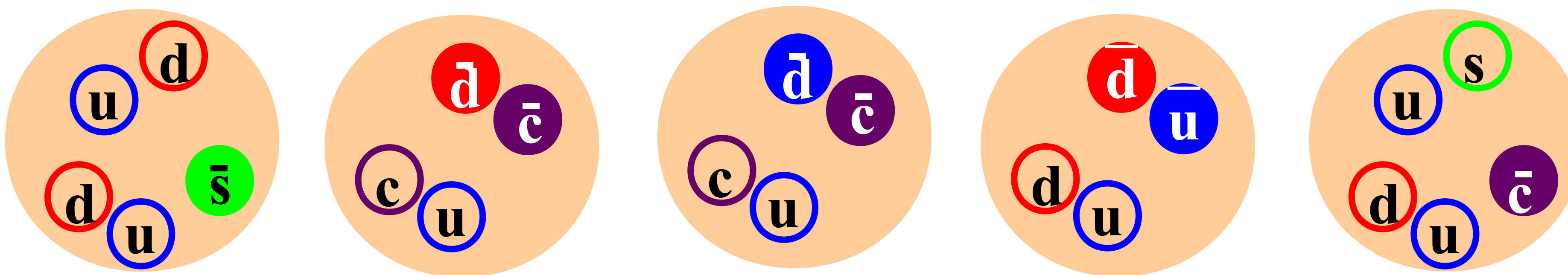
Exotics from heavy ion collisions

Akira Ohnishi (Nuclear Theory Group)

S. Cho,[1] T. Furumoto,[2, 3] T. Hyodo,[4] D. Jido,[2] C.-M. Ko,[5] S. H. Lee,[2, 1] M. Nielsen,[6] A. Ohnishi,[2] T. Sekihara,[2, 7] S. Yasui,[8] and K. Yazaki[2, 9]
(ExHIC Collaboration), arXiv:1011.0852
1 Yonsei, 2 YITP, 3 RIKEN Nishina Center, 4 TITech,
5 Texas A&M, 6 Sao Paulo, 7 Kyoto, 8 KEK, 9 RIKEN

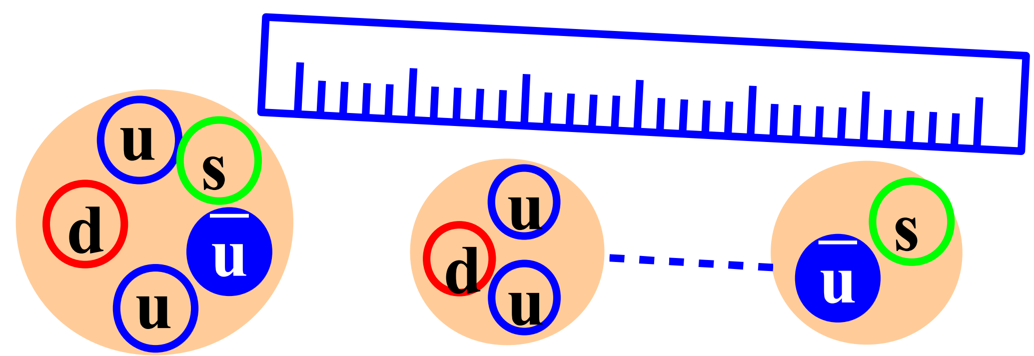
Exotic Hadrons

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



Θ^+ **Z(4430)** **X(3872)** $\mathbf{f_0}$ Θ^+_{cs}

- **Various pictures**
  - **Di-quark, Hadronic molecule, Tetraquark ($QQ^{bar}qq^{bar}$)**



uudsū **p** $\mathbf{K^-}$

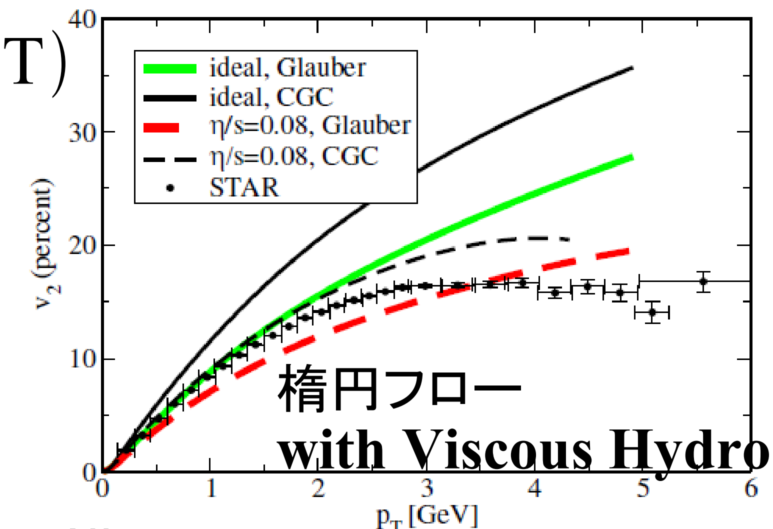
Key quantity = Size
→ Do we have any Ruler
to measure hadron size ?

Λ (1405)

What does RHIC tell us ?

