Quark and Gluon Production from an Expanding Strong Color Electric Flux Tube

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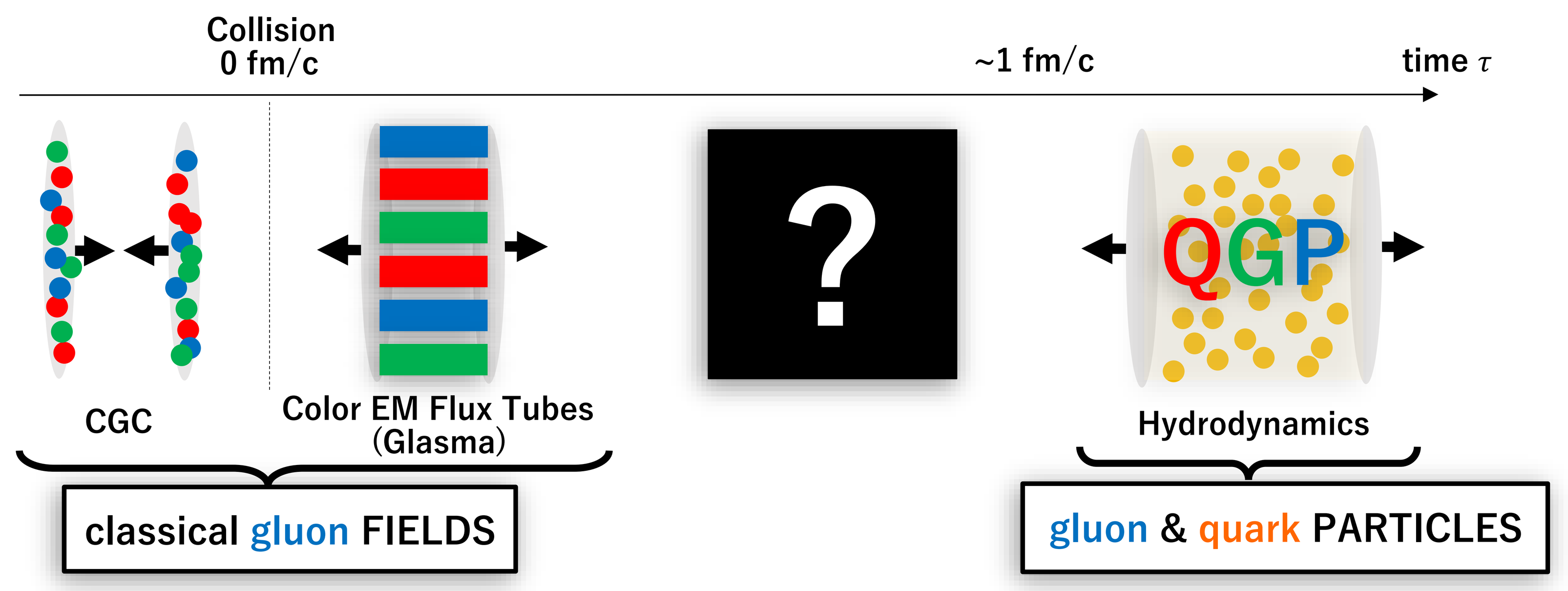
1. INTRODUCTION

1-1. Pre-equilibrium dynamics of HIC is a BIG MISSING PIECE



1-2. Aim of this study

✔ Many studies on this topic have been done:

Physical picture: Schwinger mech. ; NO instability; Weibel instability; bottom up thermalization …

Theory: classical statistical approx.; 2PI; effective kinetic theory; classical YM; flux tube model …

✔ But, there remain many unanswered questions such as

? How the transition from the classical field to quantum particles occur
? How (not only gluons but also) quarks are produced
? How the system isotropizes (or not)

✔ We discuss these points by studying quark & gluon particle production from an expanding classical gauge field based on QCD within mean field approximation

