Exotics from heavy ion collisions

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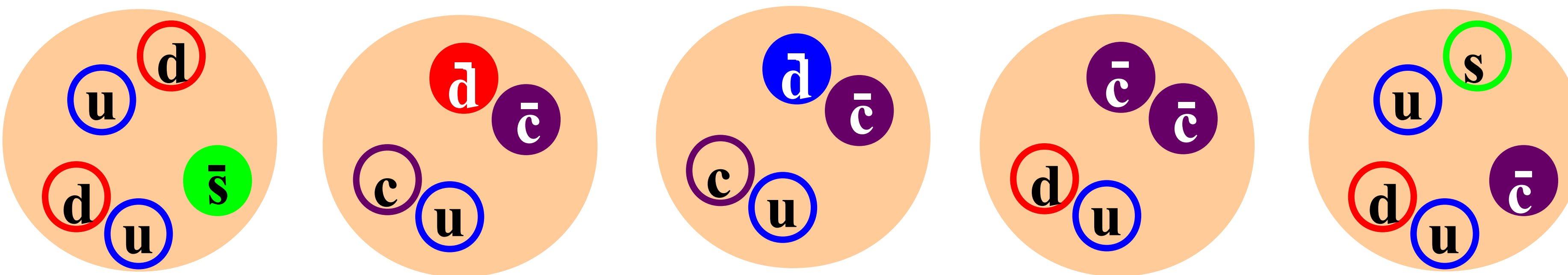
- **Introduction**
- **Statistical and Coalescence models**
- **Yields of Exotics at RHIC and LHC**
- **Summary**

S.Cho et al.(ExHIC Collab.), arXiv:1011.0852
Related talks in Baryons '10
T. Hyodo (Tue), D. Jido (Wed), S. Yasui (Wed), T. Sekihara (Fri)

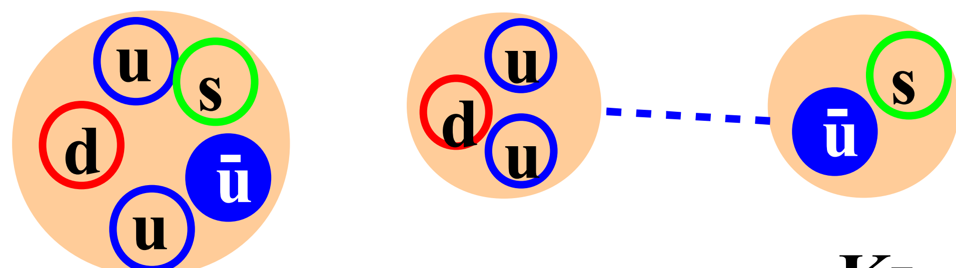
Exotic Hadrons

- Exotic hadrons
  → Θ^+, Z, X, Y, ... Discovered/Proposed at LEPS, Belle, BaBar,...



Θ^+ Z(4430) X(3872) T_{cc} Θ^+_{cs}

- Various pictures
  - Di-quark component
  - Hadronic molecule
  - QQ^{bar} couples with $QQ^{bar}qq^{bar}$



uuds$\bar{u}$ p K^-

How can we discriminate ?
→ Key quantity = Size

Λ (1405)

