
NATIONAL SCIENCE CENTRE POLAND

EXCELLENCE INITIATIVE RESEARCH UNIVERSITY

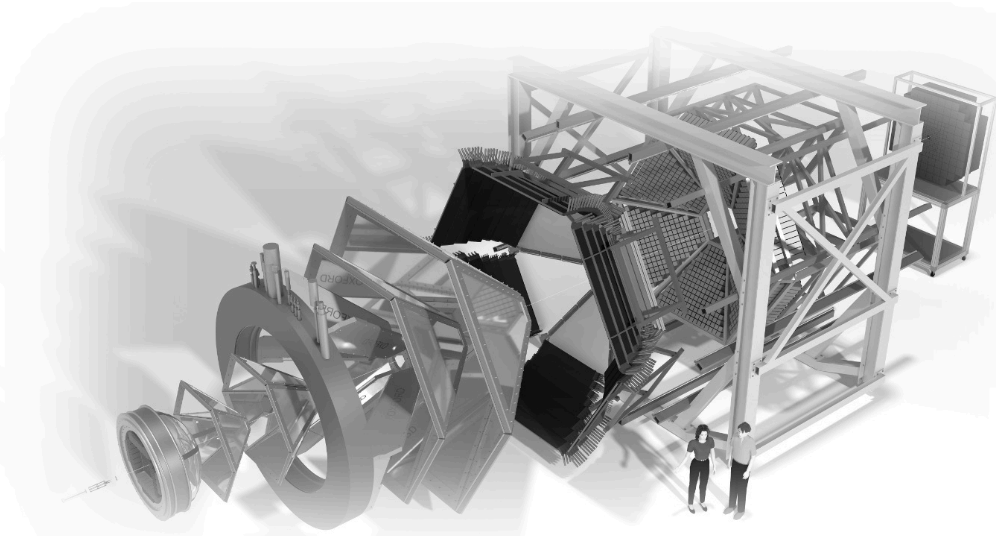
POLITECHNIKA WARSZAWSKA WARSAW UNIVERSITY OF TECHNOLOGY

# Heavy-ion program of the HADES experiment at GSI/FAIR

**Outline**

- Physics goals and detector
- Results:
  • Hadrons (fluctuations, collectivity, correlations)
  • Strangeness (including hypernuclei)
  • Dileptons
- Future

**Hanna Zbroszczyk**
Warsaw University of Technology
*hanna.zbroszczyk@pw.edu.pl*



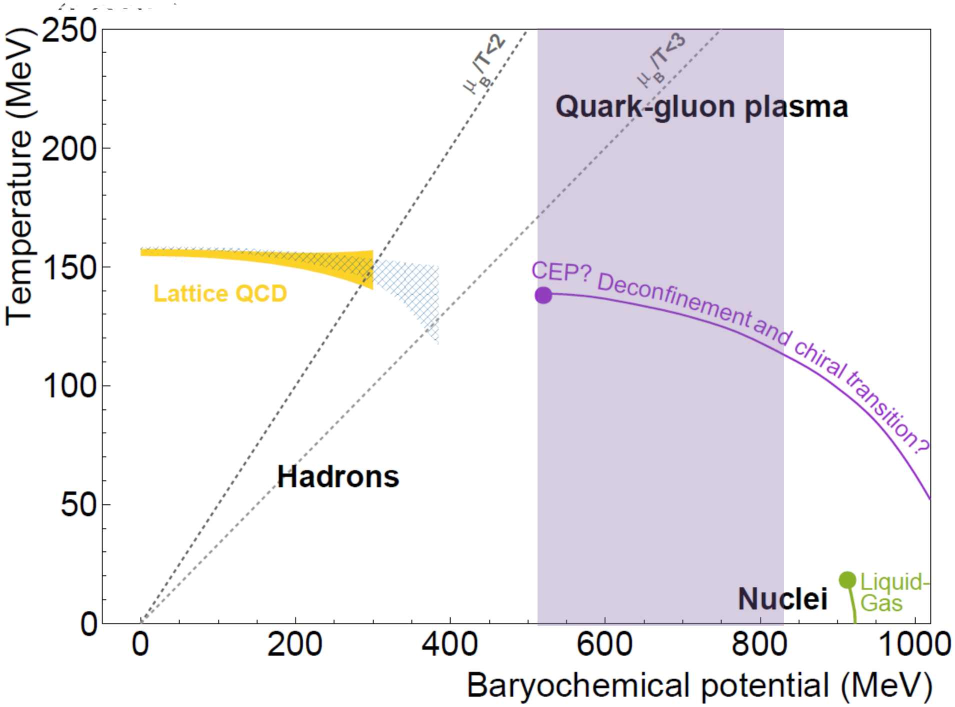
# Physics goals and detector

# QCD phase diagram

**Low $\mu_B$, hight $T$:**

- **Cross-over** transition from hadronic to quark matter - comprehensive studies of **QGP** properties
- No **critical point** anticipated for $\mu_B/T < 3$

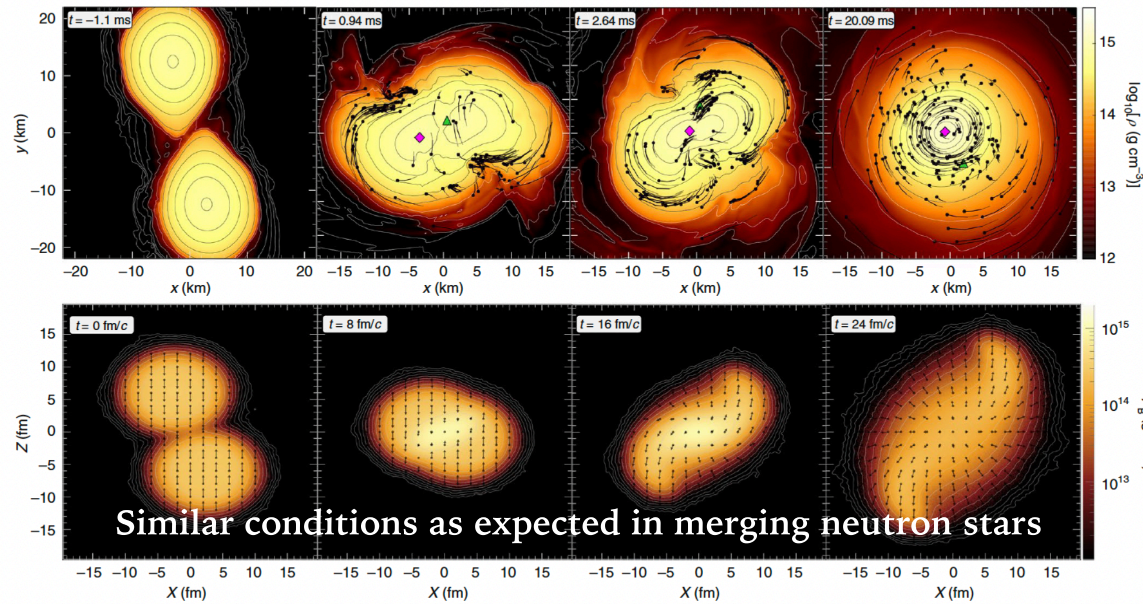
*Bazavovet al.[HotQCD], PLB 795 (2019) 15-21*
*Dinget al., [HotQCD], PRL 123 (2019) 6, 062002*
*Borsanyiet al., PRL125(2020)5,052001*
*Isserstedt et al. PRD 100 (2019) 074011*
*Gao, Pawlowski, PLB 820 (2021) 136584*




**High $\mu_B$, low $T$:**

- Unknown **phase structure** (first-order phase transition, critical point possible, mixed phases, new phases, …)
- Properties of matter to determine
- Characteristics of hadrons
- Equation of State (**EoS**) to establish
- Neutron Star (**NS**)

# HADES physics goals



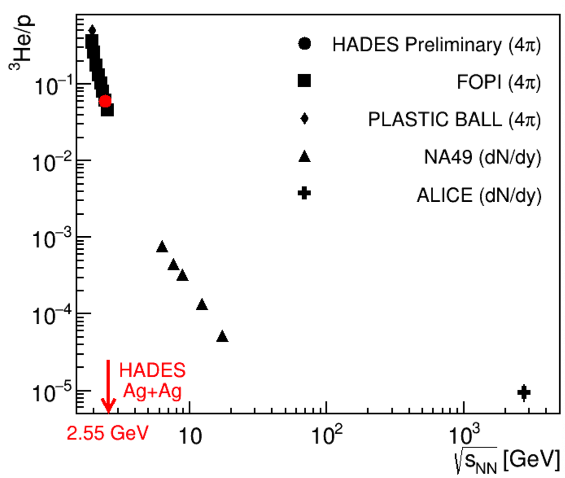

HADES, Nature Phys. 15, 1040–1045 (2019)

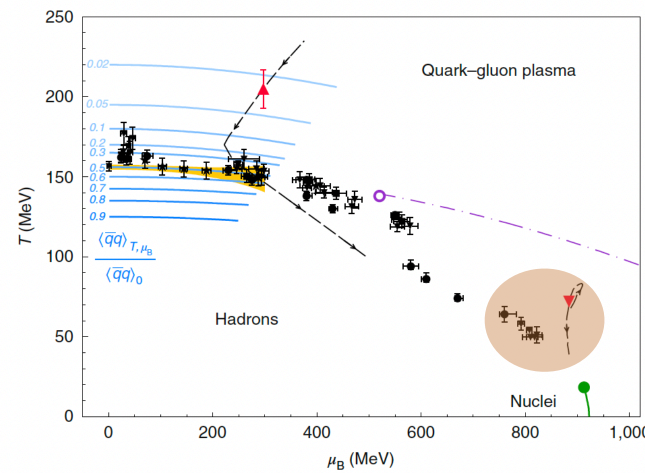
**Heavy-ion collisions at $\sqrt{s_{NN}}$ up to 2.7 GeV**

- Microscopic properties of baryon dominated matter
- EoS observables

**$\pi^-$ ($\sqrt{s}$ 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




See R. Lalik talk

# 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

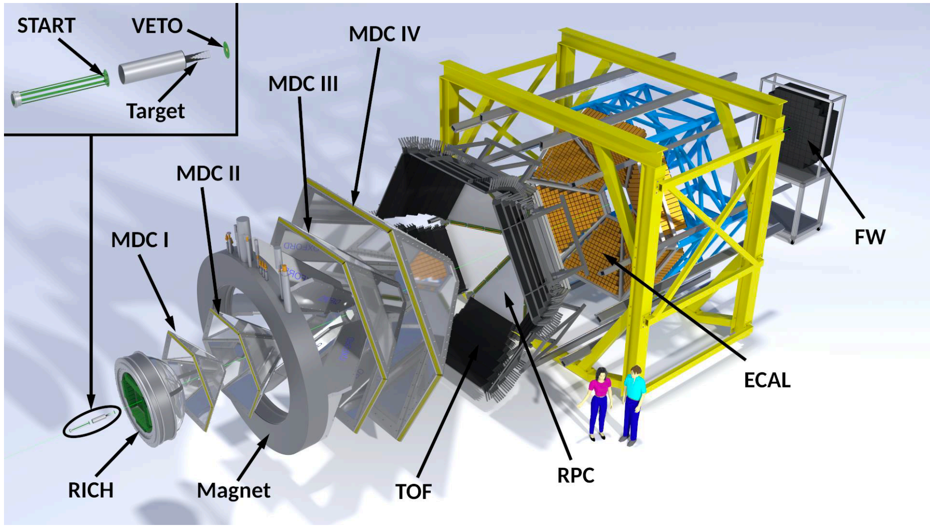
RICH and ECAL for $e^+/e^-$ and photon identification

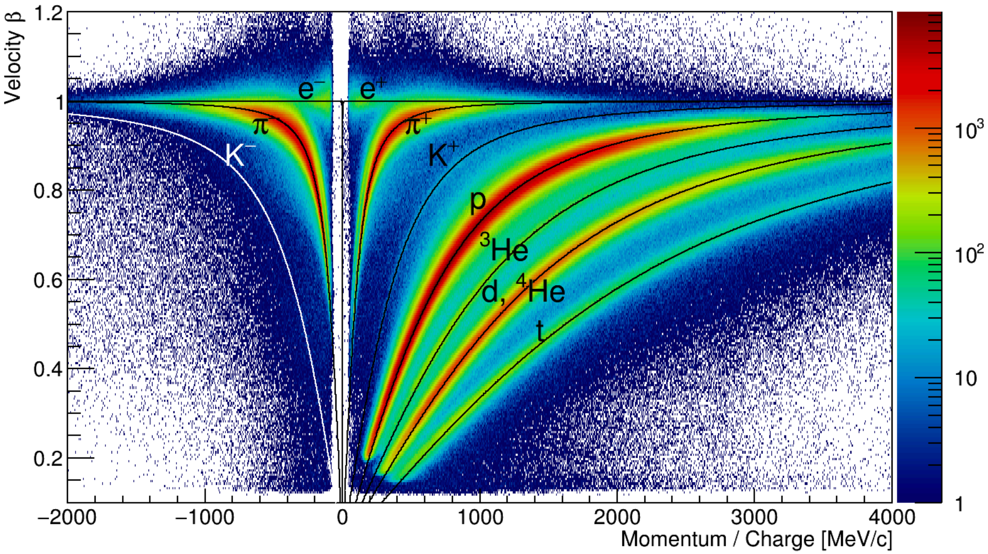
Full azimuthal angle and polar angles between 18° and 85° covered

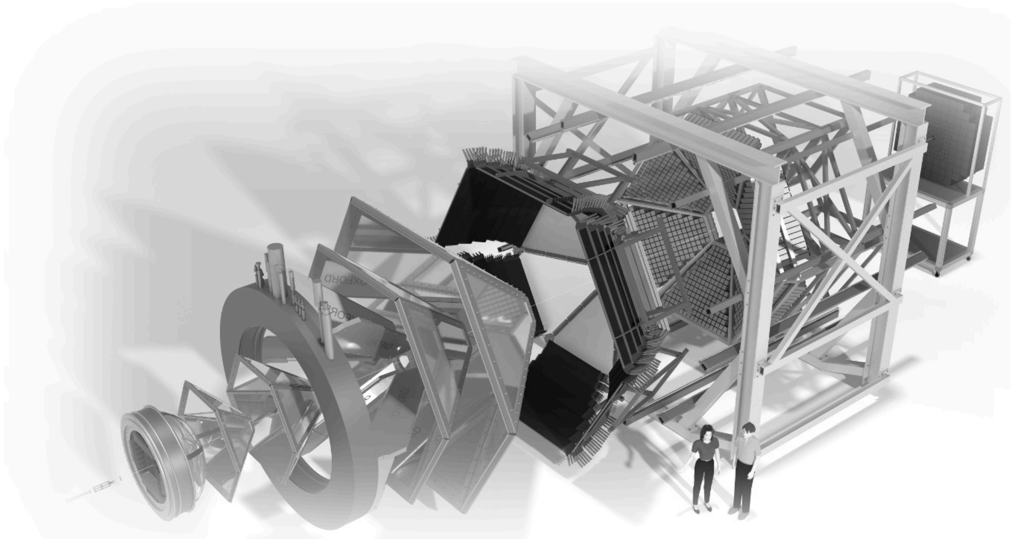
2012: Au+Au, $\sqrt{s_{NN}}$ = 2.42 GeV (7 billion)

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)





