Chemical freeze-out conditions from strangeness observables

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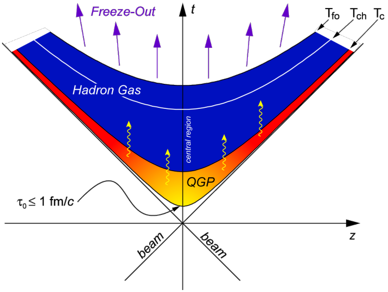
Significance of the chemical freeze-out



temporal evolution of a heavy-ion collision

simplified picture:

- after QGP phase and confinement transition, phase with hadronic interactions
- chemical freeze-out when inelastic scatterings stop $\rightarrow$ hadro-chemistry fixed!
- kinetic freeze-out when elastic scatterings cease $\rightarrow$ spectra fixed!

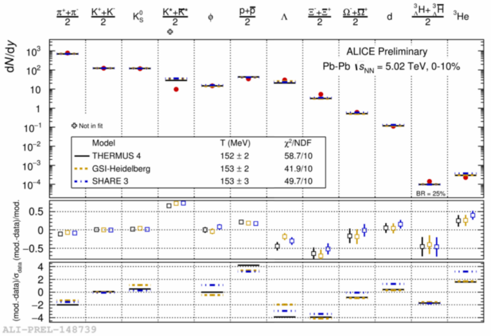
$\Rightarrow$ methods to determine chemical freeze-out conditions:

- traditionally via yields (multiplicities) and yield ratios
- alternatively via event-by-event multiplicity fluctuations

Chemical freeze-out conditions via yields

⇒ determine thermal conditions (T, μ_X) from yield ratios, volume V additionally needed for yields, via statistical hadronization model (SHM) fits

example from ALICE:



from 1808.05823

- overall satisfactory description, *p* and hyperons somewhat off!

Chemical freeze-out conditions via yields

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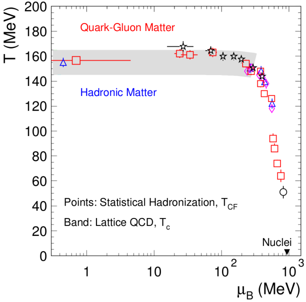
world-data analysis:



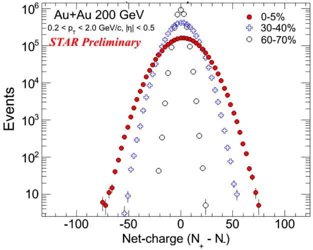
from 1710.09425

- analysis at various beam energies $\sqrt{s_{NN}}$ allows us to draw a chemical freeze-out curve

- trend: decreasing $\sqrt{s_{NN}} \rightarrow$ increasing μ_B and decreasing T

Significance of fluctuation observables

$\Rightarrow$ experimentally multiplicity fluctuations determined from event-by-event distributions



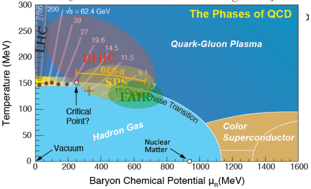
net-electric charge distributions from 1402.1558

- cumulant analysis:
  - mean: $M = \langle N \rangle = \chi_1 = C_1$
  - variance: $\sigma^2 = \langle (\Delta N)^2 \rangle = \chi_2 = C_2$
  - skewness S, kurtosis κ, ...
- net-distributions $N_+ - N_-$ often studied!
- fluctuations in conserved charges of QCD (B, S, Q) sensitive to matter composition
- requires limited phase-space acceptance!

Significance of fluctuation observables

⇒ experimentally multiplicity fluctuations determined from event-by-event distributions

[B. Müller: BEST Col. Meeting 2016]



from 1906.00936

- allows us to study the phase-structure of QCD matter!
- for a given pressure P susceptibilities follow from

$$\chi_n = VT^3 \frac{\partial^n (P/T^4)}{\partial(\mu/T)^n}$$

- volume cancels in ratios

Theoretical framework

⇒ employ a Hadron Resonance Gas (HRG) model in grand-canonical ensemble formulation

$$P = \sum_i (-1)^{B_i+1} \frac{d_i T}{(2\pi)^3} \int \mathrm{d}^3k \ln\left[1 + (-1)^{B_i+1} z_i e^{-\epsilon_i/T}\right]$$

- particle energy $\epsilon_i = \sqrt{k^2 + m_i^2}$, mass m_i, degeneracy d_i
- fugacity $z_i = e^{\mu_i/T}$ with particle chemical potential $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$ and $X_i = B_i, S_i, Q_i$ quantum numbers
- can impose physical conditions met in experiments:
  - net-strangeness neutrality $\langle n_S \rangle = 0$ and initial isospin distribution $\langle n_Q \rangle = a \langle n_B \rangle$ (Au+Au and Pb+Pb at mid-rapidity $a \simeq 0.4$) with $n_X = \sum_i X_i (\partial P/\partial \mu_i)_T$
  - phase-space acceptance limitations in k_T, y and ϕ via $\int \mathrm{d}^3k$ and $\epsilon_i = \cosh(y)\sqrt{k_T^2 + m_i^2}$
- sum over all included PDG particles 319 confirmed (2012) or 738 species (2016)

⇒ analyzed experimental data from STAR at RHIC!

