Hadronic effects on the hadron abundances in heavy ion collisions

Strangeness in Quark Matter 2013

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Outline

- Introduction
- Hadronic interactions
- The X(3872) meson
- The K* meson
- Conclusions

Introduction

– Statistical model

P. Braun-Munzinger, J. Stachel, J. P. Wessels, N. Xu, Phys. Lett. **B344**, 43 (1995)
P. Braun-Munzinger, J. Stachel, J. P. Wessels, N. Xu, Phys. Lett. **B365**, 1 (1996)

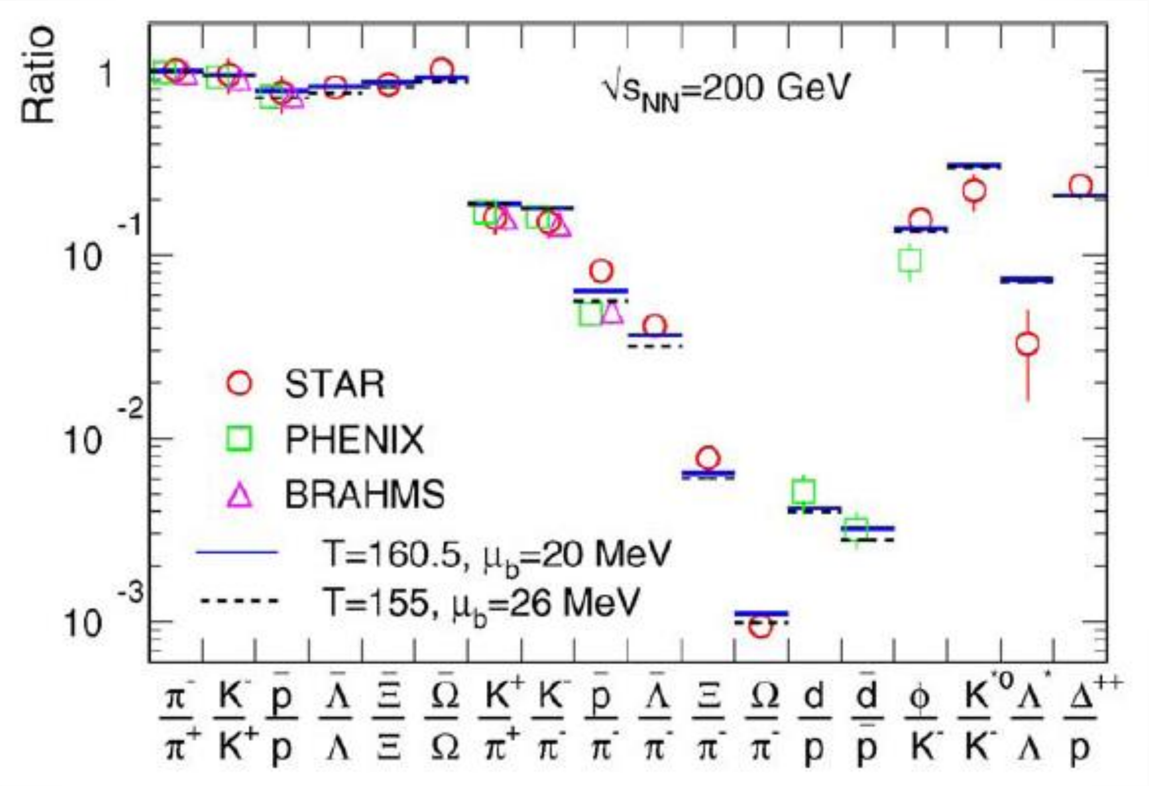
1) In a chemically and thermally equilibrated system of non-interacting hadrons and resonances, the particle production yield is given by

$$N_i = V_H \frac{g_i}{2\pi^2} \frac{1}{N_{BW}} \int_{M_0}^{\infty} dm \int_0^{\infty} \frac{\Gamma_i^2}{(m-m_i)^2 + \Gamma_i^2/4} \frac{p^2 dp}{\gamma_i^{-1} e^{E_i/T_H} \pm 1}$$

$$E_i = \sqrt{m_i^2 + p_i^2} \qquad \gamma = \gamma_c^{n_c + n_{\bar{c}}} e^{[\mu_B n_B + \mu_s n_s]}$$

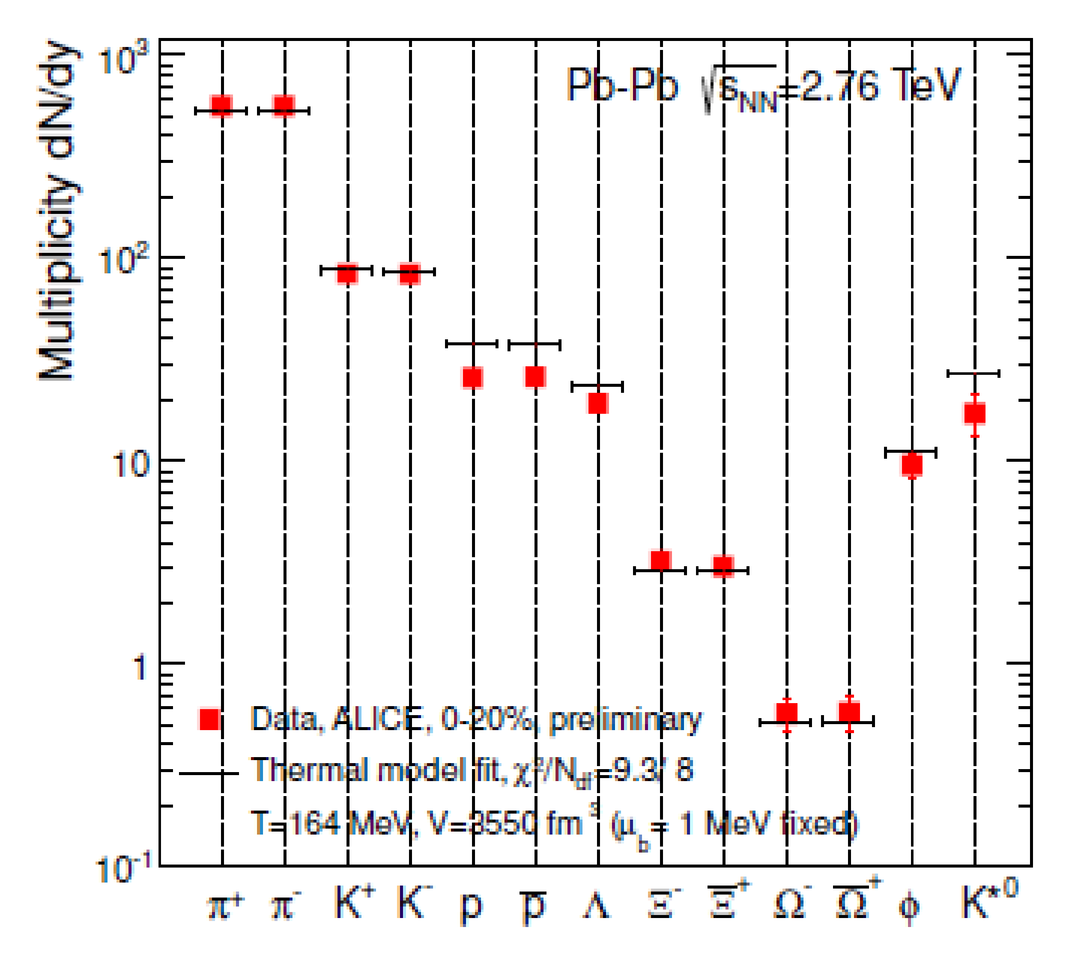
2) The hadronization temperature and the chemical potential are determined from the experimental data

