Charms in heavy ion collisions

Che-Ming Ko
Texas A&M University

- Charm flow and energy loss
- Charmed baryon-to-meson ratios
- Charmonium production and flow
- Charm at LHC
- Charmonia in dense matter

Collaborators: Su Houng Lee (Yonsei Univ.), Yongseok Oh (TAMU), Shigehiro Yasui (KEK), Ben-wei Zhang (Huazhong Normal Univ.), Bin Zhang (Arkansas State Univ.) …..

Supported by National Science Foundation and The Welch Foundation

Coalescence model

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 $f_q(x, p)$

$$\int p \cdot d\sigma \frac{d^3 p}{(2\pi)^3 E} f_q(x, p) = N_q$$

Coalescence probability function

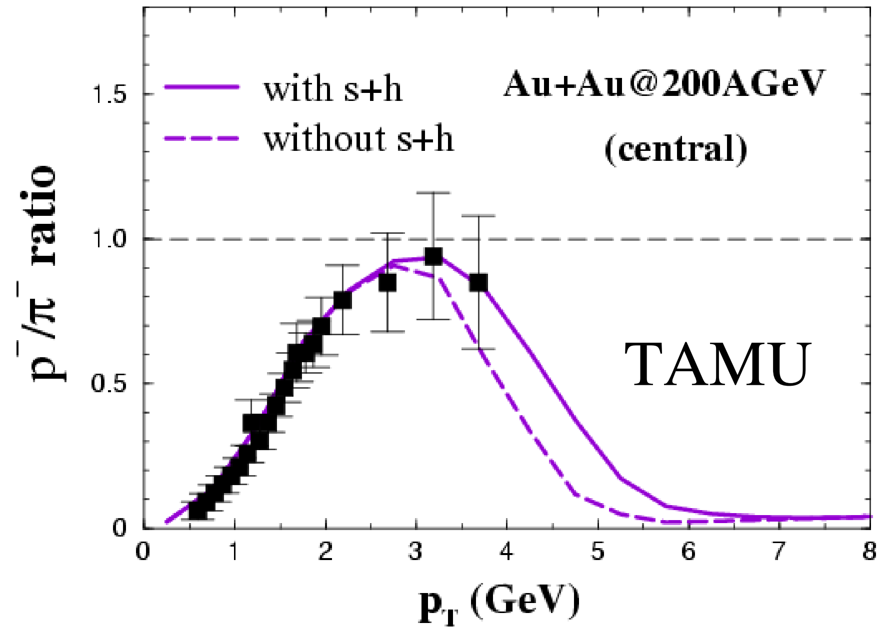
$$f_M(x_1, x_2; p_1, p_2) = f_2(x_1 - x_2; p_1 - p_2)$$
$$= \exp[(x_1 - x_2)^2 / 2\Delta_x^2]$$
$$\times \exp\{[(p_1 - p_2)^2 - (m_1 - m_2)^2]/2\Delta_p^2\}$$

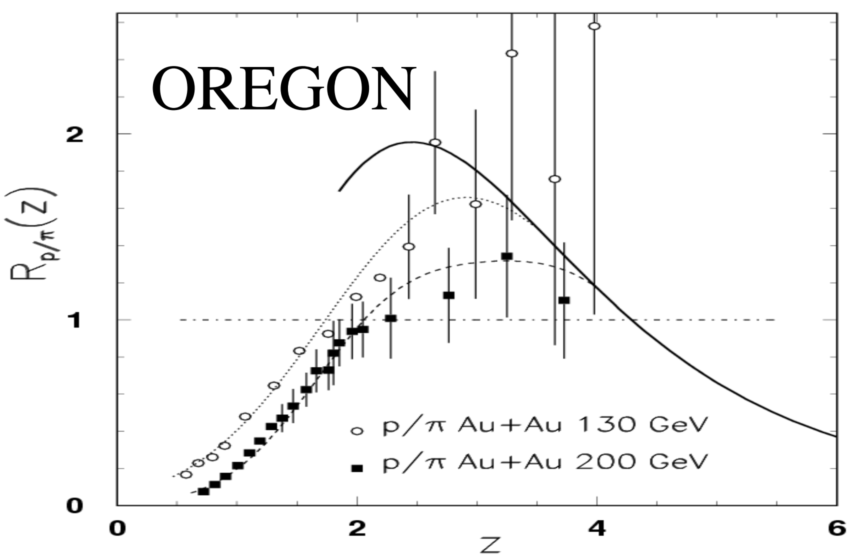
$\Delta_x \cdot \Delta_p \geq \hbar$

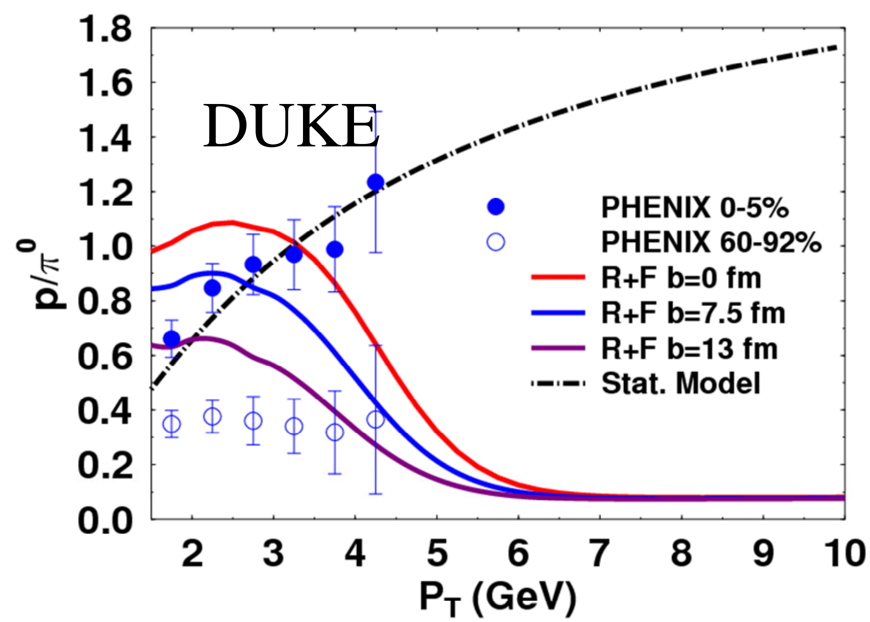
For baryons, Jacobi coordinates for three-body system are used.

Large proton to pion ratio

Quark coalescence or recombination can also explain observed large p/pi ratio at intermediate transverse momentum 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

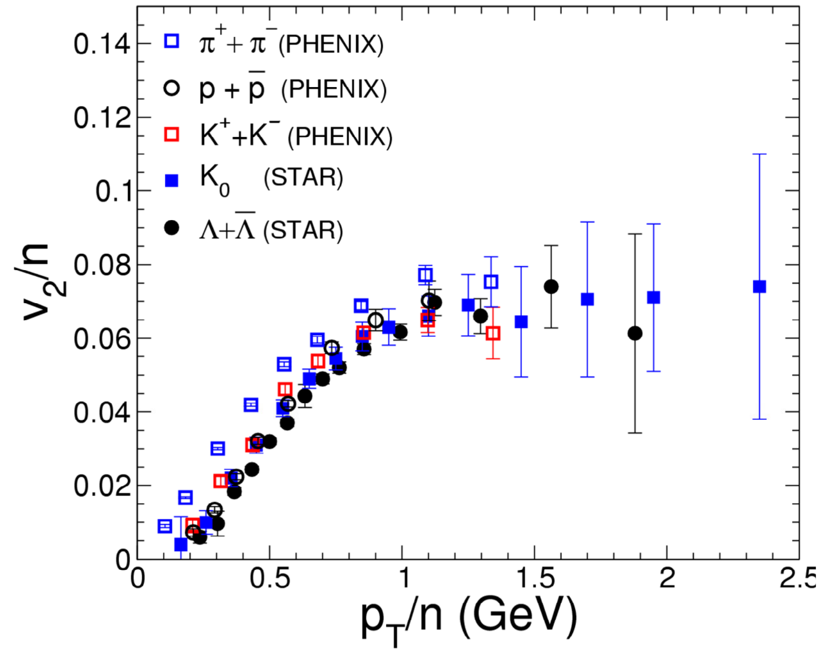
$$f_q(p_T) \propto 1 + 2v_{2,q}(p_T)\cos(2\phi)$$

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):

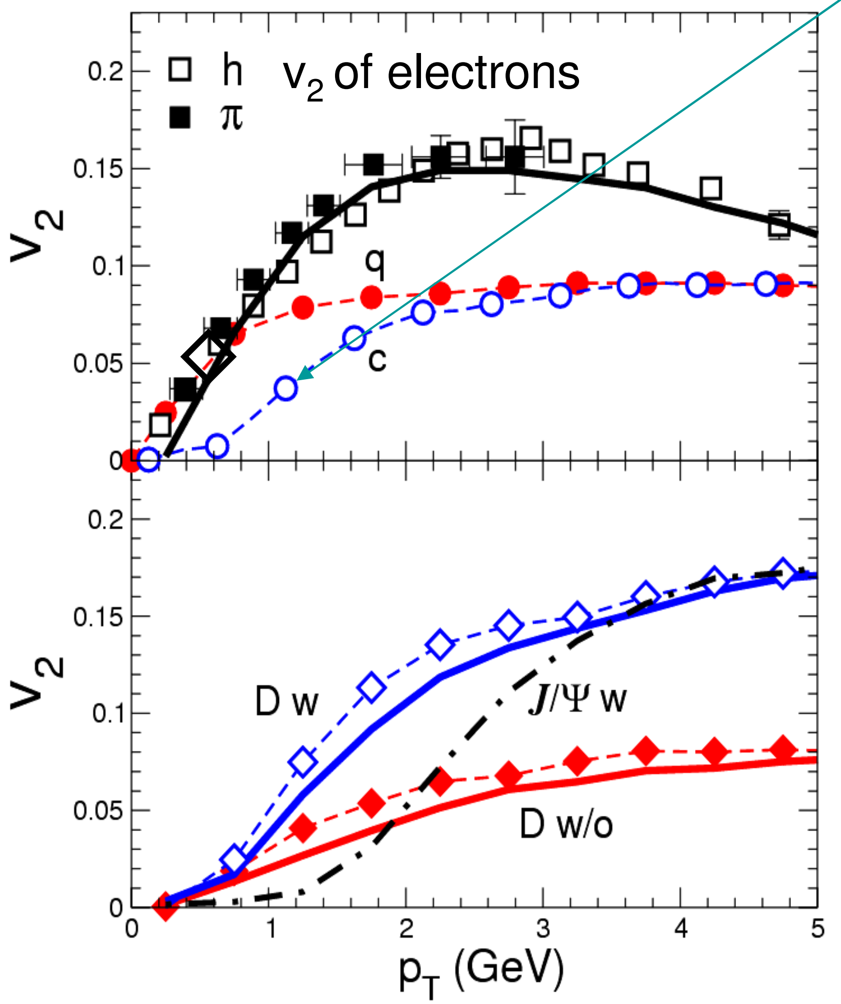
$$\frac{1}{n} v_2(p_T/n)$$

same for mesons and baryons

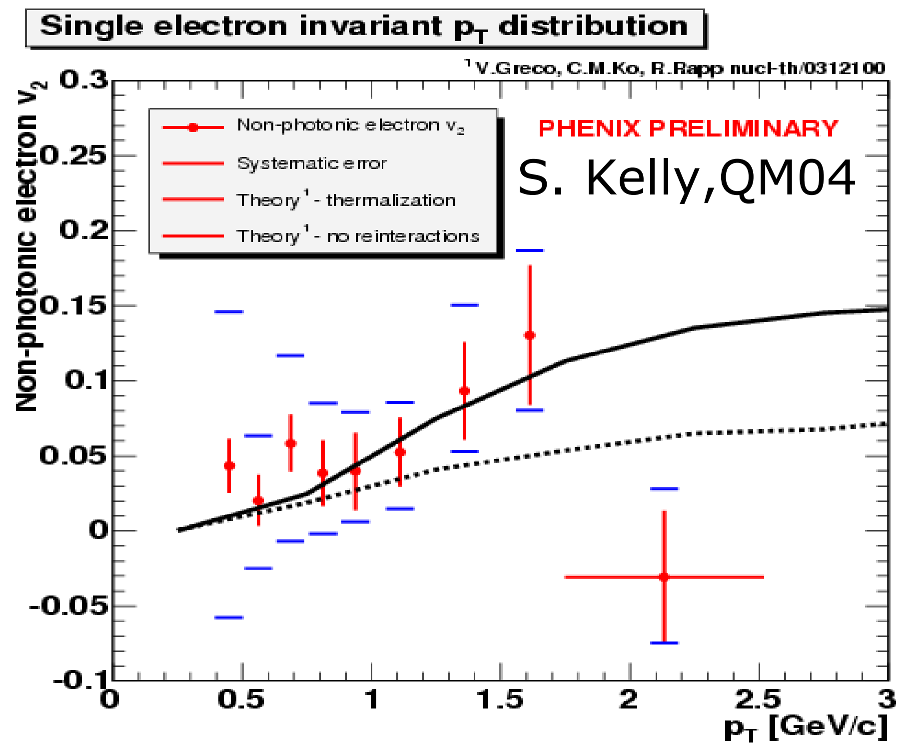
Charmed meson elliptic flow

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

Parton cascade

Bin Zhang, Comp. Phys. Comm. 109, 193 (1998)
D. Molnar, B.H. Sa, Z. Xu & C. Greiner

$$p^{\mu}\,\partial_{\mu} f_1(x,p,t) \propto \int dp_2 d\Omega \left|\vec{v}_1 - \vec{v}_2\right| \frac{d\sigma}{d\Omega}\left(f_1' f_2' - f_1 f_2\right)$$

