Heavy Quark Hadronization in LBT

Shanshan Cao

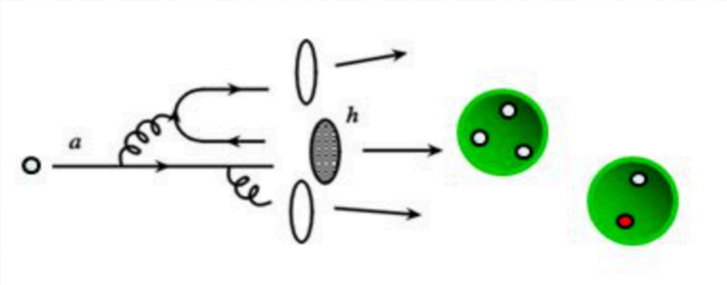
Shandong University

In collaboration with Wen-Jing Xing, Shu-Qing Li, Feng-Lei Liu, Guang-You Qin and Xin-Nian Wang

Two major hadronization mechanisms

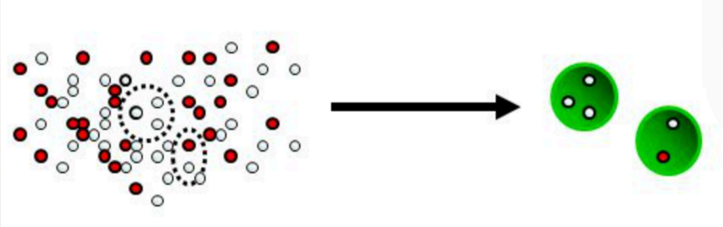
Fragmentation:

High momentum heavy quarks are more likely to fragment into hadrons
[Peterson, FONLL, Pythia, etc.]



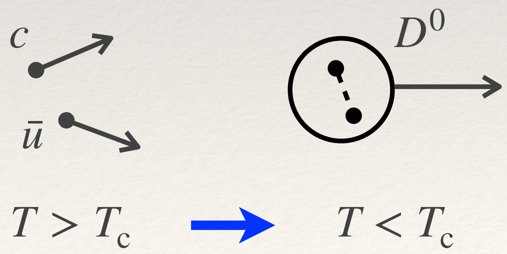
Coalescence (recombination):

Low momentum heavy quarks are more likely to combine with thermal partons into hadrons



Instantaneous coalescence: coalescence probability ~ wavefunction overlap

- Sudden approximation: $|q, g\rangle \to |h\rangle$ as T drops across T_c
- Probability: wave function projection $W_M \equiv |\langle M | q_1, q_2\rangle|^2$
- Encodes information of microscopic hadron structures



Coalescence model

- Example: 2-body system for meson formation

$$W(\vec{r}, \vec{k}) \equiv |\langle M | q_1, q_2 \rangle|^2 = g_M \int d^3 r' e^{-i\vec{k}\cdot\vec{r}'} \phi_M(\vec{r} + \vec{r}'/2) \phi_M^*(\vec{r} - \vec{r}'/2)$$

g_M: ratio of spin-color degeneracy between meson and quark states

ϕ_M: meson wavefunction (S.H.O. approximation with a frequency parameter ω)

$\vec{r} = \vec{r}_1' - \vec{r}_2'$ $\quad \vec{k} = \dfrac{1}{E_1' + E_2'}(E_2' \vec{p}_1' - E_1' \vec{p}_2')$ (r' and p' defined in the meson rest frame)

- Momentum space Wigner function (after averaging over position space) for s and p wave ϕ_M:

$W_s = g_M \dfrac{(2\sqrt{\pi}\sigma)^3}{V} e^{-\sigma^2 k^2}$ $\quad W_p = g_M \dfrac{(2\sqrt{\pi}\sigma)^3}{V} \dfrac{2}{3} \sigma^2 k^2 e^{-\sigma^2 k^2}$ ($\sigma = 1/\sqrt{\mu\omega}$, μ: reduced mass)

Coalescence model

- Hadron spectrum from coalescence

$$f_M(\overrightarrow{p}'_M) = \int d^3p_1 d^3p_2 f_1(\overrightarrow{p}_1) f_2(\overrightarrow{p}_2) W(\overrightarrow{p}_1, \overrightarrow{p}_2) \delta(\overrightarrow{p}'_M - \overrightarrow{p}_1 - \overrightarrow{p}_2)$$

