Significant D_s/D_0 Enhancement in Nuclear Collisions

Pengfei Zhuang 庄鹏飞
Tsinghua University 清华大学

- *Strangeness enhancement,*
  charm conservation,
  and high baryon density
- *Sequential coalescence model*
- $D_s/D_0(p_t)$ *and* $D_s/D_0(\sqrt{s})$

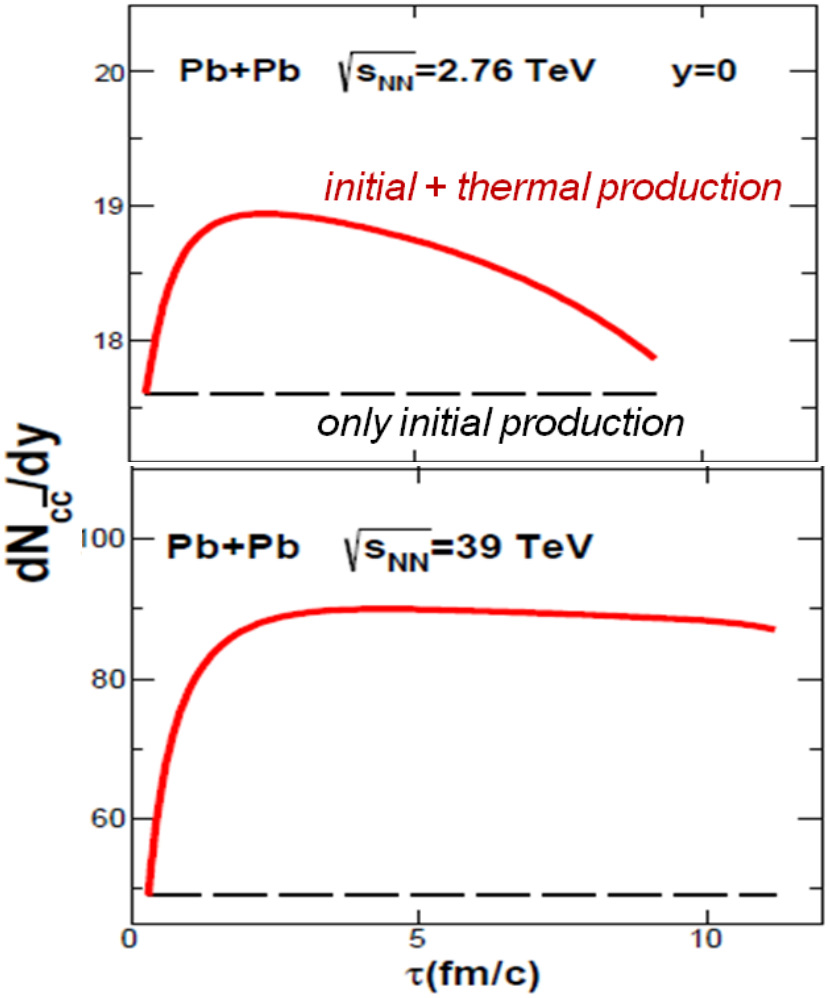
Work together with Jiaxing Zhao （赵佳星） *and Nu Xu*（许怒）

Strangeness and Charm in Nuclear Collisions

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

  See, Strangeness in Relativistic Heavy Ion Collisions, P.Koch, B.Muller and J.Rafelski, Phys. Rept. 142, 167(1986)

- *Charm conservation*



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.

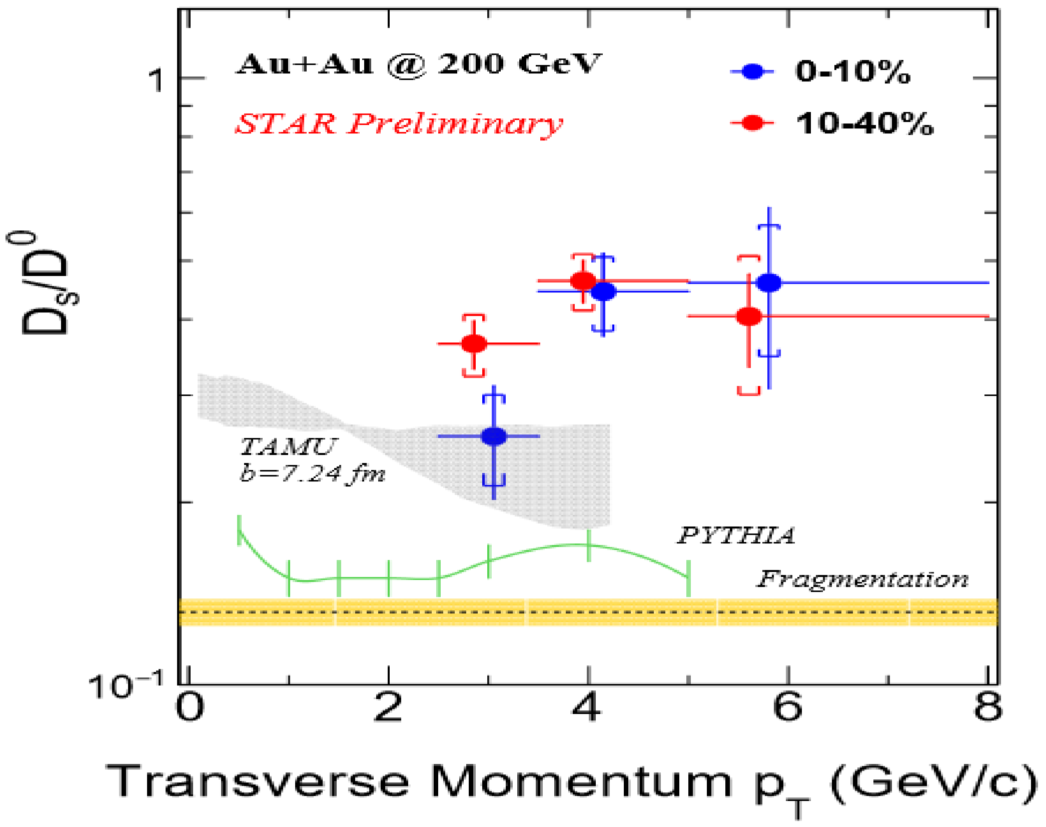
→

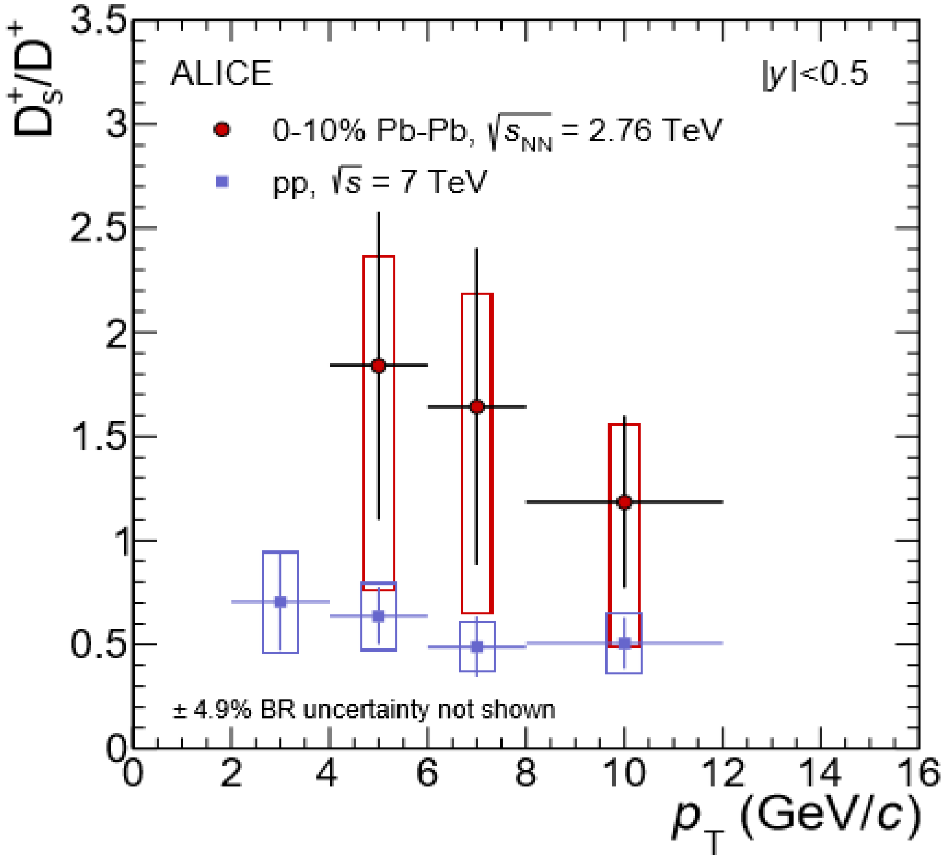
Charm quark number is conserved during the fireball evolution.

