Heavy Exotics In Heavy Ion Collisions

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– This talk is based on

Identifying Multiquark Hadrons from Heavy Ion Collisions,
ExHIC Collaboration, Phys. Rev. Lett. **106**, 212001 (2011)

Studying Exotic Hadrons In Heavy Ion Collisions,
ExHIC Collaboration, arXiv: 1107.1302

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Outline

- Introduction
- The statistical model
- Hadronization in heavy ion collisions
- The coalescence model
- Results
- Conclusion

Introduction

– Normal hadrons

: Mesons and Baryons

– Multiquark hadrons

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

$K\bar{K}$ hadronic molecule (1990)

ii) Hadronic molecules & multi-quark states

$X(3872)$ Belle (2003)

$D_{sJ}(2317)$ BaBar (2003)

Introduction

– Normal hadrons

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– Multiquark hadrons

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

$K\bar{K}$ hadronic molecule (1990)

ii) Hadronic molecules & multi-quark states

$X(3872)$ Belle (2003) $\rightarrow \bar{D}D^*, D\bar{D}^*, q\bar{q}c\bar{c}$

$D_{sJ}(2317)$ BaBar (2003) $\rightarrow DK, c\bar{s}, q\bar{q}c\bar{s}$

– The purpose of this work

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

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

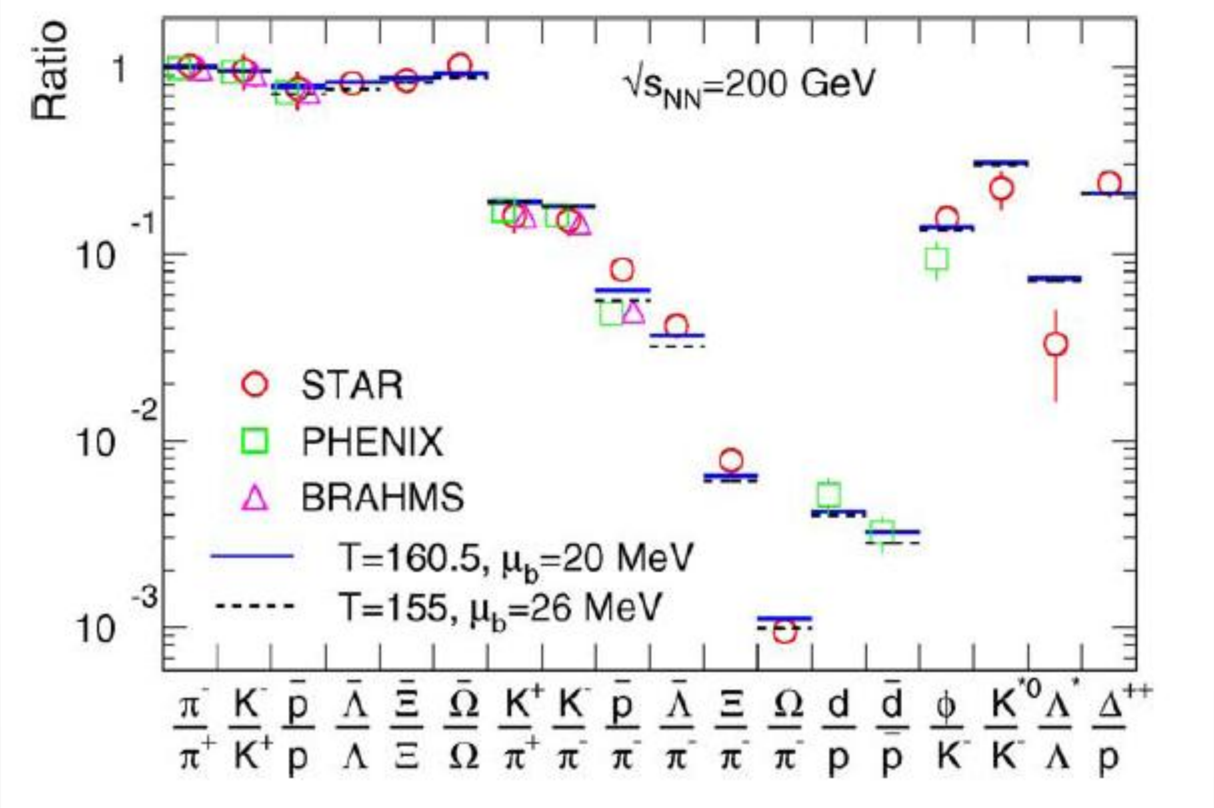
– We focus on hadron production yields

i) Normal hadron (light quark hadrons) production yields are well described by the statistical model

ii) Many aspects of the heavy ion collision experimental results can nicely be explained by the coalescence model

