Production Mechanism of Quark Gluon Plasma in Heavy Ion Collision

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Primary aim of theoretically studying URHIC is to understand

- Production of quarks and gluons that form the bulk of the plasma (t_0)

- Their space-time evolution leading to
  (a) Equilibration (t_c)
  (b) Hadronization (t_h)

- The behaviour of heavy partons in the above medium as function of space-time

In other words we wish to study the Y-M response functions

The duration of the above processes are estimated to vary from a fraction of a fermi to several fermis. It is natural for the timescales mentioned above to be overlapping. That is production, evolution, and the equilibration are not disjoint processes.

We need a simple but robust framework to study the above mentioned aspects. In doing that we seek directions from Lattice results (such as determining the form of f_{eq}), QCD and Classical Plasma Physics.

Note that we are studying a non-equilibrium phenomenon and standard thermodynamic results cannot be used.

Framework

A framework does exist and that is the semi-classical formulation of production and equilibration. Typically one writes a transport equation in extended phase-space or its generalization to multi-particles.

$$\frac{\partial f}{\partial t} + \vec{v}.\frac{\partial f}{\partial \vec{r}} + \vec{F}.\frac{\partial f}{\partial p} + Q^a \frac{\partial f}{\partial Q^a} = \Sigma + collision \ term$$

Where $\sum$ is the source term.

This has a long history dating back to the work of Landau, Fermi and Pomeranchuk (1950's). A more recent discussion is by Carruthers and Zachariasen*. This approach was first invoked for QGP by Bjorken.

Salient Features of Transport Equation

- $f \equiv f(\vec{r}, \vec{p}, Q^a)$ is described in an extended phase-space $\mathbf{P} = \mathbf{R^6} \otimes \mathbf{G}$

- $F_i = Q^a [E_i^{\ a} + (\vec{v} \times \vec{B}^a)_i]$

  where Q^a is gauge covariant quantity

- Q^a here, unlike the Maxwell charges, are dynamical variables. In fact they satisfy:

$$\frac{dQ^a}{d\tau} = f^{abc} Q^b A_c^{\ \mu} u_\mu$$

  Note that they are sensitive not to the field tensor directly but to the gauge potentials themselves.

- We have a source term which is defined over the phase space **P**.This is normally absent in the classical plasmas.

Since production of partons from vacuum is not a classical phenomenon, this has to be determined quantum mechanically. Following methods have been employed in the literature:

♦ pQCD (structure functions & S-matrix approach)

♦ Effective approaches (we will come back to it later)

- Similarily Collision term is also complicated because one cannot take over the Boltzmann ansatz without further analysis

In this talk I will concentrate entirely on source terms for gluons & quarks

Source Term

Determination of the source term cannot be done independently of the kind of transport equation we use. Self consistency is the key word.

We do not employ the pQCD approach for following reason:

➤ No method to employ multiple overlapping time scales.

➤ The required source term is for the bulk of the plasma which is composed of soft and semi-hard partons. It is unlikely that pQCD will be a valid approximation.

➤ Moreover even at equilibration we do not have an ideal gas or a small perturbation over that.

Therefore we need an effective model. Color Flux Tube Model is one such model, which provides a natural setting for discussing quark confinement, in terms of color strings, which are Chromo Electric Field (CEF) flux tubes terminating on two partons.

For effective Schwinger mechanism based models, which are strictly valid for a constant and uniform electric field:

$$\text{Rate at a given time} \; = gE(t)\exp\left(-\frac{m^2}{gE(t)}\right)$$

This is clearly wrong, for, this is not true even for classical radiation theory in Electrodynamics. Classical radiation from a particle in a LINAC, for example, depends on complete history of the particle and not merely on instantaneous field strength.

We need a mechanism which is

♣ Inherently Non-Markovian

♣ Reflects the dynamical nature of the vacuum

♣ Also reflects the quasi-particle nature of excitations

We propose a mechanism, which has inherently all the above mentioned features. We obtain it by employing time dependent perturbation theory. Non-perturbative aspects are modeled in the framework of Color Flux Tube Model. We illustrate it for 2 parton production at the lowest order.

