Introduction to Relativistic Heavy Ion Physics

Lecture 2: Experimental Discoveries

W.A. Zajc
Columbia University
• General arguments suggest that for temperatures $T \sim 200$ MeV, nuclear matter will undergo a *deconfining* phase transition.

• Similar arguments suggest the required energy density is of order

$$\varepsilon \sim ndf \frac{\pi^2}{30} (200 \text{ MeV})^4 \sim 37 \frac{1}{3} \frac{(0.2 \text{ GeV})}{\text{fm}^3} \sim 2.4 \text{ GeV} / \text{fm}^3$$

- Note 1: normal nuclear density $\varepsilon_0 \sim 0.16$ GeV/fm$^3$
- Note 2: Also true near $T = 0$, i.e., cold nuclear matter

• How to create study experimentally?
Exploring the QCD Phase Diagram

• Hot nuclear matter:
  - Study experimentally by colliding heaviest nuclei at highest energies:

• Cold nuclear matter:
  - Study by observation of neutron stars and other exotic objects
  - (Not covered in these lectures)
Expectations circa 2000

As encoded in the Nuclear Physics Wall Chart, http://www.lbl.gov/abc/wallchart/, RHIC would create a quark-gluon plasma; a “gas” of weakly interacting quarks and gluons.
RHIC Specifications

- 3.83 km circumference
- Two independent rings
  - 120 bunches/ring
  - 106 ns crossing time
- Capable of colliding
  ~any nuclear species
  on
  ~any other species

- Energy:
  - 500 GeV for p-p
  - 200 GeV for Au-Au
    (per N-N collision)

- Luminosity
  - Au-Au: \(2 \times 10^{26}\) cm\(^{-2}\) s\(^{-1}\)
  - p-p: \(2 \times 10^{32}\) cm\(^{-2}\) s\(^{-1}\)
    (polarized)
How is RHIC Different?

- **Different from p-p, e-p colliders**
  
  Atomic weight $A$ introduces new scale $Q^2 \sim A^{1/3} Q_0^2$

- **Different from previous (fixed target) heavy ion facilities**
  
  - $E_{\text{CM}}$ increased by order-of-magnitude
  
  - Accessible $x$ (parton momentum fraction) decreases by $\sim$ same factor
  
  - Access to perturbative phenomena
    
    - Jets
    
    - Non-linear $dE/dx$

- **Its detectors are comprehensive**

  - $x \sim \frac{2 p_T}{\sqrt{s}}$

  Jargon Alert:
  
  $\sqrt{s} = \text{Center-of-mass energy (per nucleon collision)}$
  
  $p_T = \text{transverse momentum} = |p| \sin \theta$
  
  $Q^2 = (\text{momentum transfer})^2$
The Plan circa 2000

• Use RHIC’s unprecedented capabilities
  - Large \( \sqrt{s} \) ⇒
    - Access to reliable pQCD probes
    - Clear separation of valence baryon number and glue
    - To provide definitive experimental evidence for/against Quark Gluon Plasma (QGP)
  - Polarized p+p collisions

• Two small detectors, two large detectors
  - Complementary capabilities
  - Small detectors envisioned to have 3-5 year lifetime
  - Large detectors ~ facilities
    - Major capital investments
    - Longer lifetimes
    - Potential for upgrades in response to discoveries
Since 2000…

- **Accelerator complex**
  - Routine operation at 2-4 x design luminosity (Au+Au)
  - Extraordinary variety of operational modes
    - Species: Au+Au, d+Au, Cu+Cu, p↑+p↑

- **Experiments:**
  - Worked!

