# ULTRACENTRAL COLLISIONS OF SMALL AND DEFORMED SYSTEMS AT RHIC

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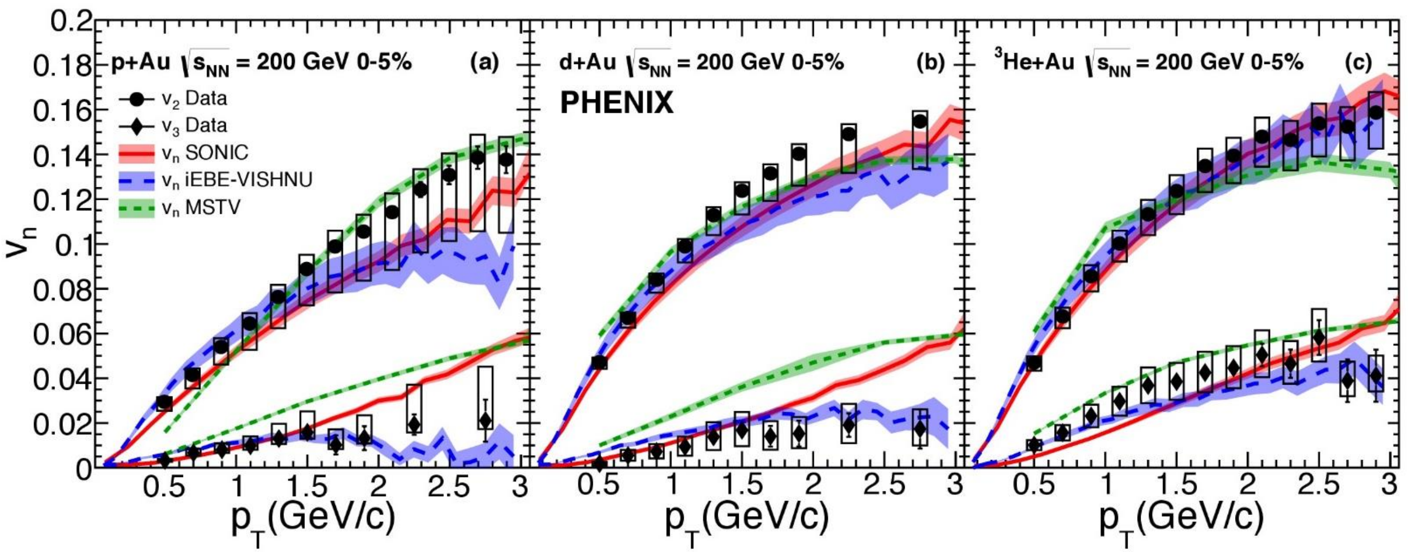
arXiv:**1905.13323**, submitted to PRC

# QGP In Small Systems

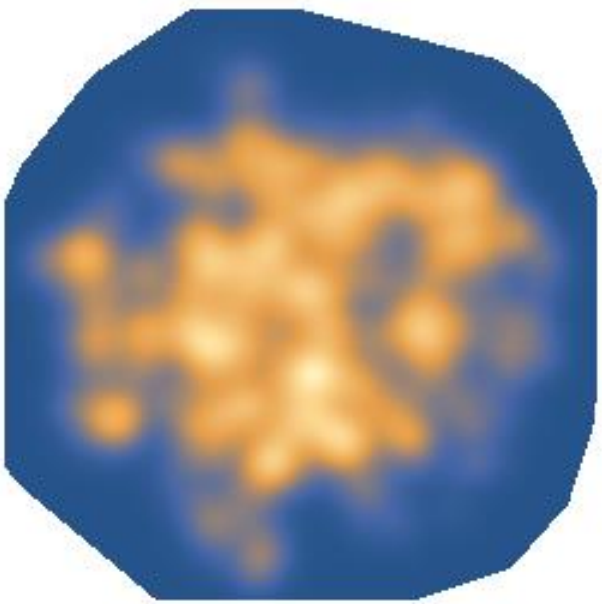



PHENIX
Nature Physics
15, 214 (2018)

(see M. Connors, J Nagle talks)

- Strong evidence for QGP in small systems
- Hydro describes data.
- CGC explanation proposed but had issues
  - MSTV, Phys. Rev. Lett. 121, 052301 (2018)
  - Erratum Phys. Rev. Lett. 123, 039901 (2019)
- Important to find ways to distinguish between various models.

