Reduction of K* meson abundance and kinetic freeze-out conditions in heavy ion collisions

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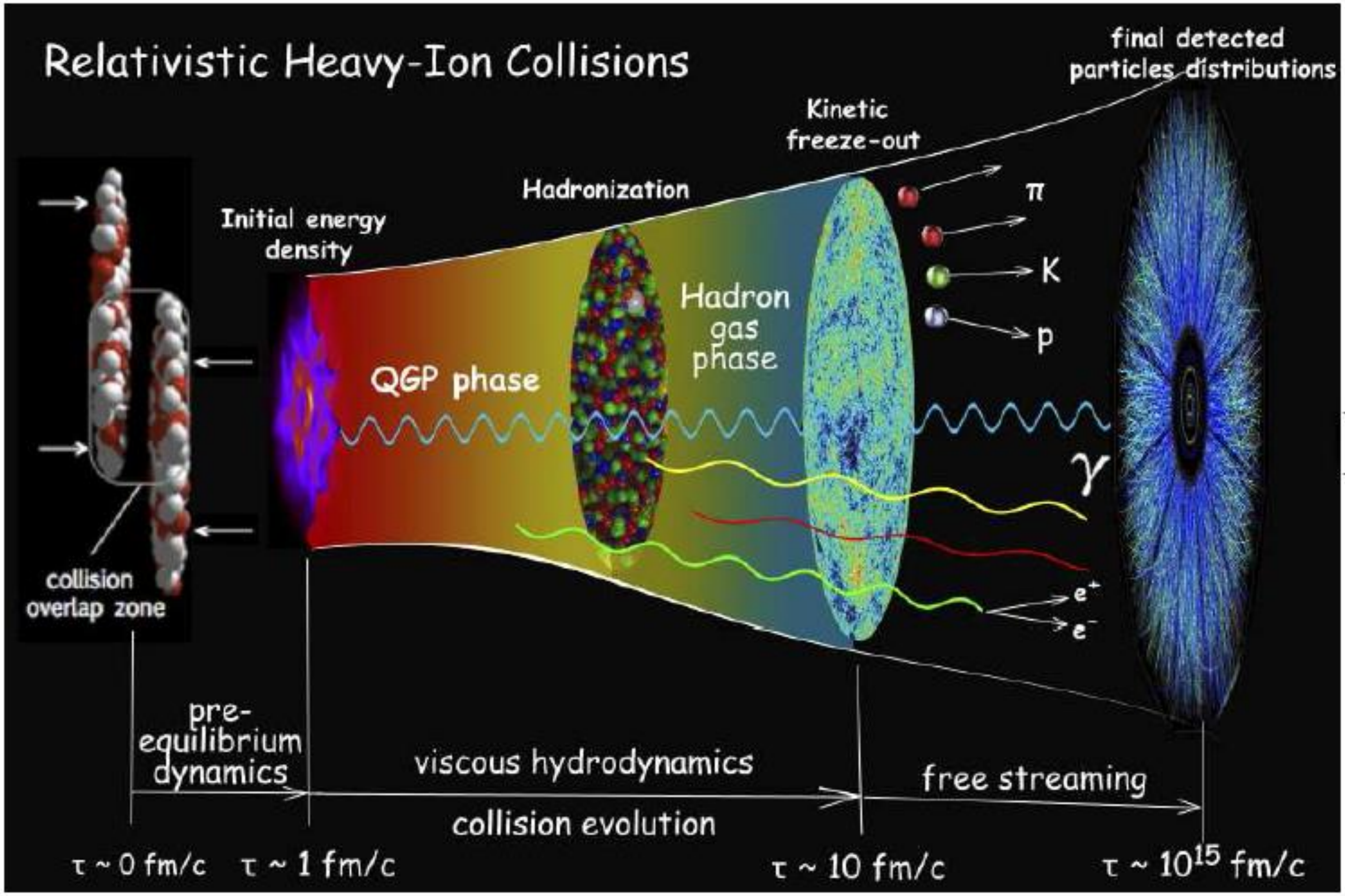
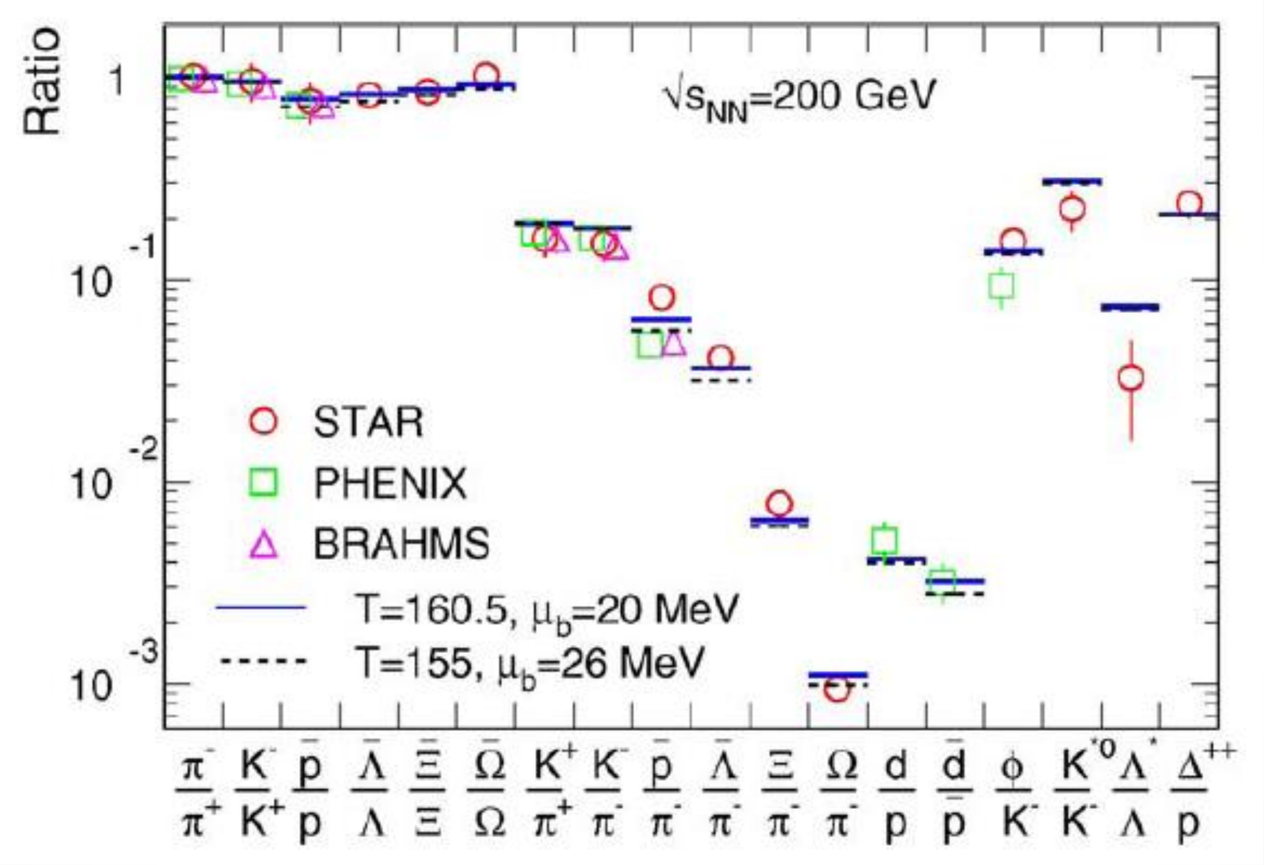
S. Cho, S. –H. Lee, arXiv : 1509.04092
S. Cho, T. Song, S. –H. Lee, arXiv : 1511.08019