Production Mechanism

After the two nuclei collide, and start receding from each other, color strings are formed between them. These strings merge to form 'color rope' (i.e. CEF is formed). Consequently the production process reduces to the instability of the QCD vacuum in the presence of a classical CEF which is in general space-time dependent.

We study both the $2g$ and $q\bar{q}$ production in the external Y-M field. Gluon case is particularly interesting because it is non-abelian with no counterpart in QED.

Formalism

Gluons:

Expand gauge potentials as sum of classical values and their fluctuations:

$$A^a{}_\mu = \left\langle A^a{}_\mu \right\rangle + \phi_\mu{}^a = C^a{}_\mu + \phi_\mu{}^a$$

Expanding YM Lagrangian, we find terms responsible for gluon production to be:

$$L_{2g} = -\frac{g}{2} f^{abc} [(\partial_\mu C_\nu{}^a - \partial_\nu C_\mu{}^a)\phi^{\mu b}\phi^{\nu c} + (\partial_\mu \phi_\nu{}^a - \partial_\nu \phi_\mu{}^a)(C^{\mu b}\phi^{\nu c} + \phi^{\mu b}C^{\nu c})]$$

where terms are kept up to quadratic in fluctuations. Making a suitable choice of background field, production rate could be determined.

Keeping in mind the model and invoking gauge covariance of CEF, we choose the gauge potential to be, with the gauge group SU(3) in mind, of the following form :

$$A_\mu{}^a = \delta_{\mu,0}(f_1(t,\vec{r})\delta_{a,3} + f_2(t,\vec{r})\delta_{a,8})$$

We project the state $|\psi(t)\rangle$ to the two gluon state $|\vec{p}_1\vec{p}_2;s_1s_2;c_1c_2\rangle$ and the amplitude is given by:

$$\langle f|T(t)|0\rangle = \frac{ig}{(2\pi)^3} \frac{(E_2 - E_1)}{2\sqrt{E_1 E_2}} \vec{\varepsilon}^{s_1}(\vec{p}_1).\vec{\varepsilon}^{s_2}(\vec{p}_2) f^{ac_1c_2} \widetilde{C}_0^a(E_1 + E_2; \vec{p}_1 + \vec{p}_2; t)$$

where

$$\widetilde{C}_0^a = \int\limits_0^t dt' e^{-i(E_1+E_2)t'} \int d^3\vec{r} e^{i(\vec{p}_1+\vec{p}_2).\vec{r}} C_0^a(t',\vec{r})$$

Similarly for quarks:

$$\langle f | T(t) | 0 \rangle = \frac{g}{(2\pi)^3} \frac{m}{\sqrt{E_1 E_2}} u_{s_1}^+(\vec{p}_1) v_{-s_2}(\vec{p}_2) T_{c_1,c_2}^a \widetilde{C}_0^a(E_1 + E_2; \vec{p}_1 + \vec{p}_2; t)$$

The final states are not standard asymptotic free states. They have overlapping projection with the unphysical degrees of freedom. We distinguish physical pairs by projecting the states onto the physical subspace.

The probability that a pair is produced any time during the interval (0,t) is given by:

$$\left| \langle f | T(t) | 0 \rangle \right|^2$$

The production rate at any time t is thus given by its derivative at that instant; however this quantity not guaranteed to be non-negative.

A Model Example and Results

We will now illustrate the results with the help of an model example drawn from its behaviour expected in real situations. Let CEF be given by:

$$E_i^a = \delta_{i,z} E_0 (\delta_{a,3} + \delta_{a,8}) e^{-(t-|z|)/t_0}$$

with initial field strength given by E_0. This itself is not an boost invariant description but it captures all the essential features.

