Sequential coalescence with charm conservation

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- Sequential coalescence:
  2(3)-body Dirac equation + hydrodynamics + coalescence
- Charm conservation
- D_s/D^0 enhancement in A-A collisions

by Jiaxing Zhao & Shuzhe Shi and Nu Xu & PZ

Hadronization

- Hadronization in vacuum

  a non-perturbative and unsolved problem.

- Hadronization of quark matter

  statistical distribution at freeze-out:

  P.Braun-Munzinger, J.Stachel, J.Wessels and N.Xu, PLB344, 43(1995)

  coalescence (recombination) models:

  V.Greco, C.Ko and P.Levai, PRL90, 202302(2003)
  R.Hwa and C.Yang, PRC70, 024905(2004), ……

$$N_{meson} \sim \int d\sigma^\mu p_\mu W(x,p) f_q(x_1,p_1) f_{\bar{q}}(x_2,p_2)$$

- Two assumptions

  1) assumed coalescence probability (Wigner function)

  $W(x,p) \sim e^{-\frac{x^2}{\langle x\rangle^2}} e^{-\frac{p^2}{\langle p\rangle^2}}$ with parameters $\langle x\rangle$ and $\langle p\rangle$

  2) assumption of simultaneous hadronization for all hadrons

- Heavy quark hadronization

  Sequential dissociation by (non-relaytivistic and relativistic) potential models

  H.Satz, JPG32, R25(2006)
  X.Guo, S.Shi and PZ, PLB718, 1439(2012)

  1) sequential dissociation temperature

  $T_{J/\psi} > T_{\psi'} \simeq T_{\chi_c}$

  → heavy flavor hadrons are sequentially produced !

  2) self-consistent Wigner function $W(x,p) = \int d^4 y e^{-ipy} \psi(x+\frac{y}{2}) \psi^*(x-\frac{y}{2})$

Sequential heavy flavor production

- *Step 1:* *From 2(3)-body Dirac equations for heavy flavor mesons and baryons*
  → *sequential production temperature* T_h
  and wave function $\psi(x)$ *[Wigner function* $W(x,p)$]

- *Step 2:* *From hydrodynamic equations for QGP evolution*
  → $T(\vec{x},t) = T_h \quad \rightarrow \quad sequential\ production\ time\ t_h(\vec{x},T_h)$

- *Step 3: Sequential coalescence*

$$N_m \sim \int d\sigma^\mu p_\mu W(x,p) f_q(x_1,p_1) f_{\bar{q}}(x_2,p_2)$$

$$N_b \sim \int d\sigma^\mu p_\mu W(x,p) f_q(x_1,p_1) f_q(x_2,p_2) f_q(x_3,p_3)$$

Step 1: Sequential production temperature

- *For heavy flavor mesons*

  T=0: see H.Crater, J.Yoon and C.Wong, PRD79, 034011(2009)

  T>0: see S.Shi, X.Guo and PZ, PRD88, 014021(2013)

- *For heavy flavor baryons*

  Sazdjian, J. Math. Phys. 28, 2618(1987):

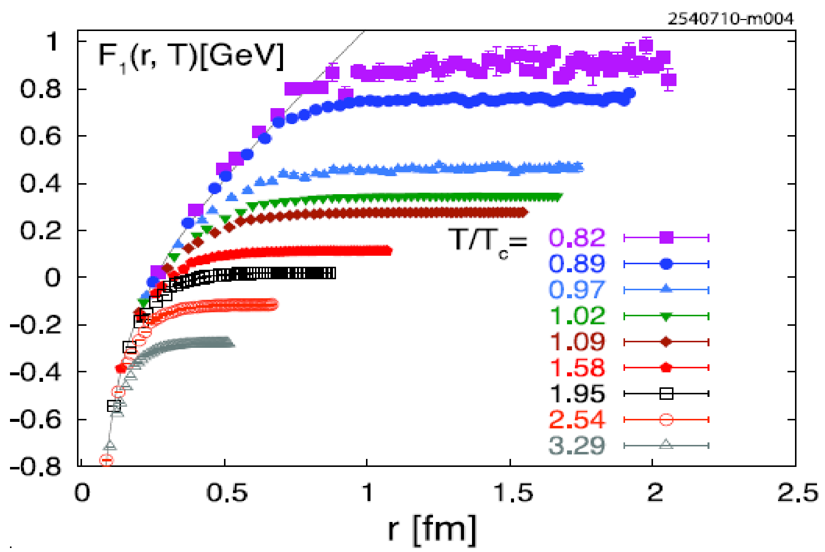
  N-body relativistic potential model

  Whitney & Crater, Phys. Rev. D89, 014023(2014)

  Schroedinger-like equation for baryon wave function

$$\left[\sum_{i=1}^{3}\frac{\mathbf{p}_i^2}{2\epsilon_i}+\sum_{i<j}^{3}\frac{\epsilon_i+\epsilon_j}{2\epsilon_i\epsilon_j}\mathcal{V}_{ij}\right]\Psi_b=E\,\Psi_b,$$

$$\begin{aligned}\mathcal{V}_{ij} \;=\;& 2m_{ij}S+S^2+2\epsilon_{ij}A-A^2+\Phi_D+\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\Phi_{SS}+\mathbf{L}_{ij}\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\Phi_{SO}+(\boldsymbol{\sigma}_i\cdot\hat{\mathbf{r}}_{ij})(\boldsymbol{\sigma}_j\cdot\hat{\mathbf{r}}_{ij})\mathbf{L}_{ij}\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\Phi_{SOT}\\ &+\mathbf{L}_{ij}\cdot(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)\Phi_{SOD}+i\mathbf{L}_{ij}\cdot(\boldsymbol{\sigma}_i\times\boldsymbol{\sigma}_j)\Phi_{SOX}+(3(\boldsymbol{\sigma}_i\cdot\hat{\mathbf{r}}_{ij})(\boldsymbol{\sigma}_j\cdot\hat{\mathbf{r}}_{ij})-\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\Phi_T \qquad (3)\end{aligned}$$



O.Kaczmarek, EPJC 61, 811(2009)

$$\begin{aligned}V_{qq}(r) &= A_{qq}(r)+S_{qq}(r),\\ A_{qq}(r) &= -\alpha_{qq}/r,\\ S_{qq}(r) &= \sigma_{qq}\,r.\end{aligned}$$

S.Shi, X.Guo and PZ, PRD88, 014021(2013)