The statistical model

– Hadron yield ratios at RHIC



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

– The thermally equilibrated system

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

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

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

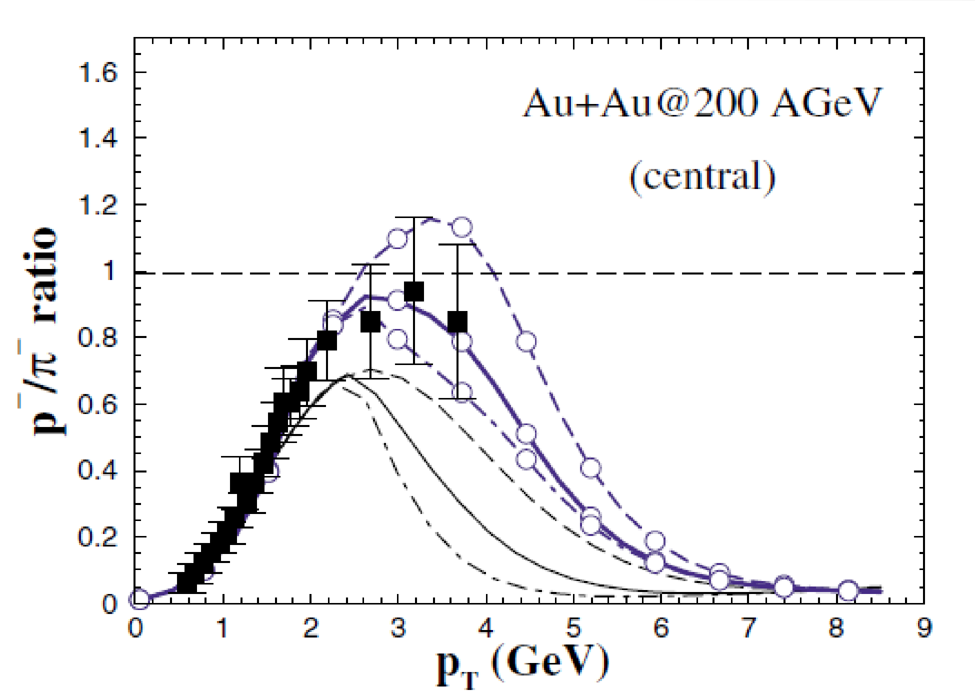
ii) We expect the statistical model to play its important role again in describing the expected multiquark hadron yields produced at heavy ion collision experiment

Hadronization in heavy ion collisions

– The fragmentation picture

i) A parton spectrum relates the probability for a parton to hadronize into a hadron, carrying a fraction z<1 of the momentum of the parent parton.

ii) The puzzle in antiproton /pion ratio
Requires a rescaling for a fraction z for all hadrons



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

– Coalescence vs. fragmentation

i) There must be a competition

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

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

– The coalescence picture

i) The quark number scaling of the elliptic flow of identified hadrons

ii) The yield of antihyperons recently discovered in heavy ion collision at RHIC

The coalescence model

– Yields of hadrons with n constituents

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

i) Wigner function : Coalescence probability function

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

ii) Covariant phase space density

$$\int p_i \cdot d\sigma_i \frac{d^3 p_i}{(2\pi)^3 E_i} f(x_i, p_i) = N_i$$

– The coalescence model can

i) consider the internal structure of hadrons

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

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

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

ii) explain both the quark and hadron coalescence

– Final results

$$N_h^{Coal} \cong g \prod_{j=1}^{n} \frac{N_i}{g_i} \prod_{i=1}^{n-1} \frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)} \frac{(2l_i)!!}{(2l_i+1)!!} \left[\frac{2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)} \right]^{l_i}$$

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

– The quark coalescence

: Reference hadrons - $\Lambda(1115),\ \Lambda_c(2286)$

– The hadron coalescence

: The relation between the binding energy and the root mean square radius

$$B.E. \cong \frac{\hbar^2}{2\mu a_0^2} \qquad \langle r^2 \rangle \cong \frac{a_0^2}{2} \qquad \omega = \frac{3}{2\mu \langle r^2 \rangle}$$

Results

– Summary of (heavy) exotics considered

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^1_{cc} †)	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	$1^+, 2^-$ *)	$c\bar{c}\ (L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$	3.6(B)	$J/\psi\pi\pi$ (strong decay)
$Z^+(4430)$ ‡)	4430	3	1	0^- *)	—	$q\bar{q}c\bar{c}\ (L=1)$	$D_1\bar{D}^*$	13.5(B)	$J/\psi\pi$ (strong decay)
T^0_{cb} †)	7123	1	0	0^+	—	$qq\bar{c}\bar{b}$	$\bar{D}B$	128(B)	$K^+\pi^- + K^+\pi^-$

