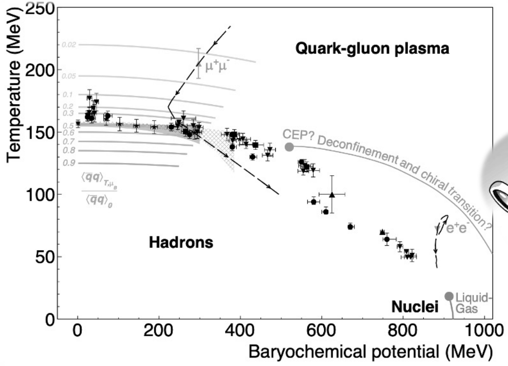
UNRAVELLING THE PHASE STRUCTURE OF QCD AT HIGH μ_B WITH HADES



Tetyana Galatyuk
Technische Universität Darmstadt / GSI
for the HADES Collaboration

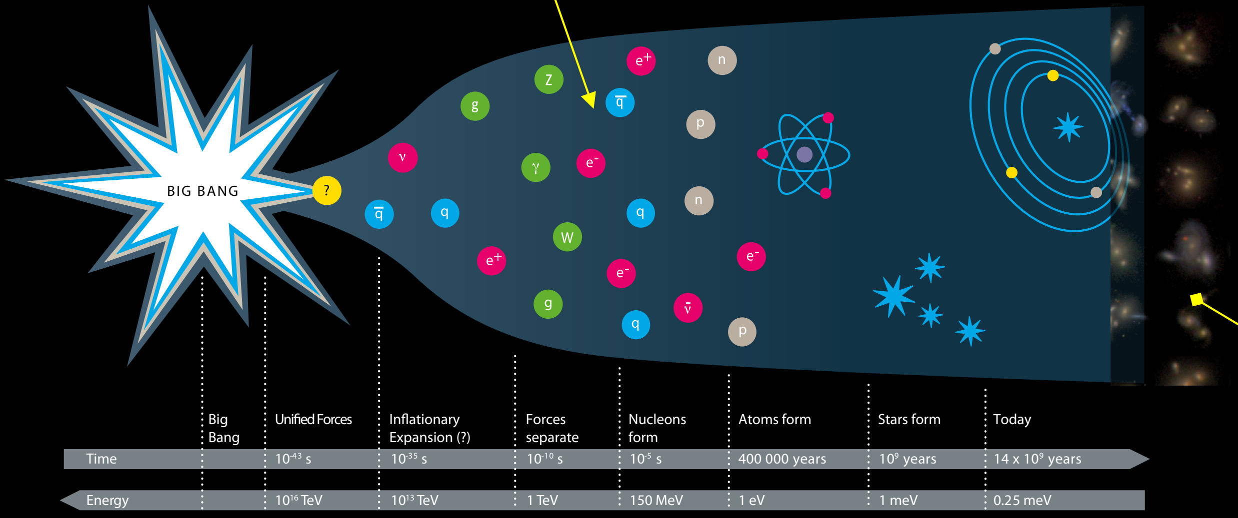
59. International Winter Meeting on Nuclear Physics
23-27 January 2023, Bormio, Italy

MISSION

Decode emergence of phases of strong-interaction matter in non-perturbative regime of QCD

Unravel role of the strong interaction in the evolution of our universe

Nature of phase transitions in strong-interaction matter?



Neutron star

$M \sim 1.4 – 2\ M_{\odot}$

$R \sim 12$ km

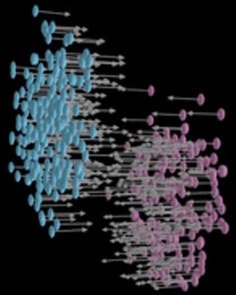
$T \sim$ keV

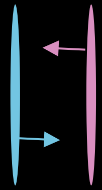
$n \lesssim 10\, n_{sat}$

Compact stellar objects matter?

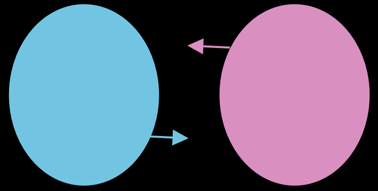
COSMIC MATTER IN THE LABORATORY

➥ Accessible through heavy-ion collisions at (ultra-)relativistic energies



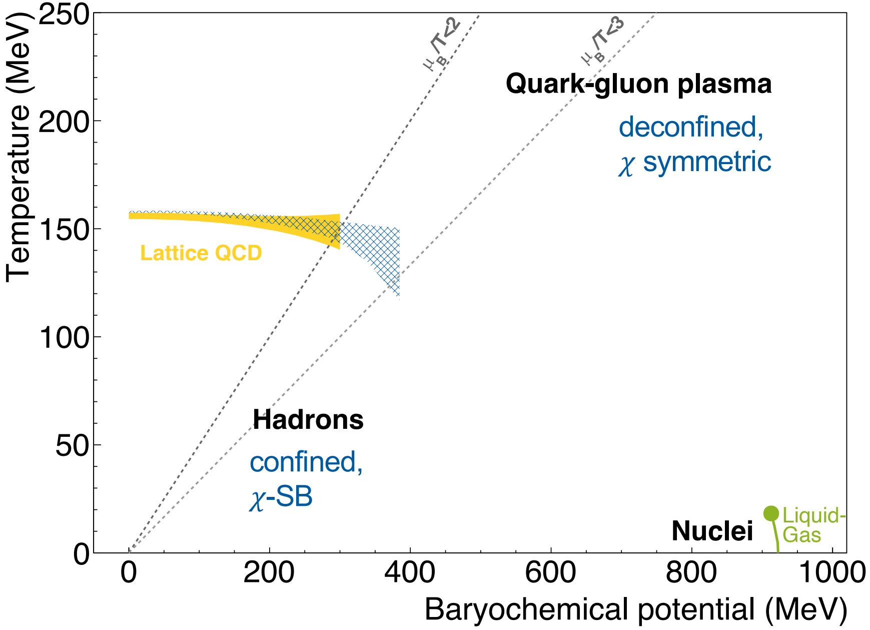


LHC energies $\sqrt{s_{NN}} = 2\ TeV$
parton+parton collisions
$N_{particles} = N_{anti-particles}$



SIS energies $\sqrt{s_{NN}} = 2 - 5\ GeV$
Nuclear stopping
$N_{particles} \gg N_{anti-particles}$

Searching for landmarks of the QCD matter phase diagram

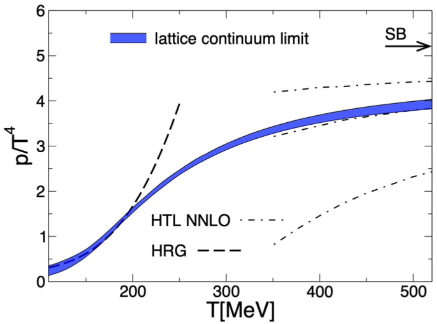


Borsanyi *et al.* [Wuppertal-Budapest], PRL 125 (2020)
Borsanyi *et al.* [Wuppertal-Budapest], PLB (2014) 730
Borsanyi *et al.* [Wuppertal-Budapest], JHEP 1009 (2010) 073

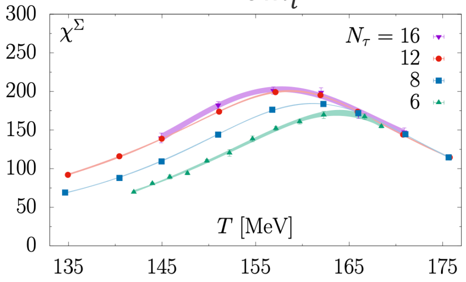
- **Vanishing μ_B, high T (lattice QCD):**
  - **crossover** from hadronic to partonic medium
    - $T_{pc} = 156.5 \pm 1.5$ MeV ($T_c = 132^{+3}_{-6}$ MeV at chiral limit)
    - $T_{pc} = 158.0 \pm 0.6$ MeV
  - **no critical point** indicated by lattice QCD at $\mu_B^{CEP}/T_c < 3$

Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Ding *et al.*, [HotQCD], PRL 123 (2019) 6, 062002
Dini *et al.*, PRD 105 (2022) 3, 034510

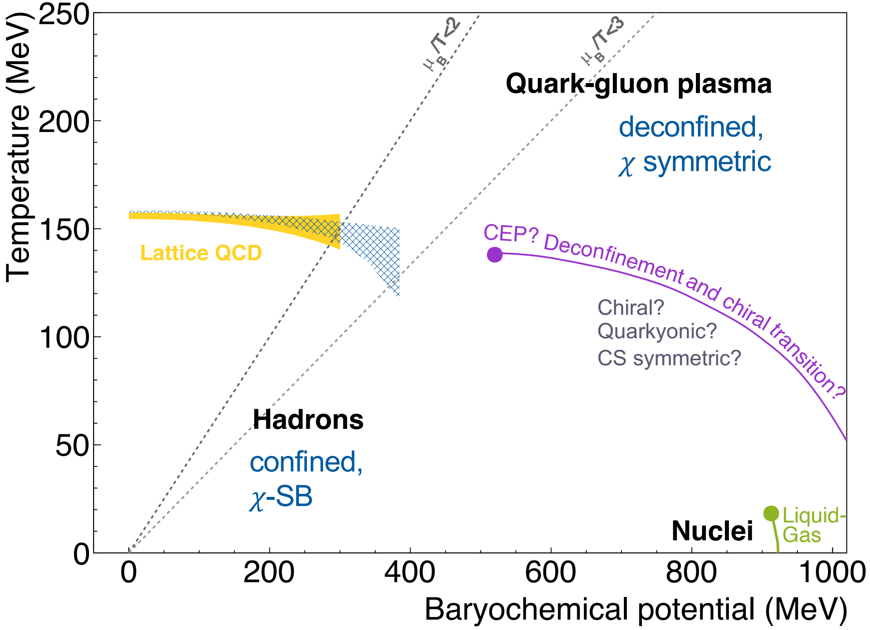
$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V,T,\vec{\mu})$$



$$\chi^\Sigma \sim \frac{\partial^2 lnZ}{\partial m_l^2}$$



Searching for landmarks of the QCD matter phase diagram



Gao, Pawlowski, PLB 820 (2021) 136584
Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141
McLerran, Pisarski, NPA 796 (2007) 83
Glozman, Philipsen, Pisarski, arXiv:2204.05083 [hep-ph]

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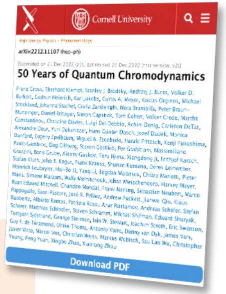
Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Ding *et al.*, [HotQCD], PRL 123 (2019) 6, 062002
Dini *et al.*, PRD 105 (2022) 3, 034510

- **Large μ_B, moderate T (lQCD inspired effective theories):**
  - limits of hadronic existence?
  - 1st order transition?
  - QCD critical point?
  - equation-of-state of dense matter?



Worldwide experimental and theory efforts

Relevance for astrophysics

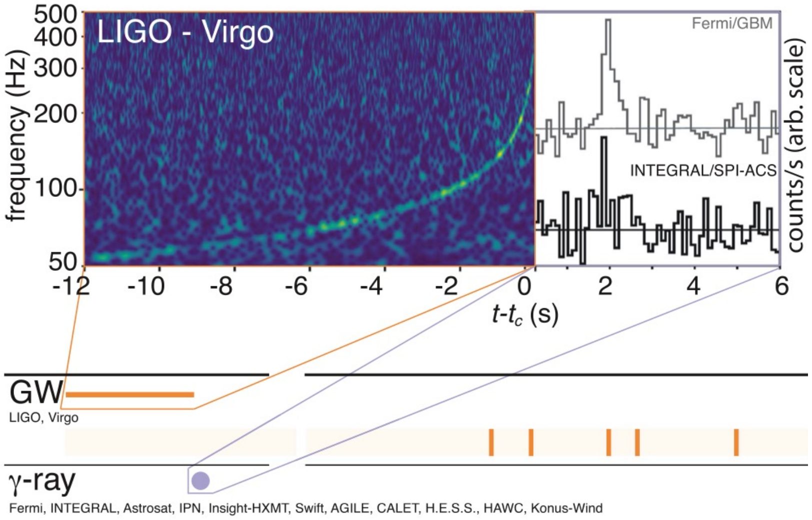
Multi-messenger signals from neutron star merger

- GW170817 17 Aug 2017 12:41:04 UTC
  First detection of a binary neutron start merger through gravitational waves

LIGO + VIRGO, PRL 119 (2017) 1611001

- GRB 170817A ~1,7 s later:
  Observation of the same event through electromagnetic waves (gamma-ray burst)

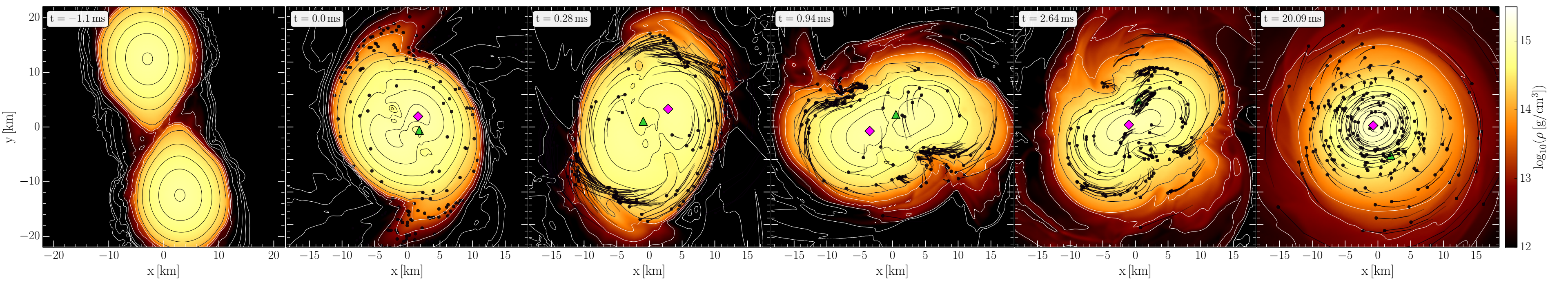
Fermi GBM + INTEGRAL + LIGO + Virgo, Astrophys.J.Lett. 848 (2017)



ASTROPHYSICAL "COLLIDER"

LS220-M132 EOS

$1.32{+}1.32 M_\odot$ $\quad \emptyset = 10\ km$ $\quad \tau \sim 20\ ms$ $\quad n \sim (2-3)\, n_{sat}$ $\quad T < 70\ MeV$

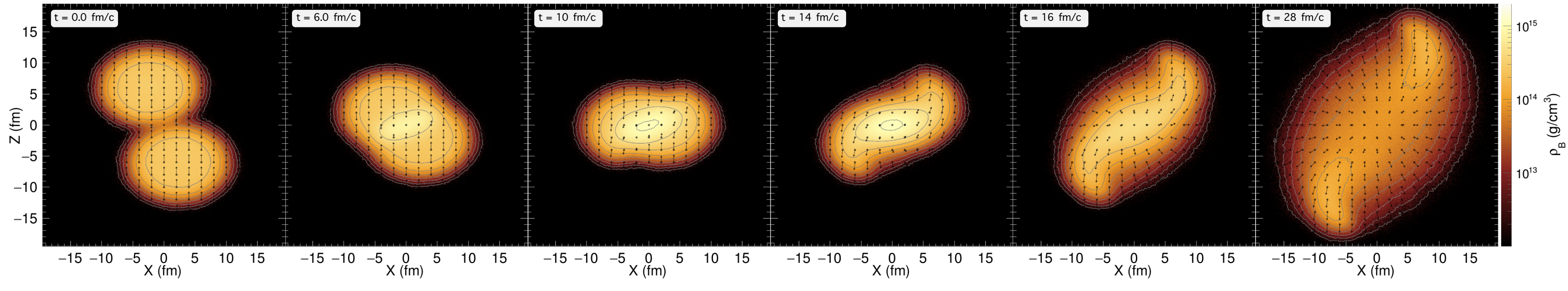


Hanauske, Journal of Phys.: Conf. Series 878 (2017) 012031
Rezzolla *et al.*, Phys. Rev. Lett. 122, no. 6, 061101 (2019)