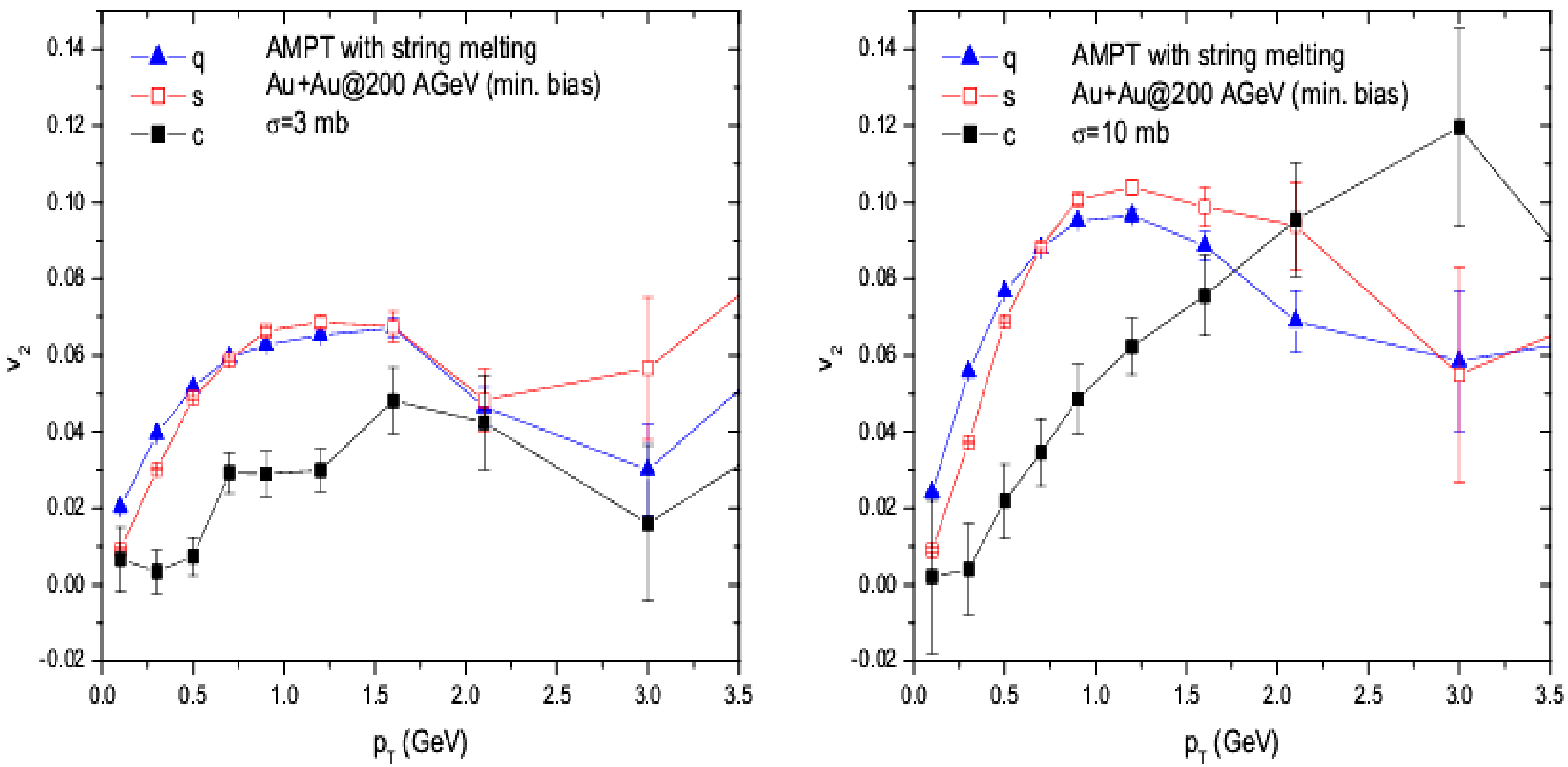
$$\frac{d\sigma}{dt} \approx \frac{9\pi\alpha_s^2}{2(t - \mu^2)^2}, \qquad \sigma = \frac{9\pi\alpha_s^2}{2\mu^2}\frac{1}{1+\mu^2/s}$$

- Using α_s=0.5 and screening mass μ=gT≈0.6 GeV at T≈0.25 GeV, then $\langle s\rangle^{1/2}$≈4.2T≈1 GeV, and pQCD gives σ≈2.5 mb and a transport cross section

$$\sigma_t \equiv \int d\Omega \frac{d\sigma}{d\Omega}(1-\cos\theta) \approx 1.5\,\text{mb}$$

- σ=6 mb → μ≈0.44 GeV, σ_t≈2.7 mb
- σ=10 mb → μ≈0.35 GeV, σ_t≈3.6 mb

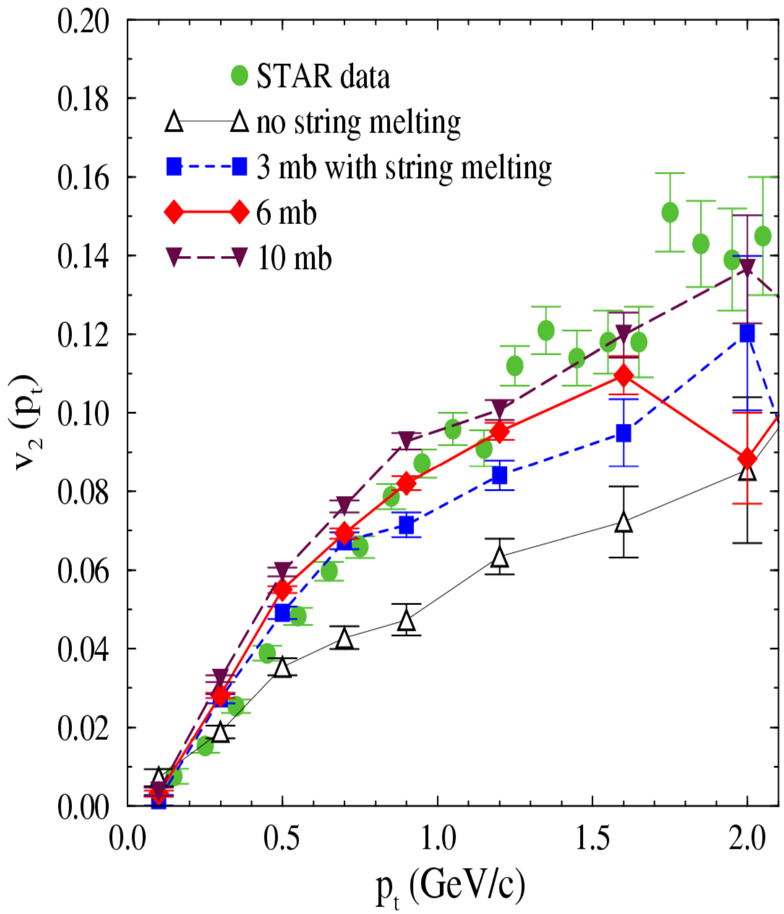
Charm quark elliptic flow from AMPT

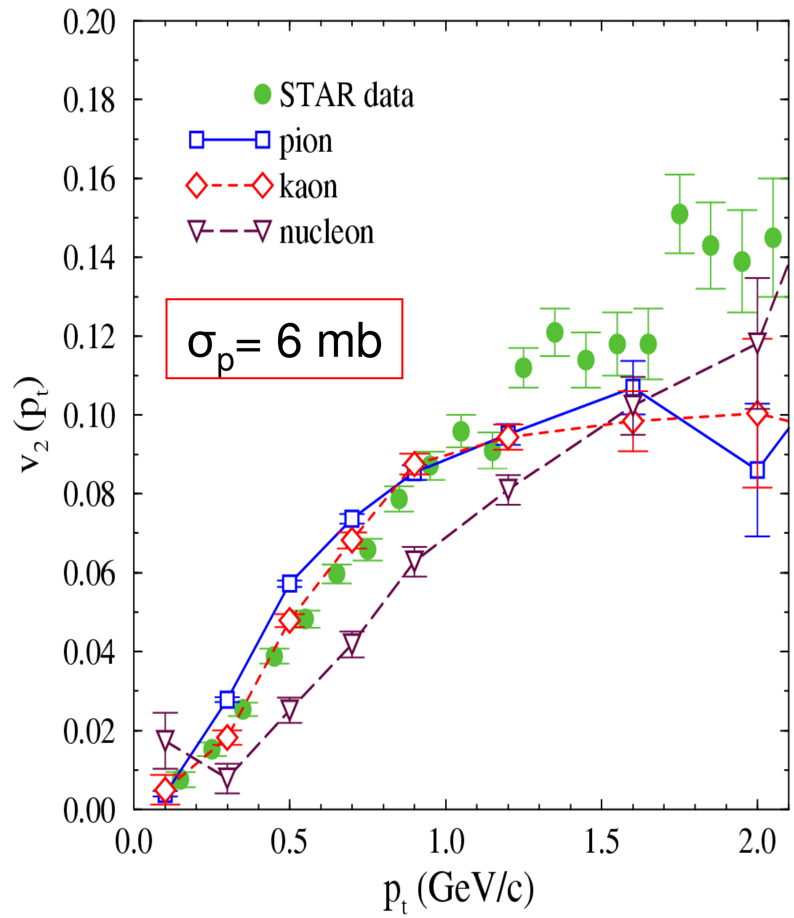


- P_T dependence of charm quark v_2 is different from that of light quarks
- At high p_T, charm quark has similar v_2 as light quarks
- Charm elliptic flow is also sensitive to parton cross sections

Elliptic flow from AMPT

Lin & Ko, PRC 65, 034904 (2002)

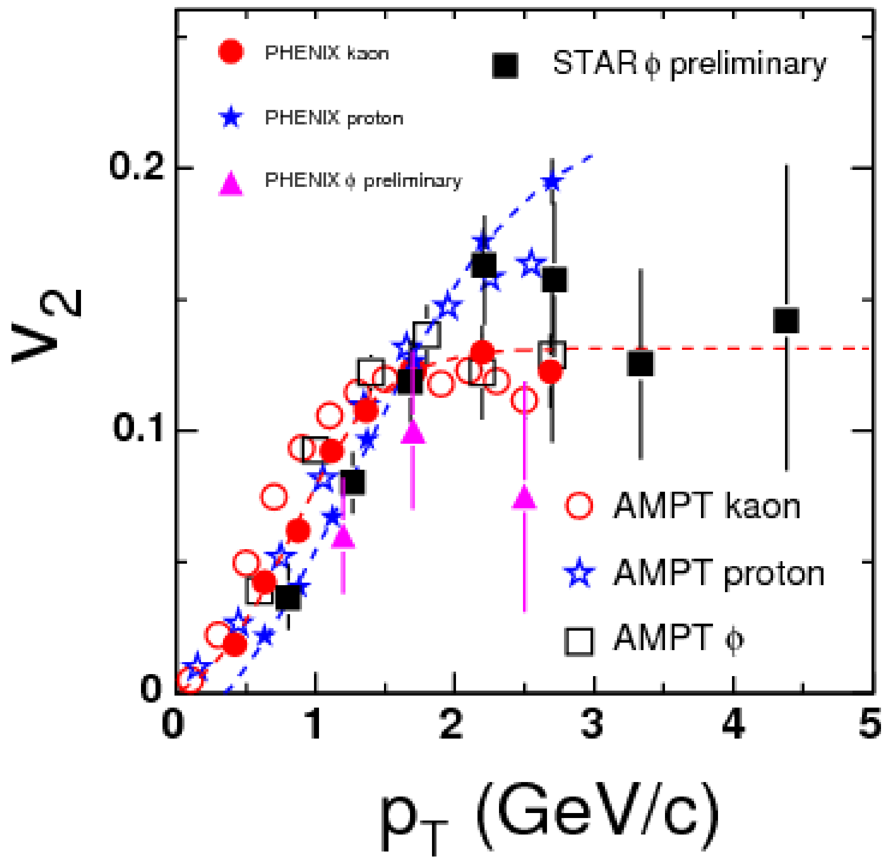


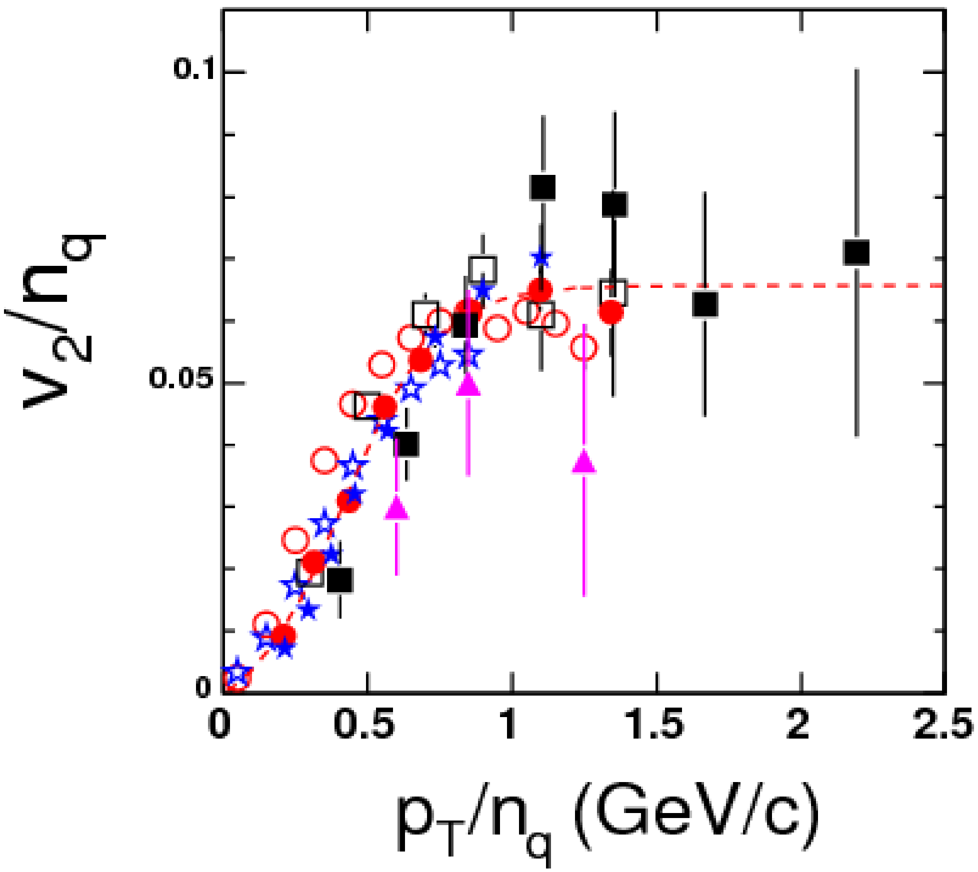


- Need string melting and large parton scattering cross section
- Mass ordering of v_2 at low p_T as in hydrodynamic model

