Quark Gluon Plasma & Heavy Ion Collisions

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What is QGP?

- A high temperature deconfined state of matter made of non-hadronized quarks and gluons.
- Theorized to be a weakly coupled ideal gas of interacting quarks and gluons, due to asymptotic freedom.
- Found to be a strongly coupled plasma in experiments instead of a weakly interacting ultra-relativistic gas.

Asymptotic Freedom

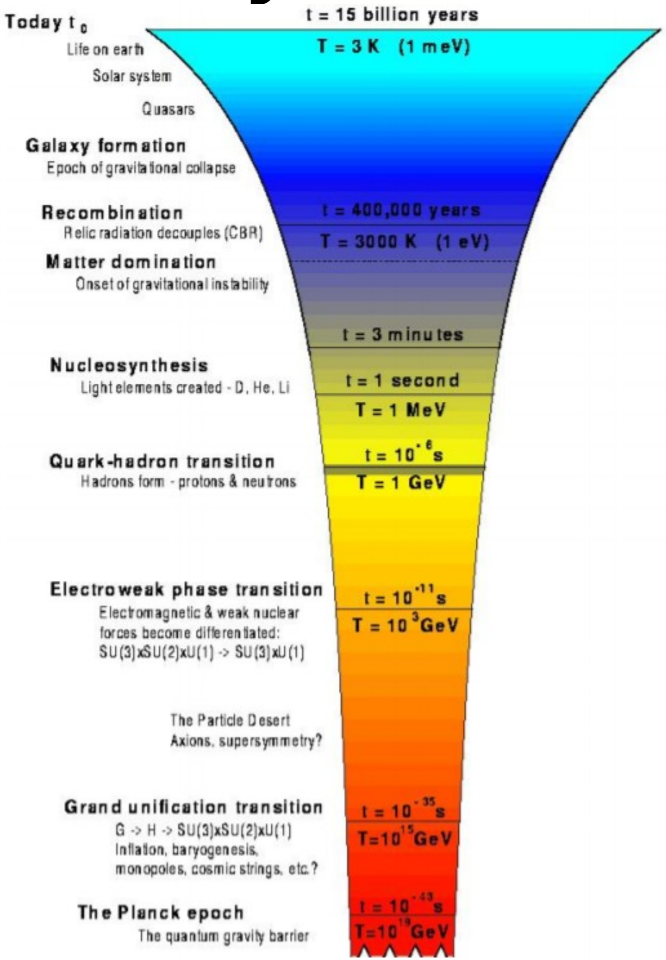
- In QCD, the coupling constant becomes weak at close range and high energy.

$$\alpha(|q^2|) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(11n - 2f)\ln\left(|q^2|/\mu^2\right)}$$

- Where q is the energy, n is the number of colours and f is the number of flavours. μ^2 is the mass scale parameter for the running constant (since at $q^2 = 0$ the constant is large and QCD is incalculable).

Spontaneous Symmetry Breaking

- 10^{-11}s at T~100GeV (~10^{15}K) electroweak phase transition. Particles acquire mass.
- 10^{-5}s at T~200MeV (~10^{12}K) strong phase transition. spontaneously breaking approximate chiral symmetry.
- In QGP, symmetry is approximately restored, owing to the strongly coupled plasma interaction observed.



Why Study QGP?

- QCD in cosmology: Study QCD in extremely hot and dense state (liquid like properties).
- QCD Phase Diagram: Understanding transitions of hot matter according to QCD scales.
- Complex Quantum Matter: Study earliest form of complex matter, and how it emerges from earlier weakly coupled high temperature state of quarks and gluons.

How do we produce QGP?

- Due to the high temperature and dense nature of QGP, we need high energies to produce it. Heavy Ion Collisions are a method of doing so.
- First produced in BEVALAC at Lawrence Berkeley National Laboratory with gold ions, then later produced at the RHIC and later at the LHC at 2.76TeV and 5.02TeV.

Ions of lead or gold are collided in a high energy collider.

Choose heavy spherical shaped ions to simplify collision geometry.

