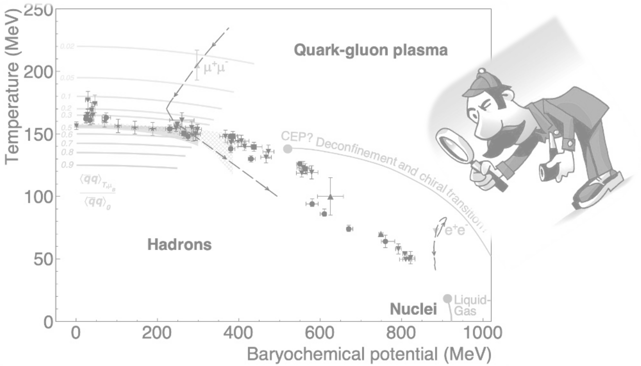
Unravelling the phase structure of strong-interaction matter with high-energy heavy-ion experiments



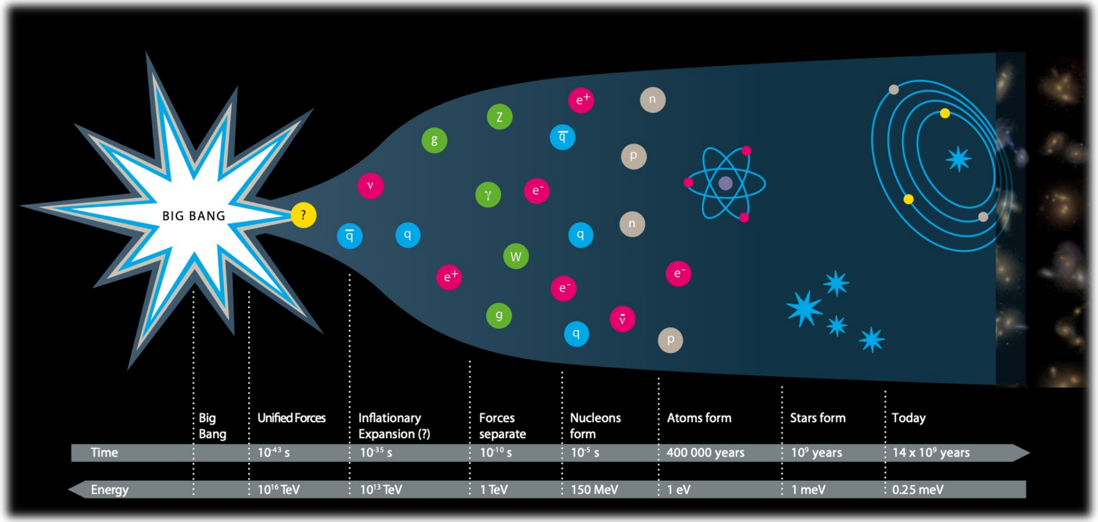
Tetyana Galatyuk, GSI / Technische Universität Darmstadt

Symposium “Strong-Interaction Matter under Extreme Conditions”, March 11-15, 2024, Gießen

Objective

Decode the phases of nuclear matter in the non-perturbative regime of QCD

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



Objective

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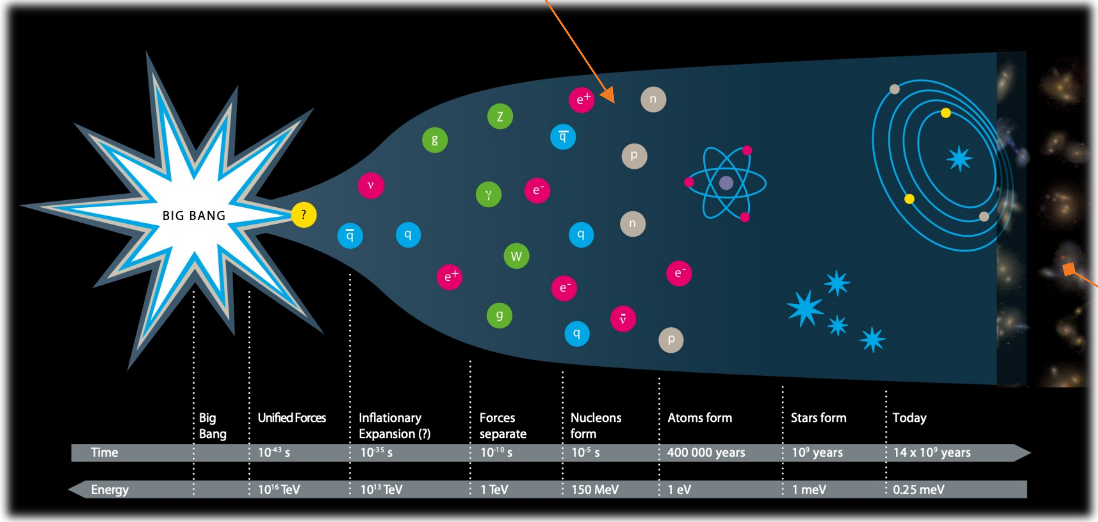
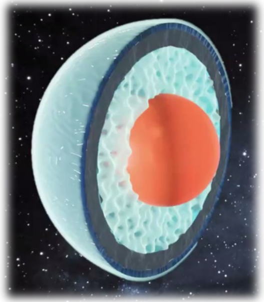
Nature of phase transitions in strong-interaction matter?



Matter properties in compact stellar objects?



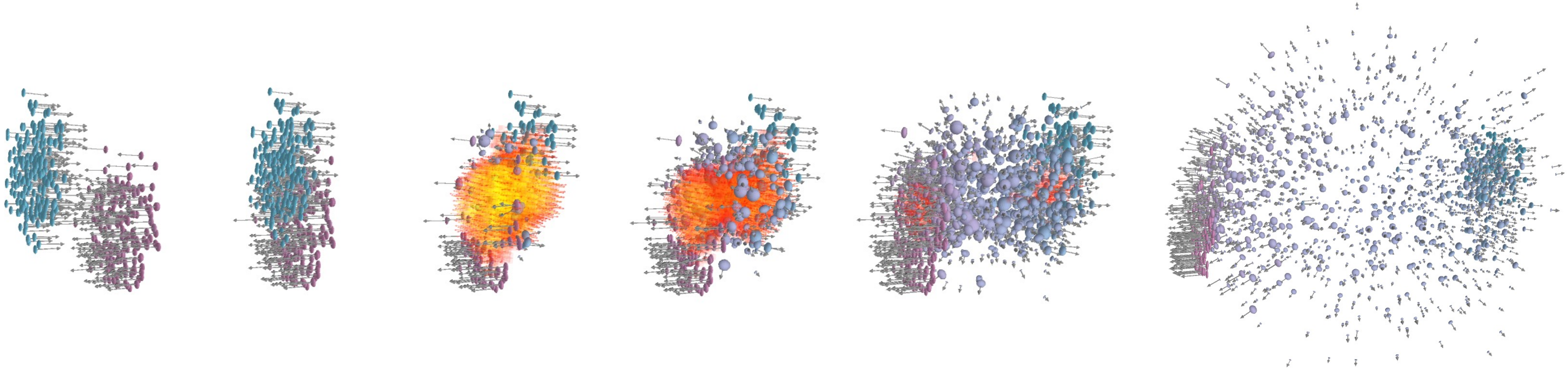
Neutron star

$M \sim 1.4 - 2\, M_\odot$
$R \sim 12$ km
$T \sim$ keV
$n \lesssim 10\, n_{sat}$

Method

Recreate various forms of cosmic matter in laboratory → high-energy heavy-ion collisions

Investigate transient states of QCD matter under extreme conditions



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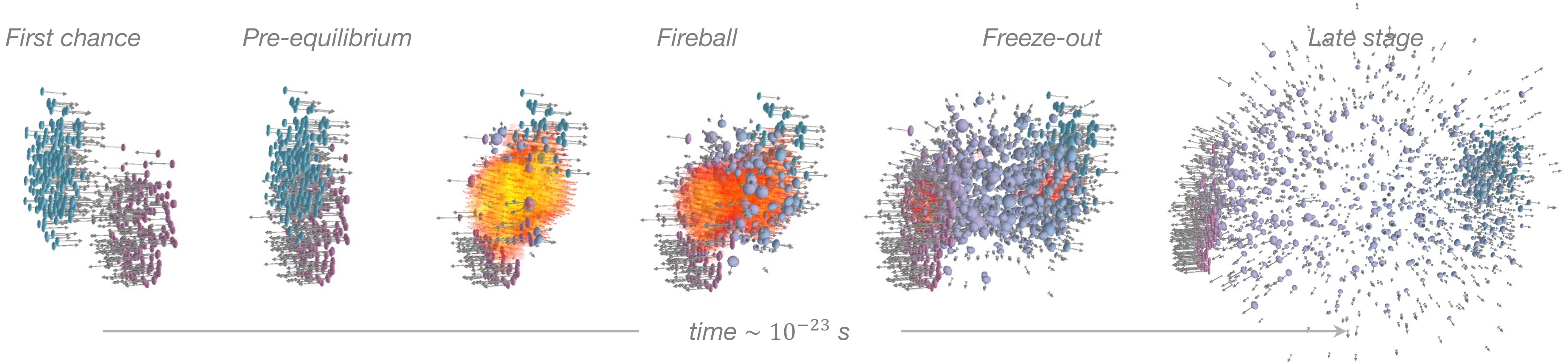
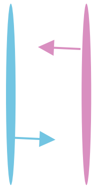
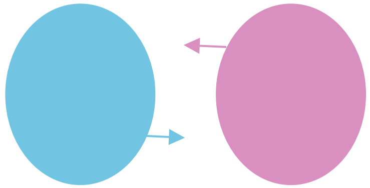


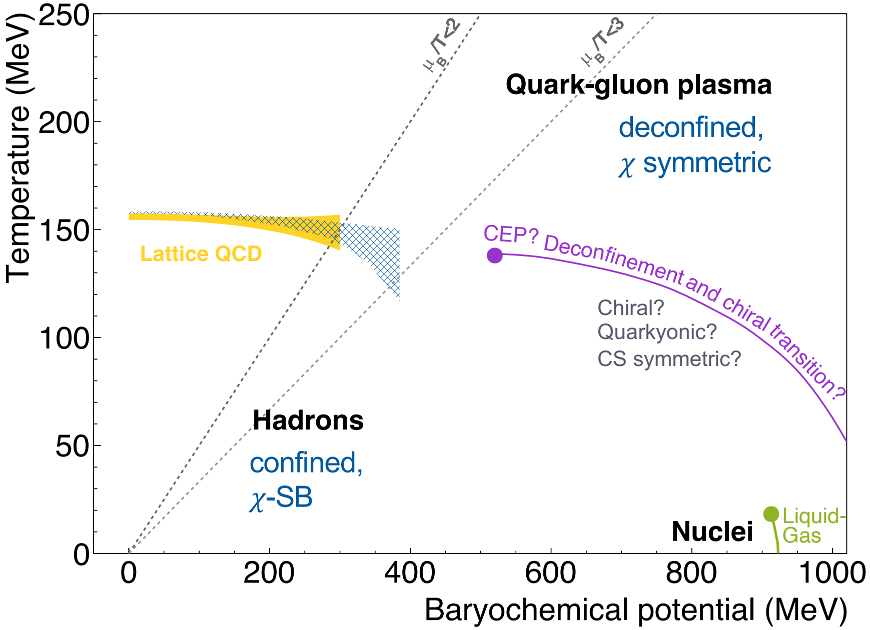


LHC energies $\sqrt{s_{NN}} = 2 - 5\ TeV$
parton parton collisions
$N_{particles} = N_{anti-particles}$

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



Experimental challenges:

- isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- probe microscopic matter properties

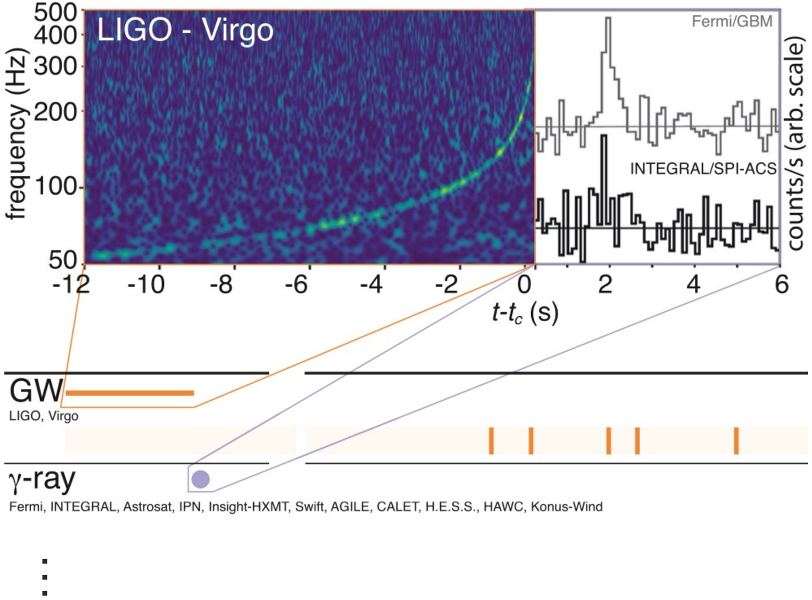
Measure with utmost precision:

