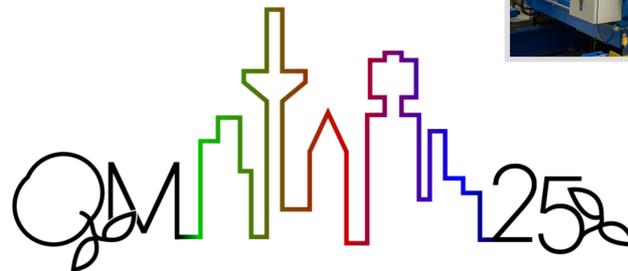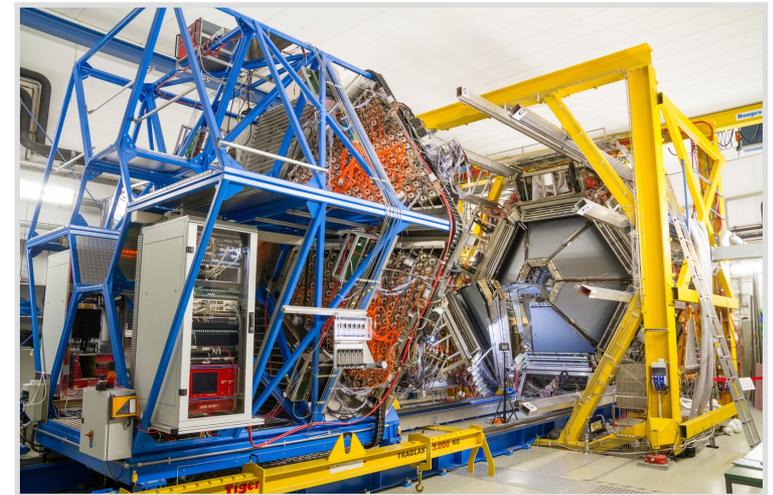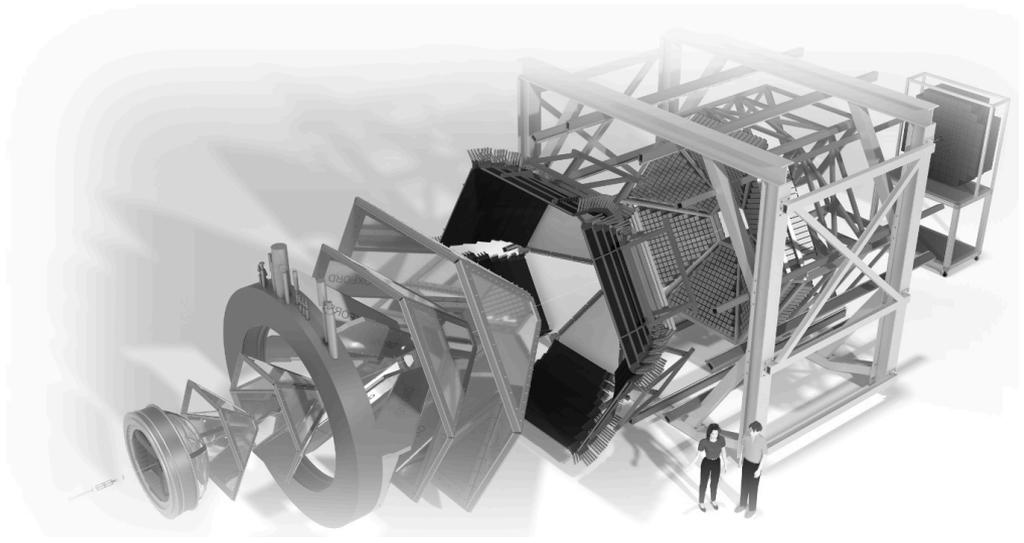# Experimental overview: HADES

Hanna Zbroszczyk for the HADES Collaboration

Warsaw University of Technology

Outline

- Physics goals and detector

- Results:

• Hadrons (fluctuations, collectivity, correlations)

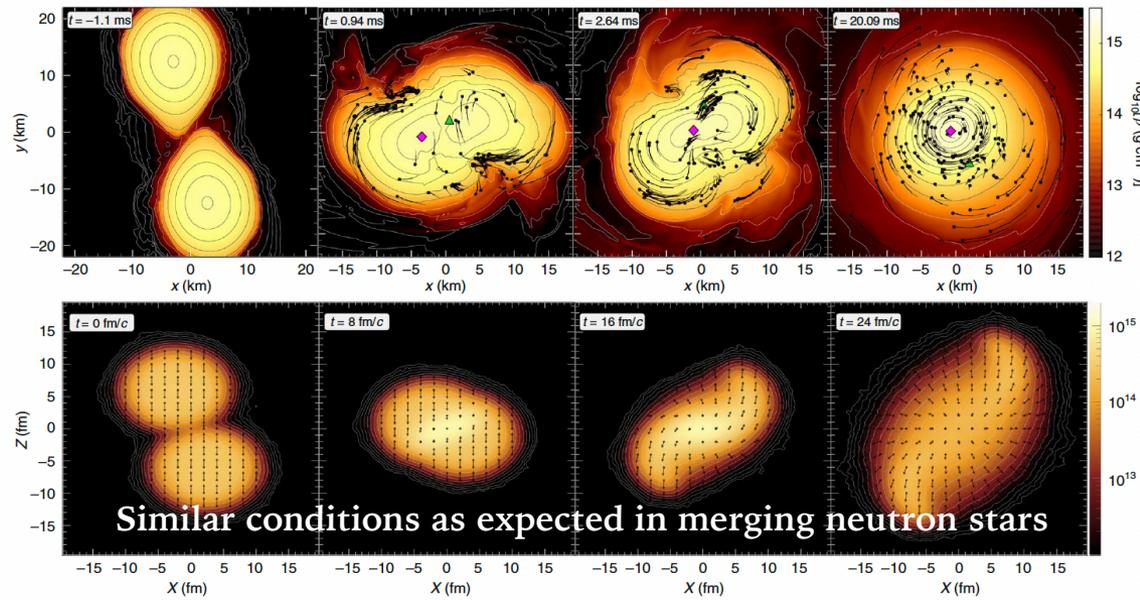• Strangeness (including hypernuclei)

• Dileptons

- Future

Quark Matter 2025, Frankfurt, Germany, April 6-12th, 2025

Physics goals and detector

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

HADES physics goals

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

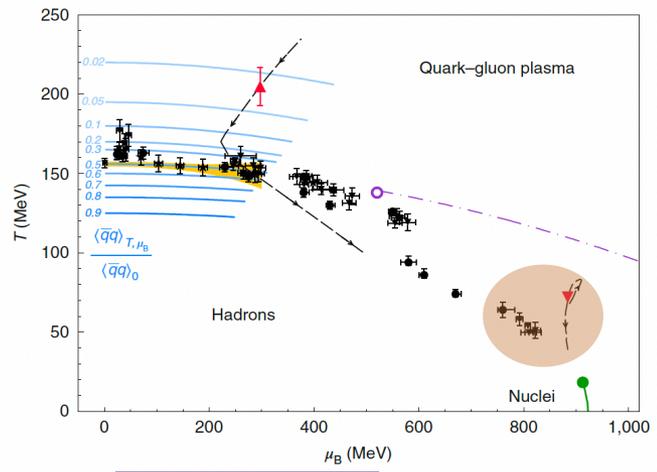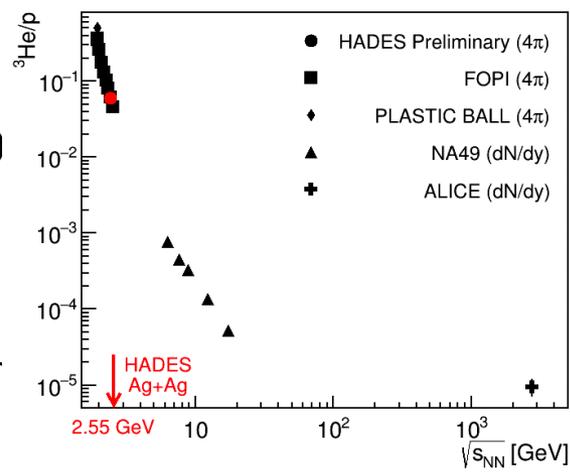- Microscopic properties of baryon dominated matter
- EoS observables

Similar conditions as expected in merging neutron stars

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

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

Marvin Kohls
Poster 576

3

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

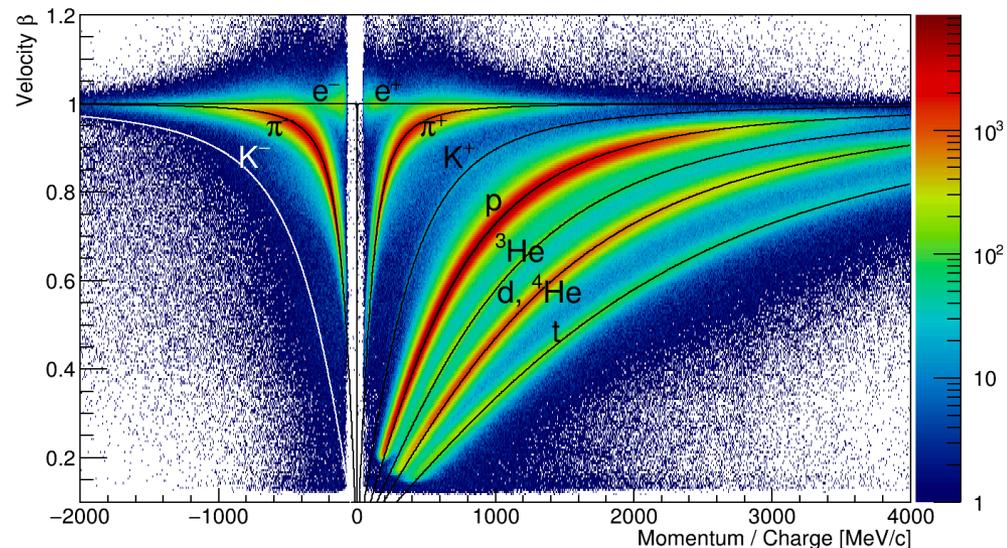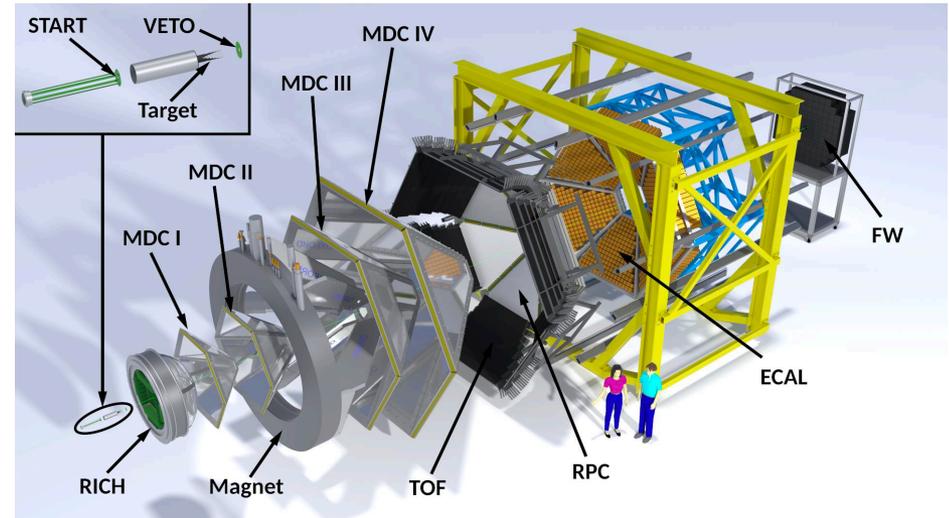RICH and ECAL for e^+/e^- and photon identification

