Exotics from heavy ion collisions

The 4th Asian Triangle
Heavy Ion Conference

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Sungtae Cho

Institute of Physics and Applied Physics
Yonsei University

Outline

- Introduction
- Production yields
- Exotic hadrons
- The X(3872) meson
- Conclusion

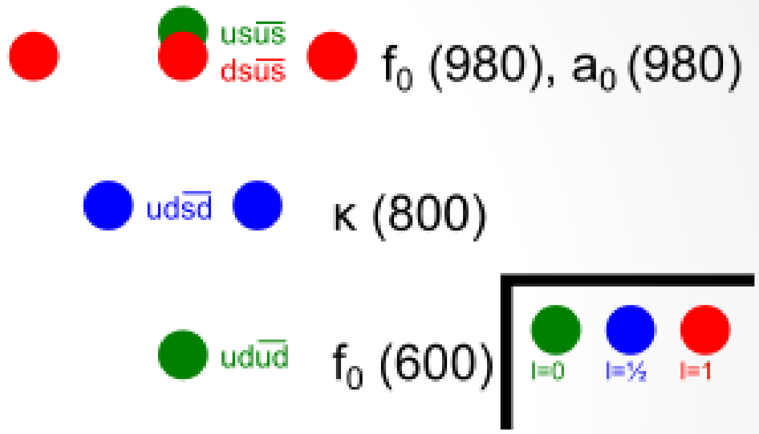
Introduction

– Multiquark hadrons

Robert L. Jaffe, Phys. Rev. D, **15**, 267 (1977)

1) H dibaryon and scalar tetra quark (1976) $f_0(980)$

$K\bar{K}$ hadronic molecule state

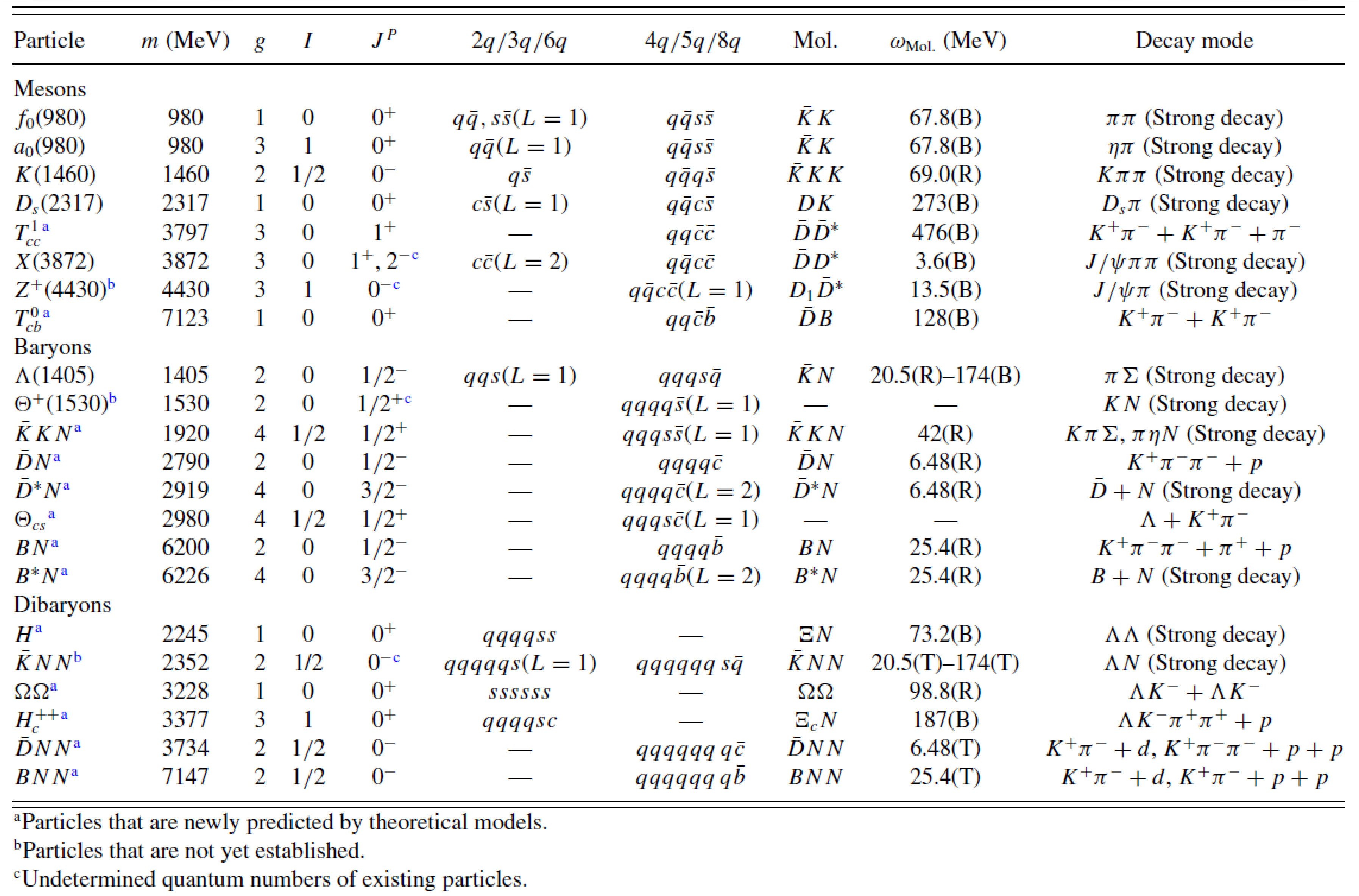


http://en.wikipedia.org/wiki/Exotic_meson

2) Hadronic molecules & multiquark states

$$X(3872) \quad \text{Belle (2003)} \quad \rightarrow \bar{D}D^*, D\bar{D}^*, q\bar{q}c\bar{c}$$
$$D_{sJ}(2317) \quad \text{BaBar (2003)} \rightarrow DK, c\bar{s}, q\bar{q}c\bar{s}$$