- light flavour (chemistry, vorticity, flow)
- event-by-event fluctuations (criticality)
- dileptons (emissivity)
- charm (transport properties)
- hypernuclei (interaction)

HK 59.2
H. Elfner

Worldwide experimental and theoretical 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 star 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

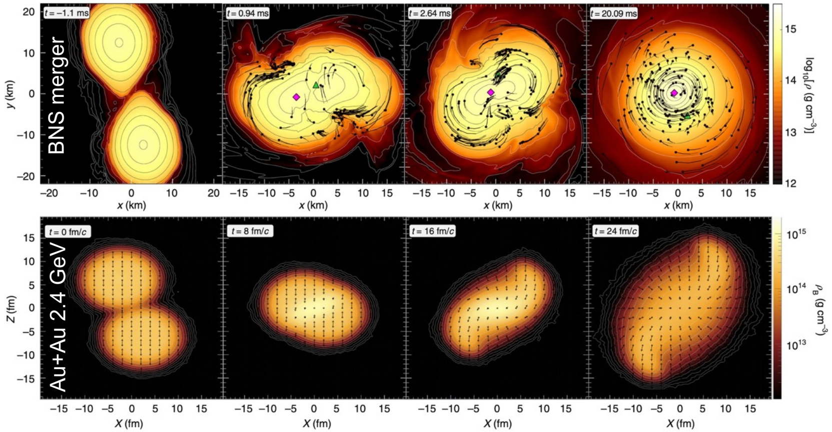
ARTICLES

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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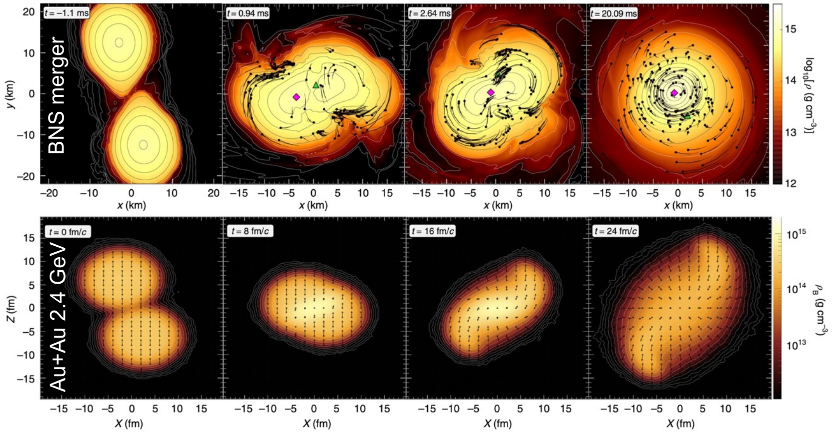
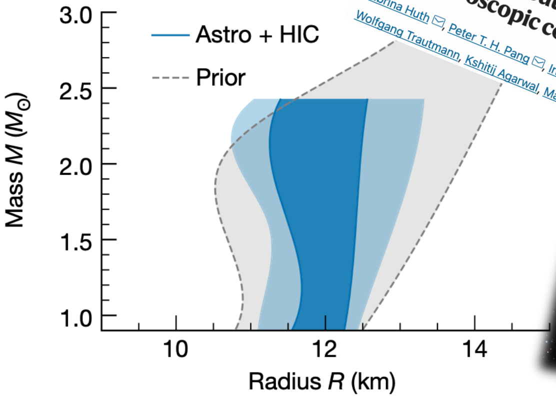


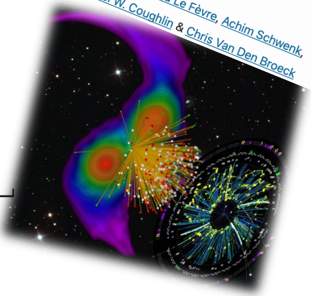
nature

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

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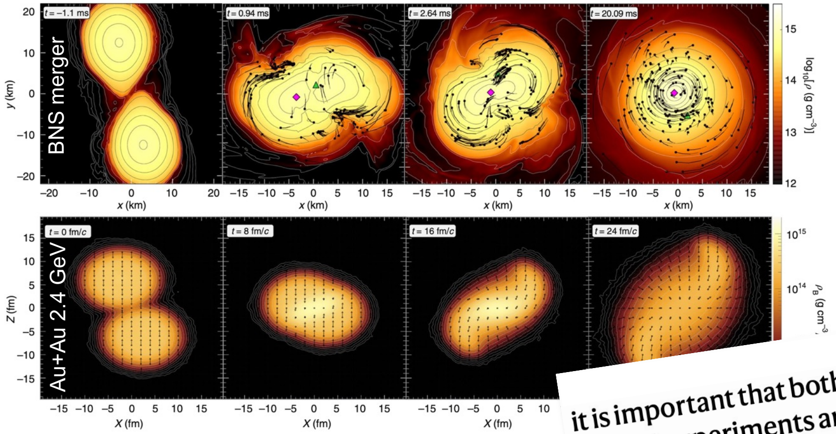

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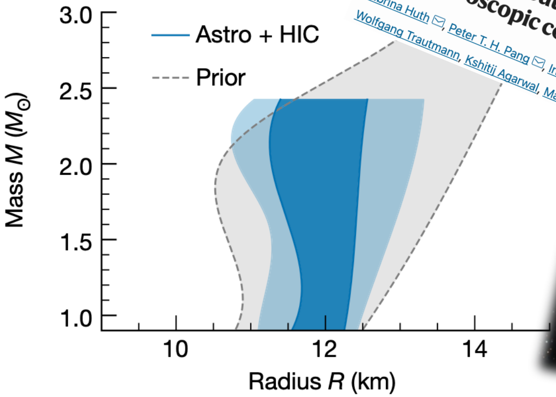
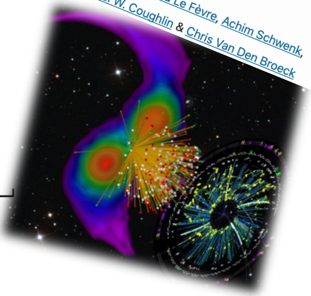


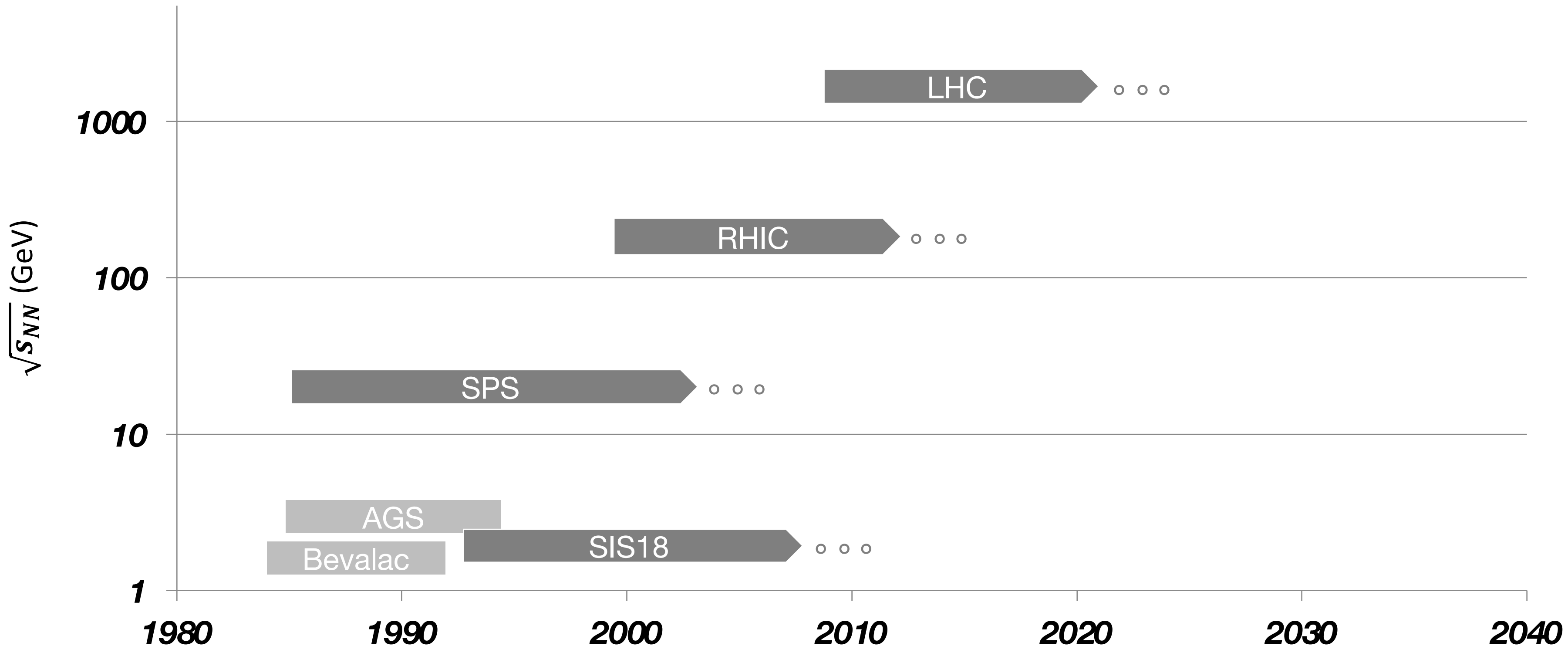


Remarkable consistency between multi-messenger observations and constraints from heavy-ion data

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

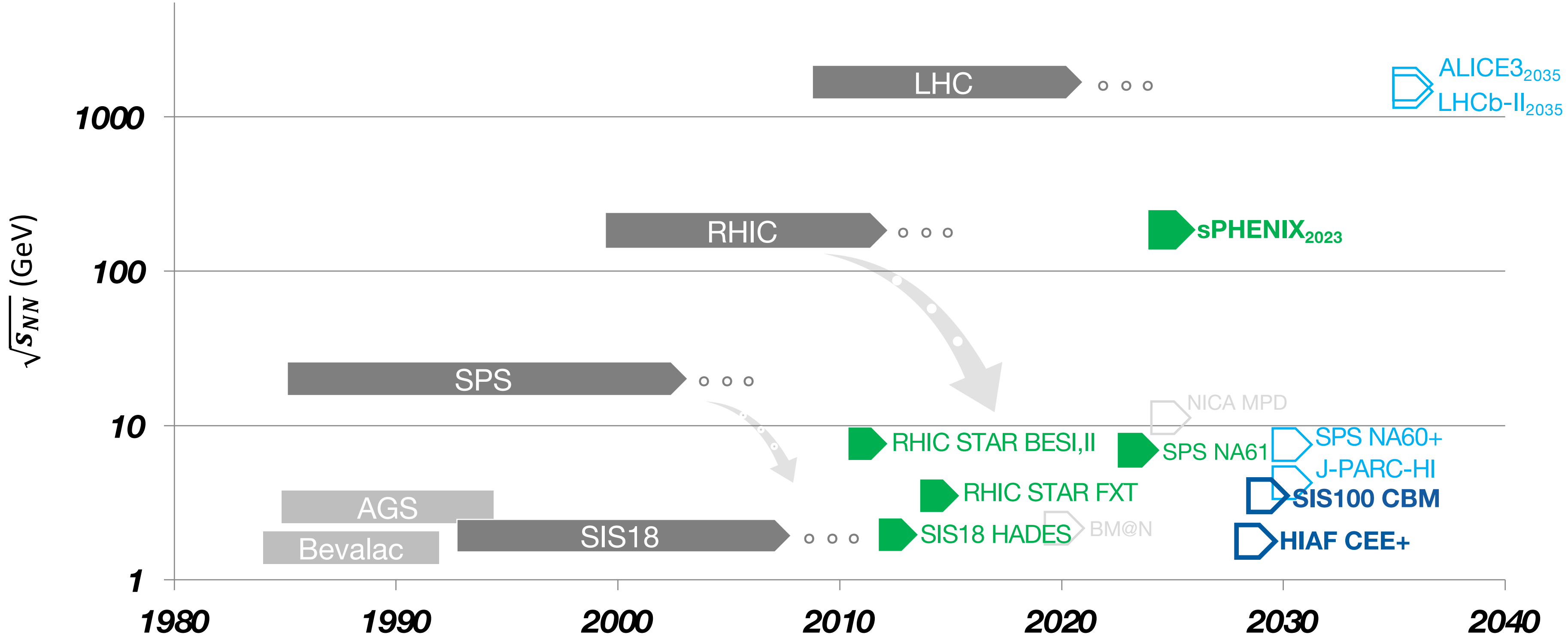
The quest for highest energy



Time ≡ advances in accelerator and detector technologies

The quest for utmost precision and sensitivity for rare signals

~25 years progress in technology since AGS (begin of high μ_B explorations)



