HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

EXPLORING BARYON-RICH MATTER WITH HADES

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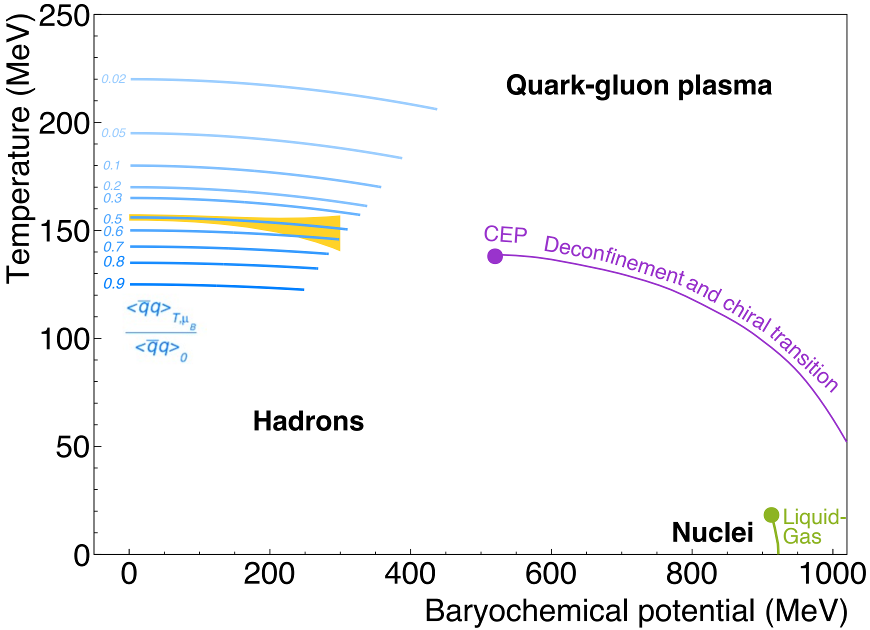
GSI / TU Darmstadt

2021 RHIC/AGS Annual Users' Meeting | 08 - 11 Jun 2021

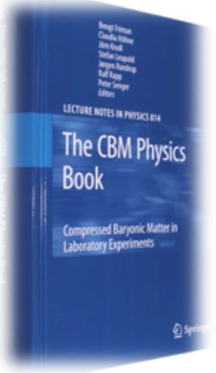
HADES GSI FAIR Phase 0 Research Program TECHNISCHE UNIVERSITÄT DARMSTADT

SEARCHING FOR LANDMARKS OF THE QCD MATTER PHASE DIAGRAM



- **vanishing μ_B, high T (lattice QCD)**
  - crossover
  - no critical point indicated by lattice QCD at μ_B < 400 MeV, T >140 MeV (for physical quark masses)
- **large μ_B moderate T (lQCD inspired models)**
  - limits of hadronic existence?
  - 1st order transition?
  - QCD critical point?
  - equation-of-state of dense matter?

high μ_B region – large discovery potential!



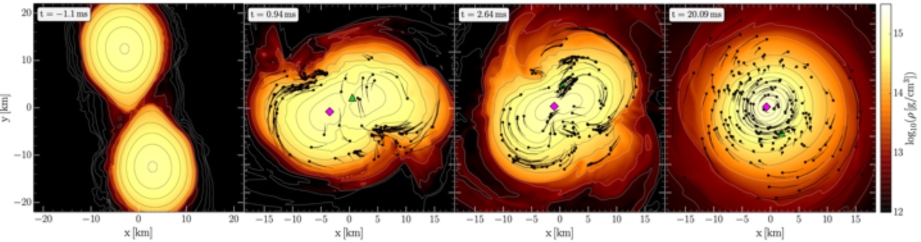
Friman *et al.*, Lect. Notes Phys. 814 (2011) 1

Bazavov *et al.*, Phys.Lett.B 795 (2019) 15-21
Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
Philipsen, Lattice 2019, 1912.04827 [hep-lat]

LABORATORY STUDIES OF THE MATTER PROPERTIES (EoS) IN COMPACT STELLAR OBJECTS

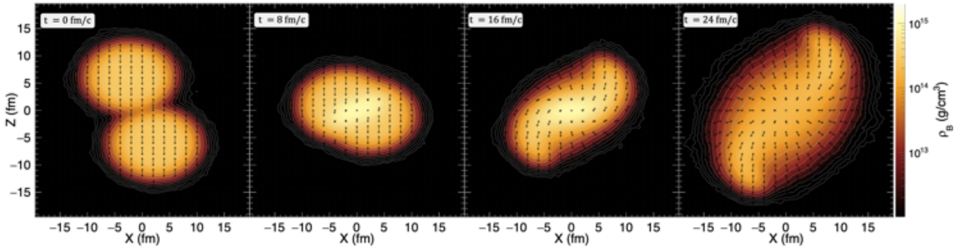
Neutron Star merger (model calculations)

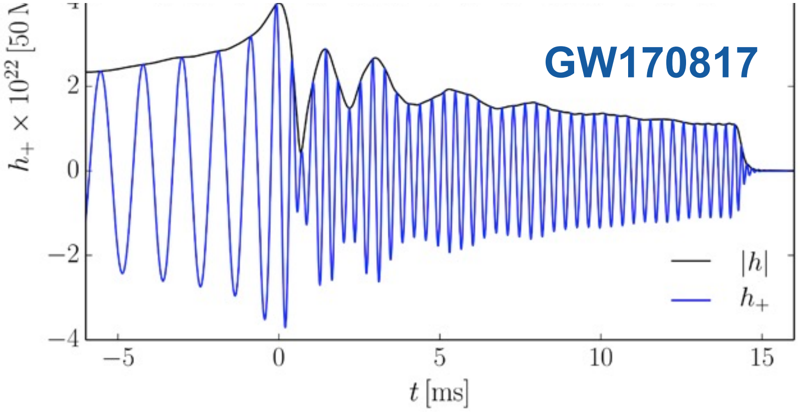
$1.35 + 1.35 M_{\odot} \quad \emptyset = 10\,km \quad \tau \sim 20\,ms$



Au+Au $\sqrt{s_{NN}} = 2.4\,GeV$ (UrQMD)

$\emptyset = 16\,fm \quad \tau \sim 10^{-23} s$





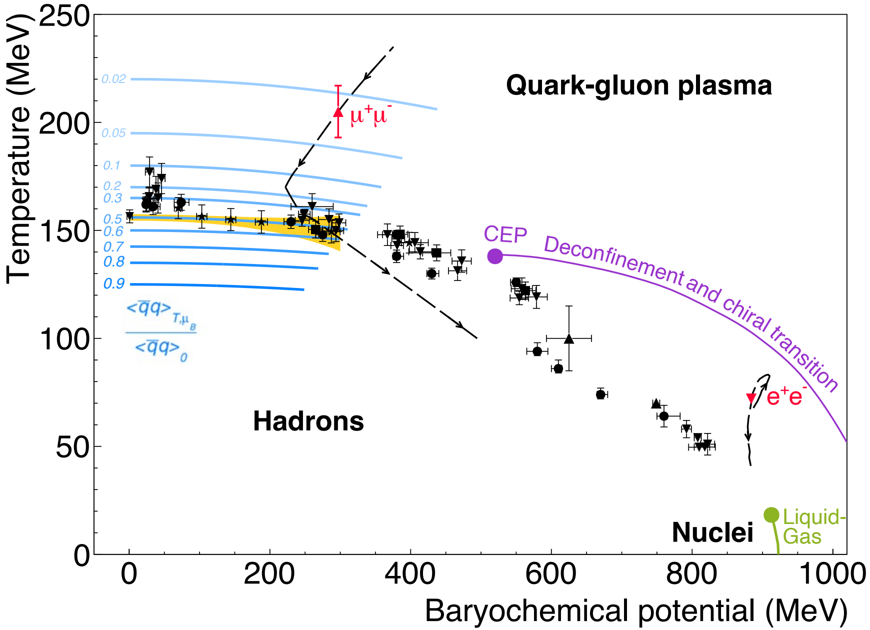
- ☐ T < 70 MeV, $\rho < 3\rho_0$ for both (note the different isospin)
- ☐ Role of YN, YY phase shifts in EOS!