Role of resonance decays

- net-kaon or net-proton numbers not conserved charges
- resonance decays can significantly modify final particle multiplicity distributions:
  $N_j = N_j^* + \sum_R N_R^* \langle n_j \rangle_R$ with N_j^* directly produced hadrons, $\langle n_j \rangle_R$ associated with branching ratios b_r^R
- event-by-event fluctuations arise from:
  - thermal fluctuations in N_j^* and N_R^*
  - probabilistic character of the decay process (b_r^R only means!)

explicit example for net-kaon number $M_K = M_{K^+} - M_{K^-}$:

$$\text{mean: } M_j = \langle N_j^* \rangle_T + \sum_R \langle N_R^* \rangle_T \langle n_j \rangle_R$$

$$\begin{aligned}\text{variance: } \sigma_K^2 = & \langle (\Delta N_{K^+}^*)^2 \rangle_T + \langle (\Delta N_{K^-}^*)^2 \rangle_T + \sum_R \langle (\Delta N_R^*)^2 \rangle_T \left(\langle n_{K^+} \rangle_R^2 + \langle n_{K^-} \rangle_R^2 \right) \\ & - 2 \sum_R \langle (\Delta N_R^*)^2 \rangle_T \langle n_{K^+} \rangle_R \, \langle n_{K^-} \rangle_R - 2 \sum_R \langle N_R^* \rangle_T \langle \Delta n_{K^+} \Delta n_{K^-} \rangle_R \\ & + \sum_R \langle N_R^* \rangle_T \left(\langle (\Delta n_{K^+})^2 \rangle_R + \langle (\Delta n_{K^-})^2 \rangle_R \right)\end{aligned}$$

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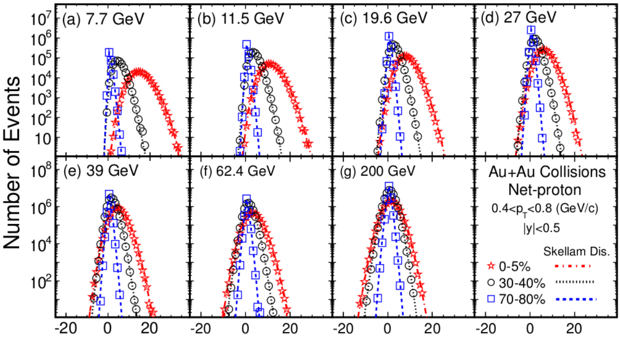
explicit example for net-kaon number $M_K = M_{K^+} - M_{K^-}$:

- resonance decays cause correlation terms
- approach allows for a proper inclusion of $N(1650)$ or $\Xi(1690)^-$ (not just derivatives w.r.t. μ_S!)
- only thermal averages $\langle \cdot \rangle_T$ can be obtained from HRG model via derivatives, i.e. via χ_n

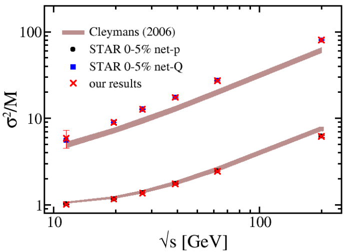
Freeze-out conditions via net-p and net-Q fluctuations

⇒ analyze lowest-order net-p and net-Q fluctuations for most central collisions simultaneously to determine chemical freeze-out conditions!

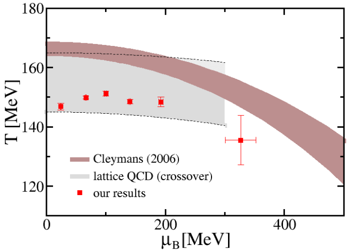


net-p distributions from 1309.5681

Freeze-out conditions via net-p and net-Q fluctuations



from 1403.4903



from 1403.4903

- theoretical approach takes into account strong resonance decays, acceptance cuts, physical side conditions, radial flow and isospin randomization
- qualitative behavior of net-Q fluctuations dominated by π and p
- freeze-out T significantly below SHM fit results
- particle ratios at $\sqrt{s} = 200$ GeV well described except for hyperon to pion ratios!