- Violent Universe can now be
  - "heard" through gravitational waves
  - seen through electromagnetic radiation

LABORATORY COLLIDER

Au+Au $\sqrt{s_{NN}} = 2.4\,GeV$ $\emptyset = 7\,fm$ $\tau \sim 10^{-23} s$ $n \sim (2-3)\,n_{sat}$ $T < 70\,MeV$

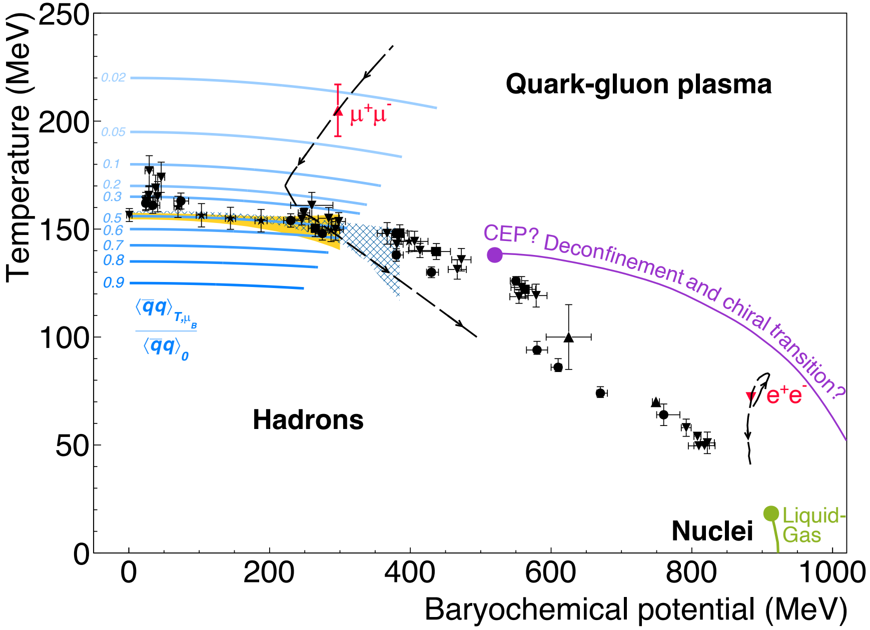


time ~ 10^{-23} s

„First chance" *„Pre-equillibrium"* *Fireball* *Freeze-out* *Late stage*

- Heavy-ion collisions at (ultra-)relativistic energies:
  - 18 orders of magnitude in scales, still similar T and n
  - unique role played by electromagnetic radiation

Searching for landmarks of the QCD matter phase diagram

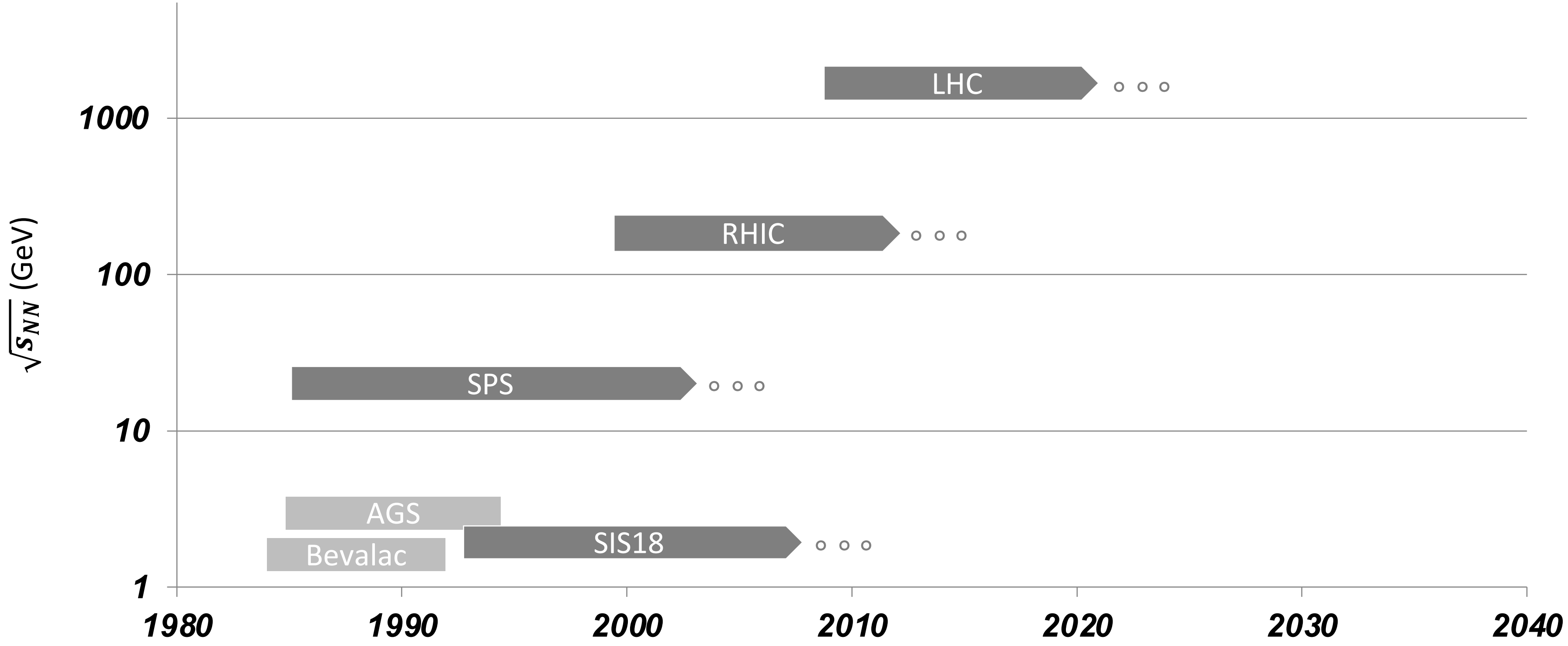


- **Experimental challenge:**
  - locate the onset of new phases of QCD
  - detect the conjectured QCD critical point
  - probe microscopic matter properties
- **Measure with utmost precision:**
  - event-by-event fluctuations (criticality)
  - strangeness (vorticity)
  - dileptons (emissivity)
  - hypernuclei (equation-of-state)
  - charm (transport properties)

Almost unexplored (not accessible) so far in the high-μ_B region

HADES, Nature Phys. 15 (2019) 10, 1040-1045
NA60, Specht *et al.*, AIP Conf.Proc. (2010) 1322
Andronic *et al.*, Nature 561 (2018) no.7723

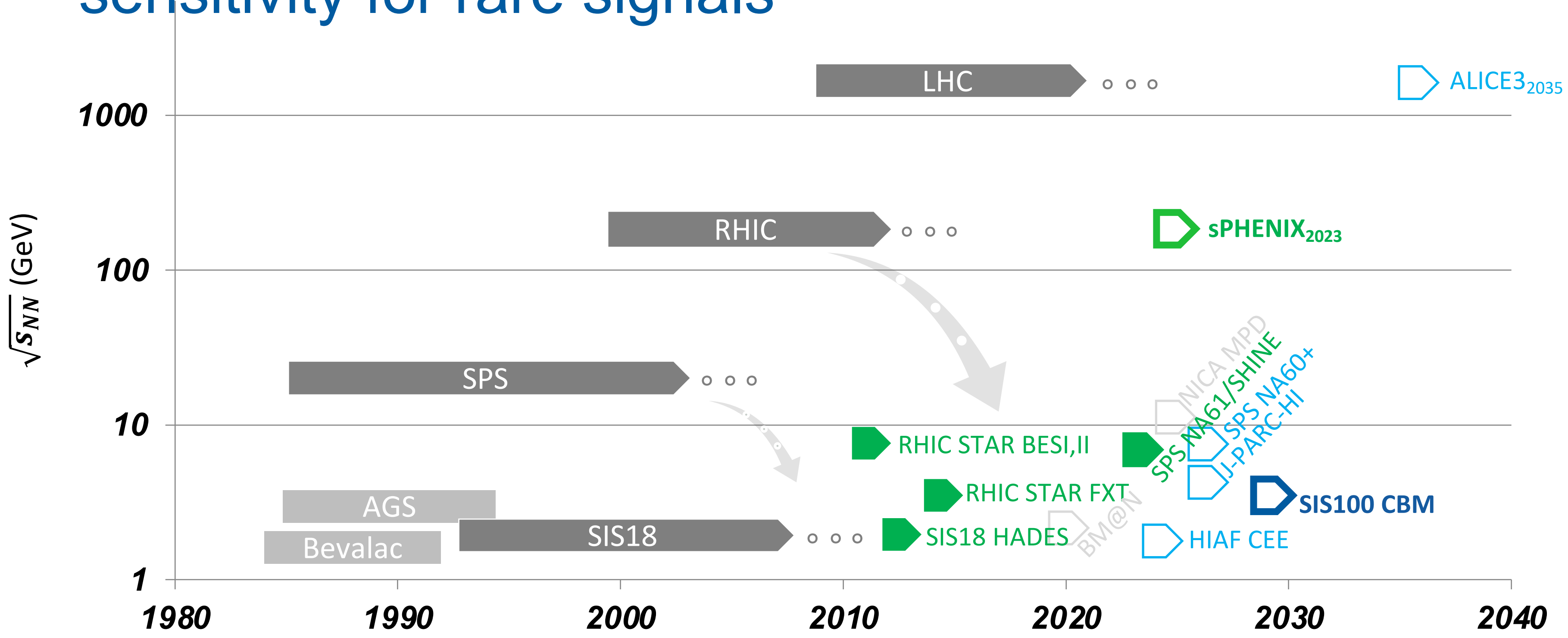
Quest for highest energy



Time ≡ advances in accelerator and detector technologies

Quest for utmost precision and sensitivity for rare signals

~20 years progress
in technology since AGS
(begin of high μ_B explorations)

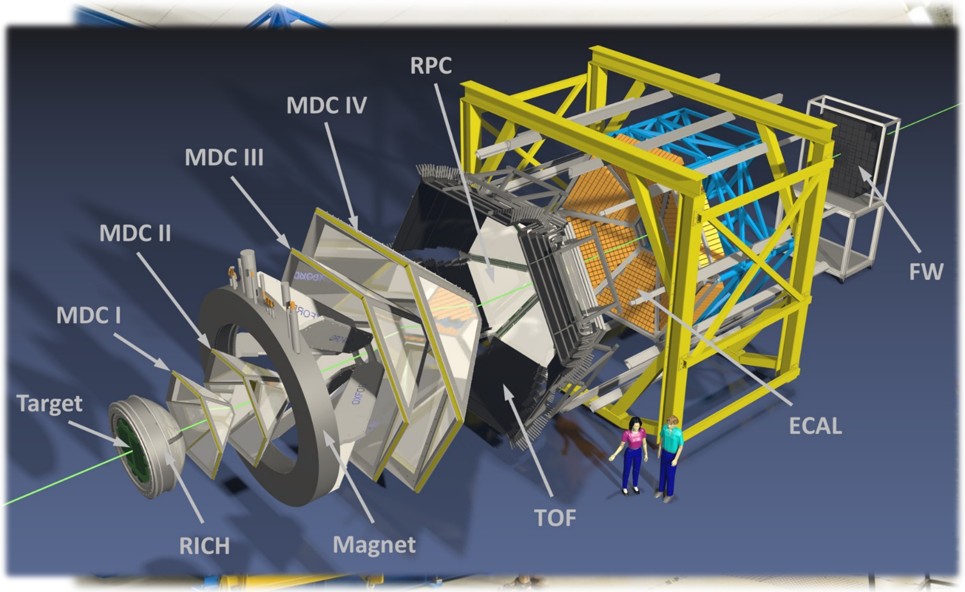


Time ≡ advances in accelerator and detector technologies

High Aceptance DiElectron Spectrometer

HADES at SIS18, GSI-Darmstadt, Germany

- **Fixed target** setup
- **High acceptance**
  - Full azimuthal coverage, 18°-85° polar angle
  - Pair acceptance ≈ 0.35
- **Efficient** track reconstruction particle identification
  - 6-coils super conducting toroid $B\rho \; => 0.36\ \mathrm{Tm}$
  - MDC – 4 planes of mini-drift chamber (~30.000 cells)
  - START, RICH, RPC, ToF, ECAL, FW
- **Precise:** mass resolution few %
- Heavy-ion, p and secondary π SIS18 beams
- **Fast:** interaction rate up to 50kHz accepted trigger rates

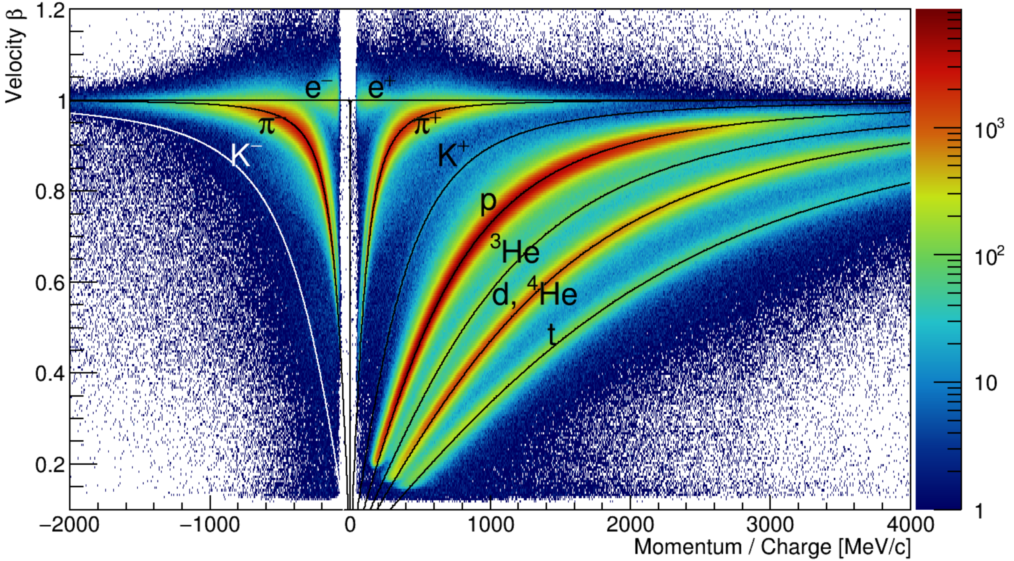


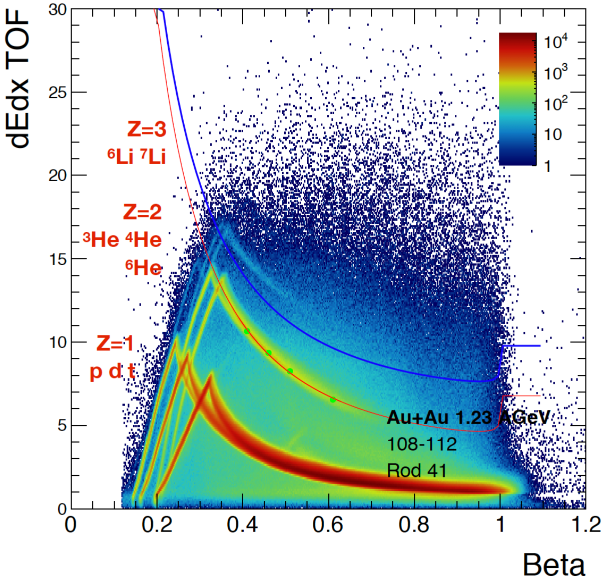
Focus on rare and penetrating probes

New detectors installed since 2019:
- RICH photodetection plane in cooperation with CBM
- Electromagnetic calorimeter
- Set of forward detectors in cooperation with PANDA
- Capability of neutron detection with R3B (ongoing)

