# LOW-MOMENTUM / LOW-MASS DILEPTONS IN HADES AND RESULTS ON PHOTON POLARIZATION FROM COARSE-GRAINING APPROACH


Florian Seck
(TU Darmstadt)


Penetrating Probes of Hot High-$\mu_B$ Matter: Theory Meets Experiment

July 21 – 25, ECT*, Trento

# 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 $\varepsilon$) 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

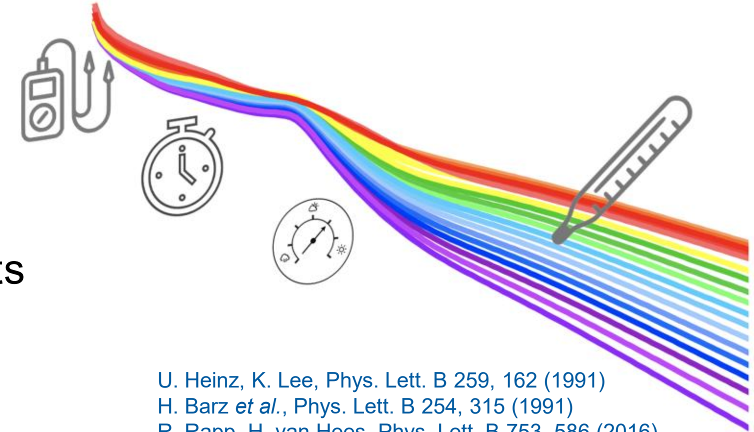
  → **access** information on **production mechanism**

- 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

- Access to exotic QCD phases

  → yield **enhancement** in vicinity of **color superconducting phase** (?)




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
G. Vujanovic et al., Phys. Rev. C 89 (2014), 034904
T. Reichert *et al.*, Phys. Lett. B 841 (2023) 137947
R. Hirayama, H. Elfner, arXiv:2408.16603

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
R. Rapp, arXiv: 2406.14656

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, Phys. Rev. C 109, 034902 (2024)

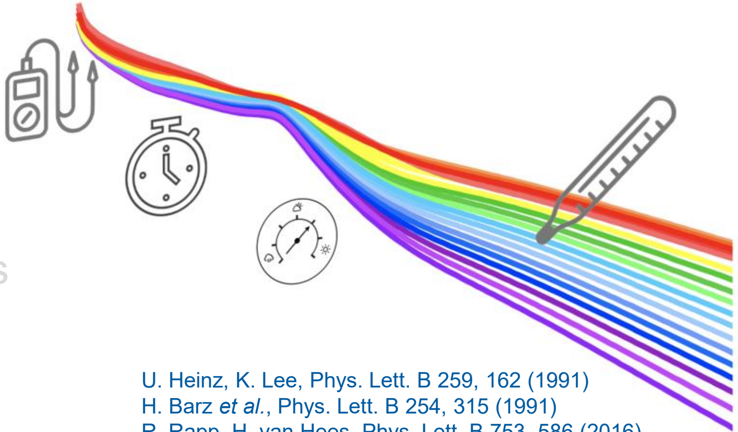
T. Nishimura *et al.*, Eur. Phys. J. A 60, 82 (2024)

## THERMAL DILEPTON RADIATION AS MULTIMETER OF THE FIREBALL

TECHNISCHE UNIVERSITÄT DARMSTADT

- 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 $\varepsilon$) 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/$c$, $M_{ee}$ → 0 MeV/$c^2$
  → **access** to **transport properties** of QCD matter
- Access to exotic QCD phases
  → yield **enhancement** in vicinity of **color superconducting phase** (?)

**Dileptons are rare probes → high-rate, high-efficiency detectors**
**→ HADES at GSI, CBM at FAIR, NA60+ at CERN**




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
G. Vujanovic et al., Phys. Rev. C 89 (2014), 034904
T. Reichert *et al.*, Phys. Lett. B 841 (2023) 137947
R. Hirayama, H. Elfner, arXiv:2408.16603

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
R. Rapp, arXiv: 2406.14656

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, Phys. Rev. C 109, 034902 (2024)

T. Nishimura *et al.*, Eur. Phys. J. A 60, 82 (2024)

## VIRTUAL PHOTON POLARIZATION: BASICS

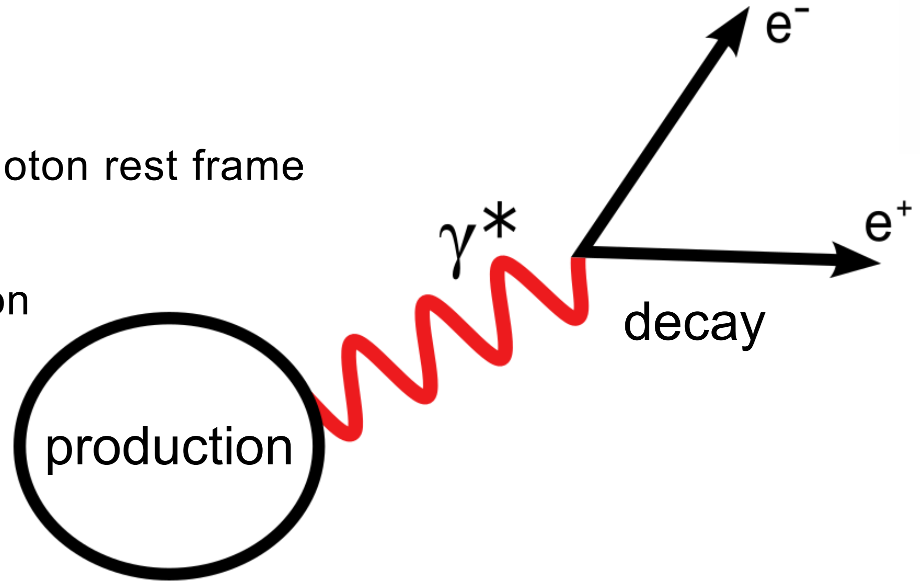
Angular distribution of the decay leptons in the virtual photon rest frame

↓

Information on the polarization states of the virtual photon

↓

Information on the production mechanism



# VIRTUAL PHOTON POLARIZATION: BASICS

TECHNISCHE UNIVERSITÄT DARMSTADT

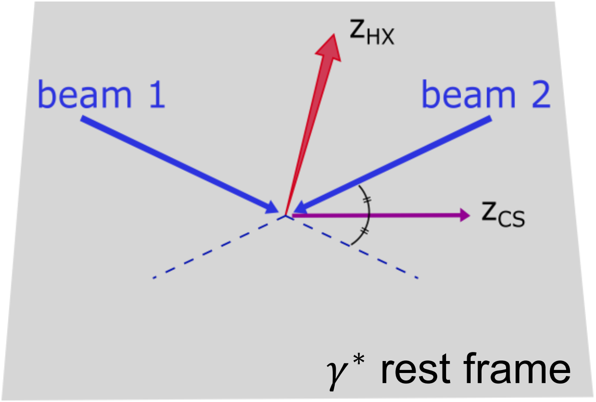
Angular distribution of the decay leptons in the virtual photon rest frame

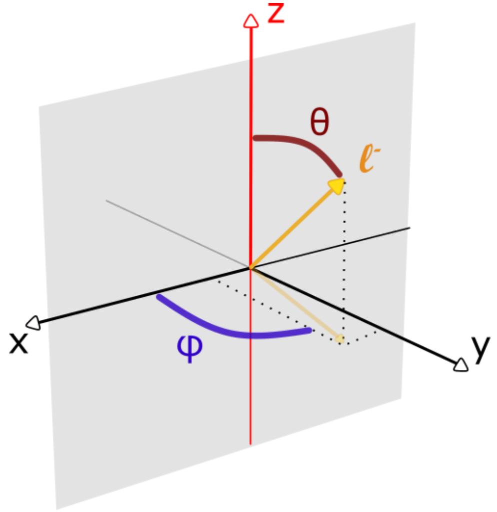
↓

Information on the polarization states of the virtual photon

↓

Information on the production mechanism

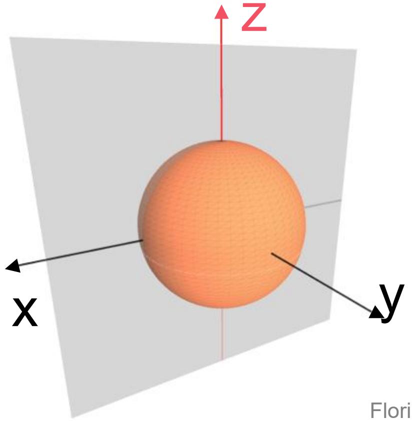


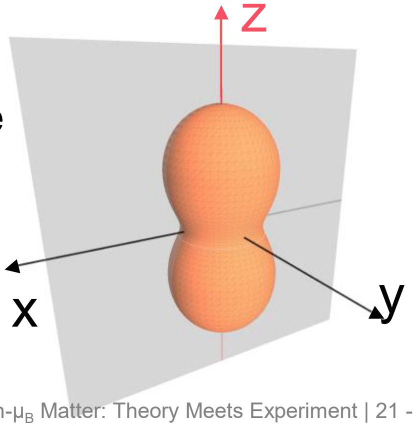

- Different choices for polarization axis possible
  - Helicity frame, Collins-Soper frame, etc.

- General angular distribution $\frac{dN}{d\cos\theta\, d\varphi} = \mathcal{N}\,(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi)$

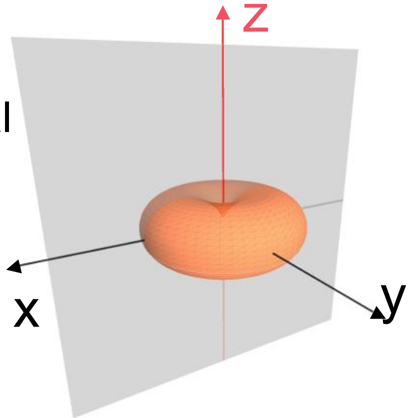
$\lambda_\theta = 0$
isotropic




$\lambda_\theta = 1$
transverse




$\lambda_\theta = -1$
longitudinal



## VIRTUAL PHOTON POLARIZATION: BASICS

TECHNISCHE UNIVERSITÄT DARMSTADT

Angular distribution of the decay leptons in the virtual photon rest frame

↓

Information on the polarization states of the virtual photon

↓

Information on the production mechanism

- Different choices for polarization axis possible
    - Helicity frame, Collins-Soper frame, etc.

- General angular distribution $$\frac{dN}{d\cos\theta\, d\varphi} = \mathcal{N}\left(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi\right)$$

- Different virtual photon **production mechanisms** imprint different anisotropy parameters λ

- Dalitz-decays of $\pi^0$, η transverse polarized to real photon momentum direction

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)

HADES, Phys. Rev. C 95, 065205 (2017)

# VIRTUAL PHOTON POLARIZATION: STATIC THERMAL MEDIUM

TECHNISCHE UNIVERSITÄT DARMSTADT

- EM emissivity of thermal QCD matter determined by the correlator of the EM current $\Pi^{\mu\nu}_{EM} = \langle j^{\mu}_{EM}\, j^{\nu}_{EM} \rangle_T$
- Dilepton emission rate given by

$$\frac{dN_{ll}}{d^4x\, d^4q} = \frac{\alpha^2\, L(M)}{6\, \pi^3\, M^2}\, f^B(q_0;\, T)\, g_{\mu\nu}\ \rho^{\mu\nu}_{EM}(M, |\vec{q}|;\, T, \mu_B) \quad \text{with} \quad \rho^{\mu\nu}_{EM} = -2\ \mathrm{Im}\ \Pi^{\mu\nu}_{EM}$$

- Decomposition using standard 4D projectors for a spin-1 particle $P^{\mu\nu}_{L,T}$

$$\rho^{\mu\nu}_{EM} = \rho_L\, P^{\mu\nu}_L + \rho_T\, P^{\mu\nu}_T \quad \text{with} \quad g_{\mu\nu}\, \rho^{\mu\nu}_{EM} = \rho_L + 2\rho_T$$

- Rotational symmetry of the medium broken by finite $|\vec{q}|$
- $\lambda$ coefficients related to **difference** between **longitudinal** and **transverse** spectral function components

  → for a static thermal medium in the helicity frame: $\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$

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

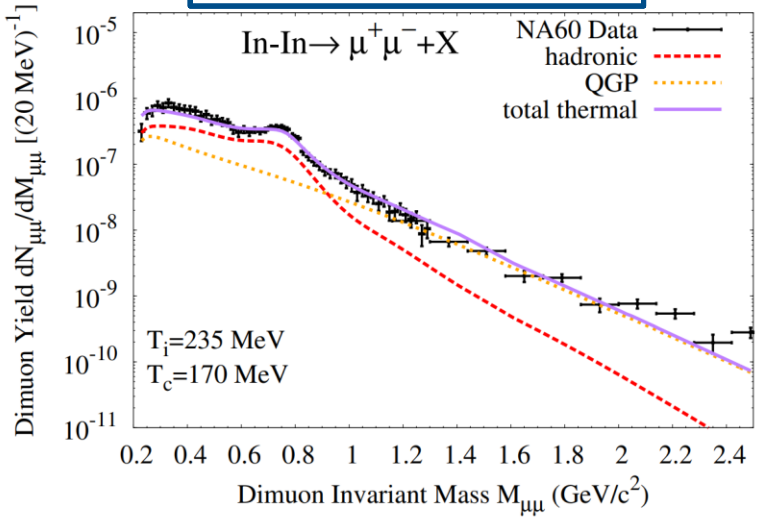
- Anisotropy coefficients in different frames related via rotations
- For moving medium: transform local coefficients to global frame accessible in experiment → comparison to data

# REALISTIC SPECTRAL FUNCTIONS

TECHNISCHE UNIVERSITÄT DARMSTADT

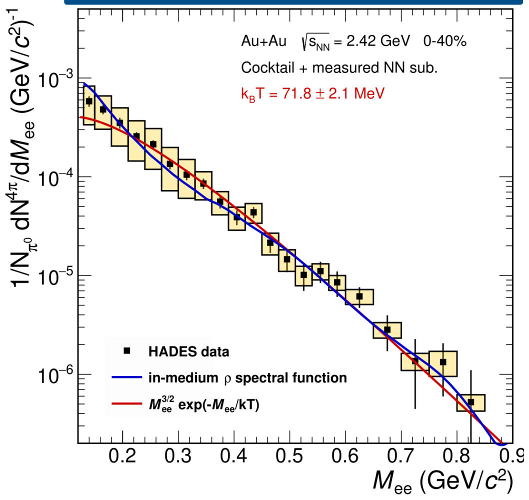
- Employ in-medium spectral functions that give fair description of available dilepton data

**In+In at $\sqrt{s_{NN}} = 17.3$ GeV**



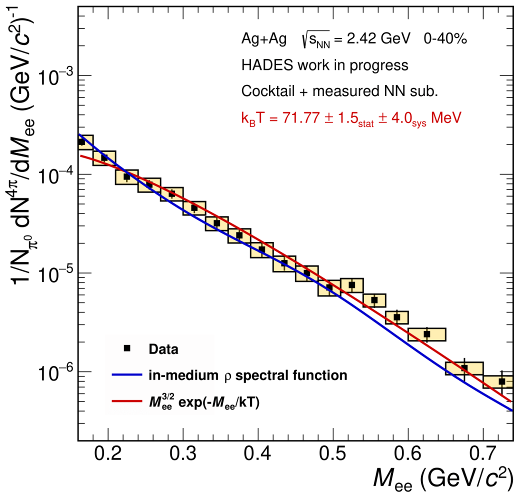

NA60, Phys. Rev. Lett. 96, 162302 (2006)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)

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

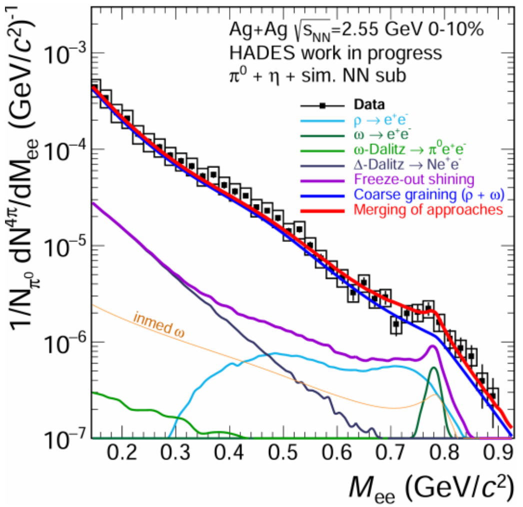



HADES, Nature Phys. 15(2019) 1040
T. Galatyuk *et al.*, Eur. Phys. J. A 52, 131 (2016)

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




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




J. Vogel, T. Galatyuk, FS, QM 2025 poster
J. Vogel, master thesis (TU Darmstadt)

- Hadronic emission with in-medium ρ-meson spectral function calculated from hadronic many-body theory based on effective Lagrangians

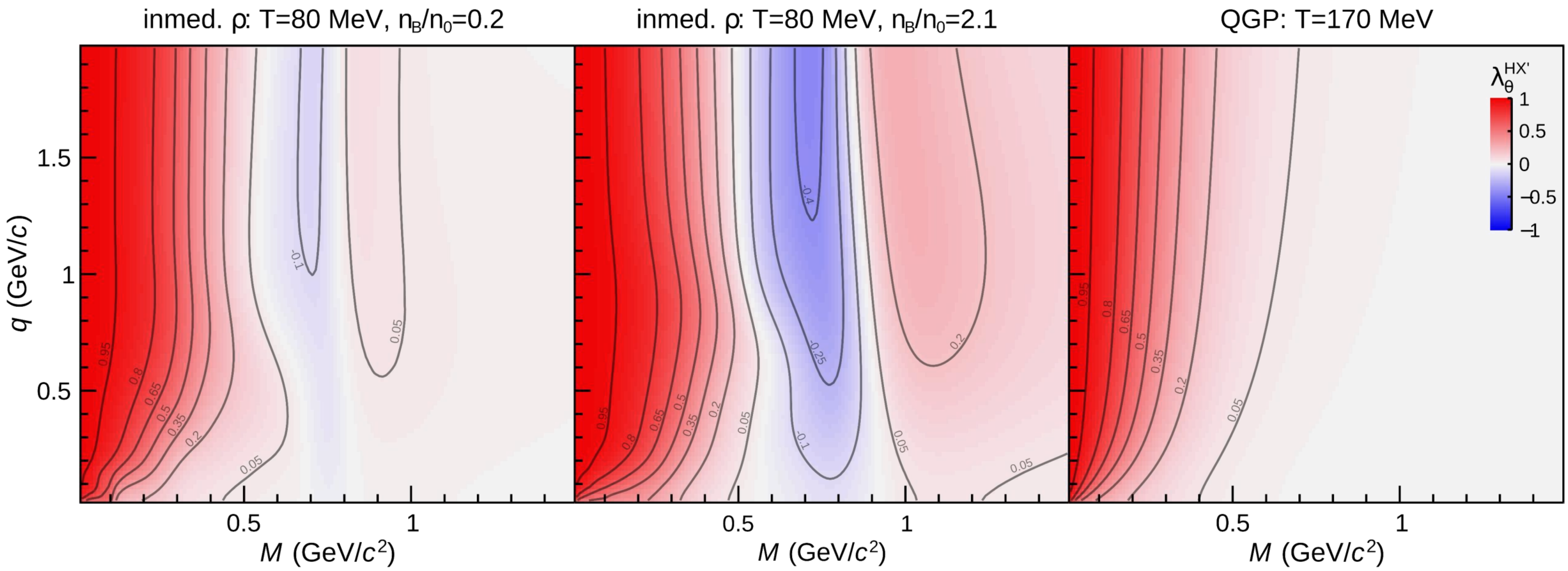
R. Rapp, J. Wambach, Eur. Phys. J. A 6, 415 (1999)
R. Rapp, G. Chanfray, J. Wambach, Nucl. Phys. A 617, 472 (1997)

- QGP emission based on perturbative $q\bar{q}$ annihilation with a low-energy transport peak constrained by lQCD data

R. Rapp, Adv. High Energy Phys. 2013, 148253 (2013)

## POLARIZATION IN STATIC THERMAL MEDIUM

- 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



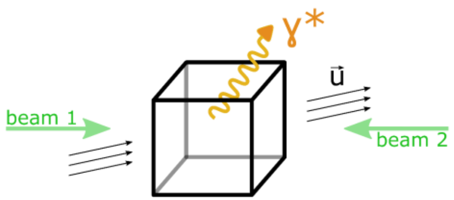

FS *et al.*, Phys. Lett. B 861, 139267 (2025)

## POLARIZATION IN MOVING MEDIUM

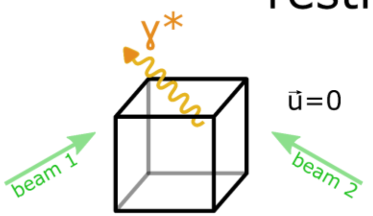
TECHNISCHE UNIVERSITÄT DARMSTADT

- Helicity frames (HX’) of individual local fluid cells misaligned
- Transform polarization coefficients from each cell into a global frame accessible to experiment: HX, CS, …
- Integration over kinematic bins with weighted mean

center of mass frame
of the collision
"lab"

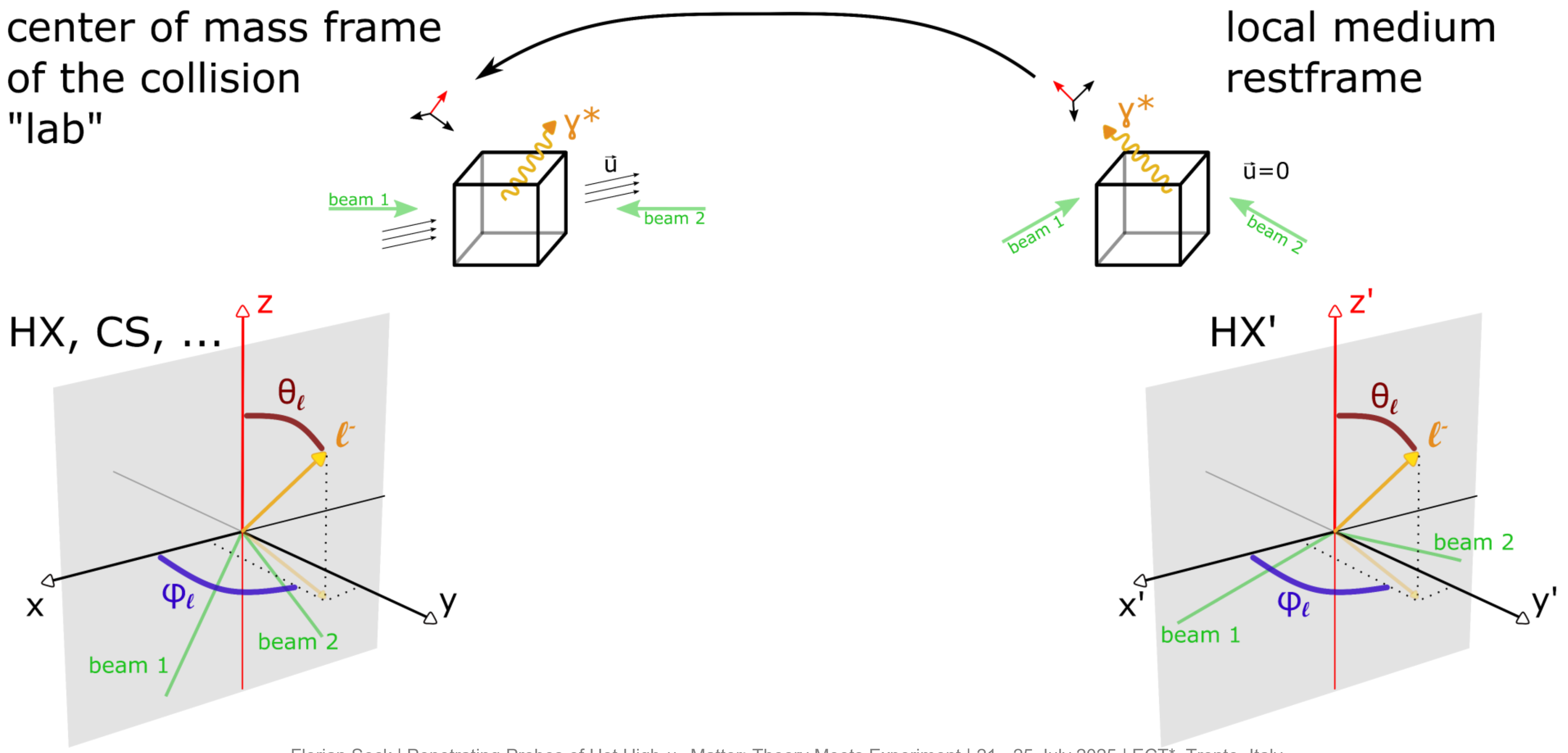



local medium
restframe



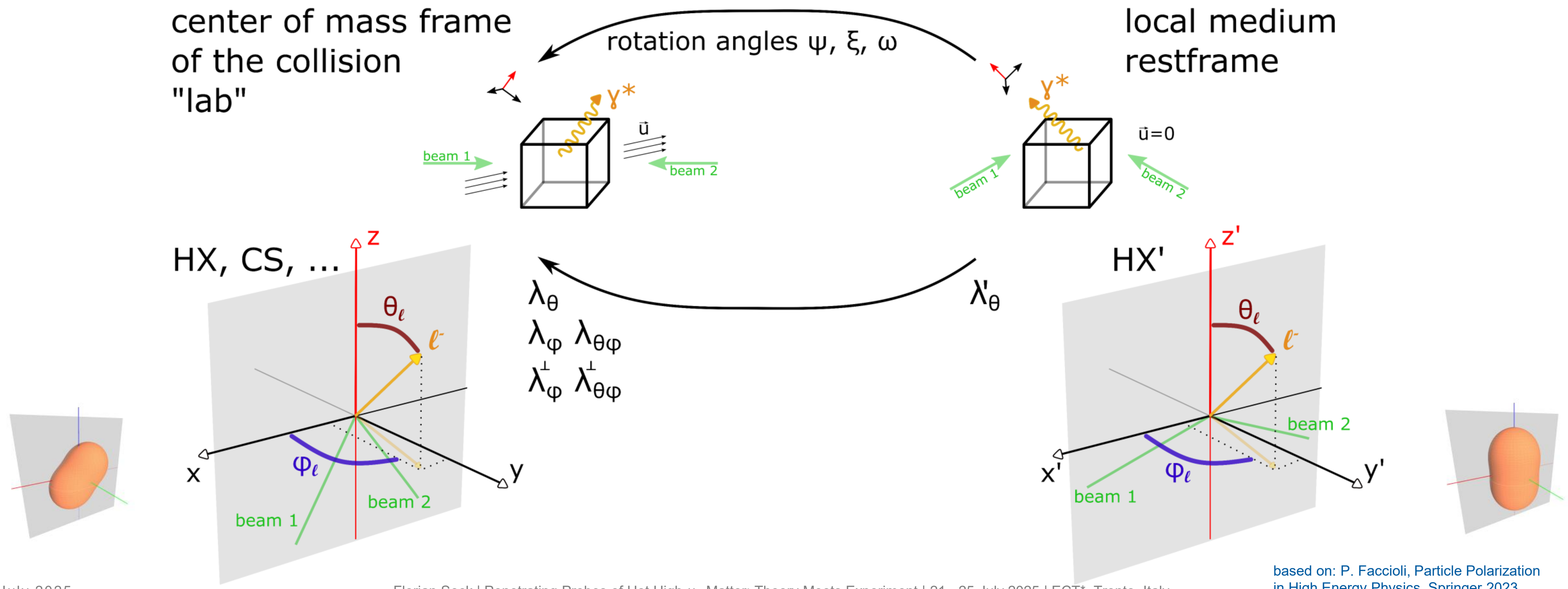
## POLARIZATION IN MOVING MEDIUM

- Helicity frames (HX') of individual local fluid cells misaligned
- Transform polarization coefficients from each cell into a global frame accessible to experiment: HX, CS, …
- Integration over kinematic bins with weighted mean



# POLARIZATION IN MOVING MEDIUM

- Helicity frames (HX') of individual local fluid cells misaligned
- Transform polarization coefficients from each cell into a global frame accessible to experiment: HX, CS, …
- Integration over kinematic bins with weighted mean



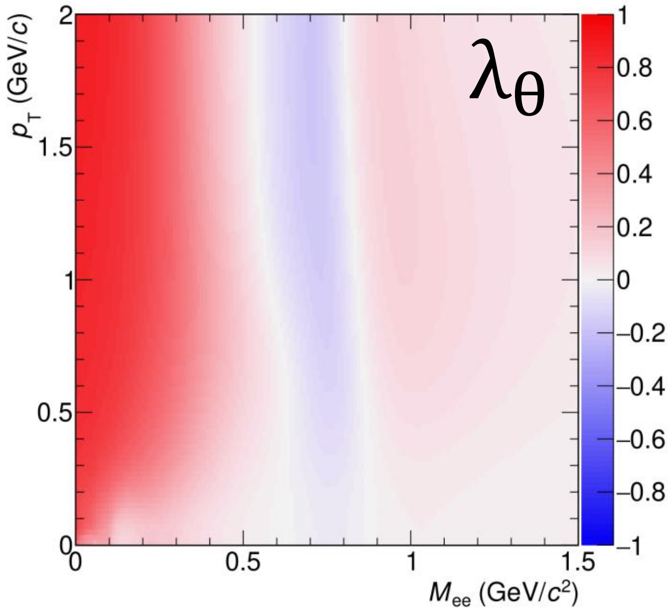

based on: P. Faccioli, Particle Polarization in High Energy Physics, Springer 2023

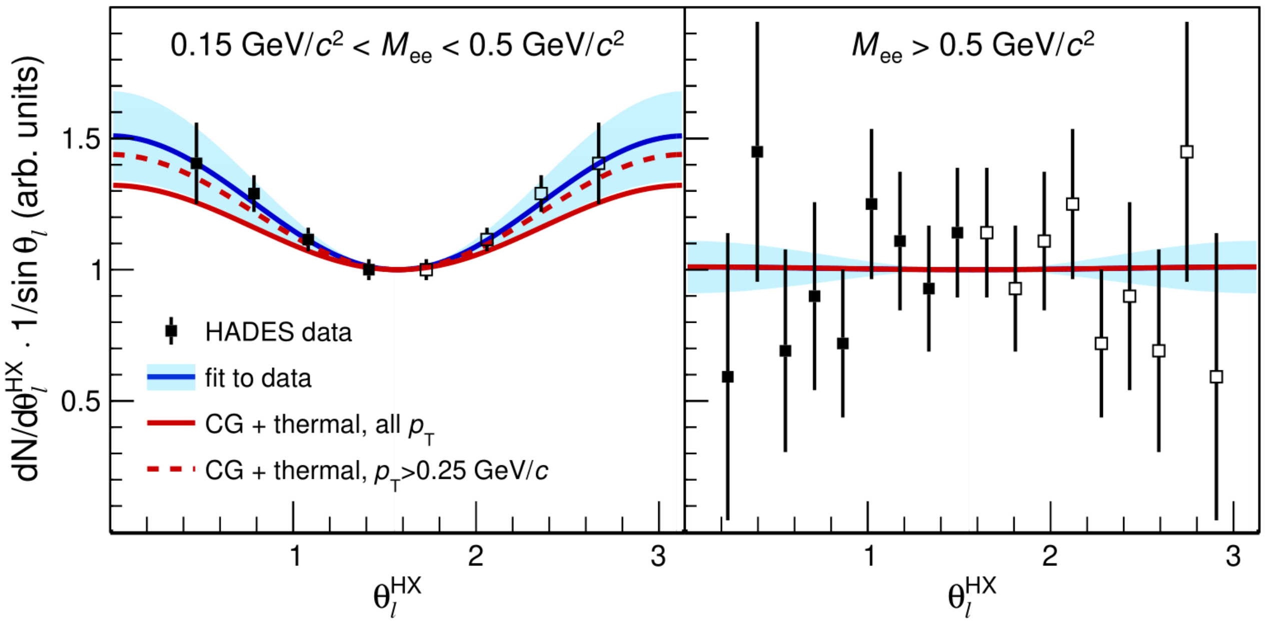
## COMPARISON TO HADES DATA

- HADES measured anisotropy coefficient $\lambda_\theta$ of excess radiation in Ar+KCl collisions at 1.76A GeV ($\sqrt{s_{NN}} = 2.62$ GeV)
- Space-time evolution via coarse-grained hadronic transport
- Polarization largely survives evolution of the expanding medium

HADES, Phys. Rev. C 84, 014902 (2011)
T. Galatyuk *et al.*, Eur. Phys. J. A 52, 131 (2016)
FS et al., Phys. Lett. B 861, 139267 (2025)

- **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



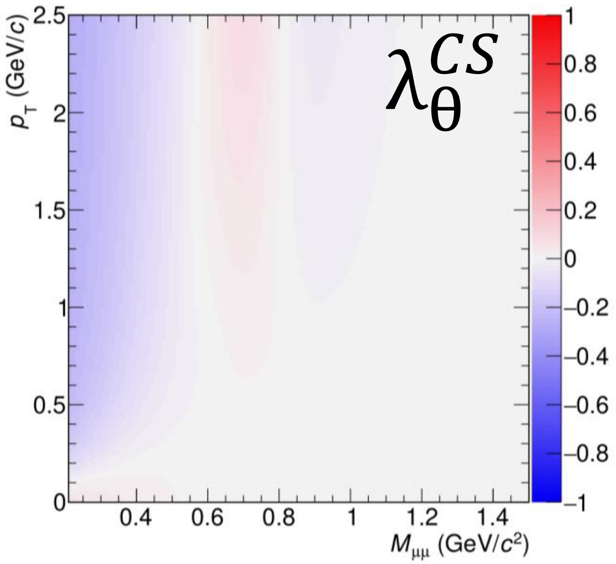



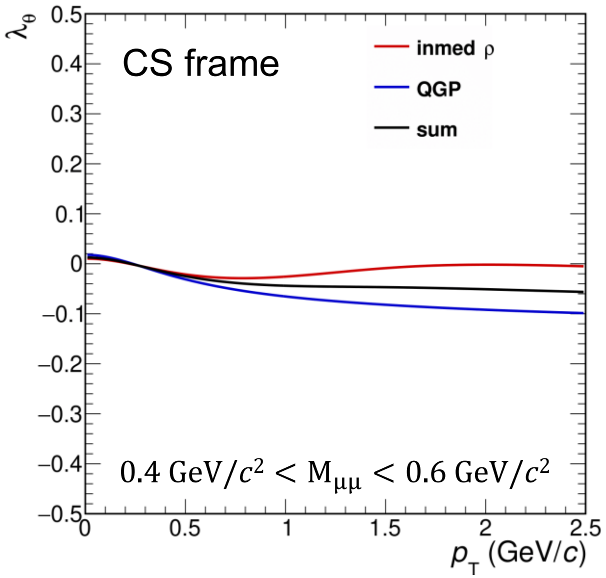
## COMPARISON TO NA60 DATA

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

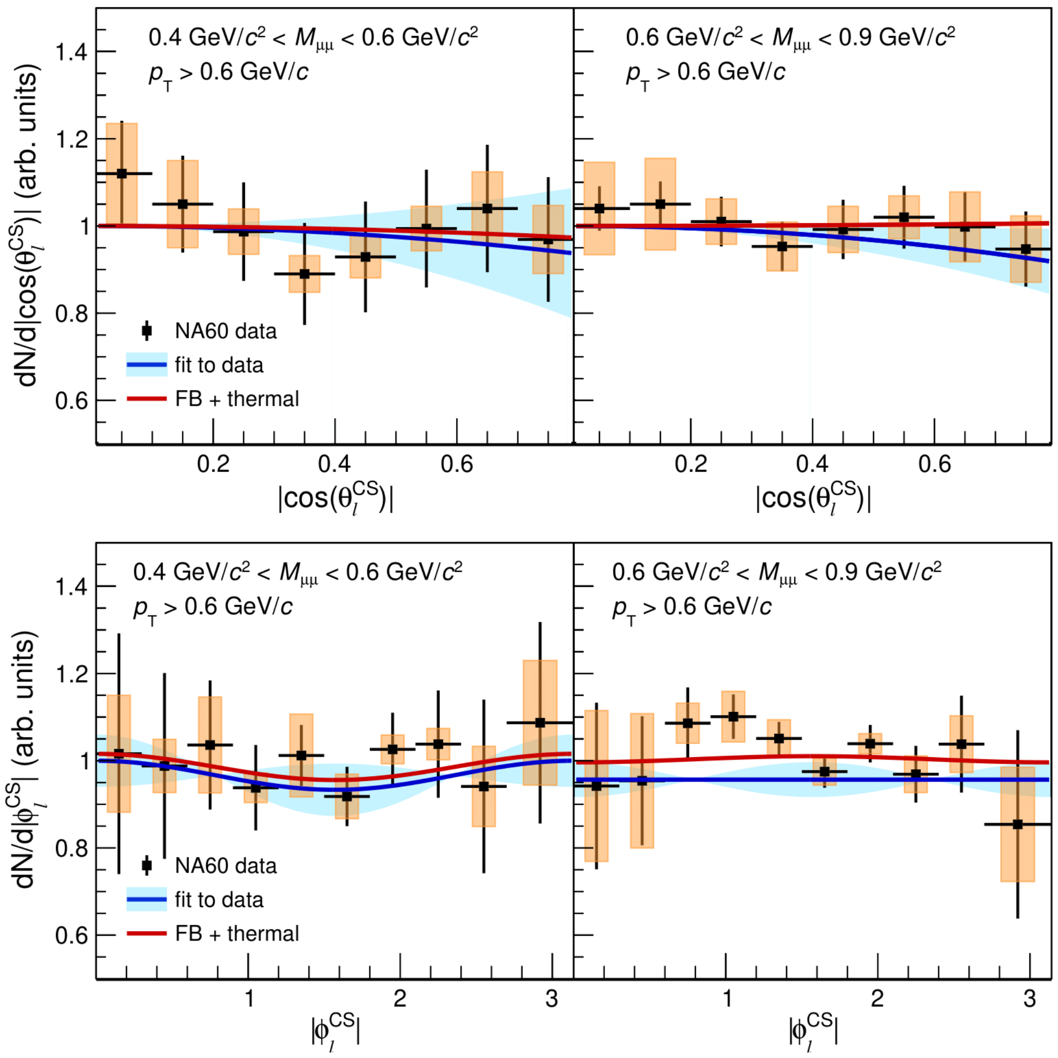
NA60, Phys. Rev. Lett. 96, 162302 (2006)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)