Phi flow from AMPT

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

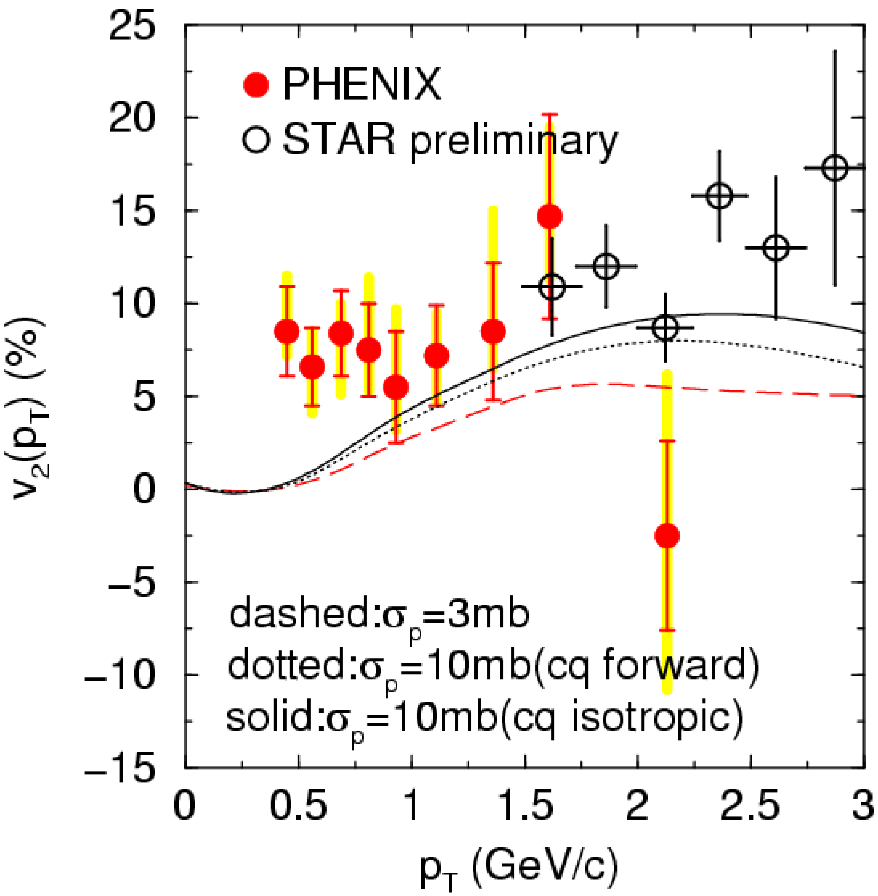


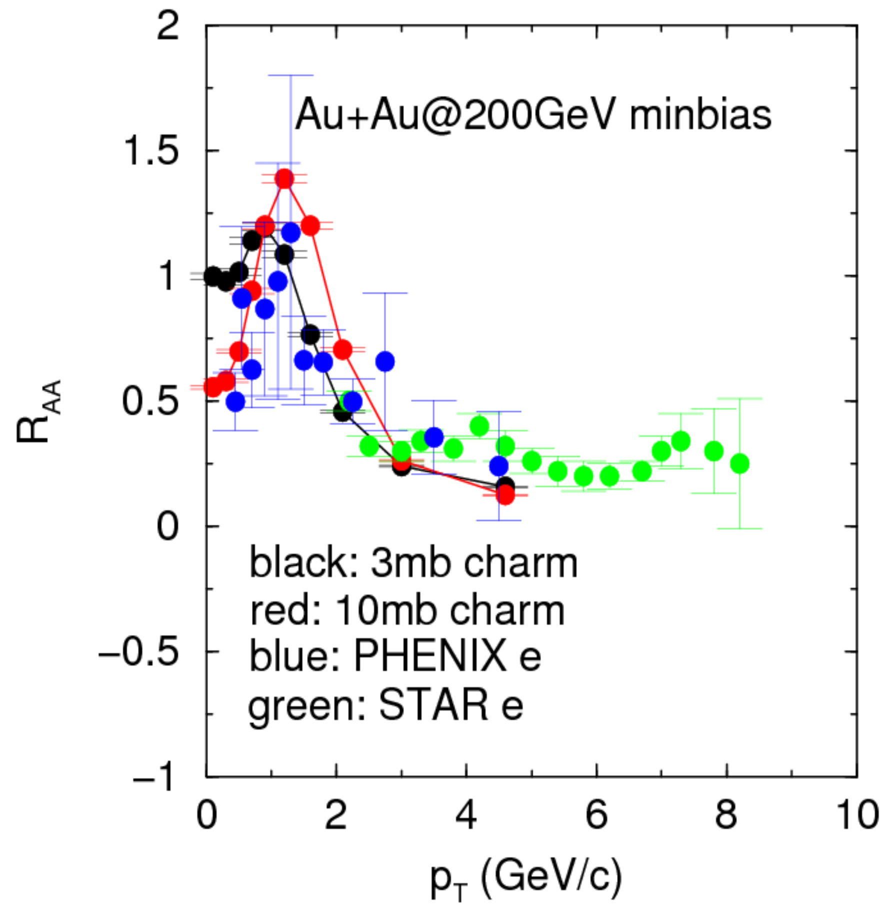


Phi meson v_2 is similar to that of kaon → quark number scaling

Charm R_{AA} and elliptic flow from AMPT

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

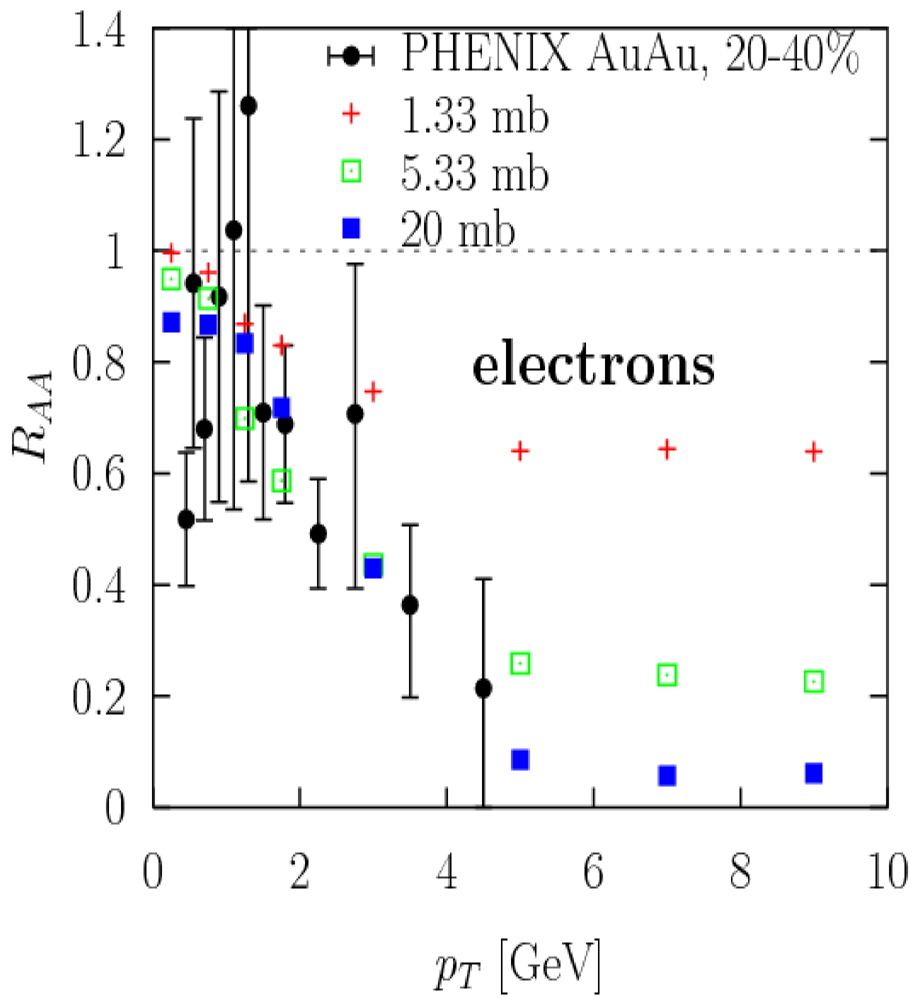


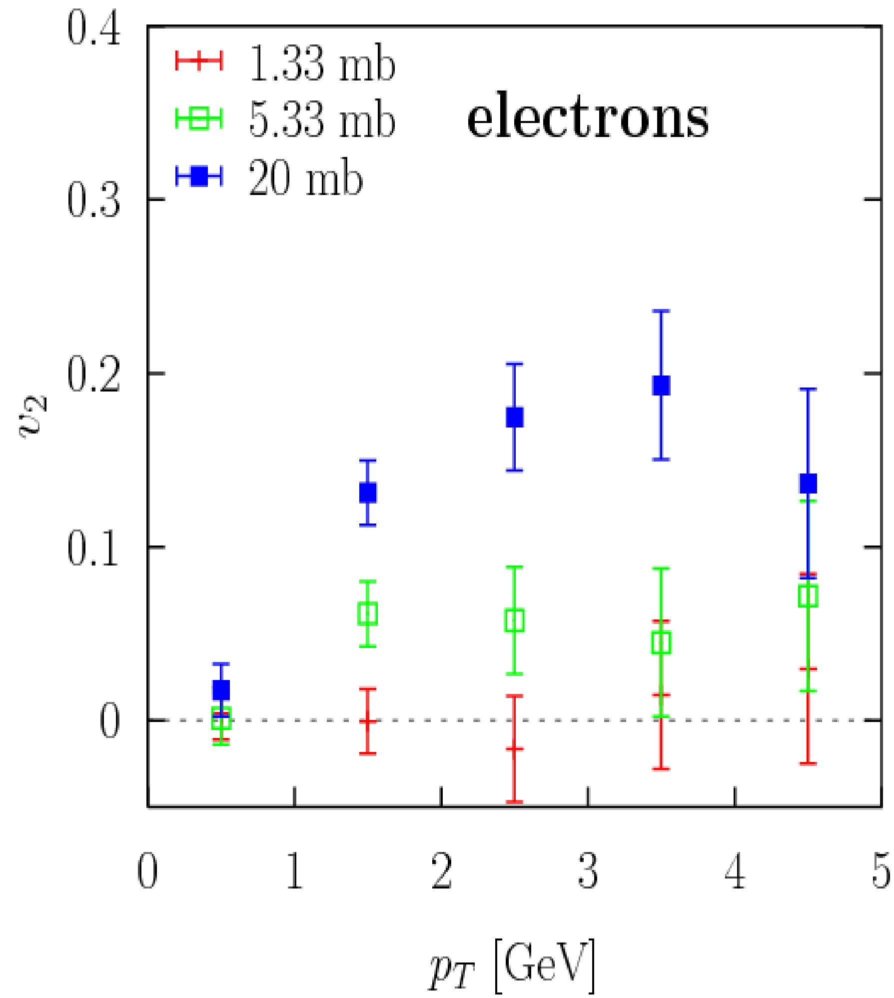


- Need large charm scattering cross section to explain data
- Smaller charmed meson elliptic flow is due to use of current light quark masses

Charm suppression and elliptic flow

D. Molnar
EPJ C49, 181 (2007)

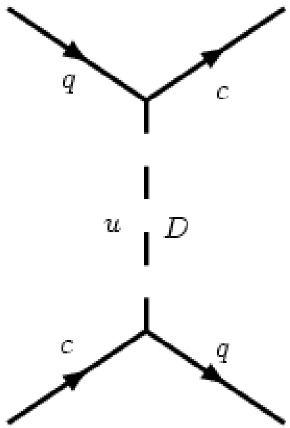




Large parton cross sections are needed to explain data

Resonance effect on charm scattering in QGP

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



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

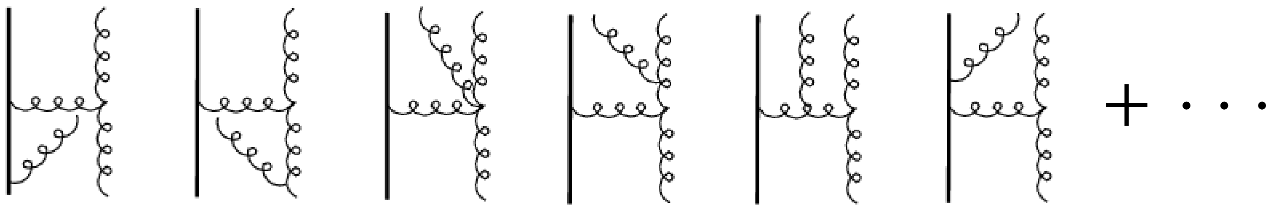
With $m_c \approx 1.5$ GeV, $m_q \approx 5\text{-}10$ MeV, $m_D \approx 2$ GeV, $\Gamma_D \approx 0.3\text{-}0.5$ GeV, and including scalar, pseudoscalar, vector, and axial vector D mesons gives

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

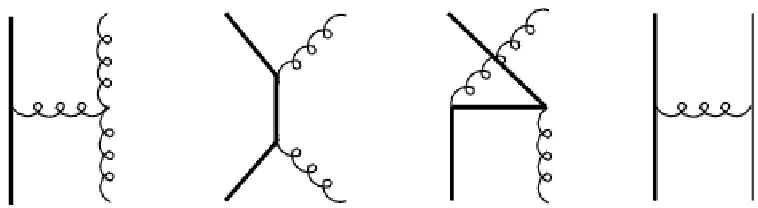
Since the cross section is isotropic, the transport cross section is 6 mb, which is about 4 times larger than that due to pQCD t-channel diagrams, leading to a charm quark drag coefficient γ ~ 0.16 c/fm in QGP at T=225 MeV.