- **Science**
  - More than 200 refereed publications, among them 100+ PRL’s
  - *Major* discoveries

- **Future**
  - Demonstrated ability to upgrade
  - Key science questions identified
  - Accelerator and experimental upgrades underway for that science
Assertion

- In these complicated events, we have *(a posteriori)* control over the event geometry:
  - **Degree of overlap**
    - Classify by “centrality”, e.g., 0-10% most central events
  - **Orientation with respect to overlap**
Outline

Will present *sample* of results from various points of the collision process:

1. Final State
   - Yields of produced particles
   - Thermalization, Hadrochemistry

2. Plasma(?)
   - Probes of dense matter

3. Initial State
   - Hydrodynamic flow from initial spatial asymmetries
Final State

Does the huge abundance of final state particles reflect a *thermal* distribution?:

1. Final State
   Yields of produced particles
   Thermalization, Hadrochemistry
Origin of the (Hadronic) Species

- Thermal? Apparently:
  - Assume all distributions described by one temperature $T$ and one (baryon) chemical potential $\mu$:
    $$dn \sim e^{-(E-\mu)/T} \, d^3p$$
  - One ratio (e.g., $\bar{p}/p$) determines $\mu/T$:
    $$\frac{\bar{p}}{p} = e^{-(E+\mu)/T} = \frac{e^{-(E-\mu)/T}}{e^{-2\mu/T}}$$
  - A second ratio (e.g., $K/\pi$) provides $T \rightarrow \mu$

Exercise 1: Find $T$ and $\mu$ from data at right

- Then predict all other hadronic yields and ratios:
- NOTE: Truly thermal implies No memory (!)
Locating RHIC on Phase Diagram

- Previous figure ➔ RHIC has net baryon density ~ 0:

130 GeV RHIC: STAR / PHENIX / PHOBOS / BRAHMS

17.4 GeV SPS: NA44, WA97

Previous Heavy Ion Experiments (CERN SPS)
Locating RHIC on Phase Diagram

- Previous figure $\Rightarrow$ RHIC has net baryon density $\sim 0$:

$\Rightarrow$ RHIC is as close as we'll get to the early universe for some time (until next year 😊)
Probes of the Plasma(?) State

Q. How dense is the matter?

A. Do Rutherford scattering on deep interior using “auto-generated” probes:

2. Plasma(?)

Probes of dense matter
Transverse Dynamics
Fundamental single-particle observable:

**Momentum Spectrum**

$$E \frac{d^3 \sigma}{dp^3}$$

**Exercise 2:** Remind yourself why this is invariant

$$y \equiv \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \Rightarrow \frac{d^3 \sigma}{d^2 p_T \ dy}$$

**Exercise 3:** Show that $y$ is additive under Lorentz transformations.

Use this to show $dy = d\beta$.

**Observation:** Roughly the same pT spectra here and here.
Aside- Estimating Energy Density

- This will be an incredibly crude (wrong) estimate:
  - Take all \sim 10,000 particles produced in Au+Au collision at RHIC
  - Assume the \sim constant \langle p_T \rangle \sim 0.4 \text{ GeV} represents “thermalized” energy
  - Initial volume
    - \( R_{Au} \sim 6.5 \text{ fm} \)
    - \( \Delta z \sim 1/T \sim 1 \text{ fm} \)
  - Energy density
    - \( \varepsilon \sim (10^4 \times 0.4 \text{ GeV}) / (\pi R_{Au}^2 \times 1 \text{ fm}) \sim 30 \text{ GeV/fm}^3 \)
Q. How to really (?) estimate initial energy density?

A. From *rapidity density* of transverse energy \( E_T \equiv \Sigma_i E_i \sin \theta_i \)


- Assumes
  - \( \sim 1\)-d hydrodynamic expansion
  - *Invariance* in \( y \) along “central rapidity plateau” (i.e., flat rapidity distribution)
  - Then
    \[
    \varepsilon = \frac{E}{V} \sim \frac{dE_T}{\pi R_T^2 \cdot dz} = \frac{1}{\pi R_T^2} \frac{dE_T}{dy}
    \]

since boost-invariance of matter

\[ dz = \tau \ dy \quad \text{where} \quad \tau \sim 1 \text{ fm/c} \]
Determining Energy Density

- What is the energy density achieved?
- How does it compare to the expected phase transition value?