– Estimated exotic hadron yields at RHIC and LHC

	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} †)	—	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}
$Z^+(4430)$‡)	—	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} †)	—	6.1×10^{-8}	1.8×10^{-7}	6.9×10^{-7}	—	6.1×10^{-6}	1.9×10^{-5}	6.8×10^{-5}

– The loosely bound exotic hadron molecules are more produced

$$2 < \frac{N_{i,molecule}^{Coal}}{N_i^{Stat}}$$

– Normal hadron zone

$$0.2 < \frac{N_{i,normal}^{Coal}}{N_i^{Stat}} < 2$$

– The exotic multiquark hadrons become suppressed

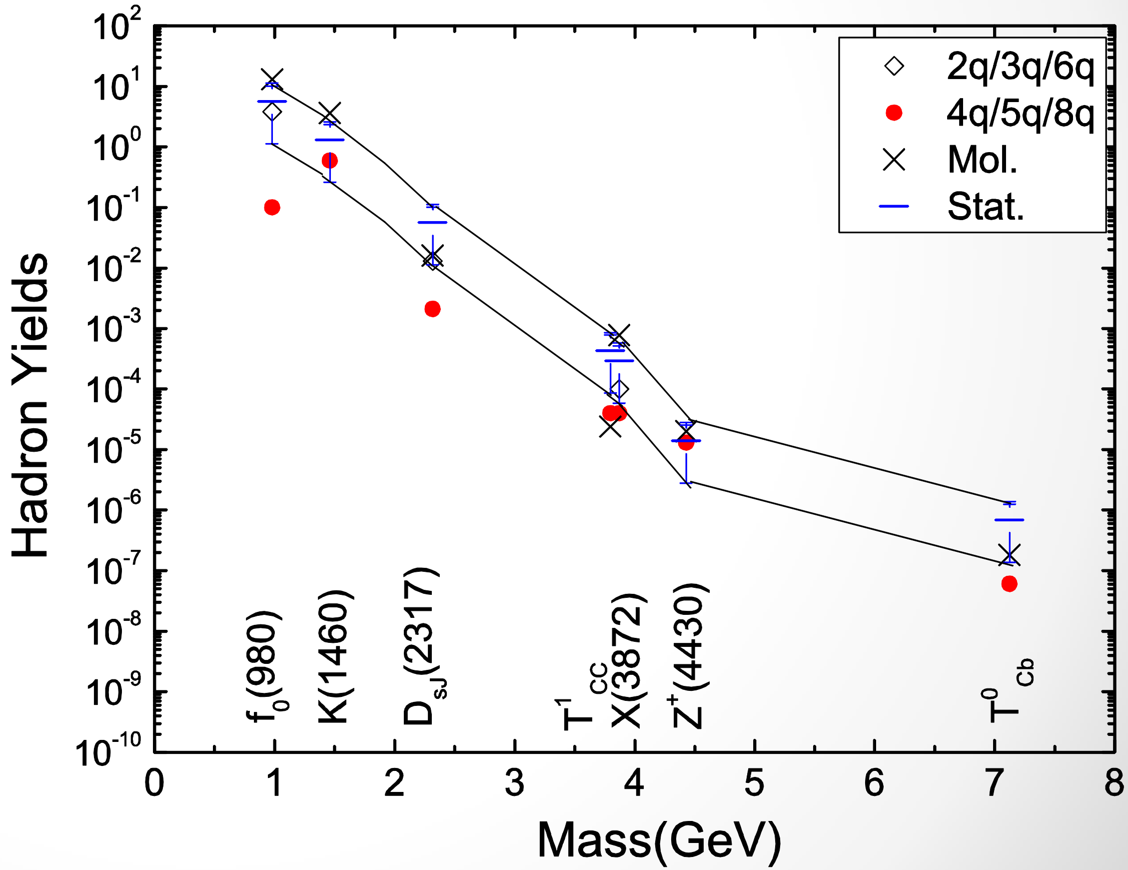
$$\frac{N_{i,multiquark}^{Coal}}{N_i^{Stat}} < 0.2$$

– Comparison to experimental data

i) Fortunately, STAR Collaboration has a preliminary measurement for $f_0(980)$ P. Fachini [STAR Collaboration], Nucl. Phys. A **715**, 462 (2003)

$$\frac{N_{f_0(980)}}{N_{\rho_0}} \sim 0.2$$

ii) Can we say whether $f_0(980)$ is a tetraquark hadron or a hadronic $K\bar{K}$ molecule?



