Exotic hadrons from relativistic heavy ion collisions

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- Charmed tetraquark mesons and pentaquark baryons
- Charm production in HIC
- Thermal vs coalescence production
- $D_{sJ}(2317)$: diquark or tetraquark
- Diomega $(\Omega\Omega)_{0+}$
- Λ_c from sQGP

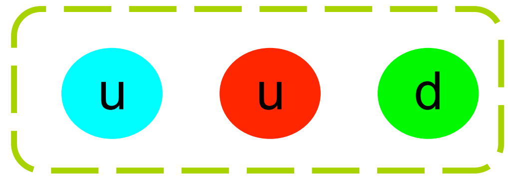
Supported by US National Science Foundation and the Welch Foundation

Quark color-spin interaction and hadron masses

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

- Baryon mass differences

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

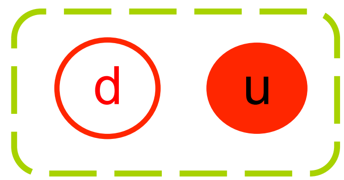


Mass Difference	$M_\Delta - M_N$	$M_\Sigma - M_\Lambda$	$M_{\Sigma_c} - M_{\Lambda_c}$
Formula	$\frac{3C_B}{2m_u^2}$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_s})$	$\frac{C_B}{m_u^2}(1-\frac{m_u}{m_c})$
Fit	290 MeV	77 MeV	154 MeV
Experiment	290 MeV	75 MeV	170 MeV

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

- 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 **$3\times C_B = C_M = 635\, m_u^2$**

Tetraquark mesons

Table 3. Tetraquark mesons $T_{q_1 q_2}(ud\bar{q}_1\bar{q}_2)$ with spin $S=1$ for $q_1=q_2$, where q_1, $q_2 = s$, c and b. Units are in MeV

$T_{q_1q_2}$ $(S=1)$ $-\frac{3}{4}\frac{C_B}{m_u^2}+\frac{1}{4}\frac{C_B}{m_{q_1}^2}$	$u\bar{q}_1$ $(S=1)$ $\frac{1}{4}\frac{C_M}{m_u m_{q_1}}$	$d\bar{q}_2$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_1}}$	$T_{q_1q_2}$ $-u\bar{q}_1-u\bar{q}_2$
T_{ss}	K^*	K	
-127	92	-285	63
T_{cc}	D^*	D	
-143	31	-95	-79
T_{bb}	B^*	B	
-145	10	-30	-124

Table 4. Tetraquark mesons $T_{q_1 q_2}(ud\bar{q}_1\bar{q}_2)$ with spin $S=0$ for $q_1 \neq q_2$. q_1, $q_2 = s$, c and b. Units are in MeV

$T_{q_1q_2}$ $(S=0)$ $-\frac{3}{4}\frac{C_B}{m_u^2}-\frac{3}{4}\frac{C_B}{m_{q_1}m_{q_2}}$	$u\bar{q}_1$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_1}}$	$d\bar{q}_2$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_2}}$	$T_{q_1q_2}$ $-u\bar{q}_1-u\bar{q}_2$
T_{sc}	K	D	
-162	-285	-95	218
T_{sb}	K	B	
-150	-285	-30	165
T_{cb}	D	B	
-146	-95	-30	-21

Pentaquark baryons

Table 7. Charm– and bottom–strange pentaquark baryons $\Theta_{qs}(uds s\bar{q})$ ($q = c$ and b) with spin $S = 1/2$. Units are in MeV

	N	$s\bar{q}$	$\Theta_{qs} - N - s\bar{q}$
	$-\frac{3}{4}\frac{C_M}{m_u^2}$	$-\frac{3}{4}\frac{C_M}{m_u m_q}$	
Θ_{qs}	Σ	$d\bar{q}$	$\Theta_{qs} - \Sigma - d\bar{q}$
$-\frac{3}{4}\frac{C_B}{m_u^2} - \frac{3}{4}\frac{C_B}{m_u m_s}$	$\frac{1}{4}\frac{C_B}{m_u^2} - \frac{C_B}{m_u m_s}$	$-\frac{3}{4}\frac{C_M}{m_u m_q}$	
	Λ	$u\bar{q}$	$\Theta_{qs} - \Lambda - u\bar{q}$
	$-\frac{3}{4}\frac{C_B}{m_u^2}$	$-\frac{3}{4}\frac{C_M}{m_u m_q}$	
	N	D_s	$\Theta_{cs} - N - D_s$
	-145	-57	-30
Θ_{cs}	Σ	D	$\Theta_{cs} - \Sigma - D$
-232	-67	-95	-69
	Λ	D	$\Theta_{cs} - \Lambda - D$
	-145	-95	8
	N	B_s	$\Theta_{bs} - N - B_s$
	-145	-18	-68
Θ_{bs}	Σ	B	$\Theta_{bs} - \Sigma - B$
-232	-67	-30	-133
	Λ	B	$\Theta_{bs} - \Lambda - B$
	-145	-30	-56

Diquark in sQGP and Λ_c enhancement

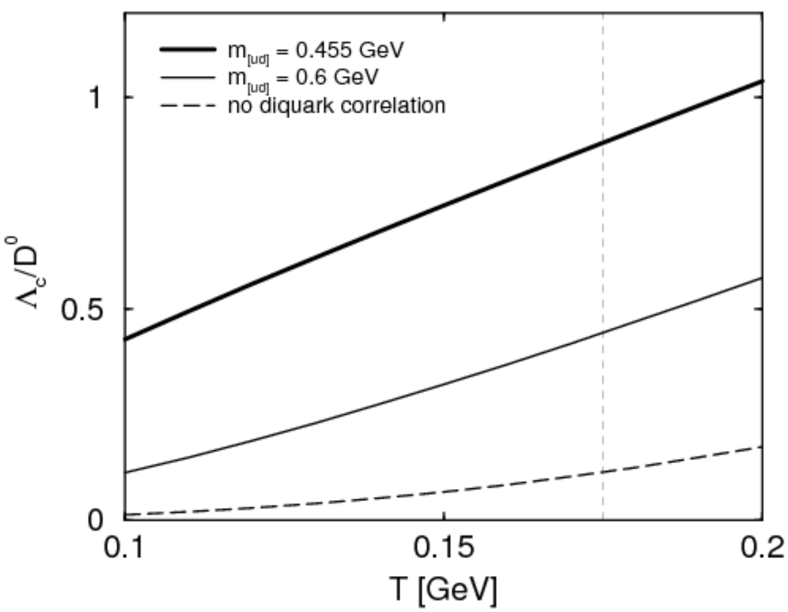
Lee, Yasui, Ohnishi, Yoo & Ko, PRL 100, 222301 (08)

