Charms in heavy ion collisions

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- Charm flow and energy loss
- Charmed baryon-to-meson ratios
- Charmonium production and flow
- Charm exotics at LHC

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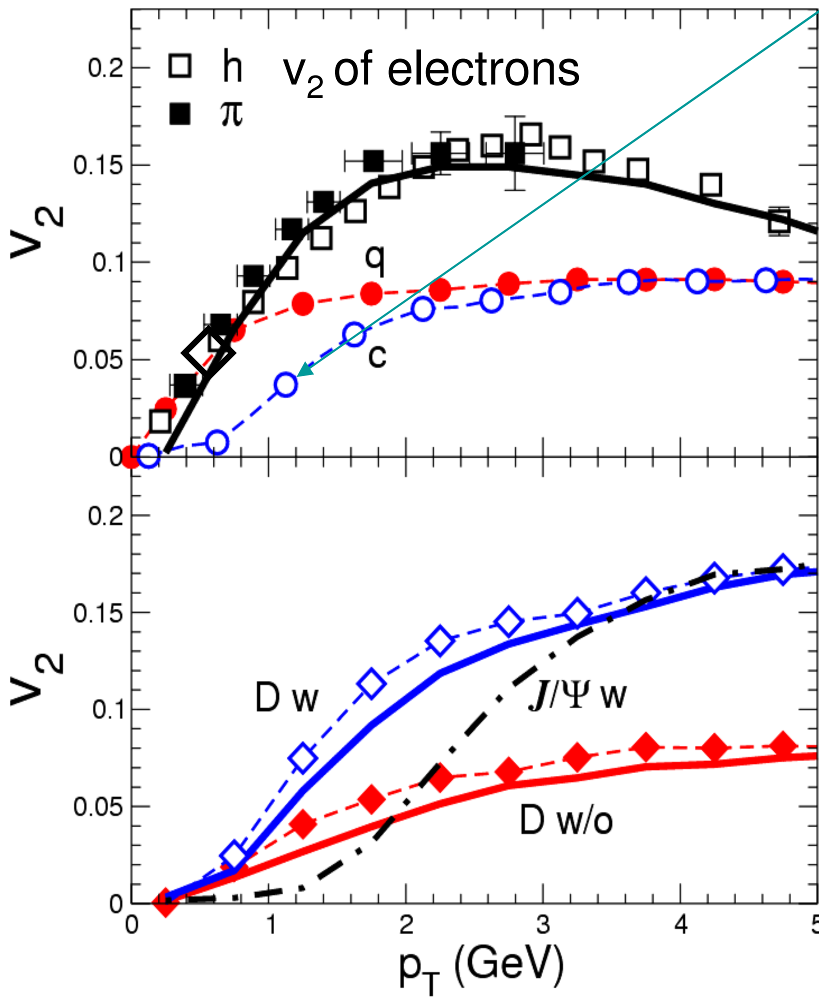
Supported by National Science Foundation and The Welch Foundation

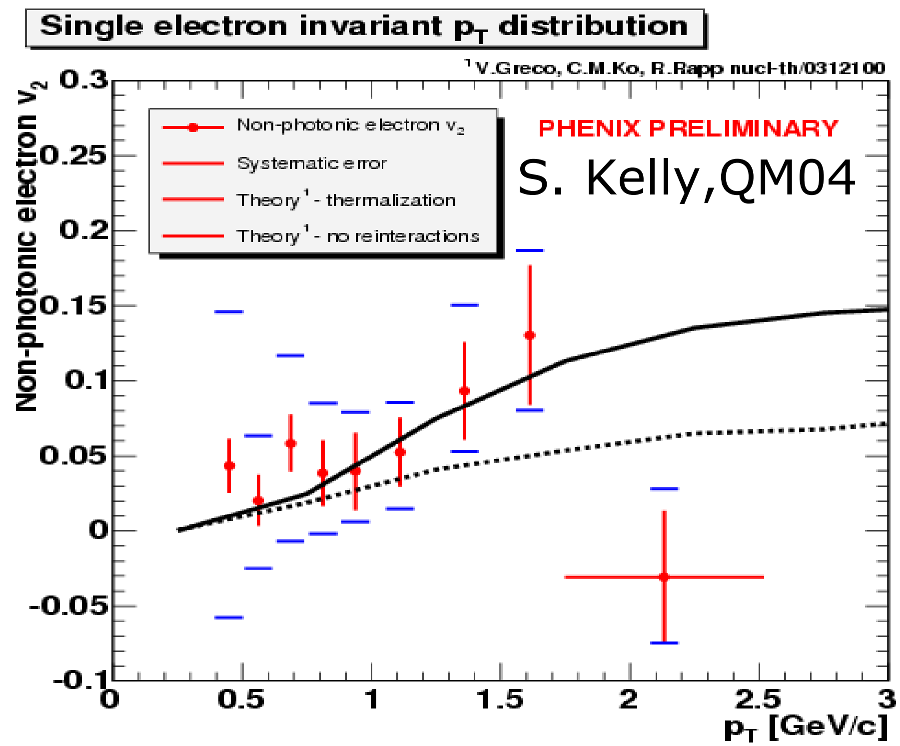
Charmed meson elliptic flow

Greco, Rapp, Ko, PLB595, 202 (04)

