High Baryon Densities Achievable in the Fragmentation Regions at RHIC and LHC

Joe Kapusta and Ming Li

University of Minnesota

ULtra-RelatIvistiCH HEavy IonZ, CERN 2016

Outline

- McLerran-Venugopalan model for glasma
- Energy-momentum conservation to compute excitation energy and rapidity loss of the projectile and target nuclei
- Use space-time picture to estimate compression of the nuclei
- Estimate initial entropy/baryon which straddles the purported critical point
- Can the experiments be done?

Energy-Momentum Conservation

$$d\mathcal{P}_P^\mu = -T^{\mu\nu}_{\mathrm{glasma}} d\Sigma_\nu$$

Projectile four-momentum/area: $\mathcal{P}_P^\mu = (\mathcal{E}_P, 0, 0, \mathcal{P}_P)$

hypersurface: $d\Sigma_\nu = (dz, 0, 0, -dt)$

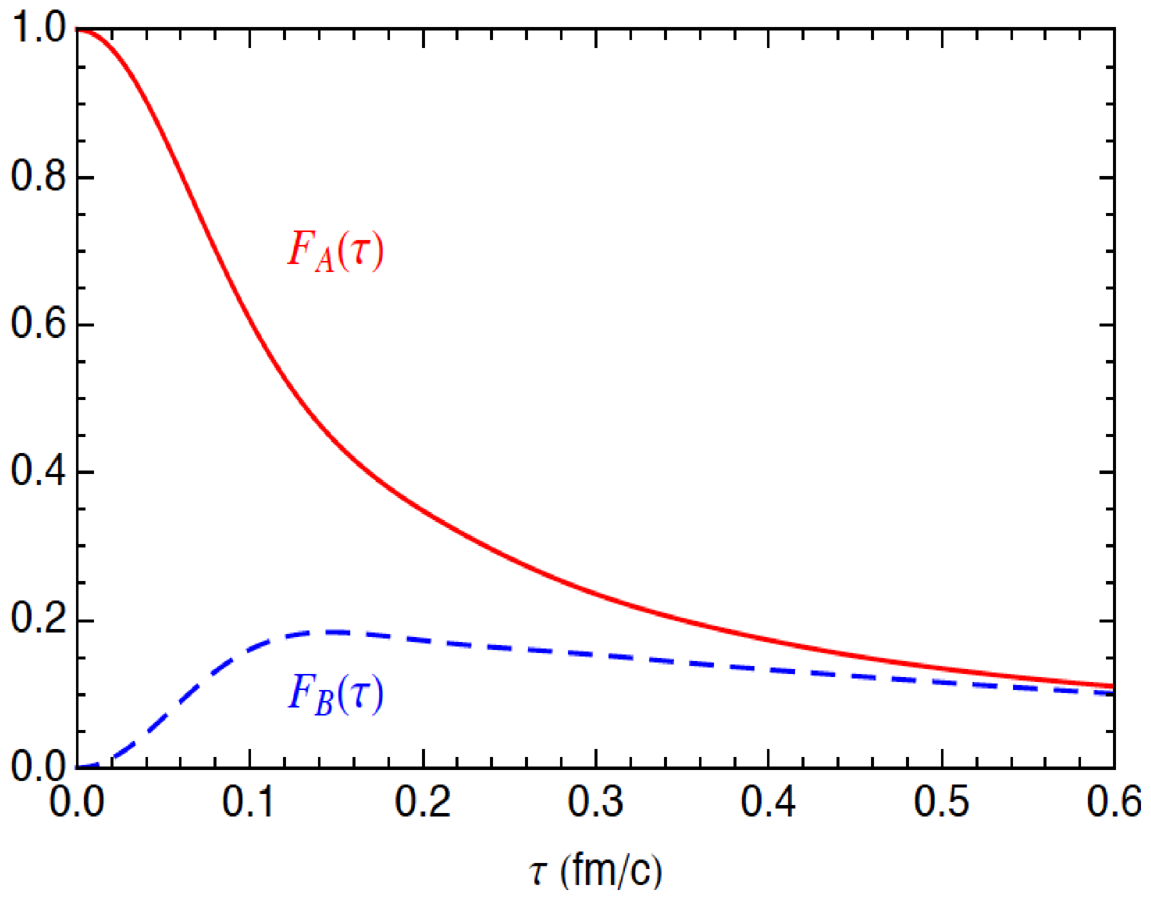
Glasma energy-momentum tensor:

$$T^{\mu\nu}_{\mathrm{glasma}} = \begin{pmatrix} \mathcal{A} + \mathcal{B}\cosh 2\eta & 0 & 0 & \mathcal{B}\sinh 2\eta \\ 0 & \mathcal{A} & 0 & 0 \\ 0 & 0 & \mathcal{A} & 0 \\ \mathcal{B}\sinh 2\eta & 0 & 0 & -\mathcal{A} + \mathcal{B}\cosh 2\eta \end{pmatrix}$$

$$\mathcal{A} = \varepsilon_0 F_{\mathcal{A}}(\ln(Q^2/\Lambda_{QCD}^2), Q\tau)$$

$$\mathcal{B} = \varepsilon_0 F_{\mathcal{B}}(\ln(Q^2/\Lambda_{QCD}^2), Q\tau)$$

M. Li and J. I. Kapusta
arXiv:1602.09060
PRC, in press



Initial Conditions and Input Parameters

UV Cut-off Scale: $3\,\mathrm{GeV} \leq \mathrm{Q} \leq 5\,\mathrm{GeV}$

Initial Energy Density from Heinz et al.