Diquark mass due to color-spin interaction:

$$m_{[ud]} \approx m_u + m_d - C\,\vec{s}_u \cdot \vec{s}_d \frac{1}{m_u m_d} \approx 450\,\mathrm{MeV}$$

for $m_u=m_d$= 300 MeV and C/m_u^2~195 Me V from m_Δ-m_N

Coalescence model



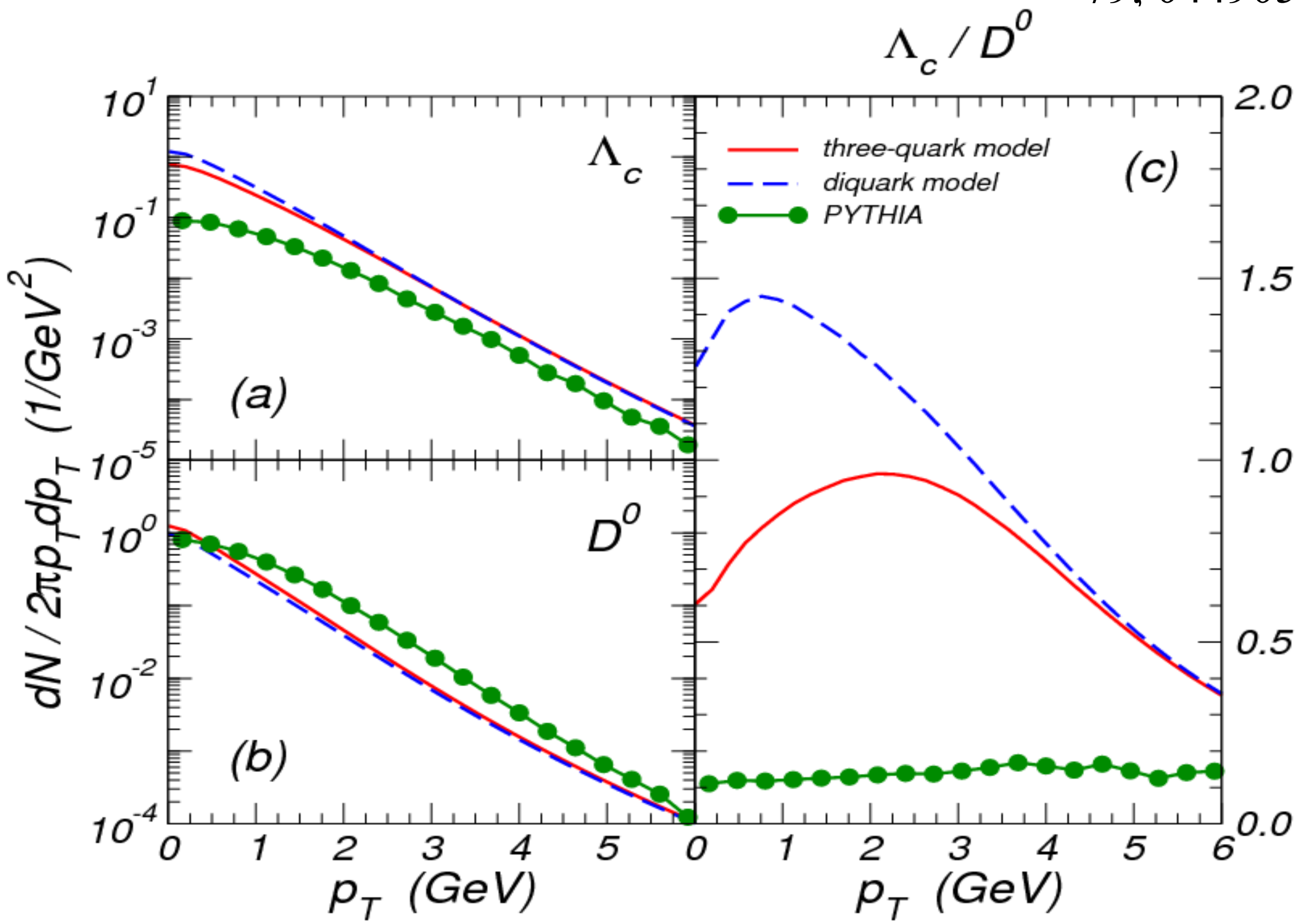
Statistical model

$$\frac{\Lambda_c}{D_0} \approx 2\left(\frac{m_{\Lambda_c}}{m_{D_0}}\right)^{3/2} e^{-(m_{\Lambda_c}-m_{D_0})/T_c} \approx 0.24$$

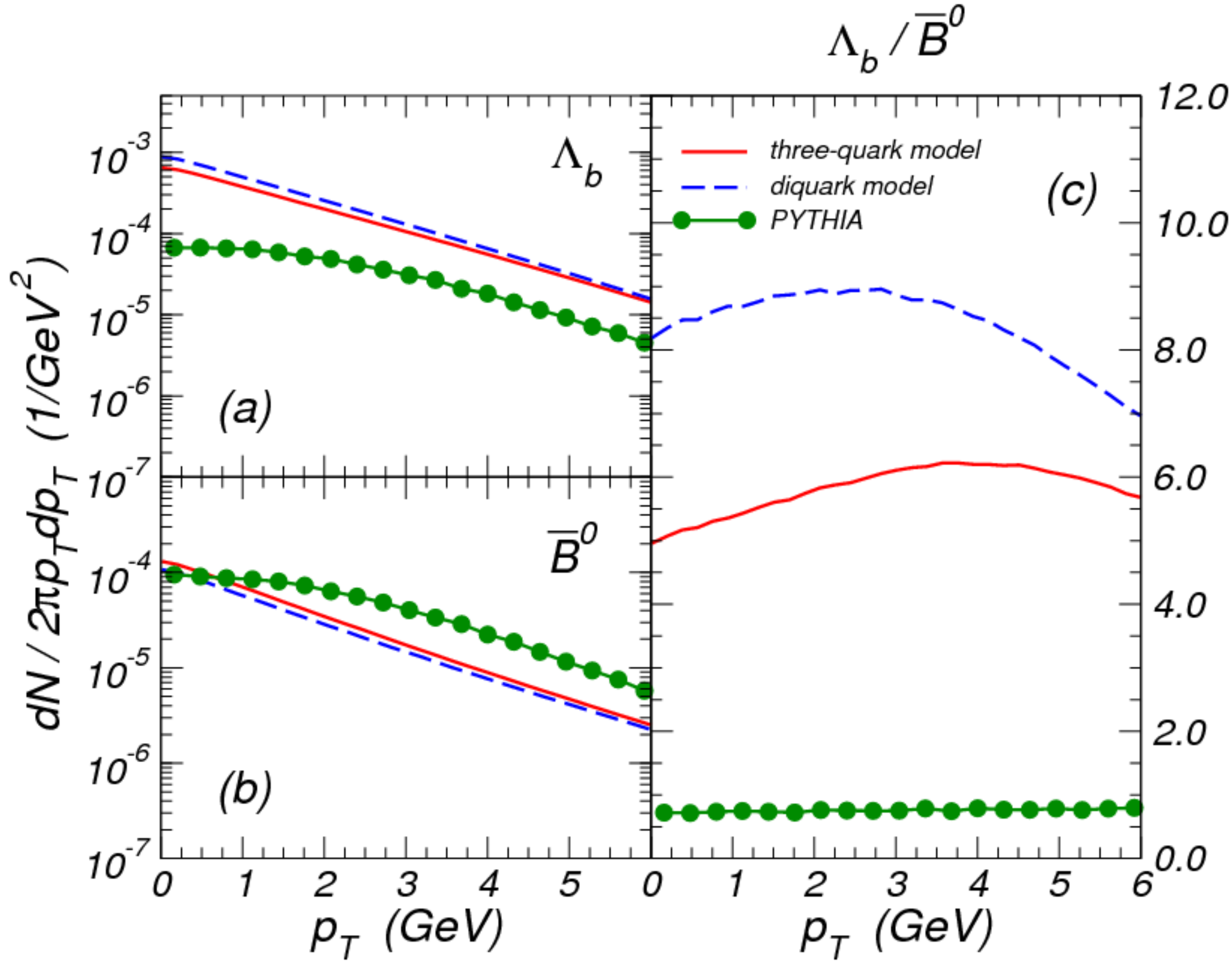
- Enhanced by a factor of 4-8
- Similar for Λ_B/B_0