Time ≡ advances in accelerator and detector technologies

Facility for Antiproton and Ion Research

multi-purpose (strong interaction) facility

Facility for Antiproton and Ion Research

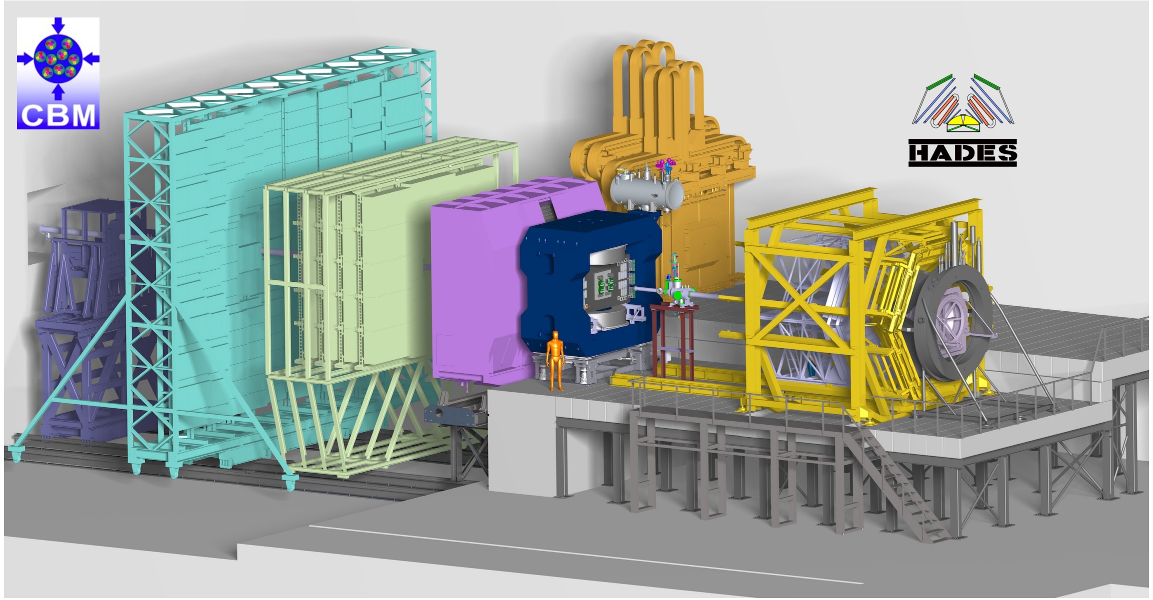
FAIR

multi-purpose (strong interaction) facility

Compressed Baryonic Matter experiment

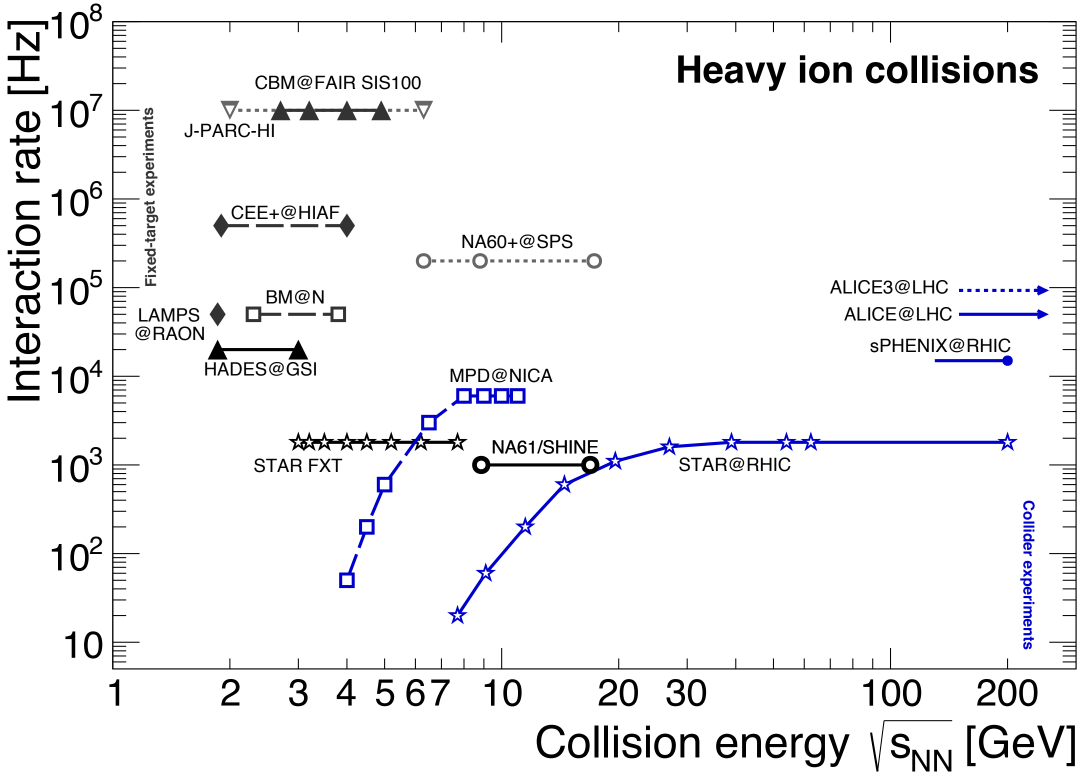
315 full members from 10 countries
47 full member institutions
10 associated member institutions

- 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
  → highly selective data reduction



Q4 2027 – installation and commissioning w/o beam
Q4 2028 – commissioning with SIS100 beam

Some basic facts on extreme matter facilities



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

- **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 20 kHz and $\sqrt{s_{NN}}$=2.4 GeV

HK 75.2 B. Kardan

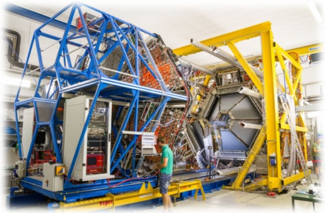
- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- Proposals: **CEE+@HIAF, J-PARC-HI, NA60+@SPS**
- **ALICE / ALICE 3:** exploit the forefront detector technologies and high luminosity potential of the LHC for ions

HK 59.3 A. Schmah

Program needs ever more precise data and sensitivity for rare signals

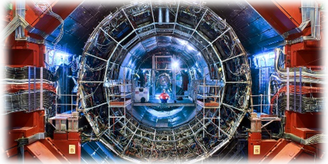
Extreme matter instruments

HADES

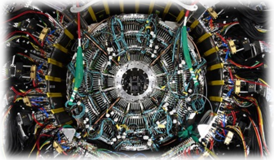


NA61/SHINE

ALICE

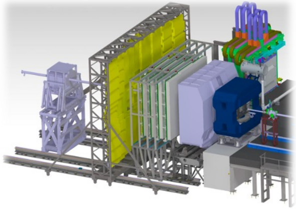


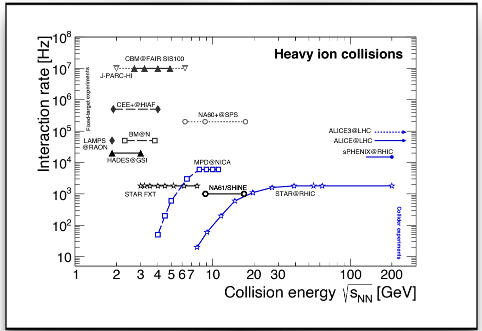
sPHENIX



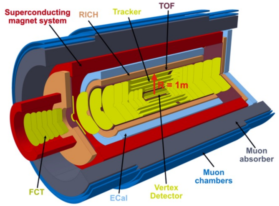
STAR

CBM

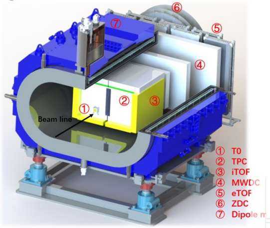




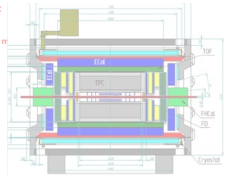
ALICE3



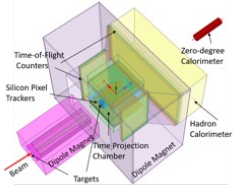
CEE+



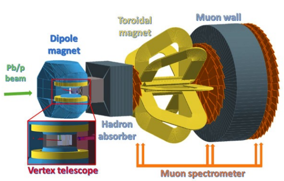
MPD



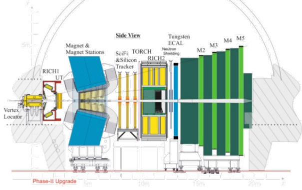
J-PARC-HI

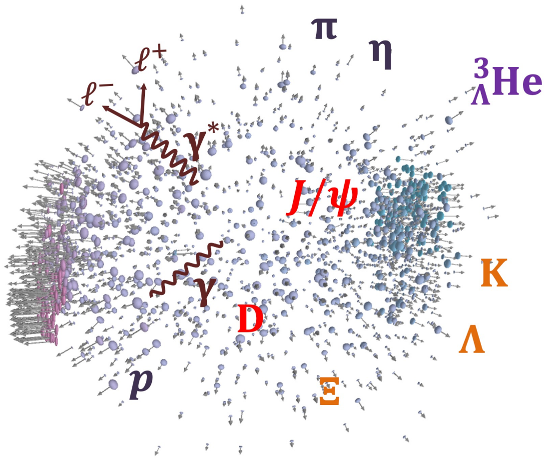


NA60+ at SPS



LHCb-II



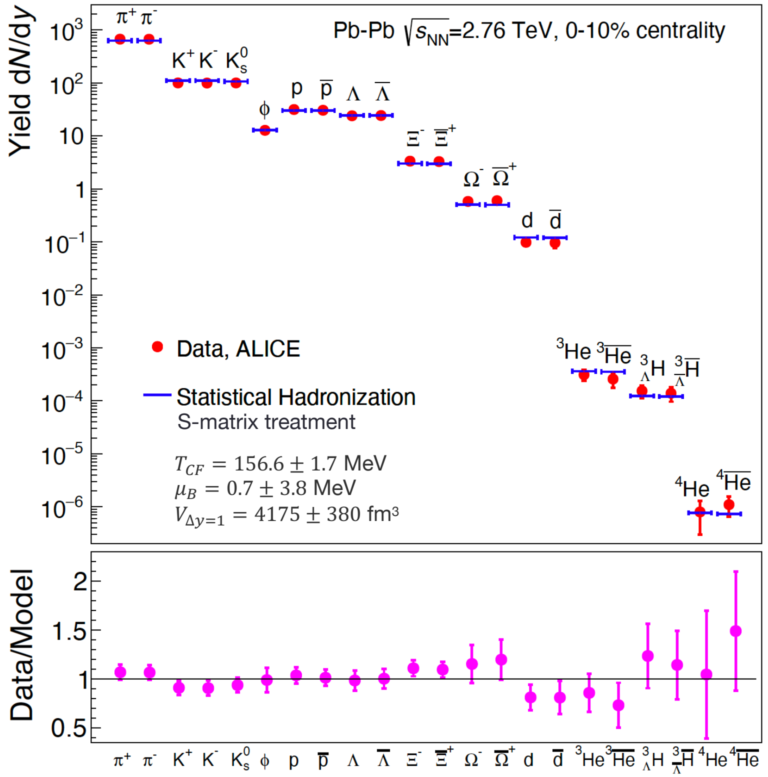


Final state “hadron-chemistry”

HADRON PRODUCTION

Hadronization of the fireball

Andronic, Braun-Munzinger, Redlich, Stachel,
Nature 561 (2018) no.7723



- Analysis of hadron yields within the statistical (thermal) model
- Test hypothesis of hadron abundancies in equilibrium $\rightsquigarrow T_{CF}, \mu_B, V$

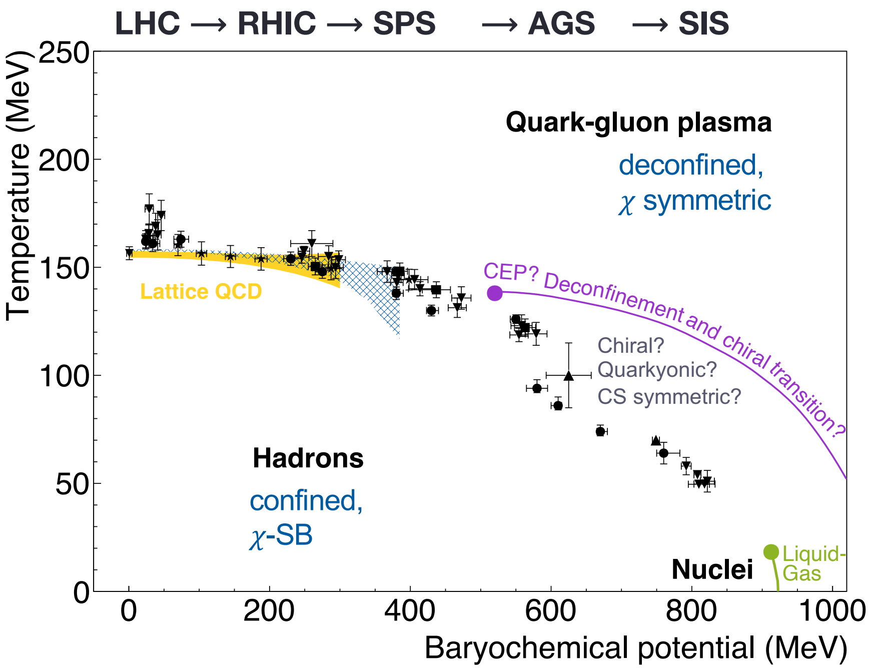
- **ALICE at LHC:**
  - grand canonical partition function
  - essentially 1 free parameter $\rightsquigarrow$ temperature T_{CF}

  $\boldsymbol{T_{CF} = 156.5 \pm 1.5 \pm 3}$ **MeV** (sys)

  Agreement over 9 orders of magnitude with QCD statistical operator prediction!

