Heavy-quark Hadron Production in Nuclear Collisions

Pengfei Zhuang
(Tsinghua University, Beijing)

- *Introduction*
- *Correlation between Strangeness and Charm*
- *Correlation between Strangeness and Baryon Density*
- *Sequential Coalescence*
- D_s/D^0 (Λ_c/D^0) *Enhancement (Suppression)*
- *Summary*

work by Jiaxing Zhao, Shuzhe Shi, Nu Xu and PZ

Hadronization

- Hadronization in vacuum

  a non-perturbative process, unsolved problem in physics

- Hadronization at finite temperature (such as in heavy ion collisions)

  statistics should play an important role in 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)

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

hydro, dynamics, statistics

- Two assumptions

  1) the 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) all the hadrons (light- and heavy-quark hadrons) are created at the same surface (time).

Limit: Quarkonia

- *Quarkonia in vacuum*

non-relativistic potential model with Cornell potential:

C.Quigg and J.Rosner, Phys. Rep. 56, 167(1979)

- *Quarkonia at finite temperature (such as in heavy ion collisions)*

non-relativistic potential model with lattice simulated potential:

H.Satz, J.Phys. G32, R25(2006)

→ *1) sequential suppression, the dissociation temperature*

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

J/ψ *is produced earlier than* ψ' *and* χ_c.

Heavy-quark hadrons are sequentially produced.

→ *2) calculable Wigner function*

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

- *Quarkonium regeneration:*

P.Braun-Munzinger and J.Stachel, PLB490, 196(2000)
R.Thews, M.Schroedter and J.Rafelski, PRC63, 054905(2001)
L.Grandchamp and R.Rapp, NPA709, 415(2002)
L.Yan, N.Xu and PZ, PRL97, 232301(2006)

Langevin equation for heavy quarks with attractive force between correlated c *and* $\bar{c}$,

C.Young and E.Shuryak, PRC79, 034907(2009)

$$\frac{d\vec{p}}{dt} = -\gamma\vec{p} + \vec{\eta} - \vec{\nabla}V$$

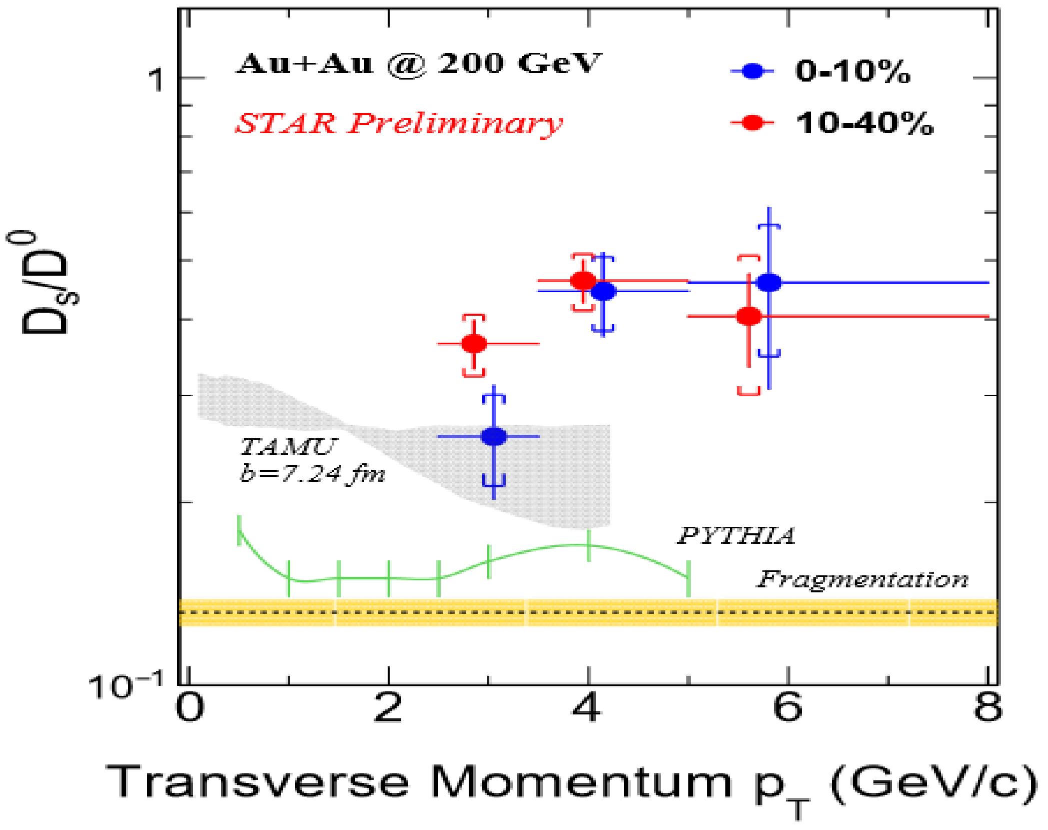
→ *increasing charmonium surviving probability.*

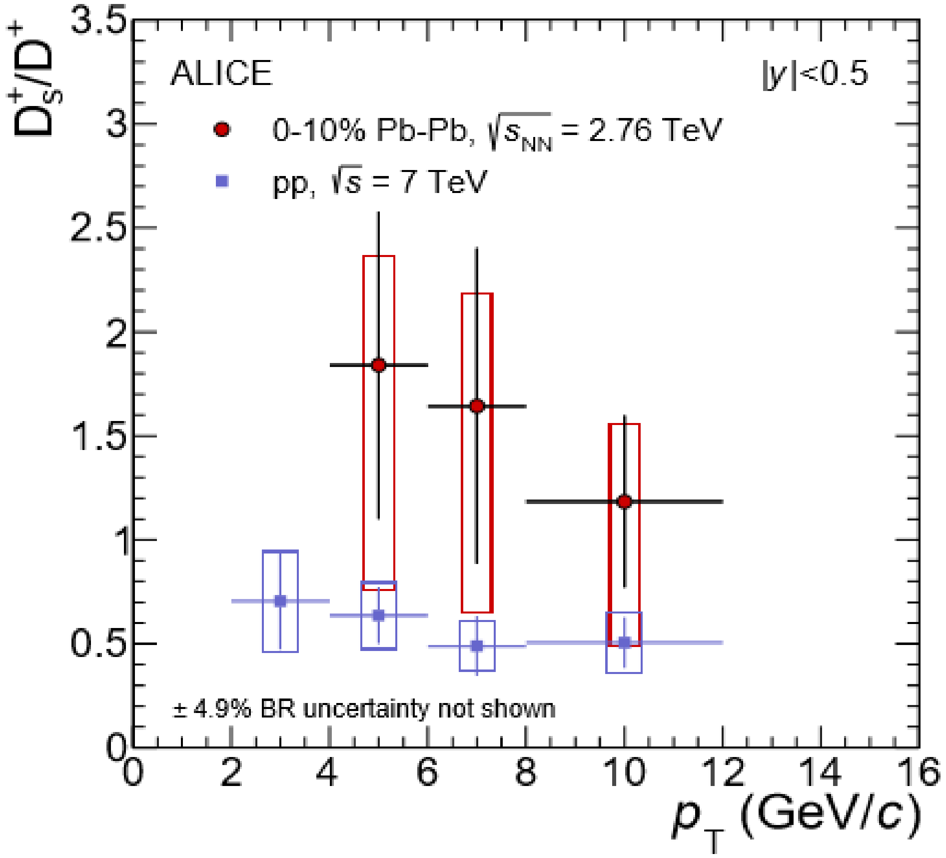
Strangeness Enhancement

- Well-known strangeness enhancement due to thermal production in QGP, supported by experimental data in heavy ion collisions.