# Deformed Systems



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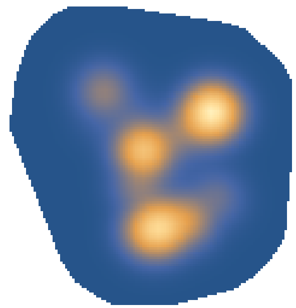
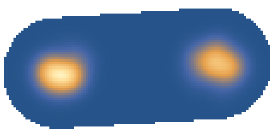


9Be



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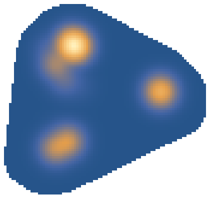
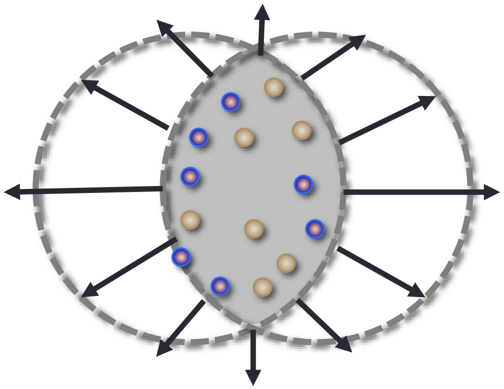


3He

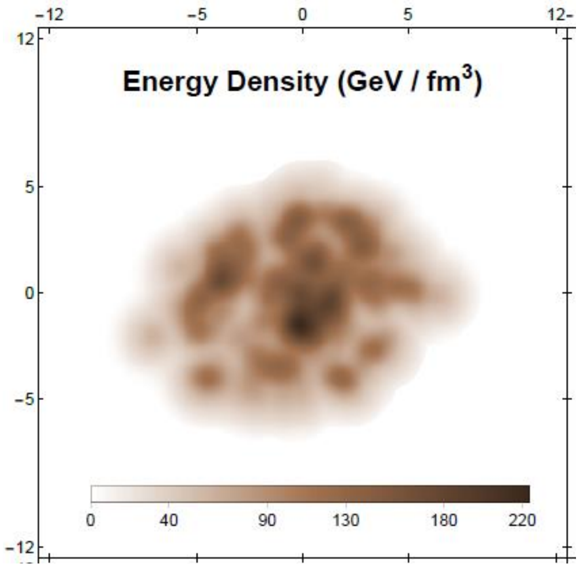
- In this talk: Deformed systems in ultra-central collisions are an excellent test bed for discerning different models.
- Drastically different initial geometries: Elliptical, triangular
- These are powerful tools to test various initial condition models
  - We focus on Hydro and CGC models

# Hydro Model

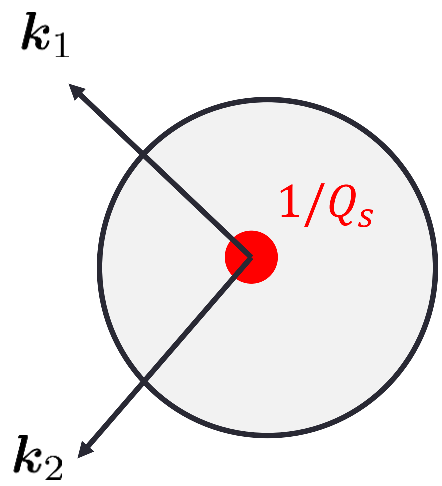
- In hydrodynamics, multiparticle correlations ($v_n\{2\}, v_n\{4\}$) are determined by the initial geometry .
- In central collisions, approximately linear response to geometry: $v_n \approx \kappa\, \varepsilon_n$
  - Linear + cubic response has been studied but linear response dominates in central collisions.
- In this talk:
  - Initial state + linear response.
  - We use Trento to model the initial energy density.
  - Can simulate full hydro if needed.



D. Teaney, L. Yan, Phys.Rev.**C83** (2011)
J. Noronha-Hostler, et. al. Phys. Rev. **C93** (2016)
M. D. Sievert, J. Noronha-Hostler, Phys. Rev. **C100** (2019)



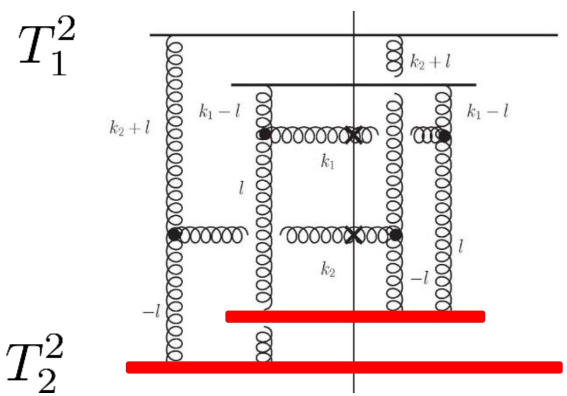
# CGC Model




- Correlations produced from multiple particles scattering in the same correlated color fields, isolated to a local area.

