MC11 La matière nucléaire : du laboratoire au cosmos

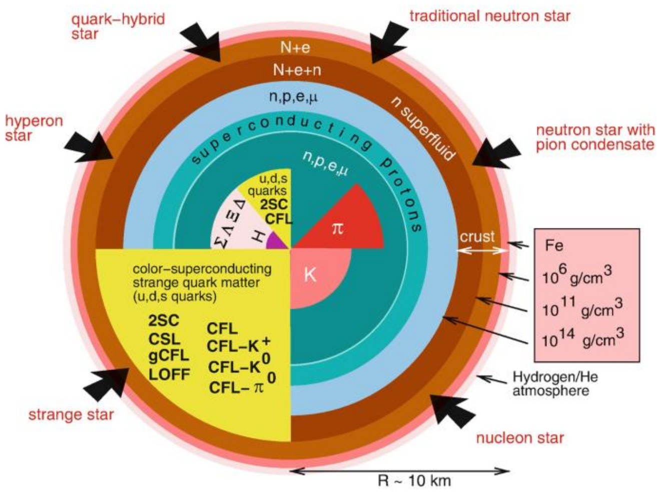
Dense hadronic matter studies using heavy ion collisions … at relativistic energies

Béatrice Ramstein, IJClab

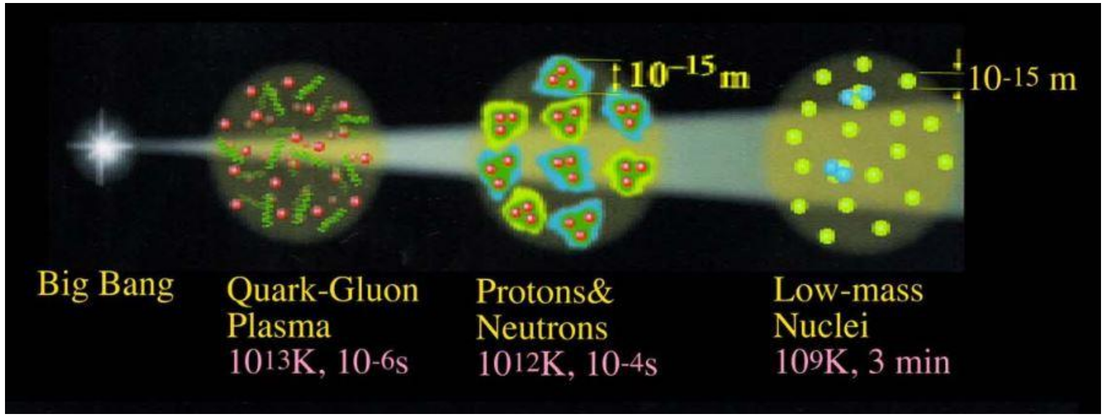
July 4, Cité des Sciences et de l'industrie, Paris

Hadrons in the universe

Neutron star composition:

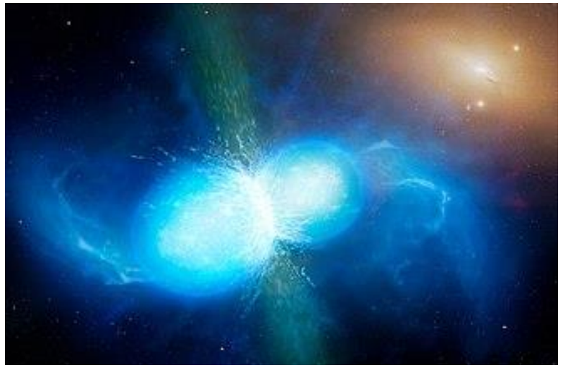


Early universe



M. Q. Haseeb, Introduction to Quark Gluon Plasma, 2009

Neutron star mergers



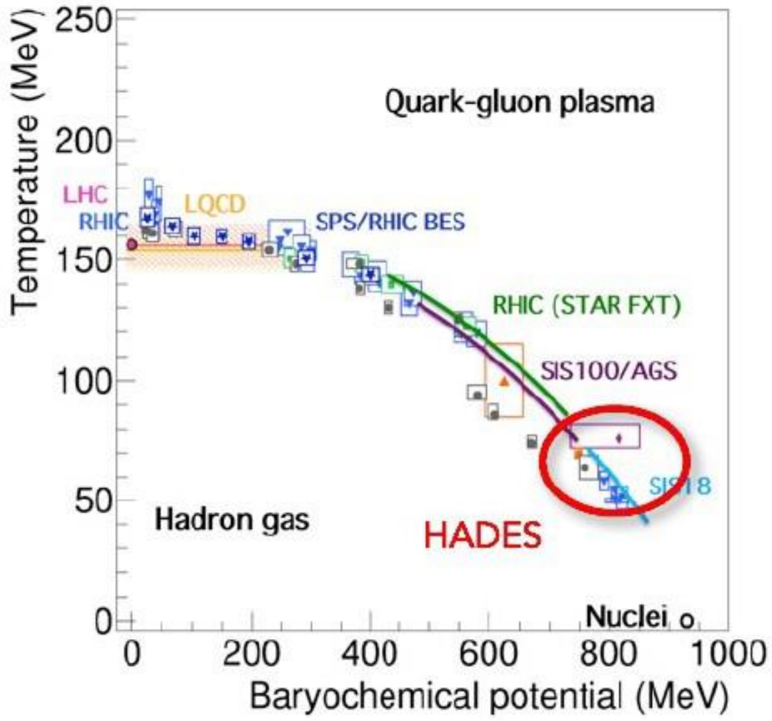
Hadronic processes governed by **Quantum Chromodynamics**

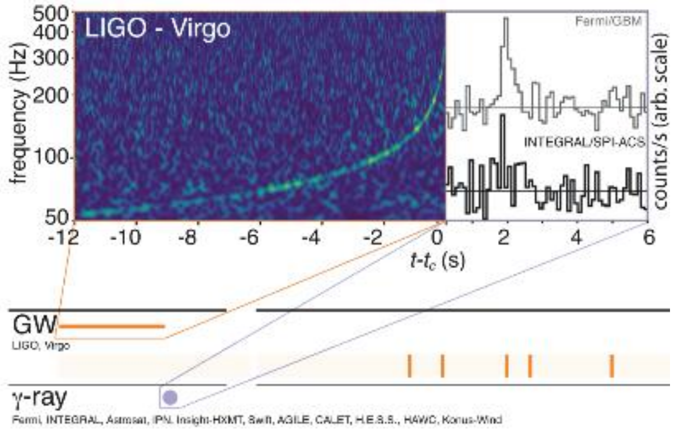
Two types of QCD studies :