P.Koch, B.Muller and J.Rafelski, Phys. Rept. 142, 167(1986)

- Strong D_s/D^0 enhancement at RHIC and LHC





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

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

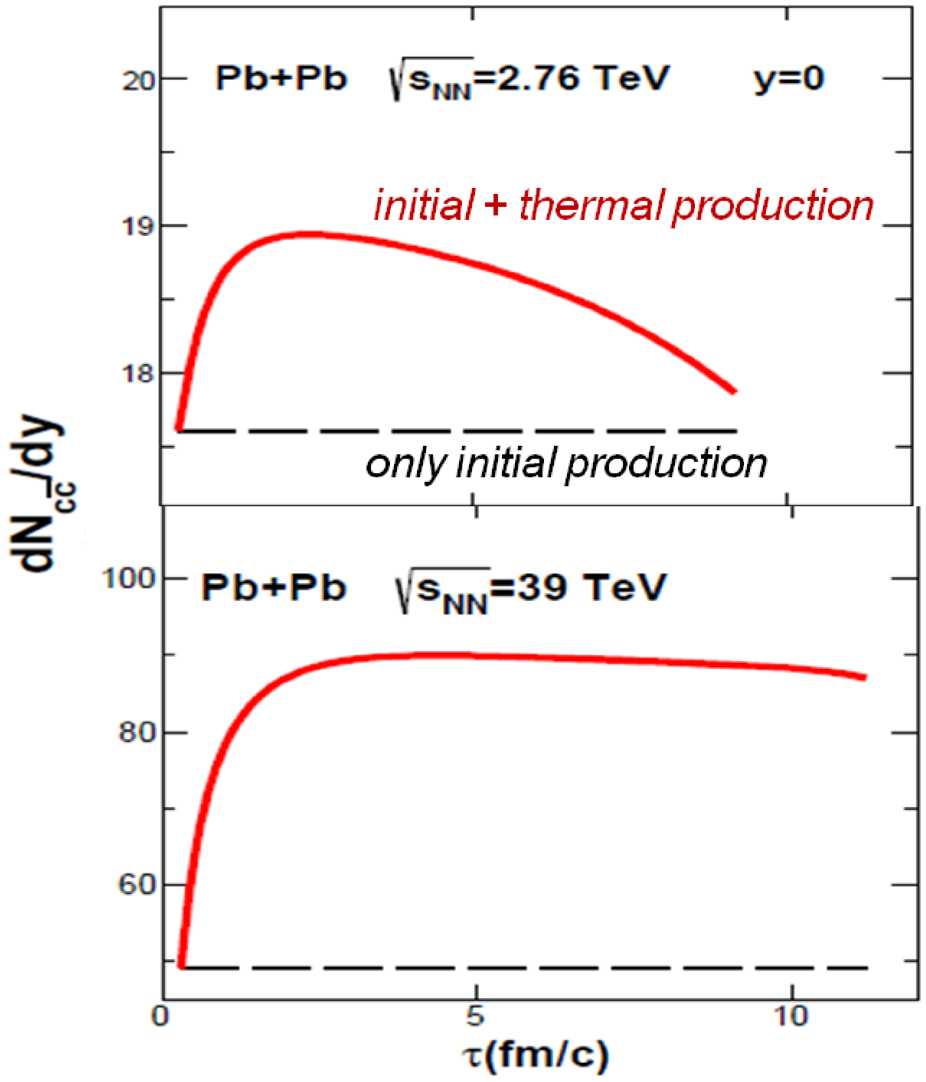
- D_s enhancement via strangeness enhanement

M.He, R.Fries and R.Rapp, PRL110, 112301(2013)

there is still a sizeable difference between strangeness enhancement and data.

Charm Conservation

- *Charm quark thermal production in QGP*



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

- *Even at LHC energy, heavy quark production is controlled by the initial hard process, the thermal production in QGP can be safely neglected.*

→ *Charm quark number is conserved during the evolution of HIC.*

Correlation between Strangeness and Charm

- *Charm conservation in heavy ion collisions*

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 all charmed hadrons are simultaneously produced, the constraint of charm conservation is introduced via a normalization constant g_c*,*

# of any singly charmed hadron $\sim g_c$
→ *no effect on the ratio* D_s/D^0 *and* Λ_c/D^0 *!*

- *If charmed hadrons are sequentially produced, more charm quarks are involved in the earlier production and less in the later production, due to charm conservation.*
  → *different charm conservation effect on different hadrons !*

- *Correlation between strangeness and charm:*

When D_s *is produced earlier than* D^0*,*

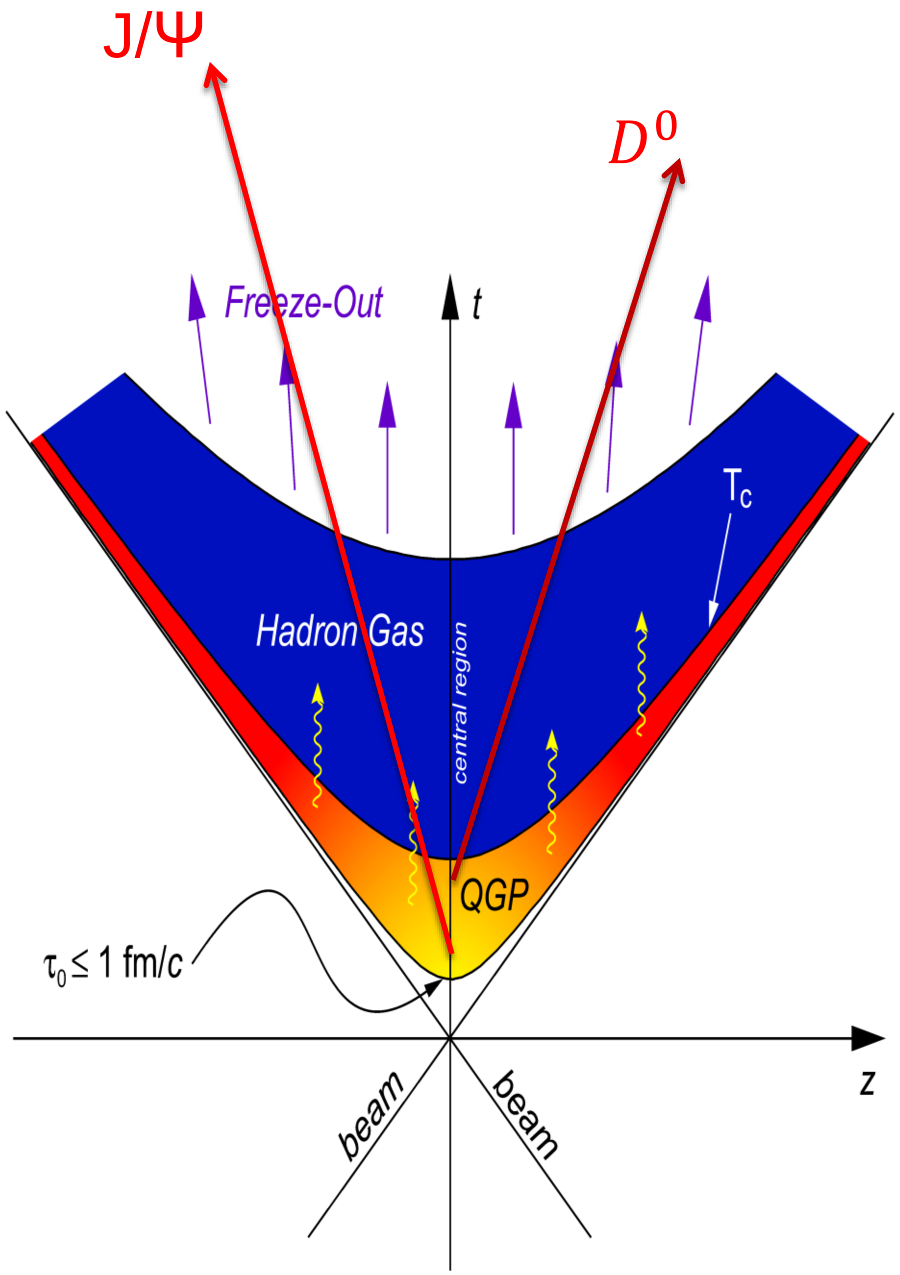
D_s *enhancement by strangeness enhancement*

→ D_0 *suppression by charm conservation*

→ *an extra* D_S/D^0 *enhancement !*

Sequential Coalescence Model

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



- *Step 1: Sequential production temperature from 2-body (3-body) Dirac equations* for $c\bar{q}$ $(q = u, d, s, c)$,

  → *1) binding energy* $\varepsilon(T)$,
  production (dissociation) temperature

  $$\epsilon(T_D) = 0$$

  2) wave function $\psi(x|T)$
  coalescence probability

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

- *Step 2: Sequential production time from hydrodynamics* for QGP evolution

  → *production time* $t(\vec{x}, T_D)$

- *Step 3: Sequential coalescence with charm conservation*

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

  total charm quark number: N_c

  total charm quark number in the sequential coalescence process:

  $$N_c - \sum (all\ used\ charm\ quarks)$$

Step 1: Sequential Production Temperature from 2-body Dirac Equations

$T=0$: H.Crater, J.Yoon and C.Wong, PRD79, 034011(2009)
$T\neq 0$: S.Shi, X.Guo and PZ, PRD88, 014021(2013)

$$\left[-\frac{d^2}{dr^2}+\frac{j(j+1)}{r^2}+2m_wB+B^2+2\epsilon_wA-A^2+\Phi_D-3\Phi_{SS}\right]u_0+2\sqrt{j(j+1)}\left(\Phi_{SOD}-\Phi_{SOX}\right)u_1^0=b^2u_0,$$

$$\left[-\frac{d^2}{dr^2}+\frac{j(j+1)}{r^2}+2m_wB+B^2+2\epsilon_wA-A^2+\Phi_D-2\Phi_{SO}+\Phi_{SS}+2\Phi_T-2\Phi_{SOT}\right]u_1^0$$
$$+2\sqrt{j(j+1)}\left(\Phi_{SOD}+\Phi_{SOX}\right)u_0=b^2u_1^0,$$

