Stopping distance for high energy jets in weakly-coupled quark-gluon plasmas[1]

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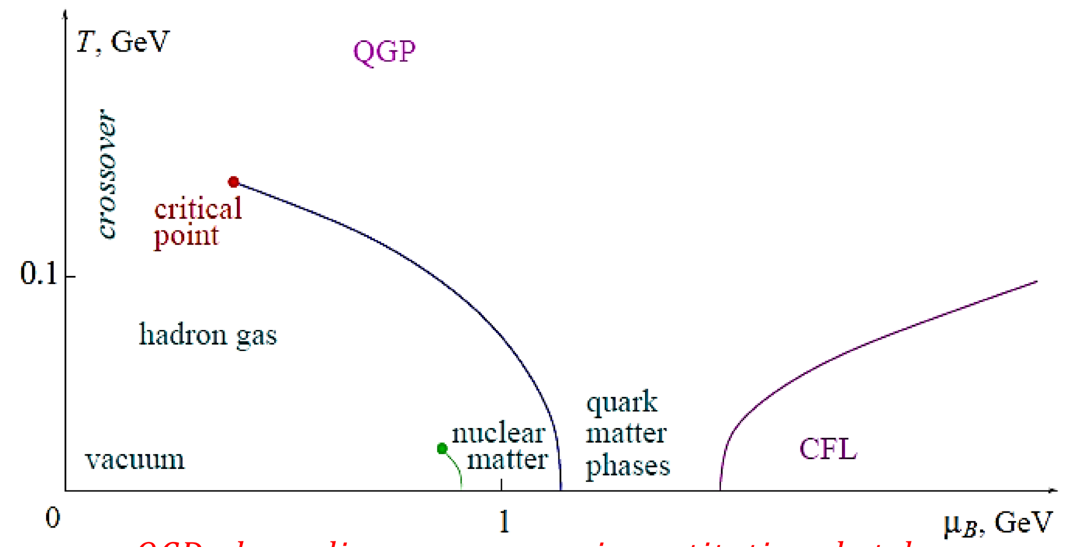
Introduction: Quark-Gluon Plasma

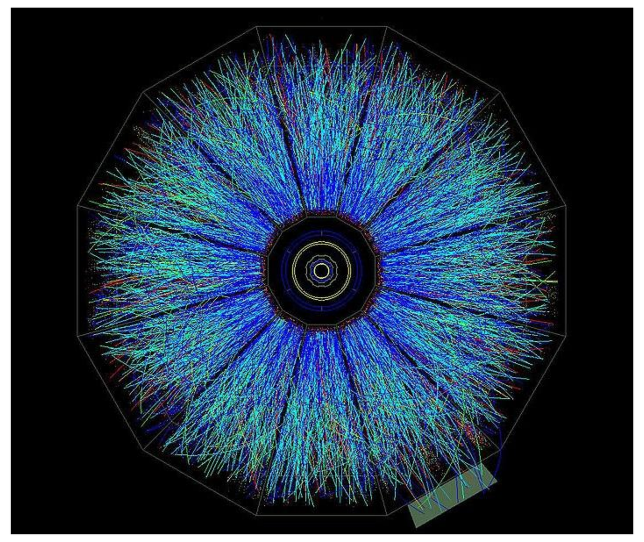
Quark-Gluon Plasma(QGP) is a phase of QCD which exists in extreme high temperature and/or high density, in which quark and gluons are almost free.



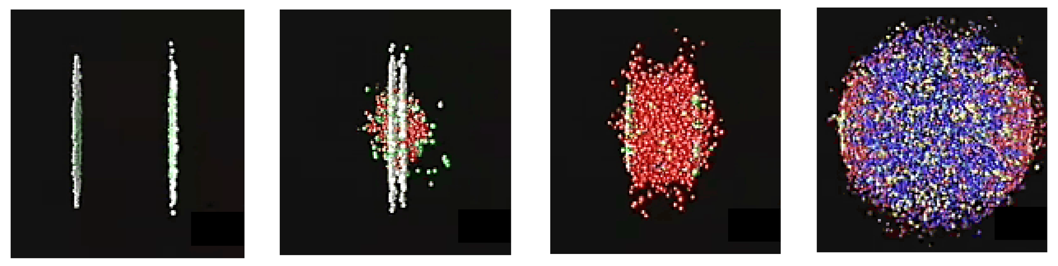
QCD phase diagram – a semiquantitative sketch
M. Stephanov hep-lat/0701002

In Brookhaven National Lab(BNL), gold nuclei are collided at $100GeV$ per nucleon at Relativistic Heavy Ion Collider(RHIC). It is believed QGP is created at $T\sim350MeV(4\times10^{12}K)$.

