Studying strong-interaction matter under extreme conditions with high-energy heavy-ion experiments

Joachim Stroth, Goethe University / GSI

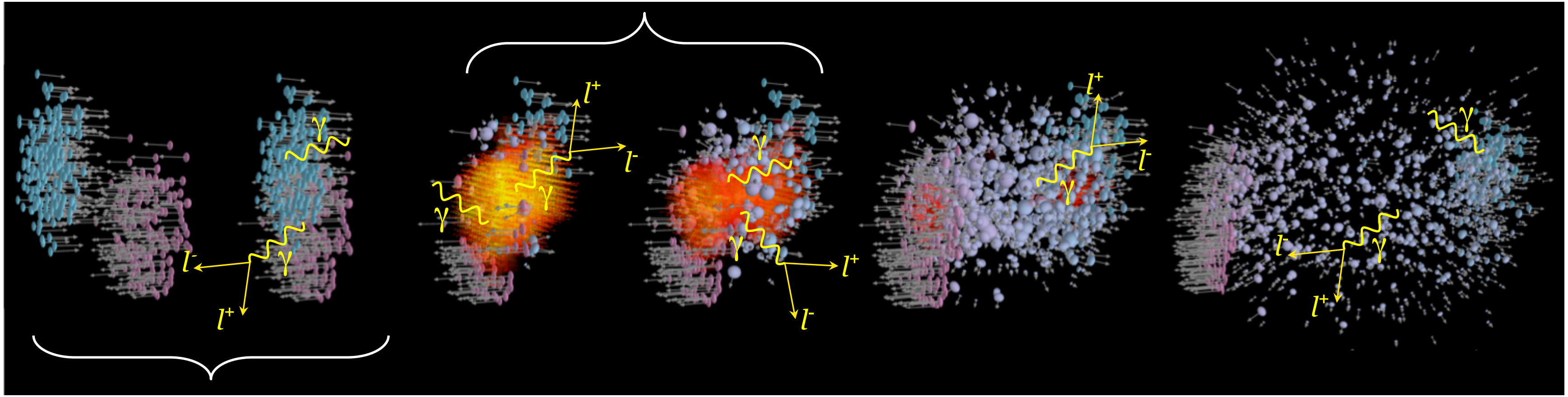
JENAS Initiative: “Gravitational Wave Probes of Fundamental Physics”

Bottom-up Workshop at Sapienza University, Rome

February 12–16, 2024

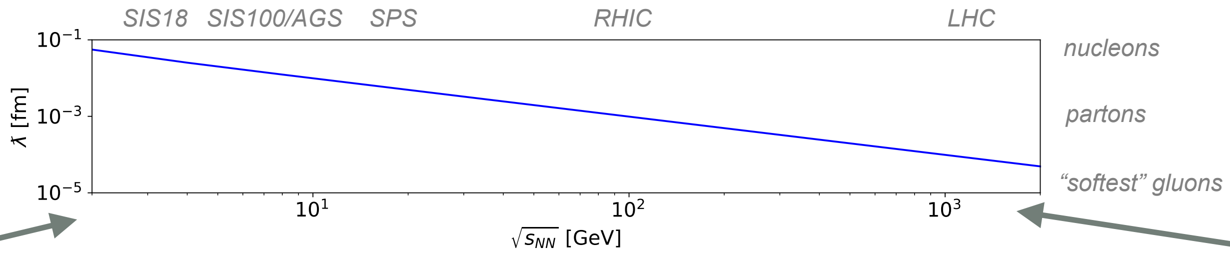
The (U)RHIC "Standard Model"

„First chance" *„Pre-equillibrium"* *Fireball* *Freeze-out* *Late stage hadrons seen in detectors*



Very different a.f.o. $\sqrt{s_{NN}}$

nearly complete baryon stopping



net-baryon free collision zone

Baryon stopping at moderate energies

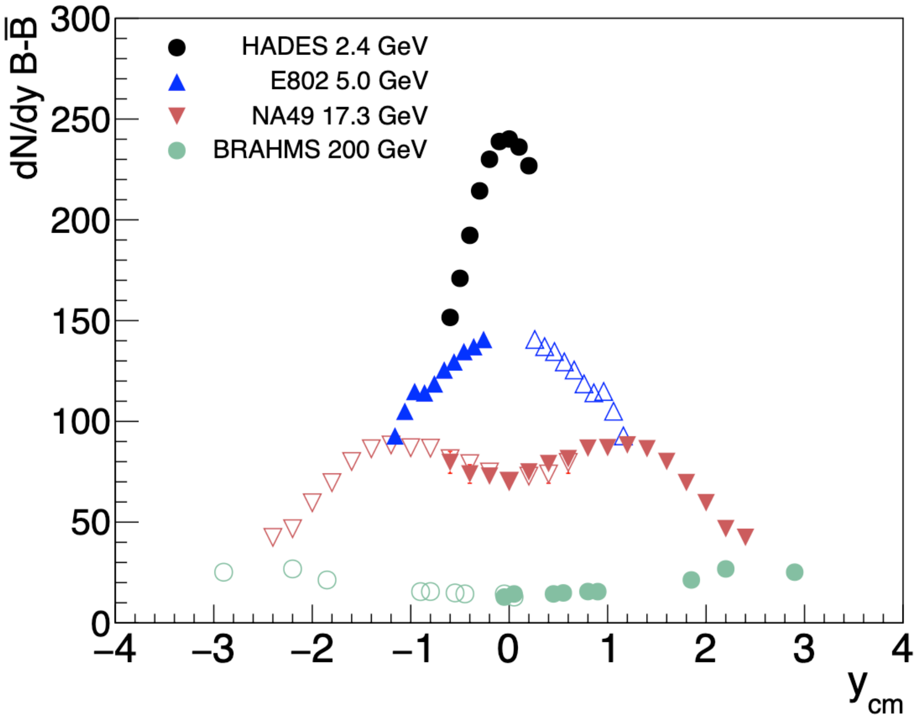
Rapidity distribution of "stopped" protons

