Review of BRAHMS experiment and results.

F. Videbœck
Physics Department
Brookhaven National Laboratory
Overview

• A brief history
• Particle Production in HI; The Hot Dense sQGP
  – Multiplicities
  – Longitudinal properties of particle production
  – Baryon stopping
  – Limiting Fragmentation, thermal aspects
    High-pt suppression (intermediate $p_t$)
      • Energy, rapidity dependence
• d-Au and the Color Glass Condensate
  – $R_{dAu}$ for charged and identified hadrons
• QCD and Spin Physics via pp
  – Understanding pp in pQCD
  – Transverse Single Spin Asymmetries
• Summary
BRAHMS proposed as LOI3 –in 1990
CDR 94, approved 95, but not funded until 1997
Construction completed in 2001
Took First data in 2000, Last data in June 2006

HI data at 200, 130 and 62.4 GeV
Au.Au, CuCu
Important Reference data from
d.Au and pp (200 GeV)
pp spin data at 200 and 62.4 GeV
Formation of Hot Matter, QGP

- Identifying and Characterizing the Hot Matter
- How does the system extend/develop? Transverse and longitudinal dynamics
- Strong constraints for theoretical modeling/interpretation

• Initial Conditions/Partonic Dynamics: High-\(p_T\) vs. \(y\)
• Thermodynamic and freeze-out properties: Temperatures, Particle composition vs \(y\)
• Baryon Transport: Net-baryon vs \(y\)
• Bulk Properties: multiplicity, \(dN/dy\)
Charged Particle Multiplicity

Energy density: Bjorken 1983

\[ e_{BJ} = \frac{3}{2} \times \left( \frac{1.38 \text{ GeV}}{R^2 \tau_0} \right) dN_{ch}/d\eta \]

assuming formation time \( t_0 = 1 \text{ fm}/c \):

- greater than 5.0 GeV/fm\(^3\) for AuAu @ 200 GeV
- greater than 4.4 GeV/fm\(^3\) for AuAu @ 130 GeV
- greater than 3.7 GeV/fm\(^3\) for AuAu @ 62.4 GeV
Limiting Fragmentation

Shift the \( dN_{ch}/d\eta \) distribution by the beam rapidity, and scale by \( \langle N_{part} \rangle \). Lines up with lower energy \( \Rightarrow \) limiting fragmentation. Collision view in rest frame of projectile nucleus.

- Au+Au \( \sqrt{s_{NN}}=200\text{GeV} \) (0-5% and 30-40%)
- Au+Au \( \sqrt{s_{NN}}=130\text{GeV} \) (0-5%)
- Pb+Pb \( \sqrt{s_{NN}}=17\text{GeV} \) (9.4%)

• “Crucial Observation” for universal QCD

May 30, 2008

RHIC/AGS users meeting
Longitudinal Scaling in pp

BRAHMS Preliminary

π^+, p
π^-, p
200 GeV
62 GeV

May 30, 2008

RHIC/AGS users meeting
Baryon Transport: How much energy available from the collision?

- AGS->RHIC : Stopping -> Transparency
- Rapidity Loss $<dy>$: 2±0.4: not linearly increase with $y_{beam}$
- Energy loss $<dE>$ per nucleon: 73±6 GeV
- Available energy for particle production: ~26 TeV
- The pp rapidity loss is consistent with $<dy> \sim 1$

May 30, 2008

RHIC/AGS users meeting
Peripheral collisions (Npart ~16) looks very much like pp
From 20-40% centrality clear change in shape.
Most central: suppressed at y>3 and increased yield at y~0
Longitudinal scaling for net-$p$ in Au+Au

Estimate of target contribution Subtracted.
Net proton dN/dy in p+p

- BRAHMS $\sqrt{s} = 200$ GeV
- BRAHMS $\sqrt{s} = 62.4$ GeV
- NA49 $\sqrt{s} = 17.2$ GeV


A$^*\cosh(y-y_{beam})$

BRAHMS Preliminary

May 30, 2008
Produced Particles

AuAu 200 GeV 0-5% central

May 30, 2008

RHIC/AGS users meeting
Longitudinal Distributions

- The dN/dy of pion distributions at all energies are Gaussian with an increasing width.
Anti-particle to particle ratios

⇒ Chemical freeze-out

• $\overline{p}/p$ verus $K^-/K^+$ : good statistical model description with $\mu_B = \mu_B(y)$ with $T \sim 170\text{MeV}$
• But this describes also energy dependency at $y=0$ ⇒ only $\mu_B$ controls the state of matter
• This extends down to SPS range of $\mu_B$

