U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

Searching for and understanding the quark-gluon plasma in heavy-ion collisions

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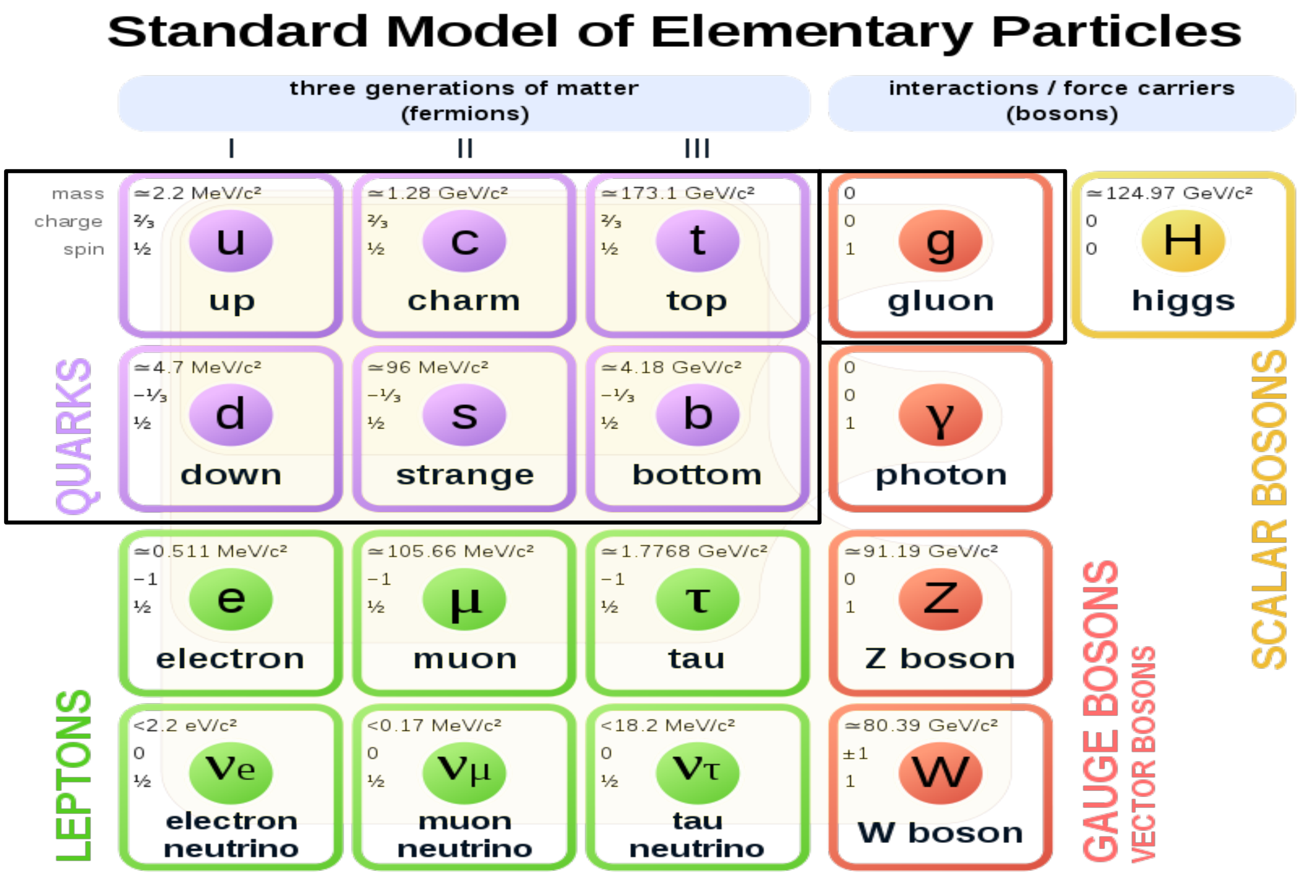
07/28/2020

Summer Student Lecture



- Color-confinement: all visible matter are color neutral

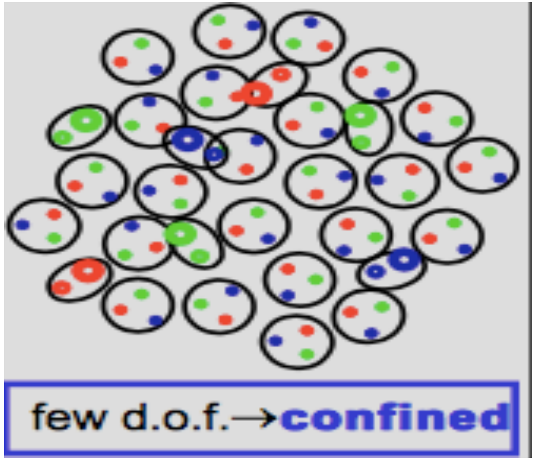
Quark-Gluon Plasma (QGP)

- **Quark-gluon plasma**: a state of matter, consisting of *asymptotically free moving quarks and gluons* which are ordinarily confined within nucleons by *color confinement*.

https://today.uic.edu/collider-reveals-sharp-change-from-quark-soup-to-atoms

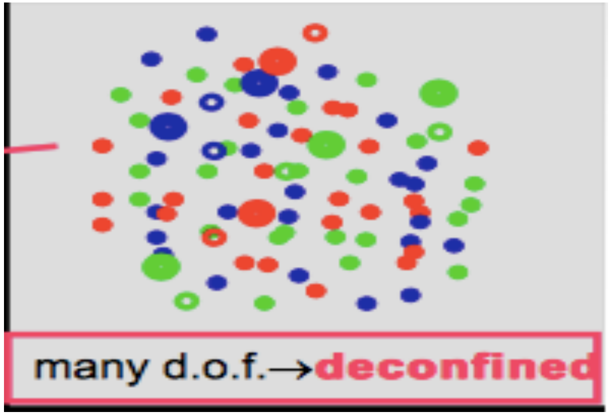
Quark-Gluon Plasma (QGP)