– Exotic hadrons discussed



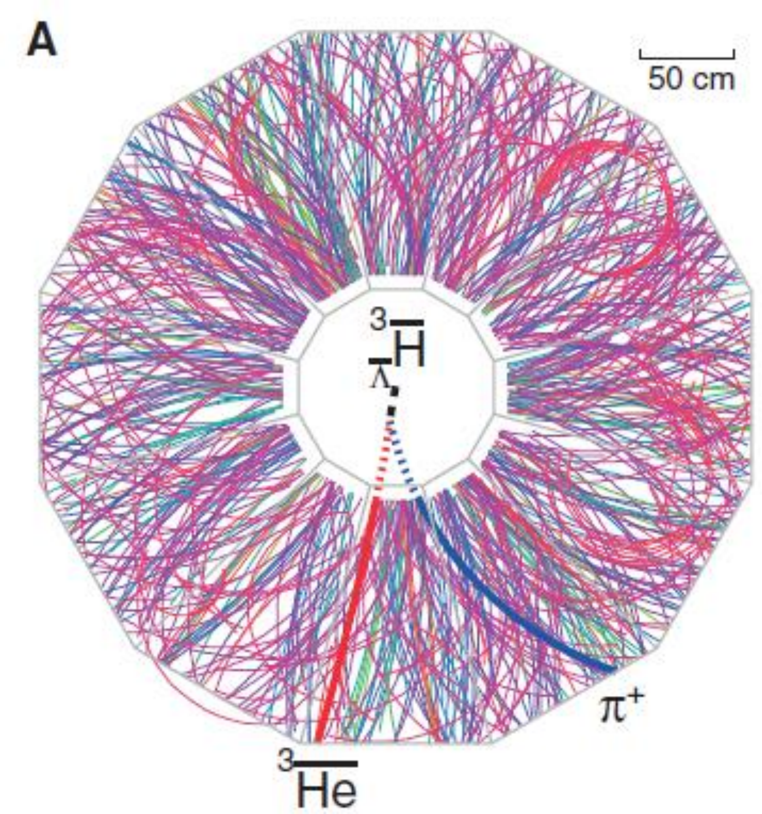
Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	$\omega_{\mathrm{Mol.}}$ (MeV)	Decay mode
Mesons									
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\pi\pi$ (Strong decay)
$a_0(980)$	980	3	1	0^+	$q\bar{q}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	67.8(B)	$\eta\pi$ (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)	$K^+\pi^- + d, K^+\pi^- + p + p$

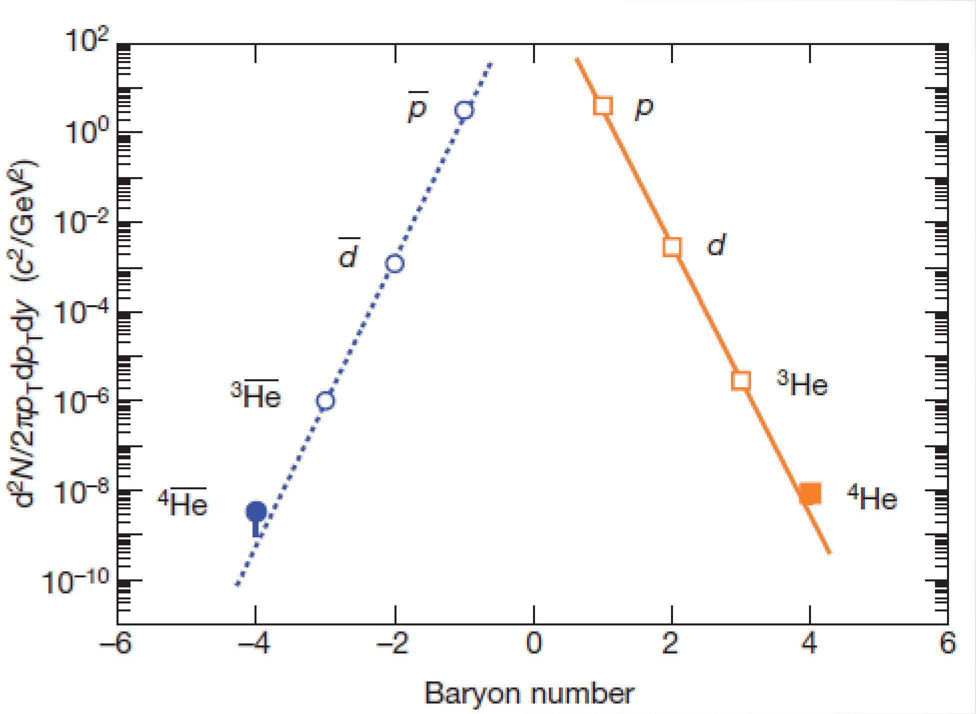
[a] Particles that are newly predicted by theoretical models.

[b] Particles that are not yet established.

[c] Undetermined quantum numbers of existing particles.

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

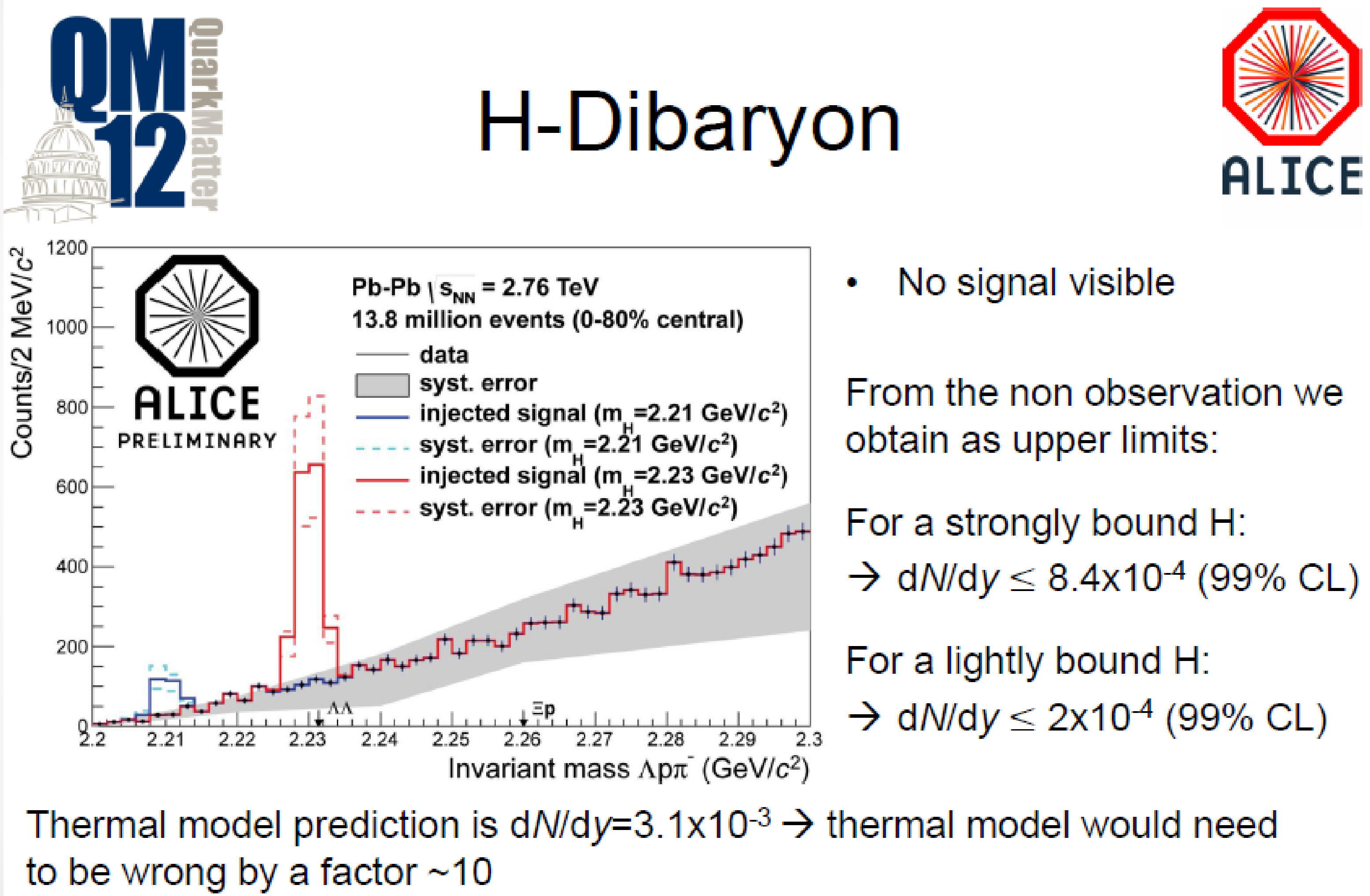




B. Abelev *et al*. [The STAR Collaboration], Science, **328**, 58 (2010)

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)