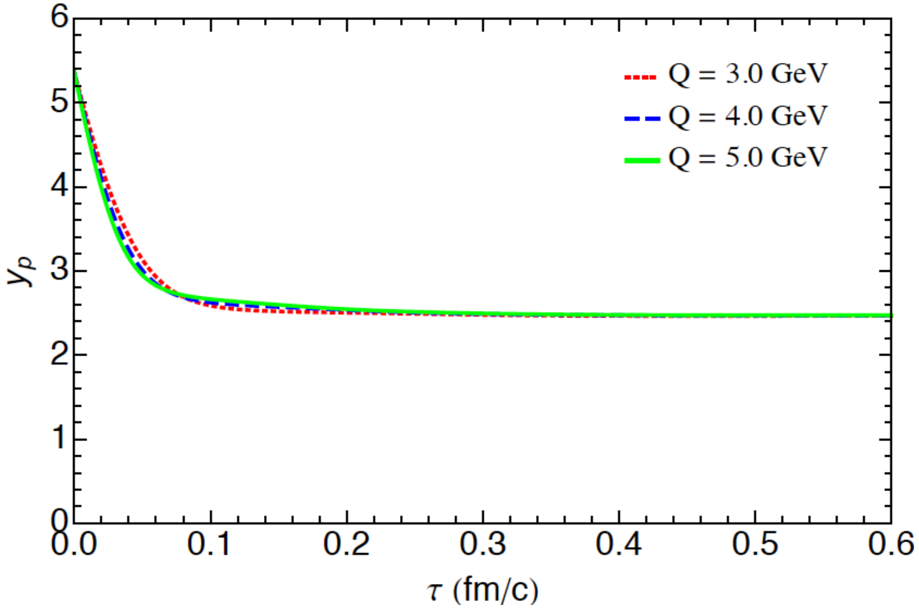
$$\varepsilon_0(r_\perp) = \varepsilon_0(r_\perp = 0)\left(\frac{T_A(r_\perp)}{T_A(0)}\right)^2$$

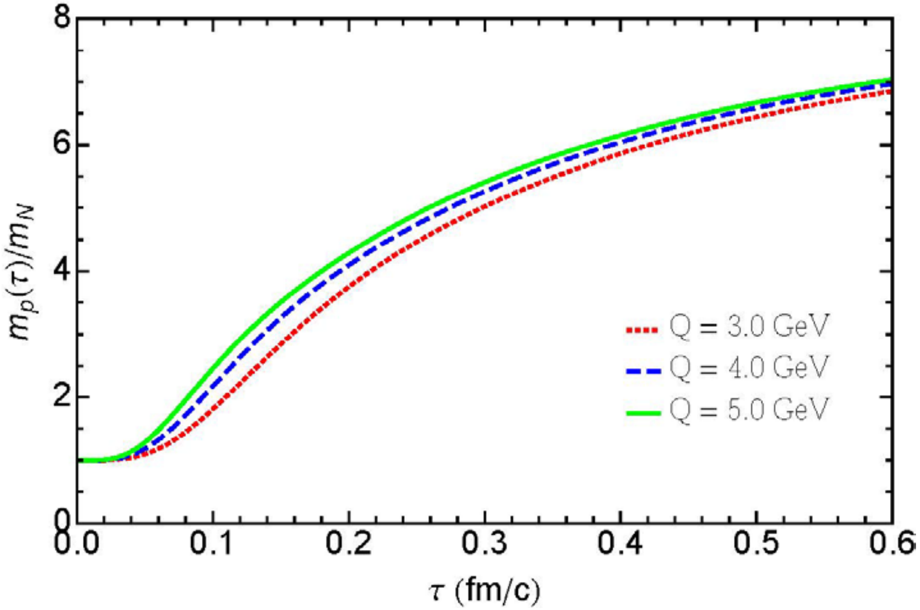
$$T_A(\vec{r}_\perp) = \int_{-\infty}^{+\infty} \rho_A(\vec{r}_\perp, z)\, dz$$