- This state is believed to exist at extremely high temperature and/or density



Phase transition

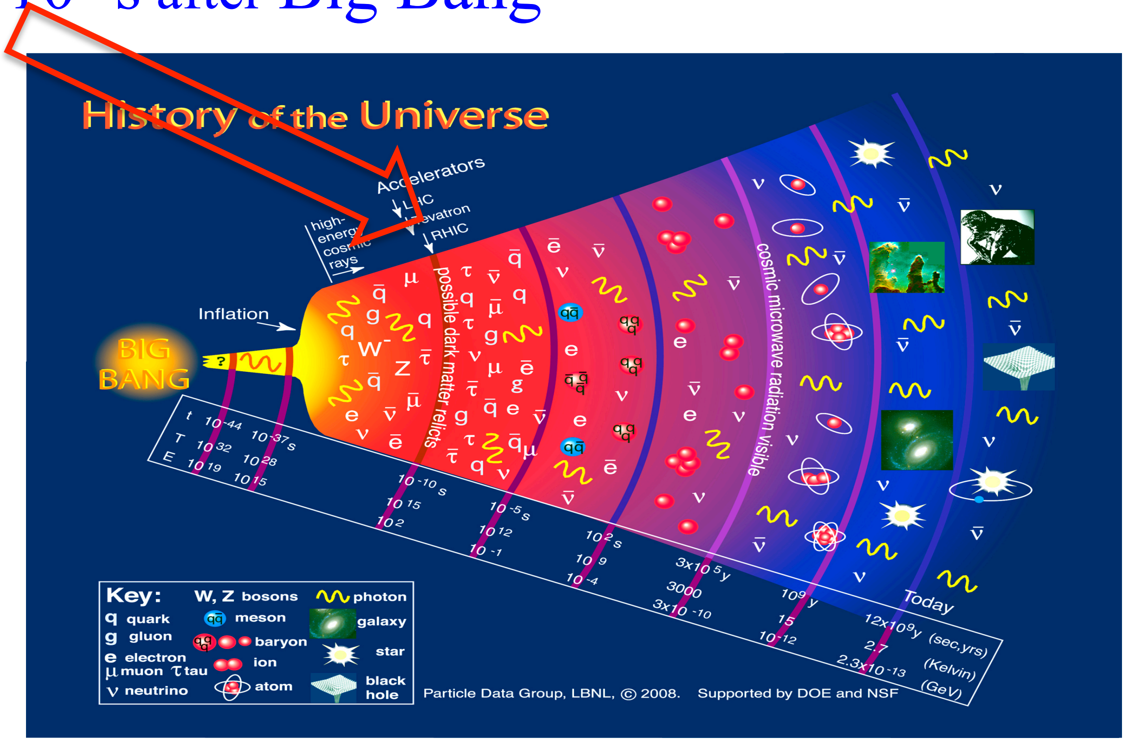
– $T_c \sim 165$ MeV



Core of sun: 1.5e7 K
$T_C \sim$ 2e12 K

Why is QGP interesting?

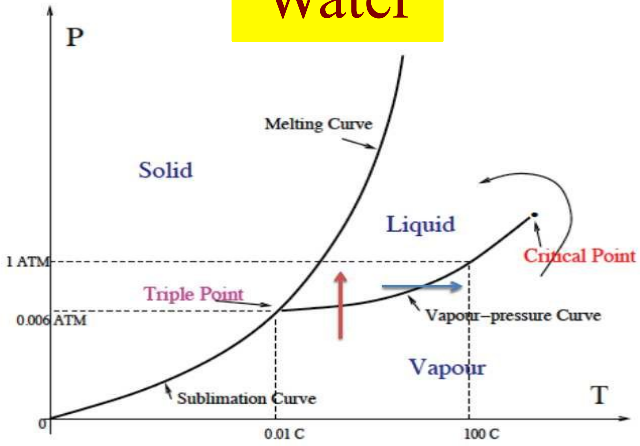
- Existed 10^{-6}s after Big Bang



Why is QGP interesting?

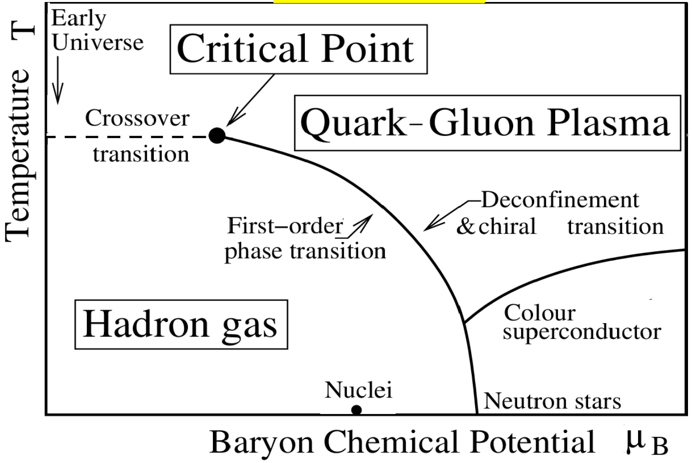
- **A rich QCD lab**
  - What does the QCD phase diagram look like? What QCD dynamics drives it?
  - …

Water



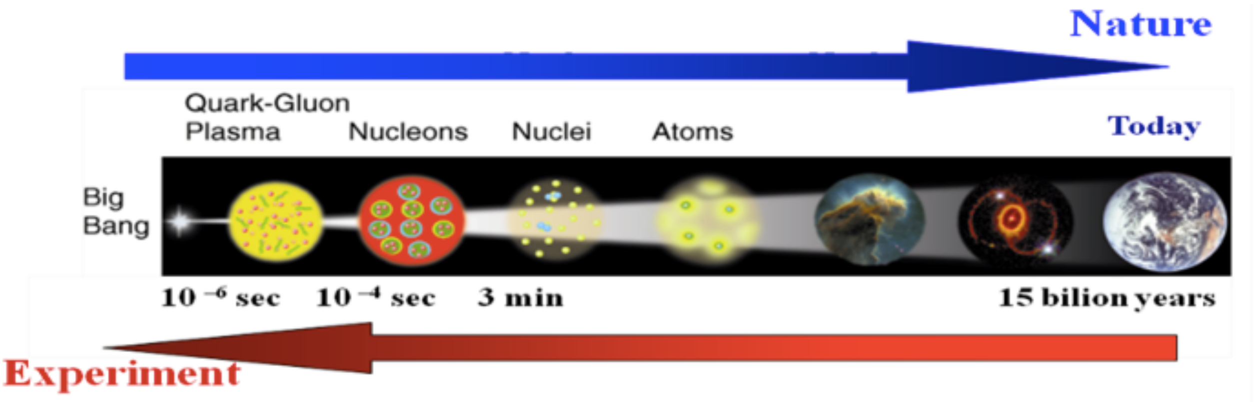
VS.

