Resonance and exotics production from heavy ion collisions

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1. Few words on Multiquark configurations
2. Particle production in heavy ion collision
3. Exotics from heavy ion collisions
4. Summary

PRL 106, 212001 (2011) **Exotic hadrons in heavy ion collisions** PHYSICAL REVIEW C 84, 064910 (2011)

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(ExHIC Collaboration) +T. Song, K. Morita, Maeda

S. Cho, SHL, arXiv:1509.04092; S. Cho, T. Song, SHL, arXiv:1511.08019

I: Few words on “Multiquark states”

X(3872), Zc(3900), … Zb(10610), Zb(10650)

+ LHCb J/ψ p PRL 115, 072001 (2015)

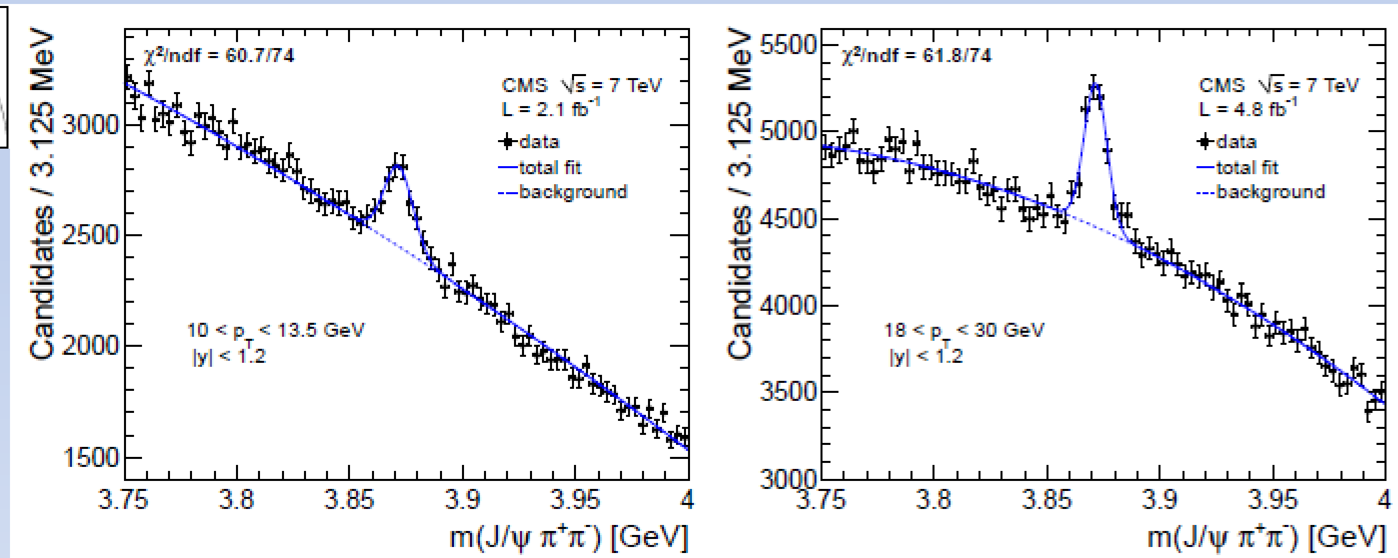
X(3872)

- 2003 -

$$B^{\pm} \to K^{\pm} \pi^{+} \pi^{-} J/\psi$$

$$M = 3872.0 \pm 0.6 \pm 0.5\,\text{MeV}$$

- 2013 -



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

Mass $m = 3871.69 \pm 0.17$ 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%

Z(4430)

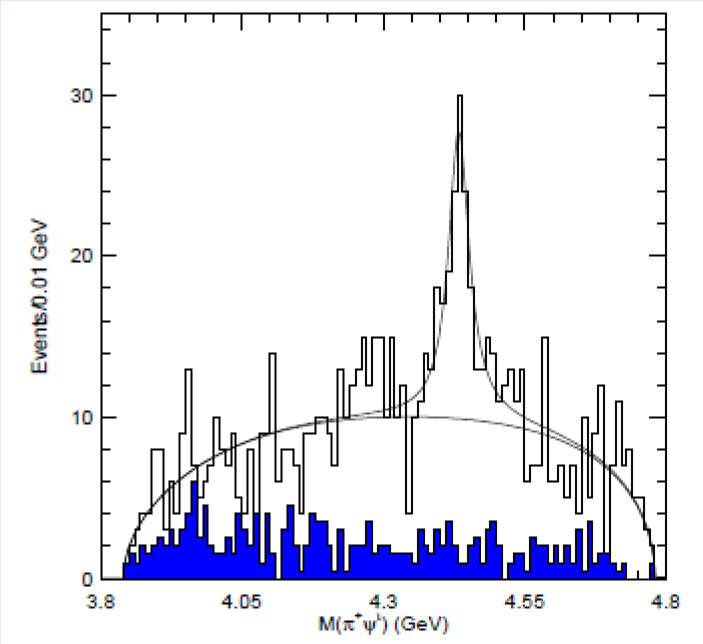
- 2007 -

BELLE

$$B \to K \pi^{\pm} \psi'$$

$$M = 4433 \pm 4 \pm 2\,\mathrm{MeV}$$

$$\Gamma = 45^{+18}_{-13}(\mathrm{stat})^{+30}_{-13}(\mathrm{syst})\,\mathrm{MeV}$$



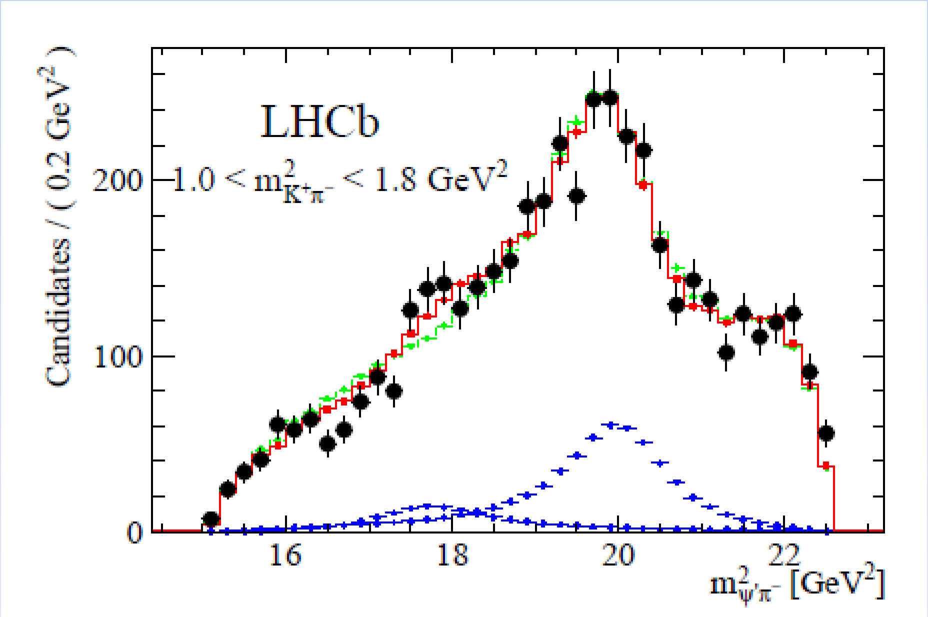
- 2014 -

LHCb

Spin parity = 1+

$$\eta_G = \eta_C (-1)^I$$

G=+ → will look at C=-



Z(3900)

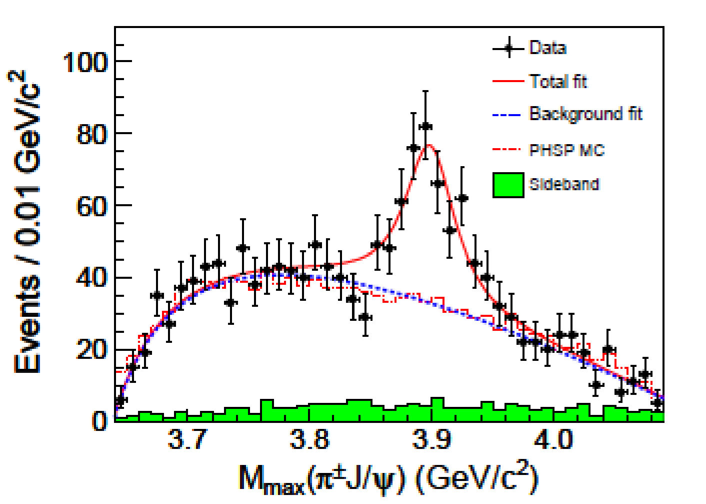
- 2013 -

BESIII (Belle)

$$e^+e^- \to \pi^+\pi^- J/\psi$$

$$M = 3899.0 \pm 3.6 \pm 4.9\,\mathrm{MeV}$$

$$\Gamma = 46 \pm 10 \pm 20\,\mathrm{MeV}$$



Probably the same Quantum Number as Z(4430)

Hence,

$$X(3872) \to I^G\left(J^{PC}\right) = 0^+\left(1^{++}\right)$$

$$Z(3900) \to \pi^0\ J/\psi$$

$$Z(4430) \to \pi^0\ \psi'$$

$$\to 1^+\left(1^{+-}\right)$$

Pentaquark - Pc

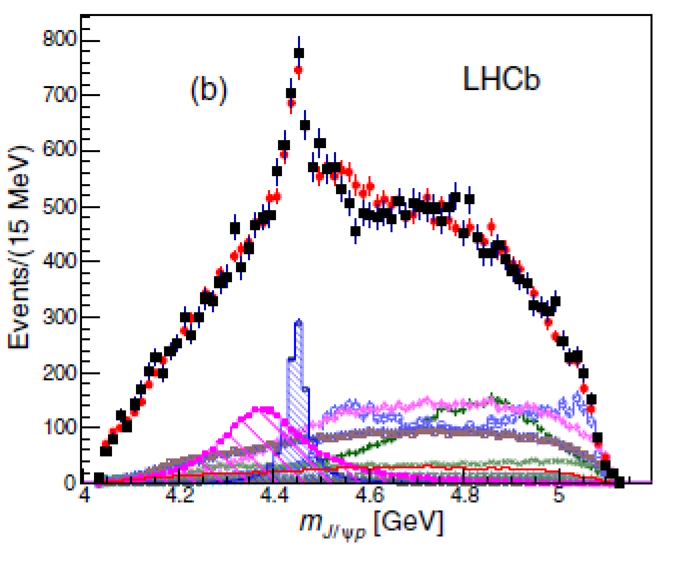
- 2015 -

LHCb

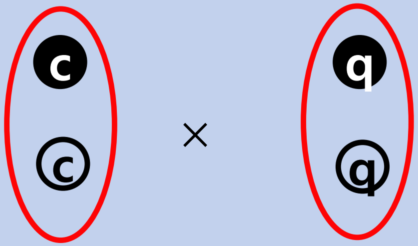
$$\Lambda_b^0 \to J/\psi\ p K^-$$

$$S = 3/2 \quad \begin{cases} M_1 = 4380 \pm 8 \pm 29\,\mathrm{MeV} \\ \Gamma_1 = 205 \pm 18 \pm 86\,\mathrm{MeV} \end{cases}$$

$$S = 5/2 \quad \begin{cases} M_2 = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV} \\ \Gamma_2 = 39 \pm 5 \pm 19\,\mathrm{MeV} \end{cases}$$



Comact multiquark configuration? Not so easy



quark

antiquark

- Color singlet configuration: $\left(1_c \otimes 1_c\right)$ or $\left(8_c \otimes 8_c\right)$
- Spin 1 configuration from : $\left(P \oplus V\right) \otimes \left(P \oplus V\right)$ where $P\left(S=0\right),\ V\left(S=1\right)$

