Elliptic flow of Ds as evidence of the sequential hadronization mechanism in the hot QCD medium

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arXiv:2510.16299

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Outline

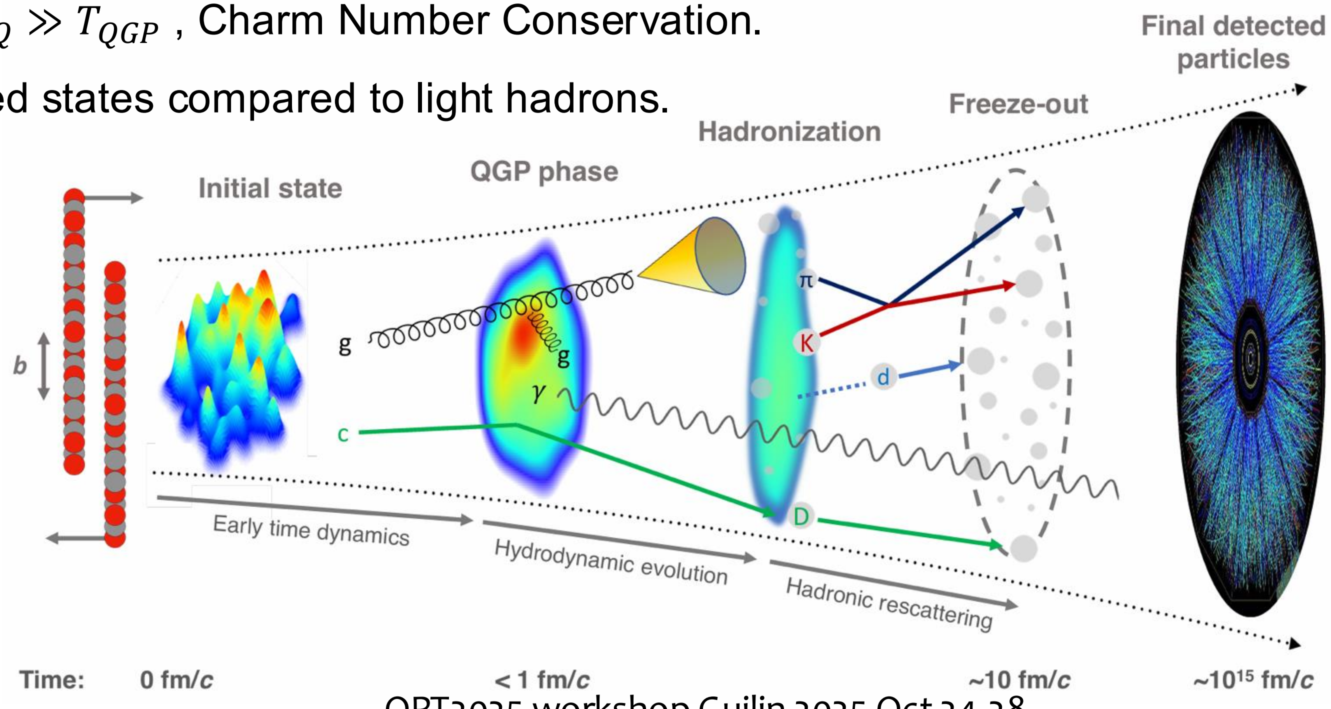
- Introduction of Sequential Coalescence
- Implementation of the Sequential Coalescence Mechanism
- Impact of the Sequential Coalescence Mechanism
- Reversal of the v_2 hierarchy between D^0 and D_s as evidence
- Summary and Outlook

Hadronization in relativistic heavy-ion collisions

- A deconfined QCD matter— quark-gluon plasma(QGP) has been created.
- Hadronization: a non-perturbative process
- Hadronization in the hot QCD medium shows a huge difference compared to the vacuum case.
- Flow information will be captured in the in-medium hadronization process.

Heavy flavor can be a nice probe to study in-medium hadronization:

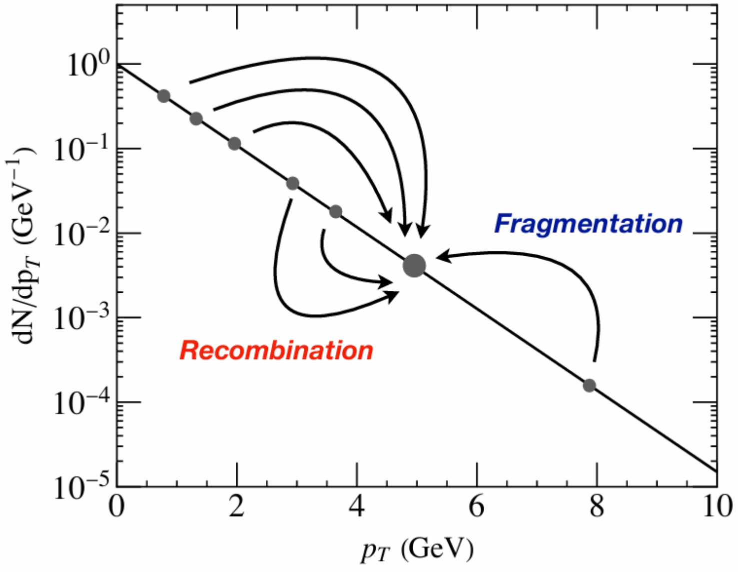
- Produced by hard scattering, described by pQCD.
- HQ mass $m_Q \gg T_{QGP}$, Charm Number Conservation.
- Fewer excited states compared to light hadrons.



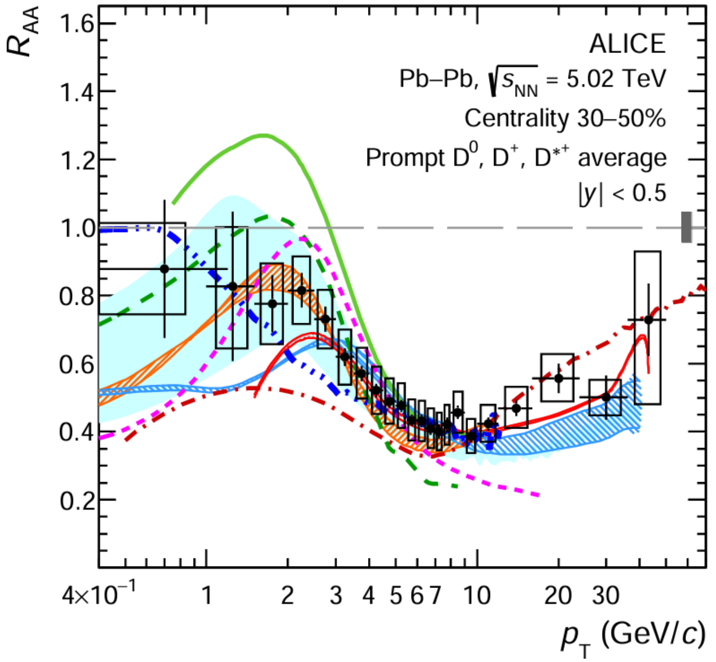
arXiv:2303.17254

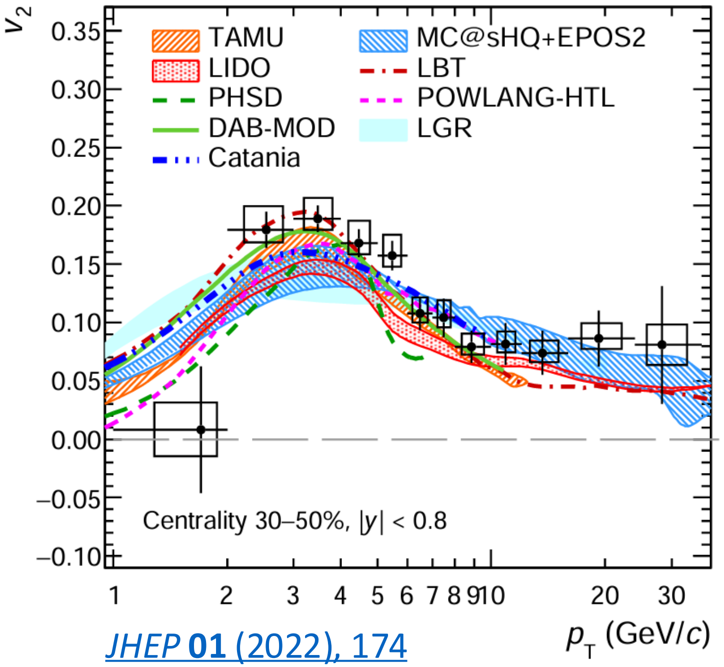
Coalescence + fragmentation hadronization

- Coalescence: a precise constraint will provide a strong probe of flow !