Inclusion of resonances and fragmentation

Oh et al., PRC 79, 044905 (09)



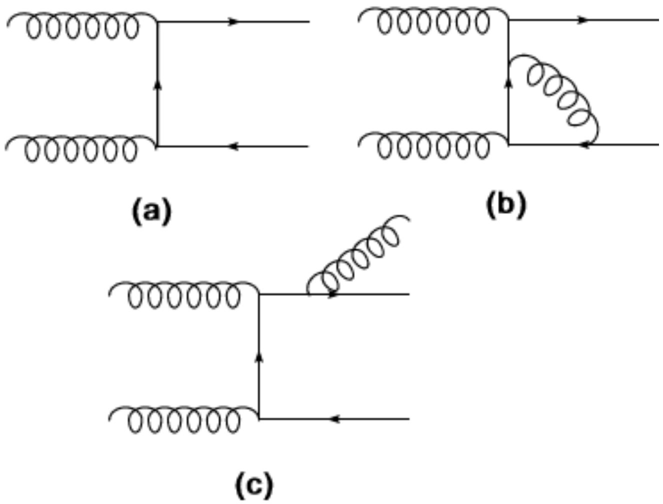
Including coalescence contribution enhances Λ_c/D^0 ratio, which is further enhanced by the presence of diquarks in QGP

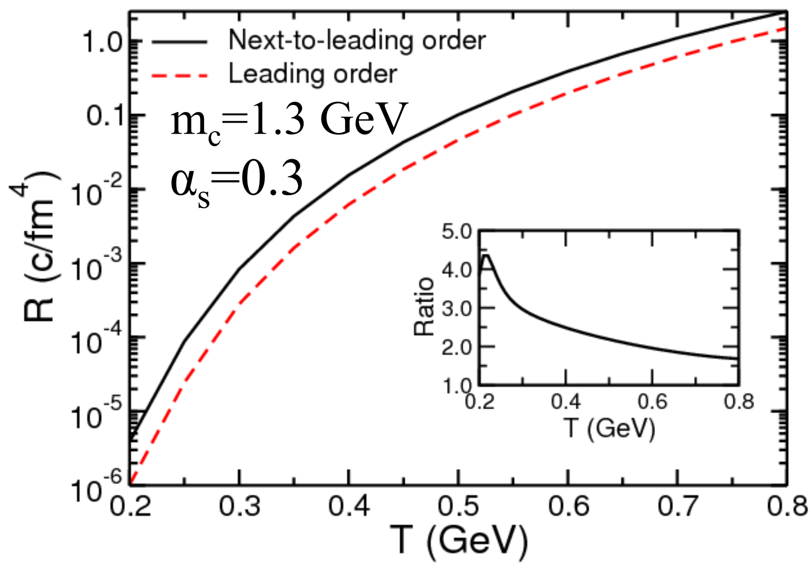


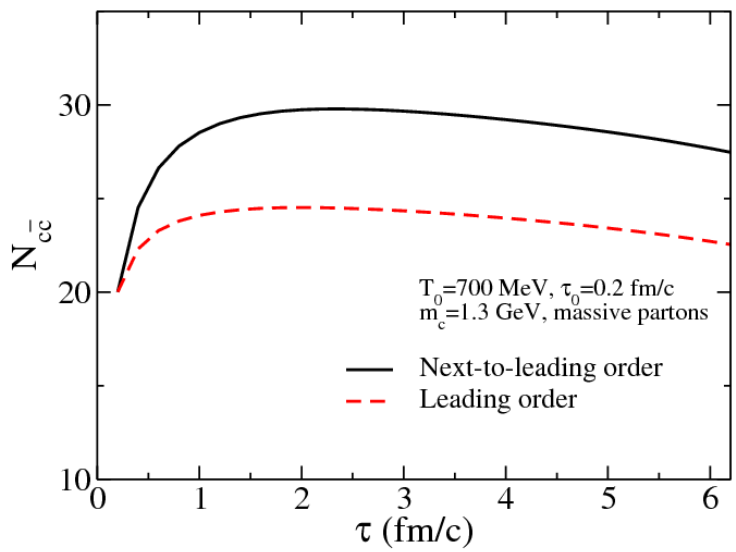
As for Λ_c/D^0, including coalescence contribution enhances Λ_b/B^0 ratio, and it is further enhanced by the presence of diquarks in QGP

Thermal charm production in QGP

Zhang, Liu & Ko,
PRC 77, 024901 (08)





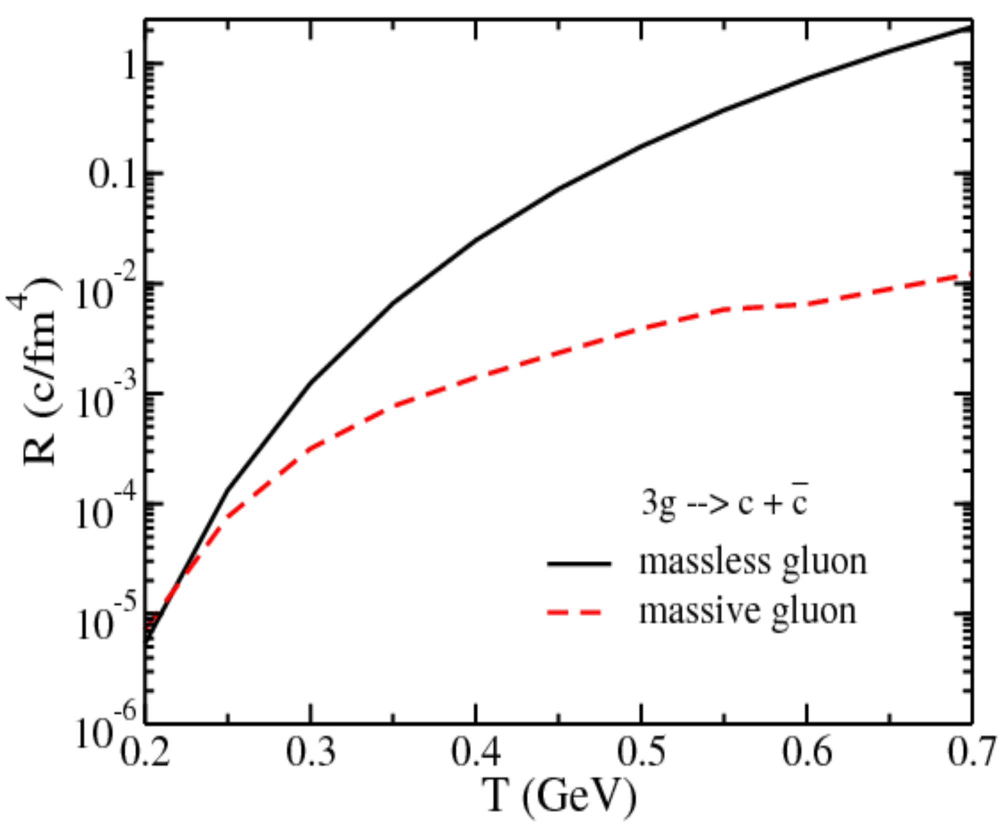


- Thermal production at LHC non-negligible
- Next-leading order and leading order contributions are comparable
- Insensitive to gluon masses
- Effect increases by about 2 for initial temperature T_0=750 MeV but decreases by ~ 2 for m_c=1.5 GeV