Y. V. Kovchegov and **DEW**. Nucl. Phys. **A906** (2013)
A. Kovner and M. Lublinsky, Int. J. Mod. Phys. **E22** (2013)
A. Dumitru et al., Nucl. Phys. **A810** (2008)

- In large pT limit the equation linearizes and the densities factorize.
  - $T_1\left(1-\exp\left[-\frac{Q_S^2}{p_T^2}\right]\right) \approx T_1\frac{Q_S^2}{p_T^2} \sim T_1\, T_2\, \frac{1}{p_T^2}$




- Density profile controls the magnitude of the correlations, not the overall shape.

# LO results for both even and odd harmonics

- Two-gluon production at LO:

Y. V. Kovchegov and **DEW**. Nucl. Phys. **A925** (2014)

$$\left.\frac{d\sigma_{corr}}{d^2k_1 dy_1 d^2k_2 dy_2 d^2B}\right|_{LO}^{even} \propto \int d^2b\, T_1^2(\boldsymbol{B}-\boldsymbol{b}) T_2^2(\boldsymbol{b}) \times \sum_{n=0} f_n(k_{\perp,1}, k_{\perp,2}) \cos(2n\phi)$$

- Odd harmonics first contribute at NLO:

Y. V. Kovchegov and V. Skokov Phys. Rev. **D97** (2018)

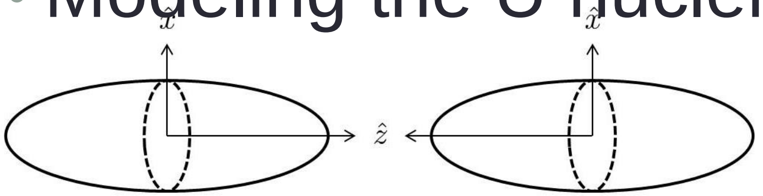
$$\left.\frac{d\sigma_{corr}}{d^2k_1 dy_1 d^2k_2 dy_2 d^2B}\right|_{NLO}^{odd} \propto \int d^2b\, T_1^3(\boldsymbol{B}-\boldsymbol{b}) T_2^3(\boldsymbol{b}) \times \sum_{n=0} g_n(k_{\perp,1}, k_{\perp,2}) \cos((2n+1)\phi)$$

- Notice the geometry dependence factorizes from the pT dependence.

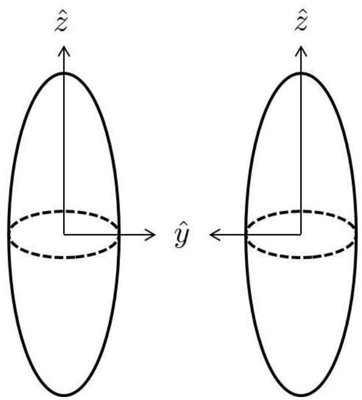
# CGC vs. Hydro in U+U collision

Y. V. Kovchegov and **DEW**. Nucl. Phys. **A925** (2014)

- Consider the deformed system of UU.
- Compare two different central collisional geometries of UU, head-on and side-on (0 impact parameter).
- Modeling the U nuclei as a prolate ellipsoids.



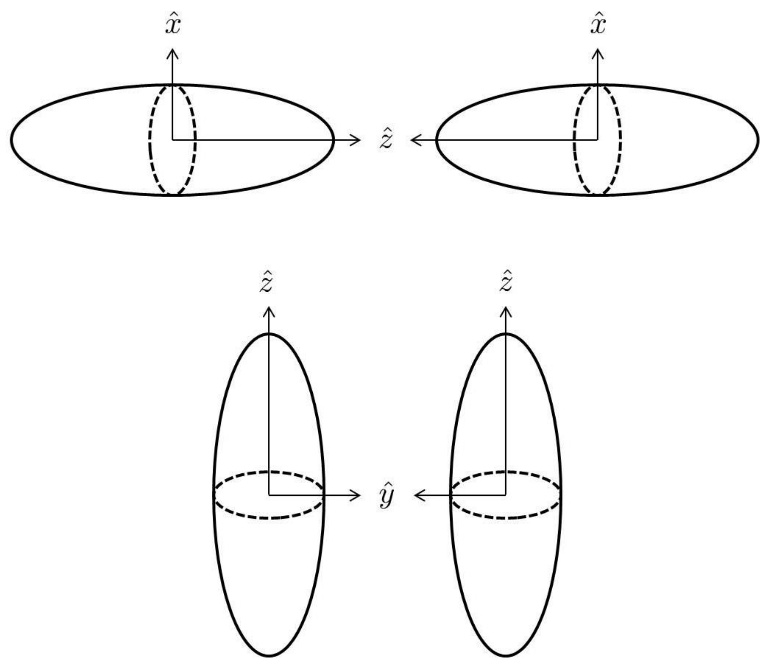

$$\rho(\vec{\boldsymbol{r}}) = \rho_0 \, e^{-\frac{x^2}{R^2} - \frac{y^2}{R^2} - \frac{\lambda^2}{R^2} z^2}$$




$$T_{head-on}(\boldsymbol{b}) = \sqrt{\pi} \, \frac{R}{\lambda} \, \rho_0 \, e^{-\frac{b^2}{R^2}}$$

$$T_{side-on}(\boldsymbol{b}) = \sqrt{\pi} \, R \, \rho_0 \, e^{-\frac{x^2}{R^2} - \frac{\lambda^2}{R^2} z^2}$$

