Exotic hadrons production in heavy ion collisions

Che-Ming Ko
Texas A&M University

- Exotic hadrons studies in HIC
- Thermal vs coalescence production
- Pentaquark $\Theta^+(udud\bar{s})$
- Diomega $(\Omega\Omega)_0$
- $D_{sJ}(2317)$: diquark or tetraquark
- Charmed tetraquark mesons and pentaquark baryons
- Other exotic mesons, baryons and dibaryons

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Exotic hadron studies in HIC

- $\Theta^+(udud\bar{s})$
  - Randrup, PRC 68, 031903 (2003); statistical model
  - Letessier et al., PRC 68, 061901(R) (2003); statistical model
  - Chen et al., PLB 601, 34 (2004); coalescence model
  - Nonaka et al., PRC 69, 031902 (2004); coalescence model, elliptic flow
  - Not observed by STAR and PHENIX
- Diomega $(\Omega\Omega)_0$
  - Zhang et al., PRC 61, 065204 (2000); based on chiral quark model
  - Pal et al., PLB 624, 210 (05); hadronic transport model
- D_{sJ}: $(c\bar{s})$ or $(c\bar{s}q\bar{q})$
  - Chen et al., PRC 76, 064903 (2007); coalescence model
- $\Theta_{cs}^+(udus\bar{c})$ and $T_{cc}(ud\bar{c}\bar{c})$
  - Lee et al., Eur. J. Phys. C 54, 259 (08); coalescence model
- Exotic mesons (8), baryons (8), and dibaryons (6)
  - Cho et al. [ExHIC Collaboration], PRL 106, 212001 (2011); PRC 84, 064910 (2011); coalescence model

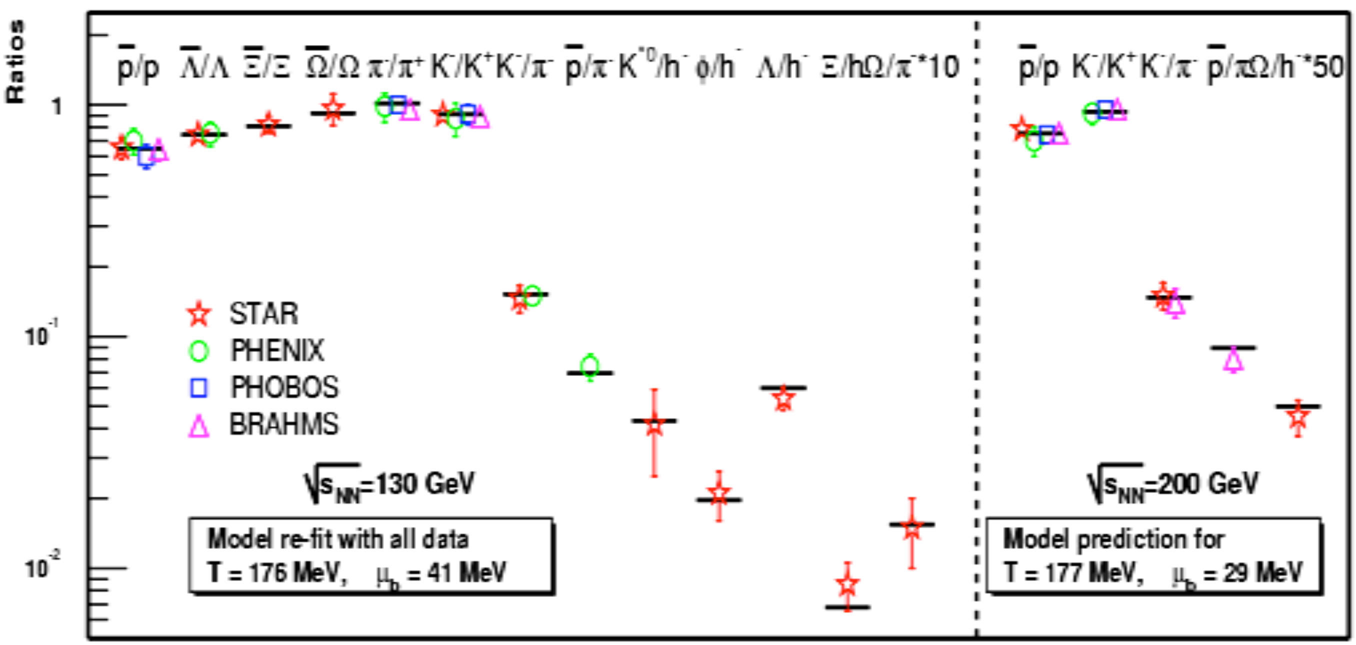
Statistical model

Andronic et al, NPA 722, 167 (2006); Wheaton et al., Phys. Commun. 180, 84 (2009)

Assume thermally and chemically equilibrated system of non-interacting hadrons and resonances with density

$$\boxed{n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2\,dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}\,, \quad E_i = \sqrt{p^2 + m_i^2}}$$

Determine chemical freeze out temperature T_{ch} and baryon chemical potential μ_B by fitting experimental data after inclusion of feed down from short-lived particles and resonances decay.



