Multiplicity-Momentum Correlations in Relativistic Heavy Ion Collisions

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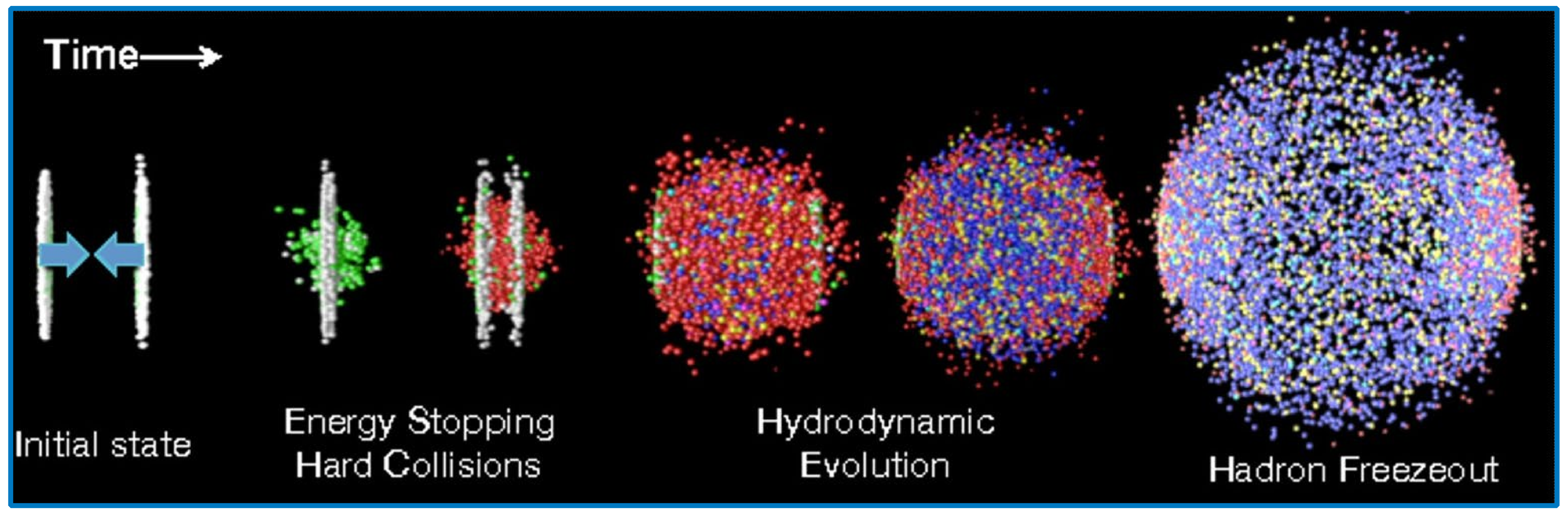
Abstract

The observation of anisotropic collective flow in the small systems produced by proton-proton and proton-nucleus collisions at the Relativistic Heavy-Ion Collider and the Large Hadron Collider has lead theorists to the radical hypothesis that hydrodynamics can occur without thermal equilibration. Viscous hydrodynamic flow has the effect of smoothing out fluctuations in particle momenta, but conversely particle "jets" have the effect of simultaneously increasing particle number and transverse momentum while inducing fluctuations. We study an observable that indicates the covariance of multiplicity and momentum of particles produced in nuclear collisions to discover if it can distinguish jet versus hydrodynamic dynamics. We use simulated events of proton-proton and nucleus-nucleus collisions to compare the behavior of our observable for collision events with high and low multiplicities.