  - matter and antimatter are formed in equal portions
  - noticeably, loosely-bound objects follow the same systematics

Energy dependence of T and μ_B



Hadron yields produced in central heavy-ion collisions from LHC down to SIS18 energies well described by statistical ensemble

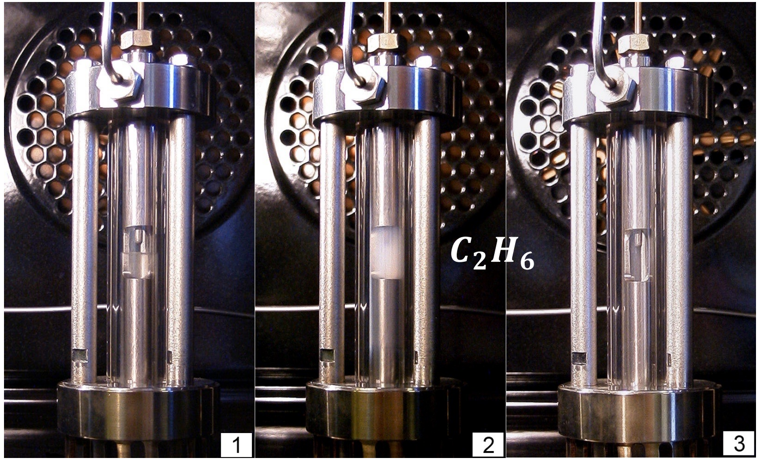
- Factor 1000 in beam energy ↔ factor ~2 in temperature
- Thermal fits exhibit a limiting temperature ($\sqrt{s_{NN}} \geq 12$ GeV):
  $T_{lim} = 158.4 \pm 1.4$ MeV Andronic, Braun-Munzinger, Stachel, PLB 673 (2009) 142
- ALICE result is in remarkable agreement with the pseudo-critical temperature from lattice QCD
  $T_{pc} = 156.5 \pm 1.5$ MeV Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
  $T_{pc} = 158.0 \pm 0.6$ MeV Borsanyi *et al.* [Wuppertal-Budapest], PRL 125 (2020)
- Chiral crossover at $\mu_B = 0$ may turn into a first-order phase transition at finite μ_B
- QCD critical point is awaiting discovery

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

CRITICALITY

Probing criticality with fluctuations

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



Critical phenomena discovered ~200 years ago by Cagniard de la Tour, using steam digester invented by Denis Papin in 1679

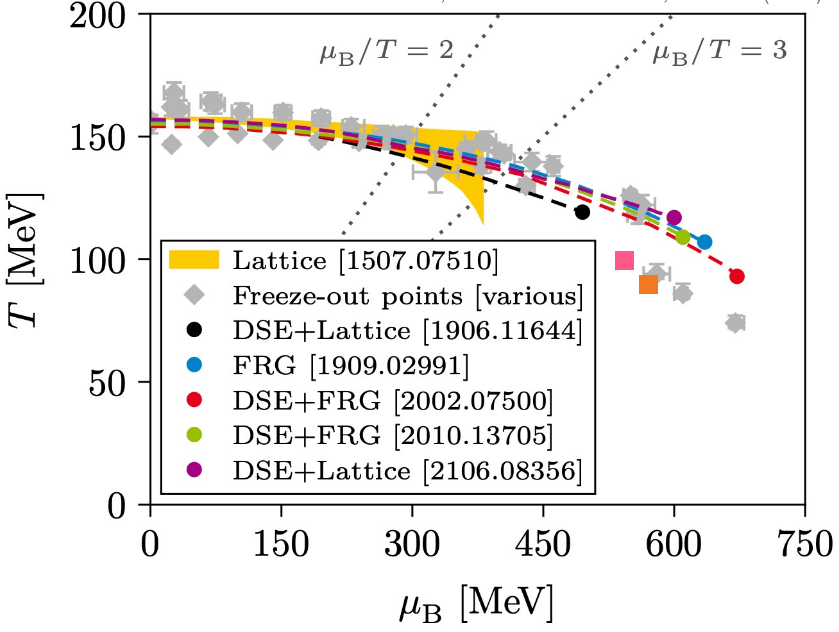
Ann. Chim. Phys., 21 (1822) 127-132

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

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

Critical point predictions from theory

[1]DSE: Bernhardt, Fischer and Isserstedt, PLB 841 (2023)



Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Borsanyi *et al*. [Wuppertal-Budapest], PRL 125 (2020)

- Lattice QCD disfavours QCD critical point at $\mu_B/T < 3$
- Effective QCD theories[1-3] and lattice-Pade[5,6] predict QCD critical point in a similar ballpark $\boldsymbol{T \sim 90 - 120}$ **MeV**, $\boldsymbol{\mu_B \sim 500 - 650}$ **MeV**
- If true, reachable in heavy-ion collisions at $\sqrt{s_{NN}} \sim \mathbf{3 - 5}$ **GeV**
- Including possibility that the QCD critical point does not exist

Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141
Vovchenko *et al.*, PRD 97, 114030 (2018)

[2]FRG: Fu, Pawlowski, Rennecke, PRD 101, 053032 (2020)
[3]BHE: Hippert et al., arXiv:2309.00579
[4]lQCD-Pade: Basar, arXiv:2312.06952
[5]lQCD-Pade: Clarke *et al.*, PoS LATTICE2023 (2024), 168

Event-by-event fluctuations and statistical mechanics

- In strong interactions, baryons, electrical charges and strangeness are conserved ($q \in \{B, Q, S\}$)
- Event-by-event fluctuations of q predicted within grand canonical ensemble

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

encodes the EoS

$$\frac{\kappa_n(N_q)}{VT^3} = \frac{1}{VT^3}\frac{\partial^n lnZ(V,T,\vec{\mu})}{\partial(\mu_q/T)^n} = \frac{\partial^n \hat{P}}{\partial \hat{\mu}_q^n} \equiv \hat{\chi}_n^q$$

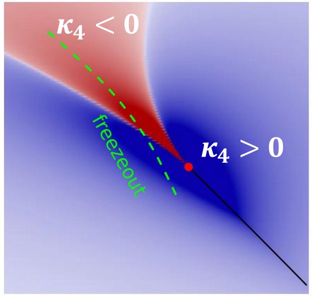
κ_n - cumulants (measurable in experiment)
$\hat{\chi}_n^q$ - susceptibilities (e.g. from lQCD)

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

Variance $\kappa_2 = \langle(\delta N)^2\rangle = \sigma^2$

Skewness $\kappa_3 = \langle(\delta N)^3\rangle$

Kurtosis $\kappa_4 = \langle(\delta N)^4\rangle - 3\langle(\delta N^2)\rangle^2$



Stephanov, RPL 107 (2011) 052301

QCD critical point: large correlation length and fluctuations

$\kappa_2 \sim \xi^2,\ \kappa_3 \sim \xi^{4.5},\ \kappa_4 \sim \xi^7$

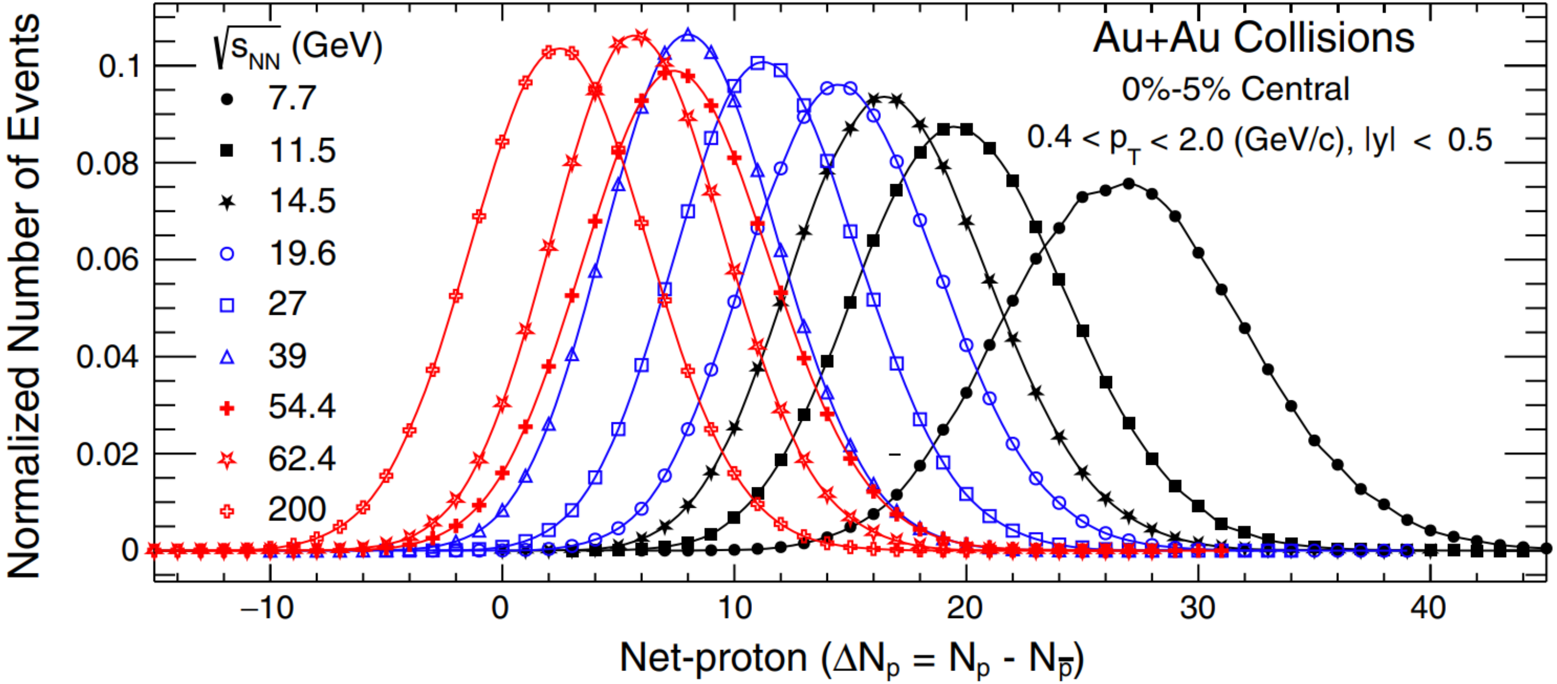
$\xi \to \infty$ **diverges at critical point**

➥ Look for **enhanced fluctuations** and **non-monotonicity**

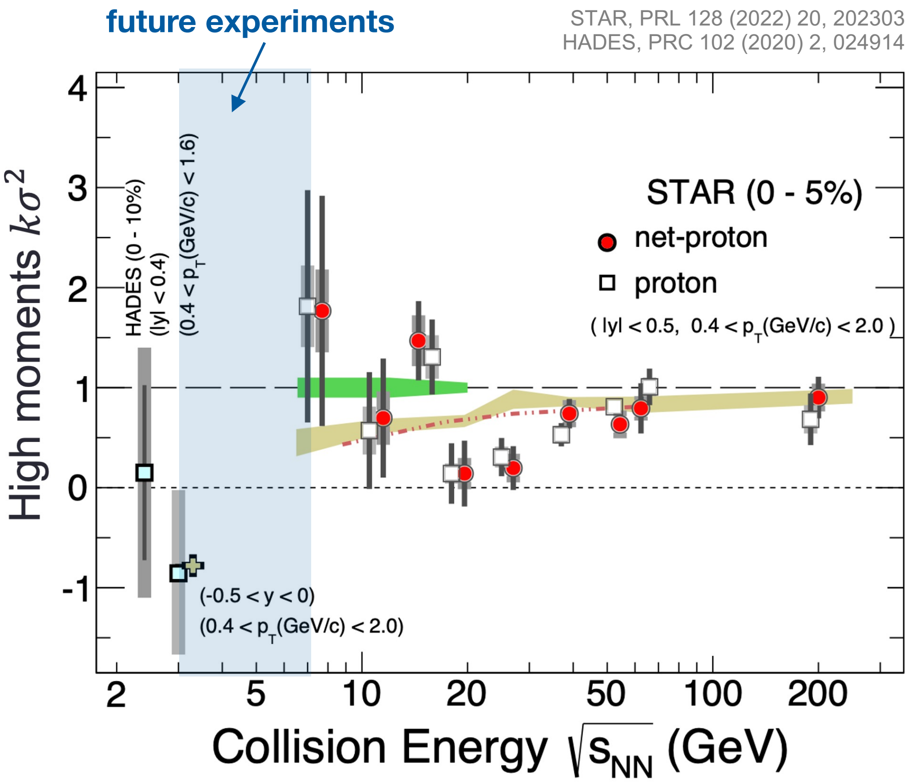
Measuring cumulants in heavy-ion collisions

- Count the number of events with given number of e.g. net-protons
- Look for subtle critical point signals → **critical signal is in these distributions**

STAR, PRL 126, 092301 (2021)



Critical point search



Non-monotonic trend of the higher moments κ_4/κ_2 of net-proton number distributions, visible in a beam energy scan?