- Well accepted scenario: → provide good descriptions of available data :
  - CATANIA *Phys. Lett. B* **821** (2021), 136622; *Eur. Phys. J. C* **78** (2018) no.4, 348
  - Duke *Phys. Rev.. C* **92** (2015) no.2, 024907; *Phys. Rev. C* **88** (2013), 044907
  - Nantes *Phys. Rev. C* **79** (2009), 044906
  - PHSD *Phys. Rev.. C* **92** (2015) no.1, 014910; *Phys. Rev. C* **93** (2016) no.3, 034906
  - TAMU *Phys. Lett. B* **655** (2007), 126-131; *Phys. Lett. B* **795** (2019), 117-121
  - … …
- ALL hadronized at the same temperature!



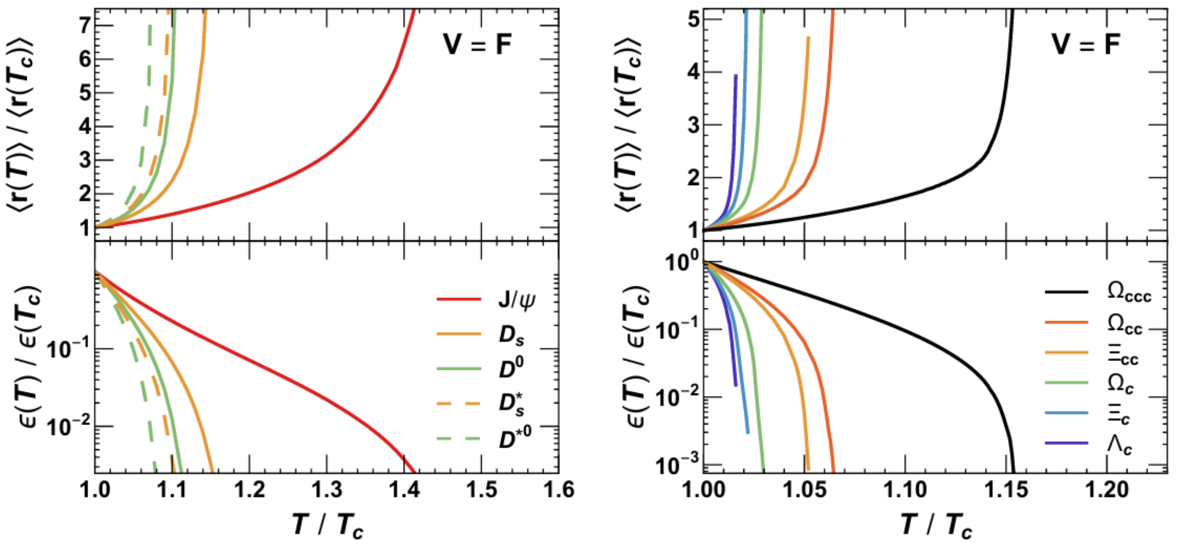


JHEP **01** (2022), 174

Sequential hadronization = realistic

- The hadrons containing heavy quarks
  - with larger binding energy,
  - survive at higher temperatures.

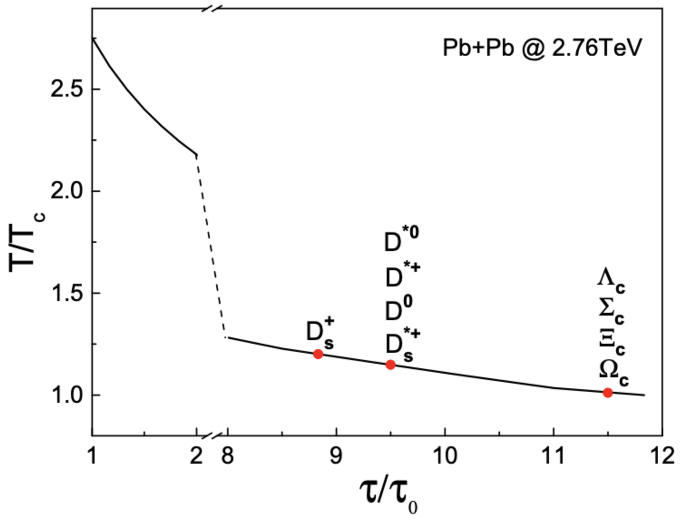
Shuzhe Shi, Jiaxing Zhao, Pengfei Zhuang CPC (2020)

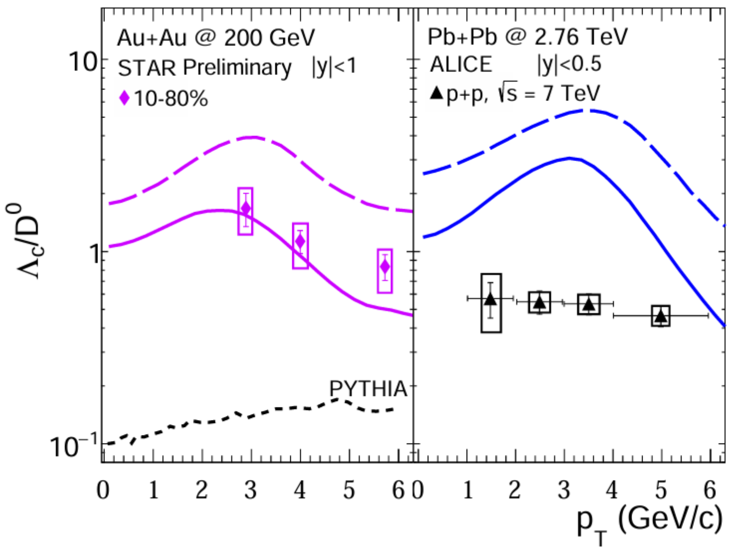


Nucl. Phys. A **1005** (2021), 121898

- The hadron dissociation (hadronization) temperature can be calculated by solving the Dirac equation with quark potential models.