# Hadrons

# E-by-e fluctuations

**Looking for signatures of phase transition**

Higher order moments of particle yields from derivates of partition function Z w.r.t $\mu_B$

$$\langle N \rangle = \frac{\partial ln(Z)}{\partial(\frac{\mu}{T})}$$

$$\langle N^2 \rangle - \langle N \rangle^2 = \frac{\partial^2 ln(Z)}{\partial(\frac{\mu}{T})^2}$$

**Cumulants:**

$$\kappa_1 = \mu$$

$$\kappa_2 = \sigma^2$$

$$\kappa_3 = \langle N^3 \rangle - 3\langle N^2 \rangle \langle N \rangle + 2\langle N \rangle^3$$

$$\kappa_4 = \langle N^4 \rangle - 4\langle N^3 \rangle \langle N \rangle - 3\langle N^2 \rangle^2 + 12\langle N^2 \rangle \langle N \rangle^2 - 6\langle N \rangle^4$$

$$\text{Skewness} = \frac{\kappa_3}{\sigma^3}$$

$$\text{Kurtosis} = \frac{\kappa_4}{\sigma^4}$$

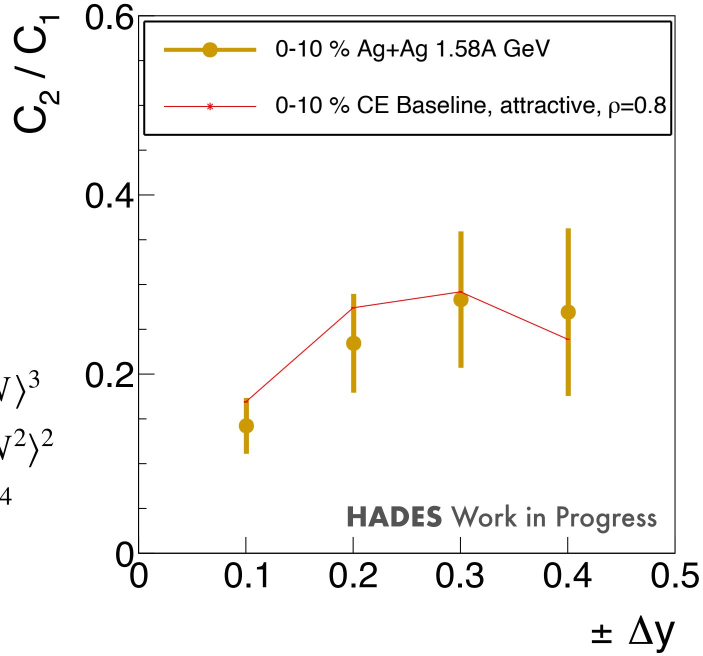
**Factorial cumulants:**

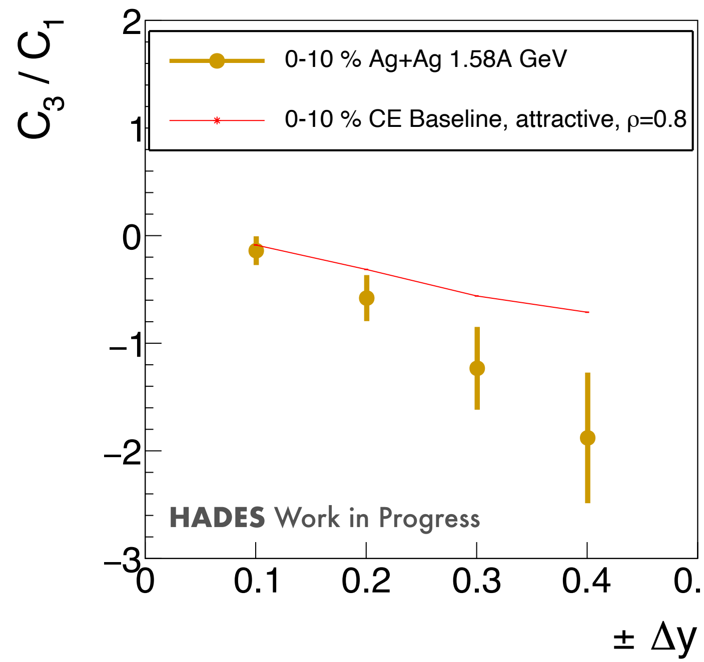
$$C_2 = \kappa_2 - \kappa_1$$

$$C_3 = \kappa_3 - 3\kappa_2 + 2\kappa_1$$

$$C_4 = \kappa_4 - 6\kappa_3 + 11\kappa_2 - 6\kappa_1$$

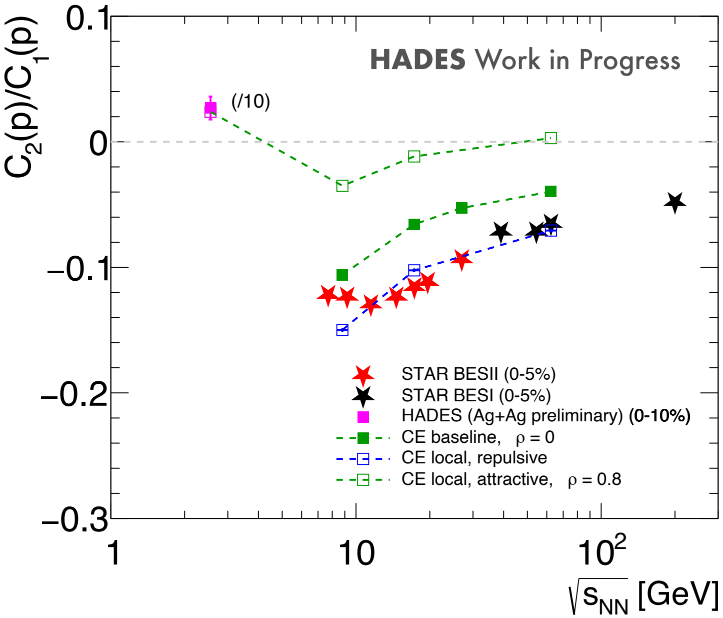
*P. Braun-Munzinger, K. Redlich, A. Rustamov, J. Stachel, JHEP 08 (2024) 113*

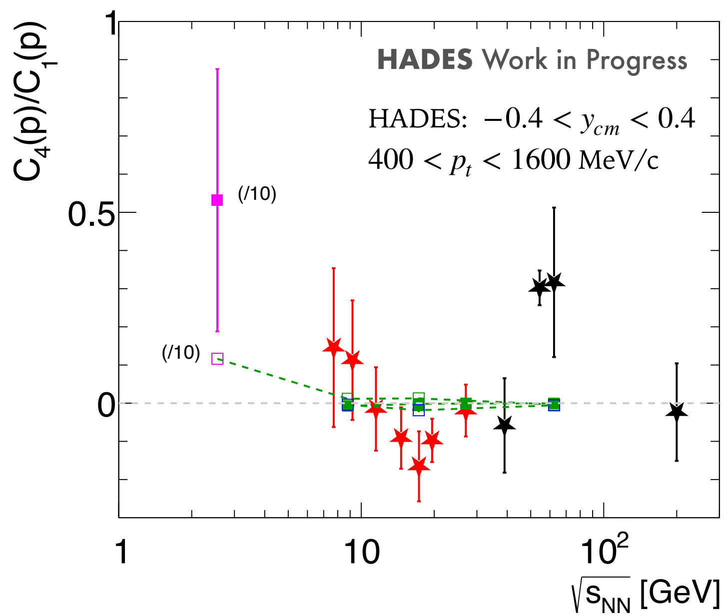


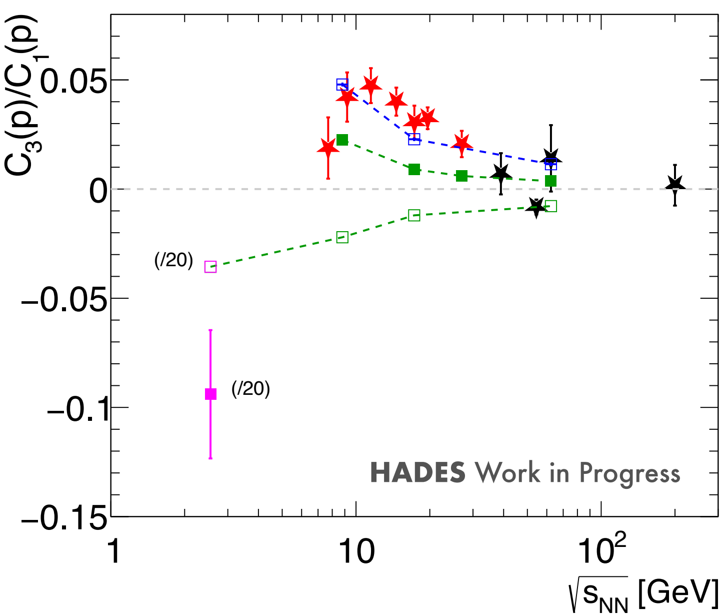

Trend of rapidity dependence of factorial cumulant ratios described by Canonical baseline considering correlations and attractive potential

# Proton factorial cumulants




*B. Friman, A. Rustamov, K. Redlich (in progress)*



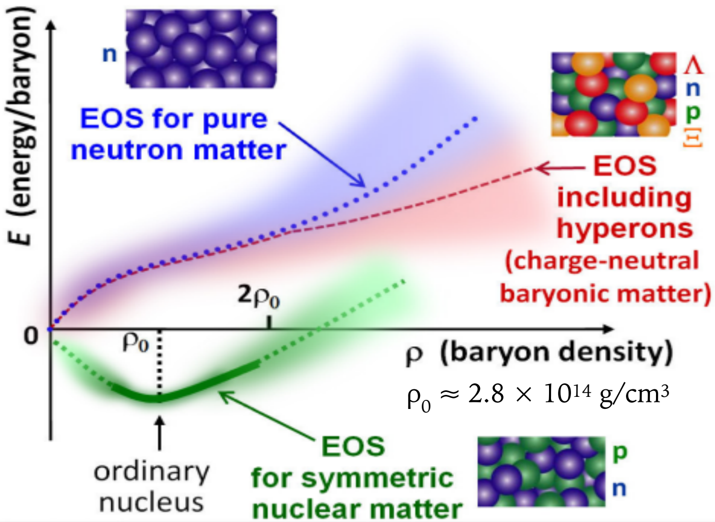

Larger factorial cumulant ratios at HADES compared to STAR

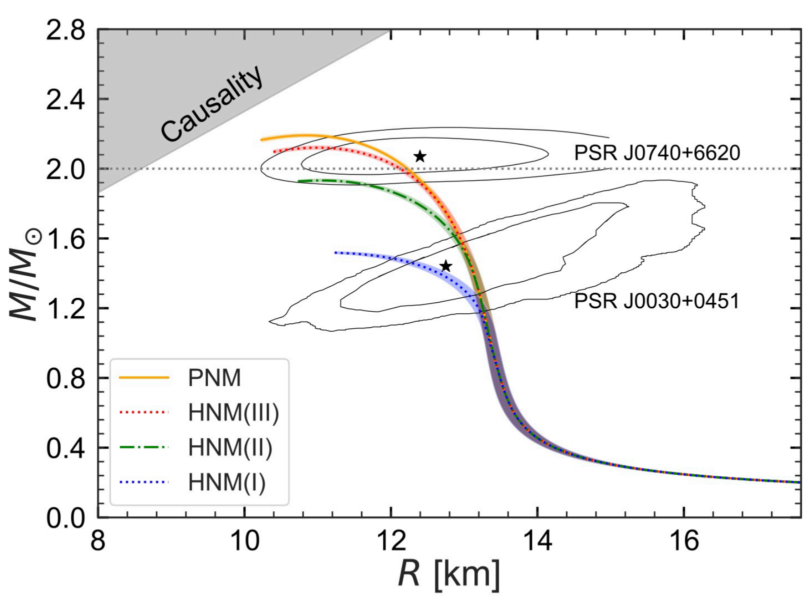
$C_3/C_1$ and $C_4/C_1$ HADES continues trend observed at STAR towards lower $\sqrt{s_{NN}}$

**The interplay of repulsive and attractive forces between protons explains the systematic trends observed in the STAR BESII and HADES data**

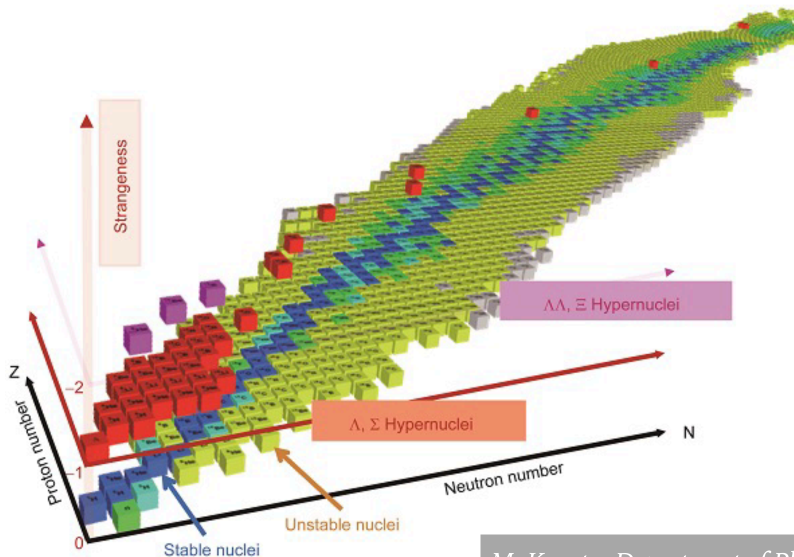
# Neutron star (NS) puzzle

*H.Tamura, JPS Conf. Proc. , 011003 (2014)*




*„To establish the EoS applicable to the neutron star has been one of the most important subjects in nuclear physics for a long time but has not been achieved yet." T. Hamura*



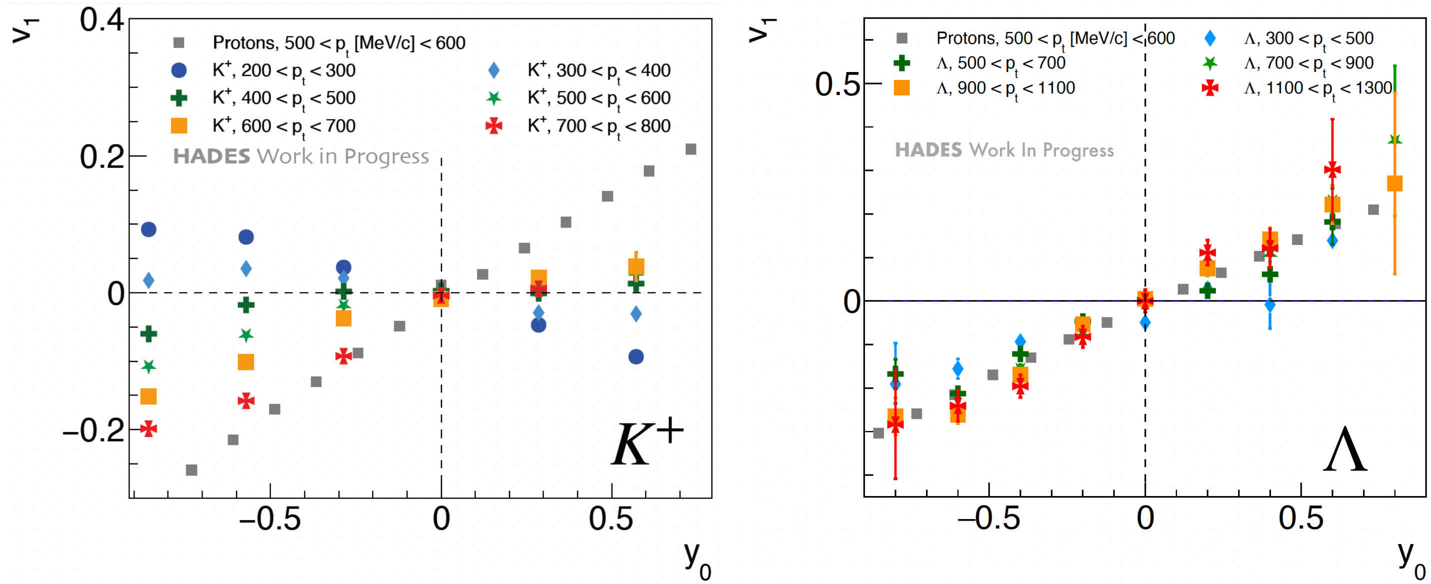

*M. Kaneta, Department of Physics, Tohoku University, Japan*

**Hypernuclei are pivotal for the EoS of the NS**

- How are nuclei and hypernuclei formed?
- What are their characteristics?
- How do nuclei (N) and hyperons (Y) interact?

