Imprinting Quantum Fluctuations on Hydrodynamic Initial Conditions

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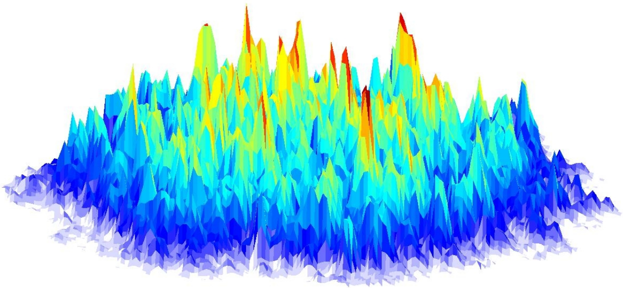
- Adding quark and gluon degrees of freedom to Monte Carlo Color-Glass Condensate initial conditions



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Duke UNIVERSITY
JET Collaboration
KRELL institute

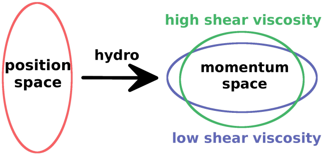
*Special thanks to U. Heinz and S. Bass for their guidance and to the Krell Institute for funding my future graduate studies.

Brief background: extracting the QGP shear viscosity

- Hybrid models using viscous hydrodynamics + Boltzmann cascade provide useful tool for extracting QGP shear viscosity η/s.

$$\eta/s \;\leftrightarrow\; \frac{v_n}{\epsilon_n} \quad \begin{array}{l} \leftarrow \text{anisotropic flow} \\ \leftarrow \text{spatial anisotropy} \end{array}$$

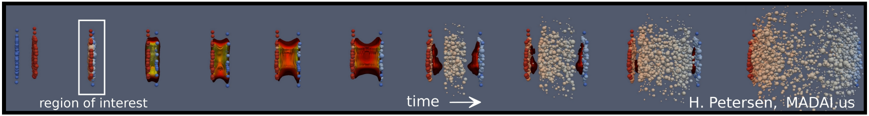
viscosity η/s dampens conversion of spatial anisotropy into flow anisotropy



1. Initial conditions (IC) simulate transverse energy (entropy) density
2. Hydrodynamic transport equations evolve IC down to T_c (critical temperature)
3. Boltzmann cascade evolves hadron resonance gas from T_c to freeze-out
4. Particle interactions cease and particles free-stream

(1) Initial Condition

(3) Hadron Resonance Gas (Boltzmann)

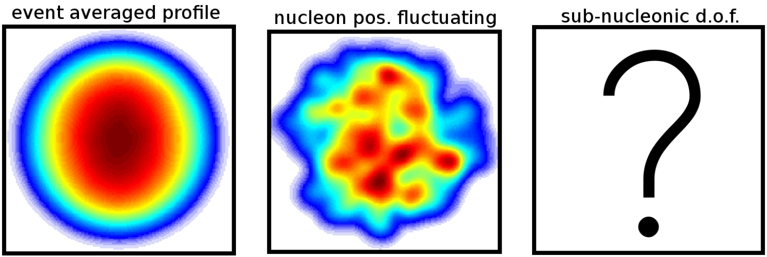


(2) QGP (Hydrodynamics)

(4) Kinetic Freezeout

Concentrating on initial conditions

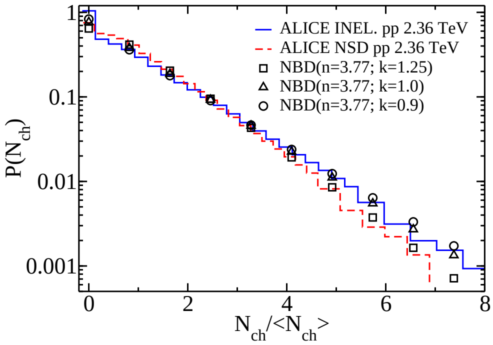
- At present, largest source of error for extracting η/s is uncertainty in initial conditions: MC-Glauber? DIPSY? AMPT? MC-KLN? MC-rcBK? NeXuS? UrQMD? IP-Sat? IP-Glasma?... It's a zoo.
- Current models not yet converging, only discovering new sources of uncertainty
- Let's concentrate on developments in fluctuations
  Classic Example: Optical nucleus → Monte Carlo nucleus w/finite nucleons