T_{ch}~T_c

Coalescence model

Greco, Ko & Levai, PRL 90, 202102 (2003); PRC 68, 034904 (2003)

Number of hadrons with n quarks and/or antiquarks

$$N_n = g \int \prod_{i=1}^{n} p_i d\sigma_i \frac{dp_i}{(2\pi)^3 E_i} f_{q,i}(x_i, p_i) f_n(x_1, \ldots, x_n; p_1, \ldots, p_n)$$

Spin-color statistical factor g_M e.g. $g_\pi = g_K = 1/36 \quad g_\rho = g_{K^*} = 1/12$

$g_p = g_{\bar{p}} = 1/108, \quad g_\Delta = g_{\bar{\Delta}} = 1/54$

Quark distribution function $f_q(x, p)$

$$\int p \cdot d\sigma \frac{d^3p}{(2\pi)^3 E} f_q(x, p) = N_q$$

Coalescence probability function

$\Delta_x \cdot \Delta_p \approx \hbar$

$$\begin{aligned} f_M(x_1, x_2; p_1, p_2) &= f_2(x_1 - x_2; p_1 - p_2) \\ &= \exp[(x_1 - x_2)^2 / 2\Delta_x^2] \\ &\times \exp[\{(p_1 - p_2)^2 - (m_1 - m_2)^2\} / 2\Delta_p^2] \end{aligned}$$

For baryons, Jacobi coordinates for three-body system are used.

Θ^+(udud sbar) production in heavy ion collisions

Chen, Greco, Ko, Lee & Liu, PLB 601, 34 (2004)

Using non-relativistic distributions for quarks and harmonic oscillator wave functions for Θ^+

$$f_q(\eta, y, \vec{p}_\perp) = g_q \delta(\eta - y) \exp(-\vec{p}_\perp^{\,2} / (2 m_q T))$$

$$f_\Theta(x; p) = 8^4 \exp\left(-\sum_{i=1}^{4} \vec{y}_i^{\,2} / \sigma_i^2 - \sum_{i=1}^{4} \vec{k}_i^{\,2} \sigma_i^2 \right)$$

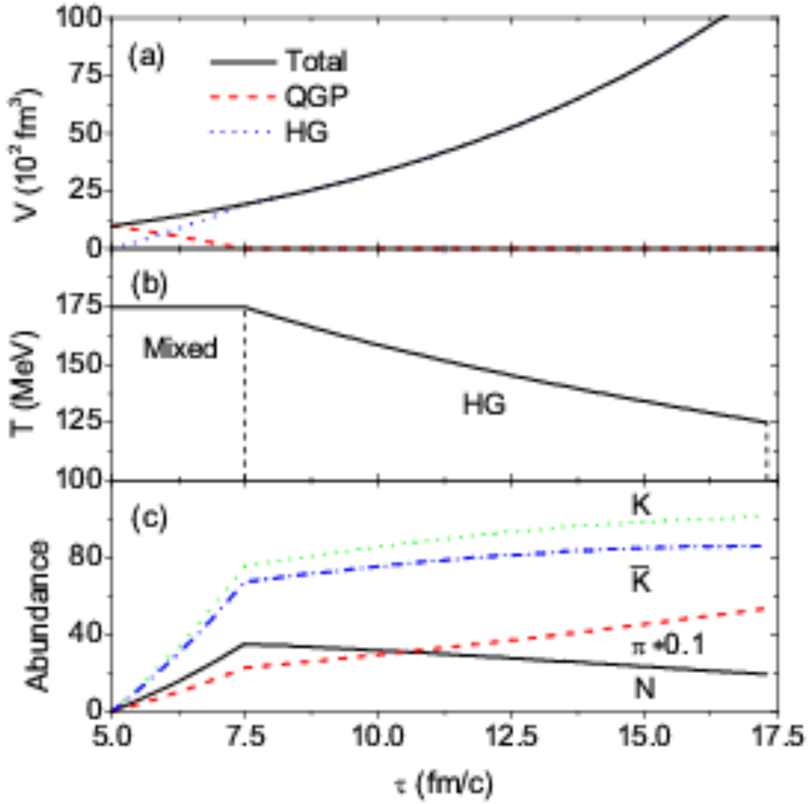
Number of Θ^+ produced in quark coalescence model

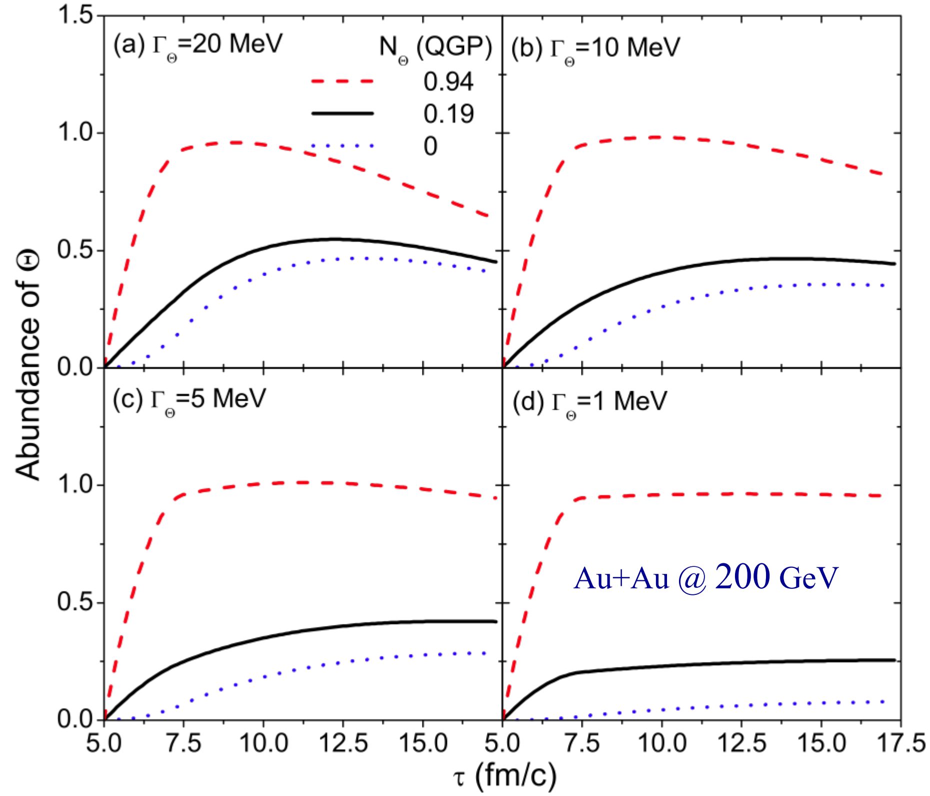
$$N_\Theta = g_\Theta \int \prod_{i=1}^{5} \frac{p_i \cdot d\sigma_i d^3 \vec{p}_i}{(2\pi)^3 E_i} f_q(x_i, p_i) f_\Theta(x_1 \cdots x_5; p_1 \cdots p_5)$$