What is the effect of strangeness enhancement and charm conservation on charmed strange hadron production ?

D_s/D_0

- *strong enhancement at RHIC and LHC*





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

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

- *Induced only by strangeness (D_s) enhancement ?*

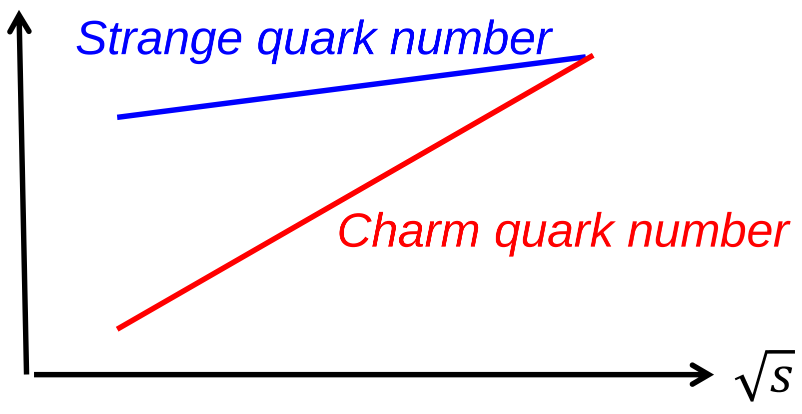
See for instance, M.He, R.Fries and R.Rapp, PRL110, 112301(2013).

- *Charm conservation effect:*

D_S enhancement → D_0 suppression → extra D_S/D_0 enhancement !

Intermediate Energy Nuclear Collisions

- *Strangeness production:* *thermal (soft) process, weak $\sqrt{s}$ dependence,*
  Charm production: *hard process, strong $\sqrt{s}$ dependence !*

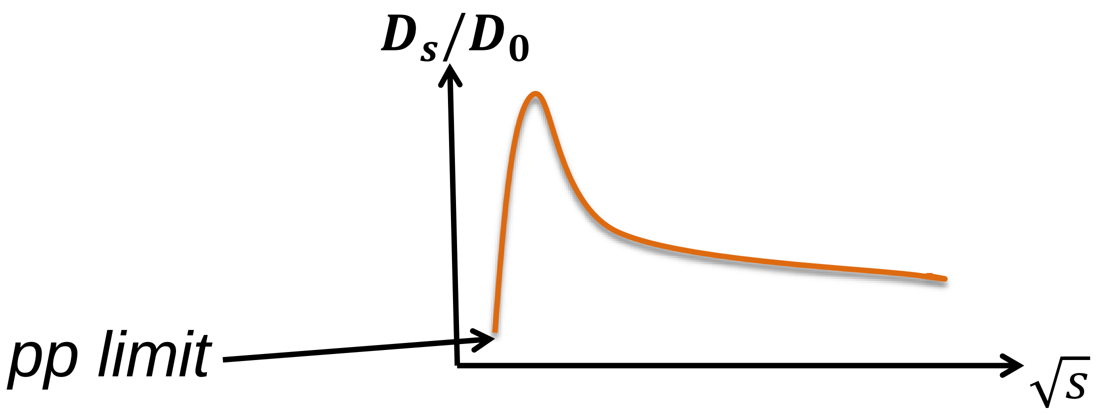


Charm conservation is extremely important in intermediate energy heavy ion collisions !

- *Baryon density effect in intermediate energy heavy ion collisions:*
  more u and d quarks, less $\bar{u}$ and $\bar{d}$ quarks, and $n_{\bar{u}} < n_{\bar{s}} < n_u$.
  See for instance, Introduction to high-energy heavy-ion collisions, Cheuk-Yin Wong, World Scientific, 1994

→ D_s $(c\bar{s})$ *enhancement in comparison with* $D_0(c\bar{u})$ *production,*
high baryon density leads to another extra D_s/D_0 *enhancement !*

- *Three effects leading to significant* D_s/D_0 *enhancement in heavy ion collisions:*
  - ***Strangeness enhancement***
  - ***Charm conservation***
  - ***High baryon density***



A Model with the Three Effects

- Hydrodynamics for the fireball evolution → $T(x),\ \mu_B(x)$
- Dirac equation for $c\bar{q}$ $(q = u, d, s)$ bound states

  binding energy $\varepsilon(T)$ and wave function $\psi(x)$

  dissociation temperature T_d: $\epsilon(T_d) = 0$

- Sequential coalescence
  - different coalescence time

  - charm conservation

  - the probability for a c and a $\bar{q}$ to combine into a $c\bar{q}$ bound state in phase space