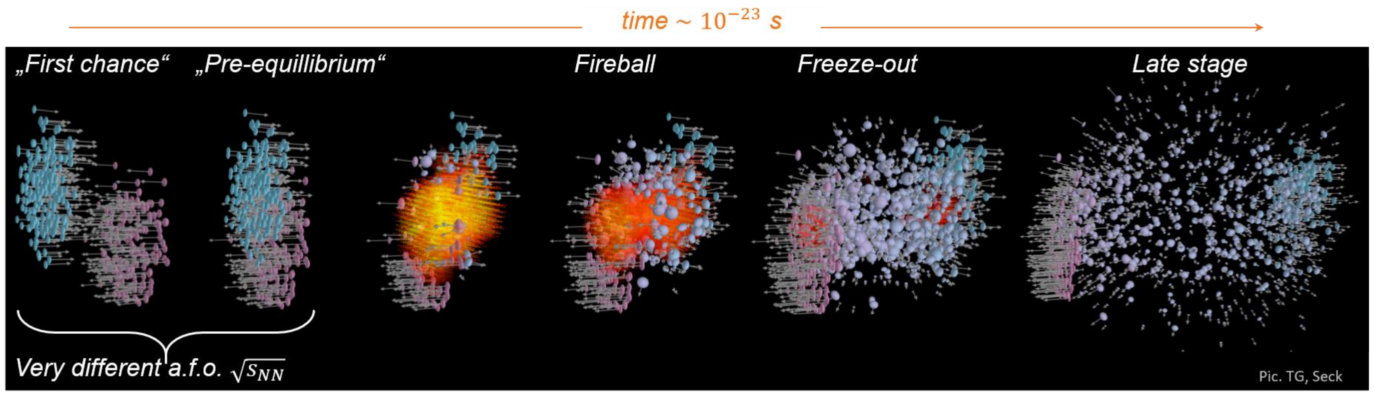
Hadron structure and interactions

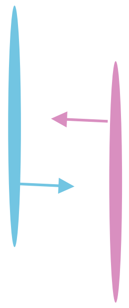
Hadronic matter

QCD phase diagram: experimental exploration

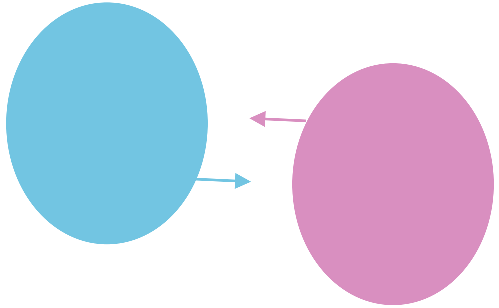








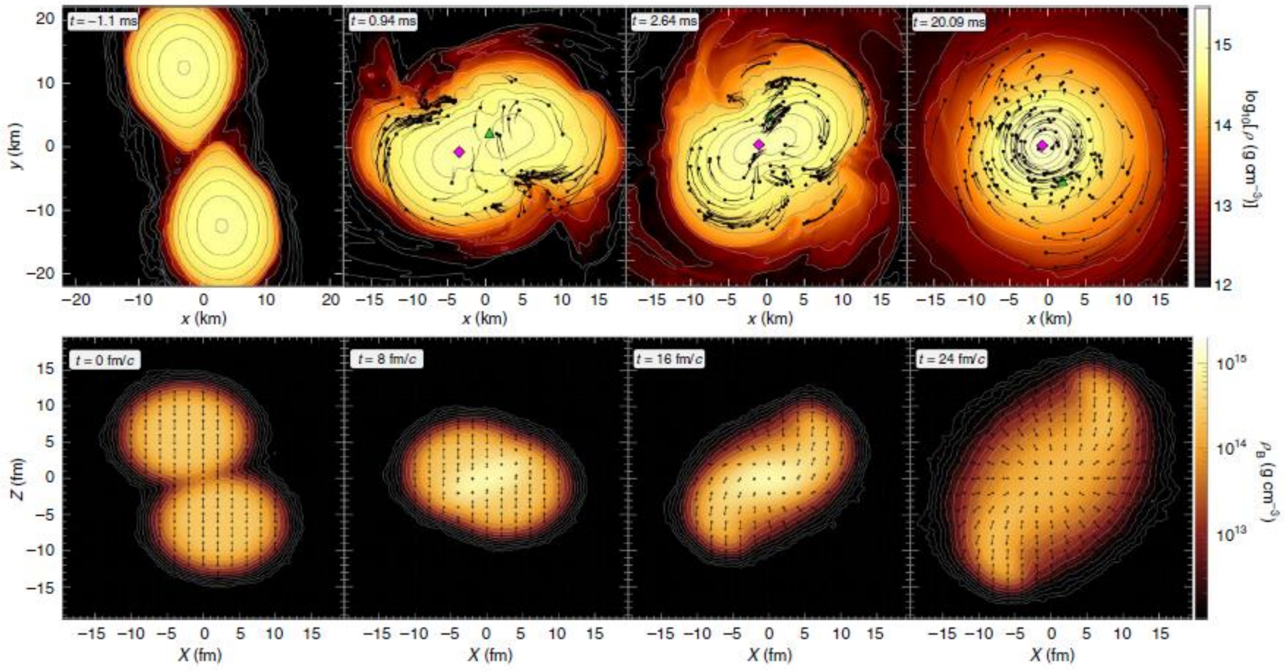
LHC energies $\sqrt{s_{NN}} = 2\ TeV$
parton+parton collisions
Early Universe in the laboratory



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

Laboratory studies of the matter properties in compact stellar objects

Neutron Star mergers ~ 10 km
$M \tilde{=} 1.35\, M_{sun}$
$\rho / \rho_0 \sim 5$



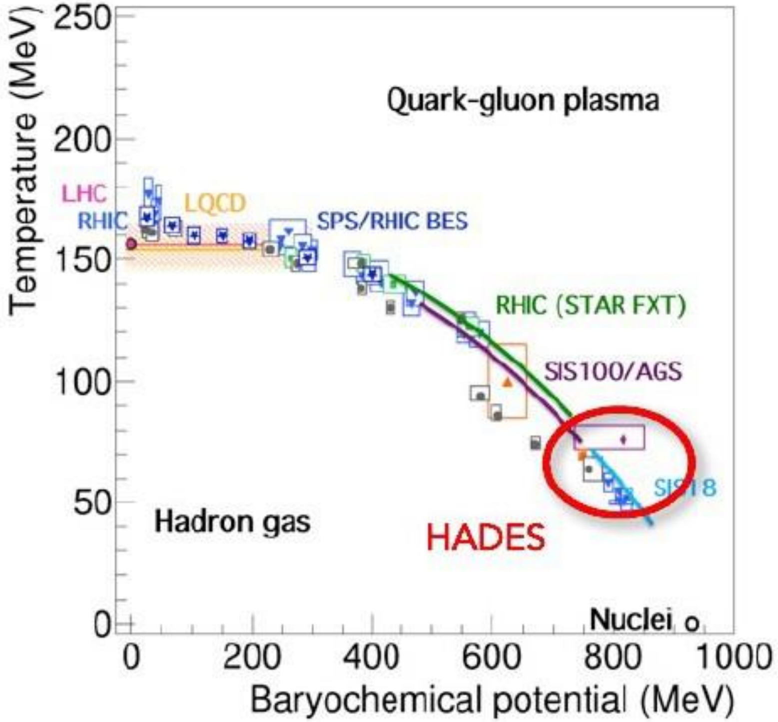
Different size and time scales !
similar T ~ 70 MeV, $\rho \sim 3\rho_0$