Heavy quark energy loss in pQCD

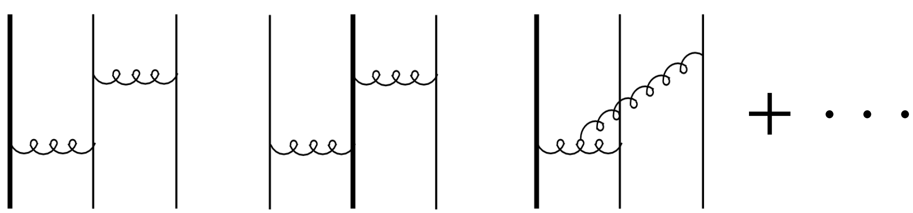
a) Radiative energy loss (Amesto *et al.,* hep-ph/0511257)



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

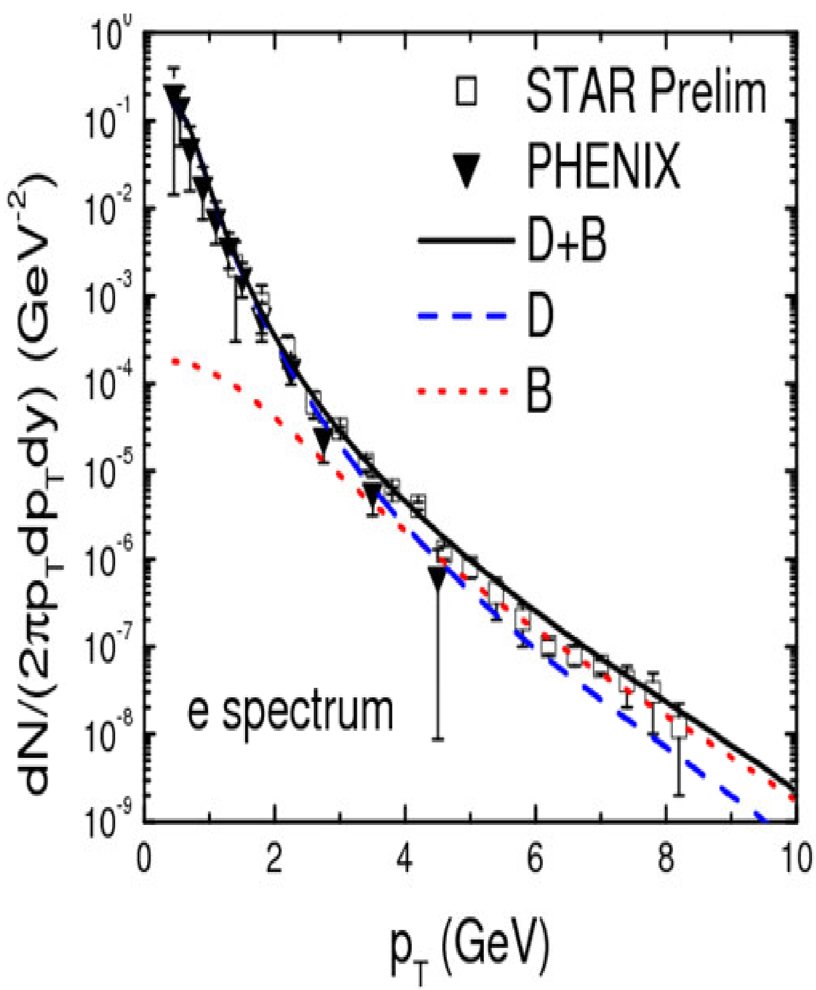
a) + 

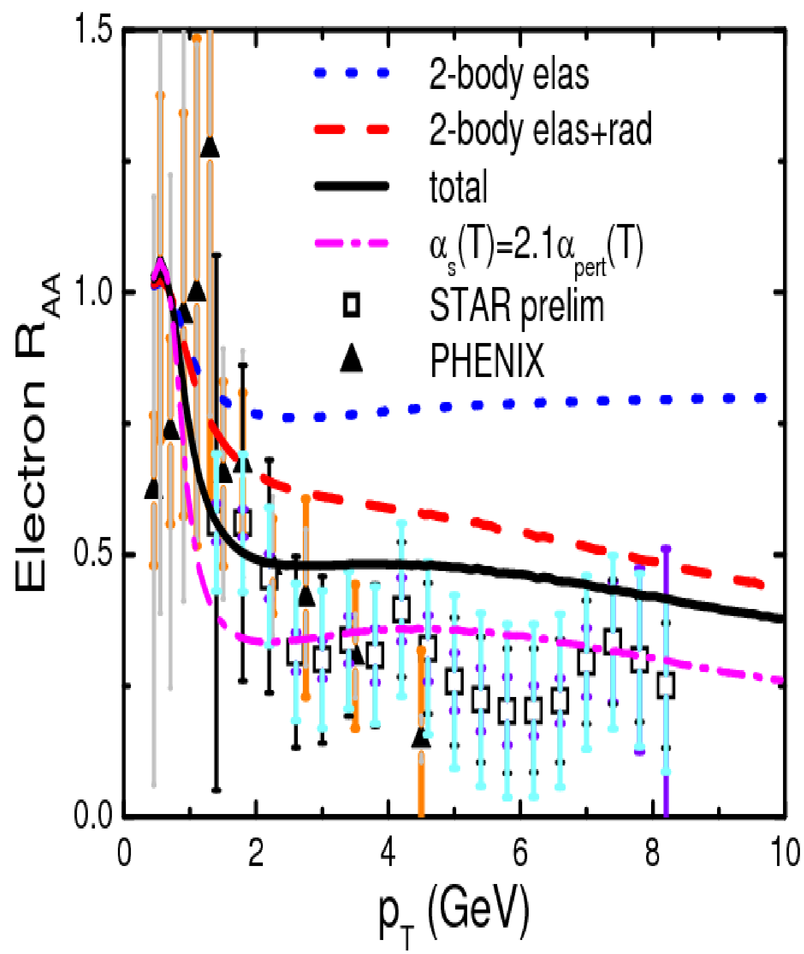
c) Three-body elastic scattering (Liu & Ko, nucl-th/0603004)

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

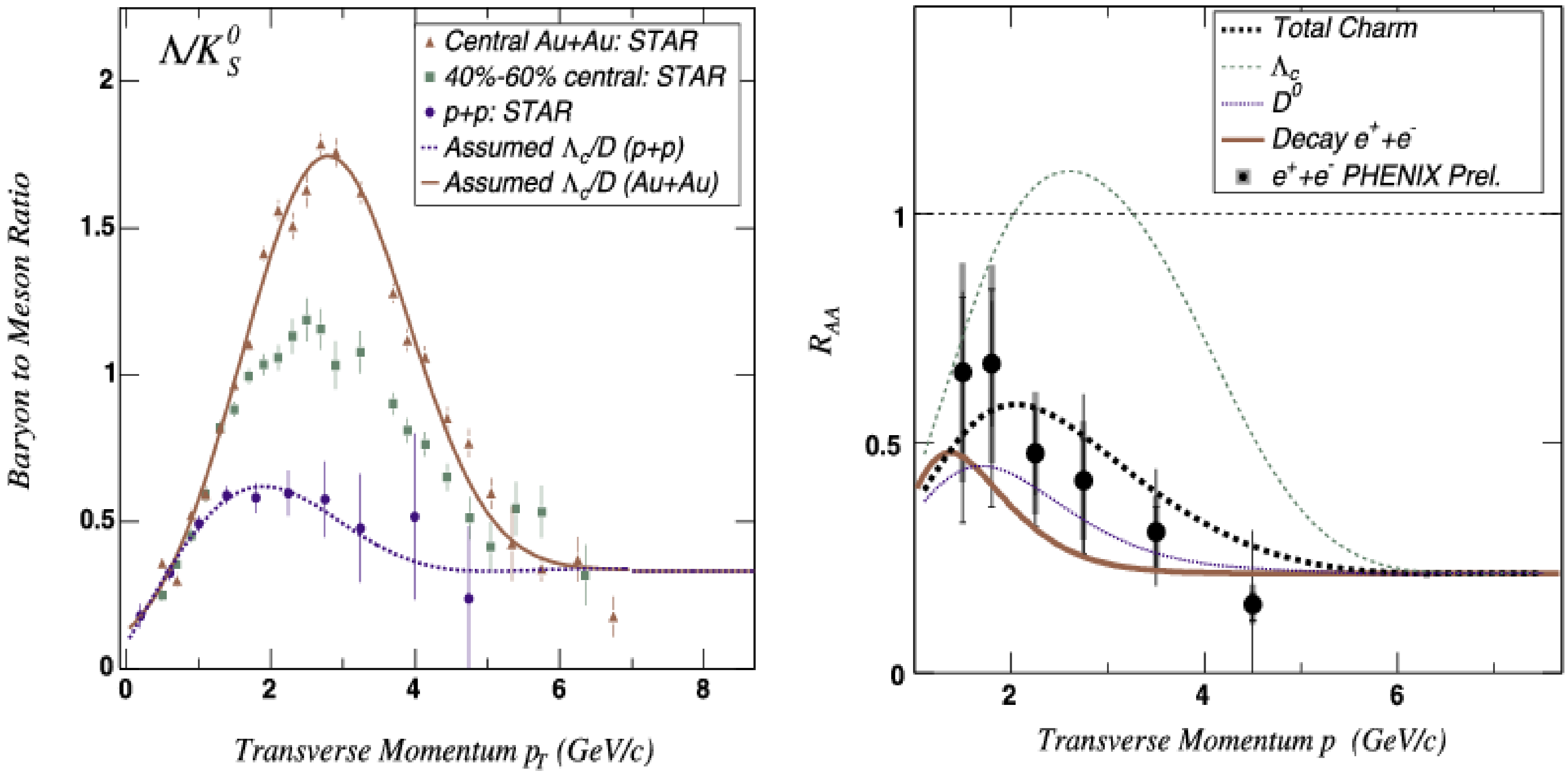




Reasonable agreement with data from Au+Au @ 200A GeV after including heavy quark three-body scattering and increasing α_s by 2 as given by lattice QCD.

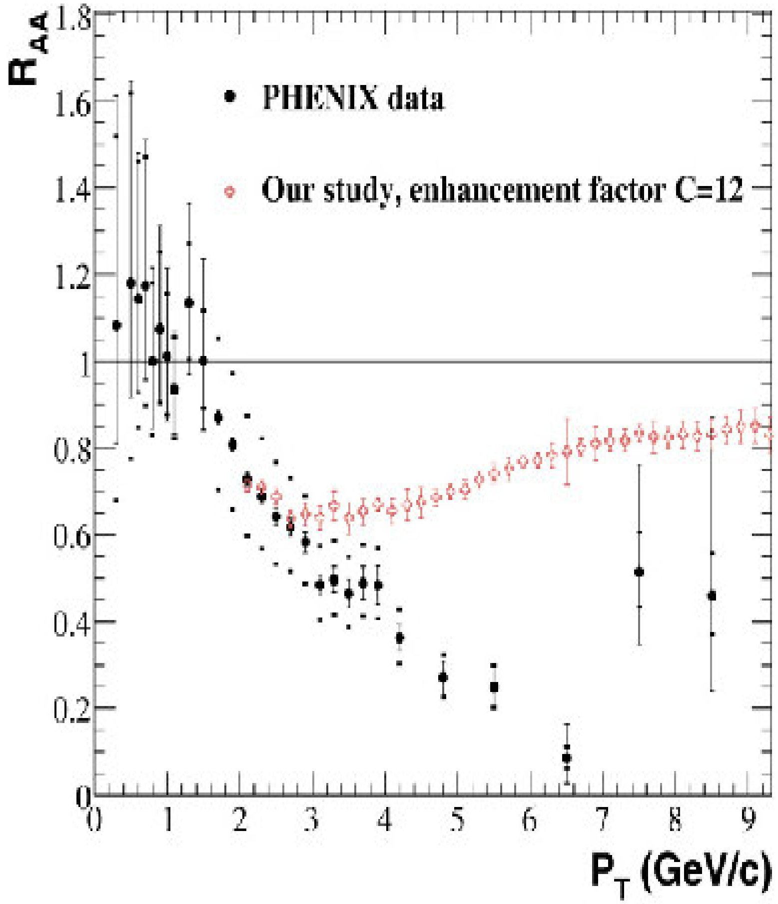
Enhancement of charmed baryon to meson ratio on non-photonic electrons in HIC