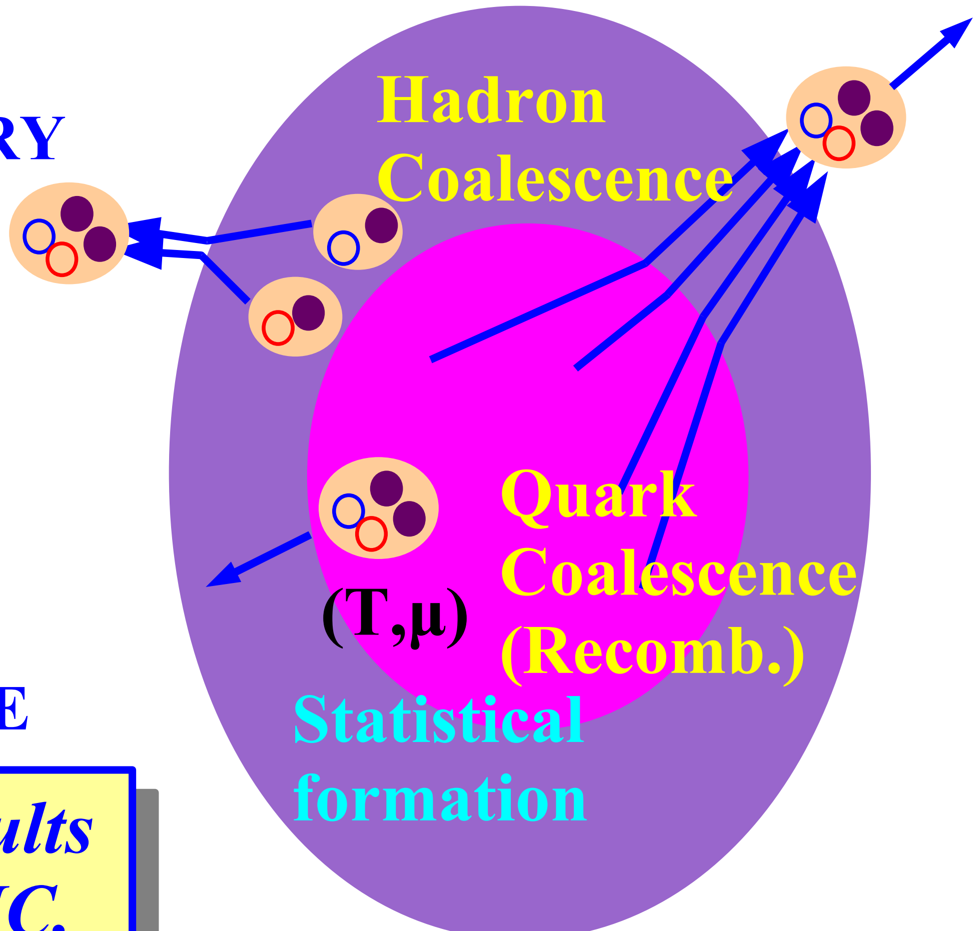
Exotics from Heavy Ion Collisions

- **High-Energy Heavy-Ion Collisions**
  - **High *T* & Large volume → Abundant hadrons**
  - **Chaotic source → Simple / well-known formation mechanism**
  - **RHIC & LHC → Nearly 4π detector / Vertex detector**

→ Let's use RHC & LHC as EXOTIC HADRON FACTORY

- **Formation mechanism of Hadrons**
  - **Statistical formation**
  - **Coalescence (Recomb.)**
  - **Parton Fragmentation**

→ In Coal. and Frag., YIELDS are sensitive to the SIZE



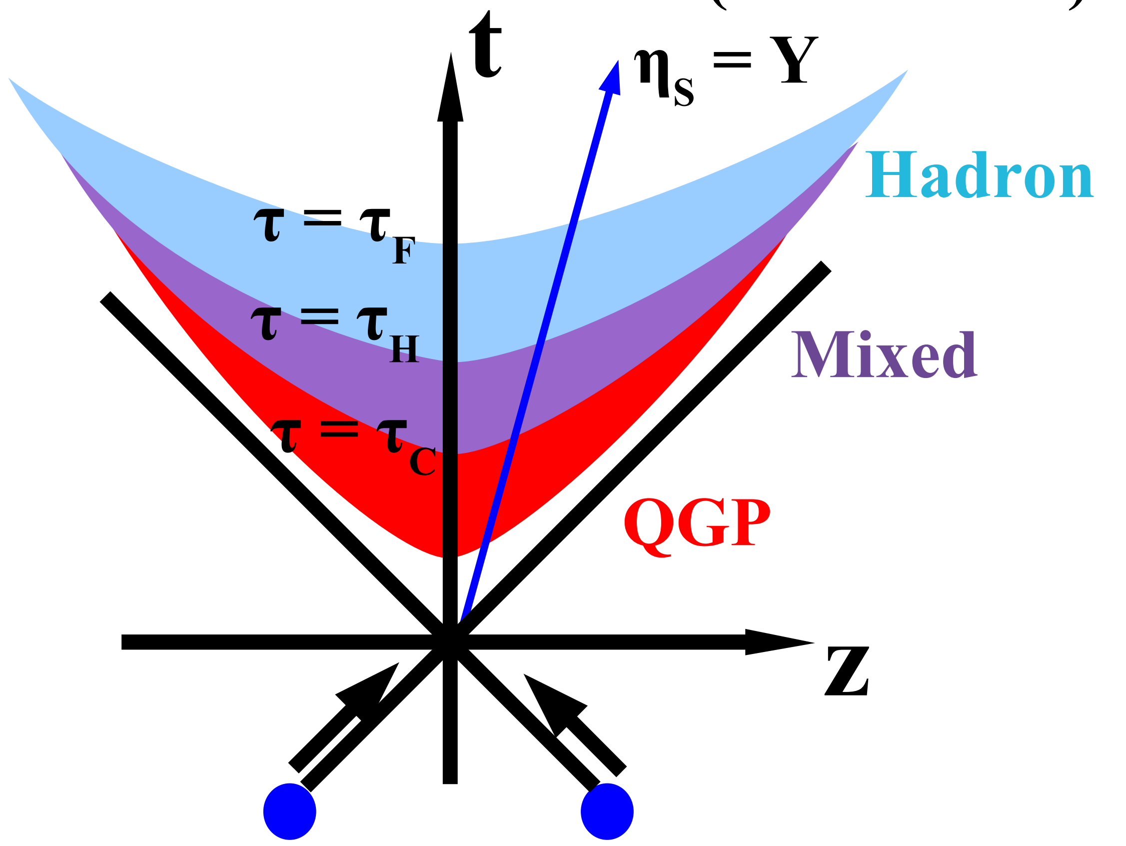
We compare Stat. & Coal. results of Exotic Hadron Yeilds in HIC.

Statistical and Coalescence models

Schematic picture of HIC

- **HIC picture based on the first order phase transition**
  - $\tau = \tau_C$, $T=T_C$, $V=V_C$ → QGP start to hadronize (quark coal.)
  - $\tau = \tau_H$, $T=T_H=T_C$, $V=V_H$ → Hadronization is over (stat. model)
  - $\tau = \tau_F$, $T=T_F$, $V=V_F$ → Hadronic Freeze-out (hadron coal.)