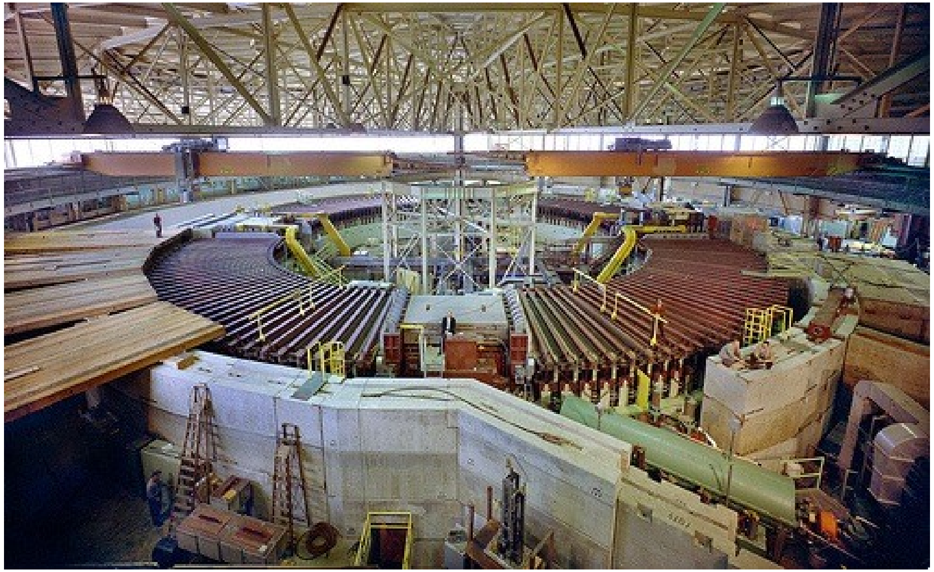
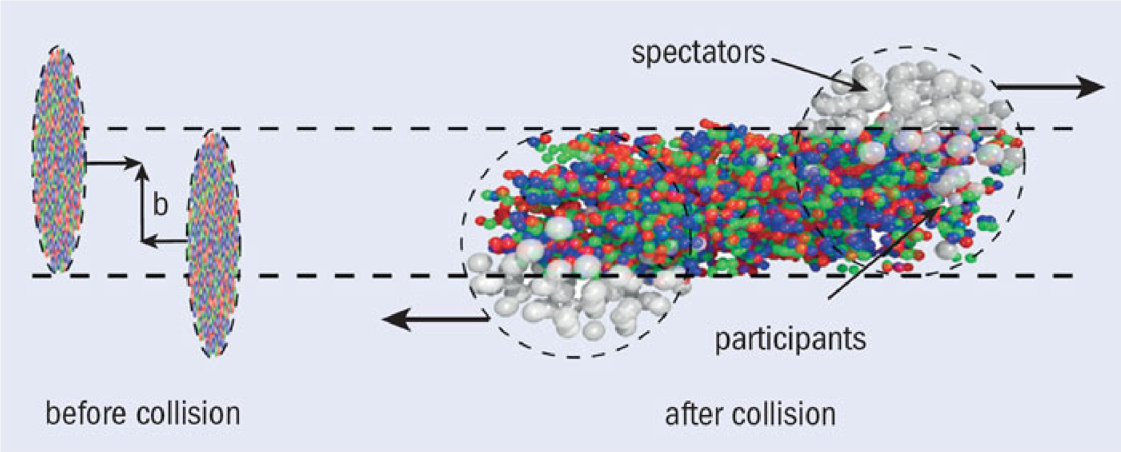


Figure: BEVALAC. *"Physics Today"* 2009

Heavy Ion Collisions

- Length contracted ions of Pb^{208} are collided, usually off center, leading to anisotropic distribution of partons.
- QGP droplet produced from the participants, usually called a “fireball”.