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




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

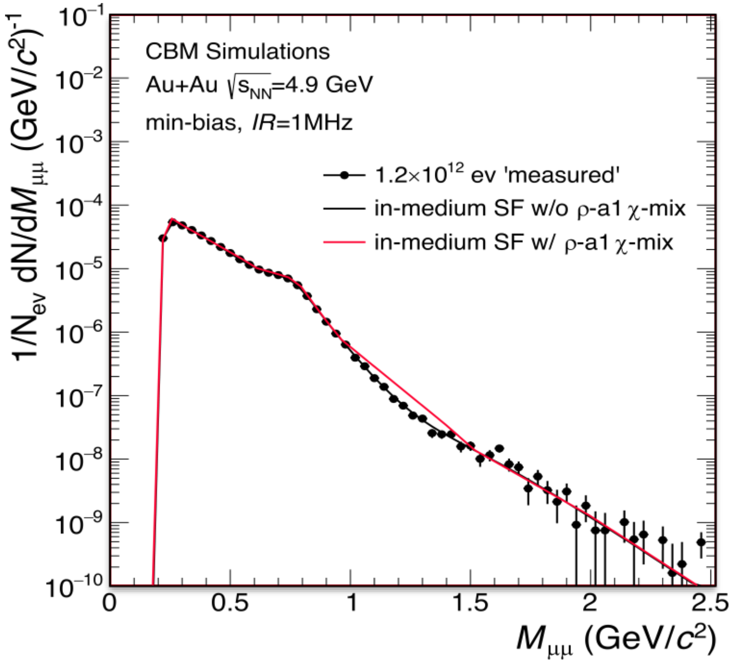


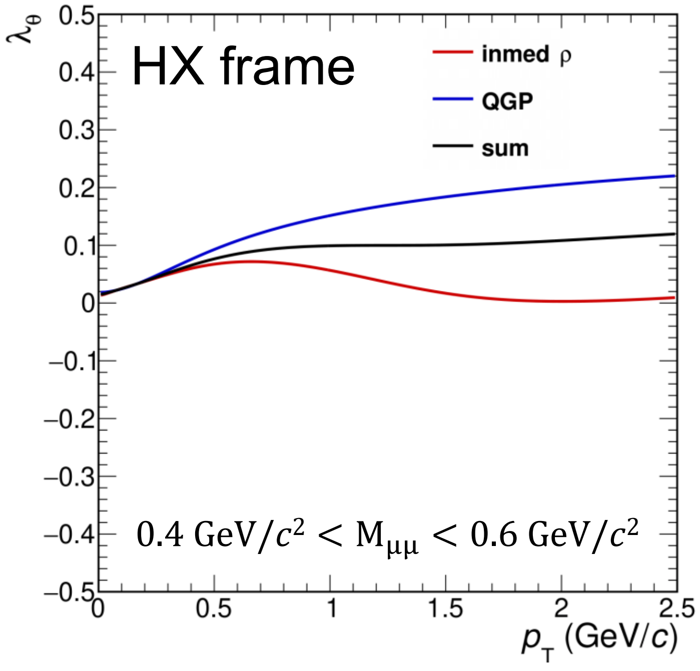

FS et al., Phys. Lett. B 861, 139267 (2025)

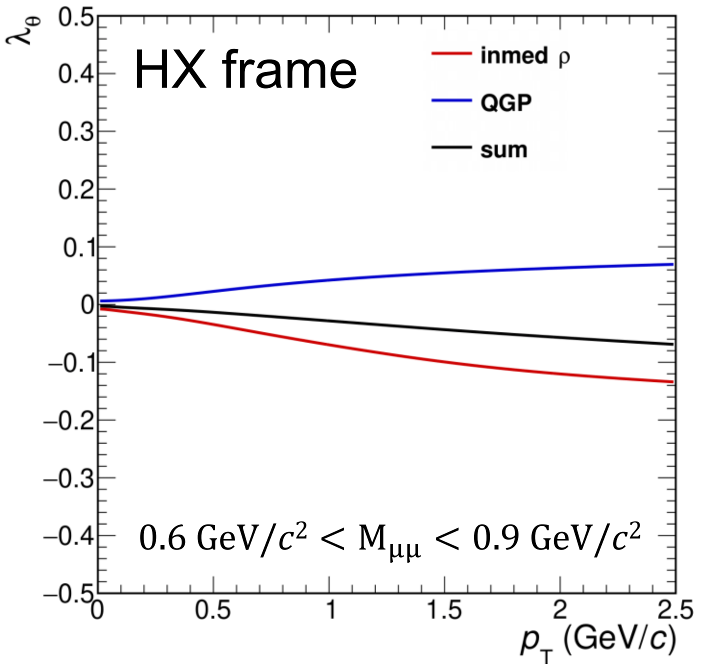
# PROSPECT OF DISENTANGLING HADRONIC AND PARTONIC SOURCES

- Polarization plays important role in exploring the mechanisms underlying EM emission
  - ρ-$a_1$ chiral mixing vs. QGP around $M_{ee}$ ~ 1.1 GeV (?)
  - Search for onset of QGP (?)

- Multi-differential measurements of the virtual photon polarization
  - Resolve mass, $p_T$, rapidity, lepton emission angles $\theta_l, \varphi_l$ → large datasets needed → CBM, NA60+, ALICE3

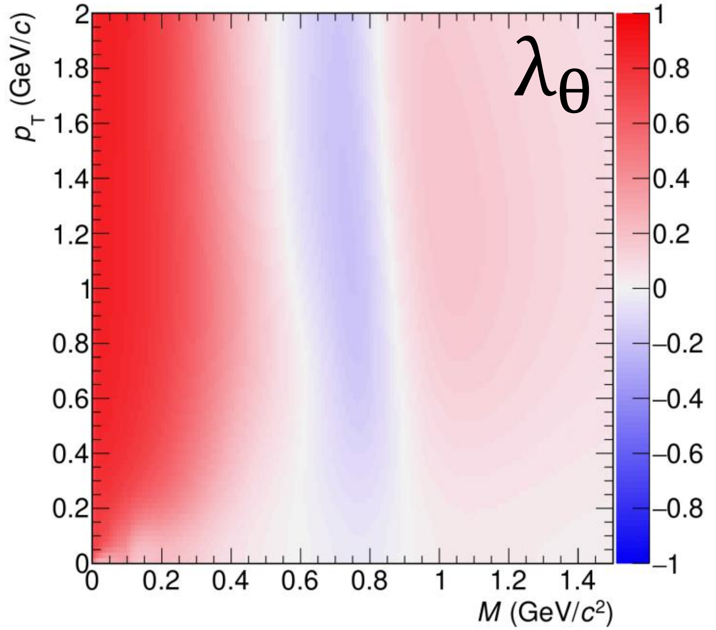


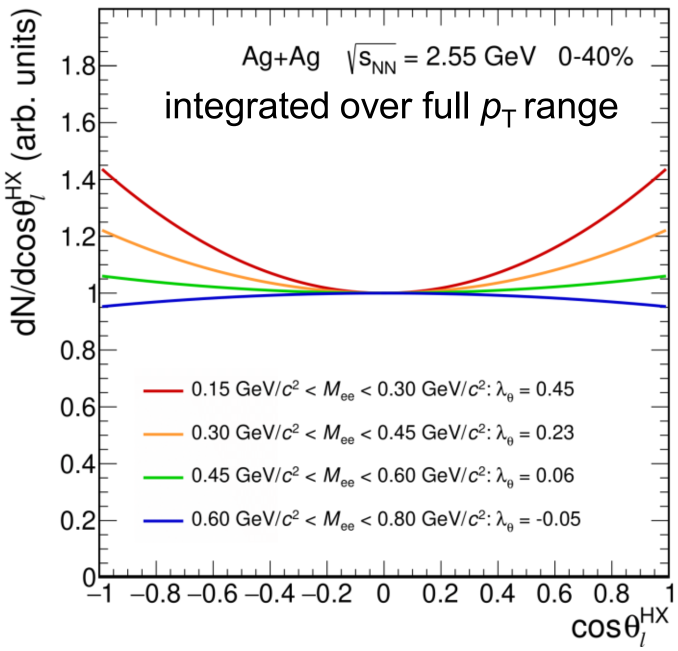



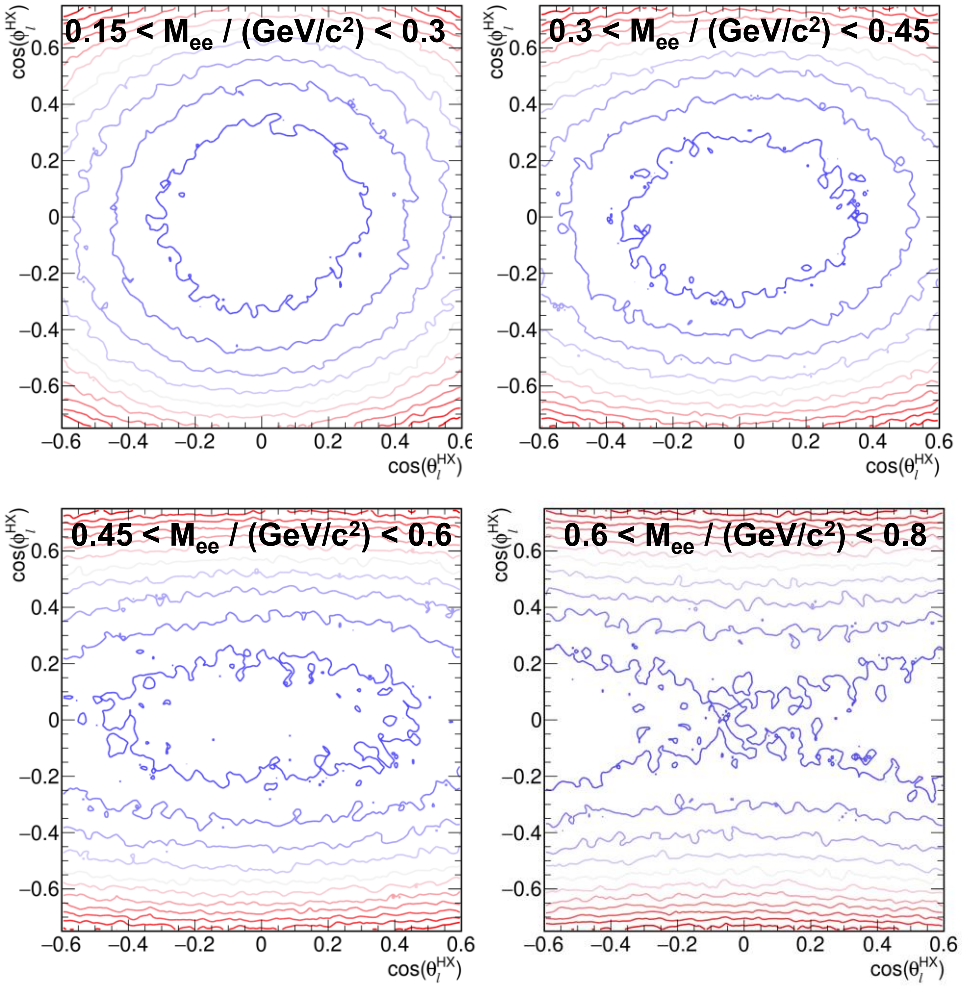
# PREDICTIONS FOR AG+AG COLLISIONS & FUTURE EXPERIMENTS

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



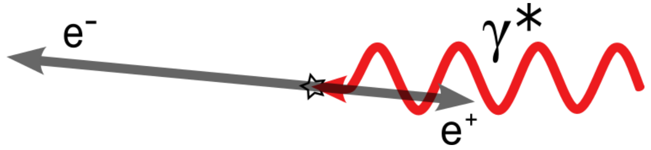

$p_T > 0.5$ GeV/$c$

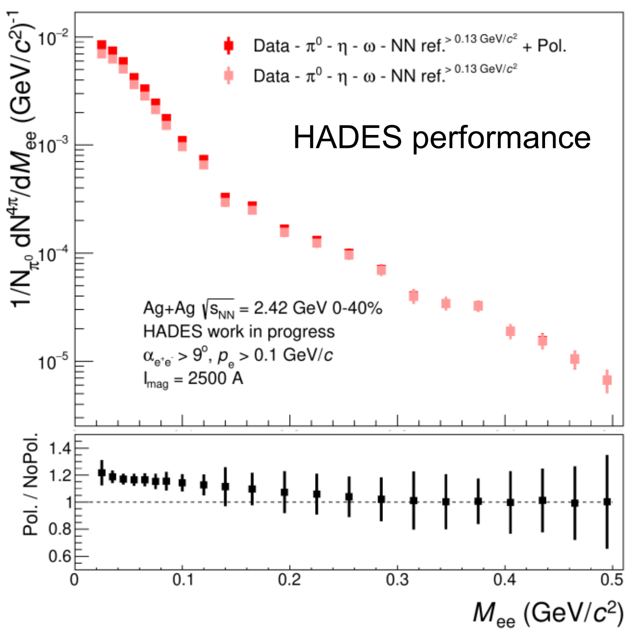


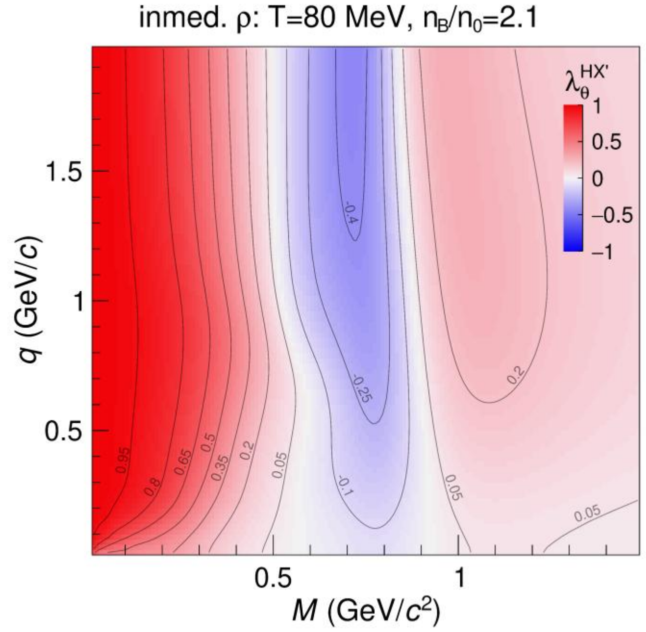
## POLARIZATION: IMPACT ON MASS SPECTRA

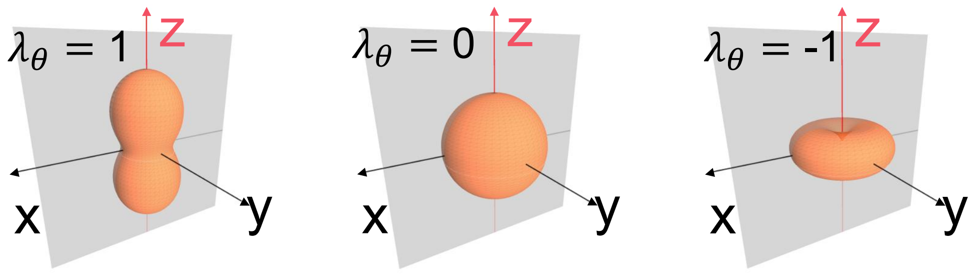
- Polarization does not affect mass spectra in 4π, but:
- Leads to up to 20% difference in the HADES acceptance at low masses
    - Low-mass virtual photons are transversely polarized ($\lambda_\theta > 0$)
    - Emission of leptons predominantly along the virtual photon momentum direction
    - Lepton traveling against the virtual photon momentum gets rejected by low-momentum cut
    - Needs to be accounted for in the pair-acceptance correction with thermal ρ

⟶ Now included in the analysis procedure



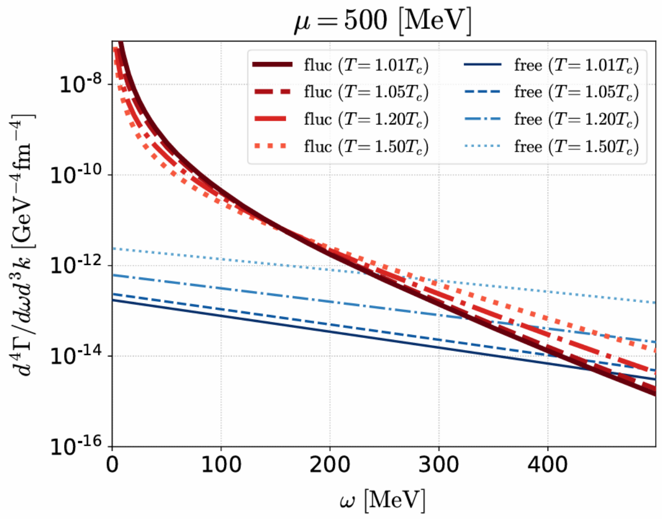



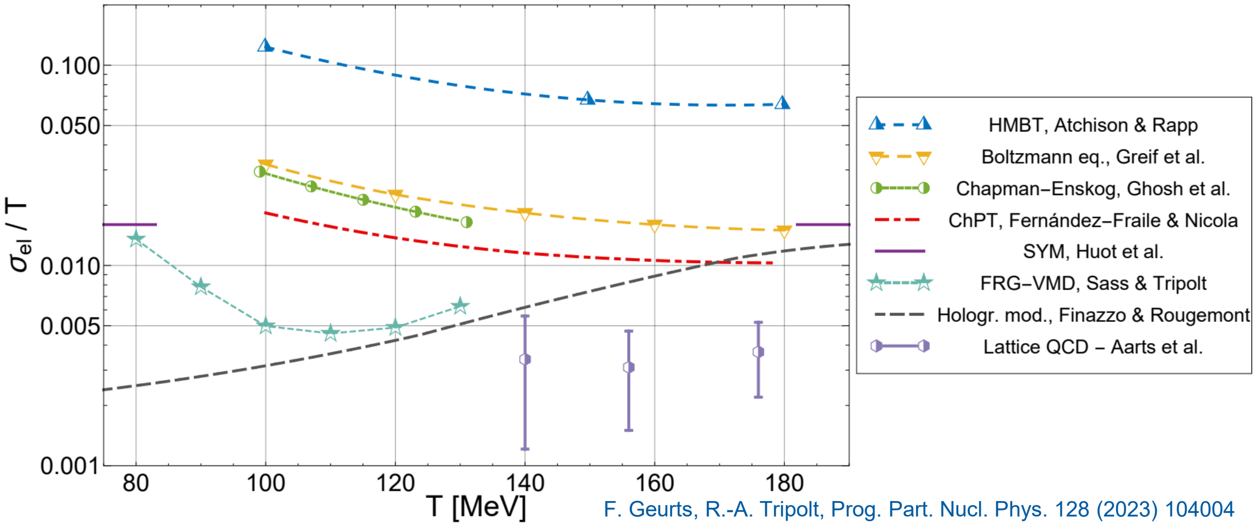



# LOW-MASS LOW-MOMENTUM DILEPTONS

- 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 electrical conductivity
- Large **theoretical uncertainty**
  → **Experimental constraints** are highly desirable
- Determines time evolution of electromagnetic fields generated by spectators
  - Important for effects related to the presence of strong magnetic fields




T. Nishimura *et al.*, PTEP 2022 (2022) 9, 093D02
arXiv:2201.01963
T. Nishimura et al., Eur. Phys. J. A 60, 82 (2024)




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]

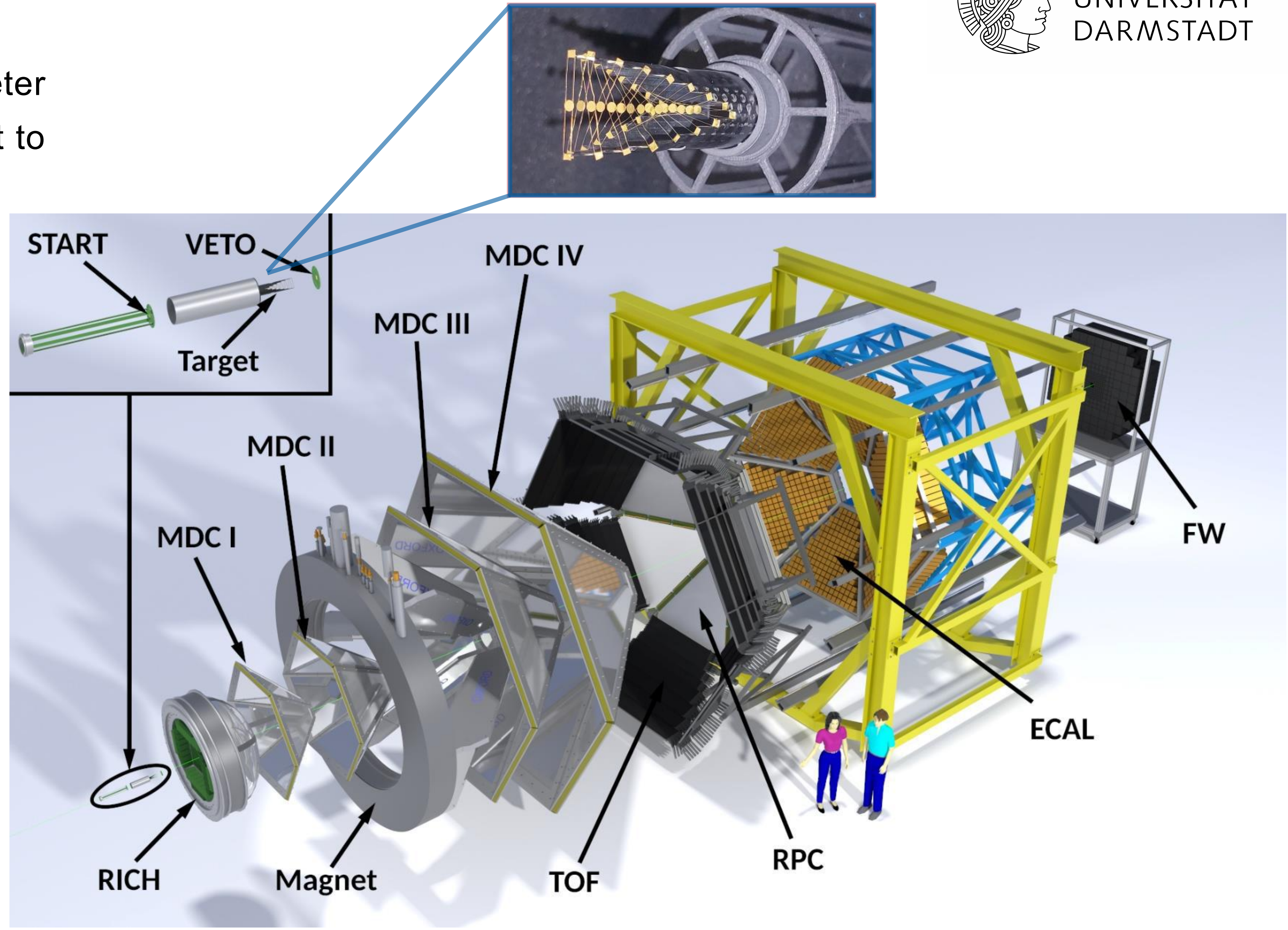
thermal dilepton emission rate

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

## HADES EXPERIMENT AT GSI

- **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**

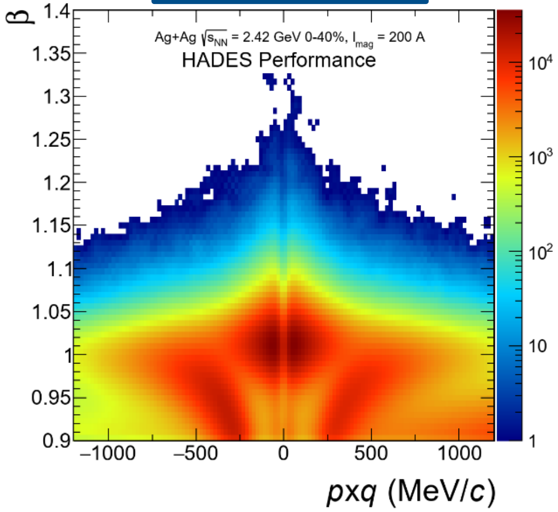


# EXPERIMENTAL CHALLENGES & STEPS TOWARDS MEASUREMENT

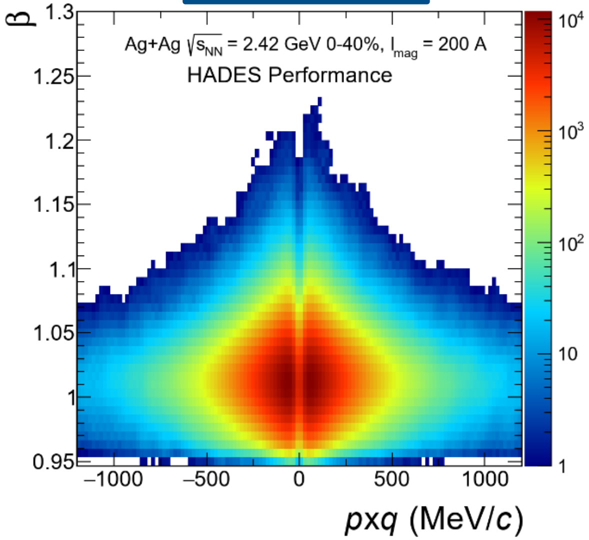
TECHNISCHE UNIVERSITÄT DARMSTADT

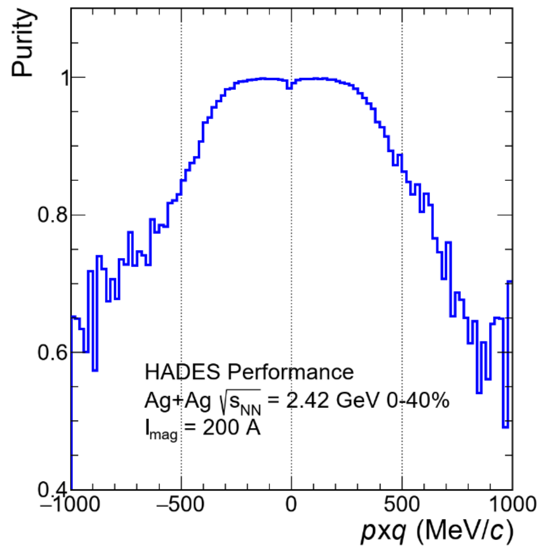
- Low momentum lepton tracks bent out of acceptance by magnetic field
  - 2019: short Ag+Ag test run with lower magnetic field → field reduced from 70% to 5% of max. field
  - Remove low-momentum cut for single leptons

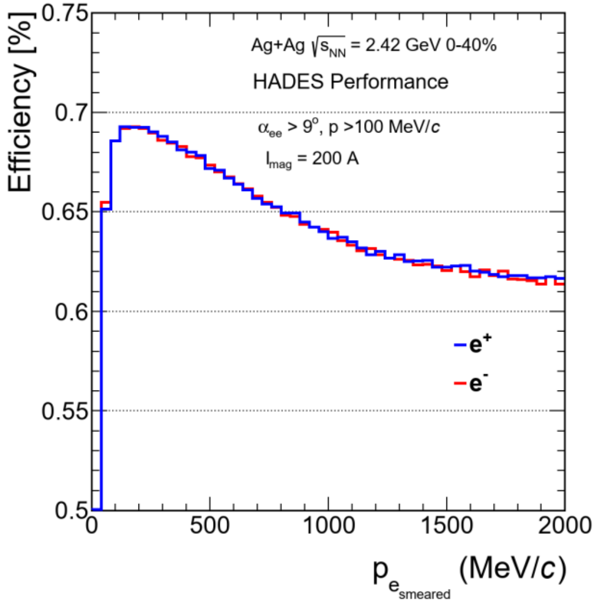
before cuts




after cuts



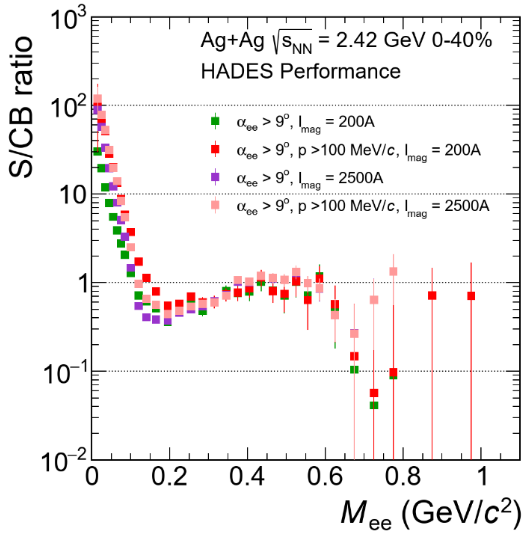



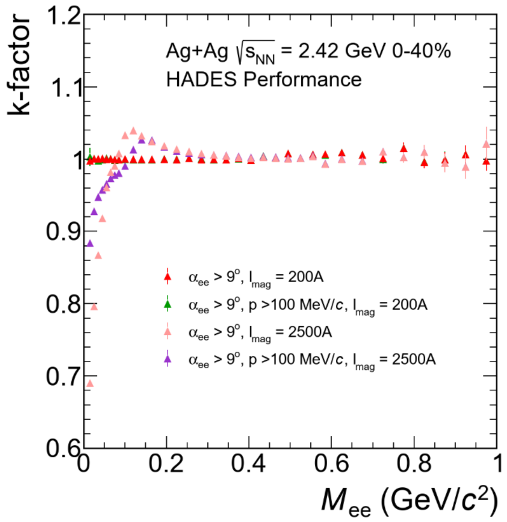



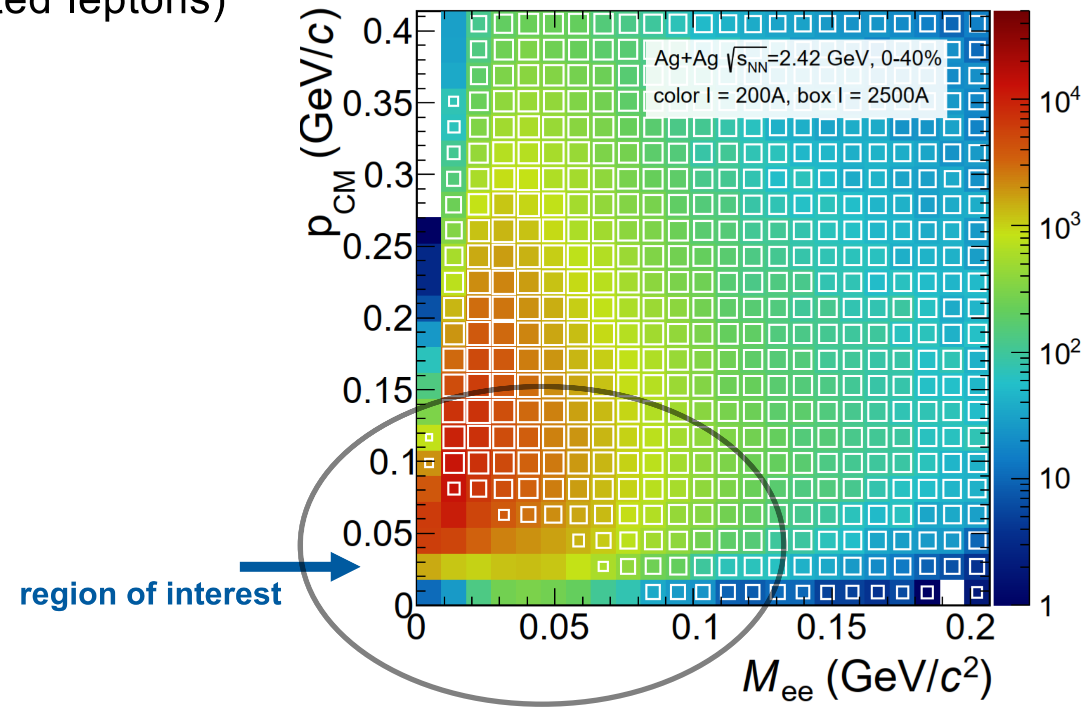

- Lower momentum resolution, but still clean lepton identification possible down to $p_e \sim 10\ \mathrm{MeV}/c$

## EXPERIMENTAL CHALLENGES & STEPS TOWARDS MEASUREMENT

- Low momentum lepton tracks bent out of acceptance by magnetic field
  - 2019: short Ag+Ag test run with lower magnetic field → field reduced from 70% to 5% of max. field
  - Remove low-momentum cut for single leptons
- Excellent S/B ratio > 10 below $M_{ee}$ = 0.1 GeV/$c^2$
- Flat k-factor (accounting for charge asymmetry of reconstructed leptons)
- Region of interest for $\sigma_{el}$ gets populated with statistics
- Photon conversion suppressed via opening angle cut
  - Study $\alpha_{ee} > 9°$ vs. $\alpha_{ee} > 5°$



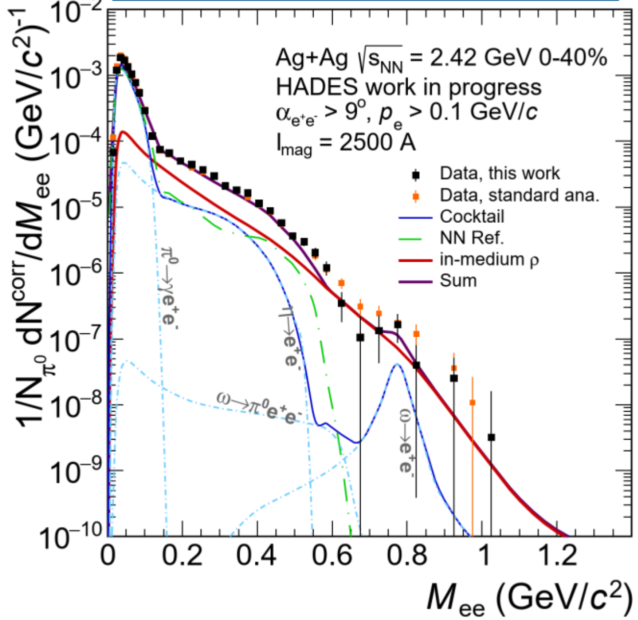

C. Udrea , QM2025 poster

# EXPERIMENTAL CHALLENGES & STEPS TOWARDS MEASUREMENT

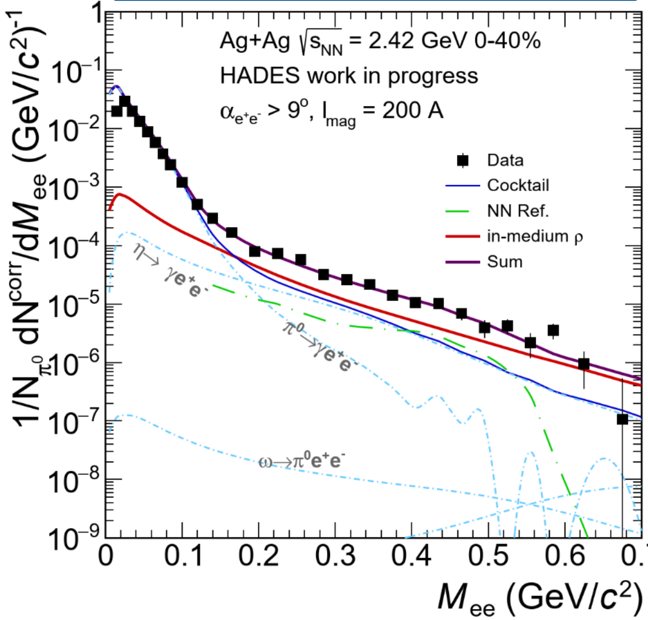
TECHNISCHE UNIVERSITÄT DARMSTADT

- Pair efficiency corrected spectra inside the HADES acceptance
- NN reference applied for $M_{ee}$ > 0.13 GeV/$c^2$ → investigation of proper momentum smearing ongoing
- Next: Extraction of excess radiation & acceptance correction
  - Correction factor at low $M_{ee}$ reduced from ~1000 to below 10
  - Physics background of $\pi^0$ and η mesons: Good signal to “physics background” ratio at HADES: ~ 10% of yield in $\pi^0$ region is excess radiation

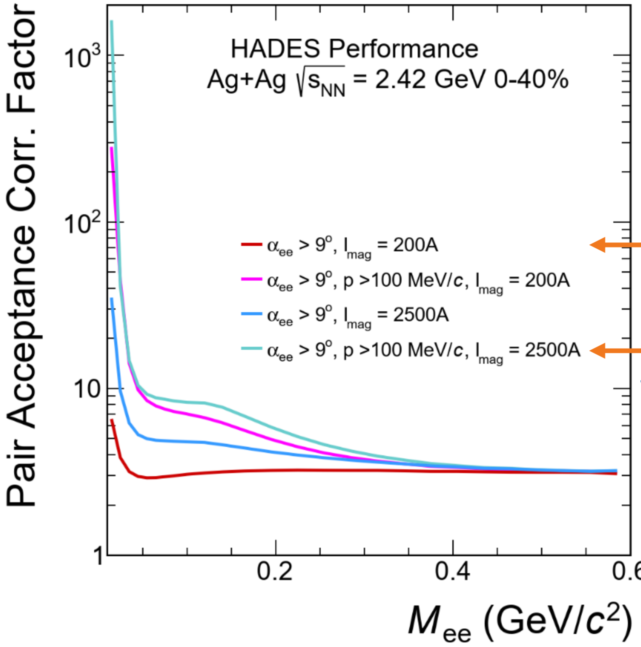
**Standard analysis: 70% B-field & momentum cut**




**Dedicated analysis: 5% B-field & no momentum cut**




C. Udrea , QM2025 poster




Dedicated analysis

Standard analysis

## EXPERIMENTAL CHALLENGES & STEPS TOWARDS MEASUREMENT

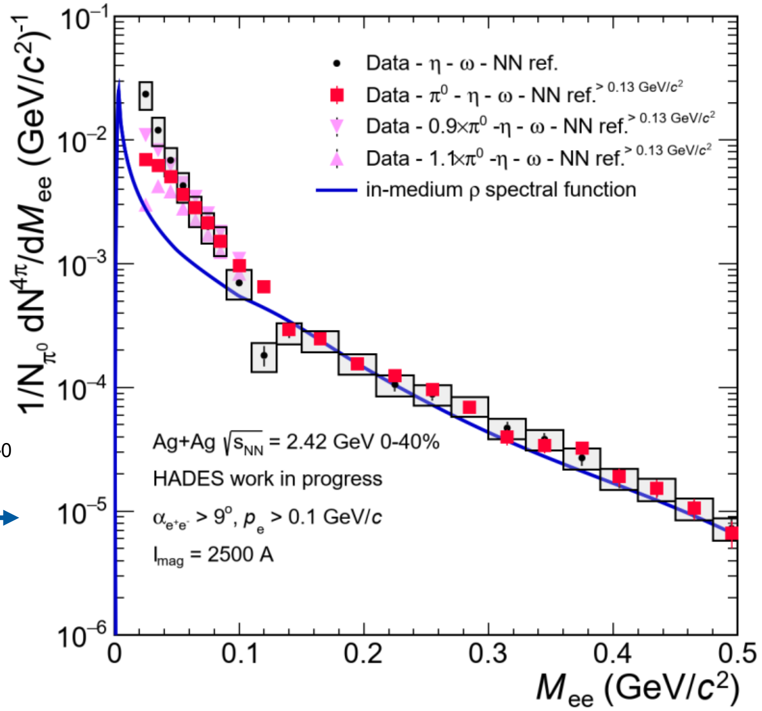
TECHNISCHE UNIVERSITÄT DARMSTADT

- Pair efficiency corrected spectra inside the HADES acceptance
- NN reference applied for $M_{ee} > 0.13$ GeV/$c^2$ → investigation of proper momentum smearing ongoing
- Next: Extraction of excess radiation & acceptance correction
  - Correction factor at low $M_{ee}$ reduced from ~1000 to below 10
  - Physics background of $\pi^0$ and η mesons: Good signal to "physics background" ratio at HADES: ~ 10% of yield in $\pi^0$ region is excess radiation

Many systematic cross-checks ongoing:

- PID
- Efficiency
- Acceptance (including polarization)
- Close pair rejection
- NN reference & cocktail contribution yields
- etc.

