Identifying the Particles Produced by Au+Au Collisions

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What is Quark Gluon Plasma?

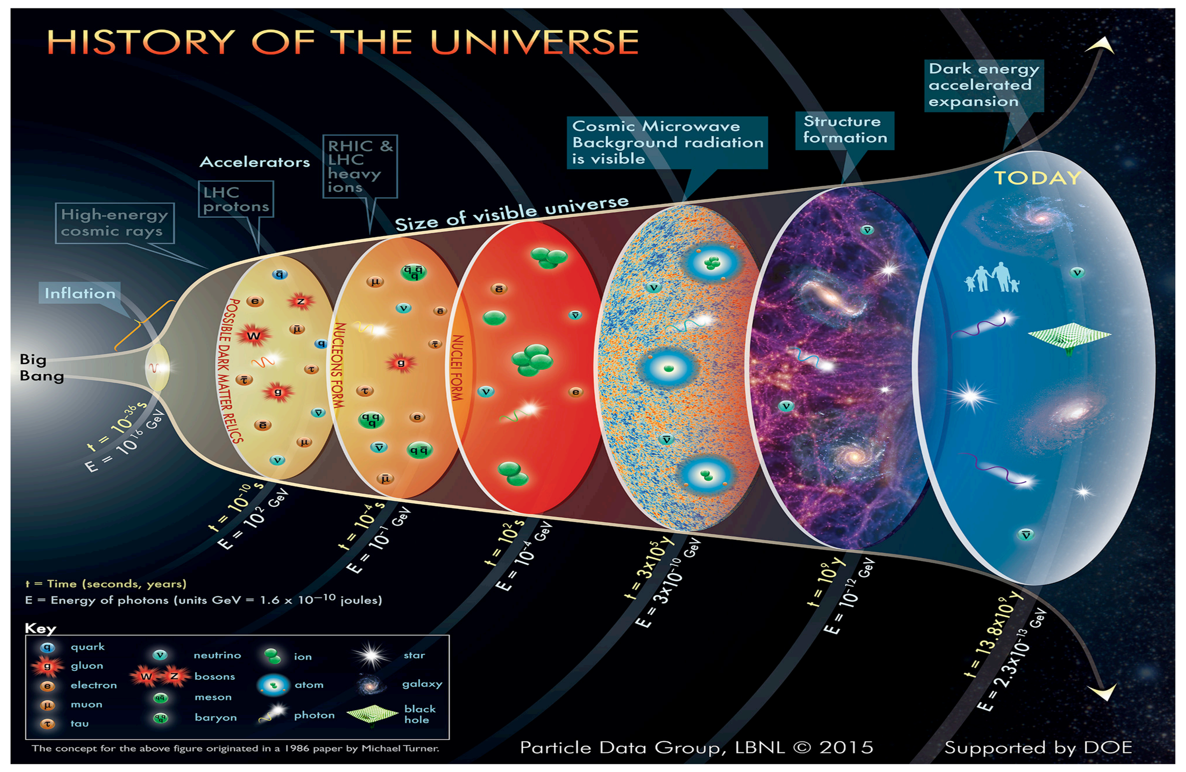
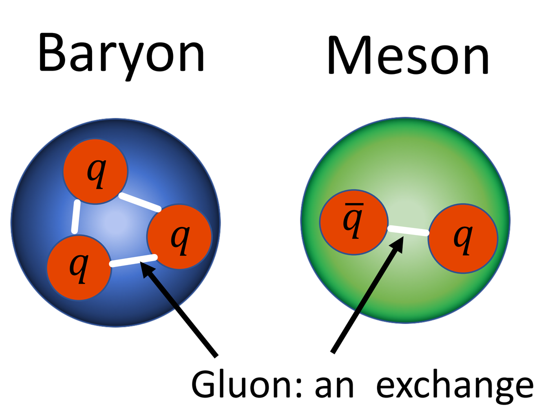