$$= g_\Theta N_u^2 N_d^2 N_{\bar{s}} \left(\frac{4 m_q}{5 m_s} + \frac{1}{5} \right)^{3/2} \left[\frac{(4\pi)^{3/2} \sigma^3}{V (1 + 2 m_q T \sigma^2)} \right]^4$$

Time evolution of Θ⁺(udud sbar) abundance

$$\frac{dN_\Theta}{d\tau} = R_{QGP}(\tau) + \langle \sigma_{\pi N \to \bar{K}\Theta} v \rangle n_\pi n_N V_H + \left(\langle \sigma_{KN \to \pi\Theta} v \rangle + \langle \sigma_{KN \to \Theta} v \rangle \right) n_K n_N V_H$$
$$- \Gamma_\Theta N_\Theta - \langle \sigma_{\bar{K}\Theta \to \pi N} v \rangle n_{\bar{K}} N_\Theta - \langle \sigma_{\pi\Theta \to KN} v \rangle n_\pi N_\Theta$$



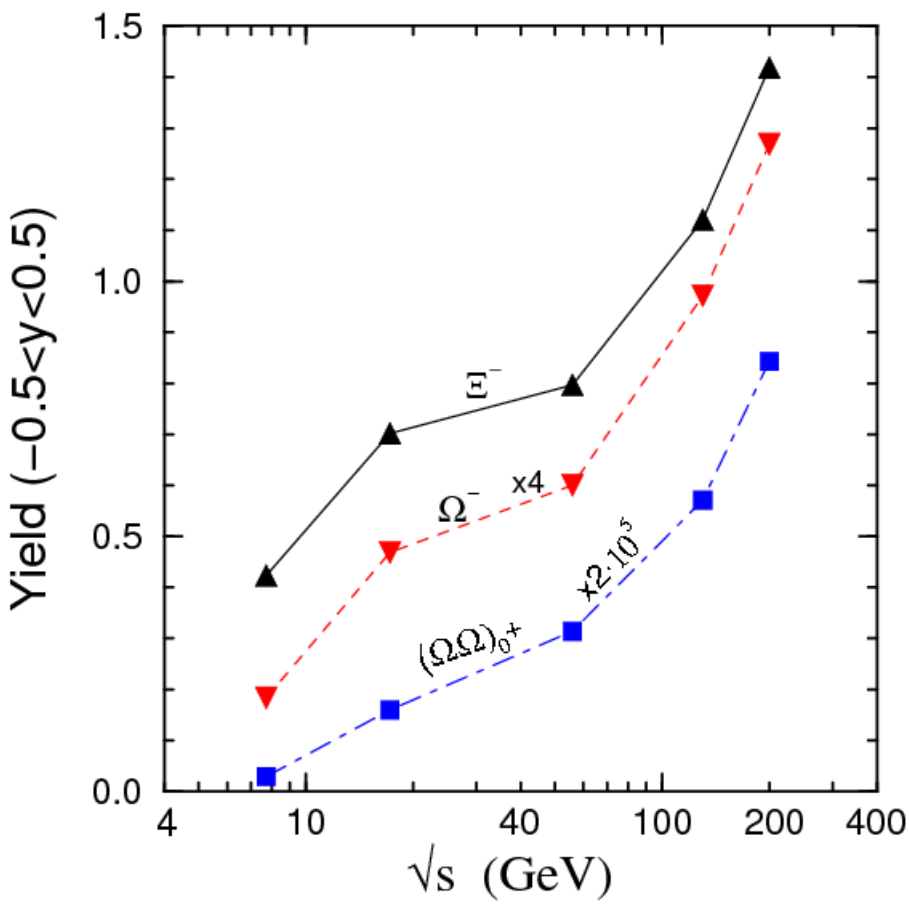


- About 0.5 Θ^+ (σ=0.86 fm and Γ_Θ=20 MeV) in central rapidity per collision, similar to predictions from statistical model (Randrup; Letessier et al.)

Diomega prodcution in HIC

According to the chiral quark model of Zhang et al. (PRC 61, 065204 (2000)), diomega $(\Omega\Omega)_{0+}$ is bound by ~ 116 MeV with a root-mean-square radius ~ 0.84 fm and lifetime ~ 10^{-10} sec.

No.	Channel
I	$\Omega+\Omega\to(\Omega\Omega)_0+\gamma$
II	$\Omega+\Omega\to(\Omega\Omega)_0+\eta$
III	$\Omega+\Omega\to(\Omega\Omega)_0+\eta'$
IV	$\Omega+\Omega\to(\Omega\Omega)_0+\phi$
V	$\Omega+\Xi\to(\Omega\Omega)_0+K$
VI	$\Omega+\Xi\to(\Omega\Omega)_0+K^*$
VII	$\Omega+N\to(\Omega N)_2+\gamma$
VIII	$\Omega+N\to(\Omega N)_2+\pi$
IX	$\Omega+(\Omega N)_2\to(\Omega\Omega)_0+N$



Pal, Ko & Zhang, PLB 624, 210 (05)

- Cross sections for I-VI are ~ 2-25 μb and thus unimportant.
- Production is dominated by two-step processes through VII, VIII (~ 50-175 μb) and IX (~ 20-50 mb).
- Yield is order of magnitude smaller than in statistical or coalescence model (neglect of three-body process?)