3) Particle yields ratio at RHIC



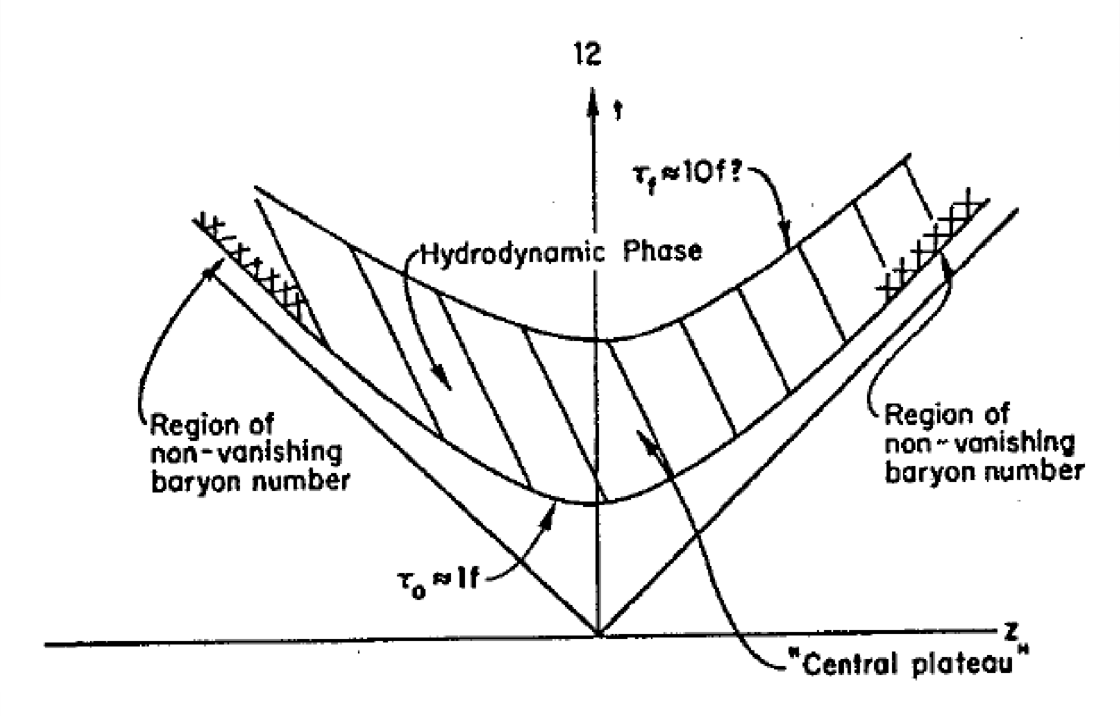
P. Braun-Munzinger, D. Magestro, K. Redlich, and J. Stachel, Phys. Lett. **B518**, 42 (2001)
A. Andronic, P. Braun-Munzinger, and J. Stachel, Nucl. Phys. A **772**, 167 (2006)

4) Particle yields ratio at LHC



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

– Time evolution of quark-gluon plasma



$$\tau = \sqrt{t^2 - z^2}$$

J. D. Bjorken, Phys. Rev. D **27**, 140 (1983)

i. Collision

ii. Pre-equilibrium state and Quark-gluon plasma

iii. Hydrodynamic expansion

iv. Chemical freeze-out v. Kinetic freeze-out

Hadronic interactions

– J/ψ suppression and Debye screening

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

1) At $T > T_C$ color charges are Debye screened in QGP
Compared to the Bohr radius r_B , the Debye screening prevents the formation of the bound states when $r_B > \lambda_D$

$$\lambda_D = \frac{1}{gT\sqrt{\frac{N_C}{3}+\frac{N_f}{6}}}$$

2) Possibilities of J/ψ absorption by hadronic interactions

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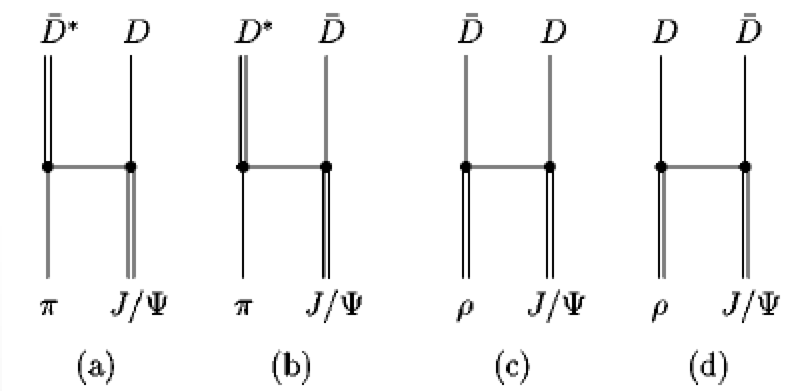
– Hadronic interactions

1) A perturbative approach at the quark level

D. Kharzeev and H. Satz, Phys. Lett. B **334**, 155 (1994)

2) A meson exchange model with an effective Lagrangian

Sergei G. Matinyan and Berndt Muller, Phys. Rev. C **58**, 2994 (1998)
Kelvin L. Haglin, Phys. Rev. C **61**, 031902(R) (2000)
Ziwei Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000)
Yongseok Oh, Taesoo Song, and Su Houng Lee, Phys. Rev. C **63**, 034901 (2000)
L. W. Chen, C. M. Ko, W. Liu, and M. Nielsen, Phys. Rev. C **76**, 014906 (2007)



The X(3872) meson

– X(3872) mesons

X(3872) $I^G(J^{PC}) = 0^?(?^{?+})$

Quantum numbers not established.

