Exotic states in heavy ion collisions

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Dense Matter from Chiral Effective Theories

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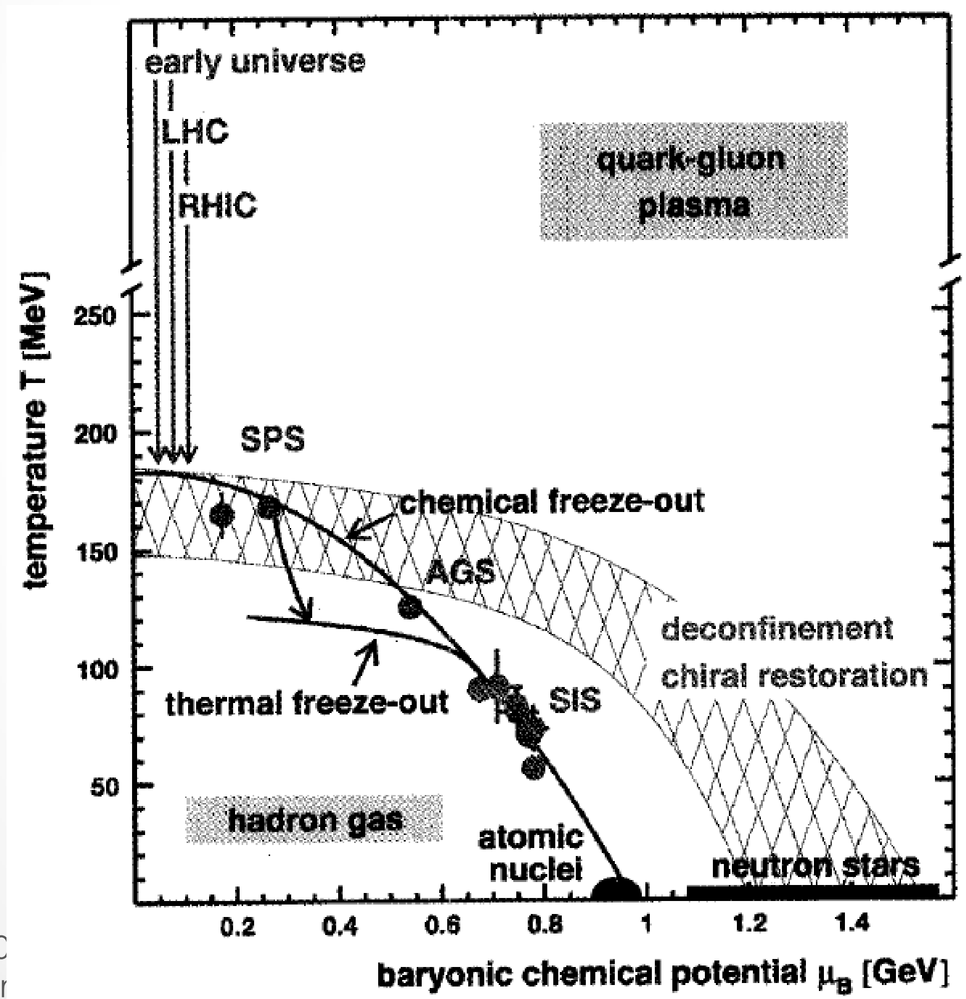
Outline

- Introduction
- Hadron production models
- Production yields of exotics
- Hadronic effects on the abundance of exotic hadrons, X(3872) mesons
- Conclusion

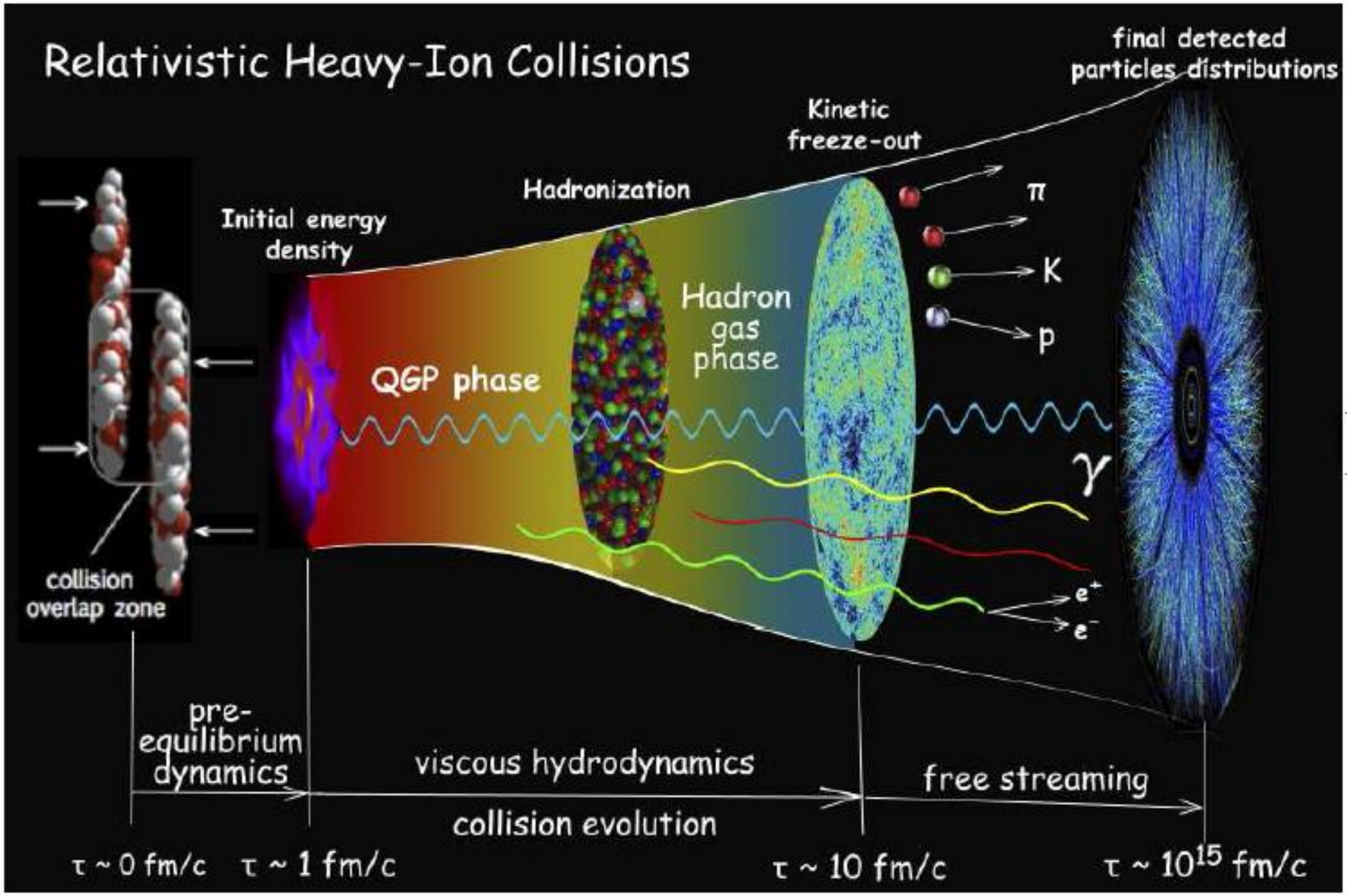
Introduction

– QCD Phase diagram



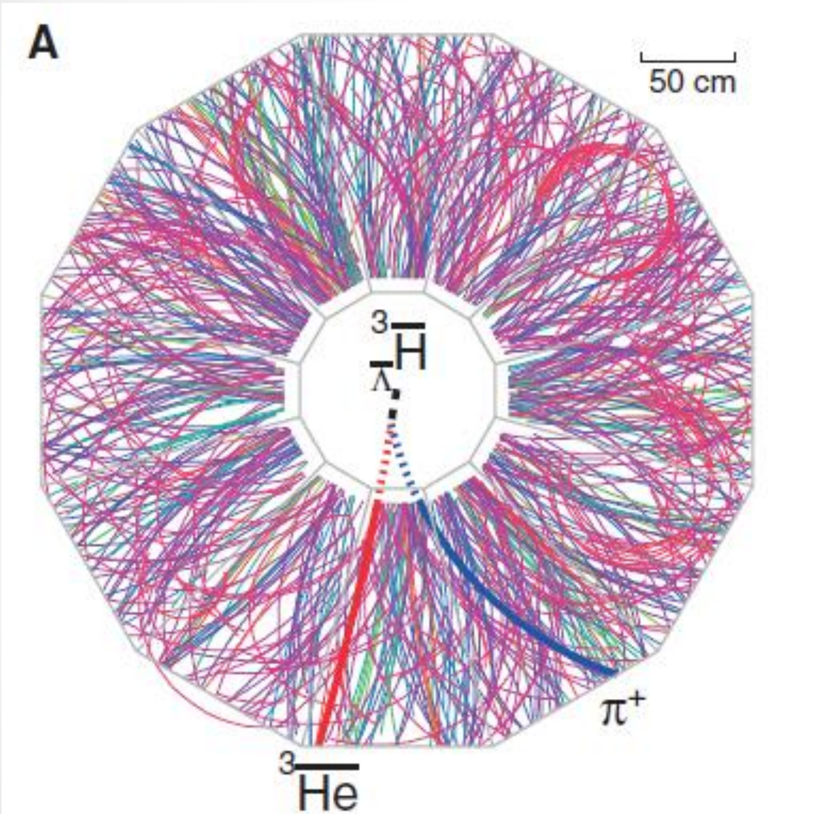
P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **690**, 119c (2001)

