Rapidity scan in high-energy heavy-ion collisions

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Introduction

Model

Results

Summary and Outlook

High baryon number density at LHC energies

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Nuclear compression + CGC

Ming Li, Ph.D thesis, U. of Minesota (2018)

M. Li and J. I. Kapusta, Phys. Rev. C **99**, 014906 (2019)

- Solving classical gluon fields of receding nuclear remnants

  ⇨ Rapidity loss Δy of nucleons

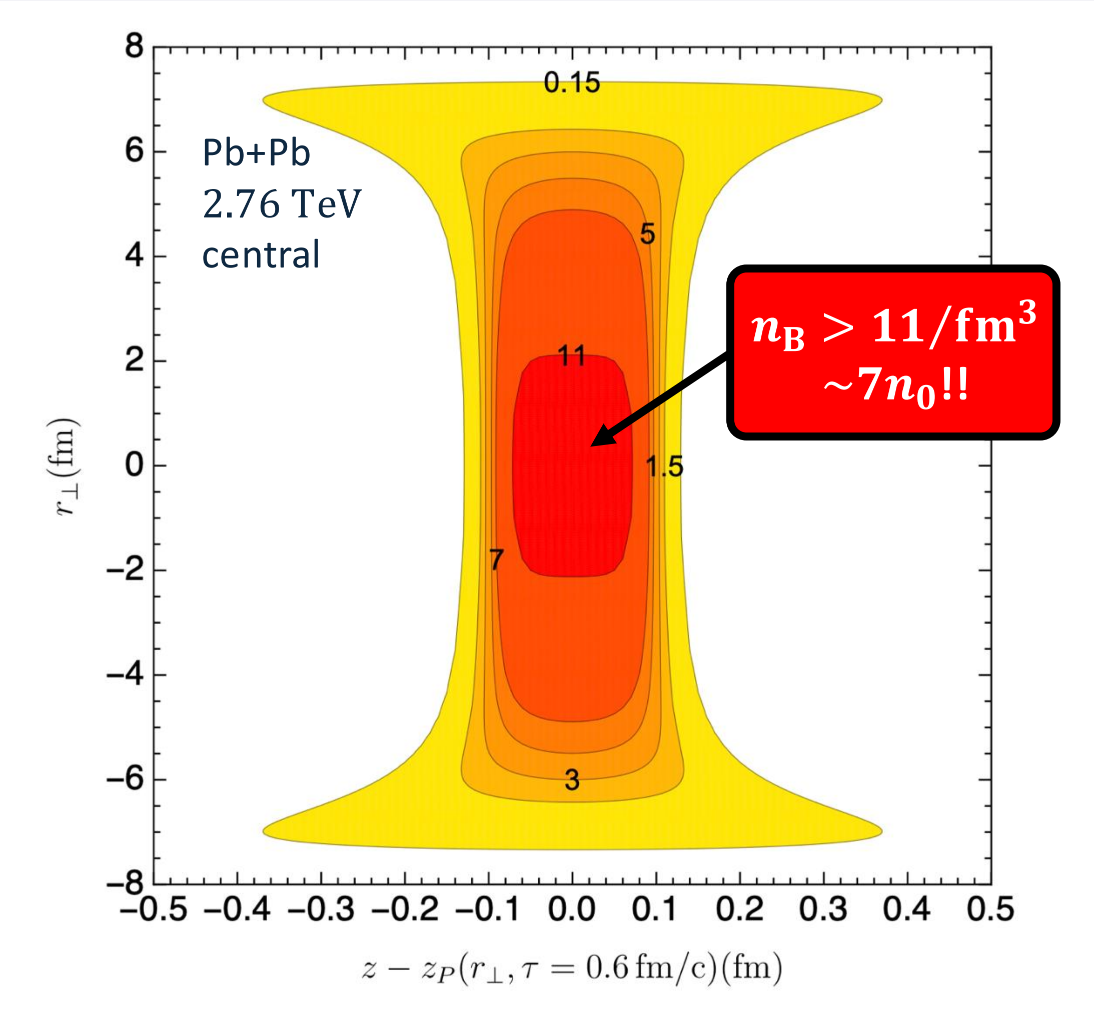
- Nuclear compression by Δy

  $n_{\mathrm{B}}(x, y, z) \approx e^{\Delta y} \rho_{\mathrm{A}}(x, y, z e^{\Delta y})$ @high energy

  M. Gyulassy and L. P. Csernai, Nucl. Phys. A **460**, 723 (1986)

➡ **Extremely high baryon number density in the fragmentation regions of high-energy heavy ion collisions**

Baryon number density of compressed Pb



Rapidity Scan

Expected high baryon number density in forward rapidity in high-energy collisions

M. Li and J. I. Kapusta, Phys. Rev. C **99**, 014906 (2019)

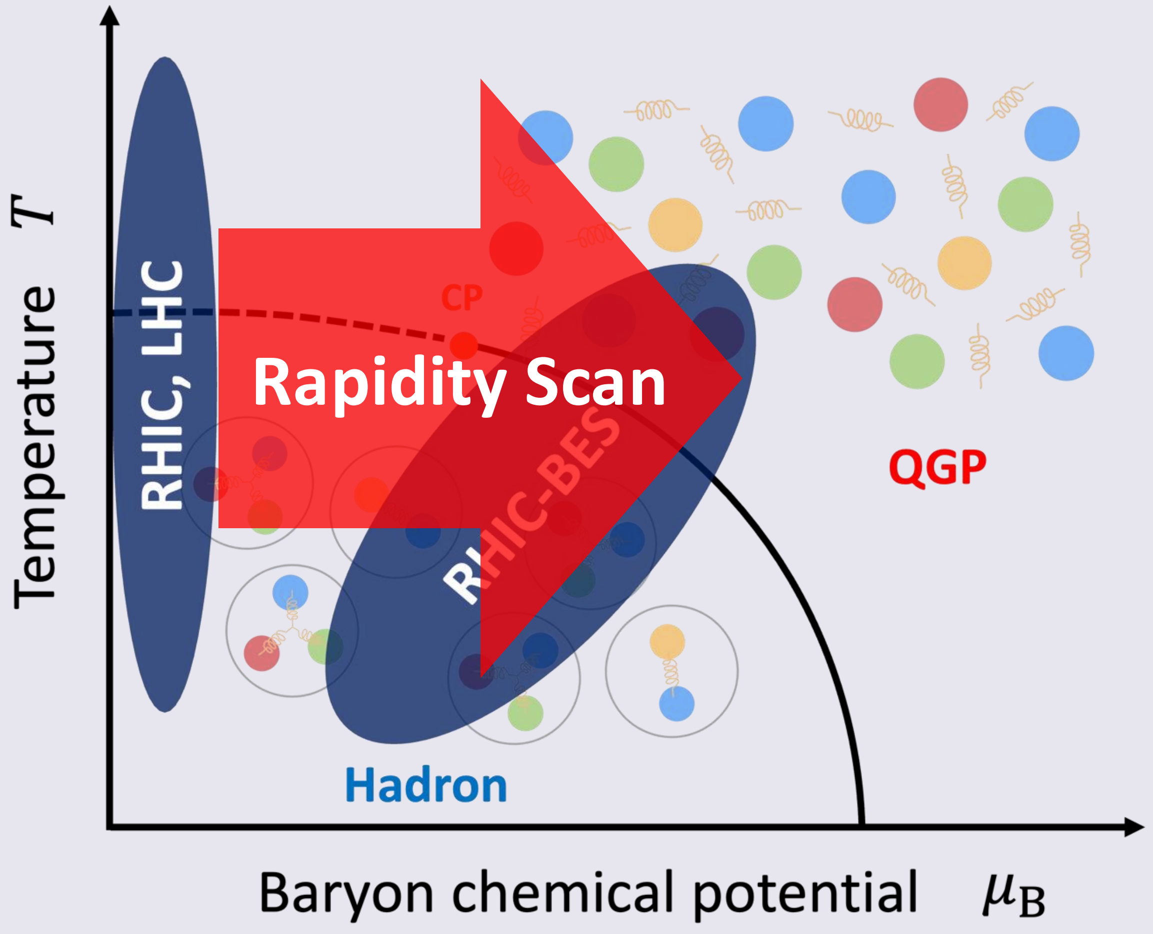
Rapidity Scan

Access high baryon chemical potential region in the QCD phase diagram

Beam Energy Scan @ low energy ⟷ **Rapidity Scan @ high energy**

Complementary study of QCD phase diagram by BES and Rapidity Scan!

QCD phase diagram and experiments



A fundamental question

How large baryon chemical potential is achieved as equilibrated matter in forward rapidity?

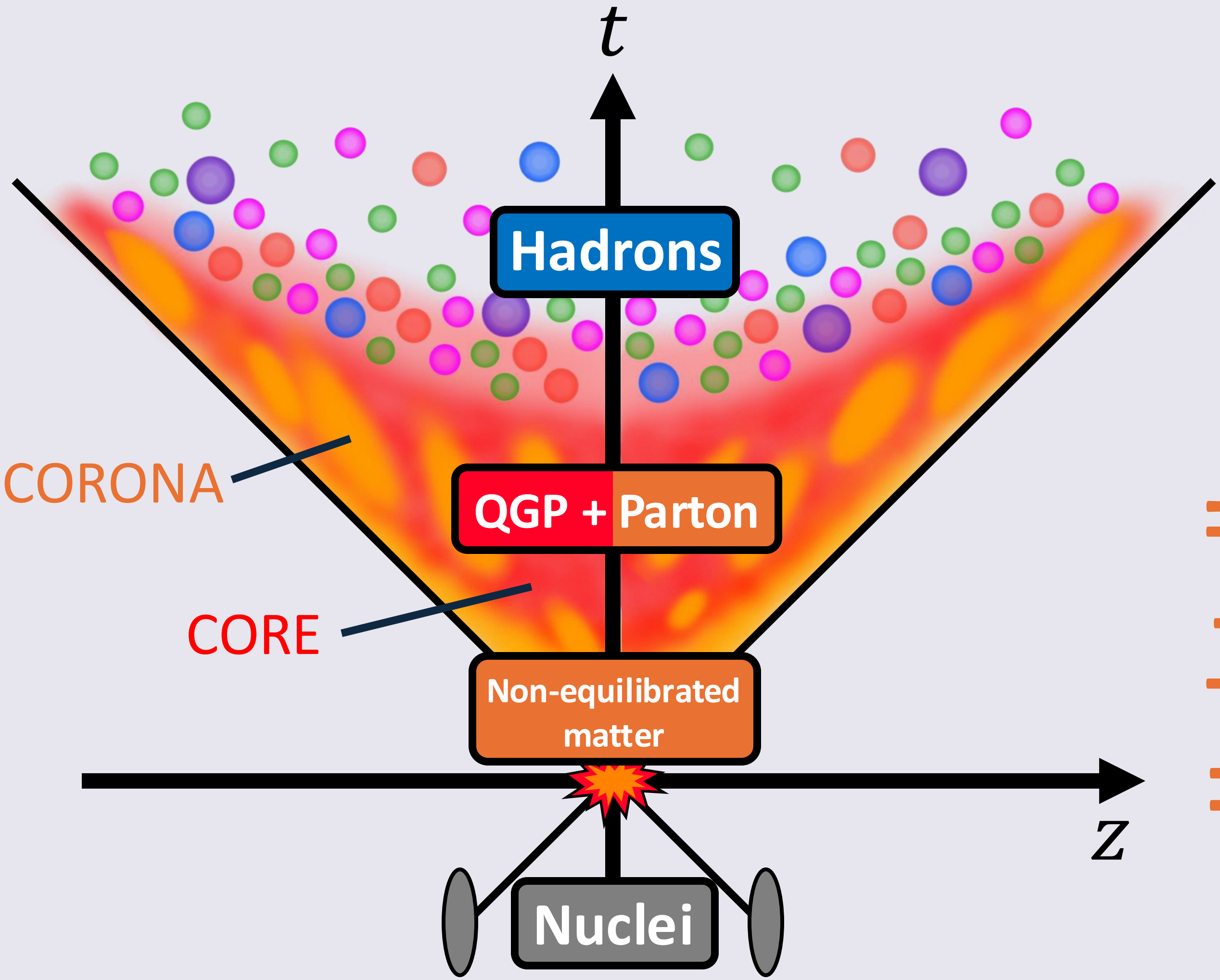
To answer the question, models must describe…

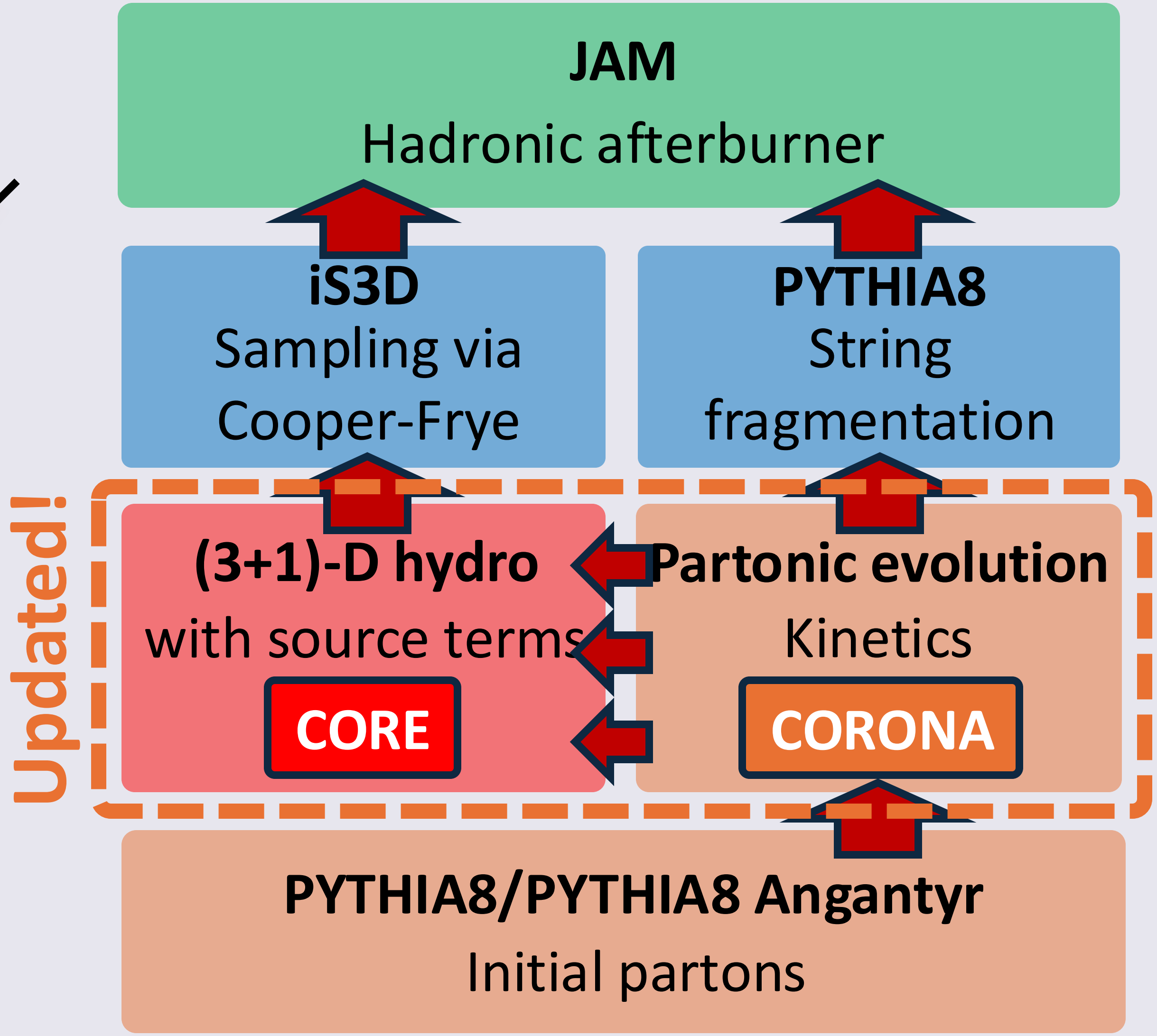
- Equilibrium and non-equilibrium components separately
- Fluidization (equilibration) of baryon number
- Hydrodynamic evolution of baryon number density

→ **DCCI + finite n_{B} extension**

Dynamical Core-Corona Initialization (DCCI) model

Y. Kanakubo *et al.*, Phys. Rev. C **105**, 024905 (2022)





Dynamical Core-Corona Initialization (DCCI) model

Y. Kanakubo *et al.*, Phys. Rev. C **105**, 024905 (2022)

Initial partons

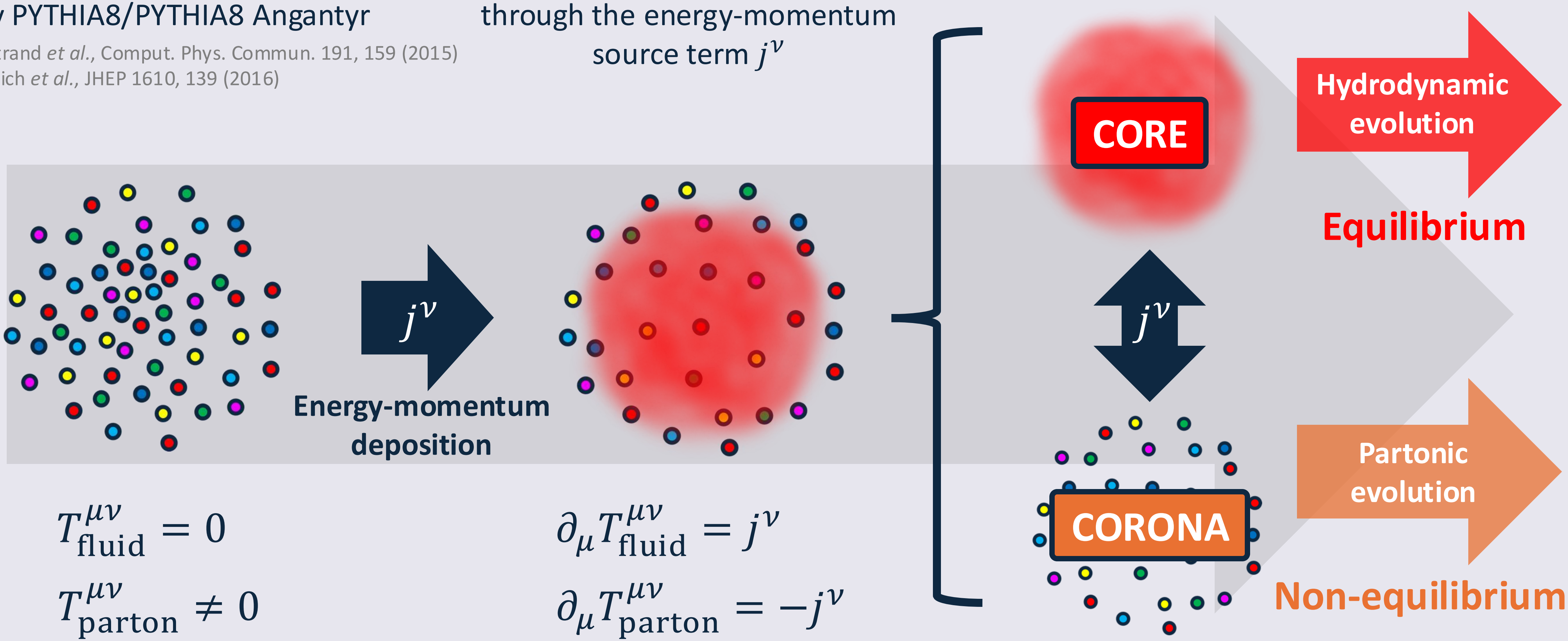
by PYTHIA8/PYTHIA8 Angantyr

T. Sjöstrand *et al.*, Comput. Phys. Commun. 191, 159 (2015)
C. Bierlich *et al.*, JHEP 1610, 139 (2016)

Dynamical initialization

through the energy-momentum source term j^ν

Core-corona picture



$$T^{\mu\nu}_{\rm fluid} = 0$$

$$T^{\mu\nu}_{\rm parton} \neq 0$$

$$\partial_\mu T^{\mu\nu}_{\rm fluid} = j^\nu$$

$$\partial_\mu T^{\mu\nu}_{\rm parton} = -j^\nu$$

Hydrodynamic module in DCCI

- **Continuity eq. for entire system**

$$\partial_\mu \left(T^{\mu\nu}_{\rm fluid} + T^{\mu\nu}_{\rm parton} \right) = 0$$

- **Hydrodynamic eqs. with E-M source term**

$$\partial_\mu T^{\mu\nu}_{\rm fluid} = j^\nu \qquad j^\nu = -\partial_\mu T^{\mu\nu}_{\rm parton}$$

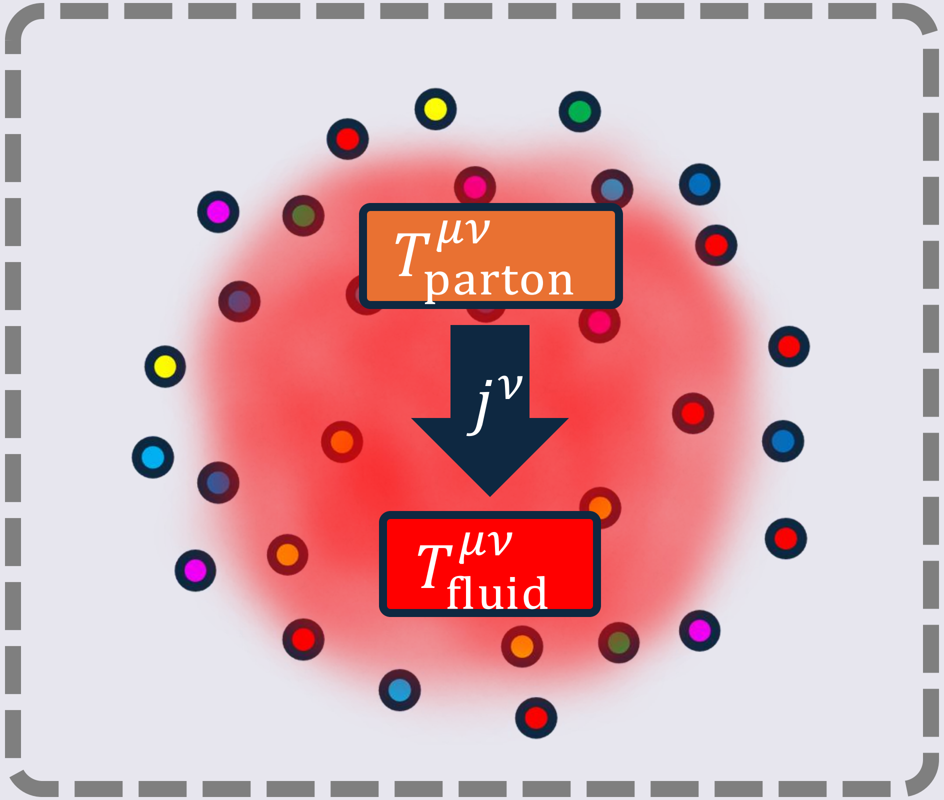
Fluidization rate

$$j^\nu = - \sum_i^{N_{\rm parton}} \frac{dp_i^\nu(t)}{dt} G\left(\boldsymbol{x} - \boldsymbol{x}_i(t)\right)$$

p_i^ν: Four-momentum of $i_{\rm th}$ parton

G: Gaussian function $\boldsymbol{x}_i$: Position of $i_{\rm th}$ parton

Entire system $T^{\mu\nu}_{\rm fluid} + T^{\mu\nu}_{\rm parton}$



Assumptions

- Straight trajectory of partons
- Instant equilibration of deposited E-M
- Gaussian profile

Energy-momentum source term

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Phenomenological fluidization rate per particle in core-corona picture

$$\frac{dp_i{}^{\mu}}{d\tau} = -\sum_{j}^{N_{\mathrm{scat}}} \rho_{i,j}\sigma_{i,j}\left|v_{\mathrm{rel},i,j}\right| p_i{}^{\mu}$$

$\rho_{i,j}$: Effective density of j_{th} seen from i_{th}

$\sigma_{i,j}$: Cross section between i_{th} and j_{th}

$v_{\mathrm{rel},i,j}$: Relative velocity between i_{th} and j_{th}

- **Collision detection**

$$b_{i,j} \leq \sqrt{\frac{\sigma_{i,j}}{\pi}}$$

- **Cross section**

$$\sigma_{i,j} = \min\left\{\frac{\sigma_0}{s_{i,j}}, \pi b_{\mathrm{cut}}^2\right\}$$

$\sigma_0 = 0.3\ \mathrm{fm}^2$ $\quad b_{\mathrm{cut}} = 1.0\ \mathrm{fm}$

Low p_{T} / Dense region ➡ CORE (QGP)

High p_{T} / Dilute region ➡ CORONA (Partons)

