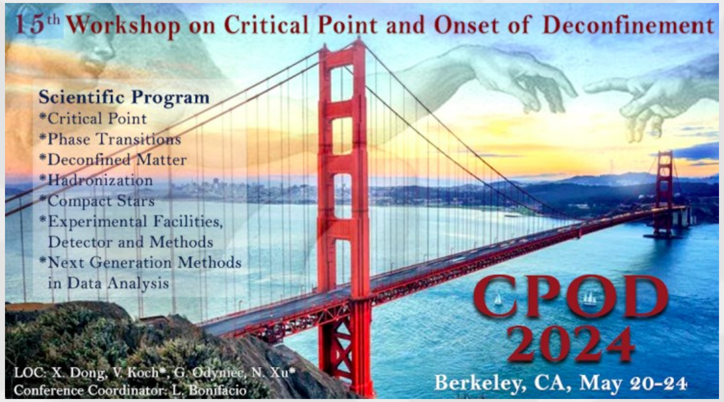
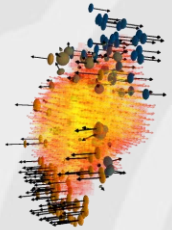
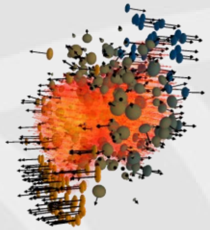


TECHNISCHE
UNIVERSITÄT
DARMSTADT

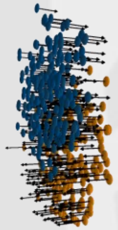
DILEPTON EMISSION AT HIGH BARYON DENSITIES

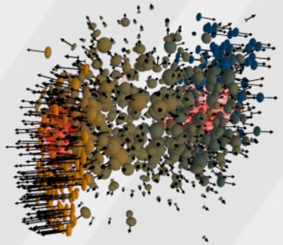


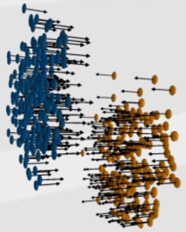


Florian Seck
(TU Darmstadt)

for the HADES collaboration





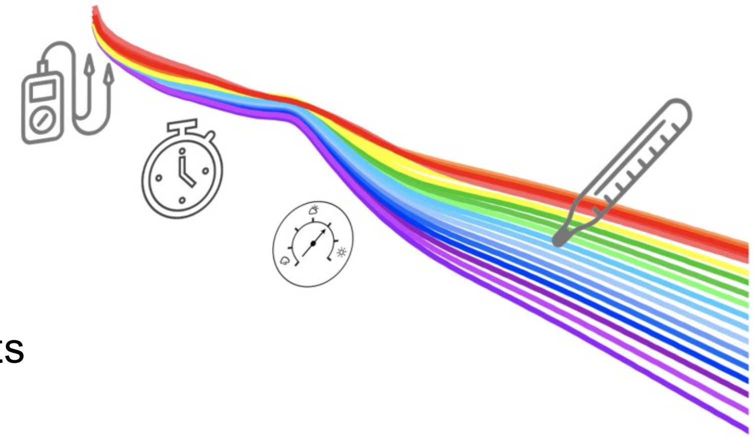


CPOD 2024
May 20-24, Berkeley

THERMAL DILEPTON RADIATION AS MULTIMETER OF THE FIREBALL

- Lifetime via low-mass yield
  → search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)
- Temperature via slope of invariant mass spectrum
  → **flattening** of caloric curve (T vs ε) sign for a **phase transition**
- Pressure anisotropies via dilepton flow
  → **access** to **EoS at high baryon density** via multi-differential measurements
- Spin polarization allows to distinguish different sources of thermal dileptons
  → **access** information on **production mechanism**
- Electric conductivity probed in the limit p_{ee} = 0 MeV/c, $M_{ee} \rightarrow$ 0 MeV/c^2
  → **access** to **transport properties** of QCD matter

Dileptons are rare probes → high-rate, high-efficiency detectors



U. Heinz, K. Lee, Phys. Lett. B 259, 162 (1991)
H. Barz *et al.*, Phys. Lett. B 254, 315 (1991)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)
T. Galatyuk, JPS Conf. Proc. 32 (2020), 010079
F. Seck *et al.*, Phys. Rev. C 106 (2022), 014904
O. Savchuk *et al.*, J. Phys G 104537 R2 (2023)

R. Chatterjee *et al.*, Phys. Rev. C 75 (2007), 054909
T. Reichert *et al.*, Phys. Lett. B 841 (2023) 137947

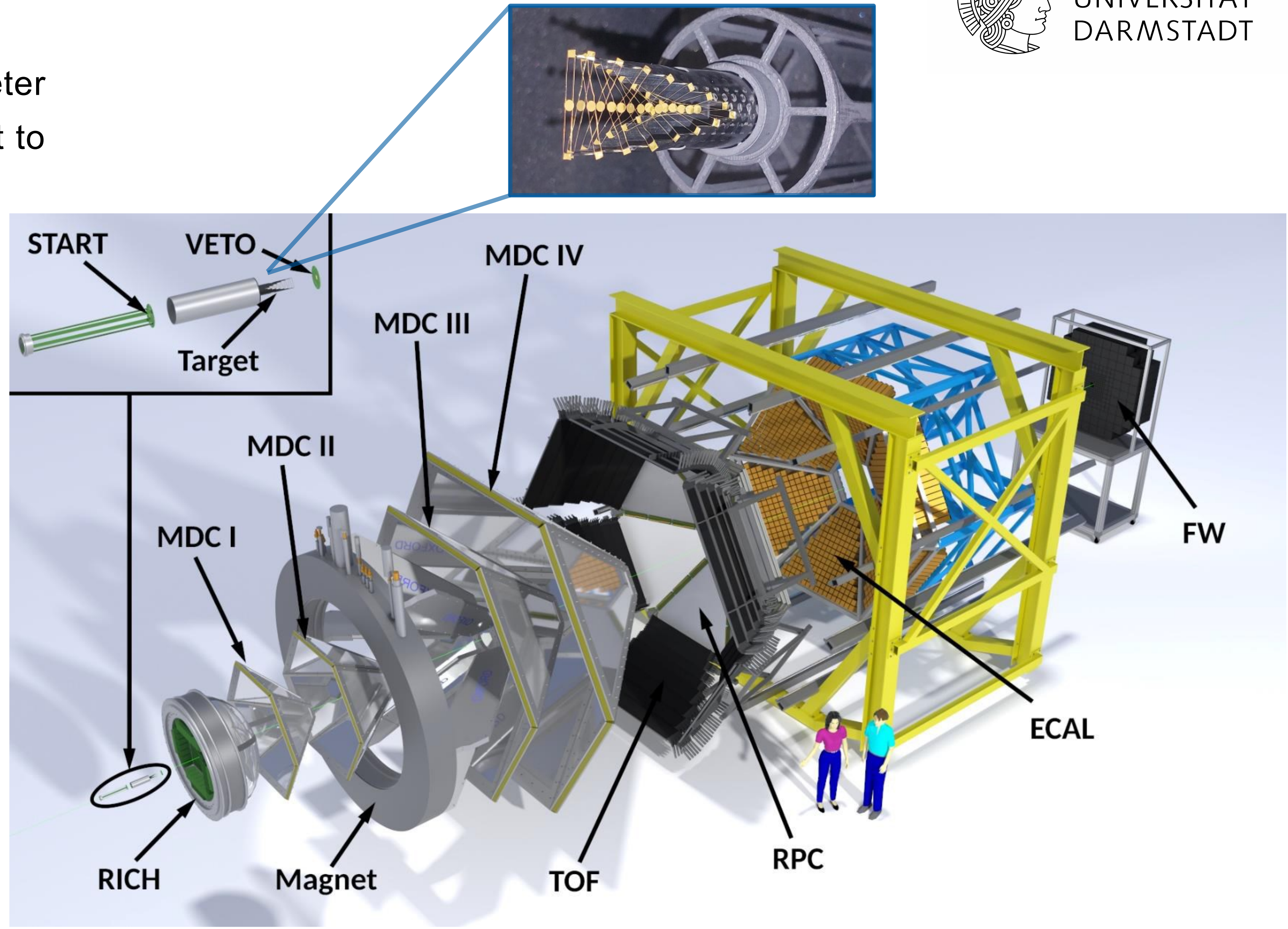
G. Moore, J. Robert, arXiv:hep-ph/0607172 (2006)
J. Atchison, R. Rapp, Nucl. Phys. A 1037 (2023) 122704
S. Flörchinger *et al.*, Phys. Lett. B 837 (2023) 137647

E. Bratkovskaya *et al.*, Phys. Lett. B 376, 12 (1996)
E. Speranza *et al.*, Phys. Lett. B 782, 395 (2018)
G. Baym *et al.*, Phys. Rev. C 95, 044907 (2017)
S. Hauksson, C. Gale, arXiv:2306.10307 [nucl-th] (2023)

TECHNISCHE UNIVERSITÄT DARMSTADT

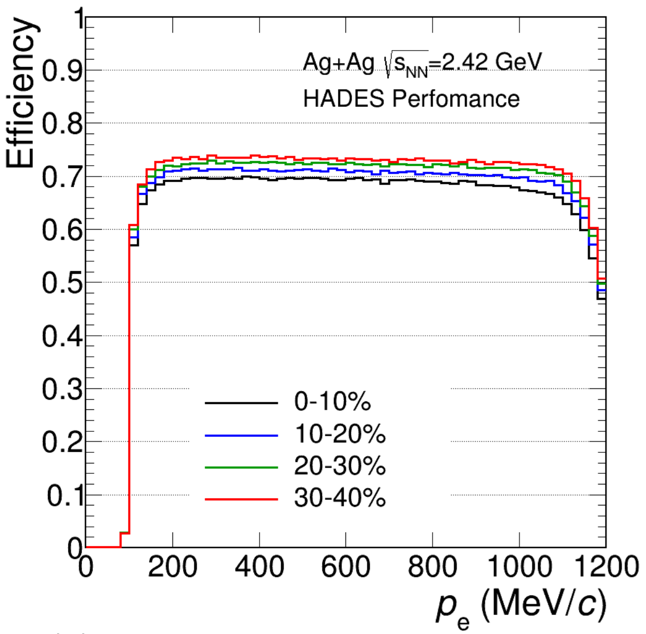
- **H**igh-**A**cceptance **D**i-**E**lectron **S**pectrometer
- Designed with a minimal material budget to reduce conversion
- Large angular coverage:
  - $15^\circ < \theta < 85^\circ$
  - $0^\circ < \phi < 360^\circ$
- Accepted trigger rate up to
  - 16 kHz for heavy-ion collisions
  - 50 kHz with proton/pion beam
- Dedicated components for e^+/e^-:
  - Time-of-Flight measurements
  - Ring-Imaging Cherenkov Detector
  - Electromagnetic Calorimeter

HADES allows for high efficiency and high purity electron sample

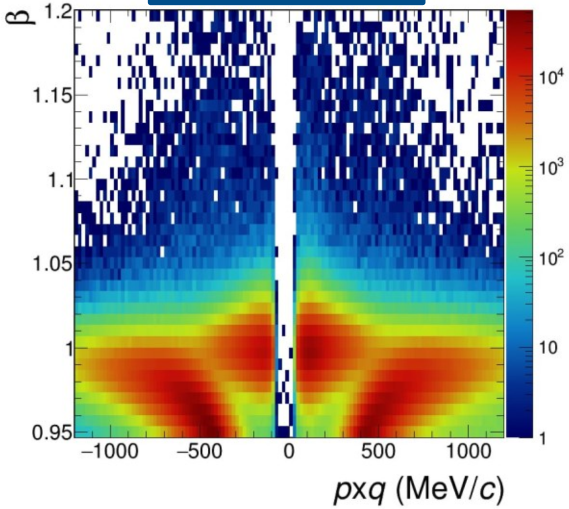


HADES LEPTON IDENTIFICATION PERFORMANCE

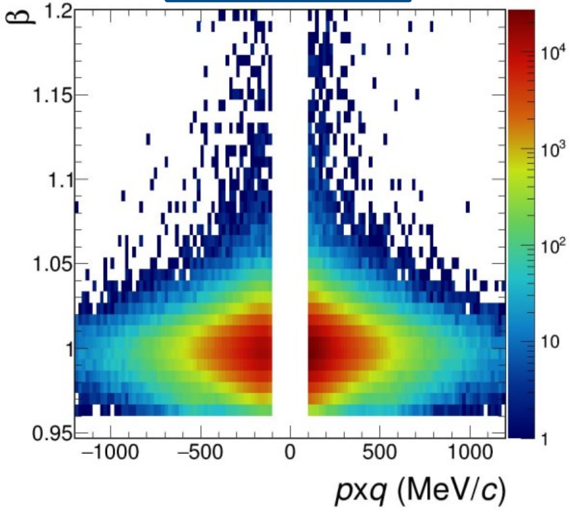
- Reconstruction efficiency ~ 70%
- Purity above 90%
- Hadron suppression of ~ 10^{-5}
- Ag+Ag run in 2019
  - $N_{y*}^{rec} \approx 1.5 \cdot \mathbf{10^6}$ for $\sqrt{s_{NN}} = 2.55$ GeV (28 days)
  - $N_{y*}^{rec} \approx 1.5 \cdot \mathbf{10^5}$ for $\sqrt{s_{NN}} = 2.42$ GeV (3 days)

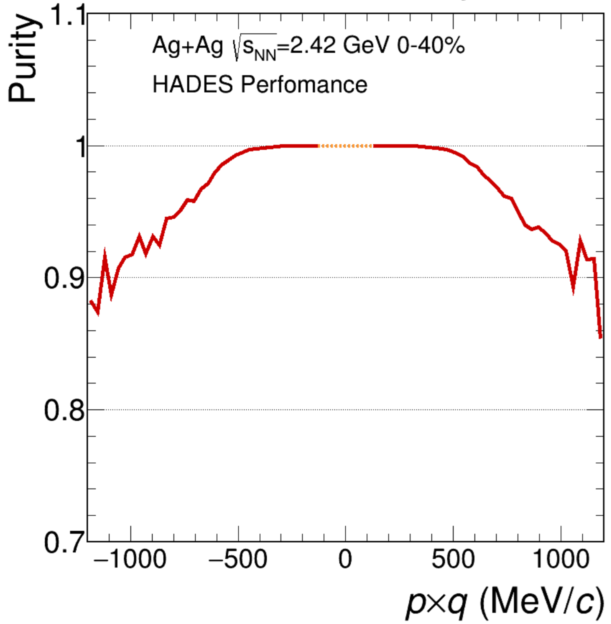


before cuts

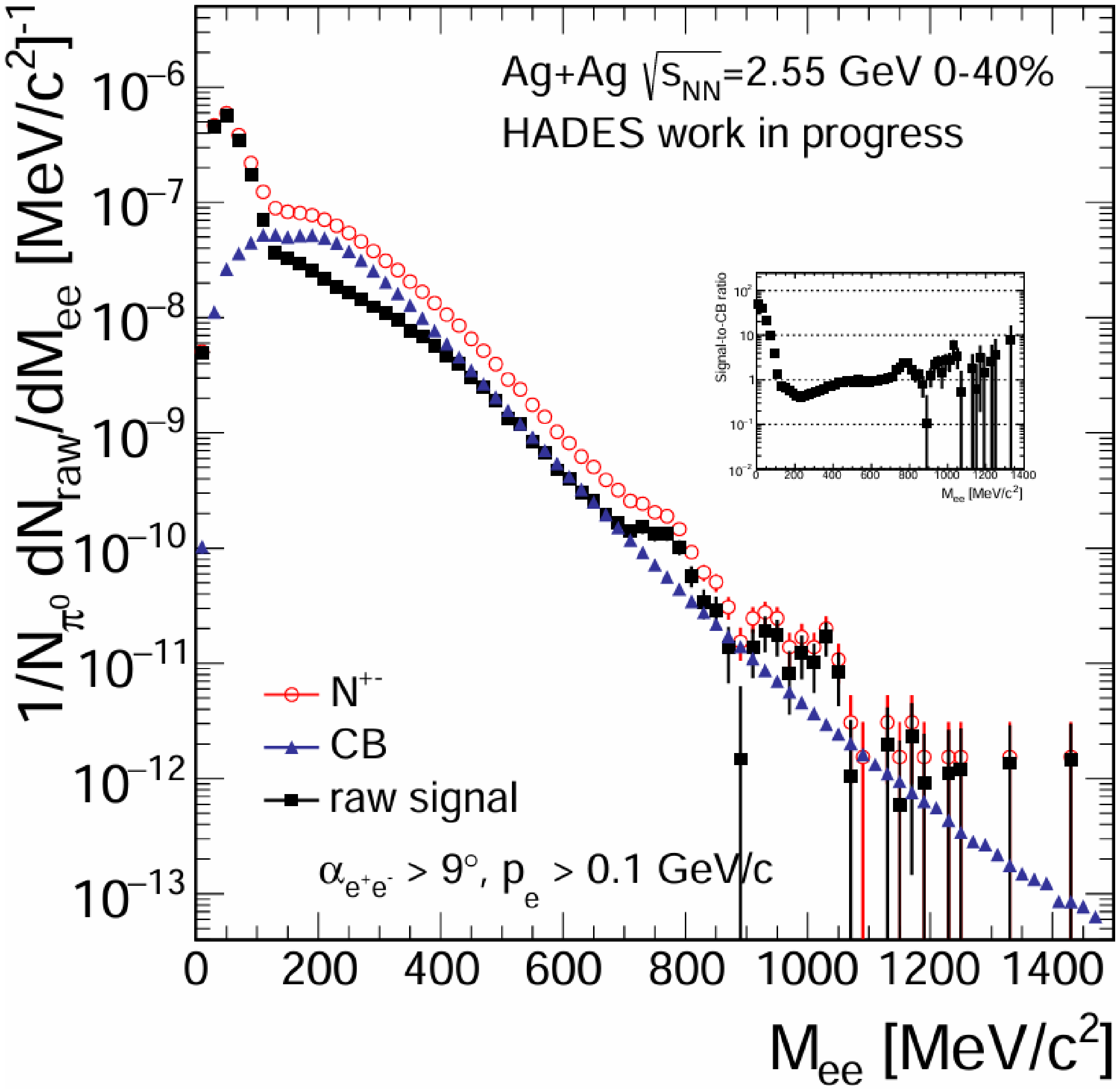


after cuts

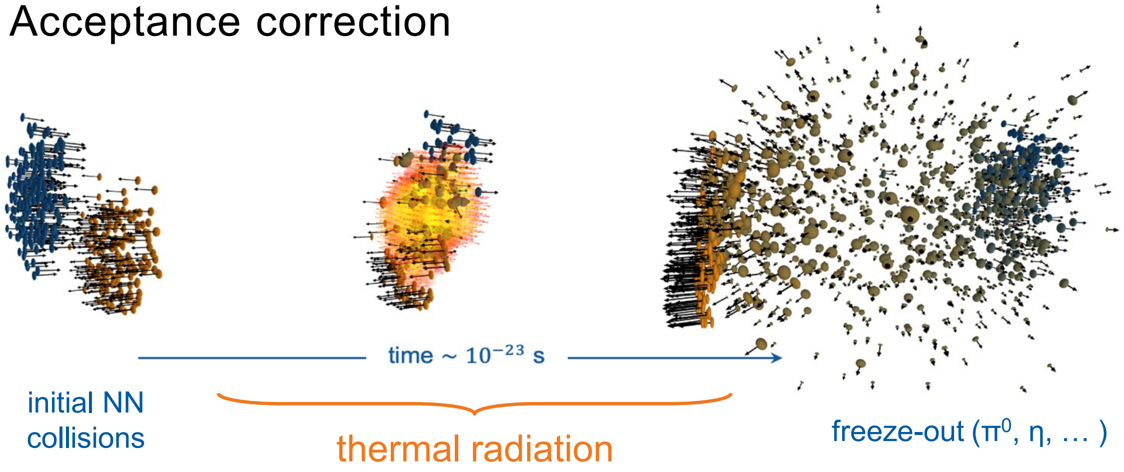




STEPS TO ISOLATE THERMAL RADIATION



- RICH photodetector upgrade
    - Employing CBM at FAIR technology (CBM FAIR phase-0)
- Efficiency correction
- NN reference subtraction
- Freeze-out cocktail subtraction
    - Simulated using Pluto event generator with measured/estimated multiplicities
- Acceptance correction

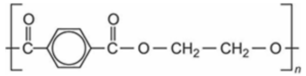


MEASUREMENT OF NN REFERENCE IN HADES

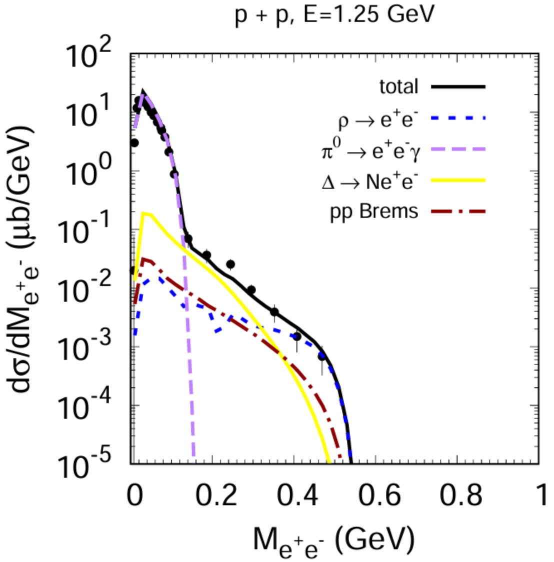
- p+p and d+p collisions at E_{kin} = 1.25 GeV
  - n+p reaction tagged by triggering on proton spectator

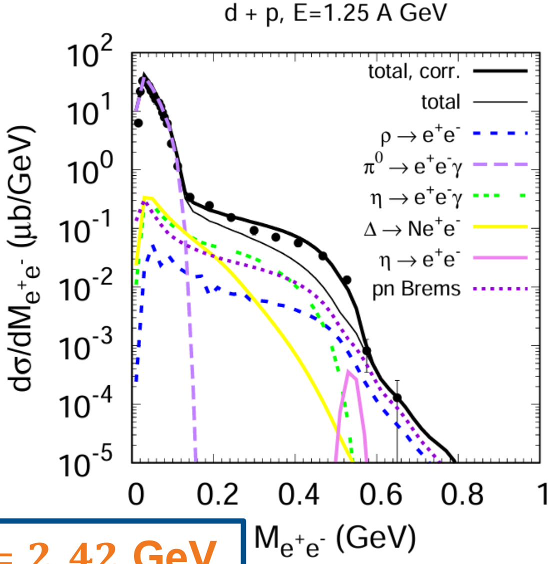
HADES, Phys. Lett. B 690 (2010) 118
A. Larionov *et al.*, Phys. Rev. C 102 (2021), 064913

- Ongoing analysis of p+p at E_{kin} = 1.58 GeV and 4.5 GeV
  - Empty target run p+C/p/O as proxy for p+p/p+n

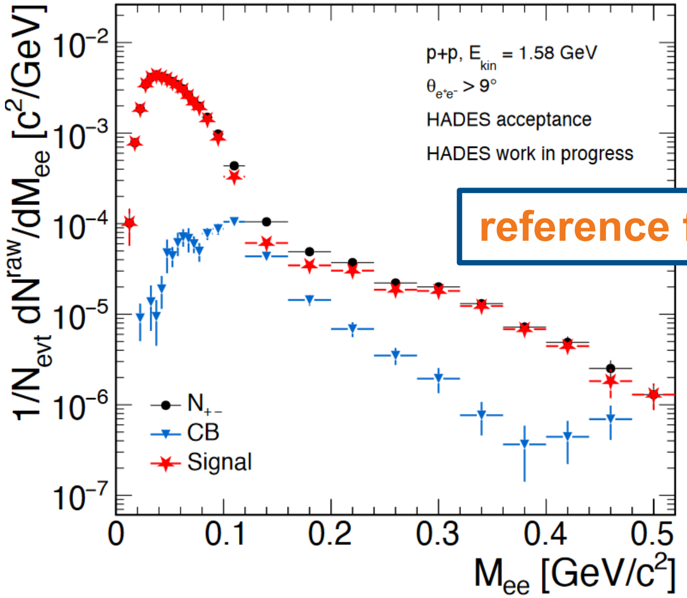


Mylar

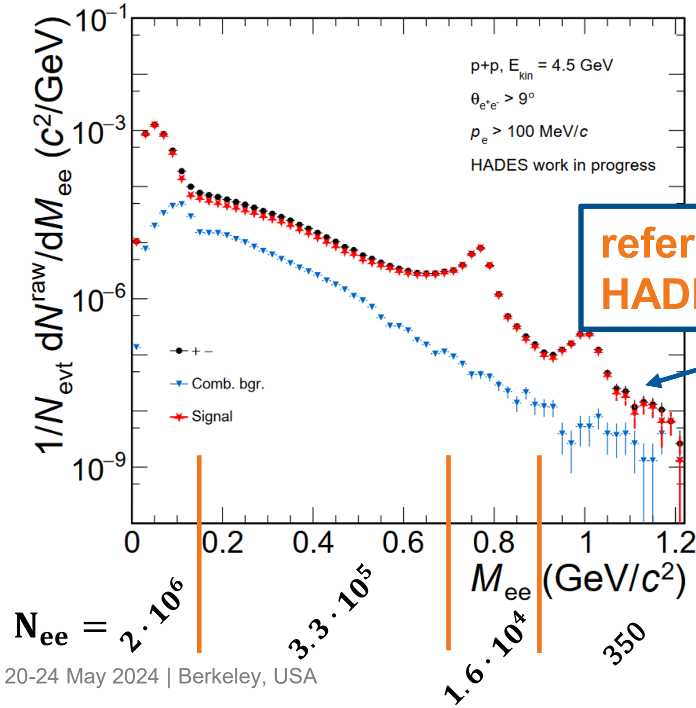




reference for $\sqrt{s_{NN}} = 2.42$ GeV



reference for $\sqrt{s_{NN}} = 2.55$ GeV

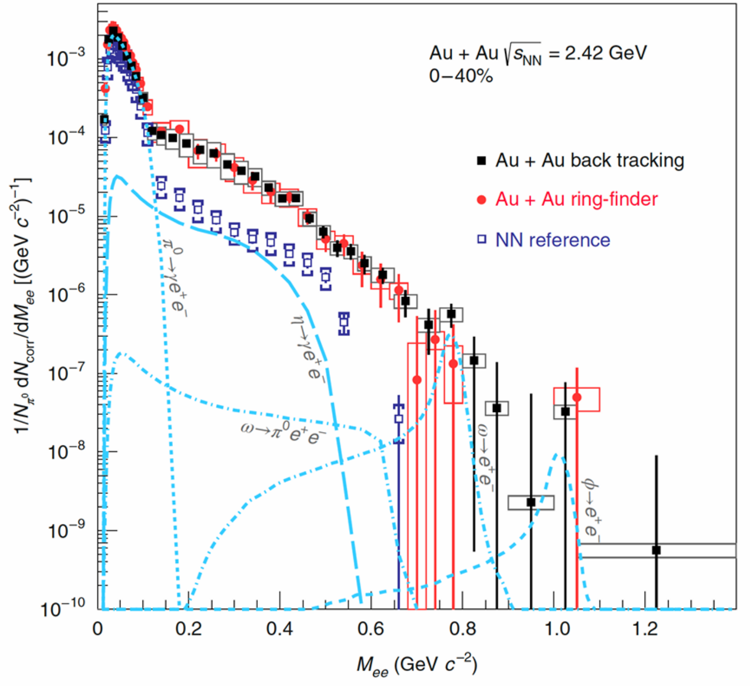


reference for future HADES/CBM runs at FAIR

DILEPTON INVARIANT MASS SPECTRA FROM HADES

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

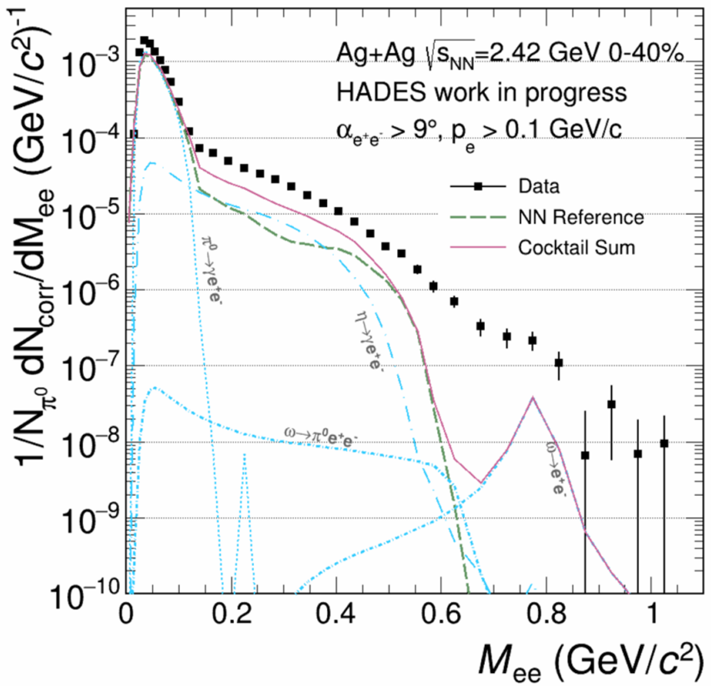
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



