Creating the Primordial Quark-Gluon Plasma at RHIC and the LHC

Cover 3 decades of energy in center-of-mass

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

5.5 TeV (2015)

\[ \sqrt{s_{NN}} = 5 - 200 \text{ GeV} \]

Investigate properties of hot QCD matter at \( T \sim 150 - 1000 \text{ MeV} \)!
Top Ten Physics Newsmakers of 2000 – 2010

http://www.aps.org/publications/apsnews/201002/newsmakers.cfm
“Stories with the most lasting physical significance & impact in physics”

The Large Hadron Collider (LHC) – modern marvel of science, last piece of standard model.

The Decade of Carbon – carbon nanotubes & graphene, will revolutionize electronics.

Negative Index of Refraction Materials – meta-materials make objects seem to disappear.

The Wilkinson Microwave Anisotropy Probe – leftover heat from Big Bang.

Quantum Teleportation – quantum information transport across macroscopic distances.

Quark-Gluon Plasma – first instances after Big Bang, all matter as hot quarks & gluons.

Gravity Probe B – observed the geodetic effect (to look for frame dragging in general relativity).

Light Stopped – actually stopped altogether and stored for up to 20 milliseconds.

Direct Evidence for Dark Matter – two colliding galaxies confirm presence of dark matter.

Advances in Computing – > $10^{15}$ calculations / sec., map bio-structures, supercomputers.
There was light!

On the “First Day”

Gravity

Electromagnetism

Strong

Weak

Courtesy Nat. Geographic, Vol. 185, No. 1, 1994 – Graphics by Chuck Carter
Consultants – Michael S. Turner and Sandra M. Faber
On the “First Day”

at 10 $\mu$-seconds & $2 \times 10^{12}$ Kelvin
Quark-to-hadron* phase transition
Quark-Gluon Plasma

Rapid inflation

gravity, strong & E-W forces separate

at $10^{-43}$ seconds

* hadrons = nuclear particles = mesons, baryons

Courtesy Nat. Geographic, Vol. 185, No. 1, 1994 – Graphics by Chuck Carter
Consultants – Michael S. Turner and Sandra M. Faber
Behavior of QCD* at High Temperature

\[ \varepsilon / T^4 \sim \# \text{degrees of freedom} \]

\[ \varepsilon = \frac{\nu \pi^2}{30} T^4 \]

\[ \varepsilon / T^4 \sim 3p / T^4 \]

\[ \varepsilon_{SB} / T^4 \]

\[ \text{TC} \sim 185 - 195 \text{ MeV} \rightarrow \varepsilon_c \sim 0.3 - 1 \text{ GeV/fm}^3 \]

Modifications to QCD Coupling Constant $\alpha_s$:

Heavy quark-antiquark coupling at finite $T$ from lattice QCD.

Constituents - Hadrons, dressed quarks, quasi-hadrons, resonances?

Coupling strength varies investigates (de-)confinement, hadronization, & intermediate objects.

Asymptotic Freedom

Confinement

$\alpha_{qq}(r,T)$ vs. $T/T_c$:
- $0.81$
- $0.90$
- $0.96$
- $1.02$
- $1.07$
- $1.23$
- $1.50$
- $1.98$
- $4.01$

high $Q^2$  low $Q^2$
Modifications to QCD Coupling Constant $\alpha_s$

Nobel Prize 2004

D. Gross
H.D. Politzer
F. Wilczek

QCD Asymptotic Freedom (1973)

“Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma.”

David Gross, Nobel Lecture (RMP 05)
Quark-Gluon Plasma (Soup)

- **Standard Model** → Lattice Gauge Calculations predict QCD Deconfinement phase transition at $T = 175$ MeV
- **Cosmology** → Quark-hadron phase transition in early Universe
- **Astrophysics** → Cores of dense stars (?)
- Can we make it in the lab?

- Establish properties of QCD at high $T$
“How Can We Make a Quark Soup?”

The temperature of the universe has been falling since the big bang. During the first microsecond, all matter is thought to have existed as quark-gluon plasma. As the universe expanded and cooled, more complex matter condensed out of the plasma, eventually forming the atoms observable today.
How to Make Quark Soup!

Strong – Nuclear Force
“confines” quarks and gluons to be in particles

- Compress or Heat Nuclei
- To melt the vacuum!

