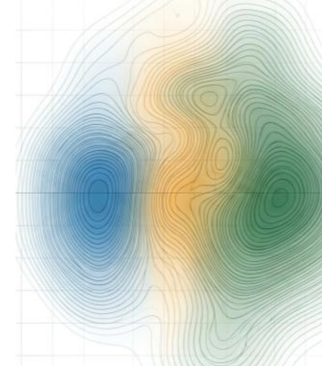

Entropy observables motivated by entanglement entropy functional forms

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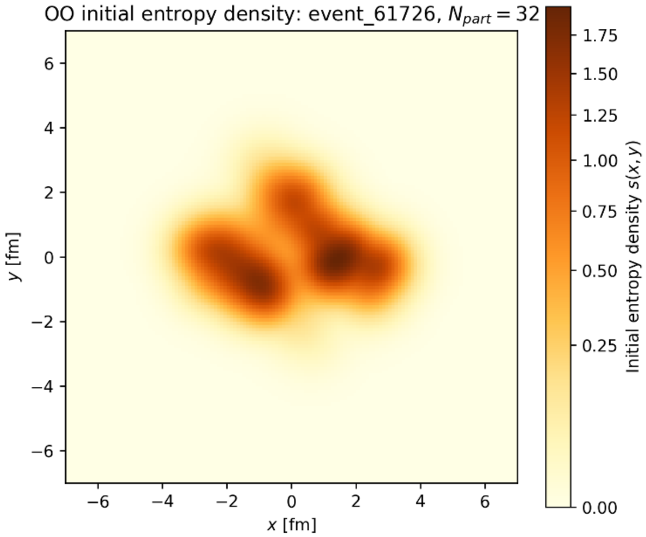
09 July 2026
Workshop “Mining for gluon saturation at the LHC and the future EIC“
GSI

Motivation – Does the final state remember the initial entropy footprint



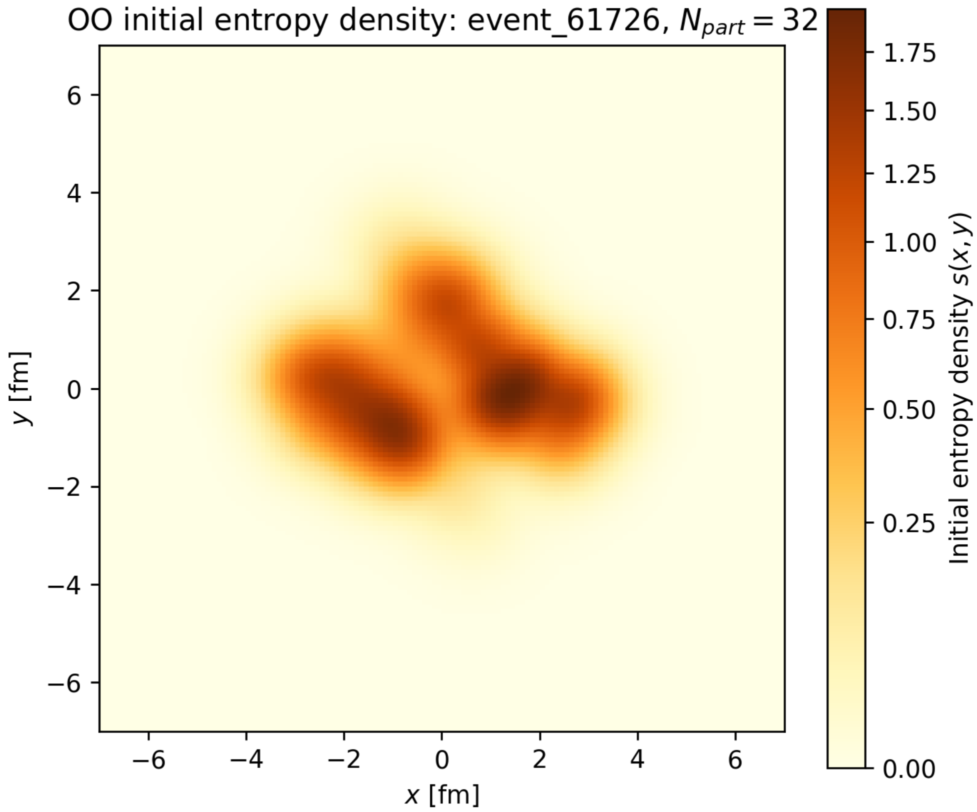
Can final observables remember the inintal entropy-density profile?

