Study hot QCD matter

Phase diagram of water (simplified)

Phase transitions

Heat ➔

Phase diagram of QCD (simplified)

Phase transition?

Compress ➔

Experimental study of QCD phase diagram by: colliding nuclei head-on to convert cold nuclear matter into a fireball of partons
Complex collision dynamics

1000s of particles

freeze out
hadrons
gluons & quarks in eq.
gluons & quarks out of eq.
strong fields
hard objects
Studying matter in the laboratory

Changing initial conditions:

<table>
<thead>
<tr>
<th>Ideal</th>
<th>Temperature</th>
<th>Matter</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical</td>
<td>Species</td>
<td>Energy</td>
<td>Size</td>
</tr>
</tbody>
</table>

Centrality (#Participants)

Probing the matter microscopically:
(Hard probes, C.Salgado next)

<table>
<thead>
<tr>
<th>Ideal</th>
<th>Microscopy</th>
<th>Tomography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical</td>
<td>Jets</td>
<td>Photons</td>
</tr>
</tbody>
</table>
Nuclear geometry and collision centrality

Nuclei are “macroscopic”: Characterize collisions by impact parameter

- Correlate yields from disconnected parts of phase space
- Correlation arises from common dependence on collision impact parameter
- Order events by centrality metric
  - Typically, classify them as “ordered” fraction of total cross section
    - e.g. 0-5% most central
- Number of participants (volume)

Charged hadrons $\eta \sim 3$
Heavy ion experiments at RHIC/LHC

- **RHIC**: First beams June 2000
  - p+p, d+Au, Cu+Cu, Au+Au (~20, 62.4, 130, 200 AGeV)
  - 2 multipurpose (PHENIX, STAR) and 2 specialized (BRAHMS, PHOBOS) experiments
    - >2006, only STAR and PHENIX
  - Beam energy scan (2010/11)

- **LHC**: First beams in Nov 2009
  - p+p (900, 2.36, 2.76, 7 TeV)
  - Pb+Pb at 2.76 ATeV in Nov 2010
  - 1 dedicated HI experiment
    - Mid-rapidity, low mass, PID
  - 2 large HEP experiments
    - Large acceptance, full calorimetry
Lattice predicts a cross-over phase transition from hadronic to partonic degrees of freedom.

\[ T_c \approx 145-175 \text{ MeV} \]

\[ \varepsilon_c \sim 1 \text{ GeV/fm}^3 \]
Initial temperature at RHIC

Direct photons: No charge, no color, i.e., they do not interact.

Emission over all lifetime convolution of all T

- Exponential (thermal) shape with T~200 MeV
- No excess in d+Au data
- Emission rate and shape consistent with that from equilibrated matter
- \( T_{\text{hydro}} = 300 - 600 \text{ MeV} (> 2 T_c) \)

First experimental observation of T>Tc

Y. Aramaki, Mon 2L
What do we know already from LHC?

**Charged-particle density**

- x2.5-3 times larger energy density
- Midrapidity $dE_T/d\eta \sim 2$ TeV at LHC

**Transverse energy density**

- ATLAS Preliminary
- ALICE

Compared to top RHIC energy

- x2.1 increase in $dN_{ch}/d\eta$ (x1.9 to pp)
- x2.5-3 times larger energy density
  - Midrapidity $dE_T/d\eta \sim 2$ TeV at LHC

$\tau \epsilon_{LHC} \geq 3 \times \tau \epsilon_{RHIC}$
How can we prove we make matter?

