Lecture 1: Introduction, soft observables

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Caveat emptor:
• I am a member of both PHENIX and ATLAS collaborations.
• I make no pretension that my coverage will be complete, but I will try to be balanced.
Pb+Pb collision in ATLAS

Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET

Heavy Ion Collision Event with 2 Jets
The Big Picture

• We know that strong interactions are well described by the QCD Lagrangian:

\[ L_{QCD} = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu}_a - \sum_n \bar{\psi}_n \left( \not\!q - ig \gamma^\mu A^a_\mu t_a - m_n \right) \psi_n \]

⇒ Perturbative limit well studied

• Nuclear collisions provide a laboratory for studying QCD outside the large Q^2 regime:

  – Deconfined matter (quark gluon plasma)
  ⇒ “Emergent” physics not manifest in L_{QCD}
  ⇒ Strong coupling ⇒ AdS/QCD (?)

  – High gluon field strength, saturation
  ⇒ Unitarity in fundamental field theory

• QCD is the only non-Abelian FT whose thermal & multi-particle behavior we can study in lab.
Heavy ion “concordance model”

- Initial particle production from strong gluon fields (saturated) in the incident nuclei.
- Created particles rapidly ($\tau < 0.5-1$ fm/c) thermalize into a strongly coupled QGP.
- QGP evolves hydrodynamically with an $\eta/s$ ratio close to conjectured lower bound.
Cross-over transition from hadron gas to quark gluon plasma at $T \sim 170-190$ MeV
- RHIC data: overwhelming evidence for QGP creation
  $\Rightarrow$ For conditions at RHIC, QGP is strongly coupled
As suggested by QCD trace anomaly $(\varepsilon - 3p)/T^4$
  "interaction measure" (what kind?)
Viscosity in Hydrodynamics

- Viscosity naturally scales with the density of particles (entropy density, \( s \)) in the system

Shear viscosity – measures the resistance to flow

- Bulk viscosity – measures the resistance to expansion
  - Volume viscosity
  - Determines the dynamics of compressible fluid
Strong coupling, $\eta/s$

**Csernai, Kapusta, and McLerran and KSS**

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

**Arnold, Moore, and Yaffe**

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

- Asymptotic freedom $\Rightarrow$ QGP is weakly coupled at very high temperatures (how high?)
- But data from RHIC and LHC (shown below) indicate that QGP at 1-2 $T_c$ is strongly coupled
  - Very close to conjectured AdS/CFT lower limit
  $\Rightarrow$ Why? How is high $T_c$ limit approached?

\begin{itemize}
  \item Water (100 MPa)  
  \item Nitrogen (3.4 MPa)  
  \item Helium (0.1 MPa)
\end{itemize}

\textbf{AdS/CFT Bound}

\textbf{Inferred from data}

\textbf{pQCD}
Big questions

• Why (how) is the QGP strongly coupled?

• How are the dynamics in the QGP changing with increasing $T$?
  – Weaker coupling? Or “simply” approaching conformal limit?

• (How) does the answer depend on $\omega$?

• Are there particle-like (quasi-particle) modes in the QGP near $T_c$?
  – if so what is their nature?

Answer by studying QGP on soft and hard momentum scales
Lecture schedule

• Monday
  – Basics, Soft physics
    ⇒ Particle multiplicities
    ⇒ Elliptic flow

• Tuesday
  – Soft physics (finish)
    ⇒ Higher order flow
    ⇒ event-by-event flow
  – Energy scan and critical point search (brief)
  – p+A measurements @ LHC
    ⇒ “Ridges”
Lecture schedule (2)

• Wednesday
  – High-\(p_T\) physics
    ⇒ RHIC single, di-hadron suppression
    ⇒ LHC reference boson measurements
    ⇒ LHC jet quenching
    ⇒ Heavy flavor suppression
  – Quarkonium suppression
• Most versatile collider ever operated
  – Collisions between many different ions
  – At center of mass energies from 7 to 200 GeV
RHIC experiments (current)

**PHENIX**
- Multi-faceted detector w/ high rate capabilities

**STAR**
- TPC-based, with extensive particle identification
• In addition to high-energy physics:
  \(-p-p, \text{ Pb+Pb @ 2.76 TeV, } p+\text{Pb @ 5.02 TeV}\)
LHC experiments

• ALICE:
  – TPC based w/ silicon inner tracking, particle identification, forward $\mu$

• ATLAS, CMS
  – Traditional particle physics experiments
STAR and ALICE measure 100’s or 1000’s of particles with many samples along particle trajectories (TPC)
• ATLAS and CMS track 1000’s of particles using high-granularity silicon pixel and silicon strip detectors
PHENIX tracks 100’s of particles using drift and pad wire chambers
Kinematics