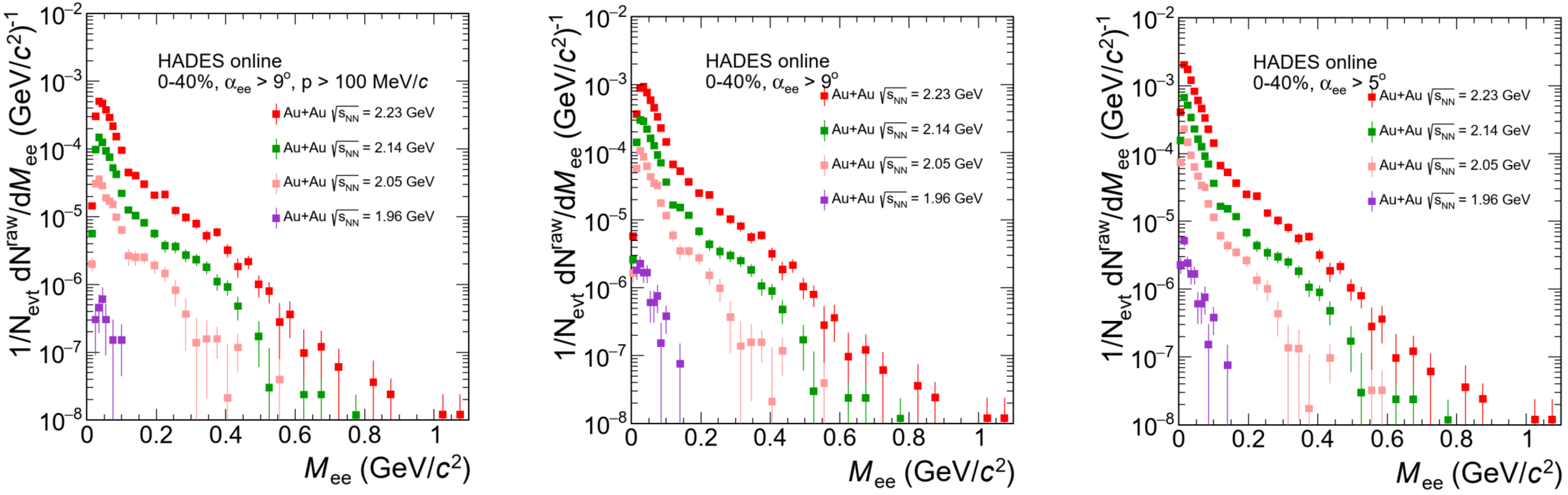
e.g. varying $\pi^0$ yield by 10%




C. Udrea , QM2025 poster

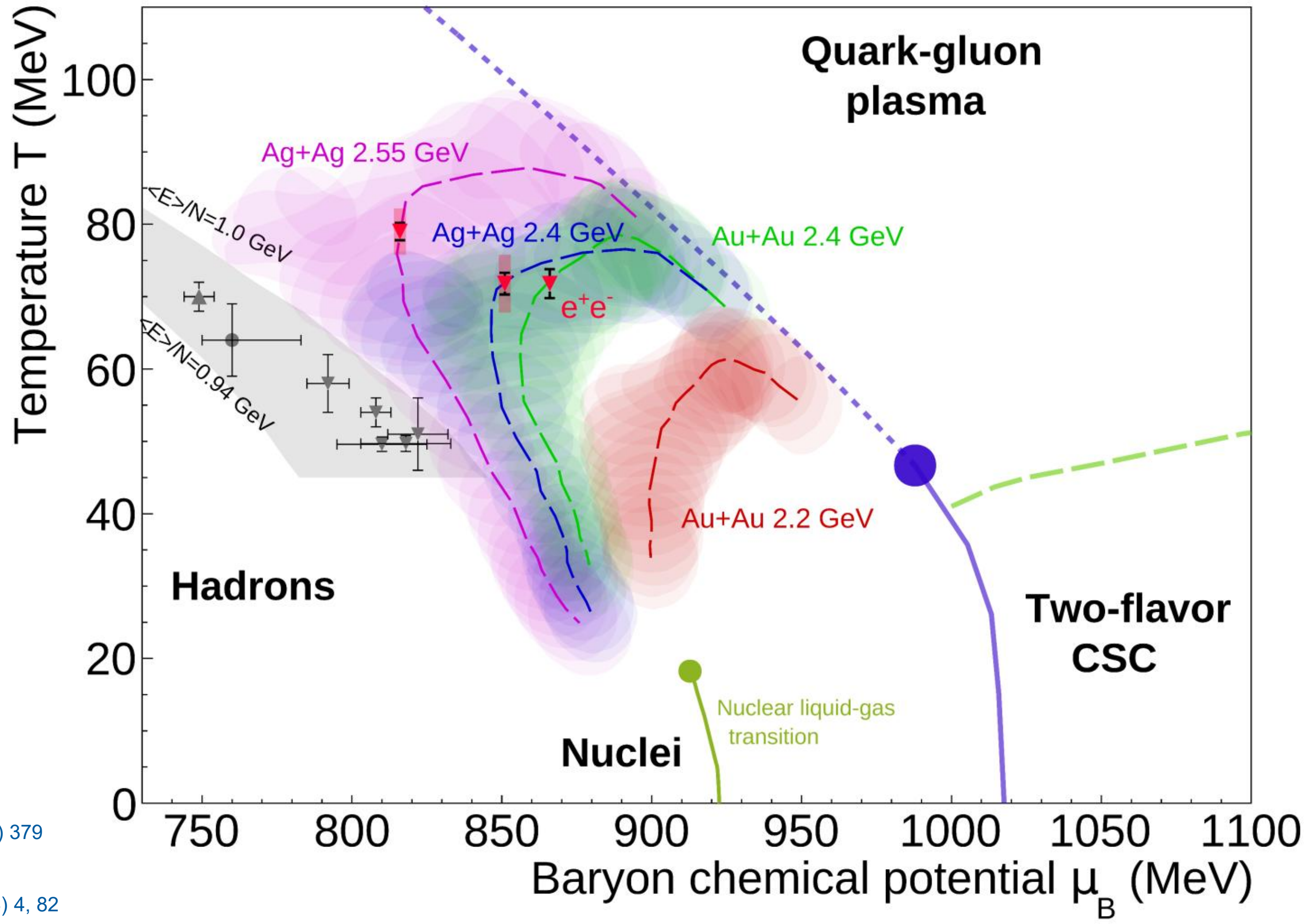
TECHNISCHE UNIVERSITÄT DARMSTADT

- HADES Au+Au beam energy scan conducted in spring 2024 & 2025
  - Data collected at $E_{kin}$ = 0.8, 0.6, 0.4, and 0.2A GeV ($\sqrt{s_{NN}} = 2.23, 2.14, 2.05, 1.96$ GeV)
    - Lowest energy below $\pi^0$ production threshold in elementary collisions → potentially no "physics background"
  - In addition, dedicated run at $E_{kin}$ = 0.8A GeV with low magnetic field → field reduced from 50% to 5% of max. field
  - Online dilepton raw spectra



# QCD PHASE DIAGRAM PROBED WITH DILEPTONS

- Trajectories from coarse-grained UrQMD
- Measured average temperatures from HADES well above universal freeze-out region
- Transition lines from two-flavor NJL model in mean-field approximation
  - Transition of chiral symmetry breaking
  - Transition to the two-flavor color superconducting (CSC) phase
- Collisions at $\sqrt{s_{NN}} = 2.2$ GeV ($E_{kin}$ = 800A MeV) might show sensitivity to precursor phenomena for the CSC phase




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
Transition curves: T. Nishimura *et al.*, Eur.Phys.J.A 60 (2024) 4, 82
Figure: FS, T.Galatyuk

## SUMMARY



- Unique possibility of characterizing the properties of baryon-rich matter with multi-differential measurements of penetrating probes
  - Polarization as a tool to disentangle production sources
  - Fundamental transport coefficients accessible with soft virtual photons

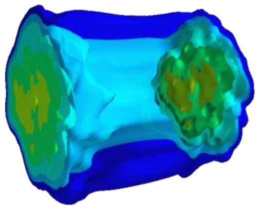
- HADES provides high-quality data of the di-electron production in heavy-ion collisions at SIS energy regime
  - Au+Au at 1.23A GeV, Ag+Ag at 1.58 and 1.23A GeV
  - Energy scan: data for Au+Au at 0.2 – 0.4 – 0.6 – 0.8A MeV on tape
  - Including a dedicated run with low magnetic field

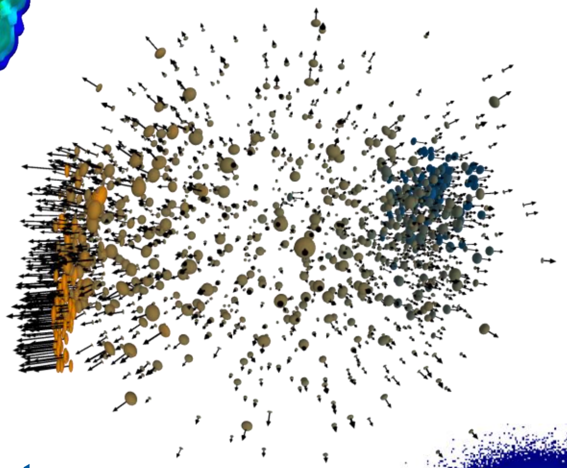
- Big discovery potential with high-rate experiments coming online in the near future

# BACKUP

## DESCRIPTION OF THE SPACE-TIME EVOLUTION

TECHNISCHE UNIVERSITÄT DARMSTADT

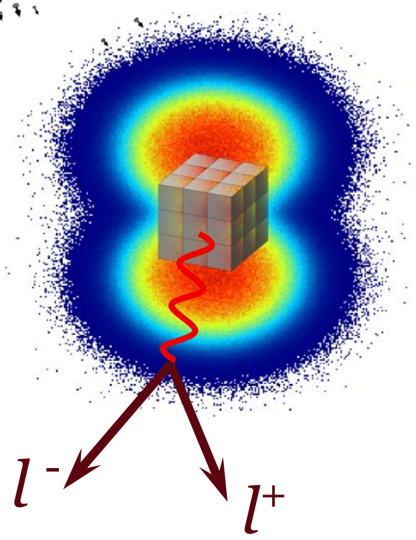




- Bulk observables are reasonably well described by simulations
  - Hydrodynamics at high collision energies
  - Microscopic transport model at low collision energies

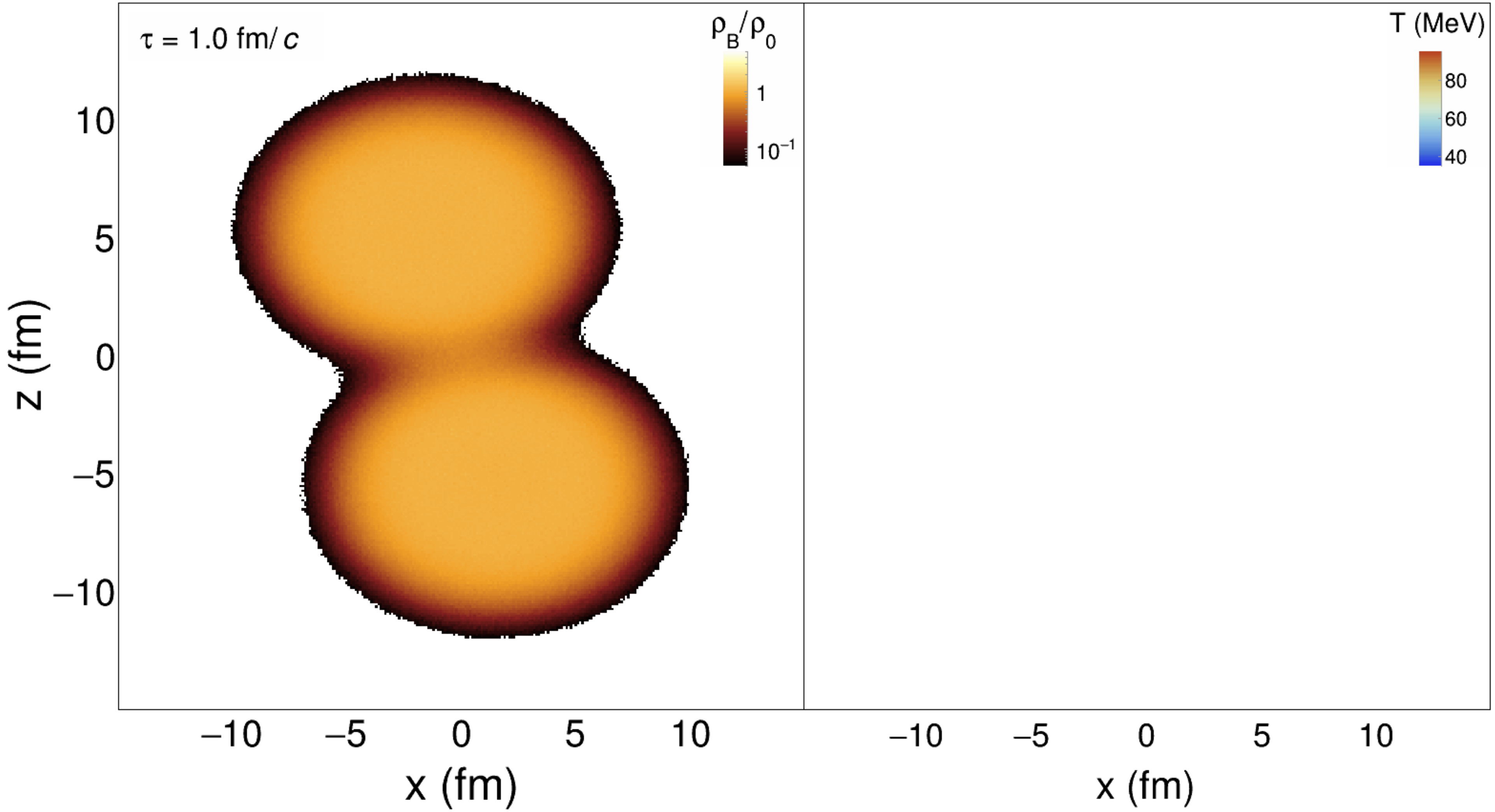
- Pure transport simulations struggle to describe dilepton data
  - “shining” or time-integration method

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

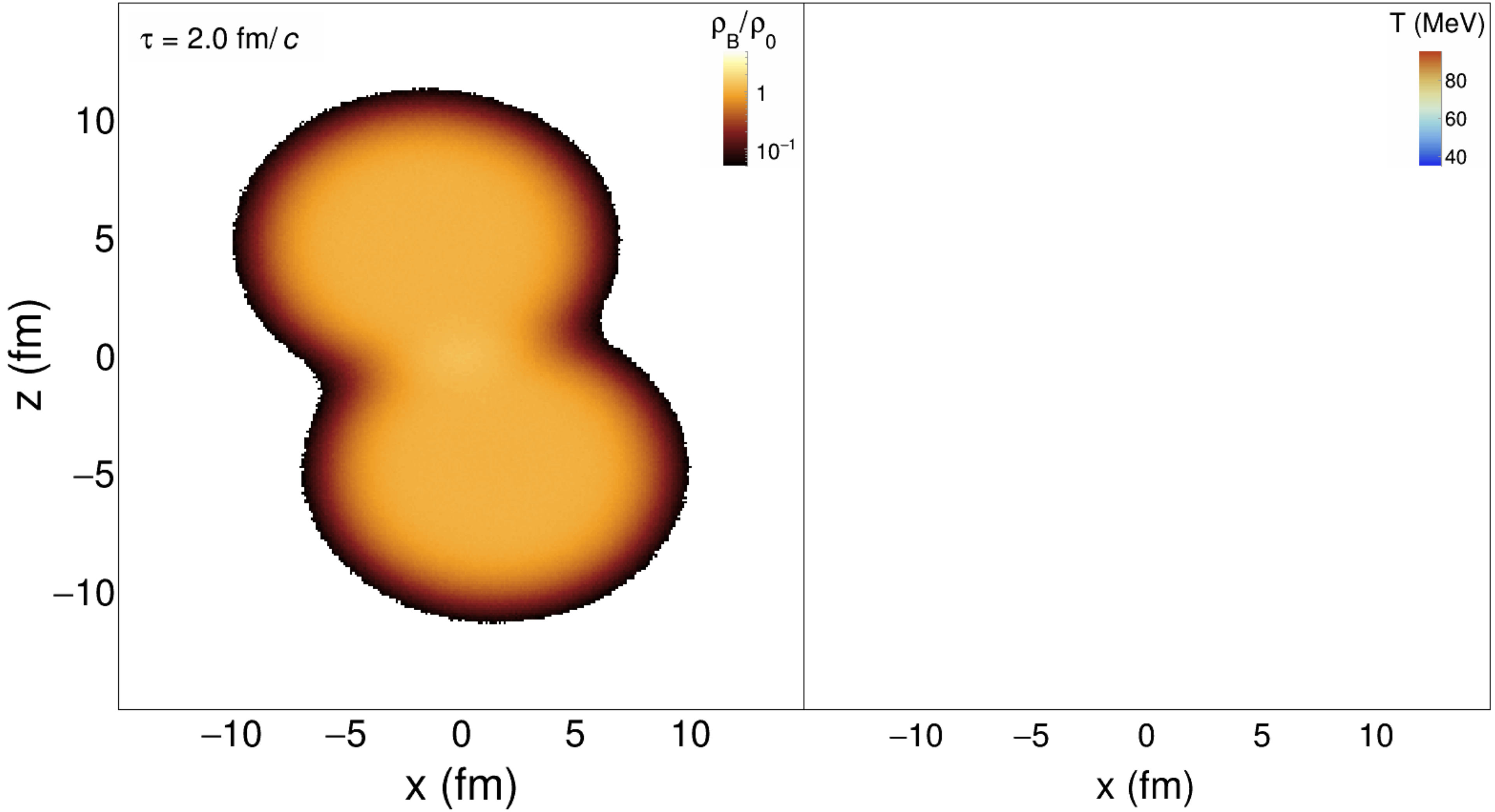



- Simulate events with a transport model & take ensemble average to obtain smooth space-time distributions
- Divide space-time into 4-dim. cells
- Check if cell is thermalized (→ enough interactions)
- Extract baryon density $\rho_B$, medium velocity $\vec{u}$, and temperature $T$ (→ $m_T$ spectra of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

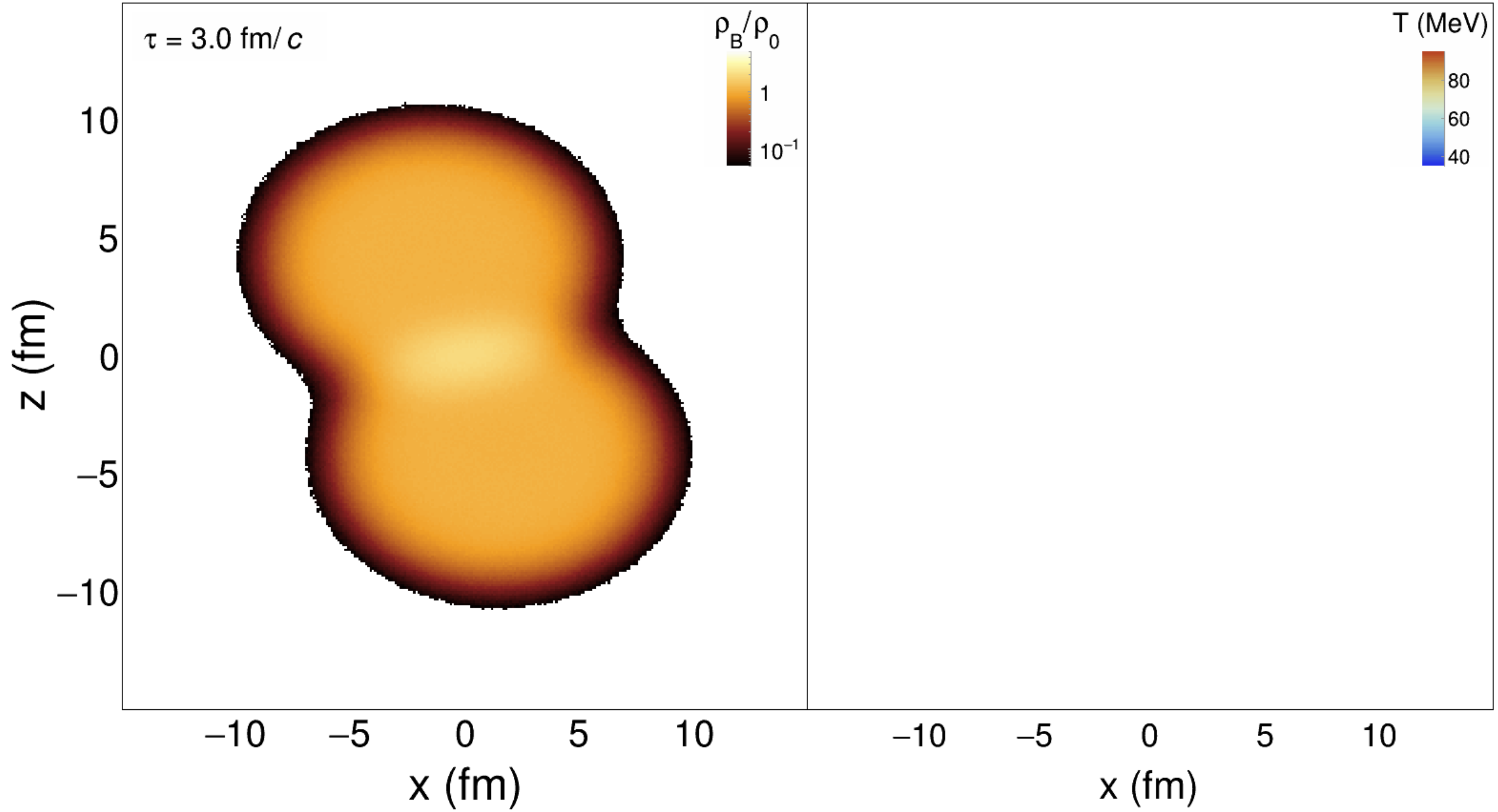
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



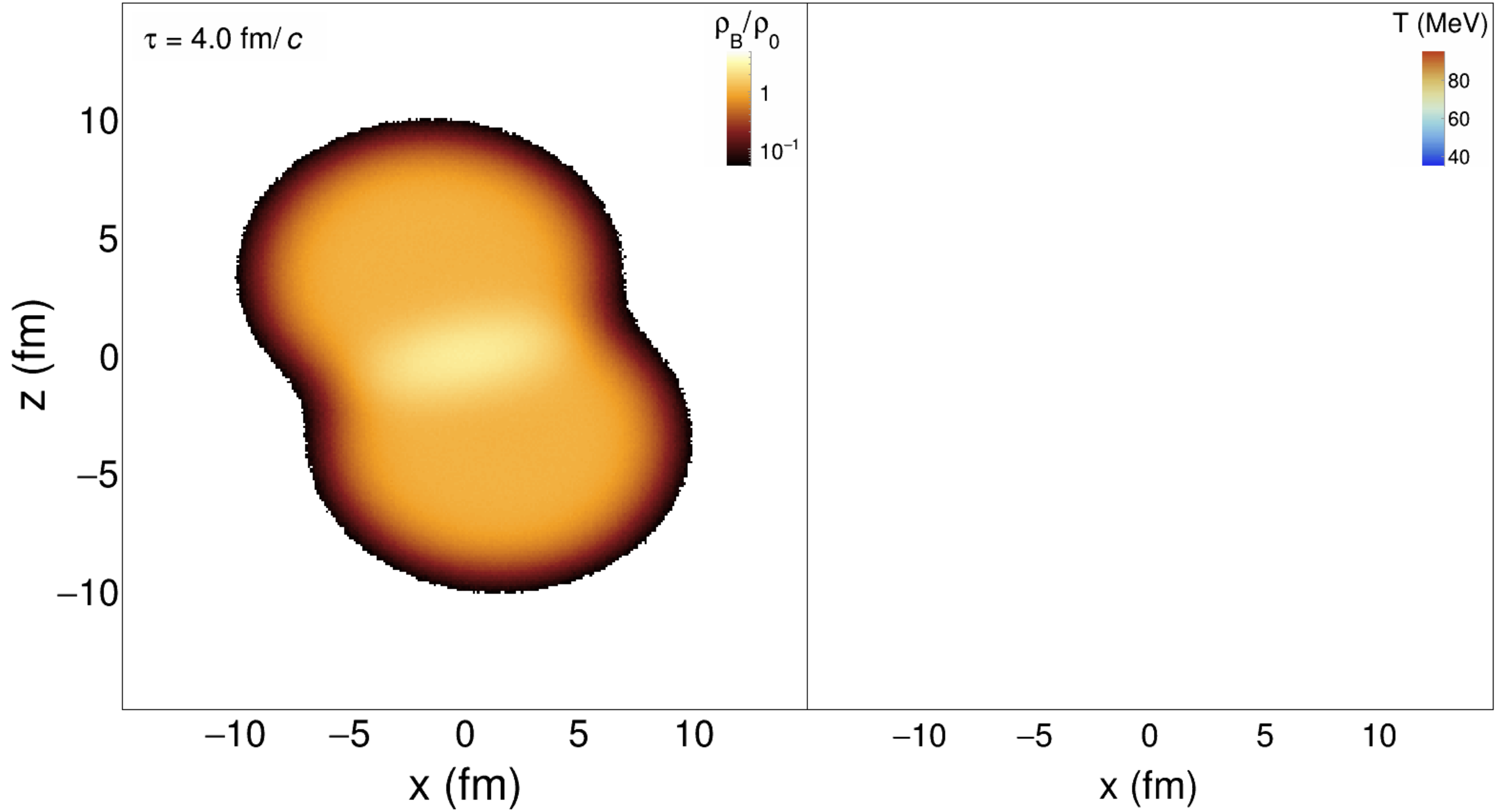
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



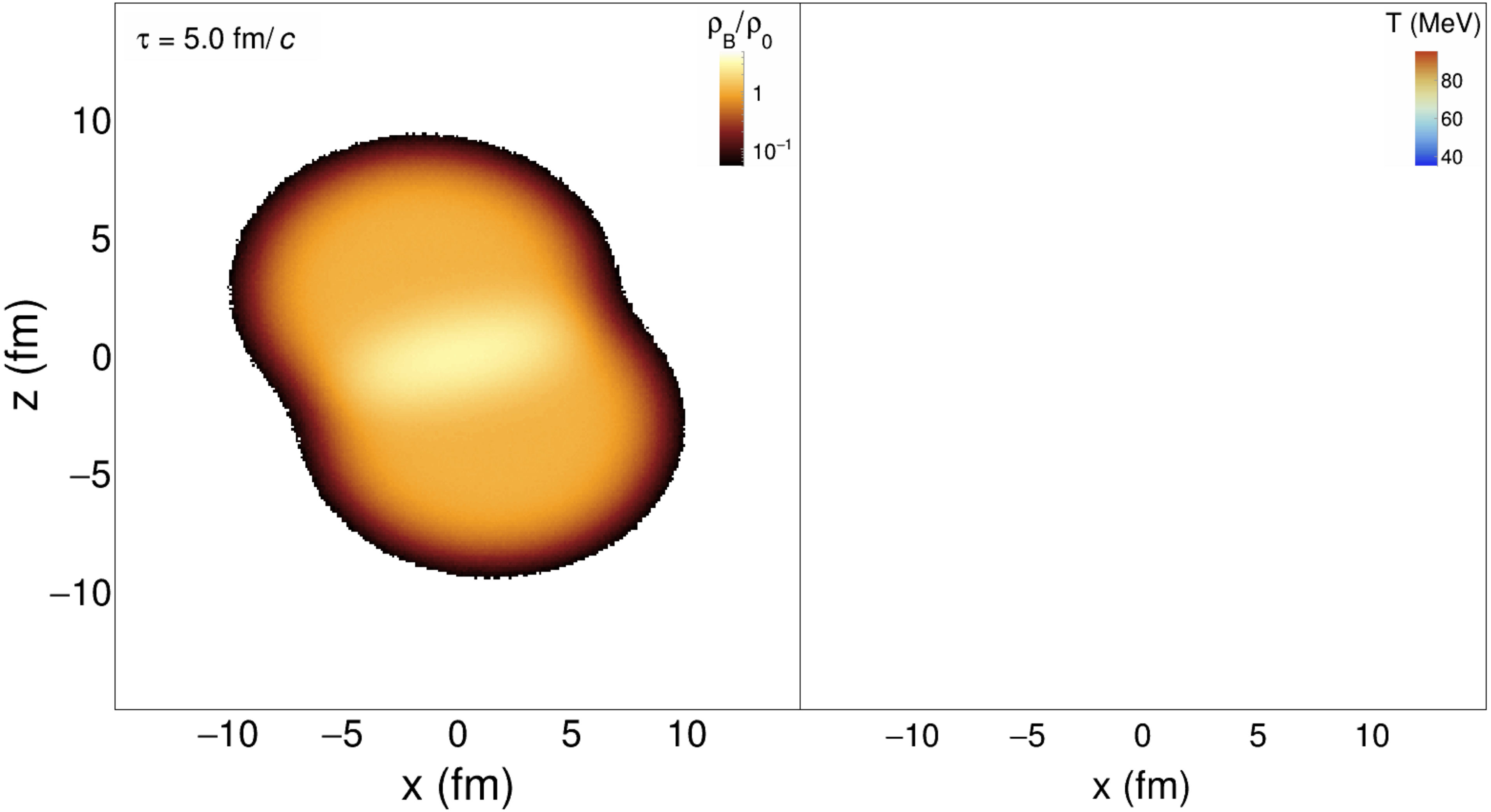
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



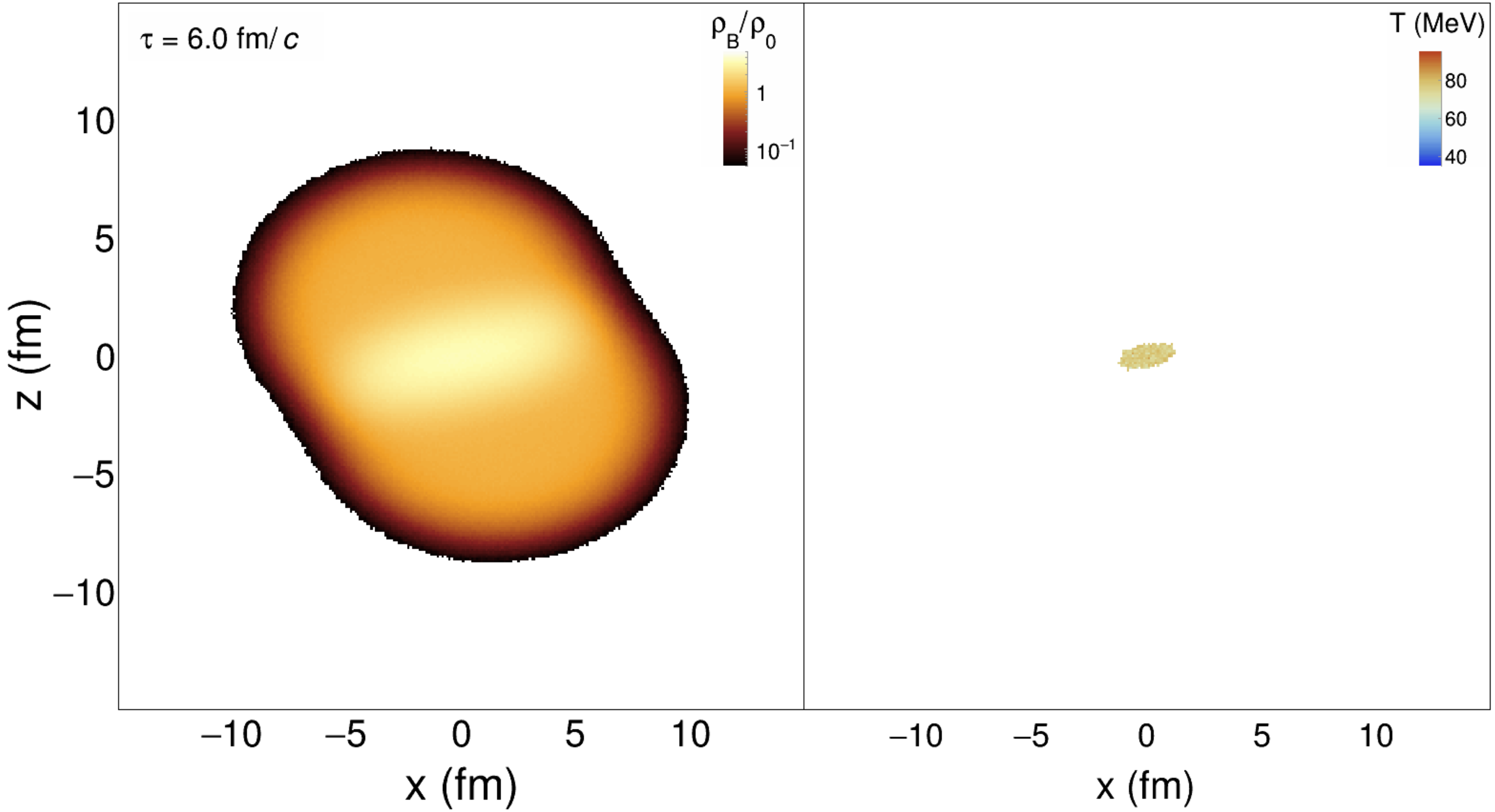
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



