Soft probes
in relativistic heavy-ion collisions

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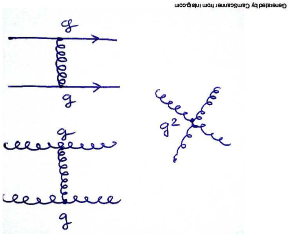
Soft physics

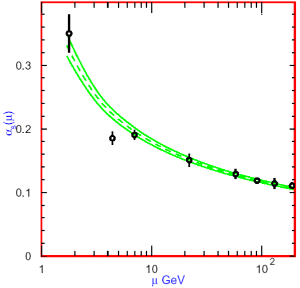
What is soft?

Soft physics

What is soft? not hard!
Small momenta exchanged, non-perturbative
Hard is easier :)

$$\alpha_s = \frac{g^2}{4\pi},\ \mu^2 = Q^2$$



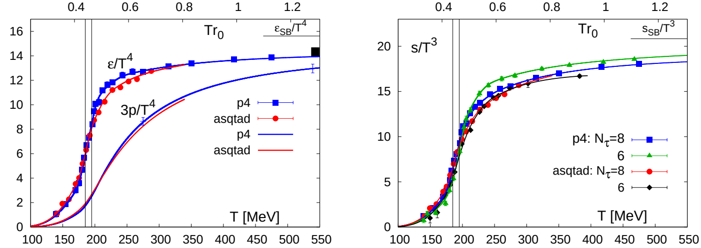


(→ asymptotic freedom)

Physics below $\mu \sim 1$ GeV is soft

QGP

At high temperatures the thermal motion is so high, that also the momenta trasferred are large. An early expectation was that weakly-interacting quark-gluon plasma (QGP) should be formed. It is not the case![1]



[Bazavov et al., PRD 80(2009)014504, arXiv:0903.4379]

QGP $\rightarrow$ sQGP – strongly interacting QGP

[1] See the discussion of flow

Reminder: Stefan-Boltzman law

(*** ***)

Thermal ideas

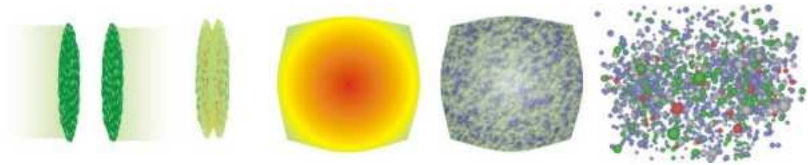
Strong (soft) interactions → so complicated that things become simple again!
It is easier for a system to reach fast the thermal equiliubrium when the interactions are strong – shorter mean free path → more collisions. How to achieve this from QCD-based approaches is a topic of current active research.

- Isotropization puzzle: how are the pressures in the longitudinal and transverse directions equilibrated
- Early thermalization puzzle: how is thermal equilibrium achieved?

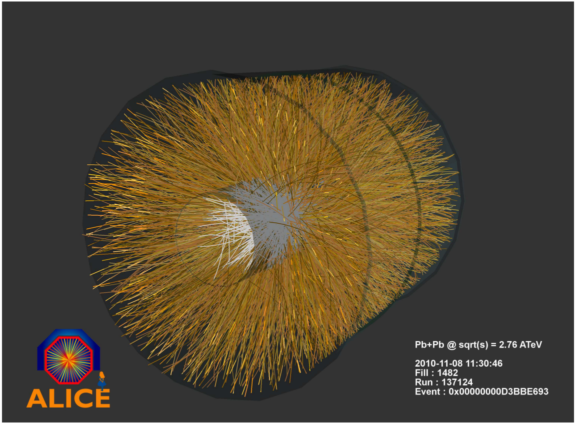
A general conviction is that at a short time of the order of 1 fm/c thermal equiliubrium in the fireball is reached.

