Exploring the QCD Phase Diagram at STAR: Proton Fluctuations in Azimuthal Partitions

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Abstract

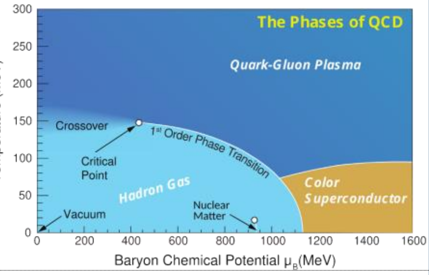
The Beam Energy Scan (BES) at RHIC was conducted primarily to search for an end to the cross-over regime in the QCD phase diagram. Meticulous measurements of higher moments of the net-proton distribution have shown hints of a non-monotonic trend in C_4/C_2 as a function of energy [1], culminating in the recently released BES-II measurement. However, the existence of a first-order phase transition necessitates the existence of a critical point, and its direct detection could help validate conclusions from the net-proton analysis. In this poster, we discuss a methodology for measuring proton clustering which is expected to occur in a first-order phase transition. Protons are counted in azimuthal partitions and the variance of these azimuthal multiplicity distributions is compared to the uncorrelated expectation to construct the novel $\Delta\sigma^2$ observable. A repulsive correlation, likely due to momentum conservation, is observed at all energies for both STAR data and the AMPT model. Under this repulsive background, however, are hints of a residual clustering signal in STAR data which increases with decreasing energy and is absent in AMPT.

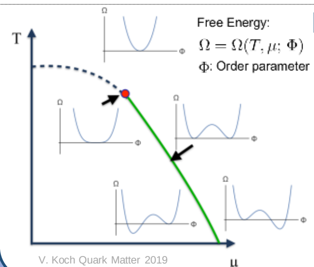
The Physics

QGP to Hadron Gas Phase Transition

QGP produced in heavy ion collisions transitions back to hadron gas as it expands and cools.

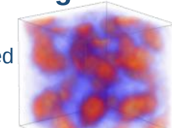
Low μ_B Crossover ✓
High μ_B First-Order ?
Between Critical Point





First-Order Clustering

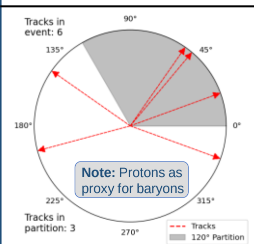
Local baryon density fluctuations are expected during first-order phase transition.



These baryon clusters in coordinate space should be translated to momentum space, though much of the clustering may be washed out [2].

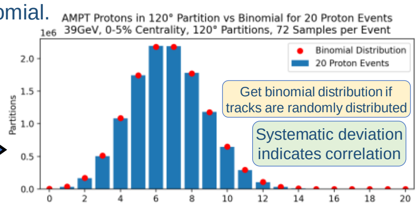
The Observable

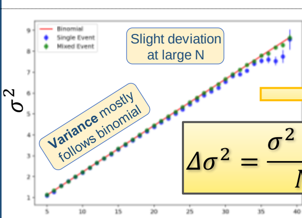
Look for Proton Clustering in Azimuthal Partitions



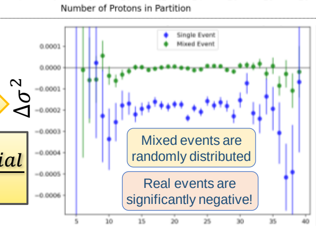
Divide each event into azimuthal partitions and count the number of protons within partition. Histogram over many events and compare to binomial.

Note: Corrections are made for contributions from elliptic flow and detector effects

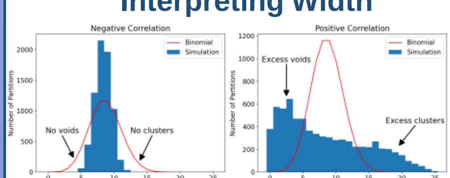




$$\Delta\sigma^2 = \frac{\sigma^2 - \sigma^2_{binomial}}{N(N-1)}$$



Interpreting Width



Positive $\Delta\sigma^2$ → Clustering
Negative $\Delta\sigma^2$ → Repulsion

Correlated protons produce both clusters and voids, resulting in a variance wider than the uncorrelated binomial expectation.

