Hadronic effects on exotic hadron production in heavy ion collisions

Heavy Ion Meeting
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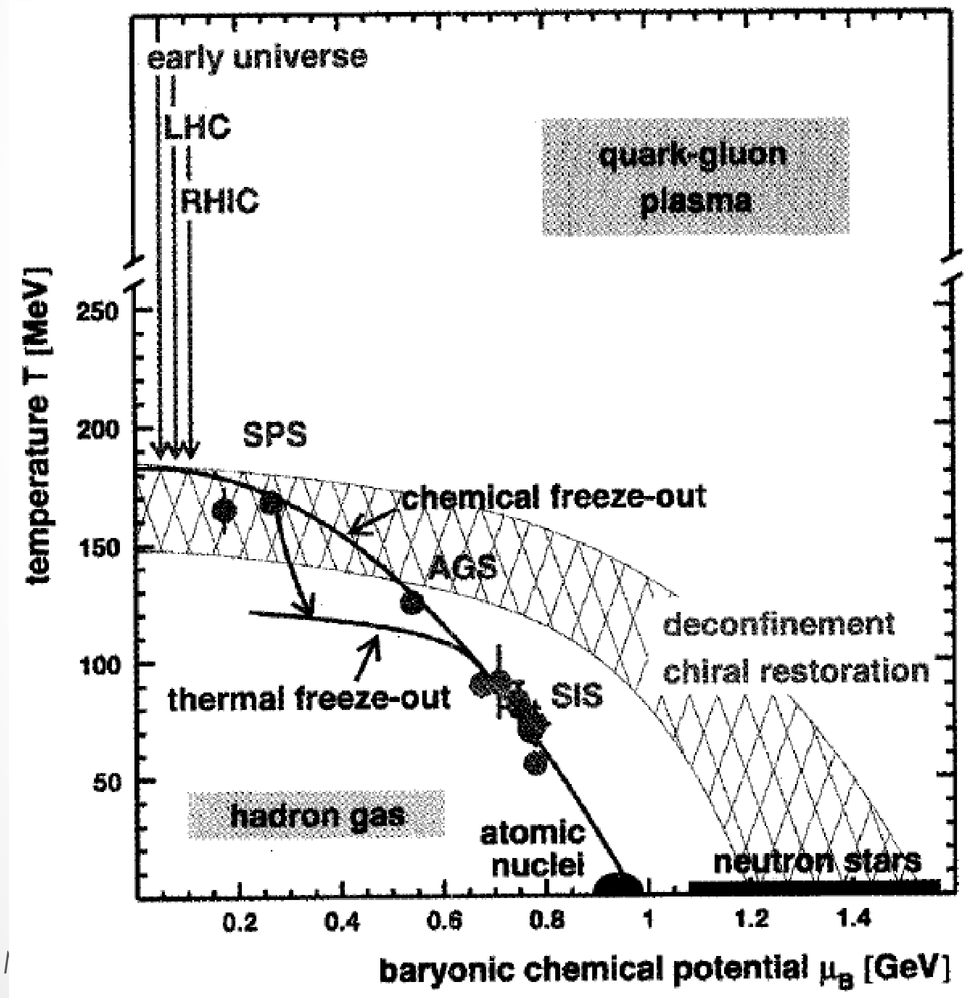
Outline

- Introduction
- Production yields
- Exotic Hadrons from heavy ion collisions
- Hadronic interactions
- The X(3872) meson
- Conclusions

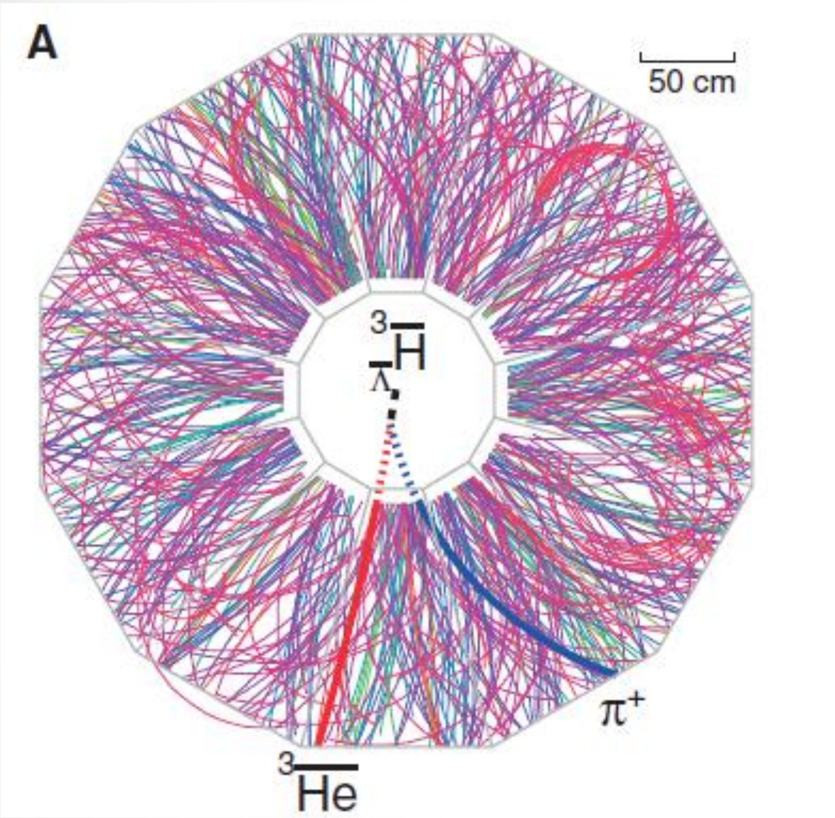
Introduction

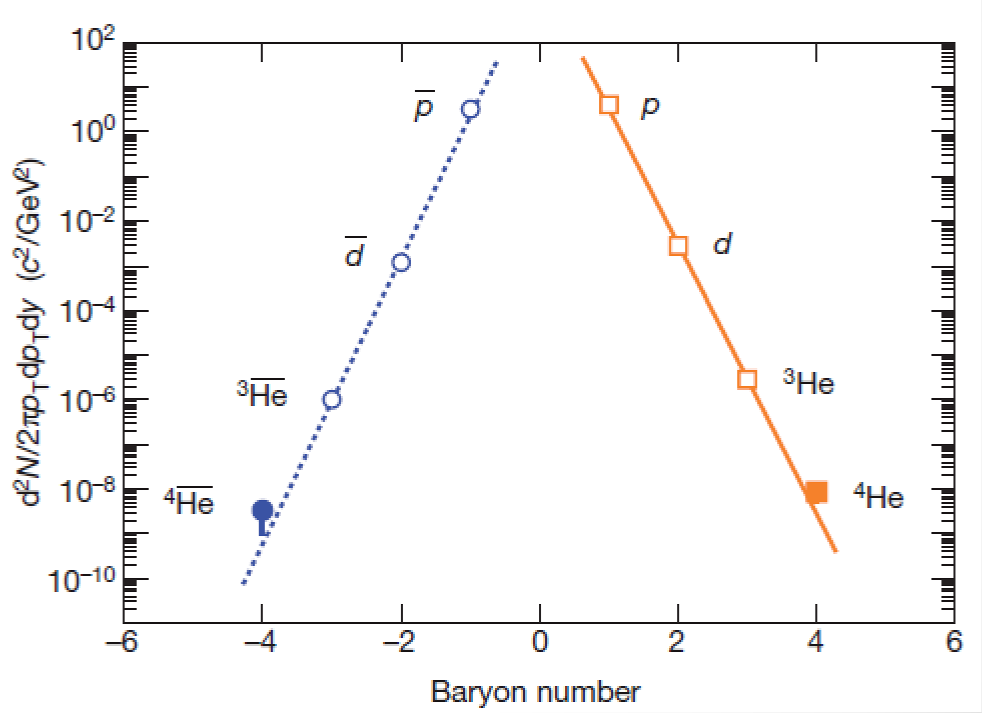
– Relativistic heavy ion collisions



P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **690**, 119c (2001)

– Observation of the antimatter hyper-nucleus and the antimatter helium-4 nucleus