Particle identification

By means of: momentum, velocity, specific energy loss, Cherenkov radiation



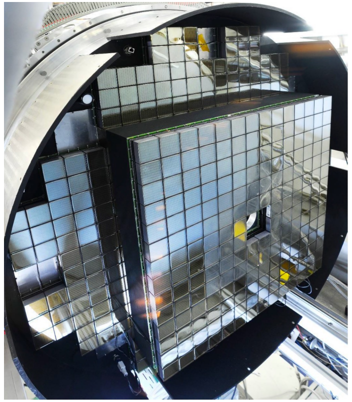


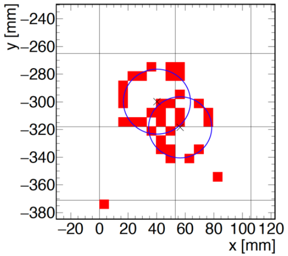
All combined in a multivariate analysis (neural network)

⇝ Best purity and efficiency

Electron pairs

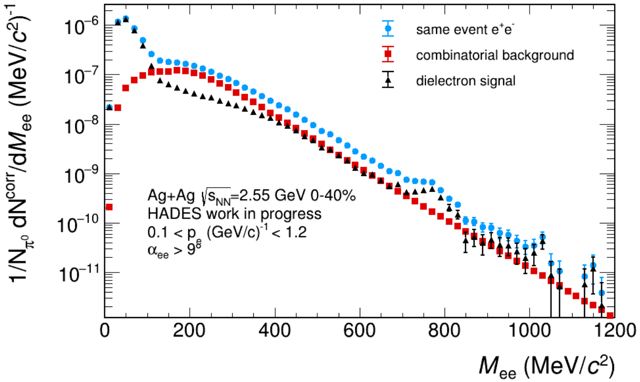
Upgrade of HADES RICH employing CBM technology - MAPMT based photo camera

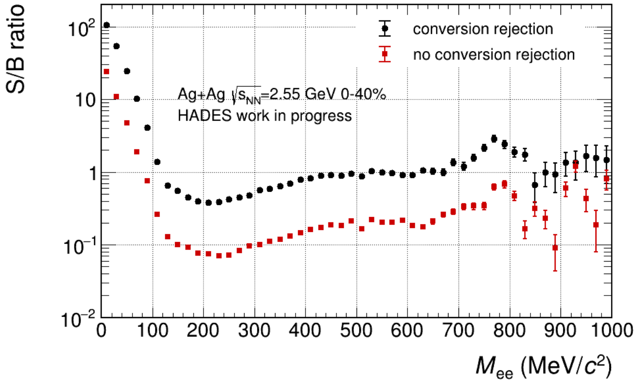




- Significantly improved lepton detection efficiency (60%)
- Pion suppression factor $\sim 10^{-4}$

- Excellent double ring detection
  - recognition of conversion pairs even with opening angle $\alpha \approx 0$
  - factor of 8 better signal-to-background ratio





FAIR Phase 0 Research Program

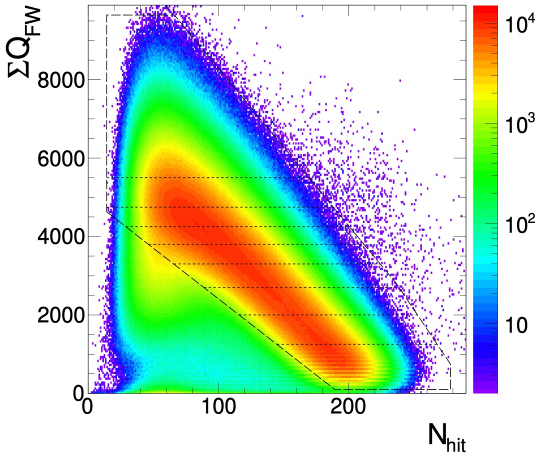
Event characterization centrality estimators

Centrality estimator

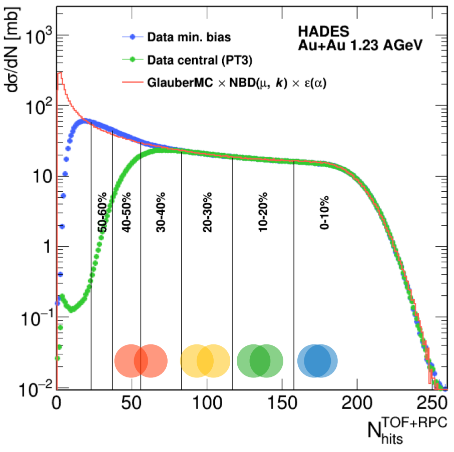
Off-line centrality selection based on hit or track multiplicity and/or Forward Wall (FW) integral charge

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

Using Glauber MC - distributions agree with transport model calculations

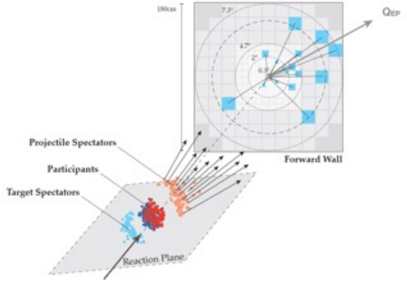


HADES, PRC 102 (2020) 2, 024914



HADES, EPJA 54 (2018) 5, 85

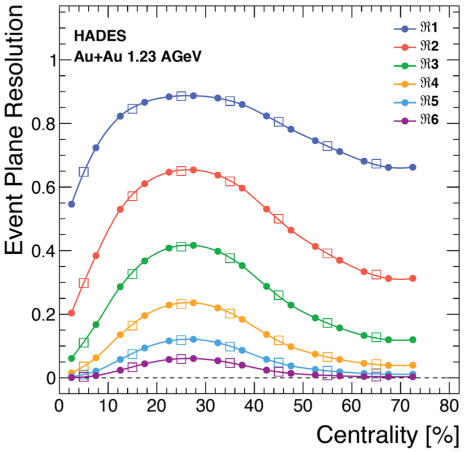
Event plane reconstruction



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

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



HADES, PRL 125 (2020) 262301

Quest for critical phenomenon connected to the 1st order phase transition

CRITICALITY

CRITICAL PHENOMENA

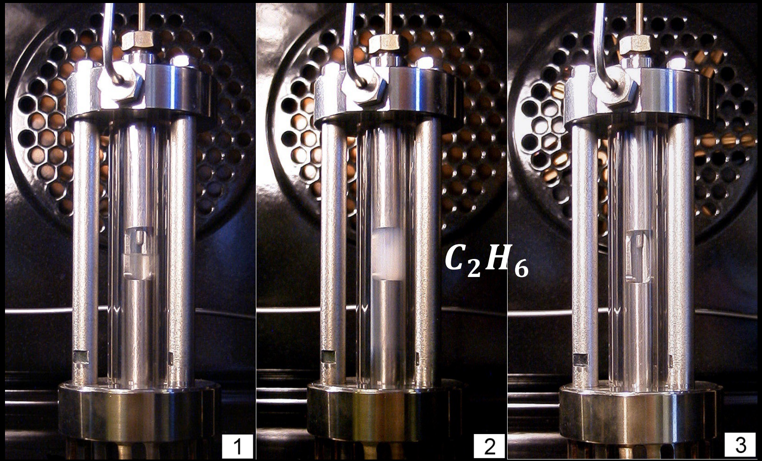
Discovered ~200 years ago

Cagniard de la Tour (1777-1859)

Ann. Chim. Phys., 21 (1822) 127-132

using steam digester invented by Denis Papin in 1679

$T < T_c$ $T = T_c$ $T > T_c$



$$\frac{\langle \rho^2 \rangle - \langle \rho \rangle^2}{\langle \rho \rangle^2} = \frac{T\chi_T}{V} \qquad \chi_T = -\frac{1}{V\left(\frac{\partial P}{\partial V}\right)_T}$$

- Increase in density fluctuations near T_c
- At T_c thermal susceptibility χ_T diverges

Probing criticality with fluctuations

Event-by-event fluctuations and statistical mechanics

cf. Friman *et al.*, EPJC 71 (2011) 1694
Stephanov, RPL 107 (2011) 052301

- In strong interactions, baryons, charges and strangeness are conserved ($N = B, Q, S$)
- These quantities N fluctuate event-by-event

Cumulant generating function

$$G_N(t) = ln\langle e^{tN}\rangle = \sum_{N=1}^{\infty} \kappa_n \frac{t^n}{n!}$$

$$\kappa_n \propto \frac{\partial^n (lnZ_{GCE})}{\partial \mu^n}$$

Grand partition function

$$lnZ_{GCE}(T,V,\mu) = ln\left[\sum_N e^{\frac{\mu N}{T}} Z_{CE}(T,V,N)\right]$$

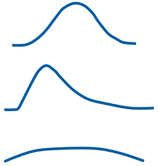
Cumulants measure chemical potential derivatives of the (QCD) equation of state

- Higher order cumulants describe the shape of measured distributions and quantify fluctuations

variance $\kappa_2 = \langle(\delta N)^2\rangle = \sigma^2$ *width*

skewness $\kappa_3 = \langle(\delta N)^3\rangle$ *asymmetry*

kurtosis $\kappa_4 = \langle(\delta N)^4\rangle - 3\langle(\delta N^2)\rangle^2$ *sharpness*



- Higher order cumulants sensitive to the correlation length $\xi \rightsquigarrow$ phase structure

$\kappa_2 = \xi^2$

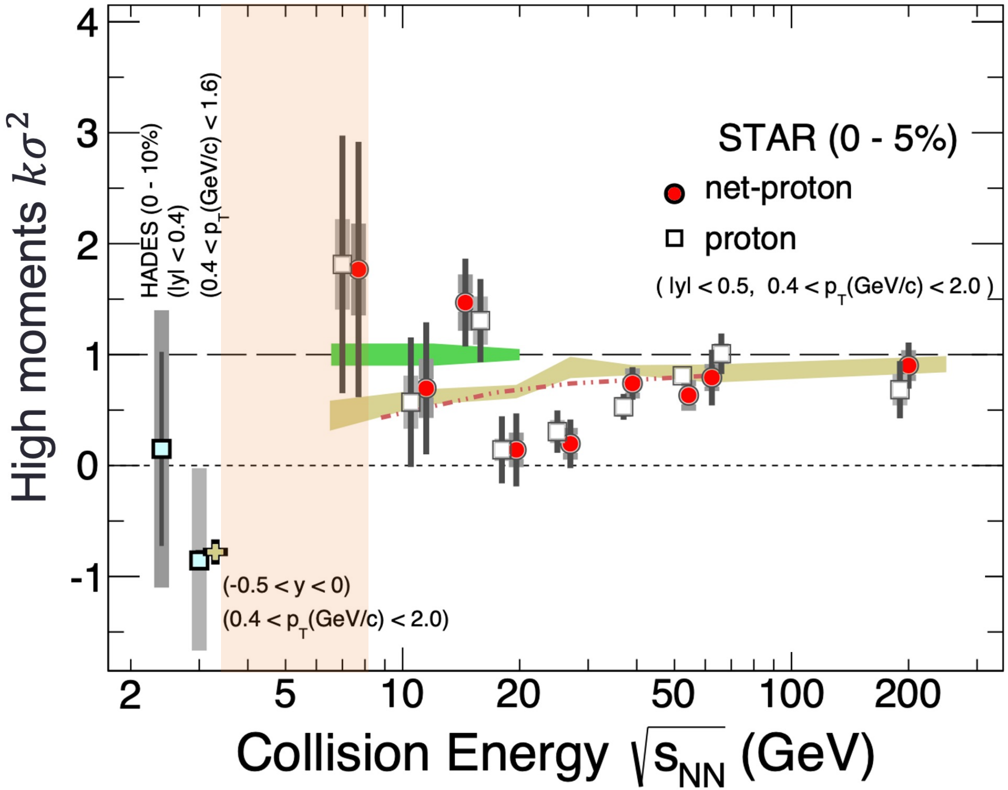
$\kappa_3 = \xi^{4.5}$

$\kappa_4 = \xi^7$

Correlation length $\xi \to \infty$ diverges at critical point

Critical point search

STAR, PRL 128 (2022) 20, 202303
HADES, PRC 102 (2020) 2, 024914



➡ **Discontinuities of the higher moments of particle number distributions, visible in a beam energy scan?**

Energy gap between 3 and 7.7 GeV, important for critical point search

→ Future experiments!

Multi-particle correlators

Cumulants k_n hold information on multi-particle correlators C_n

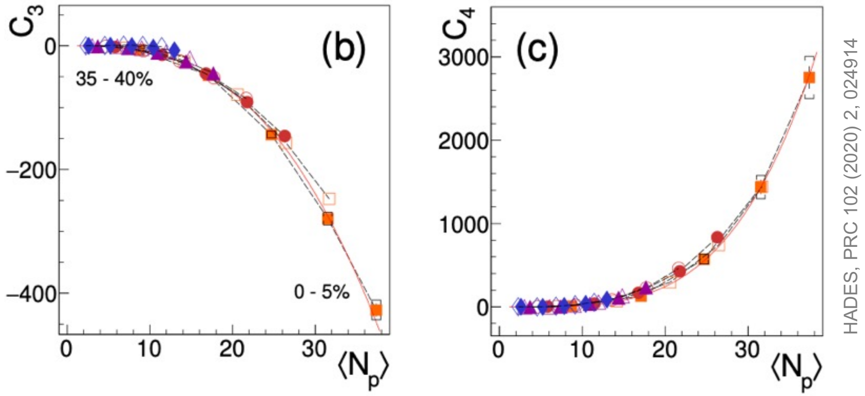
Ling, Stephanov, PRC 93 (2016) 034915

Investigate C_n vs. $\langle N_p \rangle$ to isolate relevant physics

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

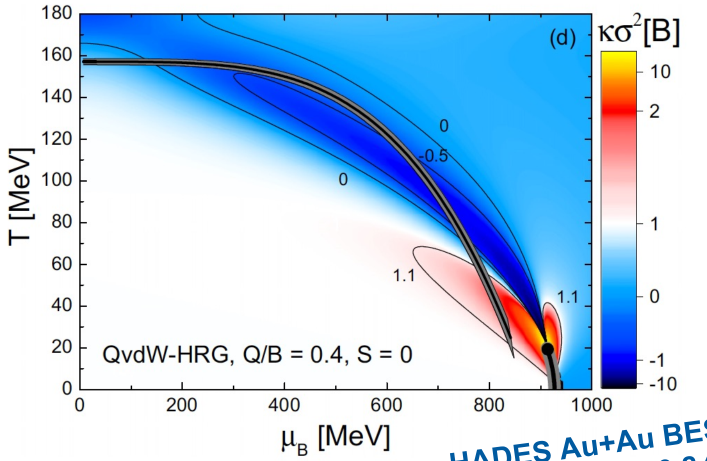
$C_3 \propto \langle N_p \rangle^{\alpha}$ $\alpha = 2.84 \pm 0.05$

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



$\alpha \simeq n$ → signature of long-range correlations ($\Delta y_{corr} > 1$)

Poberezhnyuk *et al.*, PRC100 (2019) no.5, 054904



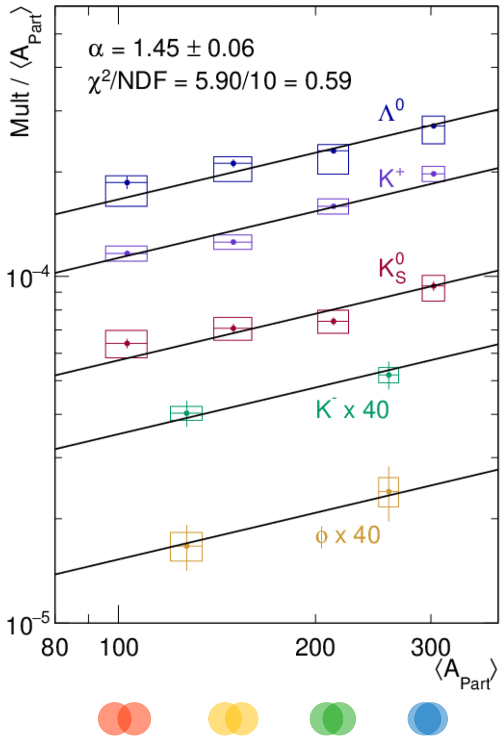
HADES Au+Au BES, 2024
0.2 - 0.4 – 0.6 - 0.8A GeV
approved by G-PAC

- Stopping of nucleons may produce multi-particle "clusters"
- Quarkyonic or baryquark matter?
- Remnants of nuclear liquid-gas phase transition?