QCD



How to study QGP?

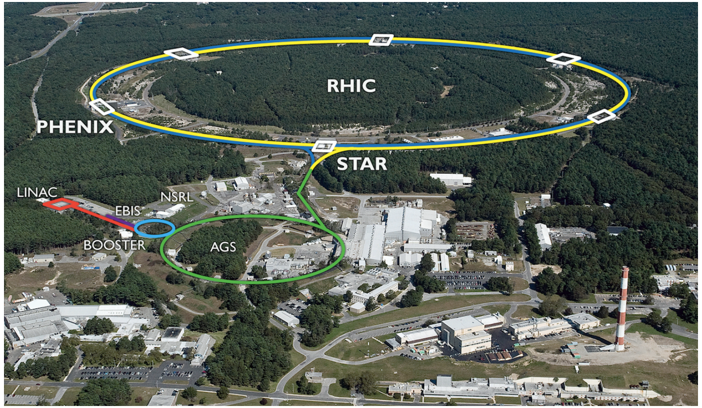
- **Re-create QGP in a lab**



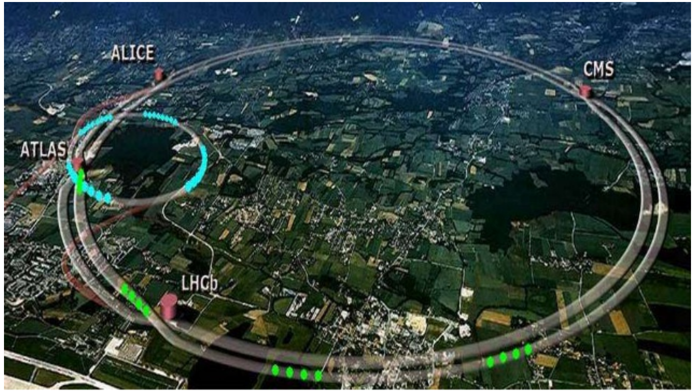
Create the QGP in a lab

- **Heavy-ion collisions**
  - T.D. Lee, 1974: We should investigate phenomena by distributing high energy or high nucleon density over a relatively large volume

RHIC: Au+Au

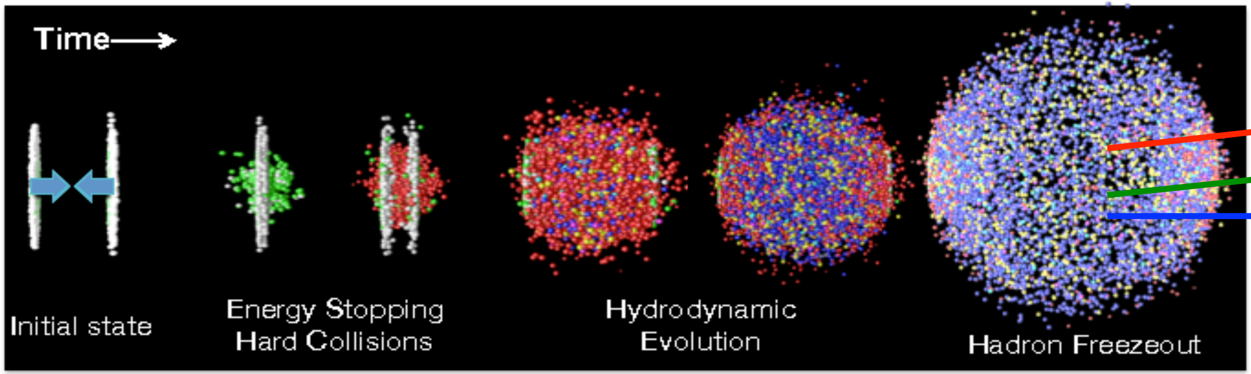


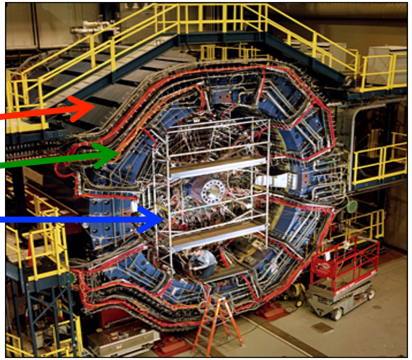
LHC: Pb+Pb



Study QGP in a lab

Heavy-ion collisions





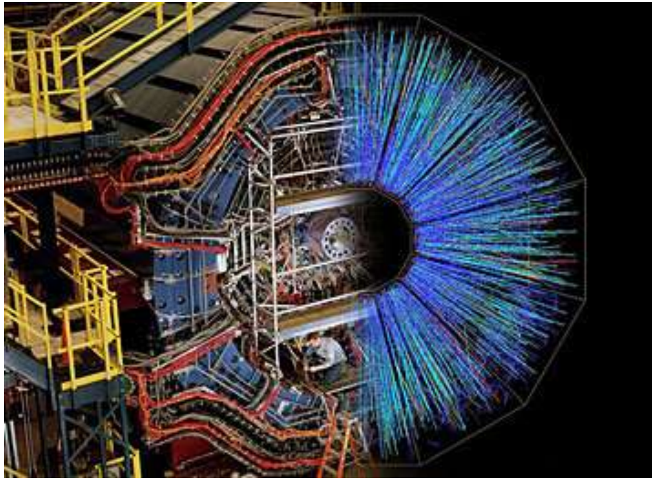
- How to measure final-state particles? → Detectors