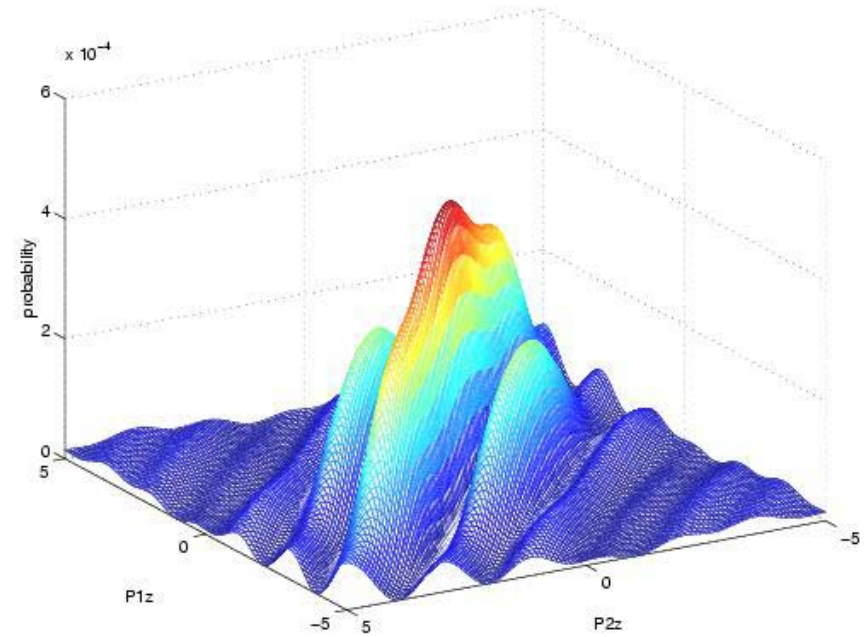# Gluon probability distribution in longitudinal momentum space
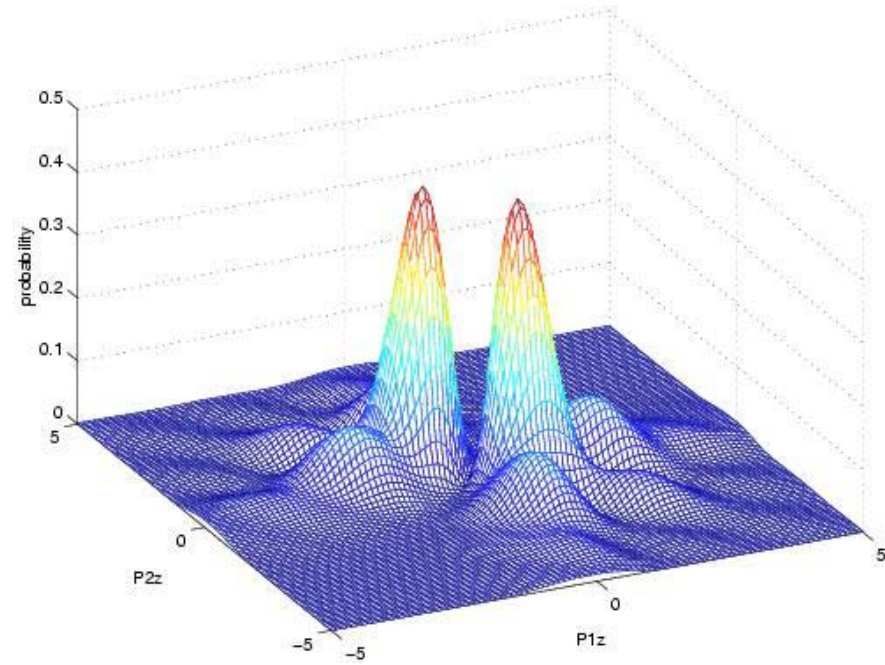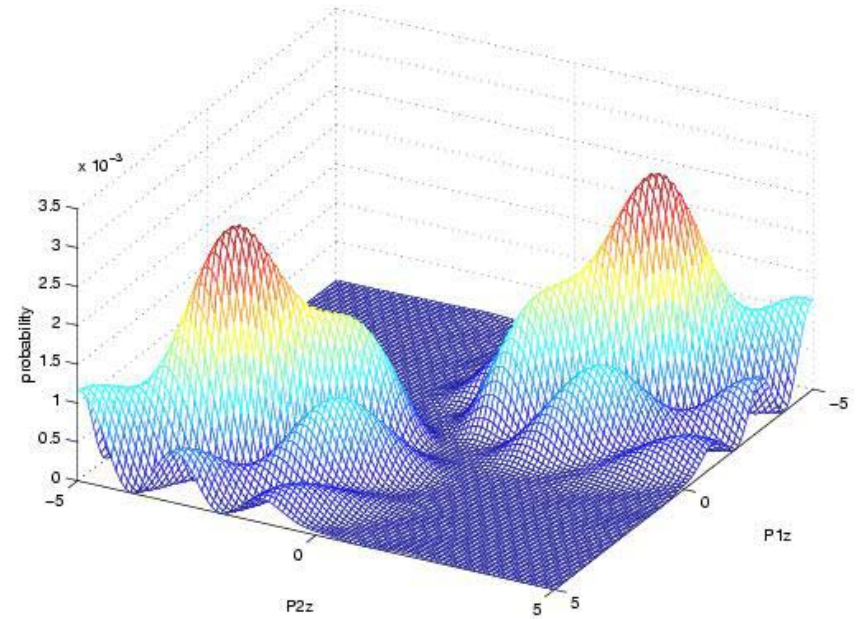
$$p_T = 1.0 \quad \& \quad t = 2.0$$

