Color Field Fluctuations… or Not

An Open Discussion About Saturation Physics

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CLASH Seminar

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The Goal

- What this talk is **not**:
    - Comprehensive answers, finished stories, decisive conclusions

- What this talk aims to be:
    - An ongoing **discussion** to better understand the nature of saturation physics and assess the evidence for it

      "Let us aim to be confused at a higher level"

Questions Offered for Discussion

- This Talk:

  How essential are the color field degrees of freedom associated with the Color Glass Condensate in heavy ion collisions?

- Other Potential Topics:

❖ How is saturation related with unitarity – in QCD and in other field theories?
❖ The CGC + Lund String model

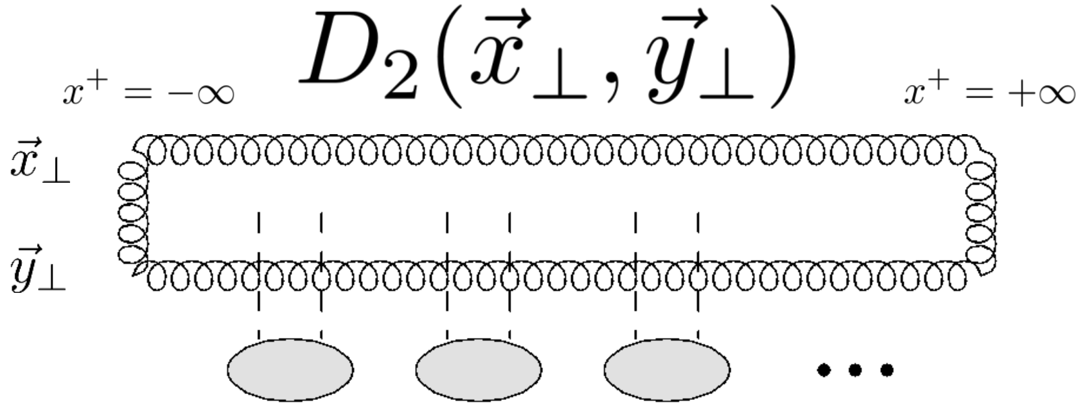
Calculations in the CGC Framework

- Color Glass Condensate:
  - Effective theory for QCD at high energies and high gluon densities
  - Resummation: $\alpha_s \, \rho \sim 1$ $\alpha_s^2 \, A^{1/3}$
  - Emergent scale: $Q_s^2 = \frac{\alpha_s \pi^2}{S_\perp \, 2C_F} xG(x, Q_s^2)$ $Q_s^2(\vec{b}_\perp) = \frac{\alpha_s \pi^2}{2N_c} T(\vec{b}_\perp) \, xG_N(x, Q_s^2)$
  - Features: High gluon densities (semi-classical)
    Degrees of freedom are Wilson lines (gauge links)

- Types of calculations:
  - Initial conditions for hydrodynamics *e.g.) IP-Glasma*
  - Direct final-state particle production *e.g) MSTV*

B. Schenke, P. Tribedy, R. Venugopalan, Phys.Rev.Lett. 108 (2012)

M. Mace, V. Skokov, P. Tribedy, R. Venugopalan, Phys.Rev.Lett. 121 (2018) , erratum ibid. 123 (2019)



$$D_2^{adj}(\vec{u}_\perp, \vec{b}_\perp) \equiv \frac{1}{N_c^2 - 1} \langle \mathrm{tr}[U_{\vec{u}_\perp} U^\dagger_{\vec{b}_\perp}] \rangle$$

$$U_{\vec{x}_\perp} = \mathcal{P} \exp \left[ig \int dz_\mu A^\mu \right]$$

- Wilson lines: line integrals of the gluon fields

$$D_2(\vec{x}_\perp, \vec{y}_\perp) \approx D_2(|x-y|_T)$$

- After color averaging: exponentiate a 2-gluon block

$$D_2(\vec{x}_\perp, \vec{y}_\perp) \approx \exp \left[-\frac{1}{4} |x-y|_T^2 Q_s^2 \ln \frac{1}{|x-y|_T \Lambda} \right]$$

Application: The MSTV Calculation for Small Systems

Hierarchy of azimuthal anisotropy harmonics in collisions of small systems from the Color Glass Condensate

Mark Mace,[1,2] Vladimir V. Skokov,[3] Prithwish Tribedy,[1] and Raju Venugopalan[1]

[1] *Physics Department, Brookhaven National Laboratory, Upton, New York 1197*

[2] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, N*

[3] *RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York*

(Dated: August 8, 2018)

Systematics of azimuthal anisotropy harmonics in proton-nucleus collisions at the LHC from the Color Glass Condensate

Mark Mace,[1,2] Vladimir V. Skokov,[3] Prithwish Tribedy,[1] and Raju Venugopalan[1]

[1] *Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

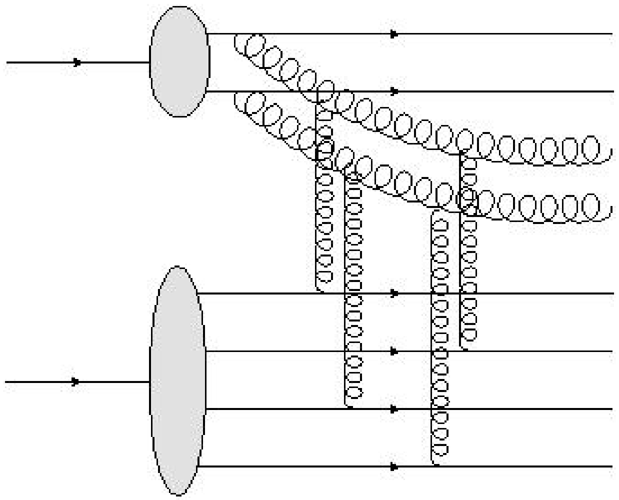
[2] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*

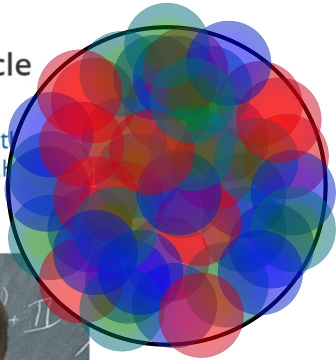
[3] *RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

(Dated: July 4, 2018)

$$\frac{dN^{\text{even}}(\mathbf{k}_\perp)}{d^2k dy}\left[\rho_p, \rho_t\right] = \frac{2}{(2\pi)^3}\frac{\delta_{ij}\delta_{lm} + \epsilon_{ij}\epsilon_{lm}}{k^2}\Omega^a_{ij}(\mathbf{k}_\perp)\left[\Omega^a_{lm}(\mathbf{k}_\perp)\right]^\star$$

$$\Omega^a_{ij}(\mathbf{k}_\perp) = g\int \frac{d^2p}{(2\pi)^2}\frac{p_i(k-p)_j}{p^2}\rho^b_p(\mathbf{p}_\perp)U_{ab}(\mathbf{k}_\perp - \mathbf{p}_\perp)$$

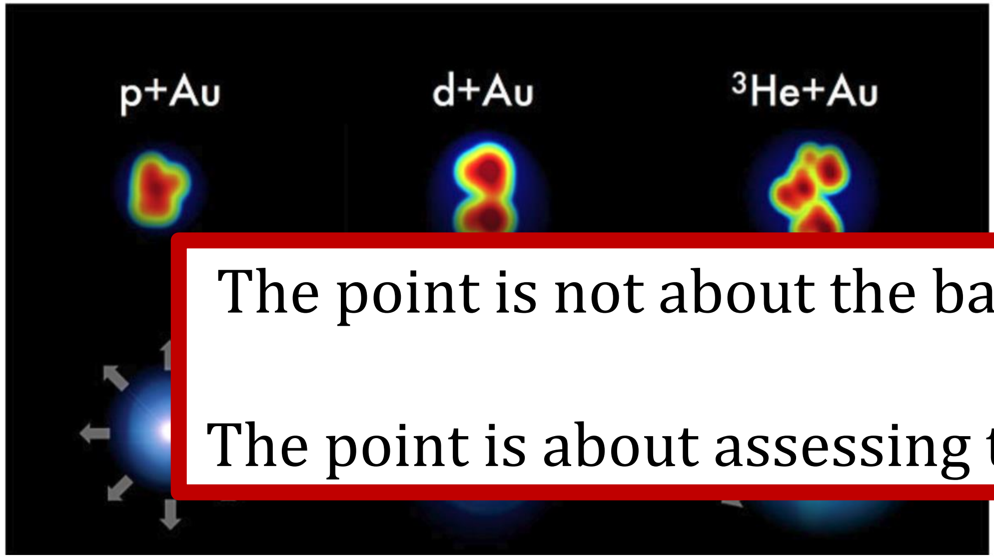




Compelling Evidence for Small Drops of Perfect Fluid

PHENIX publishes new particle-flow measurements to support their case that tiny projectiles create specks of quark-gluon plasma.