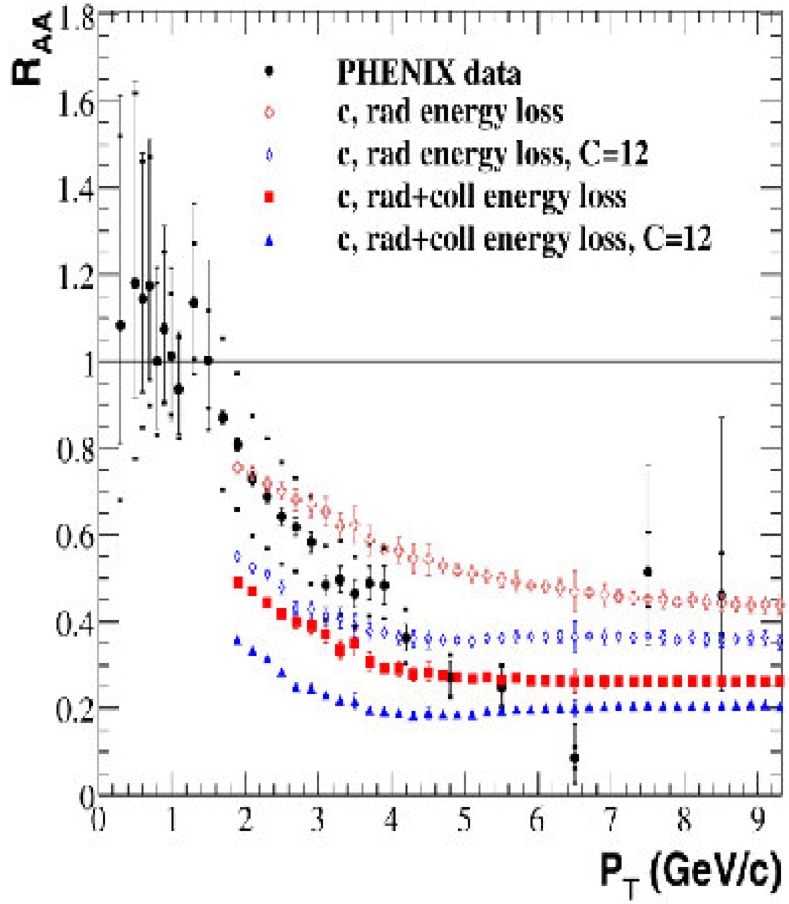
- Sorenson, EJPC 49, 379 (2007)



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

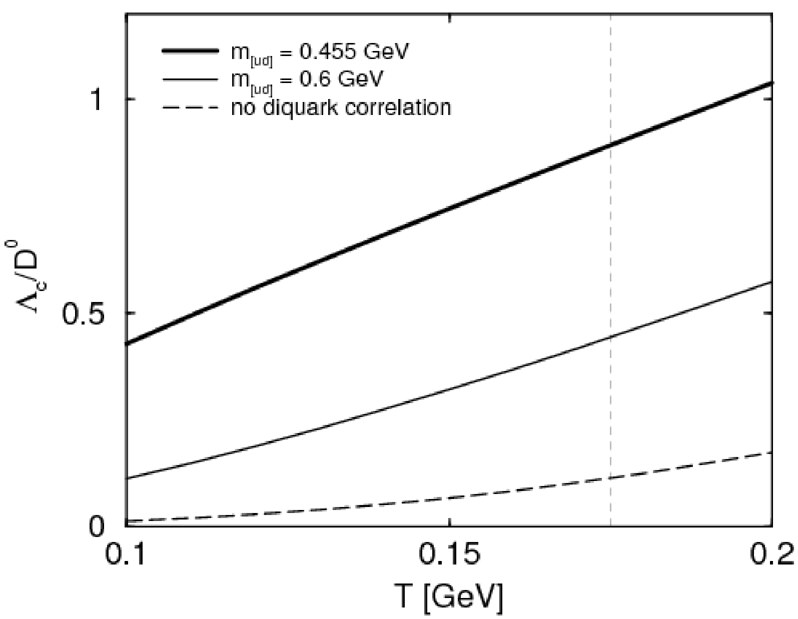
Lee, Yasui, Ohnishi, Yoo & Ko, PRL100, 222301 (2008)

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



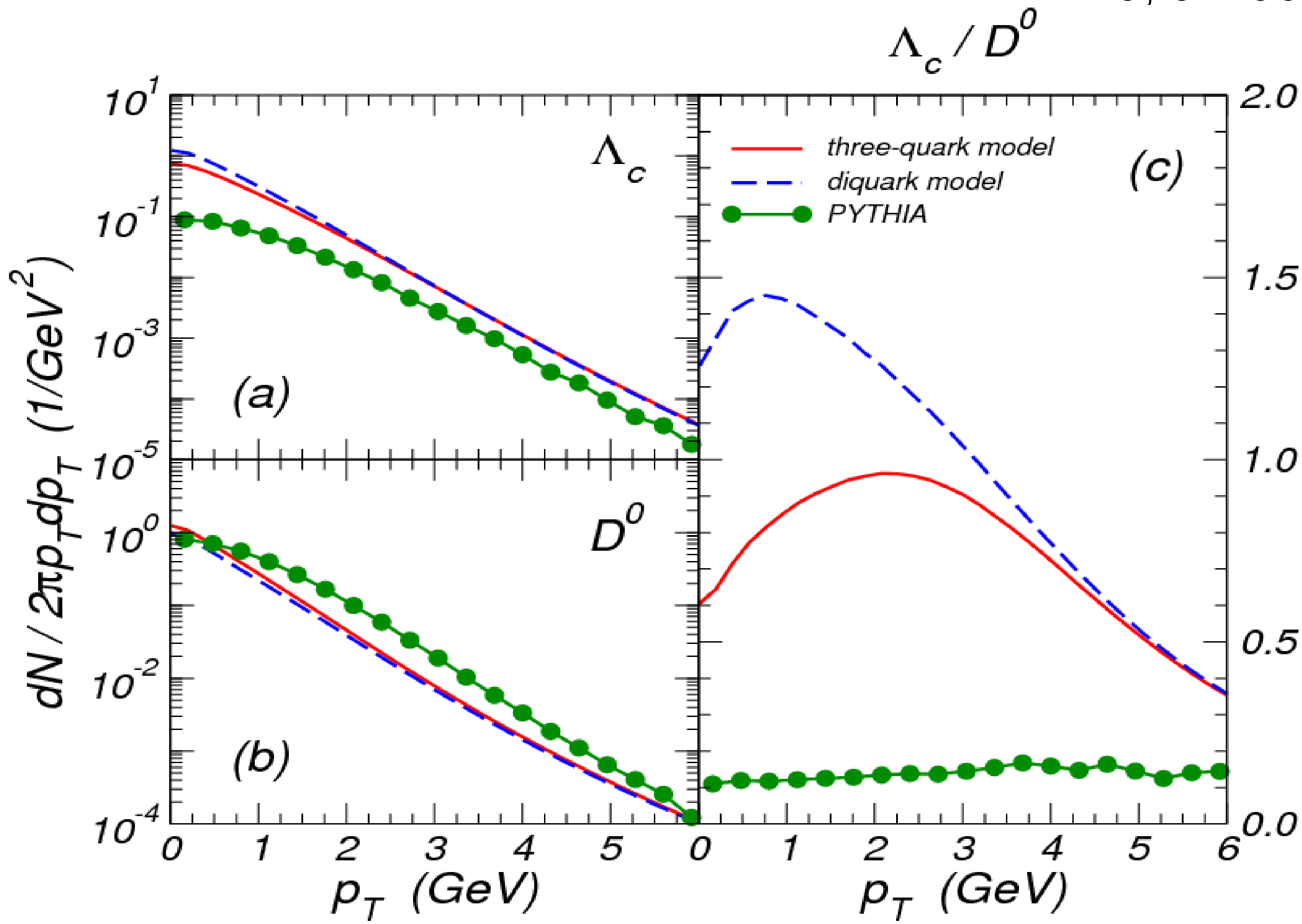
Statistical model

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

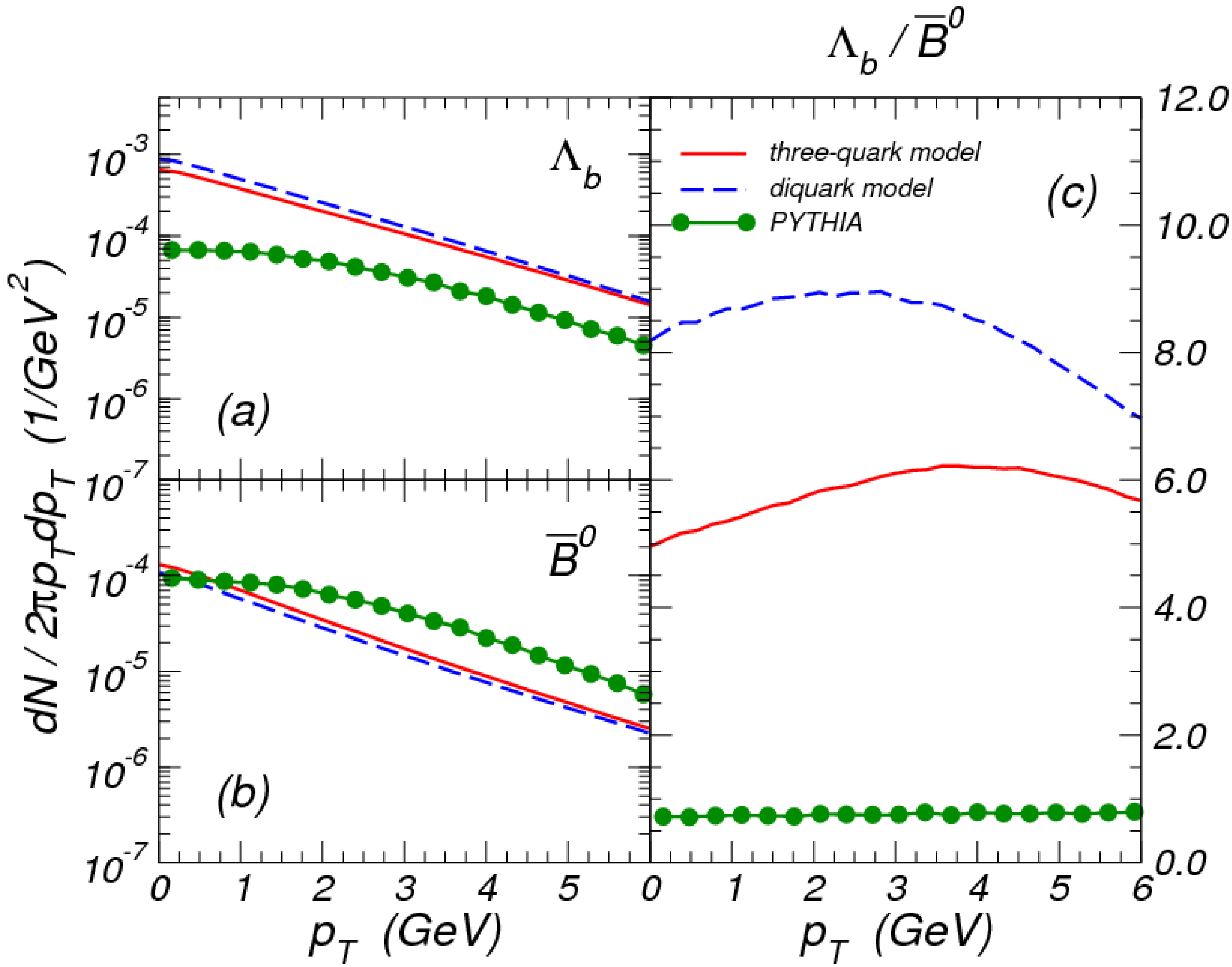
- Enhanced by a factor of 4-8
- Similar for Λ_B/B^0

Inclusion of resonances and fragmentation

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

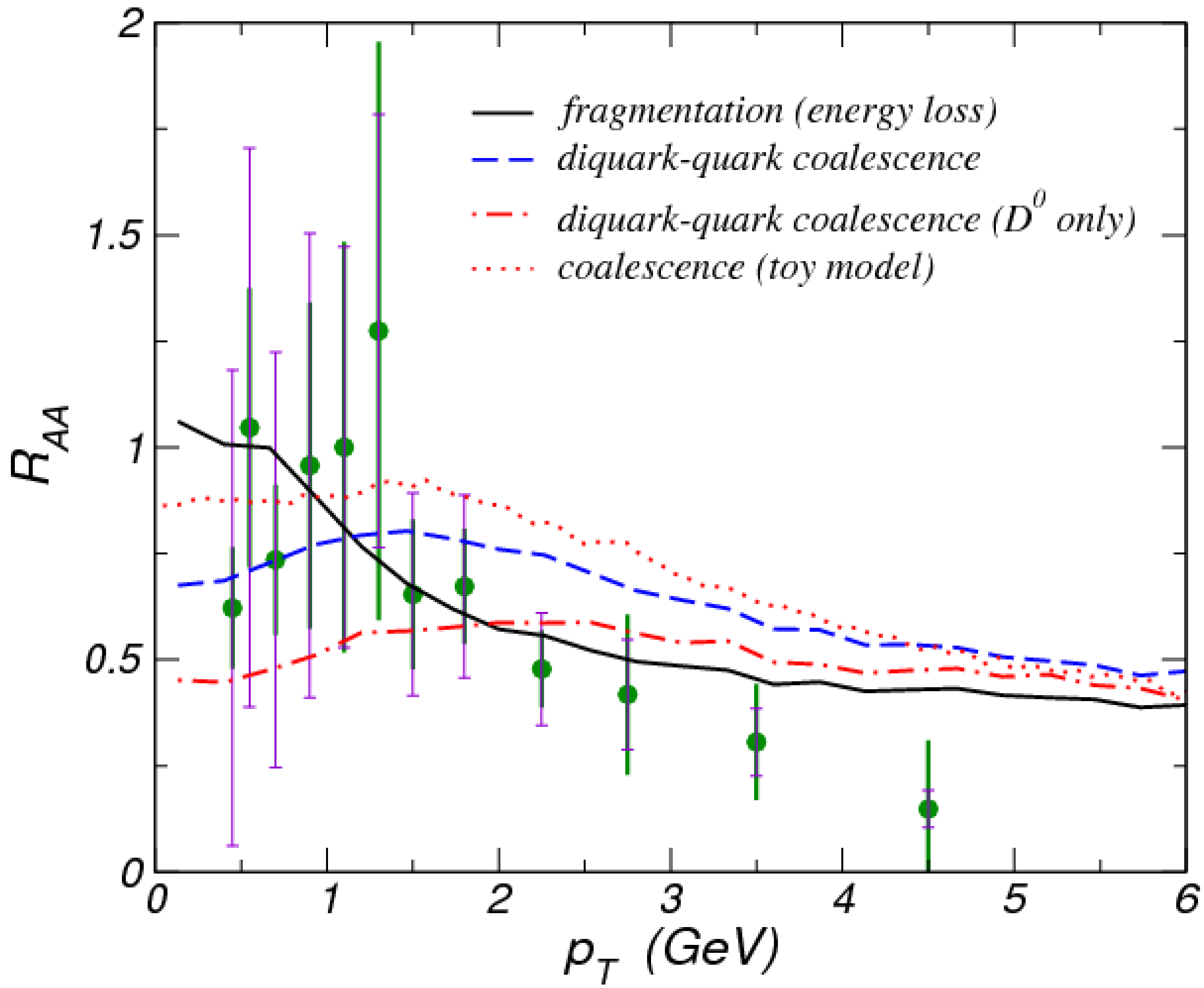


Including coalescence contribution enhances Λ_c/D^0 ratio, which is further enhanced by the presence of diquarks in QGP