$$p_T = 3.0 \quad \& \quad t = 2.0$$

Quark probability distribution in longitudinal momentum space
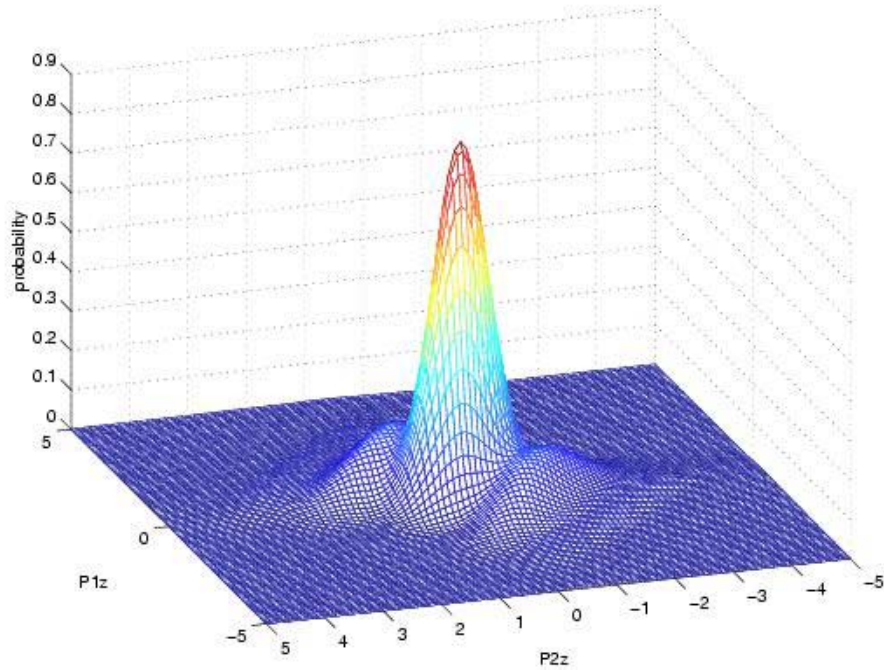
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$$p_T = 5.0 \quad \& \quad t = 2.0$$