- Full stopping at SIS18
- Net-baryon free mid-rapidity region at LHC

$$y = \tanh^{-1}\left(\frac{p_z}{E}\right)$$

$$p_z = m_\perp \sinh(y) \qquad m_\perp^2 = \left(m^2 + p_\perp^2\right)$$

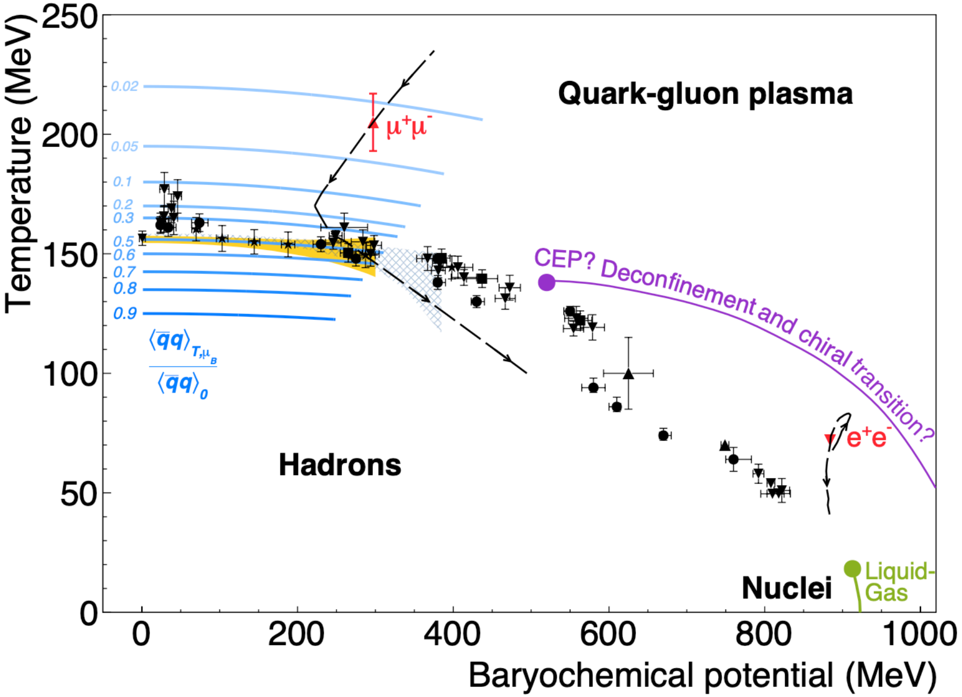
- Open symbols are reflected data points to fill rapidity regions uncovered by detectors
- All measurements are central collisions of heavy (Au, Pb) symmetric collision systems



Manuel Lorenz, priv. communication

Exploration of the Strong-interaction Phase Diagram

From medium-effects to novel phases of QCD matter



HADES, Nature Phys. 2019

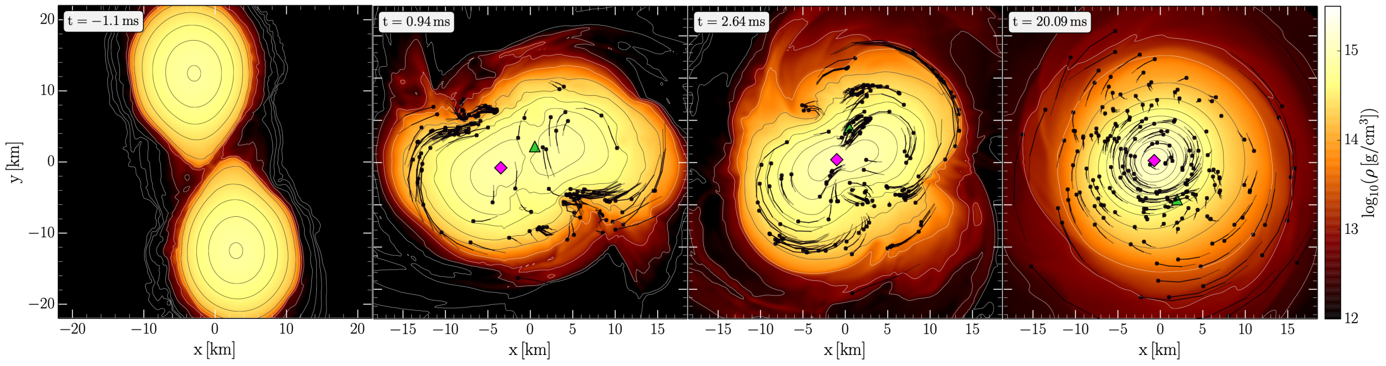
Methods for **investigations at high-μ_B:**

- Search for signs of criticality (conjectured first-order phase transition and critical point, remnants of liquid-gas critical point)
- Collectivity in the debris of the fireball
- Strangeness production
- Study of meson/baryon/hyperon coupling