$$\varepsilon(r_\perp, \tau = 0.6 \ \mathrm{fm/c}) = 30 \ \mathrm{GeV/fm}^3$$

Colliding Nuclei: Au-Au $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$

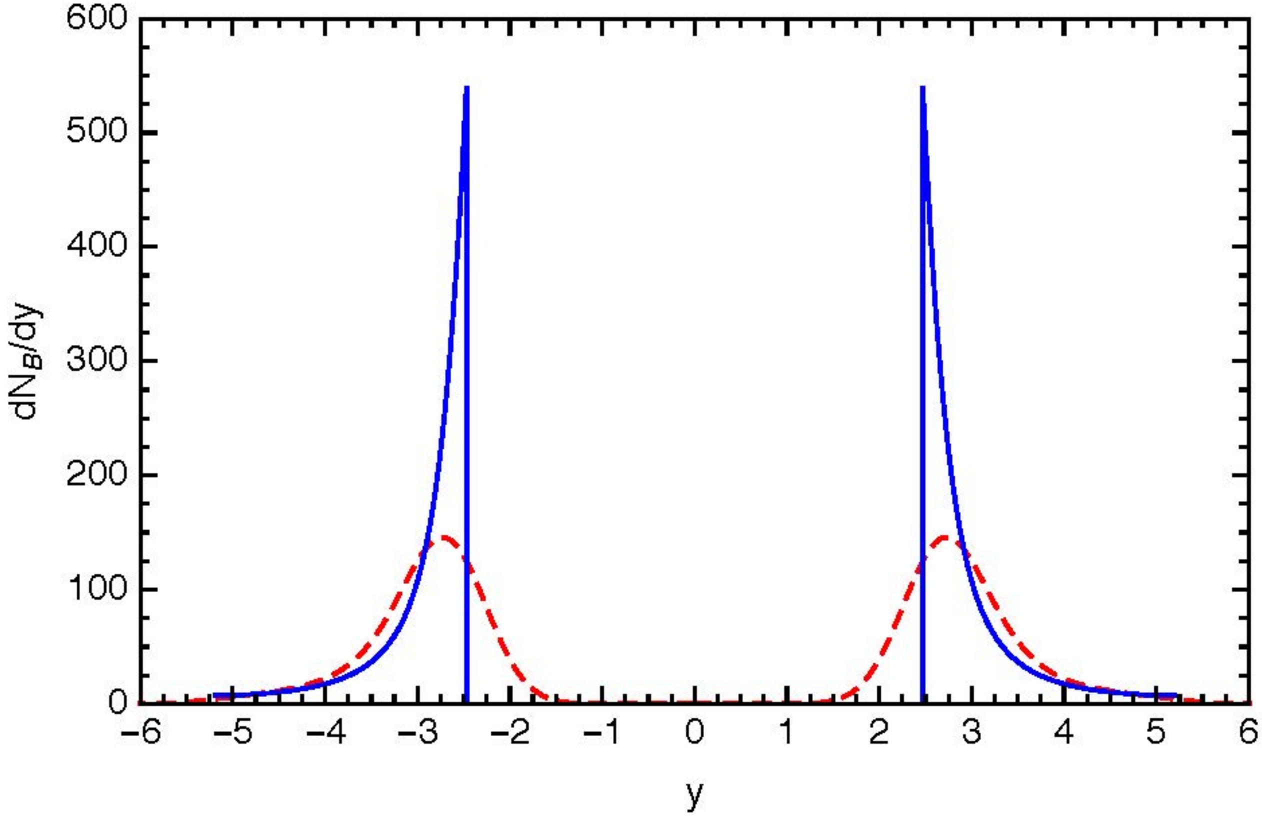
Rapidity Loss and Excitation Energy (central core)





$$y = \frac{1}{2} \ln \frac{E + P_z}{E - P_z}, \qquad v_z = \tanh y$$

Net-Baryon Rapidity Distribution



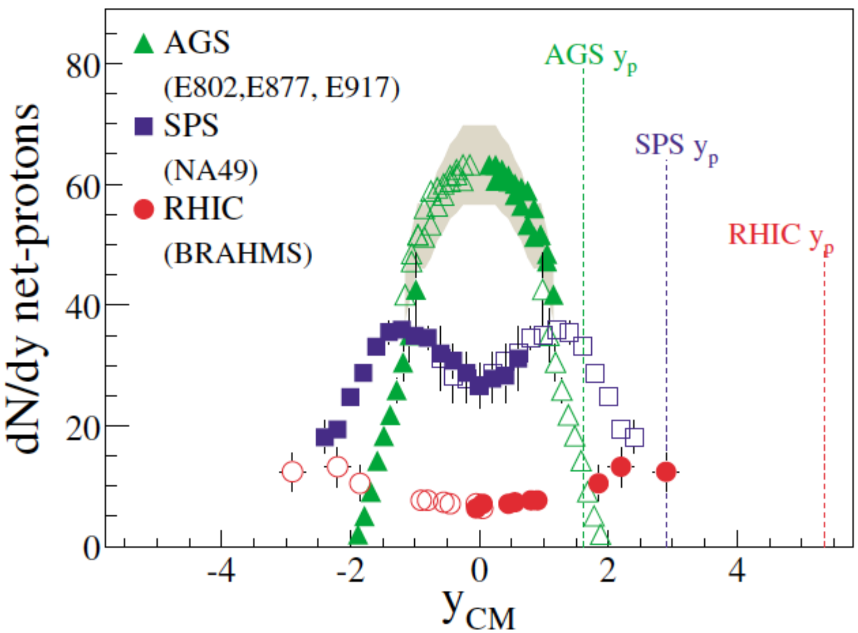
Thermal smearing

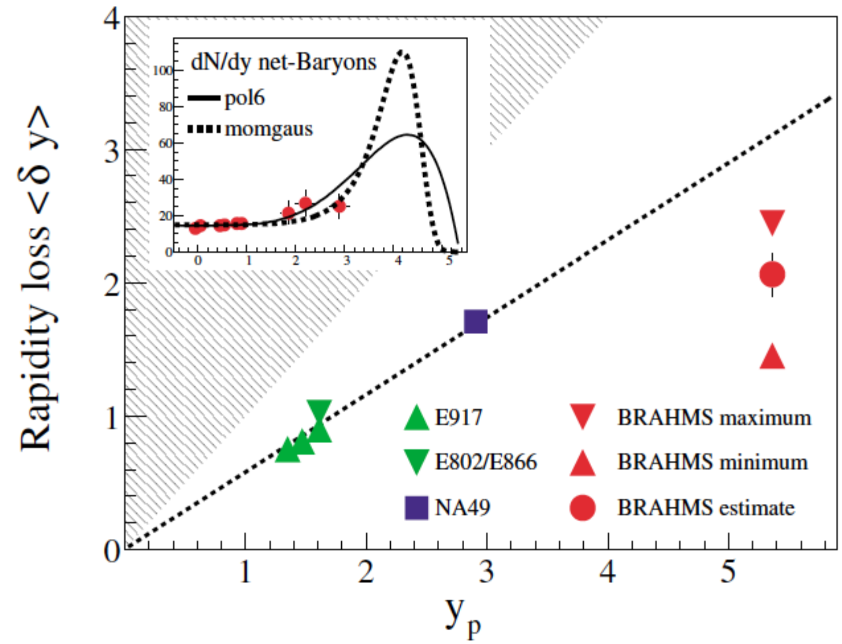
$$\exp\left(-\Delta y^2 / 2\delta^2\right)$$

$$\delta^2 = T / m = 0.16$$

$$\langle \delta y \rangle \simeq 2.42$$

Baryon Stopping Data (0-10% centrality)