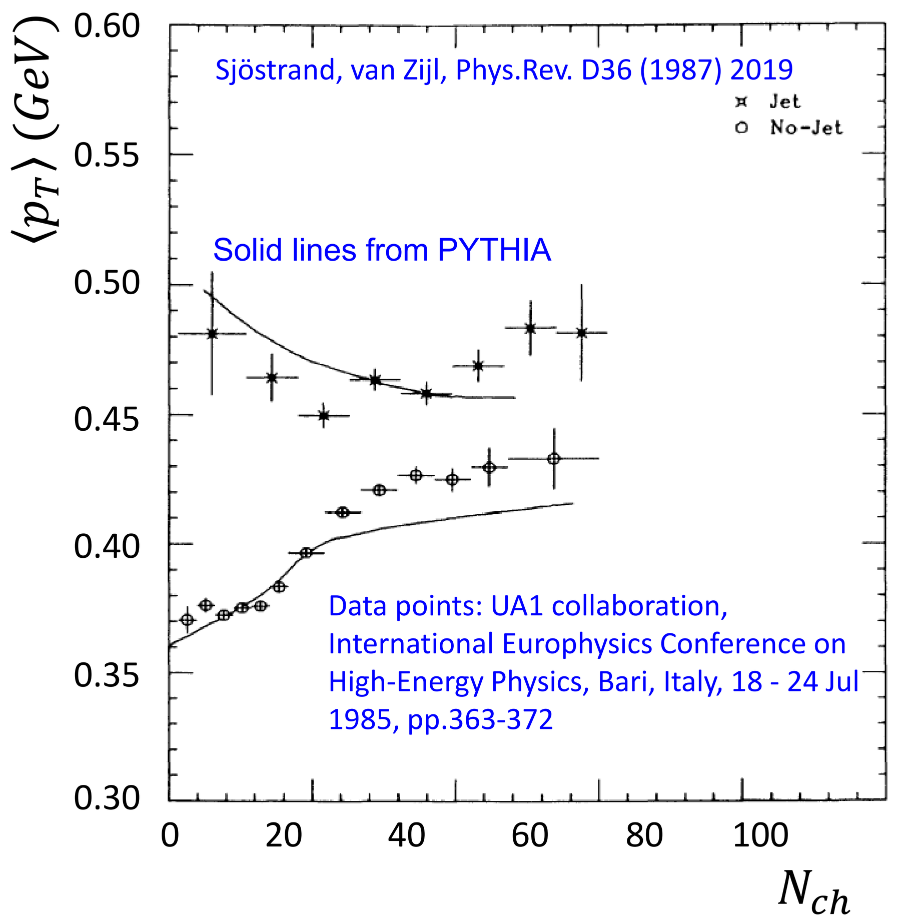
Heavy Ion Collisions



Acknowledgements

This work was supported in part by the U.S. NSF grant PHY- 1913005.

Motivation and Observable



Expectation: proton-proton collisions display positive correlation with particle number and momentum

PYTHIA

- events without jets indicate positive correlation with multiplicity.
- events with jets indicate negative correlation with multiplicity.

Multiplicity-Momentum Correlations

$$\langle N\rangle^2\mathcal{D} = \underbrace{\langle P_T N\rangle - \langle P_T\rangle\langle N\rangle}_{\text{Covariance}} - \langle p_T\rangle\underbrace{\left(\langle N^2\rangle - \langle N\rangle^2\right)}_{\text{Particle Variance}}$$

$$\langle P_T\rangle = \langle \textstyle\sum_i^N p_{Ti}\rangle \qquad \langle p_T\rangle = \langle P_T\rangle/\langle N\rangle$$

- **In equilibrium $\mathcal{D} = 0$:** Thermal production of particles yields $Var(N) = \langle N\rangle$ and $Cov(P_T, N) = \langle p_T\rangle\langle N\rangle$
- **Out of equilibrium bulk → positive $\mathcal{D}$**
- **Jets add particles with higher momentum than the equilibrium value.**
- If events are dominated by jets then high multiplicity comes with high total transverse momentum then → positive $\mathcal{D}$
- If events come with jet particles that are a small fraction of the total multiplicity but significantly increase $\langle p_T\rangle$ then → negative $\mathcal{D}$

Out of Equilibrium Correlations

$$\mathcal{D} = \mathcal{D}_0 S + \mathcal{D}_{eq}(1 - S)$$

Initial value ($\mathcal{D}_0$) — Equilibrium value ($\mathcal{D}_{eq}$)

Survival Probability S: Indicates the system's level of equilibration.

$S = 1$ → no interaction
$S = 0$ → local equilibrium

Gavin, Moschelli, Zin, Phys. Rev. C95 (2017) no.6, 064901

See poster 313 by **Brendan Koch** about two-particle correlations and partial thermalization.