Charm production from three-gluon interaction ggg→cc

Determine rate for $ggg \to c\bar{c}$ from $c\bar{c} \to ggg$ via detailed balance

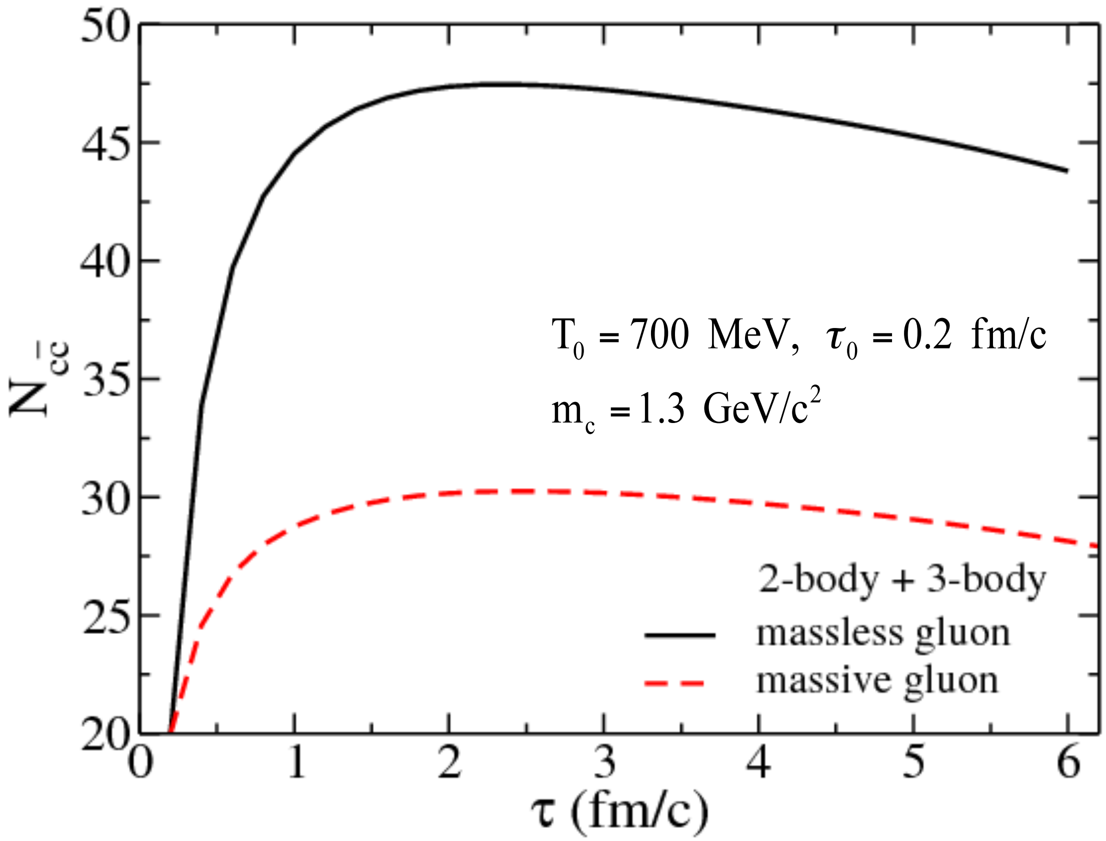
$$R \propto \frac{1}{3}\int\prod_{i=1}^{5} d^3p_i f_i(p_i)\left|M_{ggg\to c\bar{c}}\right|^2 \delta^{(4)}(p_1+p_2+p_3-p_4-p_5) \propto \left\langle \sigma_{c\bar{c}\to ggg} v\right\rangle n_c^{eq} n_{\bar{c}}^{eq}$$



Gluon density ~ 0.5/fm^3 at T_C and much larger initially

- Negligible rate for massive gluons as the threshold becomes larger than the charm pair mass
- With massless gluons, the rate is comparable to that of two-body processes

Charm production at LHC



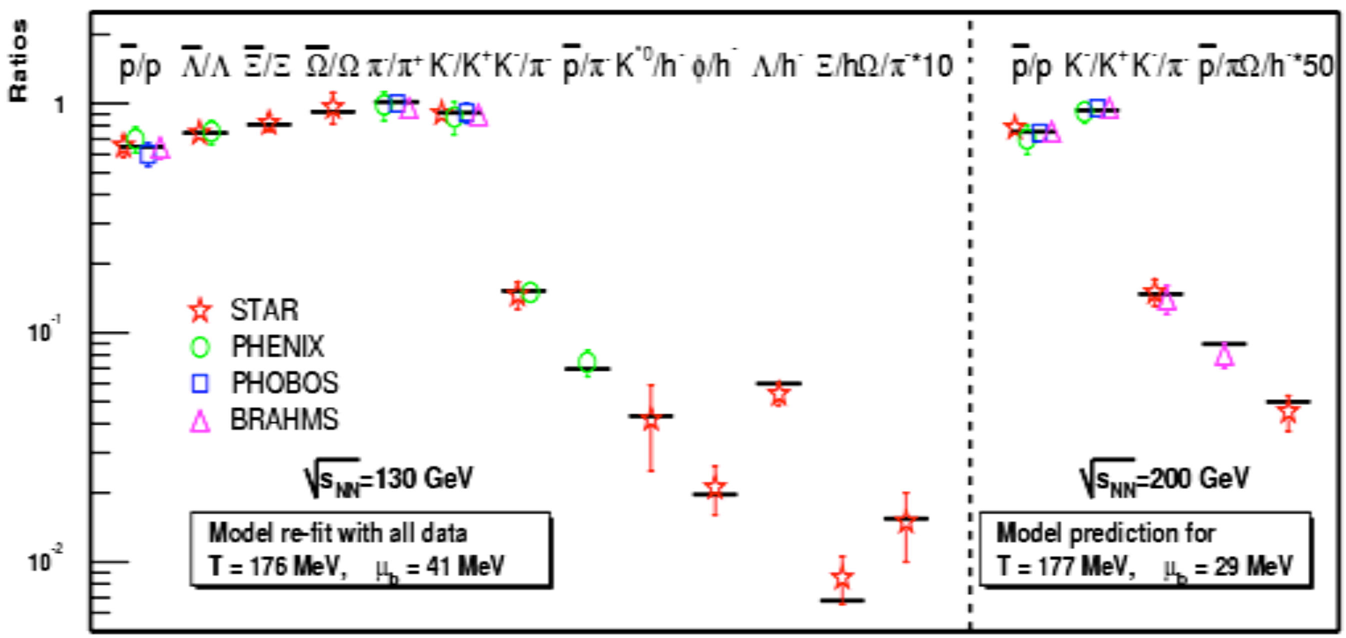
Significant thermal production of charms from QGP of massless gluons