Event by event initial condition for QGP fluid

Extension to finite charges

Extension to finite charges

Hydrodynamic eqs. with source terms

$$\partial_\mu N^\mu_{\mathrm{fluid,\,I}} = \rho_\mathrm{I} \qquad \mathrm{I: B, Q, S}$$

When i_th parton deposits all energy = dead parton

Source terms of conserved charges

$$\rho_\mathrm{I} = -\sum_j^{N_\mathrm{dead}} \frac{dN_{j,\mathrm{I}}}{dt} G\left(\boldsymbol{x} - \boldsymbol{x}_j(t)\right)$$

$N_{j,\mathrm{I}}$: Charge I of j_th dead parton

G: Gaussian function

$\boldsymbol{x}_j$: Position of j_th dead parton

Fluidization (equilibration) and Hydrodynamic evolution of conserved charges (B, Q, S)

Summary of hydrodynamic equations

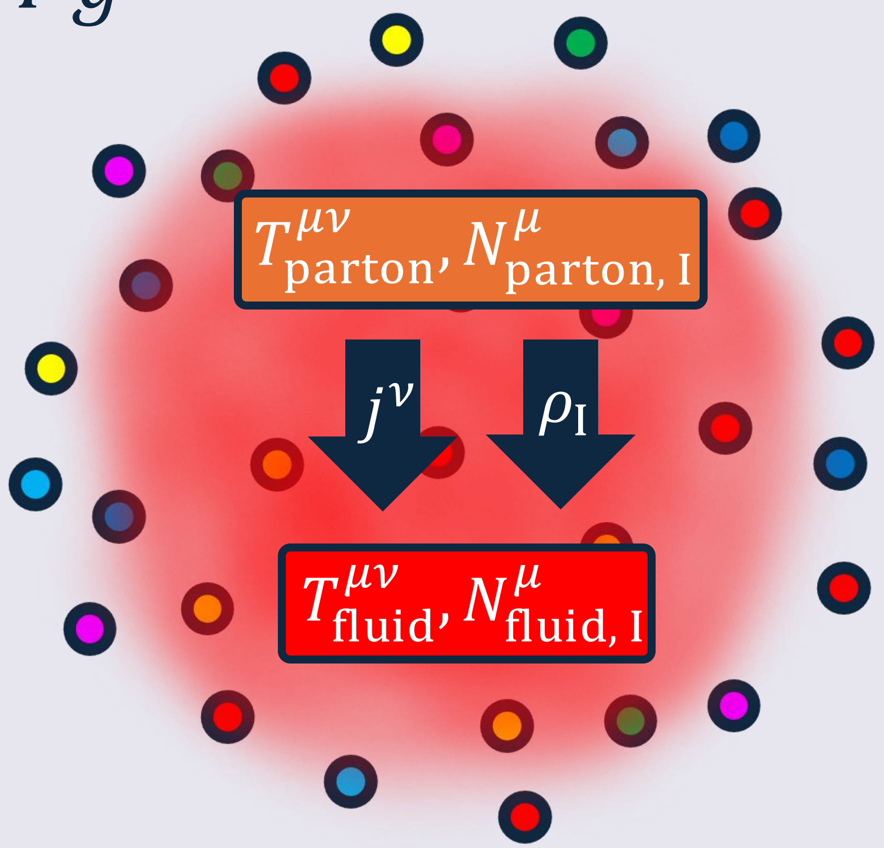
$$\partial_\mu T^{\mu\nu} = j^\nu \qquad T^{\mu\nu} = (e+P)u^\mu u^\nu - P g^{\mu\nu}$$

$$\partial_\mu N^\mu_\mathrm{B} = \rho_\mathrm{B} \qquad N^\mu_\mathrm{B} = n_\mathrm{B} u^\mu$$

$$\partial_\mu N^\mu_\mathrm{Q} = \rho_\mathrm{Q} \qquad N^\mu_\mathrm{Q} = n_\mathrm{Q} u^\mu$$

$$\partial_\mu N^\mu_\mathrm{S} = \rho_\mathrm{S} \qquad N^\mu_\mathrm{S} = n_\mathrm{S} u^\mu$$

Updated!



- Ideal hydrodynamics with source terms
- 7 independent variables
- Equation of state with d.o.f $(e, n_\mathrm{B}, n_\mathrm{Q}, n_\mathrm{S})$ is needed

NEOS-4D

A. Monnai, B. Schenke and C. Shen, Phys. Rev. C **110**, 044905 (2024)

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- **Taylor expansion using Lattice results (high T)**

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{x_{l,m,n}^{\mathrm{B,Q,S}}}{l!\,m!\,n!} \left(\frac{\mu_\mathrm{B}}{T}\right)^l \left(\frac{\mu_\mathrm{Q}}{T}\right)^m \left(\frac{\mu_\mathrm{S}}{T}\right)^n$$

- **Hadron gas (low T)**

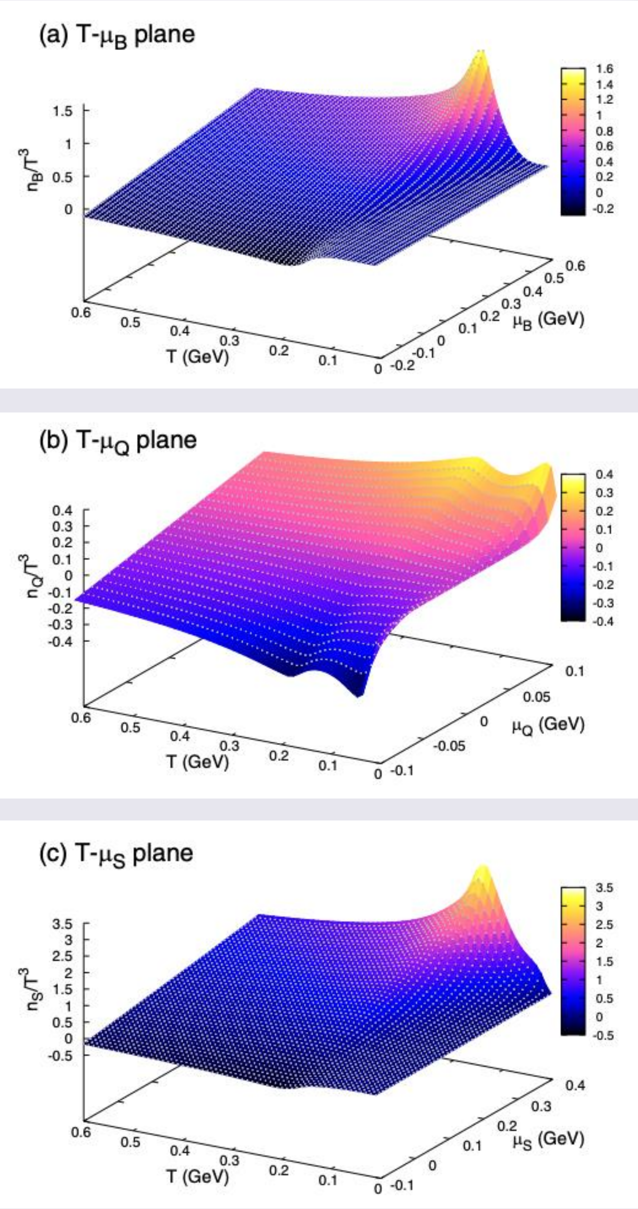
$$P = \pm T \sum_i \int \frac{g_i d^3p}{(2\pi)^3} \ln\left[1 \pm e^{-(E_i-\mu_i)/T}\right]$$

CONNECT

$$\frac{P}{T^4} = \frac{1}{2}\left[1 - \tanh\frac{T-T_c}{\Delta T_c}\right]\frac{P_\mathrm{had}}{T^4} + \frac{1}{2}\left[1 + \tanh\frac{T-T_c}{\Delta T_c}\right]\frac{P_\mathrm{lat}}{T^4}$$

NEOS-2D: $n_\mathrm{Q} = 0.4 n_\mathrm{B}, n_\mathrm{S} = 0$ NEOS-4D: No constraint

A. Monnai, B. Schenke and C. Shen, Phys. Rev. C **100**, 024907 (2019)



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Evolution of core and corona

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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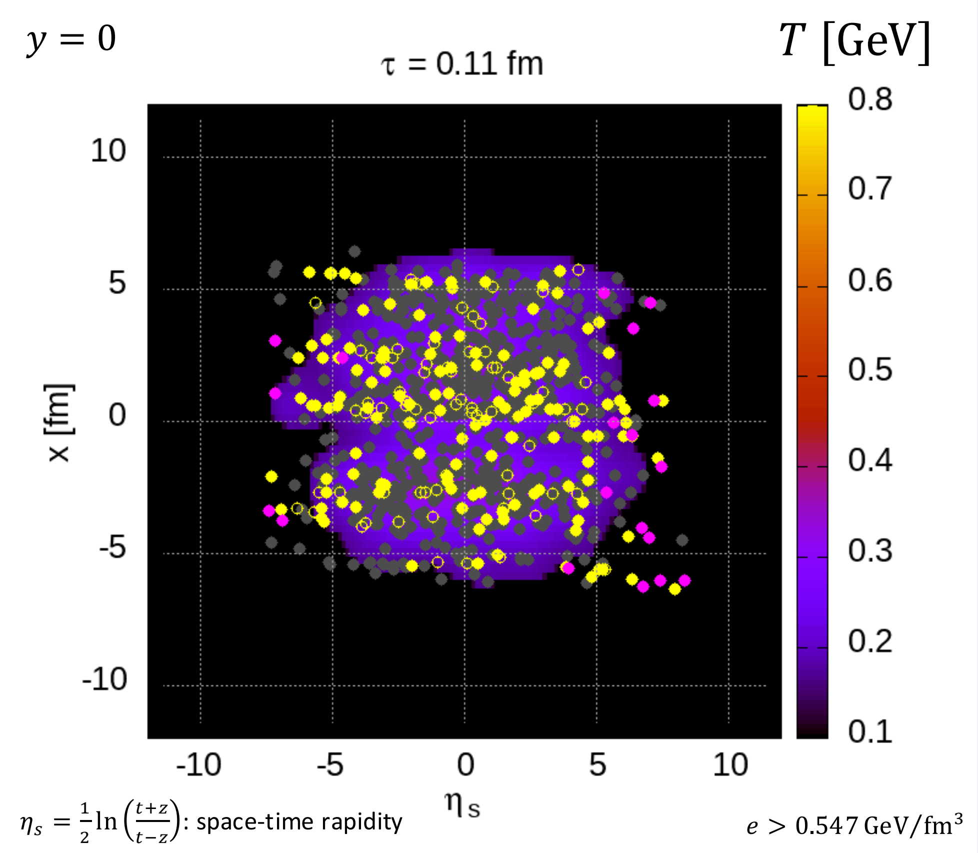
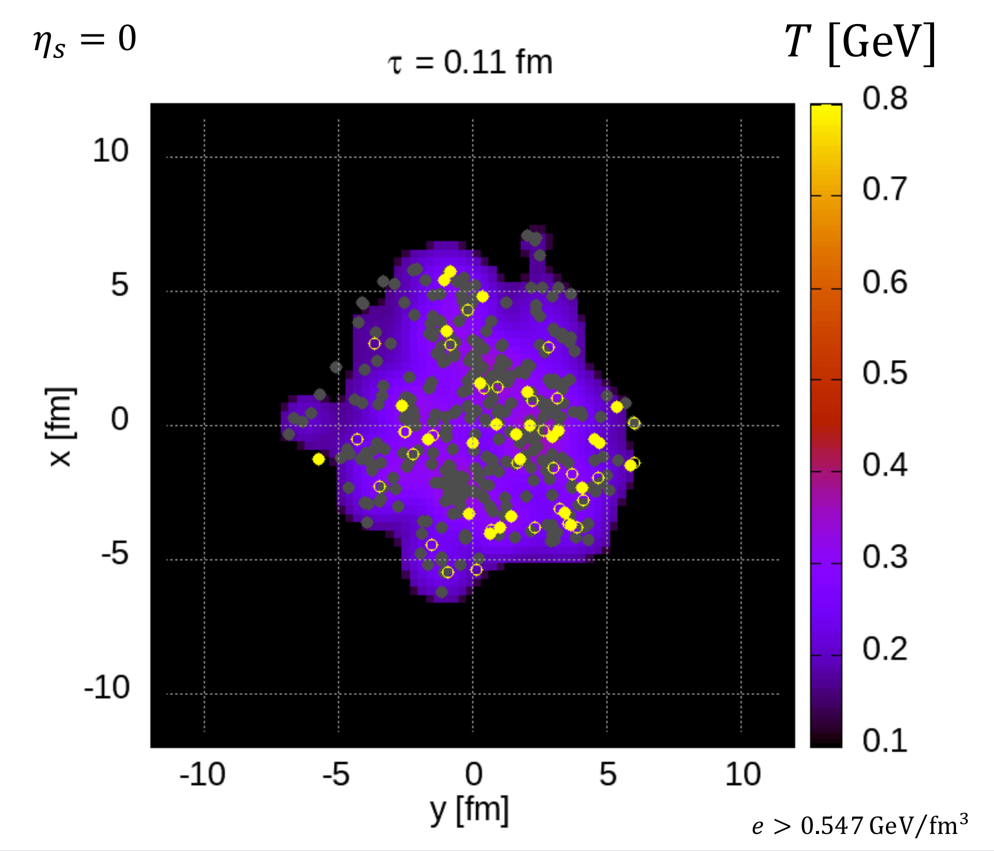
Temperature (longitudinal profile)



Temperature (transverse profile)



● : quark ● : diquark ● : gluon

○ : anti-quark ○ : anti-diquark

$\tau = 0.1 - 0.3$ fm: $\Delta\tau = 0.01$ fm → Fluid formation

$\tau > 0.3$ fm: $\Delta\tau = 0.3$ fm → Fluid evolution

Temperature

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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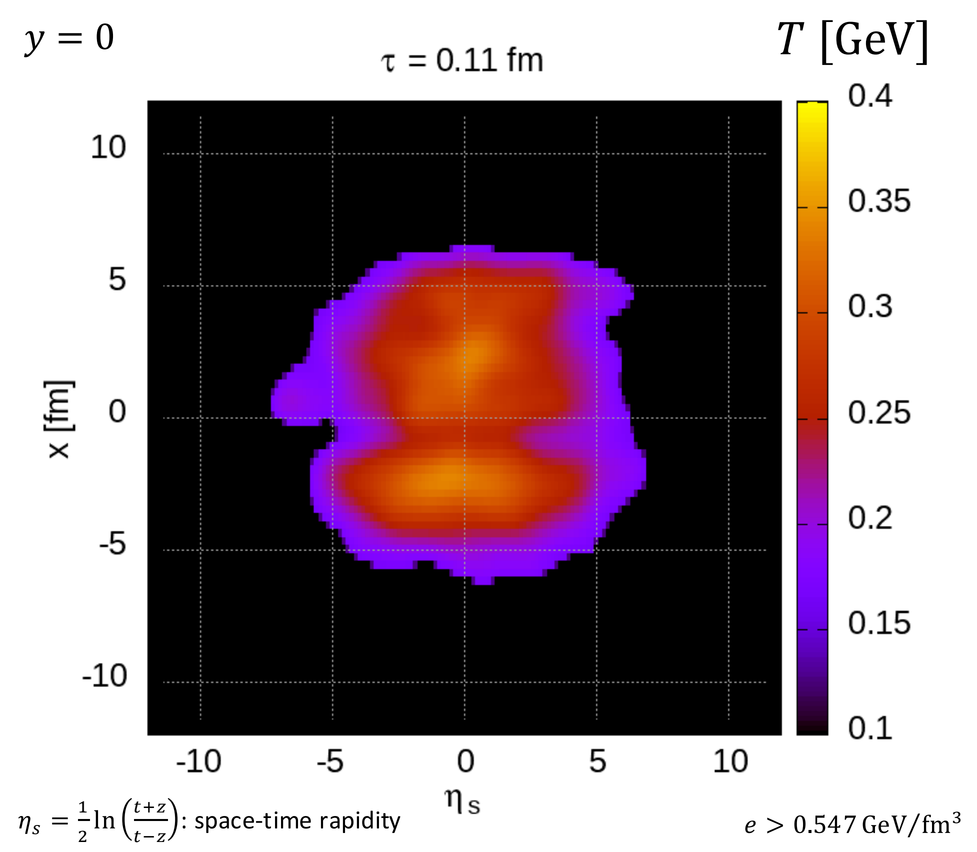
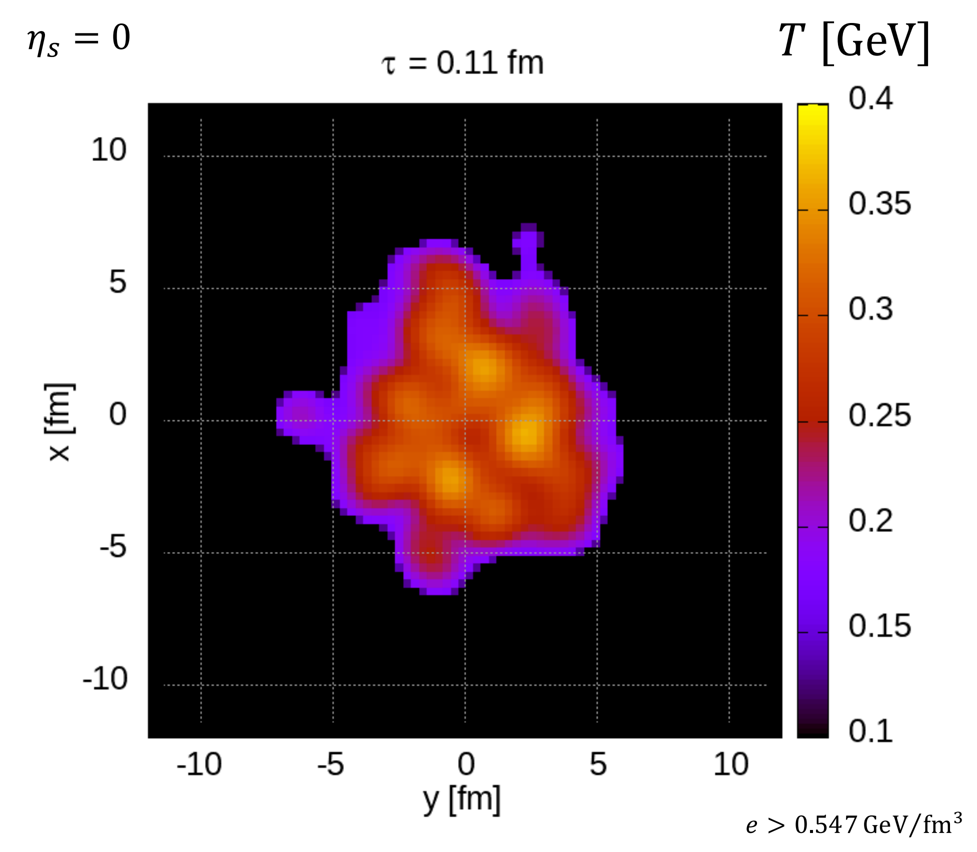
Temperature (longitudinal profile)



Temperature (transverse profile)



- Gradual formation of the core (QGP fluid) through the energy-momentum source term
- Alongside the fluid formation, the core cools down due to the hydrodynamic evolution

Evolution of core and corona

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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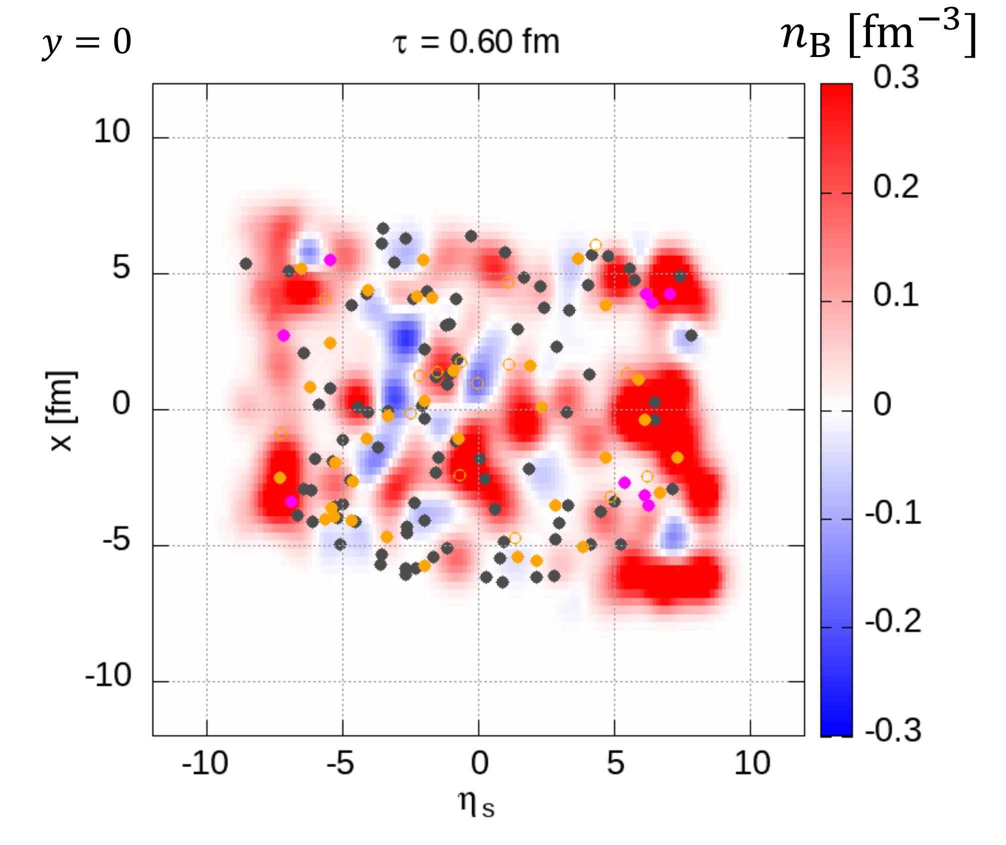
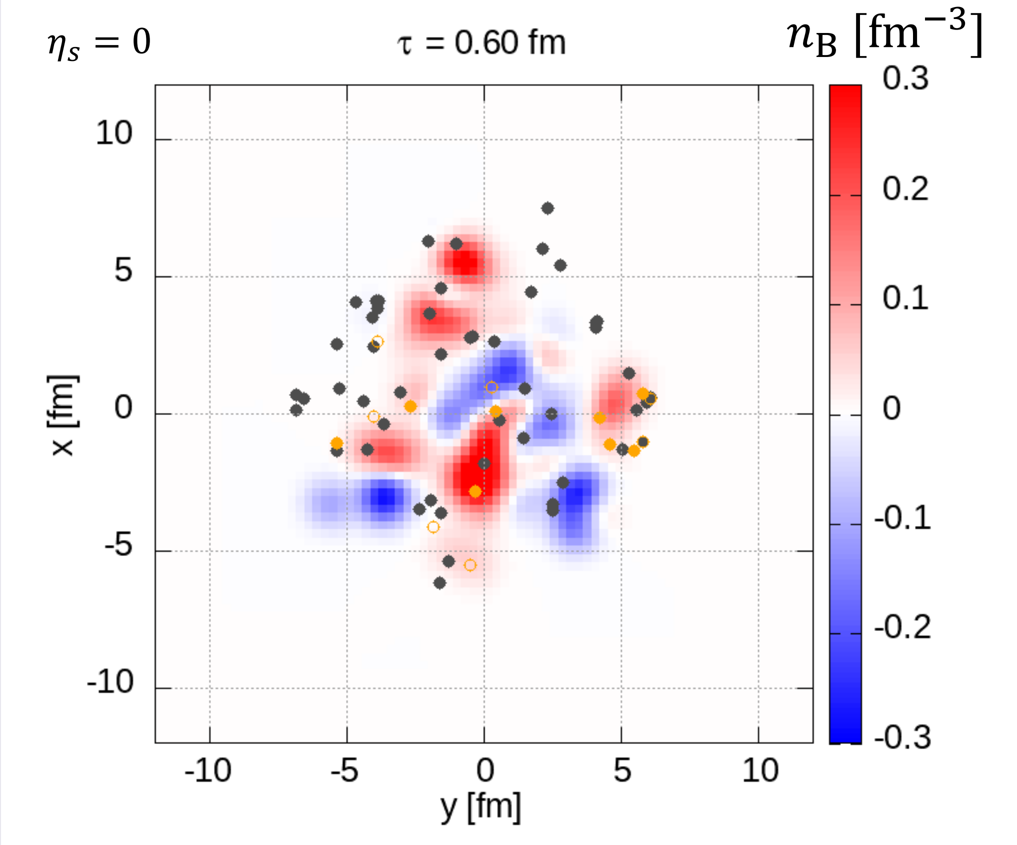
Baryon number density (longitudinal profile)



Baryon number density (transverse profile)