Fig.1 History of the universe

- Quark Gluon Plasma (QGP) consists of quarks and gluons which are no longer confined to hadrons (e.g. protons and neutrons).
- In the state of QGP, the temperature is about 10^{12} K
- 10^{-6}~10^{-5} s after the Big Bang, the universe was filled with QGP.
- The phase transition from QGP to hadrons is the last phase transition in the evolution of the universe.
- Fig.2 is the phase diagram of nuclear matter.



q: quark

$\bar{q}$: antiquark (a particle with the same as the quark but the opposite value of charge and spin)

Gluon: an exchange particle for strong force between quarks

Fig.3 Inner structure of hadron and meson

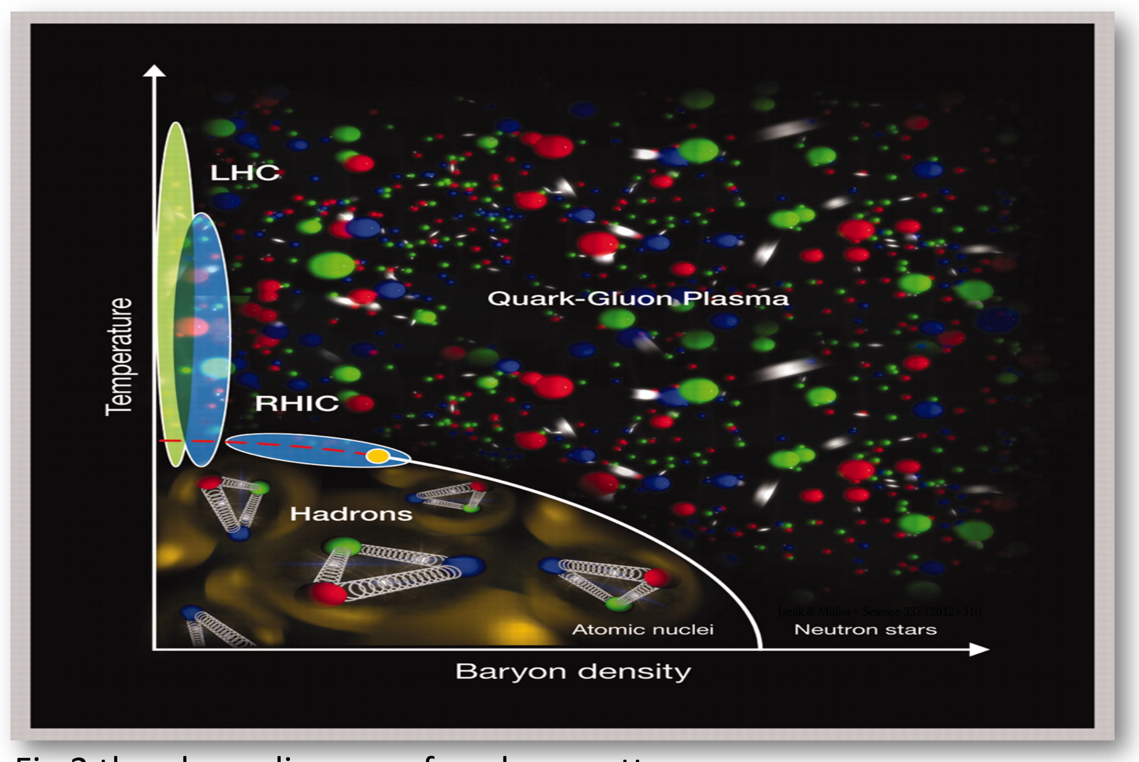


Fig.2 the phase diagram of nuclear matter Jacak & Müller – Science 337 (2012) 310