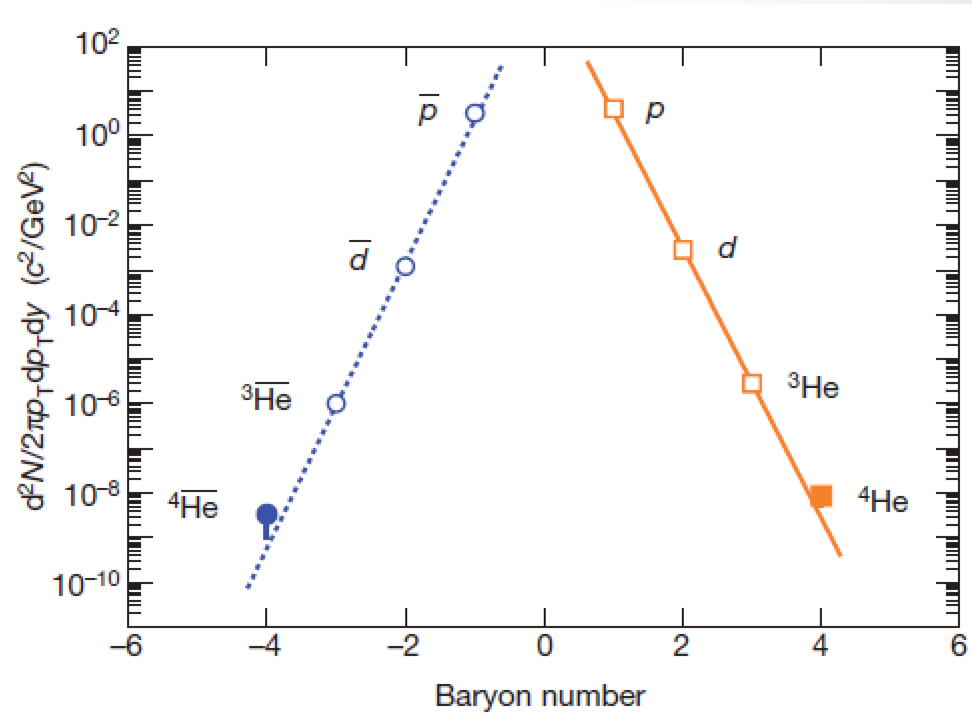
– Relativistic heavy ion collisions



U. W. Heinz, J. Phys. Conf. Ser. **455**, 012044 (2013)

– 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)

– Hadrons

1) Normal hadrons : Mesons and Baryons

2) Exotic hadrons : Hadronic molecules, Multi-quark hadrons

– Multi-quark hadrons

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

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

2) 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) $\rightarrow DK, c\bar{s}, q\bar{q}c\bar{s}$

$Z^+(4430)$ Belle (2007), LHCb (2014)

$Z^+(3900)$ Belle, BESIII (2013)

$P_C(4380)$, $P_C(4450)$ LHCb (2015)

– Production of exotic states

1) Estimate the possibility of observing predicted exotics with/without heavy quarks in heavy ion collision experiment
2) Find a possible solution to a problem of identifying hadronic molecular states and/or hadrons with multiquark components
3) Focus on exotic hadron production using both the statistical model and the coalescence model

– Hadronic effects on exotic hadron abundance during the hadronic stage

1) Study possible interactions between exotic hadrons and light hadrons in the hadronic medium
2) Investigate the hadronic effects on exotic hadron abundance during the hadronic stage

– Exotic hadrons in previous works

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)
$a_0(980)$	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.

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

– Exotic hadrons (updated)

Particle	m [MeV]	(I, J^P)	$q\bar{q}/qqq$ (L)	multiquark	Mol. (L)	ω_{Mol} [MeV]
$D_s(2317)$	2317	$(0, 0^+)$	$c\bar{s}$ (P)	$c\bar{s}q\bar{q}$	DK (S)	273(B)
$X(3872)$	3872	$(0, 1^+)$	$c\bar{c}$ (P)	$c\bar{c}q\bar{q}$	$D\bar{D}^*$ (S)	3.6(B)
$Z_c(3900)$	3900	$(1, 1^+)$	—	$c\bar{c}u\bar{d}$	—	—
$Z_c(4430)$	4430	$(1, 1^+)$	—	$c\bar{c}u\bar{d}$	$D_1\bar{D}^*$ (S)	13.5(B)
$Z_b(10610)$	10610	$(1, 1^+)$	—	$b\bar{b}u\bar{d}$	—	—
$Z_b(10650)$	10650	$(1, 1^+)$	—	$b\bar{b}u\bar{d}$	—	—
$X(5568)$	5568	$(1, 0^+)$	—	$s\bar{b}u\bar{d}$	—	—
$P_c(4380)$	4380	$(1/2, 3/2^-)^b$	—	$c\bar{c}uud$ (S)	$\bar{D}\Sigma_c^*$ (S)	60(B)
$P_c(4450)$	4450	$(1/2, 5/2^+)^b$	—	$c\bar{c}uud$ (P)	—	—
$\Theta(1530)$	1530	$(0, 1/2^+)$	—	$qqqq\bar{s}$ (P)	—	—
$\bar{K}KN$	1920	$(1/2, 1/2^+)$	—	$qqqs\bar{s}$ (P)	$\bar{K}KN$	42(R)
$\bar{K}NN$	2352	$(1/2, 0^-)$	q^5s (P)	$q^6s\bar{q}$ (S)	$\bar{K}NN$	20.5(T)
$\Omega\Omega$	3228	$(0, 0^+)$	—	s^6	—	—
T_{cc}^1	3797	$(0, 1^+)$	—	$ud\bar{c}\bar{c}$	—	—
$\bar{D}N$	2790	$(0, 1/2^-)$	—	$qqqq\bar{c}$	$\bar{D}N$	6.48(R)
$\bar{D}^*N$	2919	$(0, 3/2^-)$	—	$qqqq\bar{c}(D)$	$\bar{D}^*N$	6.48(R)
Θ_{cs}	2980	$(1/2, 1/2^+)$	—	$qqqs\bar{c}$ (P)	—	—
H_c^{++}	3377	$(1, 0^+)$	—	$qqqsc$	—	—-
$\bar{D}NN$	3734	$(1/2, 0^-)$	—	$q^7\bar{c}$	$\bar{D}NN$	6.48(T)
Λ_cN	3225	$(1/2, 1^+)$	—	$cuduud$	Λ_cN	4.24(R)
Λ_cNN	4164	$(0, 3/2^+)$	—	$cuduududd$	Λ_cNN	33.16(R)
T_{cb}^0	7123	$(0, 0^+)$	—	$ud\bar{c}\bar{b}$	—	—

S. Cho *et al*. [ExHIC Collaboration], arXiv:1612.xxxxx

Hadron production models

– Statistical Hadronization 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