# Ellipticity's effect on the correlation, CGC

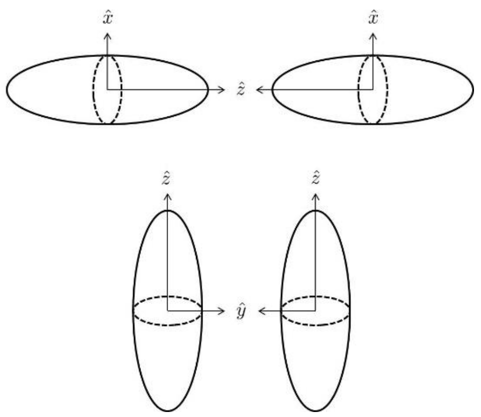


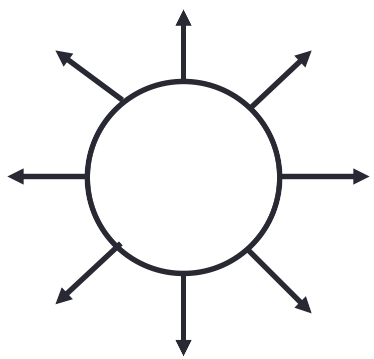

- Examining the even-harmonic term (LO correlation) we arrive at

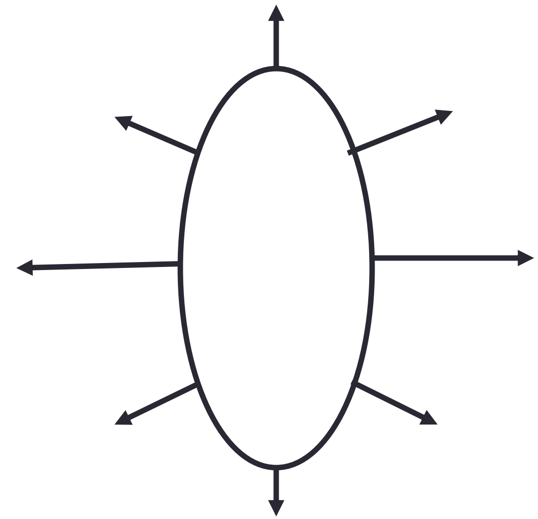
$$\frac{C_{head-on}(\boldsymbol{k}_1, y_1, \boldsymbol{k}_2, y_2)\big|_{LO}}{C_{side-on}(\boldsymbol{k}_1, y_1, \boldsymbol{k}_2, y_2)\big|_{LO}} = \frac{1}{\lambda}$$

- For Uranium $1/\lambda = 1.26$
- Enhancement for head-on collisions. Depend on density and not geometry.

# Ellipticity’s effect on the correlation, Hydro





- In hydrodynamics the ellipticity ($\varepsilon_2$) controls $v_2$, couples to geometry not density.
- Side-on system has large $v_2$
- Opposite of CGC.

# U+U ratio multiplicity

- In the large pT limit the **geometry dependence factorizes** from the pT dependence just like in the UU example.

$$v_2\{2\}^2 = N_{pairs}^{-1} \int d^2b\, T_1^2(\boldsymbol{B}-\mathbf{b})T_2^2(\mathbf{b}) \int d^2k_1\, d^2k_2\, f_2(k_{\perp,1}, k_{\perp,2}) \cos(2\Delta\phi)$$

- The only difference is now the total multiplicity (Npairs) also varies event by event.
- In a ratio the **pT dependence cancels out**.

