Monte Carlo Simulation for Elastic Energy Loss of High-Energy Partons in Quark-Gluon Plasma

J. Auvinen

Department of Physics
University of Jyväskylä, Finland

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HELSINKI INSTITUTE OF PHYSICS

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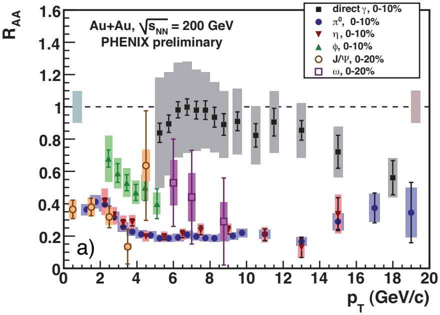
Suppression of high-energy hadrons

Nuclear modification factor:

$$R^h_{AA}(\mathbf{b}) = \frac{\frac{d^2N^{AA\to h+X}}{dp_T dy}}{\langle T_{AA}(\mathbf{b})\rangle \frac{d^2\sigma^{pp\to h+X}}{dp_T dy}}$$



Measured nuclear modification factors for direct photons and various mesons by PHENIX detector at RHIC [a].

[a] K. Reygers [for the PHENIX Collaboration], J. Phys. G **35**, 104045 (2008).

The Questions

The contribution of elastic scatterings to energy loss of hard partons?

J. Auvinen, K. J. Eskola and T. Renk,
"A Monte-Carlo model for elastic energy loss in a hydrodynamical background,"
Phys. Rev. C **82**, 024906 (2010) (arXiv:0912.2265 [hep-ph]).

The pathlength dependence of elastic energy loss?

J. Auvinen, K. J. Eskola, H. Holopainen and T. Renk,
"Elastic energy loss with respect to the reaction plane in a Monte-Carlo model,"
Phys. Rev. C **82**, 051901 (2010) (arXiv:1008.4657 [hep-ph]).

The effect of initial state density fluctuations to energy loss?

T. Renk, H. Holopainen, J. Auvinen and K. J. Eskola,
"Energy loss in a fluctuating hydrodynamical background,"
arXiv: 1105.2647.

Scattering rate

- Scattering rate for a process $ij \to kl$ in the local rest frame of the fluid:

$$\Gamma_{ij\to kl}(E_1,T) = \frac{1}{16\pi^2 E_1^2} \int_{\frac{m^2}{2E_1}}^{\infty} dE_2 f_j(E_2,T) \int_{2m^2}^{4E_1E_2} ds[s\sigma_{ij\to kl}(s)].$$

- $f_j(E_2,T)$ is the thermal distribution: Bose-Einstein for gluons, Fermi-Dirac for quarks.
- Temperature T obtained from the hydrodynamical model.
- The cross section $\sigma(s)$ is regulated by implementing $m = s_m g_s T = s_m\sqrt{4\pi\alpha_s}T$ on the integral limits.

Free parameters of the model: s_m, α_s.

Total scattering rate

The total scattering rate for a hard parton i is defined as

$$\Gamma_i = \sum_{j,(kl)} \Gamma_{ij\to kl}.$$

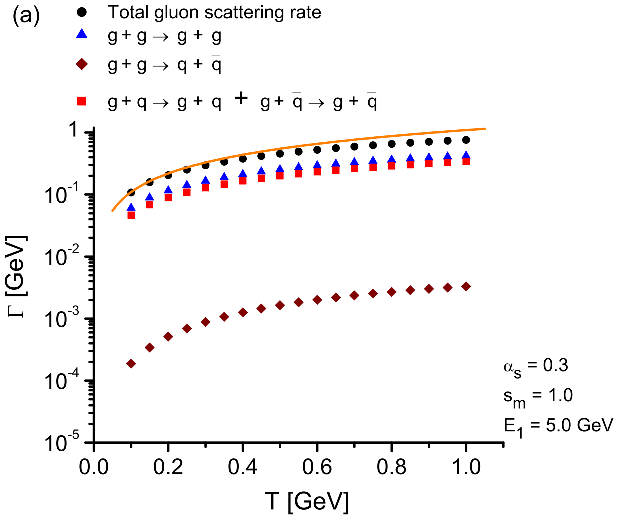
- The total scattering rate for a gluon:

$$\Gamma_g = \Gamma_{gg\to gg} + \Gamma_{gg\to q\bar{q}} + \Gamma_{gq\to gq} + \Gamma_{g\bar{q}\to g\bar{q}}$$

