News from heavy-ion collisions at RHIC and LHC

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Phase diagram: map of states and phase transitions

H₂O

- vapor
- water
- ice
- ice cube
- critical point
- triple point

QCD matter

- QGP (quark-gluon plasma)
- color superconductor
- critical point

Experimental study of QGP phase diagram by:
smashing nuclei in head-on collision and
converting cold nuclear matter into a fireball of partons
Evolution of the system created in HIC

- Initial pre-equilibrium state
  hard parton scattering & jet production
  gluonic fields (Color Glass Condensate)

- Quark-gluon plasma formation
  thermalization (hydrodynamics)

- QGP expansion and decay
  phase transition of partons into hadrons
  - Hadronization
  - Rescattering & chemical freeze out
  - Kinetic freeze out (stop interacting)

Experimentally observe only hadronic state

Many observables need to be studied to establish the properties of QGP
Modern ultra-relativistic HI colliders

### Relativistic Heavy Ion Collider

- **RHIC**
  - Location: BNL (USA)
  - Circumference: 3.8 km
  - Species: p, d, Cu, Au, U polarized protons
  - Center of mass energy per nucleon pair: in GeV
    - 7-38, 62, 200, 500 (pp only)

- **PHOBOS**
- **BRAHMS**
- **PHENIX**
- **STAR**

### Large Hadron Collider

- **LHC**
  - Location: CERN (Europe)
  - Circumference: 27 km
  - Species: p, Pb
  - Center of mass energy per nucleon pair: in TeV
    - 0.9, 2.76, 7 (pp)
    - 2.76 (Pb)

- **CMS**
- **ALICE**
- **ATLAS**
- **LHCb**

**LINAC**

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Current heavy ion experiments at RHIC and LHC

**STAR** (Solenoidal Tracker At RHIC)

**ALICE** (A Large Ion Collider Experiment)

**PHENIX** (Pioneering High Energy Nuclear Ion Experiment)

**ATLAS** (A Toroidal LHC Apparatus)

**CMS** (Compact Muon Solenoid)

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Main capabilities for heavy-ion studies:

Charge particle tracking and identification:
- full azimuth, large rapidity coverage
- wide $p_t$ range: $\sim 100$ MeV/c to $\sim 100$ GeV/c

Calorimetry and rare probes:
- neutral particles, photons, jets, heavy flavor
Experimental probes of QGP

- **Initial energy density, temperature, & chemical potential**
  - Charge multiplicity and energy density
  - Particle yields

- **Freeze out volume and decoupling time**
  - Bose–Einstein correlations

- **Viscosity, $\eta/s$, and initial conditions**
  - Elliptic, triangular, and higher order harmonic flow
  - Multiplicity, momentum, charge fluctuations

- **Medium tomography and penetrating probes**
  - Jet quenching and high $p_t$ suppression of particle production
  - Direct photons
  - Heavy flavor (charm and beauty)

- **Critical point search**
  - Scanning the different collision energies
Particle yields
Charge multiplicity and energy density: from RHIC to LHC

- x 2.1 increase in charge density
- x 1.9 increase compared to pp collisions at the same energy

- 2.5-3 times larger energy density
- Midrapidity dE/dη ~ 2 TeV at LHC
Identified particle spectra and radial expansion

Spectra shapes change significantly from RHIC to LHC

20% Stronger radial flow at LHC

Freeze-out temperature & radial velocity from blast-wave fit

transverse momentum, $p_t$ (GeV/c)

20% Stronger radial flow at LHC

ALICE Preliminary

0-5% most central

ALICE, Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
PHENIX, Au-Au, $\sqrt{s_{NN}} = 200$ GeV
STAR, Au-Au, $\sqrt{s_{NN}} = 200$ GeV

ALICE Preliminary
Bose–Einstein correlations
HBT (Hanbury-Brown-Twiss) correlations

Momentum-space two-particle correlations of identical bosons:

\[ C(\vec{p}_1, \vec{p}_2) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)} \sim \int |\Phi(\vec{r}, \vec{q})|S(\vec{r}, \vec{q})\, d\vec{r} \quad \vec{q} = \vec{p}_1 - \vec{p}_2 \]

Correlation “width” in momentum space proportional to the source size

Decompose into longitudinal, out, and side components
Study the source function in 3 dimensions
HBT radii with pions: RHIC vs. LHC