Quark coalescence

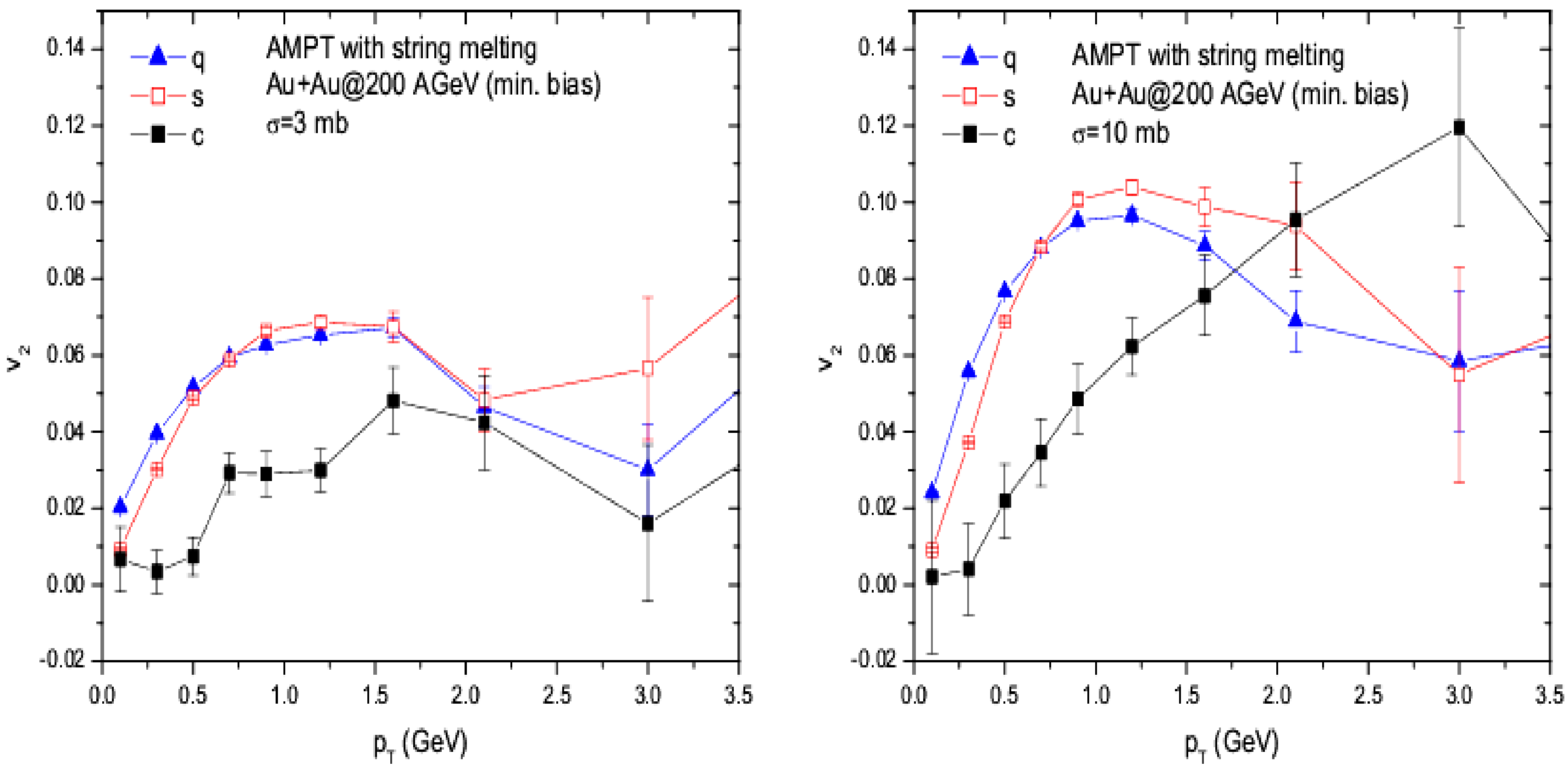


Smaller charm v_2 than light quark v_2 at low p_T due to mass effect



Data consistent with thermalized charm quarks with similar v_2 as light quarks

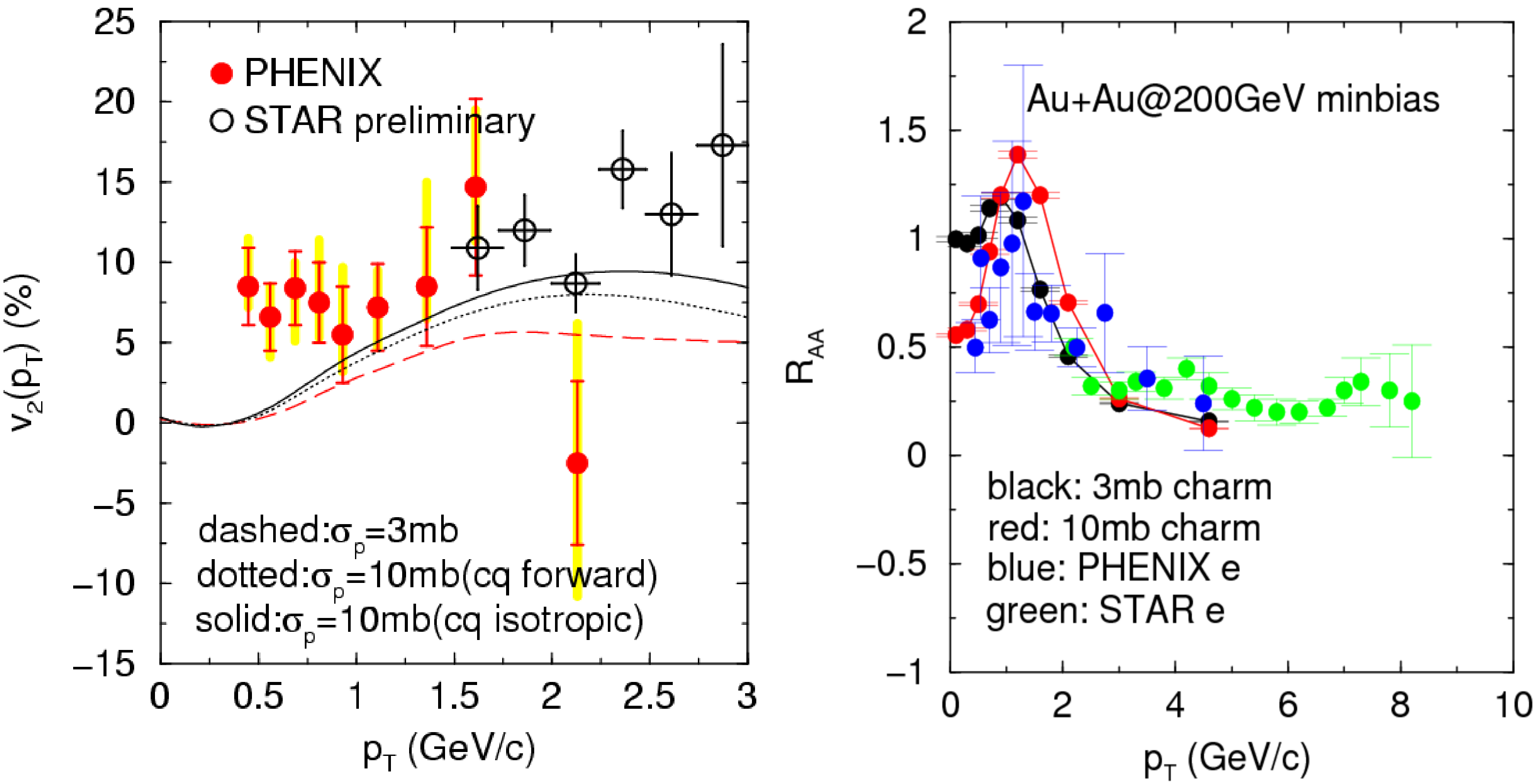
Charm quark elliptic flow from AMPT



- P_T dependence of charm quark v_2 is different from that of light quarks
- At high p_T, charm quark has similar v_2 as light quarks
- Charm elliptic flow is also sensitive to parton cross sections

Charm R_{AA} and elliptic flow from AMPT

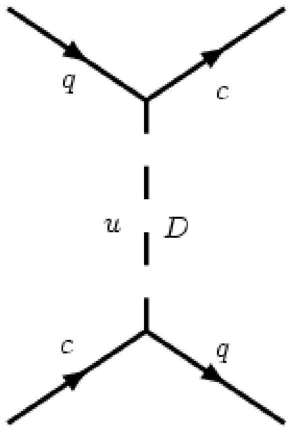
Zhang, Chen & Ko, PRC 72, 024906 (05)



- Need large charm scattering cross section to explain data
- Smaller charmed meson elliptic flow is due to use of current light quark masses

Resonance effect on charm scattering in QGP

Van Hees & Rapp, PRC 71, 034907 (2005)



$$\sigma_{c\bar{q}\to c\bar{q}} = \frac{1}{9}\frac{2J+1}{4}\frac{\pi}{k^2}\frac{\Gamma_D^2}{\left(s^{1/2} - m_D\right)^2 + \Gamma_D^2/4}$$

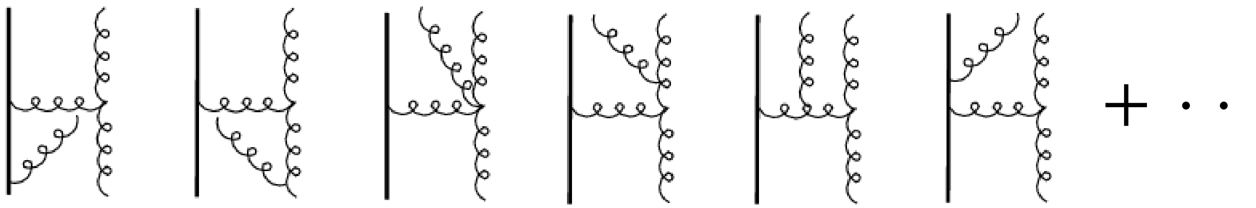
With $m_c \approx 1.5$ GeV, $m_q \approx 5$-10 MeV, $m_D \approx 2$ GeV, $\Gamma_D \approx 0.3$-0.5 GeV, and including scalar, pseudoscalar, vector, and axial vector D mesons gives

$$\sigma_{cq\to cq}(s^{1/2}=m_D) \approx 6 \text{ mb}$$

Since the cross section is isotropic, the transport cross section is 6 mb, which is about 4 times larger than that due to pQCD t-channel diagrams, leading to a charm quark drag coefficient $\gamma \sim 0.16$ c/fm in QGP at T=225 MeV.

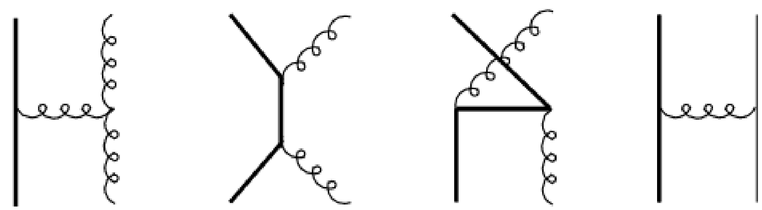
Heavy quark energy loss in pQCD

a) Radiative energy loss (Amesto *et al.,* hep-ph/0511257)