December 10, 2018



LETTERS
https://doi.org/10.1038/s41567-018-0360-0
nature physics

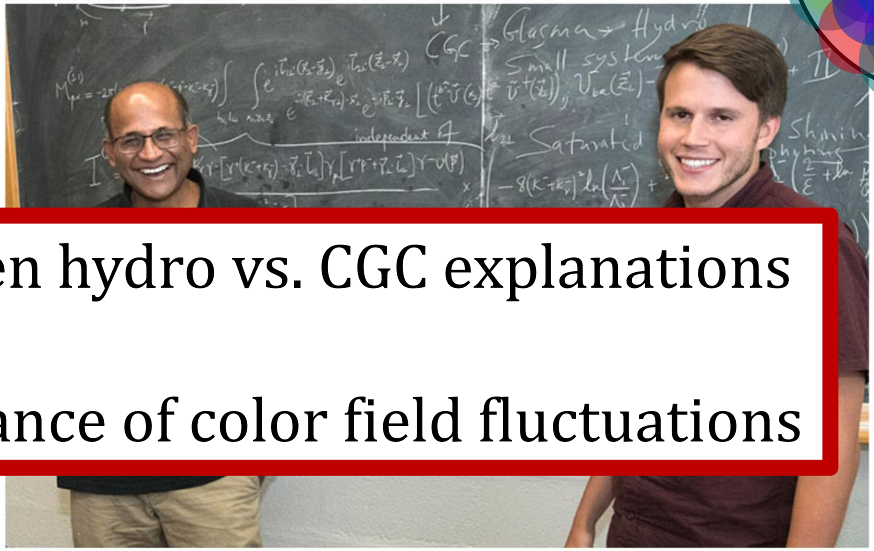
Creation of quark–gluon plasma droplets with three distinct geometries

PHENIX, Nature Physics (2018), arXiv: 1805.02973

Theory Paper Offers Alternate Explanation for Particle Patterns

Quantum mechanical interactions among gluons may trigger patterns t
mimic formation of quark-gluon plasma in small-particle collisions at RH

December 19, 2018



PHYSICAL REVIEW LETTERS **121,** 052301 (2018)

Hierarchy of Azimuthal Anisotropy Harmonics in Collisions of Small Systems from the Color Glass Condensate

Mark Mace,[1,2] Vladimir V. Skokov,[3] Prithwish Tribedy,[1] and Raju Venugopalan[1]

M. Mace et al., Phys. Rev. Lett. ***121*** *(2018)*

The point is not about the battle between hydro vs. CGC explanations

The point is about assessing the importance of color field fluctuations

Gluon Correlations in MSTSV

*Mace et al., Phys. Rev. Lett. **121** (2018), and arXiv:1901.10506*

$$\frac{dN}{d^2k_\perp}\left[\rho_p,\rho_t\right] \overset{L.O.}{=} \frac{2}{(2\pi)^3}\frac{\delta^{ij}\delta^{\ell m}+\epsilon_T^{ij}\epsilon_T^{\ell m}}{k_T^2}\,\Omega^{a\,ij}_{(\vec{k}_\perp)}\left[\rho_p,\rho_t\right]\left(\Omega^{a\,\ell m}_{(\vec{k}_\perp)}\left[\rho_p,\rho_t\right]\right)^*$$

$$\frac{dN}{d^2k_{\perp 1}\cdots d^2k_{\perp n}} = \int [\mathcal{D}\rho_p]\,[\mathcal{D}\rho_t]\,W[\rho_p]\,W[\rho_t]\;\frac{dN}{d^2k_{\perp 1}}[\rho_p,\rho_t]\cdots\frac{dN}{d^2k_{\perp n}}[\rho_p,\rho_t]$$

- Event-by-event fluctuations:
  - MC Glauber **geometry**
  - Event-by-event color fields: **operators** in ρ_p, ρ_t

- Two-gluon correlations from **semi-dilute / dense** expressions
  - Inherently **factorized** at operator level (density-enhanced)

When is "Flow" not "Hydro"?

- Sampled **one color field at a time:**
  - ➢ The single-particle distribution is **anisotropic**
  - ➢ Many-body correlations arise only through **mutual correlation** to the direction of the color fields.

$$\frac{dN}{d^2k_{\perp 1}\cdots d^2k_{\perp n}} = \int [\mathcal{D}\rho_p]\,[\mathcal{D}\rho_t]\,W[\rho_p]\,W[\rho_t]\;\frac{dN}{d^2k_{\perp 1}}[\rho_p,\rho_t]\cdots\frac{dN}{d^2k_{\perp n}}[\rho_p,\rho_t]$$

$$v_n \equiv \frac{1}{N}\left|\int_p e^{in\phi}\,\frac{dN_1}{d^2p}\right|$$

"Flow" "Non-Flow"

$$\frac{dN_2}{d^2p_1\,d^2p_2} \equiv \frac{dN_1}{d^2p_1}\,\frac{dN_1}{d^2p_2} + \delta_2(p_1,p_2)$$

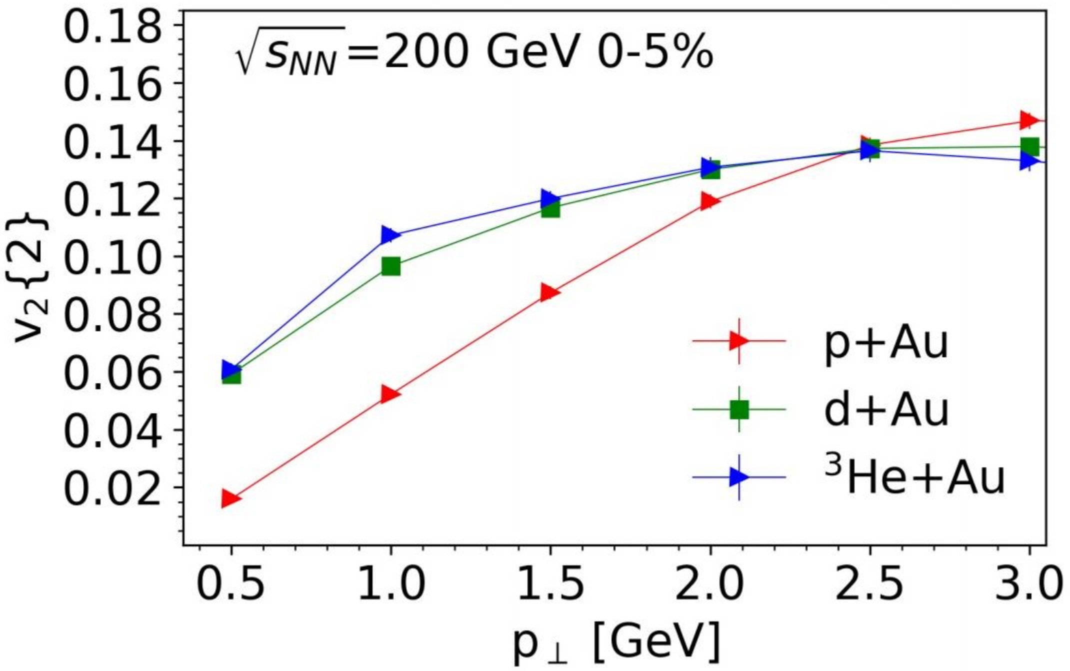
$$\left(v_n\{2\}\right)^2 \overset{flow}{=} \langle v_n^2\rangle \qquad \left(v_n\{4\}\right)^4 \overset{flow}{=} 2\langle v_n^2\rangle^2 - \langle v_n^4\rangle$$

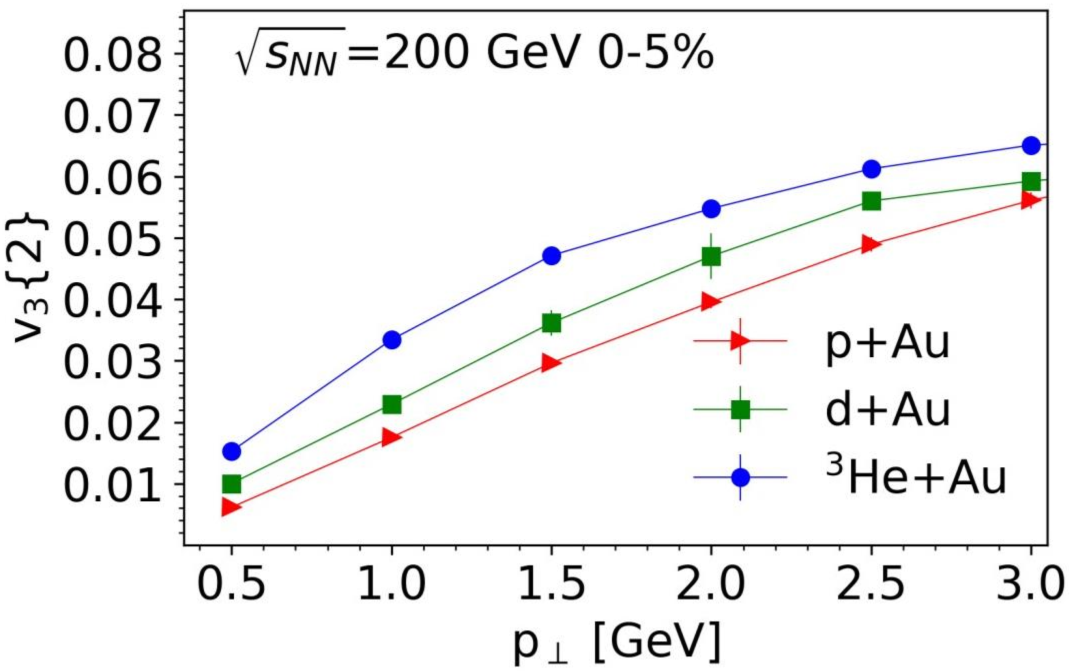
$$= \left(v_n\{2\}\right)^4 - \mathrm{Var}\left(v_n^2\right)$$