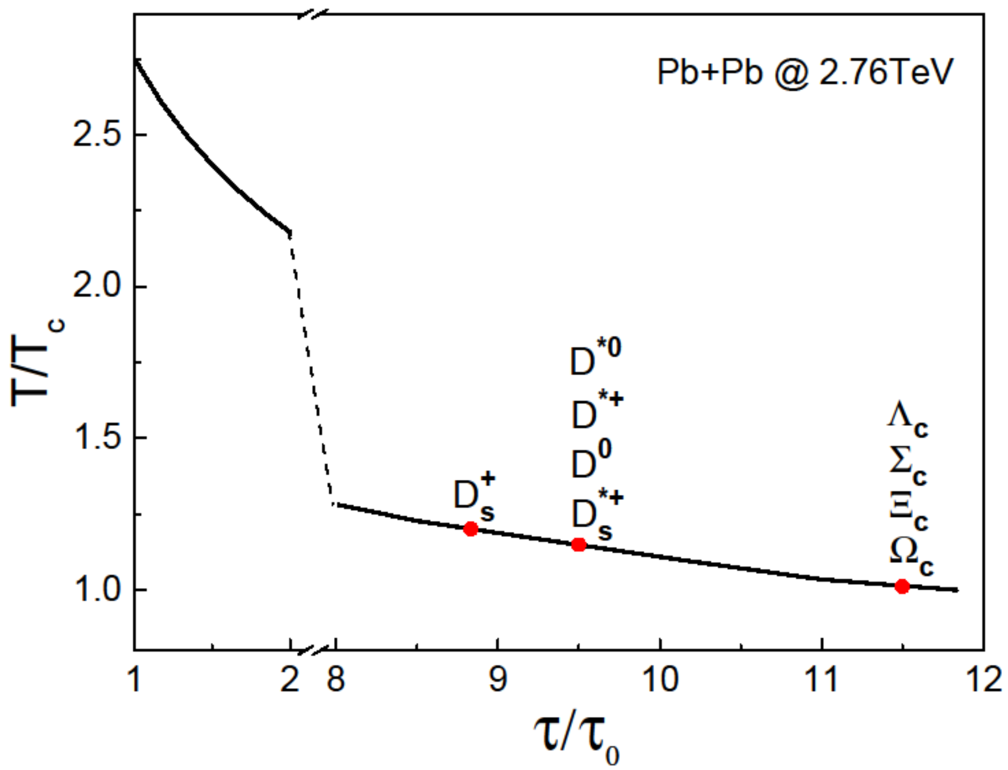
S.Shi, J.Zhao and PZ, arXiv:1905.10627

$$T_h/T_c \simeq \begin{cases}1.15 & for\ D_s\\ 1.10 & for\ D^0\\ 1 & for\ \Lambda_c\end{cases}$$

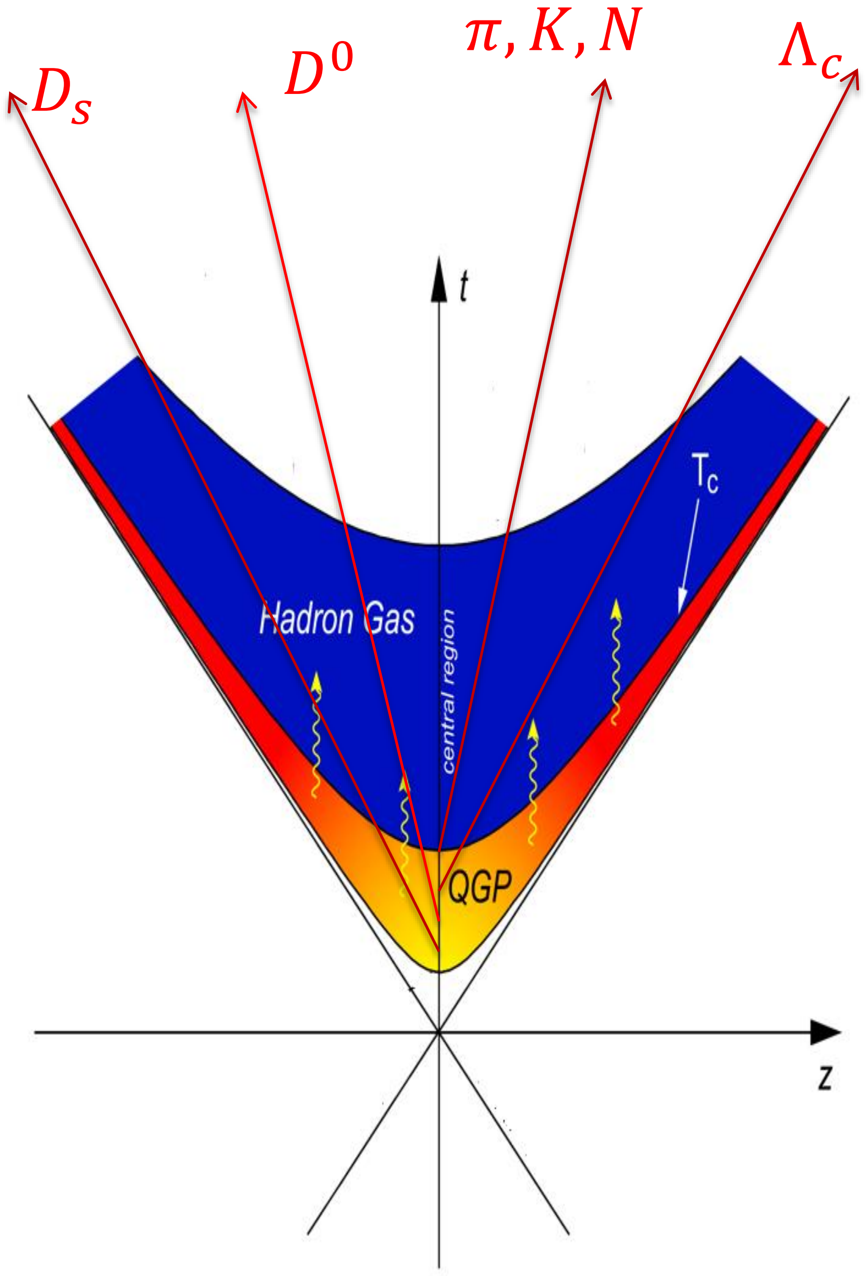
Step 2: Sequential production time

Hydrodynamic equations:

$$\partial^\mu T_{\mu\nu} = 0$$
$$\partial^\mu n_\mu = 0$$
$$\rightarrow \quad \tau(\vec{x}|T_h)$$



