Sequential Charm Hadronization: From Event-Shape Engineering to a Hadronization Chronometer

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China University of Geosciences (Wuhan)

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C3NT
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Outline

1. Introduction: The Puzzle
2. 2510.16299 PRL (2026): Sequential Hadronization
3. 2606.03552: Event-Shape Engineering Discrimination
4. 2605.21222: From O–O to Pb–Pb
5. Summary and Outlook

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Heavy Flavor as a Calibrated Probe of the QGP

- Charm/bottom quarks produced in early hard scatterings ⇒ yields are fixed before QGP formation.
- They traverse the medium, lose energy, diffuse momentum, and partially thermalize.
- Final spectra and azimuthal anisotropies encode:
  - transport history in the deconfined phase,
  - hadronization mechanism near the QCD crossover.
- At low–intermediate p_T: **coalescence** with thermal light/strange quarks dominates.

A question to begin with

Can we distinguish a temperature-ordered **sequential** hadronization mechanism from the conventional **simultaneous** baseline using flow observables?

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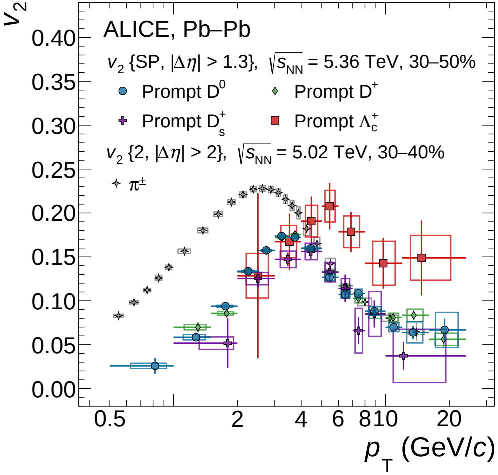
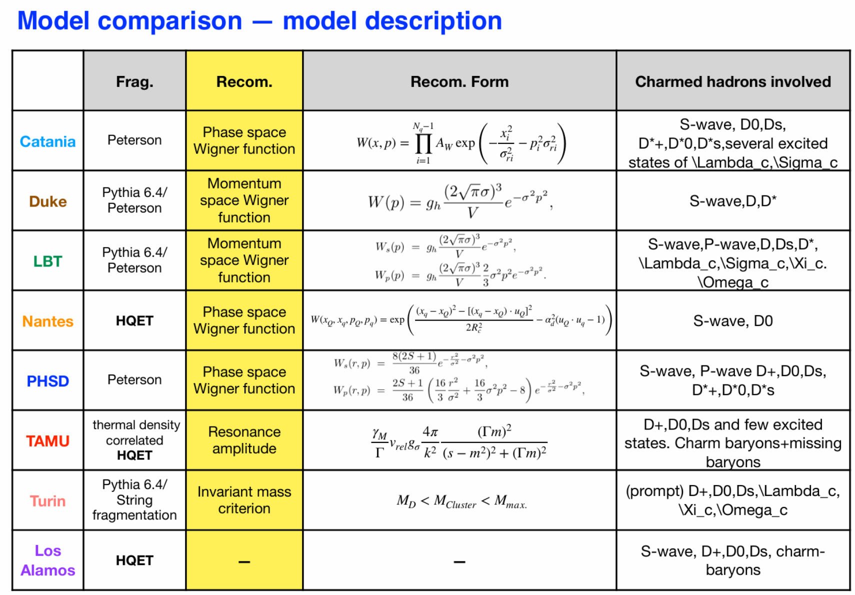
The v_2 Puzzle: $v_2(D^0) > v_2(D_s^+)$

- ALICE (Pb–Pb, $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV): arXiv:2603.18966
    - Mid-p_T (2–5 GeV/c): $v_2(D^0) > v_2(D_s^+)$
- **Almost all simultaneous models** predict the **opposite**:
    - $v_2(D_s^+) > v_2(D^0)$ due to coalescence kinematics,
    - strange-quark thermal distribution and larger fragmentation fraction to D^0
- Traditional assumption: *all* charmed hadrons form on a single common T_c hypersurface.