$f_i(\overrightarrow{p}_i)$: distribution of constituent quarks

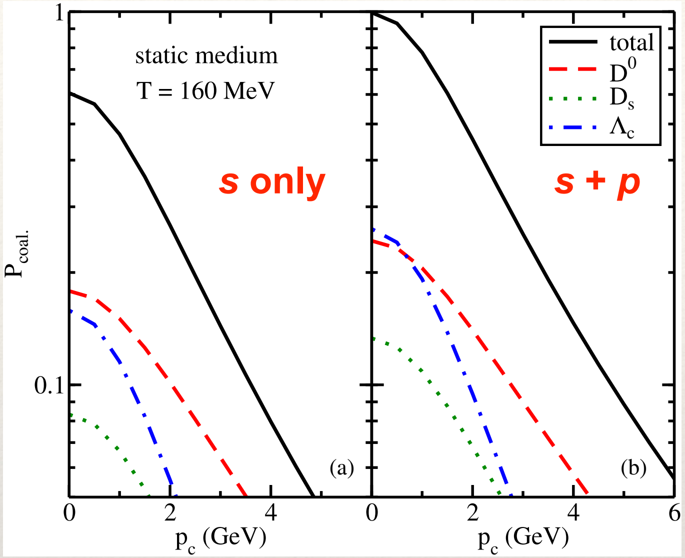
Light quarks: thermal distribution in the local rest frame of the QGP (gluons are converted to light quark pairs by $gg \rightarrow q\bar{q}$)

Heavy quarks: from a transport model simulation

- Straightforward to extend to a 3-body system for baryon formation
- Coalescence probability for a single charm quark with a given p_c into a particular hadron species

$$P_{\mathrm{coal}}(p_c) = \int d^3p'_M f_M(\overrightarrow{p}'_M) \quad \text{with} \quad f_c(\overrightarrow{p}) = \delta(\overrightarrow{p} - \overrightarrow{p}_c)$$

Coalescence probability



- Include both *s* and *p*-wave states in a full 3-D calculation

  e.g. D^0 $(c\bar{u})$ meson formation with $S = 0,\ 1$

  s wave $(L = 0)$: $S = 0 \rightarrow J = 0\ (D^0);\ S = 1 \rightarrow\ J = 1\ (D^{*0})$

  p wave $(L = 1)$: $S = 0 \rightarrow J = 1\ (D_1^0);$

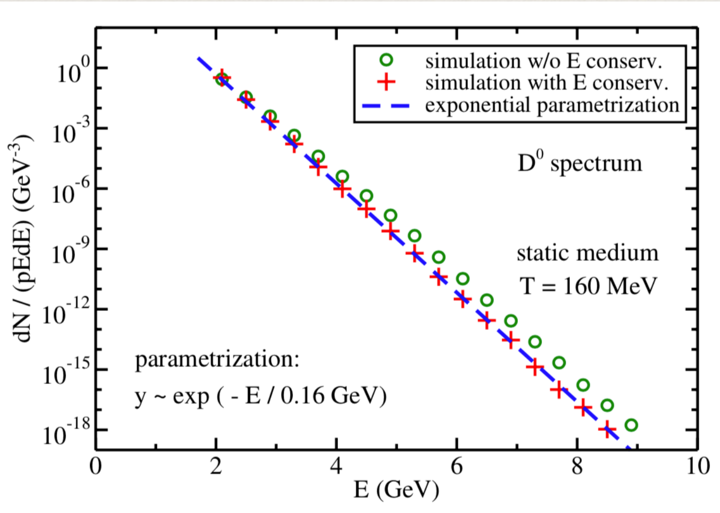
  $S = 1 \rightarrow\ J = 0\ (D_0^{*0}),\ J = 1\ (D_1^{*0}),\ J = 2\ (D_2^{*0})$

