Life, the Universe, and Everything (with a dash of Hitchhiking)

Sourendu Gupta

Contemporary and Emerging Topics
in High Energy Nuclear Physics
VECC Kolkata (November 15, 2022)

The Fireball

What is missing from this talk

I do not have time to talk about many interesting things:

- Phase diagram, BES, fluctuations and the related physics. Highly explored in many talks and conferences in the last ten years. Great advances, much new data.
- Large initial electromagnetic fields, CME, MHD, and related physics. Tremendous ferment and great new ideas. Requires a dedicated meeting to take stock of it.
- Light nuclei and hypernuclei: enormously exciting subject. Intersections with astrophysics, neo-classical nuclear physics, and hadronic physics. A dedicated meeting is needed.
- No separate discussion of γ, $W^{\pm}$, Z and dileptons. Tremendous work done by local group, among others. Highly exciting, and now firmly associated with other hard probes like heavy-quarks, quarkonia and jets.

Global properties

Initial CM energy varies between O(10) GeV/nucleon to O(10^4) GeV/nucleon. How much of it goes into the fireball? Forward calorimeters (and other detectors) can constrain this. Cross check from final state baryon chemical potential (μ). There is a change in the slope of nuclear transparency with $\sqrt{S}$. What does it tell us.

The fireball at $\sqrt{S} > 50$ GeV may not be the same as a fireball at $\sqrt{S} \simeq 10$ GeV. At high energy initial longitudinal expansion, then radial expansion. At low energy, maybe compressed nuclear matter, maybe sideward expansion. Any signals? Can global observables rule it out.

Initial angular momentum varies between O(1) to O(10^4). How much of this goes into the fireball? Does nuclear transparency explain all of it? Is there some way to constrain this in experiments? Through global observables? Complete framework for how rotation affects the final state?

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Gross properties of the fireball

What do gross measurements such as flow coefficients tell about the fireball? Is it hydrodynamics or simpler?

Poskanzer and Voloshin, 1998

Expanding proton (1970s): rising total pp cross sections imply that the proton expands. So proton v_2 can have a non-hydrodynamic explanation. How to exclude this? How to design experiments?

What other measurements tell us that matter forms? Is jet quenching a smoking gun? What about J/ψ suppression? After all there is a nuclear dependence to all of these signals. Sequence of nuclear beams of increasing A may clarify this issue.

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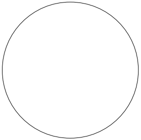

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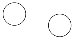

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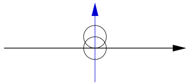

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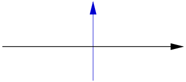

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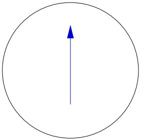

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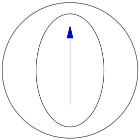

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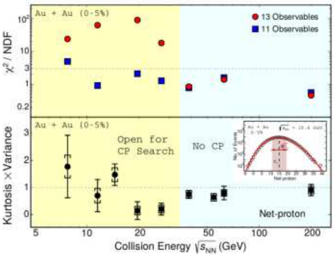
Is the fireball thermalized?

If the fireball is thermalized then at freezeout particle yields as well as E/E fluctuations should be thermalized (Corrections due to finite size). So is it explained by the hadron resonance gas picture?



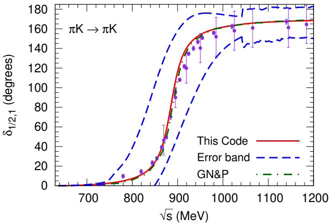
In actual fact, only region for $\sqrt{S} > 40$ seems thermalized. Below this some higher order fluctuations seem to fall out of thermal equilibrium.

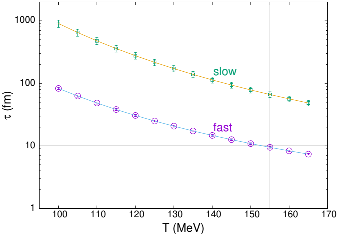
Gupta, Mallick, Mishra, Mohanty, Xu (2021)

Signal of critical point or different initial conditions? In either case, departures from local thermal equilibrium mean we need to use transport equations: beyond hydrodynamics.

Freezeout mystery

At large $\sqrt{S}$ why is $T_f \approx T_{co}$? After all T_f is non-equilibrium property and T_{co} is equilibrium. Fast equilibration possible only in plasma phase. In hadron phase use hadronic theory. Use χPT to investigate freezeout: high order unitarized matrix elements generate scalar and vector resonances. No double counting, no artificial cutoffs.