Off axis heavy ion collision

Figure: From Snellings, R. “*Elliptic Flow: A Brief Review*”

Reaction Plane

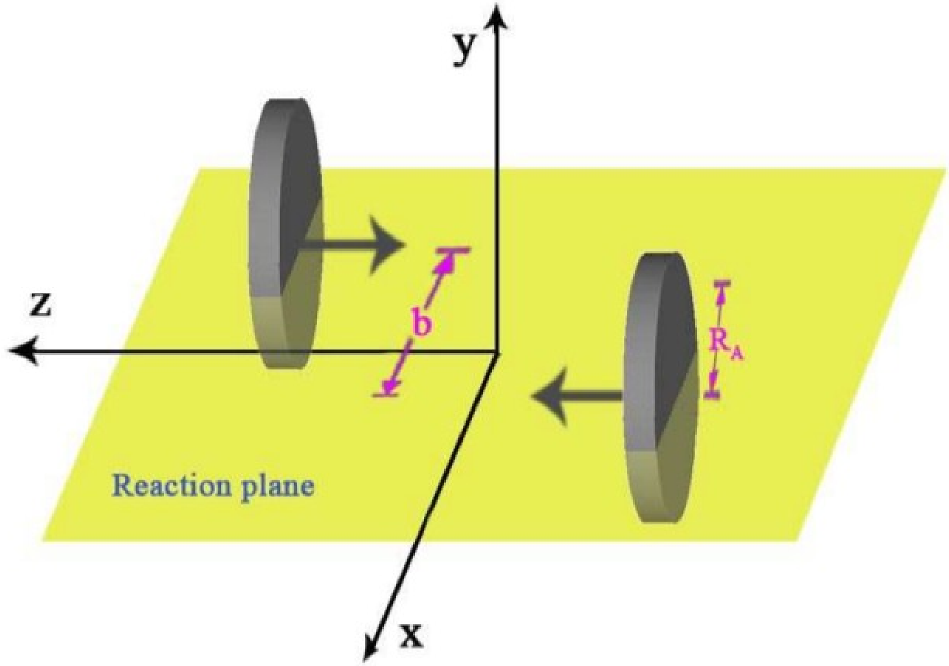


Figure: Huang, X. et al.

Plane defined by product of z-axis and impact parameter b.

Reaction plane makes angle Ψ_R relative to the x axis.

Formation of Matter

- QCD predicts asymptotic free nature of matter that quarks and gluons are weakly coupled ultra-relativistic ideal gas.
- Phase changes occur from hadronic, to thermalized and hydrodynamized system of a QGP droplet.
- When the QGP falls under ~155MeV, there is a hadronization phase crossover.
- Unknown whether the hadrons form in chemical equilibrium or quickly equilibrate after formation.