	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	20 MeV
μ_s	10 MeV	10 MeV
V_F	11322 fm^3	30569 fm^3
T_F	125 MeV	125 MeV



L.W.Chen, V.Greco, C.M.Ko, S.H.Lee, W.Liu, PLB 601('04)34.

Statistical Model

- **Statistical model**

$$N_h^{\rm stat} = V_H \frac{g_h}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\gamma_h^{-1} e^{E_h/T_H} \pm 1}$$

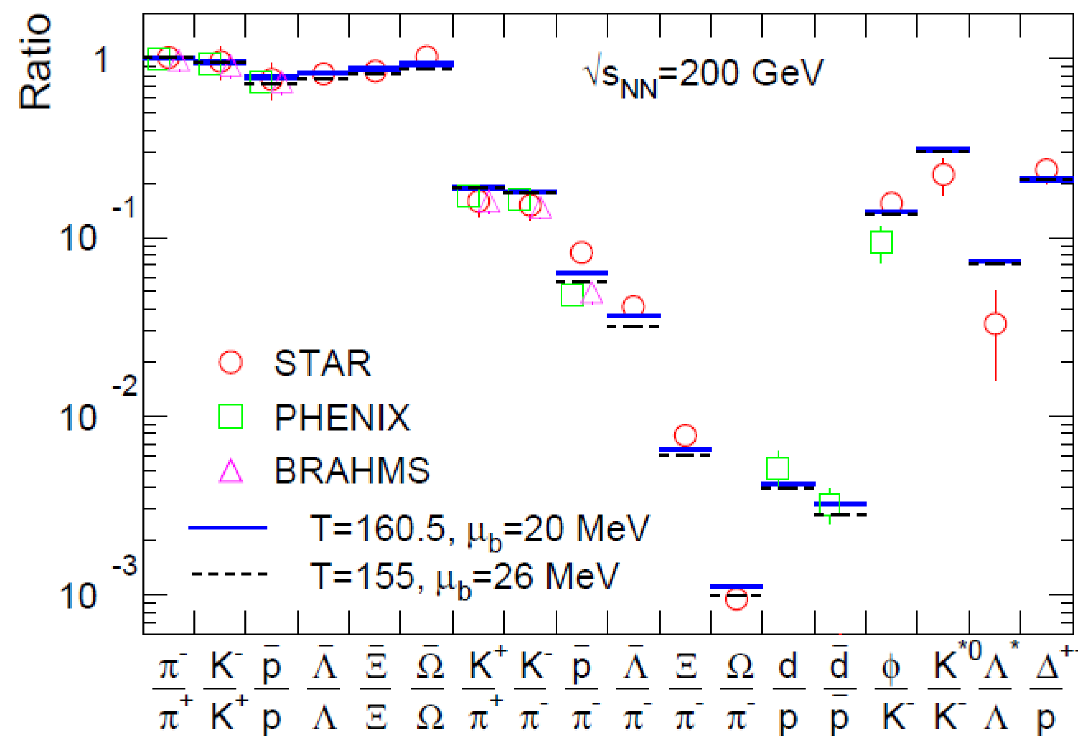
(N_h = dN_h/dy (y=rapidity), V_H=Chem. freeze-out vol.)

→ Successful to predict the hadron yield ratio at RHIC

- **Fugacity γ**
  - **u,d,s: chem. equil.**
  - **c,b: enhanced by initial hard processes**

Fugacities of c and b quarks are set to reproduce expected c and b quark numbers.

$$\gamma_h = \gamma_c^{n_c + n_{\bar c}} \gamma_b^{n_b + n_{\bar b}} e^{(\mu_B B + \mu_s S)/T_H}$$



A. Andronic, P. Braun-Munzinger, J. Stachel, NPA772('06)167.

Coalescence model (1)

- **Yield = Overlap of const. dist. & Hadron intrinsic Wigner func. (Sudden approximation)**
  Sato, Yazaki (1984), Hwa, Yang (2003), Greco, Ko, Levai (2003), Fries, Muller, Nonaka, Bass (2003), Chen, Ko, Lee (2003)

$$N_h^{\rm coal} = g_h \int \underbrace{\left[\prod_{i=1}^{n} \frac{1}{g_i} \frac{p_i \cdot d\sigma_i}{(2\pi)^3} \frac{\mathrm{d}^3\mathrm{p}_i}{E_i} f(x_i, p_i)\right]}_{\text{Dist. of constituents}} \times \underbrace{f^W(x_1, \cdots, x_n : p_1, \cdots, p_n)}_{\text{Intrinsic Wigner func.}}$$

Dist. of constituents **Intrinsic Wigner func.**

- **Yield in HIC**
  - **Quark & hadron dist. = Transverse Boltzmann + Bjorken**
    Chen, Ko, Liu, Nielsen (2007)
  - **Hadron intr. Wigner func. = s-wave and p-wave HO w.f.**
    Kanada-En'yo, Muller (2006)

$$N_h^{\rm coal} \simeq g_h \prod_{j=1}^{n} \frac{N_j}{g_j} \prod_{i=1}^{n-1} \frac{(4\pi\sigma_i^2)^{3/2}}{V(1+2\mu_i T\sigma_i^2)} \left[\frac{4\mu_i T\sigma_i^2}{3(1+2\mu_i T\sigma_i^2)}\right]^{l_i}$$

σ = Gaussian width, μ=reduced mass, N = constituent yield

Coalescence model (2)

- **Model parameter in Coal. = HO frequency (wave function width)**

$$N^{coal} \propto [\omega^{1/2}(\omega+2T)]^{-(n-1)} \qquad (\text{s-wave})$$

  - **small ω → extended w.f. → pickup const. from large vol.**

    (We assume that other quarks do not break the formed hadron.)