C=+

$\left|1_{c\bar{c}}1_{q\bar{q}}\left(V_{c\bar{c}}V_{q\bar{q}}\right)\right\rangle$ $\left|8_{c\bar{c}}8_{q\bar{q}}\left(V_{c\bar{c}}V_{q\bar{q}}\right)\right\rangle$

Color Spin

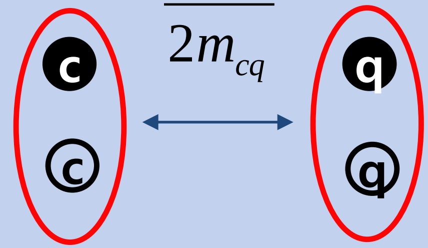
C=-

$\left|1_{c\bar{c}}1_{q\bar{q}}\left(P_{c\bar{c}}V_{q\bar{q}}\right)\right\rangle$ $\left|8_{c\bar{c}}8_{q\bar{q}}\left(P_{c\bar{c}}V_{q\bar{q}}\right)\right\rangle$

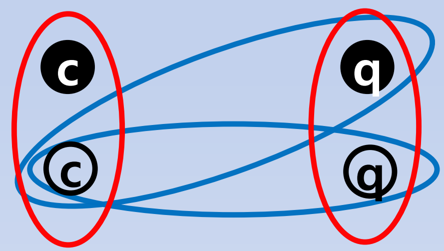
$\left|1_{c\bar{c}}1_{q\bar{q}}\left(V_{c\bar{c}}P_{q\bar{q}}\right)\right\rangle$ $\left|8_{c\bar{c}}8_{q\bar{q}}\left(V_{c\bar{c}}P_{q\bar{q}}\right)\right\rangle$

Comact multiquark configuration? Not so easy

- $H_{Kinetic} = \sum_{i=1}^{4} \left(m_i + \frac{p_i^2}{2m_i} \right)$: $\frac{p_{cc}^2}{2m_{cc}}$ $\frac{p_{cq}^2}{2m_{cq}}$ $\frac{p_{qq}^2}{2m_{qq}}$



- $H_{confine} = \sum_{i<j}^{4} \left(\lambda_i^c \lambda_j^c \right) V_{ij}^C \left(r_{ij} \right)$: → Favors $\left(1_c \otimes 1_c\right)$ over $\left(8_c \otimes 8_c\right)$



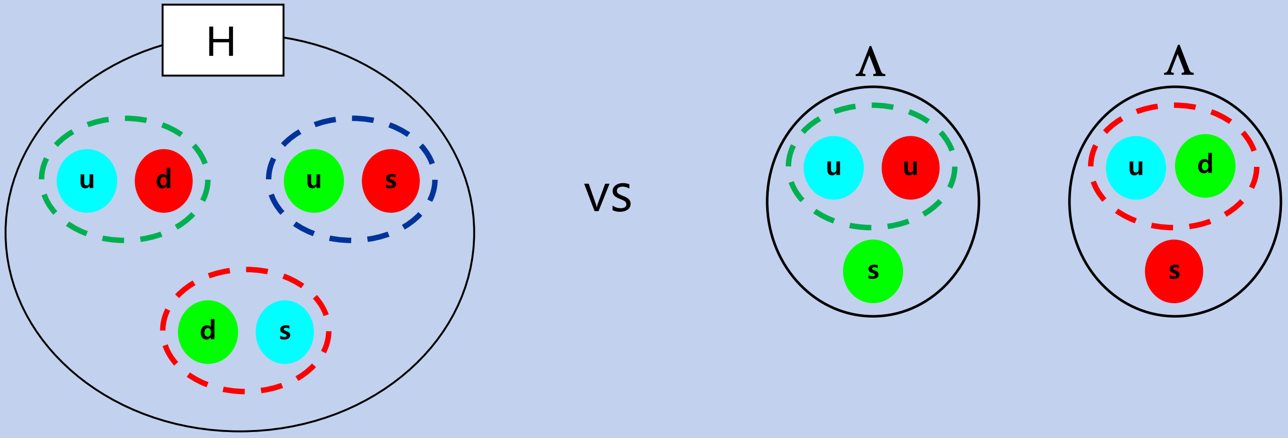
- $H_{color-spin} = \sum_{i<j}^{4} \frac{\left(\lambda_i^c \lambda_j^c \right)\left(\sigma_i \sigma_j \right)}{m_i m_j} V_{ij}^{SS} \left(r_{ij} \right)$

: should be strong enough to overcome repulsion from kinetic term

→ Otherwise can form molecular configuration

H dibaryon

$$K = -\sum_{i<j} \left(\lambda_i^c \lambda_j^c\right)\left(\sigma_i \sigma_j\right)$$



$K = -24$ $K = -8$ $K = -8$

Park, Park, SHL (PRD2016)

TABLE III: The expectation value of $-\sum_{i<j}\langle\lambda_i^c\lambda_j^c\sigma_i\cdot\sigma_j\rangle$ for H-dibaryon with flavor singlet(F^1) and ΛΛ.

$-\sum_{i<j}\langle\lambda_i^c\lambda_j^c\sigma_i\cdot\sigma_j\rangle$	$i<j=1\sim5$	$i=1\sim5, j=6$
H-dibaryon, F^1	-16	-8

$-\sum_{i<j}\langle\lambda_i^c\lambda_j^c\sigma_i\cdot\sigma_j\rangle$	$i<j=1\sim3$	$i=4, j=5$	$i=4\sim5, j=6$
ΛΛ	-8	-8	0

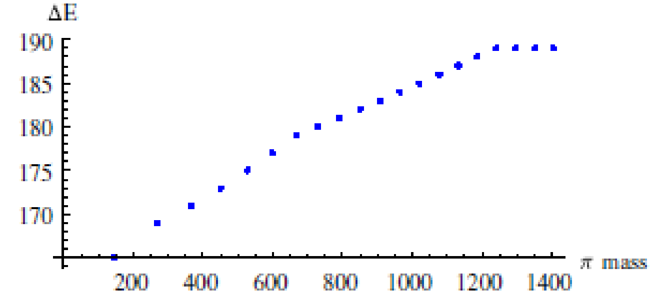


FIG. 1. The mass difference (ΔE) between the H-dibaryon and two Λ baryons as a function of the pion mass in the SU(3) limit. (Units are MeV.)

- C=+ state (Woosung Park, SHL 14)

$$\left|1_{c\bar{c}}1_{q\bar{q}}\left(V_{c\bar{c}}V_{q\bar{q}}\right)\right\rangle = \left| J/\psi + \omega \right\rangle$$

$$\left|8_{c\bar{c}}8_{q\bar{q}}\left(V_{c\bar{c}}V_{q\bar{q}}\right)\right\rangle \quad > \quad \mathrm{X}(3872)$$

Or $X(3872) \rightarrow$ molecular bound state of DD^* (Tornqvist 94)

- C=- state

$$\left|1_{c\bar{c}}1_{q\bar{q}}\left(V_{c\bar{c}}P_{q\bar{q}}\right)\right\rangle \qquad \left| J/\psi + \pi \right\rangle$$

$$\left|1_{c\bar{c}}1_{q\bar{q}}\left(P_{c\bar{c}}V_{q\bar{q}}\right)\right\rangle \qquad \left| \eta_c + \rho \right\rangle$$

$$\left|8_{c\bar{c}}8_{q\bar{q}}\left(V_{c\bar{c}}P_{q\bar{q}}\right)\right\rangle \quad > \quad Z(3900)$$

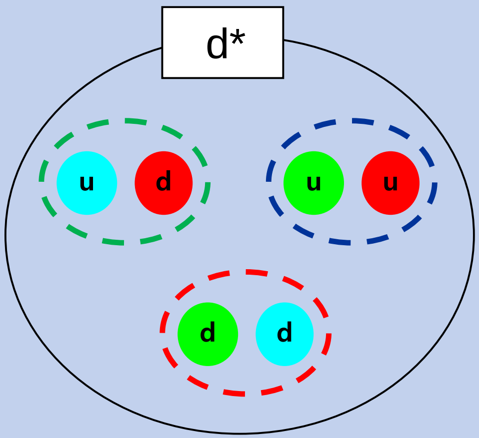
$$\left|8_{c\bar{c}}8_{q\bar{q}}\left(P_{c\bar{c}}V_{q\bar{q}}\right)\right\rangle \qquad Z(4430)$$

Or $Z(3900) \rightarrow DD^*$ is molecular states

Or $Z(4430)$ is 2s of $X(3872)$ in diquark picture (Maiani, Polosa, Riquer) d*(2380) $I(J^P) = 0(3^+)$

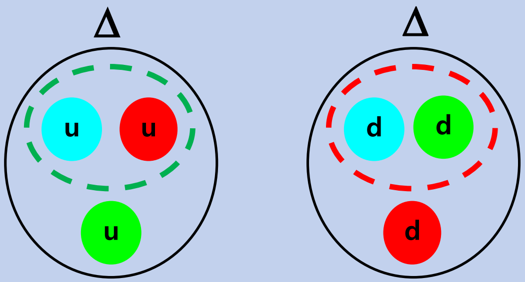
$$\Delta V = \sum_{i,j}^{n} -\lambda_i^c \lambda_j^c \, \sigma_i \cdot \sigma_j$$

- WASA-at-COSY-



$(QQ)_4 + 2(QQ)_2$

→



$3\times(QQ)_2$ $3\times(QQ)_2$

	Color	Spin	Favor	V
$(QQ)_1$	3bar	0	3bar	-2
$(QQ)_2$		1	6	2/3
$(QQ)_3$	6	0	6	1
$(QQ)_4$		1	3bar	-1/3

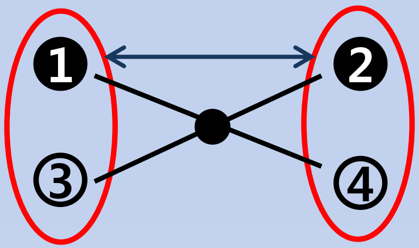
$$\Delta V = V_{\text{dibaryon}} - \left(V_{\text{baryon1}} - V_{\text{baryon2}}\right)$$

(I,S)	(3,0)	(2,1)	(1,2)	(1,0)	(0,3)	(0,1)
V_d	48	$\frac{80}{3}$	16	8	16	$\frac{8}{3}$
ΔV	32	$\frac{80}{3}$	16	24	0	$\frac{56}{3}$

W.Park, A. Park, SHL, (PRD 15)

Real compact multiquark states

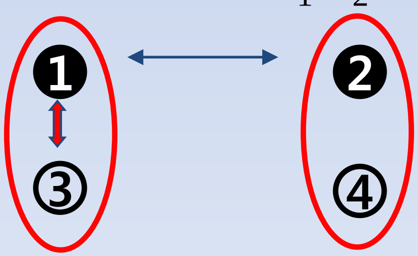
- A 3-body or 4 body force could favor $\left(8_c \otimes 8_c\right)$
  and lead to compact 4 quark state
  or artificially increase diquark correlation



