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

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Exotic hadrons from heavy ion collisions
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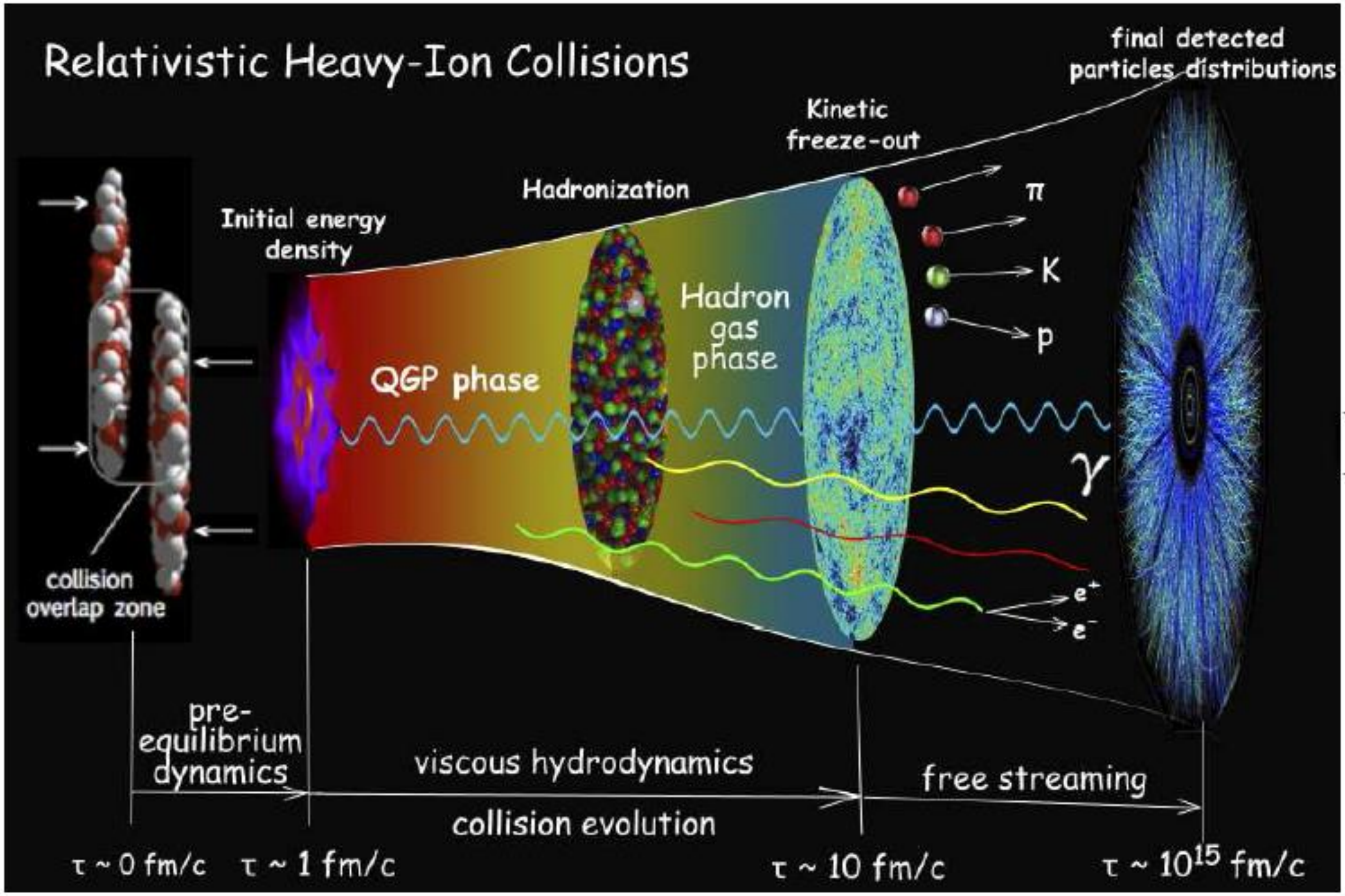
S. Cho, S. -H. Lee, arXiv : 1509.14092
S. Cho, T. Song, S. –H. Lee, arXiv : 1511.08019

