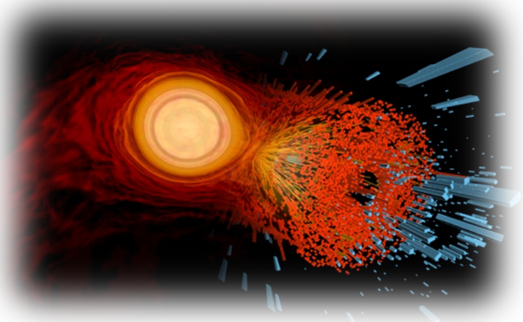
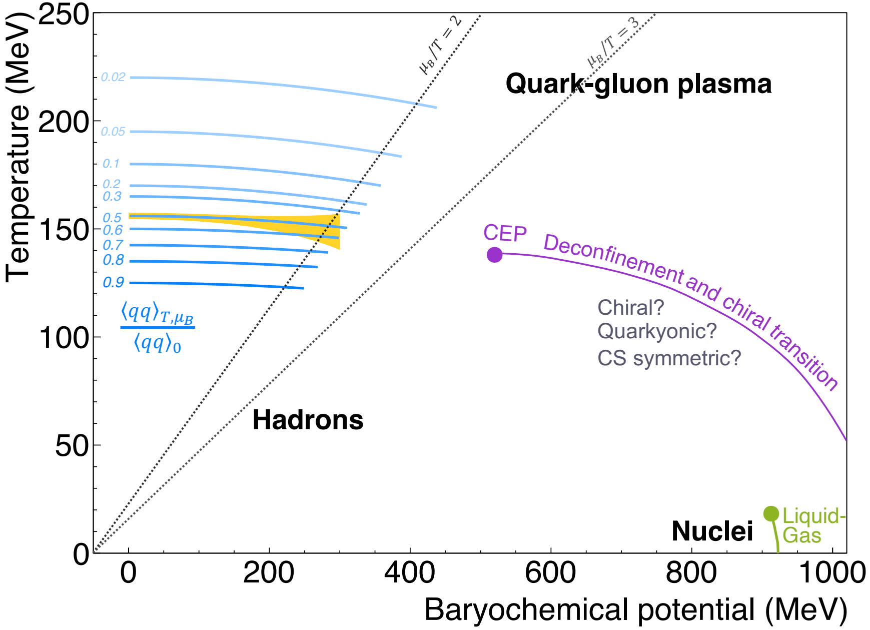
PROBING NEUTRON-STAR MATTER IN THE LABORATORY

Tetyana Galatyuk
TU Darmstadt GSI
HADES Collaboration Meeting, mini-symposium
19-23 September 2022, Coimbra



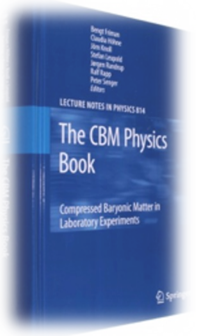
Searching for landmarks of the QCD matter phase diagram



- **Vanishing μ_B, high T (lattice QCD):**
  - crossover from hadronic to partonic medium
    - $T_{pc} = 156.5 \pm 1.5$ MeV (physical quark masses)
      $T_c = 132^{+3}_{-6}$ MeV (at chiral limit)
  - 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.*, Phys.Rev.D 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

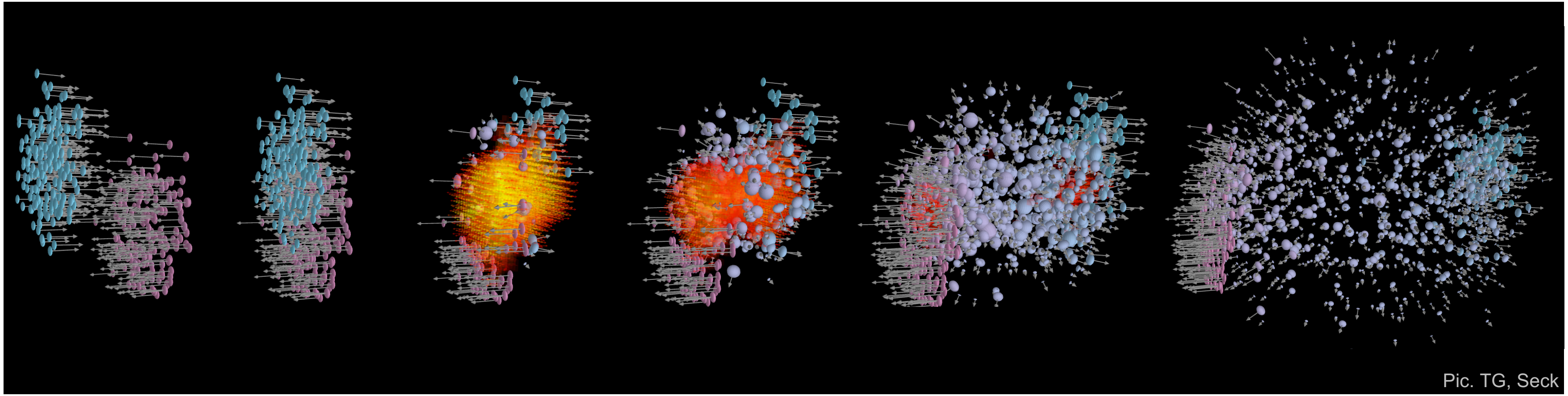
Relevance for astrophysics

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

Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011
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]

Accessible through heavy-ion collisions at relativistic energies

time $\sim 10^{-23}$ *s*



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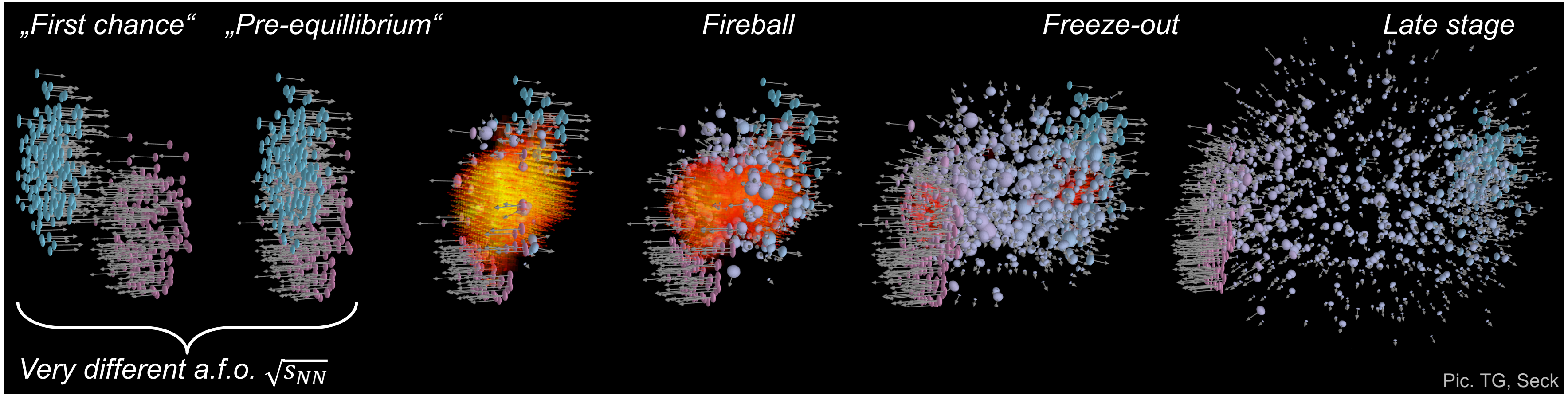
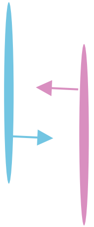
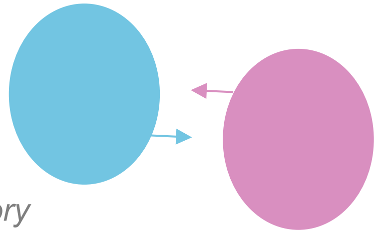


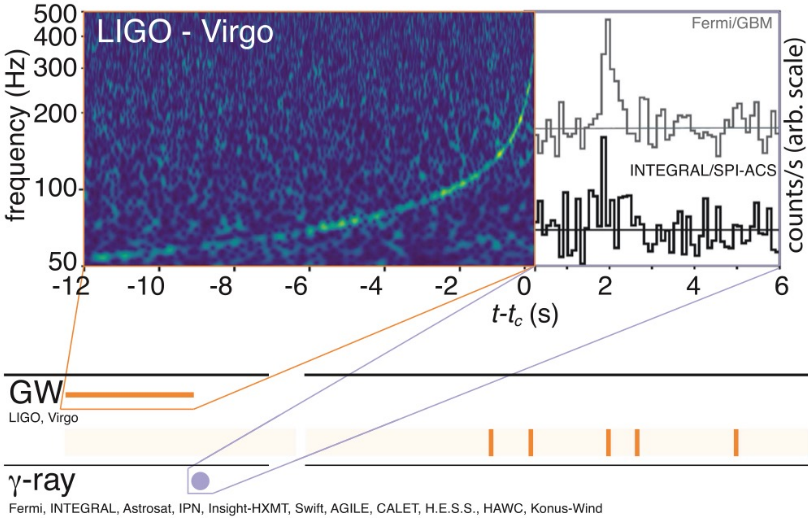


LHC energies $\sqrt{s_{NN}} = 2\,TeV$
parton+parton collisions
Early Universe in the laboratory

Energies $\sqrt{s_{NN}} \cong 2 * m_N\,GeV$
nuclear stopping
NS merger matter in the laboratory



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

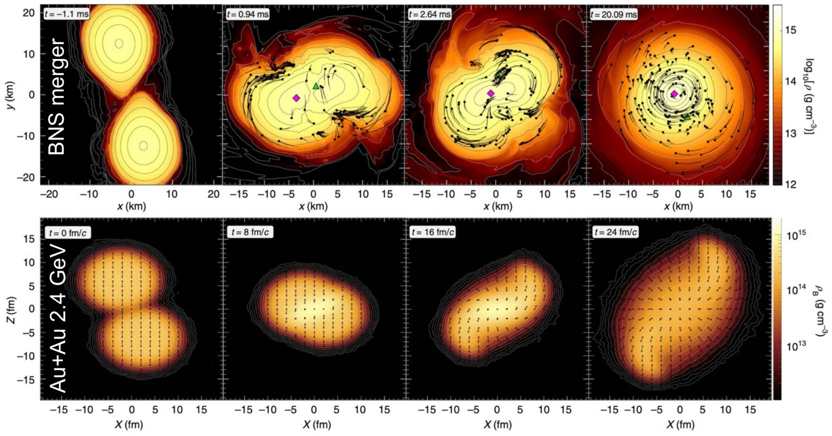
- GRB 170817A ~1,7 s later:
  Observation of the same event through electromagnetic waves (gamma-ray burst)

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

Laboratory studies of the matter properties in compact stellar objects


nature physics
ARTICLES
https://doi.org/10.1038/s41567-019-0583-8
Probing dense baryon-rich matter with virtual photons
The HADES Collaboration*

18 orders of magnitude in scales
still similar T < 70 MeV, $\rho < 3\rho_0$ for both



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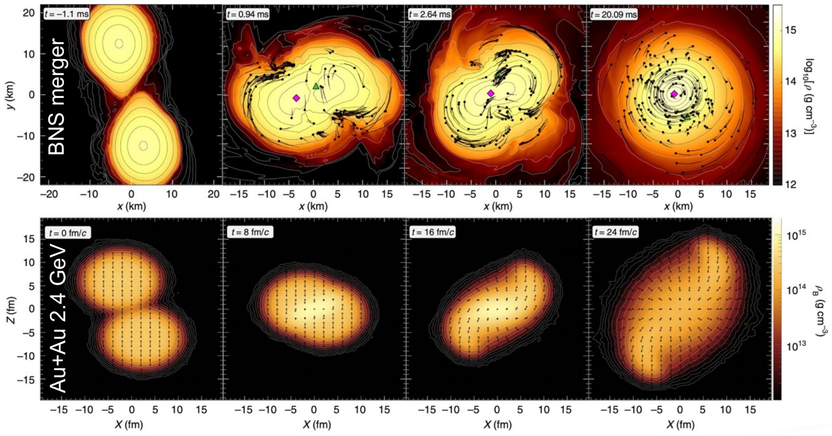
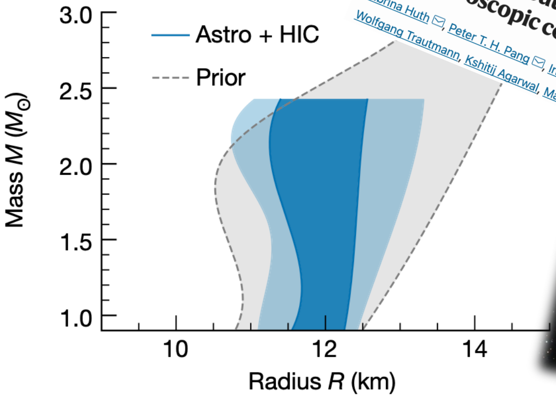
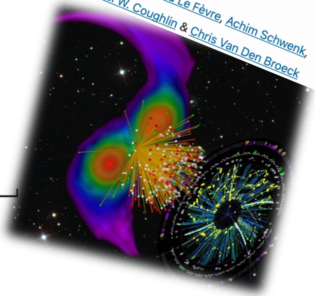




nature
Article | Open Access | Published: 08 June 2022

Constraining neutron-star matter with microscopic and macroscopic collisions

Sabrina Huth, Peter T. H. Pang, Ingo Tews, Tim Dietrich, Arnaud Le Fèvre, Achim Schwenk, Wolfgang Trautmann, Kshitij Agarwal, Mattia Bulla, Michael W. Coughlin & Chris Van Den Broeck