- **Quark coalescence**

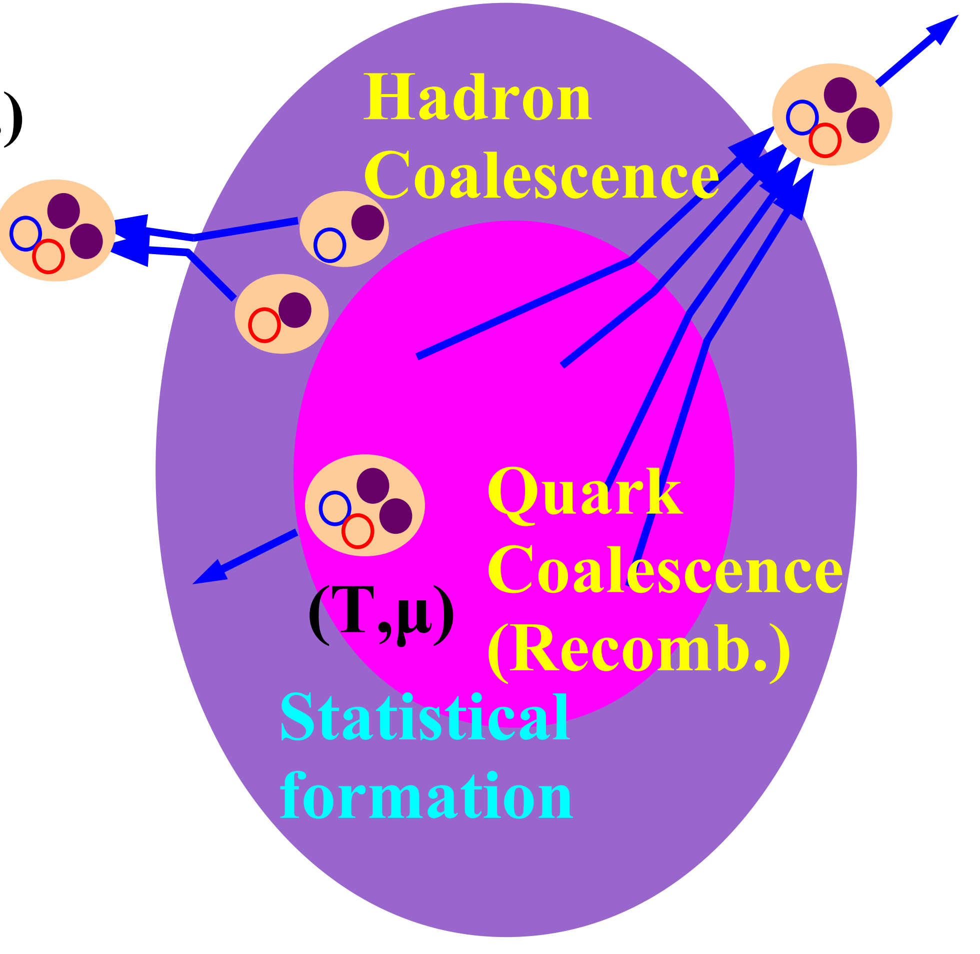
  $\omega = \omega_s, \omega_c, \omega_b$

  chosen to reproduce stat. Λ_q yield for hadrons with s, c, b quarks.

