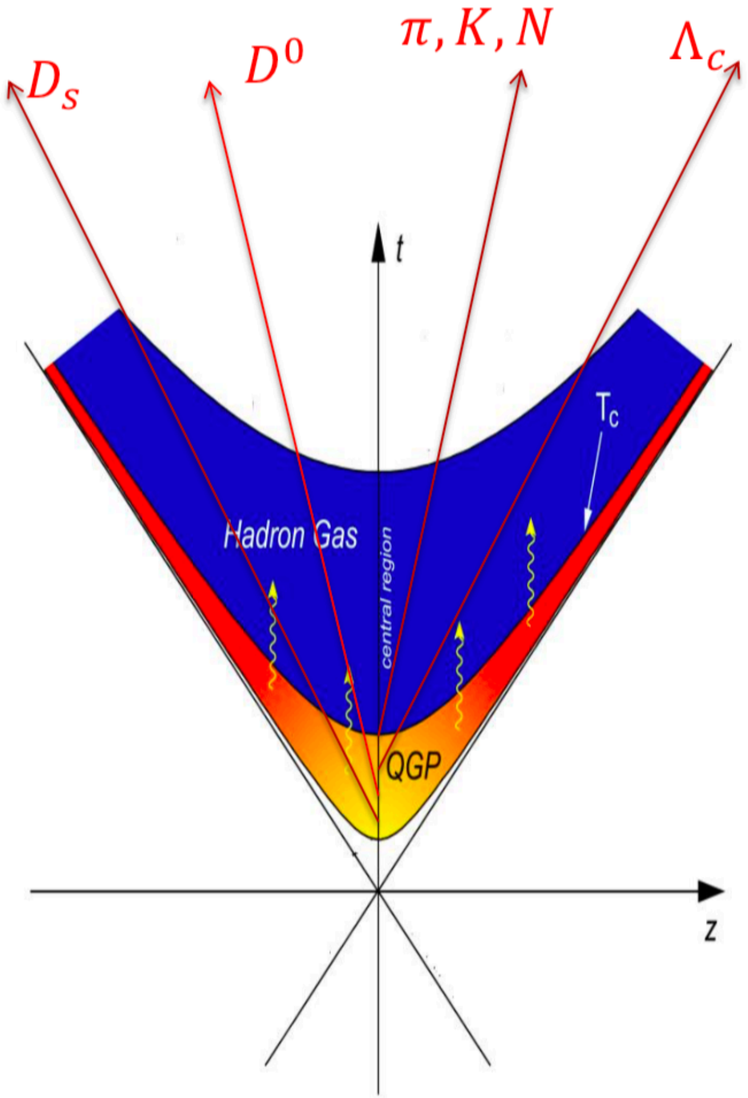
Sequential Hadronization with Charm Conservation in Heavy Ion Collisions

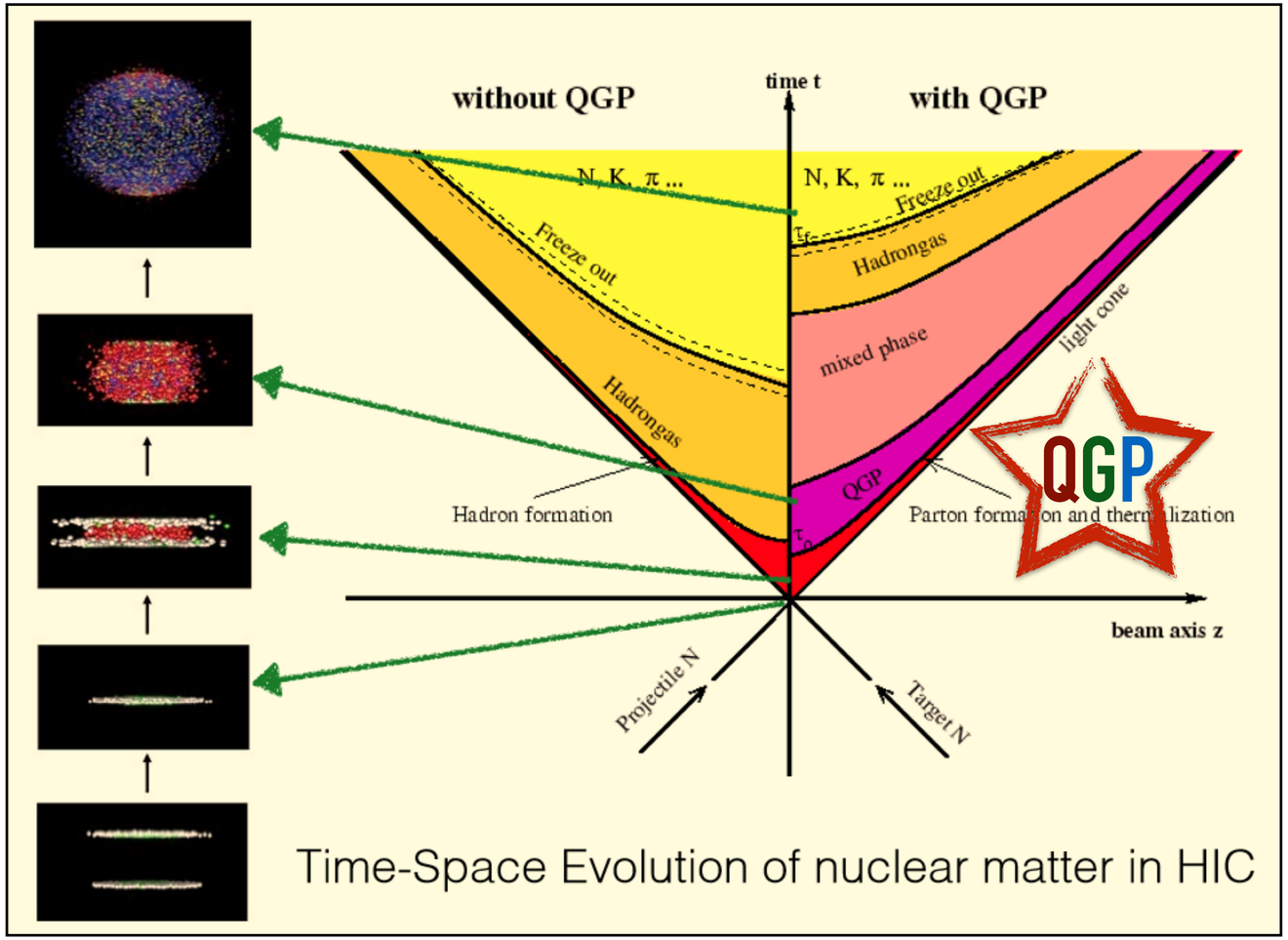
Jiaxing Zhao (Tsinghua University)