HADES, Nature Phys. 15(2019) 1040

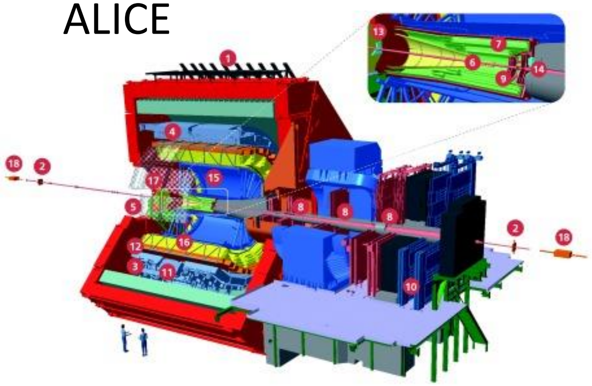
Au + Au $\sqrt{s_{NN}}$ = 2.4 GeV

QCD phase diagram: open questions

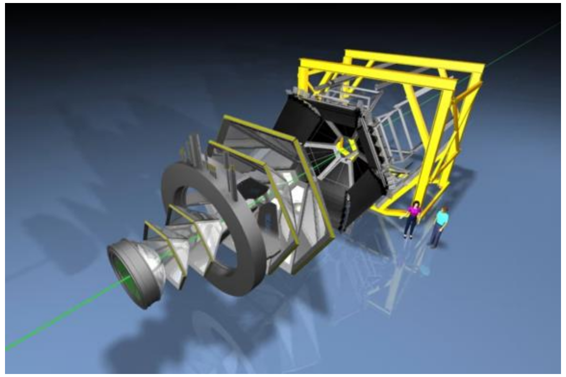
High T, low μ_B
- Lattice QCD calculations
- 2nd order transition between hadronic and quark-gluon phase = cross-over
- No critical point for $\mu_B^{CEP}/T_c < 3$
- Chiral symmetry restoration



ALICE



HADES



Low T, high μ_B
- Effective models are needed
- First order transition ?

  Search for a critical point
- Chiral symmetry restoration ?
- Microscopic structure of baryon rich matter.

Baryonic resonances, hyperons

Medium effects on hadron properties

Observables for Hadronic matter studies

Measurements:

- ✓ Yields and differential spectra : characterize thermodynamical properties of the hot and dense medium
- ✓ Dileptons: $\mu^+\mu^-$ /e^+e^- most pernetrating probe, unique access to the hot and dense phase, invariant mass
- ✓ Event-by-event observables: flow, fluctuations of conserved quantities: equation of state and critical behavior
- ✓ Charm, strangeness, baryon resonances : microscopic structure of the fireball, interaction with medium
- ✓ Two-particle correlations: two-particle interaction
- ✓ Sub-threshold production (e.g. strangeness in A+A collisions at HADES): sensitive to collective effects

……

Very demanding experiments:

→ high statistiscs for rare probes : high intensity beams , large acceptance, large efficiencies, high data rates

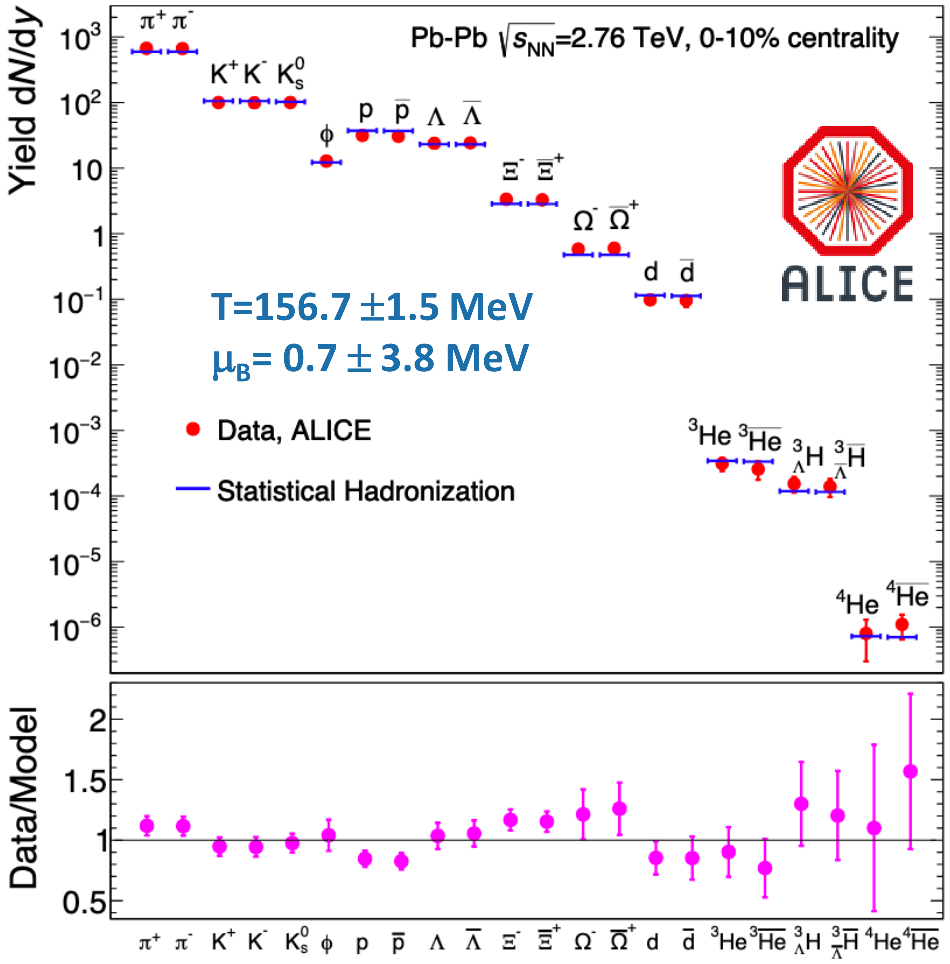
→ Selective PID, (e.g. dileptons)

To identify phase transitions or critical behavior:

- ✓ Evolution of observables as a function of $\sqrt{s_{NN}}$
- ✓ reference from nucleon-nucleon reactions

Thermal medium in heavy-ion experiments

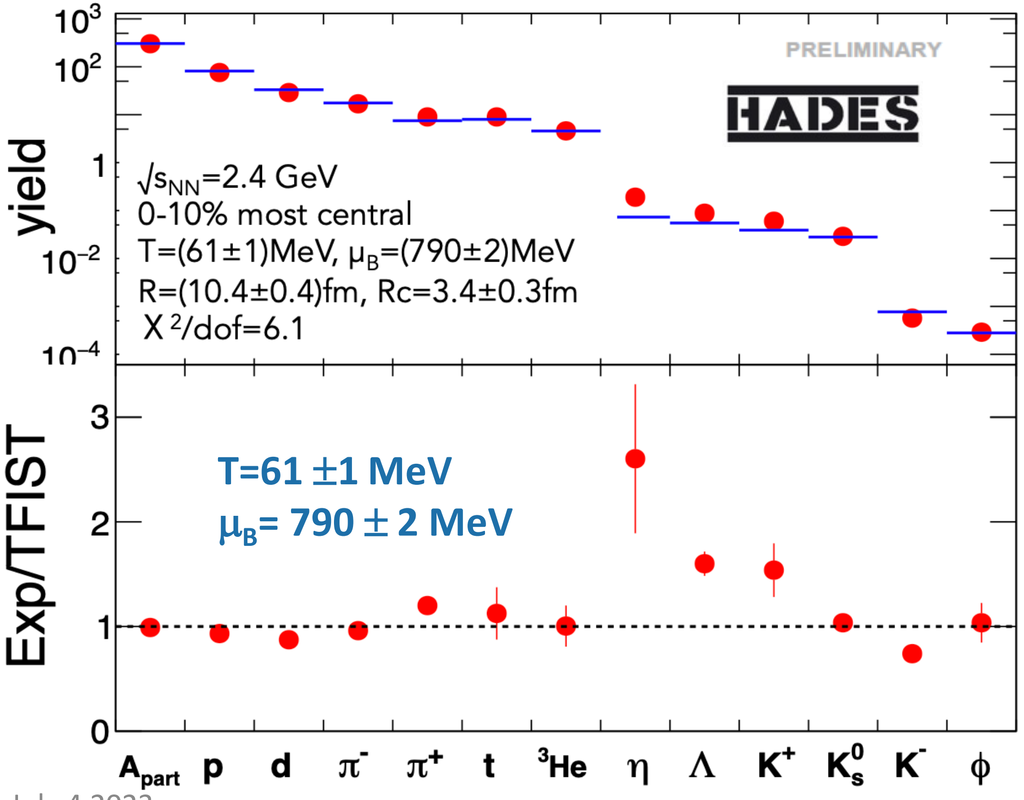
Hadron yields and statistical hadronization model (SHM)