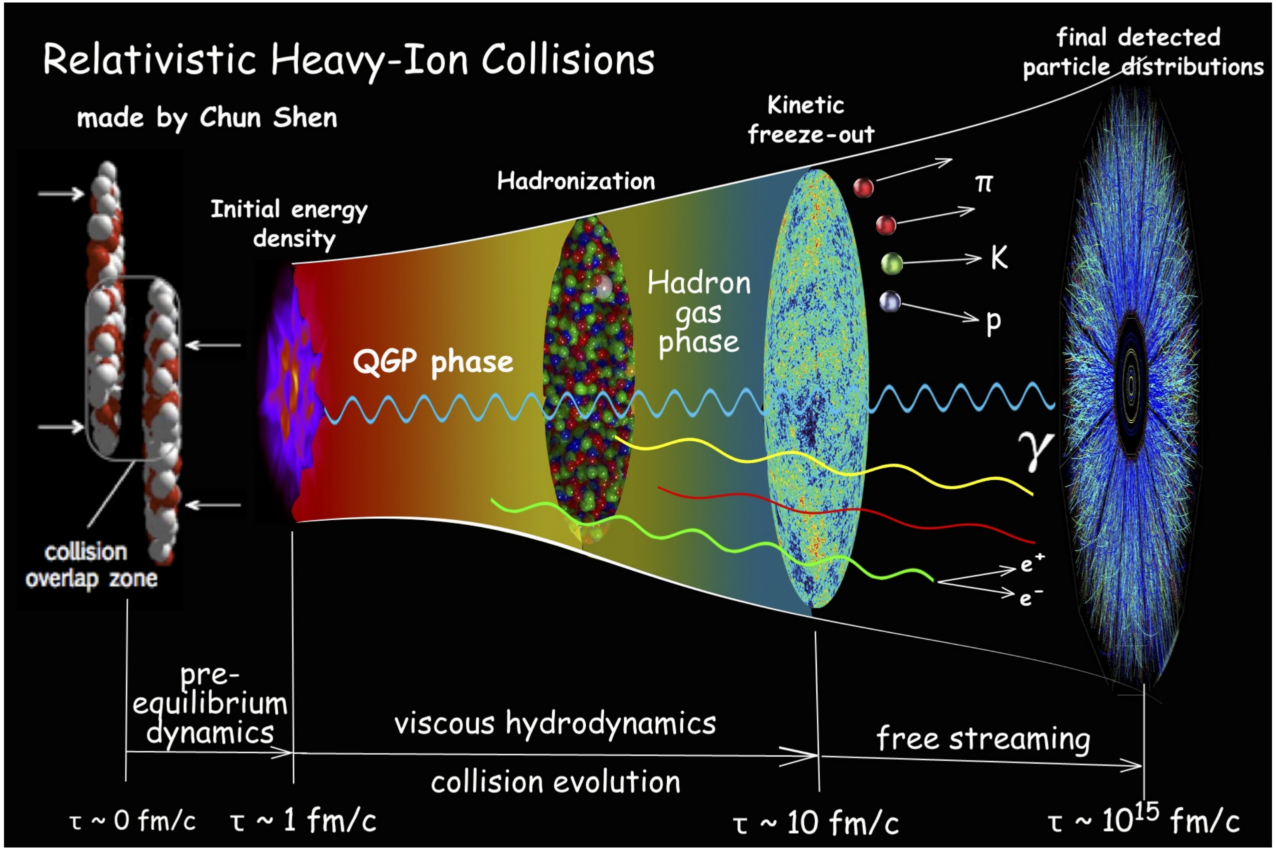


Figure: Shen,C and Heinz, U. 2015.

Experimental Challenges

- Only two parameters under control in HIC: Nuclei used and the energy.
- In p+p collisions, total of 50 on average particle collisions at 13 TeV in the LHC. In one nuclei collision of Pb^{208}, up to 416 hadrons involved.
- Computational challenging due to large distribution of partons involved, requiring a hydrodynamic approach to better model the system.

Elliptic Flow

- Flow is the collective motion of particles.
- In central collisions, the resulting particle production is isotropically distributed and no elliptic flow is observed.
- Most collisions are non-central, thus an anisotropic particle production observed. This asymmetry into a momentum anisotropy of the propagating bulk matter in the azimuthal directions.
- Observation of elliptic flow confirms fluid like property of QGP.

Jet Quenching

- Produced jets in the fireball dissipate energy as they pass through the fluid, broadening the cone of the jet.
- The energy loss corresponds to a large dE/dx, which provides direct evidence of the strongly coupled nature of the produced QGP.
- Due to anisotropy of hadronizing particles from the cooling QGP, jets are asymmetric in energy.