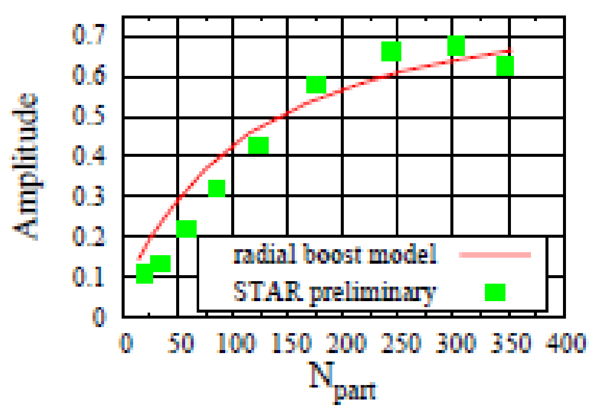
- **Large energy loss of partons → Color is deconfined.**
- **Success of ideal hydrodynamics → Perfect fluid (sQGP)**

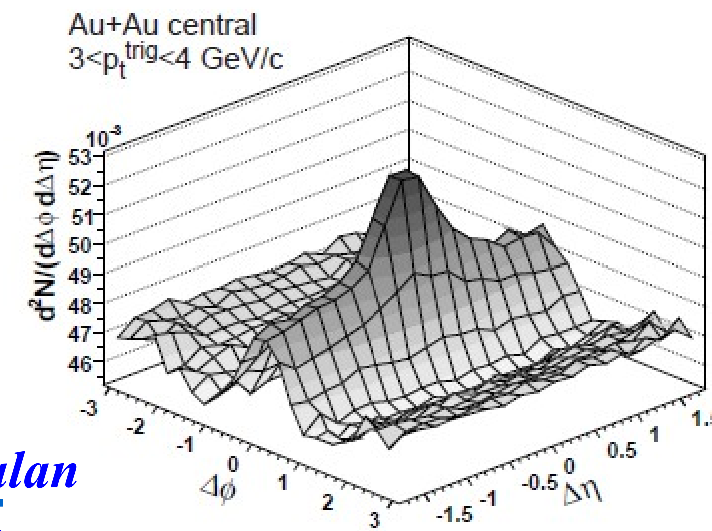
$$\frac{\eta}{s} \leq 0.1 \sim \frac{1}{4\pi} \quad \text{(KSS bound from AdS/CFT)}$$



横運動量 ***Luzum, Romatschke***

- **Ridge structure**
  → Color Glass Condensate
  (Observed also in pp collisions at LHC)
- **Mach cone → Slow sound velocity (?)**
- **Success of statistical model**
  → formation of
  thermalized
  hot matter
- **and more ?**





Dumitru, Gelis, McLerran, Venugopalan

What does RHIC tell us ?

- **Success of statistical model → formation of hot matter under equil.**

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

  - **γ_h: particle fugacity**

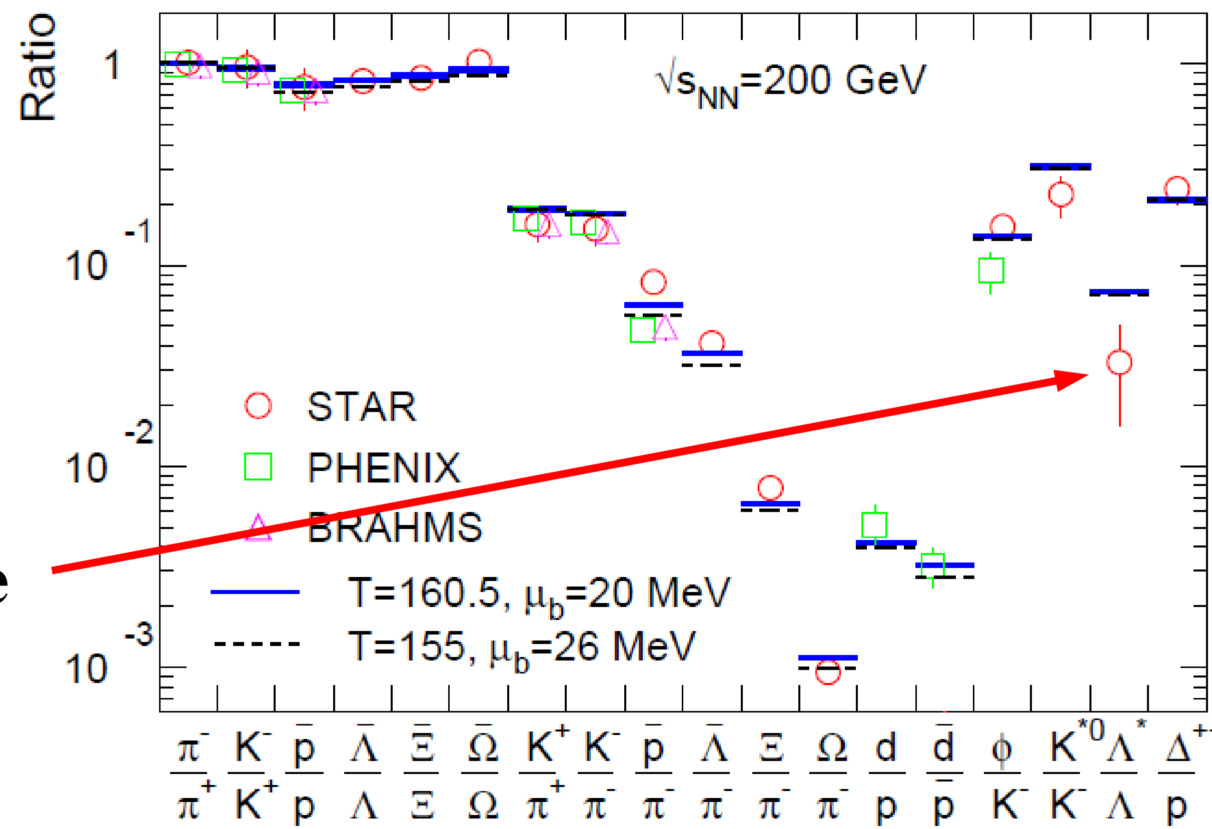
    $$\gamma_h = \exp(\mu/T_H)$$

    for hadrons made of u,d,s quarks

  - ***T, V, μ*** **→ Yield** N_h

- **Stat. model overestimate finite *L* hadrons.**
  → Coalescence picture

  Kanada-En'yo, Muller (2006)



