

Collectivity from Quantum Diffraction

Resolving the Small-System Puzzle in Particle Physics

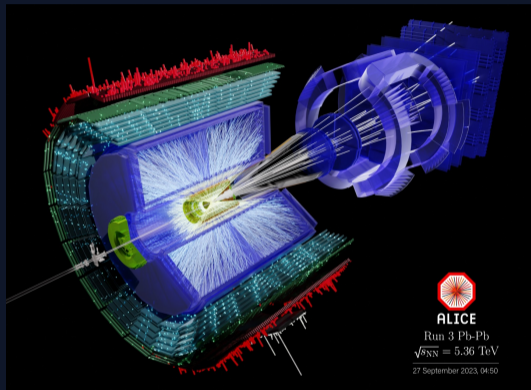
Erik Carrió

Universidad de Oviedo & ICTEA

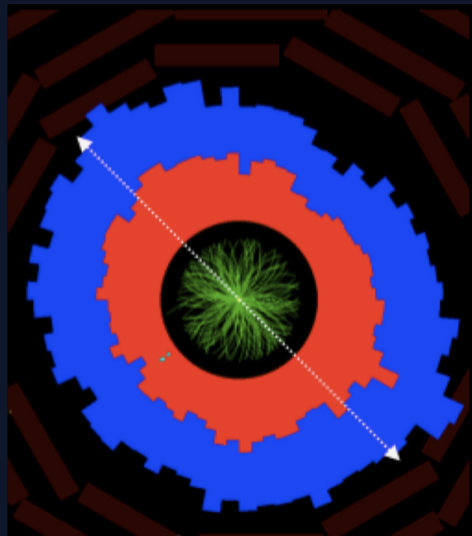
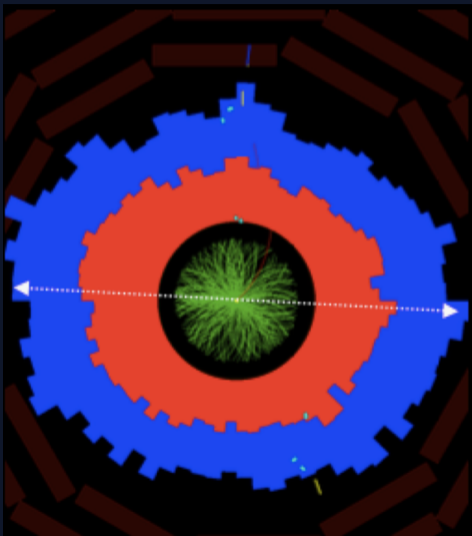


Smashing Large Ions

- ▶ Nuclei are accelerated to nearly the speed of light.
- ▶ High-energy colliders (LHC and RHIC) smash these heavy ions together.
- ▶ This creates a subatomic "fireball" of extreme energy density.
- ▶ Protons and neutrons melt, creating the **Quark-Gluon Plasma (QGP)**.