# Outline

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

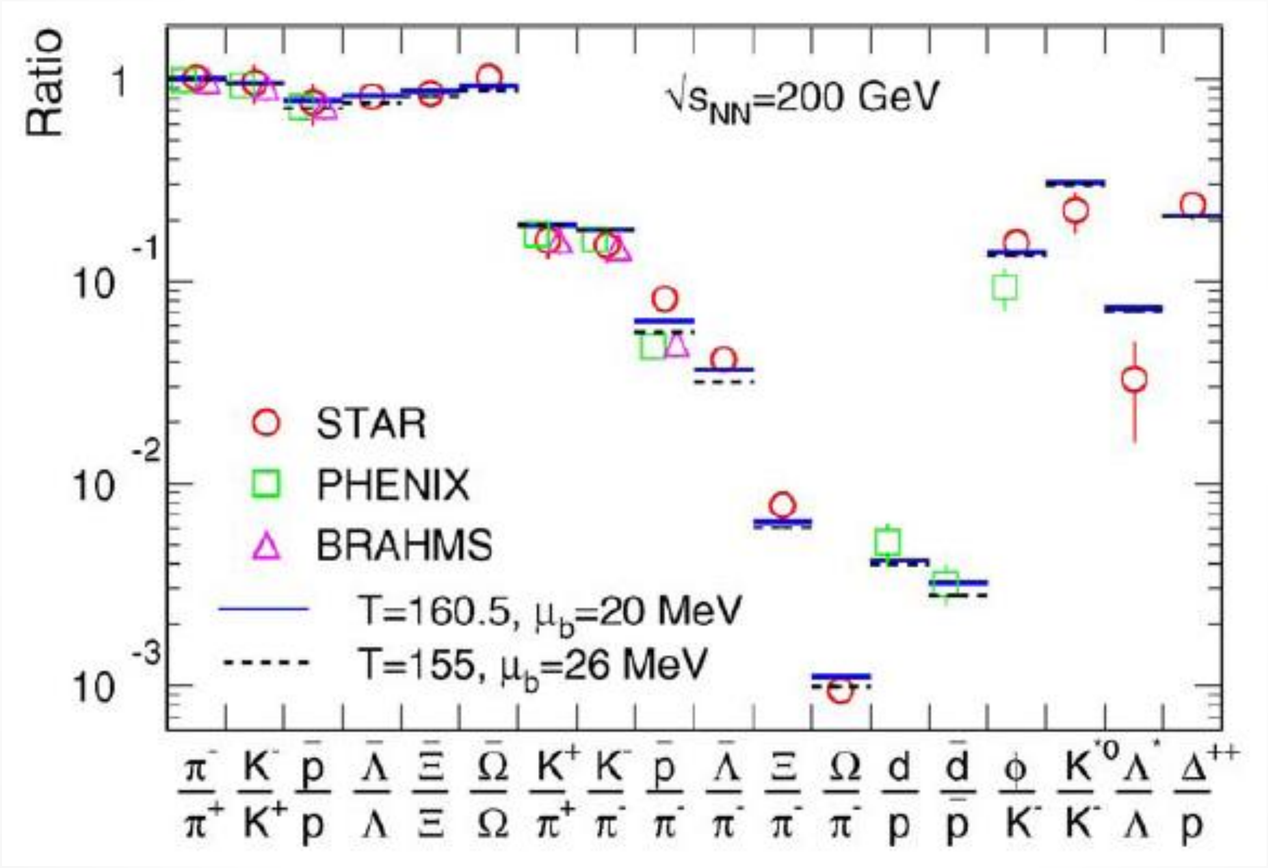
# Introduction




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

# – Statistical hadronization model

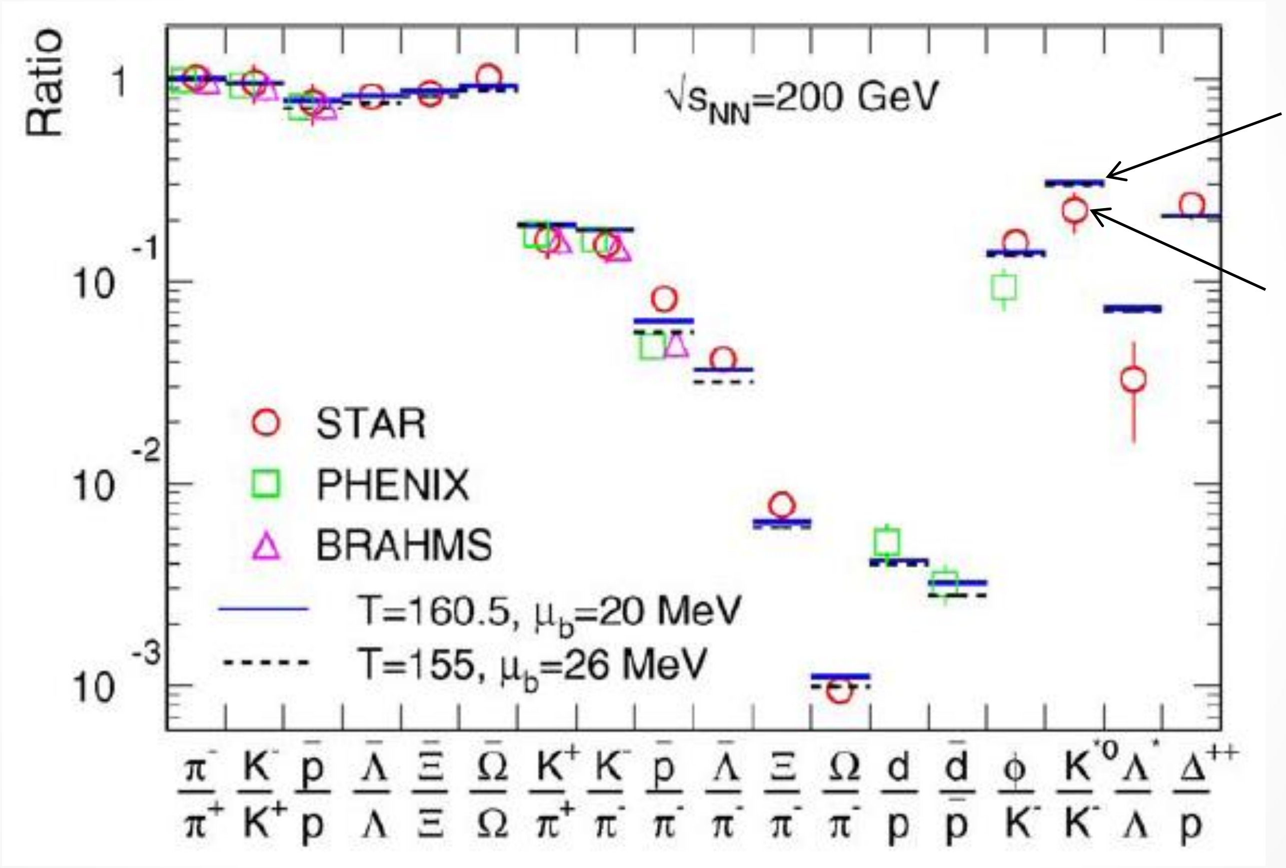
## 1) Particle yield ratios at RHIC




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