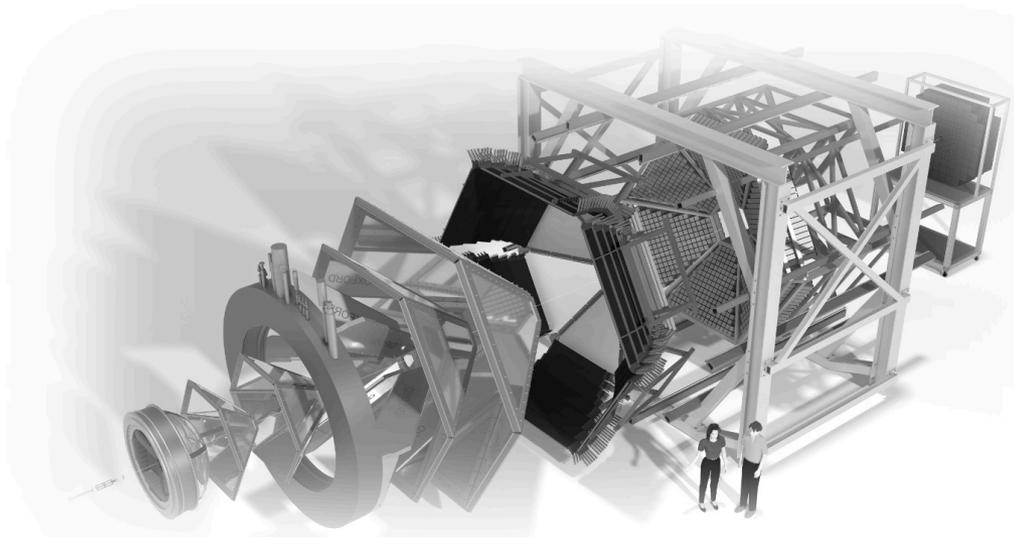Full azimuthal angle and polar angles between 18° and 85° covered

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)

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

4

Hadrons

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

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 μ_B

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

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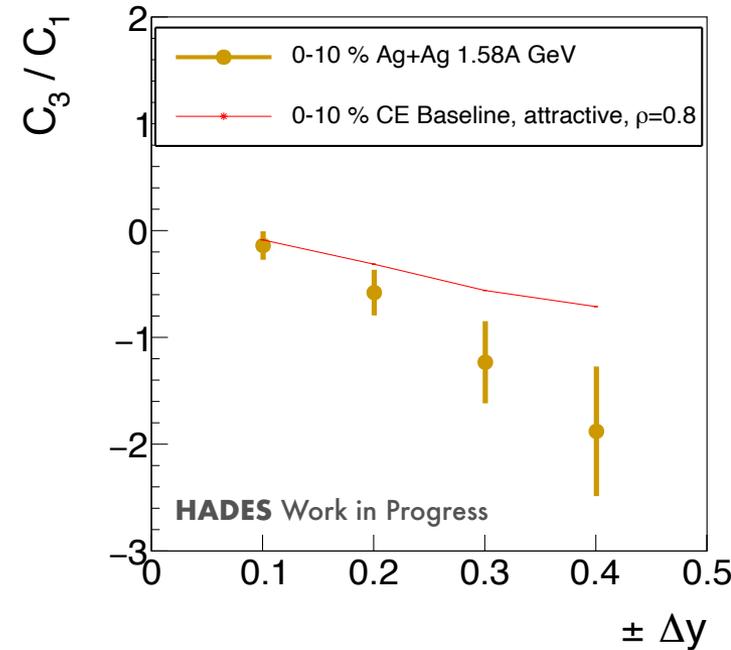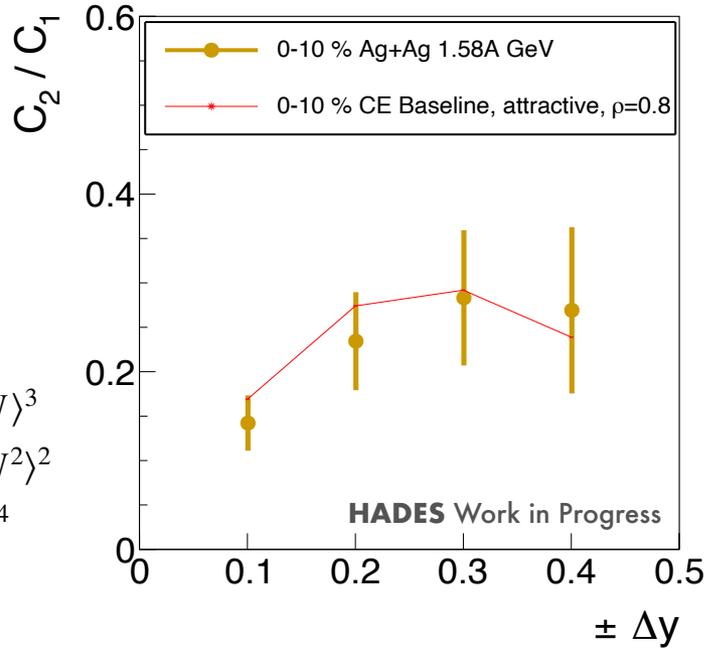
Cumulants:

$$\kappa_1 = \mu$$
$$\kappa_2 = \sigma^2$$
$$\kappa_3 = \langle N^3 \rangle - 3\langle N^2 \rangle\langle N \rangle + 2\langle N \rangle^3$$
$$\kappa_4 = \langle N^4 \rangle - 4\langle N^3 \rangle\langle N \rangle - 3\langle N^2 \rangle^2$$
$$+ 12\langle N^2 \rangle\langle N \rangle^2 - 6\langle N \rangle^4$$

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

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

Factorial cumulants:

$$C_2 = \kappa_2 - \kappa_1$$
$$C_3 = \kappa_3 - 3\kappa_2 + 2\kappa_1$$
$$C_4 = \kappa_4 - 6\kappa_3 + 11\kappa_2 - 6\kappa_1$$

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

Marvin Nabroth, PS21
Tuesday, 08.04, 17:10

Anar Rustamov
Poster 573

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

Proton factorial cumulants

HADES Work in Progress

STAR BESII (0-5%)
STAR BESI (0-5%)
HADES (Ag+Ag preliminary) (0-10%)
CE baseline, $\rho = 0$
CE local, repulsive
CE local, attractive, $\rho = 0.8$

HADES: $-0.4 < y_{cm} < 0.4$
$400 < p_t < 1600$ MeV/c
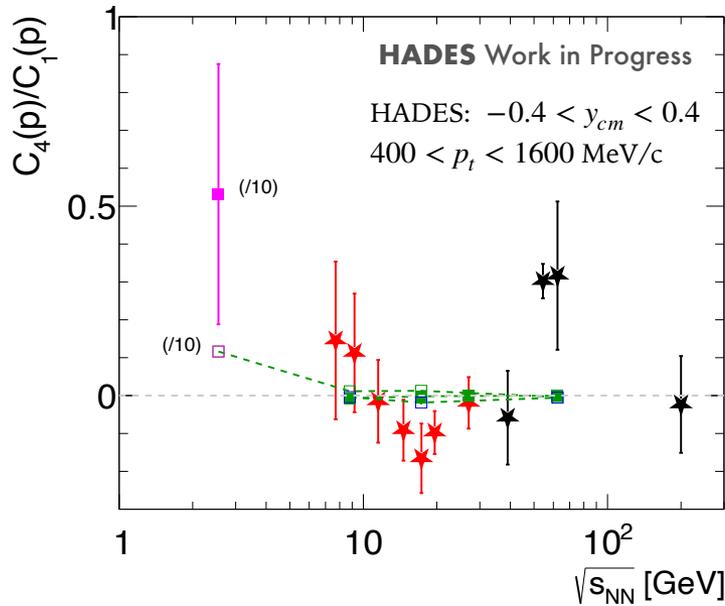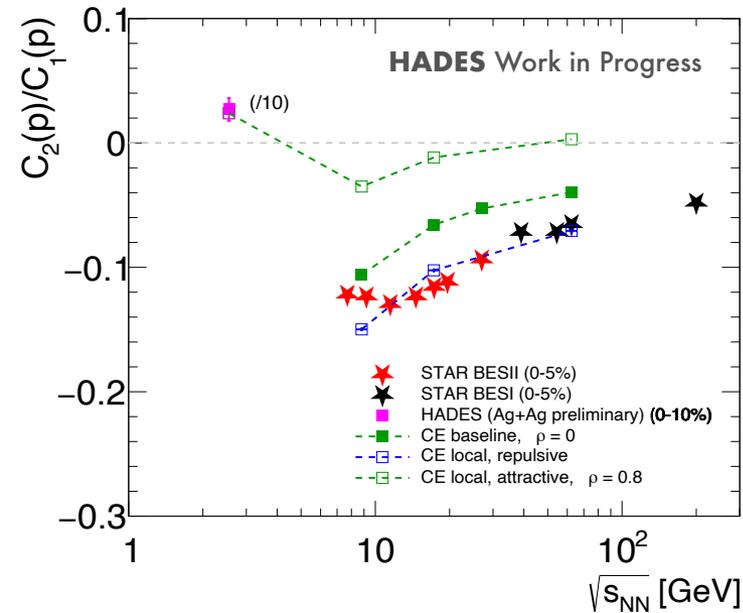
B. Friman, A. Rustamov, K. Redlich (in progress)

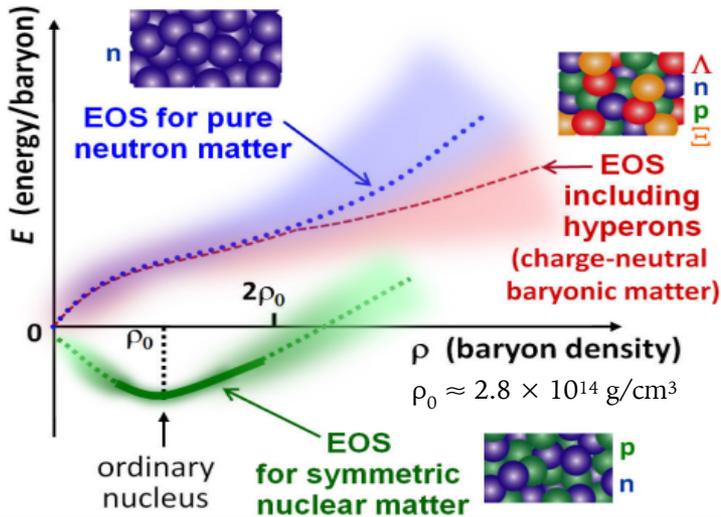Marvin Nabroth, PS21
Tuesday, 08.04, 17:10
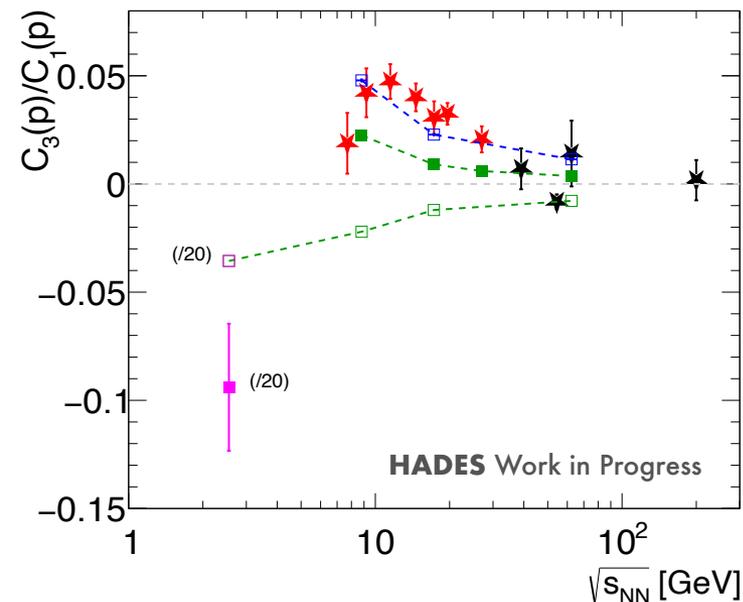
Larger factorial cumulant ratios at HADES compared to STAR