- Heavy-ion collisions start with fluctuationg initial geometry
- Standart observables do not capture the full profile
- Goal: define entropy-based initial-state classifiers

$$\boxed{s(x,y)} \rightarrow \boxed{S_q,\ S_{\text{profile}},\ \varepsilon_n} \rightarrow \boxed{v_n,\ \langle p_T \rangle,\ S_0}$$

What is the initial-state footprint?

$$s(x, y) \rightarrow \text{entropy observables} \rightarrow \text{final-state response}$$



Generated from TRENTo

From a footprint to entropy: how much information is in $s(x, y)$?

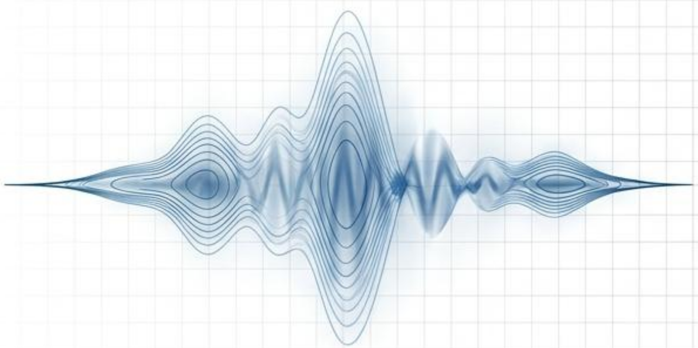
$$p_{ij} = \frac{s_{ij}}{\sum_{kl} s_{kl}}, \qquad S_{\text{profile}} = -\sum_{ij} p_{ij} \ln p_{ij}.$$

Input Normalised spacial distribution
Primary sensitivity Geometry and shape
How is the matter structured?

Why entropy? Connection to high-density gluon fields

The search for gluon saturation requires disentangling quantum signatures from classical macroscopic geometry.

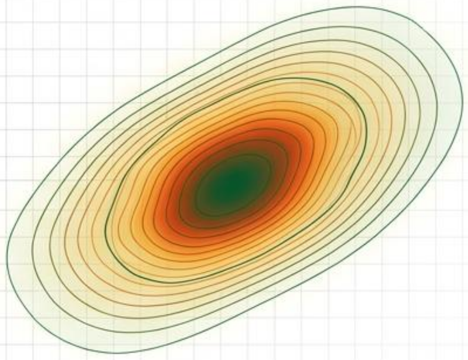
The Quantum Goal



At the LHC and EIC, the Kharzeev-Levin formalism relates the entanglement entropy of small-x partons to the accessible microstates.

$$S_{ent}(x) = \ln[xG(x)] \sim \ln N_{ch}$$

The Classical Challenge



Can simple entropy-like quantities built from initial conditions distinguish collision systems?

How much of the apparent entropy hierarchy is already explained by purely classical initial-state geometry and multiplicity?

Classical proxy– Shannon entropy

Both frameworks share a universal logarithmic scaling, but their microscopic contents differ completely.

Kharzeev-Levin Entanglement	TRENTo Profile Entropy
Domain: Pre-collision quantum wave function (Small-x).	**Domain:** Post-collision classical macroscopic geometry (Glasma).
Entropy Type: von Neumann Entropy (derived from reduced density matrix).	**Entropy Type:** Spatially-projected Wehrl Entropy (Shannon-type on a coarse-grained field).
Microstate: Partons (gluon distribution xG(x)).	**Microstate:** Effective spatial grid configurations (N_{eff}^{init}).
Meaning: Quantifies quantum information hidden in **unobserved** regions of the initial proton.	**Meaning:** Quantifies the informational complexity of classical density born from the decoherence of the quantum state.

The shared scaling behavior ($S \sim \ln N_{\mathrm{ch}}$) reveals a universal property of available phase space, bridging quantum uncertainty and classical spatial density.

Entropies

Two distinct proxies capture the total mass versus the structural spread of the initial state

The Bulk Proxy: Logarithmic Proxy

$$S_{ent}^{init} = \lambda_{ent} \ln(N_{eff}^{init} / N_0)$$

$$N_{eff}^{init} = \int s(x, y)dxdy$$

An effective measure of the initially populated transverse phase space. Counts how much total matter/entropy was deposited.

The Structural Proxy: Event-wise Profile Entropy

$$S_{profile} = -\sum p_{ij} \ln p_{ij}$$

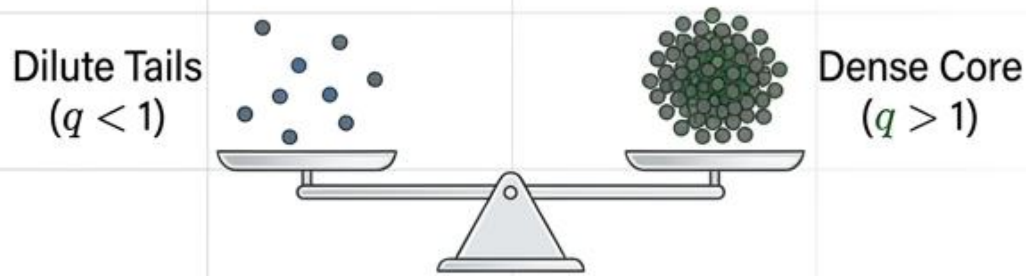
$$p_{ij} = \frac{s_{ij}}{\sum_{kl} s_{kl}}$$

Normalized spatial distribution across the transverse grid.