- Homogeneity length is 30% larger at LHC
- Stronger radial & longitudinal collective flow at LHC (strong $k_T$ dependence)
Freeze-out volume and decoupling time at LHC

Homogeneity region, $R_{\text{out}} R_{\text{side}} R_{\text{long}}$

Emission time, $\tau_f$

Larger homogeneity region at LHC

Volume $\sim (2\pi)^{3/2} R_{\text{out}} R_{\text{side}} R_{\text{long}}$

$\tau_f \sim R_{\text{long}} \sqrt{m_T/T}$

30% longer emission time at LHC
Anisotropic transverse flow
Event anisotropy in heavy-ion collision

Asymmetry of the overlap region
- non uniform density profile
- pressure gradient

Initial spacial anisotropy develops into measurable azimuthal asymmetry in momentum space:
- Reflects orientation of the reaction plane (e.g. elliptic shape results in $v_2$)
- Sensitive to fluctuations (triangular shape)
- Viscous effects dumps higher order harmonics – constrains $\eta/s$

Viscous hydrodynamic simulation
Schenke et al., PRL106:042301 (2011)
Elliptic flow at RHIC and LHC

- 30% increase of integral $v_2$: perfect liquid behavior at LHC

- $v_2(p_t)$ has similar shape and magnitude: increase of integral $v_2$ is driven by stronger radial flow (shift of mean $p_t$)
Identified particle $v_2$ and coalescence at LHC

- Observed larger mass splitting of $v_2$ agrees well with viscous hydrodynamic predictions except for anti-protons for most central collisions
- Anti-protons do not follow the universal scaling seen at RHIC
Elliptic flow fluctuations and higher harmonic at LHC

Higher flow harmonics: $v_2, v_3, v_4$

- $v_3$ originates from fluctuations in the initial geometry
- Glauber MC reproduces $v_3$ centrality dependence, while CGC MC underpredict the magnitude
- For ultra-central collisions CGC describes better $v_2$ centrality dependence

Observed non-zero $v_3$ helps to constrain initial conditions and $\eta/s$ (viscosity over entropy density ratio)
Discriminating initial conditions and $\eta/s$ at RHIC

MC-KLN: Color Glass Condensate initial conditions with $\eta/s = 2/(4\pi)$
Glauber: Glauber initial conditions with $\eta/s = 1/(4\pi)$

RHIC results favor Glauber initial condition with a smaller viscosity?
Understanding two particle correlations with higher harmonic flow

- "ridge" and "mach-cone" structures naturally described by collective flow effects
- Similar observation by RHIC experiments


ATLAS Collaboration

two particle relative azimuthal angle, $\Delta \phi$ (rad)
Hard probes
Nuclear modification factor, $R_{AA}$

Quantifying medium effects in heavy-ion collisions by deviation from particle production in pp interactions

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{Y_{AA}(p_T)}{Y_{pp}(p_T)}$$

Normalized by $N_{coll}$ ratio of $p_T$ yields in AA to that in pp

$$Y(p_T) = \frac{1}{N_{evt}} \frac{d^2N_{ch}}{d\eta dp_T}$$

$p_T$ distribution of charge particles at midrapidity

$$R_{AA}(p_T) = 1 \quad \text{no medium modification}$$

$$R_{AA}(p_T) < 1 \quad \text{suppression by medium}$$
\[ R_{AA} \] of colorless probes at RHIC and LHC

- No nuclear modifications for direct photons and Z bosons: hard scattering processes scale with number of binary collisions
- Provides baseline for study of charged particle production

**Isolated photon and Z-boson**

**Inclusive direct photons**

CMS Preliminary
\[ \text{PbPb} \sqrt{s_{NN}} = 2.76 \text{ TeV}, \int \text{L dt} = 7 \mu \text{b}^{-1} \]

PHENIX \text{Au+Au}, \sqrt{s_{NN}} = 200 \text{ GeV}, 0-10\% most central
- direct $\gamma$ (prelim.)
- $\pi^0$ (PRL101, 232301)
- $\eta$ (PRC82, 011902)
Charged particle suppression at LHC

CMS Collaboration

ALICE Collaboration

- Minimum at $p_t \sim 6-7$ GeV/c with strong raise up to $p_t \sim 50$ GeV/c
- Pronounced centrality dependence below $p_t \sim 50$ GeV/c
- For most central collisions suppression observed even at $p_t \sim 100$ GeV/c: $R_{AA} \sim 0.5$
$R_{AA}$ at RHIC and LHC vs. theoretical calculations