Model comparison



Model comparison — model description

	Frag.	Recom.	Recom. Form	Charmed hadrons involved
Catania	Peterson	Phase space Wigner function	$W(x,p) = \prod_{i=1}^{N_q-1} A_W \exp\left(-\frac{x_i^2}{\sigma_{ri}^2} - p_i^2\sigma_{ri}^2\right)$	S-wave, D0,Ds, D*+,D*0,D*s,several excited states of \Lambda_c,\Sigma_c
Duke	Pythia 6.4/ Peterson	Momentum space Wigner function	$W(p) = g_h \frac{(2\sqrt{\pi}\sigma)^3}{V} e^{-\sigma^2 p^2},$	S-wave,D,D*
LBT	Pythia 6.4/ Peterson	Momentum space Wigner function	$W_s(p) = g_h \frac{(2\sqrt{\pi}\sigma)^3}{V} e^{-\sigma^2 p^2},$ $W_p(p) = g_h \frac{(2\sqrt{\pi}\sigma)^3}{V} \frac{2}{3}\sigma^2 p^2 e^{-\sigma^2 p^2}.$	S-wave,P-wave,D,Ds,D*, \Lambda_c,\Sigma_c,\Xi_c. \Omega_c
Nantes	**HQET**	Phase space Wigner function	$W(x_Q, x_q, p_Q, p_q) = \exp\left(\frac{(x_q - x_Q)^2 - [(x_q - x_Q)\cdot u_Q]^2}{2R_c^2} - \alpha_d^2(u_Q \cdot u_q - 1)\right)$	S-wave, D0
PHSD	Peterson	Phase space Wigner function	$W_s(r,p) = \frac{8(2S+1)}{36} e^{-\frac{r^2}{\sigma^2} - \sigma^2 p^2},$ $W_p(r,p) = \frac{2S+1}{36}\left(\frac{16}{3}\frac{r^2}{\sigma^2} + \frac{16}{3}\sigma^2 p^2 - 8\right) e^{-\frac{r^2}{\sigma^2} - \sigma^2 p^2},$	S-wave, P-wave D+,D0,Ds, D*+,D*0,D*s
TAMU	thermal density correlated **HQET**	Resonance amplitude	$\frac{\gamma_M}{\Gamma} v_{rel} g_\sigma \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s - m^2)^2 + (\Gamma m)^2}$	D+,D0,Ds and few excited states. Charm baryons+missing baryons
Turin	Pythia 6.4/ String fragmentation	Invariant mass criterion	$M_D < M_{Cluster} < M_{max.}$	(prompt) D+,D0,Ds,\Lambda_c, \Xi_c,\Omega_c
Los Alamos	**HQET**	—	—	S-wave, D+,D0,Ds, charm-baryons

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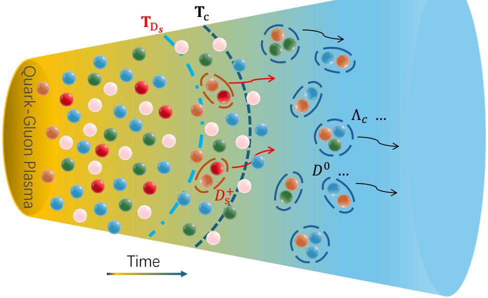
The Central Idea: Sequential Hadronization

- Inspired by quarkonium sequential formation/dissociation:
  - different binding energies ⇒ different formation temperatures
- From Dirac eq. + lattice-QCD potential:
  - $T_{D_s} \simeq 1.2\, T_c$
  - $T_{D^0} \simeq T_c$
- D_s^+ **forms earlier;** D^0 **forms later**
  - a late-stage window $1.2\, T_c \to T_c$ exists



Three connected works: Proposed Evidence → ESE control → System-size scan

The SHELL Theoretical Framework

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- **Initial state:** FONLL momentum + MC-Glauber/TRENTo geometry (with ^{16}O α-clustering when needed) + nNNPDF3.0
- **Bulk medium:** (3+1)D viscous hydrodynamics (CLVisc)
- **Charm transport:** Langevin + Higher-Twist radiative energy loss
  - $2\pi T D_s \approx 2.1$–2.5 (lattice/Bayesian constrained) Xu-Fei Xue, WD etal PRC (2026)
- **Hadronization:** hybrid coalescence + fragmentation
  - Wigner functions from Dirac-eq. radii, $1S$–$2P$ states included
- **Hadronic phase:** Langevin rescattering until $T_{\mathrm{kin}} = 137$ MeV

