Introduction to Heavy-Ion Physics
Part II

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Summer Student Lectures 2018
Recap Lecture 1

• Heavy-ion physics studies quark-gluon plasma (QGP)
  – Deconfined
  – Chiral symmetry restored
• Transition to QGP is expected at $T \sim 150 – 160 \text{ MeV}$
• Event activity depends on impact parameter $b$
• Centrality estimated by multiplicity (ALICE) / energy (ATLAS/CMS)
• Nucleon-nucleon collisions ($N_{\text{coll}}$) and participating nucleons ($N_{\text{part}}$) estimated with Glauber model
  – Hard processes scale with $N_{\text{coll}}$
  – Soft processes scale with $N_{\text{part}}$
• Nuclear modification factor

\[ R_{AA} = \frac{dN_{AA} / dp_T}{\left\langle N_{\text{coll}} \right\rangle dN_{pp} / dp_T} \]
  – Significant suppression of hadron production in central collisions

How does the medium achieve this suppression?
R_{AA} Interpretation

- p_T spectrum is power law
  \[ \frac{1}{p_T} \frac{dN}{dp_T} \sim p_T^{-n} \]
  RHIC (200 GeV): n = 7.2
  LHC (2.76 TeV): n = 5.4
- Constant energy loss
  \[ R_{AA} \approx \left( 1 - \frac{\Delta E}{p_T} \right)^n \]
  rising with p_T
- Constant fractional energy loss \( \Delta E/E \)
  \[ R_{AA} \approx \left( 1 - \frac{\Delta E}{E} \right)^{n-1} \]
  p_T independent
- Steepness of spectra influences R_{AA}
- Similar R_{AA} does not imply similar energy loss

Medium energy loss: a few GeV
Energy Loss

- Particle production in central collisions strongly suppressed

How does the medium achieve this suppression?
Energy Loss in the QGP

- QGP: high density of quarks and gluons / color sources
- Traversing quark / gluon feels color fields
- Collisional energy loss
  - Elastic scatterings
  - Dominates at low momentum
- Radiative energy loss
  - Inelastic scatterings
  - Dominates at high momentum
  - Gluon bremsstrahlung

$$\Delta E = \Delta E_{\text{coll}} + \Delta E_{\text{rad}}$$
Radiative Energy Loss

- BDPMS formalism
  - Baier, Dokshitzer, Mueller, Peigné, Schiff
  - Infinite energy limit
  - Static medium

\[ \Delta E \sim \alpha_s C_R \hat{q} L^2 \]

- Energy loss depends on
  - Path length through medium \textit{squared}
  - Casimir factor
    - \( C_R = 4/3 \) (quarks)
    - \( C_R = 3 \) (gluons)
  - Medium parameter “q hat”

L path length, driven by:
- gluon-gluon self interactions
- quantum interference

\[ \hat{q} = \frac{\mu^2}{\lambda} \]

average transverse momentum transfer

mean free path

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291
Dead Cone Effect

- Due to kinematical constraints, gluon radiation in vacuum suppressed for angles $\theta < m/E = 1/\gamma$ by $\left(1 + \frac{m}{E} \frac{\theta}{m} \right)^2$
  - Massless parton $m = 0 \rightarrow$ no suppression

- Similar effect in the medium
  - Significant for charm and beauty
  - Radiative energy loss reduced by 25% (c) and 75% (b) [$\mu = 1$ GeV/$c^2$]

- Implies quark mass dependence

$$ R_{\pi}^{AA} < R_{AA}^{D} < R_{AA}^{B} $$
Collisional Energy Loss

- For light quarks and gluons
  \[ \Delta E_{q,g} \sim \alpha_s C_R \mu^2 L \ln \frac{ET}{\mu^2} \]

- For heavy quarks additional term
  \[ \alpha_s^2 T^2 C_R \mu^2 L \ln \frac{ET}{M^2} \]