- Color Spin force

$$\kappa_{qq}\left(\bar{3}_c\right)\vec{s}_1 \cdot \vec{s}_2 \frac{1}{m_1 m_2}$$

$$\kappa_{q\bar{q}}\left(1_c\right)\vec{s}_1 \cdot \vec{s}_3 \frac{1}{m_1 m_3}$$

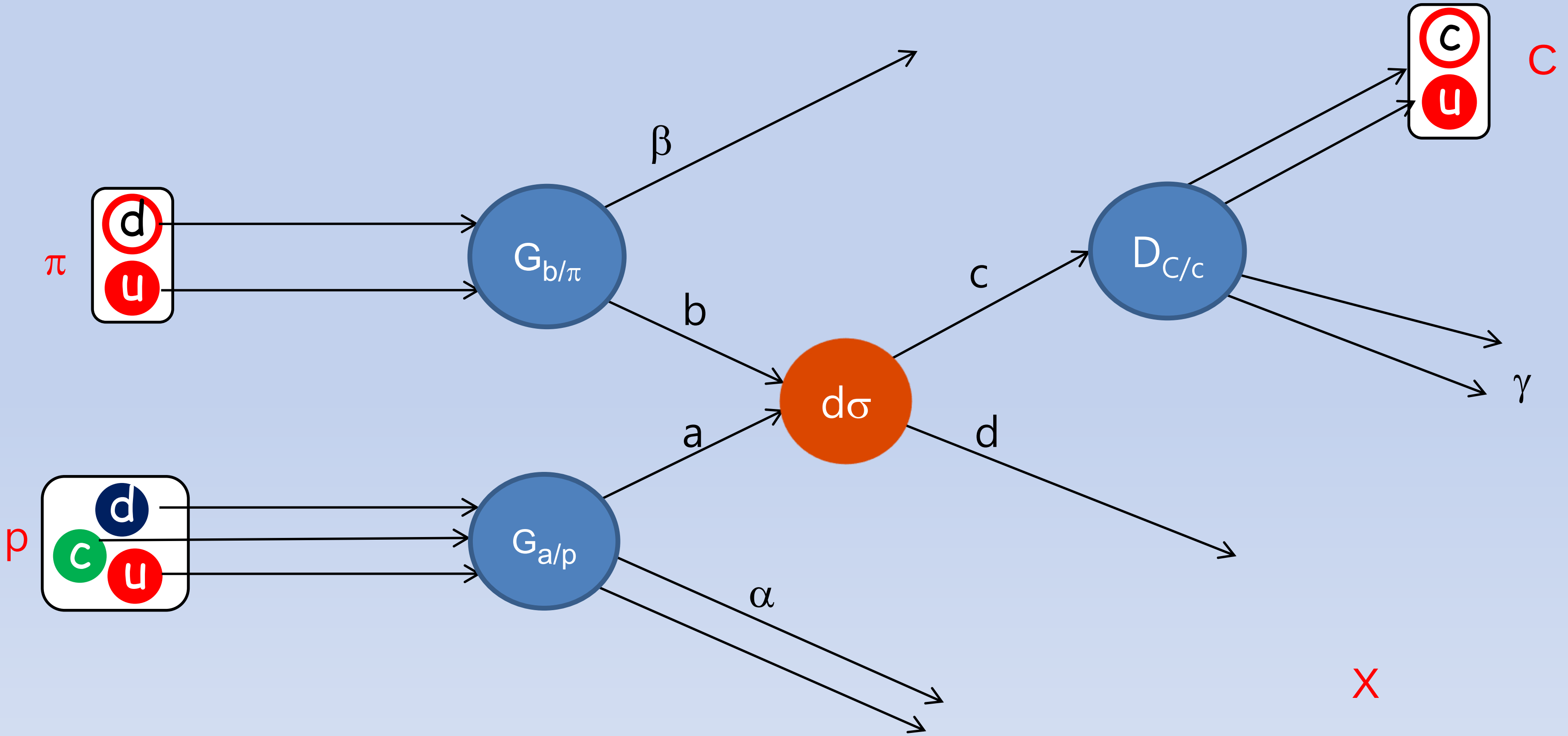


Chose $m_3, m_4 \rangle\rangle m_1, m_2$

→ T_{cc} T_{cb} : real compact flavor exotic tetraquarks

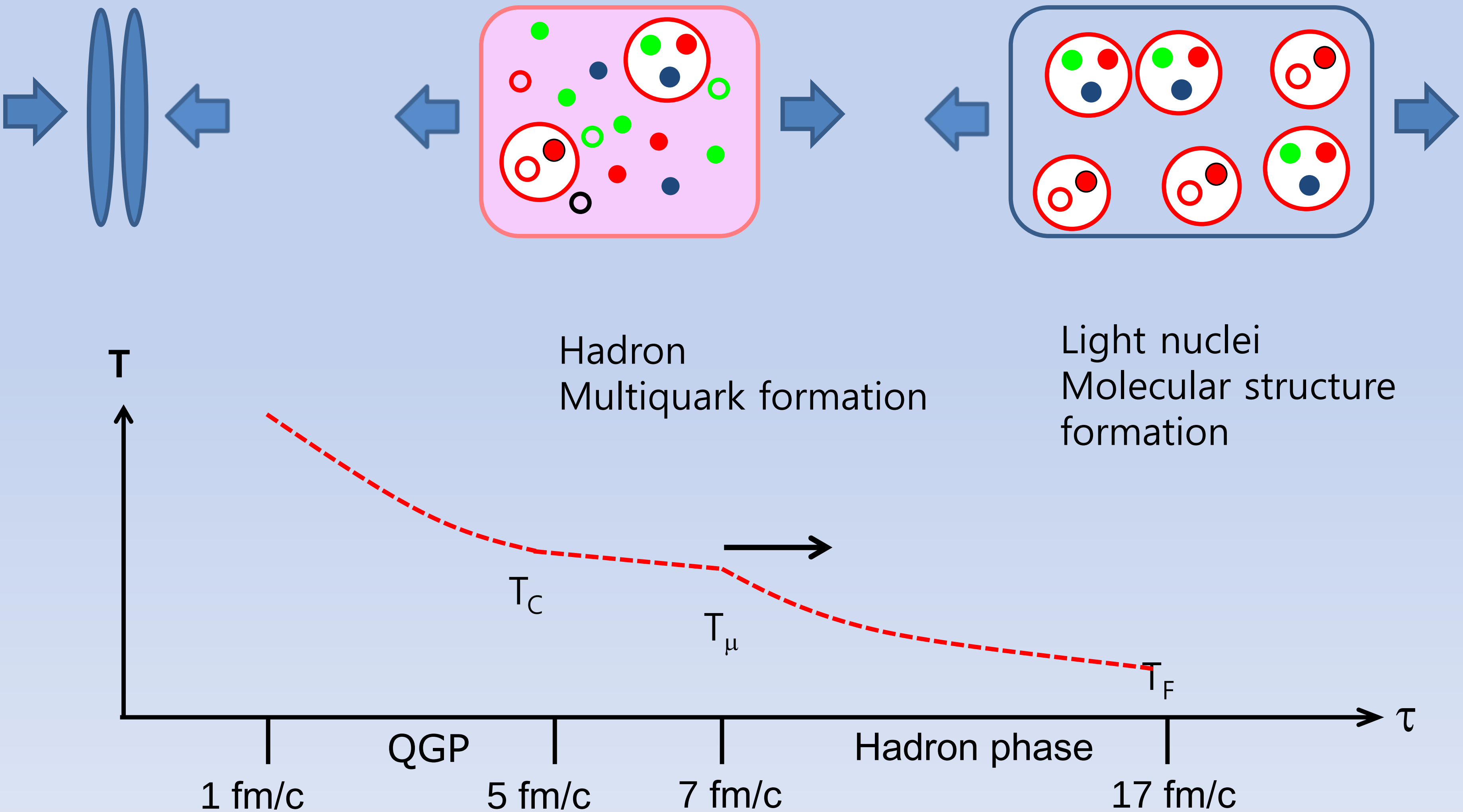
II: Particle production in Heavy Ion Collision

Hadron production in (p+π→C+X) collision

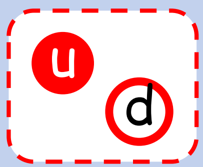
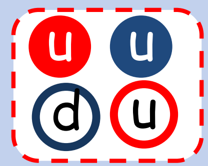
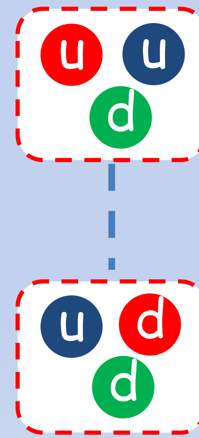
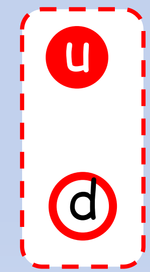


$$d\sigma\Big|_{p+\pi\to C+X} = \int G_{b/\pi}(x_b)G_{a/p}(x_a)\times\int d\sigma\Big|_{a+b\to c+d}\times D_{C/c}(x_c)$$

Particle production in heavy ion collision



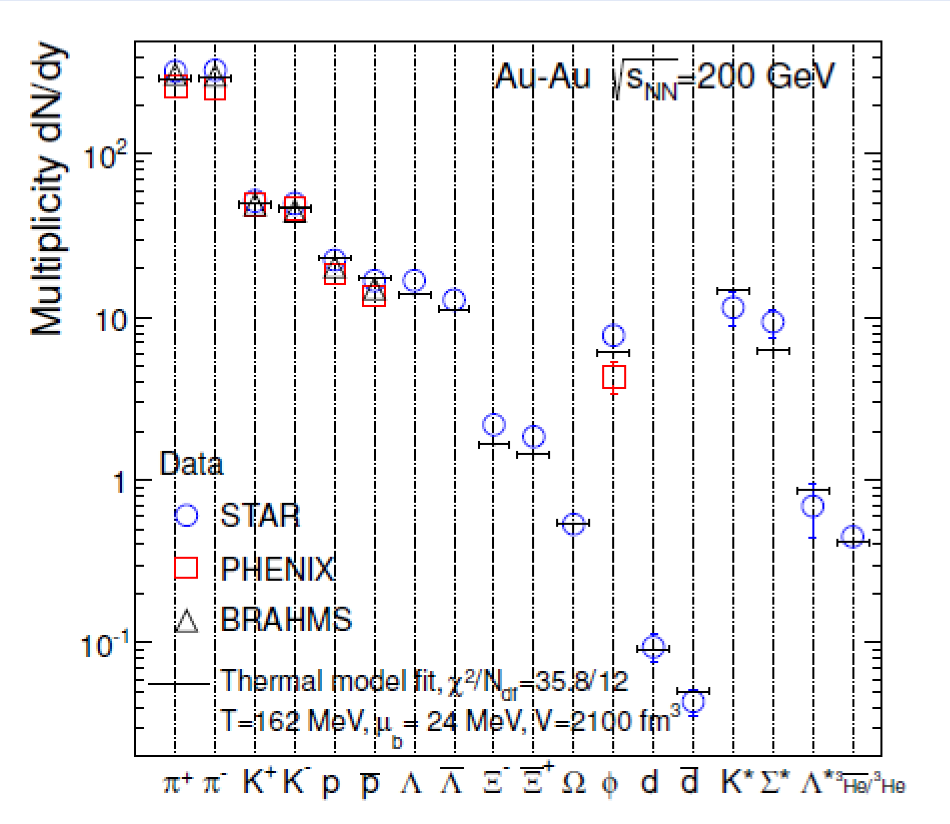
Normal meson, compact multiquark, molecules, resonances

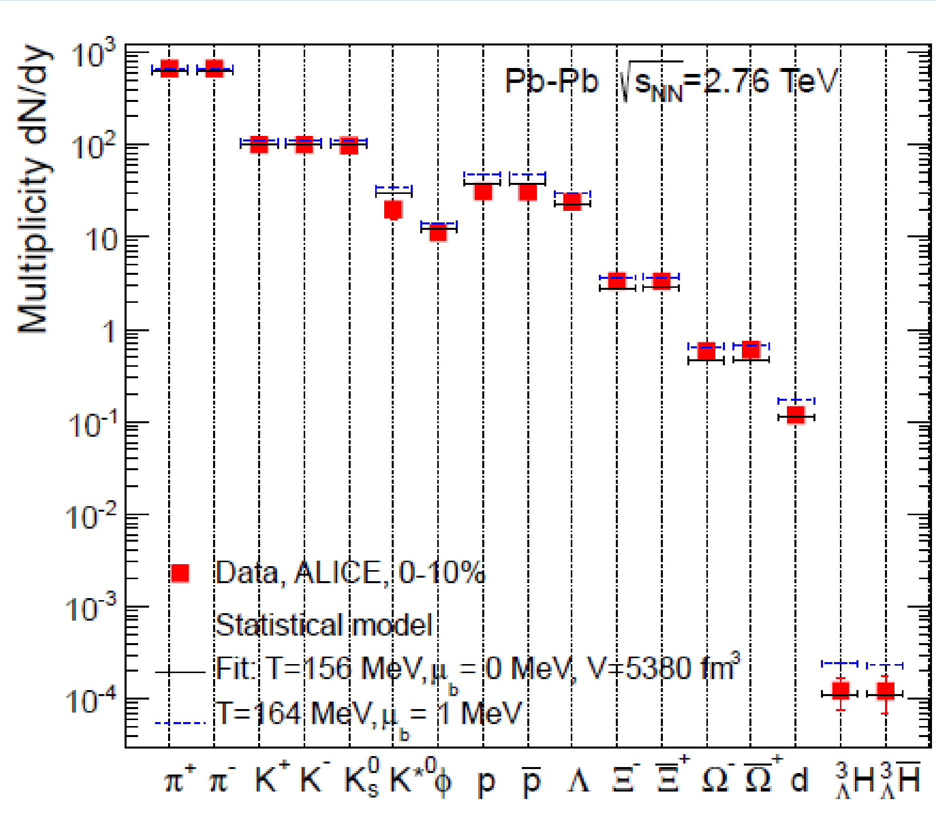
	Normal meson	Compact multiquark	Molecules	Resonance
Geometrical configuration				
Examples	Nucleon, pion, kaon	?	Deuteron, light nuclei	K*, rho meson

Production of hadrons near Tc

RHIC – Statistical model (PBM ..)