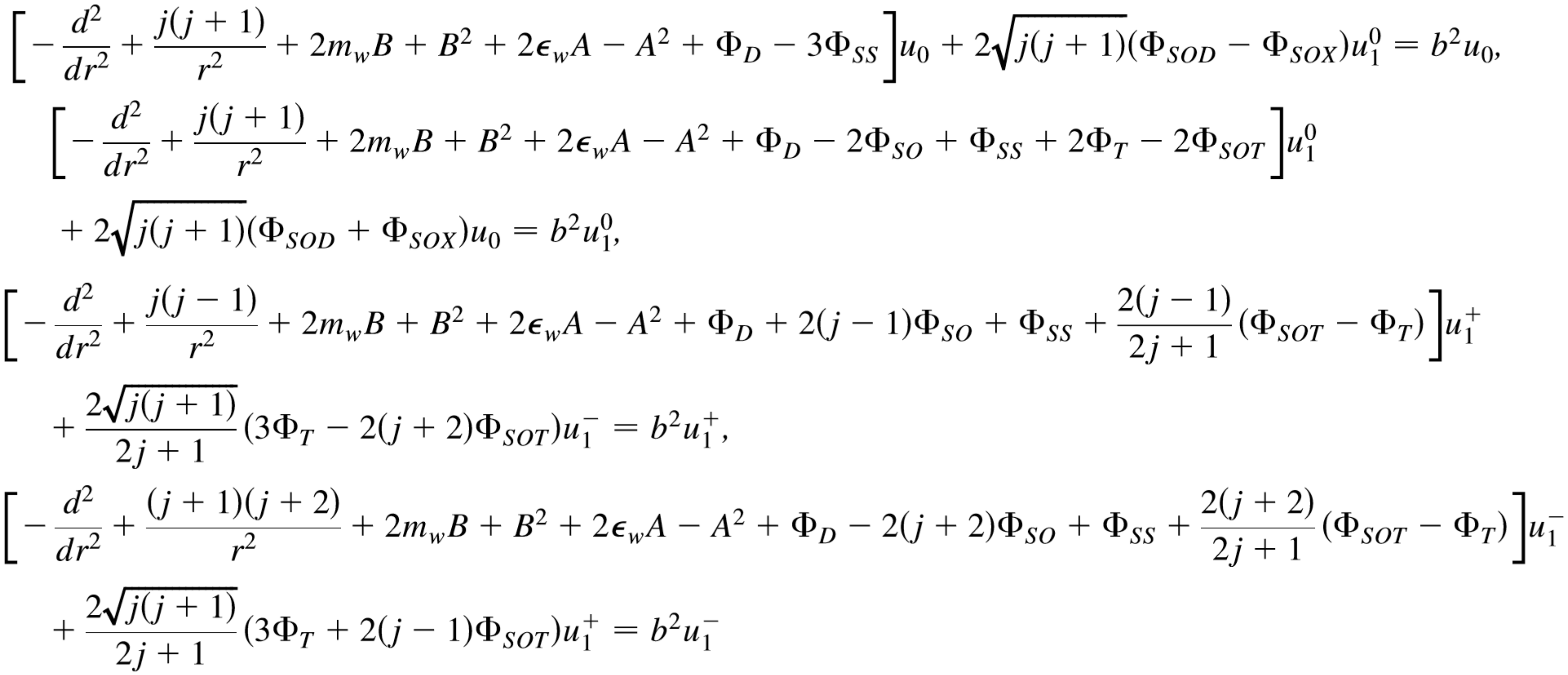
$$W(r,p) = \int d^4y e^{ipy} \psi(x + \frac{y}{2}) \psi^*(x - \frac{y}{2})$$ (Wigner function)

- Quark distributions
  - thermal and chemical equilibrium distributions for light quarks $f(T, \mu_B)$ (baryon density effect)
  - thermal distribution for s-quark with a fugacity $\lambda_s \leq 1$ (strangeness enhancement)
  - continuous thermalization for charm quarks

2-body Dirac Equation for Charmed Mesons

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

- *2-body Dirac equation with lattice simulated quark potential:*



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

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

$$+2\sqrt{j(j+1)}(\Phi_{SOD}+\Phi_{SOX})u_0=b^2u_1^0,$$

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

$$+\frac{2\sqrt{j(j+1)}}{2j+1}(3\Phi_T-2(j+2)\Phi_{SOT})u_1^-=b^2u_1^+,$$

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

$$+\frac{2\sqrt{j(j+1)}}{2j+1}(3\Phi_T+2(j-1)\Phi_{SOT})u_1^+=b^2u_1^-$$

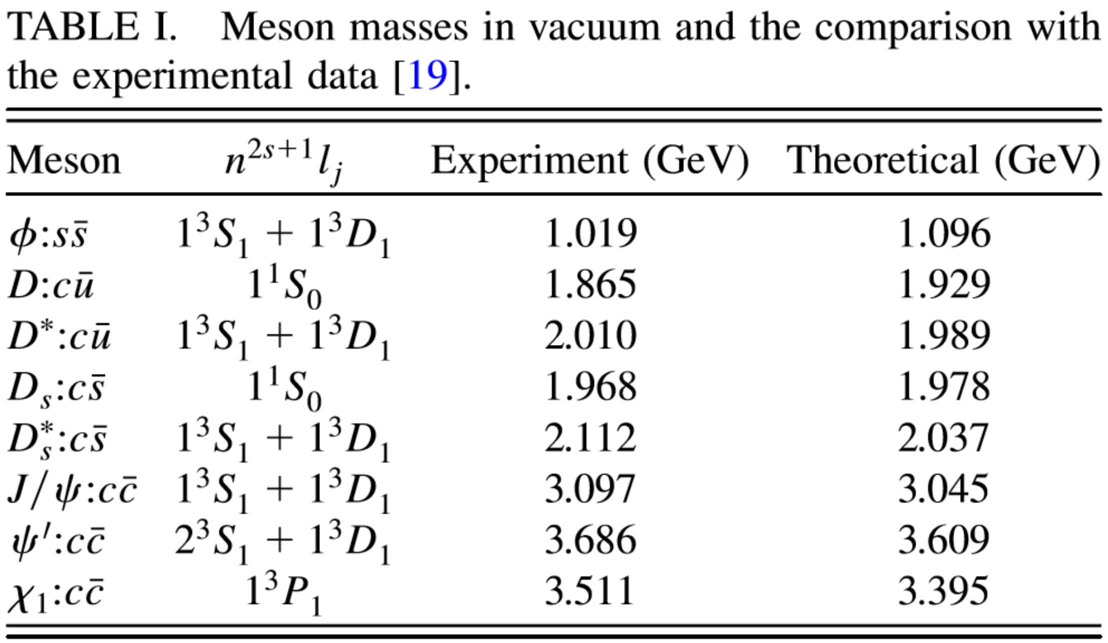


TABLE I. Meson masses in vacuum and the comparison with the experimental data [19].

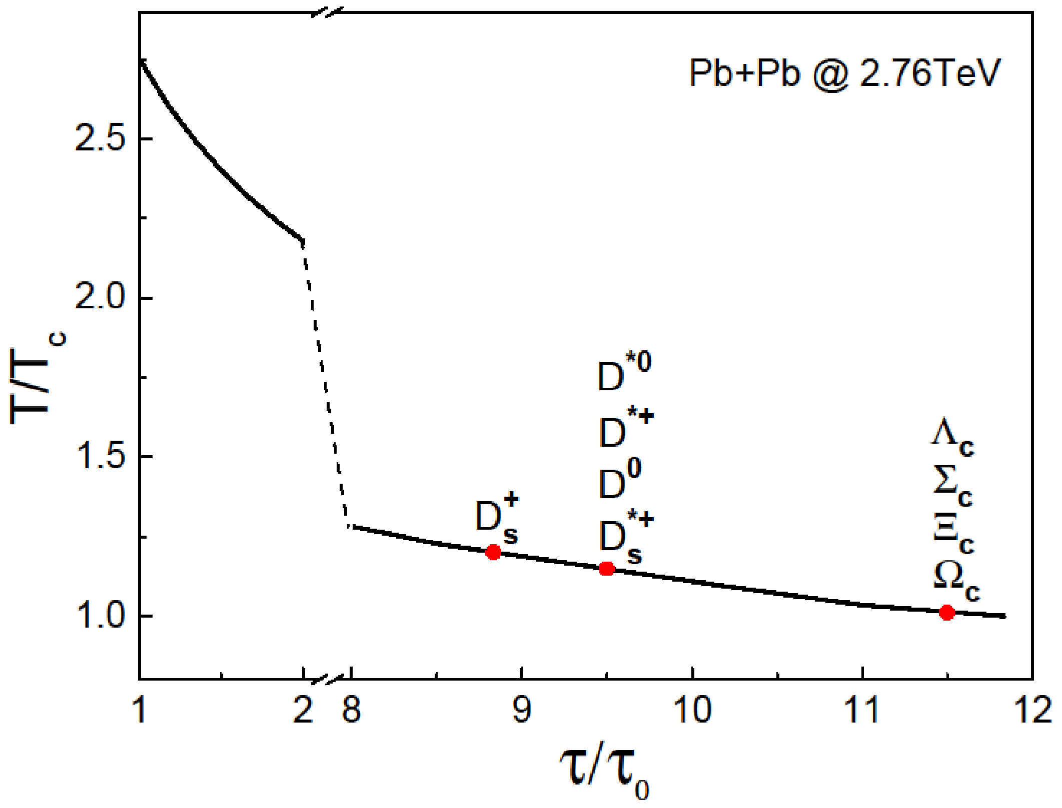
Meson	$n^{2s+1}l_j$	Experiment (GeV)	Theoretical (GeV)
$\phi:s\bar{s}$	$1^3S_1+1^3D_1$	1.019	1.096
$D:c\bar{u}$	1^1S_0	1.865	1.929
$D^*:c\bar{u}$	$1^3S_1+1^3D_1$	2.010	1.989
$D_s:c\bar{s}$	1^1S_0	1.968	1.978
$D_s^*:c\bar{s}$	$1^3S_1+1^3D_1$	2.112	2.037
$J/\psi:c\bar{c}$	$1^3S_1+1^3D_1$	3.097	3.045
$\psi':c\bar{c}$	$2^3S_1+1^3D_1$	3.686	3.609
$\chi_1:c\bar{c}$	1^3P_1	3.511	3.395