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

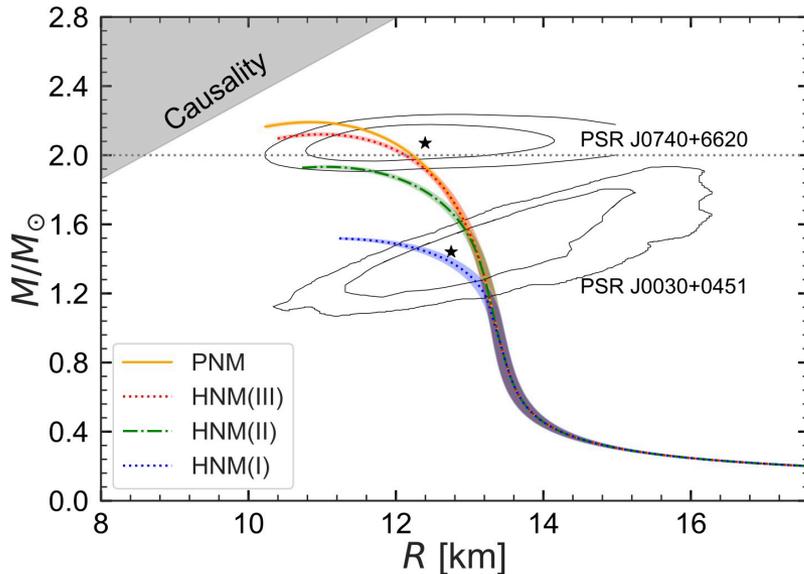Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

Neutron star (NS) puzzle

„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


$\rho_0 \approx 2.8 \times 10^{14}$ g/cm³
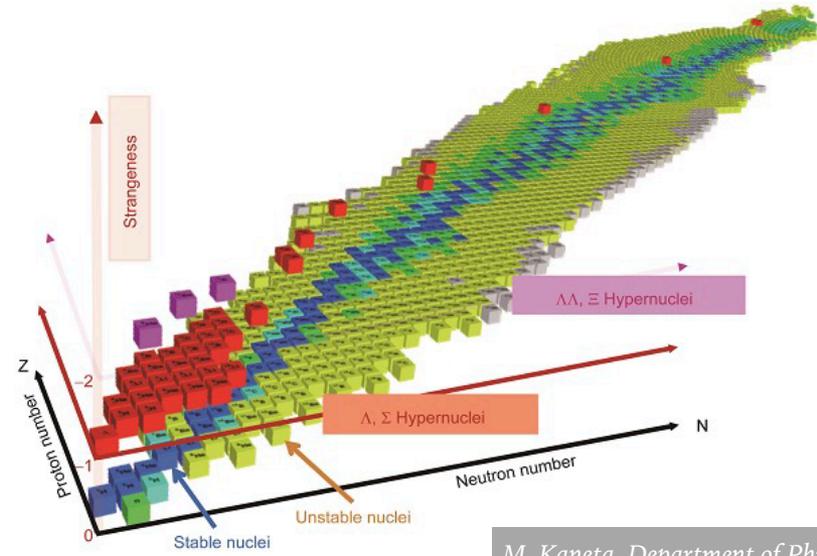
Hypernuclei are pivotal for the EoS of the NS

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

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

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
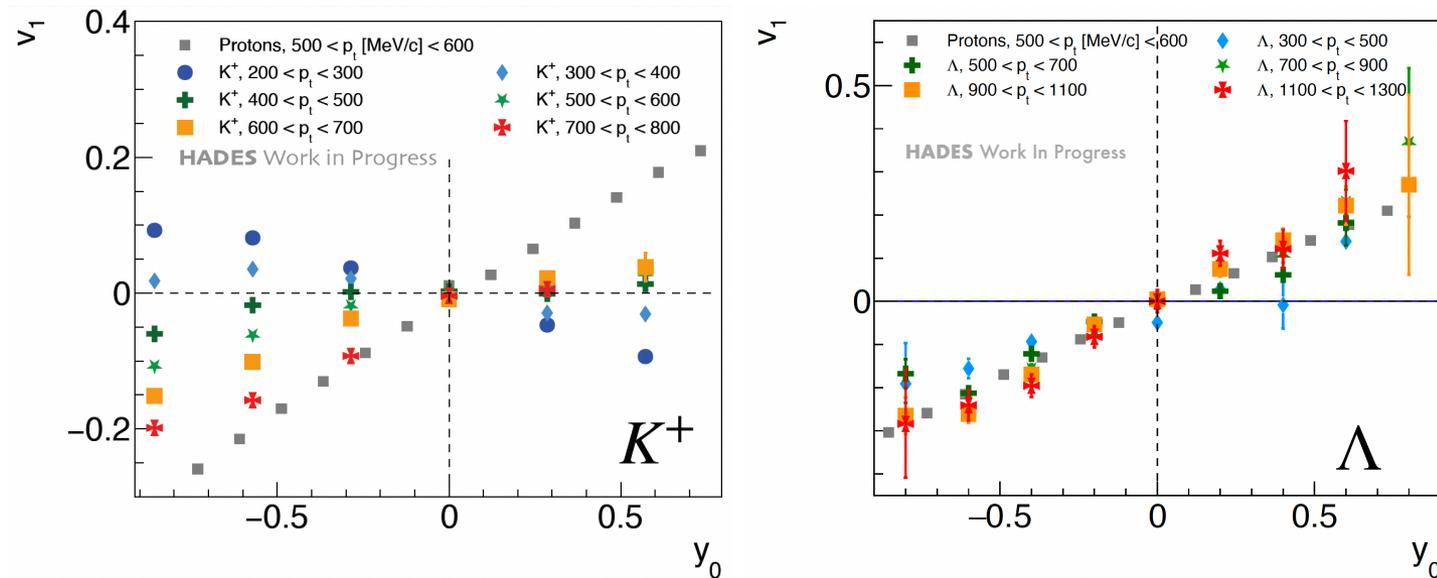
Rapidity dependence of v_1 for charged K and Λ is studied

Jan Orliński
Poster 253

Comparing these results to transport models needed to learn about nature of their interactions with nuclear matter
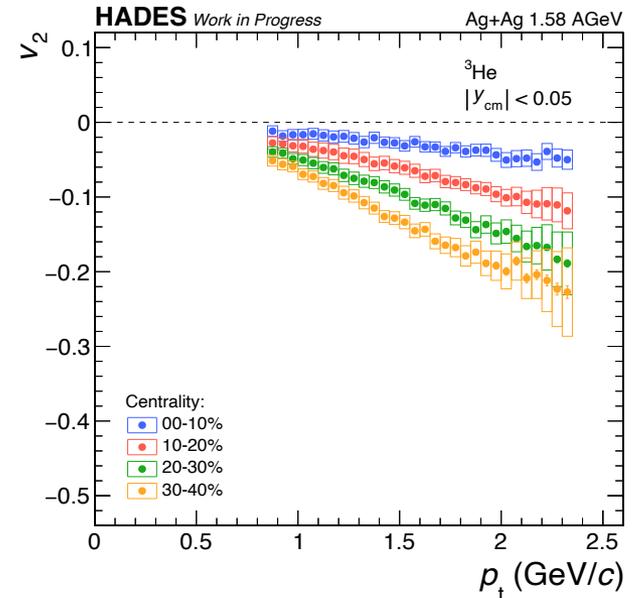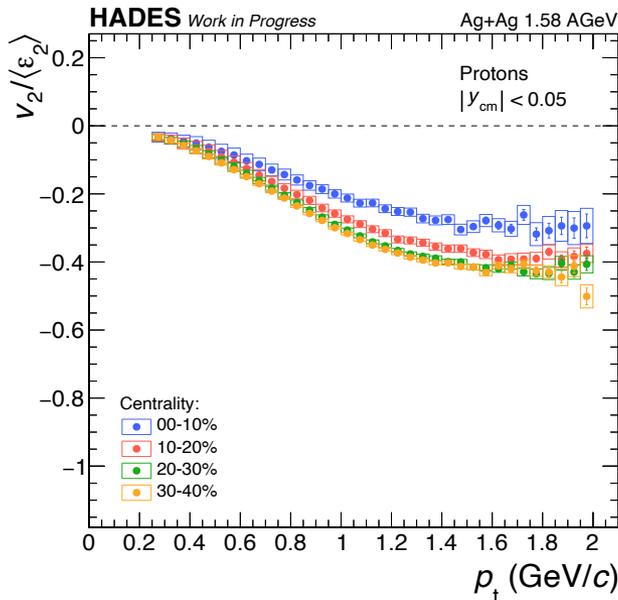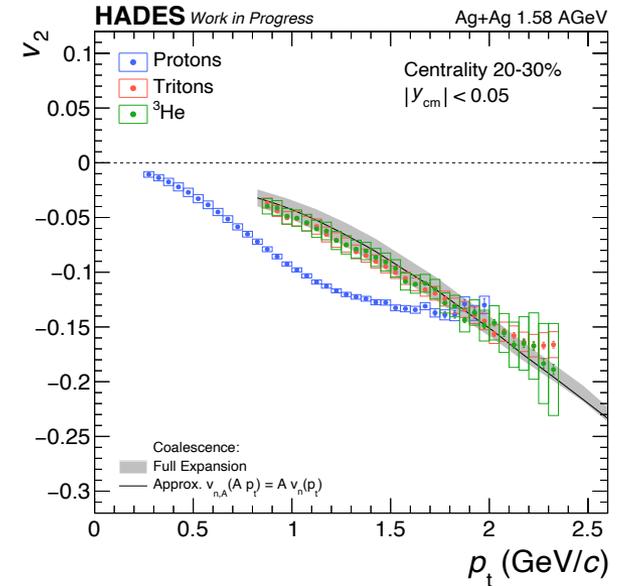
Anisotropic flow - light nuclei

Scaling of $v_2(p_t)$ with A number $v_{n,A}(Ap_t) = Av_n(p_t)$
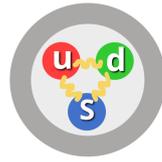
Coalescence-like scenario works well for t, ^3He