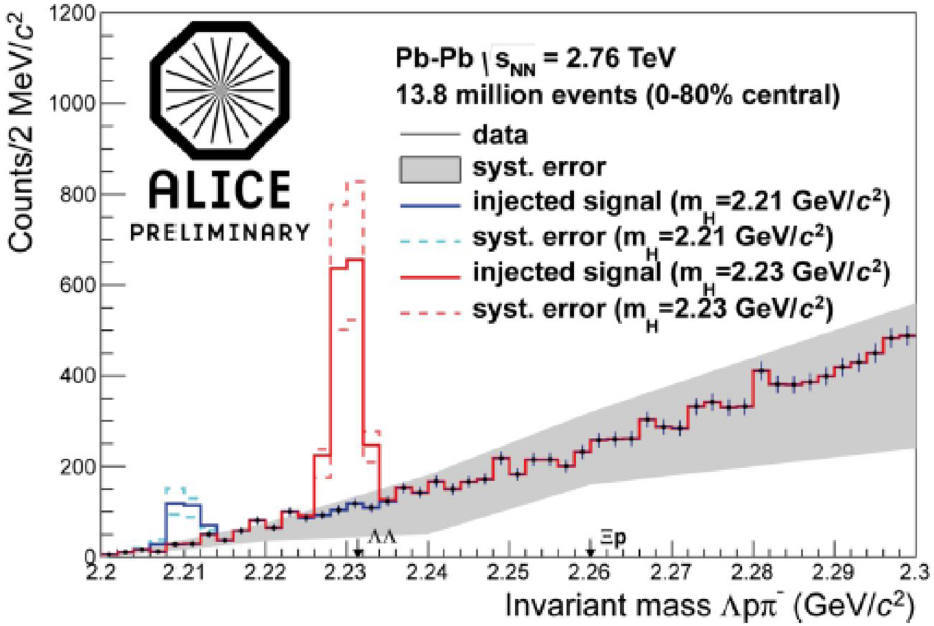




B. Abelev *et al*. [The STAR Collaboration], Science, **328**, 58 (2010)
H. Agakachiev *et al*. [The STAR Collaboration], Nature, **473**, 353 (2011)

– Search for the H-Dibaryon

H-Dibaryon



- No signal visible

From the non observation we obtain as upper limits:

For a strongly bound H:

→ d*N*/dy ≤ 8.4×10^{-4} (99% CL)

For a lightly bound H:

→ d*N*/dy ≤ 2×10^{-4} (99% CL)

Thermal model prediction is d*N*/dy=3.1×10^{-3} → thermal model would need to be wrong by a factor ~10

Benjamin Donigus, [ALICE Collaboration], Quark Matter 2012 presentation

Production yields

– Statistical model

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

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

$$N_i = V_H \frac{g_i}{2\pi^2} \int_0^{\infty} \frac{p^2 dp}{\gamma_i^{-1} e^{E_i/T_H} \pm 1} \qquad E_i = \sqrt{m_i^2 + p_i^2}$$

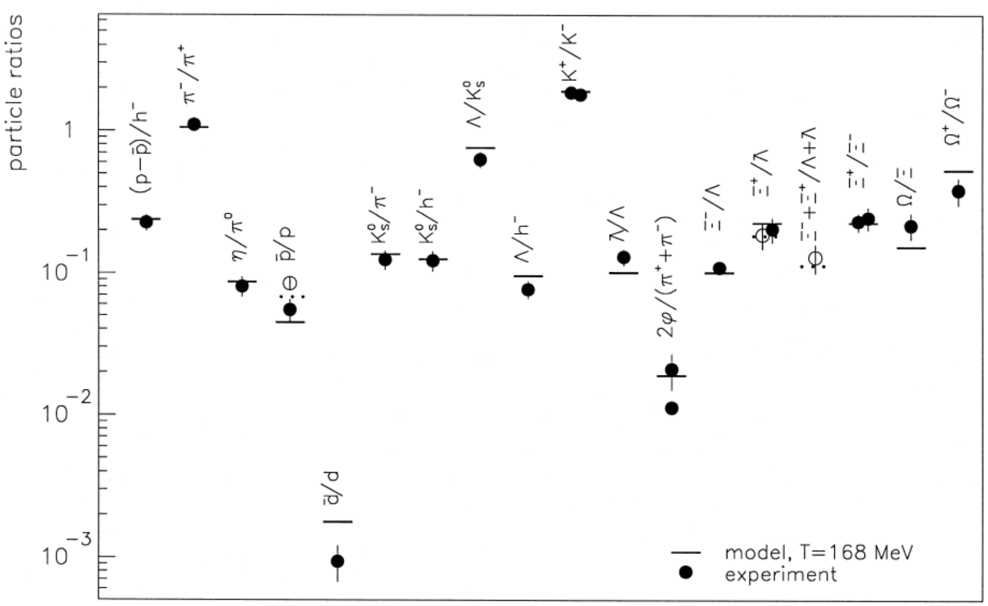
$$\gamma = \gamma_c^{n_c + n_{\bar{c}}} e^{[\mu_B n_B + \mu_s n_s]}$$

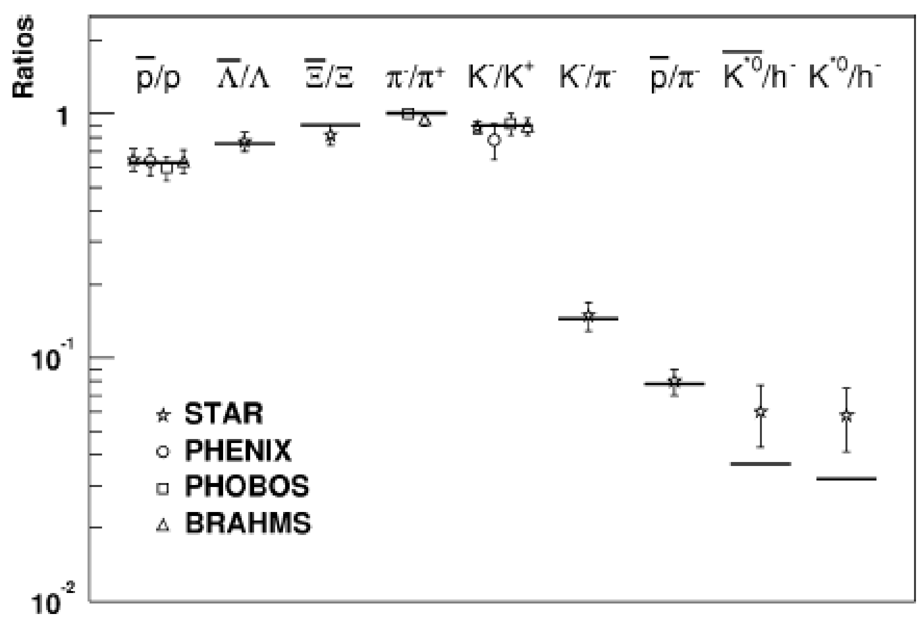
2) The hadronization temperature and the chemical potential are determined from the experimental data

3) Particle yields ratio at SPS and RHIC

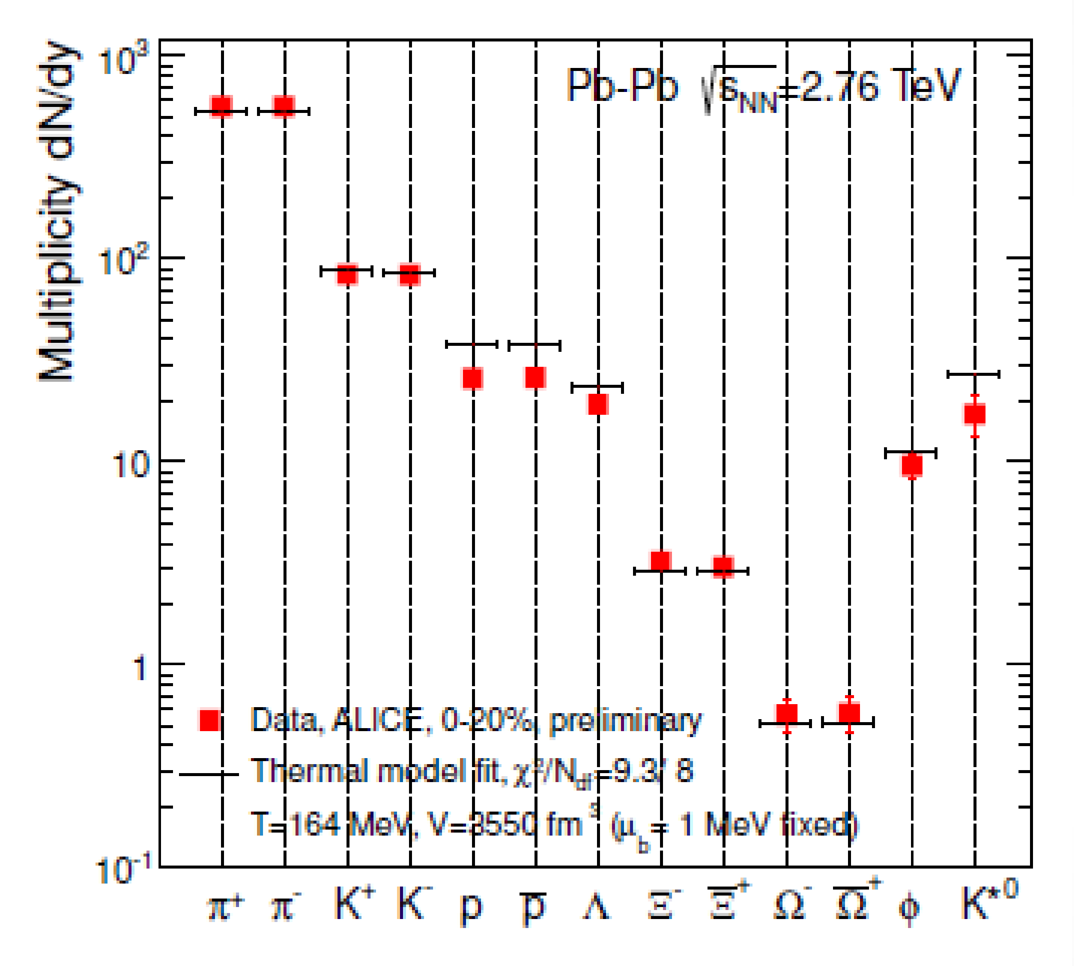
P. Braun-Munzinger, I. Heppe, and J. Stachel, Phys. Lett. **B465**, 15 (1999)
P. Braun-Munzinger, D. Magestro, K. Redlich, and J. Stachel, Phys. Lett. **B518**, 42 (2001)