Sensitive to geometric fluctuations and spatial structure independent of overall magnitude. Measures how spread out the initial profile is.

Renyi entropy

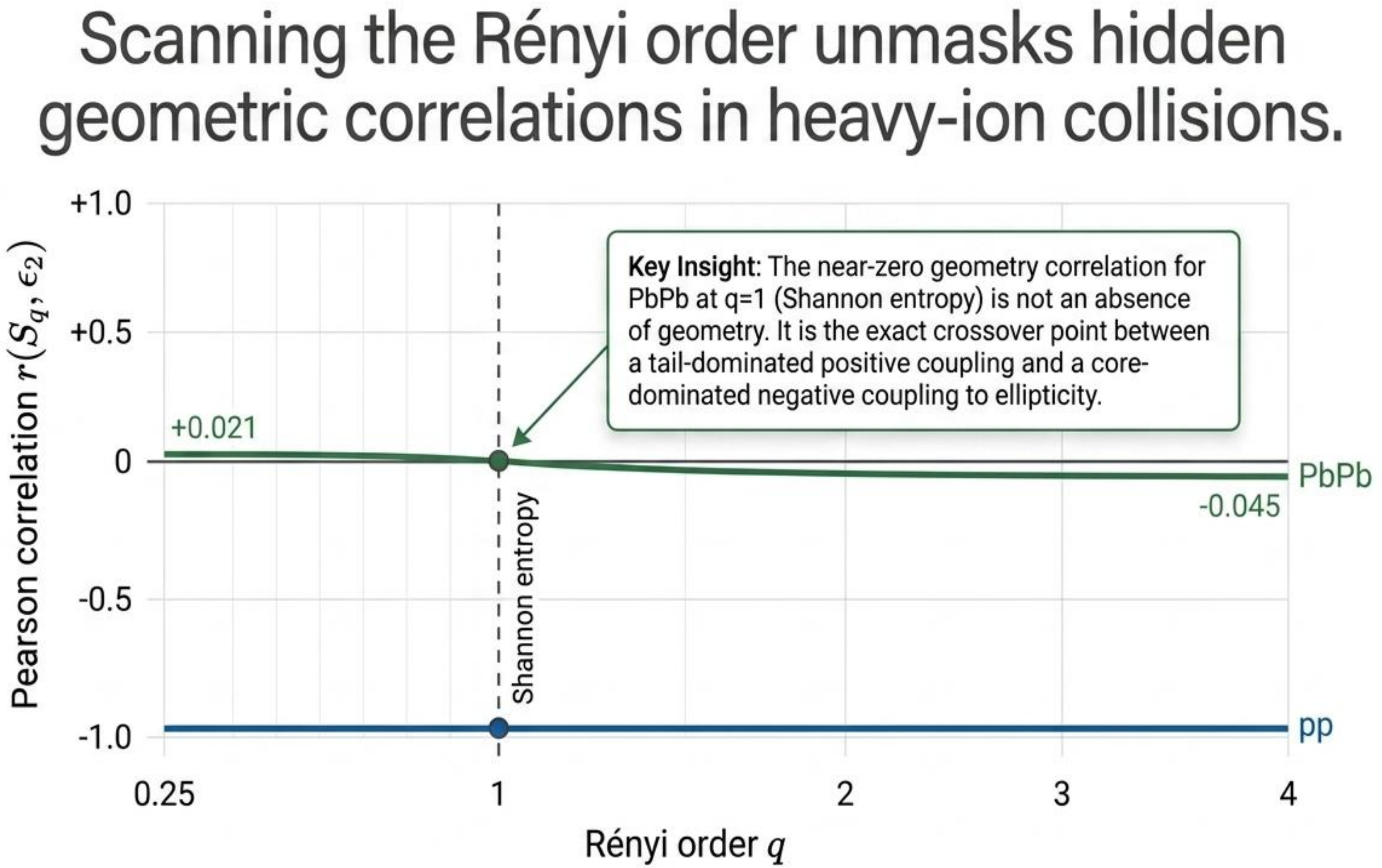
The Rényi Solution



$$S_q = \frac{1}{1-q} \ln \left(\sum p_i^q \right)$$