In collaboration with:
Shuzhe Shi, Nu Xu and Pengfei Zhuang

arXiv: 1805.10858



Hadronization in HIC



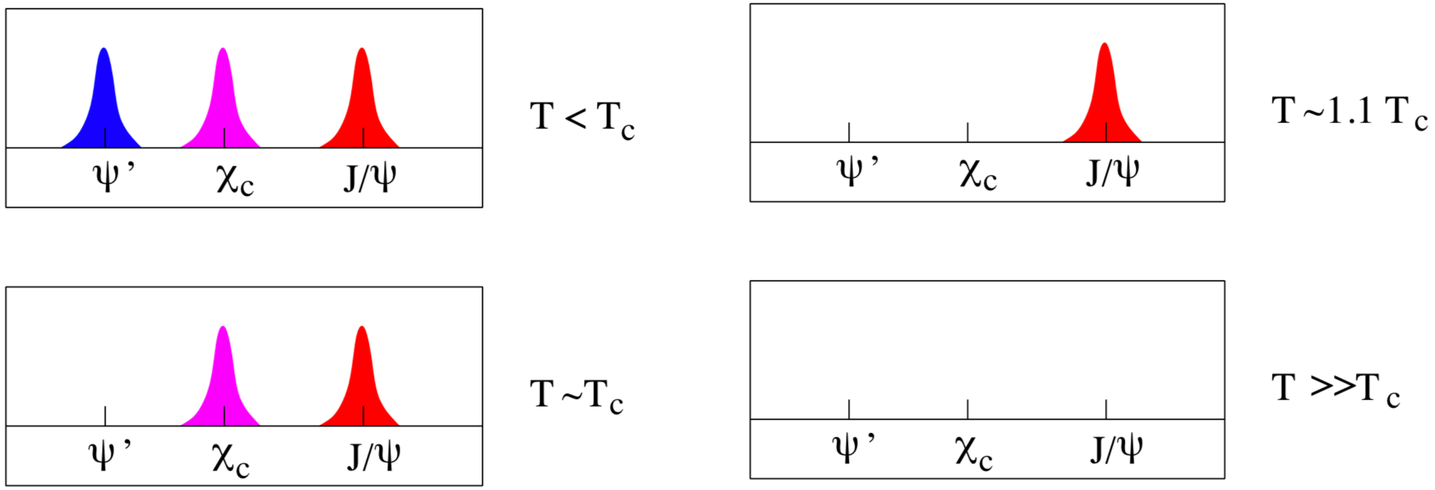
Different from the hadronization process in vacuum, the statistics plays an important role in hadronization of the quark-gluon plasma.

Thermal statistical hadronization model & Coalescence model

- *Quark number scaling of the elliptic flow*
- *Enhancement of baryon to meson ratios*

Assumption of simultaneous hadronization for all hadrons.

Sequential Hadronization

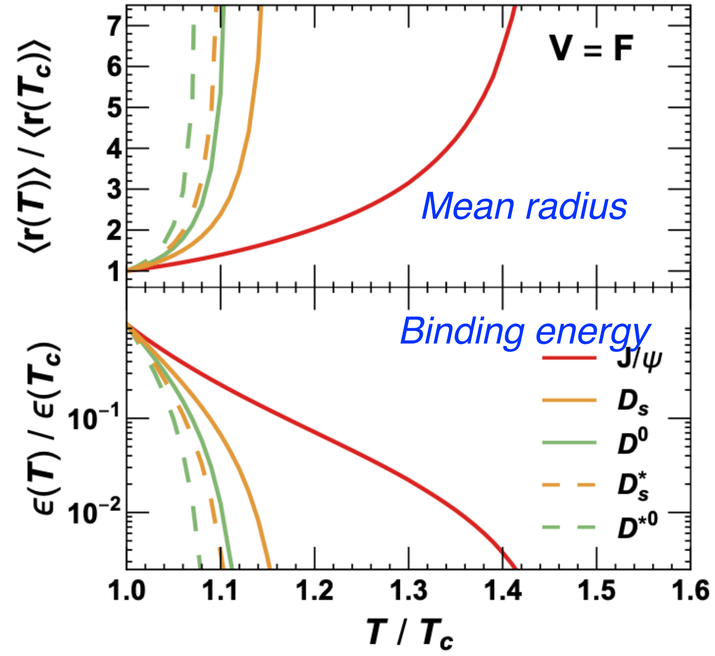


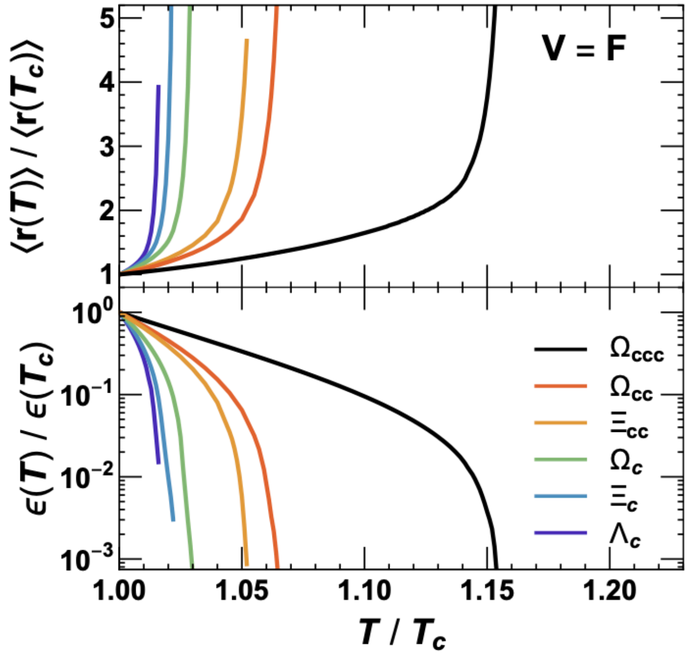
state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

The charmonium/bottomonium states are described by 2-body Schroedinger equation. With increasing temperature the charmonium states "melt" sequentially.

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

Sequential Hadronization





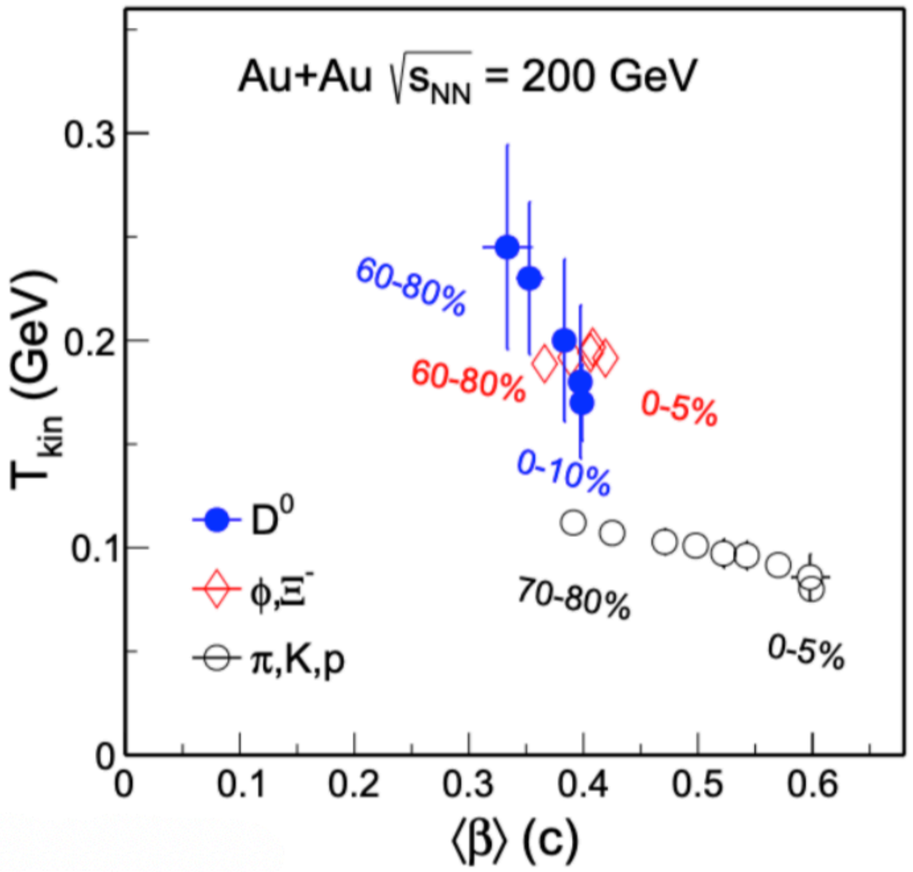
	J/ψ	χ_c	ψ'	D_s	D_s^*	D^0	D^{*0}
$V=F$	1.42	-	-	1.14	1.10	1.10	1.08
$V=U$	3.09	1.30	1.24	2.50	1.98	2.35	1.80

	Ω_{ccc}	Ω_{cc}	Ξ_{cc}	Ω_c	Ξ_c	Λ_c
$V=F$	1.15	1.06	1.05	1.03	1.02	1.02
$V=U$	2.18	1.63	1.54	1.41	1.39	1.37

The properties of heavy flavor mesons and baryons are studied by 2&3-body Dirac equations. The results show sequential heavy flavor hadronization in the hot medium!