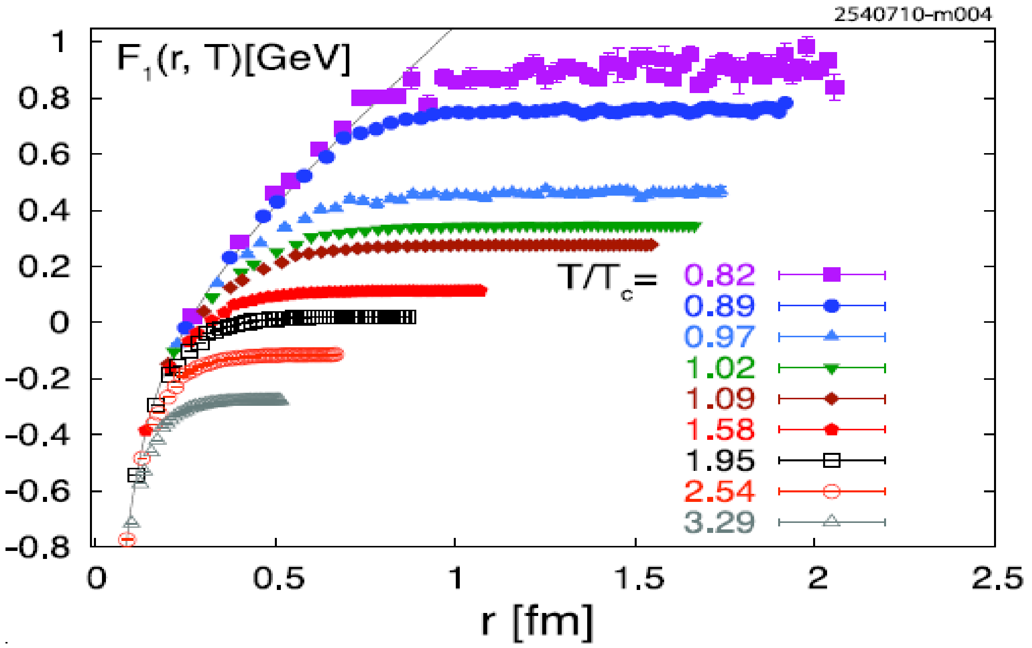
$$\left[-\frac{d^2}{dr^2}+\frac{j(j-1)}{r^2}+2m_wB+B^2+2\epsilon_wA-A^2+\Phi_D+2(j-1)\Phi_{SO}+\Phi_{SS}+\frac{2(j-1)}{2j+1}\left(\Phi_{SOT}-\Phi_T\right)\right]u_1^+$$
$$+\frac{2\sqrt{j(j+1)}}{2j+1}\left(3\Phi_T-2(j+2)\Phi_{SOT}\right)u_1^-=b^2u_1^+,$$

$$\left[-\frac{d^2}{dr^2}+\frac{(j+1)(j+2)}{r^2}+2m_wB+B^2+2\epsilon_wA-A^2+\Phi_D-2(j+2)\Phi_{SO}+\Phi_{SS}+\frac{2(j+2)}{2j+1}\left(\Phi_{SOT}-\Phi_T\right)\right]u_1^-$$
$$+\frac{2\sqrt{j(j+1)}}{2j+1}\left(3\Phi_T+2(j-1)\Phi_{SOT}\right)u_1^+=b^2u_1^- \qquad (2)$$

$$\begin{aligned}
\Phi_D &= M+F'^2+K'^2-\nabla^2F+2K'P-2\left(F'+\frac{1}{r}\right)Q,\\
\Phi_T &= \frac{1}{3}\left[N+2F'K'-\nabla^2K+\left(3F'-K'+\frac{3}{r}\right)P+\left(F'-3K'+\frac{1}{r}\right)Q\right]\\
\Phi_{SO} &= -\frac{F'}{r}+K'P-\left(F'+\frac{1}{r}\right)Q,\\
\Phi_{SS} &= O+\frac{2}{3}F'K'-\frac{1}{3}\nabla^2K+\frac{2}{3}K'P-2\left(F'+\frac{1}{3r}\right)Q,\\
\Phi_{SOT} &= -\frac{K'}{r}+\left(F'+\frac{1}{r}\right)P-K'Q,\\
F &= \frac{1}{2}L-\frac{3}{2}G,\\
G &= -\frac{1}{2}\ln\left(1-2\frac{A}{m_m}\right),\\
K &= \frac{1}{2}L+\frac{1}{2}G,\\
L &= \ln\sqrt{1+\frac{2m_wB+B^2}{m_Q^2\left(1-2A/m_m\right)}},\\
M &= -\frac{1}{2}\nabla^2G+\frac{3}{4}G'^2+G'F'-K'^2,\\
N &= \frac{1}{3}\left[\nabla^2K-\frac{1}{2}\nabla^2G+\frac{3}{2}\frac{G'-2K'}{r}+F'(G'-2K')\right]\\
O &= \frac{1}{3}\nabla^2(K+G)-\frac{1}{3}F'(G'+K')-\frac{1}{2}G'^2,\\
P &= \frac{\sinh 2K}{r},\\
Q &= \frac{\cosh 2K-1}{r}
\end{aligned}$$

$$b^2=\frac{1}{4}\left[m_m^2-2\left(m_{q1}^2+m_{q2}^2\right)+\left(m_{q1}^2-m_{q2}^2\right)^2/m_m^2\right]$$

O.Kaczmarek, EPJC 61, 811(2009)



Step 2: Sequential Production Time from Hydrodynamic Equations

- *Sequential production temperature*

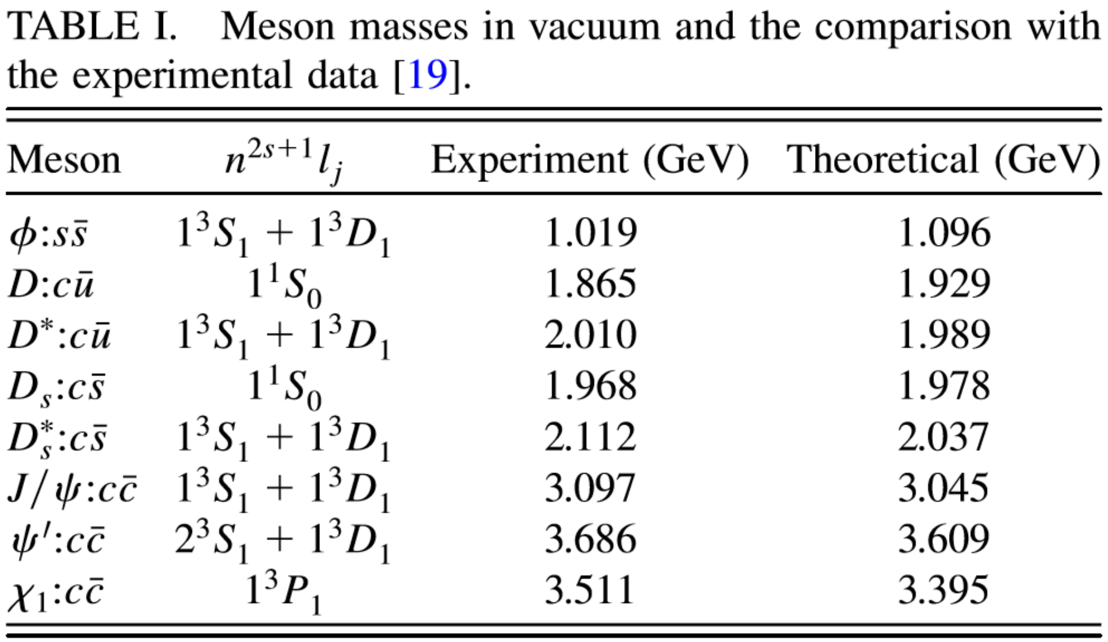


TABLE I. Meson masses in vacuum and the comparison with the experimental data [19].

