Recent QGP studies at LHC/RHIC and future plans at Fair/J-parc

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Contents
• Introduction
• Temperature
• Collective expansion
• Jet quenching
• Small system
• Beam energy scan
• Summary

QGP Seminar at JAEA, 13/May/2015, Tokai
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Quark Gluon Plasma (QGP)

to search for a new state of matter and to study property of matter
• Early universe, Neutron star
• Quark-hadron phase transition
• Non confined quark states
• Critical end point
Heavy-Ion collision simulation

High-temperature & density system
Quark Gluon Plasma

Nucleus A

Nucleus B
Relativistic Heavy-Ion Collider (RHIC) 
Brookhaven National Lab. (BNL) 
New York, USA

~ a few km 
~ 200 GeV

Large Hadron Collider (LHC) 
European Organization for Nuclear Study (CERN), Geneva, Switzerland 

~ a few 10km 
~ 5 TeV
Experiments at RHIC and LHC

PHENIX

ALICE

STAR

ATLAS

CMS
A+A central collision
A few – 10k particles in an event
Thermal freeze-out from spectra shape

The end of elastic interactions, where/when spectra are frozen.

\[ T_{\text{eff}} = T_{\text{fo}} + 0.5 m \langle v_\perp \rangle^2 \]
Chemical Freeze-out from particle yield

\[
\rho_i = \gamma_s |s_i| \frac{g_i}{2\pi^2} T_{ch}^3 \left( \frac{m_i}{T_{ch}} \right)^2 K_2 \left( \frac{m_i}{T_{ch}} \right) \lambda_q Q_i \lambda_s s_i
\]

\[
\lambda_q = \exp \left( \frac{\mu_q}{T_{ch}} \right), \quad \lambda_s = \exp \left( \frac{\mu_s}{T_{ch}} \right)
\]

The end of inelastic interactions, where/when yield/ratio are frozen.

- \(T_{ch}\): Chemical freeze-out temperature
- \(\mu_q\): light-quark chemical potential
- \(\mu_s\): strangeness chemical potential
- \(\gamma_s\): strangeness saturation factor
- \(Q_i\): 1 for u and d, -1 for u and d
- \(s_i\): 1 for s, -1 for s
- \(g_i\): spin-isospin freedom
- \(m_i\): particle mass
- \(K_2\): the second-order modified Bessel function

Simple chemical freeze-out model remarkably well agrees with data.

\(<N_{\text{part}}> = 345 \pm 7\)
Thermal photon radiation from QGP

- Virtual and real photon measurements via internal and external conversion methods with electron pair measurements
- Real photon measurements with EMcal
- Initial temperature of 300-600 MeV via measured slope of 220-240 MeV
initial temperature from the energy density
Phase transition at critical temperature
Chemical freeze-out temperature
Thermal freeze-out temperature

History of temperature

Initial temperature from thermal photons 0.3~0.6GeV

charged particle multiplicity vs. $dN_{ch}/dh$

Radial flow

$\langle \beta \rangle$

$T_{kin}$

$T_{ch}$

$T_{C}$

(a)
Blast Wave model fitting to various particle species

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Comparison between beam energies

Temperature via thermal photon

Critical end point

Comparison between beam energies
Quark momentum distribution
--- extracted from multi-strange hadron ratio ---

\[
\begin{align*}
\Xi(p_T/3) & \quad \phi(p_T/2) \\
\frac{(\Omega + \Omega')}{2}(p_T/3) & \quad \phi(p_T/2)
\end{align*}
\]

Collective radial expansion
- during the partonic phase
- before the hadronic phase

Quark coalescence or recombination mechanism for the hadronization

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Number of quark scaling in elliptic flow
--- quark coalescence feature ---

Indication of quark flow (in partonic phase)

\[ \frac{m_T - \text{mass}}{n_{q}} \]

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mass dependence of $v_2$ with hydro-model

More radial flow in data. Not enough radial flow in hydro, or hadronic afterburner.
Beam energy dependence of $v_2$ (increased radial flow)

Relative momentum shift of heavier particles (protons) are larger than light hadrons (pions), which is consistent with an increased radial flow.
Direct (thermal) photon $v_2$ and $v_3$