Similar Input, Similar Output

$$V_n(p_1,p_2) = \frac{\int_{p_1}^{p_2} k_\perp dk_\perp \frac{d\phi}{2\pi} e^{in\phi} \frac{dN(\mathbf{k}_\perp)}{d^2k dy}\Big[\rho_p,\rho_t\Big]}{\int_{p_1}^{p_2} k_\perp dk_\perp \frac{d\phi}{2\pi} \frac{dN(\mathbf{k}_\perp)}{d^2k dy}\Big[\rho_p,\rho_t\Big]}$$

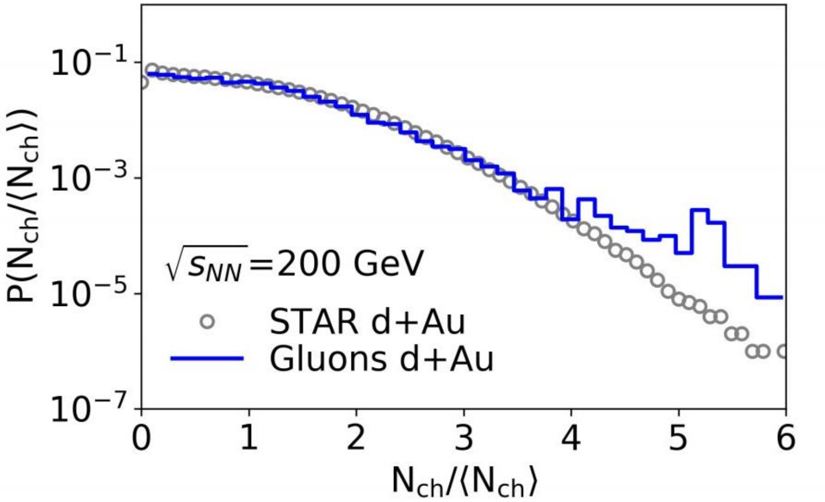
$$v_n^2\{2\}(p_\perp) = \int \mathcal{D}\rho_p \mathcal{D}\rho_t \; W[\rho_p] \; W[\rho_t] \times V_n(p_\perp - \Delta/2, p_\perp + \Delta/2) V_n^\star(0,\Lambda_{\rm UV})$$



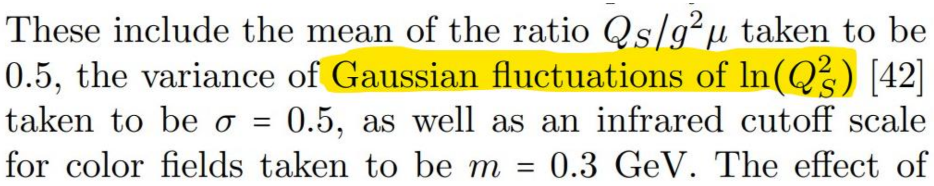


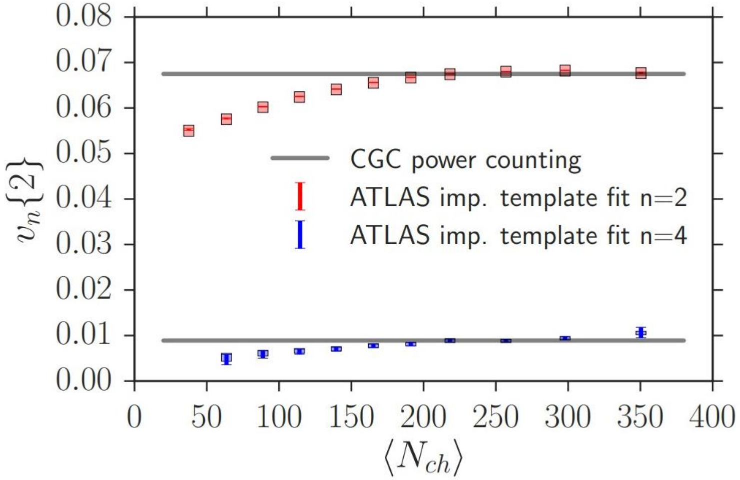
- The devil is certainly in the details, but: not surpising that MSTV gets systematics which resemble hydro (and hence the data)

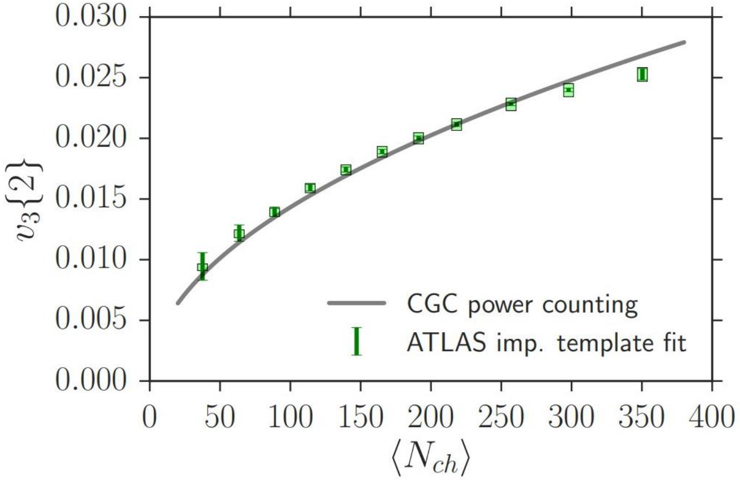
Interesting Observations on Multiplicity Dependence



- Can fit gluon multiplicity distribution to data… with help


These include the mean of the ratio $Q_S/g^2\mu$ taken to be 0.5, the variance of Gaussian fluctuations of $\ln(Q_S^2)$ [42] taken to be σ = 0.5, as well as an infrared cutoff scale for color fields taken to be m = 0.3 GeV. The effect of





- Interesting characteristic scaling with multiplicity

$$v_2\{2\} \overset{T_A T_B}{\sim} \sqrt{\frac{\int d^2x_\perp \left(\frac{dN}{d^2x}\right)^2}{\left[\int d^2x_\perp \frac{dN}{d^2x}\right]^2}} \sim \text{const}$$

$$v_3\{2\} \overset{T_A T_B}{\sim} \sqrt{\frac{\int d^2x_\perp \left(\frac{dN}{d^2x}\right)^3}{\left[\int d^2x_\perp \frac{dN}{d^2x}\right]^2}} \sim \sqrt{\frac{dN}{d^2x}}$$

...How Does this Single-Field Calculation Really Work?

$$\frac{dN}{d^2k_{\perp 1}\cdots d^2k_{\perp n}} = \int [\mathcal{D}\rho_p]\,[\mathcal{D}\rho_t]\,W[\rho_p]\,W[\rho_t]\;\frac{dN}{d^2k_{\perp 1}}[\rho_p,\rho_t]\cdots\frac{dN}{d^2k_{\perp n}}[\rho_p,\rho_t]$$

$$\left\langle \frac{d^mN}{d^2\mathbf{p_1}\cdots d^2\mathbf{p_m}}\right\rangle \equiv \left\langle \frac{dN}{d^2\mathbf{p_1}}\cdots\frac{dN}{d^2\mathbf{p_m}}\right\rangle , \qquad (7)$$

where the expectation value denotes an average over classical configurations of the target in a single event and over all events. Since each of the single-particle distributions inside the average here is a gauge-dependent functional of the classical field, we caution the reader that these distributions are qualitatively different from the gauge invariant single-particle distributions employed in hydrodynamic computations. No such simple product of gauge invariant distributions can be written in our case; indeed, as discussed at length in the Appendix, the Feynman diagrams corresponding to Eq. (7) are quantum interference diagrams.

K. Dusling, M. Mace, R. Venugopalan
Phys.Rev.D 97 (2018)

$$v_n \equiv \frac{1}{N}\left|\int_p e^{in\phi}\,\frac{dN_1}{d^2p}\right|$$

$$V_n(p_1,p_2) = \frac{\int_{p_1}^{p_2} k_\perp dk_\perp \frac{d\phi}{2\pi} e^{in\phi}\frac{dN(\mathbf{k}_\perp)}{d^2kdy}\left[\rho_p,\rho_t\right]}{\int_{p_1}^{p_2} k_\perp dk_\perp \frac{d\phi}{2\pi}\frac{dN(\mathbf{k}_\perp)}{d^2kdy}\left[\rho_p,\rho_t\right]}$$

$$\langle\rho^a\rho^b\rho^c\rho^d\rangle = \langle\rho^a\rho^b\rangle\langle\rho^c\rho^d\rangle + \langle\rho^a\rho^c\rangle\langle\rho^b\rho^d\rangle + \langle\rho^a\rho^d\rangle\langle\rho^b\rho^c\rangle$$

- Is this quantity well defined...?