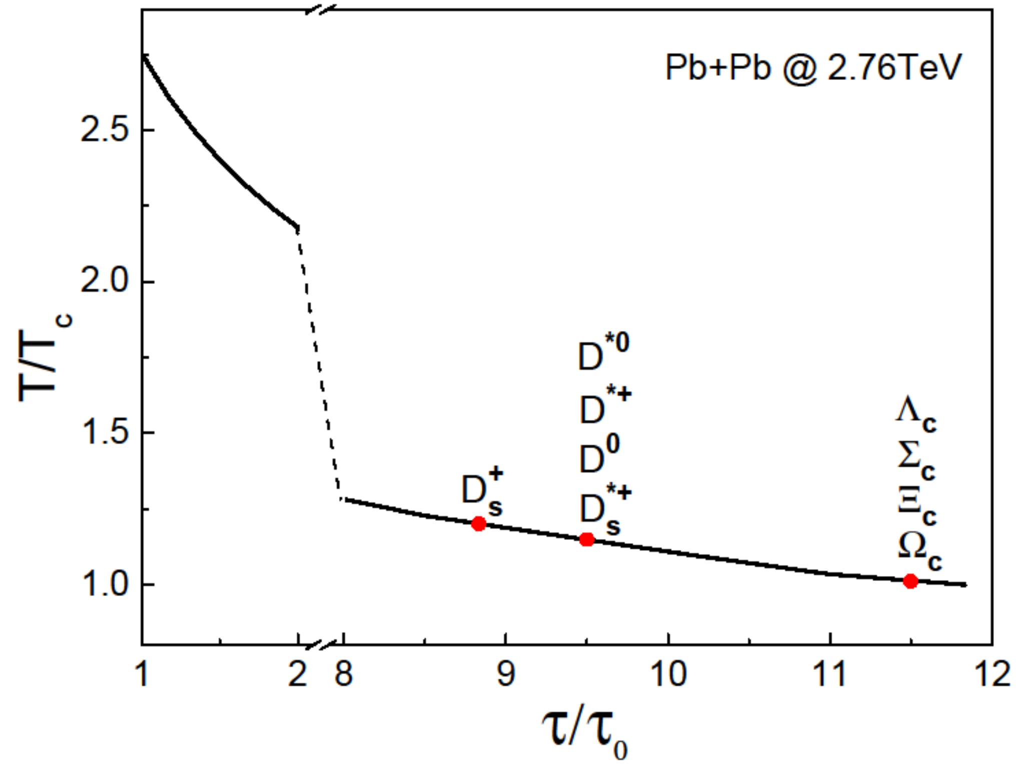
Meson	$n^{2s+1}l_j$	Experiment (GeV)	Theoretical (GeV)
ϕ:$s\bar{s}$	$1^3S_1 + 1^3D_1$	1.019	1.096
D:$c\bar{u}$	1^1S_0	1.865	1.929
D^*:$c\bar{u}$	$1^3S_1 + 1^3D_1$	2.010	1.989
D_s:$c\bar{s}$	1^1S_0	1.968	1.978
D_s^*:$c\bar{s}$	$1^3S_1 + 1^3D_1$	2.112	2.037
J/ψ:$c\bar{c}$	$1^3S_1 + 1^3D_1$	3.097	3.045
ψ':$c\bar{c}$	$2^3S_1 + 1^3D_1$	3.686	3.609
χ_1:$c\bar{c}$	1^3P_1	3.511	3.395

$$V = F$$

$$T_D/T_c \simeq \begin{cases} 1.20 & D_s \\ 1.15 & D^0 \\ 1 & \Lambda_c \end{cases}$$

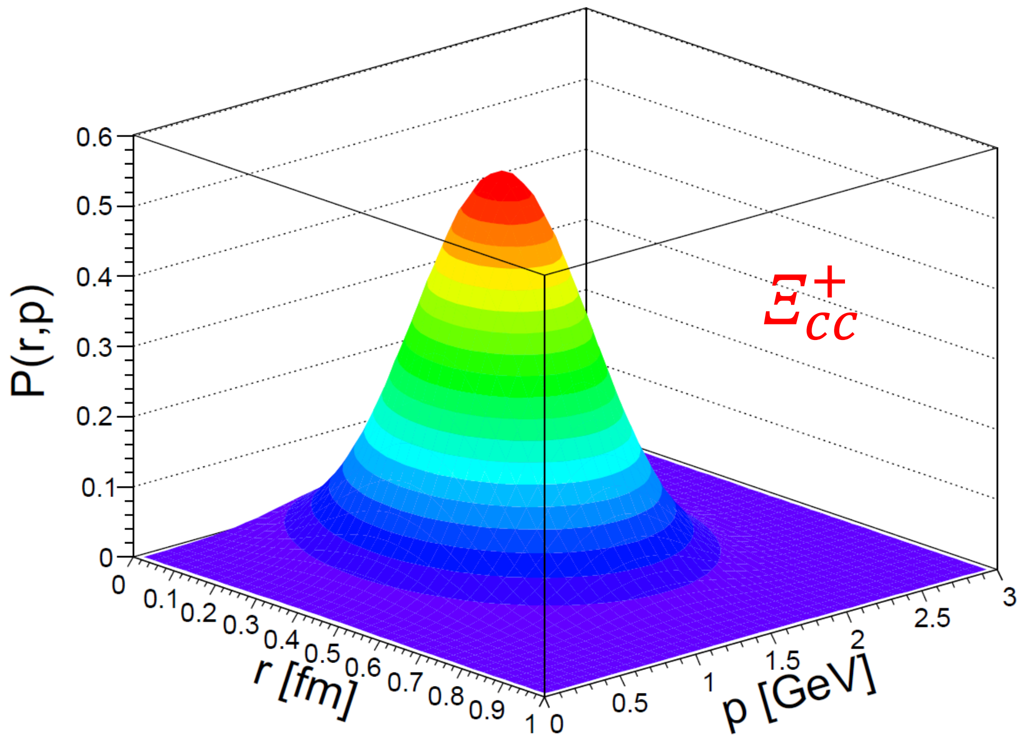
- *Sequential production time*

ideal hydrodynamics: $\partial^\mu T_{\mu\nu} = 0 \ + \ \partial^\mu n_\mu = 0 \ \rightarrow \ \tau(\vec{x}|T_D)$