Introduction



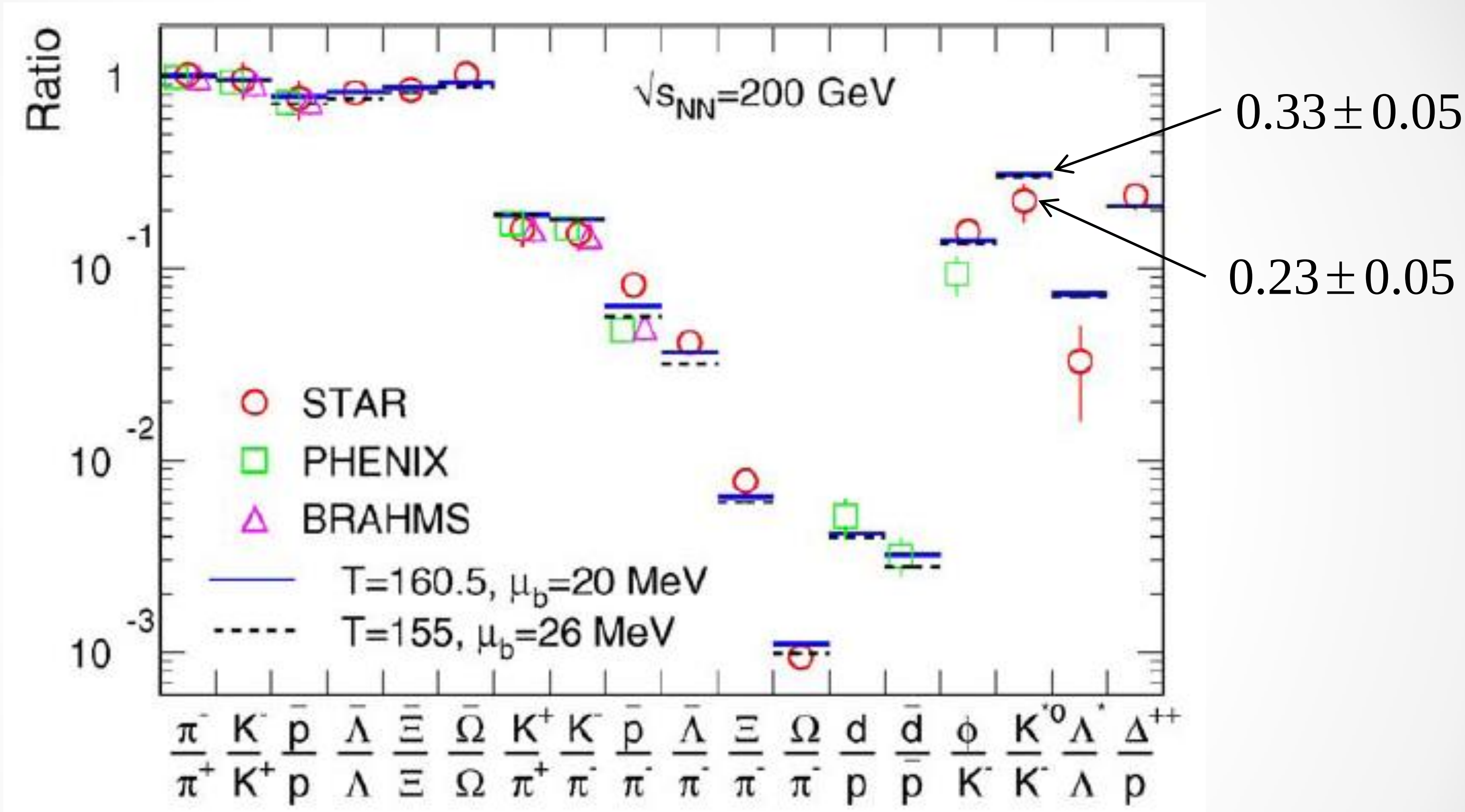
U. W. Heinz, J. Phys. Conf. Ser. **455**, 012044 (2013)