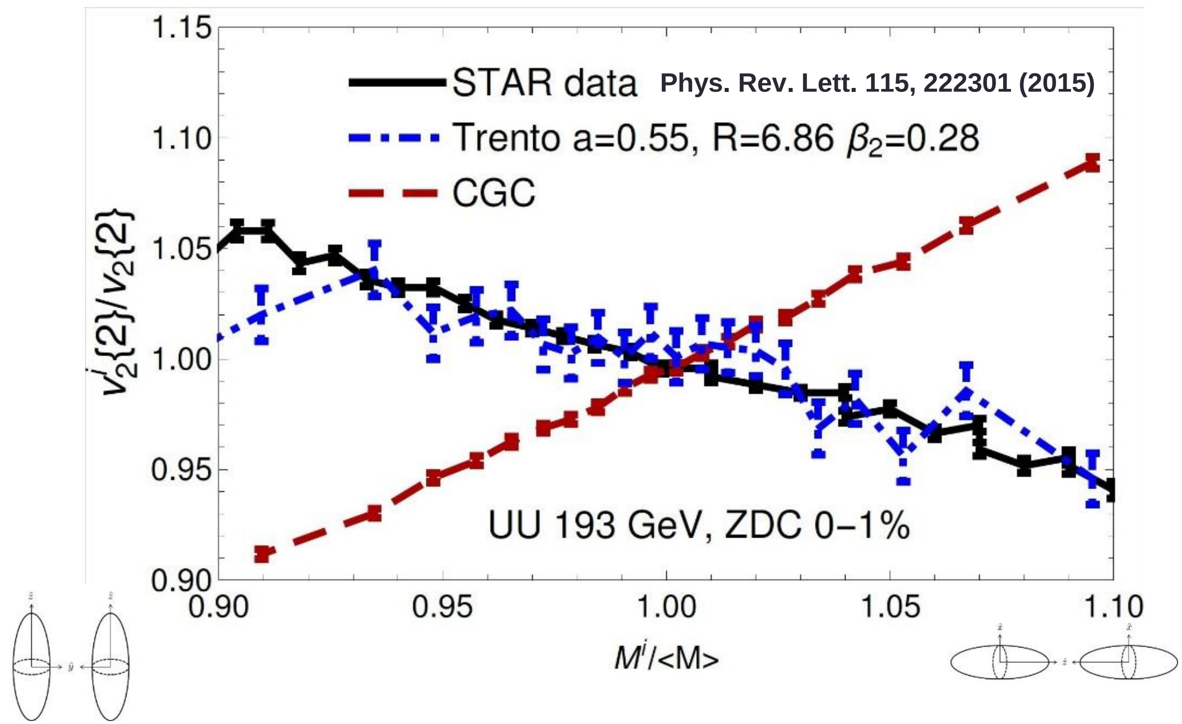
$$\frac{v_2^i\{2\}}{\langle v_2\{2\}\rangle} = \sqrt{\left(\frac{\int T_1^2 T_2^2}{N_{pairs}}\right)_i \left\langle \frac{\int T_1^2 T_2^2}{N_{pairs}} \right\rangle^{-1}}$$

- Here we assume the multiplicity goes as the geometric mean

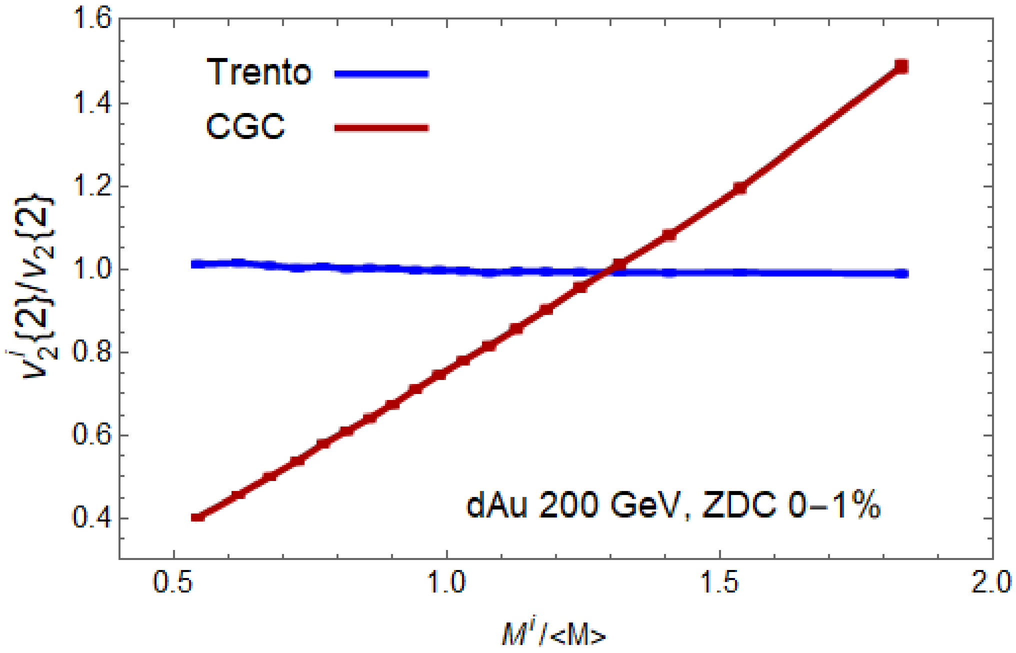
$$\sqrt{N_{pairs}} = N_{trento} \propto \sqrt{T_1 T_2}$$

# U+U Results compared with Star data

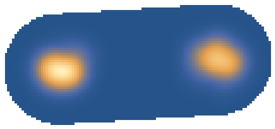
- Hydro results are due elliptical geometry.
- CGC is due to thickness of interaction.
- Give opposite results.
- Hydro matches data.