- Energy loss depends on
  - Path length through medium \textit{linear}
  - Parton type (light or heavy)
  - Temperature T
  - Mass of heavy quark M
  - Medium parameter \( \mu \) (average transverse momentum transfer)
Recap

• We have seen significantly suppression of charged hadron spectra
  – Dominated by light quarks / gluons…
  – … which at low $p_T$ are also produced within the medium

• Energy loss occurs by radiative and collisional processes

• Theoretical calculations extract medium properties like density, average momentum transfer, mean free path, $\hat{q}$

• Calculations more accurate for heavy quarks

• Dependence of energy loss on quark mass expected

Let’s measure energy loss with heavy quarks!
Heavy Quarks

- Charm ($m \sim 1.3$ GeV/c$^2$)
- Beauty ($m \sim 4.7$ GeV/c$^2$)
- Produced in hard scattering
- Essentially not produced in the QGP
- Expectation
  \[ R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA} \]
- LHC: $\sim 7$ D > 2 GeV/c per central event
D⁰ Reconstruction

- **D⁰ meson**: \( m = 1.87 \text{ GeV/c}^2 \); \( c\tau = 123 \text{ \mu m} \)
  - Rather short lived
  - Many decay modes
  - \( D⁰ \rightarrow K\pi \) (branching ratio 3.9%)

- **Standard method**: invariant mass of opposite charge pairs
  - Per central event (\( D⁰ \rightarrow K\pi, > 2 \text{ GeV/c} \), incl. efficiencies):
    - 0.001 compared to ~700 K and up to ~2500 \( \pi \)
  - Signal over background far too small to extract a peak

- **Reduce combinatorial background** (see next slides)
  - Topological cuts
  - Particle identification (PID) of K and \( \pi \)
Invariant Mass

- $D^0 \to K \pi$ without PID and without topological cuts

![Graph showing invariant mass distribution with peak not visible without cuts](Image)

- ALICE Preliminary
- $p$-Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $L_{\text{int}} = 49 \mu$pb$^{-1}$
- $D^0 \to K^-\pi^+$ and charge conj.
- $0 < p_T < 1$ GeV/c
3) Require distance of primary and secondary vertex (impact parameter) [\(\sim 100 \, \mu\text{m}\) challenging for pixel detectors!]

2) Require that \(K\) and \(\pi\) share a secondary vertex

\[c_\tau \sim 123 \, \mu\text{m}\]

1) Require large impact parameter tracks

4) Require pointing angle \(\theta\) to be small

Plane transverse to beam

reconstructed D momentum
**PID**

- **Specific Energy Loss**
  - Particles passing through matter lose energy mainly by ionization
  - Average energy loss calculated with Bethe-Bloch formula
  - Identify particle by measuring energy deposition and momentum

- **Time Of Flight**
  - Particles with the same momentum have slightly different speed due to their different mass
  - Needed flight time precision, e.g. for a particle with $p = 3\ \text{GeV}/c$, flying length 3.5 m
    - $t(\pi) \sim 12\ \text{ns} \ | \ t(K) - t(\pi) \sim 140\ \text{ps}$

- **Methods can be combined**
Invariant Mass with Cuts

- $D^0 \rightarrow K \pi$

PID reduces background, but signal peak stays of same magnitude.

D. Caffarri, thesis

PID reduces background, but signal peak stays of same magnitude
Recap: D Meson Yield

• We would like to learn about the energy loss of charm

• Reconstruct D meson decay to $K\pi$
  – Rare signal
  – Combinatorial background reduced with particle identification and topological cuts
  – Invariant mass distribution
  – Background with like-sign combinations
  – Apply fit to extract yield

