The initial-state geometry in small systems (pp, pA, dA, and ^{3}HeA)

Ulrich Heinz

The Ohio State University

In collaboration with Kevin Welsh and Jordan Singer

K. Welsh, J. Singer, UH, manuscript to be posted later this week

IS 2016, 5/23/16

What should a full dynamical simulation look like?

- Initial conditions for the phase-space distribution of the produced matter,

$$f_{\rm matter}(x_\perp, \phi_s; p_\perp, \phi_p; y_p - \eta_s; \tau_0)$$

which depends on the

- phase-space (Wigner) distribution of the glue inside the nucleons bound into small nuclei:

$$f_{\rm glue}(x_\perp, \phi_s; k_\perp, \phi_k; y_k - \eta_s; \tau_0)$$

- From $f_{\rm matter}$ we obtain the initial energy-momentum tensor

$$T^{\mu\nu}(x_\perp, \eta_s, \tau_0) = \frac{\nu_{\rm dof}}{(2\pi)^3} \int dy_p d^2 p_\perp p^\mu p^\nu f_{\rm matter}(x_\perp, \phi_s; p_\perp, \phi_p; y_p - \eta_s; \tau_0)$$

What should a full dynamical simulation look like?

- Once the initial $T^{\mu\nu}(x)$ is known, we can evolve it for some time $\tau_{\rm eq}-\tau_0$ with a pre-equilibrium model, match it to (anisotropic) viscous hydrodynamic form, e.g.

$$T^{\mu\nu} = e u^\mu u^\nu - \big(P(e) + \Pi\big)\Delta^{\mu\nu} + \pi^{\mu\nu},$$

  run it through (anisotropic) viscous hydrodynamics plus hadronic afterburner, and compare its output with experiment.
- To account for event-by-event quantum fluctuations in the initial $T^{\mu\nu}(x)$, and for thermal noise during the evolution, the dynamical evolution must be performed many times before taking ensemble averages as done in experiment.

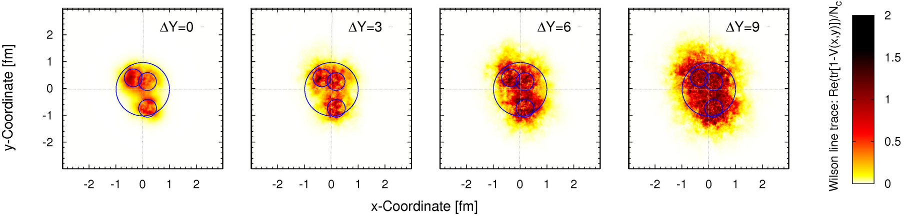
What is missing in present calculations?

Present modeling uses simplified assumptions for the initial phase-space distrib'n:

- Few models account for the initial momentum structure of the medium; most ignore it completely. $\Longrightarrow$ incorrect/unreliable initial conditions for $\Pi, \pi^{\mu\nu}$
- While granularity of the initial spatial density distribution is accounted for at the nucleon length scale, by Monte-Carlo sampling the nucleon positions from a smooth Woods-Saxon probability distribution before allowing them to collide and lose energy to create lower-rapidity secondary matter, quantum fluctuations on sub-nucleonic length scales are poorly controlled and mostly ignored. IP-Glasma includes sub-nucleonic gluon field fluctuations, but appears to get them wrong, yielding spatial gluon distributions inside protons that are too compact.
- Most approaches (e.g. PHOBOS Glauber Monte Carlo) use disk-like nucleons for computing the collision probability. More realistic collision detection using Gaussian nucleons is implemented in GLISSANDO and iEBE-VISHNU.
- Most approaches ignore quantum fluctuations in the amount of beam energy lost to lower rapidities in a NN collision. Without these, the measured KNO-like multiplicity distributions in pp collisions are not reproduced, and pp collisions produce zero ϵ_3 by symmetry. GLISSANDO and iEBE-VISHNU include pp multiplicity fluctuations, creating non-zero triangularity in pp, even without sub-nucleonic structure.

"Three quarks for Muster Mark!"

Schlichting, Schenke, PLB739 (2014) 313



- 3 valence quarks act as large-x color sources of the low-x gluon fields.
- Spatial positions of quarks at the instant of collision fluctuate from event to event and generate a lumpy color distribution at large x.
- This lumpiness is tracked by the quarks' gluon clouds, becoming more diffuse at smaller $x \Longrightarrow$ triune lumpiness of the gluon fields inside the nucleon when viewed through midrapidity particle production, with an intrinsic length scale ("gluonic radius of a quark") that appears to grow with collision energy.
- $\Longrightarrow$ Protons have just as much intrinsic triangularity as ^{3}He nuclei, just on a shorter length scale. But in p+A ***all*** particle production occurs on a smaller length scale than in ^{3}He+A! This affects mostly radial flow, though.

