The journey to seek symmetry in Quark-Gluon Plasma

Discovery of Quark-Gluon Plasma

Chiral symmetry

Our experimental approach and results

Summary
Elementary particles

- **Electron and quarks** are elementary particles.
- There are **6 flavors** of quarks with different masses.

- u and d quarks are the lightest ones.
Quantum Chromodynamics (QCD)

• Quarks are bound together to form protons and neutrons.

• Discovery of asymptotic freedom: attraction between quarks becomes weaker as quarks approach one another more closely; becomes stronger as they are separated

• QCD: correct theory of the strong nuclear force, one of the four fundamental forces in nature (Gross, Wilczek, Politzer, 2004 Nobel Prize).
Wikipedia: Quark–gluon plasma is a state of matter in which the elementary particles that make up the hadrons of baryonic matter are freed of their strong attraction for one another under extremely high energy densities. These particles are the **quarks** and **gluons** that compose baryonic matter.

Quark-Gluon Plasma is believed to exist in the moments after the Big-Bang.

At BNL and CERN, physicists trying to create Quark-Gluon Plasma (QGP) using high energy heavy ion collisions.

Study the image of QGP, will help us to understand the early universe.
RHIC @ Brookhaven National Laboratory

23 years of RHIC operation

Lijuan Ruan, BNL
Relativistic heavy ion collision

Initial state

Collision

QGP

Hadronization

Freeze out:
Chemical and kinetic

Courtesy of S. Bass
Identify and study the properties of matter with partonic degrees of freedom.

**Penetrating probes**
- “jets” and heavy flavor

**Bulk probes**
- $v_2 \rightarrow$ partonic collectivity
- spectra at low $p_T$, particle ratios.

Courtesy of S. Bass
Elliptic flow $v_2$

Non-central collisions: azimuthal anisotropy in coordinate-space

Interactions $\rightarrow$ asymmetry in momentum-space

Sensitive to early time in the system’s evolution

Measurement: Fourier expansion of the azimuthal $p_T$ distribution

\[
E \frac{d^3N}{d^3p} = \frac{1}{\pi} d^2 \frac{N}{dp_T^2dy} [1 + 2v_1 \cos(\phi - \Psi_R) + 2v_2 (2[\phi - \Psi_R]) + ...] \rightarrow v_2 = \langle \cos(2[\phi - \Psi_R]) \rangle
\]
Hydrodynamical models can reproduce **mass dependence of** \( v_2 \) and spectra at \( p_T < 2 \text{ GeV/c} \).

**STAR:** Nucl. Phys. A 757 (2005) 102

M. Calderon de la Barca Sanchez, ISMD2003
Low $p_T$: bulk property

**Particle ratios:** chemical freeze out

A few parameters in the model:
- Chemical freeze out temperature $T_{ch}$
- Baryon chemical potential $\mu_B$ ($\mu_B=0$ if $p\bar{p}/p=1$)
- Strangeness saturation factor: $\gamma_s$

$T_{ch}=163\pm4$ MeV, $\mu_B=24\pm4$ MeV
$\gamma_s=0.99\pm0.07$

$\gamma_s$ approach 1 in central Au+Au collisions: thermalization within the framework of this model.
High $p_T$: penetrating probe

In central Au+Au collisions at RHIC: Fragmentation ($q/g \rightarrow \text{hadrons}$) + energy loss at $p_T > 6$ GeV/c:

Significant suppression of inclusive charged hadron observed at $p_T > 6$ GeV/c: $dN_g/dy \sim 1000$. M. Gyulassy et al., nucl-th/0302077.
At $p_T \sim 2$ GeV/c, $p/\pi$ ratio $\sim 1$. It can not be factorized jet fragmentation.

Recombination/Coalescence at hadronization

Fragmentation works for \( p+p \) collisions for hadrons at \( p_T > 2 \) GeV/c.

If phase space is filled with partons, recombine/coalesce them into hadrons. At \( 2 < p_T < 6 \) GeV/c, baryon enhancement, \( v_2 \) number of constituent quark scaling.

R.J. Fries, QM2004

Lijuan Ruan, BNL
In 2005, BNL announced a discovery of perfect liquid at RHIC
Elementary particles

• **Electron and quarks** are elementary particles
• There are **6 flavors** of quarks with different masses.

• u and d quarks are the lightest ones, proton is much heavier.
Elementary particles

• Electrons interact with matter through the exchange of photons.

• Electrons and photons do not interact with matter strongly.

• Quarks interact with matter through the exchange of gluons. Strong interaction.

• Positron is antimatter electron.
• Anti-quark is antimatter quark.
Traditional Positron-emission Tomography (PET)

PET scan uses electron and antimatter electron (positron) annihilation into two back-to-back photons to create an image.

Lijuan Ruan, BNL
Special PET scans (electron-positron tomography)

- In our method, we detect electron and positron pairs from quark-antiquark annihilation.

- Electron-positron pairs are penetrating probes and can provide information deep into the system and early time.

- Using electron-positron tomography, we would like to study the symmetry of the Quark-Gluon Plasma.
The Quark-Gluon Plasma

• In Quark-Gluon Plasma, there are $u, d$ quarks and gluons.