What's next? Event-by-event gluon-field fluctuations

- Large event-by-event fluctuations in pp charged particle multiplicity N_{ch} evidence for sub-nucleonic initial state fluctuations

K. Aamodt et al. (ALICE Collaboration) Eur.Phys.J. C68 (2010) 89-108

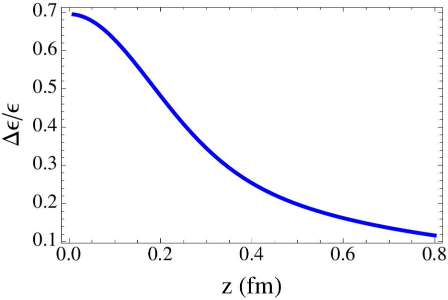


- pp multiplicity fluctuations *cannot* be explained using Glauber model for pp interaction where, $P(b) = 1 - \exp[-\sigma_{gg} T_{pp}(b)]$
- Sub-nucleonic fluctuations clearly exist in the initial state, but where to begin?

Müller & Schäfer calculate transverse energy density fluctuations in Color-Glass Condensate model

- Müller-Schäfer paper predicts structure of quantum fluctuations!
- Paper calculates mean normalized covar. $\mathrm{Cov}[\epsilon(r)/\epsilon_0] = (\Delta\epsilon(r)/\epsilon_0)^2$ for collision of two infinite sheets of nuclear matter
- Gaussian color distribution (color content contribution from each nucleon is independent).
- Correlation length *proportional* to $1/Q_s \approx 0.14$ fm (relevant Q_s at RHIC)

B. Müller, A. Schäfer, Phys.Rev.D 85, 114030 (2012)

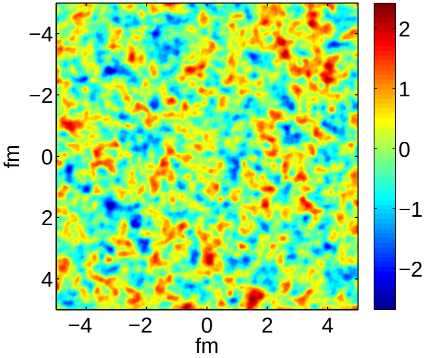


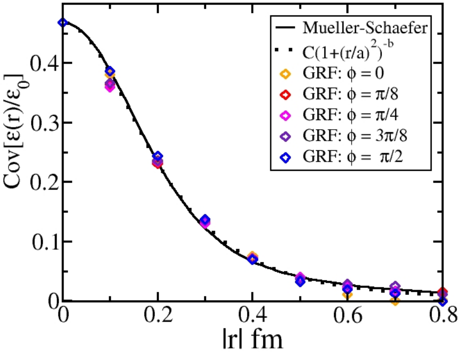
- Use Müller-Schäfer covariance of gluon-field energy density fluctuations to texture MC-KLN initial conditions

Fitting the Müller-Schäfer Gaussian random field (GRF)

We use GRF **T**urning **B**and **SIM**ulator TBSIM developed by X. Emery and C. Lantuéjoul to generate a large 4000x4000 cell GRF w/ the Müller-Schäfer covariance

X. Emery and C. Lantuéjoul, Computers and Geosciences 32, 1615 (2006)

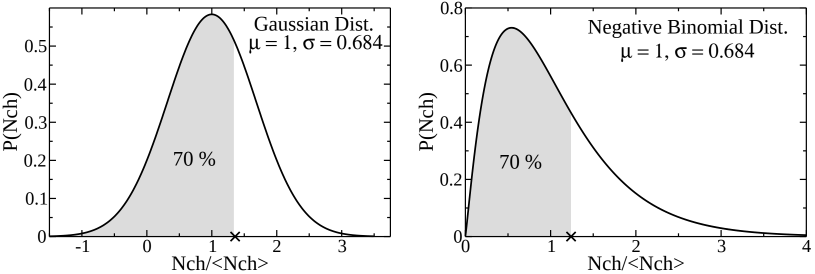




Fit to Müller-Schäfer covariance is nearly exact. One small problem: GRF allows for fluctuations $\Delta\epsilon/\epsilon_0 < -1$, negative energy densities which are, of course, non-physical.