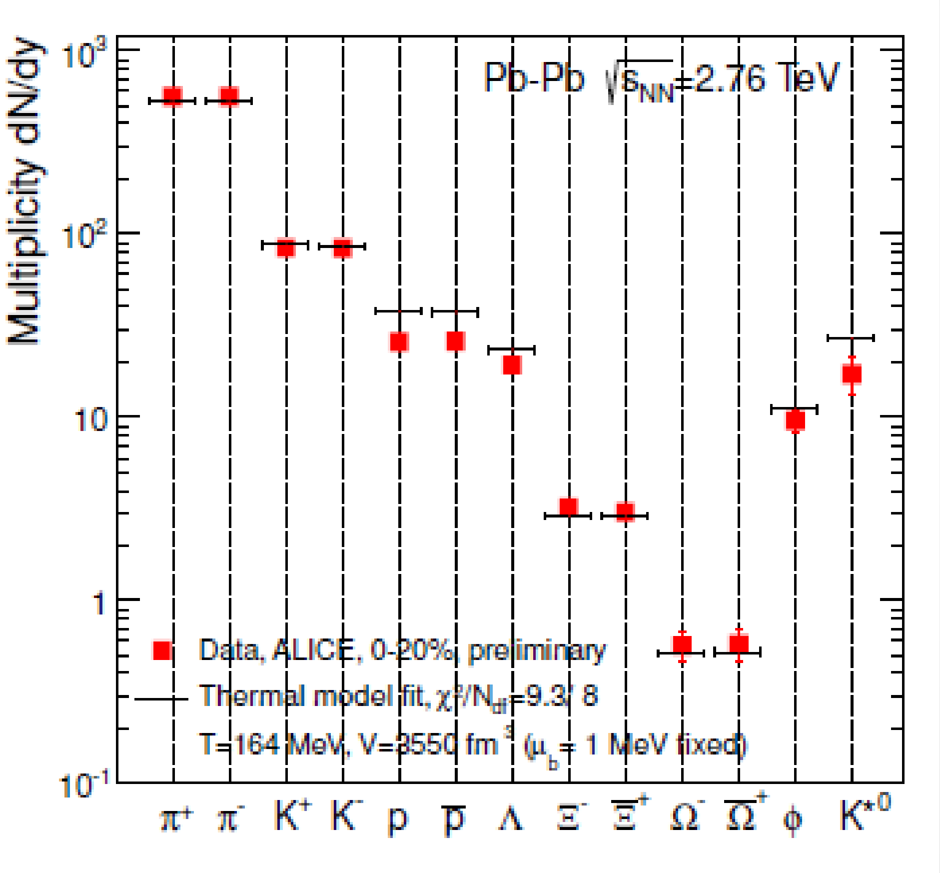
Thermal model prediction is d*N*/dy=3.1×10^{-3} → thermal model would need to be wrong by a factor ~10

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

Production yields

– Statistical model

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



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

– 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

Exotic hadrons

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

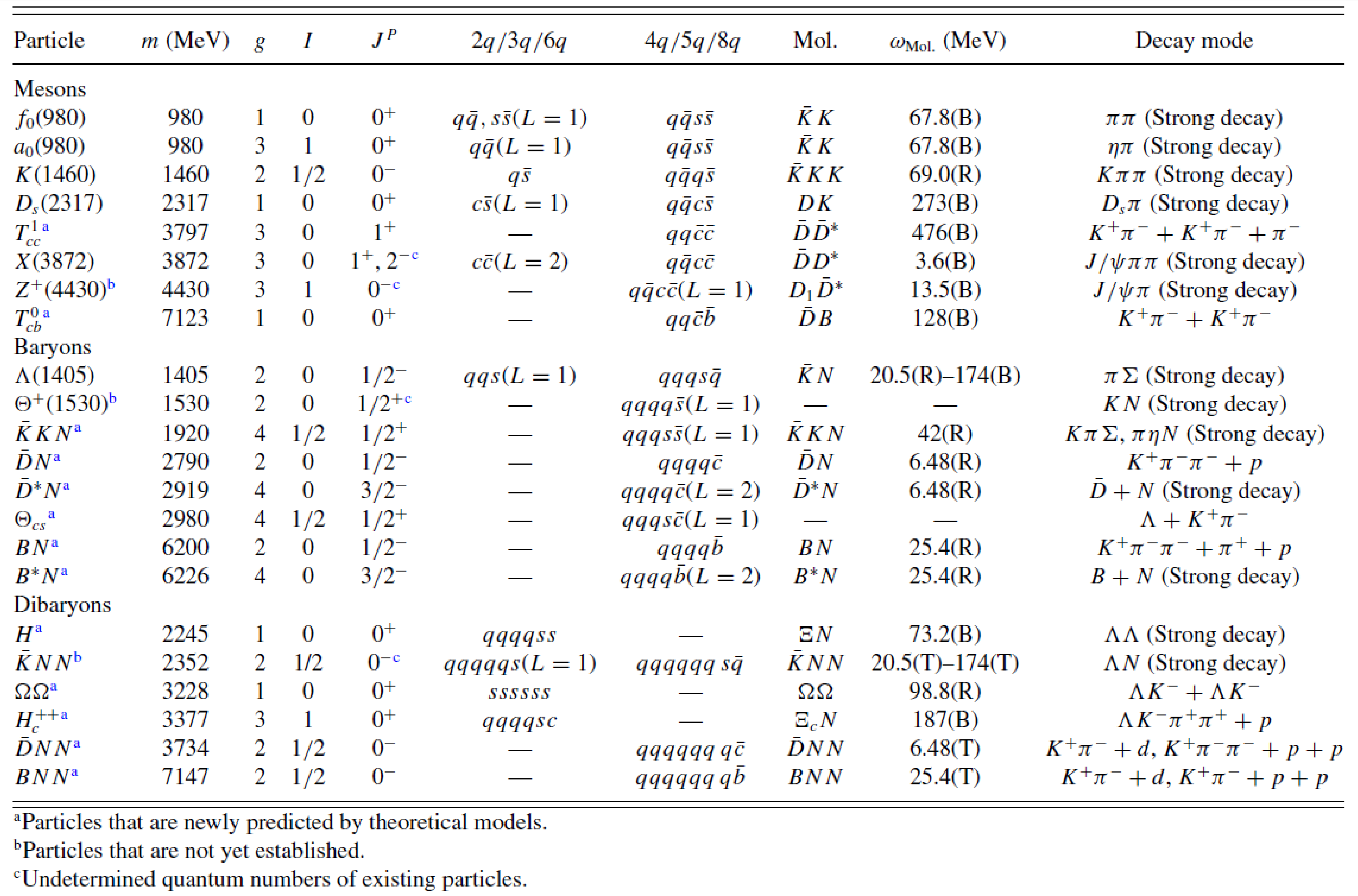
Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming Ko,[5] Su Houng Lee,[1,2] Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and Koichi Yazaki[2,3]