$v_n = \langle \cos n(\phi_{\text{particle}} - \Phi_{\text{plane}}) \rangle$
(n=2 : elliptic flow), (n=3 : triangular flow)

- comparable to hadron for both $v_2$ and $v_3$ at 2~3GeV/c
- significant contribution from photons from later stages (inconsistent with early photons from hotter period) --- direct photon puzzle
- flatter $p_T$ dependence of $v_2$ at low $p_T$
High $p_T$ direct photon as penetrating probe

<table>
<thead>
<tr>
<th>$p_T &gt; 5$ GeV/c</th>
<th>hadron</th>
<th>$\gamma^{dir}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{AA}$</td>
<td>$&lt; 1$</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>$v_2$</td>
<td>$&gt; 0$</td>
<td>$\sim 0$</td>
</tr>
</tbody>
</table>

Relative yield with respect to a simple independent superposition of pp data:

$$R_{AA} = \frac{N (A+A)}{N_{coll} N(p+p)}$$

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Energy loss at high $p_T$ and re-distribution of the lost-energy at low $p_T$ at RHIC

prompt photon - hadron correlation
$N_{PTY} =$ associate hadron yield per trigger $\gamma$
$I_{AA} = N_{PTY}(AA) / N_{PTY}(pp)$
effect on bulk

Suppression in Low $p_T$
Enhancement in high $p_T$

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Partonic energy loss and Jet quenching

RHIC-STAR


Reconstructed jet – hadron correlation
LHC CMS/ATLAS: Modification of Jet fragmentation

- re-distribution towards lower $p_T$ particles
- re-distribution at larger angle

![Graph showing re-distribution](image)

CMS PbPb, $\sqrt{s_{NN}} = 2.76$ TeV

LHC CMS/ATLAS:
Modification of Jet fragmentation

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Symmetric di-jet in p+p and peripheral A+A
Asymmetric di-jet in central A+A

Tracks

Calorimeter Towers

Asymmetric di-jet in central A+A

Run Number: 169136, Event Number: 1395684
Date: 2010-11-13 02:17:43 CET

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Jet asymmetry: $A_J$

$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$

$E_{T1} > 100$ GeV

$E_{T2} > 25$ GeV

Peripheral Pb+Pb → Central Pb+Pb

$A_J = \frac{(E_{T1} - E_{T2})}{(E_{T1} + E_{T2})}$

$
\Delta \phi = \phi_1 - \phi_2
$

**$A_j$ measurement at RHIC-STAR**

- similar effect with smaller jet cone $R \sim 0.2$ at RHIC
- lower jet energy than LHC, smaller effect than LHC
- mostly recovered jet energy within larger jet cone $R \sim 0.4$

\[
A_j = \frac{P_{T,1} - P_{T,2}}{P_{T,1} + P_{T,2}}
\]

Anti-$k_T$ $R=0.2$, $p_T,>16$ GeV & $p_T,>8$ GeV with $p_T^{cut}>2$ GeV/c

Anti-$k_T$ $R=0.4$, $p_T,>20$ GeV & $p_T,>10$ GeV with $p_T^{cut}>2$ GeV/c

The difference is mostly gone.
Systematic test of energy loss and redistribution with photons, jets and hadrons

These two effects (energy loss and redistribution) can not be clearly separated experimentally!

Jet reconstruction is to recover the lost energy to get the original parton energy.

Jet as a control tool to define path length

Closer and closer to the initial parton energy

more and more surface bias given by energy loss
Jet-medium interaction: hard-soft interplay

Jet axis dependence with respect to geometry

$\Delta \phi$ vs $\phi_{\text{Jet}} - \Phi_{\text{R.P.}}$

$\Delta \eta$ vs $\eta_{\text{Jet}}$
Higher order event anisotropy --- $v_3$ ---

black-disk collision, sign-flipping $v_3$ like $v_1$
initial geometrical fluctuation, no-sign-flipping $v_3$

Reaction Plane (x-z)
Elliptic and Triangular expansion and freeze-out geometry

Elliptic and Triangular expansion: $v_2, v_3$

Elliptic and Triangular shape: $R^{HBT}_{\Phi_2}, R^{HBT}_{\Phi_3}$

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Event shape selection $Q_2 (\sim v_2)$

Relation of $\varepsilon_2^{\text{initial}} - v_2 - \varepsilon_2^{\text{final}}$ for a given centrality.

