Baryon Stopping & Entropy Production, BNL, June 1, 2009

09:00 - 09:45  Overview and issues  Peter Steinberg (BNL)
09:45 - 10:30  Review of Proton Stopping Data  Peter Christiansen (Lund)

10:30 - 11:00  Coffee Break

11:00 - 11:45  Colliding Shock Waves in AdS_5  Yuri Kovchegov (OSU)
11:45 - 12:30  Comparing p+p vs. A+A  Mike Lisa (OSU)

12:30 - 2:00  Lunch & Discussion

2:00 - 2:45  Entropy Production in QCD  Berndt Mueller (Duke)
2:45 - 3:30  Entropy Production from the CGC  Adrian Dumitru (Baruch)

3:30 - 4:00  Coffee Break

4:00 - 4:45  Entropy Production from AdS/CFT  Amos Yarom (Princeton)
4:45 - 5:30  Measuring Bremstrahlung at the LHC  Brian Cole (Columbia)
Thoughts on Baryon Stopping & Entropy Production

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RHIC-AGS Users Meeting Workshop: “Baryon Stopping & Entropy Production”
Brookhaven National Laboratory
June 1, 2009
The “Standard Model” of Stopping

- Nuclei collide
- Nucleons “stop” → BRAHMS
- Energy is deposited
- Entropy is produced
- Hydrodynamic evolution
- Particles in final state → PHOBOS (& BRAHMS)

Do the two data sets (energy & entropy) tell the same story?
Baryon Stopping

- A topic of lots of interest in the 1980's and 1990's (Busza, Videbaek et al)
  - Particularly in the p+A programs, who were studying “proton energy loss” in “cold nuclear matter”
  - Need PID and forward coverage

- Limited recent data led to recent limited discussion of the subject
  - BRAHMS data on dN/dy very important
  - Relatively little theoretical work!
BRAHMS $dN_B/dy$

- Will be shown by P. Christiansen
  - This discussion is about general issues, not experimental details!

- General empirical interpretation: “pile-up” at low energies gives way to “transparency” at high energy

- At high energy, baryon density is clearly not piling up at midrapidity
Quantifying stopping (200 GeV)

• Average rapidity loss ~ 2 units

\[ \delta y = y_b - \frac{2}{N_{\text{part}}} \int_0^{y_b} y \cdot dN/dy \cdot dy \]

• “The rapidity distribution of the net-protons after the collision then not only determines the energy available for particle production, but also yields information on the stopping of the ions due to their mutual interactions”

• Energy loss of \( \Delta E \approx 73 \pm 6 \) GeV

\[ E = m_T \cosh(y) \]

• A combination of proton rapidity loss and transverse momentum gain \(<p_T> \sim m_p\), i.e. \( m_T \rightarrow 1.4 m_0 \)

\[ \text{arxiv:0901.0872} \]
Illustrating energy loss

Protons are slowed longitudinally and dispersed transversely.

$\langle \delta y \rangle = -2$

75% loss $\langle m_T \rangle \sim 1.4$ GeV

87% loss
Stopping is “energy independent”

- Decomposing net baryons into “target” and “projectile”, BRAHMS extracted a “per proton” $dN/dy$
  - Good for three energies, except one point at 200 GeV
- No real dependence on $\sqrt{s}$
  - Not even NN cross section!
- A+A is very different than p+p
  - $dN/dy \sim \exp(y')$ ($dN/dx \sim \text{const}$)

$p+p$ from talk by F. Videbaek
“BMS” stopping

Decoherence of partons in incoming nuclei, adding some $p_T$

In this view, stopping is “built-in” to the nucleon/nuclear PDFs: good for explaining “limiting fragmentation”, bad for standard stopping
Interlude - centrality dependence

• BRAHMS only presents the net dN/dy for 0-10% centrality

• PHOBOS measured net dN/dy vs. \(N_{\text{part}}\) for 62.4 GeV Au+Au

• Linear with \(N_{\text{part}}\) down to most peripheral collisions considered

• Why would each participant contribute equally if nuclei are transparent?

