Hadronic effects and freeze-out conditions in heavy ion collisions

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Heavy Ion Meeting 2016-05

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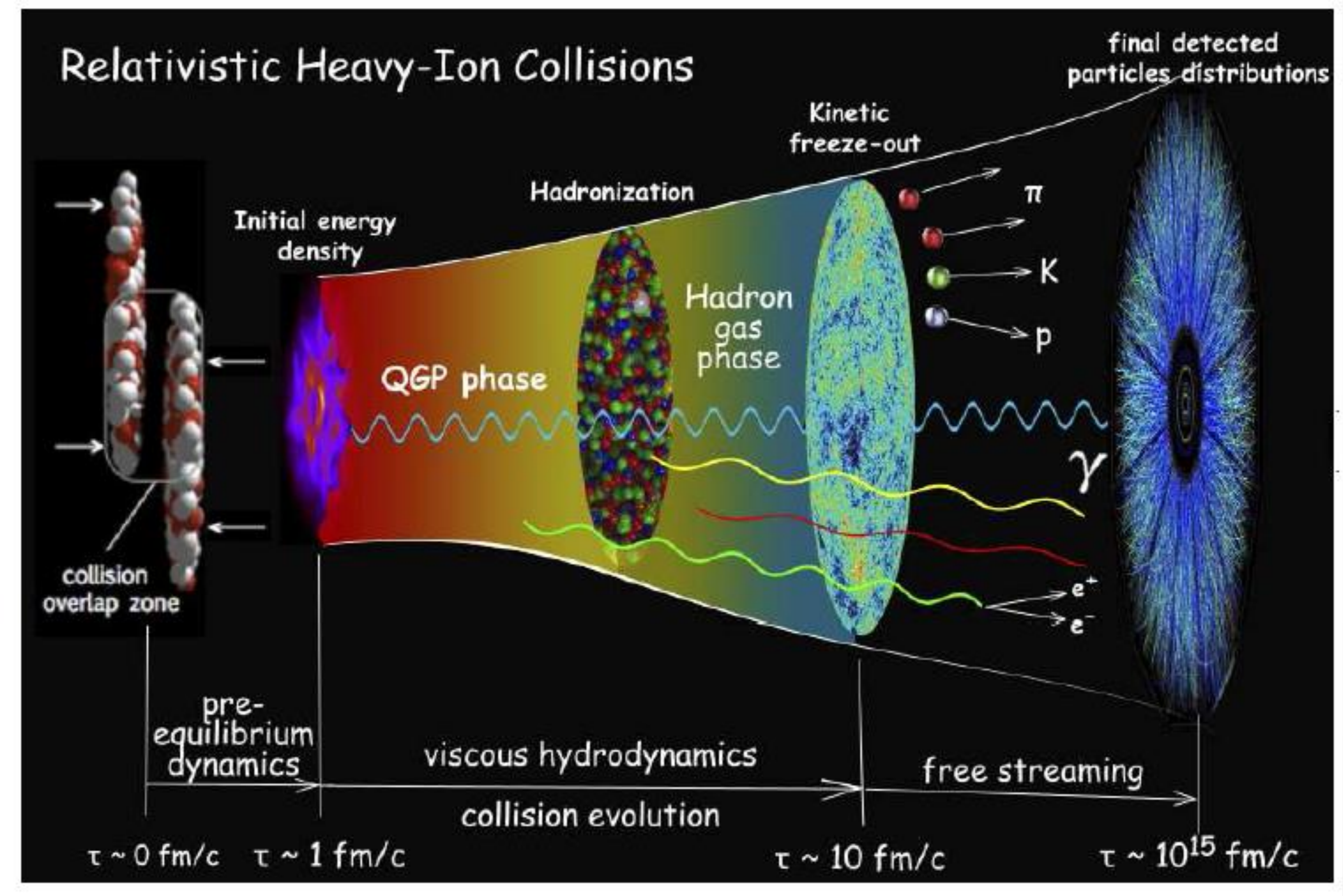
S. Cho, S. -H. Lee, arXiv : 1509.14092

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

Outline

- Introduction
- Hadronic Interactions
- Evolution of the K* and K meson abundances
- Freeze-out conditions in heavy ion collisions
- Conclusions