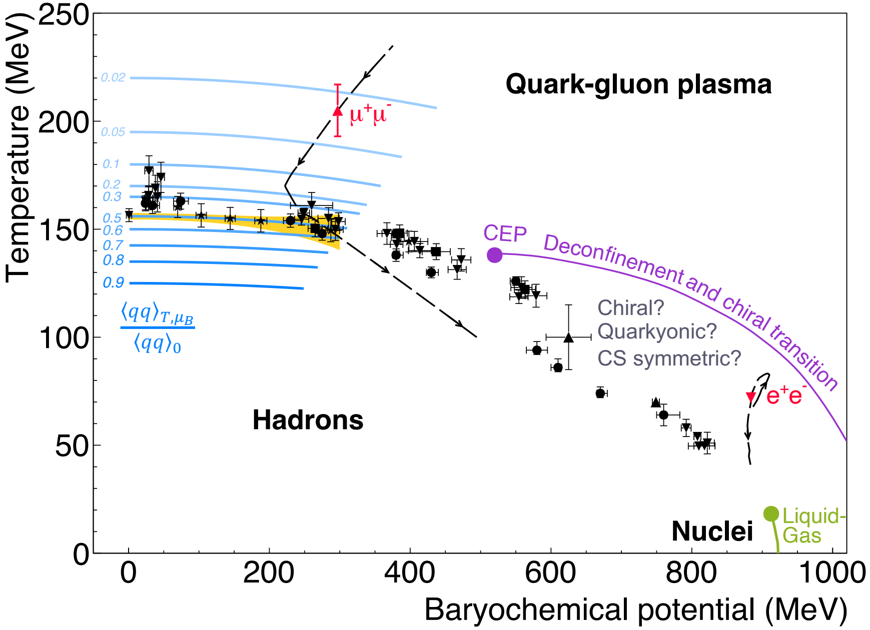


Remarkable consistency between multi-messenger observations and constraints from heavy-ion data

Going forward, it is important that both statistic and systematic sources of uncertainty for HIC experiments are further improved.

advancing HIC experiments to probe higher densities, above 2–3n_{sat}, will be key

Searching for landmarks of the QCD matter phase diagram

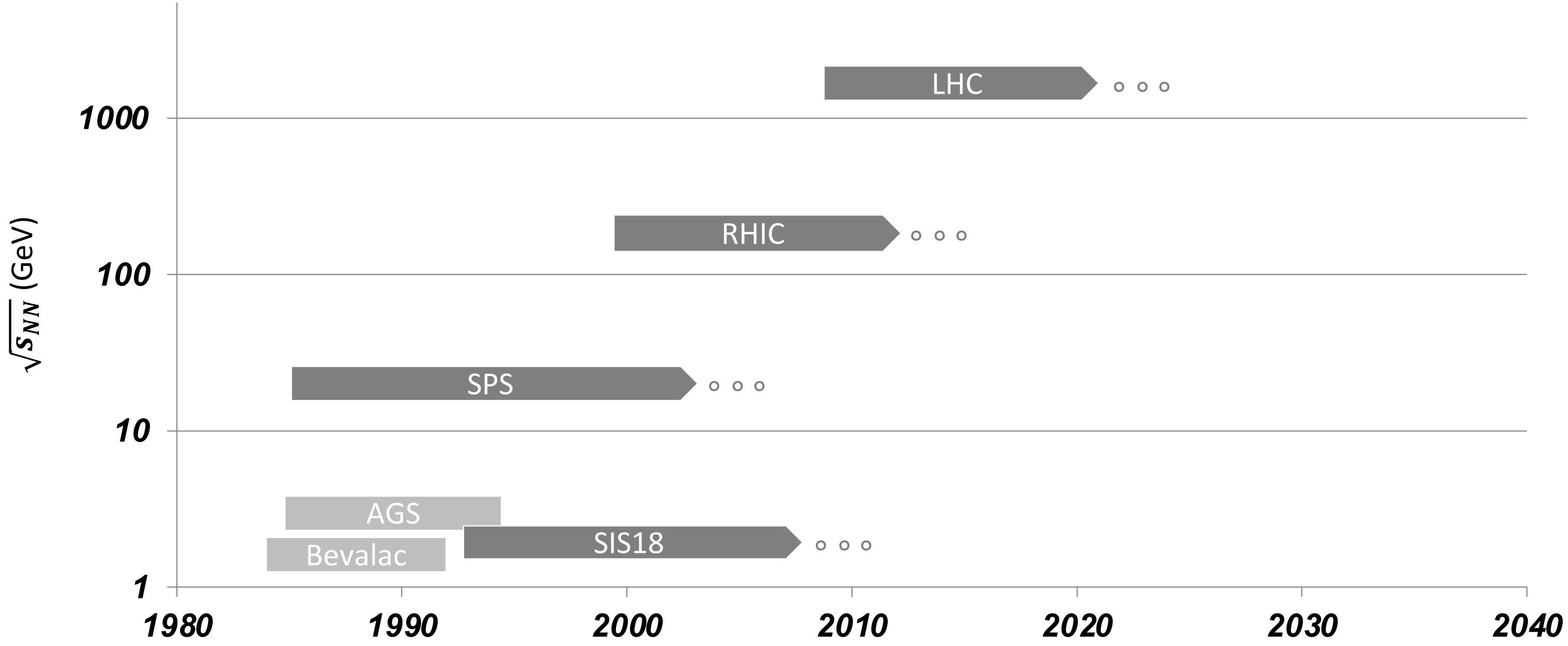


- **Experimental challenge:**
  - locate the onset of new phases of QCD
  - detect the conjectured QCD critical point
  - probe microscopic matter properties
- **Measure with utmost precision:**
  - light flavour (chemistry, vorticity)
  - charm (transport properties)
  - event-by-event fluctuations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

Challenge: isolate unambiguous signals

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

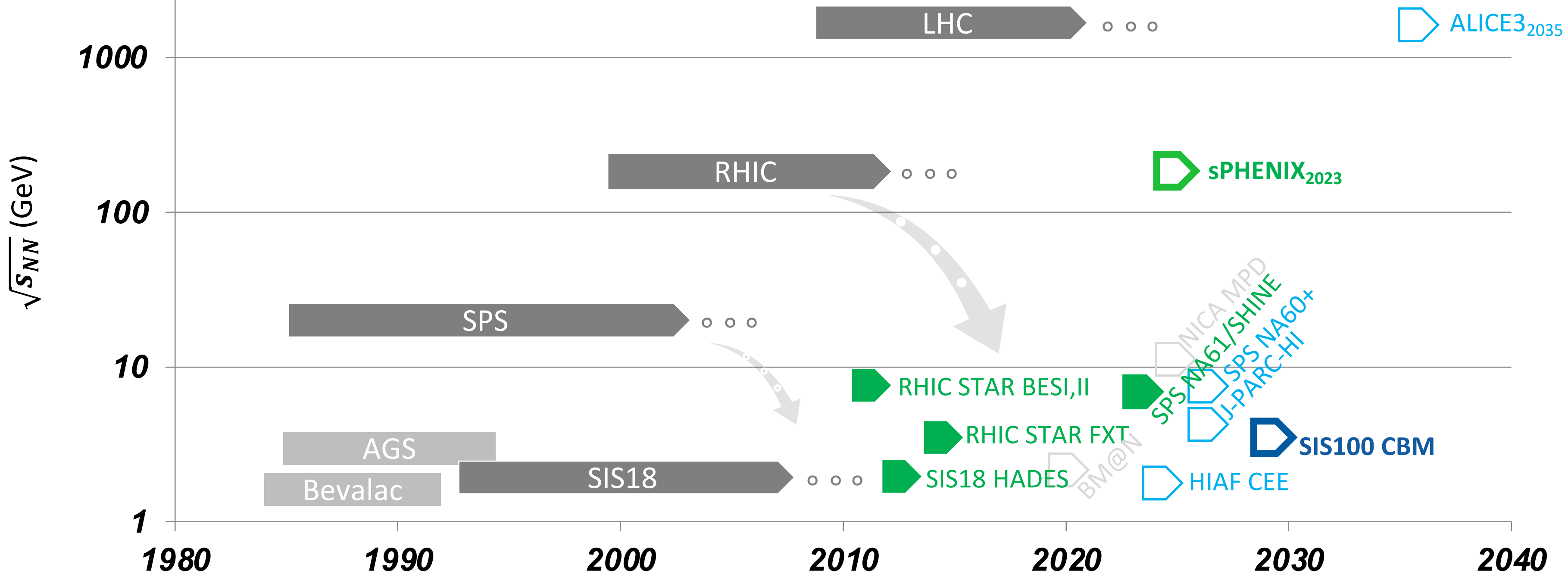
Quest for highest energy



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)



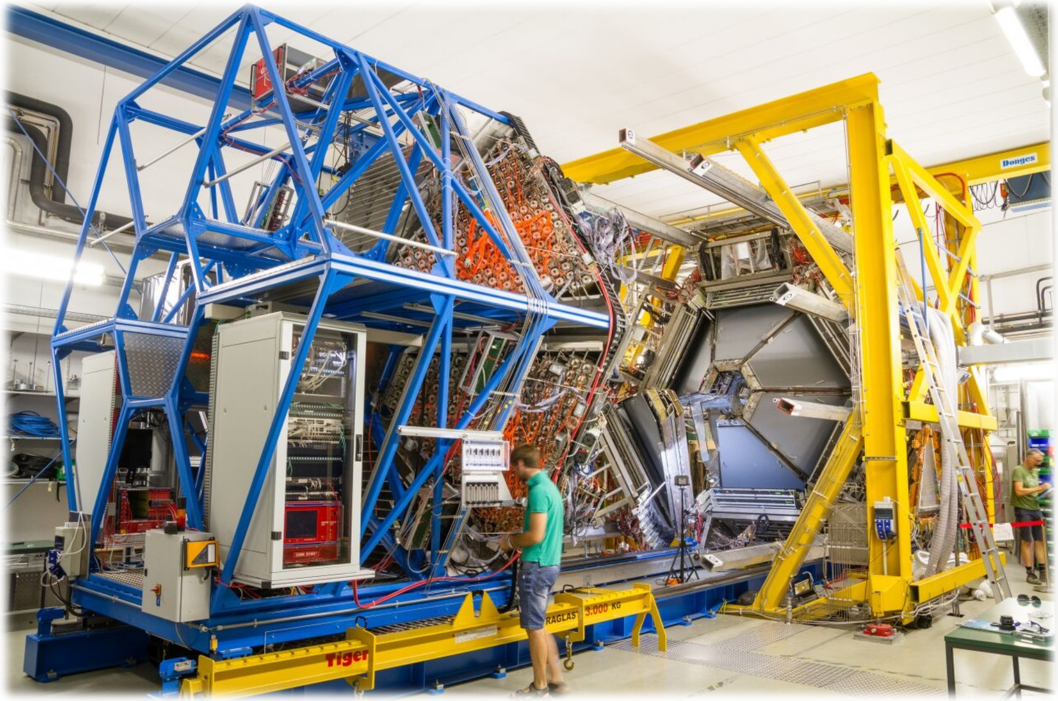
Time ≡ advances in accelerator and detector technologies

High Aceptance DiElectron Spectrometer

HADES at SIS18, GSI-Darmstadt, Germany

- Fixed target experiment
- High acceptance
  - Full azimuthal coverage, 18°-85° polar angle
- Efficient track reconstruction
  - Low-mass tracking with drift chambers
  - 0.14 – 0.3 Tm toroidal field
- Precise: mass resolution few %
- High interaction rate: up to 50kHz accepted trigger rates
- Heavy-ion, p and secondary π SIS18 beams

Focus on rare and penetrating probes



Hadron production and azimuthal anisotropy

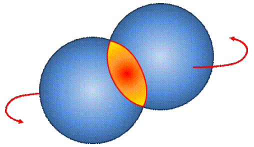
COLLECTIVITY

Azimuthal anisotropy

with respect to reaction plane (RP)

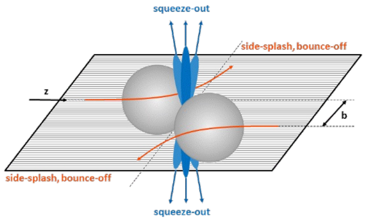
Fourier coefficients of the distribution

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

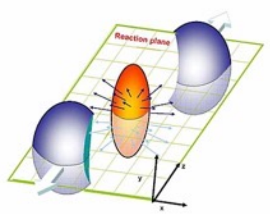


v_1 deflection of matter in the RP (signal of the phase transition?)

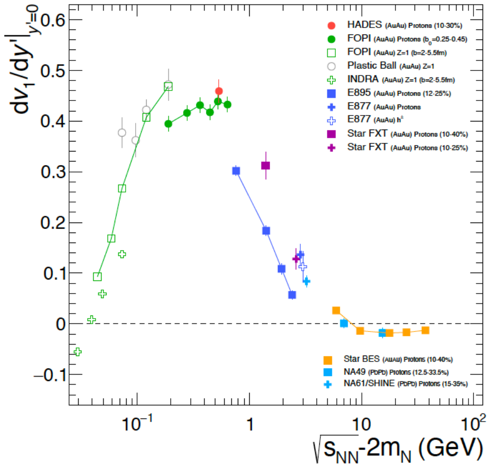
Paech *et al.*, Nucl.Phys.A 681 (2001) 41-48

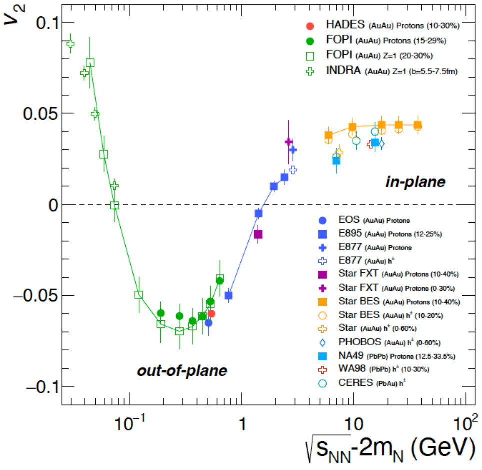


$v_2 < 0$ when spectators pass slower than fireball expands



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



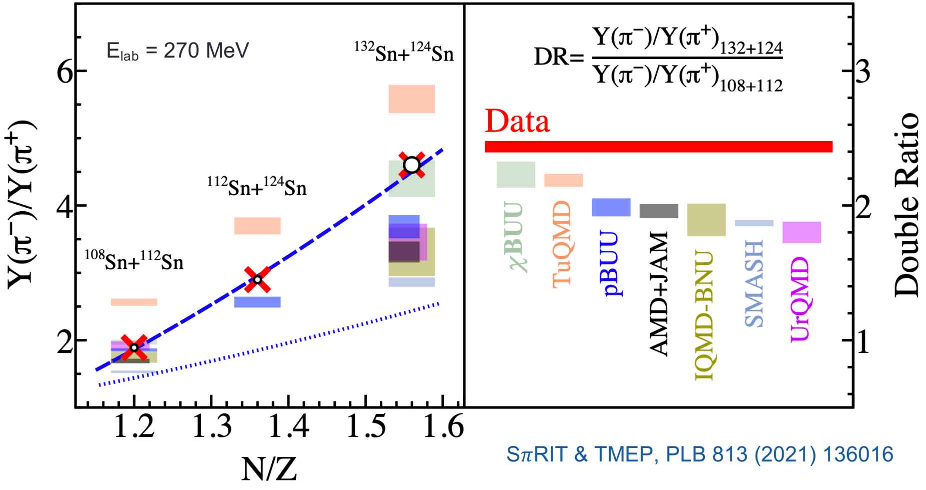


constrain EoS by means of microscopic transport model

HADES, in preparation

Known knowns and known unknowns

Predictions of the transport models differ too much to allow extraction of reliable constraints on the symmetry energy from the data



SπRIT & TMEP, PLB 813 (2021) 136016

- Density dependence of E_{sym} , L_0 is of a great importance and becomes a part of multi-messenger
- Important, but very uncertain at high-density!