- Cover nearly all charmed hadrons in PDG
- Enhance the total $P_{\rm coal}$

- Allow normalizing $P_{\rm coal}(p_c = 0) = 1$ with a proper $\omega = 0.24$ GeV, abandoning arbitrary normalization factors in literature
- Predict larger in-medium hadron size ($r_{D^0} = \sqrt{3/(2\mu\omega)} = 0.97$ fm) than in vacuum (0.83 fm), consistent with relativistic potential model prediction (Shi, Zhao, Zhuang, CPC 44 (2020) 8, 084101)
- Coalescence-fragmentation model: use Pythia to fragment heavy quarks that do not coalesce

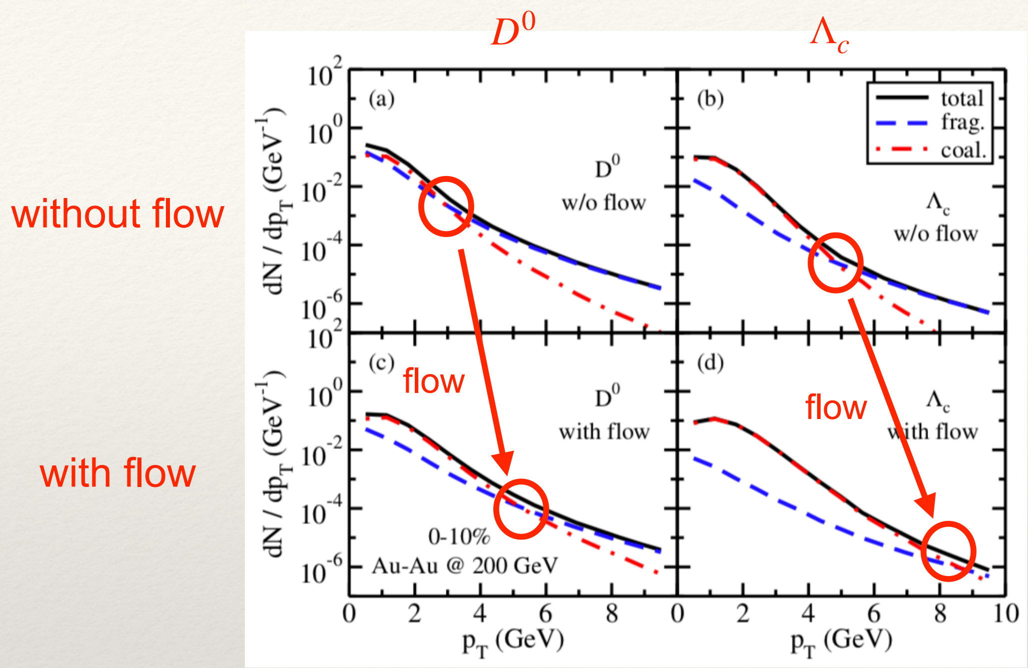
Energy conservation and thermal limit

- Recall: $f_M(\vec{p}'_M) = \int d^3p_1 d^3p_2 f_1(\vec{p}_1) f_2(\vec{p}_2) W(\vec{p}_1, \vec{p}_2) \delta(\vec{p}'_M - \vec{p}_1 - \vec{p}_2)$
- Energy is not conserved if $\vec{p}'_M$ is directly put on-shell with the hadron mass
- 3-*p* → 4-*p* conservation: coalesce to an off-shell *c*-hadron $(E'_M, \vec{p}'_M)$ and then decay it to an on-shell *c*-hadron with a pion $(E_M, \vec{p}_M) + (E_\pi, \vec{p}_\pi)$



