Quark Pair Production from Expanding Electromagnetic Flux Tube

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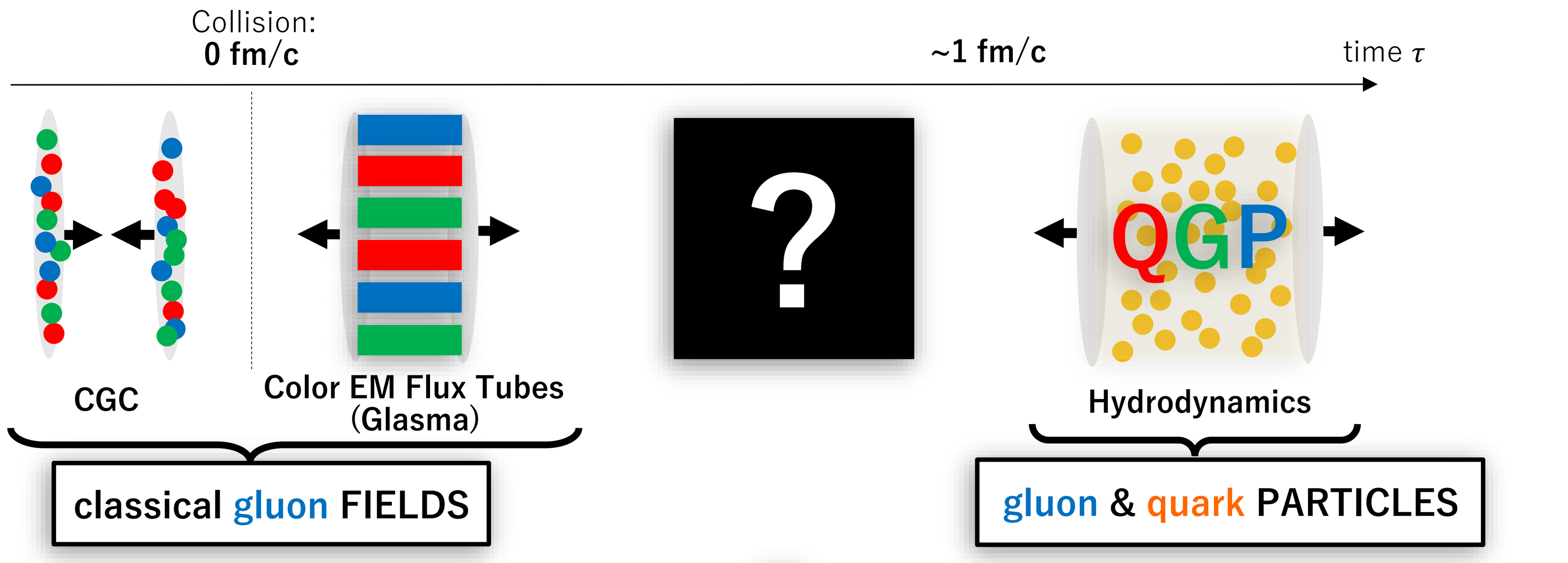
1. INTRODUCTION

1-1. Formation Process of QGP is a BIG QUESTION in HIC



Aim of this study: Try to reveal ? focusing on the quark production based on the Schwinger mechanism

1-2. Previous Studies on Quark Production via Schwinger Mech.

Some of the important properties of the flux tubes are

1. Longitudinal expansion (Bjorken expansion) of the flux tubes
2. Presence of magnetic fields in parallel to electric fields,

whose effects on the Schwinger mech. are NOT understood well in previous studies:

	Expanding?	Magnetic Field?	Quark Mass	Backreaction?
Mihaila et al.	Yes	No	Limited: $\left\|\frac{m^2}{gE}\right\| = \frac{1}{4}$	Yes
Tanji	No	Yes (with arbitrary strength)	Arbitrary	Yes
Gelis et al.	Yes	Yes, but only for $\left\|\frac{gB}{gE}\right\| \sim 1$	Limited: $m \gtrsim 60$ MeV	No

Our study gets over these limitations :

	Expanding?	Magnetic Field?	Quark Mass	Backreaction?
Our Study	Yes	Yes (with arbitrary strength)	Arbitrary	Yes

2. THEORY

2-1. Formulation

✔ Following simplifications are assumed hereafter:

1. $U(1)$ gauge theory with $N_f = 1$ fermion
2. Homogeneity in space: Boost invariance & transverse symmetry
3. Single flux tube with infinite length in the transverse direction
4. Longitudinal EM-field at initial time τ_0: $\vec{E}(\tau_0) = (0, 0, E_0), \vec{B}(\tau_0) = (0, 0, B_0)$

✔ We solve the EoMs (non-perturbatively w.r.t the strong fields gA_μ):

$$0 = [i\gamma^\mu(\partial_\mu + igA_\mu) - m]\psi, \quad F^{\nu\mu}{}_{;\mu} = g\bar{\psi}\gamma^\nu\psi$$

and canonically quantize $\psi \to \hat{\psi}$ at each instant of (proper) time τ:

$$\hat{\psi}(x) = \sum_s \sum_n \int d\lambda \left[{}_+\psi^{(\tau)}_{n,\lambda,s}(x_T, \tau)\hat{a}_{n,\lambda,s}(\tau) + {}_-\psi^{(\tau)}_{n,\lambda,s}(x_T, \tau)\hat{b}^\dagger_{n,-\lambda,s}(\tau) \right] \frac{e^{i\lambda\eta}}{\sqrt{2\pi}}$$

(positive freq. mode; negative freq. mode)

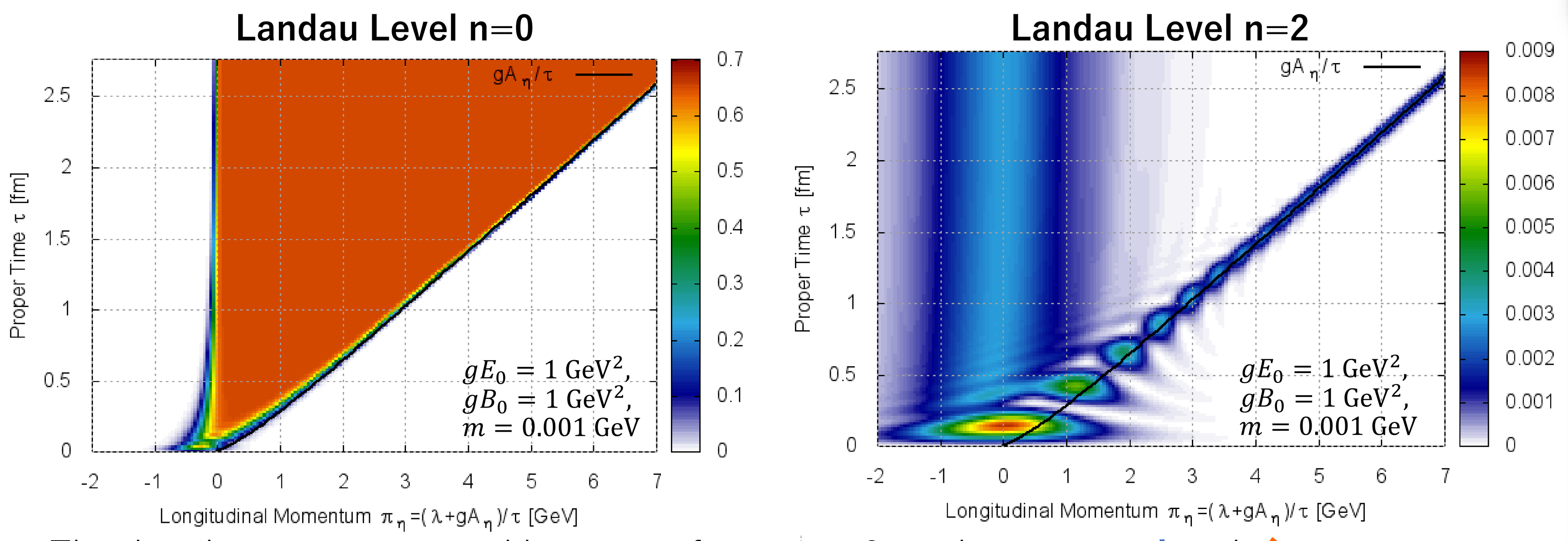
REMARK 1: 3 labels = spin s, Landau level n, and (canonical) longitudinal momentum λ.