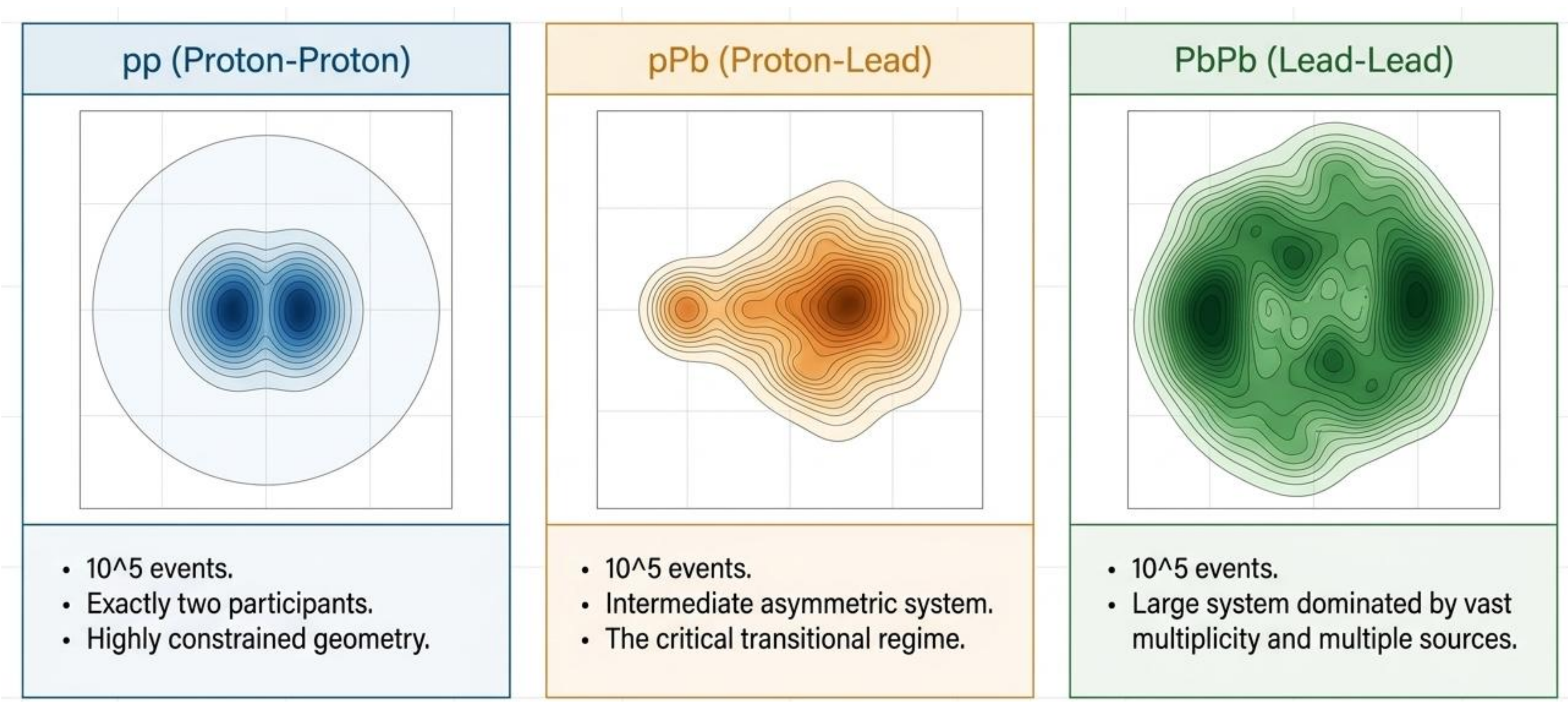
The Rényi order q changes the functional weighting of the entropy field. Lower orders up-weight the edges of the collision; higher orders up-weight the high-density center, revealing how spatial information reorganizes.