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

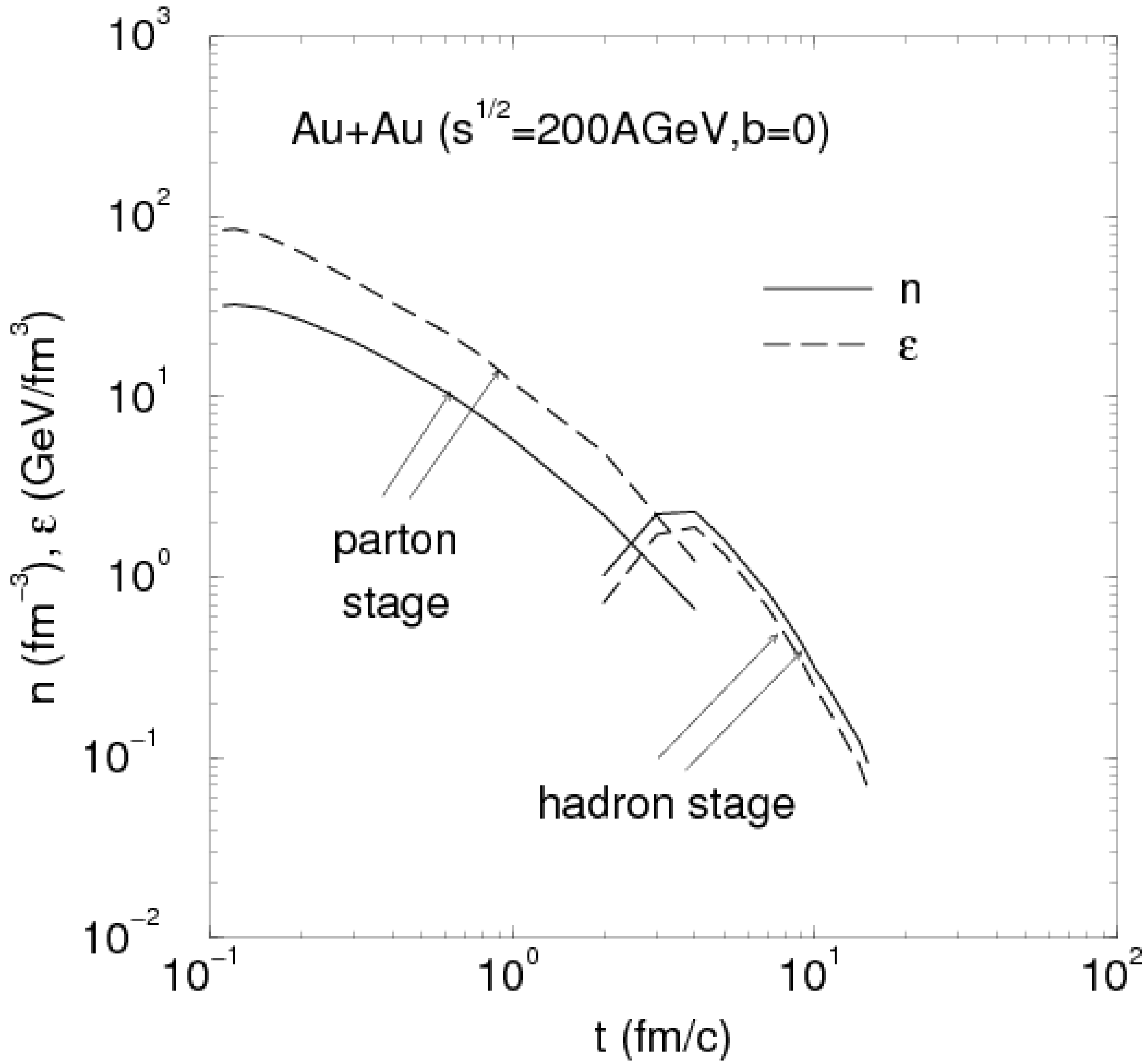
Effect of Λ_c enhancement on non-photonic electron R_{AA}



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

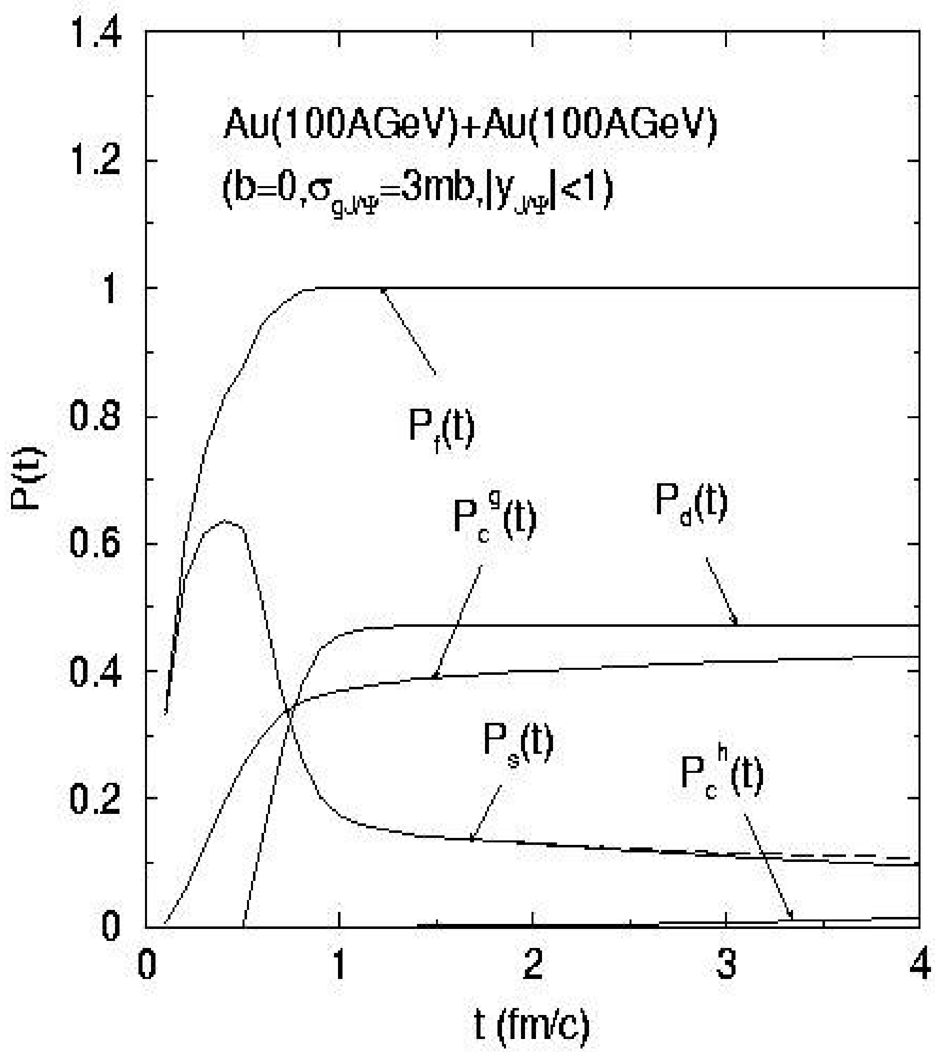
Evolution of Number and Energy Densities in AMPT

Zhang et al., PRC 62, 054905 (2000)



J/ψ absorption probability at RHIC

Zhang et al., PRC 62, 054905 (2000)



P_d : Color screening (critical density n_c~ 5/fm^3)

P_c^g : gluons (σ=3 mb)

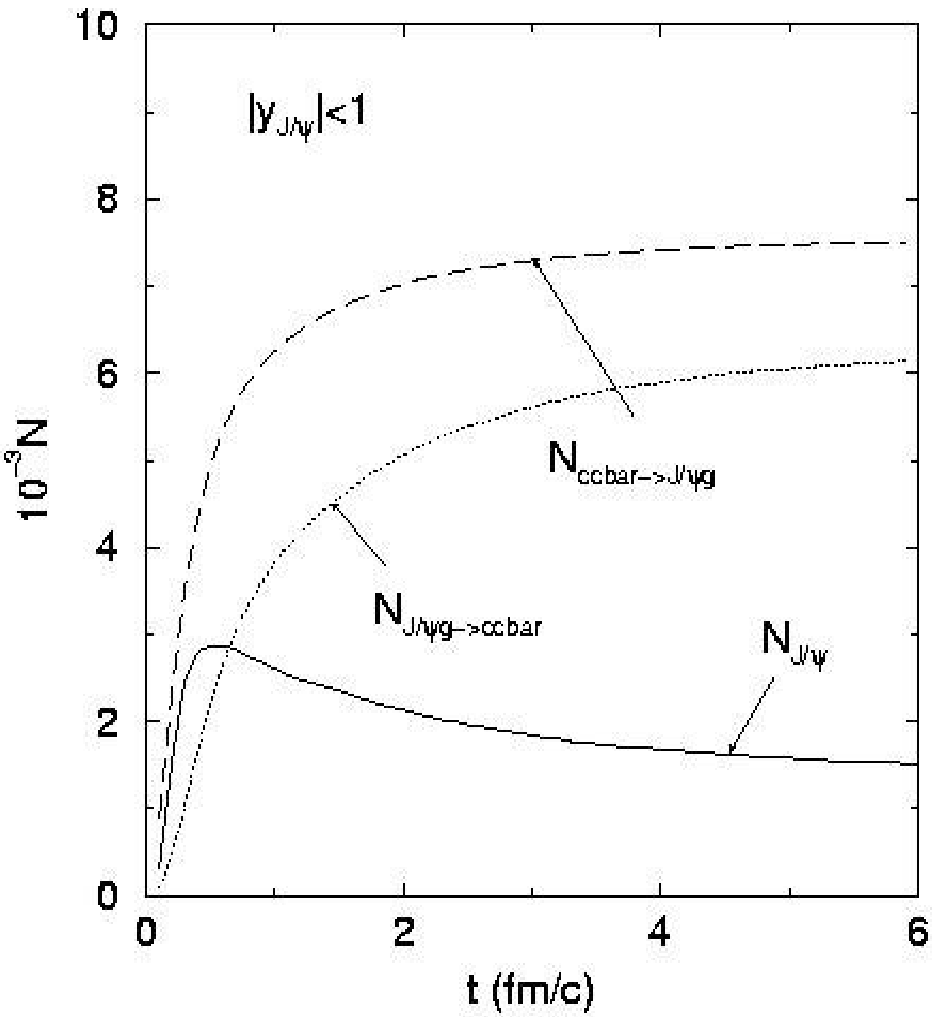
P_c^h : hadrons (σ=3 mb)

P_f : formation

P_s : survival

J/ψ evolution in partonic matter

Zhang et al., PRC 65, 054909 (2002)