$$\tau_{J/\psi} < \tau_{D_s} < \tau_{D^0} < \tau_{\Lambda_c} < \tau_{\pi,K,N}$$



Step 3: Sequential coalescence

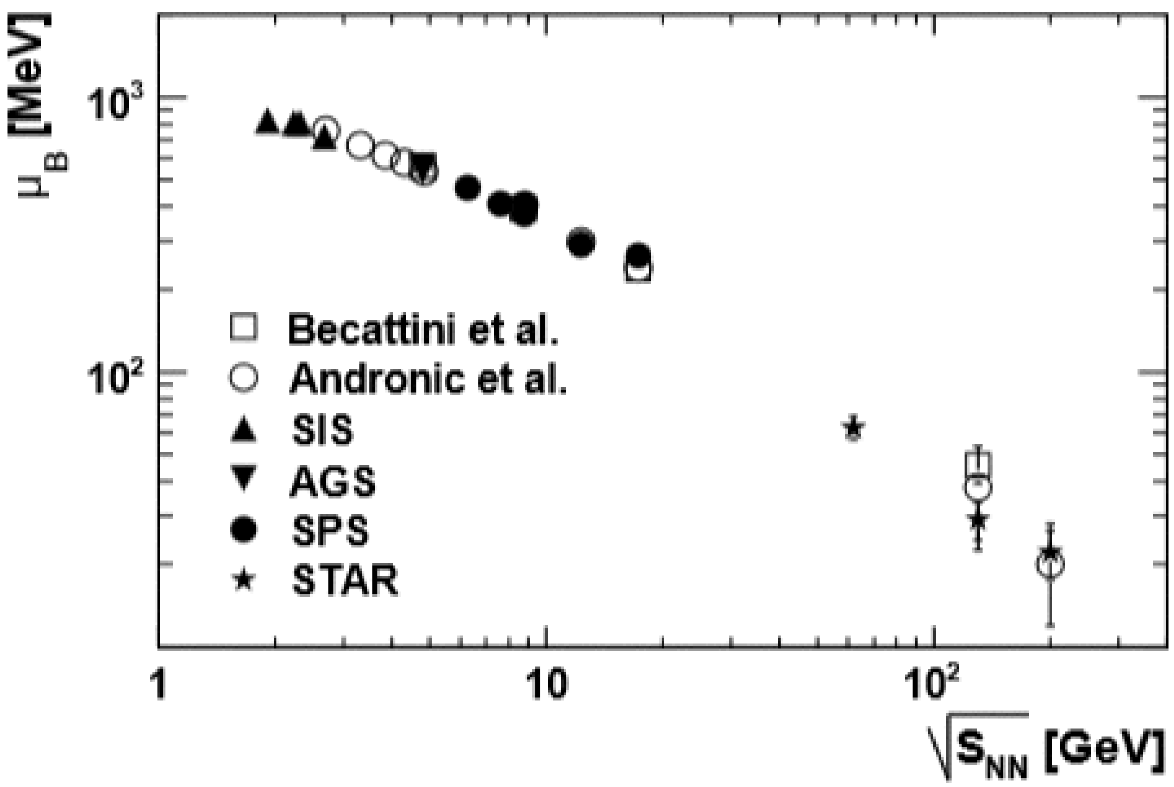
$$N_b \sim \int \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3} f_q(r_1,p_1) f_q(r_2,p_2) f_q(r_3,p_3) W(r,p)$$

Hydrodynamics *Energy loss* *Dirac equations*

- *light quarks* (u,d)*:*
  full energy loss, equilibrium distribution

$$f_q = \frac{N_q}{e^{(u^\mu p_\mu - \mu_q)/T}+1}$$

STAR Collaboration. Phys. Rev. C79,034909(2009)