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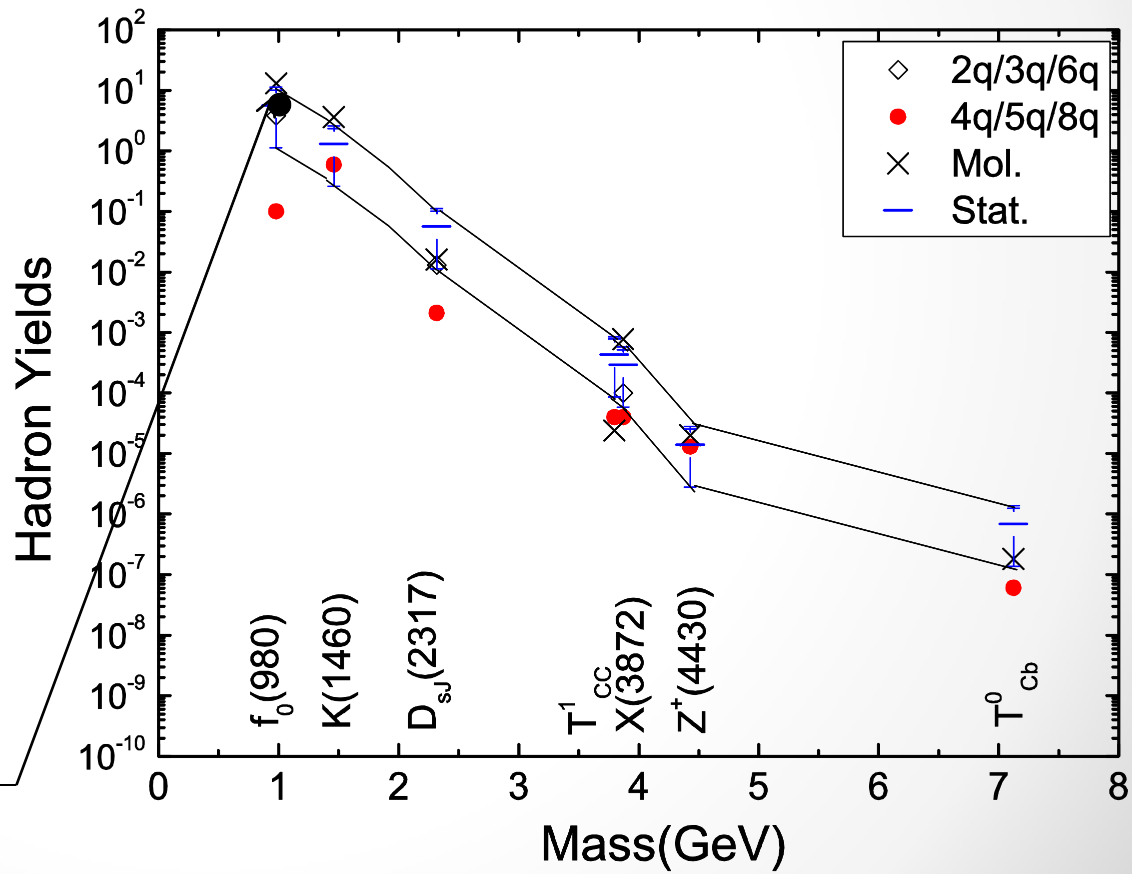
$$\frac{N_{f_0(980)}}{N_{\rho_0}} \sim 0.2$$

ii) Can we say whether $f_0(980)$ is a tetraquark hadron or a hadronic $K\bar{K}$ molecule?