HADES, Phys.Rev. C94 (2016) 025201
ALICE, Phys.Rev.C 99 (2019) 2, 024001

M. Hanauske, Journal of Phys.: Conf. Series 878 (2017) 012031
L. Rezzolla *et al.*, Phys. Rev. Lett. 122, no. 6, 061101 (2019)

Strong connections between the fields

THE HADES PHYSICS CASE



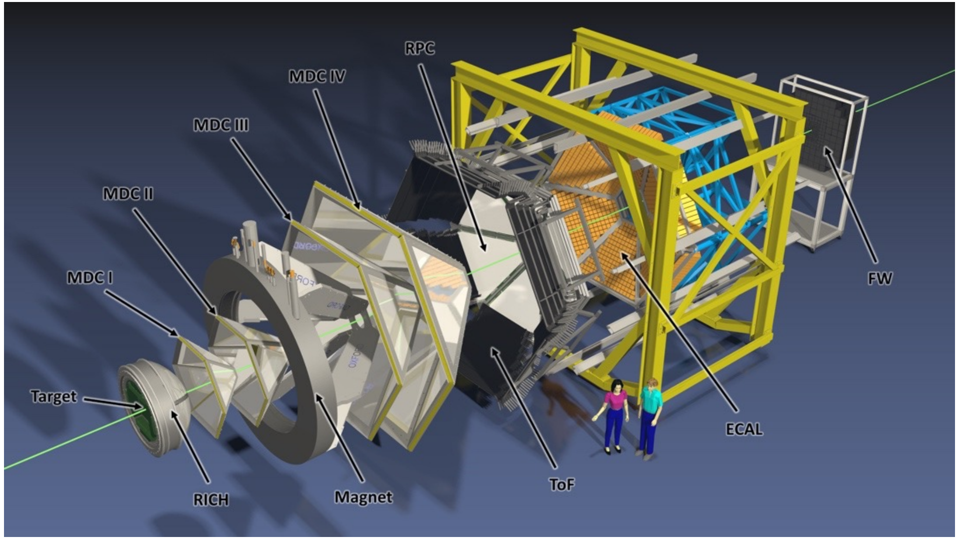
[HADES] Nature Phys. 15 (2019) 10, 1040-1045
A. Andronic *et al.*, Nature 561 (2018) no.7723
LQCD: S. Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
LQCD: A. Bazavov *et al.*, Phys.Lett.B 795 (2019) 15-21

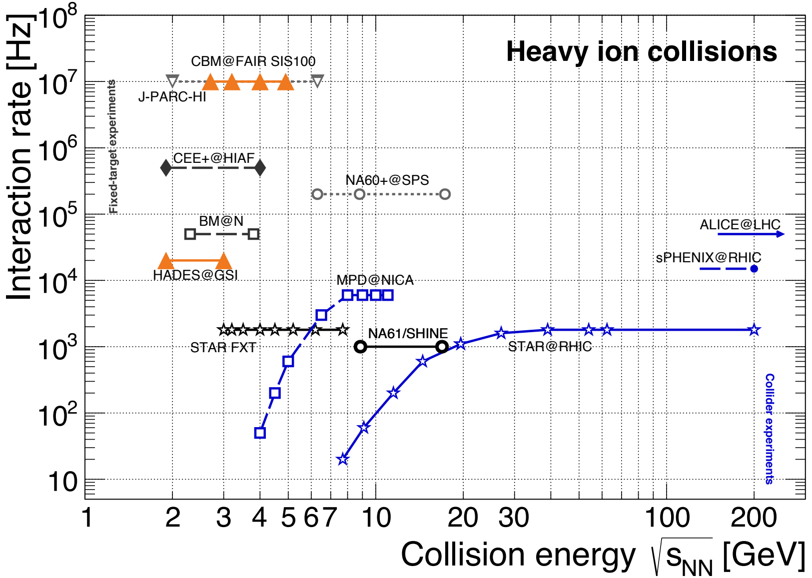
- explore high-μ_B region of the QCD phase diagram
- focus on rare and penetrating probes
- address various aspects of baryon-meson coupling

- **π and p beams:**
  - reference measurement (vacuum, cold nuclear matter)
  - em structure of baryons/hyperons in time-like region
- **Heavy-ion collisions $\sqrt{s_{NN}} = 2 - 2.55\ GeV$:**
  - microscopic properties of baryon dominated matter
  - Equation-of-State:
    - e-b-e correlations and fluctuations
    - flavour production and collective effects
    - dileptons

SOME BASIC FACTS ON HADES

https://github.com/tgalatyuk/interaction_rate_facilities
TG, Nucl.Phys. A982 (2019)
[CBM] EPJA 53 3 (2017) 60



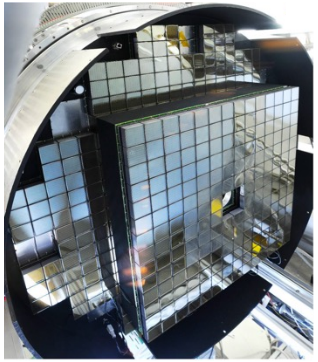


- new since 2019 RICH photo camera, ECAL (5 sectors)
- in 2021 forward detector system Sraw Tracker, RPC
- for 2022 new MDC FEE and 100 kHz DAQ upgrade

- accepted trigger rates:
  - 8 kHz in Apr 2012 Au+Au $\sqrt{s_{NN}} = 2.42\ GeV$ (7×10^9 evt)
  - 16 kHz in Mar 2019 Ag+Ag $\sqrt{s_{NN}} = 2.55\ GeV$ (14×10^9 evt) and $\sqrt{s_{NN}} = 2.42\ GeV$ (1×10^9 evt)
  - 50 kHz for hadron beams

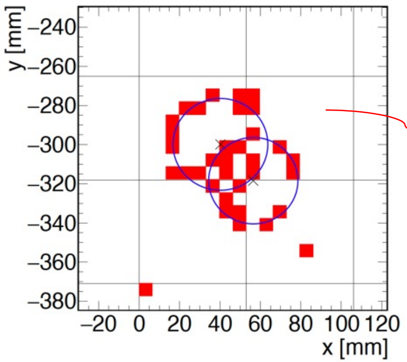
ELECTRON PAIRS

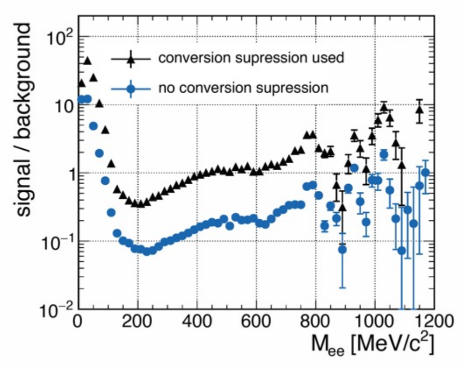
RICH photo camera upgrade, employing CBM at FAIR technology

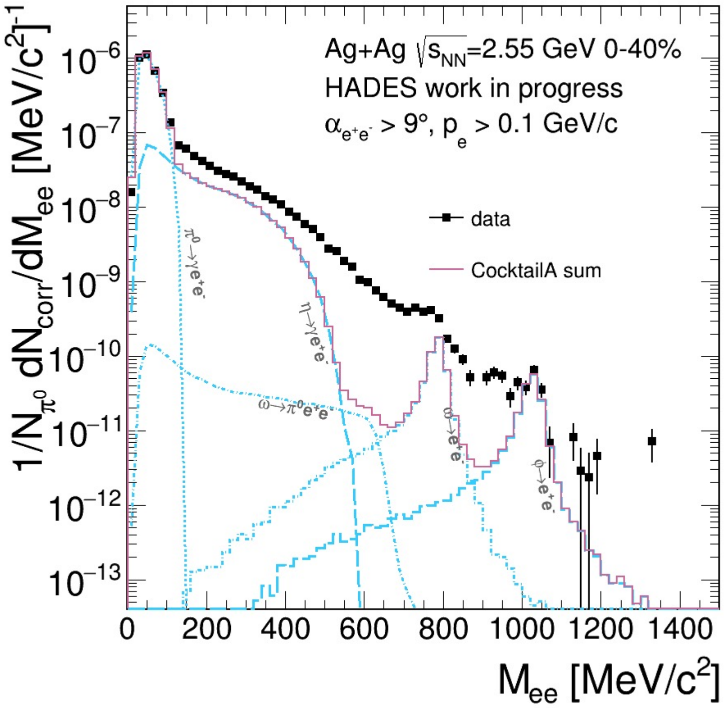


- ☐ significantly improved lepton detection efficiency
- ☐ excellent double ring detection (factor of 8 better signal-to-background ratio)

- ☐ vector-meson peaks (ω, φ) clearly visible
- ☐ first measurement of dilepton yield beyond vector meson mass region



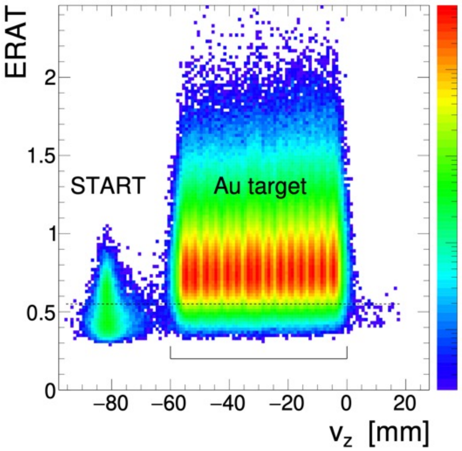




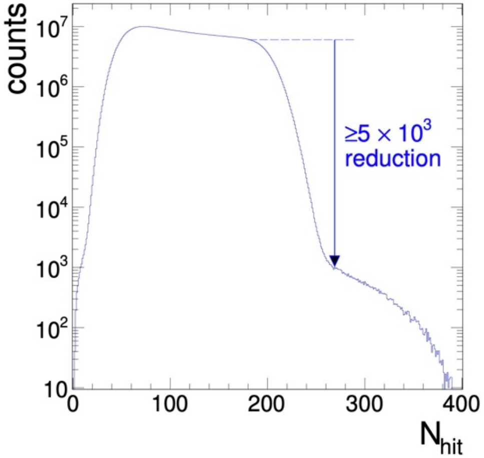
EVENT SELECTION and PARTICLE IDENTIFICATION