ALICE – Statistical model

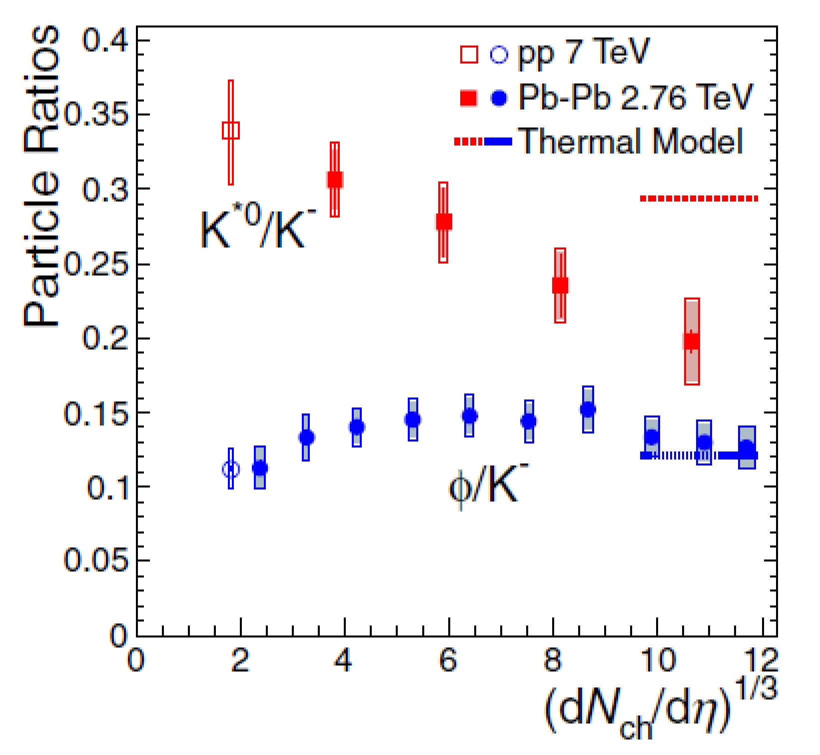




resonance

Production of resonances

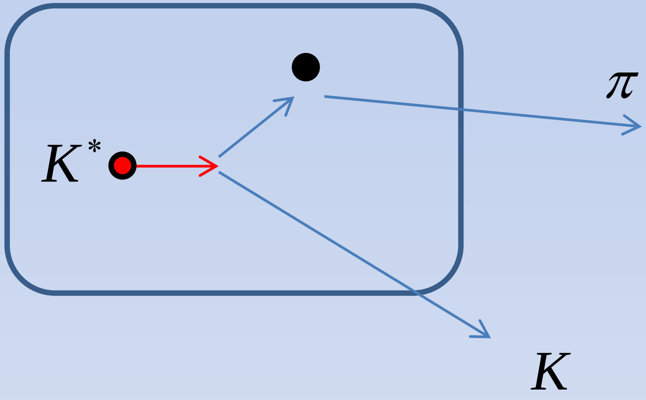
ALICE (2015 prc)



- Reconstruction

$$K^* \to K + \pi, \quad \Gamma > 50\,\mathrm{MeV}$$

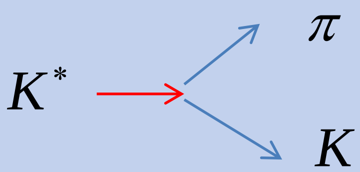
$$\phi \to K + K, \quad \Gamma > 5\,\mathrm{MeV}$$

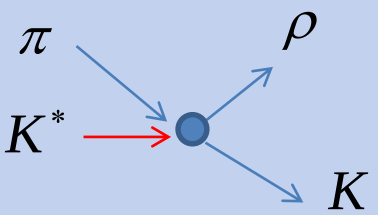


Rate equation for K* (resonance) production

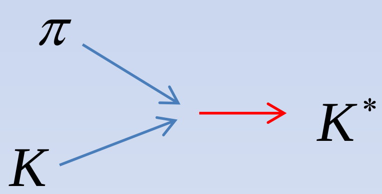
$$\frac{dN_{K*}}{d\tau} = aN_K - bN_{K*}$$

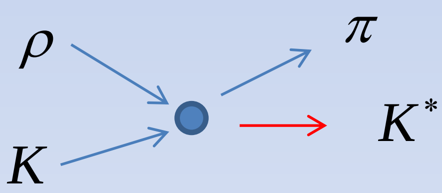
- Destruction: $b = \Gamma + \sigma_{\pi K*} v\, n_\pi$





- Creation $a = \sigma_{\pi K} v\, n_\pi + \sigma_{\rho K} v\, n_\rho$





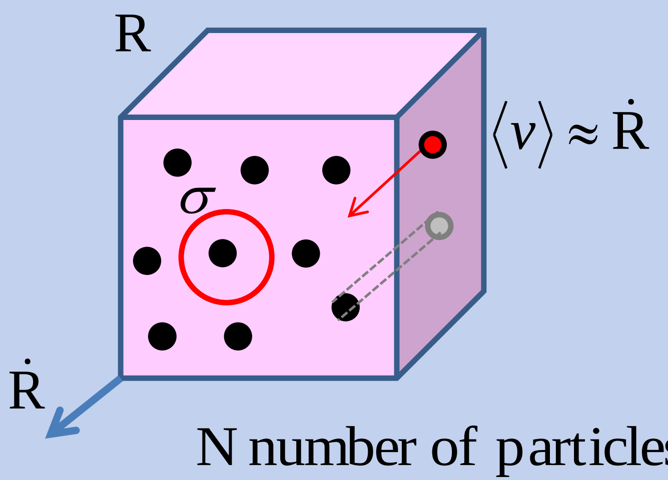
- Thermal Equilibrium $\frac{N_{K*}}{N_K} = \frac{a}{b} \propto \frac{\sigma_{hK} n_h}{\Gamma + \sigma_{hK*} n_h} \xrightarrow{\tau} 0$

Freeze out condition for a particle

- Two time scale (=cosmology)

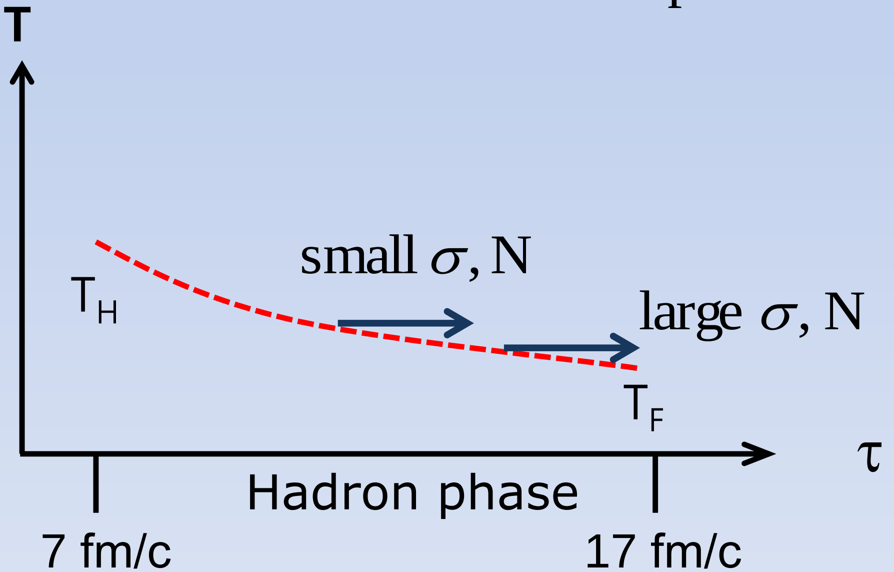
$$\tau_{\exp} \approx \frac{V}{\dot{V}} = \frac{R}{3\dot{R}}$$

$$\tau_{\text{scatt}} = \frac{1}{n\sigma\langle v\rangle}$$



- Freeze out condition

$$\tau_{\text{scatt}} = \tau_{\exp} \rightarrow \left(\frac{N}{R^2}\right) = \frac{3}{\sigma}$$



- Freeze out density

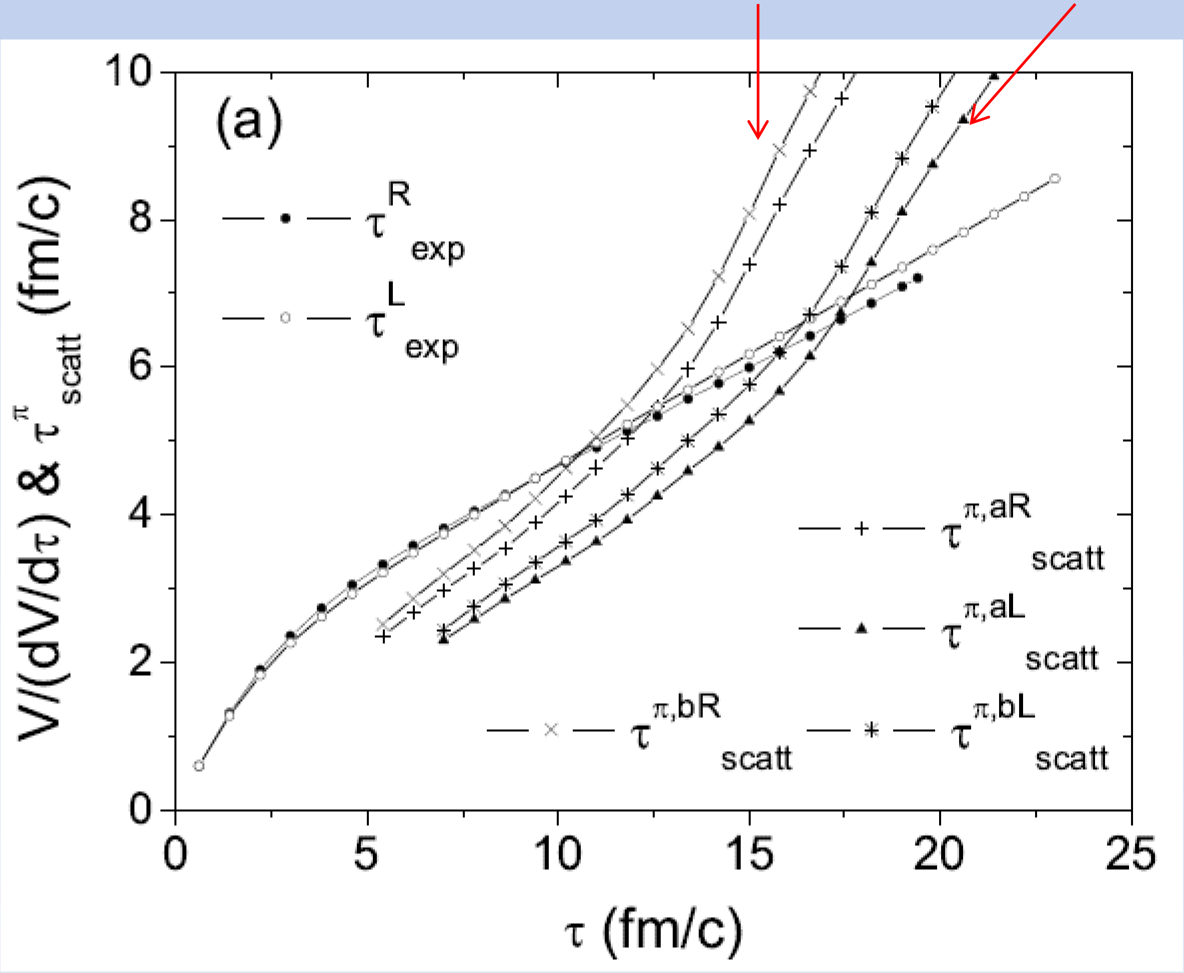
$$n_{\text{freeze-out}} \propto \frac{1}{\sigma^{3/2}\,N^{1/2}}$$

