Particle Production in Nuclear Collisions Hadronization and QCD

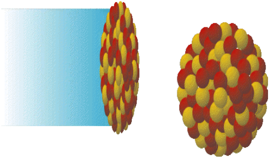
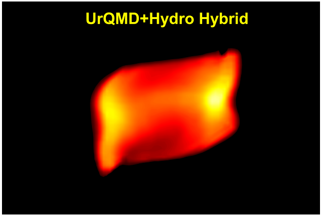
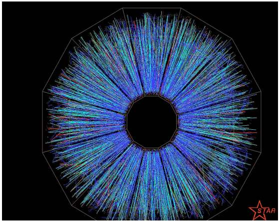
Jan Steinheimer

07/22/2014

HIC for FAIR Helmholtz International Center

FIAS Frankfurt Institute for Advanced Studies

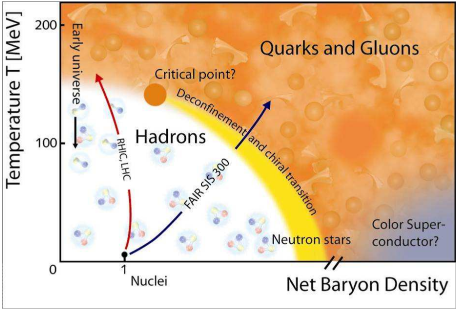
Phases of Nuclear collisions

Pre-equilibrium phase	Nearly equilibrated phase	Final stage and particle freeze-out
	 	
Equilibrating color fields.	Fluid dynamical evolution.	Hadronic freeze out.

Motivation

- Can we learn something about QCD by smashing heavy ions?

Assume a QGP is formed in relativistic HIC at the SPS, RHIC, LHC



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Main Questions for HI Physics:

[1] GSI webpage

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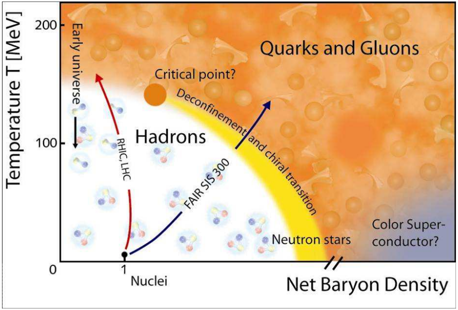

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Main Questions for HI Physics:

- What is the phase structure of QCD?
- Locate the Onset of deconfinement/hadronization!
- Is it a phase transition or crossover?
- What are the matter properties in the different phases?

[1] GSI webpage

Strangeness and Charm as probes for the QGP

The Early Idea - Strangeness

Production of (anti-)strangeness in a hadronic medium is slow, due to $m_Y >> T$.
An enhancement in nuclear collisions over p+p would indicate $s + \overline{s}$ production in a Quark Gluon Plasma.
P. Koch, B. Müller and J. Rafelski, Phys. Rept. 142, 167 (1986).

The Early Idea - Charm

Colour screening in the QGP prevents $c\overline{c}$ binding in the interaction region.
Use charm quarks as propes of the medium.
T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986).

Particle Production in High Energy Collisions

Early ideas to describe particle production in high energy collisions with statistical means goes back to the 1950's
Fermi's idea: Particles originating from an excited region evenly occupy all available phase space.

E. Fermi, Prog. Theor. Phys. **5**, 570 (1950).

Hagedorn advanced this idea with his renowned statistical bootstrap model, assuming that resonances are made of hadrons and resonances in turn.

R. Hagedorn, Nuovo Cim. Suppl. **3**, 147 (1965).

The interest in this model was also revived by the unexpected observation that it is able to accurately reproduce particle multiplicities in elementary collisions.

P. Braun-Munzinger, J. Stachel, J. P. Wessels and N. Xu, Phys. Lett. B **365**, 1 (1996)

The Statistical Hadronization Model

Starting from a (grand) canonical ensemble one can easily compute particle numbers (after decays) for any given temperature and (in the grand canonical case) chemical potential.

For the description of strangeness sometimes a factor γ_S is introduced, taking into account a possible non-equilibrium corona of the fireball.