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

Coalescence model

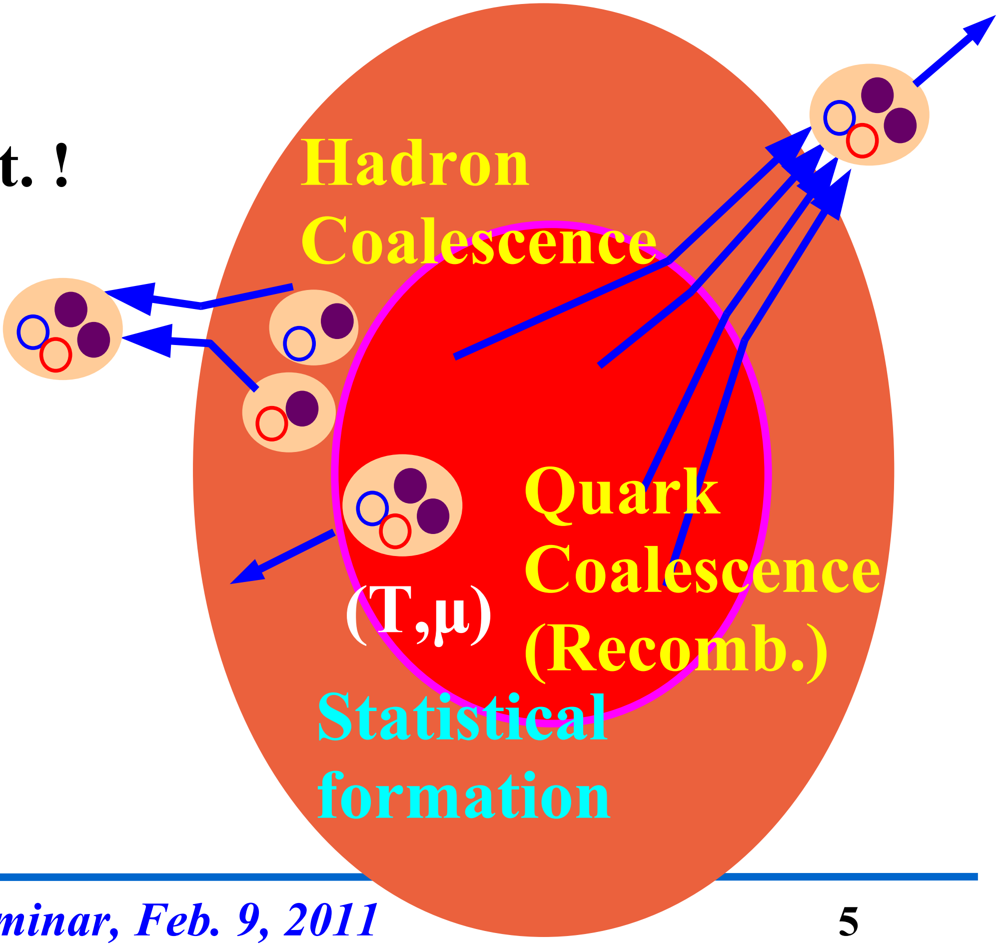
- **Yield = Overlap of Dist. & Intrinsic Wigner func. (~ wave fn.)**

$$N_h^{\mathrm{coal}} \simeq g_h \int \left[\prod_{i=1}^{n} \frac{d^3x\, d^3p}{(2\pi)^3} \underline{f(x_i, p_i)} \right] \times \underline{f^W(x_1, x_2, \ldots x_n; p_1, p_2, \ldots p_n)}$$

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

- **Successful:**
  Baryon puzzle & v2 scaling
- ***WE KNOW*** **Quark & hadron dist. !**
  (~ Transverse Boltzmann
  + Bjorken)
- ***WE ASSUME*** **Hadron w.f.**
  (s-wave and p-wave HO w.f.)

→ *WE CAN OBTAIN* the size
by comparing with data.