Right:
First gold beam-beam events recorded by STAR of BNL (from BNL web)



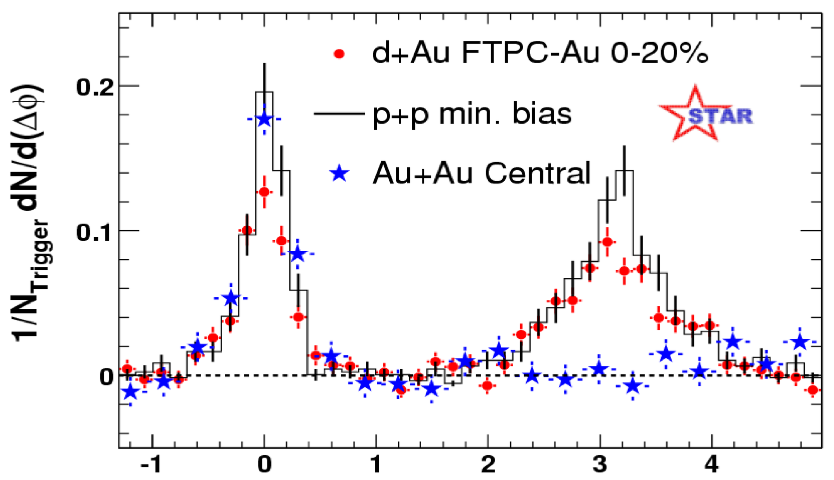
Below:
Processes of heavy ion Collision (from BNL web)



1. ions about to collide 2. ion collision 3. quars, gluons freed 4. plasma created

Motivation: Jet Quenching

In RHIC Au-Au collision, if we define azimuthal angle ϕ on the transverse plane, the correlation function shows "absence of away-side jet".



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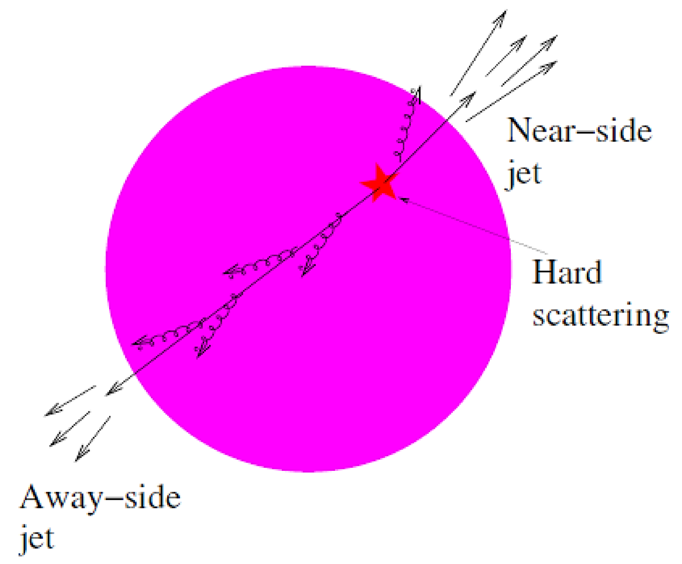
Because partons interact with thermal medium and deposit their energy into QGP before hadronization, this is so called **Jet Quenching**

Jet quenching is observed in Au-Au collision of RHIC, studying jet quenching provide insights on the properties of the hot QGP medium created in collision.