Characteristics of nucleonic matter EOS

$E(\varrho,\delta) = E_0(\varrho) + E_{\mathrm{sym}}(\varrho)\delta^2 + \mathcal{O}(\delta^4)$ nucleon specific energy

$\delta = (\varrho_n - \varrho_p)/\varrho$ isospin assymetry at $T = 0$

$E_o(\varrho)$ nucleon specific energy in symmetric NM

Taylor-expansion at ρ_0

$$E_o(\varrho) = E_0(\varrho_0) + \frac{K_0}{2}\left(\frac{\varrho-\varrho_0}{3\varrho_0}\right)^2 + \cdots$$

$$E_{\mathrm{sym}}(\varrho) = E_{\mathrm{sym}}(\varrho_0) + L\left(\frac{\varrho-\varrho_0}{3\varrho_0}\right) + \cdots$$

K_0 - incompressibility

$$L = 3\varrho_0\left[\frac{\partial E_{sym}(\varrho)}{\partial\rho}\right]\Big|_{\varrho=\varrho_0}$$

Potentials in transport models

Typically a Skyrme-type mean field potential (hard or soft density dependence)

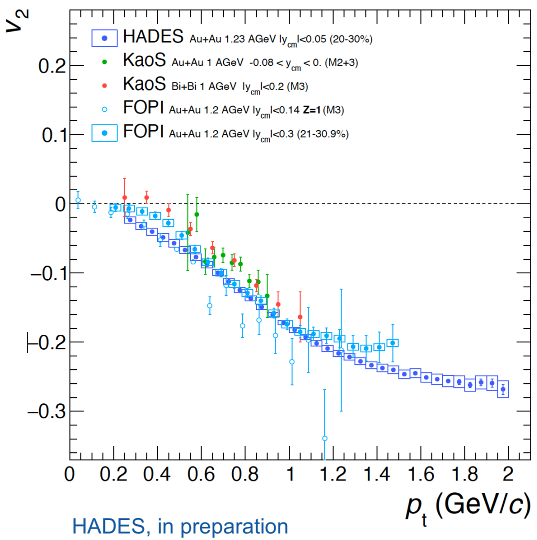
$$V_{\mathrm{Sk}} = \alpha\left(\frac{\varrho_{int}}{\varrho_0}\right) + \beta\left(\frac{\varrho_{int}}{\varrho_0}\right)^{\gamma}$$

The parameters are partly **fixed** by demanding stable nuclear matter **around saturation density**

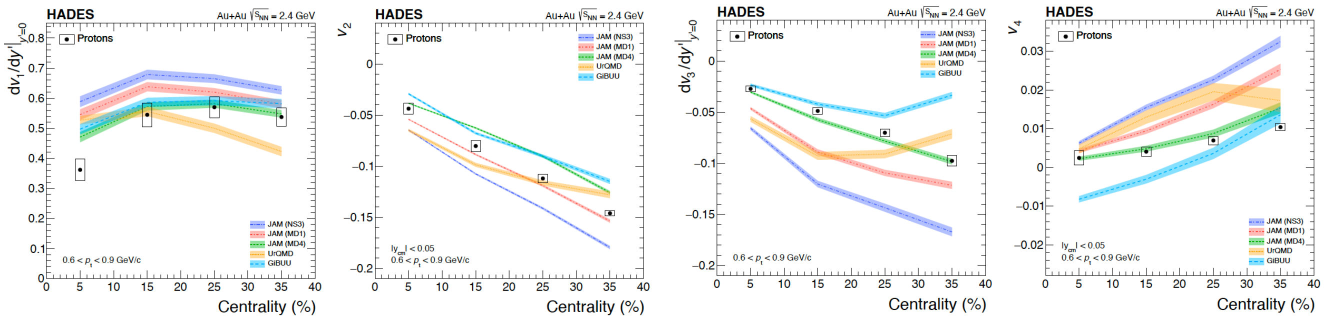
Problem of relativistic treatment

Azimuthal anisotropy and EoS

- High precision multi-differential data for protons and light nuclei $v_n, n = 1-6$ HADES, PRL 125 (2020) 262301
- 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

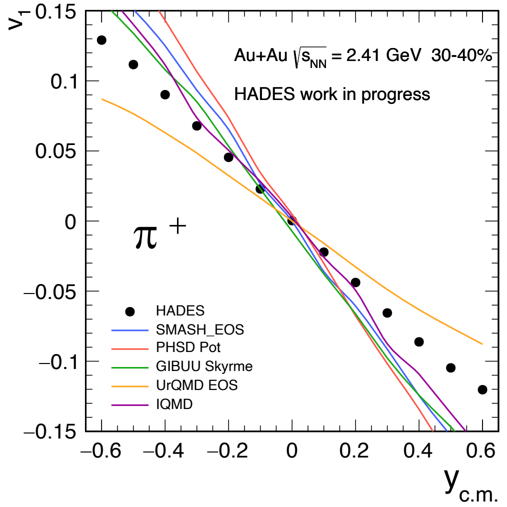


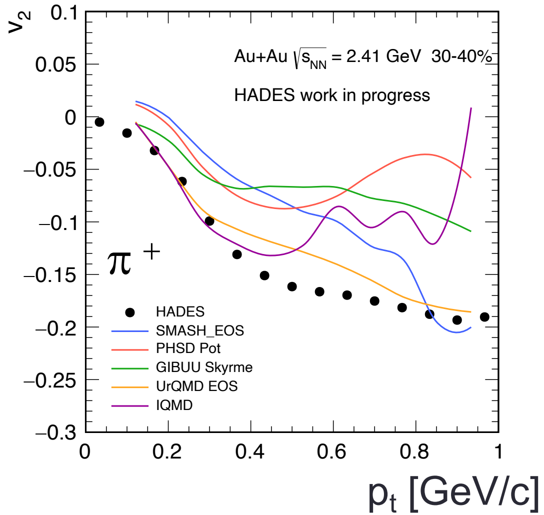
HADES, in preparation

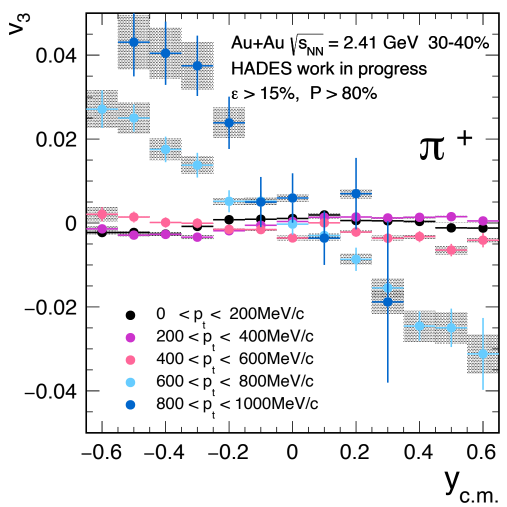


JAM (NS3)	hard momentum independent NS3
JAM (MD1)	hard momentum dependent
JAM (MD4)	soft momentum dependent MD4
UrQMD	"hard EoS" (UrQMD 3.4)
GiBUU	"soft EoS" (GiBUU 2019, Skyrme 12)

Azimuthal anisotropy of charged pions: Au+Au $\sqrt{s_{NN}} = 2.42$ GeV



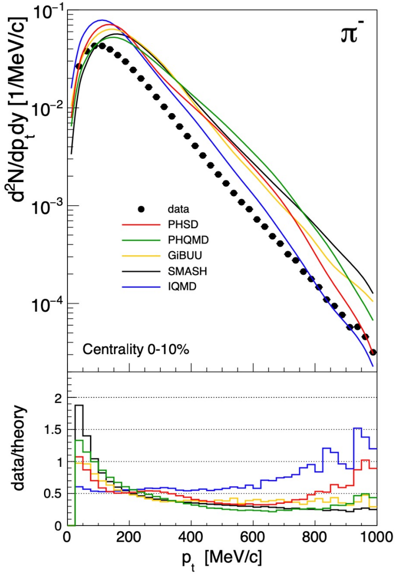




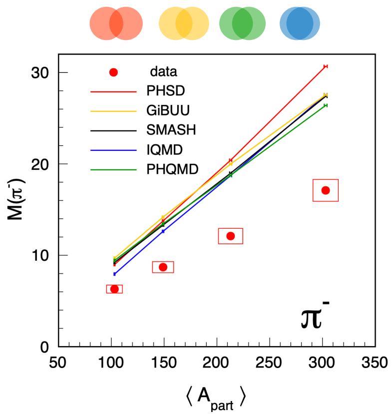
- Good statistics to constrain models and equation of state
- There is room for improvement in the models
- Simultaneous description of collision system, centrality and energy dependence (HADES data Au+Au, Ag+Ag)

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

Spectra

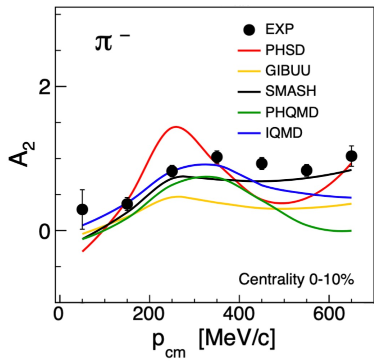


Multiplicity



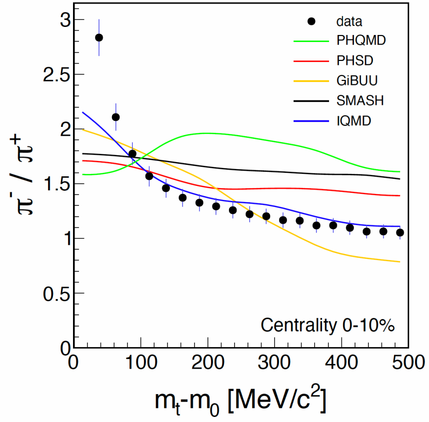
Angular distribution

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



HADES, EPJA 56 (2020) 10, 259

EM interaction

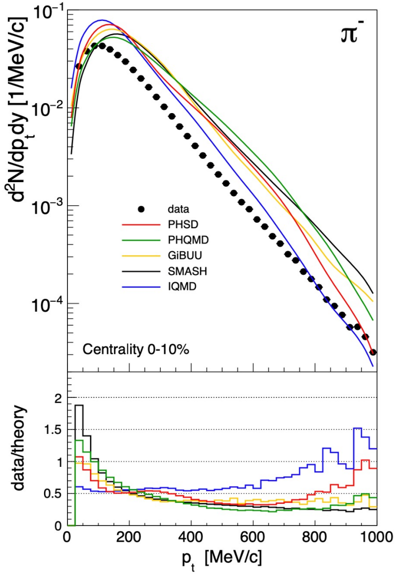


HADES, arXiv:2202.12750 [nucl-ex]

- Transport models consistently fail to describe the data
- Main source of pions – baryonic resonances propagating in hot and dense fireball

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

Spectra



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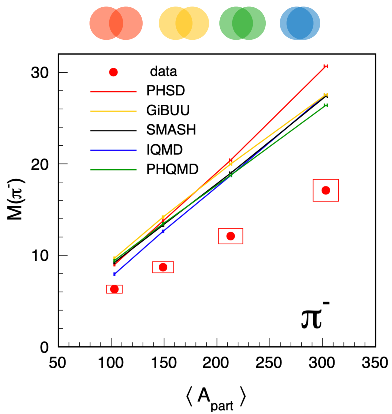

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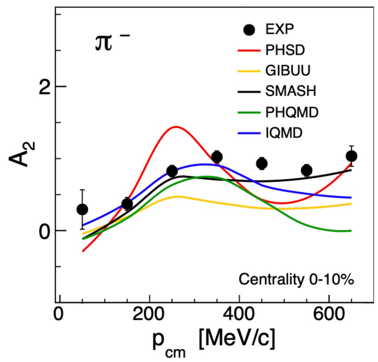