$D_{sJ}(2317)$: $J^{\pi}=0^{+}$

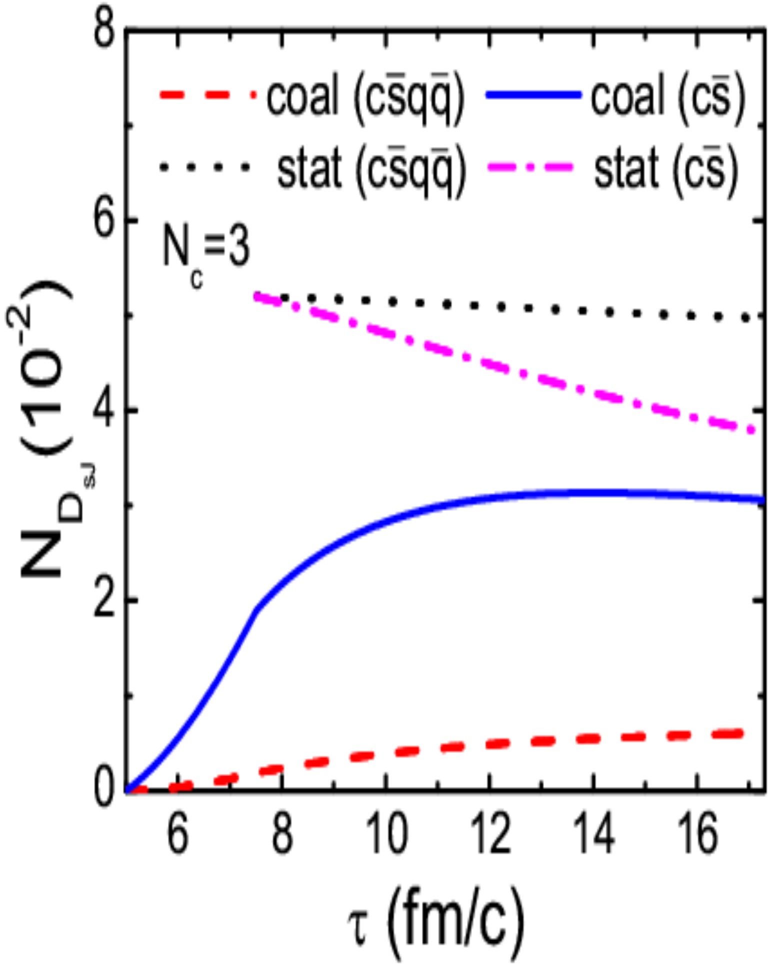
- Mass of 2317 MeV less than those predicted by quark model and QCD sum rule for two-quark state ($c\bar{s}$, p-wave) but comparable to those for four-quark state ($c\bar{s}q\bar{q}$, s-wave)

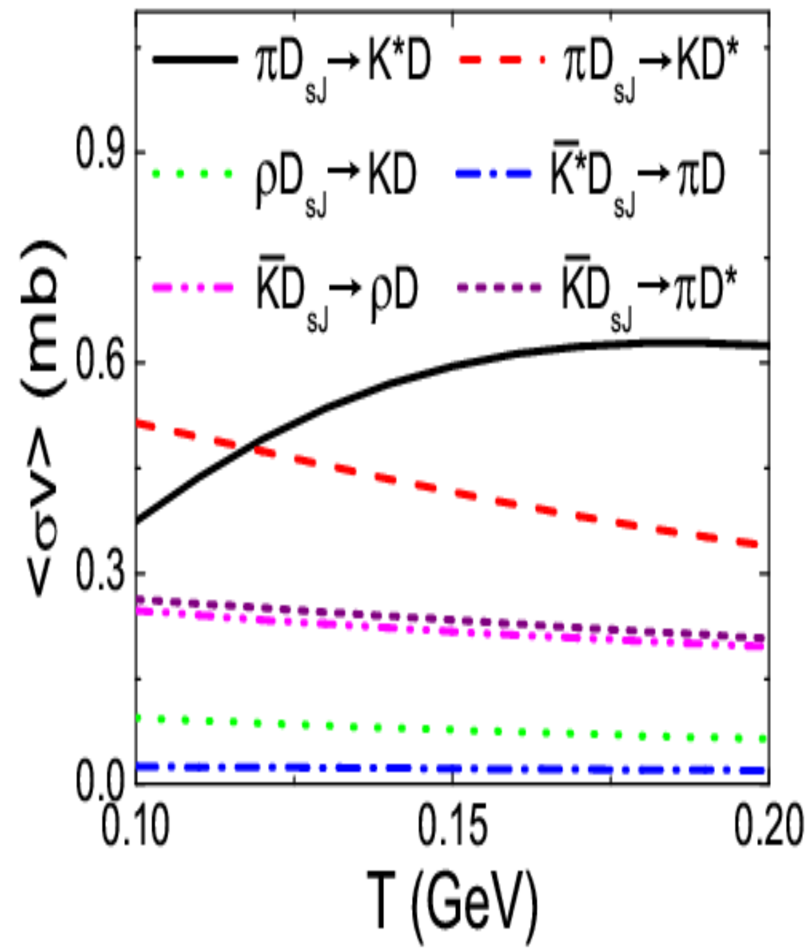
- Width of a few (four-quark) to a few tens (two-quark) keV from decay to $D_s\pi$, empirically less than 4.6 MeV limited by experimental resolution.