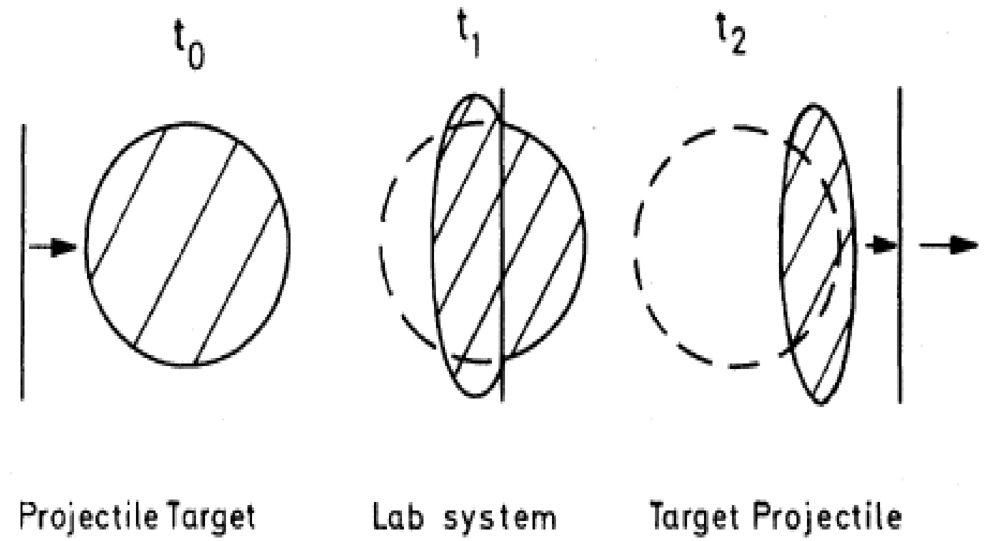




I. G. Bearden, et al. [BRAHMS Collaboration], PRL 93, 102301 (2004)

$$1.45 < \langle \delta y \rangle < 2.45$$

Nuclear Compression



$$\Delta z = (1 - v) z$$

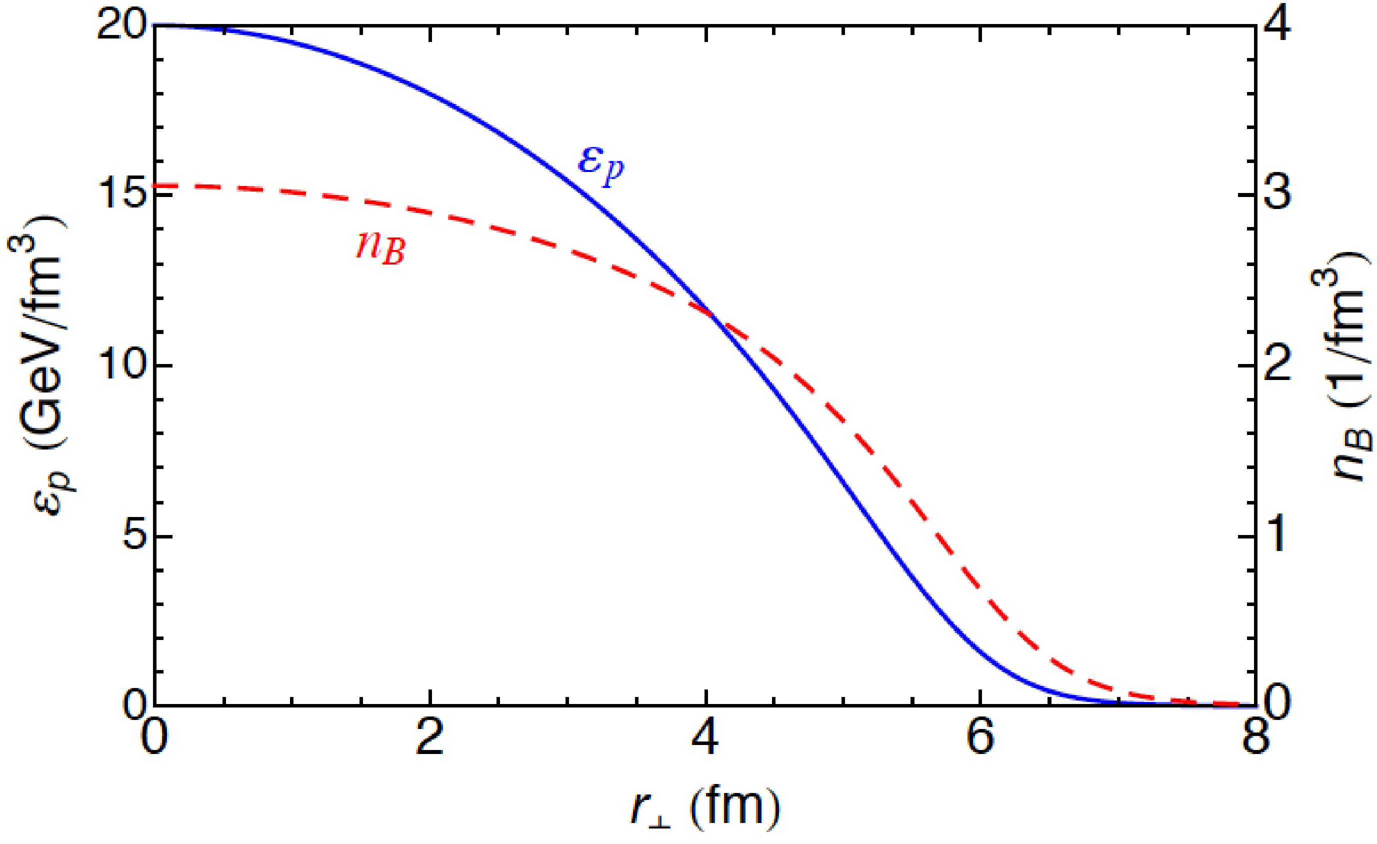
$$\Delta z' = \gamma \Delta z = e^{-y} z$$