General requirements for detectors

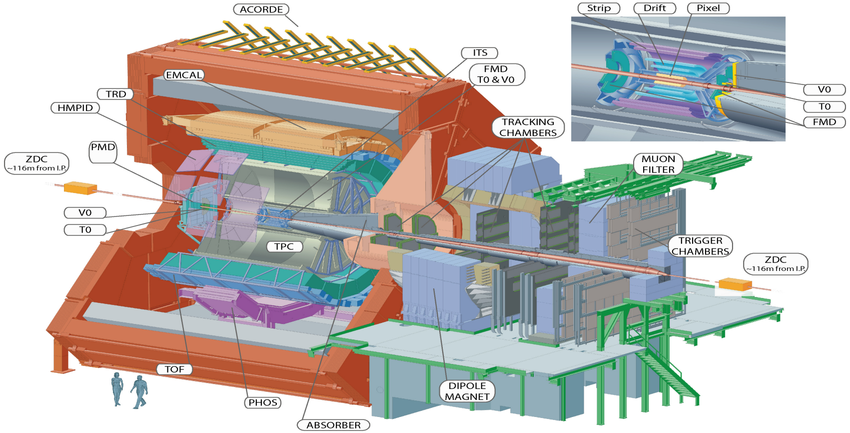
- Large acceptance
- High efficiency
  - measure as many particles as one can in acceptance
- High resolution
  - measure particles' properties as precise as one can
- *Particle identification capability*
  - identify particle species, e.g. pions, kaons, protons, etc

Heavy-ion experiments

STAR @ RHIC



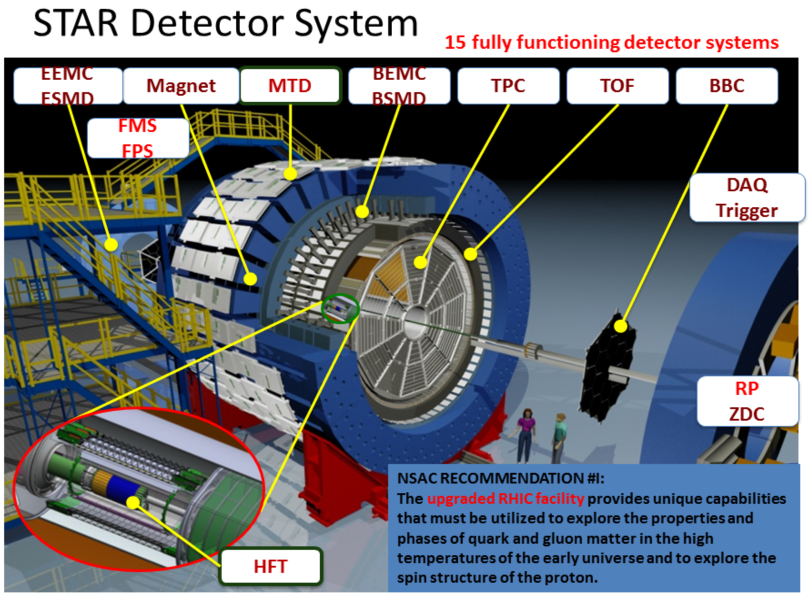
ALICE @ LHC



- RHIC: PHENIX shut down in 2016
- LHC: CMS, ATLAS and LHCb also take heavy-ion data

STAR @ RHIC

- Heavy-ion collisions happen at the center of STAR
- Cylindrical shape; magnet sits at radius ~ 3 m

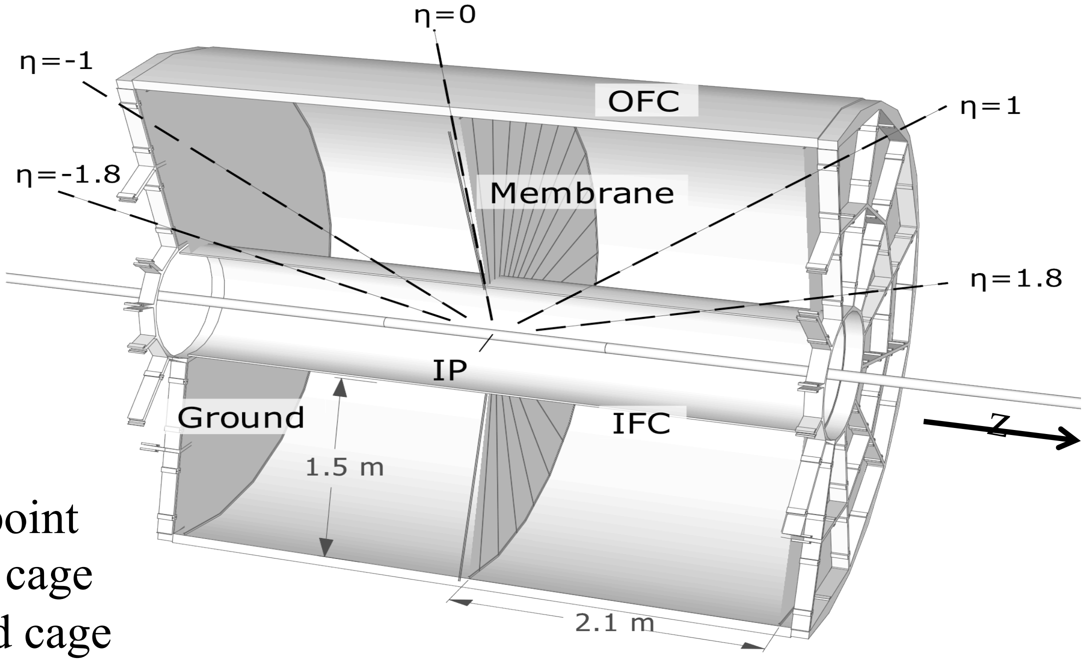


X10^3 increases in DAQ rate since 2000, most precise Silicon Detector (HFT)

- Complexity
  - Many different sub-components serving different purposes
  - Hundreds of thousands of readout channels