- 15-fold $(25\ \mu m,\ \Delta z = 3.7\ mm)$ segmented target
- LVL1 trigger on 43% most central collisions
- min. bias events scaled down (factor 8)

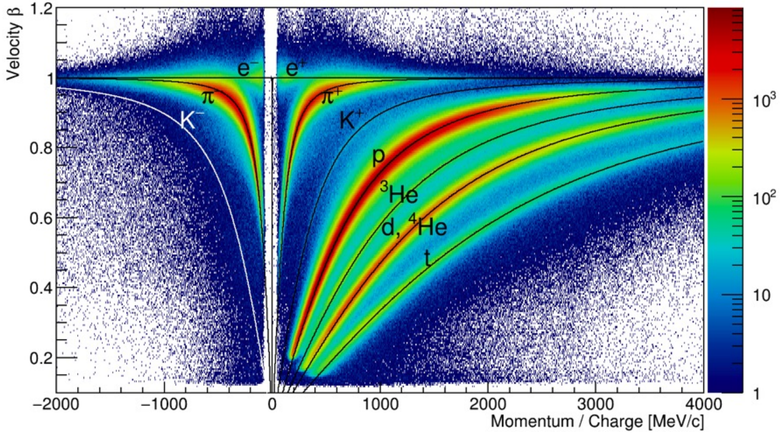
- velocity, Momentum
- dE/dx in MDC and ToF
- RICH information



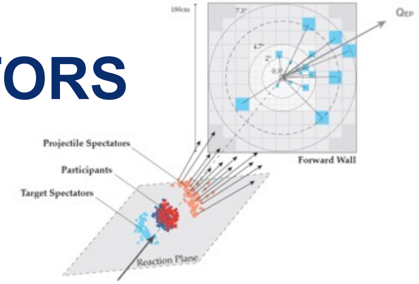
$$ERAT = \frac{E_\perp^{tot}}{E_\parallel^{tot}} = \frac{\sum_i E_{\perp,i}}{\sum_i E_{\parallel,i}} = \frac{\sum_i E_i sin\theta_i}{\sum_i E_i cos\theta_i}$$



event pile-up $\leq 2{\times}10^{-4}$
segmented target + Start + VETO



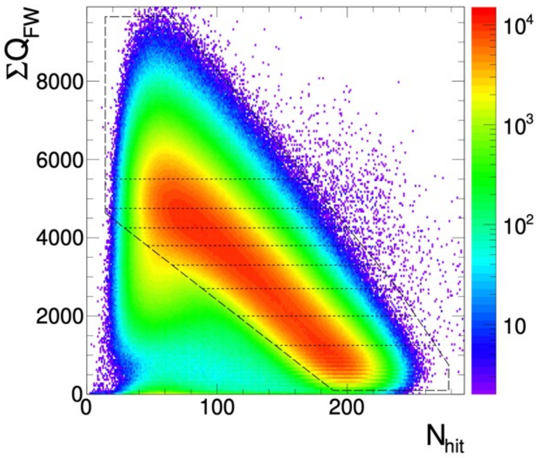
EVENT CHARACTERIZATION ENTRALITY ESTIMATORS



centrality estimator

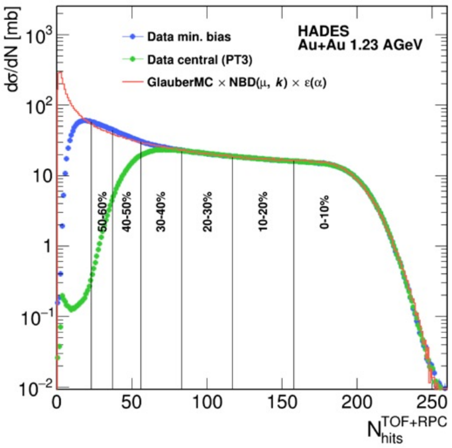
off-line centrality selection based on hit or track multiplicity and/or Forward Wall (FW) integral charge

centrality determination based on FW avoids bias on e-b-e fluctuation observables



HADES, Phys.Rev.C 102 (2020) 2, 024914

using Glauber MC - distributions agree with transport model calculations (processed by GEANT and filtered with standard analysis code)



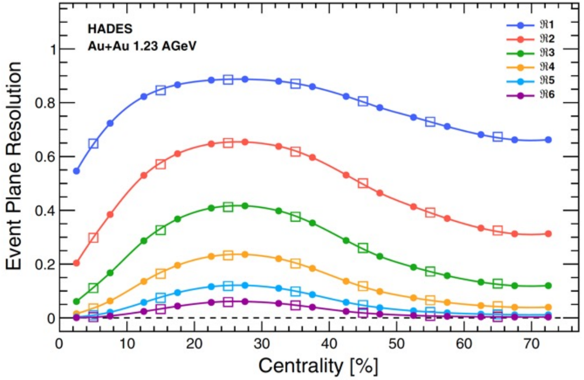
HADES, Eur.Phys.J.A 54 (2018) 5, 85

event plane reconstruction

based on hits of charged projectile spectators in the FW

resolution determined from sub-event resolution based on method by J.-Y. Ollitrault, arXiv:nucl-ex/9711003

$$v_n = v_n^{obs}/\Re_n \qquad \Re_n = \langle \cos\left[n(\Psi_n - \Psi_{RP})\right]\rangle$$



HADES, Phys.Rev.Lett. 125 (2020) 262301

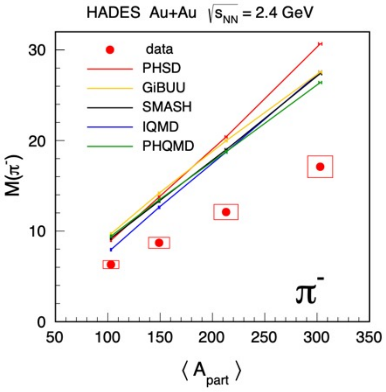
PROPERTIES OF THE MATTER

BULK PROPERTIES

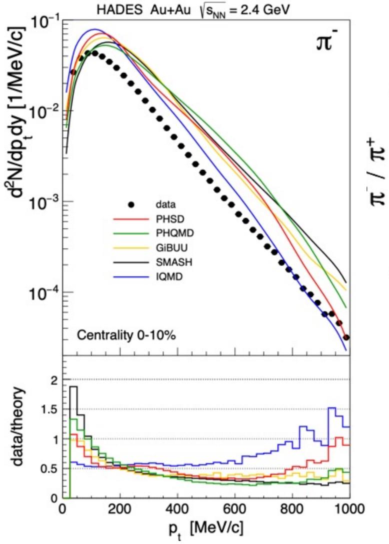
charged pions Au+Au $\sqrt{s_{NN}} = 2.42\ GeV$

- ~1 pion per 10 baryons
- large phase-space coverage, high statistics
  ↝ multi-differential analyses

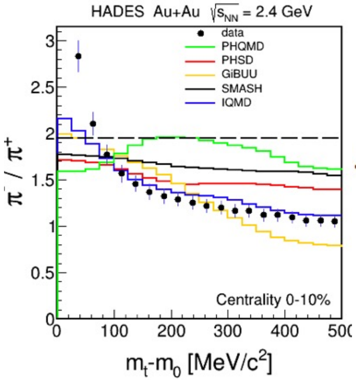
multiplicity



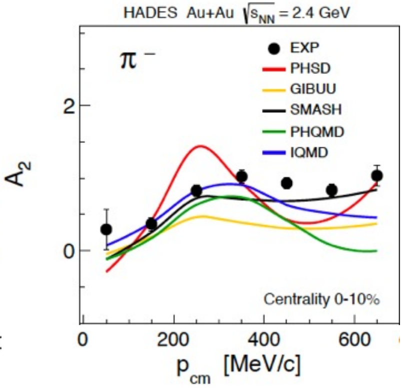
spectra



EM interaction



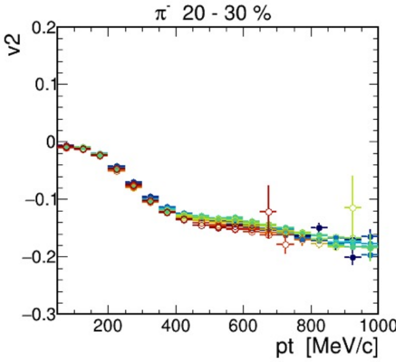
angular distribution



$$\frac{dN}{d(cos\theta_{cm})} = C(1 + A_2 cos^2\theta_{cm})$$

pion and proton "Temperatures" in HIC
R. Stock et al., Phys.Rev.Lett 1984

azimuthal anisotropy $v_n, n = 1 - 3$

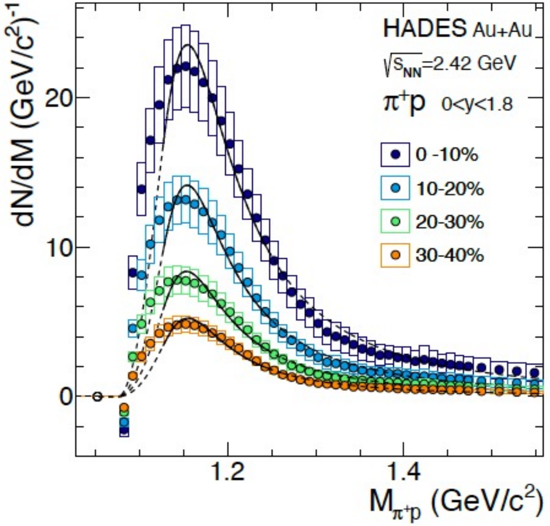


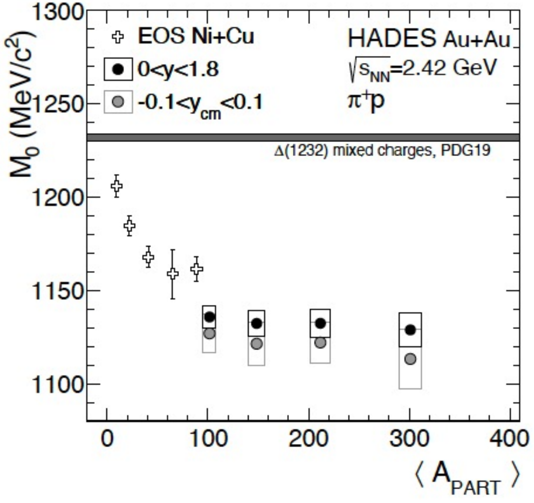
- transport models consistently fail to describe the data [HADES] Eur.Phys.J.A 56 (2020) 10, 259
- main source of pions - baryonic resonances propagating in hot and dense fireball

