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ICPAQGP, Puri (February 7, 2023)

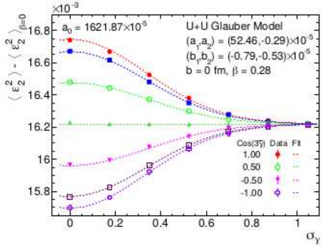
Scope

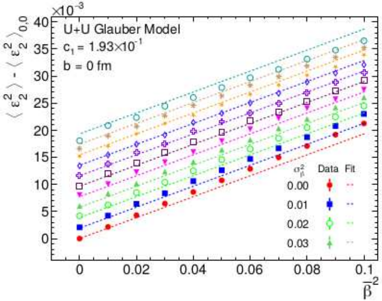
What I will not talk about

1. A whole exciting sister domain: extreme objects in the distant universe. Neutron star physics, vitalized by multi-messenger astronomy; cosmology, vicinity of merging black holes.
2. A complete field poised for take off: EIC. Very exciting times in store, lots of interesting theoretical ideas. Listen to the talks on this subject.
3. Exciting times for hydro. Connecting transport to hydro via attractors: fast hydrodynamization. Spin hydro: re-discovery and extensive use of a freedom in defining the stress tensor of a fluid, leading to a rank-3 tensor related to angular momentum. Developments in QCD MHD and transport in magnetized plasma.
4. Interesting speculations about QCD: old and new approximate symmetries, corresponding phase diagrams. Dynamical models and their tests on the lattice. Some talks coming.
5. Many survey talks: BES II, jets, heavy quarks, etc.

Global observables and the initial state

Nuclear structure and more





Shape fluctuations of nuclei (triaxility γ, quadrupole deformations β) sampled through Glauber Monte Carlo, affects initial conditions for hydrodynamic evolution of fireball.

arxiv:2301.03556: Dimri, Bhatta, Jia

Energy deposition into fireball

Initial energy in the AA system injected by accelerator is $E_0 = 2A\sqrt{S}$. Initial energy after central collisions in the fireball is

$$E_r = \epsilon \times V = cT_{in}^4 \;\; r_0^2 A^{2/3} \;\; dzA^\alpha = cA^{2/3+\alpha}(T_{in}r_0)(T_{in}dz)T_{in}$$

So the fraction of energy deposited into the fireball is

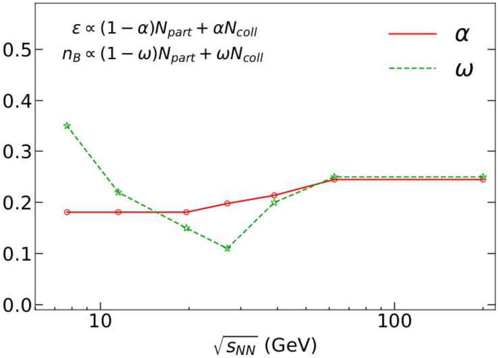
$$f = \frac{E_r}{E_0} = 1.3A^{\alpha-1/3} \times 10^{-2},$$

if we set $T_{in} = 200$ MeV and $\sqrt{S} = 200$ GeV. For nuclei with $A = 200$ we have $f = 0.2\%$ for $\alpha = 0$ and 1.3% for $\alpha = 1/3$. Expand in number of participating nucleons

$$\frac{E_r}{E_0} = f(n) = f_0 n + f_1 n^2 + \cdots \qquad \text{with} \qquad n = \left(\frac{r_{\rm hc}}{r_0}\right)^2 N_{\rm part}.$$

Linear term gives **wounded nucleon model**. Quadratic term equivalent to $N_{\rm coll}$ term introduced by Kharzeev; f_1 related to *hardness parameter*. Higher order terms possible.

Initial conditions

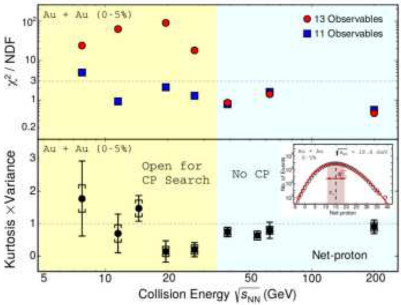


Chatterjee, Parida, 2211.15729

ω large at small $\sqrt{S}$ but decreases with $\sqrt{S}$: valence flavour becomes transparent. Flavour creation starts at larger $\sqrt{S}$, tracks energy creation.

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?