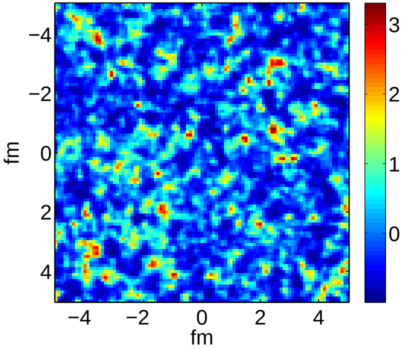
Mapping to positive definite Neg. Binom. random field

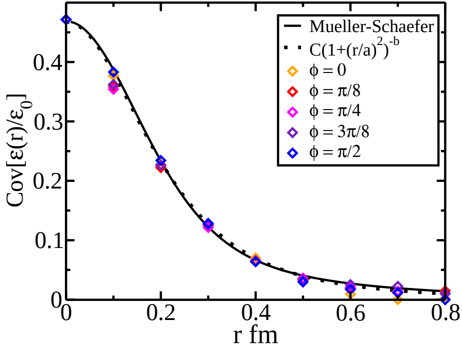
- 7.2% chance Gaussian fluctuations are negative (non-physical)
- Send Gaussian → Negative Binomial Distribution (NBD)
  motivated by p-p multiplicity fluctuations
- $\text{NBD}(\bar{n}, k; n) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$ 2-parameter function on $\mathbb{Z}$
- Generate single NBD with mean and standard deviation equal to Gaussian
- Equate random variables via their cumulative distribution functions (CDF's)
  i.e. iff $\int_{-\infty}^{x} \text{Gaussian}(x)dx = \int_{-\infty}^{y} \text{NBD}(y)dy$ then $x \leftrightarrow y$



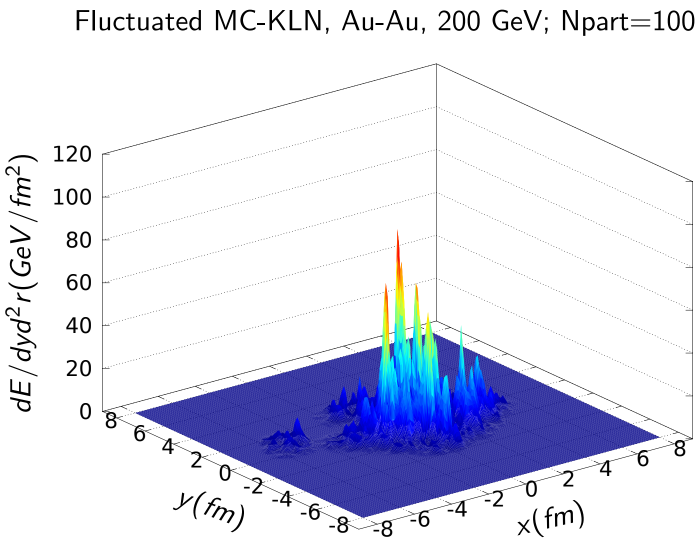
Did this transformation destroy our covariance?