● : quark ● : diquark ● : gluon

○ : anti-quark ○ : anti-diquark

$\tau > 0.3$ fm: $\Delta\tau = 0.3$ fm → Fluidization of baryon number

Baryon number density

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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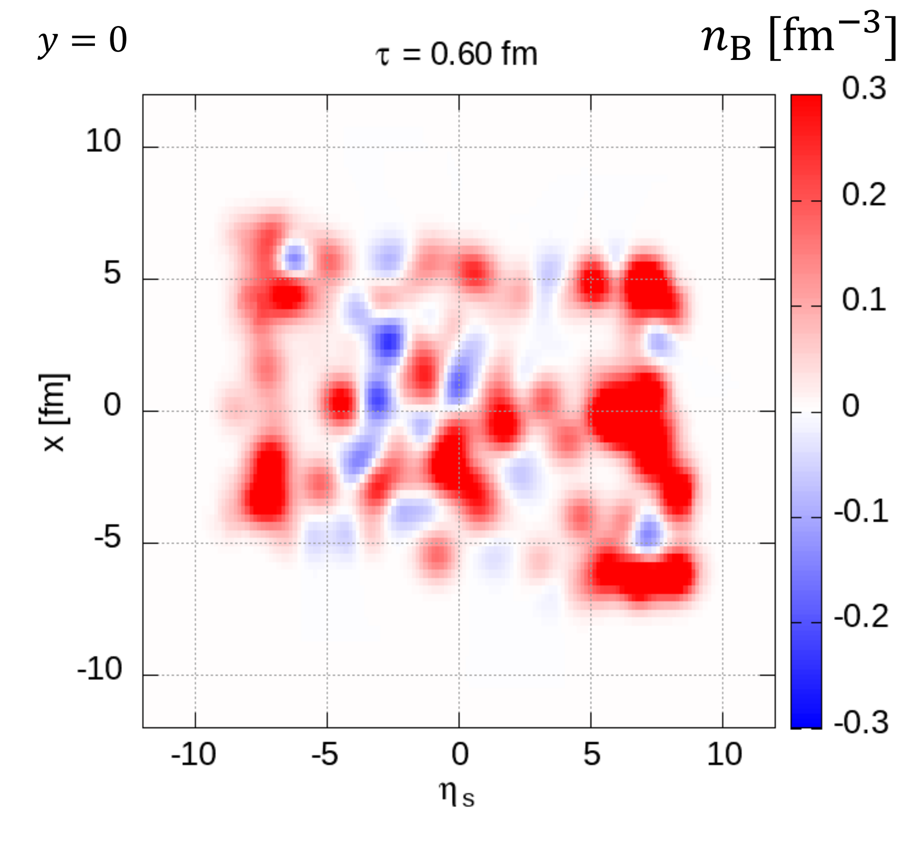
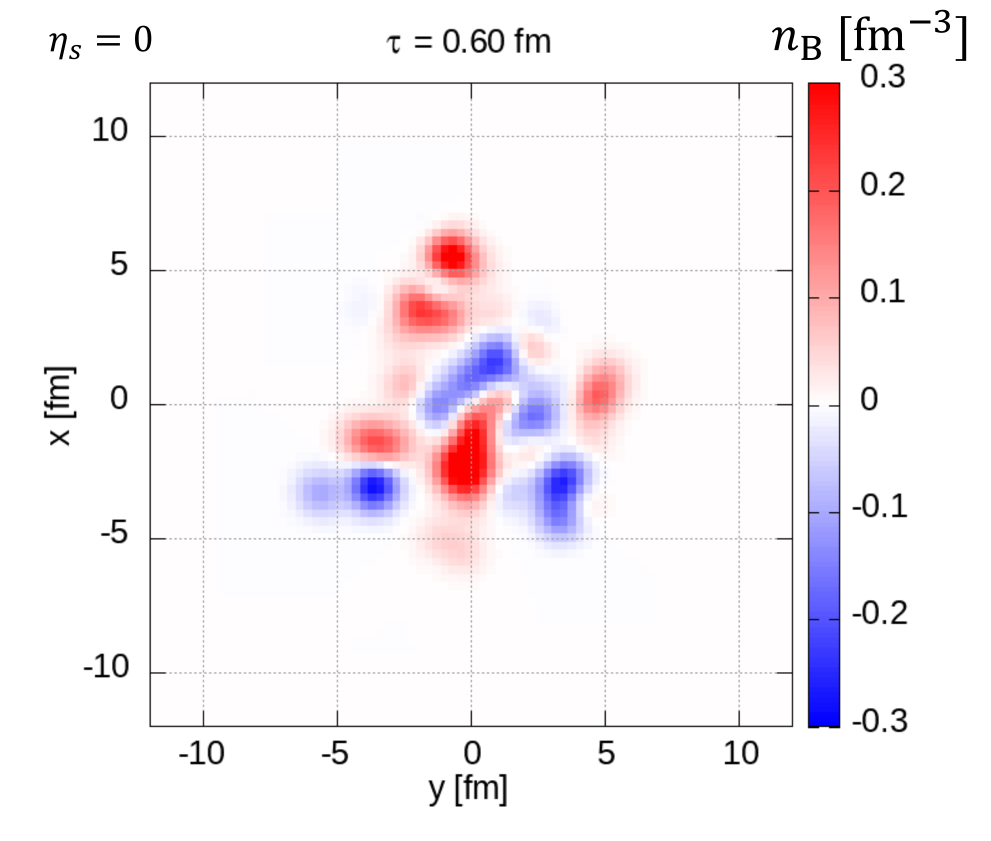
Baryon number density (longitudinal profile)



Baryon number density (transverse profile)



- Large equilibrated baryon number density in forward rapidities $5 \lesssim |\eta_s| \lesssim 10$

cf.) $y_{\mathrm{beam}}(\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}) \approx 8$

- Large fluctuations of baryon number density even in midrapidity

➡ Negative n_B region appears

Electric charge density

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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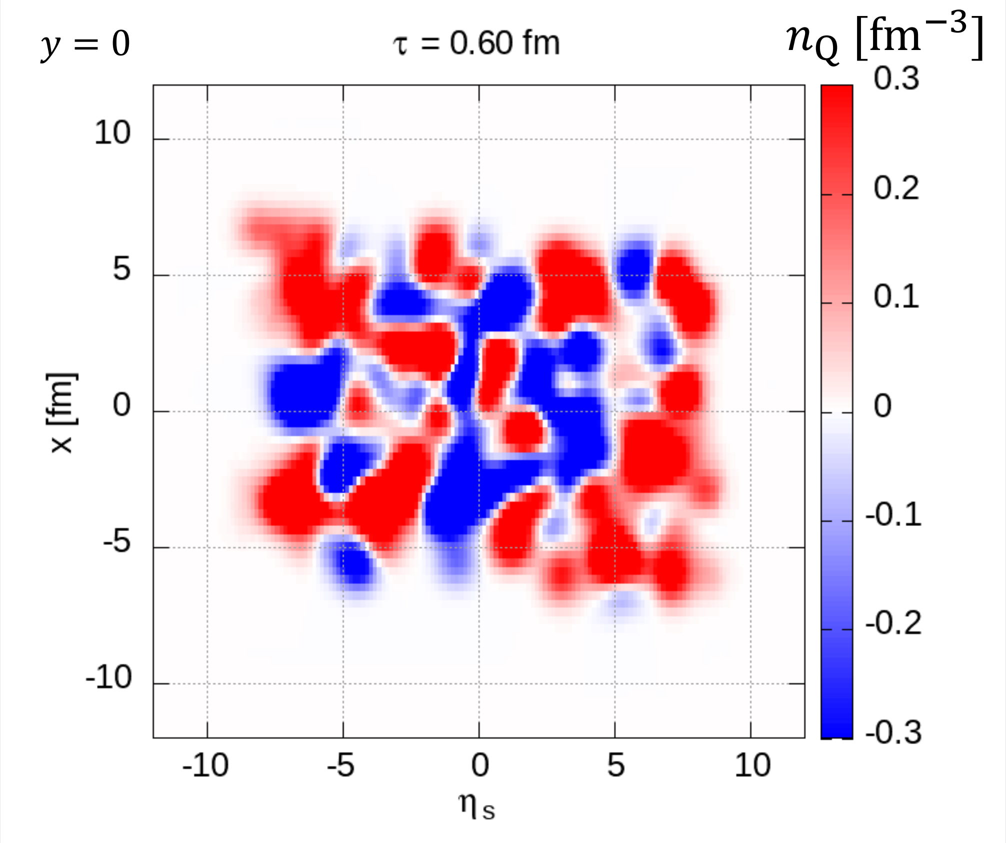
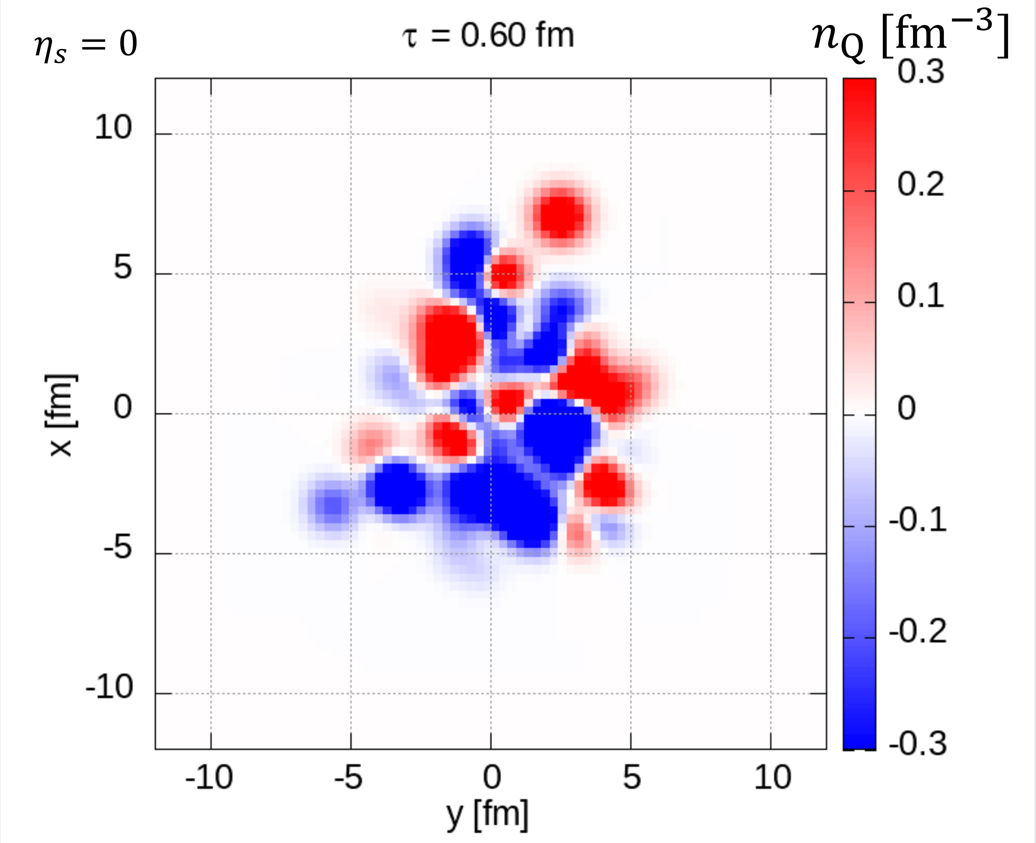
Electric charge density (longitudinal profile)



Electric charge density (transverse profile)



- Large equilibrated electric charge density in forward rapidities $5 \lesssim |\eta_s| \lesssim 10$

cf.) $n_Q \approx 0.4 n_B$ (Pb)

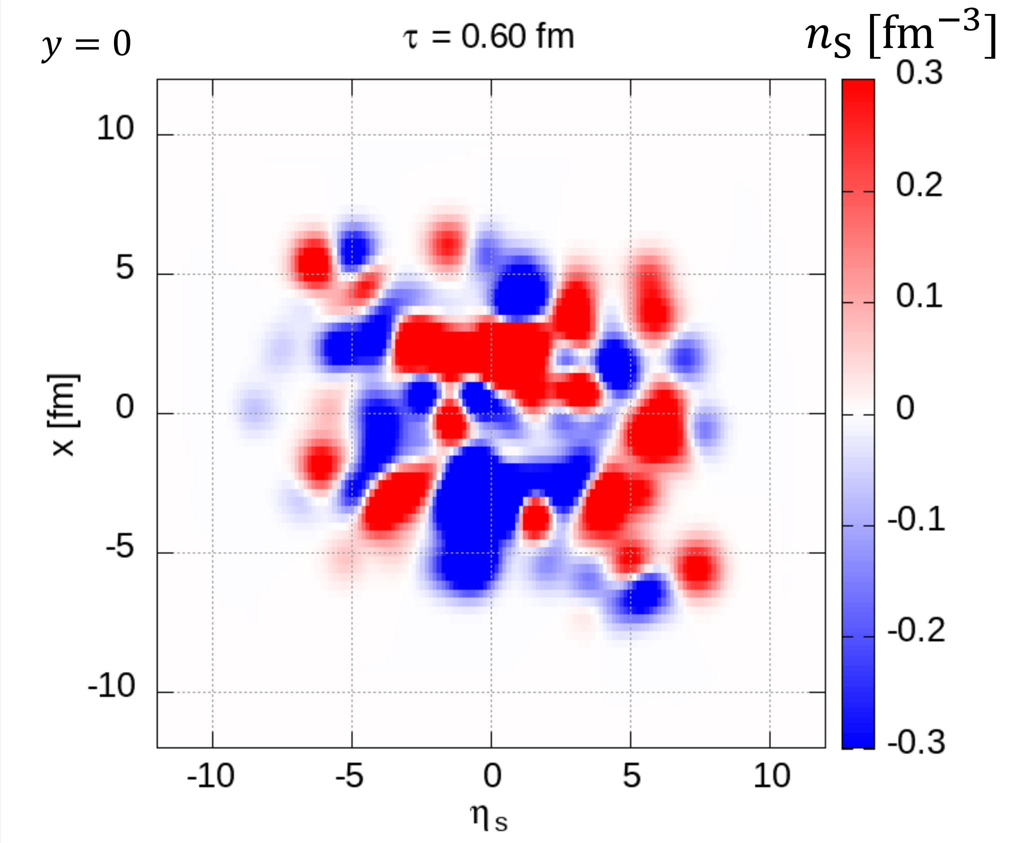
- Large fluctuations of electric charge density even in midrapidity

➡ Negative n_Q region appears

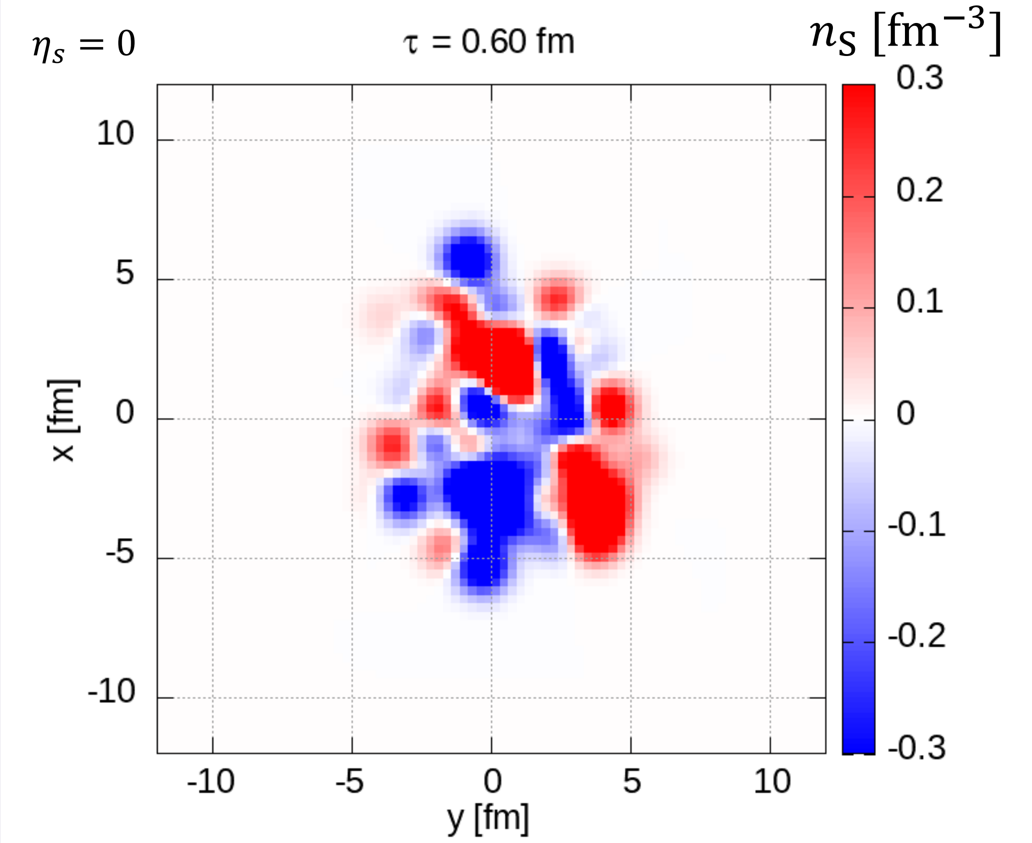
Strangeness density

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

Strangeness density (longitudinal profile)



Strangeness density (transverse profile)



- No large strangeness density region in forward rapidity

  cf.) $n_s = 0$ (Pb)

- Large fluctuations of strangeness density even in midrapidity

  ➡ Negative n_S region appears

Chemical potentials (longitudinal)

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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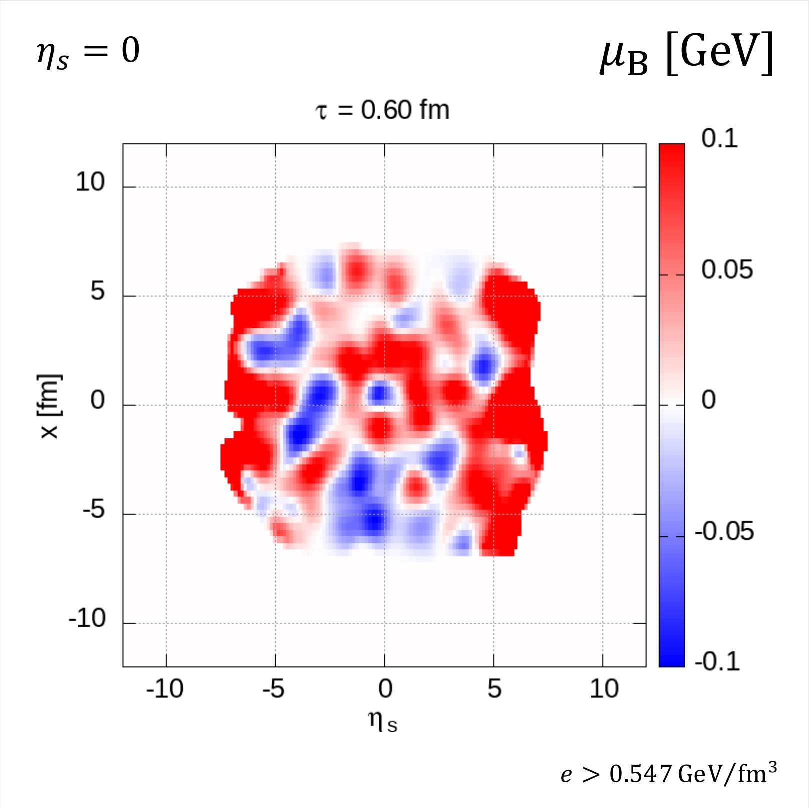
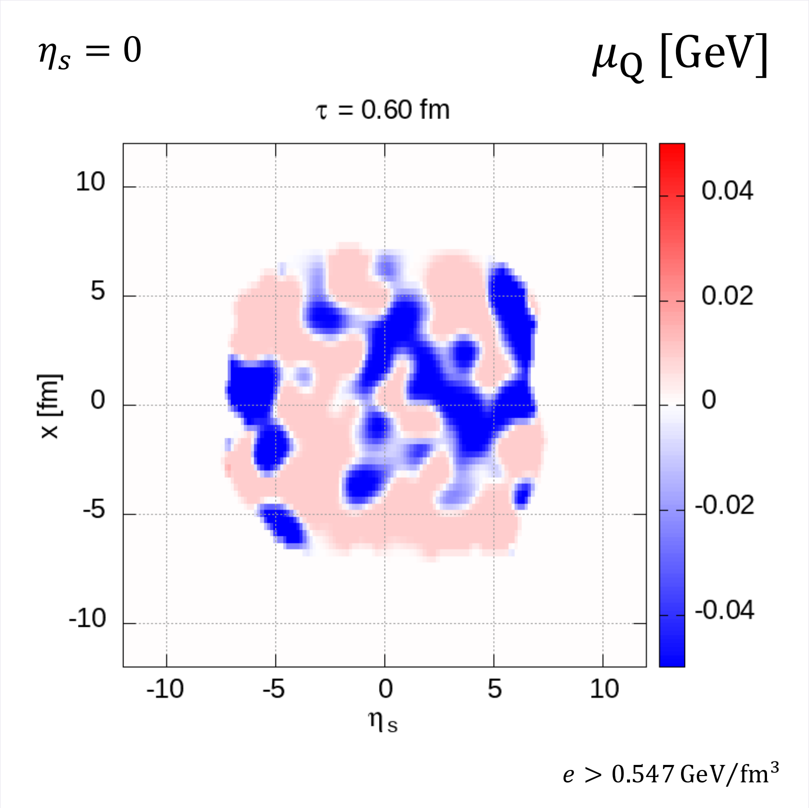
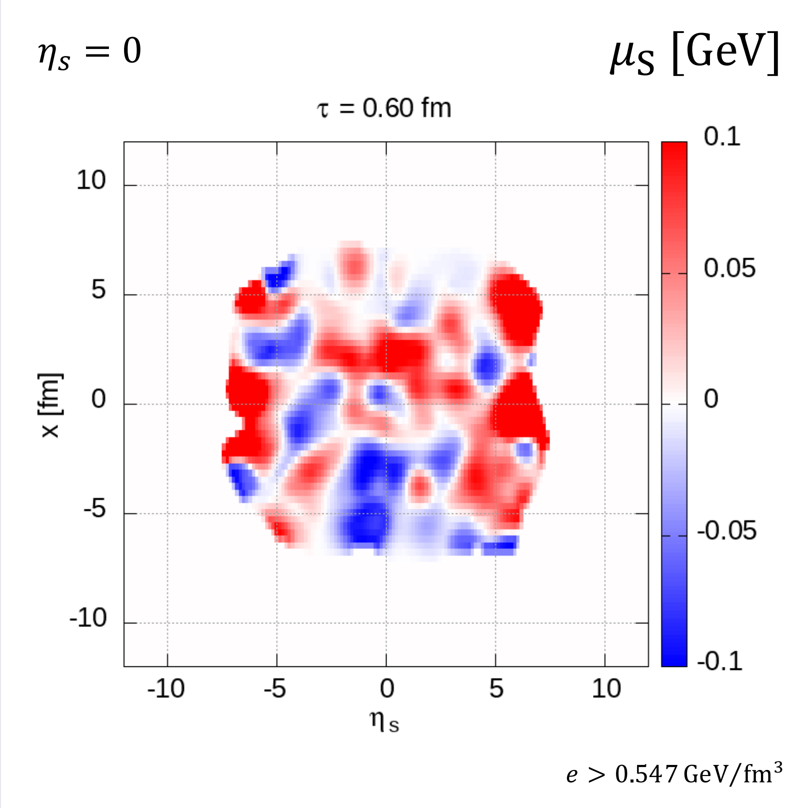
Baryon chemical potential



Electric charge chemical potential



Strangeness chemical potential



- High μ_B in forward rapidities
- Large negative μ_Q and small positive μ_Q
- Relatively high μ_S in forward rapidities

Chemical potentials (transverse)