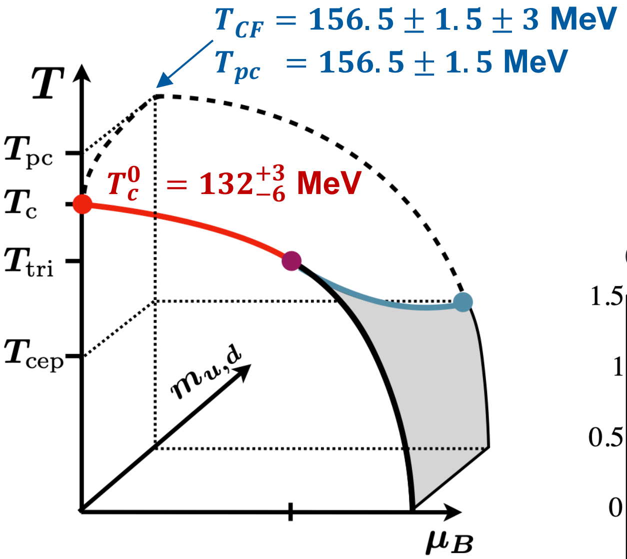
- Current data consistent with non-critical physics?
  → reduced errors to come from STAR BES-II

  Braun-Munzinger, Friman, Redlich, Rustamov, Stachel, NPA 1008 (2021) 122141

- Sensitivity to features of the QCD phase diagram grows with the order of the moment
- **Higher order moments probe the tails – statistics/artefacts!**
- Detailed **systematic** studies of experimental effects **is curtail**

Holzmann, Koch, Rustamov, Stroth, arXiv:2403.03598 [nucl-th]
Kitazawa'2012, Skokov'2013, Bzdak '2016, Kitazawa'2016, Braun-Munzinger'2017

Fingerprints of criticality at $\mu_B = 0$

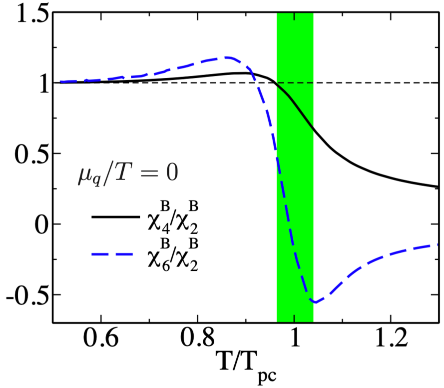


Kaczmarek *et al.*, PoS LATTICE2021 (2022) 429

- At $\mu_B = 0$ chemical freeze-out seems to occur at or near the QCD transition region for physical m_q
- In the chiral limit ($m_{u,d} \to 0$) crossover becomes a genuine 2nd-order chiral phase transition, $O(4)$ universality class

Pisarski, Wilczek, PRD 29 (1984) 338

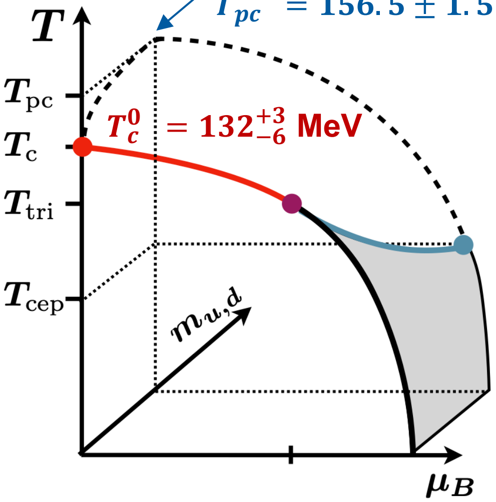
Critical behavior in k_6^B/k_2^B



T_{pc}: Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
T_{cf}: Andronic etal., Nature 561 (2018) no.7723
T_c: Ding *et al.* [HotQCD], PRL 123 (2019) 6, 062002

Ejiri, Karsch, Redlich, PLB 633 (2006) 275-282
Friman, Karsch, Redlich, Skokov, EPJC 71 (2011) 1694
Bazavov et al., PRD 95 (2017) 054504
Borsanyi et al., JHEP 10 (2018) 205

Fingerprints of criticality at $\mu_B = 0$

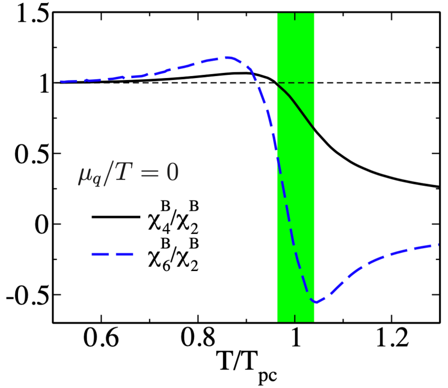


Kaczmarek *et al.*, PoS LATTICE2021 (2022) 429

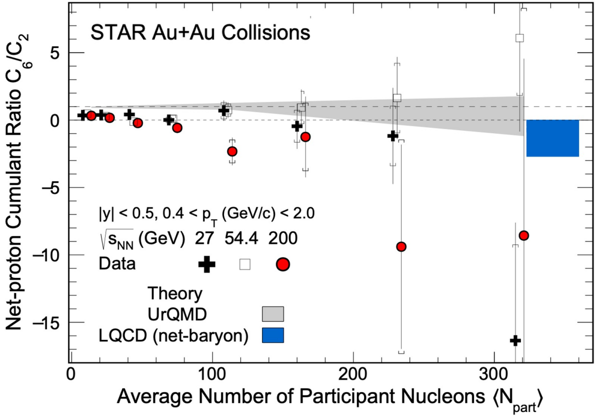
- At $\mu_B = 0$ chemical freeze-out seems to occur at or near the QCD transition region for physical m_q
- In the chiral limit ($m_{u,d} \to 0$) crossover becomes a genuine 2nd-order chiral phase transition, $O(4)$ universality class

Pisarski, Wilczek, PRD 29 (1984) 338

Critical behavior in k^B_6/k^B_2



STAR, PRL 127 (2021) 26, 262301



T_{pc}: Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
T_{cf}: Andronic etal., Nature 561 (2018) no.7723
T_c: Ding *et al.* [HotQCD], PRL 123 (2019) 6, 062002

Ejiri, Karsch, Redlich, PLB 633 (2006) 275-282
Friman, Karsch, Redlich, Skokov, EPJC 71 (2011) 1694
Bazavov et al., PRD 95 (2017) 054504
Borsanyi et al., JHEP 10 (2018) 205

Hints for negative k^B_6/k^B_2?

High statistics RHIC and LHC data needed for a firm conclusion

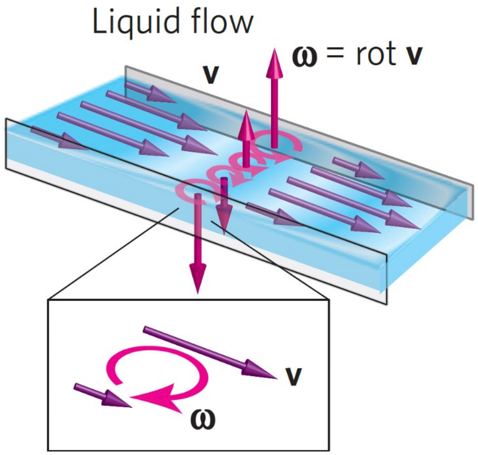
The quest to detect the initial electromagnetic field

VORTICITY

Probing vorticity with spin degrees of freedom

$$P(\vec{s}) \propto e^{-\vec{\omega}\vec{s}/k_B T}$$

- First observation of fluid vorticity-polarization coupling by Takahashi, *et al*. Nat. Phys. (2016)
  - atomic alignment directly measured
  - direction of angular momentum known



Friction with walls induces vorticity
Vorticity of bulk ⇝ polarization of constituents

Probing vorticity with spin degres of freedom

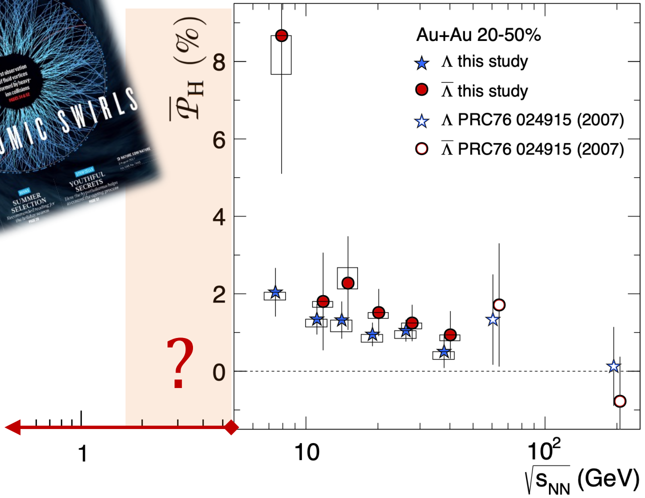
$$P(\vec{s}) \propto e^{-\vec{\omega}\vec{s}/k_B T}$$

- Non-central heavy-ion collisions ⇝ large orbital angular momenta ($\sim 1000\hbar$) ⇝ vortical structure of the system?
  - **probed via parity-violating decay of Λ hyperons**
  - estimation of angular momentum direction via spectator deflection

- First observation of fluid vorticity-polarization coupling by Takahashi, *et al*. Nat. Phys. (2016)
  - atomic alignment directly measured
  - direction of angular momentum known

STAR, Nature 548 (2017) 62-65

Global spin polarization of hyperon as a probe of fluid behavior

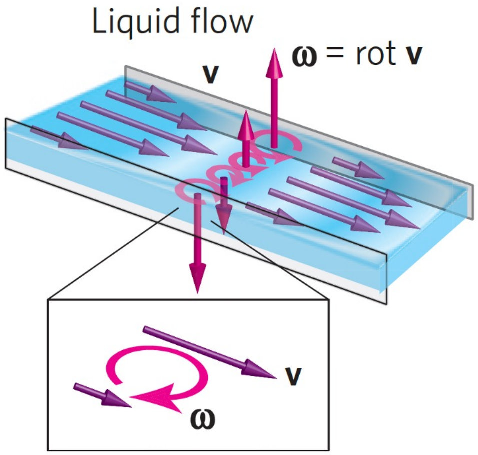


$\omega \approx (9 \pm 1) \times 10^{21}\ s^{-1}$

evidence for the **most vortical fluid**

and hint for the largest **magnetic field**

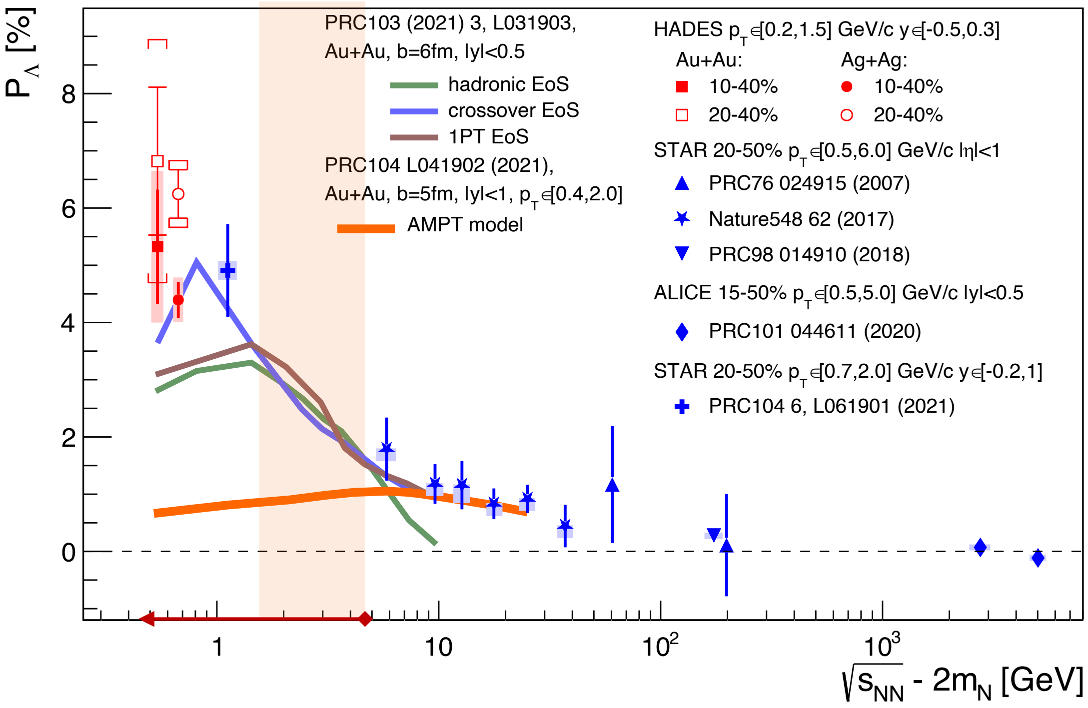
$B = 10^{14}\,T$



Friction with walls induces vorticity
Vorticity of bulk ⇝ polarization of constituents

