Forward Physics with BRAHMS at RHIC

K. Hagel
Cyclotron Institute
Texas A & M University
for the
BRAHMS Collaboration
Outline

• Description of BRAHMS
• 200 GeV Au + Au particle spectra
  – Landau Flow
  – Quark Chemistry
  – Nuclear stopping and energy loss
• Evolution of nuclear modification factors
  – Jet quenching
  – Gluon Saturation
• $p + p$ particle ratios
• Summary
BRAHMS: The forward experiment

• **FS**: TPC, TOF, DC, Cherenkov
  • $2.3^\circ - 30^\circ \quad \eta = 1.5 - 4$

• **MRS**: TPC, TOF
  • $30^\circ - 90^\circ \quad \eta = 0 - 1.5$
Global Detectors

**Beam-Beam counters:** for vertex determination.

**TMA & SiMA:** for centrality determination.

Global Detectors measure charged particles having $|\eta| < 4.2$

**Silicon Strips**

**Plastic Scintillator Tiles**

**ZDC counters:** at $\pm 18$ meters. Measure spectator neutrons.

$s NN = 200$ GeV

- 0-5%
- 5-10%
- 10-20%
- 20-30%
- 30-40%
- 40-50%

more central collisions
Particle Identification

**TIME-OF-FLIGHT**

\[ m^2 = p^2 \left( \frac{c^2 \text{TOF}^2}{L^2} - 1 \right) \]

Particle Separation: \( p_{\text{max}} (2\sigma \text{ cut}) = \)

<table>
<thead>
<tr>
<th>(2\sigma \text{ cut} )</th>
<th>TOFW</th>
<th>TOF1</th>
<th>TOF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi / K )</td>
<td>2 GeV/c</td>
<td>3 GeV/c</td>
<td>4.5 GeV/c</td>
</tr>
<tr>
<td>( K / p )</td>
<td>3.5 GeV/c</td>
<td>5.5 GeV/c</td>
<td>7.5 GeV/c</td>
</tr>
</tbody>
</table>

**CHERENKOV**

RICH: Cherenkov light focused on spherical mirror \( \rightarrow \) ring on image plane

Ring radius vs momentum gives PID

\( \pi / K \) separation 25 GeV/c
Proton ID up to 35 GeV/c
By combining all data sets and averaging over the number of collisions, we get the final invariant yields over a broad range of phase-space.

Particle Spectra

Pion invariant differential yields

Kaon invariant differential yields

Proton invariant differential yields
Particle Spectra

Top 5% central collisions

\[ \frac{d^2N}{(2\pi m_{T} d\eta)} [\text{GeV}^2 c^4] \]

- **y ≈ 0**
  - \( \pi^- \)
  - \( \text{K}^- \)
  - \( \bar{p} \)

- **y ≈ 1**
  - Pions: power law
  - Kaons: exponential

- **y ≈ 3.5**
  - Protons: Gaussian

\[ A \left( 1 + \frac{p_T}{p_0} \right)^{-n} \]

\[ A \exp \left( -\frac{m_T - m}{T} \right) \]

\[ A \exp \left( -\frac{p_T^2}{2\sigma^2} \right) \]

BRAHMS
Rapidity Densities

Integrated multiplicities (Gaussian fit)

\[ N(\pi^-) \approx 1780 \]
\[ N(\pi^+) \approx 1760 \]
\[ N(K^+) \approx 290 \]
\[ N(K^-) \approx 240 \]
\[ N(\bar{p}) \approx 85 \]

Total number of \( \pi^+K^+p > 4000 \)
Quark Chemistry
Anti-Hadron to Hadron Ratios

• Universal relationship between $\mu_{u,d}$ & $\mu_s$
• Chemical equilibration for different rapidity slices?

- Midrapidity: near matter-antimatter balance

BRAHMS130 PRL 87 (2001) 112305
• Entropy ~ Pion production
• Expansion ~ isentropic
• Simplified model prediction: \( \frac{dN}{dy} (y) = N \cdot \exp \left( -\frac{y^2}{2\sigma^2} \right) \)
  where \( \sigma^2 = \frac{1}{2} \ln \left( \frac{s}{4m_p^2} \right) \)
Landau Flow

- OK as a 1\textsuperscript{st} approximation
- systematic differences remain
  - flatter top, tails broader
  - more longitudinal flow
Nuclear Stopping

Rapidity loss: \[ \langle \delta y \rangle = y_p - \langle y \rangle = y_p - \frac{2}{< N_{\text{part}} >} \int_0^{y_p} y \frac{dN_{(B-B)}}{dy} dy \]