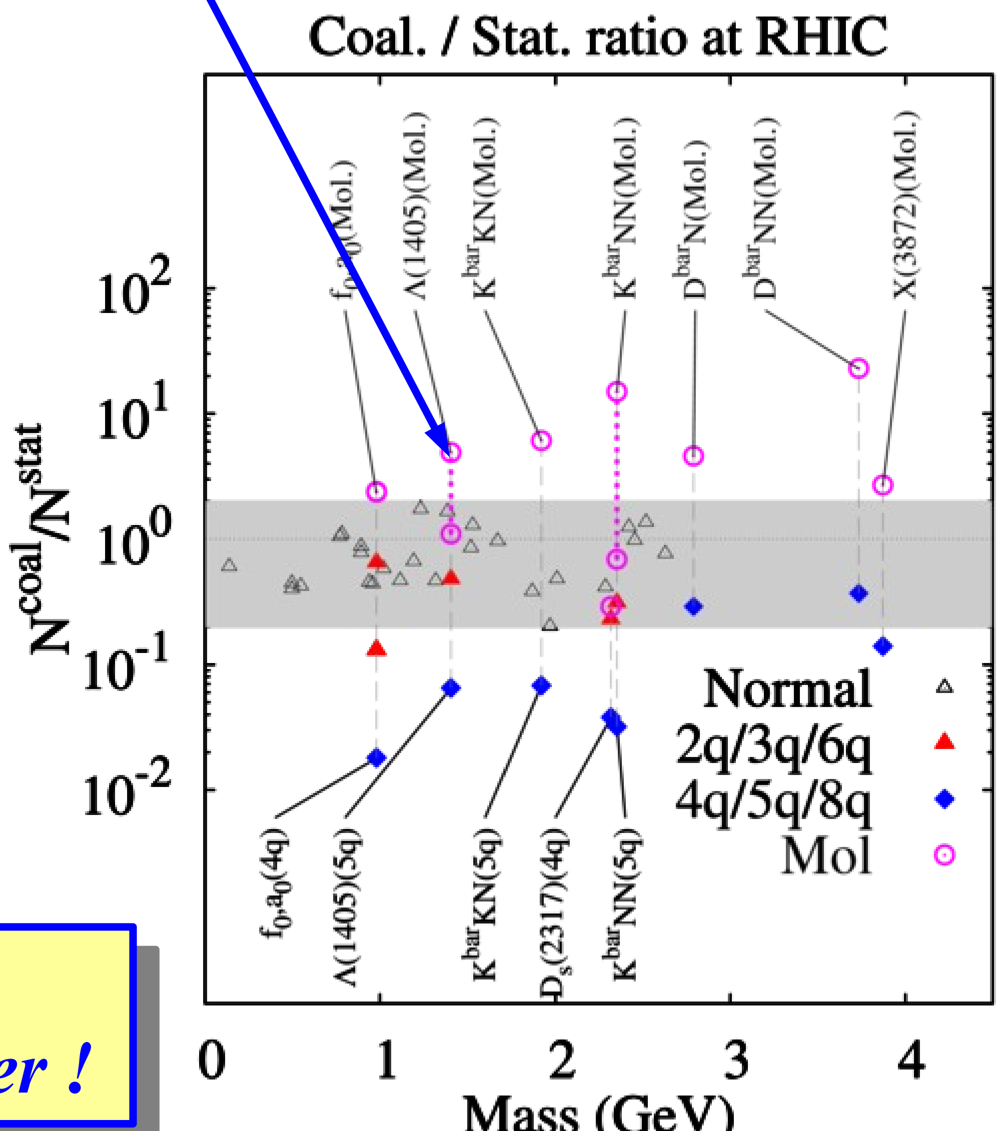


Prediction: Ratio with Statistical model results

- **Coal./Stat. ratio: $R_h = N^{coal}/N^{stat}$**
  - **Normal hadrons**
    $\rightarrow$ $0.2 < R_h < 2$ (Normal band)
  - **Multi-quark states**
    $\rightarrow$ Smaller yields in coal.
    $R_h < 0.3$
  - **Hadronic molecules**
    $\rightarrow$ Larger yields ($R^h > 2$)
    for weakly bound
    or extended sized exotics
    (f_0/a_0, $\Lambda(1405)$, …)

We can use RHIC/LHC
as a (unstable) hadron size ruler !

Sekihara, Hyodo, Jido (large size Λ(1405))



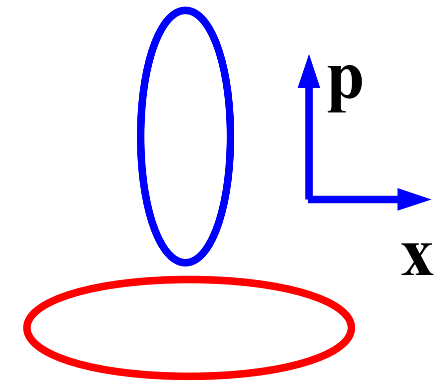
S.Cho et al.(ExHIC Collab.), arXiv:1011.0852

Why ?

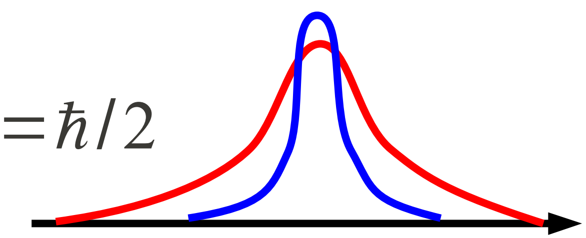
- **Size dep. of Yield**

$$N_h^{coal} \simeq g_h \int \left[\prod_{i=1}^{n} \frac{d^3x\, d^3p}{(2\pi)^3} f(x_i, p_i) \right] \times f^W(x_1, x_2, \dots x_n; p_1, p_2, \dots p_n)$$

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

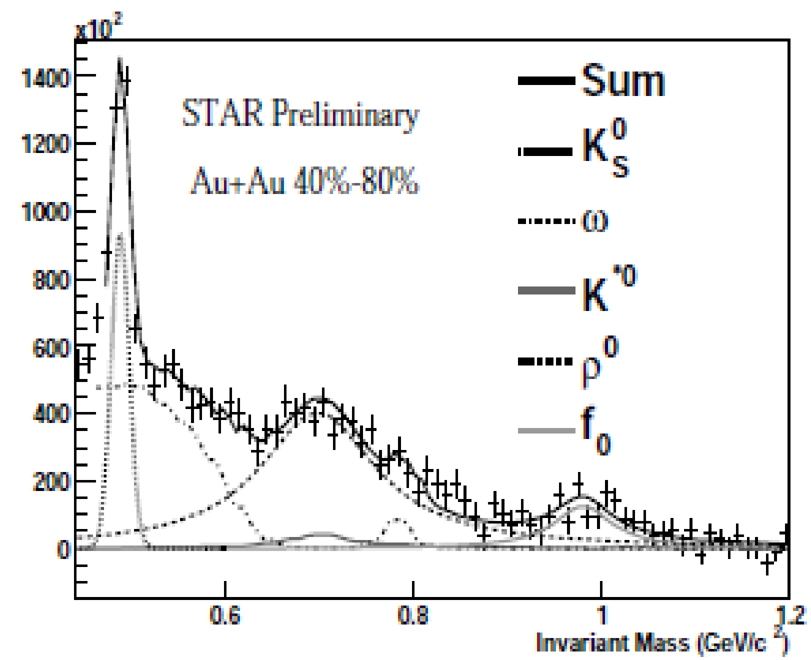


- **w/o constituent distribution**
  → Wigner fn. is normalized to unity. $\Delta p \times \Delta x = \hbar/2$



