Peering through the haze:
Experimentally Reconstructing the QGP

Mike Lisa
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• Accelerators
  • how to make the QGP

• The need for ions; hadronization
  • why physics makes the QGP hard to see
  • why we do it anyway

• Detectors, reconstruction, analysis
  • how we peer through the haze
Exploring smaller scales has always required more energetic probes:

New physics has consistently been revealed at new energy frontiers accessed by ever more powerful accelerators.

The Strong Force
-least well-understood, due to its “special” property...
-which is also what makes it of fundamental importance...

10^{-9} meters
Atoms (1800)
DNA nucleotide building block

10^{-12} meters
The Nucleus (1910)
Empty space between outer shell and nucleus

10^{-14} meters
Protons & Neutrons (1920)
Proton of a carbon atom

Quarks & Gluons (1970)

7.7 MeV  100 MeV  3 GeV  400 GeV  TeV
Quantum Chromodynamics’ special feature

Heavy Ion Physics

Low Q: Confinement
- the unique feature of QCD
- dominates almost all baryonic mass in universe
- theoretical insight limited

intrinsic scales of QCD →
- bigger is better (>> 1 fm)
- optimum energy range

focus on fundamental interaction

focus on fundamental particles

Particle Physics

Large Q: Asymptotic Freedom
- α→0 @ r→0 (anti-screening)
- perturbative calculations
- reduce “messy” QCD effects

focus on fundamental interaction

focus on fundamental particles

✓ Smaller/simpler is better (e+e, p+p)
✓ More energy is better (Minv)
The RHIC complex – Brookhaven National Lab (NY)
Relativistic Heavy Ion Collider (RHIC)

\[ \sqrt{s} = 7-200 \text{ GeV} \]
\[ v = 0.99995c \]
\[ p+p, d+Au, Cu+Cu, Au+Au \]
Step 1: Electron Beam Ion Source (EBIS): from v=0 to 5%c (replaces Van de Graaff tandems)

~ 30 m long (replacing 860m transfer line from Tandems much more efficient than tandems)
Step 1: Electron Beam Ion Source (EBIS): from v=0 to 5%c replaces Van de Graaff tandems

much wider range of isotopes than previously possible
- including, now, Uranium!
  - in a year, less uranium accelerated than in one handful of soil

delivers $10^9$ Au(+32) ions in each bunch, lasting ~50 microsec

Followed by RFQ accelerator and linac to get them up to a few MeV/A
- gamma $\approx 939/938 = 1.001 \rightarrow$ beta $\approx 0.05$ (v=5%c)
Basic operation of RF accelerators

The Linac is capable of producing up to a 35 mA proton beam at energies up to 200 MeV for injection into the AGS Booster.
One pass thru an RF cavity is usually not sufficient.

Can build a long line of many RF cavities...
- linear accelerator like SLAC, small one like pre-injector
- accelerator rings like RHIC

or... build only a few, but kick the beam each time it comes around.
- accelerator rings like RHIC
Step 2: Booster-accelerator:
1 AMeV to about 100 AMeV (5% to 43% c)
Synchrotron – a necessary step beyond a cyclotron

Cyclotron
- charged particles injected in the center
- forced to circular motion by constant B-field
- accelerate every time they cross a gap (V alternated)
- escape when orbital radius exceeds D region

- simple design & operation
- limited to about 10 AMeV (0.00001 ATeV)

K1200 @ NSCL/MSU

Square wave electric field accelerates charge at each gap crossing.
Magnetic field bends path of charged particle.
Way out: Synchrotron
Narrow beam pipe surrounded by smaller and more tightly focused magnets

Magnetic field and the electric field (to accelerate the particles) are carefully synchronized with the traveling particle beam.