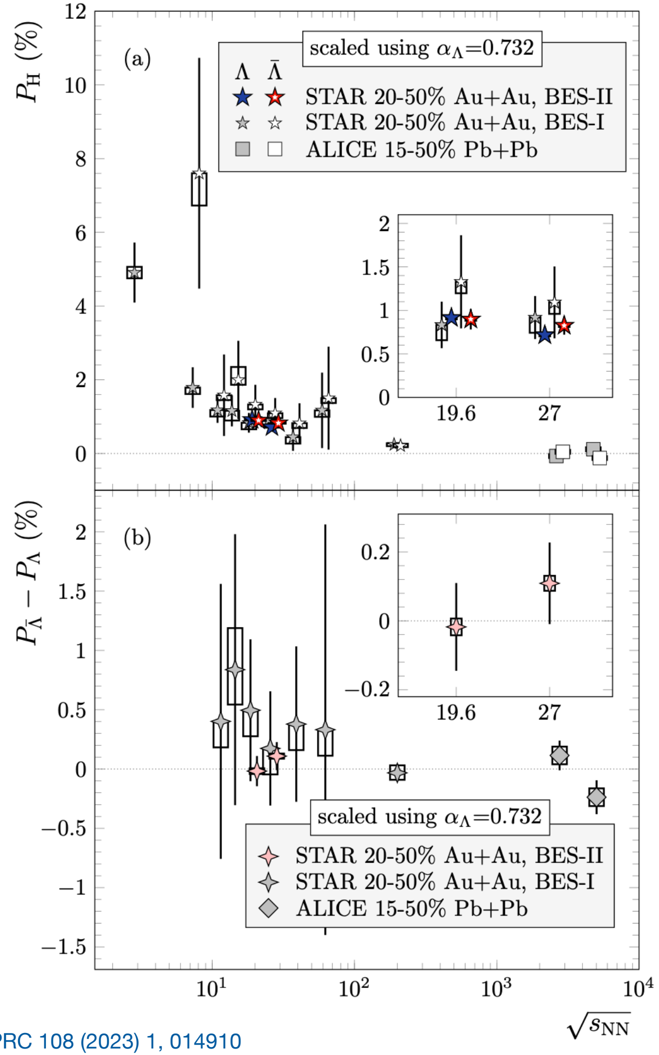
Splitting of hyperon polarization

HADES, PLB 835 (2022) 137506



- Strong increase of polarization signal towards few GeV energies
- Highest polarization measured by HADES, SIS18
- Origin of the polarization mechanism? Sensitivity to EoS?
- Mapping of the **excitation function of Λ and $\bar{\Lambda}$** (Ξ^-, Ω) with precision of 5% with CBM

Late stage magnetic field should cause splitting in Λ and $\bar{\Lambda}$ polarization



STAR, PRC 108 (2023) 1, 014910

The quest to detect the initial electromagnetic field

- **No splitting observed over wide range of beam energies in Au+Au and Pb+Pb collisions**
- None in isobar [Rz / Zr] data either

STAR, PRL 131 (2023) 20, 202301

- At 95% confidence level late stage magnetic field
  - $\mathbf{B}\ (\sqrt{s_{NN}} = 19.6\ \mathrm{GeV}) < 9.4 \times 10^{12}\ \mathrm{T}$
  - $\mathbf{B}\ (\sqrt{s_{NN}} = 27\ \mathrm{GeV}) < 1.4 \times 10^{13}\ \mathrm{T}$

  → One order of magnitude below expectation

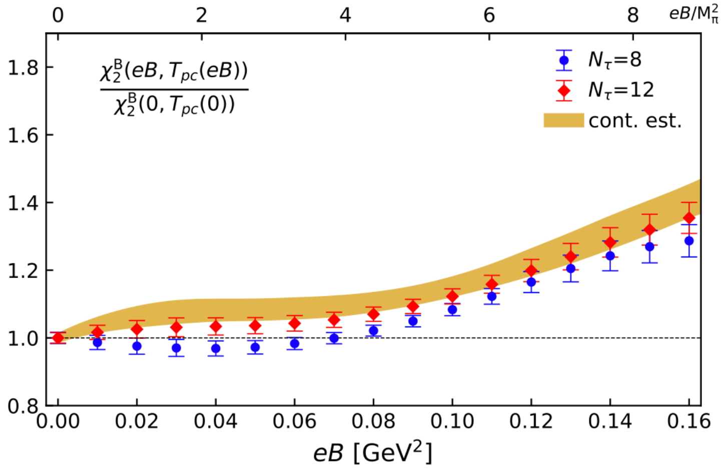
Does magnetic field fade away too quickly?

Can we probe at earlier time?

Fluctuations of baryon number in strong magnetic field

Lattice calculations suggest susceptibilities sensitive to initial electromagnetic field

Ding *et al.*, Acta Phys.Polon.Supp. 16 (2023) 1, 134



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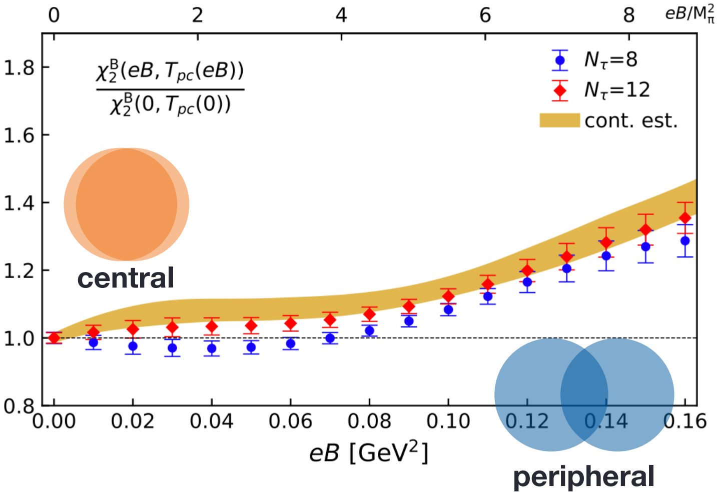
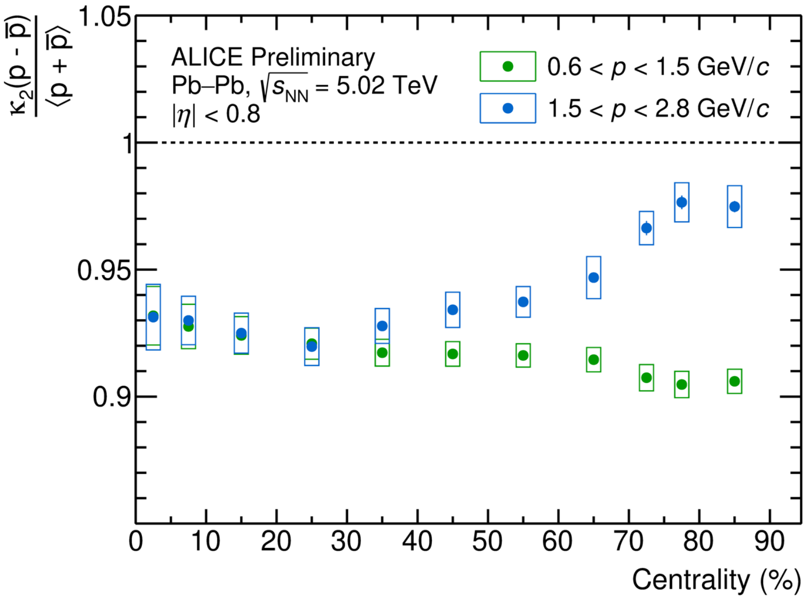
Ding *et al.*, Acta Phys.Polon.Supp. 16 (2023) 1, 134



$$\frac{\chi_2^B(eB, T_{pc}(eB))}{\chi_2^B(0, T_{pc}(0))} \Leftrightarrow \frac{k_2^{\text{cent}>0-5\%}(\mathbf{p}-\bar{\mathbf{p}})}{k_2^{\text{cent}=0-5\%}(\mathbf{p}-\bar{\mathbf{p}})}$$

Fokin [ALICE], QM23, EMMI RRTF Nov 6-10, 2023

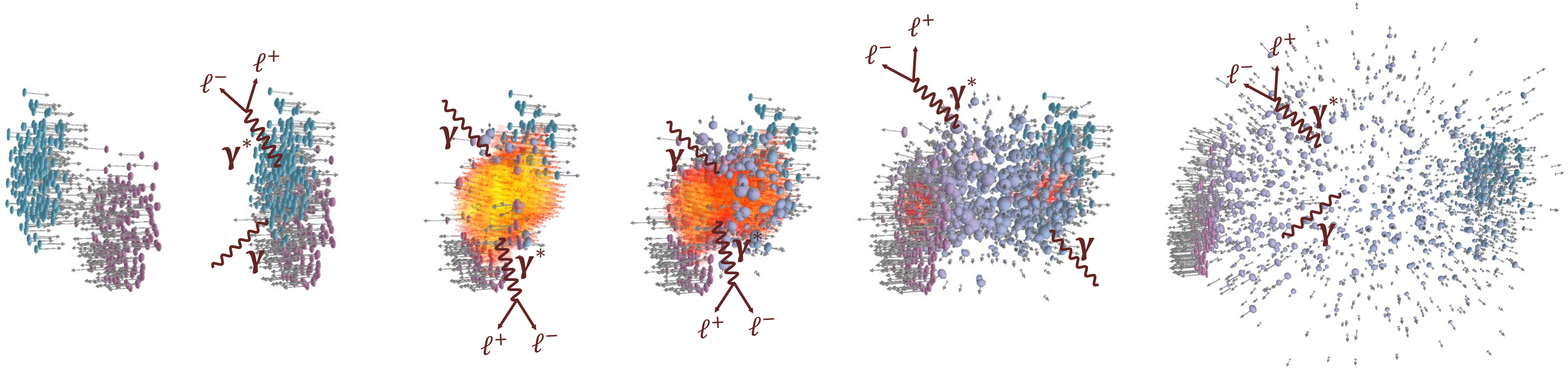


- **2[nd] order net-proton number cumulant in high p range increases in peripheral events – B-field largest**
- Check for other scenarious (cluster formation, ect.) and measurement in pp

Electromagnetic radiation

EMISSIVITY

Electromagnetic radiation as multi-messenger of fireball



Electromagnetic radiation (γ, γ^*)

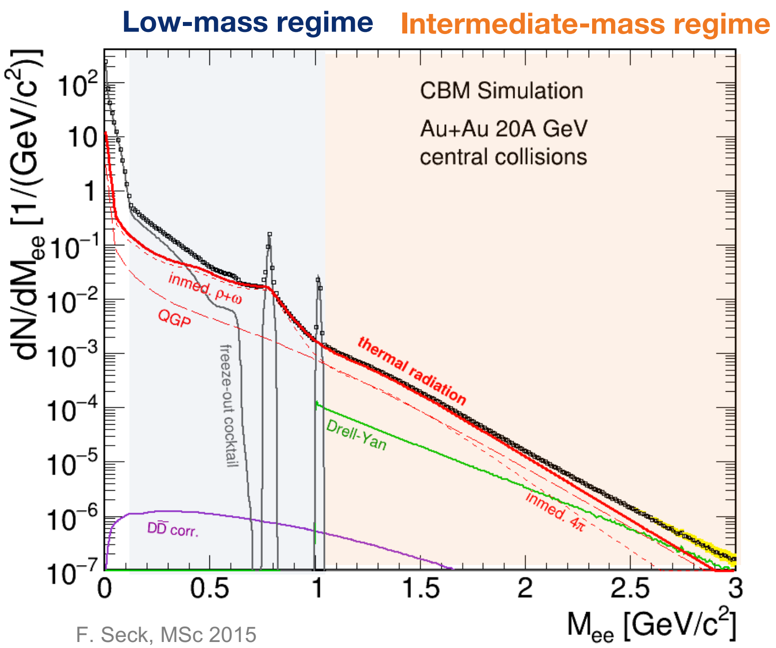
Reflect the whole history of a collision

No strong final state interaction
⇝ leave reaction volume undisturbed

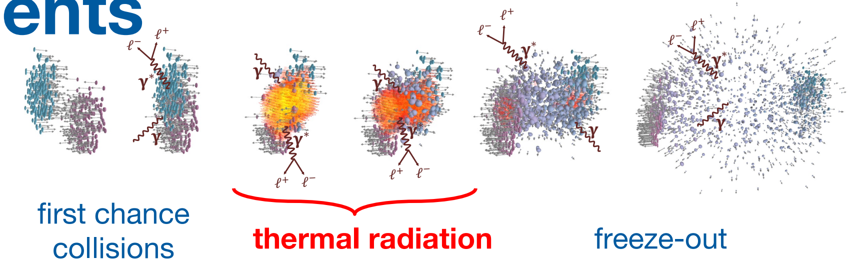
Encodes information on matter properties enabling unique measurements