![Graph showing net dN/dy vs. N_{\text{part}}](image-url)
Entropy production

- Entropy reflects the degrees of freedom available to the QGP on thermalization
  - wQGP vs. sQGP

- Several ways to estimate it (experimentally)
  - Phase space density (e.g. Pratt & Pal, at midrapidity)
  - Multiplicity density, assuming thermal freezeout, and isentropic evolution

- Current estimates are consistent (see e.g. Muller & Rajagopal), so I will stick with multiplicity estimates
  - Thermal models give $S \sim 7.2 \, N_{ch}$

- PHOBOS has discussed comparisons of multiplicities with elementary systems: useful to have an empirical context
  - Only $4\pi$ multiplicities discussed here
“free” fragmentation of quarks into hadrons

Charged primaries + some secondaries (up to 8% correction)
Multiplicity Systematics - p+p
Leading Particle Effect

“leading” particles keep arbitrary fraction of $\sqrt{s}$

flat probability distribution $\rightarrow$

$$x_F = \frac{2p_z}{\sqrt{s}}$$

$$\langle x_F \rangle \sim \frac{1}{2}$$

$$\sqrt{s_{eff}} = \langle x_F \rangle \sqrt{s} = \frac{\sqrt{s}}{2}$$

“effective energy” (a la Basile et al)
Effective energy in action

- You don’t really believe it until you try it yourself!
  - Simple 1/2 prescription does a surprisingly good job of making $e^+ e^-$ and $p+p$ overlap

- Of course $dN/dy$ cannot be the same due to larger rapidity range

- Models tuned on existing data
  - No obvious scaling built in
Entropy Production in A+A

Nominally, all of these stages have different degrees of freedom
A+A in the context of elementary systems - how much energy?

- Heavy ion data is only scaled once:
  - Divided by overall volume $N_{\text{part}}/2$
- Overlaps $e^+e^-$ and $p+p(@\sqrt{s}/2)$ over a decade in beam energy
- Old observation (2002) but germane
  - How much energy is available in A+A?
  - If $e^+e^-$ has “all”, and $p+p$ has “half” → then A+A has “all”
- At low energy, scaling broken systematically with increasing $\mu_B$
  - Is this less energy, or less entropy?
  - More on this later!
Longitudinal distributions in context

• It’s not just the multiplicity that agrees, but the longitudinal distributions over $4\pi$

• If an accident, a very detailed one
  • If you argue that $dN/dy$ has “no information”, then you have to generalize that assessment!

• If not an accident, tells us that longitudinal phase space (i.e. stopping?) is essentially similar
Do these tell the same story?

$\Delta E(200 \text{ GeV}) \sim 150 \text{ GeV} \quad \text{“transparency”}$

$\Delta E(200 \text{ GeV}) \sim 200 \text{ GeV} \quad \text{“full stopping”}$
Do these tell the same story?

they seem to be telling two very different stories:

“transparency”

“full stopping”
Bjorken’s story

“transparency”

the pancakes pass through each other and the baryons leave energy in the central region. the evolution obeys the laws of hydrodynamics

Baryons assumed to be on the “outside”, escaping at the speed of light
Landau’s story

“stopping”

the pancakes stop each other as they collide, and the energy then explodes longitudinally via hydrodynamics

Baryons assumed to be... nowhere (i.e. ignored)
Landau and Bjorken are telling a story with the same middle (hydrodynamics), and same end ($v_z = z/t$, hadronization at $T_{ch}$), but with a different beginning.

So it’s not just the amount of energy, but how it is deposited that matters (e.g. is it born expanding, or standing still -- or somewhere in between?)
Thermalization time

\[ \tau_0 \gg \frac{2R_0}{\gamma} \]

\[ \tau_0 = \frac{2R_0}{\gamma} \]

Discussions of thermalization time are not simply deciding a “property”, but the nature (and dimensionality: 2+1 vs 3+1) of the initial state!
Experimental access to stopping?