Statistical model

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

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

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

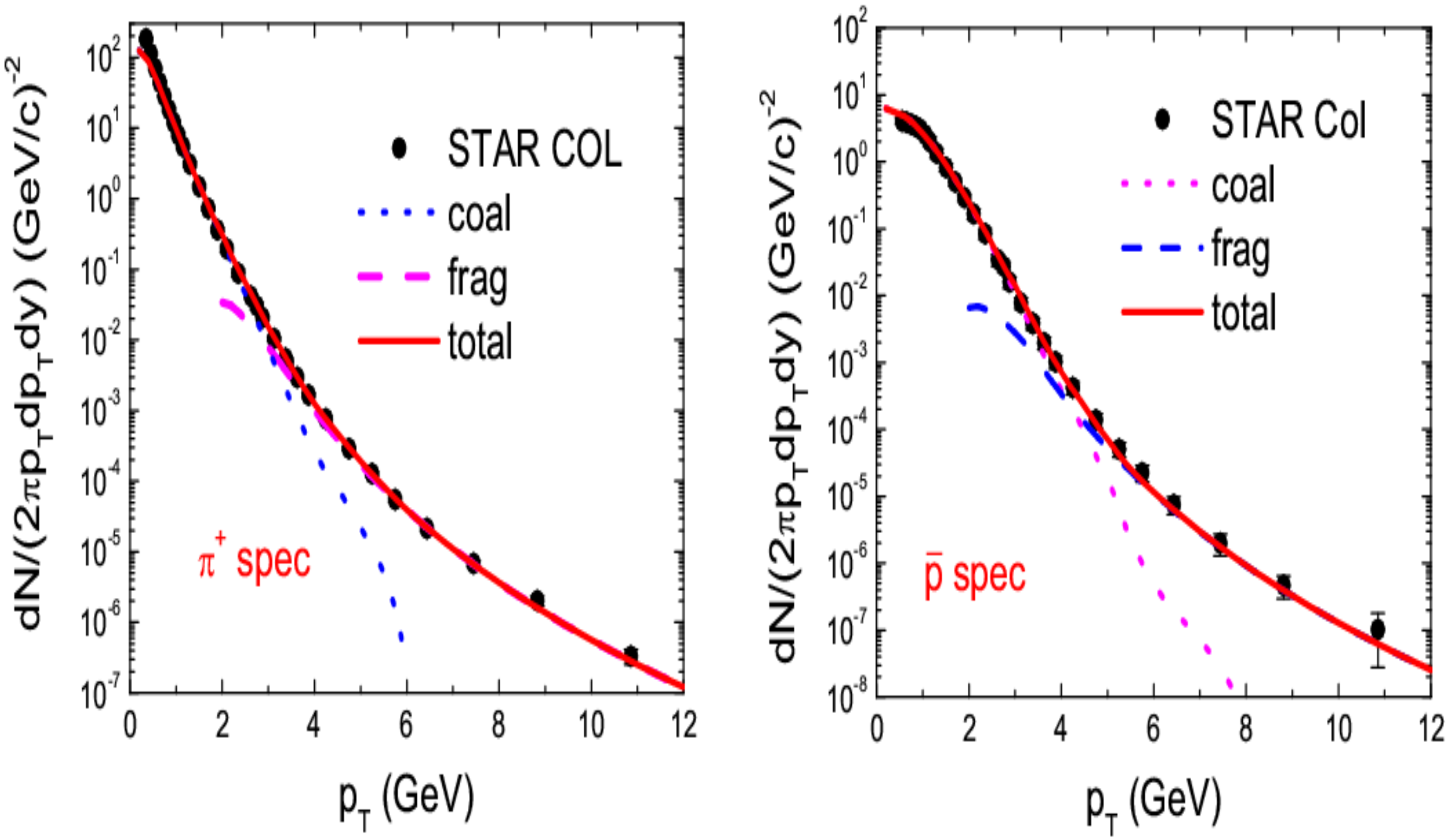
$\Delta_x \cdot \Delta_p \geq \hbar$

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

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

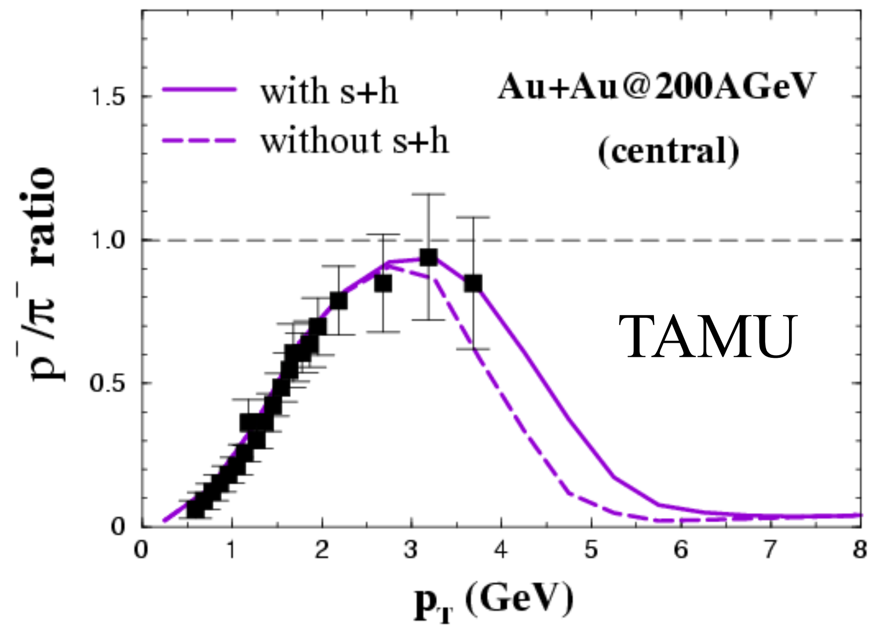
Proton and pion transverse momentum spectra

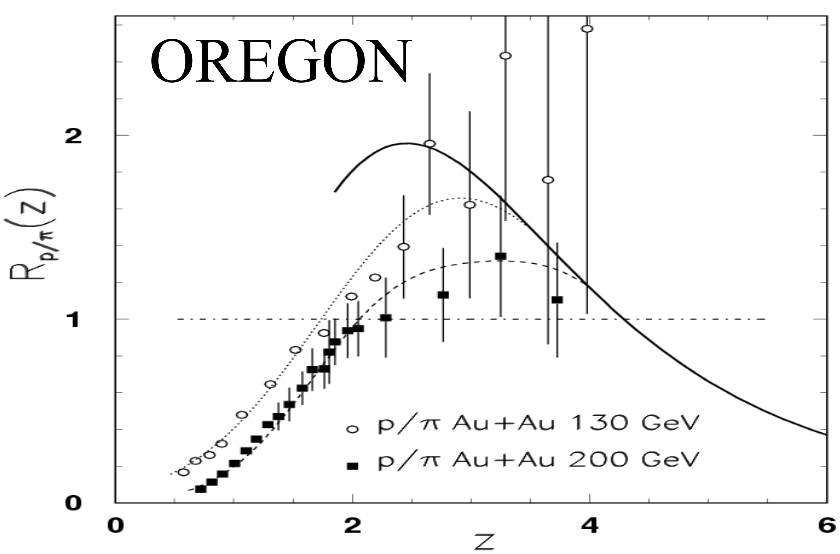
Central Au+Au collisions at $s^{1/2}$=200 GeV