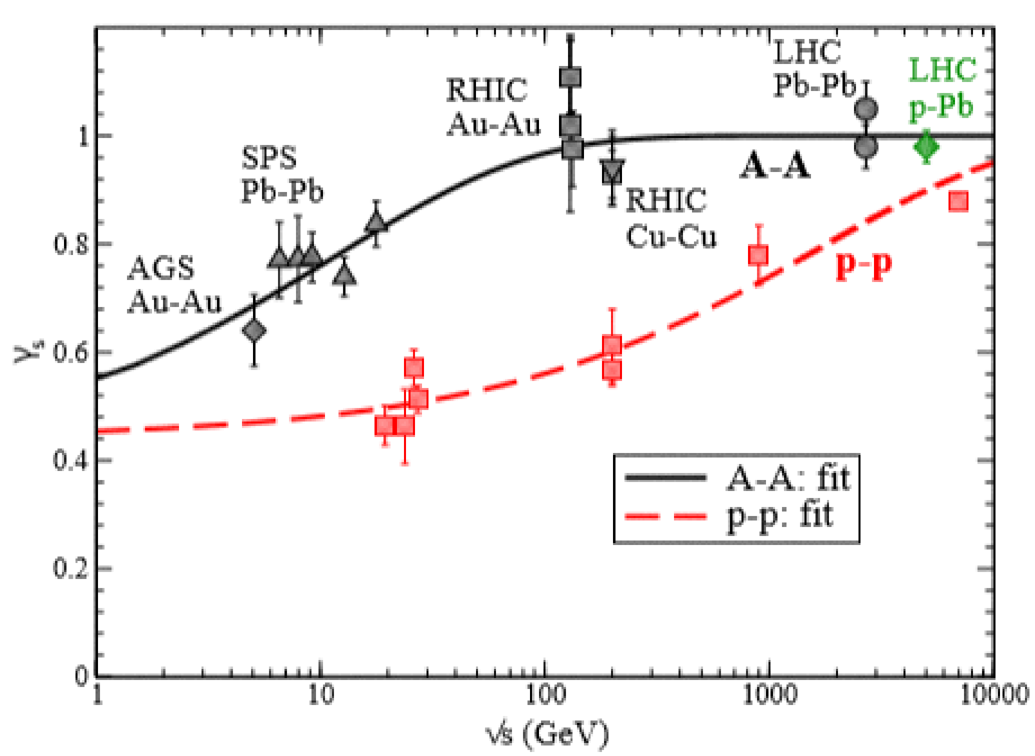


- *strange quark* s*:*
  thermal equilibrium but not chemical equilibrium

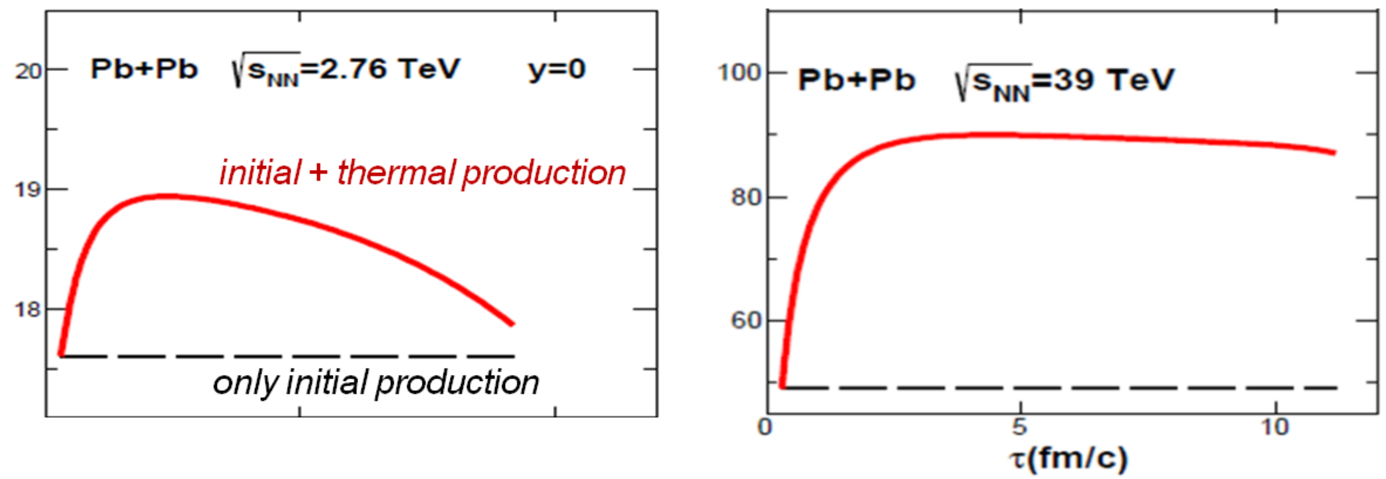
$$f_s = \frac{N_s \lambda_s}{e^{u^\mu p_\mu/T}+1}$$

$$\lambda_s = \begin{cases} 0.85 & at\ RHIC \\ 1 & at\ LHC \end{cases}$$

H.Satz et al. Int. J. Mod. Phys. E26, 1750081(2017)



Charm conservation



K.Zhou, Z.Chen, C.Greiner and PZ,. PLB758, 434(2016)

Charm quark number N_c is conserved in HIC at RHIC and LHC !

- *If all charmed hadrons are simultaneously produced, the charm conservation contributes only a normalization constant,*

  → *it does not change the particle ratios !*

P.Braun-Munzinger and J.Stachel, PLB490, 196(2000)
M.Gorenstein, A.Kostyuk, H.Stoecker and W.Greiner, PLB509, 277(2001)
Y.Oh, C.Ko, S.Lee and S.Yasui, PRC79, 044905(2009)
S.Plumari, V.Minissale, S.Das and V.Greco, EPJC78, 348(2018)
……

- *If charmed hadrons are sequentially produced, however, more charm quarks are involved in the earlier production and less in the later production,*

$$r_h = \frac{involved\ charm\ quarks}{total\ charm\ quarks\ N_c} = \begin{cases} 1 & for\ \ h = D_s \\ 1 - \frac{N_{D_s}}{N_c}\ \ (\sim 90\%) & for\ \ h = D^0 \\ 1 - (N_{D_s} + N_{D^0})/N_c\ \ (\sim 60\%) & for\ \ h = \Lambda_c \end{cases}$$

Charm quark distribution

Charm quarks are not fully thermalized:

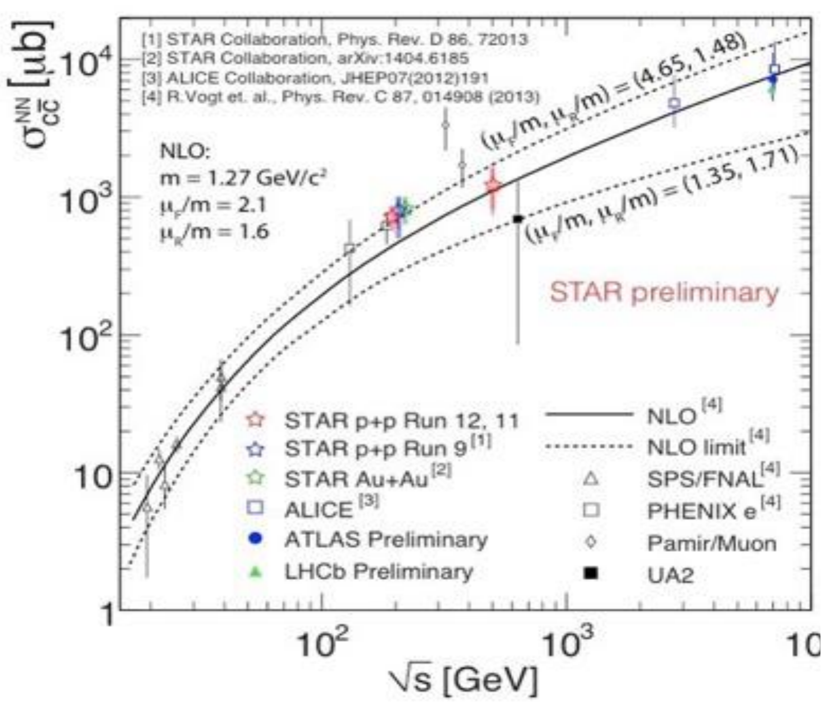
$$f_c = r_h \rho_c(x)\left[\alpha f_{th}(p) + \beta f_{pp}(p)\right]$$

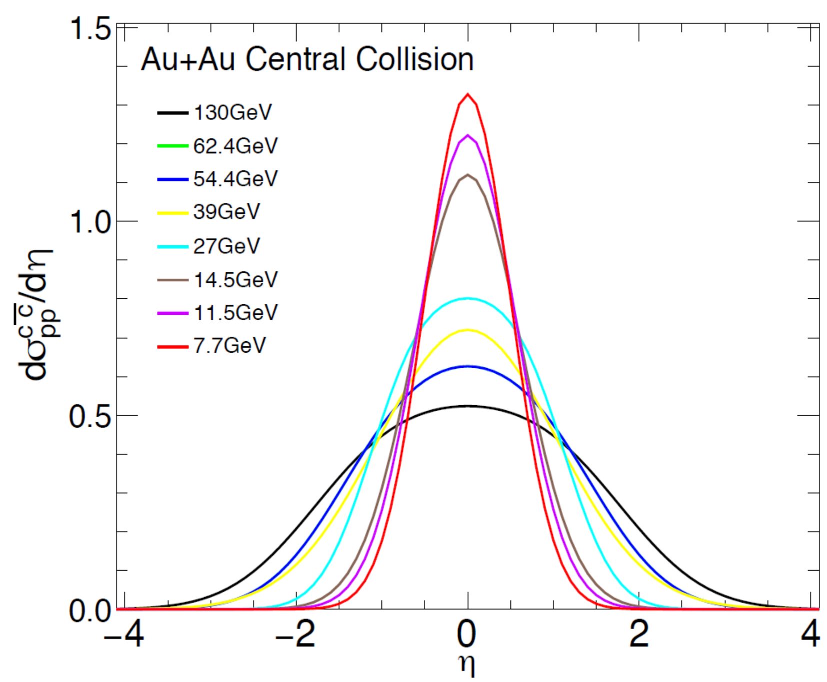
r_h is the charm conservation factor,
thermalization fraction α depends on the coalescence time:

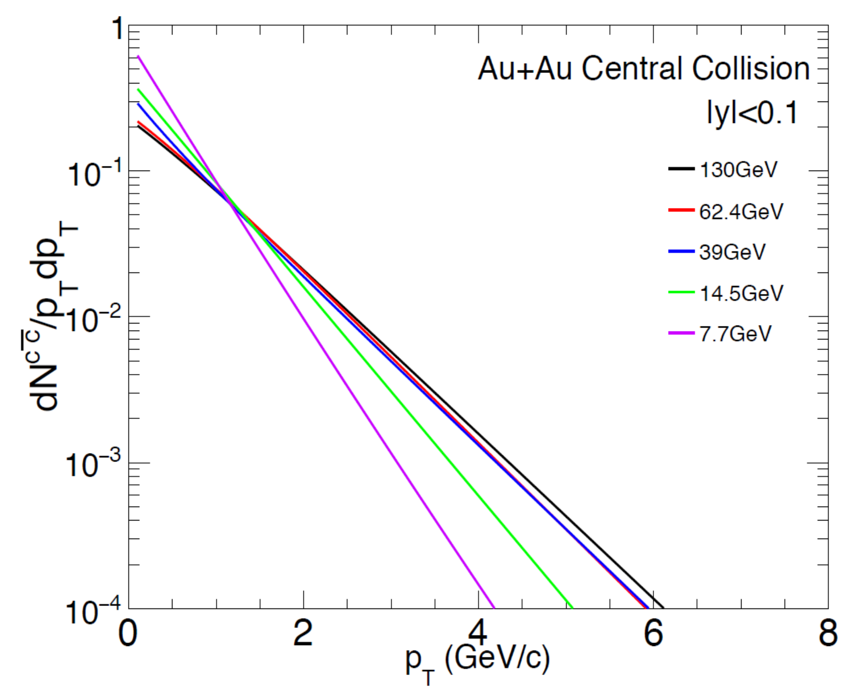
$$(\alpha,\beta) = \begin{cases} (0.4, 0.6) & D_s \\ (0.5, 0.5) & D^0 \\ (0.6, 0.4) & \Lambda_c \end{cases}$$

charm quark density

$$\rho_c(x) = T_A(x_T)T_B(x_T - b)\,\frac{\cosh\eta}{\tau}\,\frac{d\sigma_{pp}^{c\bar{c}}}{d\eta}$$



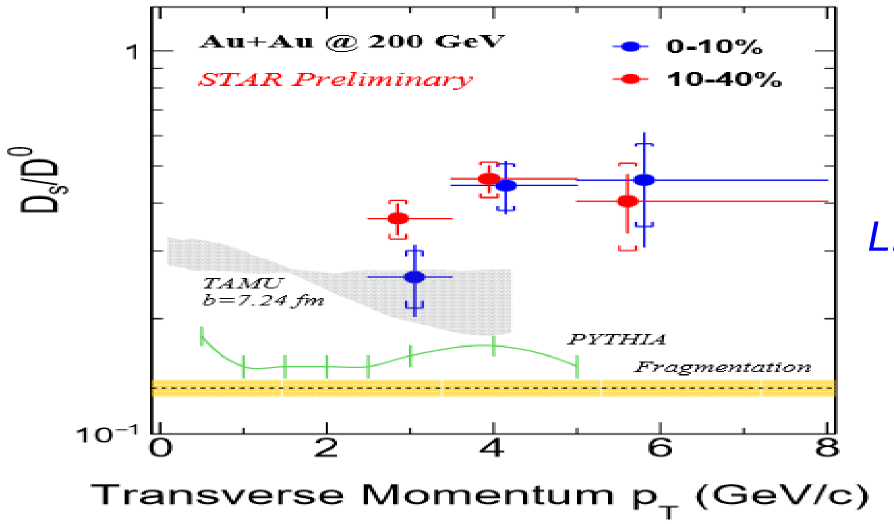




Normalized rapidity and transverse momentum distributions with PYTHIA8

D_s/D^0 enhancement

Strong D_s/D^0 enhancement at RHIC



L.Zhou [STAR], NPA967, 620(2017)

D_s enhancement due to strangeness enhancement in quark matter

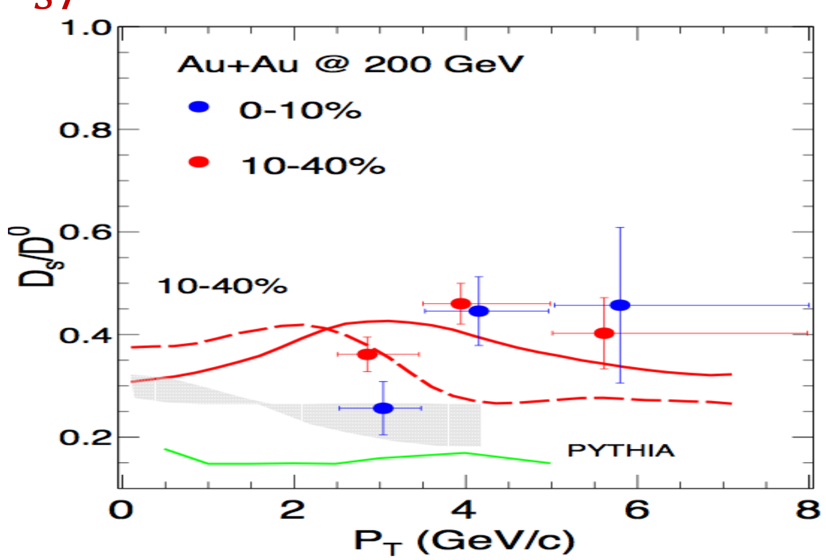
P.Koch, B.Muller and J.Rafelski, Phys. Rept. 142, 167(1986)
M.He, R.Fries and R.Rapp, PRL110, 112301(2013)