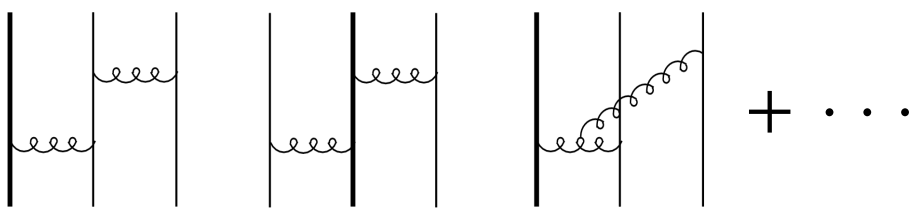
b) Radiative and elastic energy loss (Wicks *et al.,* nucl-th/0512076)

a) +



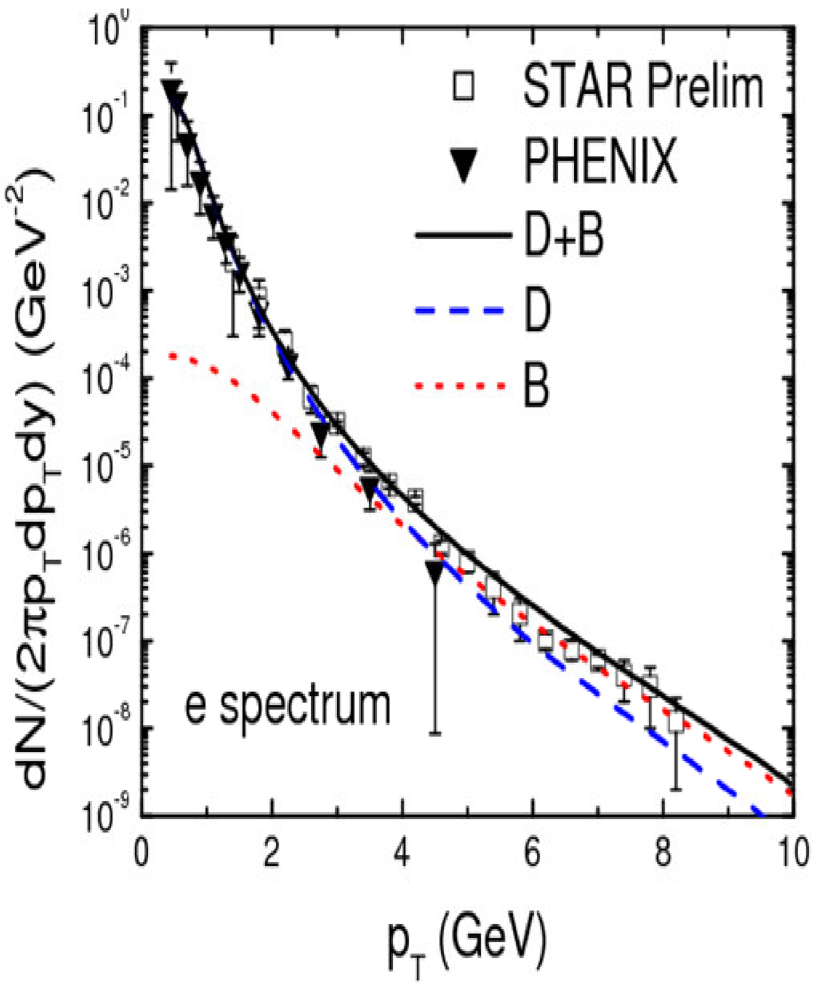
c) Three-body elastic scattering (Liu & Ko, nucl-th/0603004)

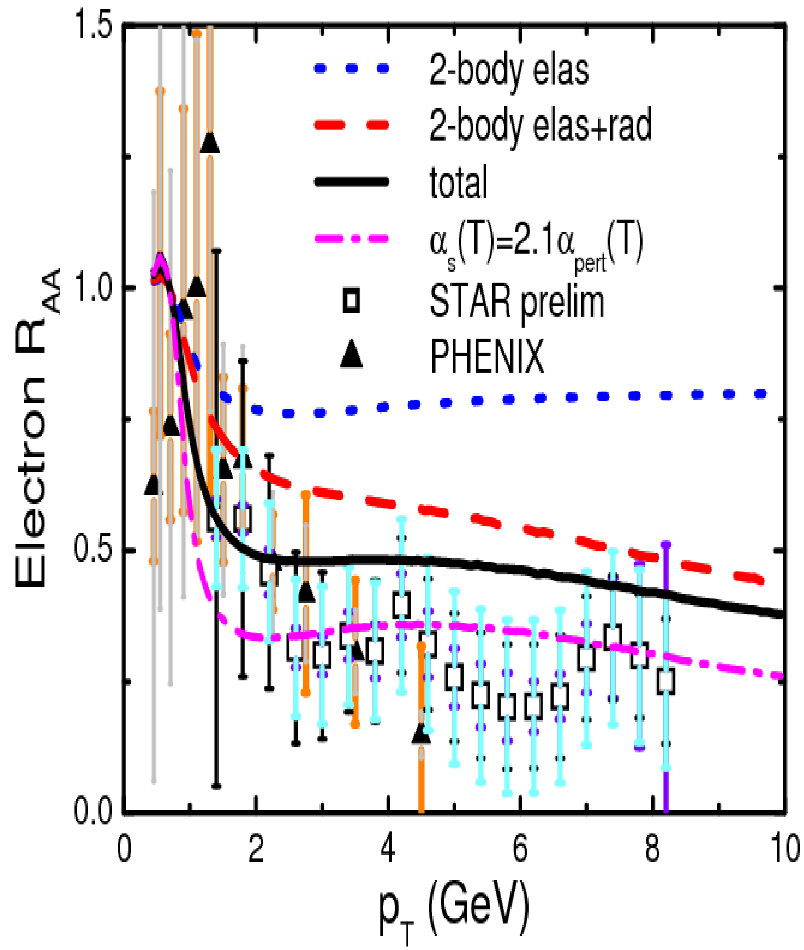
a) +b) +



- May be important as interparton distance ~ range of parton interaction
- At T=300 MeV, N_g~(N_q+N_{qbar})~ 5/fm^3, so interparton distance ~ 0.3 fm
- Screening mass m_D=gT~600 MeV, so range of parton interaction ~ 0.3 fm

Spectrum and nuclear modification factor of electrons from heavy meson decay

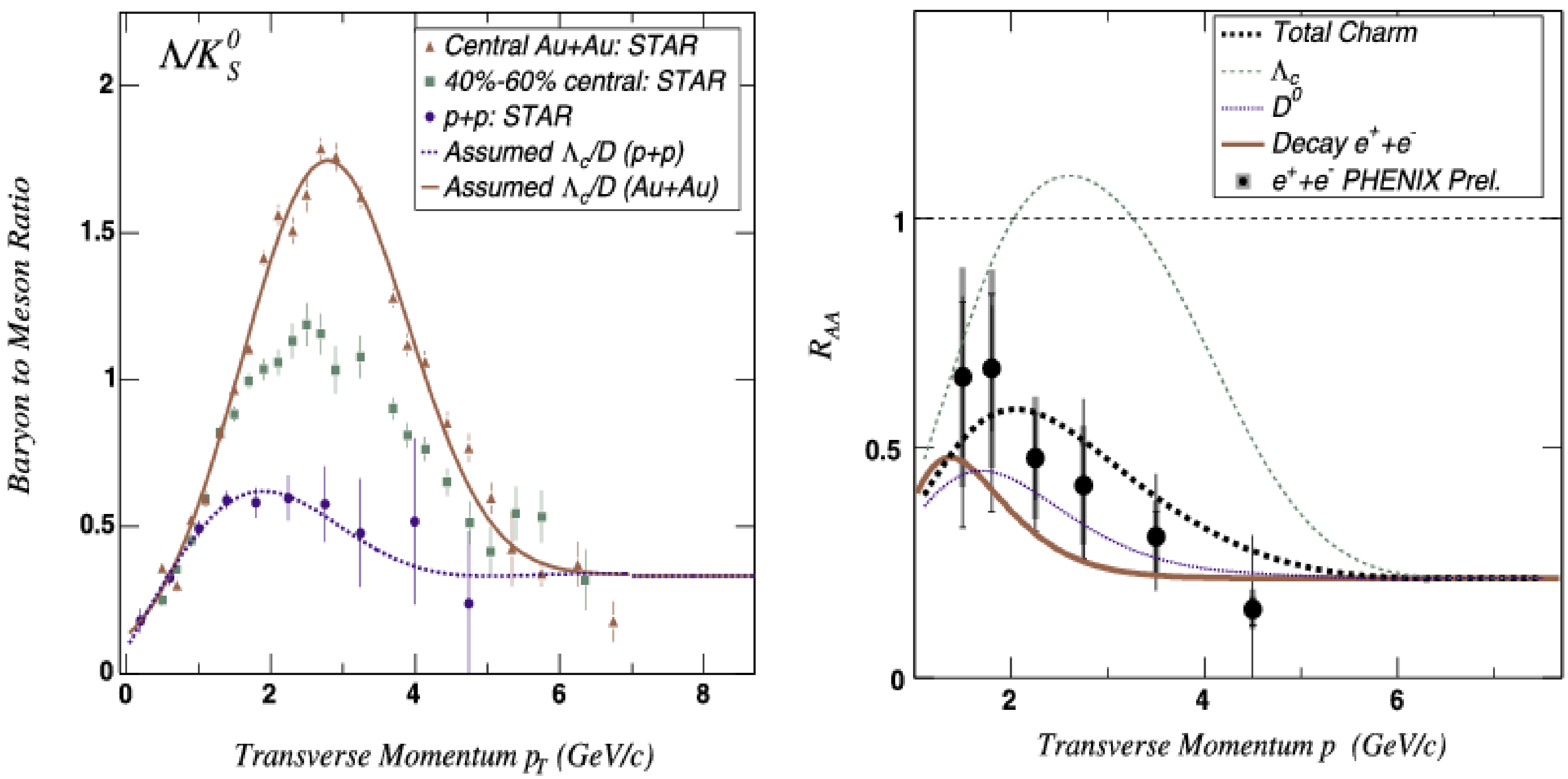




Reasonable agreement with data from Au+Au @ 200A GeV after including heavy quark three-body scattering and increasing α_s by 2 as given by lattice QCD.