[thermal approach: Fermi 1950, Landau 1953]

Will go backward in time



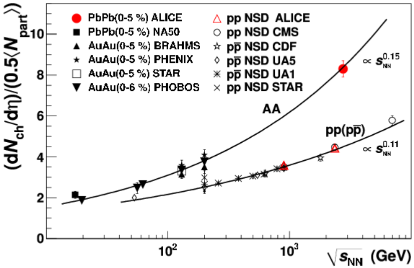
An ALICE event



In relativistic heavy-ion collisions thousands of particles are formed in a single collision

Multiplicities

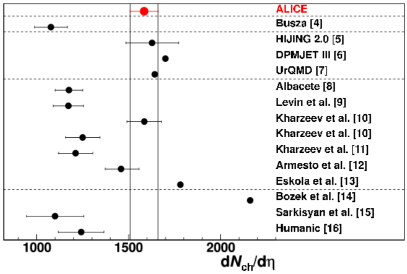
The simplest probe, growth with $\sqrt{s_{NN}}$, not superposition of p+p



[Aamodt et al. (ALICE) PRL 105(2010)252301]

– $\sqrt{s_{NN}}$ – energy per nucleon pair in the center-of-mass (CM) frame
– pseudorapidity $\eta = \frac{1}{2}\log\frac{p_\parallel + p_\perp}{p_\parallel - p_\perp} = -\log[\mathrm{tg}(\theta/2)]$, rapidity $\eta = \frac{1}{2}\log\frac{E+p_\perp}{E-p_\perp}$
– N_{part} - number of participating nucleons

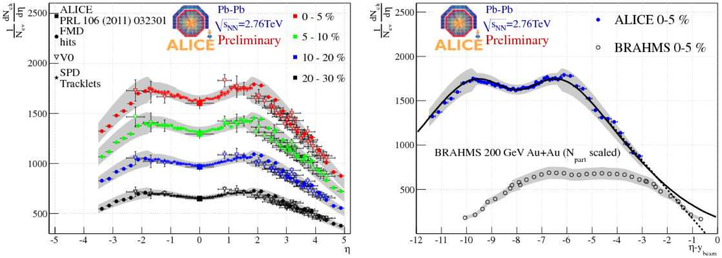
ALICE multiplicities, Pb+Pb@2.76TeV



[Aamodt et al. (ALICE) PRL 105(2010)252301]

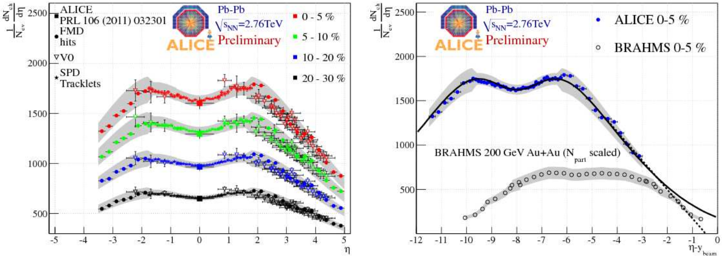
1600 of charged hadrons per unit of pseudorapidity!
(~ 2400 of all hadrons per unit of pseudorapidity)

Spectra in pseudorapidity



Kinematic range in rapidity is $y_{\mathrm{beam}} =$

Spectra in pseudorapidity



Kinematic range in rapidity is $y_{\rm beam} = \mathrm{arccos}(\sqrt{s_{NN}}/(2m_N)$ (= 8 at 2.76 TeV, =5.4 at 200 GeV)

$$y = \frac{1}{2}\log\left(\frac{\sqrt{p_t^2\cosh^2(\eta)+m^2}+p_t\sinh(\eta)}{\sqrt{p_t^2\cosh^2(\eta)+m^2}-p_t\sinh(\eta)}\right) \leq \eta,\ \frac{dy}{d\eta} = \frac{p_t}{m_t} \leq 1$$

For identified particles y is typically used. Note that η distributions are wider and lower, the central dip is of kinematic origin

Statistical (thermal) model

[Fermi,Pomeranchuk,Hagedorn,Kausta,Koch,Muller,Rafelski,Sollfrank,Heinz,Becattini,B
Munzinger,Stachel,Redlich,Cleymans,Gazdzicki,...]