• Motion of the system has chiral symmetry.
Chiral symmetry and symmetry breaking

- Early universe, **hot**, chiral symmetry

- The world we live in now, **cold**, spontaneous chiral symmetry breaking

Motion of the system: **potential + ball (ground state)**
Spontaneous chiral symmetry breaking

Microscopic picture:

• quark condensate: left-handed quark and right-handed antiquark attract each other through the exchange of gluons. Generate 99% of visible mass in the universe.

• electron condensate: electrons attract each other through the vibration of the crystal at low temperature. Generate superconductivity in the metal.
Is chiral symmetry restored in Quark-Gluon Plasma?

In the Quark-Gluon Plasma, as hot as early universe, is chiral symmetry restored?

Do we have experimental observable?
ρ and a1 resonance (spectrum function) in vacuum

Spontaneous chiral symmetry breaking: mass distributions are different

Chiral symmetry restoration: mass difference disappears
The $\rho$ resonance mass spectrum function

Observable for chiral symmetry restoration: a broadened $\rho$ spectra function and ultimately the peak structure disappears!

Model: Rapp & Wambach, priv. communication
My physics interest

Study the image of the **Quark Gluon Plasma and chiral symmetry restoration using electron-positron tomography.**

Experimentally identify the signature of chiral symmetry restoration in the Quark-gluon Plasma, as hot as early universe.
The STAR Detector

**Solenoidal Tracker at RHIC (1200 tons)**

**Time Projection Chamber**

1. Second largest device of its kind ever built
2. 3D camera to take photos of the collisions
3. Measure ionization energy loss (dE/dx) and momentum
$^{197}$Au + $^{197}$Au Collisions at RHIC

Central Event

$E = mc^2$
Electrons are difficult to find.

Need new experimental tool!
Multigap Resistive Plate Chamber (MRPC) Technology

low cost, high timing resolution $<100 \times 10^{-12}$ second

A prototype tray (TOFr) was installed in 2002-2003
Structure of MRPC Module

Read out pad size: 3.15cm × 6.3cm, gap: 6 × 0.22mm

M. Abbrescia et al., Nucl. Instr. and Meth. A 431 (1999) 413-427

M. Abbrescia et al., Nucl. Instr. and Meth. A 431 (1999) 413-427
Particle identification from TOFr

\[ \frac{1}{\beta} = \sqrt{\frac{m^2}{p^2}} + 1 \]

Curve:

STAR Collaboration, PLB616(2005)8
Electron identification

Clean electron samples!

STAR Collaboration, PRL94(2005)062301
Time of Flight Detector upgrade

US-China Collaboration, 120 units in total:
2008: 4%; 2009: 72%; 2010: 100%
The special PET scan tools are now ready

The Time of Flight Detector completes the experimental tool for electron-positron tomography.
Electron-positron emission mass spectrum

In empty space (vacuum)
Electron positron emission mass spectrum in 200 GeV Au+Au

There are “hot” contributions!
Electron-positron emission at lower energies

"Hot" contributions observed in 19.6, 39, 62.4, and 200 GeV Au+Au collisions!
The “hot” mass distribution in 200 GeV Au+Au

The “hot” contribution is modified and broadened!

Model: Rapp & Wambach, priv. communication
Electron-positron emission at lower energies

Observed “hot” distributions are broadened!
The “hot” contribution

The electron-positron spectrum from hot, dense medium is consistent with a broadened \( \rho \) resonance in medium and the production yield normalized by \( dN_{\text{ch}}/dy \) is similar from 19.6 to 200 GeV.

Coupling to the baryons plays an essential role to the modification of \( \rho \) spectral function in the hot, dense medium.
Go to lower collisions energies
7.7 GeV to 19.6 GeV

Broader and more “hot” contribution down to 7.7 GeV collision energy?

Beam Energy Scan II (BES-II) provides a unique opportunity to study chiral symmetry restoration!

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Major improvements for BES-II

**iTPC Upgrade:**
- Replaced inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends $\eta$ coverage from 1.0 to 1.5
- Lowers $p_T$ cut from 125 MeV/c to 60 MeV/c

**EPD Upgrade:**
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

**EndCap TOF Upgrade:**
- Rapidity coverage is critical
- PID at $\eta = 1$ to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR
RHIC is unique to study chiral symmetry restoration:

Beam energy scan II: collision energies 7.7, 9.1, 11.5, 14.5, 19.6 GeV.

In 2021, collected the last collider data set at 7.7 GeV, completed the BES-II program.
Back to 200 GeV Au+Au in 2023-2025

Low-mass dielectron measurement: lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at $\mu_B=0$

Intermediate mass: direct thermometer to measure temperature

Enable dielectron $v_2$ and polarization, and solve direct photon puzzle (STAR vs PHENIX)

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World-wide interest

- World interest: SPS, PHENIX, LHC, FAIR, NICA, KEK
Photon emission

Hot contribution observed in the photon energy spectrum!

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Photon emission

Quark-Gluon Plasma emission spectrum: photon energy a few $10^9$ electron volts

Sun emission spectrum: Photon energy a few electron volts.

Hottest matter in the universe: a few trillion degree Celsius!
Summary

Electron-positron tomography of Quark-Gluon Plasma:

Chiral symmetry restoration!

Lijuan Ruan, BNL
Backup
Quantum Chromodynamics (QCD)

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- QCD: correct theory of the strong nuclear force, one of the four fundamental forces in nature (Gross, Wilczek, Politzer, 2004 Nobel Prize).

S. Bethke, arXiv: hep-ex/0211012