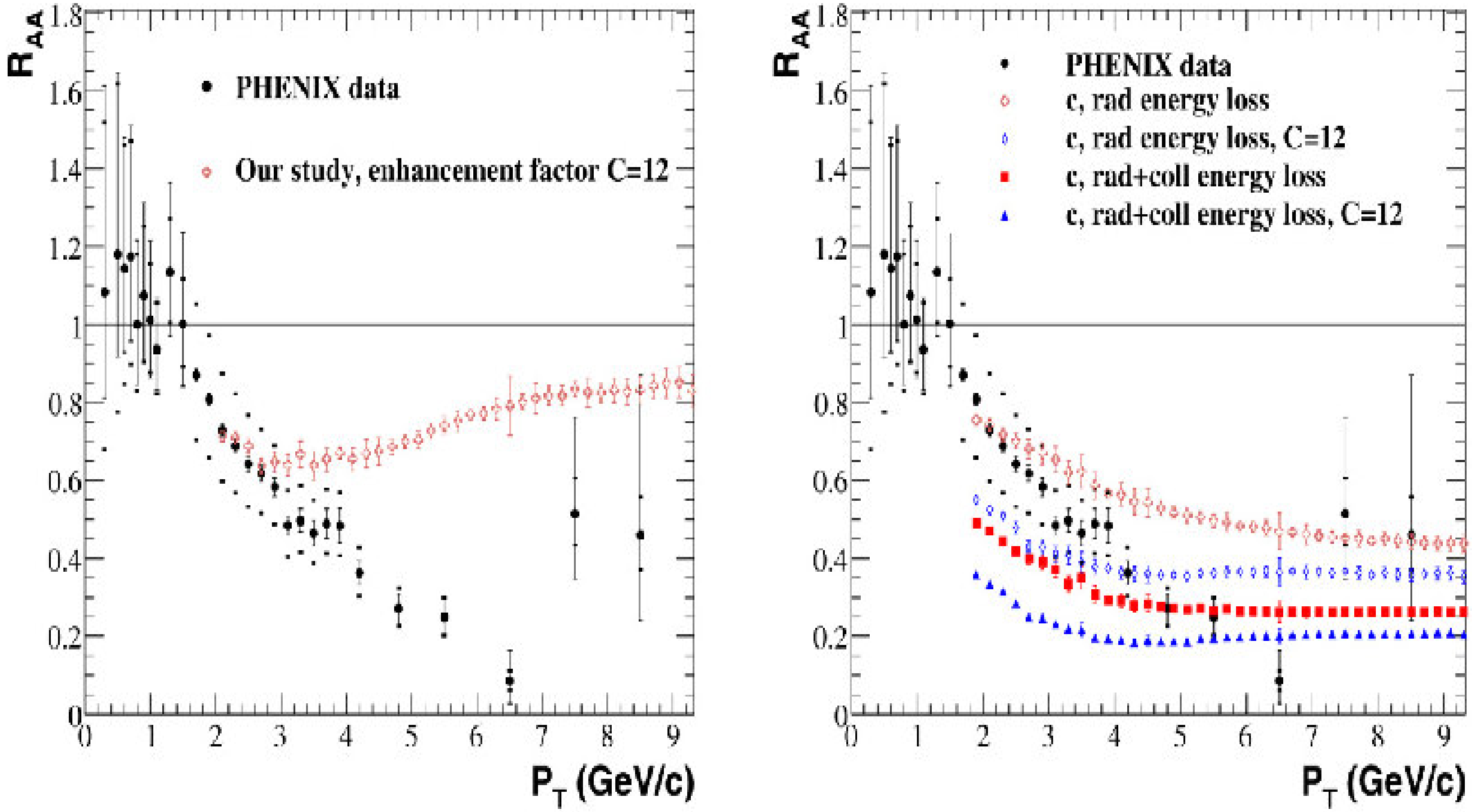
Enhancement of charmed baryon to meson ratio on non-photonic electrons in HIC

- Sorenson, EJPC 49, 379 (2007)



Assuming that same Λ_c/D^0 and Λ/K^0 ratios could also explain observed nuclear modification factor for charmed mesons

- Martinez-Garcia, Gadrat & Crotchet, PLB 663, 55 (2008)



Enhanced production of Λ_c lowers the nuclear modification factor for charm mesons

Diquark in sQGP and Λ_c enhancement

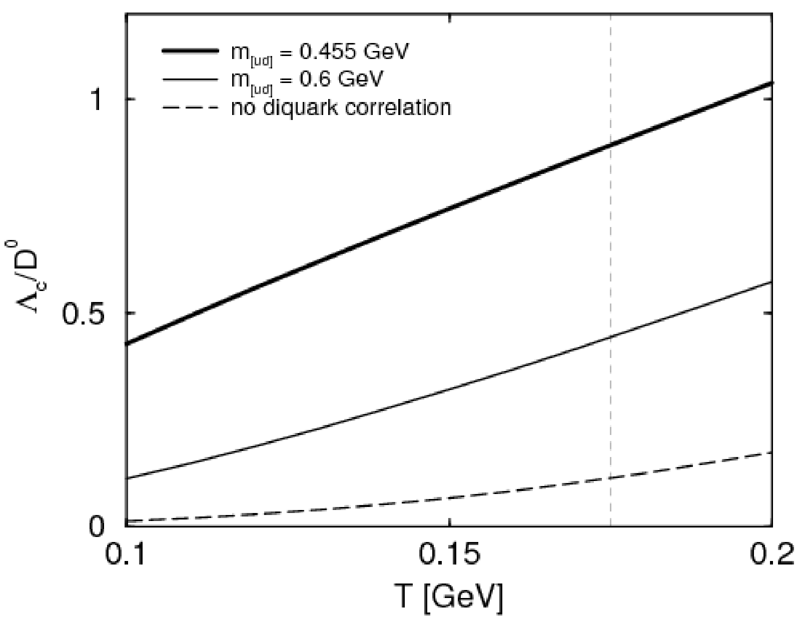
Lee, Yasui, Ohnishi, Yoo & Ko, PRL100, 222301 (2008)