# Anisotropic flow - strange hadrons

- EoS for NS including hyperons unable to explain the most massive NS
- Inclusion of hyperons favorable
- No conclusive measurement for the interaction KN potential yet
- Interactions of hadrons with nuclear matter probed by anisotropic flow




Rapidity dependence of $v_1$ for charged K and Λ is studied

**Comparing these results to transport models needed to learn about nature of their interactions with nuclear matter**

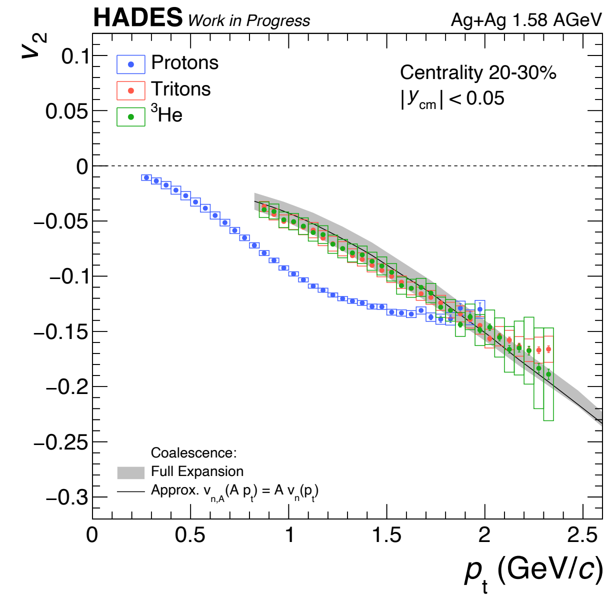
# Anisotropic flow - light nuclei

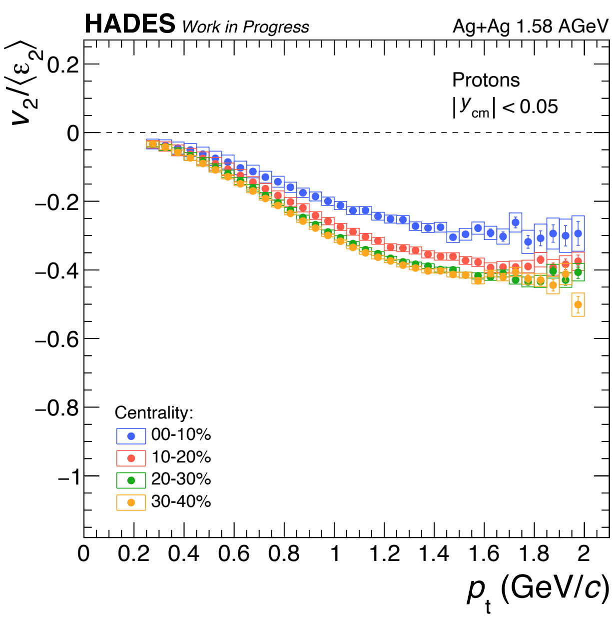
Scaling of $v_2(p_t)$ with A number $v_{n,A}(Ap_t) = Av_n(p_t)$

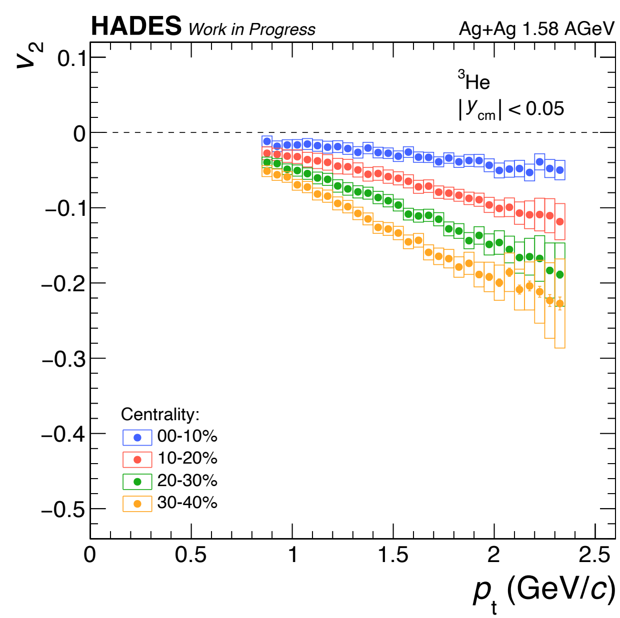
**Coalescence-like scenario works well for *t*, $^3He$**

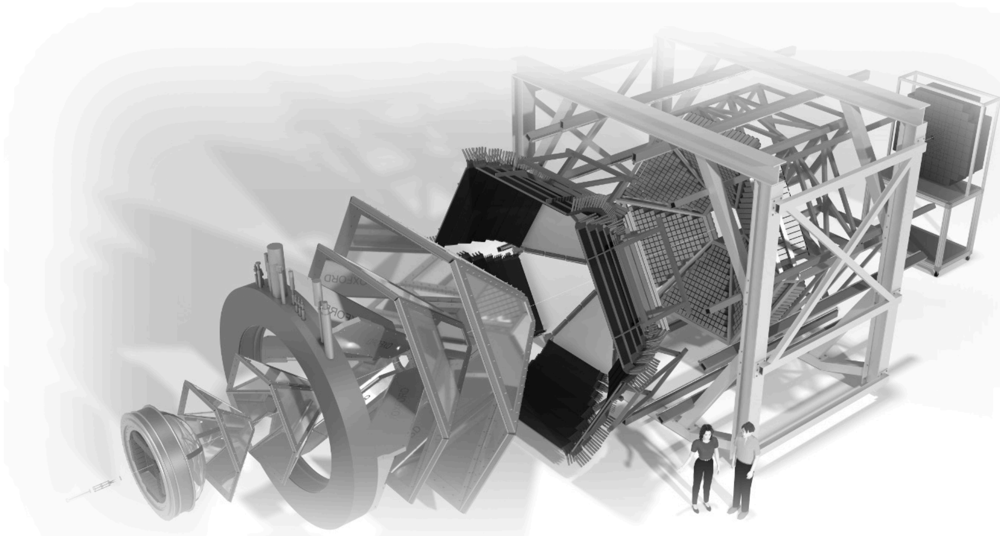
Orientation of symmetry-planes

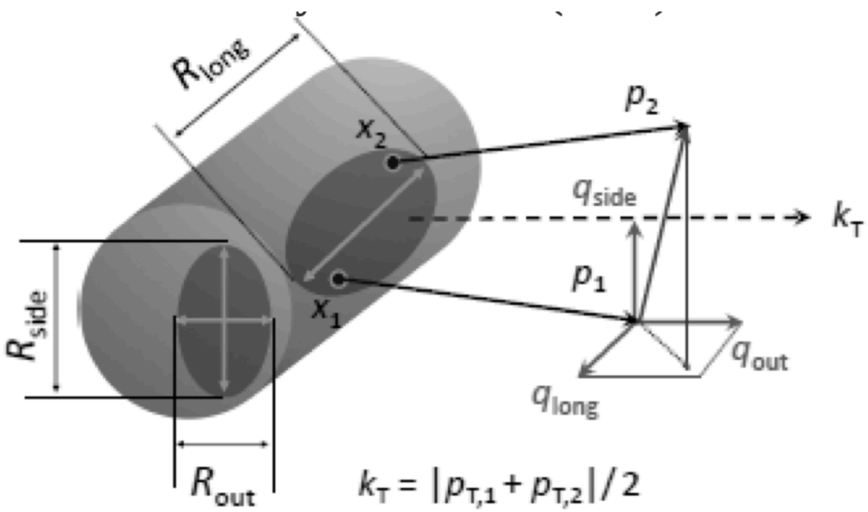
**Negative $v_2/\langle\epsilon_2\rangle \rightarrow v_2$ and eccentricity $\epsilon_2$ plane perpendicular**








# Hadrons

# *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

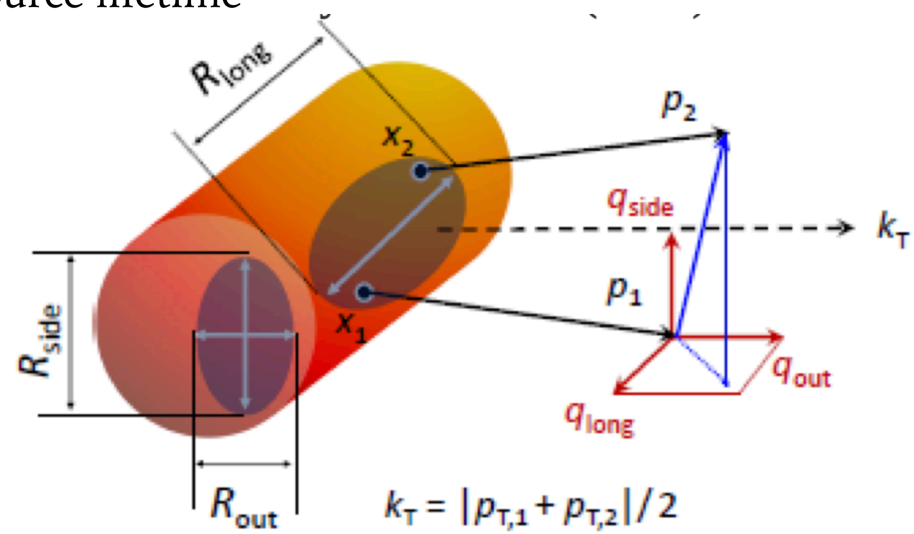
→ $R_{long}$ temperature of kinetic freeze-out and source lifetime

*long* - determined by the beam direction

*out* - determined by the pair transverse momentum

*side* - perpendicular to *long* and *side*

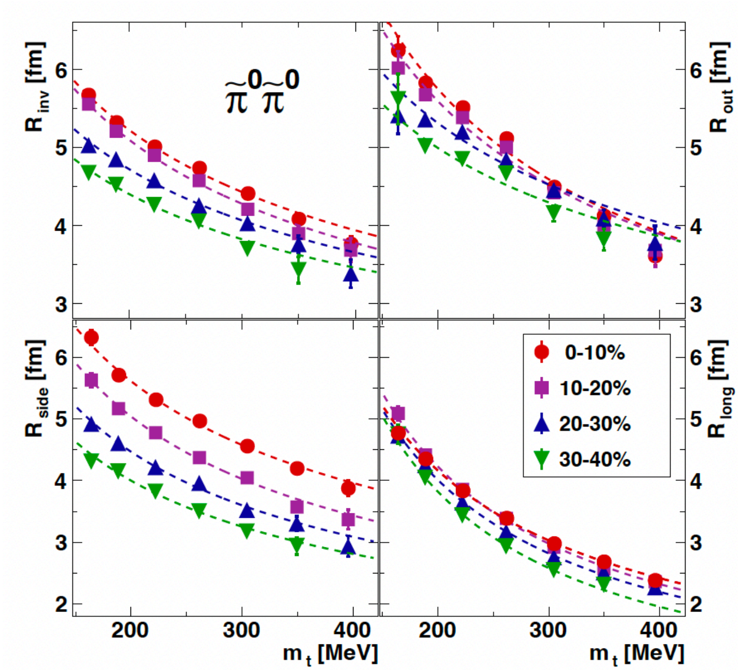
3D case is considered if statistics is enough and two-particle correlations are easy to describe (Quantum Statistics and Coulomb FSI).

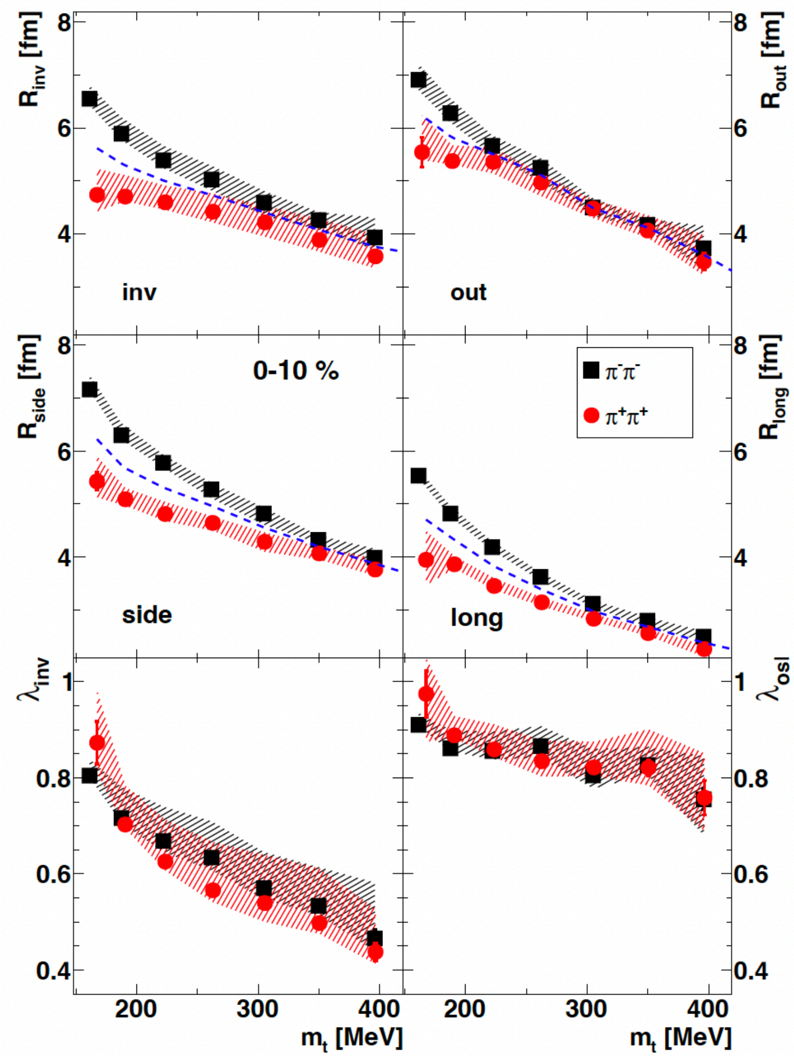



$$C(\vec{q}) = (1-\lambda) + K_{\mathrm{Coul}}(q_{\mathrm{inv}})\lambda \times \exp\left(-q_o^2R_o^2 - q_s^2R_s^2 - q_l^2R_l^2 - 2q_oq_sR_{os}^2 - 2q_oq_lR_{ol}^2\right)$$