Shuzhe Shi, JX Zhao, and Pengfei Zhuang, arXiv:1905.10627

Sequential Hadronization



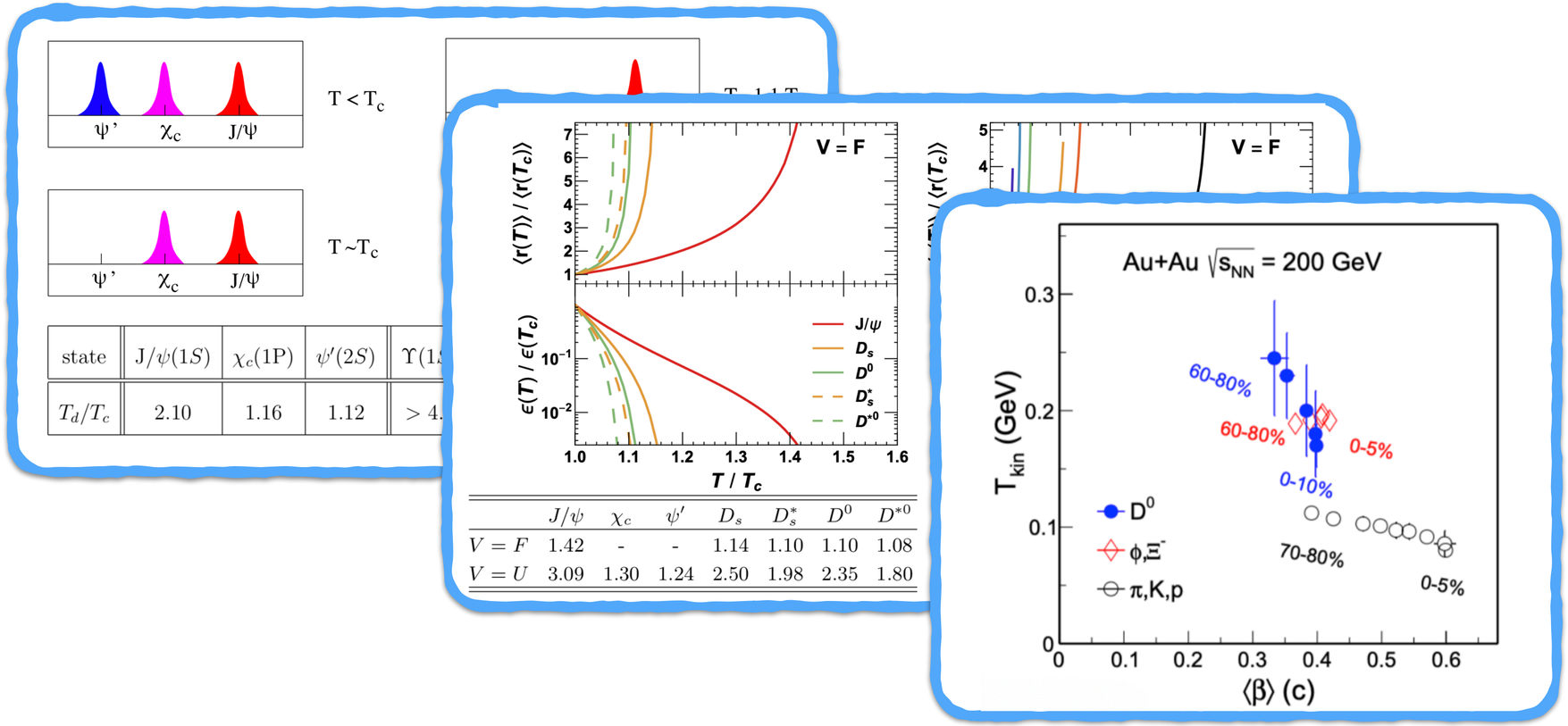
D0, ϕ , Ξ^- seem to decouple from the system earlier and gain less radial collectivity compared with light hadrons in Blast-Wave model!

STAR Collaboration. Phys. Rev. C99, 034908 (2019)

Open charmed hadrons are "melted" at temperatures close but higher than the critical temperature in lattice QCD Simulation!

S. Mukherjee, P. Petreczky, S. Sharma. Phys. Rev. D93, 014502(2016) *A. Bazavov, HT. Ding, S. Mukherjee et al. Phys. Lett. B737,210(2014)*

Sequential Hadronization



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...

Sequential dissociation $\approx$ sequential production

Hadrons with larger binding energy can survive at higher temperature and are earlier produced !

Charm Quark Conservation

- $m_c \sim 1.5GeV \gg T \sim (0.3 - 0.5)GeV$

  The thermal production of charm quarks via gluon fusion and quark and anti-quark annihilation in the QGP can be safely neglected !

- $m_c \gg \Lambda_{QCD}$

  Production can be solidly calculated through perturbative method !

- $\partial_\mu(n_{c\bar{c}}u^\mu) = r_{gain} - r_{loss};$

  production rate *annihilation rate*

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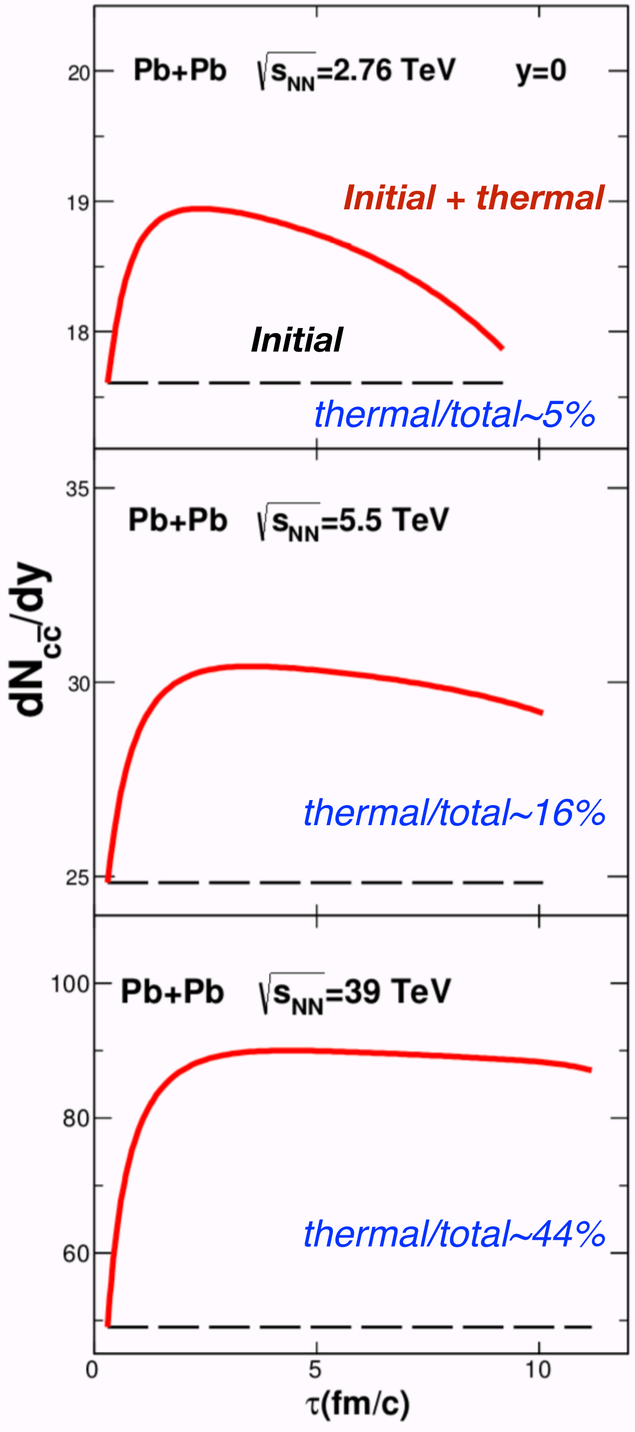
  production rate *annihilation rate*

Charm quark number :

conserved at RHIC!
almost conserved at LHC!
considerably increased at FCC!