– Particle yield ratios at RHIC



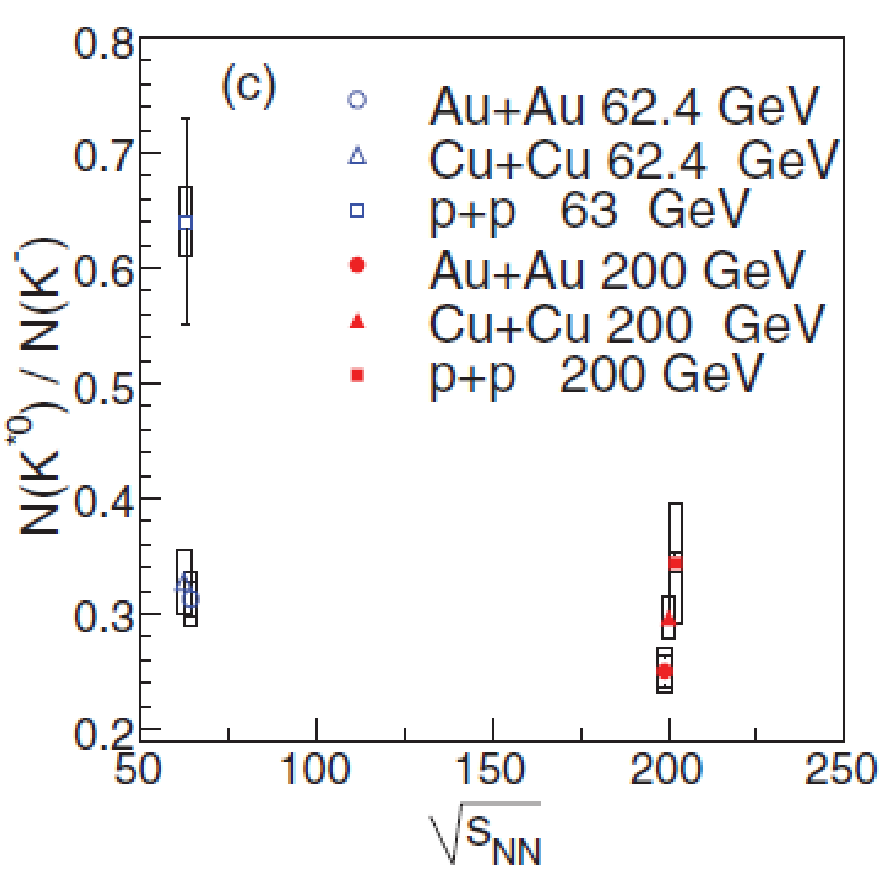
A. Andronic, P. Braun-Munzinger, and J. Stachel, Nucl. Phys. A **772**, 167 (2006)