Large multiplicities → statistical description – the higher collision energies, the better

By counting together all the particles we cannot obtain the temperature T, as we do not know the volume V. Idea: look at identified hadron multiplicities and take ratios to divide out V.

For the simplistic case of a static Boltzman distribution $(\hbar = k_B = c = 1)$

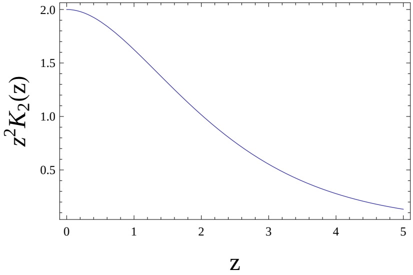
$$N = V \int \frac{d^3p}{(2\pi)^3} e^{-(E-\mu)/T} = V e^{\mu/T} \int \frac{d^3p}{(2\pi)^3} e^{-\sqrt{m^2+p^2}/T} = \frac{VT^3}{2\pi^2} e^{\mu/T} \left(\frac{m}{T}\right)^2 K_2\left(\frac{m}{T}\right)$$

In chemical equilibrium

$$\mu = B\mu_B + S\mu_S + I_3\mu_{I_3}$$

Reminder: Bessel functions

Modified Bessel function of the second kind



$$z^2 K_2(z) \sim \sqrt{\pi/2}e^{-z}z^{3/2}$$

Chemistry

For boost-invariant systems (approximately satisfied in reality) the ratio of abundances of species i and j is

$$\frac{dN_i/dy}{dN_j/dy} = \frac{N_i}{N_j} \simeq e^{(\mu_i-\mu_j)/T} \frac{m_i^2 K_2(m_i/T)}{m_j^2 K_2(m_j/T)}$$

Now we have, for instance

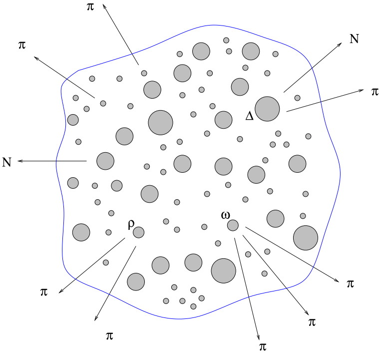
$$\frac{p}{\bar{p}} = e^{2\mu_B/T}, \; \frac{K^+}{K^-} = e^{2\mu_S/T}, \; \frac{\pi^+\pi^-}{p\,\bar{p}} = \left(\frac{m_\pi^2 K_2(m_\pi/T)}{m_p^2 K_2(m_p/T)}\right)^2$$

3 equations allow to find the thermal parameters T, μ_B, μ_S.

In practice μ_S and μ_{I_3} are determined by requiring that the strangeness of the system is zero, and the ratio of the baryon number to the electric charge densities is the same as in the colliding nuclei. Then one solves the overdetermined system of many ratios in the χ^2 sense

V should be treated as an independent parameter [Becattini, arXiv:0707.4154]

Resonance decays



Very important, 75% of pions from resonance decays

SHARE, THERMUS - publicly available codes carring out statistical hadronization

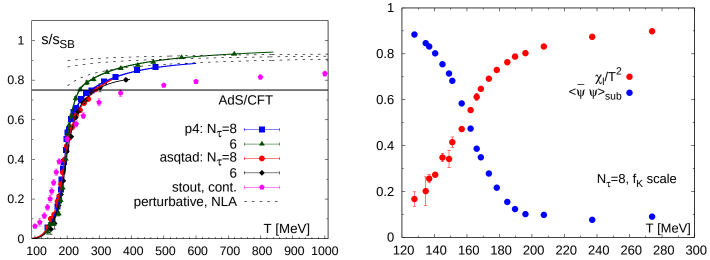
Example: Au+Au at RHIC, $\sqrt{s_{NN}} = 130$ GeV

