Studying baryon-rich matter in low energy heavy ion collisions

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for the HADES collaboration

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FAIR GSI

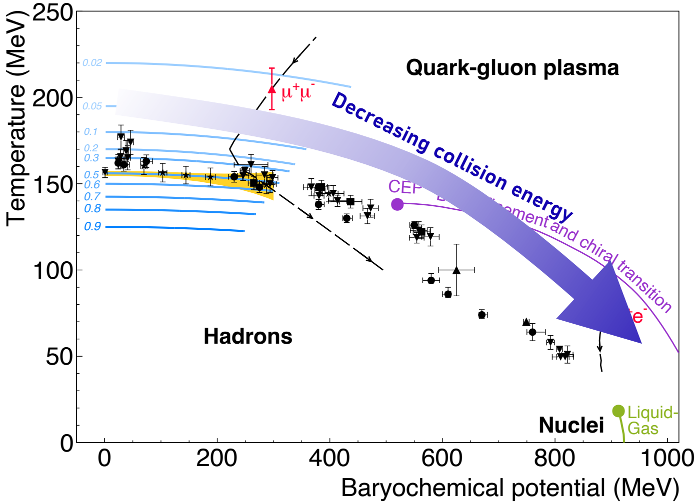
HADES

TECHNISCHE UNIVERSITÄT DARMSTADT

Contents

Strong interaction matter at extreme conditions

Statistical Hadronization Model of particle production



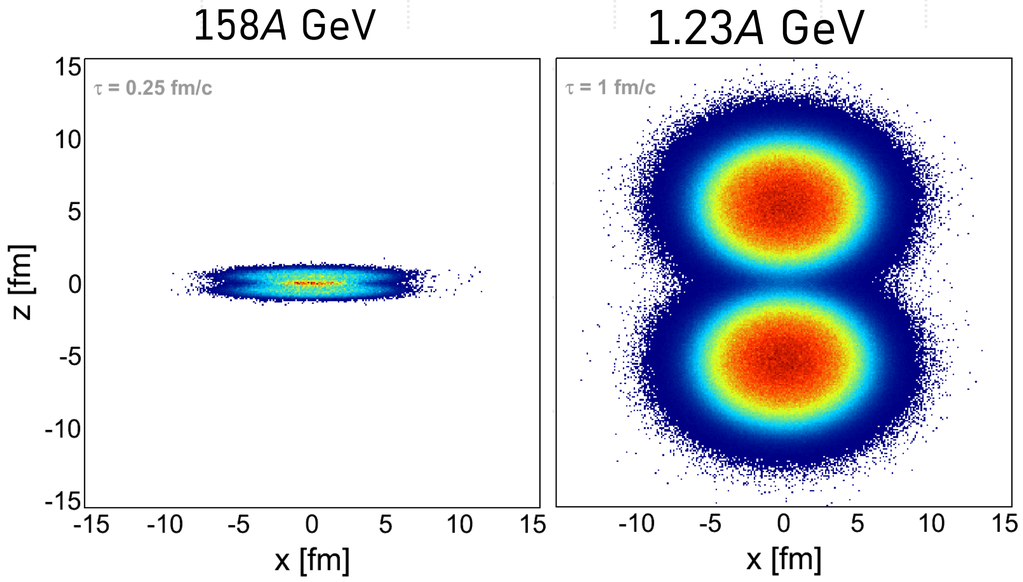
Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP **1009** 073 (2010)
Isserstedt, Buballa, Fischer, Gunkel, PRD **100** 074011 (2019)
Gao, Pawlowski, PLB **820** 136584 (2021)
Cuteri, Philipsen, Sciarra, JHEP **11** 141 (2021)
McLerran, Pisarski, NPA **796** 83 (2007)
Glozman, Philipsen, Pisarski, arXiv:2204.05083 [hep-ph]

HADES, Nature Phys. **15** 10, 1040–1045 (2019)
NA60, Specht *et al.*, AIP Conf.Proc. **1322** 1, 1-10 (2010)
Andronic *et al.*, Nature **561** no.7723 (2018)

Chemical potential is *always* related to *net* density:

$$\mu = T \ln\left(\frac{\rho}{g}\left(\frac{mT}{2\pi}\right)^{-3/2}(\hbar c)^3\right)$$

(formula for ideal classical gas of one-type particles)



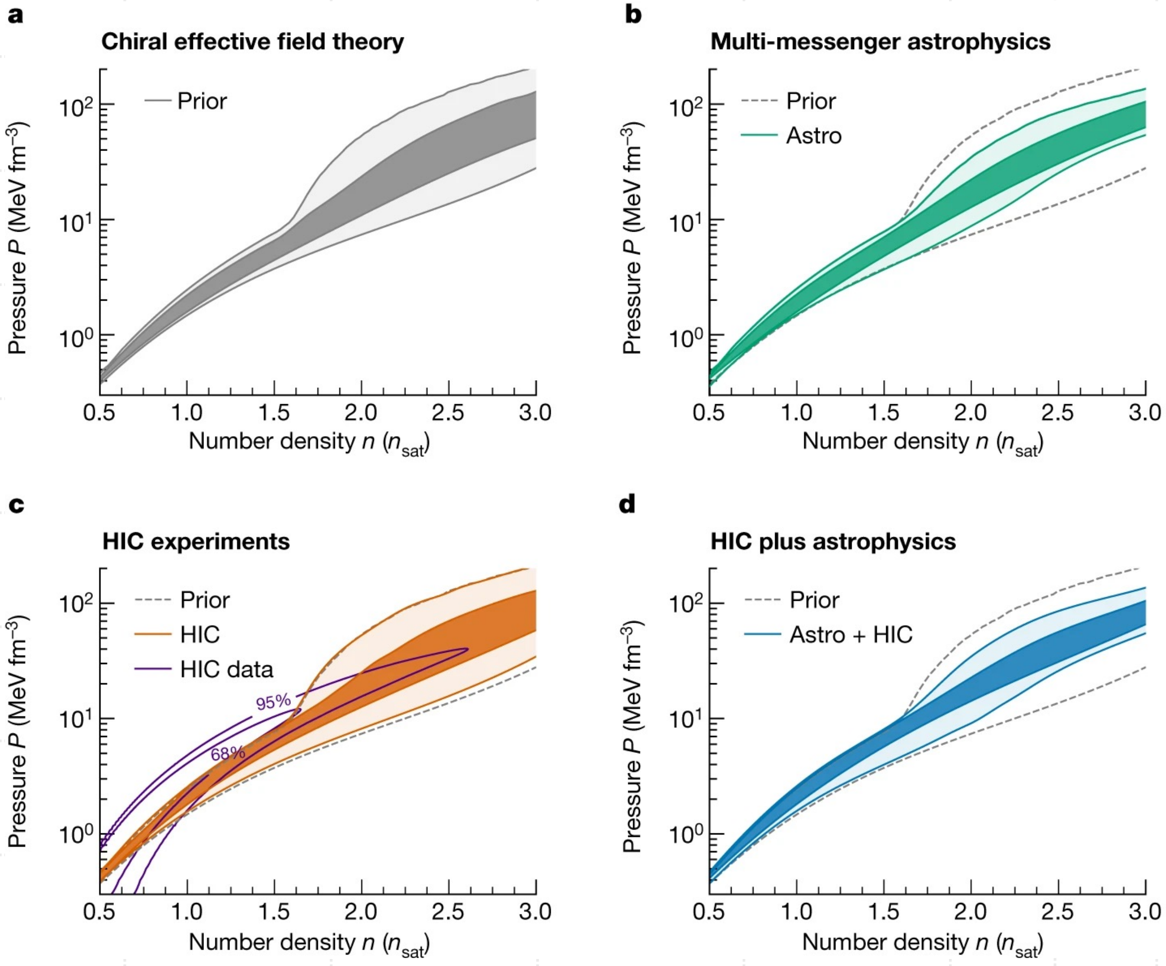
Animations: F. Seck (TU Darmstadt)
Model: UrQMD

What can we learn?