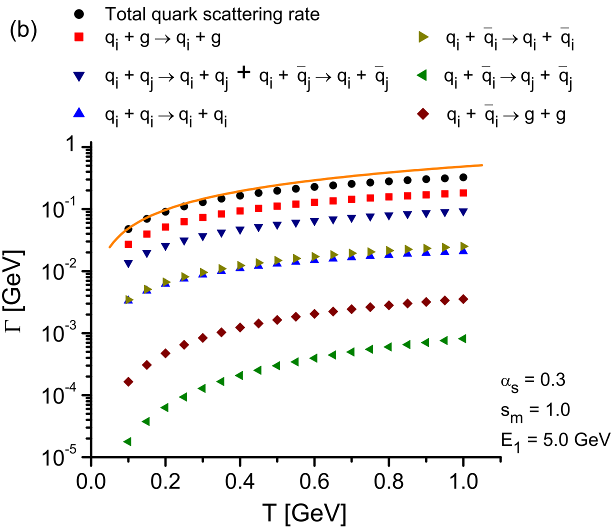
- The total scattering rate for a quark q_i:

$$\Gamma_{q_i} = \Gamma_{q_i g\to q_i g} + \Gamma_{q_i q_j\to q_i q_j} + \Gamma_{q_i q_i\to q_i q_i} + \Gamma_{q_i \bar{q}_i\to q_j \bar{q}_j} + \Gamma_{q_i \bar{q}_i\to q_i \bar{q}_i} + \Gamma_{q_i \bar{q}_i\to gg}$$

Contribution of different processes on gluon scattering rate



Contribution of different processes on quark scattering rate



The Monte Carlo simulation

- The hard parton is propagated in small time steps $\Delta t \sim O(10^{-2})$ fm.
- The probability for having (at least) one collision is $P(\text{number of collisions} \geq 1) = 1 - e^{-\Gamma_i \Delta t}$.
- $\Gamma_i = \Gamma_i(E_1, T)$ is calculated in the local rest frame of the fluid $\rightarrow$ boost $E_1, \Delta t$ to LRF.
- Finite scattering angles; non-eikonal propagation.
- After scattering, the parton with higher energy is selected as the hard parton $\rightarrow$ Flavor change possible.
- The simulation ends when the temperature of the medium is low enough (≈ 160 MeV).

Central collisions: Estimating the elastic contribution to energy loss

Hydrodynamical background [1]:

- Initial conditions from the EKRT model [2].
- Assuming longitudinal boost-invariance reduces the hydrodynamical evolution equations into (2+1) dimensions.
- The azimuthal symmetry of central collisions leaves (1+1)-dimensional evolution equations to be solved.

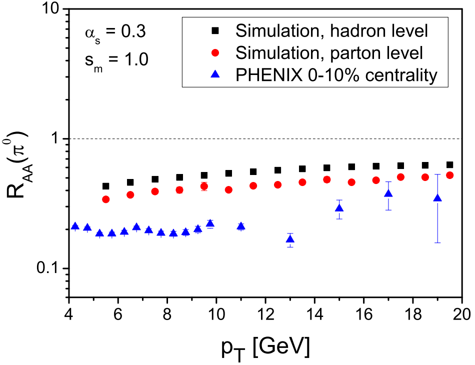
[1] K. J. Eskola, H. Honkanen, H. Niemi, P. V. Ruuskanen and S. S. Rasanen, Phys. Rev. C **72**, 044904 (2005).

[2] K. J. Eskola, K. Kajantie, P. V. Ruuskanen and K. Tuominen, Nucl. Phys. B570 (2000) 379-389.

Central collisions

Results: The nuclear modification factor R_{AA} for π^0

- The simulation is done both with and without plasma effects.
- The p_T distributions are folded with KKP fragmentation functions [3].