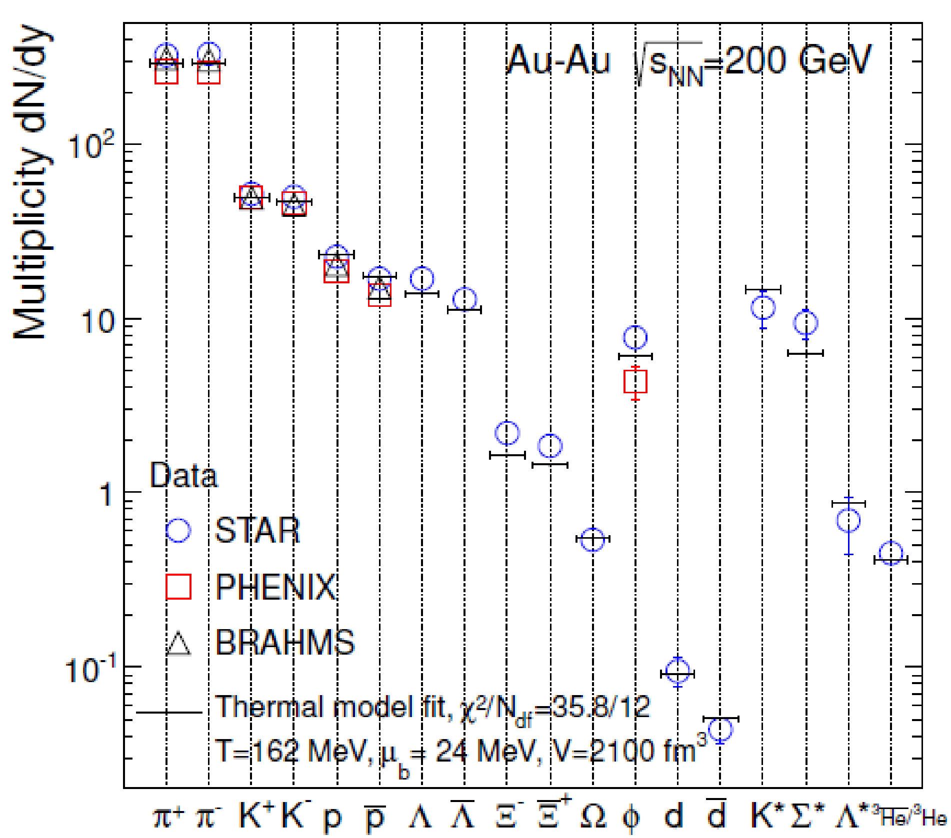
$$N_i = V_H \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\gamma_i^{-1} e^{E_i/T_H} \pm 1} \qquad E_i = \sqrt{m_i^2 + p_i^2}$$

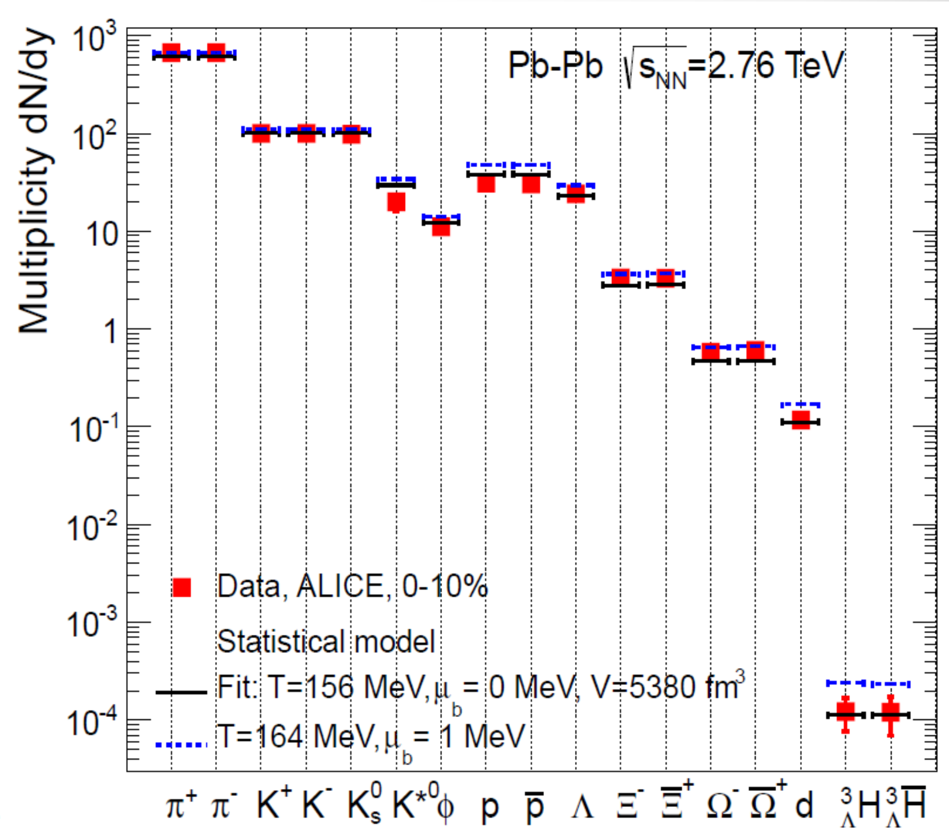
with the fugacity for incomplete strange and charm quarks equilibrium

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

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

– Recent statistical model analysis





A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nucl. Phys. A **904-905**, 535c (2013)
J. Stachel, A. Andronic, P. Braun-Munzinger, and K. Redlich, J. Phys. Conf. Ser. **509**, 012019 (2014)

– Chemical freeze-out conditions in heavy ion collisions

1) Start from the hadronization temperature and volume in the statistical hadronization model

$$T_H^{RHIC} = 162 \text{ MeV}, \quad V_H^{RHIC} = 2100 \text{ fm}^3$$
$$T_H^{LHC} = 156 \text{ MeV}, \quad V_H^{LHC} = 5380 \text{ fm}^3$$

2) Satisfy the entropy conservation during the expansion of the system, $s_H V_H = s_C V_C$ at both RHIC and LHC using the Lattice results for entropy at different temperatures

S. Borsanyi, G. Endrodi, Z. Fodor, A. Jakovac, S. D. Katz, S. Krieg, C. Ratti and K. K. Szabo, JHEP **1011**, 077 (2010)

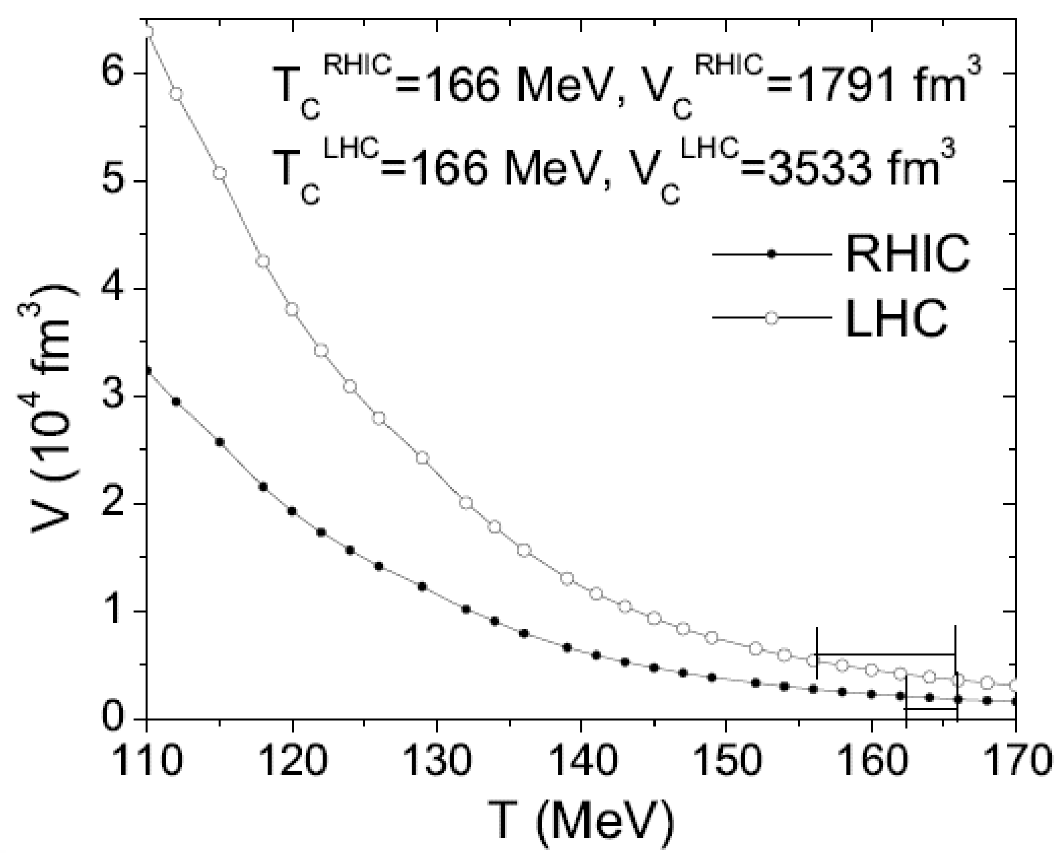
3) Require the size of rho and omega mesons produced at the critical temperature by coalescence of thermal quarks in QGP to be equal at both RHIC and LHC