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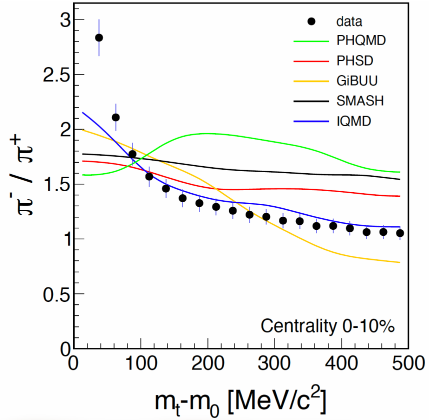
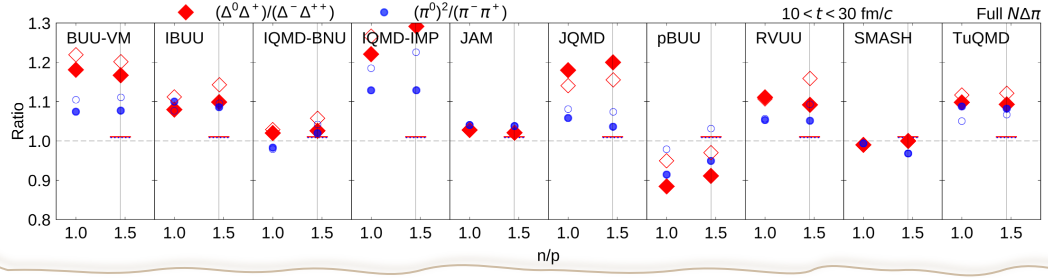


HADES, arXiv:2202.12750 [nucl-ex]

Evaluate, understand and reduce the uncertainties in transport-code results (pions and Δ resonances in a box)



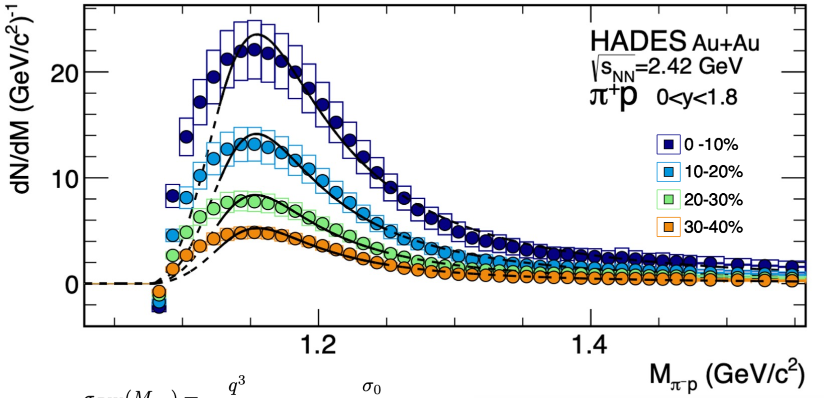
Ono *et al.*, PRC 100 (2019) 4, 044617

- Transport models consistently fail to describe the data
- Main source of pions – baryonic resonances propagating in hot and dense fireball

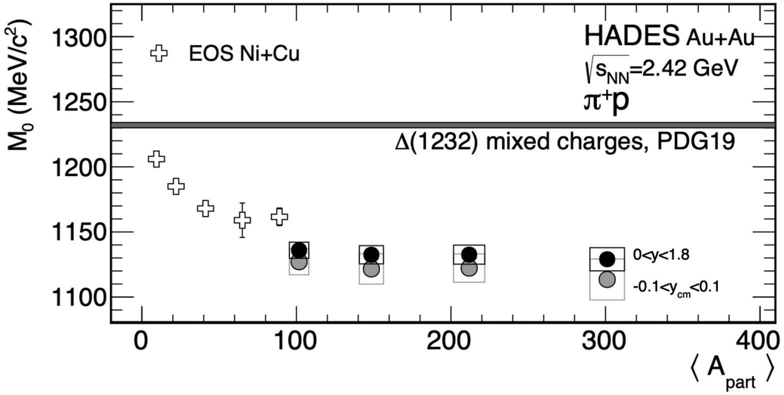
Correlated pion-proton pair emission

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

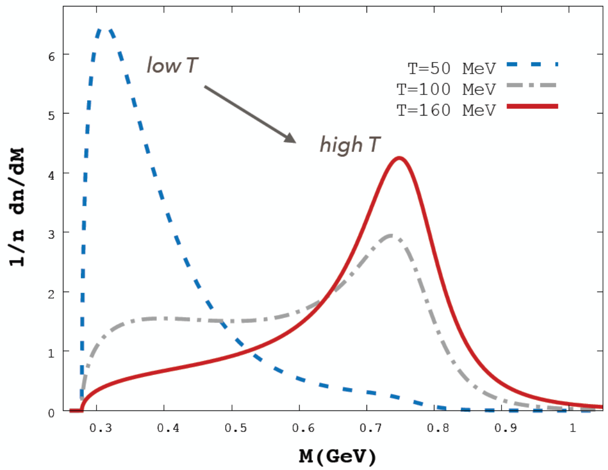
UrQMD, Reichert *et al.*, NPA 1007 (2021) 122058
RVUU, Godbey *et al.*, PLB 829 (2022) 137134

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

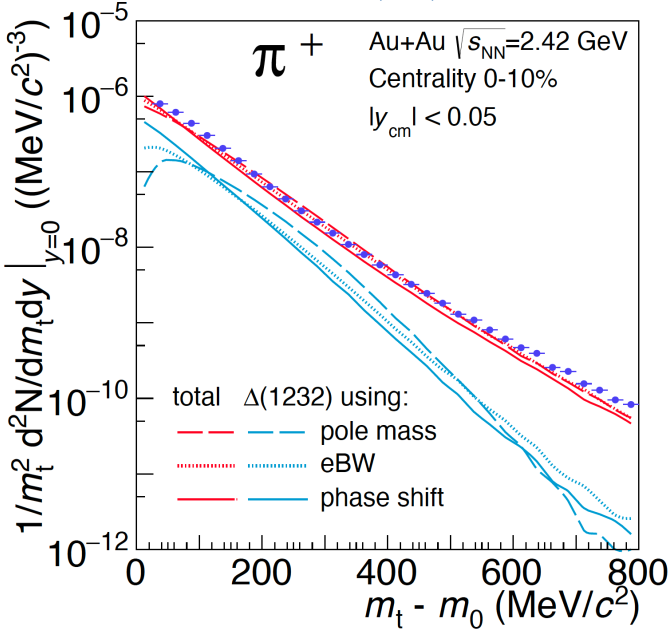
Dashen *et al.*, Phys. Rev. 187 (1969) 345

Thermodynamics of an interacting πN system

Lo *et al.*, PRC 96 (2017) 015207
Weinhold, Friman, PLB 433 (1998) 236



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



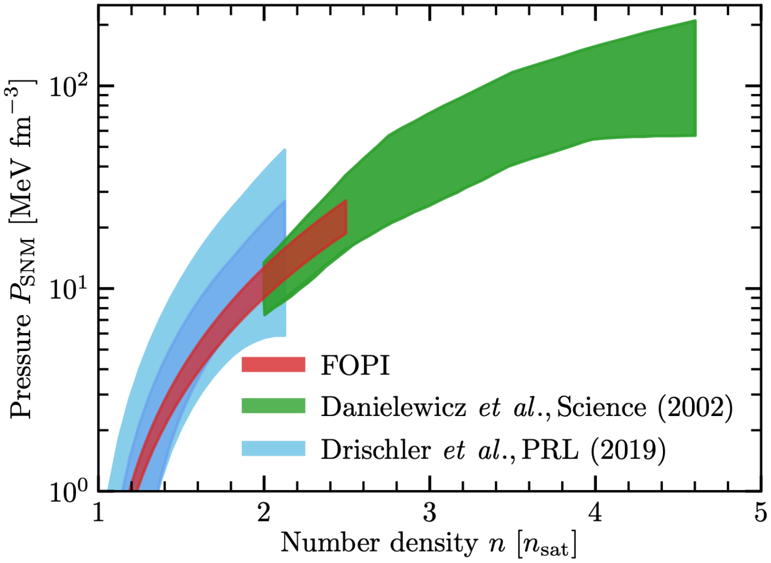
- Phase shifts fully encode hadronic interactions
- Include also non-resonant contribution not captured by Breit-Wigner parametrization
  - moves *e.g.* Δ, ρ pole towards lower *M*
  - strong effect on yields

➡ Application: analysis of hadron yields, p_T spectra

Employing trivial spectral function for the nucleon (δ-function) and the free spectral function of the Δ resonance, is incorrect

Prospects

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



- New high precision differential measurements at high and low energies
- State-of-the-art dynamical models
- Bayesian multi-parameter techniques

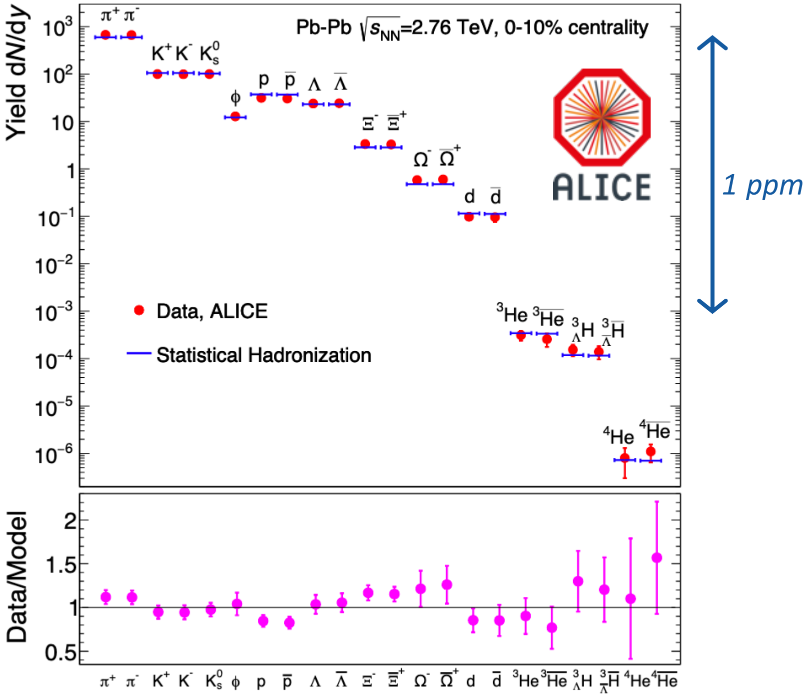
Constraints on EoS at high density including uncertainty for symmetry energy

System with multi-particle correlations

MATTER EFFECTS

Are we creating a thermal medium in experiments?

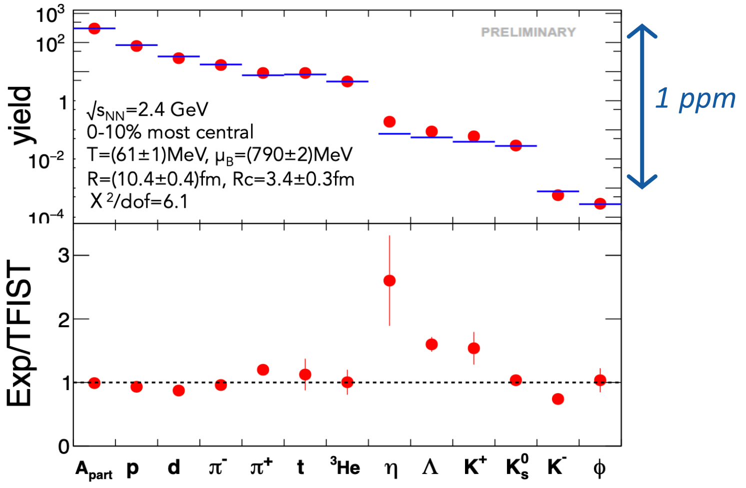
Hadron yields and statistical hadronization model (SHM)



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

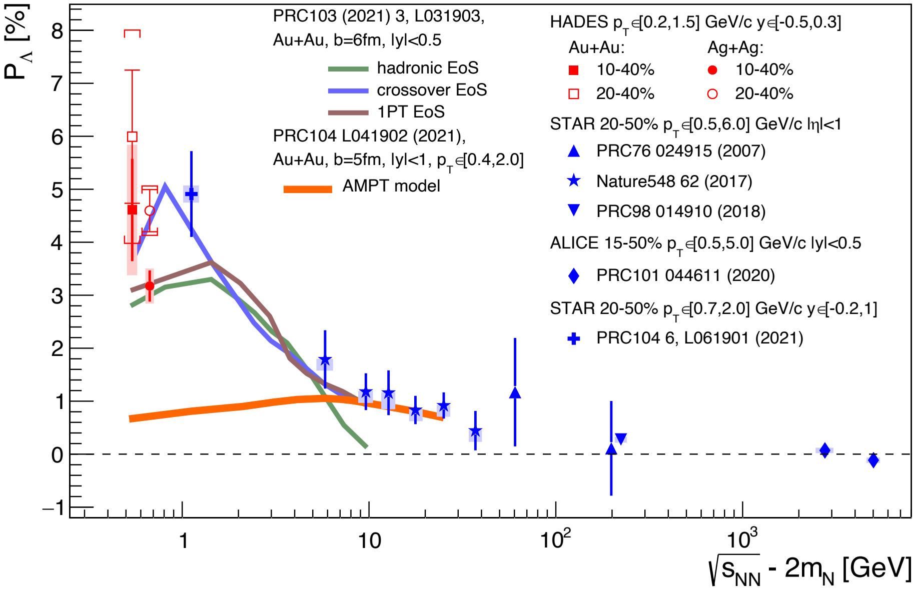


Λ polarization at HADES

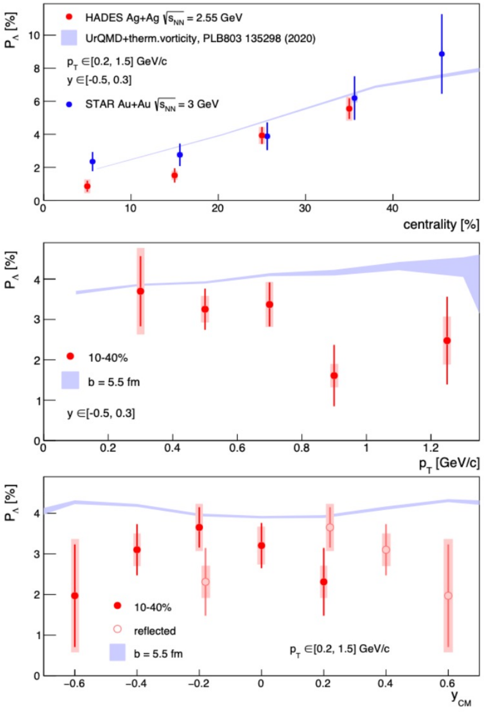
Do we observe a maximum of the global polarization at SIS18 energies?