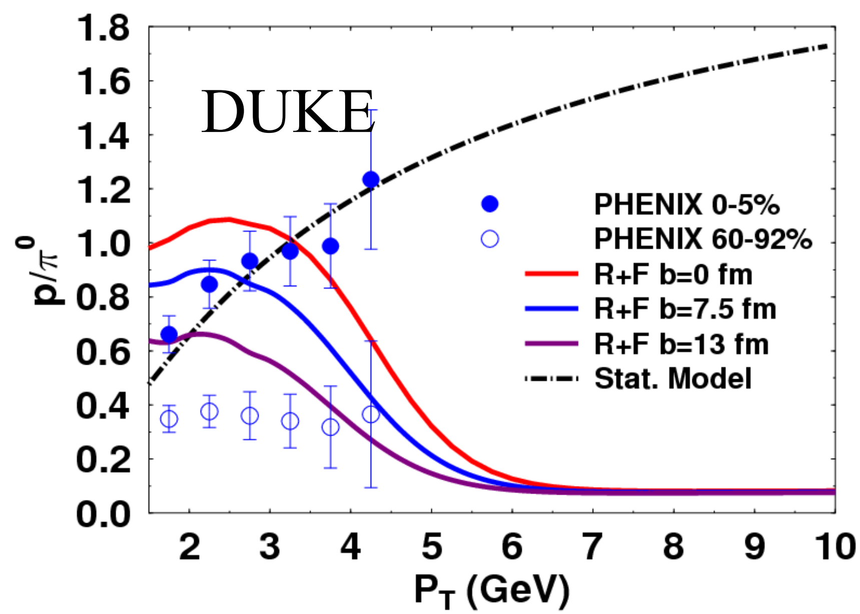


Large proton to pion ratio

Quark coalescence or recombination can explain the surprizingly large p/π ratio at intermediate transverse momentum observed in central Au+Au collisions.







Constituent quark number scaling of elliptic flow

For quarks with same momentum to coalesce, i.e., $\Delta p=0$

Quark transverse momentum distribution

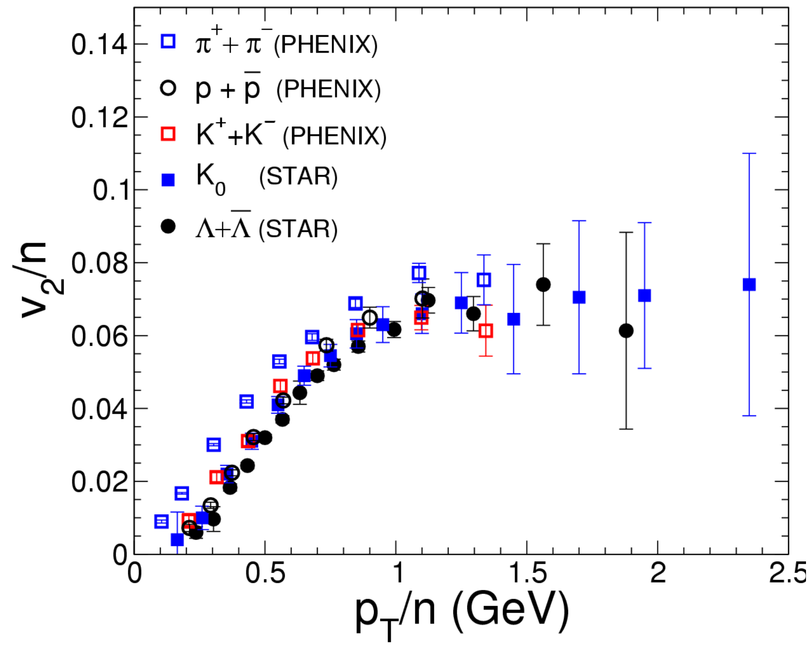
$$f_q(p_T) \propto 1 + 2v_{2,q}(p_T)\cos(2\phi)$$

Meson elliptic flow

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

Baryon elliptic flow

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



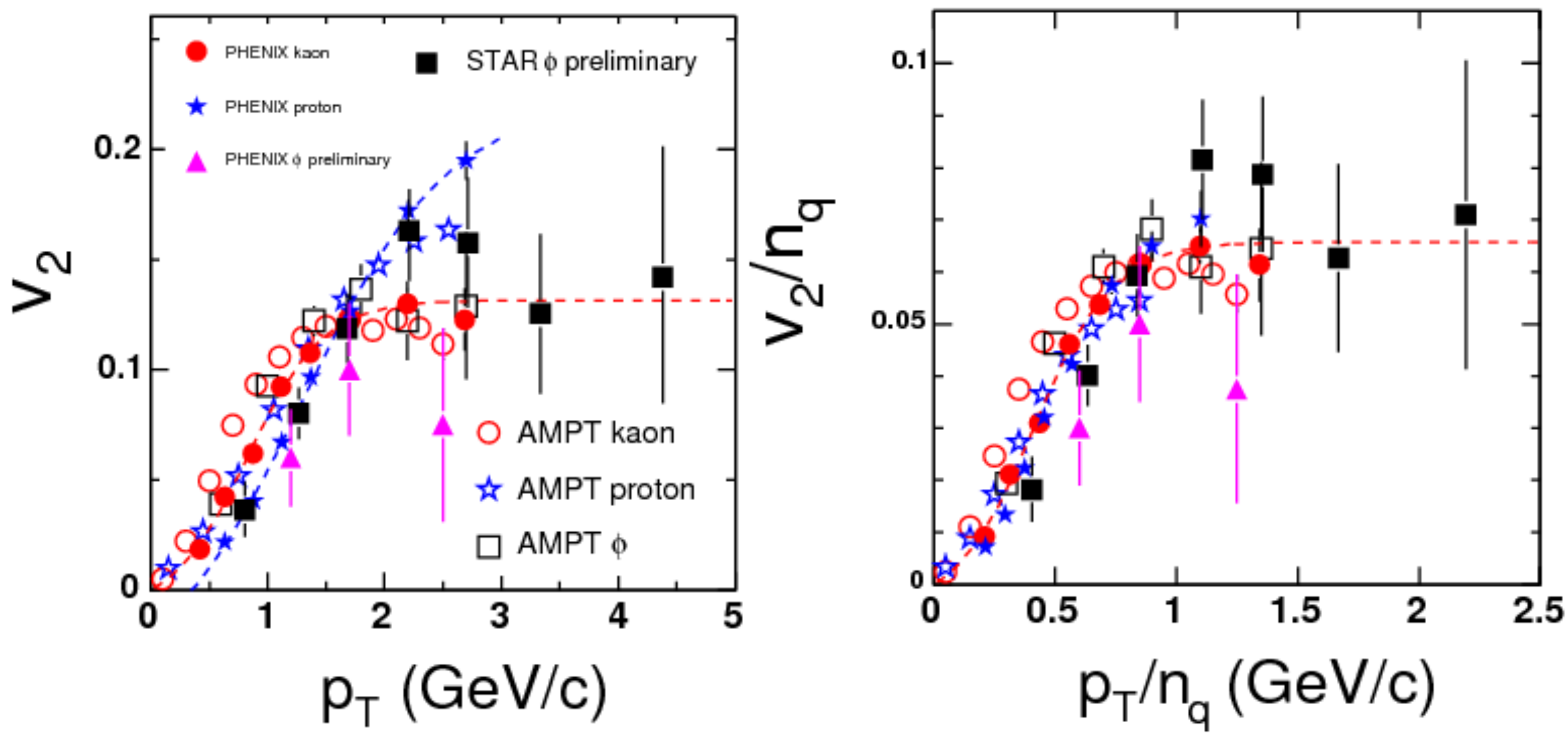
Quark number scaling of hadron v_2 (except pions):