Bjorken formula for thermalized energy density

\[ \varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy} \]

\[ d\varepsilon = \tau_0 dy \]

\[ \varepsilon_{Bj} \sim 4.6 \text{ GeV/fm}^3 \]

\[ \sim 6.5 \text{ fm} \] time to thermalize the system (\(\tau_0 \sim 1 \text{ fm/c}\))

\[ \sim 30 \text{ times normal nuclear density} \]

\[ \sim 1.5 \text{ to } 2 \text{ times higher than any previous experiments} \]
The Danger in Cartoons

- What is this thing??

- Surely not the space-time development:
Using “Hard Probes”

Systematic approach essential:

- p+p: BASELINE
- d+Au: CONTROL
- Au+Au: NEW EFFECT
Baseline p+p Measurements with pQCD

- Consider measurement of $\pi^0$'s in p+p collisions at RHIC.
- Compare to pQCD calculation

$$d\sigma = f_{a/A}(x_a, \mu^2) \otimes f_{b/B}(x_b, \mu^2)$$

- Parton distribution functions, for partons a and b
- Measured in DIS, universality

$$\bigotimes d\hat{\sigma}(a + b \rightarrow c + d)$$

- Perturbative cross-section (NLO)
- Requires hard scale
- Factorization between pdf and cross section

$$\bigotimes D_{h/c}(z_h, \mu^2)$$

- Fragmentation function
- Measured in e+e-

Systematic Measurement in Au+Au

\[
\frac{1}{2\pi p_T N_{\text{evt}}} \frac{d^2 N}{dp_T dy} (\text{GeV/c})^{-2}
\]

\( \pi^0 p_T \) spectra
- min. bias x2
- 0-10\% \( \times 10^{-1} \)
- 10-20\% \( \times 10^{-2} \)
- 20-30\% \( \times 10^{-3} \)
- 30-40\% \( \times 10^{-4} \)
- 40-50\% \( \times 10^{-5} \)
- 50-60\% \( \times 10^{-6} \)
- 60-70\% \( \times 10^{-7} \)
- 70-80\% \( \times 10^{-8} \)
- 80-92\% \( \times 10^{-9} \)

PHENIX

Au+Au \( \sqrt{s_{NN}} = 200 \text{GeV} \)
Luminosity

- Consider collision of ‘A’ ions per bunch with ‘B’ ions per bunch:

\[ L \sim \frac{A \cdot B}{S} \]
• Consider collision of ‘A’ nucleons per nucleus with ‘B’ nucleons per nucleus:

\[ L \sim \frac{A \cdot B}{S} \sim N_{Coll} \propto A \cdot B \]

not \[ N_{Part} \propto A + B \]

Provided:
No shadowing
⇒ Small cross-sections
Systematizing our Knowledge

- All four RHIC experiments have carefully developed techniques for determining
  - the number of participating nucleons \( N_{\text{PART}} \) in each collision (and thus the impact parameter)
  - The number of binary nucleon-nucleon collisions \( N_{\text{COLL}} \) as a function of impact parameter
- This effort has been essential in making the QCD connection
  - Soft physics \( \sim N_{\text{PART}} \)
  - Hard physics \( \sim N_{\text{COLL}} \)
- Often express impact parameter \( b \) in terms of “centrality”, e.g., 10-20% most central collisions
Rare Processes

- Particle production via *rare processes* should scale with \( N_{\text{coll}} \), the number of underlying binary nucleon-nucleon collisions.

- Roughly: Small \( \sigma \) $\rightarrow$ no shadowing $\rightarrow$ *per nucleon* luminosity is relevant quantity.

- Take scaling with \( N_{\text{coll}} \) as our *null hypothesis* for hard processes.

\[
T_A(d) = \int \rho(d,z)dz
\]

**Thicknes Function**

**Overlap Function**

\[
T_{AB}(b) = \int T_A(\bar{s} + \frac{b}{2})T_B(\bar{s} - \frac{b}{2})d\bar{s}
\]

If Nucleus "A" has A constituents and Nucleus "B" has B constituents which interact with cross section \( \sigma_{\text{INT}} \), the TOTAL cross section \( \sigma_{AB} \) is then

\[
\sigma_{AB} = \int d^2b \left[ 1 - e^{-\sigma_{\text{INT}}T_{AB}(b)} \right]
\]

$\rightarrow \approx A \cdot B \times \sigma_{\text{INT}}$ for "small" \( \sigma_{\text{INT}} \).