\( N_{\text{part}} = 357 \pm 10 \)

\[ \Delta E = 25.7 \pm 2.1 \text{ TeV} \]

\[ \int_{y_p}^{y_p} \langle m_r \rangle_y \frac{dN_{(B-B)}}{dy} \text{coshy} dy \]

\[ \langle \delta y \rangle = 2.03 \pm 0.16 \]

\[ \langle \delta y \rangle = 2.00 \pm 0.10 \]

I. Bearden et al., nucl-ex/0312023; Accepted for publication, PRL
Nuclear modification factors

- "Calibrate" the behavior of many-body systems (A+A or d+A) with a "simple system" like p + p.
- Compare particle production in A+A or d + A to the scaled production in p + p: ("Cronin effect" studies)
  \[ R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{N_{\text{coll}} d^2N_{pp}/dp_Td\eta} \]
  where \( N_{\text{coll}} \) is an estimate of number of binary collisions.
- \( R_{cp} \): another nuclear modification variable which is independent of p + p reference:
  \[ R_{cp} = \frac{(1/<N_{\text{coll}}^{\text{cent}}>N_{AB}^{\text{cent}}(p_T,\eta))}{(1/<N_{\text{coll}}^{\text{periph}}>N_{AB}^{\text{periph}}(p_T,\eta))} \]
- Assumption that nuclear modification is not significant for peripheral collisions
- Compare Au + Au to d + Au to determine if initial state or final state effects
Nuclear modification factors (Au+Au)

Ratio of $R_{cp}$ for $\eta=0$ and $\eta=2.2$

Initial state or final state interaction?

Compare to d+Au

Cronin enhancement

suppression at high p_T
significant medium effects
Jet suppression seen in all four RHIC experiments!
Examine d+Au at all rapidities

Cronin enhancement

suppression

clear systematic decrease with increasing $\eta$

As $x$ becomes smaller and smaller, the gluon density increases faster, and is the driving force toward saturation:

*New state in QCD! Color Glass Condensate...*

**Color**, since the gluons are *colored*!

**Glass** because of the strong analogy of the system to actual glasses. A *glass* is a disordered system which evolves very slowly relative to natural time scales.

**Condensate** because it contains a very high density of massless gluons. The gluon density saturates at a value of order $1/\alpha_s \gg 1$, corresponding to a multiparticle Bose *condensate* state.

**Iancu, Leonidov, McLerran**

*NPA 692 (2001) 583.*
- Increased role of Cronin like multiple scattering effects in the more violent collisions at $\eta = 0$
- The more central ratio is the most suppressed at forward $\eta$: a mechanism for suppression depends on the centrality of the collision

Evolution of $R_{cp}$ with $\eta$

close to the form of the saturation scale

$Q_s^2(y,A) \sim A^{1/3}e^{\lambda y}$

where $\lambda \sim 0.2$–$0.3$

Recent Quantitative Model

\[ R_{dAu} \]

\[ R_{cp} \]

\[ p_t \]

\[ p_t \]

D. Kharzeev et al., hep-ph/0405045
\( p + p \) particle ratios

- \( \pi \) ratios deviate from 1 above \( y=2.5 \)
- Pythia describes this deviation
- Baryon Junctions needed to transport protons away from beam rapidity
- Limiting fragmentation picture
- \( p+p \) ratios are similar to \( \text{Au+Au} \) ratios
p+p particle ratio correlations

Fit to A+A (Becattini et al.)

ISR data, $y=0$

SPS data at $\sqrt{s}=27.5$ GeV
Summary I

• dN/dy measurements over large rapidity range
  – Evolution of particle ratios with rapidity described by thermal model.
  – Evidence that Pions exhibit Landau flow
  – Allow measurement of energy loss due to stopping - $\Delta E = 25.7 \pm 2.1$ TeV
    $<\delta y> \sim 2.01$

• Evolution of nuclear modification factors
  – Au+Au suppressed from mid-rapidity to at least $y=2.2$
    • Smoking gun of QGP??? Observed by all four RHIC exp.
  – d+Au shows Cronin enhancement at mid-rapidity and decreases with rapidity
    • Color Glass Condensate???
    • Quantitative agreement with model
Summary II

• p+p data
  – Particle ratios similar to Au+Au ratios
  – Pions rapidity dependence described by Pythia
  – Need other mechanisms to transport protons from beam rapidity (e.g., Baryon Junctions)
  – Limiting fragmentation picture