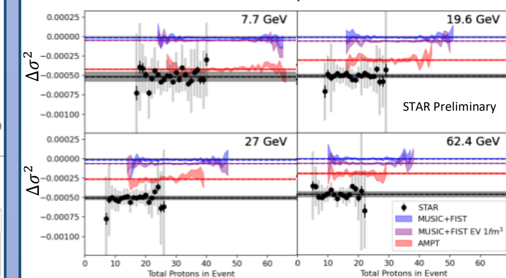
Anti-correlated protons tend to spread out, producing a relative lack of clusters and voids and resulting in a variance smaller than the uncorrelated binomial expectation.

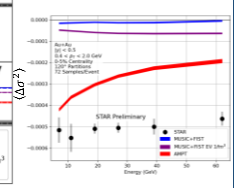
The Results

Repulsive Correlation at All Energies

Significant repulsion is observed at all energies for both STAR and AMPT [3]. No significant *N* dependence indicates that the observable's normalization is adequate and motivates averaging over *N*.

$$\Delta\sigma^2(N) \rightarrow \langle\Delta\sigma^2\rangle$$

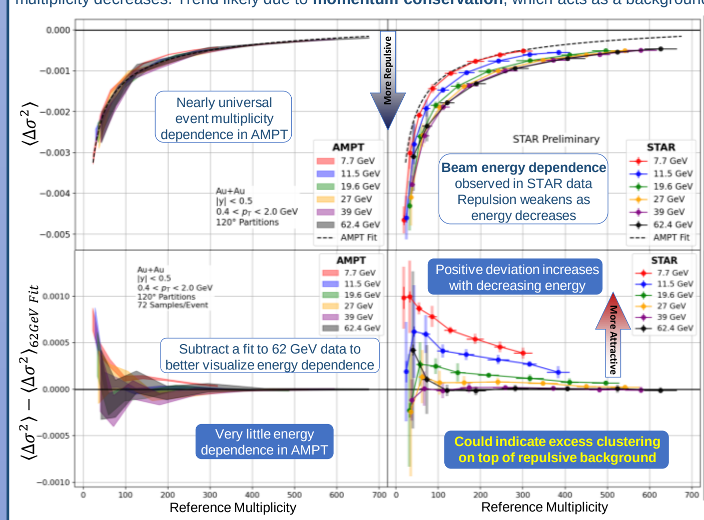




Note: MUSIC+FIST [4] model (blue) implements no momentum conservation, so does not see significant repulsion. An excluded volume effect (EV) is implemented (purple) which is expected to and observed to produce an effectively repulsive correlation.

Averaging $\Delta\sigma^2$ over *N* and plotting vs collision energy, STAR data is found to be significantly more repulsive than any of the models and shows no significant trend with energy. AMPT shows increasing repulsion with decreasing energy.

Strong dependence on event multiplicity observed. Strength of repulsion increases as event multiplicity decreases. Trend likely due to **momentum conservation**, which acts as a background.

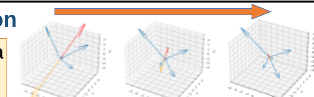


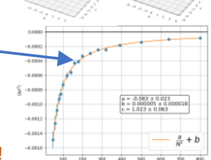
Energy dependence observed in STAR data after subtracting multiplicity dependence. Possible indication of excess clustering on top of momentum conservation background.

The Outlook

Dealing with Momentum Conservation

Interesting energy dependence in STAR data which is absent in AMPT but momentum conservation effect needs to be corrected!





Able to reproduce the multiplicity dependent repulsive trend with a simple model. 3D momentum vectors are generated randomly and iteratively rotated away from the net momentum until net momentum is zero. Gives confidence in the origin of repulsive interaction but too simplistic for a correction.

Need a robust correction for momentum conservation effect!

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[1] STAR Collaboration, Phys. Rev. Lett. 126, 092301 (2021).
[2] J. Steinheimer and J. Randrup, Phys. Rev. C 87, 054903 (2013).
[3] Y. He and Z.-W. Lin, Phys. Rev. C 96, 014910 (2017).
[4] V. Vovchenko, Phys. Rev. C 106, 064906 (2022).

The STAR Collaboration
https://drupal.star.bnl.gov/STAR/presentations