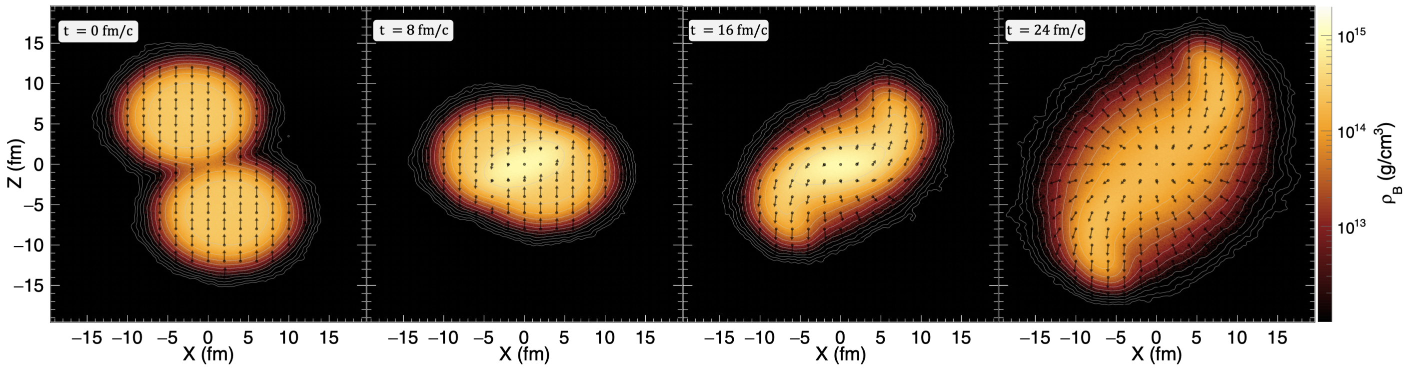
Spin-offs:

- Interpretation of observables depend on models in many cases
- No lattice QCD calculations possible at baryo-chemical potentials relevant for (merging) neutron stars
- Progress in developments based on effective field theories: Chiral Perturbation theory (χCFT), Functional Renormalization Group theory (FRG) , Dyson-Schwinger Equation (DSE))

Similarities of RHIC and NS-merger simulations



Simulation of a binary neutron star **encounter of two neutron stars** with equal masses of 1.35 $M_\odot$ finally merging into a single compact object



Time evolution of the energy density achieved in a non-central **collision of two Au nuclei** at an energy of 2.42 GeV per colliding nucleon pair

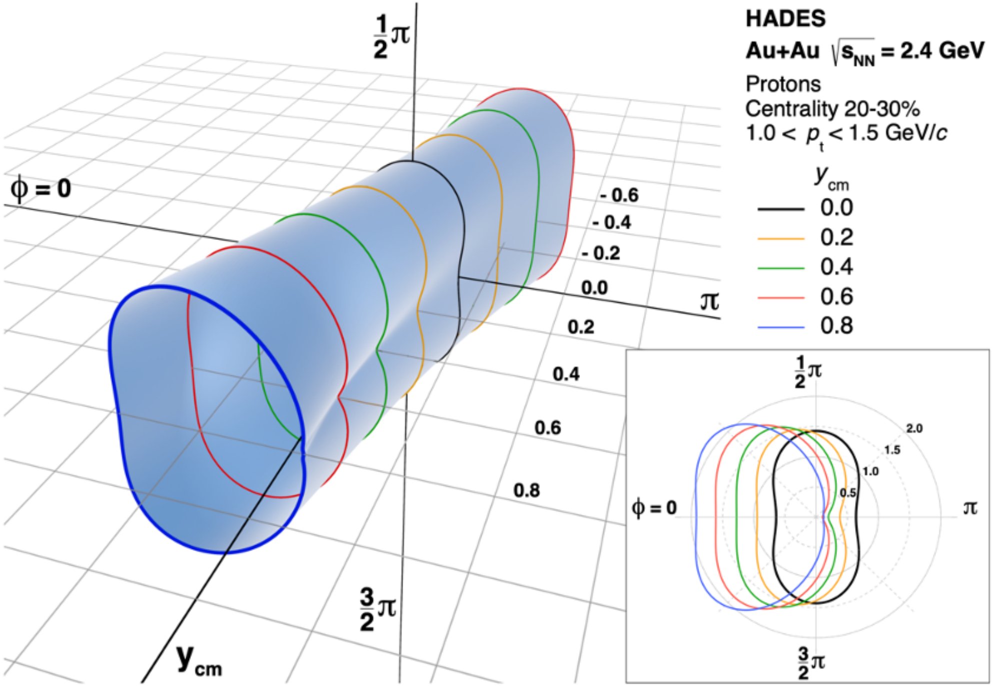
Detailed reconstruction of particle flow

The collective motion (flow) of protons, deuterons and tritons shows a distinct pattern which encodes properties of the fireball (e.g. equation-of-state).

The flow is encoded in the transverse mass spectra and in the angular variation of the yields.