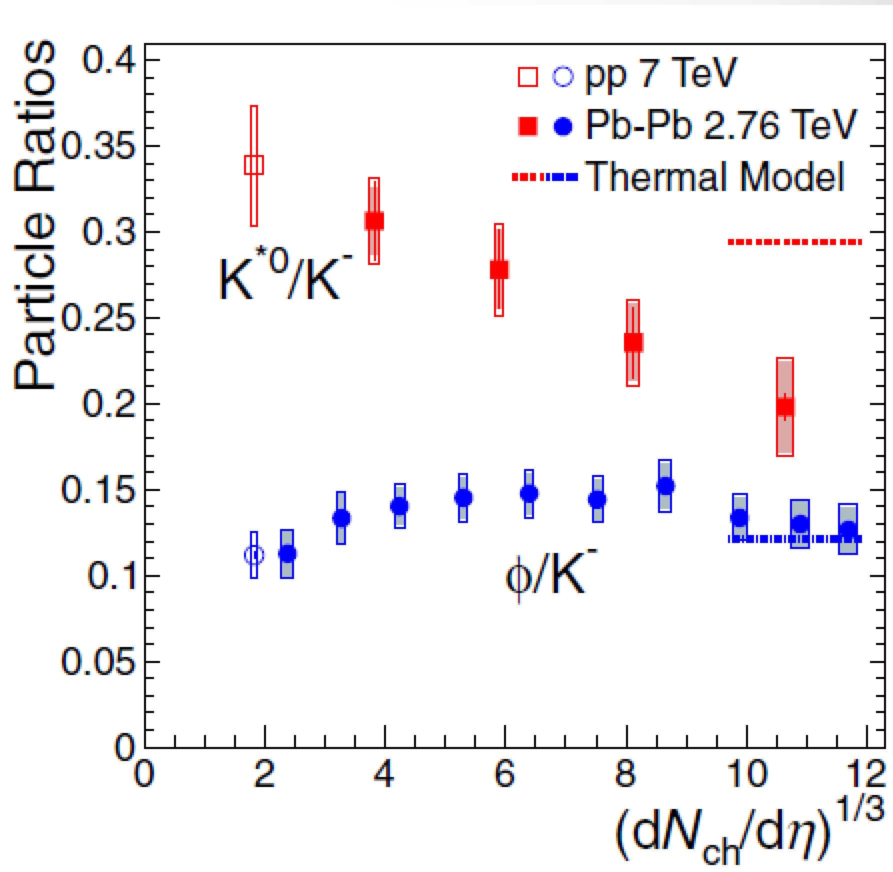
– Particle yield ratios at RHIC



A. Andronic, P. Braun-Munzinger, and J. Stachel, Nucl. Phys. A **772**, 167 (2006)
P. Braun-Munzinger, D. Magestro, K. Redlich, and J. Stachel, Phys. Lett. B **518**, 41 (2001)
J. .Adams, et al. (STAR Collaboration). Phys. Rev. C **71**, 064902 (2005)

– K* mesons in heavy ion collisions



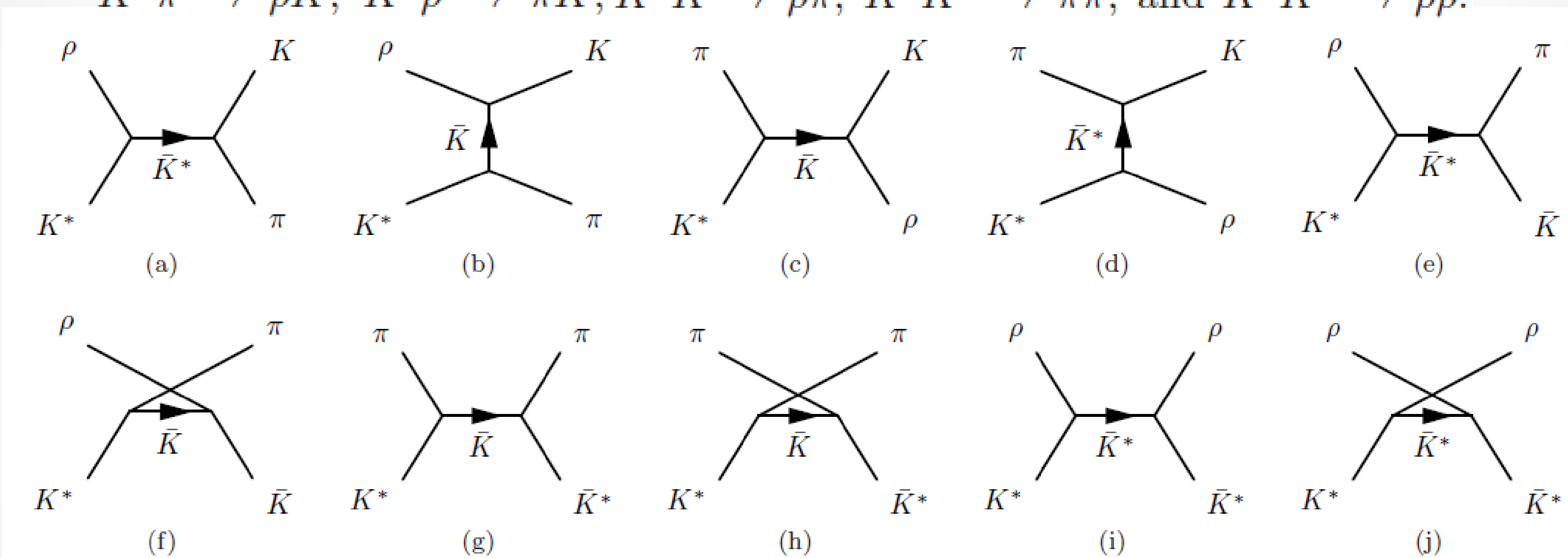


M. M. Aggarwal et al, [STAR Collaboration], Phys. Rev. C **84**, 034909 (2011)
B. Abelev et al. [ALICE Collaboration], Phys. Rev. C **91**, 024609 (2015)

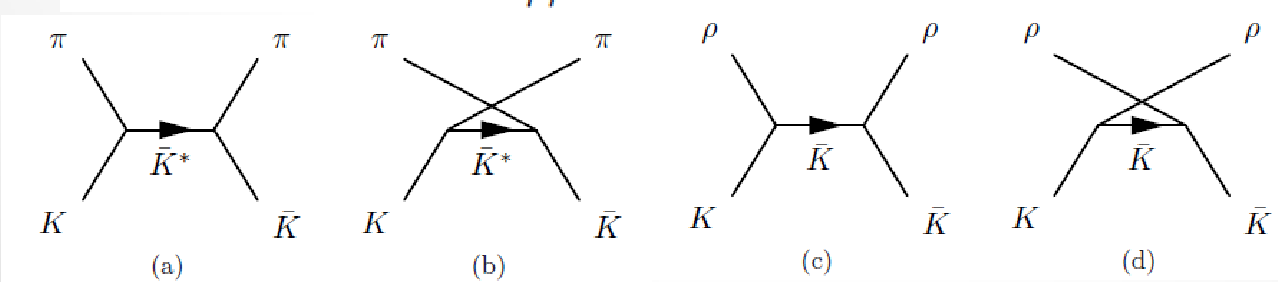
Hadronic interactions

– K* meson and kaon interactions

$K^*\pi \to \rho K,\ K^*\rho \to \pi K, K^*\bar{K} \to \rho\pi,\ K^*\bar{K}^* \to \pi\pi,$ and $K^*\bar{K}^* \to \rho\rho.$