Ultracold Fermionic Atom Fluid (\(^6\)Li)

- Optically trapped atoms
  - Degenerate Fermi gas
  - NanoKelvin temperature
- Interactions magnetically tuned to Feshbach resonance
  - Unitary limit: Largest 2-body scattering cross section
  - “Strongly-coupled” system
- Prepare system with spatial anisotropy
  - Develops momentum anisotropy
  - Analysis of spatial profile

C.Cao et al., Science, 2010
Initial anisotropy and elliptic flow

Initial spatial anisotropy

Nucleus 1

\[ \varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle} \]

Overlap (participant) region is asymmetric in azimuthal angle

Interactions present early

Elliptic flow

\[ v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle} \]

\[ \frac{dN}{d\phi} \sim 1 + 2v_2 \cos[2(\phi - \psi_R)] + \ldots \]
What's needed partonically to get $v_2$?

Need large opacity to describe elliptic flow, i.e., elastic parton cross sections as large as inelastic the proton cross-section.

Parton transport model: Bolzmann equation with 2-to-2 gluon processes

D. Molnar, M. Gyulassy
NPA 697 (2002)

HUGE cross sections needed to describe $v_2$
Elliptic flow and ideal hydrodynamics

**Ideal relativistic hydrodynamics**

\[ T^{\mu \nu} = (e + p) u^\mu u^\nu - p g^{\mu \nu} \]

\[ \delta_\mu T^{\mu \nu} = 0 \]

\[ \delta_\mu N_i^\mu = 0, \ i = B, S, \ldots \]

\[ p = p(e, n) \quad \text{Closure with EoS} \]

**Assumption:**

After a thermalization time (\(\leq 1\text{fm}/c\)) a system in local equilibrium with zero mean free path and zero viscosity is created.

**Initial conditions (IC)**

**Equation of state (EOS)**

**Freeze-out cond. (FO)**

\[ \text{Hydro} \quad \text{Observables} \]

**Perfect fluid?**
Shear viscosity in QCD

Analytic: Csernai, Kapusta and McClerran PRL 97, 152303 (2006)

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

For a large class of holographic duals (see A. Karch Wed plen.)
Two classes of models describe the multiplicity (believed to be sensitive to initial state) equally well.

Glauber IC
Two-component model
\[
\frac{dN}{d\eta} = \frac{dN}{d\eta_{pp}} \left( (1-x)N_{\text{coll}} + xN_{\text{part}}/2 \right)
\]
PRC 70 021902 (2004)

Color glass condensate
\[
\frac{dN}{d\eta} \propto N_{\text{part}}^\alpha \sqrt{s}^\lambda
\]
PRL 94 022002 (2005)
Ambiguity in description of initial state allows for various models: Size of viscous corrections and/or soft equation of state?
The hot QGP is a nearly perfect fluid ...

Combination of many calculations, including state-of-art results from Israel-Stewart theory for a conformal fluid (2+1D), hint to a low shear viscosity to entropy ratio:

\[ \frac{1}{4\pi} < \frac{\eta}{s} < \frac{3}{4\pi} \]

Largest part of uncertainties still from the ambiguity in the description of initial state.
... as are the ultracold atoms!

Ultracold Fermionic Atom Fluid ($^6$Li)

\[ \frac{\eta}{s} \leq \frac{5}{4\pi} \]

C. Cao et al., Science, 2010

\[ T=0.1\text{neV} \] (QGP \( \sim 0.3\text{TeV} \))

Low temperature: Breathing mode

High temperature: Elliptic flow
Does the picture change at the LHC?

Striking similarities between data over about two orders of collision energy. Factorization into energy and centrality.
Two-particle correlation landscape (LHC) 20

ATLAS, prelim.