Jet Quenching

γ-jet

jet

Example of jet quenching of paired photon-jet

Different energies of the photon jet pair as noted in image information

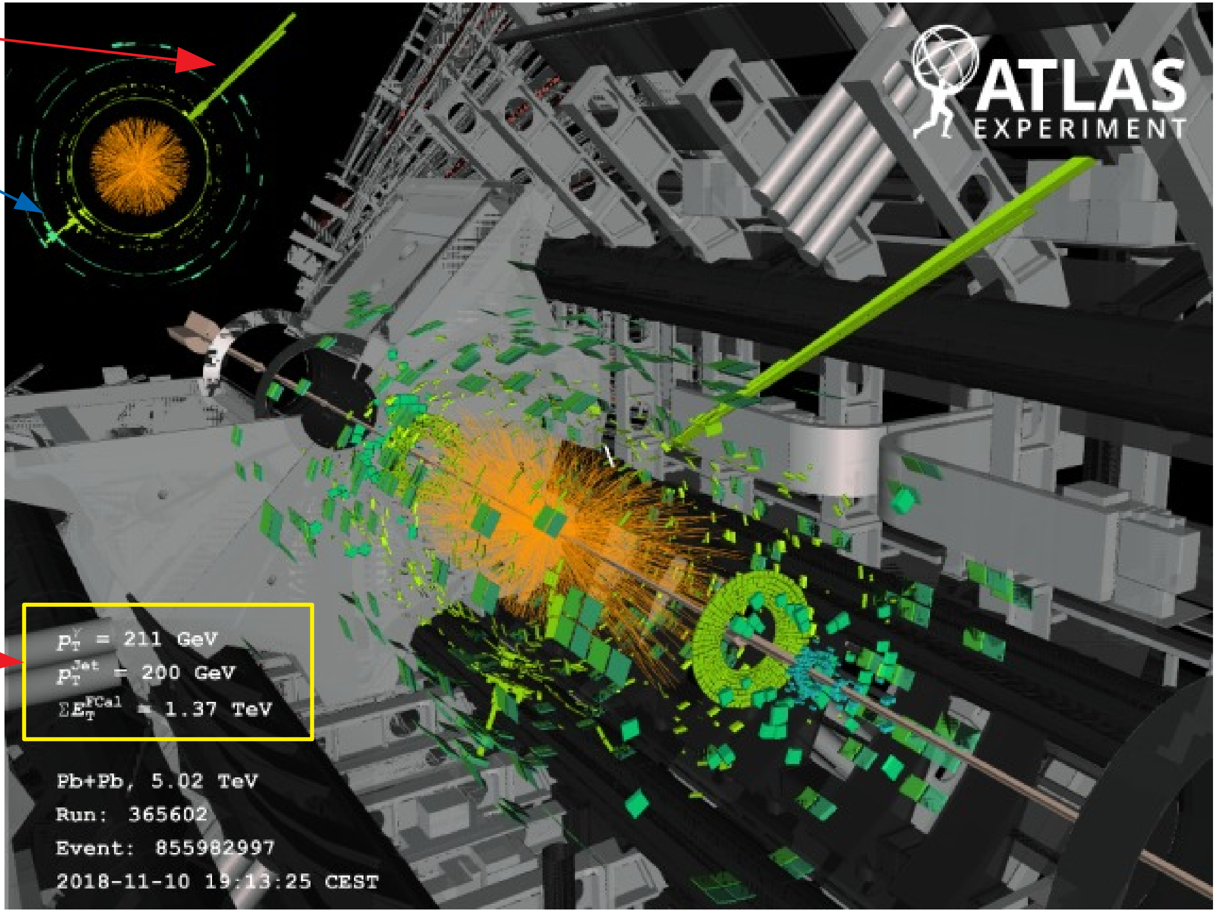


Figure: 2018 Heavy Ion Collision event (365602,855982997) Photon-Jet

Hydrodynamic Properties

- QGP has hydrodynamic properties of an ultra-relativistic fluid:
- shear viscosity η is a measurement of the resistance of the fluid flow.
- specific viscosity η/s where s is the entropy density. The ratio plays a central role of hydrodynamics equations in the governing the amount of entropy in a fluid as it flows.

Hydrodynamic Properties

Extremely low specific viscosity, an almost perfect fluid.

Hydronamical model is consistent with the gradient expansion of the QGP fluid, with small gradients in temperature and velocity. Able to model the anisotropic distribution of the partons.

Can measure the anisotropic distribution of particles in the elliptic flows.