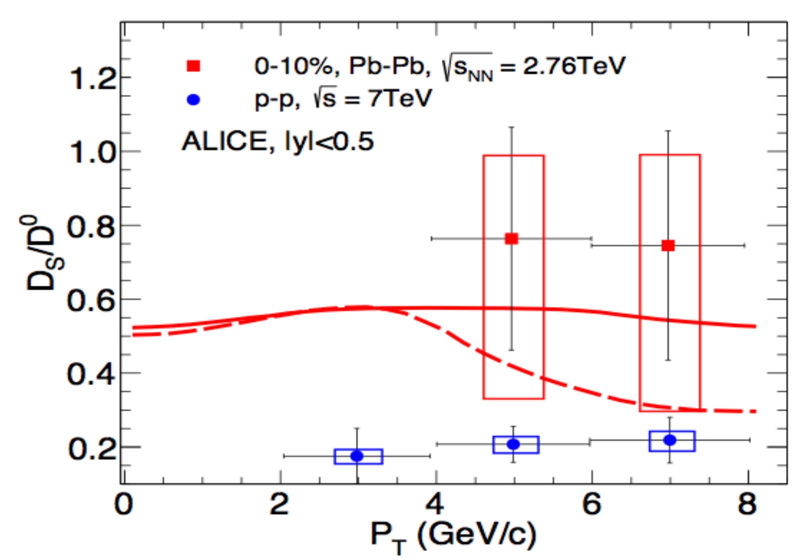
However, D_s enhancement cannot fully explain the D_s/D^0 enhancement !

D_s enhancement + charm conservation induce D^0 suppression
$\rightarrow$ a further D_s/D^0 enhancement !

J.Zhao, S.Shi, N.Xu and PZ, arXiv: 1805.10858

L.Zhou [STAR], NPA967, 620(2017)





J.Adam et. al. [ALICE], JHEP 1603, 082(2016)

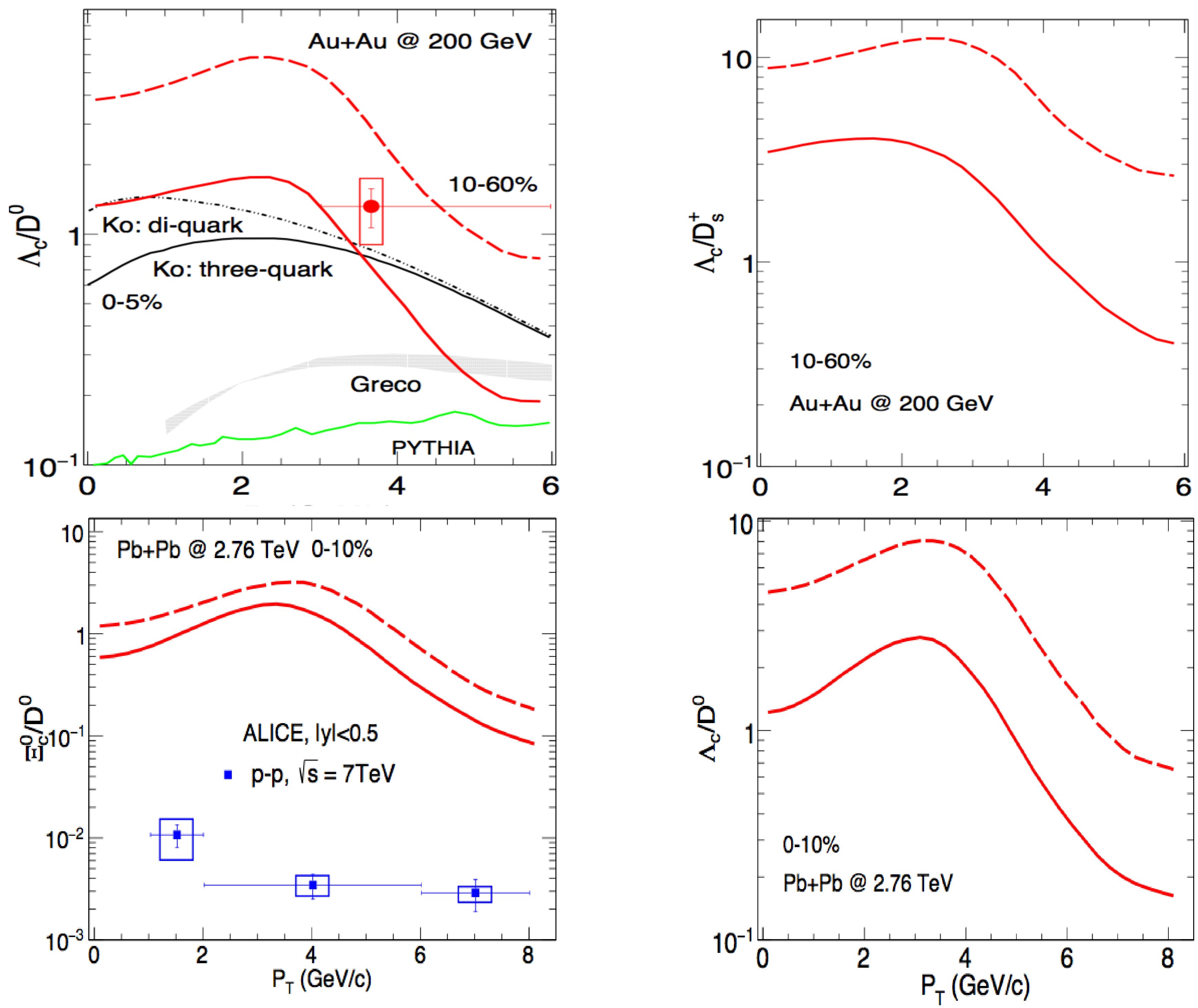
solid lines: with charm conservation, dashed lines: without charm conservation

Λ_c/D^0 and Ξ_c/D^0

J.Zhao, S.Shi, N.Xu and PZ, arXiv: 1805.10858

RHIC

LHC



D_s is produced first, then D^0, and finally Λ_c and Ξ_c.