- Observed in elementary reactions:
  - BABAR: from $D_s+\pi^0$ inclusive invariant mass distribution in e^+e^- annihilation (PRL 90, 242001 (03))
  - Belle: from B decay (PRL 91, 262002 (03))

D_{sJ} production at RHIC

Chen, Liu, Nielsen & Ko, PRC 76, 064903 (2007))





- Cross sections are for four-quark state and larger by ~9 for two-quark state.
- Final yield is sensitive to the quark structure of D_{sJ}

Orbital angular momentum dependence of coalescence probability

- Hadron Wigner functions

$$f_s^w(\vec{y},\vec{k}) = 8\exp\left(-\frac{y^2}{\sigma^2} - k^2\sigma^2\right)$$

$$f_p^w(\vec{y},\vec{k}) = \left(\frac{16}{3}\frac{y^2}{\sigma^2} - 8 + \frac{16}{3}k^2\sigma^2\right)\exp\left(-\frac{y^2}{\sigma^2} - k^2\sigma^2\right)$$

- Coalescence factors

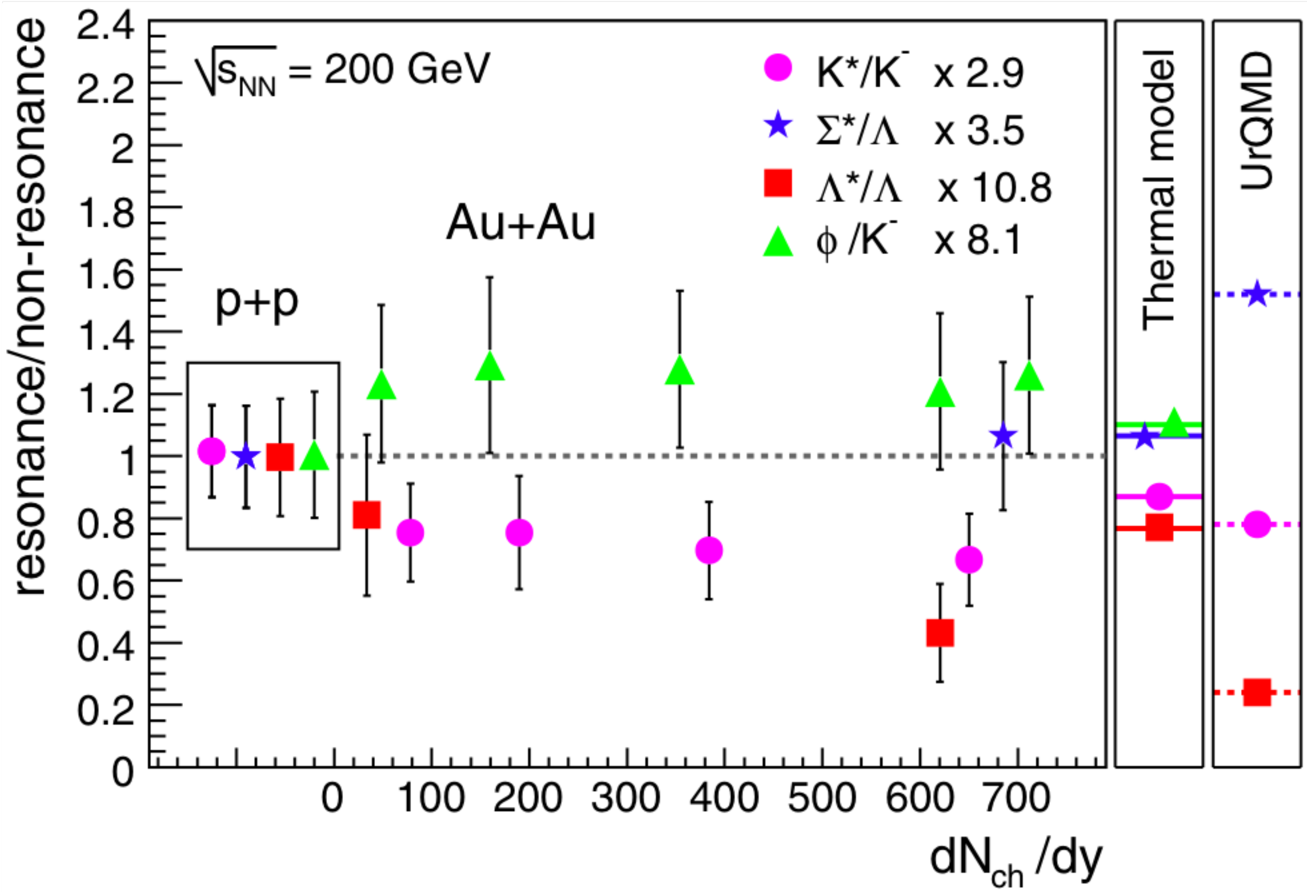
$$\frac{1}{g}\frac{N}{V}\frac{\left(4\pi\sigma^2\right)^{3/2}}{\left(1+2\mu T\sigma^2\right)^2} \approx 0.360 \quad \text{for s-wave}$$

$$\frac{1}{g}\frac{N}{V}\frac{2}{3}\frac{\left(4\pi\sigma^2\right)^{3/2} 2\mu T\sigma^2}{\left(1+2\mu T\sigma^2\right)^2} \approx 0.093 \quad \text{for p-wave}$$

- p-wave coalescence is suppressed by a factor of ~ 4 compared to s-wave coalescence.

Suppression of Λ(1520) in HIC

Abelev [Star Collaboration], PRL 97, 132301 (2006)



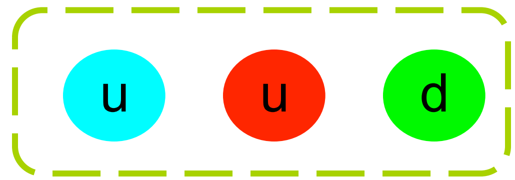
- Measured Λ(1520)/Λ(1115) ratio is significantly smaller than thermal model prediction, but can be explained by the coalescence model after taking into account the p-wave state of strang quark in Λ(1520) (Kanada-En'yo and Meuller, PRC 74, 061901(R) (2006).