HADES, Nature Phys. 15(2019) 1040

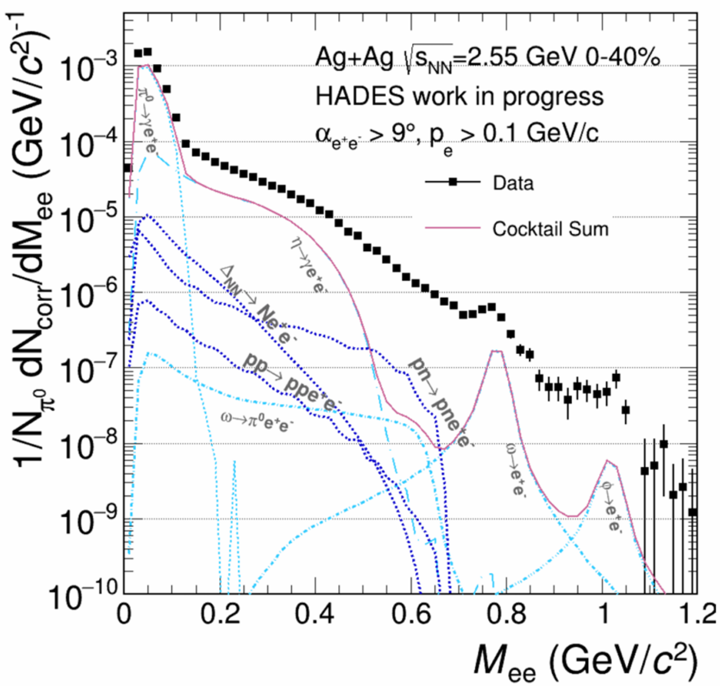
measured NN reference

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



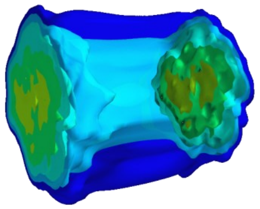
measured NN reference

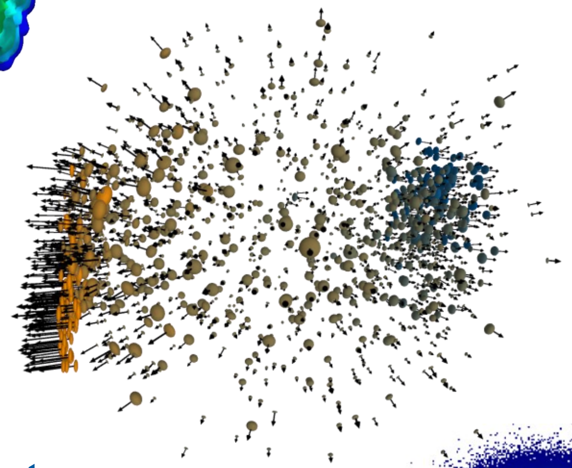
Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



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

DESCRIPTION OF THE SPACE-TIME EVOLUTION

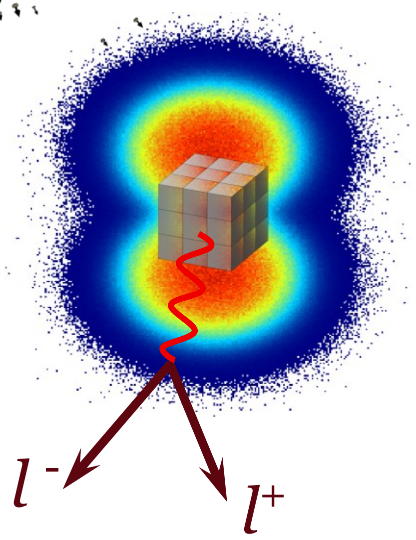




- Bulk observables are reasonably well described by simulations
  - Hydrodynamics at high collision energies
  - Microscopic transport model at low collision energies

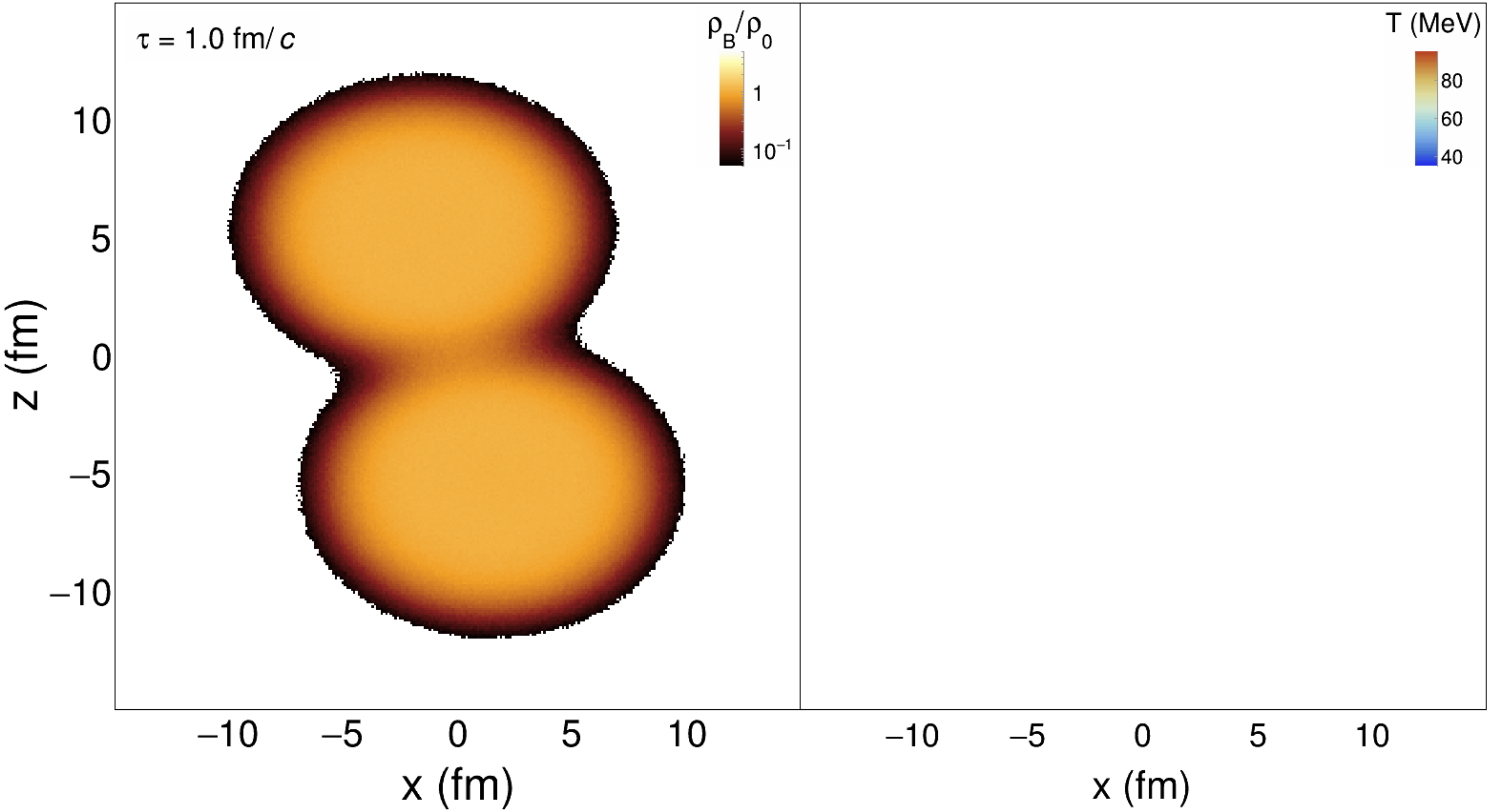
- Pure transport simulations struggle to describe dilepton data
  - “shining” or time-integration method

- “Combination” of hydrodynamics and transport model: **coarse-grained transport**

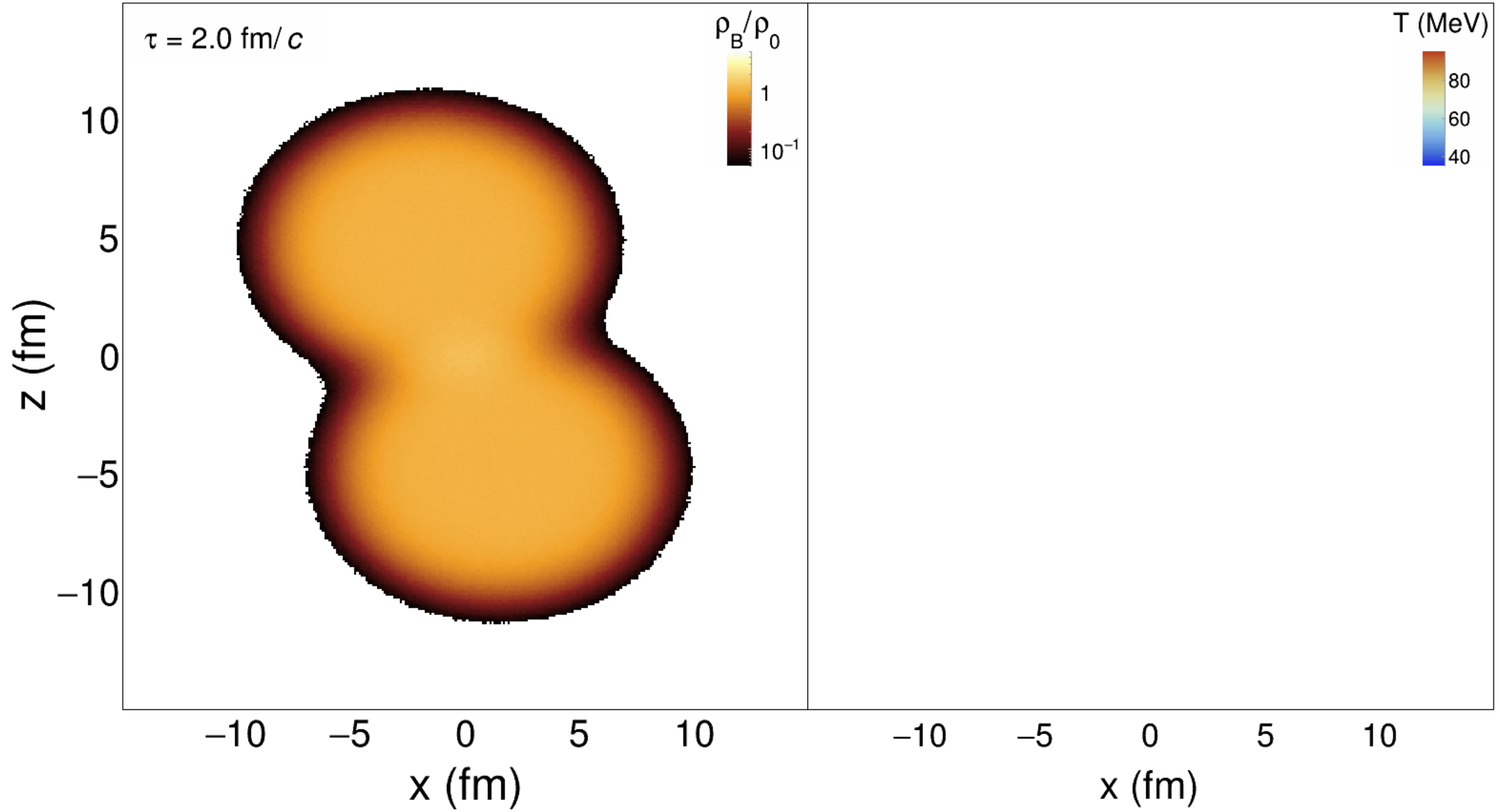


- Simulate events with a transport model & take ensemble average to obtain smooth space-time distributions
- Divide space-time into 4-dim. cells
- Check if cell is thermalized (→ enough interactions)
- Extract baryon density ρ_B, medium velocity $\vec{u}$, and temperature T (→ m_T spectra of pions)
- Calculate dilepton rates based on these inputs per cell
- Space-time integration via summation of the contributions from all cells

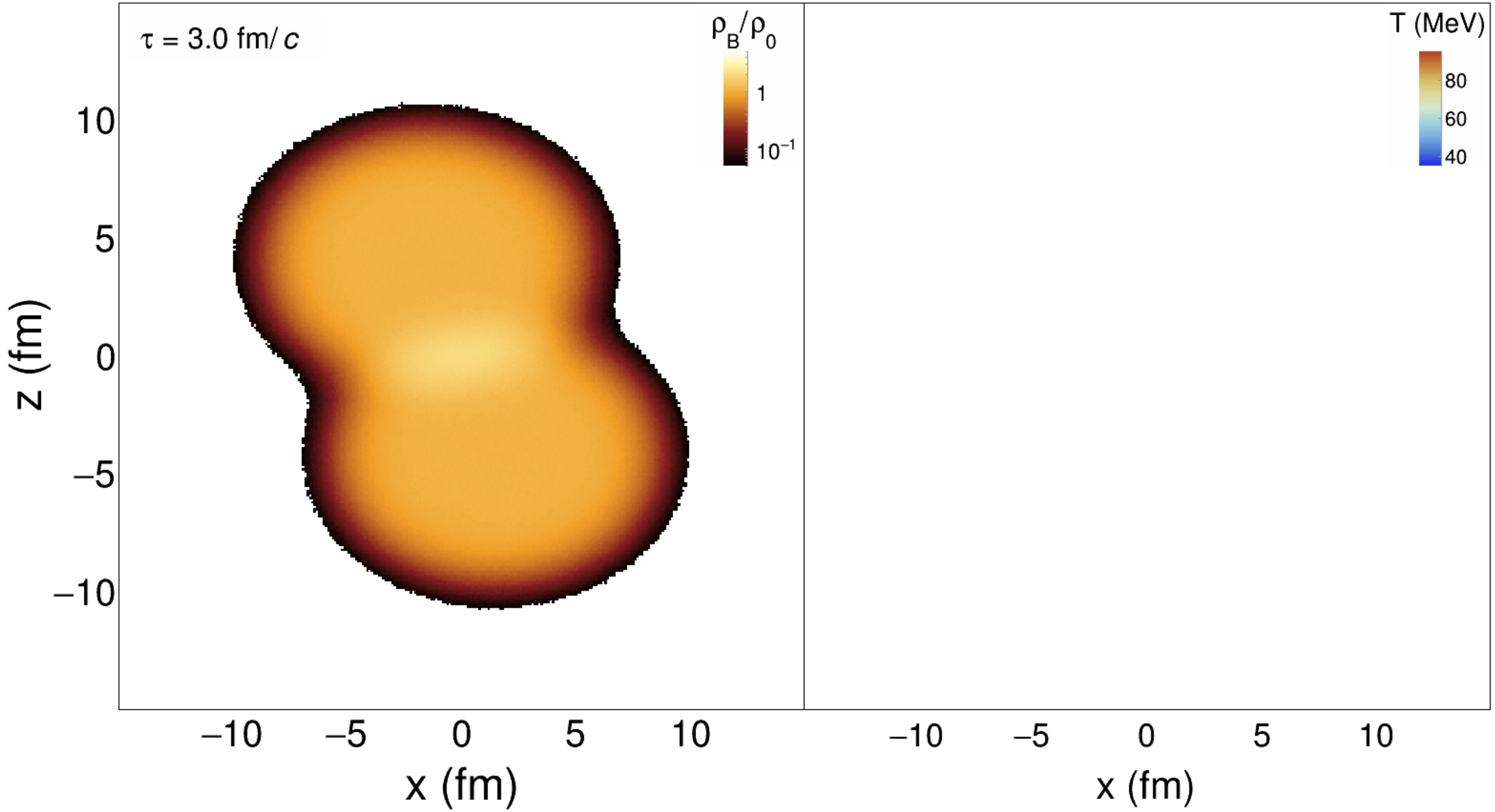
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



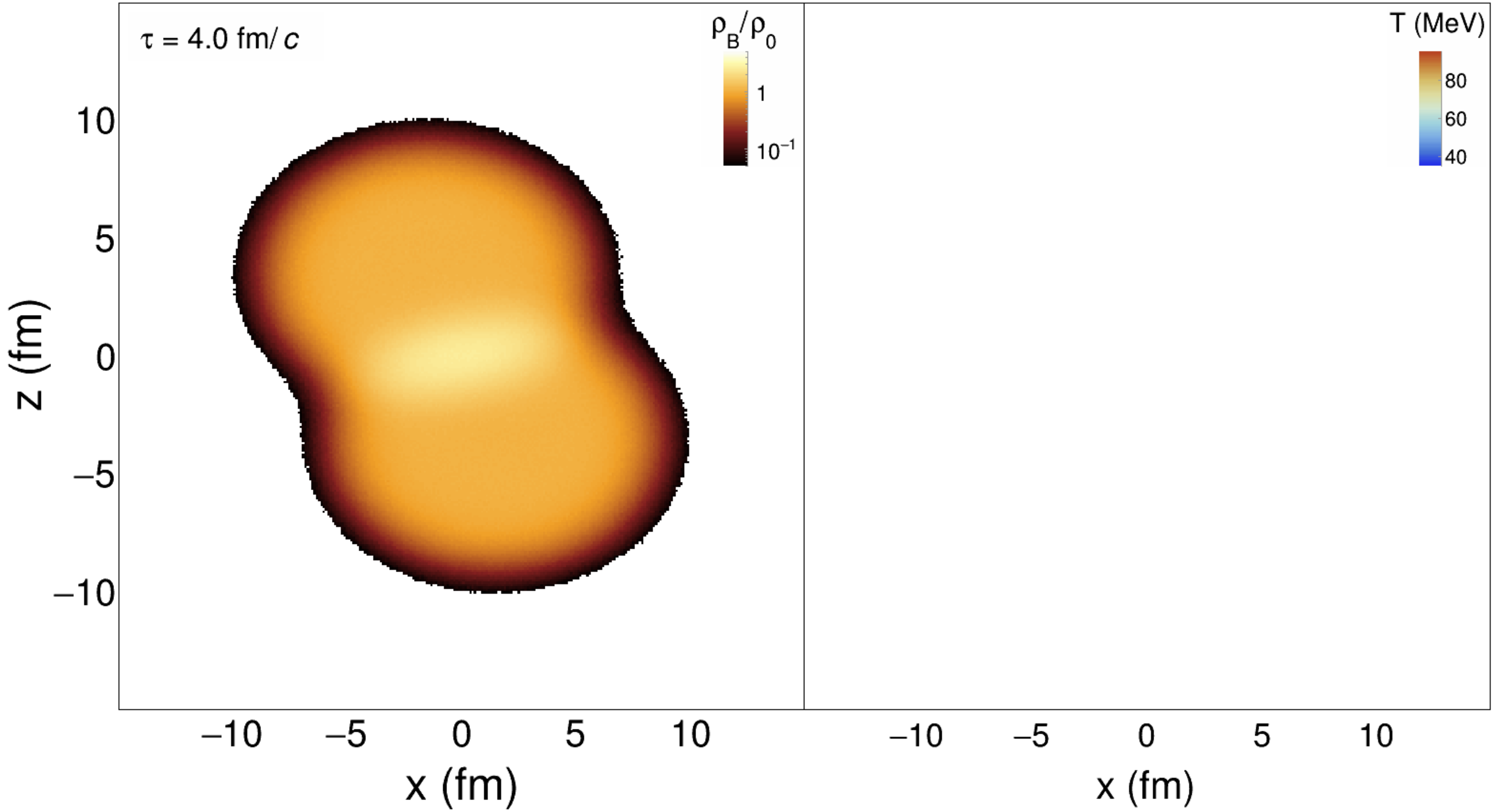
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



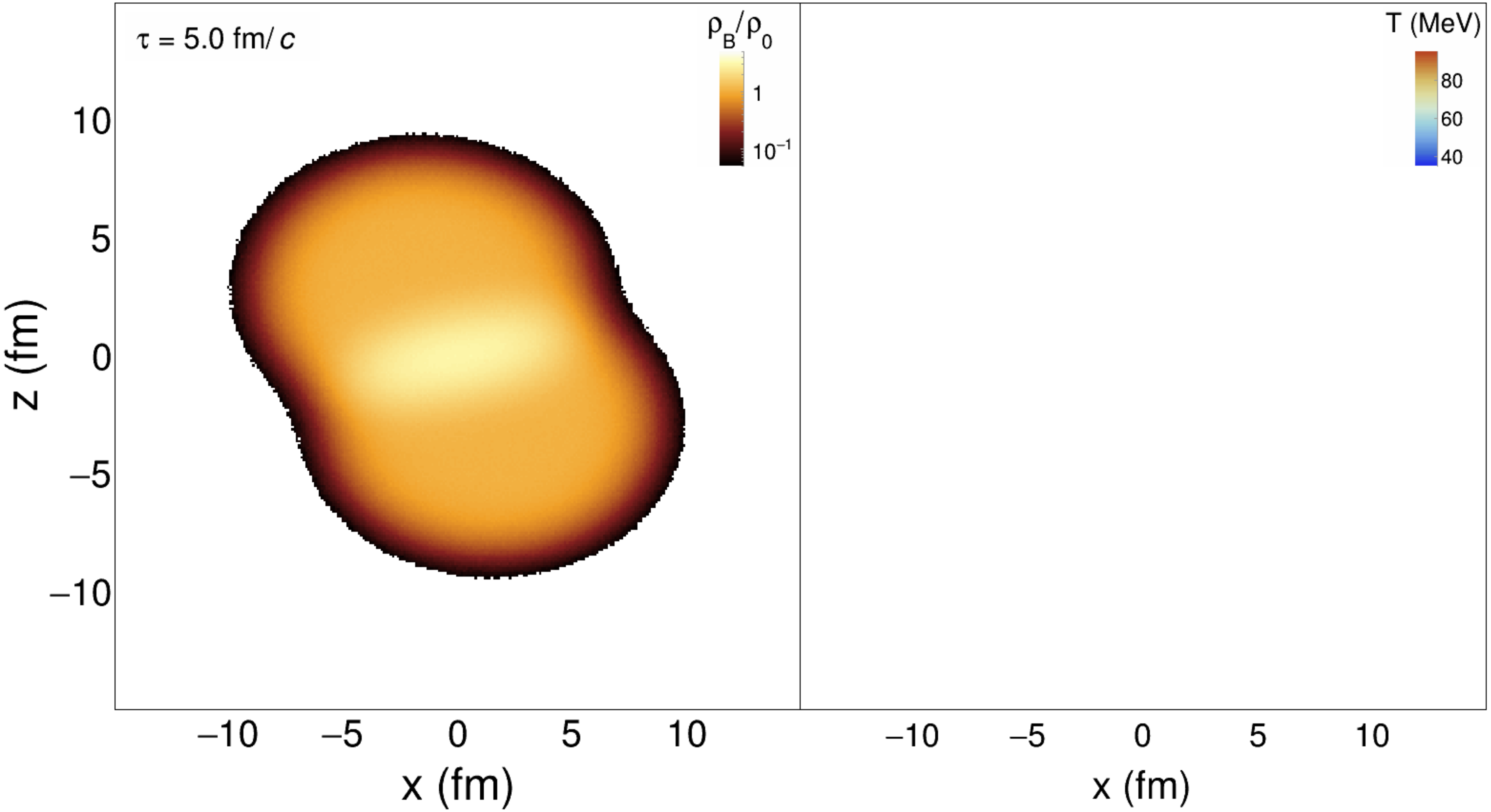
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