T=168 MeV and μ_B = 266 MeV at $\sqrt{s}$ = 17.3 GeV, the SPS
T=174 MeV and μ_B = 46 MeV at $\sqrt{s}$ =130 GeV, RHIC
T=177 MeV and μ_B = 29 MeV at $\sqrt{s}$ = 200 GeV, RHIC





4) Particle yields ratio at LHC



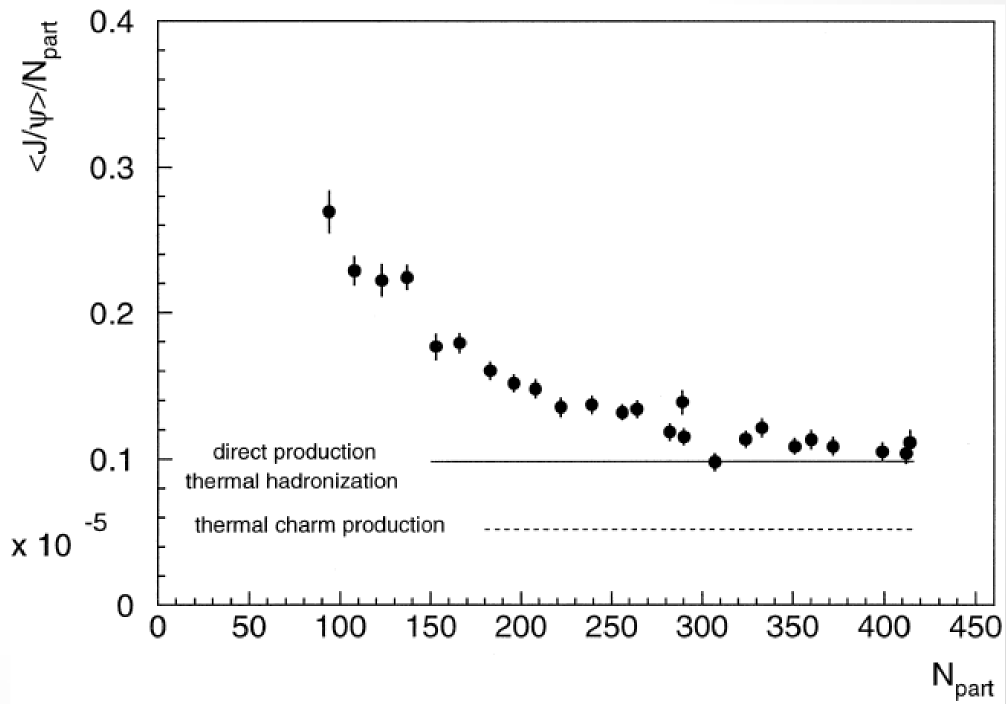
A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, arXiv:1210.7724

5) A scenario for charm quark hadron production

P. Braun-Munzinger and J. Stachel, Phys. Lett. **B490**, 196 (2000)

i. The charmonia are heavy with their masses much larger than any conceivable temperature : not of thermal origin

ii. All $c\bar{c}$ pairs are produced in direct, hard collisions. On the other hand, hadron production of charmed mesons and baryons, proceeds through a state of chemical equilibrium near or at the phase boundary between hadron matter and quark-gluon plasma



– Coalescence model

H. Sato and K. Yazaki, Phys. Lett. B **98**, 153 (1981)
Carl B. Dover, Ulrich. Heinz, Ekkard Schnedermann, Jozsef Zimanni, Phys. Rev. C **44**, 1636 (1991)

1) Yields of hadrons with n constituents

$$N^{Coal} = g \int \left[\prod_{i=1}^{n} \frac{1}{g_i} \frac{p_i \cdot d\sigma_i}{(2\pi)^3} \frac{d^3 p_i}{E_i} f(x_i, p_i) \right] f^W(x_1, \cdots, x_n : p_1, \cdots, p_n)$$

describe the dynamic process of converting constituents to a bound state in the presence of a partonic matter

$$f^W(x_1, \cdots, x_n : p_1, \cdots, p_n) = \int \prod_{i=1}^{n} dy_i e^{p_i y_i} \psi^* \left(x_1 + \frac{y_1}{2}, \cdots, x_n + \frac{y_n}{2} \right) \psi \left(x_1 - \frac{y_1}{2}, \cdots, x_n - \frac{y_n}{2} \right)$$

: Wigner function, the coalescence probability function

2) The puzzle in antiproton/pion ratio

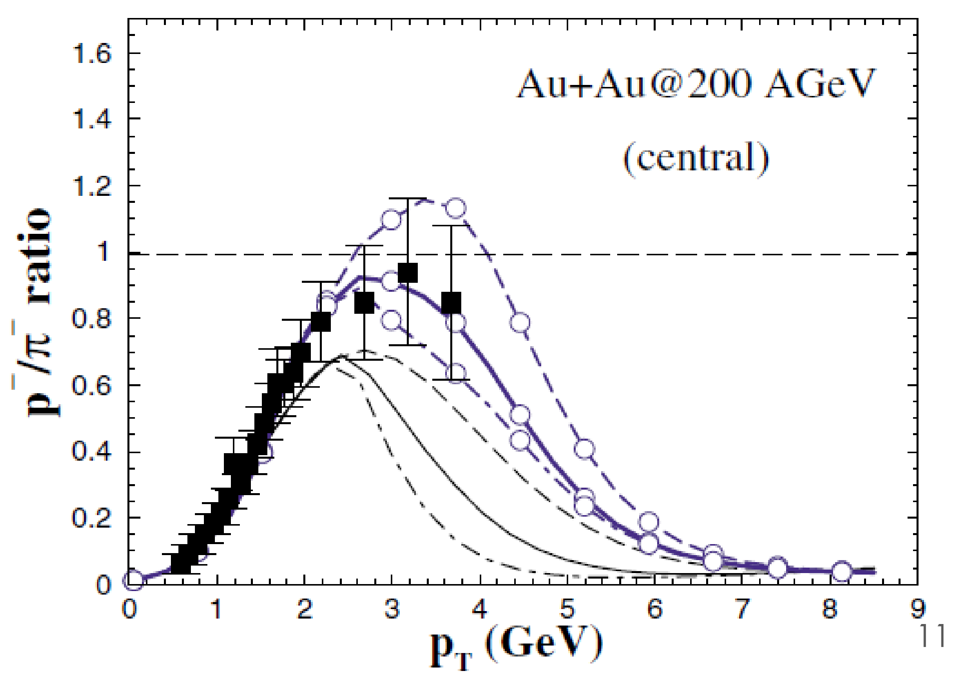
V. Greco, C. M. Ko, and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003)

R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. Lett. **90**, 202303 (2003)

i. There must be a competition between two particle production mechanisms

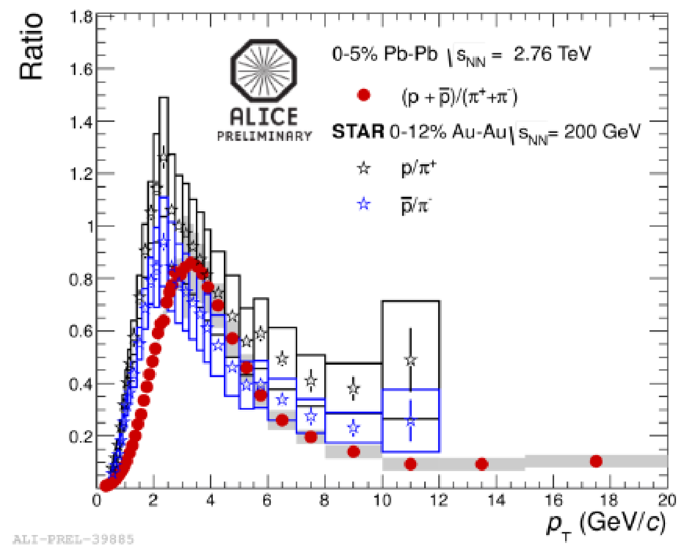
: A fragmentation dominates at large transverse momenta and a coalescence prevails at lower transverse momenta

$$p_T^{Frag} = \frac{p_T^h}{z} \quad \text{vs.} \quad p_T^{Coal} = \frac{p_T^h}{n}$$



ii. Recent results at LHC

Intermediate p_T region: comparison with RHIC



STAR data not feed-down corrected

Intermediate p_T: 3-7 GeV/c, enhancement of the baryon to meson ratio.
Qualitatively comparable to RHIC results but maximum is shifted.

