v_2 Cumulant Measurements and Eccentricity Fluctuations for the STAR Collaboration

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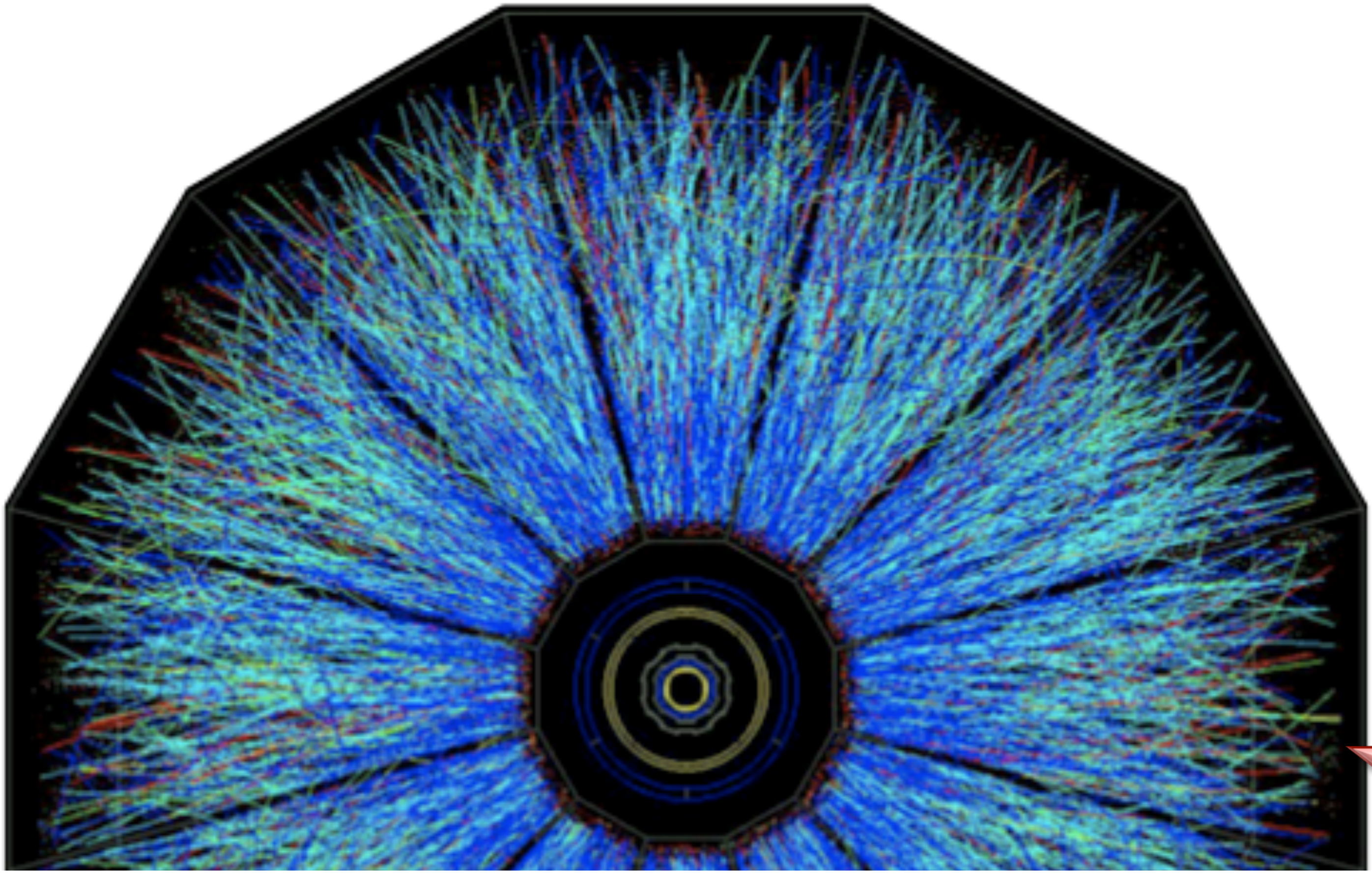
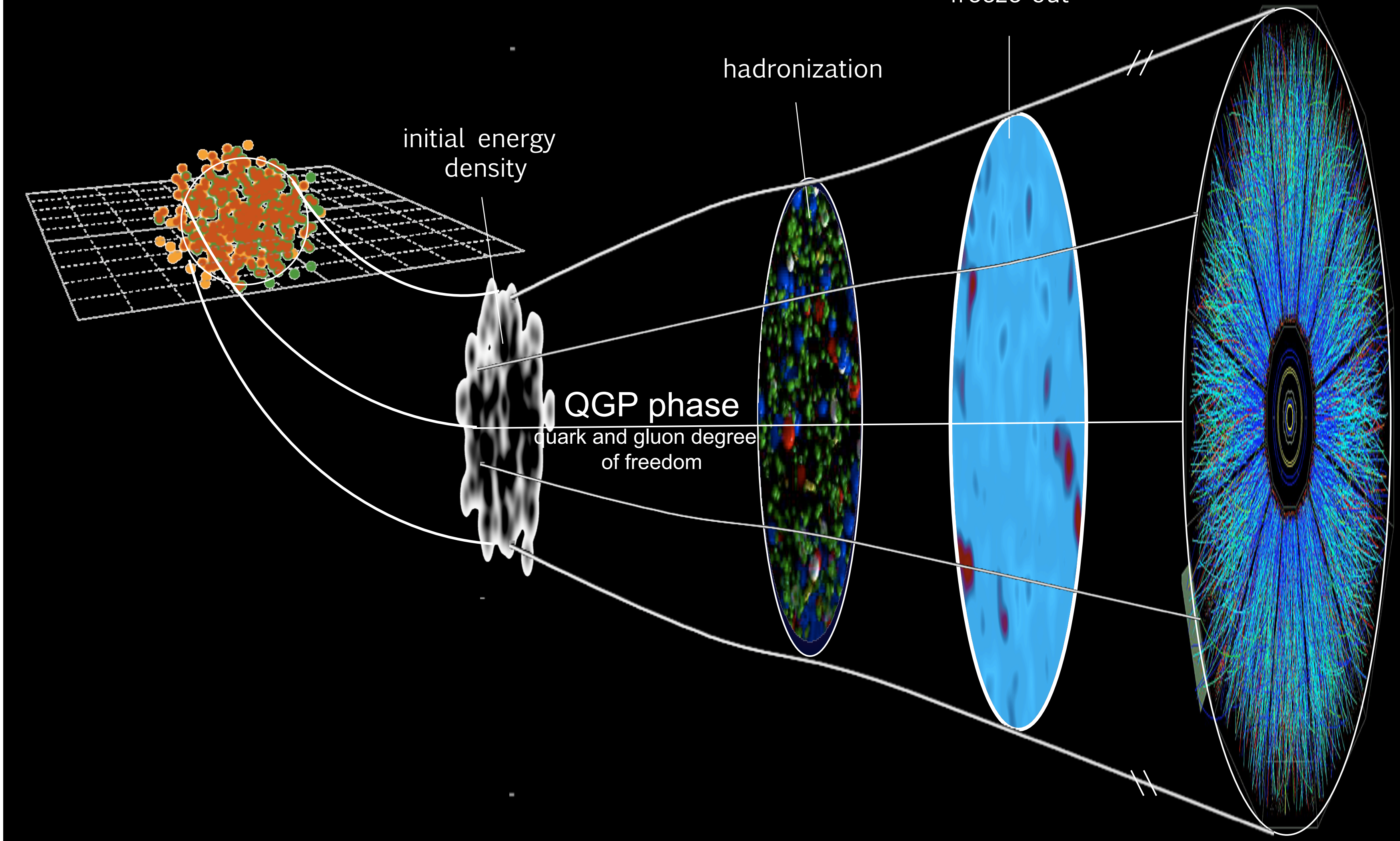