The Alternative: Keeping vs. Smearing the Color Fields

- The operators in a calculation like MSTV are factorizing (flow-like) at the level of a single color field, but not after averaging the color fields out:

$$\left\langle \hat{D}_2(\vec{x}_\perp, \vec{y}_\perp)\, \hat{D}_2(\vec{z}_\perp, \vec{w}_\perp) \right\rangle_{\text{color}} \neq \left\langle \hat{D}_2(\vec{x}_\perp, \vec{y}_\perp) \right\rangle_{\text{color}} \left\langle \hat{D}_2(\vec{z}_\perp, \vec{w}_\perp) \right\rangle_{\text{color}}$$

- The picture before and after color averaging is very different:
  - Single-particle distribution $\frac{dN}{d^2k}$ directional vs isotropic
  - Factorizable vs irreducible multiparticle correlations

Systematics of "Flow" versus "Non-Flow"

- **"Flow"** refers to any source of anisotropy in the **single-particle** distribution **in an event**

$$v_n \equiv \frac{1}{N} \left| \int_p e^{in\phi} \frac{dN_1}{d^2p} \right|$$

- Multi-particle distributions arise both from **independent** production (**flow**) and dynamical **correlations** (**non-flow**)

"Flow" "Non-Flow"

$$\frac{dN_2}{d^2p_1\, d^2p_2} \equiv \frac{dN_1}{d^2p_1} \frac{dN_1}{d^2p_2} + \delta_2(p_1, p_2)$$

- **Cumulants** are observables that are **differently sensitive** to **flow** and **non-flow**

$$(v_n\{2\})^2 \equiv \left\langle \frac{1}{N^2} \int_{p_1 p_2} e^{in(\phi_1 - \phi_2)} \frac{dN_2}{d^2p_1 d^2p_2} \right\rangle$$

M. Luzum, H. Petersen, J. Phys. ***G41*** *(2014)*

$$(v_n\{4\})^4 \equiv 2 \left\langle \frac{1}{N^2} \int_{p_1 p_2} e^{in(\phi_1 - \phi_2)} \frac{dN_2}{d^2p_1 d^2p_2} \right\rangle^2 - \left\langle \frac{1}{N^4} \int_{p_1 p_2 p_3 p_4} e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \frac{dN_4}{d^2p_1 \cdots d^2p_4} \right\rangle$$

Multiparticle Cumulants: Flow Scenario

- Usually: a **flow-only** scenario
  - ➢ **No dynamical correlations** $(\delta_2 = 0)$
  - ➢ Multiparticle production **factorizes**
  - ➢ All cumulants due to **single-particle anisotropy**
- All cumulants describe the **event-by-event distribution** of the **single-particle anisotropy v_n**

"Flow" only

$$\frac{dN_2}{d^2p_1\, d^2p_2} \equiv \frac{dN_1}{d^2p_1}\frac{dN_1}{d^2p_2}$$

$$(v_n\{2\})^2 \overset{flow}{=} \langle v_n^2 \rangle$$

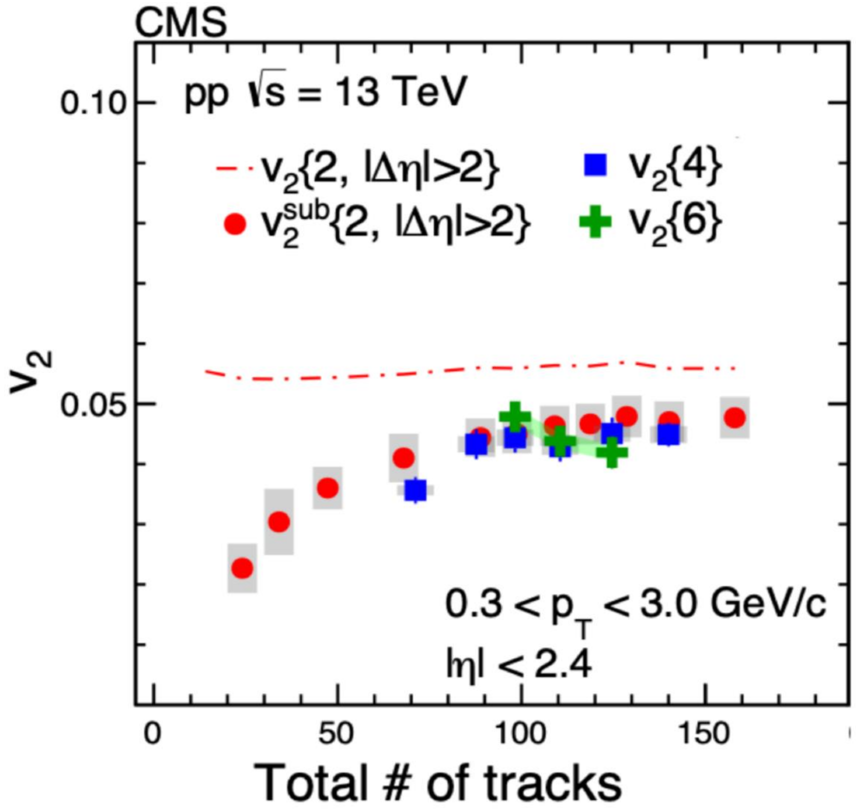
$$(v_n\{4\})^4 \overset{flow}{=} 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle$$
$$= (v_n\{2\})^4 - \mathrm{Var}\left(v_n^2\right)$$

M. Luzum, H. Petersen, J. Phys. ***G41*** *(2014)*

Multiparticle Cumulants: Flow Scenario

- Natural **hierarchy**:

$$v_n\{2\} > v_n\{4\} \approx v_n\{6\} \approx \cdots$$



Multiparticle Cumulants: Non-Flow Scenario

- Often in initial-state calculations:

M. Luzum, H. Petersen, J. Phys. ***G41*** *(2014)*

  - ➢ **Isotropic** single-particle distribution $(v_n = 0)$

$$\frac{dN_1}{d^2p} = \frac{1}{2\pi p_T}\frac{dN}{dp_T}$$

  - ➢ Only **dynamical correlations**

"Non-Flow" only

$$\frac{dN_2}{d^2p_1\, d^2p_2} \equiv \delta_2(p_1, p_2)$$

- Sequential **hierarchy** of correlations in N_c

  - ➢ $\delta_2 \gg \delta_4 \gg \cdots$

$$(v_n\{2\})^2 \overset{nonflow}{=} \langle \delta_{2,\,(n)} \rangle$$

  - ➢ Usually **imaginary** $v_n\{4\}$

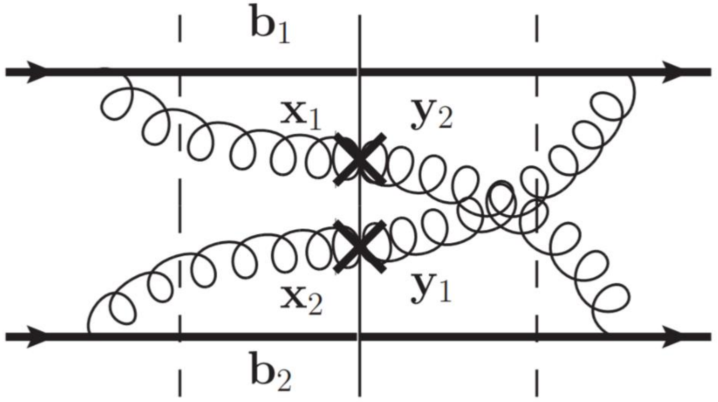
$$(v_n\{4\})^4 \overset{nonflow}{=} -2\,\mathrm{Var}\left(\delta_{2,\,(n)}\right) + \underbrace{\langle \delta_{4,\,(n)} \rangle}$$

Two-Gluon Correlations, After Color Averaging

Full semi-dilute / dense

Y. Kovchegov, D. Wertepny, Nucl. Phys. ***A906*** *(2013)*

- E.g)



$$\frac{d\sigma_{crossed}}{d^2k_1 dy_1 d^2k_2 dy_2} = \frac{1}{[2(2\pi)^3]^2} \int d^2B\, d^2b_1\, d^2b_2\, T_1(\boldsymbol{B}-\boldsymbol{b}_1)\, T_1(\boldsymbol{B}-\boldsymbol{b}_2)\, d^2x_1\, d^2y_1\, d^2x_2\, d^2y_2$$

$$\times \left[e^{-i\,\boldsymbol{k}_1\cdot(\boldsymbol{x}_1-\boldsymbol{y}_2)-i\,\boldsymbol{k}_2\cdot(\boldsymbol{x}_2-\boldsymbol{y}_1)} + e^{-i\,\boldsymbol{k}_1\cdot(\boldsymbol{x}_1-\boldsymbol{y}_2)+i\,\boldsymbol{k}_2\cdot(\boldsymbol{x}_2-\boldsymbol{y}_1)} \right]$$

$$\frac{16\,\alpha_s^2}{\pi^2} \frac{C_F}{2N_c} \frac{\boldsymbol{x}_1-\boldsymbol{b}_1}{|\boldsymbol{x}_1-\boldsymbol{b}_1|^2} \cdot \frac{\boldsymbol{y}_2-\boldsymbol{b}_2}{|\boldsymbol{y}_2-\boldsymbol{b}_2|^2} \frac{\boldsymbol{x}_2-\boldsymbol{b}_2}{|\boldsymbol{x}_2-\boldsymbol{b}_2|^2} \cdot \frac{\boldsymbol{y}_1-\boldsymbol{b}_1}{|\boldsymbol{y}_1-\boldsymbol{b}_1|^2}$$

$$\times \Big[Q(\boldsymbol{x}_1,\boldsymbol{y}_1,\boldsymbol{x}_2,\boldsymbol{y}_2) - Q(\boldsymbol{x}_1,\boldsymbol{y}_1,\boldsymbol{x}_2,\boldsymbol{b}_2) - Q(\boldsymbol{x}_1,\boldsymbol{y}_1,\boldsymbol{b}_2,\boldsymbol{y}_2) + S_G(\boldsymbol{x}_1,\boldsymbol{y}_1)$$

$$- Q(\boldsymbol{x}_1,\boldsymbol{b}_1,\boldsymbol{x}_2,\boldsymbol{y}_2) + Q(\boldsymbol{x}_1,\boldsymbol{b}_1,\boldsymbol{x}_2,\boldsymbol{b}_2) + Q(\boldsymbol{x}_1,\boldsymbol{b}_1,\boldsymbol{b}_2,\boldsymbol{y}_2) - S_G(\boldsymbol{x}_1,\boldsymbol{b}_1)$$

$$- Q(\boldsymbol{b}_1,\boldsymbol{y}_1,\boldsymbol{x}_2,\boldsymbol{y}_2) + Q(\boldsymbol{b}_1,\boldsymbol{y}_1,\boldsymbol{x}_2,\boldsymbol{b}_2) + Q(\boldsymbol{b}_1,\boldsymbol{y}_1,\boldsymbol{b}_2,\boldsymbol{y}_2) - S_G(\boldsymbol{b}_1,\boldsymbol{y}_1)$$