→ Quark-Gluon Soup!
Gold nuclei each with 197 protons + neutrons are accelerated.
With the **Relativistic Heavy Ion Collider**
*(since 2000)*

Gold nuclei each with 197 protons + neutrons are accelerated.
STAR (Solenoidal Tracker At RHIC) Detector

$0 < \varphi < 2\pi$

$|\eta| < 1$
The Experiment at Brookhaven Lab in N.Y.
Creating and Probing the Quark-Gluon Quagmire at RHIC

John Harris
Yale University
NATO ASI, Kemer, Turkey 2003
Head-on Collision
Heavy Ion Physics at the Large Hadron Collider
Heavy Ion Physics at the Large Hadron Collider

View from Hollywood 😊
The Large Hadron Collider

View from Hollywood

😊
**LHC Heavy Ion Program**

**LHC Heavy Ion Data-taking**
Design: Pb + Pb at $\sqrt{s_{NN}} = 5.5$ TeV
(1 month per year)
2010-11: Pb + Pb at $\sqrt{s_{NN}} = 2.76$ TeV
2013: p + Pb, $\sqrt{s_{NN}} = 5.02$ TeV

**LHC Collider Detectors**
ATLAS    CMS    ALICE
The LHC Experiment designed for heavy ions
Pb-Pb tracks in ALICE

ALICE data!
Heavy Ion Collisions at RHIC & LHC

Lead nucleus diameter ~ 14 fm

γ = 100 → 1,350 (Lorenz contracted)

τ ~ (14 fm/c) / γ < 0.1 → ~ 0.01 fm/c

General Orientation
Hadron masses ~ 1 GeV
Hadron sizes ~ fm

Heavy Ion Collisions
RHIC: $E_{cm} = 0.2$ TeV per nn-pair
LHC: $E_{cm} = 2.76$ TeV per nn-pair
Evolution of a Heavy Ion Collision at RHIC & LHC
(Computer Simulation for RHIC)

red → protons   white → neutrons   participants → interacting p’s & n’s
The Little Bang

Relativistic Heavy-Ion Collisions

- Initial energy density
- QGP phase
- Hadron gas phase
- Hadronization
- Kinetic freeze-out

- pre-equilibrium dynamics
- viscous hydrodynamics
- collision evolution
- free streaming

- $\tau \sim 0$ fm/c
- $\tau \sim 1$ fm/c
- $\tau \sim 10$ fm/c
- $\tau \sim 10^{15}$ fm/c

Ref: U. Heinz, Hard Probes Conference 2013
Original Conception – Paul Sorensen
What are the states of matter that exist at high temperature and density?

- Can we explore the phase structure of a fundamental gauge (QCD) theory?
  → Can we use this to understand other gauge theories (like gravity!)?
- Is the Phase Diagram of QCD featureless above $T_c$?
  → What are the constituents (are there quasi-particles, exotic states, others)?
  → Is there a critical point (can it be found in a RHIC Beam Energy Scan)?

What are the properties of the QGP?
- transport properties, $\alpha_s (T)$, sound attenuation length,
- sheer viscosity/entropy density, formation time ($\tau_f$), excited modes, ….EOS?

Are there new phenomena, new states of matter?
Definitions

- Relativistic treatment
  
  **Energy**
  
  \[ E^2 = p^2 + m^2 \]  
  or \[ E = T + m \]  
  or \[ E = \gamma m \]

  where,
  
  \[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]

  and
  
  \[ \beta = \frac{v}{c} = \frac{p}{E} \]

- Lorentz transforms
  
  \[ E' = \gamma (E + \beta p_z) \]
  
  \[ p'_z = \gamma (p_z + \beta E) \]

- Longitudinal and transverse kinematics
  
  \[ p_L = p_z \]
  
  \[ p_T = \sqrt{p_x^2 + p_y^2}, \quad m_T = \sqrt{p_T^2 + m^2} \]

  \[ y = \frac{1}{2} \ln \left[ \frac{E + p_L}{E - p_L} \right] \]

  \[ y' = y + \tanh^{-1} \beta \]

- Transverse mass
  
  \[ m_T = \sqrt{p_T^2 + m^2} \]

- Rapidity
  
  \[ \eta = -\ln (\tan \theta/2) \]

- Pseudo-rapidity
  
  \[ \eta' = \eta + \tanh^{-1} \beta \]