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



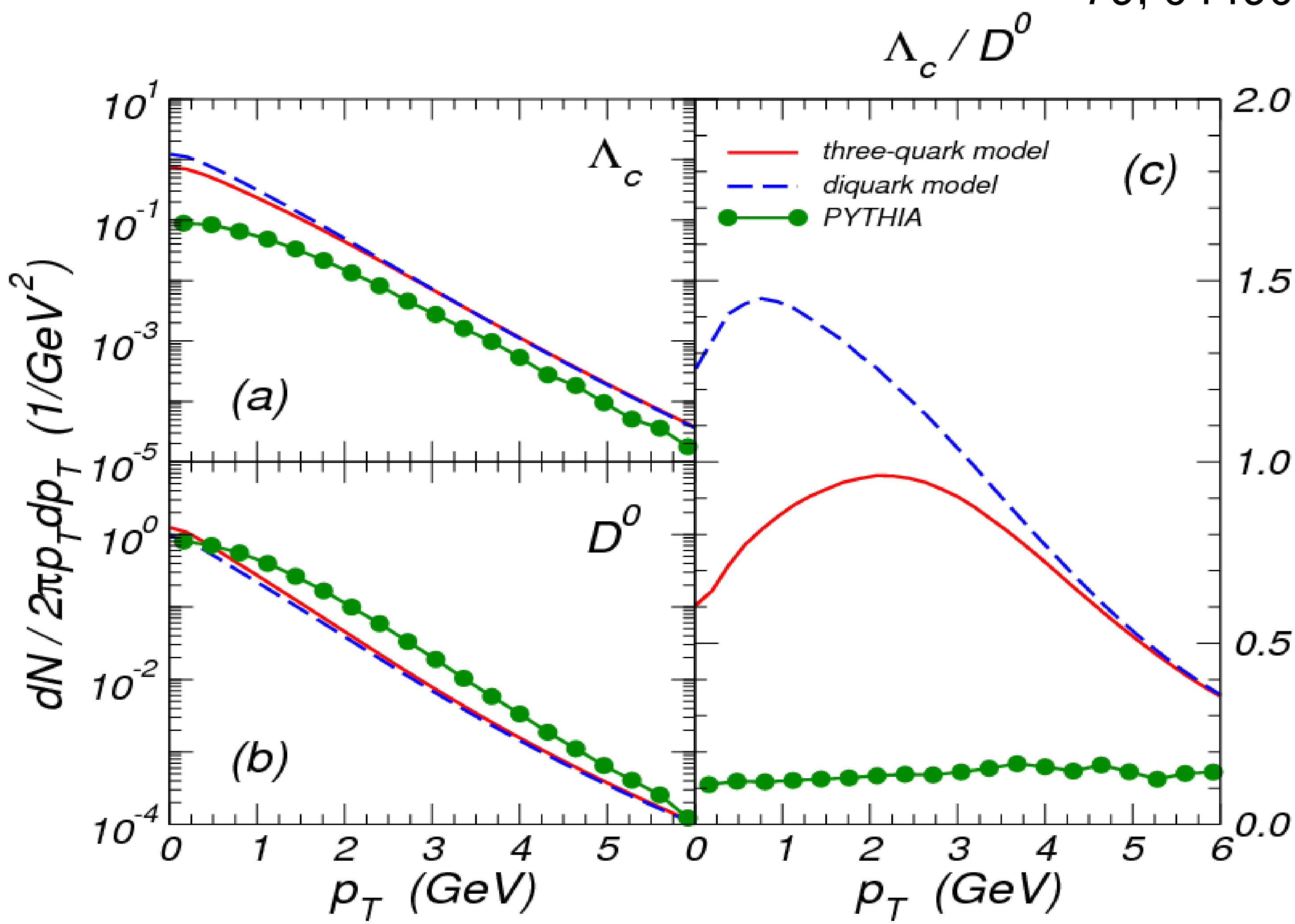
Statistical model

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

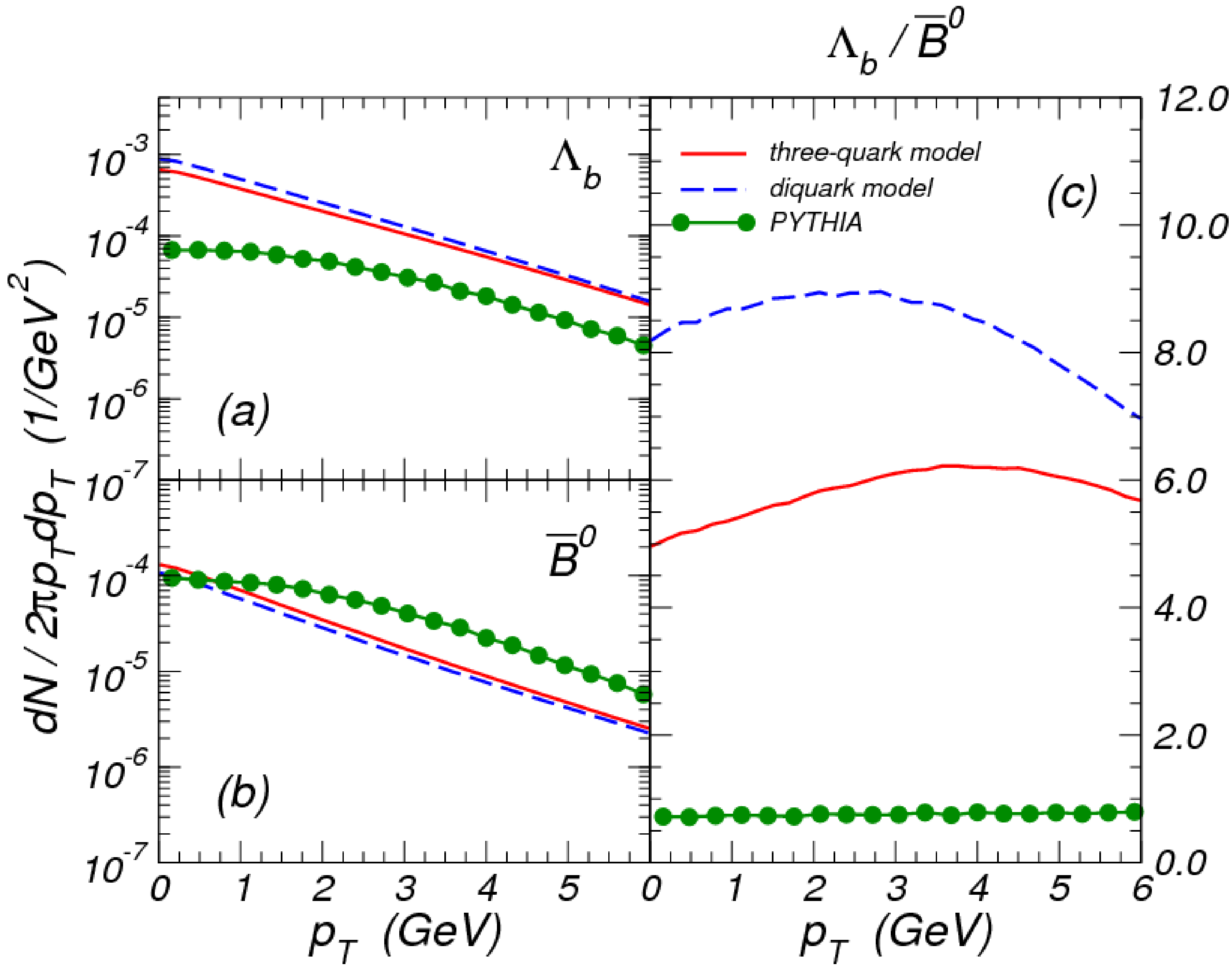
- Enhanced by a factor of 4-8
- Similar for Λ_B/B^0

Inclusion of resonances and fragmentation

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

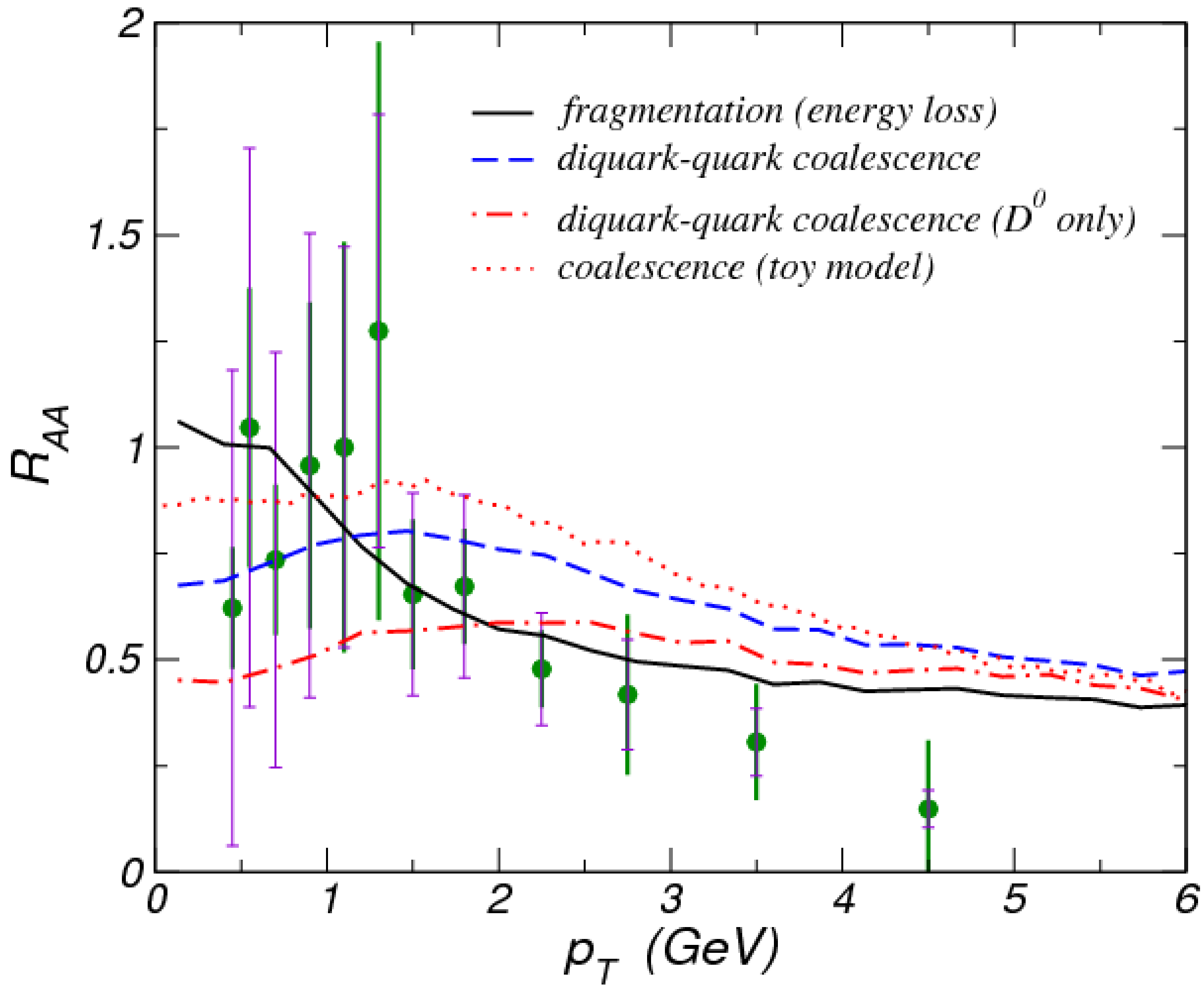


Including coalescence contribution enhances Λ_c/D^0 ratio, which is further enhanced by the presence of diquarks in QGP