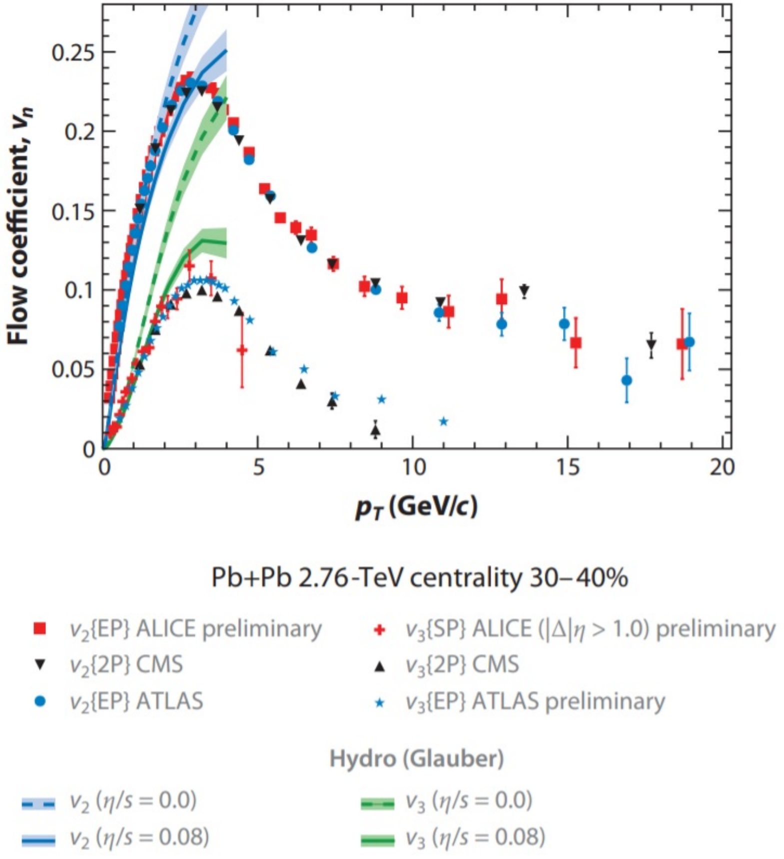
$$\frac{d\bar{N}}{d\varphi} = \frac{\bar{N}}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} \bar{v}_n \cos(n(\varphi - \bar{\Psi}_n))\right)$$

$\bar{N}$ is average number of charged hadrons in the event, $\bar{\Psi}_n$ is the angle of the reaction plane of beam line and impact parameter, φ is the azimuthal angle, n the harmonic component and the flow coefficients $\overline{v}_n$.

$$\bar{v}_n = \left\langle \cos\left(n\left(\varphi - \bar{\Psi}_n\right)\right)\right\rangle$$

Where the brackets denote a sum over all particles in a (p_T,η) bin.