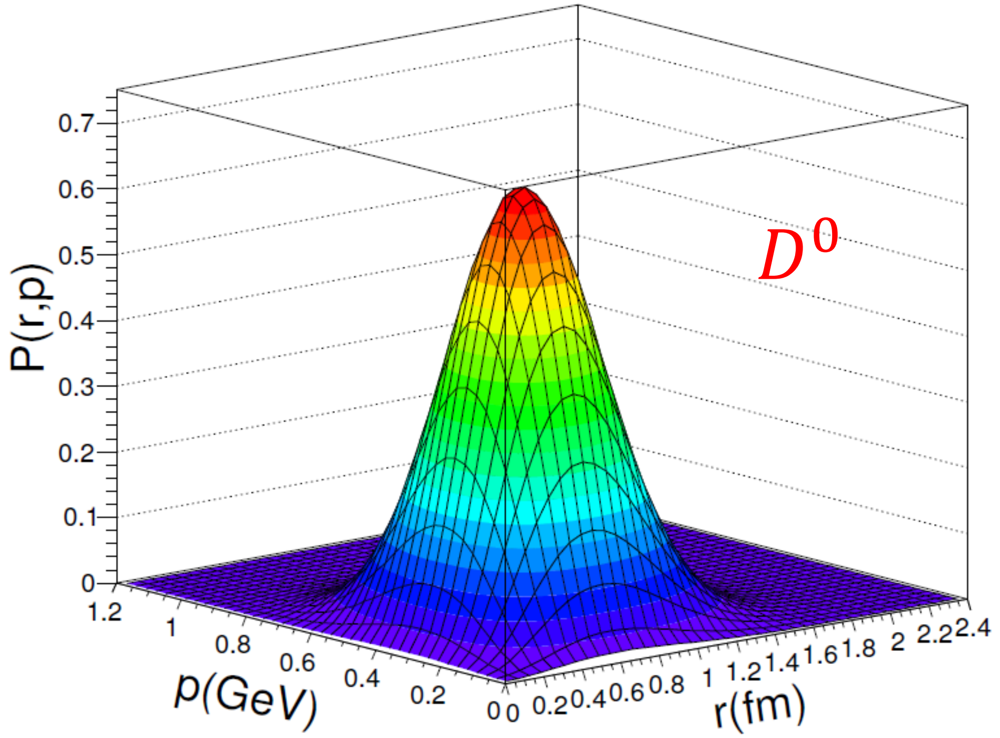


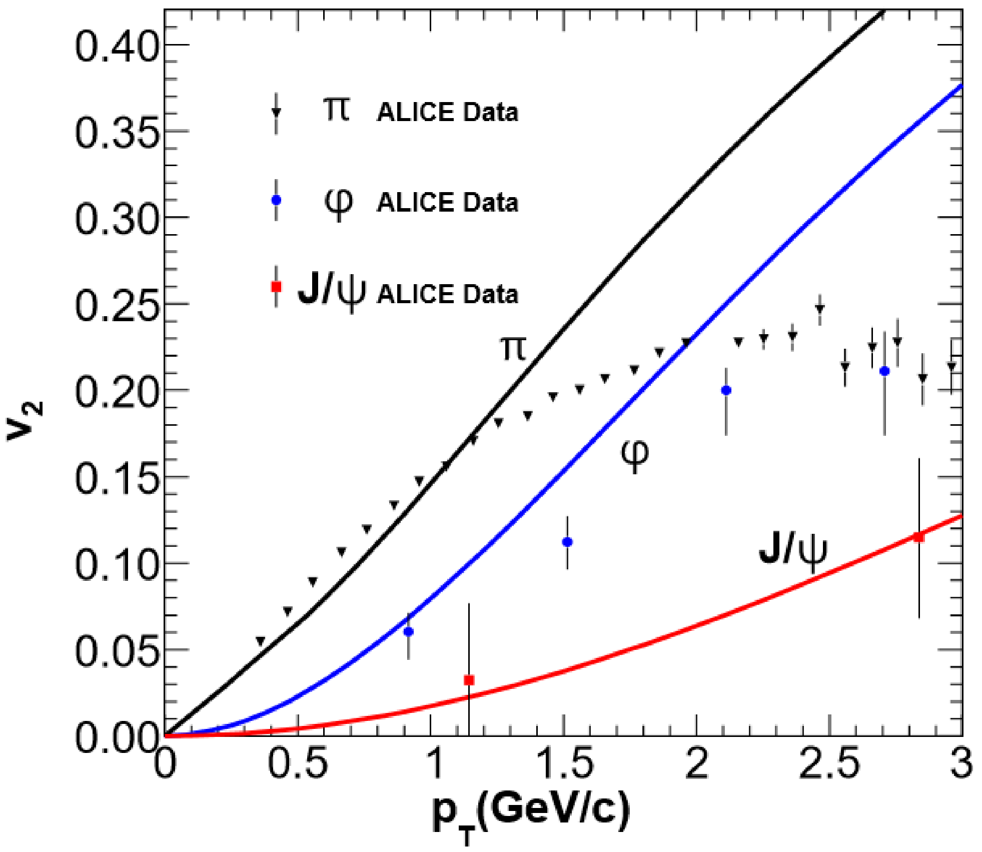
Step 3: Sequential Coalescence

$$\frac{dN}{d^2P_T d\eta} = C\int \frac{P^\mu d\sigma_{\mu\nu}(R)}{(2\pi)^3}\frac{d^4r d^4p}{(2\pi)^3} f_c(r_1,p_1) f_{\bar q}(r_2,p_2) W(r,p)$$



J.Zhao, H.He and PZ, PLB771, 349(2017)





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

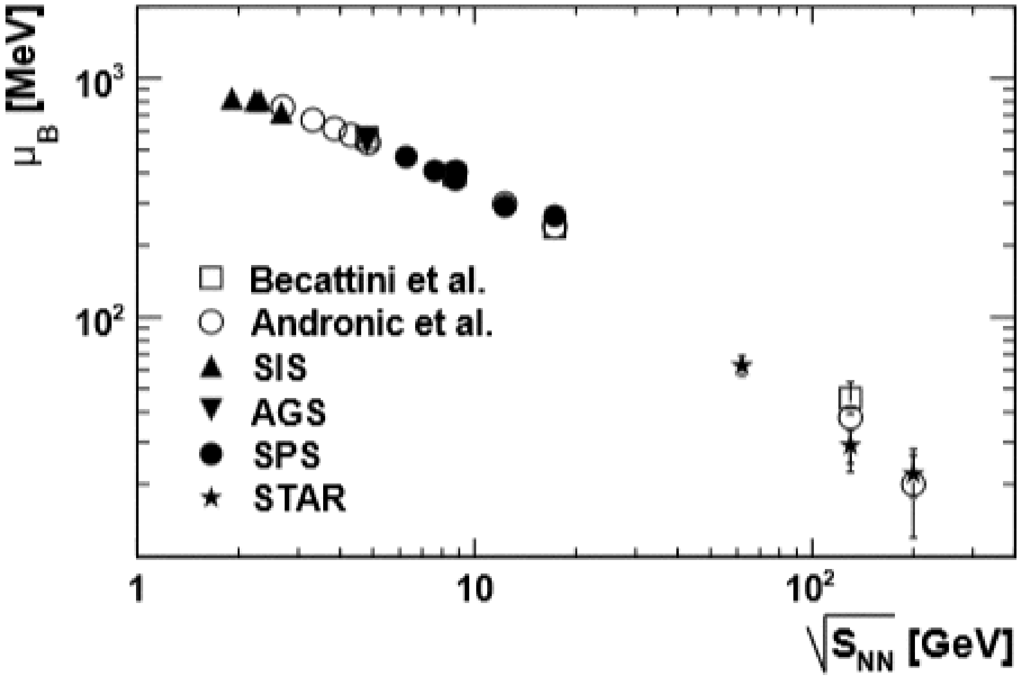
Light & Strange Quark Distributions

- *light quarks u and d:*

  equilibrium distribution

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

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



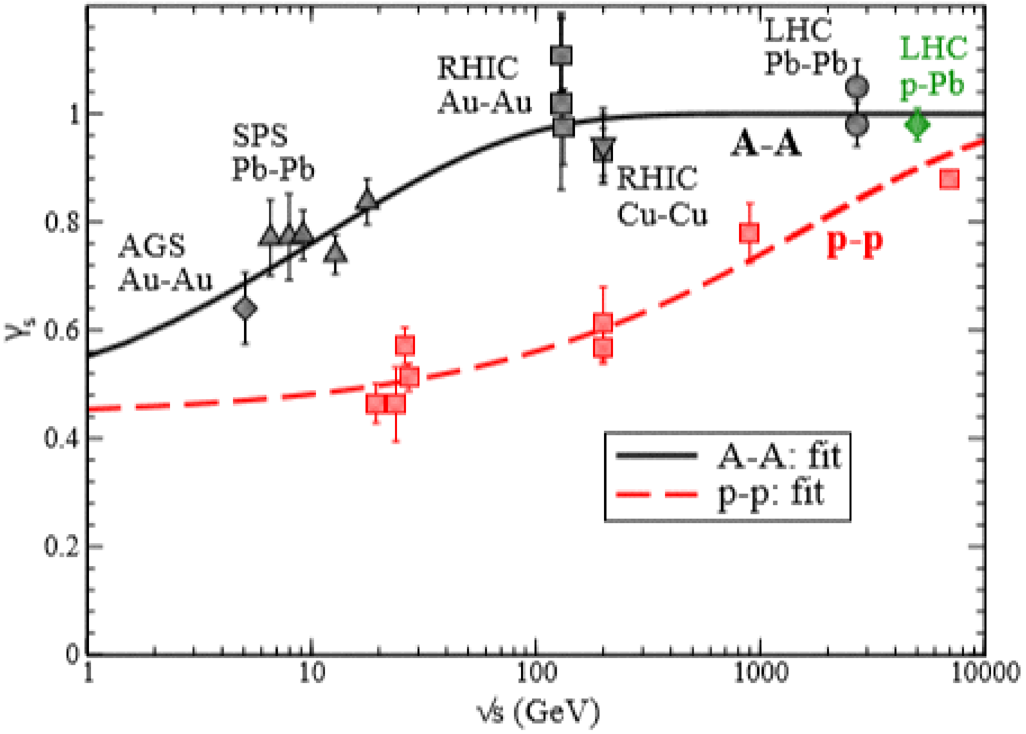
- *strange quark s:*

  equilibrium distribution with strangeness fugacity

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

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

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



Charm Quark Distribution

- *Partial thermalization:* $f_c = r_c \rho_c(x)\left[\alpha f_{th}(p) + \beta f_{pp}(p)\right]$