Quark color-spin interaction and hadron masses

Lee, Yasui, Liu, and Ko, EJPC 54, 259 (2008)

- Baryon mass differences

Diquark $\sum \frac{C_B}{m_i m_j}[s_i \cdot s_j]$

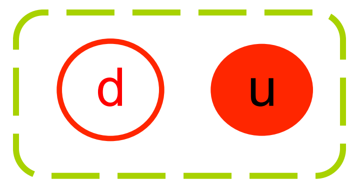


Mass Difference	$M_\Delta - M_N$	$M_\Sigma - M_\Lambda$	$M_{\Sigma_c} - M_{\Lambda_c}$
Formula	$\frac{3C_B}{2m_c^2}$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_s})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_c})$
Fit	290 MeV	77 MeV	154 MeV
Experiment	290 MeV	75 MeV	170 MeV

$$m_u = m_d = 300\text{ MeV},\ m_s = 500\text{ MeV},\ m_c = 1500\text{ MeV},\ m_b = 4700\text{ MeV}$$

- Meson mass differences

Quark-antiquark $\sum \frac{C_M}{m_i m_j}[s_i \cdot s_j]$



Mass Difference	$M_\rho - M_\pi$	$M_{K^*} - M_K$	$M_{D^*} - M_D$	$M_{B^*} - M_B$
Formula	$\frac{C_M}{m_u^2}$	$\frac{C_M}{m_u m_s}$	$\frac{C_M}{m_u m_c}$	$\frac{C_M}{m_u m_b}$
Fit	635 MeV	381 MeV	127 MeV	41 MeV
Experiment	635 MeV	397 MeV	137 MeV	46 MeV

Works very well with **$3\times C_B = C_M = 635\, m_u^2$**

Charm exotics production in HIC

Lee, Yasui, Liu & Ko
Eur. J. Phys. C 54, 259 (08)

- Charm tetraquark mesons
  - T_{cc} ($ud\bar{c}\bar{c}$) is ~ 80 MeV below D+D*
  - Coalescence model predicts a yield of ~5.5×10^{-6} in central Au+Au collisions at RHIC and ~9×10^{-5} in central Pb+Pb collisions at LHC if total charm quark numbers at mid-rapidity are 3 and 20, respectively
  - Yields increase to 7.5×10^{-4} and 8.6×10^{-3}, respectively, in the statistical model

- Charmed pentaquark baryons
  - Θ_{cs}($uds\bar{c}$) is ~ 70 MeV below D+Σ, ~ 30 MeV below N+D_s, but ~ 8 MeV above Λ+D
  - Yield is ~1.2×10^{-4} at RHIC and ~7.9×10^{-4} at LHC from the coalescence model for total charm quark numbers of 3 and 20, respectively
  - Statistical model predicts much larger yields of ~4.5×10^{-3} at RHIC and ~2.7×10^{-2} at LHC

Decay modes of T_{cc} and Θ_{cs}

Table 8. Possible decay modes of T_{cc}. In the bottom row, we would observe the correlations $(K^+\pi^-)(K^+\pi^-)\pi^-$ and $(K^+\pi^+\pi^+\pi^-)(K^+\pi^-)\pi^-$ in the final states. See the text for details

Threshold	Decay mode	Lifetime
$M_{T_{cc}} > M_{D^*} + M_D$	$D^{*-}\bar{D}^0$	hadronic decay
$2M_D + M_\pi < M_{T_{cc}} < M_{D^*} + M_D$	$\bar{D}^0\bar{D}^0\pi^-$	hadronic decay
$M_{T_{cc}} < 2M_D + M_\pi$	$D^{*-}K^+\pi^-$, $D^{*-}K^+\pi^+\pi^-\pi^-$	0.41×10^{-12} s

Table 9. Possible decay modes of Θ_{cs}

Threshold	Decay mode	Lifetime
$M_{\Theta_{cs}} > M_N + M_{D_s}$	pD_s^-	hadronic decay
$M_\Lambda + M_D < M_{\Theta_{cs}} < M_N + M_{D_s}$	$\Lambda\bar{D}^0$	hadronic decay
	ΛD^-	hadronic decay
$M_{\Theta_{cs}} < M_\Lambda + M_D$	$\Lambda K^+\pi^-$, $\Lambda K^+\pi^+\pi^-\pi^-$	0.41×10^{-12} s
	$\Lambda K^+\pi^-\pi^-$	1.0×10^{-12} s

Exotic mesons, baryons and dibaryons

Cho, Furumoto, Hyodo, Jido, Ko, Lee, Nielsen, Ohnishi, Sekihara, Yasui, and Yazaki [ExHIC Collaboration], PRL 106, 212001 (2011); PRC 84, 064910 (2011)

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

Parameters in fireball model & in hadron Wigner functions

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

$$\sigma = (\mu\omega)^{-1/2}$$ fixed by normal hadrons

TABLE I. Quark numbers at hadronization temperature T_C and volume V_C, the volume V_H at the end of hadronization, and the thermal freeze-out temperature T_F and volume V_F in central heavy ion collisions at RHIC and LHC.