HADES, arXiv:2207.05160 [nucl-ex]

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



- Directed flow slope at midrapidity follows world data
- Ag+Ag vs Au+Au collisions: effect of the different system size?



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) 135298

Matter effects on strangeness production

VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Subthreshold Kaon Production as a Probe of the Nuclear Equation of State

J. Aichelin and Che Ming Ko[(a)]
Joint Institute for Heavy Ion Research, Holifield Heavy Ion Research Facility, Oak Ridge, Tennessee 37831
(Received 11 June 1985; revised manuscript received 23 September 1985)

The production of kaons at subthreshold energies from heavy-ion collisions is sensitive to the nuclear equation of state. In the Boltzmann-Uehling-Uhlenbeck model, the number of produced kaons from central collisions between heavy nuclei at incident energies around 700 MeV/nucleon can vary by a factor of ~ 3, depending on the equation of state.

In a nutshell:

- softer EoS leads to higher compression leads to more secondary interaction
- thus larger probability to produce particles below free nucleon-nucleon production threshold

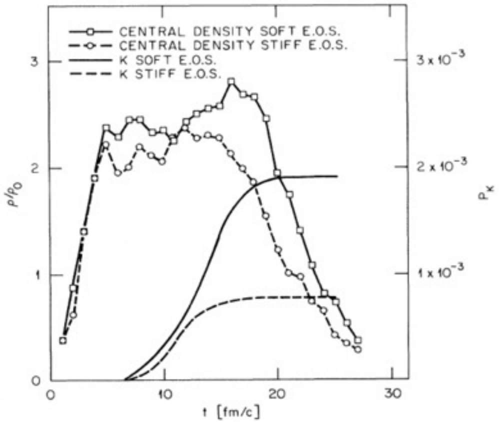
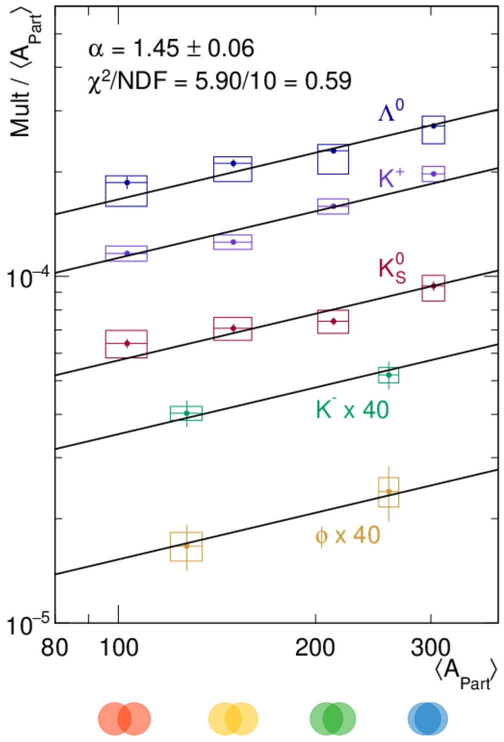


FIG. 1. Central density ρ/ρ_0 and total kaon-production probability P_K as functions of the collision time for reactions between Nb nuclei at an incident energy 700A MeV and at an impact parameter $b = 0.5$ fm.

Rare sub-threshold strangeness production

HADES, PLB 793 (2019) 457

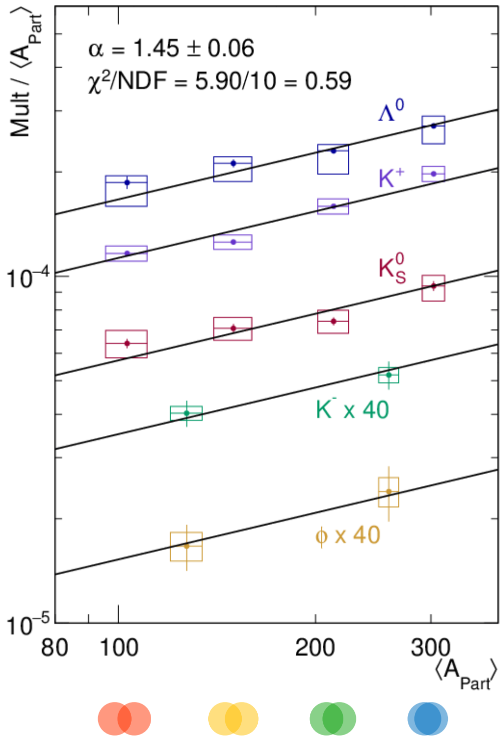


- Universal scaling with participant number $M \sim \langle A_{part} \rangle^{\alpha}$ (same observation in Ag+Ag data)
- Does not reflect the hierarchy of NN production thresholds
  - $K^{+}\Lambda$: -130 MeV
  - $K^{+}K^{-}$: -440 MeV
- Not expected if strangeness produced in *isolated* NN collisions

Scaling with absolute amount of strangeness not with individual hadron states

Rare sub-threshold strangeness production

HADES, PLB 793 (2019) 457



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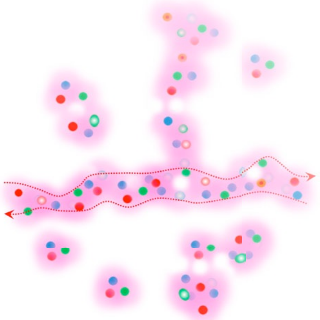
Scaling with absolute amount of strangeness not with individual hadron states



Connection to "soft deconfinement"?

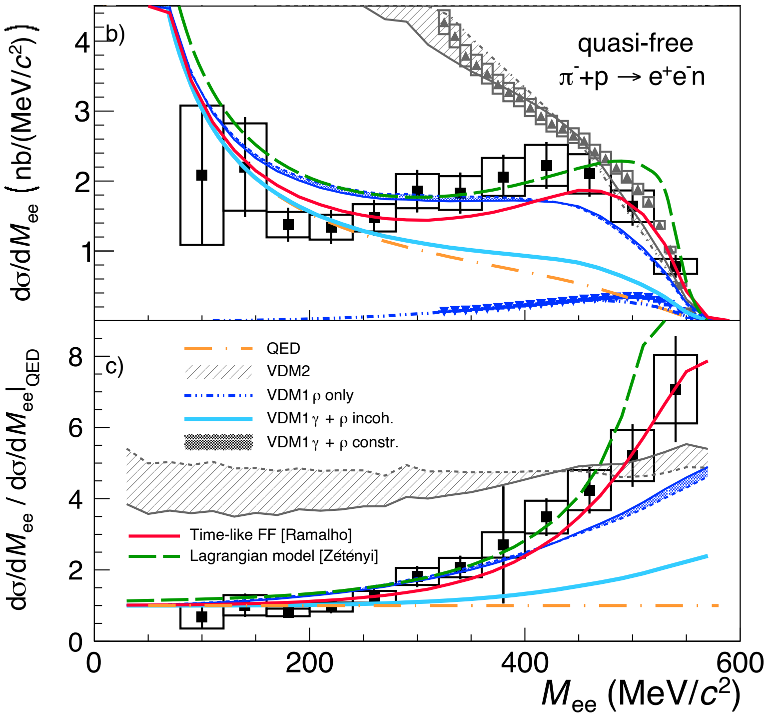
Fukushima, Kojo, Weise, PRD 102 (2020) 9, 096017

Quantum percolation at $\rho\sim1.8\rho_0$ of the interaction meson clouds

Meson cloud

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

HADES, arXiv:2205.15914 [nucl-ex]

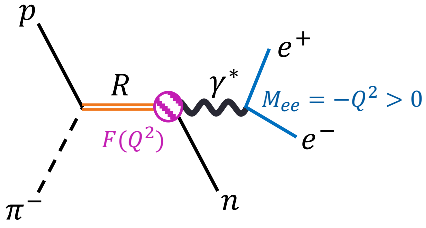


- $\pi^- p \rightarrow n + \pi^- + \pi^+$
  - included in PWA (Bonn-Gatchina) to provide partial wave decomposition

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

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

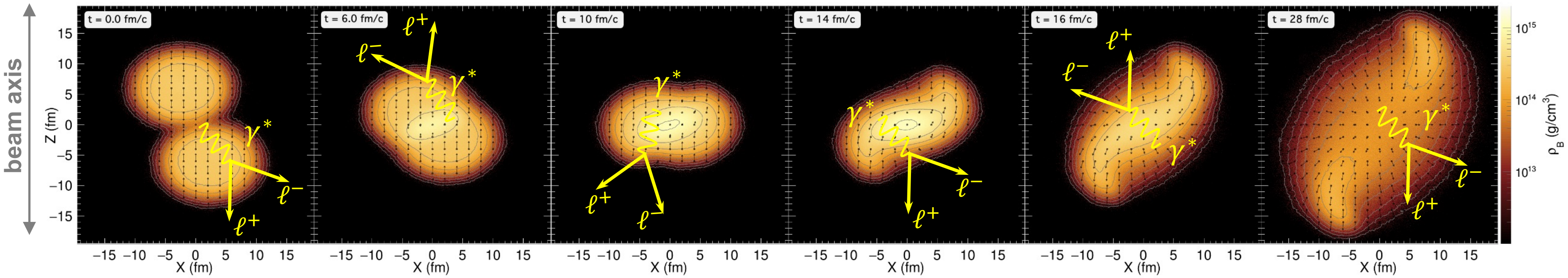
- $\pi^- p \rightarrow n + e^- + e^+$
  - study the structure of the nucleon as an extended object (quark core and meson cloud)
- Dominance of the $N^*(1520)$ resonance at $\sqrt{s_{NN}} = 1.49$ GeV
  - ρ meson as "excitation" of the meson cloud
  - **Vector Meson Dominance - basis of emissivity calculations for QCD matter**



Electromagnetic radiation

EMISSIVITY

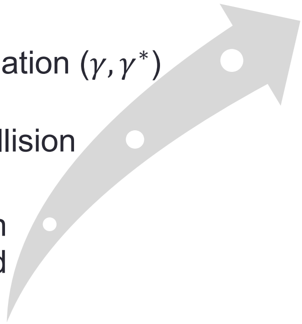
Electromagnetic radiation as multi-messenger of fireball



Electromagnetic radiation (γ, γ^*)

Reflect the whole history of a collision

No strong final state interaction
⇝ leave reaction volume undisturbed



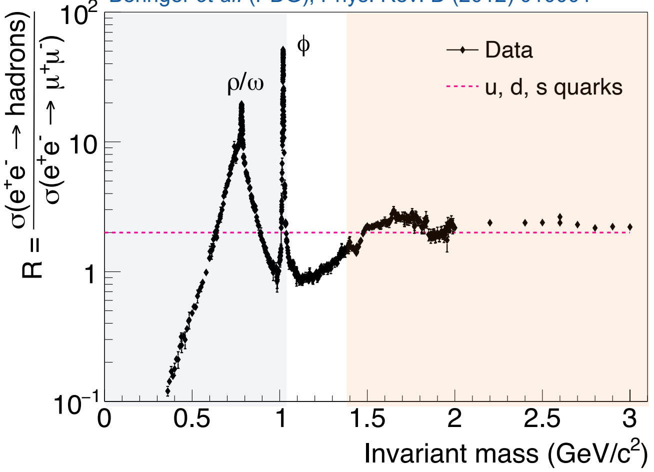
Encodes information on matter properties enabling unique measurements

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

Electromagnetic spectral function in the vacuum

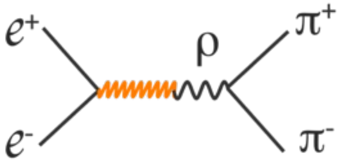
accurately known from e^+e^-annihilation $R \propto \frac{Im\Pi_{em}^{vac}}{M^2}$

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



Low-mass regime LMR

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

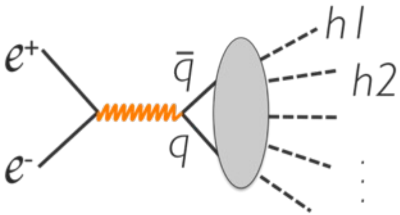


$$Im\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 ImD_v^{vac}(M)$$

Sakurai, Ann.Phys. 11 (1960)

Intermediate-mass regime IMR

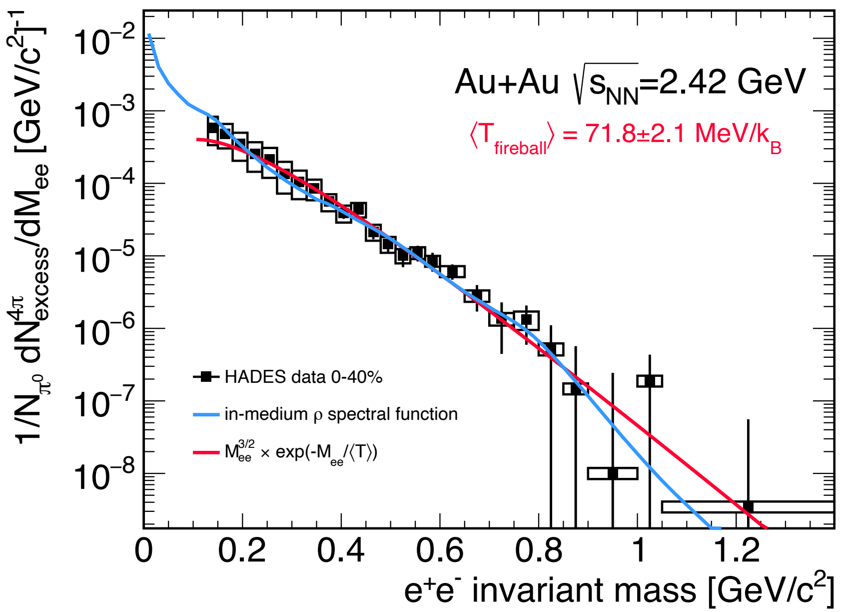
perturbative QCD continuum (quark degrees of freedom)