(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



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[a] Particles that are newly predicted by theoretical models.

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1) Study the production yields of exotic hadrons for all possible structure configurations

: It was expected that the probability to combine n quarks into a compact region is suppressed as n increases

2) The internal structure of hadrons produced is considered

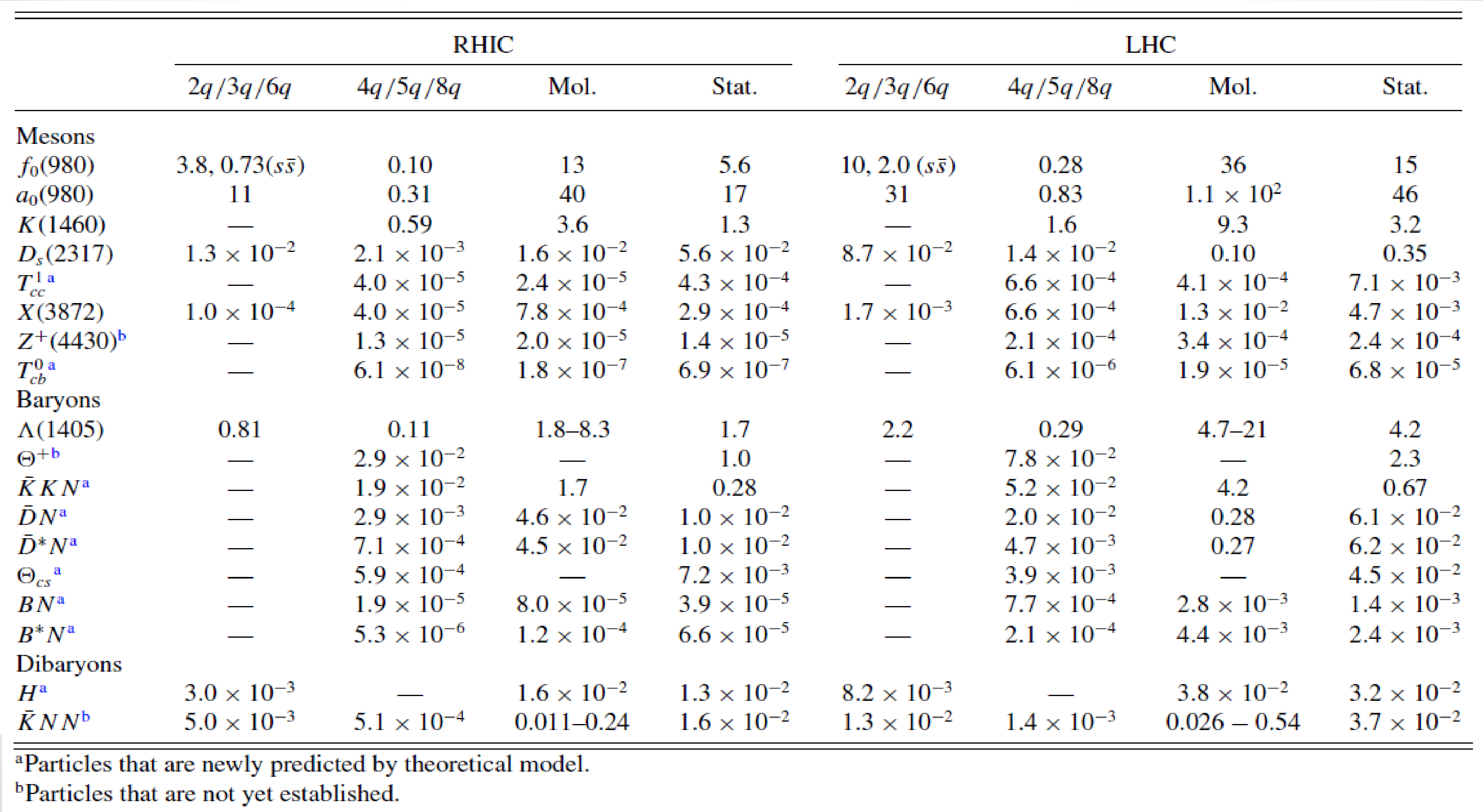
s-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)} \sim 0.360$$

p-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)}\frac{2}{3}\left[\frac{2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)}\right] \sim 0.093$$

d-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)}\frac{8}{15}\left[\frac{2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)}\right]^2 \sim 0.029$$

$$\sigma_i = \frac{1}{\sqrt{\mu_i \omega}} \qquad \frac{1}{\mu_i} = \frac{1}{m_{i+1}} + \frac{1}{\sum_j^i m_j}$$

– 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!!

– The scalar meson $f_0(980)$

Robert L. Jaffe, Phys. Rev. D, **15**, 267 (1977)