In the rest frame of the **Target**

In the rest frame of the **Fireball**

R. Anishetty, P. Koehler and L. McLerran, Phys. Rev. D22, 2793(1980)
L. P. Csernai, Phys. Rev. D 29, 1945 (1984)
M. Gyulassy and L. P. Csernai, Nucl. Phys. A460, 723(1986)

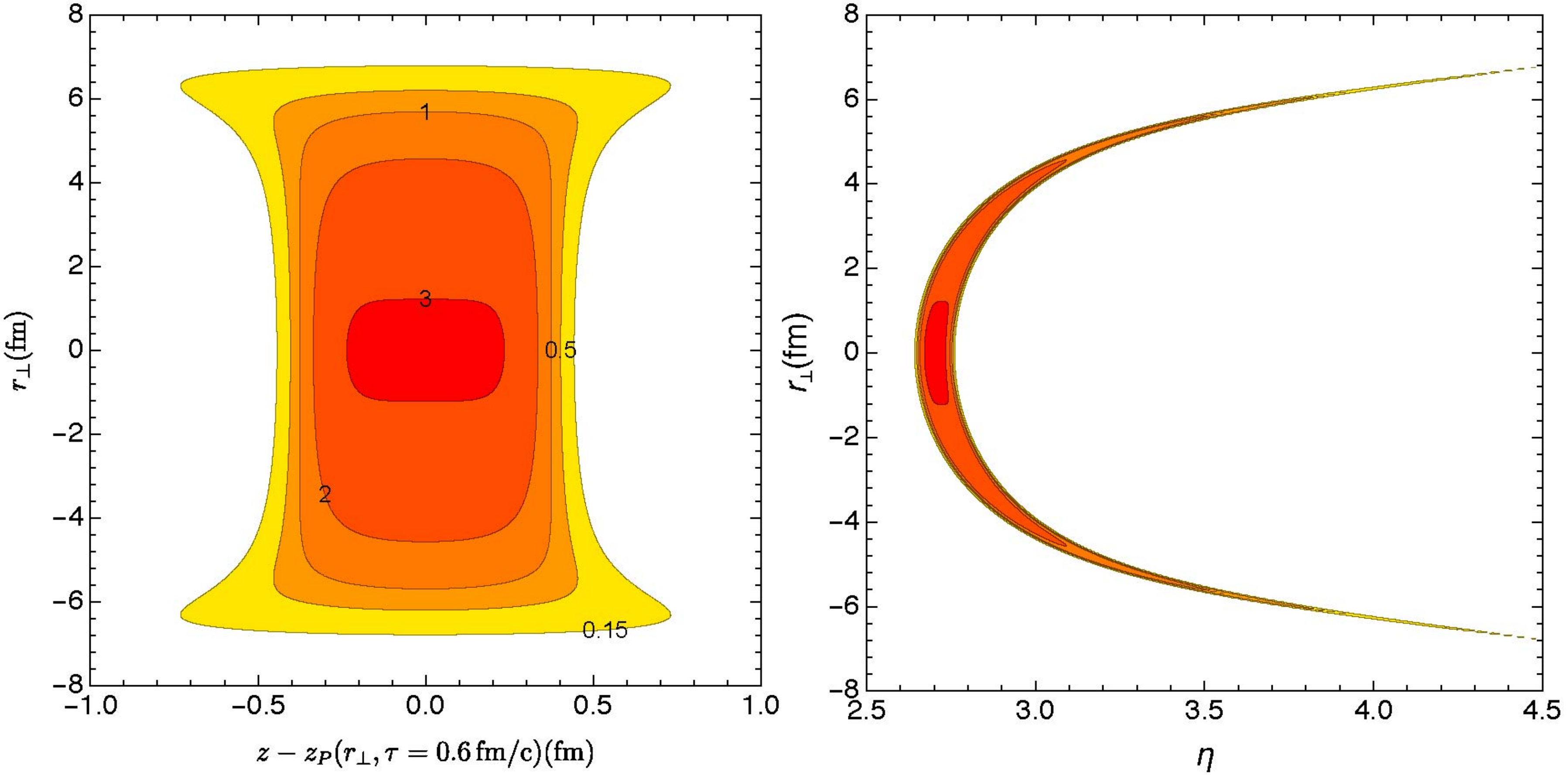
Baryon and Energy Densities



$$n_B(\vec{r}_\perp, z = 0) = e^{\Delta y} n_0(\vec{r}_\perp, z = 0)$$

$$\varepsilon_P = M_P(\tau = 0.6 \text{ fm/c})\, \mathrm{n_B}$$

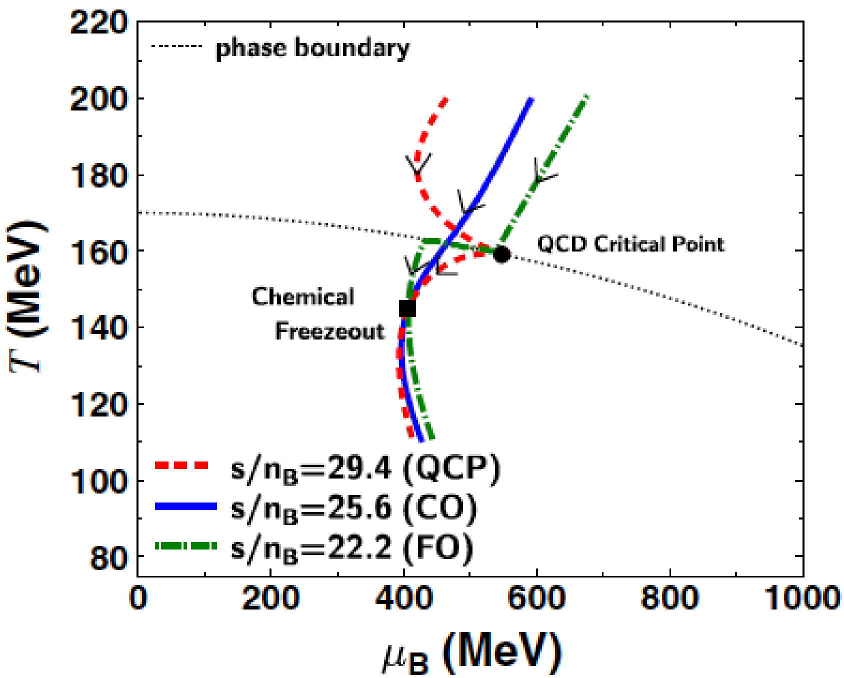
Local Baryon Density