# – Statistical hadronization model

## 1) Particle yield ratios at RHIC

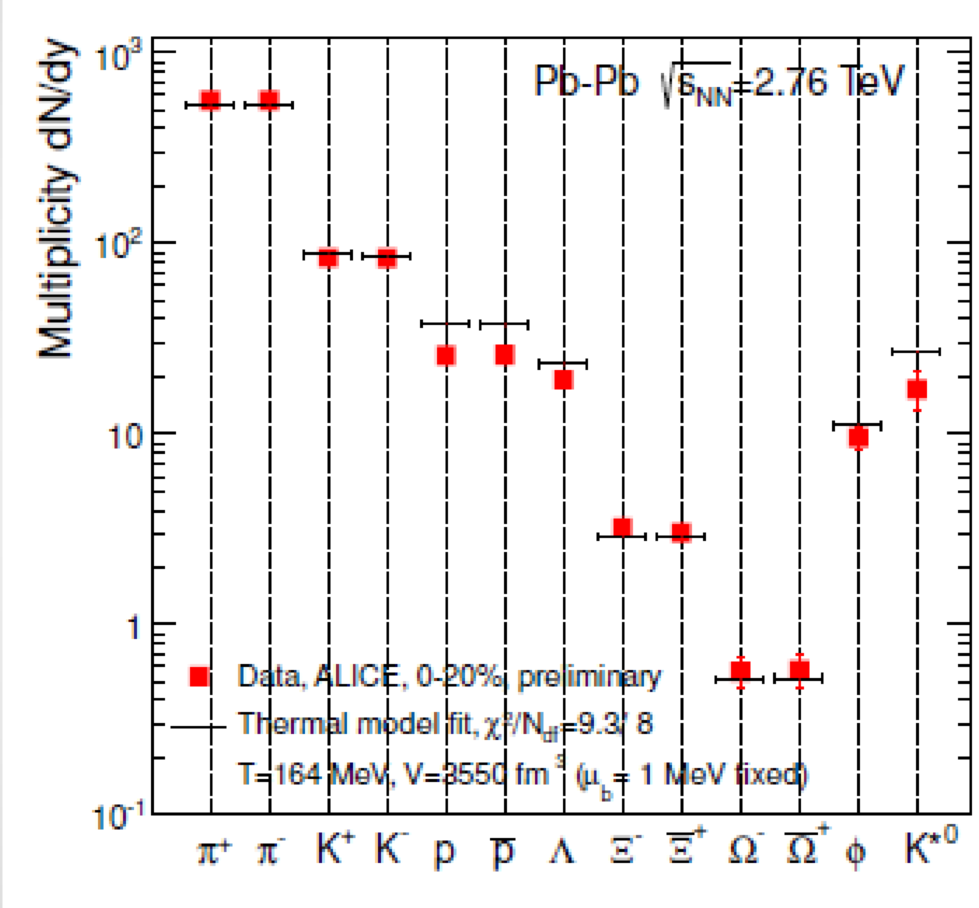



A. Andronic, P. Braun-Munzinger, and J. Stachel, Nucl. Phys. A **772**, 167 (2006)

P. Braun-Munzinger, D. Magestro, K. Redlich, and J. Stachel, Phys. Lett. B **518**, 41 (2001)

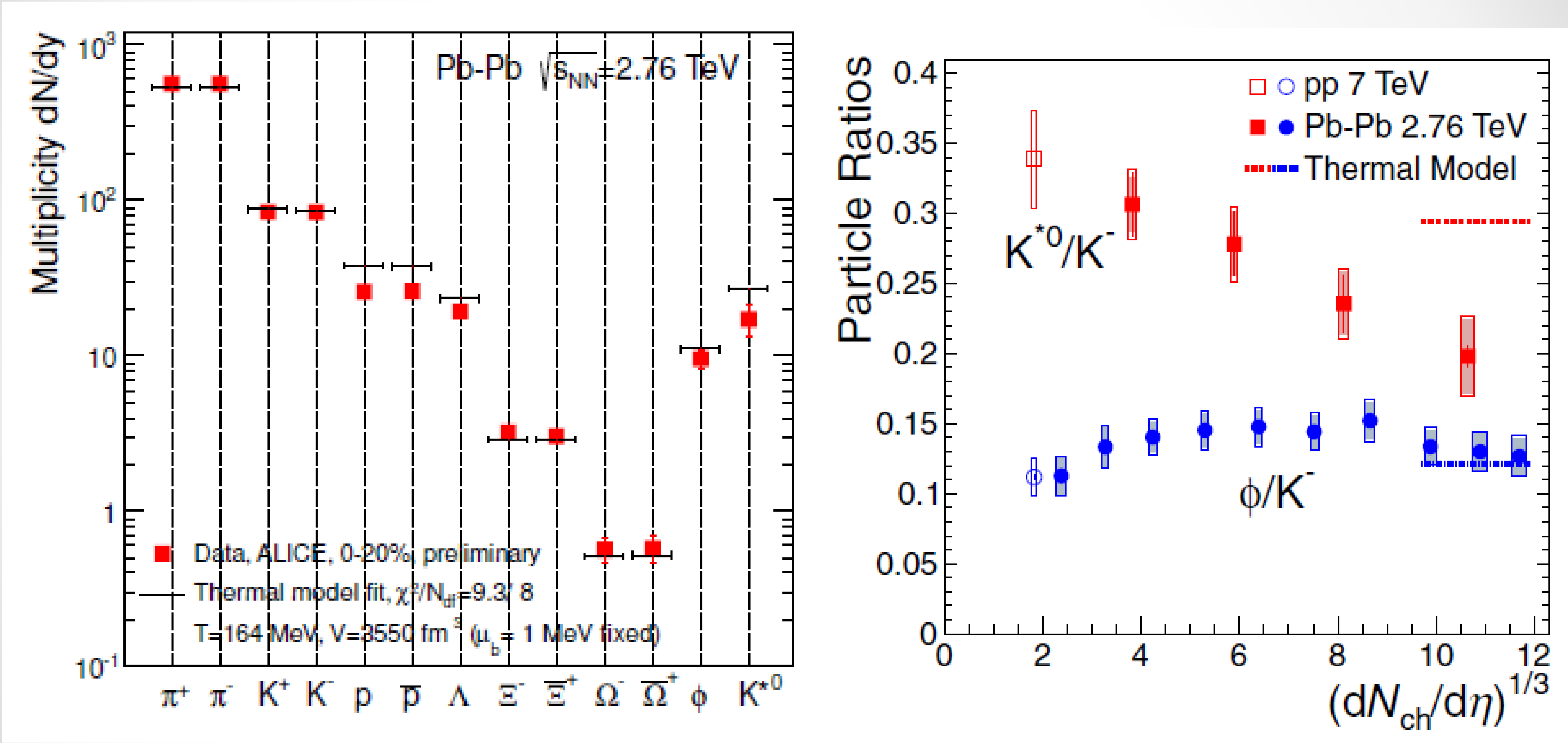
J. Adams et al. [STAR Collaboration], Phys. Rev. C **71**, 064902 (2005)