Gupta, Nayak, Singh (2021)

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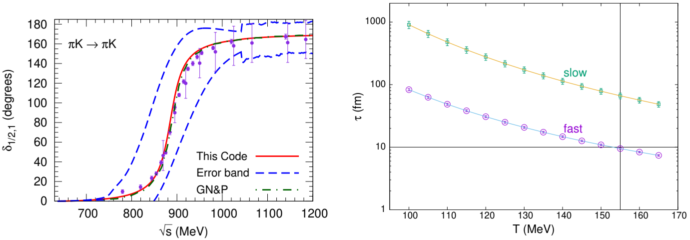

Gupta, Nayak, Singh (2021)

$\sigma_{el} \approx \sigma_{inel}$ then why is $T_f^{chem} \neq T_f^{kin}$? Comes from blast wave fits to spectra. Can T_f^{kin} be determined better?

Hard probes

Systematics of R_{AA}

Typically the ratio of cross sections in AA and pp collisions is called R_{AA}. If we take a single identified particle, then the kinematic variables are the collision centrality c, the particle mass M, rapidity y, and transverse momentum p_T. The fireball is characterized by a temperature T (at large $\sqrt{S}$ we have $\mu \simeq 0$). So dimensional analysis gives

$$R_{AA}(c, y, p_T, M, T) = R_{AA}\left(c, y, \frac{M}{p_T}, \frac{T}{p_T}\right)$$

At large p_T is the dependence on T small? Good measurements of $R_{AA}^{\rm jet}$ from LHC. Comparable results from RHIC will be important to check this. Difficulties: comparable y and p_T acceptance and jet cone ΔR.

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$$R_{AA}(c, y, p_T, M, T) = R_{AA}\left(c, y, \frac{M}{p_T}, \frac{T}{p_T}\right) \xrightarrow{p_T \to \infty} R_{AA}(c, y, 0, 0)$$

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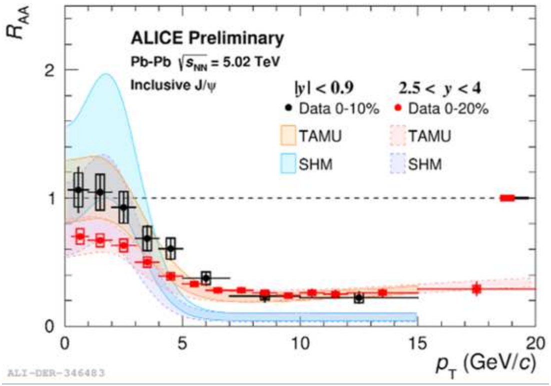
Approximate universality of R_{AA} for $p_T \gg T$ and M?



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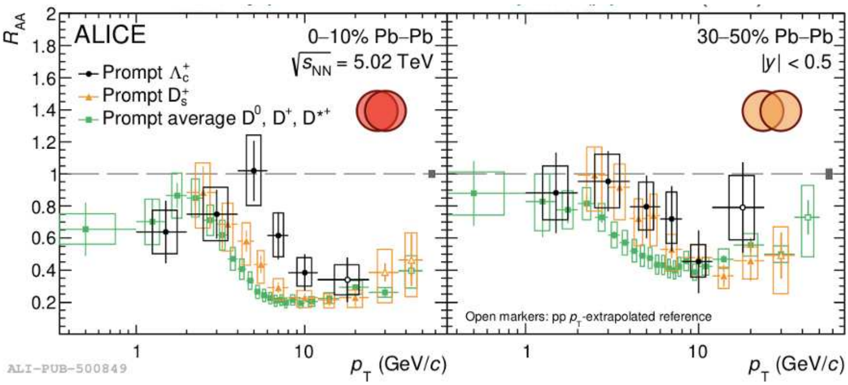