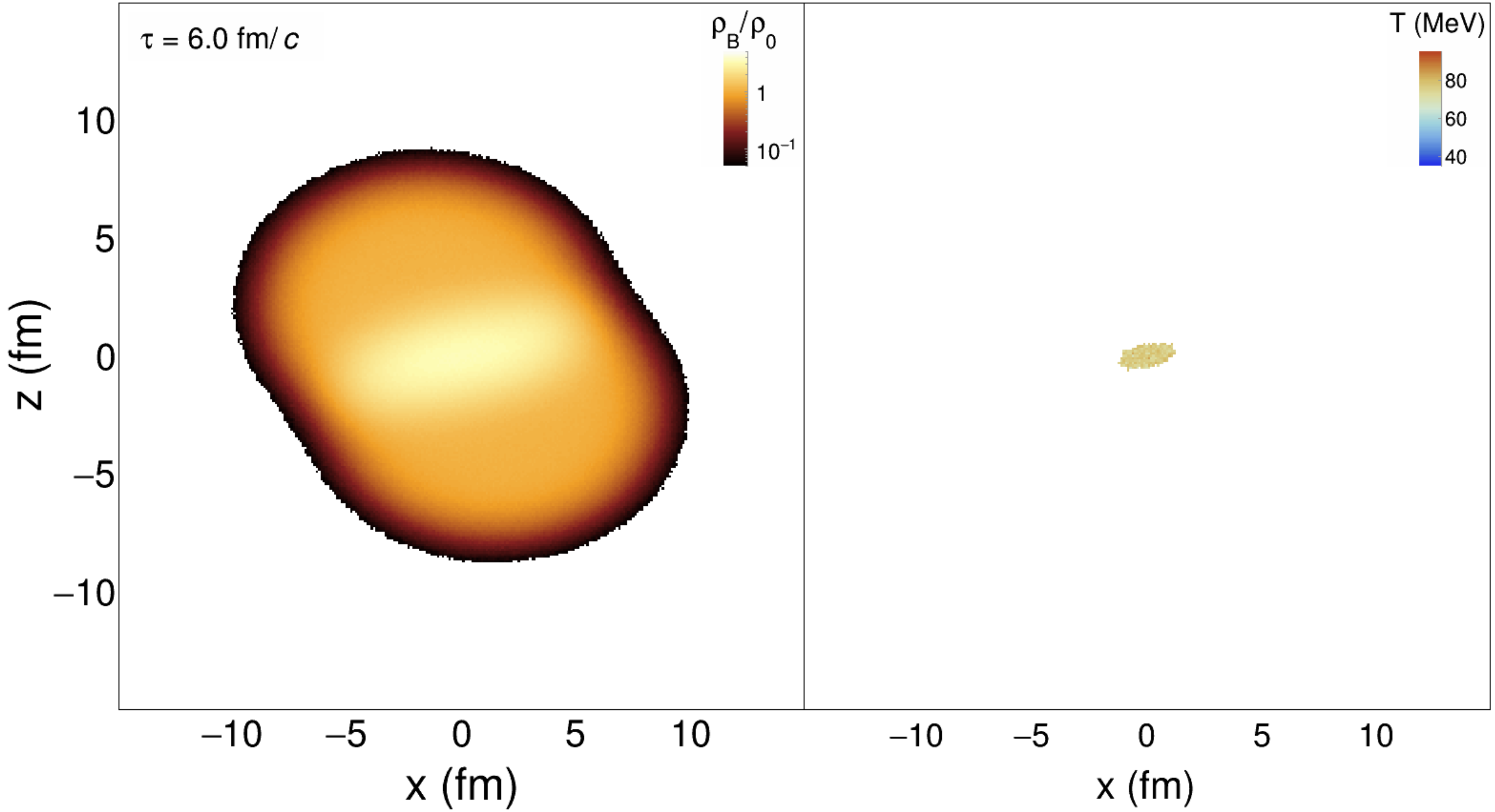


BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



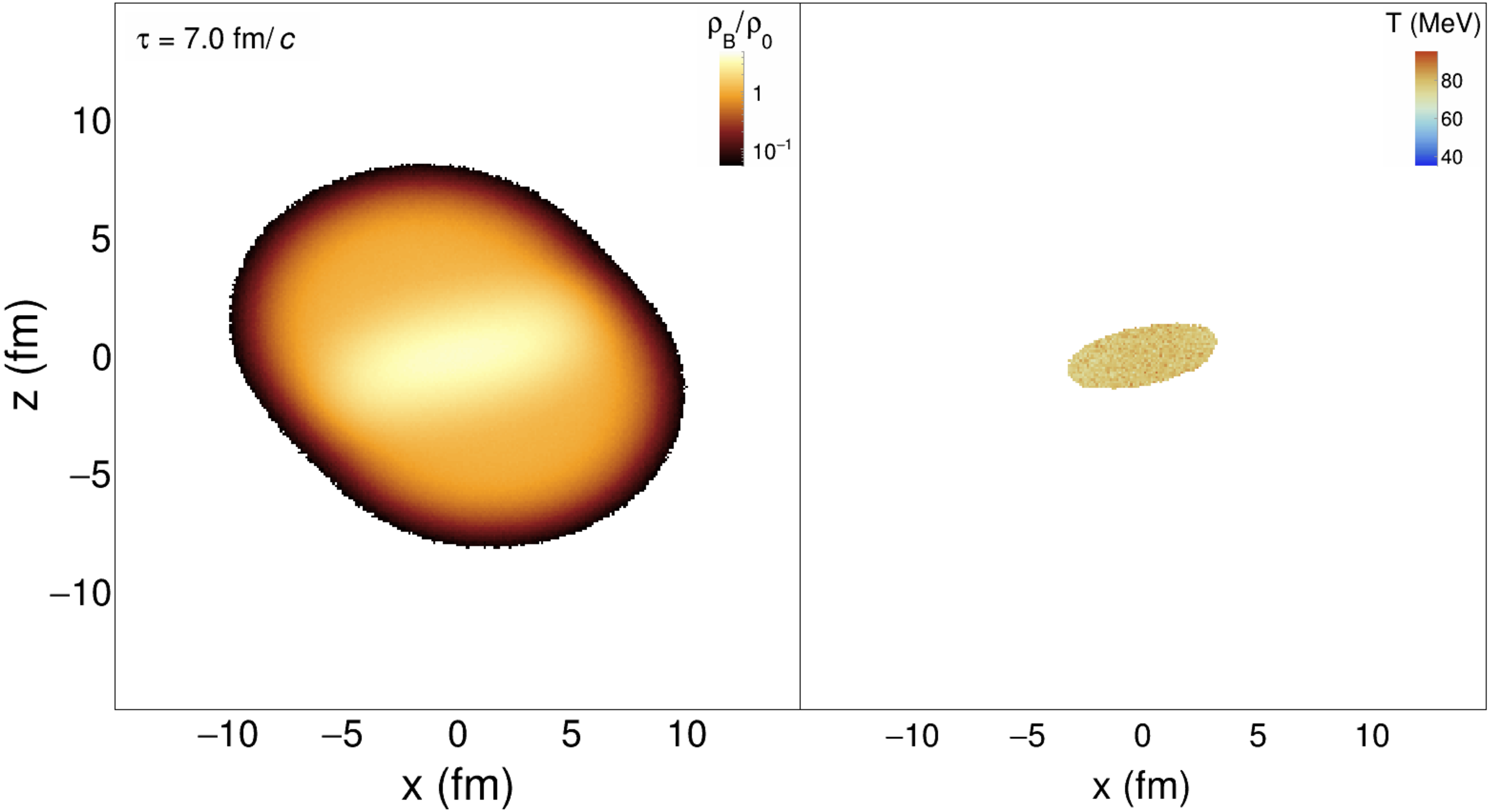
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

TECHNISCHE UNIVERSITÄT DARMSTADT

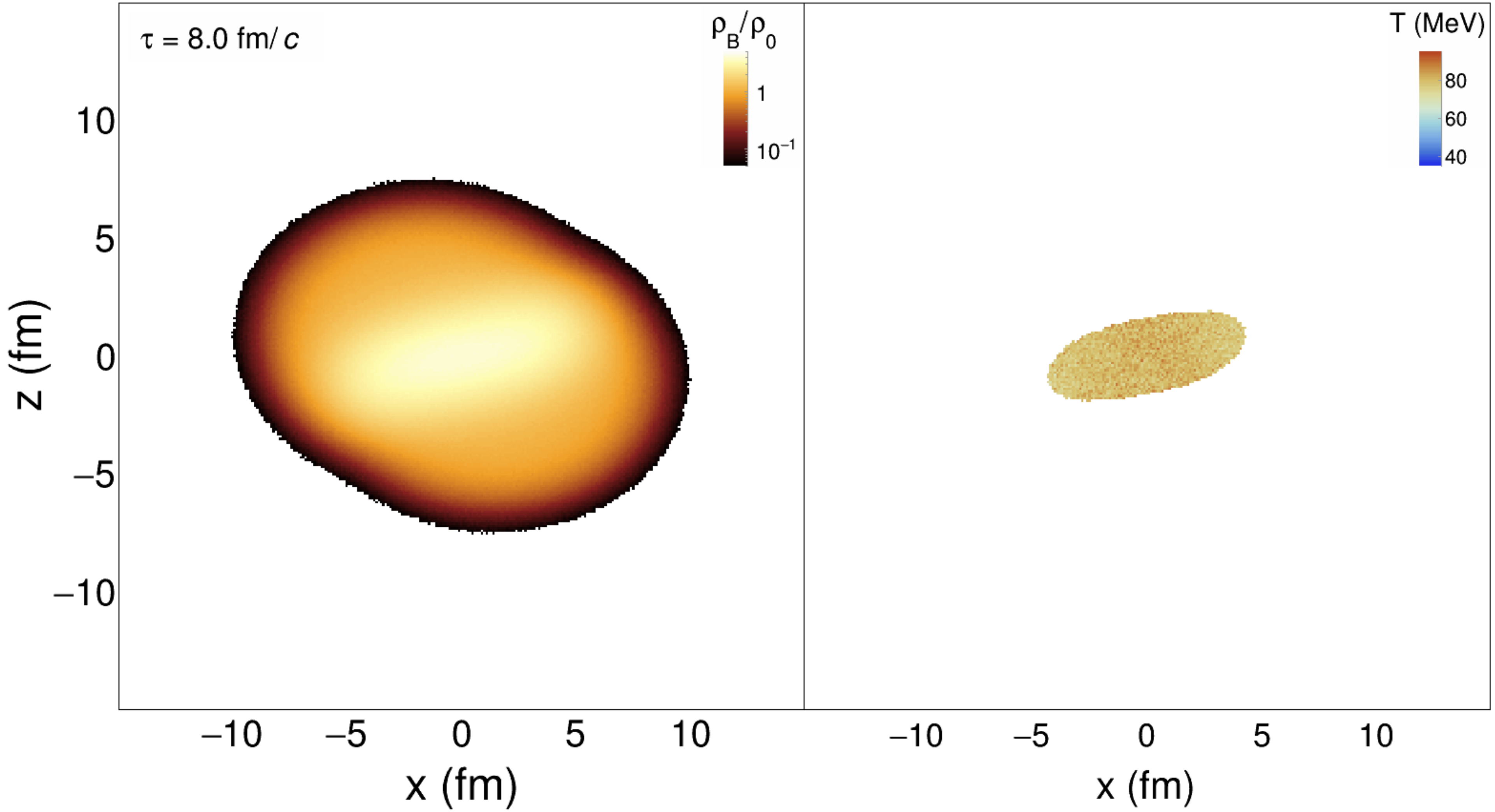


BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

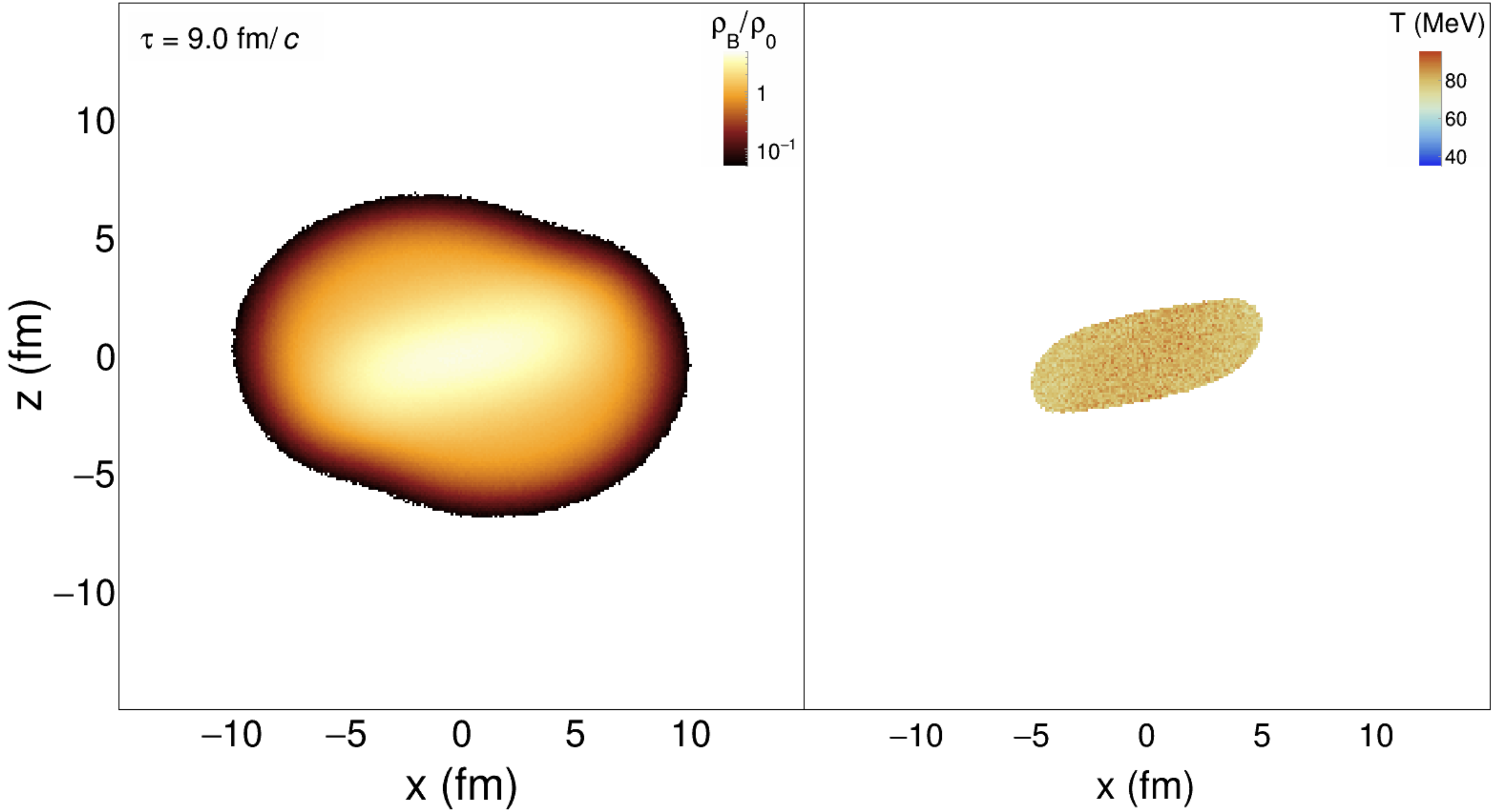
TECHNISCHE UNIVERSITÄT DARMSTADT



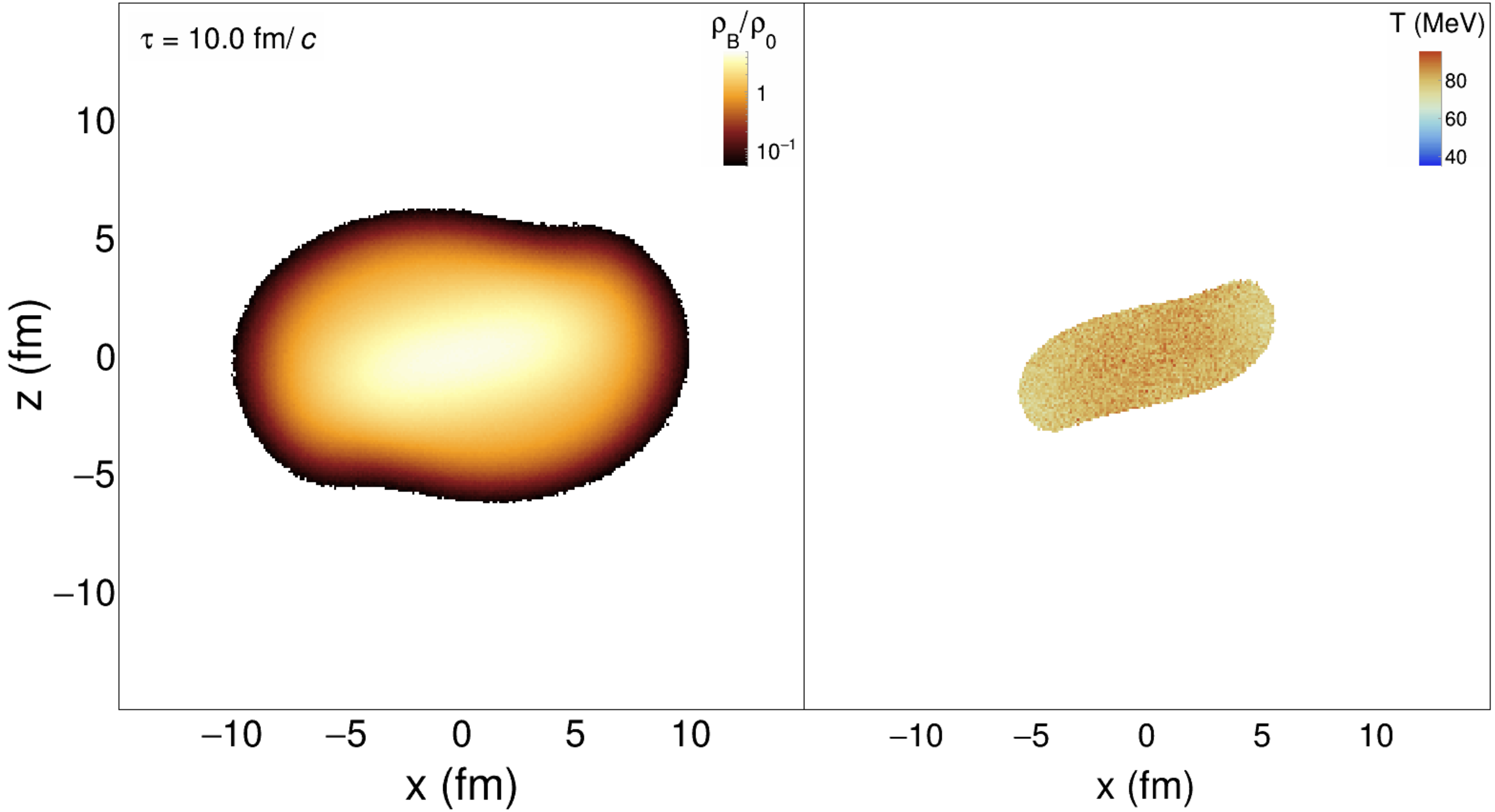
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



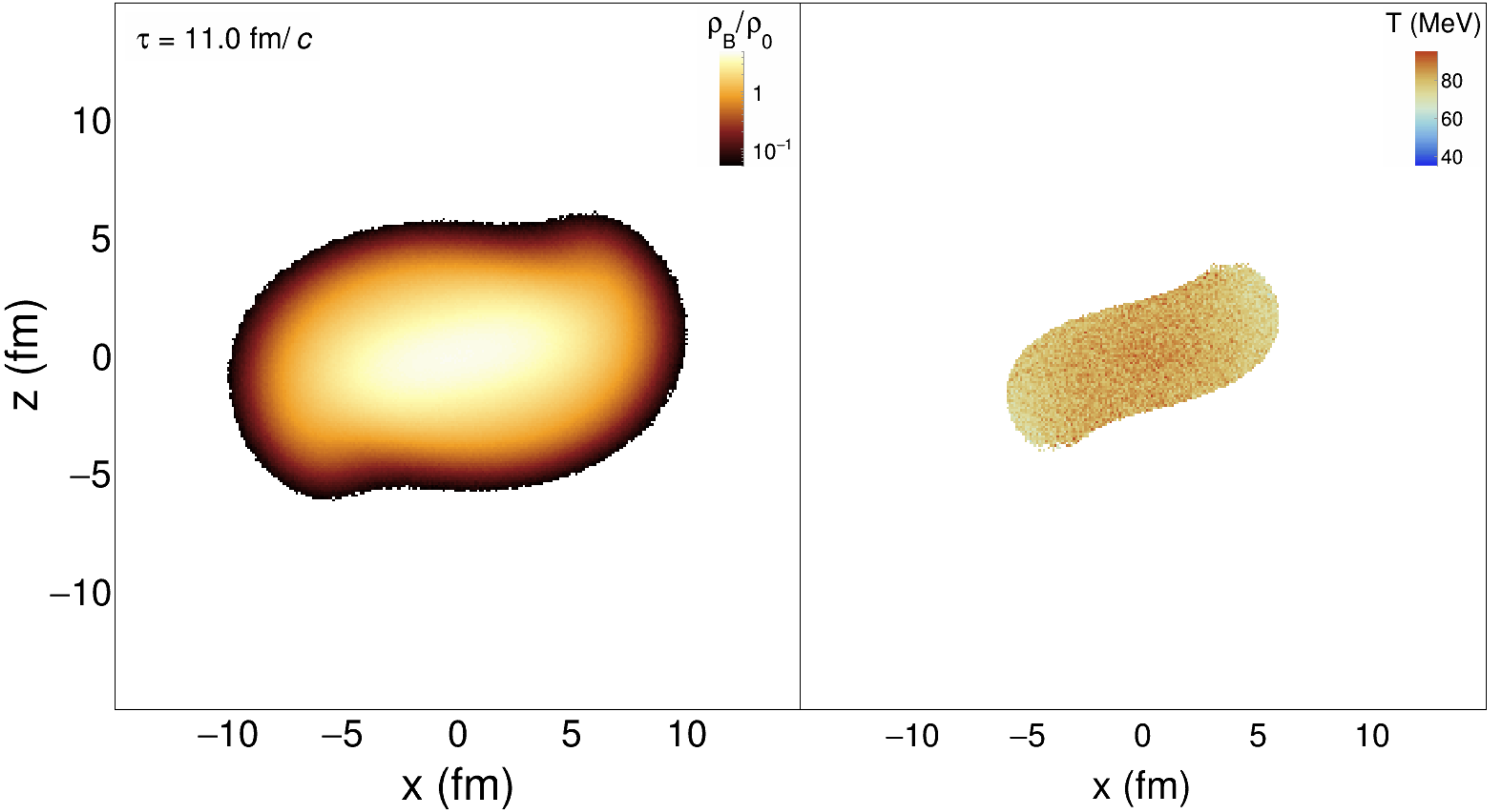
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



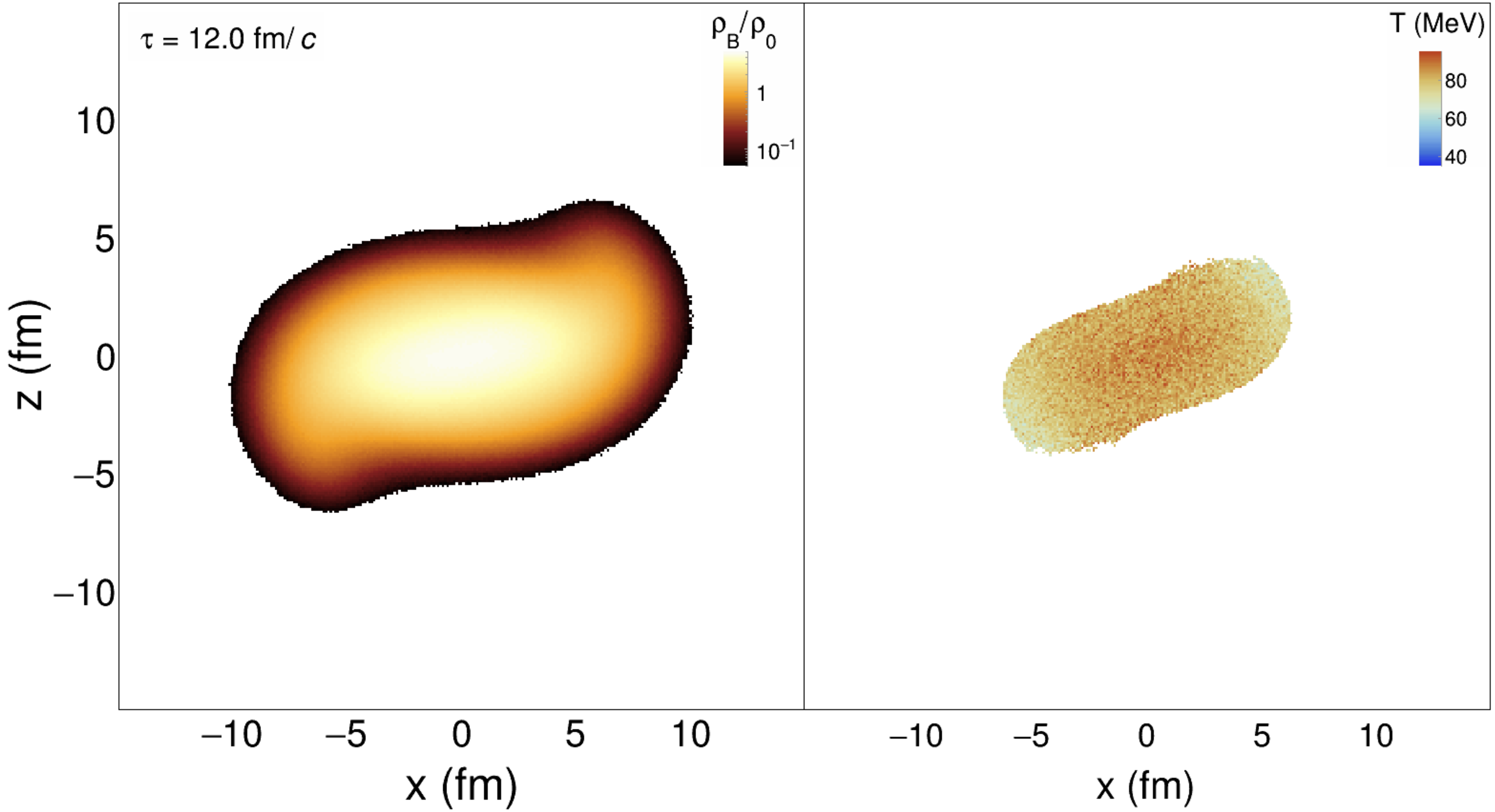
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



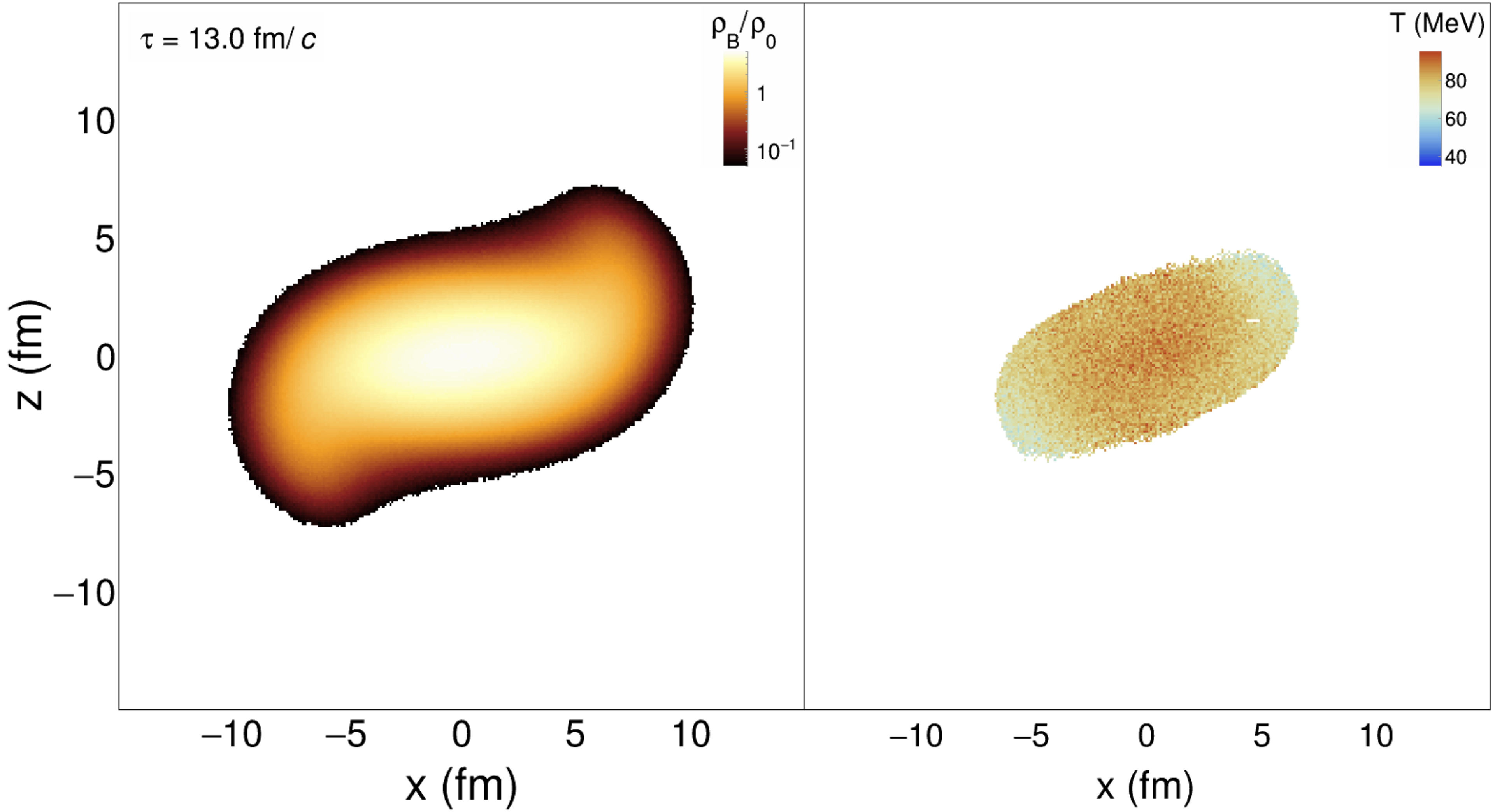
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