- Microscopic properties of baryon-dominated matter
- Equation-of-State
- First-order phase transition?
- QCD critical point?

- Observables:
  - E-b-e correlations and fluctuations
  - Flavor production
  - Collective effects
  - Dileptons

Huth *et al.*, Nature **606** 276-280 (2022)

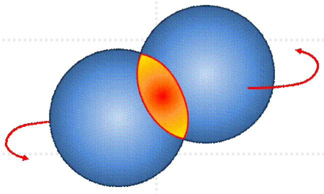


Azimuthal anisotropy (“flow”)

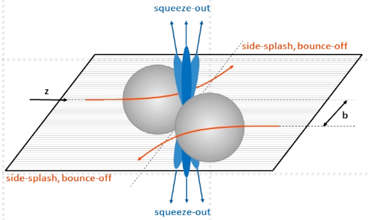
with respect to the reaction plane (RP)

Fourier coefficients of the particle emission:

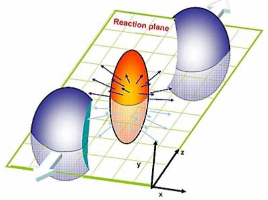
$$\frac{dN}{d(\phi - \Psi_{EP})} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_{EP}))$$



v_1 antisymmetric around y = 0

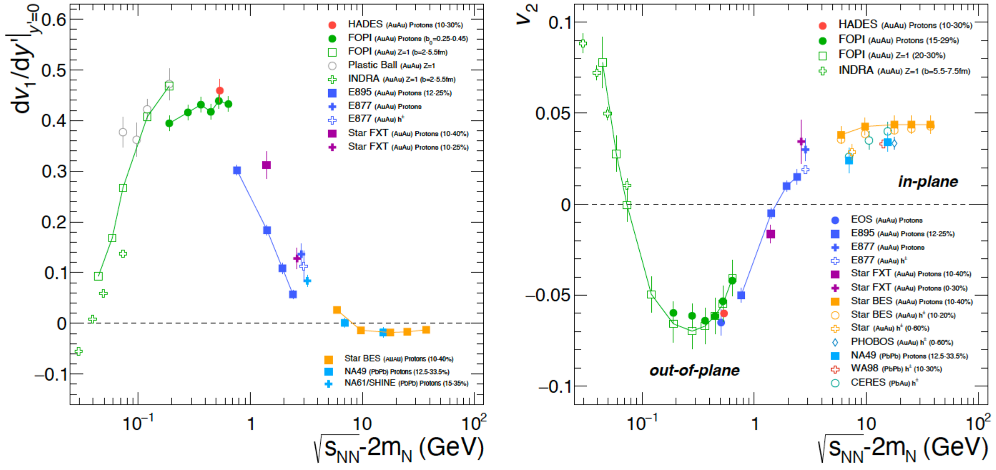


Intermediate energy, $v_2 < 0$



High energy, $v_2 > 0$

HADES, arXiv:2208.02740 [nucl-ex]



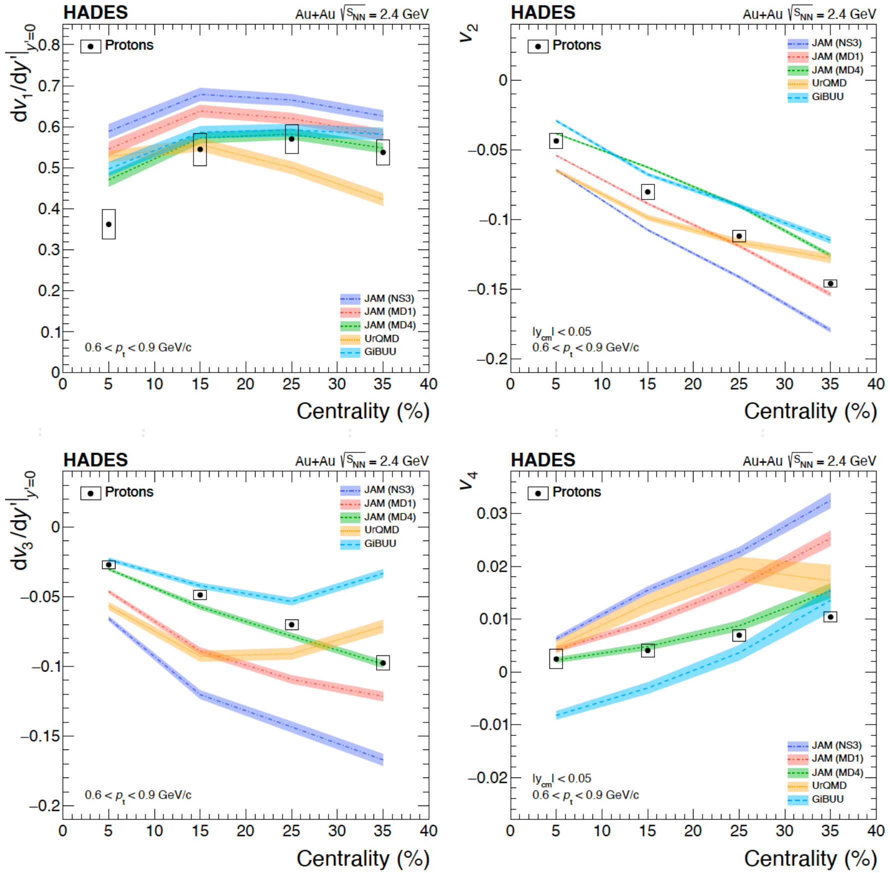
Sensitivity to:

- QCD equation of state
    - Nuclear symmetry energy [$v_2(y_{cm})$ for protons] Y. Wang *et al.*, PLB **802** 135249 (2020)
    - Constraints from comparing with predictions from microsocopic transport
- Existence of the first-order phase transition

Paech *et al.*, NPA **681** 41-48 (2001)
J. Steinheimer *et al.*, PRC **89** 054913 (2014)

Constraining the EoS with v_n and transport models

arXiv:2208.02740 [nucl-ex]



JAM (NS3)	hard, momentum-independent
JAM (MD1)	hard, momentum-dependent
JAM (MD4)	soft momentum-dependent
UrQMD	“hard EoS” (UrQMD 3.4)
GiBUU	“soft EoS” (GiBUU 2019, Skyrme 12)

Nuclear potential in transport models

- Usually implemented as a mean-field Skyrme potential:

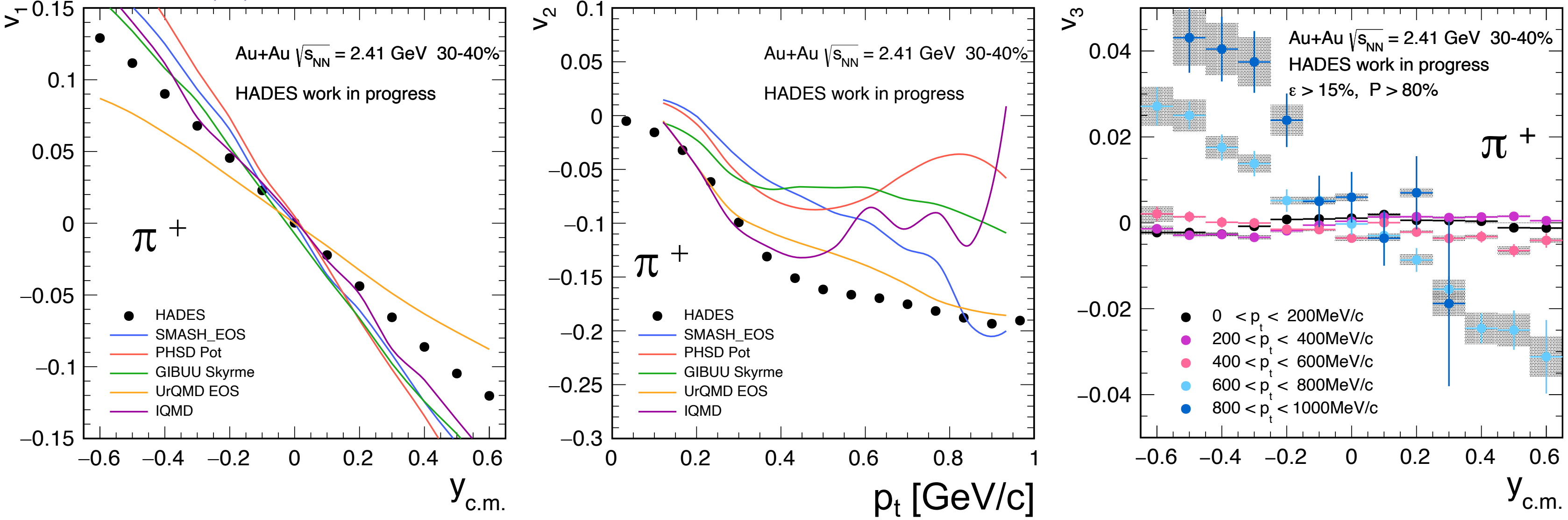
$$V_{sk} = \alpha\left(\frac{\rho_{int}}{\rho_0}\right) + \beta\left(\frac{\rho_{int}}{\rho_0}\right)^{\gamma}$$

which can have “harder” or “softer” energy dependence

  - Currently, parameters are partly fixed by requiring NM to be stable around ρ_0
  - Problem with relativistic treatment
  - Higher harmonic order – higher discriminating power
  - Consistent description of all v_n, for different phase-space regions and centrality classes is not yet there (but is necessary!)

Pion anisotropy in Au+Au collisions

HADES, MS in preparation



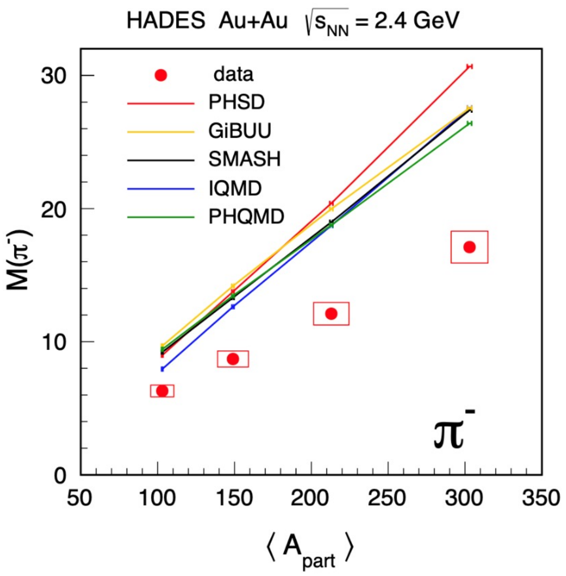
- Good statistics to constrain models and equation of state
- There is room for improvement in the models
- Need for a simultaneous description of all v_n, for different:
  - particle species (at HADES pions and kaons)
  - phase-space regions
  - centrality classes
  - colliding systems (at HADES Au+Au and Ag+Ag)

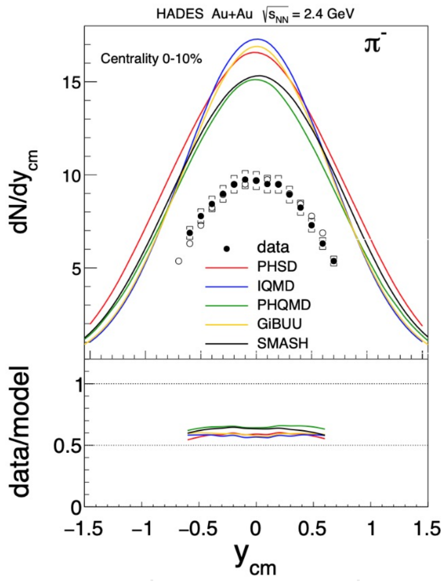
Pion yields and distributions

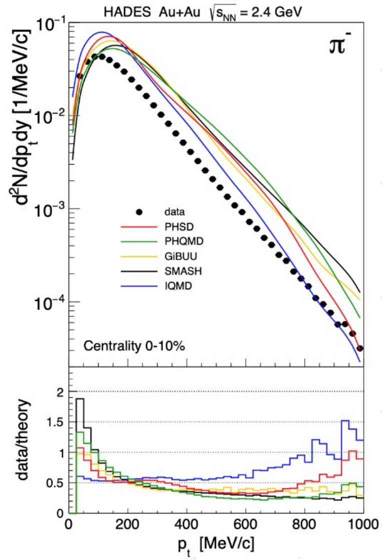
- Different calculations consistently fail to describe experimental data
- Note high net baryon density:
  - Influence of long-range EM interaction with the positively charged fireball
  - Most pions come from decays of baryonic resonances
  - Proper implementation of the in-medium spectral function of resonances is needed

Example for π^-, the same holds for π^+

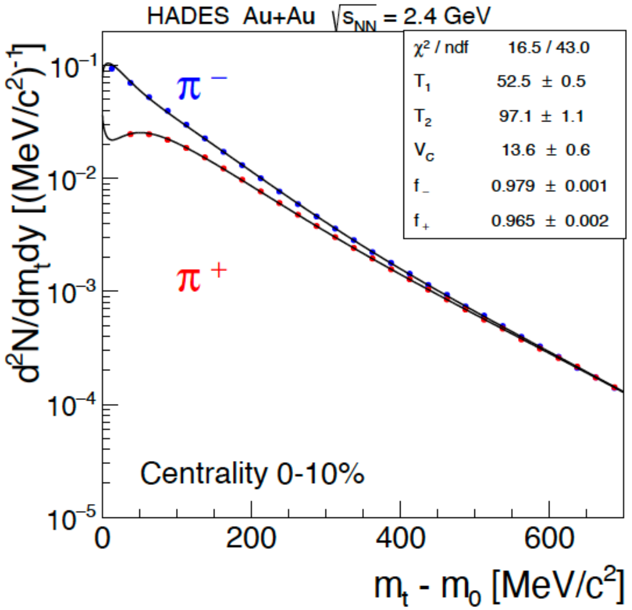
HADES Collaboration, EPJA **56** 10, 259 (2020)
https://www.hepdata.net/record/ins1796710