Gupta, Mallick, Mishra, Mohanty, Xu 2022

In actual fact, only region for $\sqrt{S} > 30$ seems thermalized. Below this some higher order fluctuations seem to fall out of thermal

EM fields before the collision

Typical nuclear binding energy, $BE \simeq 10$ MeV. For medium or heavy ions ($A > 50$) energy density due to strong interactions is

$$\mathcal{E} = \frac{BE \times A}{(4\pi/3) r_0^3 A} \simeq 13.77 \times 10^6 \ \mathrm{MeV}^4 \simeq 0.04 m_\pi^4.$$

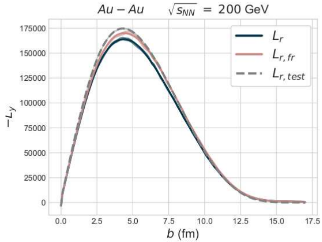
But accelerated nuclei produce EM fields and if its energy density is comparable with $\mathcal{E}$, then it changes nuclear binding. The critical EM field needed for this is

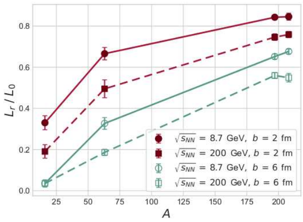
$$B_{\mathrm{crit}} \simeq \sqrt{\mathcal{E}} = 0.2 m_\pi^2.$$

Typical estimate of initial magnetic field is 0.1–$10 m_\pi^2$ **[1401.3805]**.

1. Are heavy-ions highly excited before collision?
2. How does this change the initial state of the fireball?

Angular momenta





Sass, Müller, Garcia-Montero, Elfner, 2212.14385

Uses SMASH: technical problem with conservation of angular momentum at each collision. Multiple curves explore stability of prediction.

Value of b at peak of angular momentum deposition shifts non-monotonically with $\sqrt{S}$. Up to 75% of pre-collision angular momentum deposited into the fireball at $\sqrt{S} = 200$.

Flow and small systems

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

Poskanzer and Voloshin, 1998

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

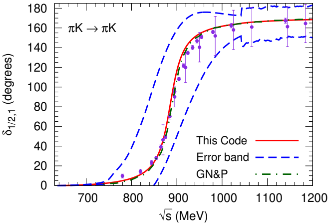
Sykora, ICHEP 2016

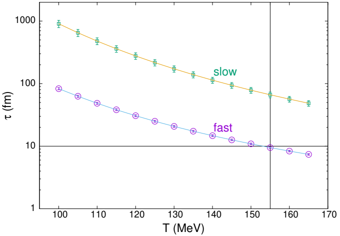
Interesting speculation about azimuthal flow coefficients in ep scattering due to vector-meson dominance. For eRHIC?

Glazek, Brodksy, Goldhaber, Brown, 1804.08847

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. In hadron phase use χPT to investigate freezeout: high order unitarized matrix elements generate scalar and vector resonances. **No double counting, no artificial cutoffs**.



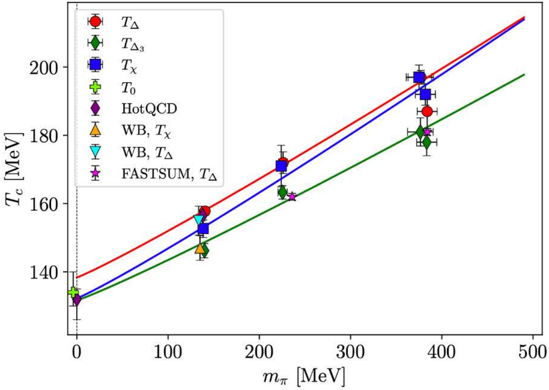


Gupta, Nayak, Singh (2021)

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

Phase diagram and excitations

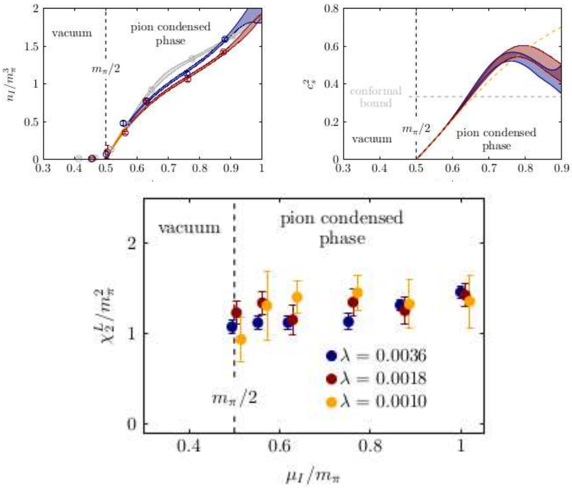
The crossover at $\mu_B = 0$



Kotov, Lombardo, Tonin 2105.09842

O(4) scaling works. Implies that critical behaviour is due to $N_f = 2$, since O(4)∼SU(2)×SU(2) chiral symmetry.

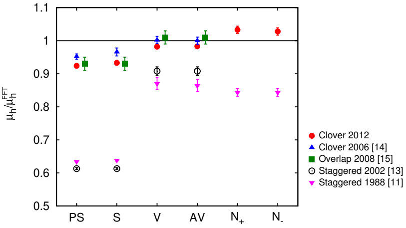
Finite μ_I and μ_B



Brandt, Cuteri, Endrödi 2212.01431

Strong coupling?