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

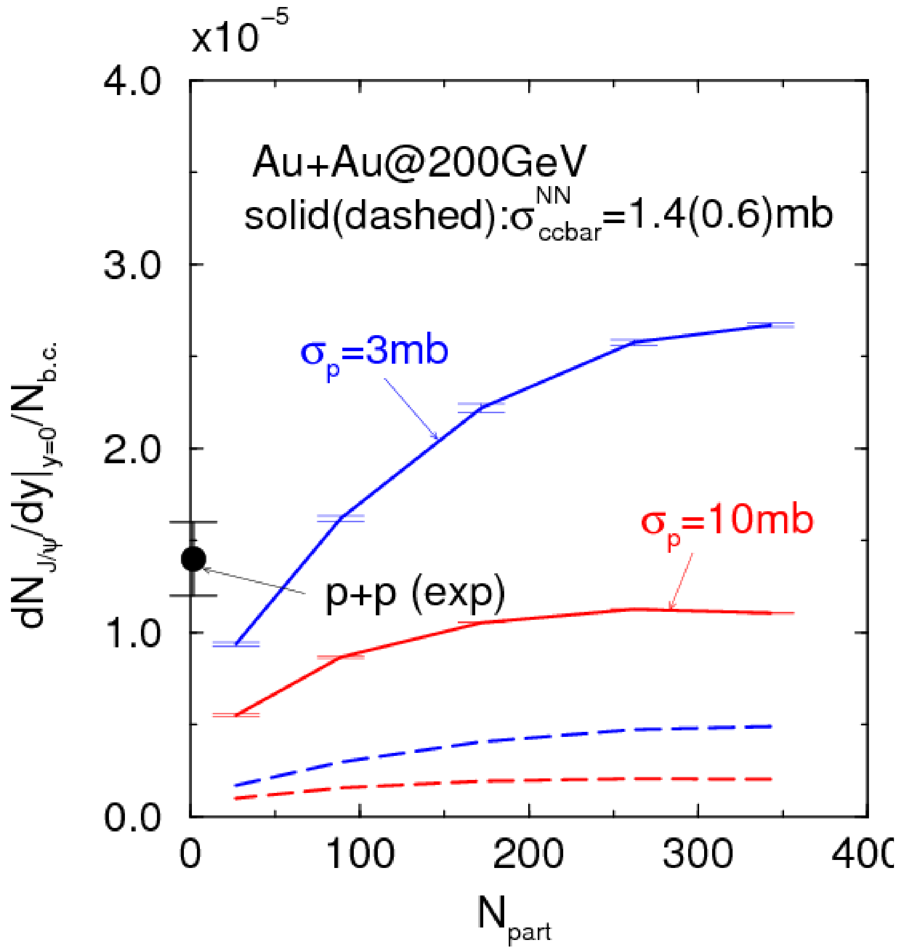
Effect of Λ_c enhancement on non-photonic electron R_{AA}

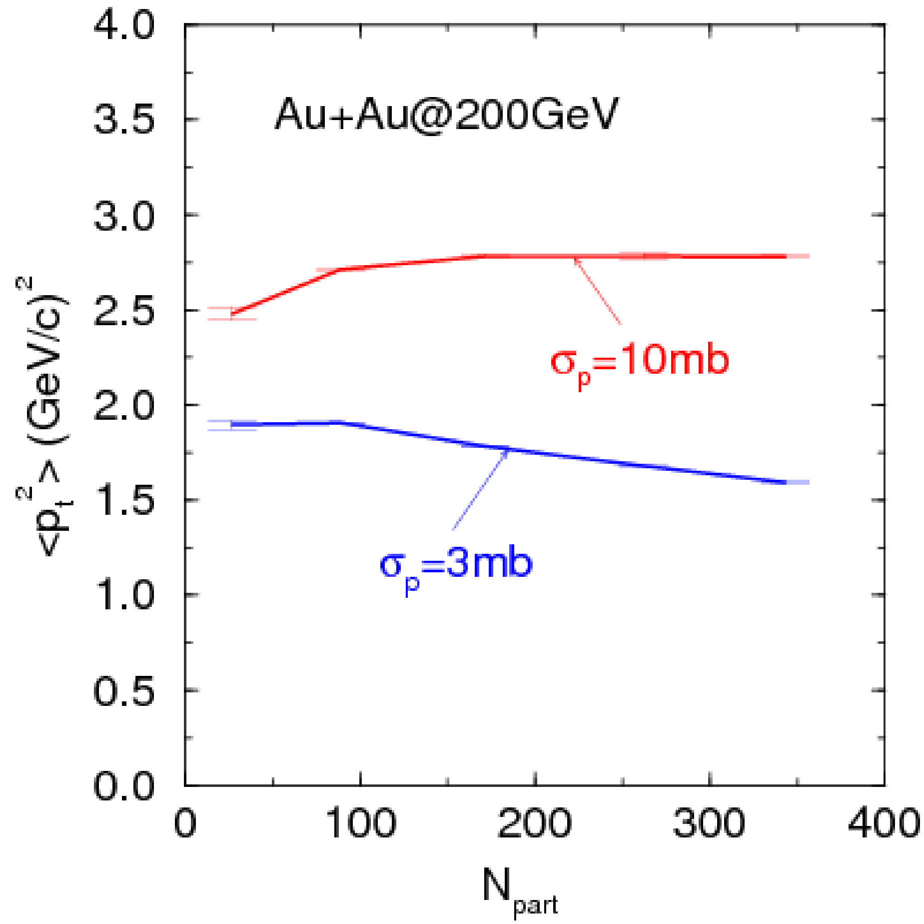


R_{AA} at large p_T increases as Λ_c enhancement is at low p_t

J/ψ production from charm quark coalescence

Zhang, PLB 647, 249 (2007)