14th August 2012 Results on identified particle spectra from ALICE - M. Ivanov (GSI) 31

Marian Ivanov, [ALICE Collaboration] Quark Matter 2012 presentation

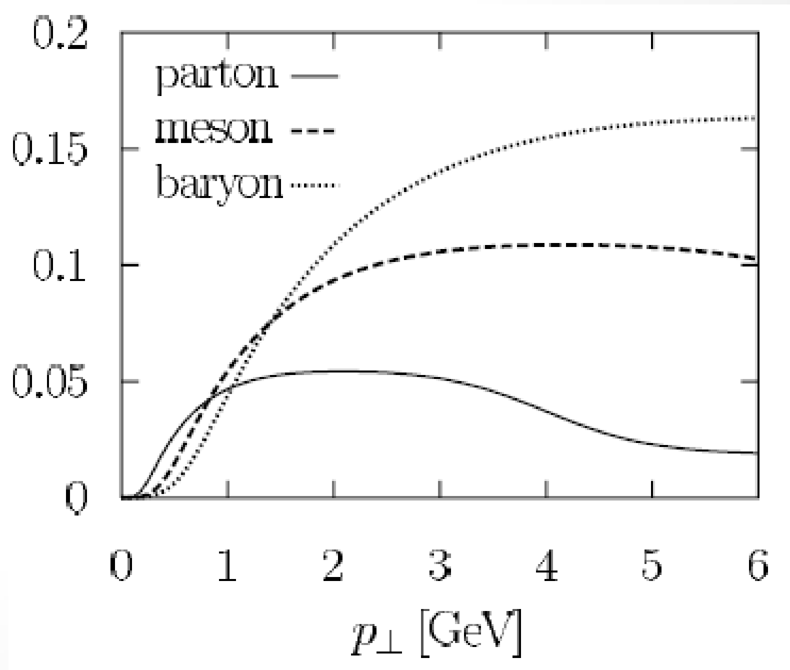
3) Quark number scaling of the elliptic flow

Denes Molnar and Sergei A. Voloshin, Phys. Rev. Lett **91**, 092301 (2003)

$$v_2(p_T) = \langle \cos 2\varphi \rangle_{p_T} = \frac{\int d\varphi \cos 2\varphi \frac{d^2N}{dp_T^2}}{\int d\varphi \frac{d^2N}{dp_T^2}}$$

i. Assumption : partons have elliptical anisotropy

$$\frac{dN_q}{p_T dp_T d\varphi} = \frac{1}{2\pi} \frac{dN_q}{p_T dp_T} \left[1 + 2v_{2,q}(p_T)\cos(2\varphi)\right]$$



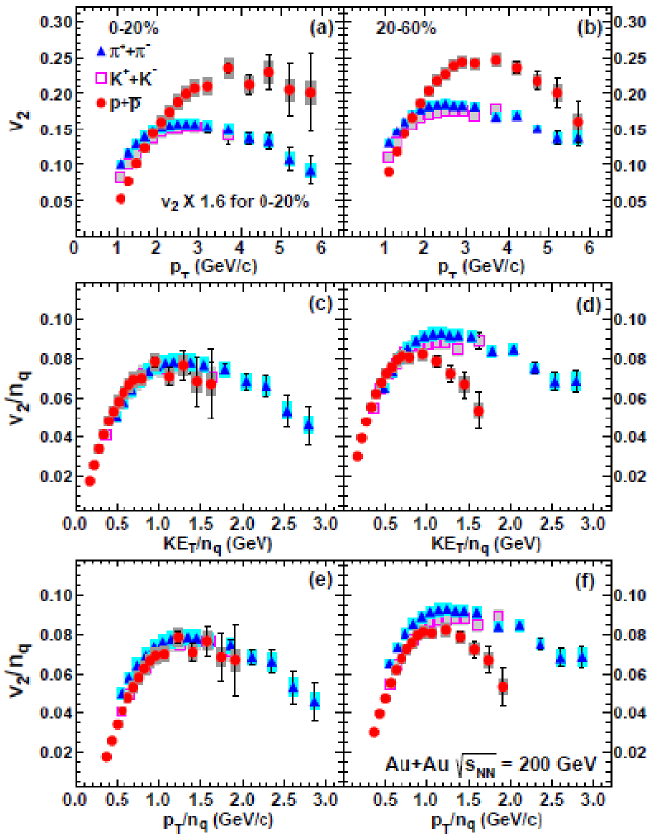
ii. Coalescence model predicts

$$v_{2,h}(p_T) \approx n v_{2,q}\left(\frac{1}{n} p_T\right)$$

iii. Recent results

PHENIX

V_2 of identified hadrons in 200 GeV AuAu



- In 0-20% central Au + Au collisions at 200 GeV, the v_2 proton is higher than that of pion still p_T of 6 GeV/c. While in 20-60% centrality, they approach each other.
- A break of n_q scaling is observed in 20-60% centrality at KE_T > 0.7 GeV. But in the 0-20% centrality, this break is still roughly held.
- It indicates the mechanisms for pion and proton production are different at intermediate p_T for different centralities

PHENIX Phys. Rev. C 85, 064914 (2012)

8/14/2012 Shengli Huang for PHENIX 10

Shengi Huang, [PHENIX Collaboration] Quark Matter 2012 presentation

Exotic hadrons from heavy ion collisions

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

Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming Ko,[5] Su Houng Lee,[1,2] Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and Koichi Yazaki[2,3]

(ExHIC Collaboration)

1) To estimate the possibility of observing predicted exotics with/without heavy quarks in heavy ion collision experiment

2) To find a possible solution to a problem of identifying hadronic molecular states and/or hadrons with multiquark components

– Exotic hadrons discussed

Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	$\omega_{\mathrm{Mol.}}$ (MeV)	Decay mode
Mesons									
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\pi\pi$ (Strong decay)
$a_0(980)$	980	3	1	0^+	$q\bar{q}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\eta\pi$ (Strong decay)
$K(1460)$	1460	2	1/2	0^-	$q\bar{s}$	$q\bar{q}q\bar{s}$	$\bar{K}KK$	69.0(R)	$K\pi\pi$ (Strong decay)
$D_s(2317)$	2317	1	0	0^+	$c\bar{s}(L=1)$	$q\bar{q}c\bar{s}$	DK	273(B)	$D_s\pi$ (Strong decay)
T_{cc}^{1}[a]	3797	3	0	1^+	—	$qq\bar{c}\bar{c}$	$\bar{D}\bar{D}^*$	476(B)	$K^+\pi^- + K^+\pi^- + \pi^-$
$X(3872)$	3872	3	0	$1^+, 2^-$[c]	$c\bar{c}(L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$	3.6(B)	$J/\psi\pi\pi$ (Strong decay)
$Z^+(4430)$[b]	4430	3	1	0^-[c]	—	$q\bar{q}c\bar{c}(L=1)$	$D_1\bar{D}^*$	13.5(B)	$J/\psi\pi$ (Strong decay)
T_{cb}^{0}[a]	7123	1	0	0^+	—	$qq\bar{c}\bar{b}$	$\bar{D}B$	128(B)	$K^+\pi^- + K^+\pi^-$
Baryons									
$\Lambda(1405)$	1405	2	0	$1/2^-$	$qqs(L=1)$	$qqqs\bar{q}$	$\bar{K}N$	20.5(R)–174(B)	$\pi\Sigma$ (Strong decay)
$\Theta^+(1530)$[b]	1530	2	0	$1/2^+$[c]	—	$qqqq\bar{s}(L=1)$	—	—	KN (Strong decay)
$\bar{K}KN$[a]	1920	4	1/2	$1/2^+$	—	$qqqs\bar{s}(L=1)$	$\bar{K}KN$	42(R)	$K\pi\Sigma, \pi\eta N$ (Strong decay)
$\bar{D}N$[a]	2790	2	0	$1/2^-$	—	$qqqq\bar{c}$	$\bar{D}N$	6.48(R)	$K^+\pi^-\pi^- + p$
$\bar{D}^*N$[a]	2919	4	0	$3/2^-$	—	$qqqq\bar{c}(L=2)$	$\bar{D}^*N$	6.48(R)	$\bar{D} + N$ (Strong decay)
Θ_{cs}[a]	2980	4	1/2	$1/2^+$	—	$qqqs\bar{c}(L=1)$	—	—	$\Lambda + K^+\pi^-$
BN[a]	6200	2	0	$1/2^-$	—	$qqqq\bar{b}$	BN	25.4(R)	$K^+\pi^-\pi^- + \pi^+ + p$
B^*N[a]	6226	4	0	$3/2^-$	—	$qqqq\bar{b}(L=2)$	B^*N	25.4(R)	$B + N$ (Strong decay)
Dibaryons									
H[a]	2245	1	0	0^+	$qqqqss$	—	ΞN	73.2(B)	$\Lambda\Lambda$ (Strong decay)
$\bar{K}NN$[b]	2352	2	1/2	0^-[c]	$qqqqqs(L=1)$	$qqqqqq\,s\bar{q}$	$\bar{K}NN$	20.5(T)–174(T)	ΛN (Strong decay)
$\Omega\Omega$[a]	3228	1	0	0^+	$ssssss$	—	$\Omega\Omega$	98.8(R)	$\Lambda K^- + \Lambda K^-$
H_c^{++}[a]	3377	3	1	0^+	$qqqqsc$	—	$\Xi_c N$	187(B)	$\Lambda K^-\pi^+\pi^+ + p$
$\bar{D}NN$[a]	3734	2	1/2	0^-	—	$qqqqqq\,q\bar{c}$	$\bar{D}NN$	6.48(T)	$K^+\pi^- + d, K^+\pi^-\pi^- + p + p$
BNN[a]	7147	2	1/2	0^-	—	$qqqqqq\,q\bar{b}$	BNN	25.4(T)	$K^+\pi^- + d, K^+\pi^- + p + p$

[a]Particles that are newly predicted by theoretical models.
[b]Particles that are not yet established.
[c]Undetermined quantum numbers of existing particles.