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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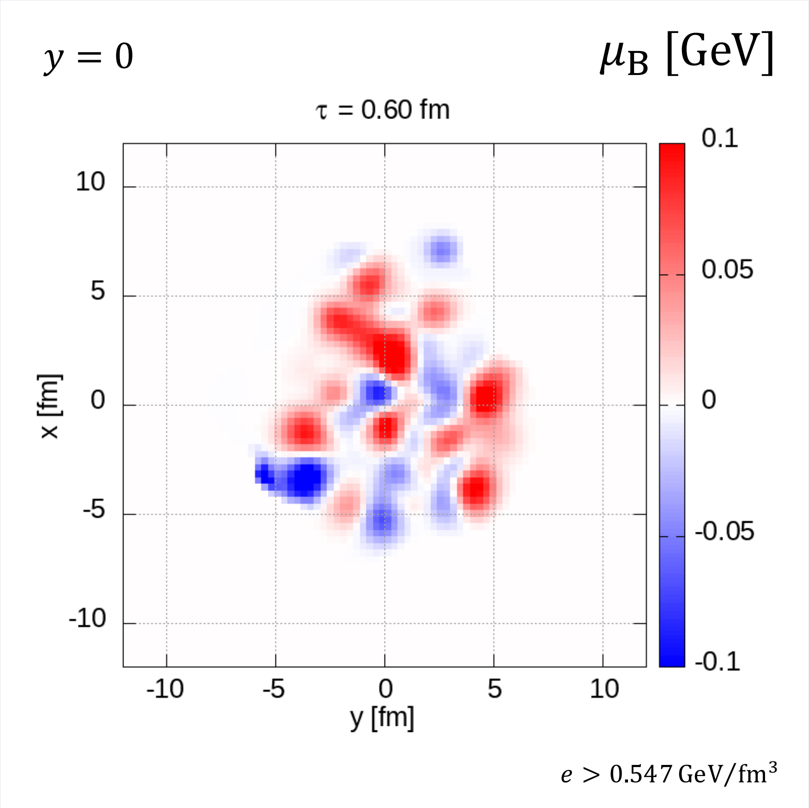
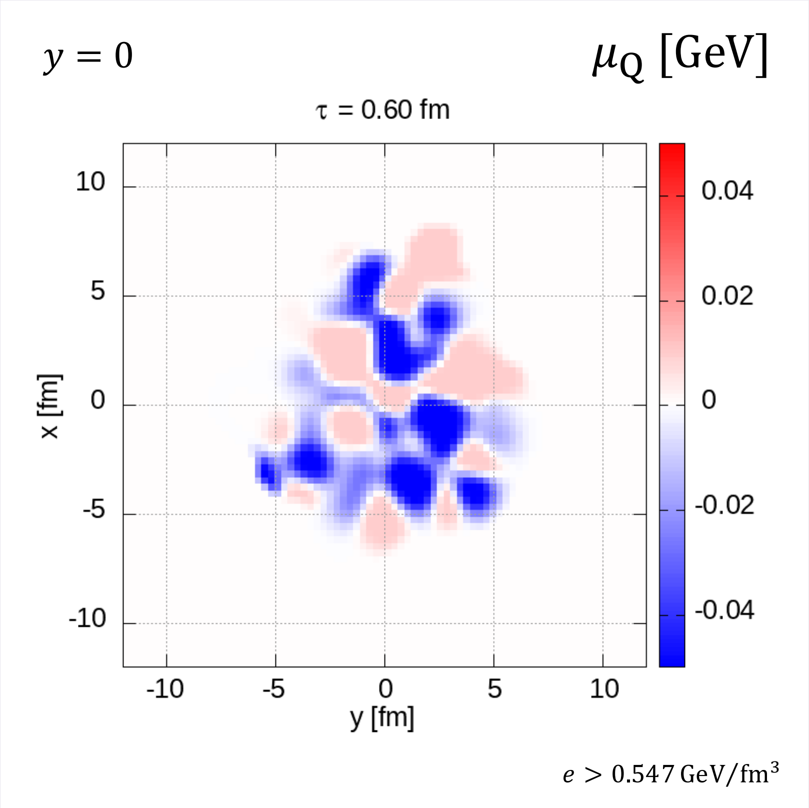
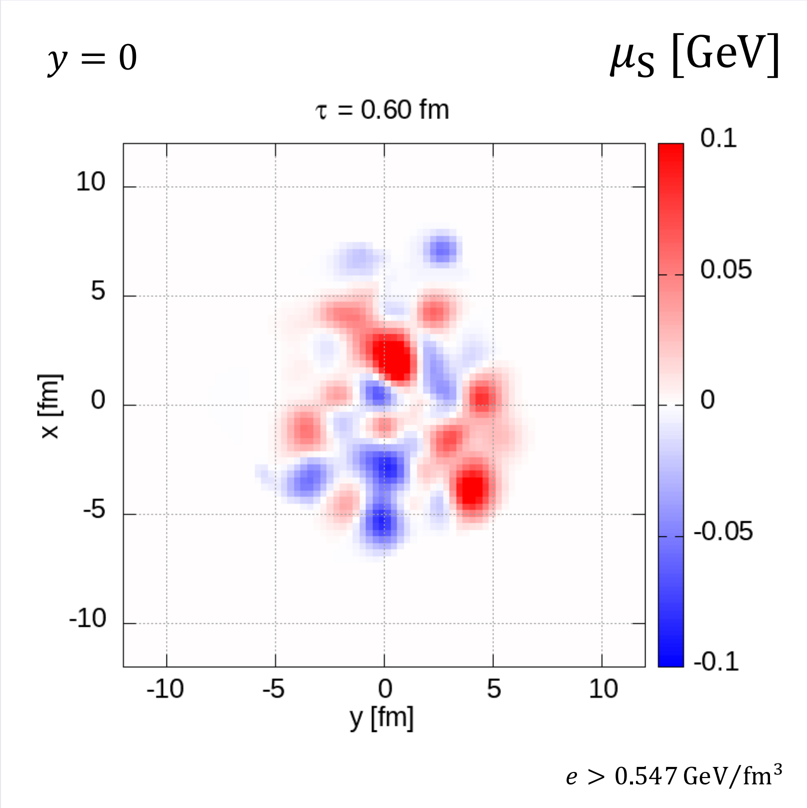
Baryon chemical potential



Electric charge chemical potential



Strangeness chemical potential



- Large fluctuations around zero chemical potential
- Large negative μ_Q and small positive μ_Q
- Large fluctuations around zero chemical potential

Rapidity dependence of freezeout hypersurface (B)

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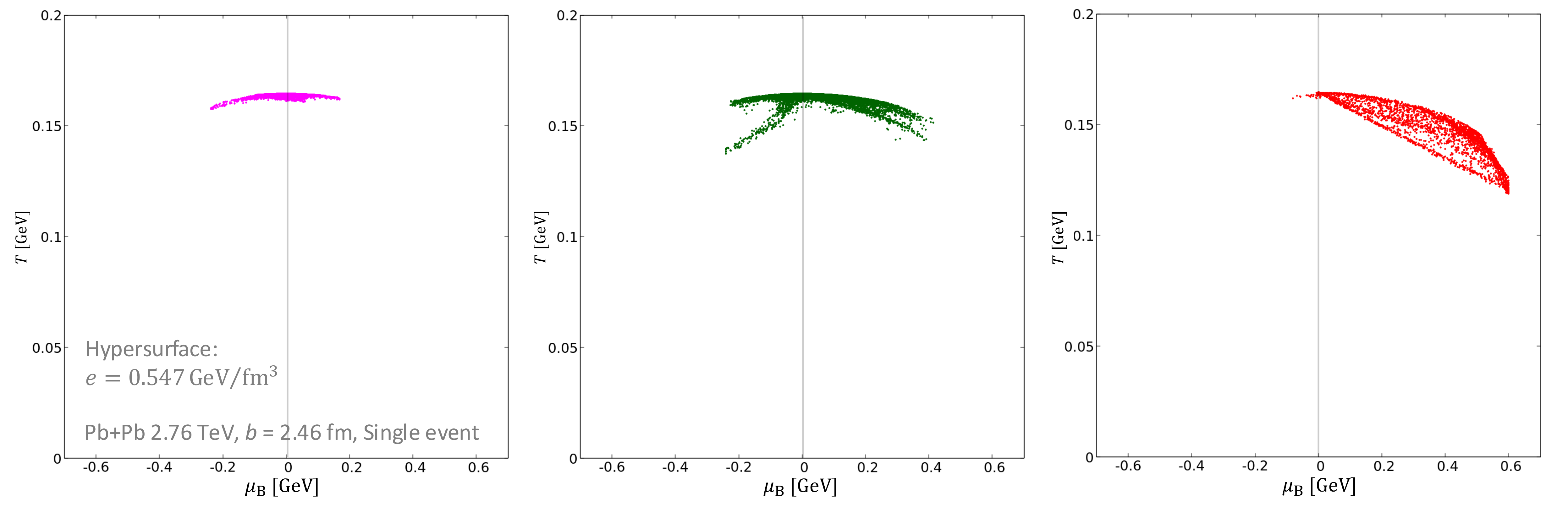
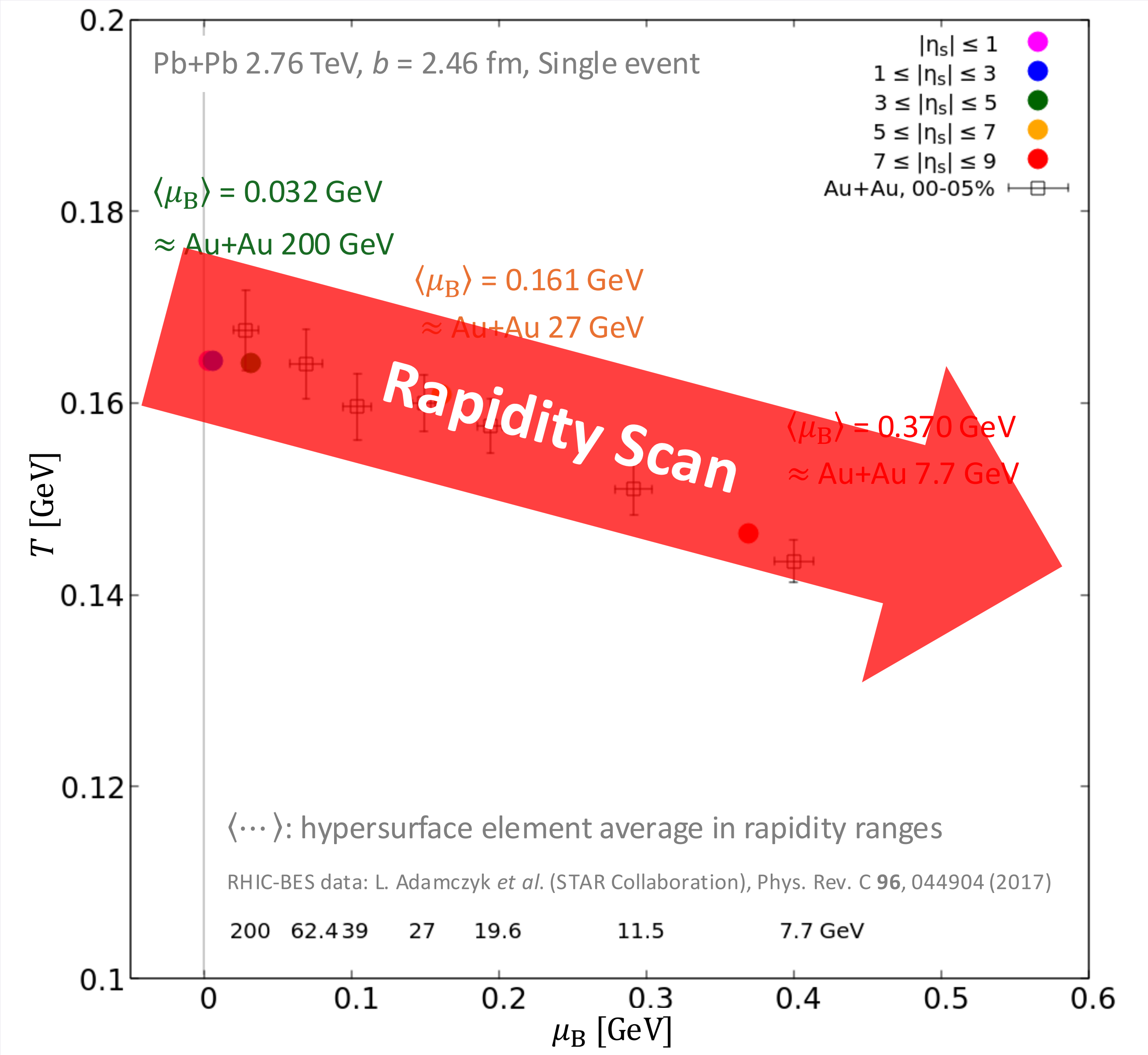
$-1 \leq \eta_s \leq 1$ $3 \leq \eta_s \leq 5$ $7 \leq \eta_s \leq 9$



- Some hypersurface element has negative baryon chemical potentials
- Significantly large baryon chemical potentials in forward rapidities

Rapidity-averaged freezeout hypersurface (B)

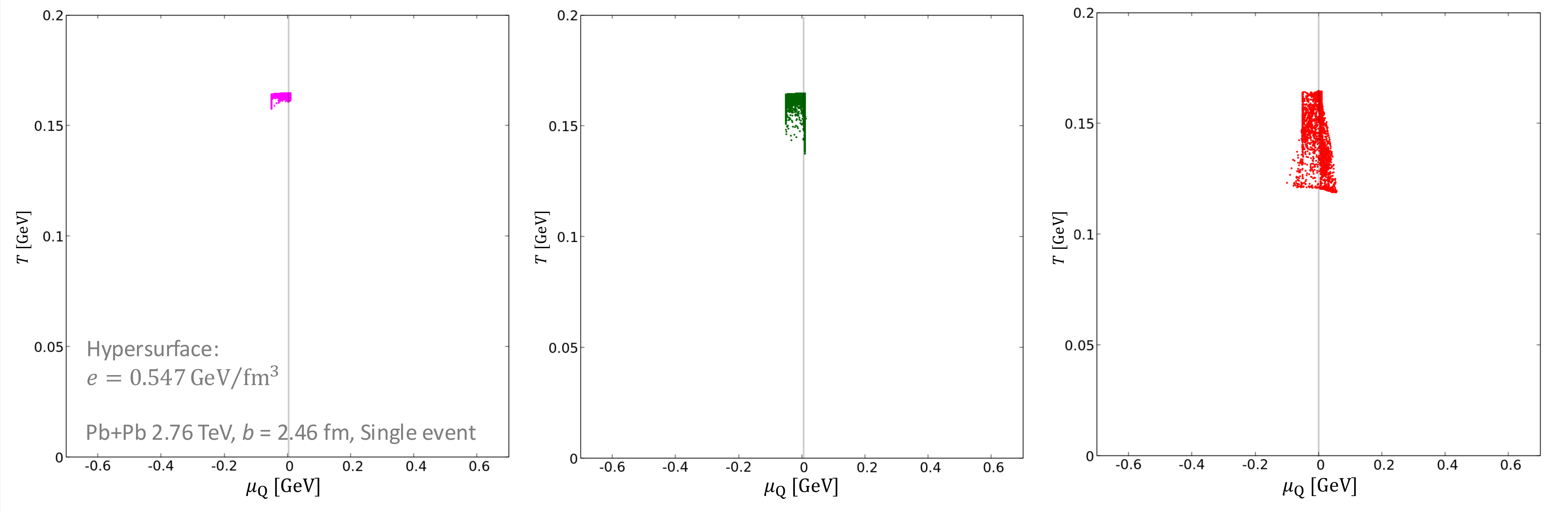


- Almost zero baryon chemical potential until $|\eta_s| \leq 5$
  - ➡ ≈ Au+Au 200 GeV
- Averaged-hypersurface in rapidity range $5 \leq |\eta_s| \leq 7$ exceeds $\mu_{\rm B} = 100$ MeV
  - ➡ ≈ Au+Au 27 GeV
- Averaged-hypersurface in rapidity range $7 \leq |\eta_s| \leq 9$ exceeds $\mu_{\rm B} = 300$ MeV
  - ➡ ≈ Au+Au 7.7 GeV

Rapidity scan is a strong tool for exploring the QCD phase diagram!!

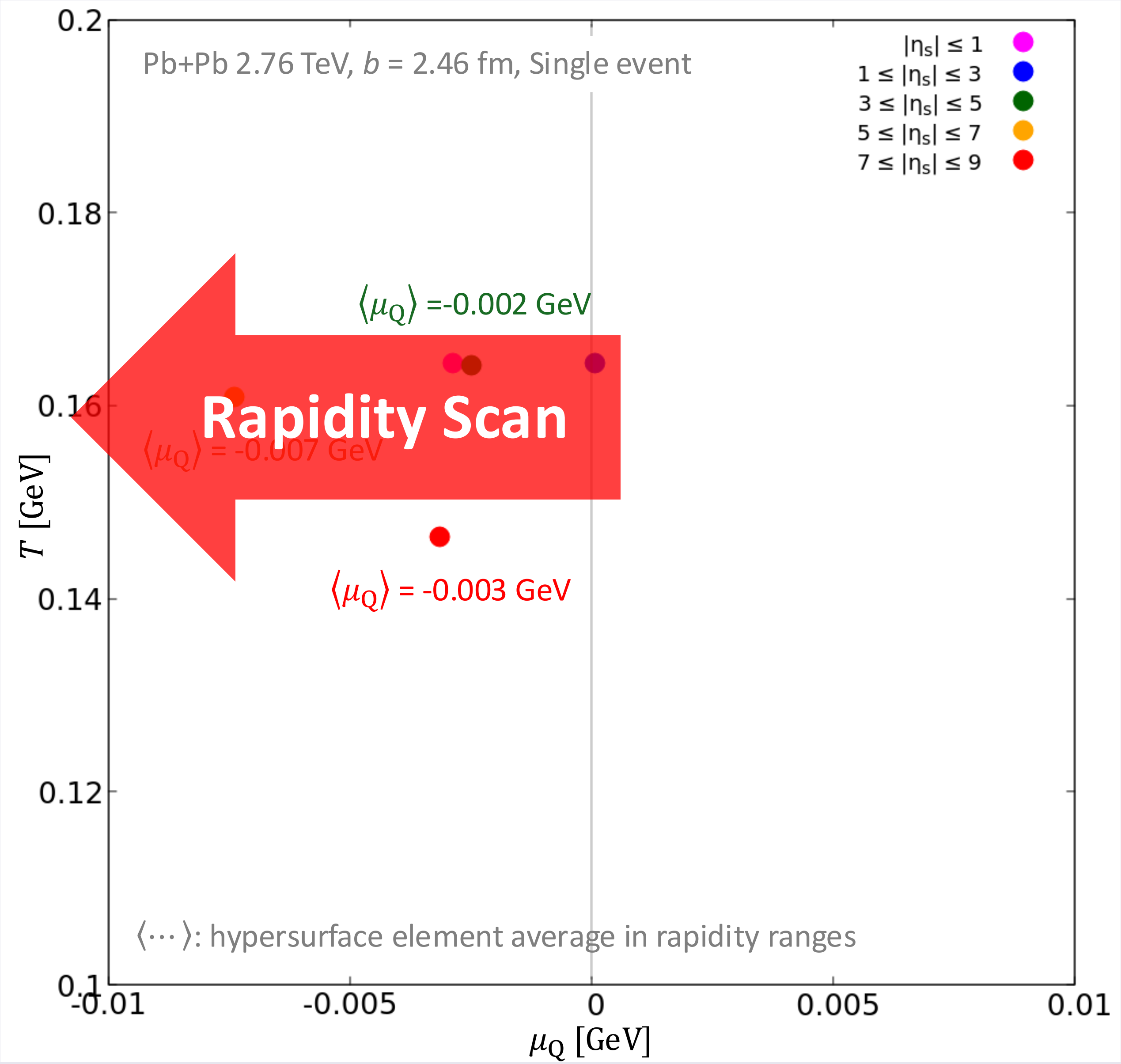
Rapidity dependence of freezeout hypersurface (Q)

$-1 \leq \eta_s \leq 1$ $3 \leq \eta_s \leq 5$ $7 \leq \eta_s \leq 9$



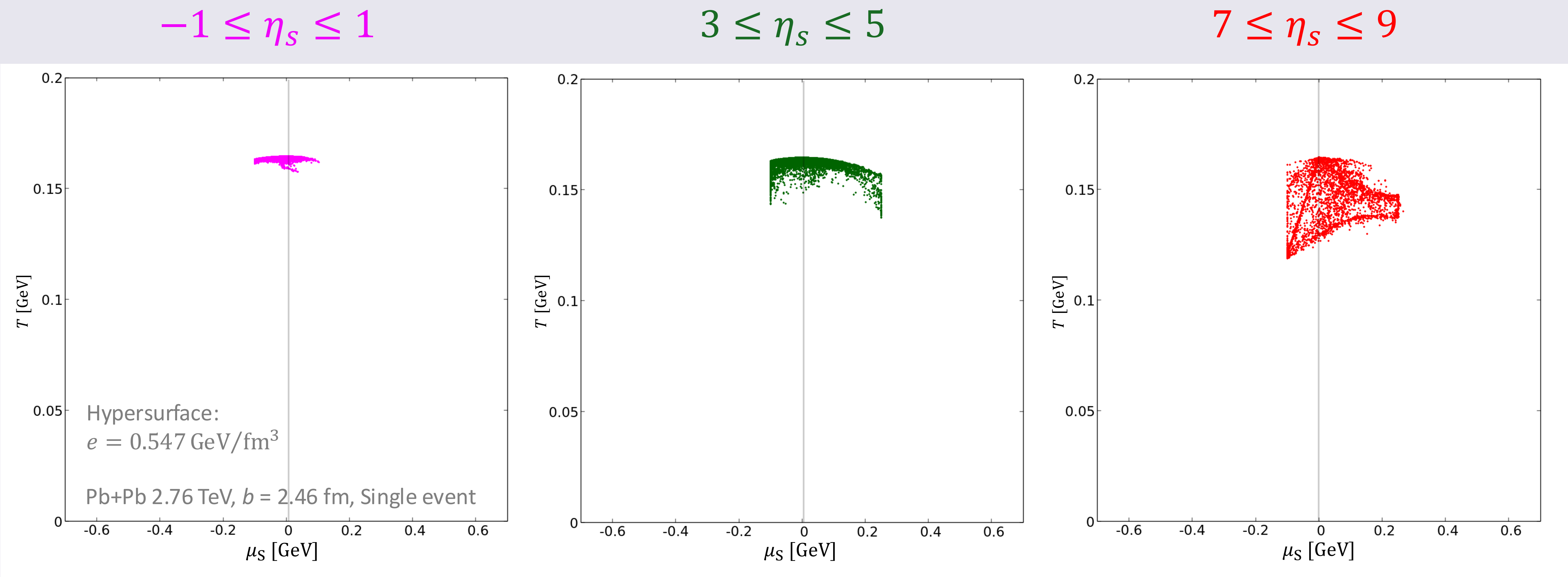
- Insufficient available range of NEOS-4D, $-0.05 < \mu_Q < 0.01$ GeV
- Tend to be negative chemical potentials in every rapidity range

Rapidity-averaged freezeout hypersurface (Q)



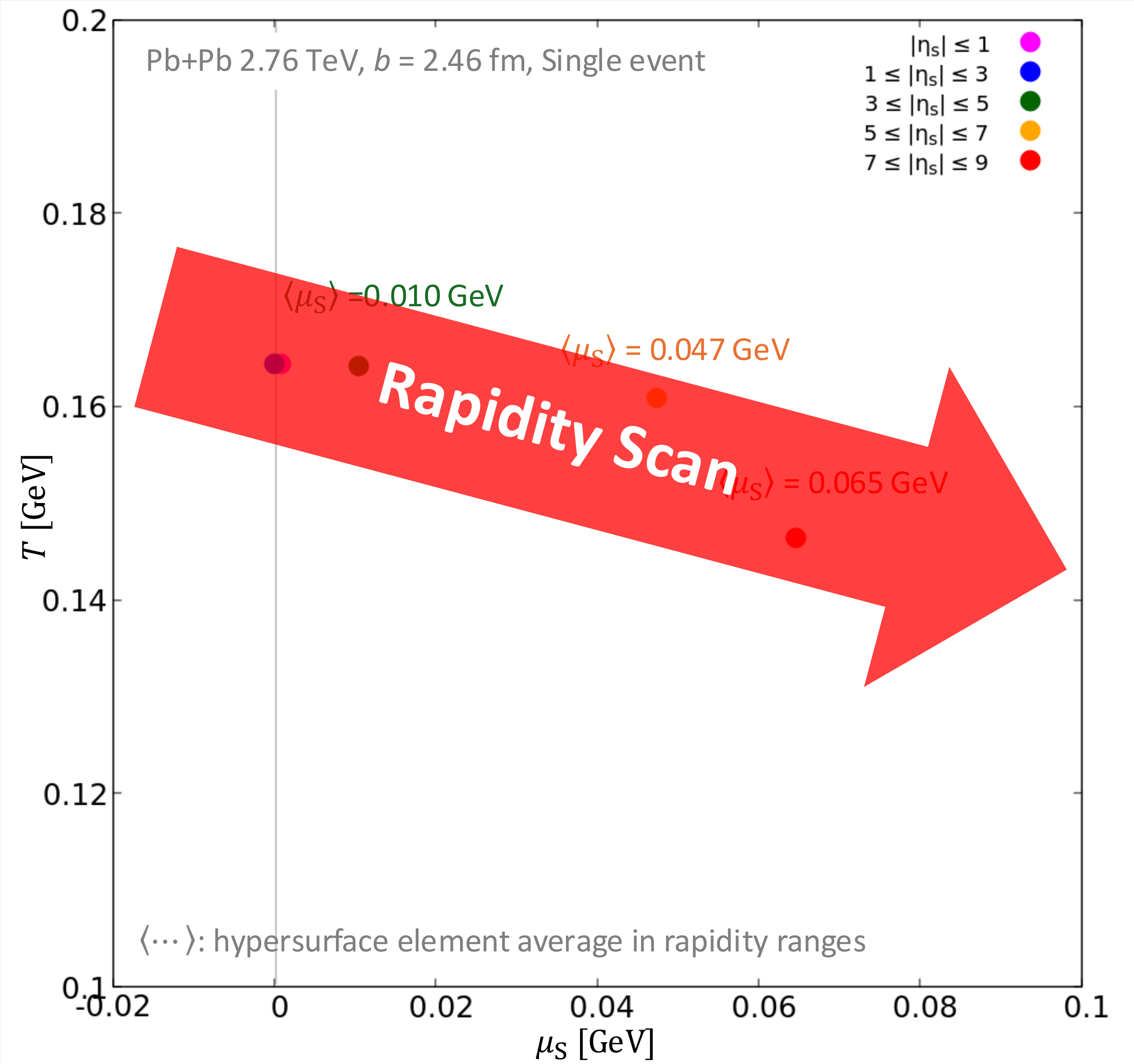
- Absolute value of electric charge chemical potentials are small
- Electric charge chemical potentials tend to be negative as go forward rapidity
- Need more statistics to make strict conclusions
- Need wider range EoS