• For studying ultra-relativistic heavy ion collisions, prefer to use boost-invariant (in beam direction) distributions:
  – Transverse momentum: 
    \[ p_T = p \sin \theta \]
    \[ \Rightarrow \text{Sometimes when using calorimeters we have } E \text{ instead of } p, \text{ so use } E_T = E \sin \theta \]
  – Rapidity: 
    \[ y = \tanh^{-1}(\beta_z) = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right) \]
    \[ \Rightarrow \text{Rapidity adds under LT: } \ y' = y + y_B \]

• Since rapidity depends on particle energy, need particle identification (m)
  – But if \( p \gg m \), neglect mass,
    \[ \Rightarrow y \rightarrow \eta = \frac{1}{2} \ln \left( \frac{1+\cos \theta}{1-\cos \theta} \right) = -\ln \left( \tan \frac{\theta}{2} \right) \]
    \[ \Rightarrow \text{pseudorapidity} \]
• Pseudorapidity of a particle can be easily measured since it only requires the angle.
ATLAS Acceptance

Bulk observables

$\gamma, \pi^0, \text{isolated } \gamma$

$J/\psi, \psi', Y \ (1S, 2S, ...)$

Jets
Pb+Pb “Bulk” dynamics controlled by classical impact parameter \( b \)

• Cannot measure impact parameter directly
  - But, particle or energy emission indirectly measures geometry
  ⇒ Energy in emitted particles increases monotonically with \( b \)
Pb+Pb (transverse) energy measurement

\[ E_T \equiv E \sin \theta \approx p_T \]

Sum \( E_T \) over different parts of calorimeter

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**Diagram Description:**
- **ATLAS**
- **Pb+Pb** \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)
- Forward calorimeter \( E_T \) (TeV)
- **Barrel + Endcap** \( E_T \) (TeV)
- **Tile barrel**
- **LAr hadronic end-cap (HEC)**
- **LAr EM end-cap (EEMC)**
- **LAr EM barrel**
- **LAr forward calorimeter (FCAL)**
“Centrality”

- Characterize collision “centrality” by $E_T$ in forward calorimeters
Simple Monte Carlo model for characterizing nuclear collision geometry:

- Distribute nucleons according to Wood Saxon $\rho(r)$
- Nucleons that pass each other within distance $r_{\perp} < \sqrt{\frac{\sigma_{NN}}{\pi}}$ scatter or collide (participate)
- Calculate number of scatterings and number of participants.
Glauber Monte Carlo

Glauber MC for Pb+Pb collisions @ LHC

Glauber MC $N_{\text{part}}$ distributions for different collisions @ RHIC, LHC
Glauber “Bootstrap”

• Use similarity between (e.g.) ATLAS FCal $\Sigma E_T$ distribution and $N_{part}$ distribution to infer a relationship
  – In fact, use “two-component” model
    \[
    \Sigma E_T^{Pb-Pb} = \Sigma E_T^{p-p} \left( x \frac{N_{part}}{2} + (1 - x) N_{coll} \right)
    \]
  – Can reproduce Pb+Pb data with $x \sim 0.1$
• Why should the number of participants be the primary variable, not the number of collisions?
  – Known for ~ 3 decades from p+A measurements
    ⇒ Multiplicity of produced particles increases proportional to number of participants


FIG. 4. The ratio $R = \langle n \rangle_{pA}/\langle n \rangle_{pp}$ versus the average number $\bar{v}(n_p)$ of projectile collisions for $p$Xe (circles), $p$Ar (triangles), and $p$Ne (squares) collisions. A line of the form $R = 0.5[\bar{v}(n_p) + 1]$ is shown for comparison.
Particle multiplicities, $dN/d\eta$
RHIC: charged particle multiplicities


• Au+Au charged particle $dN/d\eta$ and centrality dependence
  – With two-component fit, HIJING, and saturation model comparison
    ⇒ Strongest variation for peripheral collisions
LHC: charged particle multiplicities

- Rapid increase in particle multiplicity with nucleon-nucleon center of mass energy above 0.2-1 TeV
• Good agreement between 3 LHC experiments and between RHIC & LHC

⇒ After rescaling by factor of 2.15
• Comparison of ALICE $dN/d\eta$ to various theoretical/model calculations

⇒ Best described by saturation models?!
• Comparison between RHIC, LHC data and IP-Glasma calculation by Schenke et al
• Measurements over wide range of energies show “limiting fragmentation”
  – agree when measured relative to beam rapidity
→ over restricted range of $\eta'$
• Using ALICE forward multiplicity detector
  – η range large enough to match onto RHIC in η’
    ⇒ Observe breaking of limiting fragmentation for η’ < -2.5