– Estimated exotic hadron yields

	RHIC				LHC			
	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
Mesons								
$f_0(980)$	3.8, 0.73($s\bar{s}$)	0.10	13	5.6	10, 2.0 ($s\bar{s}$)	0.28	36	15
$a_0(980)$	11	0.31	40	17	31	0.83	1.1×10^2	46
$K(1460)$	—	0.59	3.6	1.3	—	1.6	9.3	3.2
$D_s(2317)$	1.3×10^{-2}	2.1×10^{-3}	1.6×10^{-2}	5.6×10^{-2}	8.7×10^{-2}	1.4×10^{-2}	0.10	0.35
T_{cc}^{1} [a]	—	4.0×10^{-5}	2.4×10^{-5}	4.3×10^{-4}	—	6.6×10^{-4}	4.1×10^{-4}	7.1×10^{-3}
$X(3872)$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	1.7×10^{-3}	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}
$Z^+(4430)$ [b]	—	1.3×10^{-5}	2.0×10^{-5}	1.4×10^{-5}	—	2.1×10^{-4}	3.4×10^{-4}	2.4×10^{-4}
T_{cb}^{0} [a]	—	6.1×10^{-8}	1.8×10^{-7}	6.9×10^{-7}	—	6.1×10^{-6}	1.9×10^{-5}	6.8×10^{-5}
Baryons								
$\Lambda(1405)$	0.81	0.11	1.8–8.3	1.7	2.2	0.29	4.7–21	4.2
Θ^+ [b]	—	2.9×10^{-2}	—	1.0	—	7.8×10^{-2}	—	2.3
$\bar{K}KN$ [a]	—	1.9×10^{-2}	1.7	0.28	—	5.2×10^{-2}	4.2	0.67
$\bar{D}N$ [a]	—	2.9×10^{-3}	4.6×10^{-2}	1.0×10^{-2}	—	2.0×10^{-2}	0.28	6.1×10^{-2}
$\bar{D}^*N$ [a]	—	7.1×10^{-4}	4.5×10^{-2}	1.0×10^{-2}	—	4.7×10^{-3}	0.27	6.2×10^{-2}
Θ_{cs} [a]	—	5.9×10^{-4}	—	7.2×10^{-3}	—	3.9×10^{-3}	—	4.5×10^{-2}
BN [a]	—	1.9×10^{-5}	8.0×10^{-5}	3.9×10^{-5}	—	7.7×10^{-4}	2.8×10^{-3}	1.4×10^{-3}
B^*N [a]	—	5.3×10^{-6}	1.2×10^{-4}	6.6×10^{-5}	—	2.1×10^{-4}	4.4×10^{-3}	2.4×10^{-3}
Dibaryons								
H [a]	3.0×10^{-3}	—	1.6×10^{-2}	1.3×10^{-2}	8.2×10^{-3}	—	3.8×10^{-2}	3.2×10^{-2}
$\bar{K}NN$ [b]	5.0×10^{-3}	5.1×10^{-4}	0.011–0.24	1.6×10^{-2}	1.3×10^{-2}	1.4×10^{-3}	0.026 – 0.54	3.7×10^{-2}

[a] Particles that are newly predicted by theoretical model.
[b] Particles that are not yet established.

Production Yields of hadrons strongly depend on their structure!!

Hadronic interactions

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– 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 $r_B > \lambda_D$

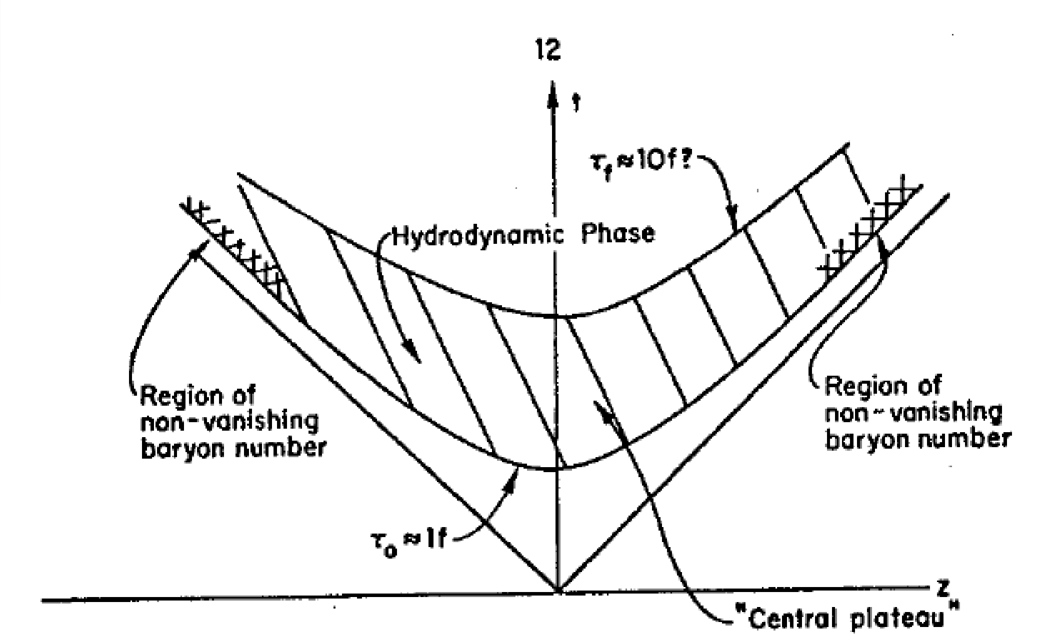
$$\lambda_D = \frac{1}{gT\sqrt{\frac{N_C}{3}+\frac{N_f}{6}}}$$

2) Possibilities of J/ψ absorption by hadronic interactions

Next we will address the question of alternative suppression mechanisms. It is possible that not only plasma formation, but also some type of nuclear absorption would prevent the J/ψ signal from appearing in nuclear collisions?

J/ψ–nucleon cross section is only about 1–3 mb, compared to the 40 mb for pp interactions. Incidentaly, this much reduced strong interaction of the J/ψ has led to some models [13] proposing the use of J/ψ's as primordial plasma signal. Our considerations, on the contrary, exclude primordial J/ψ formation in a deconfining medium.

– Time evolution of quark-gluon plasma

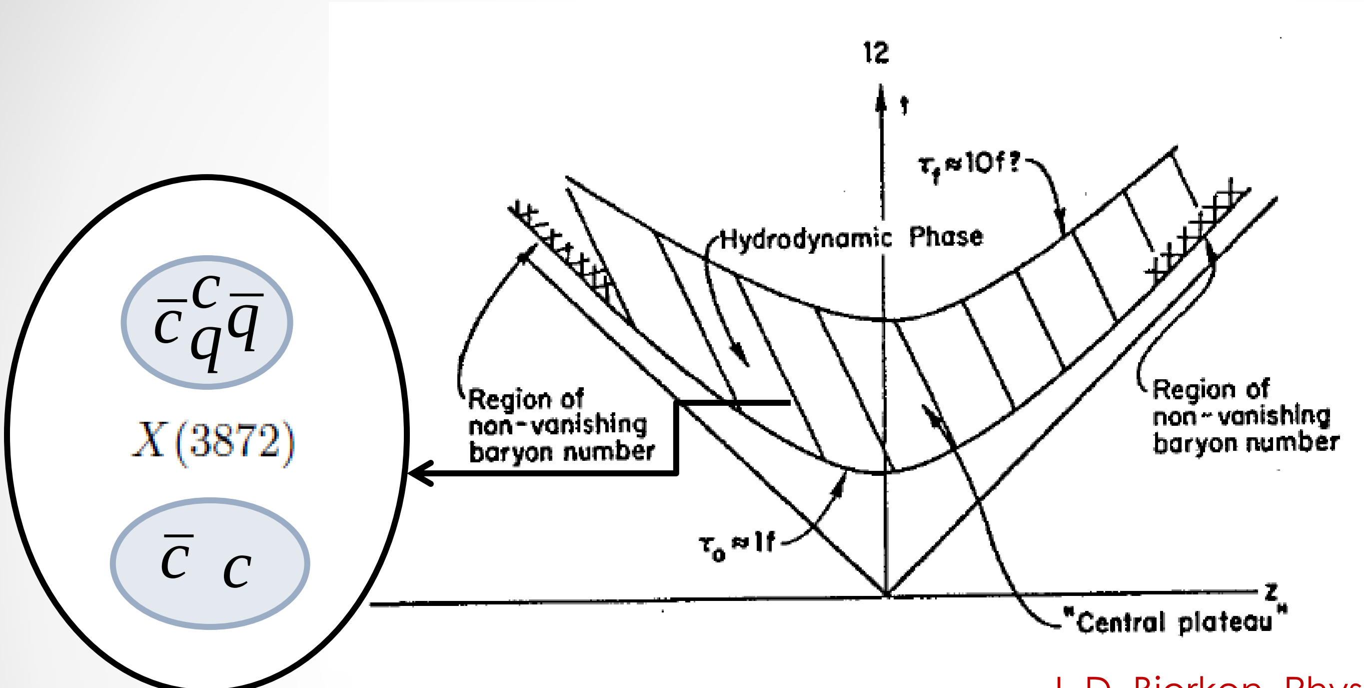


$$\tau = \sqrt{t^2 - z^2}$$

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

1) Collision
2) Pre-equilibrium : Quark-gluon plasma
3) Hydrodynamic expansion
4) Chemical freeze-out : Mixed phase
5) Kinetic freeze-out : Hadron phase