: At lease, $f_0(980)$ must not be a tetraquark hadron

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



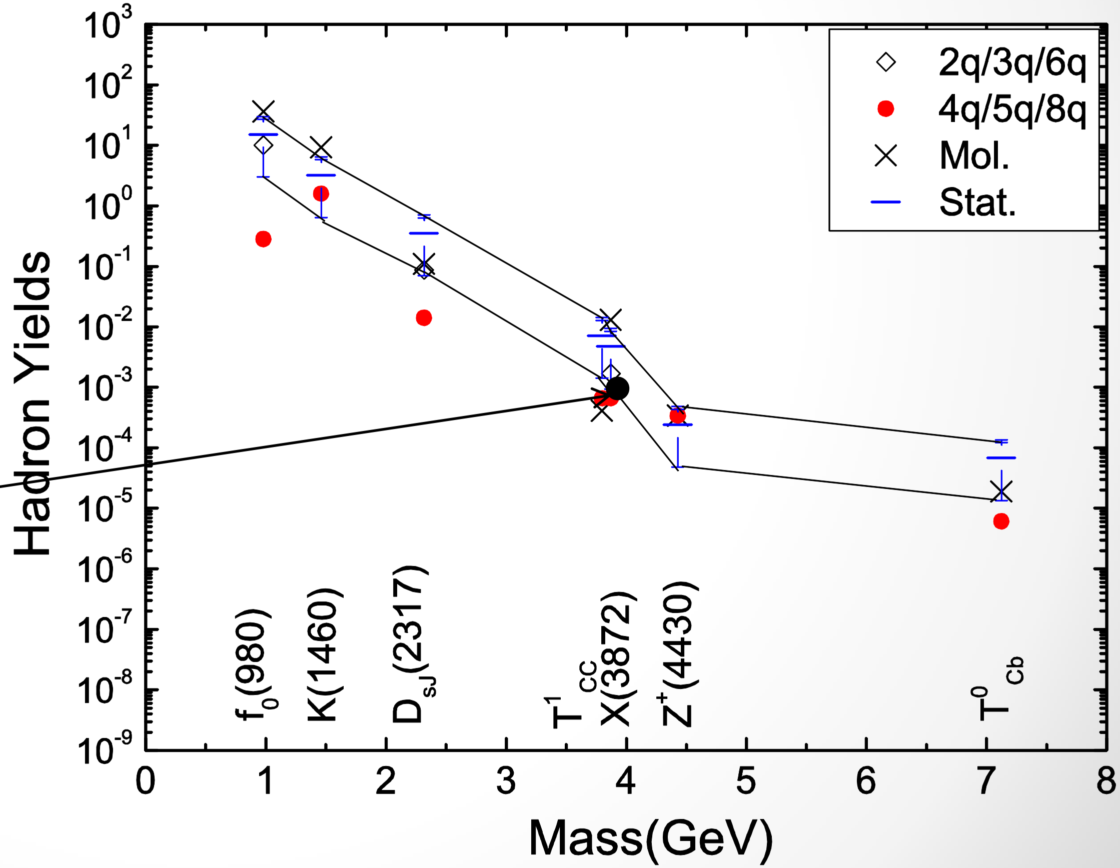
iii) More fortunately, CMS Collaboration has a measurement for X(3872)

CMS Physics Analysis Summary, [CMS Collaboration], CMS PAS BPH-10-018, 2011/04/19

$$\rightarrow R = \frac{N_{X(3872)}}{N_{\psi(2S)}} = 0.087 \pm 0.017(stat.) \pm 0.009(syst.)$$

iv) We can say that the X(3872) is may not be a hadronic molecule

$$7.83\times10^{-4} < N_{X(3872)} = 1.12\times10^{-3} < 1.45\times10^{-3}$$



Conclusion

– Exotic hadrons in relativistic heavy ion collisions

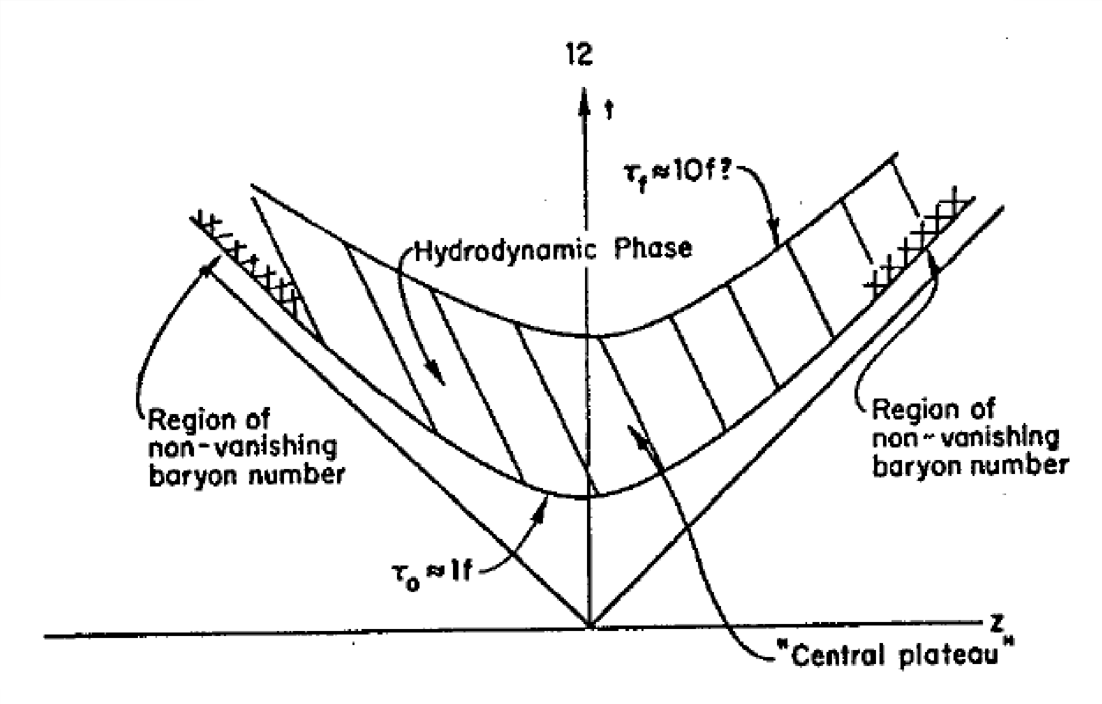
i) The yields of exotic hadrons are large enough to be measurable in experiments : Relativistic heavy ion collisions can provide an opportunity to search for exotic hadrons