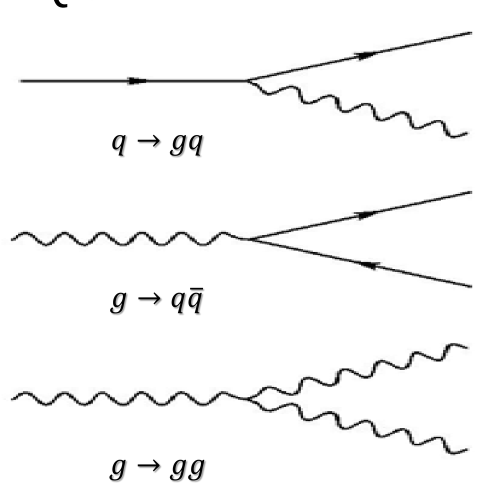


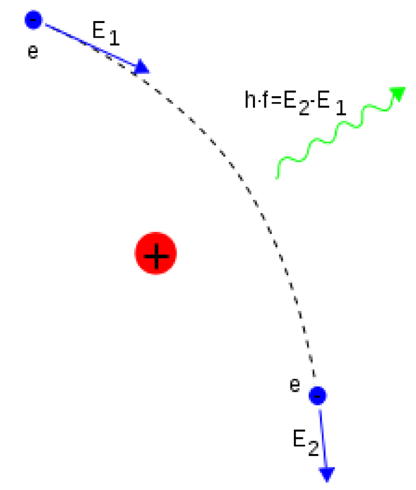
If we want to understand jet quenching theoretically, we need to study how partons interact with medium.

Parton Energy Loss in QGP

We assume the QGP is weakly-coupled so we can do perturbative calculations in QCD.

In this case, the energy loss is dominated by gluon bremsstrahlung and pair production. To lowest order in QCD, The 3 relative vertices are shown in the right figure.





In classic electrodynamics, when a electron is passing by a charged particle, it may change direction and emit a photon (bremsstrahlung)

In QCD, if quarks or gluons in the plasma kick a moving parton (through exchanging a virtual gluon), then the parton will deflect from its original direction and may lose energy through emitting a final gluon. Therefore, we are interest in this **rate of energy loss.**

In our work[2], we take into account the multiple collisions during the gluon formation time. We did a careful field theory calculation, and found a full analytical expression for the parton energy loss rate, Parametrically, it has the form:

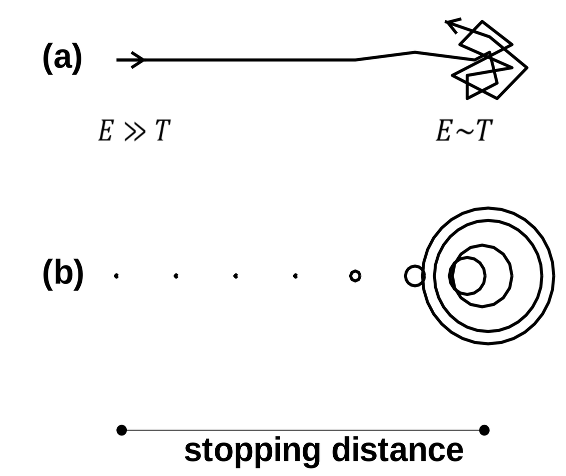
$$\Gamma\sim\alpha^2 T\sqrt{\frac{\ln(E/T)}{E/T}}\ , \qquad (1)$$

where E is initial parton energy, and T is QGP temperature($E\gg T$), and α is the strong coupling constant.

Stopping Distances: Definition

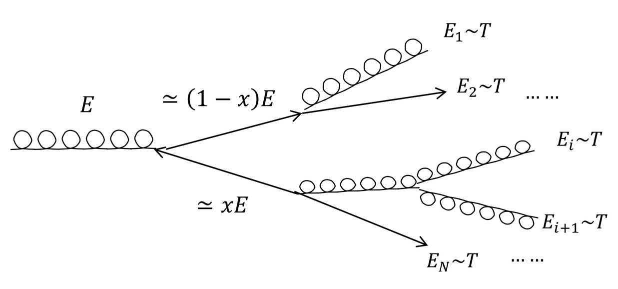
Suppose a high energy parton with initial energy E travelling through QGP with temperature T ($E\gg T$), it interacts with medium and when it drops energy to $E\sim T$, we say the parton ***stops*** in the medium.

For an initial quark, it can only split into a quark and a gluon, so we can follow the path of the quark and define **quark number stopping distance**, as shown in $Fig(a)$.



We can also draw a contour to represents the quark number distribution at a certain time, as time progresses, the center of the contour moves forward, slowing down with time, and the diameter enlarges, as shown in $Fig(b)$.