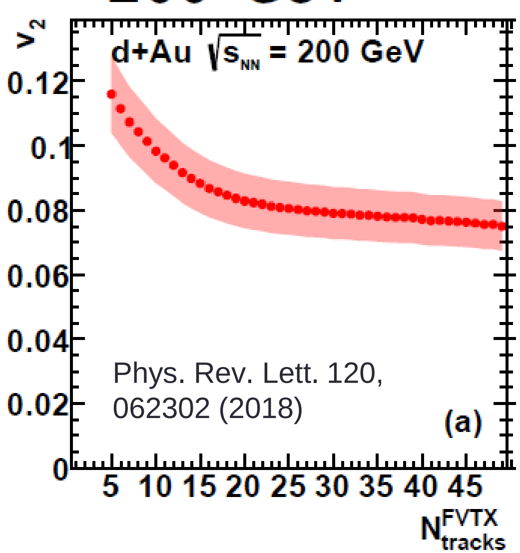
# dAu Results




- CGC trend is similar to UU case.
- Hydro is flat.
- Rough comparison with Beam Energy scan shows CGC possibly disagreeing from data.

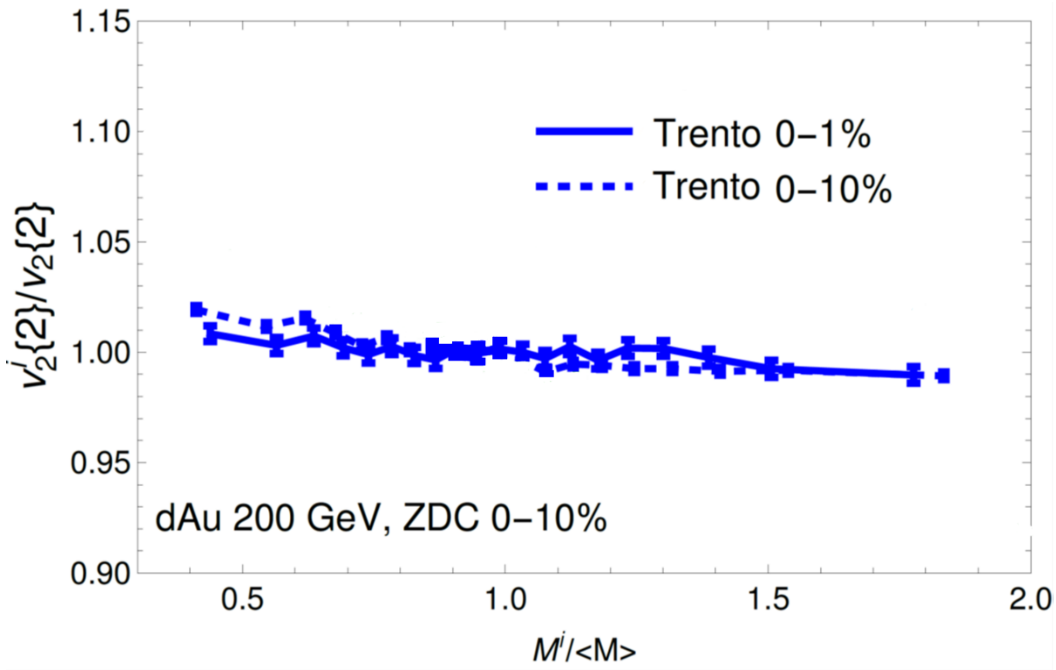


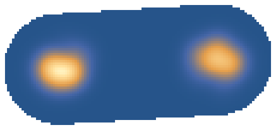
200 GeV

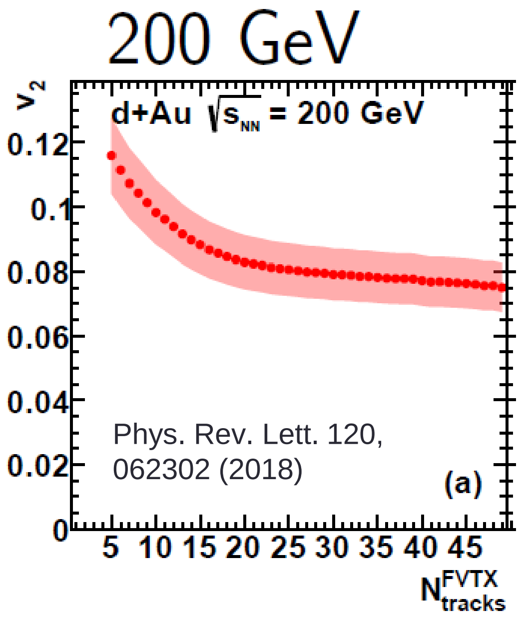


# dAu Results

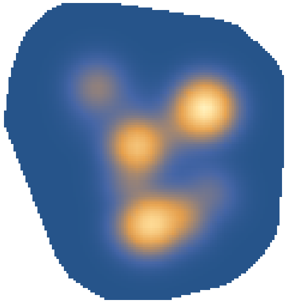
- CGC trend is similar to UU case.