$$\frac{1}{n} v_2(p_T/n)$$

same for mesons and baryons

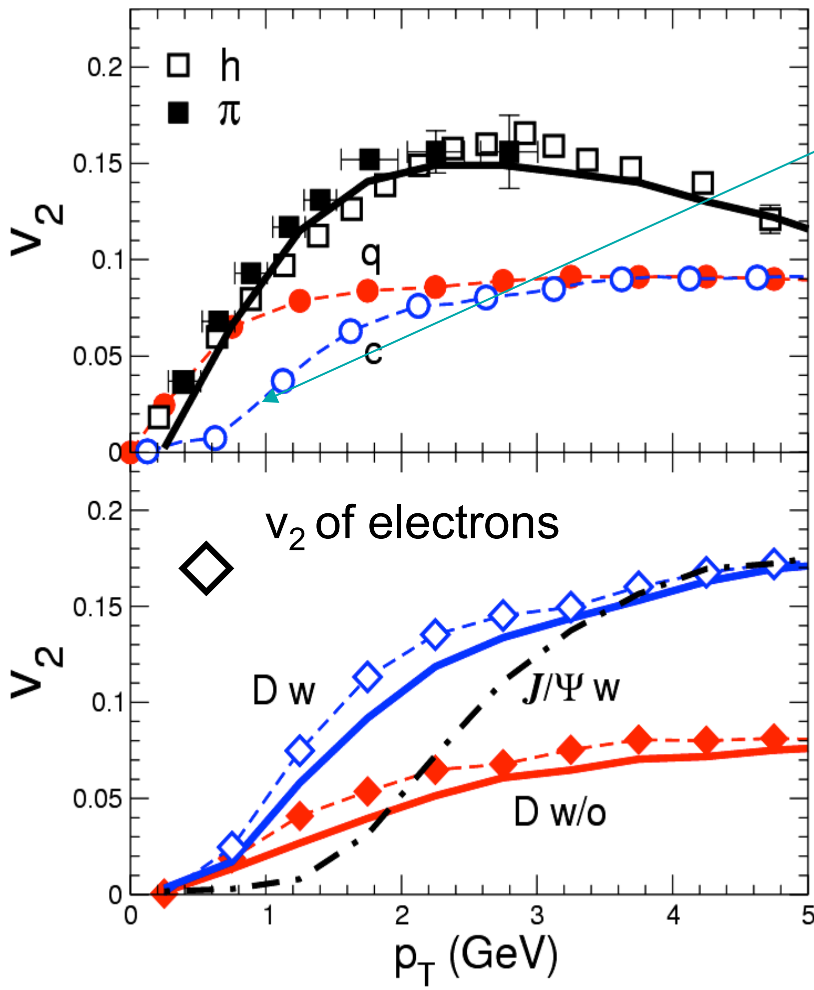
Phi flow from AMPT

J.H. Chen & Ma et al., PRC 74, 064902 (2006)



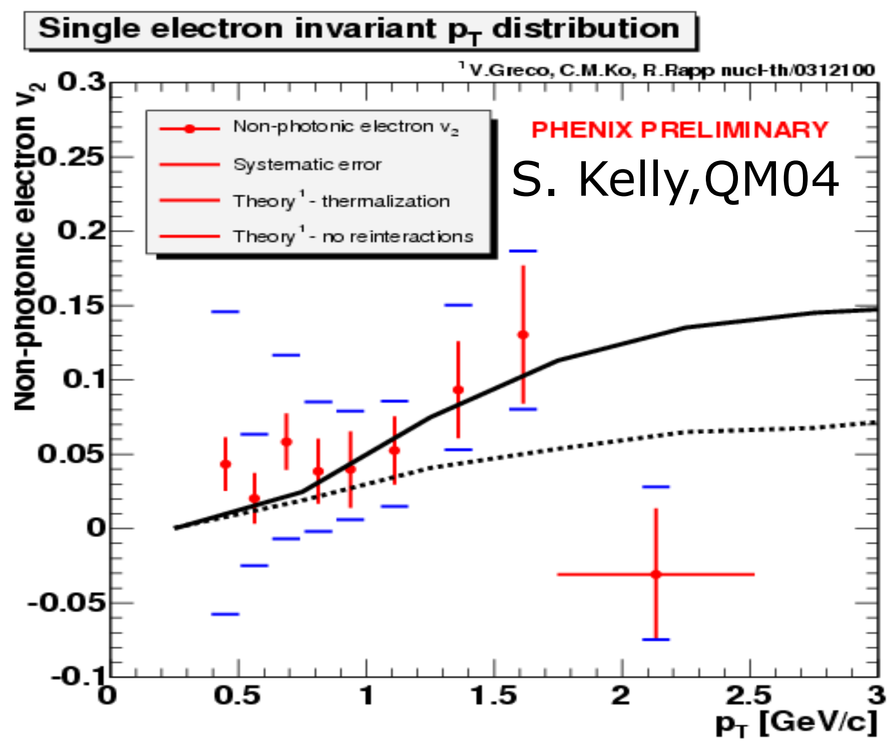
Phi meson v_2 is similar to that of kaon → quark number scaling

Charmed meson elliptic flow



Greco, Rapp, Ko, PLB595 (04) 202

Smaller charm v_2 than light quark v_2 at low p_T due to mass effect



Data consistent with thermalized charm quark with same v_2 as light quarks before boosted by radial flow

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 ~5.5X10^{-6} in central Au+Au collisions at RHIC and ~9X10^{-5} in central Pb+Pb collisions at LHC if total charm quark numbers at mid-rapidity are 3 and 20, respectively
  - Yields increase to 7.5X10^{-4} and 8.6X10^{-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 ~1.2X10^{-4} at RHIC and ~7.9X10^{-4} at LHC from the coalescence model for total charm quark numbers of 3 and 20, respectively
  - Statistical model predicts much larger yields of ~4.5X10^{-3} at RHIC and ~2.7X10^{-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

$D_{sj}(2317)$: 0^+

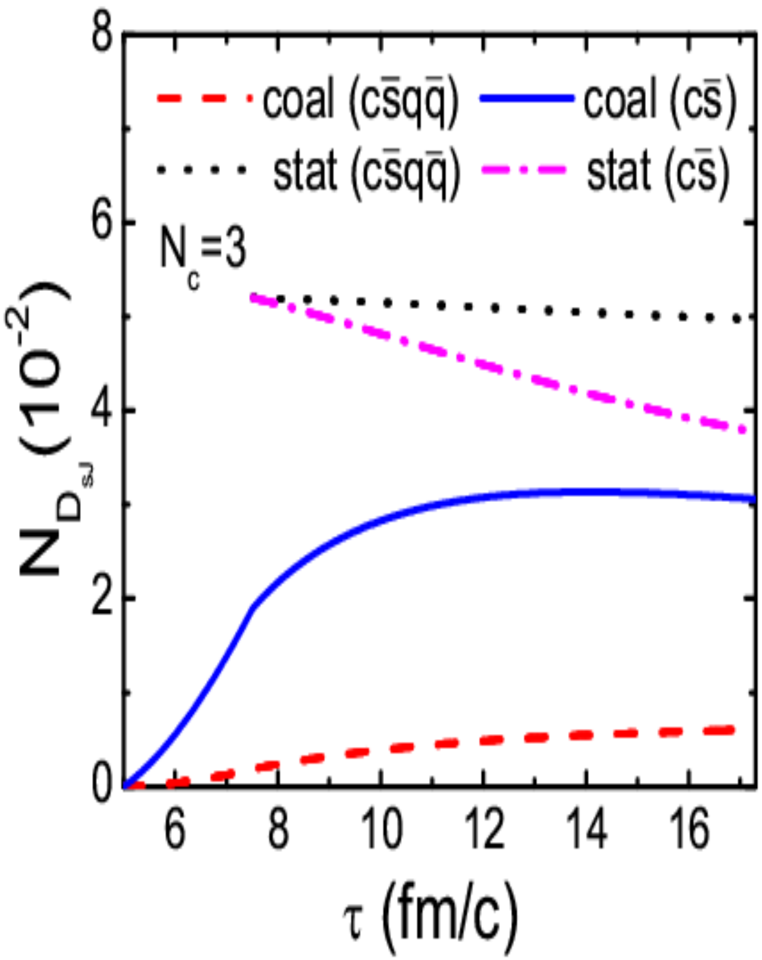
- Mass of 2317 MeV less than those predicted by quark model and QCD sum rule for two-quark state ($c\bar{s}$) but comparable to those for four-quark state ($c\bar{s}q\bar{q}$)