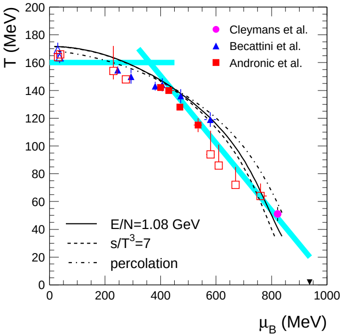
The mean primary multiplicity of the j^{th} hadron with mass m_j and spin J_j is:

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int d^3\mathrm{p}\ \gamma_S^{n_s} \left[\mathrm{e}^{\sqrt{\mathrm{p}^2+\mathrm{m_j^2}}/\mathrm{T} - \mu \cdot \mathrm{q_j}/\mathrm{T}} \pm 1 \right]^{-1} \quad (1)$$

Note: A relevant fit requires a small $\chi^2/d.o.f.$

Fit Results

Fits to several beam energies result in a freeze out curve.

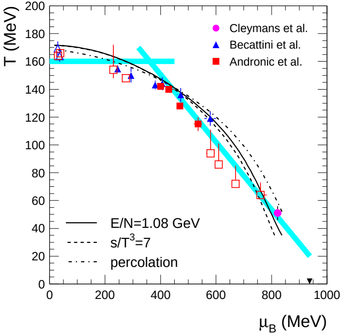


A. Andronic et al., Nucl. Phys. A 837, 65 (2010)

Fit Results

Fits to several beam energies result in a freeze out curve.

Strangeness enhancement confirmed: sets in around $\sqrt{s_{NN}} \approx 5$ GeV.



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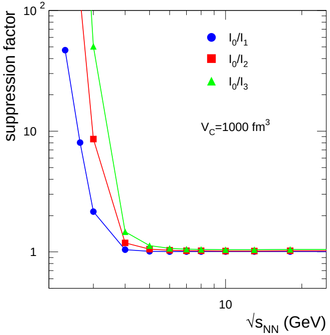

A. Andronic et al., Nucl. Phys. A 772, 167 (2006)

Fit Results

Comparing freeze out line with the lattice QCD curvature:
Sign of a problem?

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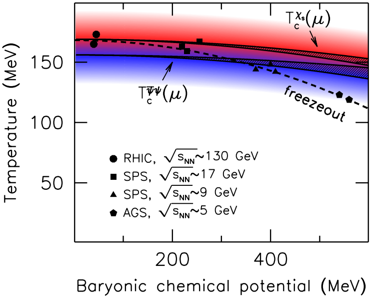
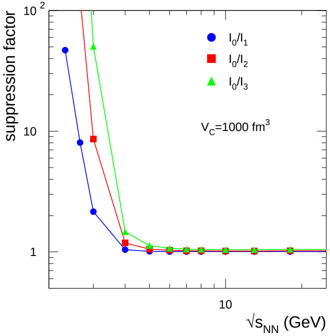


G. Endrodi et al., JHEP 1104, 001 (2011)



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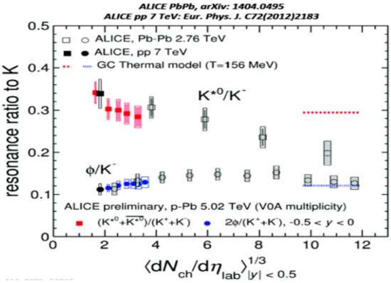
Problems of the Statistical Hadronization Model

Then come the ALICE data

Resonances show a strong centrality dependence. Rescattering!?