Orientation of symmetry-planes

Negative $v_2/\langle\epsilon_2\rangle \to v_2$ and eccentricity ϵ_2 plane perpendicular
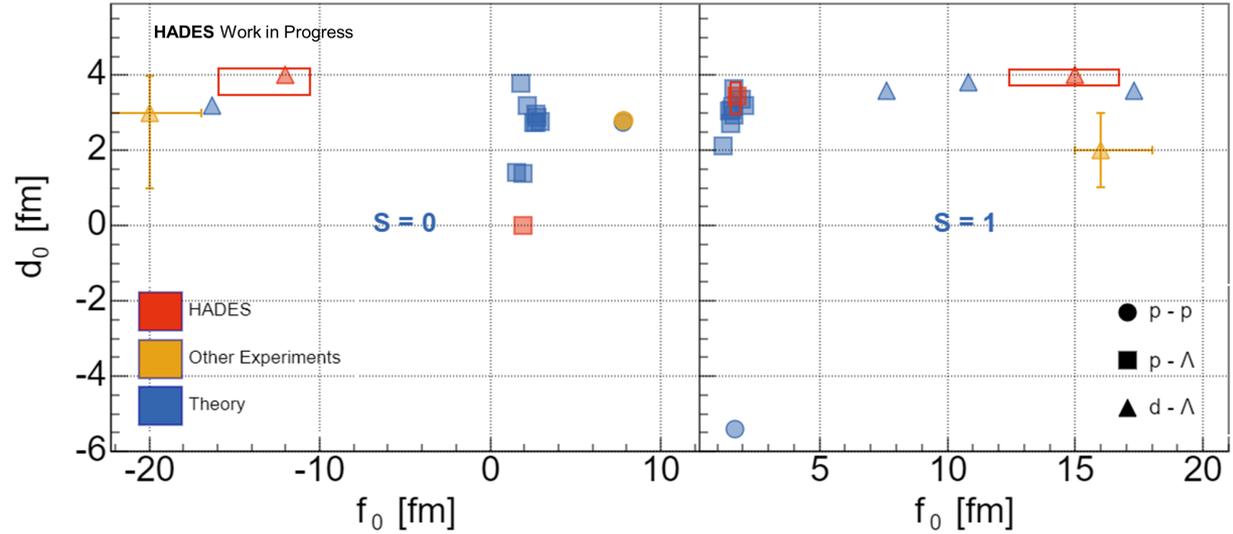

Behruz Kardan
Poster 579

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

Interactions

- Nucleons essentially stopped in collision zone

- HADES around the S production threshold

- Presence of Y in NS
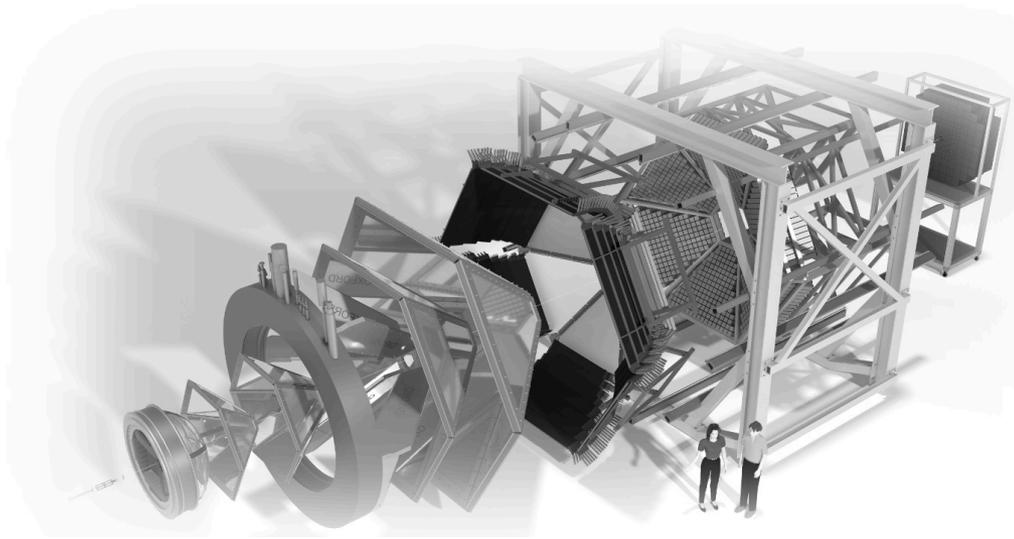
- Impact of Y to EoS

- 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

Jędrzej Kołaś
Poster 574

$$d - \Lambda$$

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

Strangeness

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany
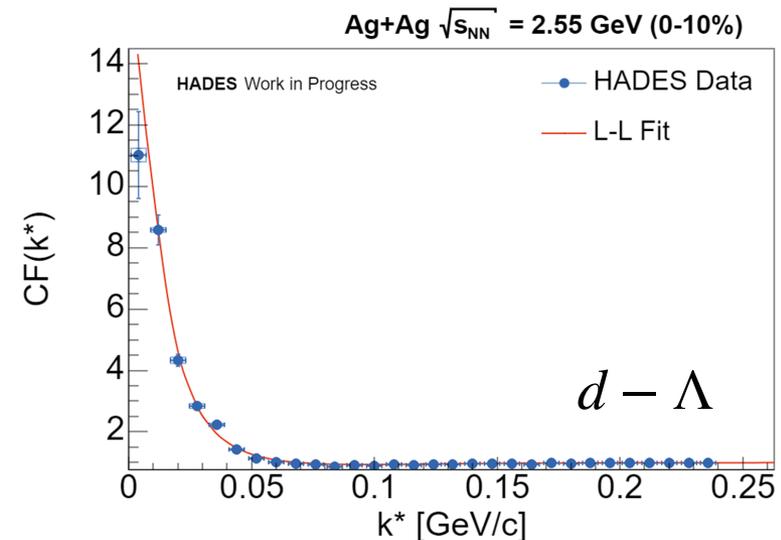
Hypernuclei - production mechanisms

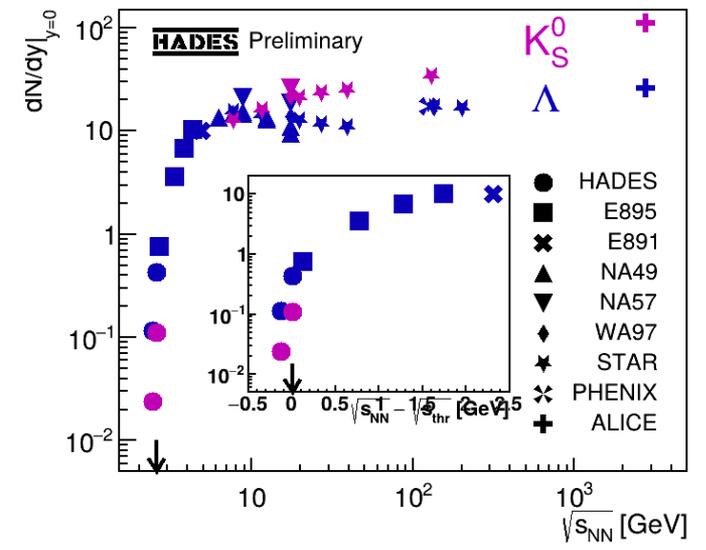Λ production close to free NN threshold

Ξ 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

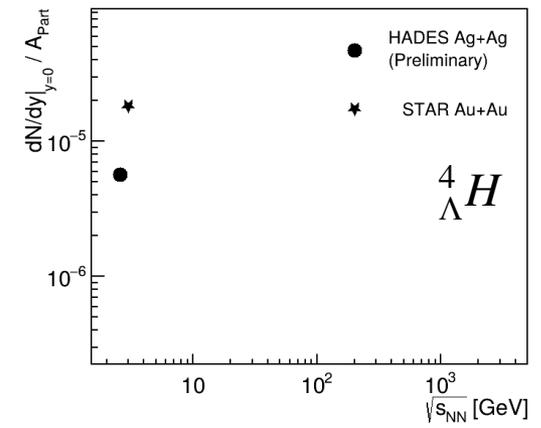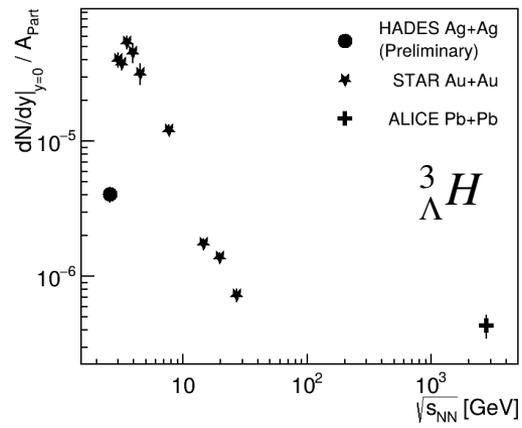Production of hypernuclei:
- favored by baryon dominance at the fireball
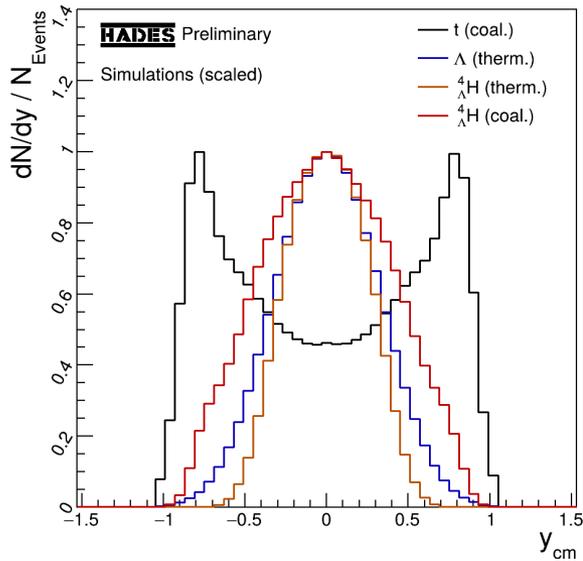- limited by the amount of produced Λ hyperons

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

$^{3}_{\Lambda}H$

$^{4}_{\Lambda}H$

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany
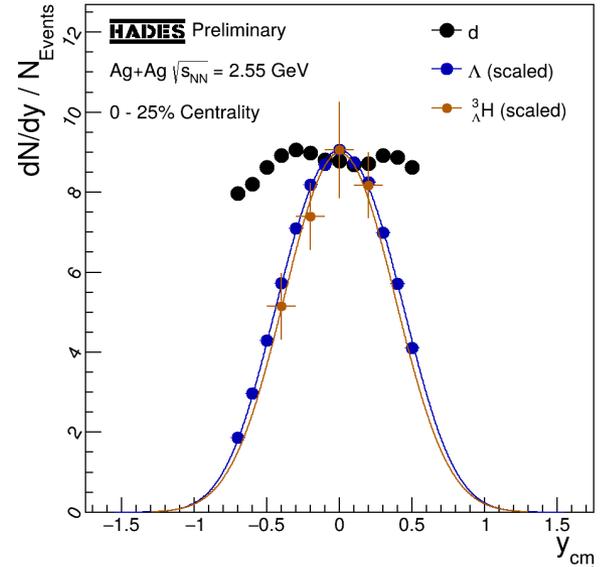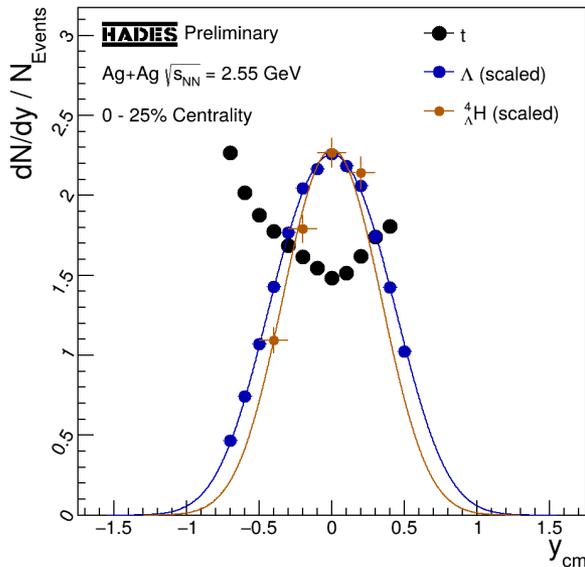
Hypernuclei - production mechanisms