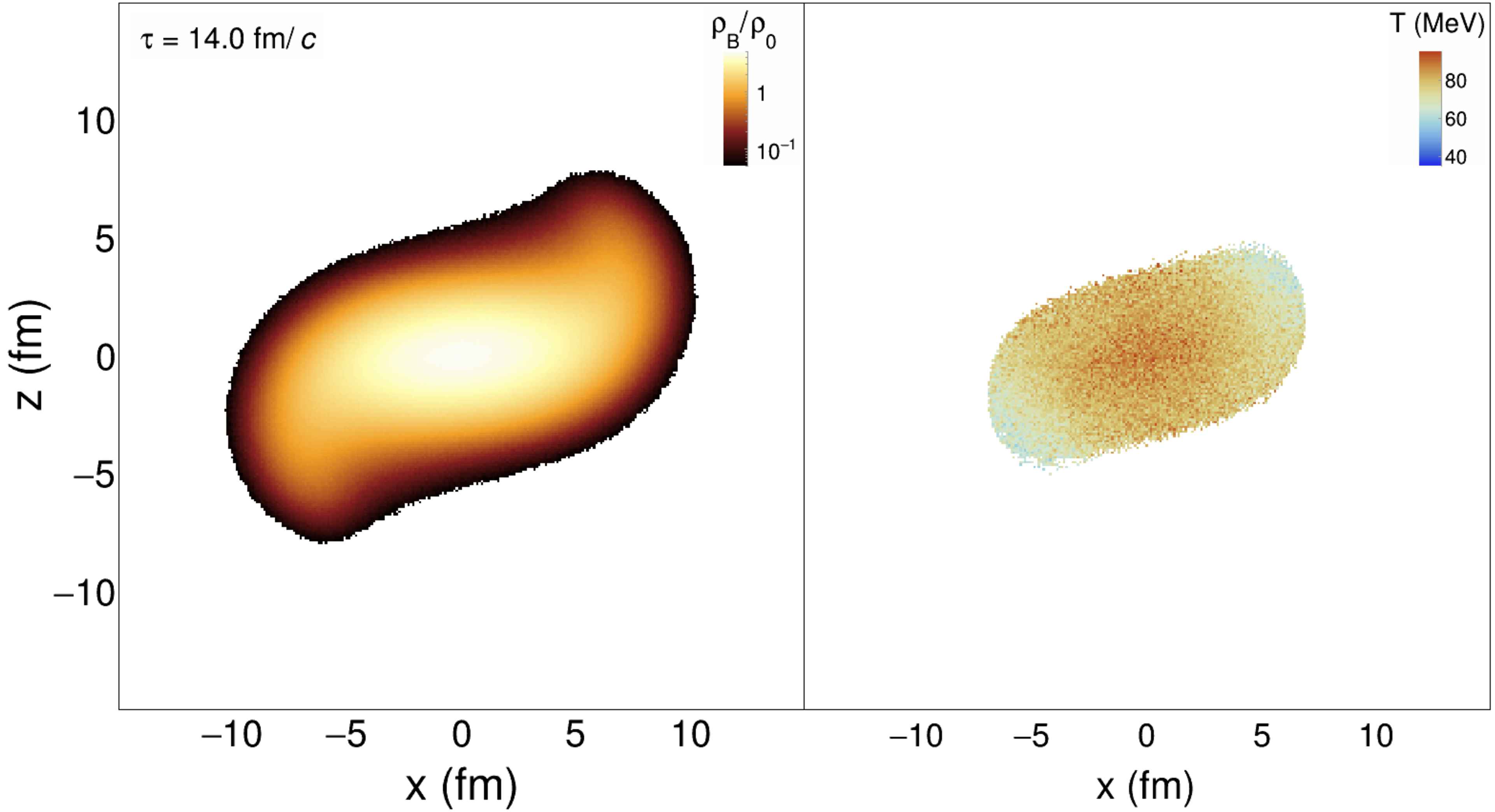
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



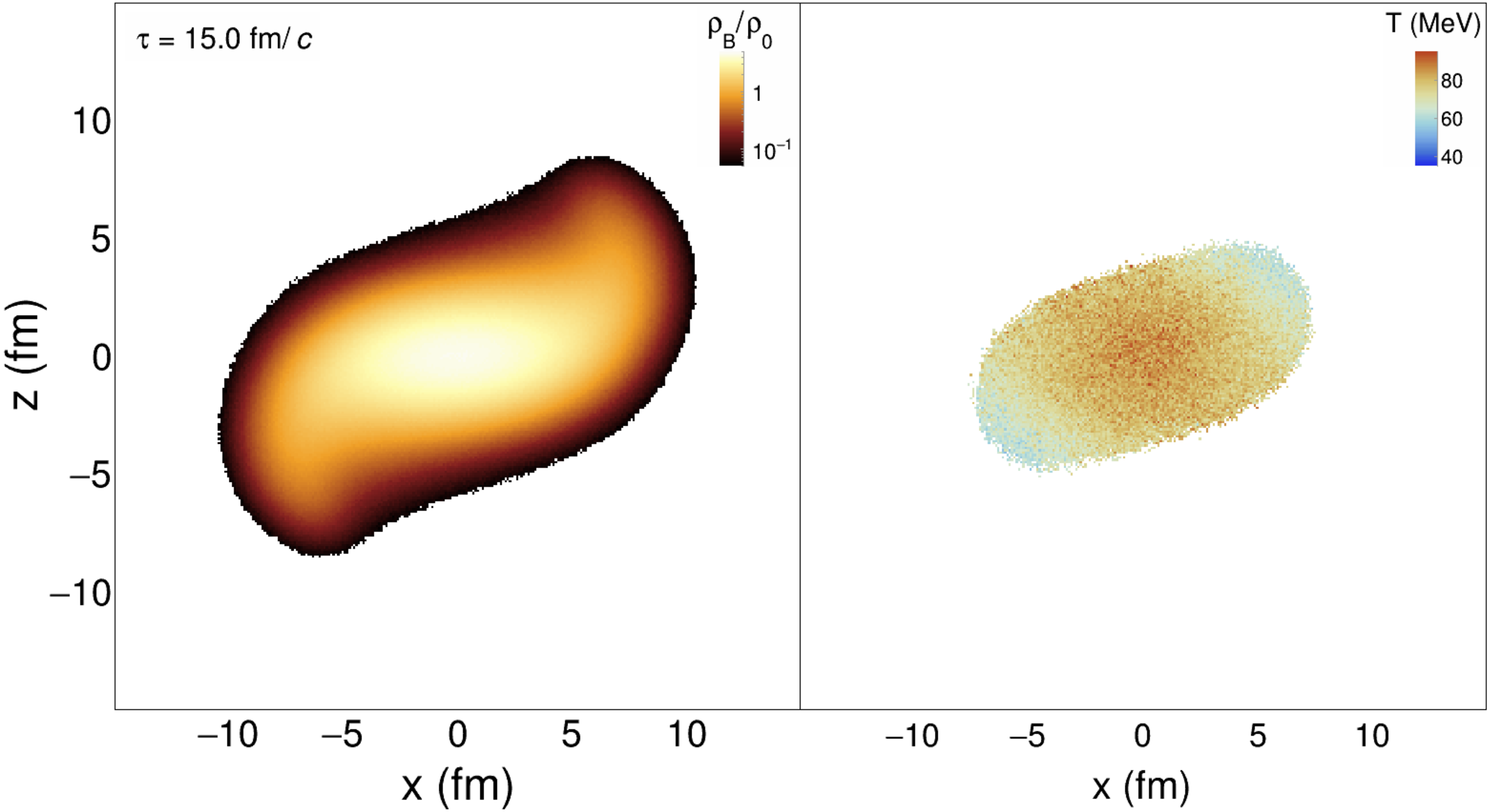
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



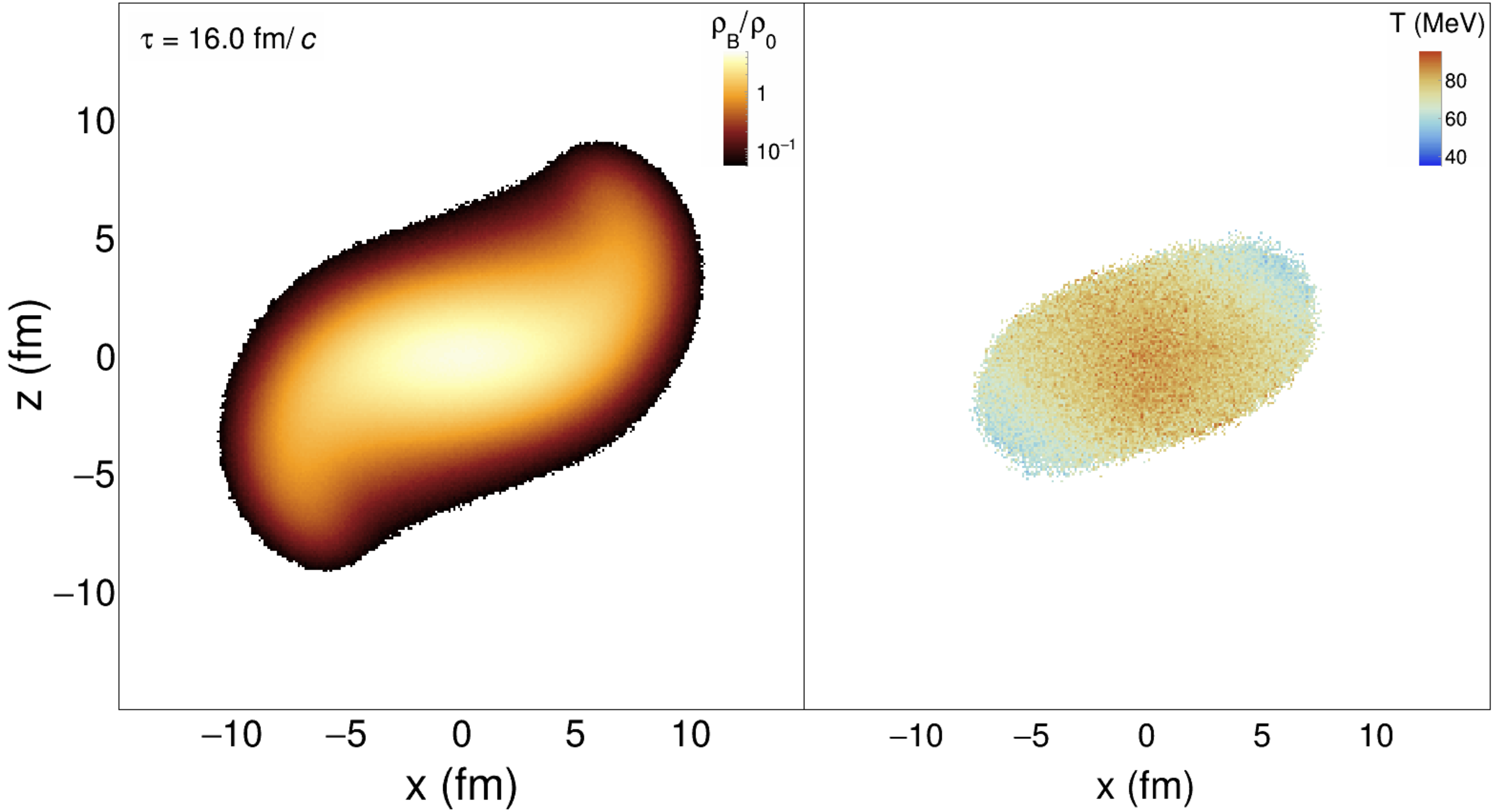
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



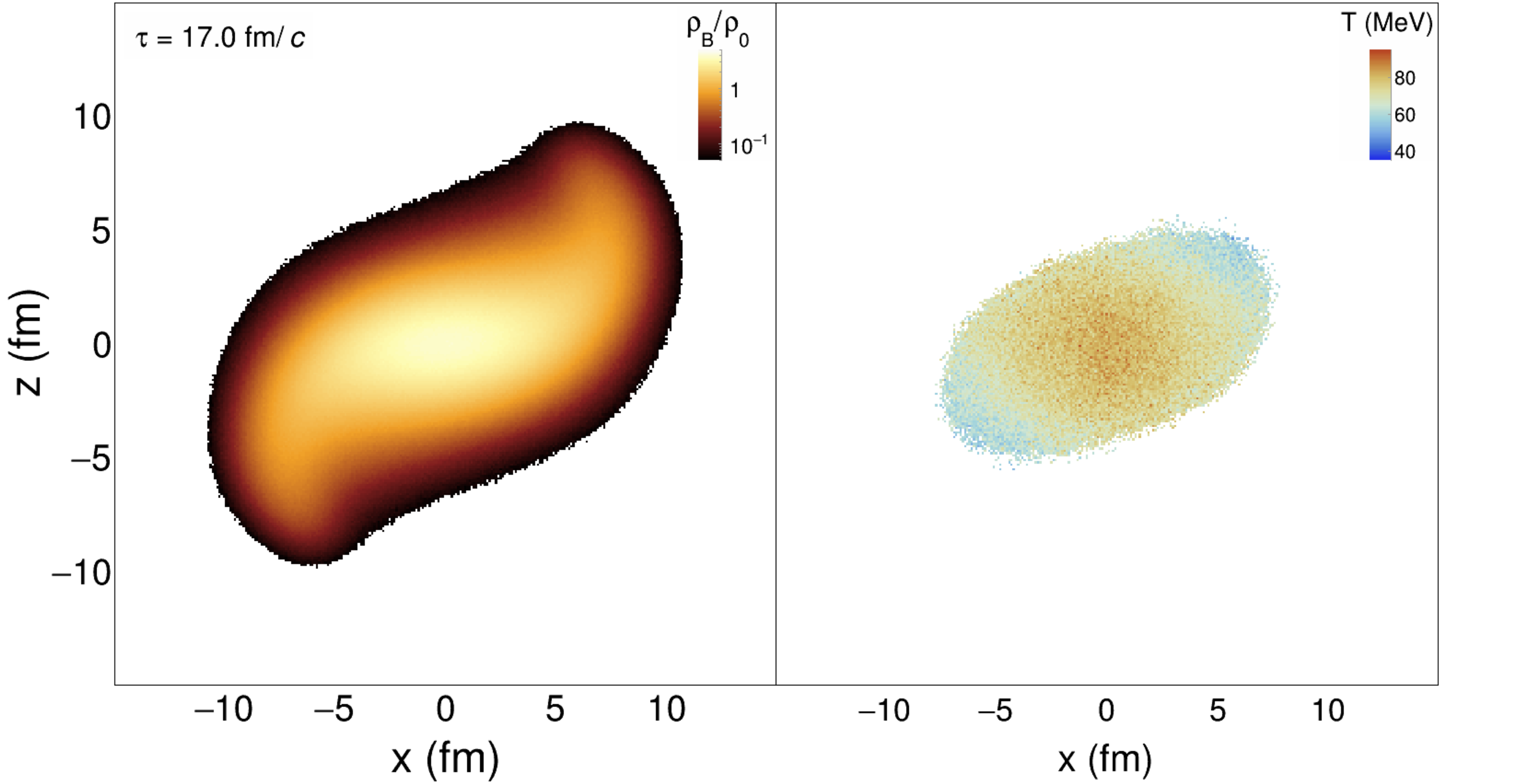
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