Time Projection Chamber

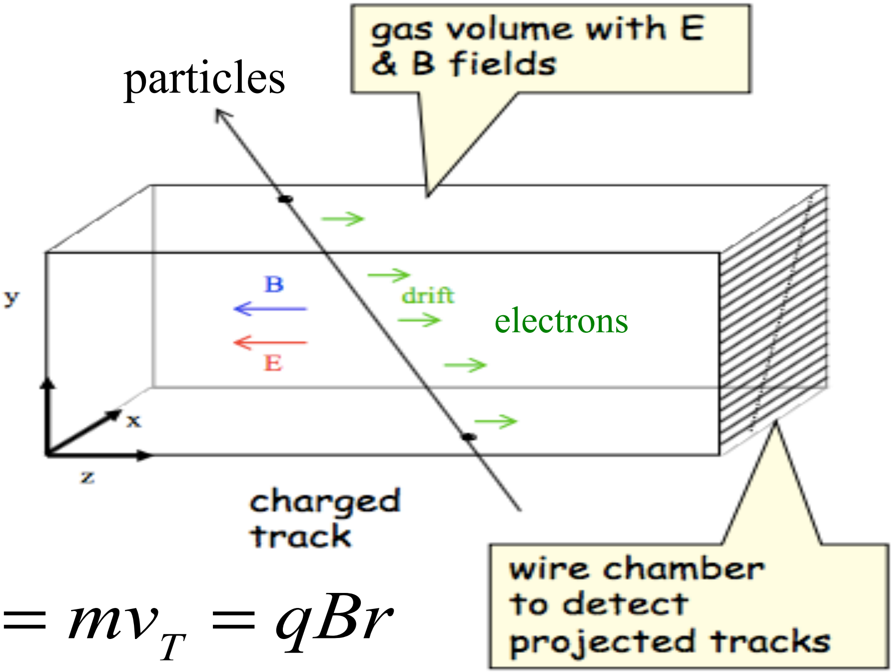
- Gas detector taking 3D photos of the tracks of passing charged particles



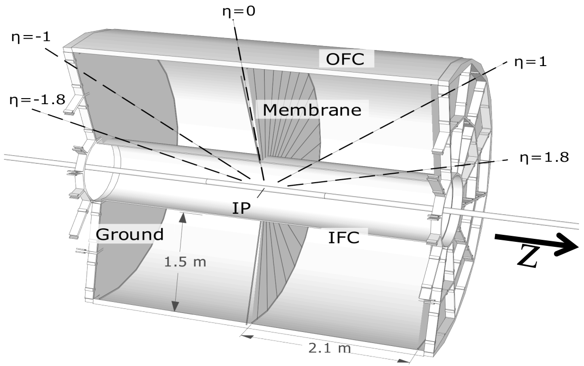
IP: interaction point
IFC: inner field cage
OFC: outer field cage

Time Projection Chamber

- Gas detector taking 3D photos of the tracks of passing charged particles



$$p_T = mv_T = qBr$$

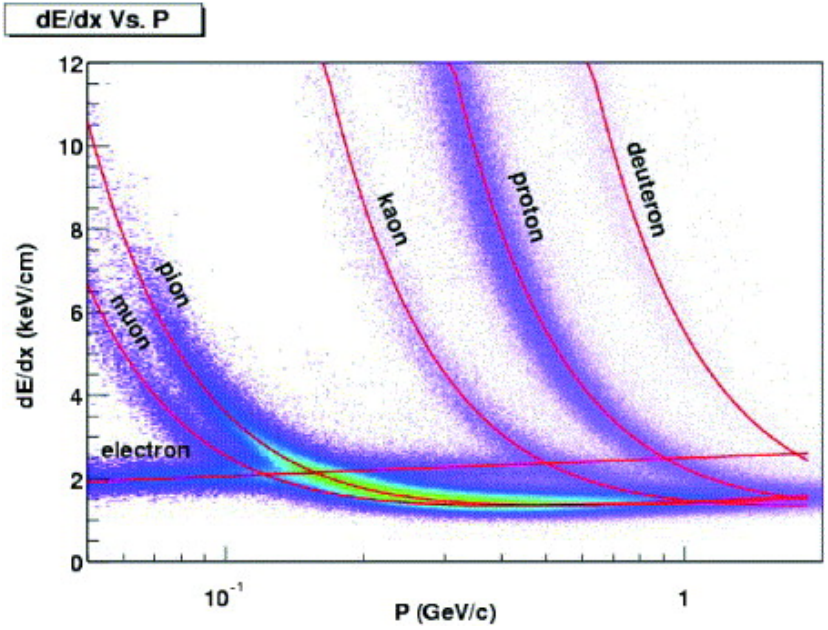


- Particles ionize gas and produce electrons
- Trajectory → momentum & charge

Can TPC measure neutron's momentum?

Time Projection Chamber

- Gas detector taking 3D photos of the tracks of passing charged particles

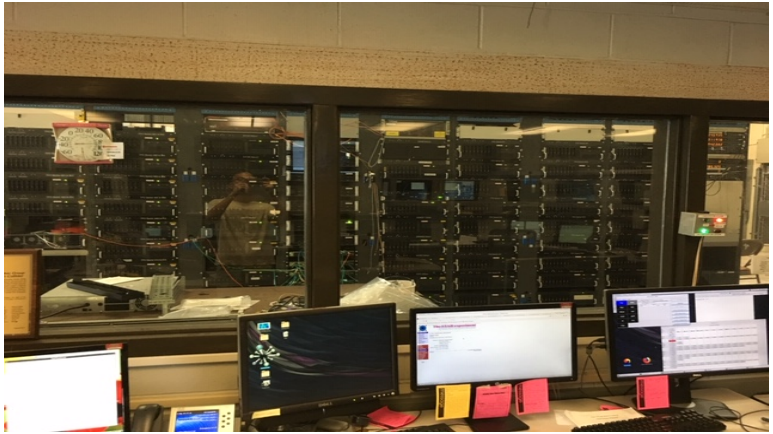


- Energy loss in the TPC is determined by particle species
- Number of drifted electrons is proportional to the energy loss
- Limited at higher momenta

From electronic signal to physics

1) Data taking

- Usually in the first half of a year
- 24/7 4-person shift to take data and monitor the status of detectors
- Rates: ~2 kHz for Au+Au @ 200 GeV, 500 TB/week



From electronic signal to physics

1) Data taking

- Usually in the first half of a year
- 24/7 4-person shift to take data and monitor the status of detectors
- Rates: ~2 kHz for Au+Au @ 200 GeV, 500 TB/week