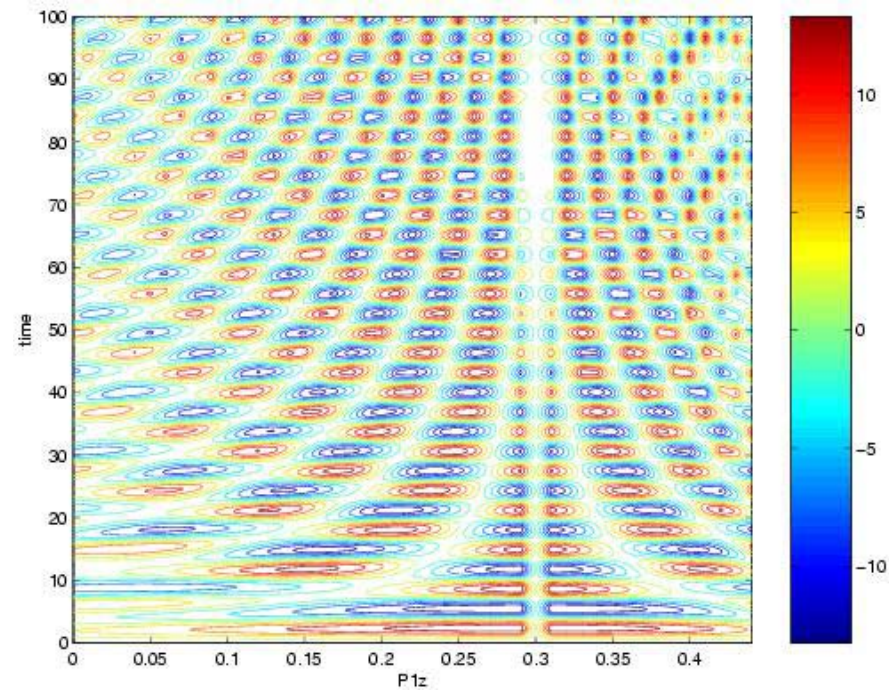
Gluon production rates for
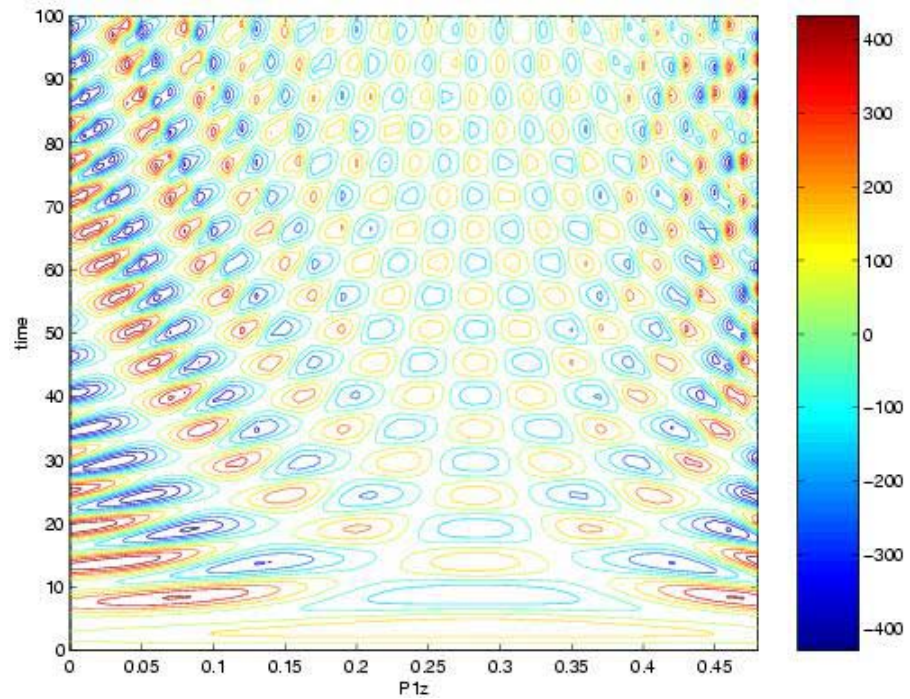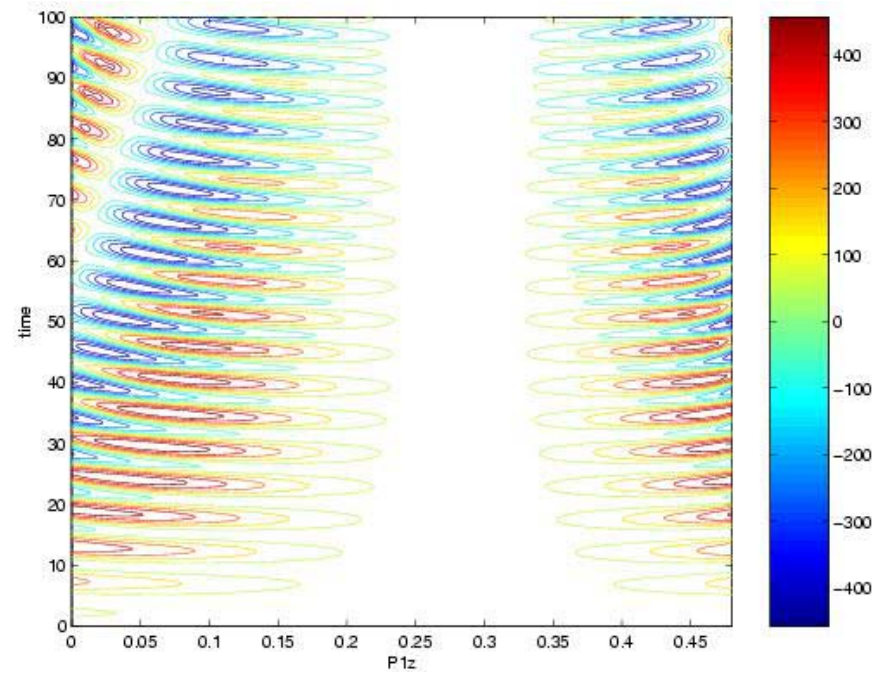
$$\sqrt{s} = 0.6 \quad \& \quad p_T = 0.1$$