Contours in units of baryons/fm^3

Temperature and Chemical Potential

$n_B(\mathrm{baryons/fm^3})$	$\varepsilon_P(\mathrm{GeV/fm^3})$	$T(\mathrm{MeV})$	$\mu_B(\mathrm{MeV})$	s/n_B
3.0	20.0	299	1061	26.2
1.5	5.5	205	1007	18.9

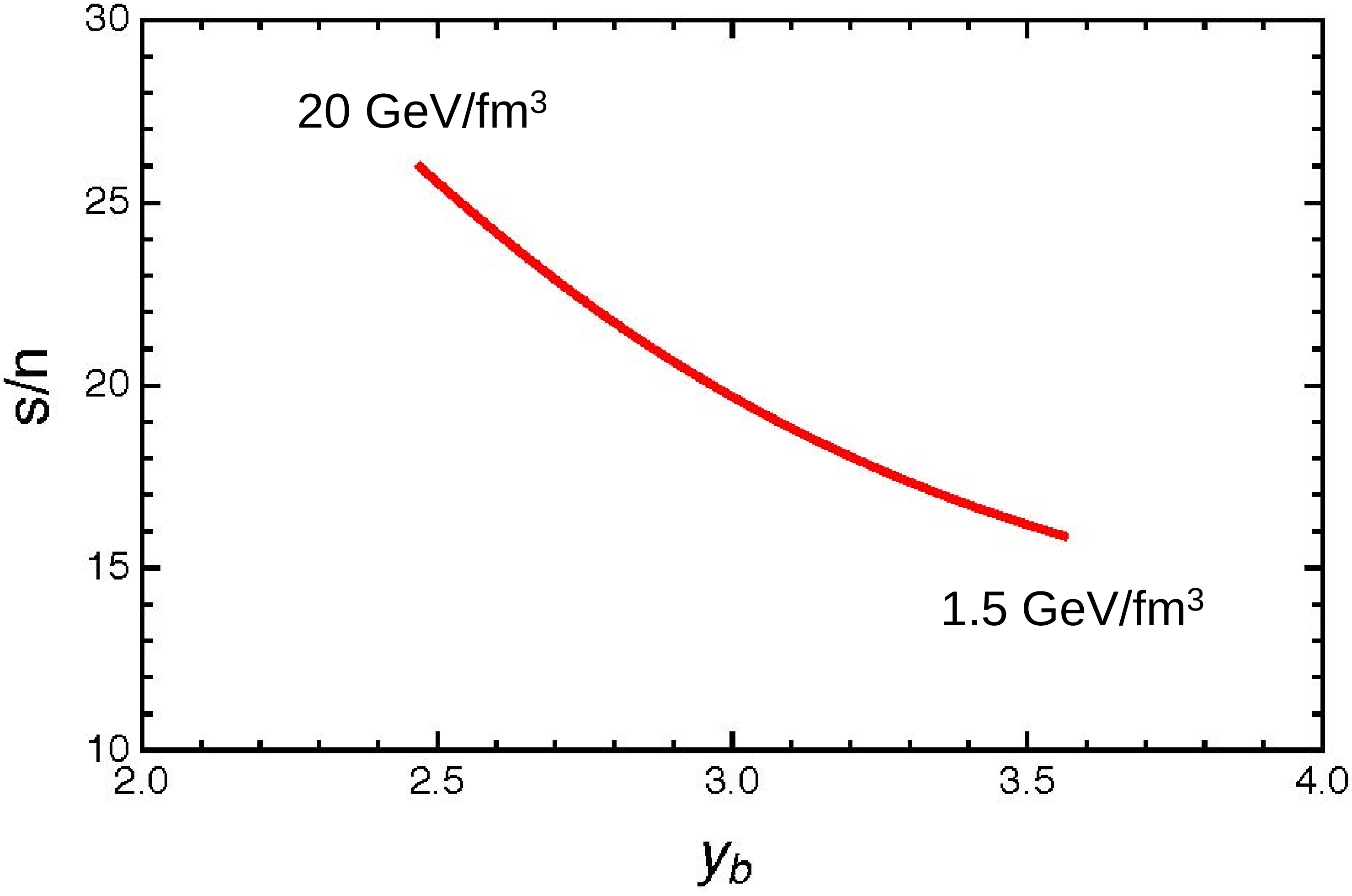


Gluons + 3 flavors of free massless quarks with zero net strangeness

$$P(T,\mu_B) = \frac{19\pi^2}{36}T^4 + \frac{1}{9}T^2\mu_B^2 + \frac{1}{162\pi^2}\mu_B^4$$

M. Asakawa, S. A. Bass, B. Muller and C. Nonaka, Phys. Rev. Lett. 101, 122302 (2008)

Beam Energy or Rapidity Scan?