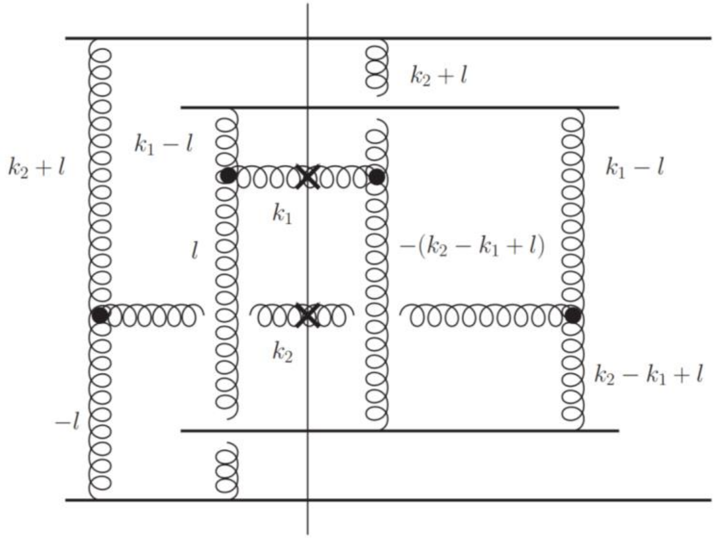
$$+ S_G(\boldsymbol{x}_2,\boldsymbol{y}_2) - S_G(\boldsymbol{x}_2,\boldsymbol{b}_2) - S_G(\boldsymbol{b}_2,\boldsymbol{y}_2) + 1 \Big]$$

Two-Gluon Correlations, After Color Averaging

High pT:
semi-dilute / semi-dilute

Y. Kovchegov, D. Wertepny, Nucl. Phys. ***A906*** *(2013)*

- E.g)

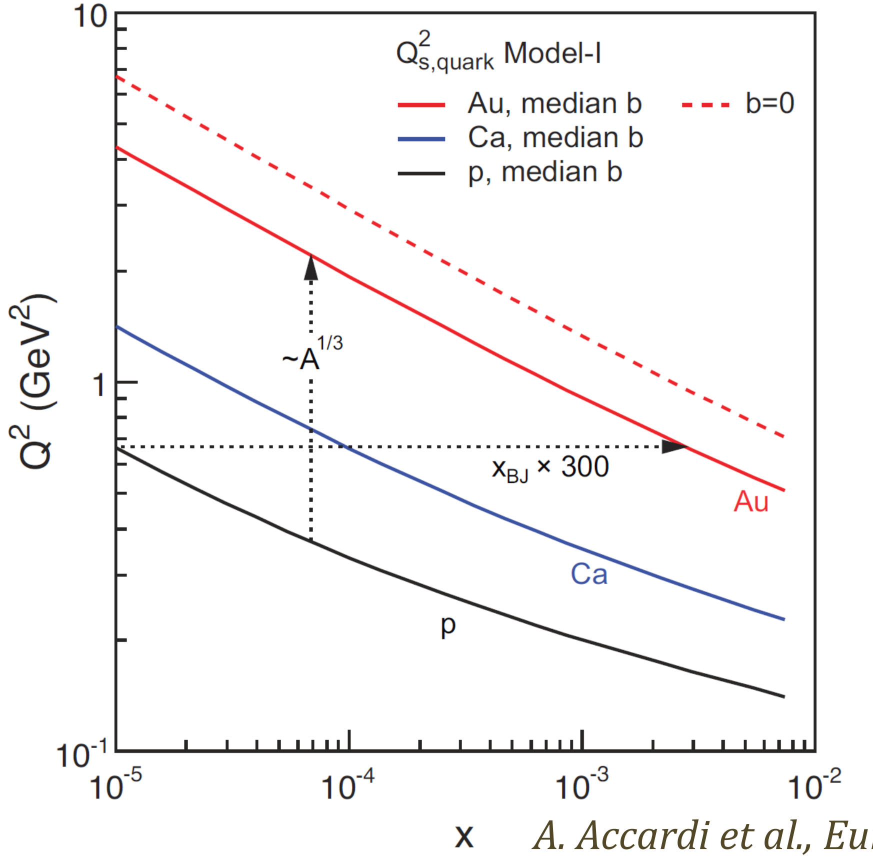


$$T_A^2(\vec{x}_\perp) \quad \propto T_B^2(\vec{x}_\perp)$$

$$\frac{d\sigma^{(corr)}_{crossed}}{d^2k_1 dy_1 d^2k_2 dy_2}\bigg|_{LO} = \frac{\alpha_s^2}{32\,\pi^4} \int d^2B\, d^2b\, [T_1(\boldsymbol{B}-\boldsymbol{b})]^2 \frac{Q_{s0}^4(\boldsymbol{b})}{\boldsymbol{k}_1^2\,\boldsymbol{k}_2^2}$$

$$\int \frac{d^2l}{(\boldsymbol{l}^2)^2\,((\boldsymbol{l}-\boldsymbol{k}_1+\boldsymbol{k}_2)^2)^2\,((\boldsymbol{k}_1-\boldsymbol{l})^2)^2\,((\boldsymbol{k}_2+\boldsymbol{l})^2)^2}$$
$$\times \left\{ \left[\boldsymbol{l}^2\,(\boldsymbol{k}_2+\boldsymbol{l})^2 + (\boldsymbol{k}_1-\boldsymbol{l})^2\,(\boldsymbol{l}-\boldsymbol{k}_1+\boldsymbol{k}_2)^2 - \boldsymbol{k}_1^2\,(\boldsymbol{k}_2-\boldsymbol{k}_1+2\,\boldsymbol{l})^2\right]\right.$$
$$\times \left[\boldsymbol{l}^2\,(\boldsymbol{k}_1-\boldsymbol{l})^2 + (\boldsymbol{k}_2+\boldsymbol{l})^2\,(\boldsymbol{l}-\boldsymbol{k}_1+\boldsymbol{k}_2)^2 - \boldsymbol{k}_2^2\,(\boldsymbol{k}_2-\boldsymbol{k}_1+2\,\boldsymbol{l})^2\right]$$
$$\left. + 4\,\boldsymbol{l}^2\,(\boldsymbol{l}-\boldsymbol{k}_1+\boldsymbol{k}_2)^2\,\left[((\boldsymbol{k}_1-\boldsymbol{l})^2)^2 + ((\boldsymbol{k}_2+\boldsymbol{l})^2)^2\right] \right\} + (\boldsymbol{k}_2 \to -\boldsymbol{k}_2)$$

High pT:
semi-dilute / semi-dilute



A. Accardi et al., Eur. Phys. J. ***A52*** *(2016)*

M.D.S. *et al., in preparation*

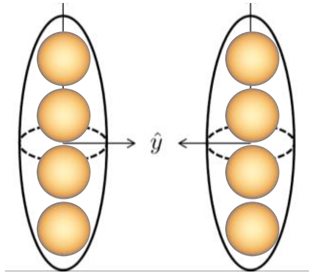
$$\delta_2(p_1,p_2) \overset{\text{L.O.}}{=} \left(\int d^2x_\perp T_A^2(\vec{x}_\perp) T_B^2(\vec{x}_\perp) \right) f(p_1,p_2)$$

$$\delta_2(p_1,p_1) \overset{\text{N.L.O.}}{=} \left(\int d^2x_\perp T_A^3(\vec{x}_\perp) T_B^3(\vec{x}_\perp) \right) g(p_1,p_2)$$