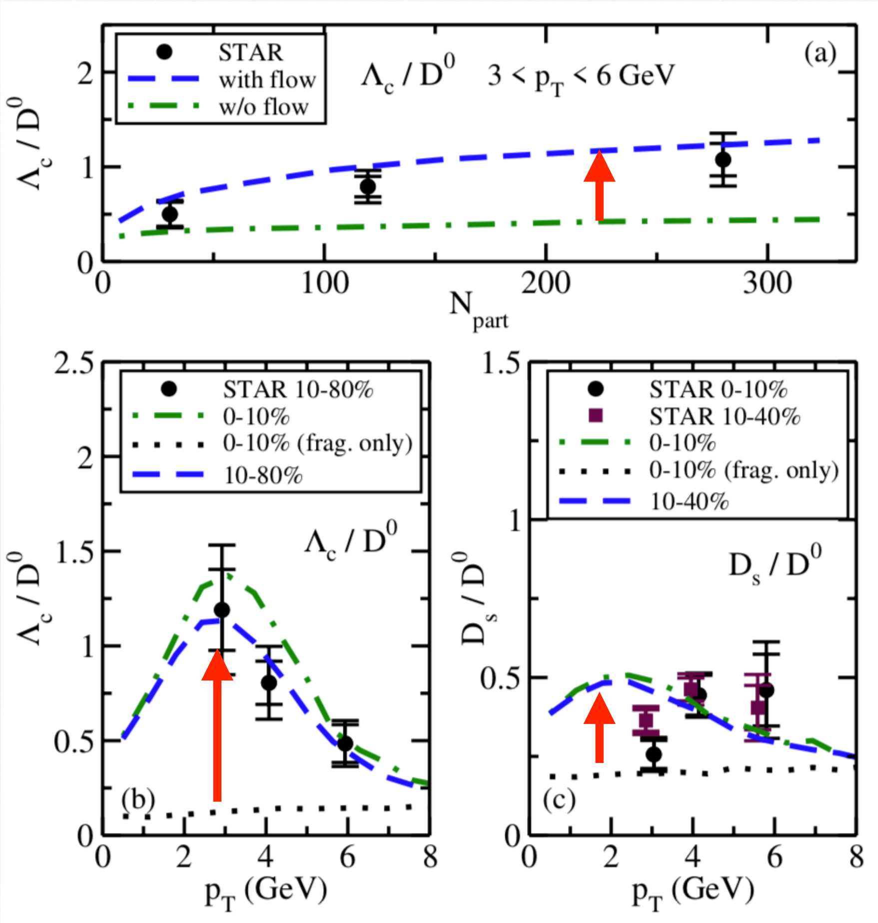
- Guarantee boost invariance
- Respect the thermal equilibrium limit of *c*-hadrons: thermal *c* + thermal *q* → thermal D^0
- Sudden approximation $|q, g\rangle \rightarrow |h\rangle$ (no inverse process) does not require the chemical equilibrium

Charmed hadron spectra: QGP flow effect



- Coalescence dominates Λ_c production over a wider p_{T} region than D^0
- The QGP radial flow significantly enhances the coalescence contribution
- The inaccuracy of default Pythia fragmentation in pp should have minor effects on AA results, could be improved later (color reconnection [Velasquez et. al., PRL 111 (2013)], or coalescence in pp [Song, Li, Shao, EPJC 78 (2018)])