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

Thermal dileptons from baryon rich matter

HADES, Nature Phys. 15(2019) 1040



'Planck-like'

In-medium spectral function

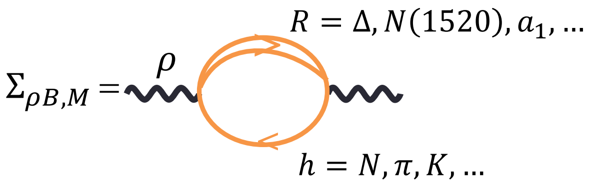
$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T)\, Im\Pi_{em}(M,q,T,\mu_B)$$

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

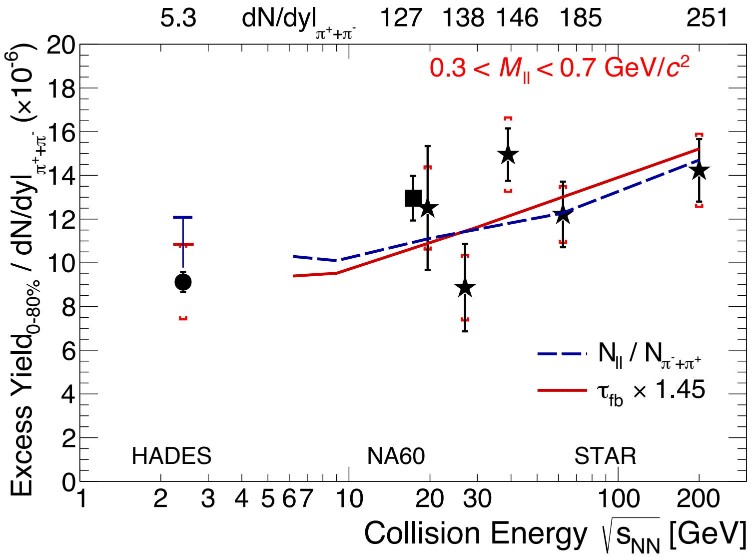
- Thermal excess radiation established at HADES (Au+Au, Ag+Ag)
  - ρ-meson peak undergoes a strong broadening in medium
  - in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

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

- Baryonic effects are crucial



The fireball lifetime



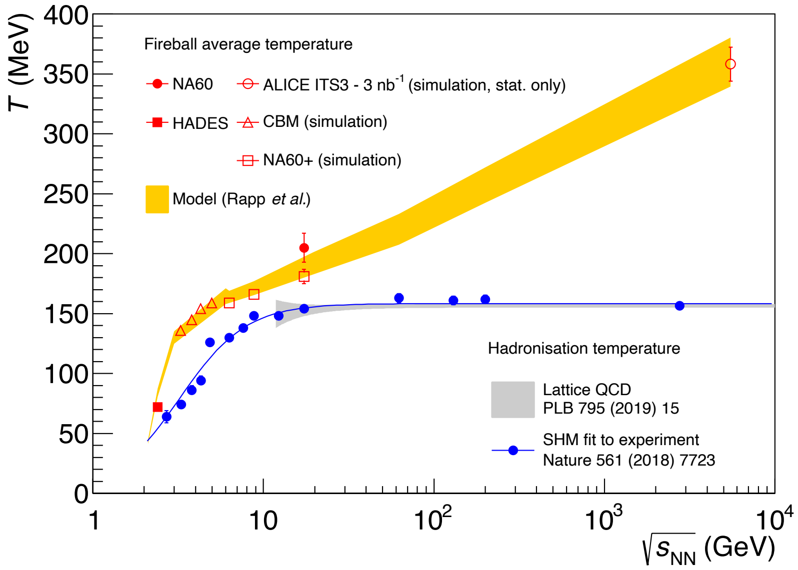
TG., JPS Conf.Proc. 32 (2020) 010079

- 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

Mapping QCD "caloric curve" (T vs ε)



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

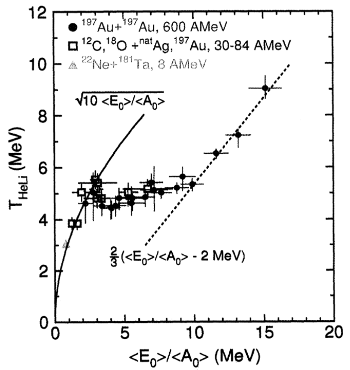
- Dilepton invariant mass slope measures radiating source temperature (independent of flow: no blue shift!)
- To date two measurements NA60 and HADES

NA60, EPJC 61(2009) 711
HADES, Nature Phys. 15(2019) 1040

- Signature for phase transition?
  ↝ phase transition may show up as a plateau!

Nuclear liquid-gas phase transition

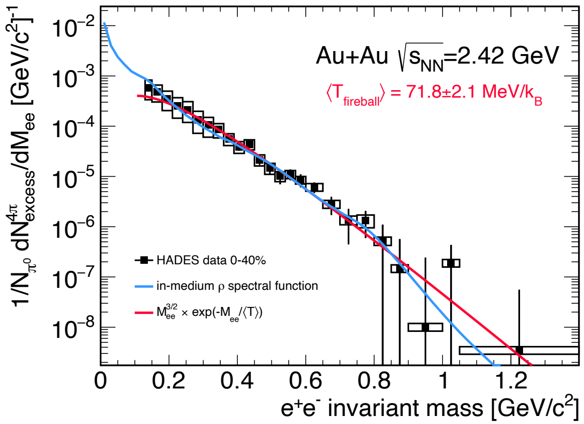
Pochodzalla *et al.*,
PRL 75 (1995) 1040-1043



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

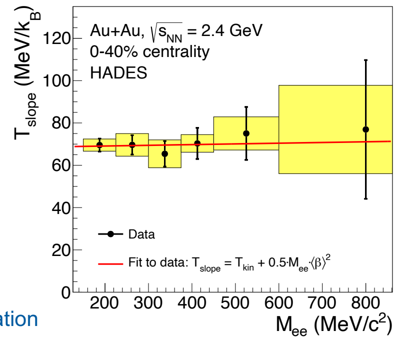
- Radiation from a source
  - long-lived ($\tau \approx 13\ fm$)
  - in local thermal equilibrium
  - $\langle T \rangle \approx 72$ MeV
  - $\varrho\ = 2 - 3\ \varrho_0$

Invariant mass



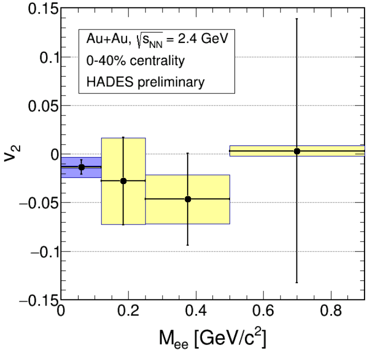
HADES, Nature Phys. 15(2019) 1040

Inverse slope (p_t)

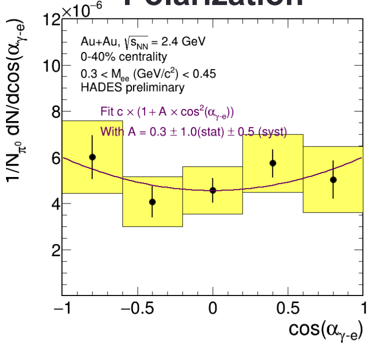


HADES, in preparation

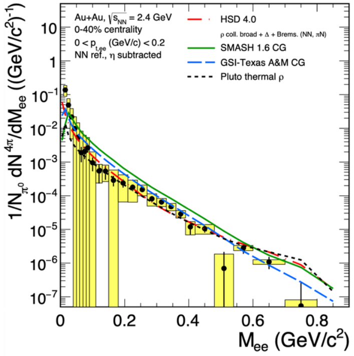
Elliptic flow (v_2)



Polarization

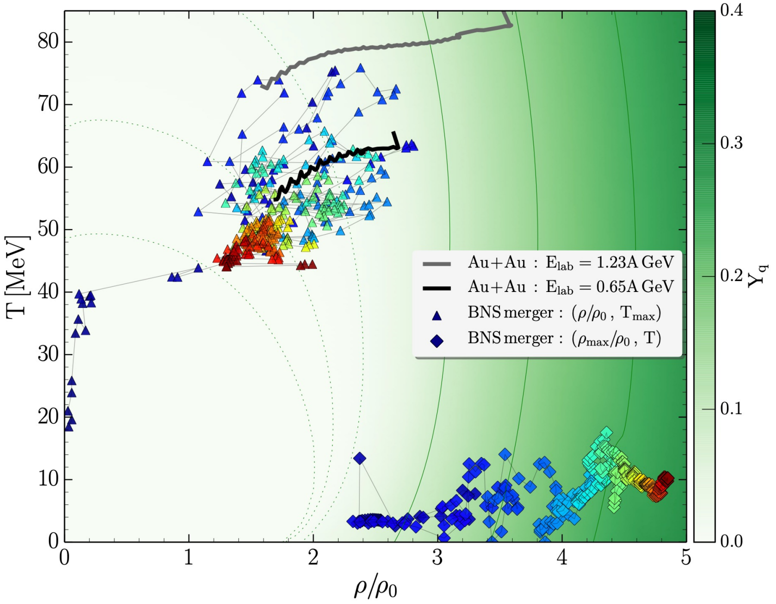


Electrical conductivity?



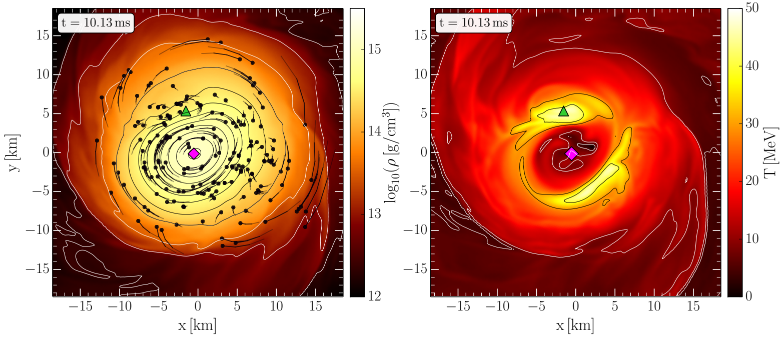
The QCD phase structure at high μ_B

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)

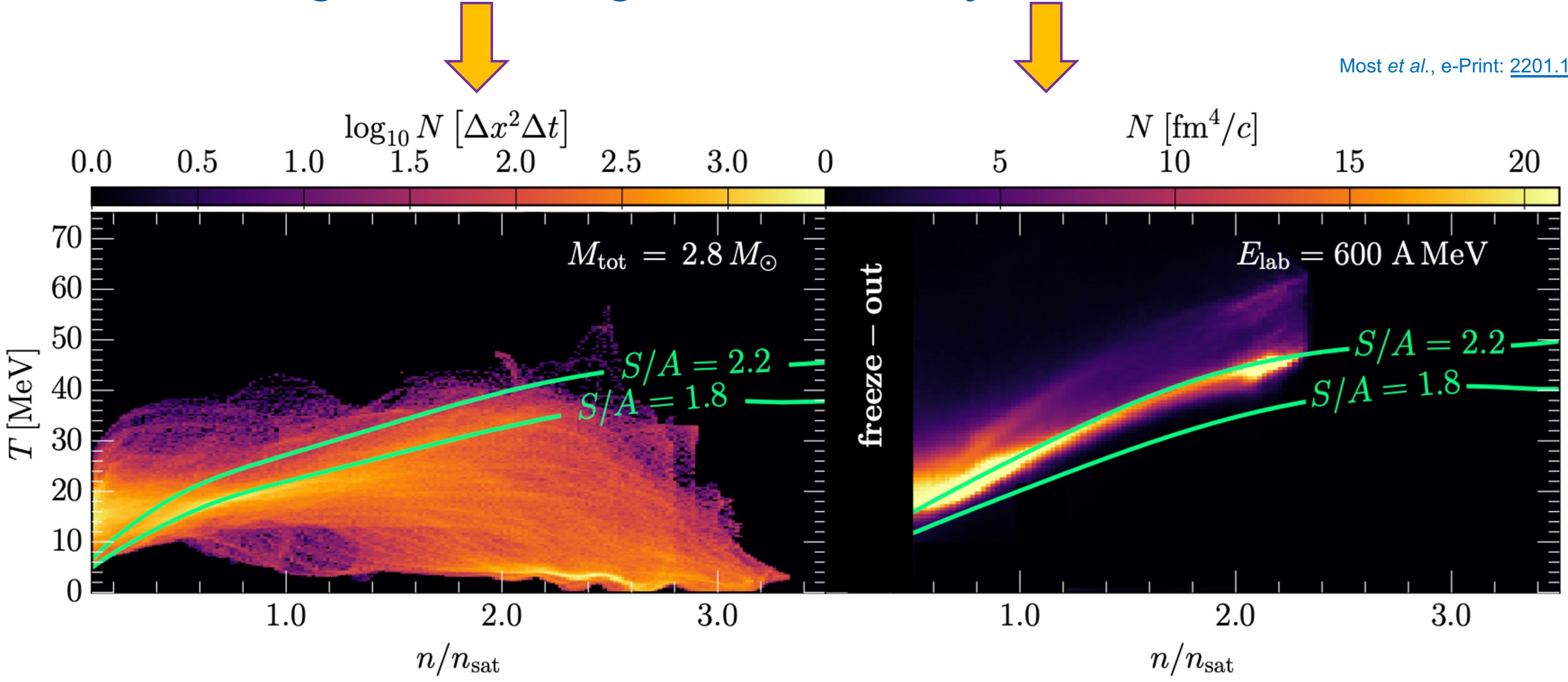


- 18 orders of magnitude in scales, still similar
- T < 70 MeV, $\varrho < 3\,\varrho_0$ for both
- Dileptons sensitive to dense phase