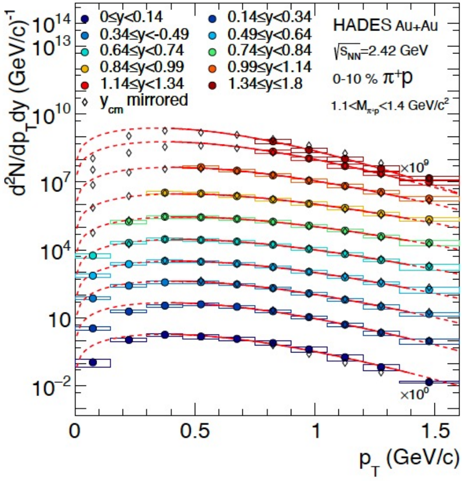
CORRELATED PION-PROTON PAIR EMISSION

$\pi^+ p$ and $\pi^- p$ analysis

$$\sigma_{BW}(M_{\pi p}) = \frac{q^3}{q^3+\mu^3}\frac{\sigma_0}{1+4[(M_{\pi p}-M_0)/\Gamma_0]^2}$$







HADES, accepted by Phys.Lett. B

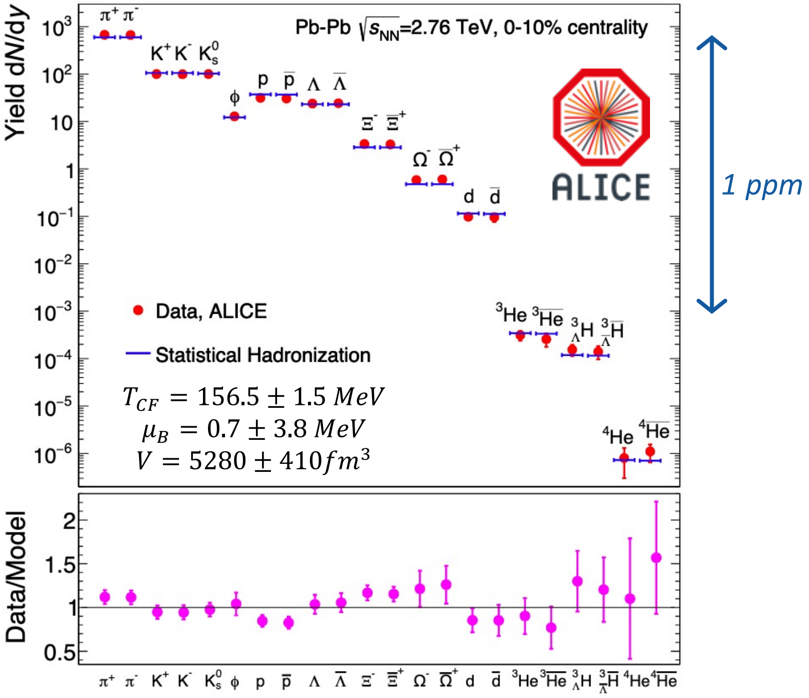
- high statistics allows multi-differential analysis
- understanding of "kinematical" mass shift with S-matrix formalism
- comparison to microscopic transport

UrQMD, T. Reichert et al., 2004.10539 [nucl-th];
Astron.Nachr. 340 (2019) 9-10, 1018-1022

Pok Man Lo, Eur. Phys.J. C77 (2017) no.8, 533
R. Dashen etal., Phys. Rev. 187 (1969) 345
R.Venugopalan et al., Nucl. Phys. A 546 (1992) 718
W. Weinhold, B. Friman, Phys. Lett. B 433 (1998) 236

ARE WE CREATING A THERMAL MEDIUM IN EXPERIMENTS?

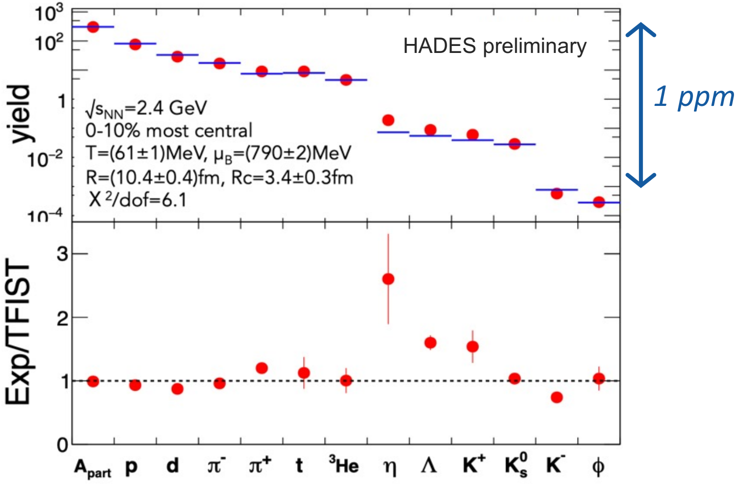
hadron yields and Statistical Hadronization Model



A. Andronic et al., Nature 561 (2018) no.7723

- Factor 1000 in beam energy / factor ~2 in temperature
- Hadron abundances described in framework of SHM
  - Strangeness canonical treatment at low beam energies
  - Include feed-down from $^4He,\ ^4H,\ ^4Li$

D. Hahn, H. Stöcker, Nucl.Phys.A 476 (1988) 718-772
E. Shuryak, J. M. Torres-Rincon Phys.Rev.C 101 (2020) 3, 034914

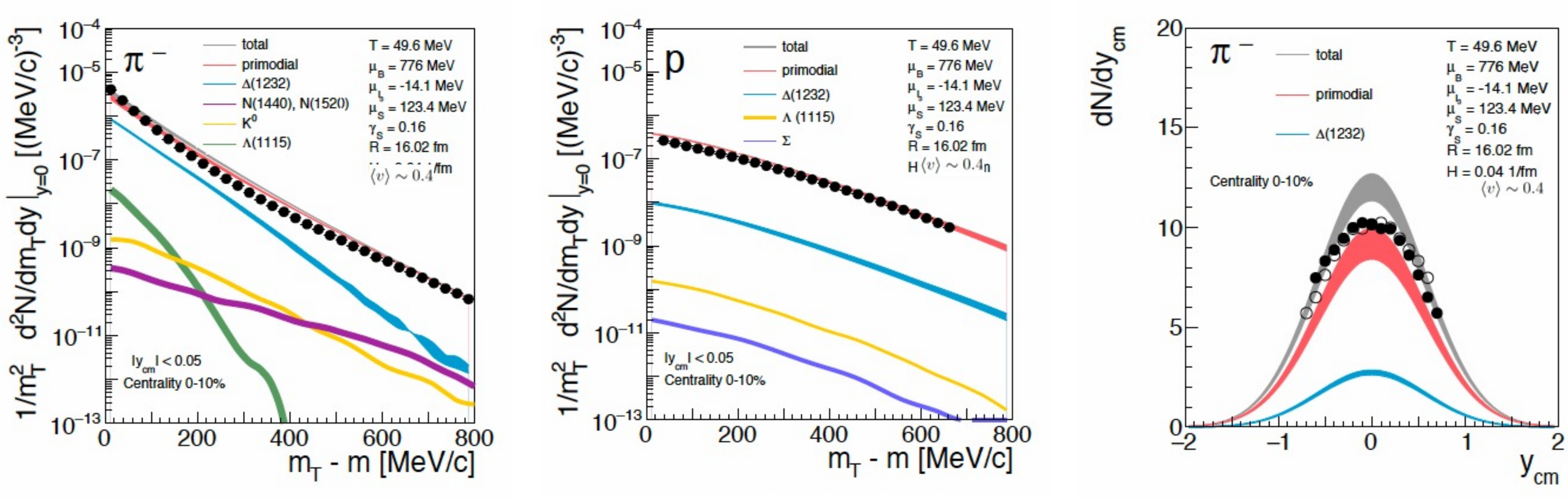


HUBBLE EXPANSION AND FREEZE-OUT AT SIS18

Thermainator 2 : extension of the model to not boost invariant systems

S. Harabasz *et al.*, PRC 102 (2020) 5, 054903

- single (chemical and kinetic) freeze-out on a spherically symmetric hypersurface(Siemens-Rasmussen blast-wave model)
- Hubble-like expansion velocity profile $\beta = \tanh(Hr)$ G. Inghirami *et al.*, arXiv:2106.04543[nucl-th]
- Δ spectral function from πN phase shift P.M. Lo et al., PRC 96 (2017) 015207