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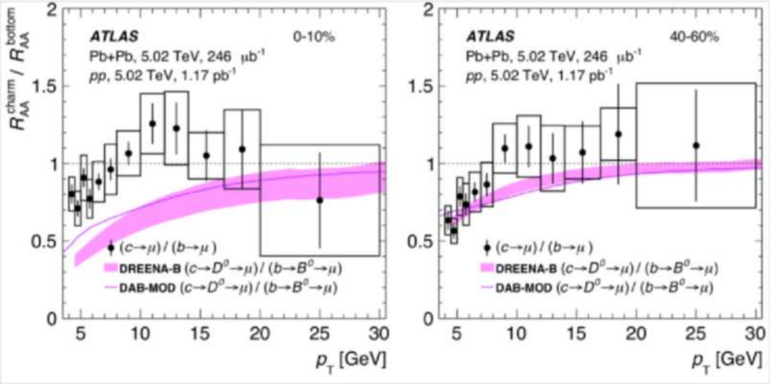

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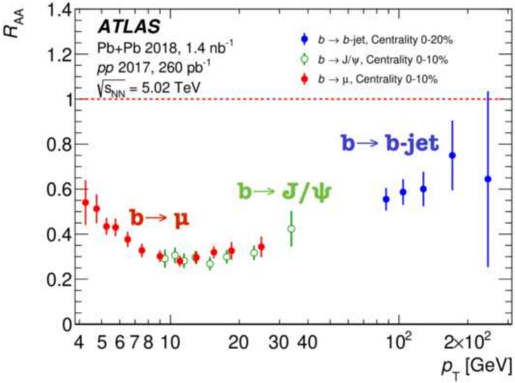
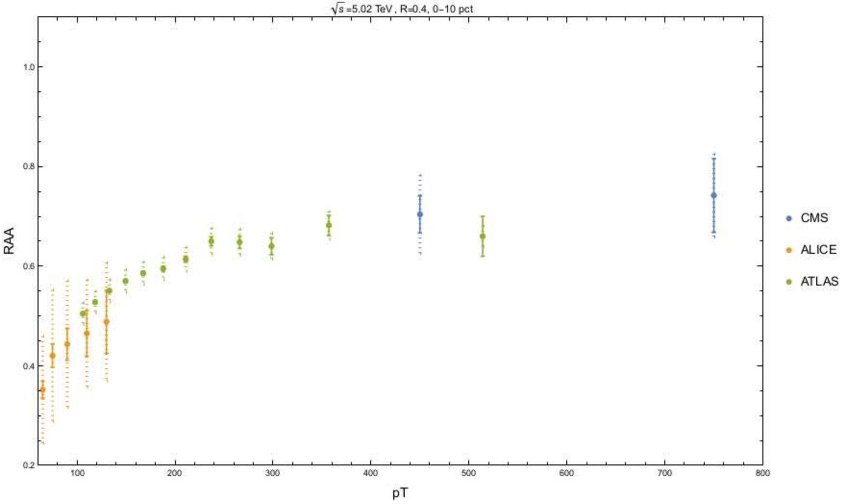


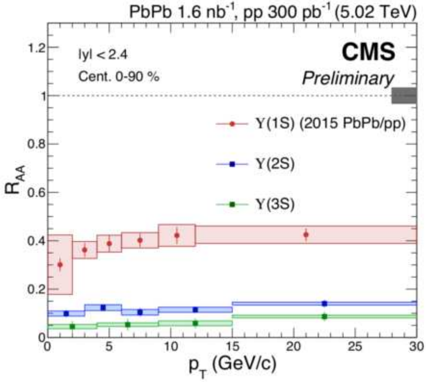
In order to understand high-p_T behaviour of R_{AA}, enough to understand jets? Are jets an universal high p_T tool?

Jet R_{AA}



Compilation by Ankita Budhraja

Light binding breaks the universality of R_{AA}



Sequential suppression gives information on binding and excitation spectra.

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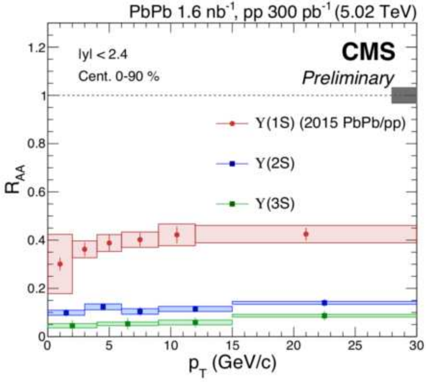

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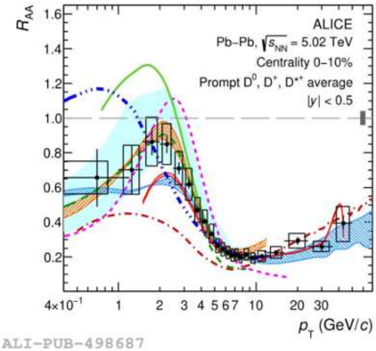
In future interesting to examine similar effects in light nuclei and hypernuclei.