For an initial gluon, it can split into two gluons with bremsstrahlung or split into two quarks with pair creation. In either case, we don't have a unique final state gluon to follow with, so the definition in $Fig(a)$ for quarks doesn't work, but we can generalize the idea in $Fig(b)$. Consider the probability distribution for energy in excess of equilibrium (rather than quark number), we can measure how far it travels before stops. This is so called **"gluon energy stopping distance".**



Consider the splitting of an initial gluon moving in the z direction, which cascades through splitting into N particle, which are "stopped" at positions $z_1, z_2, \dots, z_N$ relative to the initial position of the gluon, then:

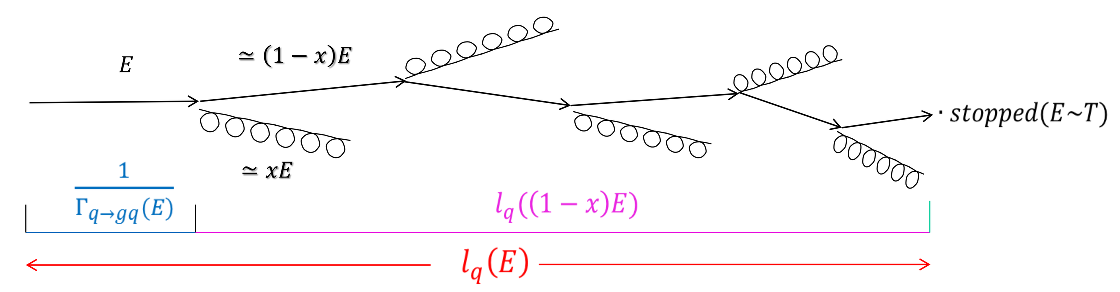
$$l_{stop,g}^{(energy)}\simeq\frac{\sum_i E_i z_i}{E} \qquad (2)$$

Discussion of stopping distances has a theoretical advantage over discussion of energy loss rate, because the stopping distances can be generalized into strong coupling, where on cannot speak of individual partons[3].

Stopping Distances: Calculation

We start from quark number stopping. To make a precise calculation, suppose initial quark's energy is E, while the gluon emitted from this quark carries energy xE. We have the self-consistent equation for stopping distance l_q:

$$l_q(E)=\frac{1}{\Gamma_{q\to gq}(E)}+\int_0^1 dx\,\frac{d\Gamma_{q\to gq}(E,x)/dx}{\Gamma_{q\to gq}(E)}\,l_q((1-x)E) \qquad (3)$$



Where $\Gamma_{q\to gq}(E)$ is the rate for a quark with energy E splits into a gluon and quark, and the 1st term on the right hand side of (3)represents the distance travelled before first splitting, the 2nd term is the remainder of the stopping distance after that, and $(d\Gamma/dx)/\Gamma$ is the probability that the emitted gluon has energy fraction x.

Parametrically, stopping distance l_q is inverse proportional to the splitting rate given in equation (1), we found the quark number stopping distances in weakly-coupled QCD has the following expression[1]:

$$l_{stop,q}\simeq\frac{1}{a\alpha^2 T}\sqrt{E/(TL)} \qquad where:\ L=\ln\left(\frac{bEL}{\alpha^c T}\right) \qquad (4)$$

Where a, b, c are numerical constants, they depend on number of flavors we take into account, and on our assumption of E and T.

For gluon energy stopping, we have a similar integral equation as (3), but we need to take both quark and gluon energy stopping distances into account, and we got a similar expression as (4), but with different a, b and c, see reference[1]

Stopping Distances: Numeric Results

Finally, we give the numerical results in 3-flavor QCD:

If we take $\alpha=\frac{1}{3}$, $T=350MeV$, $E=10GeV$, then quark number stopping distance is $l_{stop,q}\simeq 9.72\,fm$,; quark and gluon energy stopping distances are $l_g^{(e)}\simeq 8.36fm$, $l_q^{(e)}\simeq 13.53fm$, compare with the diameter of gold nucleon $d_{Au}\simeq 15fm$, the stopping distances are in the same order as gold nucleon, it can quantitatively explain jet quenching.

References

[1]. P. Arnold, S. Cantrell, and W. Xiao: Phys. Rev. D81, 045017 (2010) [arXiv: 0912.3862 [hep-ph]].
[2]. Peter Arnold, Wei Xiao: Phys. Rev. D78, 125008 (2008) [arXiv: 0810.1026]
[3]. P.M. Chesler, K. Jensen, A.Karch, and L. G. Yaffe, Phys. Rev. D79, 125015 (2009) [arXiv: 0810.1985 [hep-ph]]