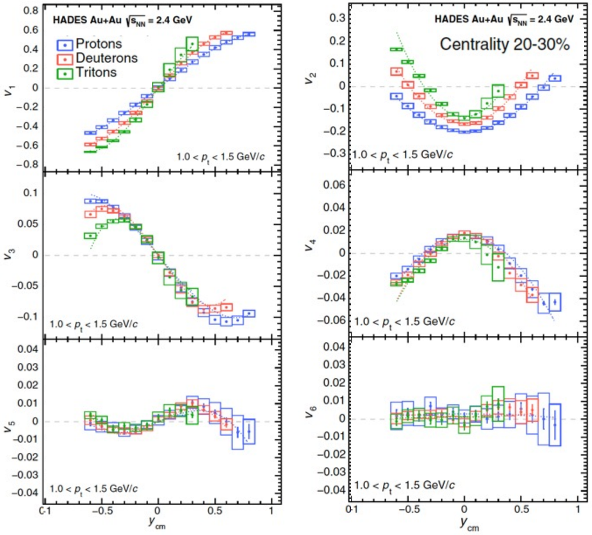
Good description of most abundant particles using a thermal model with only few simple assumptions!

AZIMUTHAL ANISOTROPY

protons and light nuclei

$v_n, n = 1 - 6$

v_1 v_2 v_3 v_4 v_5 v_6

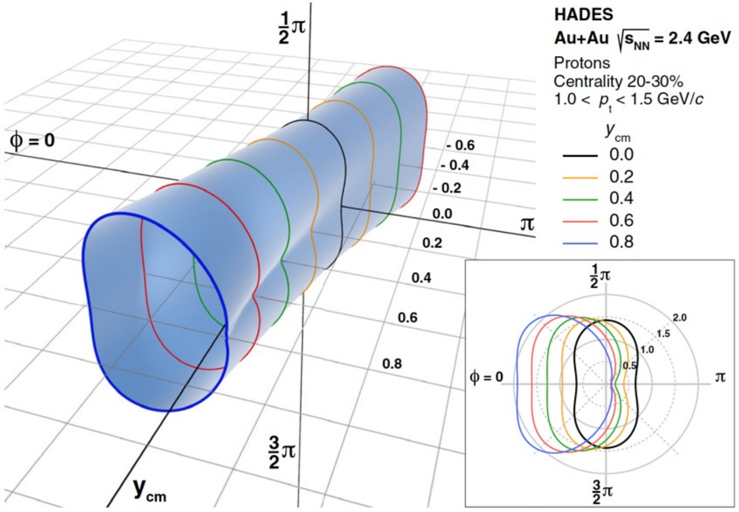


rapidity dependense paramerized with

$$v_{1,3,5}(y_{cm}) = a y_{cm} + b y_{cm}^3$$

$$v_{2,4,6}(y_{cm}) = c + d y_{cm}^2$$

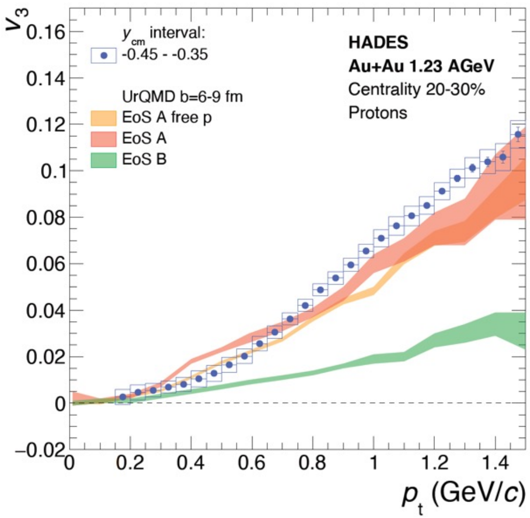
3D picture of the particle emission pattern in momentum space



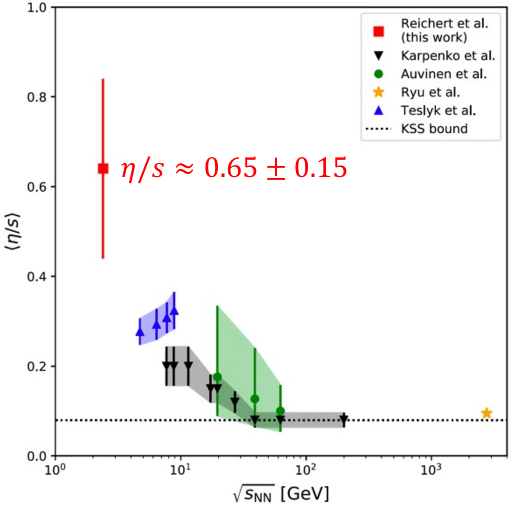
- mid-rapidity: almost elliptical shape
- forward/backward rapidity: triangular shape
  ⇝ interplay: central fireball pressure – interaction with spectator matter

SENSITIVITY TO THE EoS, TRANSPORT PROPERTIES

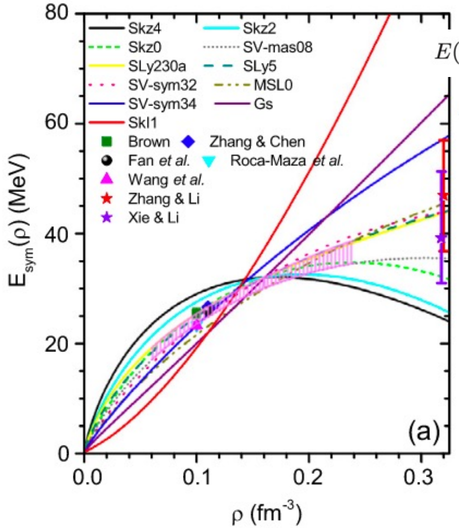
[HADES] Phys.Rev.Lett 125 (2020) 262301



T. Reichert et al., Phys.Lett.B 817 (2021) 136285



Y. Wang et al., Phys.Lett.B 802 (2020) 135249



$$E(\rho,\delta) = E(\rho) + E_{sym}(\rho)\,\delta^2$$

$$L_0 = 3\rho_0 \left(\frac{\partial E_{sym}(\rho)}{\partial \rho}\right)\Big|_{\rho=\rho_0}$$

high precision HADES data

→ narrow uncertainty range of high-density EoS

→ first time estimate of η/s of high-density matter

→ scrutinize applicability of hydro at few GeV collision energy range

- ☐ density dependence of E_{sym} , L_0 is of a great importance and becomes a part of multi-messenger
- ☐ important, but very uncertain!

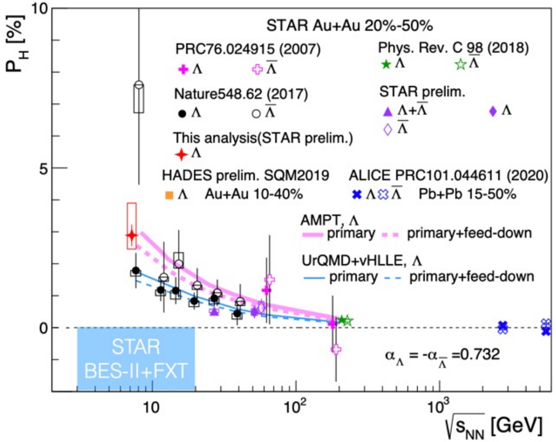
P. Danielewicz et al., Science 298 (2002) 1592-6

DO WE OBSERVE A MAXIMUM OF THE GLOBAL POLARIZATION AT SIS18 ENERGIES?