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

- Factor 1000 in beam energy / factor ~2 in temperature

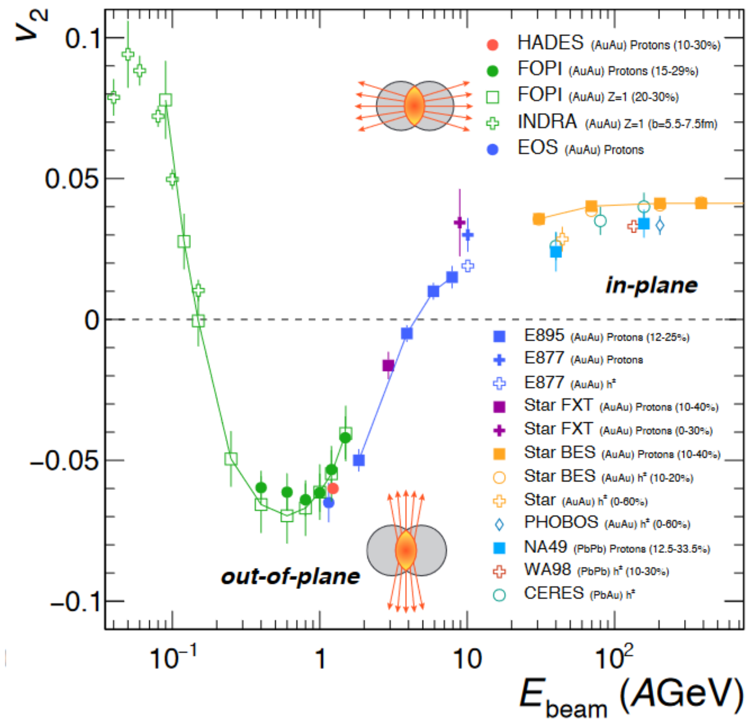
Hahn, Stöcker, NPA 476 (1988) 718-772
Shuryak, Torres-Rincon PRC 101 (2020) 3, 034914



Flow: azimuthal anisotropy

Pressure gradient → azimuthal anisotropy of emitted particles
Fourier coefficients of the angular distribution w.r;t. reaction plane (RP) are sensitive to the equation of State

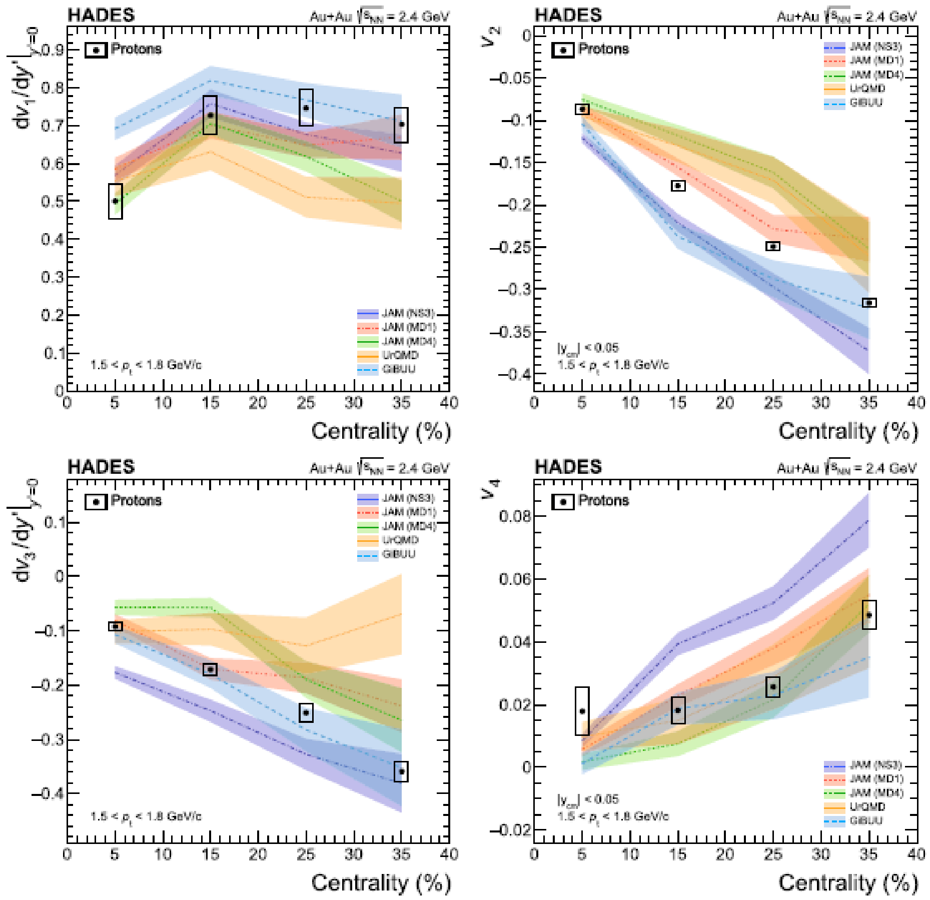
$$\frac{dN}{d(\phi - \Psi_{\mathrm{EP}})} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_{\mathrm{EP}}))$$



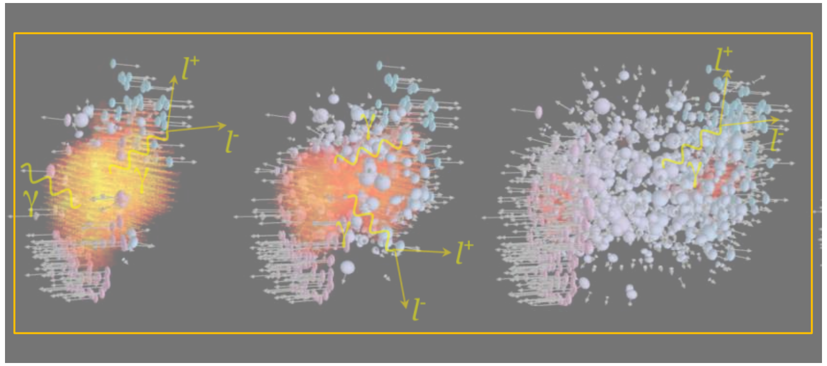
HADES, EPJA 59 (2023) 80

Comparison to microscopic transport models
→ Constraints to EoS
→ Not yet a fully coherent picture due to difference between modesl