# – Statistical hadronization model at LHC




A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Nucl. Phys. A **904** 535c (2013)

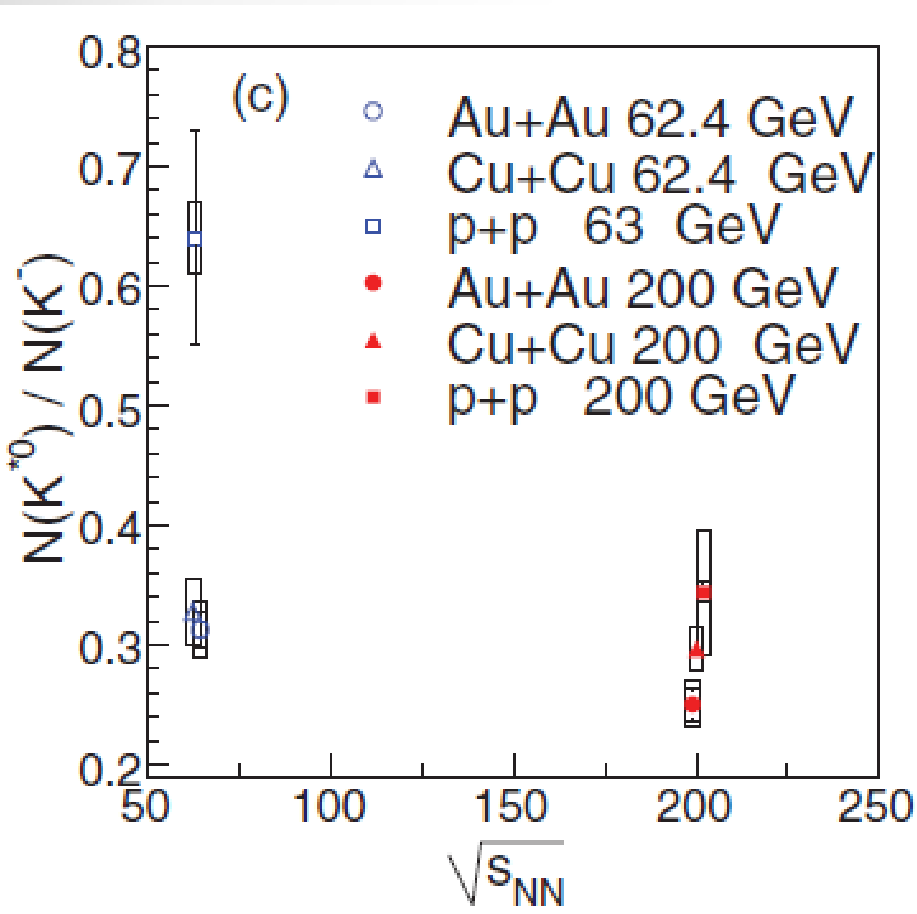
# – Statistical hadronization model at LHC