- Nope. Almost indistinguishable from GRF fit to Müller-Schäfer covariance

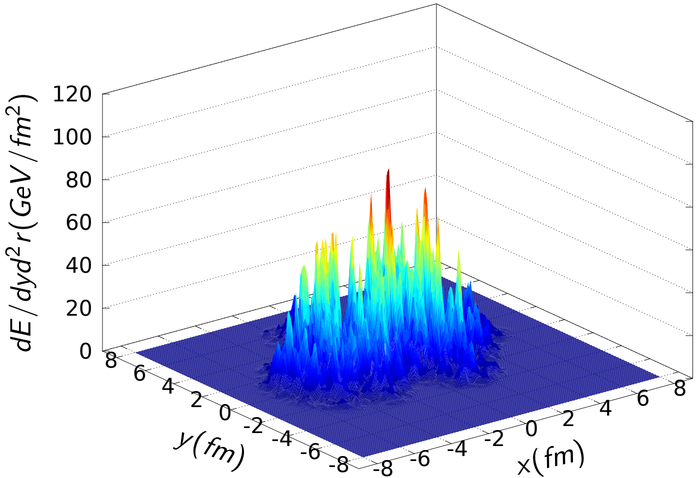




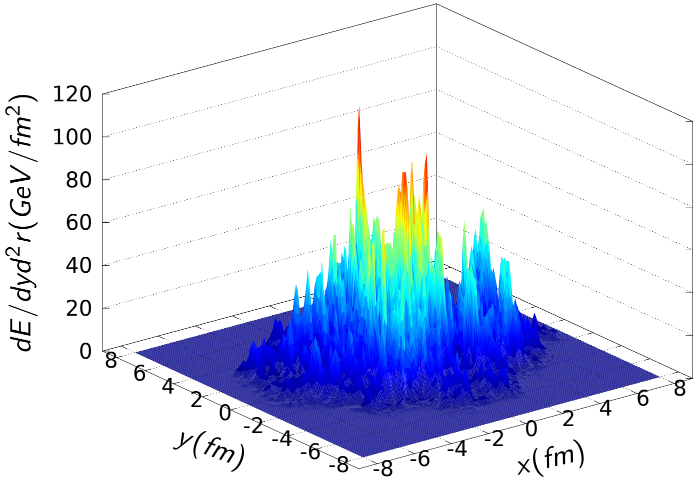
- Bulk of profile is pulled down and hot spots are more sharply peaked
- Texture can be thought of as percent fluctuation about **mean** gluon-field energy density


Fluctuated MC-KLN, Au-Au, 200 GeV; Npart=100
dE/dyd²r(GeV/fm²)
0
20
40
60
80
100
120
y(fm)
8 6 4 2 0 -2 -4 -6 -8
x(fm)
-8 -6 -4 -2 0 2 4 6 8

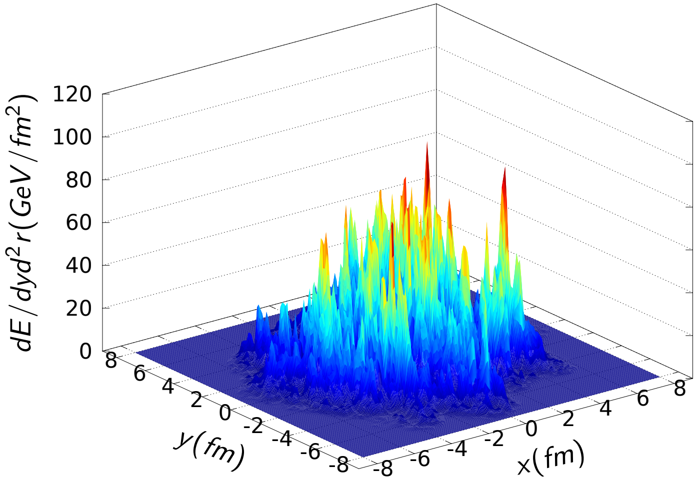
Fluctuated MC-KLN, Au-Au, 200 GeV; Npart=200