Encodes the equation-of-state of the expanding matter

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

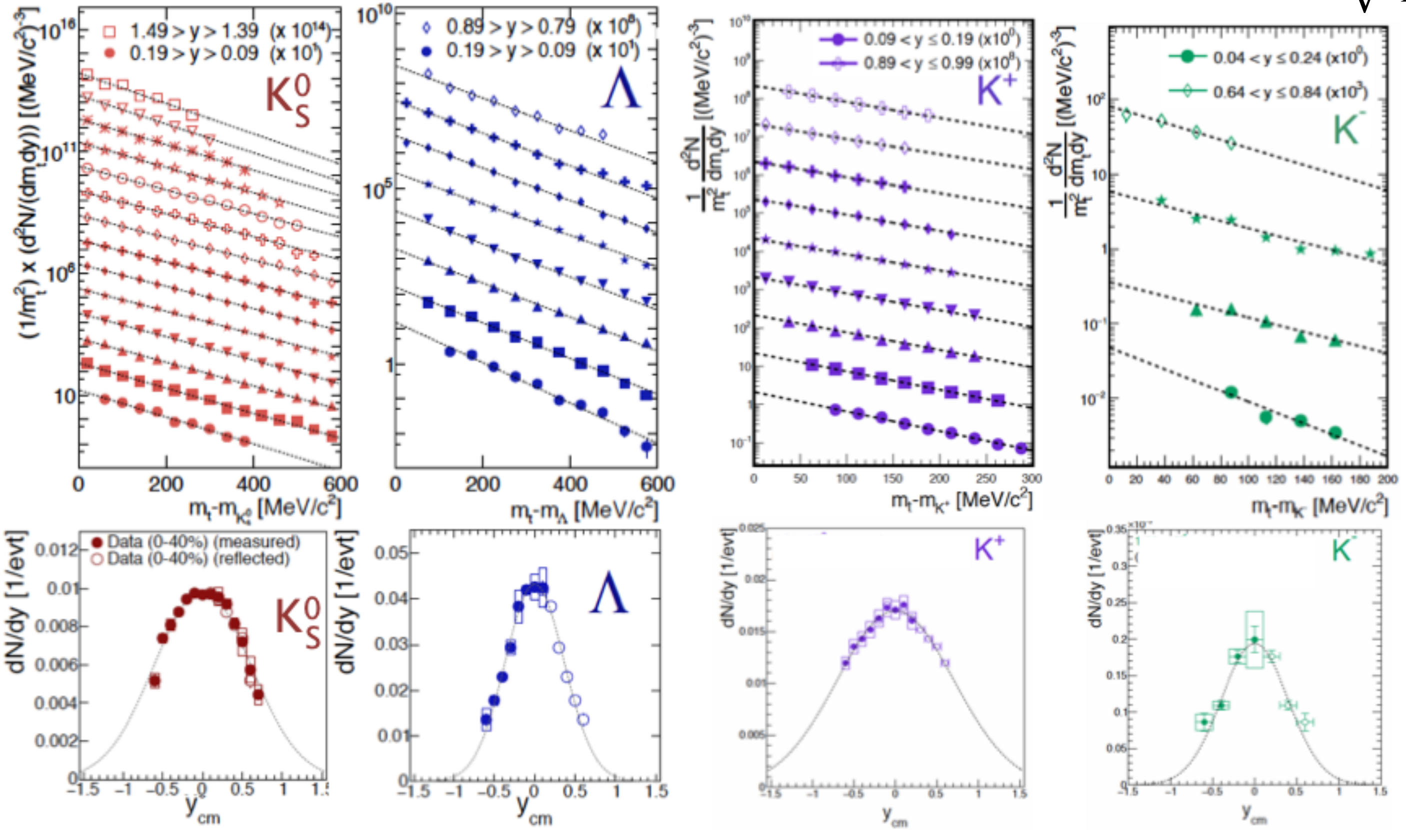


Hillmann, Steinheimer et al., J.Phys.G 45 (2018)