4) Force the yield of rho & omega mesons produced at T_C to be equal to those at T_H in the statistical hadronization model

$$N_\rho^{stat} = V_H \frac{3\cdot 3}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{\sqrt{m_\rho^2+p^2}/T_H}} = N_\rho^{coal} = \frac{3\cdot 3}{(2\cdot 3)^2} N_u N_u \frac{(4\pi/\omega_l)^{3/2}}{V_C(1+2T_C/\omega_l)}\left(\frac{M_u+M_u}{M_u^2}\right)^{3/2}$$

5) Critical volume and temperature

	RHIC	LHC
T_C	166 MeV	166 MeV
V_C	1791 fm^3	3533 fm^3
T_H	162 MeV	156 MeV
V_H	2100 fm^3	5380 fm^3
μ_B	24 MeV	0 MeV
μ_s	10 MeV	0 MeV



S. Cho *et al.* [ExHIC Collaboration], arXiv:1612.xxxxx

– Coalescence model

1) Yields of hadrons

V. Greco, C. M. Ko, and P. Levai, Phys. Rev. C **68**, 034904 (2003)
R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. C **68**, 044902 (2003)

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

with the Wigner function, the coalescence probability function

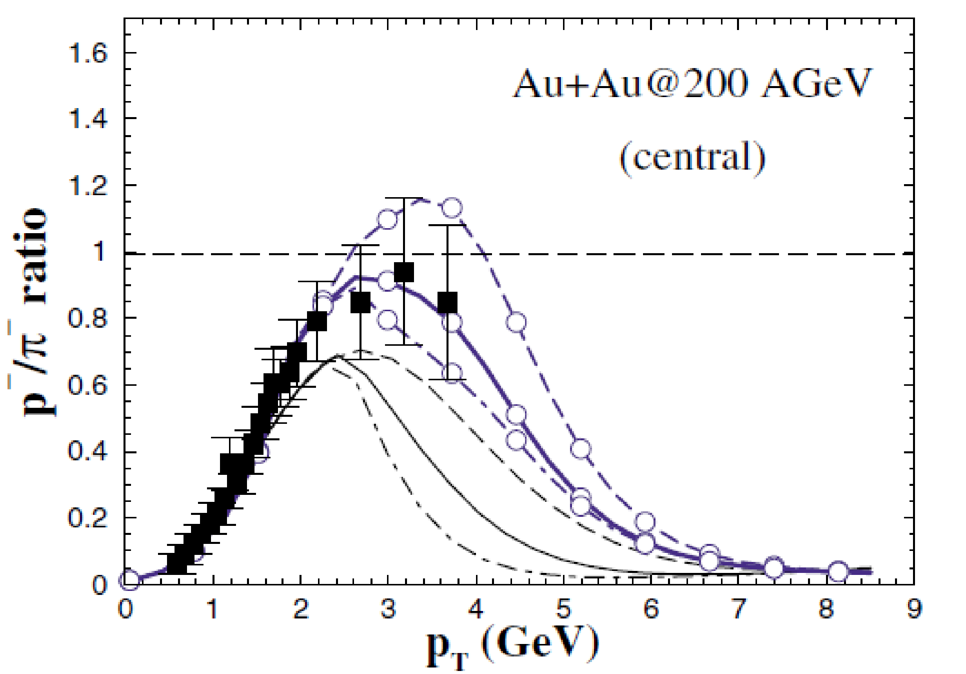
$$f^W(x_1, \cdots, x_n : p_1, \cdots, p_n)$$
$$= \int \prod_{i=1}^{n} dy_i e^{p_i y_i} \psi^* \left(x_1 + \frac{y_1}{2}, \cdots, x_n + \frac{y_n}{2} \right) \psi \left(x_1 - \frac{y_1}{2}, \cdots, x_n - \frac{y_n}{2} \right)$$

i. A Lorentz-invariant phase space integration of a space-like hypersurface constraints the number of particles in the system

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

– Quark coalescence or quark recombination in heavy ion collisions

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)



1) The puzzle in antiproton /pion ratio

i. A competition between two particle production mechanisms exists
: A fragmentation dominates at large transverse momenta and a coalescence prevails at lower transverse momenta

2) The transverse momentum spectra

$$\frac{dN_M}{d^2\mathbf{p}_T} = g_M \frac{6\pi}{\tau \Delta y R_\perp^2 \Delta_p^3} \int d^2\mathbf{p}_{1T} d^2\mathbf{p}_{2T} \frac{dN_q}{d^2\mathbf{p}_{1T}}\bigg|_{|y_1|\leqslant \Delta y/2} \frac{dN_{\bar{q}}}{d^2\mathbf{p}_{2T}}\bigg|_{|y_2|\leqslant \Delta y/2}$$
$$\times \delta^{(2)}(\mathbf{p}_T - \mathbf{p}_{1T} - \mathbf{p}_{2T}) \Theta\left(\Delta_p^2 - \frac{1}{4}(\mathbf{p}_{1T} - \mathbf{p}_{2T}) - \frac{1}{4}[(m_{1T}-m_{2T})^2 - (m_1-m_2)^2]\right).$$

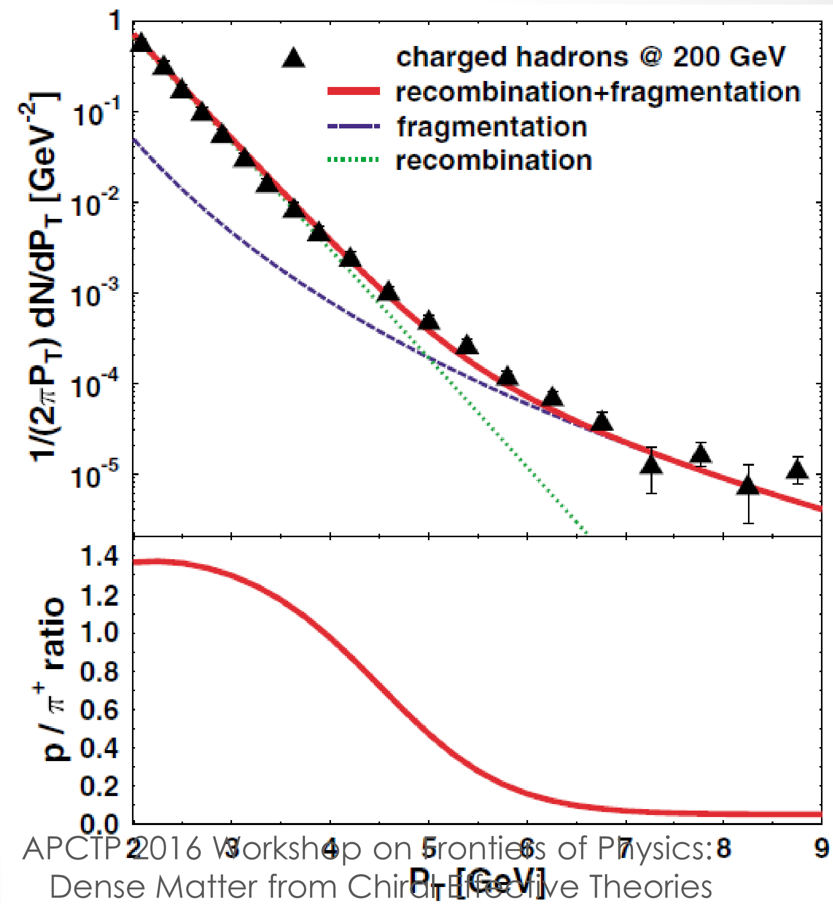
$$f_M(x_1, x_2; p_1, p_2) = \frac{9\pi}{2(\Delta_x \Delta_p)^3} \Theta(\Delta_x^2 - (x_1-x_2)^2)$$
$$\times \Theta\left(\Delta_p^2 - \frac{1}{4}(p_1-p_2)^2 + \frac{1}{4}(m_1-m_2)^2\right).$$

and

$$E\frac{dN_M}{d^3P} = C_M \int_\Sigma \frac{d^3R P\cdot u(R)}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3}$$
$$\times w_a\left(R; \frac{\mathbf{P}}{2} - \mathbf{q}\right) \Phi_M^W(\mathbf{q}) w_b\left(R; \frac{\mathbf{P}}{2} + \mathbf{q}\right)$$

$$\Phi_M^W(\mathbf{q}) = \int d^3r \Phi_M^W(\mathbf{r}, \mathbf{q})$$

$$\Phi_M^W(\mathbf{r}, \mathbf{q}) = \int d^3r' e^{-i\mathbf{q}\cdot\mathbf{r}'} \varphi_M\left(\mathbf{r} + \frac{\mathbf{r}'}{2}\right) \varphi_M^*\left(\mathbf{r} - \frac{\mathbf{r}'}{2}\right)$$