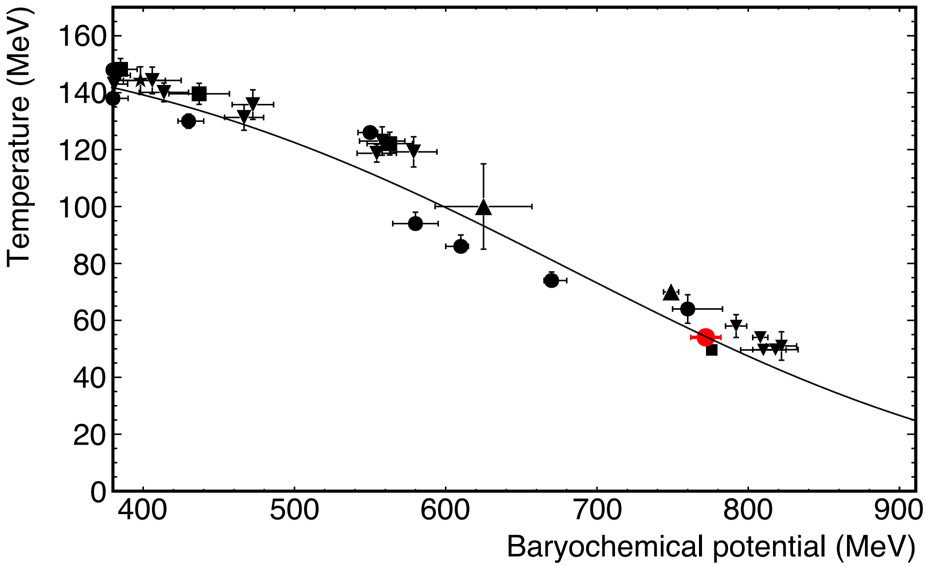




Shift of the pion energy by the Coulomb potential



HADES Collaboration, arXiv:2202.12750

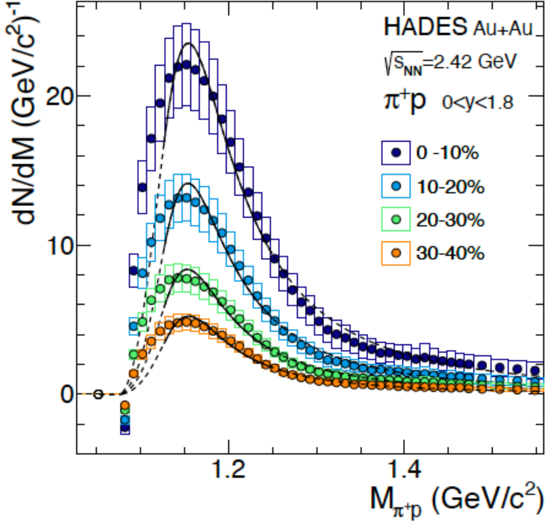


Black data points, SHM fits:
Nature **561** no.7723, 321-330 (2018), also the black curve
PLB **764**, 241-246 (2017)
PRC **73**, 034905 (2006)
PRC **96**, 044904 (2017)
PRC **76**, 052203 (2007)
EPJA **52** no.6, 178 (2016)

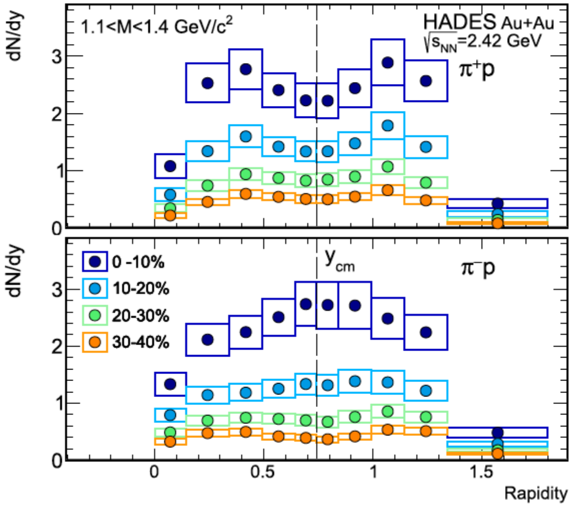
- More accurate extrapolation to low p_t/m_t
- Extracting the average value of the Coulomb potential energy
  - Improved formalism compared to previous works
- Translating it to the fireball size at the freeze-out → density → μ_B
  - Method independent from SHM fits
  - Result in good agreement

Correlated pion-proton pairs

Analysis of π^+p and π^-p pairs

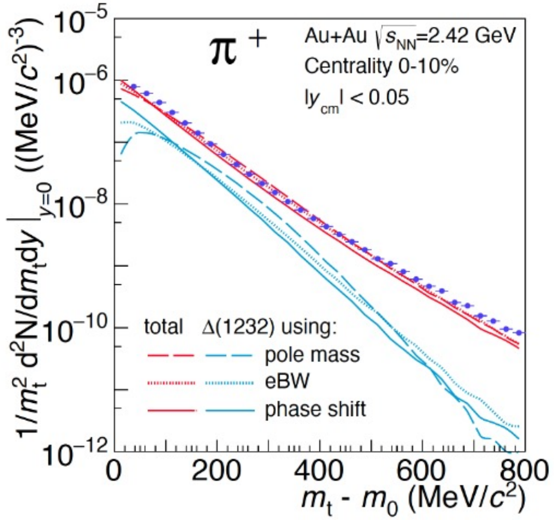


HADES Collaboration, PLB **819**, 136421 (2021)



- The dominant source of particle production at SIS18
- High statistics allows multi-differential analysis
- Understanding of “kinematical” mass shift with S-matrix formalism
- Fix in-medium cross-sections and spectral functions

Sensitivity to the shape



Phase shift: P. M. Lo, B.Friman, M. Marczenko, K. Redlich, C. Sasaki, PRC **96**, 015207 (2017)

SHM parameters: A. Motornenko, J. Steinheimer, V. Vovchenko, R. Stock, H. Stoecker, PLB **822**, 136703 (2021)