Fluctuated MC-KLN, Au-Au, 200 GeV; Npart=300

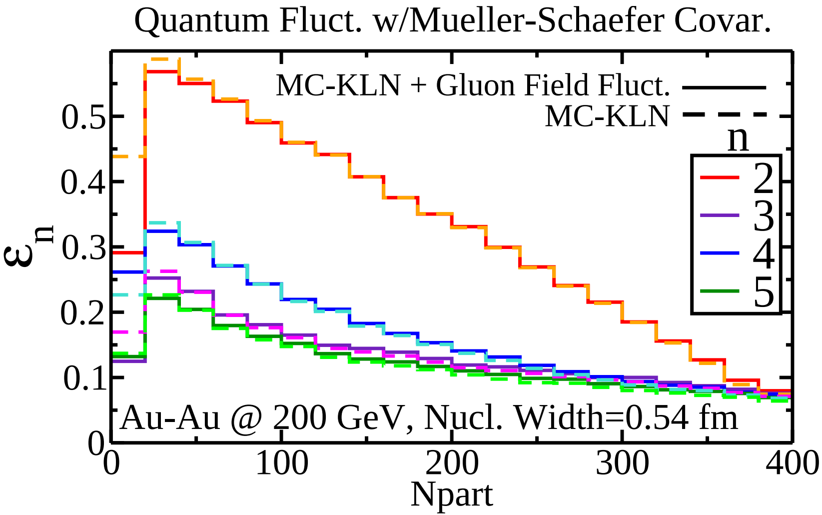


Fluctuated MC-KLN, Au-Au, 200 GeV; Npart=380

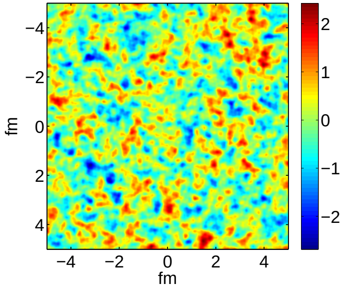


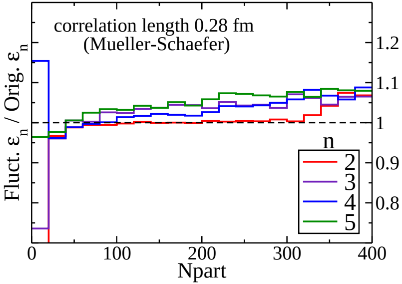
Analysis: Calculating the eccentricity harmonics

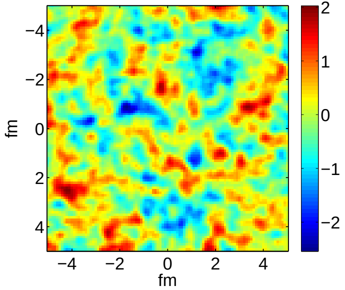
Using definition: $\epsilon_n e^{in\Psi_n^{PP}} = -\frac{\int dxdyr^2 e^{in\phi}\rho(x,y)}{\int dxdyr^2\rho(x,y)}$

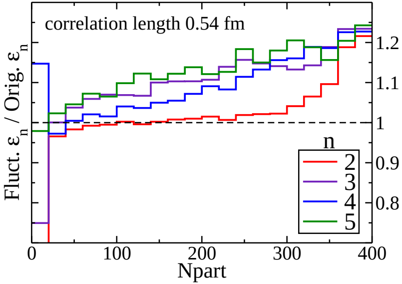


Analysis: Dependence on correlation length









Comparison with similar studies

Related Publications:

- A. Dumitru & Y. Nara
  "KNO scaling of fluctuations in pp and pA, and eccentricities in heavy-ion collisions" Phys. Rev. C 85, 034907 (2012) [arXiv:1201.6382 [nucl-th]].
- B. Schenke, P. Tribedy & R. Venugopalan
  "Fluctuating Glasma initial conditions and flow in heavy ion collisions" arXiv:1202.6646 [nucl-th].

Strengths of the present analysis:

- Realistic covariance applicable in central (hot) regions of the fireball
- Fluctuations can be turned on and off for comparison (factorized) and applied to any suitable Color-Glass Condensate model

Concluding remarks

- We have implemented gluon-field fluctuations in MC-KLN initial conditions with a uniform Müller-Schäfer covariance.
- We see a small increase in $\epsilon_2 - \epsilon_5$ in central collisions $\approx 5 - 10\%$.
- Increasing the correlation length to the width of a nucleon (as may happen for smaller Q_s values) results in $\approx 20 - 25\%$ increase of ϵ_n in central collisions.
- Increases in ϵ_2 vanish for $N_{part} < 300$.

Looking forward

- Refine model to better account for fluctuations in dilute regions, i.e. fitting pp multiplicity fluctuations
- Converge with parallel studies (B. Schenke, P. Tribedy, R. Venugopalan & A. Dumitru, Y. Nara)
- Run fluctuated profiles through hydro

Special thanks to Berndt Müller, Adrian Dumitru, Hannah Petersen, Chun Shen and Jonah Bernhard for constructive advice and illuminating discussions.