3) Quark number scaling of the elliptic flow

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

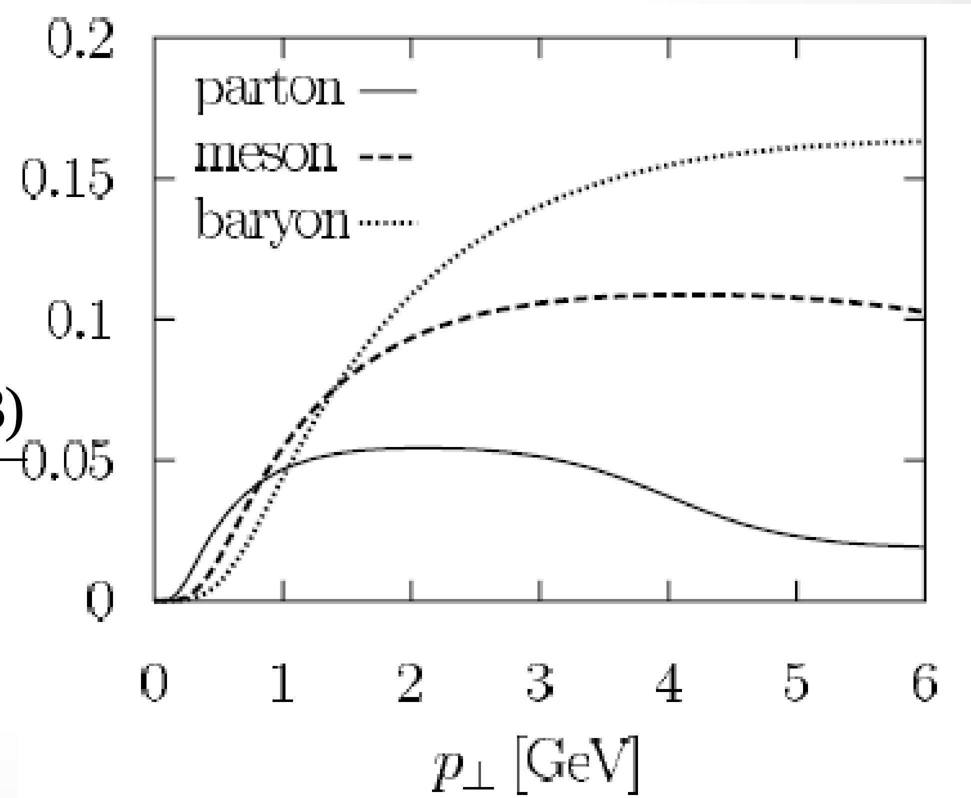
$$v_2(p_T) = \frac{\int d\varphi \cos 2\varphi \frac{d^2N}{dp_T^2}}{\int d\varphi \frac{d^2N}{dp_T^2}} \quad , \quad \frac{dN_q}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN_q}{p_T dp_T}\left[1 + 2v_{2,q}(p_T)\cos(2\varphi)\right]$$

i. Coalescence model predicts by assuming that partons have elliptical anisotropy

$$v_{2,M}(p_T) = \frac{2v_{2,q}(p_T/2)}{1+2v_{2,q}^2(p_T/2)}$$

$$v_{2,B}(p_T) = \frac{3v_{2,q}(p_T/3)+3v_{2,q}^3(p_T/3)}{1+6v_{2,q}^2(p_T/3)}$$

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



Production yields of exotics

– Combine statistical and coalescence model

1) Quark coalescence :

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

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

2) Monte-Carlo Glauber model + PHYTHIA

	RHIC	LHC @2.76 TeV	LHC @5.02 TeV
Without shadowing			
$N_c = N_{\bar{c}}$	4.5	17	23
$N_b = N_{\bar{b}}$	0.034	0.68	1.2
With shadowing			
$N_c = N_{\bar{c}}$	4.1	11	14
$N_b = N_{\bar{b}}$	0.031	0.44	0.71

3) Parameter determinations

	RHIC		LHC (2.76 TeV)		LHC (5.02 TeV)	
	Sc. 1	Sc. 2	Sc. 1	Sc. 2	Sc. 1	Sc. 2
γ_c	22		39		50	
γ_b	4.0×10^7		8.6×10^8		1.4×10^9	
T_C (MeV)	162	166	156	166	156	166
V_C (fm^3)	2100	1791	5380	3533	5380	3533
ω(MeV)	590	608	564	609	564	609
ω_s(MeV)	431	462	426	502	426	502
ω_c(MeV)	222	244	219	278	220	279
ω_b(MeV)	183	202	181	232	182	234
$N_u = N_d$	320	302	700	593	700	593
$N_s = N_{\bar{s}}$	183	176	386	347	386	347
$N_c = N_{\bar{c}}$	4.1		11		14	
$N_b = N_{\bar{b}}$	0.03		0.44		0.71	
T_F (MeV)	119		115			
V_F (fm^3)	20355		50646			

S. Cho *et al.* [ExHIC Collaboration], arXiv:1612.xxxxx

– Try all possible constituent combinations for yields of exotic states

1) Evaluate the yields of exotic hadrons for all possible structure configurations
; normal hadrons, multiquark hadrons, hadronic molecules

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

– Try all possible constituent combinations for yields of exotic states

1) Evaluate the yields of exotic hadrons for all possible structure configurations
; normal hadrons, multiquark hadrons, hadronic molecules

$$N^{Coal}_{X(3872)} = g\int \left[-\cdots \quad \begin{matrix} c\bar{c} \\ q\bar{q}c\bar{c} \\ \bar{D}D^* \end{matrix} \quad \cdots - \right] f^W(x_1,\cdots,x_n : p_1,\cdots,p_n)$$

2) Yields in coalescence model at mid-rapidity

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

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

3) The internal structure of hadrons is taken into consideration

s-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)} \sim 0.168$$

p-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)}\frac{2}{3}\left[\frac{2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)}\right] \sim 0.040$$

d-wave $$\frac{N_i}{g_i}\frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)}\frac{8}{15}\left[\frac{2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)}\right]^2 \sim 0.011$$

: Yields of multi-quark hadrons are suppressed

4) Summary of exotic hadron yields evaluation at RHIC and LHC (partial)

RHIC

Particle	$q\bar{q}/qqq$	multiquark	$q\bar{q}/qqq$	multiquark	Mol.	Stat.
	scenario 1		scenario 2			
$D_s(2317)$	2.3×10^{-2}	2.4×10^{-3}	2.3×10^{-2}	2.5×10^{-3}	6.5×10^{-3}	6.6×10^{-2}
$X(3872)$	5.4×10^{-4}	5.0×10^{-5}	5.6×10^{-4}	5.3×10^{-5}	9.1×10^{-4}	5.7×10^{-4}
$Z_c(3900)$	—	1.5×10^{-4}	—	1.6×10^{-4}	—	1.5×10^{-3}
$Z_c(4430)$	—	1.5×10^{-4}	—	1.6×10^{-5}	5.0×10^{-5}	6.5×10^{-5}
$Z_b(10610)$	—	2.0×10^{-9}	—	2.1×10^{-9}	—	2.1×10^{-8}
$Z_b(10650)$	—	2.0×10^{-9}	—	2.1×10^{-9}	—	1.6×10^{-8}
$X(5568)$	—	5.1×10^{-5}	—	5.2×10^{-5}	—	2.3×10^{-3}
$P_c(4380)$	—	2.5×10^{-5}	—	2.6×10^{-5}	2.9×10^{-5}	9.2×10^{-5}
$P_c(4450)$	—	1.5×10^{-5}	—	1.5×10^{-5}	—	9.1×10^{-5}

LHC (2.76 TeV)

Particle	$q\bar{q}/qqq$	multiquark	$q\bar{q}/qqq$	multiquark	Mol.	Stat.
	scenario 1		scenario 2			
$D_s(2317)$	5.2×10^{-2}	4.3×10^{-3}	5.0×10^{-2}	4.5×10^{-3}	1.4×10^{-2}	1.5×10^{-1}
$X(3872)$	1.6×10^{-3}	1.1×10^{-4}	1.7×10^{-3}	1.3×10^{-4}	2.7×10^{-3}	1.7×10^{-3}
$Z_c(3900)$	—	3.4×10^{-4}	—	4.0×10^{-4}	—	4.3×10^{-3}
$Z_c(4430)$	—	3.4×10^{-4}	—	4.0×10^{-4}	1.4×10^{-4}	1.7×10^{-4}
$Z_b(10610)$	—	1.3×10^{-7}	—	1.5×10^{-7}	—	1.9×10^{-6}
$Z_b(10650)$	—	1.3×10^{-7}	—	1.5×10^{-7}	—	1.5×10^{-6}
$X(5568)$	—	5.0×10^{-4}	—	5.2×10^{-4}	—	3.1×10^{-2}
$P_c(4380)$	—	5.0×10^{-5}	—	5.8×10^{-5}	6.4×10^{-5}	2.1×10^{-4}
$P_c(4450)$	—	2.9×10^{-5}	—	3.2×10^{-5}	—	2.0×10^{-4}