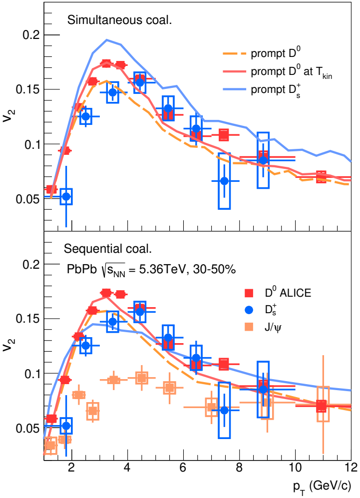
Crucial control

Both sequential and simultaneous scenarios use the **same** hydro background and transport parameters. Differences arise **only** at the hadronization stage.

2510.16299 Result I: The Reversed v_2 Hierarchy

- **Simultaneous baseline:**
  - $v_2(D_s^+) > v_2(D^0)$ (wrong order)
- **Sequential scenario:**
  - $v_2(D^0) > v_2(D_s^+)$ (correct order)
  - quantitative agreement with ALICE data
- Predicted full hierarchy:

$$v_2(D^0) > v_2(D_s^+) > v_2(J/\psi)$$



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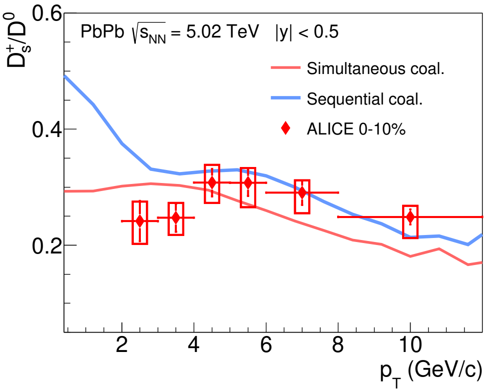
2510.16299 Result II: The D_s^+/D^0 Yield Ratio

- **Simultaneous:** low-p_T ratio saturates to a **plateau**
- **Sequential:** D_s^+ forms earlier ⇒ charm-quark number conservation enhances early channel
  - low-p_T ratio shows a **peak** (hill) instead of plateau
- An **independent** prediction that can be tested by future low-p_T measurements.



Why Event-Shape Engineering (ESE)?

- Inclusive measurements mix two effects:
  - initial geometry (eccentricity)
  - hadronization-time duration ($\Delta\tau$)

- Need a second "knob" to separate them, full picture of the sequential:
  - Knob 1: centrality (average lifetime and geometry)
  - Knob 2: **event-shape** q_2 (select different initial eccentricity at fixed centrality)

- ESE provides a **geometry-resolved** differential measurement.

Key question

Whether D^0 and D_s^+ respond **differently** to ESE? 2606.03552 work (黄雨杰，罗覃).

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ESE Methodology in the SHELL Framework

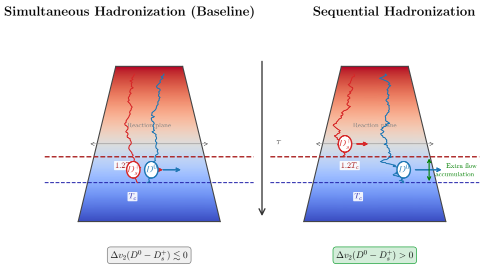
- Within fixed centrality (0–10%, 30–50%), sort events by

$$q_2 = \frac{|\vec{Q}_2|}{\sqrt{M}}$$

- Select Top 20% (large-q_2) and Bottom 20% (small-q_2)
- Run event-by-event hydro + Langevin + hadronization for each class
- Define **ESE response slope**:

$$v_2 = \chi\, q_2 + v_2^{(0)}$$

  - χ isolates susceptibility to geometric changes



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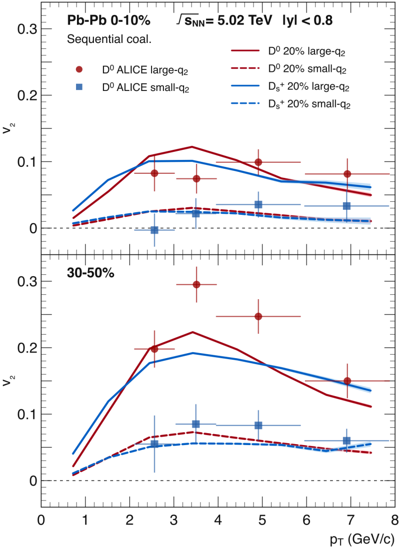
2606.03552 Result I: $\Delta v_2(D^0 - D_s^+)$ under ESE