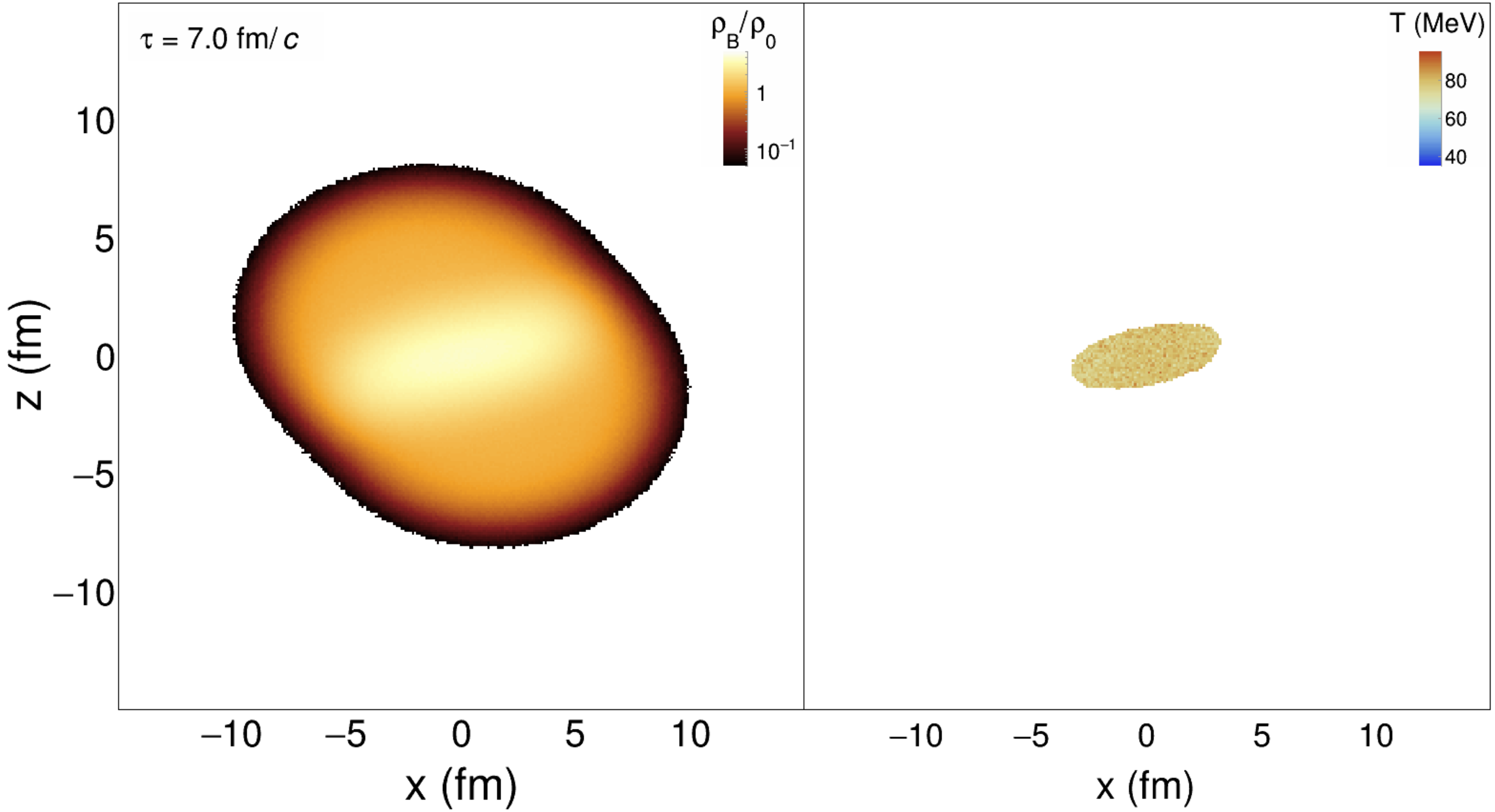
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



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

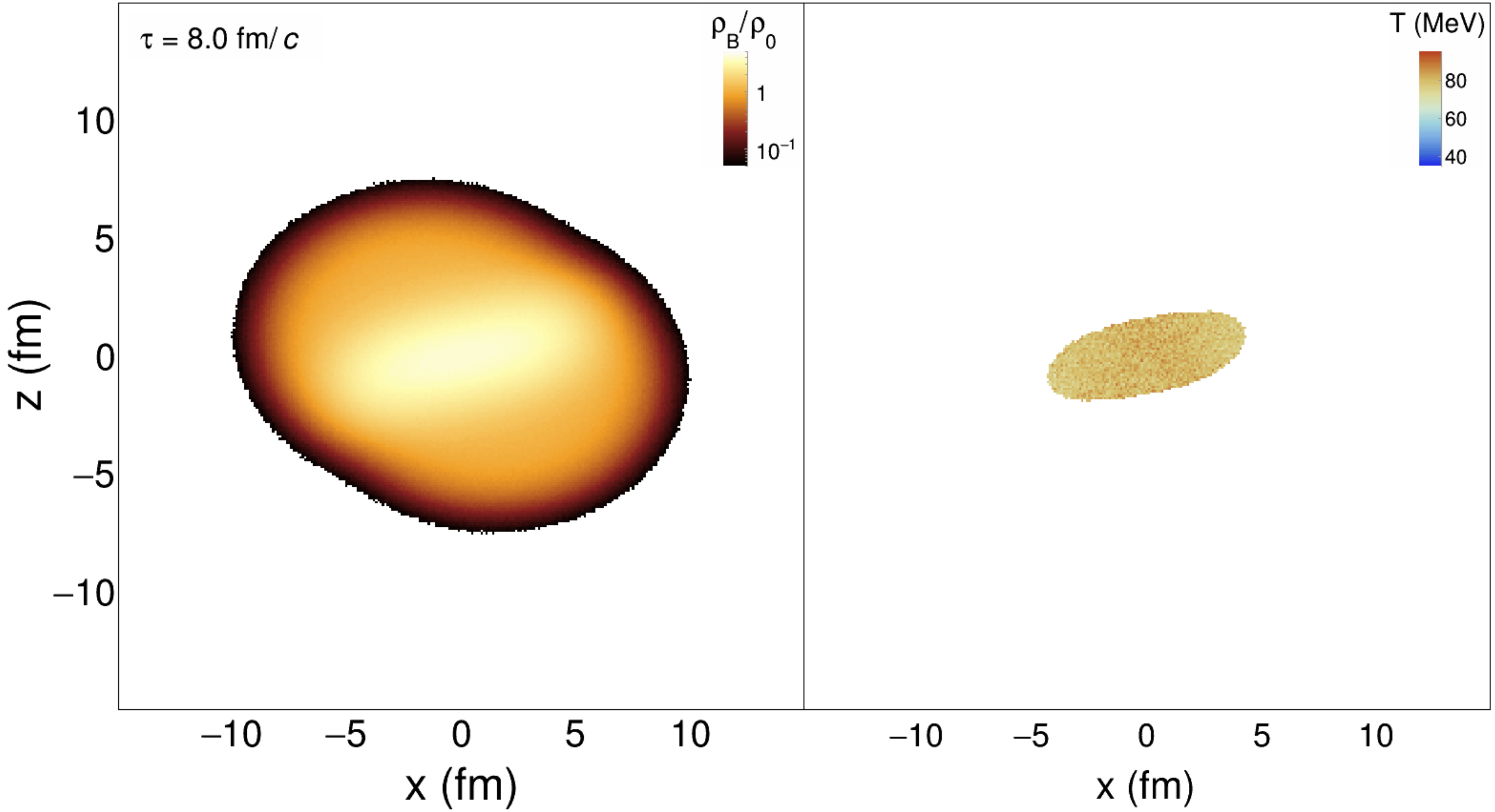


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

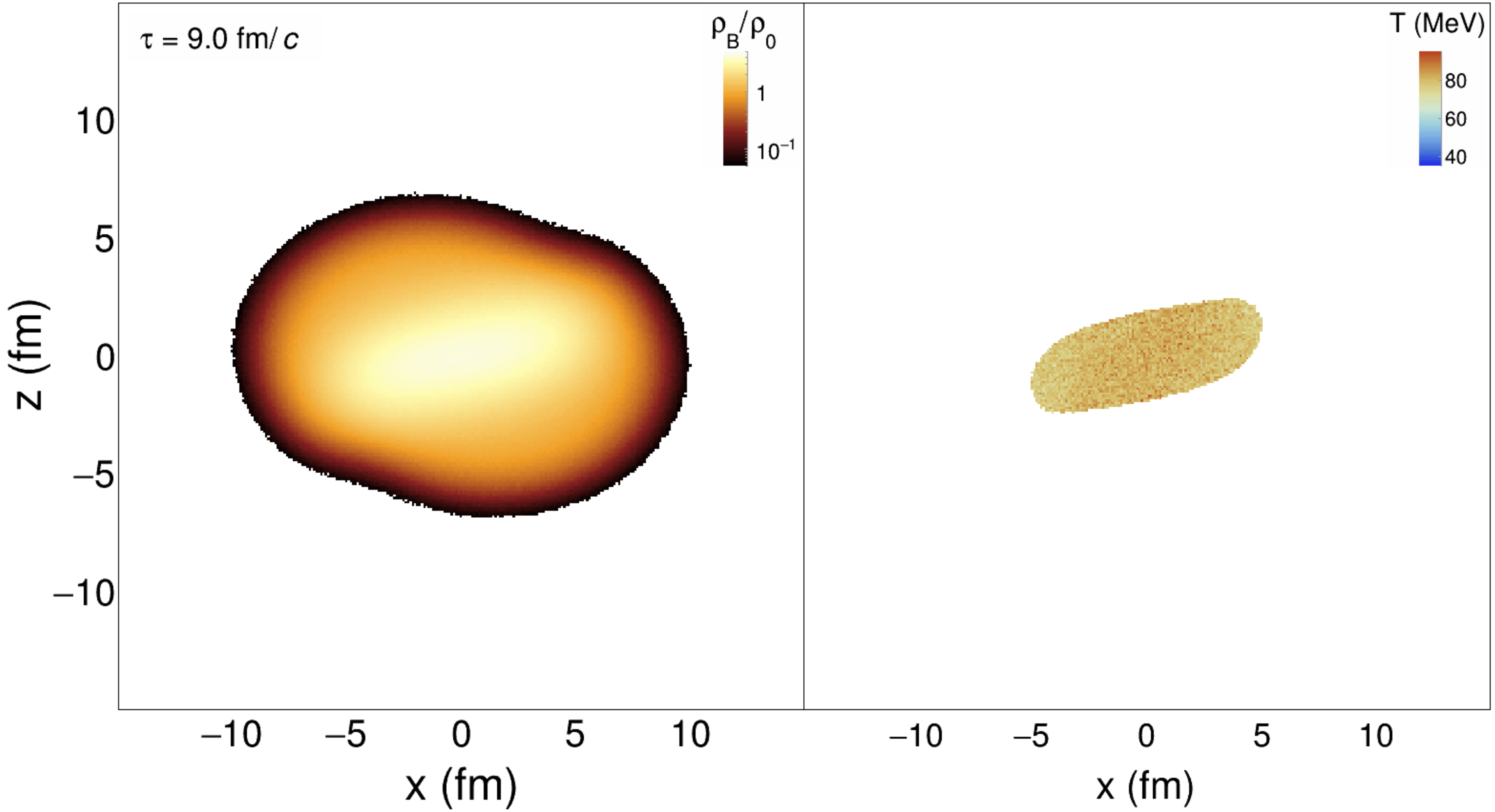


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

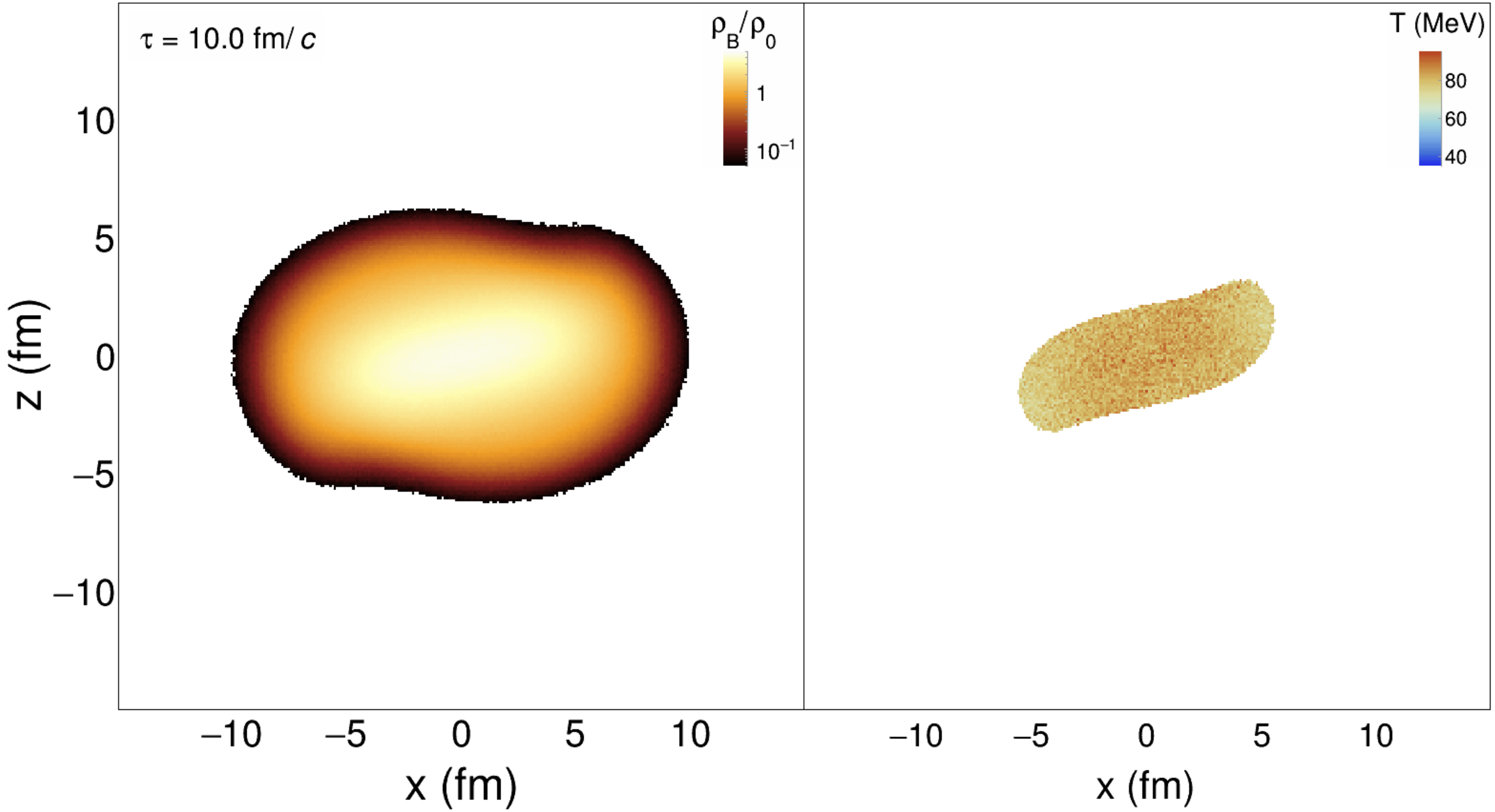
TECHNISCHE
UNIVERSITÄT
DARMSTADT



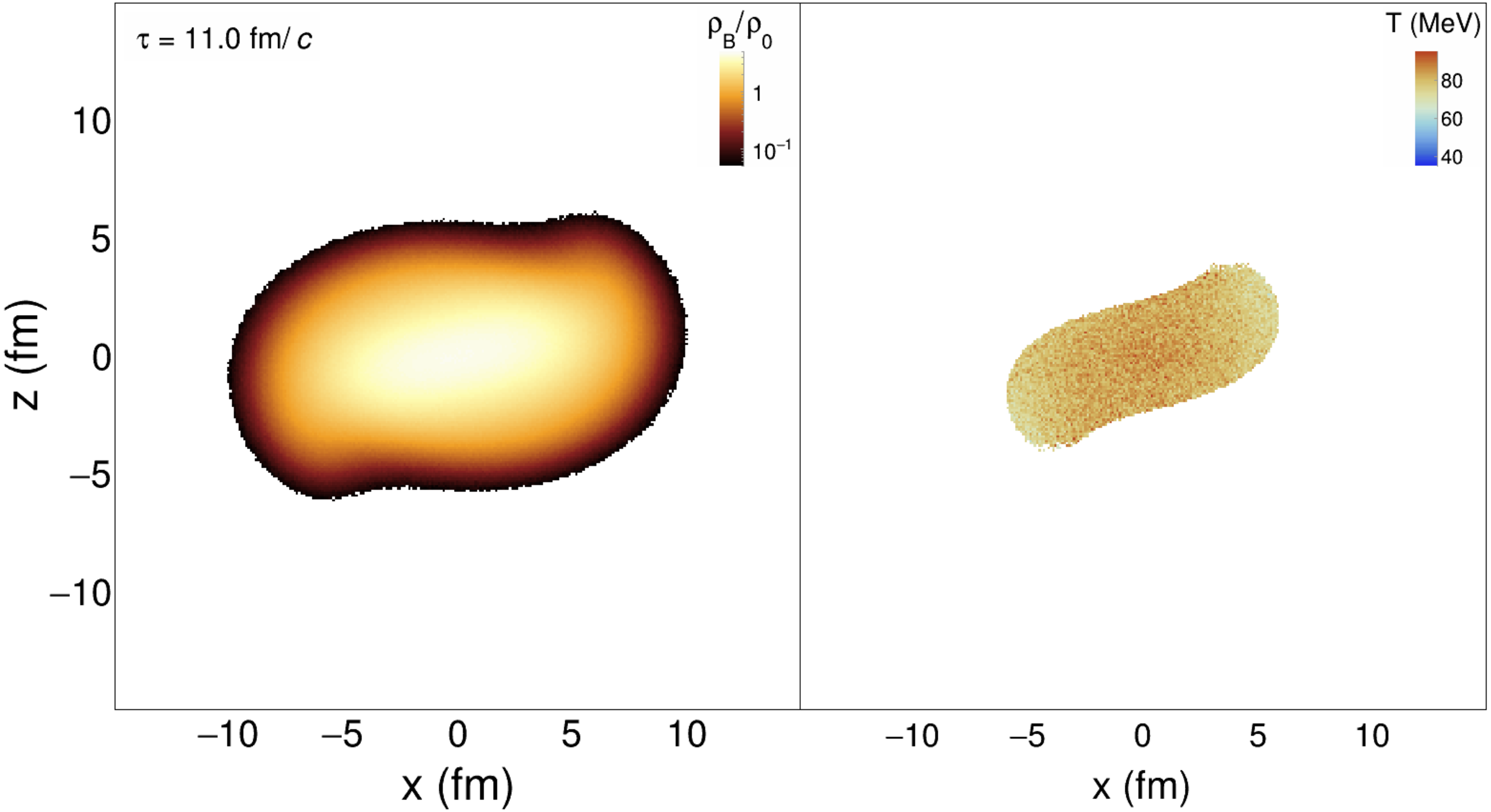
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



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

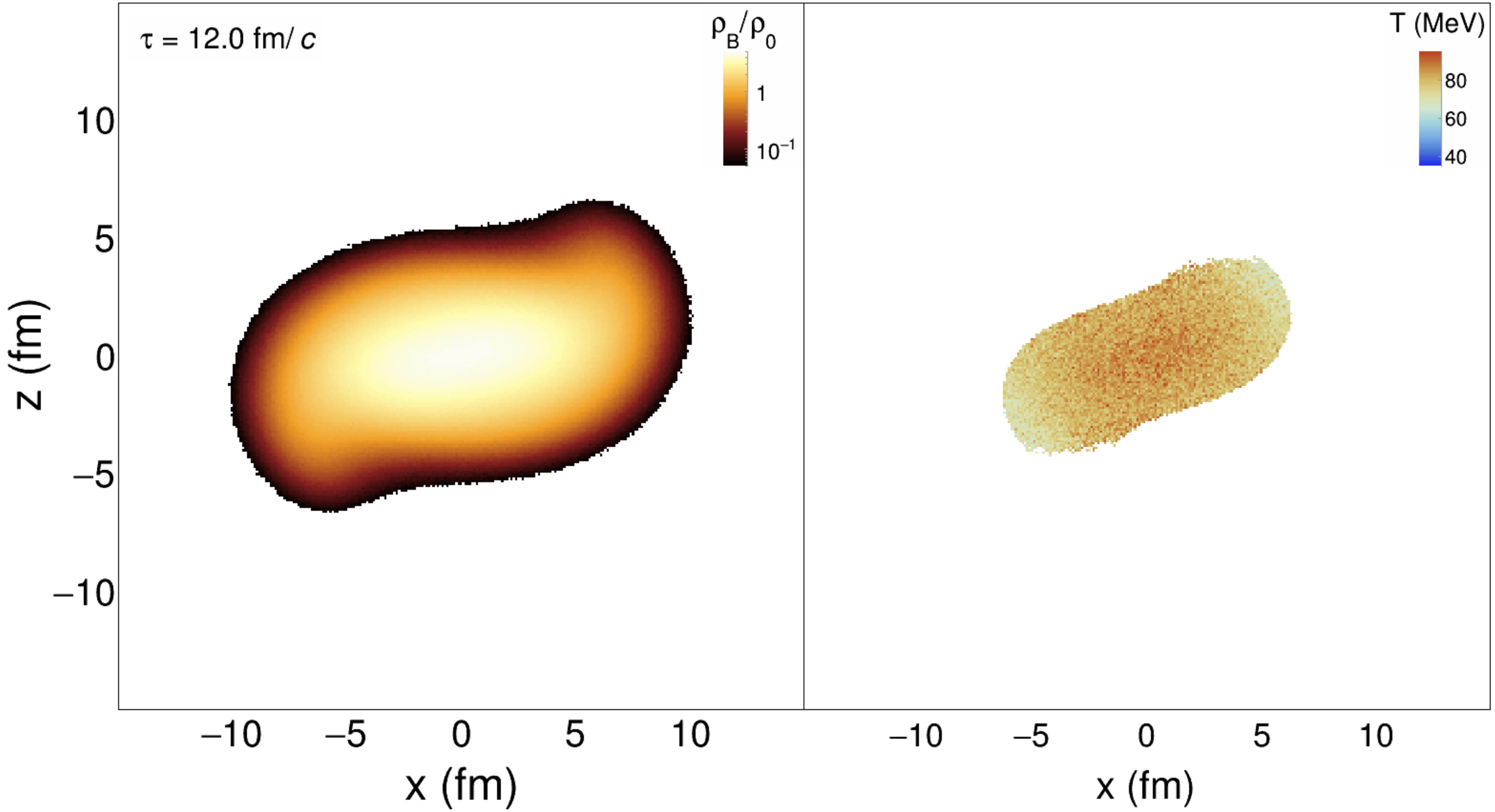


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



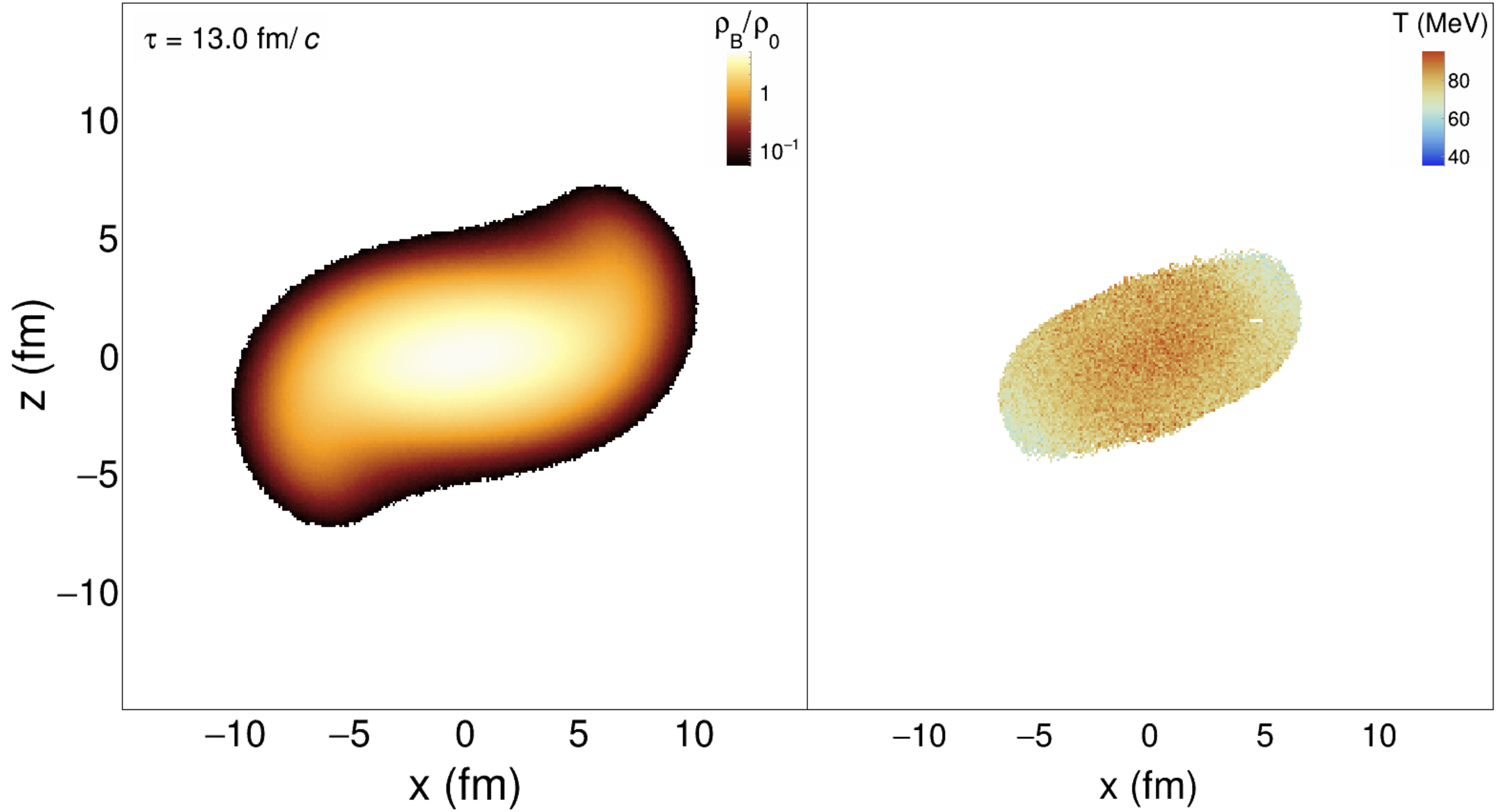
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV





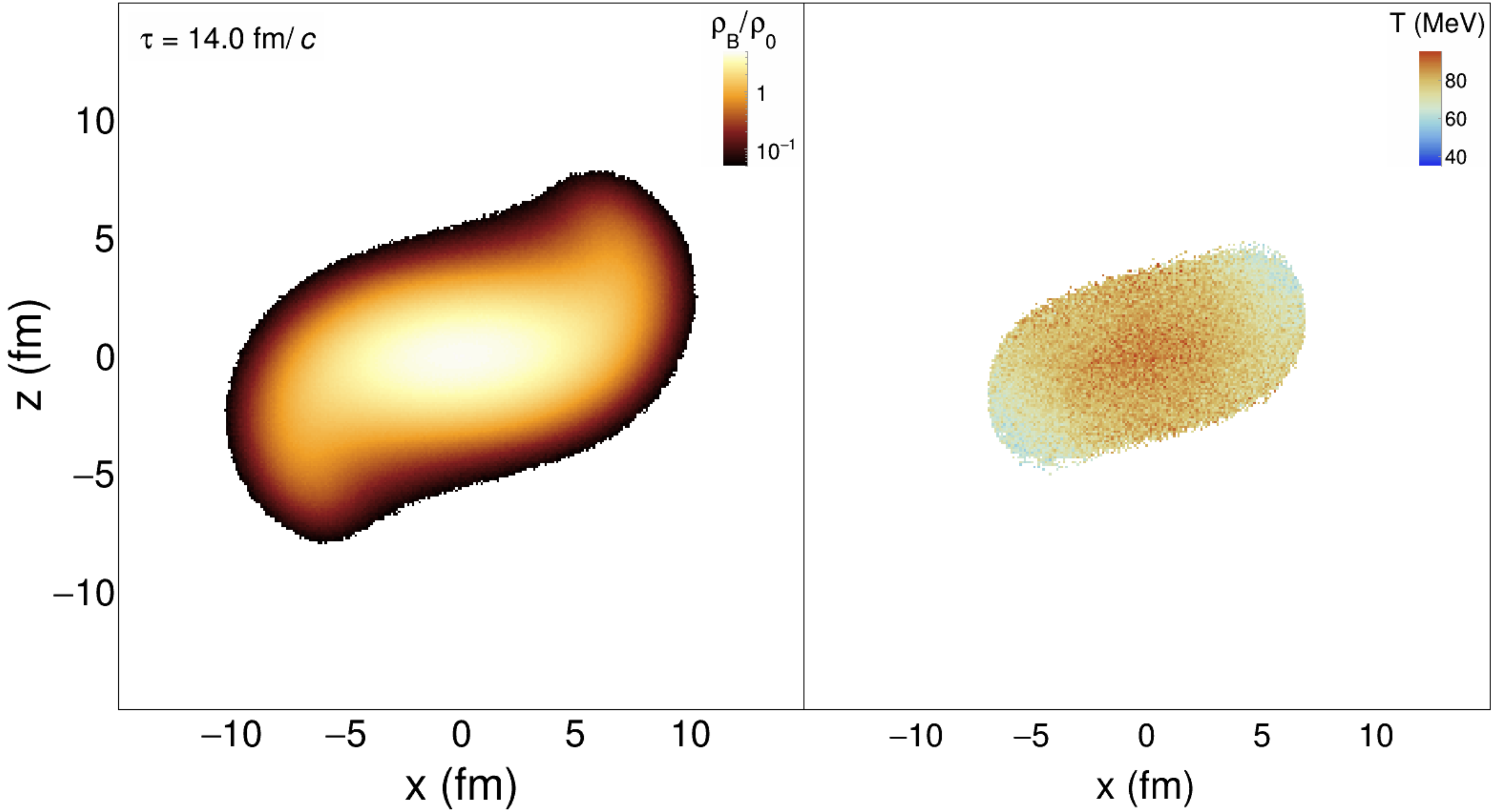
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