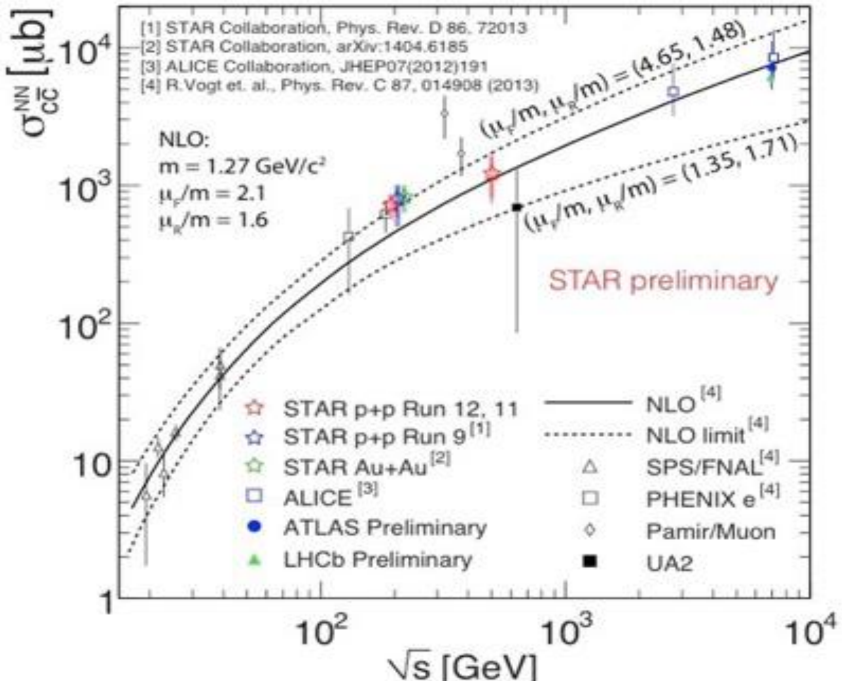
$$\rho_c(x) = T_A(x_T)T_B(x_T - b)\frac{\cosh\eta}{\tau}\frac{d\sigma_{pp}^{c\bar{c}}}{d\eta}$$

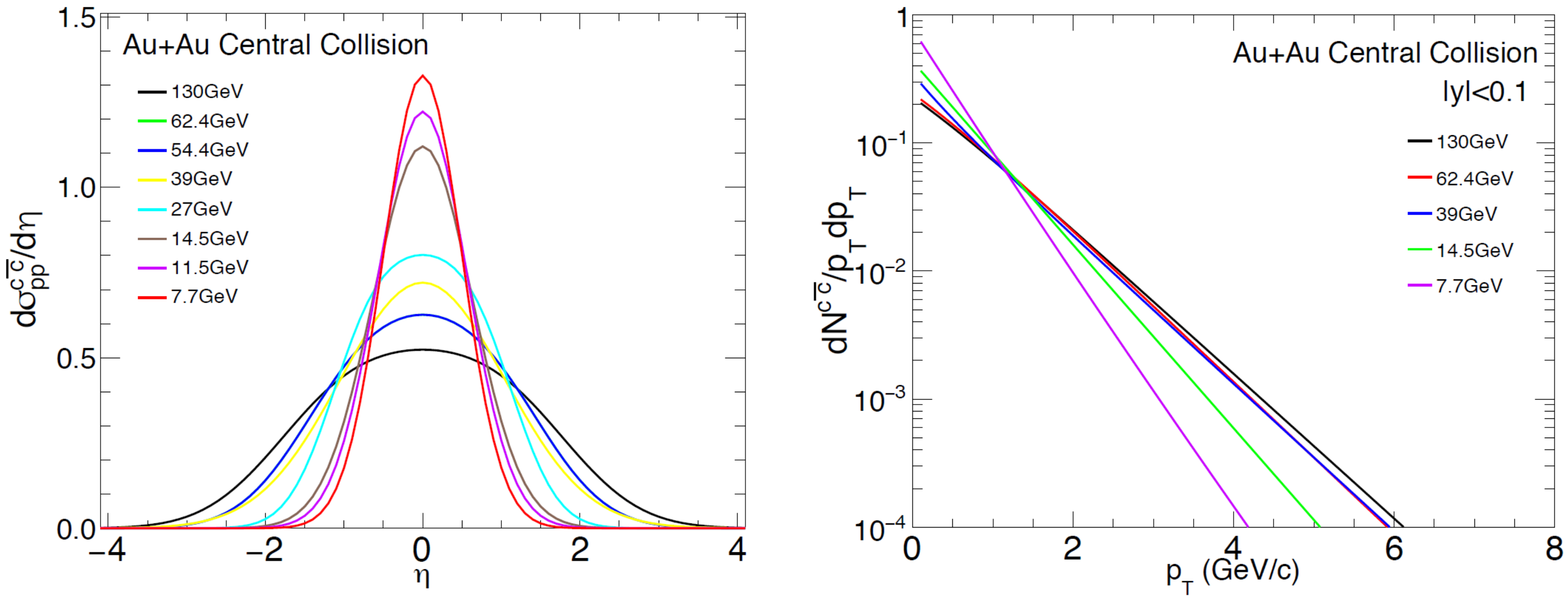
- *Sequential thermalization:*

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

- *Charm conservation:*

$$r_c = \begin{cases} 1 & D_s \\ 1 - N_{D_s}/N_c\ (\sim 90\%) & D^0 \\ 1 - N_D/N_c\ \ (\sim 60\%) & \Lambda_c \end{cases}$$





Normalized rapidity and transverse momentum distributions with PYTHIA8

Hadron Decay after Coalescence

Decay from excited states to ground state (from PDG book)