2) Calibration

- Convert electronic signal to physical quantities, such as energy

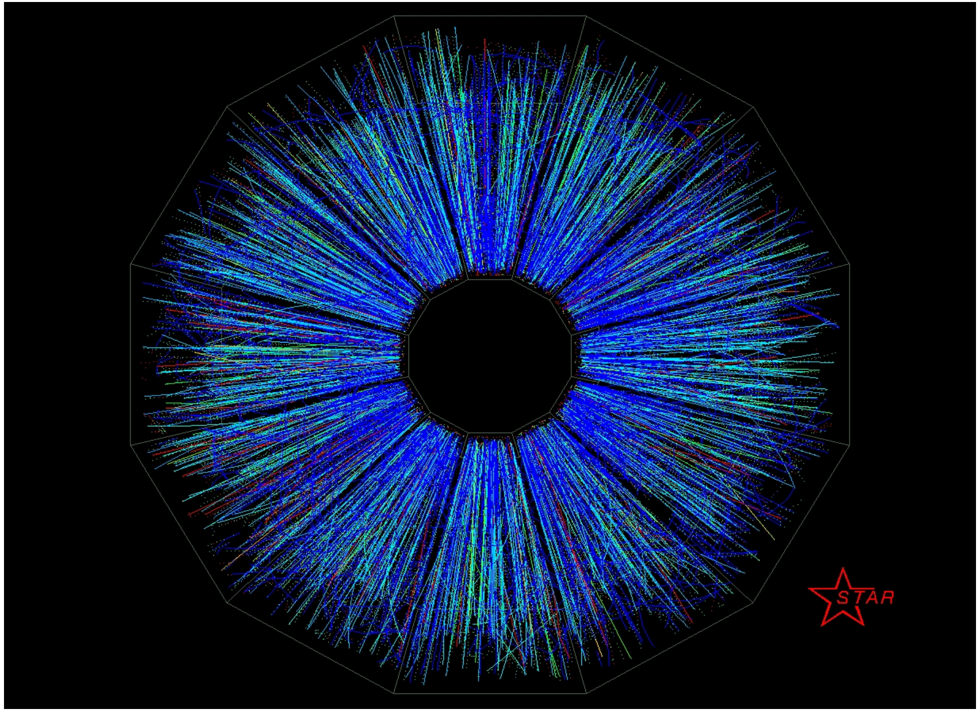
3) Data production

- Vertex: position where the collision happens
- Charged particles: momentum, position, charge …

4) Analysis

- Correct for detector acceptance, efficiency and resolution

A real event taken by STAR



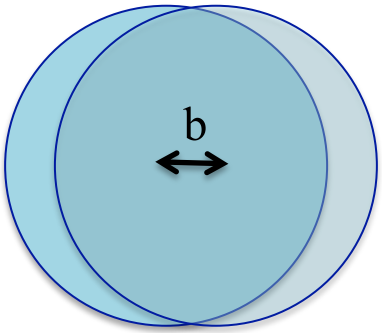
Characterize QGP

- Global properties
  - Bulk of produced particles, mainly of low energies
- Penetrating probes of high energies
  - Analogous to shooting laser through a volume of gas
  - External probes not possible due to QGP's short life time ($\sim 10^{-23}$ s)
- *Which group has more particles? Why?*

Centrality

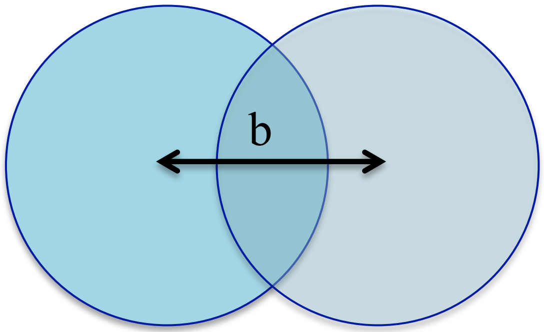
- Used to quantify how much the colliding ions overlap

central



VS.

peripheral



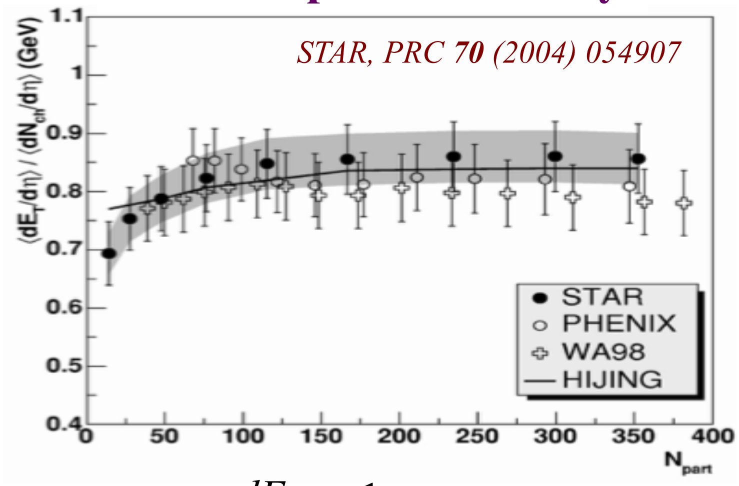
- Head-on
- Smaller b
- **Larger/hotter medium**