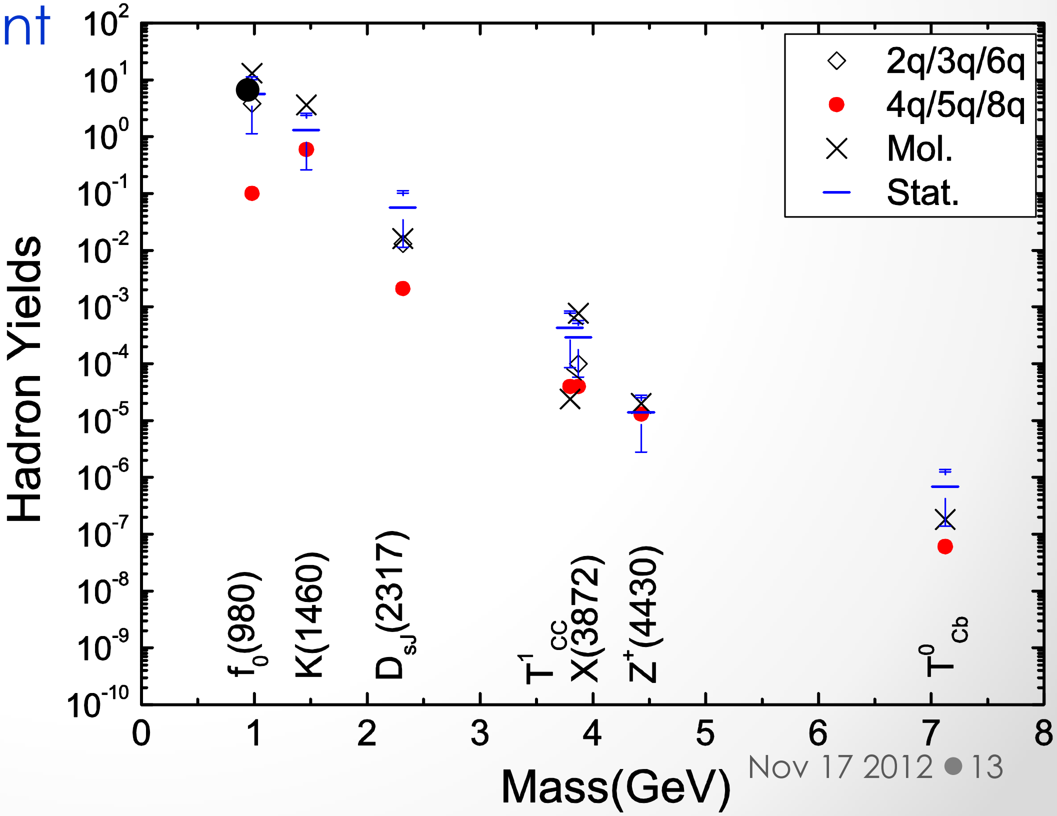
: the tetraquark state or $K\overline{K}$ hadronic molecule state

1) The STAR Collaboration has a preliminary measurement for $f_0(980)$

$$\rightarrow N_{f(980)} \approx 8$$

P. Fachini [The STAR Collaboration], Nucl. Phys. A **715**, 462 (2003)

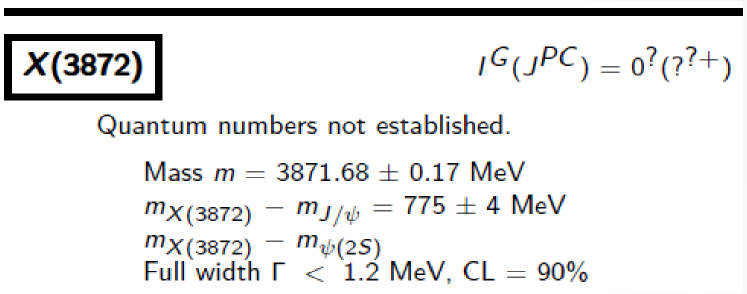
: The measured yield does not seem to support the tetra-quark state



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 ± 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

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

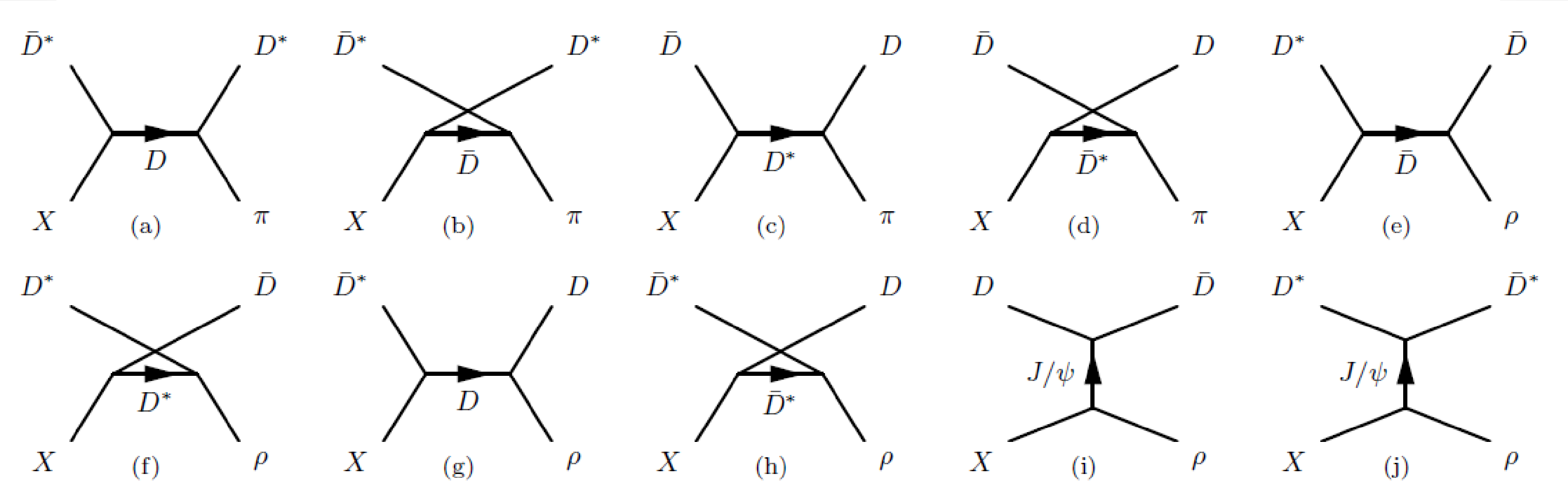
Only $J^{PC} = 1^{++}, 2^{-+}$ states are allowed : $X_1(3872)$ $X_2(3872)$