$p_T \leq M$ interesting non-universal physics



Peak at $p_T \approx M$ due to charm quark transport. Inclusive bottom peak shifted to higher p_T. Exciting possibility of comparing transport from experiment and lattice.

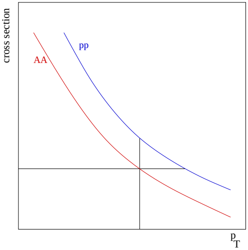
See talk by Saumen Datta

Δp_T: another representation of R_{AA}

As an alternative to R_{AA}, we can define Δp_T as

$$\left.\frac{d\sigma_{AA}}{dp_T dy}\right|_{p_T} = \left.\frac{d\sigma_{pp}}{dp_T dy}\right|_{p_T+\Delta p_T}$$

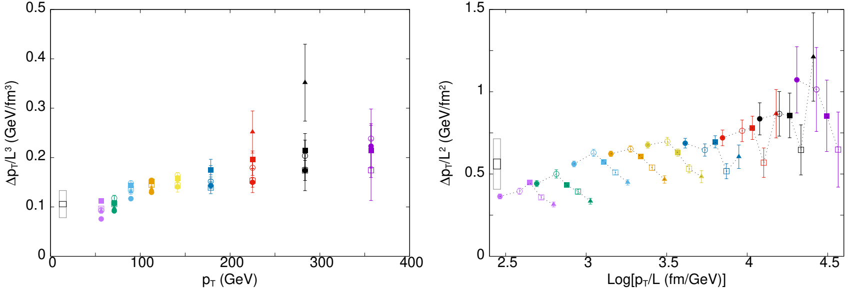
Gupta, Sharma (2022)



The centrality dependance of any hard probe can be converted to a path length (L) dependance on the medium. In particular interesting to examine Δp_T as L changes for fixed p_T.

Extreme sQGP implies $\Delta p_T \propto L^3$ at fixed p_T. Simple BDMPS-Z arguments indicate $\Delta p_T \propto L^2$ at fixed p_T/L. Harder to disentangle path length dependance in R_{AA}.

Weak or strong coupling?



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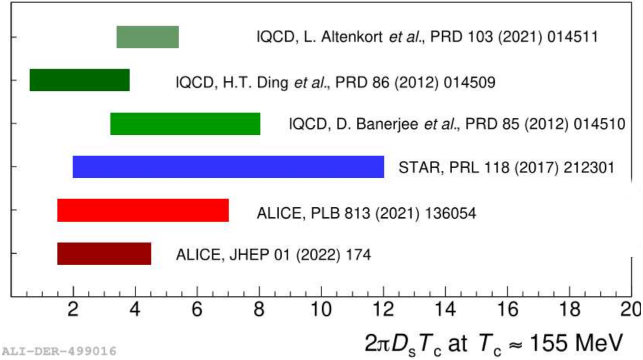
Angular momenta

Almost certainly the fireball angular momentum in mid-central collisions is large. How can experiments measure this? How can initial state models estimate how much angular momentum is deposited in the fireball?

Understanding the overall evolution with angular momentum has not been tried seriously. For example, there is no longitudinal flow; what is an early time approximation to the flow? Dissipation and entropy production in the merger of vortices has not been explored for QGP. Spin hydro is an interesting new development.

Experiments see polarization of baryons and vector mesons. How is this related to overall spin? The QCD mechanism of coupling microscopic components (hadrons) to macroscopic motion (fireball spin) is yet to be understood.

Heavy quarks



Impressive advances in the determination of transport of heavy quarks. Good agreement between lattice QCD estimates and first estimates from data. The second instance of agreement between first principles theory and experiment.

Jets

Jets are the universal underlying physics of all of hard probes in matter. We need to understand them in detail.

Lots of constraints on energy loss from looking at jets with γ, $W^{\pm}$, Z on the opposite side.

Many new ideas on jet energy loss: full event reconstruction, path length dependance, quartile measurements, etc.

All of this is needed for a detailed understanding of how to use hard probes to understand soft physics. Main problem is that $T \ll p_T$, and a "physics amplifier" is needed. For quarkonia the quark mass provides the amplifier. For jets it seems to be the path length in matter.

Jets are so important; we need new variables to understand its physics.