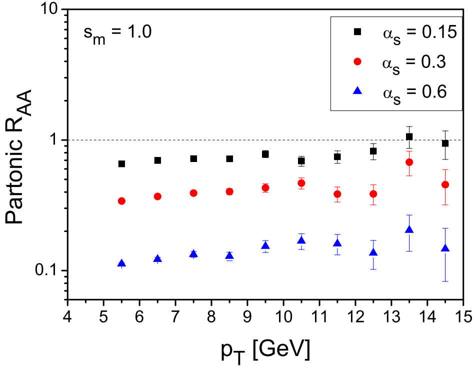


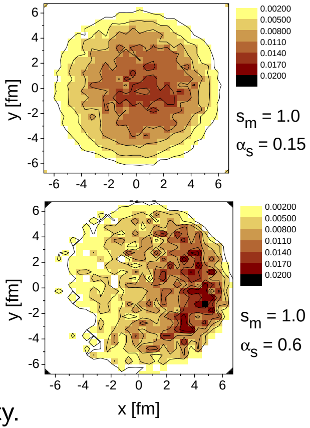
PHENIX data from A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **101**, 232301 (2008).

[3] B. A. Kniehl, G. Kramer and B. Potter, Nucl. Phys. B **582**, (2000) 514.

Central collisions

Sensitivity to the value of the strong coupling constant:





We have also studied the degree of non-eikonality.

Non-central collisions:
The pathlength dependence of elastic energy loss

Hydrodynamical background [4]:

- The smooth sWN profile [5] is used as an initial state.
- Assuming longitudinal boost-invariance reduces the hydrodynamical evolution equations into (2+1) dimensions.
- Centrality classes defined using the optical Glauber model.

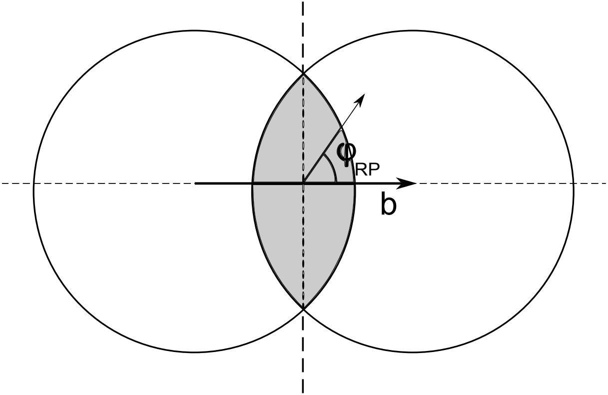
[4] H. Holopainen, H. Niemi and K. J. Eskola, Phys. Rev. C **83**, 034901 (2011).

[5] P. F. Kolb, U. W. Heinz, P. Huovinen, K. J. Eskola and K. Tuominen, Nucl. Phys. A **696**, 197 (2001).

Non-central collisions

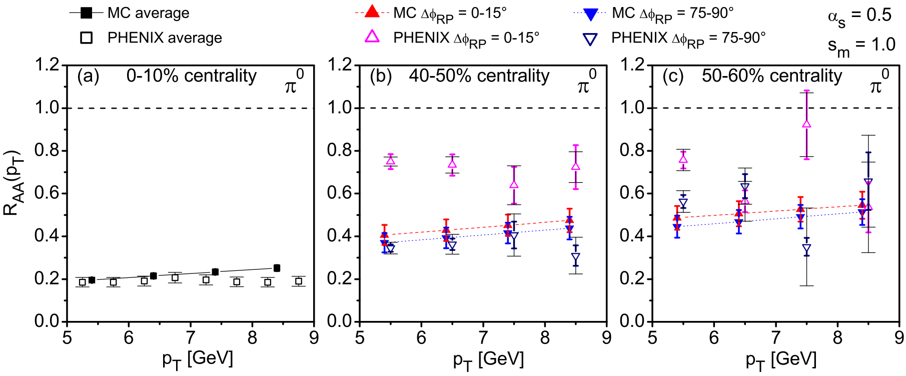
The π^0 nuclear modification as a function of the reaction plane angle $\Delta\phi_{RP}$:

- More matter in out-of-plane direction than in-plane
- R_{AA} varies with reaction plane angle ϕ?



Non-central collisions

The π^0 nuclear modification as a function of the reaction plane angle $\Delta\phi_{RP}$:



$R_{AA}(\phi_{RP})$ data from S. Afanasiev *et al.* [PHENIX Collaboration], Phys. Rev. C **80**, 054907 (2009).