Bzdak, Koch, Skokov, EPJC (2017) 288
Kojo, Hidaka, McLerran, Pisarski, NPA 843 (2010), 37
Koch and Vovchenko, arXiv:2211.14674 [nucl-th]

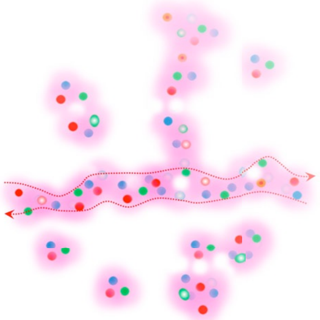
Rare sub-threshold strangeness production Au+Au $\sqrt{s_{NN}} = 2.4\,GeV$

HADES, PLB 793 (2019) 457



- Universal scaling with participant number $M \sim \langle A_{part} \rangle^{\alpha}$ (same observation in Ag+Ag data)
- Does not reflect the hierarchy of NN production thresholds
  - $K^{+}\Lambda$: -130 MeV
  - $K^{+}K^{-}$: -440 MeV
- Not expected if strangeness produced in *isolated* NN collisions

Quarks are easily reshuffled between hadron states?



Quantum percolation at $\rho \sim 1.8\rho_0$ of the interaction meson clouds

Fukushima, Kojo, Weise, PRD 102 (2020) 9, 096017

Connection to "soft deconfinement"?

Hadron production and flow

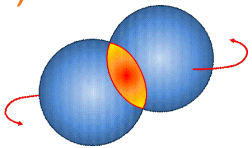
COLLECTIVITY

Azimuthal anisotropy

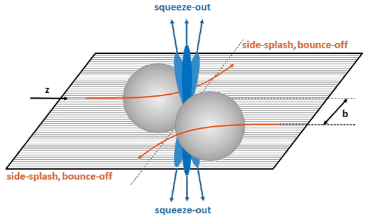
with respect to reaction plane (RP)

Fourier coefficients of the distribution

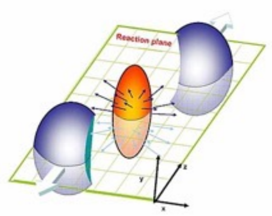
$$\frac{dN}{d(\phi-\Psi_{EP})} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi-\Psi_{EP}))$$



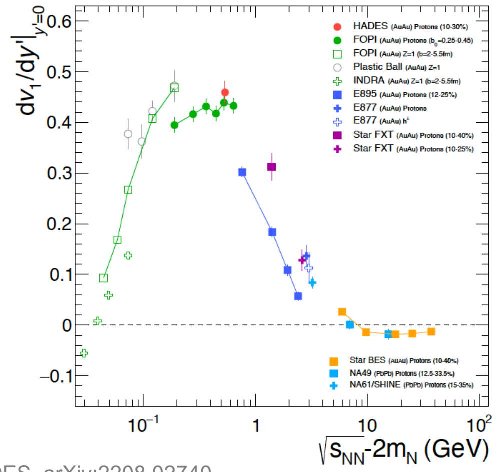
v_1 deflection of matter in the RP (signal of the phase transition?)
Paech *et al.*, NPA 681 (2001)

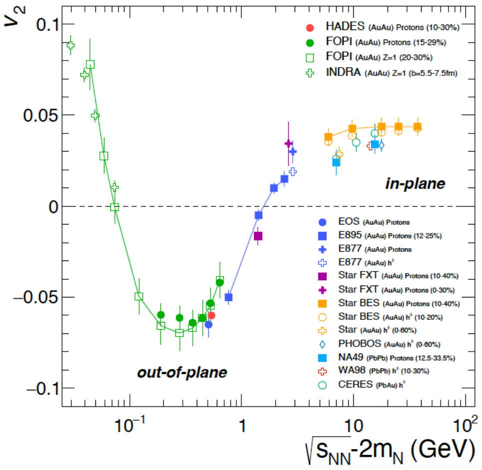


$v_2 < 0$ long spectator passing time $\tau_{passing} \approx \tau_{expansion} \Rightarrow$ "squeeze-out"



$v_2 > 0$ when spectators pass faster than fireball expands



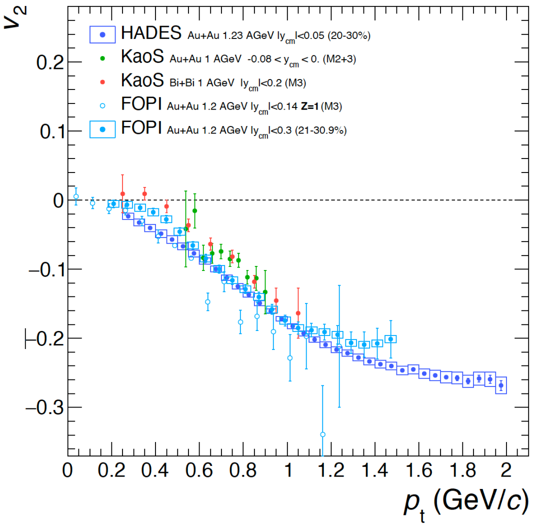


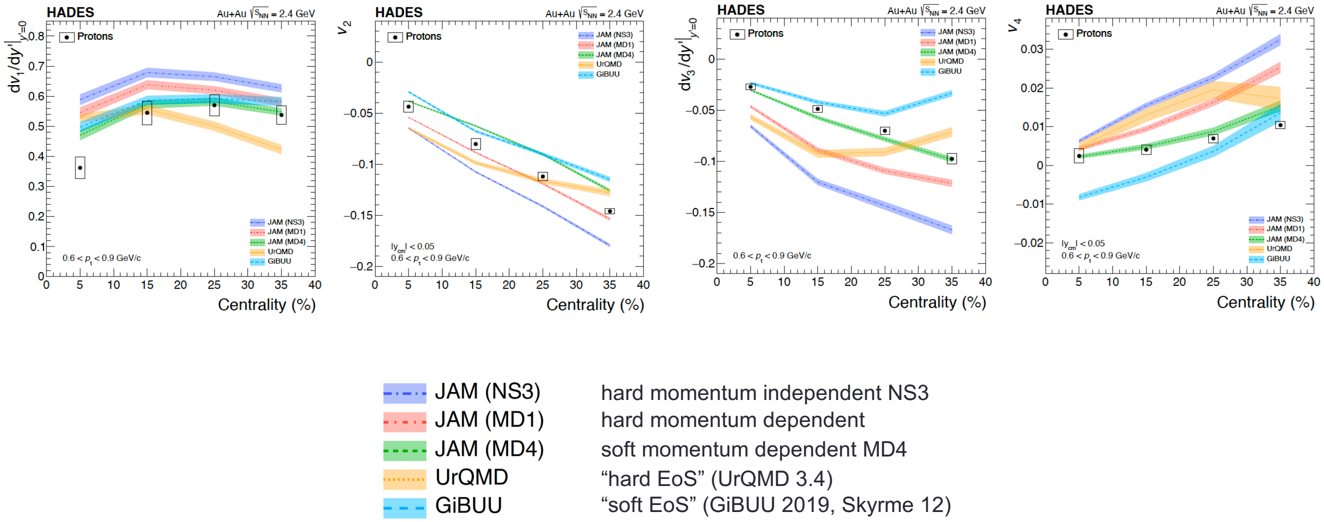
HADES, arXiv:2208.02740

constrain equation-of-state by means of microscopic transport model

Azimuthal anisotropy and EoS

- High precision multi-differential data for protons and light nuclei
- Data compared to QMD and BUU models
  - ➥ higher moments provide more discriminating power
  - ➥ consistent description of all flow harmonics over the whole phase space and at all centralities is missing





HADES, arXiv:2208.02740

Higher-order flow components

Allow to reconstruct 3D picture of the particle emission pattern in momentum space

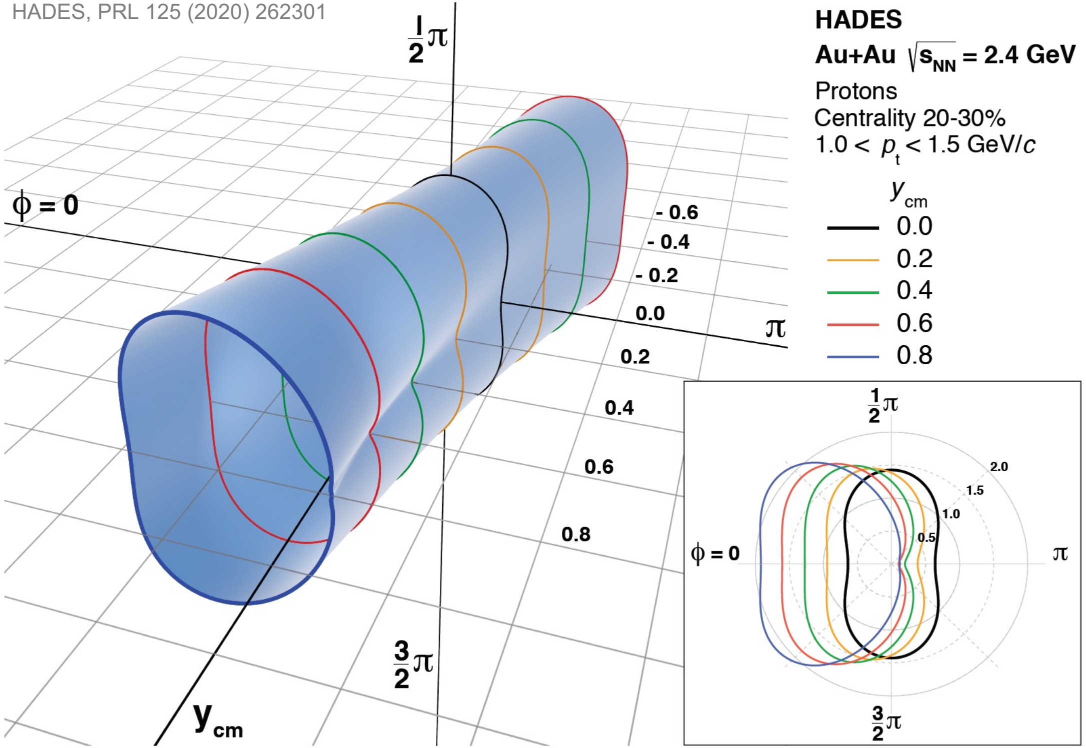
Shape determined by flow coefficients $v_1 - v_6$

Complex evolution of shape as function of rapidity paramerized with

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

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

HADES, PRL 125 (2020) 262301



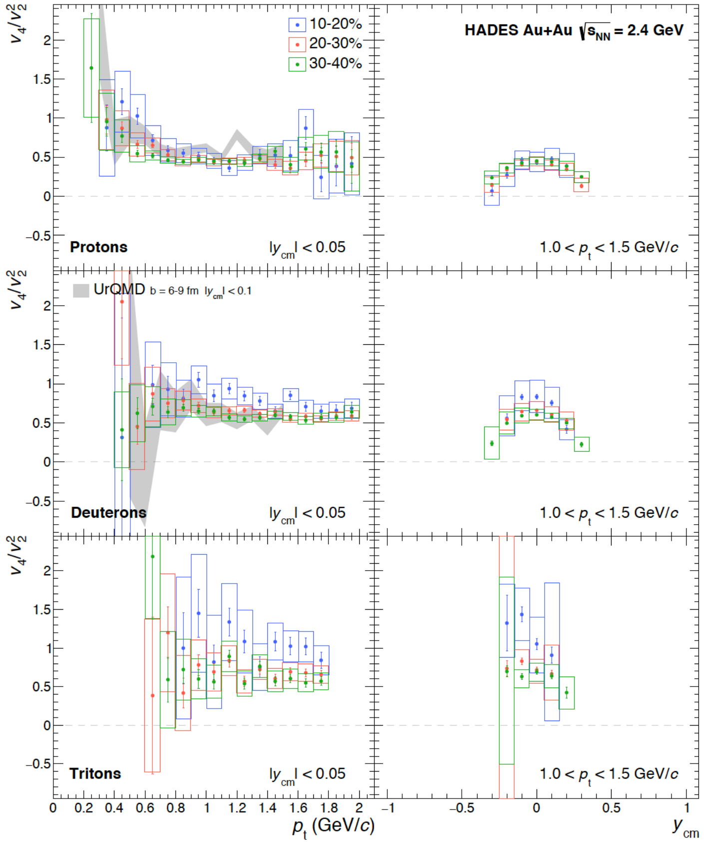
- Mid-rapidity: almost elliptical shape
- Forward/backward rapidity: triangular shape
  ⇝ interplay: central fireball pressure – interaction with spectator matter

"Ideal fluid scaling" (relation between v_2 and v_4)

HADES, PRL 125 (2020) 262301

- Scaling properties
  - prediction for ideal fluid: $v_4(p_t)/v_2^2(p_t)=1/2$
  - slightly higher values (~ 0.6) expected in more realistic scenario

Kolb, PRC 67 (2003) 031902
Borghini, Oliitrault, PLB 642 (2006) 227
Gombeaud, Ollitrault, PRC 81 (2010) 014901



- Observed ratios for p, d and t
  - independent of p_t and centrality
  - close to predicted value of ~ 0.6
  - confirmed by transport models

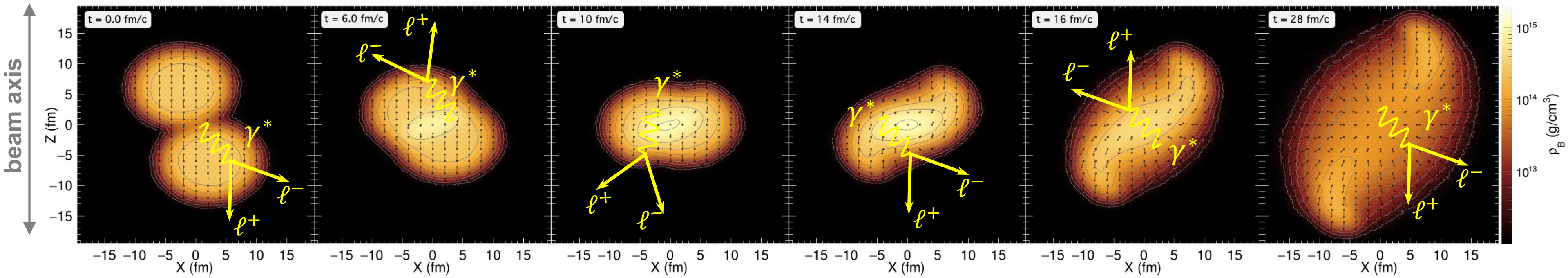
Wang et al., PRC 90 (2014) 054601 IQMD
Hillmann et al., J.Phys. G 47 (2020) 5, 055101 UrQMD
Mohs et al., PRC 105 (2022) 034906 SMASH

Hydro-like matter at SIS energies?