Sequential Coalescence

- *2-body Dirac equation at finite temperature + ideal hydrodynamics*

$$\partial^\mu T_{\mu\nu} = 0$$
$$\partial^\mu n_\mu = 0$$

→ *sequential coalescence time*



- *Coalescence*

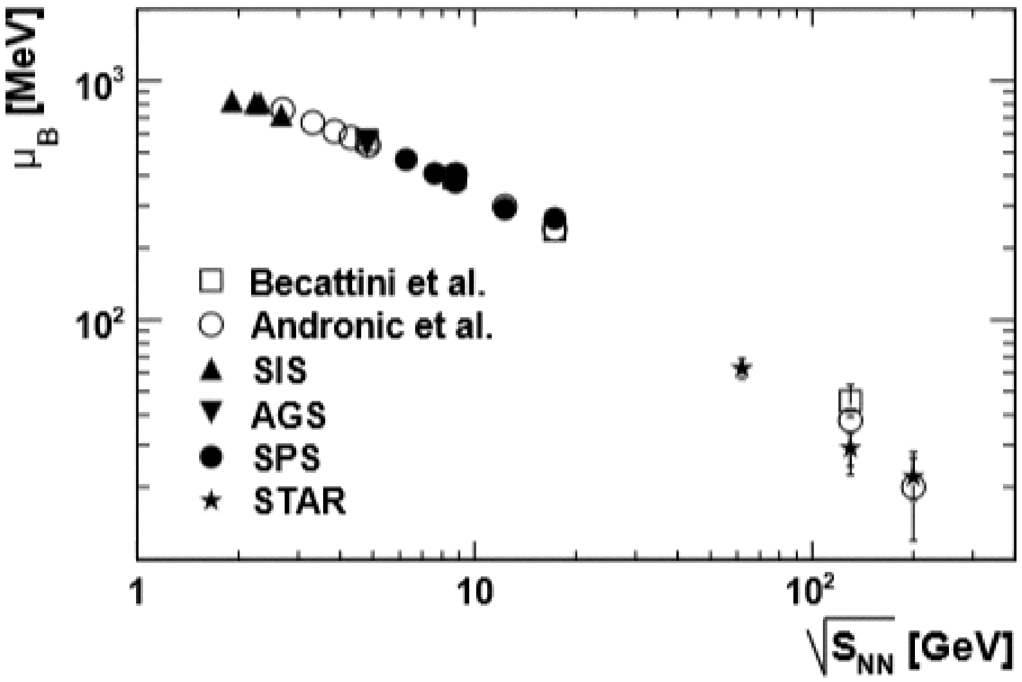
$$\frac{dN}{d^2P_T d\eta} = C\int \frac{P^\mu d\sigma_{\mu\nu}(R)}{(2\pi)^3}\frac{d^4r d^4p}{(2\pi)^3} f_c(r_1,p_1) f_{\bar{q}}(r_2,p_2) W(r,p)$$

Light & Strange Quark Distributions

- *light quarks u and d:*
  thermal distribution

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

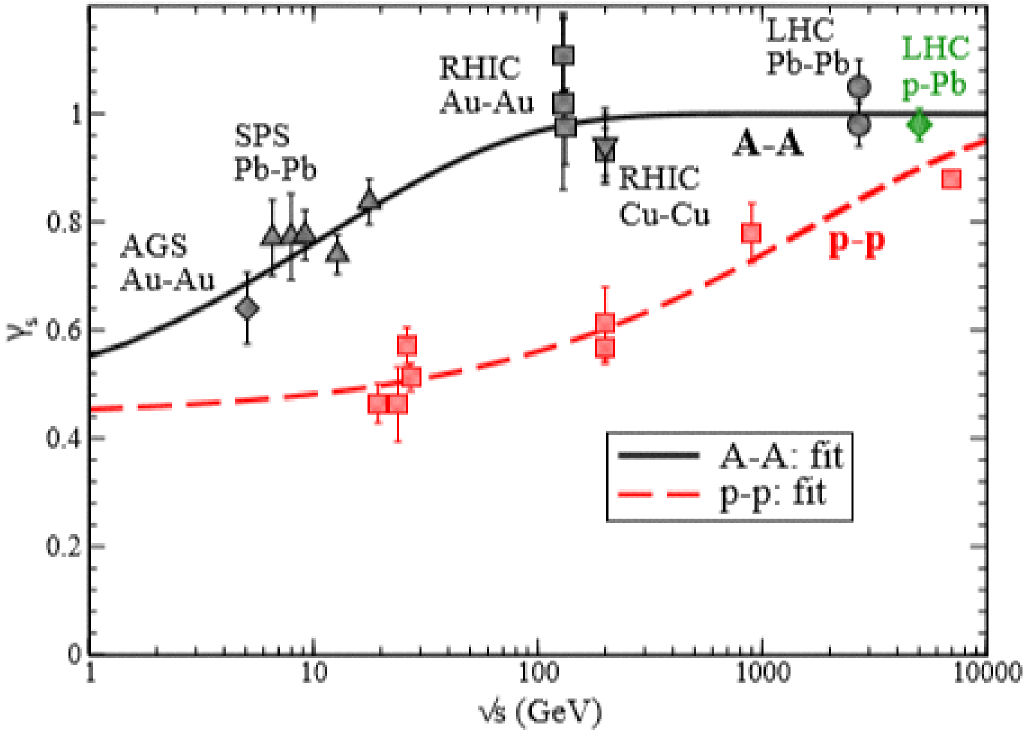
STAR Collaboration. Phys. Rev. C79,034909(2009)