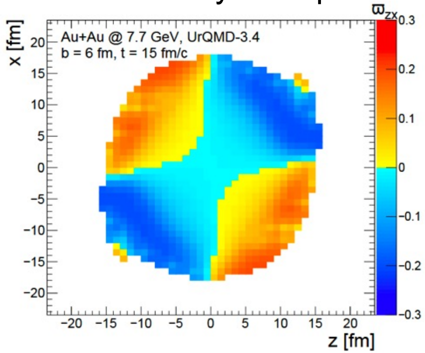
non-central heavy-ion collisions →
large orbital angular momenta →
vortical structure of the system?

global spin polarization of the particles

$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{\langle \sin(\Psi_{EP} - \phi_p^*) \rangle}{R_{EP}}$$

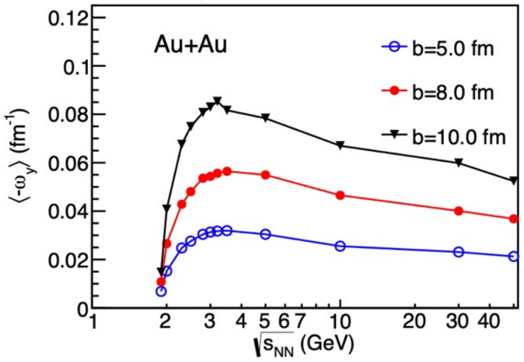


thermal vorticity in xz-plane



O. Vitiuk *et al.*, PLB803 (2020) 135298

maximum kinetic/thermal vorticity around 3 GeV



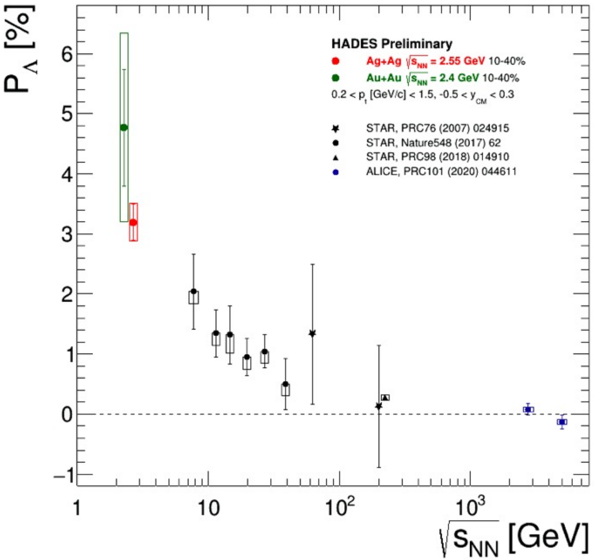
X.-G. Deng *et al.*, PRC101.064908 (2020)

increasing trend toward lower energies in data and various models

I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
H. Li et al., PRC96, 054908 (2017), AMPT
Y. Sun and C.-M. Ko, PRC96, 024906 (2017), CKE
Y. Xie et al., PRC95, 031901(R) (2017), PICR
Y. B. Ivanov et al., PRC100, 014908 (2019), 3FD model

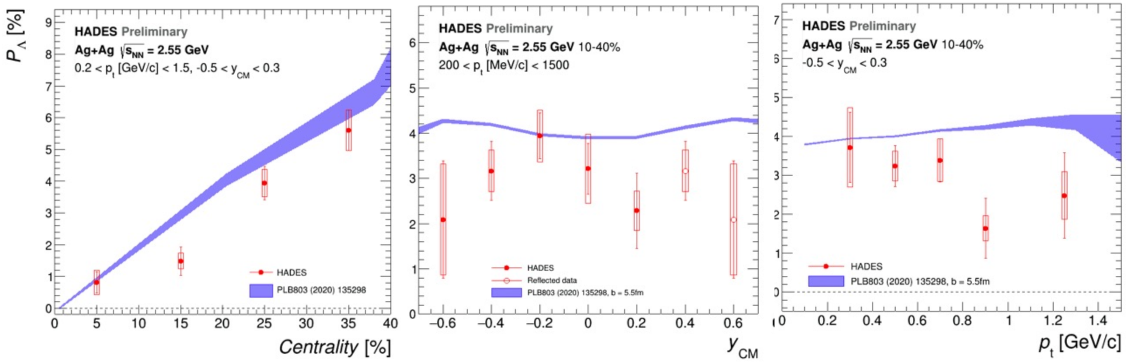
Λ POLARIZATION AT 2.4 Au+Au AND 2.55 Ag+Ag

P_Λ still shows the increasing trend from 7.7 GeV down to 2.4 GeV



P_Λ grows towards peripheral collisions (in line with expectations for larger orbital angular momentum)

within uncertainties no clear p_t and y dependence is observed



O. Vitiuk *et al.*, PLB803 (2020) 13529
Y.B.Ivanov: arXiv:2012.07597

- HADES data consistent with 3FD and CG UrQMD model calculations
- directed flow slope at midrapidity follows world data
- Ag+Ag vs Au+Au collisions: effect of the different system size?

CRITICAL FLUCTUATIONS

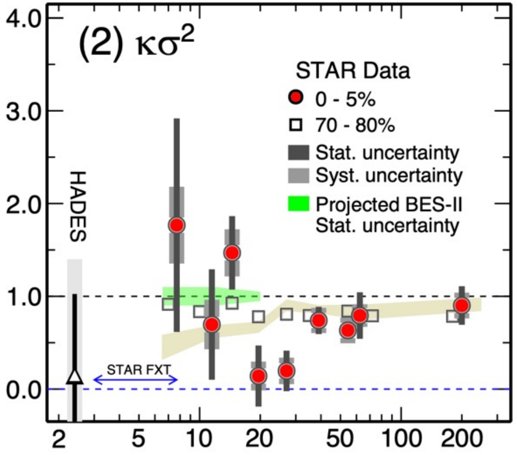
Ling, Stephanov, PRC 93, 034915 (2016)

Cumulants k_n hold information on multi-particle correlators C_n

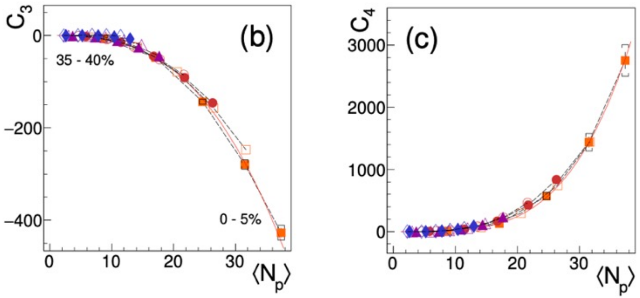
Bzdak, Koch, Strodthoff, PRC 95, 054906 (2017)

Investigate C_n vs. $\langle N_p \rangle$ to isolate relevant physics, $C_n \propto \langle N_p \rangle^{\alpha}$

STAR, PRL 126 (2021) 092301



HADES, PRC102(2020) 2,024914



$C_3 \propto \langle N_p \rangle^{\alpha}$
$\alpha = 2.84 \pm 0.05$

$C_4 \propto \langle N_p \rangle^{\alpha}$
$\alpha = 3.89 \pm 0.14$

$\alpha \simeq n \rightarrow$ signature of multi-particle correlations ($\Delta y_{corr} > 1$)

Direct link to EoS $\frac{1}{VT^3} k_n = \frac{\partial^n \hat{p}}{\partial \hat{\mu}^n}$

$\hat{p} = \frac{p}{T^4}$ reduced pressure

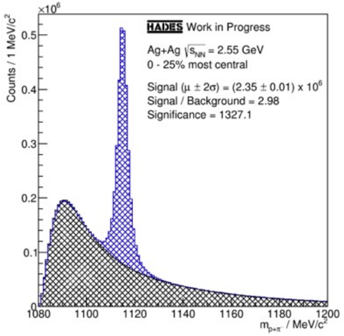
$\hat{\mu} = \frac{\mu}{T}$ reduced chemical potential

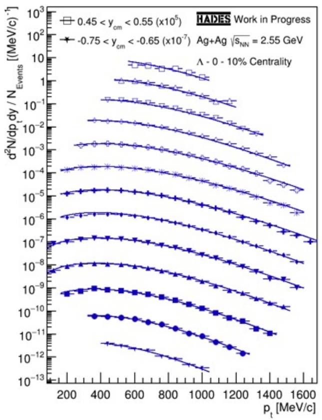
cf. B. Friman *et al.*, EPJC 71 (2011) 1694
M. Stephanov, Phys.Rev.Lett.107 (2011) 052301

- Stopping of nucleons may produce multi-particle “clusters”
- Quarkyonic matter?
- Remnants of nuclear liquid-gas phase transition?

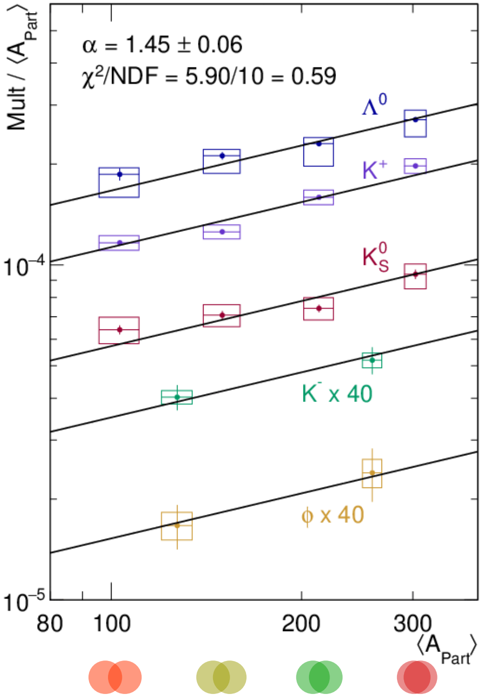
Bzdak, Koch, Skokov, EPJC (2017) 288
Shuryak, Torres-Rincon Phys.Rev.C 101 (2020) 3, 034914
Kojo, Hidaka, McLerran, Pisarski, Nucl. Phys. A843 (2010), 37
R. Poberezhnyuk et al., Phys.Rev. C100 (2019) no.5, 054904

SYSTEM WITH MULTI-PARTICLE CORRELATIONS



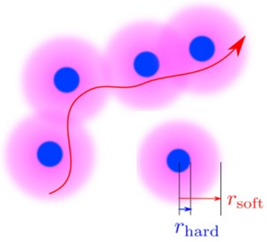


HADES, Phys.Lett.B 793 (2019) 457



- universal scaling with participant number $M \sim \langle A_{part} \rangle^{\alpha}$
  - Au+Au $\sqrt{s_{NN}} = 2.42\ GeV$: $\alpha = 1.45 \pm 0.06$
  - Ag+Ag $\sqrt{s_{NN}} = 2.55\ GeV$: $\alpha = 1.38 \pm 0.03$
- does not reflect the hierarchy of NN production thresholds
- not expected if strangeness produced in *isolated* NN collisions