– Time evolution of quark-gluon plasma



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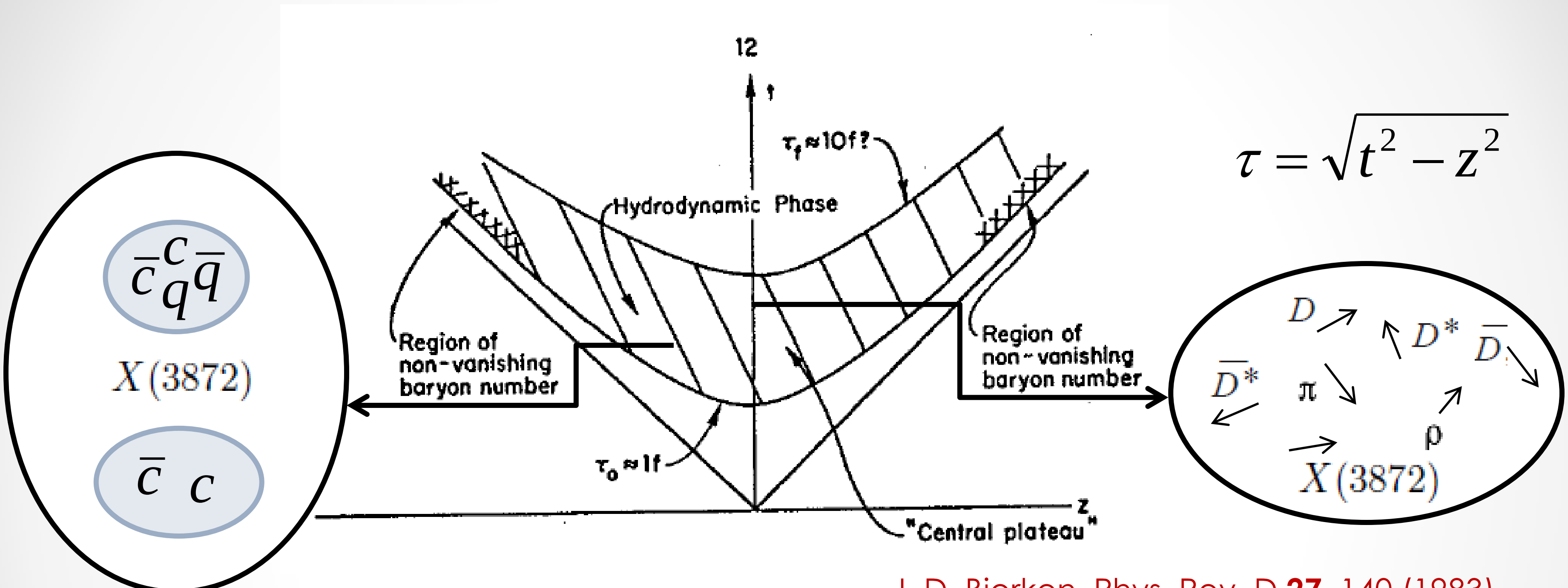
– Time evolution of quark-gluon plasma



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

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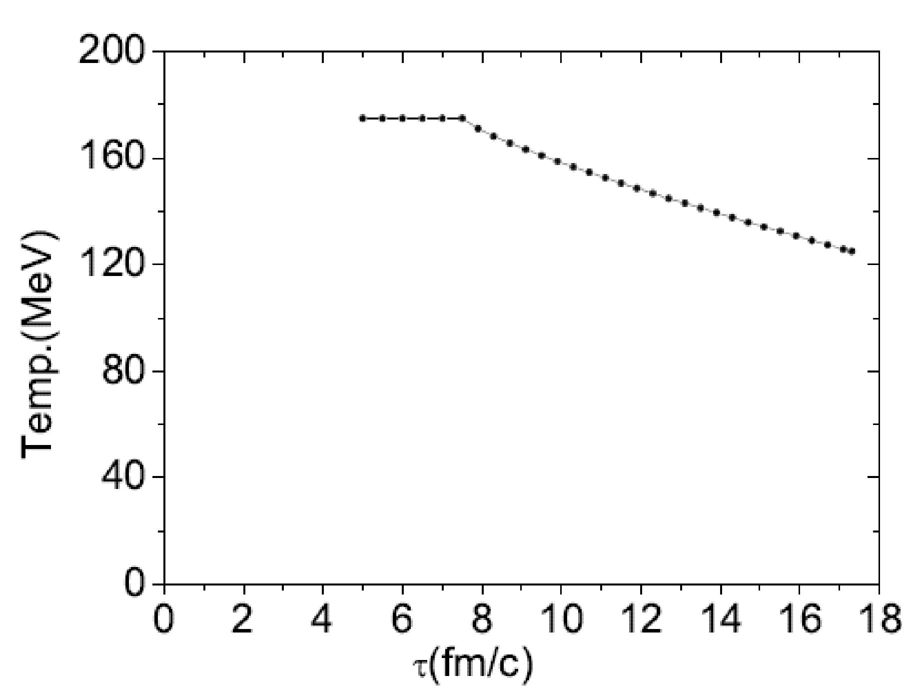
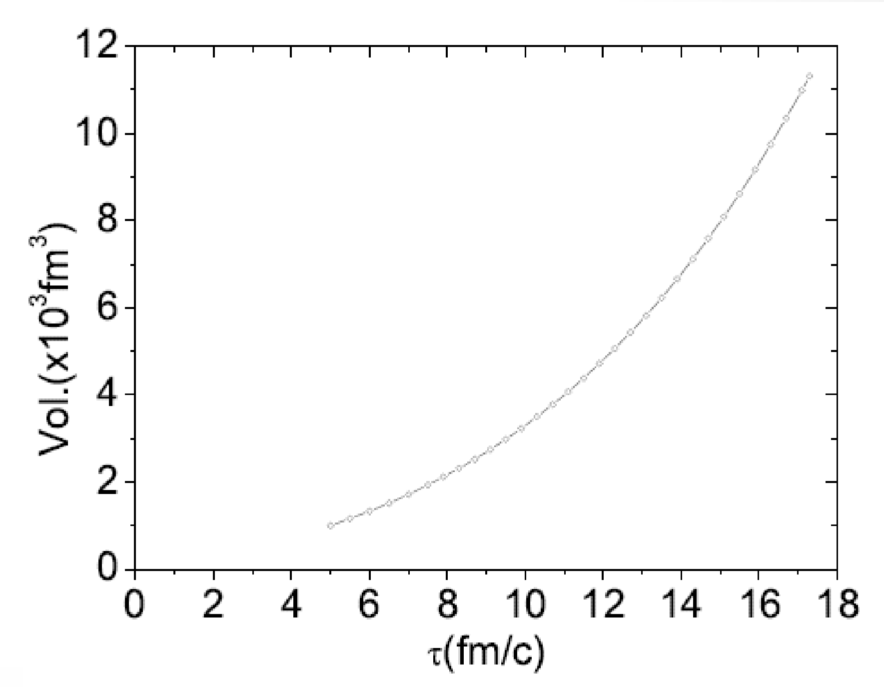
– Dynamics of relativistic heavy ion collisions

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

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

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





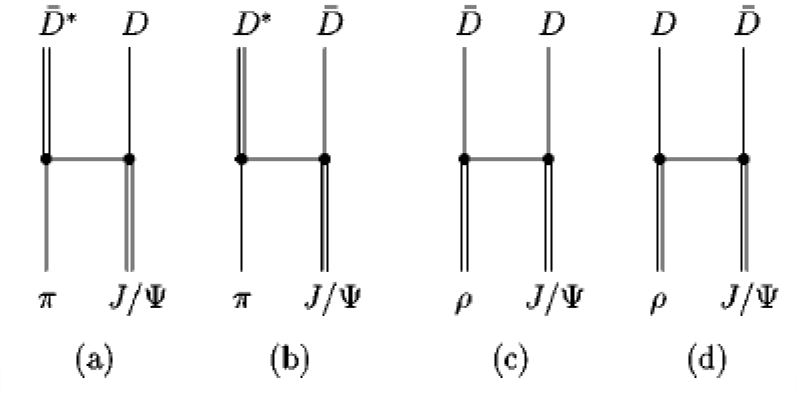
– Hadronic interactions

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



i. The interaction Lagrangians from the pseudoscalar and vector mesons free Lagrangians