- **Sequential** (upper):
  - $\Delta v_2 > 0$ at intermediate p_T
  - large-q_2 > small-q_2
  - 30–50% large-q_2 reaches ∼2–3%
- **Simultaneous** (lower):
  - $\Delta v_2 \approx 0$ or negative
  - no significant q_2 dependence
- The positive splitting is **not** a trivial centrality/ q_2 effect.



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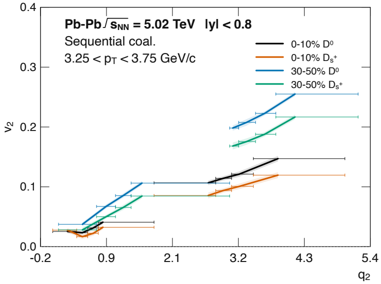
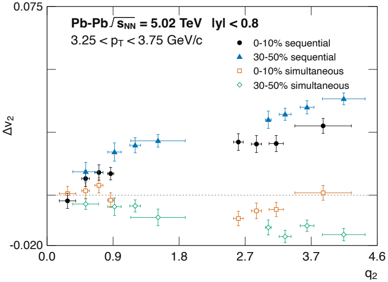
2606.03552 Result II: Continuous q_2 and Response Slope χ

- v_2 vs q_2 (continuous bins):
  - D^0 rises more steeply than D_s^+
- Δv_2 vs q_2:
  - sequential: positive slope
  - simultaneous: flat or negative
- **Falsifiable prediction**:

$$\chi(D^0) > \chi(D_s^+) \quad \text{(sequential)}$$

$$\chi(D^0) \leq \chi(D_s^+) \quad \text{(simultaneous)}$$





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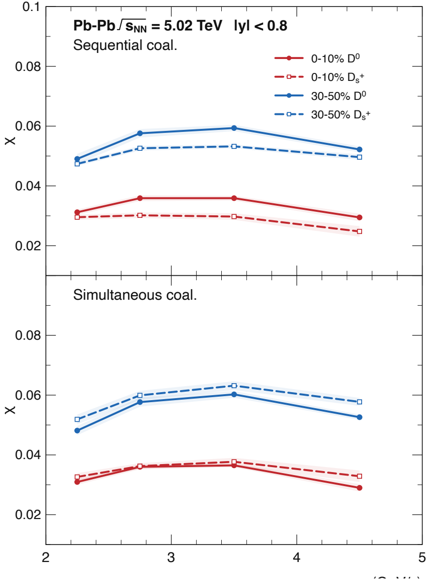
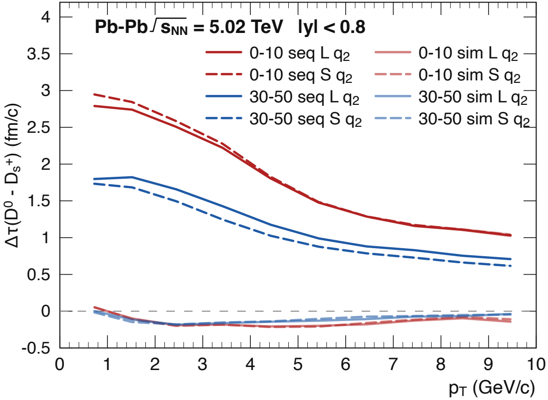


2606.03552 Result III: Hadronization Time Difference

- Sequential gives finite $\Delta\tau = \langle\tau_{D^0}\rangle - \langle\tau_{D_s^+}\rangle > 0$
- Low-p_T: $\Delta\tau \sim$ 2–3 fm/c in Pb–Pb
- **Key finding:**
  - 0–10% has **larger** $\Delta\tau$ than 30–50%
  - But 0–10% has **smaller** flow splitting!
- Δv_2 is **not** a direct map of $\Delta\tau$; it probes the **dynamical response** of the medium during the window.