⤳ **One EoS for simultaneous description of nuclear physics and observations**

Connecting BNS mergers to heavy-ion collisions

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



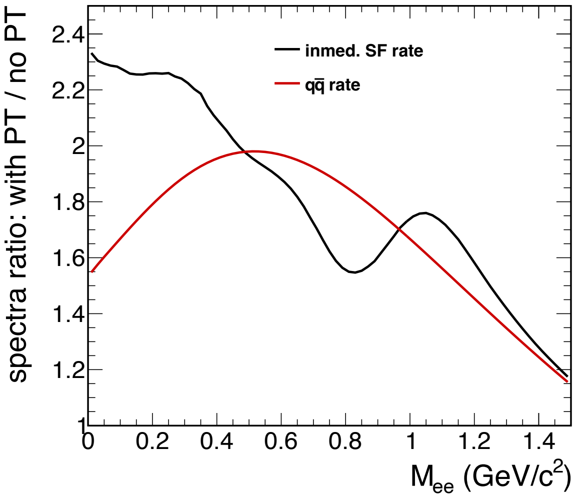
Employing same equation-of-state for simultaneous description of BNS merger and HIC

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

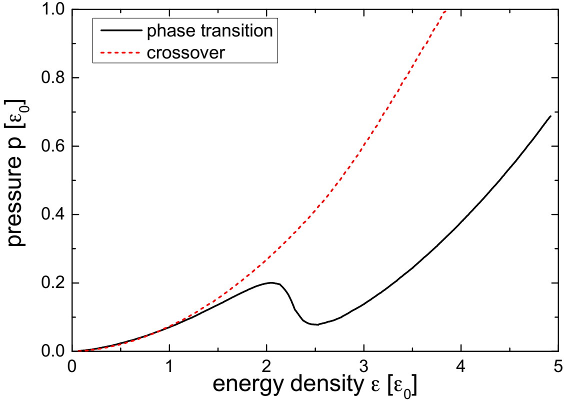
Dilepton signature of a 1st order phase transition

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

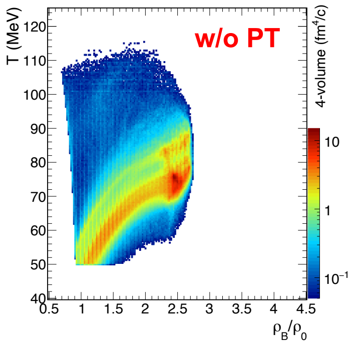
- CMF model that matches lattice QCD at low μ_B and neutron-star constraints at high density
  Motornenko *et al.*, PRC 101 (2020) no.3, 034904
- 3+1 D fluid dynamics with and w/o first order nuclear matter – quark matter phase transition

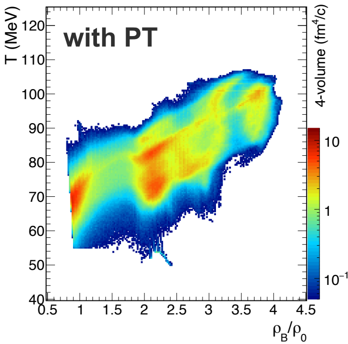


Pressure vs energy density along the line of constant S/A



Fireball trajectories (hydro)





Different dilepton rates give both an increase of factor ~2 due to extended “cooking”

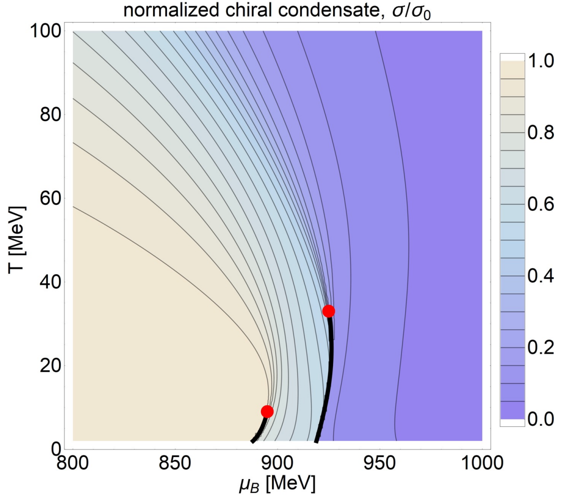
see also Li and Ko, PRC 95 (2017) no.5, 055203

Strong increase of the dilepton emission for a phase transition

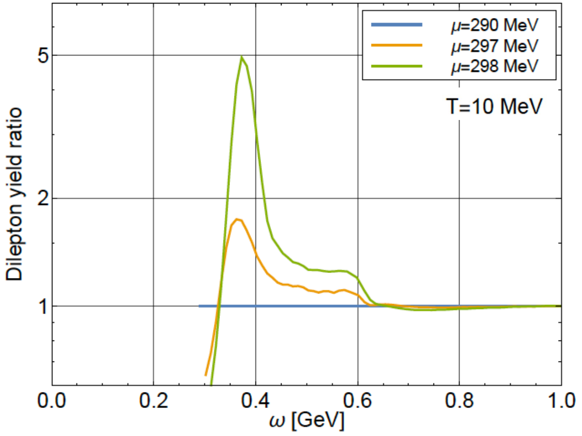
Effective hadronic theory for nuclear matter

- **Parity-doublet model** describes nuclear liquid-gas transition together with a chiral phase transition
- Thermodynamically consistent spectral functions from aFRG flows

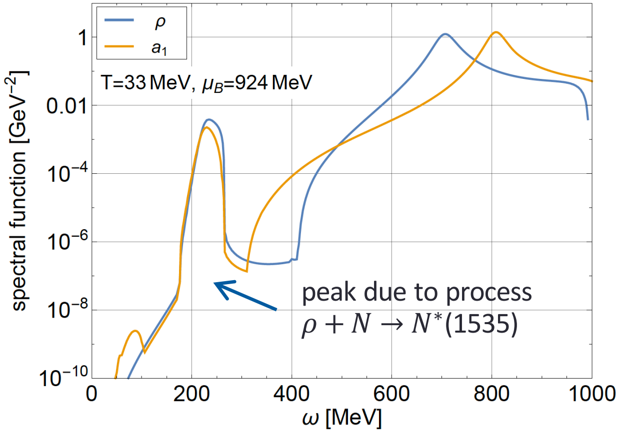
Tripolt, Jung, Smekal, Wambach, PRD 104, 054005 (2021)



Dilepton rates at CEP
$T = 10$ MeV, $\mu_B = 292$ MeV



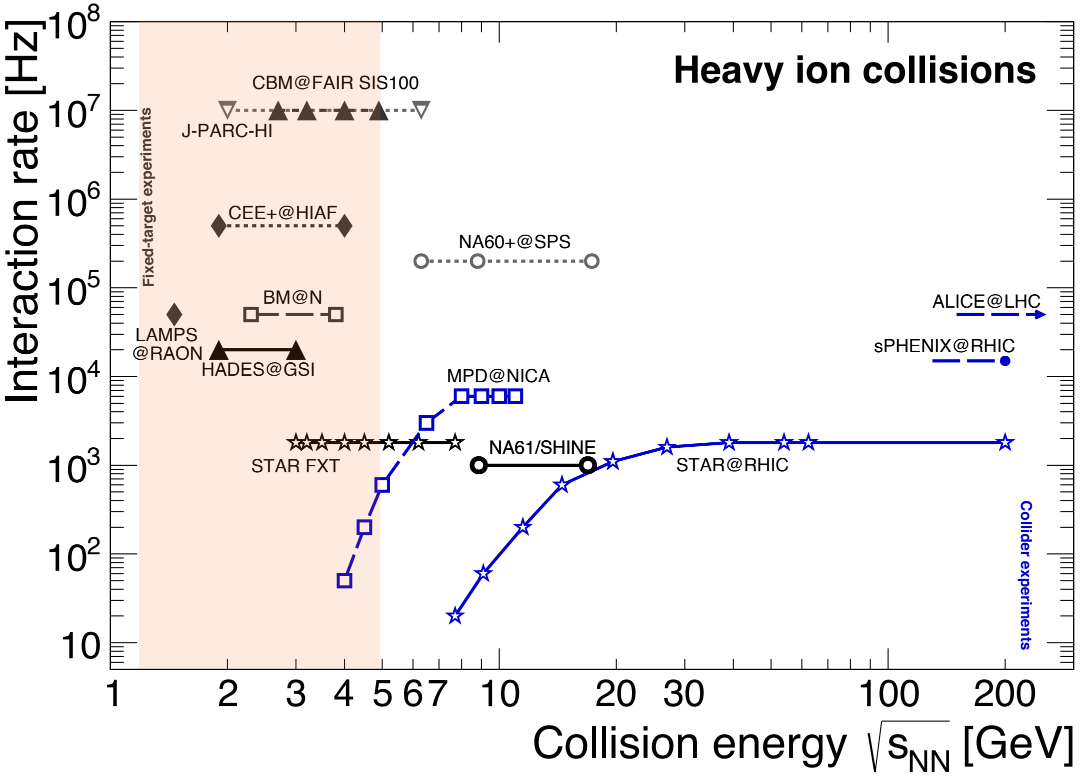
ρ and $a1$ spectral functions near chiral CEP in FRG



Tripolt *et al.*, NPA 982 (2019) 775
Jung *et al.*, PRD 95 (2017) 036020

OUTLOOK

The future is bright



Future experiments aim at utmost precision measurements for rare probes

- High intensity beams
- Multipurpose detectors:
  - large acceptance, high efficiency
  - trigger-less, free streaming read-out electronics with high bandwidth online event selection
  - substantial progress in detector technologies
- High-performance / scientific computing

New theoretical developments

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

HADES during FAIR Phase-0

FAIR Phase 0 Research Program

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

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

submitted to G-PAC

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

submitted to G-PAC

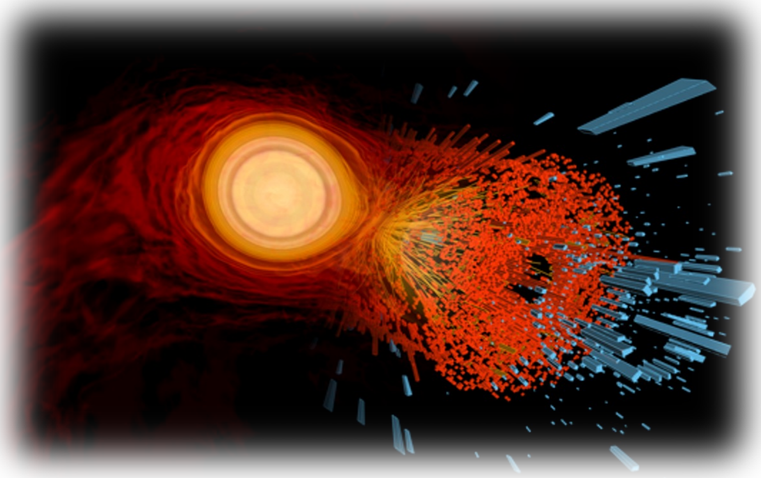
Cold matter effects including line shapes and SRC p+Ag 4.5 GeV

Studying Medium Effects in Proton Induced Reactions
p+Ag reactions at 4.5 GeV
The HADES Collaboration

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

How can heavy-ion experiments help us understand neutron star mergers?



How can neutron star mergers help us understand heavy-ion experiments?

- Our goal is to understand QCD matter, not neutron star matter or heavy ion collision matter. The latter are mere inputs for simulations.
- BNS mergers + HICs superb tools to explore nuclear matter under extreme conditions.

Thank you for your attention!

BACKUP

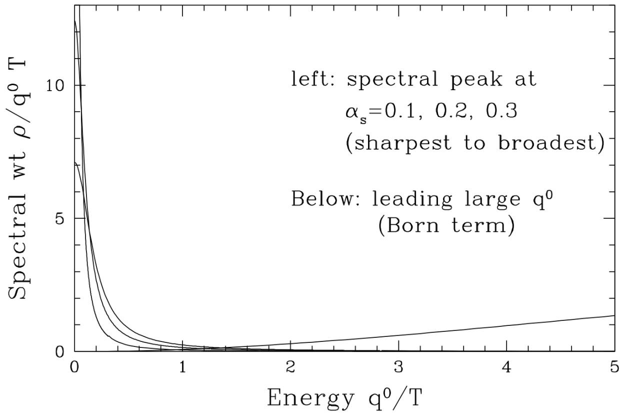
Transport properties of the medium

Electrical conductivity

can be directly obtained from the low-energy limit of the EM spectral function (at vanishing momentum)

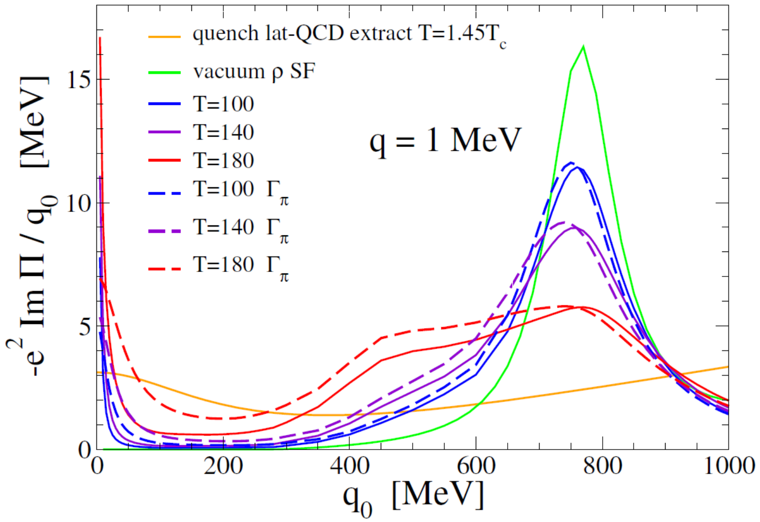
$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$$

Transport peak in the limit of very low mass and p_T



Moore and Robert, arXiv:hep-ph/0607172

Rapp, EMMI RRTF 2021



- Conductivity is reduced when thermal-pion interactions included
- Transport peak broadens