- **Boltzmann dist. suppresses Δp-dep.**
  → Integral is larger for larger Δx

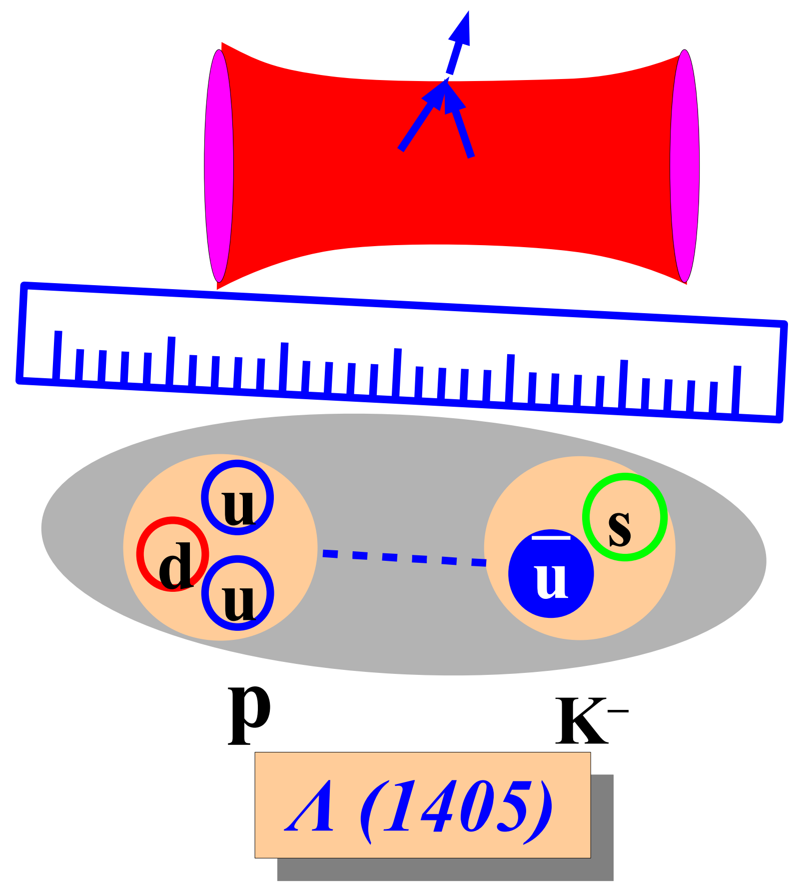
- **Experimental suggestions**
  f_0(980)) ~ 8.4 (STAR, 2003)
  Stat: 5.6, 2q:0.76-3.8, 4q:0.1, Mol: 13
  → Tetra-quark picture
  underestimate the measured yield.



Summary

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

- **Exotic component is a long-standing problem in hadron physics.**
- **Exotic hadron yields from heavy-ion collisions are studied systematically, and we predict that extended hadronic molecule yields would be enhanced compared with normal hadrons.**
- **RHIC experimentalists (H.Z.Huang, I.-K. Yoo) start identifying D and $\bar{D}$ mesons by using vertex detector.**
  c.f. X(3872)= $c\bar{c}$, $c\bar{c}q\bar{q}$ or $D\bar{D}^*$
- **It is fun to utilize RHIC & LHC to measure (unstable) hadron sizes.**



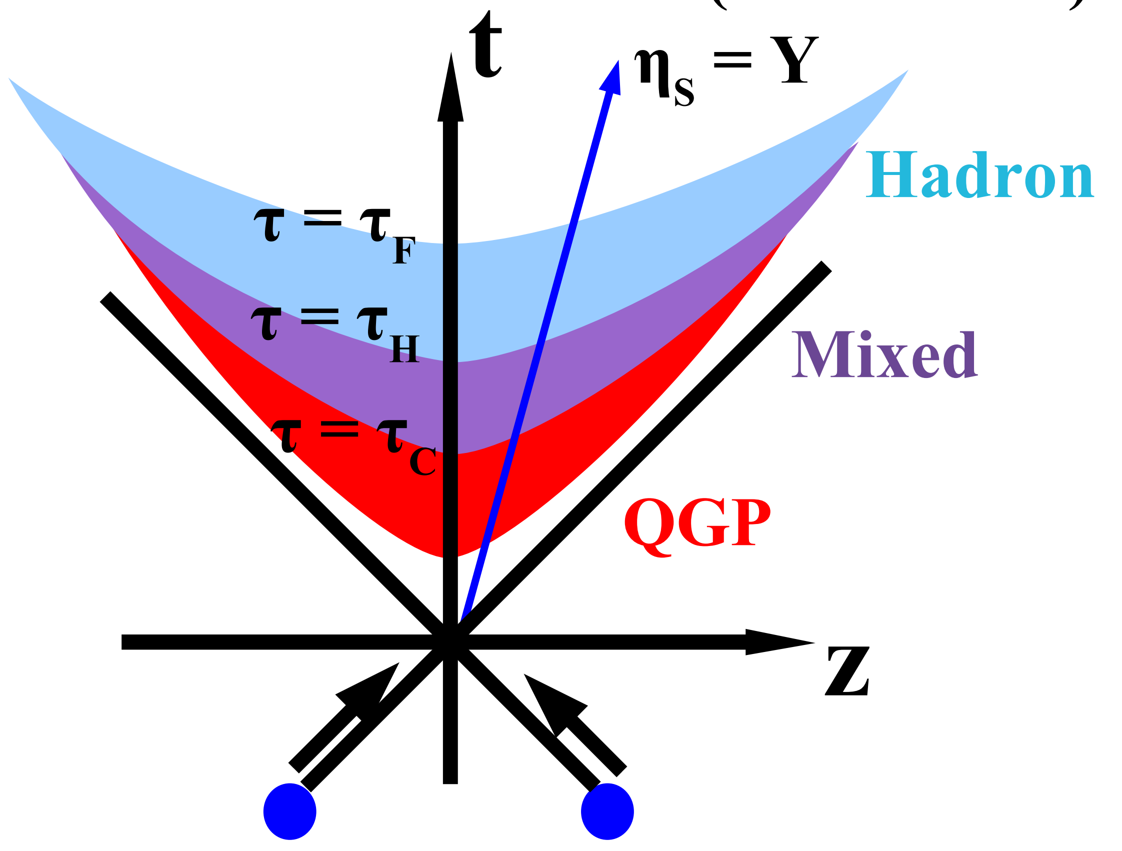
Thank you !

I'm sorry that I did not cite proper references.
Please check the references in our paper,
S. Cho,[1] T. Furumoto,[2,3] T. Hyodo,[4] D. Jido,[2] C.-M. Ko,[5]
S. H. Lee,[2,1] M. Nielsen,[6] A. Ohnishi,[2] T. Sekihara,[2,7]
S. Yasui,[8] and K. Yazaki[2,9] (ExHIC Collaboration),
arXiv:1011.0852

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.