arXiv:1805.10858

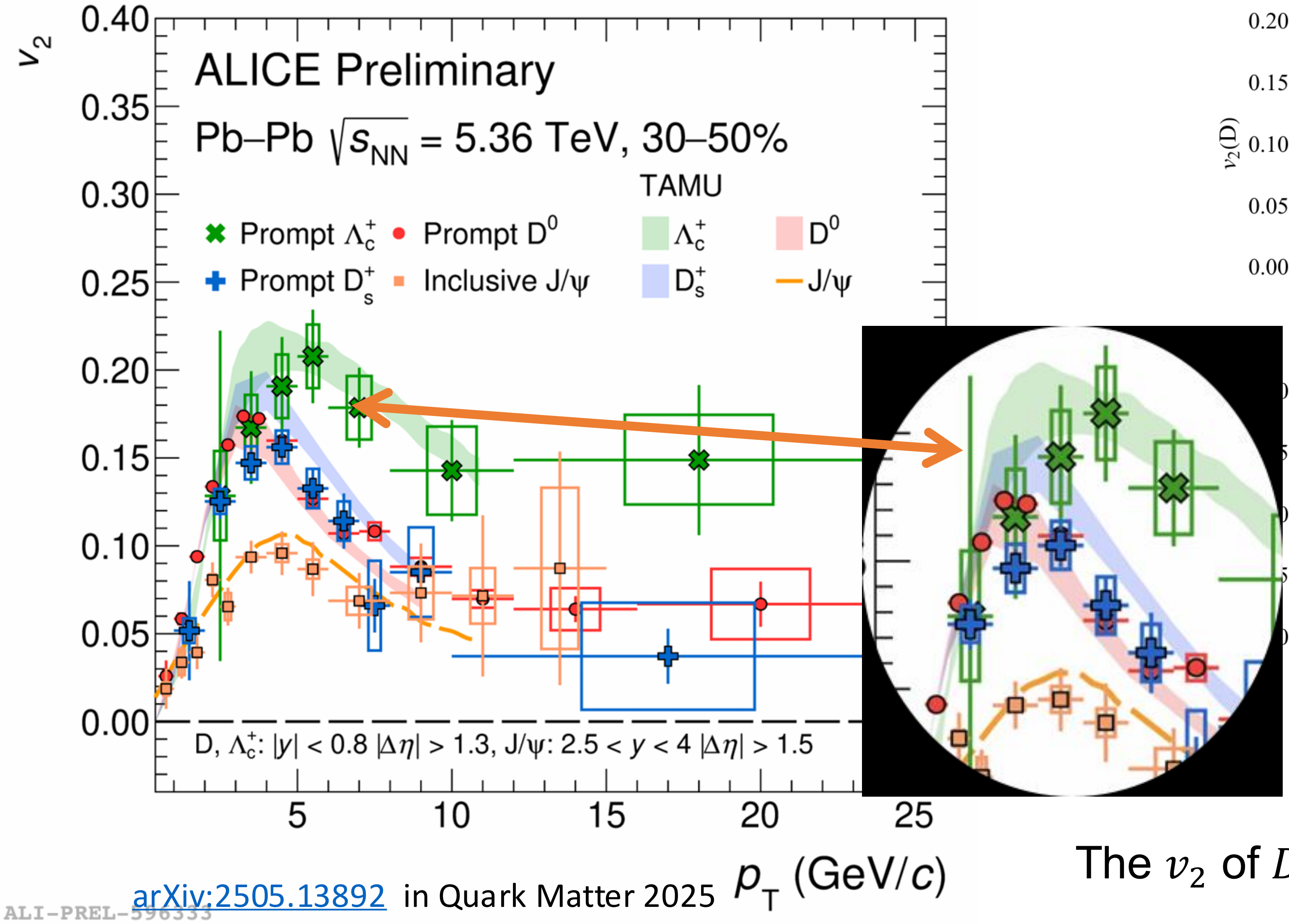




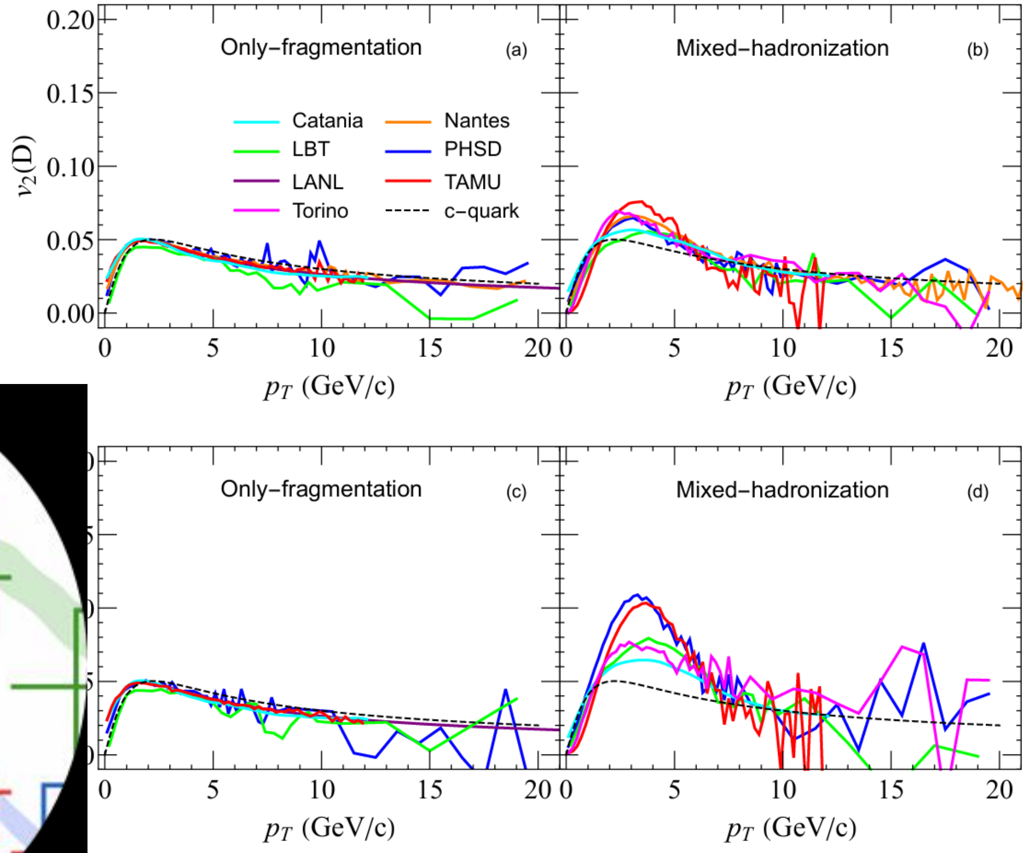
Dissociation sequence :

$$T_d^{J/\psi} > T_d^{D_s} > T_d^{\Omega_{ccc}} > T_d^{D^0} > T_d^{\Omega_{cc},\Xi_{cc}} > T_d^{\Omega_c,\Xi_c,\Lambda_c} > T_d^{\pi,K,N} \approx T_c$$