- **Hadron Coalescence**

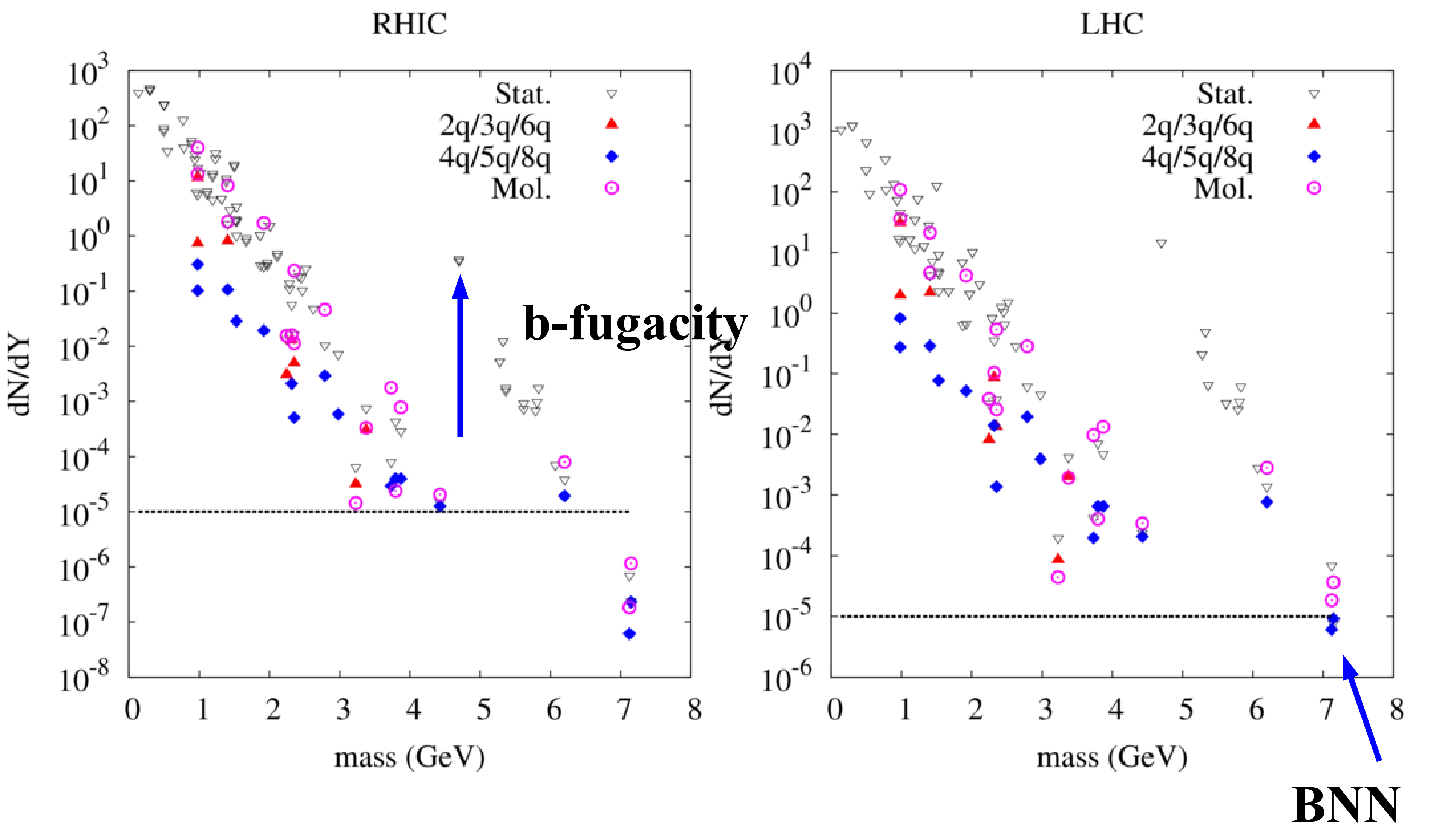
  Low E scatt. formula is applied.

$$\omega = \frac{3\hbar^2}{2\mu_R\langle r^2\rangle} \quad \text{or} \quad \omega = 6\times\text{B.E.}$$