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)

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

- **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**

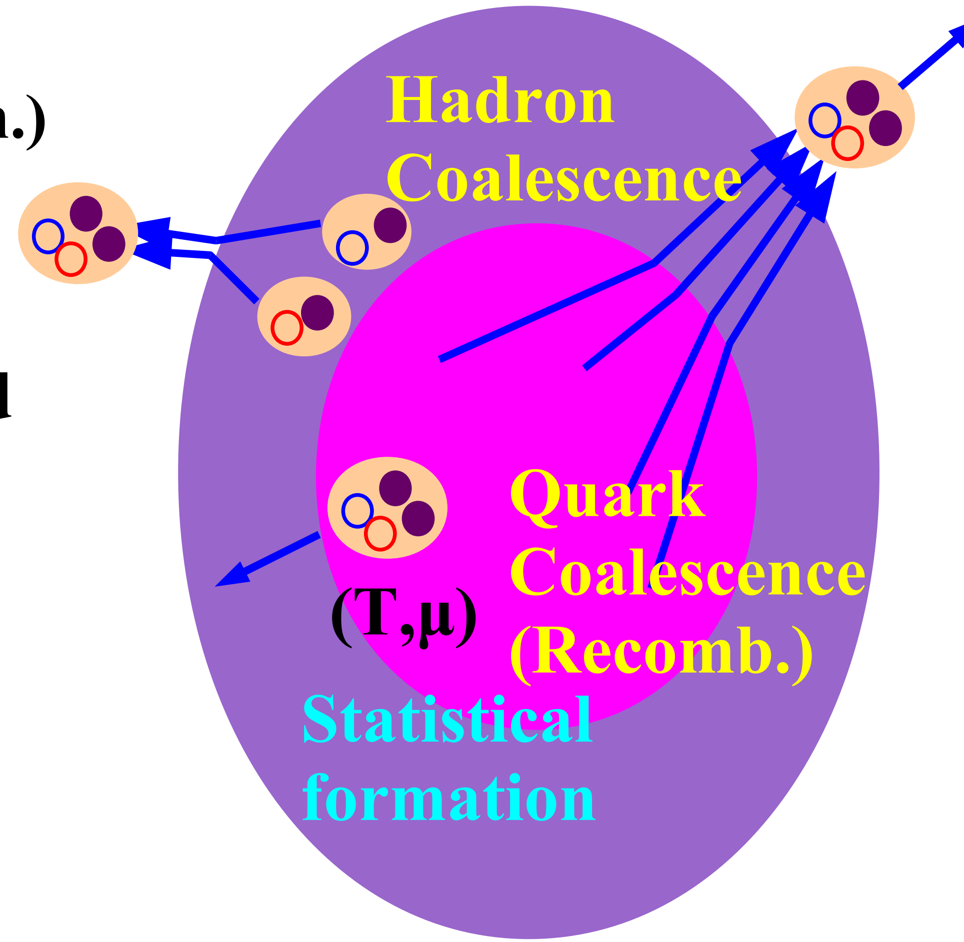
  $\omega = \omega_s, \omega_c, \omega_b$

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

- **Hadron Coalescence**

  Low E scatt. formula is applied.

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



Why are extended configs. enhanced ?

- **Finite Temperature & Large Volume**

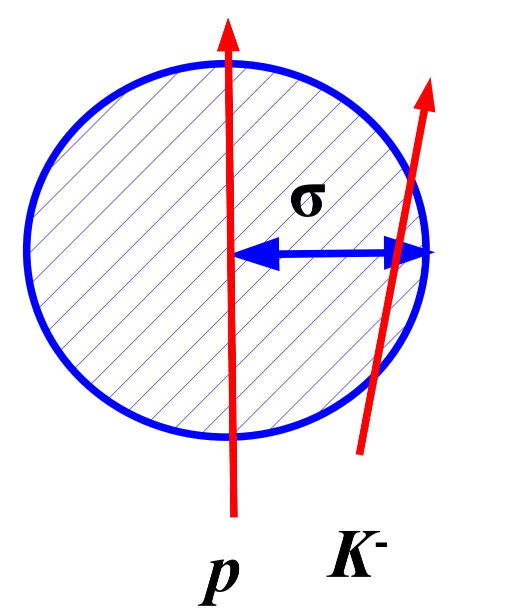
$$N_h \propto \prod_i \int d^3 y_i \, d^3 k_i \exp\left(-\frac{\boldsymbol{y}_i^2}{\sigma_i^2} - \sigma_i^2 \boldsymbol{k}_i^2\right) \times \exp\left(-\frac{\boldsymbol{k}_i^2}{2\mu_i T}\right) \times \delta\left(\frac{y_z}{t} - \frac{k_z}{\mu_i}\right)$$

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

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

(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^-)

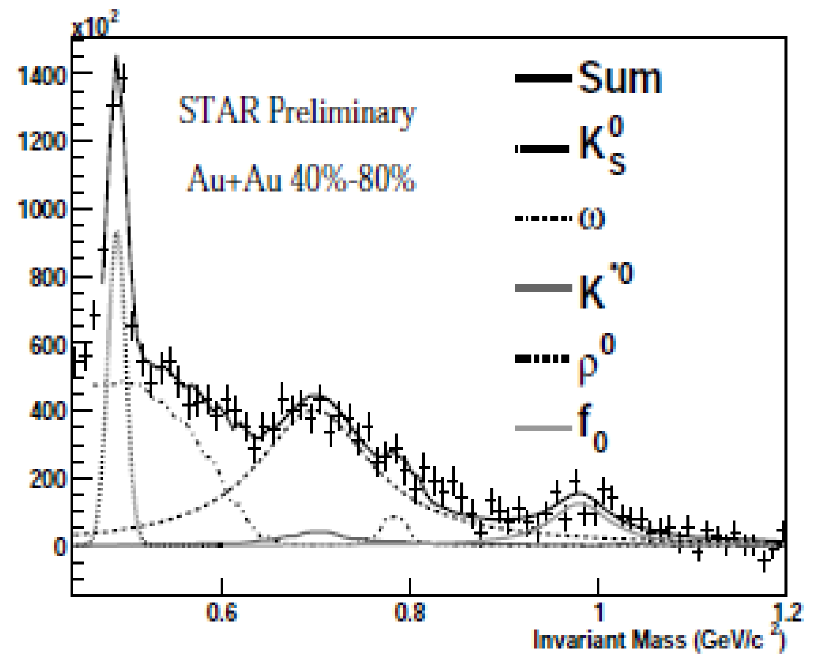
Why are Multi-quark Configs. Suppressed ?