Scaling with absolute amount of strangeness not with individual hadron states



"Soft Deconfinement"

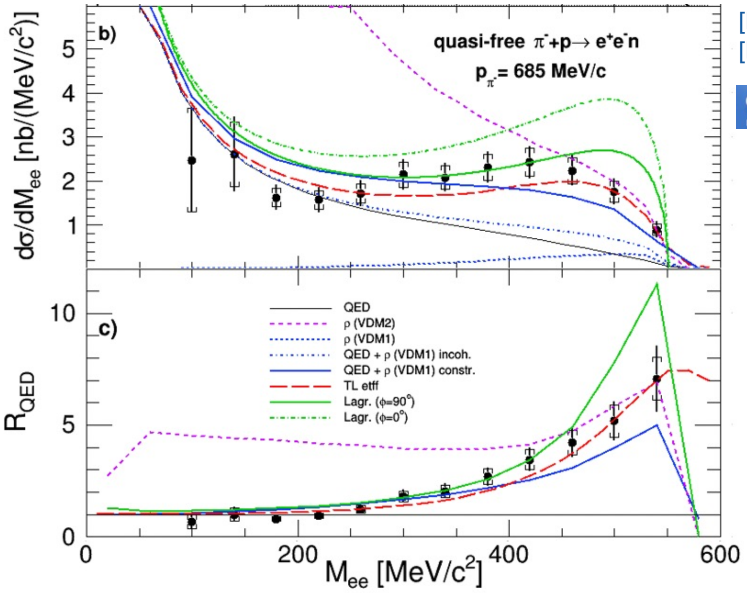
percolation of the interaction meson clouds

Fukushima, Kojo, Weise, Phys.Rev.D 102 (2020) 9, 096017

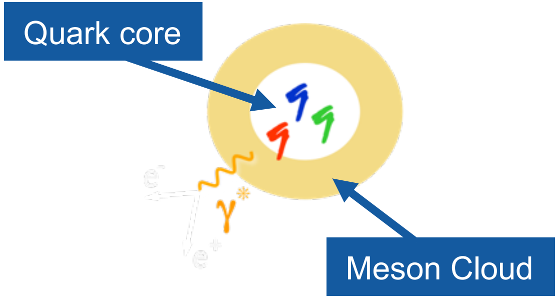
MESON CLOUD

exclusive analysis $\pi^- p \rightarrow e^+ e^- n$

HADES, in preparation



Ramalho, Pena, Phys. Rev. D95 (2017) 014003
Zetenyi, Nitt, Buballa, Galatyuk, arXiv:2012.07546
Speranza *et al.*, Phys.Lett. B764 (2017) 282



[HADES] Phys.Rev.C 102 (2020) 2, 024001
[HADES] Phys.Rev.C 95 (2017) 065205

4 first entries ($N\rho$)
4 additional entries
first entry BR $\Delta \rightarrow pe^+e^-$

- study the structure of the nucleon as an extended object (quark core and meson cloud)
- dominance of the $N^*(1520)$ resonance

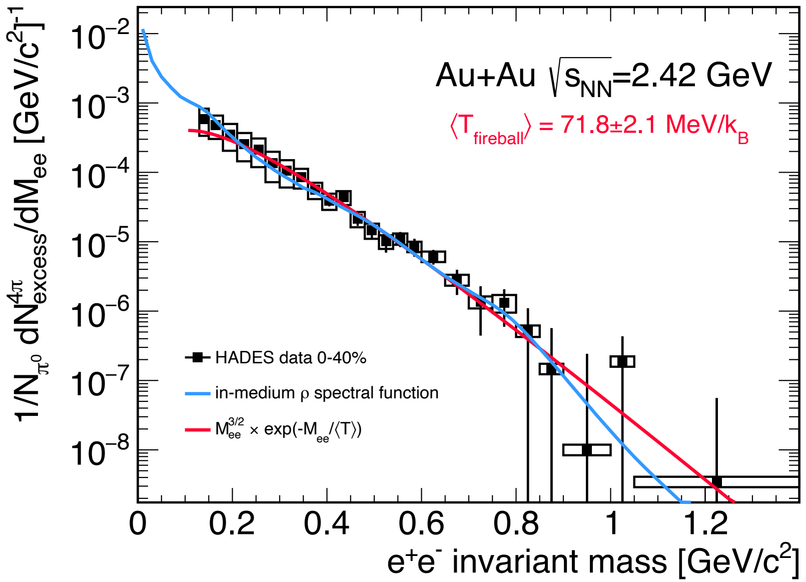
excitation of a baryon can be carried by the meson cloud

Vector Meson Dominance (the basis of emissivity calculations for QCD matter)

ELECTROMAGNETIC RADIATION

dilepton invariant mass ⇝ unique direct access to in-medium spectral function

[HADES] Nature Phys. 15(2019) 1040



CG GSI-Texas A&M: Eur. Phys. J. A, 52 5 (2016) 131
CG FRA: Phys. Rev. C 92, 014911 (2015)
CG SMASH: Phys.Rev.C 98 (2018) 5, 054908

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{em}^2}{\pi^3 M^2} L(M^2) f^B(q\cdot u;T) \boxed{Im\Pi_{em}(M,q;\mu_B,T)}$$

McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

measured excess dilepton invariant-mass spectra (from SIS18-SPS-RHIC-LHC)

[STAR], Phys. Rev. Lett.113 (2014) 2, 022301
[STAR], Phys. Rev., C92 (2015) 2, 024912
[STAR], Phys.Lett. B750 (2015) 64–71
[STAR], arXiv:1810.10159, 2018

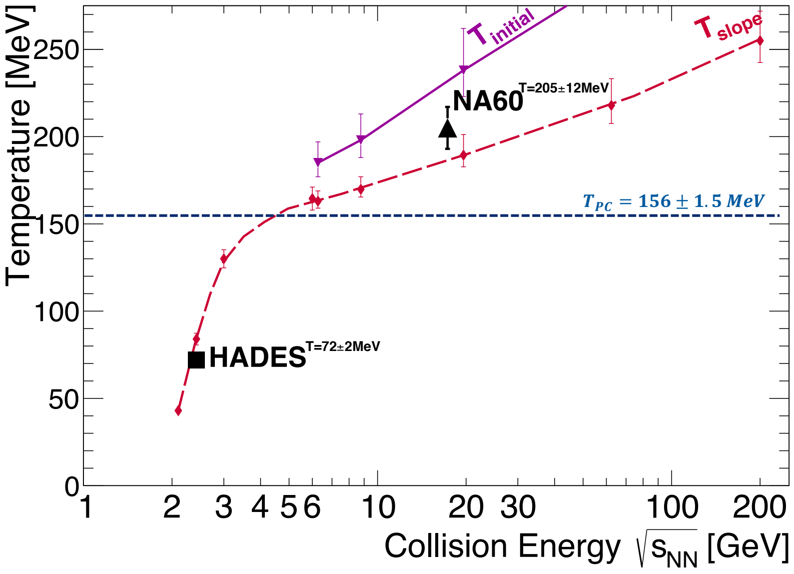
[NA60] EPJC 61(2009) 711
[CERES/NA45], Phys.Lett.B 666 (2008) 425
[PHENIX] Phys.Rev. C93 (2016) 1, 014904
[ALICE] Phys.Rev.C 99 (2019) 2, 024002

- strongly supports **melting of ρ**
- spectrum falls exponentially $\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp(-\frac{M}{T})$
- thermometer: independent of flow, no blue shift*!*

Rapp, Wambach, Eur.Phys.J. A6 (1999) 415-420 (1999)

MAPPING QCD CALORIC CURVE (T VS ε)

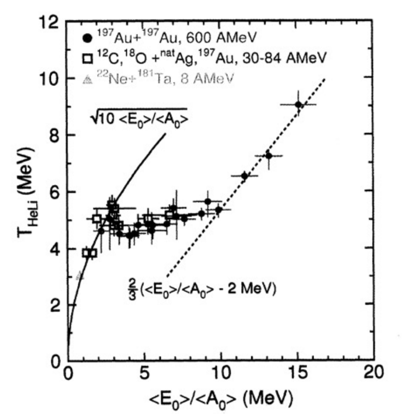
Rapp and v. Hess, PLB 753 (2016) 586
TG *et al.*: EPJA 52 (2016) 131



[NA60] Chiral 2010, AIP Conf.Proc. 1322 (2010)
[HADES] Nature Phys. 15(2019) 1040

- Signature for phase transition?
  - ⇝ **phase transition may show up as a plateau!**
  - ⇝ future high statistics experiments,
    future opportunity for STAR FXT 3 GeV (2 billion events)