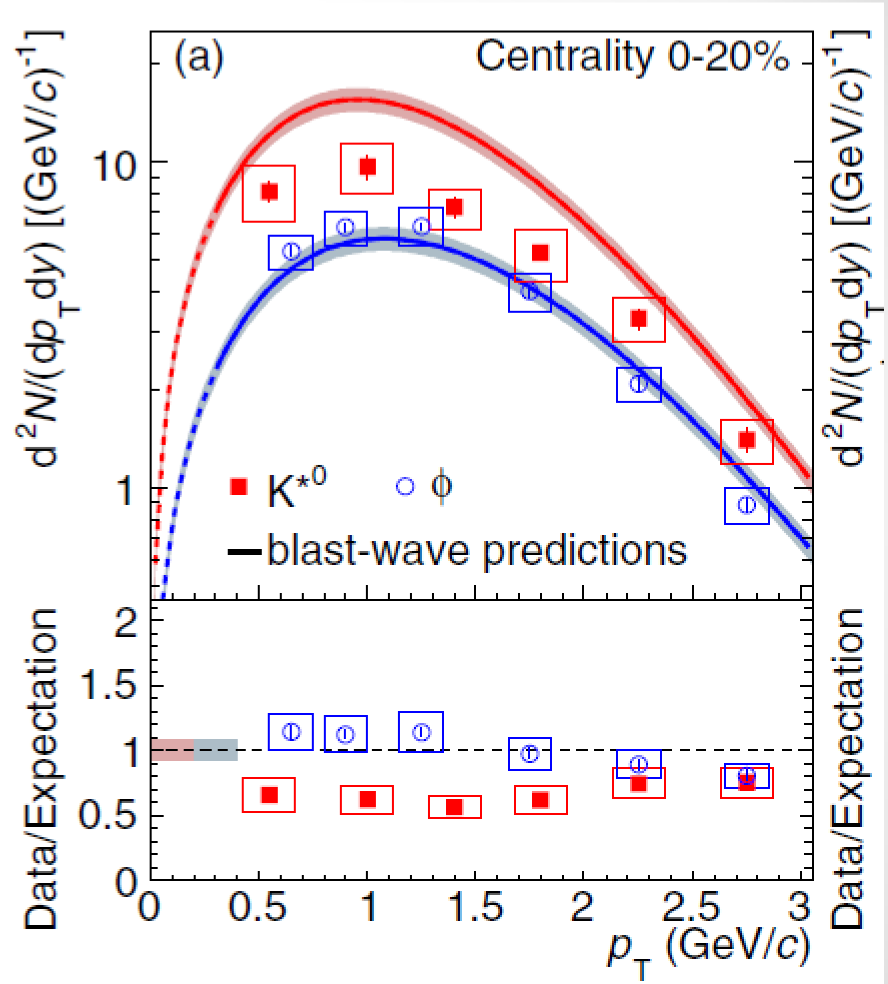



A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Nucl. Phys. A **904** 535c (2013)

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)

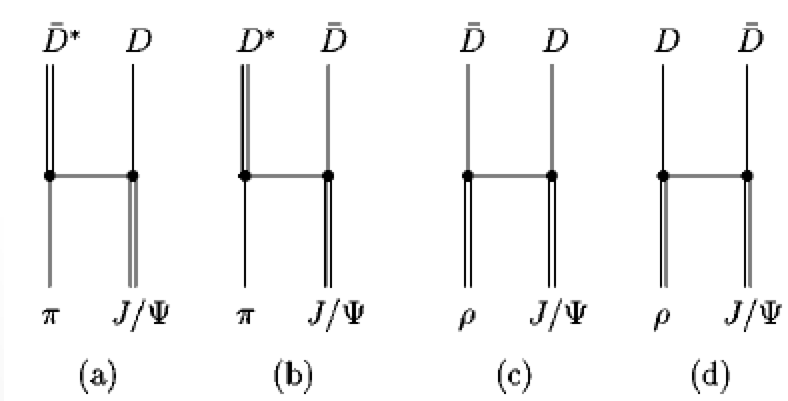
## 1) A meson exchange model with an effective Lagrangian

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

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

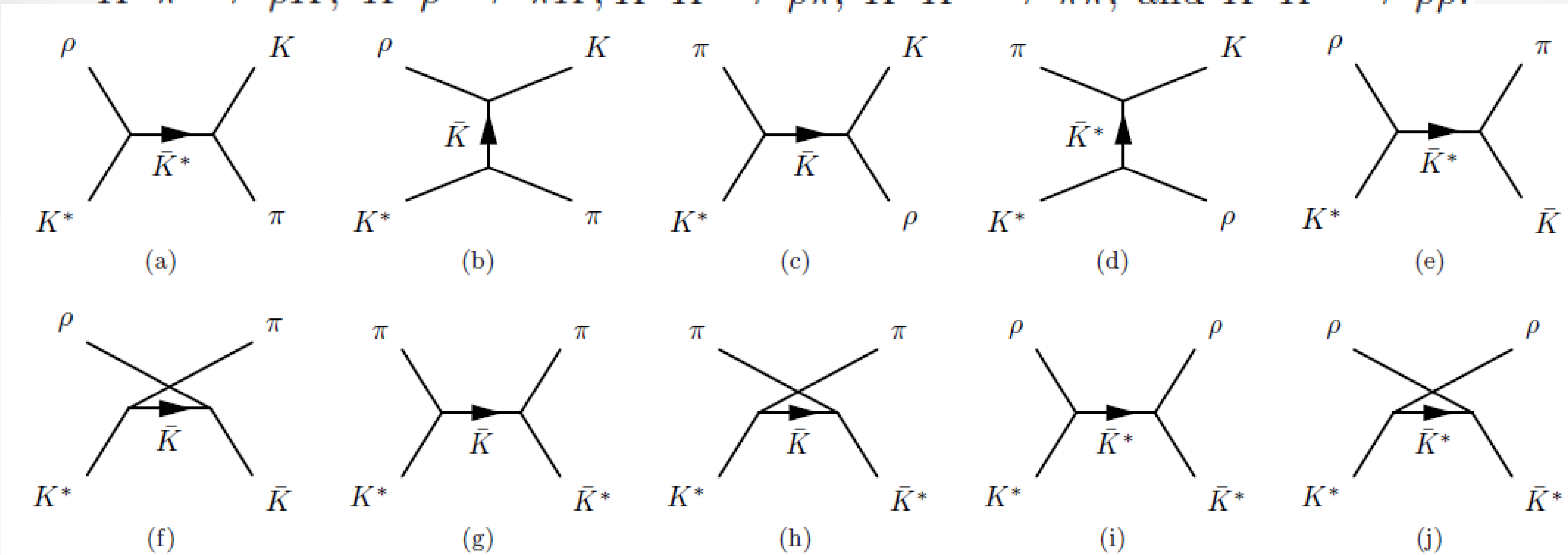
Z. Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000)