Geometric correlations

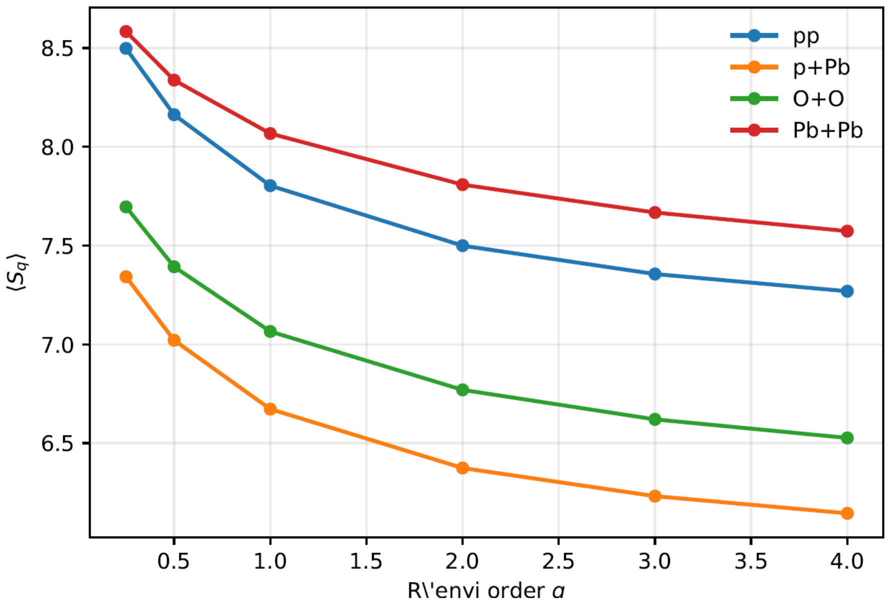


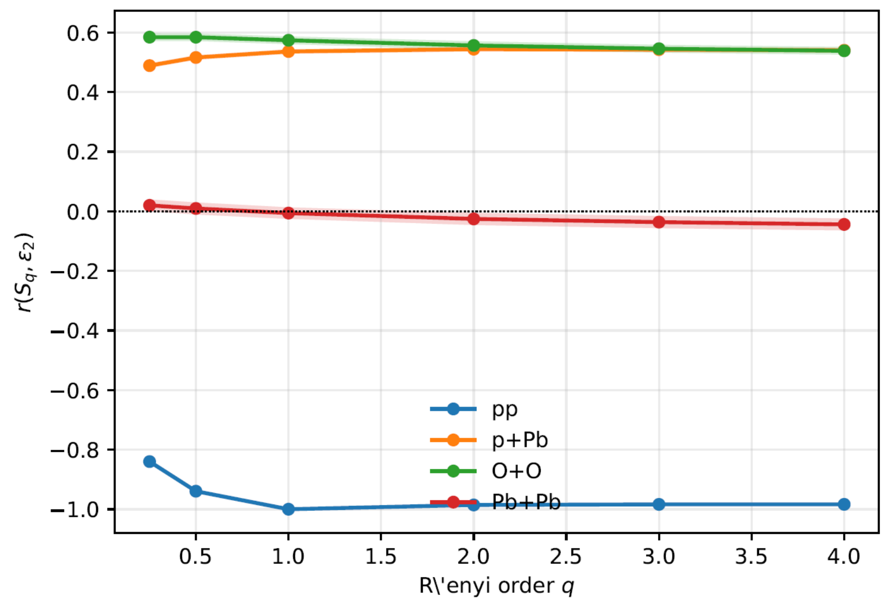
System studied

- pp pPb OO PbPb at LHC



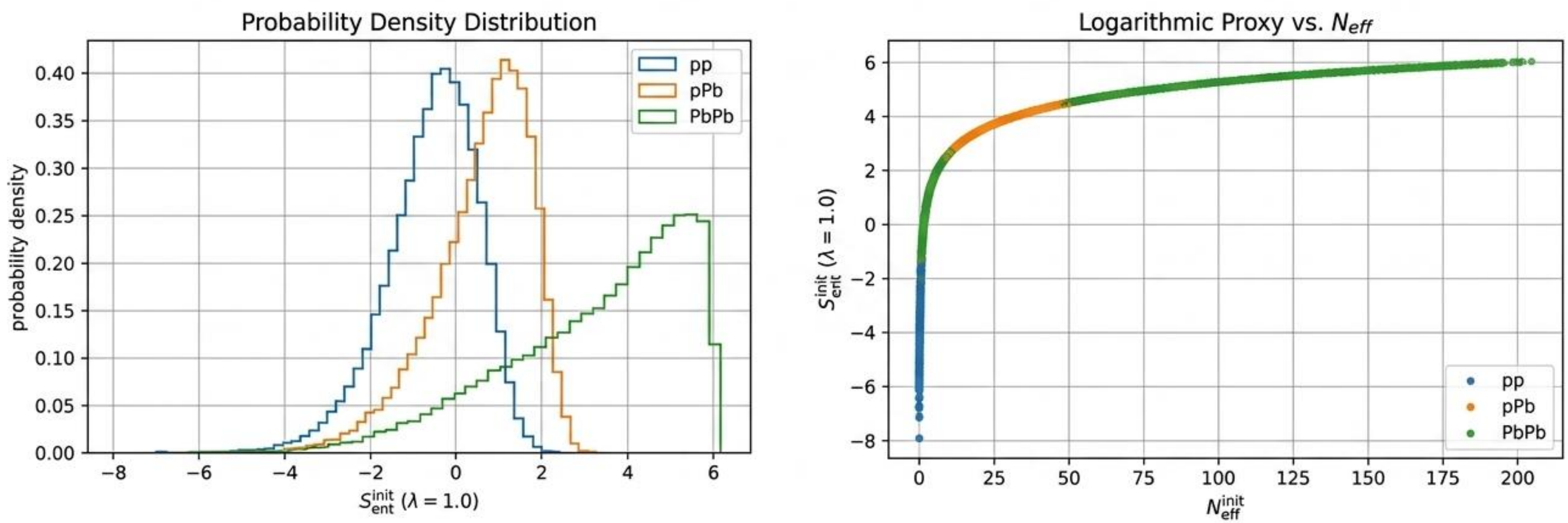
System size dependence





System Separation

The logarithmic proxy perfectly separates collision systems, but primarily functions as a phase-space counter.

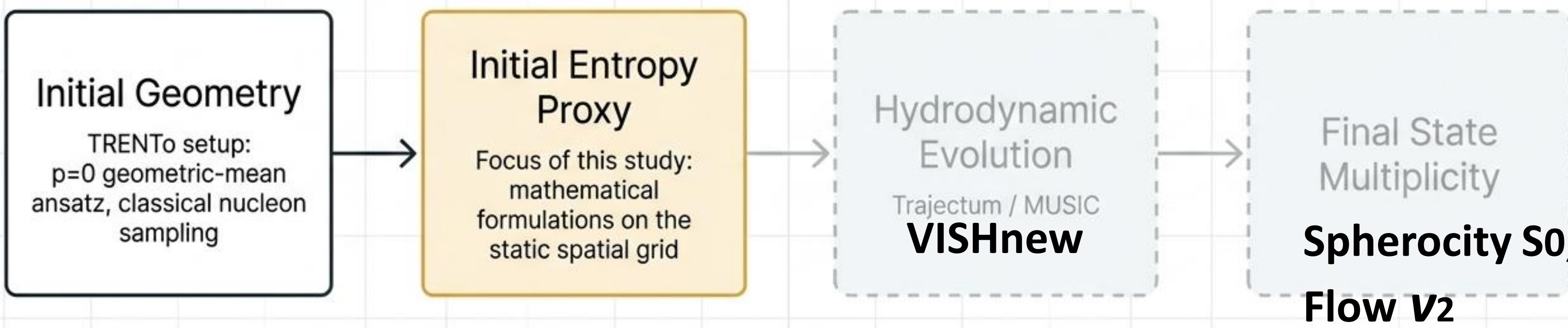


Key Takeaways

- **Strong System Separation**: Mean values cleanly stratify (pp $= -0.456$, pPb $= 0.687$, PbPb $= 3.286$). KS statistic resolves separation well beyond statistical limits.
- **The Multiplicity Mechanism**: $S_{\mathrm{ent}}^{\mathrm{init}}$ forms a **near-deterministic** curve with $N_{\mathrm{eff}}^{\mathrm{init}}$. Because larger nuclei deposit exponentially more matter, the logarithmic proxy scales directly with final expected multiplicity ($\ln N_{\mathrm{ch}}$).

From initial state to observables

TRENTo provides an idealized, purely classical laboratory to test spatial density proxies