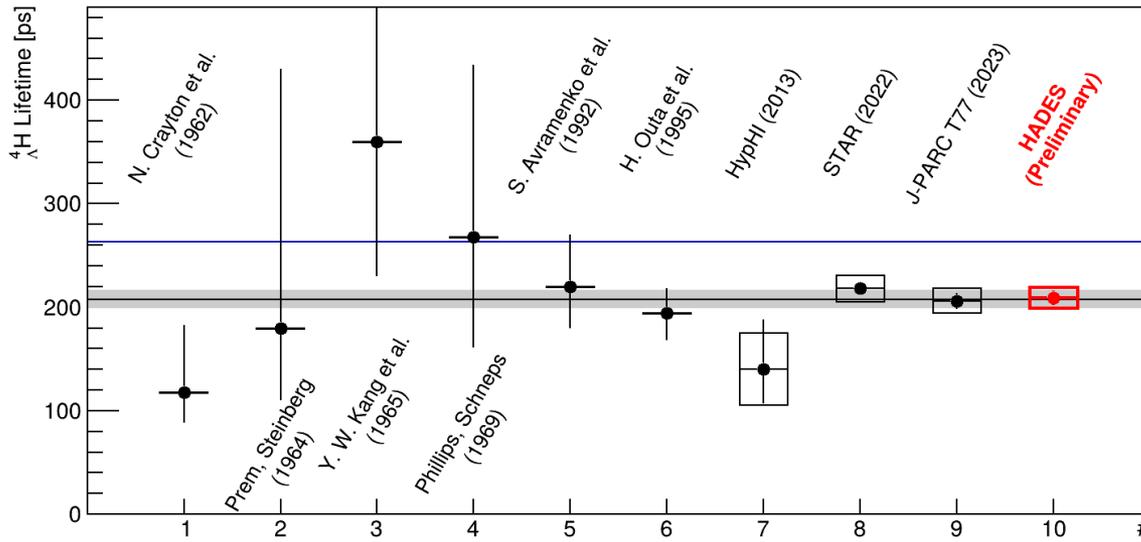**d, t** - „coalescence-like" scenario favorable

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

Simon Spies, PS23
Tuesday, 08.04, 16:30

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany
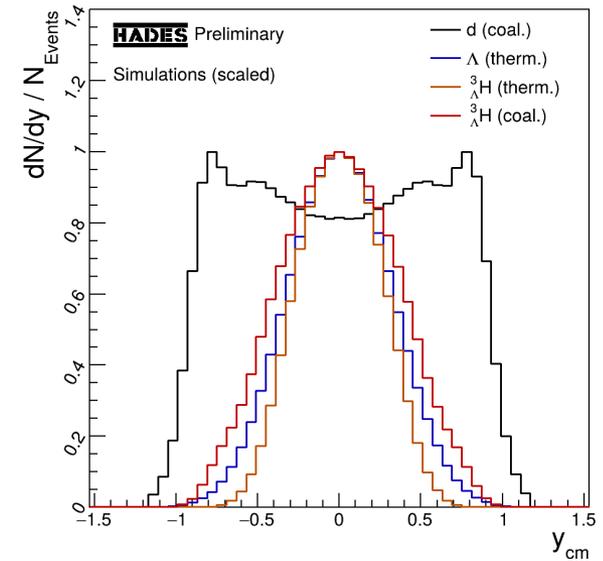
Hypernuclei - lifetime
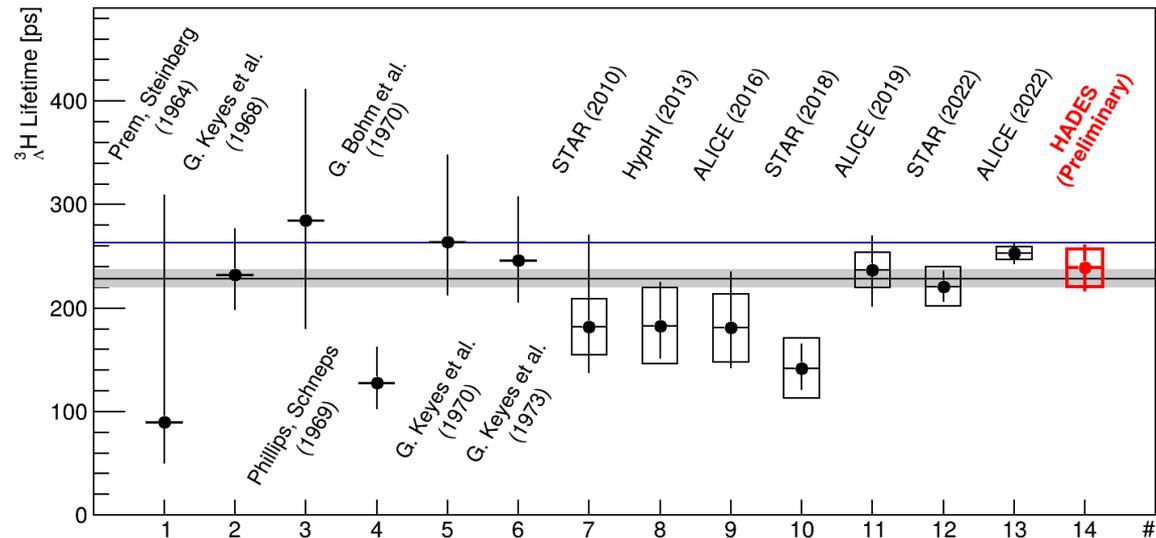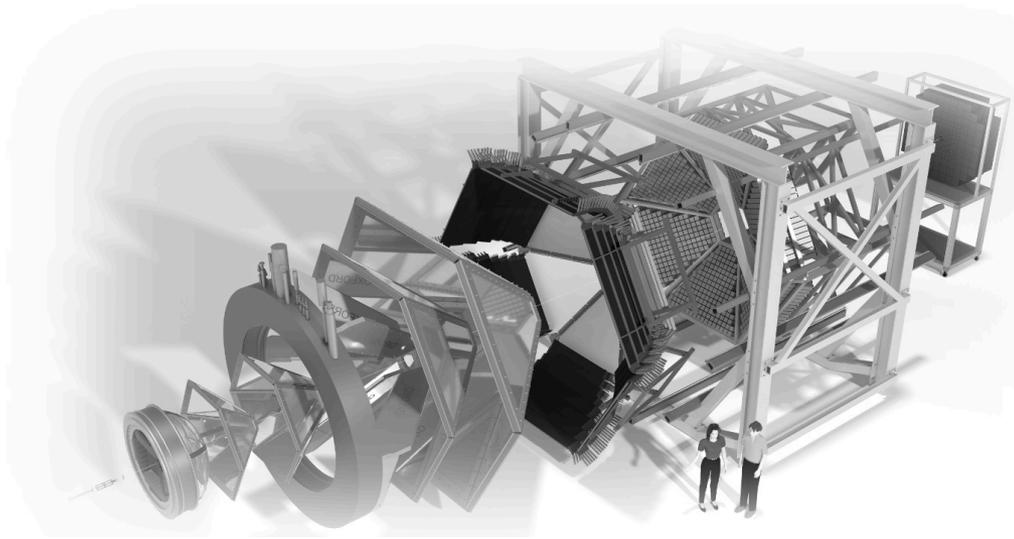

$^3_\Lambda H$ lifetime: $239 \pm 23 \pm 18$ ps

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

Simon Spies, PS23
Tuesday, 08.04, 16:30

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

Dileptons

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany
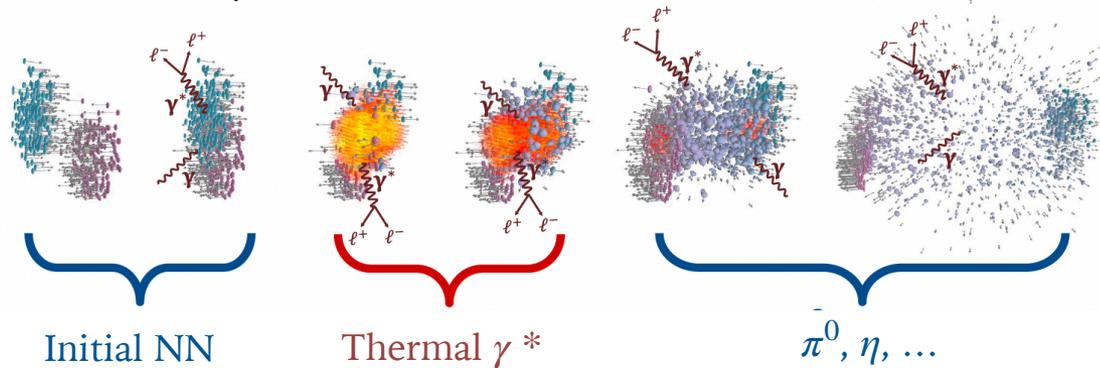
Dilepton measurements

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

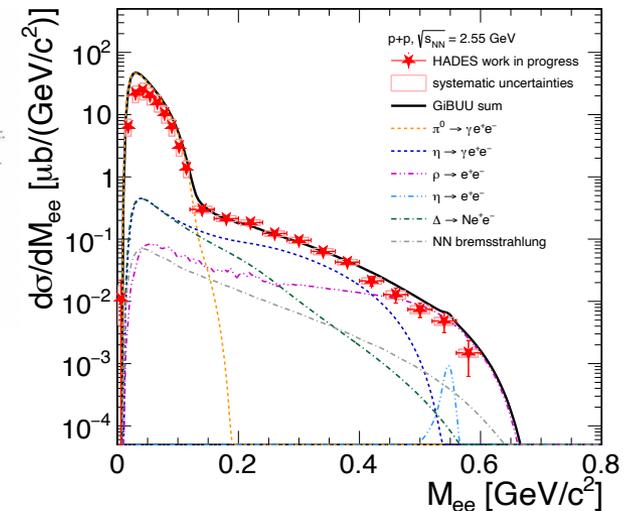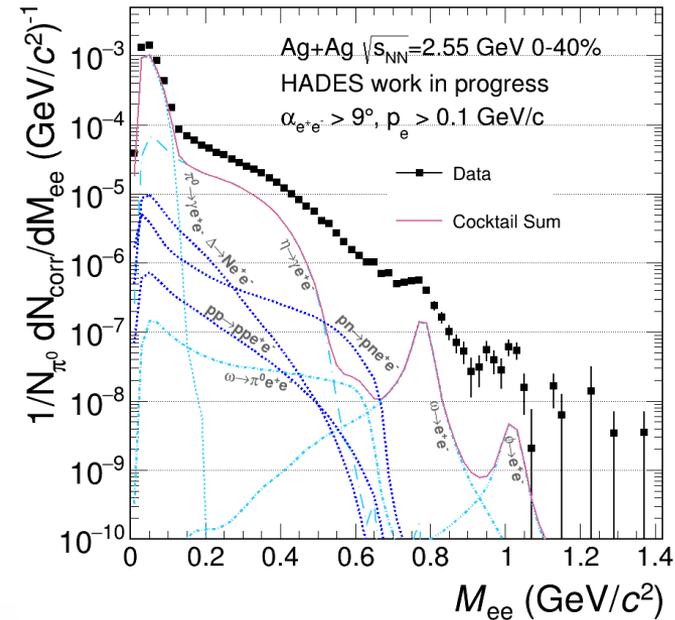Penetrating probes unaffected by strong interactions