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

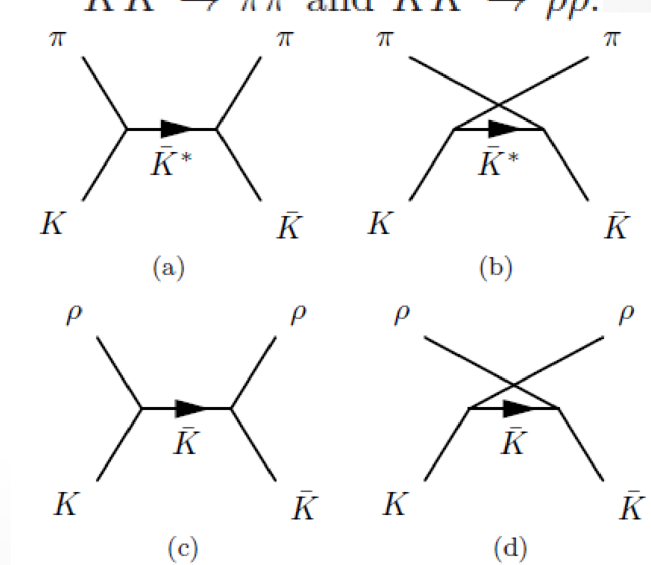


# – K* meson and kaon interactions

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

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

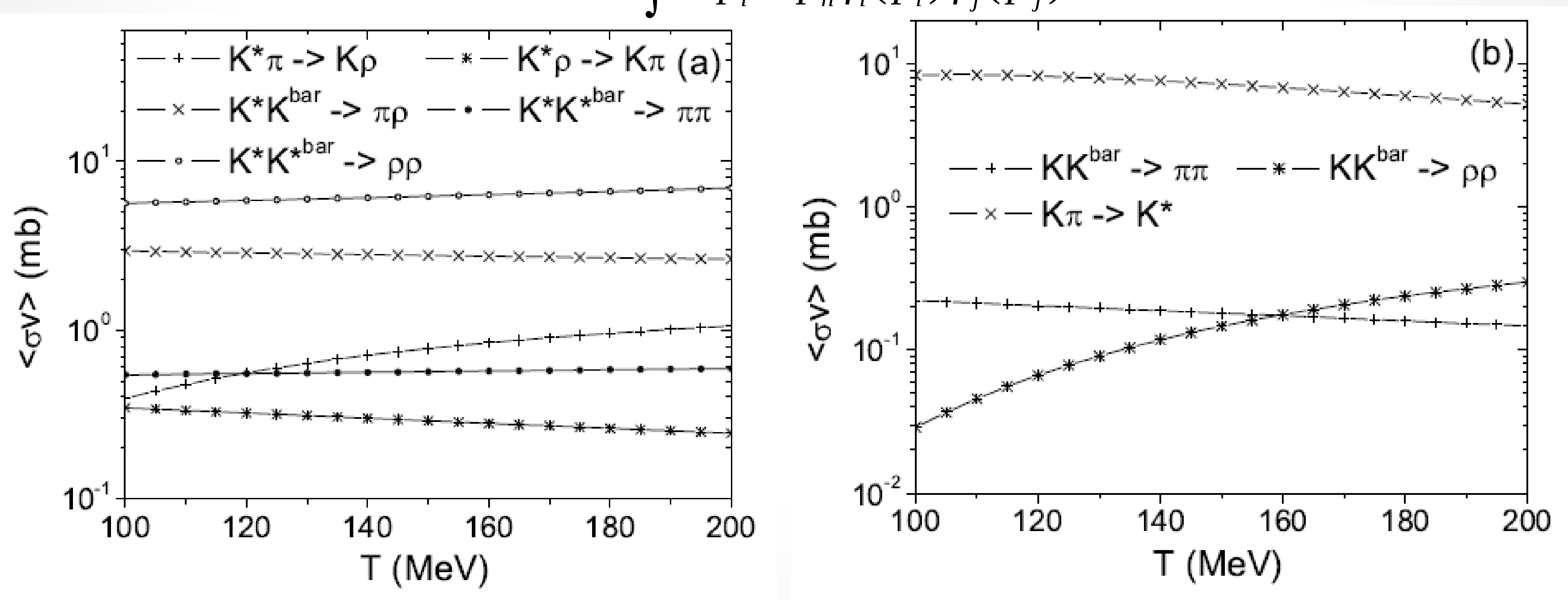
## 2) K* meson production from kaons and pions
## & K* meson decay to kaons and pions