Rapidity dependence of freezeout hypersurface (S)



- Insufficient available range of NEOS-4D, $-0.1 < \mu_S < 0.25$ GeV
- Tend to be positive chemical potentials as go forward rapidity

Rapidity-averaged freezeout hypersurface (S)



- Similar trend with baryon chemical potentials, but absolute values are smaller
- Need more statistics to make strict conclusions
- Need wider range EoS

Summary and Outlook

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Summary

- Extended the DCCI model to finite baryon number
  - ➡ descriptions of thermalized baryon number
  - ➡ Rapidity Scan!!
- Negative $n_{\mathrm{B}}(\mu_{\mathrm{B}})$ region appears due to the depositions of anti-quarks
- At LHC energies, high baryon chemical potentials are realized in forward rapidities

Outlook

- Event averaged analysis, centrality dependence, different initial conditions, etc.
- Rapidity dependent analysis (strangeness enhancement, etc.)
- Study of QCD phase diagram with rapidity scan (as a complementary way to BES)

Backups

Space-time evolution of core

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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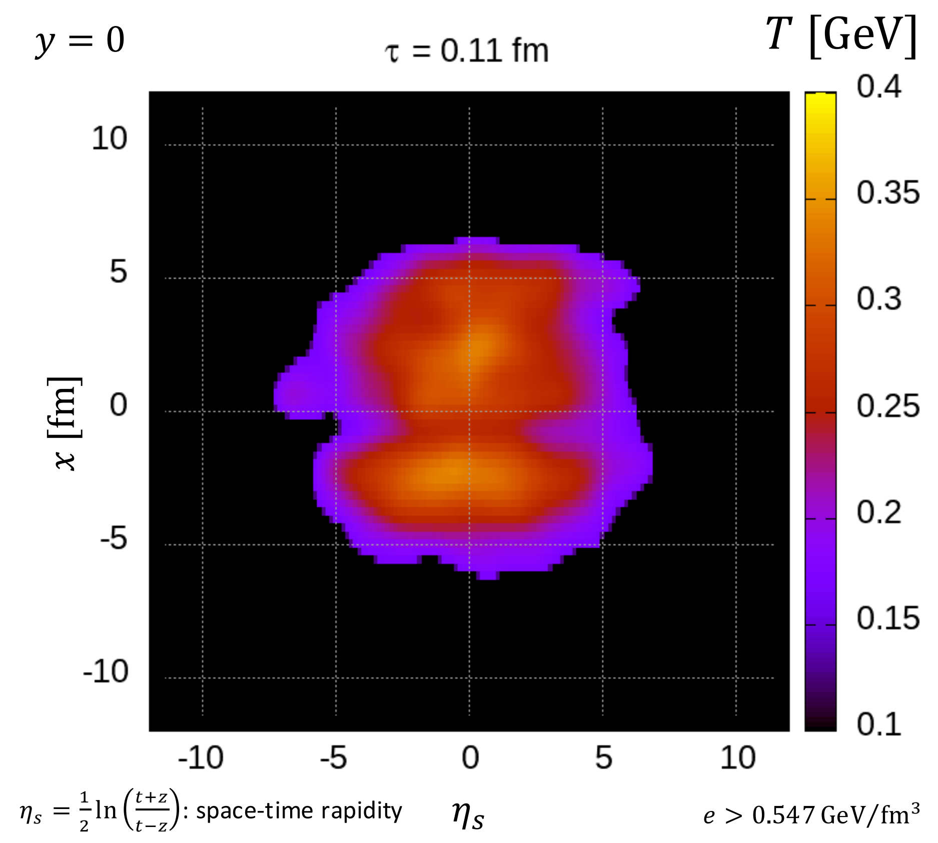
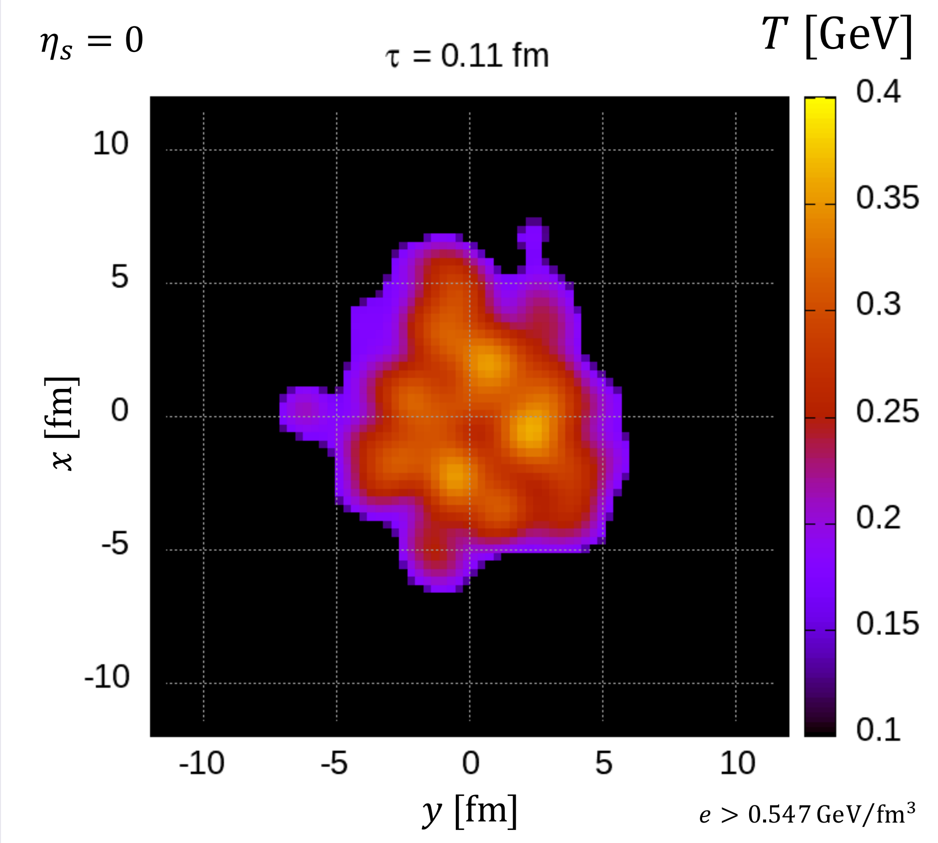
Temperature (longitudinal profile)



Temperature (transverse profile)

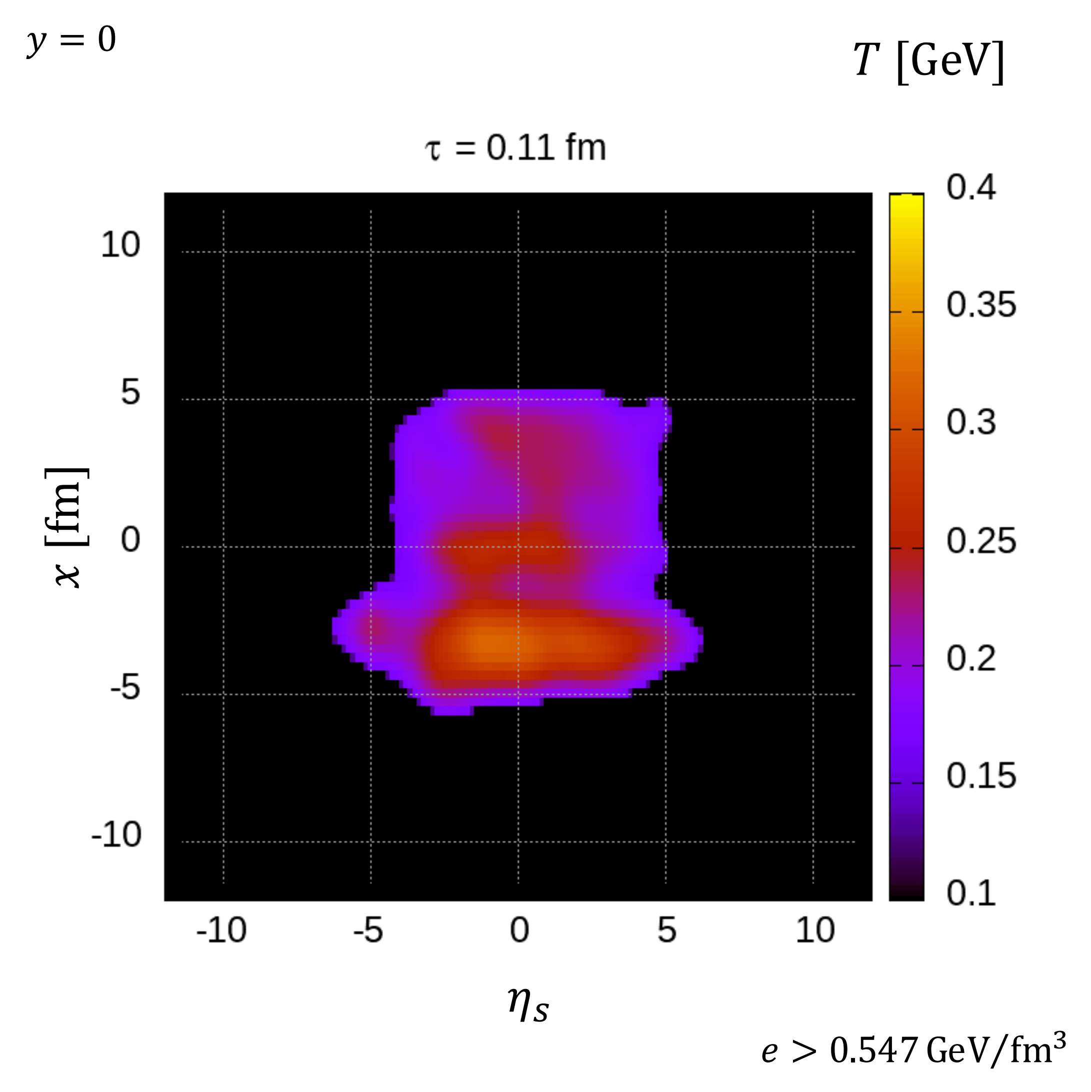


- Gradual formation of the core (QGP fluid) through the energy-momentum source term
- Alongside the fluid formation, the core cools down due to the hydrodynamic evolution

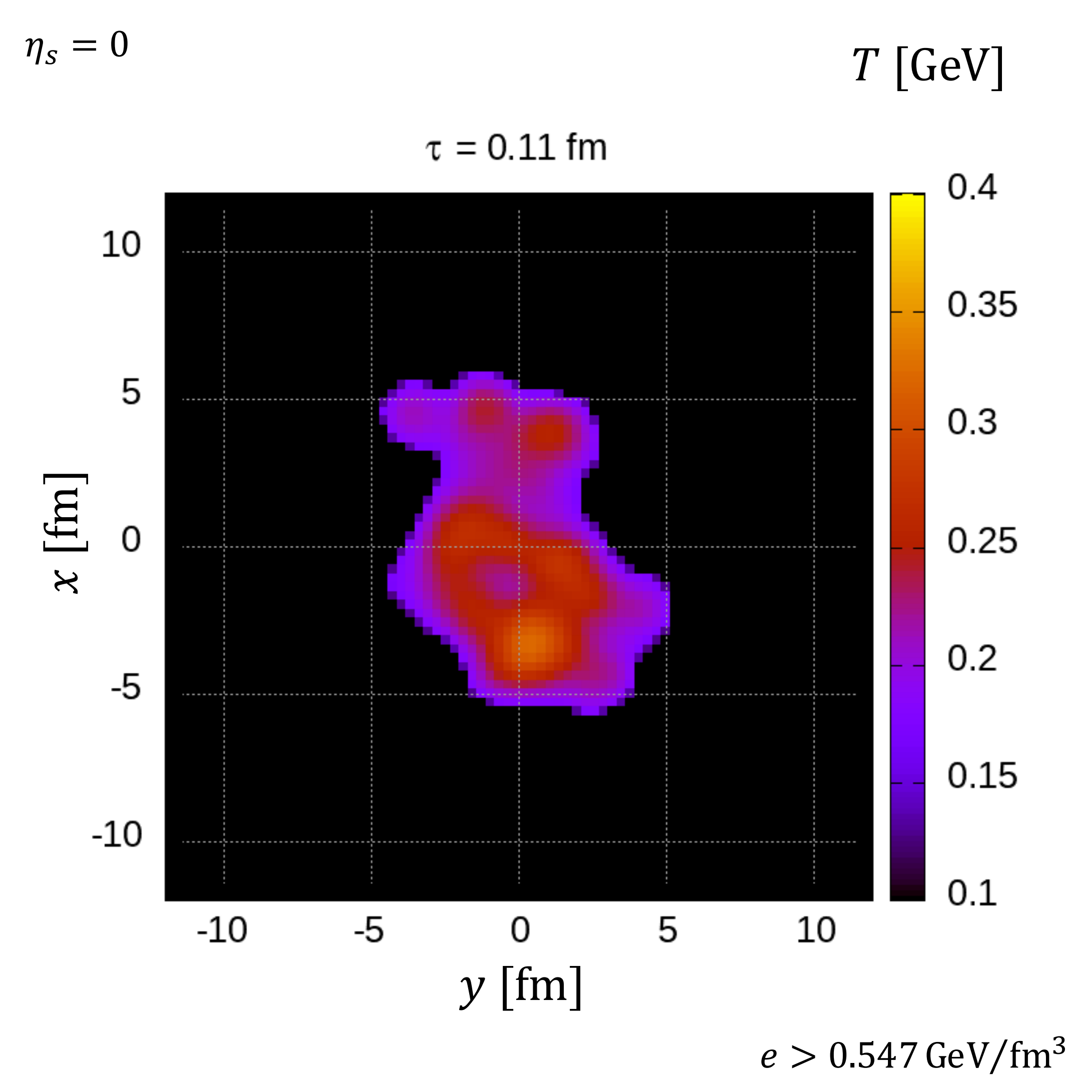
Space-time evolution of core

Pb+Pb 2.76 TeV, b = 6.12 fm
Single event

Temperature (longitudinal profile)



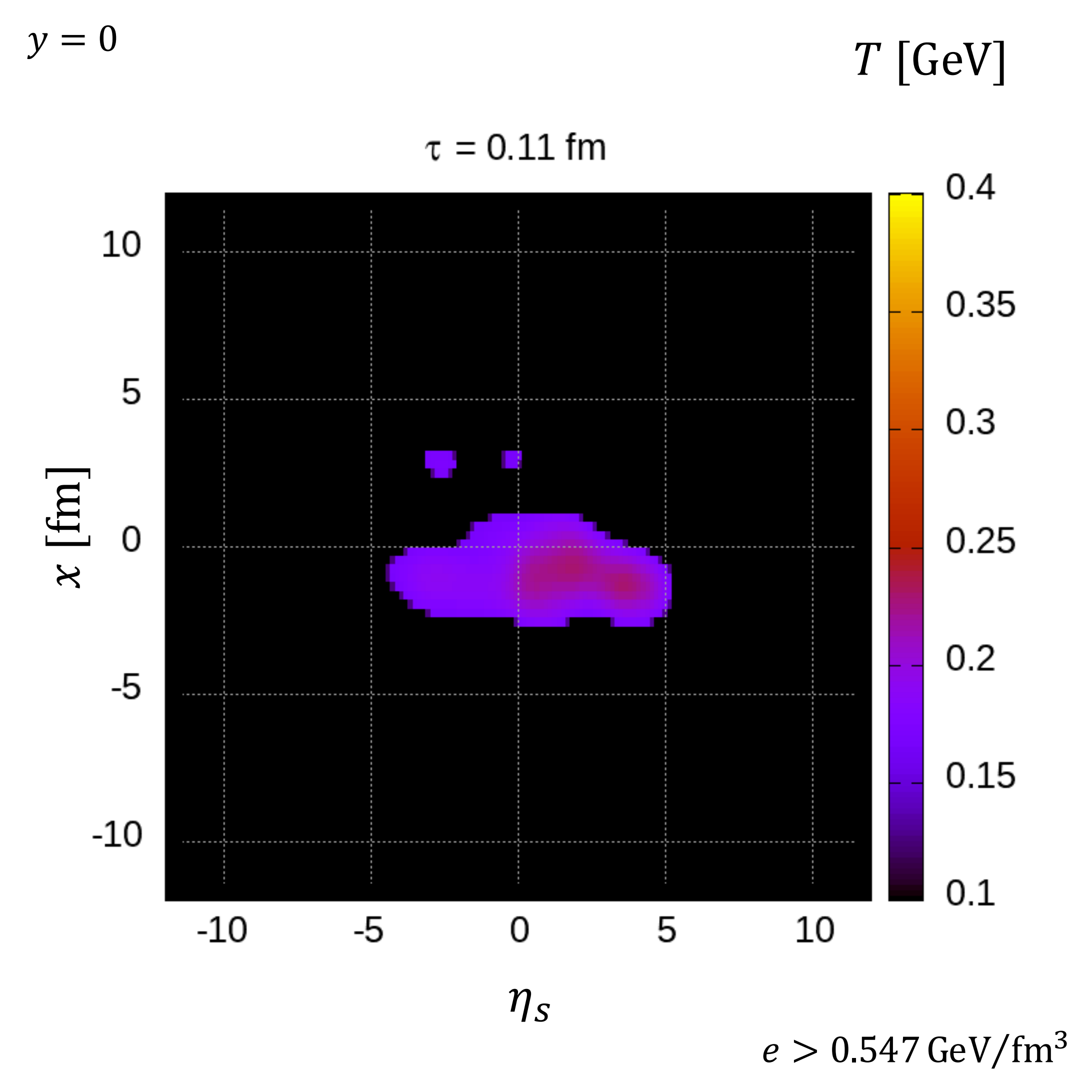
Temperature (transverse profile)



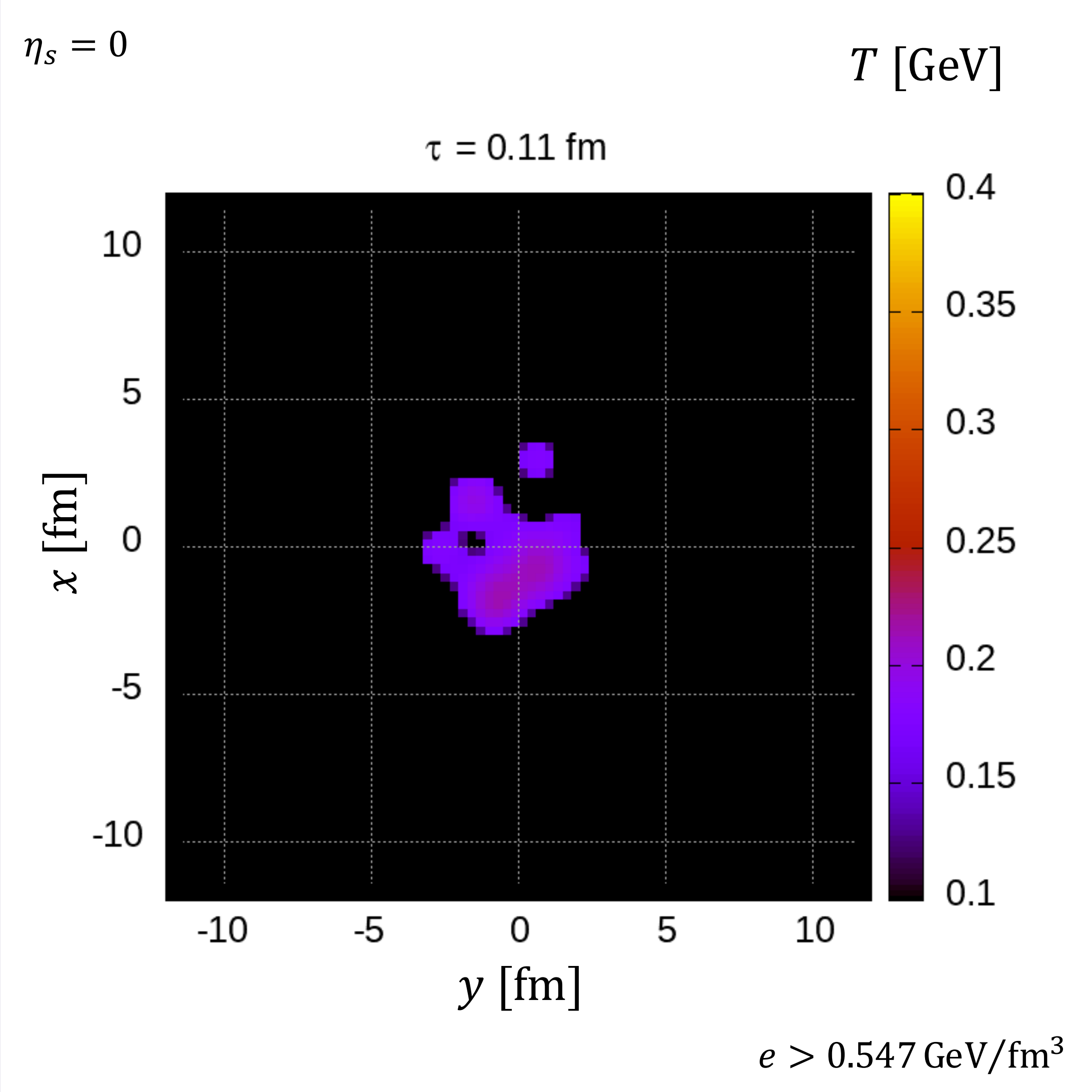
Space-time evolution of core

Pb+Pb 2.76 TeV, b = 10.1 fm
Single event

Temperature (longitudinal profile)



Temperature (transverse profile)