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

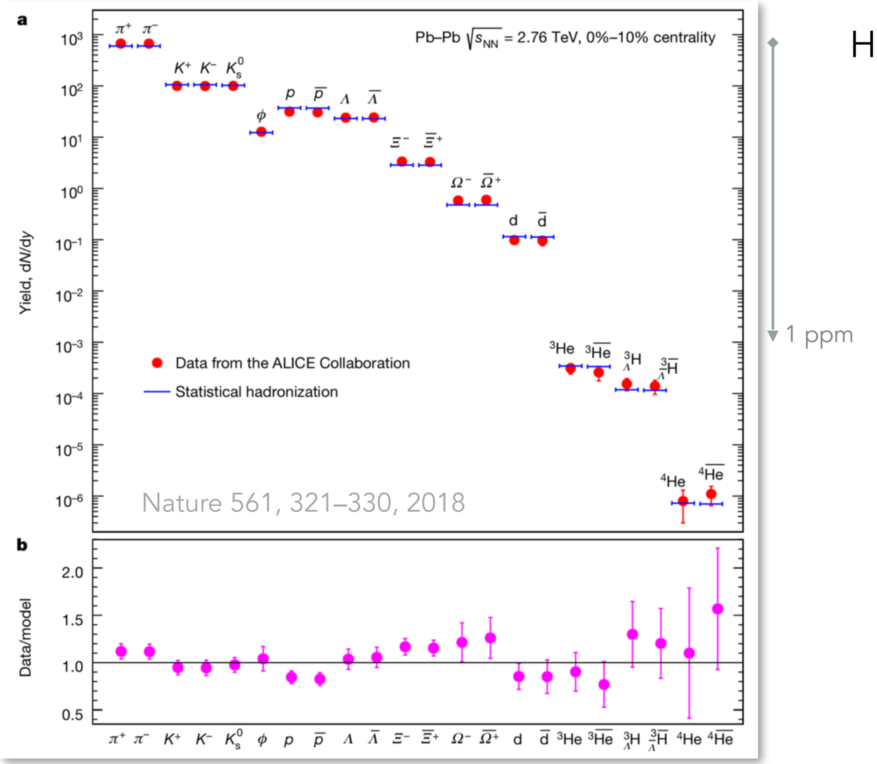
Production of Strangeness

$$\mathrm{Au} + \mathrm{Au}\ @ \sqrt{s_{\mathrm{NN}}} = 2.4\,\mathrm{GeV}$$



Freeze-out conditions from SIS18 to LHC

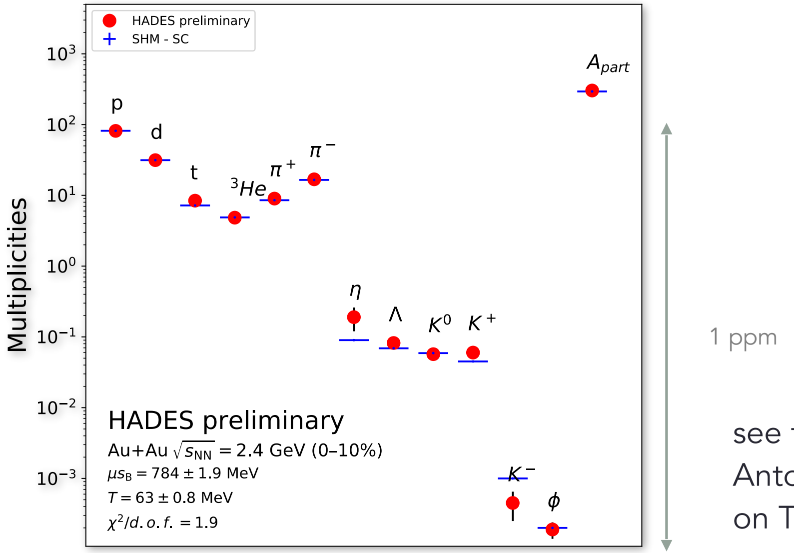
ALICE data



ALICE ($\sqrt{s} = 2.76$ ATeV): $T_{ch} = 156.5\ (1.5);\ \mu_B = 0.7\ (3.8)$

HADES ($\sqrt{s} = 2.4$ AGeV): $T_{ch} = 68.2\ (1.5);\ \mu_B = 883\ (25)$

- Factor ~1000 in beam energy / factor ~2 in temperature
- Much different multiplicities for nuclear clusters



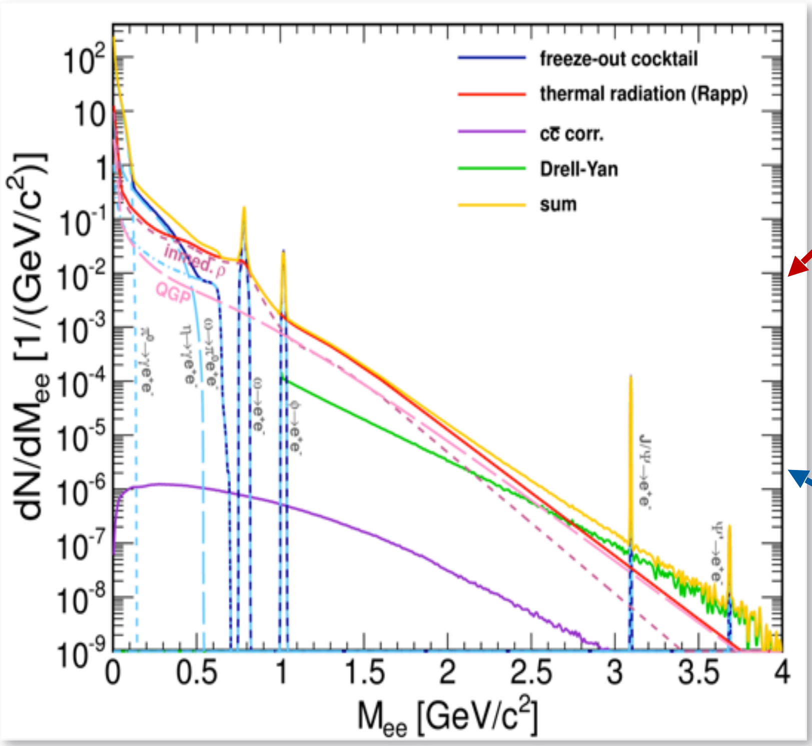
see talk by Anton Andronic on Tuesday 1 pm

Medium Radiation as “Standard Candle” for (U)RHIC

Medium radiation from *Thermal Emission Rates* (ϵ):

$$\frac{d^4N}{dMdydp_td\alpha} = \int \frac{\alpha^2}{\pi^3 M^2} f_B(q_0;\ T)\ \mathrm{Im}\Pi_{\mathrm{EM}}\left[M, q; T, \mu_B, \vec{v}\right] dx$$

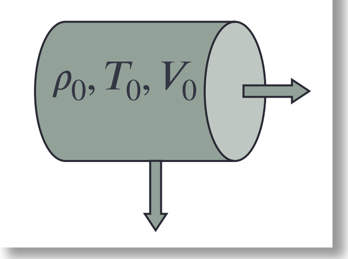
$$\equiv \int \frac{d^4\epsilon}{d\boldsymbol{q}}\left[T(\boldsymbol{x}), \mu_B(\boldsymbol{x}), \vec{v}(\boldsymbol{x})\right] d\boldsymbol{x}$$