- Similar shape between LHC and RHIC above $p_t \sim 6$ GeV/c
- Strong constraint on parton energy loss models
Suppression of heavy flavor production at RHIC and LHC

Open charm

Heavy flavor production at LHC is suppressed similar to light quarks

Other talks at Hadron 2011 on heavy flavor at LHC:

Plenary:

Y. Gao (quarkonia)
H. Evans (heavy mesons)
N. Leonardo (bottomonium)

Parallel:

F. Kramer (quarkonia)
K. Schweda (open charm)
Highly asymmetric di-jets observed at LHC

Sample di-jet event reconstructed by ATLAS in central Pb+Pb collision

Leading jet with $p_T > 100$ GeV/c

No away side jet?
Energy diluted over wide range in azimuth

leading jet (escaped)

away side jet (quenched)

surface
Dijet energy imbalance and angular correlations

Energy imbalance

- Strong imbalance - away side jet quenched by dense medium
- Back-to-back Δφ~π for all centralities
Dijet missing momentum and jet fragmentation

- Momentum difference is balanced by low momentum particles spread at large angles relative to the away side
- Fragmentation function similar for Pb-Pb and pp: in Pb-Pb jet fragments in vacuum

Hadron2011: Ilya Selyuzhenkov 15/06/2011
Beam energy scan at RHIC: search for critical point
- $v_2$ of $\phi$ meson does not follow the trend for other hadrons at 11.5 GeV
- Significant difference between baryon/anti-baryon $v_2$ @ 7.7&11.5 GeV
  No scaling between particles and anti-particles
Higher moments of net-proton distribution

Moments of net proton distribution ($\chi$):
- $1^{st}$ - mean, $2^{nd}$ - variance ($\sigma^2$)
- $3^{rd}$ - skewness ($S$), $4^{th}$ - kurtosis ($k$)

- Connected to hydrodynamic susceptibilities
- Sensitive to the correlation length of the system

$$
S \sigma = \frac{\chi^{(3)}}{\chi^{(2)}} \quad k \sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}}
$$

- Consistent with Lattice QCD and Hadron Resonance Gas (HRG) model at higher energies
- Deviates from HRG below 39 GeV
Change in $R_{AA}$ between 22.4 and 39 GeV

- Suppression $p_t > 3$ GeV/c consistent with parton energy loss at 62.4, 200 GeV:
- No suppression at 22.4 GeV
- Enhancement consistent with Cronin enhancement
- Some hints from Beam Energy Scan program at RHIC on critical points between 7 and 20 GeV - stay tuned!

PRL101, 162301 (2008)

PHENIX Collaboration
Physics beyond the study of QGP properties

- Probes of local parity violation in strong interactions
- Observation of anti-matter particles
Probes of local parity violation

Search for event-be-event charge fluctuations. 

P-even observable but sensitive to P-violation: \[ \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \]

Voloshin PRC70, 057901 (2004)

- RHIC and LHC observe charge separation
- Separation disappears between 11.5 and 7.7 GeV energies
- Recent progress in understanding parity even backgrounds, i.e. large flow fluctuations in the first harmonic but still a long way to go before any final conclusion
Anti matter production at RHIC and LHC

STAR Collaboration
Nature 473, 353-356, (May 2011)

- STAR discovered 18 anti-\(^4\)He particles (heaviest anti-matter observed so far). Yields are consistent with thermal & coalescence model expectations
- ALICE Collaboration sees 4 candidates for anti-\(^4\)He (after one month of Pb-Pb!)
- Analysis on strange antimatter (e.g. anti-hyper-triton) is ongoing

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Summary

Field of heavy-ion collisions provides valuable information on:

● Fundamental properties of strong interactions (deconfinement, chiral symmetry restoration, etc)

● Existence of QCD phase transition & deconfined quark matter (QGP)

● Gives insights on the properties of early universe, just after a few microseconds after Big Bang

Exciting results from first heavy ion run at LHC in November 2010 and new high statistics data from RHIC:

● Provides an additional constrain on the models of heavy-ion collisions

● Key ingredients for building a consistent picture of QGP phase diagram

Looking forward to further studies and more results from LHC and RHIC communities!