Charmed hadron chemistry at RHIC



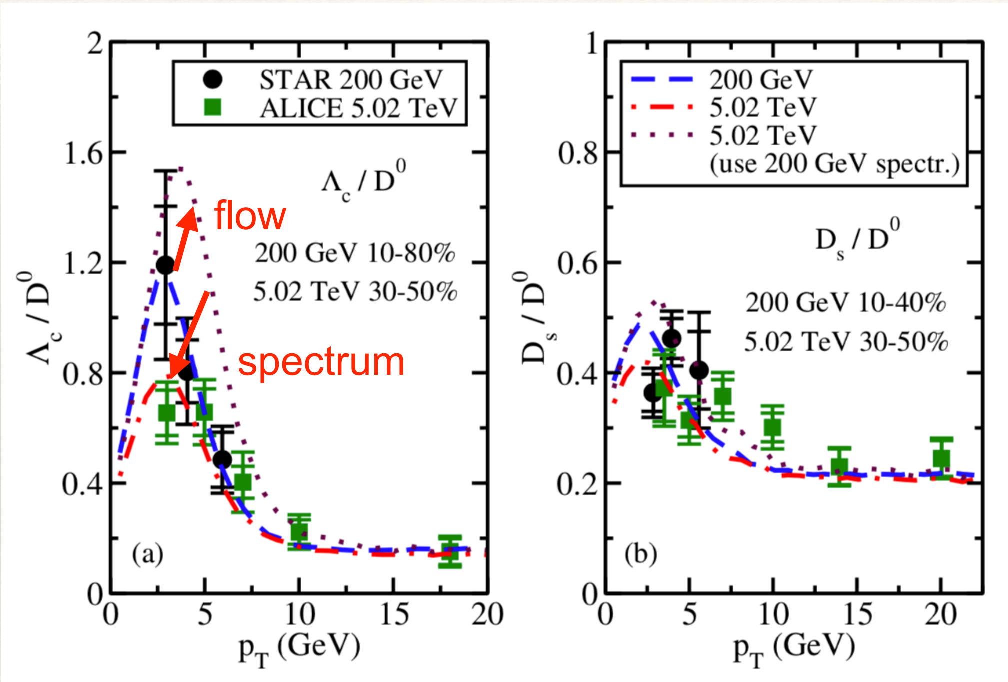
effects of the QGP flow

effects of coalescence

- (a) Stronger QGP flow boost on heavier hadrons => increasing Λ_c/D^0 with N_{part}
- (b) Coalescence significantly increases Λ_c/D^0, larger value in more central collisions (stronger QGP flow)
- (c) Enhanced D_s/D^0 due to strangeness enhancement in QGP and larger D_s mass than D^0

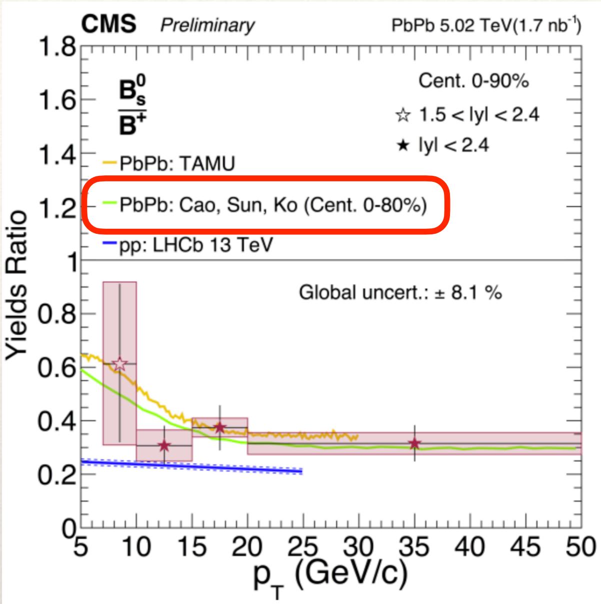
RHIC vs. LHC

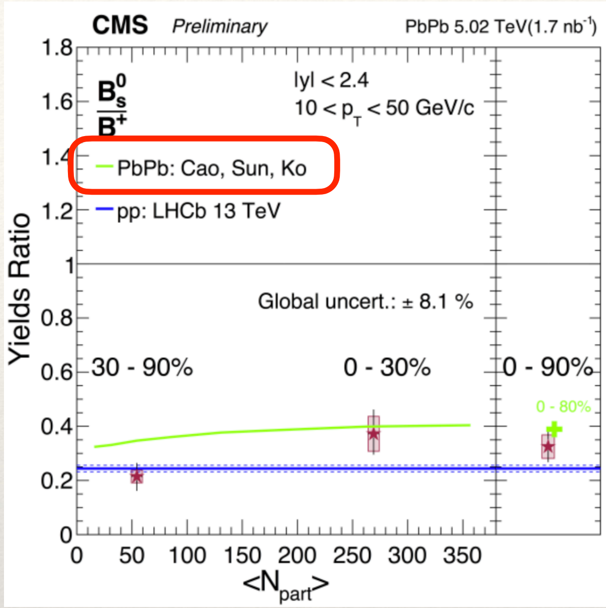
Λ_c/D^0 D_s/D^0



- IF charm quarks have the same initial spectrum at RHIC and LHC, Λ_c/D^0 would be larger at LHC than RHIC due to the flow effect
- The harder initial charm quark spectra at LHC reduces Λ_c/D^0
- Similar theoretical prediction on D_s/D^0

Prediction on bottom hadron chemistry





taken from CMS presentation at HP2020 by Z. Shi

- More constraints on the mass (velocity/momentum) dependence of hadronization models
- Assume same diffusion coefficient D_s between *c* and *b* quarks
- Only difference: $\omega_c = 0.24\ \mathrm{GeV} \ \rightarrow \ \omega_b = 0.14\ \mathrm{GeV}$ so that $P_{\mathrm{coal}}(p_b = 0) = 1$ for *b* quarks