v_2 Hierarchy between D^0 and D_s^+ due to conventional Coalescence



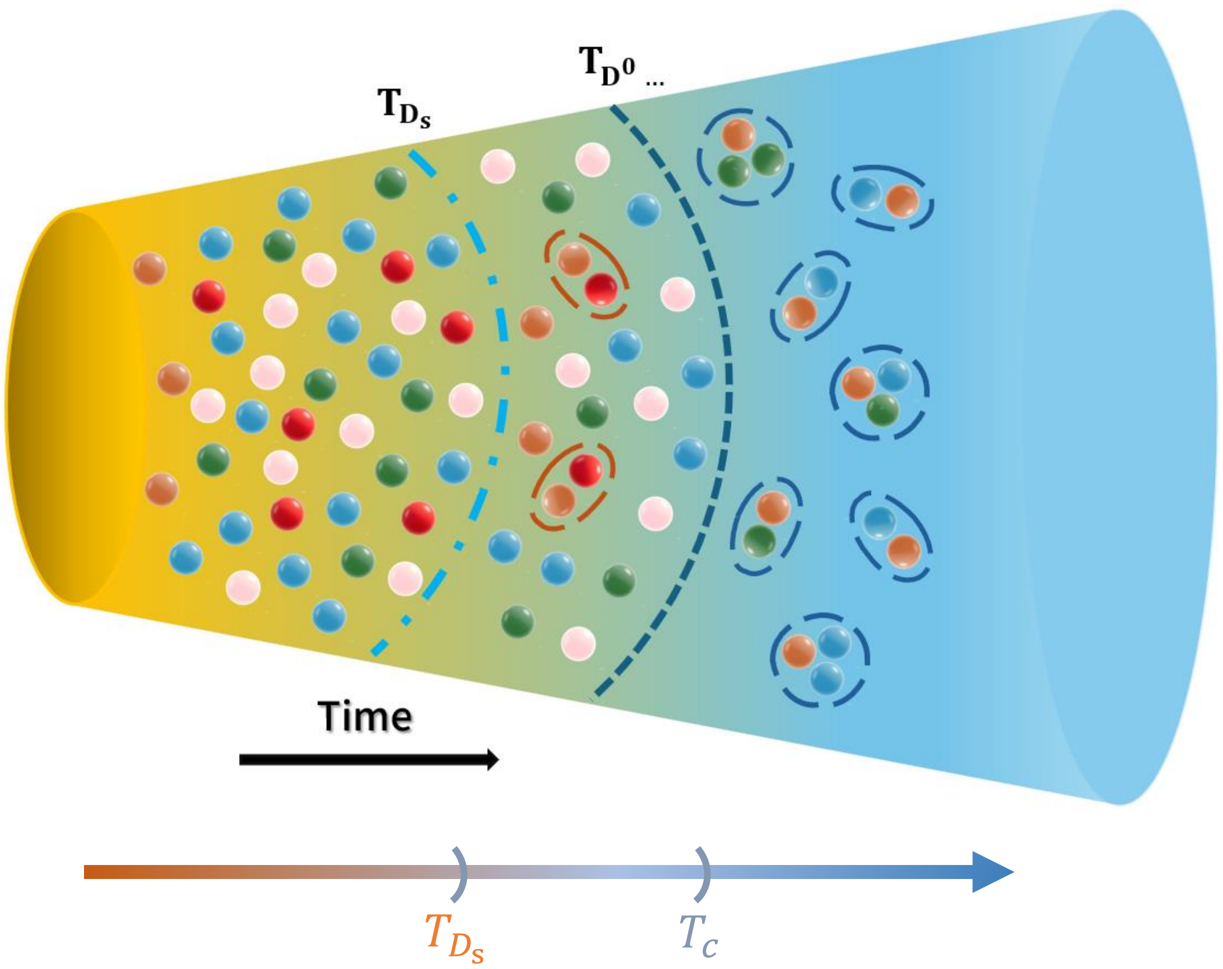
arXiv:2505.13892 in Quark Matter 2025



Phys. Rev. C **109** (2024) no.5, 054912

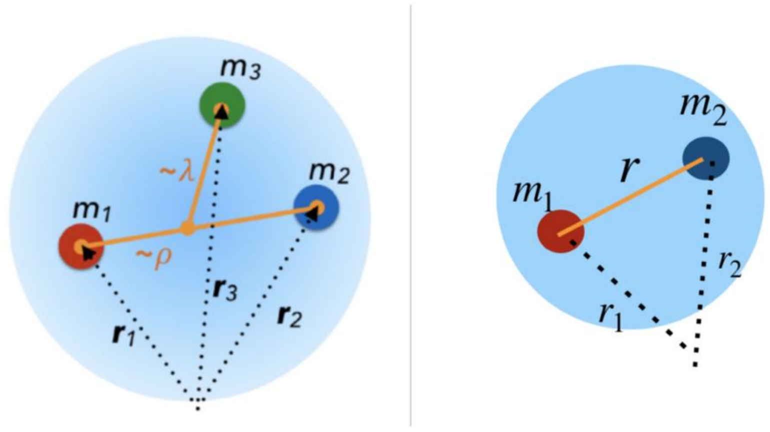
The v_2 of D_s^+ is lower than D^0 in the intermediate-p_T region, contradict to model predictions.

How to consider Sequential Coalescence ?



- D_s coalesce before other hadrons at a temperature $T_{D_s} = 1.2\ T_c$ (By solving Dirac Equation)
- All other heavy-flavor hadrons hadronize on a separate hypersurface at $T = T_c$

Coalescence Hadronization



The momentum distribution of hadrons produced from coalescence:

$$P_h = g_h \int \prod_{i=1}^{n} \frac{d^3x_i d^3p_i}{(2\pi)^3} f_i(x_i, p_i) \cdot W_h(x_1, \cdots, x_i, p_1, \cdots, p_i)$$

- Quark distribution function $f_i(x_i, p_i)$

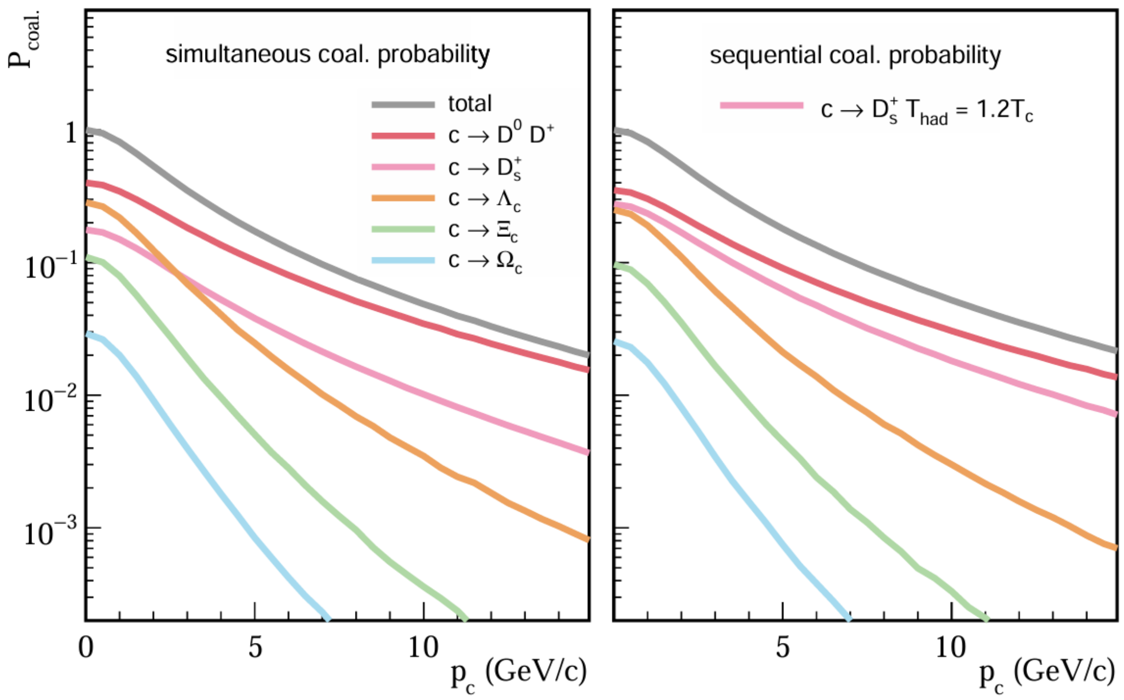
  For light quark $f_i(p_i) = N_i/(e^{u_\mu p_i^\mu/T} + 1)$

- Wigner function $W_h(\boldsymbol{r}, \boldsymbol{p}) = \int d^3\boldsymbol{y} e^{-i\boldsymbol{p}\cdot\boldsymbol{y}}\, \psi\left(\boldsymbol{r} - \frac{\boldsymbol{y}}{2}\right) \psi^*\left(\boldsymbol{r} - \frac{\boldsymbol{y}}{2}\right)$

The total sequential coalescence probability:

$$P_{coal}(p_c) = C \cdot \left(P_{D_s}(p_c, T_{D_s}) + \sum P_{D^0,\ldots}(p_c, T_c) \right)$$

C normalize the total coalescence probability when $P_c \to 0$



⭐ Sequential mechanism

1. Enhance the earlier-produced hadron yield via coalescence;

2. more coalescence → more v_2 ?

Parton-level elliptic flow at different hypersurface

- **Initial momentum and position:**

  FONLL *JHEP* 10 (2012) 137

  Monte Carlo Glauber model *EPJC* 72 (2012) 1896

- **In-medium evolution:**

  Improved SHELL model *WD et al Chin.Phys.C* 44 (2020) 104105

  Spatial diffusion coefficient is taken as

  $(2\pi T)D_s = 2.5$ based on lattice QCD calculation.