$K\bar{K} \to \pi\pi$ and $K\bar{K} \to \rho\rho.$



1) K* meson production from kaons and pions & K* meson decay to kaons and pions

$$\sigma_{K\pi\to K^*} = \frac{g_{K^*}}{g_K g_\pi}\frac{4\pi}{p_{cm}^2}\frac{s\Gamma^2_{K^*\to K\pi}}{(m_{K^*}-\sqrt{s})^2+s\Gamma^2_{K^*\to K\pi}}, \quad \Gamma_{K^*\to K\pi}(\sqrt{s}) = \frac{g^2_{\pi K^* K}}{2\pi s}p^3_{cm}(\sqrt{s}),$$

2) Rate equations for K* & K meson abundances

$$\begin{aligned}
\frac{dN_{K^*}(\tau)}{d\tau} =& \langle\sigma_{K\rho\to K^*\pi}v_{K\rho}\rangle n_\rho(\tau)N_K(\tau) - \langle\sigma_{K^*\pi\to K\rho}v_{K^*\pi}\rangle n_\pi(\tau)N_{K^*}(\tau) + \langle\sigma_{K\pi\to K^*\rho}v_{K\pi}\rangle n_\pi(\tau)N_K(\tau)\\
&- \langle\sigma_{K^*\rho\to K\pi}v_{K^*\rho}\rangle n_\rho(\tau)N_{K^*}(\tau) + \langle\sigma_{\rho\pi\to K^*\bar{K}}v_{\rho\pi}\rangle n_\pi(\tau)N_\rho(\tau) - \langle\sigma_{K^*\bar{K}\to\rho\pi}v_{K^*\bar{K}}\rangle n_K(\tau)N_{K^*}(\tau)\\
&+ \langle\sigma_{\pi\pi\to K^*\bar{K}^*}v_{\pi\pi}\rangle n_\pi(\tau)N_\pi(\tau) - \langle\sigma_{K^*\bar{K}^*\to\pi\pi}v_{K^*\bar{K}^*}\rangle n_{\bar{K}^*}(\tau)N_{K^*}(\tau) + \langle\sigma_{\rho\rho\to K^*\bar{K}^*}v_{\rho\rho}\rangle n_\rho(\tau)N_\rho(\tau)\\
&- \langle\sigma_{K^*\bar{K}^*\to\rho\rho}v_{K^*\bar{K}^*}\rangle n_{K^*}(\tau)N_{K^*}(\tau) + \langle\sigma_{\pi K\to K^*}v_{\pi K}\rangle n_\pi(\tau)N_K(\tau) - \langle\Gamma_{K^*}\rangle N_{K^*}(\tau),
\end{aligned}$$

$$\begin{aligned}
\frac{dN_K(\tau)}{d\tau} =& \langle\sigma_{\pi\pi\to K\bar{K}}v_{\pi\pi}\rangle n_\pi(\tau)N_\pi(\tau) - \langle\sigma_{K\bar{K}\to\pi\pi}v_{K\bar{K}}\rangle n_{\bar{K}}(\tau)N_K(\tau) + \langle\sigma_{\rho\rho\to K\bar{K}}v_{\rho\rho}\rangle n_\rho(\tau)N_\rho(\tau)\\
&- \langle\sigma_{K\bar{K}\to\rho\rho}v_{K\bar{K}}\rangle n_{\bar{K}}(\tau)N_K(\tau) + \langle\sigma_{K^*\pi\to K\rho}v_{K^*\pi}\rangle n_\pi(\tau)N_{K^*}(\tau) - \langle\sigma_{K\rho\to K^*\pi}v_{K\rho}\rangle n_\rho(\tau)N_K(\tau)\\
&+ \langle\sigma_{K^*\rho\to K\pi}v_{K^*\rho}\rangle n_\rho(\tau)N_{K^*}(\tau) - \langle\sigma_{K\pi\to K^*\rho}v_{K\pi}\rangle n_\pi(\tau)N_K(\tau) + \langle\sigma_{\rho\pi\to K^*\bar{K}}v_{\rho\pi}\rangle n_\pi(\tau)N_\rho(\tau)\\
&- \langle\sigma_{K^*\bar{K}\to\rho\pi}v_{K^*\bar{K}}\rangle n_{\bar{K}}(\tau)N_{K^*}(\tau) + \langle\Gamma_{K^*}\rangle N_{K^*}(\tau) - \langle\sigma_{\pi K\to K^*}v_{\pi K}\rangle n_\pi(\tau)N_K(\tau).
\end{aligned}$$