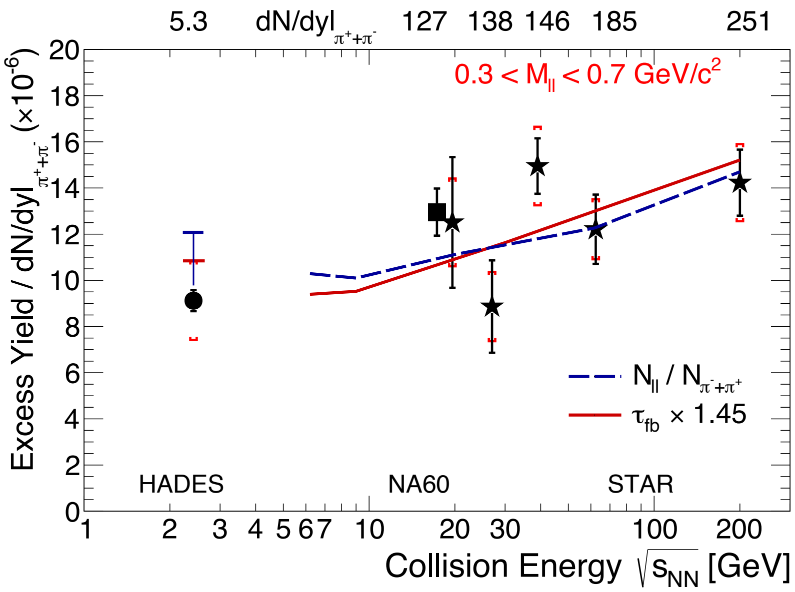
Nuclear liquid-gas phase transition



Pochodzalla *et al.*,
PRL 75 (1995) 1040

DILEPTONS AS A CHRONOMETER

TG., JPS Conf.Proc. 32 (2020) 010079



opportunity for STAR FXT 3 GeV

- Integrated low-mass radiation $0.3 < M < 0.7\ GeV/c^2$ tracks the fireball lifetime

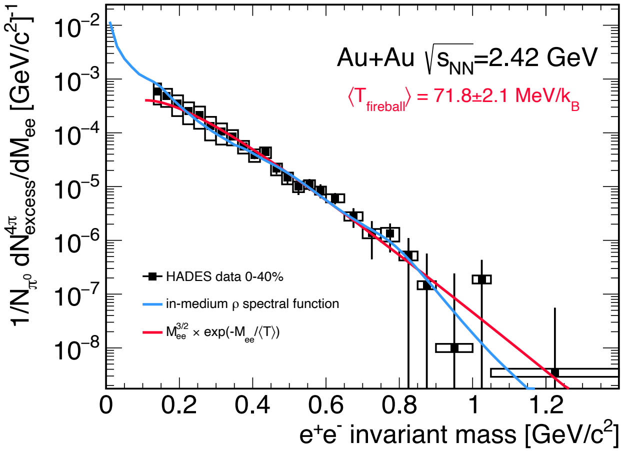
  Heinz and Lee, PLB 259, 162 (1991)
  Barz, Friman, Knoll and Schulz, PLB 254, 315 (1991)
  Rapp, van Hees, PLB 753 (2016) 586

- Signature for phase transition (and critical point)?
  ⇝ latent heat ⇝ longer life time ⇝ extra radiation

  Seck, TG, Mukherjee, Rapp, Steinheimer, Stroth, arXiv:2010.04614 [nucl-th]
  Tripolt, Jung, Tanji, v. Smekal, Wambach, Nucl. Phys. A982 (2019) 775
  Li and Ko, Phys. Rev. C 95 (2017) no.5, 055203

THERMAL DILEPTONS AT SIS18

invariant mass



[HADES] Nature Phys. 15(2019) 1040

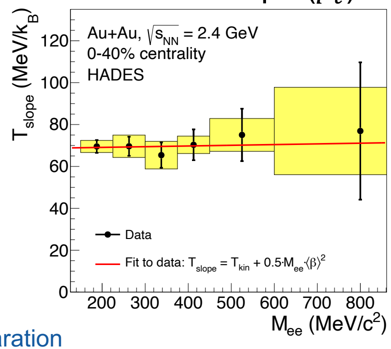
What have we learnt from excess radiation Au+Au $\sqrt{s_{NN}}$=2.4 GeV?

Radiation from a source

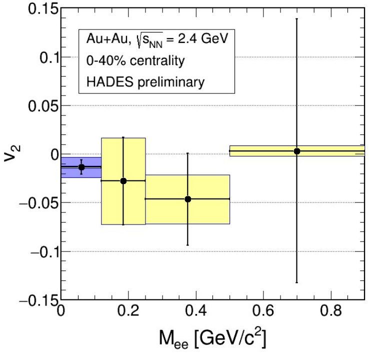
- ☐ long-lived (τ≈13 fm)
- ☐ in local thermal equilibrium
- ☐ $\langle T \rangle \approx$ 72 MeV
- ☐ $\rho = 2 - 3\, \rho_0$

$$\sigma_{el} = \lim_{p_0 \to 0} \frac{\delta}{\delta p_0} Im\Pi_{em}(p_0, |\vec{p}| = 0)$$

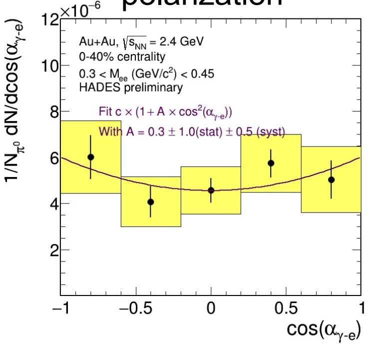
inverse slope (p_t)



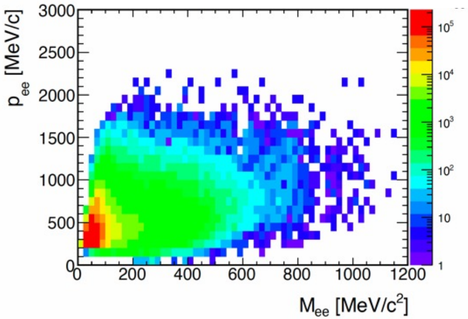
elliptic flow (v_2)



polarization

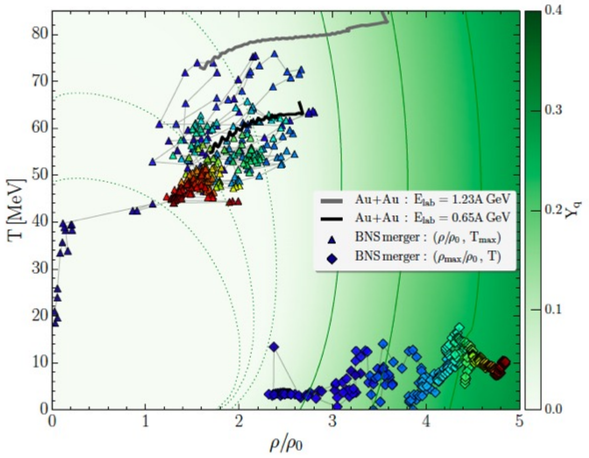


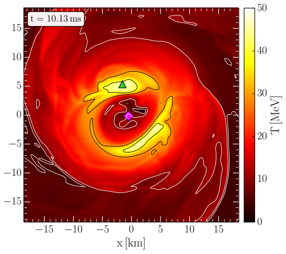
electrical conductivity?

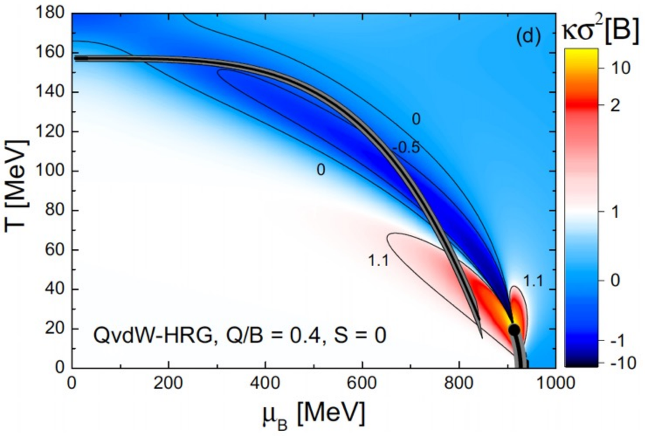


[HADES] in preparation

WHY MEASURING Au+Au AT EVEN LOWER ENERGIES?







Hanauske *et al.*, Particles 2 (2019) no.1
Rezzolla *et al.*, Phys. Rev. Lett. 122 (2019) no. 6, 061101

R. Poberezhnyuk *et al.*, Phys.Rev. C100 (2019) no.5, 054904

- ☐ **Laboratory studies of the matter properties (EoS) in compact stellar objects (neutron star mergers)**

- ☐ **What are the measurable consequences of phase transition and critical point in the QCD phase diagram?**

⇝ **strong connections between the fields**

RÉSUMÉ AND PROSPECTS

Encouraging prospects for studying baryon dominated QCD matter with HADES

- Results from Au+Au collisions suggest a thermalized strongly interacting medium created at $\sqrt{s_{NN}} = 2.42\ GeV$
  - Thermal models fit yield and spectra
  - Data sensitive to the EoS
  - Thermal origin of dilepton excess spectrum
  - System with multi-particle correlations
- Complementary program on exclusive measurements in π, p induced reactions
- Strong scientific program for FAIR Phase 0
- … and for FAIR Phase 1

movie FAIR status Apr 2020

THE HADES COLLABORATION