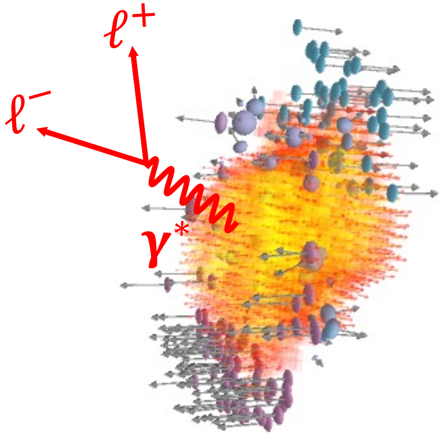
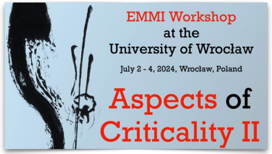
Thermal dileptons as a probe of QCD phase structure at high baryon density

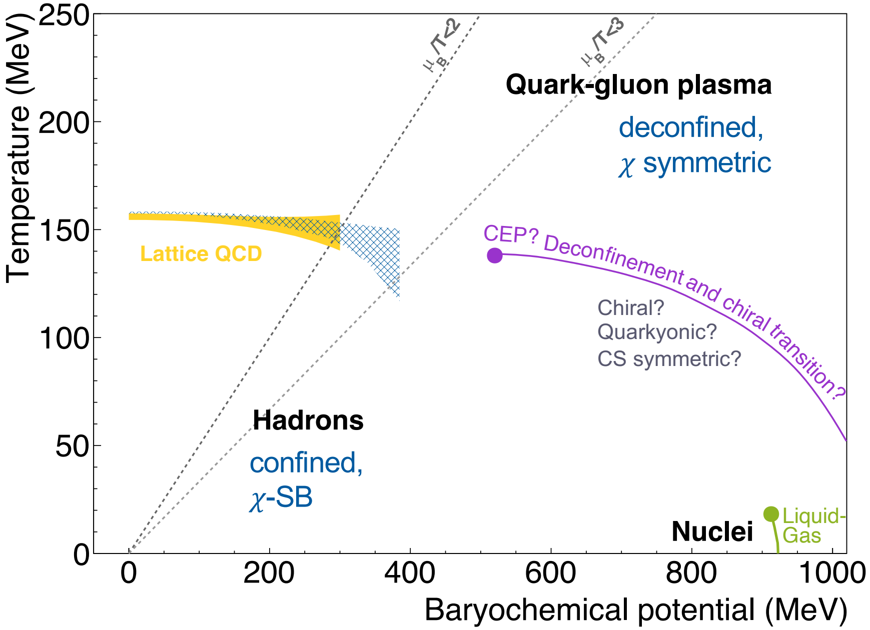




Tetyana Galatyuk, GSI / Technische Universität Darmstadt

EMMI Workshop at the University of Wrocław - Aspects of Criticality II, July 2-4, 2024, Wroclaw

Searching for landmarks of the QCD matter phase diagram



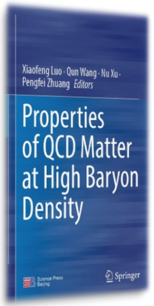
Experimental challenges:

- 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:

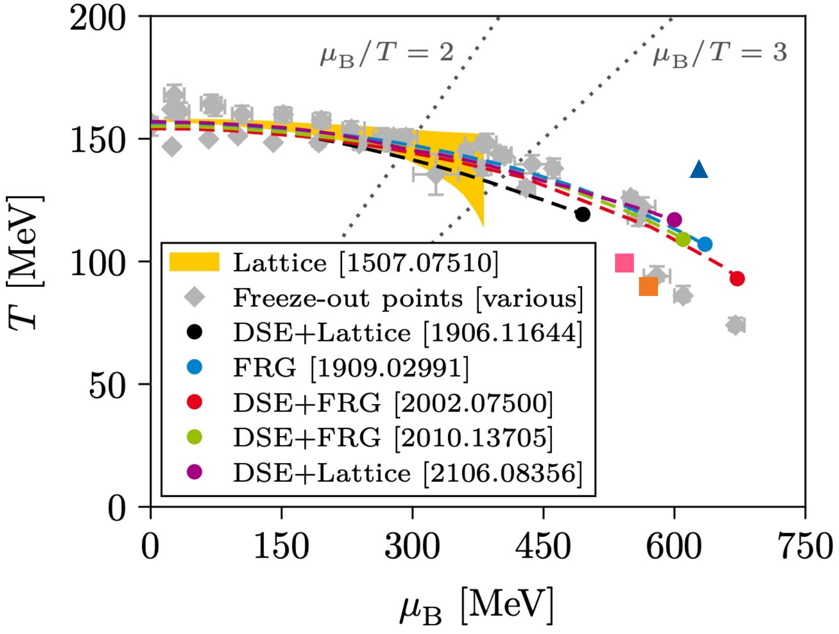
- light flavour (chemistry, vorticity, flow)
- event-by-event fluctuations (criticality)
- charm (transport properties)
- hypernuclei (interaction)
- **dileptons (emissivity)**

Worldwide experimental and theoretical efforts



Chen, Dong, Fukushima, Galatyuk, *et al.*, doi:10.1007/978-981-19-4441-3_4 (2022)

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



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[1-5] and lattice-Pade[6,7] predict QCD critical point in a similar ballpark $\boldsymbol{T \sim 90 - 120\ \mathrm{MeV}, \mu_B \sim 500 - 650\ \mathrm{MeV}}$
- 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)

[1]DSE: Bernhardt, Fischer and Isserstedt, PLB 841 (2023)
[2]FRG: Fu, Pawlowski, Rennecke, PRD 101, 053032 (2020)
[3]BHE: Hippert et al., arXiv:2309.00579
▲ [4]FSS: Sorensen and Sorensen, arXiv:2405.10278 [nucl-th]
■ [5]lQCD-Pade: Basar, arXiv:2312.06952
■ [6]lQCD-Pade: Clarke *et al.*, PoS LATTICE2023 (2024), 168

Role played by thermal radiation?

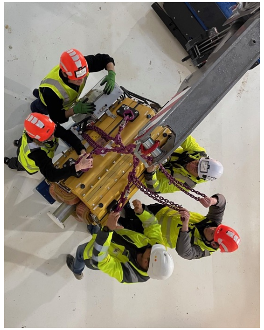
Not measured in the $\sqrt{s_{NN}} \sim 3 - 8$ GeV regime


April 2024
FAIR GmbH – Facility for Antiproton and Ion Research
Emerging facility: FAIR (Ground-breaking: 2017)
GSI GmbH – Helmholtzzentrum für Schwerionenforschung
Existing facility: GSI Darmstadt (Foundation: 1969)

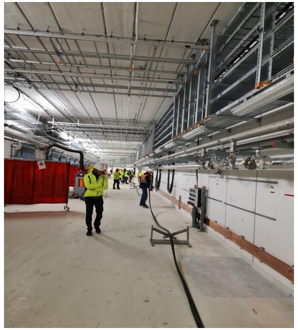
FAIR project status

installation of SIS100 dipoles Apr’24

transport of the first quadrupole magnet in tunnel, Mar‘24



start of cable pulling work, Q3/23



Apr’24
six He tanks of the cryo facility were installed

cryogenic bypass lines placed in SIS100 tunnel, Apr’24

construction area south

CBM cave, Jun‘24

FAIR project status

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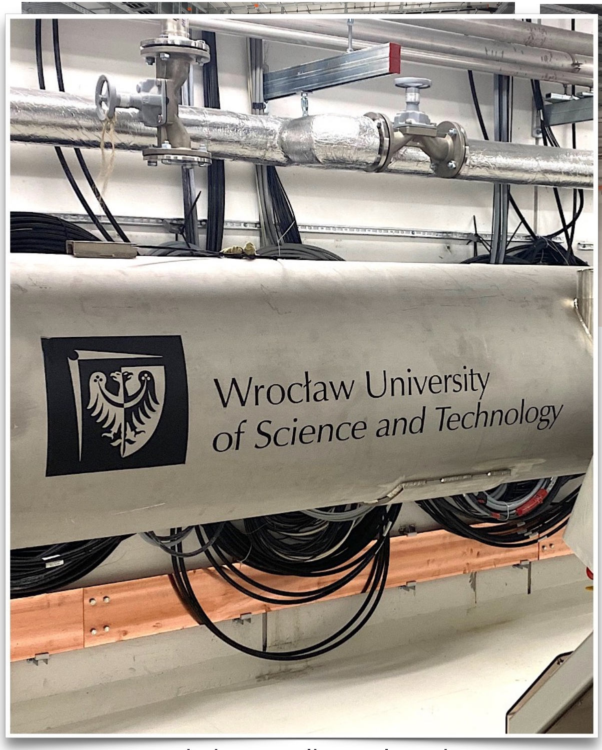

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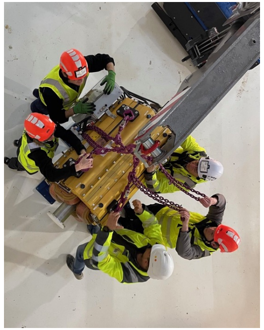

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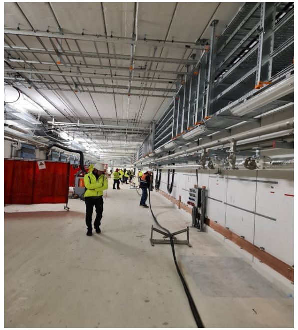

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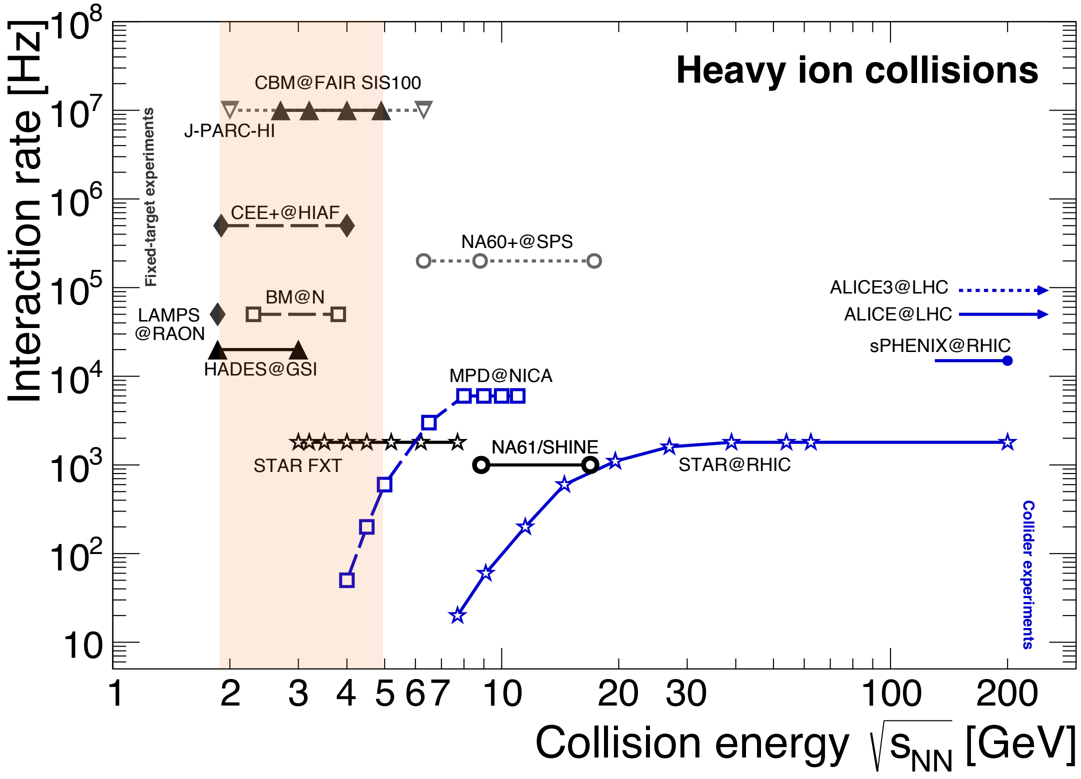
CBM cave, Jun‘24

Exploring the “terra incognita” with EM probes



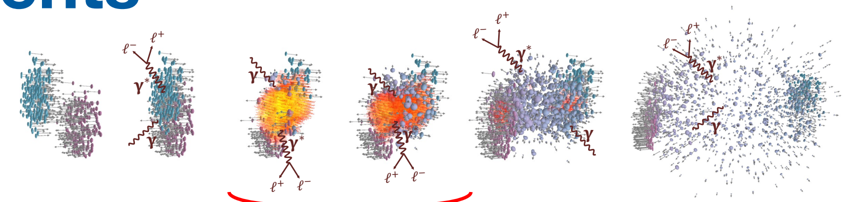
TG, NPA 982 (2019), update 2021 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

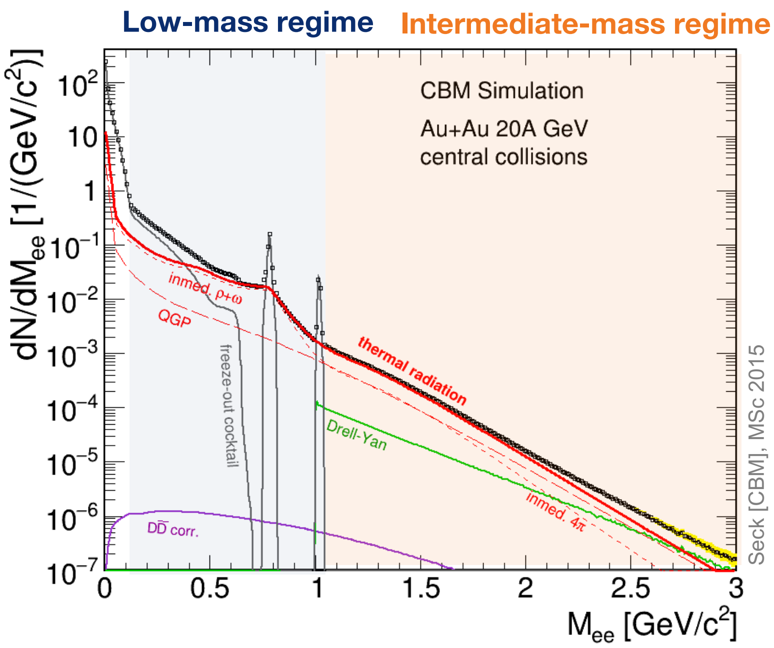
- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high μ_B with rare and electromagnetic probes: high rate capability, **energy range 3** $< \sqrt{s_{NN}} <$ **5 GeV**
- **HADES:** established thermal radiation at high μ_B, limited to 20 kHz and $\sqrt{s_{NN}}$=2.4 GeV

- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- **NA60+ proposal:** dimuon spectrometer at SPS, energy range $6 < \sqrt{s_{NN}} < 17$ GeV, >10⁵ Hz rate capability
- **ALICE / ALICE 3:** exploit the forefront detector technologies and high luminosity potential of the LHC for ions

Program needs ever more precise data and sensitivity for rare signals

Thermal dilepton measurements



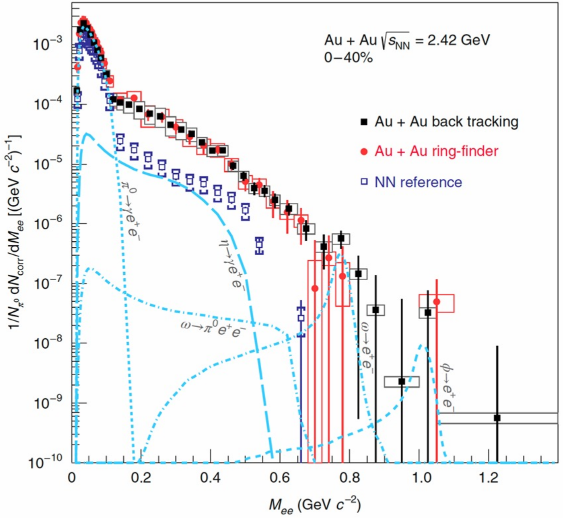


- Dileptons are rare probes!
- Decisive parameters for data quality:
  interaction rates (IR) and signal-to-combinatorial background ratio (S/CB): effective signal size: $S_{eff} \sim IR \times S/CB$
- Needs coverage of mid-rapidity, low-$M_{\ell\ell}$, and low-p
- Isolation of thermal radiation by subtraction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

Dilepton invariant mass spectra from HADES

➡ Clear excess visible above contributions from initial NN reference and freeze-out cocktail

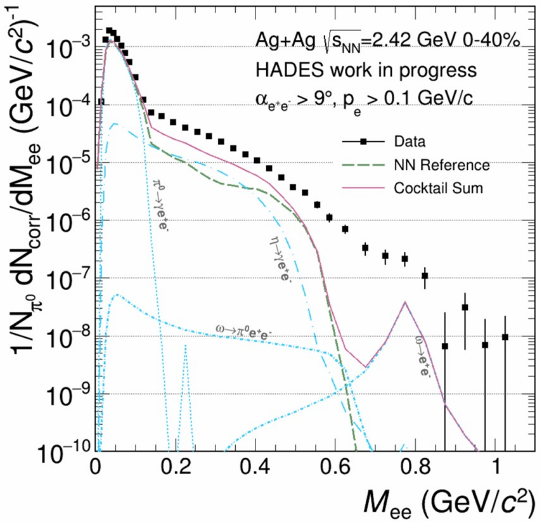
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



HADES, Nature Phys. 15 (2019) 1040

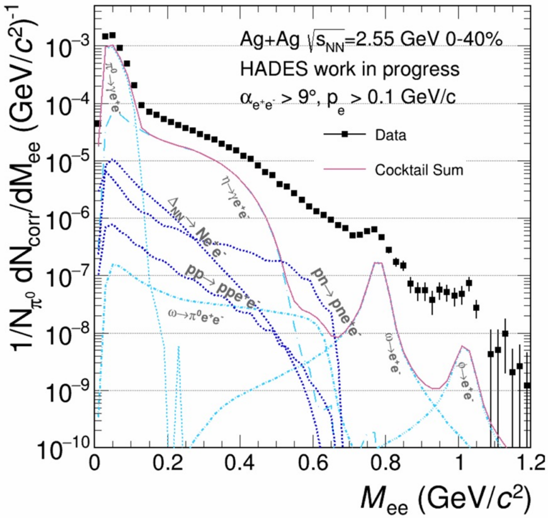
strongest isospin effect seen in np vs pp
⇝ measured NN reference

Ag+Ag at $\sqrt{s_{NN}} = 2.42$ GeV



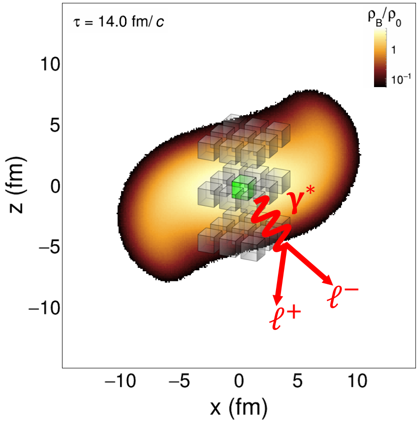
strongest isospin effect seen in np vs pp
⇝ measured NN reference

Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



simulated reference (GiBUU)
⇝ analysis of NN measurement at the same collision energy ongoing

Thermal dileptons at few GeV energies?



- Necessary ingredients to understand dilepton production in HIC:
  - accurate description of fireball evolution
  - realistic emission rates
  - sensitivity studies for the Equation of State

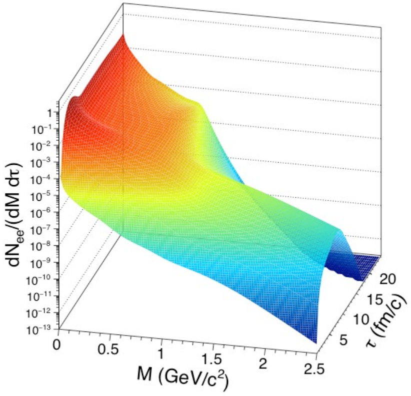
Coarse-Grained transport approach CG GSI-Texas A&M: TG *et al.*, EPJ A52 (2016) no.5, 131

➡ bulk evolution from microscopic transport

➡ apply equilibrium rates locally

Rapp and Wambach, Adv.Nucl.Phys. (2000) 25
Jung, Rennecke, Tripolt, *et al.*, PRD95 (2017) 036020
Sasaki, PLB 801 (2020) 135172

- Simulate events with a transport model
  ⇝ ensemble average to obtain smooth space-time distributions
- Divide space-time into 4-dim. cells
- Check if cell is thermalized (→ enough interactions)
- Determine baryon density ρ_B, medium velocity $\vec{u}$, and temperature T (→ m_{T} spectra of pions)
- Use in-medium spectral functions to compute EM emission rates

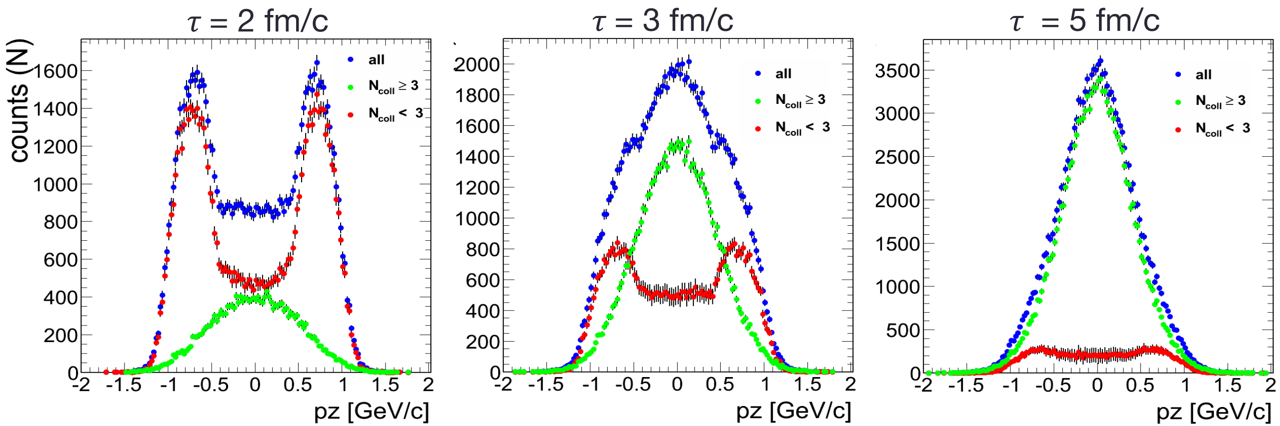


Huovinen *et al.*, PRC 66 (2002) 014903
CG FRA: Endres *et al.*, PRC 92 (2015) 014911
CG SMASH: PRC 98 (2018) 5, 054908

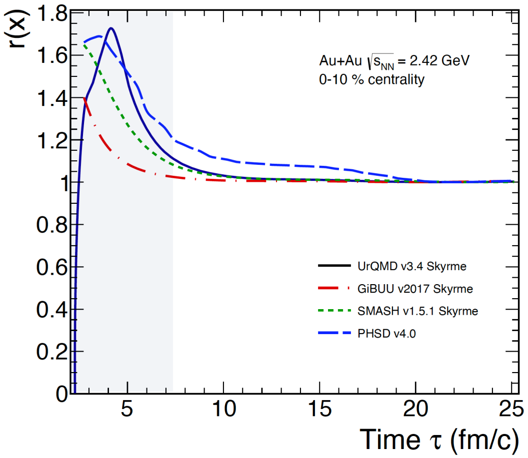
Justifying local thermal equilibrium

Au+Au $\sqrt{s_{NN}} = 2.42$ GeV, central cell

Momentum distributions of nucleons



Relaxation function $r(x)$ vs time

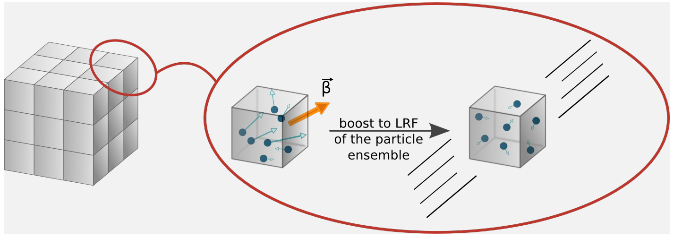


Check for every cell:

- Gaussian shaped p_z distribution builds up for nucleons with $N_{coll} \geq 3$
- $r(x)$ deviates from 1 by $< 5\%$
- m_T spectra have exponential shape

Determination of bulk properties

- Baryon density via 4-current
- Lorentz-boost to local rest frame (LRF) where the baryon current vanishes



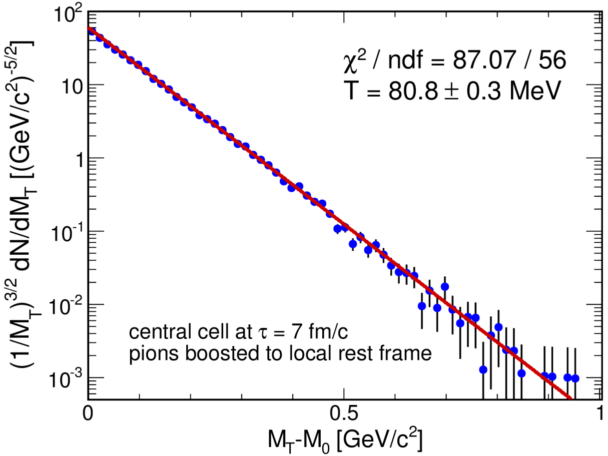
- In Boltzmann approximation

$$\frac{d^3N}{d\vec{p}} = \frac{d^3N}{dp_z p_T dp_T d\theta} \propto \exp(-E/T)$$

$$\Downarrow$$

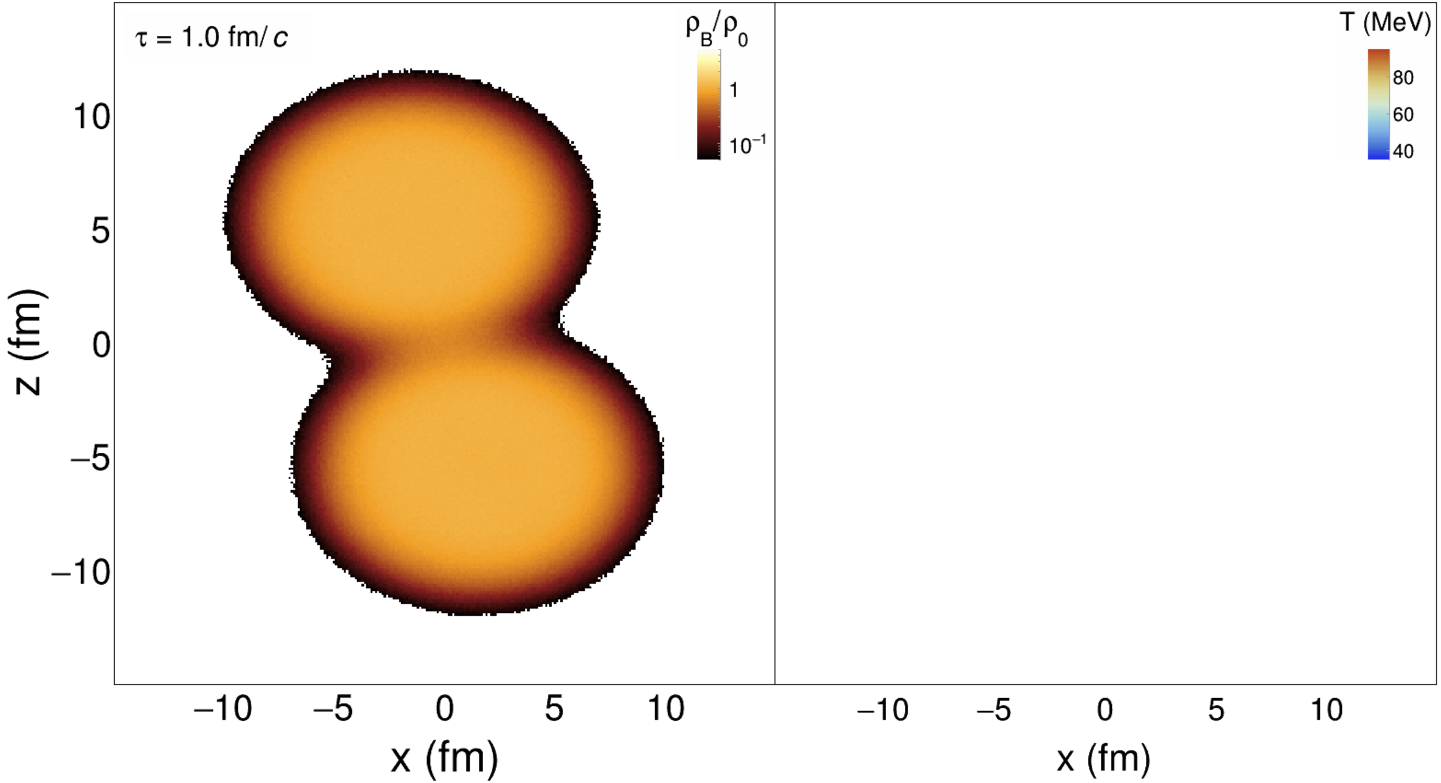
$$\frac{1}{m_T^{3/2}} \frac{dN}{dm_T} \propto \exp(-m_T/T)$$

- Fill m_T spectra with particle momenta in LRF (mean flow v_{coll} vanishes)
- Fit exponential function to extract T (species of choice: pions)



Baryon density and temperature profile

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



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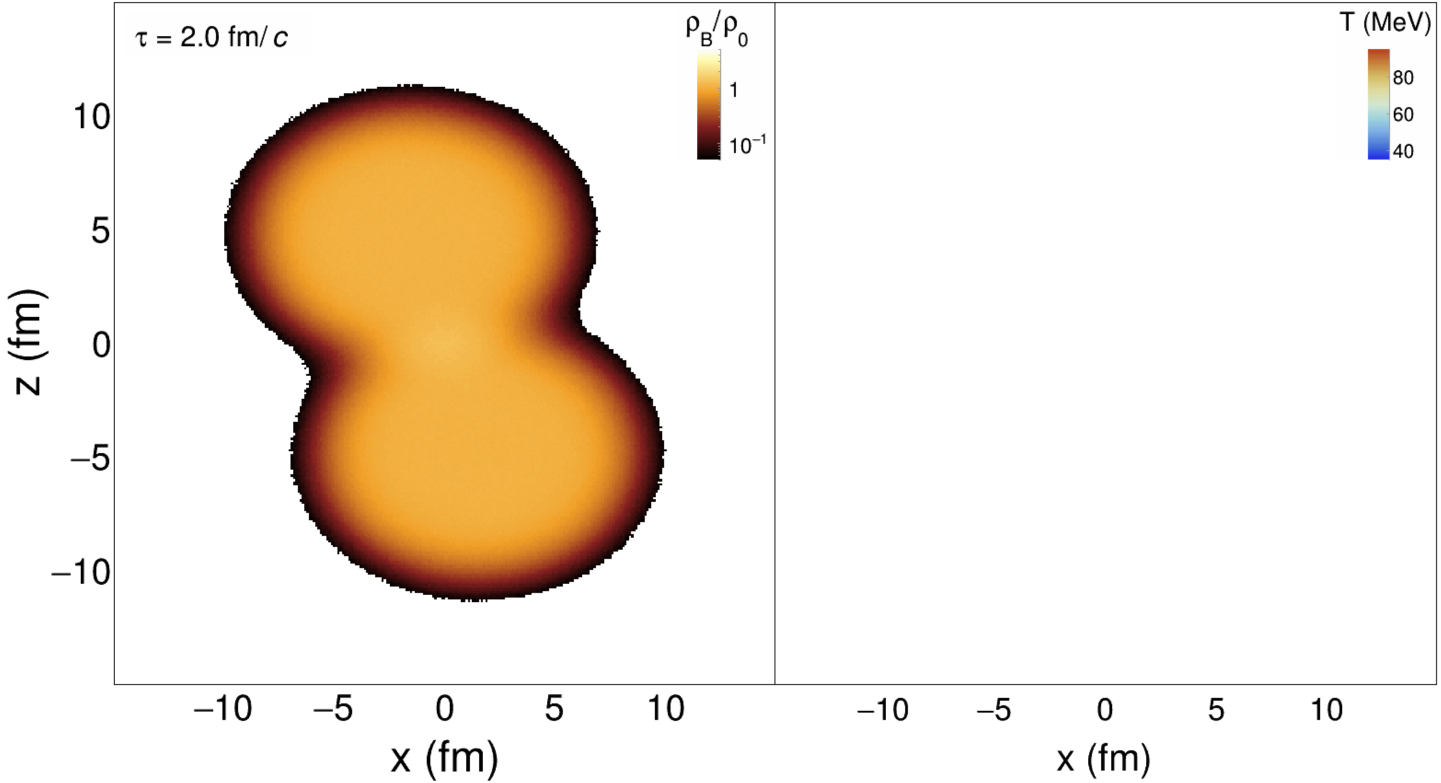

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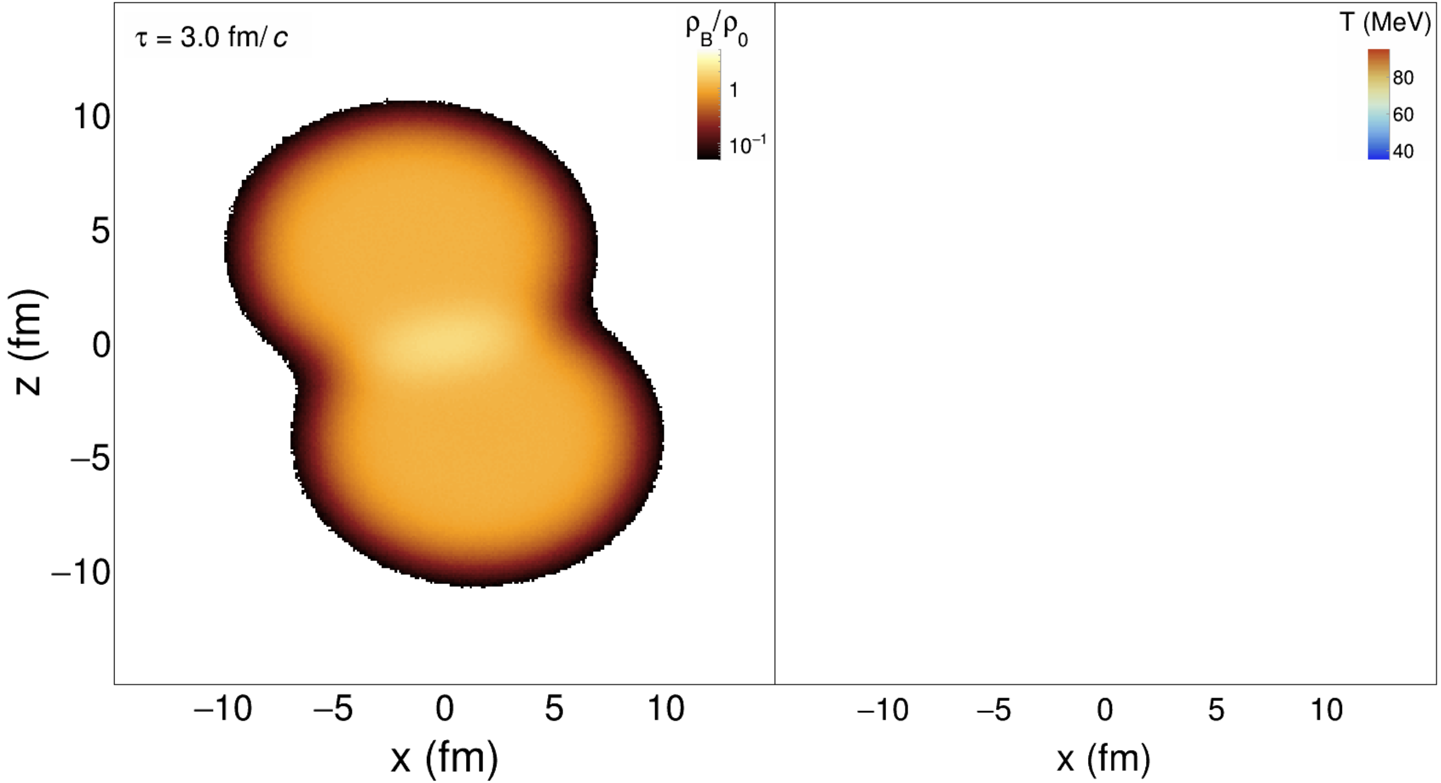

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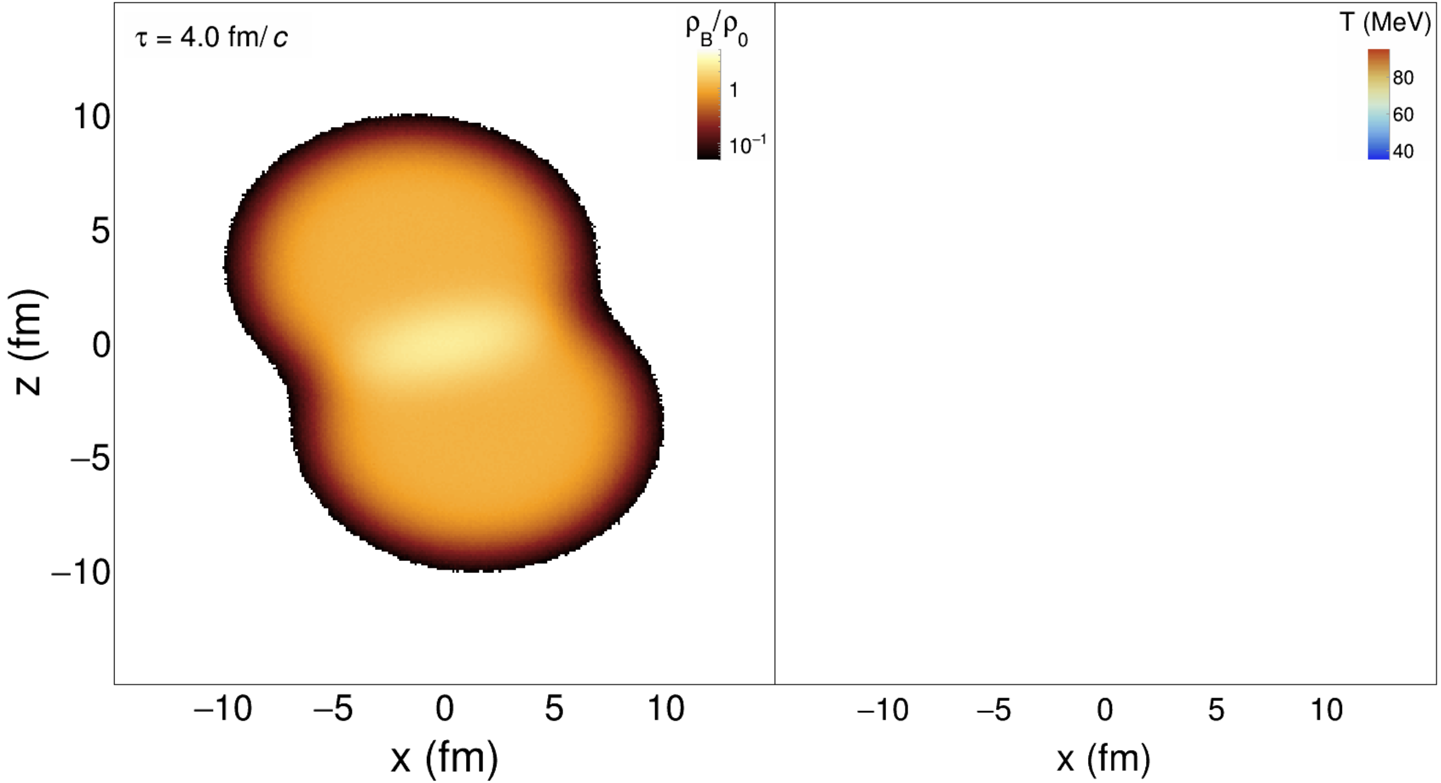

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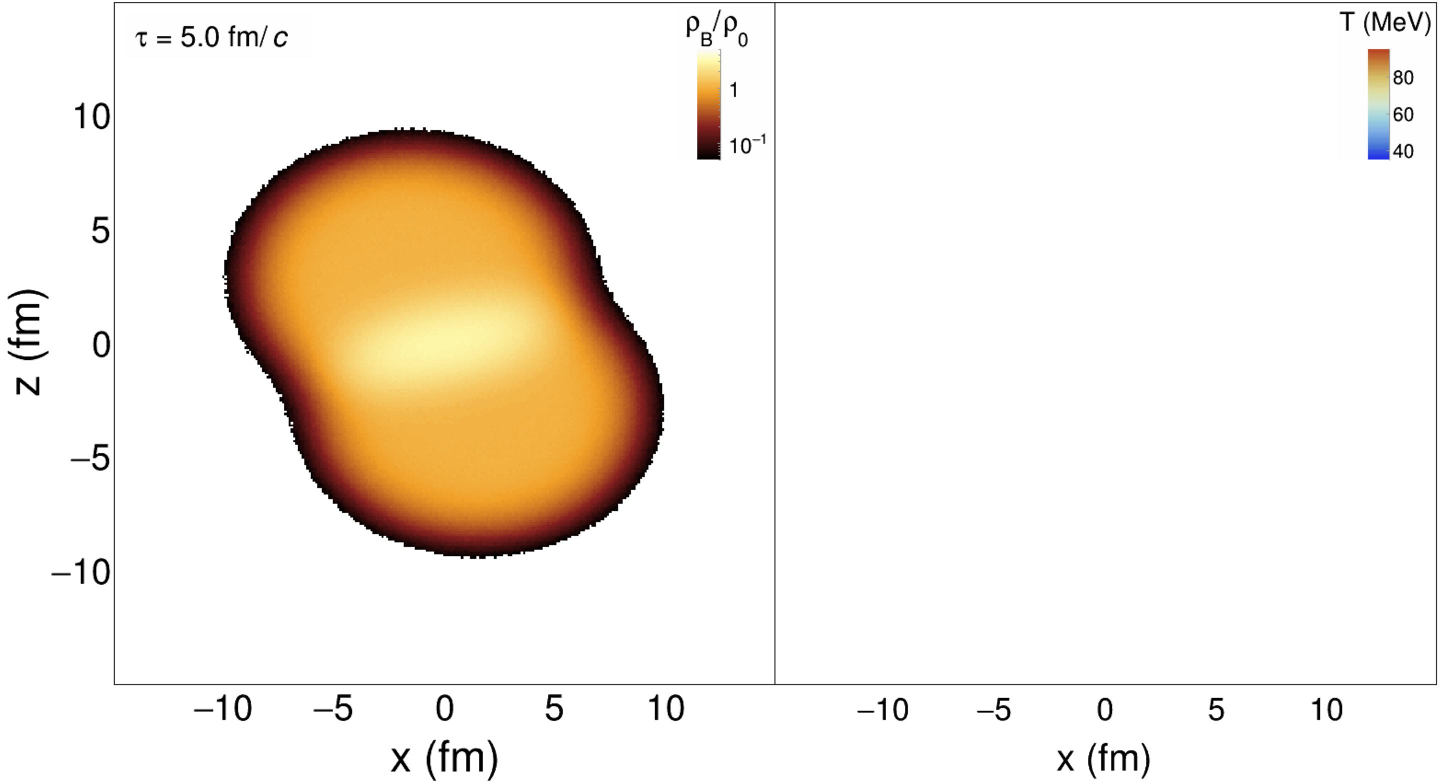

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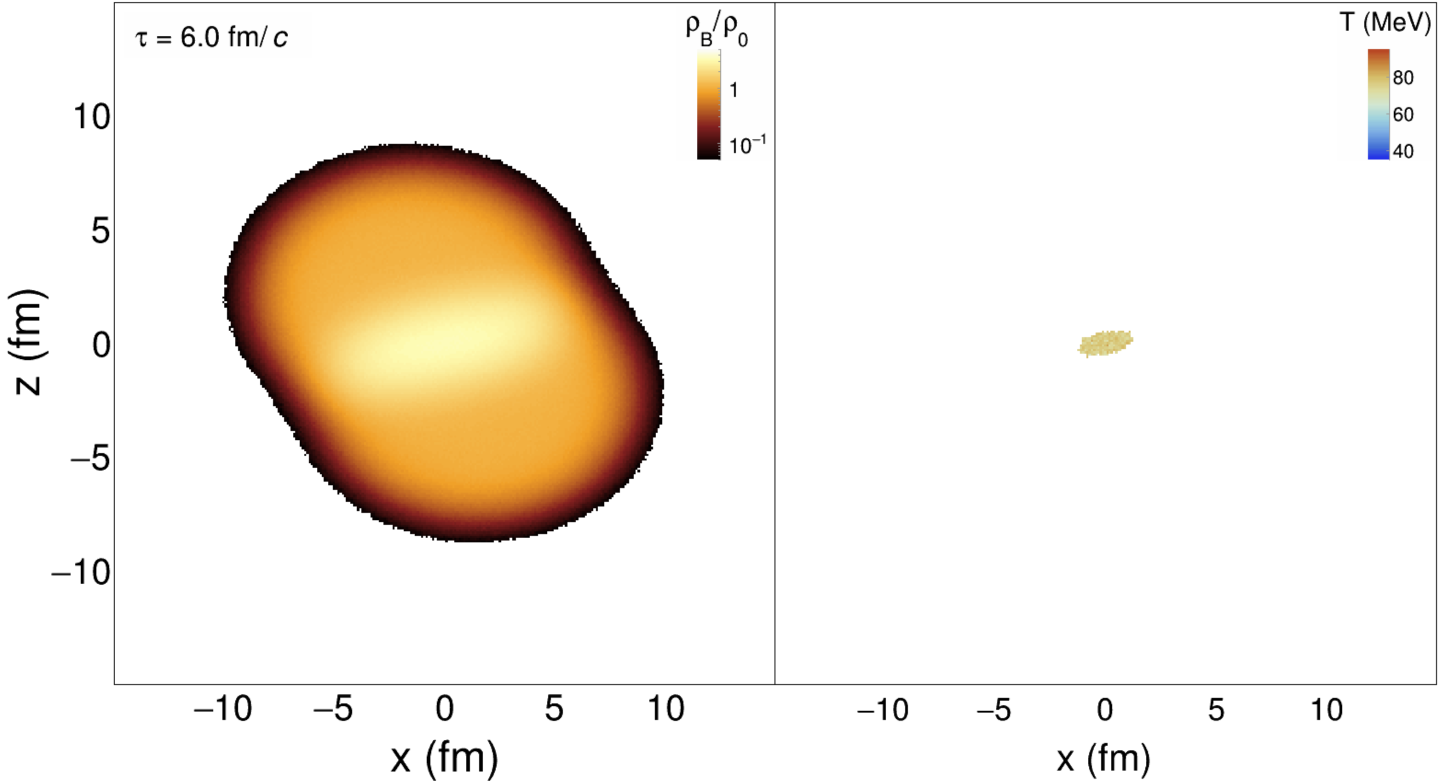