Exotics from HIC: Results

Hadron Yields at RHIC & LHC

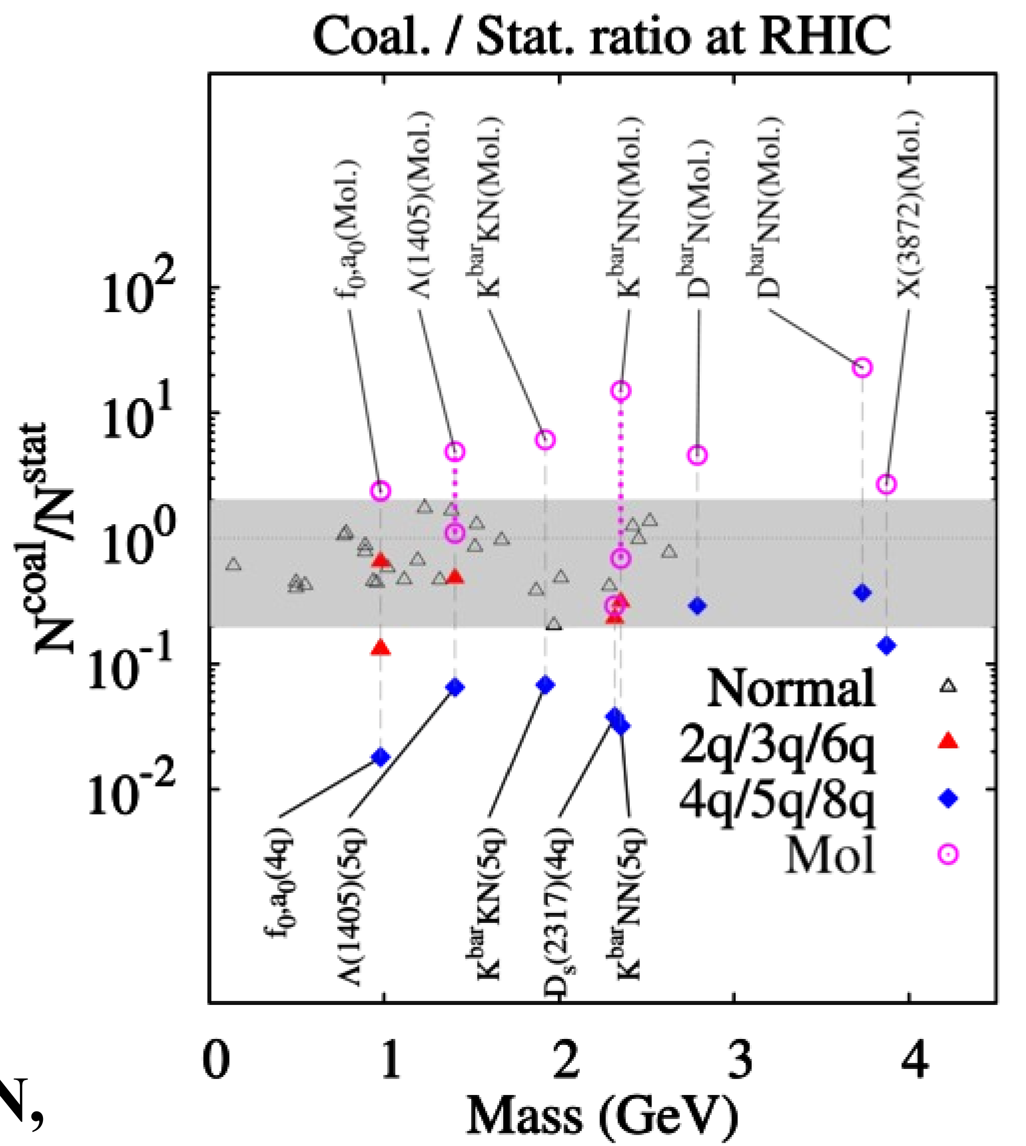


- **Most of the exotic hadrons are abundantly produced ($N>10^{-5}$)**

S.Cho et al.(ExHIC Collab.), in prep.

Coalescence / Statistical Ratio

- **Coal./Stat. ratio: $R_h = N^{coal}/N^{stat}$**
  - **Normal hadrons (& Normal component) → $0.2 < R_h < 2$ (Normal band)**
  - **Multi-quark states → Smaller yields in coal. $R_h < 0.3$ (f_0/a_0, Λ(1405), $K^{bar}KN$, D_{sJ}, $K^{bar}NN$)**
  - **Hadronic molecules → Larger yields ($R^h > 2$) for weakly bound or extended sized exotics (f_0/a_0, Λ(1405), $K^{bar}KN$, $K^{bar}NN$, $D^{bar}N$, $D^{bar}NN$, …)**



S.Cho et al.(ExHIC Collab.), arXiv:1011.0852

Why are extended configs. enhanced ?

- **Finite Temperature & Large Volume**

$$N_h \propto \prod_i \int d^3 y_i d^3 k_i \exp\left(-\frac{\boldsymbol{y}_i^2}{\sigma_i^2} - \sigma_i^2 \boldsymbol{k}_i^2\right) \times \exp\left(-\frac{\boldsymbol{k}_i^2}{2\mu_i T}\right) \times \delta\left(\frac{y_z}{t} - \frac{k_z}{\mu_i}\right)$$

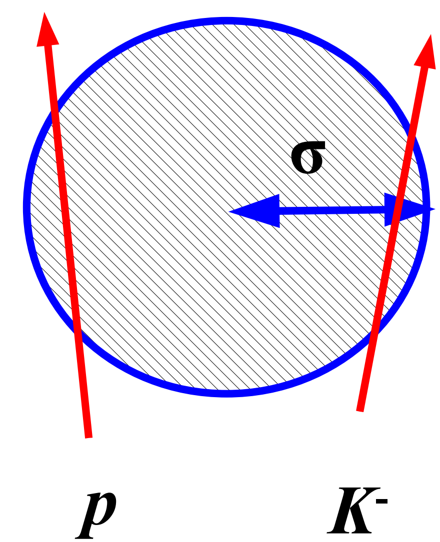
$$\propto \prod_i \frac{\sigma_i^3}{1 + 2\mu_i T \sigma_i^2}$$

Wigner fn. **Boltzmann** **Bjorken**

(σ_i= spatial width = 1/ $\sqrt{\mu_i \omega}$, y_i=Jacobi coord.,)

→ Finite *T* smoothens momentum dist., then extended hadron picks up constituents from a large *V*.

(No enhancement in e^+e^-)



Why are Multi-quark Configs. Suppressed ?