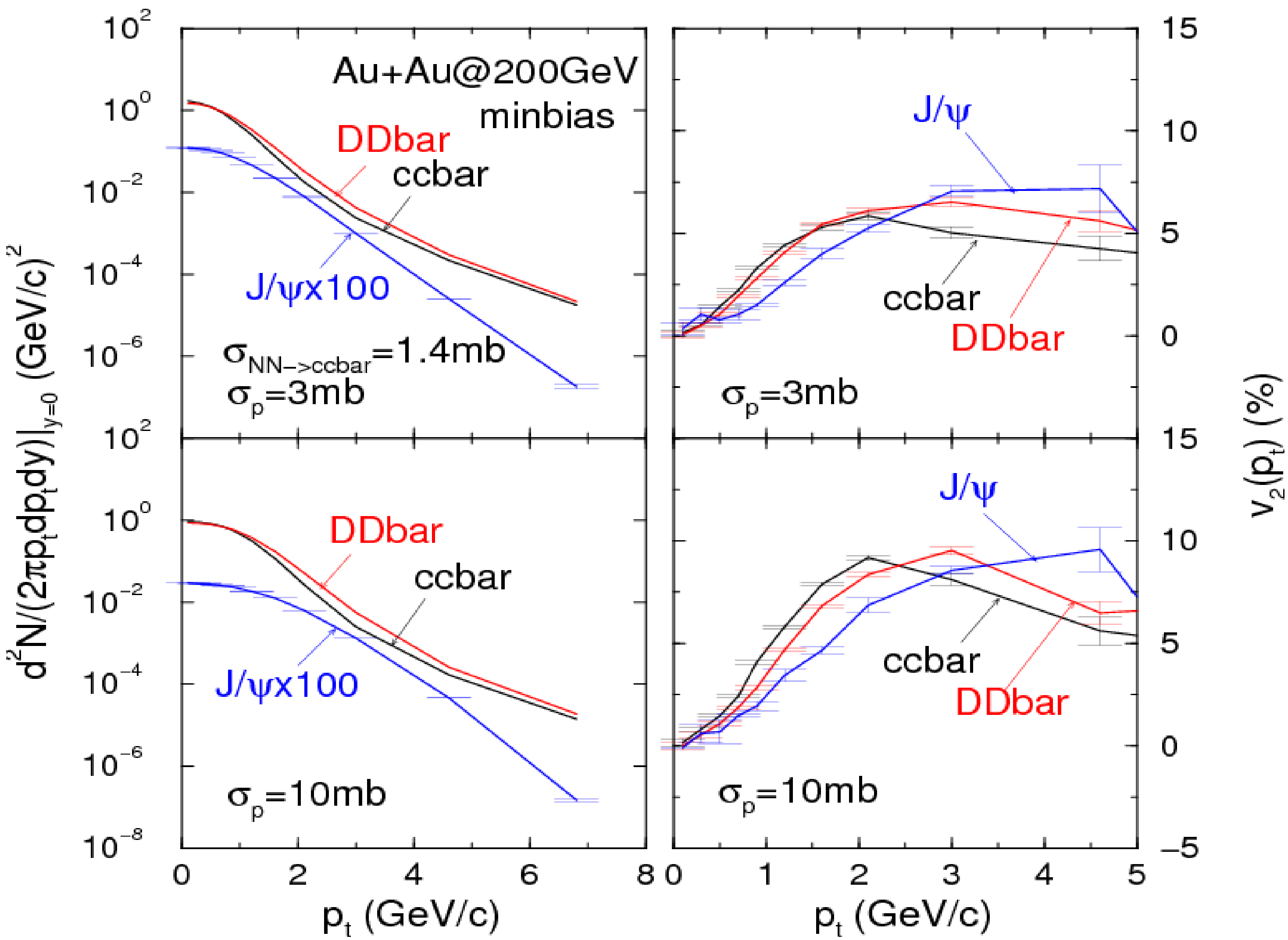




In AMPT, large (small) charm quark scattering cross section leads to suppressed (enhanced) yield but larger (smaller) average squared p_t.

Charmonium spectra and elliptic flow

Zhang, PLB 647, 249 (2007)



AMPT shows that charmonium elliptic flow is appreciable and increases with increasing parton cross sections

Charm production in HIC

- Direct production: Meuller, Wang (92); Vogt (94); Gavin (96) …..
  - Mainly from initial gluon fusions
  - About 3 pairs in mid-rapidity at RHIC (from STAR collaboration)
  - About 20 pairs in mid-rapidity at LHC

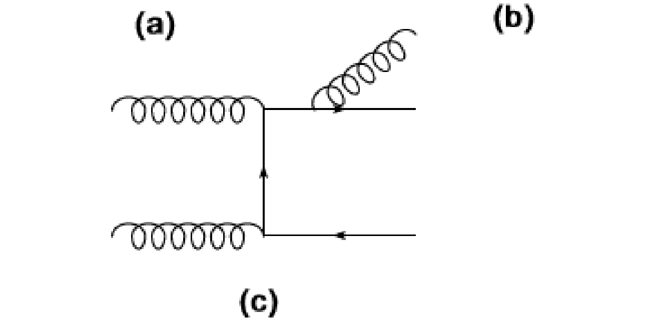
- Pre-thermal production: Lin, Gyulassy (95), Levai, Meuller, Wang (95)…..
  - Not important based on minijet gluons
  - Production from initial strong color field?

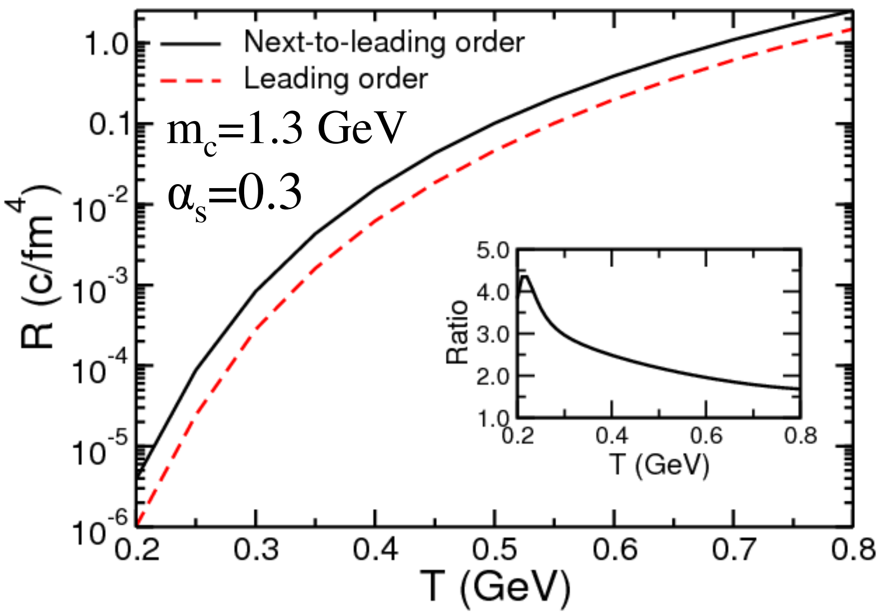
- Thermal production from QGP: Levai, Vogt (97), Braun-Munzinger, Redlish….
  - Based on leading-order calculations
  - Important if initial temperature of QGP is high

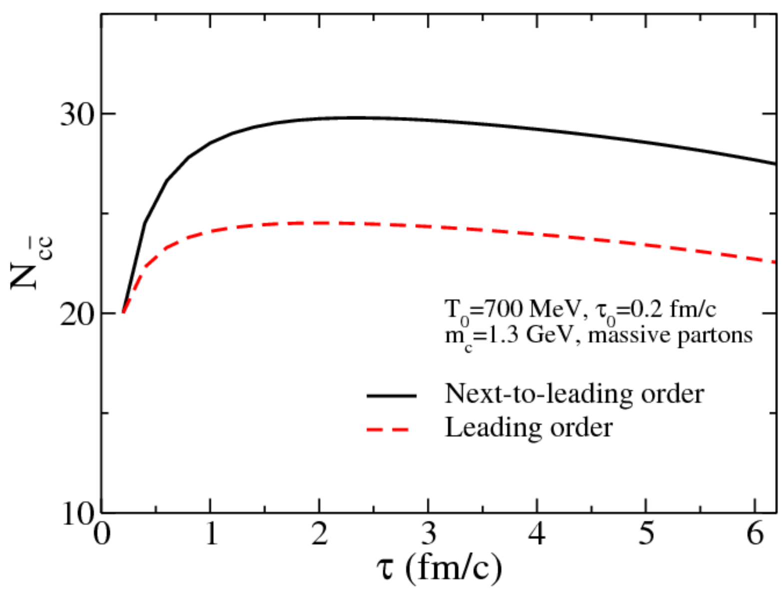
- Thermal production from hadronic matter: Cassing et al. (99), Liu & Ko (02)
  - $\pi N \rightarrow \Lambda_c D$ and $\rho N \rightarrow \Lambda_c D$
  - Small effect on charm production in HIC