Foil @ exit charges beam to +77 [only K-shell e\(^-\) remain]

Exit with K.E. \(\sim 100\) AMeV
\[E = (938+100)\text{ AMeV}\]
\[\gamma = (938+100)/938 = 1.107\]
\[\beta = 0.43\]

Usually less than x2 loss factor from EBIS thru Booster
Step 3: AGS (once the world’s highest energy machine. today a booster)
Fully strip the ion and boost to truly relativistic energy (~9 GeV)
Alternating Gradient Synchrotron (AGS)

AGS is filled in 4 Booster cycles with 24 bunches
- debunched and rebunched into 4 bunches (1 bunch = 1 Booster filling = (later) 1 RHIC bunch)
- accelerated to 8.86 GeV/u with $Q=+77$ (Au)
- at exit ions fully stripped via AtR beamline to RHIC

The AGS name is derived from the concept of alternating gradient focusing

Produced 3 Nobel prices (J/$\psi$, CP with K, $\nu_\mu$)

240 "warm" magnets

Luminosity now at 7,600 times the design value

Larger version of booster, accelerating to 8.9 AGeV →
$\gamma=10.5$, $\beta=0.995$

Beam fully stripped at exit of AGS (before AtR beamline)

Produced 3 Nobel Prizes: J/$\psi$, CP violation with K, $\nu_\mu$
Step 4: AGS to RHIC (AtR) transfer line.

Switching magnet at injection arcs to blue & yellow rings
Beam injection box-car style – one bunch at a time
Fill RF buckets (360 typical)
Welcome to the machine
Beam is accelerated by Radio Frequency (RF) cavities:
28 MHz for acceleration
200 MHz for storage to reduce bunch length

28 MHz defines the number of “buckets” = 360, length is 35 ns each (or ~10.7 m)

Note: a continuous beam (no bunch structure), cannot be accelerated

Bunched (or captured) beam: every 6th (3rd) bucket, i.e. 55+5 (110+10) bunches per ring with 10^9 ions

circumference: 3833 m (2.4 miles)
Transit time T = (3833 m)/(2.99E8 m/s) = 12.8 microsec
f = 1/T = 78 kHz (→ ion completes a rotation 78 thousand times/sec)
360 buckets → each bucket (3833 m)/360 ~ 10.7 m (or 35 ns)
frequency of RF cavities = 360*(78 kHz) = 28 MHz (also = (2.99E9 m/s)/(10.7 m))
Injection and acceleration – what the experiment sees

The beam is accelerated from Injection Energy (10 GeV) to Storage Energy (100 GeV). The acceleration process is called “ramp”.

$(3.6 \times 10^8 \text{ Au/bunch})$
“Stochastic cooling” has greatly increased beam brightness, lifetime.

If there is a perturbation in the orbit, a signal is sent via straight-line “short-cut” to produce a corrective “kick”
RHIC is big
RHIC is big... but the LHC is bigger
HEAVY ION PHYSICS – CHARACTERISTICS & SPECIAL NEEDS
C = Collider. RHIC and LHC are the only nuclear colliders in the world

Remarkably similar accelerator complexes:
- Electron-current-based **source** & **linac** – ions partially stripped & accelerated to ~2 AMeV
- Followed by **synchrotrons** (LEIR, PS & SPS for LHC, Booster & AGS for RHIC)
- Finally transferred to **two counter-rotating rings** in the collider with **4 major expts**

But very different size:
- RHIC: circumference = 3.8 km \(\sqrt{s}=200\) GeV
- LHC circumference = 26.7 km \(\sqrt{s}=5500\) GeV

The reason is in the “H”
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**QED vs QCD**

- \( e^+ e^- \rightarrow e^+ e^- \) (screened)
- \( e^+ e^- \rightarrow \text{Gluon} \) (unscreened)

- Vacuum fluctuations (e.g. \( e^+ e^- \) pairs) screen electric charge
- Electric charge appears longer at smaller distance (e.g. \( \alpha \approx 1/128 \) at 90 GeV)

- Gluons (unlike photons) carry color-anticolor charge

- Contribution of Gluons (Spin 1) to vacuum fluctuations leads to anti-screening
- Color charge appears smaller at smaller distance (higher momentum interactions)