Possibility to extract the temperature and lifetime of the medium

Elementary collisions serve as baseline for the heavy-ion data
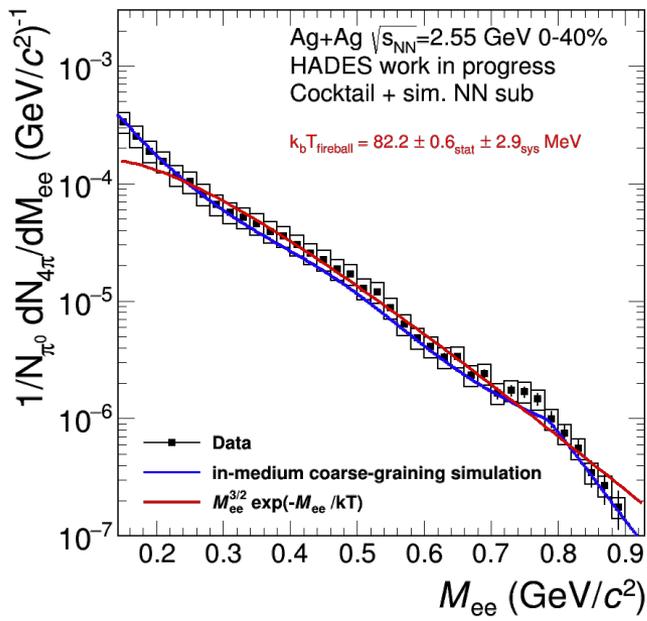

Initial NN   Thermal γ * $\pi^0, \eta, ...$

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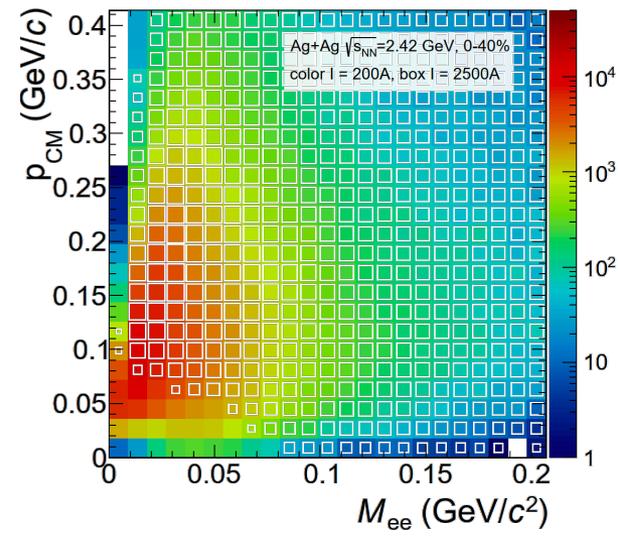- Freeze-out cocktail ($\pi^0, \eta, \omega, \phi$)

Karina Scharmann
Poster 622

Dilepton excess

Ag+Ag $\sqrt{s_{NN}}$=2.55 GeV 0-40%
HADES work in progress
Cocktail + sim. NN sub

$k_b T_{fireball}$ = 82.2 ± 0.6$_{stat}$ ± 2.9$_{sys}$ MeV

- Data
- in-medium coarse-graining simulation
- $M_{ee}^{3/2}$ exp(-M_{ee} /kT)

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

Fireball temperature determined
Extended lifetime of a fireball

HADES work in progress
Integral in 0.3 < M_{ee} (GeV/c^2) < 0.7

Ag+Ag, $\sqrt{s_{NN}}$ = 2.55 GeV
Ag+Ag, $\sqrt{s_{NN}}$ = 2.42 GeV

Niklas Schild, PS26
Wednesday, 09.04, 9:20

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

Ag+Ag $\sqrt{s_{NN}}$=2.42 GeV, 0-40%
color I = 200A, box I = 2500A
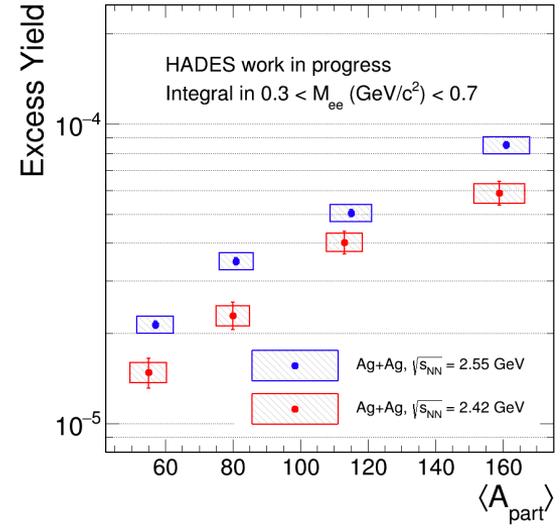
Carina Udrea
Poster 369

Dilepton flow

Ag+Ag $\sqrt{s_{NN}}$=2.55 GeV 0-40%
HADES work in progress
— ■ — Experimental Data
■ γ^* from π^0-Dalitz (UrQMD EOS)
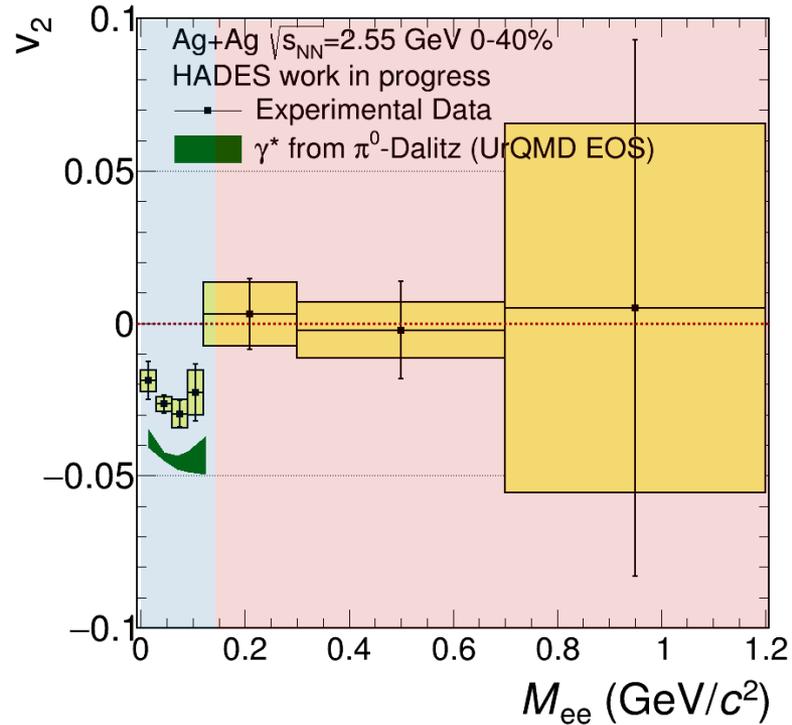
Isolating thermal contribution in di-lepton v_2

sim. $v_2^{\pi^0}$ subtracted
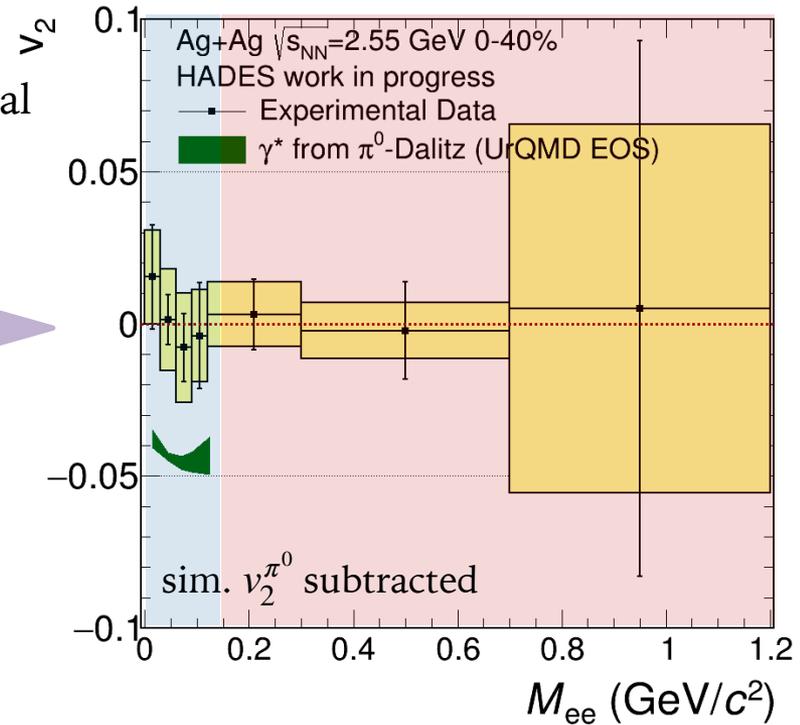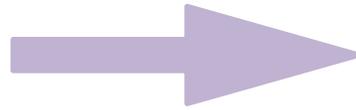
Niklas Schild, PS26
Wednesday, 09.04, 9:20

Sukyung Kim
Poster 775

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

Future

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany
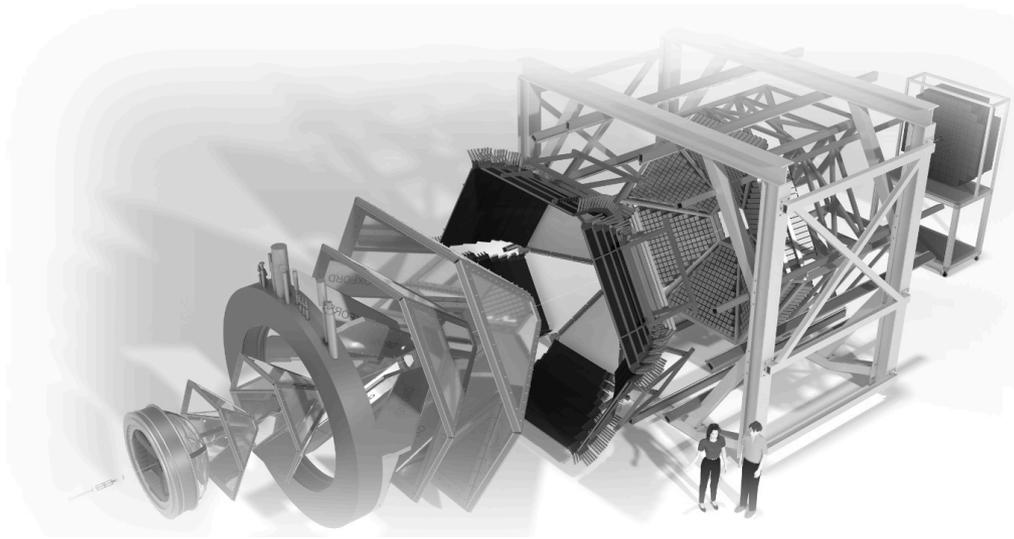
Future of HADES

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 6th 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)*