Electromagnetic radiation

EMISSIVITY

Electromagnetic radiation from QCD fireball



Electromagnetic radiation (γ, γ^*)

Reflect the whole history of a collision

No strong final state interaction
⇝ leave reaction volume undisturbed

Encodes information on matter properties enabling unique measurements

- degrees of freedom of the medium
- fireball lifetime, temperature, acceleration, polarization
- transport properties
- restoration of chiral symmetry

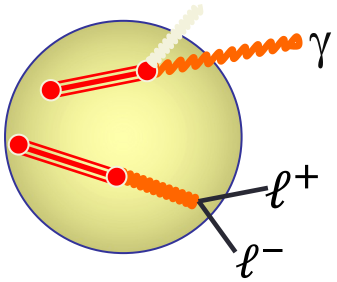
Electromagnetic production rate

- em current-current correlation function

$$\Pi_{em}^{\mu\nu}(q_0, q) = -i \int d^4x \, e^{iq\cdot x} \theta(x^0) \langle [j^\mu(x), j^\nu(0)] \rangle$$

- Photons characterized by "transverse" momentum:

$$q_0 \frac{dN_\gamma}{d^4x d^3q} = -\frac{\alpha_{em}}{\pi^2} f^B(q\cdot u; T) \, Im\Pi_{em}(q_0 = q; \mu_B, T)$$



spectral function

determines both photon and dilepton rates

- Dileptons carry extra information: invariant mass
  → unique direct access to in-medium spectral function

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

lepton phase space factor

thermal Bose distribution

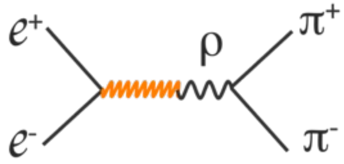
McLerran, Toimela, PRD 31, 545 (1985)
Weldon, PRD42, 2384-2387 (1990)
Gale, Kapusta, PRC 35, 2107 (1987) & NPB 357, 65-89 (1991)

Electromagnetic correlator in the vacuum

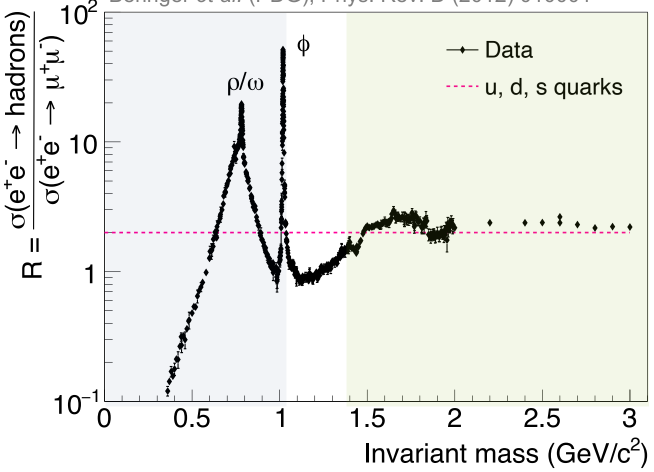
accurately known from e^+e^-annihilation $R \propto \frac{Im\Pi_{em}^{vac}}{M^2}$

Low-mass regime LMR

em spectral function is saturated by light vector mesons (VMD $J^P = 1^-$ for both γ^* and VM, ***ρ* playing a dominant role**)

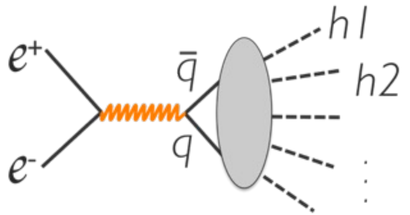


Beringer *et al.* (PDG), Phys. Rev. D (2012) 010001



Intermediate-mass regime IMR

perturbative QCD continuum (quark degrees of freedom)



$$Im\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 ImD_v^{vac}(M)$$

$$Im\Pi_{em}^{vac} = -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\cdots\right)N_c \sum_{q=u,d,s}(e_q)^2$$

Sakurai, Ann.Phys. 11 (1960)

In-medium spectral functions from hadronic many body theory

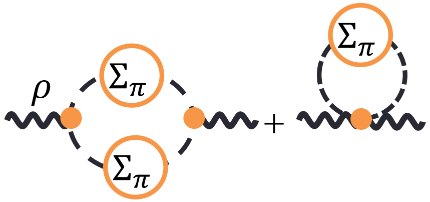
➥ ρ meson in medium interacts with hadrons from heat bath

additional contributions to the ρ-meson self-energy

$$D_\rho(M,q,T,\mu_B) = \frac{1}{[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]}$$

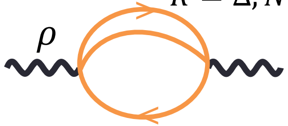
in-medium pion cloud

$\Sigma_{\rho\pi\pi} =$



direct ρ-hadron scattering

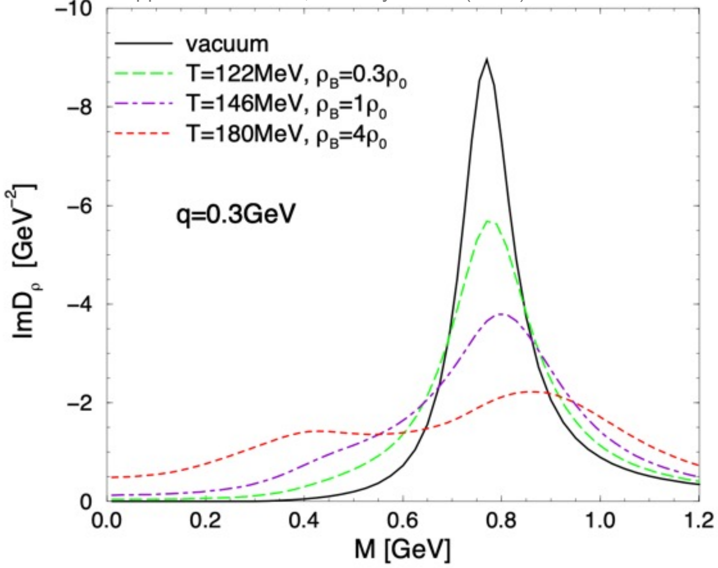
$\Sigma_{\rho B,M} =$



$R = \Delta, N(1520), a_1, \ldots$

$h = N, \pi, K, \ldots$

Rapp and Wambach, Eur.Phys.J. A6 (1999)

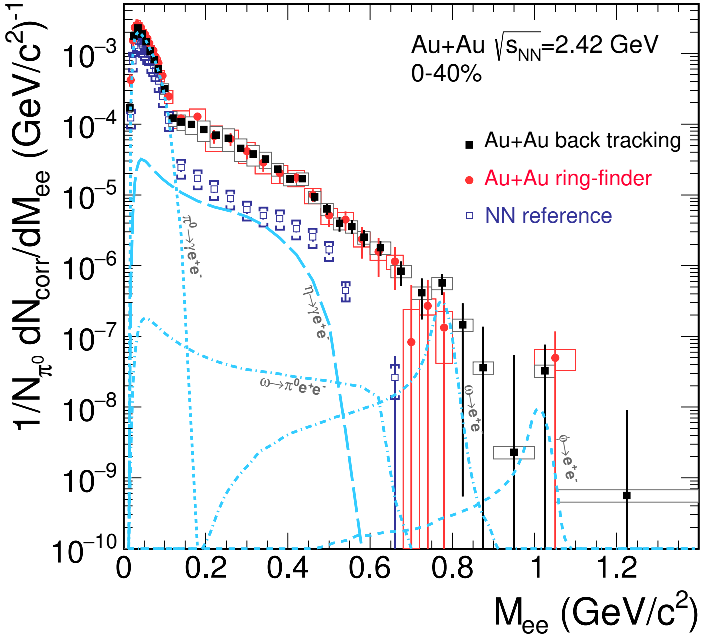


↝ **ρ-peak undergoes a strong broadening**
↝ **baryon effects important**
(even at $\rho_{B_{net}} = 0$! sensitive to $\rho_{B_{tot}} = \rho_B + \rho_{\bar{B}}$)

Alam *et al.*, Annals Phys.286 (2001) 159 (2001)
Leupold, Metag, Mosel, Int.J.Mod.Phys. E19 (2010) 147
Rapp, Acta Phys.Polon. B42 (2011) 2823-2852

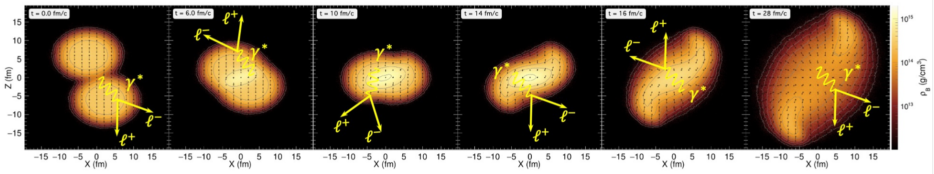
Thermal dilepton measurements

There is no such thing as a free lunch



$$M^2 = (P_{e^+} + P_{e^-})^2$$

- Decisive parameters for data quality:
  - interaction rates (IR) and signal-to-combinatorial background ratio (S/CB): effective signal size: $S_{\text{eff}} \sim IR \times S/CB$
- Isolation of thermal radiation by subtraction of measured decay cocktail
- Mid-rapidity, low-$M_{\ell\ell}$, low-p_T coverage (acceptance correction)



first chance collisions

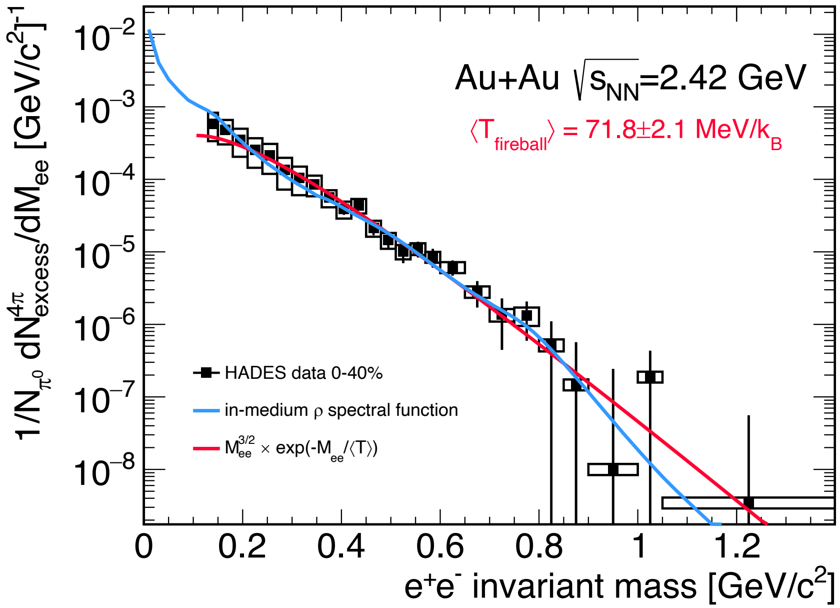
thermal radiation

freeze-out

Thermal dileptons from baryon rich matter

There is no mission impossible

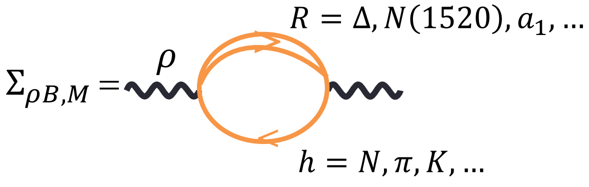
HADES, Nature Phys. 15(2019) 1040



- Thermal excess radiation established at HADES (Au+Au, Ag+Ag)
  - ρ-meson peak undergoes a strong broadening in medium
  - in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

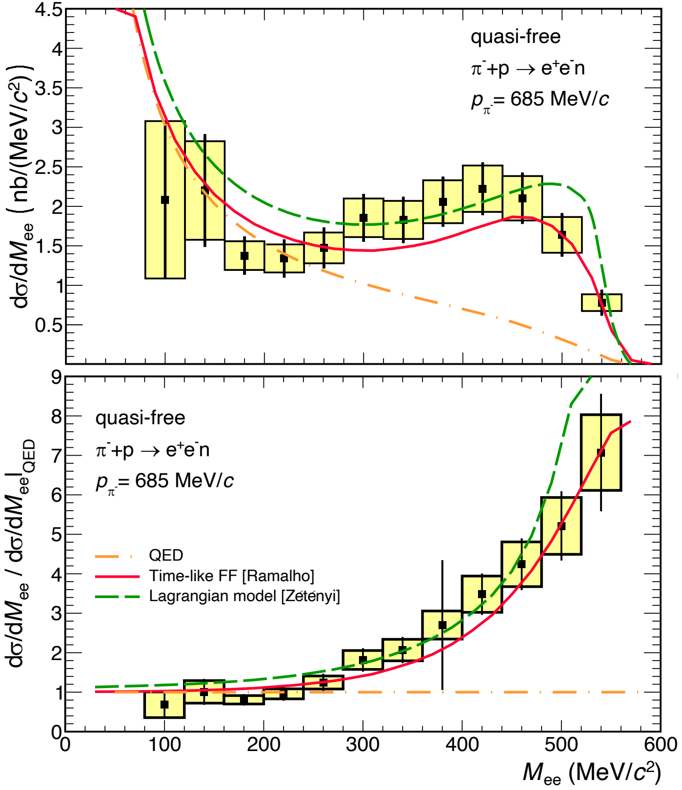
Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

- Baryonic effects are crucial



First measurement of massive γ^* emission from N^* baryon resonances

HADES, arXiv:2205.15914 [nucl-ex]



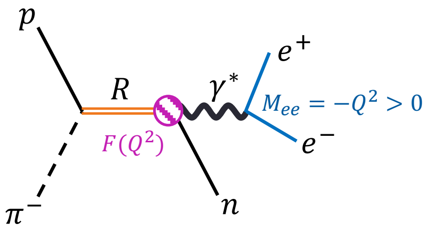
- $\pi^- p \to n + \pi^- + \pi^+$
  - included in PWA (Bonn-Gatchina) to provide partial wave decomposition

HADES, PRC 102 (2020) 2, 024001
HADES, PRC 95 (2017) 065205

PDG particle data group: 4 first entries ($N\rho$), 4 additional entries

- $\pi^- p \to n + e^- + e^+$
  - probe baryon resonance – nucleon transition

- Dominance of the $N^*(1520)$ resonance at $\sqrt{s_{NN}} = 1.49$ GeV
  - ρ meson as "excitation" of the meson cloud
  - **Vector Meson Dominance - basis of emissivity calculations for QCD matter**

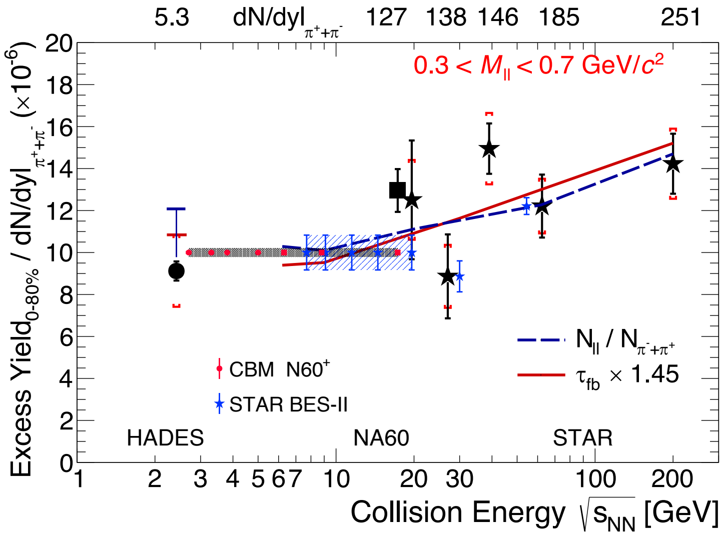


Dielepton excitation functions

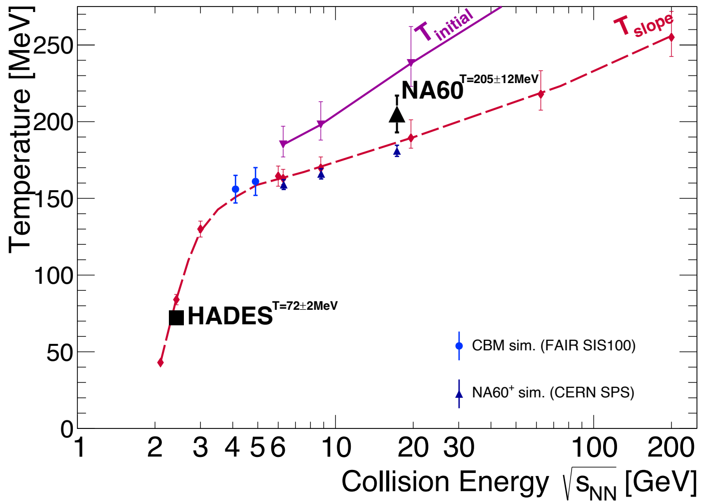
➥ search for emerging signatures indicative of a first-order phase transition

Excess yield in LMR tracks fireball lifetime: **extra radiation**" due to latent heat around **phase transition** (& CEP?)