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

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

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

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

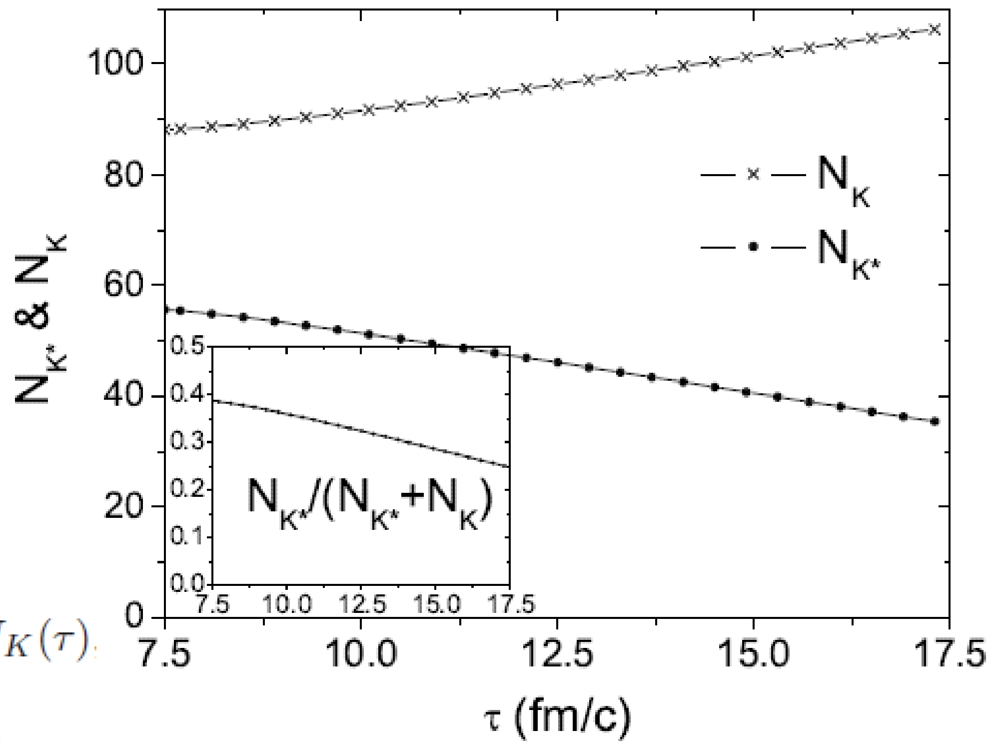


# Evolution of the K* and K meson abundances

## – Rate equations for K* & K meson abundances

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

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



# – Time evolutions of the K* and K meson abundances

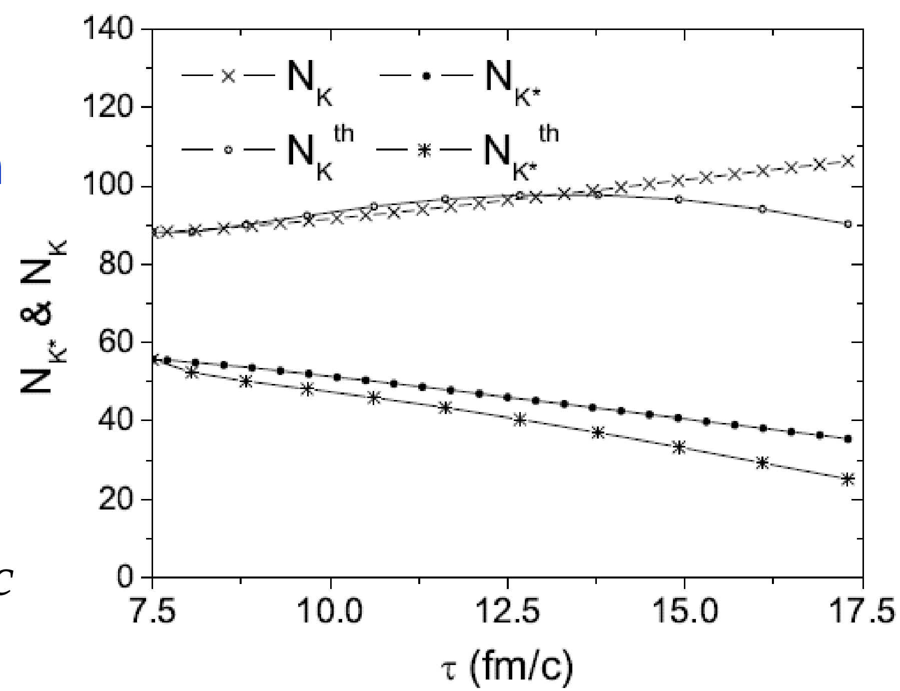
1) About 36% of K* mesons produced at chemical freeze-out disappears during the hadronic stage : Hadronic interactions are responsible for about 6% of the total K* meson loss

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 | $T_c = 175$ | $\tau_c = 5.0$ |
| $v_c = 0.4c$ | $T_h = 175$ | $\tau_h = 7.5$ |
| $a_c = 0.02c^2/\text{fm}$ | $T_f = 125$ | $\tau_f = 17.3$ |

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

$$\frac{dN_{K^*}(\tau)}{d\tau} = \gamma_K N_K(\tau) - \gamma_{K^*} N_{K^*}(\tau), \quad \gamma_{K^*} = \langle \sigma_{K^*\rho\to K\pi} v_{K^*\rho}\rangle n_\rho + \langle \sigma_{K^*\pi\to K\rho} v_{K^*\pi}\rangle n_\pi + \langle \Gamma_{K^*}\rangle,$$

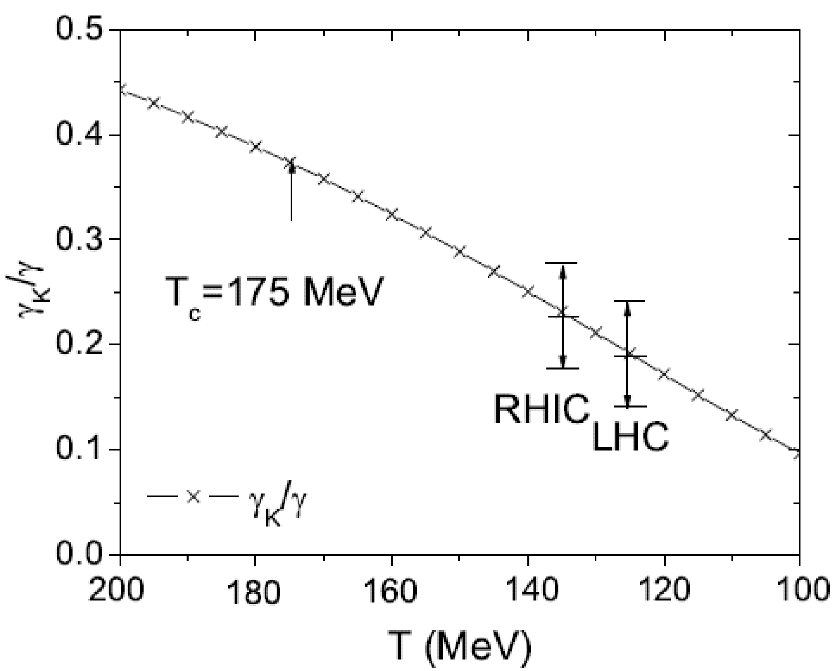
$$\frac{dN_K(\tau)}{d\tau} = -\gamma_K N_K(\tau) + \gamma_{K^*} N_{K^*}(\tau), \quad \gamma_K = \langle \sigma_{K\pi\to K^*\rho} v_{K\pi}\rangle n_\pi + \langle \sigma_{K\rho\to K^*\pi} v_{K\rho}\rangle n_\rho + \langle \sigma_{K\pi\to K^*} v_{K\pi}\rangle n_\pi .$$