Detailed hydrodynamic calculation - 1

S. Cho, SHL, arXiv:1509.04092; S. Cho, T. Song, SHL, arXiv:1511.08019

$$\tau_{\rm exp} \approx \frac{V}{\dot{V}} = \frac{R}{3\dot{R}} \qquad \tau^{\rm RHIC}_{\rm scatt} = \frac{1}{n\sigma\langle v\rangle} \qquad \tau^{\rm LHC}_{\rm scatt} = \frac{1}{n\sigma\langle v\rangle}$$

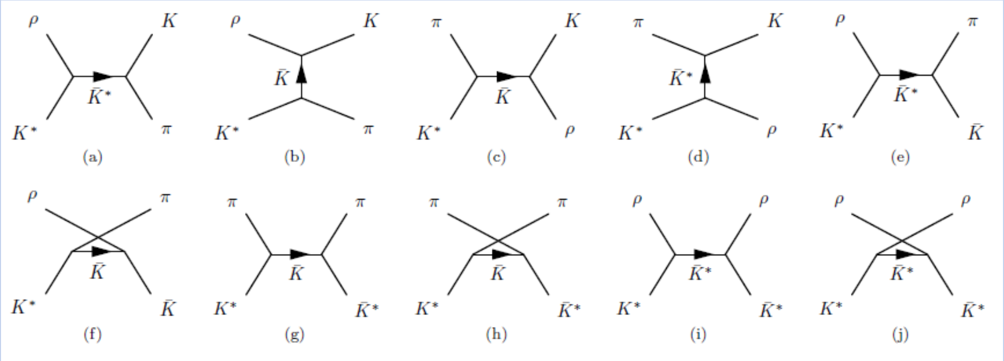
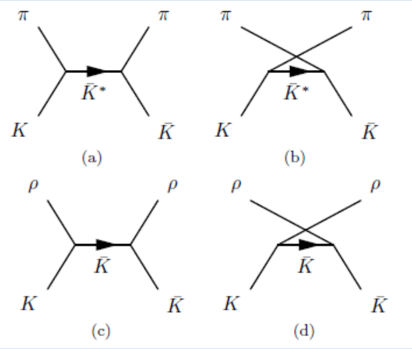
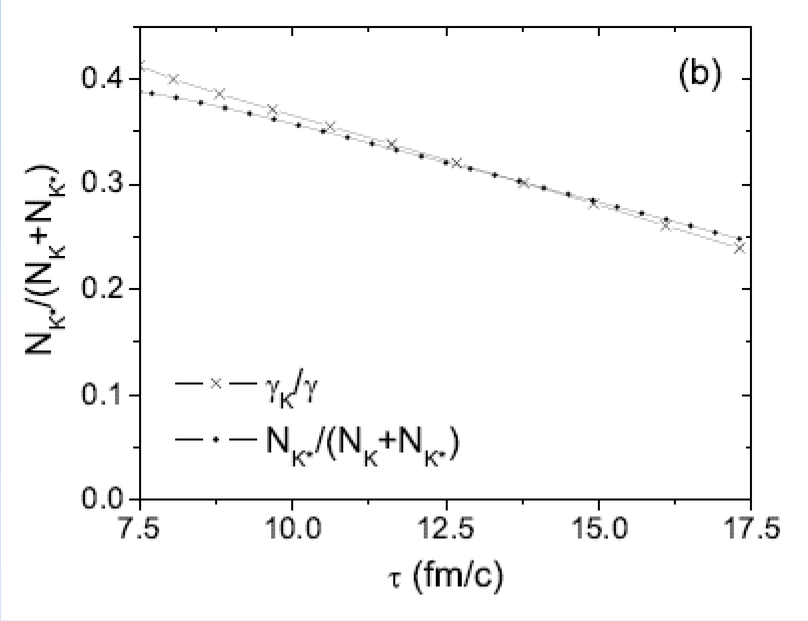
Later time

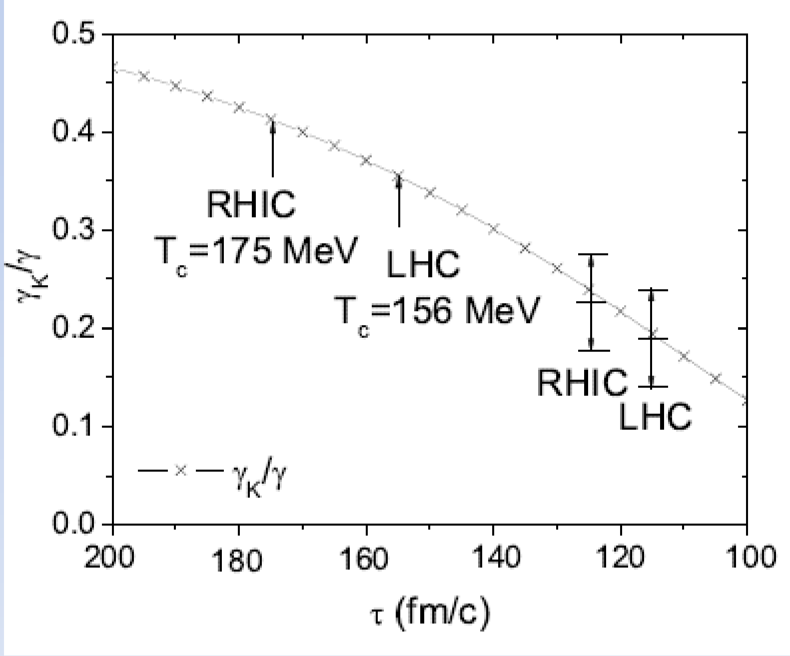


Low density

Detailed calculation - 2

S. Cho, SHL, arXiv:1509.04092; S. Cho, T. Song, SHL, arXiv:1511.08019

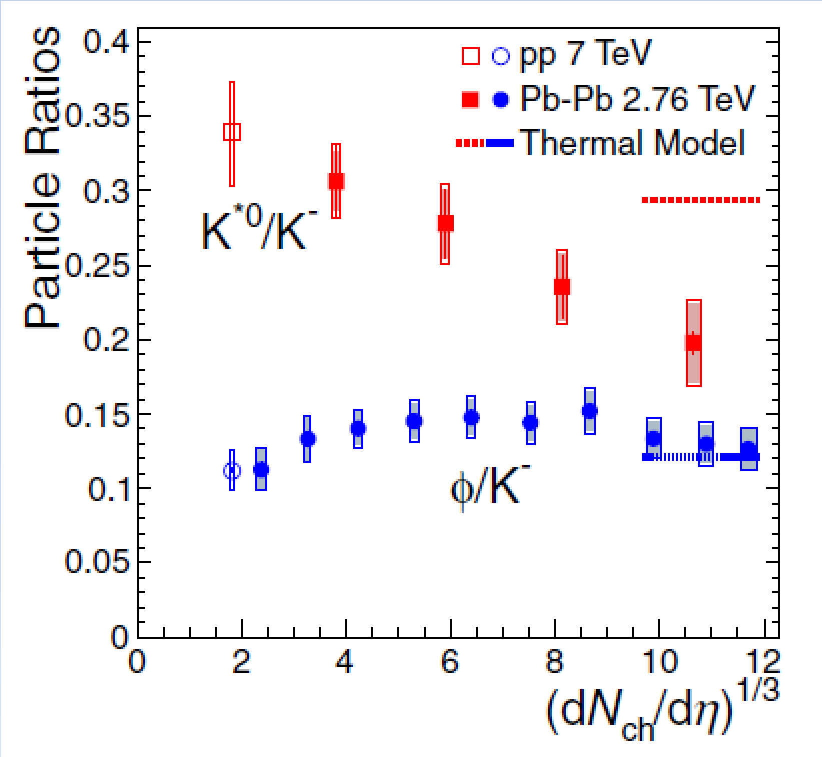






Detailed calculation

- Two time scale (=cosmology)

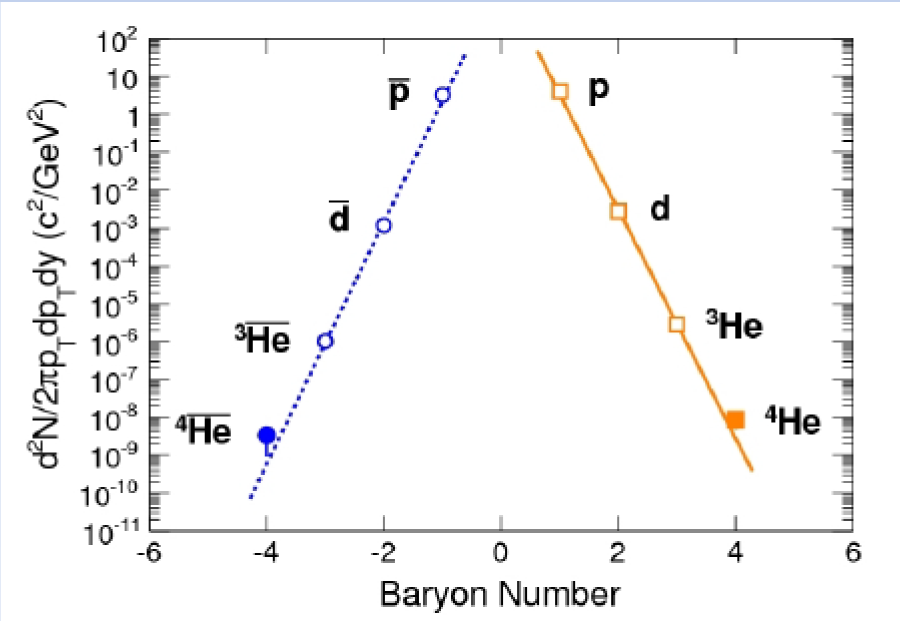
ALICE (2015 prc)