LHC (5.02 TeV)

Particle	$q\bar{q}/qqq$	multiquark	$q\bar{q}/qqq$	multiquark	Mol.	Stat.
	scenario 1		scenario 2			
$D_s(2317)$	6.5×10^{-2}	5.4×10^{-3}	6.4×10^{-2}	5.7×10^{-3}	1.8×10^{-2}	1.9×10^{-1}
$X(3872)$	2.5×10^{-3}	1.8×10^{-4}	2.7×10^{-3}	2.1×10^{-4}	4.5×10^{-3}	2.8×10^{-3}
$Z_c(3900)$	—	5.4×10^{-4}	—	6.4×10^{-4}	—	7.1×10^{-3}
$Z_c(4430)$	—	5.4×10^{-4}	—	6.4×10^{-4}	2.3×10^{-4}	2.8×10^{-4}
$Z_b(10610)$	—	3.4×10^{-7}	—	3.9×10^{-7}	—	5.0×10^{-6}
$Z_b(10650)$	—	3.4×10^{-7}	—	3.9×10^{-7}	—	3.9×10^{-6}
$X(5568)$	—	7.9×10^{-4}	—	8.2×10^{-4}	—	5.0×10^{-2}
$P_c(4380)$	—	7.9×10^{-5}	—	9.3×10^{-5}	1.0×10^{-4}	3.4×10^{-4}
$P_c(4450)$	—	4.7×10^{-5}	—	5.0×10^{-5}	—	3.4×10^{-4}

S. Cho *et al.*
[ExHIC Collaboration],
arXiv:1612.xxxxx

5) Ratio of normal hadron yields in coalescence model to those in statistical model satisfy,

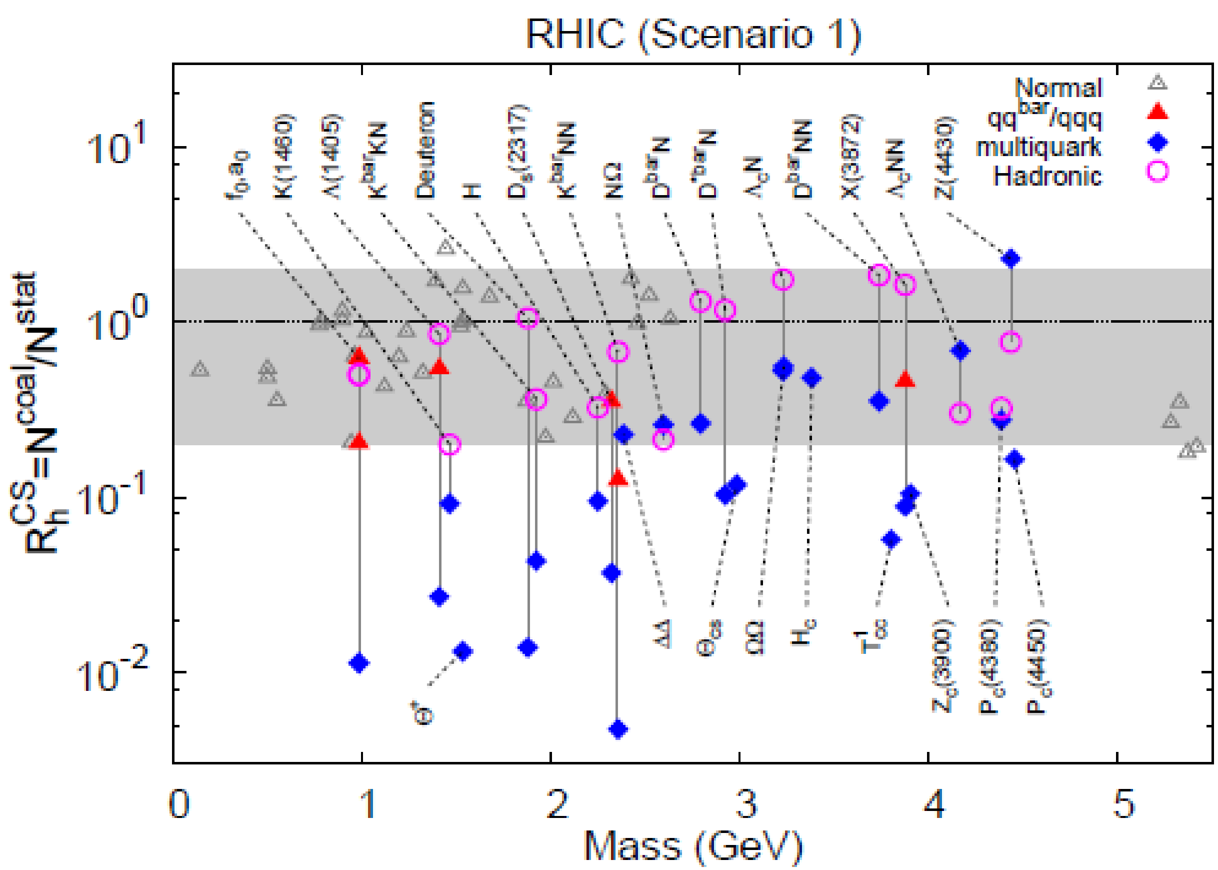
$$0.2 < \frac{N^{Coal}_{i,normal}}{N^{Stat}_{i}} < 2$$

And also similarly for loosely bound hadron molecules,

$$0 < \frac{N^{Coal}_{i,molecule}}{N^{Stat}_{i}} < 2$$

whereas the exotic multiquark hadrons become suppressed

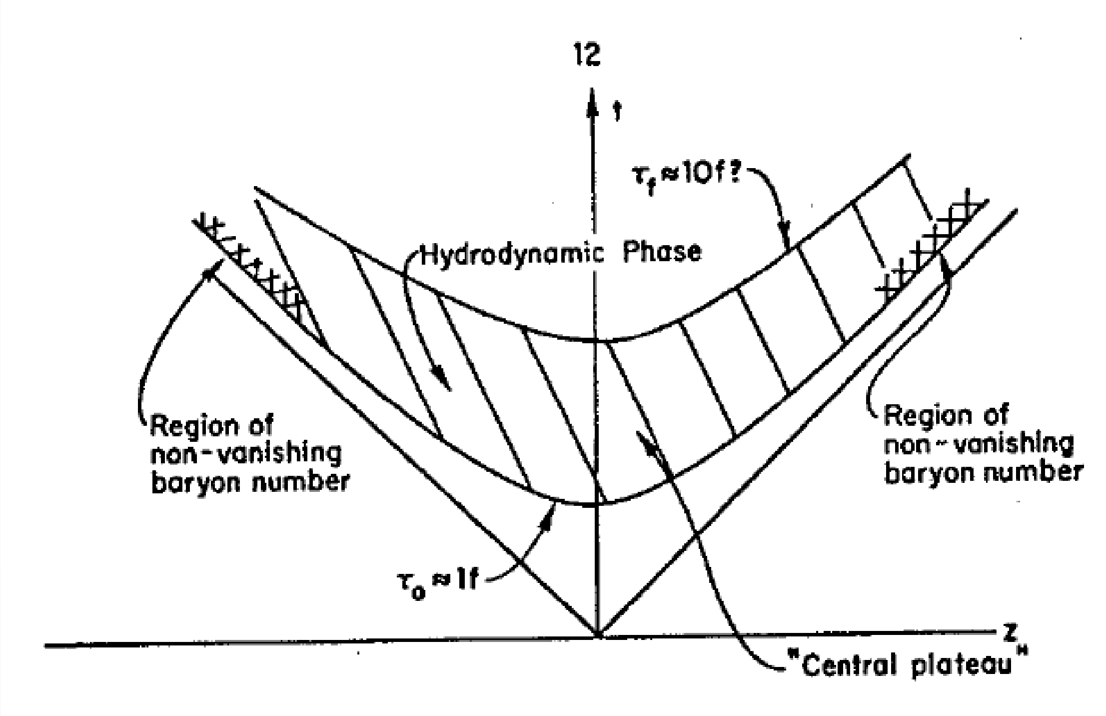
$$\frac{N^{Coal}_{i,multiquark}}{N^{Stat}_{i}} < 0.2$$



The yield of a hadron in relativistic heavy ion collision reflects its structure!