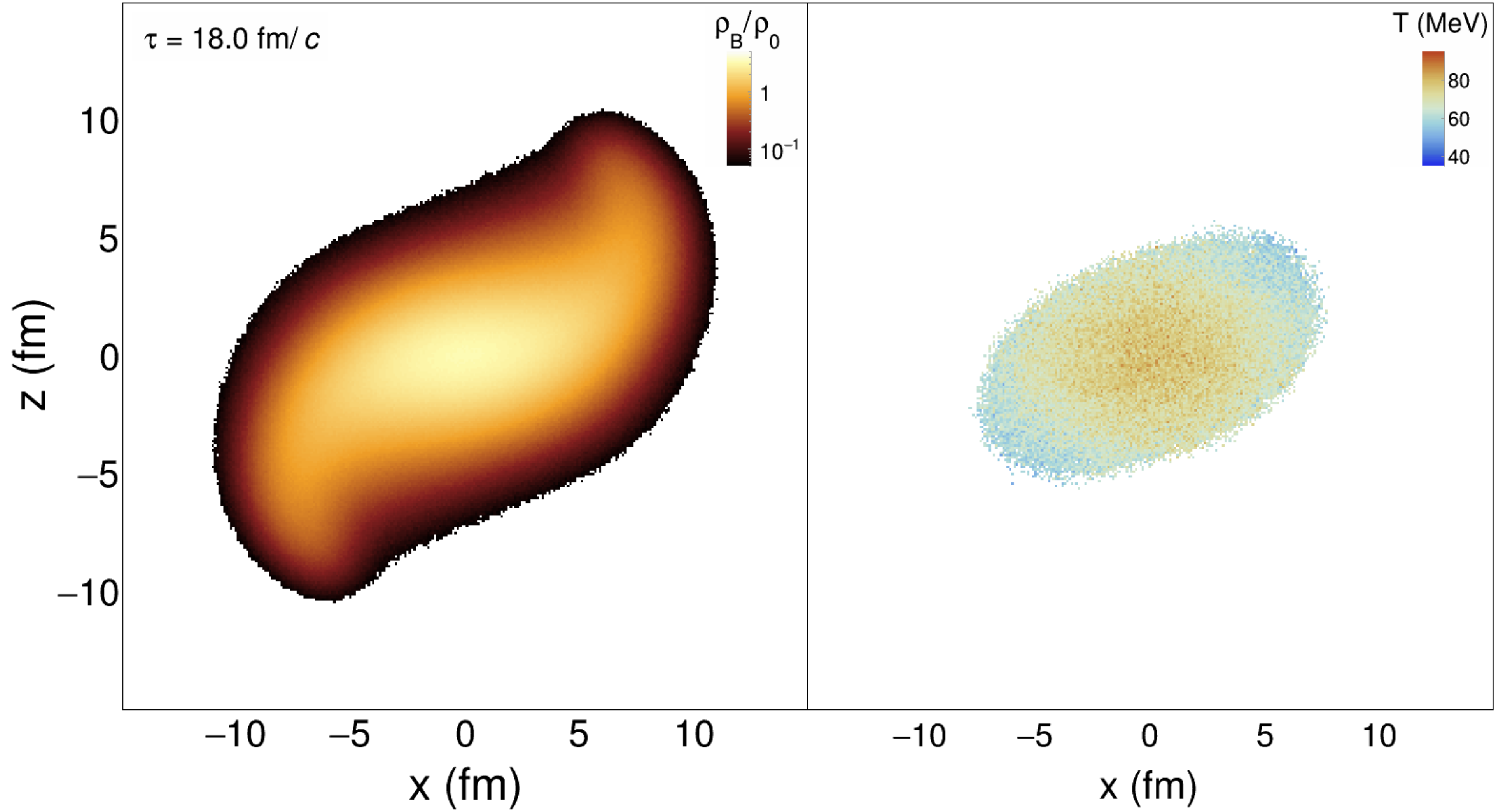


BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

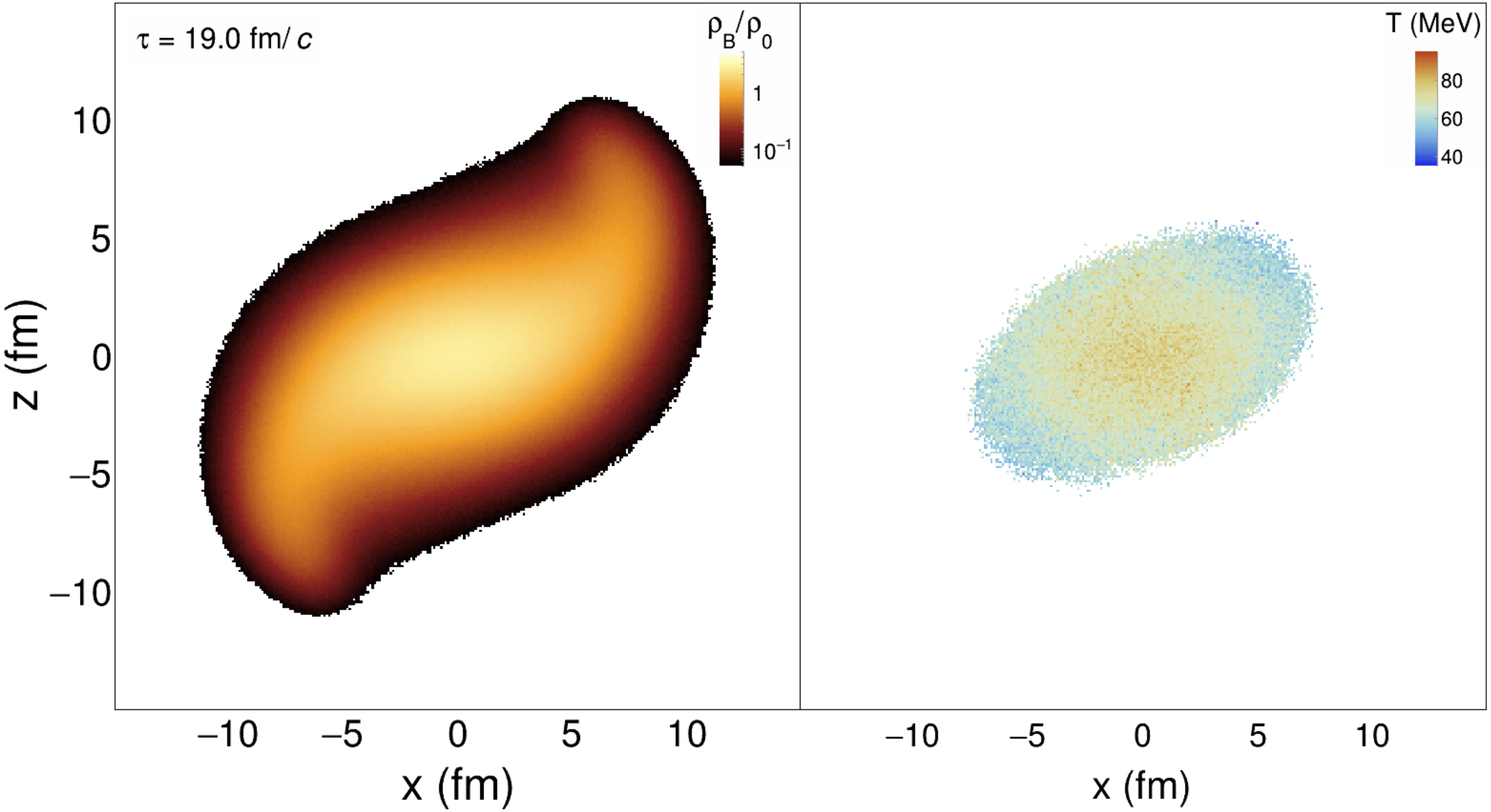


BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

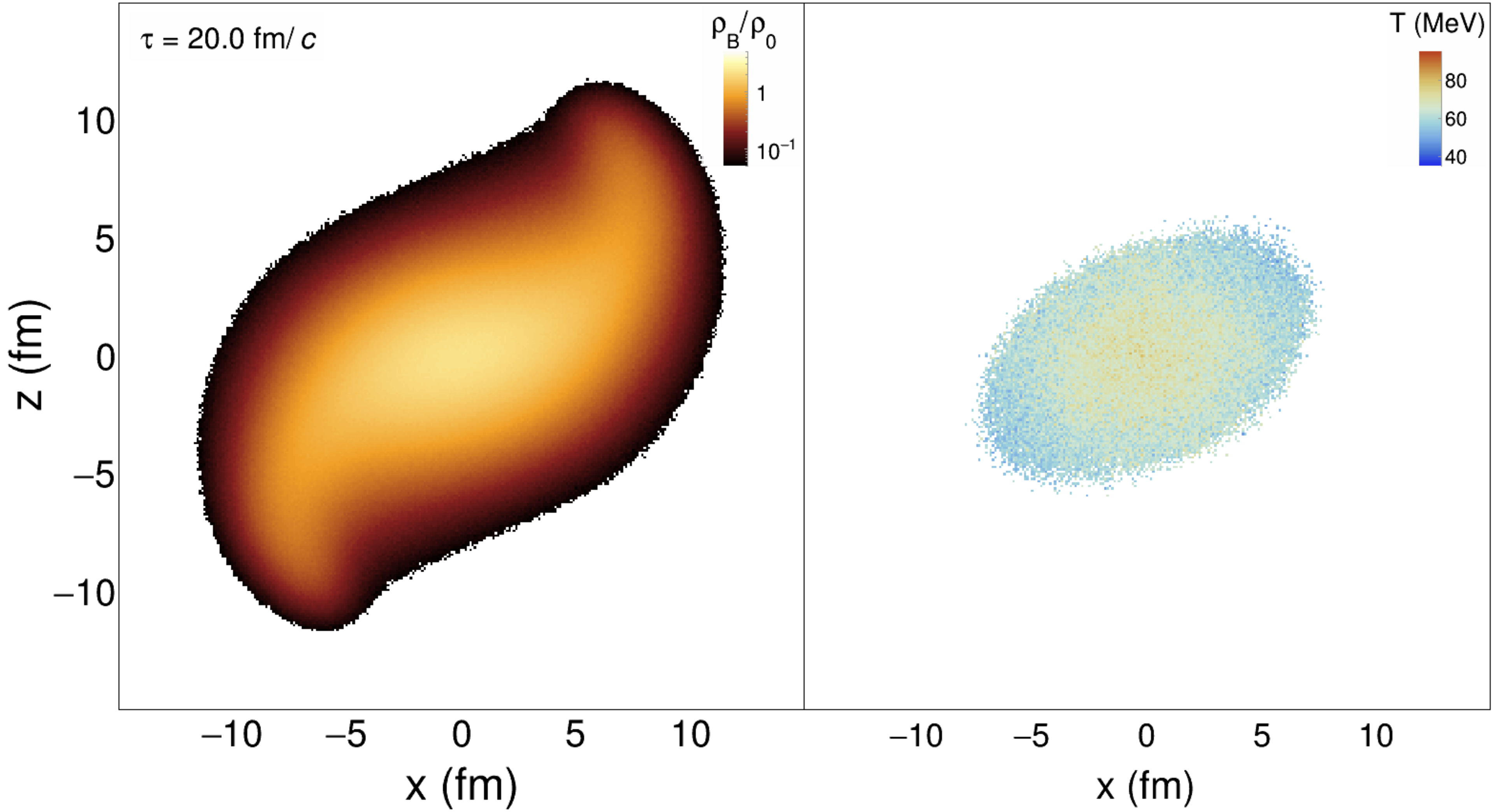
TECHNISCHE
UNIVERSITÄT
DARMSTADT



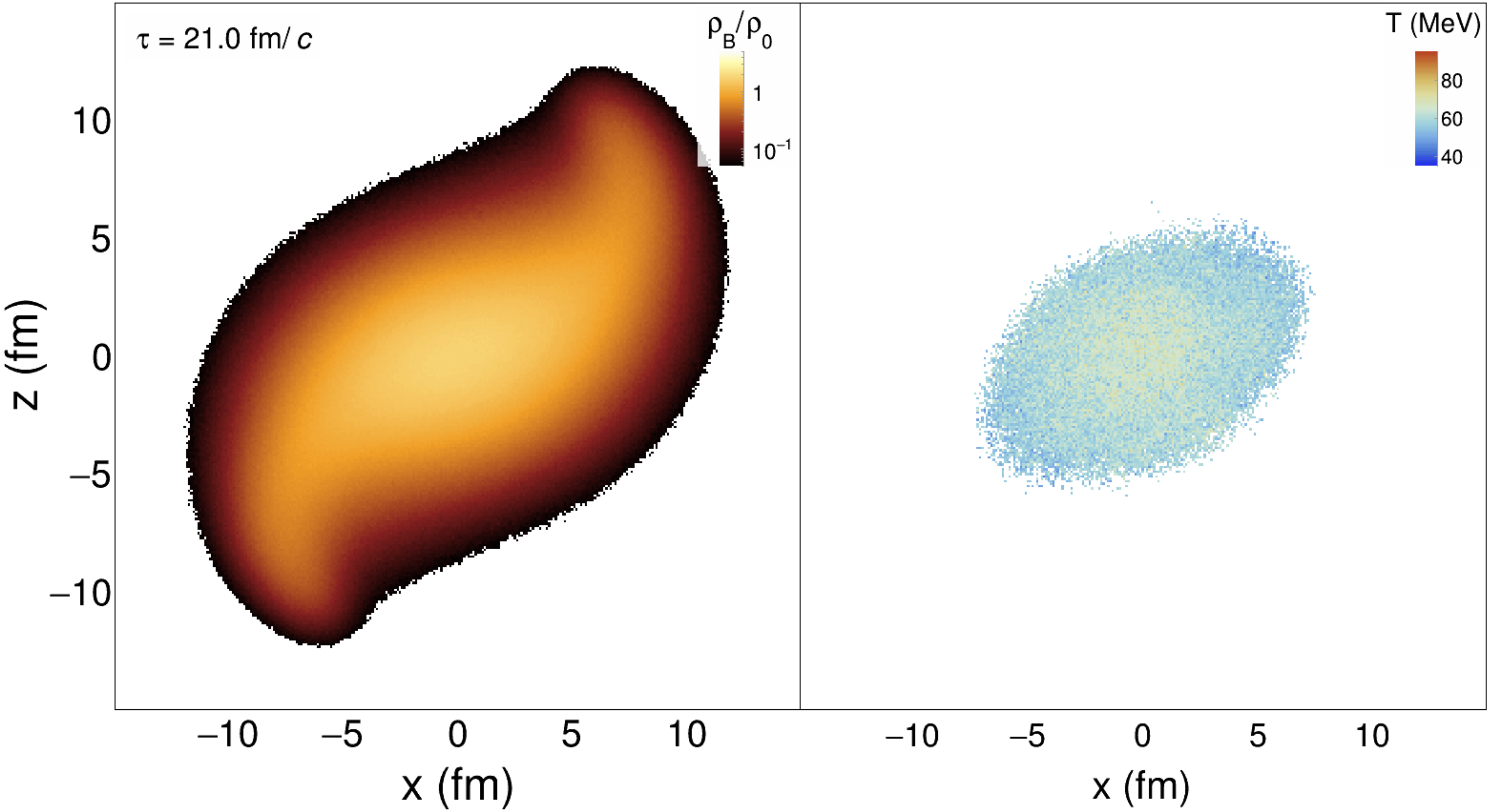
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

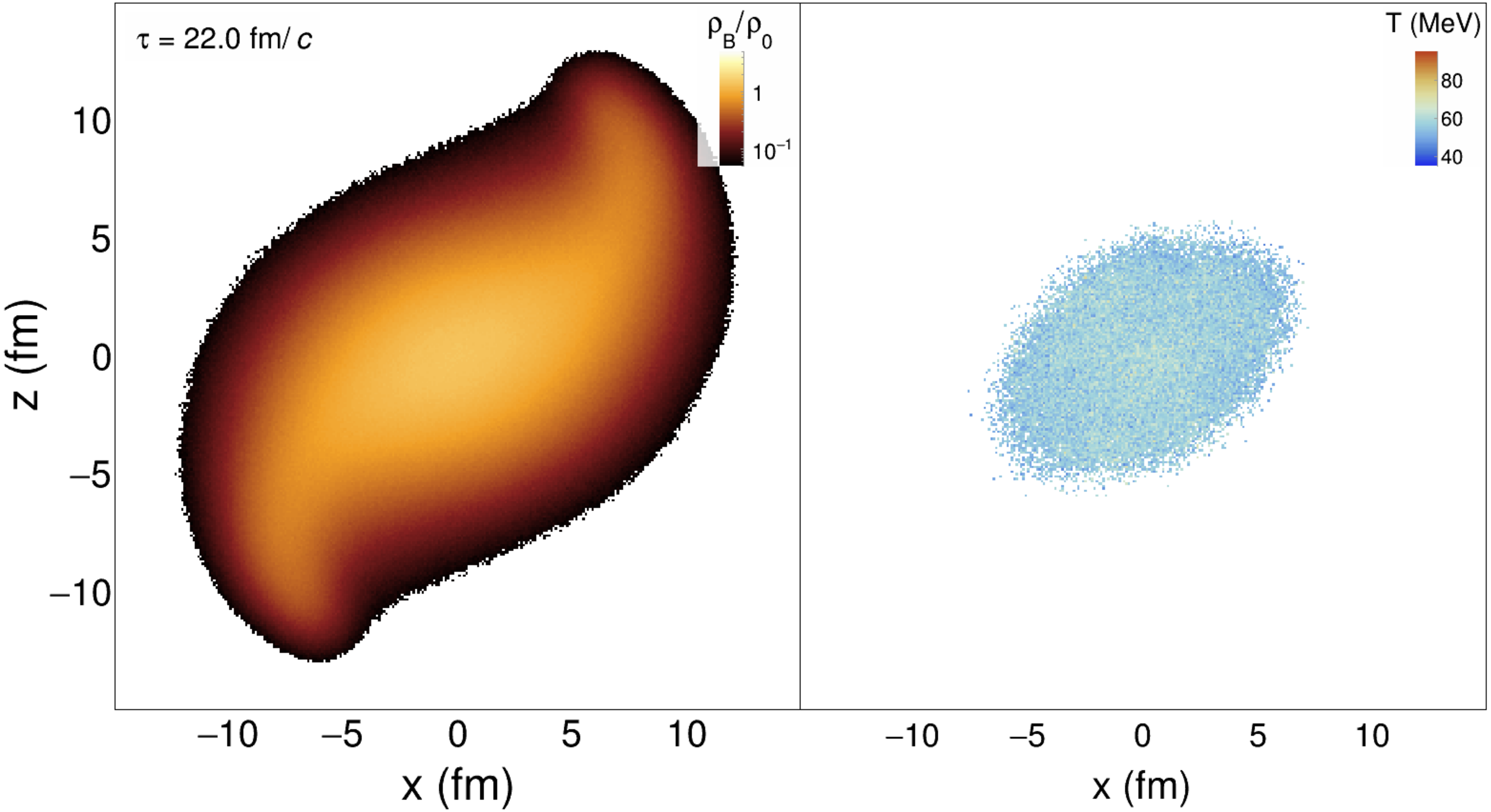


BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

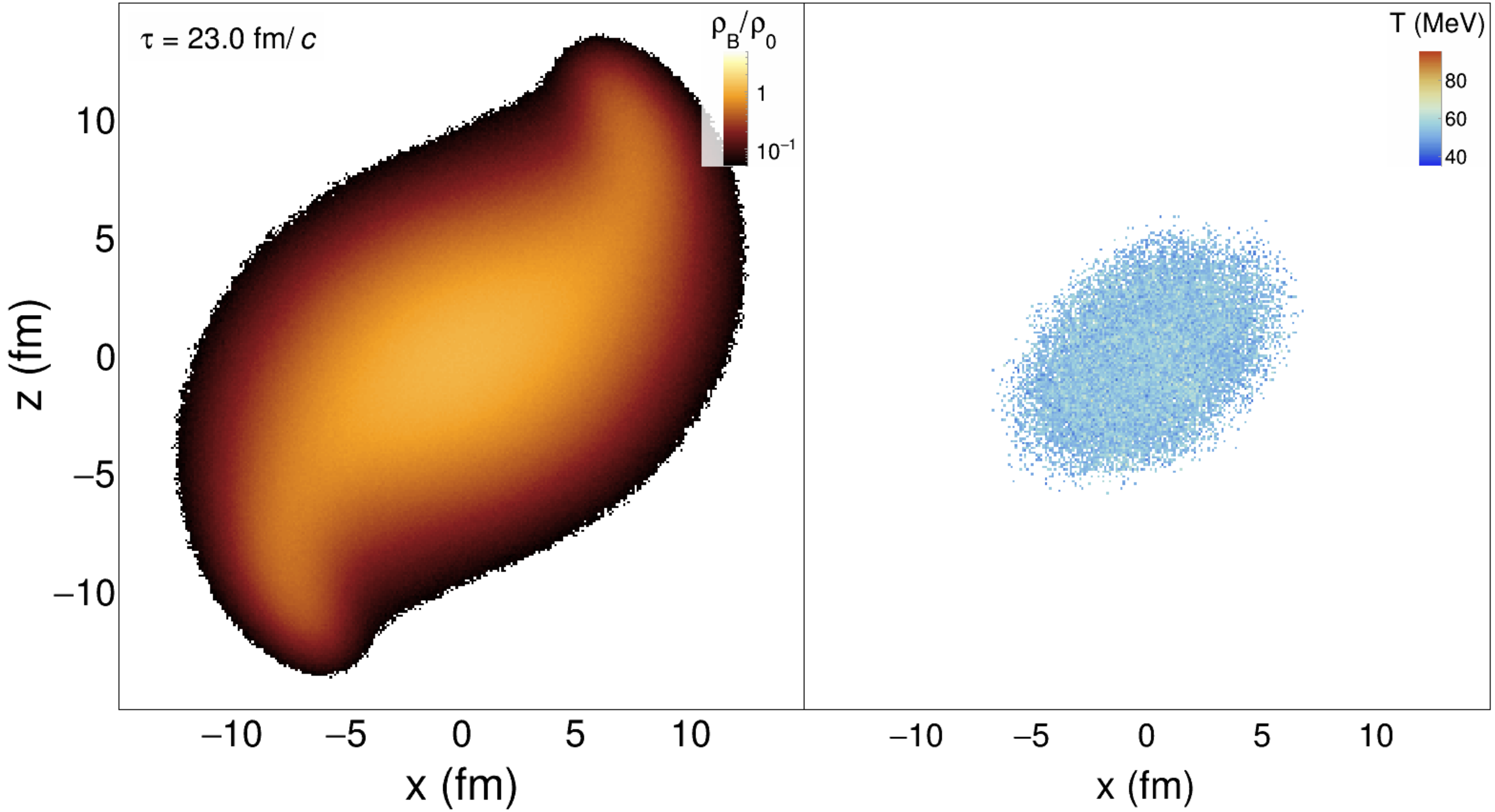


BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

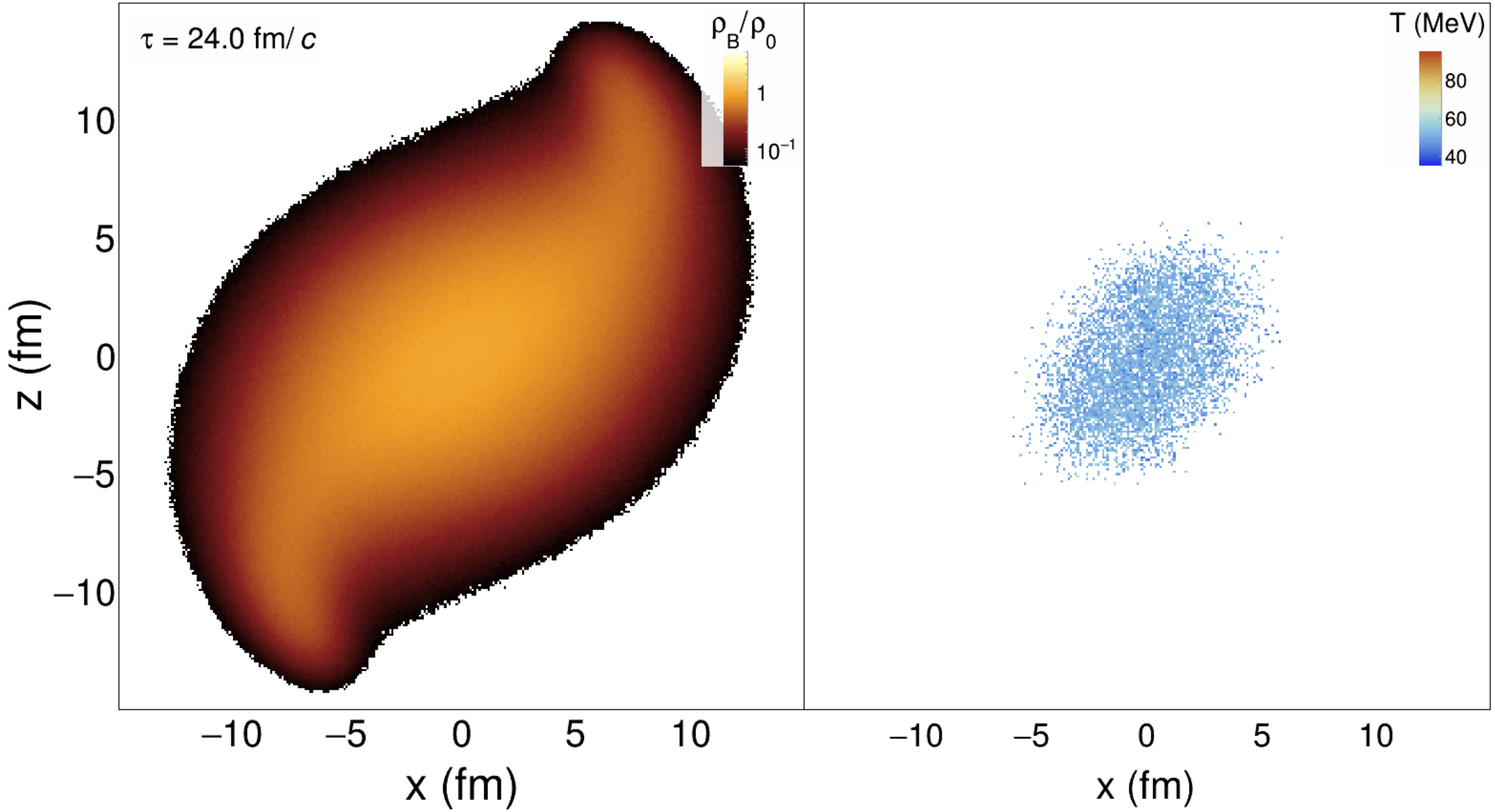
TECHNISCHE UNIVERSITÄT DARMSTADT



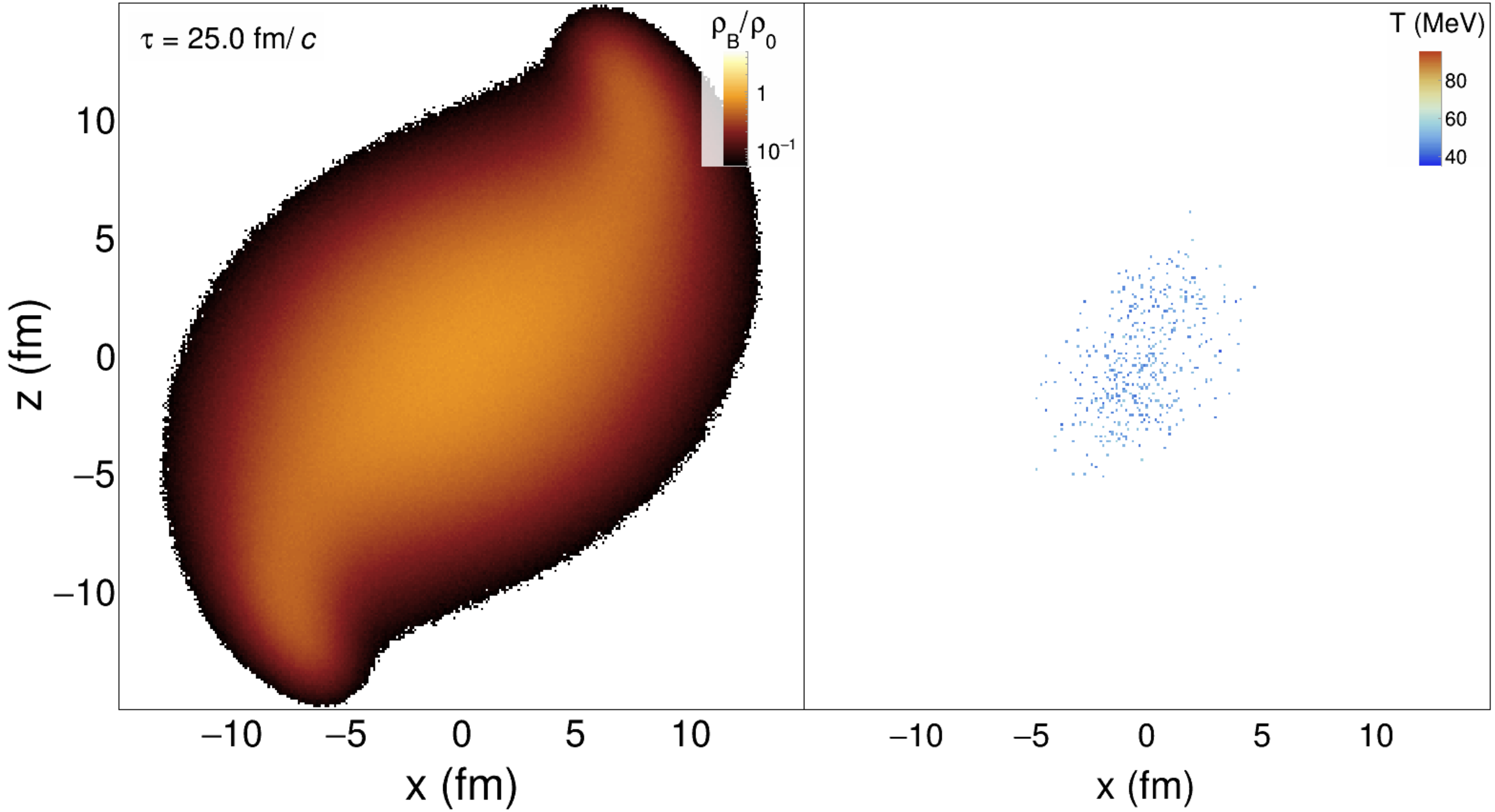
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



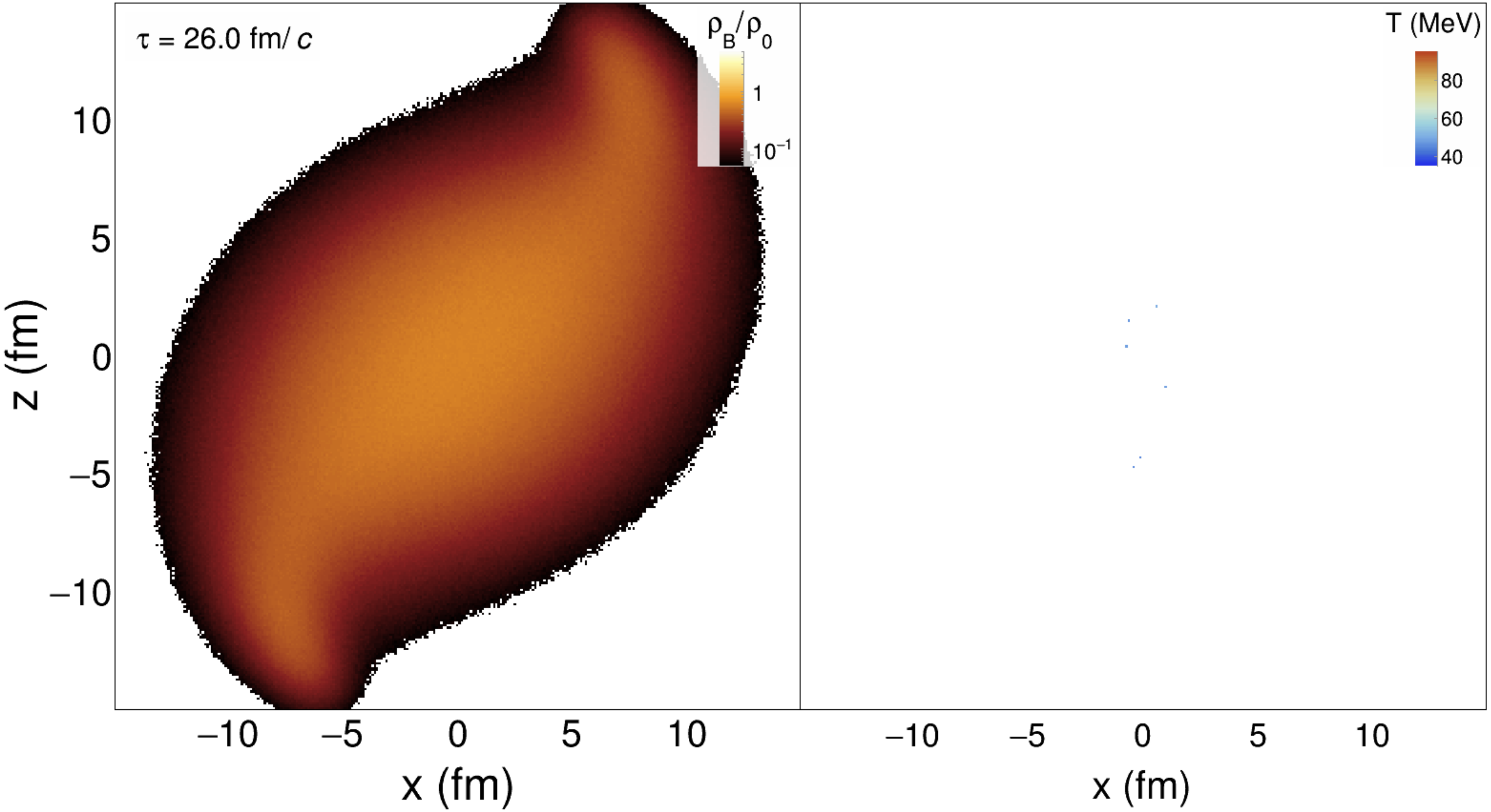
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



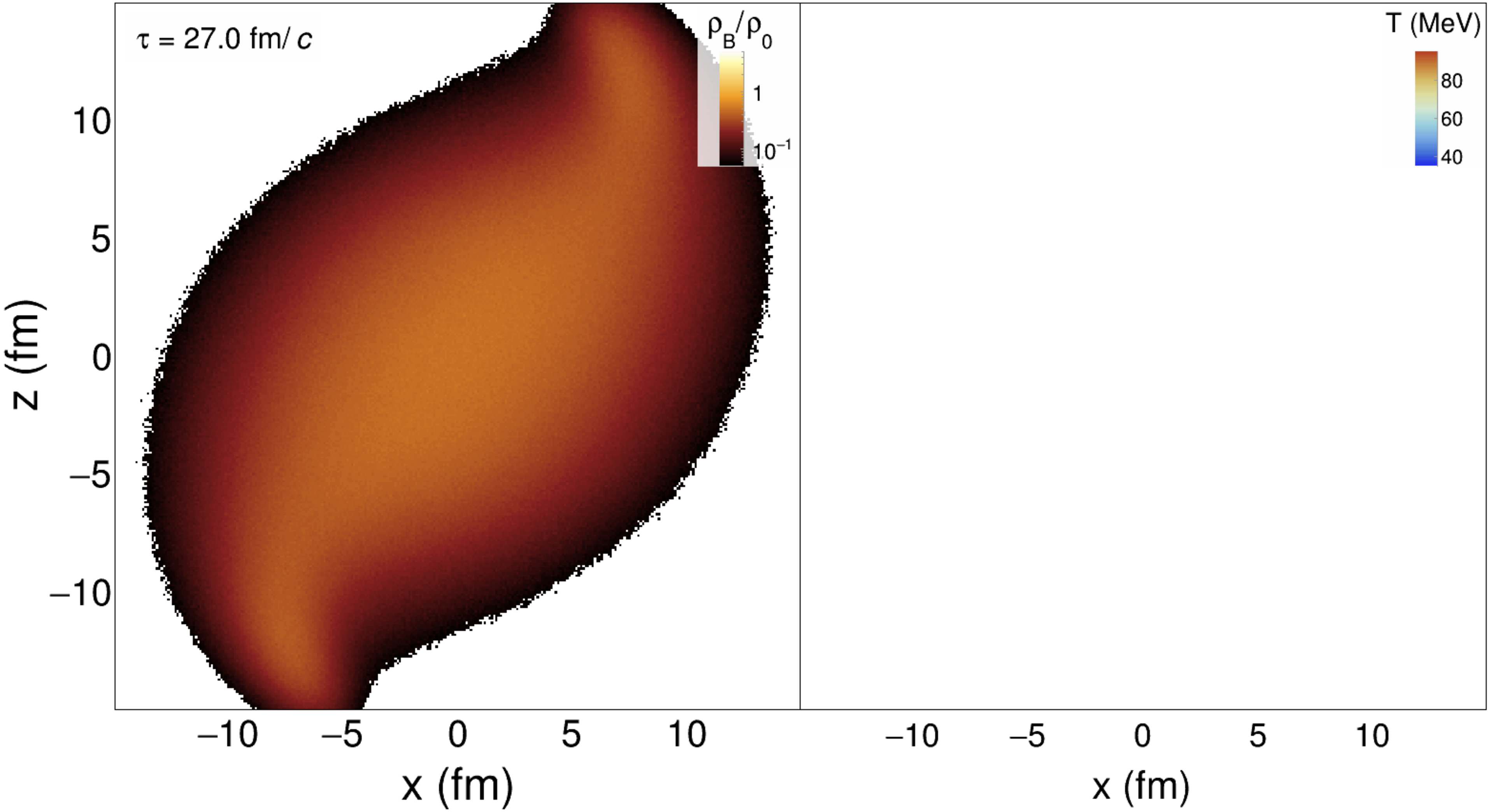
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