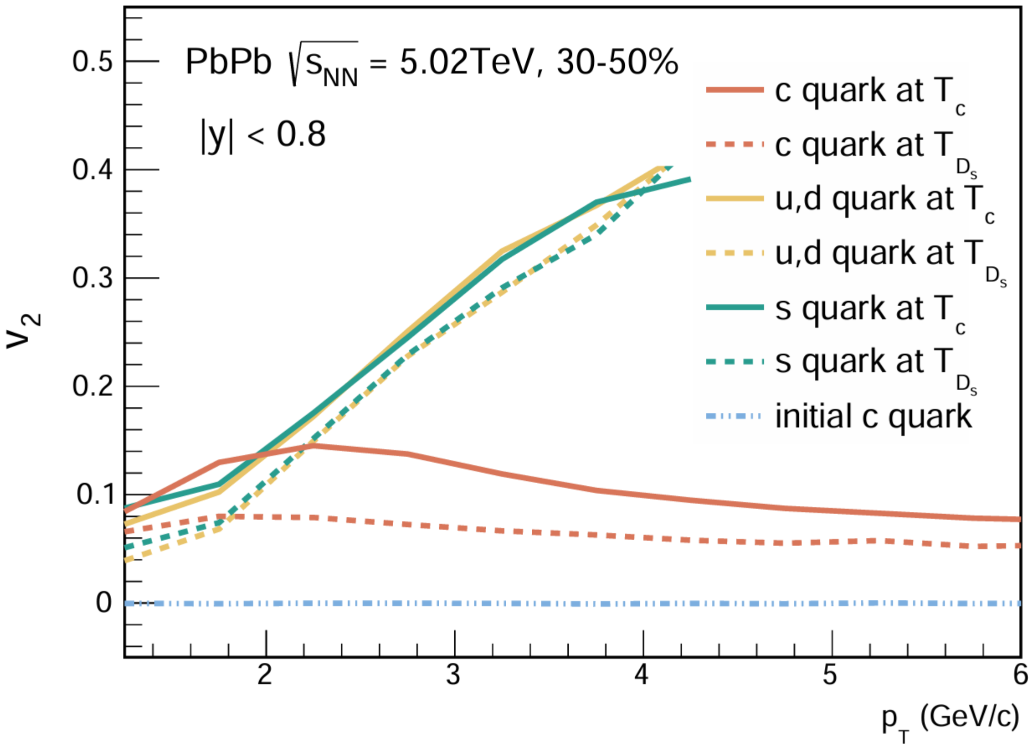
  The jet transport coefficient $\hat{q} = \hat{q}_0(\frac{T}{T_0})^3\frac{p^{\mu}u_{\mu}}{p^0}$

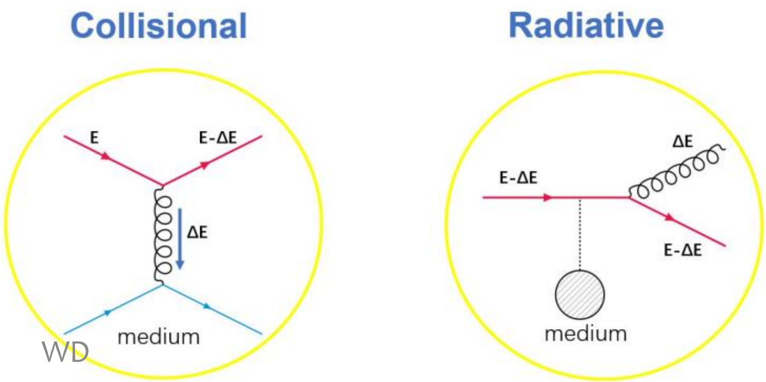
  We take $\hat{q}_0 = 1.5\ \mathrm{GeV}^2/\mathrm{fm}$

  Hydrodynamic information:

  (3+1)D CLVisc hydro

  Phys.Rev.C 97 (2018) 6, 064918

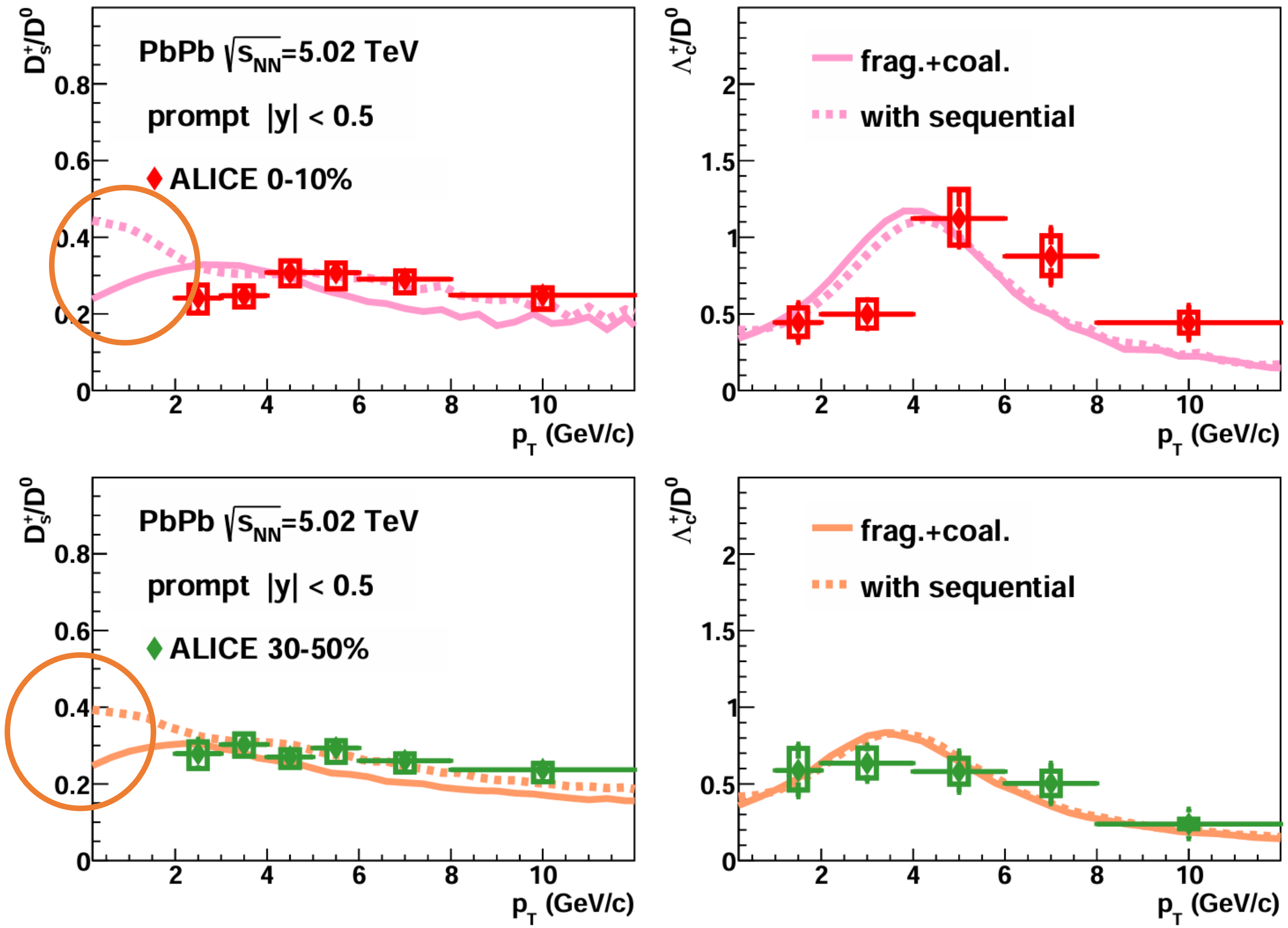


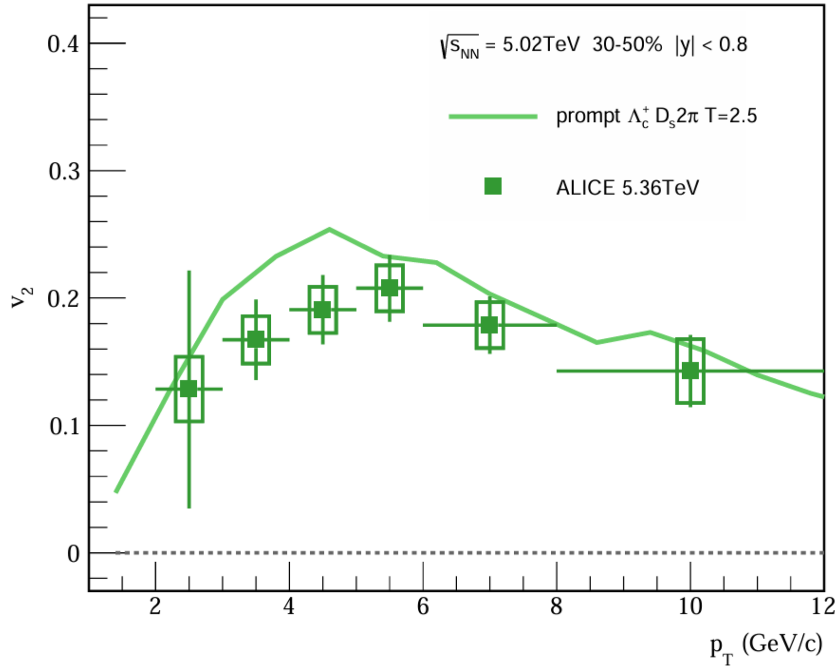


- The elliptic flow v_2 of charm quark at T_c is clearly larger than that at T_{D_s}.
- Thermal s quark v_2 is slightly higher than u,d quark at p_T < 2GeV/c.
- v_2 of thermal u, d, s obtained at T_c and T_{D_s} are nearly identical.

the earlier-coalesced charm hadron obtain a smaller v_2, mainly attribute to different degree of charm quark thermalization.

Model constraint by spectrum, particle ratios and v_2





Enhancement of D_s/D^0 in the lower p_T might also be phenomenon for *sequential Coalescence.*

Calculation for different centralities is on the way.

Hadronic re-scattering

Treatment :
Min He, Ralf et al 1204.4442

D-meson hadronic re-scattering is realized in Langevin simulation:

$$dx_j = \frac{p_j}{E} dt$$

$$dp_j = -\Gamma(p) p_j dt + \sqrt{\kappa dt} \rho_j$$

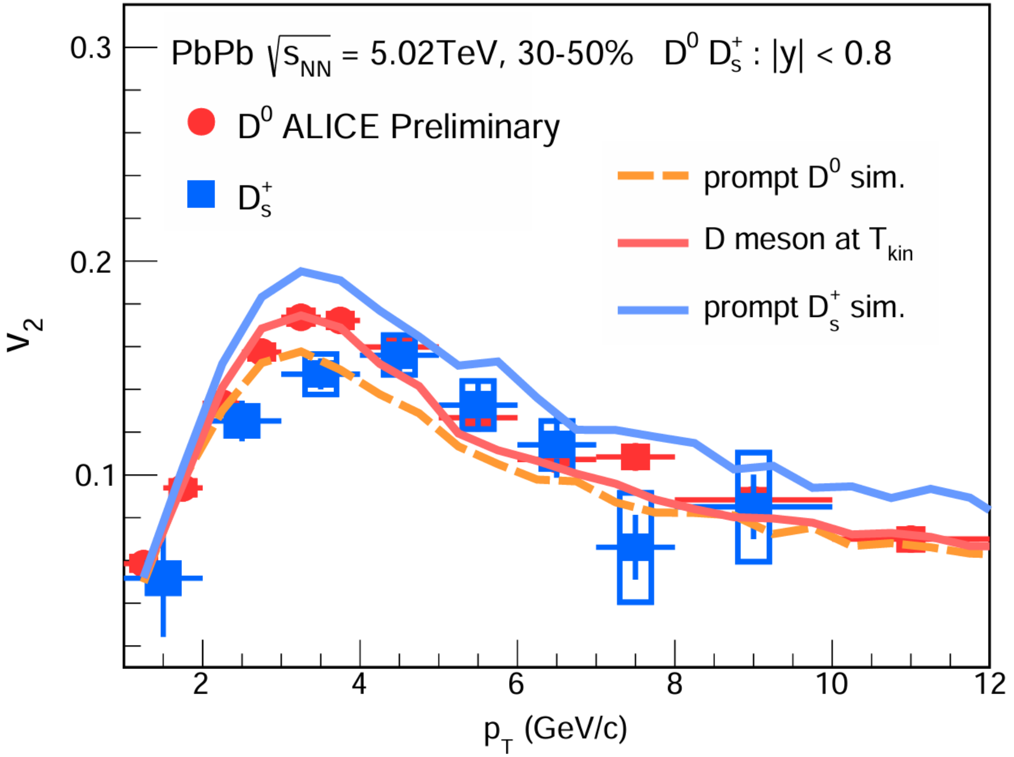
The fluctuation-dissipation relationship:

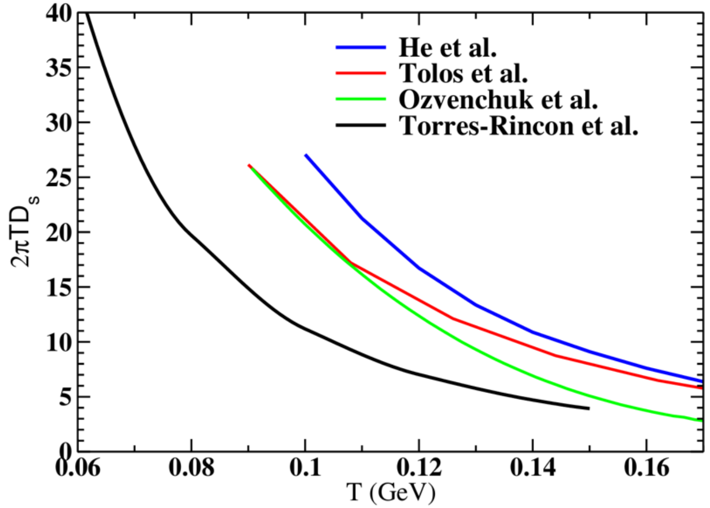
$$\kappa = 2\Gamma E T = \frac{2T^2}{D_s}$$

The spatial diffusion coefficient D_s for D meson is taken from *Torres-Rincon et al.*

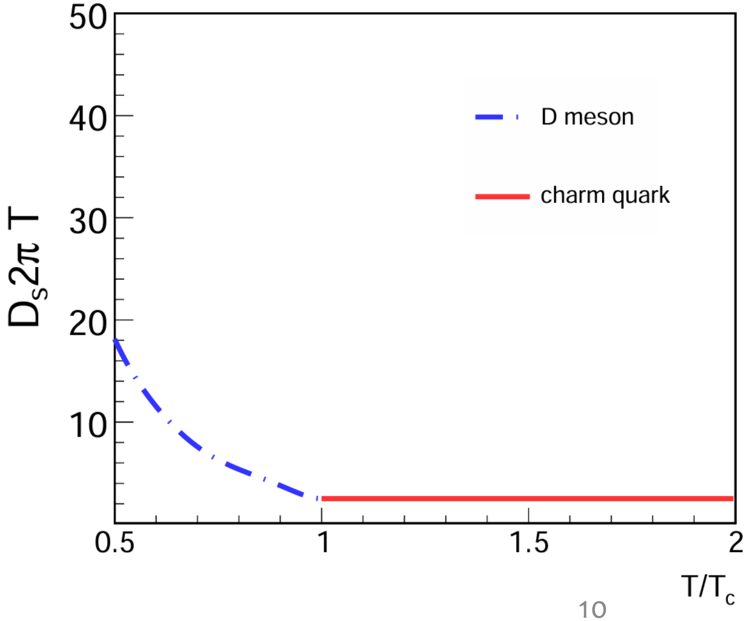
Phys. Rev. C **105** (2022) no.2, 025203

: BREAKING v_2 hierarchy for D^0 and D_s requires a mechanism beyond hadronic scattering !