Mass $m = 3871.68 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

J. Beringer *et al*. (PDG), Phys. Rev. D**86**, 010001 (2012)

Only $J^{PC} = 1^{++}, 2^{-+}$ states are allowed :

A. Abulencia et al, [CDF Collaboration], Phys. Rev. Lett. **98**, 132002 (2007)

1) Expected production yields of X(3872) mesons

S. Cho *et al*. [ExHIC Collaboration], Phys. Rev. Lett. **106**, 212001 (2011)
S. Cho *et al*. [ExHIC Collaboration], Phys. Rev. C **84**, 064910 (2011)

$X(3872)$	Coal.(2q)	Coal.(4q)	Stat.
spin-1		4.0×10^{-5}	2.9×10^{-4}
spin-2	1.7×10^{-4}		4.8×10^{-4}

2) Interaction Lagrangians from the pseudoscalar and vector mesons free Lagrangians

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

$$P = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta + \frac{\eta_c}{\sqrt{12}} & D_s^- \\ D^0 & D^+ & D_s^+ & -\frac{3\eta_c}{\sqrt{12}} \end{pmatrix} \quad V = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega'}{\sqrt{6}} + \frac{J/\psi}{\sqrt{12}} & \rho^+ & K^{*+} & \overline{D^{*0}} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega'}{\sqrt{6}} + \frac{J/\psi}{\sqrt{12}} & K^{*0} & D^{*-} \\ K^{*-} & \overline{K^{*0}} & -\sqrt{\frac{2}{3}}\omega' + \frac{J/\psi}{\sqrt{12}} & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & -\frac{3J/\psi}{\sqrt{12}} \end{pmatrix}$$

$$\mathcal{L}_{\pi DD^*} = i g_{\pi DD^*} D^{*\mu} \vec{\tau} \cdot (\bar{D} \partial_\mu \vec{\pi} - \partial_\mu \bar{D} \vec{\pi}) + \mathrm{H.c.},$$

$$\mathcal{L}_{\psi DD} = i g_{\psi DD} \psi^\mu (D \partial_\mu \bar{D} - \partial_\mu D \bar{D}),$$

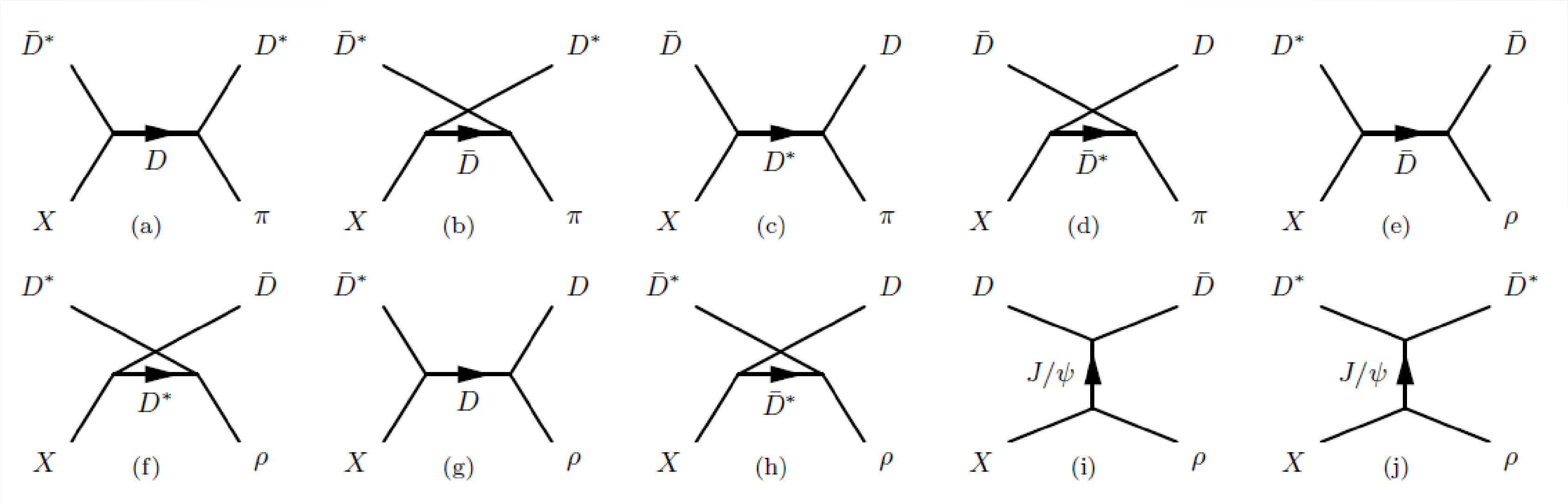
$$\begin{aligned}\mathcal{L}_{\psi D^* D^*} = i g_{\psi D^* D^*} [& \psi^\mu (\partial_\mu D^{*\nu} \bar{D}^*_\nu - D^{*\nu} \partial_\mu \bar{D}^*_\nu) \\ & + (\partial_\mu \psi^\nu D^*_\nu - \psi^\nu \partial_\mu D^*_\nu) \bar{D}^{*\mu} \\ & + D^{*\mu} (\psi^\nu \partial_\mu \bar{D}^*_\nu - \partial_\mu \psi^\nu \bar{D}^*_\nu)],\end{aligned}$$

$$\mathcal{L}_{\rho DD} = i g_{\rho DD} (D \vec{\tau} \partial_\mu \bar{D} - \partial_\mu D \vec{\tau} \bar{D}) \cdot \vec{\rho}^\mu,$$

$$\begin{aligned}\mathcal{L}_{\rho D^* D^*} = i g_{\rho D^* D^*} [& (\partial_\mu D^{*\nu} \vec{\tau} \bar{D}^*_\nu - D^{*\nu} \vec{\tau} \partial_\mu \bar{D}^*_\nu) \cdot \vec{\rho}^\mu \\ & + (D^{*\nu} \vec{\tau} \cdot \partial_\mu \vec{\rho}_\nu - \partial_\mu D^{*\nu} \vec{\tau} \cdot \vec{\rho}_\nu) \bar{D}^{*\mu} \\ & + D^{*\mu} (\vec{\tau} \cdot \vec{\rho}^\nu \partial_\mu \bar{D}^*_\nu - \vec{\tau} \cdot \partial_\mu \vec{\rho}^\nu \bar{D}^*_\nu)],\end{aligned}$$

3) The absorption of X(3872) by pions and rho mesons

$$X\pi \to D^*\bar{D}^*,\ X\pi \to D\bar{D},\ X\rho \to D\bar{D}^*,\ X\rho \to \bar{D}D^*,\ X\rho \to \bar{D}D,\ X\rho \to \bar{D}^*D^*$$



