Solving the RHIC puzzles with hydro + statistical hadronization[1]

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The statistical model of hadron formation and the nature of the QCD hadronization process
ECT*, 4 September 2008

[1] Based on research with M. Chojnacki, W. Florkowski, and A. Kisiel

All experimental info must be used: abundances, momentum spectra, v_2, HBT, other correlations, ...

Puzzle for the hydro+stat. approach: impossibility to fit simultaneously the spectra, v_2, and HBT $\rightarrow R_{\rm out}/R_{\rm side} \sim 1.5$ instead of ~ 1

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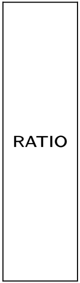

Hirano and Tsuda, QM'2002

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RATIO

Hirano and Tsuda, QM'2002

- Possible solution: Sharper initial condition than from Glauber (typically used) or initial flow
- azHBT also right
- Possible extrapolation to LHC

fsfs

pre-hydro stage $\longrightarrow$

$\longrightarrow$ initial condition for hydro $\longrightarrow$

$\longrightarrow$ hydrodynamics $\longrightarrow$

evolution sequence: $\longrightarrow$ freeze-out $\longrightarrow$

[Heinz ... many] $\longrightarrow$ hadrons

In most calculations the (static) initial condition taken from the Glauber model or from Color Glass

hydro = equations + initial conditions

Physics of the initial partonic (pre-hydro) stage is complicated (Glauber-like models, CGC, flux tubes, ...)

Explore it to get out of the deadlock!

ggcomp

Left: initial energy-density profiles for $c = 20 - 30\%$

We take Gaussian at early time $\tau_0 = 0.25$ fm:

$n_0 \sim \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2}\right)$

The profile is important

ggcomp2

Volume integrals and rms's the same

Left: initial radial energy-density profiles for $c = 20 - 30\%$

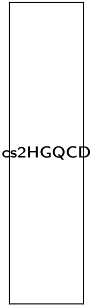
$n_0 \sim \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2}\right)$

Parameters a and b from GLISSANDO (GLauber Initial State Simulation AND mOre ...), include increased eccentricity from fluctuations ...

Equation of state

Inviscid, baryon-free, boost-invariant (for mid-rapidity) hydro
Equation of state encoded solely in the sound velocity, c_s
[Chojnacki+Florkowski, 2005]

$c_s^2 = dp/d\epsilon = \frac{s}{T}\frac{dT}{ds}$
(one-parameter liquid, $\mu_B = 0$)



$T_c = 170$ MeV

The "soft-hard" equation: below 1/3 at high T, no phase transition but smooth cross-over
Lattice from [Aoki, Fodor, Katz, Szabo, 2005 - full QCD, physical m_π]

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cs2HGQCD

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The "soft-hard" equation:
below 1/3 at high T, no phase transition but smooth cross-over
Lattice from [Aoki, Fodor, Katz, Szabo, 2005 - full QCD, physical m_π]
low T: $c_s^2 \sim \frac{T}{m_\pi}$
extremely high T: $c_s^2 \to \frac{1}{3}$
No shock waves, as

$$\frac{d}{dT}\frac{sc_s}{T} > 0$$

[Blaizot+Ollitrault]

thermo

Other quantities follow from thermodynamic relations thermo

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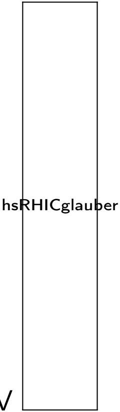
Entropy constraint:

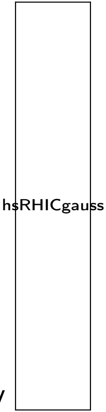
$$s(T) = s(T_0) \times \exp\left\{ \int_{T_0}^{T} \frac{dT'}{T' c_S^2(T')} \right\}$$

- Initial temperature profile obtained from the energy-density profile
- Initial central temperature T_i adjusted to reproduce the multiplicities
- Equations solved with the help of method of characteristics with Mathematica (Lhyquid - M. Chojnacki)
- 3 parameters: T_i, T_f, τ_0 (+profile) - painful!

- Entropy conservation test at the relative level of 10^{-4} or better

Freeze-out hypersurfaces





GLAUBER, $T_f = 150$ MeV GAUSS, $T_f = 145$ MeV

- Standard Cooper-Frye, GC ensemble, THERMINATOR - single f.o.
- Large flow $\rightarrow$ practically no hadrons fall back into the hydro zone
- $\sim$ 50% from volume, $\sim$ 50% from surface
- Gauss: larger size, shorter time!

Parameters

Gauss: $\tau_0 = 0.25$ fm, $T_f = 145$ MeV, Glauber: $\tau_0 = 1$ fm, $T_f = 150$ MeV

a and b from GLISSANDO, $\epsilon^* = (b^2 - a^2)/(b^2 + a^2)$

Lower T_f than in thermal fits to all particle species, we consider only π, K, p and $\bar{p}$

Only about 1.5 trajectory crossings per pion - small rescattering effects after freeze-out

Value of kinetic freeze-out temperature entangled with the freeze-out hypersurface / flow profile!