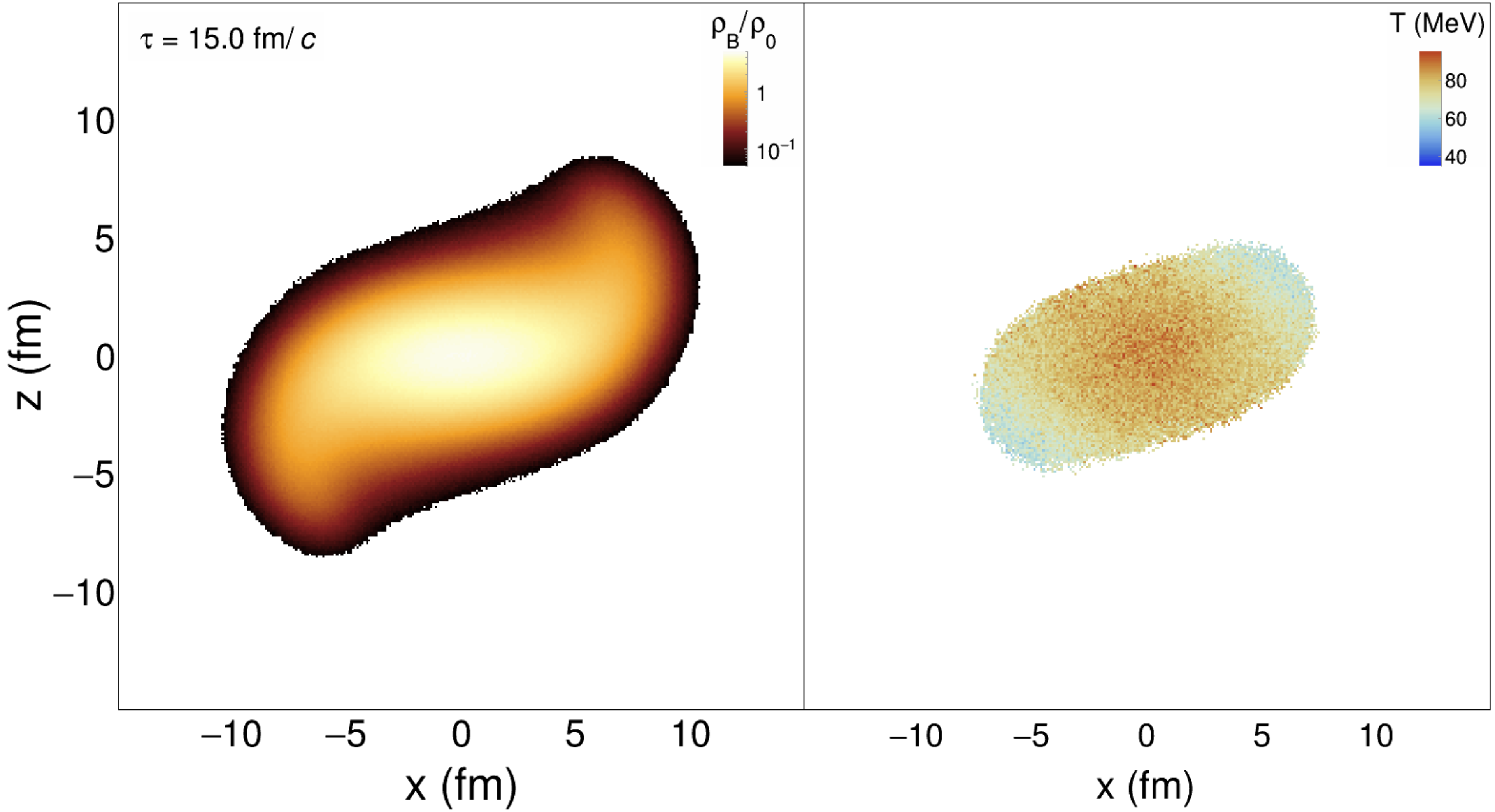


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



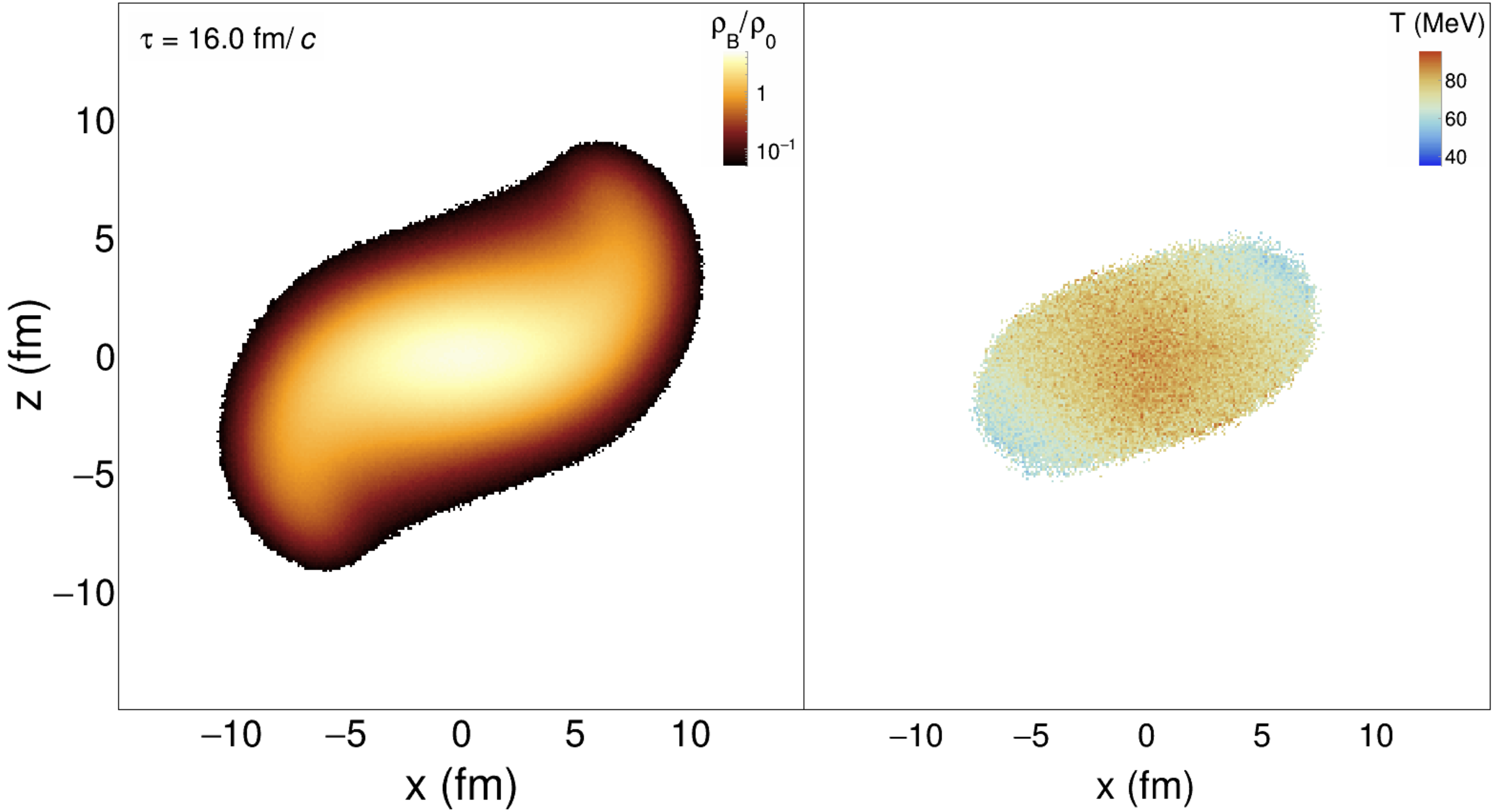


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

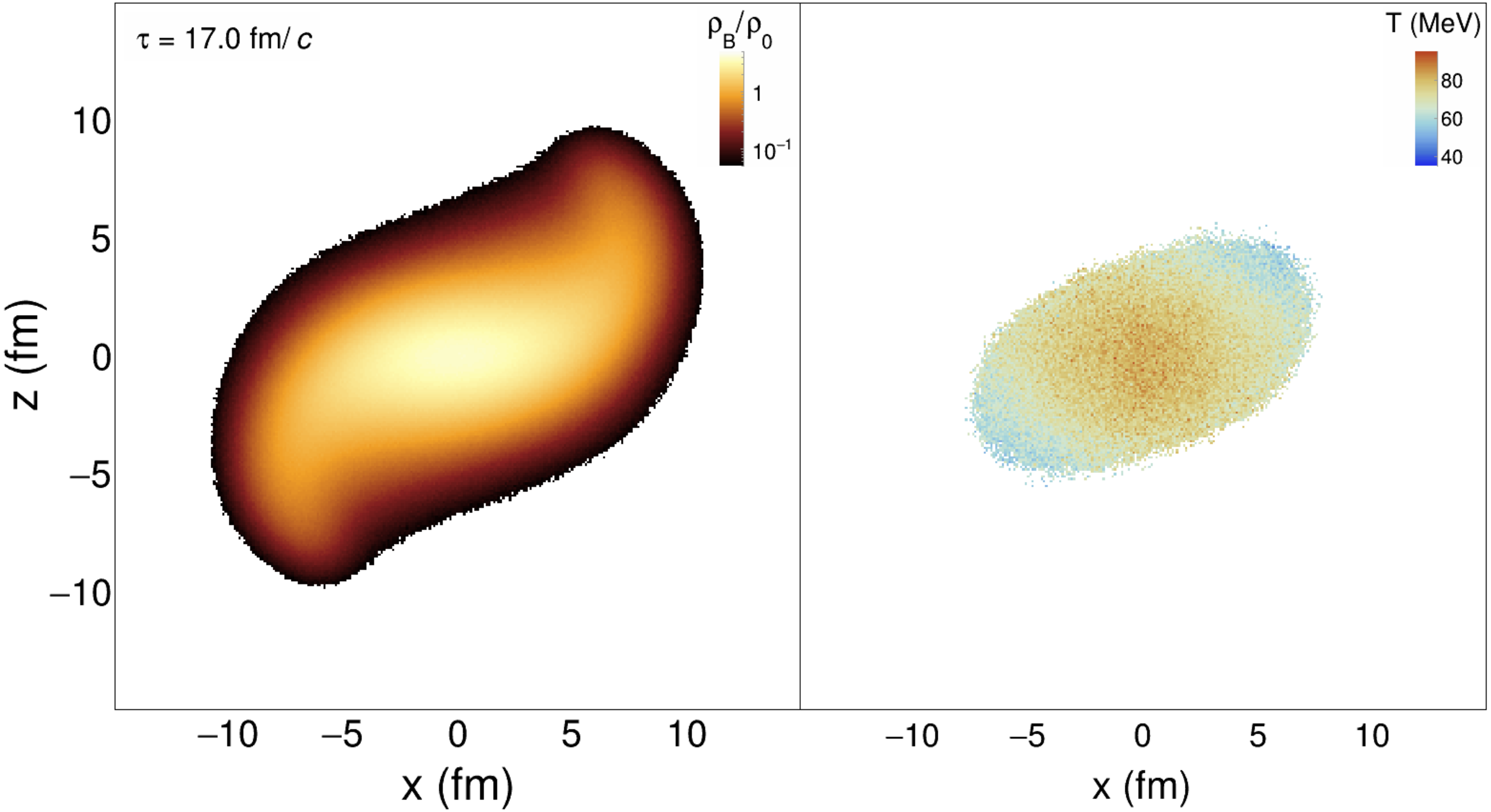


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



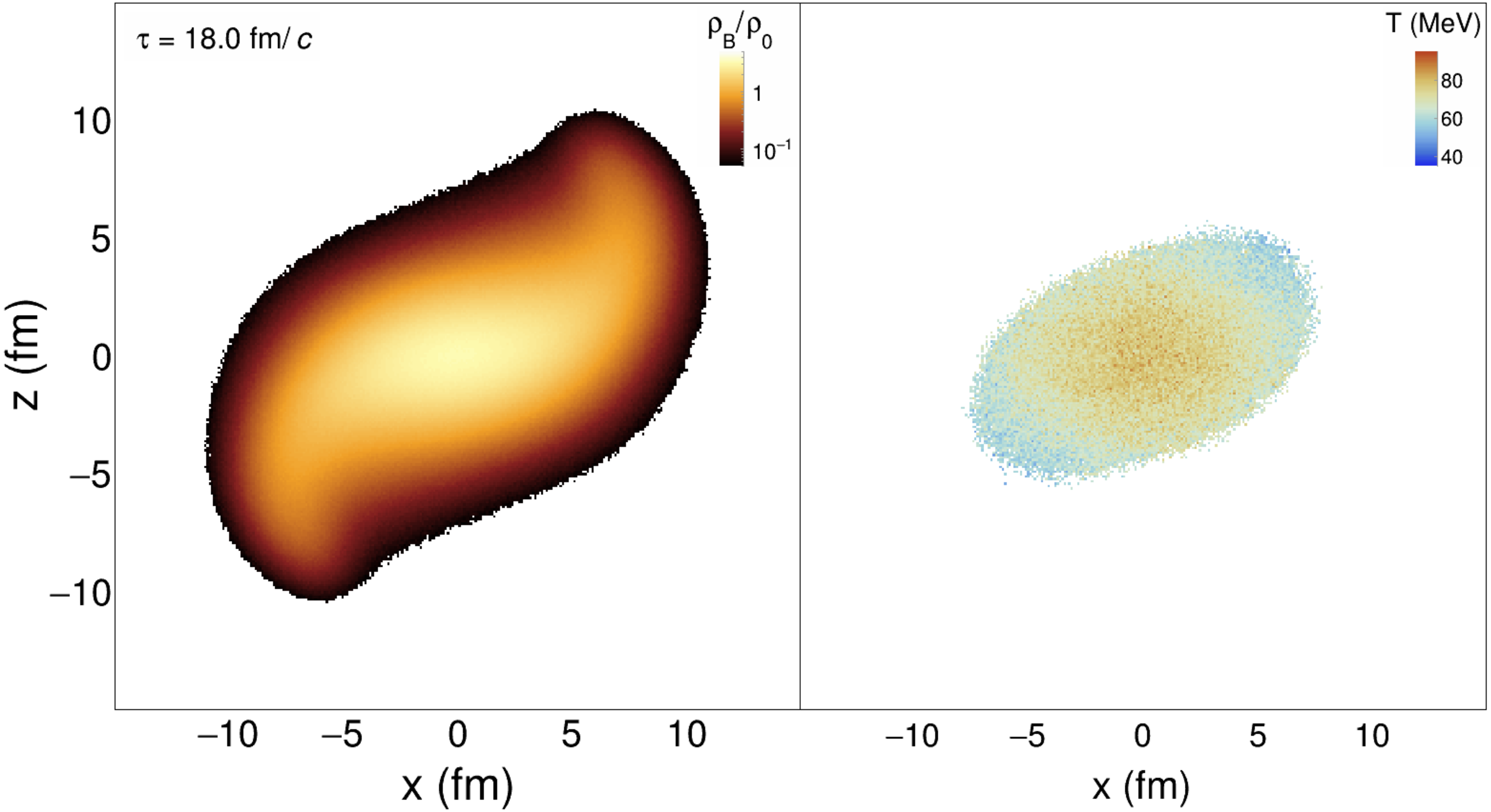


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



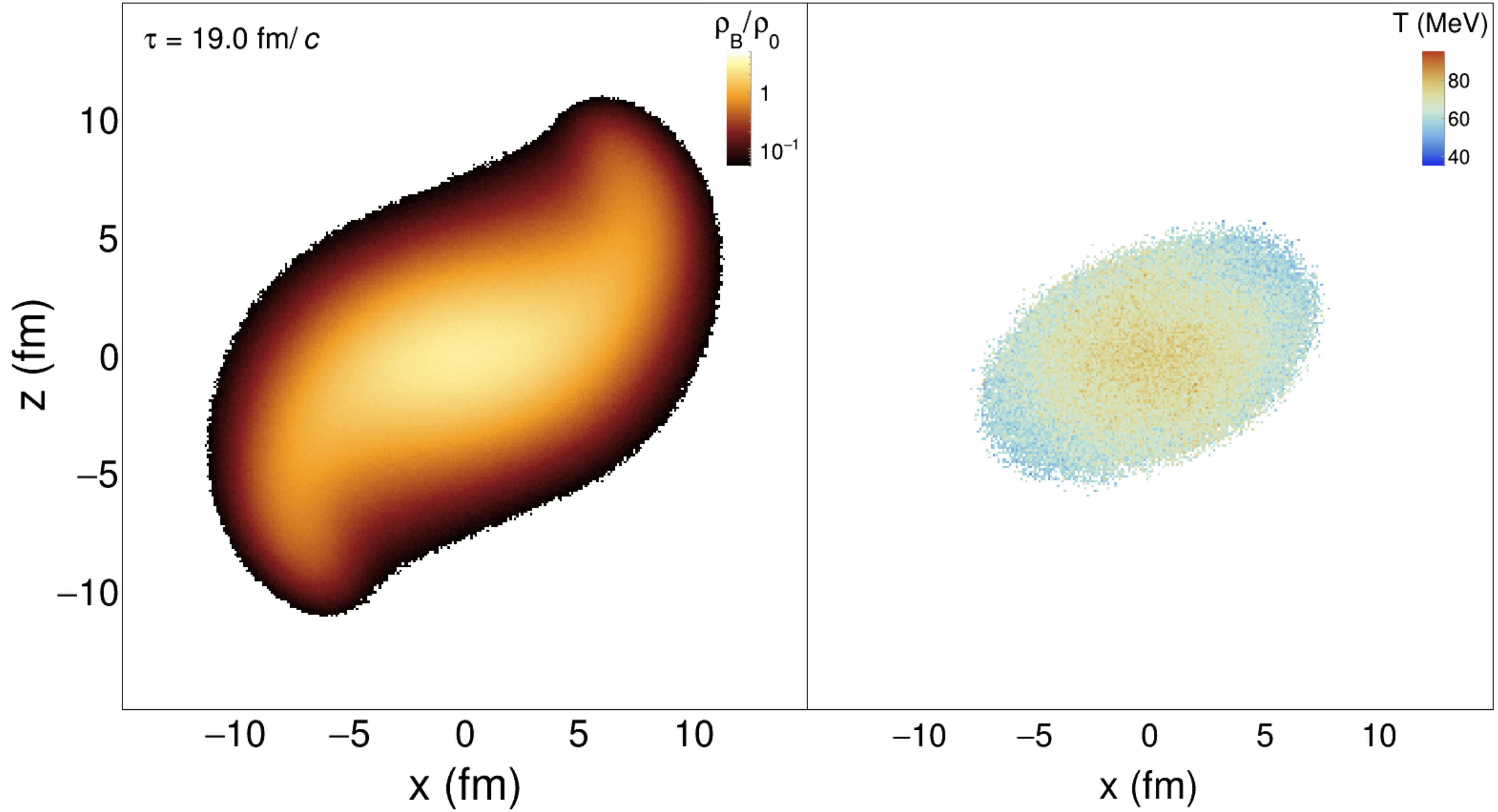
# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