Exercise 4: Make a plausibility argument for \( \sigma_{AB} \) formula, and verify approximation.
Describe in terms of \textit{scaled ratio} $R_{AA}$

\[ R_{AA} = \frac{\text{Yield in Au + Au Events}}{(A \cdot B)(\text{Yield in p + p Events})} \]

= 1 for “baseline expectations”

> 1 “Cronin” enhancements (as in proton-nucleus)

< 1 (at high $p_T$) “anomalous” suppression
Systematizing Our Expectations

Describe in terms of \textit{scaled ratio} $R_{AA}$

\[ R_{AA} = \frac{\text{Yield in Au + Au Events}}{(A \cdot B)(\text{Yield in } p + p \text{ Events})} \]

- $R = 1$ for “baseline expectations”
- $R > 1$ “Cronin” enhancements (as in proton-nucleus)
- $R < 1$ (at high $p_T$) “anomalous” suppression

![Graph showing $R$ as a function of $p_T$ (GeV/c)]

**Legend**
- no effect $\Rightarrow R = 1$
- "hard"
- "soft"
Systematic Suppression Pattern

\[ R_{AA} \]

\( \pi^0 \) 0-5% Central

PHENIX

\( p \) (GeV/c)
Unique to Heavy Ion Collisions?

• YES! : Run-3: *a crucial control measurement* via d+Au collisions
Unique to Heavy Ion Collisions?

- YES! : Run-3: a crucial control measurement via d+Au collisions

d+Au results from BRAHMS, PHENIX, PHOBOS, and STAR presented at a press conference at BNL on June, 18th, 2003.

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Energy Loss of Fast Partons

- Many approaches
  - 1983: Bjorken
  - 1997: BDMPS- depends on path length(!)
  - 1998: BDMS

- Numerical values range from
  - ~ 0.1 GeV / fm (Bj, elastic scattering of partons)
  - ~several GeV / fm (BDMPS, non-linear interactions of gluons)

J. P. BJOREN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The $dE/dx$ is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy $dE_t/dy$ in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-$p_t$ quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.
STAR azimuthal correlation function shows \( \sim \) complete absence of “away-side” jet

\[
C_2(Au + Au) = C_2(p + p) + A^\ast(1 + 2v_2^2 \cos(2\Delta\phi))
\]

That is, “partner” in hard scatter is absorbed in the dense medium

\[\Rightarrow\text{Density} \sim 50 \times \text{normal nuclear } \varepsilon_0\]
Scattered partons on the “near side” lose energy, but emerge; those on the “far side” are totally absorbed.
Photons shine, Pions don’t

- Direct photons are *not* inhibited by hot/dense medium
- Rather: *shine* through consistent with pQCD
Precision Probes

- This one figure encodes rigorous control of systematics

- Photons shine, Pions don’t

- Direct photons are **not** inhibited by hot/dense medium
  - Rather: **shine** through consistent with pQCD

- in four different measurements over many orders of magnitude
Schematically (Photons)

Scattered partons on the “near side” *lose energy*, but emerge;

the direct photon *always* emerges.
• Suppression of high momentum probes requires densities $> 50 \times \varepsilon_0$

• High $T_{\text{init}}$ ~ 300 MeV
to

• Low $T_{\text{final}}$ ~ 100 MeV

Exercise 5: Use the statement about energy density to verify upper edge of band for RHIC
Summary - Lecture 2

- Au+Au collisions at top RHIC energy produces *thermal* matter with energy density
  \[ \varepsilon >> \varepsilon_0 \text{ and } \varepsilon >> \varepsilon_{\text{QGP}} \]
  - From simple estimates
  - From detailed pQCD probes

- Suppression not seen in
  - d+Au control
  - Photons

- Results consistent with the formation of QGP with a temperature \( T \sim 2T_C \)

- Next time: How fluid is the densest matter ever studied?