REMARK 2: The instantaneous mode functions ${}_\pm\psi^{(\tau)}_{n,\lambda,s}(x_T, \tau)$ are defined by the approximate sol. of the Dirac eq. under an adiabatic assumption: $\partial_\tau A^\mu = 0$

Tanji; Schmidt, Blashke, Smolyansky …; Kluger, Mottola, Eisenberg …

3. RESULT I – WithOUT Backreaction g=0 (Analytical)

3-1. Longitudinal Distribution $d^2N/dyd\lambda/S_\perp$ [fm^{-2}]



✔ The distribution is saturated because of Pauli's principle.

✔ Particles are created constantly with 0 longitudinal momentum.

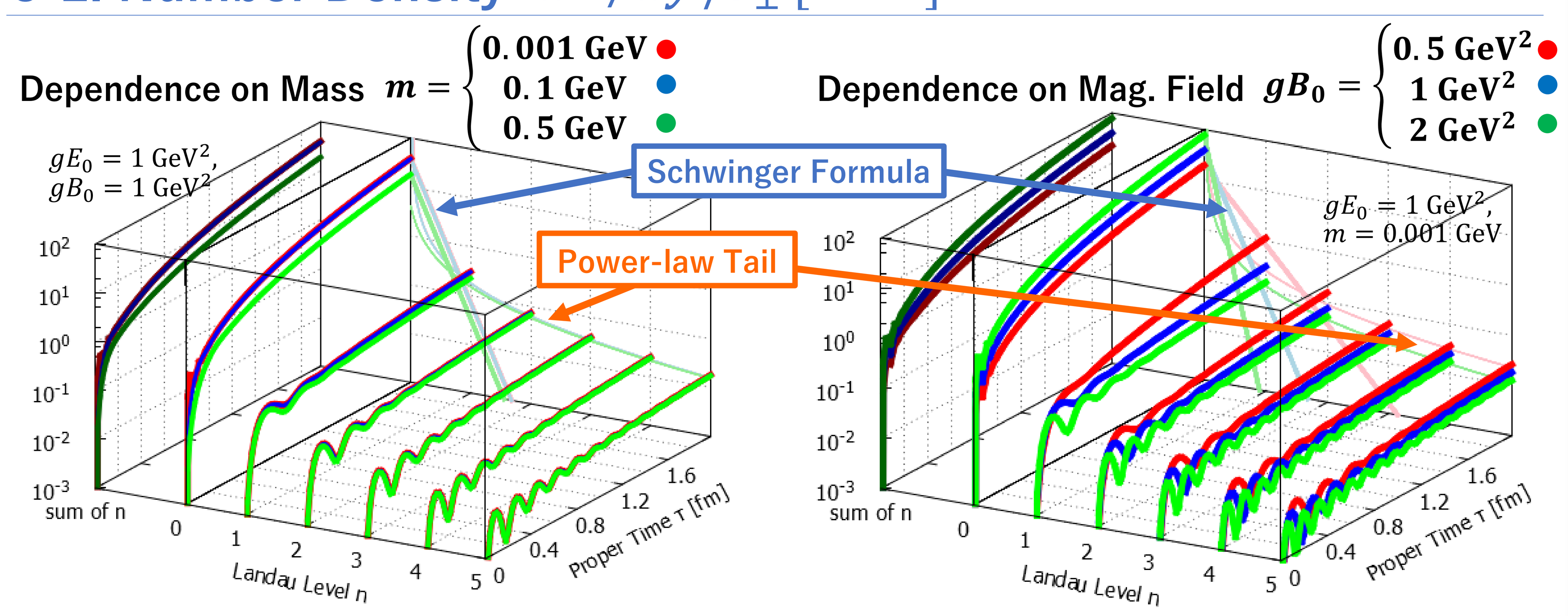
✔ After being created, particles are accelerated by electric fields in the long. direction obeying the classical EoM: $0 = d\lambda/d\tau$

✔ 2-peak structure: I and /.

✔ I : Particles which annihilate w/ their pair immediately after their creation. This peak depends on the choice of the instantaneous particle picture.

✔ I has pwr-dep. on n: $\sim ((m^2 + 2ngB)/gE)^{-2}$

3-2. Number Density $dN/dy/S_\perp$ [fm^{-2}]



✔ The density is consistent w/ Schwinger's formula $\propto \exp[-\pi|(m^2 + 2ngB)/gE|]$ for small n (m_T), while it has a power-law tail $\propto |(m^2 + 2ngB)/gE|^{-2}$ for large n (m_T). cf. Mihaila et al. (2009)

✔ Lowest Landau contribution (n=0) dominates the particle production.