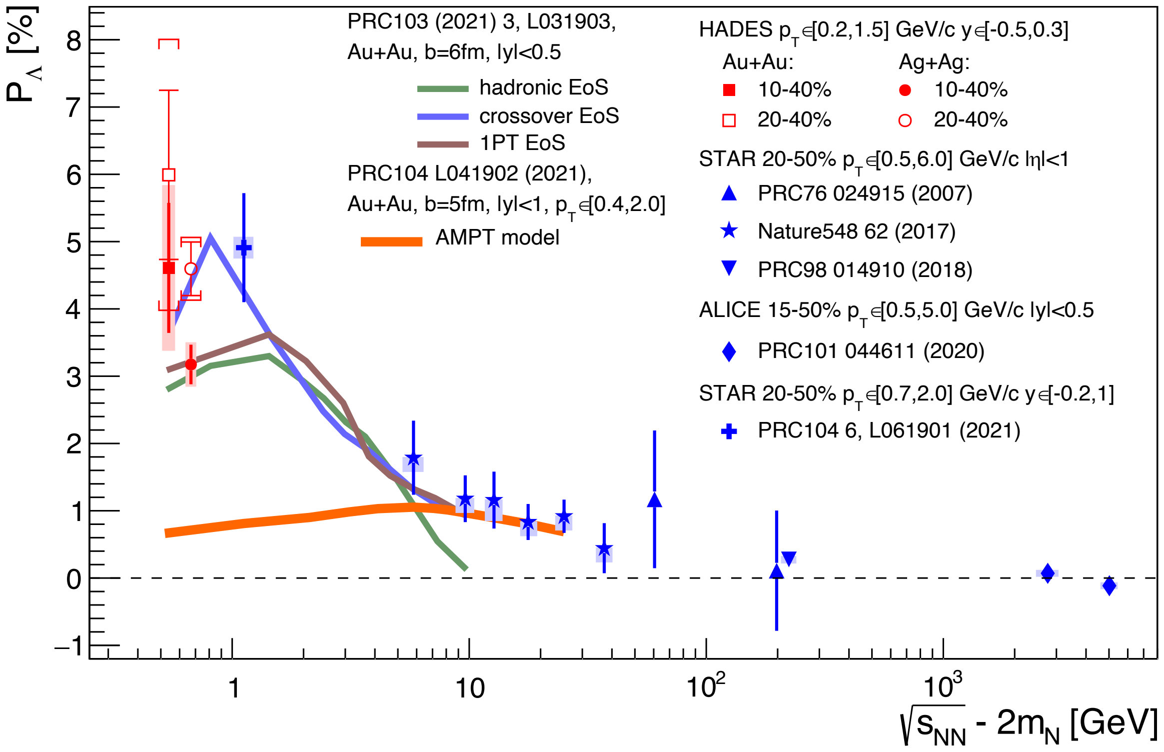
Event generator: M.Cojnacki, A.Kisiel, W.Florkowski, W.Broniowski, Comput.Phys.Comm **181**, 746-773 (2012)

Adapting to HADES energies: SH *et al.*, PRC **102**, 054903 (2020)

Global spin polarization

- First observed at RHIC: "most vortical fluid"
- What is the mechanism of converting $\vec{L}$ to $\vec{S}$?
  - Do we see hydrodynamic fluid with spin?
  - Hydrodynamics description requires (local) thermal equilibrium
- Now: thorough systematics study and support from Ag+Ag data
- Note that $|\vec{L}|$ is substantially lower in Ag+Ag than in Au+Au:

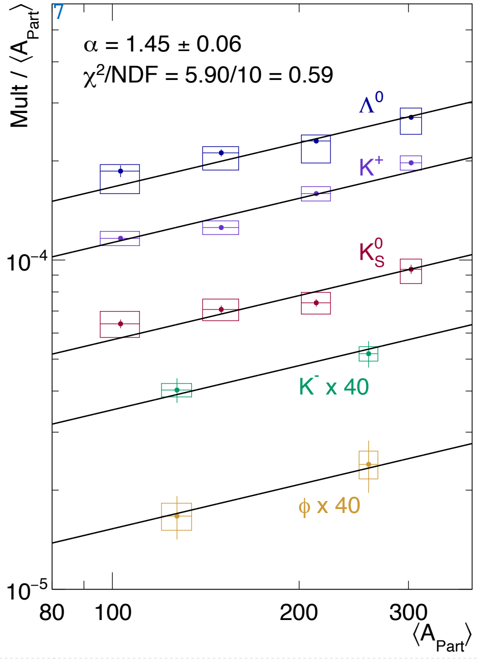
$$L_y \approx \frac{1}{2} A b \sqrt{s}\sqrt{1-(2M/\sqrt{s})^2}$$



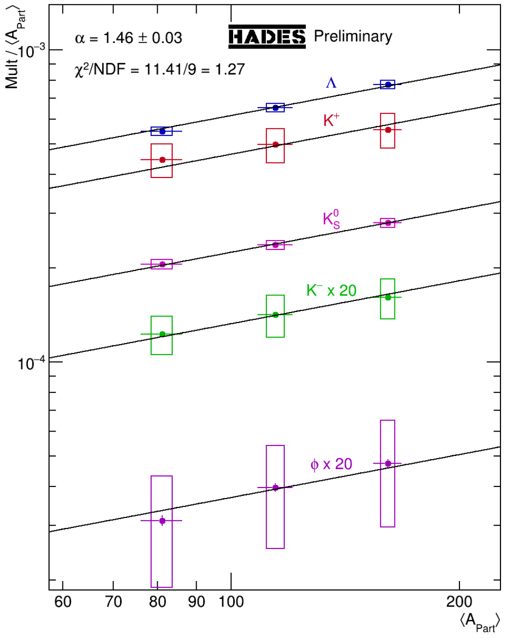
System with Multi-Particle Correlations?

Au+Au

HADES Collaboration, PLB **793** 457 (2019)
https://www.hepdata.net/record/ins1709767



Ag+Ag



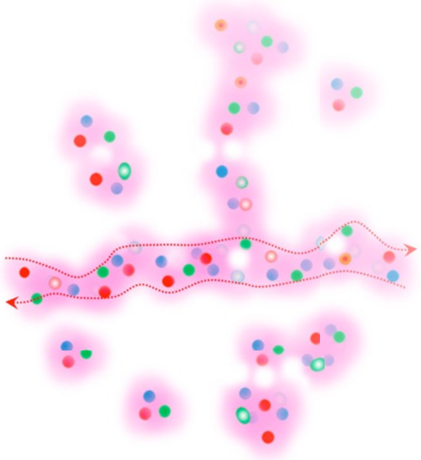
Quantum percolation at $\rho \sim 1.8\rho_0$

K. Fukushima, T. Kojo, W. Weise, PRD **102**, 096017 (2020)

- Different particles
- Different production mechanisms
- Different thresholds

but

- Common scaling with participant number



- Quarks are easily reshuffled between hadron states?

Long-range correlations

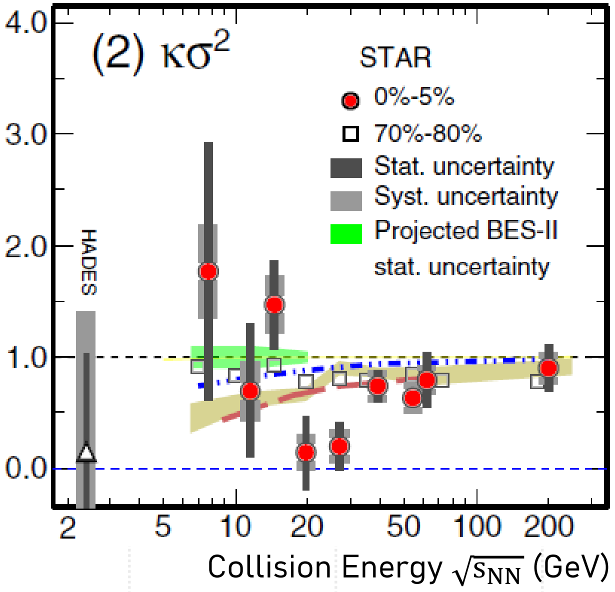
- Study event-by-event distributions of conserved charges (like baryon number) in a selected phase-space window
- Quantified by moments or cumulants well known from statistics
- Will deviate from the Poisson baseline if the matter is in the vicinity of the phase transition/critical point

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** 1694 (2011)
M. Stephanov, PRL **107** 052301 (2011)