Modeling quark substructure of the nucleon I

- The gluon field density inside the proton is the sum of three 3-d Gaussians of norm $\frac{1}{3}$ and width σ_g (representing the gluon clouds around the valence quarks). Default value: $\sigma_g = 0.3\,\mathrm{fm}$ (best fit of pPb mult. dist. at LHC)
- The quark positions (centers of the gluon clouds) are sampled from a 3-d Gaussian with width σ_q around the center of the nucleon, requiring their center of mass to coincide with the nucleon center.
- The widths are constrained by $\sigma_g^2 + \frac{2}{3}\sigma_q^2 = B$ such that the average proton density is a normalized Gaussian

$$\langle \rho_p(\boldsymbol{r}) \rangle = \frac{e^{-\frac{r^2}{2B}}}{(2\pi B)^{2/3}}$$

with $\sqrt{s}$-dependent width $B(\sqrt{s}) = \frac{\sigma_{\mathrm{NN}}^{\mathrm{inel}}(\sqrt{s})}{8\pi}$, to reproduce the measured inelastic NN cross section.

Modeling quark substructure of the nucleon II

- Projecting ρ_p along z gives the nucleon thickness function $T_N(\boldsymbol{r}_\perp)$ in the transverse plane.

- Folding two nucleon thickness functions yields the nucleon-nucleon overlap function $T_{NN}(\boldsymbol{b})$ at impact parameter $\boldsymbol{b}$ (which actually depends on all 6 quark positions), from which the probability for each of the two nucleons to get wounded in the collision is computed as

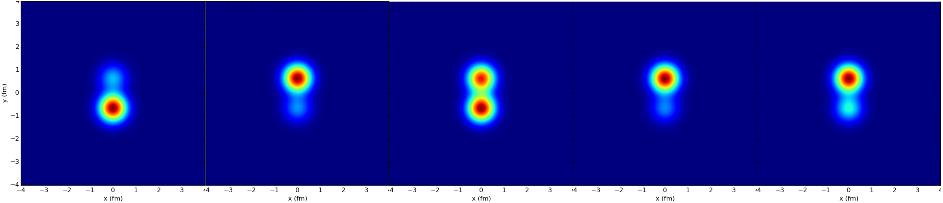
$$P_{ij}(\boldsymbol{r}_{\perp i}-\boldsymbol{r}_{\perp j}) = 1 - \exp\left[-\sigma_{gg}\, T_{NN}(\boldsymbol{r}_{\perp i}-\boldsymbol{r}_{\perp j})\right]$$

  where i and j are from projectile and target, respectively. The gluon-gluon cross section σ_{gg} is determined by the normalization of P_{ij} to the inelastic NN cross section.

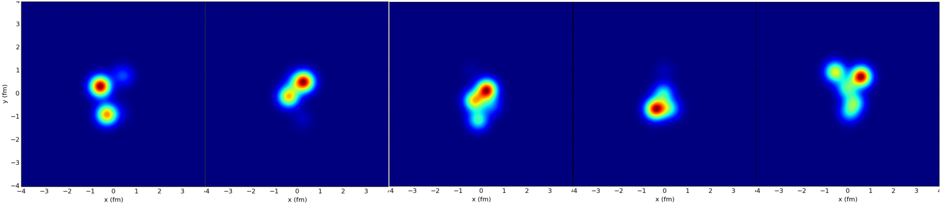
- For each wounded nucleon, all three quarks are assumed to contribute to energy production at midrapidity, with a Gaussian density profile of width σ_g and independently fluctuating (Γ-distributed) normalization, with variance adjusted to reproduce measured pp multiplicity distributions.

Initial entropy density in b=1.3 fm pp collisions

smooth Gaussian protons:

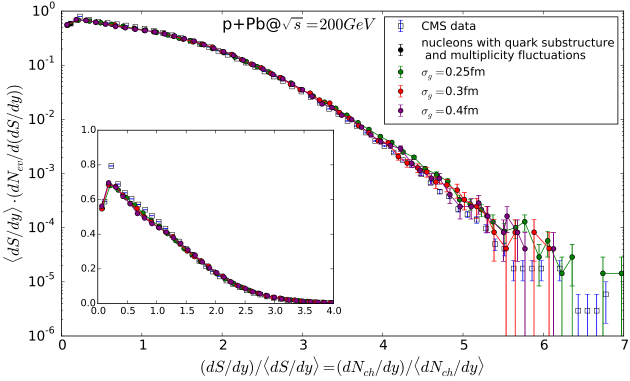


protons with fluctuating quark substructure ($\sigma_g = 0.3\,\mathrm{fm}$):