- *strange quark s:*
  thermal distribution

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

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



Charm Quark Distribution

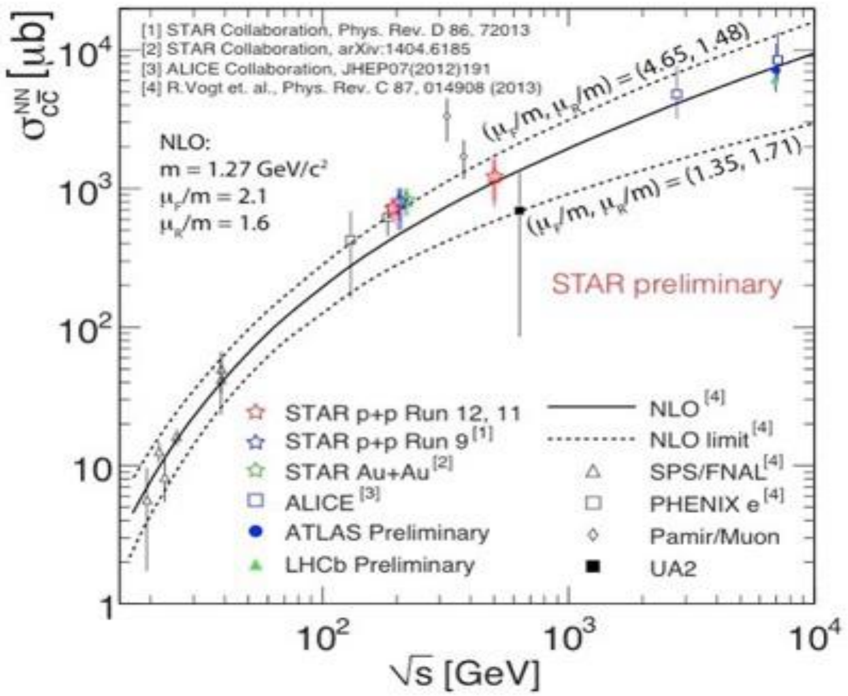
- *charm quark c:*

  continuous thermalization due to energy loss

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

$$(\alpha,\beta) = \begin{cases}(0.4,0.6) & for\ D_s \\ (0.5,0.5) & for\ D_0\end{cases}$$

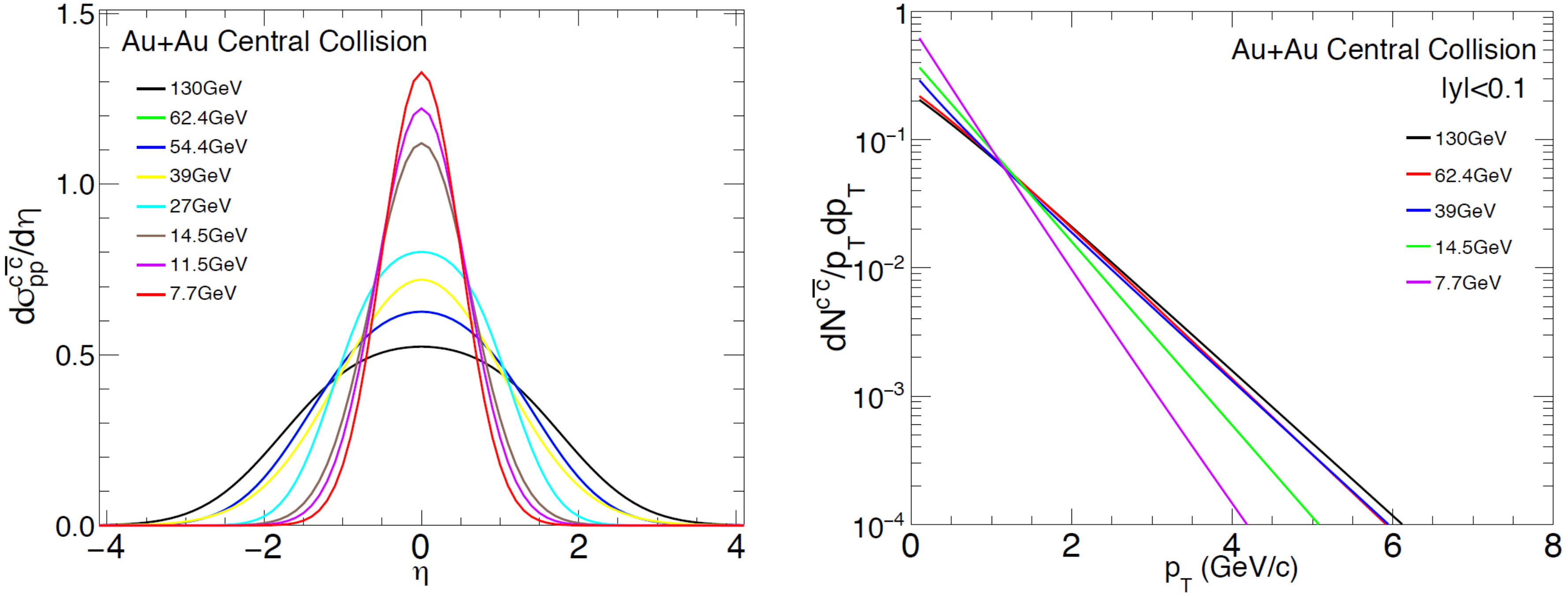
$$\rho_c(x|\mathbf{b}) = r(\tau)T_A(\mathbf{x}_T)T_B(\mathbf{x}_T-\mathbf{b})\frac{\cosh\eta}{\tau}\frac{d\sigma_{pp}^{c\bar{c}}}{d\eta}$$



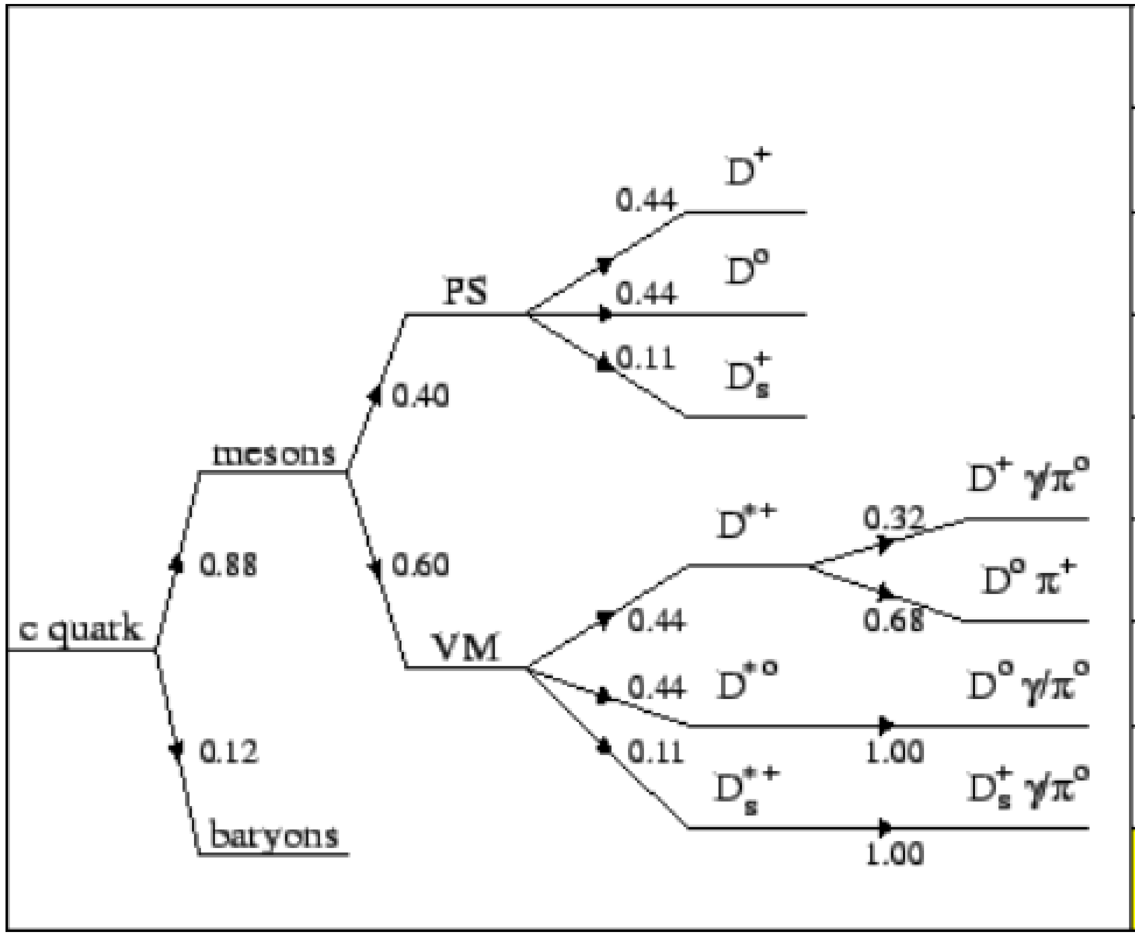
Charm conservation:

$$r(\tau) = \begin{cases}1 & \tau \le \tau_{D_s^+} \\ 1 - N_{D_s^+}/N_c & \tau_{D_s^+} < \tau \le \tau_{D^0} \\ 1 - N_D/N_c & \tau_{D^0} < \tau\end{cases}$$