- Hydro is flat.
- Rough comparison with Beam Energy scan shows CGC possibly disagreeing from data.
- Results don't have to be ultra central to see the effects.



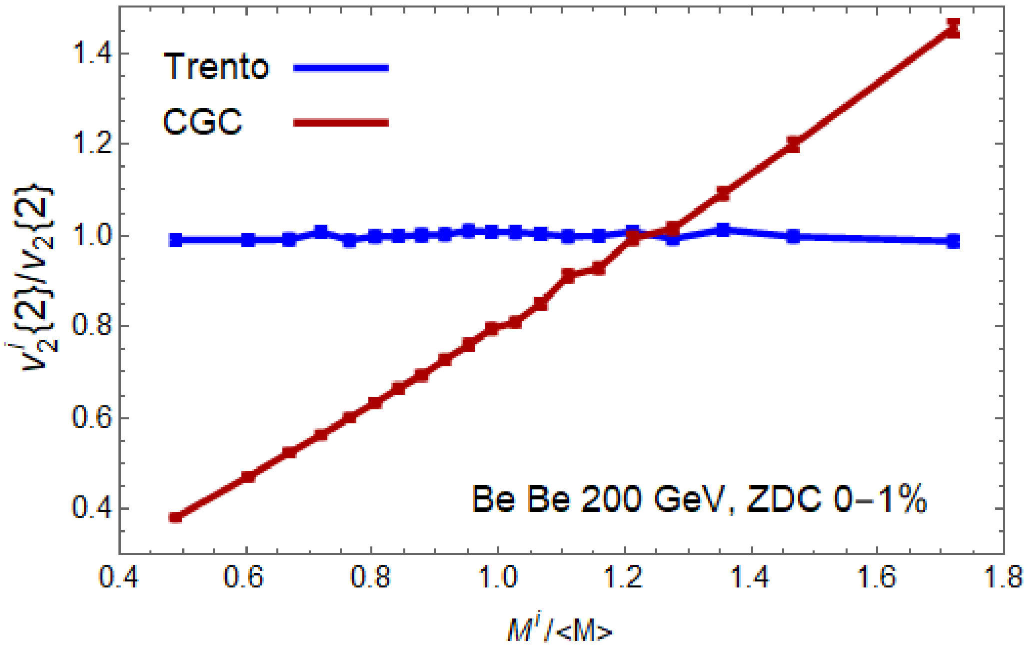





# 9Be-9Be Results

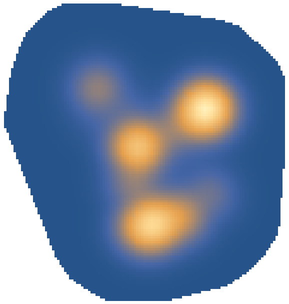


- Highly deformed and intermediate in size between dAu and UU
- Results are similar to dAu
- System is of interest for studying light polarized nuclei