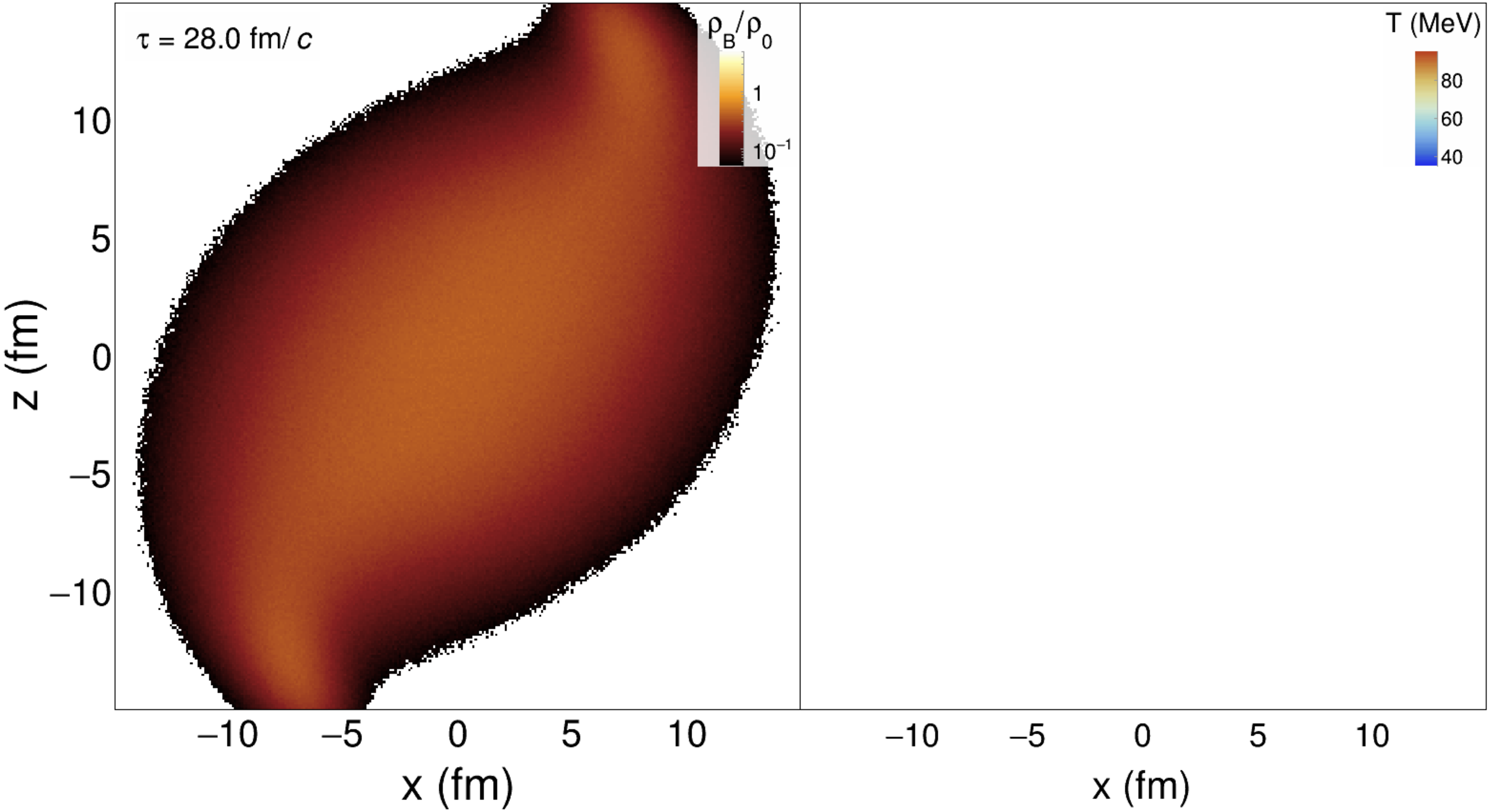
BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



THERMAL DILEPTON PRODUCTION

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

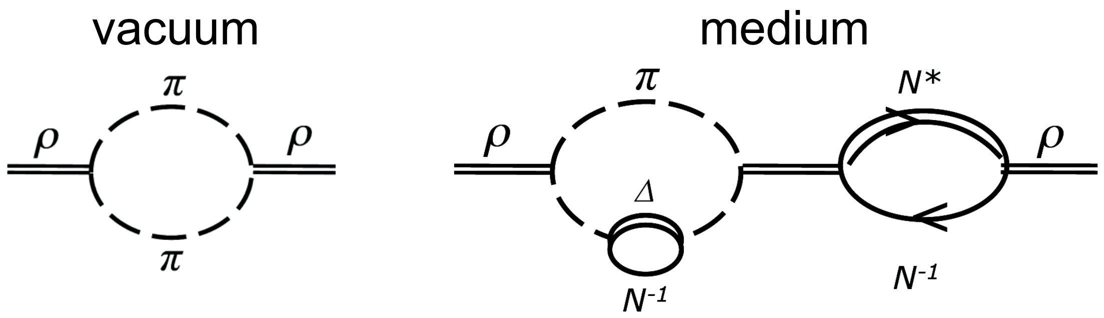
Bose-Einstein distribution (f^B) — electromagnetic spectral function ($Im\Pi_{EM}$)

L. McLerran, T. Toimela, Phys. Rev. D 31 (1985) 545

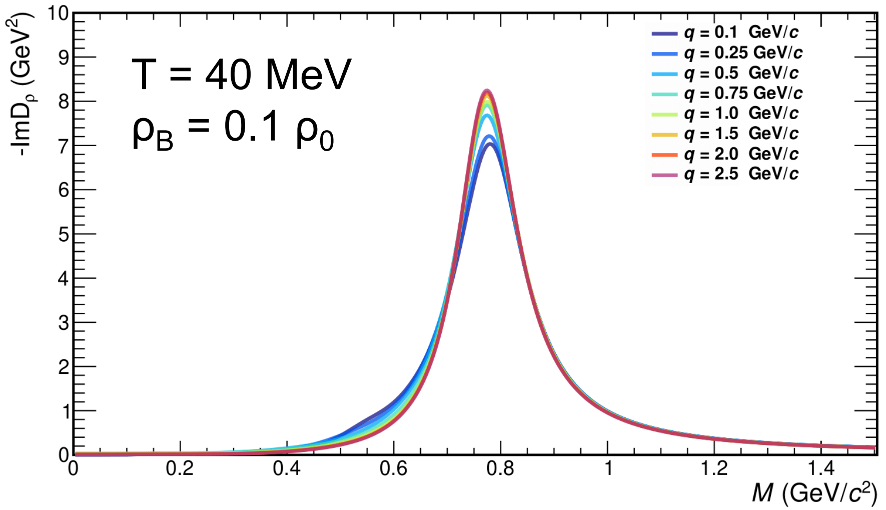
- ρ-meson spectral function broadens
  - Additional contributions to the self-energy in the medium through coupling to (anti-)baryons and mesons

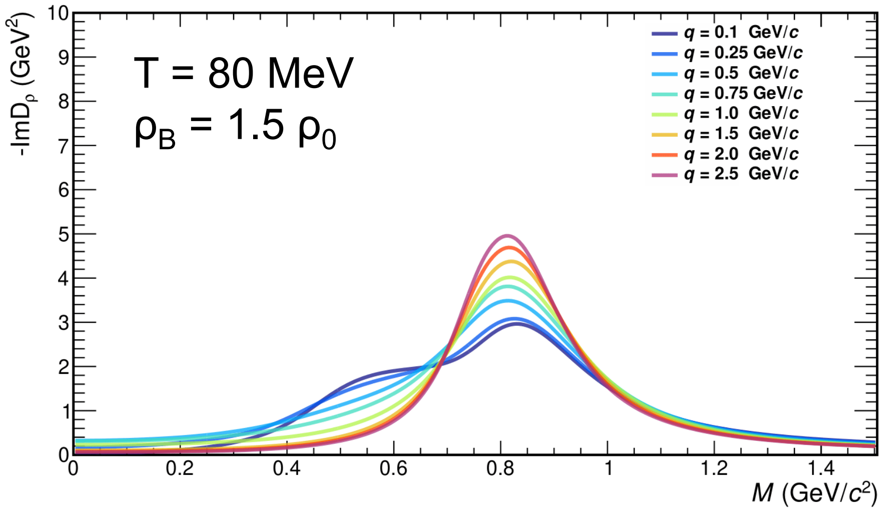
$$D_\rho(M,q;\mu_B,T) = \frac{1}{M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}}$$

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



R. Rapp, J. Wambach: Eur. Phys. J. A **6** (1999) 415



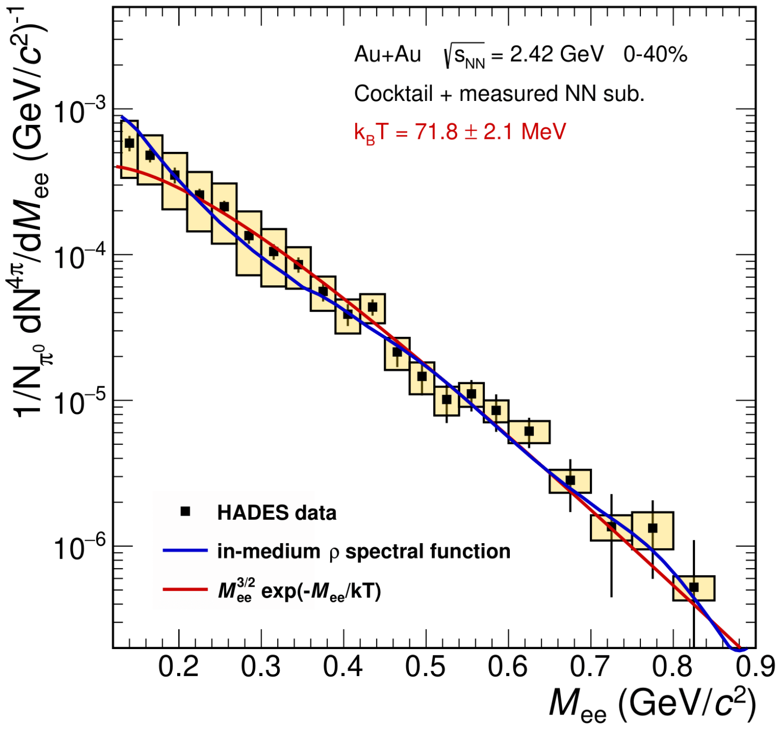


COMPARISON OF THERMAL EXCESS DATA WITH THEORY

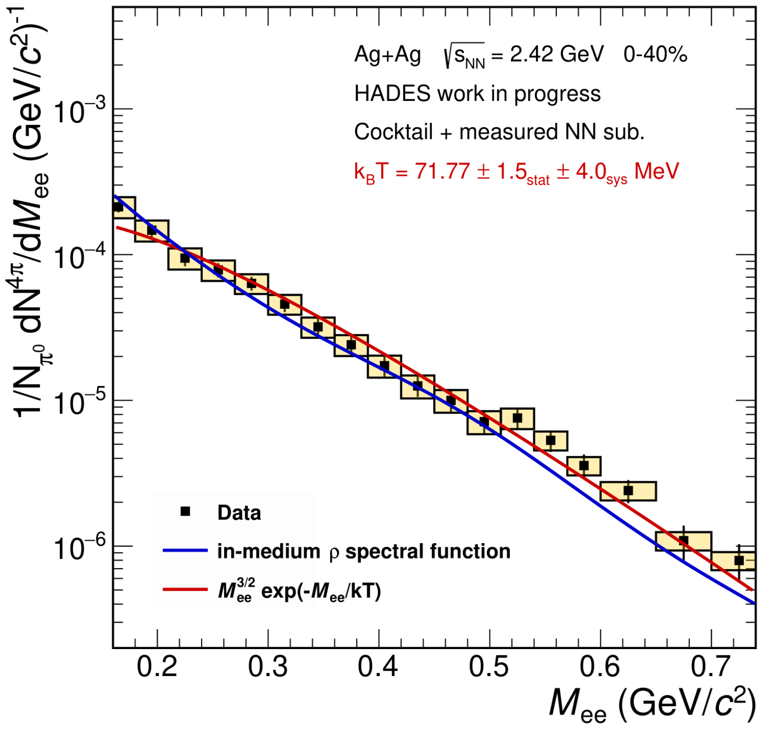
TECHNISCHE UNIVERSITÄT DARMSTADT

- Good agreement between experiment and theory for excess radiation

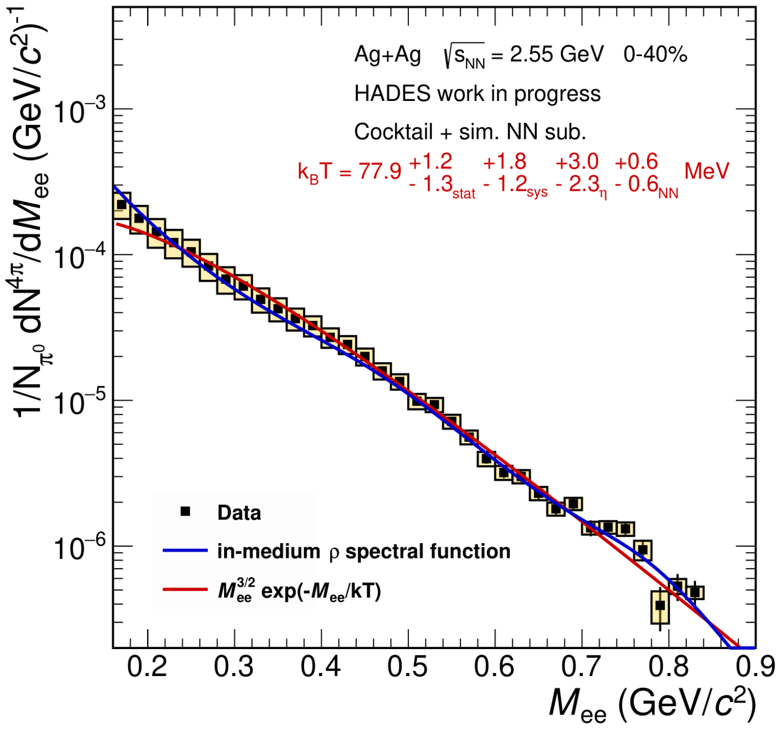
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



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

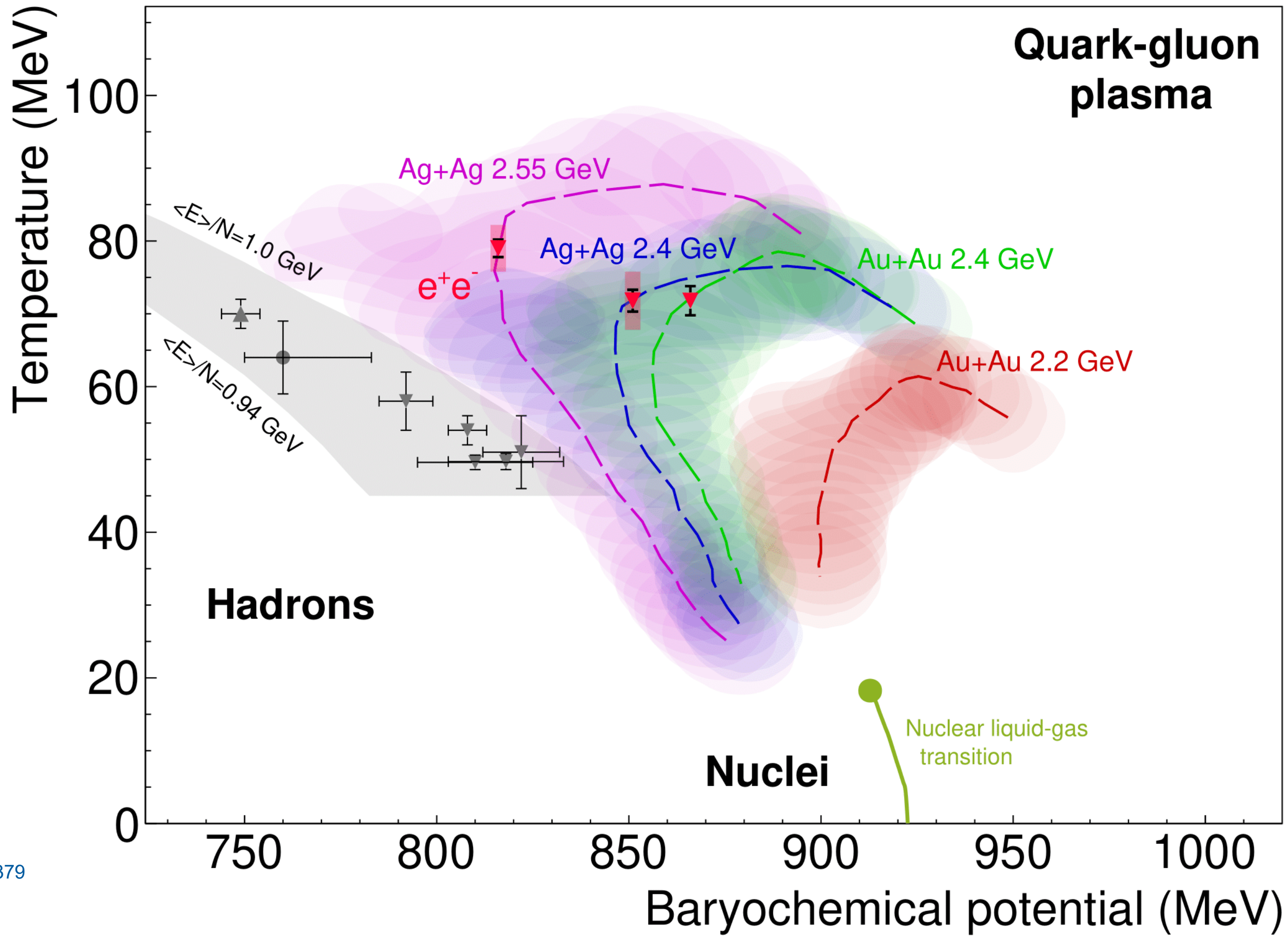


Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



QCD PHASE DIAGRAM PROBED WITH DILEPTONS

- Trajectories from coarse-grained UrQMD
- Measured average temperatures from HADES well above universal freeze-out region



FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Ag+Ag data: HADES preliminary
figure: FS, T.Galatyuk

DILEPTON FLOW

TECHNISCHE UNIVERSITÄT DARMSTADT

- Azimuthal anisotropies with respect to reaction plane

$$\frac{dN}{d\phi} \propto \left(1 + 2\textstyle\sum_n v_n \cos(n\phi)\right), \text{ with } v_n = \langle \cos(n\phi) \rangle$$

- Interplay between medium 4-velocity u and temperature T

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

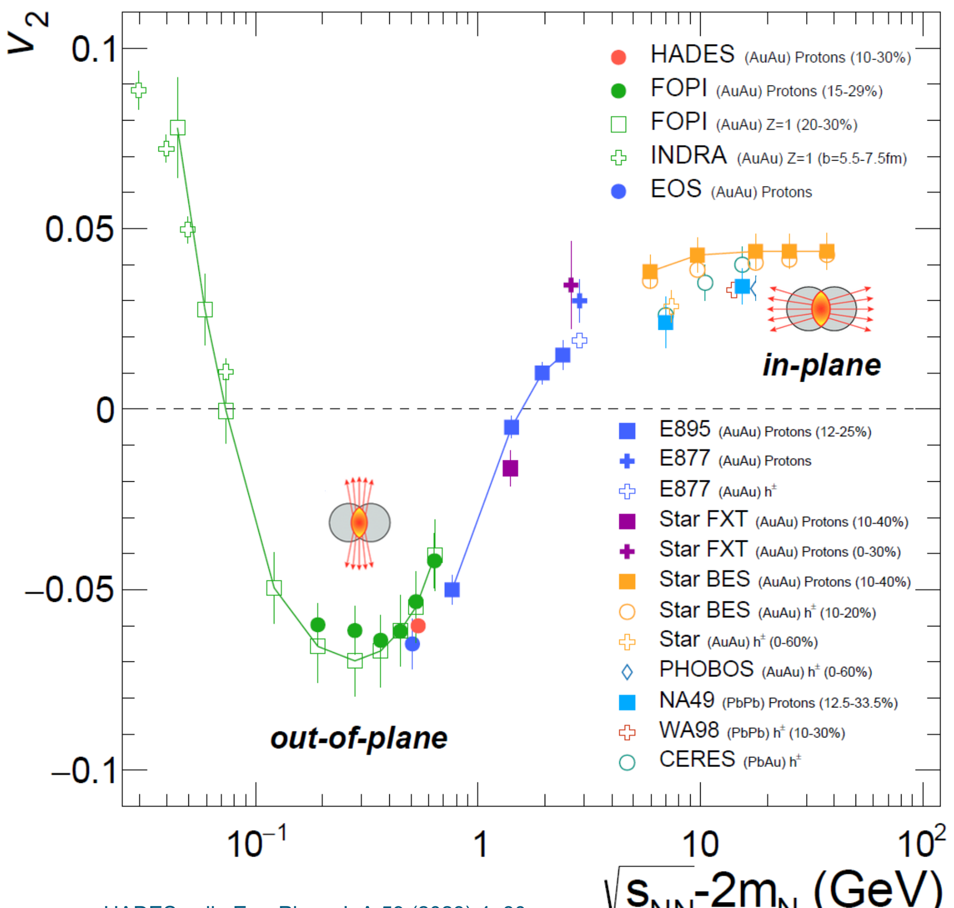
R. Chatterjee et. al, Phys. Rev. C 75 (2007) 054909
G. Vujanovic et al., Phys. Rev. C 89 (2014) 3, 034904

- Pressure anisotropies in underlying space-time evolution
  → collective velocities of medium cells

- Dileptons probe earlier times (high ρ_B, high T) compared to hadron flow

Possible sensitivity to the EoS at high μ_B

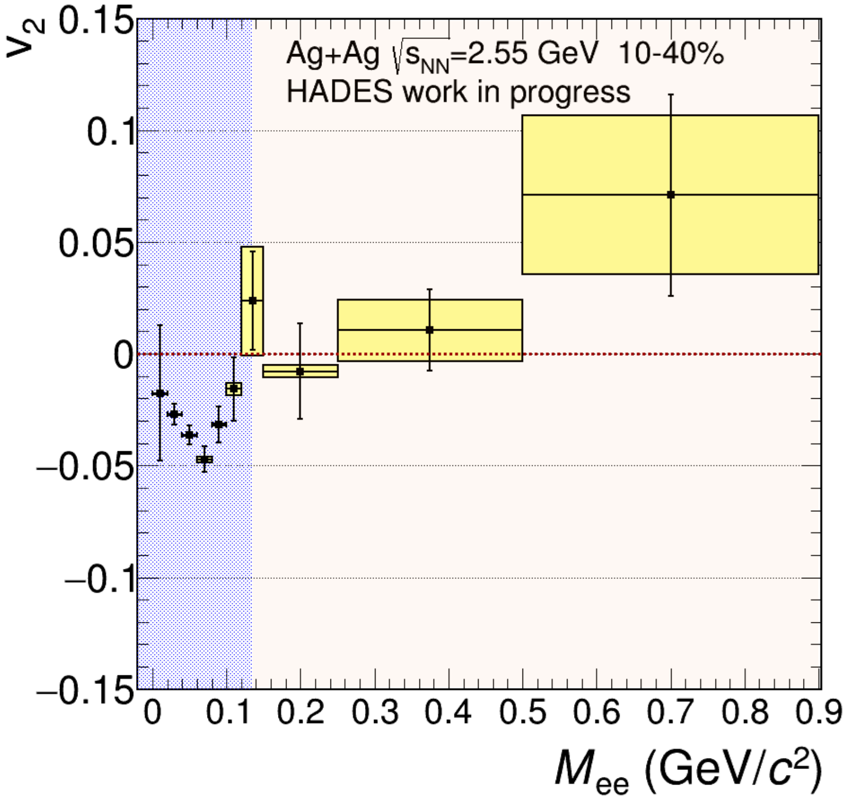
proton v_2



HADES coll., Eur. Phys. J. A 59 (2023) 4, 80

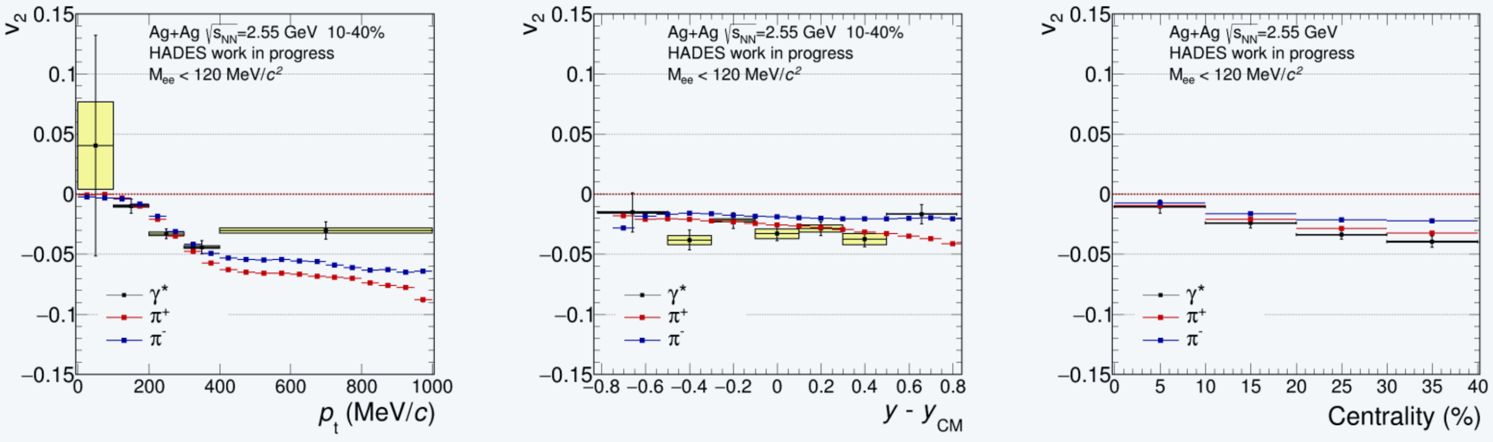
DILEPTON V2 IN AG+AG COLLISIONS

TECHNISCHE UNIVERSITÄT DARMSTADT



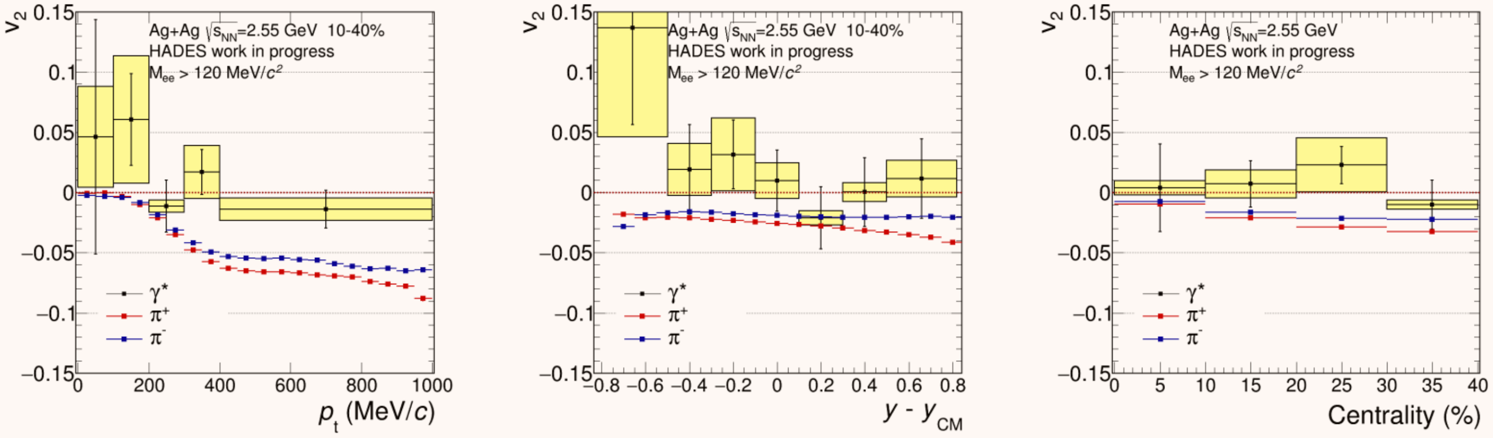
M_{ee} < 0.12 GeV/c^2: inclusive yield dominated by π^0 decays