# Identical pion correlations

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

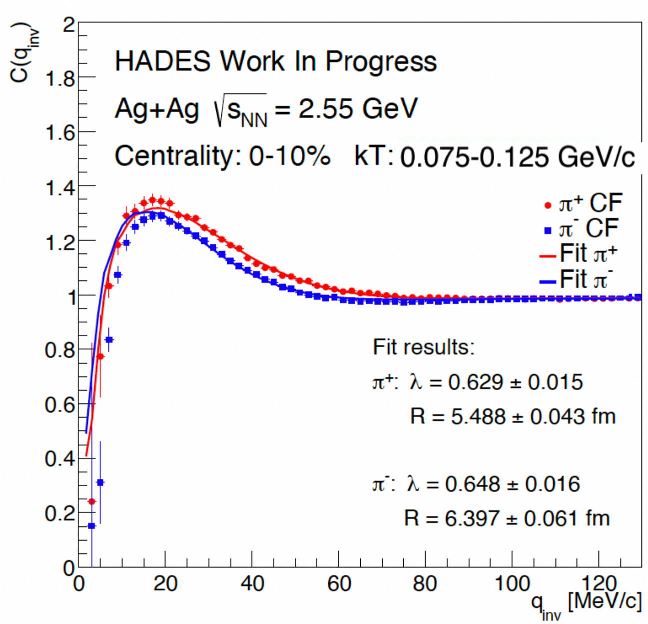


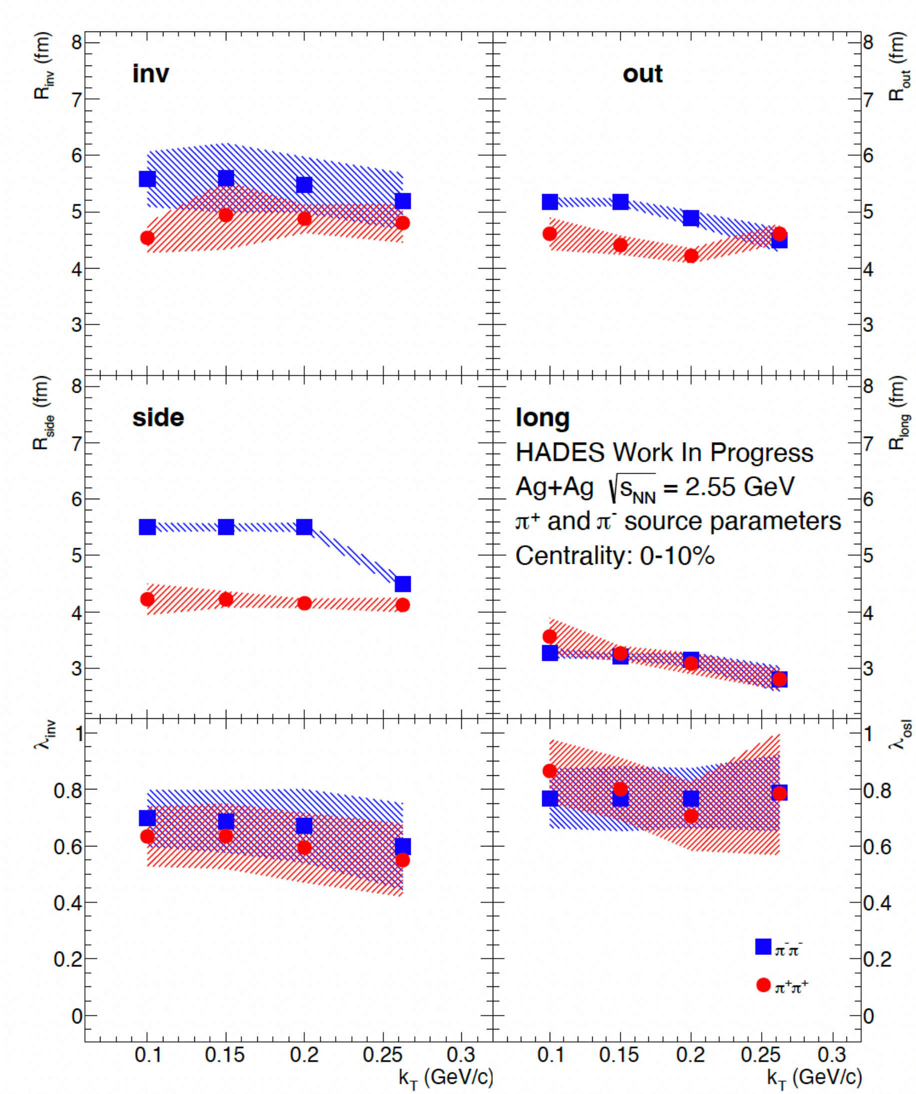



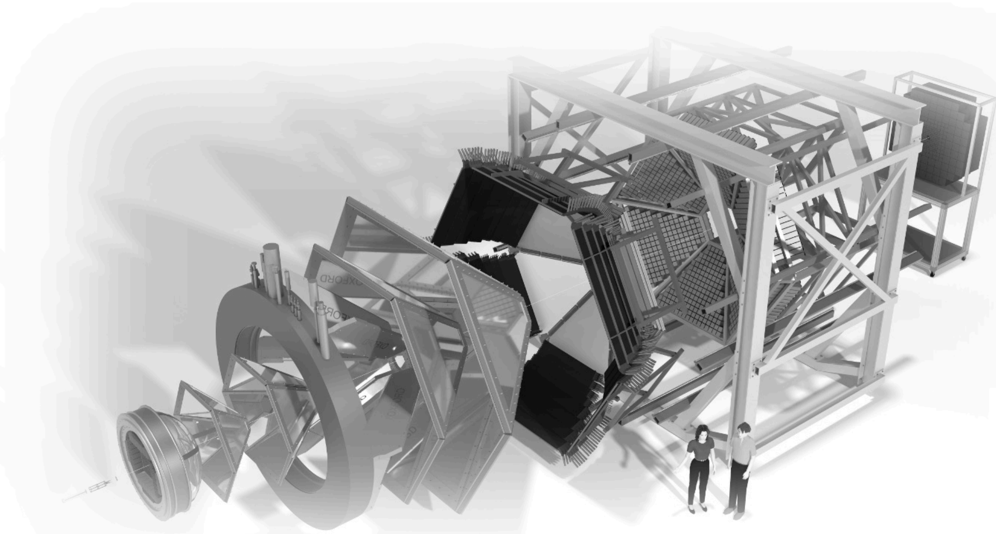

Eur. Phys. J. A 56, 140 (2020)

# Identical pion correlations

- 10% of most central collisions.
- 4 $k_T$ intervals.
- Differences in HBT parameters for $\pi^-$ and $\pi^+$ (especially low $p_T$) due to Coulomb effect.
- Other centralities considered as well





# Hadrons

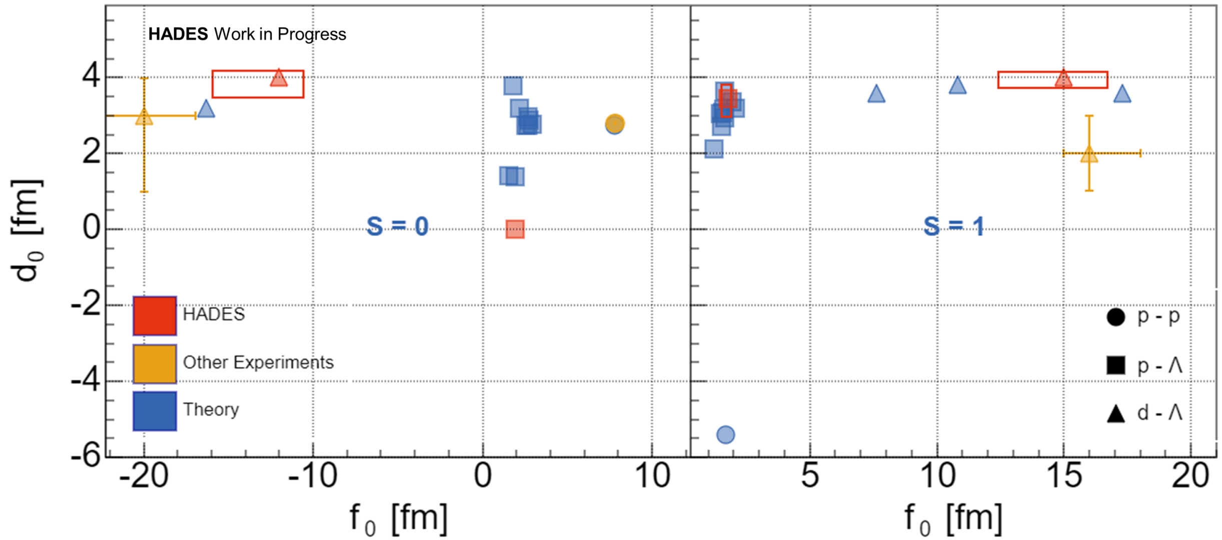
# *NN, NY interactions*

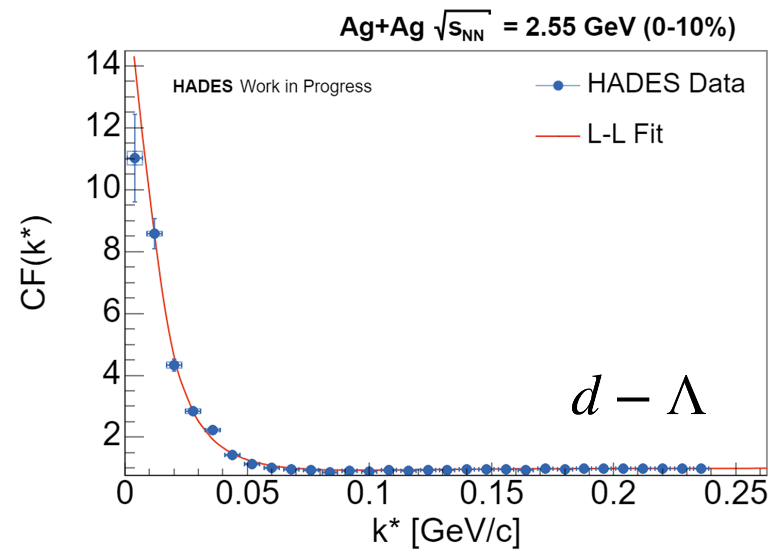
# Interactions

*Phys. Rev. C 99.2 (2019): 024001*
*EPJ Web of Conferences. Vol. 296, 2024*
*A. Rijken, Phys. Rev. C, Nucl. Phys. 73.4 (2006): 044007*
*A. ES Green, M. H. MacGregor, and R. Wilson. Conf. 1967*

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

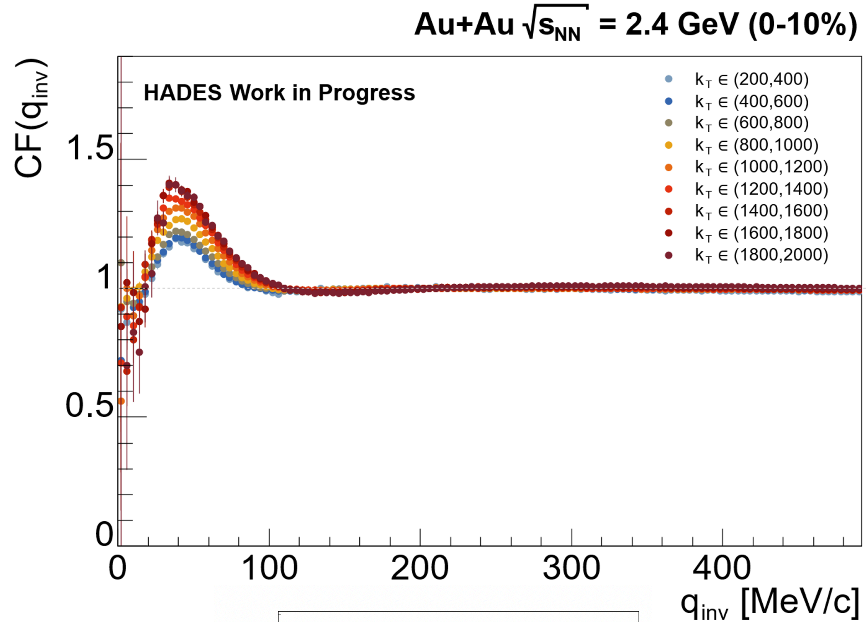
- Nucleons essentially stopped in collision zone
- HADES around the S production threshold
- Presence of Y in NS
- Impact of Y to EoS
- Modest of NN, NY, and YY interaction measurements
- Scattering length ($f_0^S$) and effective range ($d_0^S$) of p - p, p - Λ, and d - Λ interaction estimated
- Inline with the world data



# Proton - proton correlations

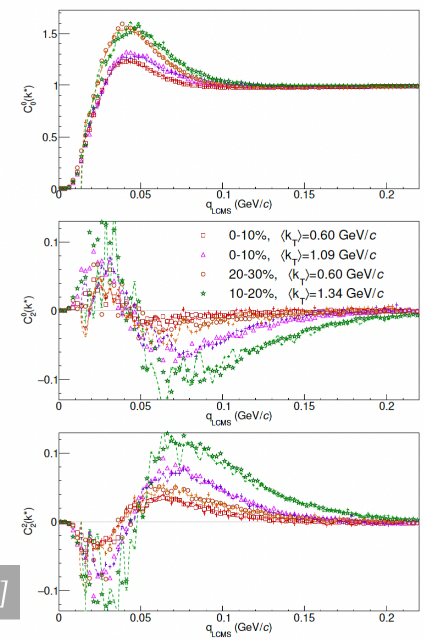
- High stopping in HADES implies large abundance of protons
- Protons expected to be more sensitive to the EOS
- So far only 1D analysis done, 3D analysis coming soon, BP parameters from protons to compare to pions




- Plan to use SH decompositions

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

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




e-Print: 2505.05276 [hep-ex]

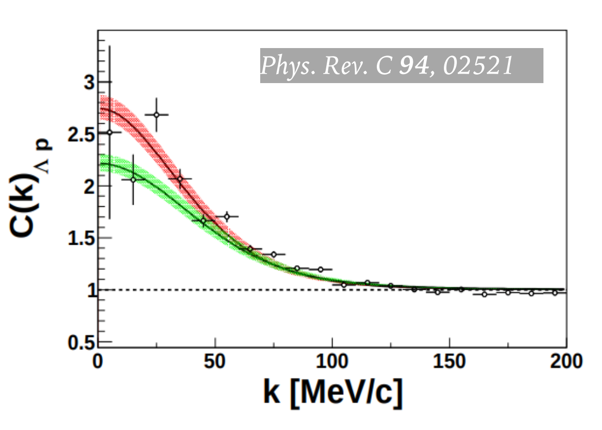
# Proton - lambda correlations

| Model | | $f_0^{S=0}$ (fm) | $f_0^{S=1}$ (fm) | $d_0^{S=0}$ (fm) | $d_0^{S=1}$ (fm) | $n_\sigma$ |
|---|---|---|---|---|---|---|
| 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 |
| $\chi$EFT | 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*