2-particle correlation

Flow BG subtracted jet correlation

$\varepsilon_{\text{final}}$ via HBT interferometry

PHENIX, QM14

ATLAS, QM14

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A+A collision : a large system

\[ \text{p+p collision : a small system} \]

LHC-ALICE

LHC-CMS

high temperature and density system \( \rightarrow \) small and high multiplicity system

Probability distribution of event with “n” particles production

estimated initial energy density distribution in central A+A collision

\[ n : \text{particle multiplicity} \]
Two particle $\Delta\phi-\Delta\eta$ correlation

(b) MinBias, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

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minimum bias p+p events  

high multiplicity p+p events

(b) MinBias, 1.0GeV/c<p_T<3.0GeV/c

(d) N>110, 1.0GeV/c<p_T<3.0GeV/c

- inter-correlation between di-jets
- correlated multi-parton interactions
- collective behavior in small and dense system

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CMS Preliminary

\[ p+\text{A collisions} \]

Initial-state geometry +
collective expansion

\[ A+A \text{ collisions} \]

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LHC p+Pb centrality dependence

CMS Preliminary
\[ pPb \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ 1 < p_T < 3 \text{ GeV/c} \]

- \( N_{\text{trig}}^{\text{offline}} \geq 110 \)
- \( 35 \leq N_{\text{trig}}^{\text{offline}} < 90 \)
- \( 90 \leq N_{\text{trig}}^{\text{offline}} < 110 \)
- \( N_{\text{trig}}^{\text{offline}} < 35 \)
100 billion (1.78 pb⁻¹) sampled minimum bias events from high-multiplicity trigger

High multiplicity
pp collisions

LHC-CMS

Jet1 peaked at $p_T = 2\sim4$ GeV/c (ridge region $|\Delta\eta| = 2\sim4$)

No ridge when correlating to high $p_T$ particles!

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Elliptic flow in small system?

* New $^3\text{He}+\text{Au}$ collision data from RHIC-RUN14
* $p+p$, $p+\text{Al}$, $p+\text{Pb}$ in Run15 will come

Glauber model

* New $^3\text{He}+\text{Au}$ collision data from RHIC-RUN14
* $p+p$, $p+\text{Al}$, $p+\text{Pb}$ in Run15 will come

$C(\Delta\phi)$
RHIC beam energy scan program
--- from high-temperature to high density ---
Directed flow $v_1$

- strong anti-flow of pion (and p-bar)
- small but significant anti-flow of proton
- sign change of $v_1$ slope around 10GeV
- minimum around 10-20GeV

J. Brachmann et al., PRC 61, 24909 (2000).
Beam energy dependence of $v_2$ and $v_3$

Smooth trend (not not?) of $v_2$ and $v_3$ with beam energy

Beam energy dependence of 2-particle interferometry measurement (HBT effect)

arXiv:1410.2559

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Local parity violation in a strong magnetic field

Fluctuation of conserved quantity vs beam energy

- Higher order moments ($\sigma$, $S$, $\kappa$) of net-baryon (net-proton) and net-charge distribution
- Non-monotonic behavior is expected around Critical Point.

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Patrick Huck, QM14

M_{ee}^{inv.} spectra and direct $\gamma^{thermal}$ from STAR experiment

Chi Yang, QM14

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sPHENIX at RHIC-BNL (New York, USA)

ALICE at LHC-CERN for Luminosity upgrade (Geneva, Switzerland)

Di-jet calorimeter
Forward calorimeter
High-speed read-out

FAIR at GSI (Darmstadt, Germany)

J-PARC at JAEA/KEK for heavy-ion collisions (Tokai, Japan)
Summary

from SPS to RHIC, LHC

• Temperature
• Collective expansion
• Jet quenching
• Small system
• Beam energy scan

slide from H. Sako, ATHIC14, Aug/2014, Osaka