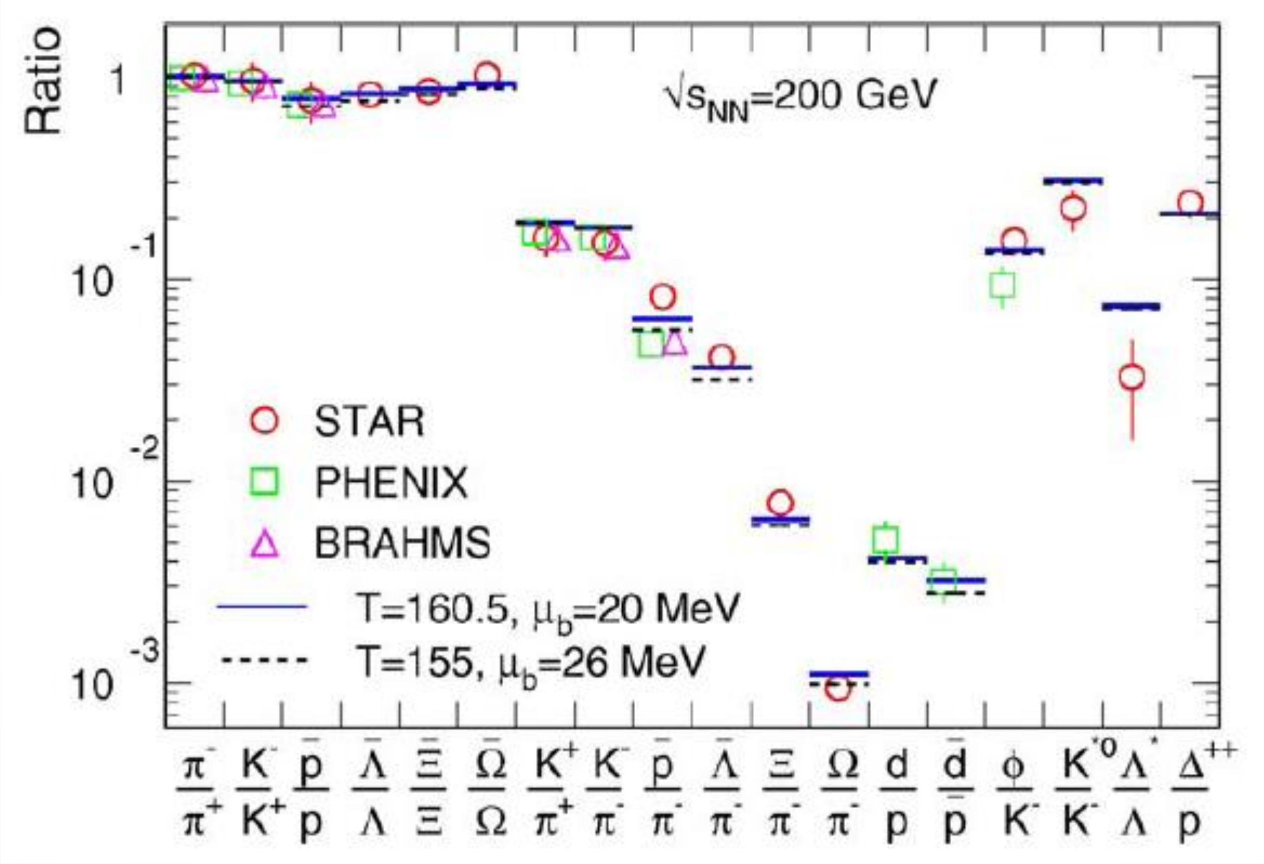
Introduction



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

– Statistical hadronization model

1) Particle yield ratios at RHIC



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

– Statistical hadronization model

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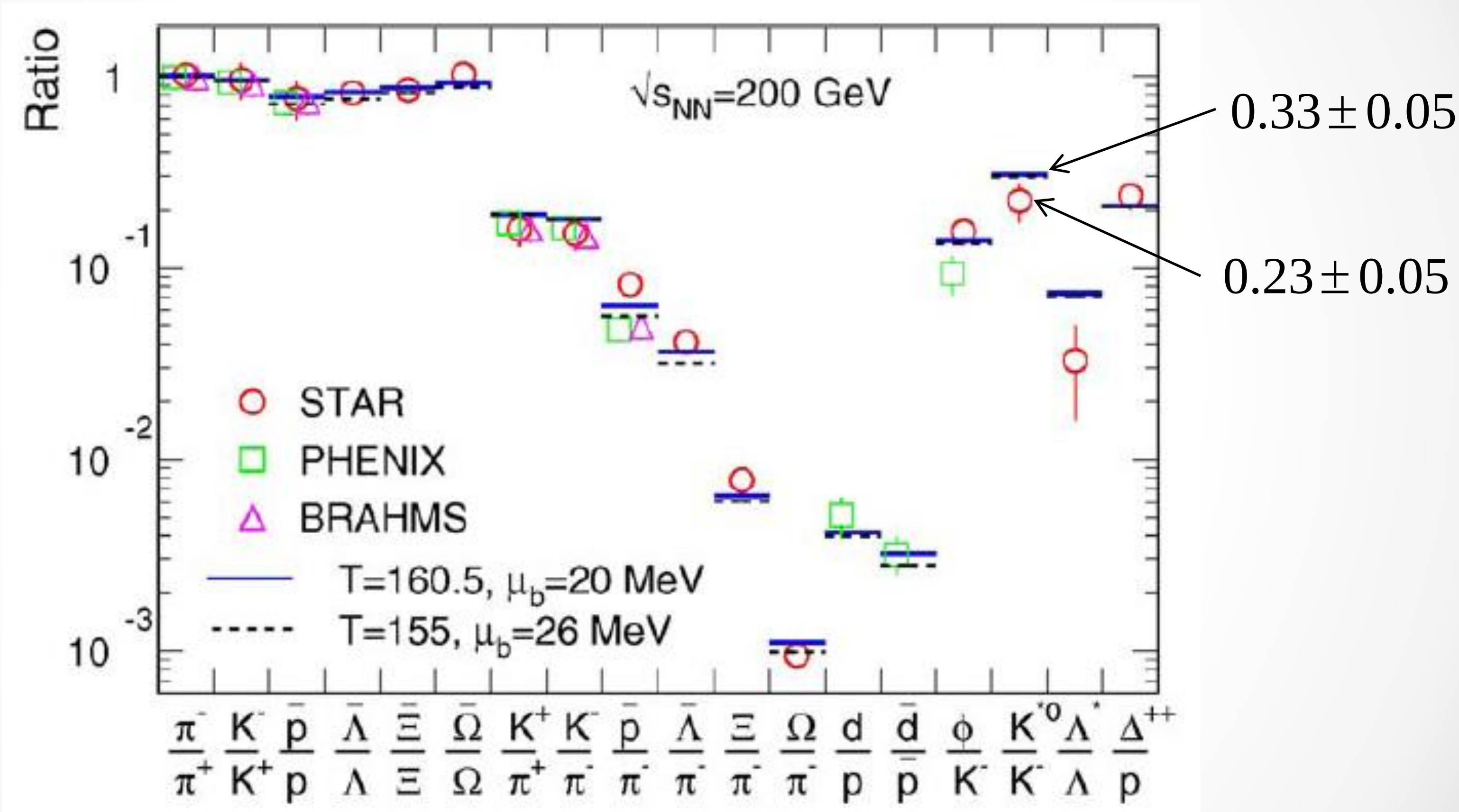
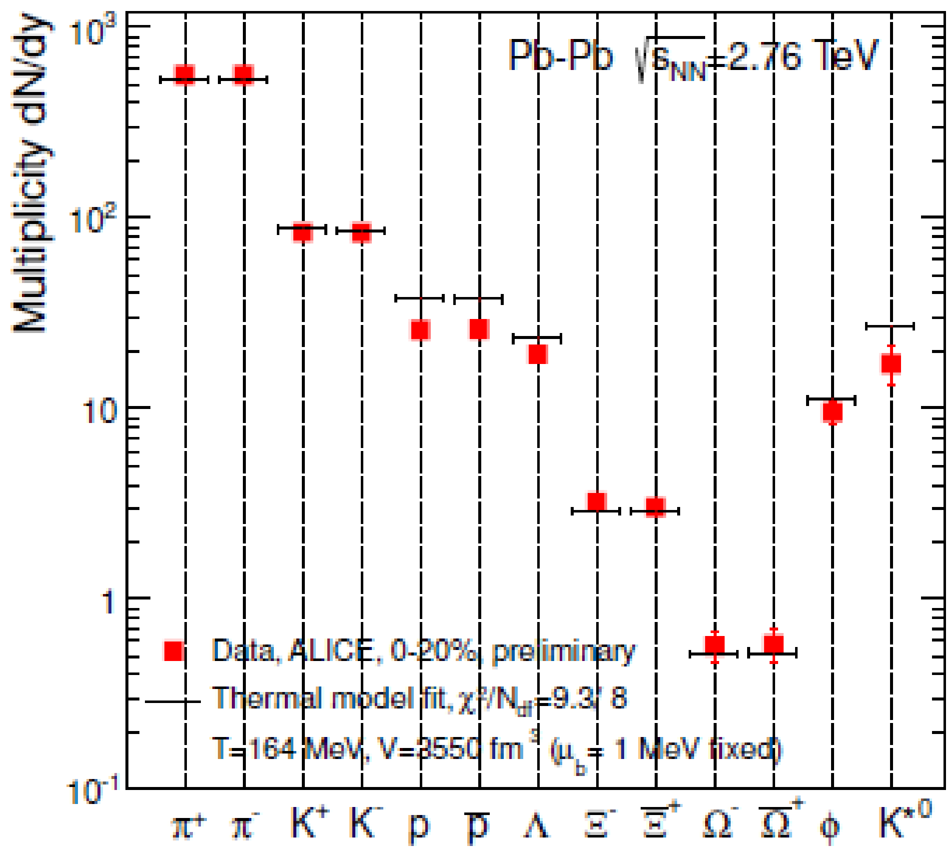