Flow Coefficient Plots



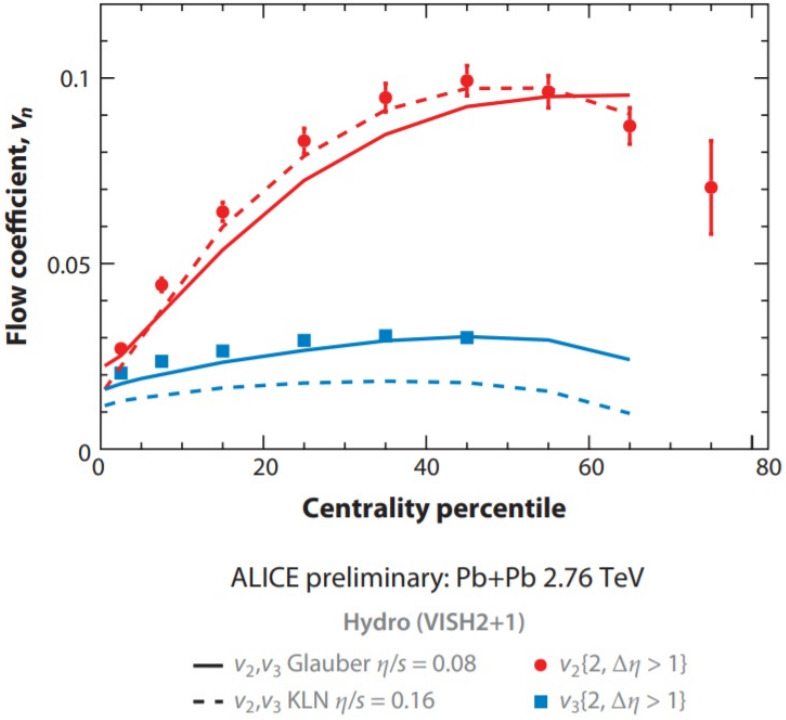


Figure: Mueller, B. "*First Results from Pb+Pb Collisions at the LHC*".2012

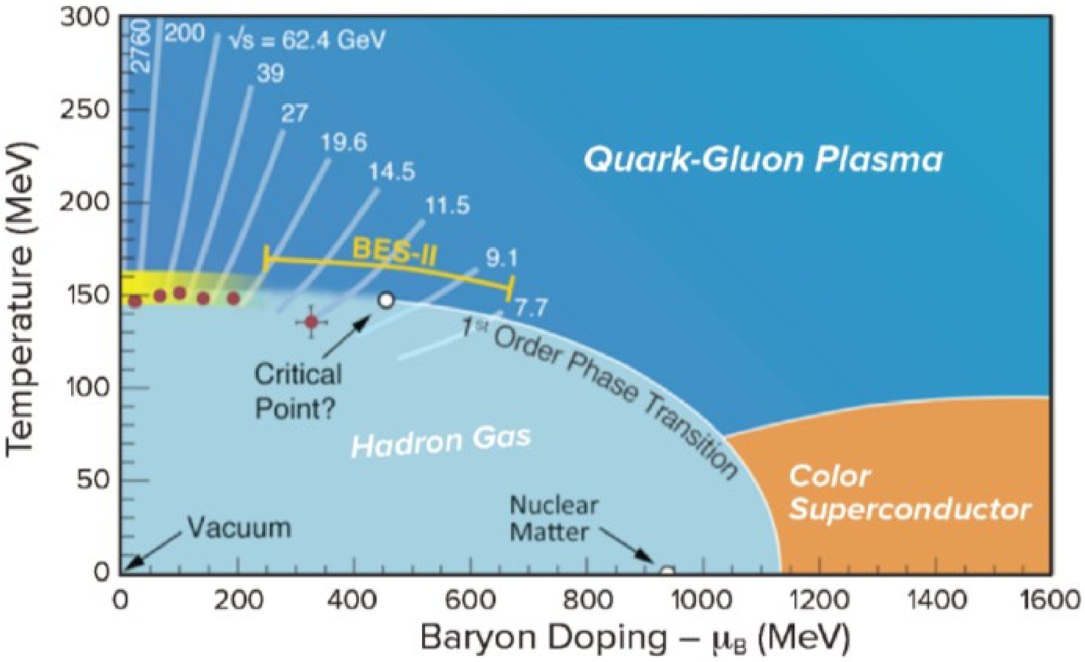
Phase Diagram

Matter to QGP phase transition occurs around 160-170MeV for μ_B=0.

Need to determine if there is a smooth crossover or if there is a first order QCD critical point transition to QGP.

Possible colour superconductor phase of quark Cooper pairs to be examined.

Figure: Busza, W. et al.



μ_B – the excess of quarks over anti-quarks parameterized by the chemical potential

Future Goals

- Analysis of jets in heavy ion collisions may yield insights into how QGP forms as a function of time in addition to revealing how QGP emerges as we coarsen the resolution scale of the microscope with which we probe.
- Understanding the QCD what the regions of phase transitions are and whether they are critical points.
- Possible lower bound of specific viscosity at $1/4\pi$ using Ads/CFT correspondence of strongly interacting systems of QGP.

Questions?

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Quarkonium Suppression

- Heavy quark chirality symmetry still broken in QGP, still hadronize.
- Heavy quarkonia production supressed in HIC compared to pp collisions.