Useful relations

\[ \gamma = \cosh y \]

\[ \beta = \tanh y \]

\[ E = m_T \cosh y \]

\[ p_L = m_T \sinh y \]
Particle Identification in ALICE Detectors

**ITS**

**TPC**

**ToF**

**RICH**
Vertex Identification in ALICE Detectors

\[ K^0_s \rightarrow \pi\pi \]
\[ \Lambda \rightarrow p\pi \]
\[ \Xi \rightarrow \Lambda\pi \]

ALICE, arXiv:1307.5543
“What Have We Learned” from RHIC & LHC

1) Consistent Picture of Geometry, Dynamics & Evolution of RHI Collisions
Dynamics & Evolution of RHIC Collisions

Multiplicities (per participant nucleon) from RHIC to LHC

- vs. C.M. energy
- vs. # of participants

Small differences due to initial conditions?
Gluon shadowing vs geometry,
Hard scattering ~ # binary collisions
Are there differences at LHC & RHIC?

Initial state fluctuations?
Degree of shadowing?
See → data from 2013 p-Pb run!
System Size & Lifetimes


System size

Size → Volume ~ dN/dη

i.e. ~ multiplicity density

Lifetimes

Lifetime \( \tau_f \sim \left< \frac{dN_{ch}}{d\eta} \right>^{1/3} \)

\( \tau_f \) (central PbPb) ~ 10 – 11 fm/c

Lifetime → hydrodynamic expansion

\( V_{LHC} \sim 2 \times V_{RHIC} ! \)

\( \tau_f (LHC) \sim 1.4 \times \tau_f (RHIC) ! \)
“What Have We Learned” from RHIC & LHC

2) Particle ratios reflect equilibrium abundances
   → universal hadronization $T_{\text{critical}}$
   → Confirm lattice predictions for $T_{\text{critical}}$, $\mu_B$
Particles Formed at Universal Hadronization $T_{\text{critical}}$

Particles yields $\rightarrow$ equilibrium abundances $\rightarrow$ universal hadronization $T_{\text{critical}}$

Confirm lattice predictions for $T_{\text{critical}}$, $\mu_B$
“What Have We Learned” from RHIC & LHC

3) Strong flow observed $\rightarrow$ ultra-low shear viscosity
   Strongly-coupled liquid $\rightarrow$ quark-gluon plasma
1) Superposition of independent p+p:

momenta random relative to reaction plane
How do Heavy Ion Collisions Evolve?

1) Superposition of independent p+p:
   momenta random relative to reaction plane

2) Evolution as a **bulk system**
   Pressure gradients (larger in-plane) push bulk “out” → flow
   more, faster particles seen in-plane

High density pressure at center

“zero” pressure in surrounding vacuum
Azimuthal Angular Distributions

1) Superposition of independent p+p:
   momenta random
   relative to reaction plane

2) Evolution as a **bulk system**
   Pressure gradients (larger in-plane)
   push bulk “out” → flow
   more, faster particles
   seen in-plane
Large Elliptic Flow Observed at RHIC and LHC!

Azimuthal asymmetry of particles:
\[
dn/d\phi \sim 1 + 2v_2(p_T)\cos(2\phi) + \ldots
\]

Beams-eye view

Normalized counts

\(b \approx 6.5\) fm
\(b \approx 4\) fm
Large Elliptic Flow Observed at RHIC and LHC!

Azimuthal asymmetry of particles: $\frac{dn}{d\phi} \sim 1 + 2 v_2(p_T) \cos(2\phi) + \ldots$

Beams-eye view:

- $b \approx 10$ fm
- $b \approx 6.5$ fm
- $b \approx 4$ fm

$\phi_{lab} - \Psi_{plane}$ (rad)
Elliptic Flow Saturates
Hydrodynamic Limit

• Azimuthal asymmetry of charged particles:
  \[ \frac{dN}{d\phi} \sim 1 + 2v_2(p_T)\cos(2\phi) + \ldots \]

Mass dependence of \( v_2 \)

Initial studies require -

• Early thermalization (0.6 fm/c)
• Ideal hydrodynamics (zero viscosity)
  \[ \rightarrow \text{“nearly perfect fluid”} \]
• \( \varepsilon \sim 25 \text{ GeV/fm}^3 \) (\( \gg \varepsilon_{\text{critical}} \))
• Quark-Gluon Equ. of State
Elliptic Flow in Viscous Hydrodynamics

- Azimuthal asymmetry of charged particles:
  \[ \frac{dn}{d\phi} \sim 1 + 2 v_2(p_T) \cos(2\phi) + \ldots \]