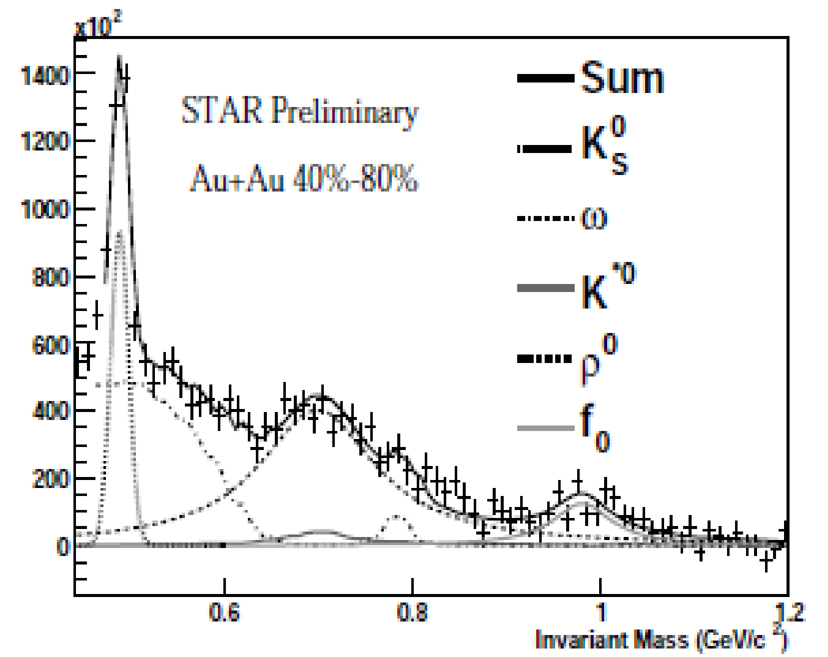
- **Hadron yield is sensitive to the structure in coal.**
  - **Additional q penalty factor**

s-wave $$\frac{1}{g_i}\frac{N_i}{V}\frac{(4\pi\sigma_i^2)^{3/2}}{(1+2\mu_i T\sigma_i^2)}$$ **~ 0.36**

p-wave $$\frac{1}{g_i}\frac{N_i}{V}\frac{2}{3}\frac{(4\pi\sigma_i^2)^{3/2}2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)^2}$$ **~ 0.09**

(Nonaka et al., 2004, Kanada-En'yo and B. Muller, 2006)
Large V disfavors multi-quarks !

- **STAR data (2003): N(f_0(980)) ~ 8.4**
  [f_0(980)/ ρ^0 ~ 0.2, stat. N(ρ^0) ~ 42]
  Stat: 5.6, 2q:0.76-3.8, 4q:0.1, Mol: 13
  → Tetra-quark picture underestimate the m.easured yield of f_0 .