The effect of initial state density fluctuations

Event-by-event hydro calculations with fluctuating initial state [6]:

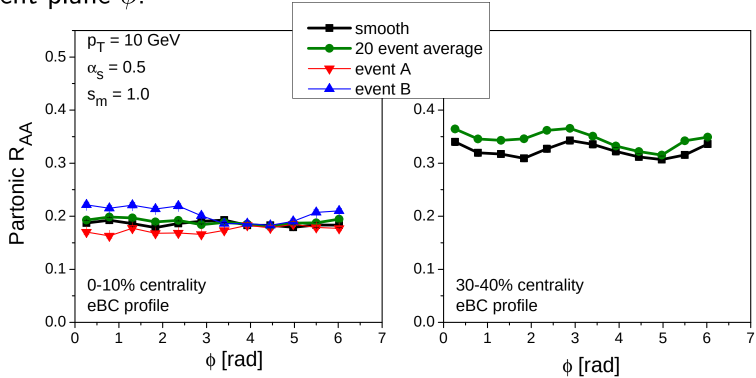
- The eBC profile [7] is used as an initial state.
- Centrality classes defined using the Monte Carlo Glauber.

[6] H. Holopainen, H. Niemi and K. J. Eskola, Phys. Rev. C **83**, 034901 (2011).

[7] P. F. Kolb, U. W. Heinz, P. Huovinen, K. J. Eskola and K. Tuominen, Nucl. Phys. A **696**, 197 (2001).

Initial state fluctuations

R_{AA} at $p_T = 10$ GeV as a function of the angle of outgoing partons with the event plane ϕ:



- The initial state fluctuations average out in central collisions, no re-tuning of α_s required.
- In non-central collisions, the average over fluctuations gives slightly less suppression compared to smooth hydro.

The Answers

The contribution of elastic scatterings to energy loss of hard partons?

With reasonable parameter values, elastic scattering would seem to give notable contribution to the suppression of high-energy hadrons. However...

The pathlength dependence of elastic energy loss?

This kind of fully incoherent model fails to reproduce the measured dependencies on the reaction plane angle and centrality.

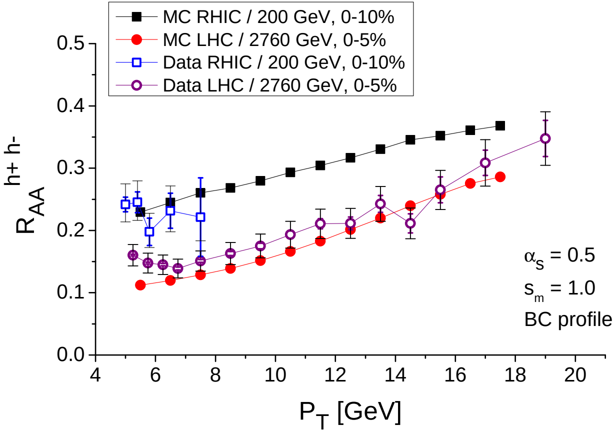
The effect of initial state density fluctuations to energy loss?

The fluctuations average out in central collisions; they do seem to have small but clear effect on the nuclear modification in non-central case.

What next?

Implement also radiative energy loss (inelastic collisions) and coherence effects. Running coupling? Heavy quarks?

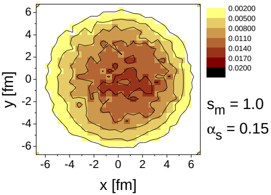
Good news: No re-tuning of α_s required for LHC!

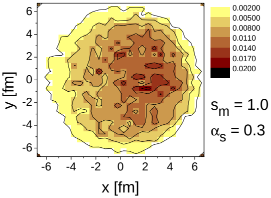


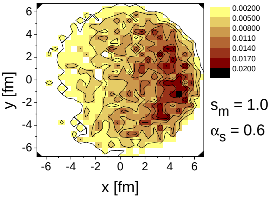
RHIC data from S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **69**, 034910 (2004). LHC data from K. Aamodt *et al.* [ALICE Collaboration], Phys. Lett. B **696**, 30 (2011).