2. THEORY

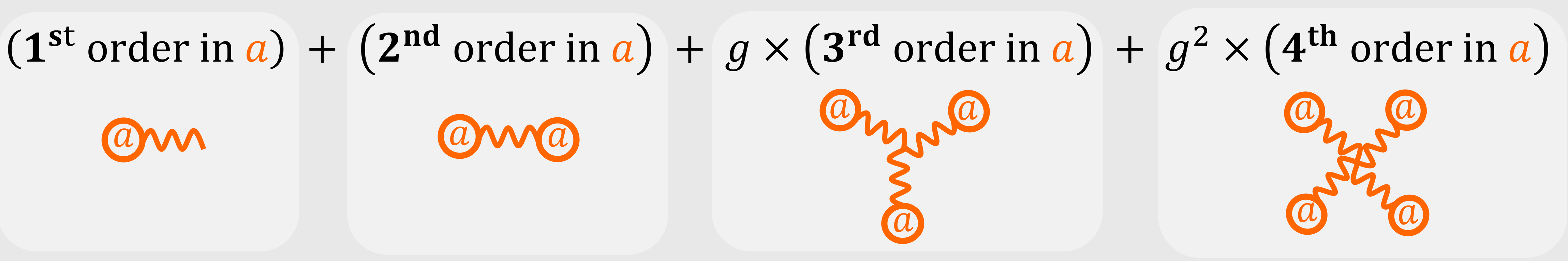
＊ Only the gluon part is explained here. The quark and ghost parts can be formulated in the same way.

$$L_{\rm QCD} = -\frac{1}{2}{\rm tr}[F^{\mu\nu}F_{\mu\nu}] + L_{\rm quark} + L_{\rm FP+GF}$$

STEP 1: Separate the total gauge field (A) into a classical field ($\bar{A} \equiv \langle A \rangle$) and a quantum fluctuation (a) as $A = \bar{A} + a$ (total, classical, quantum)

STEP 2: Expand Lagrangian in terms of the quantum fluctuation a

$$L_{\rm QCD} = -\frac{1}{2}{\rm tr}[\bar{F}^{\mu\nu}\bar{F}_{\mu\nu}] + (1^{\rm st}\text{ order in } a) + (2^{\rm nd}\text{ order in } a) + g\times(3^{\rm rd}\text{ order in } a) + g^2\times(4^{\rm th}\text{ order in } a) + L_{\rm quark} + L_{\rm FP+GF}$$



＊ a's propagator non-perturbatively includes multiple-interactions b/w the classical field $\bar{A}$ as (propagator) = (free) + (one $\bar{A}$ insertion) + (two $\bar{A}$ insertions) + ⋯

STEP 3: Adopt *mean field approximation* for the non-linear (higher than 3rd order in a) terms

$a\,a\,a \rightarrow a\langle a\,a\rangle$ = current from produced particles $\langle j\rangle$

$a\,a\,a\,a \rightarrow a\,a\langle a\,a\rangle$ = (partial) effects of scatterings $\langle M\rangle$

$L_{\rm QCD}$ = (up to 2nd order in the quantum fluctuation a)

STEP 4: Solve the Euler-Lagrange equations for a and $\bar{A}$

$$\mathbf{0} = [(\nabla + ig\bar{A})^2 g^{\mu\nu} + \langle M^{\mu\nu}\rangle]a_\nu \quad \text{for the quantum fluctuation } a, \quad \text{and} \quad \langle j^\mu\rangle = \nabla_\nu[\bar{F}^{\nu\mu} + \langle f^{\nu\mu}\rangle] \quad \text{for the classical field } \bar{A}$$