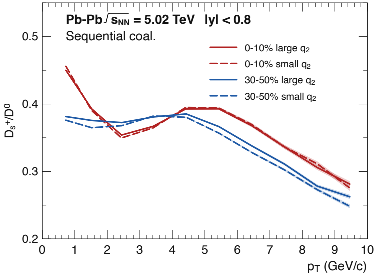


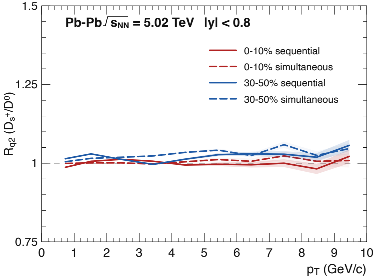
2606.03552 Result IV: Chemistry Control Test

- Is the flow splitting due to q_2-induced yield reorganization?
- Test 1: D_s^+/D^0 ratio
  - large-q_2 vs small-q_2 curves nearly identical
- Test 2: q_2 double ratio

$$R_{q_2} \equiv \frac{(D_s/D^0)_{\mathrm{large}}}{(D_s/D^0)_{\mathrm{small}}} \approx 1$$

- Conclusion: ESE probes **pure dynamics**; the splitting is not a chemical yield effect.





2606.03552 Stage Summary: A Fingerprint Table

Observable	Simultaneous	Sequential
Δv_2 sign	$\lesssim 0$	> 0
$\Delta v_2(q_2)$ slope	flat / negative	positive
$\chi(D^0) - \chi(D_s^+)$	≤ 0	> 0
$R_{q_2}(D_s/D^0)$	≈ 1	≈ 1
$\Delta\tau(D^0 - D_s^+)$	≈ 0	finite, positive

- 30–50% centrality is the optimal window (best balance of lifetime vs. eccentricity).
- **Next question:** Does the signal survive in small systems?

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From Small to Large Systems

- O–O collisions: QGP is smaller and shorter-lived
  - the $1.2T_c \to T_c$ window is severely compressed
- ALICE Run-3 preliminary data: $v_2(D^0) > v_2(D_s^+)$ **persists** in O–O, but with smaller magnitude.
- Core questions:
  1. Can sequential hadronization quantitatively describe O–O?
  2. How does system size regulate the splitting magnitude?
  3. Is the partonic-to-hadronic mapping universal across systems?

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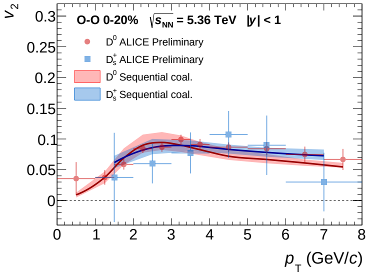
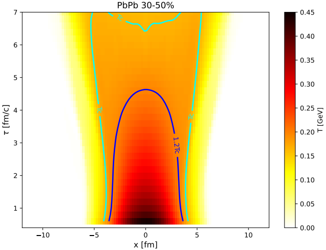
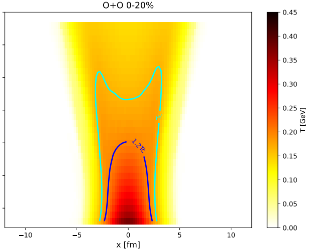
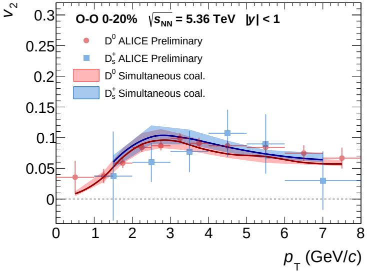
O–O Predictions vs. ALICE Preliminary Data

- **Sequential:** reproduces $v_2(D^0) > v_2(D_s^+)$ in O–O 0–20%
- **Simultaneous:** again fails, giving inverted ordering
- Theory uncertainty bands ($2\pi T\mathcal{D}_s = 2.1 \pm 0.4$, $\hat{q}_0 = 1.4 \pm 0.3$) cover data
- Peak Δv_2:
  - Pb–Pb 30–50% $\gg$ O–O 0–20%









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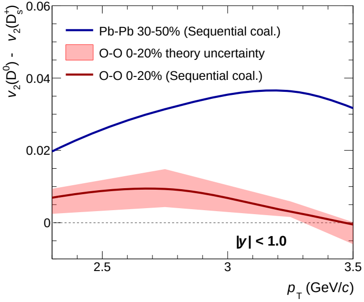
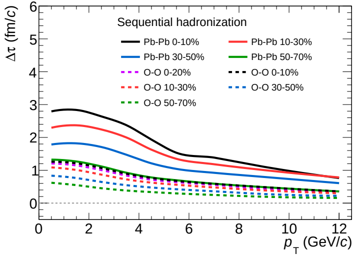
  - Pb–Pb 30–50% $\gg$ O–O 0–20%
- **system differences:** arise from late-stage life time ?