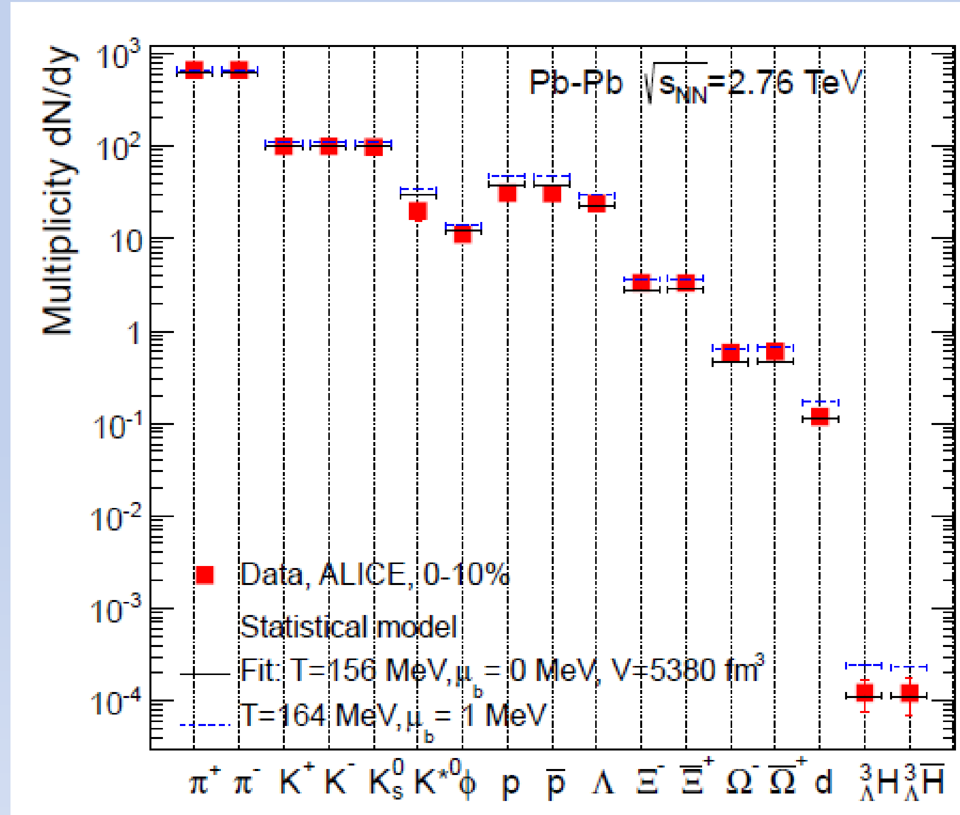


Production of light nuclear

RHIC/STAR (Yugang Ma)

ALICE – Statistical model



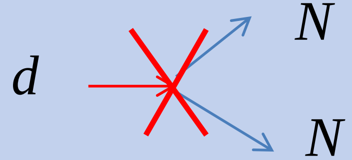


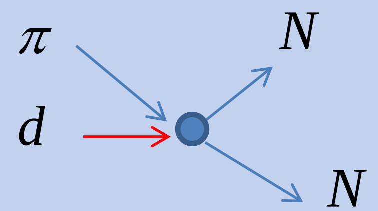
S/N i conserved (Siemens, Kapusta 79)

Rate equation for deuteron (bound states) production

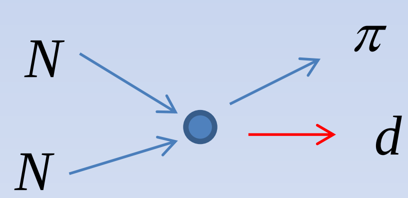
$$\frac{dN_d}{d\tau} = aN_N - bN_d$$

- Destruction: $b = \cancel{\Gamma} + \sigma_{\pi d} v\, n_\pi$





- Creation $a = \sigma_{NN} v\, n_N$



- Thermal Equilibrium $\frac{N_d}{N_N} = \frac{a}{b} \propto \frac{\sigma_{NN}\, n_N}{\sigma_{hd}\, n_h} \xrightarrow{\tau} \text{constant}$

Non equilibrium

- Number of Ground state particles remain almost constant

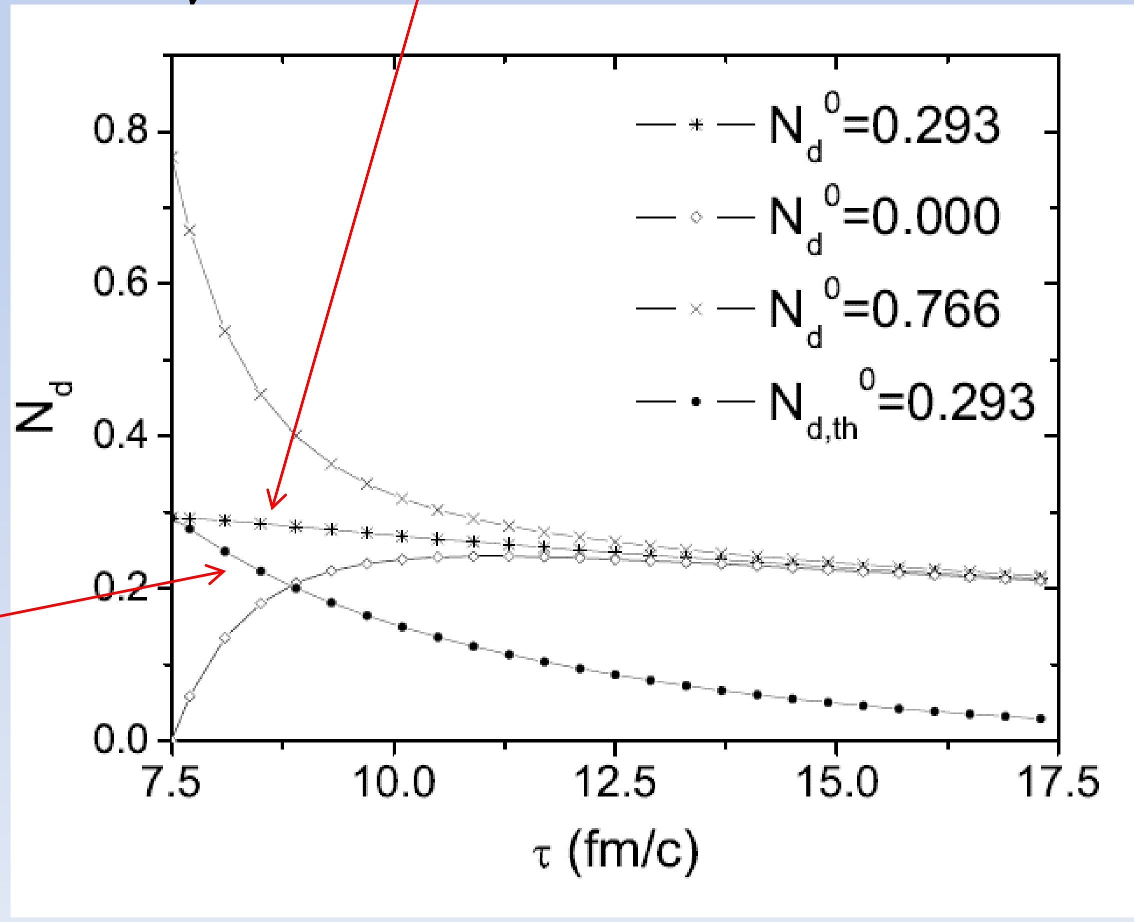
$$\frac{N_d}{N_N}=\frac{a}{b}=\frac{\sigma_{NN} v n_N}{\sigma_{\pi c} v n_\pi} \rightarrow \frac{\sigma_{NN} v \frac{N_N}{V}}{\sigma_{\pi c} v \frac{N_\pi}{V}}=\frac{\sigma_{NN} v N_N}{\sigma_{\pi c} v N_\pi}$$

- Deuteron

$$\frac{dN_d}{d\tau}=aN_N-bN_d$$

$$\sigma_{\pi d} > 50\ \mathrm{mb}$$

$N_d^{Thermal}(\tau_0)$



Comparison

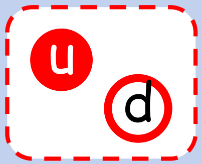
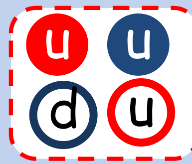
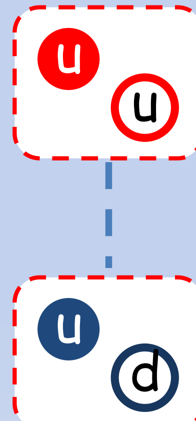
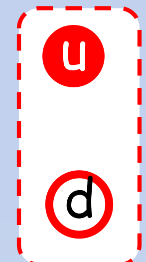
- K* (Resonance) production

$$\frac{N_{K*}}{N_K} = \frac{\sigma_{NN} v n_N}{\Gamma_{K*} + \sigma_{\pi c} v n_\pi} \rightarrow \frac{\sigma_{NN} v \frac{N_N}{V}}{\Gamma_{K*} + \sigma_{\pi c} v \frac{N_\pi}{V}} = \xrightarrow{V \to \infty} 0$$

- Deuteron (bound state) production

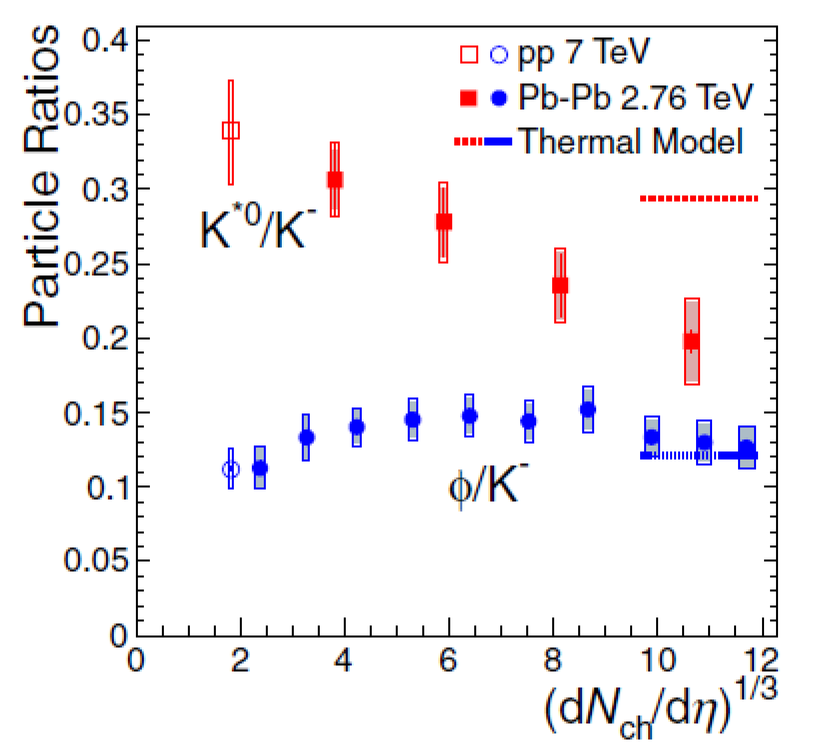
$$\frac{N_d}{N_N} = \frac{a}{b} = \frac{\sigma_{NN} v n_N}{\sigma_{\pi c} v n_\pi} \rightarrow \frac{\sigma_{NN} v \frac{N_N}{V}}{\sigma_{\pi c} v \frac{N_\pi}{V}} = \frac{\sigma_{NN} v N_N}{\sigma_{\pi c} v N_\pi} \xrightarrow{V \to \infty} \text{constant}$$

Normal meson, compact multiquark, molecules, resonances

	Normal meson	Compact multiquark	Molecules	Resonance
Geometrical configuration				
Yields /Statistical model	1	< 0.1	~ 1	~ 0.5

Production of resonances

ALICE (2015 prc)