STAR

Saturation, CGC, and Glasma, May 10th, 2010

Schematic Diagram of the Conjectured Expansion



initial energy density

QGP phase

quark and gluon degree of freedom

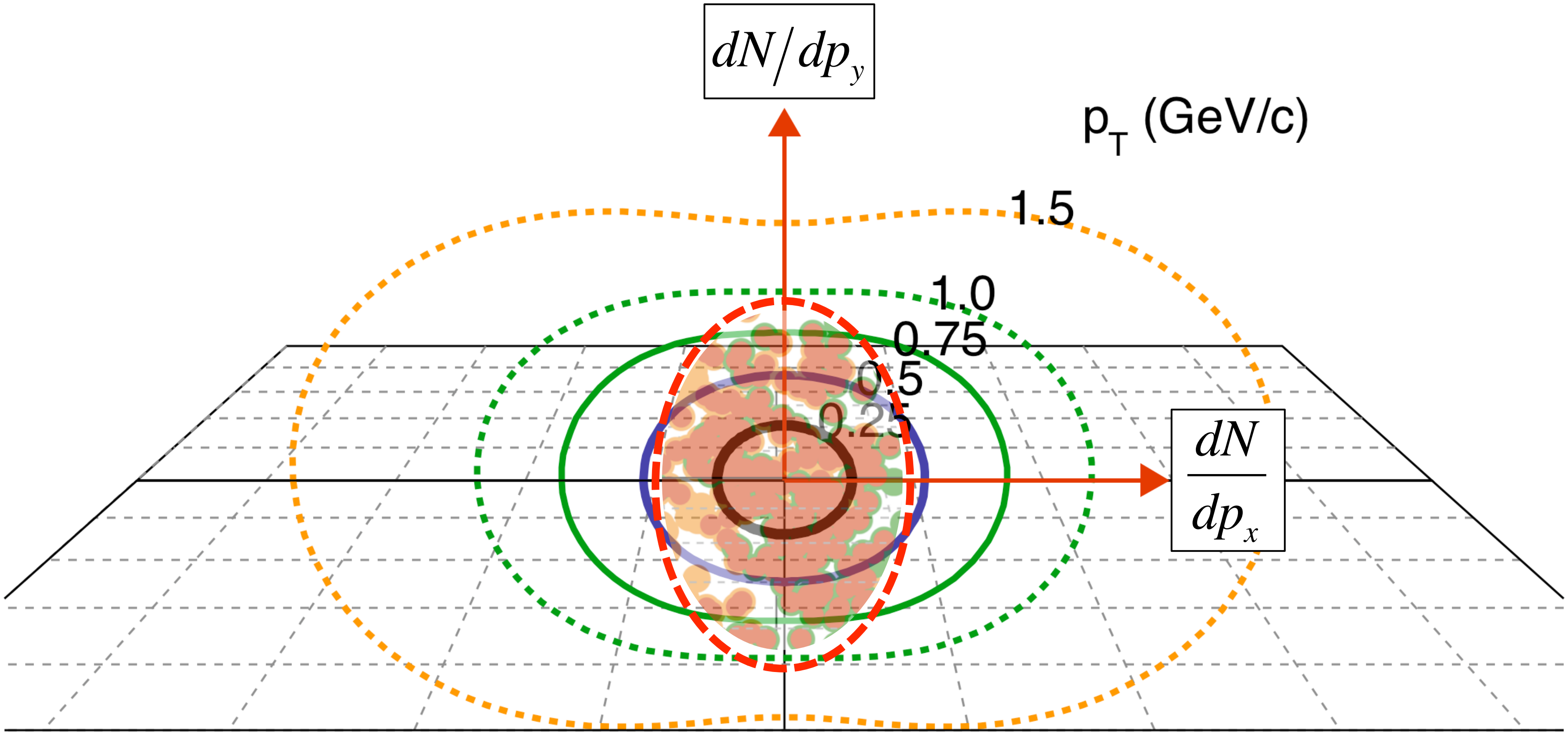
hadronization

kinetic freeze-out

distributions and correlations of produced particles

Azimuthal Distributions

Collision of two Lorentz contracted Gold nuclei



Are particles emitted at random angles?