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

Thermal dilepton measurements



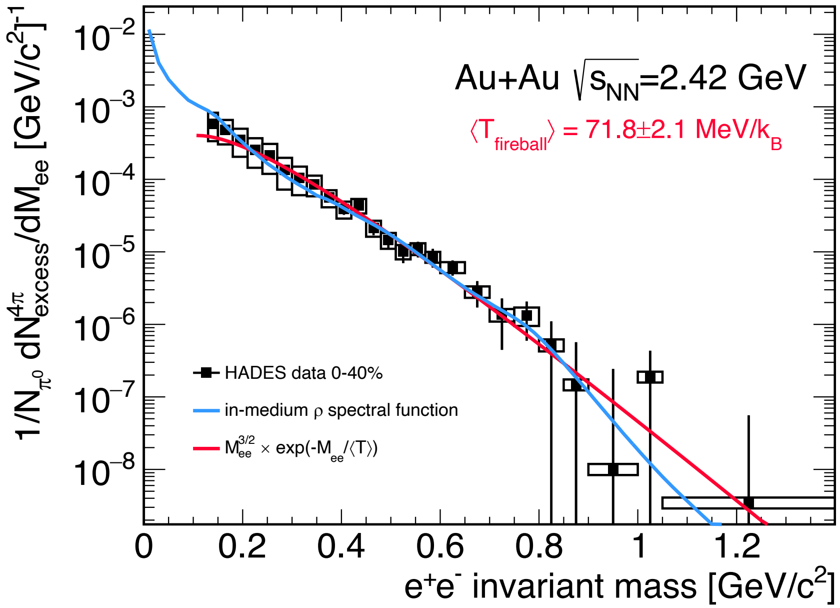
F. Seck, MSc 2015

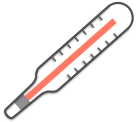


- Dileptons are rare probes!
- Decisive parameters for data quality:
  interaction rates (IR) and signal-to-combinatorial background ratio (S/CB): effective signal size:
  $S_{eff} \sim IR \times S/CB$
- Needs coverage of mid-rapidity, low-$M_{\ell\ell}$, and low-p
- Isolation of thermal radiation by subtraction of measured decay cocktail $(\pi^0, \eta, \omega, \varphi)$, Drell-Yan, $c\bar{c}$ $(b\bar{b})$

Thermal dileptons from baryon rich matter

HADES, Nature Phys. 15 (2019) 1040





'Planck-like' **In-medium spectral function**

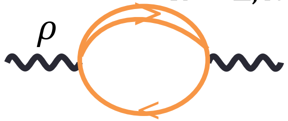
$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T)\, Im\Pi_{em}(M,q,T,\mu_B)$$

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

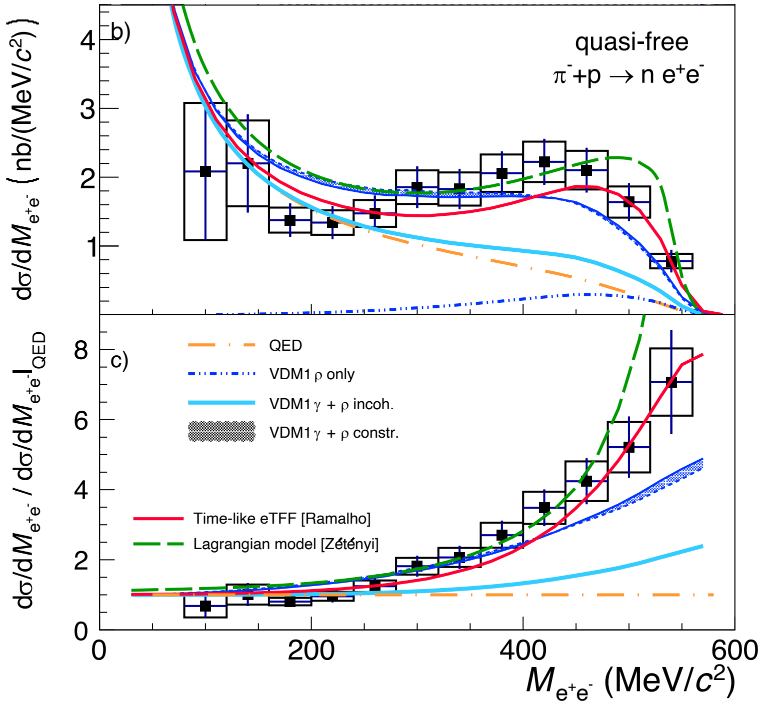
Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

- Baryonic effects are crucial

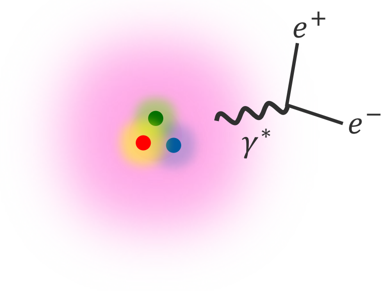
$\Sigma_{\rho B,M} =$


First measurement of massive γ^* emission from N^* baryon resonances (exclusive analysis $\pi^- p \rightarrow e^+ e^- n$)

HADES, arXiv:2205.15914 [nucl-ex], with PRL
HADES, arXiv:2309.13357 [nucl-ex], with PRC

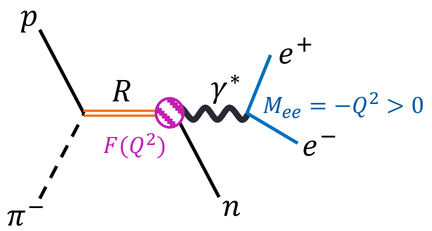


Ramalho, Pena, PRD95 (2017) 014003
Zetenyi, Nitt, Buballa, TG, PRC 104 (2021) 1, 015201
Speranza *et al.*, PLB764 (2017) 282



- 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**

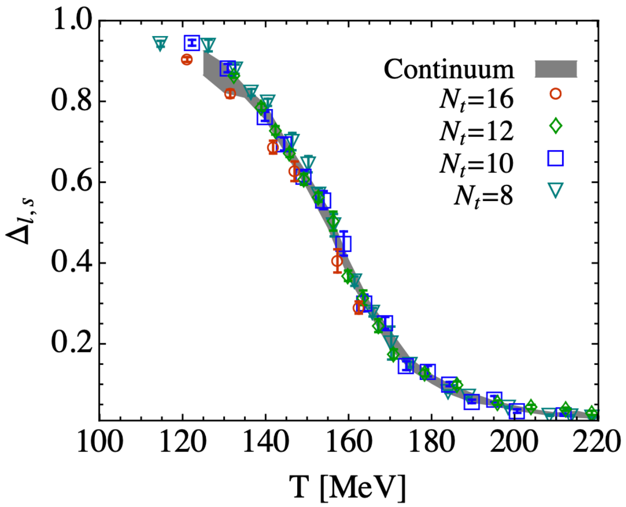


Dileptons and chiral symmetry of QCD

Spontaneously broken in the vacuum

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

Condensates $\langle\bar{q}q\rangle$ calculated by lattice QCD

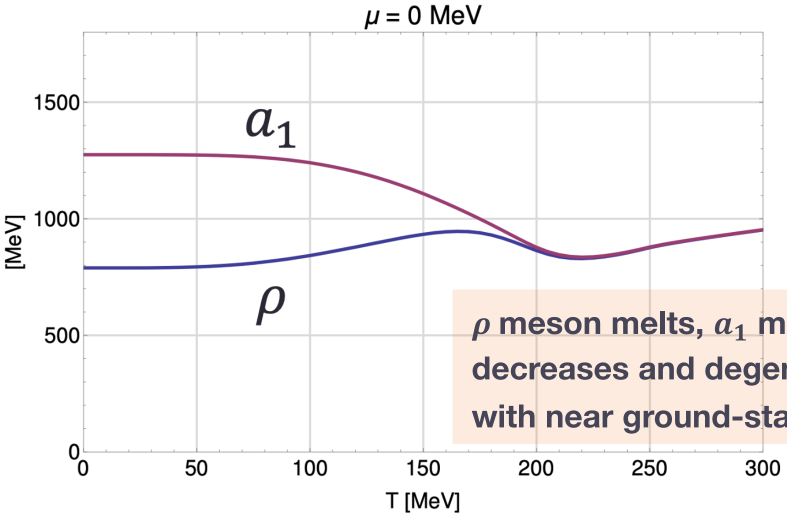


Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

S. Weinberg, PRL 18 (1967) 507

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

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

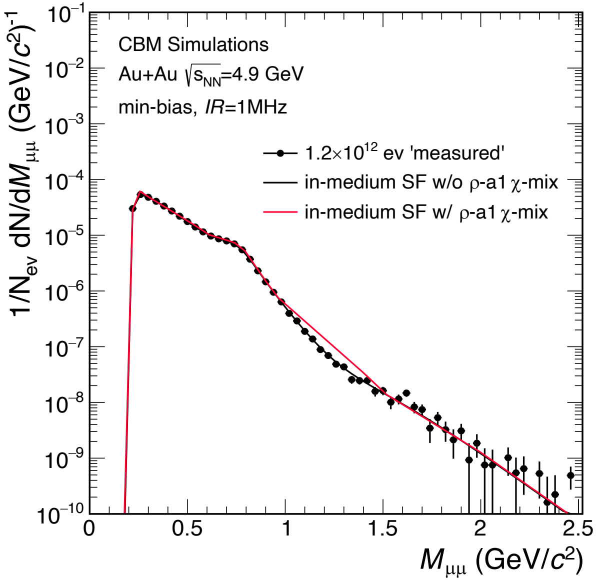
Hadronic many-body theory Hohler and Rapp, PLB 731 (2014)

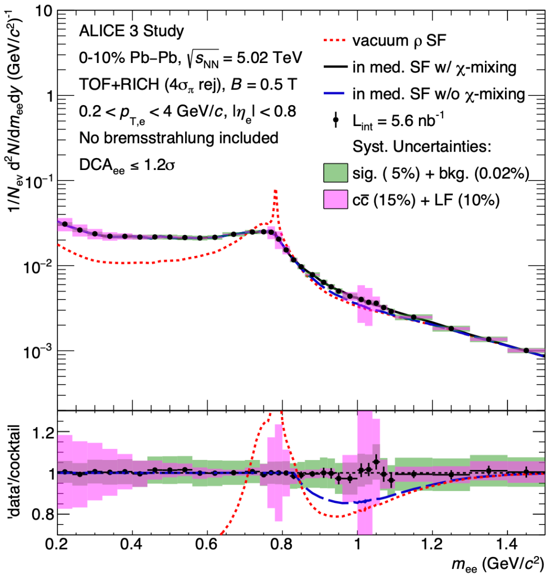
FRG Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020

Light mesons and baryons from lattice QCD, Aartz, QM2022, April 2022

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

➡ **experimental challenge: physics background ($M_{\ell\ell}$ > 1 GeV)**





CBM energies: negligible correlated charm contribution, decrease of QGP, Drell-Yan contribution pp, pA

LHC energies: large contribution from $c\bar{c}, b\bar{b}$ and **QGP,** negligible Drell-Yan

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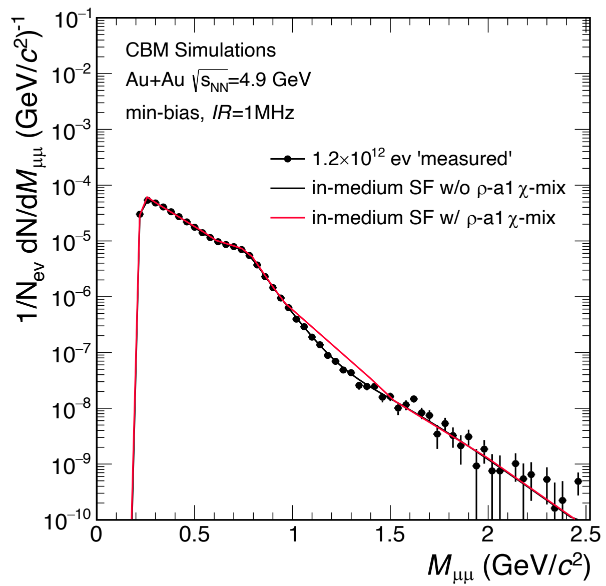
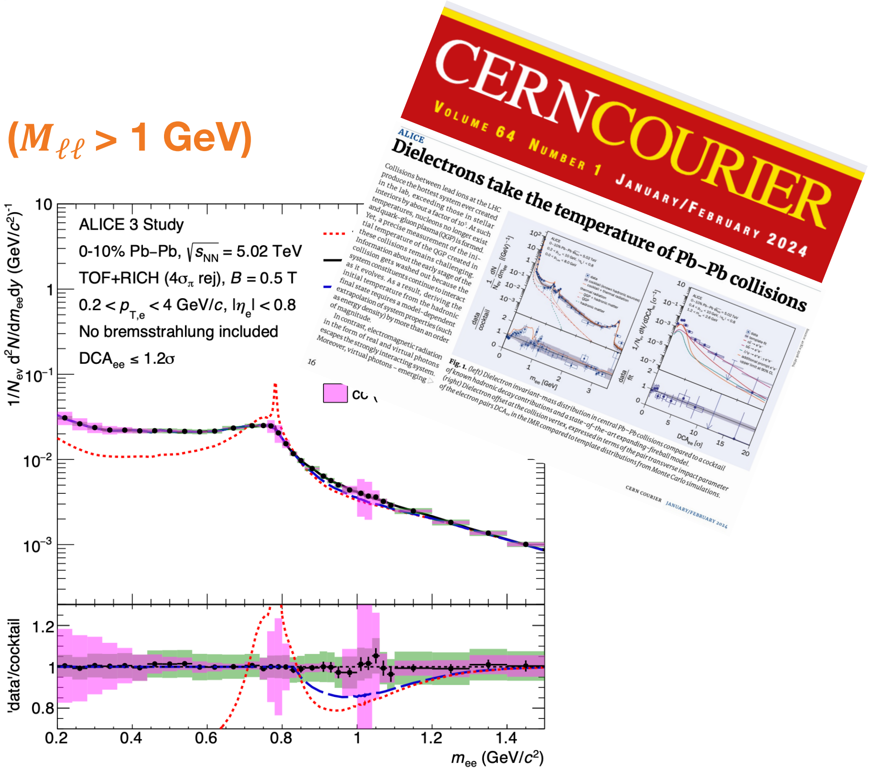
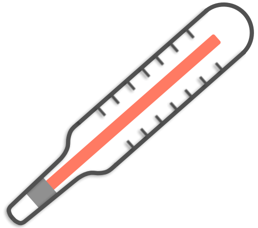