Thermal charm production in QGP

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





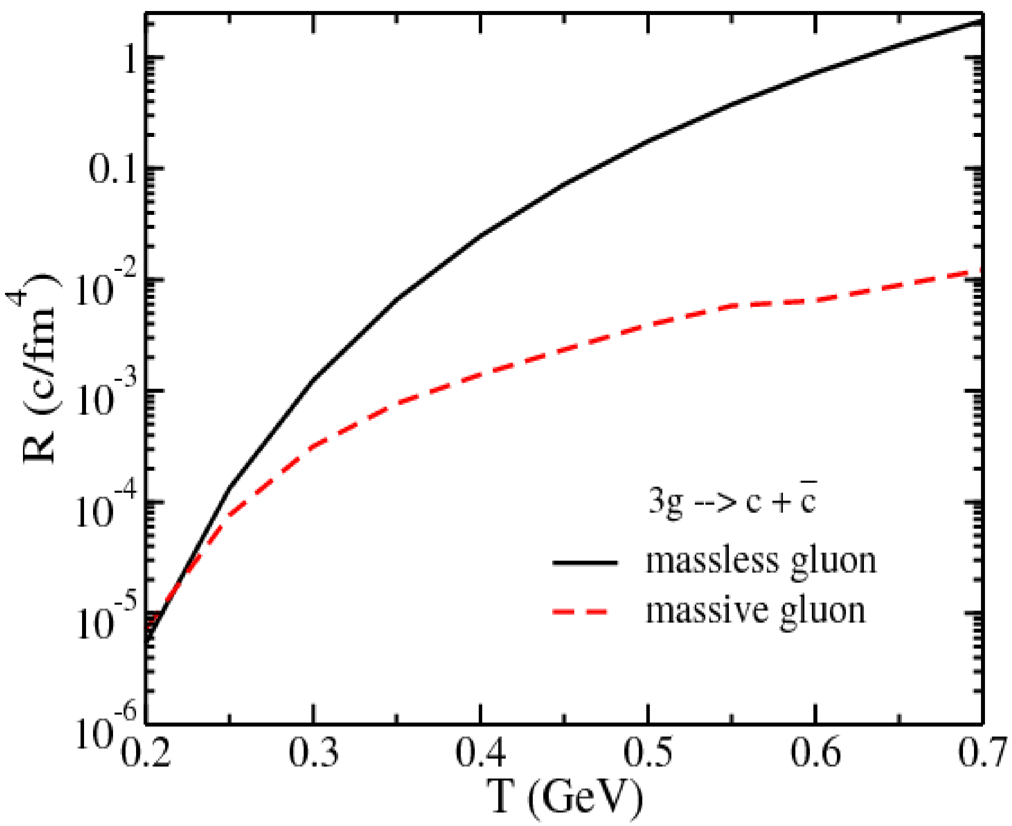


- Thermal production of c barc from gg, gq, and $q\bar{q}$ at LHC non-negligible
- Next-leading order and leading order contributions are comparable
- Insensitive to gluon masses
- Effect increases by about 2 for initial temperature T_0=750 MeV but decreases by ~ 3 for T_0=630 MeV

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

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



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

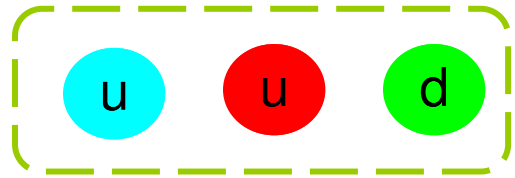
Quark color-spin interaction and hadron masses

Lee, Yasui, Liu & Ko, EPJC 54, 259 (2007))

- 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

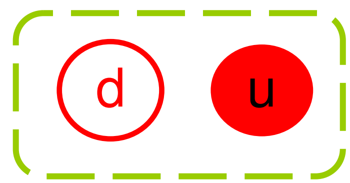


$$m_u = m_d = 300\,\text{MeV},\ m_s = 500\,\text{MeV},\ m_c = 1500\,\text{MeV},\ m_b = 4700\,\text{MeV}$$

- 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 ($ud\bar{q}_1\bar{q}_2$) mesons

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

$T_{q_1q_2}$ $(S=0)$ $-\frac{3}{4}\frac{C_B}{m_u^2}-\frac{3}{4}\frac{C_B}{m_{q_1}m_{q_2}}$	$u\bar{q}_1$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_1}}$	$d\bar{q}_2$ $(S=0)$ $-\frac{3}{4}\frac{C_M}{m_u m_{q_2}}$	$T_{q_1q_2}$ $-u\bar{q}_1-u\bar{q}_2$
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 (udus$\bar{q}$) baryons

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

Charm exotics production in HIC

Lee, Yasui, Liu & Ko, EPJC 54, 259 (2007)

- Charm tetraquark mesons

  - T_{cc} ($ud\bar{c}\bar{c}$) is ~ 80 MeV below D^+D^* according to quark model
  - 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 midrapidity charm quark numbers 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 in quark model
  - Yield is ~$1.2X10^{-4}$ at RHIC and ~$7.9X10^{-4}$ at LHC from the coalescence model for midrapidity 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

$D_{sj}(2317)$: $J^{\pi}=0^{+}$

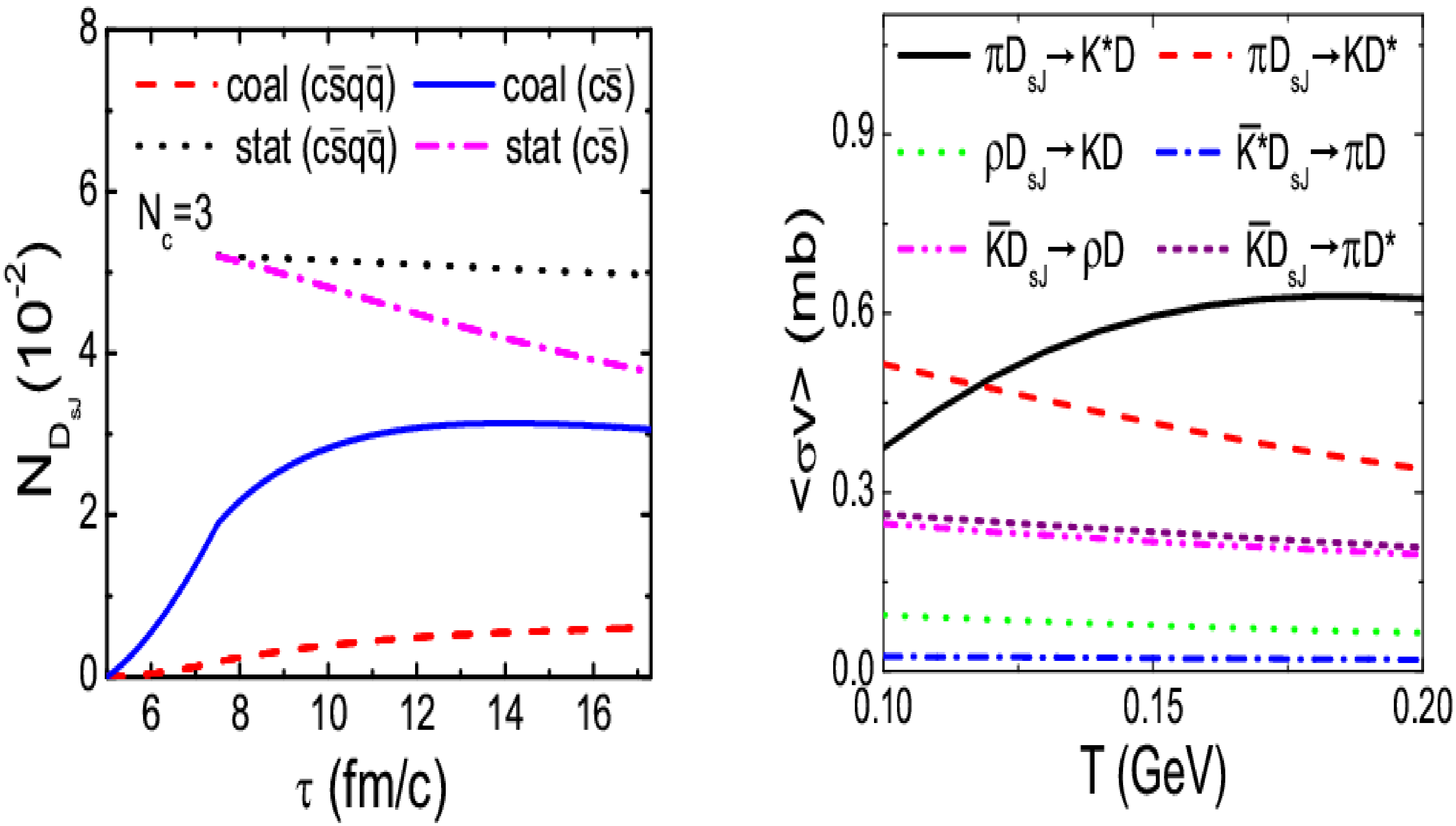
- Mass of 2317 MeV less than those predicted by quark model and QCD sum rule for two-quark state ($c\bar{s}$) but comparable to those for four-quark state ($c\bar{s}q\bar{q}$)

- Width of a few (two-quark) to a few tens (four quark) keV from decay to isospin violated channel of $D_s\pi$, empirically less than 4.6 MeV limited by 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, 014906 (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}

Summary

- Charm quarks interact strongly in QGP and including heavy quark three-body scattering in QGP helps to explain observed nuclear modification factor of electrons from heavy meson decays.
- Existence of diquarks in QGP enhances Λ_c and Λ_b production at RHIC and affects the yield of heavy mesons and thus the nuclear modification factor of electrons from charm meson decays.
- Charmonium regeneration is non-negligible at RHIC and expect appreciable charmonium elliptic flow.
- Thermal charm production could be important at LHC as the production rate increases exponentially with the temperature of QGP.
- Enhanced charm production at LHC offers the opportunity to search for possible charmed exotics such as T_{cc}, Θ_{cs} and D_{sj}.