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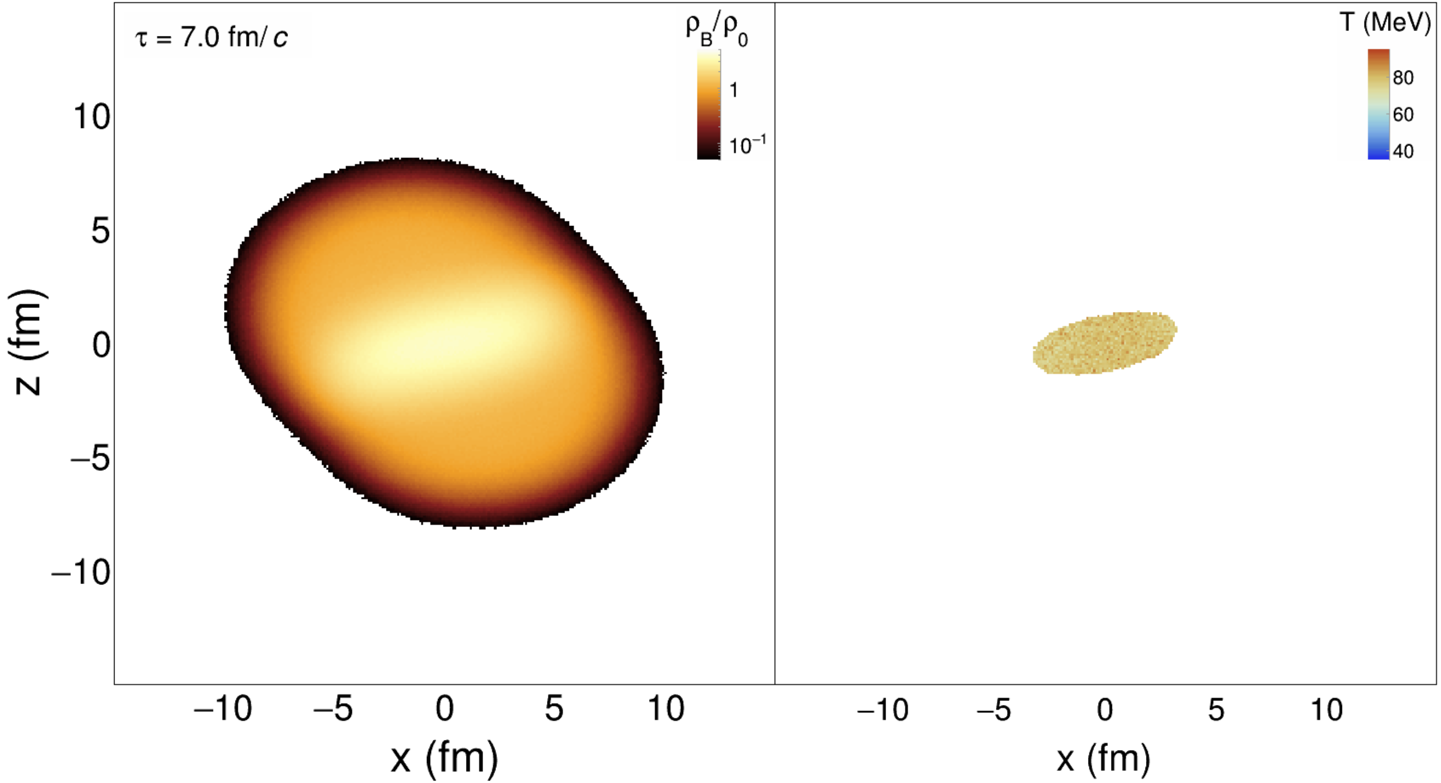

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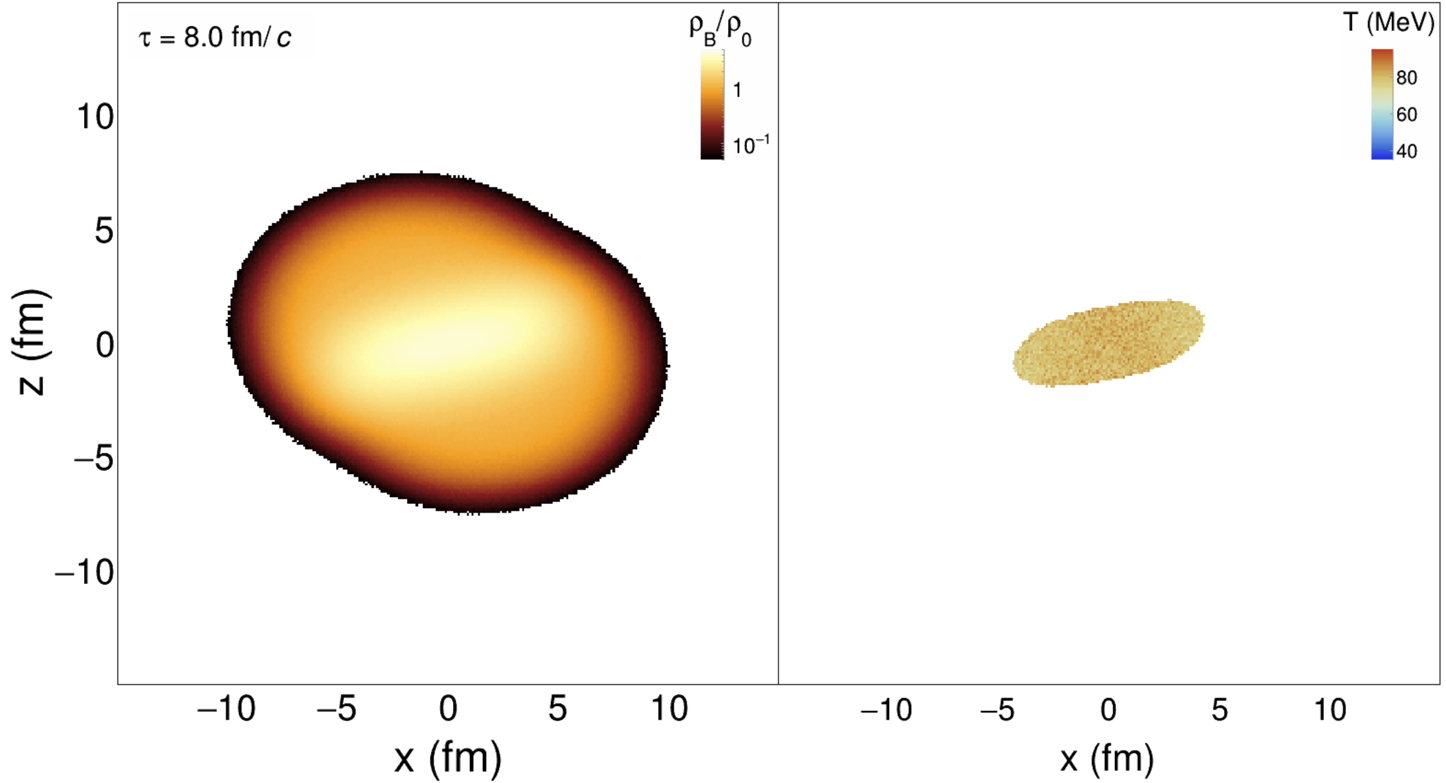

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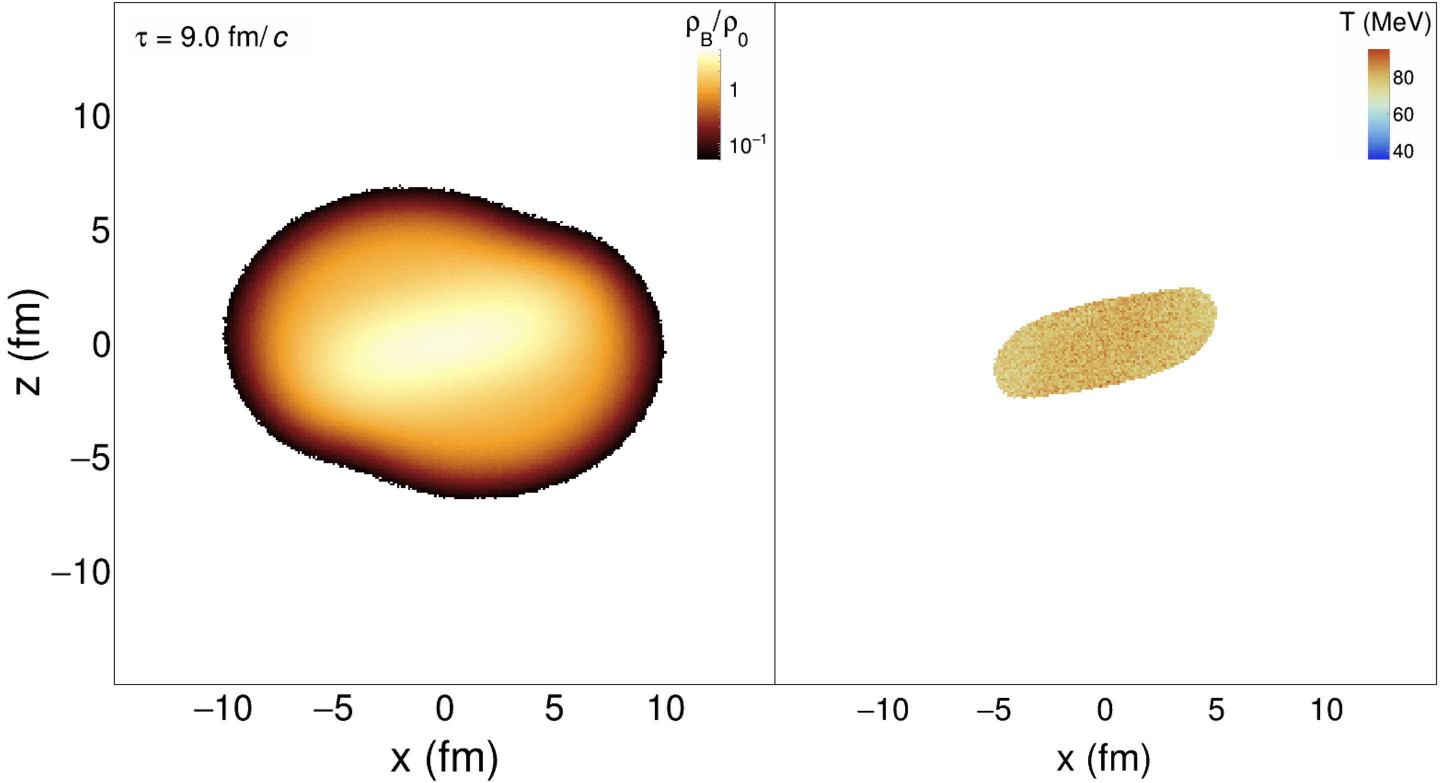

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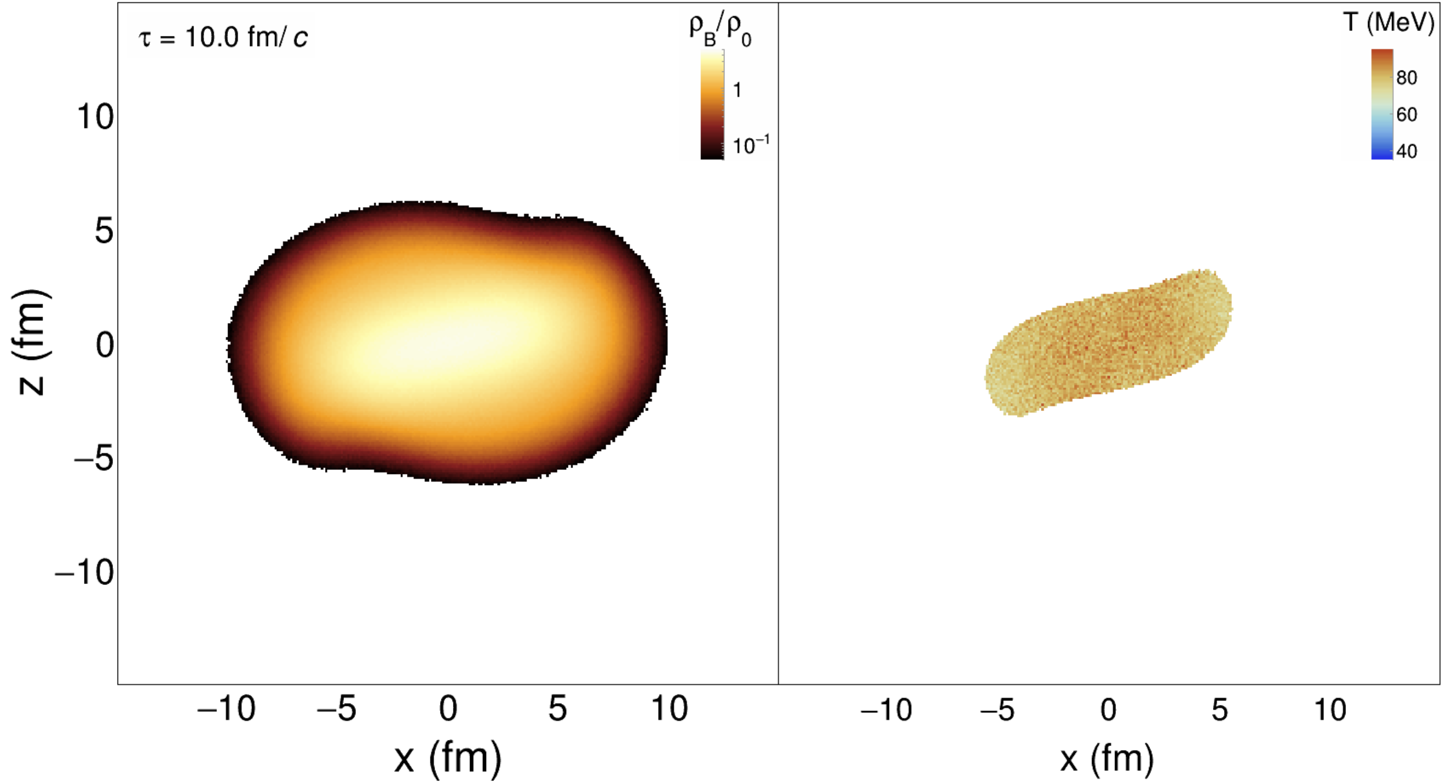

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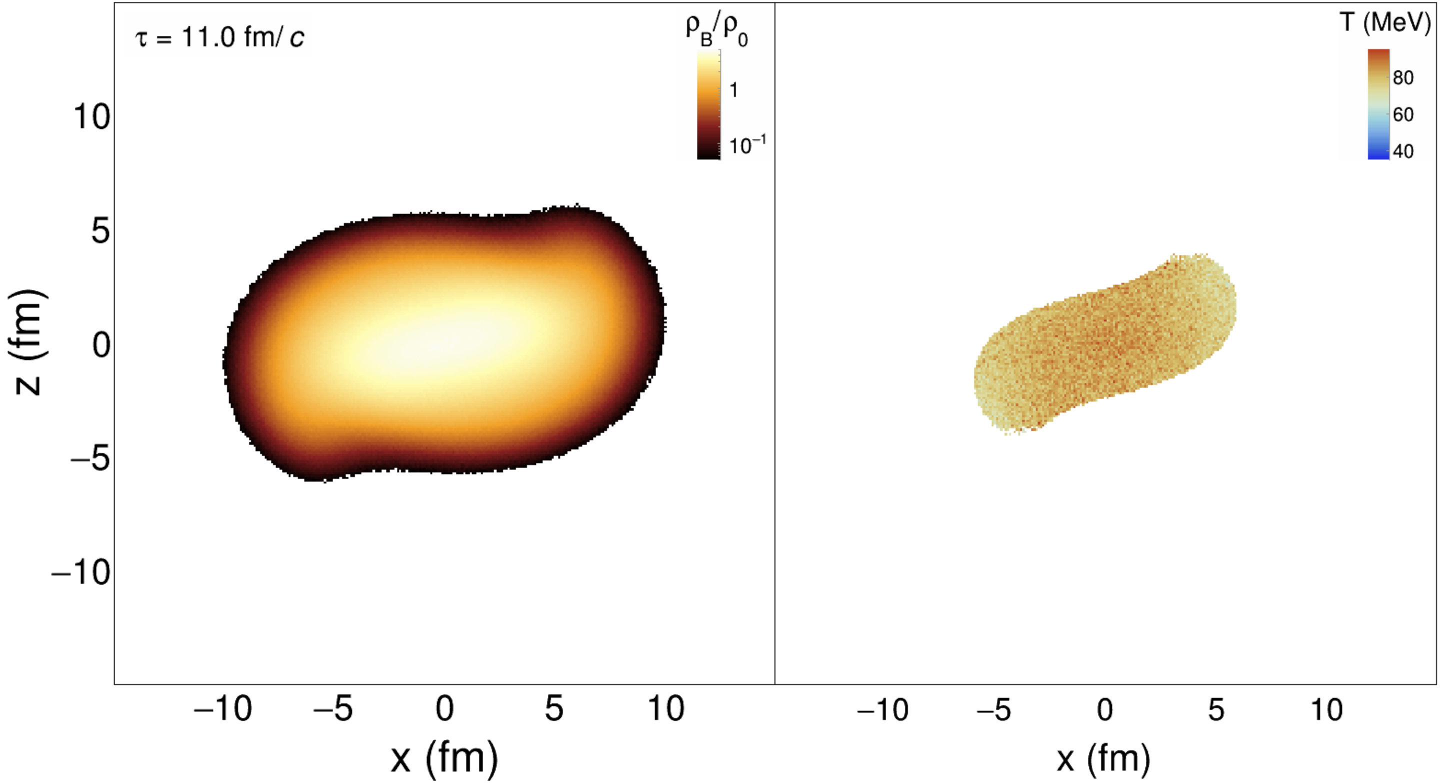

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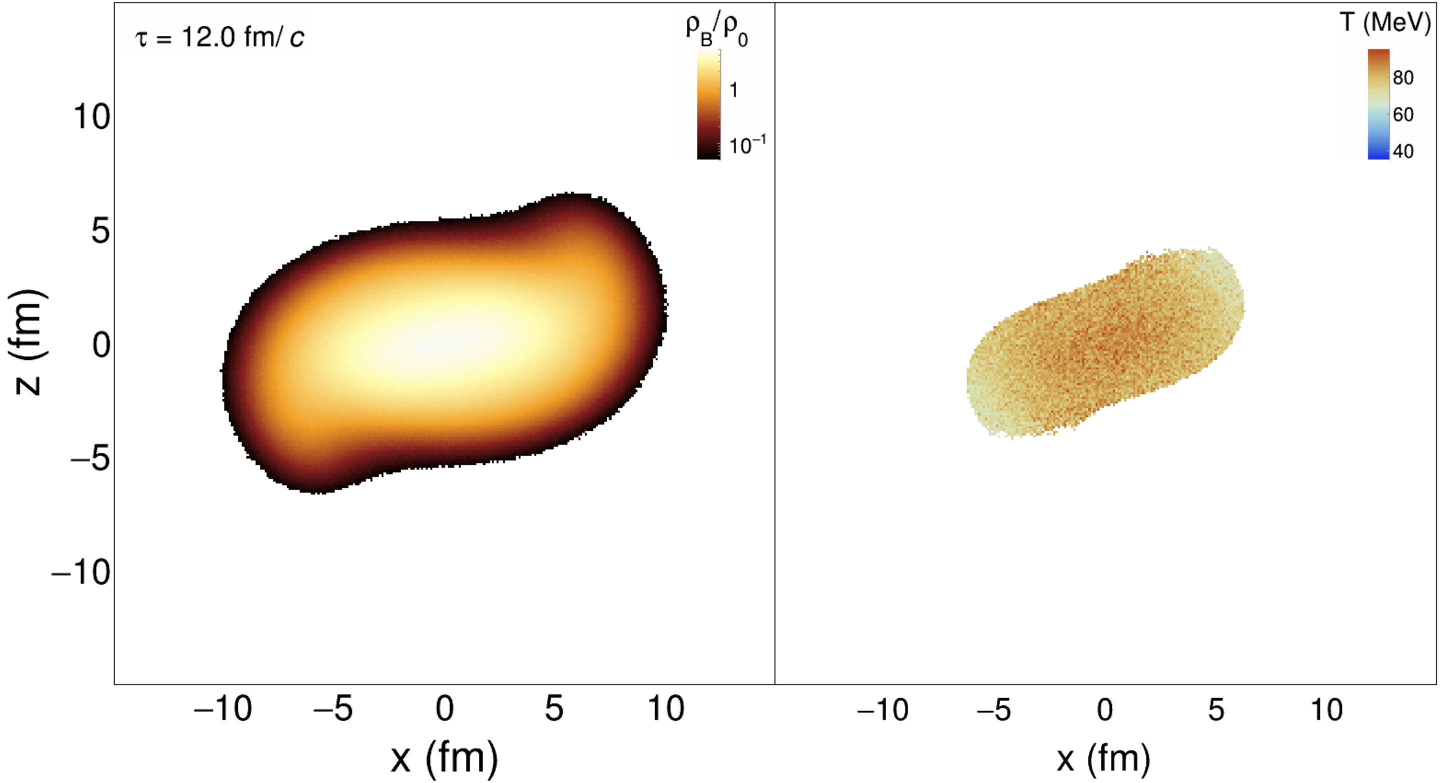

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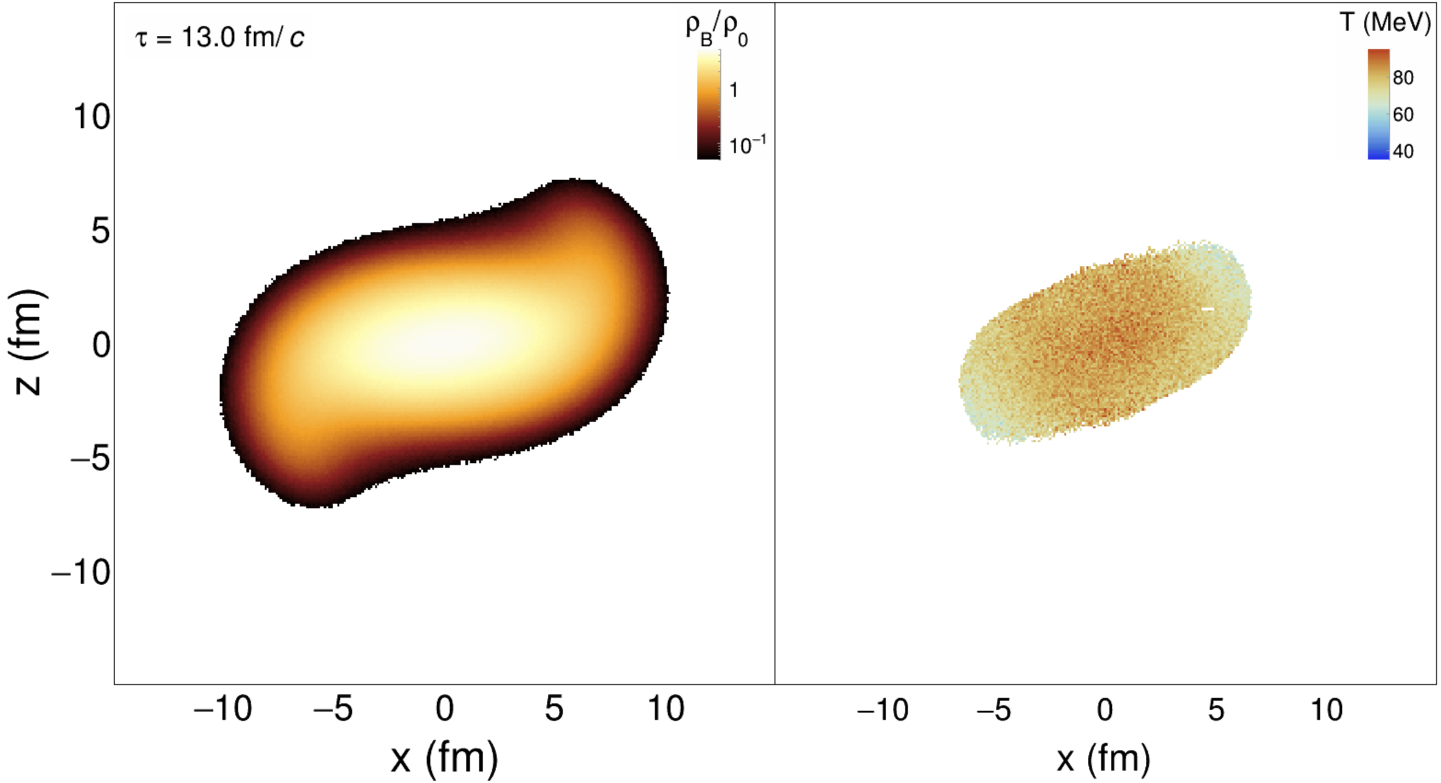