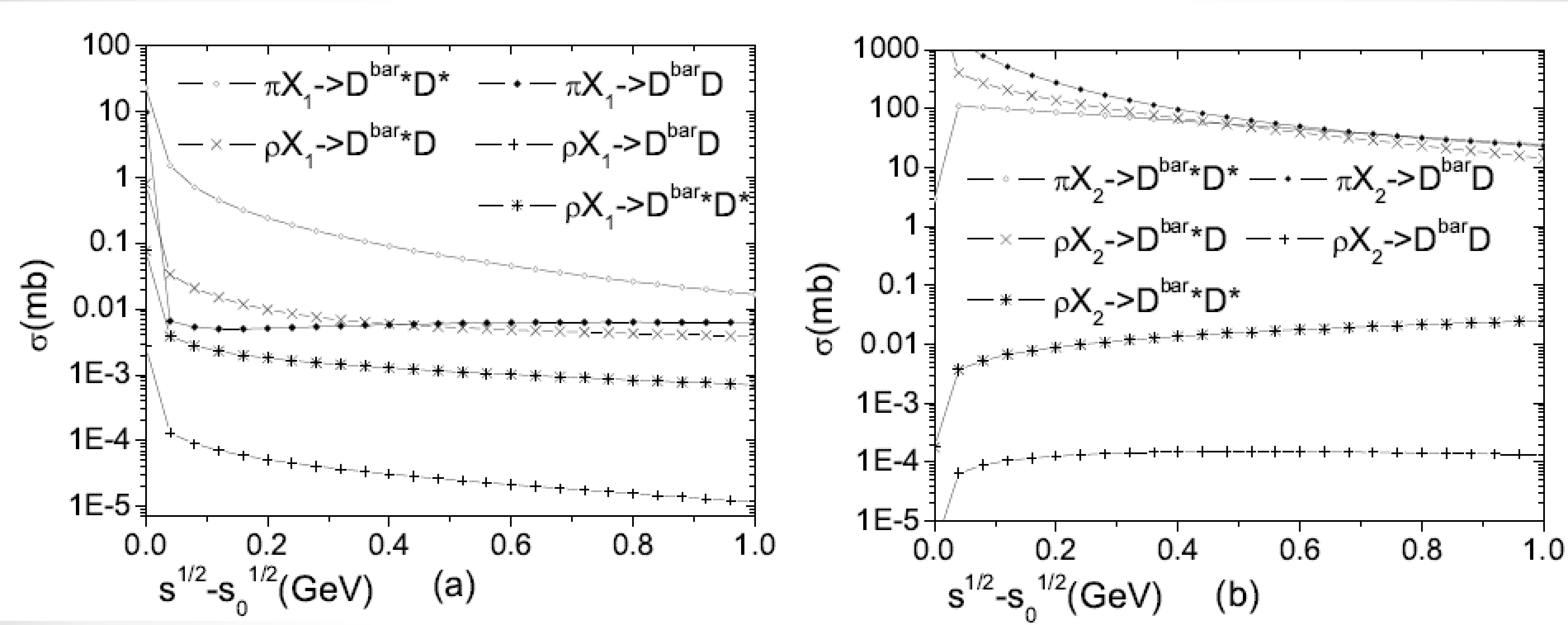
4) Interaction Lagrangians for two kinds of X(3872) mesons

F. Brazzi, B. Grinstein, F. Piccinini, A. D. Polosa, and C. Sabelli, Phys. Rev. D **84**, 014003 (2011)

$$\begin{aligned}
\mathcal{L}_{X_1 D^* D} &= g_{X_1 D^* D} X_1^{\mu} \bar{D}^*_{\mu} D, \\
\mathcal{L}_{X_1 \psi\rho} &= i g_{X_1 \psi\rho} \epsilon^{\mu\nu\rho\sigma} \psi_{\nu} \rho_{\rho} \partial_{\sigma} X_{1\mu}, \\
\mathcal{L}_{X_2 D^* D} &= -i g_{X_2 D^* D} X_2^{\mu\nu} \bar{D}^*_{\mu} \partial_{\nu} D, \\
\mathcal{L}_{X_2 \psi\rho} &= -g_{X_2 \psi\rho} \epsilon^{\mu\nu\rho\sigma} X_{\mu\alpha} (\partial_{\nu}\psi^{\alpha}\partial_{\rho}\rho_{\sigma} - \partial_{\nu}\psi^{\alpha}\partial_{\rho}\rho_{\sigma}) \\
&\quad + g'_{X_2 \psi\rho} \epsilon^{\mu\nu\rho\sigma} \partial_{\nu} X_{\mu\alpha} (\partial^{\alpha}\psi_{\rho}\rho_{\sigma} - \psi_{\rho}\partial^{\alpha}\rho_{\sigma}).
\end{aligned}$$

5) Cross sections for different X(3872) meson quantum numbers

Sungtae Cho and Su Houng Lee, arXiv:1302.6381



Thermally averaged cross sections

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

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

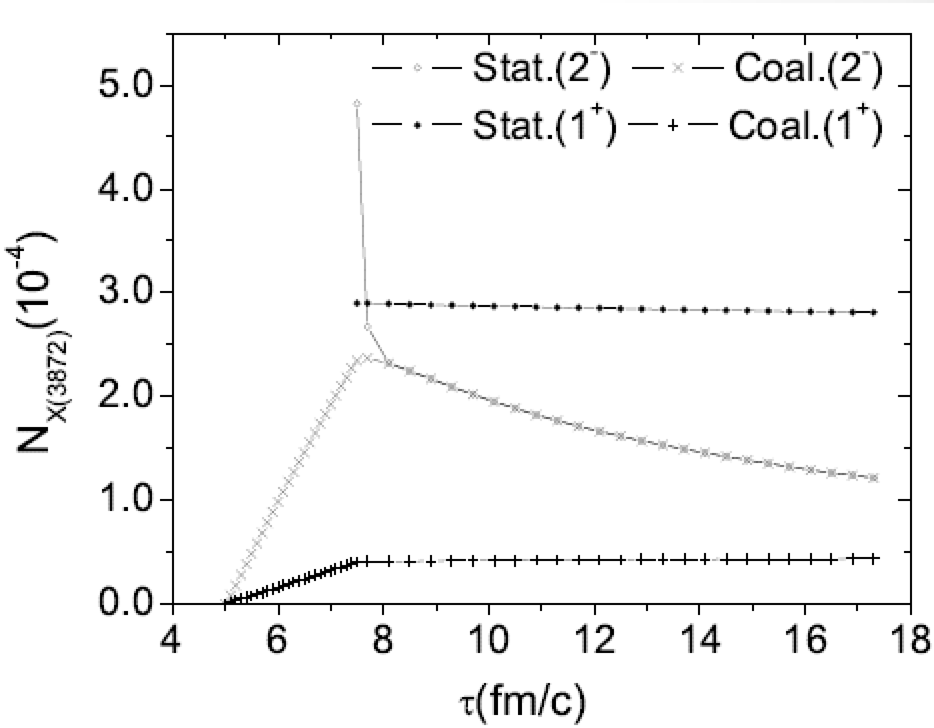
– Time evolution of the X(3872) meson yields

$$\frac{dN_X(\tau)}{d\tau} = R_{QGP}(\tau) + \sum_{a,c,c'} \left(\langle \sigma_{cc' \to aX} v_{cc'} \rangle n_c(\tau) N_{c'}(\tau) - \langle \sigma_{aX \to cc'} v_{aX} \rangle n_a N_X(\tau) \right)$$