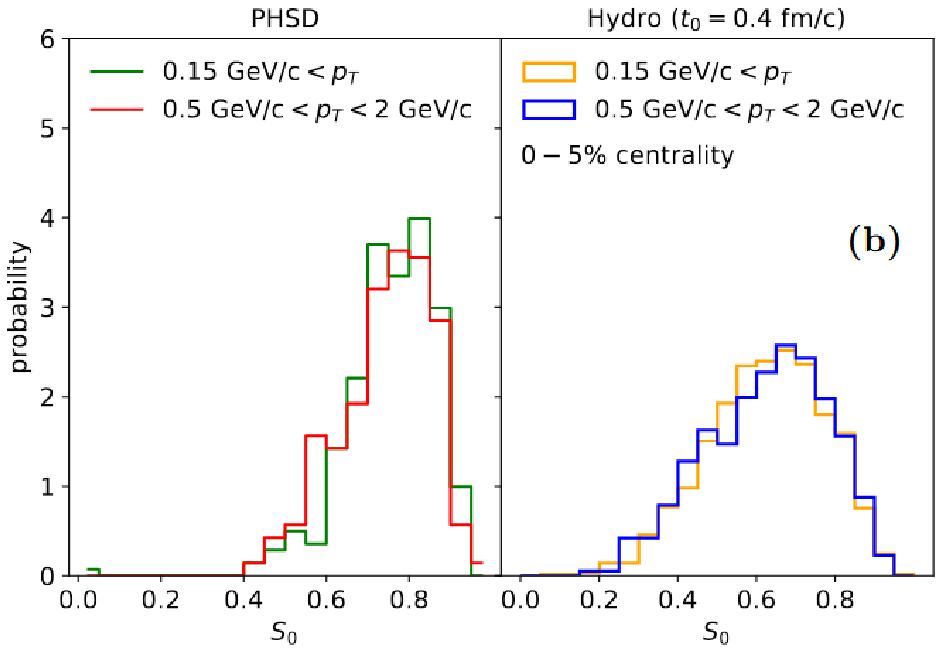


Core Insight: This study isolates the first step. By analyzing classical Shannon-type information measures on a deterministic classical density field s(x,y), we establish a rigorous baseline before committing to a full dynamical-evolution pipeline or making quantum mechanical claims.

Transverse Spherocity

$$S_0 \equiv \frac{\pi^2}{4} \min_{\hat{\mathbf{n}}_\mathbf{s}} \left(\frac{\sum_i |\mathbf{p_{Ti}} \times \hat{\mathbf{n}}_\mathbf{s}|}{\sum_i p_{Ti}} \right)^2$$

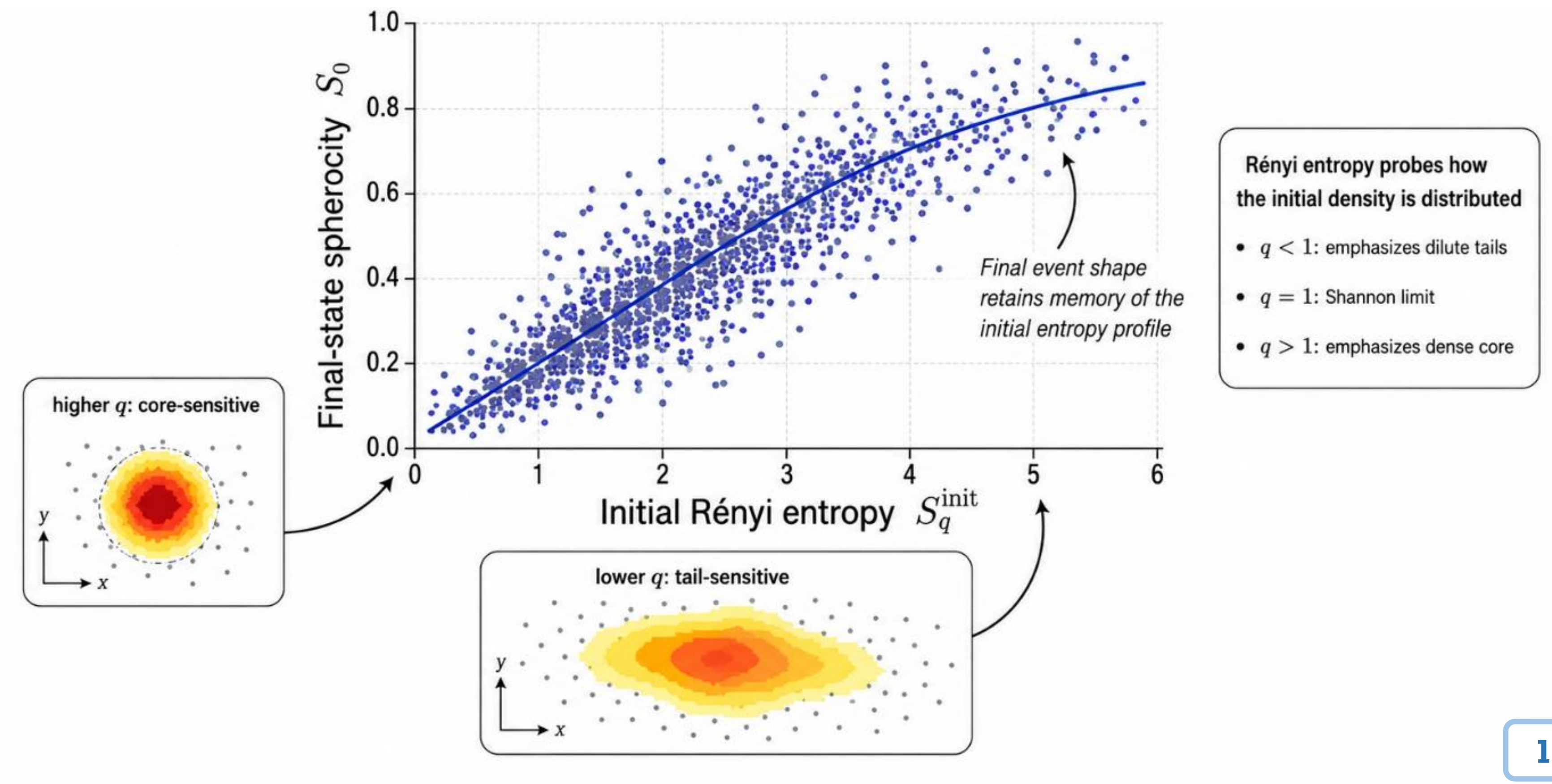
- $S_0 \rightarrow 0$: "jetty" events, where all transverse momentum vectors are (anti)parallel or their sum is dominated by a single track;
- $S_0 \rightarrow 1$: "isotropic" events, where the transverse momentum vectors are isotropically distributed.