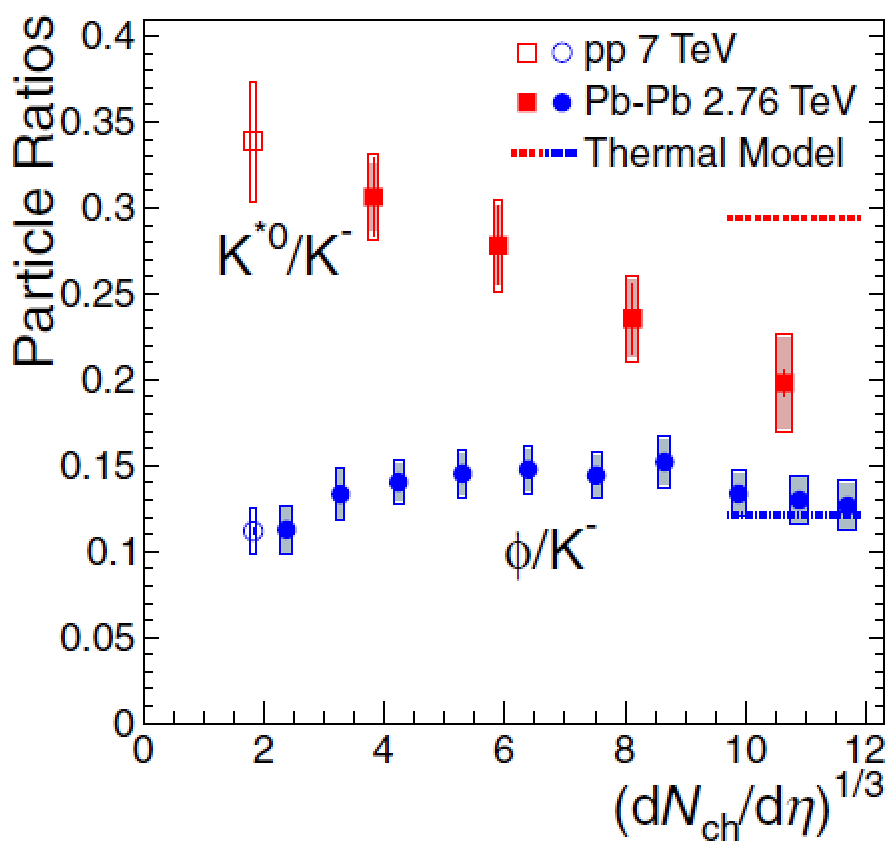
A. Andronic, P. Braun-Munzinger, and J. Stachel, Nucl. Phys. A **772**, 167 (2006)

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)

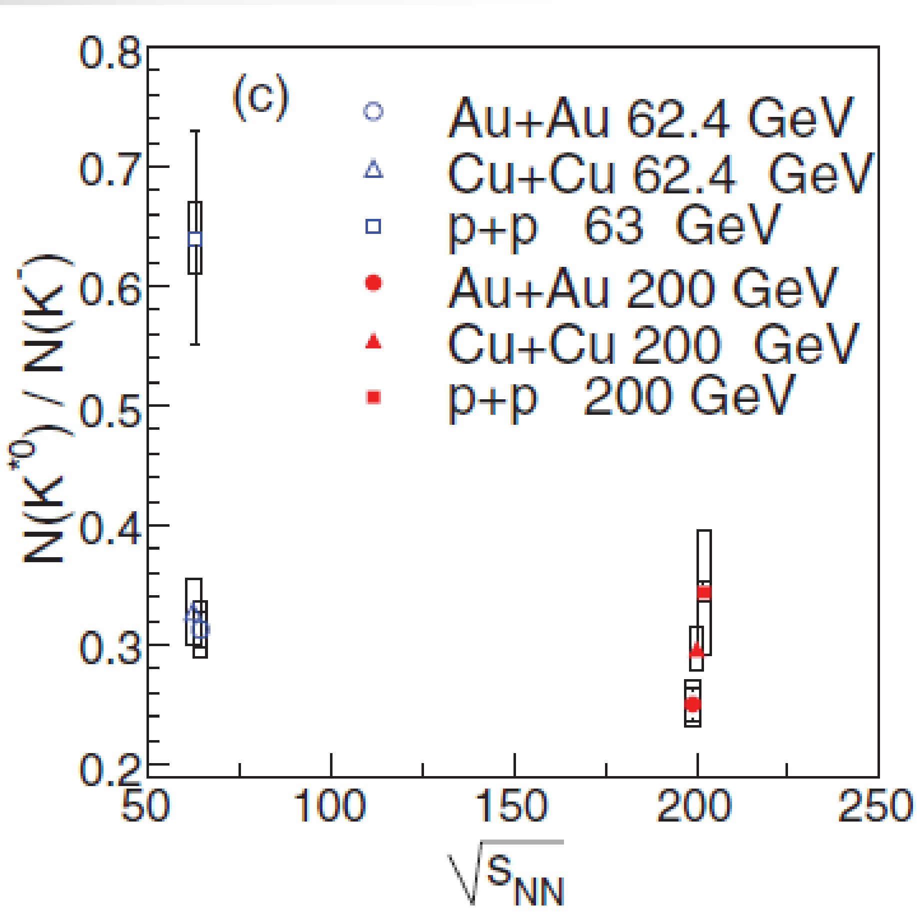
– Statistical hadronization model at LHC