HADES, EPJA 59 (2023) 80



Electromagnetic radiation from the fireball



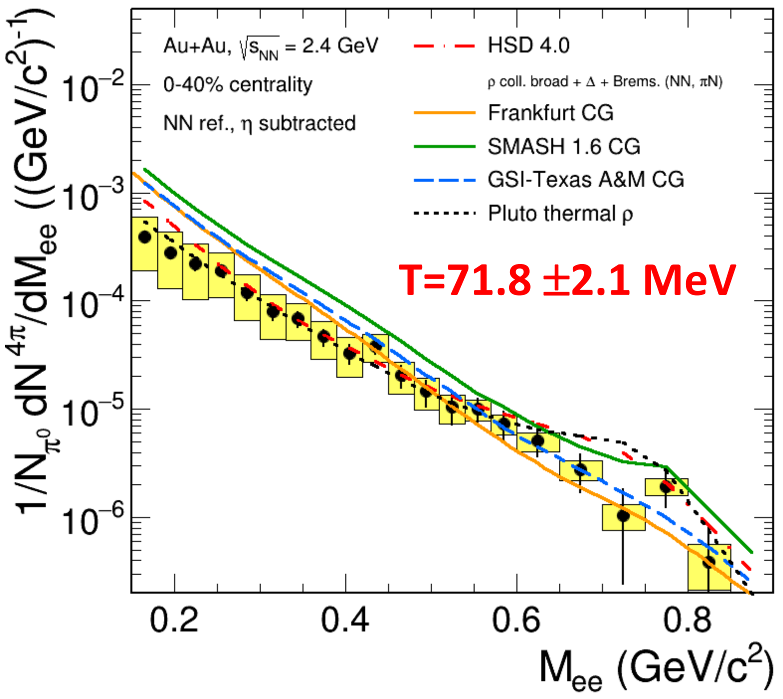
No strong interaction !

→Reflect the whole history of a collision

→First chance collisions and meson decay can be subtracted

→Unique access to dense matter properties

Thermal radiation measured by HADES (Au+Au, Ag+Ag, on-going)



HADES, Nature Phys.15(2019) 1040

'Planck-like'

In-medium spectral function

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

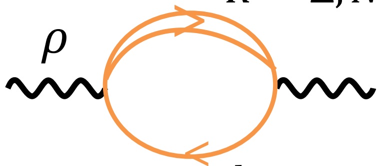
McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

ρ-meson "melting" :

in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

Baryonic effects are crucial

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



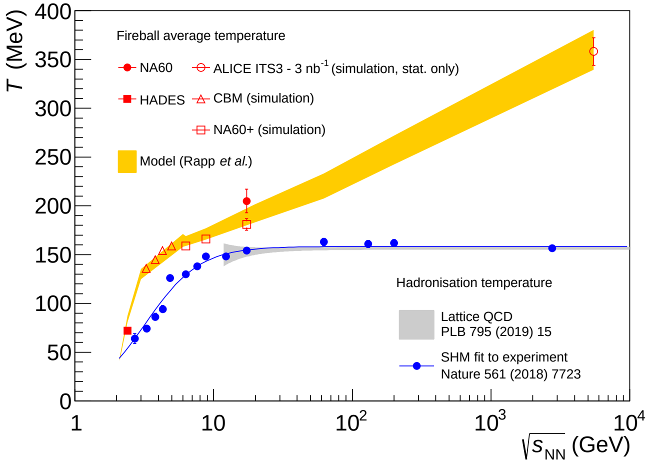
$h = N, \pi, K, \ldots$

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

The high potential of dilepton measurements

QCD caloric curve

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

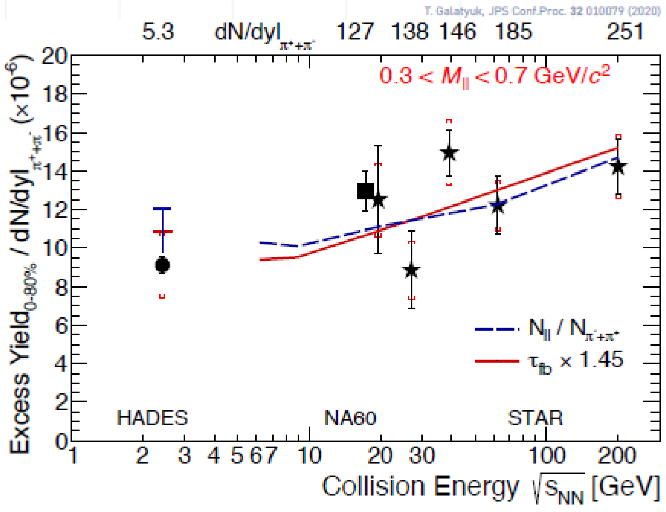


Signatures for phase transition

- Plateau in the temperature measurements
- Extra radiation (latent heat → longer life time)

Signatures of chiral symmetry restoration:

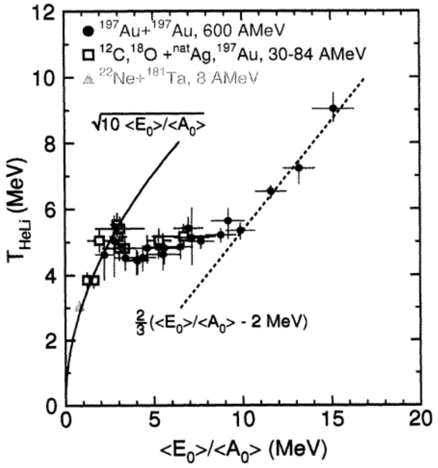
ρ/a1 mixing : $1 < M_{ee}$ (GeV/c^2) < 2



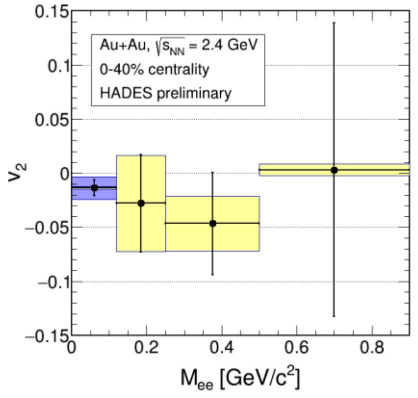
- Only two Tp measurements up to now (NA60 and HADES)

Nuclear liquid-gas phase transition

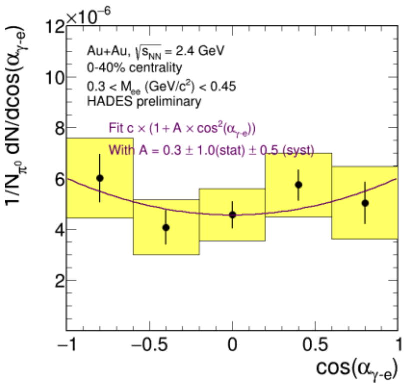
Pochodzalla *et al.*,
PRL 75 (1995) 1040-1043



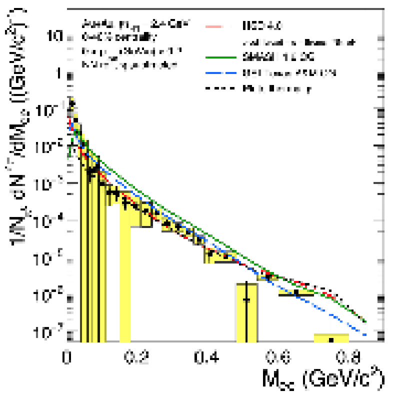
Elliptic flow (v_2)



Polarization



Electrical conductivity?