- Glance through
- Larger b
- Smaller/no medium

Initial energy & temperature

- Recall: $\varepsilon_c \sim 1$ GeV/fm^3; $T_c \sim 165$ MeV

Measure particle density

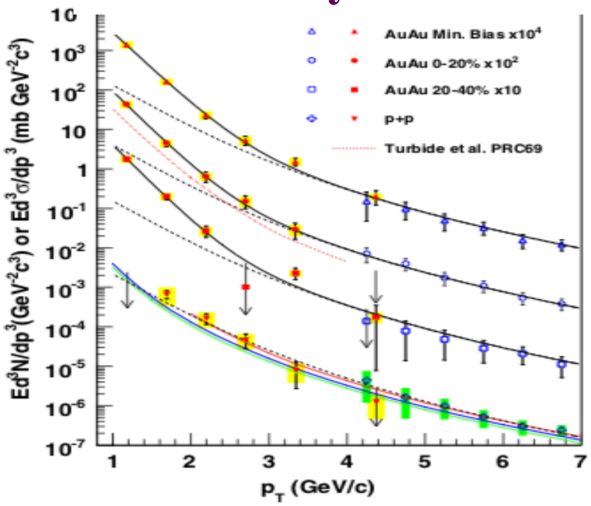


$$\varepsilon_0 = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$

$$\tau_0 \sim 1 \text{ fm}/c,\ R \approx 1.2 A^{1/3} \text{ fm}$$

$$\varepsilon_0 = 4.9 \pm 0.3 \text{ GeV/fm}^3$$

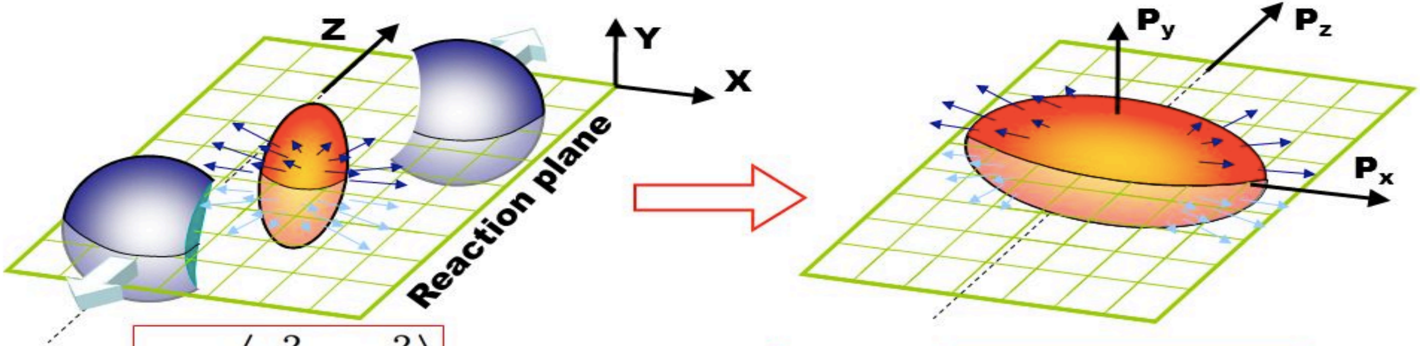
Black-body radiation



- $T \sim 221$ MeV for central collisions
- $T_0 = 1.5\text{-}3 \times T$

PHENIX: PRL 104 (2010) 132301

Elliptic flow (v_2)

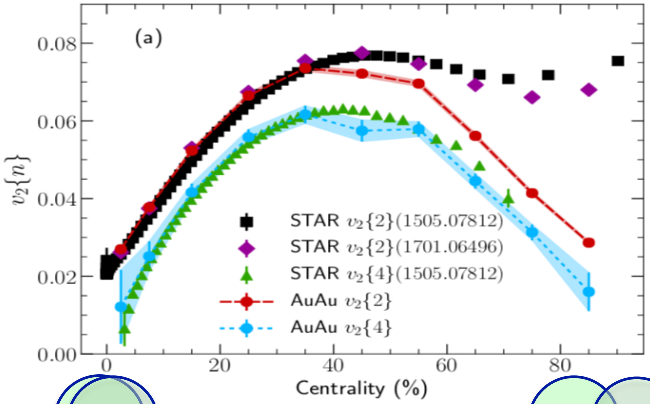


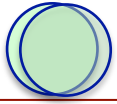
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \Rightarrow v_2 = \langle \cos 2\phi \rangle$$

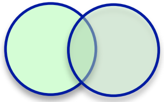
- Spatial asymmetry → yield asymmetry in azimuth
  - Different pressure gradients along x- and y-direction
  - Depends on overlapping geometry, etc

A nearly “perfect” fluid

B. Schenke, et. al, PRC 99 (2019) 044908

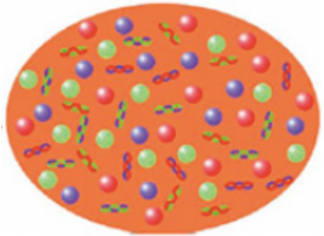






- Described by theory calculation for nearly “perfect” fluid
- Initial space asymmetry is well preserved.

Viscosity



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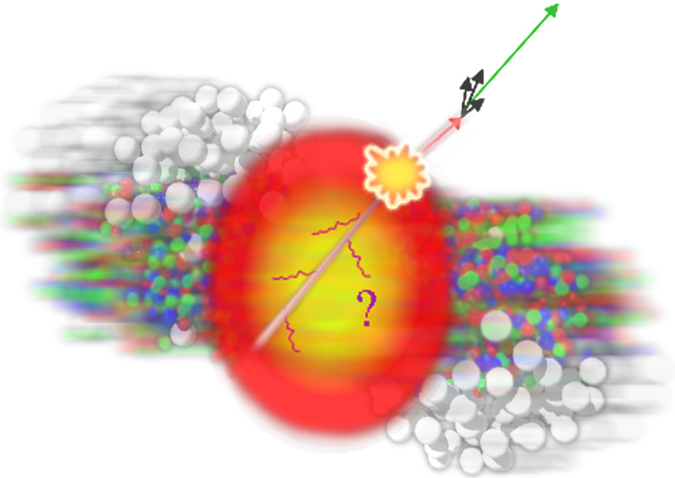
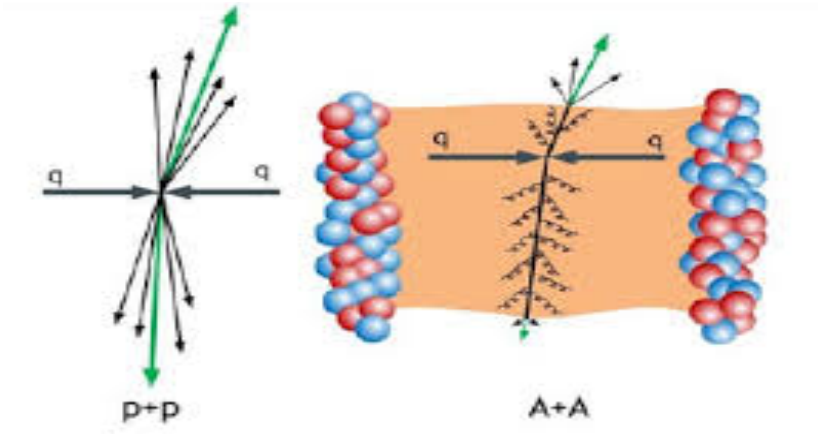
Jet quenching