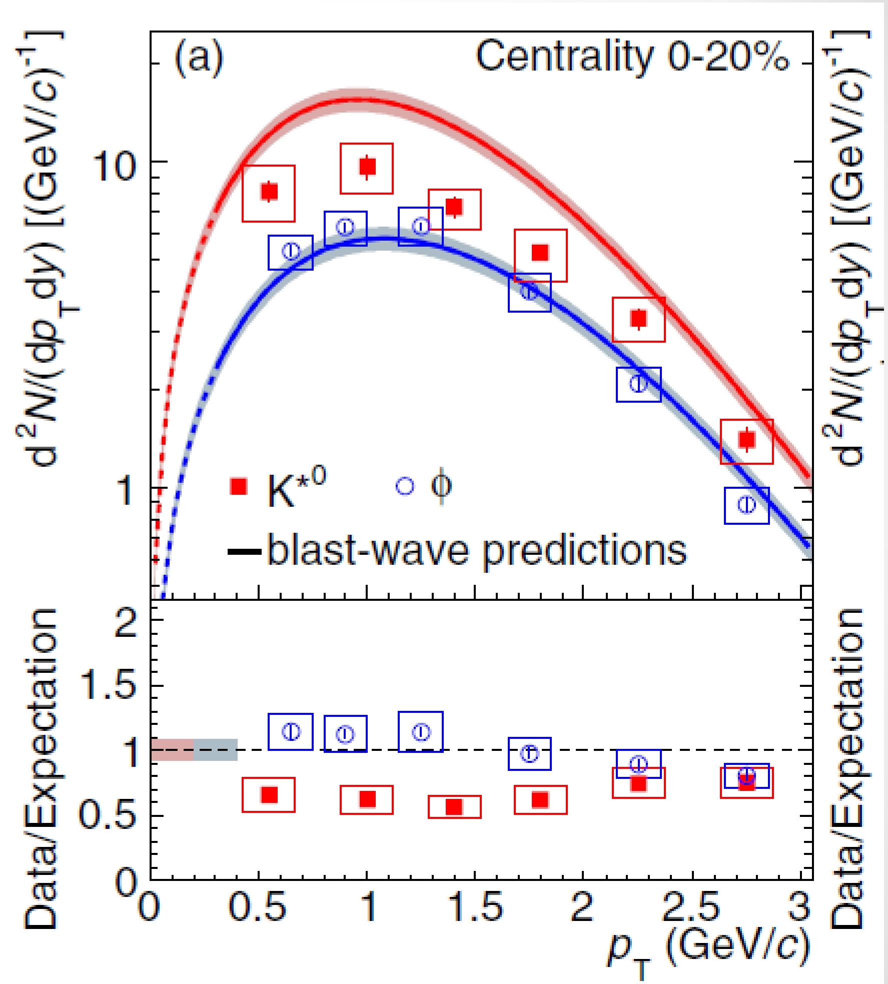




A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Nucl. Phys. A **904** 535c (2013)
B. Abelev et al. [ALICE Collaboration], Phys. Rev. C **91**, 024609 (2015)

– 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

– J/ψ absorption by hadronic interactions

T. Matsui and H. Satz, Phys. Lett. **B178** 416 (1986)

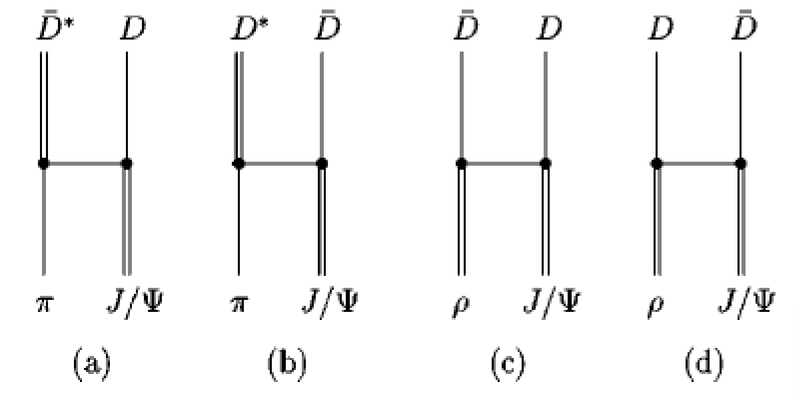
1) A meson exchange model with an effective Lagrangian

S. G. Matinyan and B. Muller, Phys. Rev. C **58**, 2994 (1998)

K. L. Haglin, Phys. Rev. C **61**, 031902(R) (2000)

Z. Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000)

Y. Oh, T. Song, and S. –H. Lee, Phys. Rev. C **63**, 034901 (2000)



– Hadronic effects on the K* meson

1) The interaction Lagrangians from the pseudoscalar and vector mesons free Lagrangians

$$\mathcal{L}_0 = \mathrm{Tr}(\partial_\mu P^\dagger \partial^\mu P) - \frac{1}{2}\mathrm{Tr}(F^\dagger_{\mu\nu} F^{\mu\nu}),$$