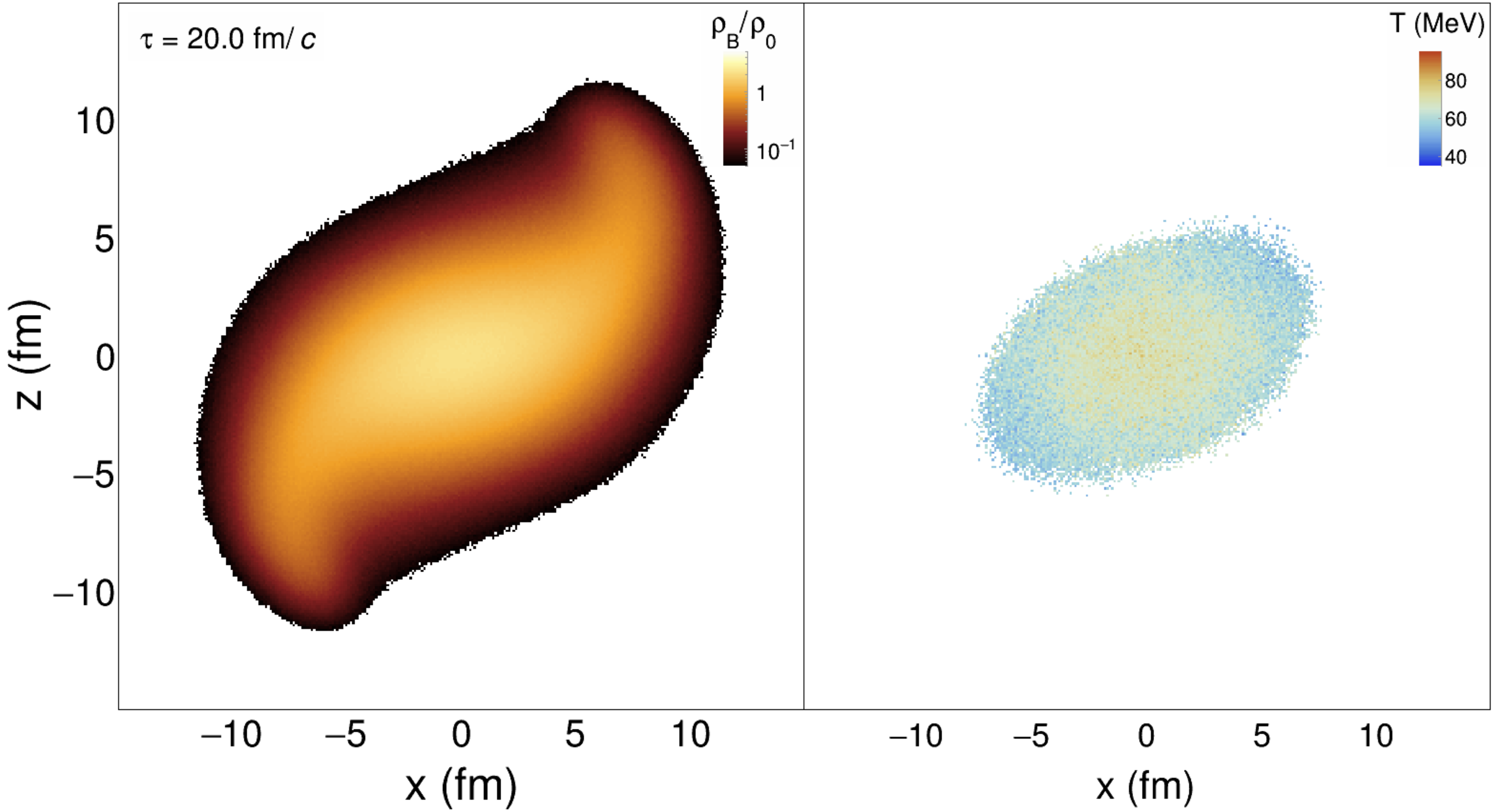


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

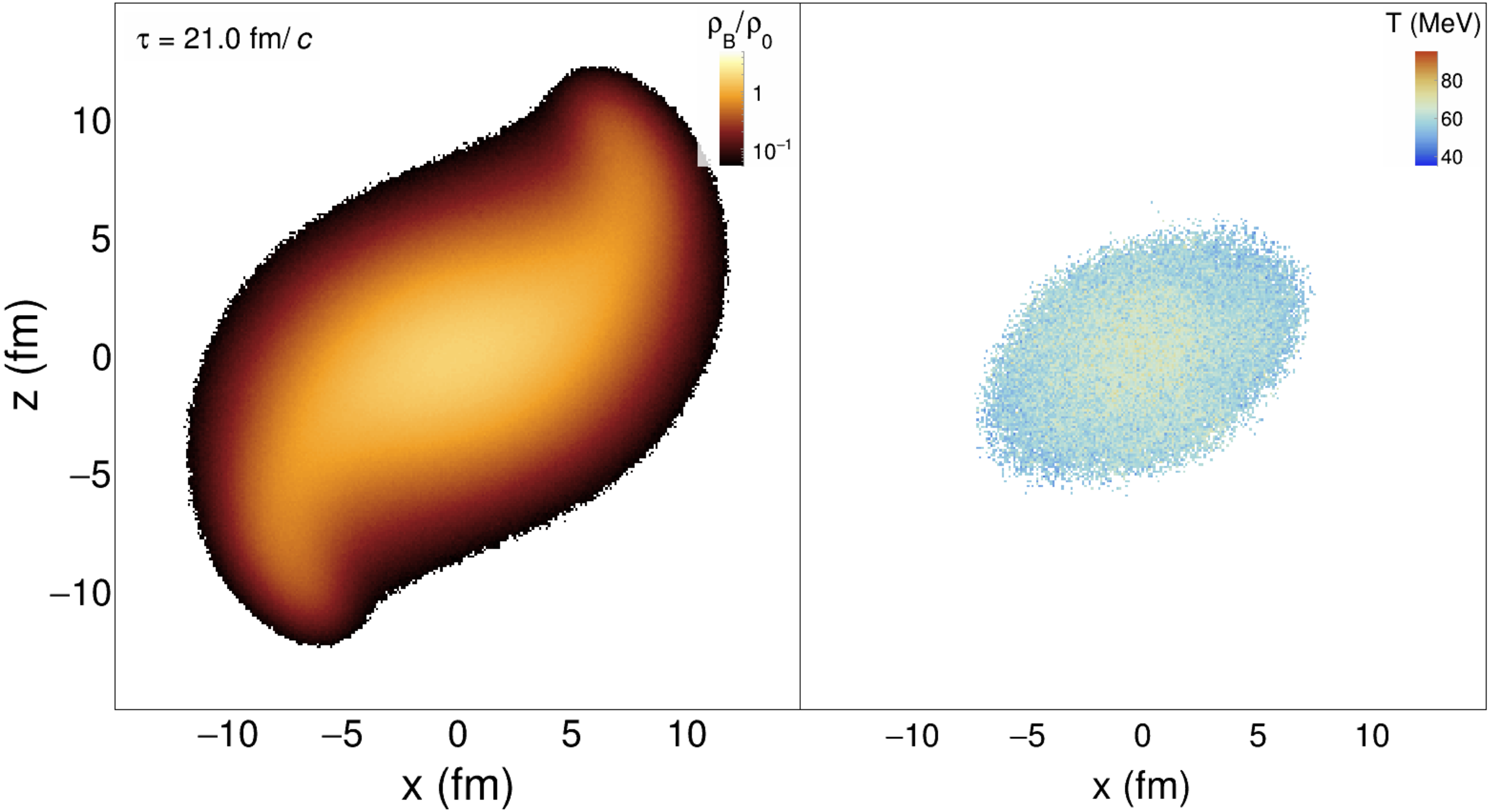




# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

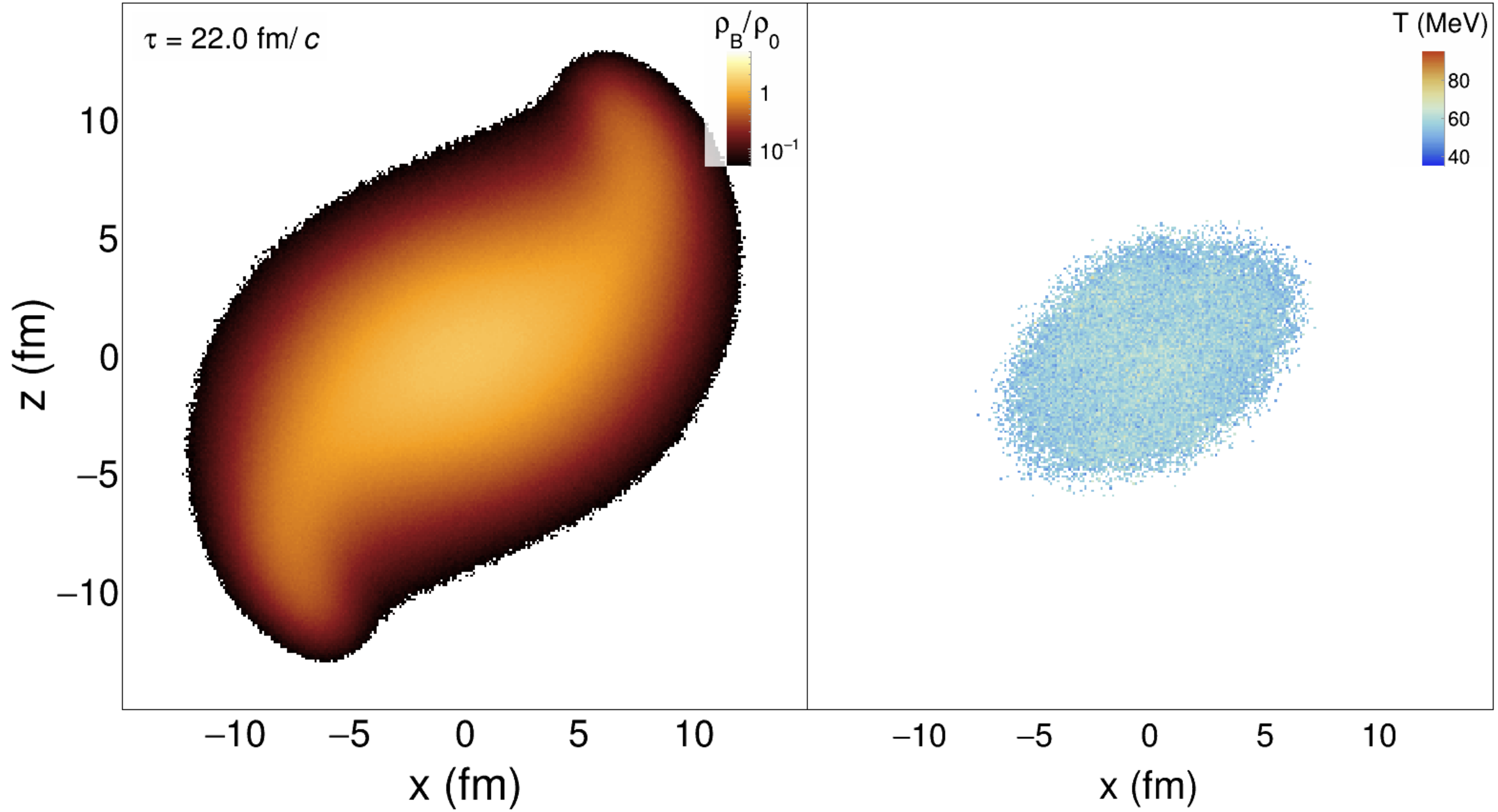


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

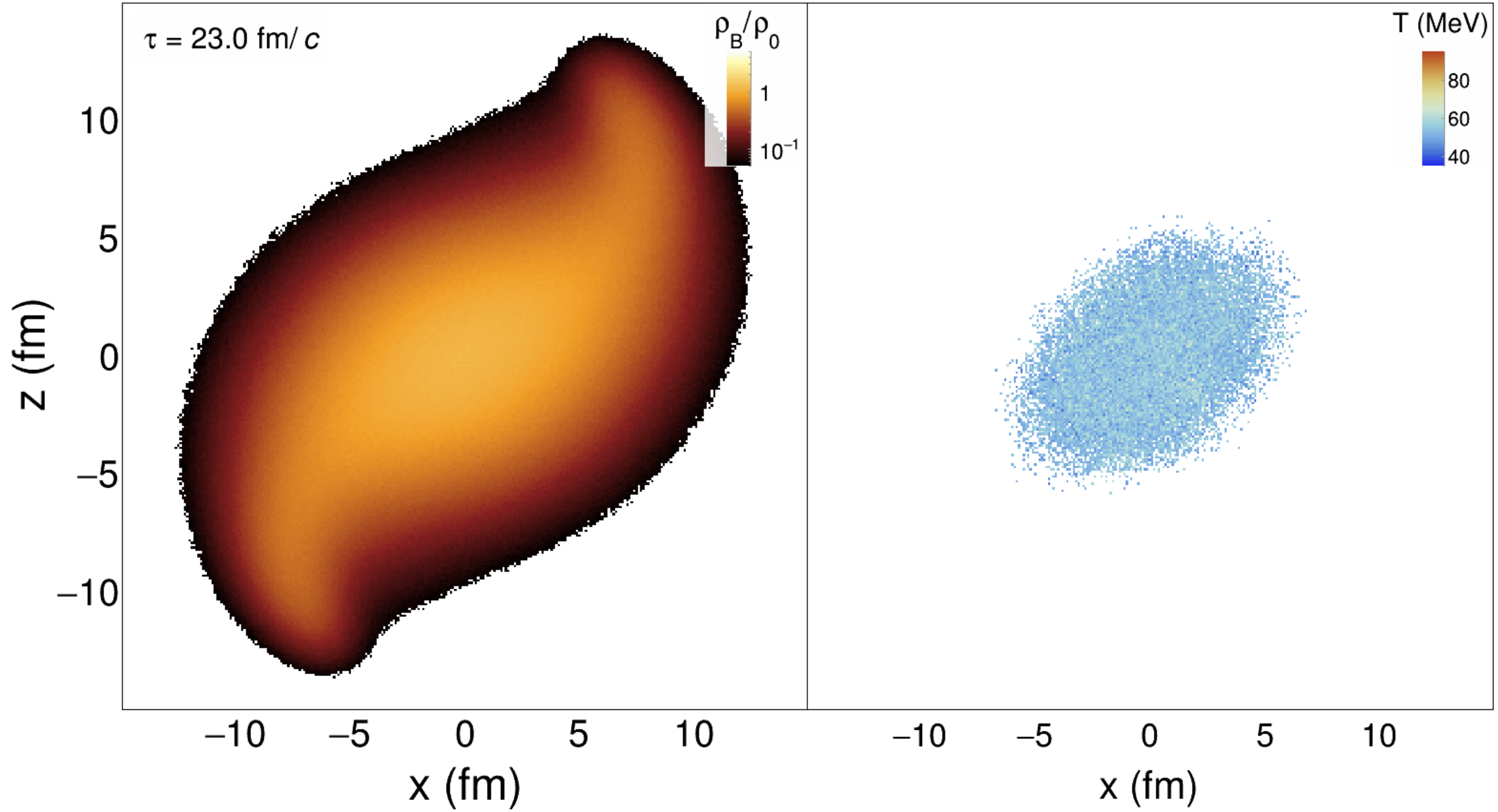


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV



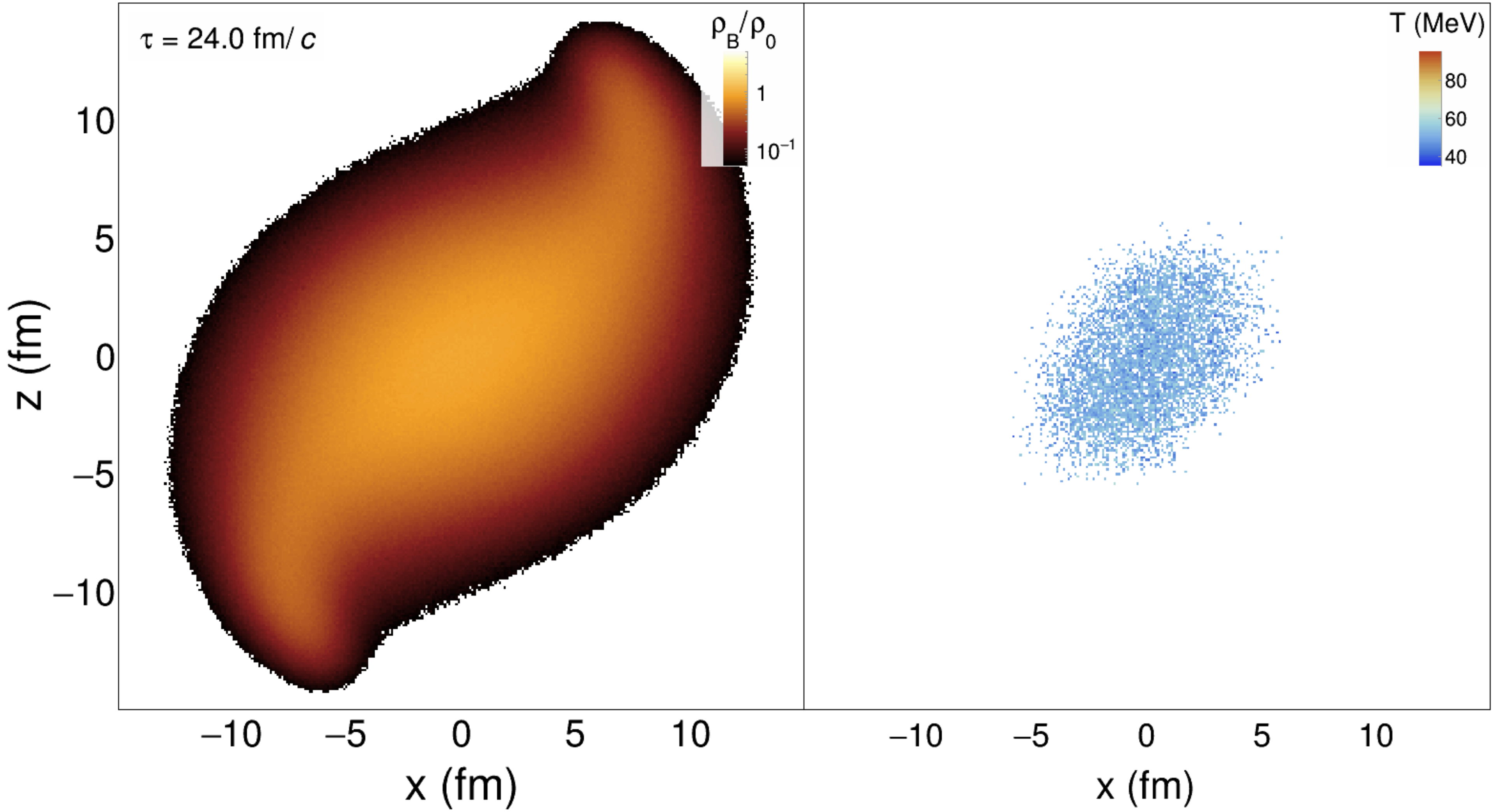


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

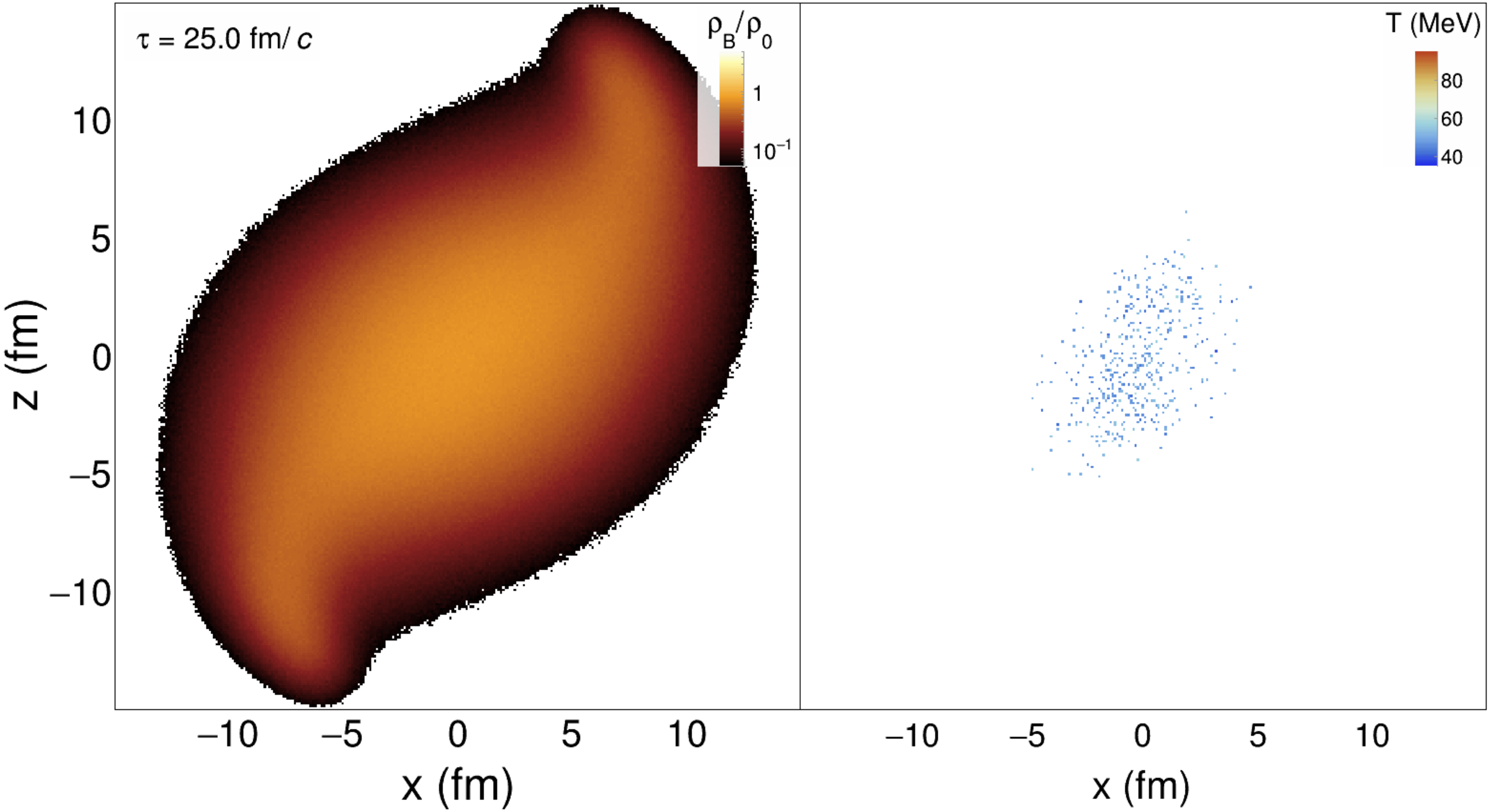


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

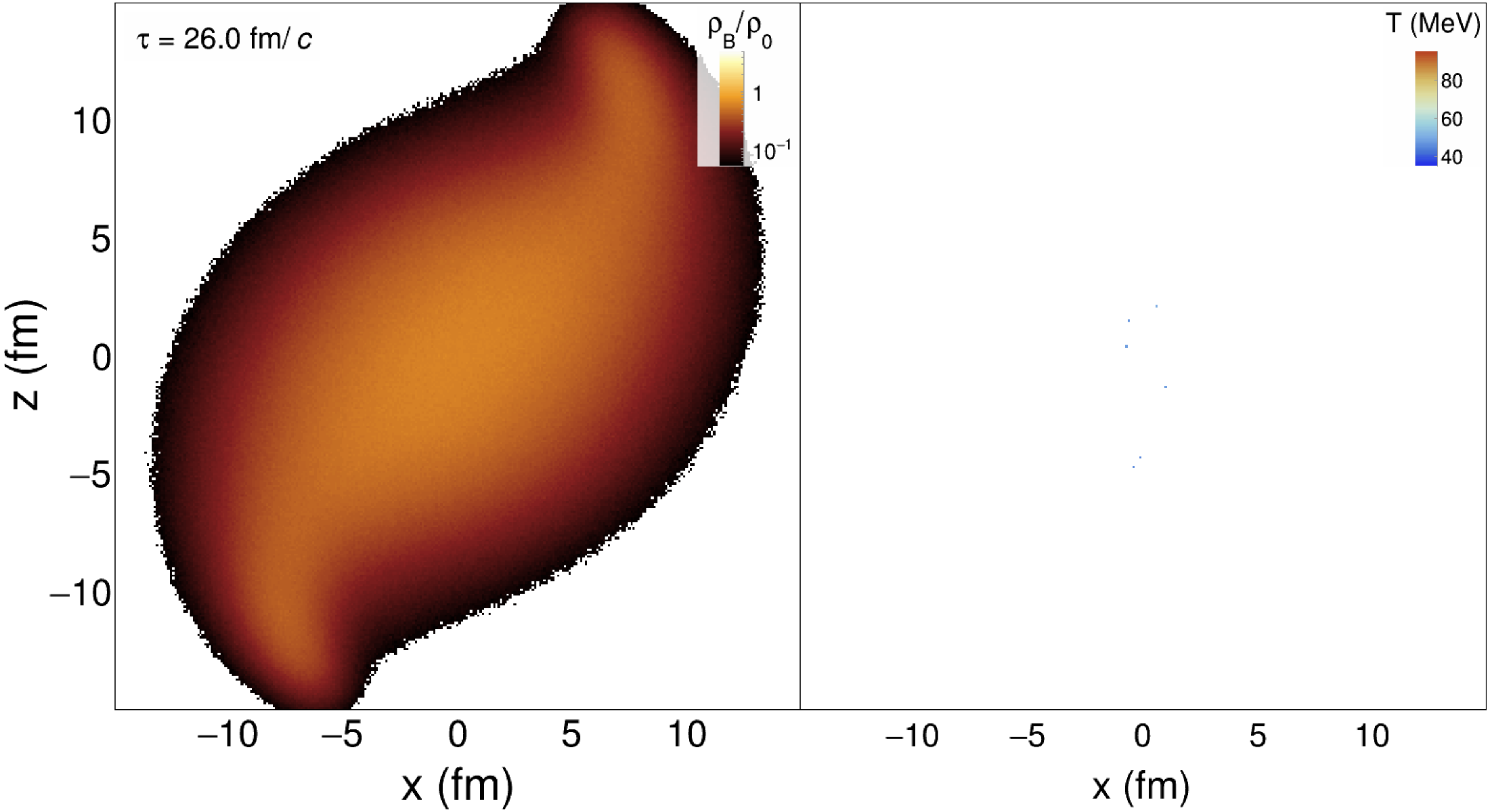
TECHNISCHE UNIVERSITÄT DARMSTADT



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

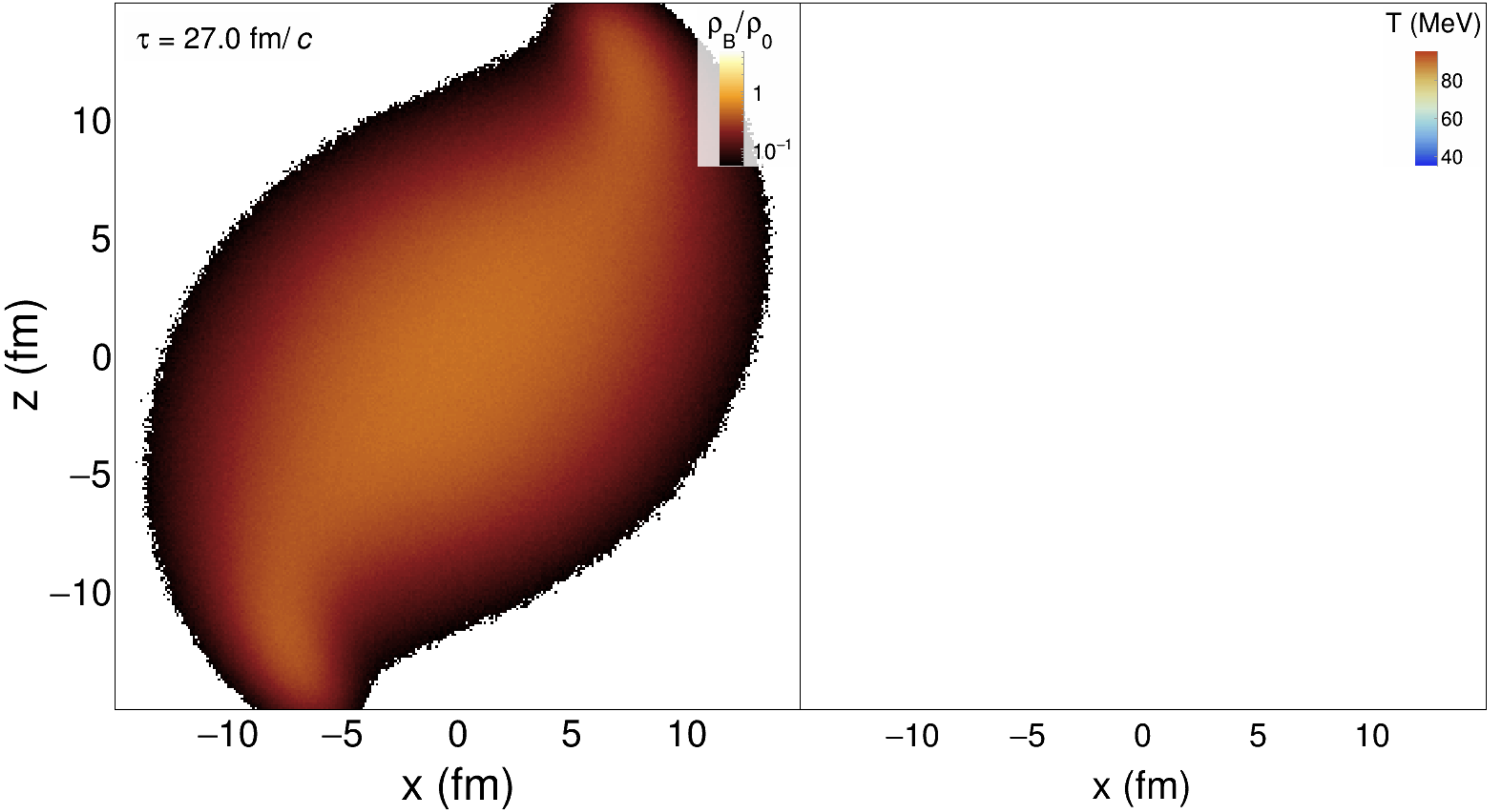


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

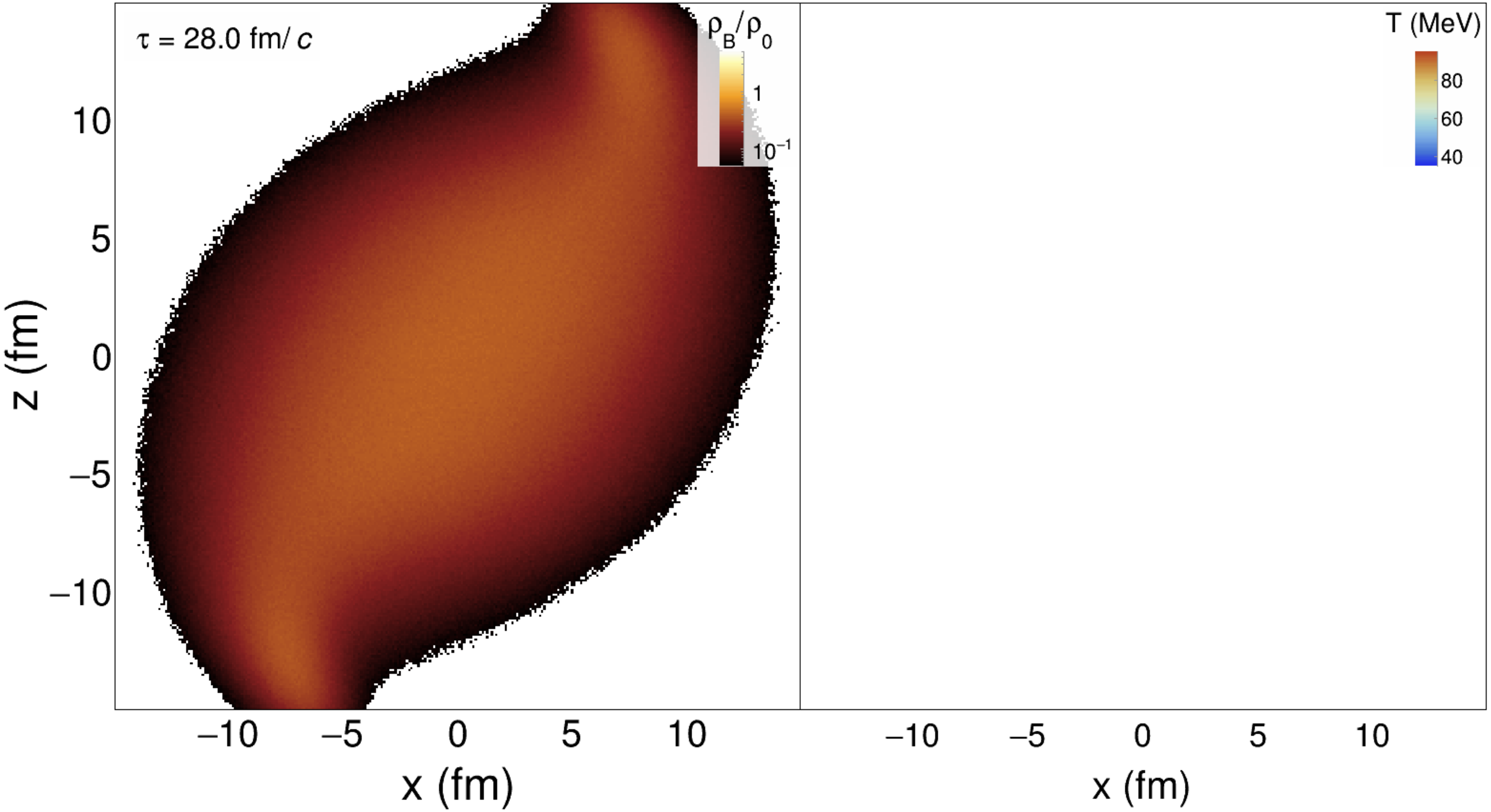


# BARYON DENSITY AND TEMPERATURE PROFILE IN AU+AU AT 1.23 AGEV

TECHNISCHE UNIVERSITÄT DARMSTADT



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



# THERMAL DILEPTON PRODUCTION



Bose-Einstein distribution

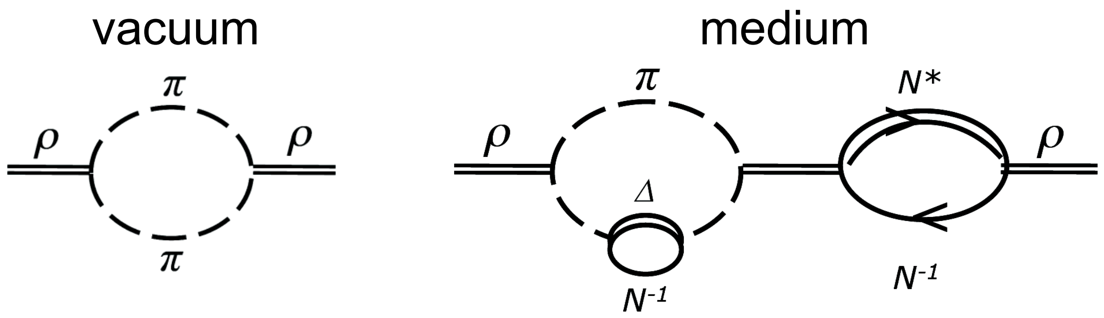
electromagnetic spectral function

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

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

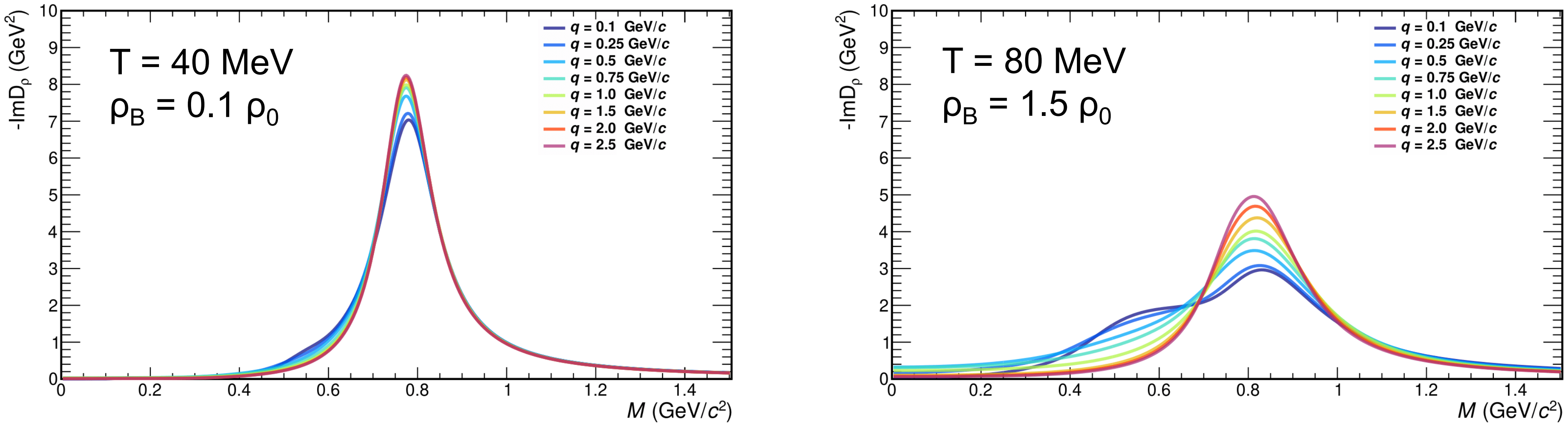
- ρ-meson spectral function broadens
  - Additional contributions to the self-energy in the medium through coupling to (anti-)baryons and mesons

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




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

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

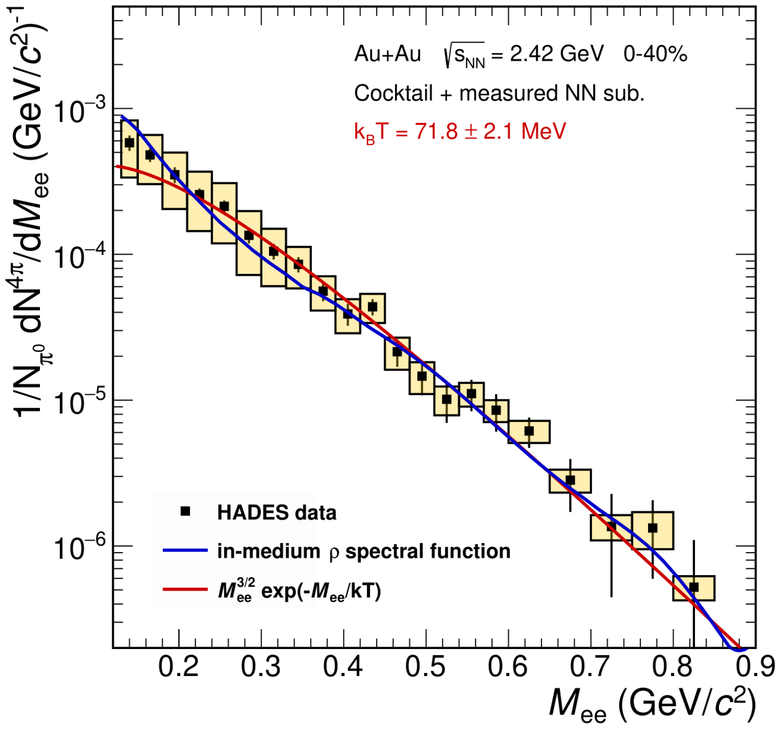


TECHNISCHE UNIVERSITÄT DARMSTADT

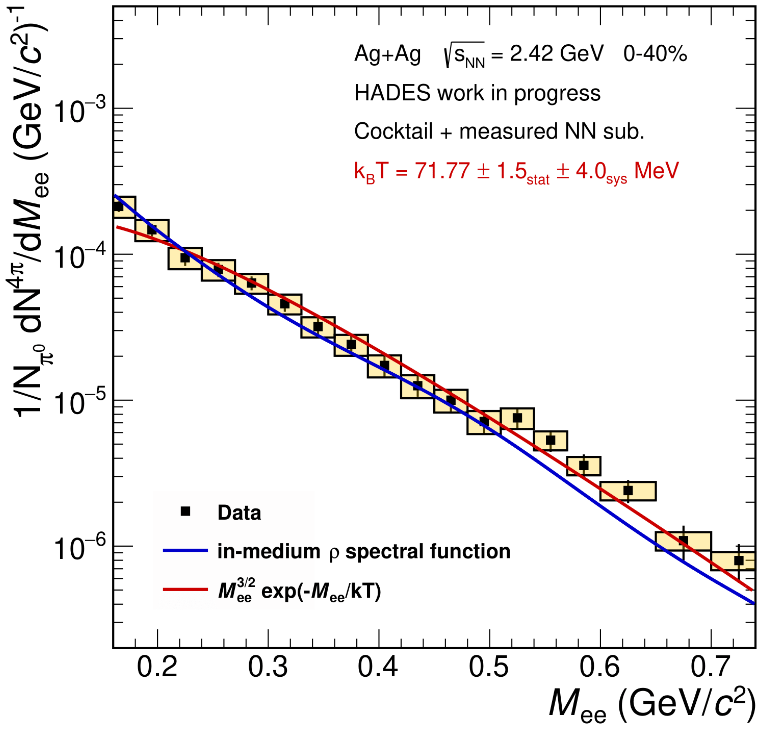
# COMPARISON OF THERMAL EXCESS DATA WITH THEORY

- Good agreement between experiment and theory for excess radiation

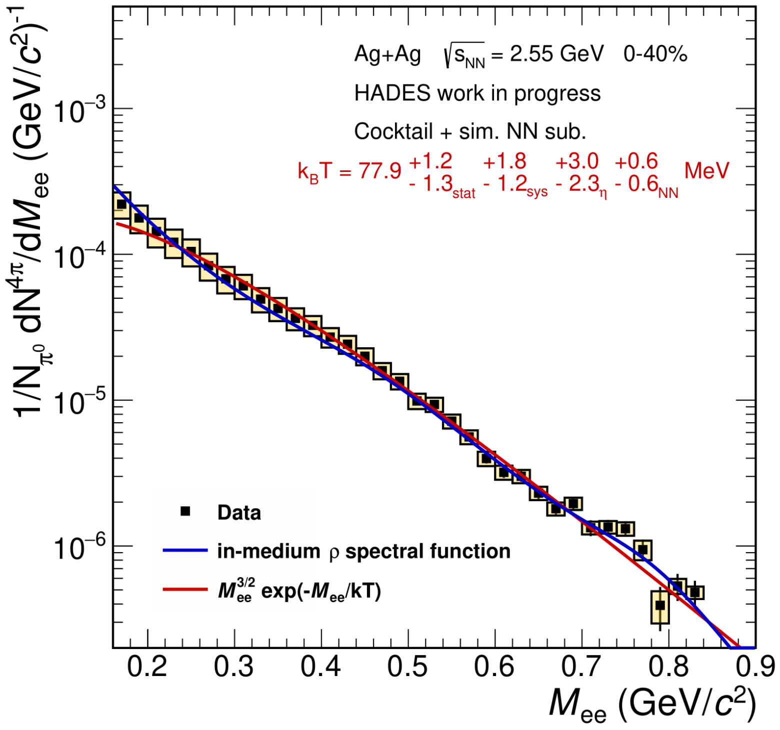
**Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV**




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




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



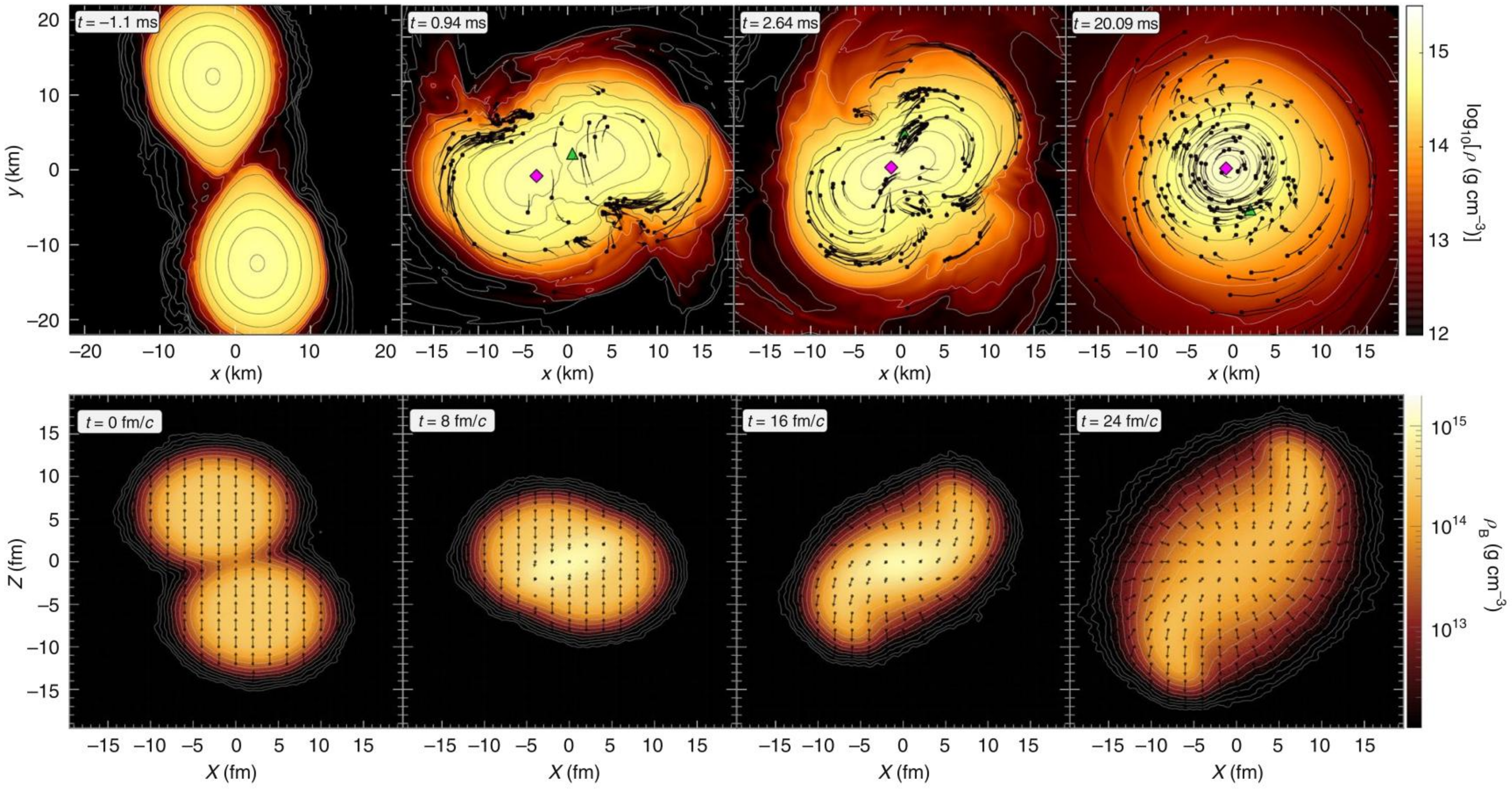
TECHNISCHE UNIVERSITÄT DARMSTADT

- Remarkable similarities between matter in neutron star mergers and HIC in the few GeV regime

  - Laboratory studies of the matter properties (EoS) in compact stellar objects (neutron star mergers)

M. Hanauske *et al.,* Particles 2 (2019) no.1
L. Rezzolla *et al.,* Phys. Rev. Lett. 122 (2019) no. 6, 061101
E. Most et al., Phys. Rev. D 107 (2023) 4, 043034

  - What are the measurable consequences of phase transition and critical point in the QCD phase diagram?




HADES, Nature Phys. 15 (2019) 1040

TECHNISCHE UNIVERSITÄT DARMSTADT

- Excess yield in LMR tracks fireball lifetime

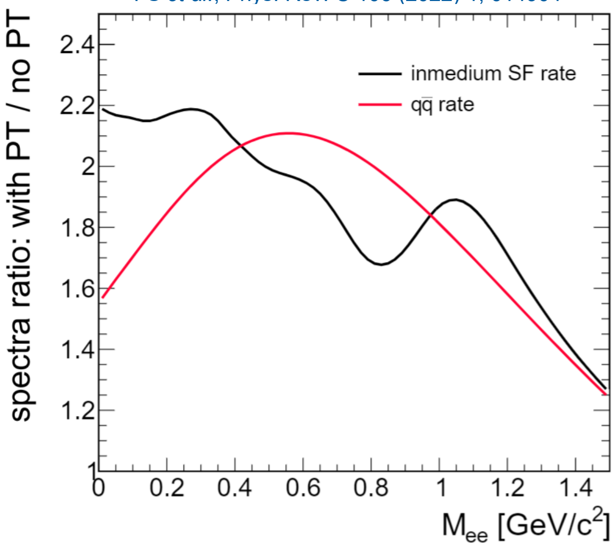
$$\tau_{Life} \propto \frac{N_{ll}}{N_{charged\ pions}}$$

R. Rapp & H. van Hees, Phys. Lett. B 753 (2016) 586-590

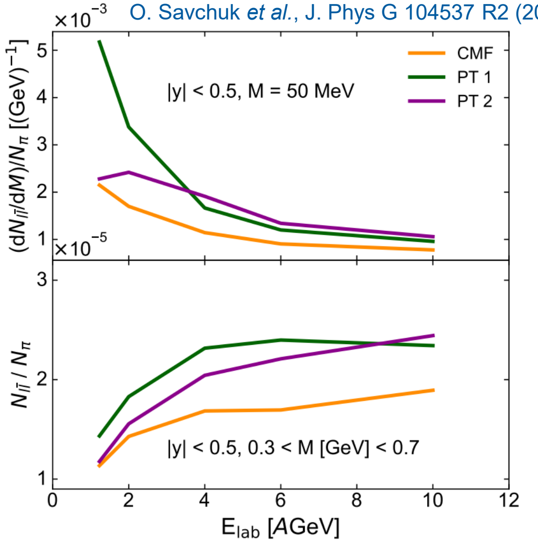
- Search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)

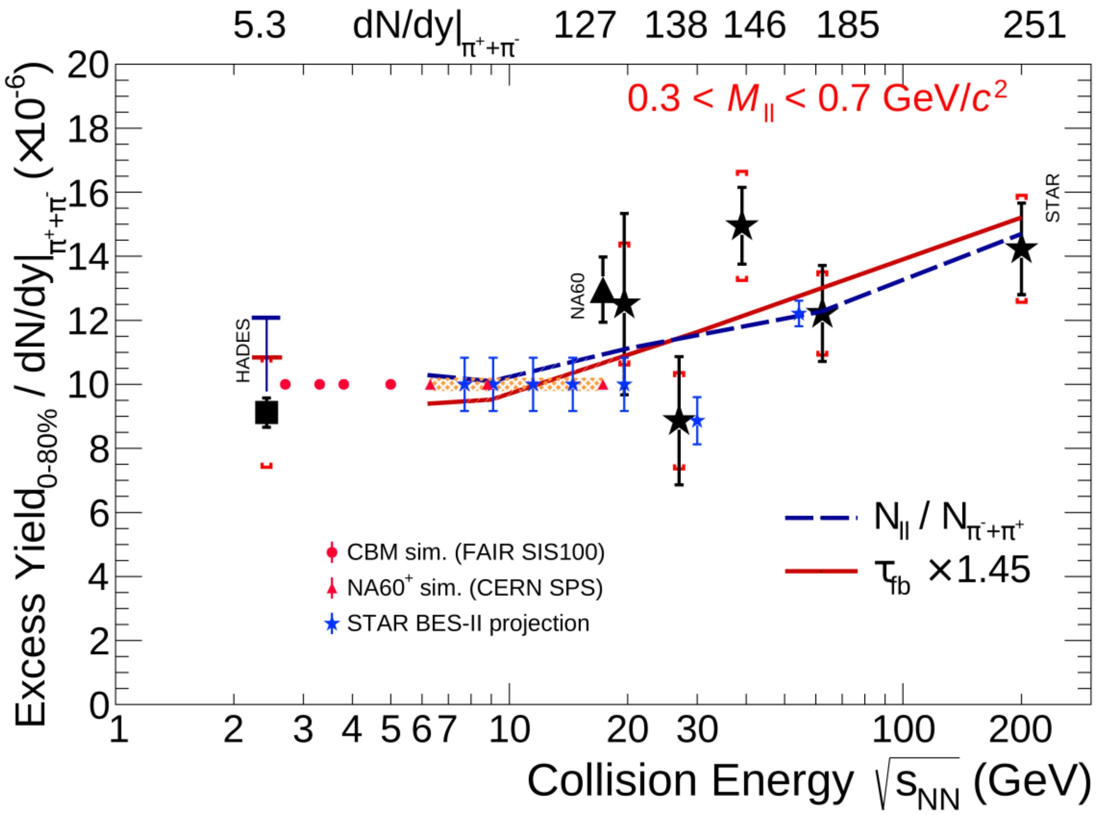
- 1st order phase transition could result in factor 2 larger yield
  - Detectable by current & future experiments

FS *et al.*, Phys. Rev. C 106 (2022) 1, 014904




O. Savchuk *et al.*, J. Phys G 104537 R2 (2023)




Galatyuk, JPS Conf. Proc. 32 (2020) 010079
Galatyuk, Rapp, et al., doi:10.1007/978-981-19-4441-3_4 (2022)

# EXCITATION FUNCTION OF THE TEMPERATURE OF THE FIREBALL

- Invariant mass slope measures radiating source temperature (free from blue-shift effects)

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

R. Rapp & H. van Hees, Phys. Lett. B 753 (2016) 586-590

„black body radiation“

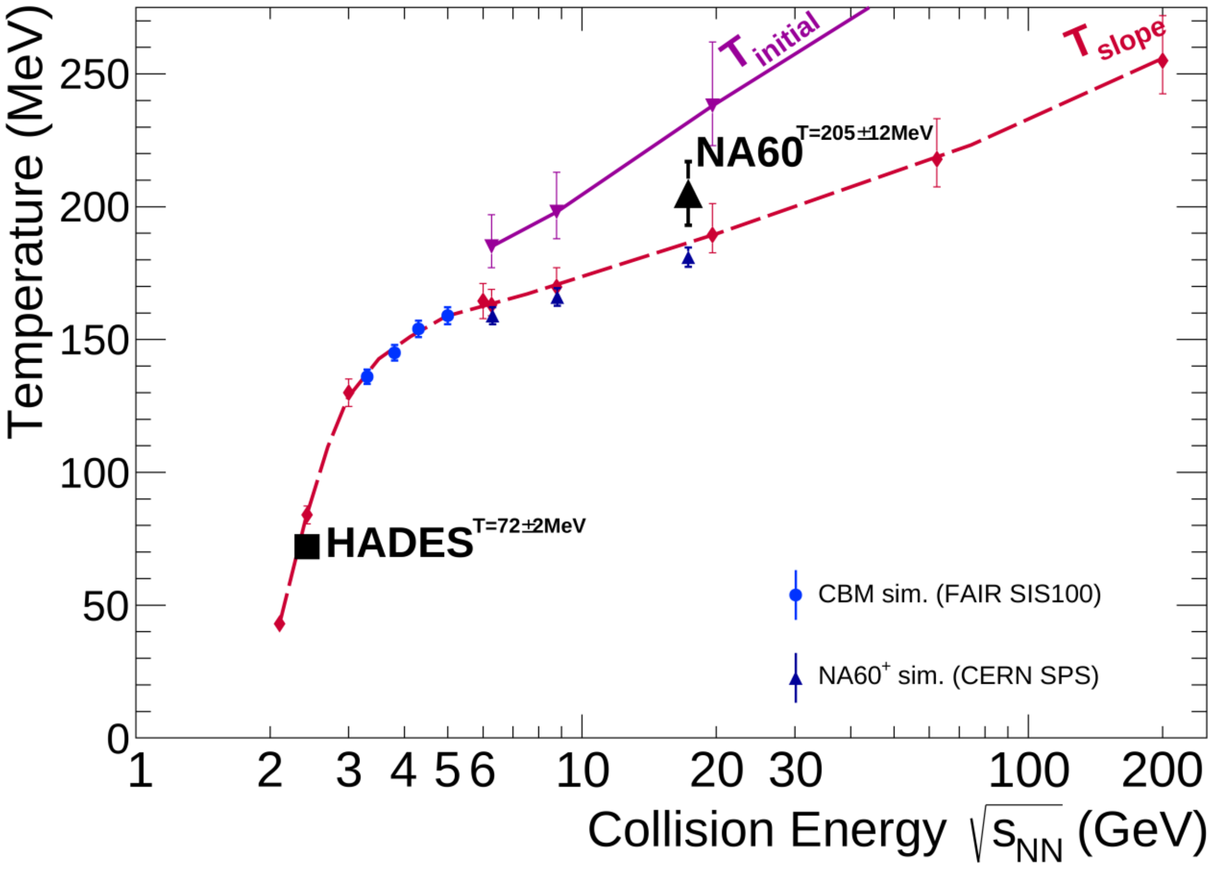
- Assumption: $\frac{Im\Pi_{EM}}{M^2} \sim$ constant
  - Generally justified in the IMR ($M_{ee}$ > 1.5 GeV/c²)
  - Strong melting of $\rho$ meson allows temperature extraction in the LMR ($M_{ee}$ = 0.3-0.7 GeV/c²)

FS, T. Galatyuk et al., Eur. Phys. J. A 52 (2016) 5, 131

- $T_{LMR}$ and $T_{IMR}$ different:
  - $T_{IMR}$ probes hottest regions
  - $T_{LMR}$ probes average fireball temperature

**Flattening** of caloric curve ($T$ vs $\varepsilon$)

→ evidence for a **phase transition**




NA60, AIP Conf. Proc. 1322 (2010) 1
HADES, Nature Phys. 15 (2019) 1040
Rapp and v. Hess, PLB 753 (2016) 586
TG *et al.*, EPJA 52 (2016) 131
https://github.com/tgalatyuk/QCD_caloric_curve

# DILEPTON FLOW

- Azimuthal anisotropies with respect to reaction plane

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

- 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

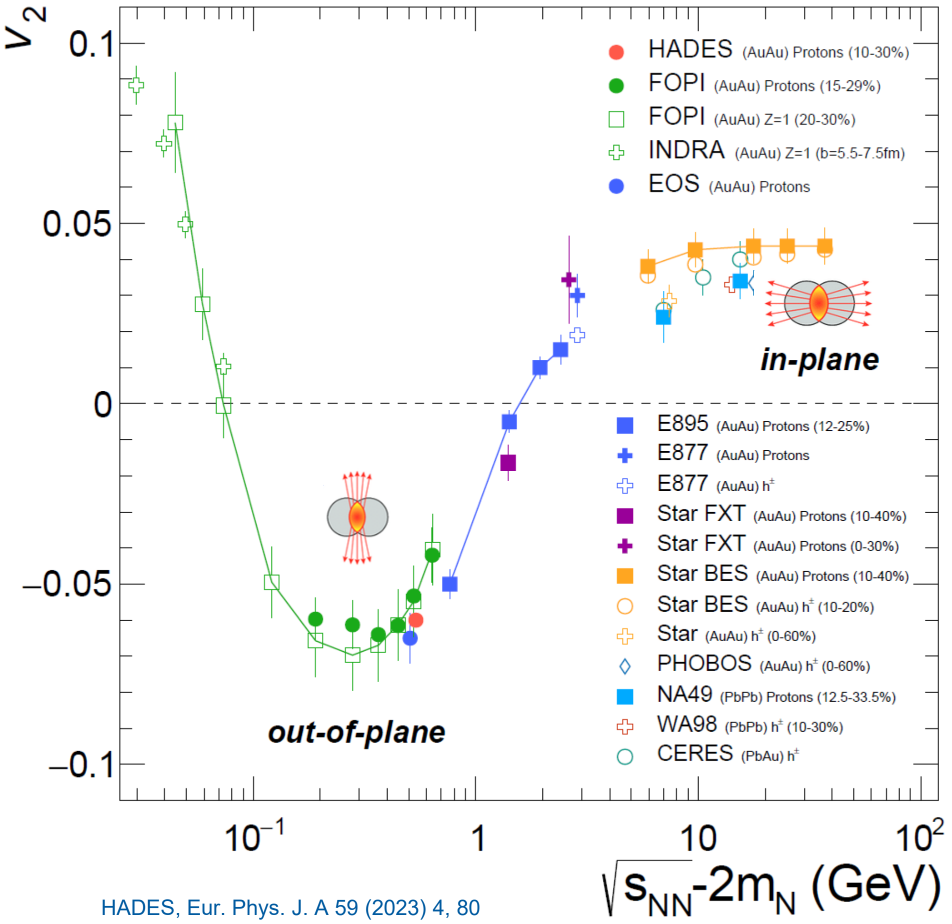
- Pressure anisotropies in underlying space-time evolution
  → collective velocities of medium cells