The Future

Other projectile-target combinations, non-central collisions

Other models for the glasma energy-momentum tensor

Initial conditions for 2^{nd} order viscous hydrodynamics

Can measurements be made at these high rapidities?

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BWTM!

How is the Viscous Distortion of the Single Particle Distribution to be Determined?

Joe Kapusta and

Purnendu Chakraborty

$$f_a = (1+\phi_a)\, f_a^{eq}$$

$$\phi_a = -A_a \nabla \bullet \mathrm{v} + 2C_a p^i p^j \left(\partial_i \mathrm{v}_j + \frac{1}{3} \delta_{ij} \nabla \bullet \mathrm{v} \right)$$

$$f_a = (1+\phi_a)\, f_a^{eq}$$

$$\phi_a = -A_a \nabla \bullet \mathrm{v} + 2C_a p^i p^j \left(\partial_i \mathrm{v}_j + \frac{1}{3} \delta_{ij} \nabla \bullet \mathrm{v} \right)$$

Zeroth order approximation (Teaney 2007 following deGroot)

$$C_a = \frac{\eta / s}{2T^3} \qquad A_a = 0$$

$$f_a = (1+\phi_a)\, f_a^{eq}$$

$$\phi_a = -A_a \nabla \bullet \mathrm{v} + 2C_a p^i p^j \left(\partial_i \mathrm{v}_j + \frac{1}{3}\delta_{ij} \nabla \bullet \mathrm{v} \right)$$

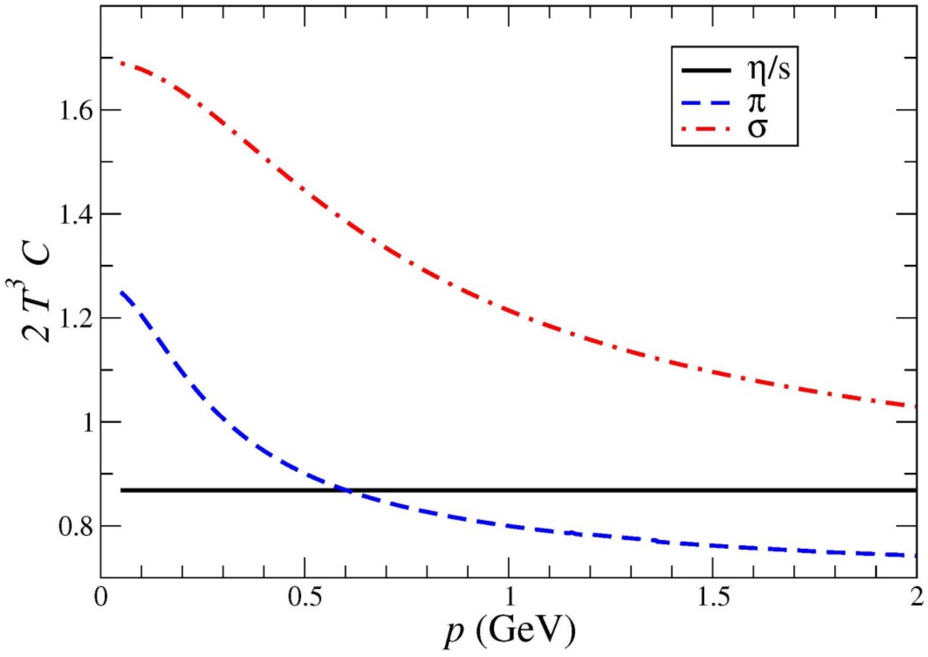
Zeroth order approximation (Teaney 2007 following deGroot)

$$C_a = \frac{\eta/s}{2T^3} \qquad\qquad A_a = 0$$

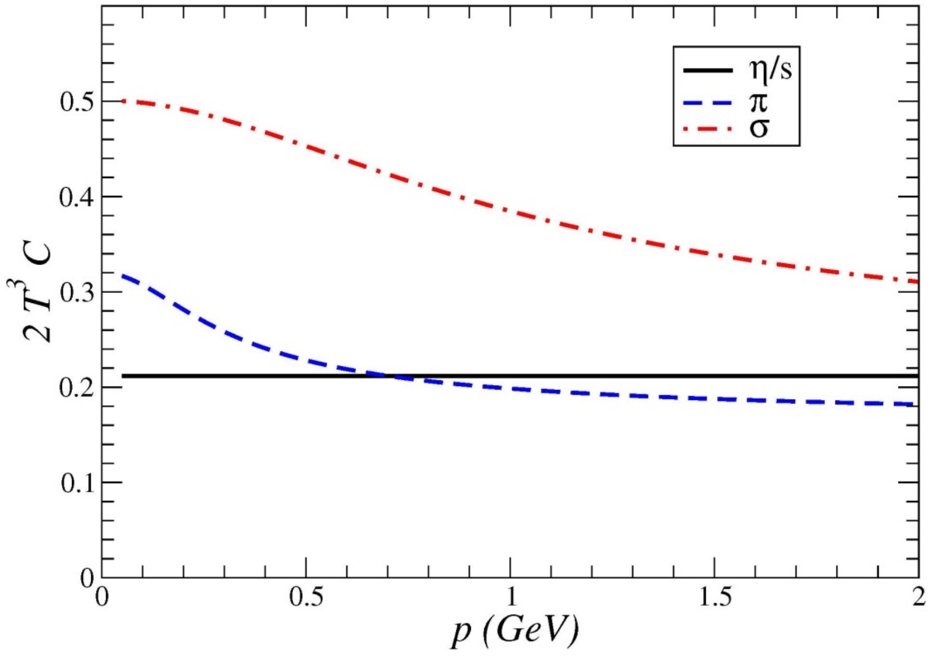
Momentum-dependent relaxation time approximation