Preferred orientation



Flow Coefficients

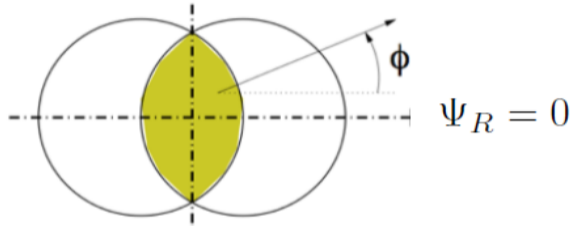
v_2



v_3

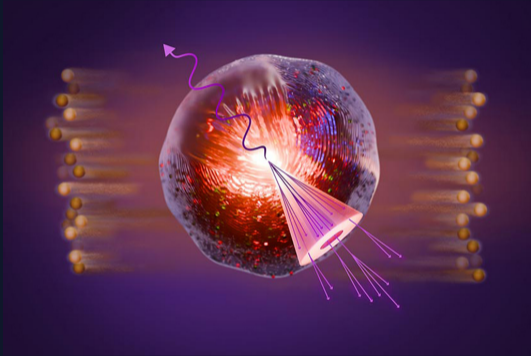


v_4

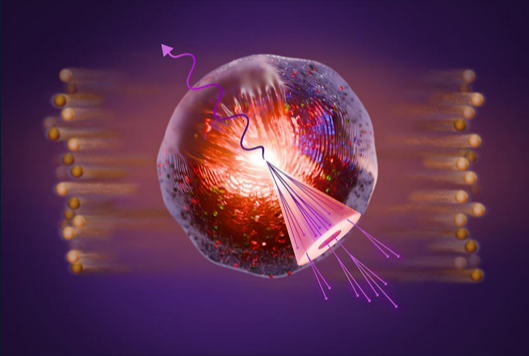


$$E \frac{dN}{d^3p} = \frac{1}{2\pi} \frac{dN}{p_t dp_t dy} \left[1 + \sum_{n \geq 1} 2v_n \cos(n(\phi - \psi_R)) \right]$$

| The Perfect Fluid State

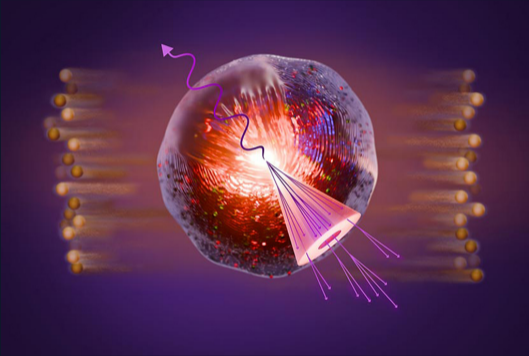


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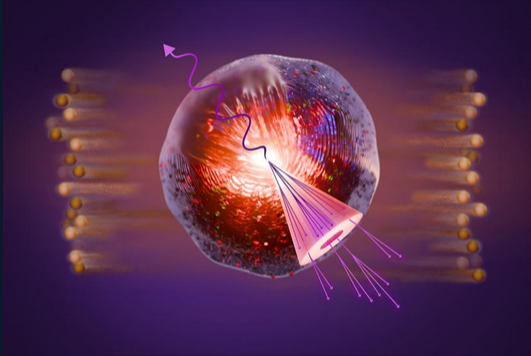
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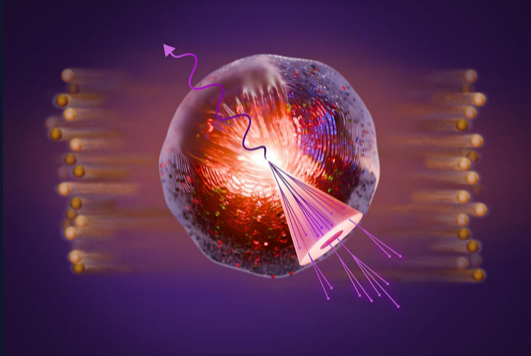
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- ▶ **Classical Hydrodynamics:** High pressure gradients expand outward faster along the short axis.

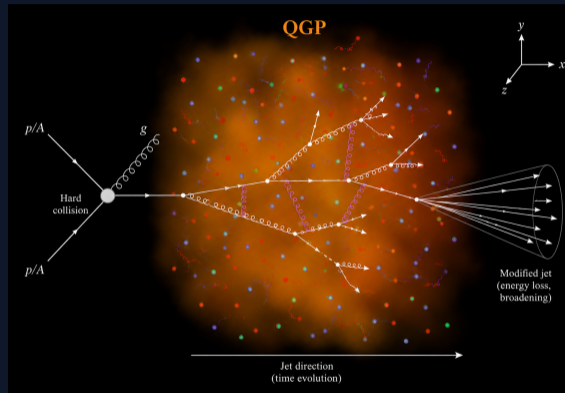
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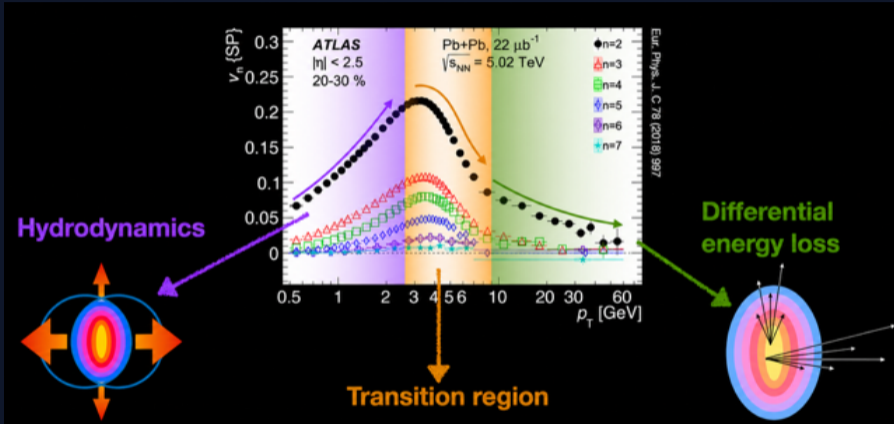
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- ▶ It possesses the **lowest viscosity-to-entropy density ratio** of all known substances in nature.
- ▶ **Classical Hydrodynamics:** High pressure gradients expand outward faster along the short axis.
- ▶ This converts spatial geometry into a final momentum orientation.