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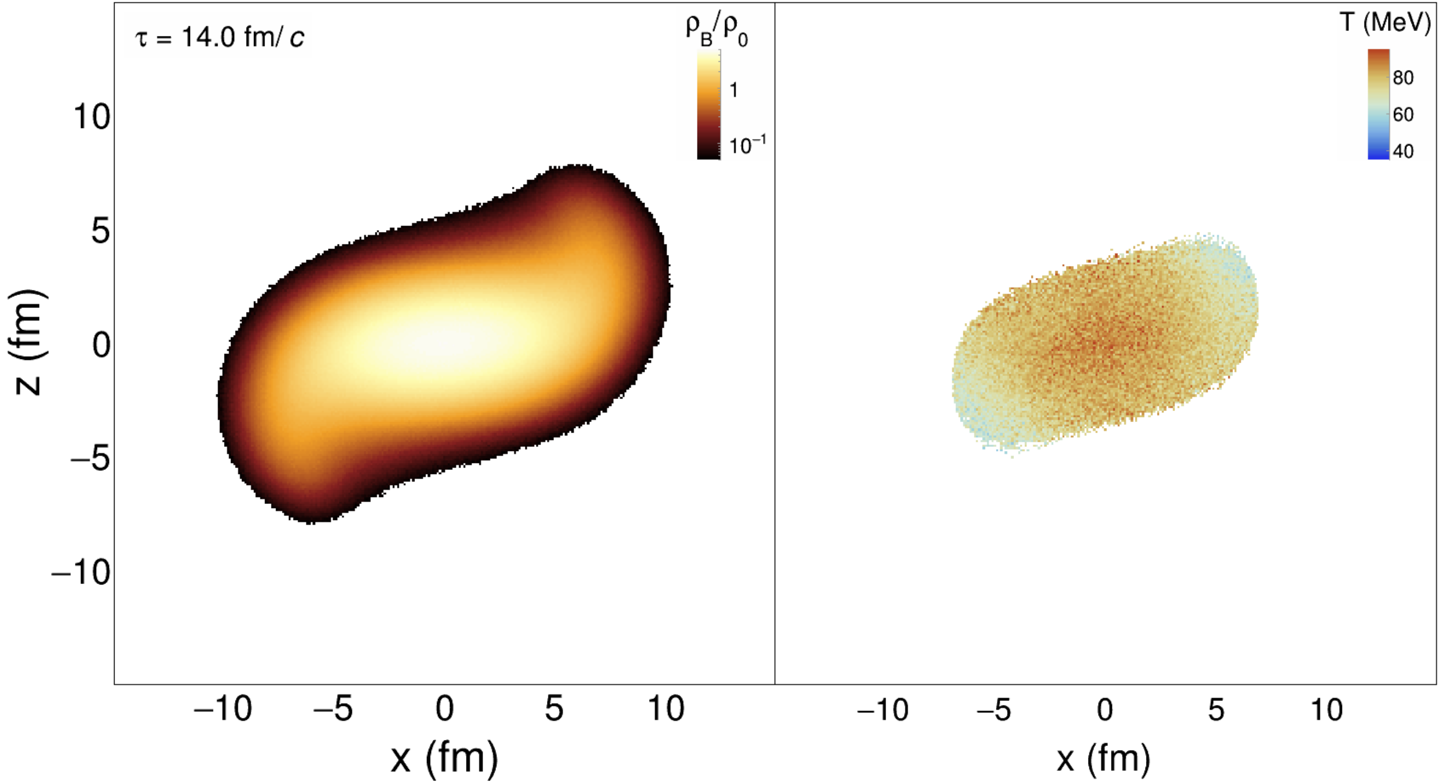

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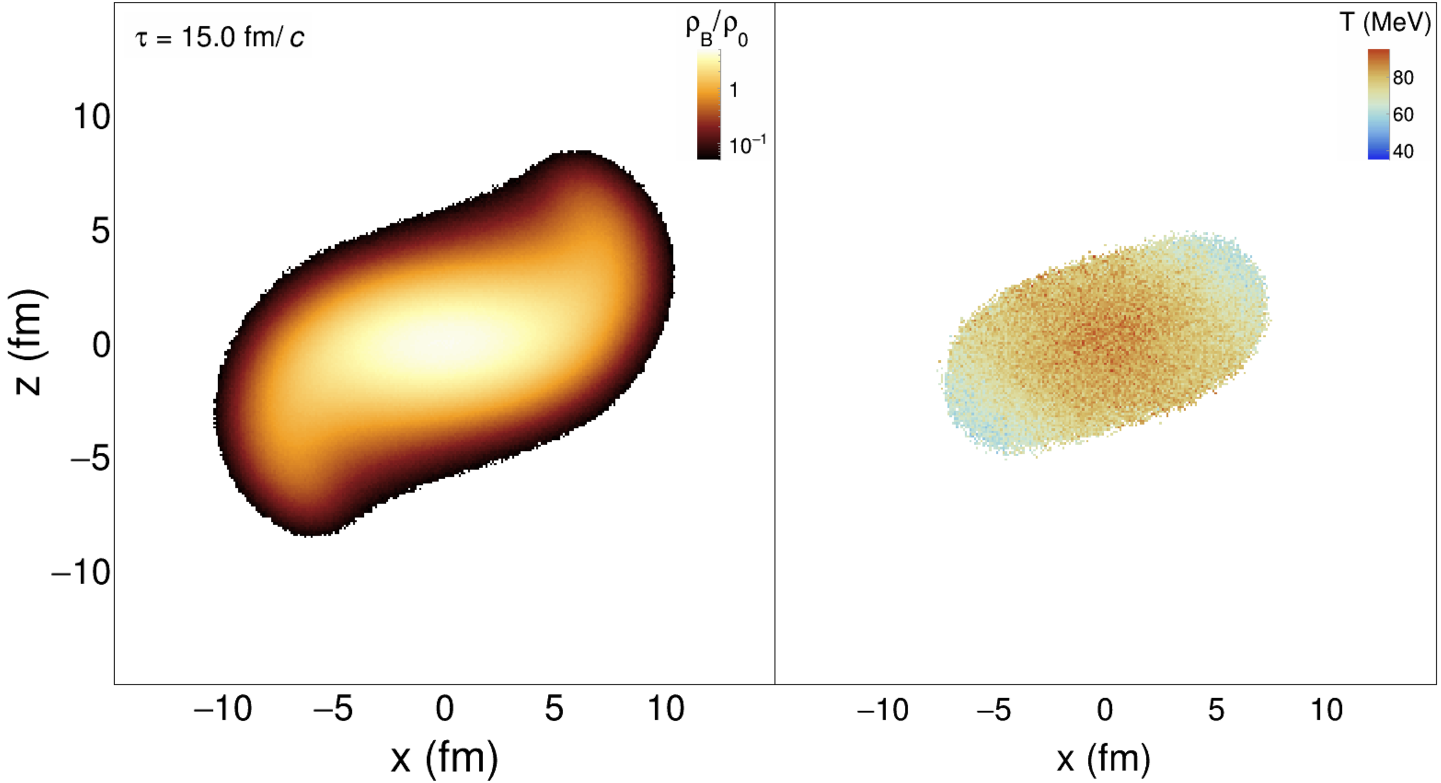

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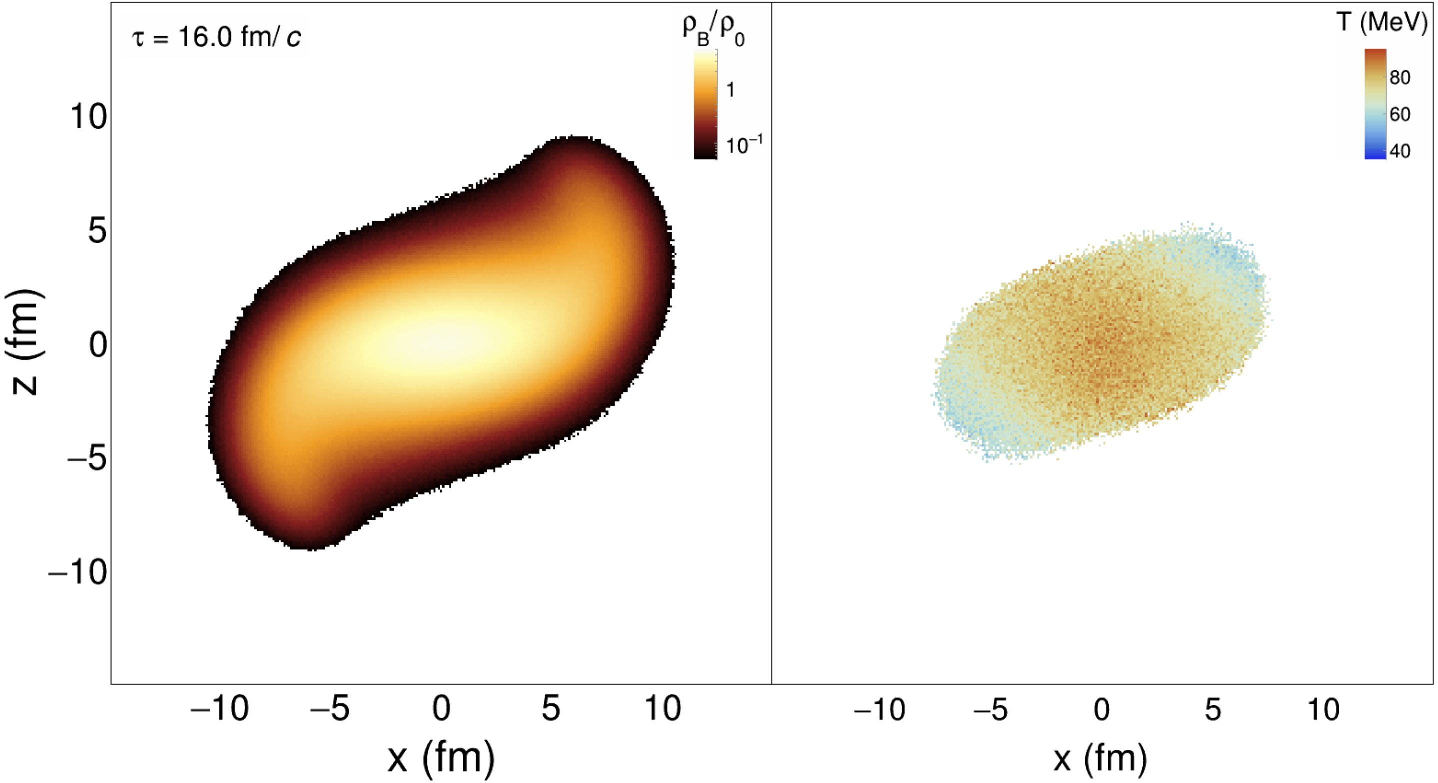

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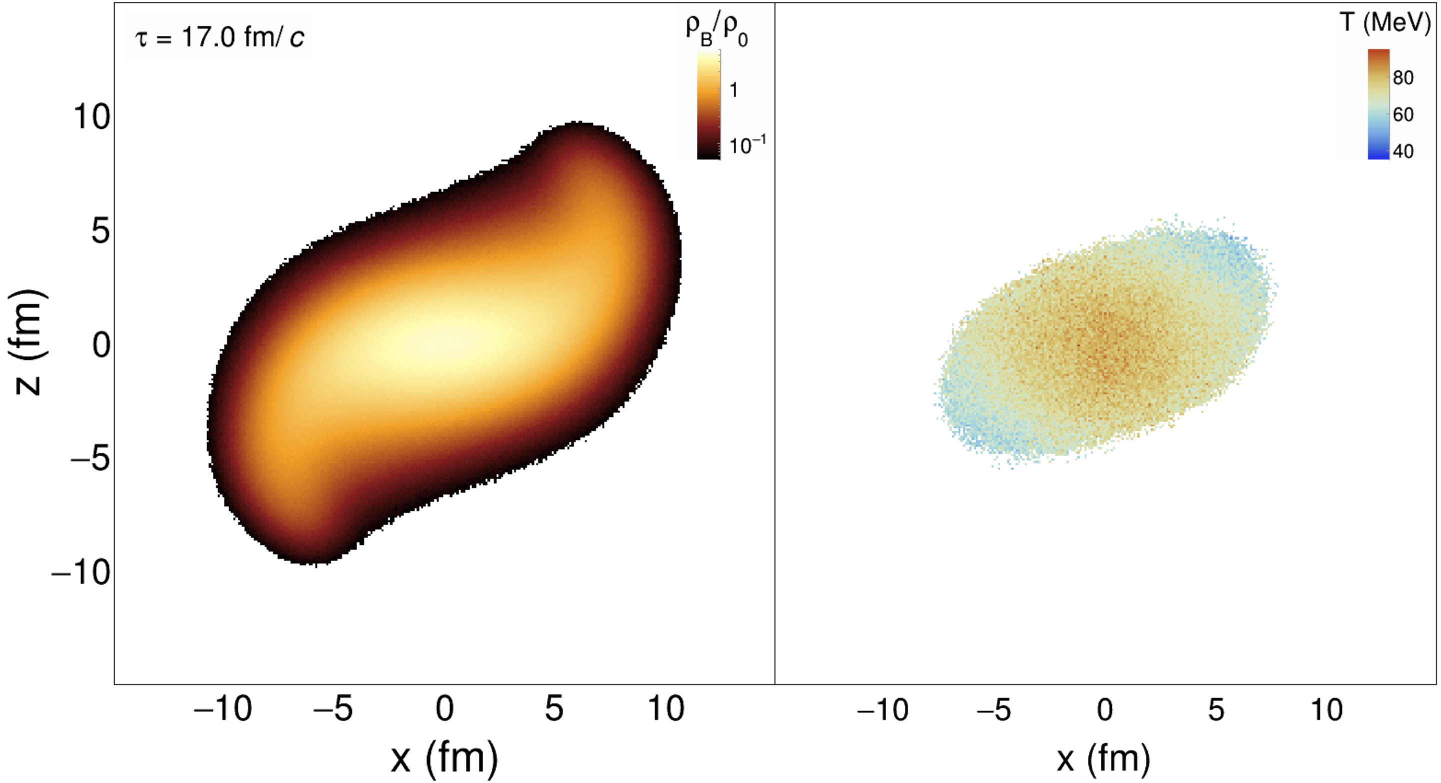

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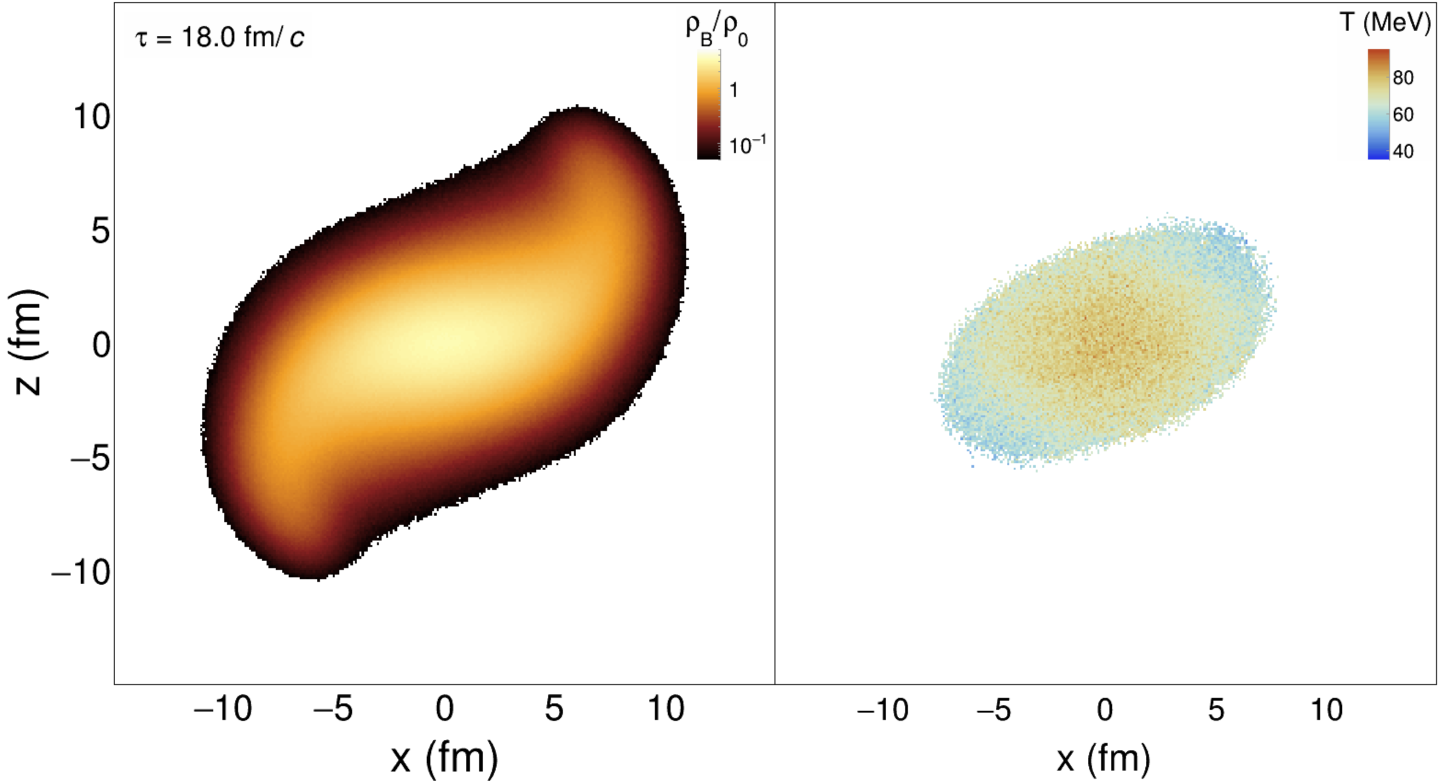

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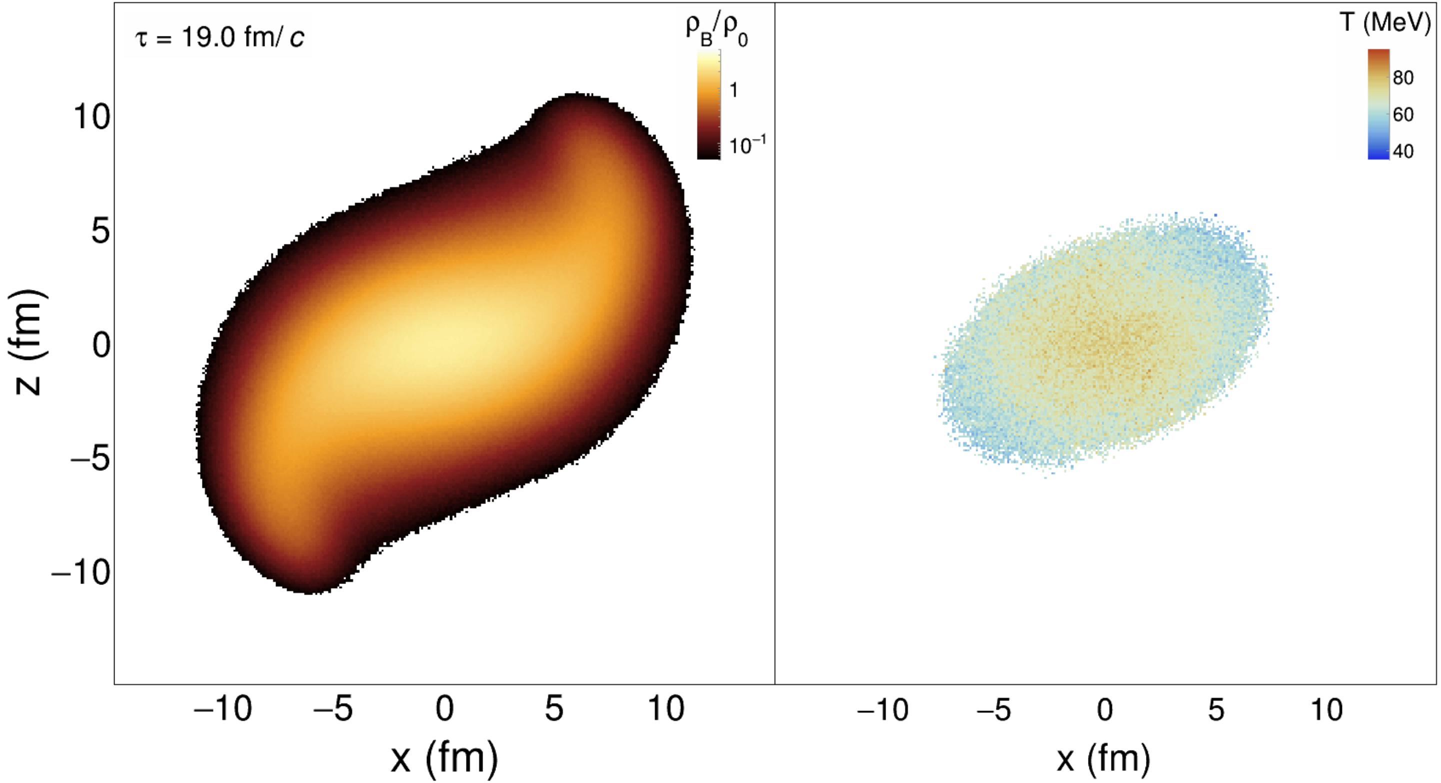

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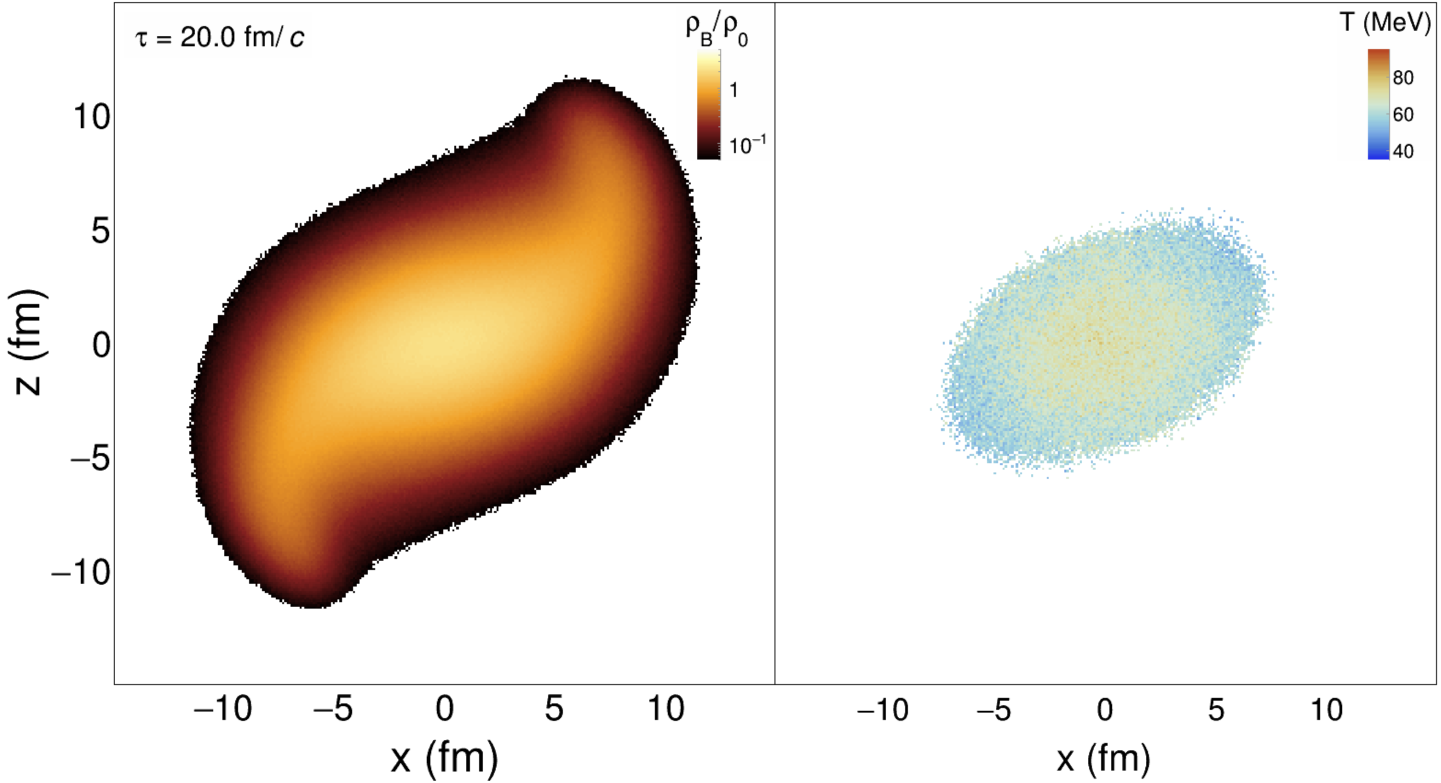