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





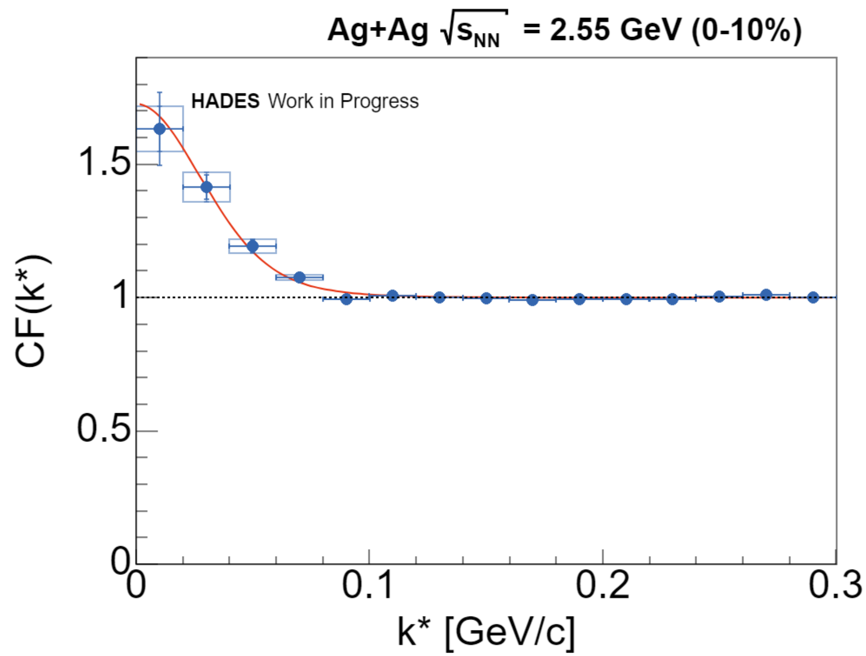

| Parameters | p-Nb (LO) | p-Nb (NLO) |
|---|---|---|
| $f_{0s}$ | 1.91 fm | 2.91 fm |
| $d_{0s}$ | 1.40 fm | 2.78 fm |
| $f_{0t}$ | 1.23 fm | 1.54fm |
| $d_{0t}$ | 2.13 fm | 2.72fm |
| $r_0$ | 1.71$\pm$ 0.10 | 1.62$\pm$ 0.02 |

# 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

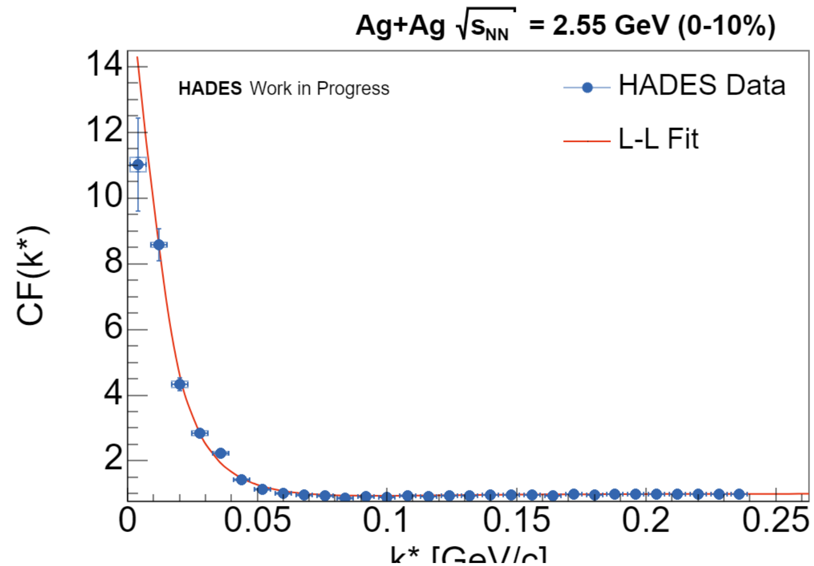


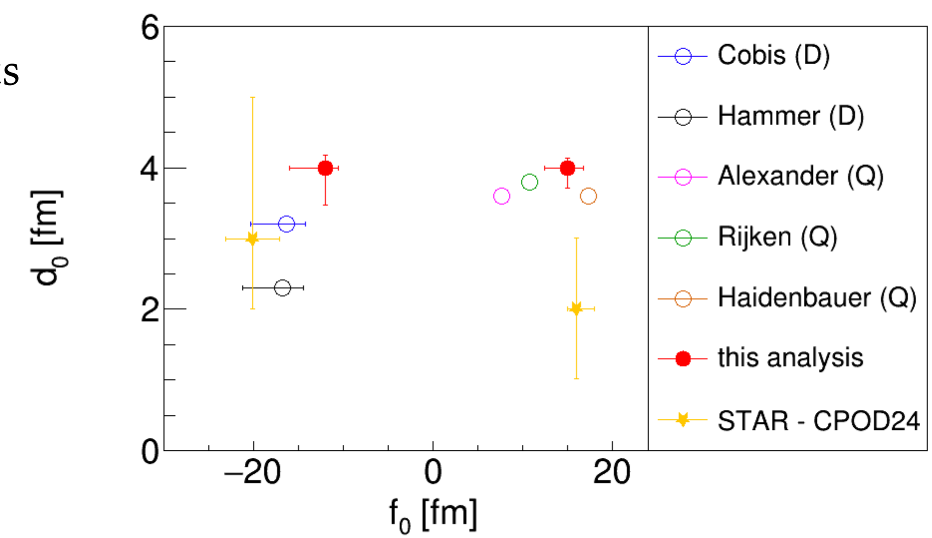
# Deuteron - lambda correlations

- $d - \Lambda$ 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:

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

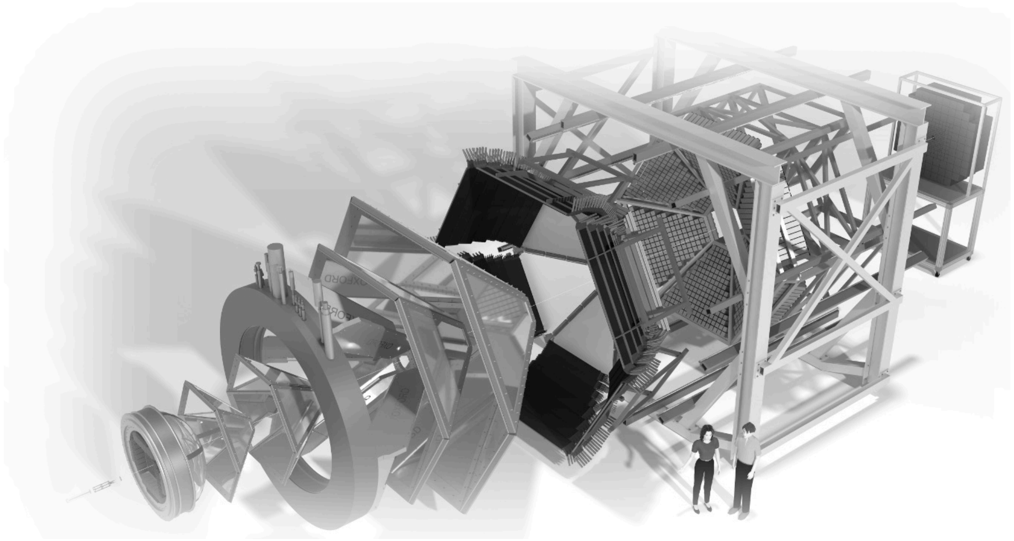
$f_0 = 15^{+1.73}_{-2.58}$ $d_0 = 4^{+0.13}_{-0.28}$ Quartet






See M. Grunwald talk
See M. Prędota talk



# Strangeness

# Hypernuclei - production mechanisms

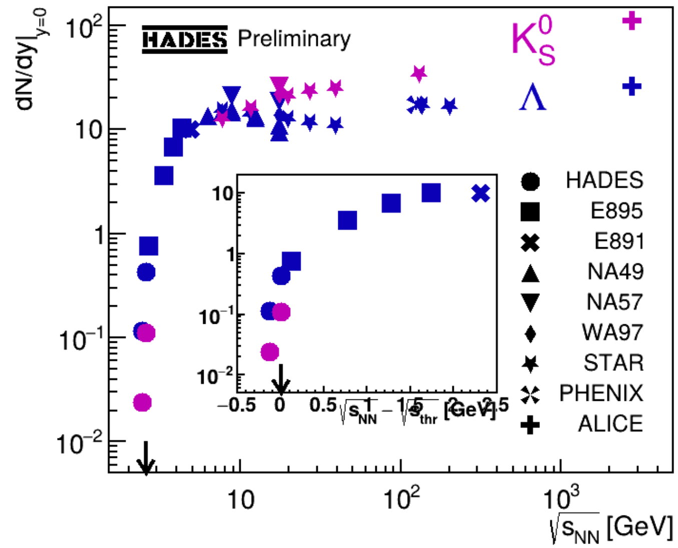
$\Lambda$ production close to free NN threshold

$\Xi$ production below free NN threshold:

$N + N \rightarrow Y + K + N$: $\sqrt{s_{NN}} = 2.55$ GeV

$N + N \rightarrow \Xi + K + N$: $\sqrt{s_{NN}} = 3.25$ GeV

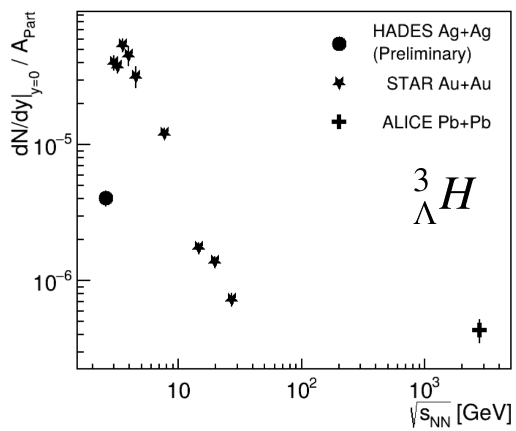
Phys. Lett. B793 (2019) - 457 - 463

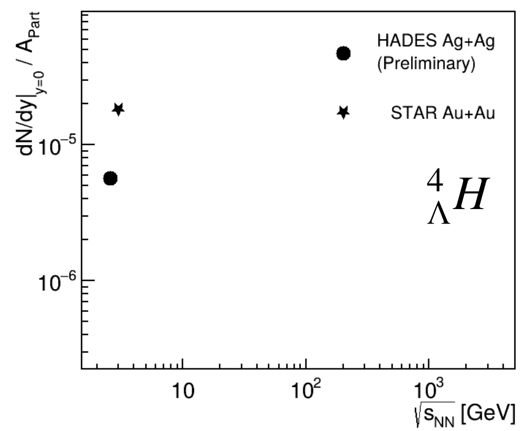



Production of hypernuclei:

- favored by baryon dominance at the fireball
- limited by the amount of produced $\Lambda$ hyperons

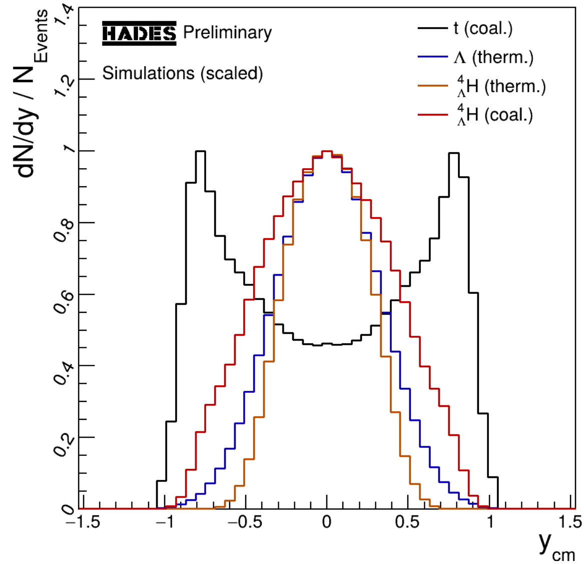
Production mechanism of light nuclei and hypernuclei explored: **statistical production** and **coalescence scenario** verified

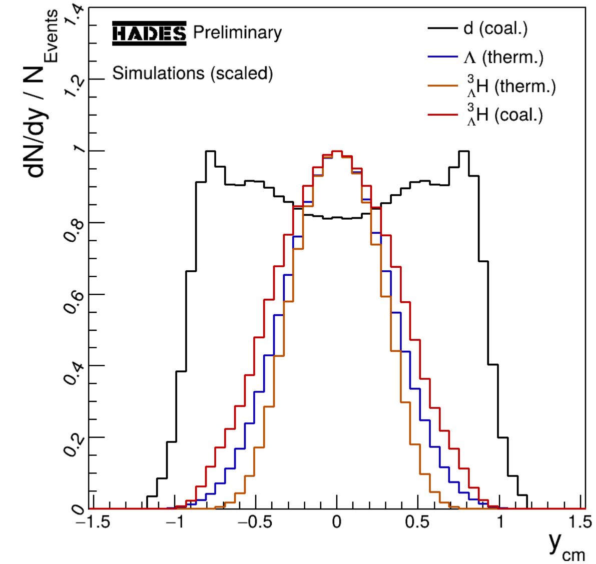



Phys.Rev.Lett. 128 (2022) 20, 202301
STAR BES-II Data:
EPJ Web Conf.296(2024)02004