Critical fluctuations

Fluctuations of conserved quantities, are an indicator of critical behavior (sensitive to change of degrees of freedom) e.g. baryon number

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

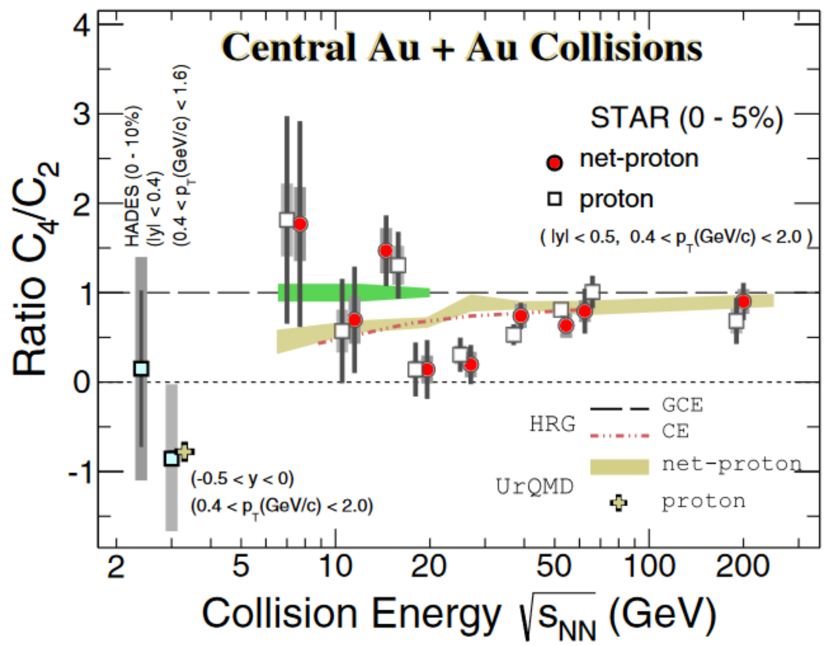
Study of cumulants of proton number :

Direct relation to EOS

$$\kappa_n = V\,T^{n-1}\,\frac{\partial^n P(T,\mu_B)}{\partial \mu_B^n}$$

$$\propto \xi^{\frac{5n}{2}-3}$$ Correlation length

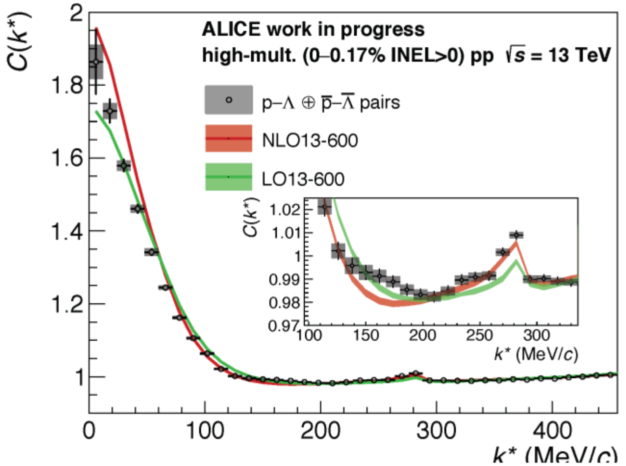
M. Stephanov PRL 102 (2009)

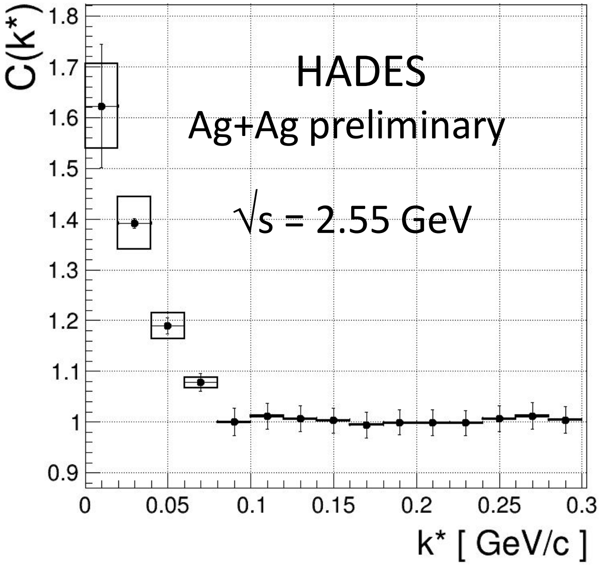


Critical point, if any, is located above $\sqrt{s_{NN}}$ =3 GeV
More to come soon from HADES Ag+Ag experiments

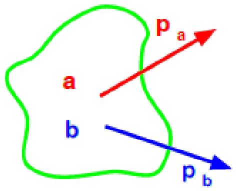
Probing particle interactions with correlation functions

ALICE Coll. PLB 832 (2022) 137272





Interferometry/femtoscopy



$$C^{ab}(P,q) = \frac{\mathbb{P}(\vec{p_a},\vec{p_b})}{\mathbb{P}(\vec{p_a})\mathbb{P}(\vec{p_b})} = \int d^3r' \, S_p(r') |\phi(q,r')|^2$$

Mixed events

1 — **Source fonction**

2 — **Particle interaction**

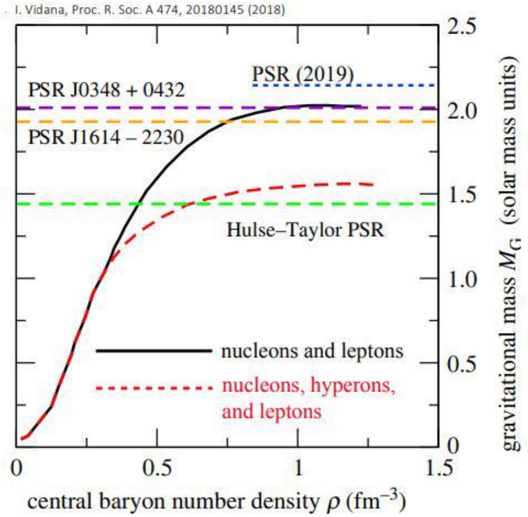
Interferometry results (strangeness)

- ALICE : pΛ, pΩ^-, pΞ^-, pΣ, pΣ^0, pϕ, p K^-
- HADES : pΛ *Phys. ReV. C 94 (2016) in p+Nb*

\+ on-going analysis in Ag+Ag $\sqrt{s}$ = 2.55 GeV pΛ, pK^-,….