coarse graining

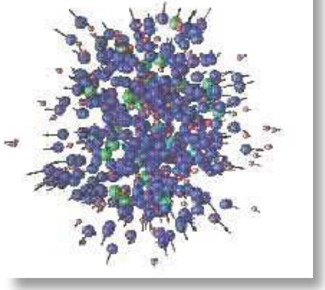
or

isentropic expansion



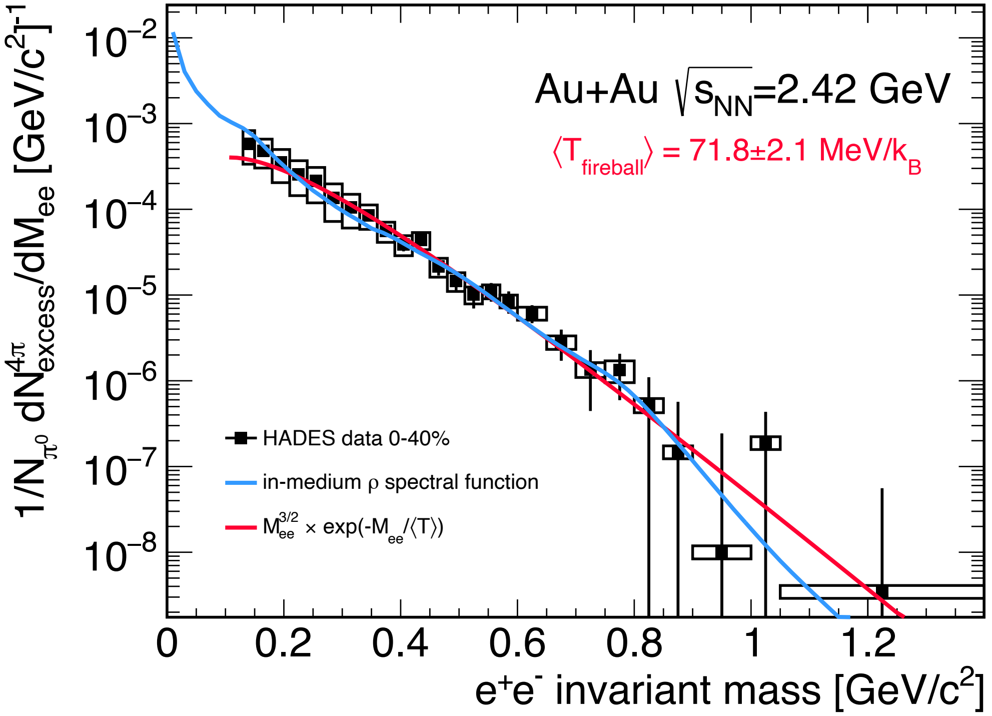
shining

UrQMD



Dilepton emission from *Microscopic Transport.*

Thermal Dileptons from HADES Au + Au @ $\sqrt{s_{NN}} = 2.4$ GeV



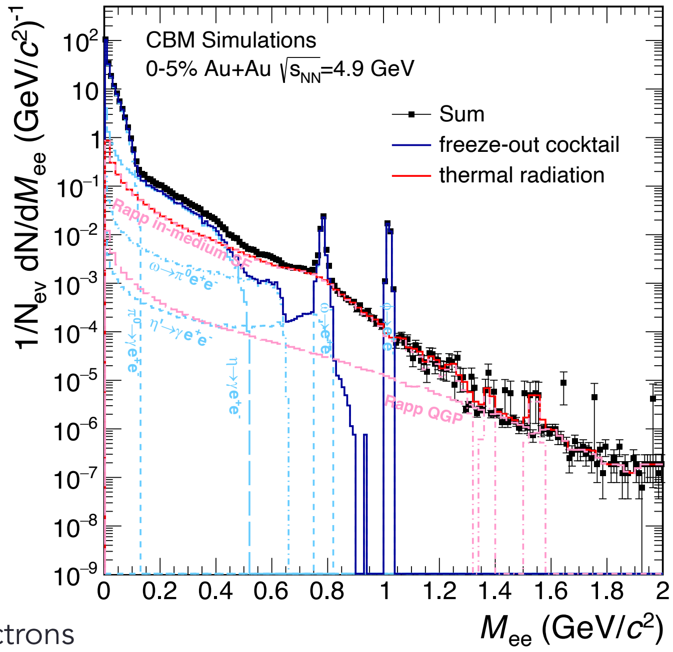
- Microscopic transport(2):
  - Vacuum ρ spectral function and Δ regeneration
  - Explicit broadening and density dependent mass shift
- Coarse-grained UrQMD(3)
  - thermal emissivity with(1)
  - in-medium propagator (4)
  - $\rho - a_1$ chiral mixing(5) (not measured so far)

(1) Rapp, van Hees; arXiv:1411.4612v
(2) E. Bratkovskaya;
(3) CG FRA Endres, van Hees, Bleicher; arXiv:1505.06131
CG GSI-TAMU; Galatyuk, Seck, et al. arXiv:1512.08688
(4) Rapp, Wambach, van Hees; arXiv:0901.3289
(5) Rapp, Hohler; arXiv:1311.2921v

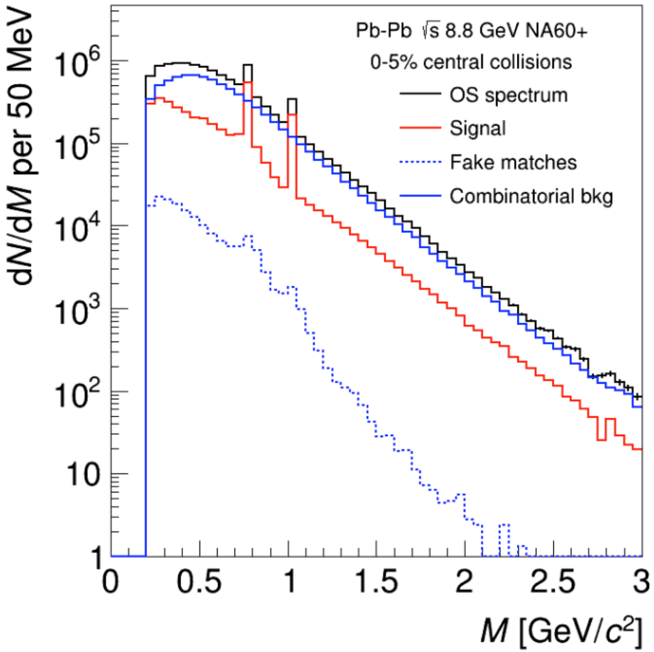
Prospects for higher densities CBM / NA60+

Planned high-rate fixed-target experiments will boost the precision in dilepton spectroscopy

- Di-electrons provide reach down to $M_{\ell\ell} \rightarrow 0$ – important for electric conductivity measurement
- Dimuons have advantages at higher mass region $M_{\ell\ell} \rightarrow m_{J/\psi}$