Space-time evolution of core

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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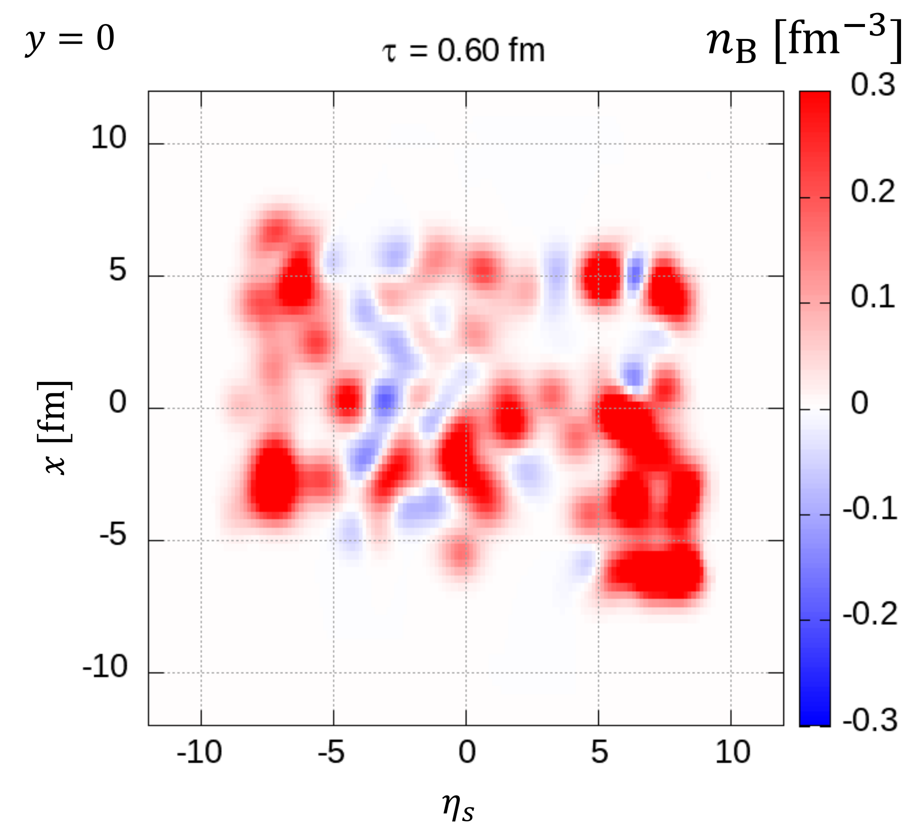
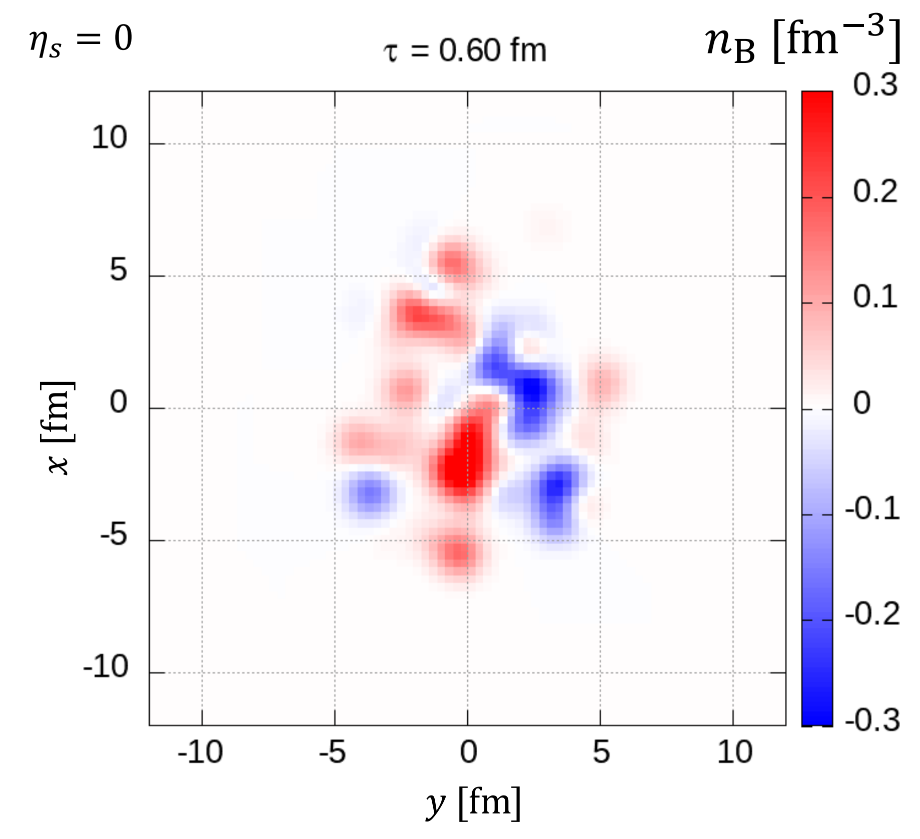
Baryon number density (longitudinal profile)



Baryon number density (transverse profile)



- Large baryon number density is realized in forward rapidities $5 \lesssim |\eta_s| \lesssim 10$

  cf.) $y_{\mathrm{beam}}(\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}) \approx 8$

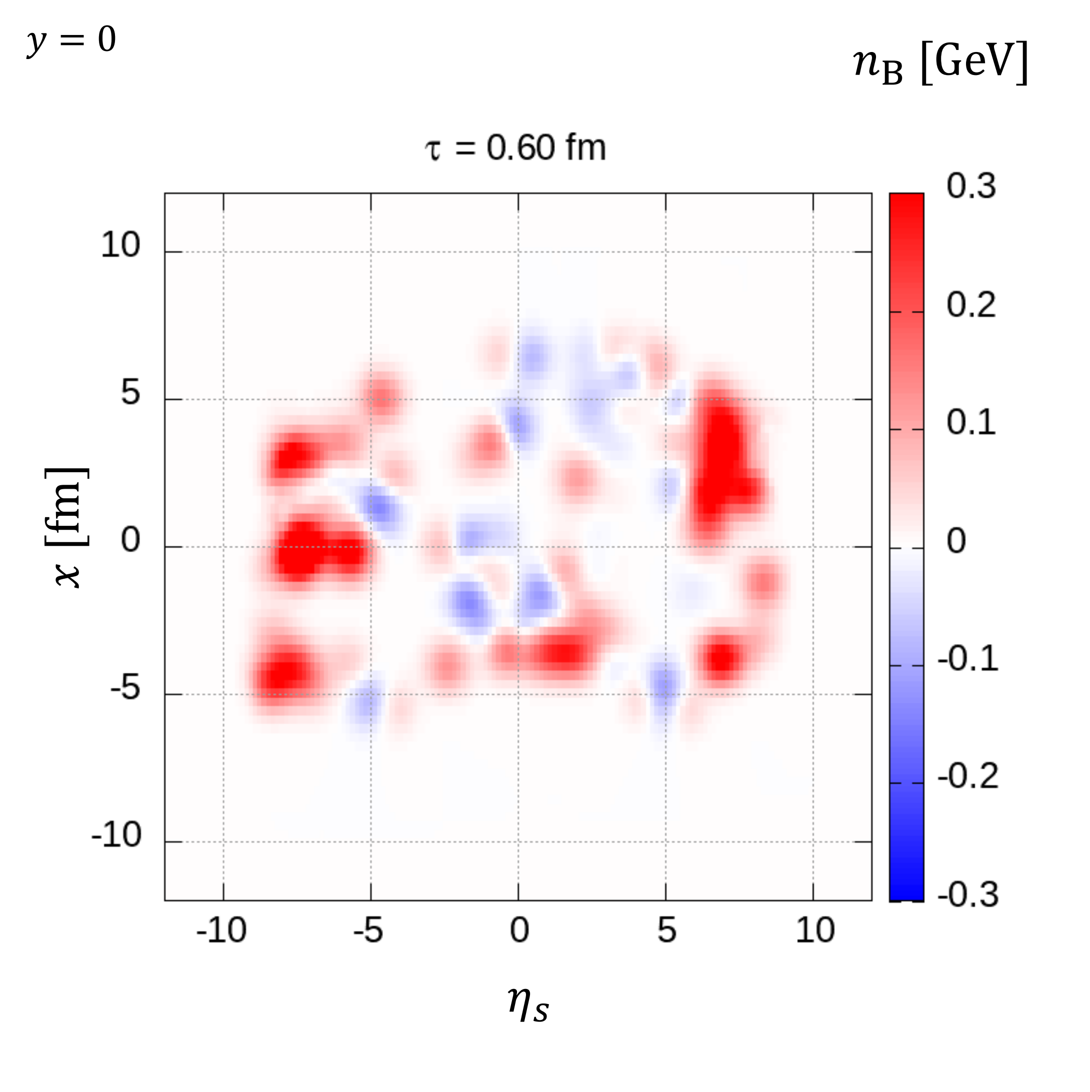
- Large fluctuations of baryon number density even in midrapidity

  ➡ Negative n_B region appears

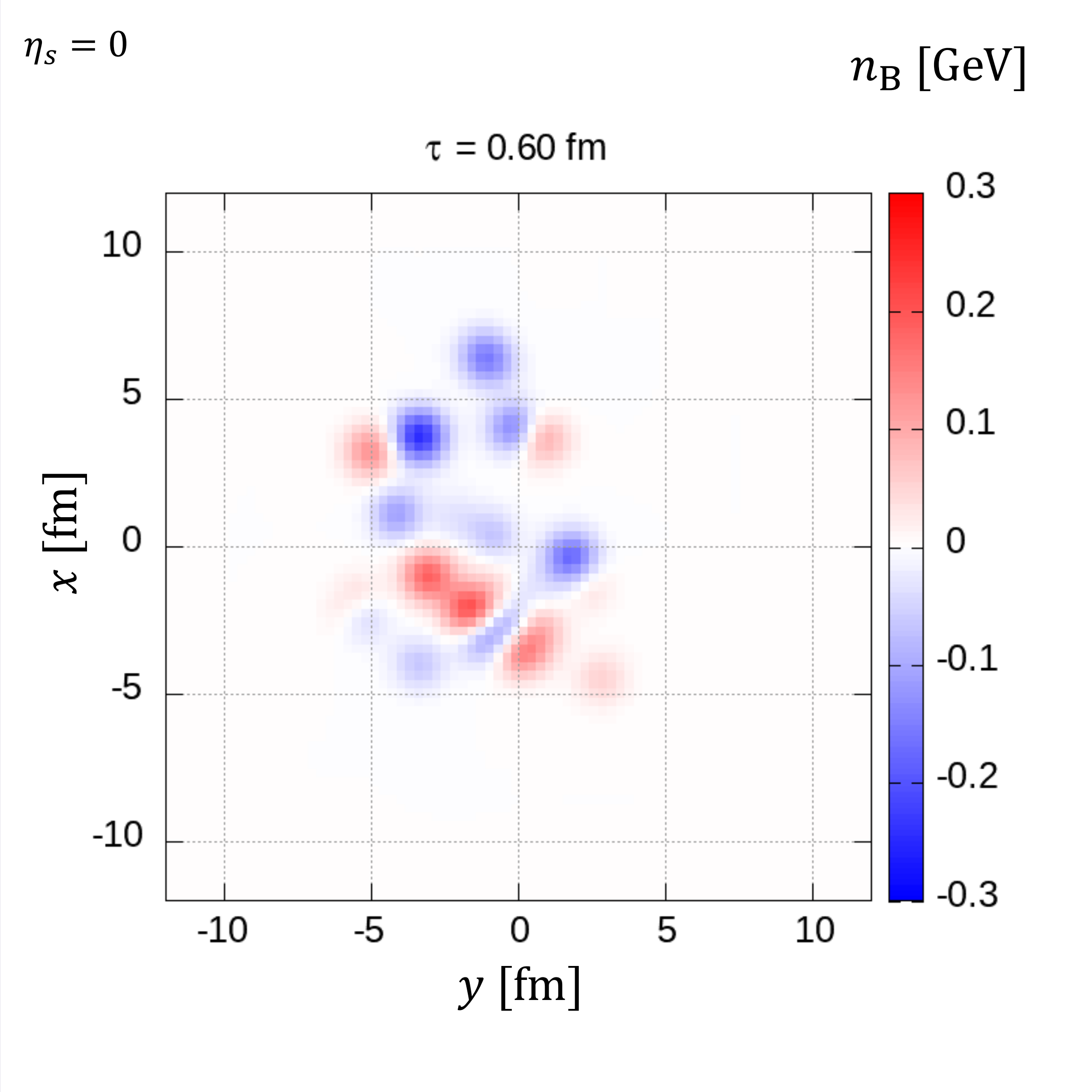
Space-time evolution of core

Pb+Pb 2.76 TeV, b = 6.12 fm
Single event

Baryon number density (longitudinal profile)



Baryon number density (transverse profile)



Space-time evolution of core

Pb+Pb 2.76 TeV, b = 10.1 fm
Single event

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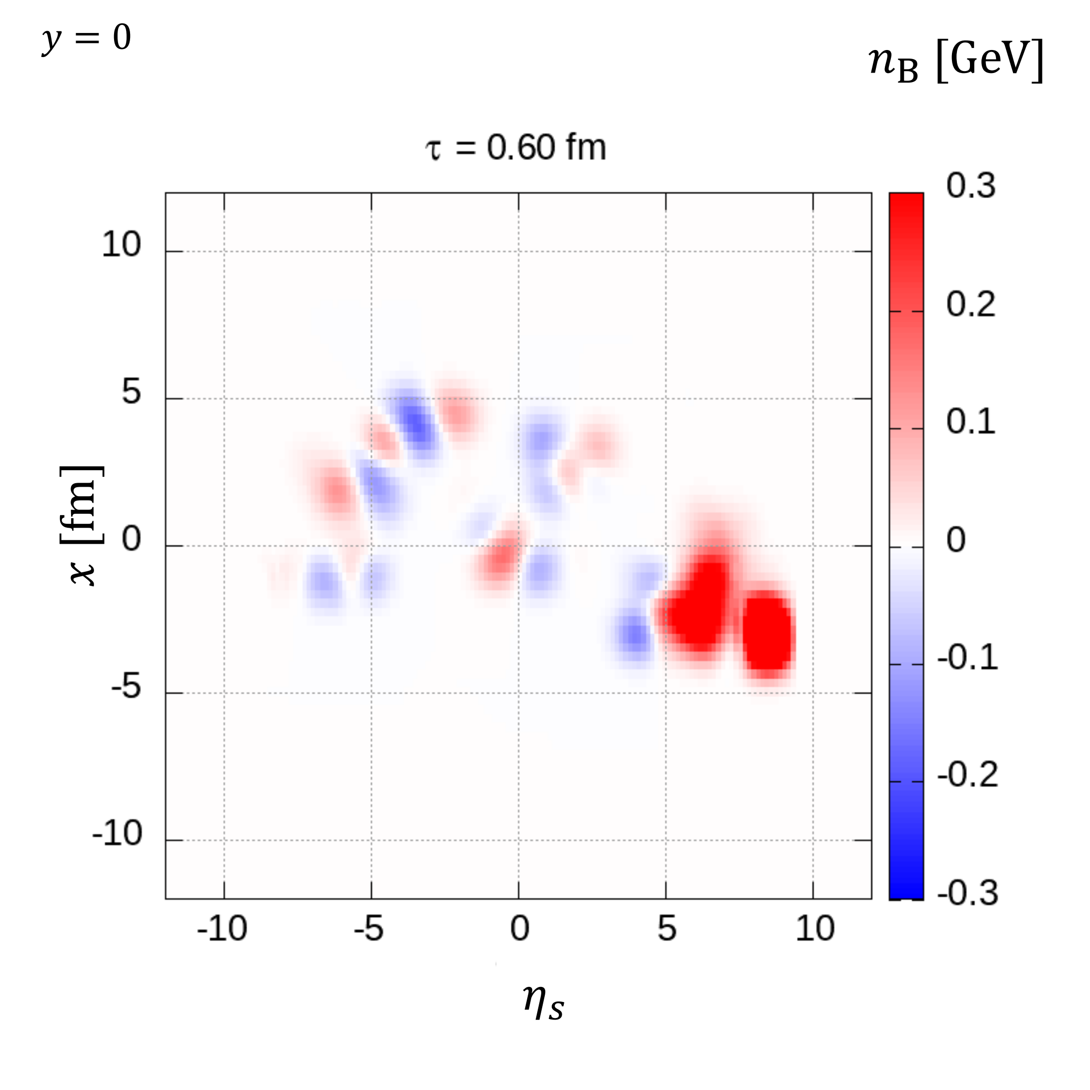
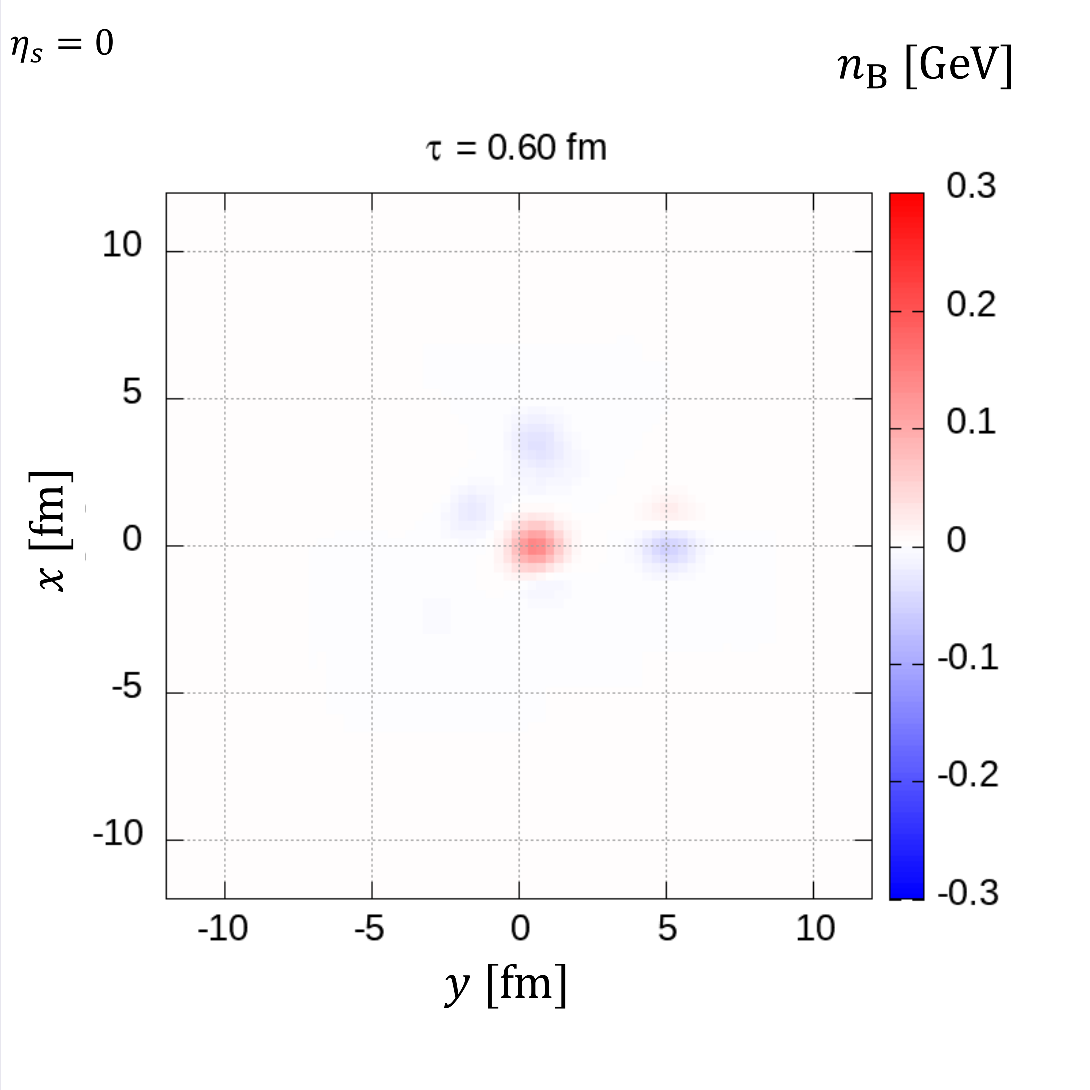
Baryon number density (longitudinal profile)



Baryon number density (transverse profile)



Space-time evolution of core

Pb+Pb 2.76 TeV, b = 2.46 fm
Single event

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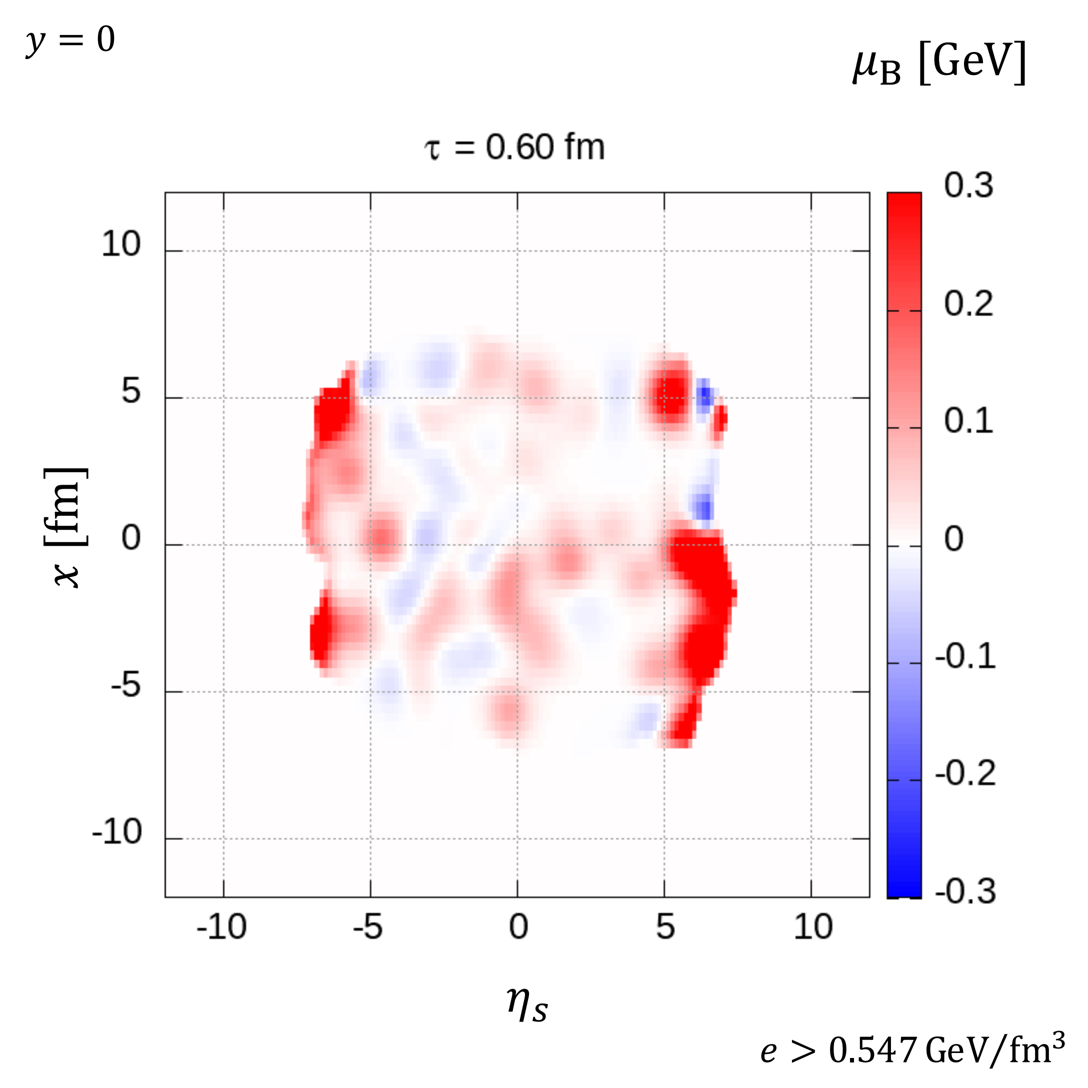
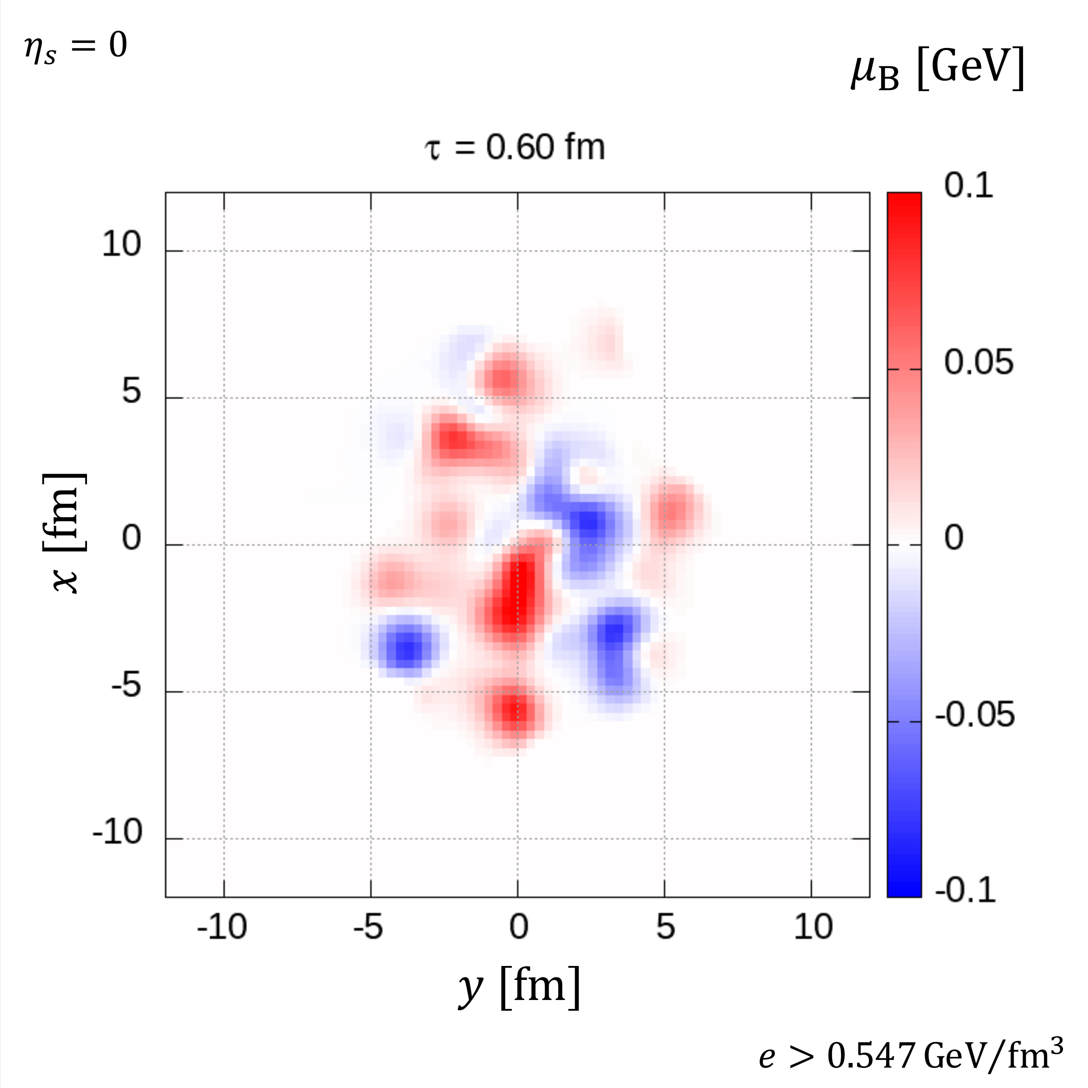
Baryon chemical potential (longitudinal profile)