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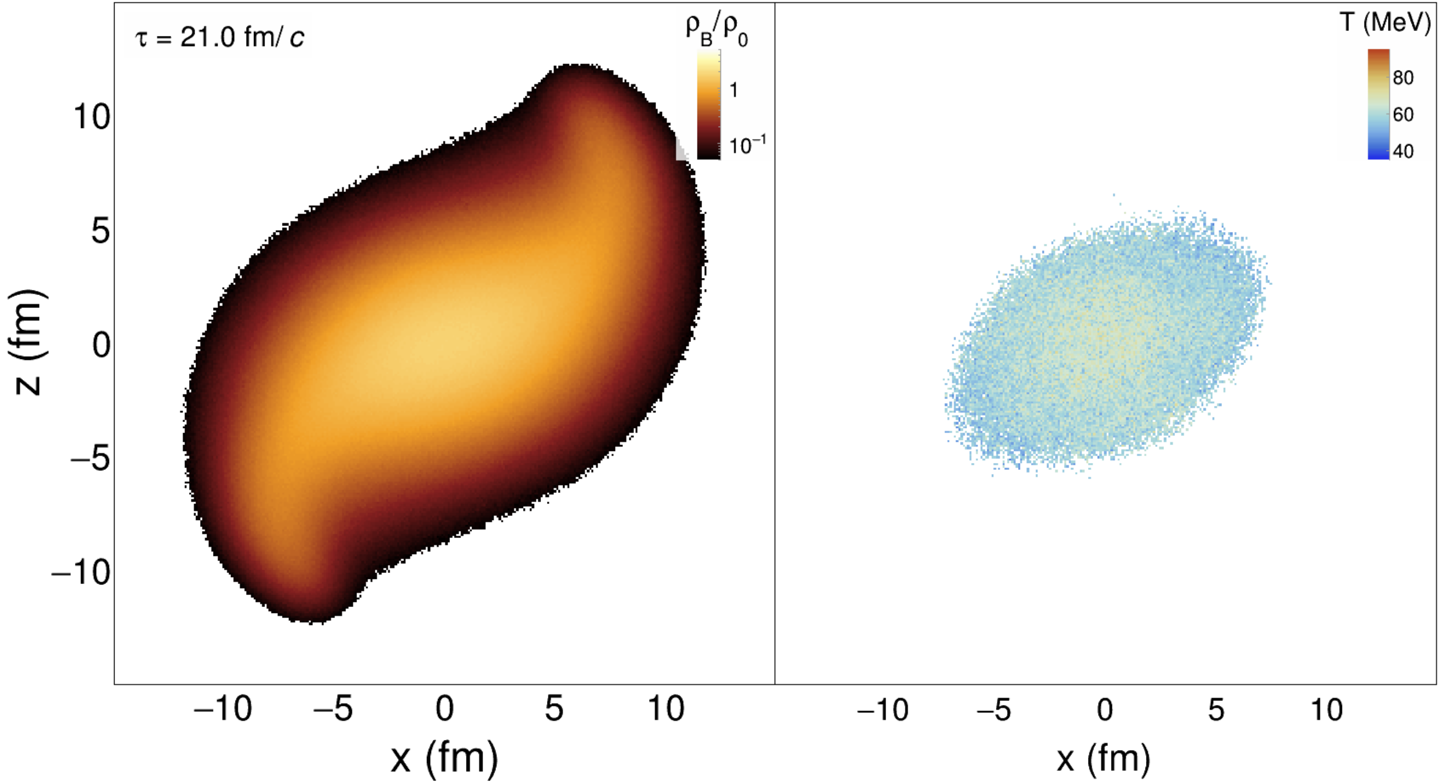

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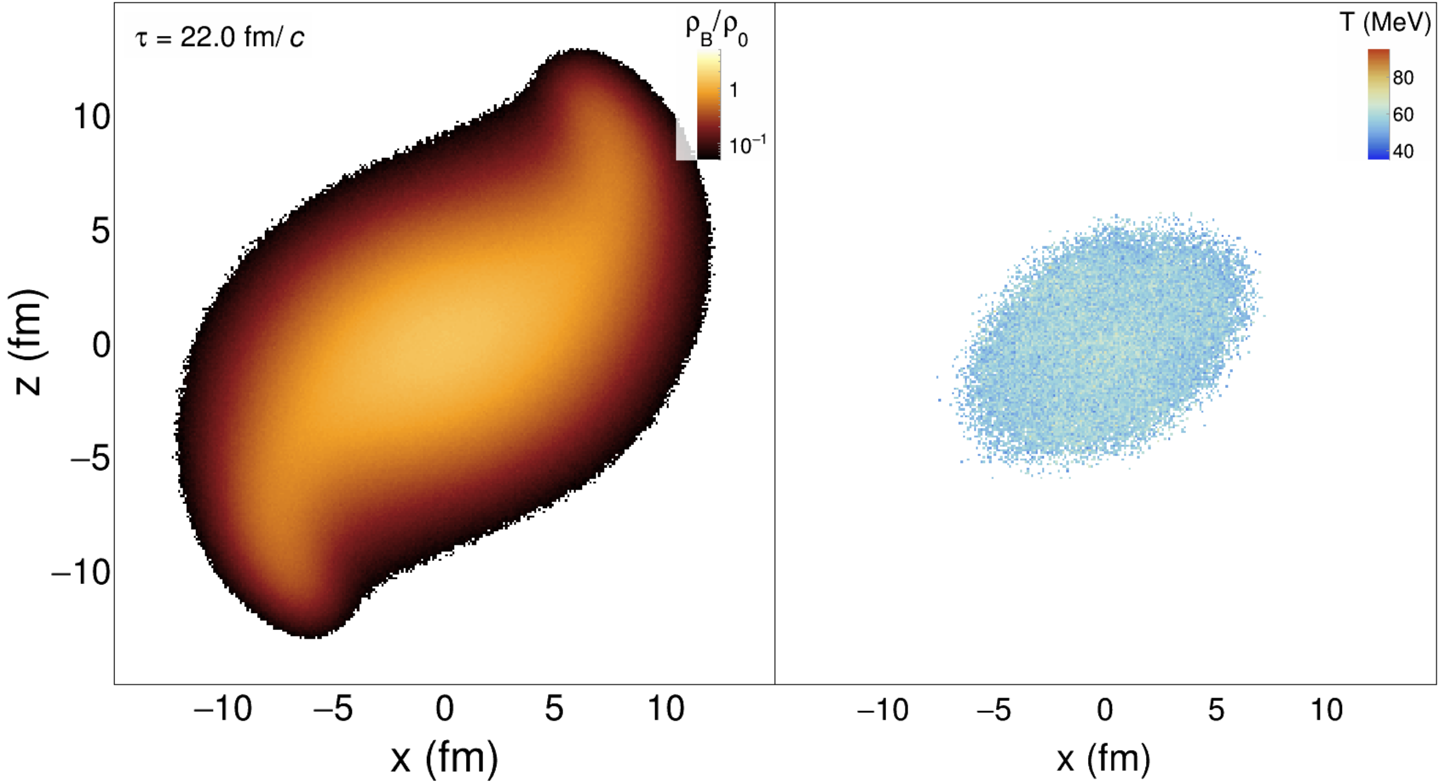

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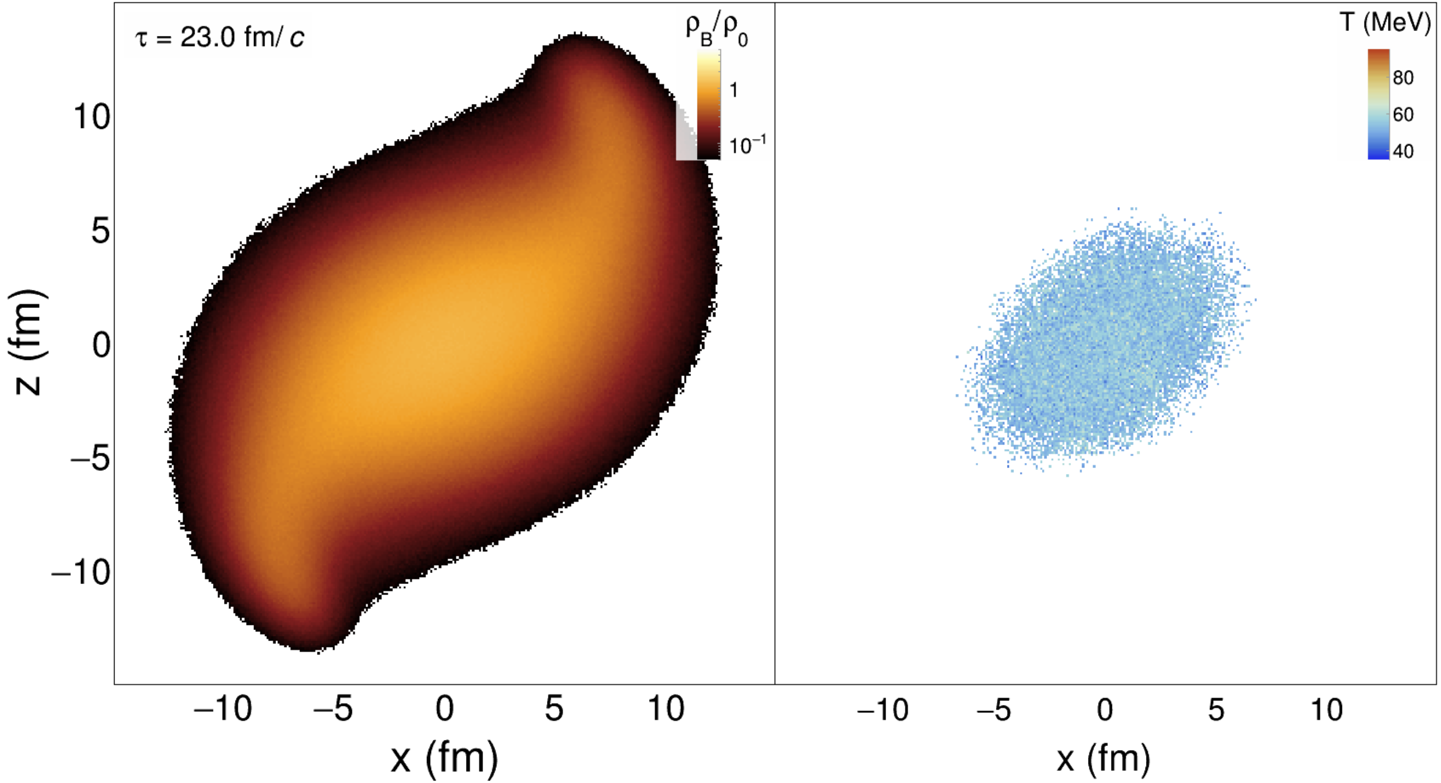

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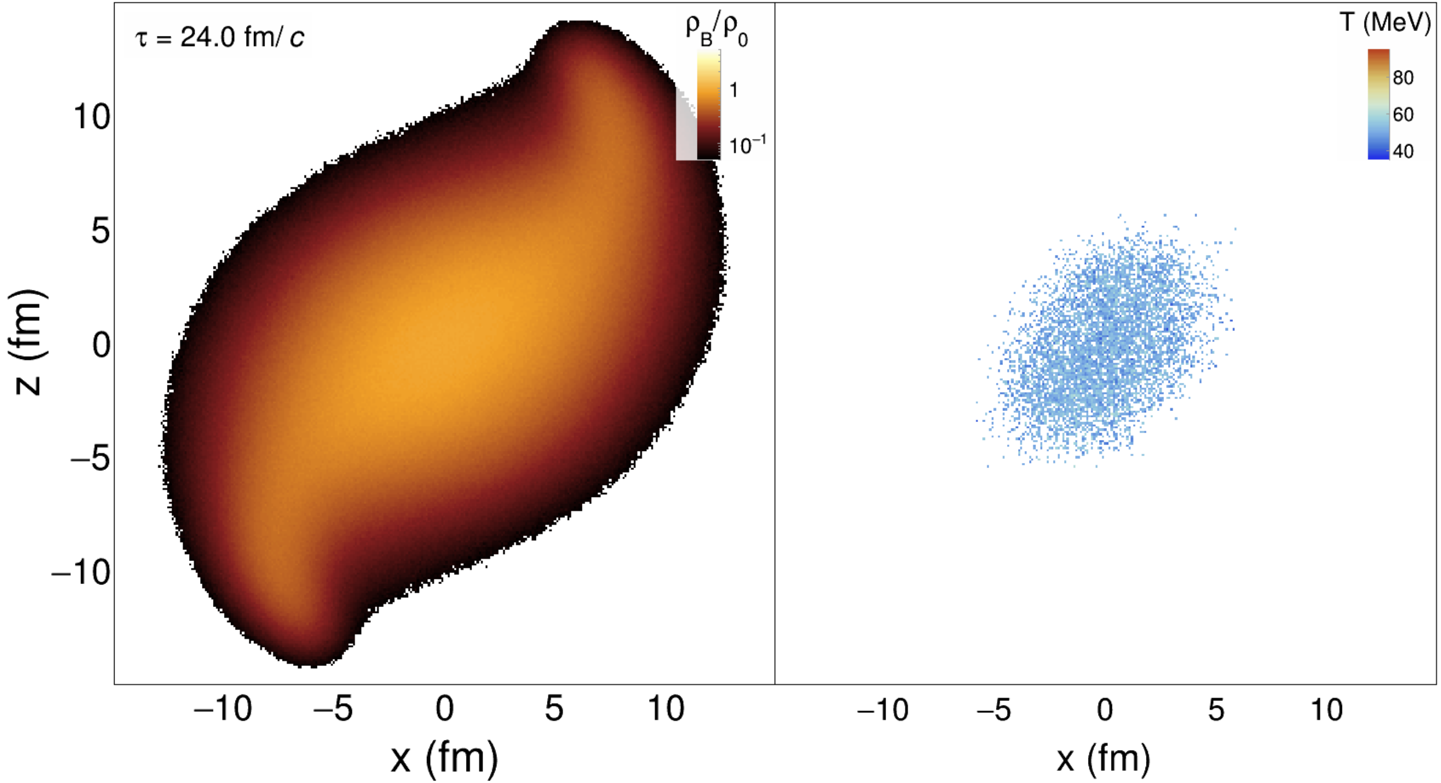

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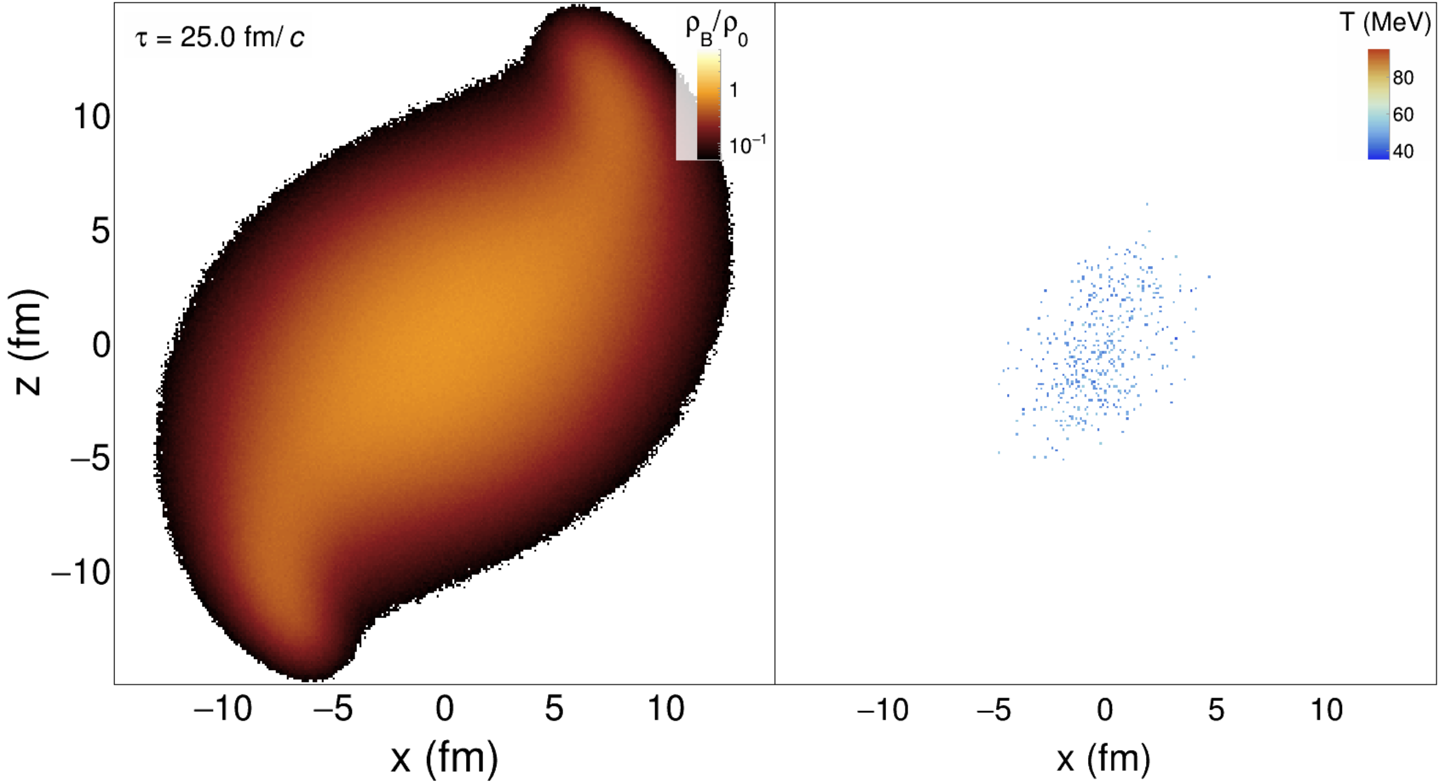

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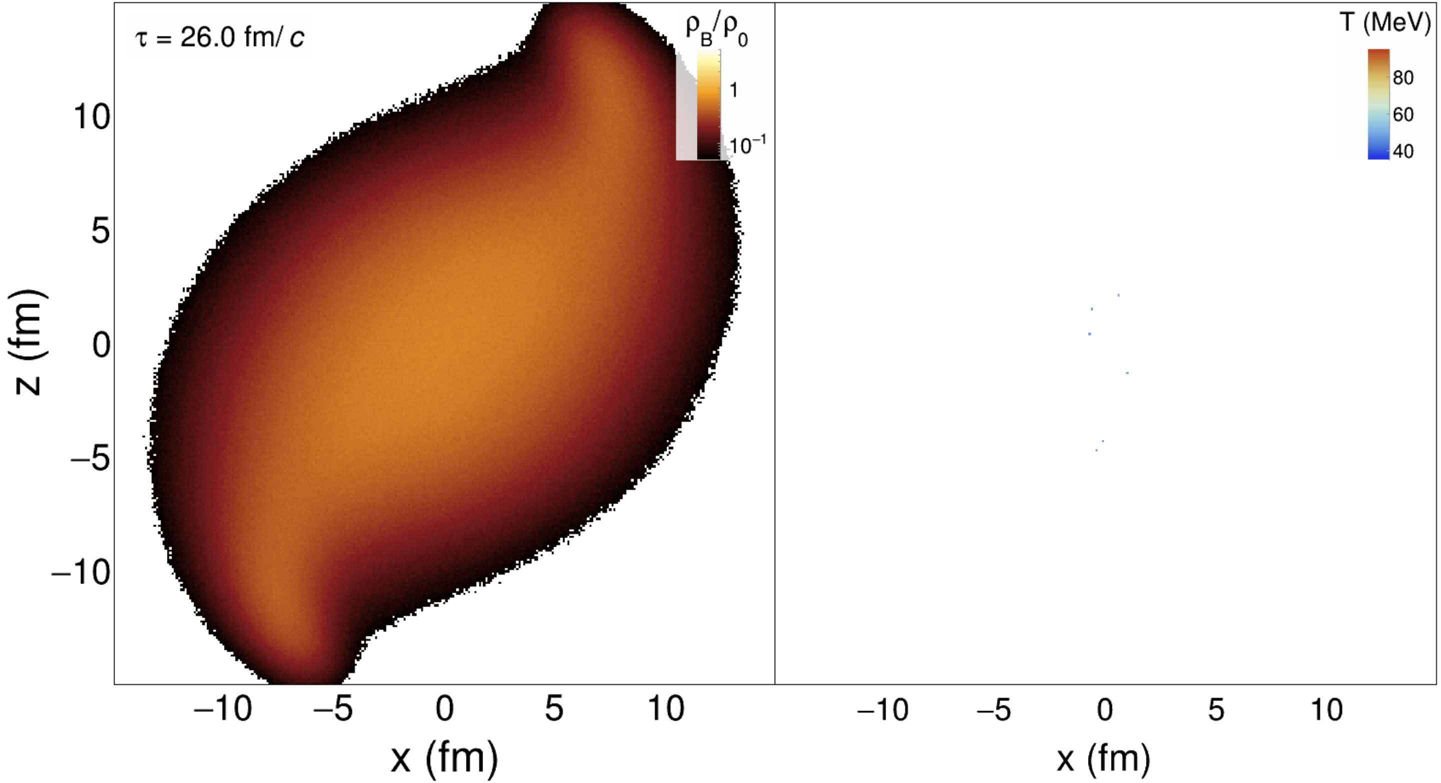