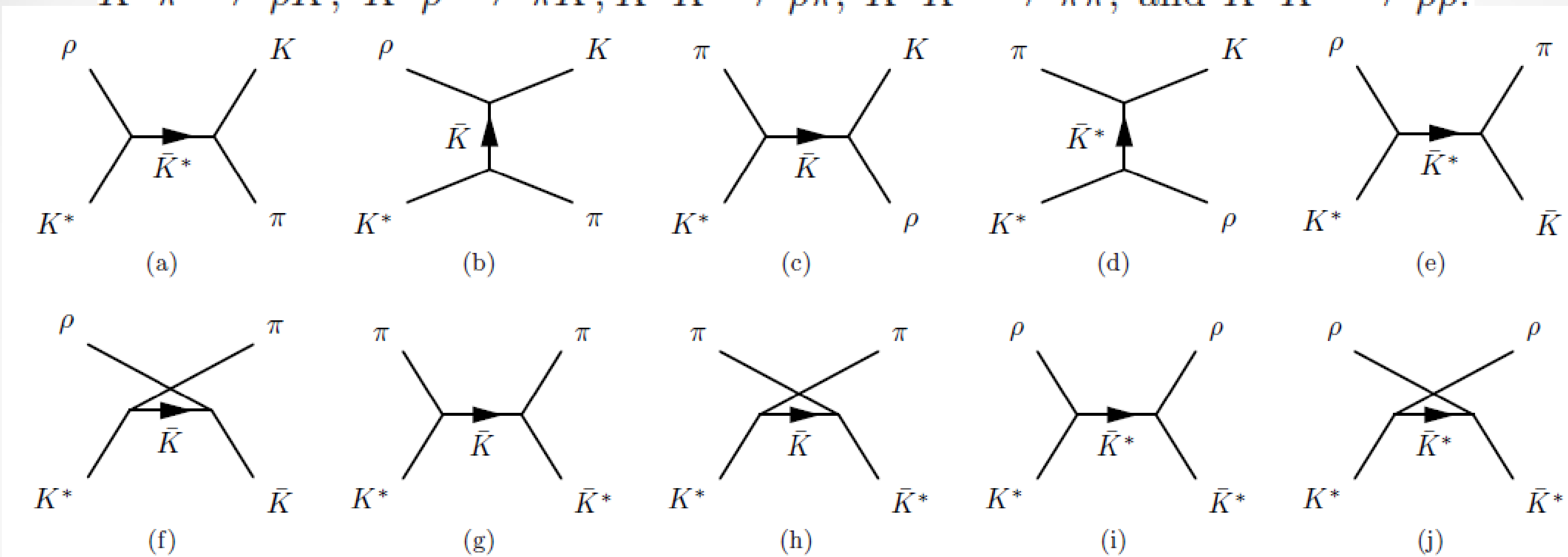
$$V = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

$$P = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta_8 + \frac{\eta_1}{\sqrt{3}} \end{pmatrix}$$

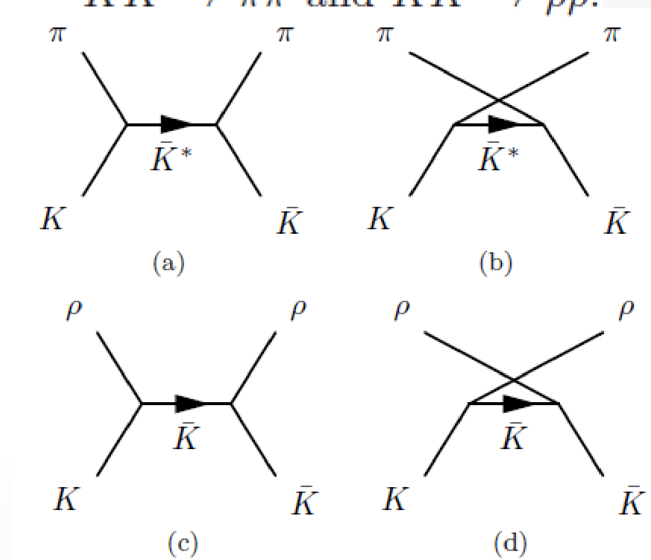
$$\begin{aligned}
\mathcal{L}_{\pi K K^*} &= i g_{\pi K K^*} K^{*\mu} \vec{\tau} \cdot (\bar{K}\partial_\mu \vec{\pi} - \partial_\mu \bar{K} \vec{\pi}) + \mathrm{H.c.}, \\
\mathcal{L}_{\rho K K} &= i g_{\rho K K} (K \vec{\tau} \partial_\mu \bar{K} - \partial_\mu K \vec{\tau} \bar{K}) \cdot \vec{\rho}^\mu, \\
\mathcal{L}_{\rho K^* K^*} &= i g_{\rho K^* K^*} \left[(\partial_\mu K^{*\nu} \vec{\tau} \bar{K}^*_\nu - K^{*\nu} \vec{\tau} \partial_\mu \bar{K}^*_\nu) \cdot \vec{\rho}^\mu \right. \\
&+ (K^{*\nu} \vec{\tau} \cdot \partial_\mu \vec{\rho}_\nu - \partial_\mu K^{*\nu} \vec{\tau} \cdot \vec{\rho}_\nu) \bar{K}^{*\mu} \\
&+ \left. K^{*\mu} (\vec{\tau} \cdot \vec{\rho}^\nu \partial_\mu \bar{K}^*_\nu - \vec{\tau} \cdot \partial_\mu \vec{\rho}^\nu \bar{K}^*_\nu) \right],
\end{aligned}$$

– 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) Cross sections for K* mesons

$$\sigma = \frac{1}{64\pi^2 s g_1 g_2} \frac{|\vec{p}_f|}{|\vec{p}_i|} \int d\Omega \overline{|\mathcal{M}|^2} F^4$$