Hadronic effects on the abundance of exotic hadrons

– 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 state and Quark-gluon plasma
iii. Hydrodynamic expansion iv. Chemical freeze-out
v. Kinetic freeze-out

– X(3872) mesons

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) The first measurement in 2003

S.K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **90**, 242001 (2003)

Particle	m [MeV]	(I, J^P)	$q\bar{q}/qqq$ (L)	multiquark	Mol. (L)	$\omega_{\rm Mol}$ [MeV]
$X(3872)$	3872	$(0, 1^+)$	$c\bar{c}$ (P)	$c\bar{c}q\bar{q}$	$D\bar{D}^*$ (S)	3.6(B)

2) Expected production yields of X(3872) mesons

Particle	$q\bar{q}/qqq$ (scenario 1)	multiquark (scenario 1)	$q\bar{q}/qqq$ (scenario 2)	multiquark (scenario 2)	Mol.	Stat.
RHIC						
$X(3872)$	5.4×10^{-4}	5.0×10^{-5}	5.6×10^{-4}	5.3×10^{-5}	9.1×10^{-4}	5.7×10^{-4}
LHC (2.76 TeV)						
$X(3872)$	1.6×10^{-3}	1.1×10^{-4}	1.7×10^{-3}	1.3×10^{-4}	2.7×10^{-3}	1.7×10^{-3}
LHC (5.02 TeV)						
$X(3872)$	2.5×10^{-3}	1.8×10^{-4}	2.7×10^{-3}	2.1×10^{-4}	4.5×10^{-3}	2.8×10^{-3}

– Hadronic interactions

1) Possibilities of J/ψ absorption by hadronic interactions

T. Matsui and H. Satz,
Phys. Lett. B **178**, 416 (1986)

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?

2) A meson exchange model with an effective Lagrangian

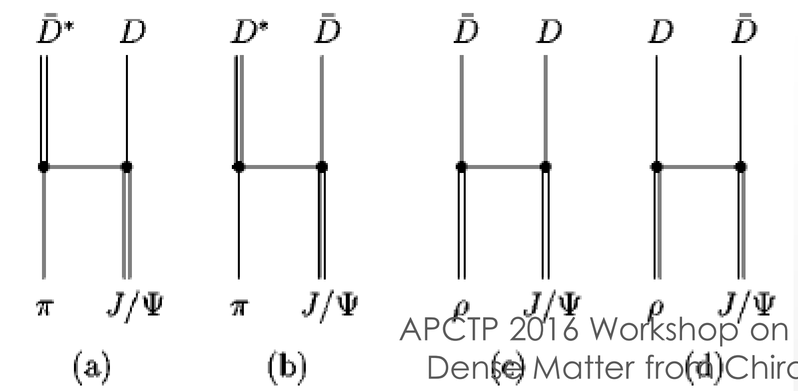
S. G. Matinyan and B. Muller, Phys. Rev. C **58**, 2994 (1998)

K. L. Haglin, Phys. Rev. C **61**, 031902(R) (2000)

Z. Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000)

Y. Oh, T. Song, and S-H. Lee, Phys. Rev. C **63**, 034901 (2000)

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



3) Interaction Lagrangians from the pseudoscalar and vector mesons free Lagrangians

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

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

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

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

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

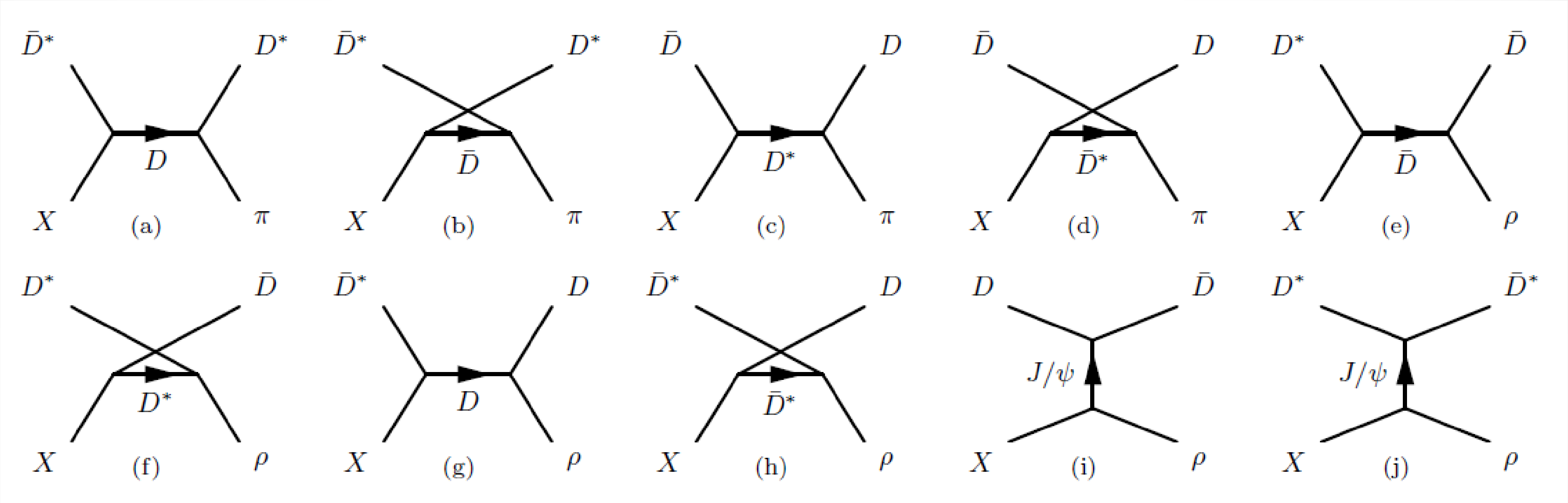
$$\mathcal{L}_{\psi D^* D^*} = ig_{\psi D^* D^*}[\psi^\mu(\partial_\mu D^{*\nu} \overline{D}^*_\nu - D^{*\nu} \partial_\mu \overline{D}^*_\nu) + (\partial_\mu \psi^\nu D^*_\nu - \psi^\nu \partial_\mu D^*_\nu)\overline{D}^{*\mu} + D^{*\mu}(\psi^\nu \partial_\mu \overline{D}^*_\nu - \partial_\mu \psi^\nu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

$$\mathcal{L}_{\rho DD} = ig_{\rho DD}(D \vec{\tau} \partial_\mu \overline{D} - \partial_\mu D \vec{\tau} \overline{D}) \cdot \vec{\rho}^\mu,$$

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

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

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



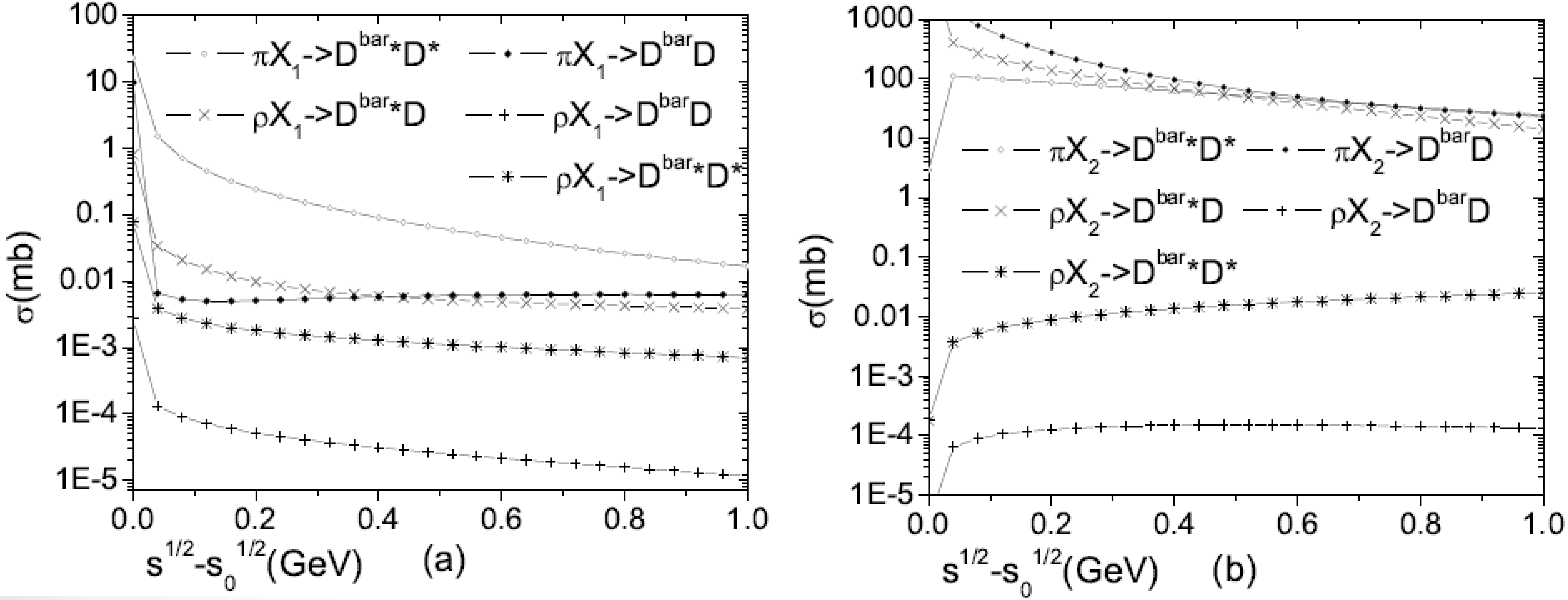
5) Interaction Lagrangians for two kinds of X(3872) mesons