In free theory, all "meson" screening masses are equal to $2\pi T$ on the continuum. **Eletskii, Ioffe 1988**

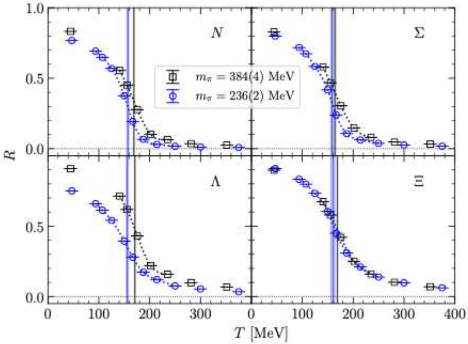


Datta, Gupta, Padmanath, Maiti, Mathur 1212.2927

Is there an approximate SU(4) global symmetry in QCD above T_{co}? If yes, QCD medium dominated by electric gluons. If the medium is strongly coupled then why are there single particle excitations behind the screening masses?

Philipsen, Glozman, Lowdon, Pisarski 2211.11628

Baryon parity doubling



FASTSUM 1703.09246

$$R = \sum_t \frac{G^+(t) - G^-(t)}{G^+(t) + G^-(t)}$$

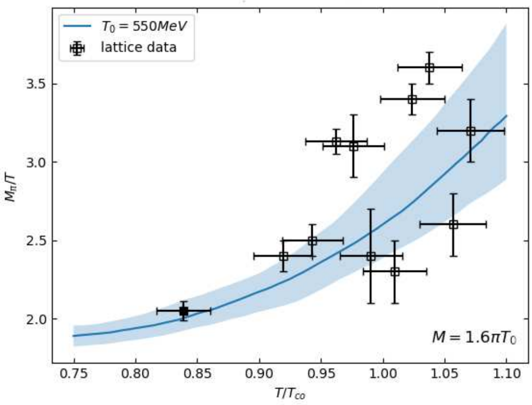
Effective theory of QCD near T_{co}

$T < T_{co}$: coloured modes screeened, hadronic description may work well. No gluons, but flavour visible at long distances. Colour bleached quarks may be used. Write EFT at finite temperature:

$$L = \overbrace{c^3 \Lambda_{UV} \overline{\psi}\psi}^{mass} + \overbrace{\frac{1}{2}\overline{\psi} i\gamma_4\partial_4\psi + \frac{c^4}{2}\overline{\psi} i\not\nabla\psi}^{kinetic}$$
$$+ \overbrace{\frac{c^{61}}{\Lambda_{UV}^2}\left\{(\overline{\psi}\gamma_5 T^a\psi)^2 + (\overline{\psi}\psi)^2\right\}}^{NJL\ \ type} + \text{other } J\cdot J + \text{higher derivs}$$

Cutoff on energy $p_4 \ll \Lambda_{UV}$. Chiral symmetry requires π but does not need ρ, so $\Lambda_{UV} < m_\rho$. Match low-energy couplings to lattice data at one temperature. Everything else is prediction.

Screening mass ties to phase structure



$T_c = 140 \pm 13$ MeV; in agreement with lattice extrapolations.
Curvature of the critical line $N_f = 2$: $\kappa_2 = (17.3 \pm 0.4) \times 10^{-3}$
Lattice [Bonati et al, 2018 $N_f = 2 + 1$]: $\kappa_2 = (14.5 \pm 2.5) \times 10^{-3}$

Sen, Sharma, SG, in preparation

Hard probes

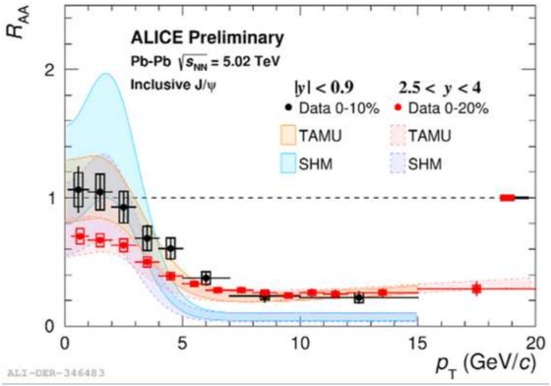
Systematics of R_{AA}

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

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

- 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.
- At large p_T the dependence on M is small. Makes sense since light particles are obtained by fragmentation from jets. Heavy mesons arise significantly from heavy-quark jets. Testable

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



To understand high-p_T behaviour of R_{AA} for all ground state hadrons, is it enough to understand a single underlying object? This is the not-jet.