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

$$P = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{12}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta + \frac{\eta_c}{\sqrt{12}} & D_s^- \\ D^0 & D^+ & D_s^+ & -\frac{3\eta_c}{\sqrt{12}} \end{pmatrix}$$

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

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

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

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

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

The X(3872) meson

– The X(3872) meson

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

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%

1) Discovered by Belle collaboration (2003)

2) Hadronic molecules, multi-quark, and hybrid states

$$\rightarrow \bar{D}D^*, D\bar{D}^*, q\bar{q}c\bar{c}, c\bar{c}$$

Only $J^{PC} = 1^{++}, 2^{-+}$ states are allowed : $X_1(3872)$ $X_2(3872)$

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

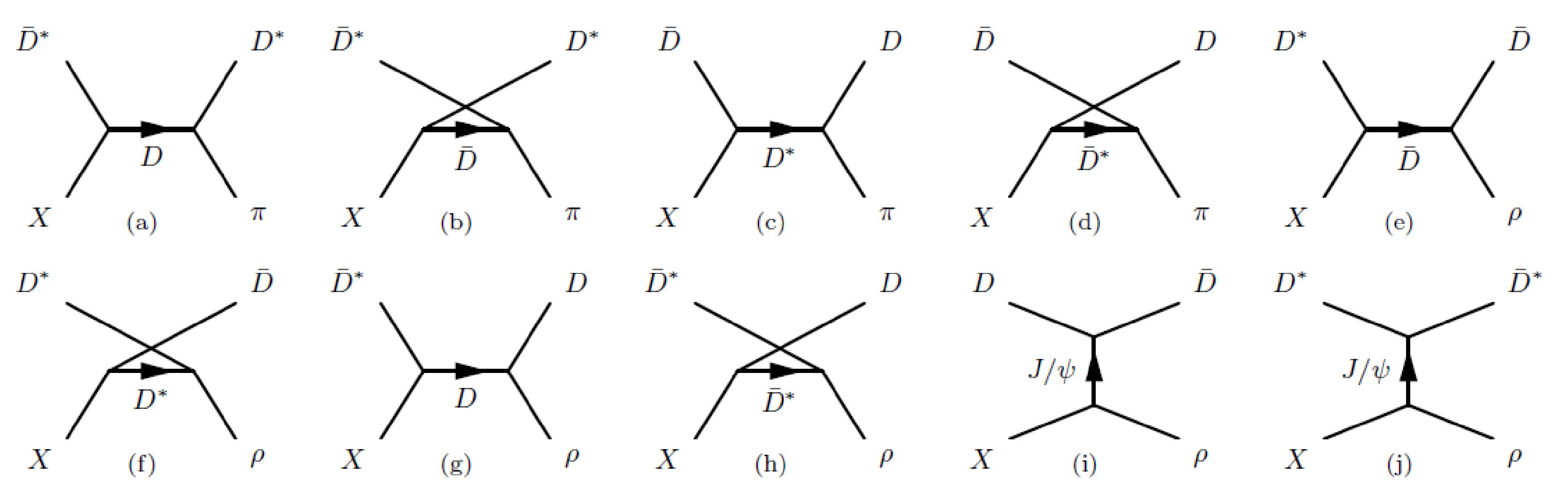
– The production yield of the X(3872) meson

	RHIC			
	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
$X(3872)$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}

– Hadronic effects on the X(3872) meson

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

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



2) The interaction Lagrangians for X(3872)

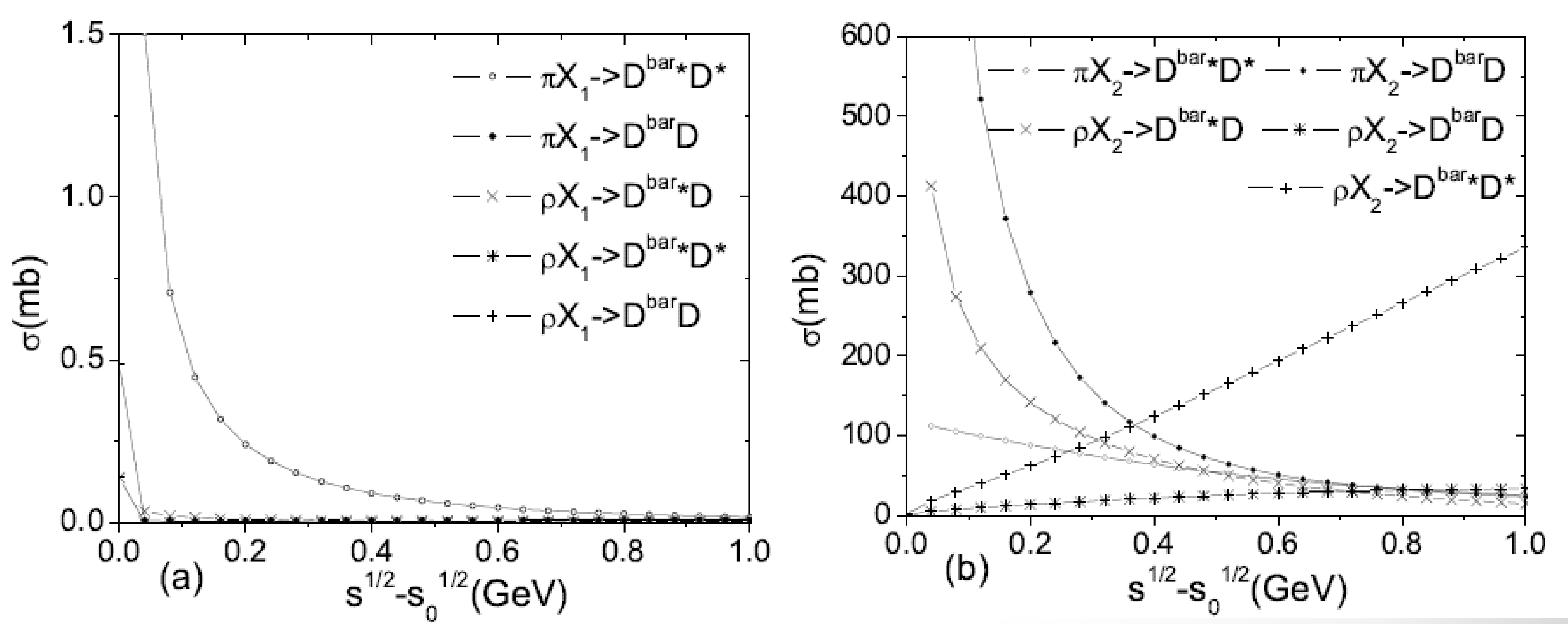
$$
\begin{aligned}
\mathcal{L}_{X_1 D^* D} &= g_{X_1 D^* D} X_1^\mu \bar{D}_\mu^* D, \\
\mathcal{L}_{X_1 \psi\rho} &= i g_{X_1 \psi\rho} \epsilon^{\mu\nu\rho\sigma} \psi_\nu \rho_\rho \partial_\sigma X_{1\mu}, \\
\mathcal{L}_{X_2 D^* D} &= -i g_{X_2 D^* D} X_2^{\mu\nu} \bar{D}_\mu^* \partial_\nu D, \\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

3) Spin 2 particle polarization

$$
\begin{aligned}
\sum_{\text{pol}} \pi_{\mu\nu}(k) \pi^*_{\alpha\beta}(k) &= \frac{1}{2} (g_{\mu\alpha} g_{\nu\beta} + g_{\mu\beta} g_{\nu\alpha} - g_{\mu\nu} g_{\alpha\beta}) - \frac{1}{2m^2} (g_{\mu\alpha} k_\nu k_\beta + g_{\nu\beta} k_\mu k_\alpha + g_{\mu\beta} k_\nu k_\alpha + g_{\nu\alpha} k_\mu k_\beta) \\
&+ \frac{1}{6} (g_{\mu\nu} + \frac{2}{m^2} k_\mu k_\nu)(g_{\alpha\beta} + \frac{2}{m^2} k_\alpha k_\beta),
\end{aligned}
$$