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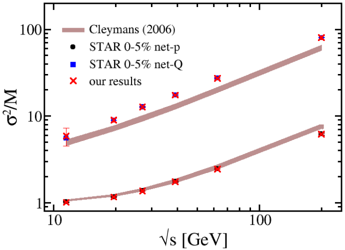

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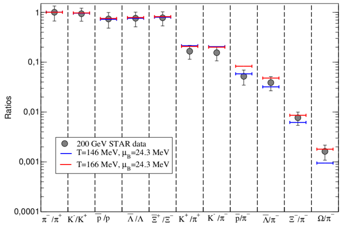

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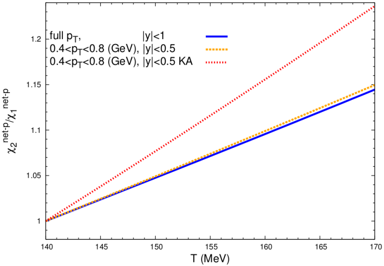
Impact of isospin randomization processes

reactions of the form

$$p(n) + \pi^0(\pi^+) \rightarrow \Delta^+ \rightarrow n(p) + \pi^+(\pi^0)$$

modify primordial protons into undetected neutrons

$\Rightarrow$ isospin of nucleons randomized after 2 cycles; depends on pion density and duration of hadronic phase compared to time for resonance regeneration plus decay



for $\mu_B = 0$ from 1504.03262

- KA-effect can be taken into account 1107.2755, 1205.3292
- can cause up to $5-10\%$ deviations in lowest-order fluctuations
- was essential for the determination of freeze-out conditions from net-*p* and net-*Q* fluctuations!

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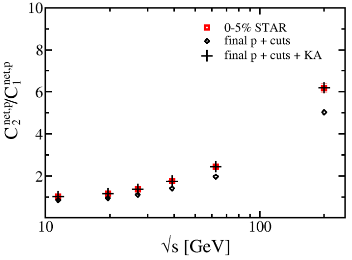

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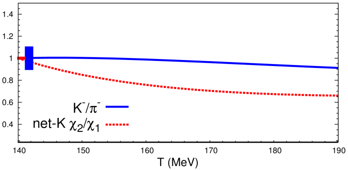
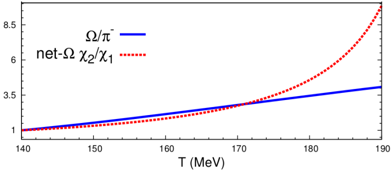
Sensitivity - fluctuations vs. yields

⇒ higher-order cumulants of particle multiplicity distributions more sensitive to thermal conditions than particle yield ratios for certain final state hadrons 1504.03262



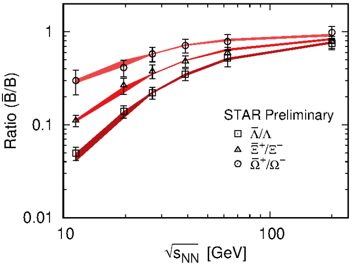
for $\mu_B = 0$



for $\mu_B = 0$

- net-kaon σ_K^2 / M_K sensitivity resolves experimentally achievable accuracy! $\rightarrow$ reliable determination of freeze-out conditions!
- motivates the use of net-kaon fluctuations!
- (anti-)hyperon sensitivity indifferent!

Data analysis - yield ratios

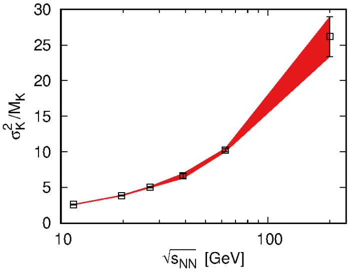


data from nucl-ex/0606014; 1010.0142; and preliminary data from CPOD 2013, 036 (2013)

- anti-hyperon–hyperon ratio $\bar{B}/B$ for Λ, Ξ^- and Ω^- from ϕ- and k_T-integrated yields for given Δy-window
- significant contributions from strong resonance decays
- for Λ electromagnetic decay contributions from Σ^0
- preliminary data on $\bar{B}/B$ confirmed recently 1906.03732

$\Rightarrow$ heavier (anti-)hyperons add some sensitivity to the determination of T, lighter (anti-)hyperons influence stronger μ_B

Data analysis - net-kaon fluctuations



data from 1709.00773

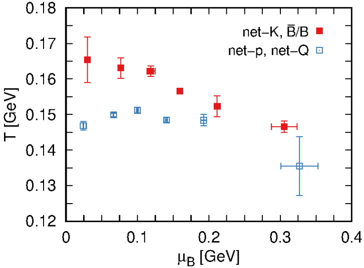
- lowest-order net-kaon fluctuations σ_K^2 / M_K
- data corrected for detector efficiency and centrality bin width
- systematic errors taken into account in the analysis
- acceptance limitations: $0.2 \leq k_T / (\mathrm{GeV/c}) \leq 1.6$ and $|y| \leq 0.5$ with full azimuthal coverage

$\Rightarrow$ significant correlations between K^+ and K^- arise from strong resonance decays