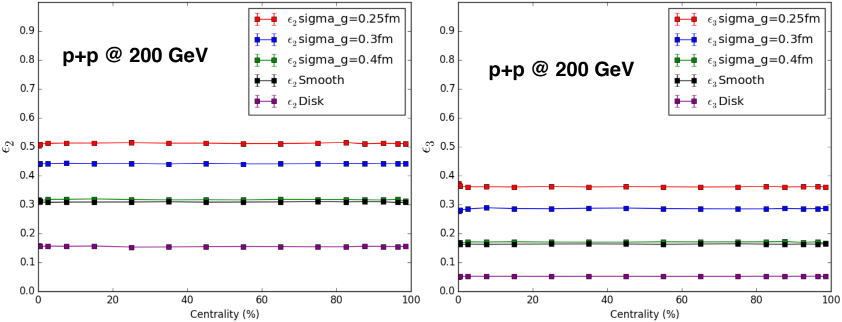


For protons with quark substructure the Gaussian collision criterium appears to favor somewhat more compact distributions of produced entropy density

pPb multiplicity distribution

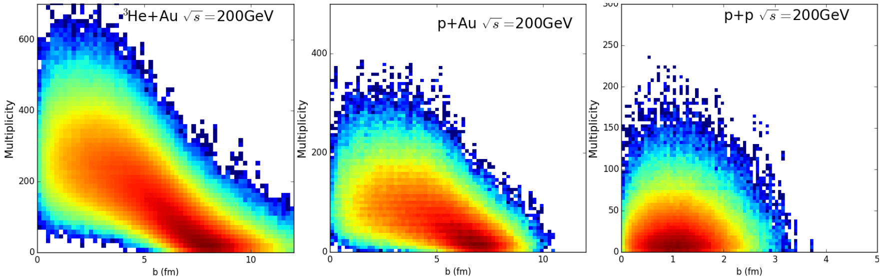


$\varepsilon_{2,3}$ vs. centrality: pp @ $\sqrt{s}$=200 A GeV



- Ellipticity and triangularity show strong sensitivity to σ_g.
- Since $\sqrt{B} = 0.408$ fm at $\sqrt{s} = 200$ GeV, quark subdivision with $\sigma_g = 0.4$ fm is almost indistinguishable from a smooth Gaussian proton.
- Disk-like collision detection gives smallest eccentricities.

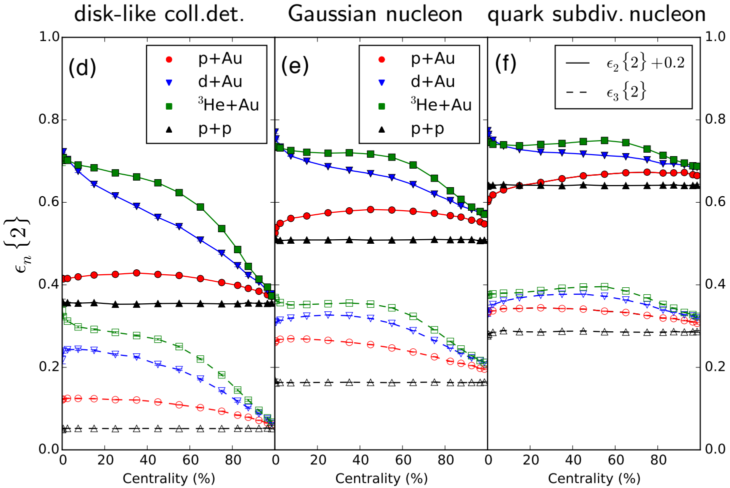
In p+p and light+heavy "centrality" does not measure b!



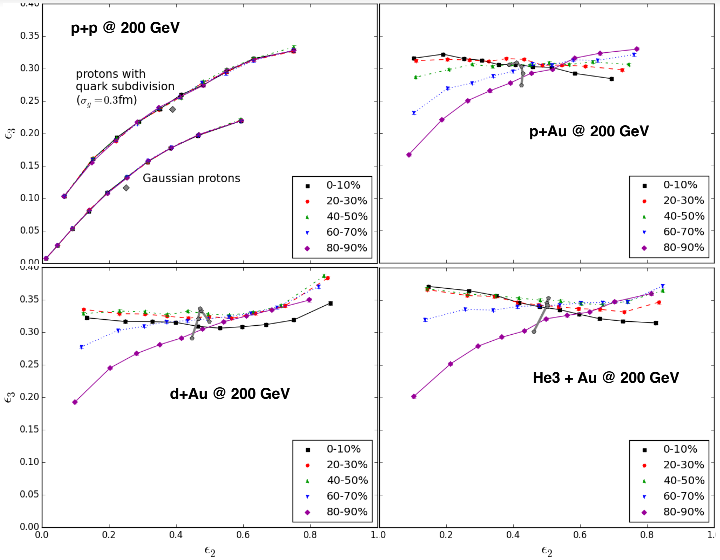
pp multiplicity fluctuations destroy strong anticorrelation between multiplicity and impact parameter seen in Au+Au and Pb+Pb

$\Longrightarrow$ "centrality" measured by multiplicity is a misnomer in collisions involving light projectiles

$\varepsilon_{2,3}$ vs. "centrality" for different collision systems



ε_2-ε_3 correlations: pp & light-heavy collisions, $\sigma_g = 0.3\,\text{fm}$



The End