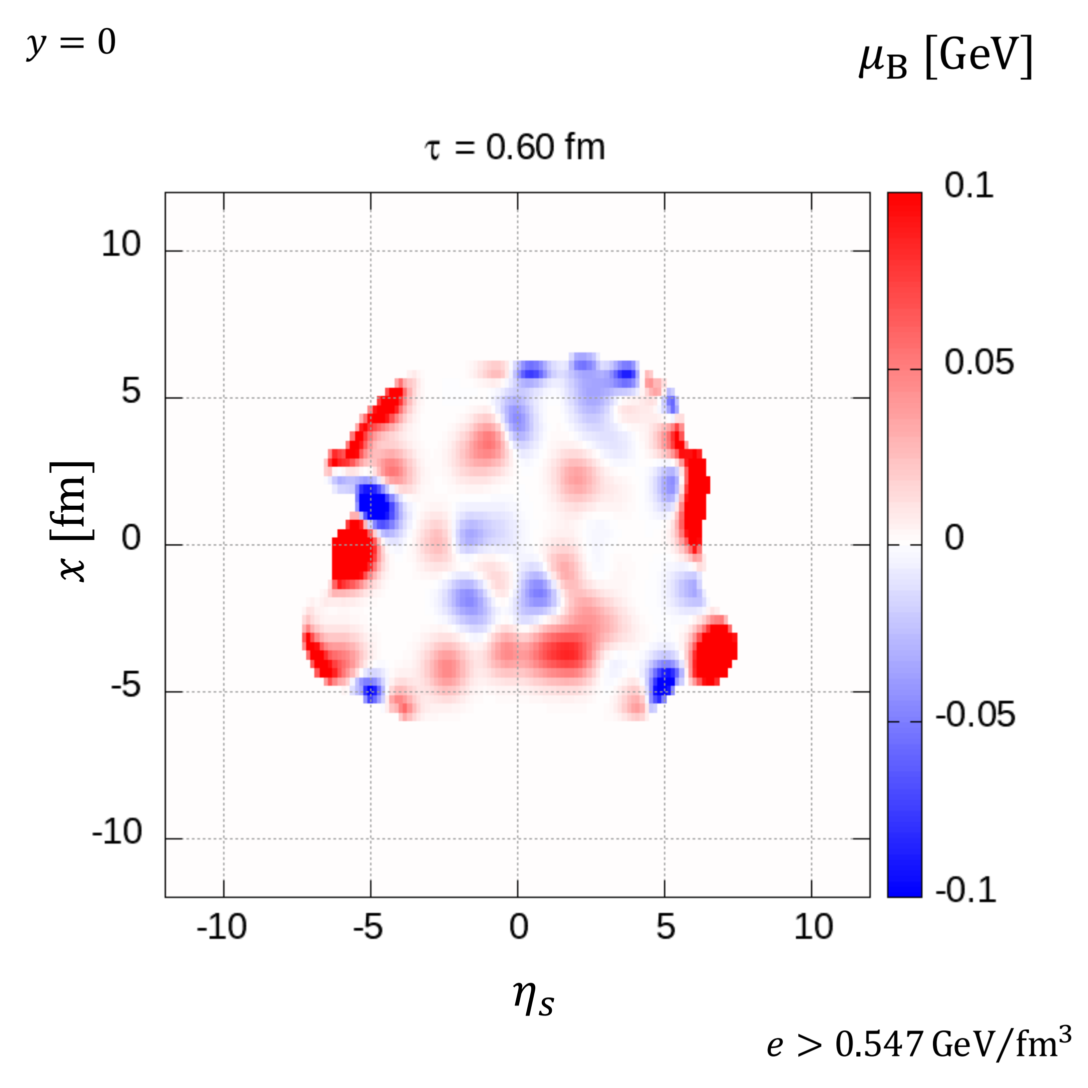
Baryon chemical potential (transverse profile)



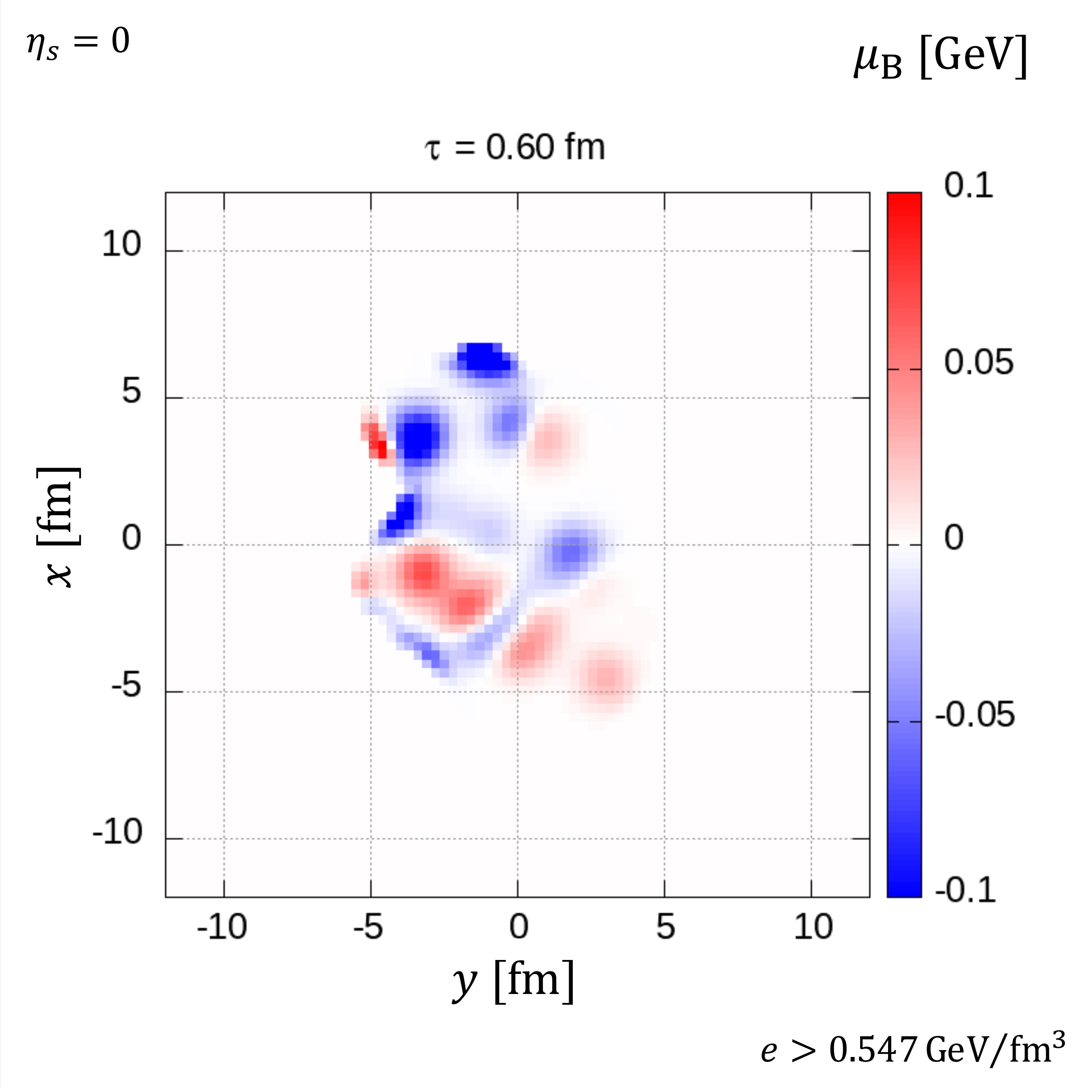
Space-time evolution of core

Pb+Pb 2.76 TeV, b = 6.12 fm
Single event

Baryon chemical potential (longitudinal profile)



Baryon chemical potential (transverse profile)



Space-time evolution of core

Pb+Pb 2.76 TeV, b = 10.1 fm
Single event

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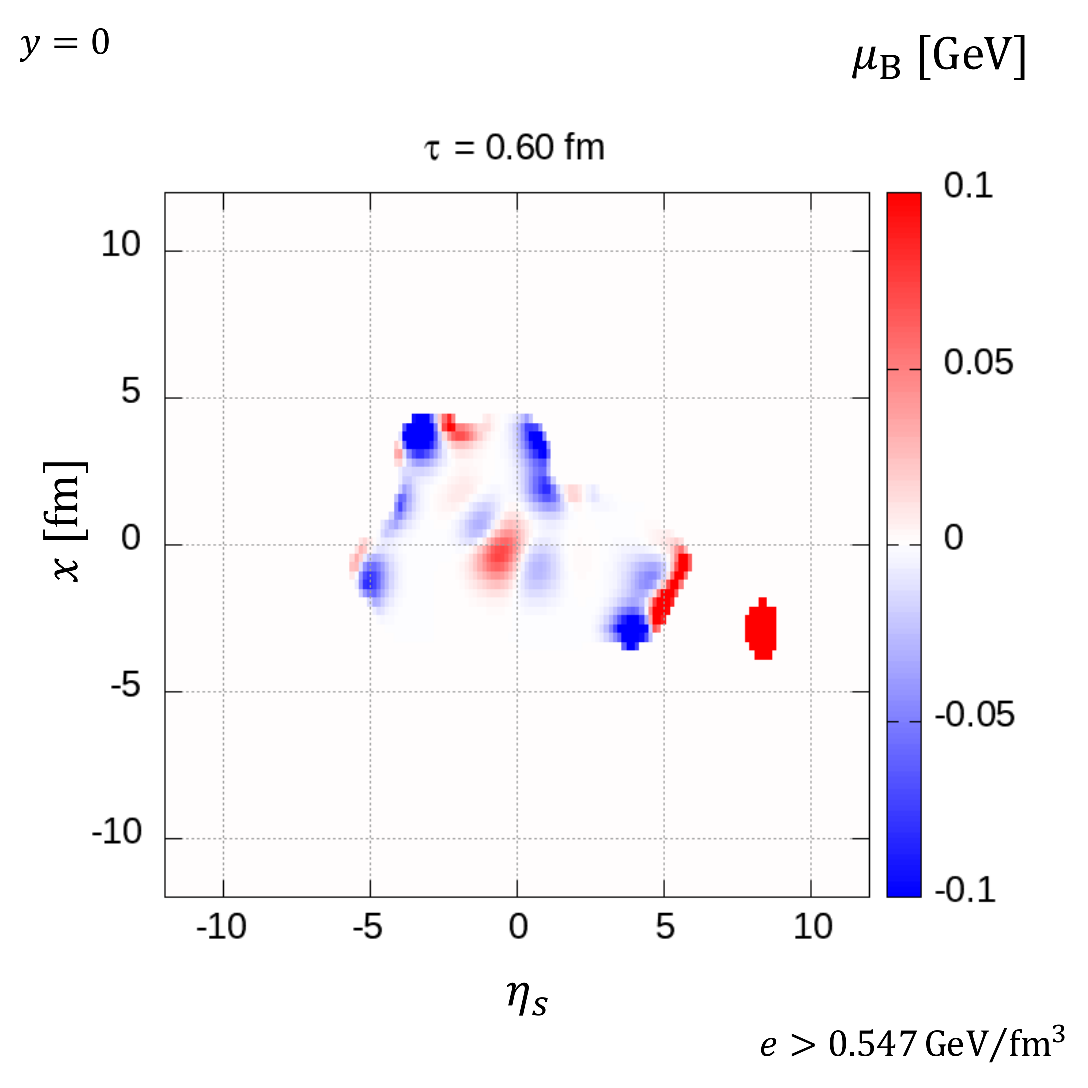
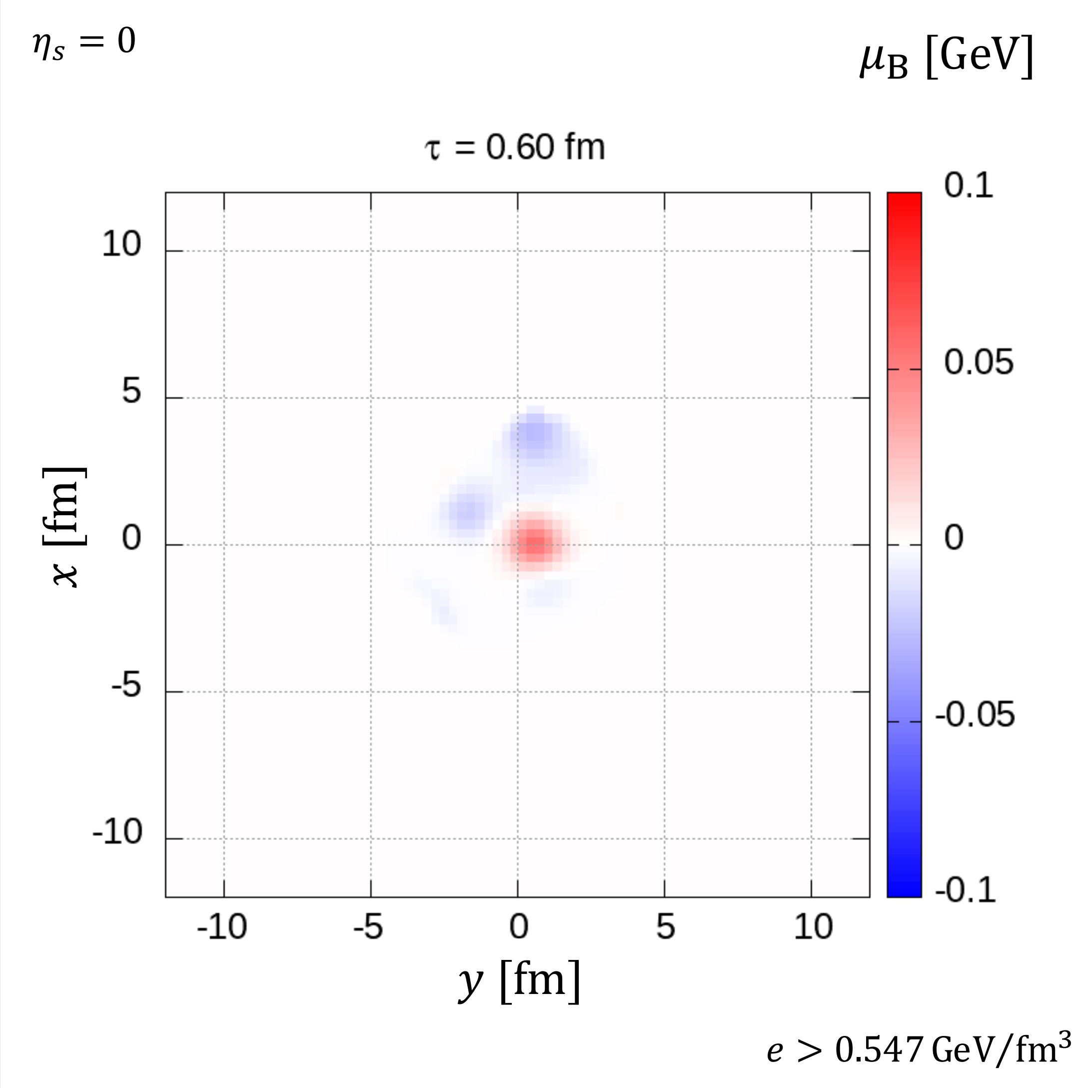
Baryon chemical potential (longitudinal profile)



Baryon chemical potential (transverse profile)



Rapidity dependence of freezeout hypersurface

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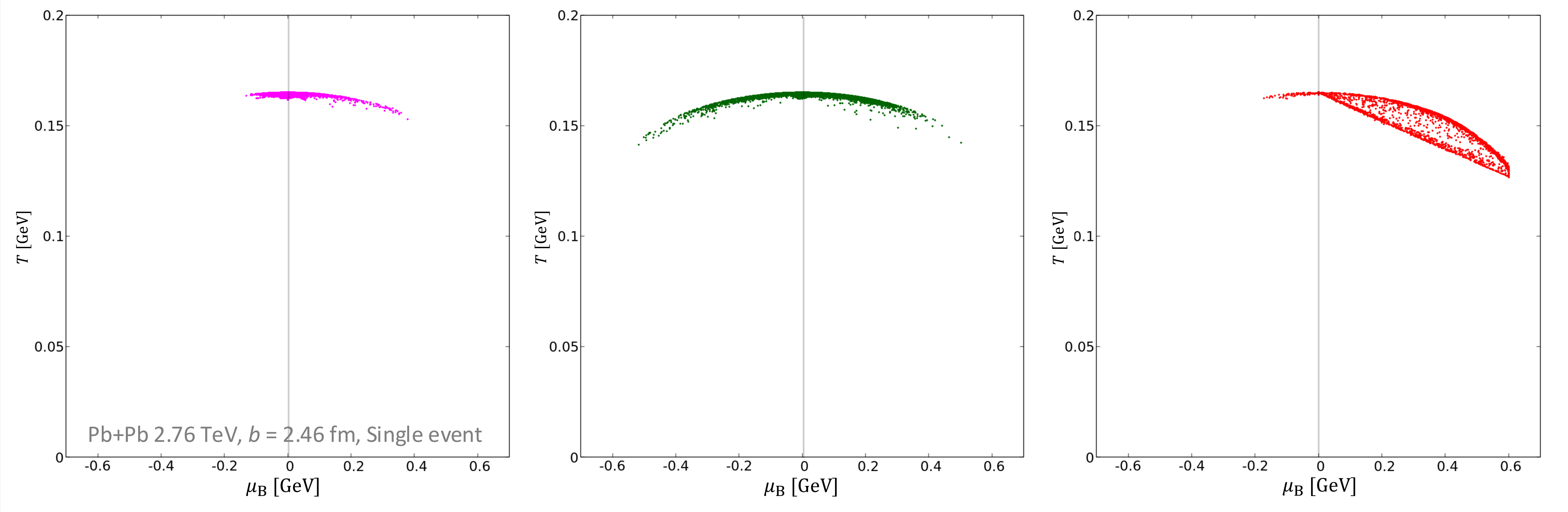
$-1 \leq \eta_s \leq 1$ $3 \leq \eta_s \leq 5$ $7 \leq \eta_s \leq 9$



- Some hypersurface element has negative baryon chemical potentials
- Significantly large baryon chemical potentials in forward rapidities

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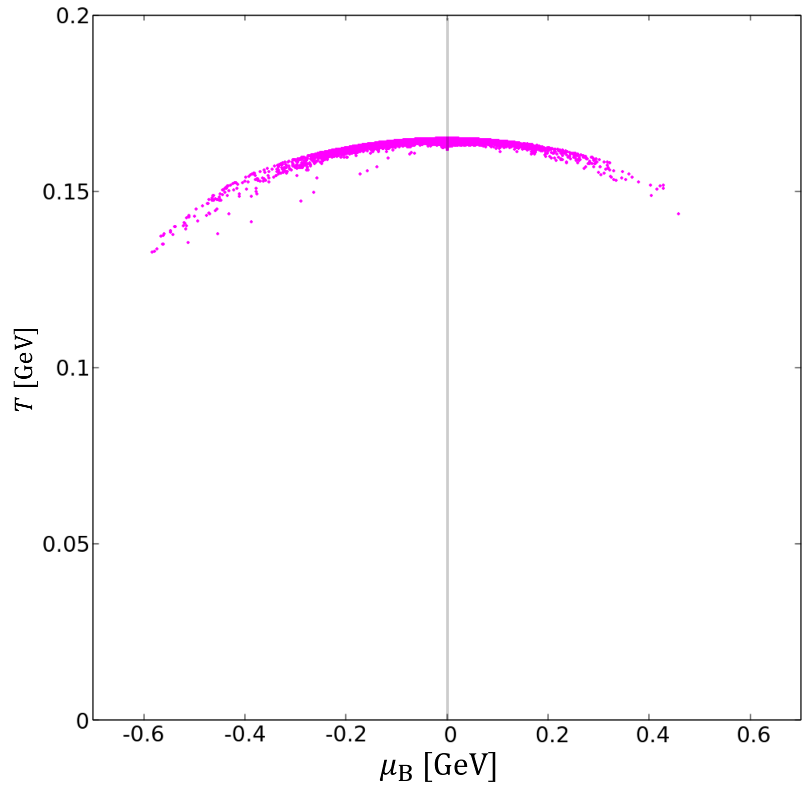
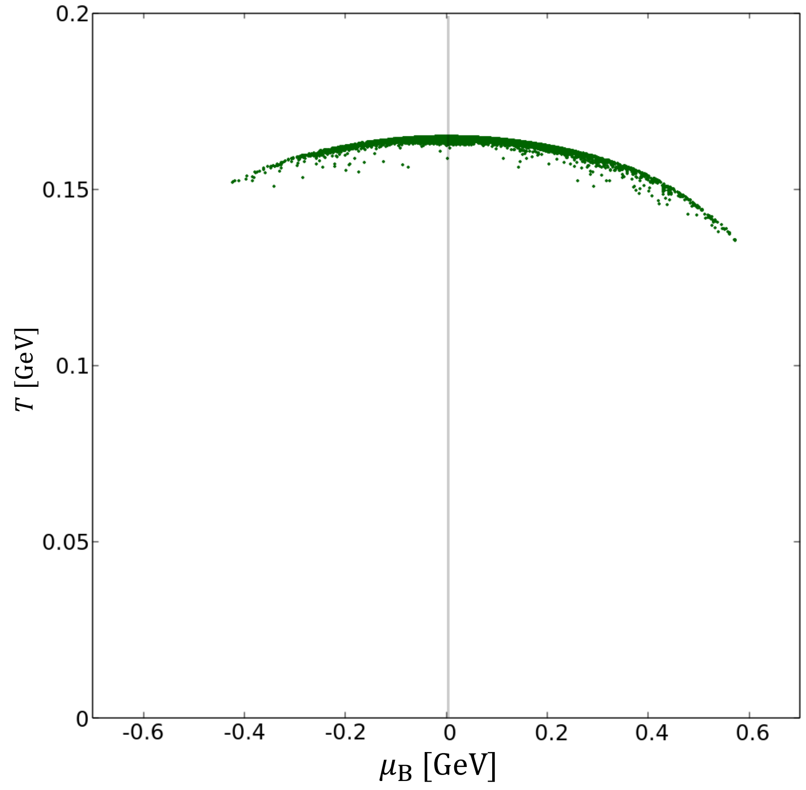
Rapidity dependence of freezeout hypersurface