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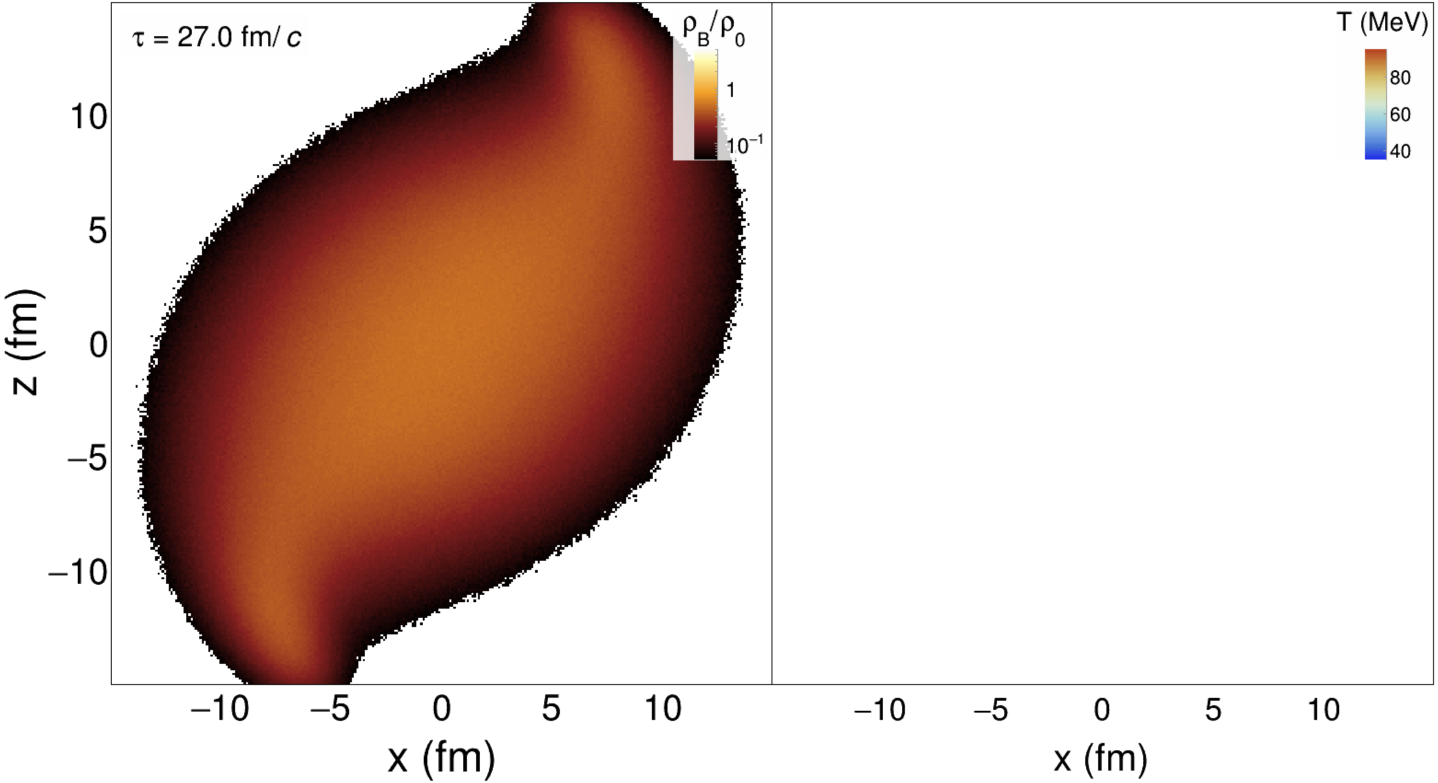

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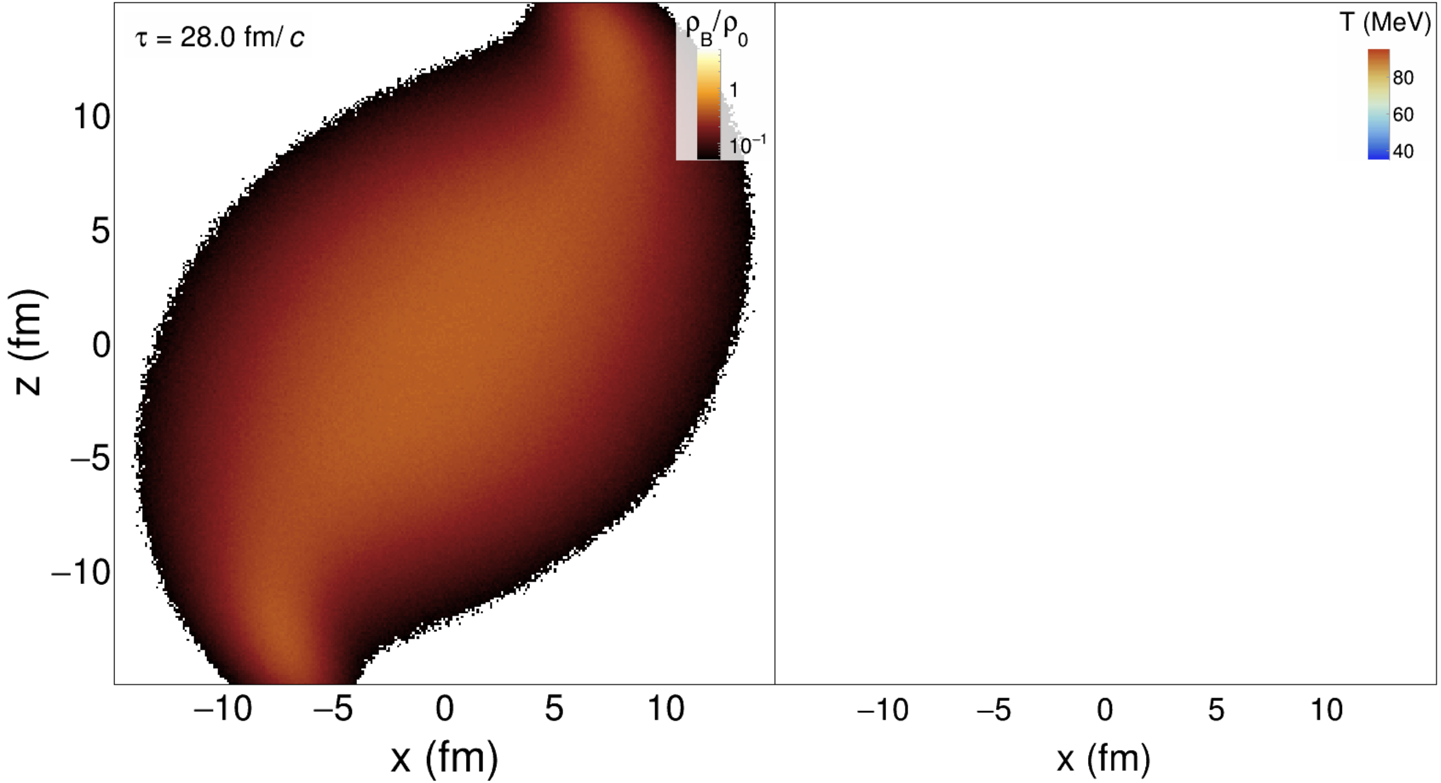


Thermal dilepton production

thermal Bose distribution

electromagnetic spectral function

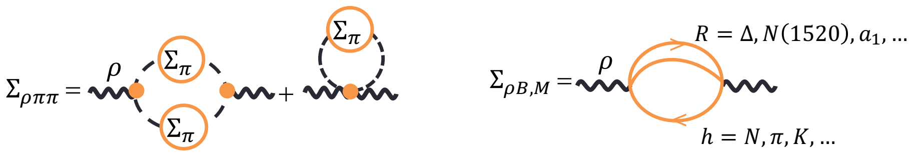
- McLerran-Toimela formula

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

McLerran - Toimela, PRD 31 (1985) 545
Gale, Kapusta, PRC 35, 2107 (1987) & NPB 357, 65-89 (1991)
Weldon, PRD42, 2384-2387 (1990)

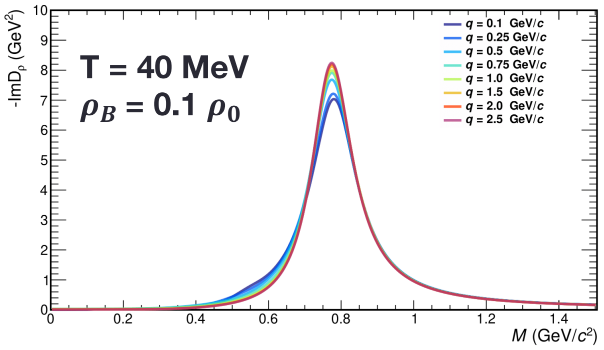
- In-medium ρ-meson undergoes a strong broadening
  - additional contributions to the self-energy in the medium through coupling to (anti-)baryons and mesons

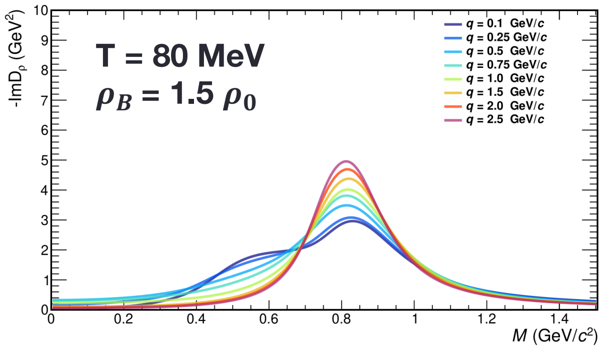
$$D_\rho(M,q,T,\mu_B) = \frac{1}{[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]}$$



- If $\frac{Im\Pi_{em}}{M^2} \sim const.$ ➥ thermometer

Rapp, Wambach, EPJA 6 (1999) 415

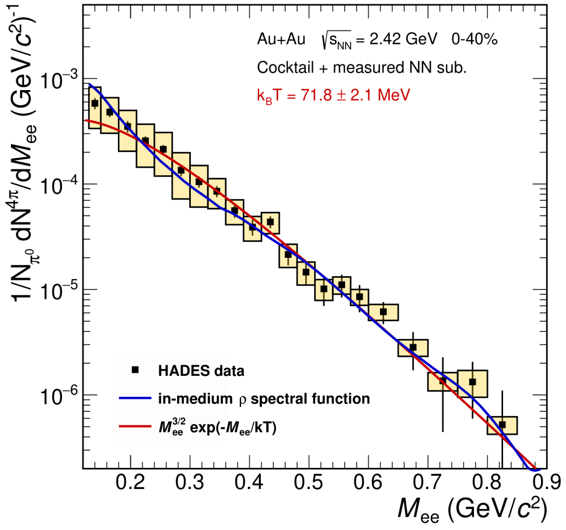




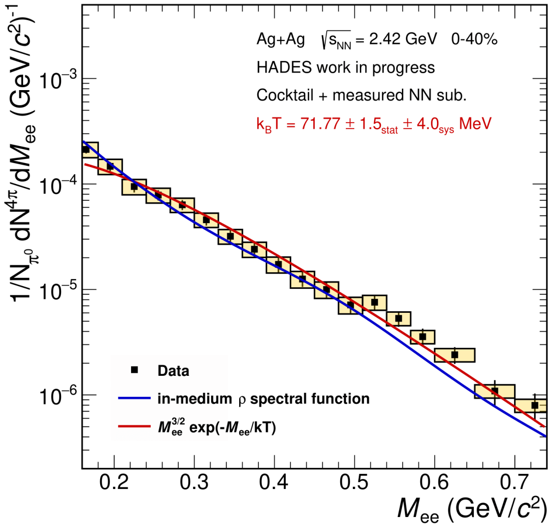
Thermal dileptons HADES systematics

➡ very good agreement between experiment and theory for excess radiation

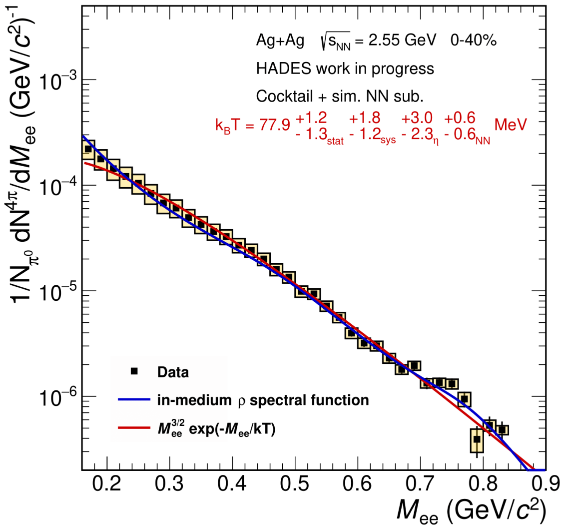
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



Ag+Ag at $\sqrt{s_{NN}} = 2.42$ GeV



Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV

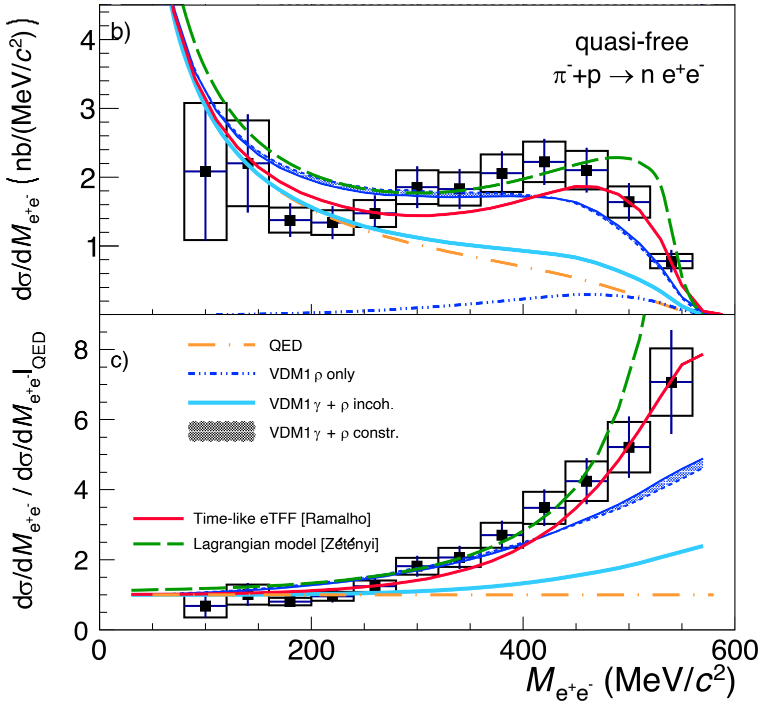


- in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies
- ρ-meson peak undergoes a strong broadening in medium, baryonic effects are crucial!

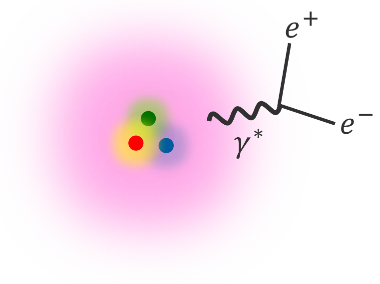
Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

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

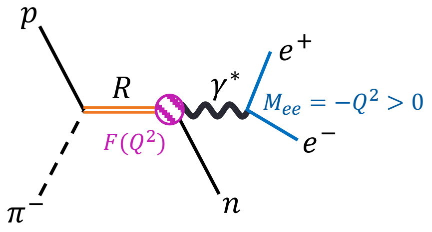
HADES, arXiv:2205.15914 [nucl-ex], with PRL
HADES, arXiv:2309.13357 [nucl-ex], with PRC



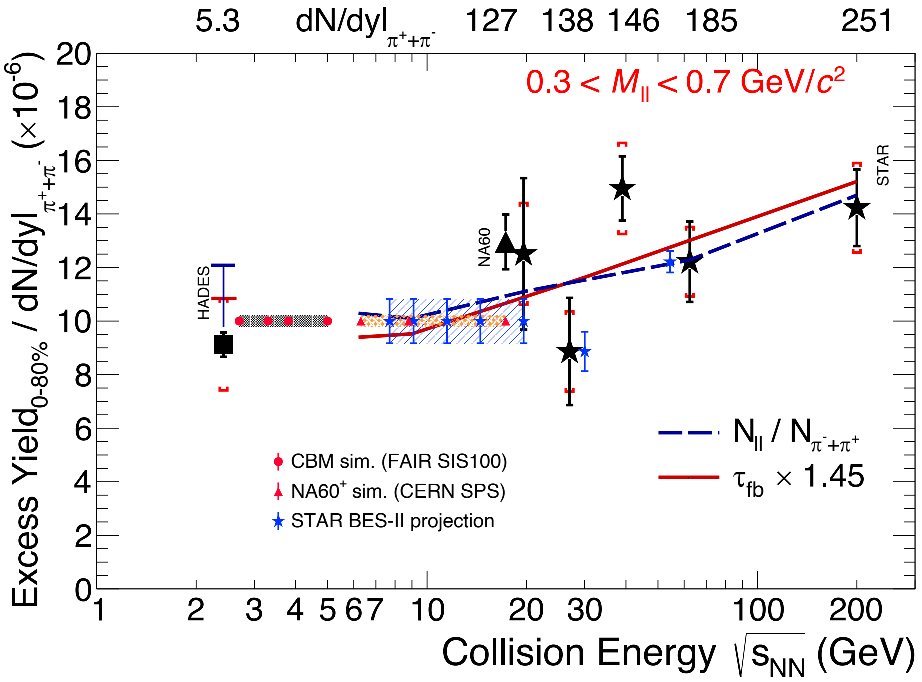
Ramalho, Pena, PRD95 (2017) 014003
Zetenyi, Nitt, Buballa, TG, PRC 104 (2021) 1, 015201
Speranza *et al.*, PLB764 (2017) 282



- 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**



Lifetime of the interacting medium



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

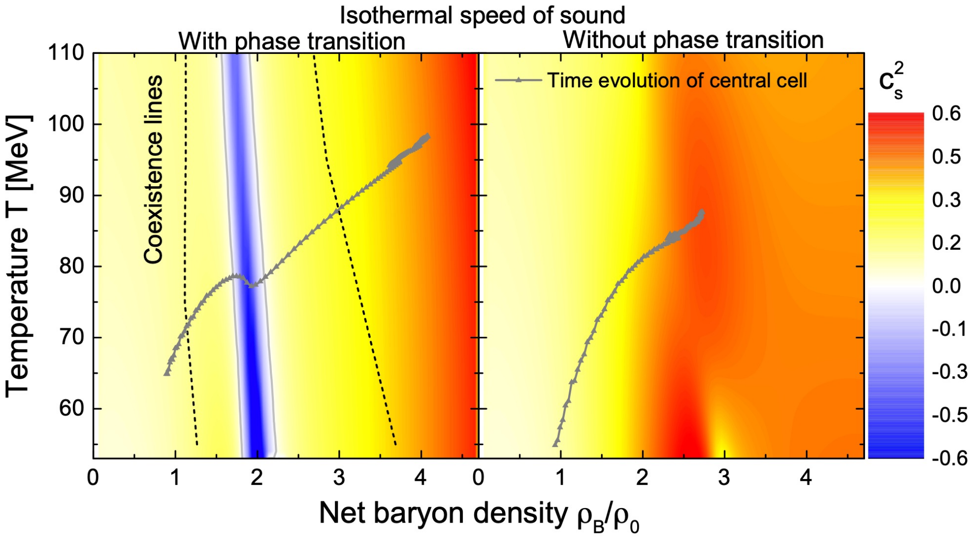
- Integrated low-mass **excess yield** radiation $0.3 < M < 0.7$ GeV/c^2 tracks the fireball **lifetime**

Heinz and Lee, PLB 259, 162 (1991)
Barz, Friman, Knoll and Schulz, PLB 254, 315 (1991)
Rapp, van Hees, PLB 753, 586 (2016)

- CBM, NA60+ performance studies with realistic detector geometries, material budget, response, S/B and statistics ⤳ precision 1.5 – 4.5%

- Search for emerging signatures indicative of a 1st order **phase transition** (and critical point?):
  - prolonged lifetime of the system due to latent heat → "**excess excess-radiation**"?

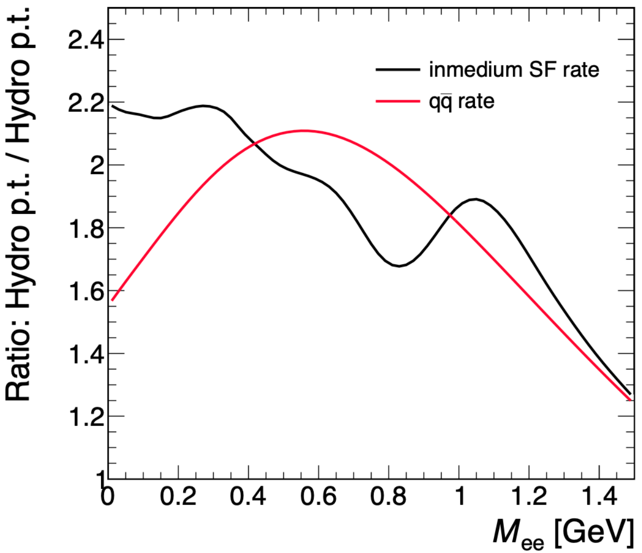
Dilepton signature of a 1st order phase transition



- Ideal hydro simulations with and w/o 1st 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

Seck, TG, *et al.*, PRC 106 (2022) 1, 014904
See also Savchuk, TG, *et al.*, J.Phys.G 50 (2023) 12, 125104

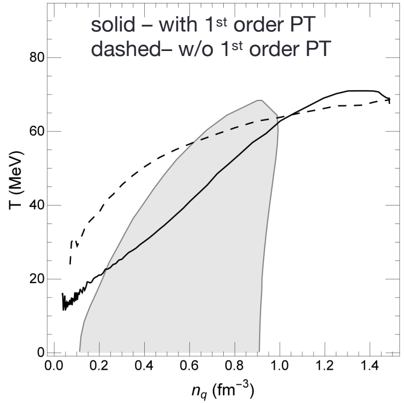


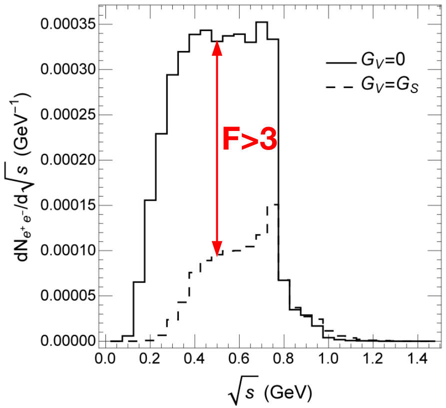
Dilepton emission shows a significant effect: factor 2 enhancement of dilepton emission due to extended "cooking"

Dilepton signature of a 1st order phase transition & critical point

- Spinodal instabilities of baryon-rich quark matter
  - NJL blast-wave initial conditions (F>3)
  - NJL with AMPT initial conditions (F~2)

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





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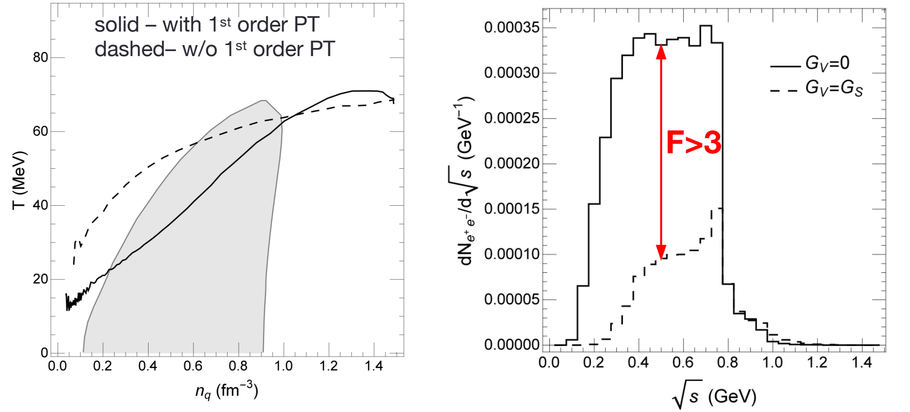
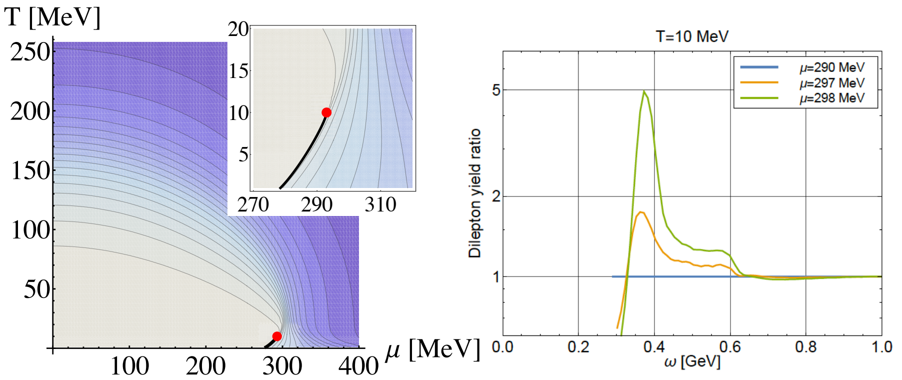
Li and Ko, PRC 95 (2017) no.5, 055203