– The abundance ratio of K* mesons to kaon in heavy ion collisions

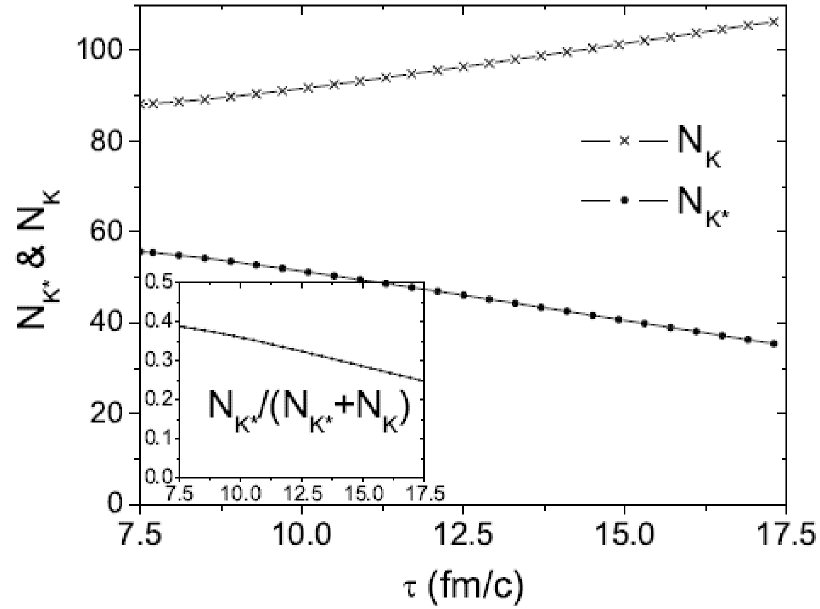
1) Simplified rate equations

$$\frac{dN_{K^*}(\tau)}{d\tau} = \gamma_K N_K(\tau) - \gamma_{K^*} N_{K^*}(\tau),$$

$$\frac{dN_K(\tau)}{d\tau} = -\gamma_K N_K(\tau) + \gamma_{K^*} N_{K^*}(\tau),$$

$$\gamma_{K^*} = \langle \sigma_{K^*\rho\to K\pi} v_{K^*\rho} \rangle n_\rho + \langle \sigma_{K^*\pi\to K\rho} v_{K^*\pi} \rangle n_\pi + \langle \Gamma_{K^*} \rangle,$$

$$\gamma_K = \langle \sigma_{K\pi\to K^*\rho} v_{K\pi} \rangle n_\pi + \langle \sigma_{K\rho\to K^*\pi} v_{K\rho} \rangle n_\rho + \langle \sigma_{K\pi\to K^*} v_{K\pi} \rangle n_\pi.$$

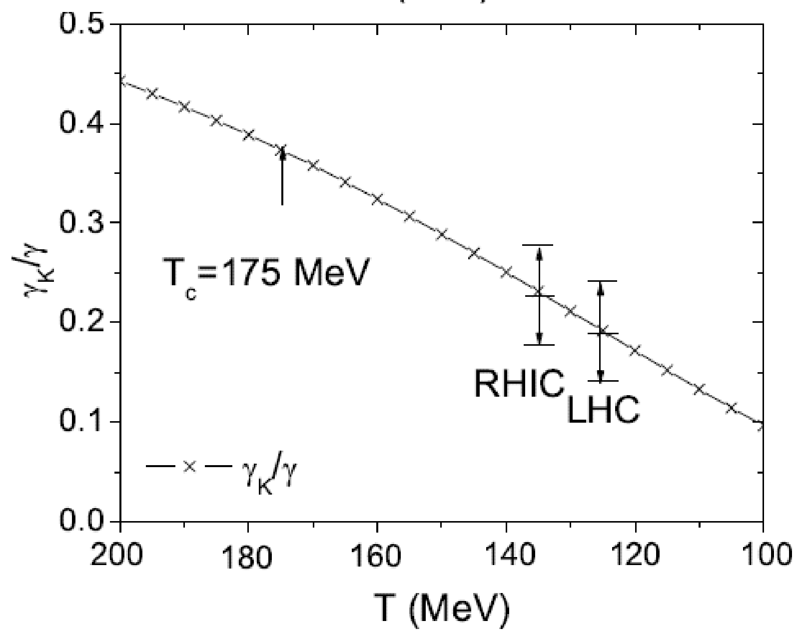


2) K* and K meson abundances

$$N_{K^*}(\tau) = \frac{\gamma_K}{\gamma} N^0 + \left(N^0_{K^*} - \frac{\gamma_K}{\gamma} N^0\right) e^{-\gamma(\tau-\tau_h)},$$

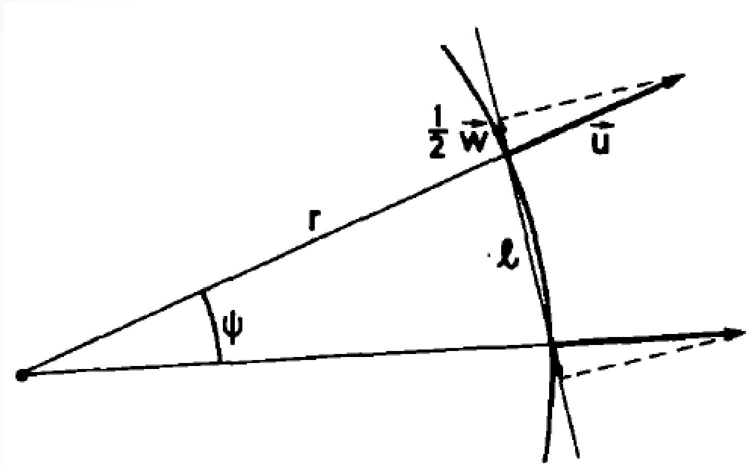
$$N_K(\tau) = \frac{\gamma_{K^*}}{\gamma} N^0 + \left(N^0_K - \frac{\gamma_{K^*}}{\gamma} N^0\right) e^{-\gamma(\tau-\tau_h)},$$

$$R(\tau) = \frac{N_{K^*}(\tau)}{N_{K^*}(\tau) + N_K(\tau)} = \frac{N_{K^*}(\tau)}{N^0} = \frac{\gamma_K}{\gamma} + \left(\frac{N^0_{K^*}}{N^0} - \frac{\gamma_K}{\gamma}\right) e^{-\gamma(\tau-\tau_h)}.$$