- Dileptons probe earlier times (high $\rho_B$, high T) compared to hadron flow

**Possible sensitivity to the EoS at high density**

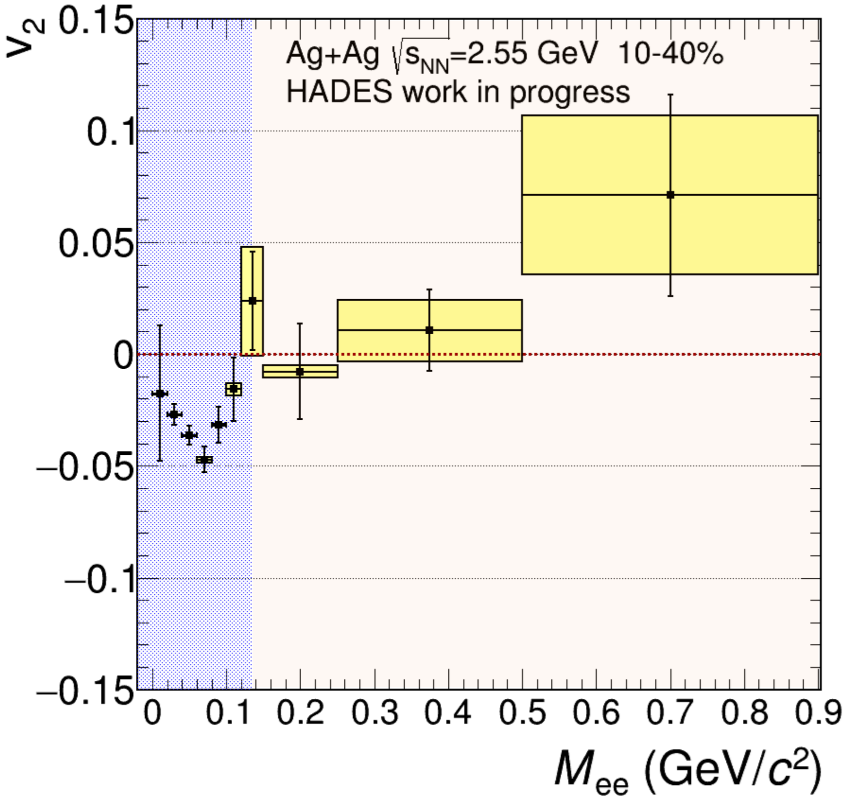
T. Reichert *et al.*, Phys.Lett.B 841 (2023) 137947

proton $v_2$



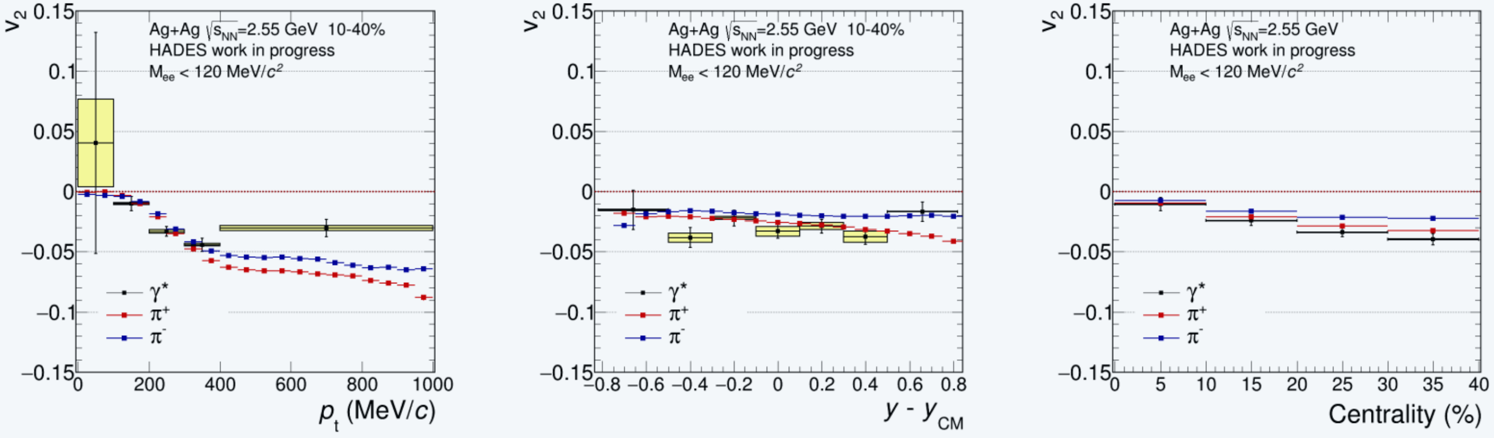

HADES, Eur. Phys. J. A 59 (2023) 4, 80

## DILEPTON V2 IN AG+AG COLLISIONS



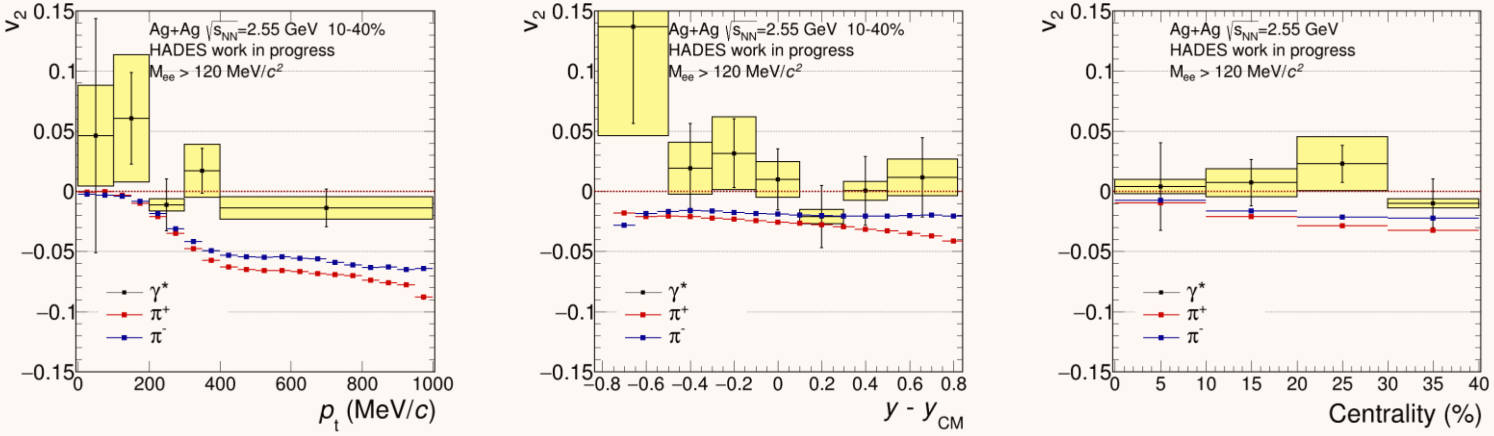

$M_{ee}$ < 0.12 GeV/$c^2$: inclusive yield dominated by $\pi^0$ decays

- Dilepton $v_2$ consistent with charged pion $v_2$



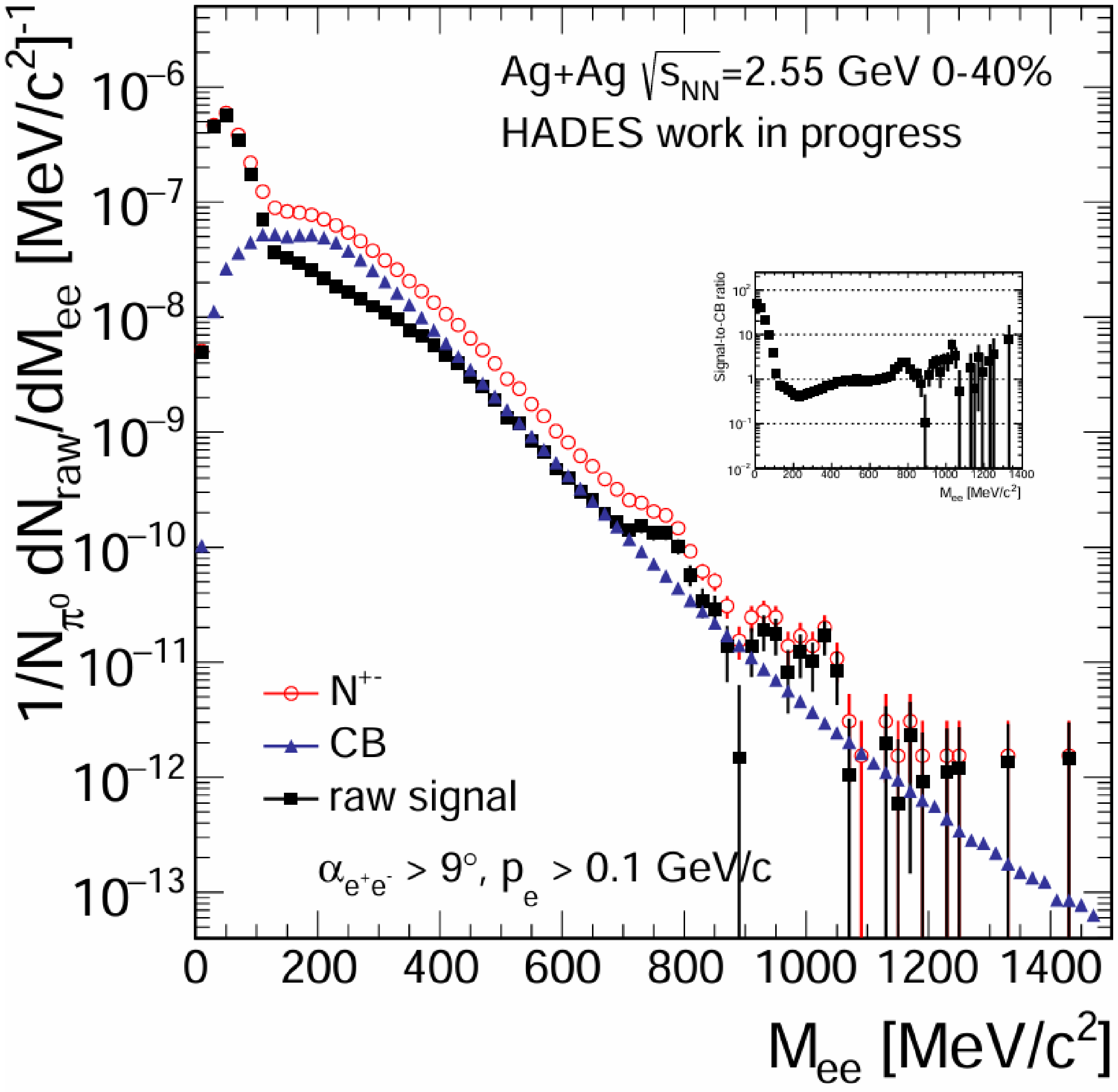

$M_{ee}$ > 0.12 GeV/$c^2$: inclusive yield dominated by thermal radiation

- Dilepton $v_2$ consistent with zero → early emission

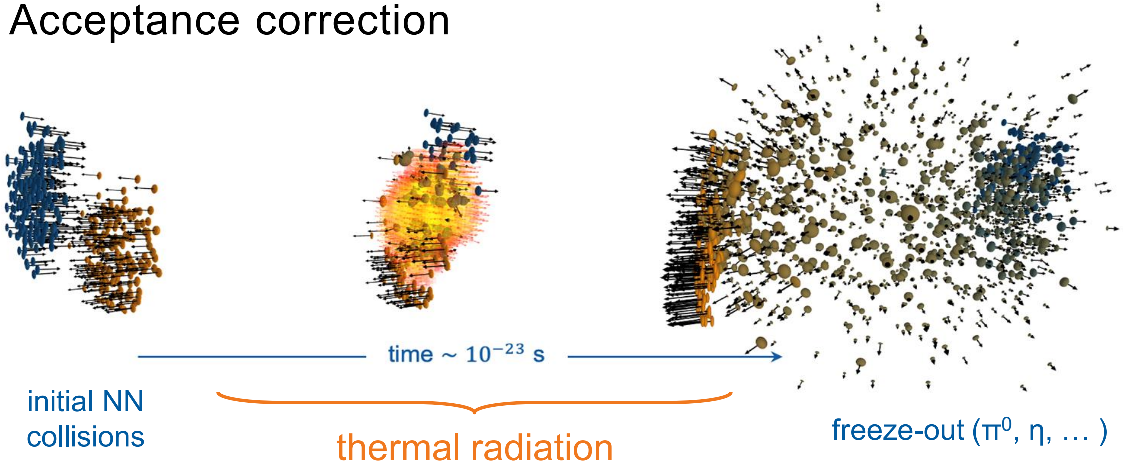


## STEPS TO ISOLATE THERMAL RADIATION



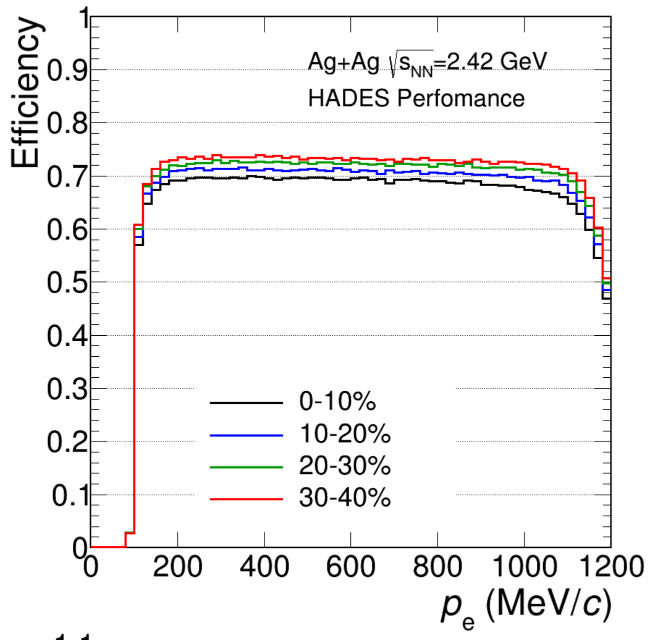



- RICH photodetector upgrade
  - Employing CBM at FAIR technology (CBM FAIR phase-0)
- Efficiency correction
- NN reference subtraction
- Freeze-out cocktail subtraction
  - Simulated using Pluto event generator with measured/estimated multiplicities
- Acceptance correction

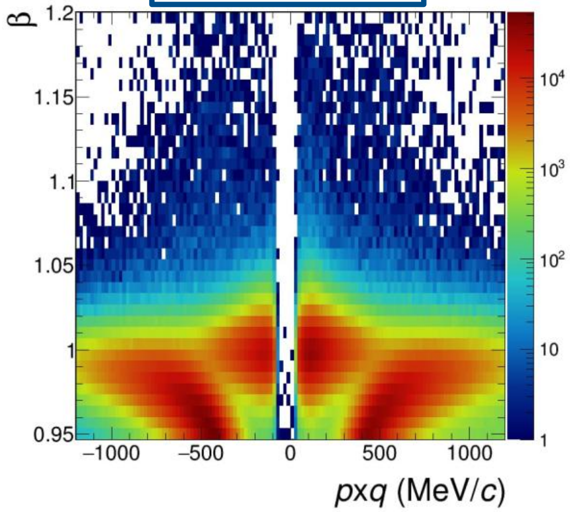


# HADES LEPTON IDENTIFICATION PERFORMANCE

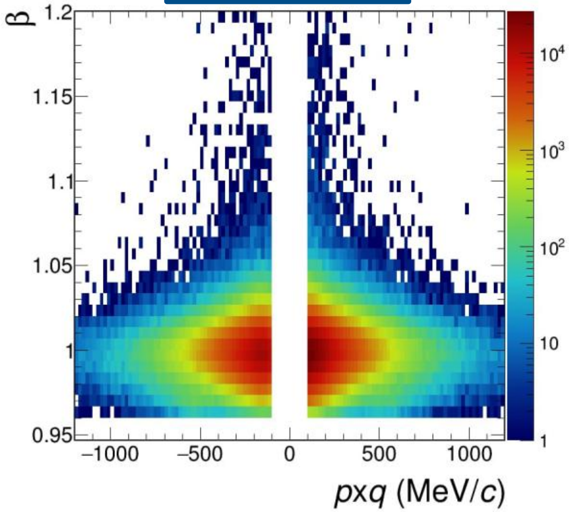
- Reconstruction efficiency ~ 70%
- Purity above 90%
- Hadron suppression of ~ $10^{-5}$
- Ag+Ag run in 2019
  - $N_{y*}^{rec} \approx 1.5 \cdot \mathbf{10^6}$ for $\sqrt{s_{NN}} = 2.55$ GeV (28 days)
  - $N_{y*}^{rec} \approx 1.5 \cdot \mathbf{10^5}$ for $\sqrt{s_{NN}} = 2.42$ GeV (3 days)

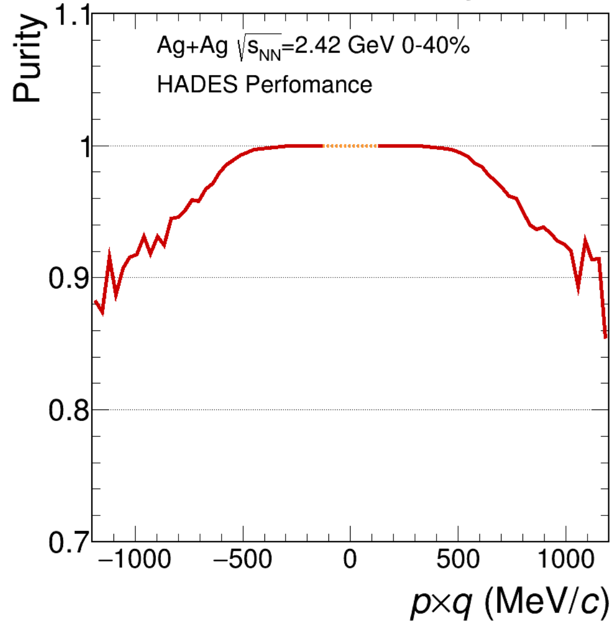



before cuts




after cuts

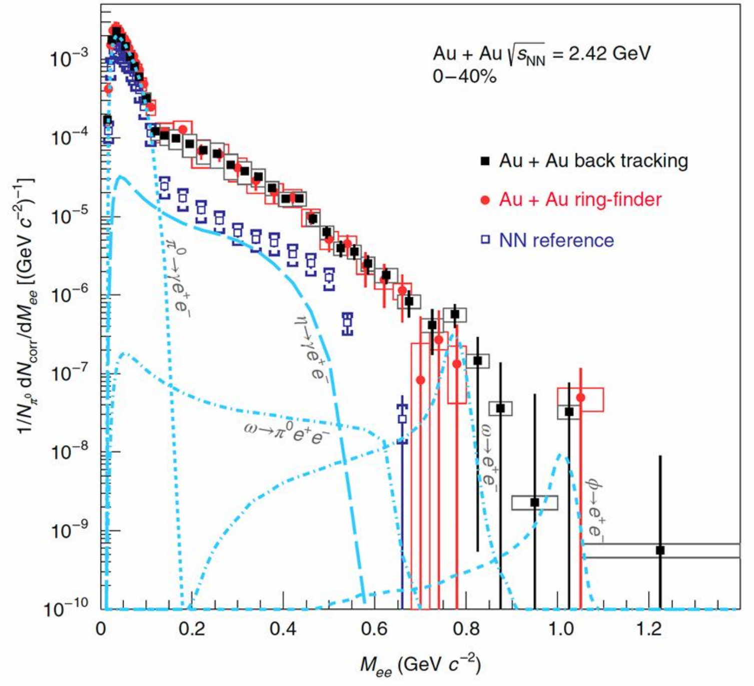


TECHNISCHE UNIVERSITÄT DARMSTADT

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

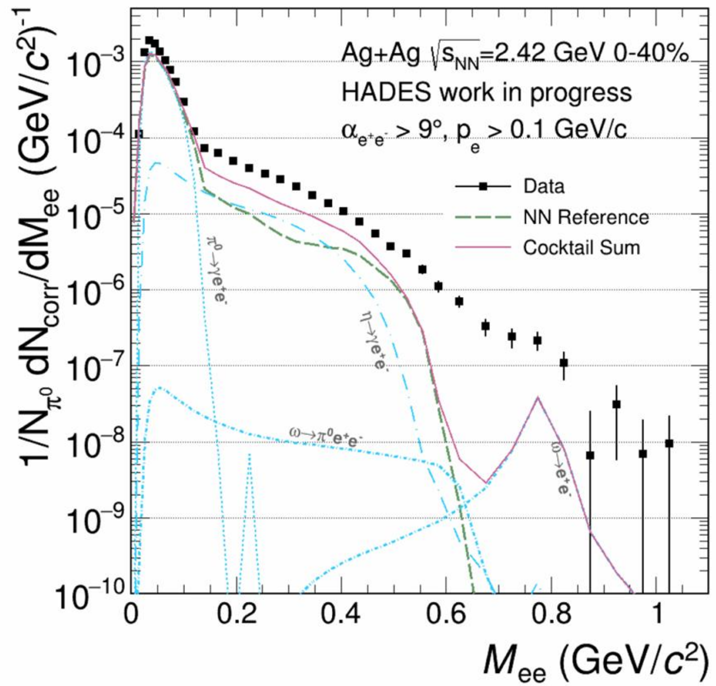
**Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV**




HADES, Nature Phys. 15 (2019) 1040

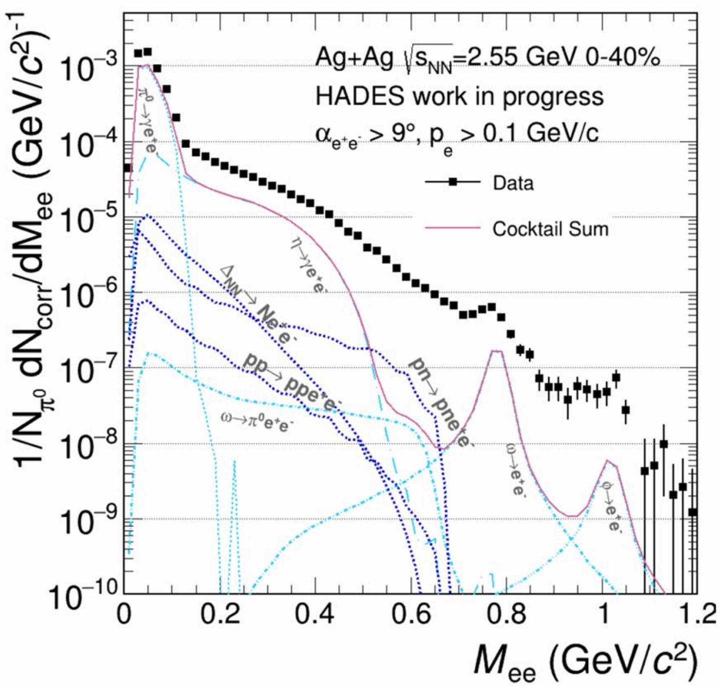
measured NN reference

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




measured NN reference

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



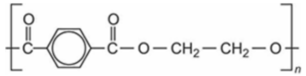

simulated reference (GiBUU)
→ analysis of NN measurement at the same collision energy ongoing

# MEASUREMENT OF NN REFERENCE IN HADES

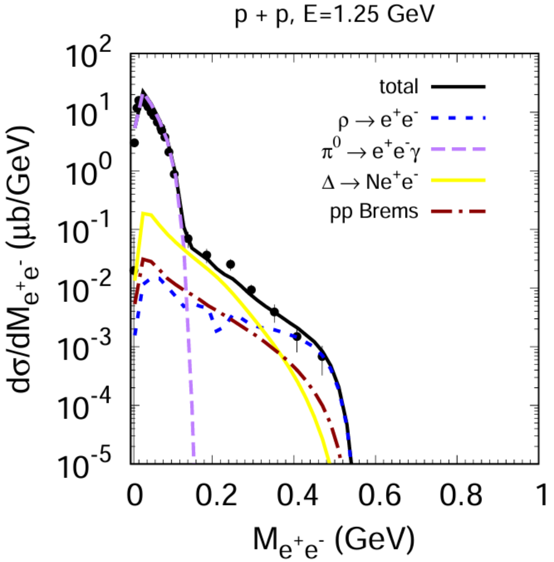
- p+p and d+p collisions at $E_{kin}$ = 1.25 GeV
  - n+p reaction tagged by triggering on proton spectator

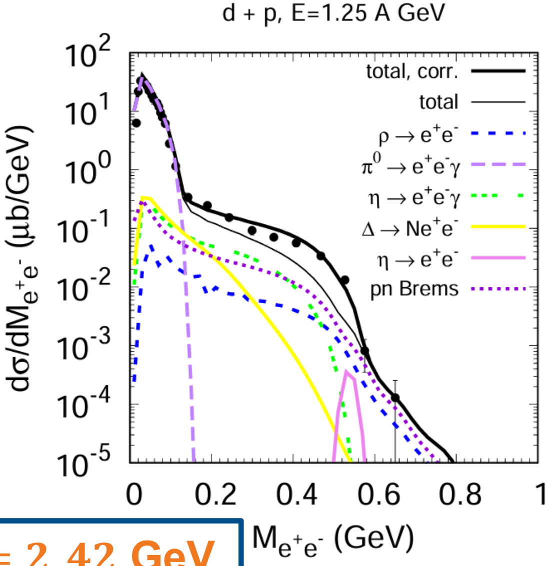
HADES, Phys. Lett. B 690 (2010) 118
A. Larionov *et al.*, Phys. Rev. C 102 (2021), 064913

- 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

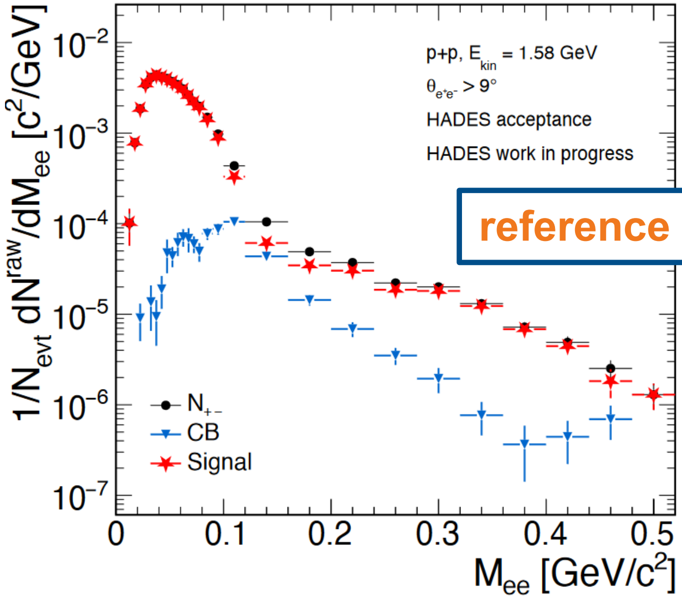


Mylar

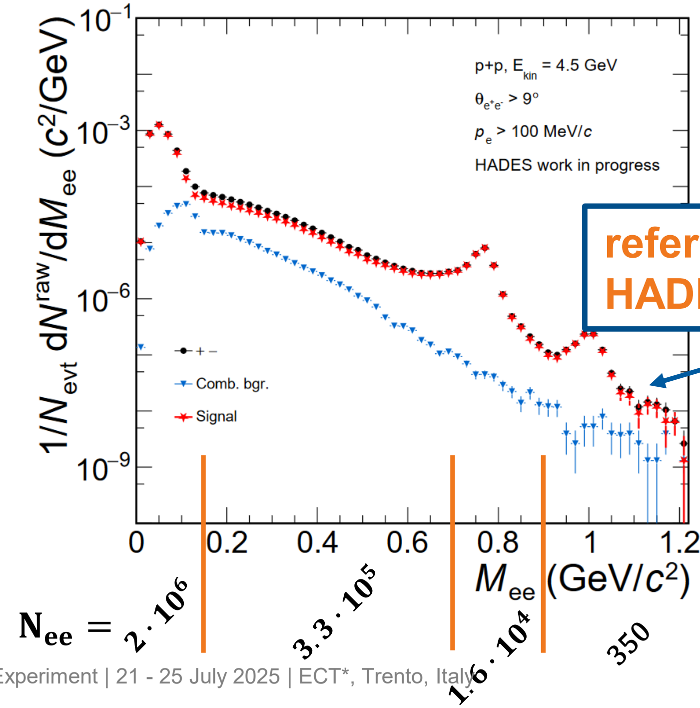



reference for $\sqrt{s_{NN}} = 2.42$ GeV

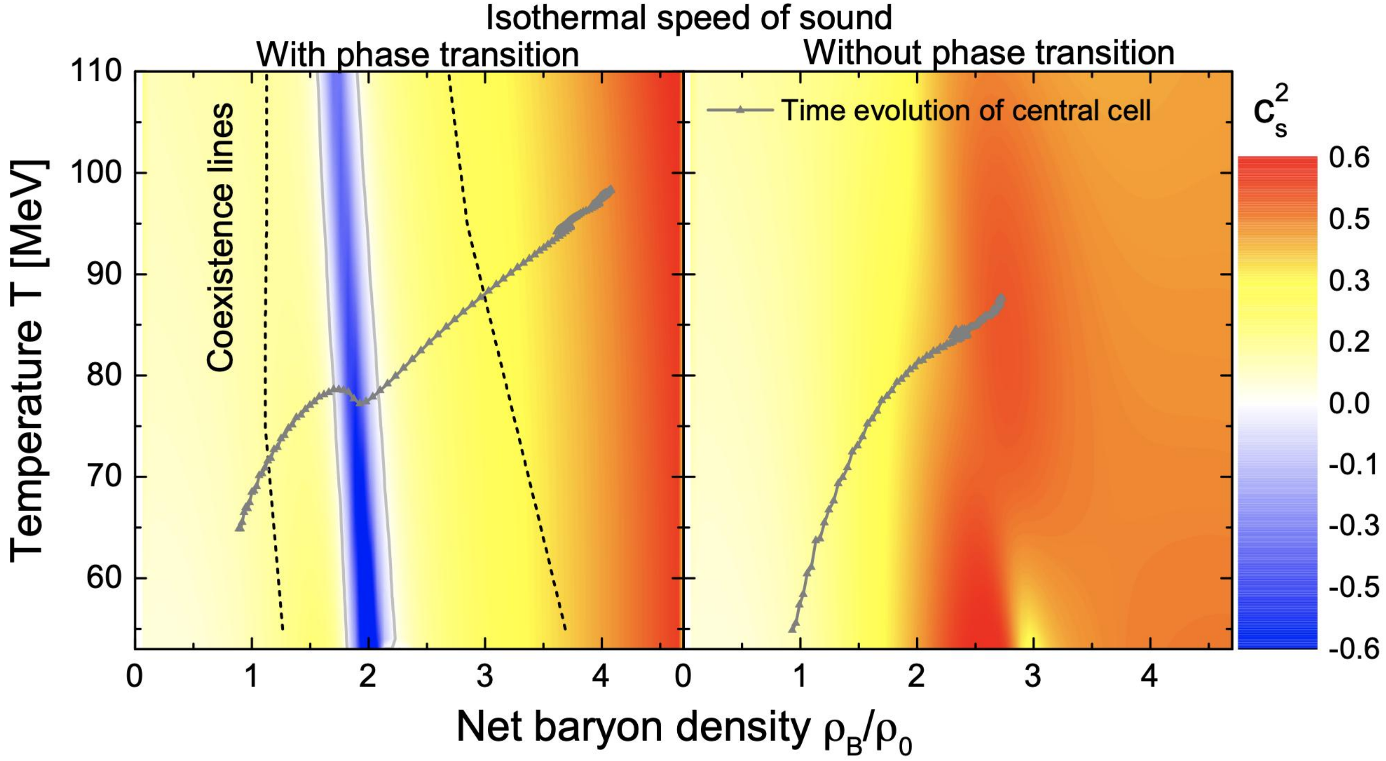



reference for $\sqrt{s_{NN}} = 2.55$ GeV

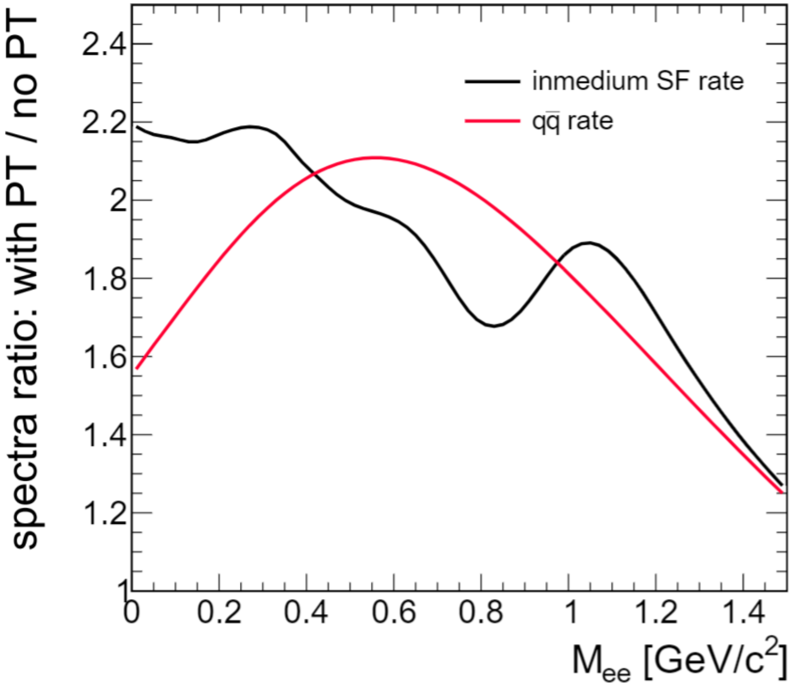



reference for future HADES/CBM runs at FAIR

- 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 $\mu_B$ and neutron-star constraints at high density

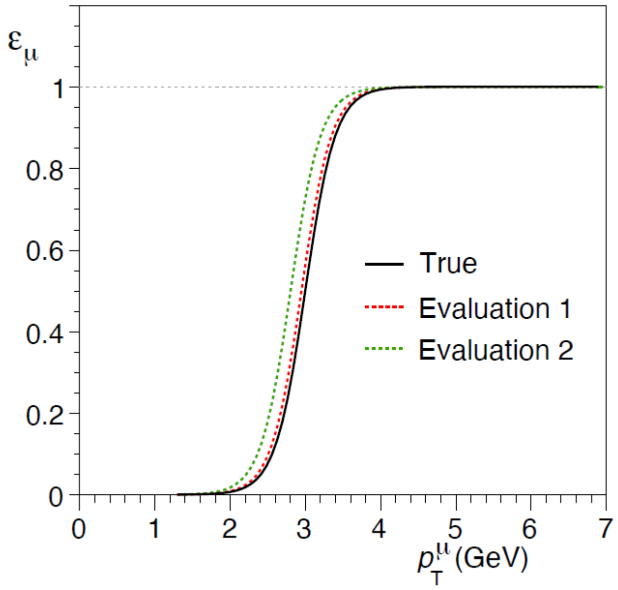


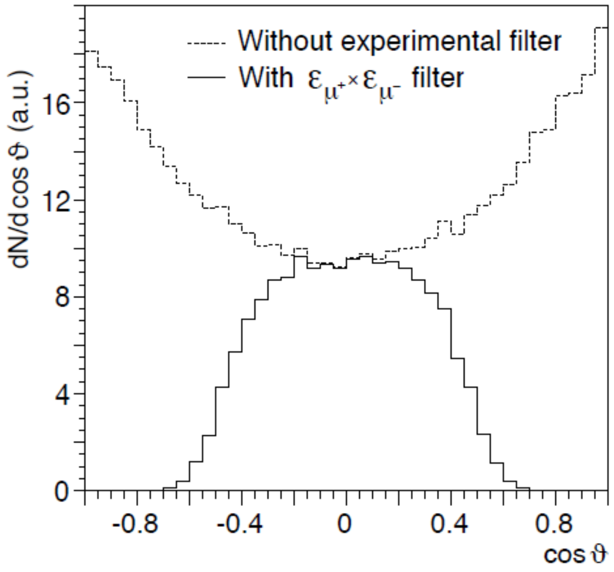

FS *et al.*, Phys. Rev. C 106 (2022) 1, 014904



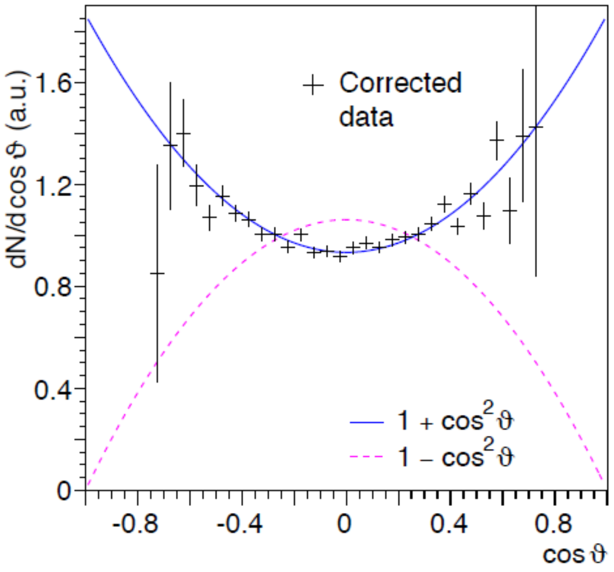
# EXPERIMENTAL DIFFICULTIES

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

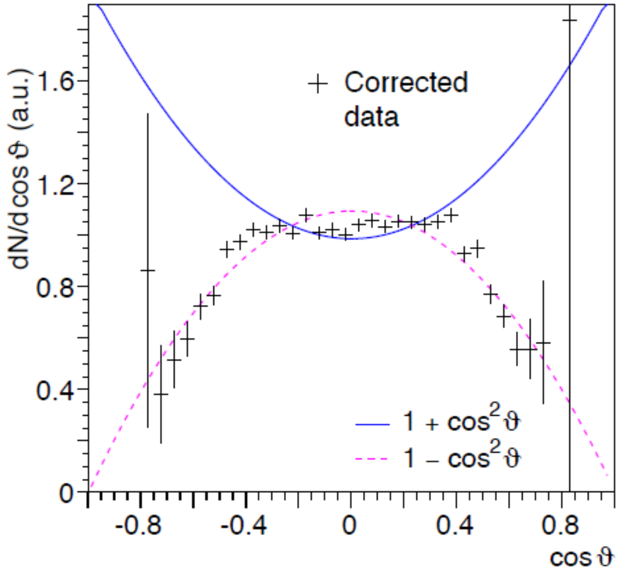



correction with good efficiency evaluation




correction with bad efficiency evaluation

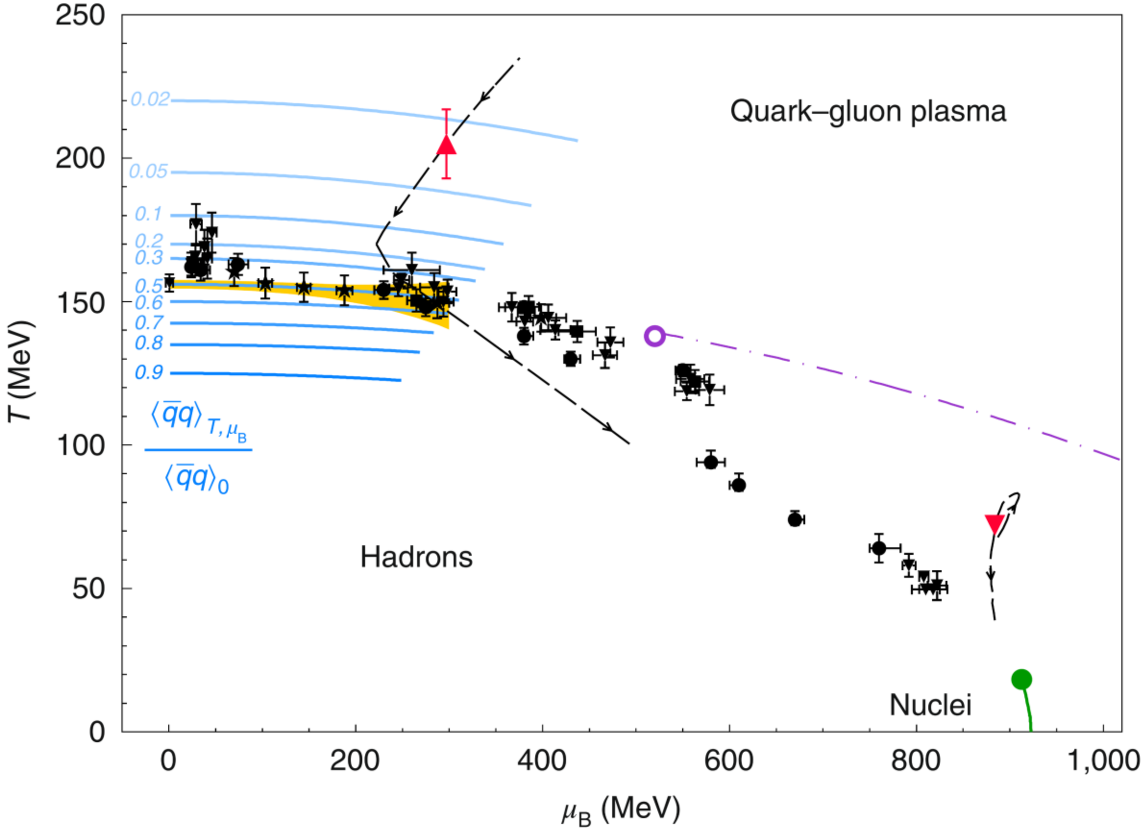



P. Faccioli, Particle Polarization in High Energy Physics, Springer 2023

## SEARCH FOR LANDMARKS IN THE QCD PHASE DIAGRAM

- Search for
  - Phase boundaries
  - Changes in microscopic degrees of freedom
  - Restoration of chiral symmetry
- Bulk observables and rare probes offer different tools to understand the nature of the matter created in HIC
- Electromagnetic radiation $(\gamma, \gamma^*)$
  - Reflects the whole history of a collision
  - No strong final state interaction
    ⇝ leaves reaction volume undisturbed
  - Virtual photons reconstructed via their dilepton decay
    ⇝ extra information: invariant mass