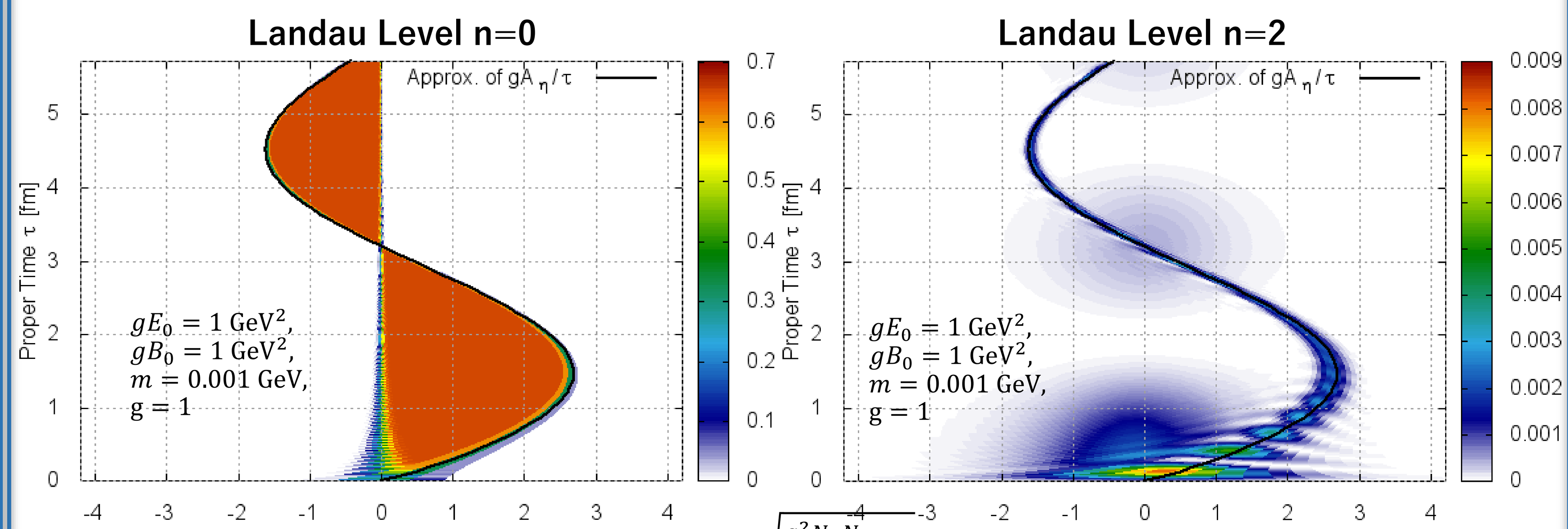
✔ Larger particle production $\propto gB$ for increasing gB.

✔ **Very fast quark production**: For example, $dN/dy/S_\perp \sim 1$ fm^{-2} particles are produced at $\tau \sim 0.2$ fm, which roughly corresponds to $dN_q/dy \sim N_c \times N_f \times 1 \times S_\perp \sim 1000$ in HIC. cf. Gelis et al. (2006)

✔ Combining with the experimental fact $dN_h/dy \lesssim 1000$, **classical gluon fields should have decayed very fast $\tau \lesssim 0.2$ fm**, otherwise we would have too huge # of particles.