- **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**

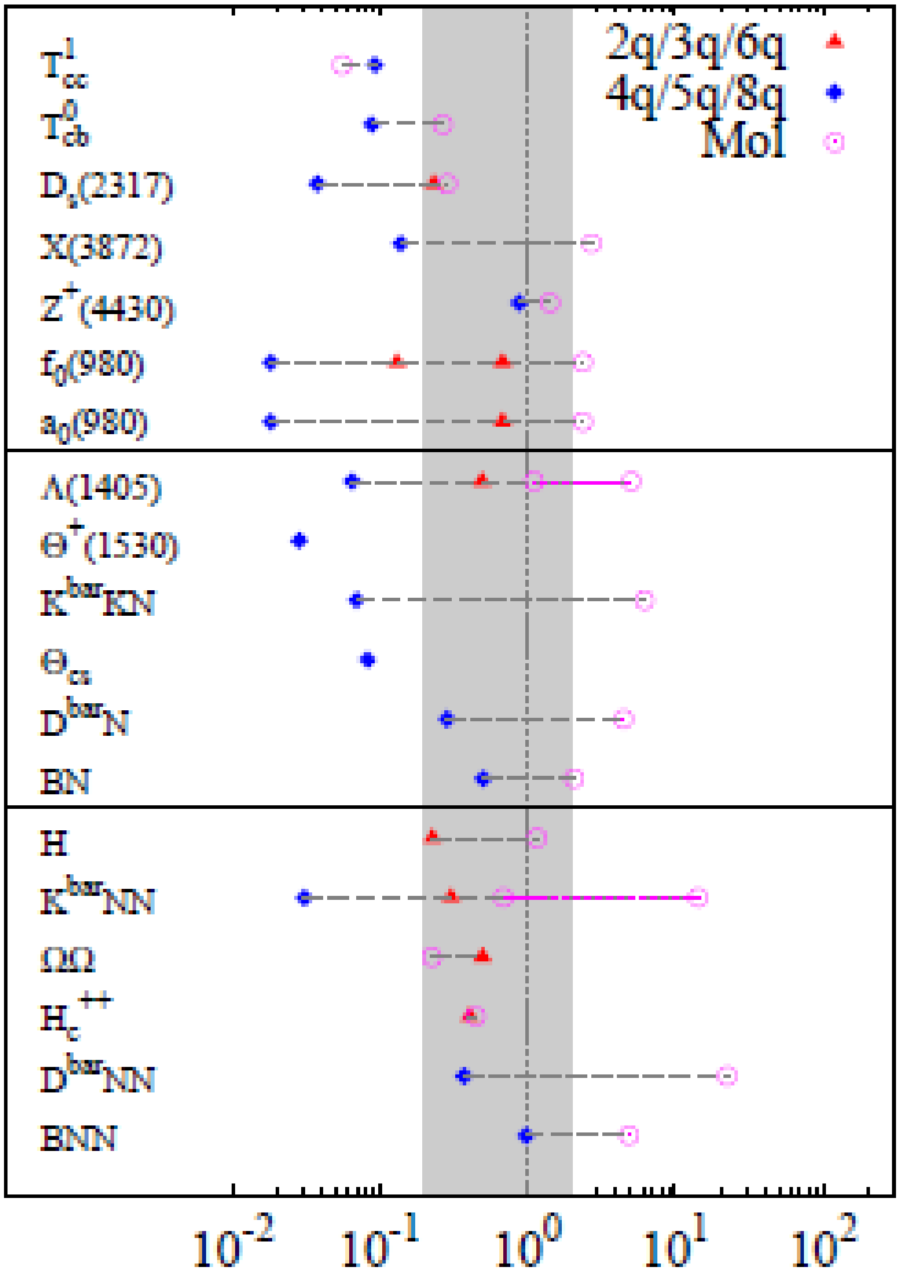
p-wave $$\frac{1}{g_i}\frac{N_i}{V}\frac{2}{3}\frac{(4\pi\sigma_i^2)^{3/2}2\mu_i T\sigma_i^2}{(1+2\mu_i T\sigma_i^2)^2}$$ **~ 0.09**

