Suppression of Hadrons with Large Transverse Momentum in Central Au+Au Collisions at RHIC

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1. Motivations
2. PHENIX experimental results
3. Questions and speculations
An experiment you'd like to do:

![Diagram of QCD probe of known energy](image)

**Modifications?**
- Energy loss?
- Induced radiation?
- Fragmentation altered?

An experiment you can do:

1. **Two nuclei just before collision (view along beam)**
2. **At point of overlap hard scattered parton is created travelling transversely**
3. **Eventually the parton results in hadronic fragments which are detected**
4. **At \( t = 0.1 \text{ fm/c} \) the medium has formed around the parton**
5. **By several \( \text{fm/c} \) the parton has moved through the medium as it expands and cools.**
<table>
<thead>
<tr>
<th>A+A</th>
<th>Parton Distributions q(x), g(x)</th>
<th>Nuclear PDF Effects</th>
<th>Multiple Scattering</th>
<th>Initial State Radiation &quot;Kt&quot; Broadening</th>
<th>Jet Energy Loss, Broadening</th>
<th>Fragmentation</th>
<th>Decay</th>
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Suppression of Hadrons with Large Transverse Momentum in Central Au+Au Collisions at $\sqrt{s_{NN}} = 130$ GeV

Transverse momentum spectra for charged hadrons and for neutral pions in the range $1 \text{ GeV}/c < p_T < 5 \text{ GeV}/c$ have been measured by the PHENIX experiment at RHIC in Au+Au collisions at $\sqrt{s_{NN}} = 130 \text{ GeV}$. At high $p_T$ the spectra from peripheral nuclear collisions are consistent with scaling the spectra from p+p collisions by the average number of binary nucleon-nucleon collisions. The spectra from central collisions are significantly suppressed when compared to the binary-scaled p+p expectation, and also when compared to similarly binary-scaled peripheral collisions, indicating a novel nuclear medium effect in central nuclear collisions at RHIC energies.

PACS numbers: 25.75.Dw

Ultrarelativistic heavy ion collisions provide the opportunity to study strongly interacting matter at high temperature and density. At Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC), nuclei as heavy as gold (Au) are accelerated to energies of $\sqrt{s_{NN}} = 200 \text{ GeV}$ per nucleon-nucleon pair. In the early stages of a central collision, energy densities are expected to be sufficient to dissolve normal nuclear matter into a phase of deconfined quarks and gluons, the “Quark Gluon Plasma” (QGP). The PHENIX experiment is designed to investigate nuclear collisions with a wide variety of probes, focusing primarily on those produced in the early stages of the collision.

Of particular interest are the products of parton scatterings with large momentum transfer (“hard scatterings”). In p+p collisions hard-scattered partons fragment into jets of hadrons; these fragments are the primary source of hadrons at high transverse momentum ($p_T$), typically above $\sim 2 \text{ GeV}/c$. In a high-energy nuclear collision, hard scattering will occur at the earliest time during the collision, well before the QGP is expected to form, and thus the scattered partons will subsequently experience the strongly interacting medium created in the collision. These partons are expected to lose energy [2] in hot and dense nuclear matter through gluon bremsstrahlung, effectively quenching jet produc-
Reconstructing charged hadrons \( \frac{(h^+ + h^-)}{2} \)

Drift Chamber and Pad Chambers
Reject decays and non-vertex sources
Correct for momentum resolution, combinatorics

Reconstructing neutral pions \( \pi^0 \)

Two-photon decay (standard)
Two separate calorimeters: PbSc and PbGl
Two separate analyses: "peak fitting" "window integral"
Energy scale fixed by MIPs, \( \pi^0 \) peak, electron E/p
...sparing the experimental details....