# Hypernuclei - production mechanisms

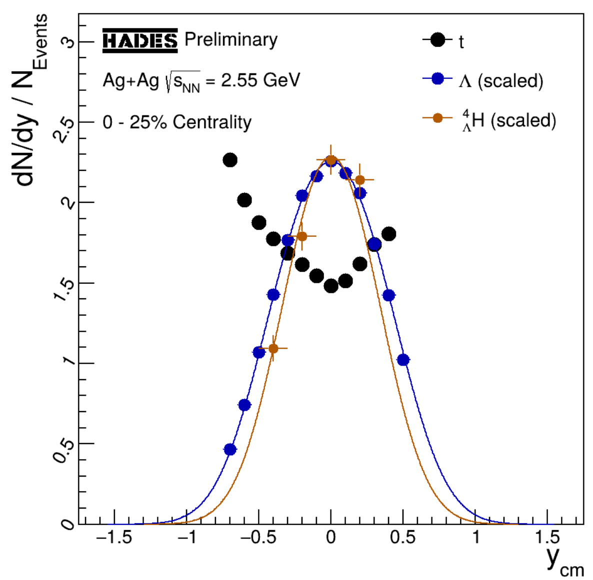


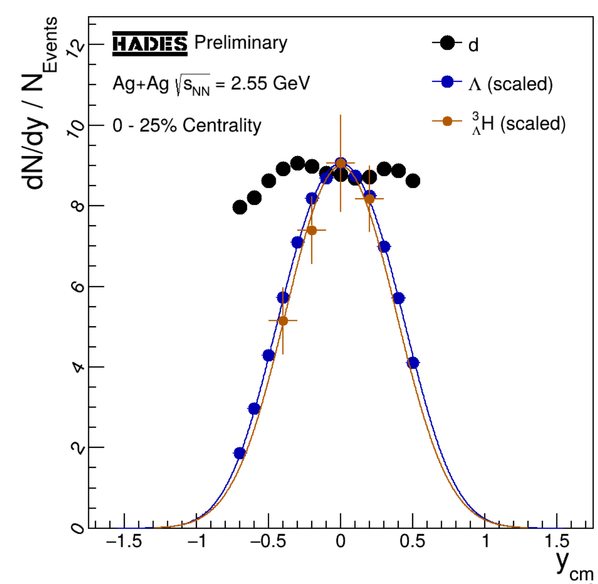




**d, t** - „coalescence-like" scenario favorable

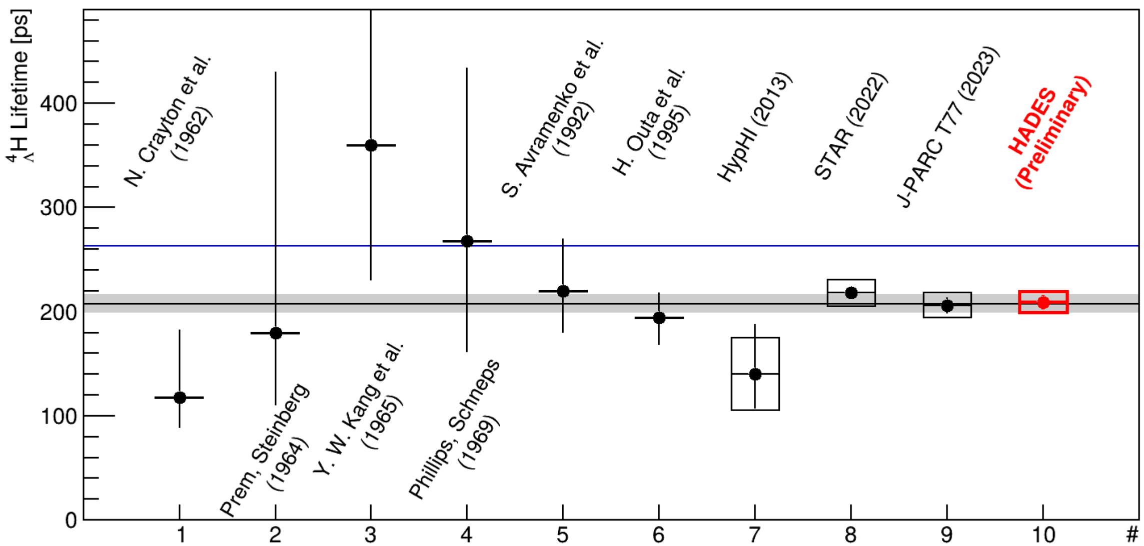
Λ - „thermal-like” production preferred

$^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ - low $p_T$ distributions could help to distinguish between two production mechanisms, a tendency of the „thermal-like” production visible



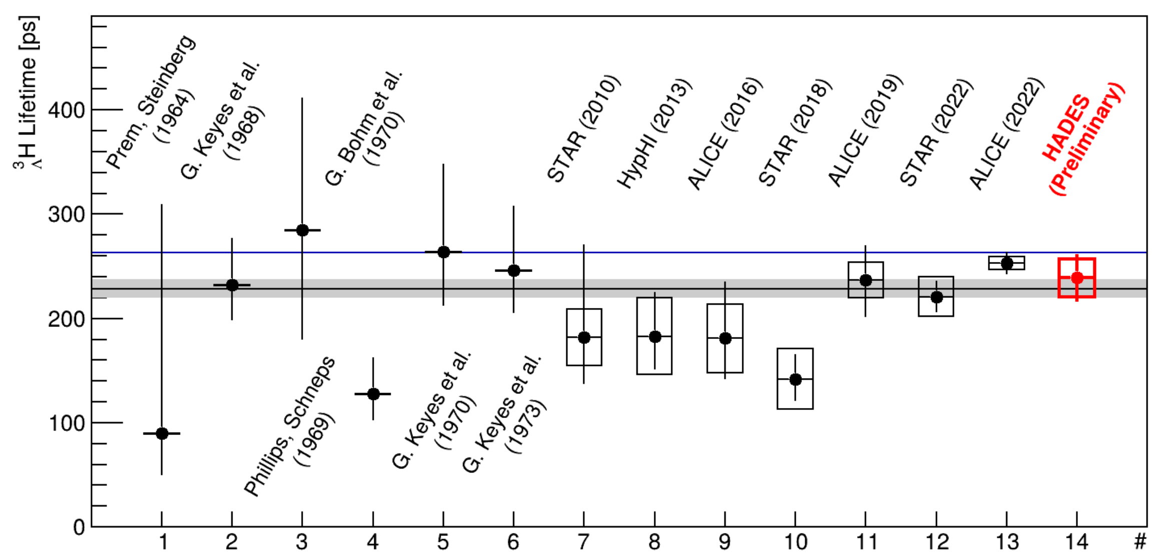
# Hypernuclei - lifetime

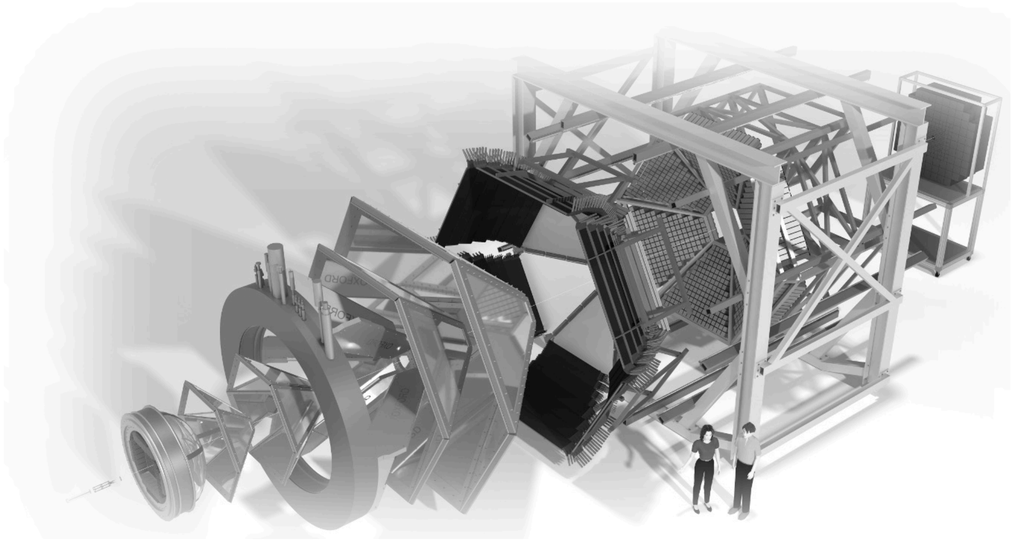



$^3_\Lambda H$ lifetime: $239 \pm 23 \pm 18$ ps

$^4_\Lambda H$ lifetime: $209 \pm 7 \pm 10$ ps

$^3_\Lambda H$, $^4_\Lambda H$ lifetime measurements compatible with recent data from STAR, ALICE and J-PARC





# Dileptons

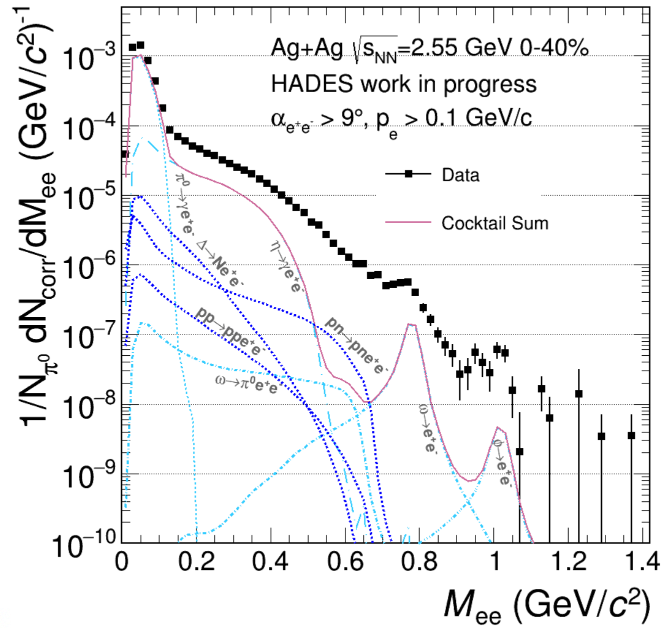
# Dilepton measurements

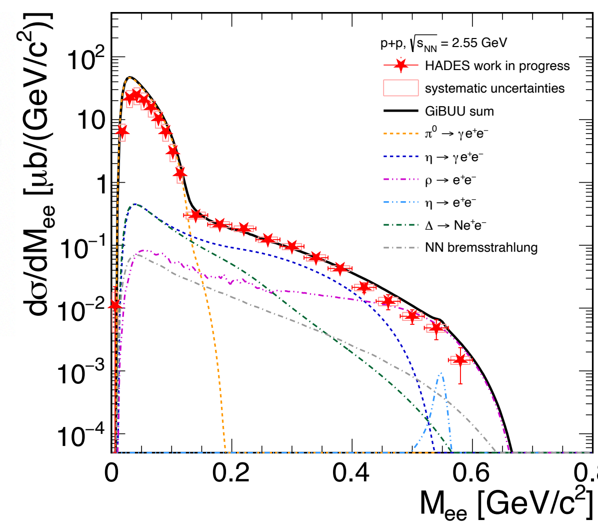
EM probes offer direct access to all stages of heavy-ion collision

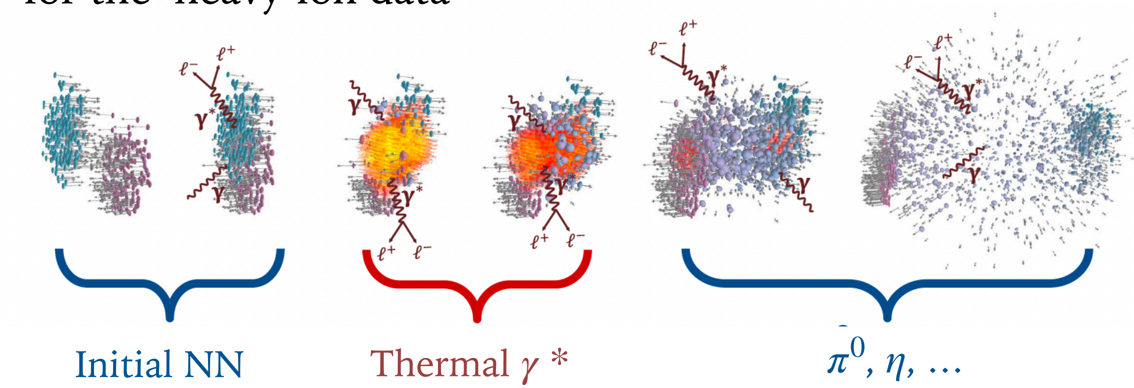
Penetrating probes unaffected by strong interactions

Possibility to extract the temperature and lifetime of the medium

Elementary collisions serve as baseline for the heavy-ion data



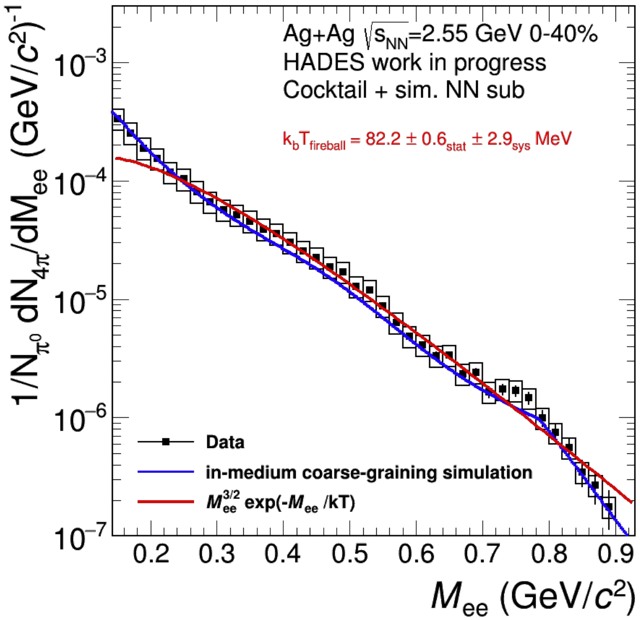




Measured signal:

- Initial NN reference spectrum
- Thermal probes
- Freeze-out cocktail ($\pi^0$, $\eta$, $\omega$, $\phi$)

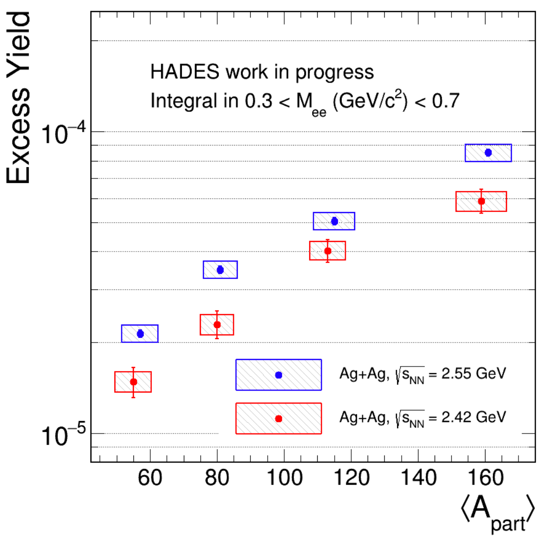
# Dilepton excess



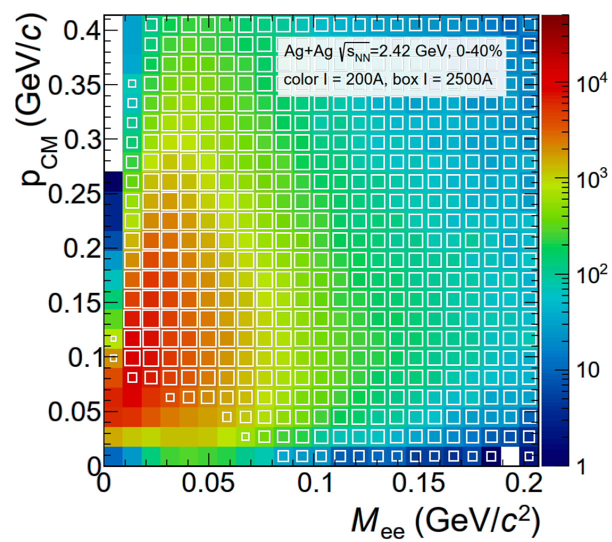

Spectra cutting low-mass of isolated dielectron pairs originating from **thermal radiation** extracted