Normalized rapidity and transverse momentum distributions with PYTHIA8



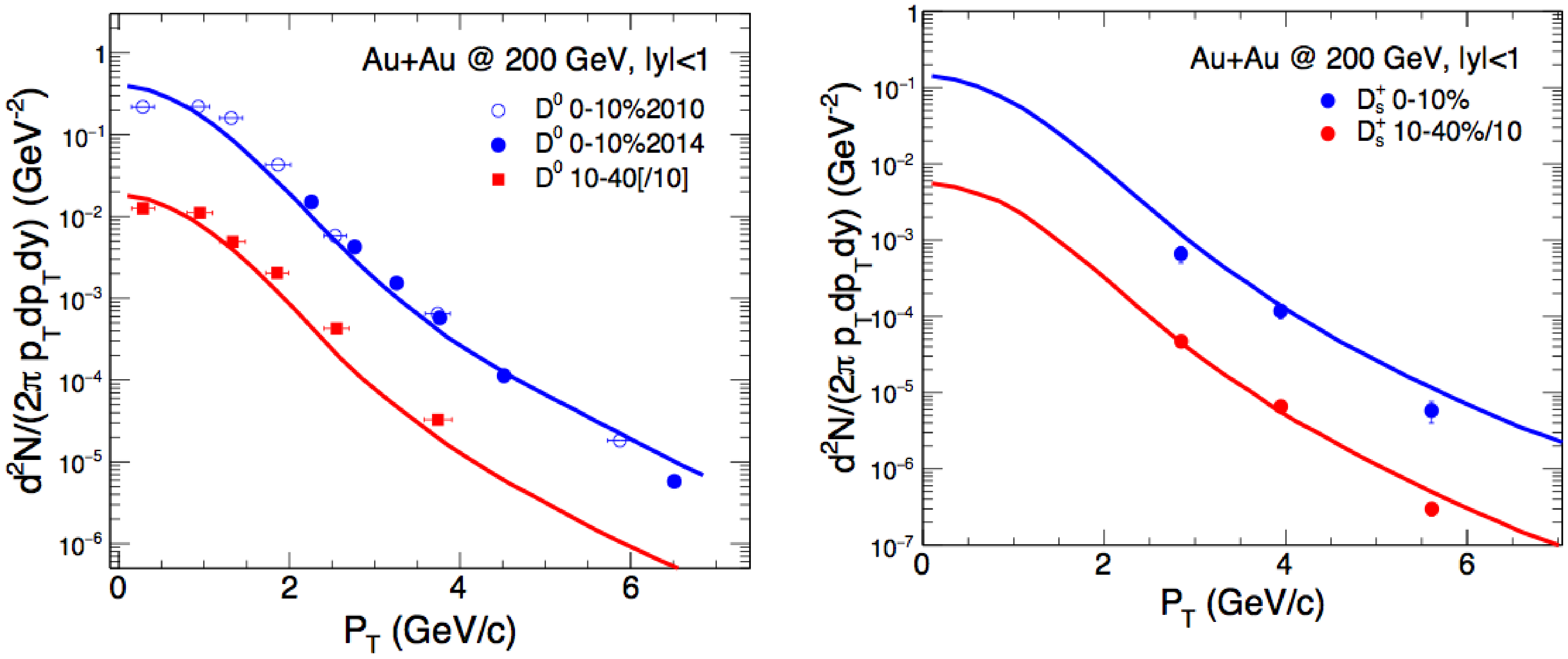
Hadron Decay after Coalescence



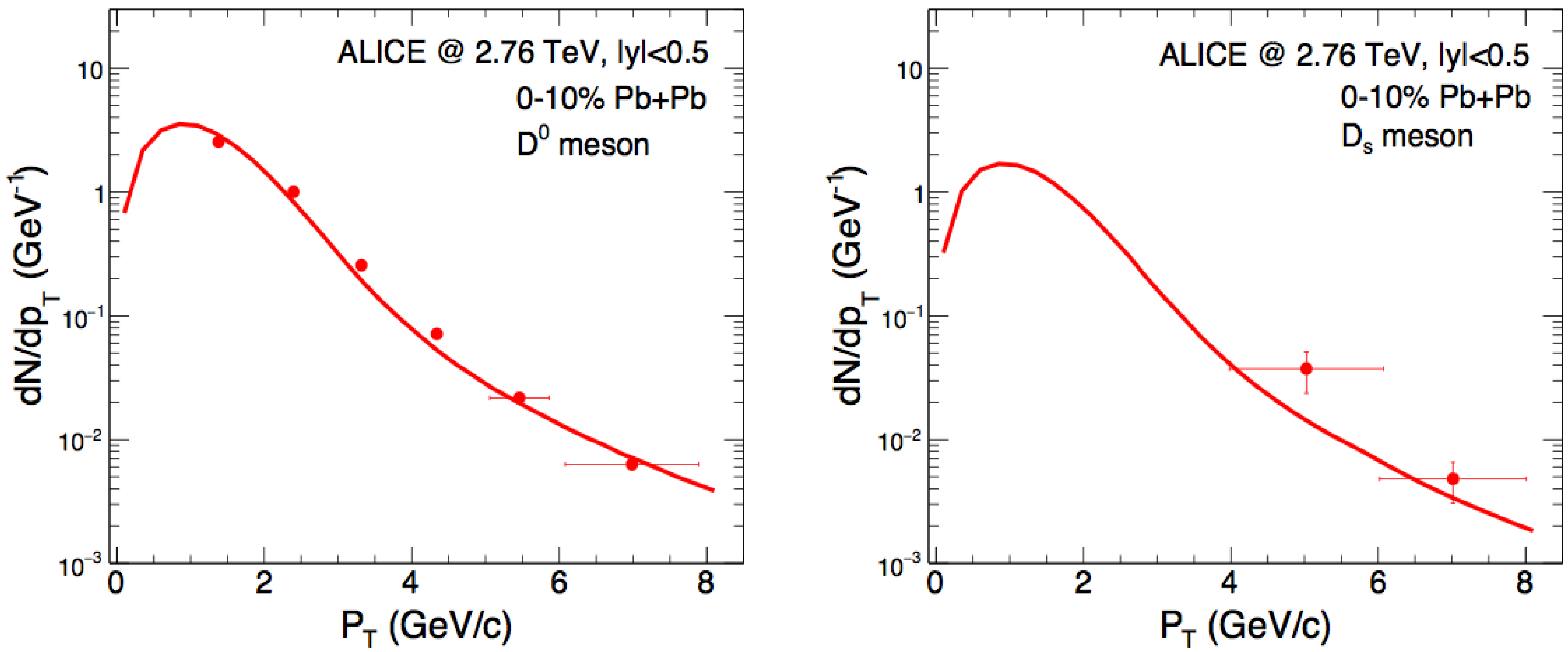
D^+	D^0	D_s^+
0.156		
	0.156	
		0.040
0.076		
	0.159	
	0.234	
		0.061
0.232	0.549	0.101