to D^0: 100% of D^{*0} and 68% of D^{*+}

to D_s^+:100% of D_s^{*+}

92% of $\Lambda_c s$ is from the excited state decay

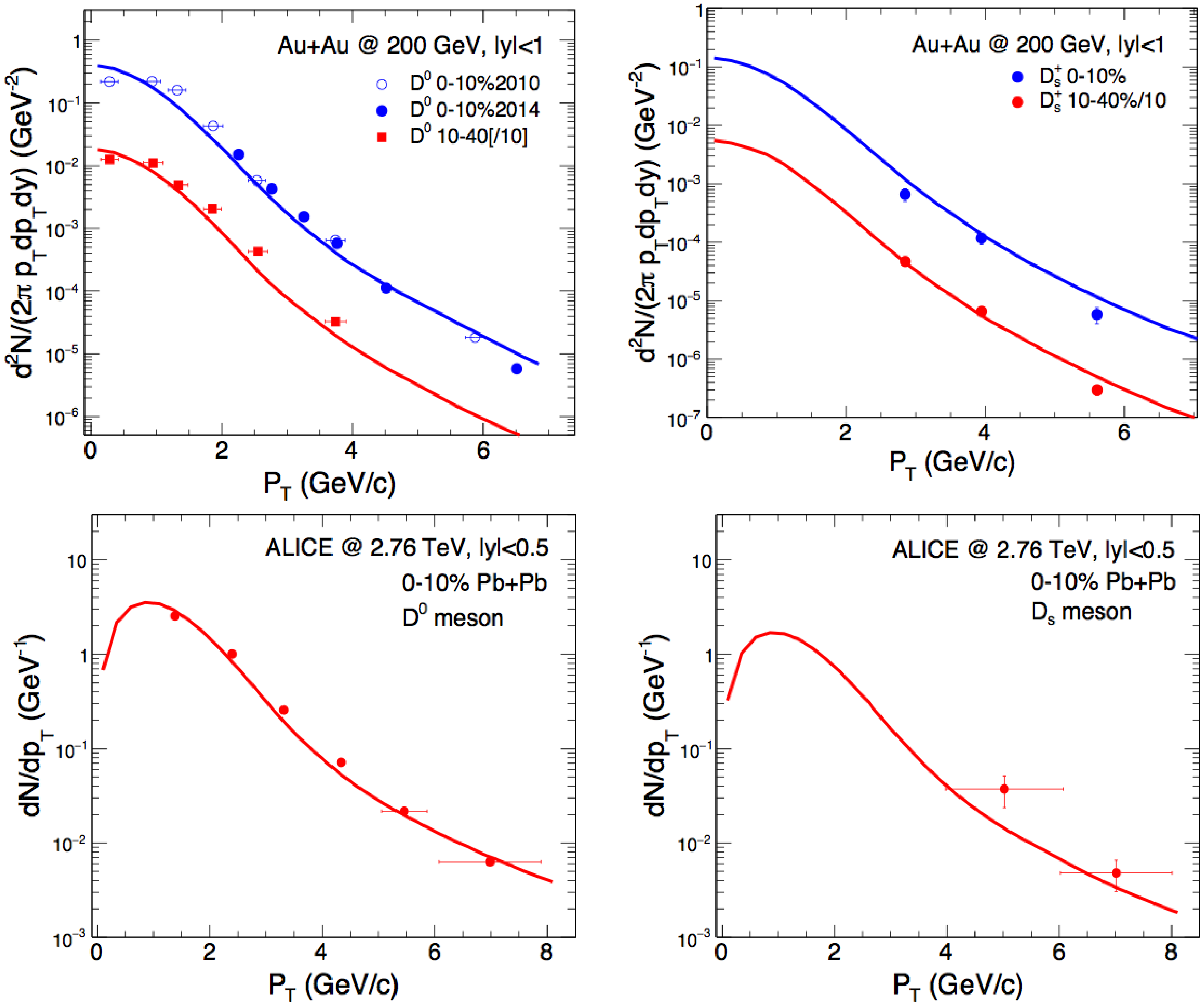
Charmed Hadron P_T Distribution

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

D^0 D_s

RHIC

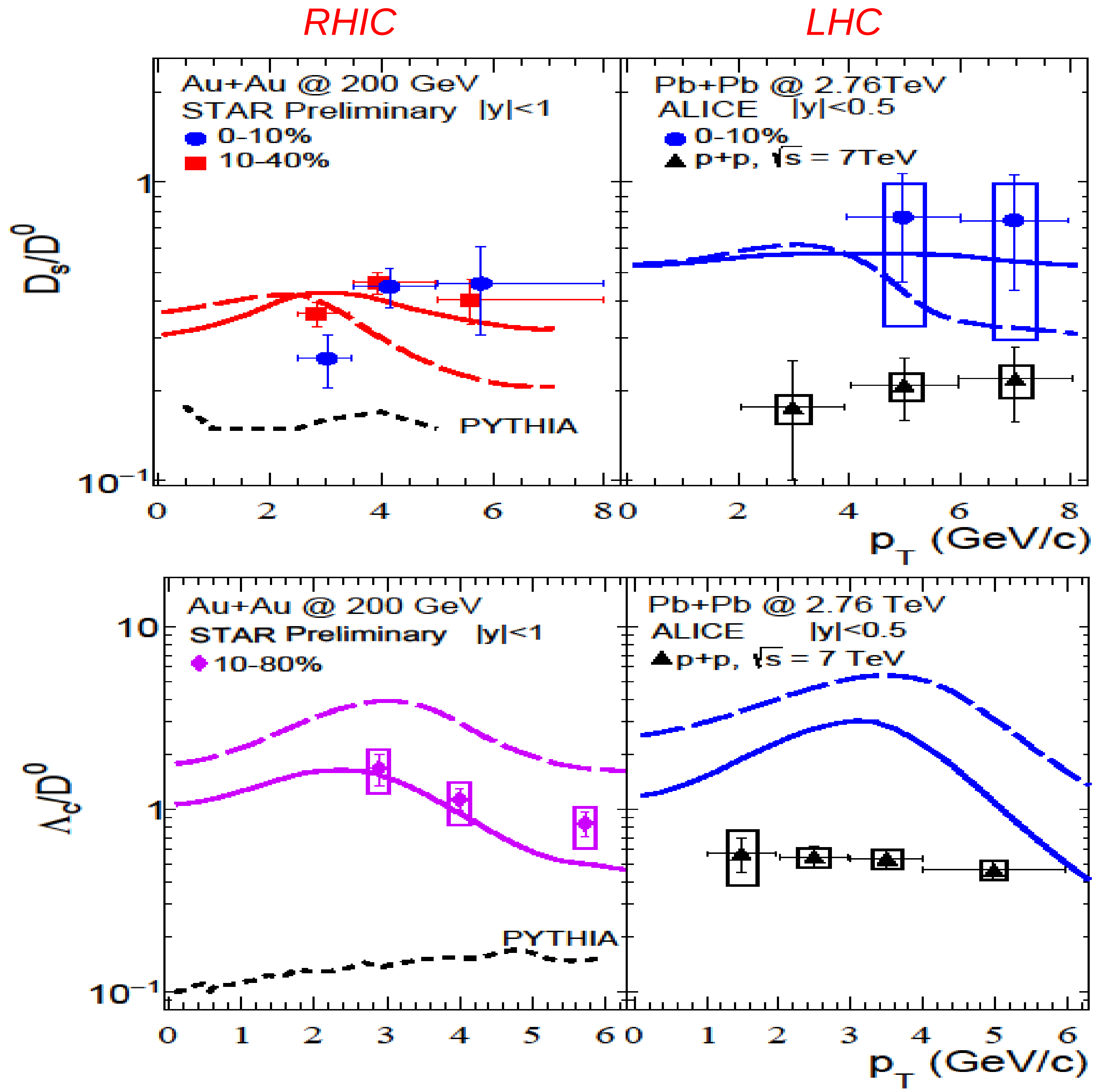
LHC



the shape is controlled by charm quark thermalization, namely the value of α.

Yield Ratios

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



Solid lines:
with charm conservation

Dashed lines:
without charm conservation

Charm conservation increases the ratio D_s/D^0,
but sequential thermalization decreases the ratio at low p_T and increases the ratio at high p_T.

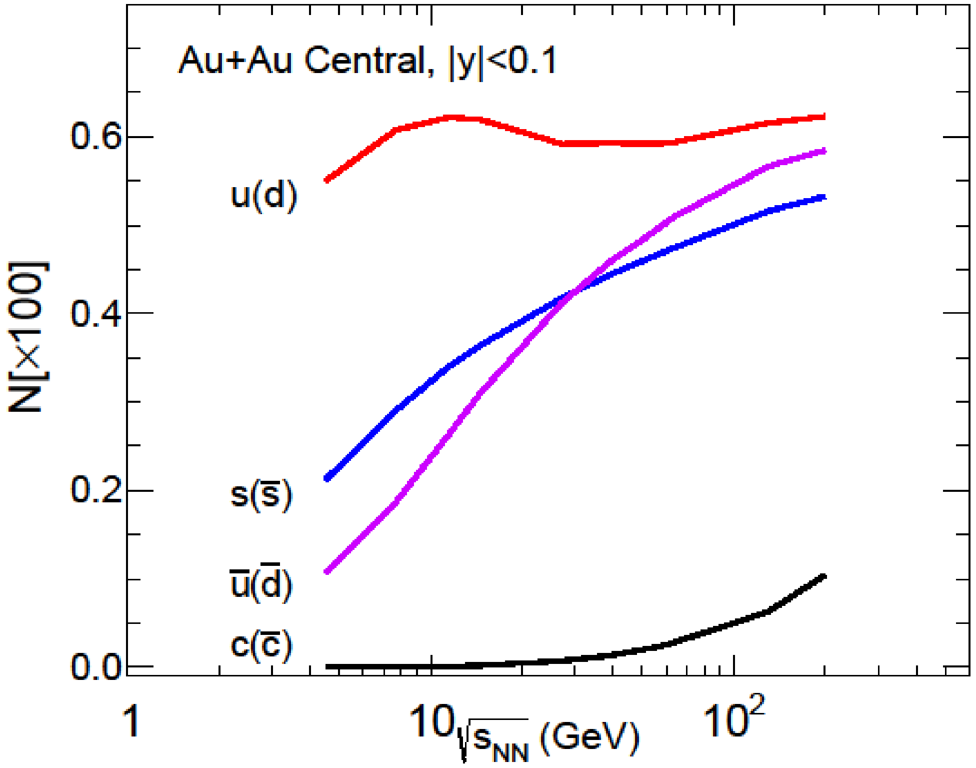
Correlation between Strangeness and Baryon Density

- *Baryon density effect*

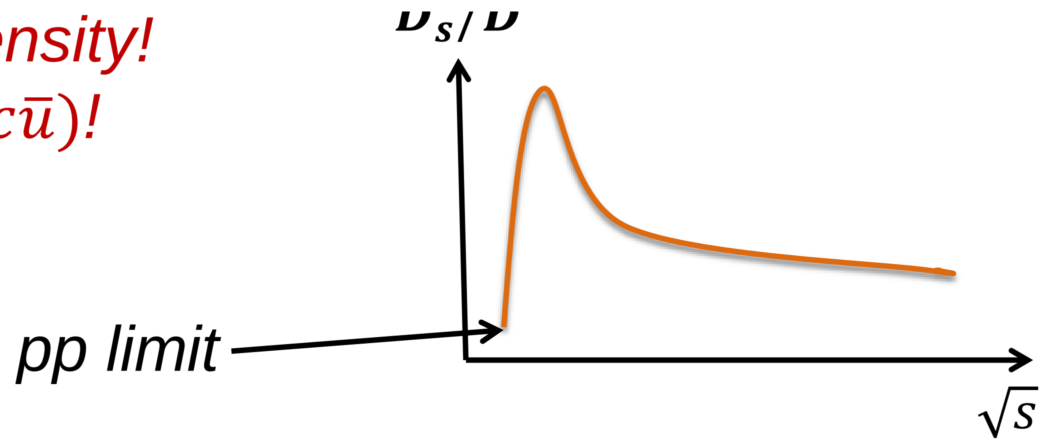
$$f_{u,d} = \frac{N_{u,d}}{e^{(u^\mu p_\mu - \mu_B/3)/T} + 1} \qquad\qquad f_s = \frac{N_s \lambda_s}{e^{u^\mu p_\mu/T} + 1}$$