$\Rightarrow$ determination of chemical freeze-out temperature sensitively influenced by net-kaon fluctuation data

Chemical freeze-out conditions

$\Rightarrow$ conditions for T and μ_X determined from a combined analysis (optimal fits) of $\bar{B}/B$-ratios and net-kaon fluctuations σ_K^2/M_K



from 1806.04499

- T and μ_B from strangeness observables
  $\sqrt{s_{NN}}$/GeV= 200, 62.4, 39, 27, 19.6, 11.5 left to right
- error bars from bands in fits
- T and μ_B from net-p and net-Q fluctuations
- significant difference in T for large $\sqrt{s_{NN}}$, approaching each other with decreasing $\sqrt{s_{NN}}$

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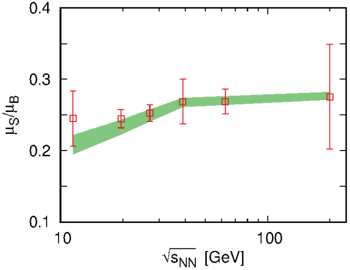
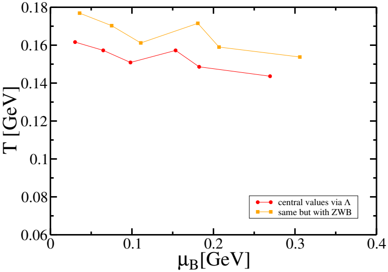


from 1806.04499

- $\mu_Q/\mu_B \lesssim 0$
- strangeness neutrality requires sizeable μ_S/μ_B
- μ_S/μ_B from strangeness observables
- μ_S/μ_B from lattice QCD (Taylor expansion)
- agreement shows impact of unconfirmed strange sector particles in HRG model

Improper inclusion of resonance decays

- probabilistic character of resonance decays (ZWB) has non-negligible effect on the results!



exemplary study with and without ZWB

- means unaffected, only σ_K^2 influenced
- combined analysis of $\bar{B}/B$ and σ_K^2/M_K data yields 5% reduction in T and up to 18% reduction in μ_B when ignoring probabilistic contributions!
- consequence of missing correlations between K^+ and K^-

Limitations of the approach

- shown error bars base entirely on systematic errors in the analyzed data!
- theoretical uncertainties may stem from:
  - ⇒ regeneration and subsequent decay of K^* resonances not taken into account - isospin randomization effect on net-kaon fluctuations

    requires large pion density and long hadronic stage!
  - ⇒ exact global charge conservation on an event-by-event basis not taken into account

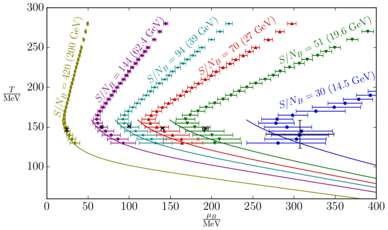
    makes canonical ensemble formulation necessary!
  - ⇒ fluctuations in the number of participants for a given centrality class not taken into account

    stronger for higher-order fluctuations and smaller beam energies!
  - ⇒ resonance decays and elastic scatterings in and out of acceptance window not taken into account

    earlier estimates indicate rather small impact!

Complementary approach

$\Rightarrow$ analysis of lowest-order net-kaon fluctuations supplemented by information on isentropic trajectories from lattice QCD



from 1607.02493

- isentropic fireball evolution for $\langle S/N_B \rangle = \text{const.}$
- suitable trajectories for given $\sqrt{s_{NN}}$ determined via freeze-out conditions from net-p and net-Q fluctuations

Complementary approach

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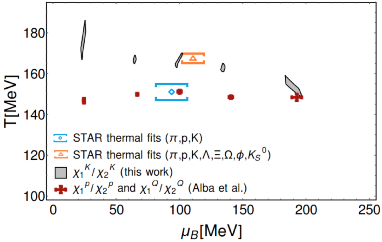

from 1805.00088

- determined freeze-out conditions overlap within errors with 1806.04499 indicating similar spread and convergence
- still, systematically larger in T and smaller in μ_B
- show agreement with SHM fits to yields

Conclusions

- determination of chemical freeze-out conditions from strangeness observables at different $\sqrt{s_{NN}}$ within HRG model
- analyzed lowest-order net-kaon fluctuations and anti-hyperon to hyperon yield ratios from RHIC simultaneously
- in general fluctuations more sensitive to freeze-out conditions than yields and/or their ratios 1504.03262
- freeze-out T and μ_B significantly enhanced compared to results from an analysis of net-p and net-Q fluctuations 1403.4903, 1806.04499
- with increasing $\sqrt{s_{NN}}$ results from both analyses converge
- freeze-out conditions from strangeness observables compatible with SHM fits to hadron yields
- qualitative agreement with results of complementary approach using lattice QCD isentropes 1805.00088