B. W. Zhang, C. M. Ko and W. Liu, Phys. Rev. C 77, 024901 (2008)
K. Zhou, Z.Chen, C.Greiner and P. Zhuang. Phys. Lett. B 758, 434 (2016)

MODEL SETUP

(Sequential Hadronization + Charm Conservation)

&

RESULTS

Sequential Hadronization

2&3-body Dirac equations are used to study charmed bound hadrons.

Need to include the relativistic corrections: kinematics, spin.

The dissociation temperature T_d :

$$\epsilon(T_d) = 0 \qquad < r(T_d) > \rightarrow \infty$$

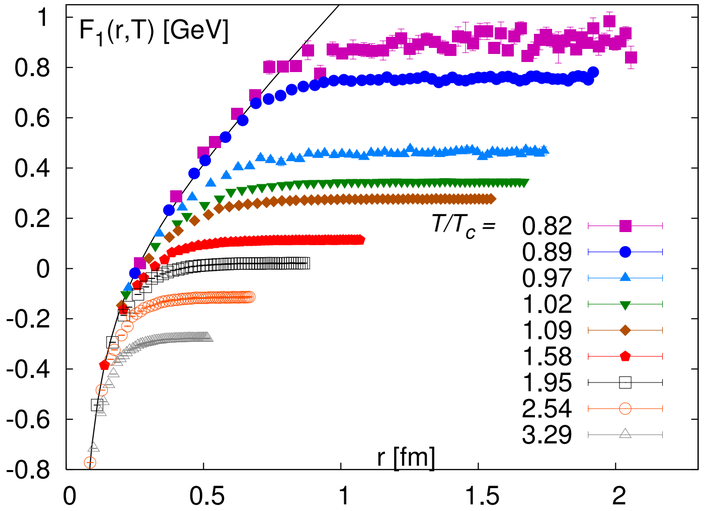
H. Crater, J. Yoo and C. Wong. PRD 79. 034011(2009)

S. Shi, X. Guo and Pengfei Zhuang. PRD 88. 014021(2013)

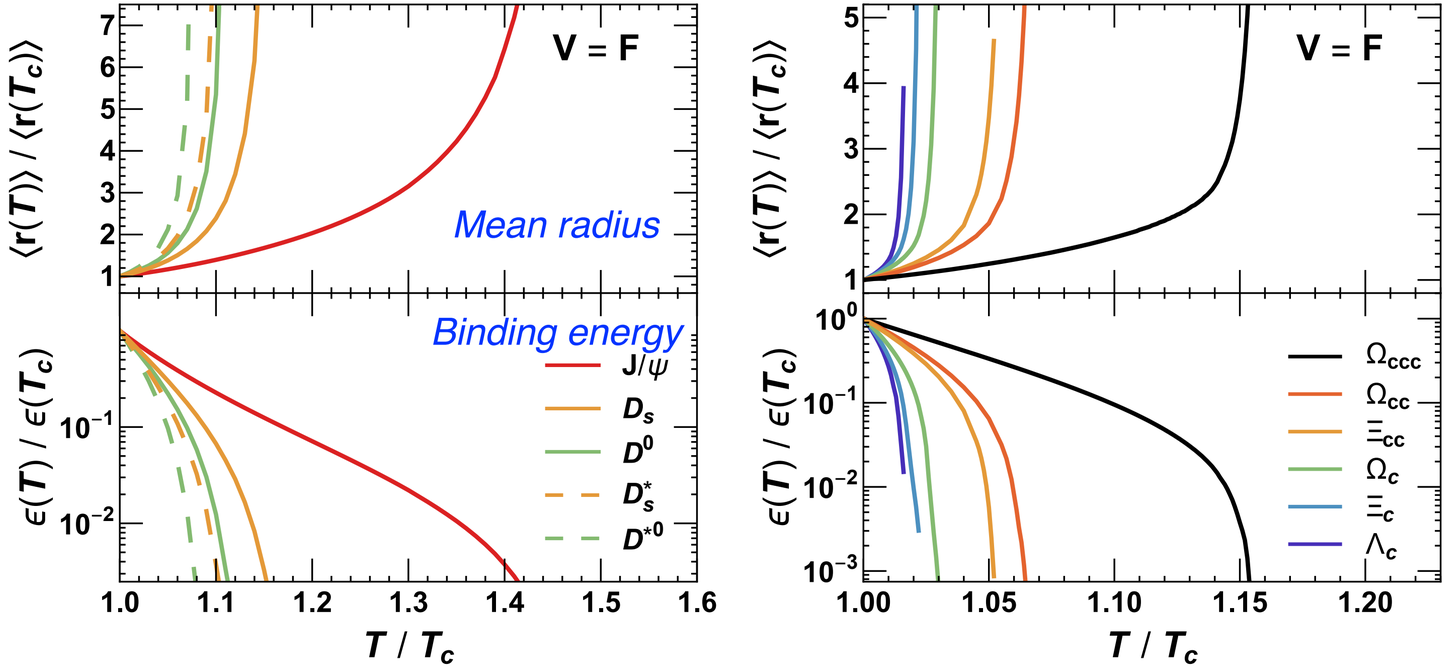
Sazdjian, J. Math. Phys. 28, 2618(1987)

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

S. Shi, J. Zhao and P. Zhuang, arXiv:1905.10627.



O' Kaczmarek, EPJC 61, 811(2009)



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

Shuzhe Shi, JX Zhao, and Pengfei Zhuang, arXiv:1905.10627

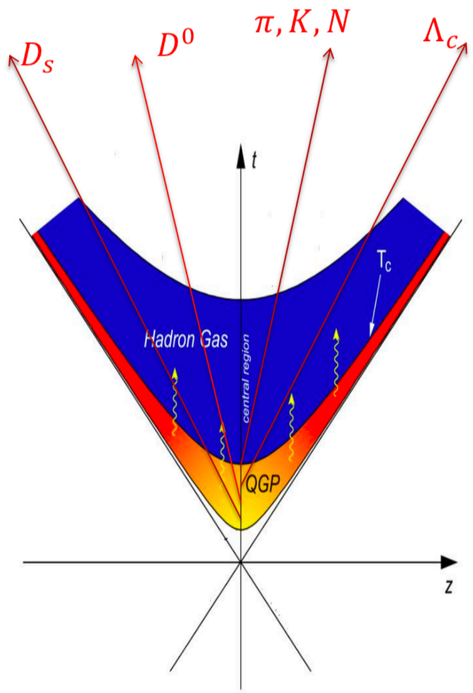
Sequential Hadronization

2&3-body Dirac equations are used to study charmed bound hadrons.

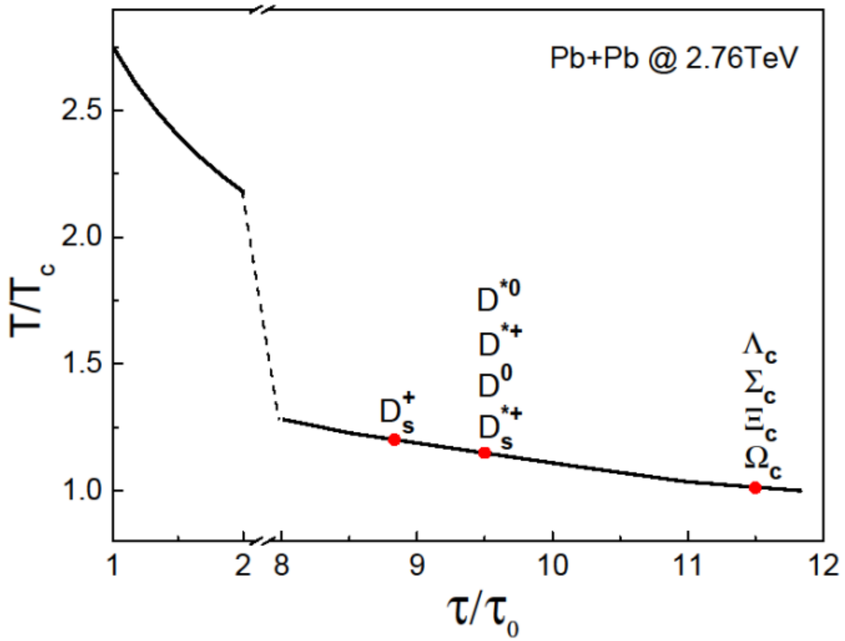
$$T_{J/\psi} > T_{D_s} > T_{D^0} > T_{\Lambda_c} > T_{\pi,K,N}$$

