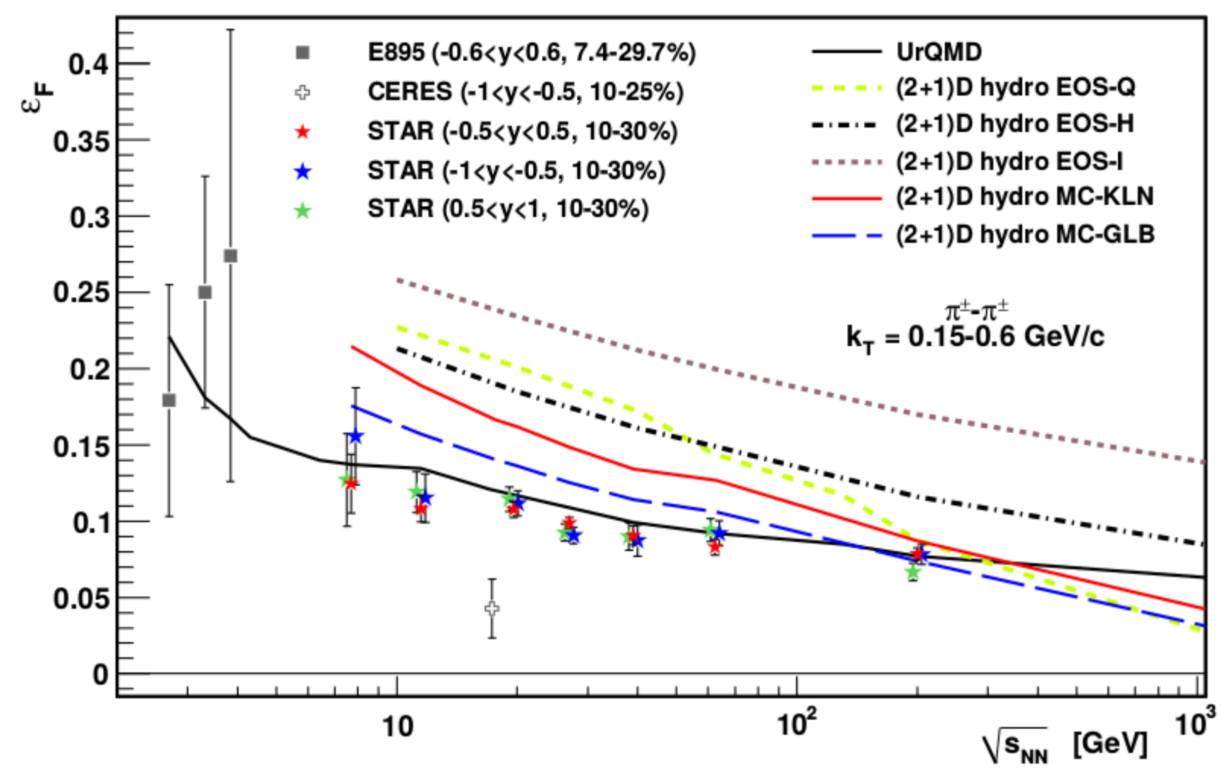

System evolves faster in the reaction plane

Phys. Rev. C 92 (2015) 14904