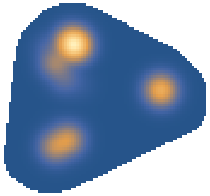


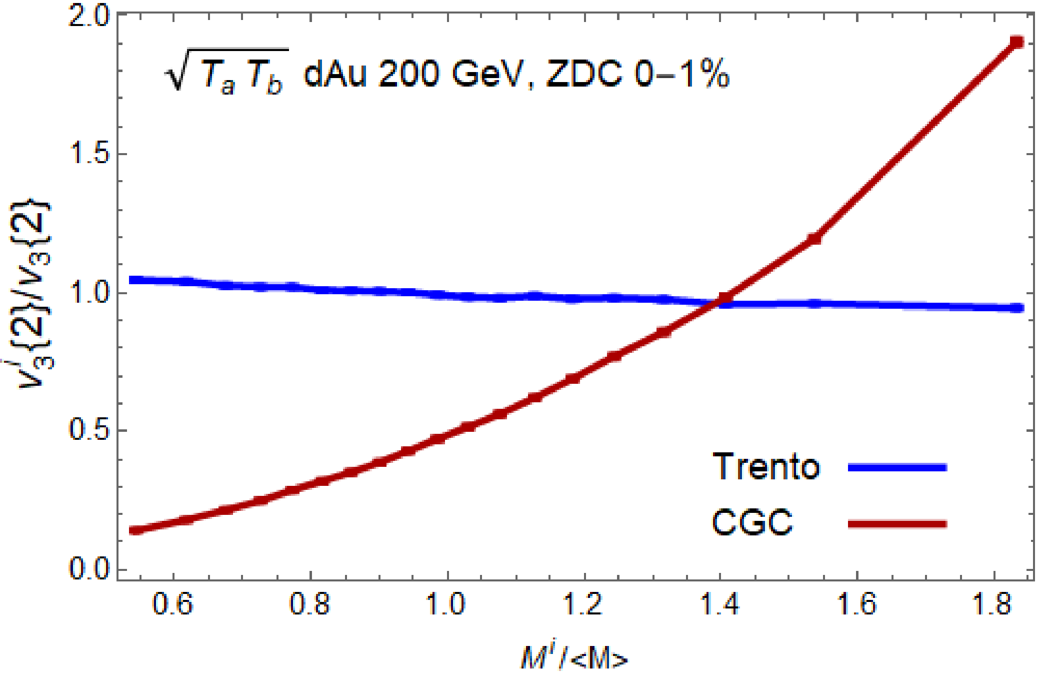

W. Broniowski, E. R. Arriola, Phys.Rev.Lett. **112** (2014)

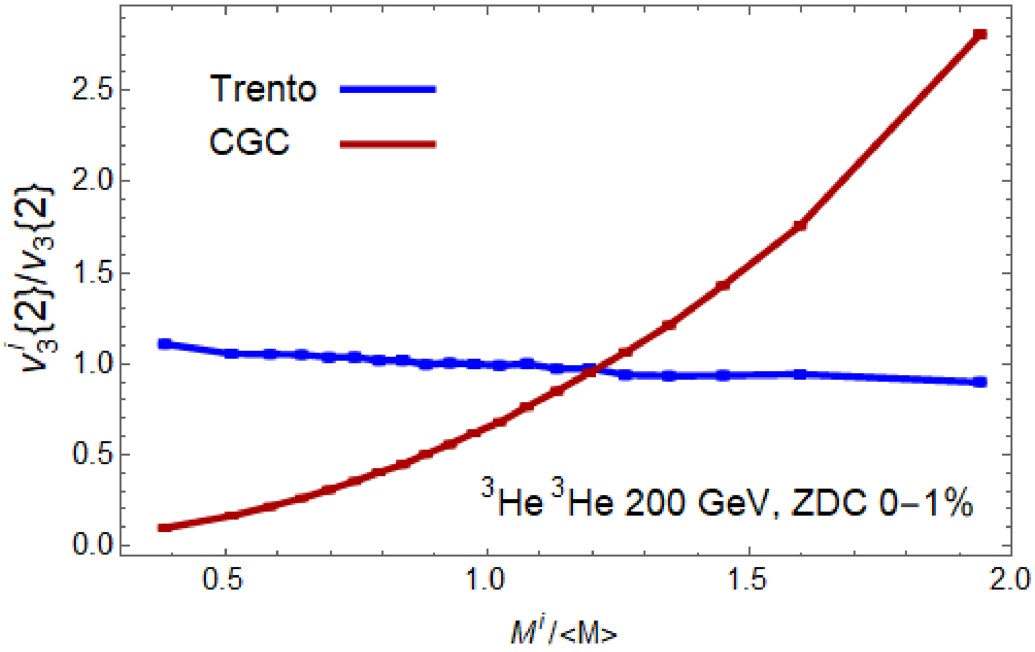
# v3 Results



- Can do similar analysis for $v_3$.
- CGC is opposite of Hydro.
- Can turn hydro on and off by going from dAu to 3He-3He (there is a difference but it is subtle)





# Conclusions

- Ultra central collisions of deformed systems are an excellent test bed for various models.
- In hydro the $v_n$'s decrease as a function of multiplicy.
- In CGC the $v_n$'s increase.
- Hydro agrees with the UU results.
- Could compare with dAu data if the data was re-analyzed. On tape but we just need the right plots.

# Multiplicity scaling comparison

- Using Trento one often uses the geometric mean for the entropy scaling, but we also will use the CGC multiplicity scaling and compare the results.

$$N_{trento} \propto \sqrt{T_1 T_2}$$

$$N_{CGC} \propto T_1 T_2$$