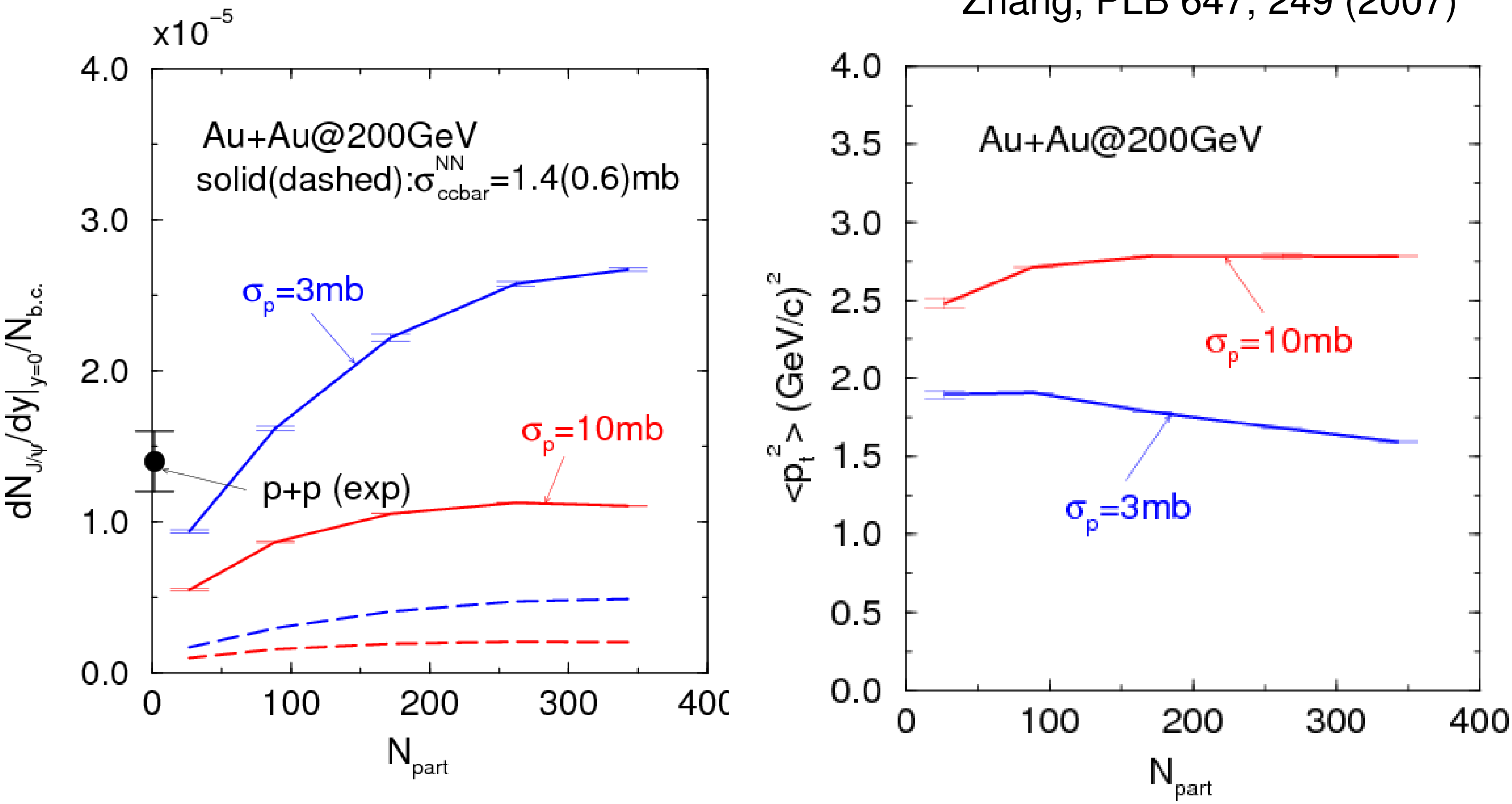
- Charm quark mass m_c=1.35 GeV
- Au+Au @ 200A GeV
- Initial $\frac{dN_{c\bar{c}}}{dy}|_{y=0} \approx 1.73$

  $\frac{dN_{J/\psi}}{dy}|_{y=0} \approx 0.019$
- Final $\frac{dN_{J/\psi}}{dy}|_{y=0} \approx 0.0014$

$\frac{dN_{J/\psi}}{dy}|_{y=0} \approx 0.0007$ with screening

J/ψ production from charm quark coalescence

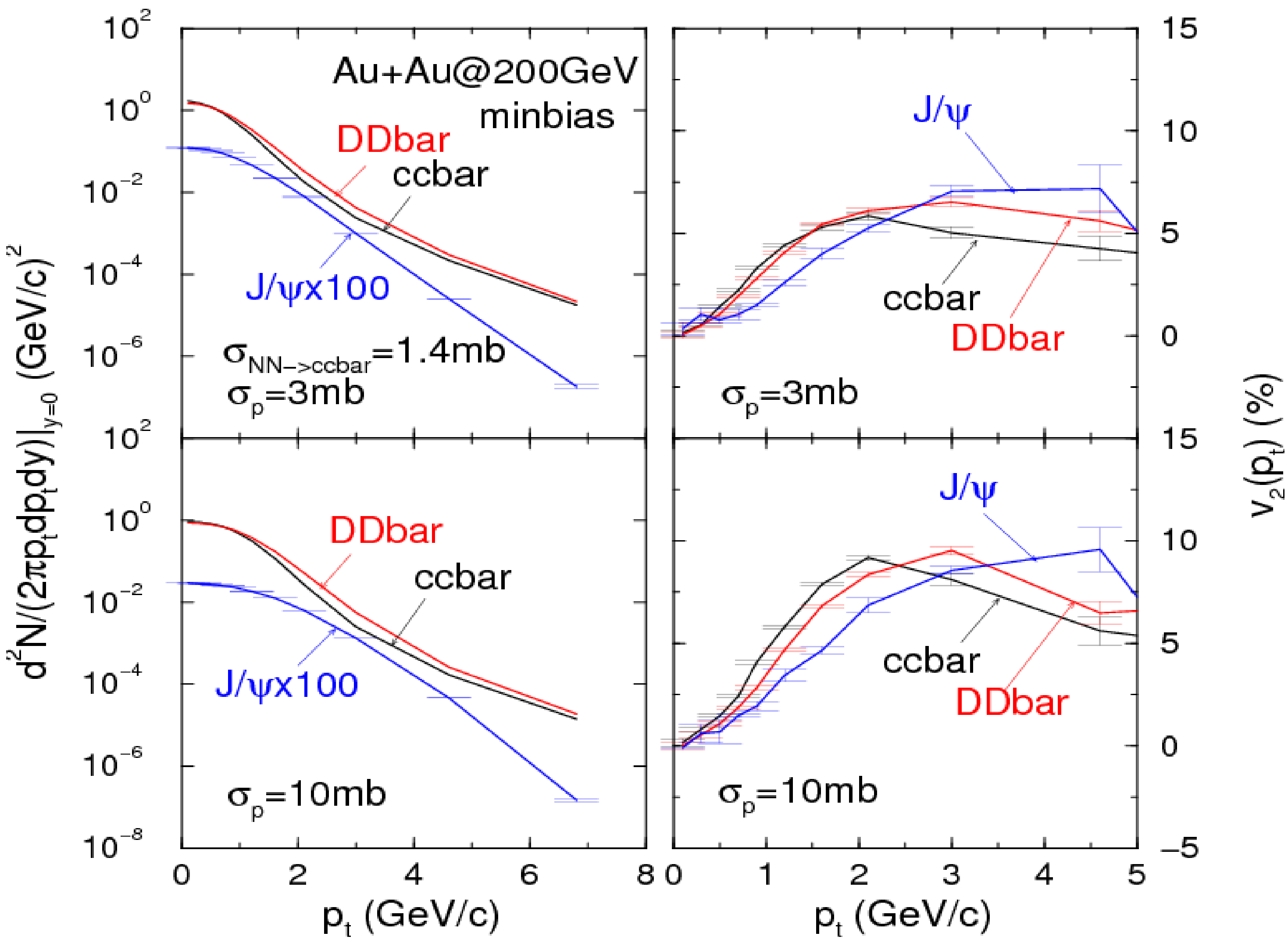
Zhang, PLB 647, 249 (2007)



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

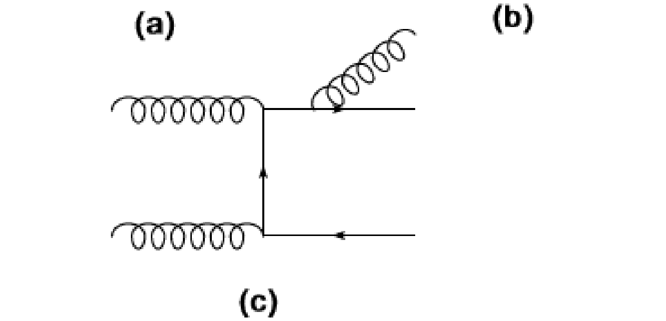
- Pre-thermal production: Lin, Gyulassy (95), Levai, Meuller, Wang (95)…..
  - Not important based on minijet gluons
  - Production from initial strong color field?

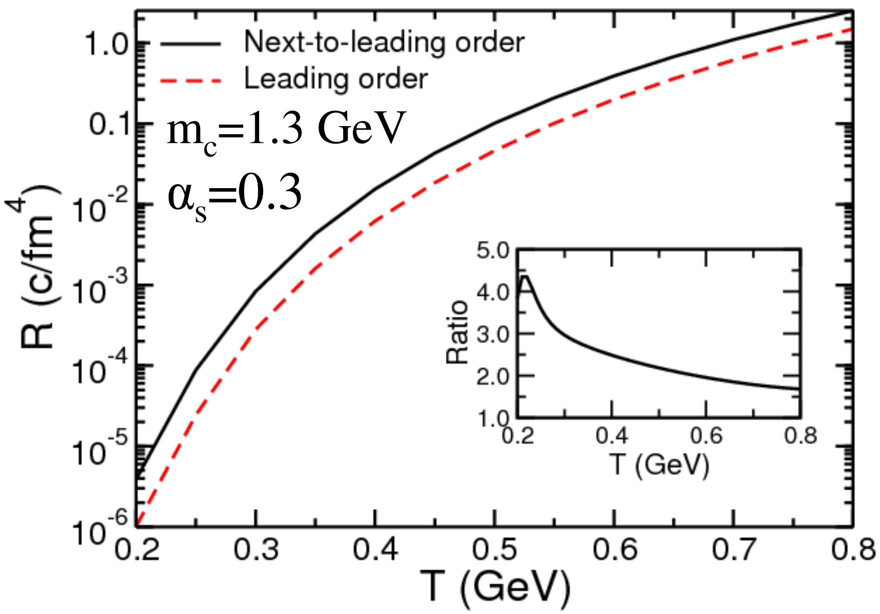
- Thermal production from QGP: Levai, Vogt (97) …..
  - Based on leading-order calculations
  - Important if initial temperature of QGP is high

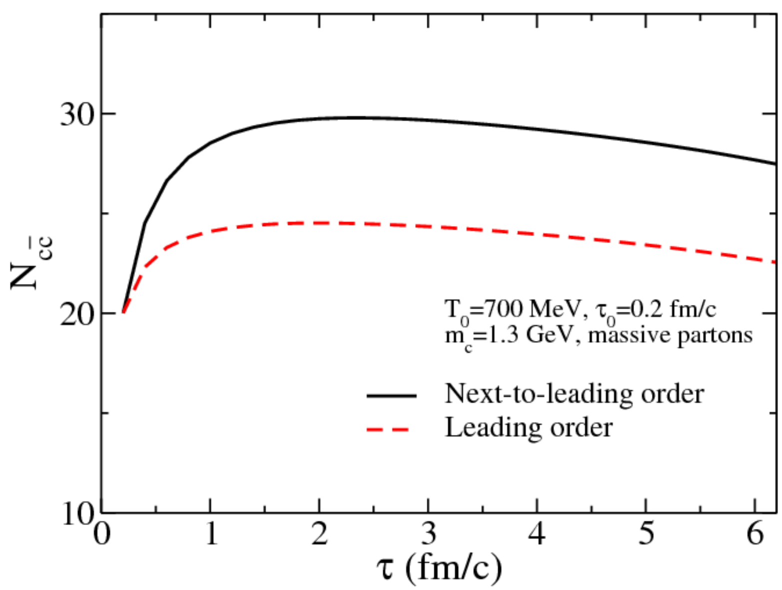
- Thermal production from hadronic matter: Cassing et al. (99), Liu & Ko (02)
  - $\pi N \rightarrow \Lambda_c D$ and $\rho N \rightarrow \Lambda_c D$
  - Small effect on charm production in HIC

Thermal charm production in QGP

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





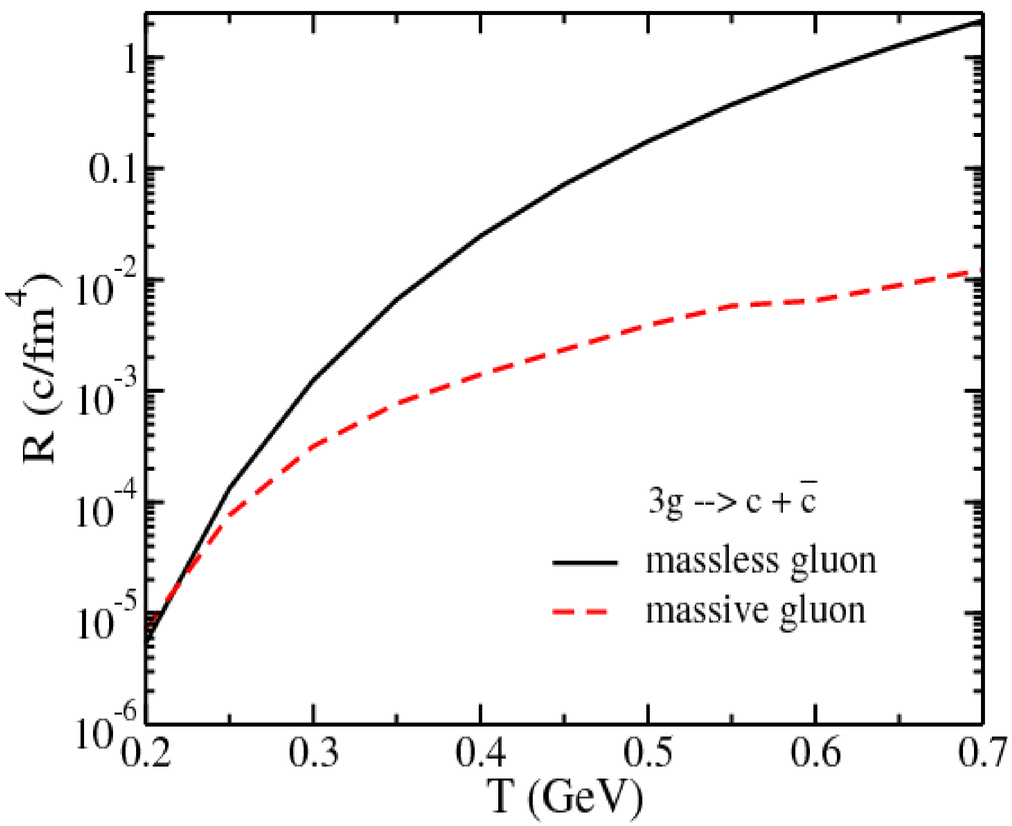


- Thermal production of c barc from gg, gq, and $q\bar{q}$ at LHC non-negligible
- Next-leading order and leading order contributions are comparable
- Insensitive to gluon masses
- Effect increases by about 2 for initial temperature T_0=750 MeV but decreases by ~ 3 for T_0=630 MeV