Pb+Pb 2.76 TeV, *b* = 6.12 fm, Single event

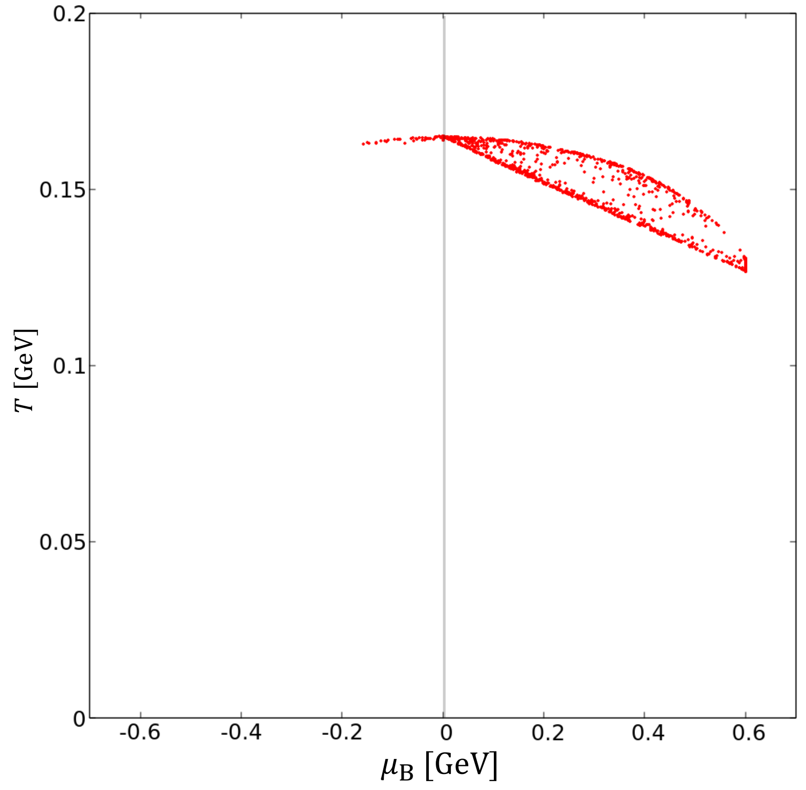
$-1 \leq \eta_s \leq 1$



$3 \leq \eta_s \leq 5$



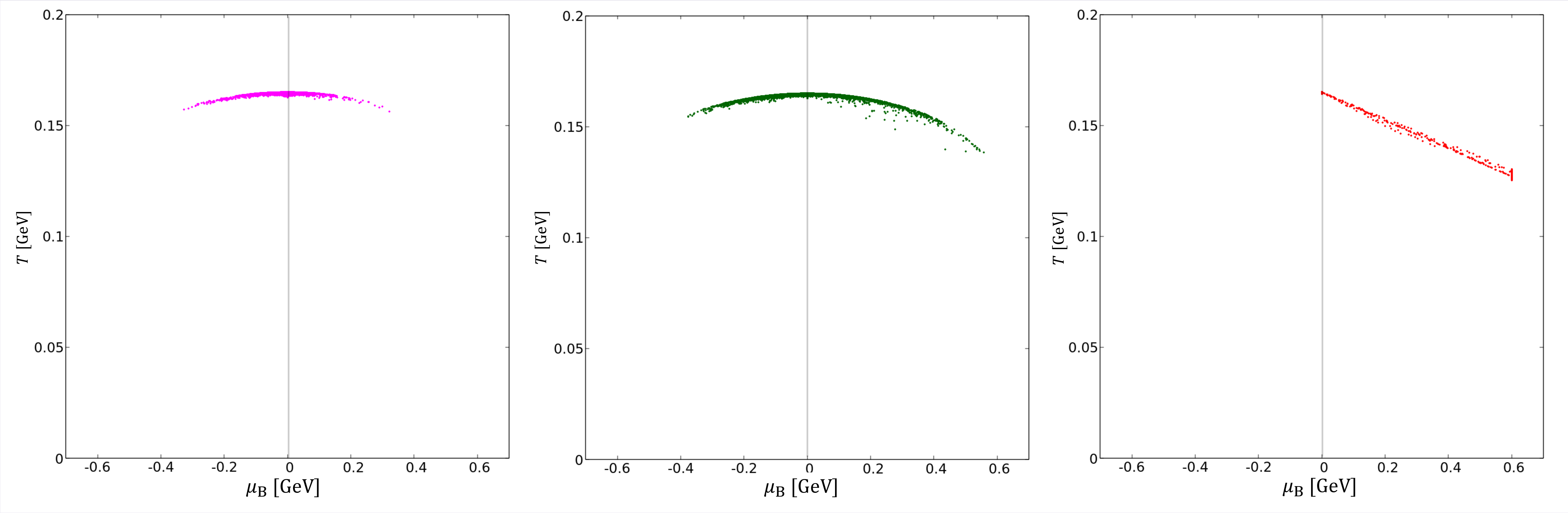
$7 \leq \eta_s \leq 9$



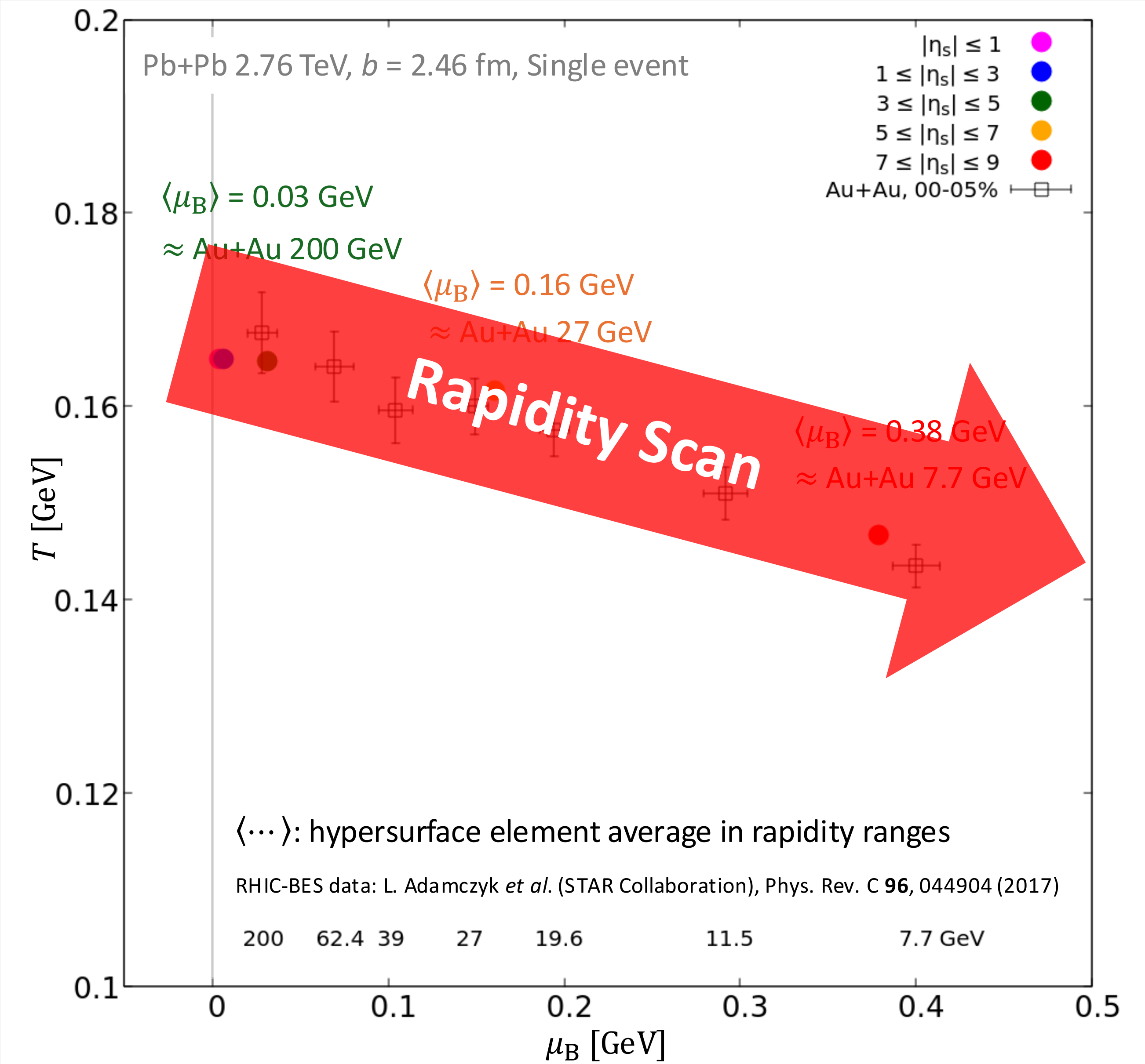
Rapidity dependence of freezeout hypersurface

Pb+Pb 2.76 TeV, b = 10.1 fm, Single event

$-1 \leq \eta_s \leq 1$ $3 \leq \eta_s \leq 5$ $7 \leq \eta_s \leq 9$



Rapidity-averaged freezeout hypersurface

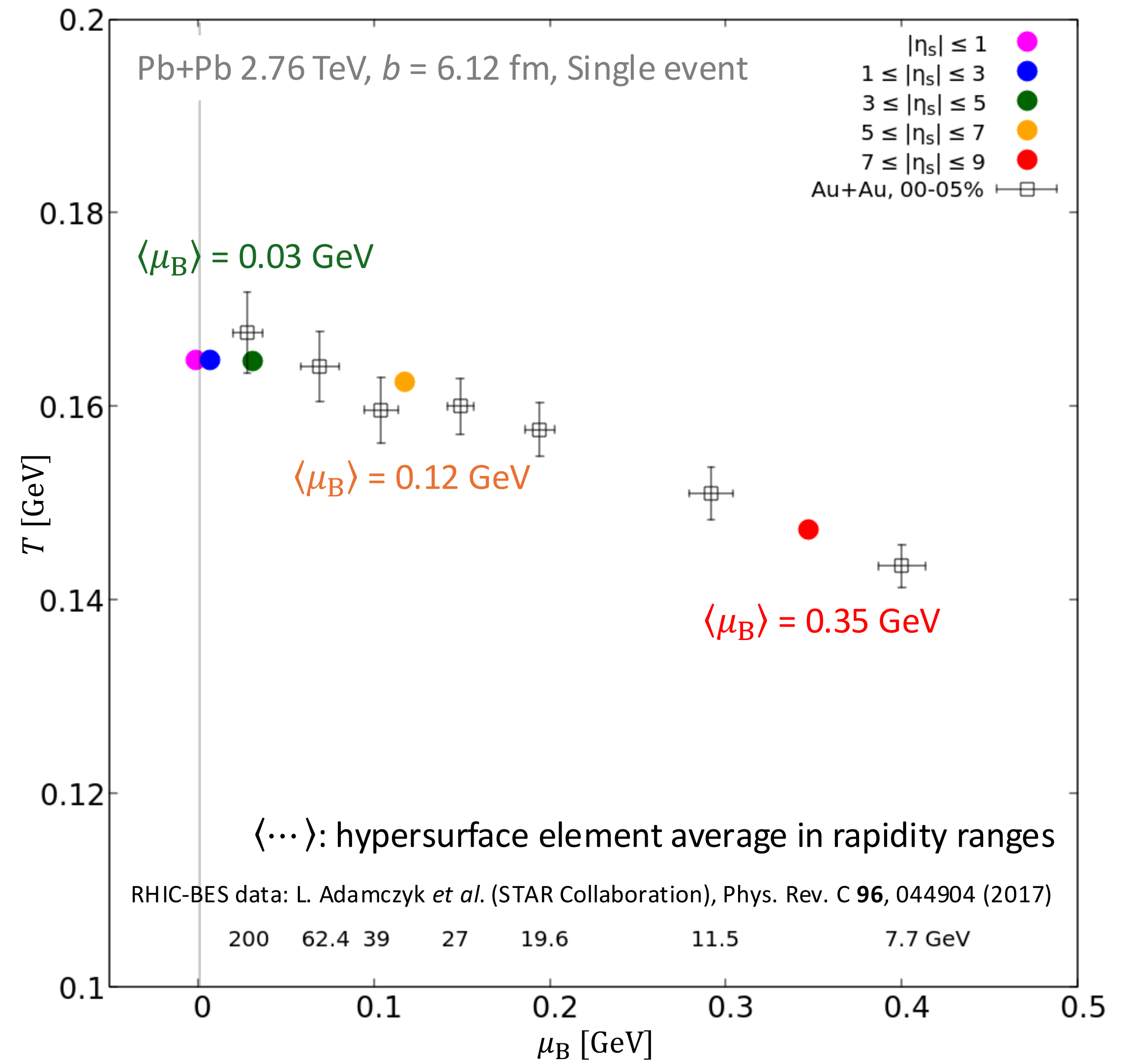


- Almost zero baryon chemical potential until $|\eta_s| \leq 5$
  - ➡ ≈ Au+Au 200 GeV
- Averaged-hypersurface in rapidity range $5 \leq |\eta_s| \leq 7$ exceeds $\mu_B = 100$ MeV
  - ➡ **≈ Au+Au 27 GeV**
- Averaged-hypersurface in rapidity range $7 \leq |\eta_s| \leq 9$ exceeds $\mu_B = 300$ MeV
  - ➡ **≈ Au+Au 7.7 GeV**

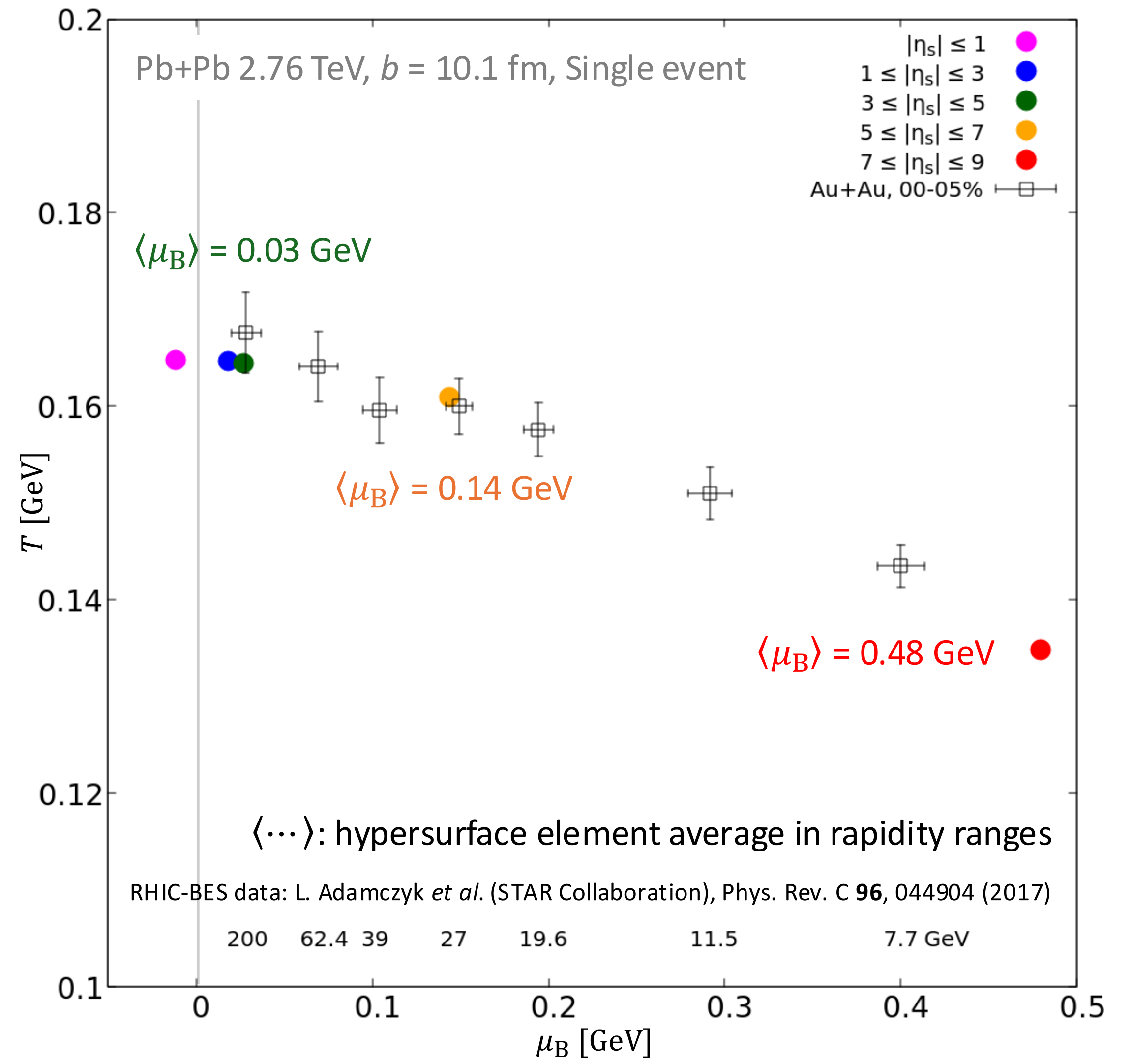
Rapidity scan is a strong tool for exploring the QCD phase diagram!!

Rapidity-averaged freezeout hypersurface

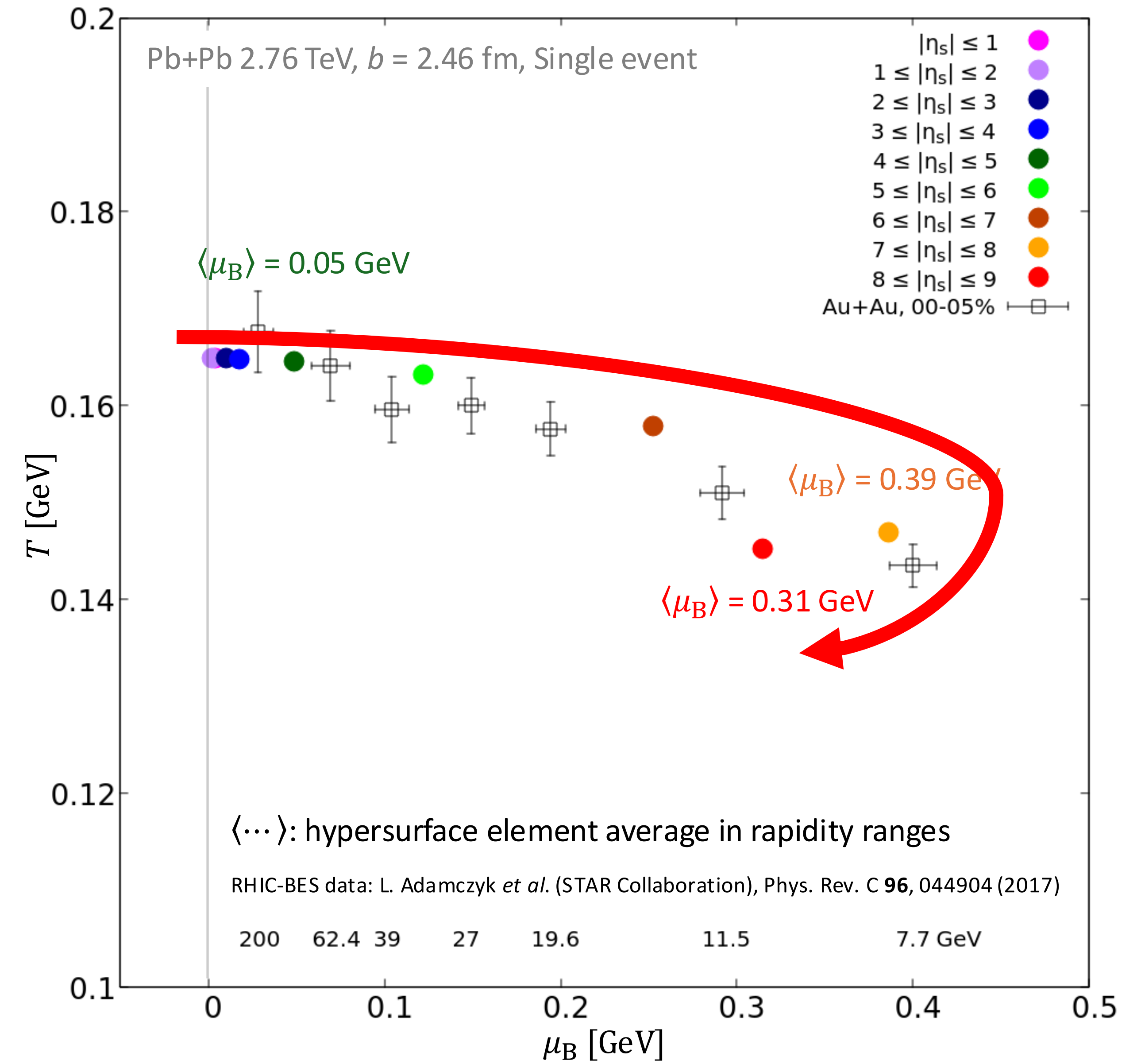
b = 6.12 fm



b = 10.1 fm



Rapidity-averaged freezeout hypersurface



- μ_B becomes maximum in $7 \leq |\eta_s| \leq 8$

cf.) $y_{\mathrm{beam}}\left(\sqrt{s_{\mathrm{NN}}} = 2.76\ \mathrm{TeV}\right) \approx 8$

NEOS-BQS

A. Monnai, B. Schenke and C. Shen, Phys. Rev. C **100**, 024907 (2019)

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Taylor expansion using Lattice results (high T)

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{x^{B,Q,S}_{l,m,n}}{l,m,n} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

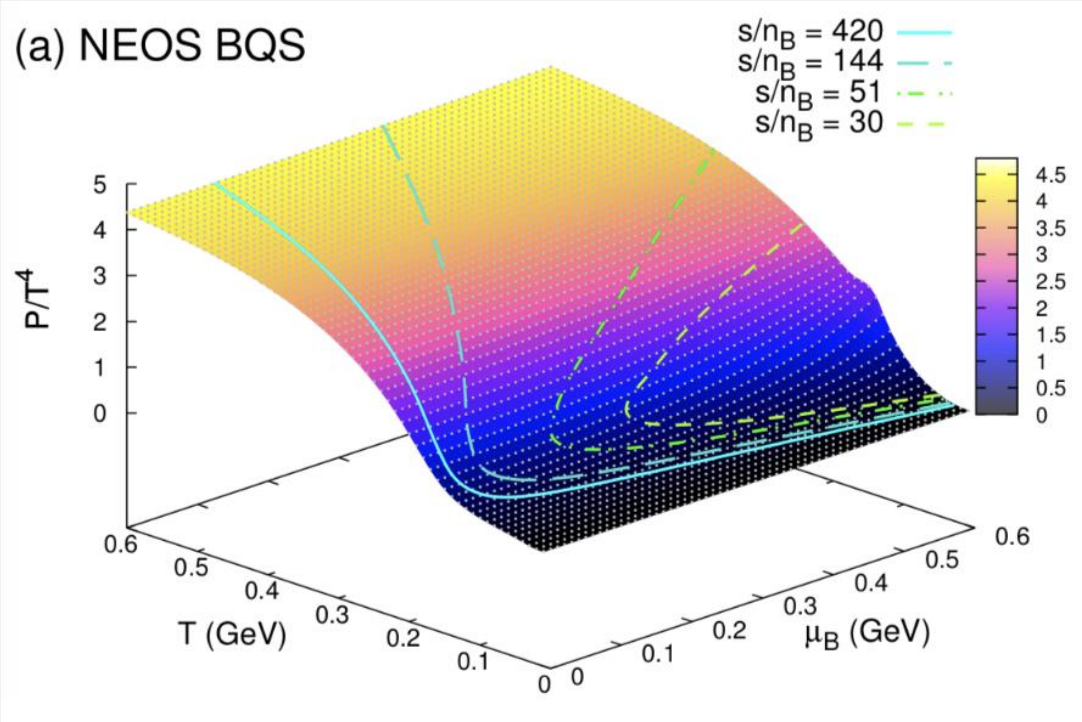
Hadron gas (low T)

$$P = \pm T \sum_i \int \frac{g_i d^3p}{(2\pi)^3} \ln\left[1 \pm e^{-(E_i-\mu_i)/T}\right]$$

$$= \sum_i \sum_k (\mp 1)^{k+1} \frac{1}{k^2} \frac{g_i}{2\pi^2} m_i^2 T^2 e^{k\mu_i/T} K_2\left(\frac{km_i}{T}\right)$$

CONNECT

$$\frac{P}{T^4} = \frac{1}{2}\left[1 - f(T,\mu_J)\right] \frac{P_{\mathrm{had}}(T,\mu_J)}{T^4} + \frac{1}{2}\left[1 + f(T,\mu_J)\right] \frac{P_{\mathrm{lat}}(T,\mu_J)}{T^4}$$



Constraints: $n_Q = 0.4 n_B, \quad n_S = 0$

$$e(T,\mu_{\mathrm{B}}) = e(0.165\ \mathrm{GeV}, 0) = 0.547\ \mathrm{GeV/fm^3}$$

➡ e_{sw} for core

Hydrodynamic module in DCCI

Energy-momentum conservation

$$\partial_\mu T^{\mu\nu}_{\mathrm{fluid}} = j^\nu$$

$$T^{\mu\nu}_{\mathrm{fluid}} = e u^\mu u^\nu - p\Delta^{\mu\nu}$$ ← ideal hydro

$$j^\nu = -\sum_i \frac{dp_i^\nu(t)}{dt} G(\boldsymbol{x} - \boldsymbol{x}_i(t))$$

Baryon number conservation

$$\partial_\mu N^\mu_{\mathrm{fluid}} = \rho$$

$$N^\mu_{\mathrm{fluid}} = n_{\mathrm{B}} u^\mu$$ ← ideal hydro

$$\rho = -\sum_{i_{\mathrm{dead}}} \frac{dB_{i_{\mathrm{dead}}}}{dt} G\left(\boldsymbol{x} - \boldsymbol{x}_{i_{\mathrm{dead}}}(t)\right)$$

$$G_{\mathrm{Milne}} = \frac{1}{\sqrt{2\pi\sigma_\eta^2\tau^2}} \exp\left(-\frac{\left(\eta_{s,\mathrm{parton}} - \eta_{s,i}\right)^2}{2\sigma_\eta^2}\right) \times \frac{1}{2\pi\sigma_{xy}^2} \exp\left(-\frac{\left(x_{\mathrm{parton}} - x_i\right)^2 + \left(y_{\mathrm{parton}} - y_i\right)^2}{2\sigma_{xy}^2}\right)$$

Default: $\sigma_\eta = 0.5$, $\sigma_{xy} = 0.6$ fm

RHIC-BES data

L. Adamczyk *et al*. (STAR Collaboration), Phys. Rev. C **96**, 044904 (2017)