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

– Hadronic effects

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

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



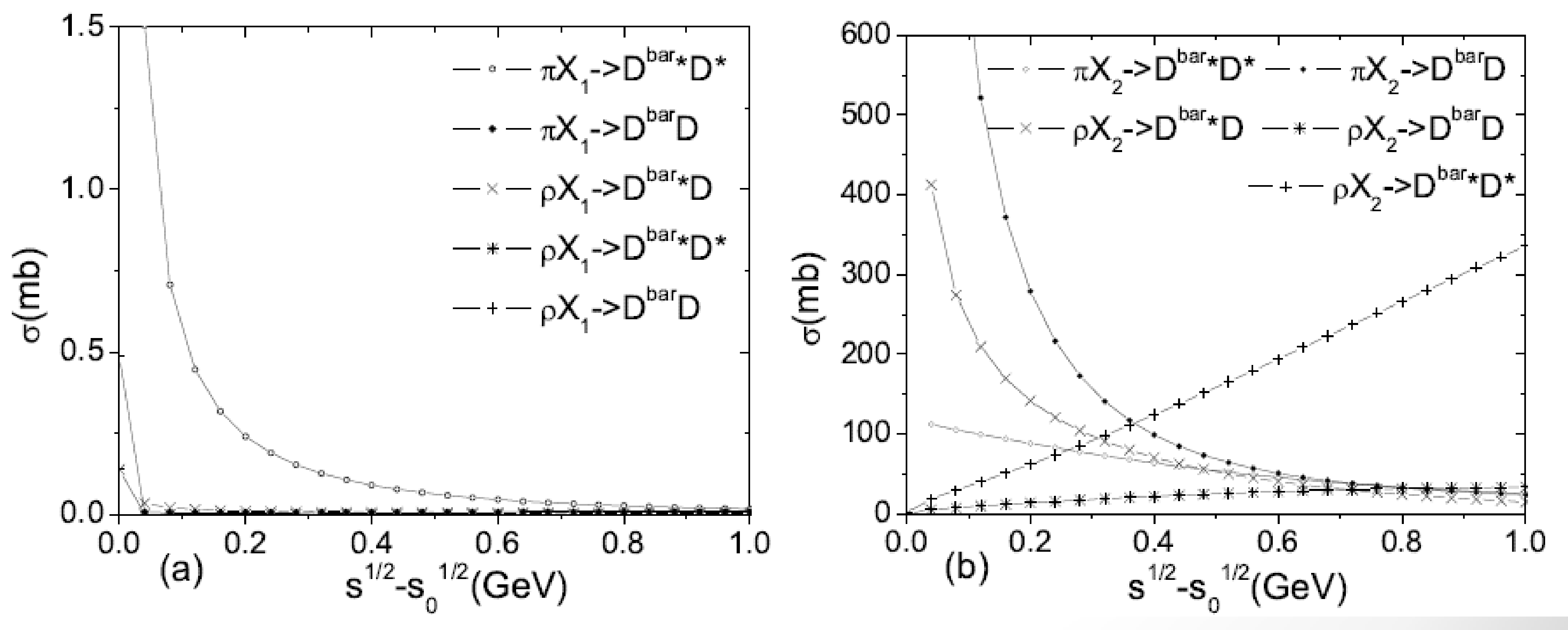
2) Spin 2 particle polarization

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

$$+ \frac{1}{6}(g_{\mu\nu} + \frac{2}{m^2}k_\mu k_\nu)(g_{\alpha\beta} + \frac{2}{m^2}k_\alpha k_\beta),$$

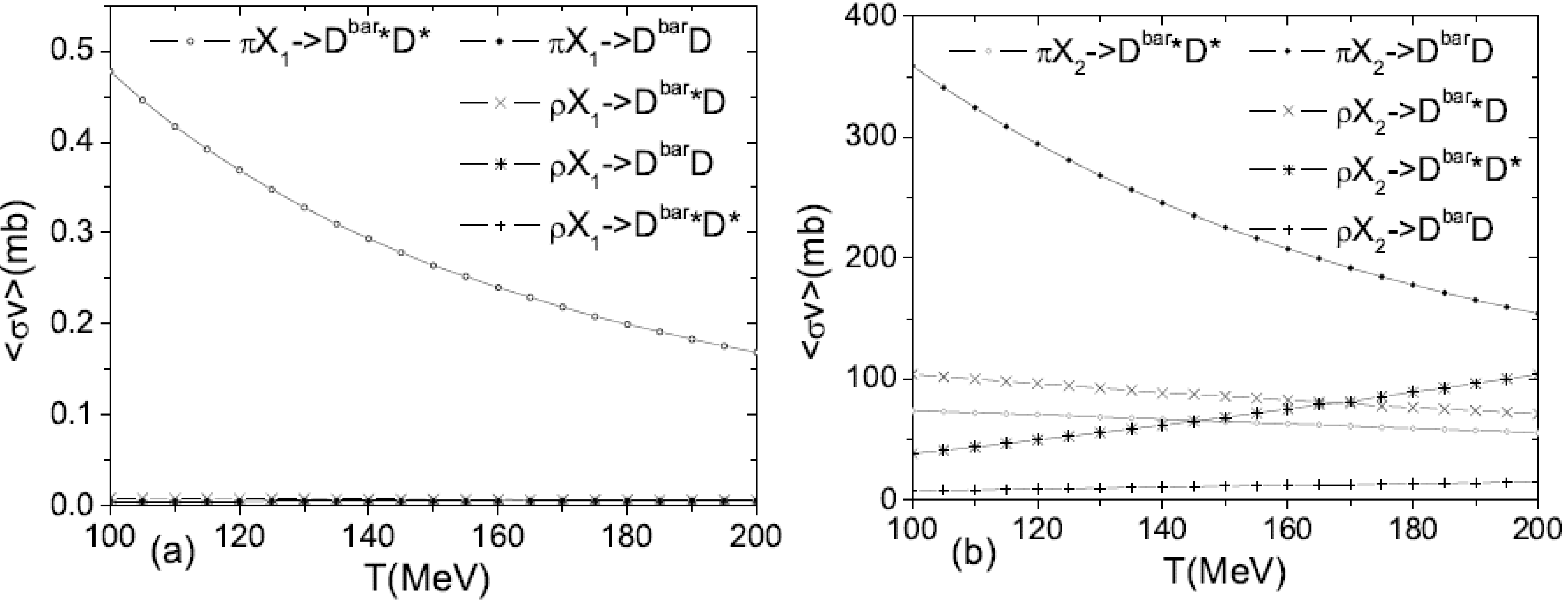
– Cross sections for different X(3872) meson quantum numbers