Critical fluctuations

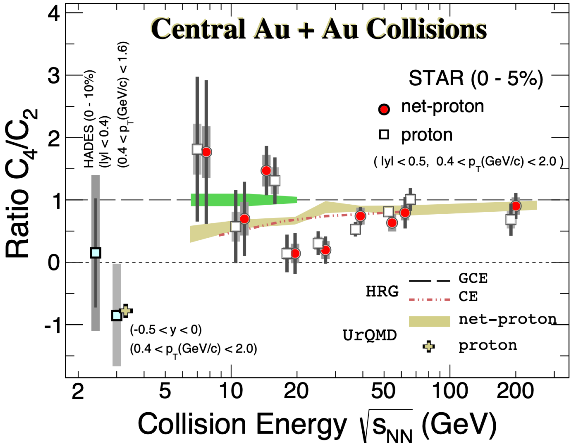
Ling, Stephanov, PRC 93, 034915 (2016)

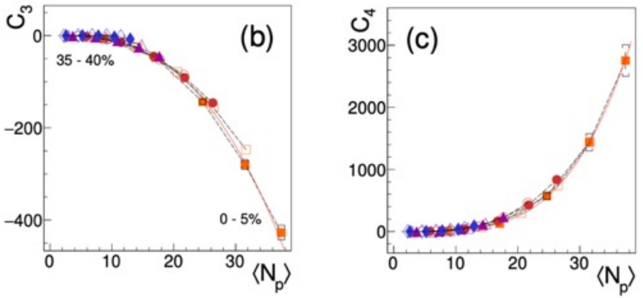
Cumulants k_n hold information on multi-particle correlators C_n

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





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

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

$\alpha \simeq n$ → 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

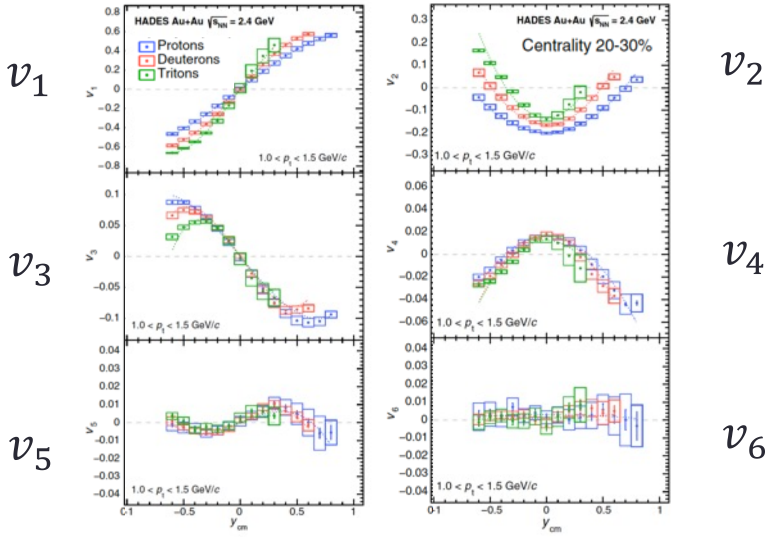
cf. B. Friman *et al.*, EPJC 71 (2011) 1694
M. Stephanov, Phys.Rev.Lett.107 (2011) 052301

- ☐ 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

AZIMUTHAL ANISOTROPY

protons and light nuclei $v_n, n = 1 - 6$

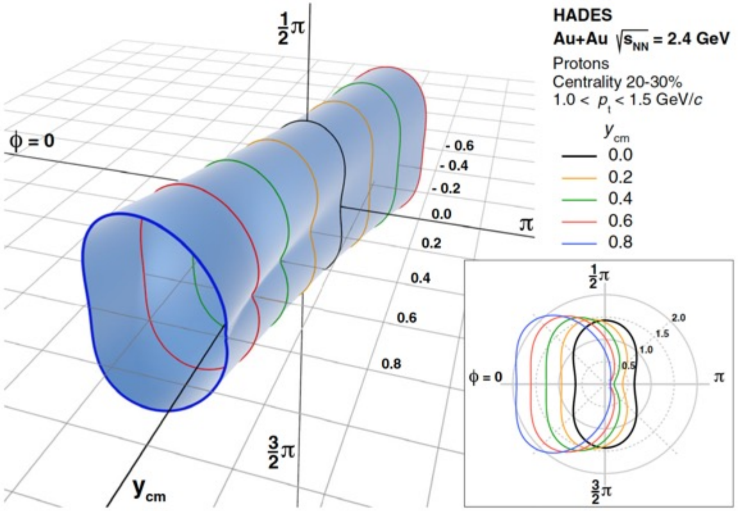


rapidity dependense paramerized with

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

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

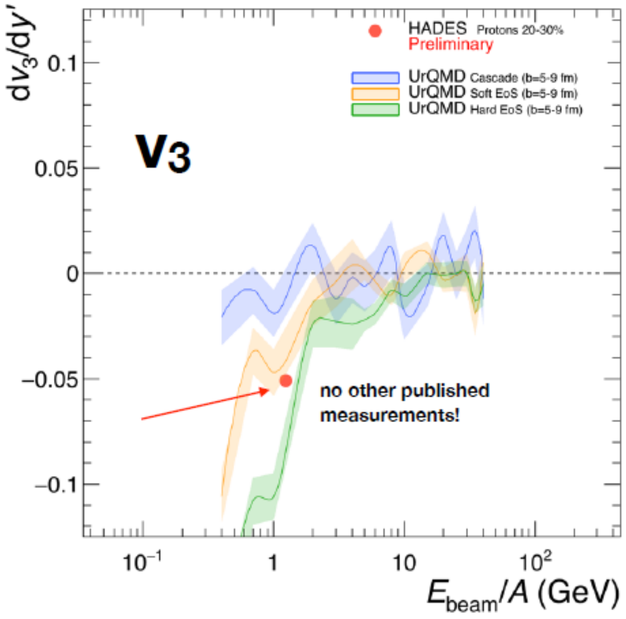
3D picture of the particle emission pattern in momentum space



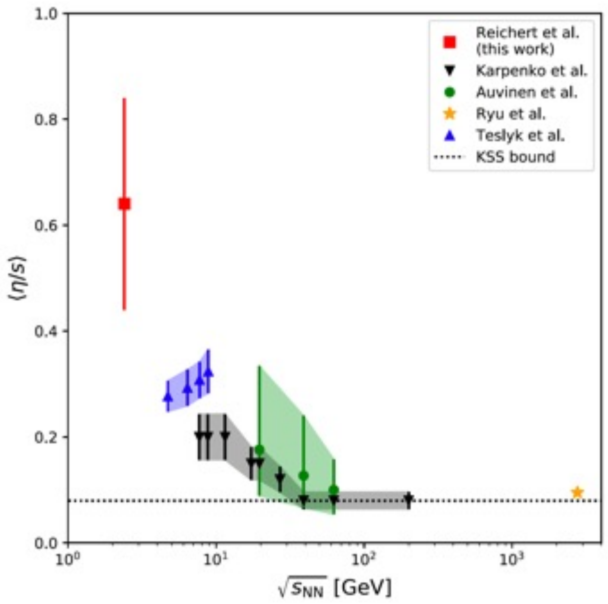
- mid-rapidity: almost elliptical shape
- forward/backward rapidity: triangular shape
  ⤳ interplay: central fireball pressure – interaction with spectator matter

Transport properties

HADES, PRL 125 (2020) 262301

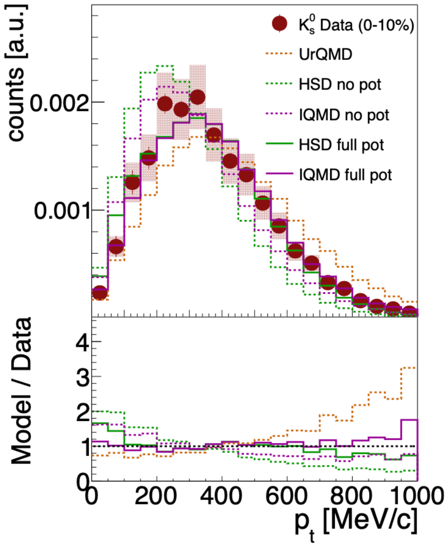


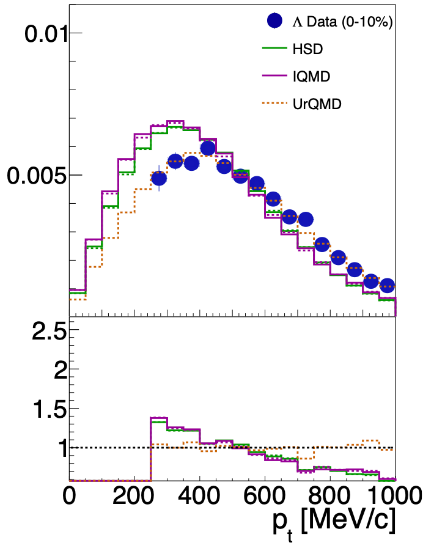
Reichert *et al.*, PLB 817 (2021) 136285

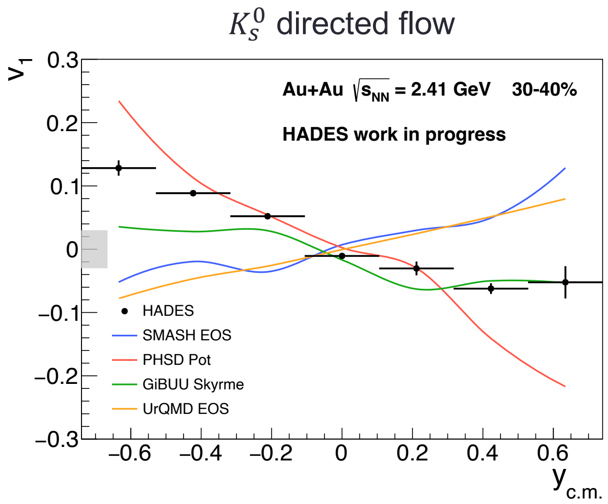


Kaon and Λ production and anisotropy in Au+Au

HADES, PLB 793 (2019) 457-463







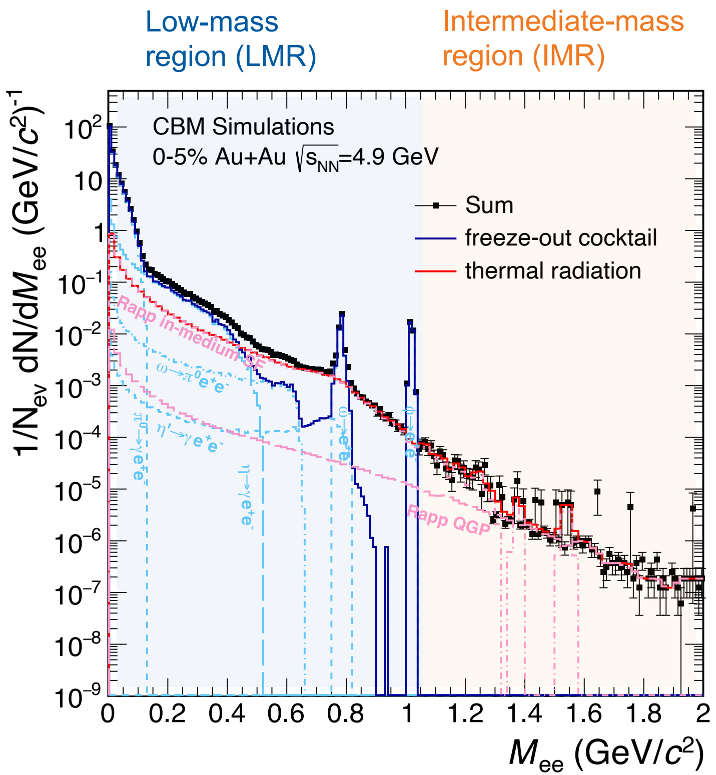
HADES, in preparation

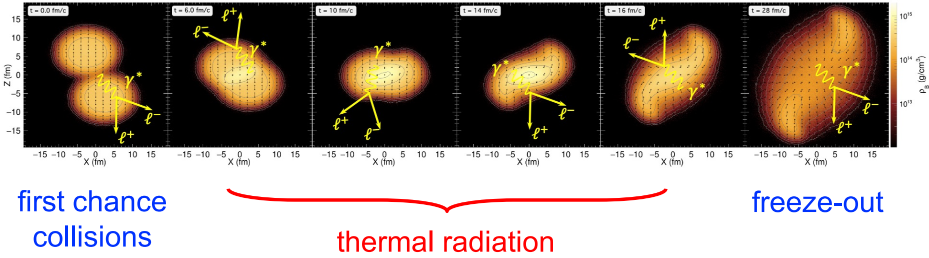
$$U_{opt} = +40\ MeV \cdot \frac{\rho}{\rho_0}$$

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

No simultaneous description of K^0_S and Λ results

Thermal dilepton measurements





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

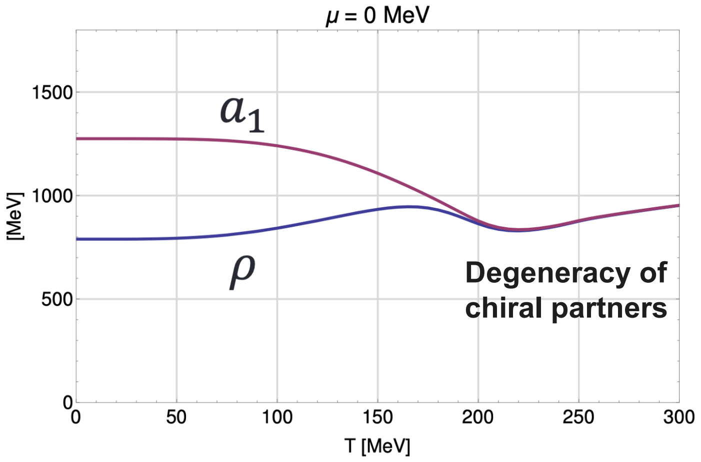
- LMR: total yield ~ fireball lifetime
- IMR: slope ~ emitting source temperature

Dileptons and chiral symmetry of QCD

Spontaneously broken in the vacuum

$$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$$

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



Jung *et al.*, PRD 95, 036020 (2017)
Hohler and Rapp, PLB 731 (2014)