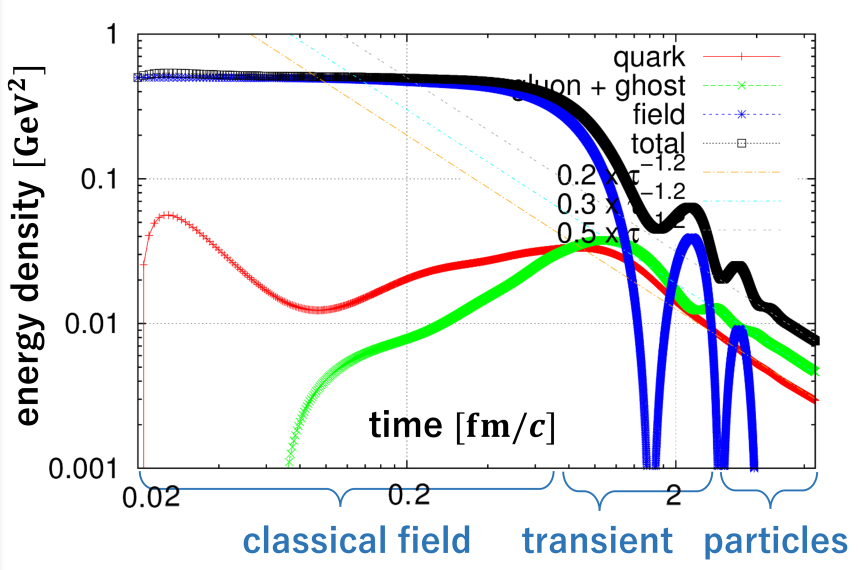
Advantages: The equations
✔ are simple and easy to understand their physical meanings
✔ include higher order quantum effects (within the mean field treatment)
✔ describe a smooth transition from the classical field to quantum particles
✔ are numerically feasible

3. NUMERICAL RESULTS

3-1. Numerical Setup

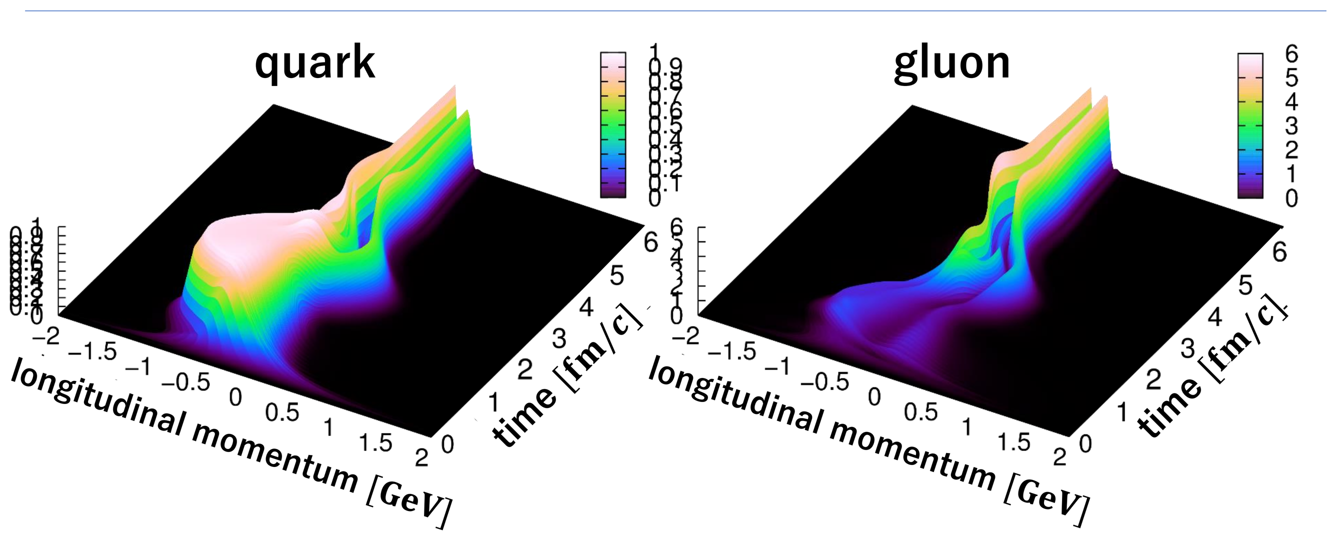
✔ $SU(N_c=3)$ QCD with $N_f=3$ massless quarks
✔ Homogeneity in space: Boost invariance & transverse symmetry
✔ Longitudinal color *electric* field at an initial time τ_0: $\vec{E}(\tau_0) = (0,0,E_0), \vec{B}(\tau_0) = (0,0,0)$
✔ Neglect the higher order term $\langle M\rangle = 0$ (i.e., collisionless limit)
✔ Parameter setting: $E_0 = 1\,{\rm GeV}^2, g=1, \tau_0 = 0.1\,{\rm GeV}^{-1}$