Invariant mass slope measures radiating source temperature: **flattening** of caloric curve (T vs ε) → evidence for a **phase transition**



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

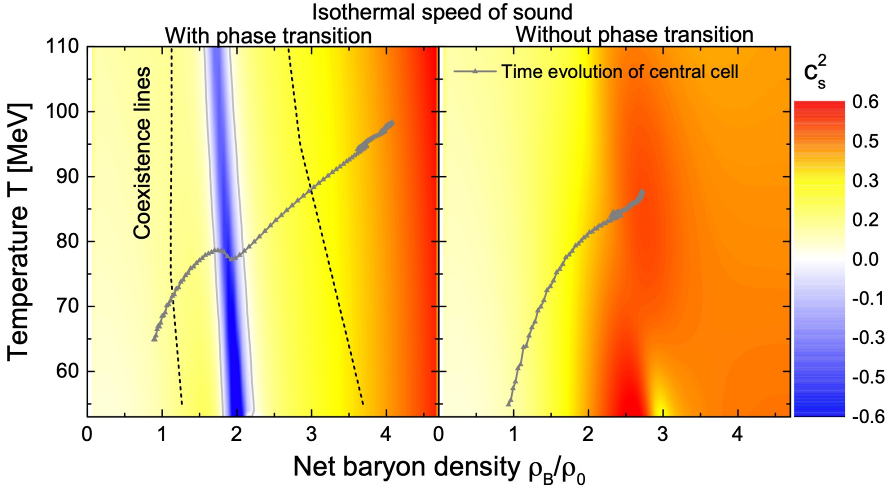


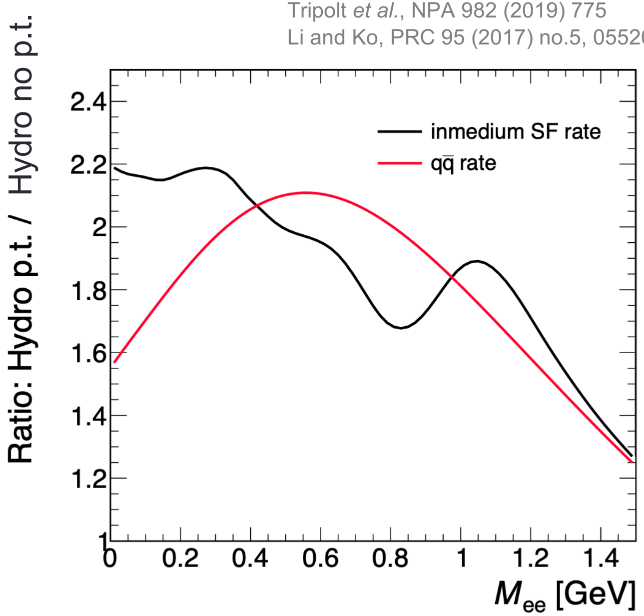
Rapp and v. Hess, PLB 753 (2016) 586
TG *et al.*, EPJA 52 (2016) 131
https://github.com/tgalatyuk/QCD_caloric_curve

Dilepton signature of a 1st order phase transition

Seck, TG, *et al.*, PRC 106 (2022) 1, 014904

See also:
Savchuk, TG, *et al.*, arXiv:2209.05267 [nucl-th]
Tripolt *et al.*, NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203





- Ideal hydro simulations with and w/o first order nuclear matter – quark matter phase transition
- Chiral Mean Field model that matches lattice QCD at low μ_B and neutron-star constraints at high density

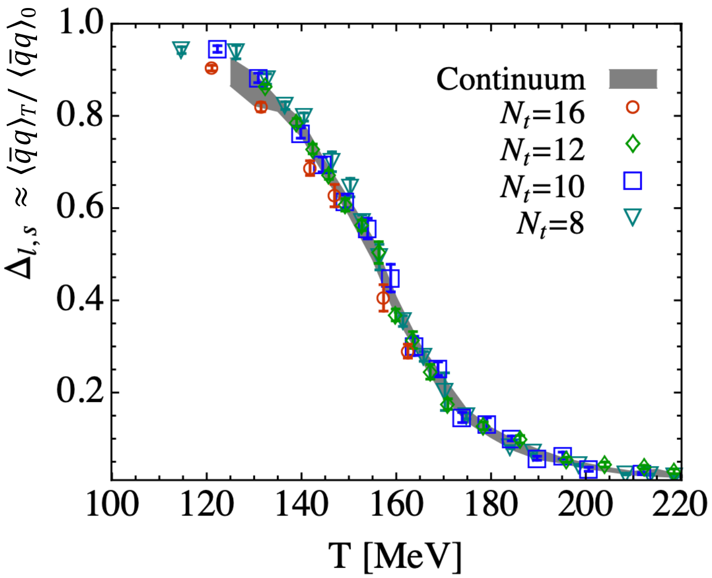
Dilepton emission shows a significant effect: factor 2 enhancement of dilepton emission due to extended “cooking”

Most et al., e-Print: 2201.13150 [nucl-th]

Dileptons and chiral symmetry of QCD

S. Weinberg, PRL 18 (1967) 507

- **Spontaneously broken** in vacuum by dynamical formation of a quark condensate
  $\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$



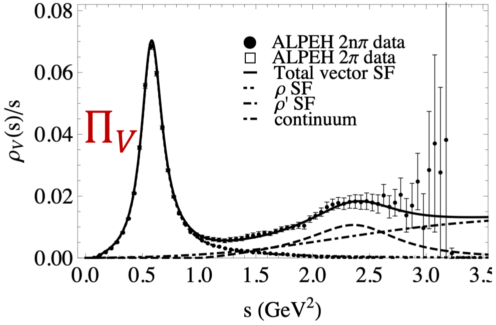
Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

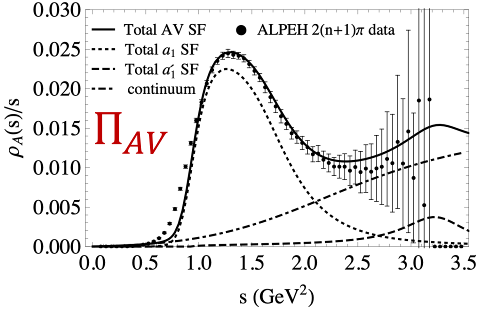
- **QCD** and **chiral sum rules …**

$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

- … accurately satisfied in vacuum

Hohler, Rapp, Annals Phys. 368 (2016)
Holt, Hohler, Rapp, PRD87 (2013) 076010

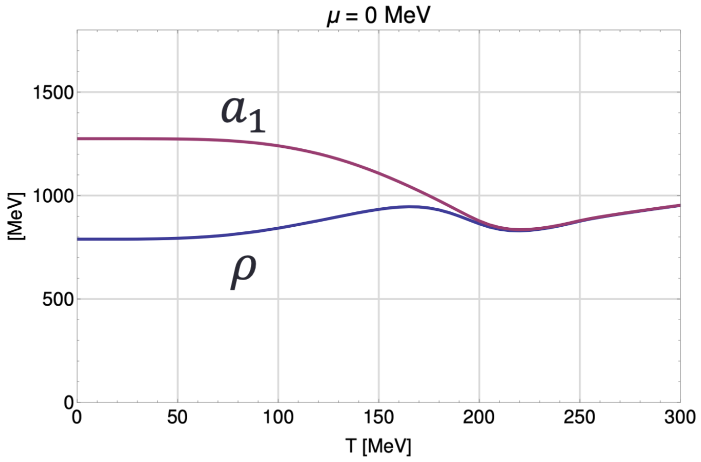




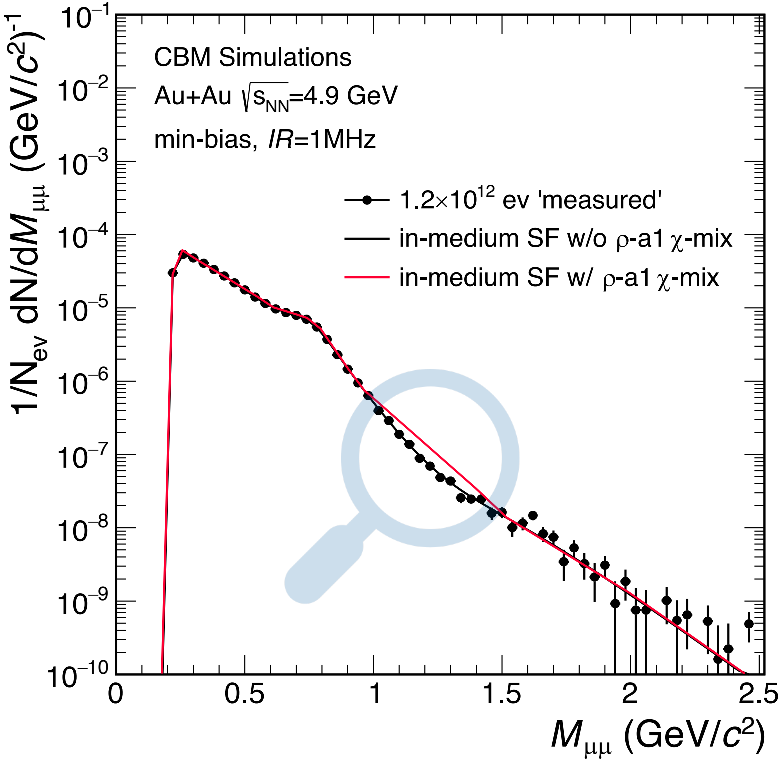
How does chiral symmetry restoration at finite T and μ_B manifests itself?

Signature for chiral symmetry restoration: $\rho - a_1$ chiral mixing

Restoration at finite T and μ_B manifests itself through mixing of vector and axial-vector correlators

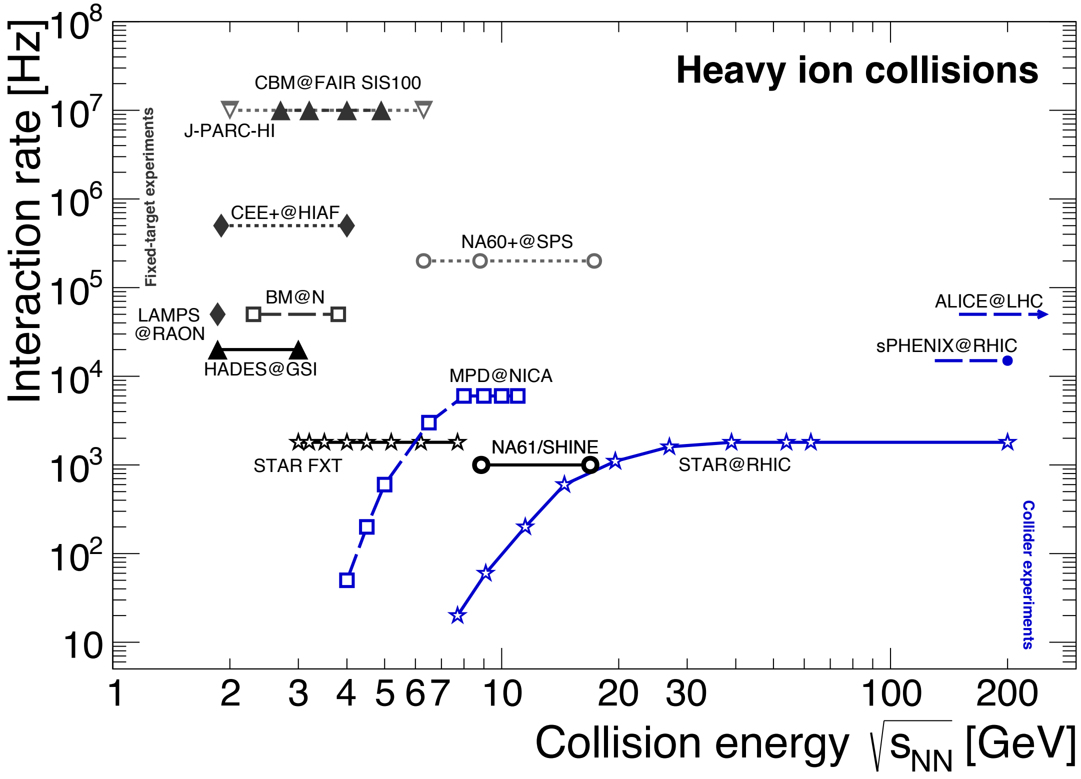


ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass



Hadronic many-body theory Hohler and Rapp, PLB 731 (2014)
Functional Renormalization Group Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020
Light mesons and baryons: lattice QCD results, Aartz, QM2022, April 2022

"You may say I'm a dreamer… … but I'm not the only one"

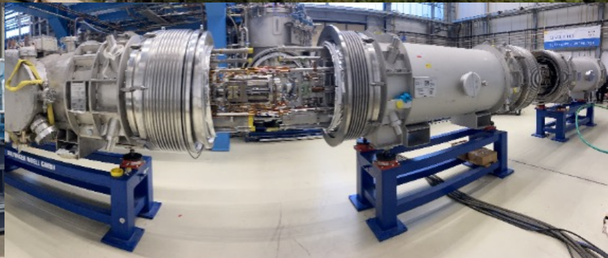


Program needs ever more precise data and sensitivity for rare signals

- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high μ_B with rare and electromagnetic probes: high rate capability
- **HADES**: established thermal radiation at high μ_B, limited to 20kHz and $\sqrt{s_{NN}}$=2.4 GeV
- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- **CEE+@HIAF proposal**: multipurpose detector based on TPC, anticipated rate capability 500 kHz
- **J-PARC-HI proposal**: highest proton beam intensities, addition of heavy-ion option (HI booster)
- **ALICE → ALICE 3:** exploit the high luminosity potential of the LHC for ions