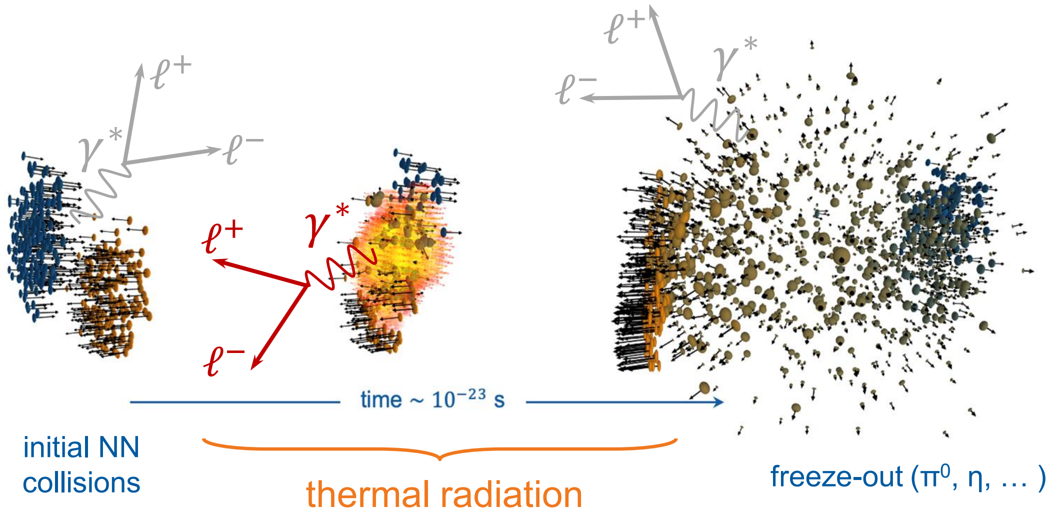
HADES, Nature Phys. 15 (2019) 1040

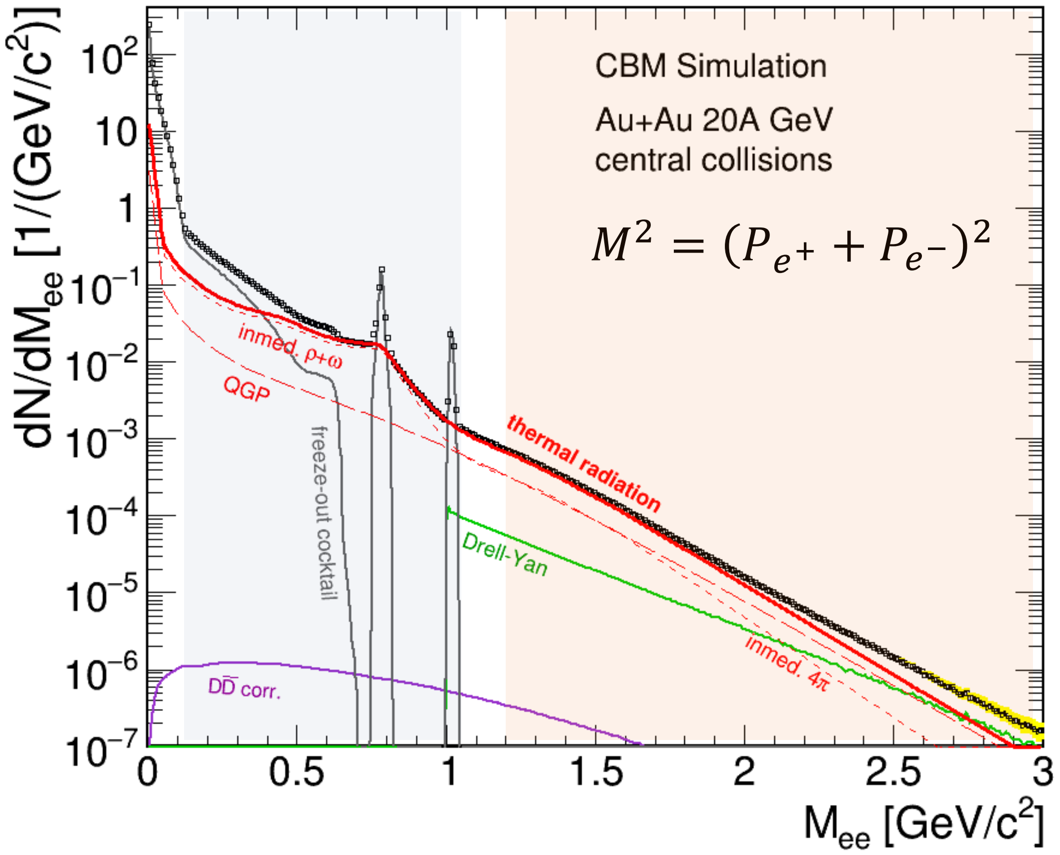


# EXPERIMENTAL CHALLENGES

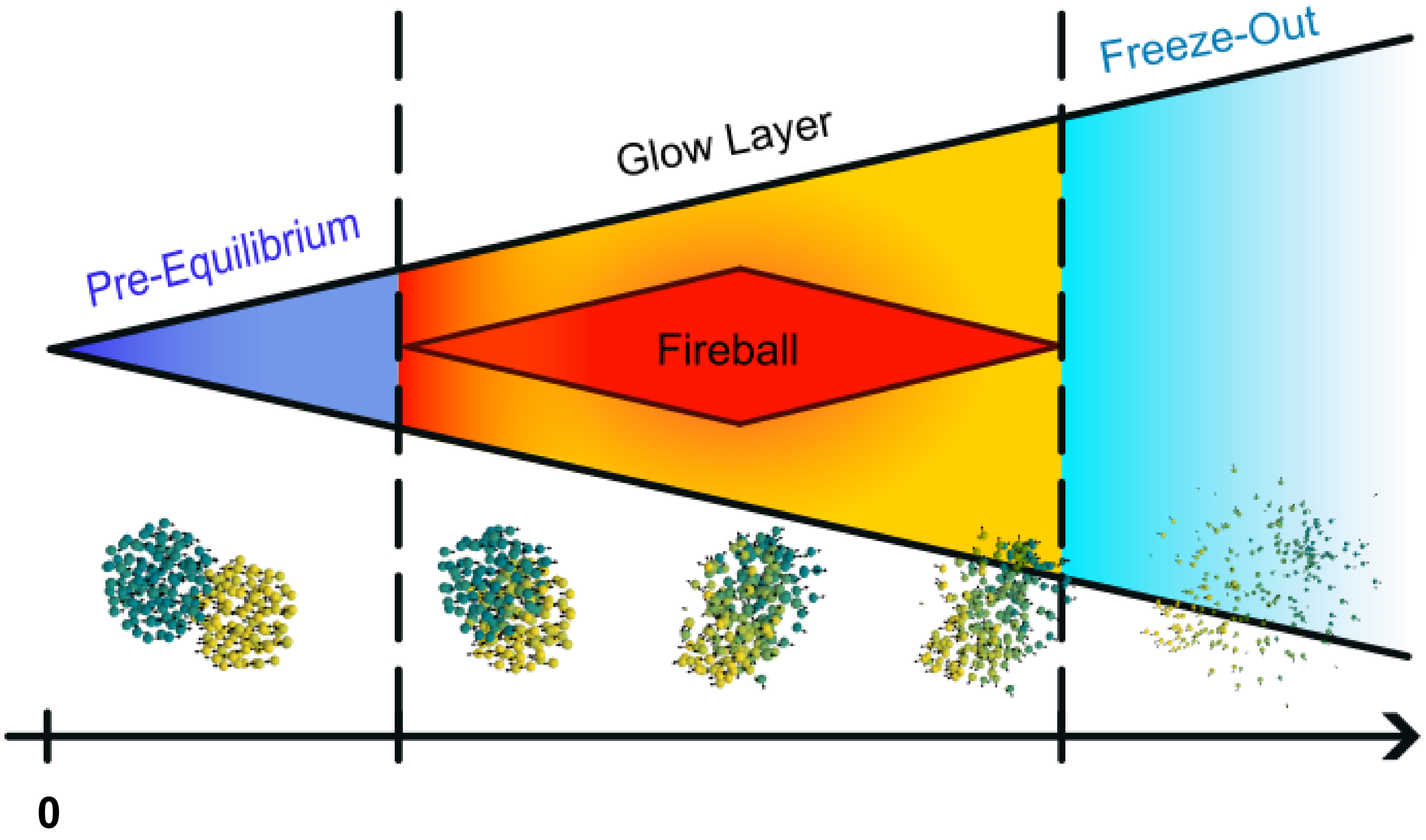
- Dileptons are rare probes
  - High interaction rates
  - Good signal-to-combinatorial background ratio $(S/CB)$
  - High acceptance (Mid-rapidity, low-$M_{\ell\ell}$, low-$p_{\mathrm{T}}$ coverage)

- Isolation of thermal radiation by subtraction of measured decay cocktail $(\pi^0, \eta, \omega, \varphi)$, Drell-Yan, $c\bar{c}$ $(b\bar{b})$



TECHNISCHE UNIVERSITÄT DARMSTADT

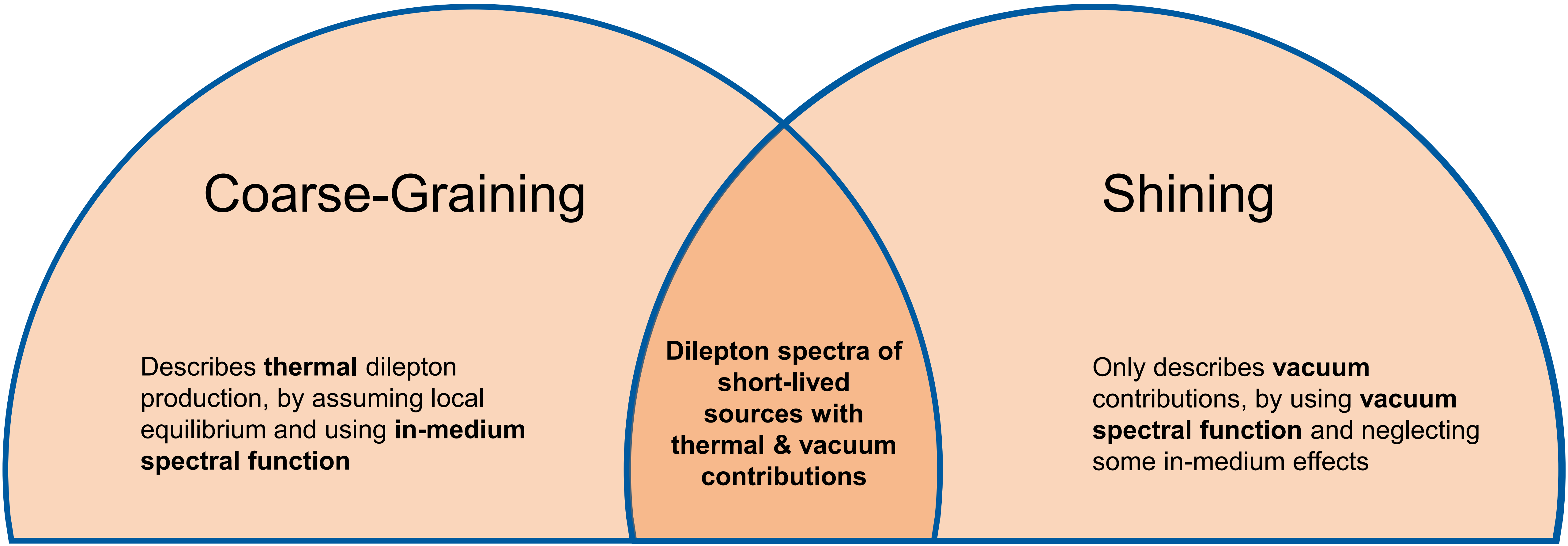



Thermal Contribution:
Fireball

Vacuum Contribution:
Glow Layer + Freeze-Out

J. Vogel, T. Galatyuk, FS, QM 2025 poster
J. Vogel, master thesis (TU Darmstadt)

TECHNISCHE UNIVERSITÄT DARMSTADT

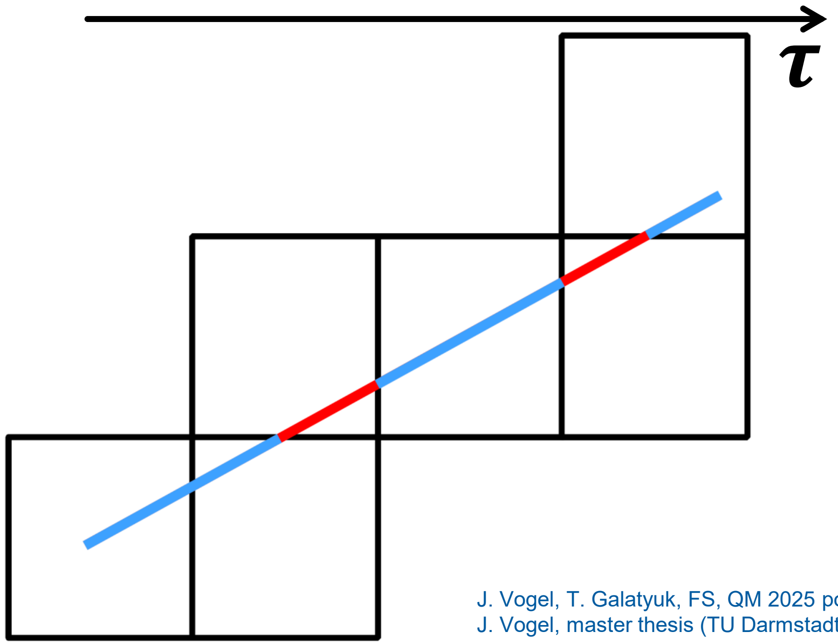


## MERGING OF APPROACHES

TECHNISCHE UNIVERSITÄT DARMSTADT

- Divide fireball evolution into 4-dimensional **space-time cells** like in Coarse-Graining
- Calculate trajectory of each particle
- Check for each particle which boxes are crossed & at what time they are crossed
- Set up thermal map: Check if an individual cell is **thermalized** at the time it is crossed by the particle
- Calculate the fraction of time the particle spends in thermalized cells compared to its lifetime:

$$\mathbf{F} = \frac{\textbf{time particle spends in thermalized cells}}{\textbf{lifetime}}$$

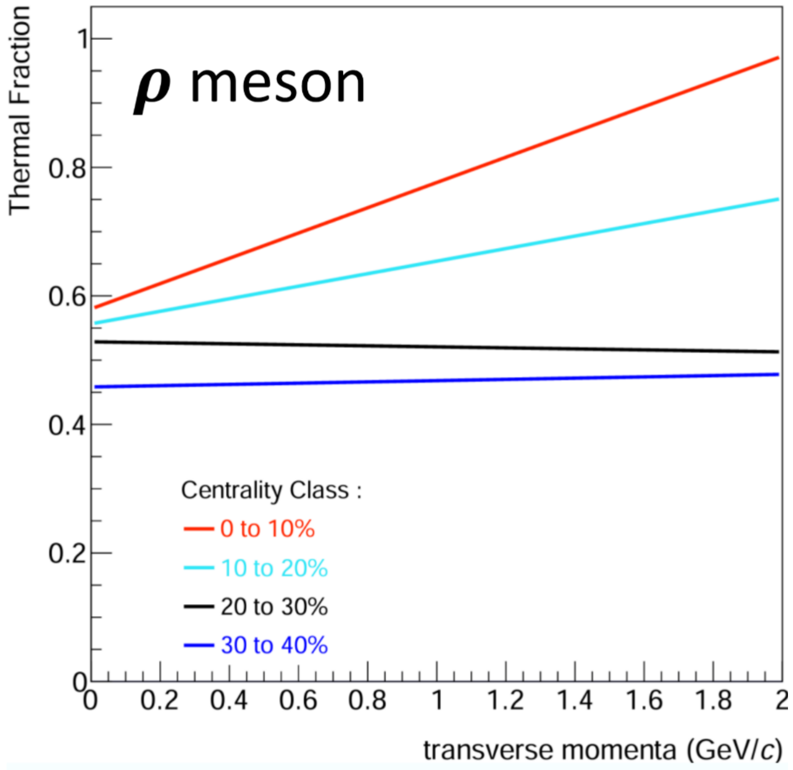


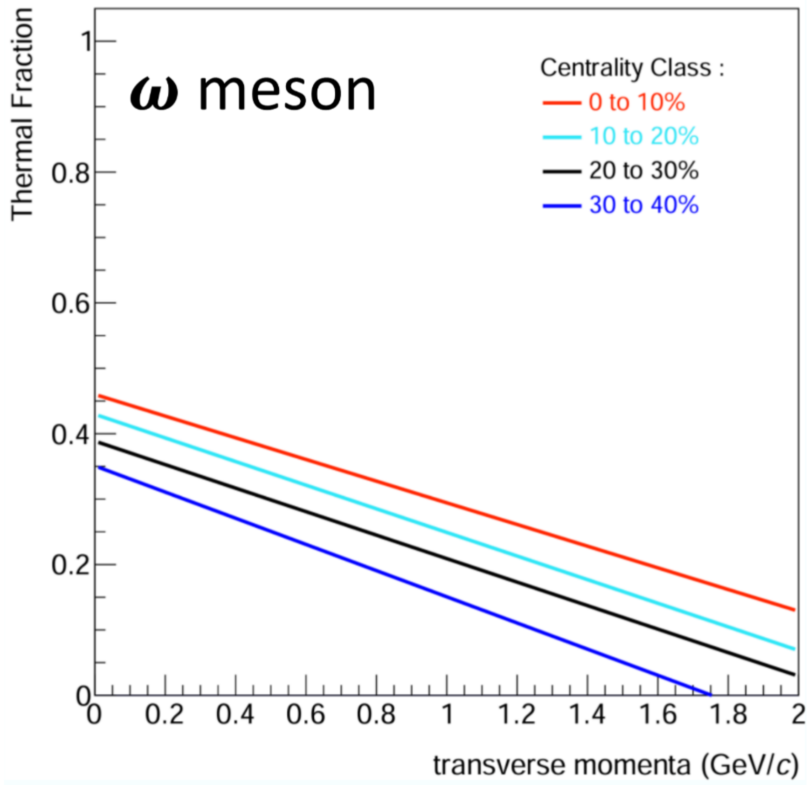

J. Vogel, T. Galatyuk, FS, QM 2025 poster
J. Vogel, master thesis (TU Darmstadt)

# MERGING OF APPROACHES

- Transverse momentum and centrality dependence of the thermal fraction:

$$\mathbf{F} = \frac{\textbf{time particle spends in thermalized cells}}{\textbf{lifetime}}$$



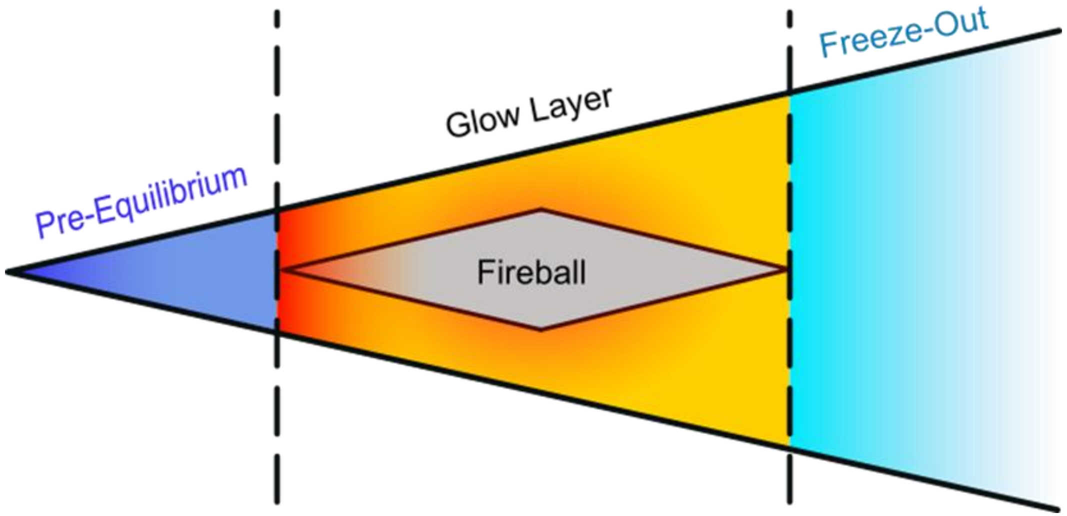

J. Vogel, T. Galatyuk, FS, QM 2025 poster
J. Vogel, master thesis (TU Darmstadt)

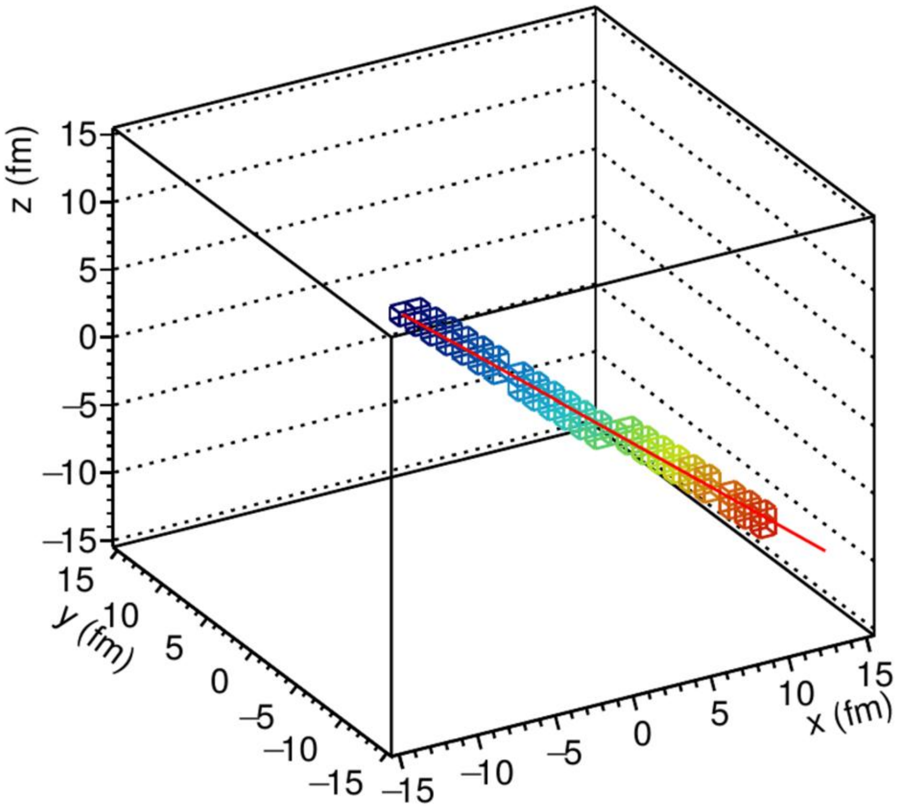
# MERGING OF APPROACHES

Calculate dilepton rates with:

$$\frac{dN}{dM}_{total} = (1 - F)\,\frac{dN}{dM}_{Shining}$$

**Vacuum spectral function**
**Vacuum contribution**




J. Vogel, T. Galatyuk, FS, QM 2025 poster
J. Vogel, master thesis (TU Darmstadt)

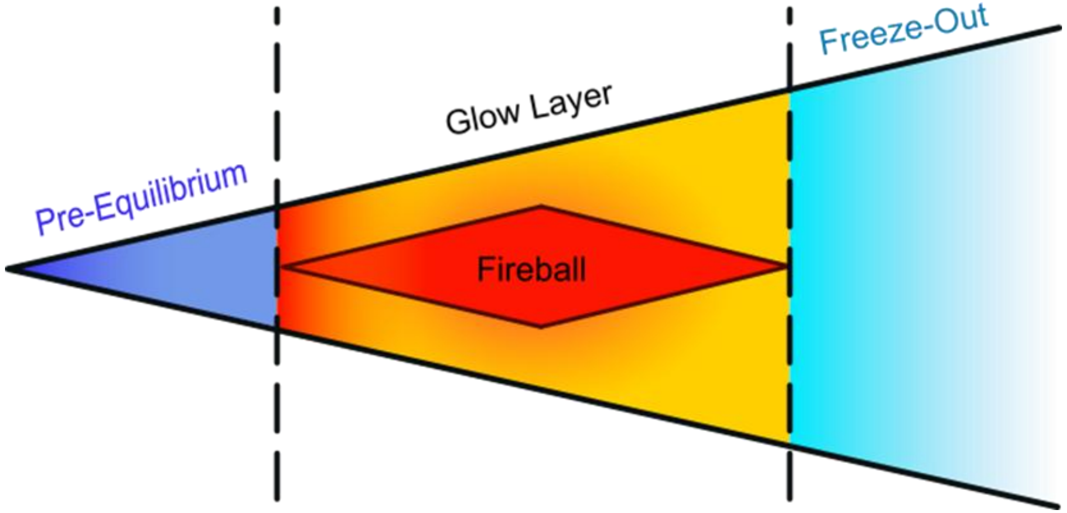
## MERGING OF APPROACHES

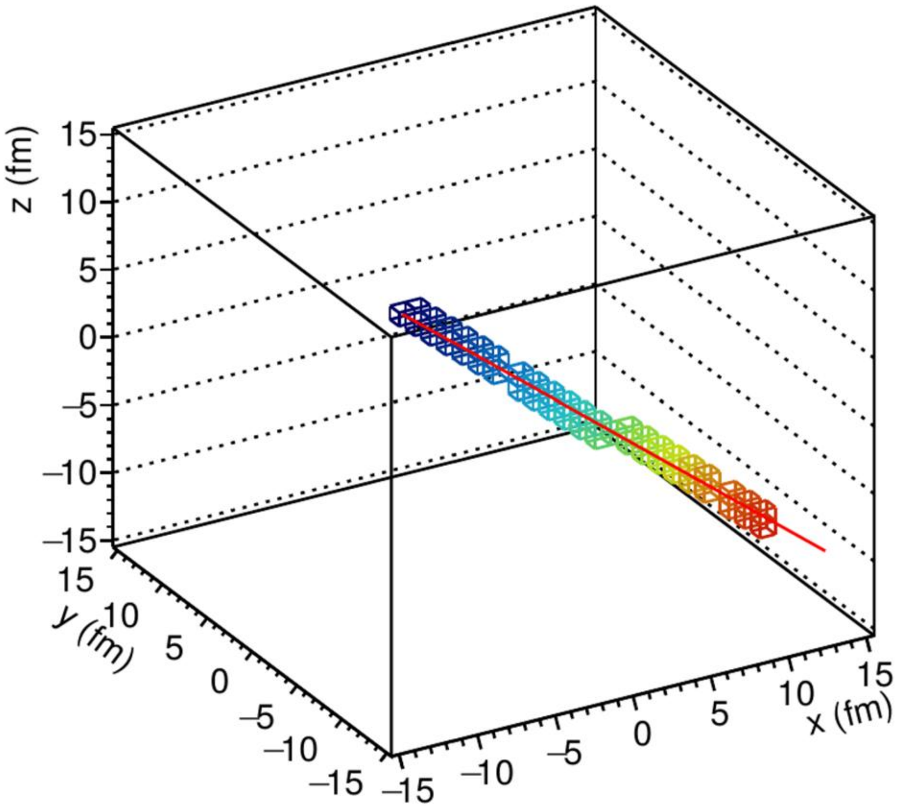
Calculate dilepton rates with:

$$\frac{dN}{dM}_{total} = (1 - F)\,\frac{dN}{dM}_{Shining} + \frac{dN}{dM}_{CG}$$

**Vacuum spectral function**
**Vacuum contribution**

**In-medium spectral function**
**Thermal contribution**

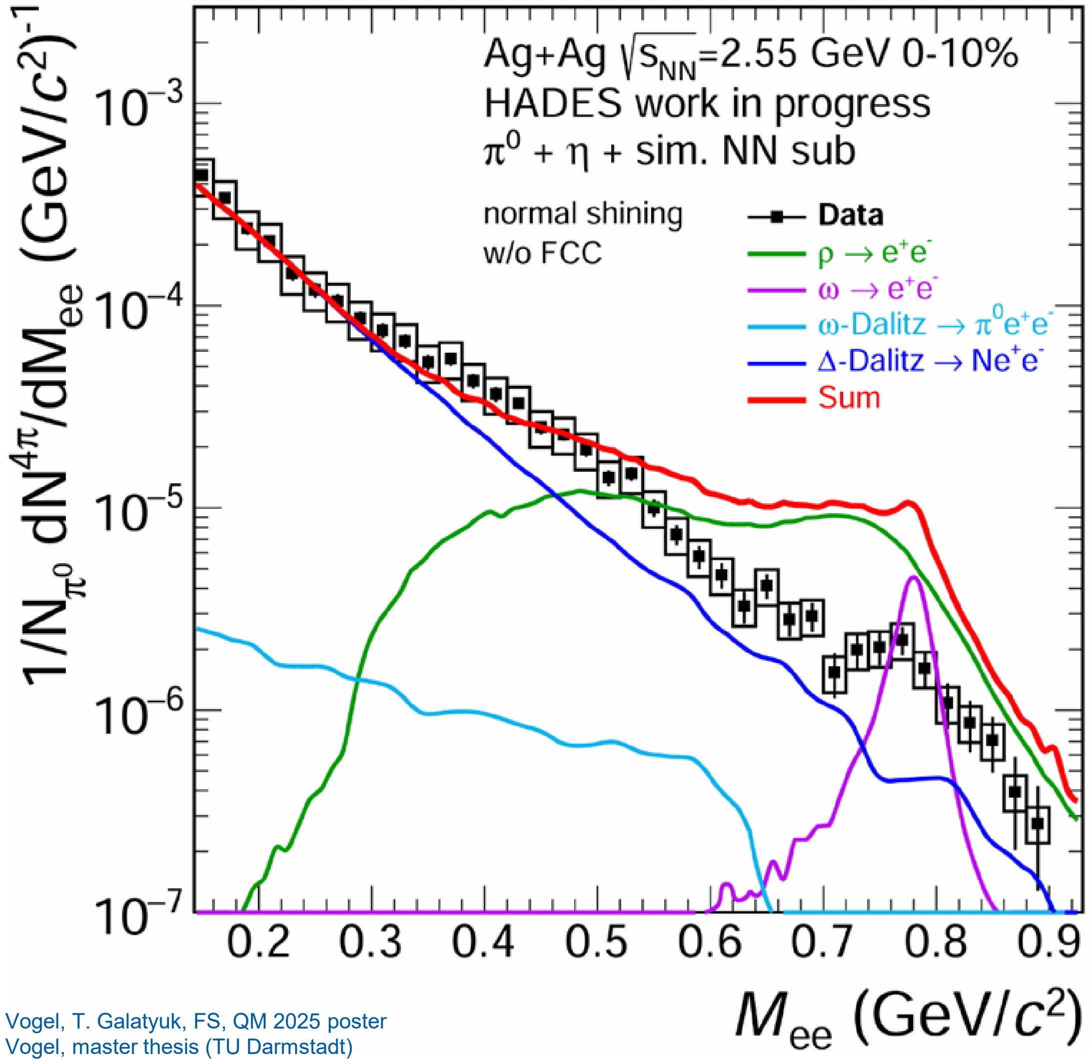



J. Vogel, T. Galatyuk, FS, QM 2025 poster
J. Vogel, master thesis (TU Darmstadt)

# DATA COMPARISON WITH SHINING

- Excess spectrum of HADES data
- Full dilepton spectrum according to standard shining
  - Contributions of different dilepton sources
- Overestimation around ρ/ω mass region




J. Vogel, T. Galatyuk, FS, QM 2025 poster
J. Vogel, master thesis (TU Darmstadt)

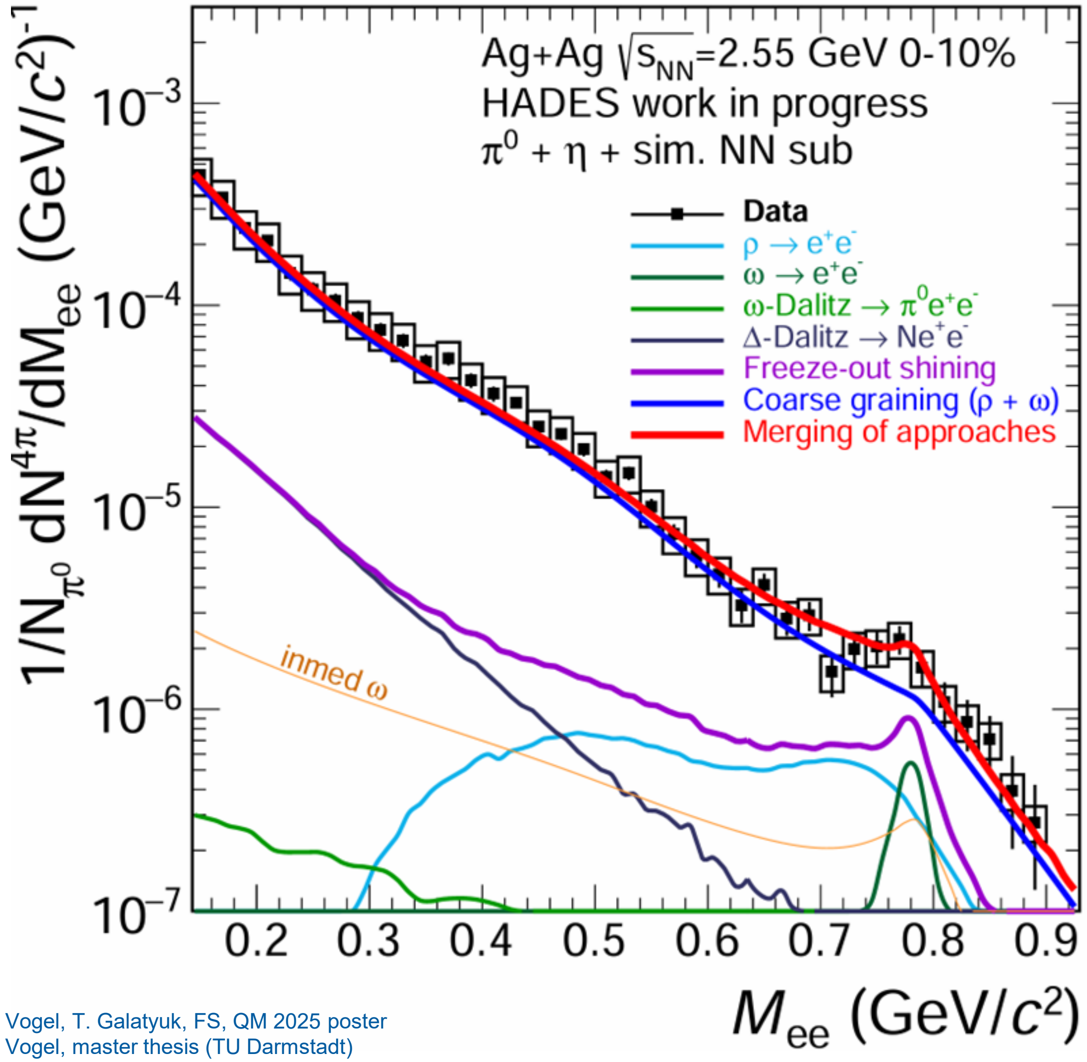
# DATA COMPARISON WITH CG + CORRECTED SHINING

TECHNISCHE UNIVERSITÄT DARMSTADT

- Excess spectrum of HADES data

- Coarse-graining of in-medium $\rho$ and $\omega$
- Corrected shining and its contributions from different sources
  - Spectrum of merged approaches

- Coarse-graining gives good description apart from bump in ρ/ω mass region
- Description of bump given by corrected shining, coming from direct ρ/ω decay




J. Vogel, T. Galatyuk, FS, QM 2025 poster
J. Vogel, master thesis (TU Darmstadt)