4. RESULT II – With Backreaction g≠0 (Numerical)

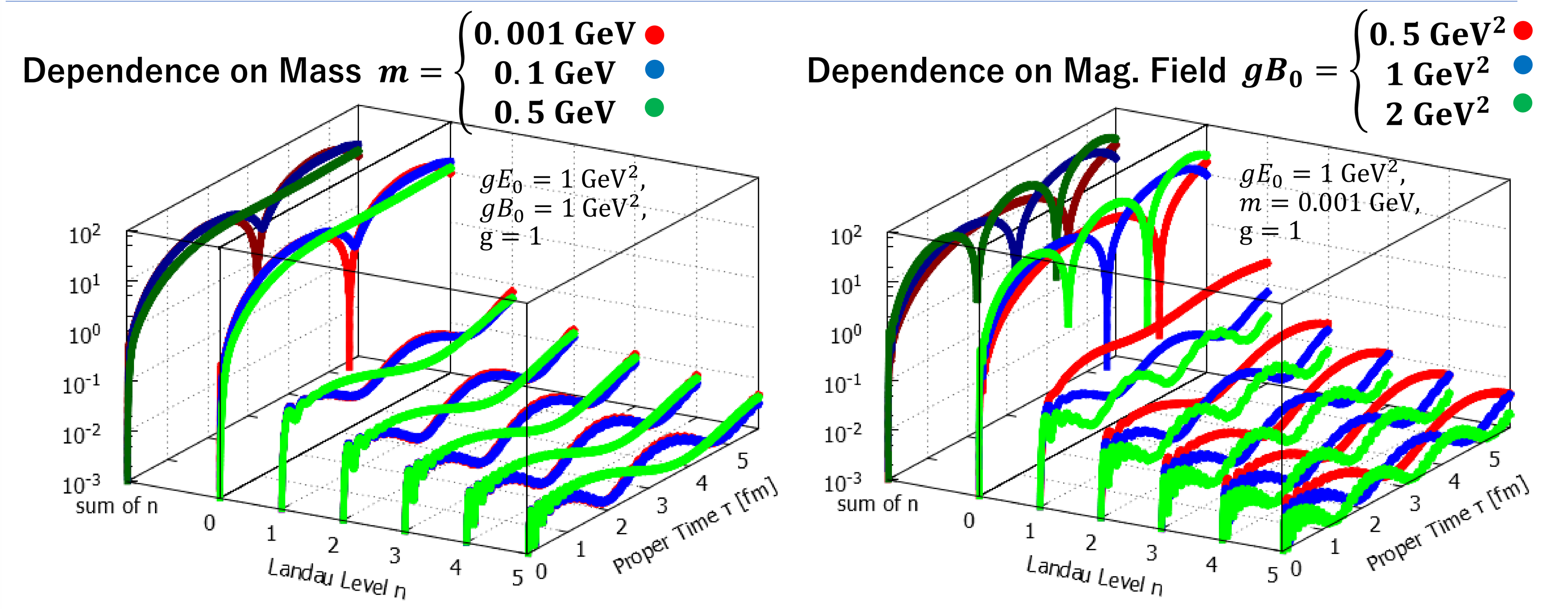
4-1. Longitudinal Distribution $d^2N/dyd\lambda/S_\perp$ [fm^{-2}]



✔ **Plasma oscillation** with timescale $\tau_{osc} \sim 1/\sqrt{\frac{g^2 N_f N_c}{2\pi^2} gB}$ occurs as a result of the backreaction.

✔ In addition to the oscillating behavior, the longitudinal momentum π_η decreases as $\sim 1/\sqrt{\tau}$ reflecting the longitudinal expansion of the system.

4-2. Number Density $dN/dy/S_\perp$ [fm^{-2}]