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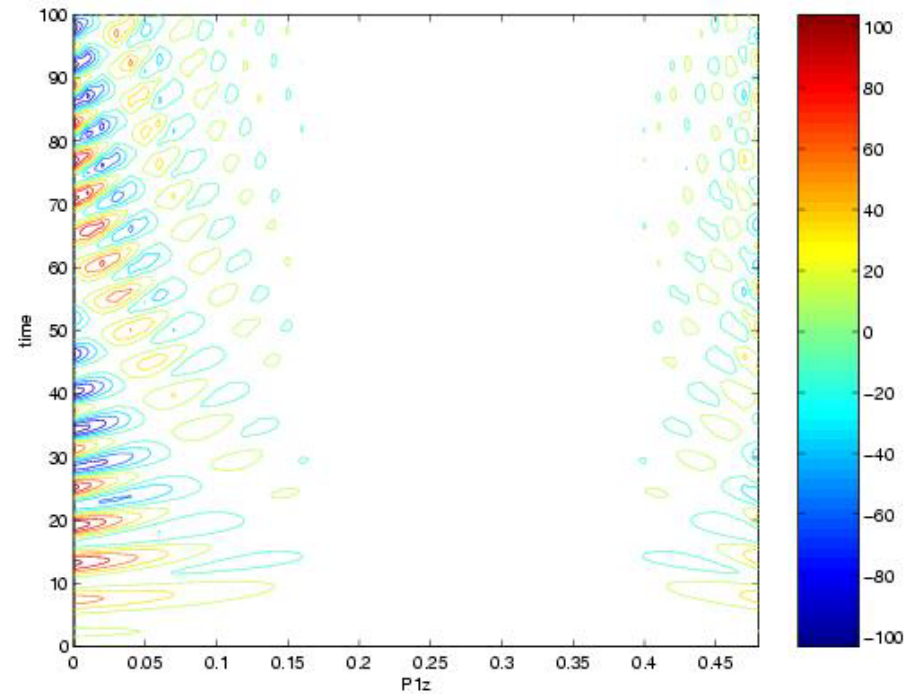(+,+) channel