$2 < p_t^{\text{trigger}} < p_t^{\text{associated}} < 3 \text{ GeV/c}$
Multi-particle correlation studies (cumulant) studies extract the genuine multi-particle correlation.
Collision energy dependence

Integrated $v_2$: 30% increase from 0.2 TeV (STAR) to 2.76 TeV (ALICE)
Over all centrality classes, due to the increase of $<p_T>$

Centrality dependence

No qualitative change in the observable at the LHC

PRL, 105, 252302 (2010), arXiv:1011.3914
Remarkable precision across two systems and experiments.
Low viscosity fluid also at the LHC

Increase well within the range of viscous hydro predictions

Calculation: M. Luzum, arXiv:1011.5173
Importance of initial state fluctuations

Standard Eccentricity

PHOBOS preliminary
- 200 GeV
- 130 GeV, Star
- 17 GeV, Na49
- 4 GeV, E877

Cu+Cu

1/⟨S⟩ ⟨dN_{\text{ch}} / dy⟩ [fm^{-2}]

Participant Eccentricity

PHOBOS preliminary
- 200 GeV, tracks
- 130 GeV, hits
- 17 GeV, Na49
- 4 GeV, E877

Au+Au

1/⟨S⟩ ⟨dN_{\text{ch}} / dy⟩ [fm^{-2}]

Nucleus 1
Nucleus 2
Higher azimuthal harmonics

Analogous to power spectrum extracted from cosmic microwave background radiation

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

Initial spatial anisotropy not an almond, may lead to higher harmonic anisotropies in the final state

\[ \frac{dN}{d\phi} \sim 1 + 2v_2 \cos [2(\phi - \psi_2)] + 2v_3 \cos [3(\phi - \psi_3)] + 2v_4 \cos [4(\phi - \psi_4)] + 2v_5 \cos [5(\phi - \psi_5)] + \ldots \]
Sizeable triangular flow observed. As expected, centrality dependence is different to that of elliptic flow. Measurements vs reaction planes yield zero as it should if from fluctuations.
Common origin interpreted by hydro

Hydro: Shen et al., arxiv:1105.3226 (no afterburner)

Same mass splitting for $v_3$ as predicted for $v_2$ by hydro.

(Note also that the crossing between (anti-) protons and pions happens at the same $p_T$, which for $v2$ was considered a sign of recombination.)
The overall dependence of $v_2$ and $v_3$ is described. However, not yet for a single $\eta/s$ value. More constraints on initial conditions provided by $v_3$ and higher harmonics.
Many higher moments measured up to $v_6$. Power spectrum of QGP. (Results by all collaborations at RHIC/LHC.)
Structures seen in two particle correlations (reported mainly at RHIC) are naturally explained by measured anisotropic flow coefficients.
Where does the decomposition break?

\[ \frac{dN_{\text{pairs}}}{d\Delta \phi} \propto 1 + \sum_n 2V_n \Delta(p_T^t, p_T^a) \cos(n \Delta \phi) \]

\[ \frac{dN}{d\phi} \propto 1 + \sum_n 2v_n(p_T) \cos(n(\phi - \Psi_n)) \]

If bulk flow then:

\[ V_n \Delta(p_T^t, p_T^a) = v_n(p_T^t) v_n(p_T^a) \]

Perform global fit for each harmonics

Two particle correlations are well described via bulk flow decomposition up to about 4 GeV. Similar for other harmonics (except \( v_1 \)). Challenge the jet heating picture (next talk)?
Melting of Upsilon (2S,3S)

Direct access to the deconfined matter state? Stay tuned
Melting temperatures from the lattice are about 1.2 and 1.6 Tc.

$\frac{\gamma(2S + 3S)}{\gamma(1S)} \bigg|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$

$\frac{\gamma(2S + 3S)}{\gamma(1S)} \bigg|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

$\frac{\gamma(2S + 3S)}{\gamma(1S)} \bigg|_{PbPb} = 0.31^{+0.19}_{-0.15} \pm 0.03$

M.Calderon, Mon 1L
Exciting and stimulating time in our field with fruitful interplay of heavy-ion experiments at RHIC and LHC.