The STAR Experiment

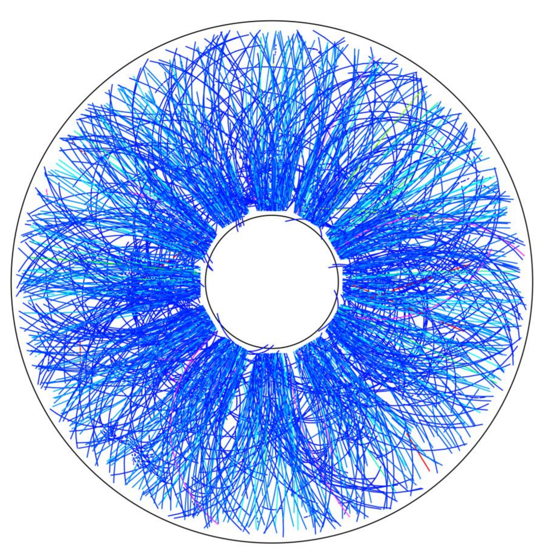


Fig.4 The tracks of a single Au+ Au collision https://www.star.bnl.gov/central/physics/

- Au+Au collisions in the Relativistic Heavy-Ion Collider at BNL create mini Big Bangs in the lab
- Baryon and mesons are created when the QGP quickly cools down.
- Here, a QGP only lasts for 30-50 yoctoseconds (1 yoctosec = 10^{-24} sec!!)
- STAR detects and identifies many types of particles.

To identify particles, we have to determine their mass and charge.

One method is to measure its time-of –flight, momentum, and path length.