- Dilepton v_2 consistent with charged pion v_2



M_{ee} > 0.12 GeV/c^2: inclusive yield dominated by thermal radiation

- Dilepton v_2 consistent with zero → early emission



VIRTUAL PHOTON POLARIZATION

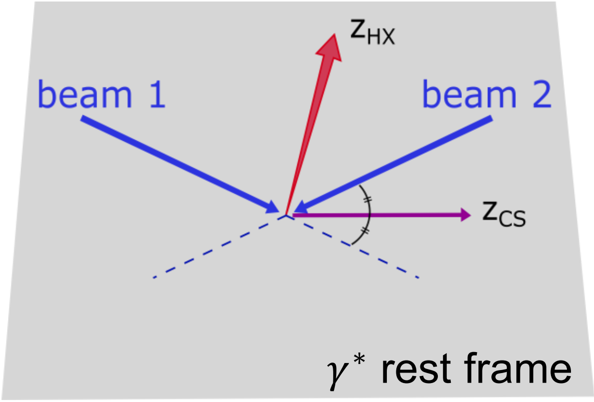
TECHNISCHE UNIVERSITÄT DARMSTADT

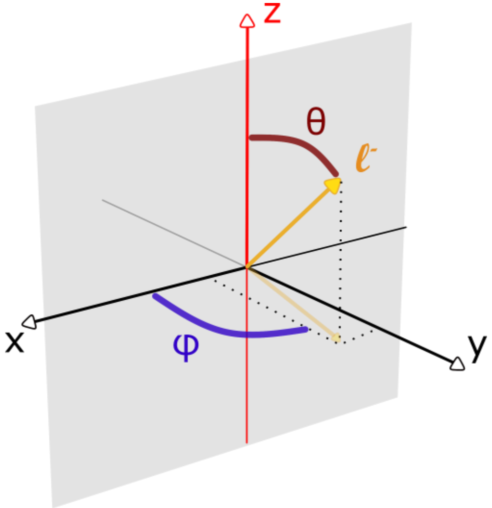
- Decompose spectral function using projectors for a spin-1 particle $\rho_{EM}^{\mu\nu} = \rho_L \, P_L^{\mu\nu} + \rho_T \, P_T^{\mu\nu}$ with $g_{\mu\nu} \, \rho_{EM}^{\mu\nu} = \rho_L + 2\rho_T$
- Angular distribution of single lepton in γ^* rest frame depends on polarization of γ^*

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

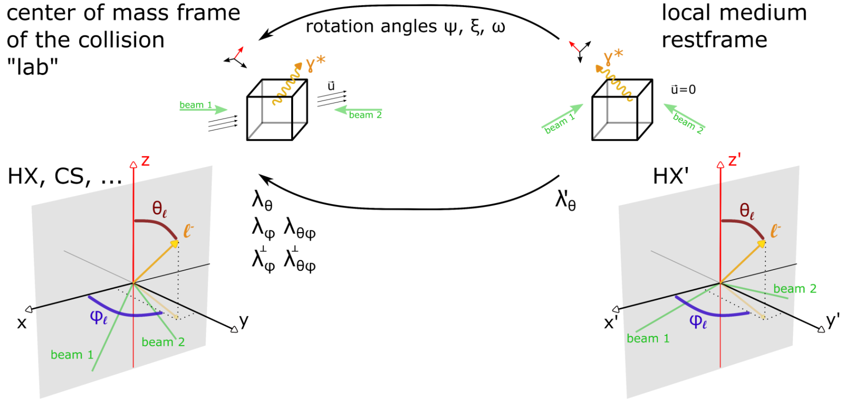
E. Speranza *et al.*, Phys. Lett. B 782, 395 (2018)
G. Baym *et al.*, Phys. Rev. C 95, 044907 (2017)
E. Bratkovskaya *et al.*, Phys. Lett. B 376, 12 (1996)

- Different virtual photon **production mechanisms** imprint different anisotropy parameters λ
- λ coefficients related to **difference** between **longitudinal and transverse components** of spectral function: $\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$
- Rotational symmetry of static thermal medium broken by virtual photon's momentum direction
- For moving medium: transform local coefficients to global frame accessible in experiment → comparison to data





FS et al., arXiv: 2309.03189
QM23 talk

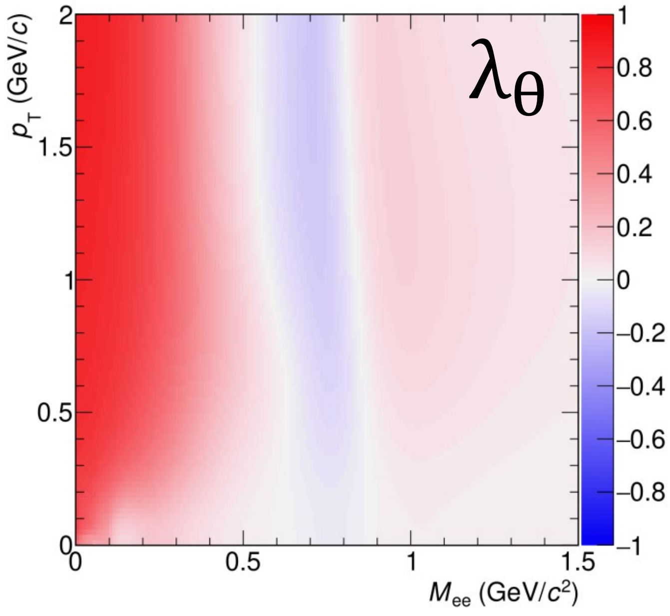


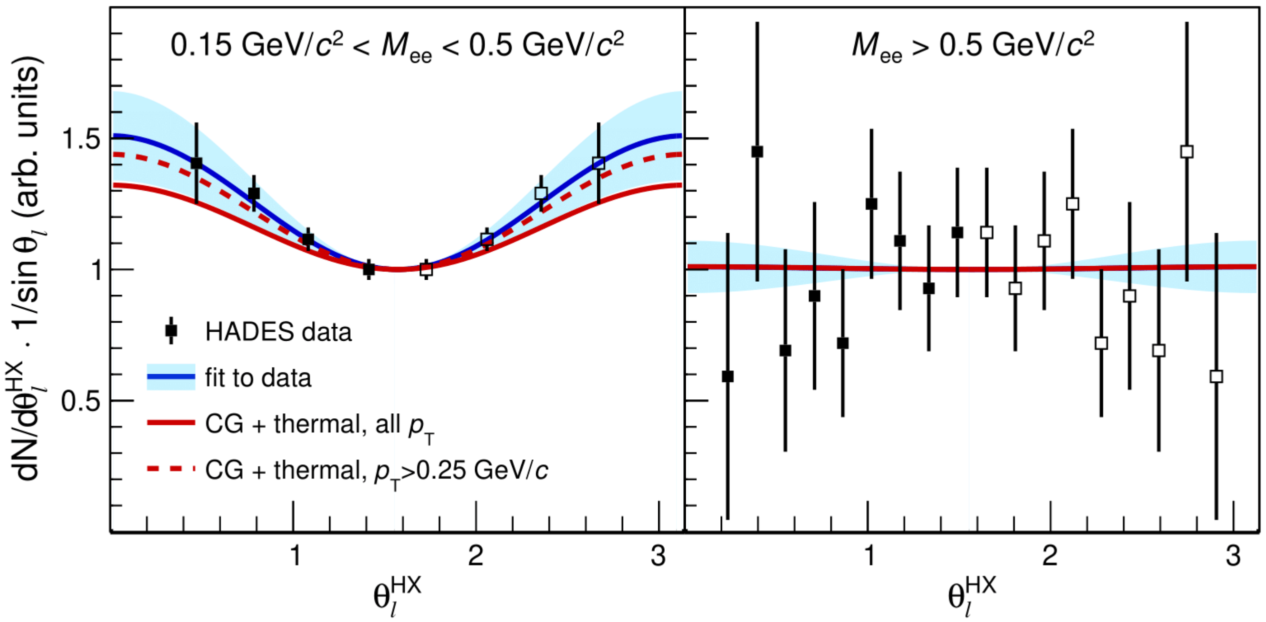
COMPARISON TO HADES DATA

TECHNISCHE UNIVERSITÄT DARMSTADT

- HADES measured anisotropy coefficient λ_θ of excess radiation in Ar+KCl collisions at 1.76 AGeV ($\sqrt{s_{NN}} = 2.62$ GeV)
- Polarization largely survives evolution of the expanding medium
- **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

HADES coll,, Phys. Rev. C 84, 014902 (2011)
T. Galatyuk *et al.*, Eur. Phys. J. A 52, 131 (2016)
FS et al., arXiv: 2309.03189





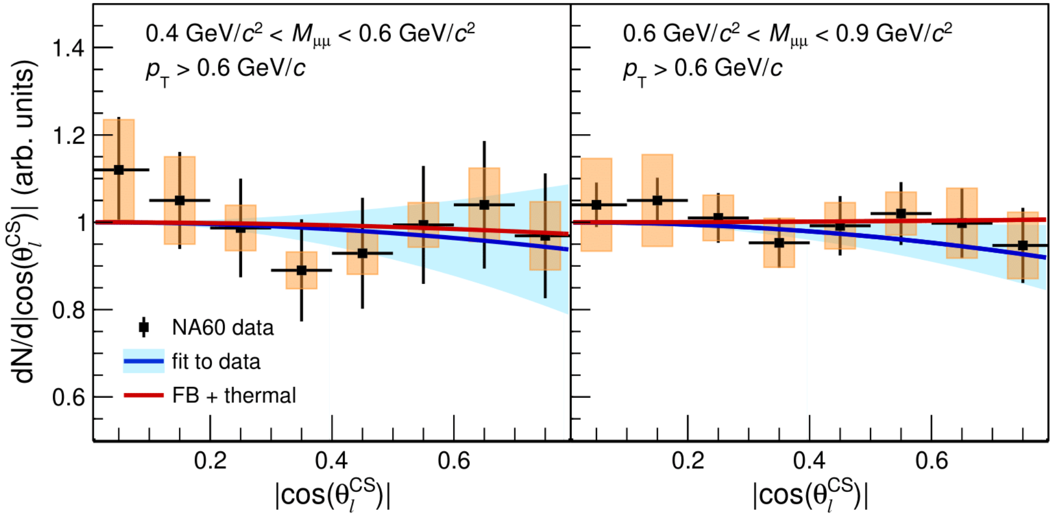
COMPARISON TO NA60 DATA

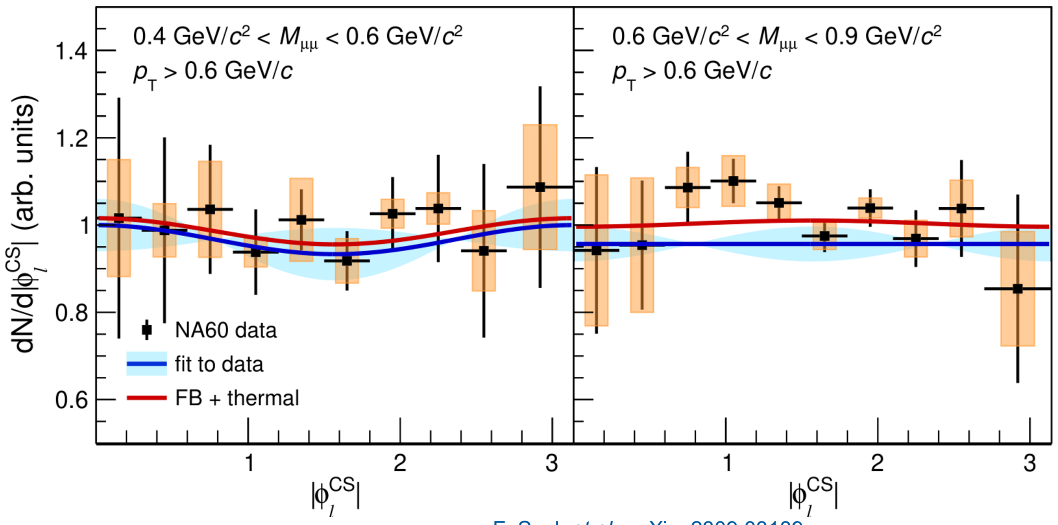
- NA60 measured polarization coefficients λ_θ, λ_φ and $\lambda_{\theta\varphi}$ of excess radiation in the CS frame in In+In collisions at 158 AGeV
- Space-time evolution via isentropic fireball model with transition from QGP to hadronic rates at T=170 MeV

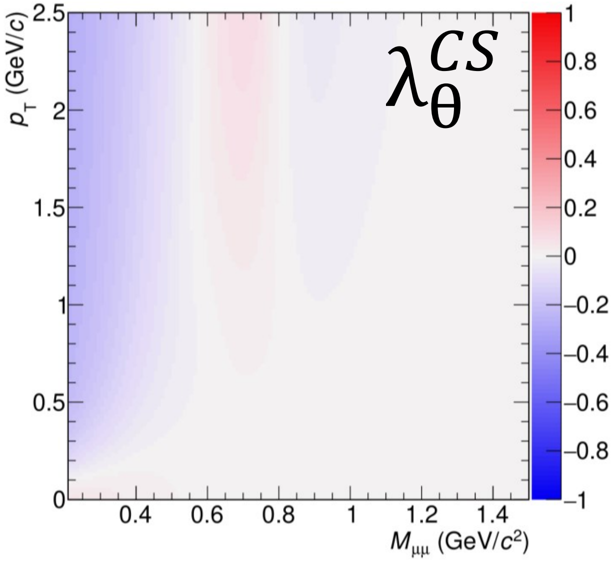
NA60 coll., Phys. Rev. Lett. 96, 162302 (2006)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)

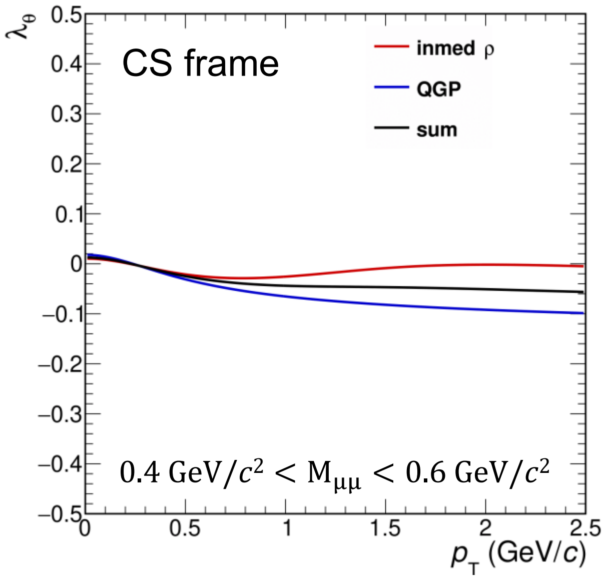
- Good agreement between data and theory → size and trend
- Near absence of a net polarization not related to thermal isotropy arguments

data points: NA60 coll,, Phys. Rev. Lett. 102, 222301 (2009)







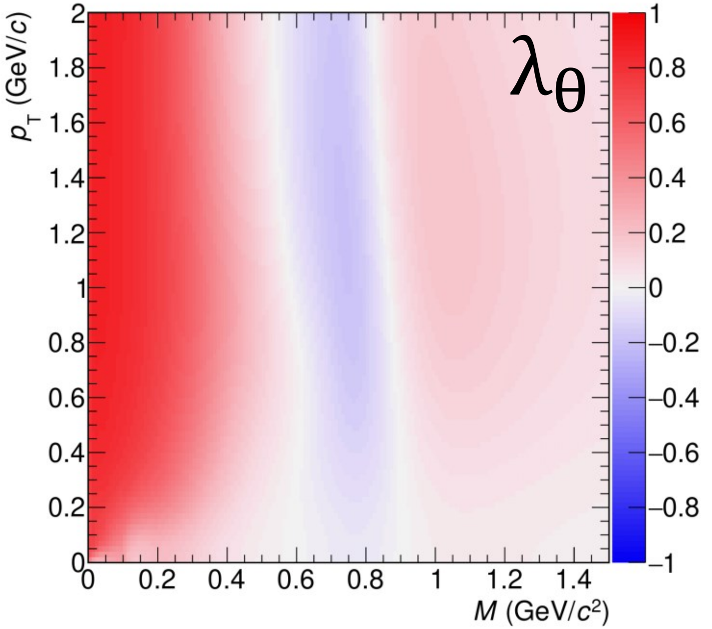


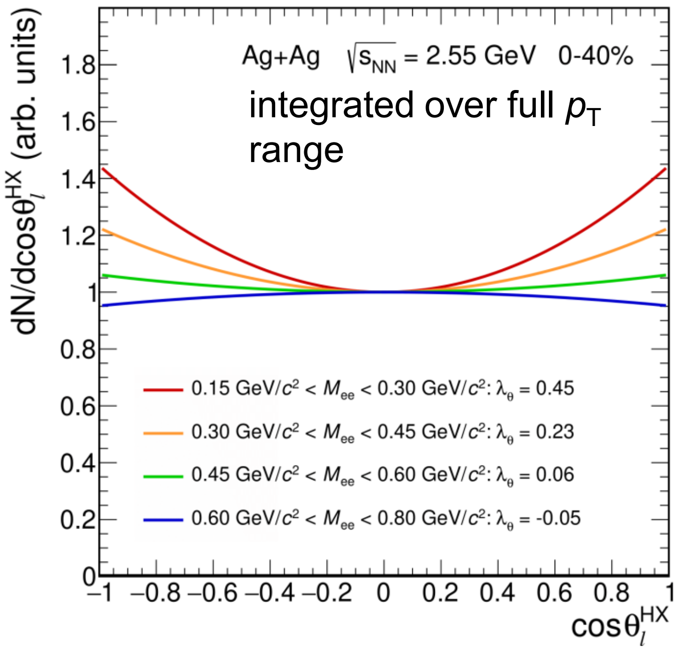
F. Seck *et al.*, arXiv: 2309.03189

PREDICTIONS FOR AG+AG COLLISIONS & FUTURE EXPERIMENTS

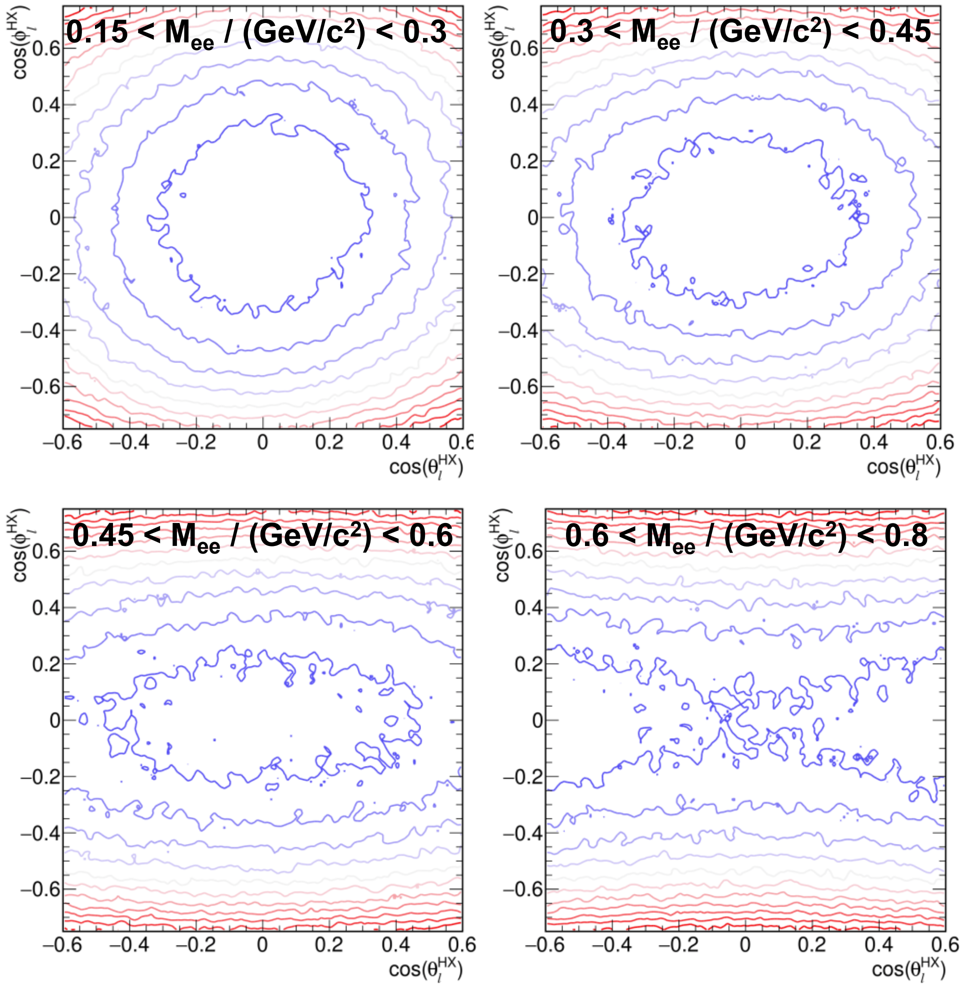
TECHNISCHE UNIVERSITÄT DARMSTADT

- Predictions for λ_θ in Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV
- Anisotropy coefficients integrated over p_T in several mass ranges





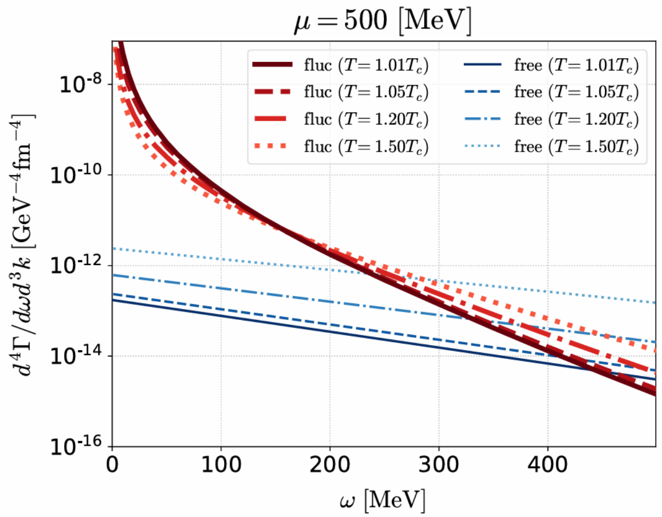
$p_T > 0.5$ GeV/c



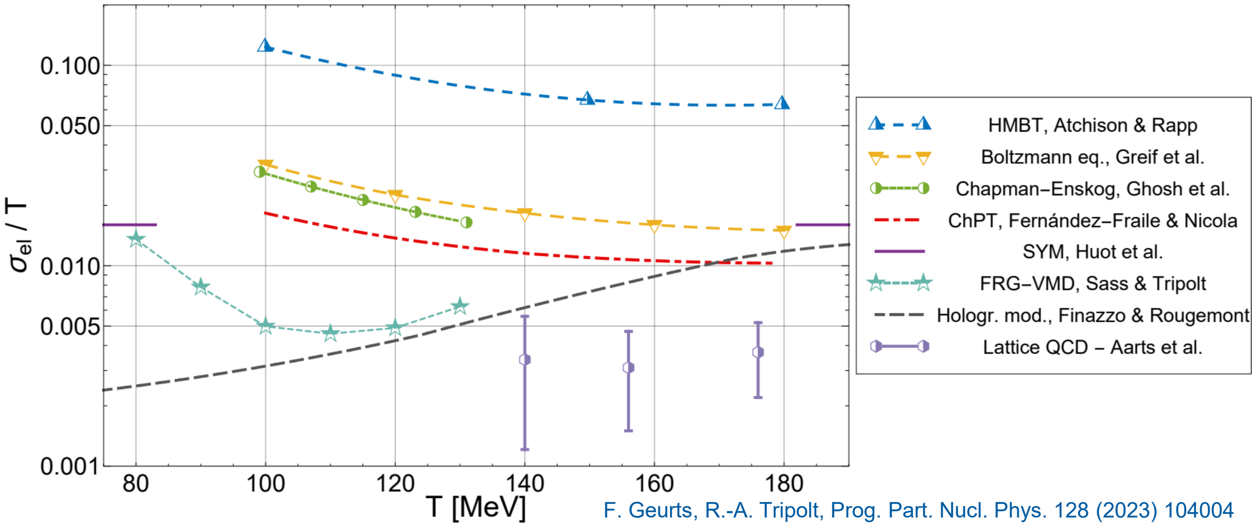
- Multi-differential measurements of the virtual photon polarization
  → large datasets needed: CBM, NA60+ and ALICE3
  - Search for onset of QGP
  - ρ-a_1 mixing vs. QGP around M_{ee} ~ 1.1 GeV

LOW-MASS LOW-MOMENTUM DILEPTONS

- Color superconductivity could manifest itself in an enhanced yield of low-energy dileptons
- Thermal dileptons encode information on matter properties
  - yield in p_{ee} = 0 MeV/c, $M_{ee} \rightarrow$ 0 MeV/c^2 limit proportional to conductivity
- Large **theoretical uncertainty**
  → **experimental constraints** highly desirable
- Determines time evolution of electromagnetic fields generated by spectators
  - Important for effects related to presence of strong magnetic fields



T. Nishimura *et al.*, arXiv:2201.01963 (2022)



F. Geurts, R.-A. Tripolt, Prog. Part. Nucl. Phys. 128 (2023) 104004

electrical conductivity

$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\rho_{EM}(q_0, \vec{q} = 0, T, \mu_B)}{q_0}$$