Extra slides

Results: Tomography (Central collisions)



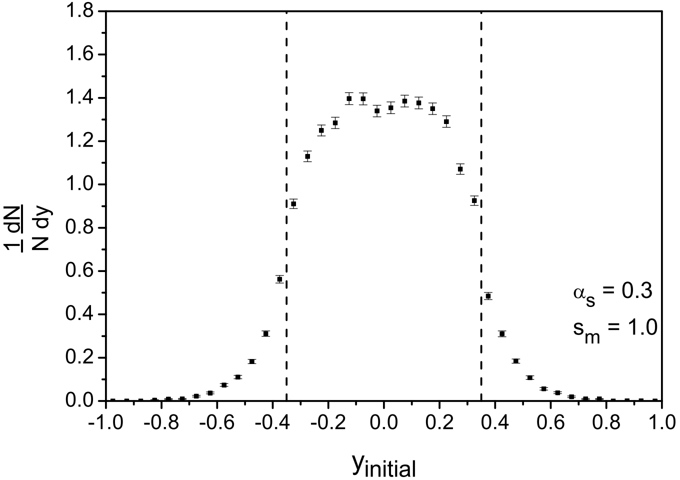




The initial production points of the punch-through partons in (transverse) xy-plane. The coordinates of the particle are rotated in the transverse plane so that it moves in the direction of x-axis.

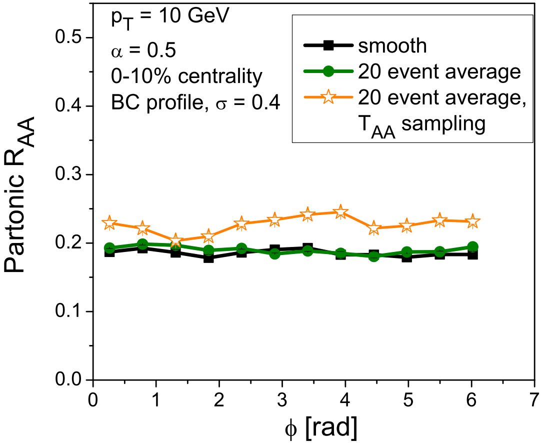
Rapidity distribution

The initial rapidity distribution of the punch-through partons. The final interval $|y| \leq 0.35$ is shown by the dashed lines.

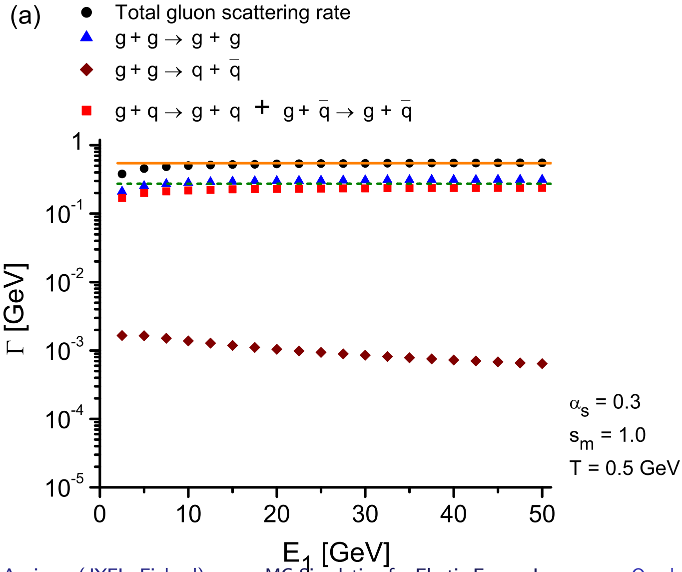


Parton starting points and binary collision vertices

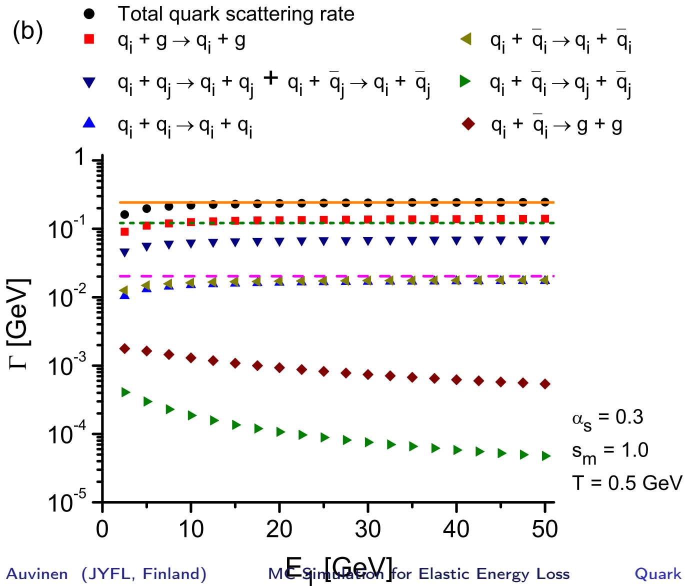
Parton starting points correlated with binary collision vertices vs. parton starting points sampled from the corresponding nuclear overlap function $T_{AA}(\mathbf{b})$.