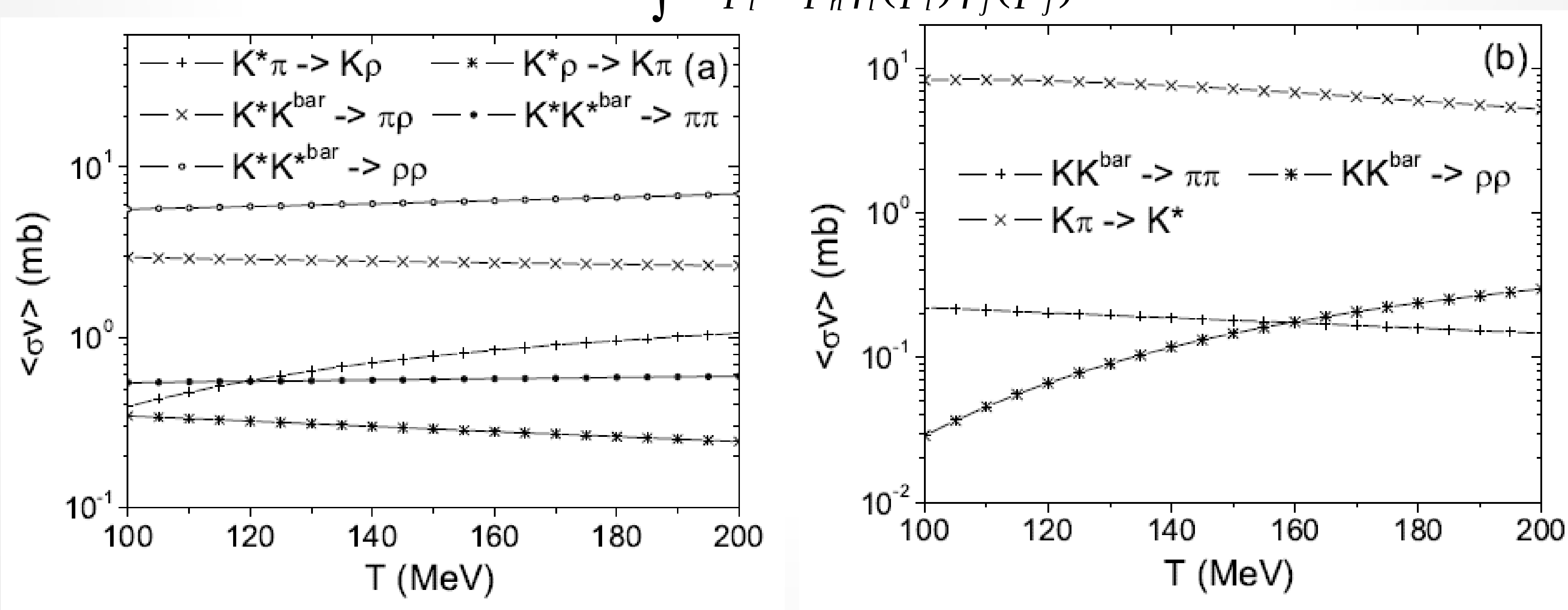
2) K* meson production from kaons and pions
& K* meson decay to kaons and pions

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

3) Thermally averaged cross sections for K* mesons and kaons

P. Koch, B. Muller, and J. Rafelski, Phys. Rept., **142**, 167 (1986)

$$\left\langle \sigma_{ih\to jk} v_{ih} \right\rangle = \frac{\int d^3p_i d^3p_h f_i(p_i) f_j(p_j) \sigma_{ih\to jk} v_{ih}}{\int d^3p_i d^3p_h f_i(p_i) f_j(p_j)}$$

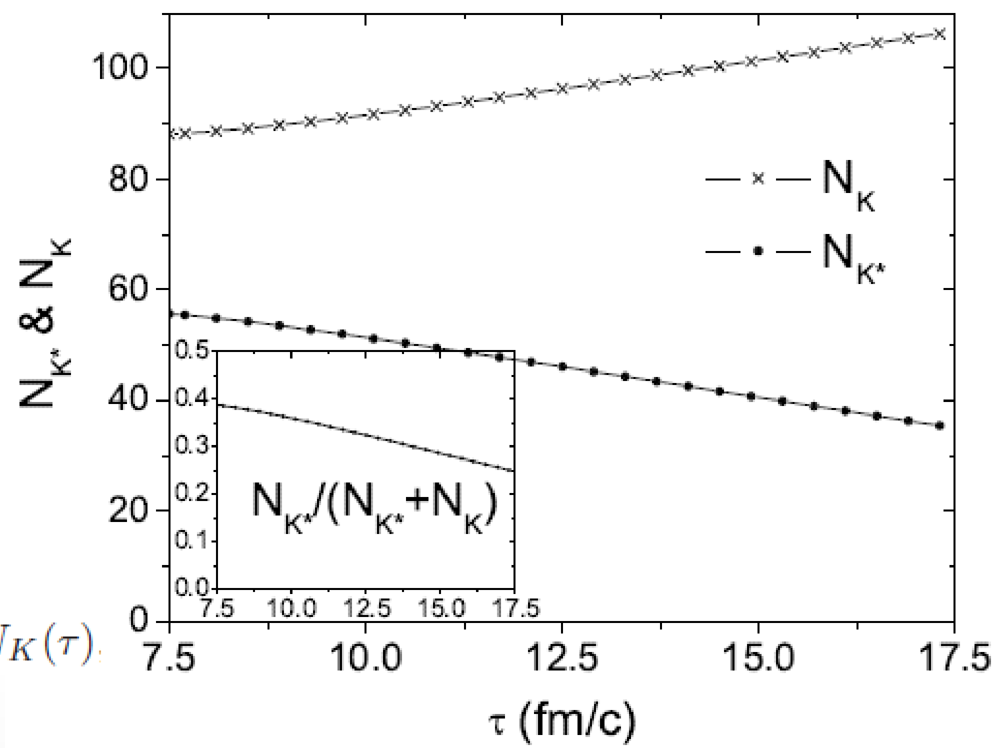


Evolution of the K* and K meson abundances

– Rate equations for K* & K meson abundances

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

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



– Time evolutions of the K* and K meson abundances

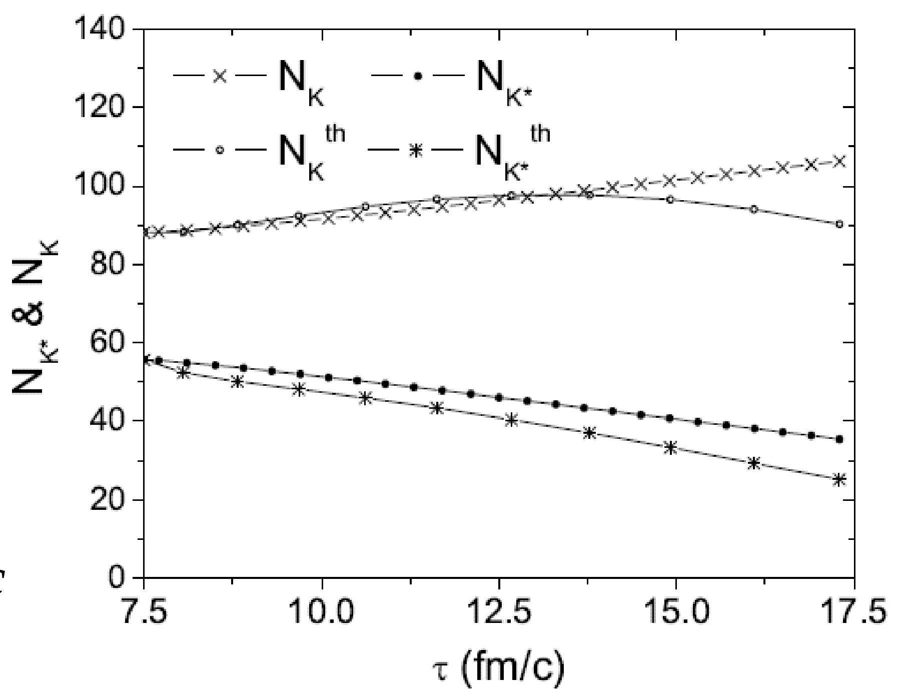
1) About 36% of K* mesons produced at chemical freeze-out disappears during the hadronic stage : Hadronic interactions are responsible for about 6% of the total K* meson loss