$$C_a = \frac{\tau_a(E_a)}{2TE_a} \qquad\qquad A_a = \frac{\tau_a(E_a)}{3TE_a p^2}\left[p^2 - 3\mathrm{v}_s^2 \left(E_a^2 - T^2 \frac{dm_a^2}{dT^2} \right) \right]^2$$

Linear sigma model T=150 MeV



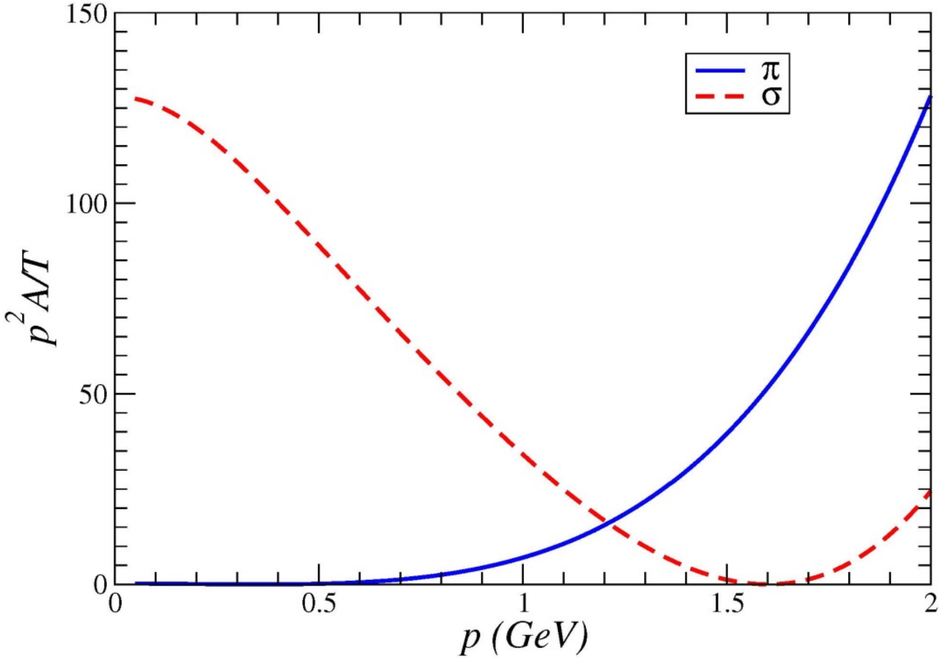
$m_\sigma = 600$ MeV



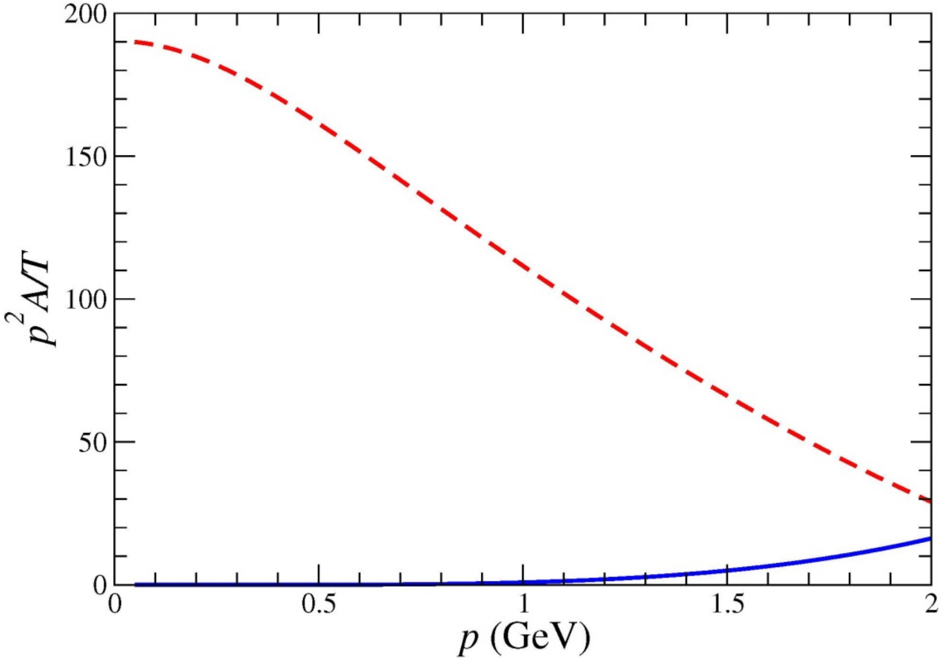
$m_\sigma = 900$ MeV

$$C_a = \frac{\tau_a(E_a)}{2TE_a}$$

Linear sigma model T=150 MeV



$m_\sigma = 600$ MeV



$m_\sigma = 900$ MeV

$$A_a = \frac{\tau_a(E_a)}{3TE_a p^2}\left[p^2 - 3v_s^2\left(E_a^2 - T^2\frac{dm_a^2}{dT^2}\right)\right]^2$$

We are calculating and tabulating the distortion functions for a hadron resonance gas for use in hydrodynamic models. We are also studying the more sophisticated Chapman-Enskog approximation.