- Characterization of LHC bulk properties well underway
  - No big picture changes (unlike the transition from SPS to RHIC)
- Also first results from beam-energy scan (not discussed)

Tremendous progress in the measurement of the QGP viscosity

- The most perfect known fluids are the coldest and the hottest
- QGP power spectrum ($V_n$) from fluctuations extracted
  - Expected to provide further constraints on $\eta/s$
- Too early to conclude about precise value of $\eta/s$ at the LHC

Special thanks to ALICE, ATLAS, CMD, STAR+PHENIX collaborations for their exiting new results and apologies to what I could have not shown for space-time restrictions.
Number of quark scaling (Beam-Scan)

- $v_2$ of $\phi$ meson does not follow the trend for other hadrons at 11.5 GeV
- Significant difference between baryon/anti-baryon $v_2$ at 7.7 & 11.5 GeV
  - No scaling between particles and anti-particles
Higher moments (Beam Scan)

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!
Even heaviest particles flow

Partonic collectivity at RHIC:
Heavy multi-strange particles flow as protons and pions

PHENIX π and p: nucl-ex/0604011v1
Constituent quark scaling

All particles flow as if frozen out from a flowing soup of constituent quarks.
Flow methods

Two-particle cumulant

\[ v \{ 2 \} = \sqrt{\langle \cos(\phi_1 - \phi_2) \rangle} \]

Measures:

\[ v \{ 2 \}^2 = \langle v \rangle^2 + \sigma_{v_2}^2 + \delta \]
\[ v \gg 1/\sqrt{M} \]

Four-particle cumulant

\[ v \{ 4 \} = \left( 2 \langle \cos(\phi_1 - \phi_2) \rangle^2 - \langle \cos(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle \right)^{1/4} \]

Measures:

\[ v \{ 4 \}^2 = \langle v \rangle^2 - \sigma_{v_2}^2 \]
\[ v \gg 1/M^{3/4} \]

\[ v \{ \text{subEP} \} = \frac{\langle \cos(\phi - \psi_A) \rangle}{R} \]
\[ R = \sqrt{\langle \cos(\psi_A - \psi_B) \rangle} \]

Measures:

\[ v \{ \text{subEP} \}^2 = \langle v \rangle^2 + \left( 1 - f(R) \right) \sigma_{v_2}^2 + \left( 1 - 2f(R) \right) \delta \]

NB: For simplicity, n (as index and in cos terms) dropped

Ollitrault, Poskanzer, Voloshin
PRC 80 80 014904 (2009)
Observation of ridge in high density proton-proton collisions

W.Li, Session 1L
Shear viscosity in fluids

Shear viscosity characterizes the efficiency of momentum transport

\[ \frac{F}{A} = \eta \frac{v}{L} \]

\[ \eta = \rho \langle v \rangle \lambda_{mf} \sim \left( \frac{1}{\sigma} \right) \]

Comparing relativistic fluids: \( \eta / s \)

- \( s = \) entropy density
- scaling param. \( \eta / s \) emerges from relativistic hydro eqns.
- generalization for non-rel. fluids: \( \eta / w \) (\( w = \) enthalpy)
  

Large \( \sigma \) \( \rightarrow \) small \( \eta / s \)

\( \rightarrow \) Strongly-coupled matter

\( \rightarrow \) "perfect liquid"
Structures seen in two particle correlations (reported mainly at RHIC) are naturally explained by measured anisotropic flow coefficients.

From Jamie Nagle's talk at QM'09
Final state: Kinetic equilibrium

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

Spectra consistent with common temperature plus radial flow velocity. 20% stronger radial flow at LHC.
Final state: Chemical equilibrium

Grand-canonical ensemble analysis

\[ N_i \propto V \int \frac{d^3 p}{2 \pi^3} \frac{1}{e^{(E_i - \mu_B B_i)/T_{ch}} \pm 1} \]

- \( T_{ch} \): Chemical freeze-out temperature
- \( \mu_B \): Baryochemical potential

All hadron species emitted from a thermal source: \( T_{ch} = 163 \pm 4 \text{ MeV}, \mu_B = 24 \pm 4 \text{ MeV} \)

System decouples at \( T_{ch} \sim T_c \)