Gavin, Moschelli, and Zoulfekar Mazloum, *in preparation, C. Zin Ph.D. Thesis*

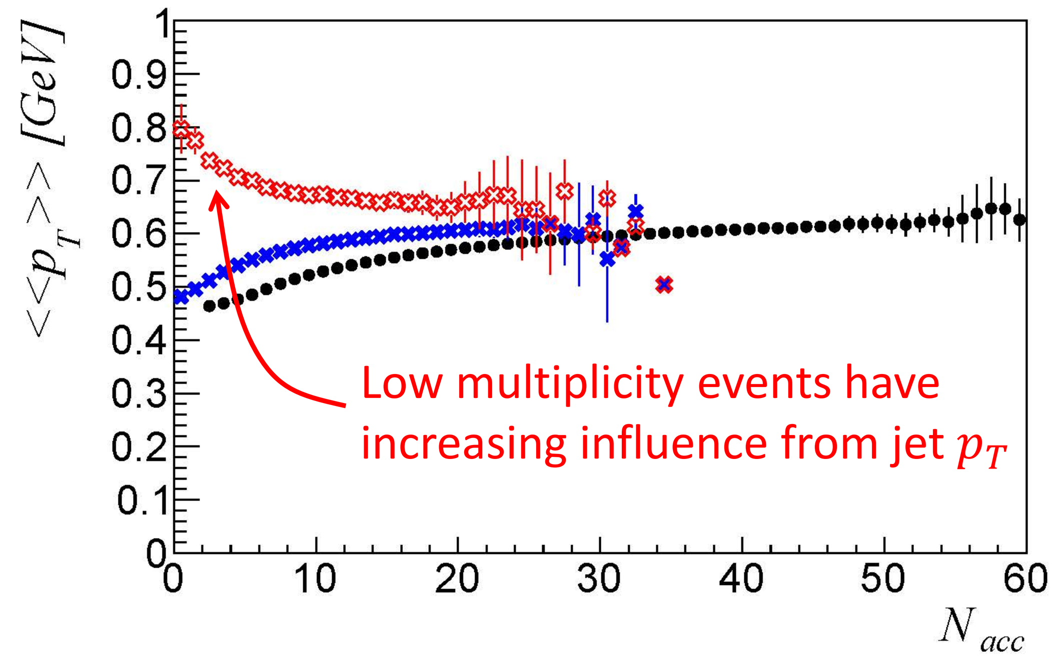
Consequential Behaviors

- $\mathcal{D} \sim 1/\langle N\rangle$ in equilibrium
- $\langle N\rangle\mathcal{D}$ follows the behaviors of S where $\langle N\rangle\mathcal{D}$ travels from the initial condition to the equilibrium condition

Multiplicity-Momentum Correlations in Proton-Proton Collisions

Negative correlation for jet events.

Positive correlation for inclusive events.



Black Circles: "min-bias"

- Centrality N_{acc} = particels in $|\eta| < 0.8$
- Calculation with particles in $|\eta| < 0.8$

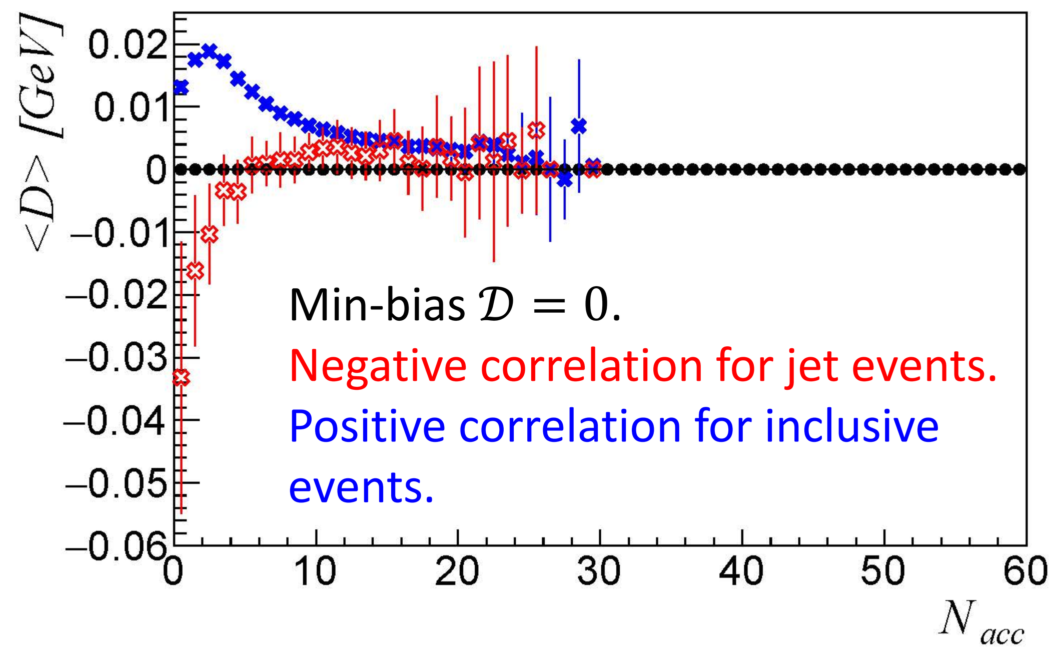
Blue Crosses:

- Centrality N_{acc} = particels in $0.5 < |\eta| < 0.8$
- Calculation with particles in $|\eta| < 0.5$
- Similar to STAR Phys. Rev. C 99 (2019) 4, 044918

PYTHIA 8.2 pp collisions

- $\sqrt{s} = 2760\ GeV$
- $25M$ min bias events
- $21M$ separated centrality events (blue crosses)
- 85486 jet events (red open crosses)
- $0.15 < p_T < 2\ GeV$
- Only charged hadrons

PYTHIA8.2, Comput. Phys.Commun. 191 (2015) 159

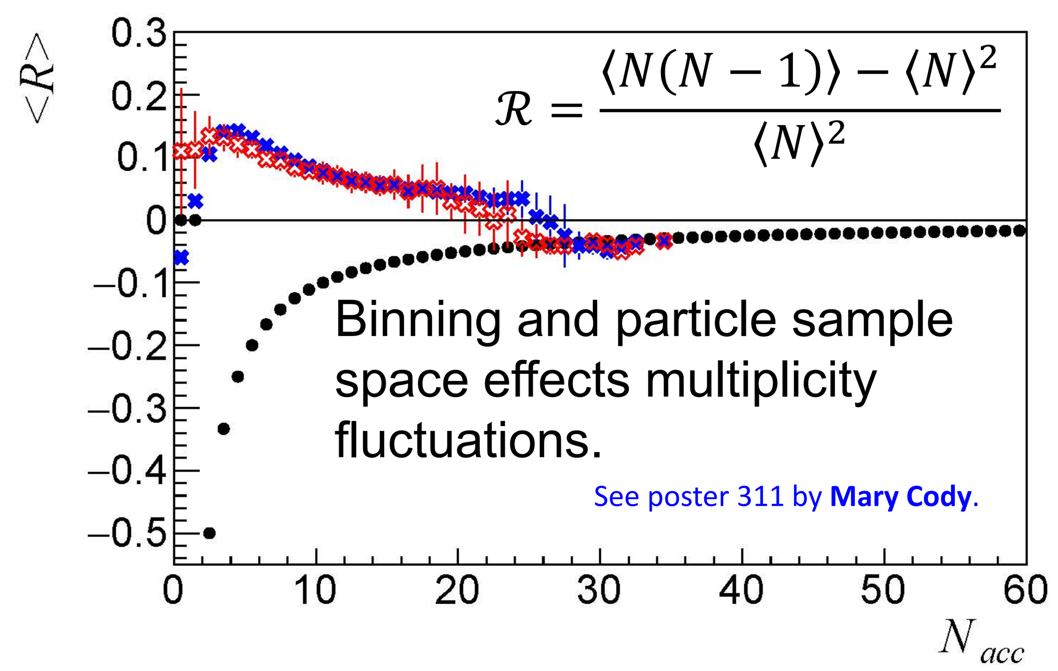


Open Red Crosses: "jet events"

- Centrality N_{acc} = particels in $0.5 < |\eta| < 0.8$
- Calculation with particles in $|\eta| < 0.5$
- Event tagged as a "jet event" if at least one particle from an identified jet is in the global acceptance.

Error Estimates: Sub-group method

- 30 groups of 1M events.
- Observables calculated in each group.
- Values are averaged over subgroups.
- Error bars are subgroup standard deviations.



Jet Definition

- Jet cone radius $R = 0.4$
- Require back-to-back jets.
  Tolerance $0.4\ rad$
- Total jet momentum $P_T > 5\ GeV$
- Leading particle $p_T > 8\ GeV$
- Sub-leading particle $p_T > 5\ GeV$
- Constituents $0 < p_T < 1\ GeV$