R. Kubo, J. Phys. Soc. Jap. 12 (1957) 570-586
G. Moore, J. Robert, arXiv:hep-ph/0607172 [hep-ph]

thermal dilepton emission rate

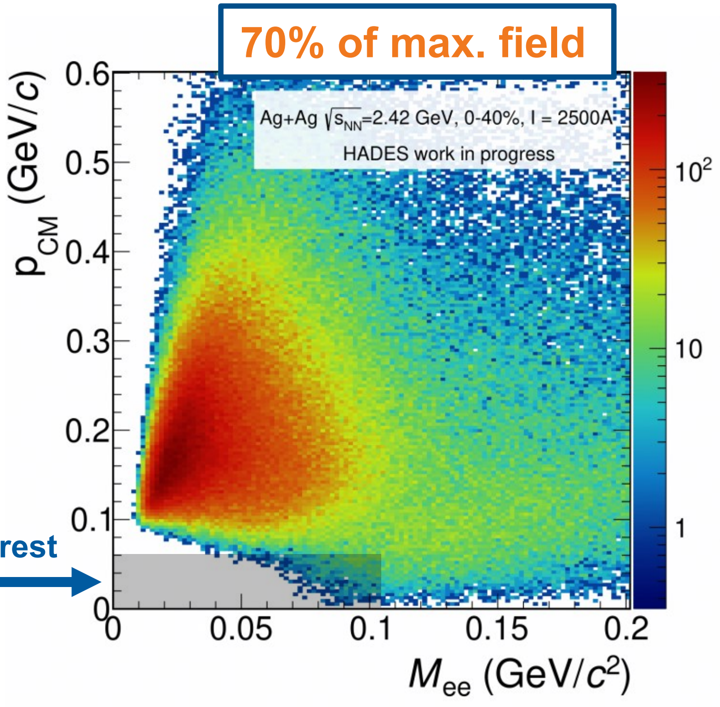
$$\frac{d^8N}{d^4q\, d^4x} = \frac{-\alpha_{EM}^2}{\pi^3 M^2} f_B(q_0, T) \underbrace{Im\Pi_{EM}(M, q, T, \mu_B)}_{\rho_{EM}}$$

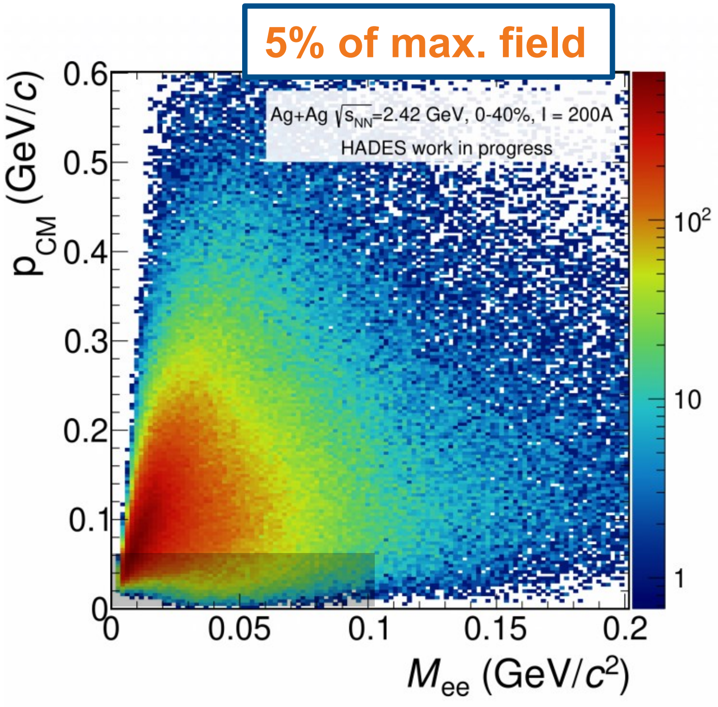
EXPERIMENTAL CHALLENGES

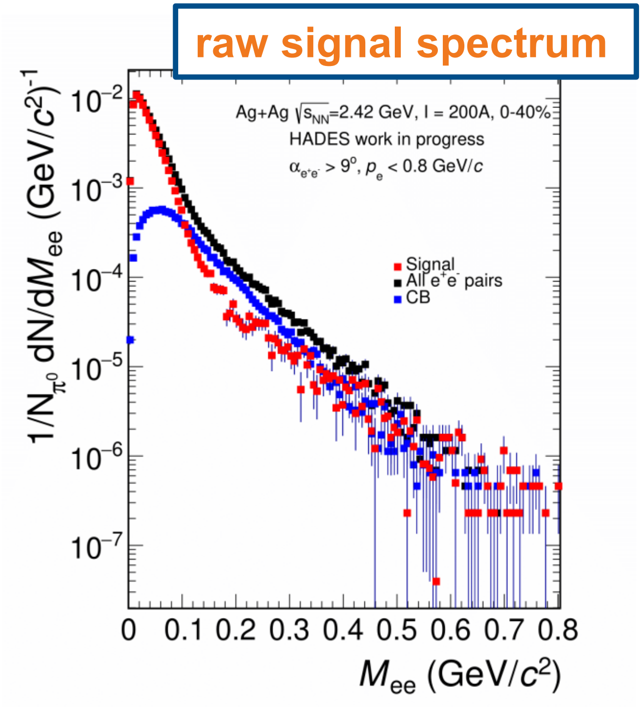
TECHNISCHE UNIVERSITÄT DARMSTADT

- 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

region of interest



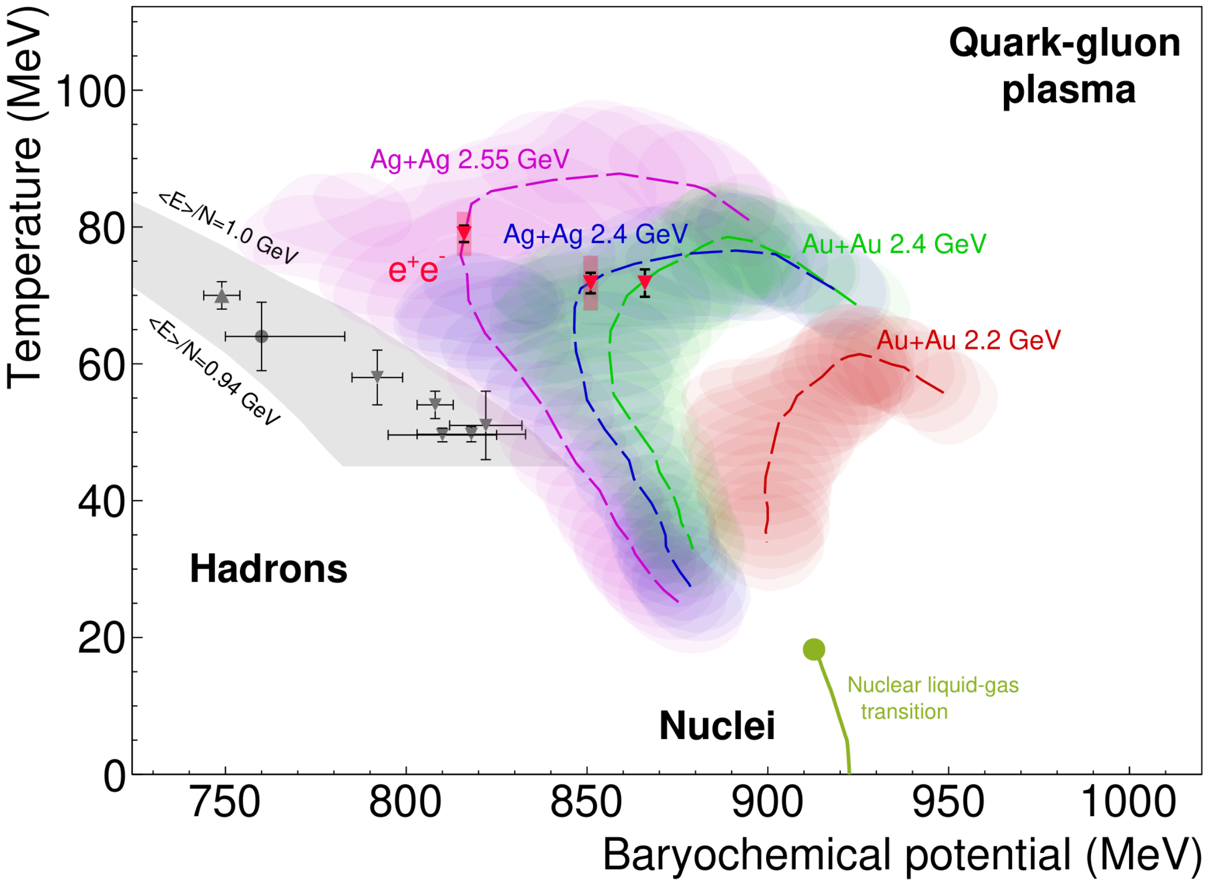




SUMMARY

- HADES provides high-quality data of the di-electron production in elementary and heavy-ion collisions at SIS energy regime

- Unique possibility of characterizing the properties of baryon dominated matter with multi-differential measurements of penetrating probes
  - Establish thermal nature of the radiation
  - Flow, polarization, transport coefficients
  - Possible new phases at high μ_B



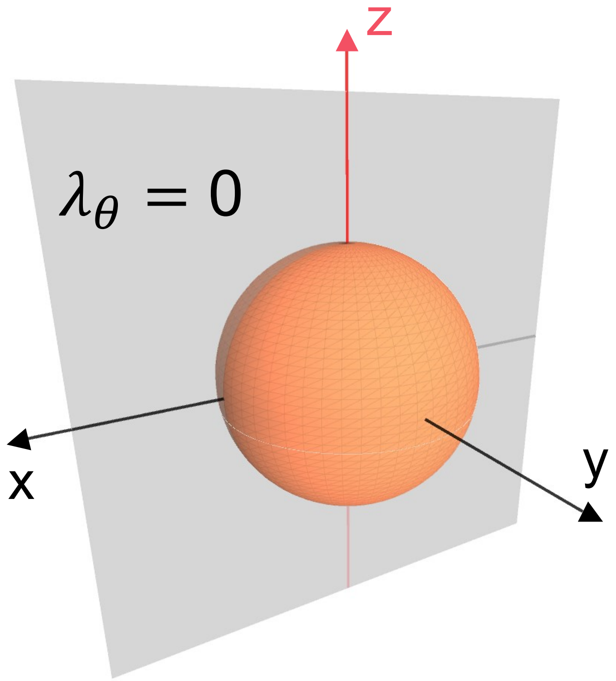
FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Ag+Ag data: HADES preliminary
figure: FS, T.Galatyuk

BACKUP

STATIC THERMAL MEDIUM

- Rotational symmetry only broken by virtual photon's momentum direction
- In the helicity frame HX the only non-zero coefficient is $\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$

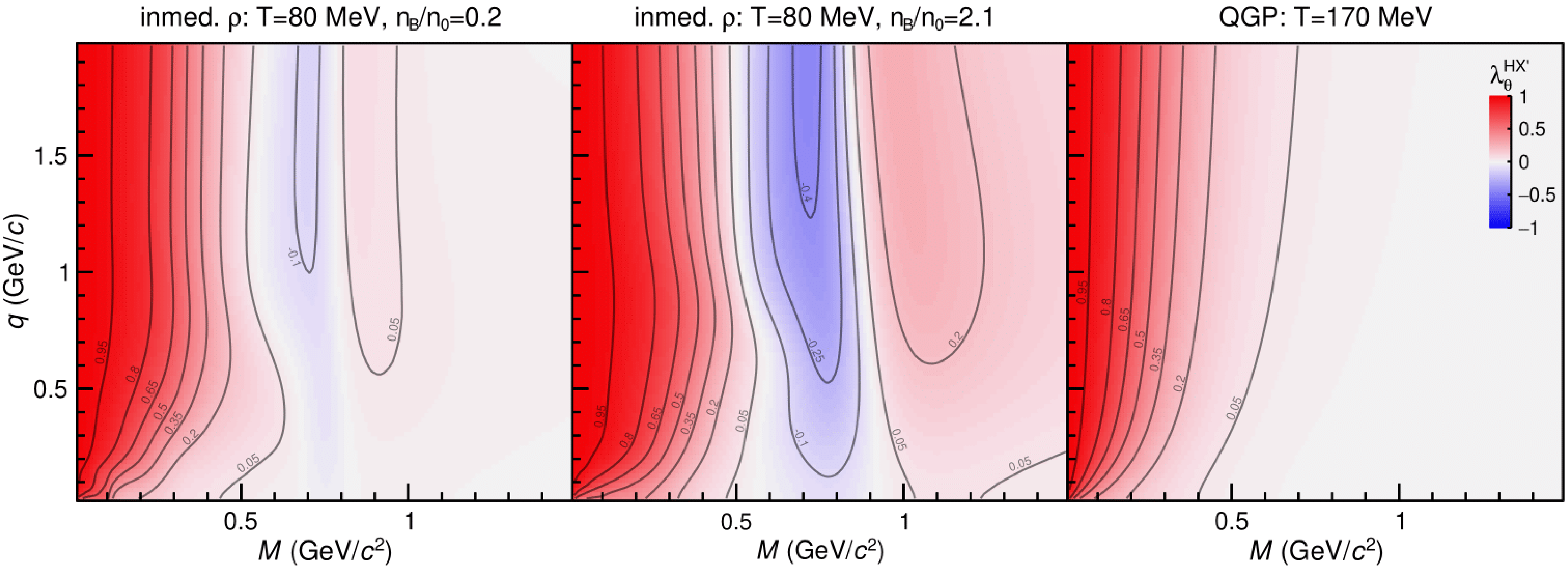
E. Speranza *et al.*, Phys. Lett. B 782, 395 (2018)
G. Baym *et al.*, Phys. Rev. C 95, 044907 (2017)



POLARIZATION IN STATIC MEDIUM

TECHNISCHE UNIVERSITÄT DARMSTADT

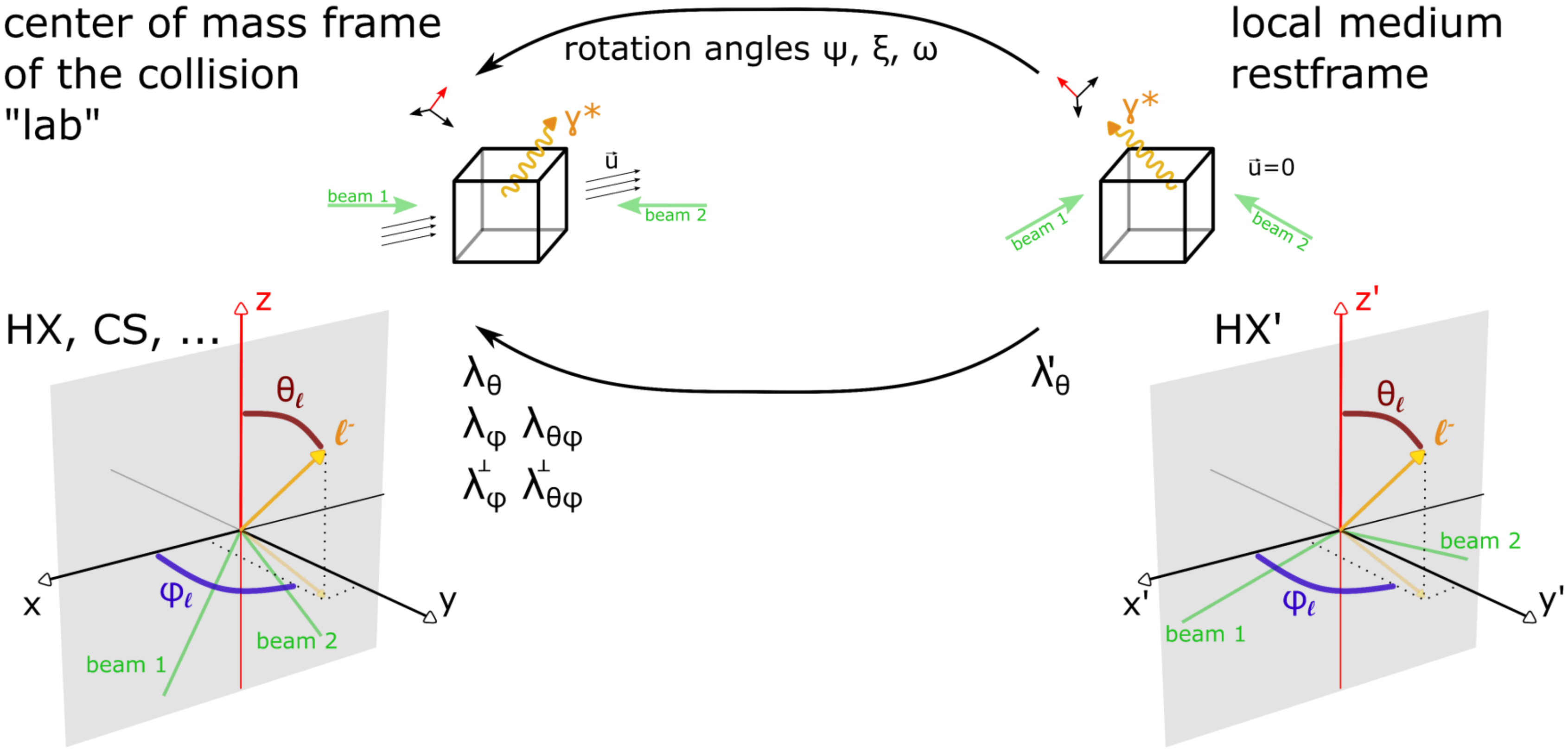
- Strong dependence on mass, momentum and baryon density for hadronic medium
- Rather small polarization for QGP except for M_{ee} < 0.5 GeV/c^2 approaching the photon point



FS *et al.*, arXiv: 2309.03189

POLARIZATION IN MOVING MEDIUM

- Helicity frames (HX') of individual local fluid cells misaligned
- Transform local coefficients to global frame → accessible to experiment: HX, CS, …



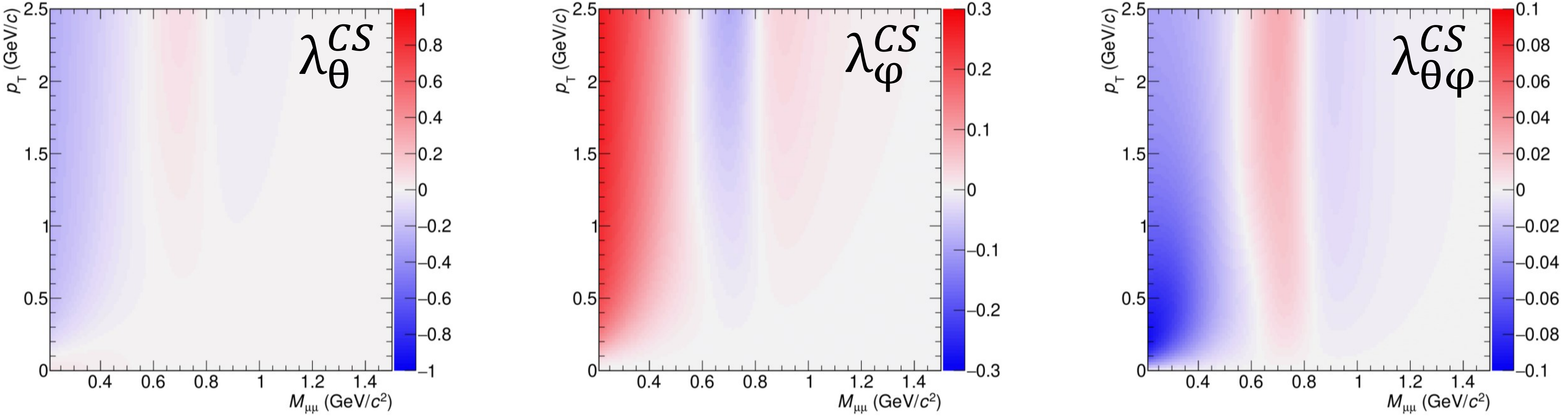
TECHNISCHE UNIVERSITÄT DARMSTADT

- NA60 measured polarization coefficients λ_θ, λ_φ and $\lambda_{\theta\varphi}$ of excess radiation in the CS frame in In+In collisions at 158 AGeV beam energy

NA60 coll., Phys. Rev. Lett. 96, 162302 (2006)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)

- Space-time evolution via isentropic fireball model with transition from QGP to hadronic rates at T=170 MeV

- Strong dependence on the polarization frame as function of mass and momentum



COMPARISON TO NA60 DATA

- Good agreement between data and theory → size and trend

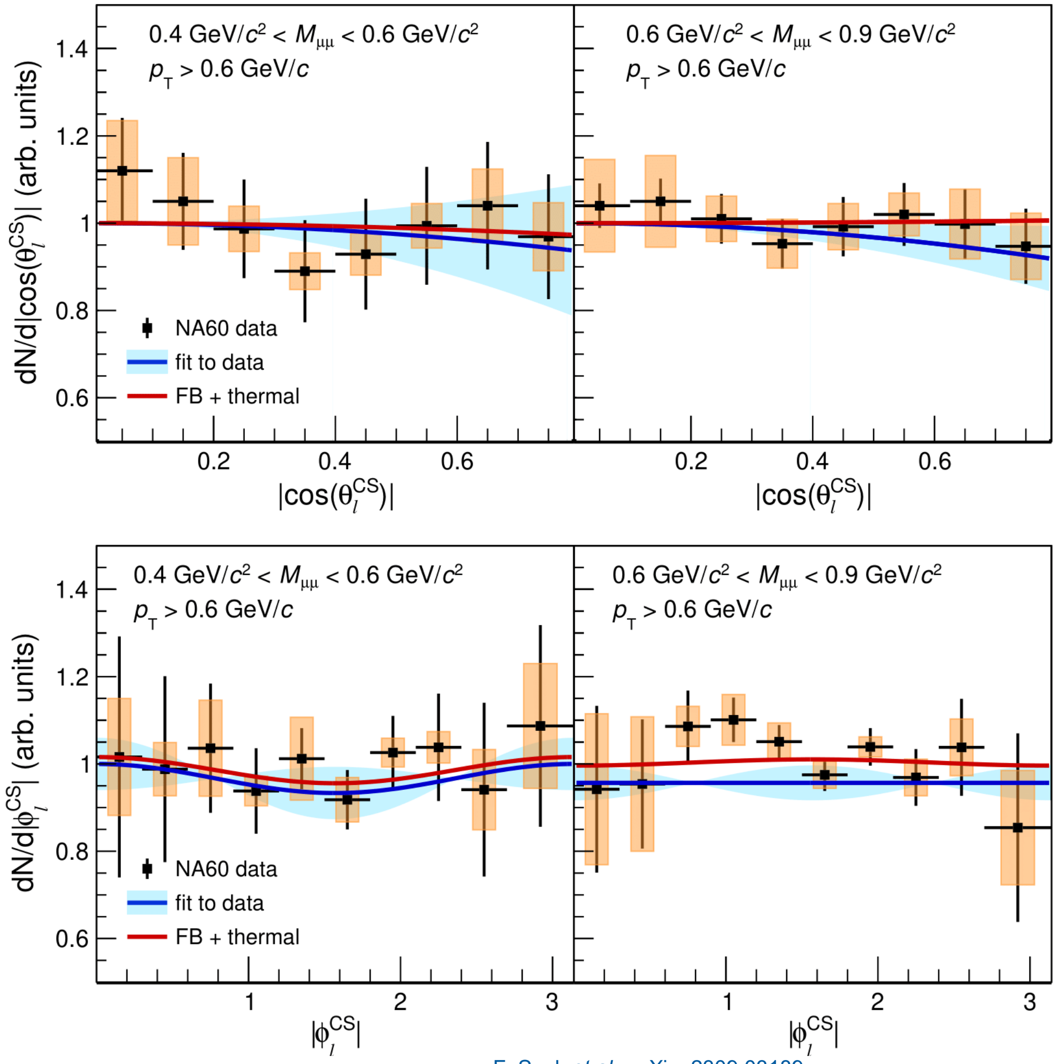
- Near absence of a net polarization
  - not related to thermal isotropy arguments
  - thermal properties of the EM spectral function

- **Best fit** to data gives $\lambda_\theta = -0.10 \pm 0.24$ and $\lambda_\theta = -0.13 \pm 0.12$ in the two mass windows
- **Calculation** results in $\lambda_\theta = -0.04$ and $\lambda_\theta = 0.01$ respectively

- **Best fit** to data gives $\lambda_\varphi = 0.05 \pm 0.09$ and $\lambda_\varphi = 0.00 \pm 0.06$ in the two mass windows
- **Calculation** results in $\lambda_\varphi = 0.04$ and $\lambda_\varphi = -0.01$ respectively

- **Best fit** to data gives $\lambda_{\theta\varphi} = -0.04 \pm 0.10$ and $\lambda_{\theta\varphi} = 0.05 \pm 0.03$ in the two mass windows
- **Calculation** results in $\lambda_{\theta\varphi} = -0.02$ and $\lambda_{\theta\varphi} = 0.01$ respectively

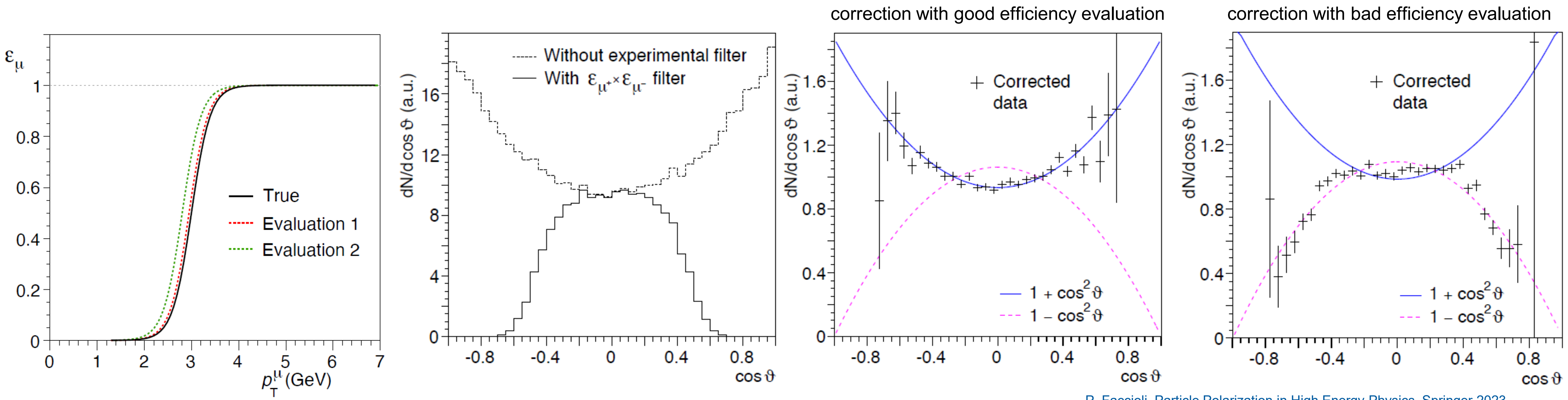
data points: NA60 coll,, Phys. Rev. Lett. 102, 222301 (2009)



F. Seck *et al.*, arXiv: 2309.03189

EXPERIMENTAL DIFFICULTIES

- Virtual photon polarization influences detection efficiency
- Efficiency + acceptance corrections need to be done carefully
- Wrong efficiency evaluation can lead to wrong sign of polarization



P. Faccioli, Particle Polarization in High Energy Physics, Springer 2023

PROSPECT OF DISENTANGLING HADRONIC AND PARTONIC SOURCES

- Polarization plays important role in exploring the mechanisms underlying EM emission
- Multi-differential measurements of the virtual photon polarization
  - resolve mass, p_T, rapidity, lepton emission angles θ_l, φ_l → large datasets needed
  - future high-rate experiments CBM, NA60+ and ALICE3