	RHIC	LHC
$N_u = N_d$	245	662
$N_s = N_{\bar{s}}$	150	405
$N_c = N_{\bar{c}}$	3	20
$N_b = N_{\bar{b}}$	0.02	0.8
V_C	1000 fm^3	2700 fm^3
$T_C = T_H$	175 MeV	175 MeV
V_H	1908 fm^3	5152 fm^3
μ_B	20 MeV	0 MeV
μ_s	10 MeV	0 MeV
V_F	11322 fm^3	30569 fm^3
T_F	125 MeV	125 MeV

TABLE III. Yields of normal hadrons at RHIC and LHC in the coalescence and statistical models with oscillator frequencies $\omega = 550$ MeV, $\omega_s = 519$ MeV, $\omega_c = 385$ MeV, and $\omega_b = 338$ MeV are determined by fitting the statistical model results for $\Lambda(1115)$, $\Lambda_c(2286)$, and $\Lambda_b(5620)$ marked with * at RHIC after taking account of resonance decays. Numbers in the parentheses are those without the decay contribution.

Configuration	Particle	RHIC		LHC	
		Coalescence	Statistical	Coalescence	Statistical
$\bar{q}q$	$\omega(782)$	44.2	40.2	119	108
	$\rho(770)$	132	127	358	342
	$\bar{K}^*(892)$	41.2	47.2	111	135
	$K^*(892)$	41.2	52.9	111	135
qqs	$\Lambda(1115)$	29.8*	29.8	80.5	77.5
		(3.0)	(6.5)	(8.1)	(16.5)
	$\Lambda(1520)$	1.6	1.9	4.4	4.8
qqQ	$\Lambda_c(2286)$	0.60*	0.60	4.0	3.6
		(0.058)	(0.14)	(0.39)	(0.83)
	$\Lambda_b(5620)$	3.6×10^{-3}*	3.6×10^{-3}	0.14	0.13
		(3.6×10^{-4})	(9.2×10^{-4})	(0.014)	0.033

Exotic hadron yields at RHIC and LHC

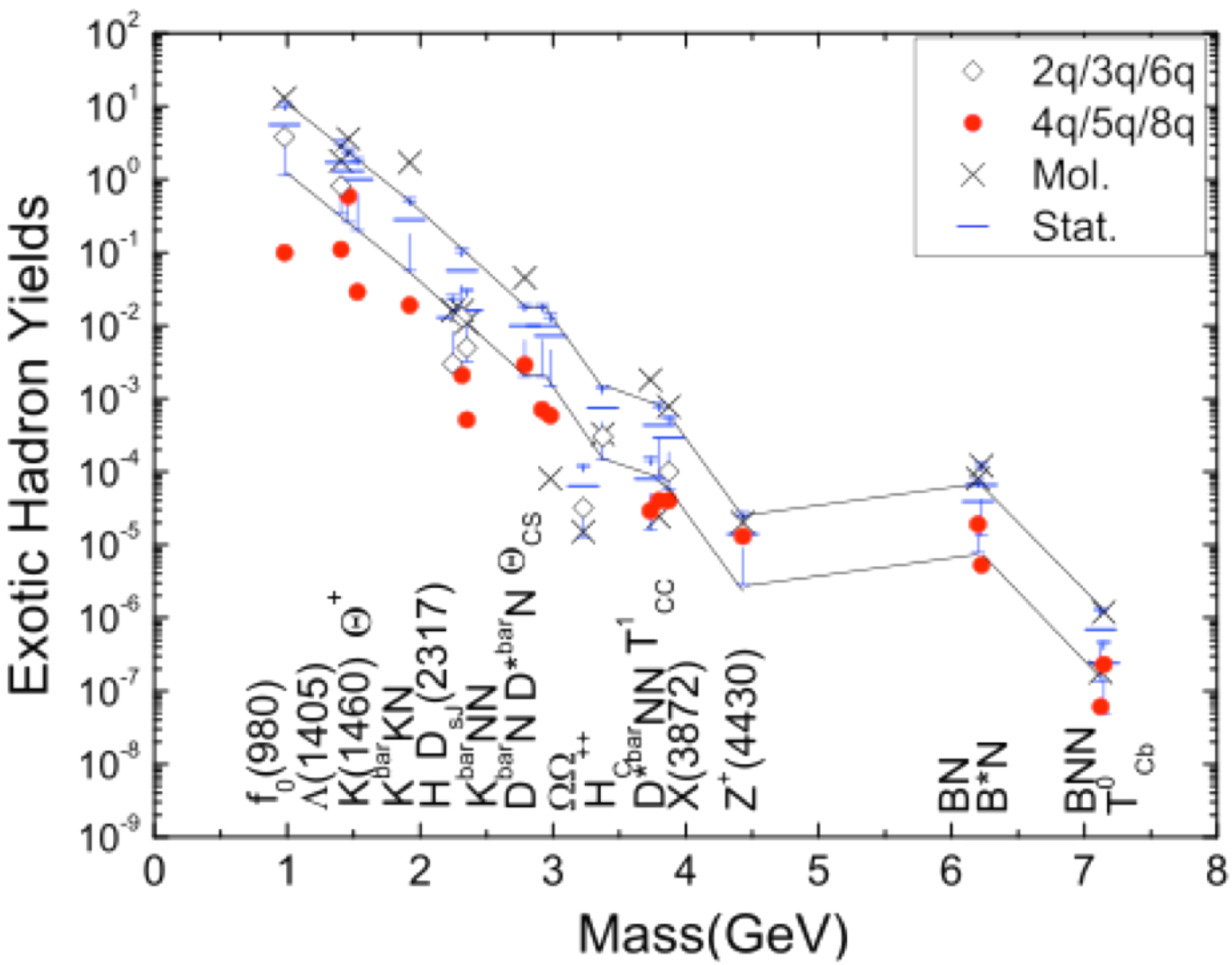
TABLE V. Exotic hadron yields in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC and in central Pb + Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV at LHC from the quark coalescence ($2q/3q/6q$ and $4q/5q/8q$) and the hadron coalescence (Mol.), as well as from the statistical model (Stat.)