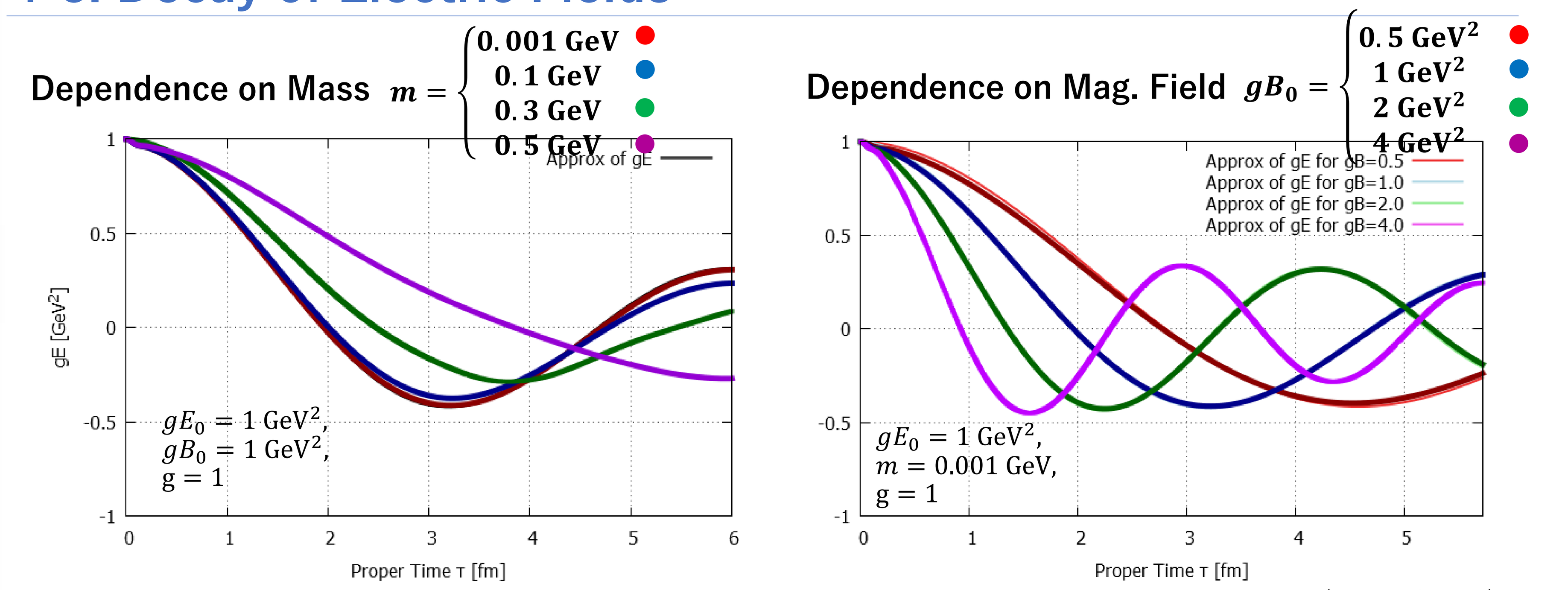


✔ The oscillation is "flattened" with increasing the mass.

✔ Faster oscillation with increasing gB.

✔ Effect of backreaction is small for small values of $\tau \lesssim 0.2$ fm, while it is not for large values of $\tau \gtrsim 0.2$ fm, where $dN/dy/S_\perp \propto \sqrt{\tau}$ (τ^2) with(without) backreaction.

4-3. Decay of Electric Fields



✔ gB never decays: Rotational sym. always holds due to the simplification 2&3 (i.e., $j^\theta = 0$)

✔ Faster decay and slower oscillation with increasing mass.

✔ Faster oscillation for stronger gB.

✔ Long. expansion makes the field decay faster $\propto 1/\sqrt{\tau}$ compared to the non-expanding case.

Note: Approximate Solution for the Backreaction Problem

If we take LLL approx. and massless limit, we can analytically solve the backreaction eqs. to find

$$E(\tau) = E_0\left[\frac{J_1(s\tau_0)}{J_1(s\tau_0)Y_0(s\tau_0)}Y_0(s\tau) - \frac{Y_1(s\tau_0)}{Y_1(s\tau_0)J_0(s\tau_0)}J_0(s\tau)\right], \quad \frac{1}{S_\perp}\frac{dN}{dy}(\tau) = \frac{gE_0}{2}s\tau\left|\frac{J_1(s\tau_0)}{J_1(s\tau_0)Y_0(s\tau_0)}Y_1(s\tau) - \frac{Y_1(s\tau_0)}{Y_1(s\tau_0)J_0(s\tau_0)}J_1(s\tau)\right|,$$

where $s^2 = \frac{g^2}{2\pi^2}gB$ (which roughly corresponds to $s^2 \sim \frac{N_c N_f g^2}{2\pi^2}gB$ in QCD).

5. SUMMARY

What we did

The quark production in the early stage dynamics of HIC based on the Schwinger mechanism is extensively studied.

What we have learned

1. Effects of the longitudinal expansion and the longitudinal magnetic fields on the Schwinger mech., which are the missing pieces of previous studies, are clarified.
2. The Schwinger mech. can explain a fast quark production and, combining w/ the experimental result on the multiplicity, it suggests that the classical gluon fields should have decayed very fast (though we did not say anything about its physics).
3. The backreaction effects from the produced quarks are also investigated, and an approximate formula is obtained in the LLL approximation and the massless limit.

There are several topics (energy density, pressure, anomalous current, etc) which I could not cover in this poster. If you are interested in these topics, feel free to ask me!