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

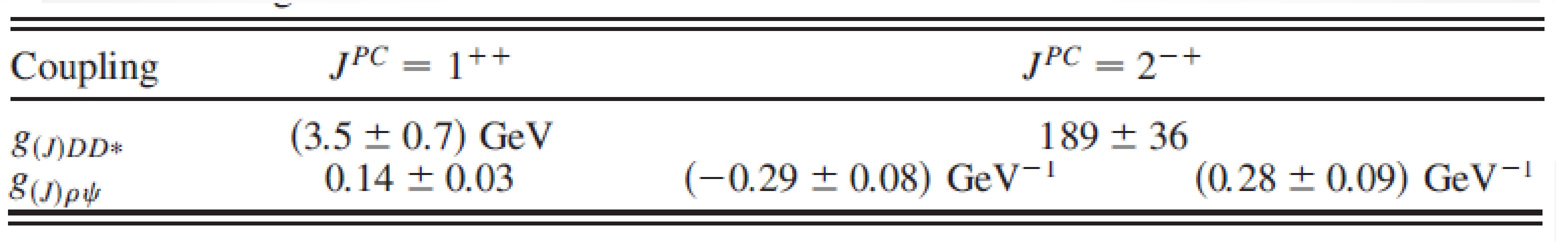


– Thermally averaged cross section of the X(3872) meson abundances

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



– 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}

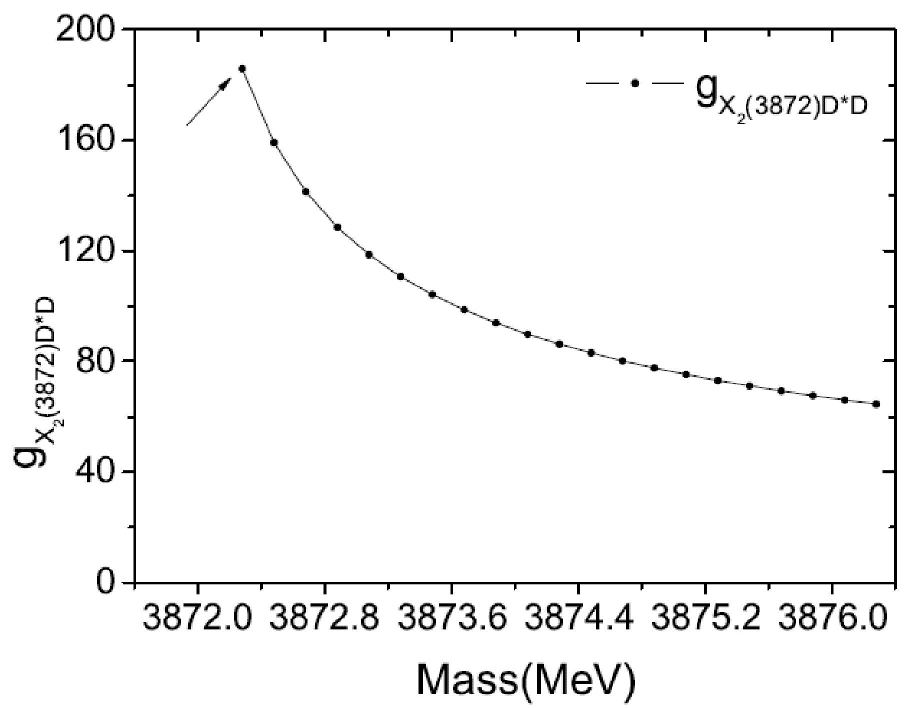
F. Brazzi, B. Grinstein, F. Piccinini, A. D. Polosa, and C. Sabelli, Phys. Rev. D **84**, 014003 (2011)

1) The phase space should be same for both cases

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

2) The coupling constant of X(3872) mesons depends on its mass ; the X(3872) is also measured near 3875.2 GeV

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



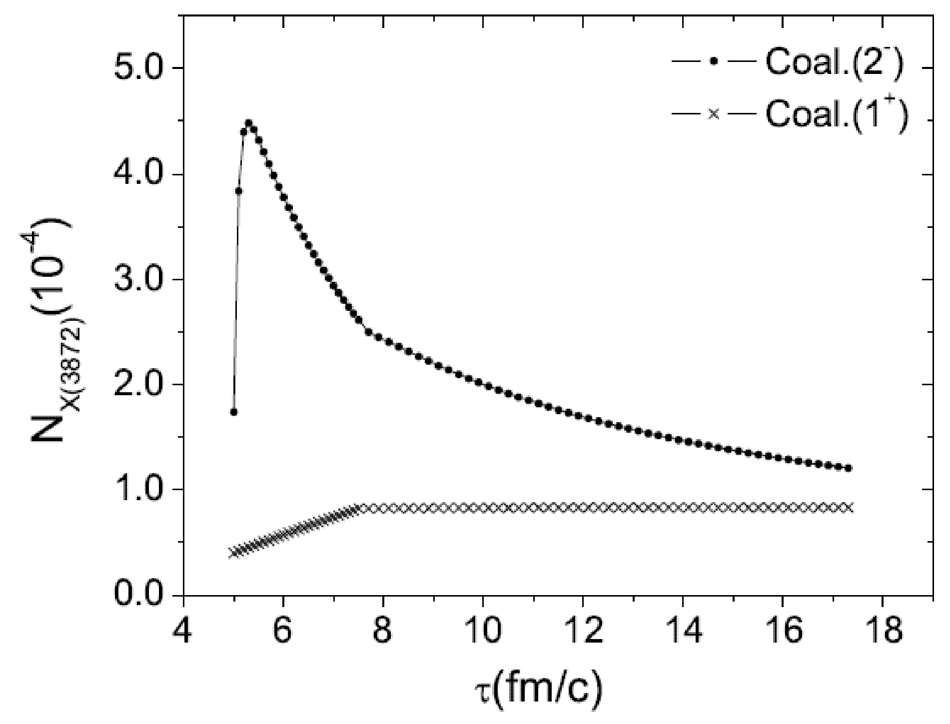
– Time evolution of X(3872)

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

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



– Time evolution of X(3872)

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

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

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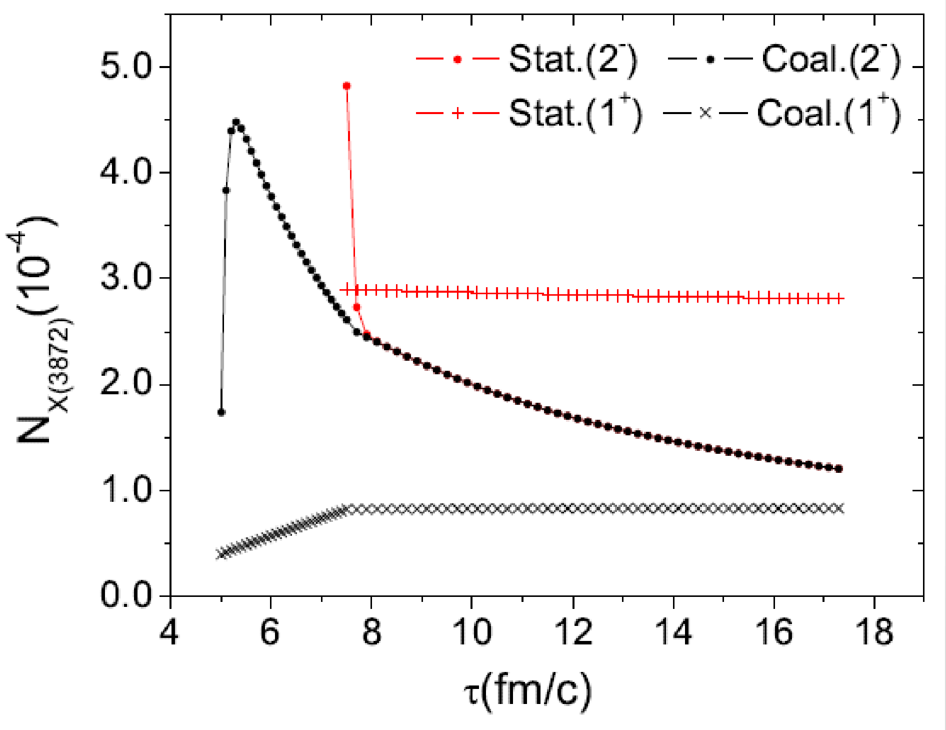


3) Time evolution of the X(3872) meson abundance is strongly dependent also on its quantum number and its structure