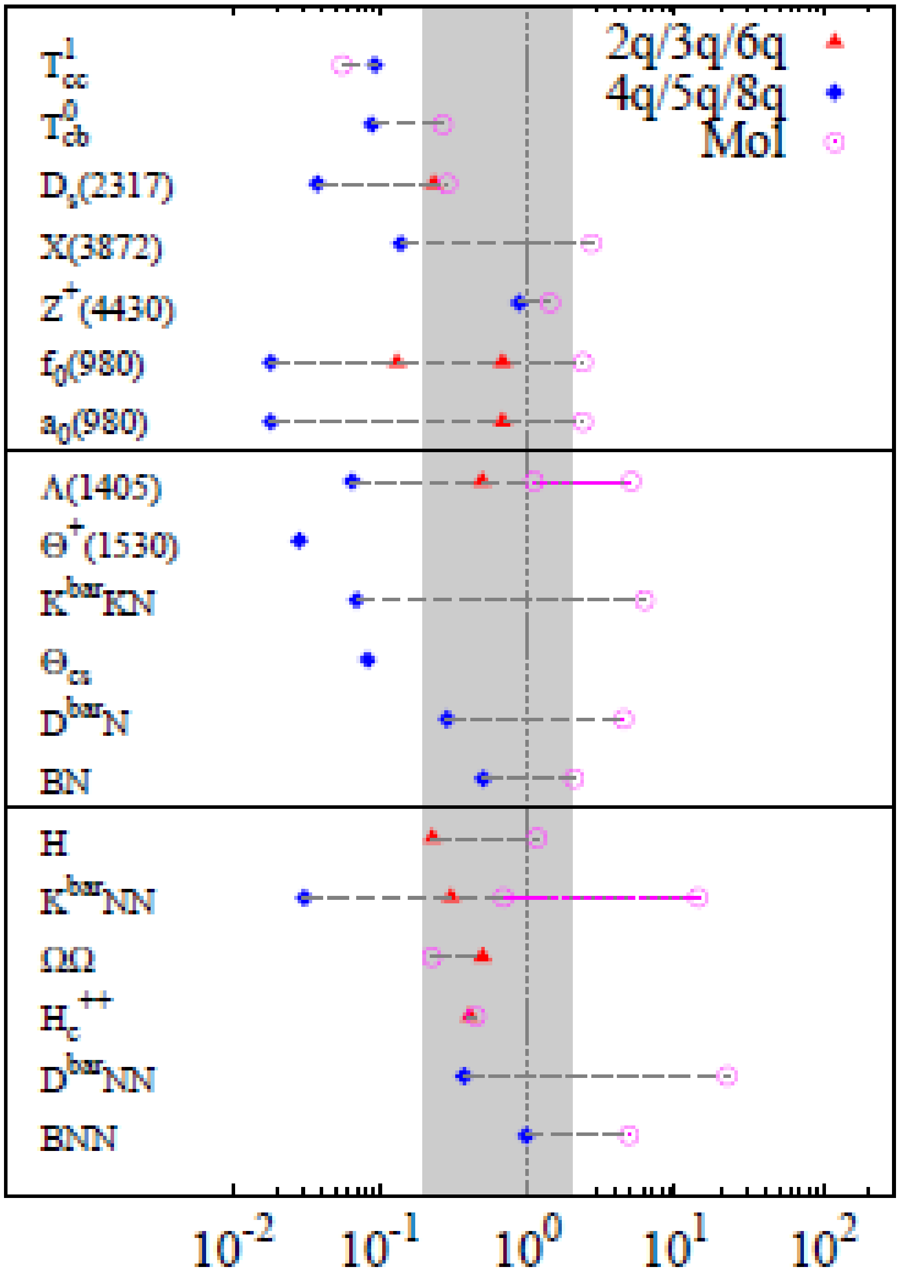
Summary

S.Cho et al.(ExHIC Collab.), arXiv:1011.0852

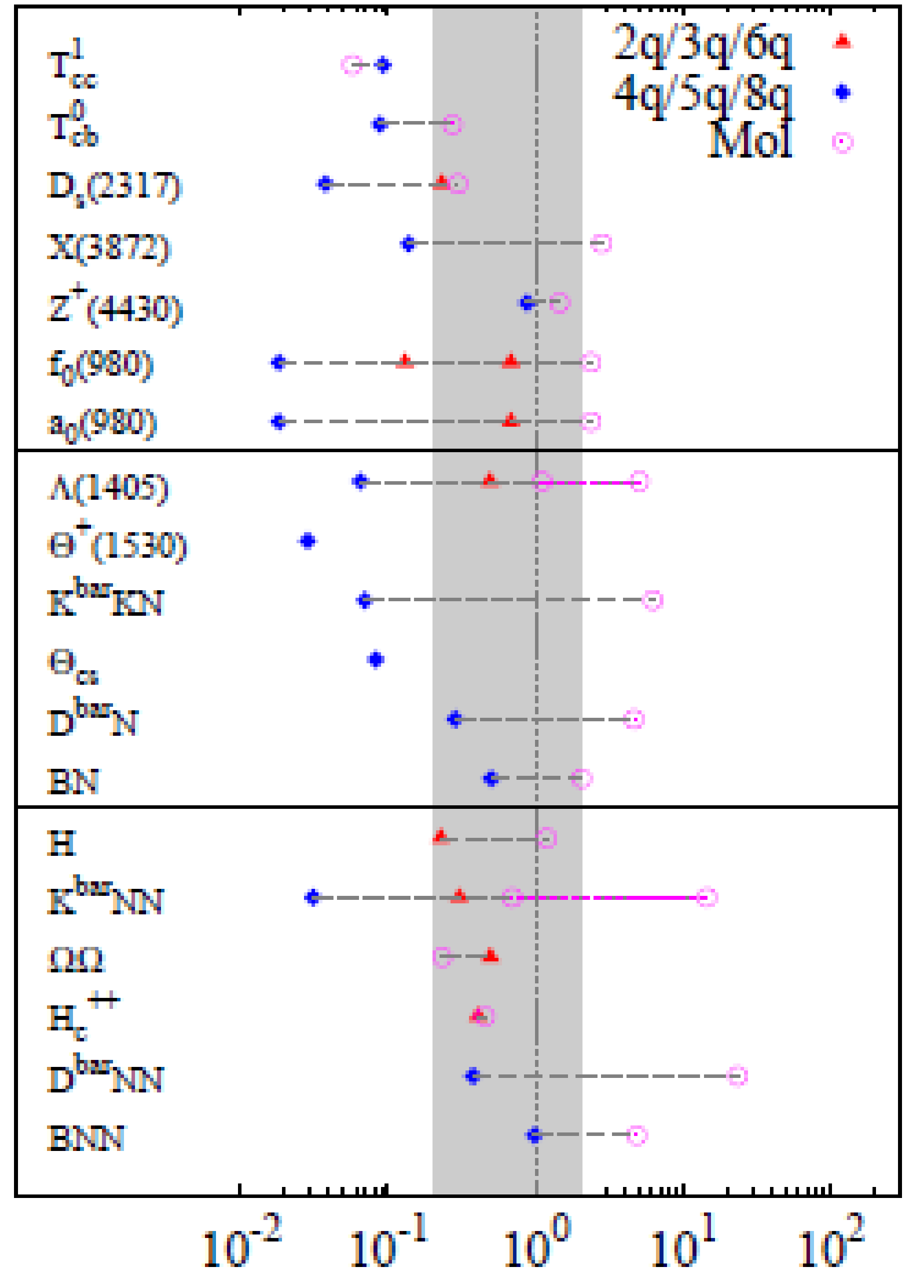
- **It is proposed to use heavy-ion collisions as exotic hadron factories.**
  - **Large size, Large number of heavy-quarks, Vertex detectors**
    → Abundant exotics having various quark combination
    with suppressed backgrounds by detecting weak decays
- **Exotic hadron yields are calculated based on statistical and coalescence models.**
  - **Parameters in coal. are tuned to reproduce stat. yield in average.**
- **HICs are found to be promising to investigate exotics**
  - **Exotic hadrons, including unobserved new species, will be formed with high enough yield at RHIC and LHC.**
  - **It may be possible to measure hadron size via their yields normalized by the stat. model results.**
- **To experimentalists: Please measure exotics in HIC !**

Thank you !

Coalescence / Statistical model ratio at RHIC



Coalescence / Statistical model ratio at LHC



S., Cho et al.(ExHIC Collab.), in prep.