- Experimental challenge:

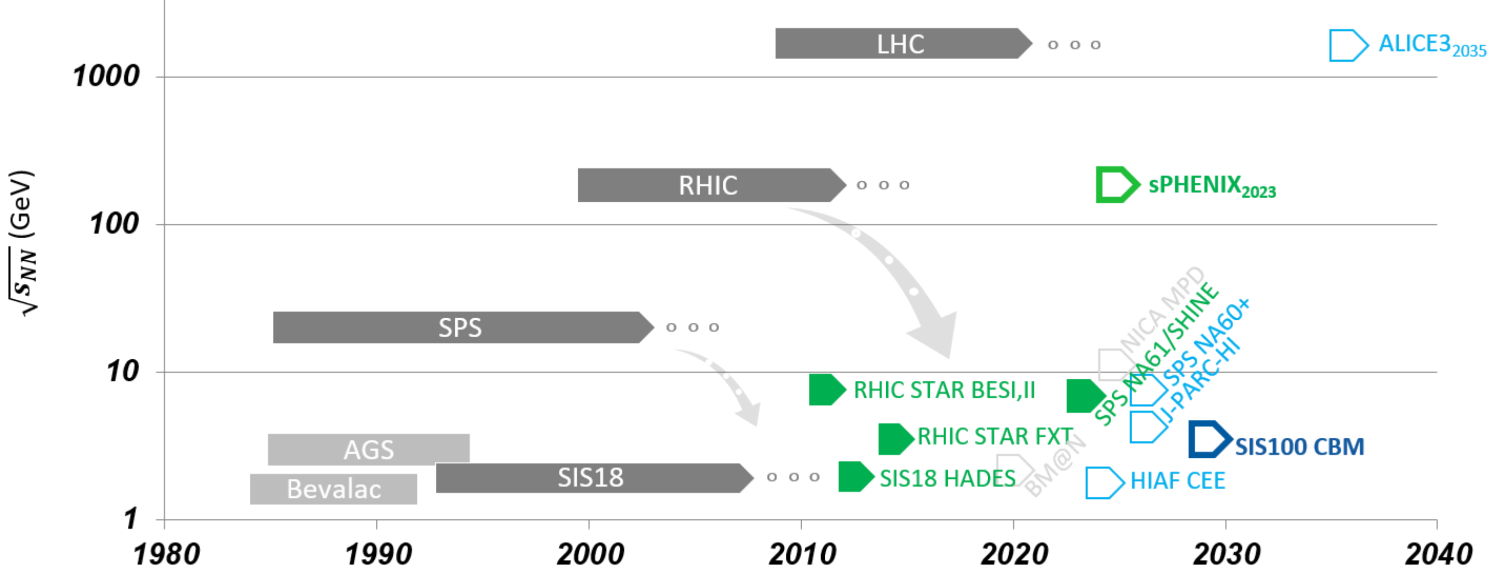
Highest sensitivity to the interaction at small k*



Indication of more attractive ΛN interaction
→ need for 3 body ΛNN interactions to solve the hyperon puzzle ? (can be checked with ALICE 3body correlations)

Prospects for heavy-ion experiments

Experimental projects



Courtesy from T. Galatyuk

Theoretical developments:

- Chiral Effective Field Theory S. Huth Nature 606 (2022) 276-280
- CMF parity-doublet model: matches lattice QCD at low μ_B and neutron-star constraints at high density, A. Motornenko et al. PhysRevC.101.034904
- Bayesian approach using transport models to extract EOS parameters Kuttan et al. 2022, arXiv:2211.11670 [nucl-th]

Conclusion

- The study of baryon-rich matter with heavy ions at relativistic energies has recently attracted much interest due to the access to Neutron Star Merger exploration
  - ✓ very rich experimental field: HADES@SIS18 (Implication of French teams), RHIC
  - ✓ in future: CBM@SIS100 (under construction, beams 2029), other projects Na60+@SPS ,….

- on-going studies with the femtoscopy technique are also very promising,
  → direct information on strangeness interactions (ALICE, HADES,…)

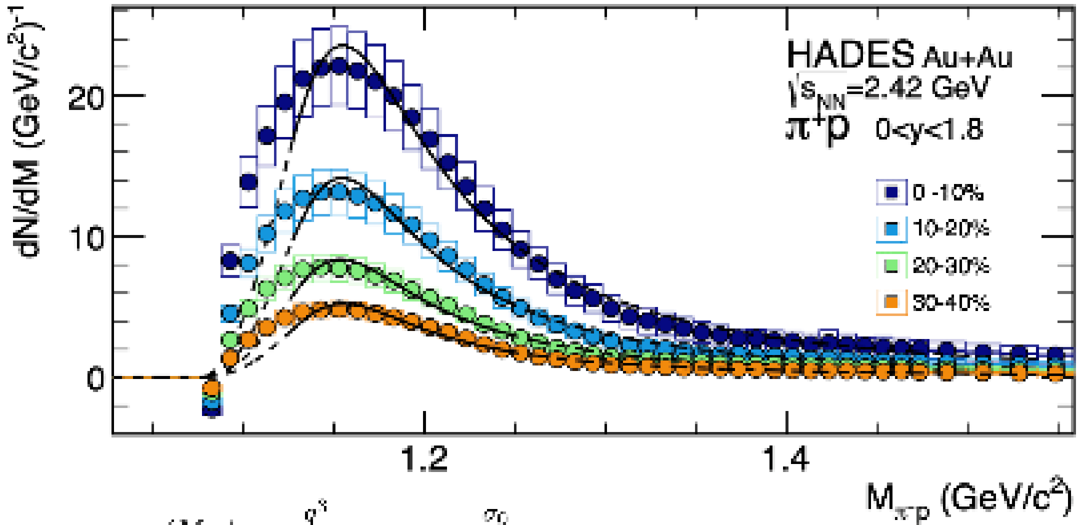
- New theoretical developments (Chiral Effective Field Theory,..) describing neutron star merger and hadronic matter
- Bayesian analysis to extract EOS parameters from both astrophysical and Heavy-Ion measurements