ii) The probability to combine n quarks into a compact region is suppressed as n increases

iii) The yield of a hadron in relativistic heavy ion collision reflects its structure : Therefore, yields can be used to discriminate the different pictures for the structure of exotic hadrons

Backup slides

– 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 : QGP
iii) Hadronization : Mixed phase
iv) Freeze-out : Hadron gas

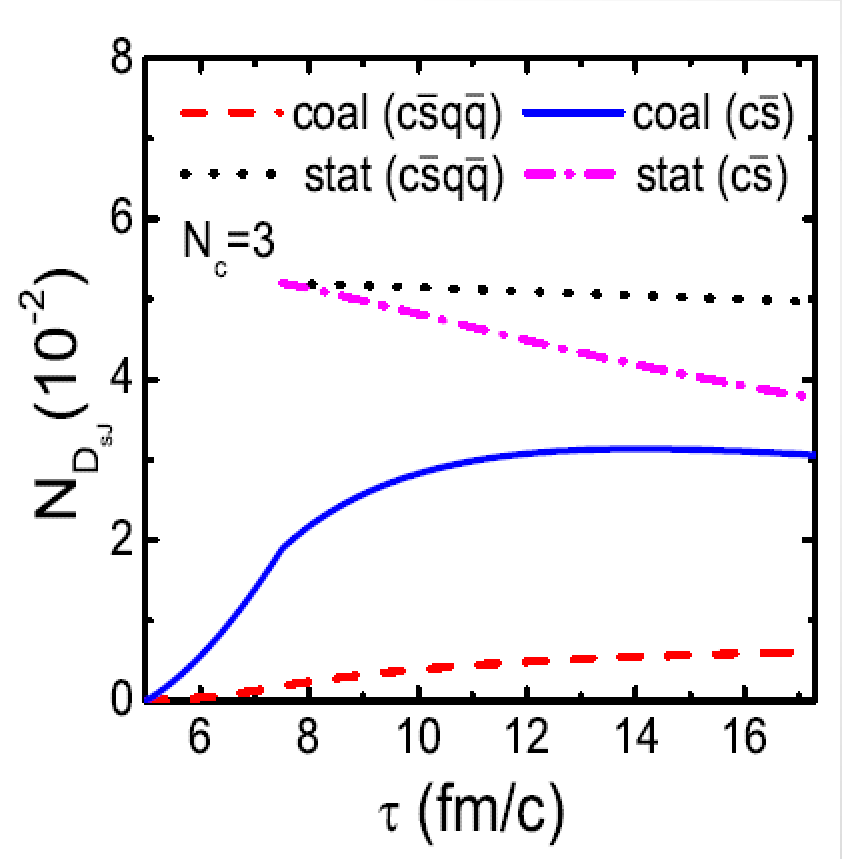
– Time evolution of exotics : D_{sJ}(2317)

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

i) Time evolution of the D_{sJ}(2317) meson abundance in central Au+Au collision at $\sqrt{s_{NN}}$=200 GeV

ii) The yield of the D_{sJ}(2317) meson increases during the hadronic evolution in the coalescence model

iii) The yield decreases or remains almost unchanged depending on whether the D_{sJ}(2317) meson is a two-quark or a four-quark meson



– Quark coalescence

: Reference hadrons - $\Lambda(1115)$, $\Lambda_c(2286)$

$$N^{Stat,total}_{\Lambda_C(2286)} = N^{Stat}_{\Lambda_C(2286)} + N^{Stat}_{\Sigma_C(2455)} + N^{Stat}_{\Sigma_C(2520)} + 0.67 \times N^{Stat}_{\Lambda_C(2625)} = N^{Coal,total}_{\Lambda_C(2286)}(\omega_c)$$

$$\rightarrow \omega_s = 519 MeV, \quad \omega_c = 385 MeV$$

– Hadron coalescence

: The relation between the binding energy and the root mean square radius

$$B.E. \cong \frac{\hbar^2}{2\mu a_0^2}$$

$$\langle r^2 \rangle \cong \frac{a_0^2}{2}$$

$$\omega = \frac{3}{2\mu\langle r^2 \rangle}$$

$$\rightarrow \omega_{\Lambda(1405)} = \frac{3}{2\mu_{\Lambda(1405)}\langle r^2 \rangle_{\Lambda(1405)}} = 20.5 MeV$$