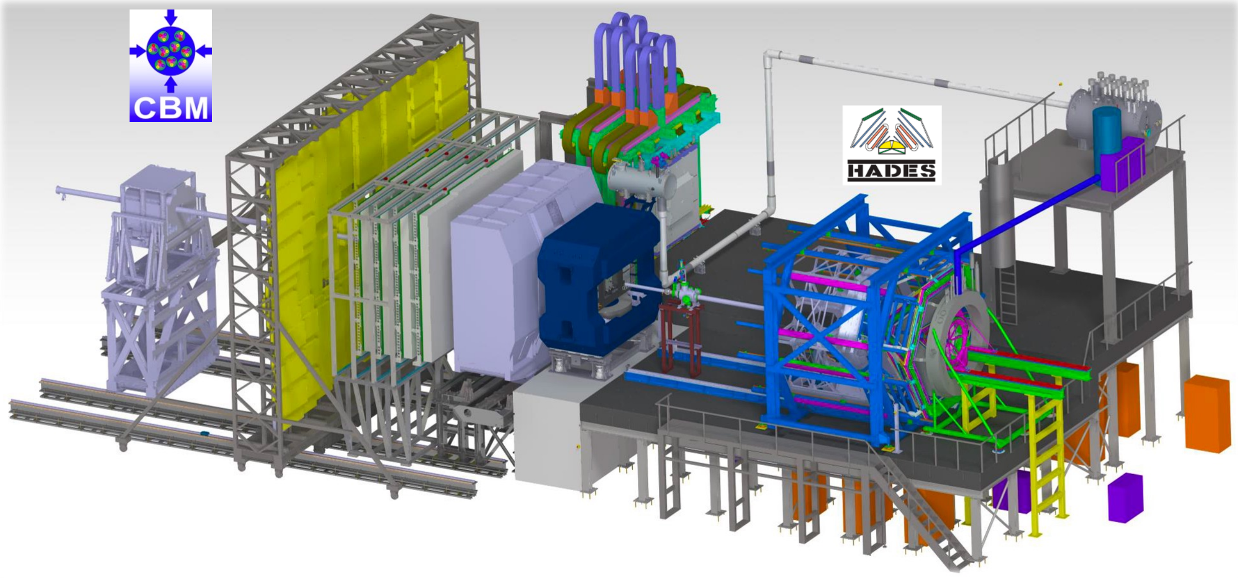
TG, NPA 982 (2019), update 2021 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

Shell construction accelerator tunnel finished



The Compressed Baryonic Matter experiment strategy

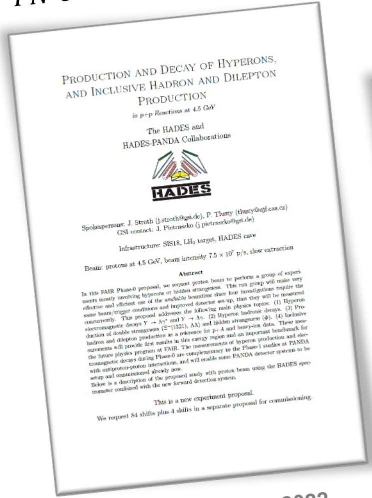
- Fixed target experiment
  →obtain highest luminosities
- Versatile detector systems
  →optimal setup for given observable
- Tracking based entirely on silicon
  →fast and precise track reconstruction
- Free-streaming FEE
  →nearly dead-time free data taking
- On-line event selection
  →high-selective data reduction



- 2027 – installation and commissioning w/o beam, Q4 2027 ready for beam
- 2028 – commissioning with SIS100 beam
- 2029 – HADES moves to CBM cave

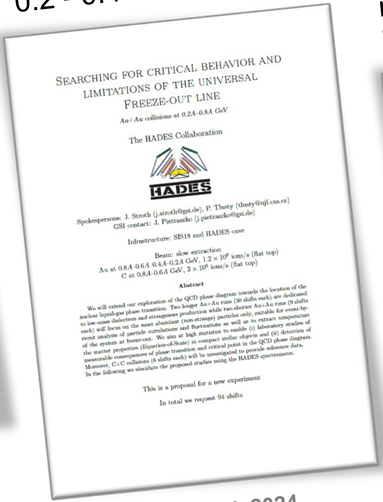
HADES during FAIR Phase-0

EM transition form factors of hyperons, YN and YY interaction


Production and Decay of Hyperons, and Inclusive Hadron and Dilepton Production
in p+p Reactions at 4.5 GeV
The HADES and HADES-PANDA Collaborations
This is a new experiment proposal.

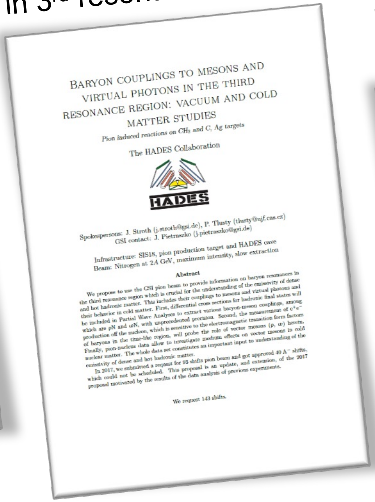
completed Mar-Feb 2022

Au+Au BES
0.2 - 0.4 - 0.6 - 0.8A GeV

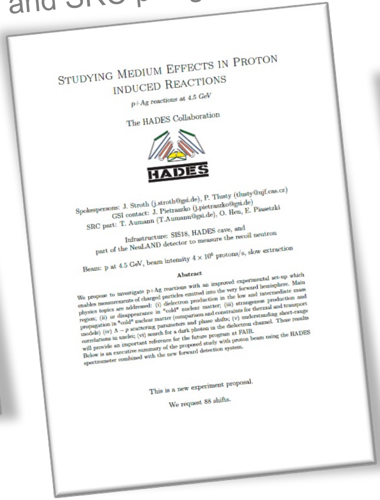

Searching for critical behavior and limitations of the universal freeze-out line
Au+Au collisions at 0.2A-0.8A GeV
The HADES Collaboration
This is a proposal for a new experiment
In total we request 94 shifts

approved, 2024

Baryon resonances, meson-baryon coupling in 3[rd] resonance region


Baryon couplings to mesons and virtual photons in the third resonance region: vacuum and cold matter studies
Pion induced reactions on CH_2 and C, Ag targets
The HADES Collaboration
We request 143 shifts.

Cold matter effects including line shapes and SRC p+Ag 4.5 GeV


Studying Medium Effects in Proton Induced Reactions
p+Ag reactions at 4.5 GeV
The HADES Collaboration
This is a new experiment proposal.
We request 88 shifts.

Iso-spin effects in dilepton production p+p, d+p (~n+p)


Scrutinizing Iso-spin Effects in N+N Bremsstrahlung and Dibaryon D*(2380) Formation in N+P Collisions
A Beam Energy Scan for proton and neutron induced reactions on protons
The HADES Collaboration
This is a new experiment proposal.
We request 106 shifts.

Summary: **The future is bright!**

Encouraging prospects for studying hot and dense matter in the laboratory

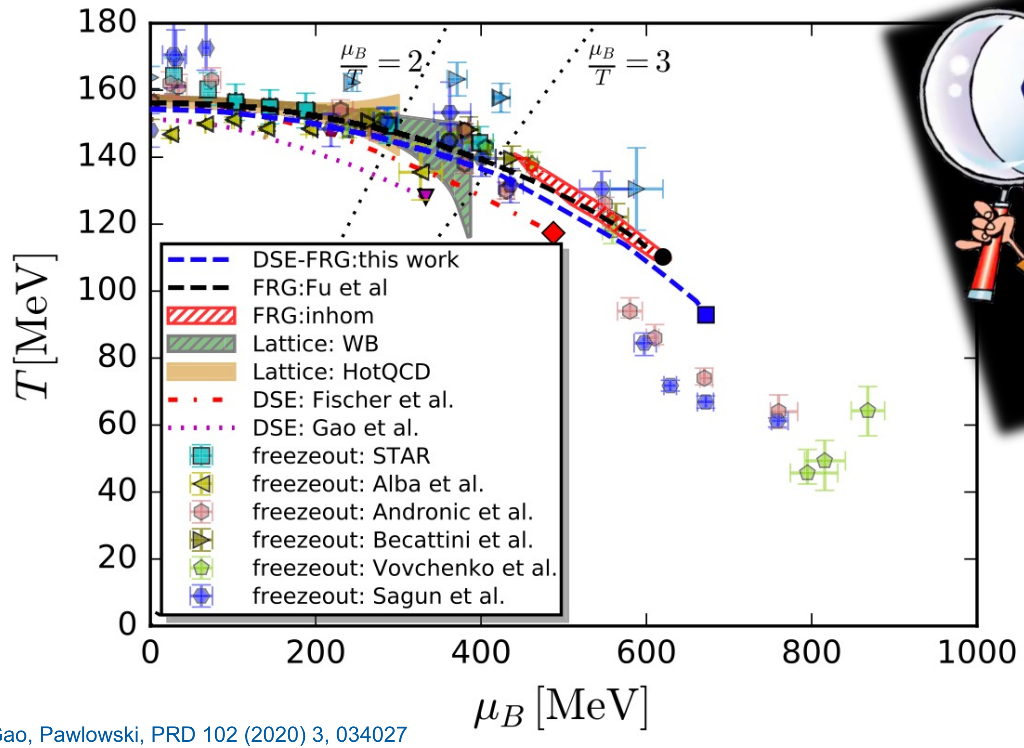
- Results from Au+Au suggest a thermalized strongly interacting medium created at $\sqrt{s_{NN}} = 2.42\ GeV$
  - Thermal models fit yield and spectra
  - Data sensitive to the EoS
  - Thermal origin of dilepton excess spectrum
  - System with multi-particle correlations
- Complementary program on exclusive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

Thank you for your attention!

The HADES Collaboration

Bonus slides

How to find CEP with heavy-ion collisions?

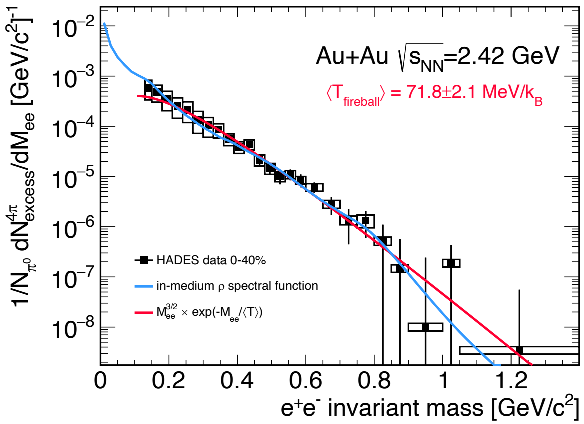


Gao, Pawlowski, PRD 102 (2020) 3, 034027

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

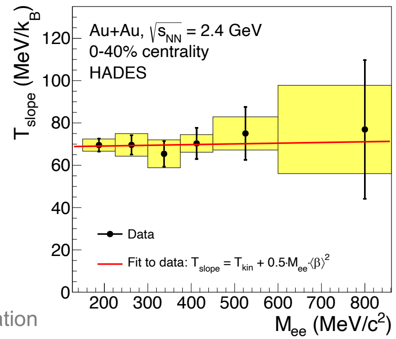
- Radiation from a source
  - long-lived ($\tau \approx 13\ fm$)
  - in local thermal equilibrium
  - $\langle T \rangle \approx 72$ MeV
  - $\varrho = 2 - 3\ \varrho_0$

Invariant mass

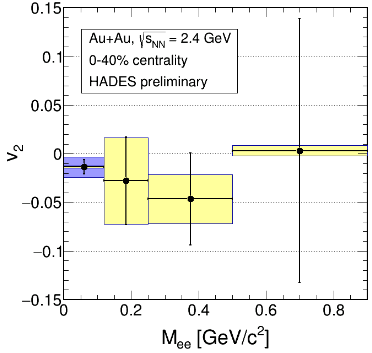


HADES, Nature Phys. 15(2019) 1040

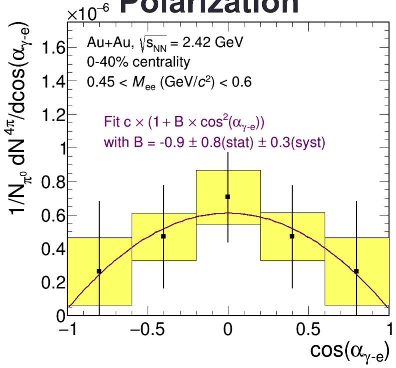
Inverse slope (p_t)



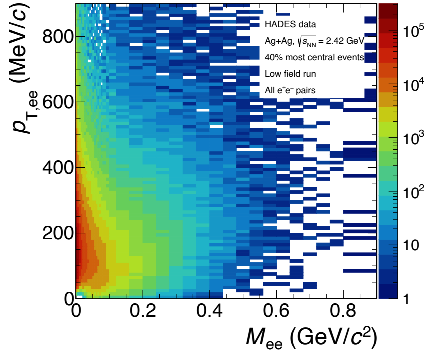
Elliptic flow (v_2)



Polarization



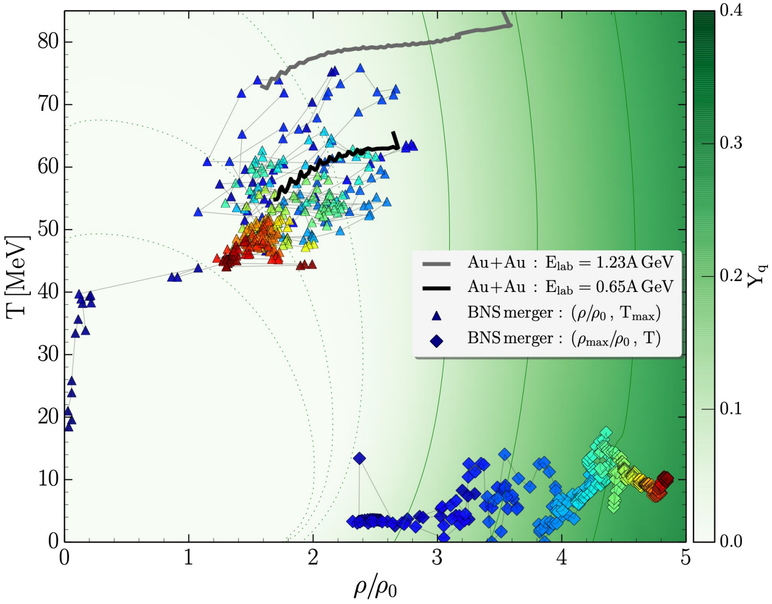
Electrical conductivity?