Freeze-out conditions in heavy ion collisions

– Geometrical concept of the freeze-out



$$w(r,t) = \frac{l(r,t)}{r}\,u(r,t)$$

$$w(r,t_b) = v(r,t_b).$$

J. P. Bondorf, S. I. A. Garpman, J. Zimanyi, Nucl. Phys. A **296**, 320 (1978)

The freeze-out criterion : the time for a macroscopic flow element is equal to the microscopic interaction time which is a function of local density, mean speed, and cross sections

– The kinetic freeze-out condition

1) The scattering time = the expansion time

$$\tau_{exp} = \frac{1}{\partial \cdot u} = \tau^{i}_{scatt} = \frac{1}{\sum_j \langle \sigma_{ij} v_{ij} \rangle n_j}$$

2) The kinetic freeze-out condition for a spherically expanding fireball with its radius R : $dR/dt \approx \langle v \rangle$

F. Becattini, M. Bleicher, E. Grossi, J. Steinheimer, and R. Stock, Phys. Rev. C **90**, 054907(2014)

$$\tau_{\exp} = \frac{V}{dV/dt} = \frac{R}{3dr/dt}$$

$$\frac{N}{R^2_{fo}} = \frac{4\pi}{\sigma_{fo}} \qquad \frac{N}{R^3_{fo}} = \left(\frac{4\pi}{\sigma_{fo}}\right)^{3/2} \frac{1}{N^{1/2}}.$$

For higher collisions energies and/or when the initial temperature and/or the number of particles increases, the 3-dimentional density at which freeze-out takes place becomes smaller

– Hadronic effects on the K* meson abundance and kinetic freeze-out condition

1) Rate equations for the abundances of K* and K mesons

$$\frac{dN_{K*}(\tau)}{d\tau} = \frac{1}{\tau_{scatt}^{K}} N_K(\tau) - \frac{1}{\tau_{scatt}^{K*}} N_{K*}(\tau),$$
$$\frac{dN_K(\tau)}{d\tau} = \frac{1}{\tau_{scatt}^{K*}} N_{K*}(\tau) - \frac{1}{\tau_{scatt}^{K}} N_K(\tau),$$

with $1/\tau_{scatt}^{K*} = \sum_i \langle \sigma_{K^*i} v_{K^*i} \rangle n_i, \; 1/\tau_{scatt}^{K} = \sum_j \langle \sigma_{Kj} v_{Kj} \rangle n_j.$

2) The yield ratio between K* mesons and kaons

$$R(\tau) = R_0 + \left(\frac{N_{K*}^0}{N^0} - \frac{\tau_{scatt}}{\tau_{scatt}^{K}} \right) e^{-\frac{\tau - \tau_h}{\tau_{scatt}}}.$$

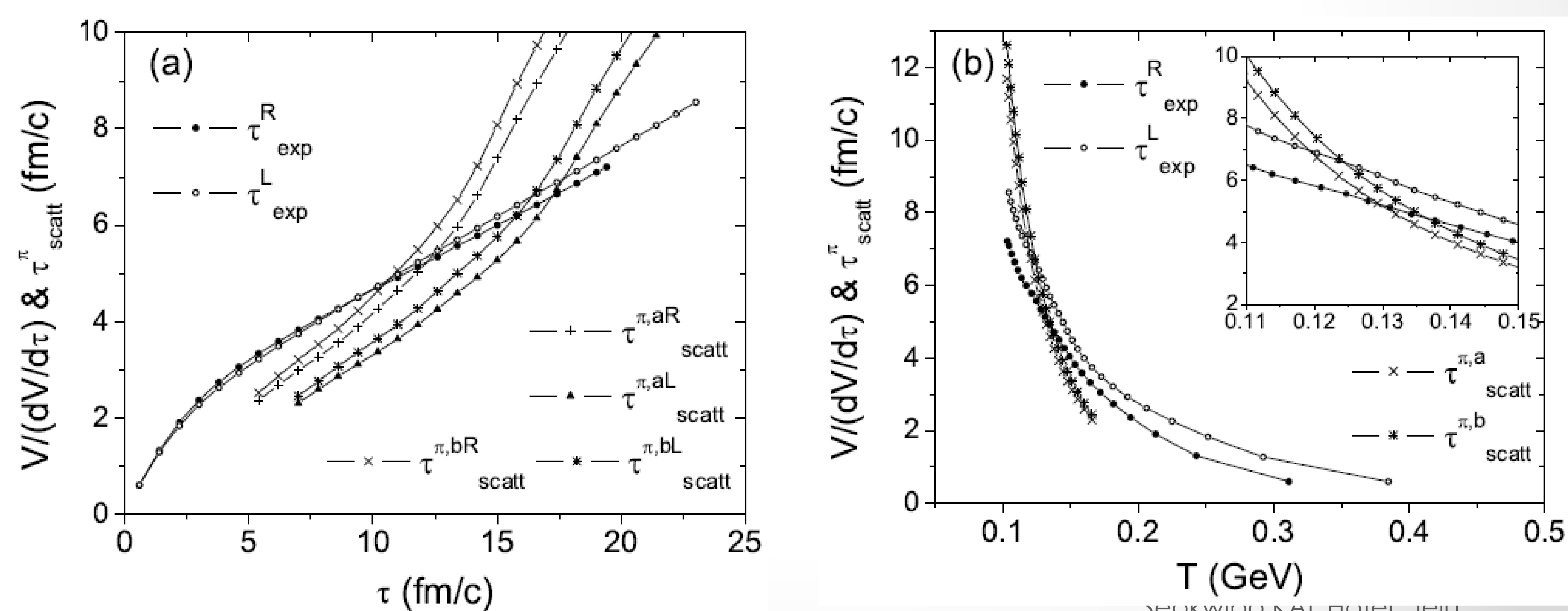
with $R_0 = \frac{\tau_{scatt}}{\tau_{scatt}^{K}} = \frac{\tau_{scatt}^{K*}}{\tau_{scatt}^{K} + \tau_{scatt}^{K*}}$ and $\tau_{scatt} = \frac{\tau_{scatt}^{K} \tau_{scatt}^{K*}}{\tau_{scatt}^{K} + \tau_{scatt}^{K*}}$