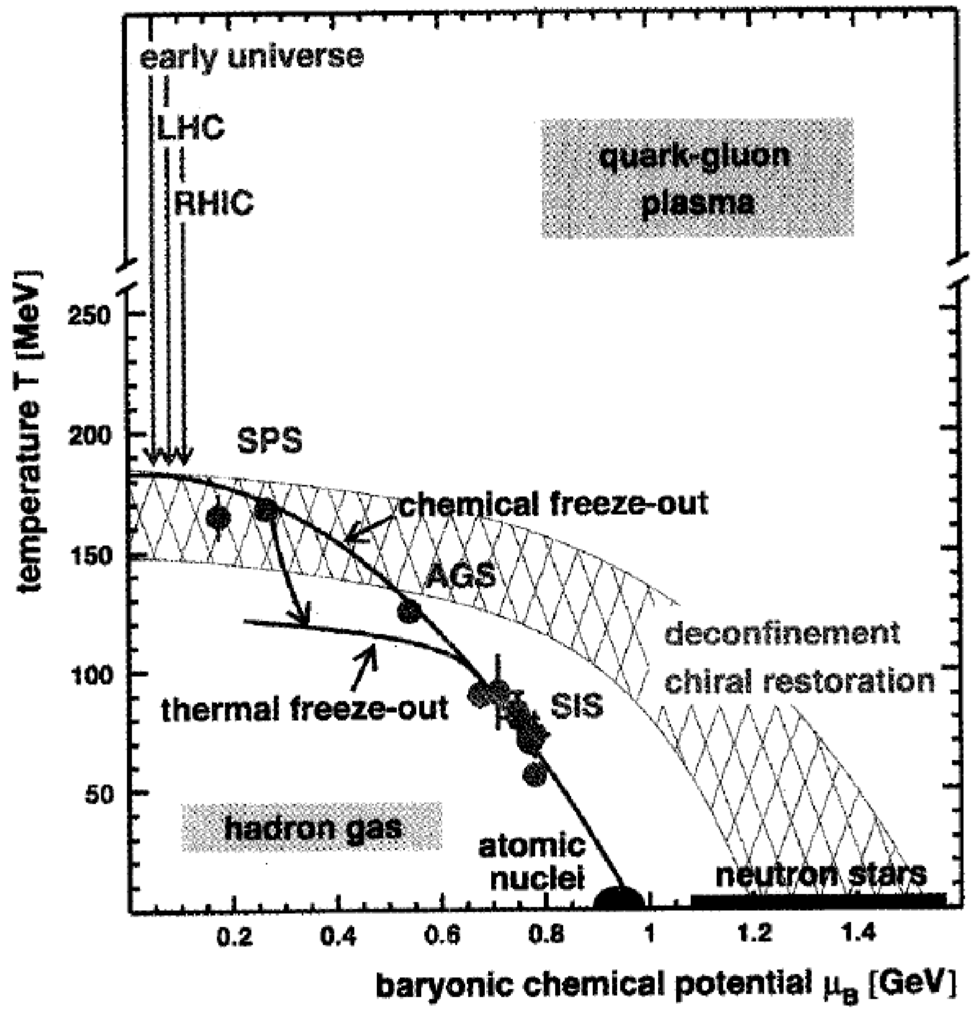
Conclusion

– Exotic hadrons from 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

Backup Slides

– Relativistic heavy ion collisions



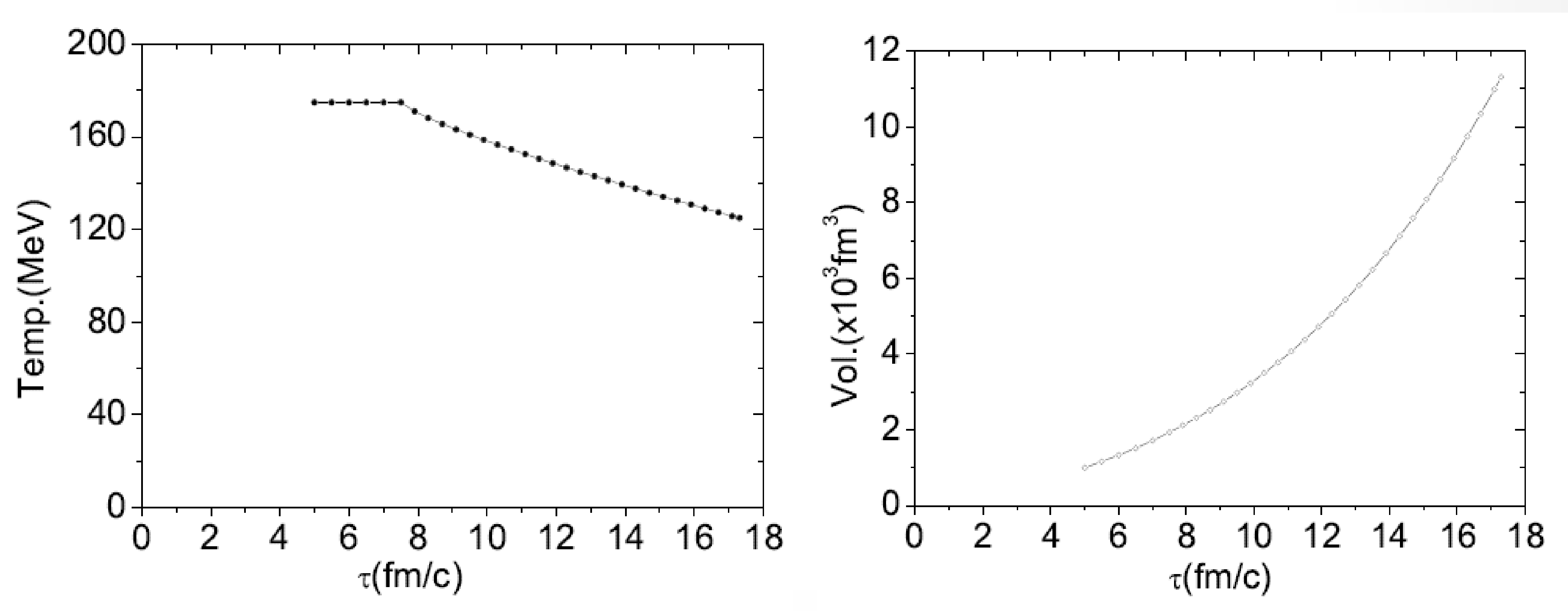
P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **690**, 119c (2001)

– Dynamics of relativistic heavy ion collision

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

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

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



– Interaction Lagrangians

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

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

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

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

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

2) The interaction Lagrangians for X(3872)

$$\begin{aligned} \mathcal{L}_{X_1 D^* D} &= g_{X_1 D^* D} X_1^\mu \bar{D}_\mu^* D, \\ \mathcal{L}_{X_1 \psi \rho} &= i g_{X_1 \psi \rho} \epsilon^{\mu\nu\rho\sigma} \psi_\nu \rho_\rho \partial_\sigma X_{1\mu}, \\ \mathcal{L}_{X_2 D^* D} &= -i g_{X_2 D^* D} X_2^{\mu\nu} \bar{D}_\mu^* \partial_\nu D, \end{aligned}$$

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