![Plot of D meson yield](image-url)
$D \left( R_{AA} \right)$

$R_{AA} = \frac{dN_{AA} / dp_T}{\langle N_{coll} \rangle dN_{pp} / dp_T}$

**$R_{AA}$ vs. centrality**

- Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
- Average $D^0, D^+, D^{*-}$, $8 < p_T < 16$ GeV/c, $|y| < 0.5$
- Correlated systematic uncertainties
- Uncorrelated systematic uncertainties

**$R_{AA}$ vs. $p_T$**

- Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
- Average $D^0, D^+, D^{*-}$, $|y| < 0.5$, 0-7.5%
- with pp $p_T$ - extrapolated reference
- Charged particles, $|\eta| < 0.8$, 0-10%
- Charged pions, $|\eta| < 0.8$, 0-10%

**Strong suppression $\sim 0.2$**

**D and $\pi$ $R_{AA}$ compatible**

arXiv:1506.06604
• Expectation $R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$

• However $R_{AA}^{\pi} \approx R_{AA}^{D}$

• Are the energy loss models wrong?

• Not necessarily
  – Effect expected for $p_T$ close to charm mass (~1.3 GeV/c$^2$)
  – Uncertainties on $D R_{AA}$ large for $p_T < 5$ GeV/c
  – Fragmentation ($\rightarrow$ hadron) different for gluons and quarks

Let’s have a look at particles containing a heavier b…
Comparison B and D

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

B $\rightarrow$ (J/ψ $\rightarrow$ μμ) + X identified by displaced secondary vertices (see backup)

D is stronger suppressed than B! $\Rightarrow$ hint of quark mass dependence
Summary
Jet Quenching & Energy Loss

• Particle production strongly suppressed in central heavy-ion collisions
  – Mass dependence observed

• Radiative and collisional energy loss
  – Radiative energy loss dominates at high $p_T$ for u, d, c, g
  – Radiative and collisional e-loss play similar role for b quarks

• Theoretical models used to constrain medium properties like density, average momentum transfer, mean free path

\[ R^{\pi}_{AA} \approx R^{D}_{AA} < R^{B}_{AA} \]

A dense strongly coupling medium is produced in HI collisions

Measurement of $b \to J/\psi$ requires displaced vertices. What about $J/\psi$ stemming directly from the interaction?
Quarkonia

How does a quark-gluon plasma affect c-cbar and b-bbar states?
Quarkonia

- c-cbar ($J/\psi$, $\psi'$) and b-bbar ($\Upsilon$, $\Upsilon'$, $\Upsilon''$) from hard process
- High density of quarks and gluons causes screening

- Changes (binding) potential

\[ V(r) = -\frac{\alpha}{r} + \sigma r \quad \rightarrow \quad V(r) = -\frac{\alpha}{r} e^{-\mu r} + \sigma r \left[ \frac{1 - e^{-\mu r}}{\mu r} \right] \]

- Quarks with distance larger than $1/\mu$ do not see each other
  - Dissociation of q-qbar pair!
  - Quarkonia “melt”
J/ψ Suppression

• Observed at SPS in Pb-Pb collisions ($\sqrt{s_{NN}} = 17$ GeV)

In: $A = 105$
Pb: $A = 208$

EPJC (2011) 71:1534
J/ψ Suppression (2)

• ... and at RHIC ($\sqrt{s_{NN}} = 200$ GeV)

Wouldn’t we expect a stronger suppression at larger $\sqrt{s_{NN}}$?
J/ψ Suppression (3)

\[ R_{AA} \text{ vs. multiplicity} \]

LHC \rightarrow RHIC : \( \sqrt{s_{NN}} \) 14 times larger … but the suppression is smaller !
Charm Abundances

- Number of c-cbar pairs increase with cms energy
- In a central event
  - SPS \( \sim 0.1 \) c-cbar
  - RHIC \( \sim 10 \) c-cbar
  - LHC \( \sim 100 \) c-cbar
- c from one c-cbar may combine with cbar from another c-cbar at hadronization to form a \( \text{J}/\psi \)
J/ψ Regeneration