- "Polarization of the Vacuum"

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**Intrinsic scales of QCD**

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**Focus on fundamental interaction**

- Data
- Theory
- NLO
- NNLO
- Lattice
Heavy Ion physics looks like particle physics, but the focus is very different
• understand the special nature of a theory (QCD) that has a scale
• study phase structure → bulk (multiparticle/low momentum)
RHIC and LHC

Relativistic Heavy Ion Collider
- energy tuned to probe QCD @ interesting scale
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The other H: Higgs:
- it’s what’s responsible for mass, right?
- um, not really
- >99% of your mass comes from energy associated with dynamical quarks & gluons in nucleons: QCD

constituent quarks
This is what Heavy looks like (Pb+Pb @LHC)
"If you still don’t understand p+p, why study 180p+180p?"

Similar to “If we are still studying atomic physics, why study condensed matter physics?”

Because we are interested in phases of matter

A process

\[ q \rightarrow W, Z \rightarrow H^0 \]

A system “Condensed matter QCD”

p+p vs=14 TeV

p+p vs=200 GeV

Pb+Pb vs_{NN}=5.5 TeV

Au+Au vs_{NN}= 200 GeV
You can’t freeze one molecule of water
Confinement itself makes it even harder

Free quarks cannot be measured. Our job: identify patterns in the hadronic debris.
Did this hadronic debris come from a QG plasma? How could we tell? &... how can we measure this mess in the first place?!
DETECTORS, COMPUTING & ANALYSIS
The Big Picture
Simulated collision in ATLAS @ LHC
Muon Spectrometer

Hadronic Calorimeter

Electromagnetic Calorimeter

Solenoid magnet

Tracking

- Transition
- Radiation
- Tracker

Pixel/SCT detector

The dashed tracks are invisible to the detector

Muon

Proton

Neutron

Electron

Photon

Neutrino

ATLAS Experiment

http://atlas.ch
“Natural” geometry

CMS@LHC: $d = 15\, \text{m}$

ATLAS@LHC: $d = 25\, \text{m}$
“Natural” geometry

CMS@LHC: $d = 15$ m

ALICE@LHC: $h = 15$ m

ATLAS@LHC: $d = 25$ m
“Natural” geometry

CMS@LHC: $d = 15$ m
ALICE@LHC: $h = 15$ m
ATLAS@LHC: $d = 25$ m
STAR@RHIC: $d=7$ m
Solenoidal Tracker At RHIC - STAR
Solenoidal Tracker At RHIC

goal: track “all” charged hadrons (bags of quarks) emitted in each collision
End-plane instrumentation – pads and wires

Sector Operation for 20:1 signal to noise

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Sector Operation for 20:1 signal to noise

Sector gas gain anode voltage
inner 3000 1150
outer 1100 1380
Charged particle flies thru TPC gas...
Anode wires with +HV sitting ~5 mm above pads
..generating a cluster of liberated electrons

“Avalanche” as electrons approach anode wire...
..capacitively inducing a signal on nearby pads...

plifying and digitizing electronics connected to each pad...
..which is amplified, digitized, and recorded for later analysis
One collision seen by STAR TPC

Momentum determined by track curvature in magnetic field...

...and by direction relative to beam
Challenges – even for “just” $p+p$ collisions

ATLAS Online 2011, $\sqrt{s}=7$ TeV $\int Ldt=5.2$ fb$^{-1}$

$Z\rightarrow \mu\mu$ with 25 pile-up interactions in 2012
Data storage

RHIC experiments:
presently ~ 6-10 PB each of raw, “derived” data

LHC experiments:
~15 PB of new data each year.

~1000x more data discarded pre-storage by filtering triggers

50 PB =
• entire written works of all mankind, from beginning of recorded history
• 660 years of HD-TV video
• 10 million DVDs

(source: Mozy.com)
Grids – OSG, ...