Hydrodynamics: $\partial_\mu T^{\mu\nu} = 0$

$$T(\mathbf{x}, \tau_h) = T_h \longrightarrow \tau_h = \tau(\mathbf{x}, T_h)$$



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



Coalescence Mechanism

$$\frac{dN_h}{d^2P_T d\eta} = C \int P^\mu d\sigma_\mu \prod_{i=1}^{n} \frac{d^4x_i d^4p_i}{(2\pi)^3} f_i(x_i, p_i) \times W_h(x_1, ..., x_i, p_1, ..., p_i).$$

V. Greco, C. M. Ko and R. Rapp, Phys. Lett. B 595, 202 (2004).
D. Molnar and S. A. Voloshin, Phys. Rev. Lett. 91, 092301 (2003).
R. J. Fries, B. Muller, C. Nonaka and S. A. Bass. Phys. Rev. C68, 044902(2004).
...

- *The hadronization hypersurface is determined by hydrodynamics and dissociation temperature.*

$$\partial_\mu T^{\mu v} = 0 \qquad T(\mathbf{x}, \tau_h) = T_h$$

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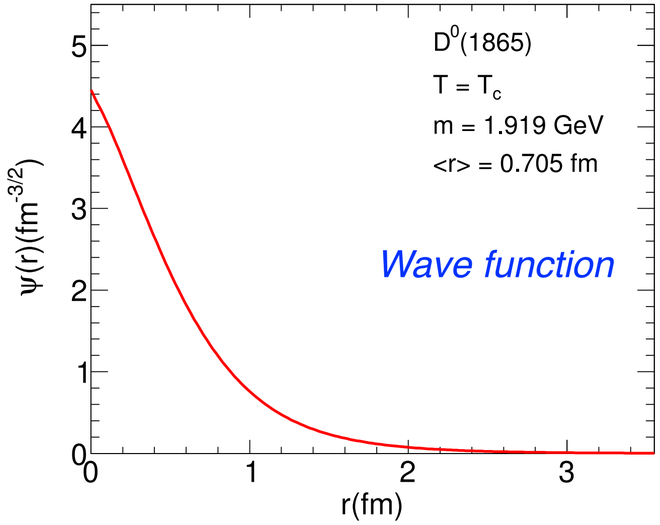
- *The hadronization hypersurface is determined by hydrodynamics and dissociation temperature.*

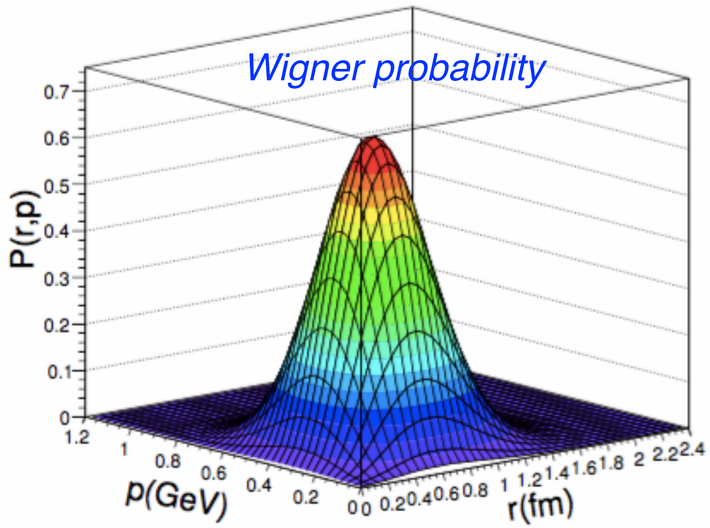
$$\partial_\mu T^{\mu v} = 0 \qquad T(\mathbf{x},\tau_h) = T_h$$

- *The Wigner function can self-consistently be determined by the wavefunction. Instead of taking a Gaussian distribution with the width as a free parameter.*

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



Fourier transformation



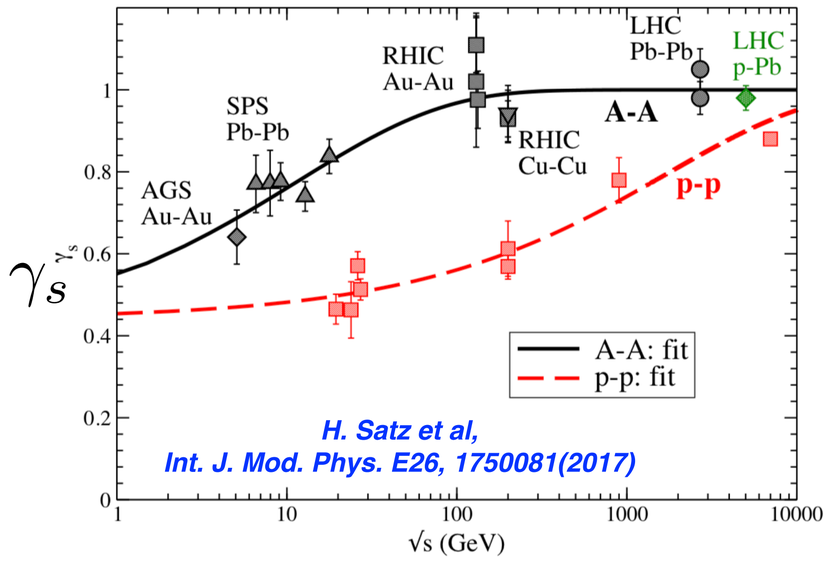
Quark Distribution Function

- *Light quark: thermal and chemical equilibrium*

$$f_q(x,p) = \frac{N_q}{e^{p^\mu u_\mu(x)/T(x)} + 1}, \quad q = u, d$$

- *Strange quark: thermal and non-chemical equilibrium*

$$f_s(x,p) = \frac{N_s \gamma_s}{e^{p^\mu u_\mu(x)/T(x)} + 1} \qquad \gamma_s = \begin{cases} 0.85 & at\ RHIC \\ 1 & at\ LHC \end{cases}$$



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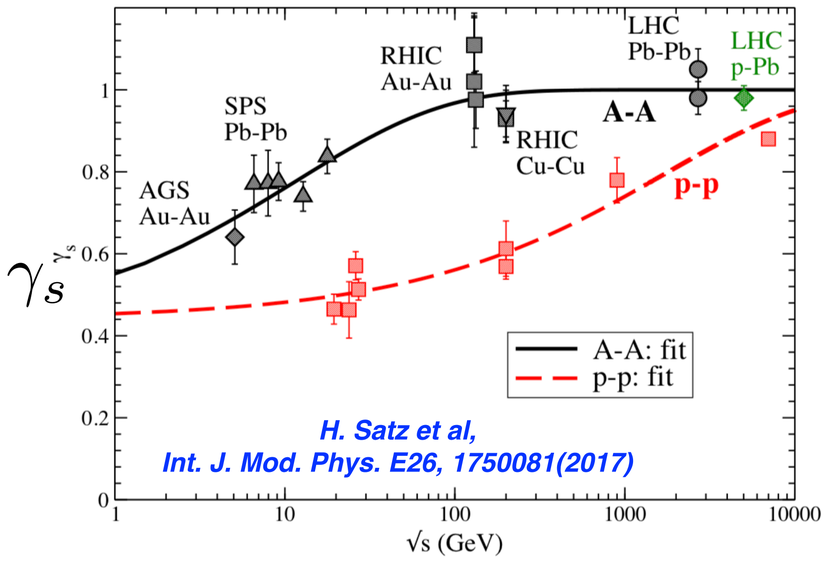
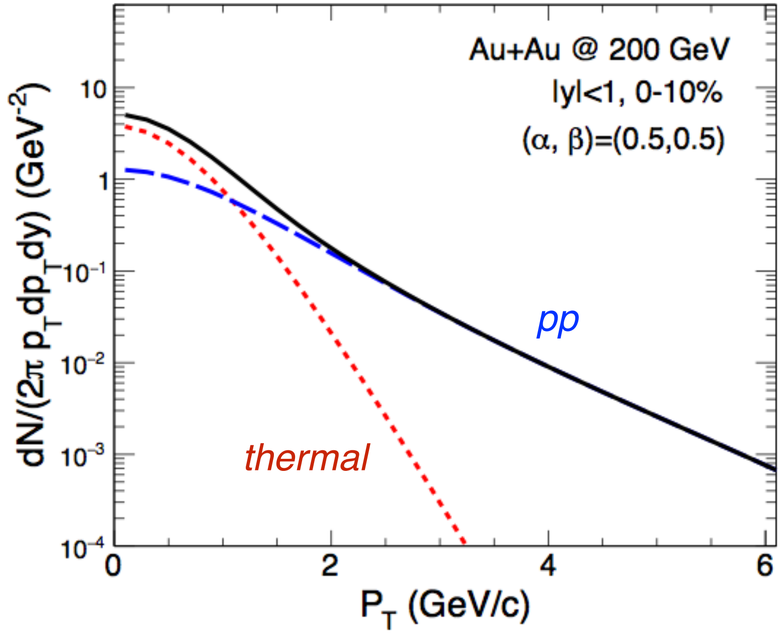
- *Charm quark: non-thermal and non-chemical equilibrium*