## 2) K* and K meson abundances

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

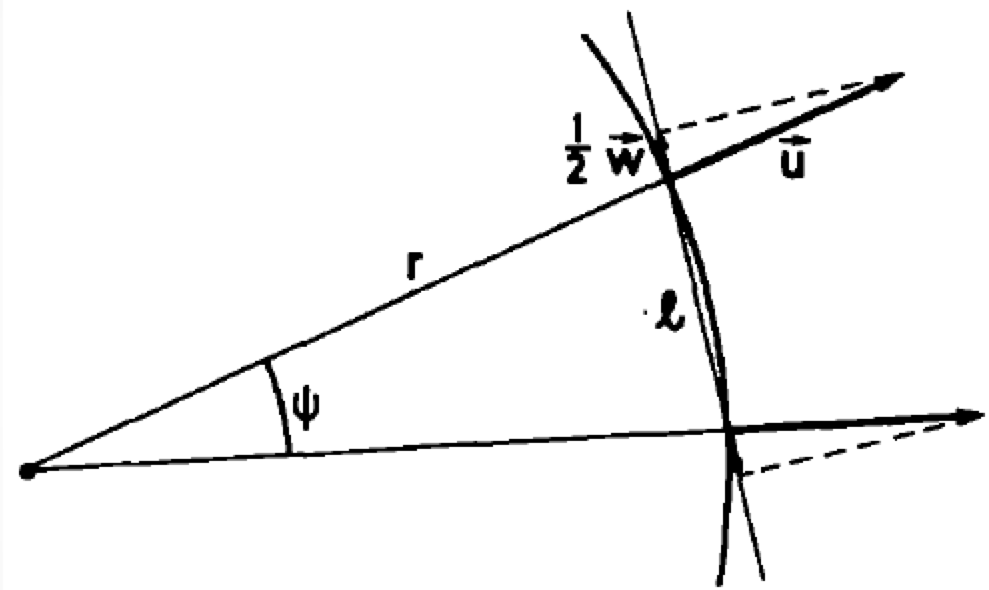
$$N_K(\tau) = \frac{\gamma_{K^*}}{\gamma} N^0 + \left(N^0_K - \frac{\gamma_{K^*}}{\gamma} N^0\right) e^{-\gamma(\tau-\tau_h)},$$

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



# 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 : $dR/dt \approx \langle v \rangle$

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

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 $\tau_{scatt} = \frac{\tau^{K}_{scatt} \tau^{K^*}_{scatt}}{\tau^{K}_{scatt} + \tau^{K^*}_{scatt}}$

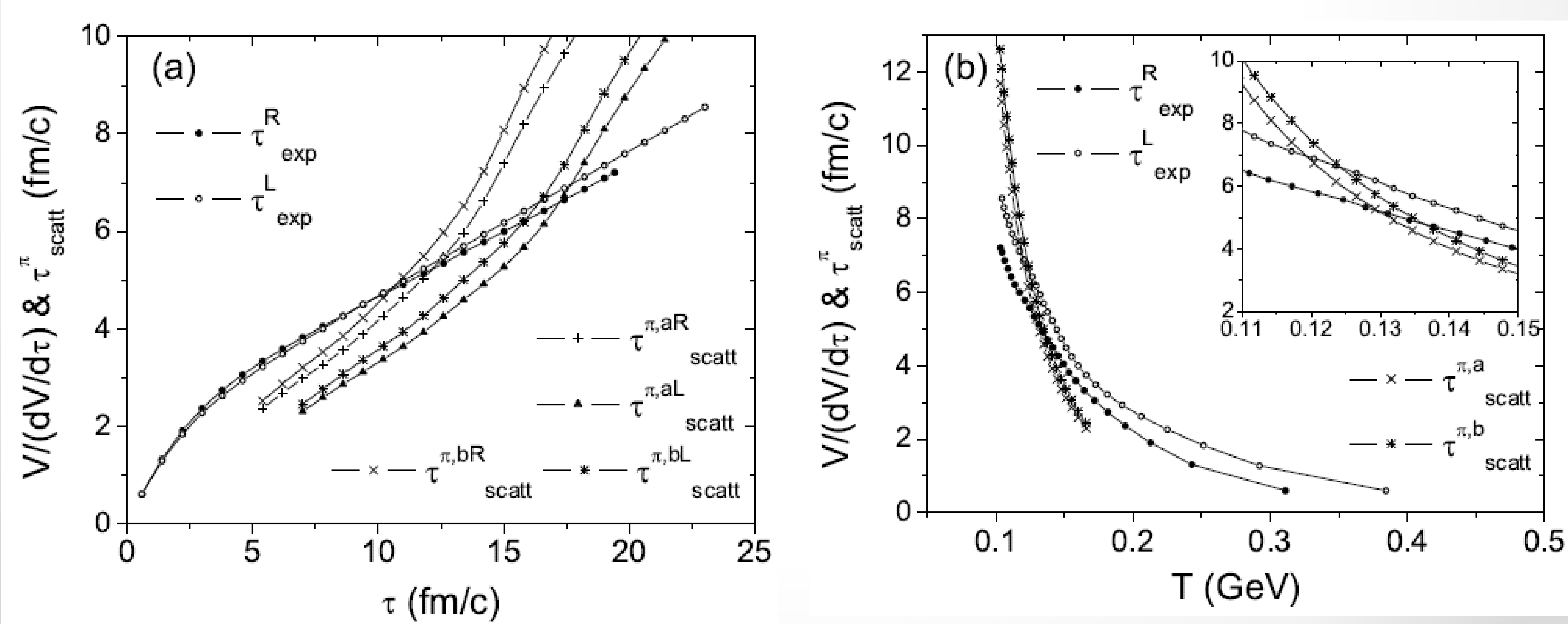
# – The freeze-out condition of the pion

## 1) The scattering time for pions

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

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)



# Conclusions

– Reduction of the K* meson abundance 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