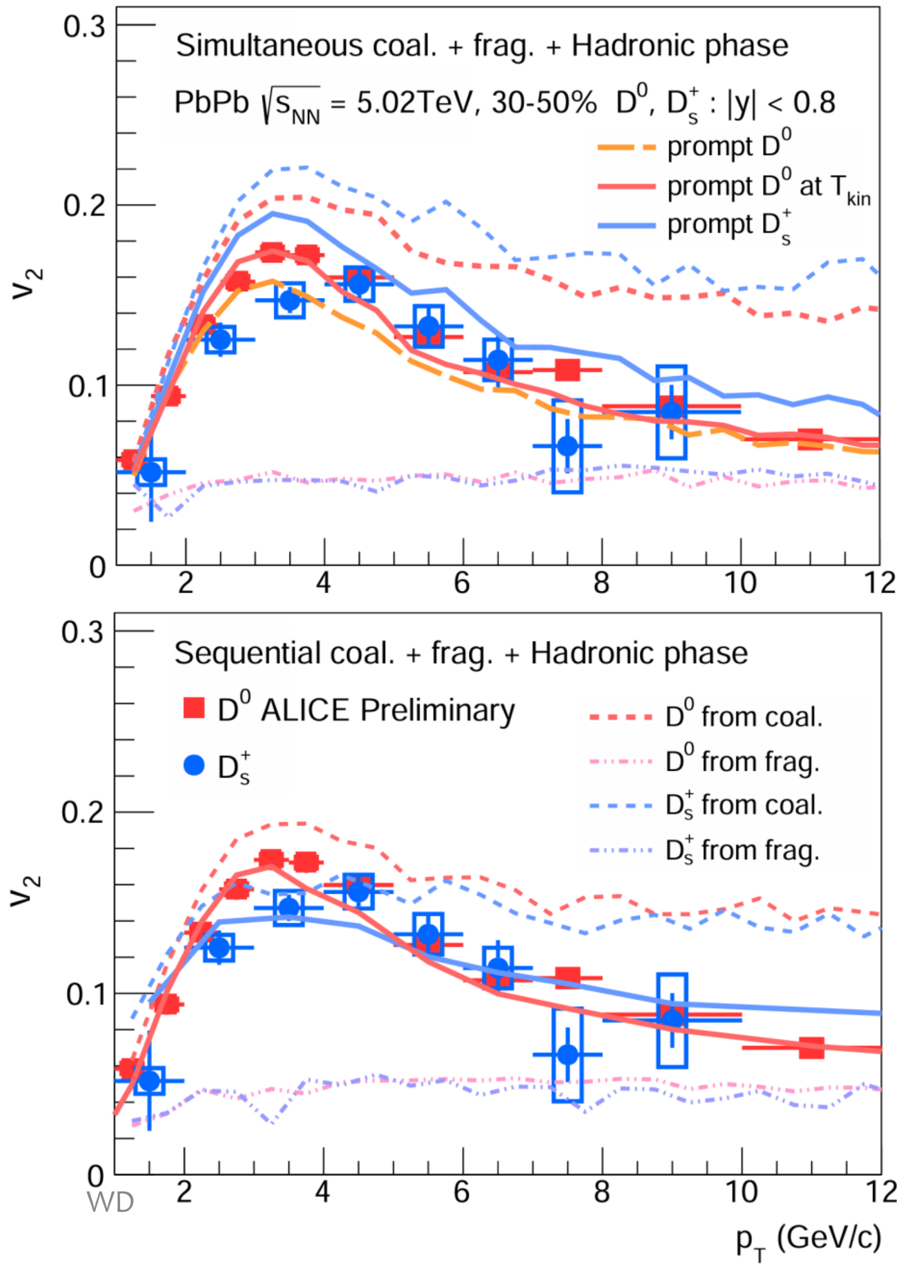




Phys. Rept. **1129-1131** (2025), 1-53



Sequential & simultaneous coalescence + Hadronic phase



- The coalescence mechanism dominates the contribution to the elliptic flow at lower and intermediate-p_T.

- Simultaneous coalescence leads to

$$v_2\,(D^0) < v_2\,(D_s)\,.$$

After considering sequential mechanism -

- The coalescence contribution for v_2 of D_s drops dramatically after considering sequential mechanism.
- Sequential coalescence + Hadronic rescattering reproduces the ALICE measurements.
- The reverse of such a v_2 hierarchy is observed