Problems of the Statistical Hadronization Model

F. Becattini, E. Grossi, M. Bleicher, J.S. and R. Stock, arXiv:1405.0710 [nucl-th].

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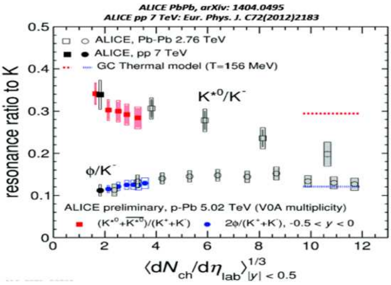
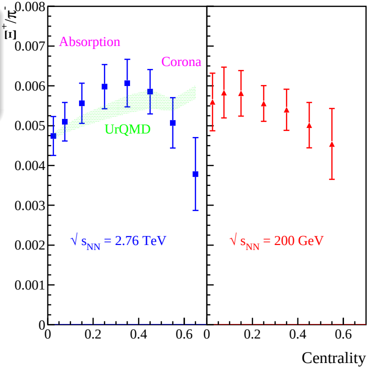
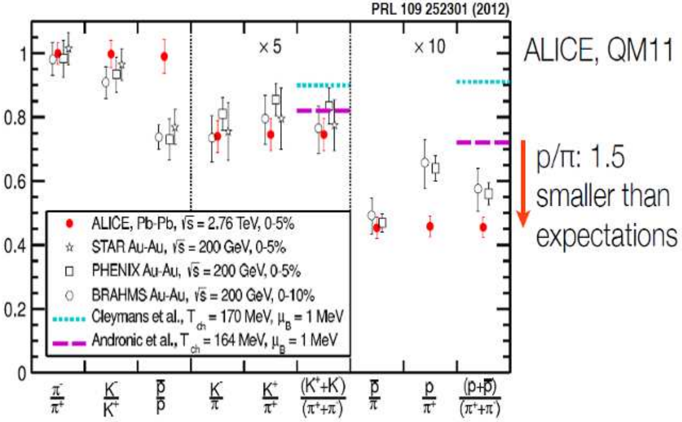




Also for multi-strange hyperons: opposite to s-enhancement idea!

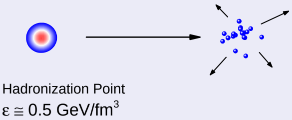
Problems of the Statistical Hadronization Model

All baryon yields are smaller than expected $\rightarrow$ smaller T_c from fit!
Curve is spoiled!



Schematic View

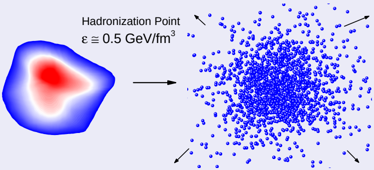
Elementary Collisions



- Hadrons are born into equilibrium.
- They are few and escape the reaction volume immediately.

F. Becattini and R. Fries, arXiv:0907.1031 [nucl-th].

Heavy Ion Collisions

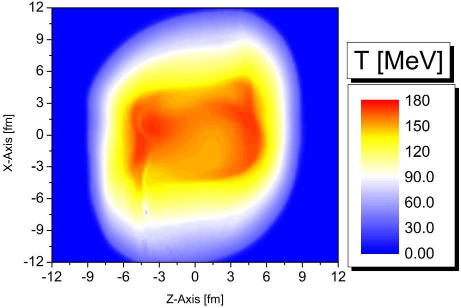


- Hadrons are born into equilibrium.
- They need more time to escape the reaction volume.
- They can undergo inelastic collisions.

The Method

Employ fluid dynamical simulation until a 'hadronization' Temperature is reached. Then produced hadrons are propagated in a transport approach based on hadron-hadron crossections.

- Hadronization at a fixed temperature, e.g. 165 MeV
- Cooper Frye Prescription $E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$



The Freeze-Out

Employ fluid dynamical simulation until a 'hadronization' Temperature is reached. Then produced hadrons are propagated in a transport approach based on hadron-hadron crossections.

- Hadronization at a fixed temperature, e.g. 165 MeV
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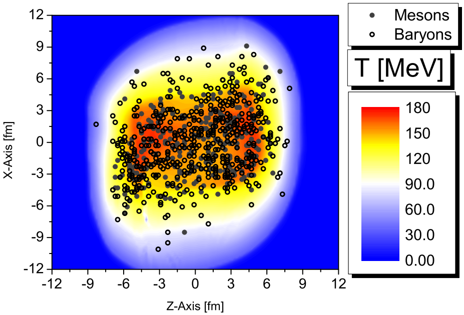
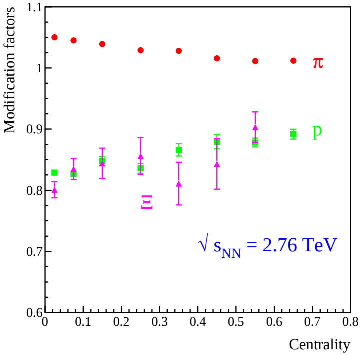


Hadrons are produced and then can rescatter according to measured crossections until they dynamically decouple.

A Solution: Hadronic Interactions

Define survival factor

$$= \frac{\text{Number of final particles}}{\text{Number of particles at hadronization}}$$



Survival factors are centrality dependent.