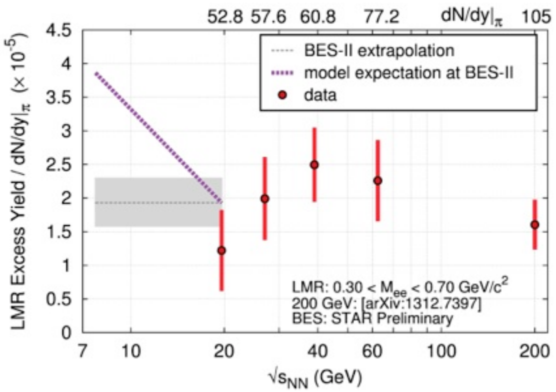


CBM di-electrons



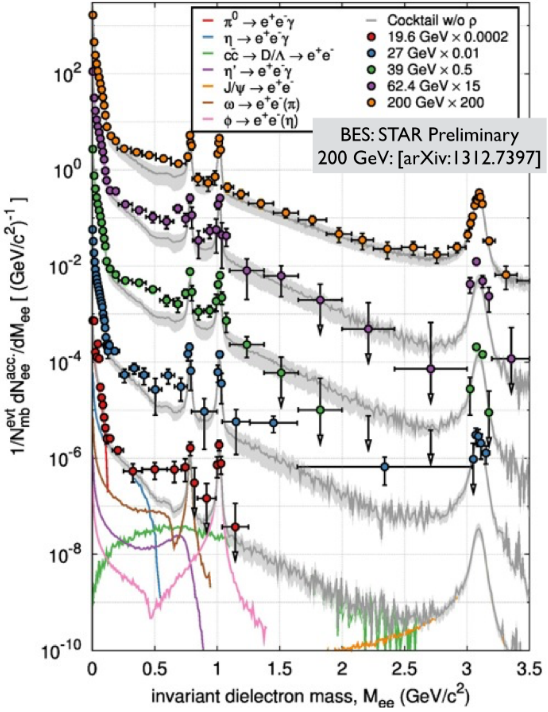
NA60+ dimuons

Dilepton Excitation Functions

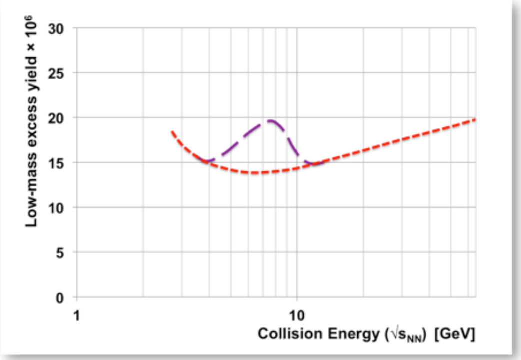


All data from STAR (preliminary)

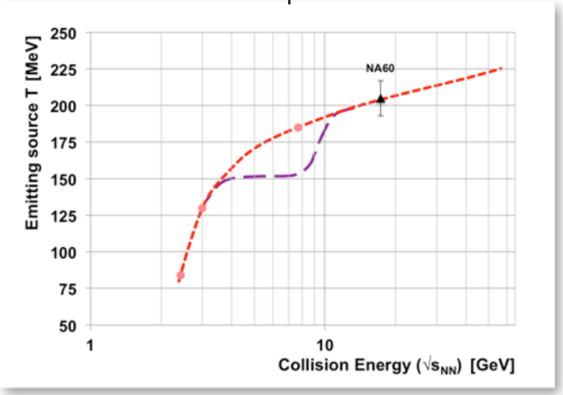
Patrick Huck, QM2014
also e-Print: 2402.01998 [nucl-ex]



Excess yield



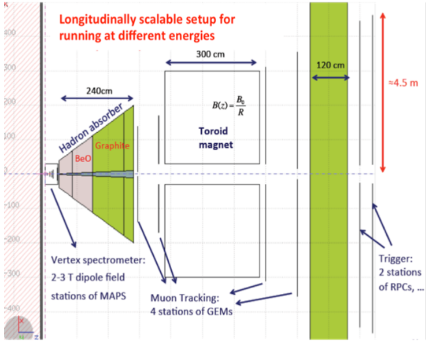
Mean temperature



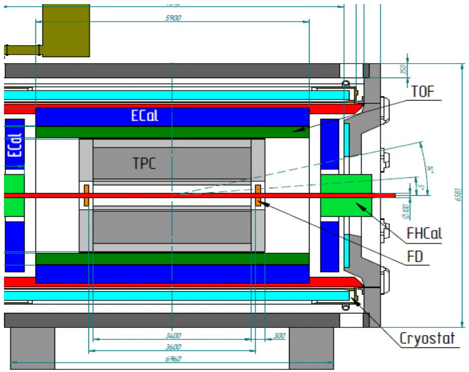
Conjecture (very suggestive) for the case of a 1st order phase transition ☛