Au+Au	model	experiment
T_{chem} [MeV]	**165±7**	
μ^B_{chem} [MeV]	**41±5**	
μ^S_{chem} [MeV]	9	
μ^I_{chem} [MeV]	-1	
χ^2/n	**0.97**	
π^-/π^+	1.02	1.00 ± 0.02 , 0.99 ± 0.02
$\overline{p}/\pi^-$	0.09	0.08 ± 0.01
K^-/K^+	0.92	0.88 ± 0.05, 0.78 ± 0.12 0.91 ± 0.09, 0.92 ± 0.06
K^-/π^-	0.16	0.15 ± 0.02
K^*_0/h^-	0.046	0.060 ± 0.012
$\overline{K^*_0}/h^-$	0.041	0.058 ± 0.012
$\overline{p}/p$	0.65	0.61 ± 0.07, 0.54 ± 0.08 0.60 ± 0.07, 0.61 ± 0.06
$\overline{\Lambda}/\Lambda$	0.69	0.73 ± 0.03
$\overline{\Xi}/\Xi$	0.76	0.82 ± 0.08

[Florkowski, WB, Michalec, Acta Phys. Polon. B33(2002)761]

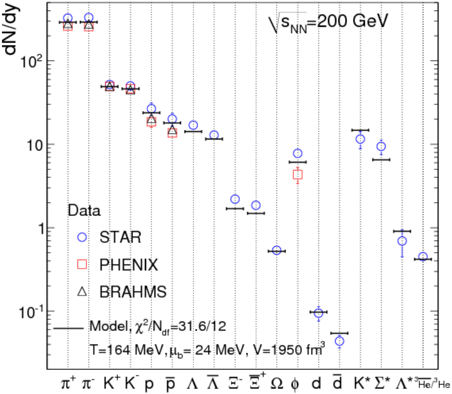
Lattice

lattice temperature of the cross-over transition $\sim 150 - 160$ MeV



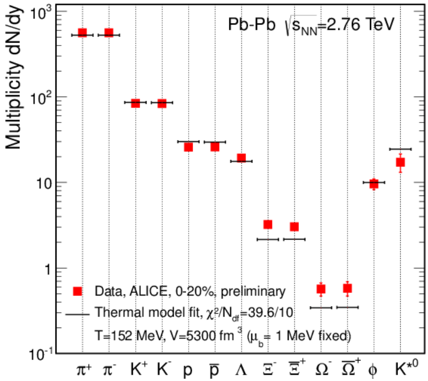
[Petreczky, J. Phys. G 39(2012)093002, arXiv:1203.5320]

RHIC success



[Andronic et al., PLB 697(2011)203, arXiv:1010.2995]

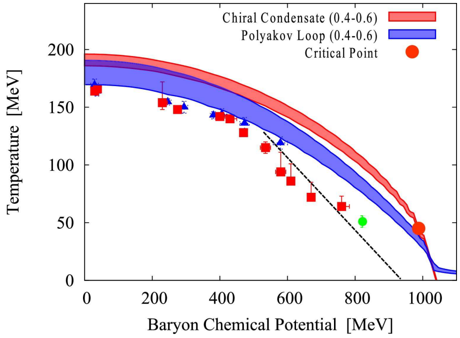
LHC "proton anomaly"



[Andronic et al., arXiv:1210.7724]

50% or so discrepancy for p and $\bar{p}$

T-μ_B plots



[Fukushima, PLB 695(2011)387]

The experimental line, which by construction must be in the hadronic phase, poses an "inner boundary" for the models of the phase transitions

Strangeness enhancement

Historically, probe of QGP
enhencement, smoking gun for QGP

Modifications

inequilibrium factors
canonical and microcanonical ansätze
excluded volume
hierarchy of freezeouts

More about resonances

resonance -> phaseshift formula, reonance approximation
Hagedorn
limiting temperature