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

$$\begin{aligned}
\mathcal{L}_{X_1D^*D} &= g_{X_1D^*D}X_1^{\mu}\bar{D}_{\mu}^{*}D, \\
\mathcal{L}_{X_1\psi\rho} &= ig_{X_1\psi\rho}\epsilon^{\mu\nu\rho\sigma}\psi_{\nu}\rho_{\rho}\partial_{\sigma}X_{1\mu}, \\
\mathcal{L}_{X_2D^*D} &= -ig_{X_2D^*D}X_2^{\mu\nu}\bar{D}_{\mu}^{*}\partial_{\nu}D, \\
\mathcal{L}_{X_2\psi\rho} &= -g_{X_2\psi\rho}\epsilon^{\mu\nu\rho\sigma}X_{\mu\alpha}(\partial_{\nu}\psi^{\alpha}\partial_{\rho}\rho_{\sigma} - \partial_{\nu}\psi^{\alpha}\partial_{\rho}\rho_{\sigma}) \\
&\quad + g'_{X_2\psi\rho}\epsilon^{\mu\nu\rho\sigma}\partial_{\nu}X_{\mu\alpha}(\partial^{\alpha}\psi_{\rho}\rho_{\sigma} - \psi_{\rho}\partial^{\alpha}\rho_{\sigma}).
\end{aligned}$$

6) Cross sections for different X(3872) meson quantum number

S. Cho and S. H. Lee, Phys. Rev. C **88**, 054901 (2013)



Thermally averaged cross sections

P. Koch, B. Muller, and J. Rafelski, Phys. Rept., **142**, 167 (1986)

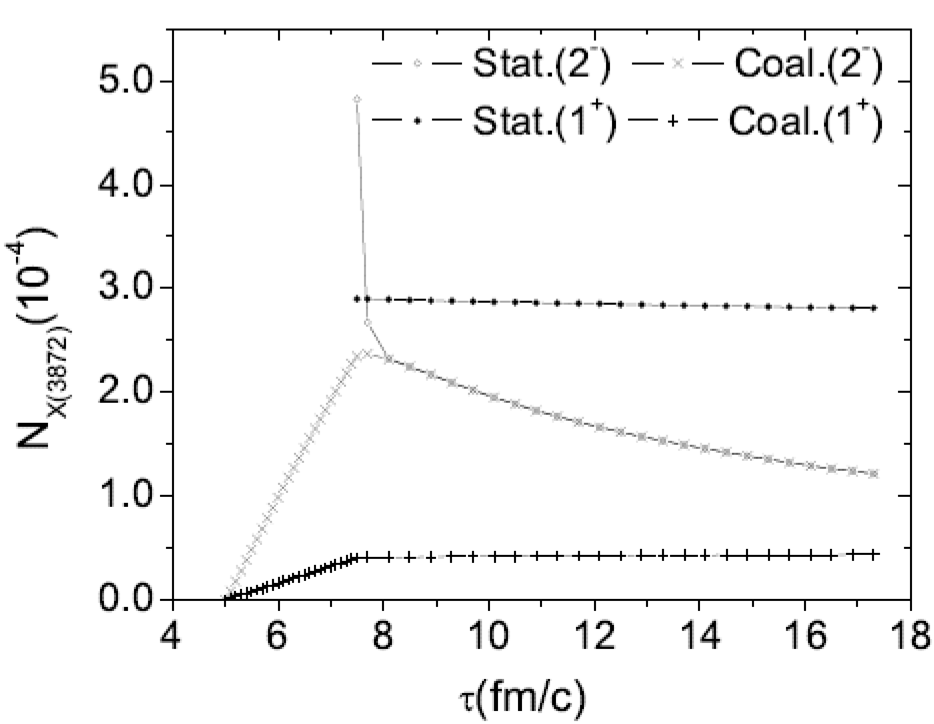
$$\left\langle \sigma_{ih\to jk} v_{ih} \right\rangle = \frac{\int d^3 p_i d^3 p_h f_i(p_i) f_j(p_j) \sigma_{ih\to jk} v_{ih}}{\int d^3 p_i d^3 p_h f_i(p_i) f_j(p_j)}$$

– 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

4) The spin of the X(3872) meson

PRL **110**, 222001 (2013) PHYSICAL REVIEW LETTERS week ending 31 MAY 2013

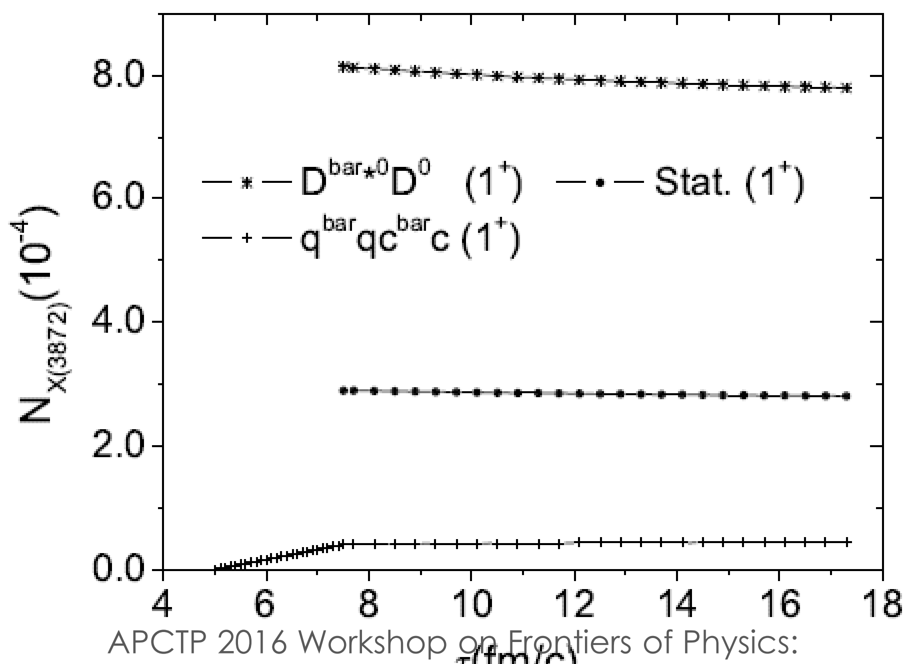
Determination of the *X*(3872) Meson Quantum Numbers

R. Aaij *et al.**
(LHCb Collaboration)
(Received 25 February 2013; published 29 May 2013)

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

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%

5) Time evolutions of the spin-1 X(3872) meson abundance



S. Cho and S-H. Lee,
Phys. Rev. C **88**, 054901 (2013)

Conclusion

– Exotic states in heavy ion collisions

1) Heavy ion collision experiments provide chances to observe exotic hadrons, e.g., hadronic molecules or multi-quark states
2) The yields of exotic hadrons are large enough to be measurable in experiments. In addition, since the yield of a hadron is strongly dependent on its structure, the internal structure as well as constituents of an exotic hadrons can be identified from its yields measured in heavy ion collisions
3) Studying both the initial production yields of hadrons and their evolution in time during the hadronic stage is essencial to have a better understanding of the hadronization in heavy ion collisions
4) The spin and structure of the exotic hadron can be identified by investigating the interaction of the hadron with light hadrons in the hadronic medium