HADES, in preparation

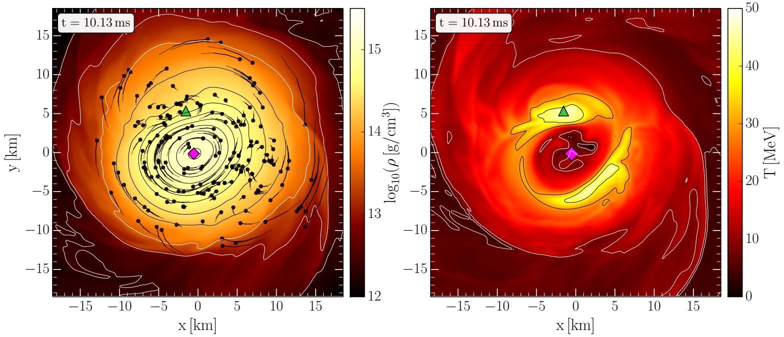
The QCD phase structure at high μ_B

Possible HIC trajectories and NS merger simulations within an effective hadronic model



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

LS220-M135 simulation (Lattimer-Swesty, NPA 535 (1991) 331-376)



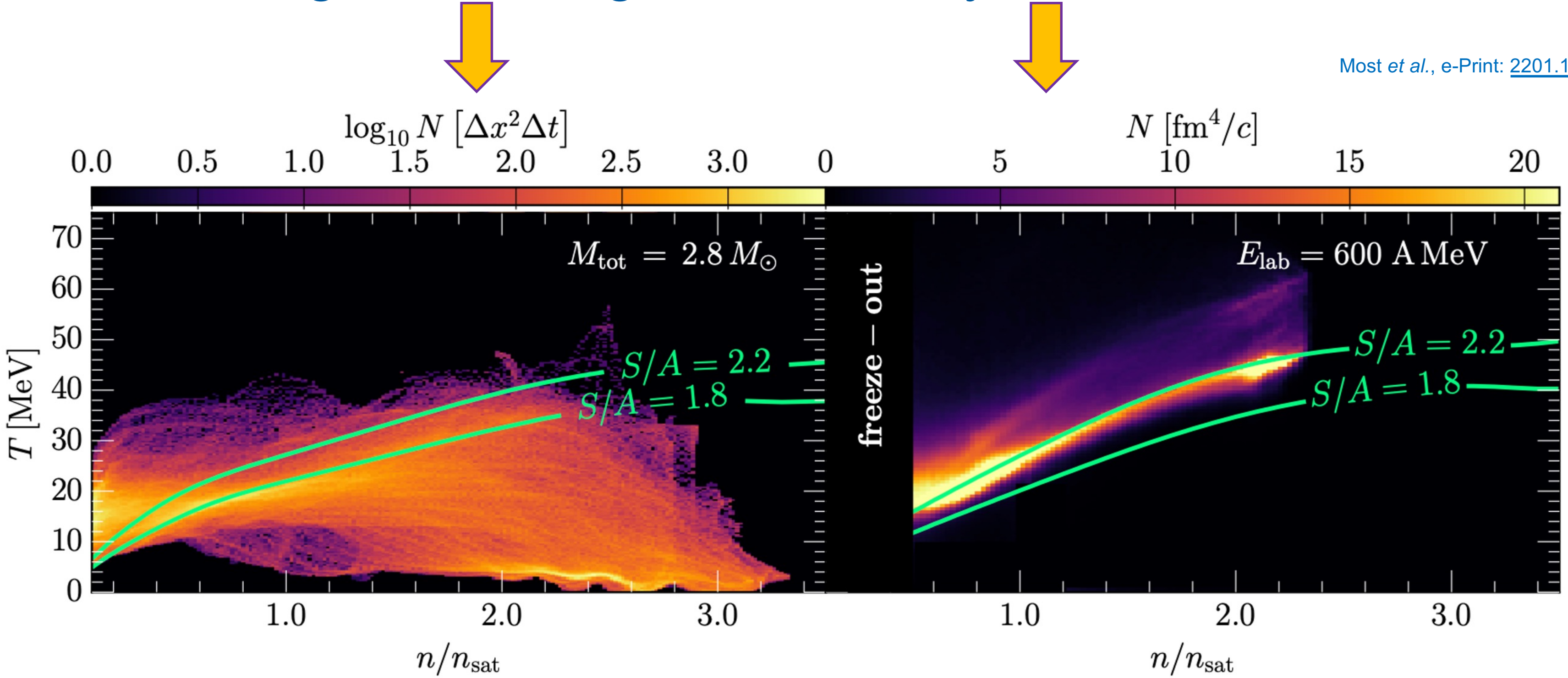
- 18 orders of magnitude in scales, still similar
- T < 70 MeV, $\varrho < 3\ \varrho_0$ for both
- Dileptons sensitive to dense phase

⇝ One EoS for simultaneous description of nuclear physics and observations

Most et al., e-Print: 2201.13150 [nucl-th]

Connecting BNS mergers to heavy-ion collisions

Most *et al.*, e-Print: 2201.13150 [nucl-th]



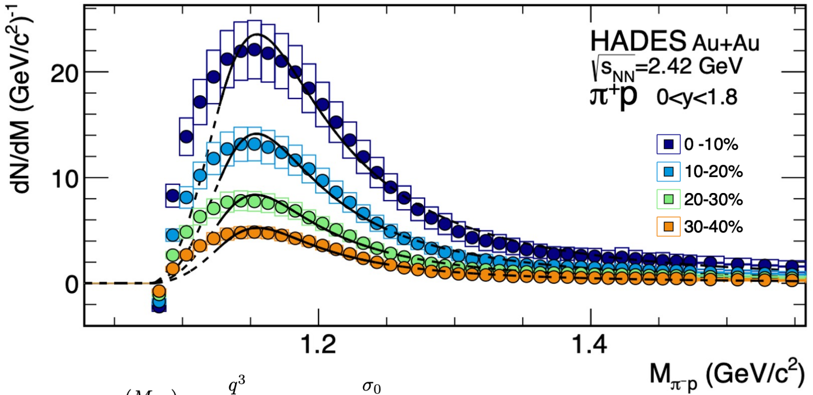
Employing same equation-of-state for simultaneous description of BNS merger and HIC

Entropy per baryon (S/A) similar ⇝ BNS merger and HIC E_{lab} < 1 GeV

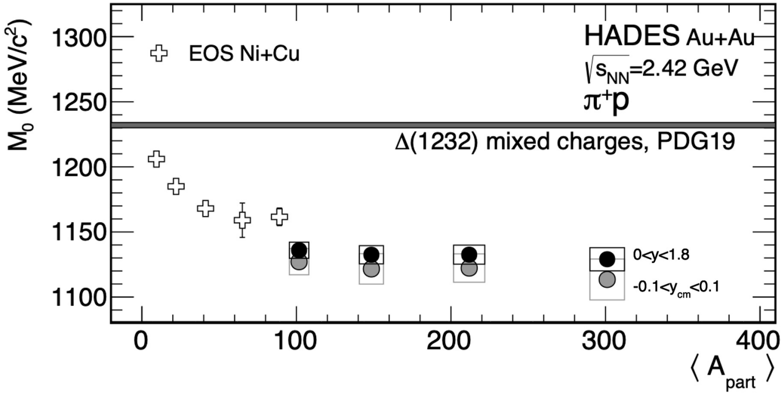
Correlated pion-proton pair emission

π^+p and π^-p analysis

HADES, PLB 819 (2021) 136421



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



- High statistics allows multi-differential analysis
- Input to transport model calculations (*i.e.* fix in-medium $NN \leftrightarrow N\Delta$ cross sections)
- Sensitivity to in-medium spectral function
- Understanding of “kinematical” mass shift with S-matrix formalism

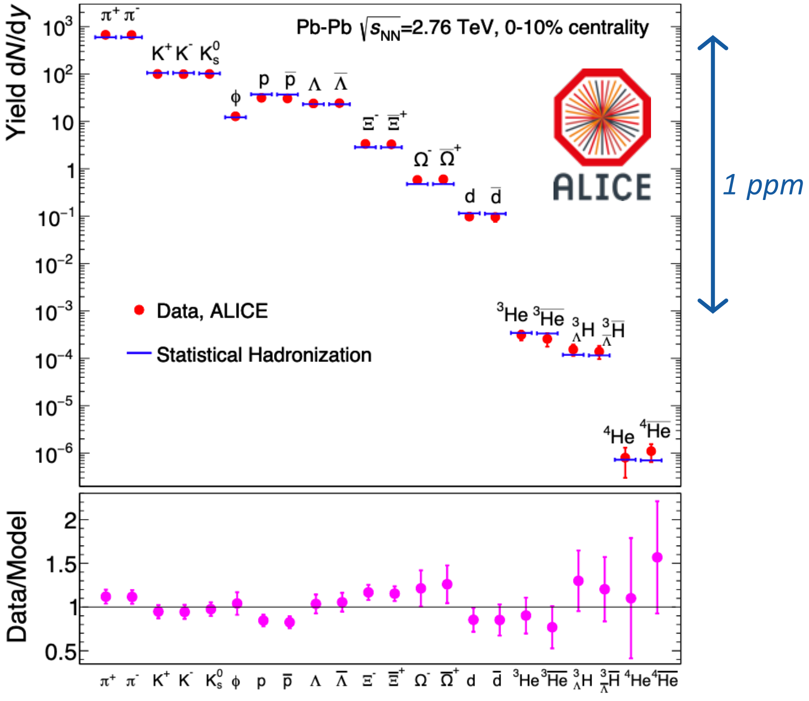
UrQMD, Reichert *et al.*, NPA 1007 (2021) 122058
RVUU, Godbey *et al.*, PLB 829 (2022) 137134

cf. Hees and Rapp, PLB 606 (2005) 59-66

Dashen *et al.*, Phys. Rev. 187 (1969) 345

Are we creating a thermal medium in experiments?

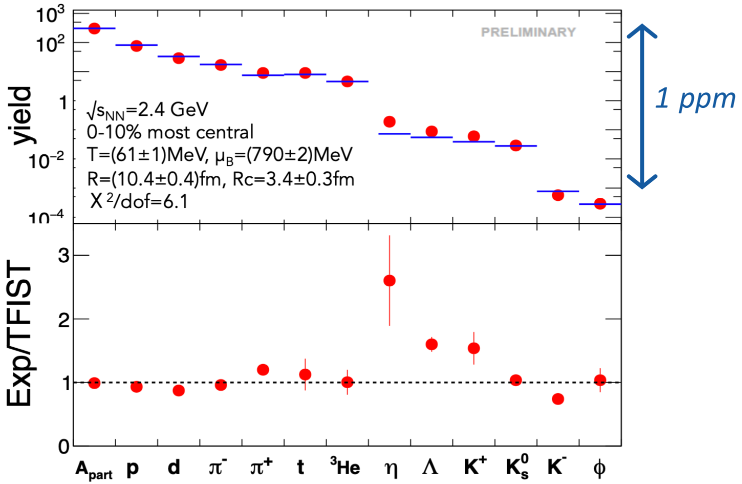
Hadron yields and statistical hadronization model (SHM)



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

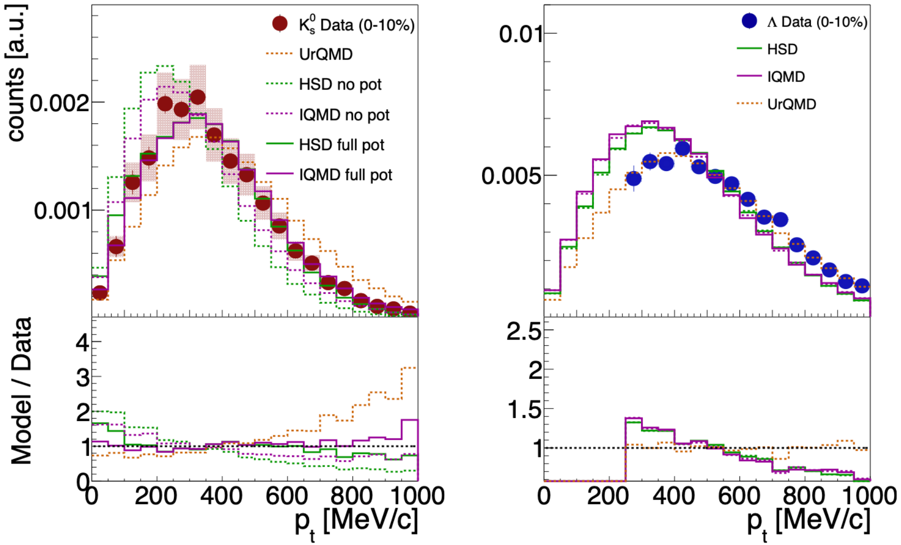
- Factor 1000 in beam energy / factor ~2 in temperature
- Hadron abundances described in framework of SHM
  - calculation carried out with vacuum masses
  - strangeness canonical treatment at low beam energies
  - include feed-down from ^4He, ^4H, ^4Li

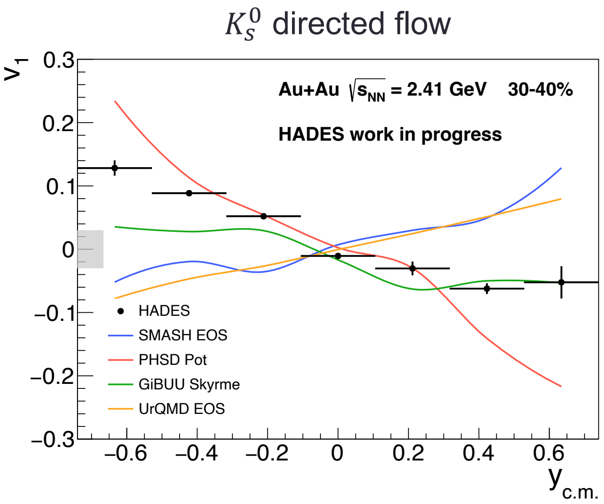
Hahn, Stöcker, NPA 476 (1988) 718-772
Shuryak, Torres-Rincon PRC 101 (2020) 3, 034914



Kaon and Λ production and anisotropy in Au+Au

HADES, PLB 793 (2019) 457-463





HADES, in preparation

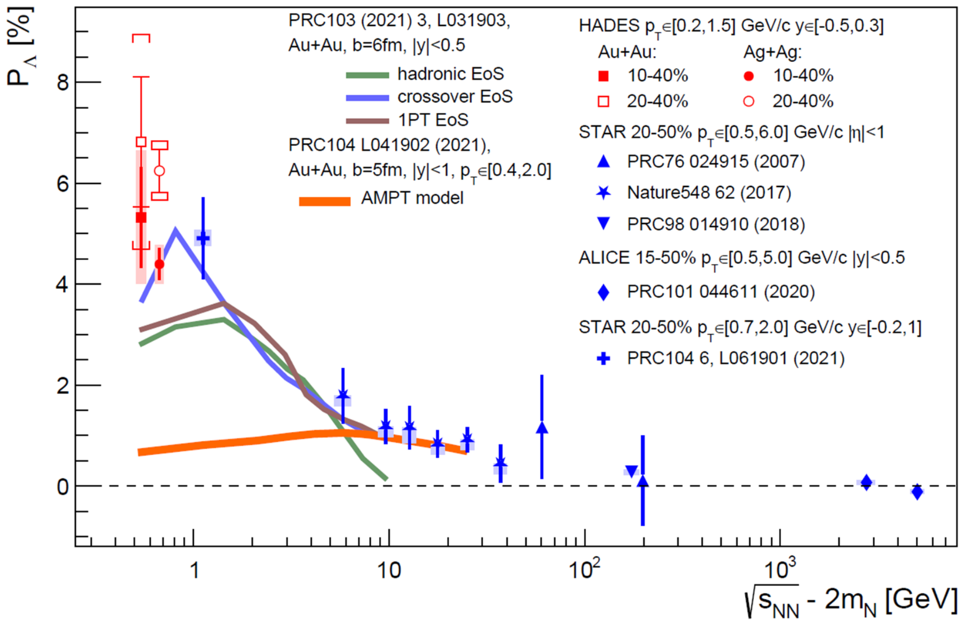
$$U_{opt} = +40\ MeV \cdot \frac{\rho}{\rho_0}$$

(repulsive) KN potential relevant to describe K_S^0 distribution but not acting on (helping) Λ?

No simultaneous description of K_S^0 and Λ results

Λ polarization at HADES

HADES, PLB 835 (2022) 137506



Strongest polarization signal observed at SIS18 energies

- Performed multi-differentially in transverse momentum, rapidity and centrality
- Further constraints for the EoS of compressed baryonic matter