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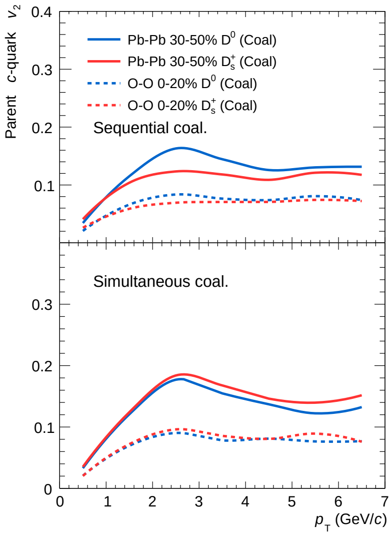
Microscopic Decomposition: Partonic Origin

- Partonic $v_{2,c}$ (coalescence channel):
  - sequential: $v_{2,c}(D^0) > v_{2,c}(D_s^+)$
  - simultaneous: $v_{2,c}(D_s^+) > v_{2,c}(D^0)$ (phase-space selection)
- Fragmentation: lower v_2, same in both scenarios
- Chemical mixing: D^0 has higher frag fraction $\Rightarrow$ further suppression
- **Hadronic rescattering as amplifier:**
  - D^0 scatters more strongly $\Rightarrow$ extra v_2 boost
  - Essential to restore correct ordering in O–O!



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A Universal Scaling: The Hadronization Chronometer

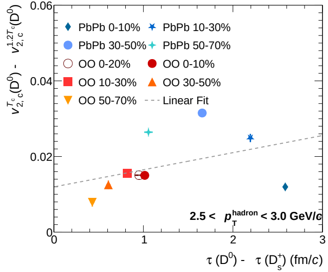
- Scan **9 LHC configurations** at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV
  - Pb–Pb: 0–10%, 10–30%, 30–50%, 50–70%
  - O–O: 0–10%, 10–30%, 30–50%, 50–70%, plus 0–20%
- Define partonic flow increment:

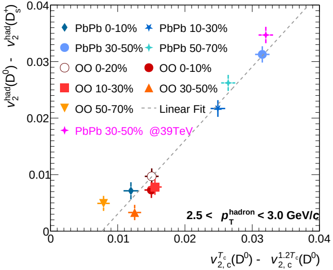
$$\Delta v_{2,c} = v_{2,c}^{D^0}(T_c) - v_{2,c}^{D^0}(1.2T_c)$$

- **All 9 points collapse onto one line:**

$$\Delta v_2^{\mathrm{had}} \propto \Delta v_{2,c}$$

- Physical meaning:
  - hadronic splitting is dictated **entirely** by the partonic anisotropy accumulated during the $1.2T_c \to T_c$ window
  - not by the global collision history prior to $1.2T_c$





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Summary: Three Steps:

Stage	Work	Core Question	Solution
1	**2510.16299**	Why $v_2(D^0) > v_2(D_s^+)$?	Sequential hadronization signal
2	**2606.03552**	How to further prove the distinguish?	χ sign + q_2 fingerprint
3	**2605.21222**	Is the signal universal?	Hadronization chronometer

- **space-time structure of heavy-flavor hadronization** as a new probe.

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Outlook

Experiment proposal

- Extract $\chi(D^0)$ and $\chi(D_s^+)$ from existing ALICE ESE data
- Test the sign prediction: $\chi(D^0) > \chi(D_s^+)$

Theory extensions

- $v_0 p_\mathrm{T}$ signal of sequential formation
- In-jet production of Λ_c to constrain in-medium fragmentation
- Test Multi-stage multi-messenger analysis to probe deformation nuclear $oxygen$

Long-term vision: use heavy-flavor flow to constrain nuclear structure.

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Thank you!

Questions & Discussion

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