Dissociation and regeneration work in opposite directions

J/ψ modification vs. energy density

H. Satz

regeneration

sequential suppression

Energy Density

RHIC

LHC
J/ψ Regeneration (2)

- J/ψ regeneration / statistical hadronization models

Other quarkonia states melt at different temperatures → QGP thermometer (see backup)
• High density of color charges in QGP leads to melting of quarkonia (c-cbar and b-bar)

• Large abundance of charm quarks at LHC results in regeneration of the amount of J/ψ

• States with smaller binding energies are more suppressed (“QGP thermometer”)
Particle Yields & Statistical Model

What can particle abundances tell about the transition between QGP and hadrons?
Chemical Freeze-Out

- Hadronization has occurred
- Inelastic collisions stop
- Particle yields fixed

- Elastic collisions may still occur until kinetic freeze-out

- Assume system to be in chemical equilibrium
- Particle yields can be calculated with statistical models
- Calculated in framework of statistical thermodynamics

Courtesy B.Hippolyte
Statistical Model

- Relativistic ideal quantum gas of hadrons
- Partition function $Z$ for grand-canonical ensemble
  - How is probability distributed between available states?
  - For particle $i$ (out of $\pi$, $K$, $p$, ..., all known particles)

\[
\ln Z_i(T,V,\mu) = \pm g_i V \int \frac{d^3p}{(2\pi\eta)^3} \ln \left(1 \pm \exp \left(-\frac{E_i(p) - \mu_i}{T}\right)\right)
\]

- $E_i = \sqrt{p^2 + m_i^2}$
- Chemical potential (conserved quantities)
  
  $\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i$

- Volume
- Spin degeneracy
- Temperature
- Baryon number
- Strangeness
- Charm
- Isospin

E.g. NPA722(2006)167
Statistical Model (2)

- Chemical potential constrained with conservation laws
  \[ \mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i \]
  - Sum over considered particles (results depend on particle list)
- 3 free parameters remain \((V, T, \mu_B)\)
- Thermodynamic quantities can be calculated from \(Z\)

\[
\begin{align*}
n &= \frac{N}{V} = -\frac{1}{V} \frac{\partial (T \ln Z)}{\partial \mu} \\
P &= \frac{\partial (T \ln Z)}{\partial V} \\
S &= \frac{1}{V} \frac{\partial (T \ln Z)}{\partial T}
\end{align*}
\]

Particle densities \hspace{1cm} Pressure \hspace{1cm} Entropy

- In particle ratios \(V\) cancels \(\rightarrow\) two free parameters \((T, \mu_B)\)

Let’s have a look at the data…
Particle Identification

Direct particle identification

\[ \pi K p d \, ^3He \, ^3H \]

Large impact parameter

\[ K^0_S \rightarrow \pi \pi \ (c \tau = 2.7 \, \text{cm}) \]
\[ \Lambda \rightarrow p \pi \ (c \tau = 7.9 \, \text{cm}) \]

“Kink” in detector volume

\[ K \rightarrow \mu \nu \ (c \tau = 3.7 \, \text{m}) \]

Invariant mass

\[ \phi \rightarrow K K \]
\[ K^* \rightarrow K \pi \]

Cascade

\[ \Xi \rightarrow \Lambda + \pi \rightarrow p \pi \pi \]
\[ \Omega \rightarrow \Lambda + K \rightarrow p \pi K \]
Statistical Model at LHC

12 different particles

\[ \frac{\pi^+ + \pi^-}{2} \quad \frac{K^+ + K^-}{2} \quad K^0_s \quad \frac{K^* + \bar{K}^*}{2} \quad \phi \quad \frac{p + \bar{p}}{2} \quad \Lambda \quad \frac{\Xi^- + \Xi^+}{2} \quad \frac{\Omega^- + \Omega^+}{2} \quad d \quad \frac{^3\text{H} + ^3\text{H}}{2} \quad ^3\text{He} \]