3-2. Energy Density



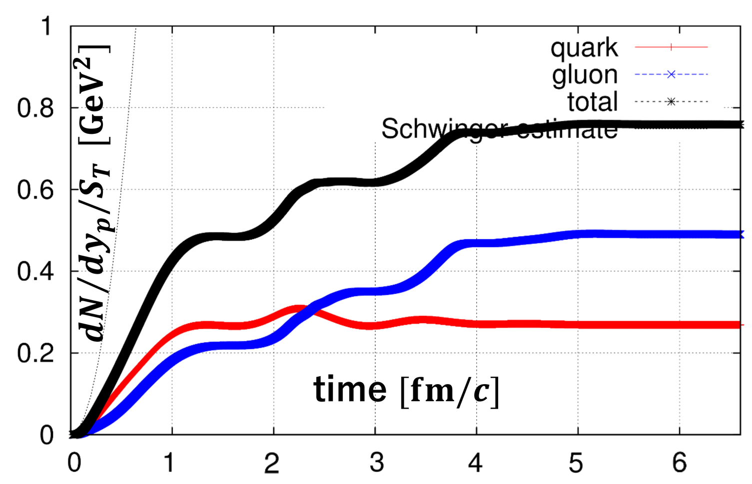
✔ The classical field decays into quark & gluon particles within a few fm/c

3-3. Longitudinal Distribution $(2\pi)^3 \frac{d^6N}{dp_T^2 dp_\eta dx_T^2 d\eta}$ at $p_T \sim 0$



✔ Plasma oscillation
✔ Pauli blocking for quarks & Bose enhancement for gluons
✔ Red shift due to the longitudinal expansion

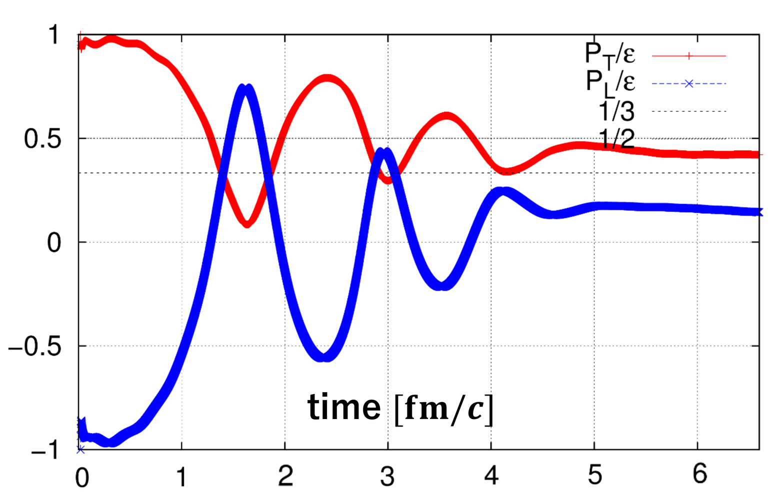
3-4. Number Density $dN/dy_p/S_T$



✔ Fast particle production
- In particular, quark production is very fast $\tau \lesssim 1\,{\rm fm}/c$

✔ Huge number of particles
- Gluon dominates
- 1,000 quarks + 2,000 gluons (for $S_T \sim \pi(7\,fm)^2$)

3-5. Isotropization



✔ System becomes less anisotropic as the classical field decays
- $P_L/P_T \sim 0.5$ (even if collisionless)

4. SUMMARY

What we did

We studied quark & gluon production from an expanding classical gauge field to discuss the pre-equilibrium dynamics of HIC

What we have learned

Adopting mean field approx. to QCD, we have learned that
✔ classical field decays into quarks & gluons within a few fm/c
✔ how the transition from the classical field to particles occurs
✔ huge number of quarks & gluons are produced quickly
✔ the anisotropy becomes moderate as $P_L/P_T \sim 0.5$

What to do

✔ higher order effects (e.g. collisions)
✔ inhomogeneity in transverse plane
✔ longitudinal magnetic field
✔ photon/di-lepton production