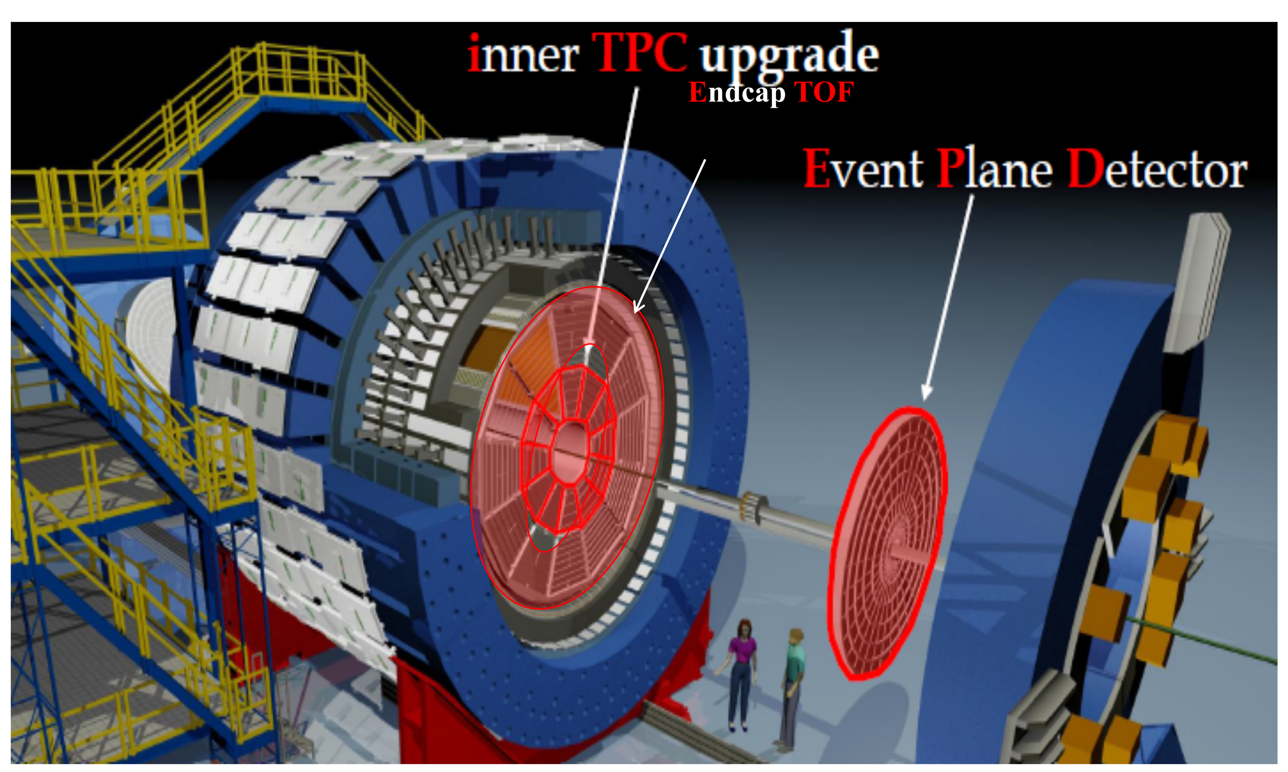


Fig.5 The main detectors in STAR https://www.star.bnl.gov/central/experiment/

Example: If a particle is accelerated and its energy becomes 100GeV then the velocity of the particle is 99.996% of the speed of light.

Considering the special relativity…

$$m = p\frac{1}{v}\sqrt{1-\frac{v^2}{c^2}} \quad \left(v=\frac{s}{\Delta t}\right)$$

m: mass, p: momentum, v: velocity

s: flight length, Δt: time of flight, c: speed of light

$$\frac{1}{\beta}=\frac{v}{c}=\sqrt{\frac{m^2}{p^2}+1} \quad -(*)$$

→ 1/β vs p graph (Fig.6) can distinguish the type of particles.

Results

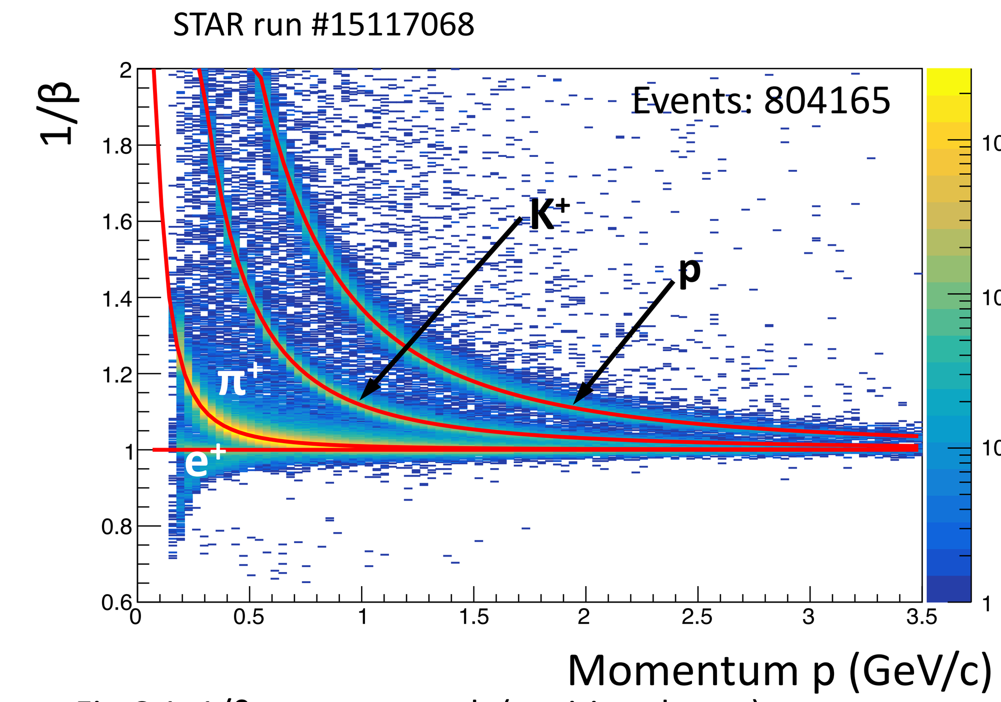


Fig.6.1 1/β versus p graph (positive charge)