Charmed Hadron P_T Distribution

RHIC



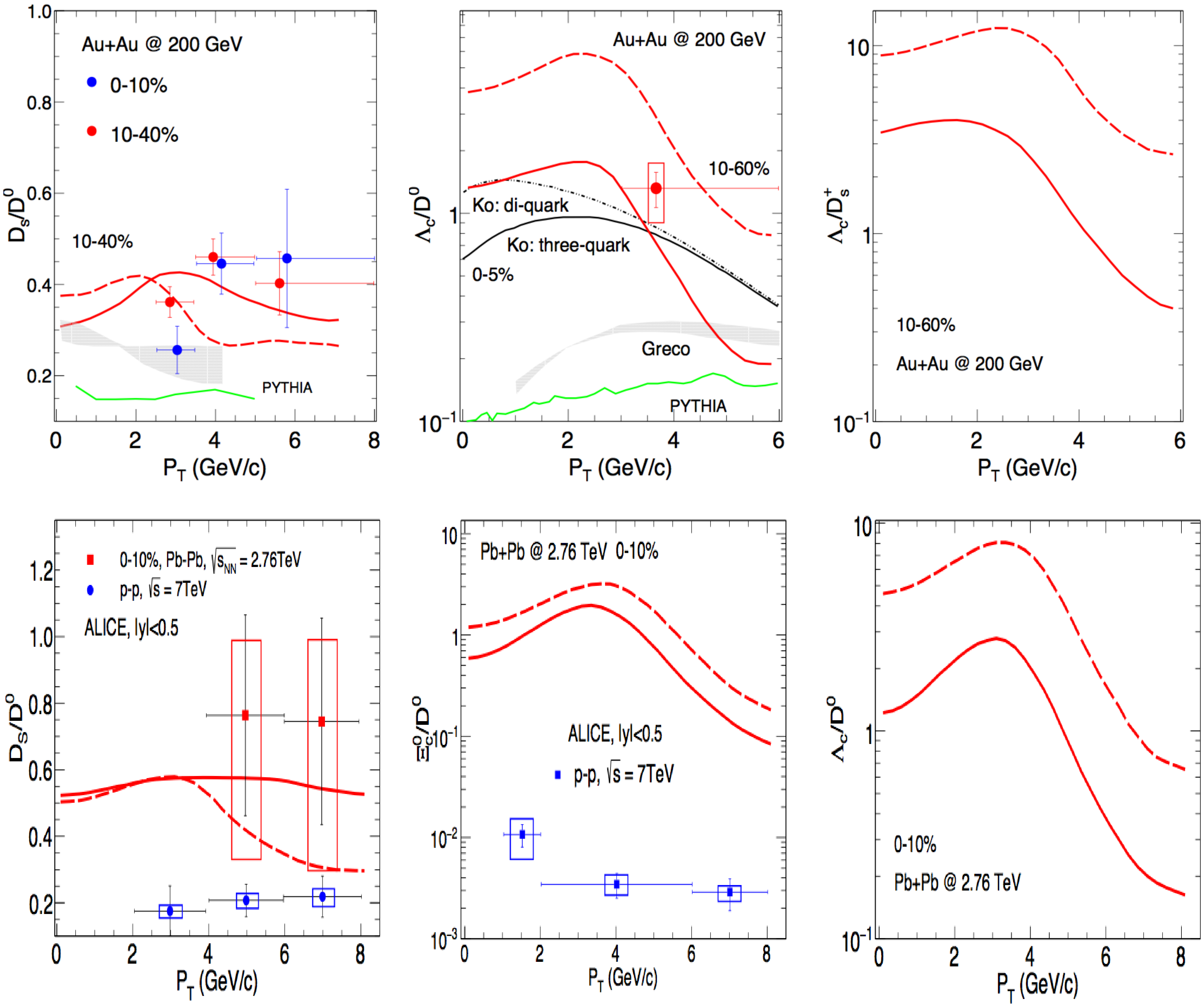
LHC



Yield Ratios

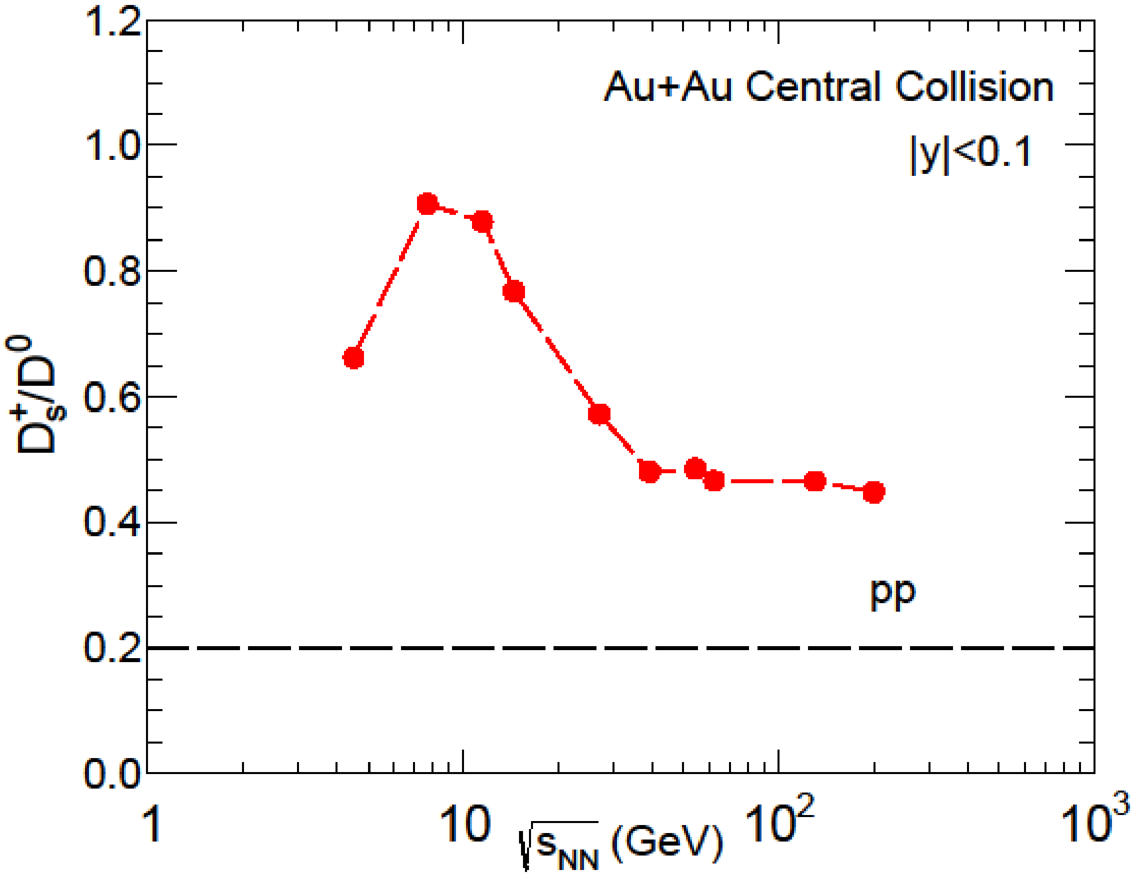
RHIC

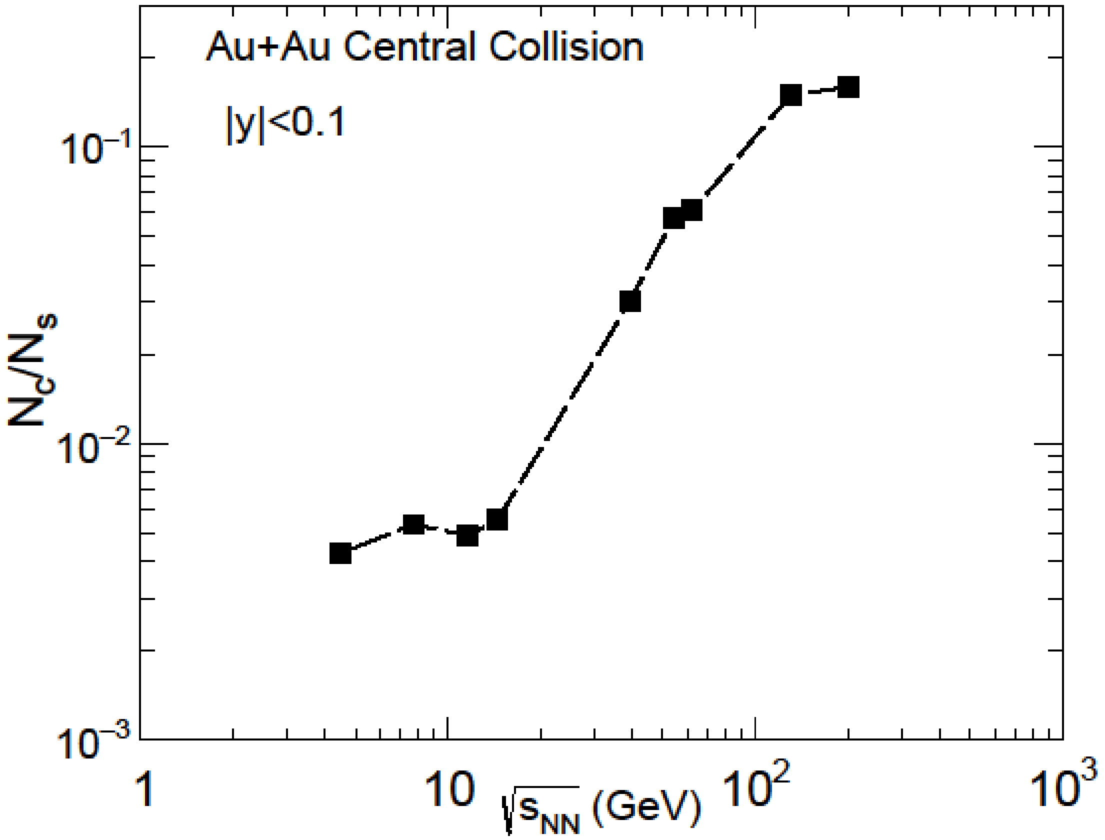
LHC



$D_s/D_0(\sqrt{s})$

preliminary calculation



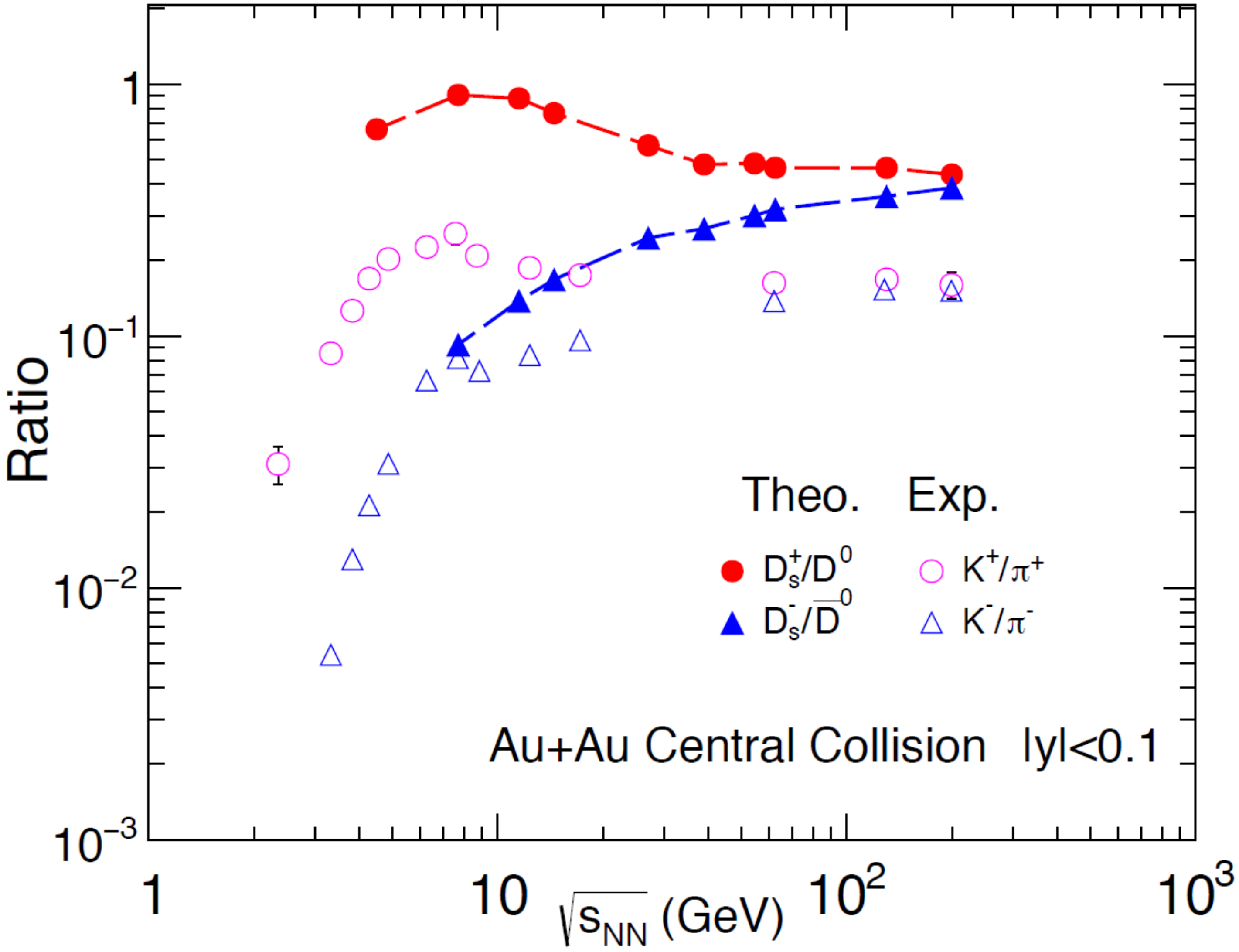


- *There is a strong D_s/D_0 enhancement, especially around $\sqrt{s} = 10$ GeV, due to strangeness enhancement, charm conservation, and baryon density effects.*

- *The shape should be model independent, while the location and the height of the peak depends on the details of the calculation.*

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

Comparison with K/π



■ *All the lines are controlled by strangeness enhancement, charm conservation and baryon density effects.*

Summary

● *There is a significant* D_s/D_0 *enhancement in nuclear collisions, especially at FAIR/NICA/HIAF energies, due to the strangeness enhancement, charm conservation, and baryon density effect.*

● *The peak of* $D_s/D_0(\sqrt{s})$ *in the energy region of FAIR/NICA/HIAF can be considered as a signal of deconfinement phase transition.*