High Momentum Energy Loss Selection Bias

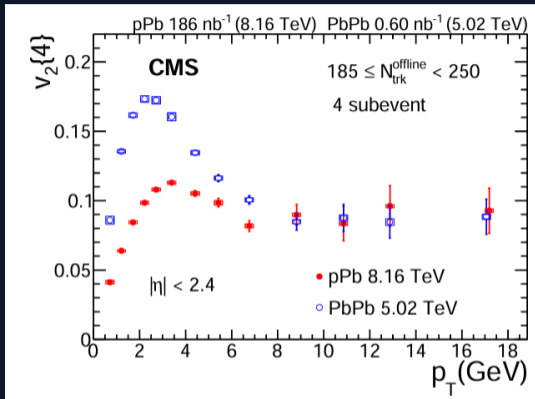
- ▶ Energetic particles ("jets") are produced in the initial hard collision.
- ▶ As they escape, they interact with the dense background medium.
- ▶ Particles traveling along the long axis lose significantly more energy.
- ▶ This **selection bias** means the surviving high-energy particles align with the short axis.



The v_2 Landscape: Hydro to pQCD

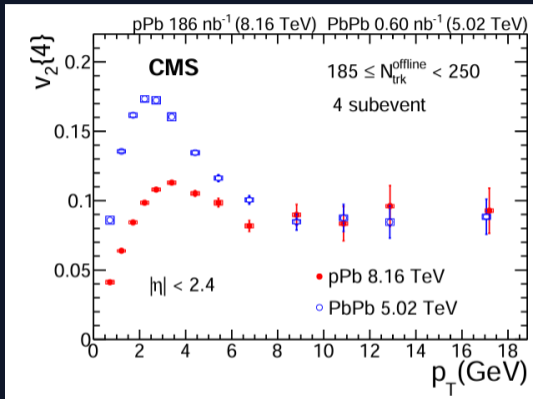


The Puzzle of Small Collision Systems



The Small-System Puzzle

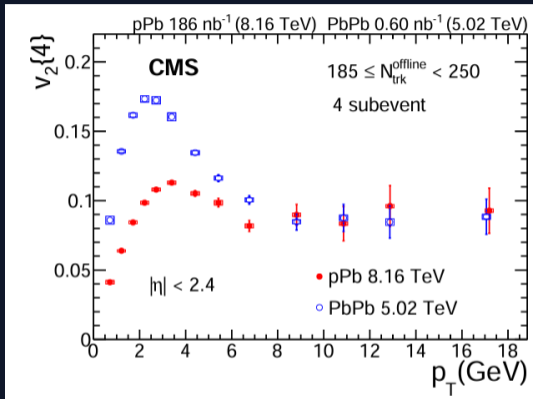
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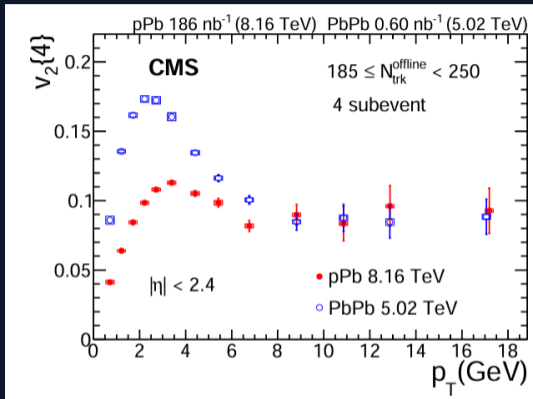
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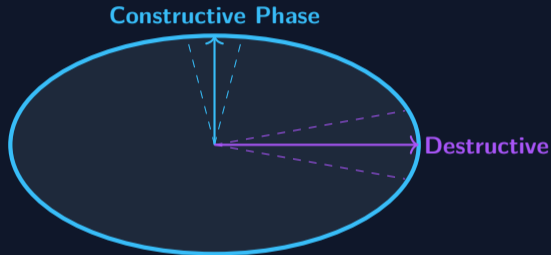