Can the final (pseudo) rapidity distribution (mesons or baryons) tell us how the energy was stopped?
Using final rapidity distributions to probe the initial state

Bjorken initial conditions suggest a widening plateau in $dN/dy$

Landau implies $dN/dy$ is Gaussian with $\sigma^2 = \frac{1}{2}\ln(s/m^2)$
Using final rapidity distributions to probe the initial state

\[ \frac{dN}{d\eta} \] shows a “plateau” that gets wider with increasing beam energy

\[ \frac{dN}{dy} \] has no plateau, width follows prediction from Landau (1955)

\[ \sigma^2 = \frac{1}{2} \ln(s/m^2) \]
Which side are you on?

The “same” data (dN/dy or dN/d\(\eta\)) is used to defend both stories! and BRAHMS and PHOBOS are used to defend the opposite of what their respective experiments promote in papers...
A recurring situation (Carruthers 1975)
Putting the baryons back

• **Neither Bjorken nor Landau tell us how baryons stop**
  • “Something happens” and energy is deposited in the collision zone

• **Bjorken better fit to “standard” stopping scenario**
  • Partially-stopped nuclei end up in the fragmentation region and can be ignored

• **Complete stopping seems at odds with BRAHMS data**
  • Why would pions/kaons and protons be so different if all come from “stopped” energy

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**Figure 1:** Invariant transverse mass lines are fits to the data, namely a power law in \( m \) and an exponential in \( m \) were obtained by combining data from several spectrometers. Statistical spectra have been rescaled by powers of 10 for clarity. The dashed lines in (a) are Gaussian fits to the contributions (following an exponential in \( m \)). The fraction of particles originating from the phase-space covered in this analysis. The fraction of hadrons accepted according to the same data cuts applied to the experimental data. It has been found a...
Where do the baryons go?

- The “standard” stopping scenario takes a reasonable approach
  1. Each baryon loses energy in the oncoming nucleus
  2. Baryons then decouples from the subsequent longitudinal evolution
- However a baryon strongly-coupled to expanding fluid can reaccelerate
  - If this is the case, then the standard scenario is not measuring energy loss at all
- The net baryon dN/dy is then measuring net rapidity loss
  - If so, then baryons decoupled from entropy!
“Fireball Sandwich” scenario

1. Incoming nuclei (beam rapidities)
2. First collision: partial stopping of baryons
3. Second collisions: full baryon stopping, displaced centroids, thermalization (spectators decouple)
4. Longitudinal expansion of matter, baryons reaccelerated

baryons outside, fireball inside

entropy produced by now!
Try this in 1D hydro

1+1D hydro from A. Dumitru, baryons from rest are accelerated!
One last thing: How do net-baryons affect entropy?

“Deviation” of multiplicity at low energy correlates with “pileup” of baryons.
Thermal models at high $\mu_B$

Fits give:

$\mu_B & T$ vs. $\sqrt{s}$

$$\mu_B(\sqrt{s}) = \frac{1.2735}{(1 + 0.2576\sqrt{s})}$$

Entropy is suppressed at high $\mu_B$!

Cleymans, Wheaton, Stankiewicz, PAS, et al, nucl-th/0506027
Same thermal model: nDOF is constant...

Despite all of the changes in the composition:

“baryon/meson”
“fermion/boson”
“matter/radiation”

the system decouples at same “nDOF” \((s/T^3)\)!

what is this magic number?
Discussion points

• **Baryon stopping**
  • How is the energy released (not even discussed so far)!?
  • How much of it is released in the initial stages
  • do baryons decouple immediately from system, or can they be reaccelerated?
  • p+p vs. A+A: how does the leading particle effect work?

• **Entropy production**
  • How does the available energy turn into entropy (how do baryons affect this?)
  • What are the degrees of freedom in the early stages which determine entropy?
  • How good of an assumption is isentropic evolution (e.g. viscous effects?)

• **Bjorken vs. Landau is a good way of setting issues into relief**
  • Thermalization time is not just a number!
Rapidity Distributions in pQCD (QCD prefers Landau?)

Fig. 1. The translational invariance. Except for the small rapidity region, the rapidity distribution is on the same universal curve (measured from $y_{\text{max}}$).

Fig. 2. The rapidity distribution at high energies. The height grows faster than the width, and there is no widening central plateau.

pQCD: Limiting fragmentation and $\sigma^2 = \frac{1}{2} \ln(s/m^2)$...what gives?