2) Abundances of the K* meson and kaon in thermal equilibrium

3) Volume and temperature as functions of time

$$T(\tau) = T_C - (T_H - T_F)\left(\frac{\tau - \tau_H}{\tau_F - \tau_H}\right)^{4/5}$$

$$V(\tau) = \pi\left[R_C + v_C(\tau - \tau_C) + a/2(\tau - \tau_C)^2\right]^2 \tau c$$



	Temp.(MeV)	Time (fm/c)
$R_c = 8.0$ fm	$T_c = 175$	$\tau_c = 5.0$
$v_c = 0.4c$	$T_h = 175$	$\tau_h = 7.5$
$a_c = 0.02c^2$/fm	$T_f = 125$	$\tau_f = 17.3$

L. W. Chen, C. M. Ko, W. Liu, and M. Nielsen, Phys. Rev. C **76**, 014906 (2007)

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

1) Simplified rate equations

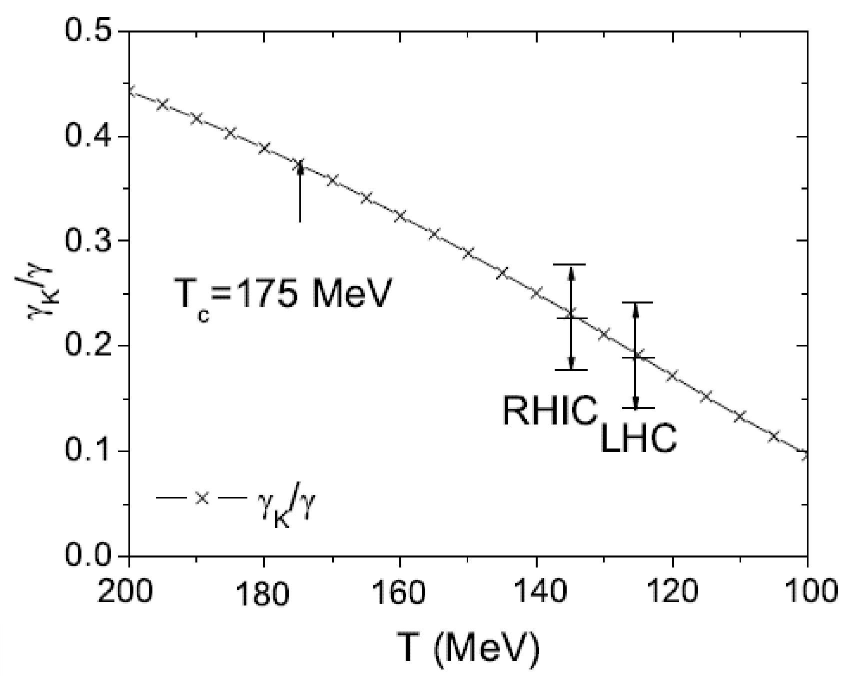
$$\frac{dN_{K^*}(\tau)}{d\tau} = \gamma_K N_K(\tau) - \gamma_{K^*} N_{K^*}(\tau),$$
$$\frac{dN_K(\tau)}{d\tau} = -\gamma_K N_K(\tau) + \gamma_{K^*} N_{K^*}(\tau),$$

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

2) K* and K meson abundances

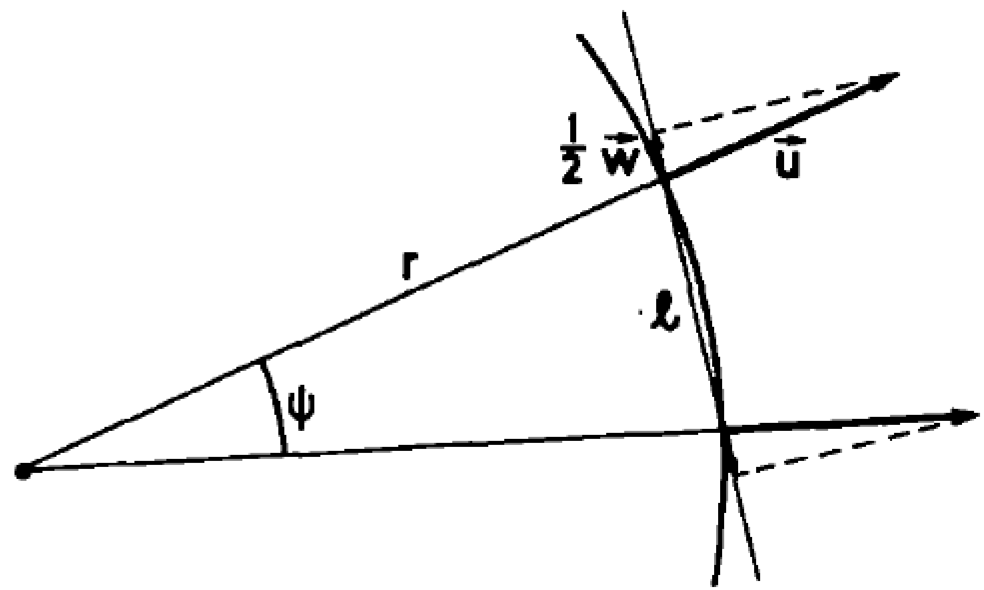
$$N_{K^*}(\tau) = \frac{\gamma_K}{\gamma}N^0 + \left(N^0_{K^*} - \frac{\gamma_K}{\gamma}N^0\right)e^{-\gamma(\tau-\tau_h)},$$
$$N_K(\tau) = \frac{\gamma_{K^*}}{\gamma}N^0 + \left(N^0_K - \frac{\gamma_{K^*}}{\gamma}N^0\right)e^{-\gamma(\tau-\tau_h)},$$

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



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 rate and expansion rate

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

2) The kinetic freeze-out condition for a spherically expanding fireball with its radius R