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

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



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



Charm Distribution Function

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

r_h *Charm conservation factor!*

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

It does not change the particles ratios!

Y.Oh, C.Ko, S.Lee and S.Yasui, PRC79, 044905(2009)

P. Braun-Munzinger and J. Stachel. Phys. Lett. B 490, 196(2000)

M. Gorenstein, A. Kostyuk, H. Stoecker and W. Greiner. Phys. Lett. B 509, 277(2001)

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

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

J. Zhao, S. Shi, Nu Xu and P. Zhuang, arXiv:1805.10858.

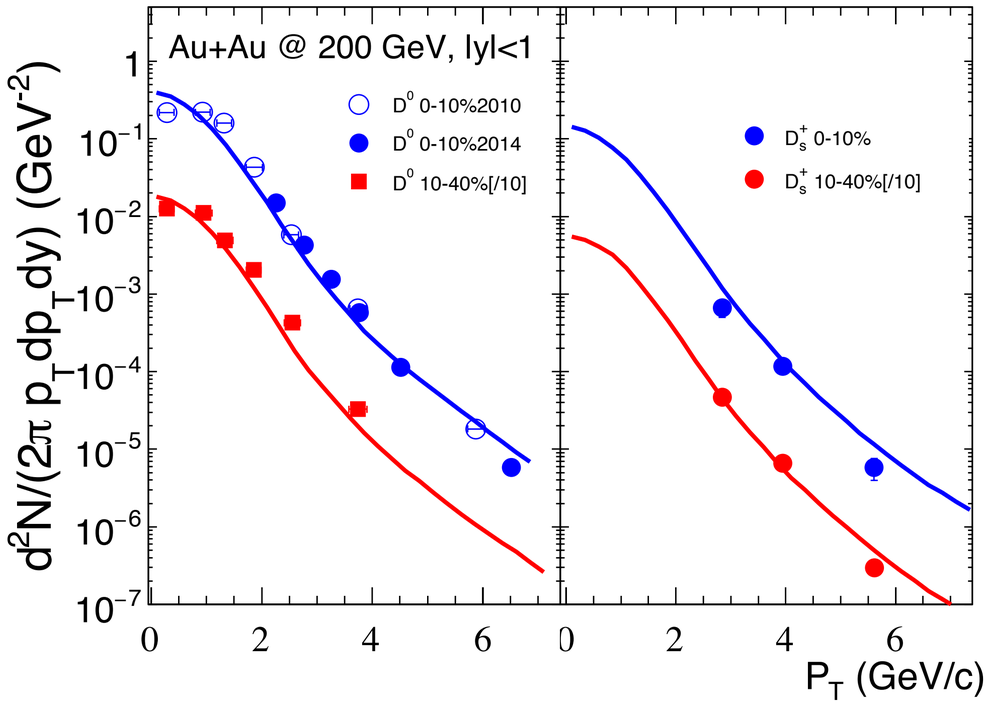
Charm conservation:

Enhances the earlier produced hadrons

Suppresses the later produced hadrons.

Results

Transverse momentum spectrum of Ds, D0 and charmed baryons



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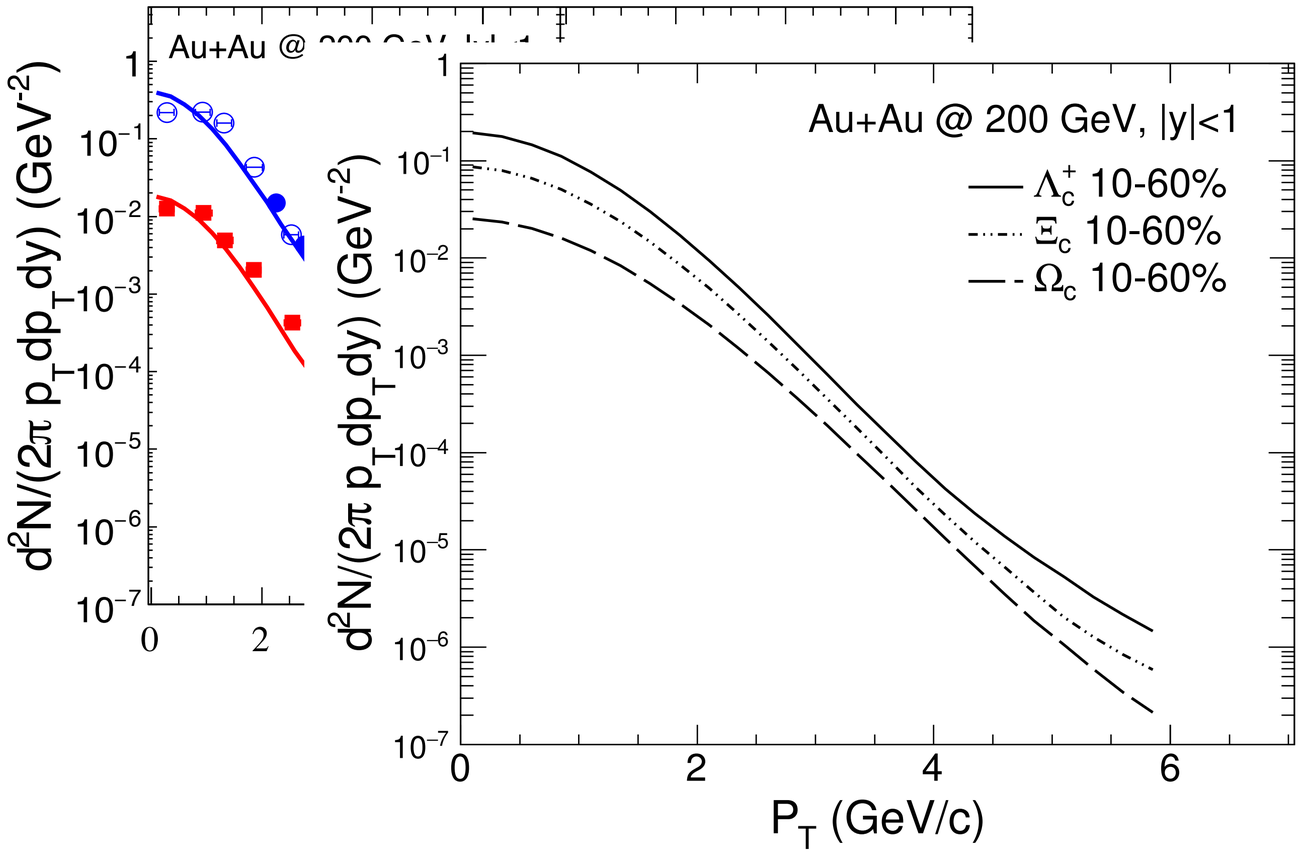