7 orders of magnitude

\[ dN/dy \]

Good description of particle production at LHC

<table>
<thead>
<tr>
<th>Model</th>
<th>T (MeV)</th>
<th>V (fm^3)</th>
<th>(\chi^2/\text{NDF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>THERMUS 2.3</td>
<td>155 ± 2</td>
<td>5924 ± 543</td>
<td>23.6/9</td>
</tr>
<tr>
<td>GSI-Heidelberg</td>
<td>156 ± 2</td>
<td>5330 ± 505</td>
<td>17.4/9</td>
</tr>
<tr>
<td>SHARE 3</td>
<td>156 ± 3</td>
<td>4476 ± 696</td>
<td>14.1/9</td>
</tr>
</tbody>
</table>

T = 155 MeV
\(\mu_B \sim 1 \text{ MeV} \)
V ~ 5000 fm^3
(200 x V_{pp})

ALICE Preliminary
Pb-Pb \(s_{NN} = 2.76 \text{ TeV}, 0-10\% \)

84
$\sqrt{s}$ Dependence

Temperature increases with $\sqrt{s}$ and reaches plateau of about 160 MeV at $\sqrt{s_{NN}} > 20$ GeV

Baryochemical potential drops with $\sqrt{s_{NN}}$ → transport of baryon number from nuclei to mid-rapidity is more and more difficult
QCD Phase Diagram

- Fit results from $\sqrt{s_{NN}} = 2$ to 2760 GeV
- Defines chemical freeze-out line in QCD phase diagram

adapted from PRC 73, 034905 (2006)
QCD Phase Diagram (2)

- Statistical model provides $T$ where inelastic collisions stop

Chemical freeze-out temperature $\neq$ phase transition temperature

LHC, RHIC, top SPS energies
Chemical freeze-out close to phase transition

Phase transition from lattice QCD

SPS and below
Chemical freeze-out at lower $T$
Summary
Particle Yields & Statistical Model

• After chemical freeze-out particle composition is fixed
• More than 10 species of hadrons measured at LHC
• Statistical model allows extraction of freeze-out temperature and baryochemical potential
• At high $\sqrt{s_{NN}}$ chemical freeze-out temperature close to phase transition temperature

Statistical models describe hadron production from $\sqrt{s_{NN}} = 2$ to 2760 GeV

Matter created in HI collisions is in local thermal equilibrium
Collective Flow & Hydrodynamics

How does a strongly coupled pressurized system affect particle production?

Collective flow has nothing to do with the particle flow method to reconstruct tracks and jets in ATLAS/CMS
Expansion

- After collision, QGP droplet in vacuum
- Energy density very high
- Strong pressure gradient from center to boundary
- Consequence: rapid expansion ("little bang")
- Partons get pushed by expansion → Momentum increases
- Measurable in the transverse plane ($p_T$)
  - Called *radial flow*

Longitudinal expansion (in beam direction) not discussed here.
Have a look at for example: [http://www.physi.uni-heidelberg.de/~reygers/lectures/2015/qgp/qgp2015_06_space_time_evo.pdf](http://www.physi.uni-heidelberg.de/~reygers/lectures/2015/qgp/qgp2015_06_space_time_evo.pdf)
Radial Flow

Particle $p_T$ increases
Spectra pushed outwards

Effect larger for $p \gg K \gg \pi$
$\rightarrow$ mass dependence

$p = m \beta \gamma$
common velocity field ($\beta \gamma$ fixed)
$\rightarrow$ mass dependence

$d^2N/(dp_T dy)$ (arbitrary units)

Arbitrary normalization

$\pi$  $K$  $p$

Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
$pp$, $\sqrt{s} = 2.76$ TeV
Blast-Wave Fits