The effect of energy on gluon scattering rate



The effect of energy on quark scattering rate



Initial state

- Initial p_T distribution of the hard partons produced using CTEQ6L1 [8] parametrization for parton distribution functions $x_i f_i(x, Q^2)$:

$$\frac{d\sigma^{AA\to f+X}}{dp_T^2 dy_1} = \int dy_2 \sum_{ijk} x_1 f_{i/A}(x_1, Q^2) x_2 f_{j/A}(x_2, Q^2) \frac{d\sigma^{ij\to fk}}{dt}.$$

- The initial rapidity interval is chosen to be $|y_i| \leq 1.0$.

[8] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky, W. K. Tung, JHEP 0207:012(2002), hep-ph/0201195

Initial state

- Starting point on xy-plane determined by sampling the nuclear overlap function

$$T_{AA}(\mathbf{b}) = \int d^2\mathbf{s}\, T_A(\mathbf{s}+\mathbf{b}/2) T_A(\mathbf{s}-\mathbf{b}/2).$$

  Nuclear density is given by Woods-Saxon distribution

$$n_A(r) = n_0(1 + e^{\frac{r-R_A}{d}})$$

  with $n_0 = 0.17$ fm^{-3}, $R_A = 1.12A^{1/3} - 0.86A^{-1/3}$ fm, $d = 0.54$ fm.
- The initial rapidity and the starting (proper) time τ_0 define the time $t_0 = \tau_0 \cosh(y_i)$ and z-coordinate $z_0 = \tau_0 \sinh(y_i)$.

The Monte Carlo simulation: Producing the thermal particle

The energy E_2 and the collision angle θ_{12} of the plasma particle are sampled from the expression of Γ as follows.

- The scattering rate for any particular process can be written in the form

$$\Gamma_X \sim \int_{\frac{m^2}{2E_1}}^{\infty} dE_2\, f(E_2, T)(H(\frac{4E_1E_2}{m^2}) - H(2)),$$

  where $H(x)$ is the integral function of $\sigma_X(s)$ with the variable $x = \frac{s}{m^2} = \frac{2E_1}{m^2}E_2(1 - \cos\theta_{12})$. E_2 can be sampled from this expression.

- After E_2 has been found, the collision angle can be determined by picking a random number r from the interval $[H(2), H(\frac{4E_1E_2}{m^2})]$. Solving now x_0 from the equation $H(x_0) - r = 0$ gives $\cos\theta_{12} = 1 - \frac{x_0 m^2}{2E_1E_2}$.

The Monte Carlo simulation: Scattering angle

The cross section of the process determines the distribution of scattering angle θ_{13}.

- The scattering angle is determined in the CMS frame of the collision. The method is very similar to one used with finding the collision angle.
- The integral function is now $\Sigma_X(t) = \int dt\, |M|^2_X$. Picking a random number R from the interval $[\Sigma_X(-s+m^2), \Sigma_X(-m^2)]$ and solving t_0 from the equation $\Sigma_X(t_0) - R = 0$ gives the scattering angle as $\cos\theta_{13} = \frac{2t_0}{s} + 1$.

Mixed phase (Central collisions)

- In the mixed phase, temperature stays constant ($T = T_C$) while energy density ϵ keeps decreasing.
- The scattering rate Γ depends on T but not $\epsilon \rightarrow$ How to implement the effect of mixed phase?
- Effective temperature $T_{eff}(R,\tau) = \frac{30}{g_Q \pi^2}(\epsilon(R,\tau) - B)^{1/4}$ with bag constant $B = (239 \text{ MeV})^4$.
- The simulation ends when the boundary of mixed phase and hadron gas phase is reached (i.e. when $T < T_C$).