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

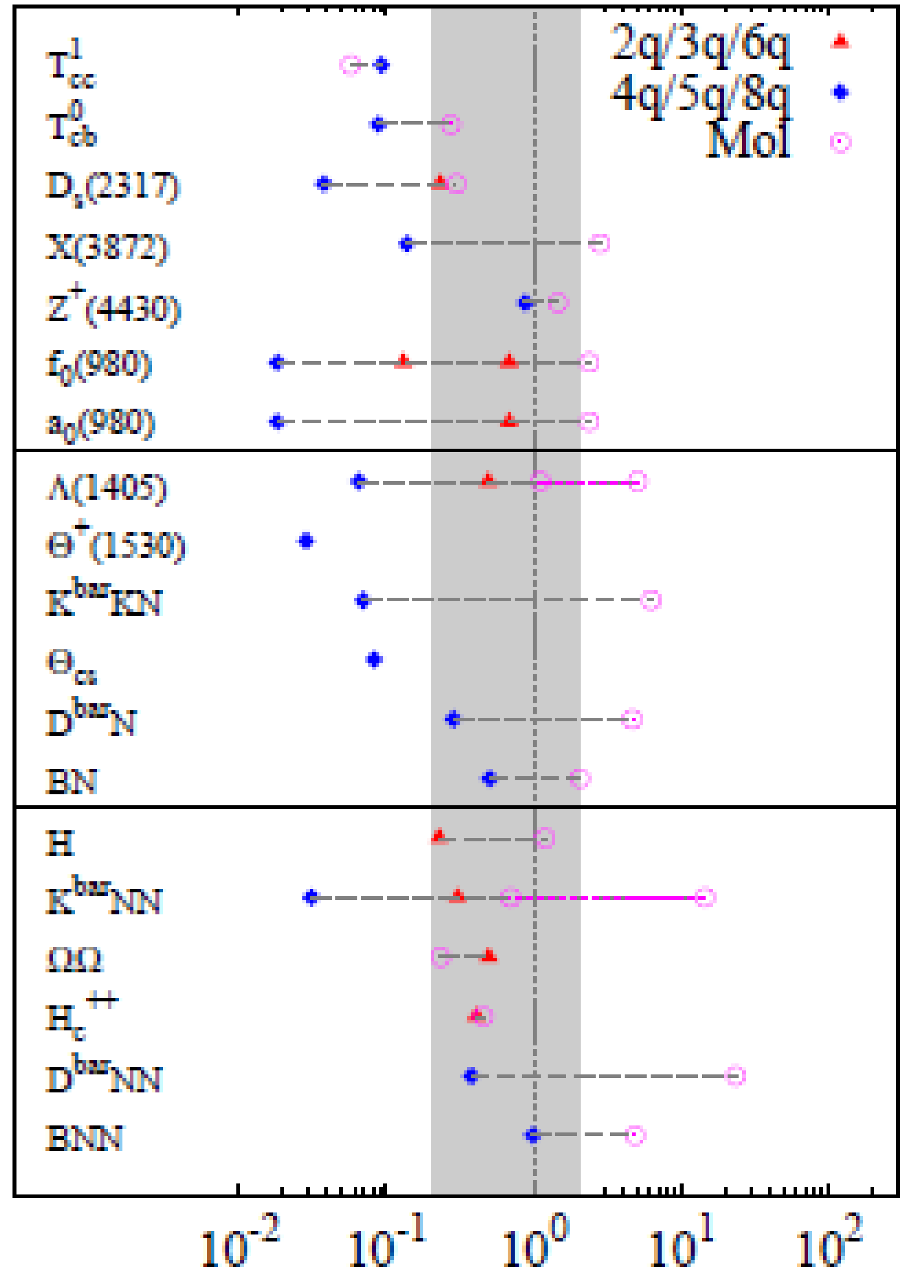


- **STAR data (2003): N(f_0(980)) ~ 8.4**
  [f_0(980)/ ρ^0 ~ 0.2, stat. N(ρ^0) ~ 42]
  Stat: 5.6, 2q:0.76-3.8, 4q:0.1, Mol: 13
  → Tetra-quark picture
  underestimate the m.easured yield of f_0 .

Coalescence / Statistical model ratio at RHIC



Coalescence / Statistical model ratio at LHC



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

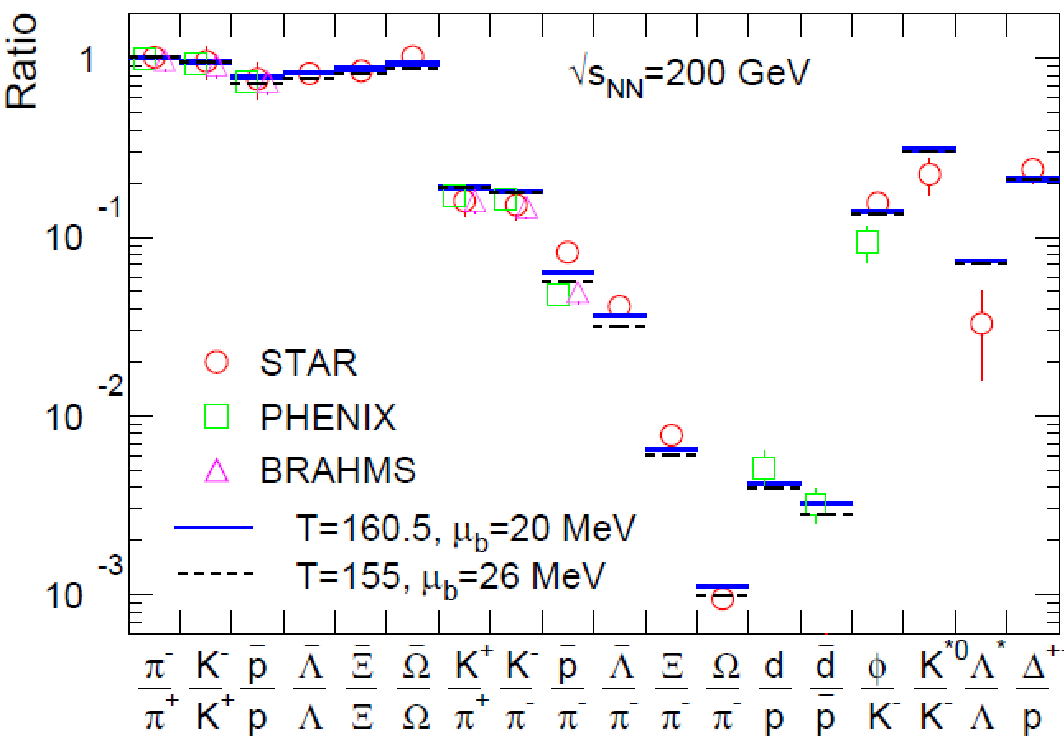
Statistical Model

- **Formation of hadrons under thermal and "chemical" equilibrium → Very successful to predict the hadron yield ratio at RHIC**

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

- **N_h = Yield per unit rapidity**
- **V_H=Chem. freeze-out vol.**
- **γ = particle fugacity**
  u,d,s → chem. equil.
  c,b → hard process

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



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