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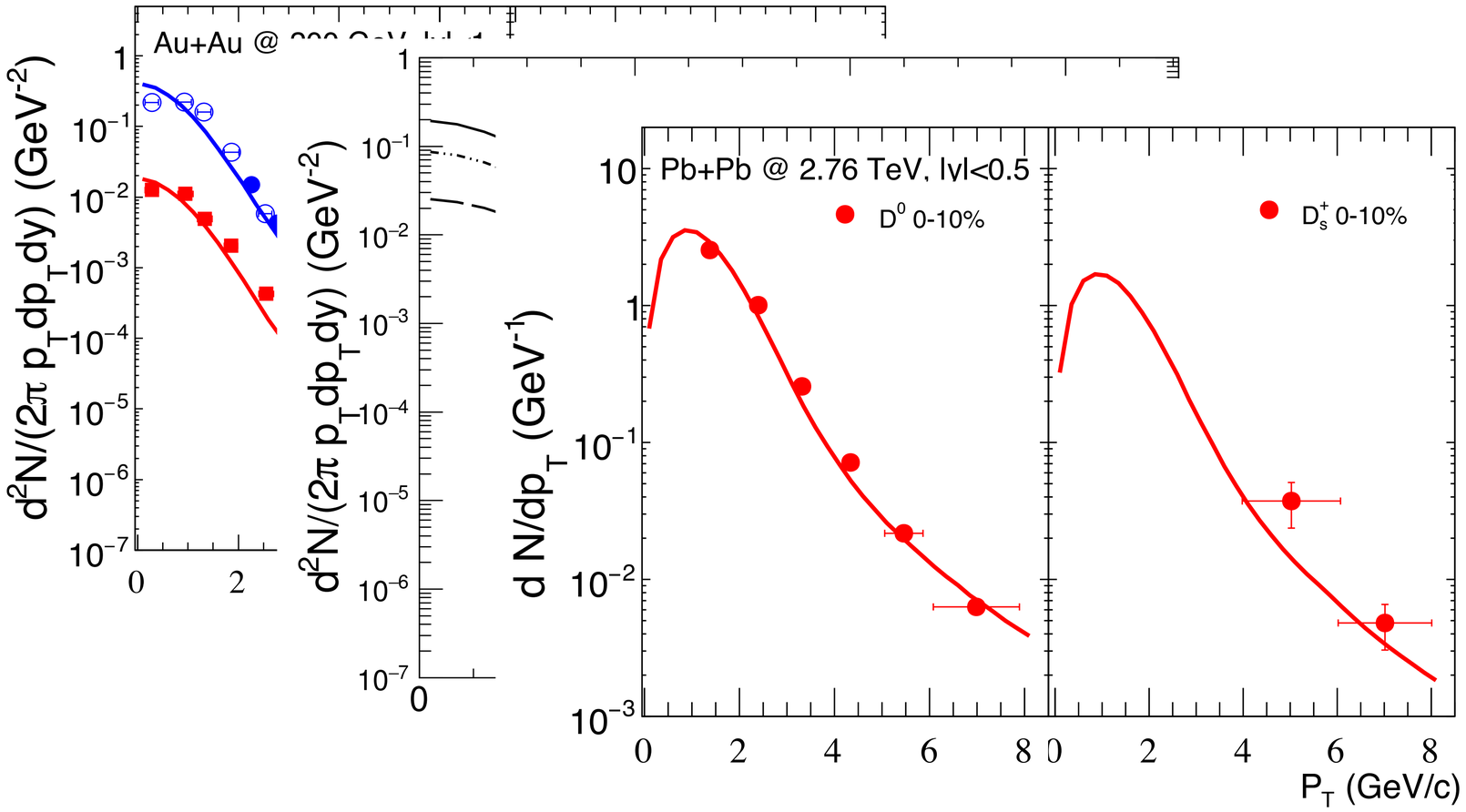

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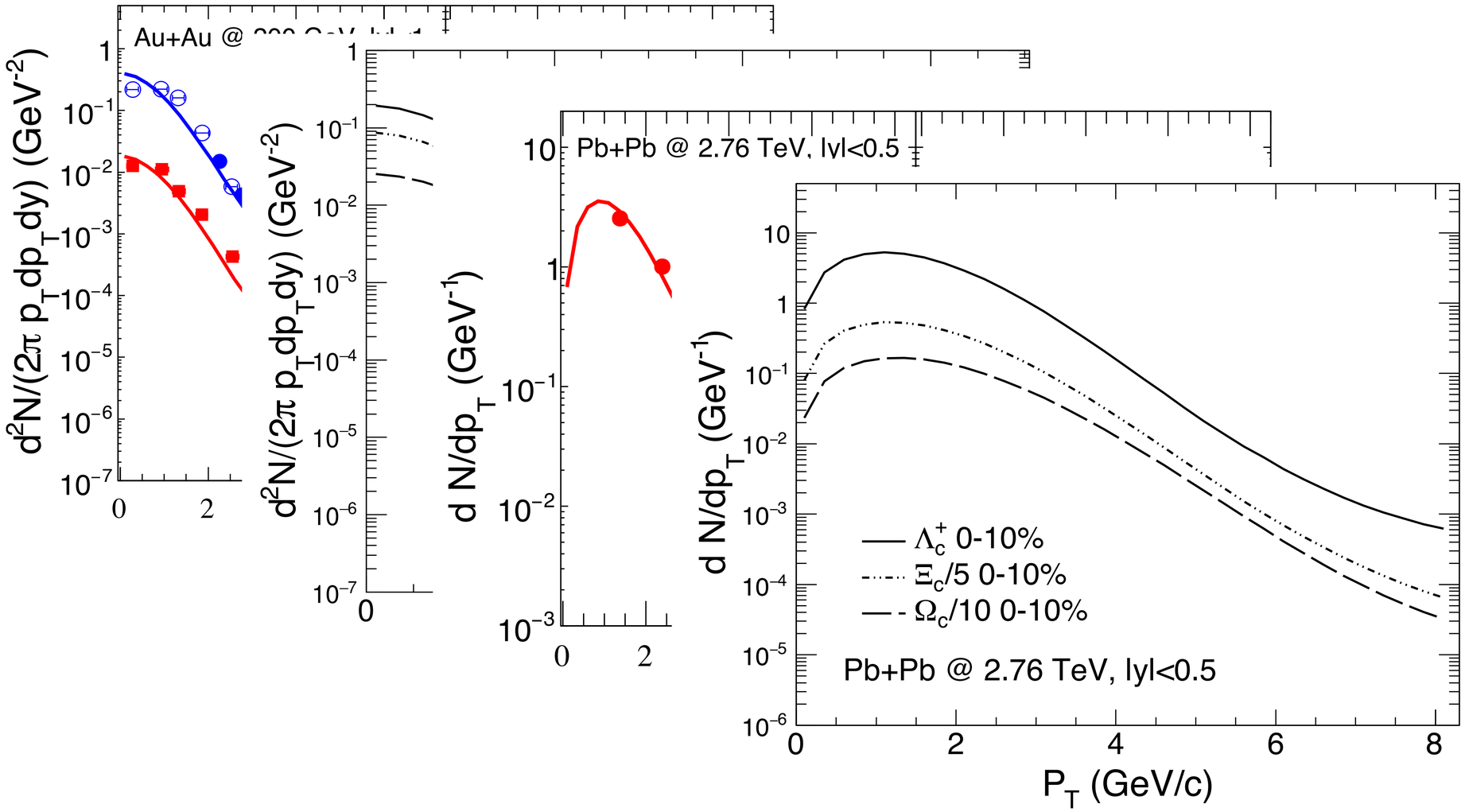