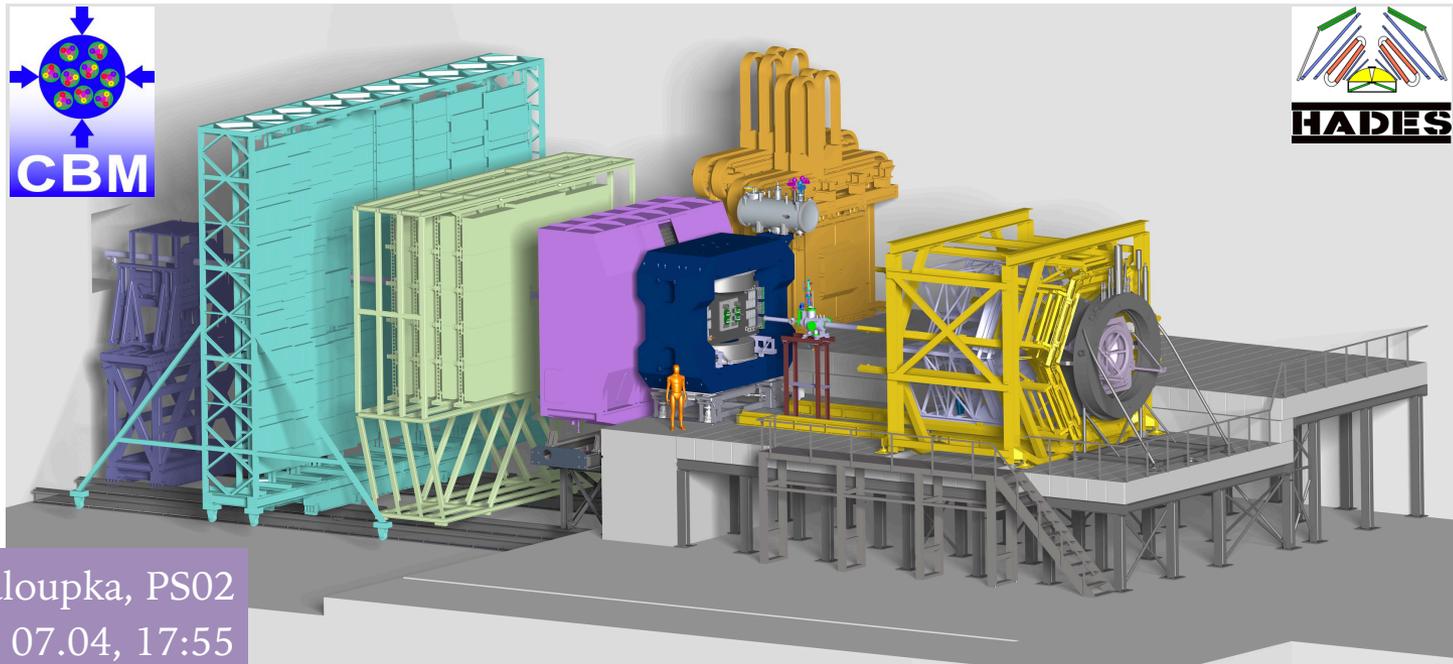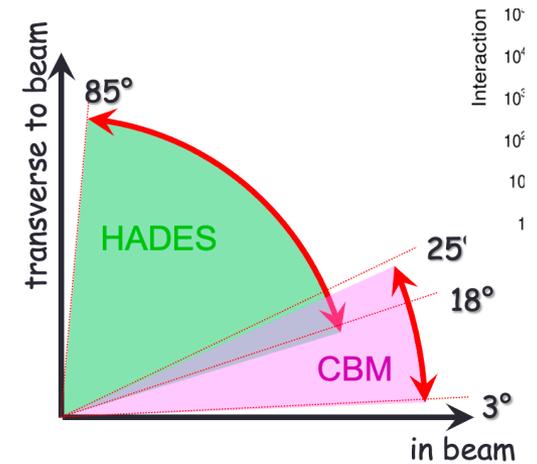HADES plans to be operational at least untill **2030**

In the following years HADES plans to explore high-μ_B region together with **CBM**
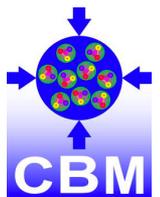
HADES and CBM experiments

Fixed-target experiments → highest rates achievable

Versatile subsystems → tailored for the physics program

Angular coverage → complementary for HADES and CBM
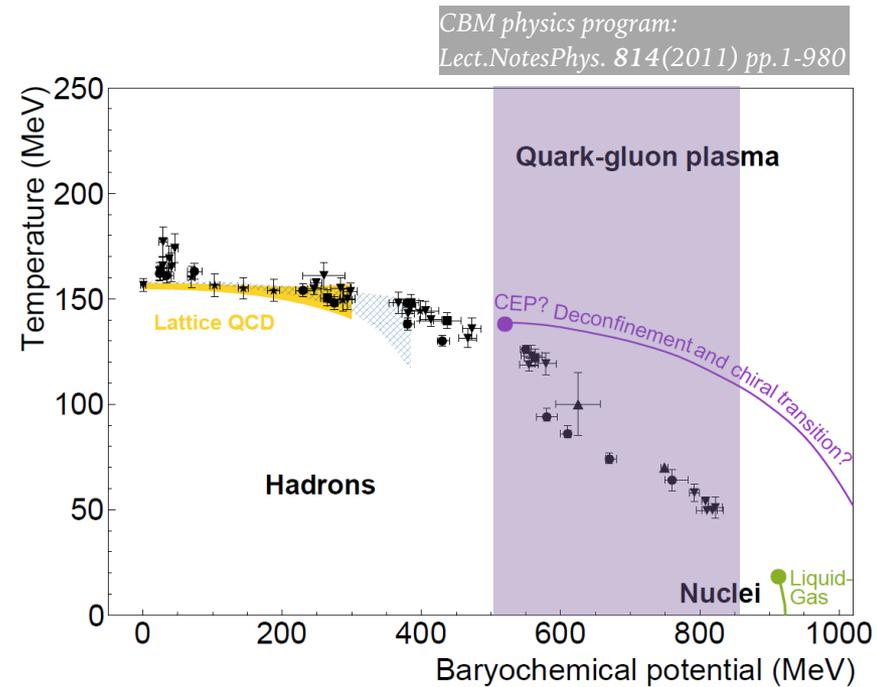
First beams in 2028/2029

Petr Chaloupka, PS02
Monday, 07.04, 17:55

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
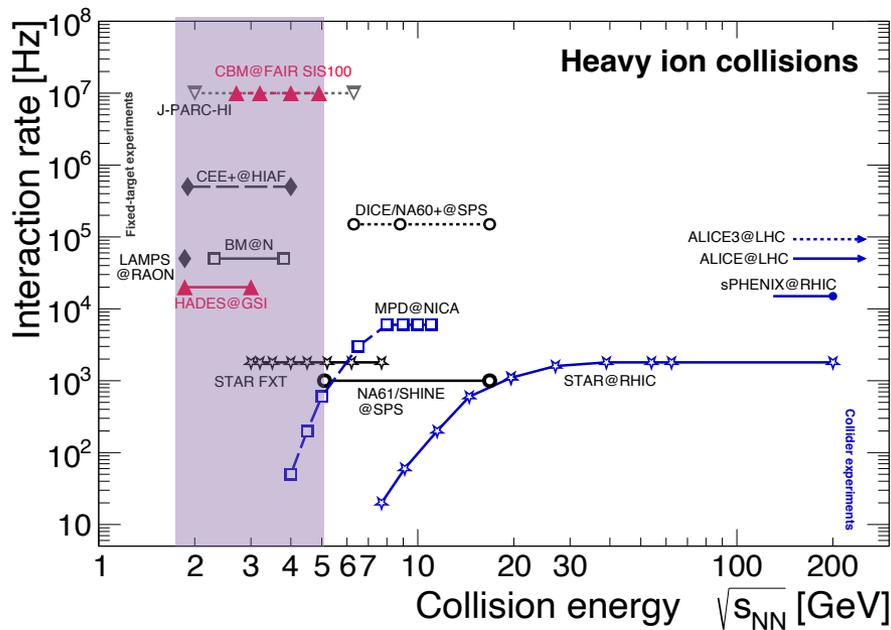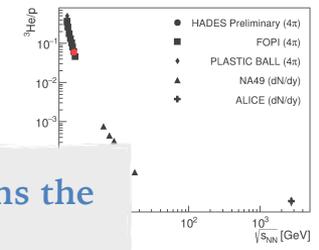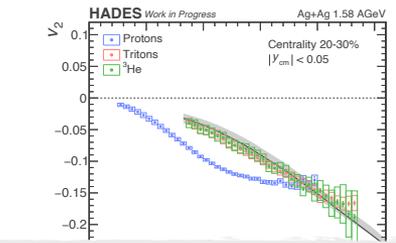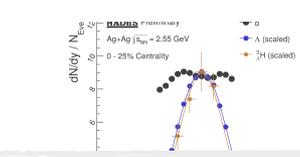

T. Galatyuk, NPA 982 (2019), update 2023
https://github.com/tgalatyuk/interaction_rate_facilities

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

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

Hanna Zbroszczyk for the HADES Collaboration, Quark Matter, April 6-12, 2025, Frankfurt, Germany

HADES at QM'25
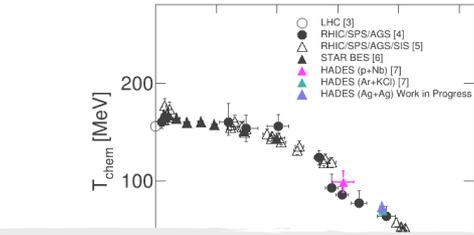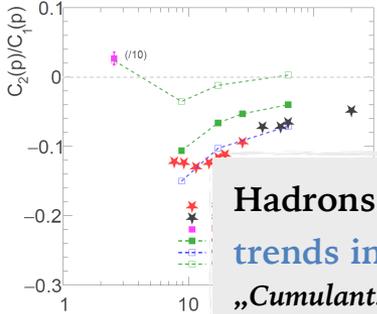
Hadrons: The interplay of repulsive and attractive forces between protons explains the trends in fluctuation measurements

„Cumulants of the multiplicity distributions of identified particles measured in heavy-ion collisions by HADES", M. Nabroth, Tuesday, 17:10
„Probing the properties of dense baryonic matter with collective flow measurements at HADES", B. Kardan, Poster 579
„Preliminary results on the transverse flow of strange hadrons emitted from Ag+Ag collisions at beam energy of 1.58AGeV measured with HADES", J. Orliński, Poster 253
„Investigation of NN and NY interaction using femtoscopy at HADES", J. Kołaś, Poster 574
„Precision Determination of Global Matter Properties with Updated HADES Data", M. Kohls, Poster 576
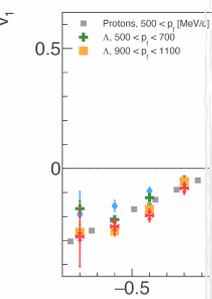
Strangeness: Extrapolation of hypernuclei formation mechanism at high μ_B

*„Study of Hypernuclei Production Mechanisms and Formation Regions with HADES", S. Spies, Tuesday, 16:30*