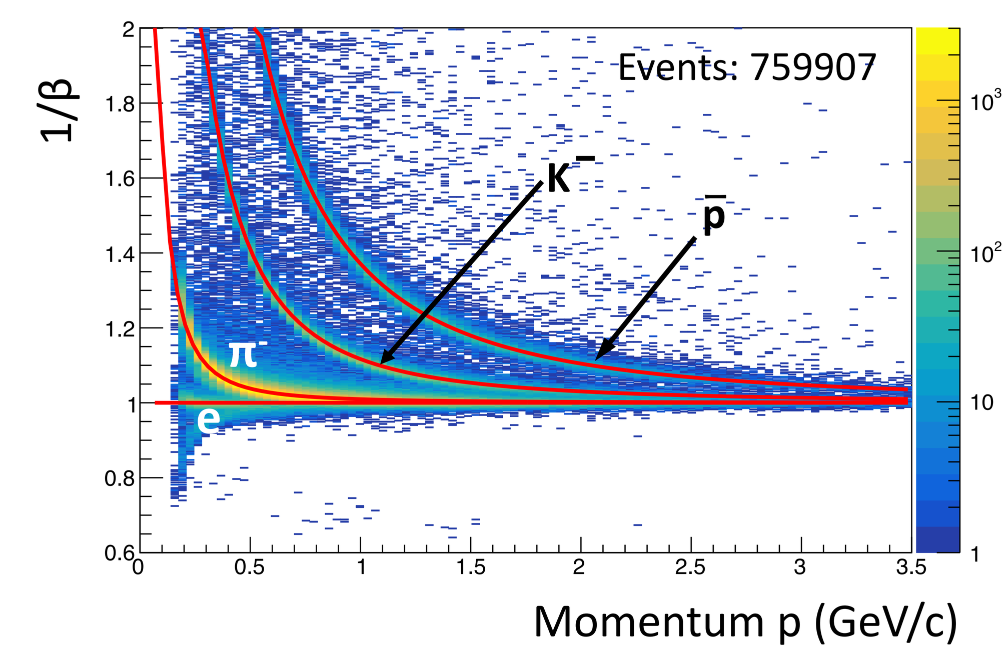


Fig.6.2 1/β versus p graph (negative charge)

- Fig.5-1,2 made with ROOT, a modular scientific software toolkit data is 7,500 out of >10^9 Au+Au collisions taken in 2014.
- Figures shows the distribution of measured particles (positive and negative charge) with each 1/β and momentum p (GeV/c).
- more than 1.5 million tracks (particles!) in these figures.
- The red line is the theoretical line by using equation (∗),
- Each theoretical line was drawn by substituting the value of the rest mass (see table 7)
- The color shows how many particles were detected with that momentum and that 1/β. Considering the color bar with log scale, pion was detected the most.

proton: is made of 3 quarks ($uud, \bar{u}\bar{u}\bar{d}$).
kaon: is made of 2 quarks ($u\bar{s}, \bar{u}s$)
pion: is made of 2 quarks. ($u\bar{d}, \bar{u}d$)
electron : can't divided anymore (called lepton)

Table 7 Rest mass of each particle

Particle	Rest Mass (MeV/c²)
electron (e)	0.511
pion (π)	139
kaon (K)	497
proton (p)	938

http://pdg.lbl.gov/2018/reviews/contents_sports.html

Discussion

- We can identify 8 particles: proton, antiproton, electron, positron, K^+, K^- and π^+, π^-).
- pion is a meson (a particle made of 2 quarks) and the lightest of all the 3 hadrons. → It is the easiest to produce pion.
- The rest mass of the electron is so light that the graph is almost straight.
- Measurements agree with theoretical expectation.
- N(pos)≅N(neg)
- Slightly more positively charged particles because Au-ion is positively charged and charge is conserved.

Future Research

The STAR experiment and this analyzing data leads to the solution of the following questions:

- What are the properties of a strongly interacting nuclear many-body system in very high temperatures?
- What does the phase diagram of QCD matter look like?
- What are the properties of the phase transition?
- Is there also a QGP in neutron star collision?

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