Gluon production rates for

$$\sqrt{s} = 1.0 \quad \& \quad p_T = 0.4$$

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Quark production rates for
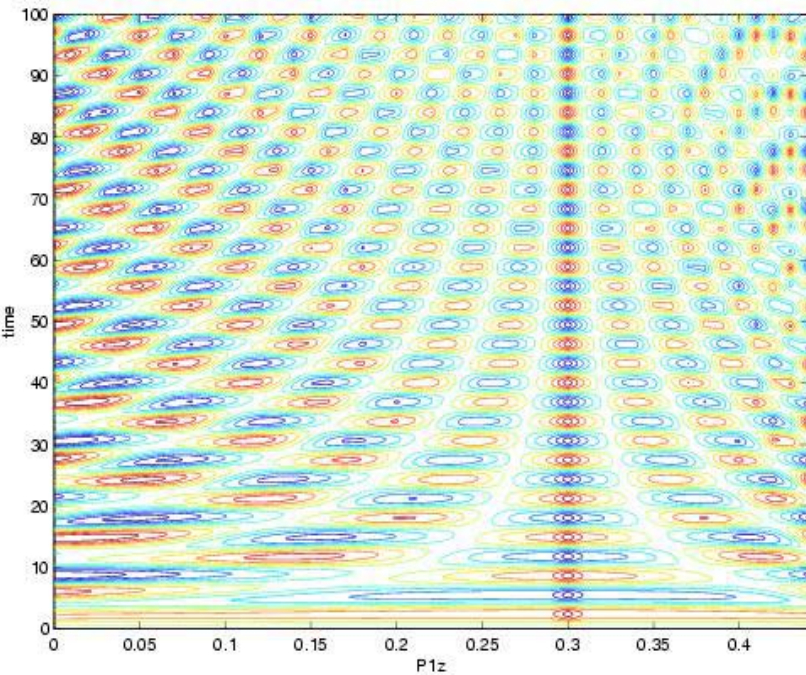
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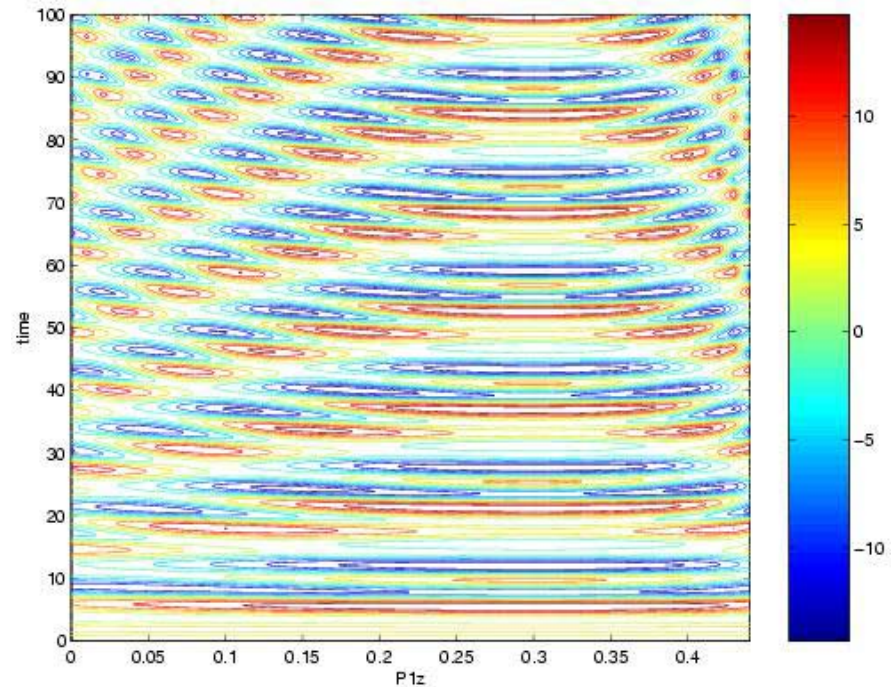

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Quark production rates for

$$\sqrt{s} = 1.0 \quad \& \quad p_T = 0.4$$

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