A Solution: Hadronic Interactions

Define survival factor

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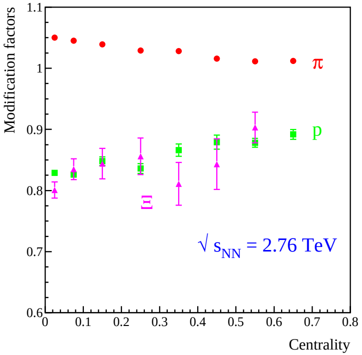
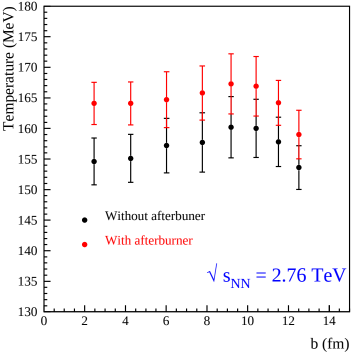
Apply to SHM

- Upward shift in T_c.





Survival factors are centrality dependent.

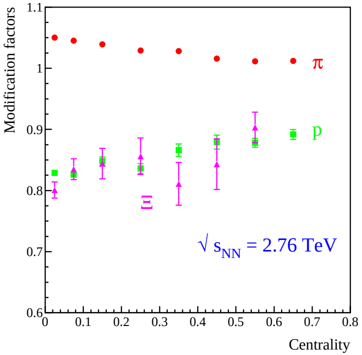
A Solution: Hadronic Interactions

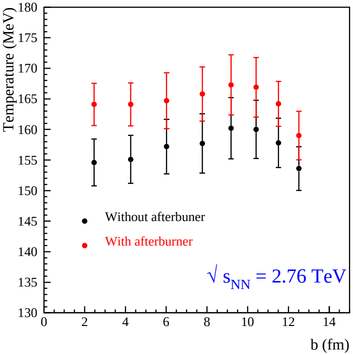
Define survival factor

$$= \frac{\text{Number of final particles}}{\text{Number of particles at hadronization}}$$

Apply to SHM

- Upward shift in T_c.
- Nice centrality dependence.





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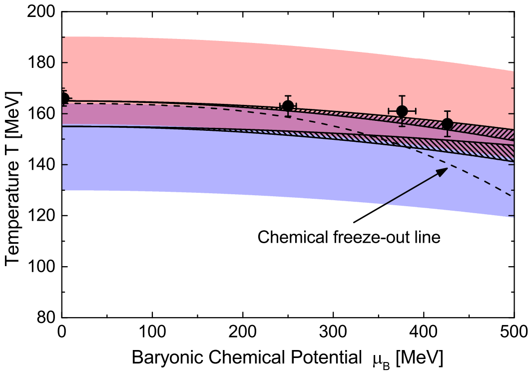
Reinvestigating the Fit

Fitting LHC and SPS data with survival factors

Revised version of the freeze out curve.



F. Becattini, M. Bleicher, T. Kollegger, T. Schuster, J.S. and R. Stock, Phys. Rev. Lett. 111, 082302 (2013)

Conclusion

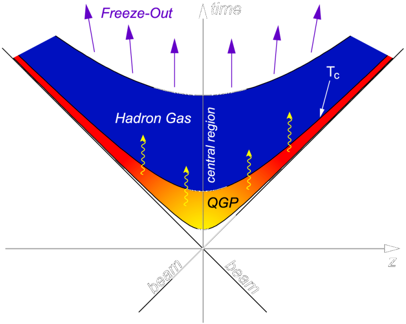
Hadron production in heavy ion collisions seems to proceed through the following steps:

- Hadronization $\rightarrow$ coincides with the crossover line. It appears to be a local equilibrium process. Hadrons are born in equilibrium.
- Expansion of Hadronic matter $\rightarrow$ inelastic hadronic collisions in an expanding system drive it out of equilibrium. Particularly baryon abundances get educed compared to their initial, equilibrium, values.
- Chemical Freeze Out $\rightarrow$ occurs when inelastic collisions cease, but this happens when the system is out of chemical equilibrium.

Lesson Learned

To understand the QGP (Hadronization) we need to understand hadronic interactions. Even at the LHC.

Charm as Probe of the QGP?



Charm is transported not produced

- Production similar to p+p (p+A?)