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

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

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

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

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

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

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

2) The yield ratio between K* mesons and kaons

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

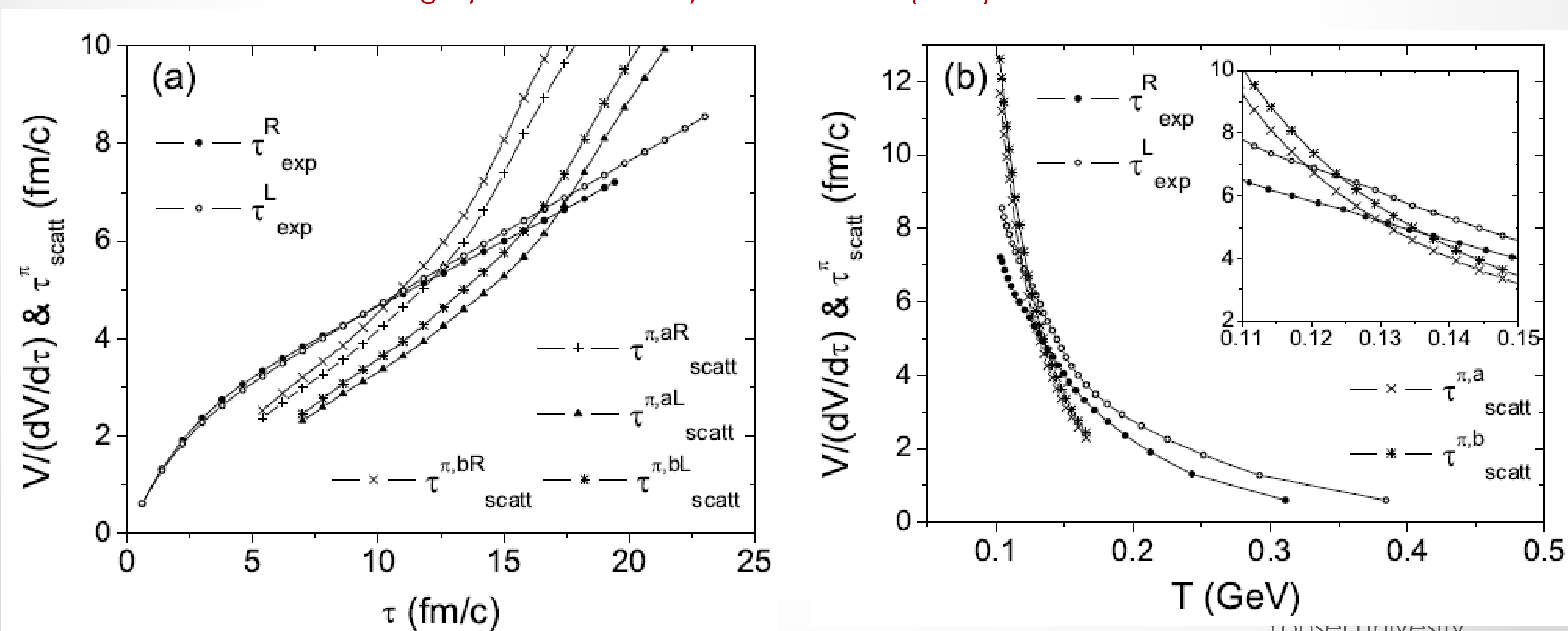
with $R_0 = \frac{\tau_{scatt}}{\tau^K_{scatt}} = \frac{\tau^{K^*}_{scatt}}{\tau^K_{scatt} + \tau^{K^*}_{scatt}}$ and $\tau_{scatt} = \frac{\tau^K_{scatt}\tau^{K^*}_{scatt}}{\tau^K_{scatt} + \tau^{K^*}_{scatt}}$

– 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 Edward V. Shuryak, Phys. Rev. C **57**, 1891 (1998)
Ulrich Heinz and Gregory Cestin, Eur. Phys. J. ST, **155**, 75 (2008)



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

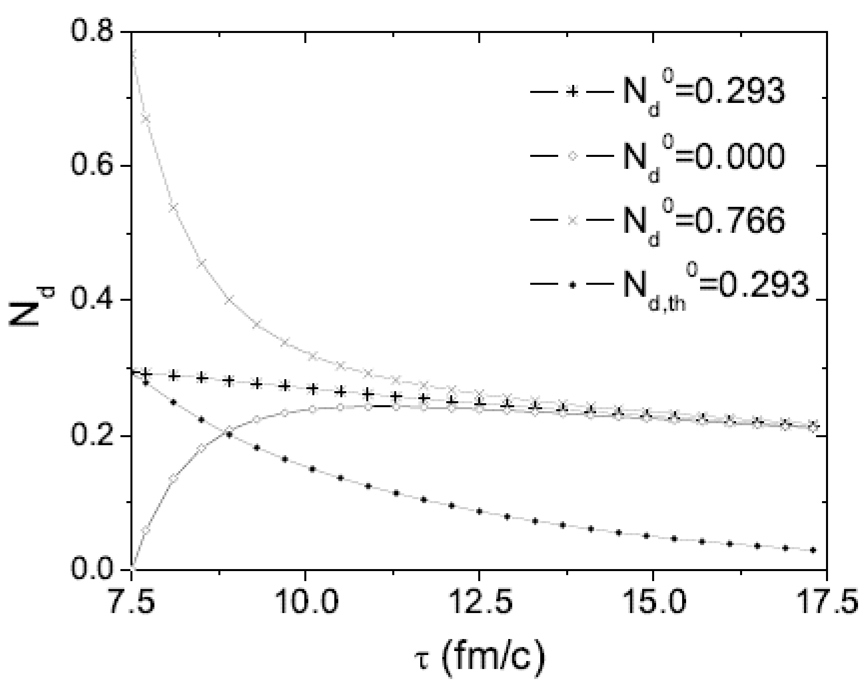
1) Rate equation for deuterons

$$\frac{dN_d(\tau)}{d\tau} = \frac{1}{\tau^N_{scatt}} N_N(\tau) - \frac{1}{\tau^d_{scatt}} N_d(\tau). \qquad \begin{aligned} 1/\tau^d_{scatt} &= \sum_i \langle \sigma_{di} v_{di} \rangle n_i, \\ 1/\tau^N_{scatt} &= \sum_j \langle \sigma_{Nj} v_{Nj} \rangle n_j. \end{aligned}$$

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

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

Conclusions

– Hadronic effects and 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 may reflect 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 may indicate 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.