- High energy quarks and gluons, produced early, traverse the QGP
- QGP is believed to be “opaque” to them; expect **energy loss** due to strong interactions



Nuclear modification factor (R_{AA})

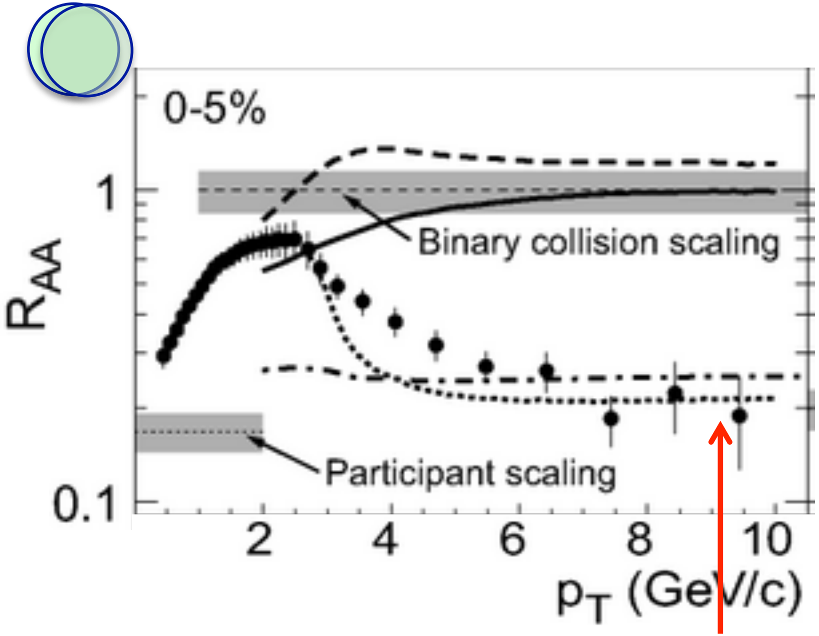


$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{N_{AA}}{N_{pp}}$$

no medium effects → $R_{AA} = 1$

Jet quenching?  → $R_{AA} < 1$

Charged particle R_{AA}



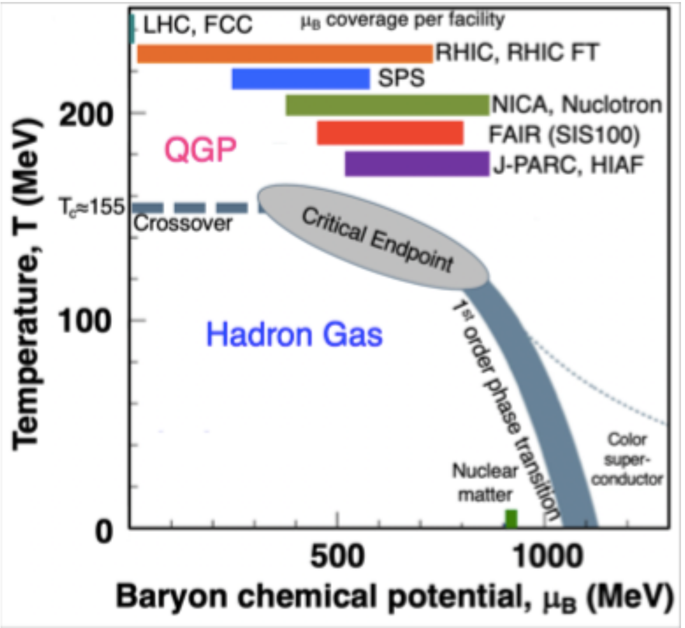
STAR, PRL 91 (2003) 172302

- Up to a factor of 4-5 suppression at large momenta → jet quenching

Will R_{AA} become larger or smaller in peripheral events?

Future of heavy-ion experiments

- **Explore QCD phase diagram and QGP properties** with **detector upgrades, significantly more recorded events and new facilities**



Courtesy of A. Dainese, QM2019

Summary

- What is the Quark-Gluon Plasma (QGP)?
  - ✓ A state of matter with **deconfined** quarks and gluons
- Why is the QGP interesting?
  - ✓ Existed at early Universe; QCD phase diagram
- How to create the QGP in a lab?
  - ✓ Heavy-ion collisions
- How to study the QGP in a lab?
  - How do we access the QGP? → Detectors
  - What have we learnt about the QGP? → "Perfect" fluid; quench jets …
- What is the future of heavy-ion experiments?
  - ✓ Exciting 10 years of physics program ahead and more …
  - ✓ Electron-Ion Collider to be built at BNL

Backup

Future of HI experiments: low √s

- **Explore QCD phase diagram** and QGP properties with detector upgrades, significantly more recorded events and new facilities

Facility	SIS18	HIAF	Nuclotron	J-PARC-HI	SIS100	NICA	RHIC	SPS	SPS
Experiment	HADES / miniCBM	CEE	BM@N	DHS, D2S	CBM / HADES	MPD	STAR	NA61	NA60+
Start	2012, 2018	2023	2019 (Au)	>2025(?)	2025	2021	2010,2019	2009, 2022	>2025(?)
$\sqrt{s_{NN}}$, GeV	2.4 – 2.6	1.8 – 2.7	2 – 3.5	2 – 6.2	2.7 – 5	2.7 - 11	3 – 19.6	4.9 – 17.3	4.9 – 17.3
μ_B, MeV	880 – 670	880 – 750	850 – 670	850 – 490	780 – 400	750 – 330	720 – 210	560 – 230	560 – 230

Courtesy of T. Galatyuk, QM2018

Future of HI experiments: high $\sqrt{s}$

- Explore QCD phase diagram and **QGP properties** with detector upgrades, significantly more recorded events and new facilities