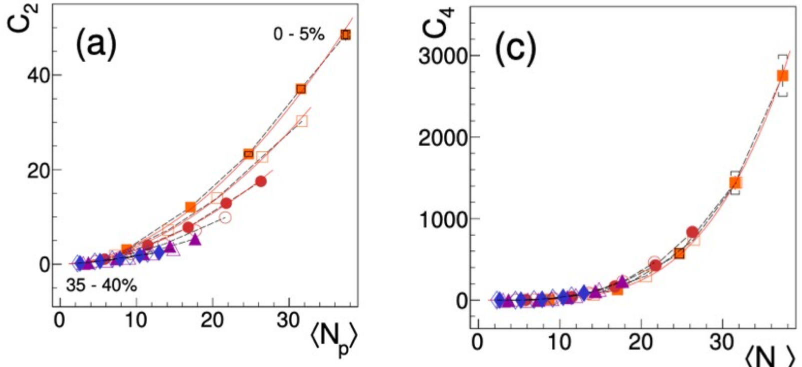
STAR Collaboration, PRL **126** 092301 (2021)



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, $C_n \propto \langle N_p \rangle^{\alpha}$

HADES Collaboration, **PRC** 102 2, 024914 (2020)
https://www.hepdata.net/record/ins1781493



$C_2 \propto \langle N_p \rangle^{\alpha}$
$\alpha = 1.86 \pm 0.04$

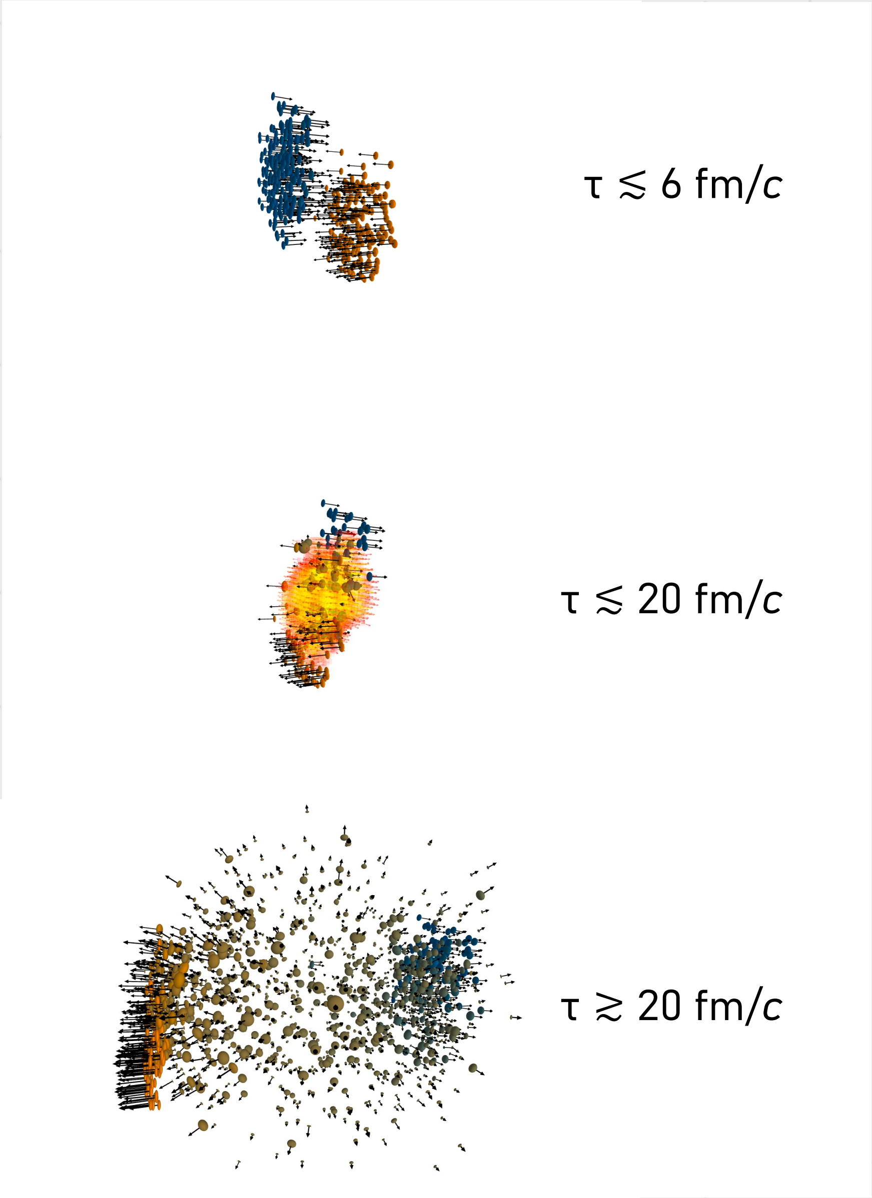
$C_4 \propto \langle N_p \rangle^{\alpha}$
$\alpha = 3.89 \pm 0.14$

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

A. Rustamov, M.I. Gorenstein, PRC **86** 044906 (2012)

Electromagnetic probes

- Photons (virtual and real):
  - Don’t undergo strong interaction
  - Probe all the stages of heavy-ion collisions
- Radiation from hot and dense matter is isolated by subtracting:
  - First-chance NN collisions
  - Meson decays at the freeze-out



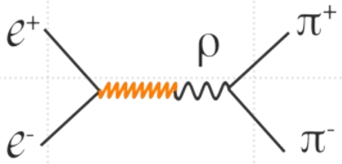
Electromagnetic spectral function

- In vacuum, it is measured in e⁺e⁻ anihilation experiments:

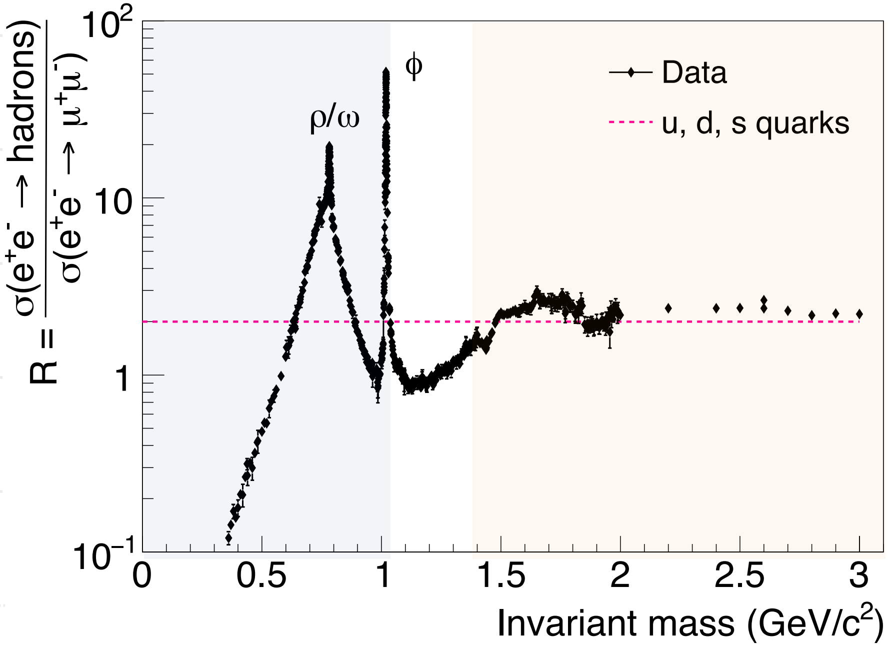
$$R \propto \frac{Im\Pi_{em}}{M^2}$$

Low mass region LMR

EM spectral function is saturated by light vector mesons – with $J^P = 1^-$, same as for (virtual) photon, mainly ρ^0