– The freeze-out condition of the pion

1) The scattering time for pions

$$\frac{1}{\tau_{scatt}^{\pi,a}} \approx \langle v \rangle n \sigma \qquad \frac{1}{\tau_{scatt}^{\pi,b}} = 59.5\, fm^{-1} \left(\frac{T}{GeV} \right)^{3.45}$$

C. M. Hung and E. V. Shuryak, Phys. Rev. C **57**, 1891 (1998)
U. Heinz and G. Cestin, Eur. Phys. J. ST, **155**, 75 (2008)



– Hadronic effects on the hadronic molecule and the kinetic freeze-out condition

1) Rate equation for deuterons

$$\frac{dN_d(\tau)}{d\tau} = \frac{1}{\tau^N_{scatt}} N_N(\tau) - \frac{1}{\tau^d_{scatt}} N_d(\tau).$$

$$1/\tau^d_{scatt} = \sum_i \langle \sigma_{di} v_{di} \rangle n_i,$$
$$1/\tau^N_{scatt} = \sum_j \langle \sigma_{Nj} v_{Nj} \rangle n_j.$$

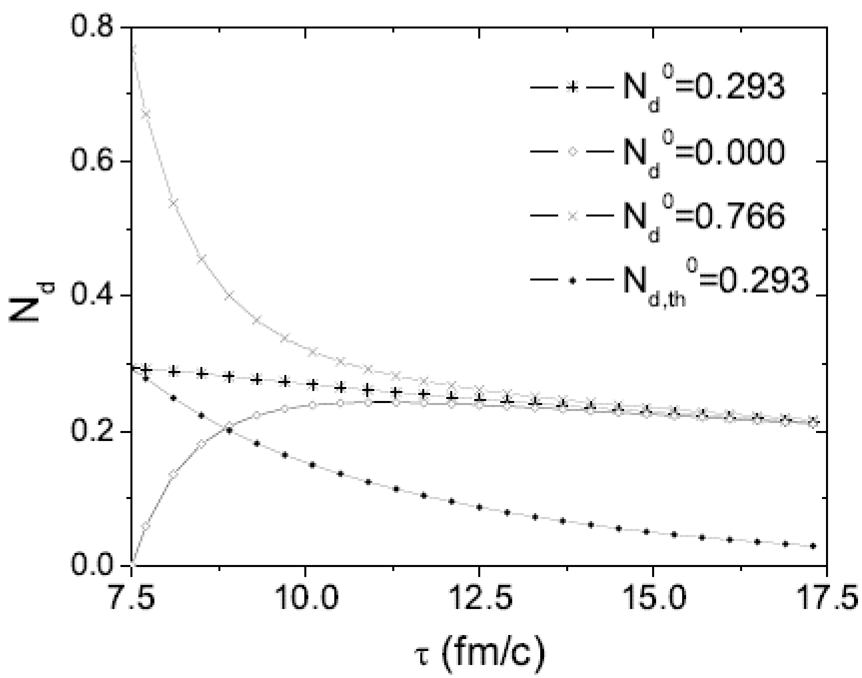
2) The deuteron abundance at kinetic freeze-out

$$N_d^{asym}(\tau) = \frac{\tau^d_{scatt}}{\tau^N_{scatt}} N_N \sim \frac{\langle \sigma_{NN\to d\pi} v_{NN} \rangle n_N}{\langle \sigma_{d\pi\to NN} v_{d\pi} \rangle n_\pi} N_N.$$

$$N_d^{asym}(\tau) = \frac{\langle \sigma_{NN\to d\pi} v_{NN} \rangle N_N}{\langle \sigma_{d\pi\to NN} v_{d\pi} \rangle N_\pi} N_N,$$

compared to that of K* mesons

$$N_{K^*}^{asym}(\tau) = \frac{\sum_j \langle \sigma_{K^*j} v_{K^*j} \rangle N_j}{\sum_i \langle \sigma_{Ki} v_{Ki} \rangle N_i + \sum_j \langle \sigma_{K^*j} v_{K^*j} \rangle N_j + V(\tau) \langle \Gamma_{K^*} \rangle} N_K.$$



Conclusions

– Reduction of K* meson abundance and kinetic freeze-out conditions in heavy ion collisions

1) The interplay between interactions of K* mesons and kaons with light meson in the hadronic medium controls the reduction or production of the K* meson.
2) The final yield ratio between K* mesons and kaons reflects the condition at the last stage of the hadronic effects on K* and K mesons, or the kinetic freeze-out temperature.
3) The smaller ratio of K*/K measured at the LHC energy indicates a lower kinetic freeze-out temperature compared to that at RHIC.
4) The qualitative analysis on the freeze-out conditions for pions supports the decreasing kinetic freeze-out temperatures for larger initial collisions energies.