• Also for $K/\pi$ do the forward rapidities fall in same range as SPS data
Rapidity Dependent High-$p_T$ (intermediate) Measurement

- At the RHIC energies, hard scattering processes at high-$p_T$ become important
- Partons are expected to loose energy in the dense matter
- Different rapidities provide different densities of the medium: Sensitive to the dynamics
- Largest medium effect at mid-rapidity ("Scale" to multiplicity)? increasing "Dissipative Viscous Hadronic Corona"?
- Rapidity dependent high-$p_T$ suppression factors: provide information on dynamical medium effect
\( R_{AA} \) for identified particles (AuAu 200GeV)

- The charged pion yields are suppressed by a factor of ~ 2-3 as compared with binary scaled p+p pion yields.
- \( R_{AA} \) for pions is independent of rapidity.
- The proton and antiproton yields in central Au+Au at 200 GeV do not show suppression, baryon meson difference remains.
Example of model comparison

Barnafoldi et al. hep-ph 0609023

opacity $n = \frac{L}{\lambda}$

$L$ – effective length of matter

$\lambda$ – mean free path

less jet quenching +

stronger initial effects at higher rapidities

maintain rapidity independent NMF
Initial and final effects – dAu at 200 GeV

- **Initial effects**
  - Wang, Levai, Kopeliovich, Accardi

- **Especially at forward rapidities:**
  - HIJING
  - D.Kharzeev et al., PLB 561 (2003) 93

- **Others**
  - B. Kopeliovich et al., hep-ph/0501260
  - J. Qiu, I, Vitev, hep-ph/0405068
  - R. Hwa et al., nucl-th/0410111
  - D.E. Kahana, S. Kahana, nucl-th/0406074

**“Cronin effect”**

- Initial state elastic multiple scattering leading to Cronin enhancement ($R_{AA} > 1$)

**Nuclear shadowing**

- Depletion of low-x partons

**Gluon saturation**

- Depletion of low-x gluons due to gluon fusion
  - "Color Glass Condensate (CGC)"

**Suppression due to**

- Dominance of projectile valence quarks, energy loss, coherent multiple scattering, energy conservation, parton recombination, ...
Exciting First Results From Deuteron-Gold Collisions at RHIC

Findings intensify search for new form of matter

'PRL 91 (2003) 072305'

May 30, 2008

RHIC/AGS users meeting
$x_F = x_1 - x_2$

$x_1 x_2 = \frac{m_T^2}{s}$

$x_1 \sim \frac{m_T}{\sqrt{s}} e^y \quad x_2 \sim \frac{m_T}{\sqrt{s}} e^{-y}$

Mid rapidity

Forward rapidity

D. Kharzeev et al.  

CGC at $y=0$

Very high energy
Access to range of $Q^2$ and $x$

The $x$-$Q^2$ region accessible is illustrated in the following. Note the region reachable at RHIC. In $p(d)A$ the saturation will decrease the effective $x$-range by $A^{1/3}$. At RHIC at $y \sim 3$ can reach into $x_2 \sim 10^{-3}$.
BRAHMS d+Au results as function of rapidity and centrality

\[ R_{dAu} = \frac{Y_{dAu}}{N_{coll}Y_{pp}} \]

Normalized ratio of measured (integrated) dN/dη scaled.

The data have given rise to many interpretations and additional measurements.

R_{cp} ratios are constructed in wide η bins.

May 30, 2008

RHIC/AGS users meeting
Identified Particle $R_{dAu}$

Figure 2. $R_{dAu}$ of $\pi^+$, $K^+$ and protons at forward rapidity $y = 3.0$ in minimum bias d+Au collisions ($<N_{coll}> = 7.2$). A 8% systematic error is included.

$R_{dAu}$ for identified particle consistent with charged hadrons and all exhibiting $R_{dA} \leq 1$ for $p_T < 3$ GeV/c.

The protons may exhibit less suppression.
Impact on Theory / comparison...

- CGC model describes $R_{dAu}$ and $R_{CP}$
- Suppression comes in at $y > 0.6$

Shadowing vs. CGC
pp

• How well understood is pp in terms of pQCD
Un-polarized Cross-sections at $\sqrt{s}=200$ GeV.

Good description at 200 GeV over all rapidities down to $p_T$ of 1-2 GeV/c.