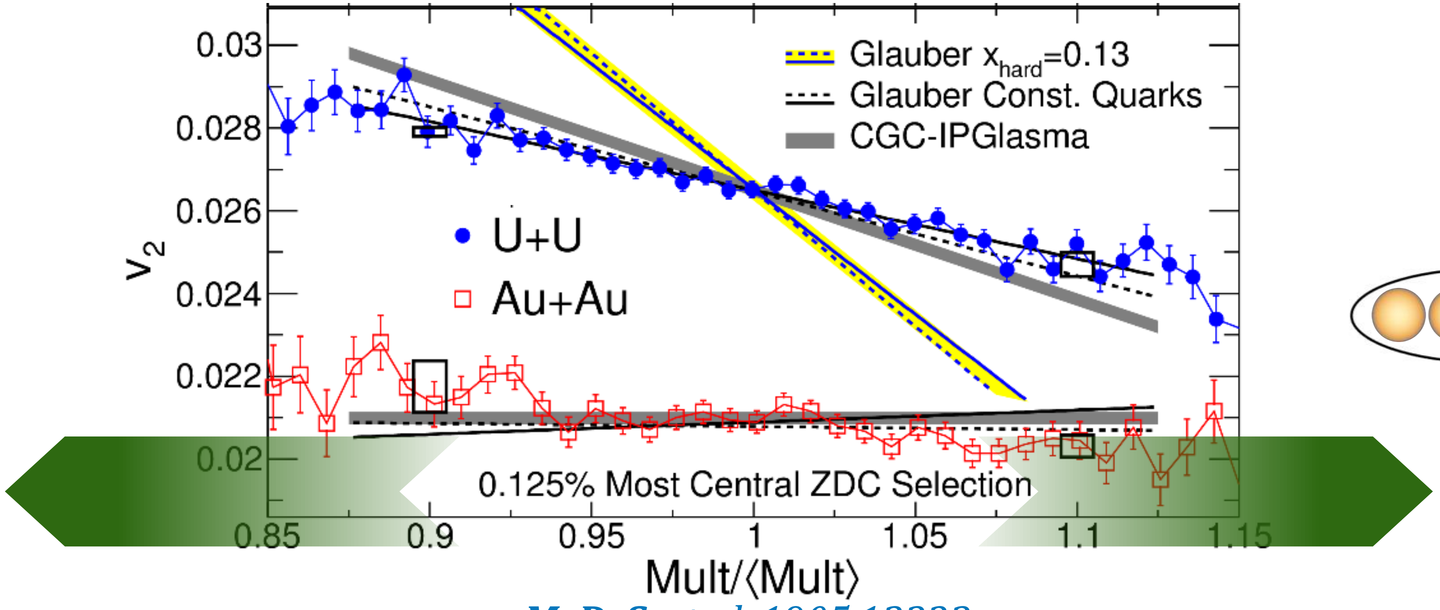
- Two-gluon correlations at high-pT
  - Momentum dependent coefficients **cancel in ratios**
  - **Can compare apples to apples between hydro and CGC**

Ultracentral Collisions of Deformed Ions

$N\,(1 \times 1)$

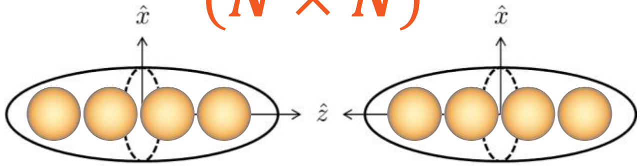


Side-On Geometry



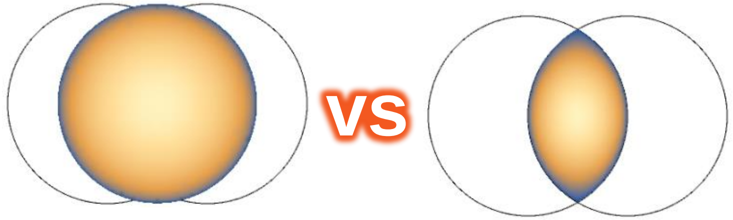
M. D. S. et al, 1905.13323

$(N \times N)$



Tip-On Geometry

Model sensitivity



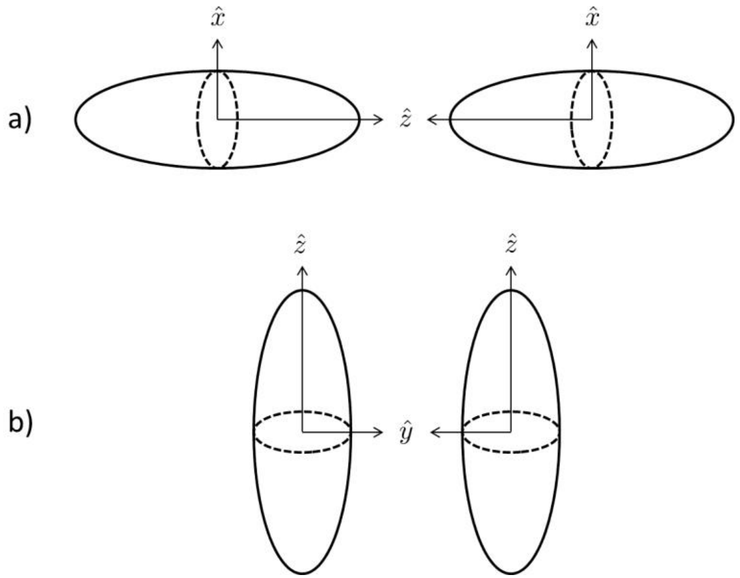
Binary collision: Same for all b

Overlap region: b-dependent

- Ultracentral $(b \approx 0)$ collisions are sensitive to **nonspherical deformations** of the nuclear structure

❖ Sensitive to the microscopic **sub-nucleonic mechanisms of entropy deposition**

Deformed Ions as Model Discriminators



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

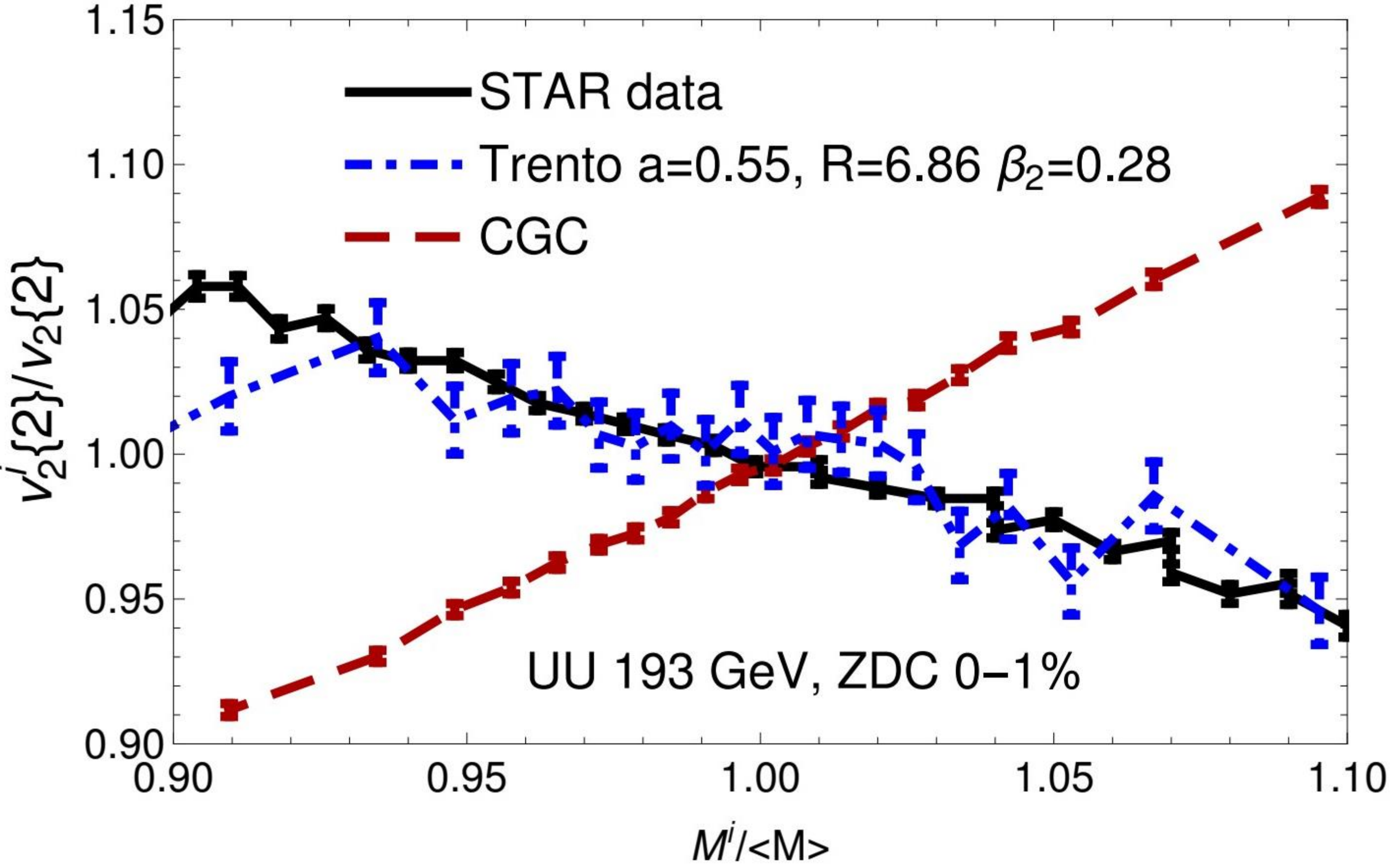
$$\frac{C_{tip-on-tip}(\boldsymbol{k}_1, y_1, \boldsymbol{k}_2, y_2)\big|_{LO}}{C_{side-on-side}(\boldsymbol{k}_1, y_1, \boldsymbol{k}_2, y_2)\big|_{LO}} = \frac{1}{\lambda} \approx 1.26 \quad (\text{for } U+U)$$

Y. Kovchegov, D. Wertepny, Nucl. Phys. ***A925*** *(2014)*

We conclude that, at least at the lowest order, the two-gluon correlations behave in an exactly opposite way from hydrodynamics: while hydrodynamic contribution to v_2 is ellipticity-driven, and is hence larger in the side-on-side

- For ultracentral collisions of ellipsoidal uranium, the multiplicity dependence is expected to be opposite from hydro
  - ➢ CGC doesn't care about the geometry itself; only the multiplicity