- Reconstruction

$$K^* \to K + \pi, \quad \Gamma > 50\,\mathrm{MeV}$$

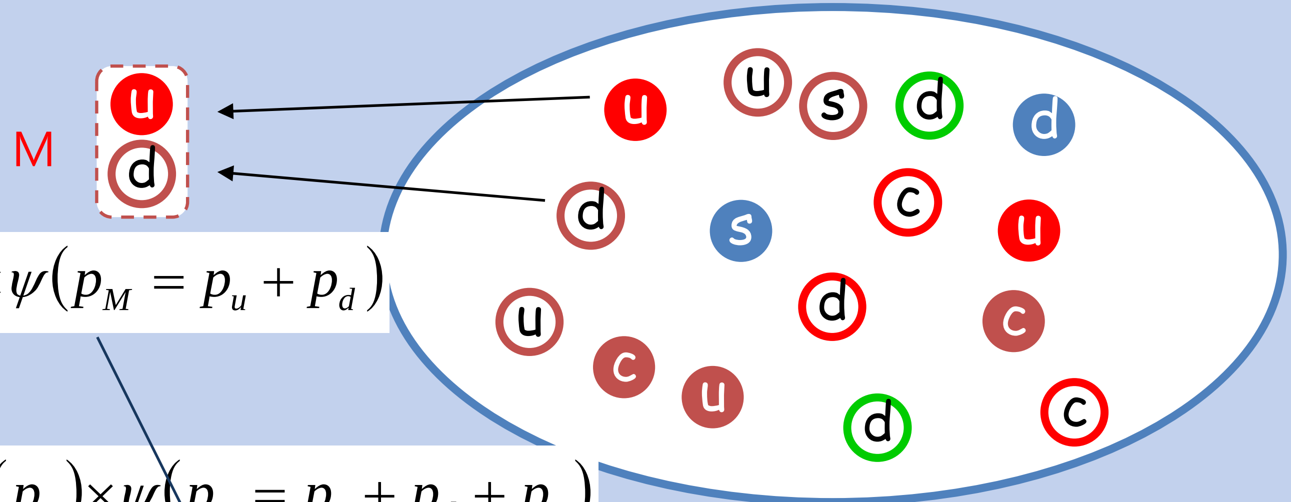
$$\phi \to K + K, \quad \Gamma > 5\,\mathrm{MeV}$$

$$\Lambda(1529) \to \bar{K} + N, \quad \Gamma > 15\,\mathrm{MeV}$$

STAR collaboration (PRL 2006) find

$$\frac{\Lambda(1529)_{Au+Au}}{\Lambda(1529)_{Stat}} \approx 0.4$$

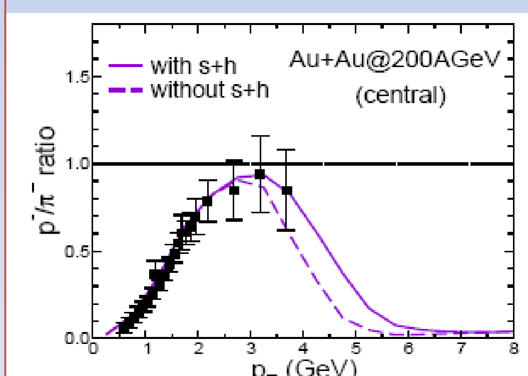
Coalescence model



$$N_M = C\int f_u(p_u) f_d(p_d) \times \psi(p_M = p_u + p_d)$$

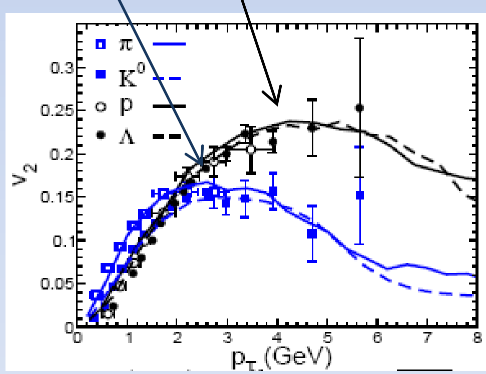
$$N_B = C\int f_u(p_u) f_d(p_d) f_u(p_u) \times \psi(p_B = p_u + p_d + p_u)$$

P_T dependence of ratio



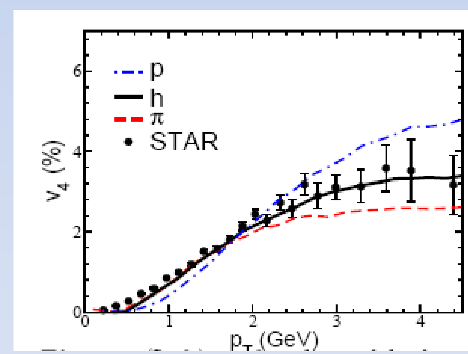
Greco, et al

Quark number scaling of v2



Greco et al

v4

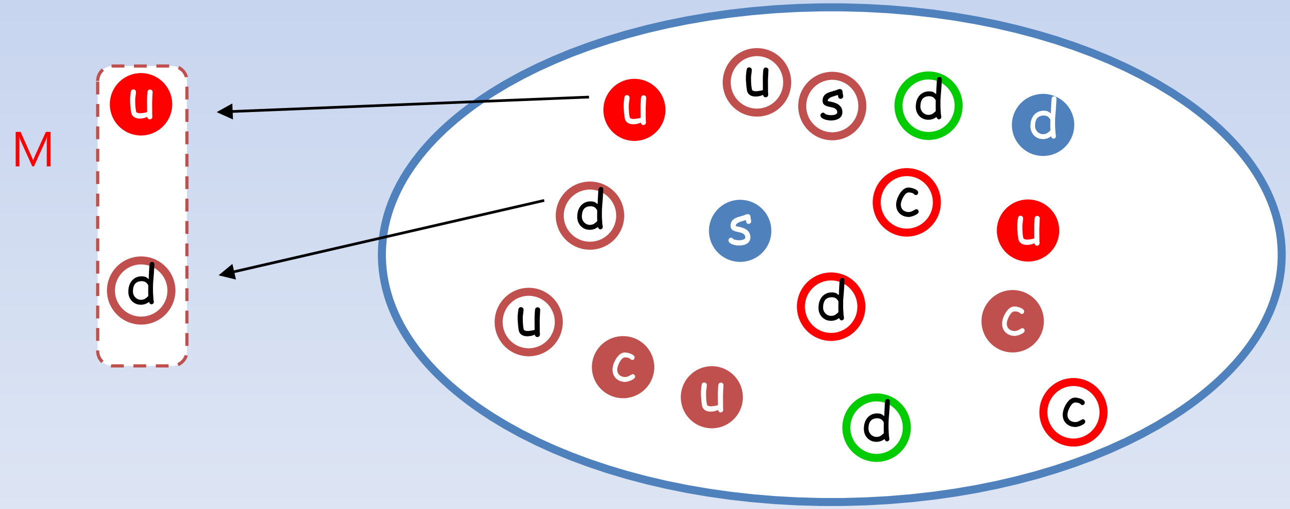


Coalescence model = Statistical model + overlap

$$\frac{dN_H}{d^2P_T} = g_H \int \prod_{i=1}^{n} \frac{p_i \cdot d\sigma_i d^3\mathbf{p}_i}{(2\pi)^3 E_i} f_q(x_i, p_i) f_H(x_1..x_n; p_1..p_n)\, \delta^{(2)}\left(P_T - \sum_{i=1}^{n} p_{T,i}\right)$$

Suppression of p-wave resonance
(Muller and Kadana En'yo)

$$\left(\Lambda^*(1520)/\Lambda\right)_{Au-Au} \Big/ \left(\Lambda^*(1520)/\Lambda\right)_{Statistical} < 0.5$$



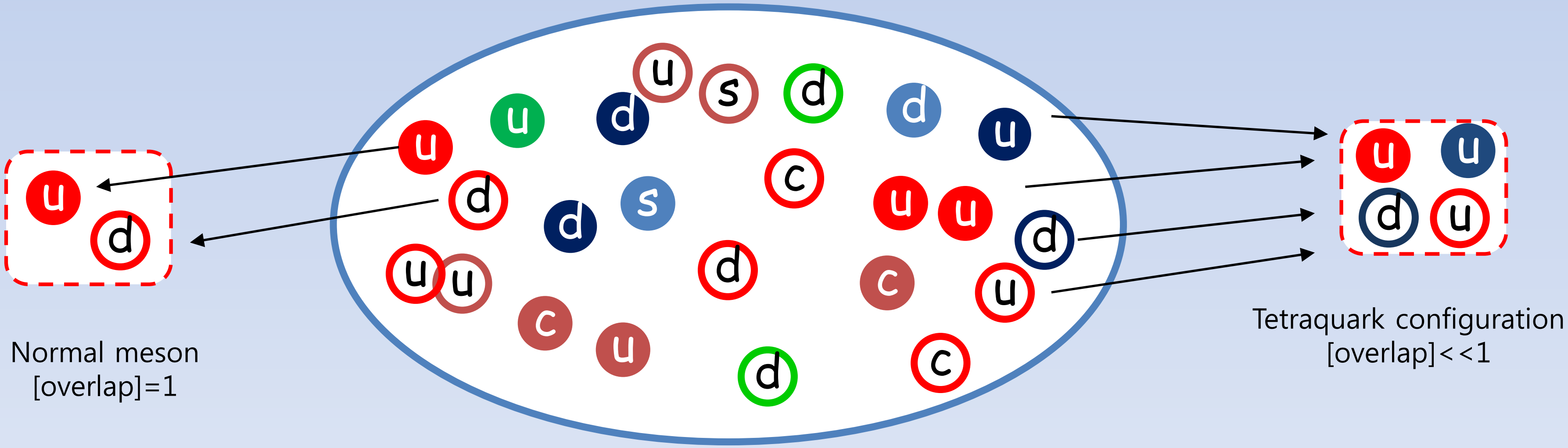
Production of multiquark states are suppressed

Coalescence model = Statistical model + overlap

$$\frac{dN_H}{d^2P_T} = g_H \int \prod_{i=1}^{n} \frac{p_i \cdot d\sigma_i d^3\mathbf{p}_i}{(2\pi)^3 E_i} f_q(x_i, p_i) f_H(x_1..x_n; p_1..p_n)\, \delta^{(2)}\left(P_T - \sum_{i=1}^{n} p_{T,i}\right)$$

$$\text{s-wave} \quad \frac{1}{\mathrm{g_i}} \frac{N_i}{V} \frac{\left(4\pi\sigma^2\right)^{3/2}}{\left(1+2\mu_D T_F \sigma^2\right)} \approx 0.360$$

$$\text{p-wave} \quad \frac{1}{\mathrm{g_i}} \frac{N_i}{V} \frac{2}{3} \frac{\left(4\pi\sigma^2\right)^{3/2} 2\mu_i T \sigma_i^2}{\left(1+2\mu_D T_F \sigma^2\right)} \approx 0.093$$



III: Exotics from Heavy Ion Collision

PRL **106**, 212001 (2011)

PHYSICAL REVIEW C **84**, 064910 (2011)

Exotic hadrons in heavy ion collisions

Sungtae Cho,[1] Takenori Furumoto,[2,3] Tetsuo Hyodo,[4] Daisuke Jido,[2] Che Ming Ko,[5] Su Houng Lee,[1] Marina Nielsen,[6] Akira Ohnishi,[2] Takayasu Sekihara,[2,7] Shigehiro Yasui,[8] and Koichi Yazaki[2,9]
(ExHIC Collaboration)

- large number of c , b quark production

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

- Vertex detector: weakly decaying exotics : FAIR 10^4 D^0 /month,
  LHC 10^5 D^0/month

- T_{cc} production

T_{cc}/D > 0.34×10^{-4} RHIC

> 0.8×10^{-4} LHC

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} sec.