Charm production from three-gluon interaction $ggg \rightarrow cc$

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

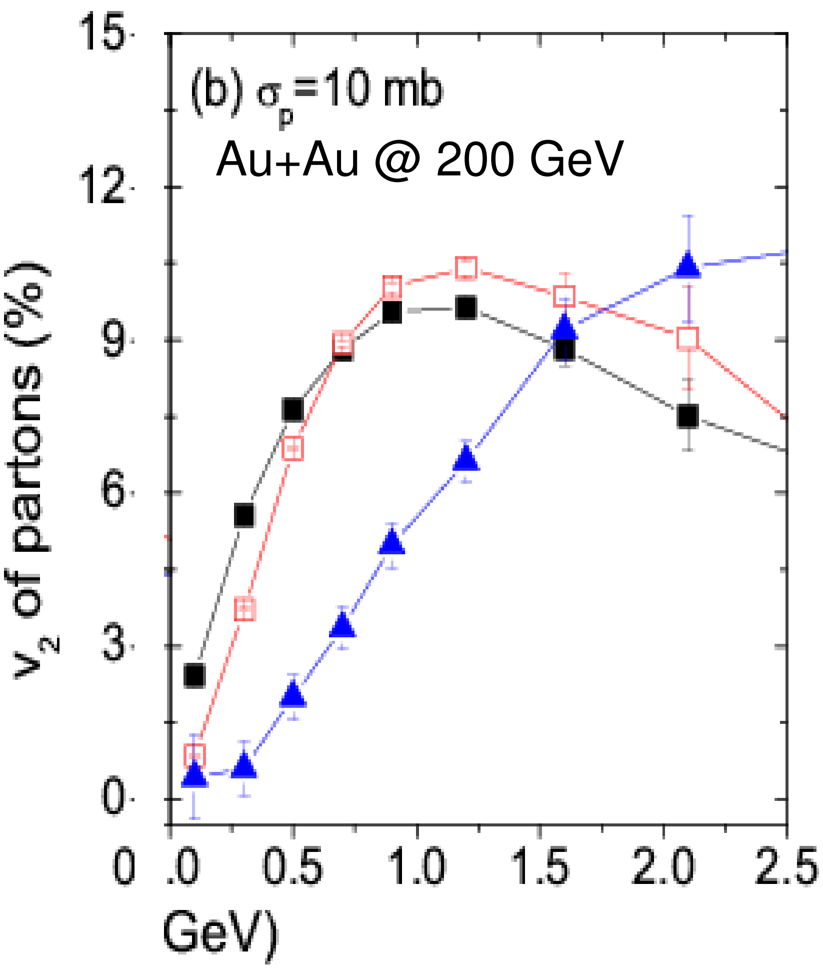
$$R \propto \frac{1}{3}\int \prod_{i=1}^{5} d^3p_i f_i(p_i) \left|M_{ggg\rightarrow c\bar{c}}\right|^2 \delta^{(4)}(p_1+p_2+p_3-p_4-p_5) \propto \left\langle \sigma_{c\bar{c}\rightarrow ggg} v \right\rangle n_c^{eq} n_{\bar{c}}^{eq}$$

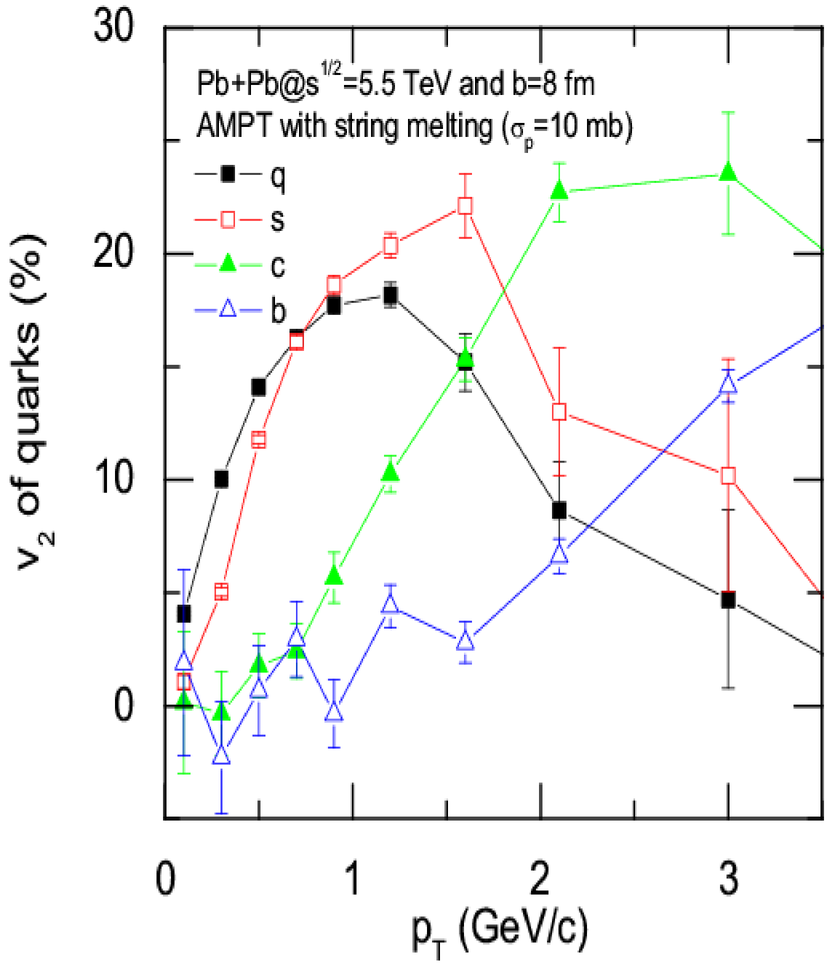


Gluon density ~ 0.5/fm^3 at T_C and much larger initially

- 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

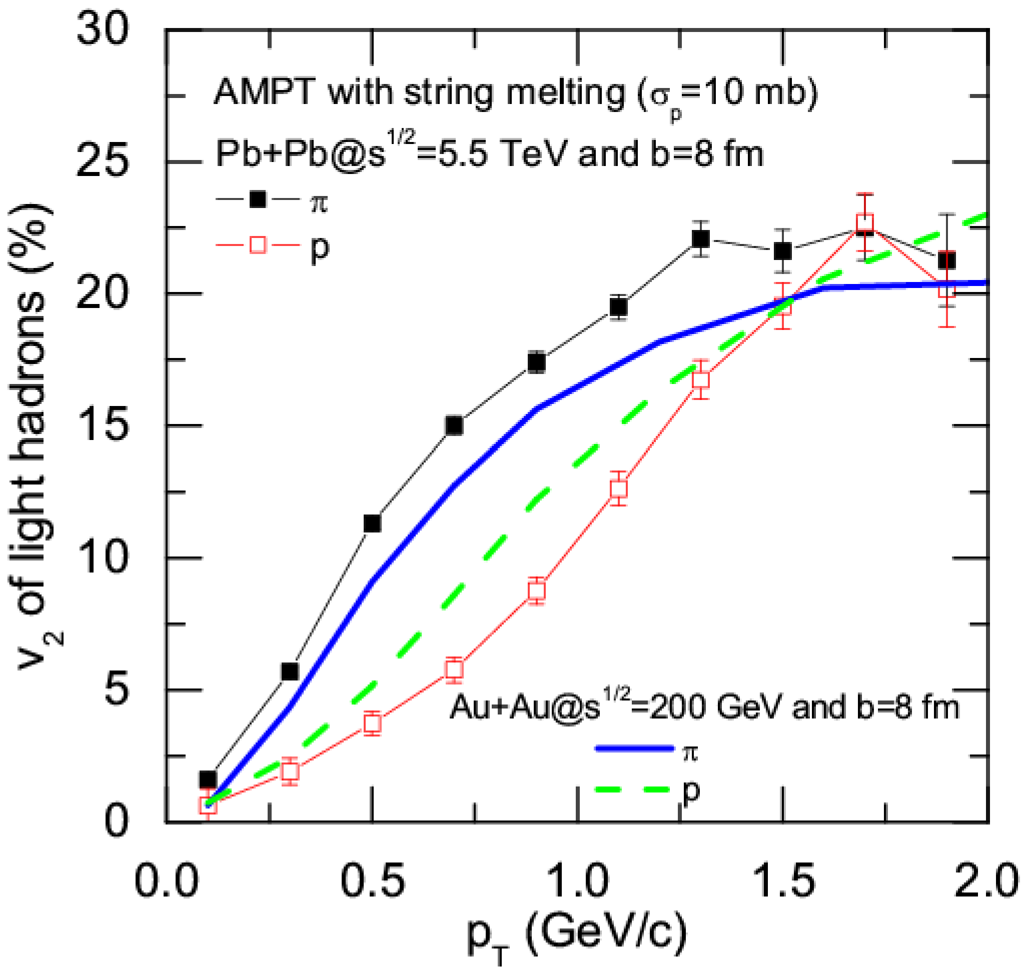
Quark elliptic flows at LHC





Quark elliptic flows are larger at LHC than at RHIC, reaching ~ 20%

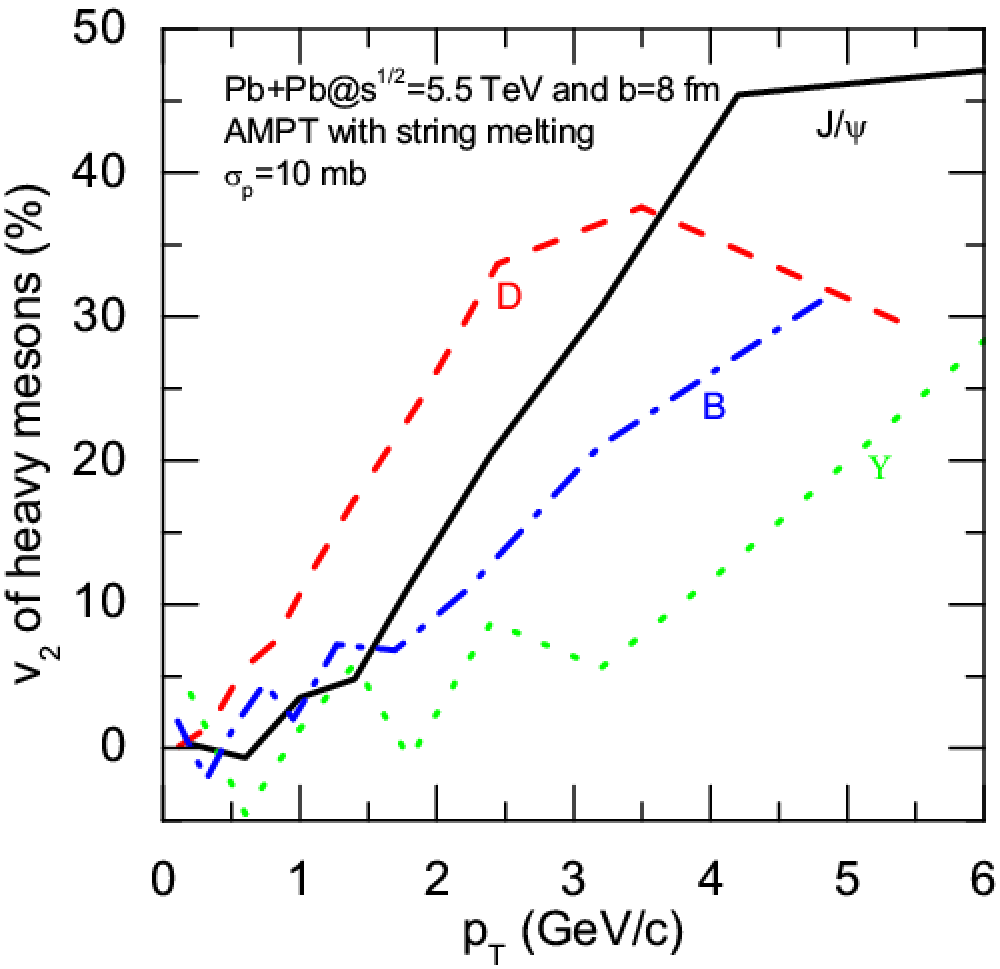
Pion and proton Elliptic flow at LHC



Elliptic flow is larger for pions but smaller for protons at LHC than at RHIC

Heavy meson elliptic flows at LHC

Quark coalescence model



$$v_{2M}(p_T) \cong v_{2,q_1}((m_{q_1}/m_M)p_T) + v_{2,q_2}((m_{q_2}/m_M)p_T)$$

Charmonia masses in nuclear medium

Lee & Ko, PRC 67, 038202 (2003)

- QCD second-order Stark effect

$$\Delta m(\varepsilon) = -\frac{1}{9}\int dk^2 \left|\frac{\partial\psi(k)}{\partial k}\right|^2 \frac{k}{k^2/m_c + \varepsilon}\left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle_N \frac{\rho_N}{2m_N}$$

- Charmed meson loop correction

$\Delta m_{J/\psi}$=-8+3 MeV

Δm_{ψ}(3686)=-100-30 MeV

Δm_{ψ}(3770)=-140+15 MeV

Can be studied at FAIR with antiproton beam on nuclei

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.
- Quark coalescence enhances Λ_c and Λ_b production at RHIC, which affects the yield of heavy mesons but not very significantly the nuclear modification factor of electrons charmed hadrons.
- Charmonium regeneration is non-negligible and appreciable charmonium elliptic flow is expected at RHIC.
- Thermal charm production might be important at LHC as the production rate increases exponentially with the temperature of formed QGP.
- Masses of charmonia are reduced in nuclear matter and can be studied at FAIR.