– Summary of all exotic hadrons considered

Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	$\omega_{\text{Mol.}}$ (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)
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$X(3872)$	3872	3	0	$1^+, 2^-$ *)	$c\bar{c}$ $(L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$	3.6(B)	$J/\psi\pi\pi$ (strong decay)
$Z^+(4430)$ ‡)	4430	3	1	0^- *)	—	$q\bar{q}c\bar{c}$ $(L=1)$	$D_1\bar{D}^*$	13.5(B)	$J/\psi\pi$ (strong decay)
T^0_{cb} †)	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)
$\Theta^+(1530)$ ‡)	1530	2	0	$1/2^+$ *)	—	$qqqq\bar{s}$ $(L=1)$	—	—	KN (strong decay)
$\bar{K}KN$ †)	1920	4	1/2	$1/2^+$	—	$qqqs\bar{s}$ $(L=1)$	$\bar{K}KN$	42(R)	$K\pi\Sigma$, $\pi\eta N$ (strong decay)
$\bar{D}N$ †)	2790	2	0	$1/2^-$	—	$qqqq\bar{c}$	$\bar{D}N$	6.48(R)	$K^+\pi^-\pi^- + p$
$\bar{D}^*N$ †)	2919	4	0	$3/2^-$	—	$qqqq\bar{c}$ $(L=2)$	$\bar{D}^*N$	6.48(R)	$\bar{D} + N$ (strong decay)
Θ_{cs} †)	2980	4	1/2	$1/2^+$	—	$qqqs\bar{c}$ $(L=1)$	—	—	$\Lambda + K^+\pi^-$
BN †)	6200	2	0	$1/2^-$	—	$qqqq\bar{b}$	BN	25.4(R)	$K^+\pi^-\pi^- + \pi^+ + p$
B^*N †)	6226	4	0	$3/2^-$	—	$qqqq\bar{b}$ $(L=2)$	B^*N	25.4(R)	$B + N$ (strong decay)
Dibaryons									
H †)	2245	1	0	0^+	$qqqqss$	—	ΞN	73.2(B)	$\Lambda\Lambda$ (strong decay)
$\bar{K}NN$ ‡)	2352	2	1/2	0^- *)	$qqqqqs$ $(L=1)$	$qqqqqq\,s\bar{q}$	$\bar{K}NN$	20.5(T)-174(T)	ΛN (strong decay)
$\Omega\Omega$ †)	3228	1	0	0^+	$ssssss$	—	$\Omega\Omega$	98.8(R)	$\Lambda K^- + \Lambda K^-$
H^{++}_c †)	3377	3	1	0^+	$qqqqsc$	—	$\Xi_c N$	187(B)	$\Lambda K^-\pi^+\pi^+ + p$
$\bar{D}NN$ †)	3734	2	1/2	0^-	—	$qqqqqq\,q\bar{c}$	$\bar{D}NN$	6.48(T)	$K^+\pi^- + d$, $K^+\pi^-\pi^- + p + p$
BNN †)	7147	2	1/2	0^-	—	$qqqqqq\,q\bar{b}$	BNN	25.4(T)	$K^+\pi^- + d$, $K^+\pi^- + p + p$