Thank you

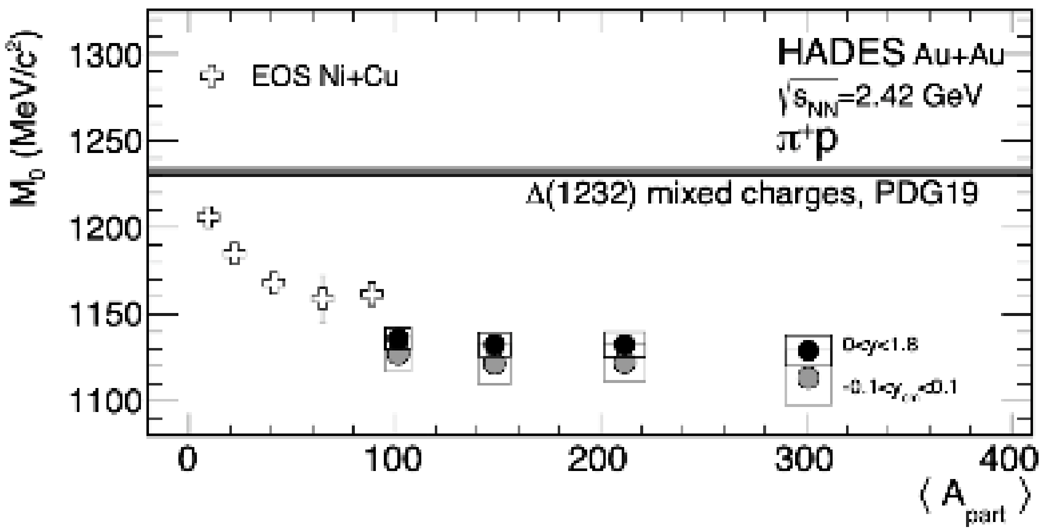
Correlated pion-proton pair emission

$\pi^+ p$ 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

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

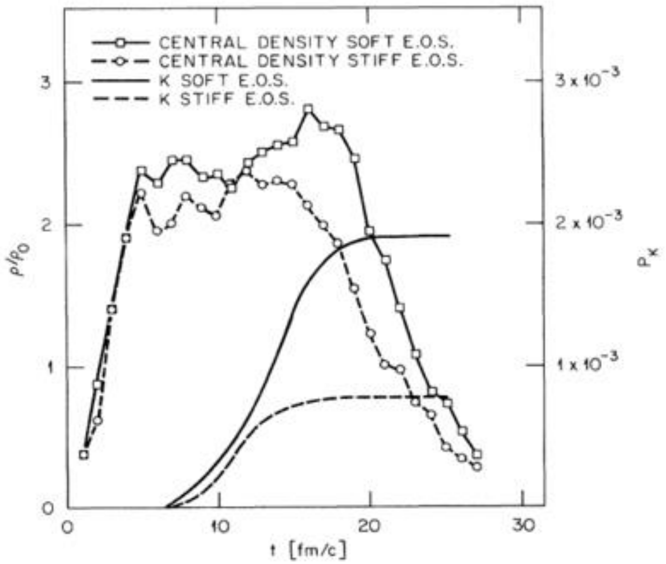
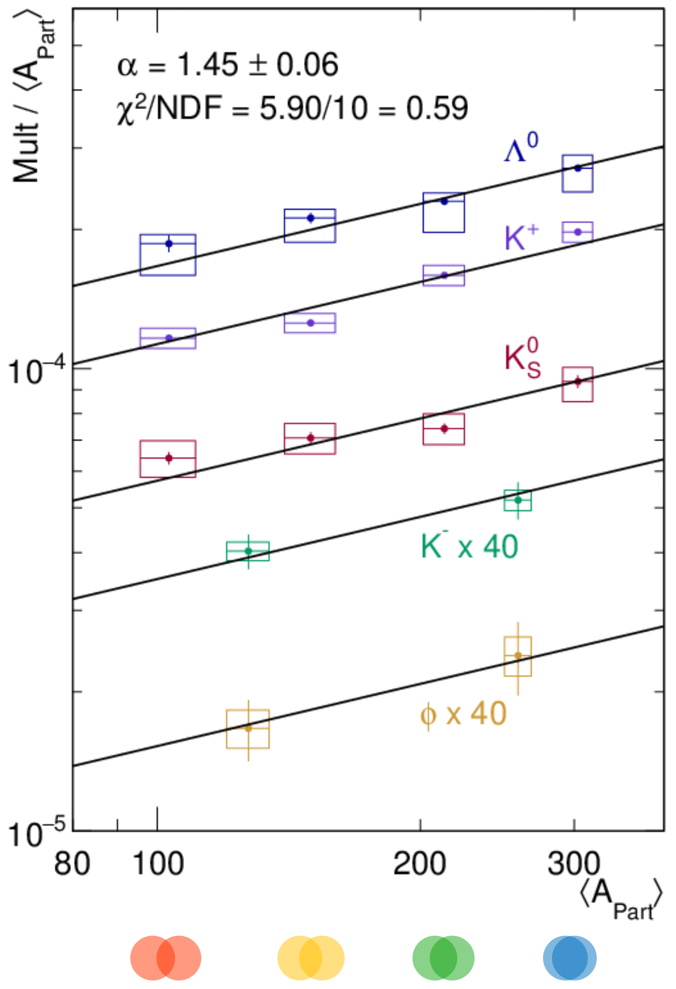


FIG. 1. Central density ρ/ρ_0 and total kaon-production probability P_K as functions of the collision time for reactions between Nb nuclei at an incident energy 700A MeV and at an impact parameter $b = 0.5$ fm.

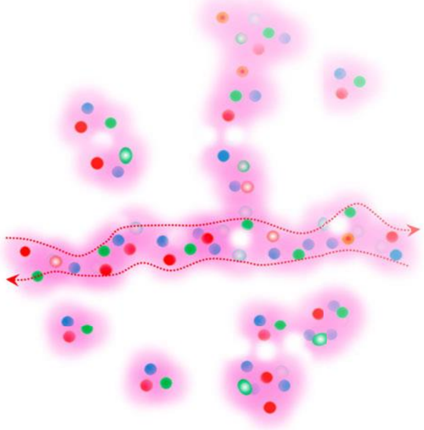
Rare sub-threshold strangeness production

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

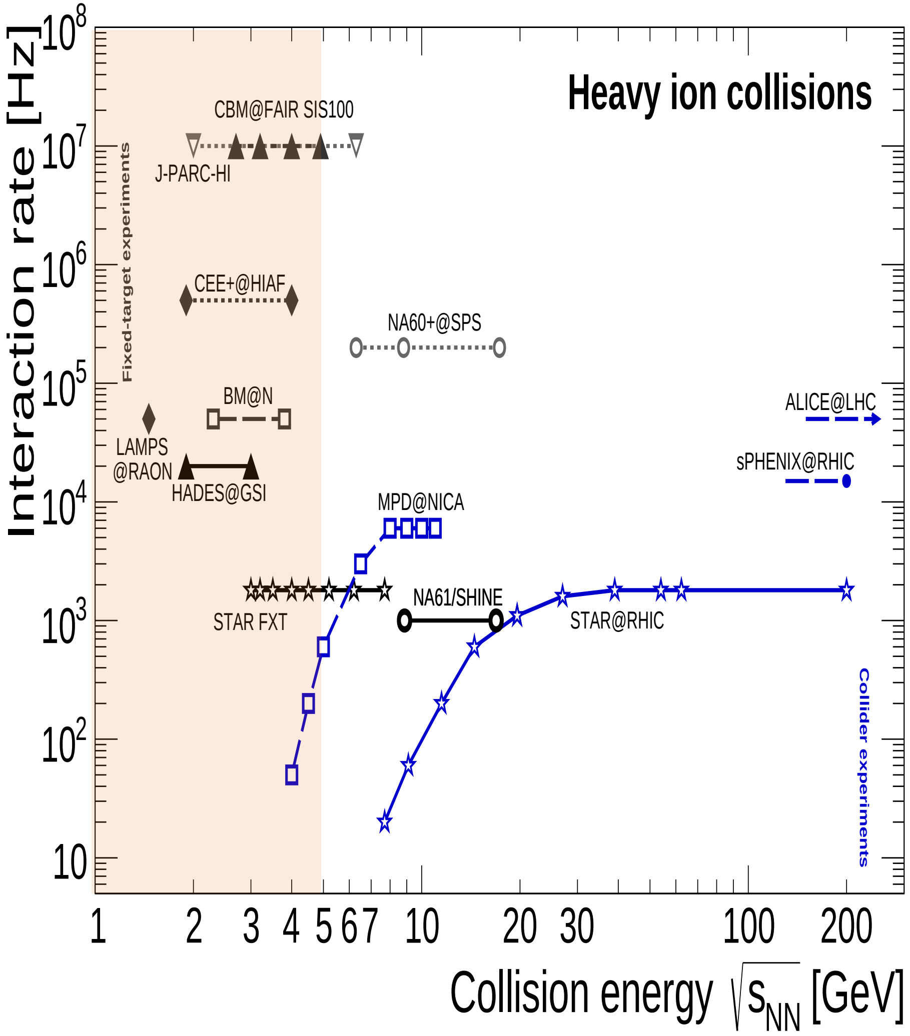


Connection to "soft deconfinement"?

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

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

The future is bright



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

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