- Thermodynamically consistent spectral functions from FRG
- Dilepton rates at CEP $T=10\ MeV$, $\mu=292\ MeV$

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



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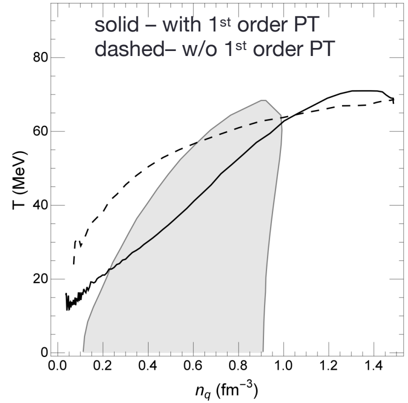
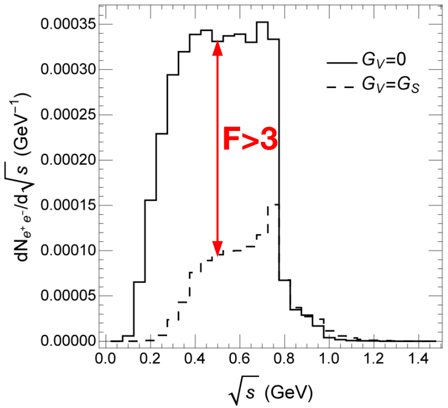
Li and Ko, PRC 95 (2017) no.5, 055203





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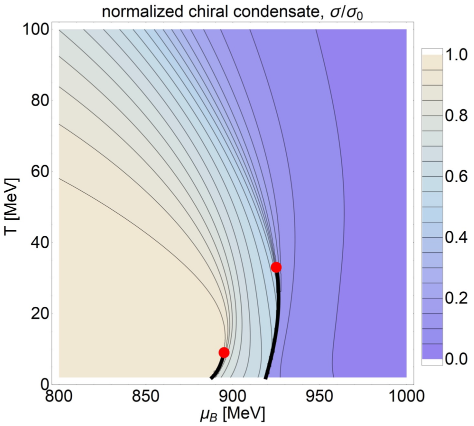
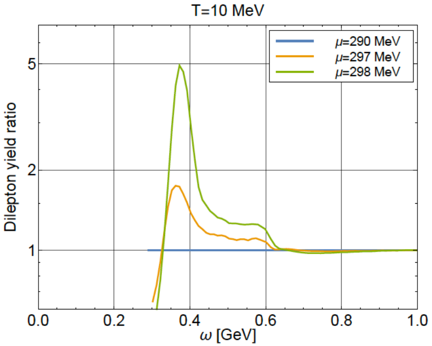
Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD 95 (2017) 036020
Tripolt *et al.*, NPA 982 (2019) 775

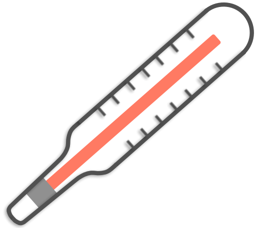
- Current developments: realistic chirally-symmetric effective hadronic theory for nuclear and neutron matter
  ➥ **parity-doublet model**

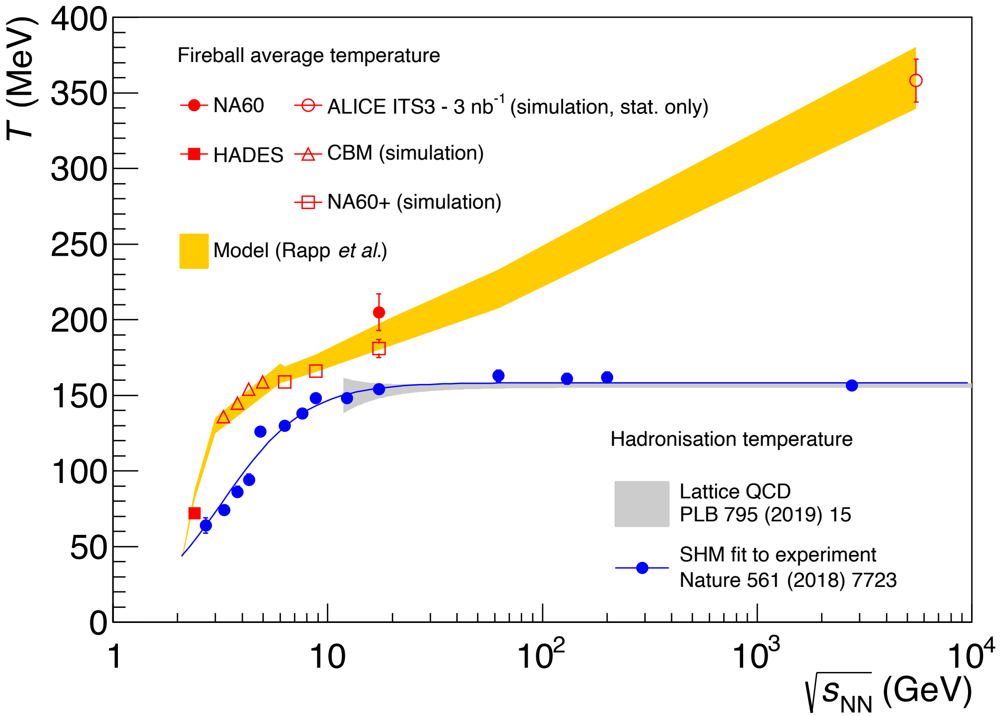
Tripolt, Jung, v. Smekal, Wambach, PRD 104, 054005 (2021)





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:

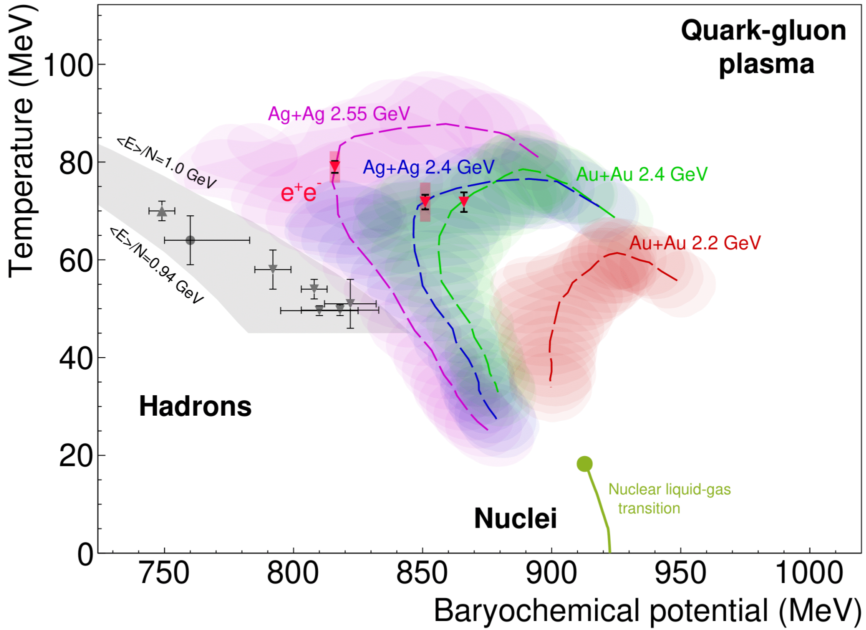
$$\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp(-\frac{M}{T})$$

- Probe time dependence of fireball temperature: *$M_{\ell\ell}$ versus v_2, photon polarization* → access to hottest fireball T

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

High μ_B region of QCD phase diagram probed with dileptons

- Measured by HADES average **temperatures** from 'Planck-like' fit to **invariant mass** Ag+Ag, Au+Au
- Trajectories from coarse-grained UrQMD



FO curve: Cleymans, Redlich, NPA 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Ag+Ag data: HADES preliminary
figure: Seck, TG

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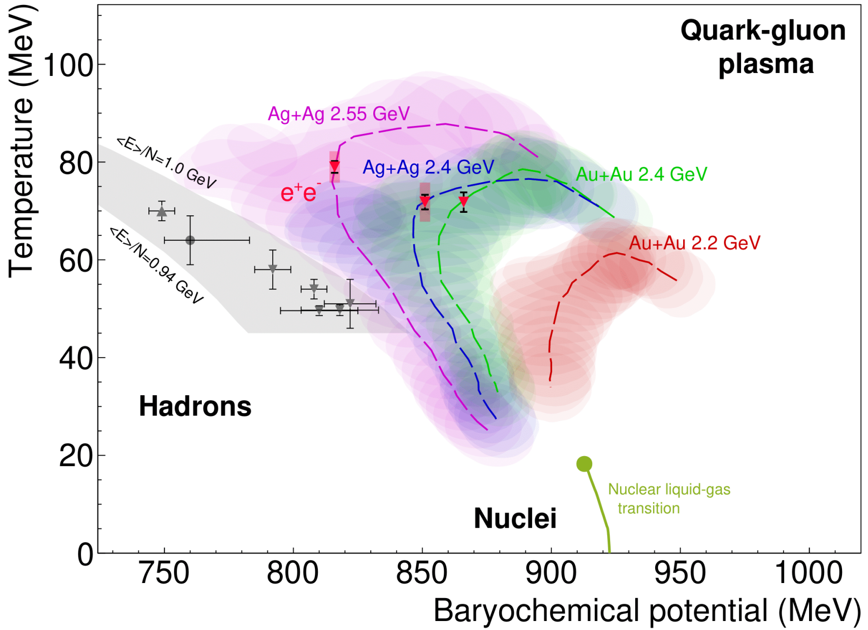
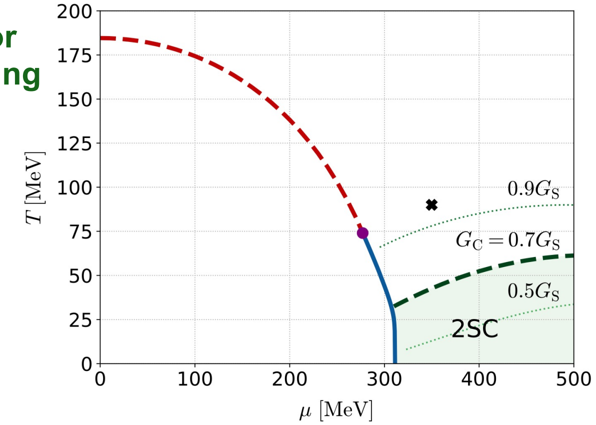


FO curve: Cleymans, Redlich, NPA 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Ag+Ag data: HADES preliminary
figure: Seck, TG

Exploring color superconducting phase with dileptons?

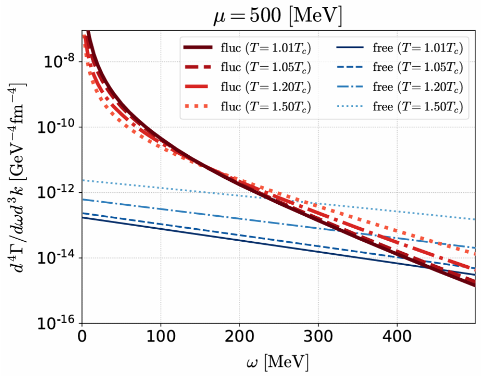


Nishimura, Nara, Steinheimer, Eur.Phys.J.A 60 (2024) 4, 82
Nishimura *et al.*, PTEP 2022 (2022) 9, 093D02
Jaikumar, Rapp, Zahed, PRC 65, 055205 (2002)

Low-mass low-momentum dileptons

- Color superconductivity could manifest itself in an enhanced yield of low-energy dileptons

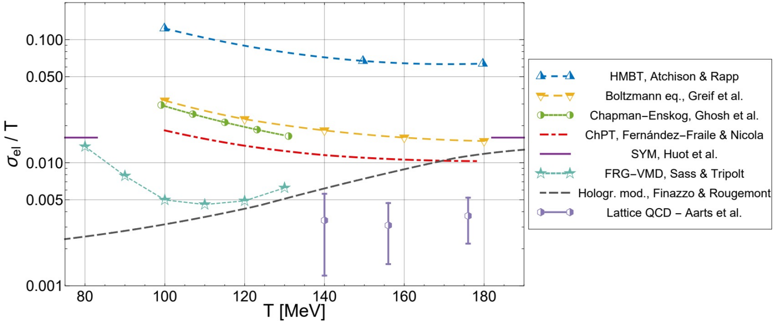
Nishimura *et al.*, PTEP 2022 (2022) 9, 093D02



- Transport properties of the medium - electrical conductivity - can be directly obtained from the low-energy limit of the EM spectral function (at vanishing momentum)

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

Kubo, J. Phys. Soc. Jap. 12 (1957) 570-586
Moore, Robert, arXiv:hep-ph/0607172 (2006)
Atchison, Rapp, NPA 1037 (2023) 122704
Flörchinger *et al.*, PLB 837 (2023) 137647
Nishimura, Kitazawa, Kunihiro, arXiv:2312.09483 [hep-ph]



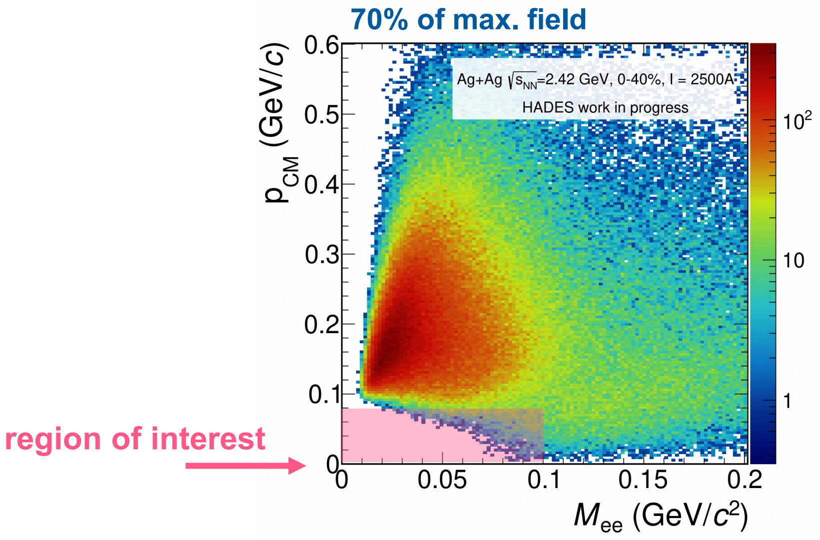
Geurts, Tripolt, PPNP 128 (2023) 104004

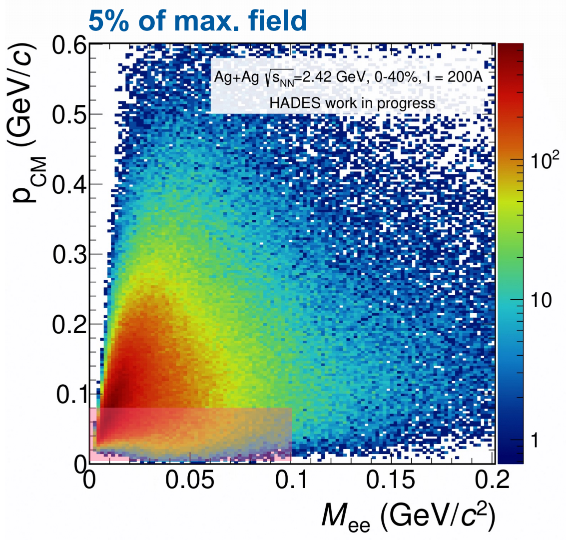
Non-monotonic trend of σ_{el} as the phase transition occurs? visible in a beam energy scan?

Low-mass low-momentum dileptons

➥ experimental challenges

- Low momentum lepton tracks bent out of acceptance by magnetic field
- Photon conversion suppressed via opening angle cut
- Physical background of π^0 and η mesons
- Step towards measurement:
  - dedicated Ag+Ag test run at HADES with low magnetic field
  - new Au+Au at $\sqrt{s_{NN}} = 2.23$ GeV data recorded this year with 50% field + low field run scheduled for 2025





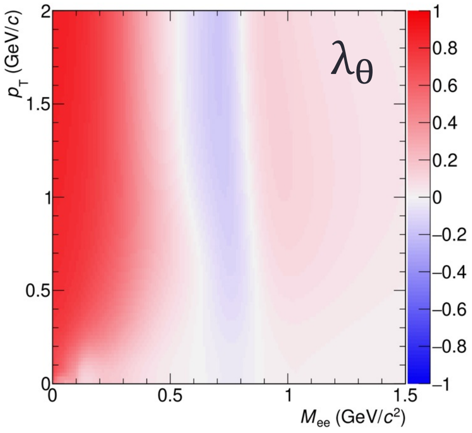
Virtual photon polarization

- Decompose spectral function using projectors for a spin-1 particle $\rho_{EM}^{\mu\nu} = \rho_L P_L^{\mu\nu} + \rho_T P_T^{\mu\nu}$ with $g_{\mu\nu}\,\rho_{EM}^{\mu\nu} = \rho_L + 2\rho_T$
- Angular distribution of single lepton in γ^* rest frame depends on polarization of γ^*

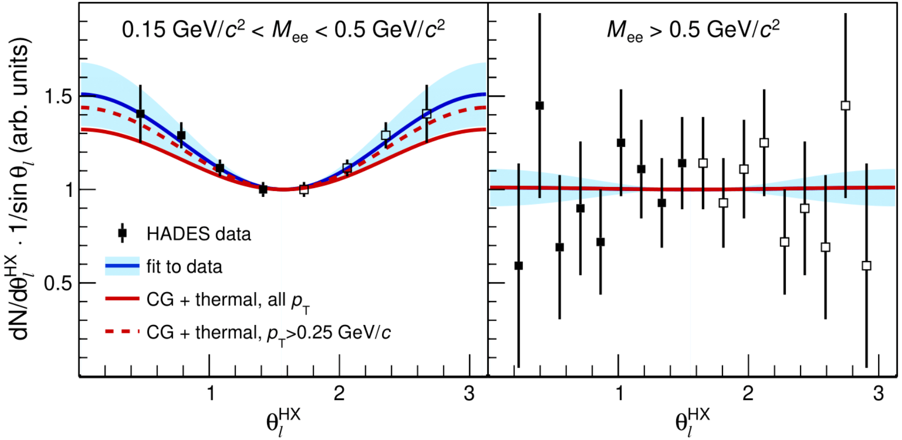
$$\frac{dN}{d^4x d^4q d\Omega} = \mathcal{N}(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi^\perp \sin^2\theta \sin 2\varphi + \lambda_{\theta\varphi}^\perp \sin 2\theta \sin\varphi)$$

- Different virtual photon **production mechanisms** imprint different anisotropy parameters λ
- λ coefficients related to **difference** between **longitudinal and transverse** spectral function components $\lambda_\theta = \frac{\varrho_T - \varrho_L}{\varrho_T + \varrho_L}$

HADES, PRC 84 (2011) 014902
Seck *et al.*, arXiv: 2309.03189



HADES, Ar+KCl at $\sqrt{s_{NN}} = 2.62$ GeV



- **Best fit** to data gives $\lambda_\theta = 0.51 \pm 0.17$ and $\lambda_\theta = 0.01 \pm 0.10$ in the two mass windows
- **Calculation** result gives $\lambda_\theta = 0.32$ and $\lambda_\theta = 0.01$ respectively

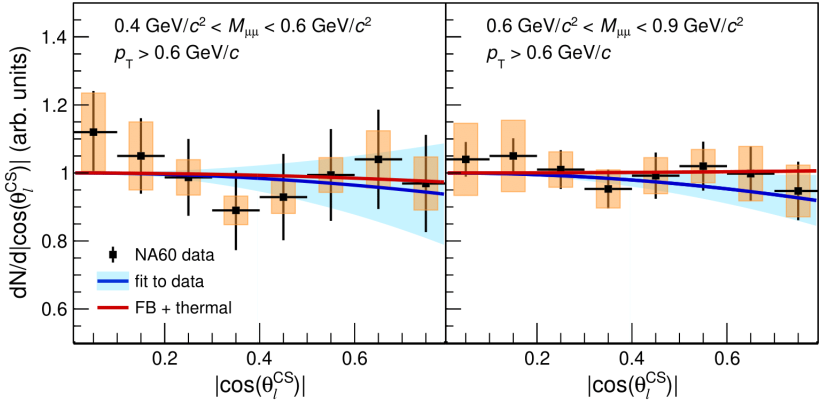
Comparison to NA60 data

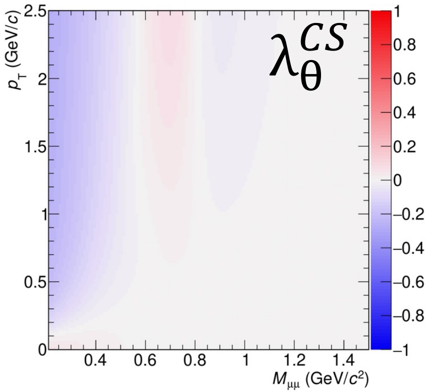
- NA60 measured polarization coefficients λ_θ, λ_φ and $\lambda_{\theta\varphi}$ of excess radiation in the CS frame in In+In collisions at $\sqrt{s_{NN}} = 17.2$ GeV
- Space-time evolution via isentropic fireball model with transition from QGP to hadronic rates at T=170 MeV

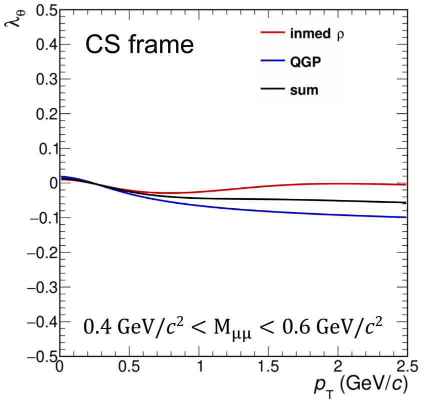
NA60, PRL 96, 162302 (2006)
Rapp, van Hees, PLB 753 (2016) 586

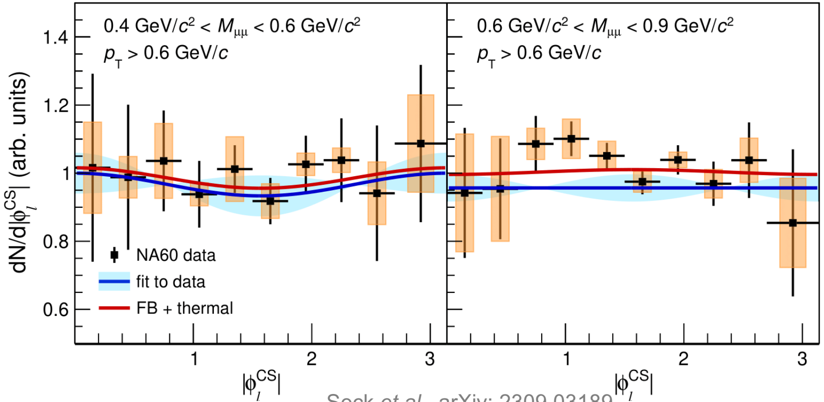
- Good agreement between data and theory → size and trend
- Near absence of a net polarization not related to thermal isotropy arguments

data points: NA60, PRL 102 (2009) 222301









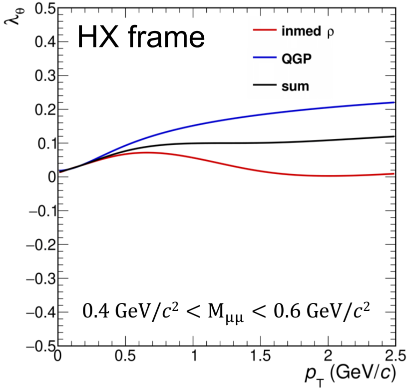
Seck *et al.*, arXiv: 2309.03189

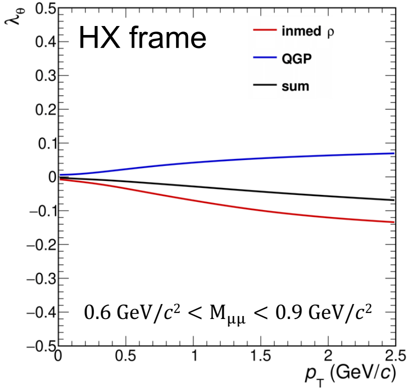
Prospect of disentangling hadronic and partonic sources