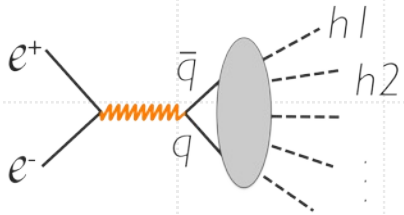


Beringer *et al.* (PDG), PRD **86** 010001 (2012)



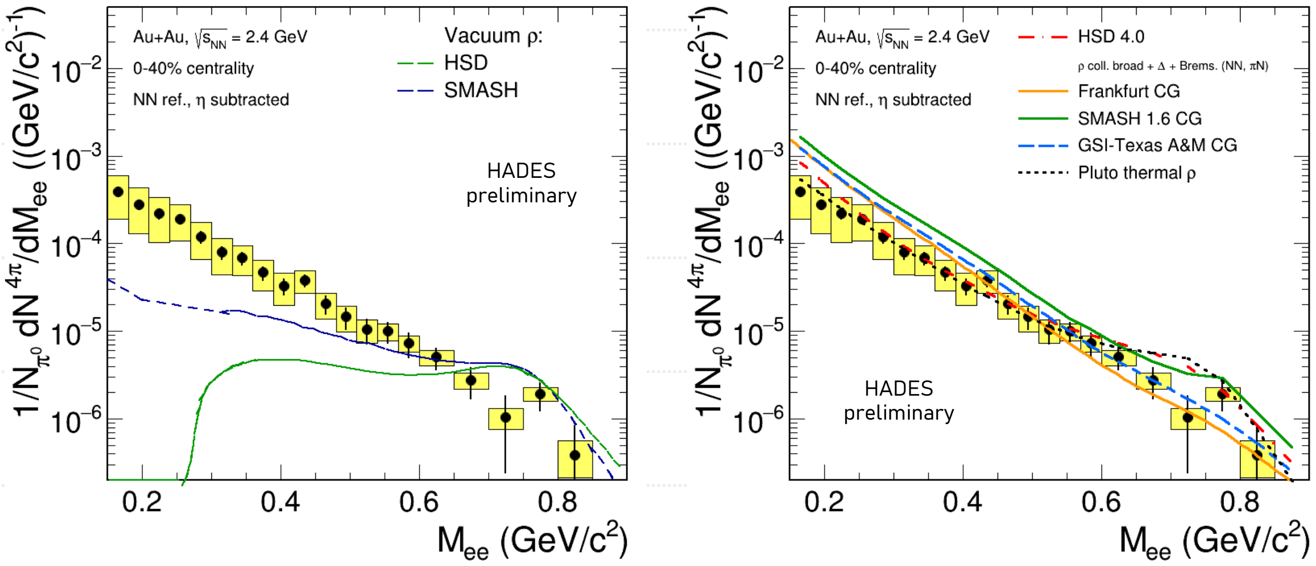
Intermediate mass region IMR

Perturbative QCD continuum, quark degrees of freedom



Thermal dileptons at high μ_B

HADES Collab., MS in preparation, cf. also Nature Physics **15** 1040 (2019)



- Thermal dilepton production rates

L. D. McLerran, T. Toimela, PRD **31** 545 (1985)

$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T)\boxed{Im\Pi_{em}(M,q,T,\mu_B)}$$

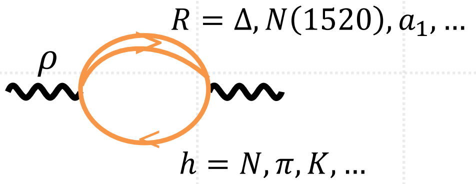
Spectral function

- Melting of ρ clearly visible
- Collisional broadening is not sufficient to account for that

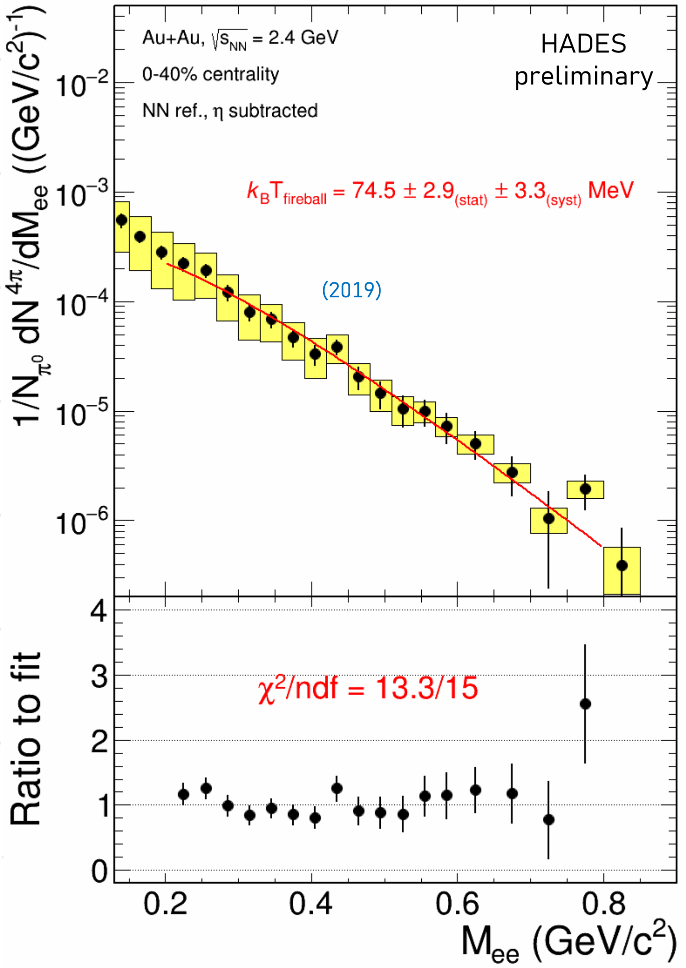
ρ melting handled properly by the local thermal equilibrium approach (CG)

CG FRA: PRC **92** 014911 (2015)
CG GSI-Texas A&M: EPJA, **52** 5 131 (2016)
CG SMASH: PRC **98** 054908 (2018)
HSD: PRC **87** 064907 (2013)
PLUTO: J. Phys. Conf. Ser **219** 032039 (2010)

Role of medium effects - coupling of ρ to resonances



Thermal dileptons at high μ_B



HADES Collab., MS in preparation, cf. also Nature Physics **15** 1040 (2019)