- ▶ **The Observation:** Strong collective alignment signatures are still seen in tiny proton-lead and proton-proton collisions.
- ▶ **The Conflict:** These systems are too small, dilute, and brief to support fluid behavior or significant jet energy loss.
- ▶ **The Core Question:** How can preferred spatial directions look identical in tiny droplets without standard energy loss?

The Small-System Puzzle

The Mechanism: Geometry + Quantum Mechanics

- ▶ We propose a new model requiring no energy loss.
- ▶ Energetic particles travel through the finite medium as quantum wave packets.
- ▶ The wave packets explore all trajectories simultaneously (**Sum-over-paths**).
- ▶ The interaction between the medium's spatial shape and wave interference generates a natural diffraction pattern.



Methodology: Analytical vs. Exact Solutions

1. Kirchhoff / SPA Approach

- ▶ **Limit:** High-momentum ($kR \gg 1$).
- ▶ **Logic:** Stationary Phase Approximation (SPA) at the boundary.
- ▶ **Result:** An analytical law for v_2 based on local curvature κ .

$$v_2 \sim \frac{V(2 - e^2)e^2}{4(1 - e^2)k_o + 2e^4V}$$

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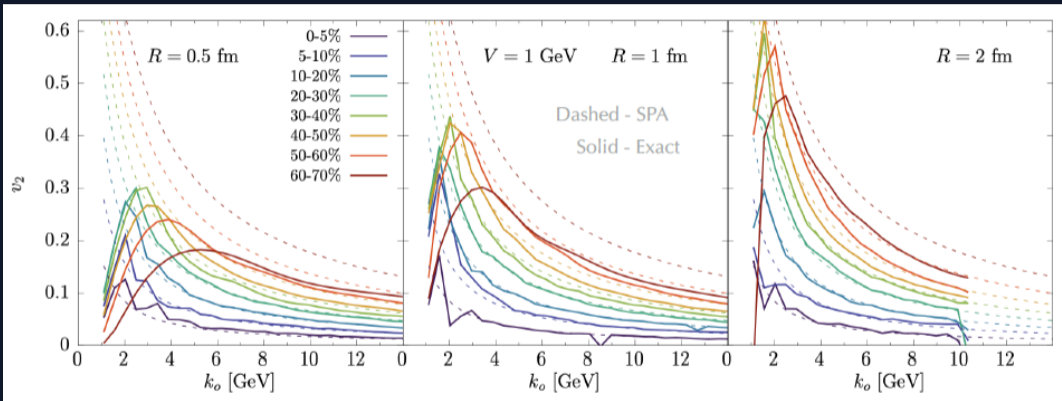
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2. Mathieu Function Solution

- ▶ **Limit:** Valid for all wavelengths.
- ▶ **Logic:** Schrödinger equation solved by separation of variables in elliptic coordinates.
- ▶ **Result:** Validates the SPA result and extends to arbitrarily low p_T .

Universal Anisotropy Across Scale Ranges



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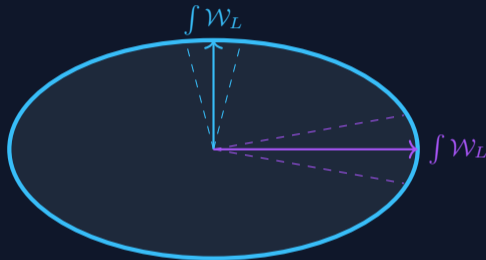
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Thank you for your attention!