solid lines: with charm conservation, dashed lines: without charm conservation

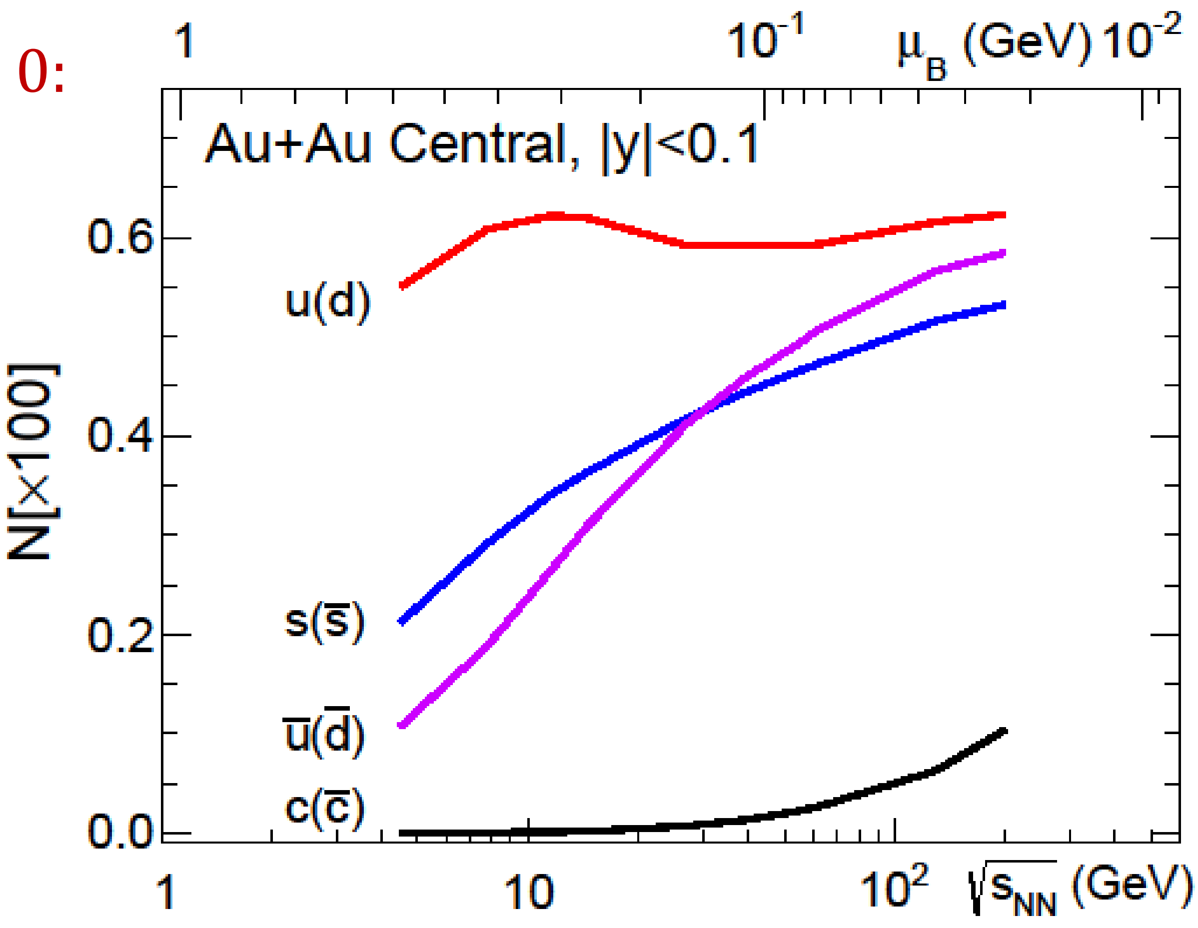
Baryon density effect

- *quark distributions at finite baryon density*

$$f_{u,d} = \frac{N_{u,d}}{e^{(u^\mu p_\mu - \mu_B/3)/T} + 1} \qquad f_s = \frac{N_s \lambda_s}{e^{u^\mu p_\mu/T} + 1}$$

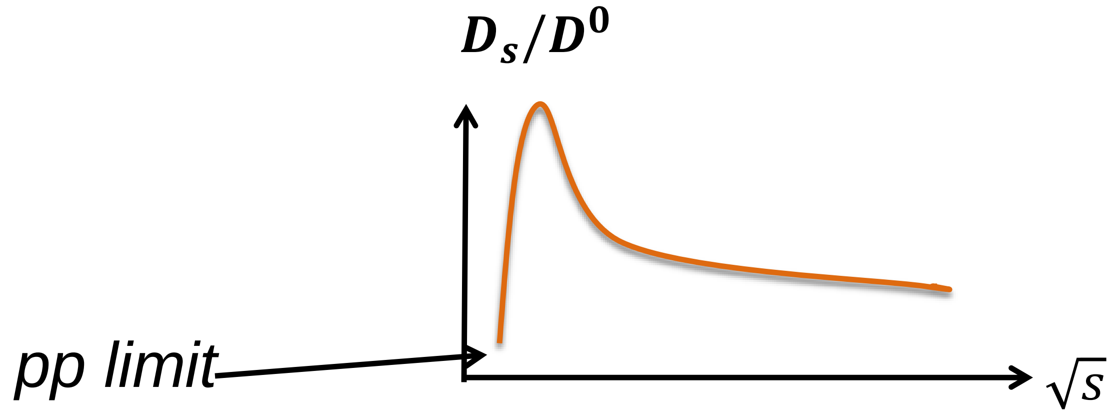
at high baryon density, more u and d quarks, less $\bar{u}$ and $\bar{d}$ quarks, and probably $n_{\bar{u}} < n_{\bar{s}}$!

Calculated quark number density at $\vec{r} = 0$:

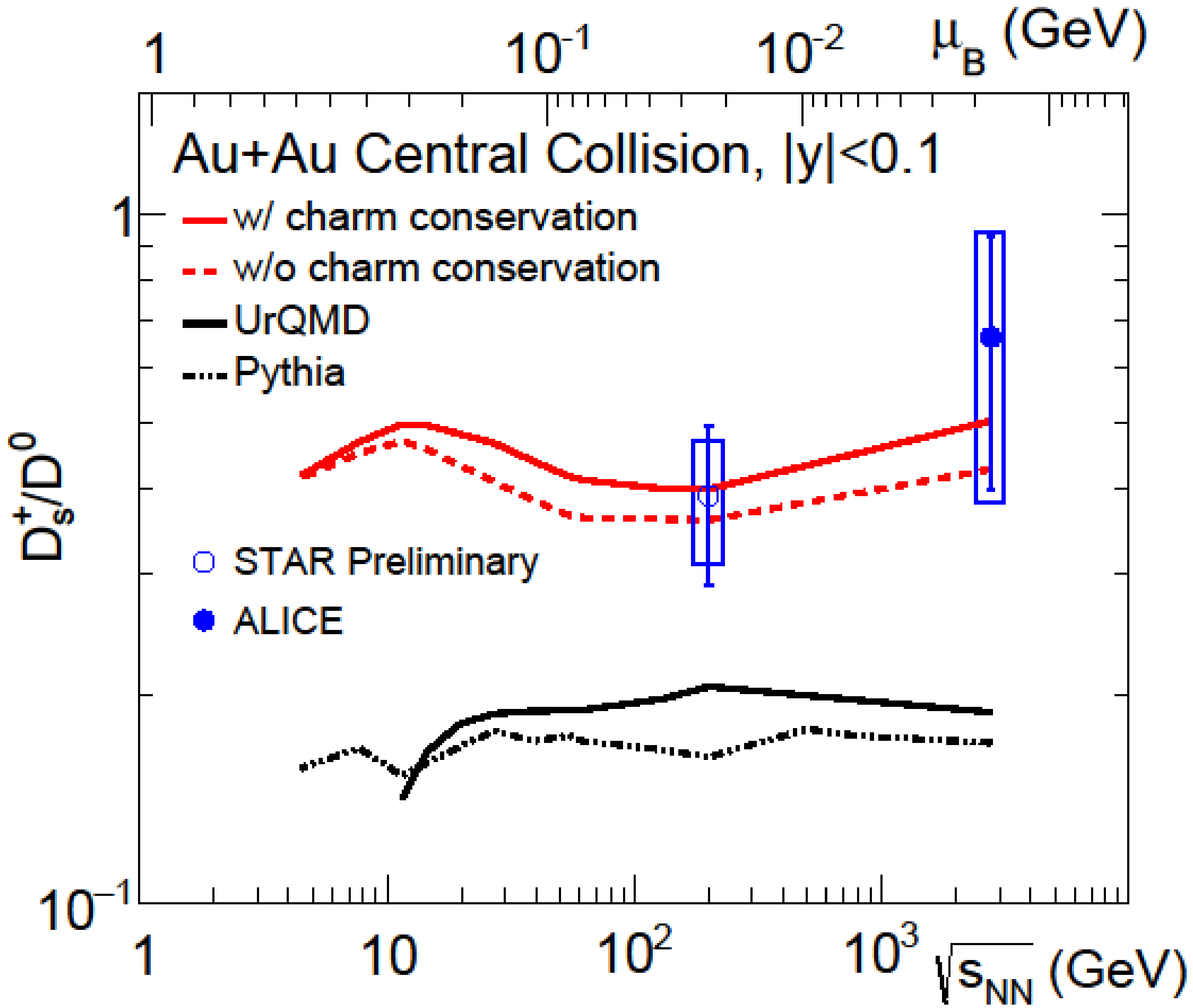


J.Zhao, S.Shi, N.Xu and PZ, in progress

- *$D_s(c\bar{s})$ enhancement and $D^0(c\bar{u})$ suppression at high μ_B!*



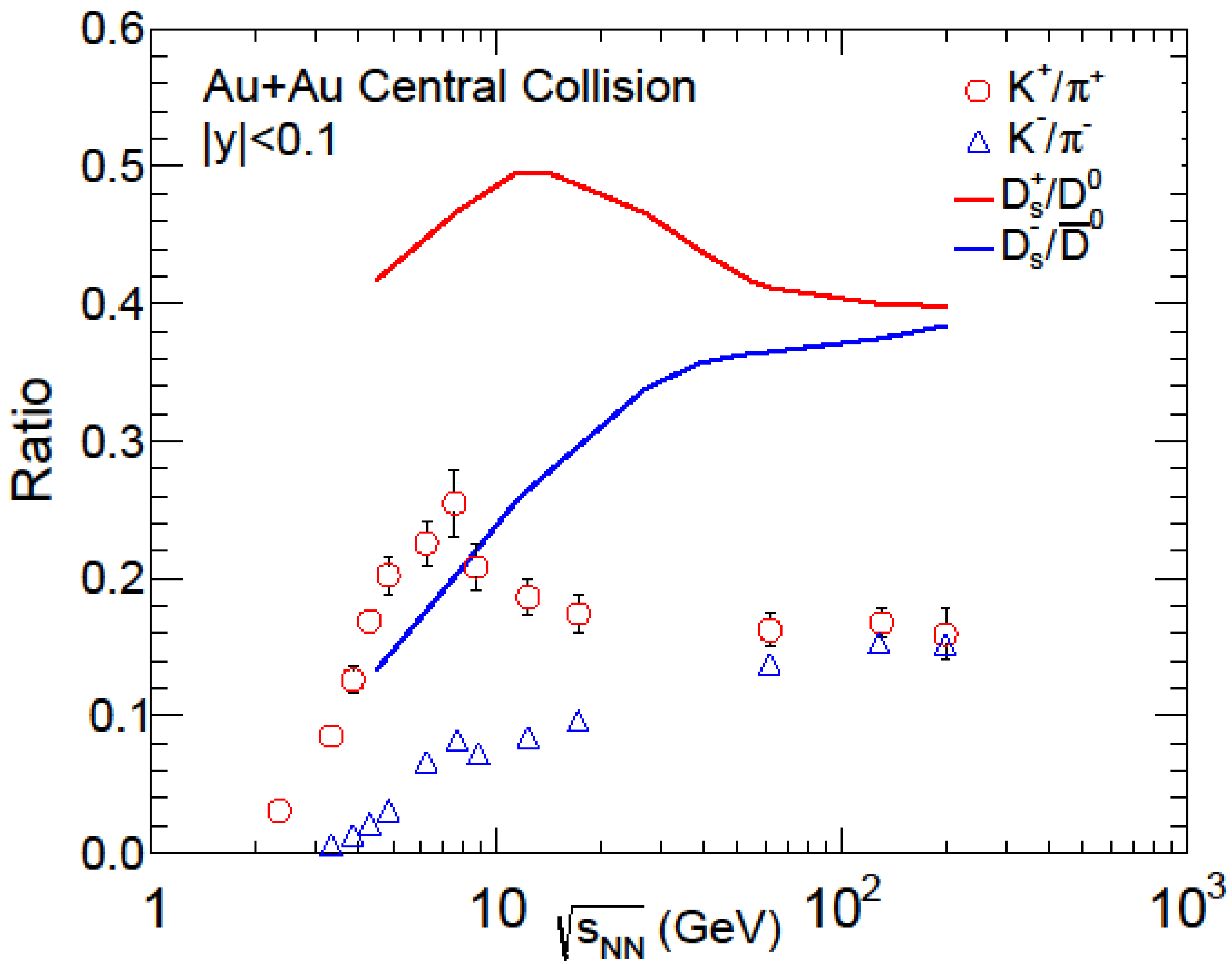
$D_s/D^0(\sqrt{s})$



J.Zhao, S.Shi, N.Xu and PZ, in progress

A significantly strong D_s/D^0 enhancement at about $\sqrt{s} = 10$ GeV where the baryon density is the largest.

Comparison with K/π



J.Zhao, S.Shi, N.Xu and PZ, in progress

- *The behavior of D_s^+/D^0 ($D_s^-/\overline{D}^0$) is similar to K^+/π^+ (K^-/π^-) .*
- *The two peaks locate at the largest baryon density.*

Summary

- We developed a sequential coalescence model for heavy flavor hadron production: 2(3)-body Dirac equations + hydrodynamic equations + coalescence.
- Charm conservation enhances significantly the ratio D_s/D^0.
- D_s/D^0 is further enhanced at high baryon density.