Centers around the world form a Supercomputer
• The EGEE and OSG projects are the basis of the Worldwide LHC Computing Grid Project WLCG
Inter-operation between Grids is working!

“Average: ~14 hr/sec”

Computation Hours Per Week
52 Weeks from Week 37 of 2010 to Week 37 of 2011

Cumulative Computation Hours
52 Weeks from Week 37 of 2010 to Week 37 of 2011

QM 2012 / Teachers' Day - Washington D.C. - 12 Aug 2012 - Mike Lisa
TOF and TPC

- clean separation of pi/K to pT~1.6 GeV
- full azimuthal coverage
- |η|<1
TOF and TPC
- clean separation of π/K to pT~1.6 GeV
- full azimuthal coverage
- |η|<1
- topological/combinatoric reconstruction of weak decays

\[ K_S^0 \rightarrow ^+ ^+ \quad \text{preliminary} \]
\[ \rightarrow K^+ + K \quad \text{preliminary} \]
\[ \rightarrow p + \quad \text{preliminary} \]

G. Odyniec, SQM 2011
Impact parameter vector $\vec{b}$:
- beam direction
- connects centers of colliding nuclei

$b = 0 \rightarrow$ “central collision”
many particles produced

“peripheral collision”
fewer particles produced
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Reaction plane:
spanned by beam direction and $\vec{b}$
How do semi-central collisions evolve?

1) Superposition of independent p+p:

momenta pointed at random relative to reaction plane
How do semi-central collisions evolve?

1) Superposition of independent p+p:
   momenta pointed at 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
How do semi-central collisions evolve?

1) Superposition of independent $p+p$:
   momenta pointed at 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
Azimuthal distributions at RHIC

STAR, PRL90 032301 (2003)

Midcentral collisions

$\ell \approx 4 \text{ fm}$

$\ell \approx 6.5 \text{ fm}$
Azimuthal distributions at RHIC

STAR, PRL90 032301 (2003)

peripheral collisions

- $b \approx 4$ fm
- $b \approx 6.5$ fm
- $b \approx 10$ fm
Keyword: Elliptic Flow

STAR, PRL 90 032301 (2003)

What about the LHC?

Elliptic flow 10% larger at LHC:
Stronger initial push due to higher density

Comparison to state-of-the-art hydro calculations suggests:

\[ \eta/s(LHC) \sim \eta/s(RHIC) \]

Song, Heinz et al, PANIC 2011

ALICE data

\[ N(\phi) \mu 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + 2v_3 \cos(3\phi) + \ldots \]
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Song, Heinz et al, PANIC 2011
ALICE data

\( v_2 \)

strongly self-interacting fluid (!!)
**Hydrodynamics:** conservation laws for long wavelength modes

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

Generally:

\[ T^{\mu \nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu \nu} + \pi^{\mu \nu}. \]

First order Navier Stokes theory:

\[ \pi^{\mu \nu} = \pi_0^{\mu \nu} = \eta (\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3} \Delta^{\mu \nu} \nabla_\alpha u^\alpha). \]

**\( \eta \):** Shear viscosity

Large \( \eta \) = transport of momentum across fluid layers

+ initial conditions (nontrivial!)

+ Equation of State (fundamental)
Data support
Lattice QCD EoS near zero net baryon density
• Cross-over transition.

Also: almost zero viscosity
• surprise!
Summary

• Relativistic Heavy Ion physics “resembles” High-Energy Particle physics...
  – ~1000-person collaborations, distributed worldwide
  – accelerators, computing & detectors at (& pushing) the limits of possibility
  – fully quantum, fully relativistic; fundamental forces, particles

• ...but is distinctly different
  – focus is on QCD confinement and phase structure
  – requires heaviest systems – special pressures on detectors/analysis

• peering through the QCD mist to short-lived (10E-23 sec) color-deconfined stage requires every effort of a ~10^4-person world-wide community
  – check out some of our most exciting findings this week