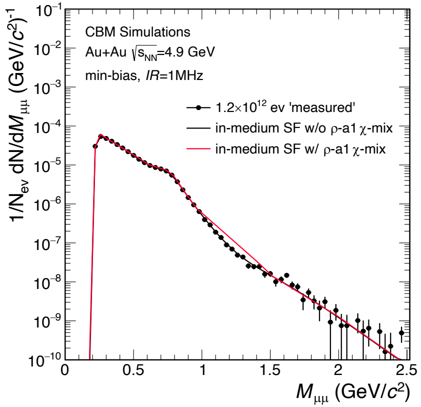
- Polarization plays important role in exploring the mechanisms underlying EM emission

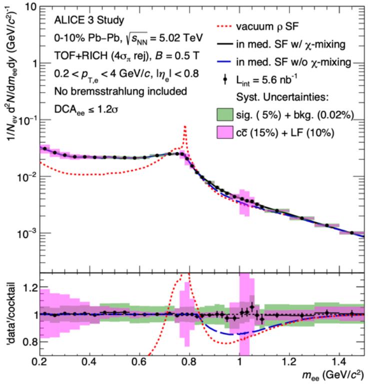
  Seck *et al.*, arXiv: 2309.03189
  Coquet, Winn, Du, Ollitrault, Schlichting, PRL132 (2024) no.23, 232301
  Speranza *et al.*, PLB 782, 395 (2018)
  Baym *et al.*, PRC95, 044907(2017)
  Bratkovskaya *et al.*, PLB 376, 12 (1996)

- Multi-differential measurements of the virtual photon polarization
  - resolve mass, p_T, rapidity, lepton emission angles θ_l, φ_l
    $\rightarrow$ large datasets needed
  - future high-rate experiments CBM, NA60+ and ALICE3
  - search for onset of QGP
  - important in disentangling $\rho - a_1$ chiral mixing from QGP around M_{ll} ~ 1.2 GeV/c^2









Multi-differential ($M_{\ell\ell}$, p_T, v_n, λ_θ) emission probability of dileptons, >2030

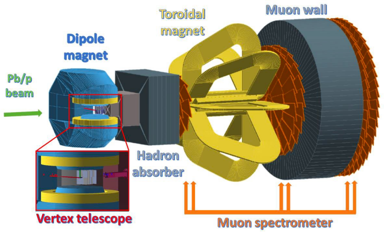
LoI, http://arxiv.org/abs/arXiv:2212.14452

ALICE, Run3 & Run4

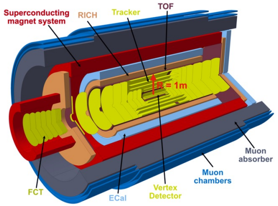
https://cds.cern.ch/record/2703140

STAR

NA60+ at SPS

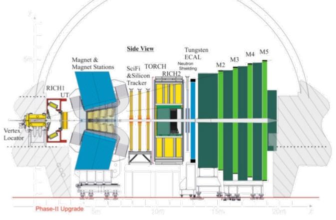


ALICE 3

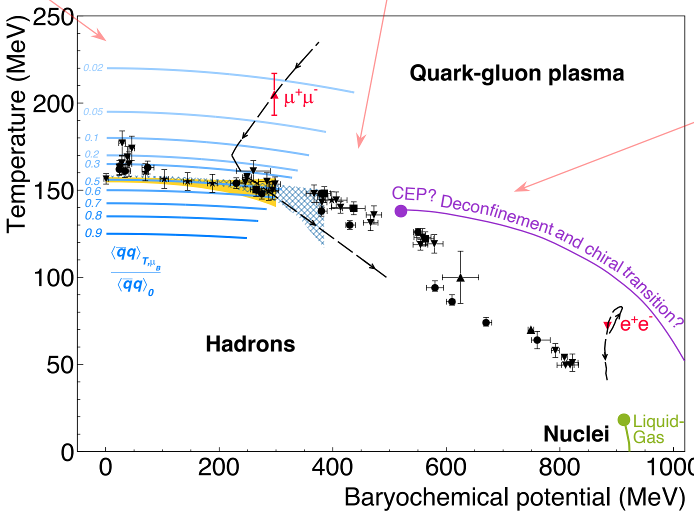


http://cds.cern.ch/record/2803563

LHCb-II

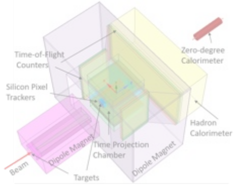


CERN-LHCC-2021-012

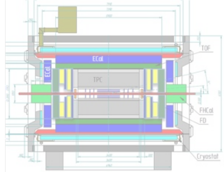


CBM / HADES$_{100kHz}$ at FAIR

J-PARC-HI



MPD



Résumé: The future is bright

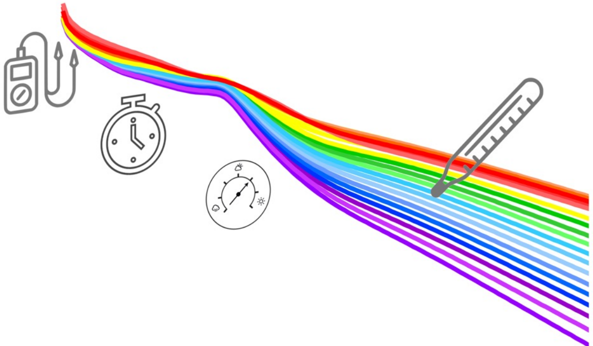
Unique possibility of characterizing properties of hot and dense QCD matter with dileptons

- Robust understanding of low-mass dilepton excess radiation through ρ-baryon coupling (at LHC, RHIC, SPS and SIS18 energies)

- 1^{st} order phase transition and QCD critical point is awaiting discovery
  ➥ might be detected in dileptons excitation functions

- Complementary program on exclusive measurements in π, p induced reactions with HADES

- Thermal dileptons enable unique measurements
  - degrees of freedom of the medium
  - restoration of chiral symmetry
  - transport properties
  - fireball lifetime, temperature, acceleration, polarization



Résumé: The future is bright

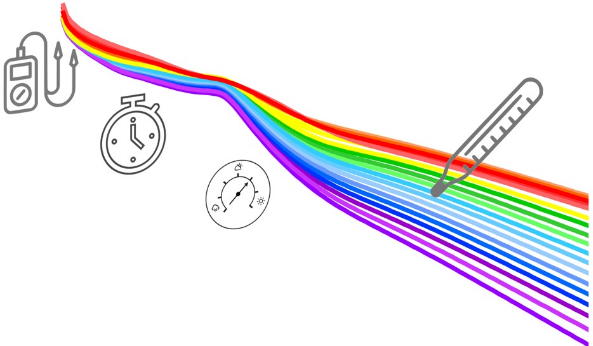
Unique possibility of characterizing properties of hot and dense QCD matter with dileptons

- Robust understanding of low-mass dilepton excess radiation through ρ-baryon coupling (at LHC, RHIC, SPS and SIS18 energies)

- 1^{st} order phase transition and QCD critical point is awaiting discovery
  ➥ might be detected in dileptons excitation functions

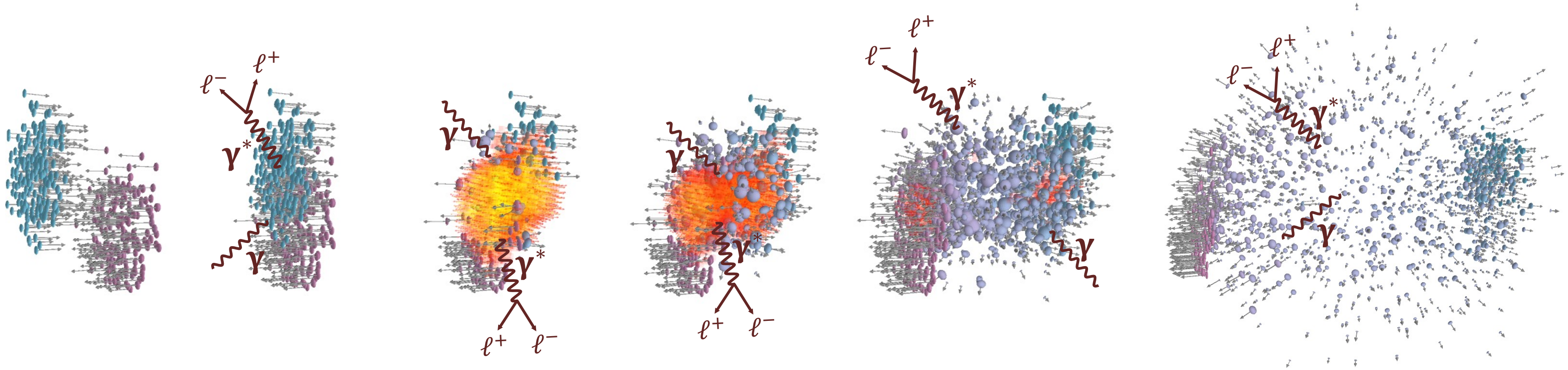
- Complementary program on exclusive measurements in π, p induced reactions with HADES

- Thermal dileptons enable unique measurements
  - degrees of freedom of the medium
  - restoration of chiral symmetry
  - transport properties
  - fireball lifetime, temperature, acceleration, polarization



BONUS SLIDES

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

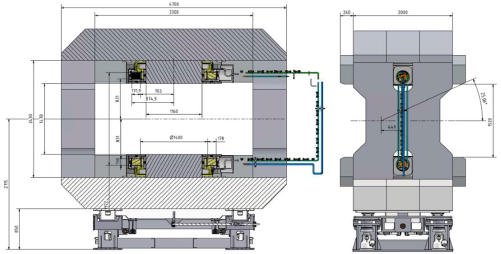
- degrees of freedom of the medium
- fireball lifetime, temperature, acceleration, polarization
- transport properties
- restoration of chiral symmetry

CBM subsystems are on the verge of series production

➥ pre-production is ongoing in all systems

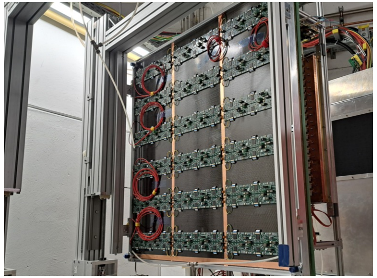
Superconducting dipole magnet

award of contract to Bilfinger Noell GmbH 20.12.2023



Beam monitoring system

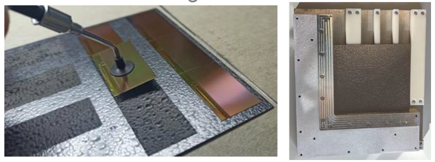
Transition Radiation Detector



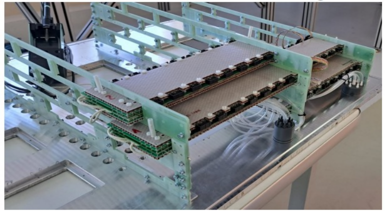
pre-production modules of 1D and 2D options ready

Micro Vertex Detector

sensor/module integration



Time of flight detector

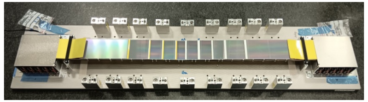


module pre-production concluded

MUon CHamber system

test of full-size GEM and RPC prototypes

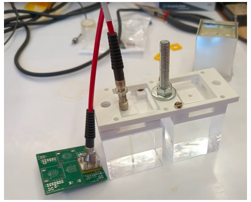
Silicon Tracking System



first STS series ladder

> 100 modules assembled

Forward Spectator Detector

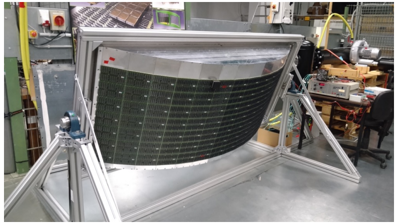


ZnS scintillators and LYSO crystals read-out via SiPM or/and PMT

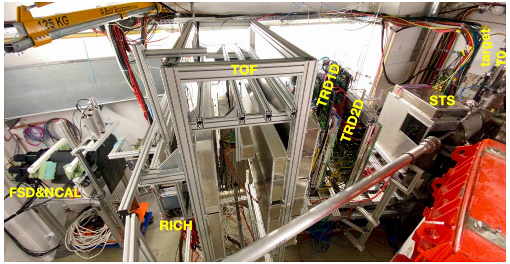
Ring Imaging Cherenkov detector

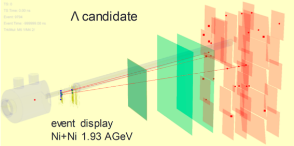
1 of 2 photo cameras ready

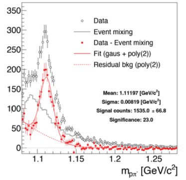
50% FEE produced



Prototype of CBM online data processing tests with mCBM







Dileptons and chiral symmetry of QCD

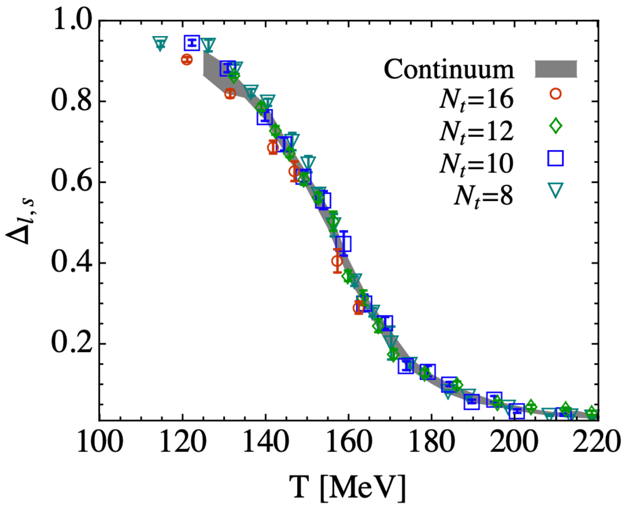
S. Weinberg, PRL 18 (1967) 507

Spontaneously broken in the vacuum

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

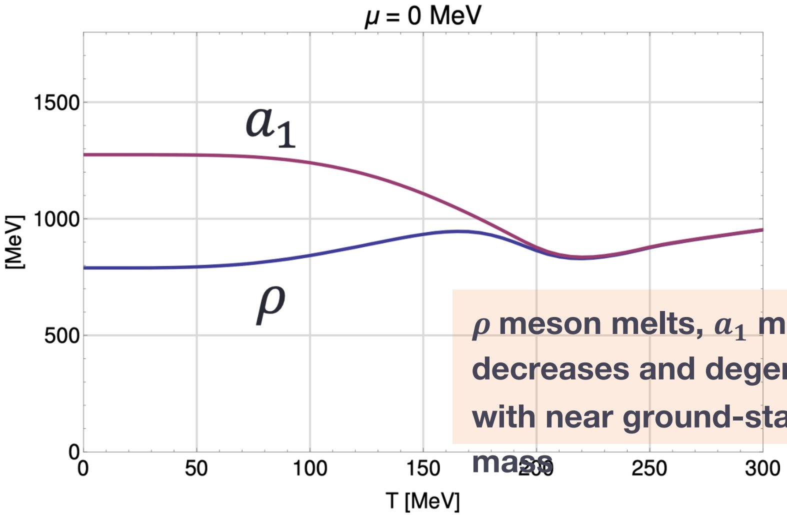
$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

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



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

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

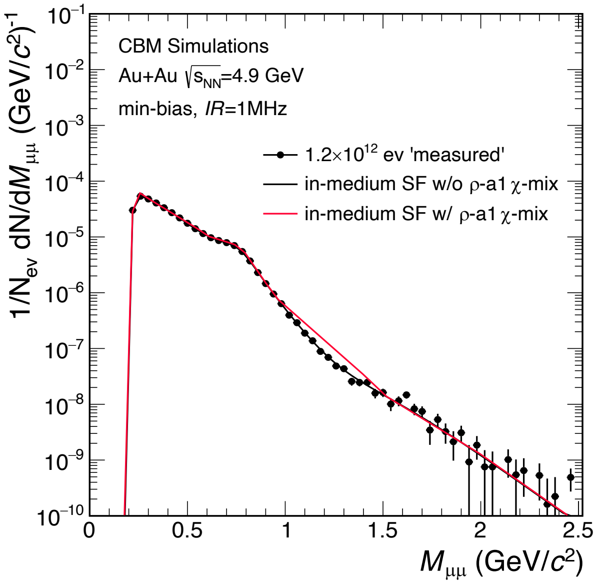


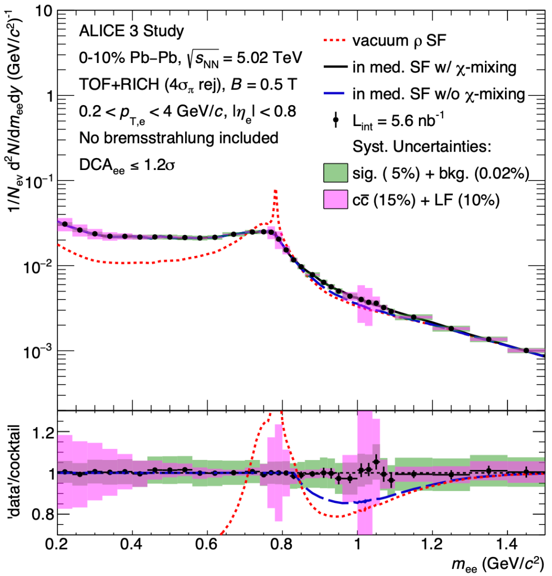
ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass

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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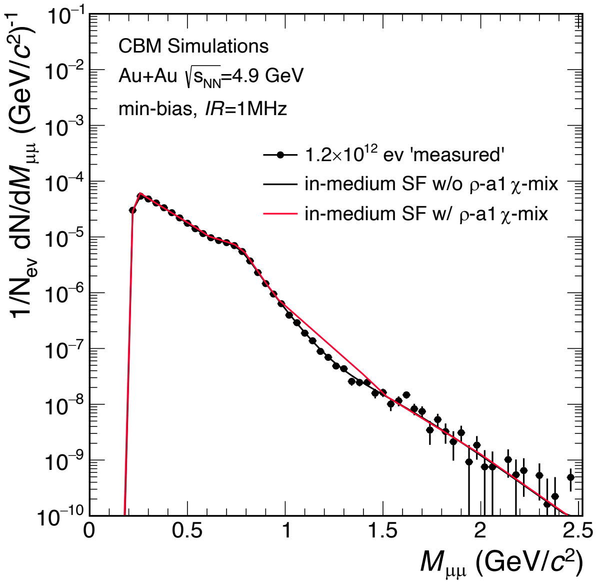

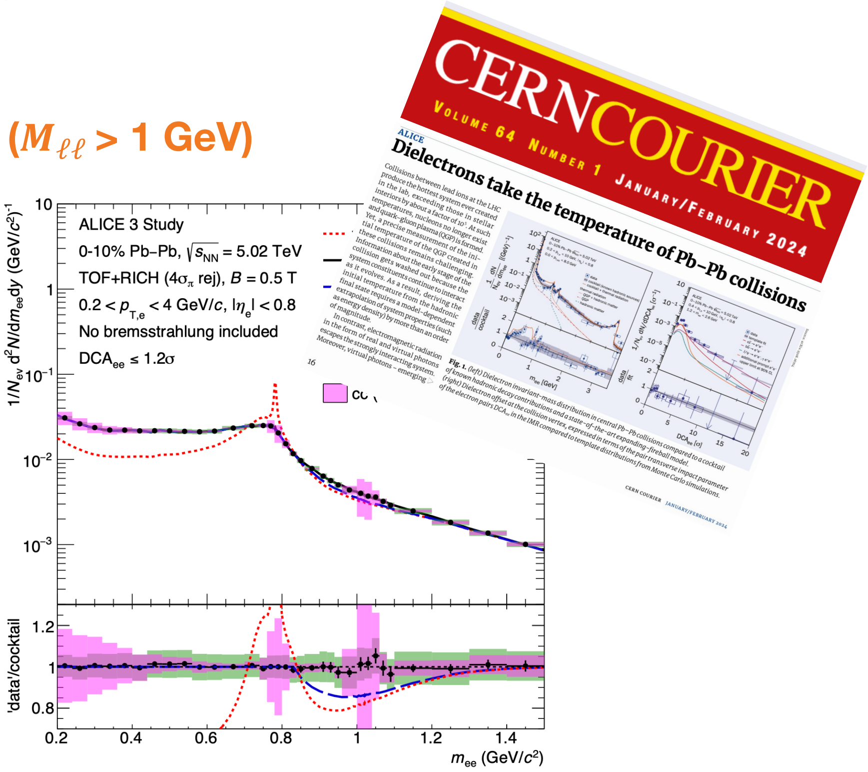

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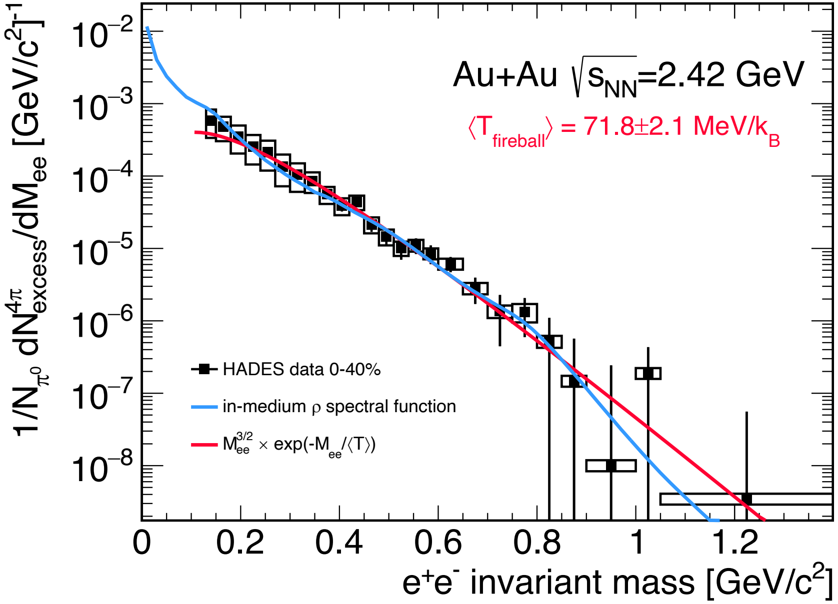
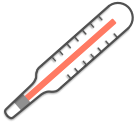
Thermal dileptons from baryon rich matter

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

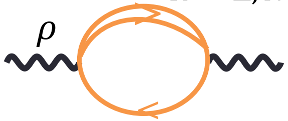
- Thermal excess radiation established at HADES (Au+Au, Ag+Ag)
  - ρ-meson peak undergoes a strong broadening in medium
  - in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

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

- Baryonic effects are crucial

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

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



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