Future facilities for high μ_B physics

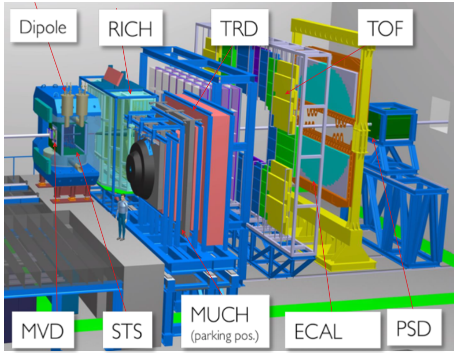
NA60+ – SPS



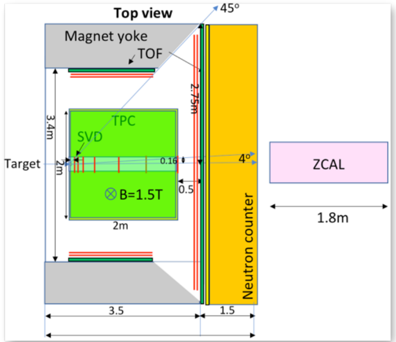
MPD – NICA



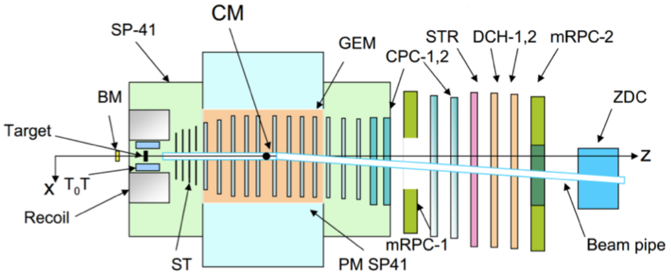
CBM– FAIR



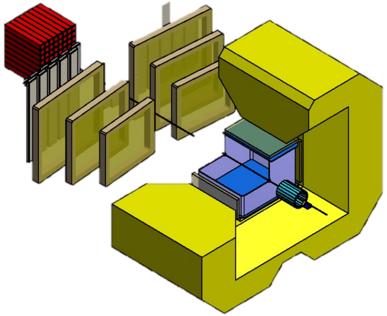
DHS – JPARC-HI



BM@N – NICA



CEE– HIAF



FAIR – Cosmic Matter in the Laboratory

APPA

Atomic processes in highly ionized isotopes

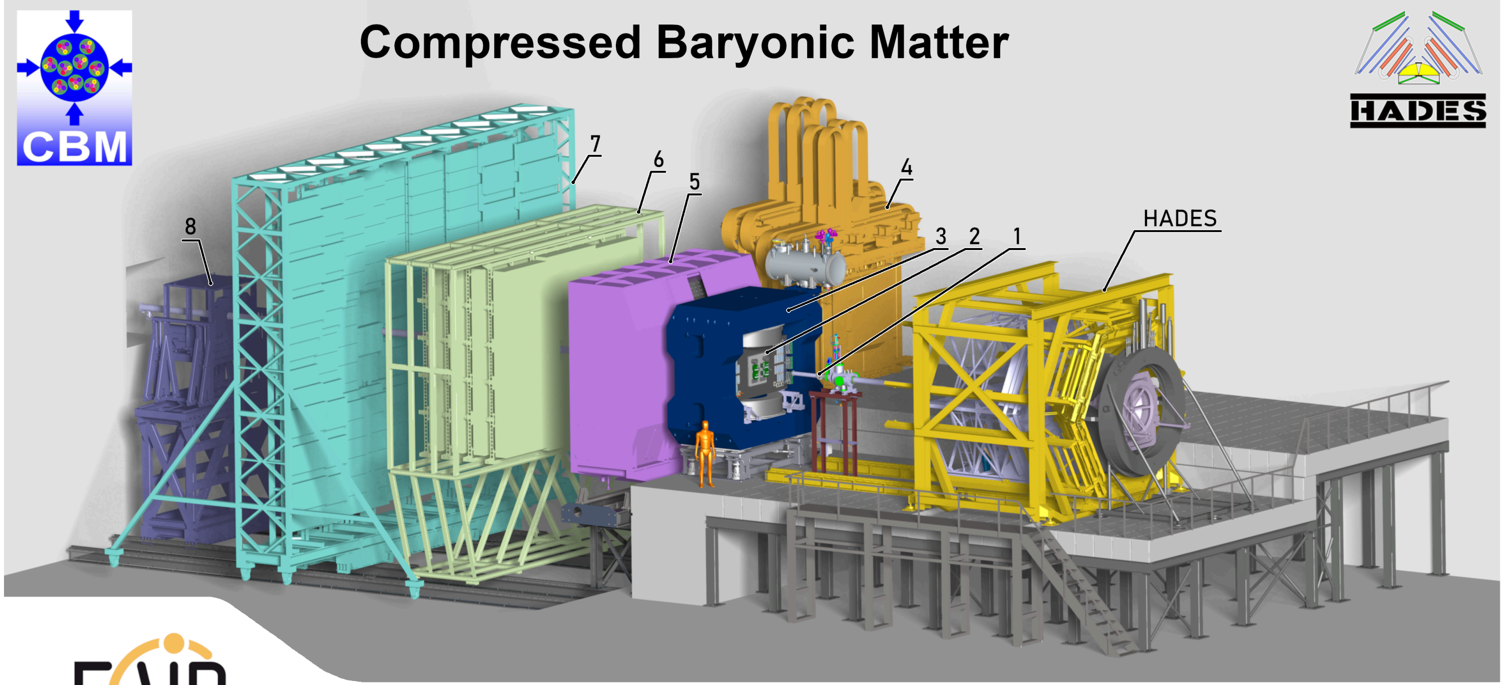
NUSTAR

Experiments with rare (neutron-rich) isotopes

CBM

Investigation of compressed baryonic matter

The Compressed Baryonic Matter Experiment(s)



1: Time-Zero Detector & Beam Diagnostics
2: Silicon Tracking System / Micro Vertex Detector
3: Superconducting Dipole Magnet
4: Muon Chambers
5: Ring Imaging Cherenkov Detector
6: Transition Radiation Detector
7: Time of Flight Detector
8: Forward Spectator Detector

Conclusion

- RHIC – heavy-ion collisions at relativistic energies – enable studies of dense baryonic matter in the laboratory
  - FAIR will contribute to with many different experiments also addressing nuclei synthesis and the kilonova signal (APPA, CBM, NUSTAR)
- Information about the **Equation-of-State** of dense matter can be extracted from final state hadrons using observables but needs modelling – work on systematics ongoing
- Dilepton emission probes the dense and hot phase directly
  - Reduced model dependence and direct access to microscopic properties
  - **standard candle** for the fireball evolution
- Combined effort from experiment and theory –
  see e.g. Nature 606 (2022) 276-280 e-Print: 2107.06229 [nucl-th]