Brahms data: PRL 98, 252001 (2007)
Recently deFlorian, Sassot and Stratman performed a global fit including new data from Brahms at high rapidity. PRD 75, 114010 (2007)

• Charged separated fragmentation functions
• Fragmentation functions significantly constrained compared to previous “state of the art” when adding RHIC data into fits.
Comparison of NLO pQCD calculations (Vogelsang) with BRAHMS $\pi$ data at high rapidity. The calculations are for KKP (solid) and a scale factor of $\mu=p_T$, DSS with CTEQ5 and CTEQ6.5 are also shown. The agreement is reasonable, in apparent disagreement with earlier analysis of ISR $\pi^0$ data at 53 GeV.
BRAHMS and SPIN

- There is no mentioning of SPIN in LOI, CDR.
- The RHIC spin group and RBRC by the frequent meetings brought the idea to fruition.

The first talk on this was at the RHIC SPIN physics meeting in 98, where I quoted
“The BRAHMS detector has capabilities for XF=0.3-0.5”
“need additional effort” – got that from Gerry, Brendan Fox
“1 mo running” - optimistic
BRAHMS and Transverse Spin

- Early (naive) QCD predicted this effect to be small
- Non-zero Single Transverse Spin Asymmetry (SSA/ $A_n$) requires Spin Flip Amplitude and phase difference in intrinsic states
- Such studies may clarify properties of transverse quark structure of the nucleon
  Flavor dependent correlation between the proton spin, momentum and transverse momentum of the un-polarized partons inside the proton.
- **Collins effect** [Nucl Phys B396 (1993) 161]
  Correlation between the quark spin, momentum and transverse momentum of the pion.

$$A_n = (\sigma^+ - \sigma^-) / (\sigma^+ + \sigma^-)$$

Where the spin cross section is determined with the spin direction defined by $k_b \times k_{pi}$
$A_N(\pi)$ at $\sqrt{s} = 62$ GeV

- Large $A_N(\pi)$: 0.3-0.4 at $x_F \sim 0.6$ $p_T \sim 1.3$ GeV
- Strong $x_F$ - $p_T$ dependence. Though $|A_N(\pi^+)| \sim |A_N(\pi^-)|$
  $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with $x_F$-$p_T$

May 30, 2008

RHIC/AGS users meeting
$A_N \times F - p_T$ dependence at $\sqrt{s} = 62, 200$ GeV

62.4 GeV acceptance, 3 angle settings of spectrometer (2, 3 and 6 deg)
**$A_N(\pi)$ at $\sqrt{s} = 200$ GeV**

- $A_N(\pi^+)$: positive $\sim(<) A_N(\pi^-)$: negative: 4-6% in $0.15 < x_F < 0.3$
- Behavior consistent with a slight decrease with increasing $p_T$ as evident in going from $\sim 4$ deg to 2.3 deg setting
- Good agreement with twist-3 calculations which also has the $1/pt$-dependence at higher $p_T$

May 30, 2008

RHIC/AGS users meeting
$x_F$ dependence in $p_T$ slices

To gain more insight the data are separated in $p_T$ bin to study $x_F$ dependence 200 GeV $\pi^+$ and $\pi^-$

- At all $p_T$ increasing $A_N$ with $x_F$.
- Magnitude is approximately constant at $p_T>1.5$ GeV/c
At low-\(p_T\) \(A_N(\pi)\) increases from low \(p_T\).
(Constraint must be 0 at \(p_T=0\))
Unifying 62 and 200 GeV

BRAHMS Preliminary

\[ A_N(\pi) \]

200 GeV
62.4 GeV

0.5 < p_T(\pi) < 0.8 GeV/c
Unifying 62 and 200 GeV

BRAHMS + E704

E704 data – all pt (small star) pt>0.7 red star.
• If main contribution to AN at large $x_F$ is from valence quark: $A_N(K^+) \sim A_N(\pi^+)$ and $A_N(K^-) \sim 0$
• Observation clearly different
• Show different models comparisons (only $p_T>1$)
Summary

The RHIC program made enormous progress during the years going from the first surveys, the discoveries, and now precision measurements in heavy ion and pp reactions leading to fundamental understanding of hot dense matter and QCD.

The presence of 4 experiments with the different strengths and competition has been very good for the RHIC program.

- Some questions on RHIC PHYSICS where BRAHMS have had an impact.
  
  "How does matter behave at very high temperature and/or density?"
  - Jet-quenching suppression in AA, not d-A
  - Au-Au, Cu-Cu, pp. Bulk properties energy dependence

  "What is the nature of gluonic matter? and how does it behave inside of strongly interacting particles?"
  - d Au at high rapidities (low-x)

  "What is the spin structure of the nucleon ?"
  - Single Spin Asymmetries at large x_F