Qualitatively Different Multiplicity Dependence

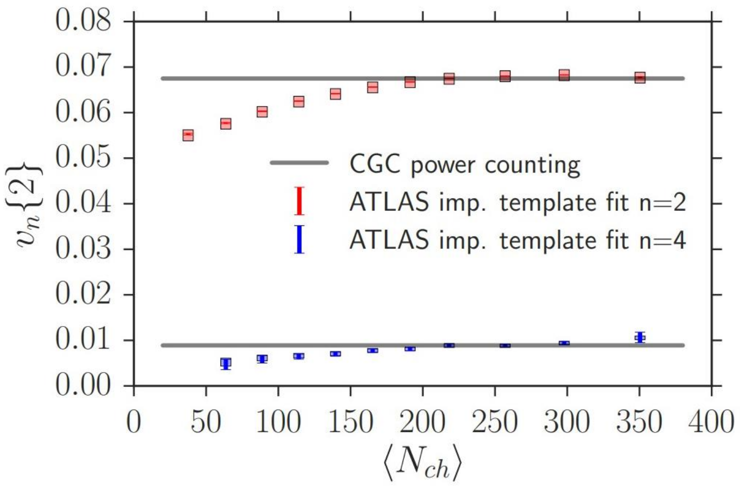


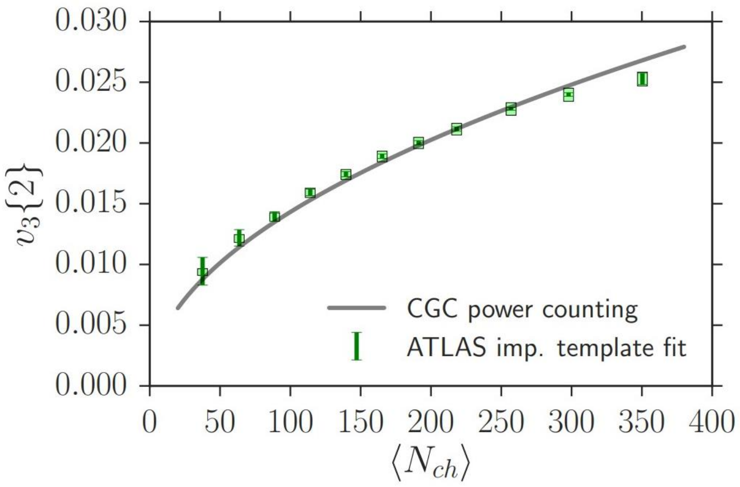
***M. D. S.** et al, 1905.13323*

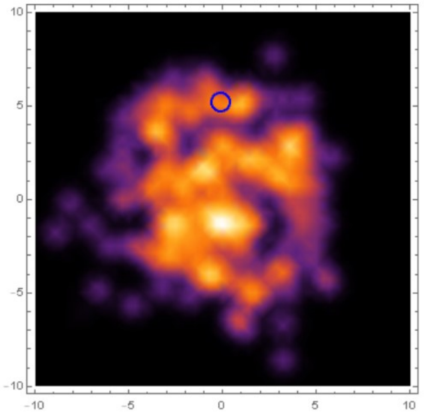
A Continuation of the MSTSV Multiplicity Story

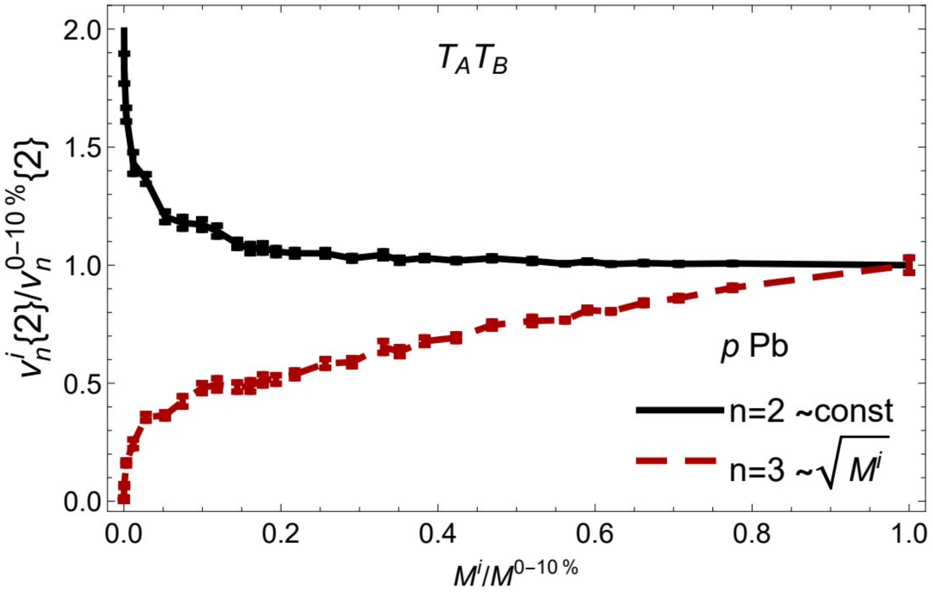
- MSTV: Loose power counting based on gluon densities

- Even for a "lumpy" system, that scaling is seen in our simulations (here p Pb)