1) The yield of the X(3872) meson with spin 2 varies drastically and follows the statistical model predictions

2) The yield increases or remains almost unchanged in both the statistical model and coalescence model for the spin 1 state of X(3872)

3) Time evolution of the X(3872) meson abundance is strongly dependent also on its quantum number and its structure



4) The spin of the X(3872) meson

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PRL **110,** 222001 (2013) PHYSICAL REVIEW LETTERS week ending 31 MAY 2013

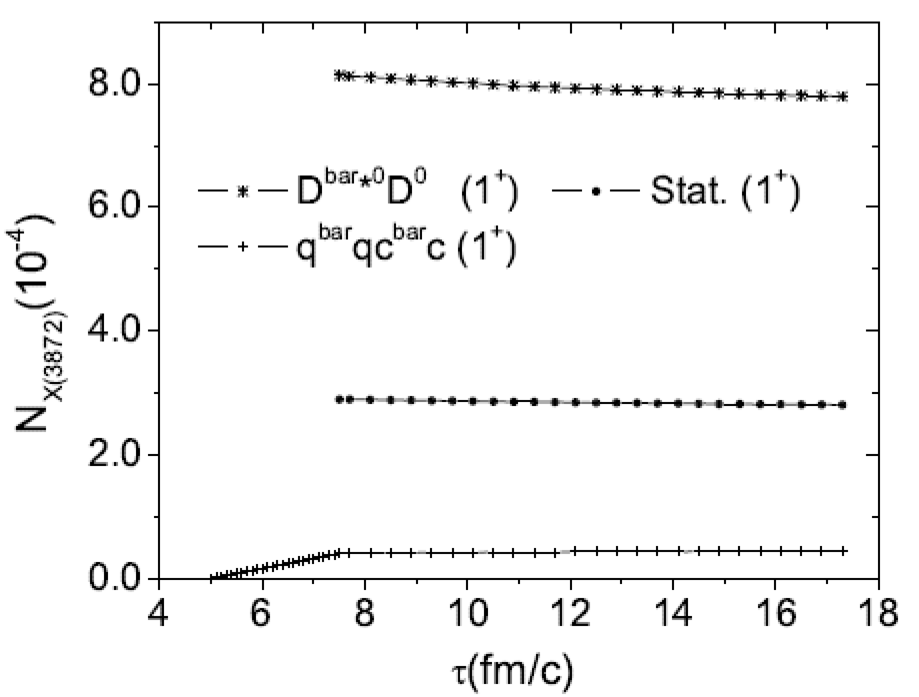
Determination of the *X*(3872) Meson Quantum Numbers

R. Aaij *et al.**
(LHCb Collaboration)
(Received 25 February 2013; published 29 May 2013)

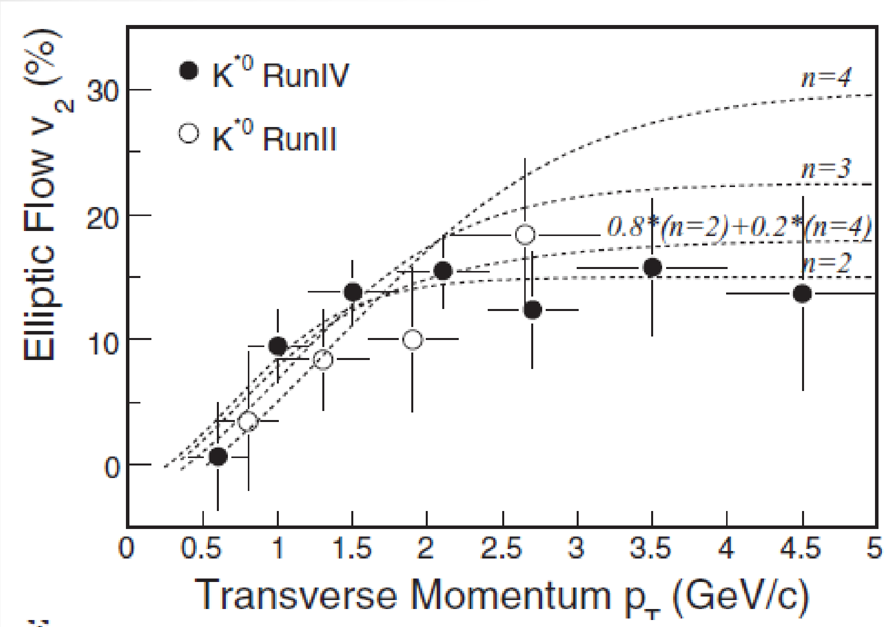
***X*(3872)** $I^G(J^{PC}) = 0^+(1^{++})$

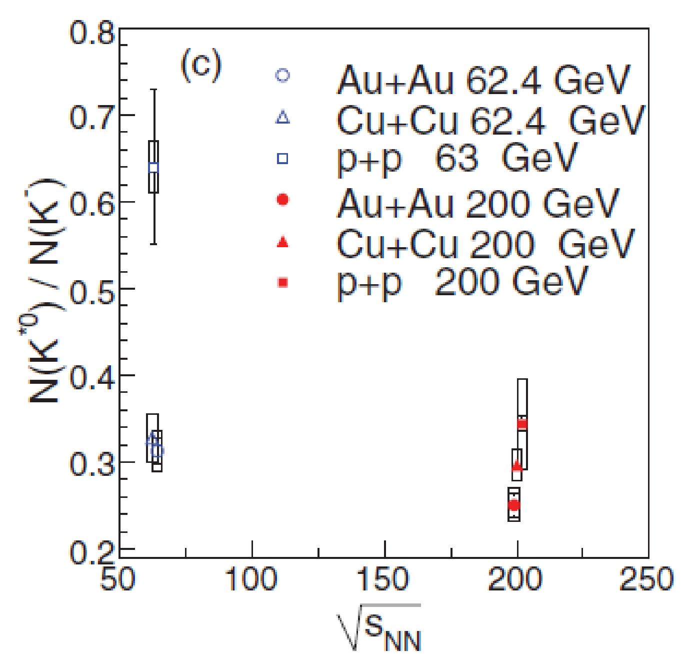
Mass $m = 3871.68 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