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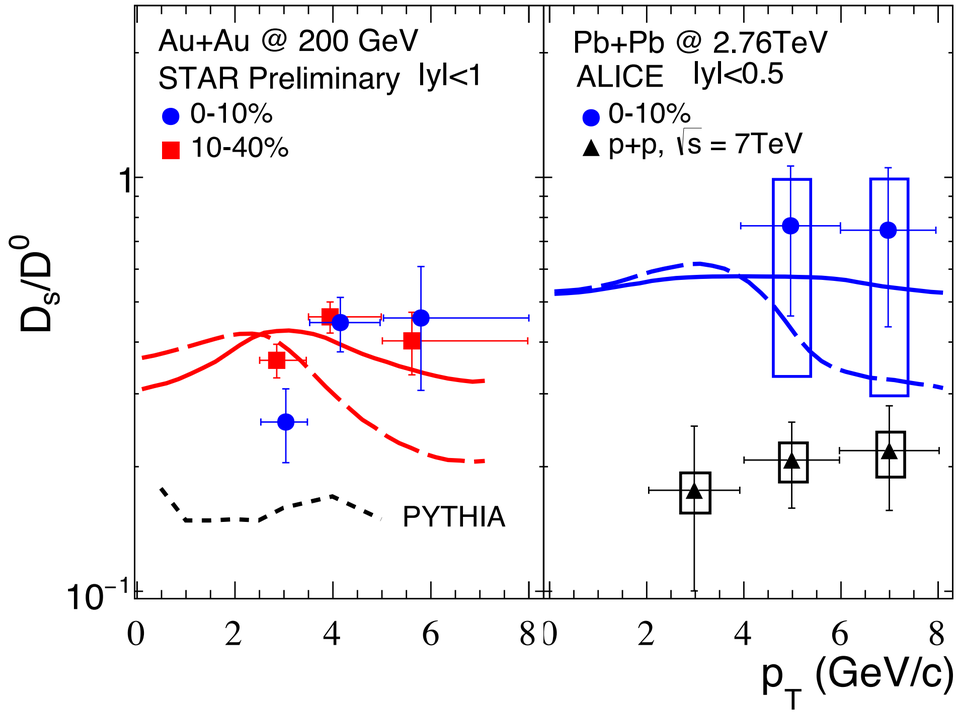

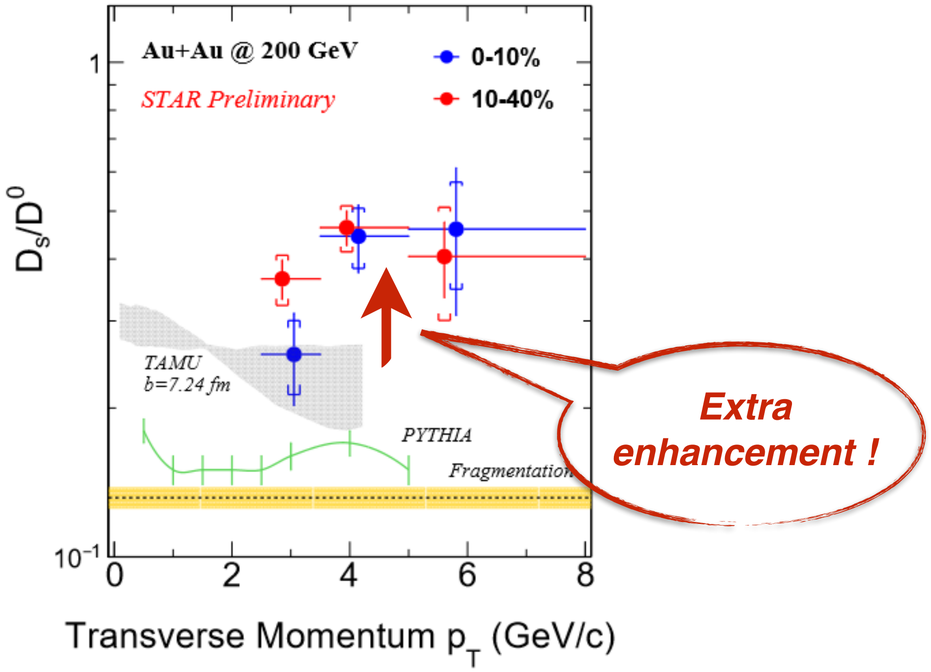

L. Zhou [STAR Collaboration] NPA967. 620(2017)

Solid line: sequential coalescence

Dashed line: simultaneous coalescence at Tc

Strangeness enhancement + Sequential coalescence + Charm conservation

Ds enhancement —> D0 suppression —> an extra enhancement !

Ratio is sensitive to the hadronization mechanism and charm conservation law !

J. Zhao, S. Shi, Nu Xu and P. Zhuang, arXiv:1805.10858. J. Rafelski and B. Muller. Phys. Rev. Lett. 48, 1066 (1982) M. He, R. Fries and R. Rapp, PRL110. 112301(2013)

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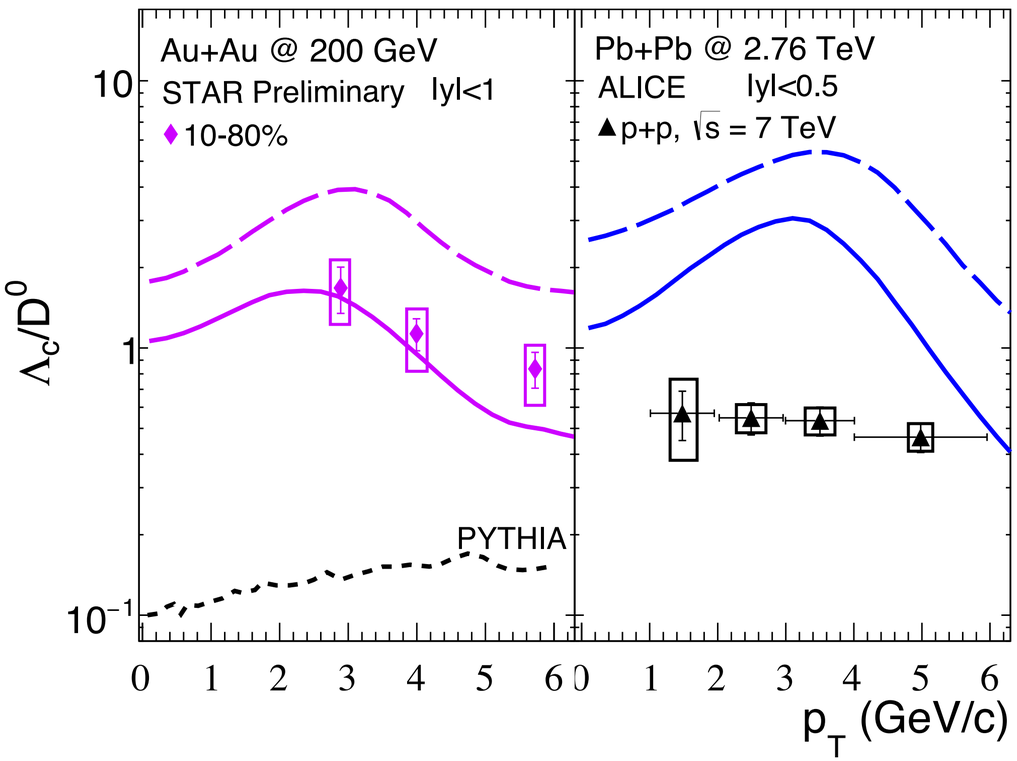

Solid line: sequential coalescence

Dashed line: simultaneous coalescence at Tc

Charm conservation:

Enhances the earlier produced hadrons

Suppresses the later produced hadrons.

Charm conservation reduces the charmed baryon/meson ratio!

J. Zhao, S. Shi, Nu Xu and P. Zhuang, arXiv:1805.10858.

SUMMARY

1. We have built a framework to realize sequential hadronization with charm conservation in HIC! Reasonable agreement between our theoretical calculation and experimental data.

2. Hadronization sequence and coalescence probability of charmed hadrons are determined by 2&3-body Dirac equation.

3. Charm conservation leads to
an enhancement for earlier produced hadrons and
a suppression for later produced hadrons.

Need more exp. data to constrain the hadronization mechanism !

THANK YOU !

BACKUP

For charmed mesons we can solve Tow Body Dirac Equation to get wave functions and masses!