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

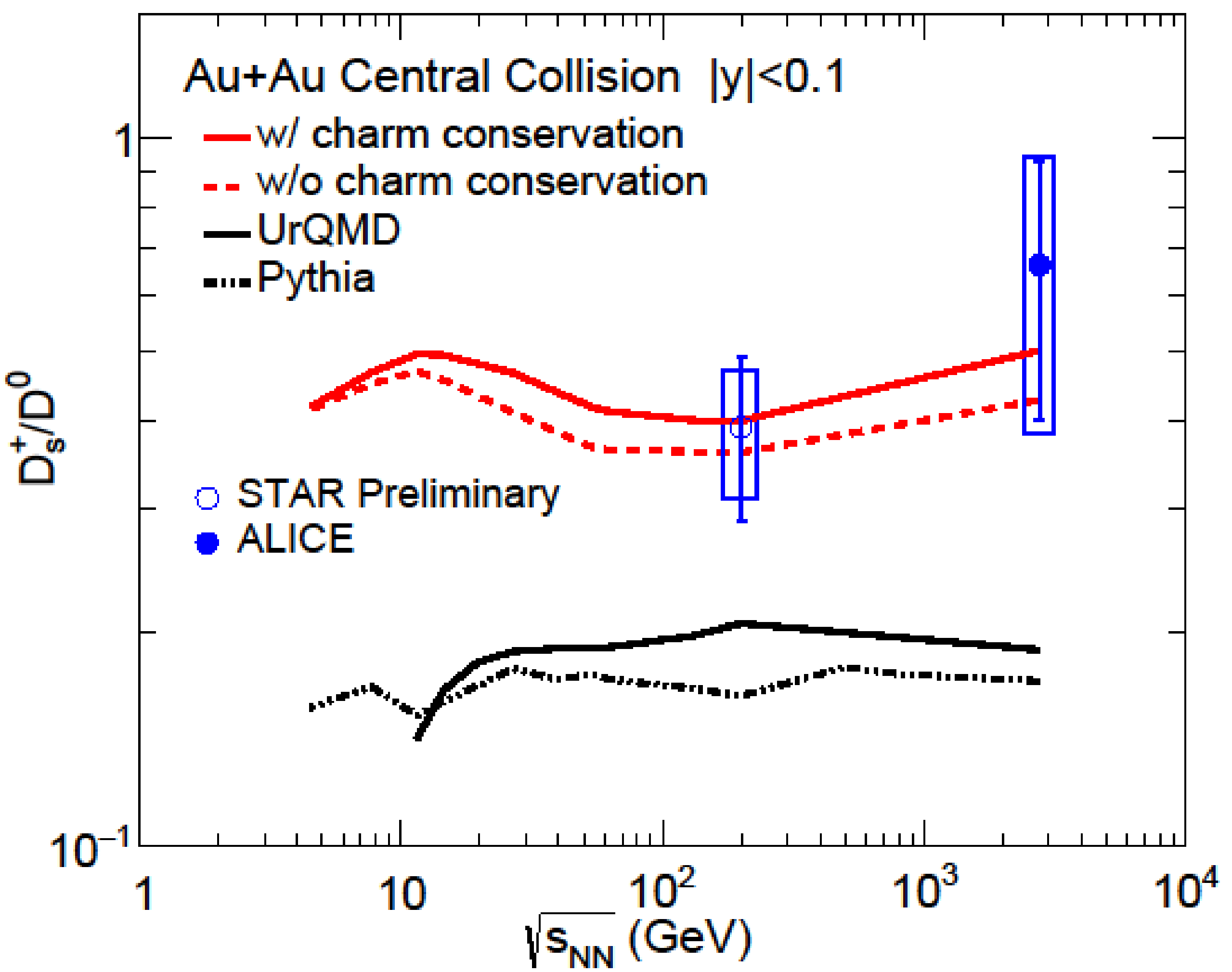
Quark number density at $\vec{r} = 0$:



- *Strangeness enhancement at high baryon density!*
  $D_s(c\bar{s})$ enhancement in comparison with $D^0(c\bar{u})$!



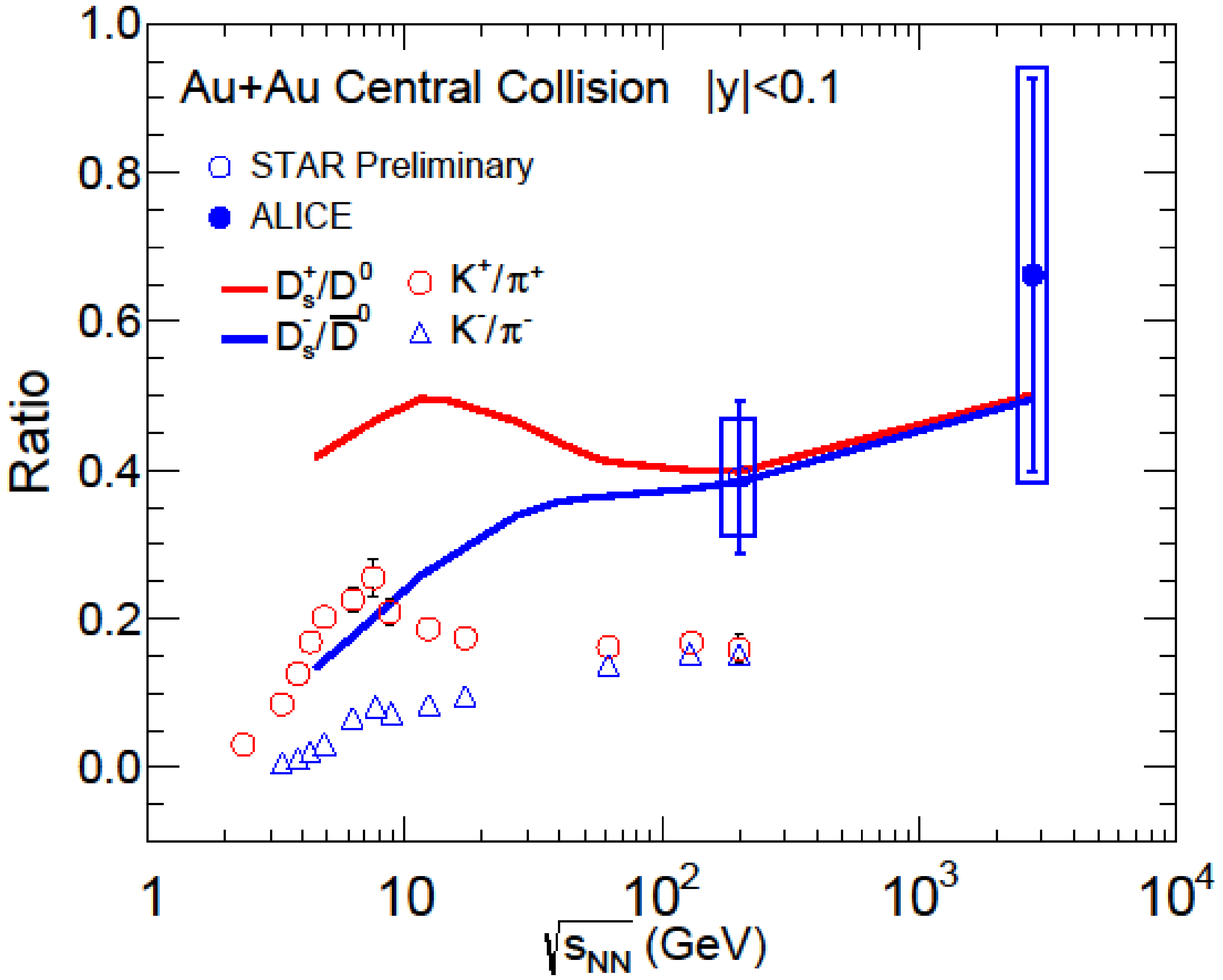
$D_s/D^0(\sqrt{s})$



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

- *The decreasing ratio at very low $\sqrt{s}$ is due to the disappearance of s-quark thermal production, or the disappearance of the QGP fireball.*

Comparison with K/π



- 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 with charm conservation and continuous charm thermalization.*

- *The charm conservation significantly enhances (suppresses) the ratio* D_s/D^0 (Λ_c/D^0).

- *The peak of* $D_s/D^0(\sqrt{s})$ *in the energy region of FAIR/NICA/HIAF can be considered as a signal of QGP phase transition.*

Chirality Workshop 2019

The 5th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

The 1st (2015), 2nd(2016), and 3rd (2017) workshops at UCLA
The 4th workshop at Florence

- *Place:* *Tsinghua University, Beijing*
- *Date:* *April 8-12, 2019*

You are welcome to join the workshop!