**Fireball temperature determined**

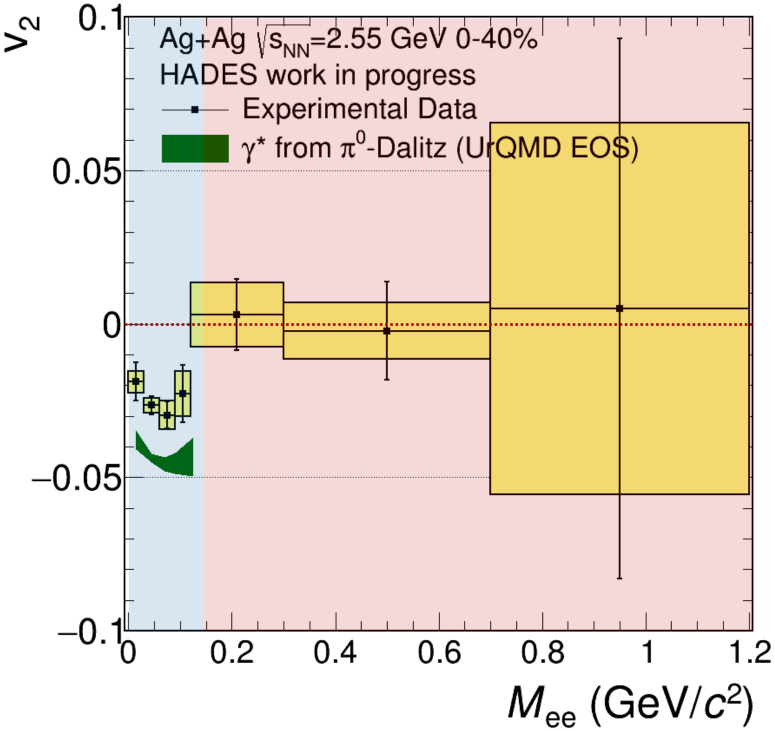
Extended lifetime of a fireball



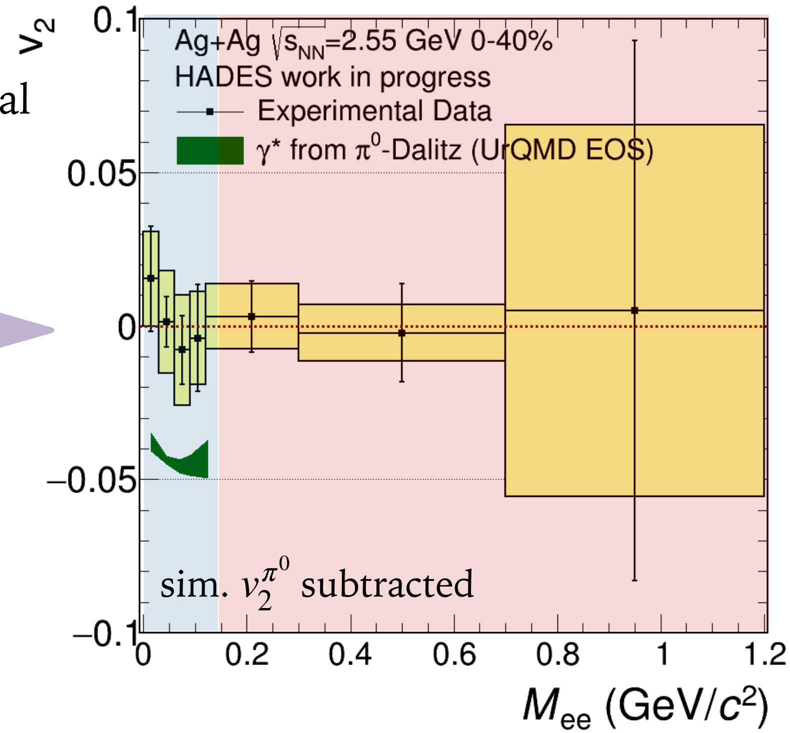

Towards extraction of electrical conductivity for QCD matter at high-density



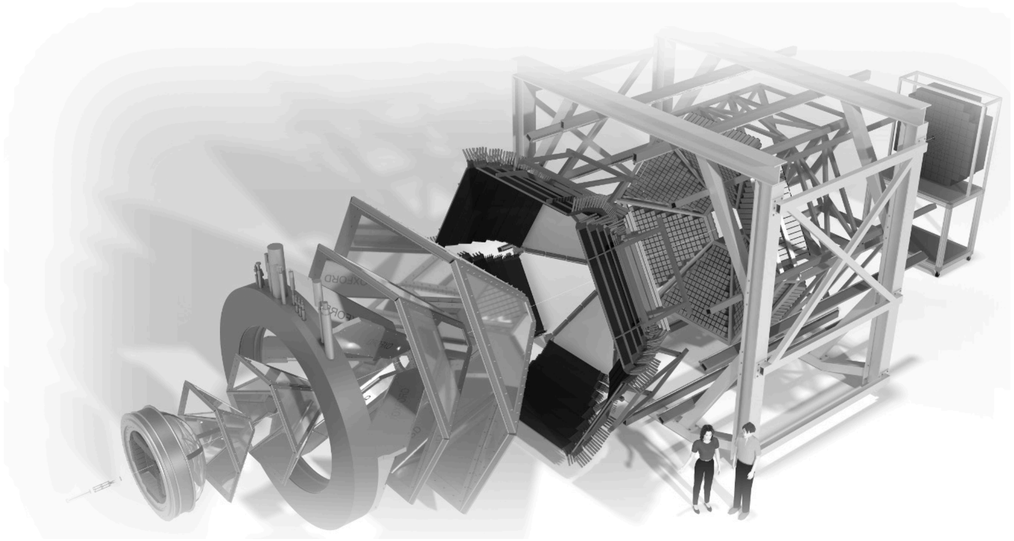
# Dilepton flow




Isolating thermal contribution in di-lepton $v_2$




Change in $v_2$ in $M_{ee}$ region dominated by **$\pi^0$ decays ($M_{ee}$ < 0.12 GeV/$c^2$ )** and dominated by **thermal radiation ($M_{ee}$ > 0.12 GeV/$c^2$ )**



# Future

# Future of HADES

In **2025** HADES continues data taking for energy scan of Au+Au collisions

**Searching for critical behavior and limitations of the universal freeze-out line**

**Au+Au collisions at 0.2 – 0.8 AGeV** ($\sqrt{s_{NN}} = 1.96 - 2.23$ GeV)

*measurements of e-by-e particle correlations and fluctuations, dielectrons, strange hadrons, light nuclei (up to $Z = 3$) and their flow (up to $6^{th}$order)*

HADES plans to take data in **2026/27** and continue its extended ***π*-QCD** program:

**Cold matter** *(in-medium vector-mesons, strangeness)*

**Hadron spectroscopy, structure and exotics** *(baryon-meson couplings, EM couplings, exotic mesons, rare η decay)*

**Effective interactions** *(hyperon polarization, hypernuclei formation, hyperon-meson interaction)*

HADES plans to be operational at least untill **2030**

In the following years HADES plans to explore high-$\mu_B$ region together with **CBM**

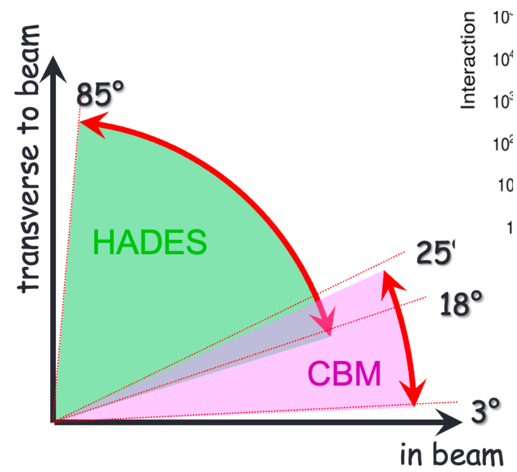
# HADES and CBM experiments

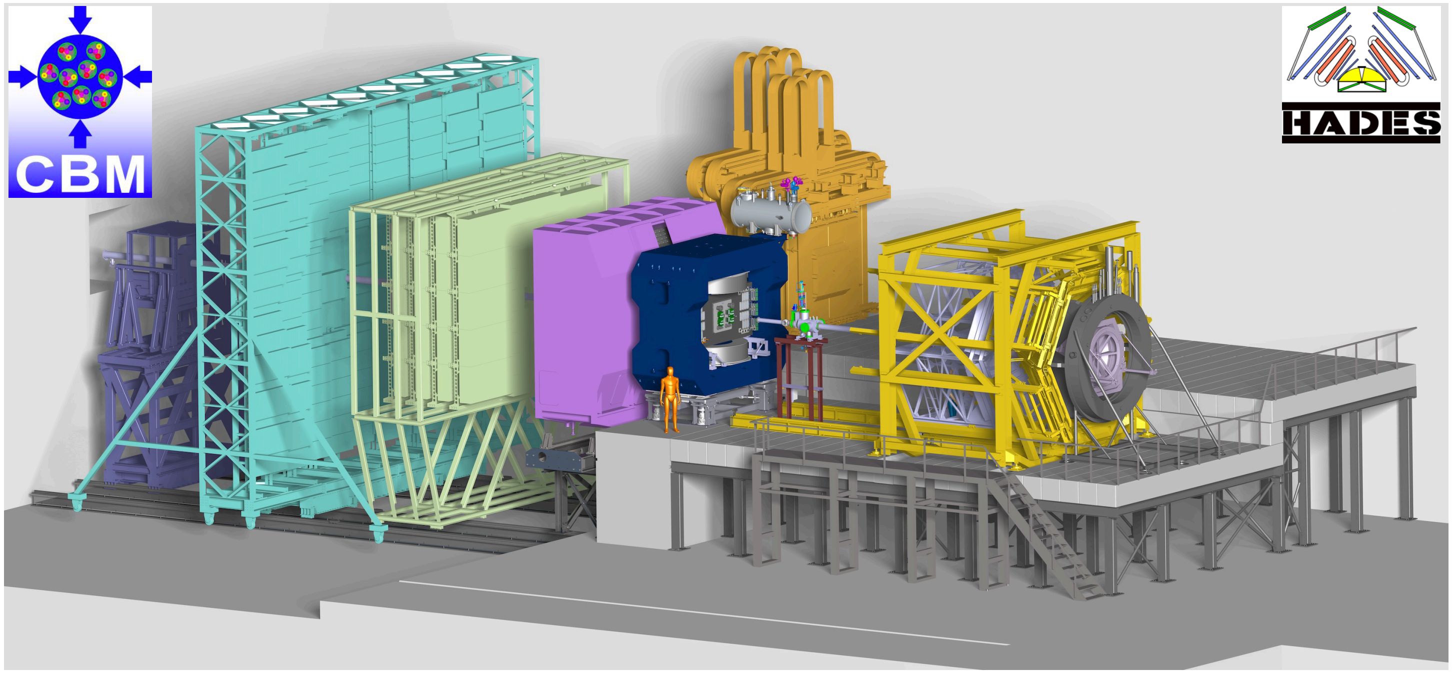
Fixed-target experiments → highest rates achievable

Versatile subsystems → tailored for the physics program

Angular coverage → complementary  for HADES and CBM

**First beams in 2028/2029**

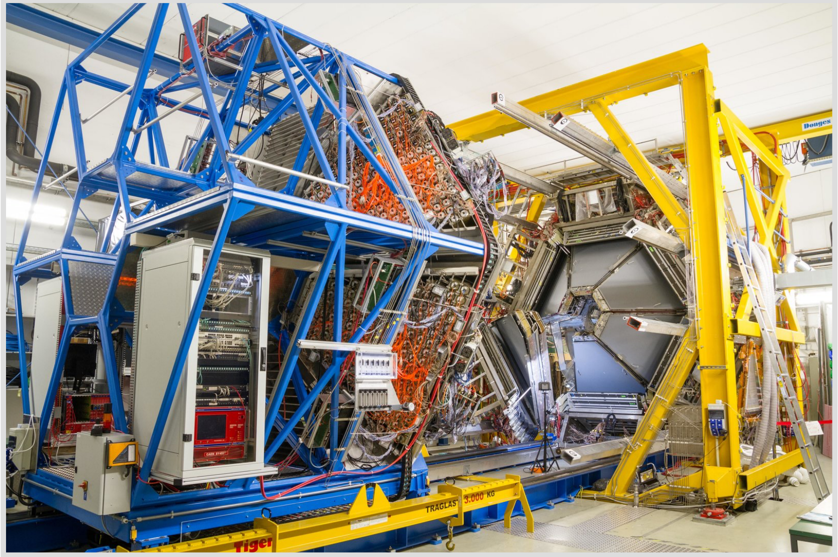



*See K. Piasecki talk*

# Wrap-up

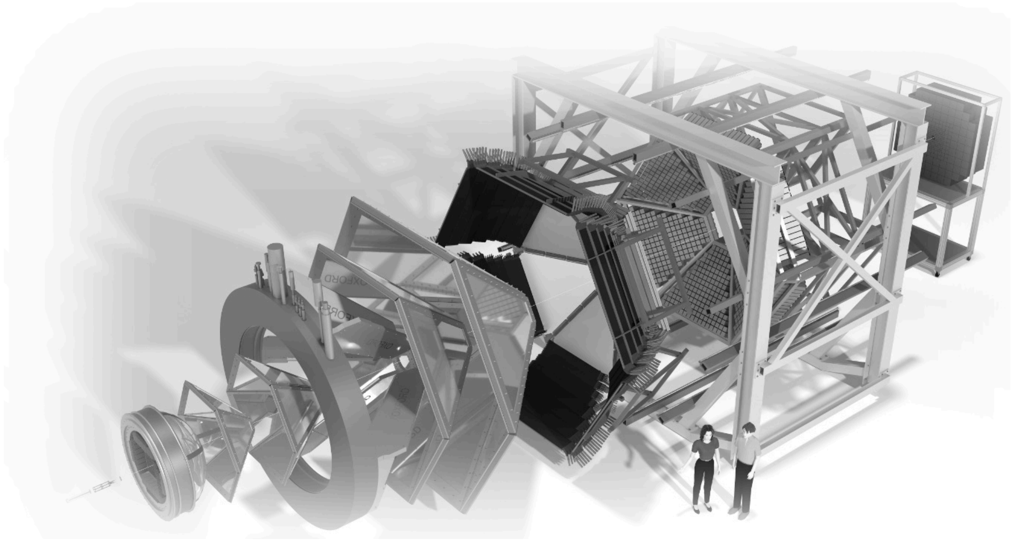
- HADES is versatile experiment oriented on heavy-ion and hadron physics;
- Physics goal is to explore baryon-rich matter describing neutron starts and neutron star mergers with unique hadron and electromagnetic probes;
- Recent physics findings:
  - the role of attractive / repulsive interaction describing fluctuation measures;
  - System space-time / dynamics and FSI parameters studied;
  - light nuclei and hyper nuclei production mechanism tested;
  - dilepton pairs coming from thermal radiation detected;
- HADES plans to continue operating together with CBM.