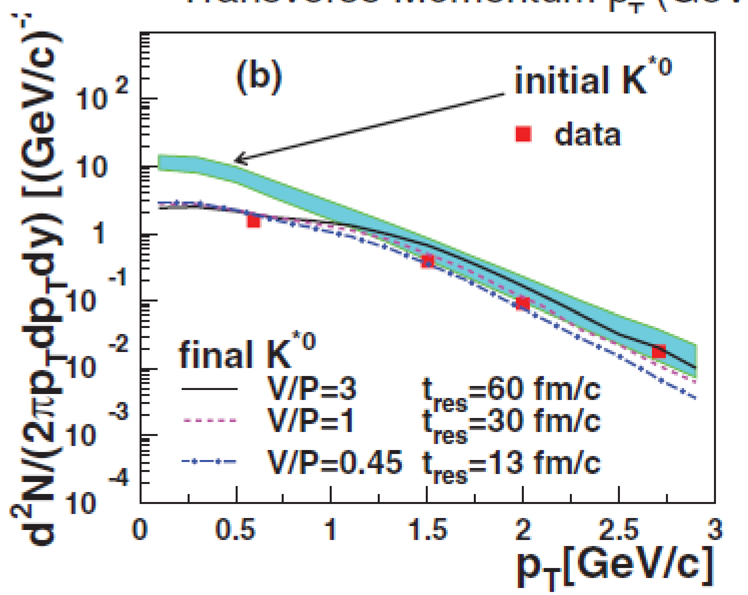
5) Time evolutions of the spin-1 X(3872) meson abundance



The K* meson







M. M. Aggarwal et al, [STAR Collaboration],
Phys. Rev. C **84**, 034909 (2011)

Kai. Zhang, Jun Song, and Feng-lan Shao,
Phys. Rev. C **86**, 014906 (2012)

– Hadronic effects on the K* meson

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

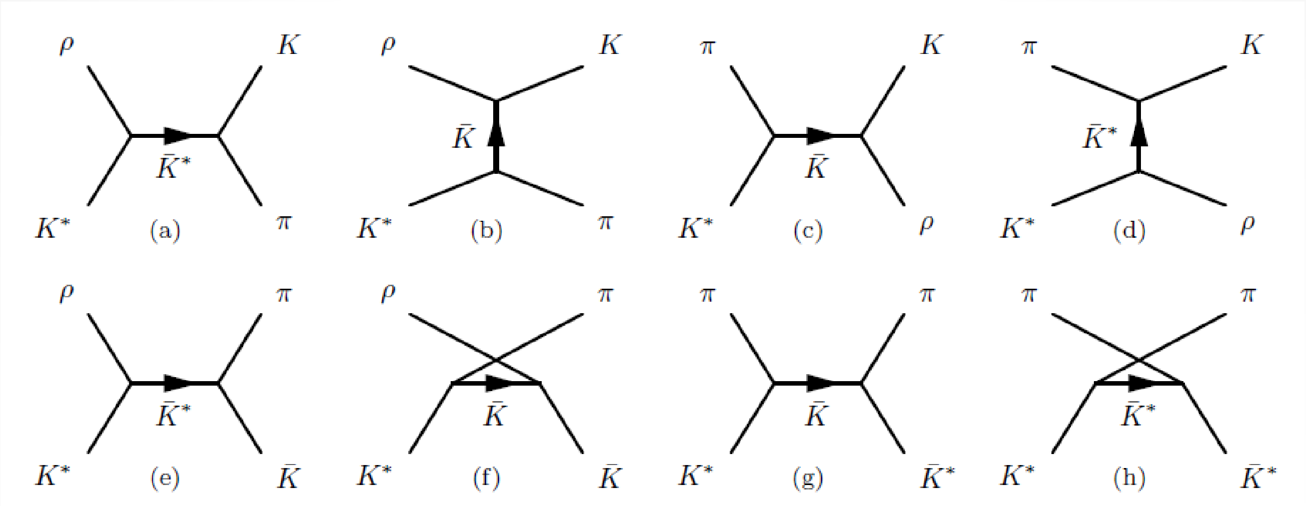
$$\mathcal{L}_0 = \mathrm{Tr}(\partial_\mu P^\dagger \partial^\mu P) - \frac{1}{2}\mathrm{Tr}(F^\dagger_{\mu\nu} F^{\mu\nu}),$$

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

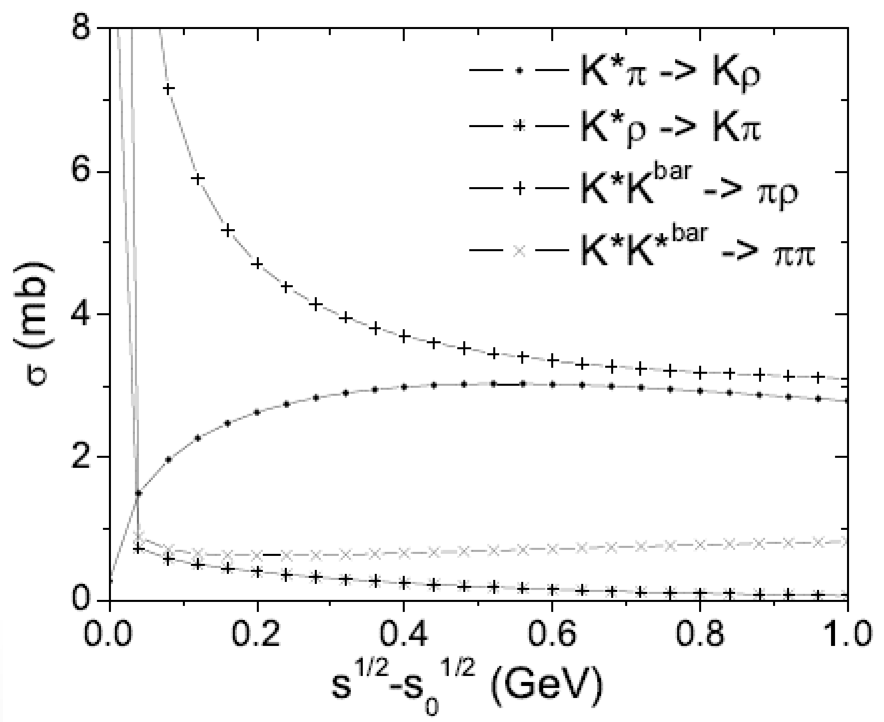
$$P = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_1}{\sqrt{3}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta_8 + \frac{\eta_1}{\sqrt{3}} \end{pmatrix}$$