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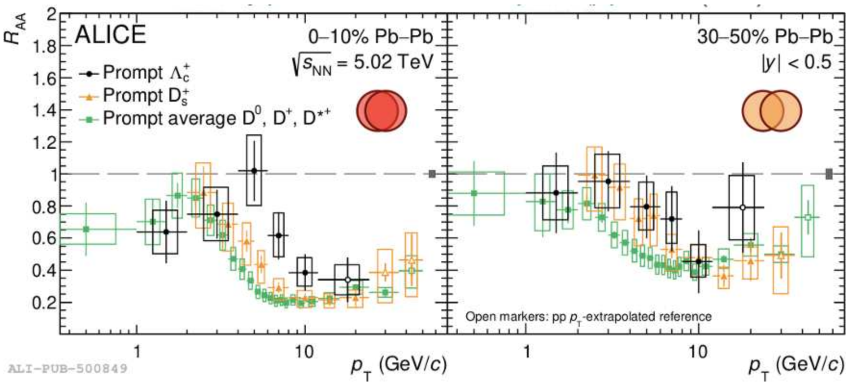

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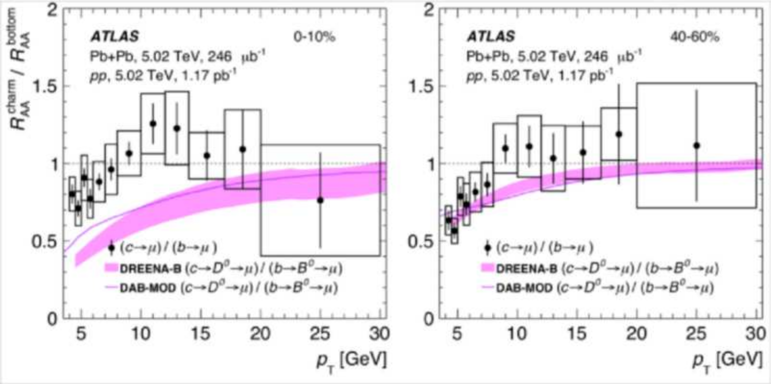

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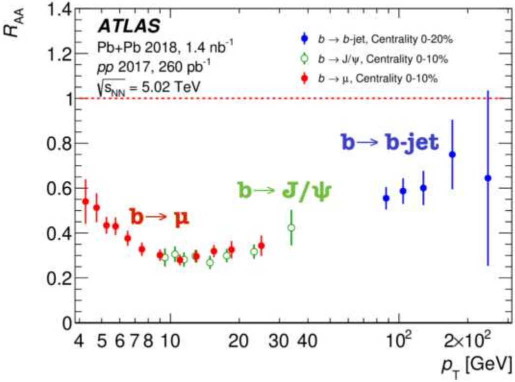
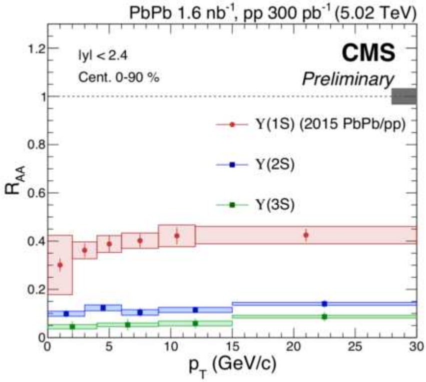
Not-jet to jet continuity



Not-jet is likely to be a hard parton whose shower cannot be controlled in perturbation theory.

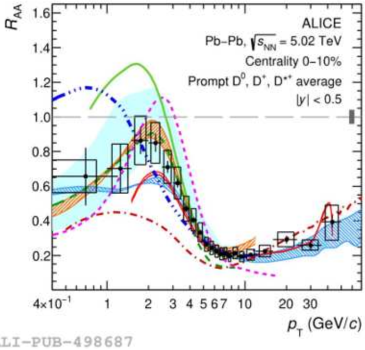
Light binding breaks the universality of R_{AA}



Sequential suppression gives information on binding and excitation spectra.

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 stage of comparing transport from experiment and lattice.

Future

Some open questions

- Is there something anomalous about baryon number stopping in the collision for $\sqrt{S} < 30$ GeV? Or is the lifetime of the system too small for baryons to come to complete equilibrium?
- Is the initial state more diffuse than the usual Woods-Saxon parametrization used in Glauber models? How would this affect energy, flavour, and angular momentum deposition?
- χPT at high order can be used to control hadron-phase transport extremely well, and gives an understanding of the surprising coincidence of $T_{\mathrm{fo}}^{\mathrm{chem}}$ and T_{co}. What is $T_{\mathrm{fo}}^{\mathrm{kin}}$?
- Complete quantitative understanding of the connection between chiral symmetry and the phase diagram in terms of an EFT of interacting pions? Transport coefficients?
- Simple dimensional arguments point to a regularity in the data on R_{AA} which seems to imply the involvement of hard but non-perturbative partons. How can this be used?