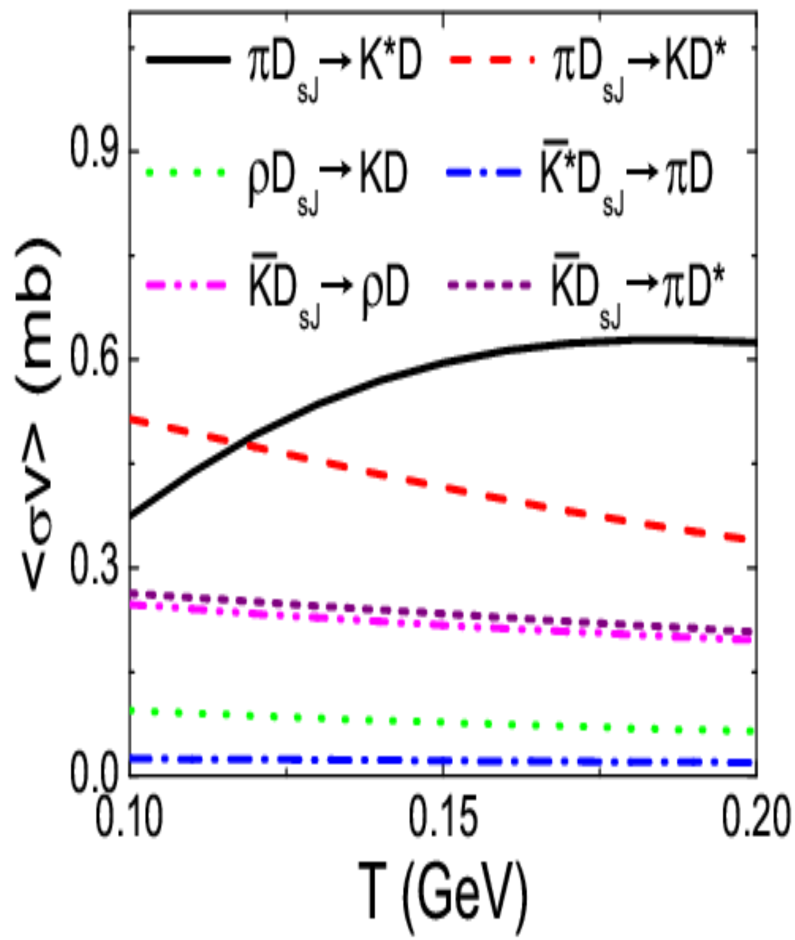
- Width of a few (four-quark) to a few tens (two-quark) keV from decay to $D_s\pi$, empirically less than 4.6 MeV limited because of experimental resolution.

- 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))

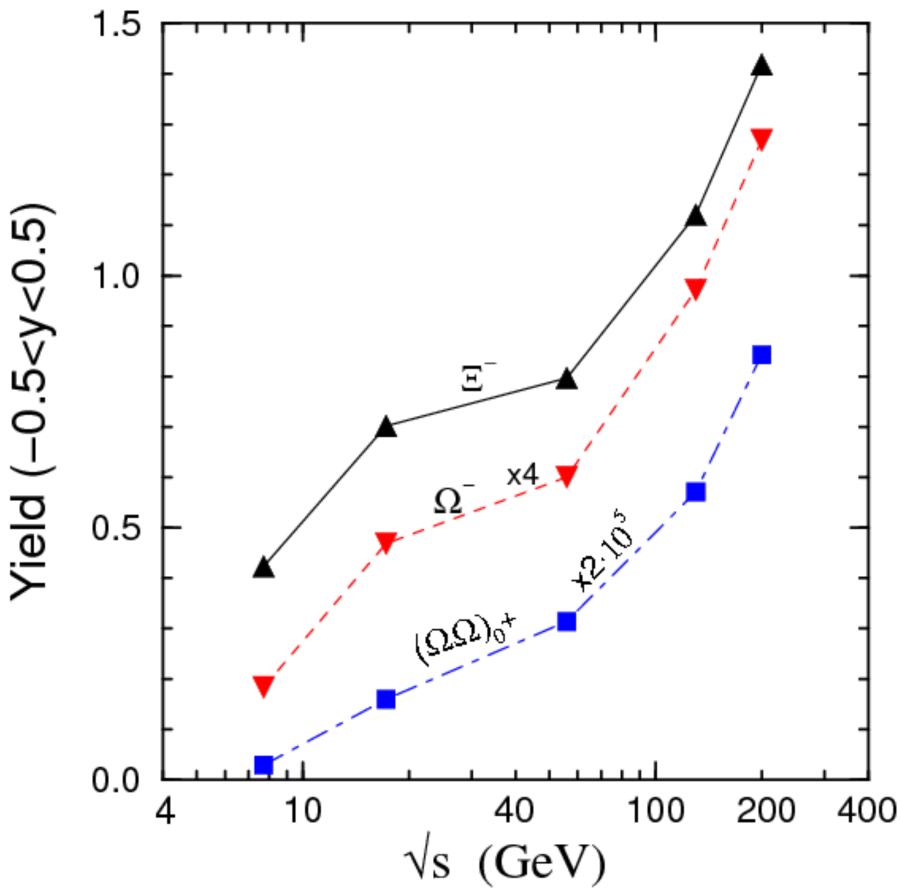




- Cross sections shown are for four-quark state and are larger by ~9 for two-quark state.
- Final yield is sensitive to the quark structure of D_{sJ}

Diomega

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.



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

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

- 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 larger in statistical or coalescence model.

Summary

- Possible existence of tetraquark meson $T_{cc}(ud\bar{c}\bar{c})$ and pentaquark baryon $\Theta_{cs}(uds\bar{c})$ due to attractive diquark spin-spin interaction
- Diquarks leads to enhanced Λ_c production in sQGP
- Enhanced charm production at LHC → factory for studying charmed exotics
- Thermal vs quark coalescence production of hadrons
- Larger yield of exotic hadrons in thermal production than from quark coalescence
- Yield of D_{sJ} (2317) in HIC is sensitive to its quark structure
- HIC allows for the study of ΩΩ interaction and possible existence of $(\Omega\Omega)_{0+}$