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

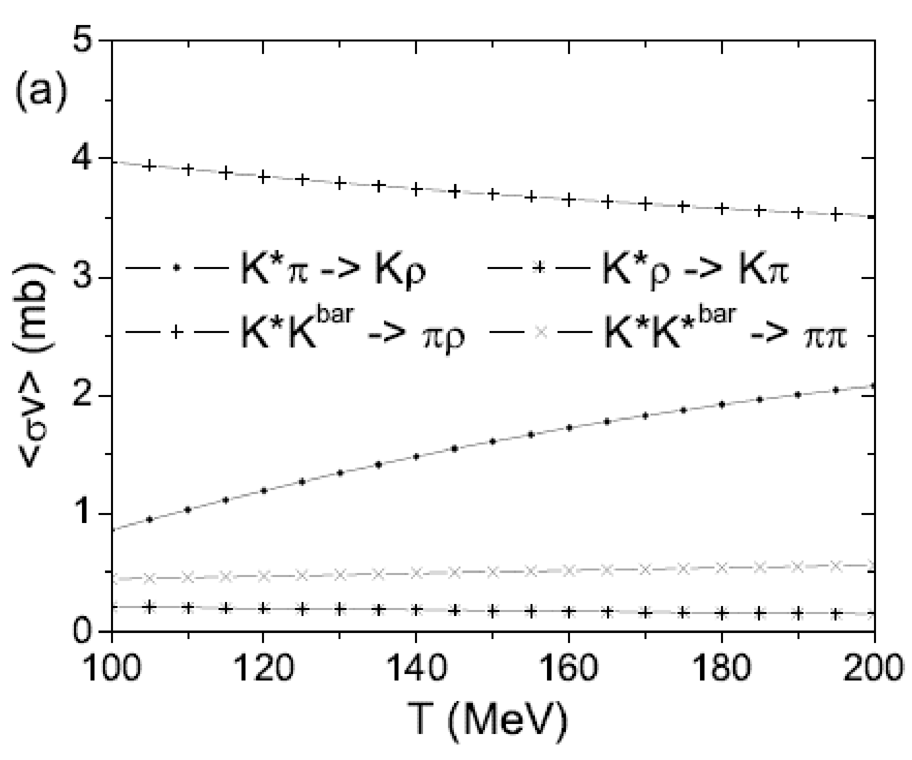
2) The absorption of K* mesons by pions, rho and K mesons

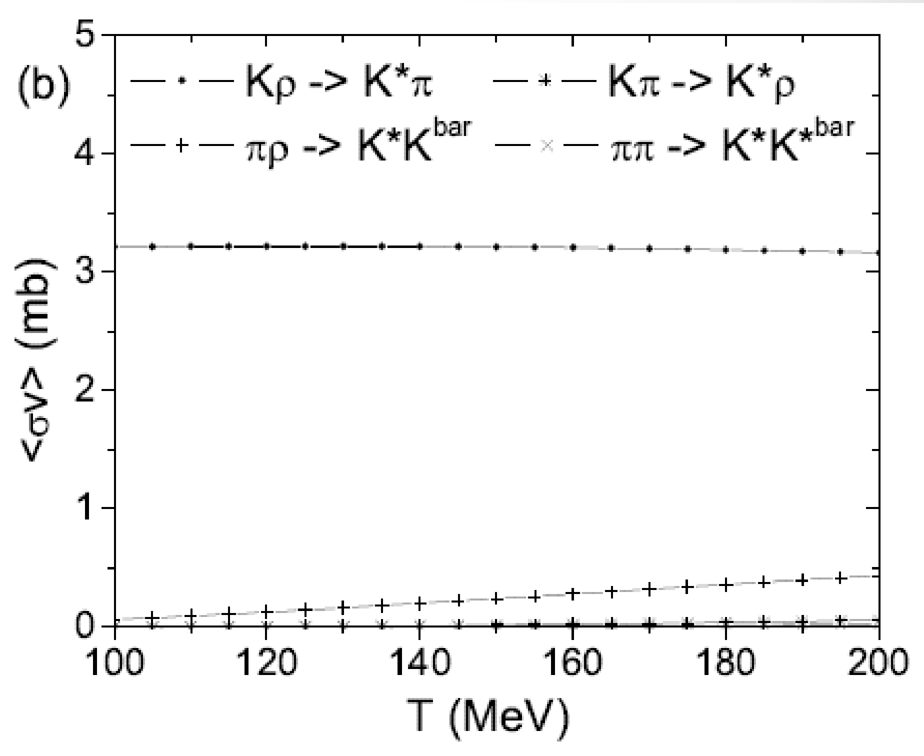


3) Cross sections for K* meson



4) Thermally averaged cross sections

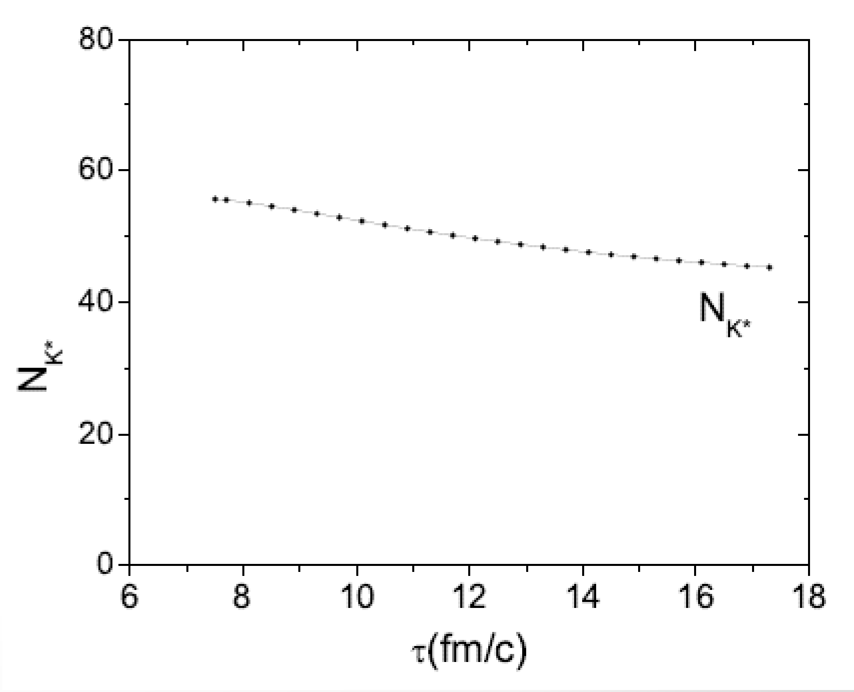




5) Time evolution of the K* meson abundances

$$\frac{dN_{K^*}(\tau)}{d\tau} = \sum_{a,b,c}\left(\langle\sigma_{ab\to cK^*}v_{ab}\rangle n_a(\tau)N_b(\tau) \ -\langle\sigma_{cK^*\to ab}v_{cK^*}\rangle n_c(\tau)N_{K^*}(\tau)\right)$$