Viscous hydrodynamics -
- CGC Initial State
- Early thermalization (0.5 fm/c)
- Shear viscosity / entropy \((\eta/s \sim 0.2)\)
- \(\varepsilon >> \varepsilon_{\text{critical}}\)

Ref: Song, Bass, Heinz, arXiv:1311.0157
It’s a Strongly-Coupled Medium with Ultra-Low Shear Viscosity

Universal lower bound on shear viscosity / entropy ratio ($\eta/s$):

$\eta/s = 1/4\pi$ for the “perfect liquid”

Viscous hydrodynamics calculations: Schenke, et al. PRL 106 (2011) 042301

$1/4\pi < \eta/s < 1/2\pi$

The strong-coupling limit of non-Abelian gauge theories with a gravity dual (ref: Kovtun, Son, Starinets, PRL 94, 111601 (2005))
Universality of Classical Strongly-Coupled Systems?

Transport in gases of strongly-coupled atoms

RHIC fluid behaves like this – a strongly coupled fluid.

Universality of classical strongly-coupled systems?
→ Atoms, sQGP, ... AdS/CFT (String Theory)

Quantum lower viscosity bound: $\eta/s > 1/4\pi$ \hspace{1cm} (Kovtun, Son, Starinets) 

from strongly coupled $N = 4$ SUSY YM theory.

3-d Rel. Hydro describes RHIC/LHC $v_2$ data with $\eta/s \sim 1/2\pi$ near lower bound!
Event-by-Event Initial Conditions Vary!

Initial conditions vary event-to-event.

Overlap region (1 event): Kowalski, Lappi, Venugopalan, PRL 100:022303

Final observation

Hydro evolution of overlap region: Schenke, et al. PRL 106:042301

Final observation

Azimuthal RHI harmonics provide information on viscous damping & spatial correlations:

\[ N_{\text{pairs}} \propto 1 + 2v_1^2 \cos \Delta \varphi + 2v_2^2 \cos 2\Delta \varphi + 2v_3^2 \cos 3\Delta \varphi + 2v_4^2 \cos 4\Delta \varphi + \ldots \]
Higher order harmonics provide extent to which initial inhomogeneity propagates thru the QGP:

\[ N_{\text{pairs}} \propto 1 + 2v_1^2 \cos \Delta \varphi + 2v_2^2 \cos 2\Delta \varphi + 2v_3^2 \cos 3\Delta \varphi + 2v_4^2 \cos 4\Delta \varphi + \ldots \]

Initial State

Ideal \( \eta/s = 0 \)

Final observation

Sound attenuation length:
\[ \Gamma_s = \eta/s \times 1/T \]
governs linear fluctuations.

Reynolds # ~ \( 1/\Gamma_s \)
governs non-linear fluctuations.

Final observation

\( \eta/s = 1/4\pi \)
Higher Order Components at LHC and RHIC

\[ \frac{\eta}{s} = \frac{1}{2} \pi \]

\[ \frac{\eta}{s} = \frac{1}{2} \pi \]

\[ \frac{\eta}{s} = \frac{1}{4} \pi \]

**ALICE Pb-Pb** \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

**v_2 (ALICE)**

**v_3 (ALICE)**

**v_4/\eta (ALICE)**

**v_2 (ATLAS)**

**v_3 (ATLAS)**

**v_4/\eta (ATLAS)**

**v_2 (CMS)**

**v_2 (STAR)**

**p_T (GeV/c)**
Identified Hadron Elliptic Flow Complicated

Complicated $v_2(p_T)$ flow pattern is observed for identified hadrons $\rightarrow d^2n/dp_Td\phi \sim 1 + 2 v_2(p_T) \cos(2\phi)$

If flow established at quark level, it is predicted to be simple $\rightarrow$

$KE_T \rightarrow KE_T / n_q$, $v_2 \rightarrow v_2 / n_q$, $n_q = (2, 3$ quarks$)$ for (meson, baryon)
Large Elliptic Flow Observed at RHIC and LHC!