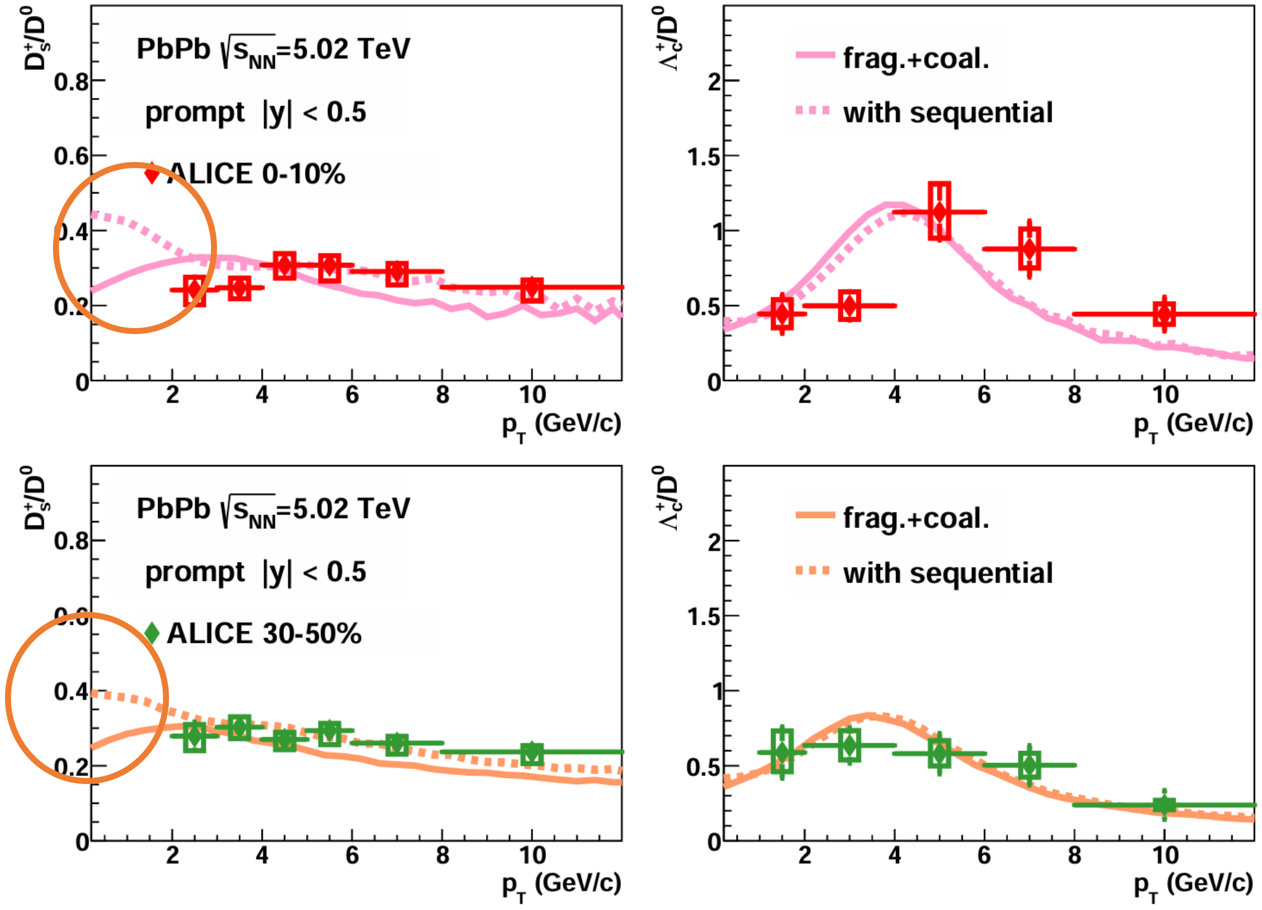
$$v_2\,(D^0)\; > \; v_2\,(D_s)\,.$$

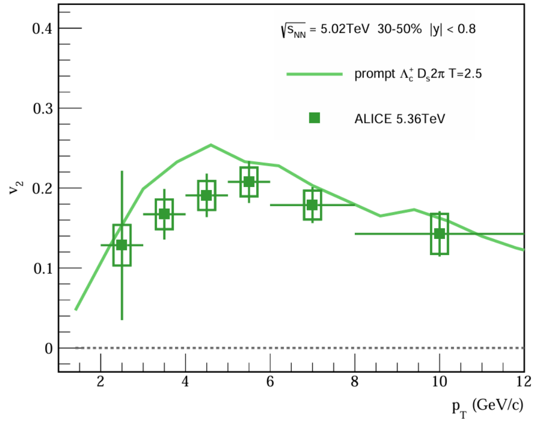
Summary and Outlook

- An updated Langevin dynamic description with sequential coalescence plus fragmentation approach to successfully predict the elliptic flow of D^0 and D_s in 30-50% centrality Pb+Pb collisions.
- Although the hadronic re-scattering indeed contributes additional elliptic flow to D^0 , it can still not lead to the reversal of the v_2 hierarchy between D^0 and D_s.
- Sequential coalescence effect cause the v_2 of D_s mesons significant suppressed at $p_T \approx 2-5$ GeV/c, the reverse of such a v_2 hierarchy is observed.
- The elliptic flow of D_s provides compelling evidence of the sequential hadronization mechanism and supplies a unique opportunity to further constrain the hadronization processes of charm hadrons.

Thank you !

Model constraint by spectrum, particle ratios and v_2





Meson	M(GeV)	J^P	$\langle r \rangle_{T_c}$(fm)	B.R.
D^+	1.869	0^-(1S)	0.7	-
D^0	1.865	0^-(1S)	0.7	-
$D^{*0}(2007)$	2.007	1^-(1S)	0.77	100% $\to D^0$
$D^{*+}(2010)$	2.010	1^-(1S)	0.77	68% $\to D^0$
$D_0^*(2300)$	2.343	0^+(1P)	0.77	68% $\to D^0$
$D_1(2420)$	2.422	1^+(1P)	0.77	68% $\to D^0$
$D_1^0(2430)$	2.412	1^+(1P)	0.77	68% $\to D^0$
$D_2^*(2460)$	2.461	2^+(1P)	0.77	68% $\to D^0$
$D_0^0(2550)$	2.549	0^-(2S)	0.77	68% $\to D^0$
D_s^+	1.968	0^-(1S)	0.66	-
D_s^{*+}	2.112	1^-(1S)	0.72	100% $\to D_s^+$
$D_{s0}^{*\pm}(2317)$	2.318	0^+(1P)	0.72	100% $\to D_s^+$
$D_{s1}^{\pm}(2460)$	2.460	1^+(1P)	0.72	100% $\to D_s^+$
$D_{s1}^{\pm}(2536)$	2.535	1^+(1P)	0.72	79% $\to D^0$, 21% $\to D^+$
$D_{s2}^*(2573)$	2.569	2^+(1P)	0.72	34% $\to D^0$, 16% $\to D^+$, 50% $\to D_s^+$
$D_{s0}^+(2590)$	2.591	0^-(2S)	0.72	50% $\to D^+$, 50% $\to D_s^+$

Baryon	M (GeV)	J^P	$\langle\rho\rangle_{T_c}$ (fm)	$\langle\lambda\rangle_{T_c}$ (fm)	B.R.
Λ_c^+	2.286	$0(\frac{1}{2}^+)$(1S)	0.75	0.75	-
$\Lambda_c(2595)^+$	2.592	$0(\frac{1}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Lambda_c(2625)^+$	2.628	$0(\frac{3}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Lambda_c(2860)^+$	2.856	$0(\frac{3}{2}^+)$(1D)	0.8	0.8	50% $\to \Lambda_c^+$
$\Lambda_c(2880)^+$	2.881	$0(\frac{5}{2}^+)$(1D)	0.8	0.8	50% $\to \Lambda_c^+$
$\Lambda_c(2765)^+$	2.766	$0(\frac{1}{2}^+)$(2S)	0.8	0.8	100% $\to \Lambda_c^+$
$\Lambda_c(2940)^+$	2.939	$0(\frac{3}{2}^-)$(2P)	0.8	0.8	50% $\to \Lambda_c^+$
$\Sigma_c(2455)^{(++,+,0)}$	2.453	$1(\frac{1}{2}^+)$(1S)	0.75	0.75	100% $\to \Lambda_c^+$
$\Sigma_c(2520)^{(++,+,0)}$	2.518	$1(\frac{3}{2}^+)$(1S)	0.75	0.75	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	2.713	$1(\frac{1}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	2.799	$1(\frac{1}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	2.773	$1(\frac{3}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c(2800)^{(++,+,0)}$	2.800	$1(\frac{3}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	2.789	$1(\frac{5}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	3.041	$1(\frac{1}{2}^+)$(1D)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	3.040	$1(\frac{3}{2}^+)$(1D)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	3.043	$1(\frac{3}{2}^+)$(1D)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	3.038	$1(\frac{5}{2}^+)$(1D)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	3.023	$1(\frac{5}{2}^+)$(1D)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	3.013	$1(\frac{7}{2}^+)$(1D)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	2.901	$1(\frac{1}{2}^+)$(2S)	0.8	0.8	100% $\to \Lambda_c^+$
$\Sigma_c^{(++,+,0)}$	2.936	$1(\frac{3}{2}^+)$(2S)	0.8	0.8	100% $\to \Lambda_c^+$
$\Xi_c^{(+,0)}$	2.469	$\frac{1}{2}(\frac{1}{2}^+)$(1S)	0.75	0.75	-
$\Xi_c'^{(+,0)}$	2.578	$\frac{1}{2}(\frac{1}{2}^+)$(1S)	0.75	0.75	100% $\to \Xi_c$
$\Xi_c(2645)^{(+,0)}$	2.645	$\frac{1}{2}(\frac{3}{2}^+)$(1S)	0.75	0.75	100% $\to \Xi_c$
$\Xi_c(2790)^{(+,0)}$	2.792	$\frac{1}{2}(\frac{1}{2}^-)$(1P)	0.8	0.8	100% $\to \Xi_c$
$\Xi_c(2815)^{(+,0)}$	2.818	$\frac{1}{2}(\frac{3}{2}^-)$(1P)	0.8	0.8	100% $\to \Xi_c$
$\Xi_c(2923)^{(+,0)}$	2.923	$\frac{1}{2}(\frac{3}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Xi_c(2930)^{(+,0)}$	2.940	$\frac{1}{2}(\frac{5}{2}^-)$(1P)	0.8	0.8	100% $\to \Lambda_c^+$
$\Xi_c(2970)^{(+,0)}$	2.965	$\frac{1}{2}(\frac{3}{2}^-)$(1P)	0.8	0.8	50% $\to \Lambda_c^+$, 50% $\to \Xi_c$
Ω_c^0	2.695	$0(\frac{1}{2}^+)$(1S)	0.75	0.75	-
$\Omega_c(2770)^0$	2.765	$0(\frac{3}{2}^+)$(1S)	0.75	0.75	100% $\to \Omega_c^0$
$\Omega_c(3000)^0$	3.000	$0(\frac{1}{2}^-)$(1P)	0.8	0.8	100% $\to \Omega_c^0$
$\Omega_c(3050)^0$	3.050	$0(\frac{1}{2}^-)$(1P)	0.8	0.8	100% $\to \Omega_c^0$
$\Omega_c(3065)^0$	3.065	$0(\frac{3}{2}^-)$(1P)	0.8	0.8	100% $\to \Omega_c^0$
$\Omega_c(3090)^0$	3.090	$0(\frac{1}{2}^+)$(2S)	0.8	0.8	100% $\to \Omega_c^0$
$\Omega_c(3120)^0$	3.119	$0(\frac{3}{2}^+)$(2S)	0.8	0.8	100% $\to \Omega_c^0$

Enhancement of D_s/D^0 in the lower p_T might also be phenomenon for *sequential Coalescence*