Dileptons: Temperature of early stage and lifetime of a fireball measured

„Studying properties of baryon-dominated matter with dileptons", N.Schild, Wednesday, 9:20,
„Dielectron analysis in p+p collisions at 1.58 GeV beam energy with HADES", K. Scharmann, Poster 622
„First Look at Dilepton Flow in Au+Au collisions at $\sqrt{s_{NN}}$ = 2.55 GeV with HADES", S. Kim, Poster 775
„Low-mass, low-momentum virtual photon measurements with HADES", C. Udrea, Poster 369
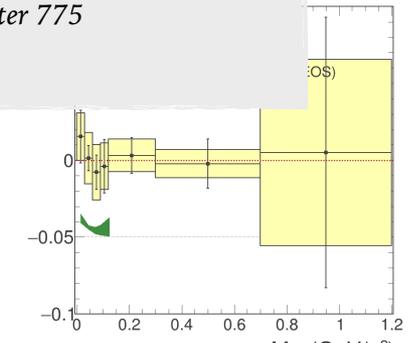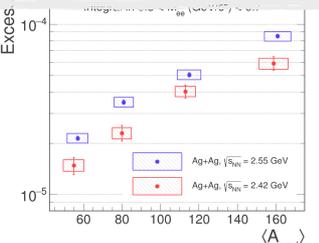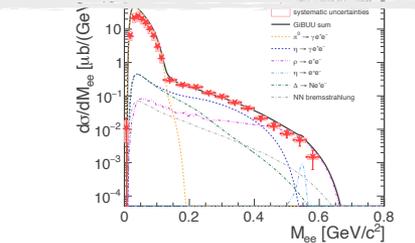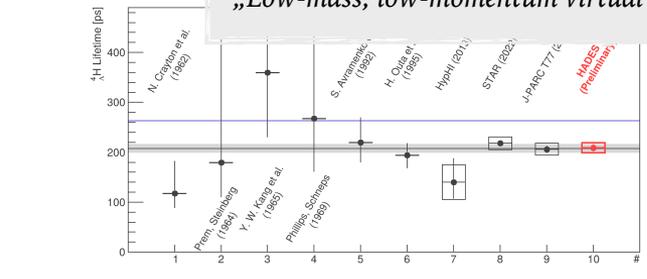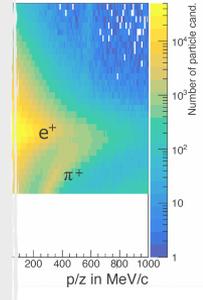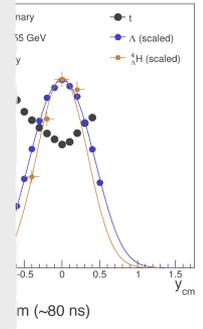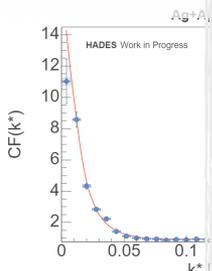
HADES Collaboration

Collaboration Meeting,
March 16th - 21st, 2025
GSI, Darmstadt

Thank you

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Extra slides

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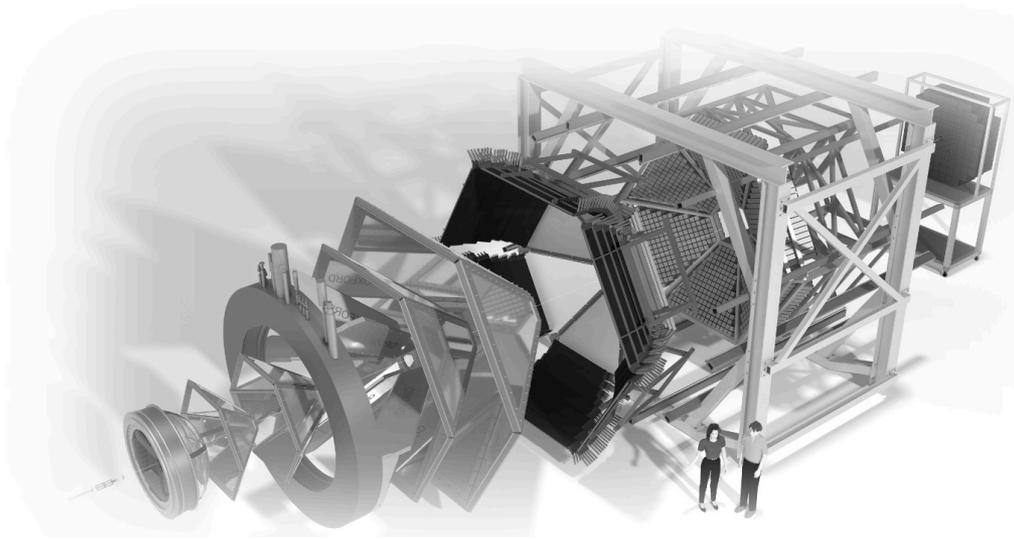
HADES data taking
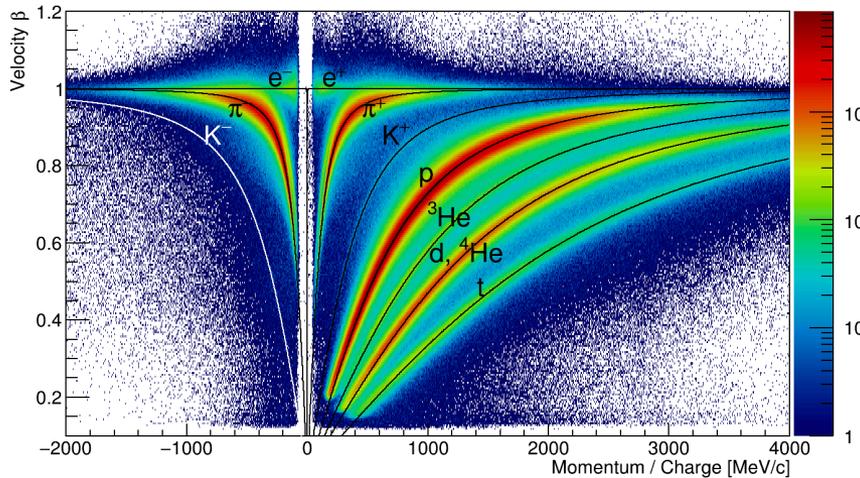
PID primarily via. momentum and velocity
Separation of multiple charged particles through
specific energy loss

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: π+W, π+C, π+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)**

Current prospects and timeline

FAIR

APPA Laser

SIS100

UNILAC

SIS18

HITRAP

ESR

CRYRING

CBM

Super-FRS

NUSTAR HEB

First Science +
Next steps
MSV completion
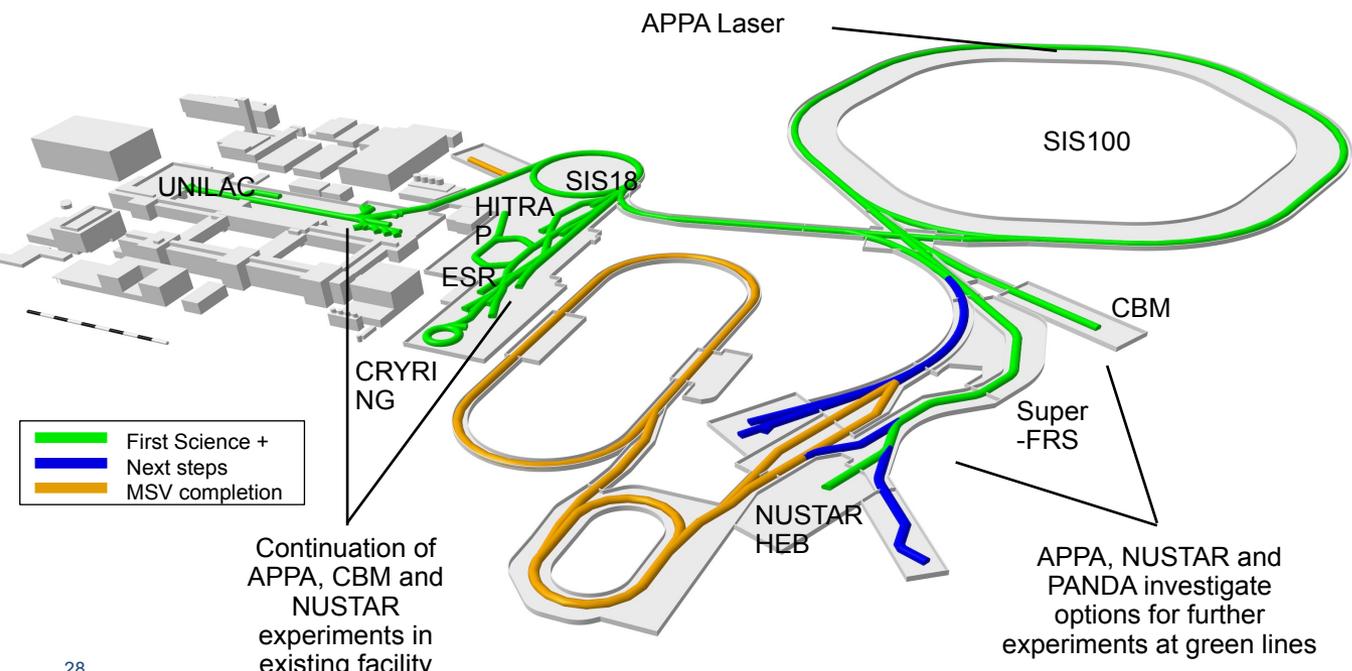
until 2028

FAIR Phase-0

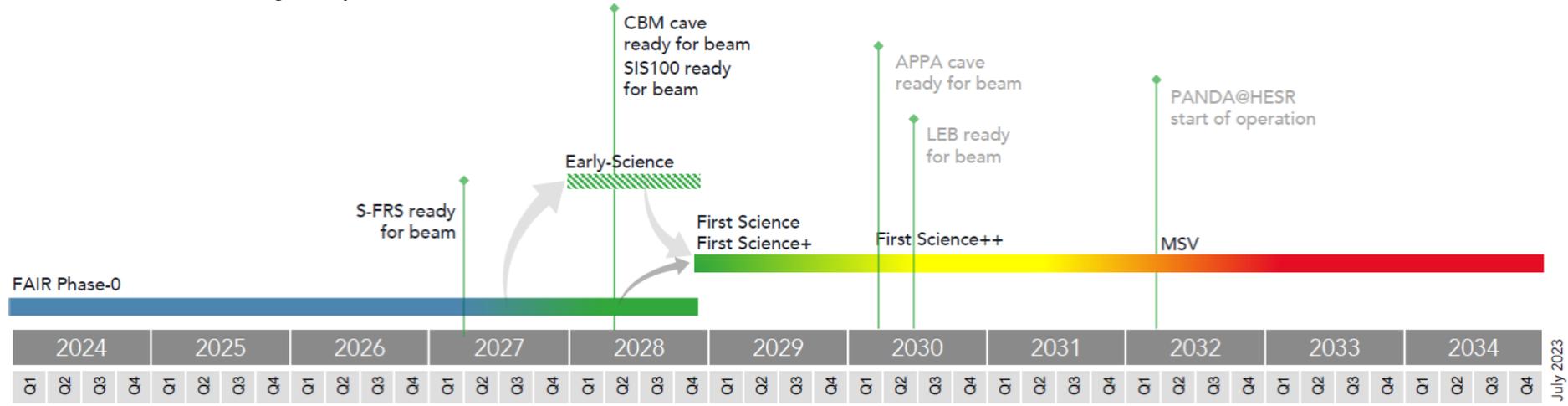after 2028

Staged implementation recommended by the Heuer/Tribble Commission's report (2022) with the First Science stage endorsed by the FAIR Council as "the most appropriate starting scenario to achieve world-leading science."

Continuation of APPA, CBM and NUSTAR experiments in existing facility

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

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CBM cave ready for beam
SIS100 ready for beam

APPA cave ready for beam

PANDA@HESR start of operation

LEB ready for beam

Early-Science

S-FRS ready for beam

First Science
First Science+

First Science++

MSV

FAIR Phase-0

| 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 |

July 2023

Facility for Antiproton and Ion Research

SIS100 magnets
April, 2024

CBM/HADES cave
February, 2024

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