Azimuthal asymmetry of particles:
\[ \frac{dN}{d\phi} \sim 1 + 2 v_2(p_T) \cos(2\phi) + \ldots \]

Predicted by hydrodynamics with very low shear viscosity

Increase in \( v_2 \) from RHIC to LHC
If baryons and mesons form from independently flowing quarks then quarks are deconfined for a brief moment (~ 10^{-23} s), then hadronization!
“What Have We Learned” from RHIC & LHC

4) QGP radiation (thermal photons) → exhibit time-integrated temperatures >> $T_{\text{critical}}$

Low mass di-leptons (virtual photons) → broadening of mass spectrum → medium modifications?
A thermal component of direct photons:

Exponential fit for $p_T < 2.2 \text{ GeV/c}$

- **inv. slope $T = 304 \pm 51 \text{ MeV}$**

**LHC (ALICE):** $T = 304 \pm 51 \text{ MeV}$

for $\sqrt{s_{NN}} = 2.76 \text{ TeV Pb-Pb}$

**RHIC (PHENIX):** $T = 221 \pm 19 \pm 19 \text{ MeV}$

for $\sqrt{s_{NN}} = 0.2 \text{ TeV Au–Au}$

Note: $T$ is integral over entire evolution!
Virtual photons – Di-leptons

Medium modification of resonance & hadron masses
Initial studies at SPS → Chiral symmetry restoration?

Virtual photons from decays in QGP
Must subtract all hadronic decays outside medium (scale pp data)

Low mass di-lepton enhancement!
The original case for medium effects!
Increases with centrality.

Space-time evolution?
Shuryak, arXiv:1203.1012v1

Centrality dependence:
PHENIX, PRC81, 034911(2010), arXiv:0912.0244
Low Mass Di-Leptons at RHIC

Minbias (value ± stat ± sys)

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<th></th>
<th>STAR</th>
<th>PHENIX</th>
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<tbody>
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<td></td>
<td>1.53 ± 0.07 ± 0.41 (w/o ρ)</td>
<td>4.7 ± 0.4 ± 1.5</td>
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<tr>
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<td>1.40 ± 0.06 ± 0.38 (w/ ρ)</td>
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<td>1.72 ± 0.10 ± 0.50 (w/o ρ)</td>
<td>1.54 ± 0.09 ± 0.45 (w/ ρ)</td>
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Central (value ± stat ± sys)

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<tbody>
<tr>
<td></td>
<td>1.72 ± 0.10 ± 0.50 (w/o ρ)</td>
<td>7.6 ± 0.5 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>1.54 ± 0.09 ± 0.45 (w/ ρ)</td>
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Difference

|       | 2.0 σ | 4.2 σ |

Enhancement factor in 0.15<M_{ee}<0.75 GeV/c^2

Disagreement & very difficult “task”!

Note: Acceptance differences etc.
Beam Energy Scan shows low mass enhancement at all $\sqrt{s_{NN}}$

$\rho$ melting sensitive to total baryon density not net baryon density

model describing data include chirally symmetric phase
“What Have We Learned” from RHIC & LHC

5) Baryon-Meson Anomaly?
   → Another mechanism producing hadrons at $p_T < 7$ GeV/c
   (i.e. not parton fragmentation!)
\( \pi, K, p: \) Baryon-Meson Anomaly & Suppression

\[ \frac{p}{\pi} \text{ and } \frac{\Lambda}{K^0_s} \]

1.5 < \( p_T \) < 8 GeV/c

- Increases for more central collisions
- Peripheral Pb-Pb similar to pp

→ Effects of medium? Quark recombination? Radial flow? Stan’s?

\( p_T > 8 \text{ GeV/c} \)

- No dependence on centrality / system → Parton fragmentation (unmodified)
**Baryon-Meson Anomaly – ALICE & STAR**

Baryon / meson ratio ($p/\pi$ and $\Lambda/K^0_s$)

1.5 < $p_T$ < 8 GeV/c

- Increases for more central collisions
- Peripheral Pb-Pb similar to pp

→ Effects of medium?    Quark recombination?    Radial flow?    Stan’s?
“What Have We Learned” from RHIC & LHC

1) Consistent Picture of Geometry, Dynamics and Evolution of RHIC Collisions

2) Particle ratios $\rightarrow$ equilibrium abundances $\rightarrow$ universal hadronization $T_{\text{critical}}$
   Confirm lattice predictions for $T_{\text{critical}}, \mu_B$

3) It has characteristics of a quark-gluon plasma
   Flows with ultra-low shear viscosity
   Strongly-coupled liquid

4) QGP radiation (thermal photons) $\rightarrow$ time-integrated temperatures $>> T_{\text{critical}}$
   Low mass di-leptons (virtual photons) $\rightarrow$ in-medium modification?

5) Baryon-meson anomaly $\rightarrow$
   Hadron production not fragmentation for $p_T < 7$ GeV/c

Next Monday: Using Hard Probes to Investigate the QGP
The Real Impact of the LHC!