The abundance of the K* meson decreases by about 20% during the hadronic stage of heavy ion collisions



Conclusions

– Hadronic effects on the hadron abundances in heavy ion collisions

1) Studying both the initial production yields of hadrons and their evolution in time during the hadronic stage is necessary in order to have a better understanding of the hadronization process in heavy ion collision experiments

2) The spin and structure of the X(3872) meson can be identified by investigating the interaction of X(3872) mesons with light hadrons in the hadronic medium

3) The decrease of the K* meson abundance can be explained by the hadronic interaction during the hadroni stage of heavy ion collisions

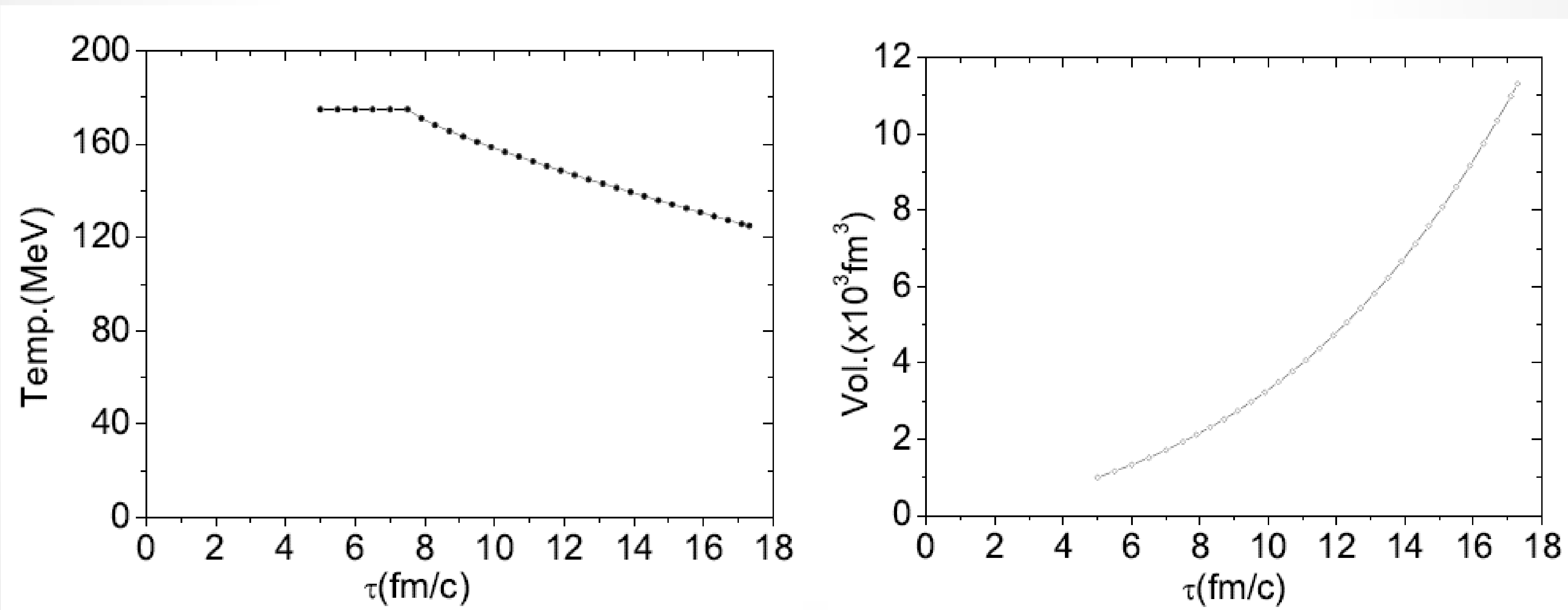
Backup slides

– Dynamics of relativistic heavy ion collisions

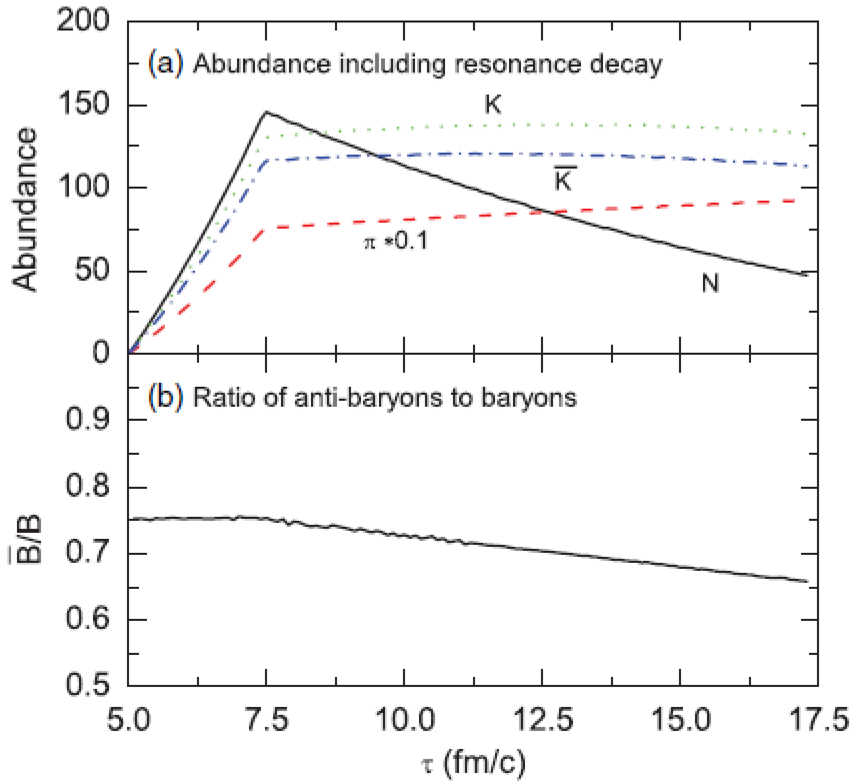
$$T(\tau) = T_C - (T_H - T_F)\left(\frac{\tau - \tau_H}{\tau_F - \tau_H}\right)^{4/5}$$

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

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



– Time evolution of hadron abundances



Lie-Wien Chen, V. Greco, C. M. Ko, S. H. Lee, W. Lin, Phys. Lett. B **601**, 34 (2004)

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