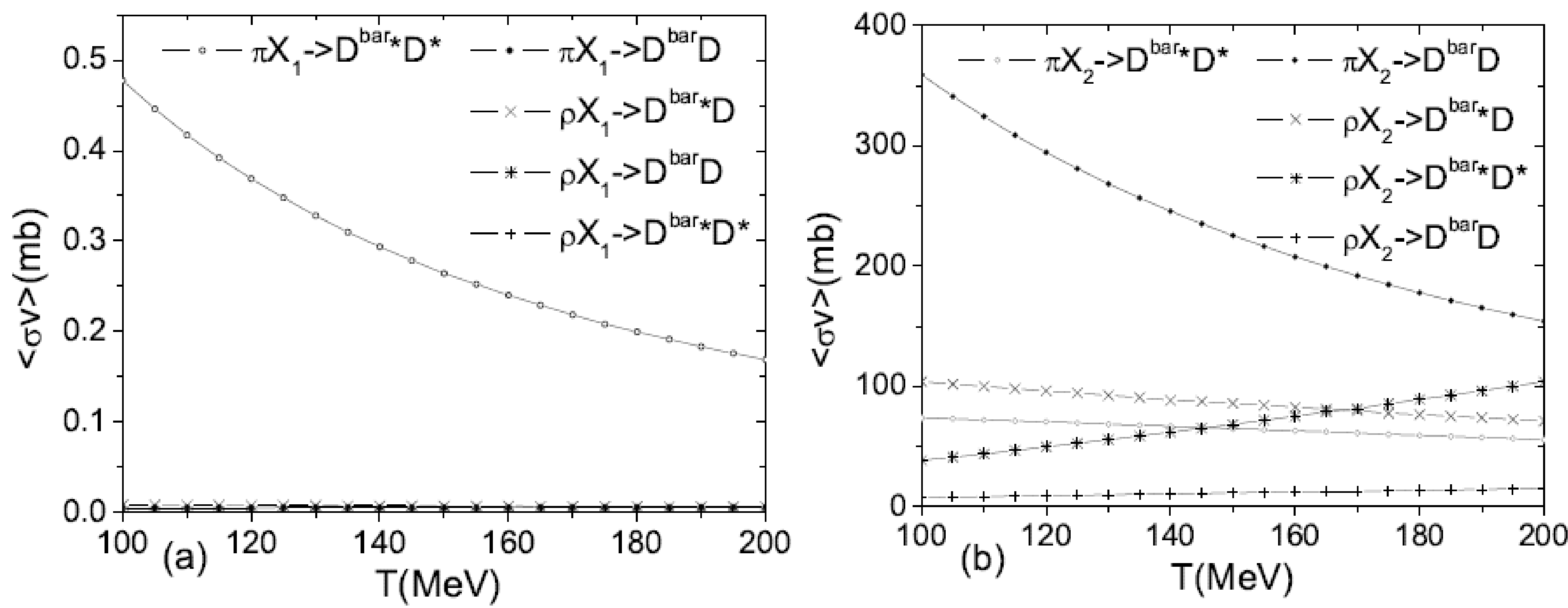
– Cross sections for different X(3872) meson quantum numbers

Sungtae Cho and Su Houng Lee, to appear (2012)



– Thermally averaged cross section of the X(3872) meson abundances

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



– The coupling constants of X(3872)

Coupling	$J^{PC} = 1^{++}$	$J^{PC} = 2^{-+}$	
$g_{(J)DD*}$	(3.5 ± 0.7) GeV	189 ± 36	
$g_{(J)\rho\psi}$	0.14 ± 0.03	(-0.29 ± 0.08) GeV^{-1}	(0.28 ± 0.09) GeV^{-1}

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

1) The decay of the spin-2 X(3872) meson to $\bar{D}^0 D^{*0}$ is disfavored because of the angular momentum suppression associated with the small energy relative to $\bar{D}^0 D^{*0}$ threshold

G. Gokhroo *et al*. [Belle Collaboration], Phys. Rev. Lett. **97,** 162002 (2006)
B. Aubert *et al*. [Babar Collaboration], Phys. Rev. D **77,** 011102 (2008)

2) The phase space should be same for both cases

$$\mathcal{L}_{X_1 D^* D} = g_{X_1 D^* D} X_1^\mu \bar{D}_\mu^* D, \qquad \mathcal{L}_{X_2 D^* D} = -i g_{X_2 D^* D} X_2^{\mu\nu} \bar{D}_\mu^* \partial_\nu D.$$

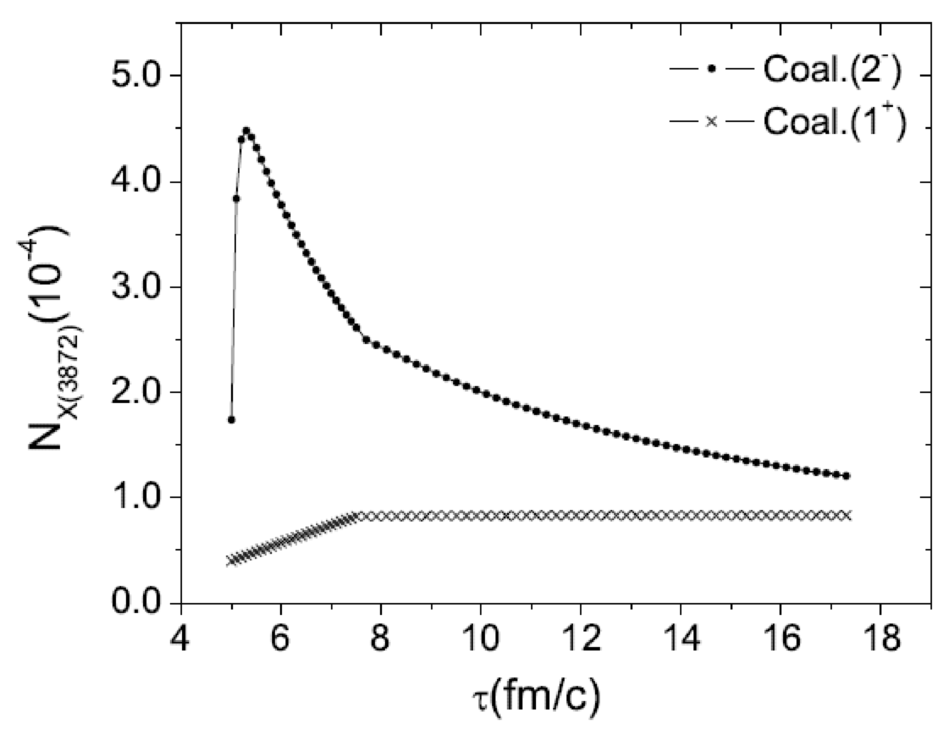
$$\frac{1}{3} \sum_{polarizations} |g_{1DD*} \lambda^\mu(k) \epsilon_\mu^*(q)|^2 = \frac{1}{5} \sum_{polarizations} |g_{2DD*} \pi^{\mu\nu}(k) \epsilon_\mu^*(q) p_\nu|^2$$

– 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

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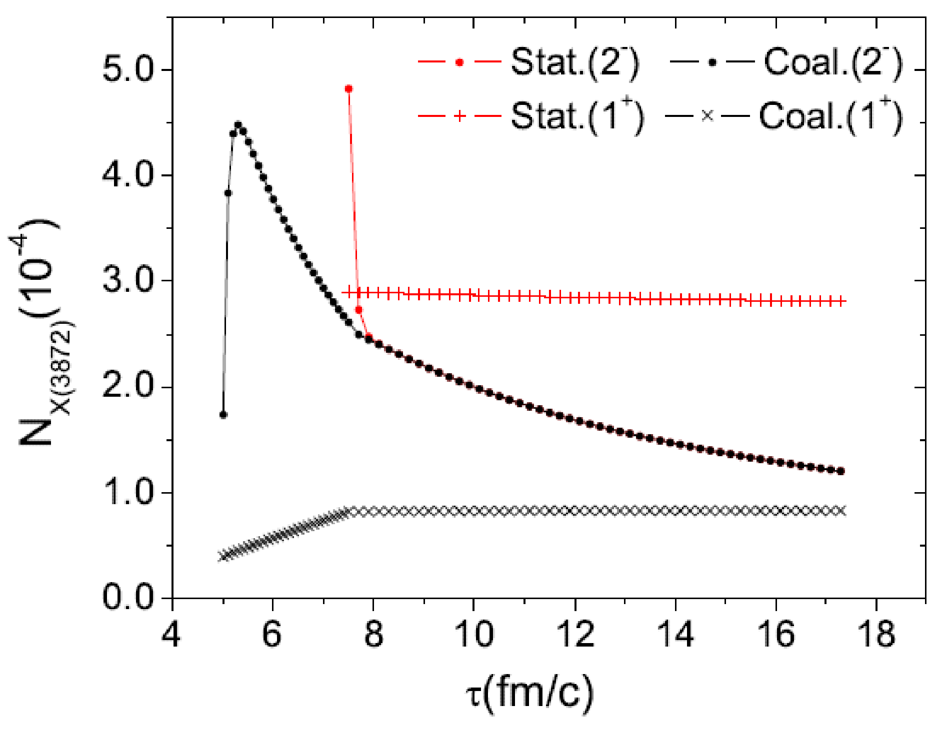

Conclusions

– Hadronic effects on exotic hadron production in heavy ion collisions

1) Relativistic heavy ion collisions provide us a perfect environment to explore the production of various particles
2) The statistical model & the coalescence model
3) The yield of a hadron in relativistic heavy ion collision is strongly dependent on its structure
4) Thermal yields decrease or remain almost unchanged while the the production yields from coalescence increases during the hadronic stage of heavy ion collisions
5) Studying both the initial abundances of exotic hadrons at hadronization and their absorption by hadrons during the hadronic stage provide a chance to infer their structure and production mechanism in heavy ion collisions