Reference: \[\text{Yield}(N+N) \times <N_{\text{binary}}>-\]

Central class 0\% – 10\%, \[<N_{\text{binary}}>=905 +/- 96\]

Peripheral class 60\%–80\%, \[<N_{\text{binary}}>=20 +/- 6\]
1. Presume spectra $p+p = p+p\bar{p}$ (good to 5% at ISR)
2. Presume spectra for $(h^+ + h^-)$ from $p+p = N+N$
3. Presume $(\pi^+ + \pi^-)/(h^+ + h^-) = \pi^0/(h^+ + h^-)/2$
Au+Au $\sqrt{s_{NN}} = 130$ GeV  
central 0-10%

- $(h^+ + h^-)/2$
- $\pi^0$

$\alpha + \alpha$ CERN-ISR

$\Delta \pi^0$

Pb+Pb(Au) CERN-SPS

binary scaling

$$R_{AA} = \frac{\frac{1}{N} \frac{1}{z \pi Pr} \frac{dN}{dPr d\eta}}{\langle N_{\text{binary}} \rangle \frac{1}{z \pi Pr} \frac{d\sigma}{dPr d\eta} / \sigma_{\text{inelastic}}(pp)}$$

Observe significant depletion relative to 1.0, in contrast to "standard" Cronin–effect behavior

Observe different depletion for charged hadrons compared to neutral pions
Alternatively, the larger nuclear enhancement of $K^+$ could reflect a nuclear enhancement of the $K^+/\pi^+$ ratio in high-z quark or gluon fragmentation. High-$p_t$ protons

![Graph showing the W-to-Be ratio of per-nucleon cross sections, $R_{W/Be}$, vs $p_t$ for each hadron species. Also shown are results [2] at $\sqrt{s} = 27.4$ GeV and model calculations [12] for $\pi^-$ at $\sqrt{s} = 27.4$ GeV (upper curve) and $\sqrt{s} = 51.3$ GeV (lower curve).](image)

from Straub, et al., PRL 68, p452 (1992)
Depletion also visible in (central)/(peripheral)

Difference between hadrons and pions remains
Experimental Observations

Hadron spectra at high Pt are suppressed in central Au+Au when compared to the binary-scaling expectation.

The suppression is seen both when comparing to interpolated N+N spectra and in situ measured peripheral spectra.

Suppression is seen in both charged hadrons and neutral pions, which are measured in PHENIX with very different systematics.

The magnitude of the suppression is different for hadrons compared to pions.
Speculations and Questions (I)

1. Jets + fragmentation is the primary source of the spectra we measure; parton energy loss accounts for depletion compared to scaled N+N

   A: Simple
   D: In factorization scheme, parton energy loss cannot explain changes in flavor ratios

2. There are two sources for our spectra: a jet + fragmentation source which is suppressed, and heavier particles (protons?) being produced by soft processes and boosted to high Pt through a multi-collision process ("thermal" + "flow")

   A: Uses words we understand
   D: Do you believe in thermal + flow out as far as $E = 20 \times T$?
Speculations and Questions (II)

3. The spectra are produced primarily from jets + fragmentation, but an effect similar to that seen in p+A is changing the flavor ratios (ie flavor–dependent Cronin effect), while depletion comes from energy loss

   A: Simple; uses "known" p+A physics
   D: Requires very large Cronin effect; where would it come from?

4. The dense medium is affecting the fragmentation process in addition to energy loss, ie a breakdown of factorization. Could baryon junctions become attached to parton strings? and increase heavy hadron fraction?

   A: Most interesting possibility
   D: Most speculative possibility
A delicious menu ahead!

1. Single inclusive spectra to higher Pt
   Yields and flavor ratios (see Julia Velkovska's talk)
   Do we ever recover "normal" jet+fragment behavior

2. Near-side correlations: examining possible changes to the fragmentation process
   Look for changes compared to p+p in correlating:
   - Angle (see Craig Ogilvie's talk)
   - Momentum
   - Number
   - Flavor, charge

3. Opposite-side correlations: "smoking gun" for hard parton-parton process
   - Hadron-hadron correlations (basic)
   - Hadron-direct photon correlations (advanced)
   - Measure pseudo-fragmentation functions, acoplanarity, etc

4. Measure "cold" nuclear matter effects in p+A/d+A
   Needed to calibrate shadowing+Cronin effects