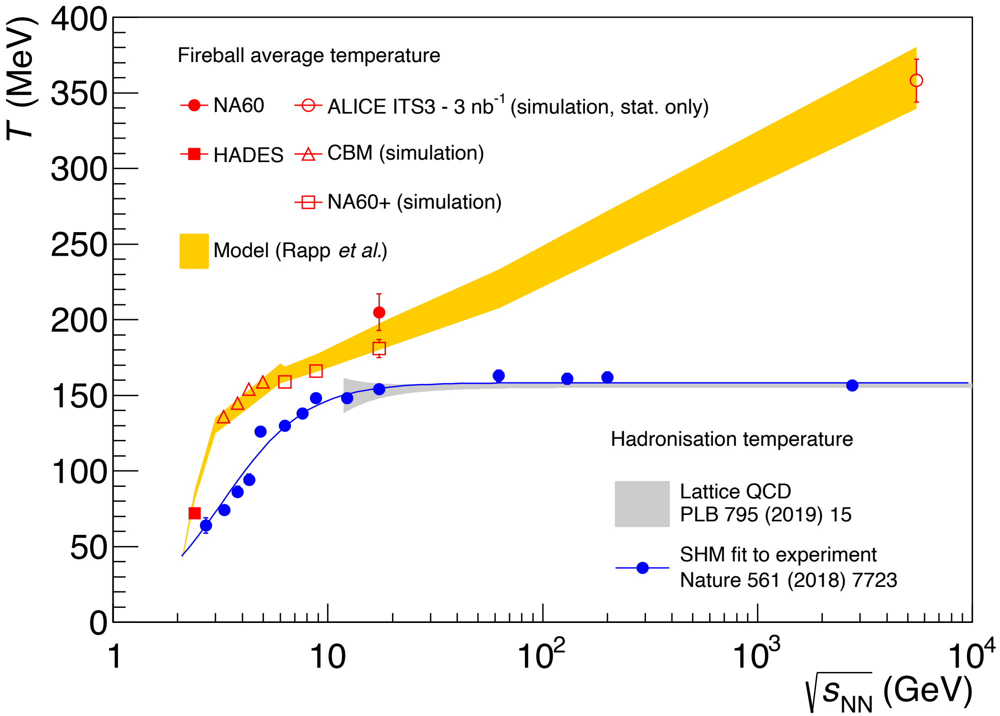
CBM energies: negligible correlated charm contribution, decrease of QGP, Drell-Yan contribution pp, pA



LHC energies: large contribution from $c\bar{c}, b\bar{b}$ and **QGP,** negligible Drell-Yan

Mapping the QCD "caloric curve" (T vs ε)





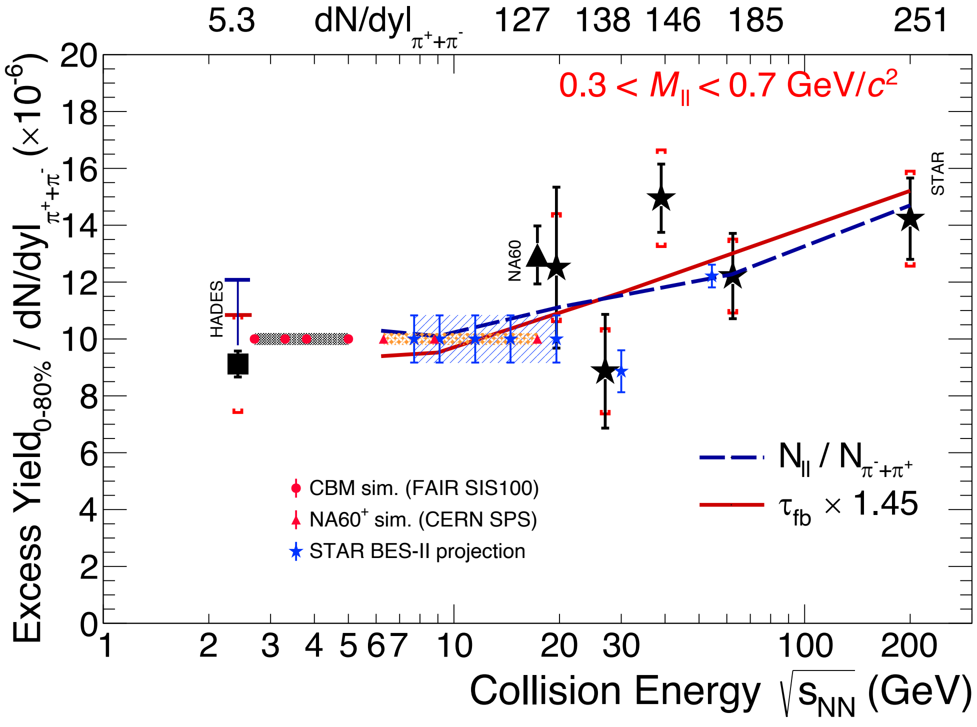
https://github.com/tgalatyuk/QCD_caloric_curve

Invariant mass slope measures true (no blue shift!) radiating source temperature

- To date measurements by NA60 and HADES
- Access to hottest fireball with ALICE
- Probe time dependence of fireball temperature:
  $M_{\ell\ell}$ versus v_2, photon polarization

- Search for flattening of caloric curve (T vs ε) → evidence for a **phase transition**

The fireball lifetime



- Integrated **excess yield** 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, 586 (2016)

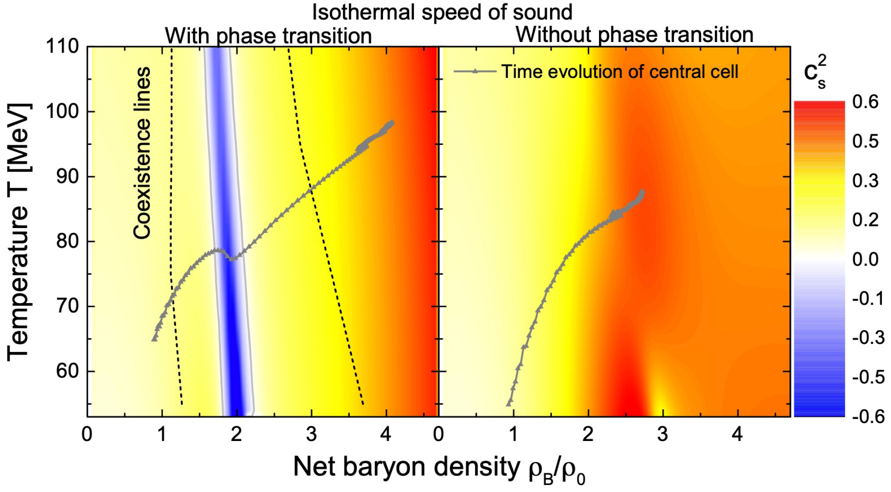
- Search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)

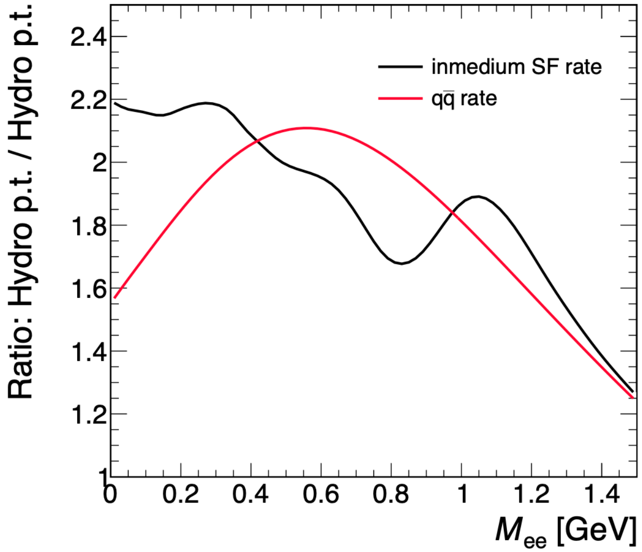
TG., JPS Conf.Proc. 32 (2020) 010079

Dilepton signature of a 1st order phase transition

See also:
Savchuk, TG, *et al.*, J.Phys.G 50 (2023) 12, 125104
Tripolt *et al.*, NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203

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





- 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

Most et al., PRD 107 (2023) 4, 043034

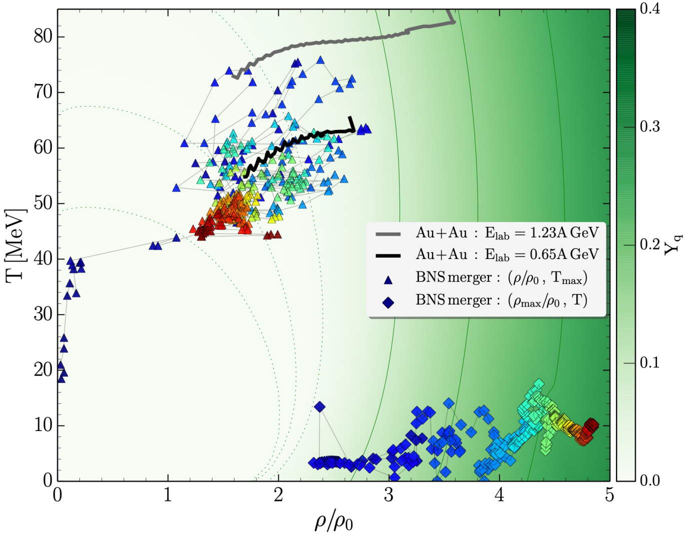
Dilepton emission shows a significant effect: factor 2 enhancement of dilepton emission due to extended “cooking”

Connection to

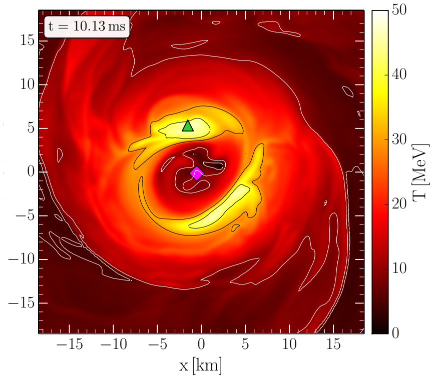
ASTROPHYSICS

The QCD phase structure at high- and low μ_B

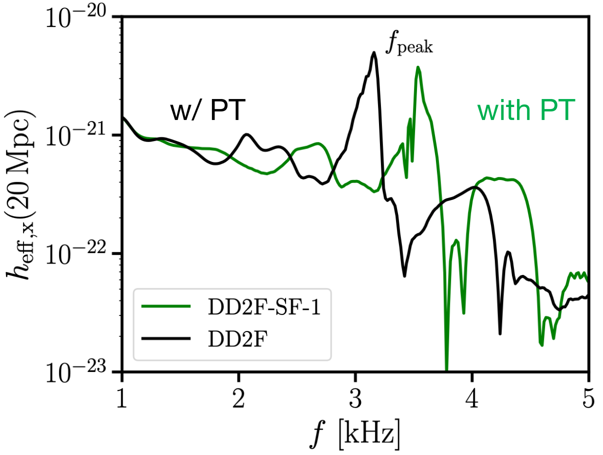
Possible HIC trajectories and NS merger simulations within an effective hadronic model



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



Bauswein *et al.*, PRL 122 (2019) 6, 061102



- NS mergers probe bulk properties of EoS – microphysics only accessible through combined effort

Blacker *et al.*, PRD 109 (2024) 4, 043015
Vijayan *et al.*, PRD 108 (2023) 2, 023020

- Consistency between EOS infer from observables from BNS mergers and new high precision HIC

Most *et al.*, PRD 107 (2023) 043034

- Footprints of the QCD crossover on cosmological GW

Franciolini *et al.*, PRL 132 (2024) 8, 081001

Summary: The future is bright!

Encouraging prospects for studying extreme matter in the laboratory

- **Challenges**
  - rare and statistics „hungry“ observables, systematic effects
  - many aspects **–** nature of transitions between the various phases, relevant EoS, spectral properties of hadrons in the medium, collective and transport properties of the medium, **… –** await a better understanding
- **Opportunities**
  - discoveries, EoS of dense matter and connection to violent stellar processes
  - development of forefront detector technologies
- **Success through perfect teamwork** of experts in many fields (accelerators, detectors, high-performance computing, data analysis and interpretation)

➥ **Understand quantitatively the microscopic properties of quark-gluon plasma and baryon-rich matter**

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