– Estimated hadrons yields at RHIC and LHC

	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
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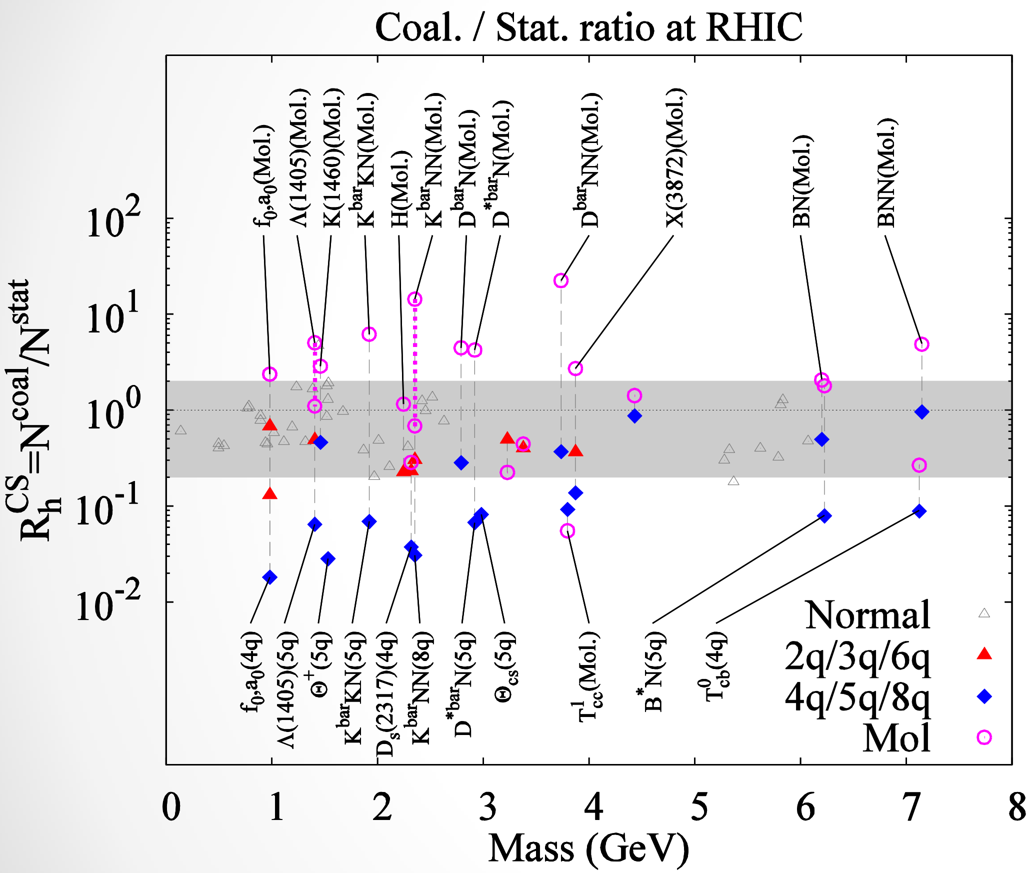
$K(1460)$	—	0.59	3.6	1.3	—	1.6	9.3	3.2
$D_s(2317)$	1.3×10^{-2}	2.1×10^{-3}	1.6×10^{-2}	5.6×10^{-2}	8.7×10^{-2}	1.4×10^{-2}	0.10	0.35
T_{cc}^{1} †)	—	4.0×10^{-5}	2.4×10^{-5}	4.3×10^{-4}	—	6.6×10^{-4}	4.1×10^{-4}	7.1×10^{-3}
$X(3872)$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	1.7×10^{-3}	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}
$Z^{+}(4430)$‡)	—	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} †)	—	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^{+} ‡)	—	2.9×10^{-2}	—	1.0	—	7.8×10^{-2}	—	2.3
$\bar{K}KN$ †)	—	1.9×10^{-2}	1.7	0.28	—	5.2×10^{-2}	4.2	0.67
$\bar{D}N$ †)	—	2.9×10^{-3}	4.6×10^{-2}	1.0×10^{-2}	—	2.0×10^{-2}	0.28	6.1×10^{-2}
$\bar{D}^{*}N$ †)	—	7.1×10^{-4}	4.5×10^{-2}	1.0×10^{-2}	—	4.7×10^{-3}	0.27	6.2×10^{-2}
Θ_{cs} †)	—	5.9×10^{-4}	—	7.2×10^{-3}	—	3.9×10^{-3}	—	4.5×10^{-2}
BN †)	—	1.9×10^{-5}	8.0×10^{-5}	3.9×10^{-5}	—	7.7×10^{-4}	2.8×10^{-3}	1.4×10^{-3}
$B^{*}N$ †)	—	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 †)	3.0×10^{-3}	—	1.6×10^{-2}	1.3×10^{-2}	8.2×10^{-3}	—	3.8×10^{-2}	3.2×10^{-2}
$\bar{K}NN$ ‡)	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}
$\Omega\Omega$ †)	3.2×10^{-5}	—	1.5×10^{-5}	6.4×10^{-5}	8.6×10^{-5}	—	4.4×10^{-5}	1.9×10^{-4}
H_{c}^{++} †)	3.0×10^{-4}	—	3.3×10^{-4}	7.5×10^{-4}	2.0×10^{-3}	—	1.9×10^{-3}	4.2×10^{-3}
$\bar{D}NN$ †)	—	2.9×10^{-5}	1.8×10^{-3}	7.9×10^{-5}	—	2.0×10^{-4}	9.8×10^{-3}	4.2×10^{-4}
BNN †)	—	2.3×10^{-7}	1.2×10^{-6}	2.4×10^{-7}	—	9.2×10^{-6}	3.7×10^{-5}	7.6×10^{-6}

– Graphs



Coalescence / Statistical model ratio at RHIC