Constant $\tau \simeq$ 165 MeV, blast-wave - lower, some hydro - even lower, etc.

Challenge: obtain the freeze-out surface / flow dynamically

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How about other particles? Different decoupling times, hydro-kinetic model, ...

rhic-cent-pTsp

GLAUBER

rhic-pery-pTsp

rhic-pery-pTv2

fig1

GAUSS

Pionic HBT radii

GLAUBER GAUSS - shocking!

hbt$_r hic$

[PRL 101 (2008) 022301]

(two-particle method (as in experiment), resonances, Bowler-Sinyukov)

Why does it work?

Gausian → faster and more smooth buildup of flow, hence v_2 generated faster and one may stop the evolution at earlier times

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In essence, rather than solving we have moved the HBT puzzle to earlier stages. What is the initial condition for hydro? What happens in the partonic phase, what shape and flow is generated?
Proposal: explore the initial stage with courage!

azHBT vs. k_T

$$C(q_{\rm out}, q_{\rm side}, q_{\rm long}) = 1 + \lambda e^{-R^2_{\rm out} q^2_{\rm out} - R^2_{\rm side} q^2_{\rm side} - R^2_{\rm long} q^2_{\rm long} - R_{\rm out-side} q_{\rm out} q_{\rm side} - R_{\rm out-long} q_{\rm out} q_{\rm long} - R_{\rm side-long} q_{\rm side} q_{\rm long}}$$

$$R^2_{\rm i}(\phi) = R^2_{\rm i,0} + 2R^2_{\rm i,2}\cos(2\phi), \quad i = {\rm out, side, long}$$
$$R_{\rm out-side}(\phi) = 2R_{\rm out-side,2}\sin(2\phi),$$
$$R_{\rm out-long}(\phi) = 0, \quad R_{\rm side-long}(\phi) = 0 \quad \text{(boost invariance)}$$

fig4

azHBT vs. centrality

$0.15 < k_T < 0.25$, $0.25 < k_T < 0.35$, $0.35 < k_T < 0.6$ [GeV]

out side long

canstaraspubl$_horiz$

filled - exp., empty - model [arXiv:0808.3363]

RHIC vs. LHC

RHIC hsRHICgauss

LHC hsLHCgauss

cananat

cananat$_{a}ll$

RHIC vs. LHC, $c = 0 - 5\%$

canazhbt1

Early thermalization puzzle

fsfs

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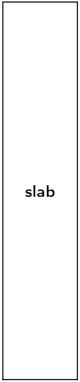
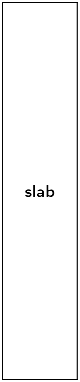
fsfs2

Free streaming + Landau matching



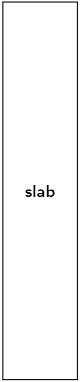
Free streaming + Landau matching



free streaming + equilibration (Landau matching) $\longrightarrow$ anisotropic flow of the fluid

driven by the gradient of density

Free streaming + Landau matching



free streaming + equilibration (Landau matching) $\rightarrow$ anisotropic flow of the fluid

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Initial flow is asymmetric! $T_{\mu\nu}u^{\nu} = \lambda g_{\mu\nu}u^{\nu}$ - Landau matching
(similar ideas in [Gyulassy, Sinyukov, Karpenko, Nazarenko, 2007])

Early thermalization puzzle

fig1fs

fig2fs

dark: f.s. from $\tau = 0.25$ fm to 1 fm, then hydro, light: hydro from $\tau = 0.25$ fm

Same results, but start of hydro comfortably delayed

Conclusion

- It is possible to fit uniformly the soft RHIC data for π, K, p, $\bar{p}$ with hydrodynamics+ stat. hadronization, provided the initial condition is somewhat sharper that the typically used Glauber profile (here Gaussian)
- This generates flow more efficiently
- Realistic equation of state, inviscid hydro, efficient solving method
- THERMINATOR and all resonances $\rightarrow$ increased HBT size
- At RHIC a "rectangular" shape of the freeze-out hypersurface, large flow, volume and surface emission almost equal, no back-flow problem
- azHBT works beautifully for side and out fluctuations, out-side correlation missed
- LHC extrapolations possible, increase initial temperature T_i. One prediction: $R_{\rm out}/R_{\rm side} < 1$
- Free streaming + Landau matching to thermalized phase allow to delay the start of hydro to realistic times. The mechanism generates the initial azimuthal asymmetry of the flow of the liquid.

Advertisement

- GLISSANDO: GLauber Initial State Simulations AND mOre ... [WB, Rybczyński, Bożek, arXiv:0710.5731] http://www.pu.kielce.pl/homepages/mryb/GLISSANDO/ (includes the eccentricity fluctuations, harmonic profiles, various Glauber models, written in ROOT), to appear in CPC