L.Oliva et. al arxiv:2204.04194

Initial Renyi entropy leaves an imprint on final spherocity

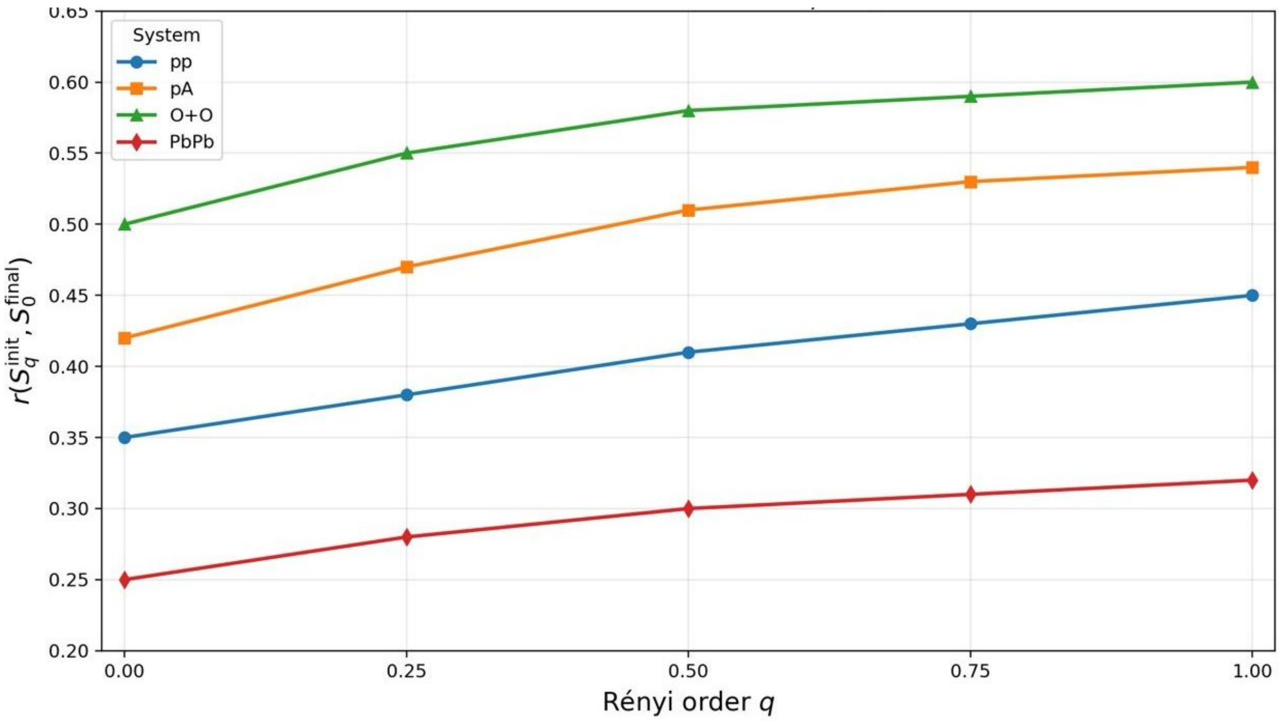
- At fixed Nch the correlation between Sq and spherocity S0 indicates sensitivity beyond trivial multiplicity



O+O and pA

- q-dependence of correlation initial entropy and final observable - r(Sq,S0) is visisible for O+O and almost flat for PbPb

preliminary



Conclusion and outlook

- Entropy observables compress the initial profile into event-wise classifiers
- Shannon entropies **$S_{profile}$, S_q** probes core-tail structure of the initial state
- OO and pA are especially interesting intermediate states
- Shannon entropies are useful to build classifiers to select interested events, as an example for QGP trigger

Thank you for your attention!

Where does new classifier can be applied – online data selection!

CNN based QGP trigger
https://arxiv.org/abs/2605.26280