Details of coalescence model calculation (ExHIC PRL, PRC 2011)

	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

- Model central rapidity, central collision
- Introduce charm fugacity

$$N_c = N_D + N_{D^*} + \frac{1}{2}(N_{D_s} + N_{\bar{D}_s}) + \frac{1}{2}(N_{\Lambda_c} + N_{\bar{\Lambda}_c}) = 1.04 + 1.53 + \frac{0.33 + 0.29}{2} + \frac{0.14 + 0.11}{2} = 3$$

- Coalescence model model and Wigner function

$$N_h^{\text{coal}} = g_h \prod_{j=1}^{n} \frac{N_j}{g_j} \prod_{i=1}^{n-1} \frac{\int d^3y_i d^3k_i f_i(k_i) f^W(y_i, k_i)}{\int d^3y_i d^3k_i f_i(k_i)}$$

$$f_s^W(y_i, k_i) = 8\exp\left(-\frac{y_i^2}{\sigma_i^2} - k_i^2\sigma_i^2\right)$$

$$\sigma_i = 1/\sqrt{\mu_i \omega}$$

- Parameters to fit normal hadron production including resonance feedown from statistical model

$$m_{u,d} = 300\,\text{MeV},\ m_c = 500\,\text{MeV},\ m_c = 1500\,\text{MeV} \quad \omega_{u,d} = 550\,\text{MeV},\ \omega_s = 519\,\text{MeV},\ \omega_c = 385\,\text{MeV}$$

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

- Hadron coalescence

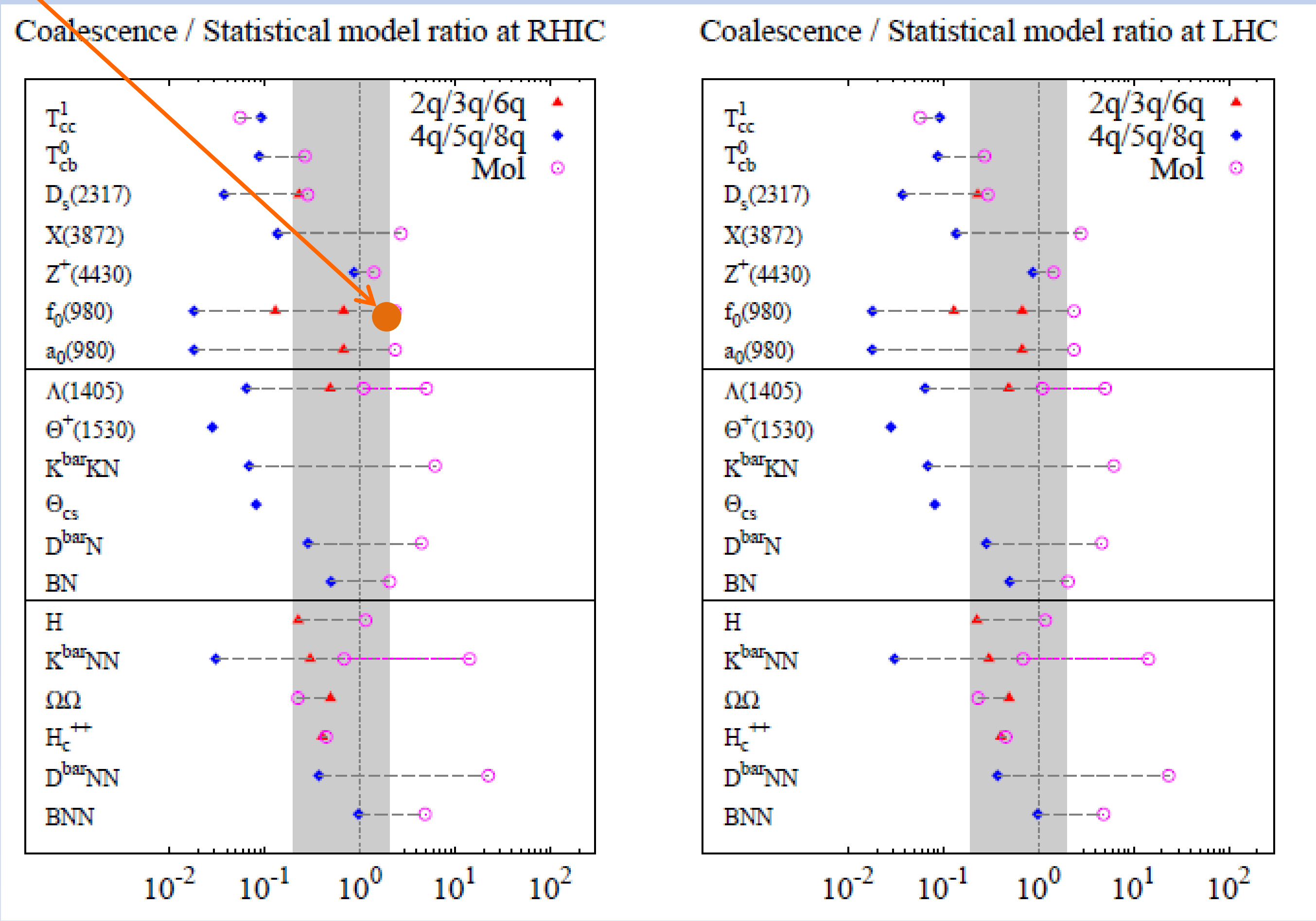
$$\omega = \frac{3}{2\mu_R\langle r^2\rangle} \qquad \text{or} \qquad B \approx \frac{\hbar^2}{2\mu_R a_0^2}, \quad \langle r^2\rangle \approx \frac{a_0^2}{2}$$

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)	$K^+\pi^- + d, K^+\pi^- + p + p$

Expectations [overlap] at LHC

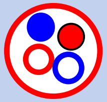
Fachini [STAR]

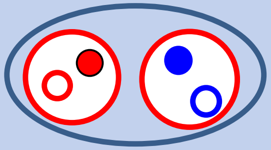
$Z(3900)$



Summary

- Whats the difference between compact multiquark states and molecular states
  - → Need heavy quarks to enhance diquark correlation
  - → Multiquarks will tell us about 3,4-body QCD force





- Measurements from Heavy Ion can discriminate the structures

	Normal meson	Compact multiquark	Molecules	Resonance
Yields /Statistical model	1	< 0.1	1~ 2	~ 0.5

- Flavor exotics will involves two heavy quarks→ Heavy ion can easily produce

Suggestions

1. Lambda (1405): two poles? $\Lambda(1405) \rightarrow \pi^+ + \Sigma^- \rightarrow \pi^+ + n + \pi^-$

$$\Lambda(1405) \rightarrow \pi^- + \Sigma^+ \xrightarrow{50\%} \pi^- + p + \pi^0$$

2. Dibayrons: d*(2323)→ $\Delta+\Delta$

H, N-Omega, Hc(uuudsc)

3. Light molecules or tetraquarks $f_0(980) \rightarrow \pi^+\pi^-$, $a_0(980) \rightarrow \eta\pi^\pm$

4. Heavy Tetraquarks $Z(3900) \rightarrow J/\psi + \pi^+$, $Z(4430) \rightarrow J/\psi + \pi^+$, or $\psi' + \pi^+$

$$X(5568) \rightarrow B_s^0 \pi^\pm \quad [bd][\bar{s}\bar{u}]$$

$$\mathrm{T}_{\mathrm{cb}}^0(\mathrm{ud}\bar{\mathrm{c}}\bar{\mathrm{b}}) \rightarrow (\bar{D}^0 + B^0) \rightarrow K^+\pi^- + K^+\pi^-$$

$$\mathrm{T}_{\mathrm{sb}}^0(\mathrm{ds}\bar{\mathrm{u}}\bar{\mathrm{b}}) \rightarrow (K^- + B^0) \rightarrow K^- + K^+\pi^-$$

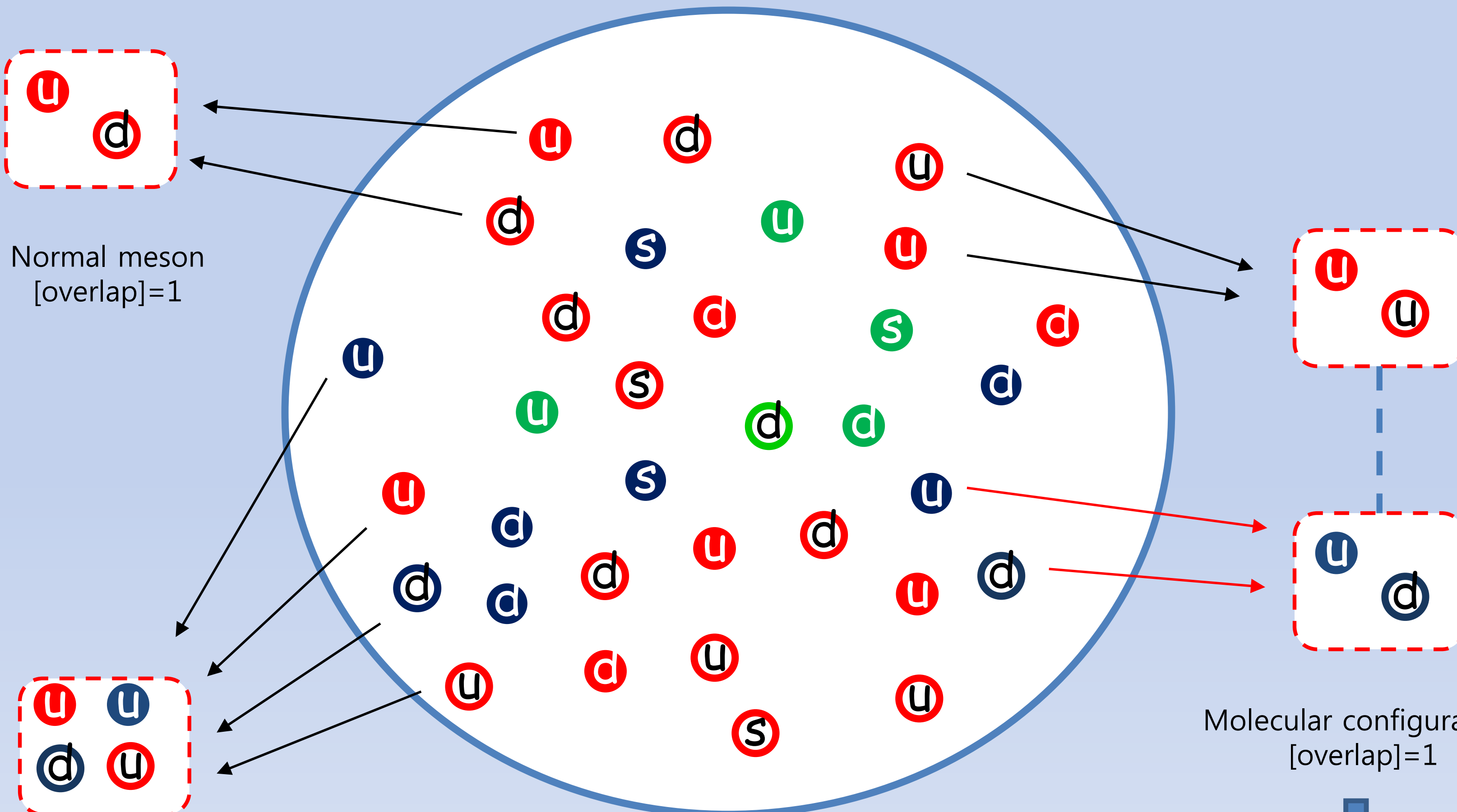
$$\rightarrow (\pi^- + B_s^0) \rightarrow \pi^- + J/\psi + \phi$$

$$\mathrm{T}_{\mathrm{cc}}^1(\mathrm{ud}\bar{\mathrm{c}}\bar{\mathrm{c}}) \rightarrow (\bar{D}^0 + D^{*-}) \rightarrow K^+\pi^- + K^+\pi^-\pi^-$$

5. Heavy Pentaquarks $\mathrm{P_c} \rightarrow J/\psi + p$

Back up slides

Hadron production through coalescence $\rightarrow c \times \exp\left(-\frac{M}{T}\right) \times [\text{overlap}]$



Normal meson
[overlap]=1

Molecular configuration:
[overlap]=1

Tetraquark configuration
[overlap]<<1

⇨ Coalescence model at Tc → ratio of yield $= \left(\frac{V_{\text{Molecule}}}{V_{\text{Mulitiquark}}}\right)$