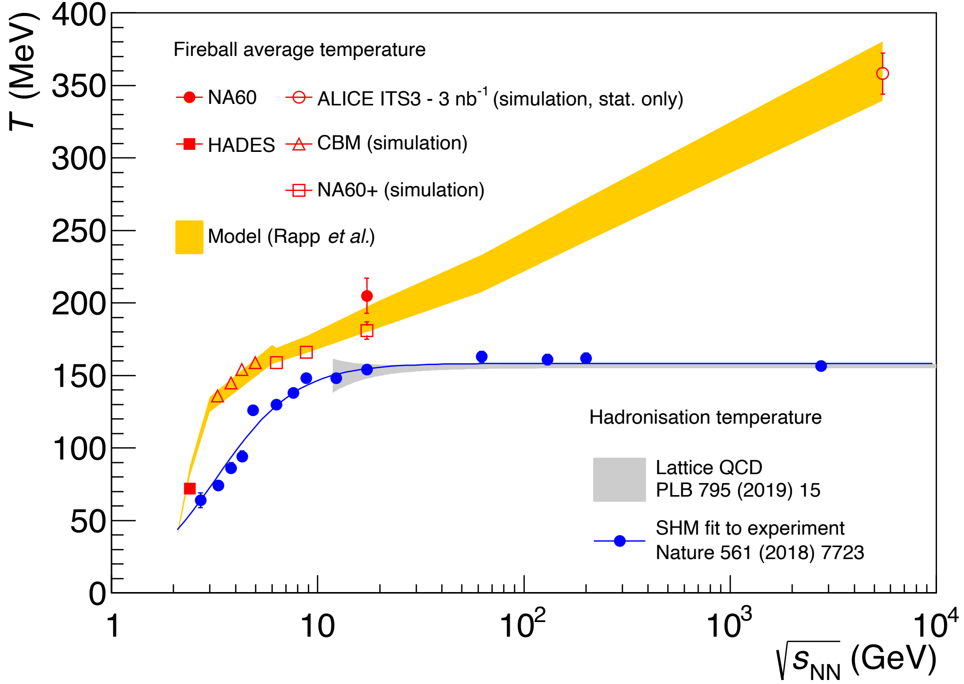
$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2}\boxed{f^B(q_0,T)}Im\Pi_{em}(M,q,T,\mu_B)$$

Boltzmann factor

- Boltzmann factor dominates the exponential shape of the spectrum if $\mathrm{Im}\Pi_{\mathrm{EM}}/M^2$ does not change much with M
- Slope of the invariant mass not affected by the fireball expansion
- True (average) source temperature – not affected by the blue shift

Discovering the QCD “caloric curve”

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



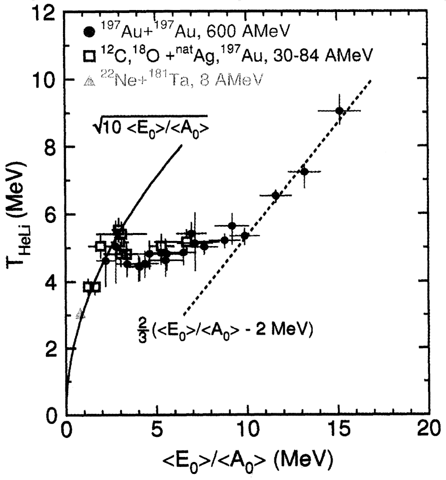
Temperature vs. energy density (collision energy as a proxy)

Up to now, only published data from HADES and NA60

Phase transition may manifest itself as a plateau

Nuclear liquid-gas phase transition

Pochodzalla *et al.*, PRL **75** 1040-1043 (1995)

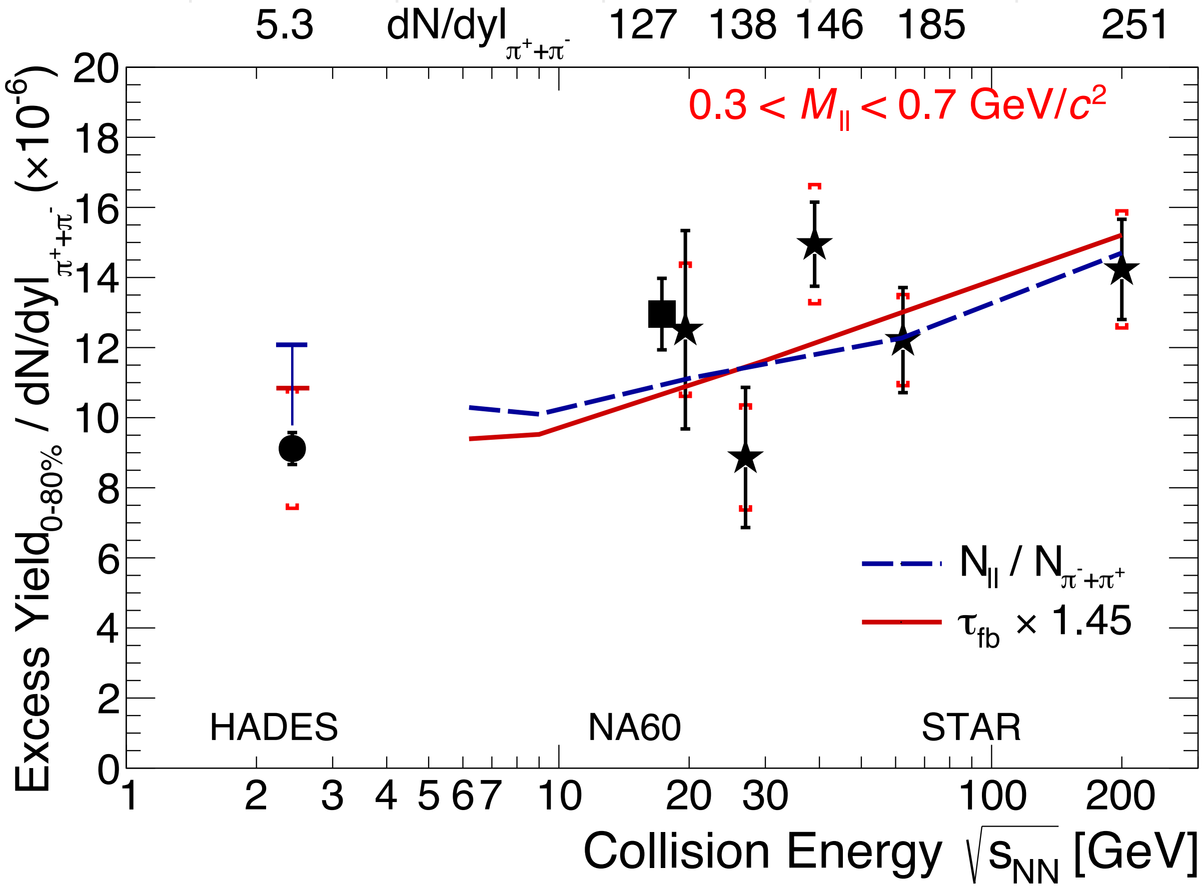


Lifetime of the fireball

- Thermal radiation is emitted during the whole lifetime of the system
- The integrated yield in 0.3 < Mee / (GeV/c2) < 0.7 is the most sensitive to measure the lifetime

  Heinz and Lee, PLB 259, 162 (1991)
  Barz, Friman, Knoll and Schulz, PLB 254, 315 (1991)
  Rapp, van Hees, PLB 753 (2016) 586
- At a phase transition “production” of the latent heat would increase the lifetime

T. Galatyuk, JPS Conf.Proc. **32** 010079 (2020)



Summary

- A comprehensive comparison of flow harmonics between experiment and transport models is a great tool to contrain the EoS
- More work must be done to get good agreement of phase-space distributions
    - Coulomb effect
    - Description of resonances
- Interactions in the system:
    - Global hyperon polarization keeps growing with decreasing collision energy
    - Common power-law scaling for all strange particles (in a given collision system)
    - Proton number cumulants consistent with long-range multi-particle correlations
- Electromagnetic probes:
    - Measurement of temperature and lifetime of the fireball
    - Structures in the excitation functon will signify a phase transition