# HADES Collaboration


Collaboration Meeting,
March 16$^{th}$ - 21$^{st}$, 2025
GSI, Darmstadt

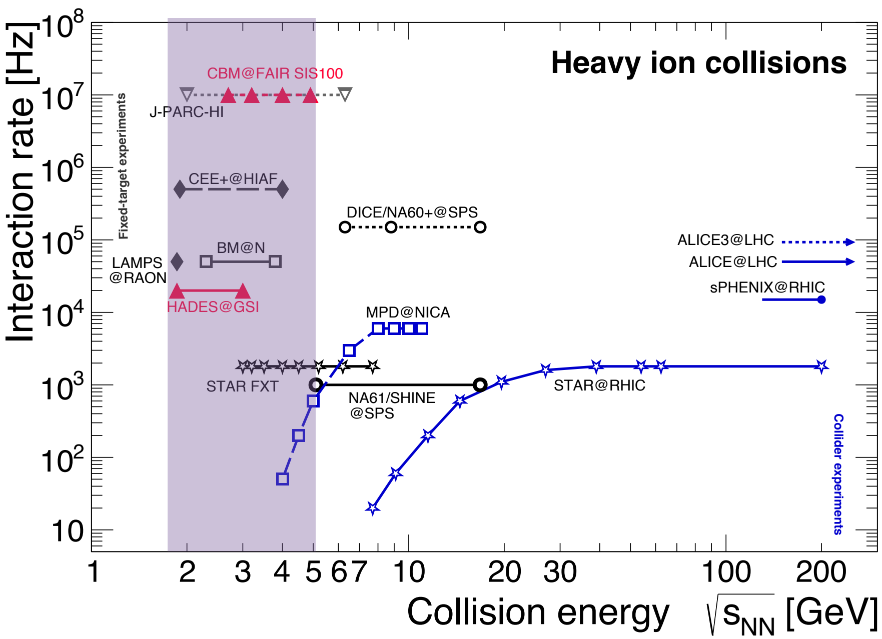
Thank you



# Extra slides

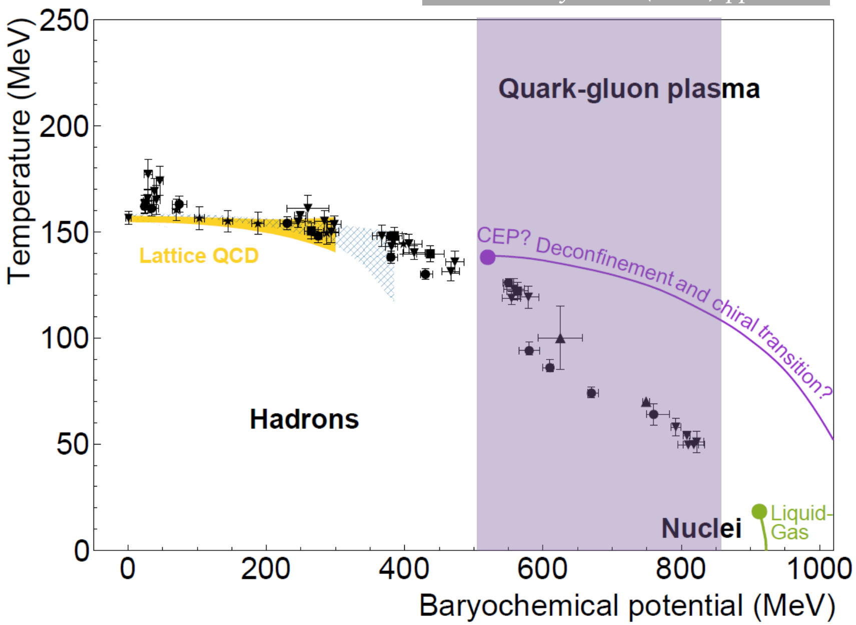
# HADES and CBM - key measurements

- **Fluctuations**: System alteration through first-order phase transition, critical point
- **Dileptons** : Emissivity: system's lifetime, temperature, density, in-medium characteristics
- **Hadrons (strangeness, charm, hypernuclei, bound states):** EoS: vorticity, collectivity, NN, YN, YY correlations, multi-body interactions



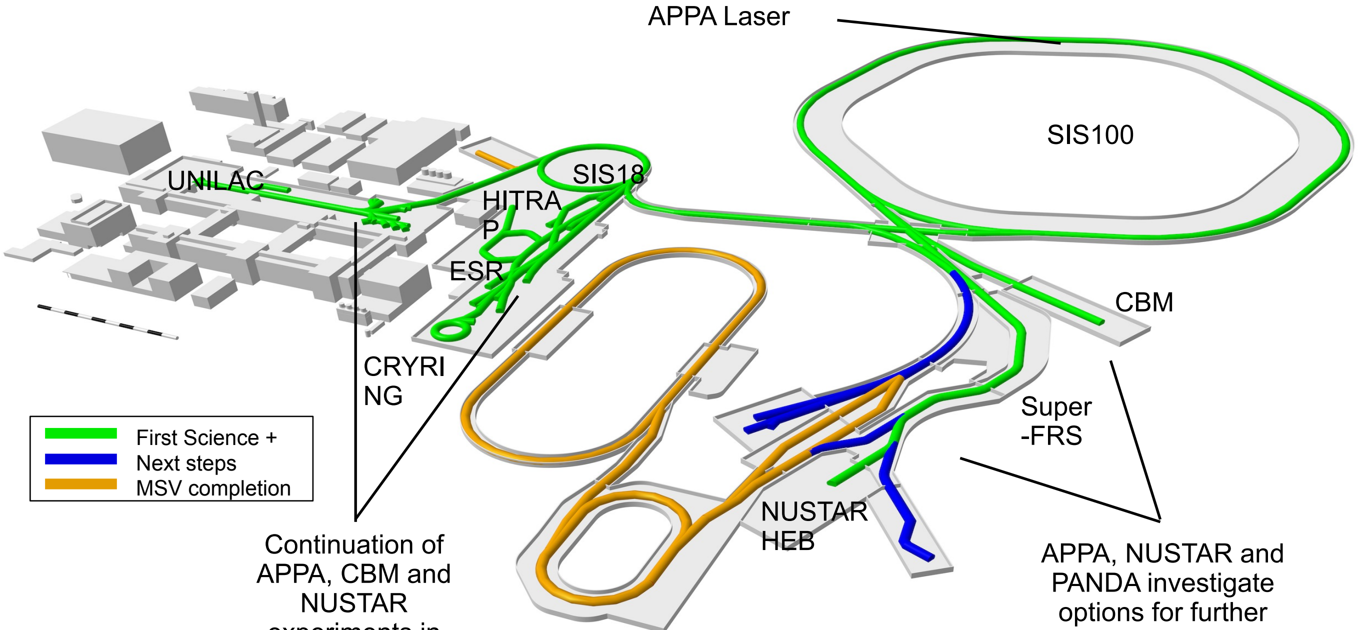

*T. Galatyuk, NPA 982 (2019), update 2023*
*https://github.com/tgalatyuk/interaction_rate_facilities*

*CBM physics program: Lect.NotesPhys. 814(2011) pp.1-980*




*HADES; Nature Physics 15 (2019) 10, 1040-1045*

# Current prospects and timeline



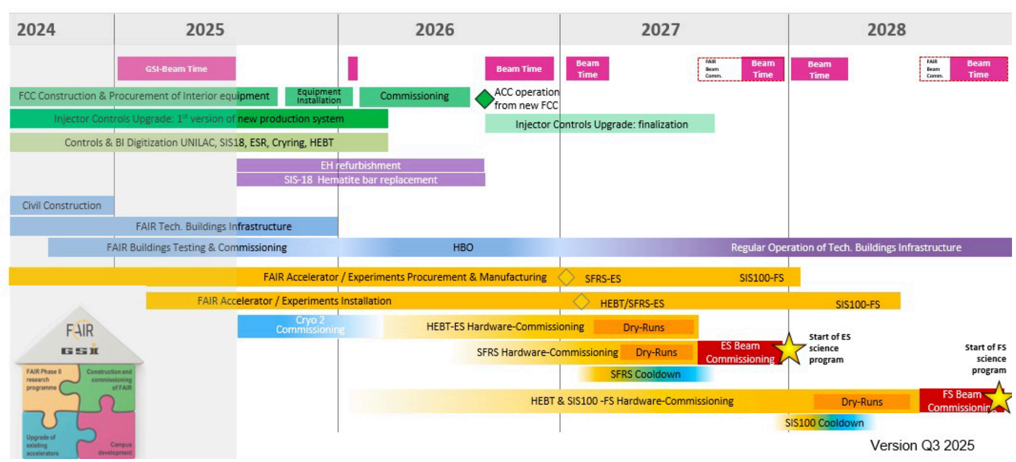

Continuation of APPA, CBM and NUSTAR experiments in existing facility

APPA, NUSTAR and PANDA investigate options for further experiments at green lines

until 2028

**FAIR Phase-0**

after 2028



# Facility for Antiproton and Ion Research

# Facility for Antiproton and Ion Research

CBM cave, 2025

SIS100 magnets

# Facility for Antiproton and Ion Research

## NuPECC LRP2024 Executive Summary

https://nupecc.org/lrp2024/Draft_Executive_Summary_LRP2024.pdf

### Introduction

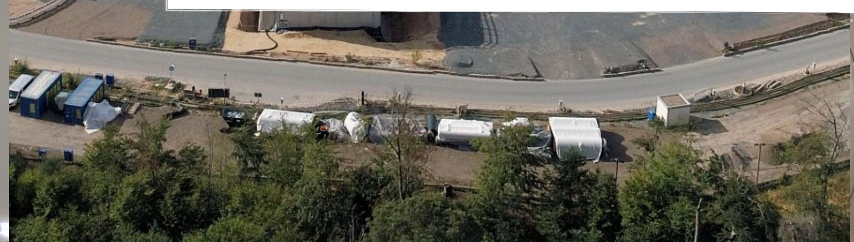
#### *What does nuclear physics stand for?*

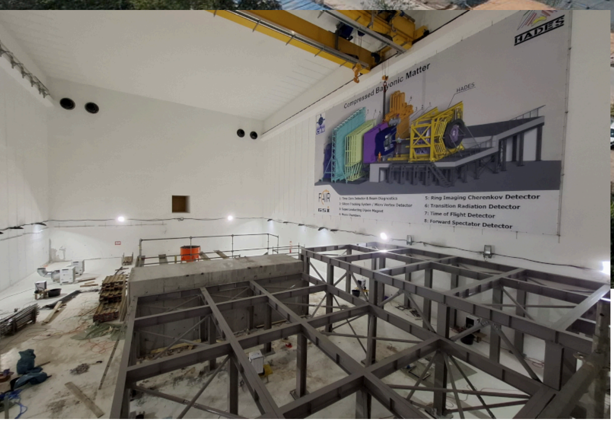
Nuclear physics is the study of the atomic nucleus, its constituents, structure, reactions and the properties of strongly interacting matter in its various forms. It is a key basic scientific field that investigates the properties of matter at the subatomic level. This domain of research affects not only our fundamental understanding of nature but also has many peaceful applications in all areas of modern life. Nuclear physics research originally started in Europe in the late 19th century. Now, in the 21st century, Europe is still at the forefront of nuclear physics research and applications. This leading European role is due to a rich and diverse landscape of research institutions and infrastructures in all European countries.
The present Long Range Plan for European nuclear physics summarises progress in the field in the last decade, provides an outlook on expected developments in the next decades, and presents recommendations for scientific institutions, policymakers, and research funding organisations.

## Recommendations for Nuclear Physics Infrastructures

The NuPECC Long Range Plan 2024 resulted in the following main recommendations for infrastructures of importance for nuclear physics:

- The first phase of the international **FAIR** facility is expected to be operational by 2028, facilitating experiments with SIS100 using the High-Energy Branch of the Super-FRS, the CBM cave and the current GSI facilities. Completing the full facility including the **APPA**, **CBM**, **NUSTAR** and **PANDA** programs will provide European science with world-class opportunities for decades and is highly recommended.

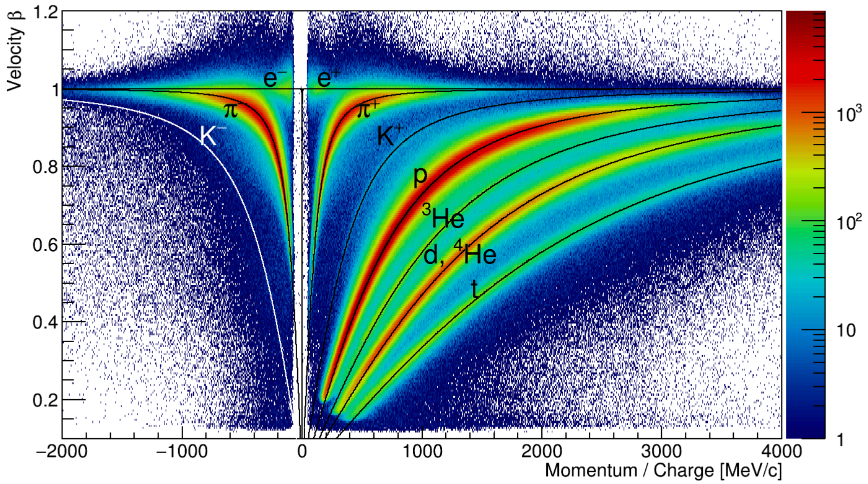




CBM cave, 2025

SIS100 magnets

# HADES data taking

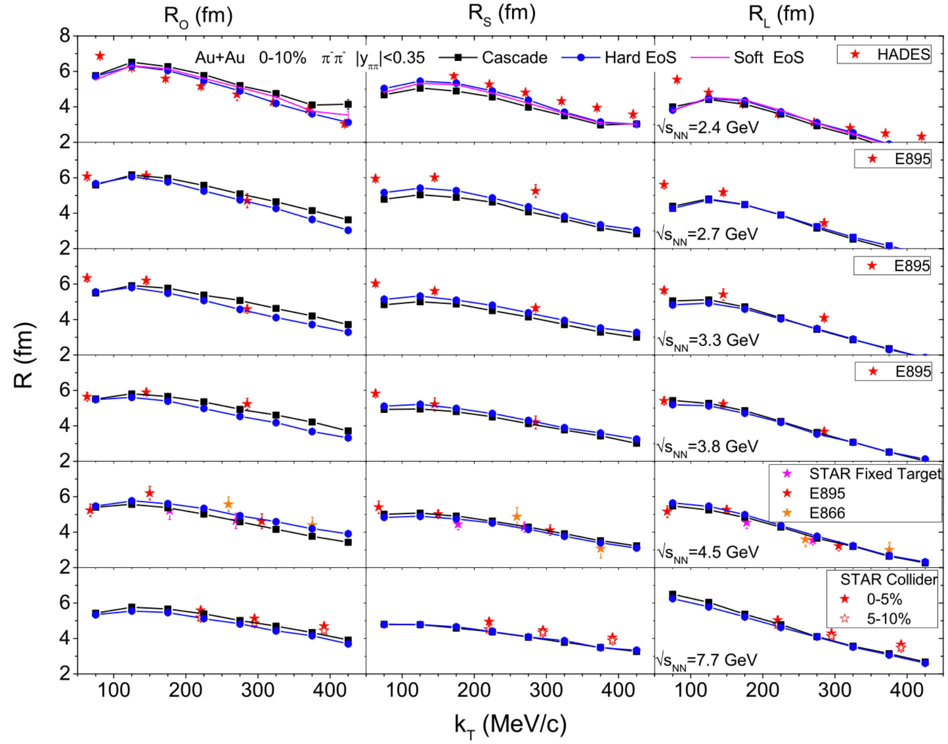



PID primarily via. momentum and velocity
Separation of multiple charged particles through specific energy loss

2002: C+C @$\sqrt{s_{NN}}$ = 2.7 GeV
2004: p+p @$\sqrt{s}$ = 2.77 GeV
2004: C+C @$\sqrt{s_{NN}}$ = 2.32 GeV
2005: Ar+KCl @$\sqrt{s_{NN}}$ = 2.61 GeV
2006: p+p @$\sqrt{s}$ = 2.42 GeV
2007: p+p @$\sqrt{s}$ = 3.18 GeV, d+p @$\sqrt{s_{NN}}$ = 2.42 GeV
2008: p+Nb @$\sqrt{s_{NN}}$ = 2.7 GeV
**→ 2012: Au+Au @$\sqrt{s_{NN}}$ = 2.42 GeV (7 billion)**
Jul-Aug-Sep 2014: $\pi$+W, $\pi$+C, $\pi$+PE @$\sqrt{s}$=1.5 GeV
**→ 2019: Ag+Ag @$\sqrt{s_{NN}}$ = 2.55 GeV**
**and 2.42 GeV (14 billion)**
2022: p+p @$\sqrt{s}$ = 3.46 GeV
**→ 2024: Au+Au at $\sqrt{s_{NN}}$ = 2.24 GeV (1.8 billion)**

# 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)