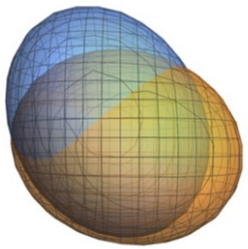


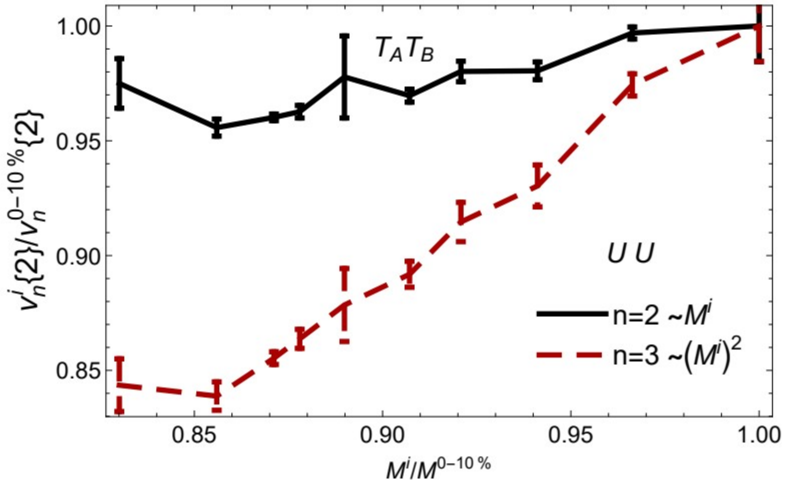


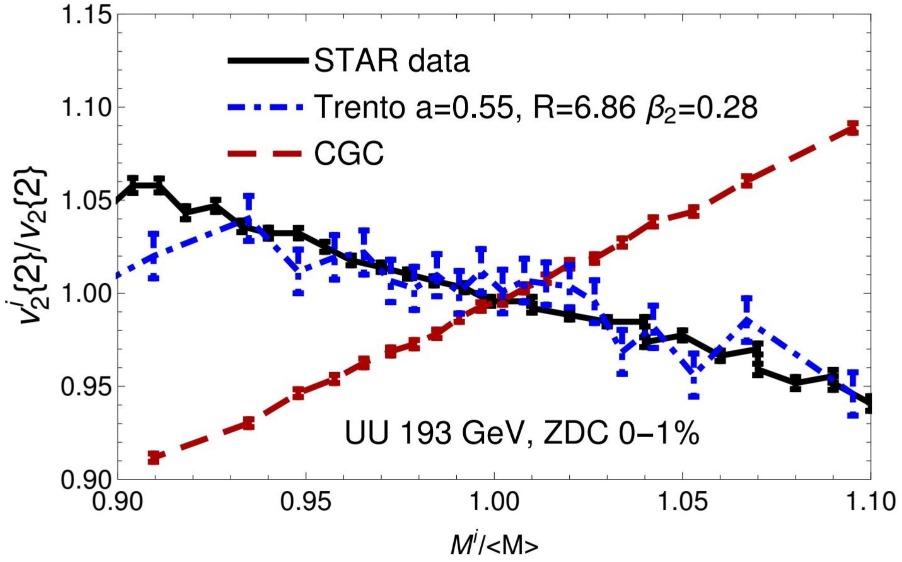




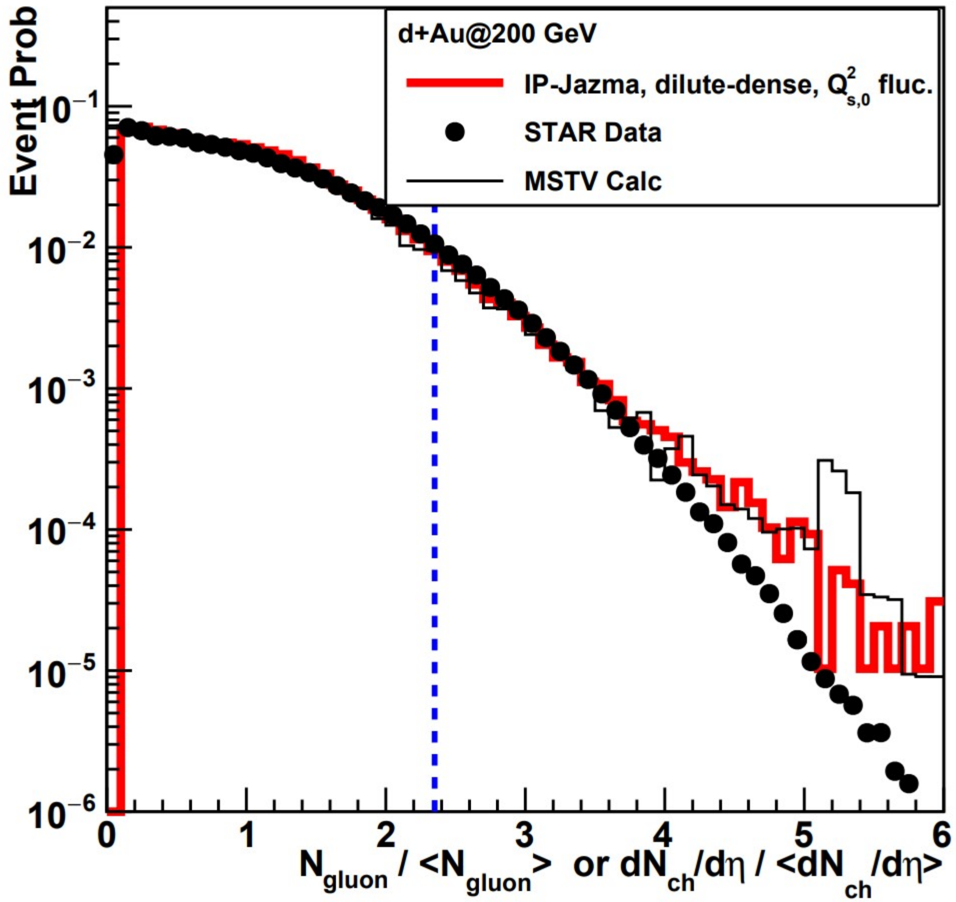
- MSTV: Loose power counting based on gluon densities
- Even for a “lumpy” system, that scaling is seen in our simulations (here p Pb)
- Non-spherical deformations qualitatively change the multiplicity dependence



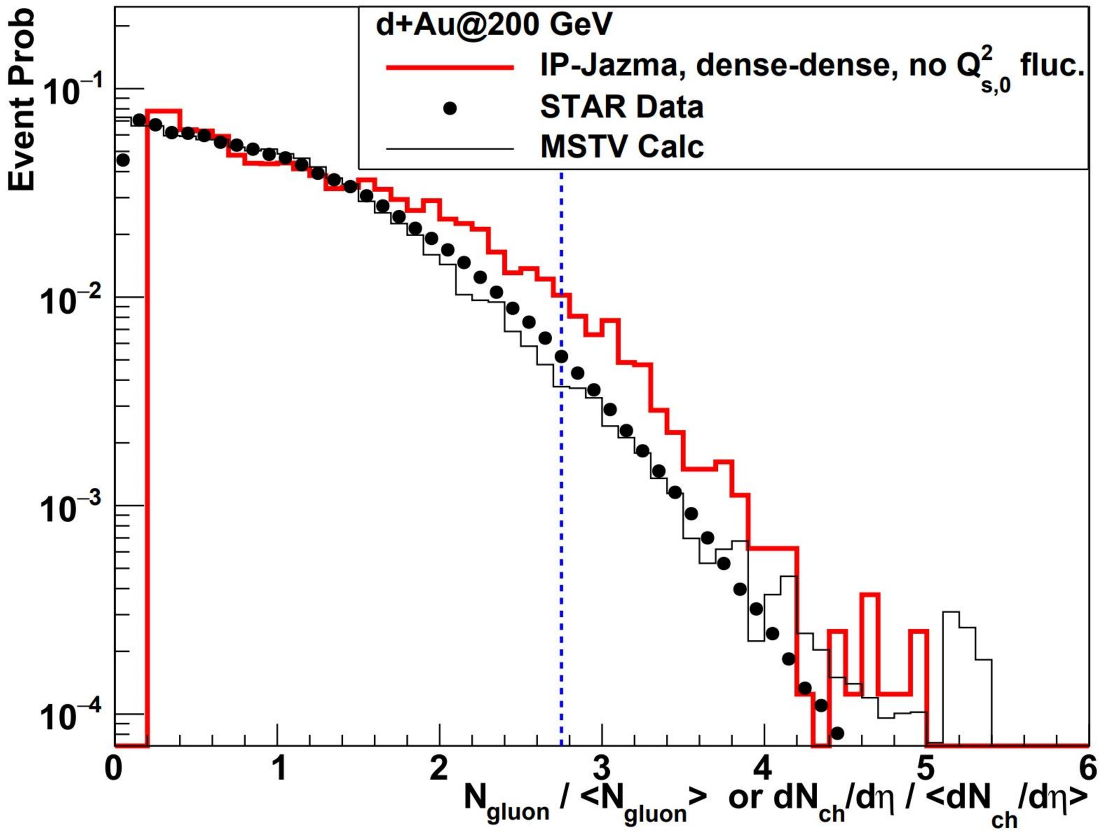




IP-Jazma: The Null Hypothesis



J. Nagle and W. Zajc, Phys.Rev.C 99 (2019)



- Many crucial features of the CGC calculations can be reproduced **without** event by event color field fluctuations

Initial Eccentricities Without Color Fields

- Flow harmonics from IP-Glasma are well approximated by an initial-state model with no color field fluctuations

$$s_0 \sim \sqrt{T_A T_B}$$

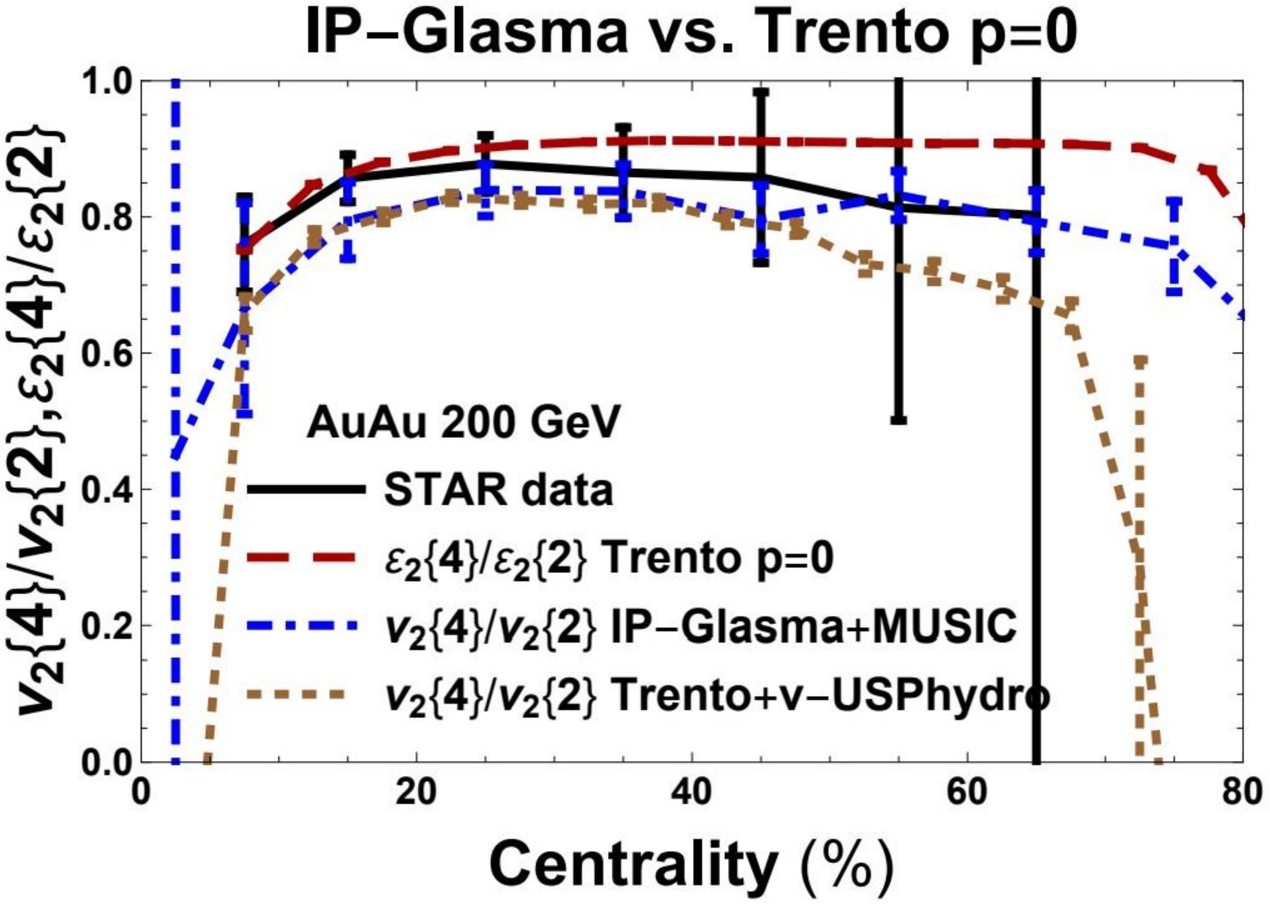
J. E. Bernhard et al., Phys.Rev.C 94 (2016)

Closest allowed functional form to the initial energy density?

$$\epsilon_0 \sim T_A T_B$$

G. Chen et al., Phys.Rev.C 92 (2015)

***M. D. S.** et al,*
arXiv:1910.03677



Questions to Ponder...

- What are the implications for the many-body cumulants of keeping versus averaging over event-by event color fluctuations?

- Are individual color-field configurations well-defined “events”?

- Is the positive / negative slope of the multiplicity dependence $v_2(N_{ch})$ in ultracentral collisions of deformed ions a robust discriminator of hydro vs. non-hydro models?

- Are any color field fluctuations **required** to describe the gross features of the data?