	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}
$\Omega\Omega$[a]	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^{++}[a]	3.0×10^{-4}	—	3.3×10^{-4}	7.5×10^{-4}	2.0×10^{-3}	—	1.9×10^{-3}	4.2×10^{-3}
$\bar{D}NN$[a]	—	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[a]	—	2.3×10^{-7}	1.2×10^{-6}	2.4×10^{-7}	—	9.2×10^{-6}	3.7×10^{-5}	7.6×10^{-6}

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

- Most yields are sufficient large ($>10^{-5}$)

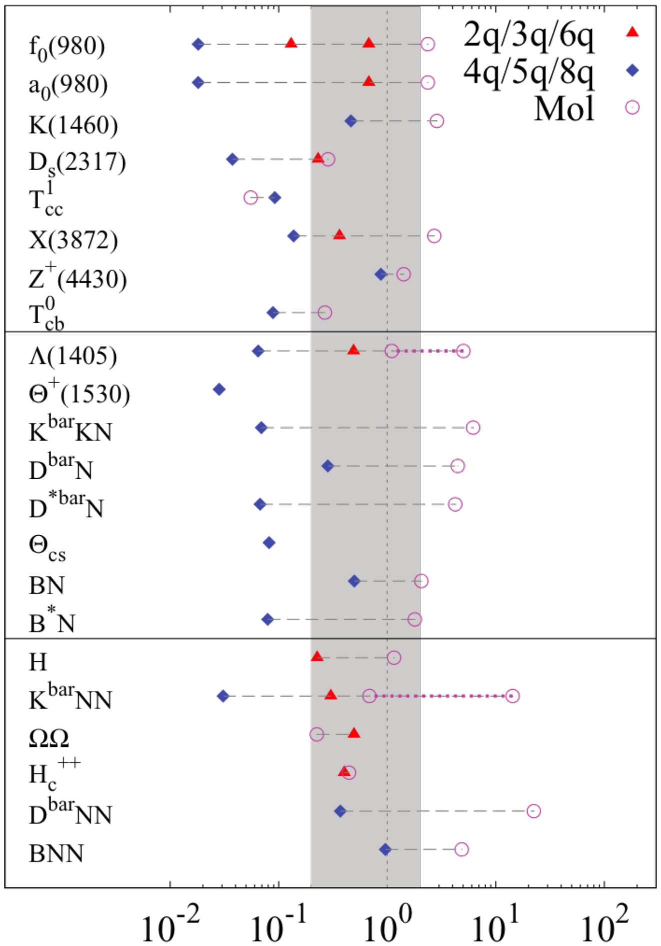
Yields of exotic hadrons at RHIC



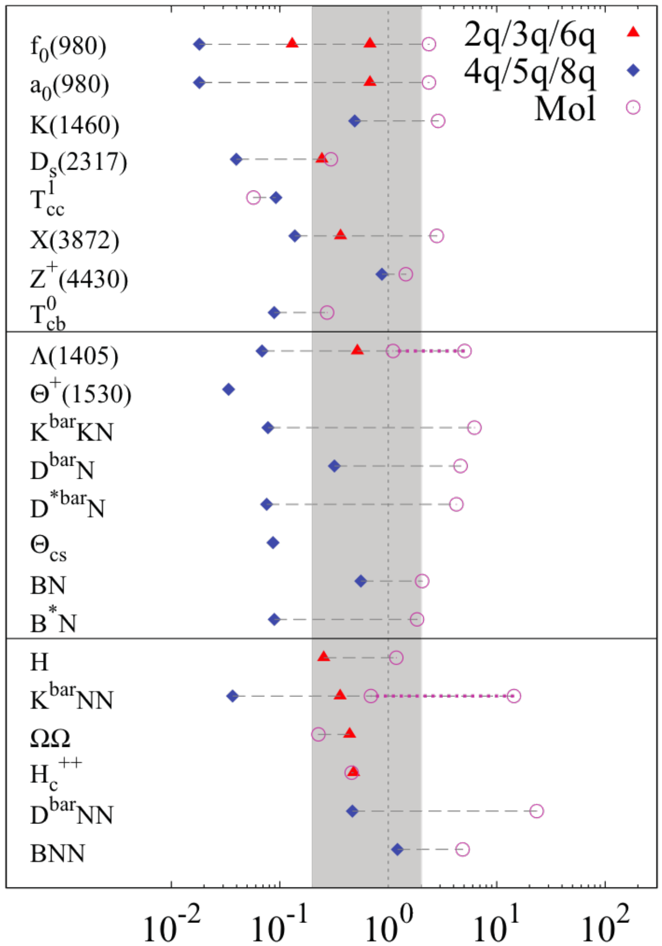
- Most exotic hadrons are abundantly produced (>10^{-5})

Ratio of exotic hadron yields from coalescence and statistical models

Coalescence / Statistical model ratio at RHIC



Coalescence / Statistical model ratio at LHC



- Multiquark hadrons are suppressed while hadronic molecules are enhanced in coalescence model, compared to the statistical model predictions

Summary

- Expected yield of $\Theta^+(udud\bar{s})$ in HIC is large but it is not observed.
- Possible existence of tetraquark meson $T_{cc}(ud\bar{c}\bar{c})$ and pentaquark baryon $\Theta_{cs}(udus\bar{c})$ due to attractive diquark spin-spin interaction
- HIC allows for the study of $\Omega\Omega$ interaction and possible existence of $(\Omega\Omega)_{0+}$
- Yield of D_{sj} (2317) in HIC is sensitive to its quark structure
- Yields of exotic hadrons are appreciable in HIC ($>10^{-5}$)
- In the coalescence model, yields of exotic hadrons are sensitive to their structures with molecular-state configurations enhanced and multiquark configurations suppressed relative to statistical production