- Quantification of radial flow
  - Reproduce basic features of hydrodynamic modeling (discussed later)
- Locally thermalized medium
- Common velocity field
- Instantaneous freeze-out
- All particle species described with three parameters

\[
\frac{1}{m_T} \frac{dN}{dm_T} = \int r \, dr \, m_T \, I_0 \left( \frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_T \cosh \rho}{T_{\text{kin}}} \right) \\
\rho = \tanh^{-1} \beta_T \left( \frac{r}{R} \right)^n
\]

Bessel functions \( I_0 \) \( K_1 \)

kinetic freeze-out temperature
radial flow velocity
velocity profile

PRC 48, 2462 (1993)
Blast-Wave Fits (2)

Fits describe well at low $p_T$ (high $p_T$, also hard processes)

Peripheral $\rightarrow$ Central
Expansion 0.35 c $→$ 0.65 c
$T_{\text{kin}}$ 150 MeV $→$ 90 MeV

Denser system in central collisions decouples at lower $T$

PRL109, 252301 (2012)
Backup
$B \rightarrow J/\psi$

- $B^\pm; m = 5.28$ GeV; $c\tau = 492$ µm (4 times larger than D)
- $B^0; m = 5.28$ GeV; $c\tau = 455$ µm

- $B^\pm \rightarrow J/\psi + X$ (branching ratio $\sim 0.5\%$)
- $B^0 \rightarrow J/\psi + X$ (branching ratio $\sim 0.5\%$)
- $J/\psi \rightarrow \mu\mu$ (branching ratio $\sim 6\%$)

- Identification by displaced secondary vertex
  - No reconstruction of full decay chain
B Identification

- Most probably transverse b-hadron decay length
  - Transverse because vertex is better known in this direction

- Convert to pseudo-proper decay length as estimate of b-hadron decay length (time dilatation)

\[
L_{xy} = \frac{\hat{u}^T S^{-1} \rho}{\hat{u}^T S^{-1} \hat{u}}
\]

**u J/ψ vector**
**r primary vertex**
**S cov. matrices**

**Plane transverse to beam**

\[
l_{J/\psi} = L_{xy} m_{J/\psi} / p_T
\]

**J/ψ candidate mass and \( p_T \)**
Decay Length Distribution

Events vs. $l_{J/\psi}$

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV

Events / (0.035 mm)

$l_{J/\psi}$ vs. $l_{J/\psi}$

Events

$l_{J/\psi} < 0$
combinatorics resolution

$l_{J/\psi} > 0$
combinatorics resolution b decays

$\rightarrow$ Experimental handle on resolution of $l_{J/\psi}$

CMS, HIN-12-014
Yield Extraction

- (Multi-dimensional) fit to $I_{J/\psi}$ and invariant mass $m_{\mu\mu}$
  - Total number of $J/\psi$ and fraction of displaced $J/\psi$

**Events vs. $I_{J/\psi}$**

**Events vs. $m_{J/\psi}$**

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 2.76$ TeV
$L_{\text{int}} = 150 \mu$b$^{-1}$

- $|y| < 2.4$
- $6.5 < p_T < 30$ GeV/c
- Cent. 0-100%

Data
- total fit
- background

**Prompt $J/\psi$**

**Displaced $J/\psi$**

**Background**

CMS, HIN-12-014
Other Quarkonia

\[ \mu = \frac{1}{r_D} \text{ increases with } T \text{ of QGP} \]
- Lattice estimate: \( \mu(T) \approx 4T \)

\[ T \text{ controlled by centrality and center of mass energy} \]
- “Spectroscopy” / “Thermometer” of QGP

\( T < T_c \)
- \( \psi, \chi_c, \psi' \)
- \( \chi_b, \chi_b' \)

\( T \approx 1.2 T_c \)
- \( \psi, \chi_b, \chi_b', \psi' \)

\( T \approx 3 T_c \)
- \( \chi_b, \chi_b' \)

Table, Cartoon: H. Satz
QGP Thermometer

States with lower binding energies more suppressed!