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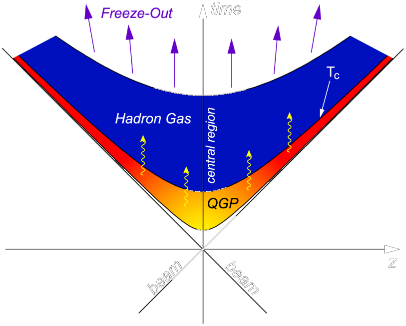

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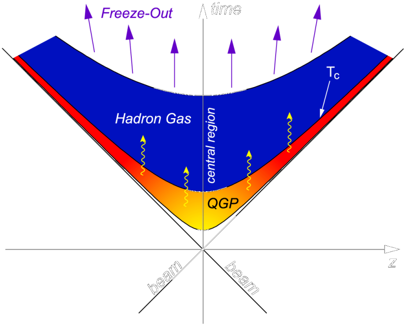


Charm is transported not produced

- Production similar to p+p (p+A?)
- Do charm quarks adopt the collective properties of the expanding QGP?
- → Model studies to learn about the QGP properties.

Charm Transport

- Again: Use fluid dynamics as background for the QGP evolution $\rightarrow$ tuned to describe the light quark sector.

Langevin approach, drag and diffusion in the medium

The propagation of the charm quarks is governed by Langevin equation:

$$\begin{aligned} dx_j &= \frac{p_j}{E} dt \\ dp_j &= -\Gamma p_j dt + \sqrt{dt} C_{jk} \rho_k \end{aligned}$$

where Γ and C_{jk} are the drag and diffusion coefficients and must be inferred from a model (resonance model or lattice QCD inspired)

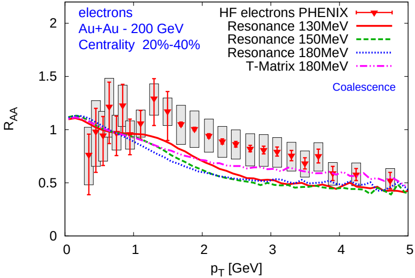
- Give us information on the medium properties.

G. D. Moore and D. Teaney, Phys. Rev. C 71, 064904 (2005)

D-Meson Transport Results

R_{AA}

Ratio of the A+A and p+p transverse spectra, scaled with the number of binary scatterings.



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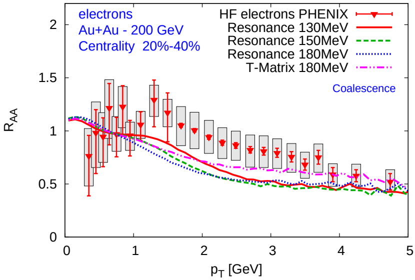
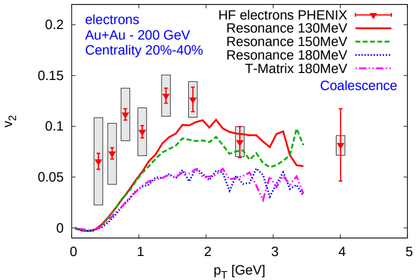
v_2

Elliptic flow: Quantifies the momentum anisotropy in the transverse plane.





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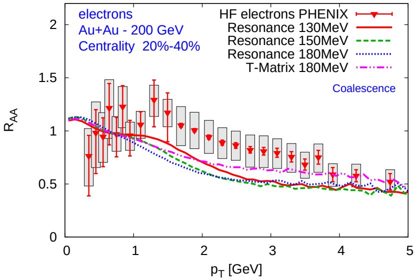

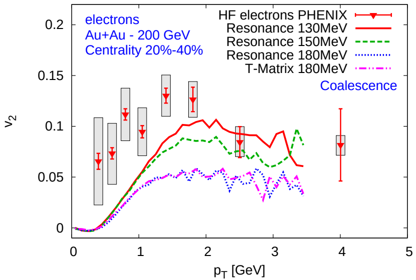

Best description for late freeze out, $T_{FO} < 130$ MeV.
Importance of hadronic rescattering of D-mesons.

Conclusions Charm

- Hydro model + Langevin transport + coalescence + low decoupling temperature seems to work for D mesons ar RHIC.
- Need to understand hadronic interactions of charmed quarks.
- Even more important for ALICE data with larger hadronic phase effects.