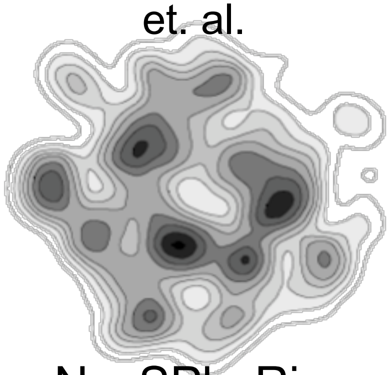
No. They remember the initial geometry.

Geometry Fluctuations

And the initial geometry can be complex.

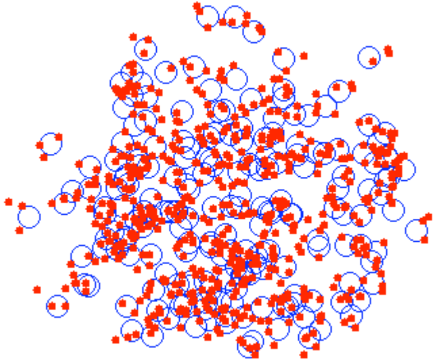
v_2 fluctuations from eccentricity fluctuations will lead to a difference between $v_2\{2\}$ and $v_2\{4\}$

Hama, Grasi, Kodama, et. al.



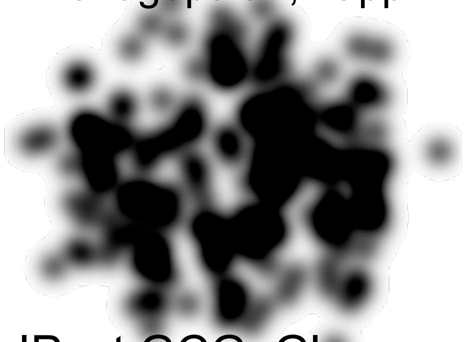
NexSPheRio

Kumar Pruthi, Sorensen



Additive Quark Model

Dumitru, Gelis, McLerran, Venugopalan, Lappi



IPsat GCG, Glasma

H. Kowalski, T. Lappi and R. Venugopalan, Phys. Rev. Lett. **100**, 022303 [arXiv:0705.3047 [hep-ph]].

I'll present STAR data on $v_2\{2\}$ and $v_2\{4\}$ and compare that data to models for the initial eccentricity

v_2 Fluctuations Test Initial Conditions

Data show v_2 depends on eccentricity: $v_2 = c^*\varepsilon$ where c can depend on dN/dy, √snn, etc.

$$\sigma_{v2}^2 \approx c^2\sigma_\varepsilon^2 + \varepsilon^2\sigma_c^2 + \text{cross-terms}$$

When we compare to initial eccentricity models we will neglect σ_c so that

$$\sigma_{v2}/v_2 = \sigma_\varepsilon/\varepsilon$$

Vogel, Torrieri, and Bleicher argue that $\varepsilon^2\sigma_c^2$ (Δ_{dyn}^2) is proportional to the Knudsen number (nucl-th/0703031) so $\sigma_c^2=0$ is equivalent to assuming zero viscosity

Relationship of σ_{v2} to $v_2\{2\}$ and $v_2\{4\}$

$$\sigma_{v_n}^2 = \langle v_n v_n \rangle - \langle v_n \rangle \langle v_n \rangle$$

$$v_2^2\{2\} = \left\langle \cos\left(2(\varphi_1 - \varphi_2)\right)\right\rangle = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + \delta_{non-RP}$$

$$v_2^2\{4\} = \sqrt{2v_2^2 v_2^2 - v_2^4} \approx \langle v_2 \rangle^2 - \sigma_{v_2}^2$$

$$\boxed{v_2^2\{2\} - v_2^2\{4\} \equiv \sigma_{tot}^2 \approx \delta_2 + 2\sigma_{v_2}^2}$$

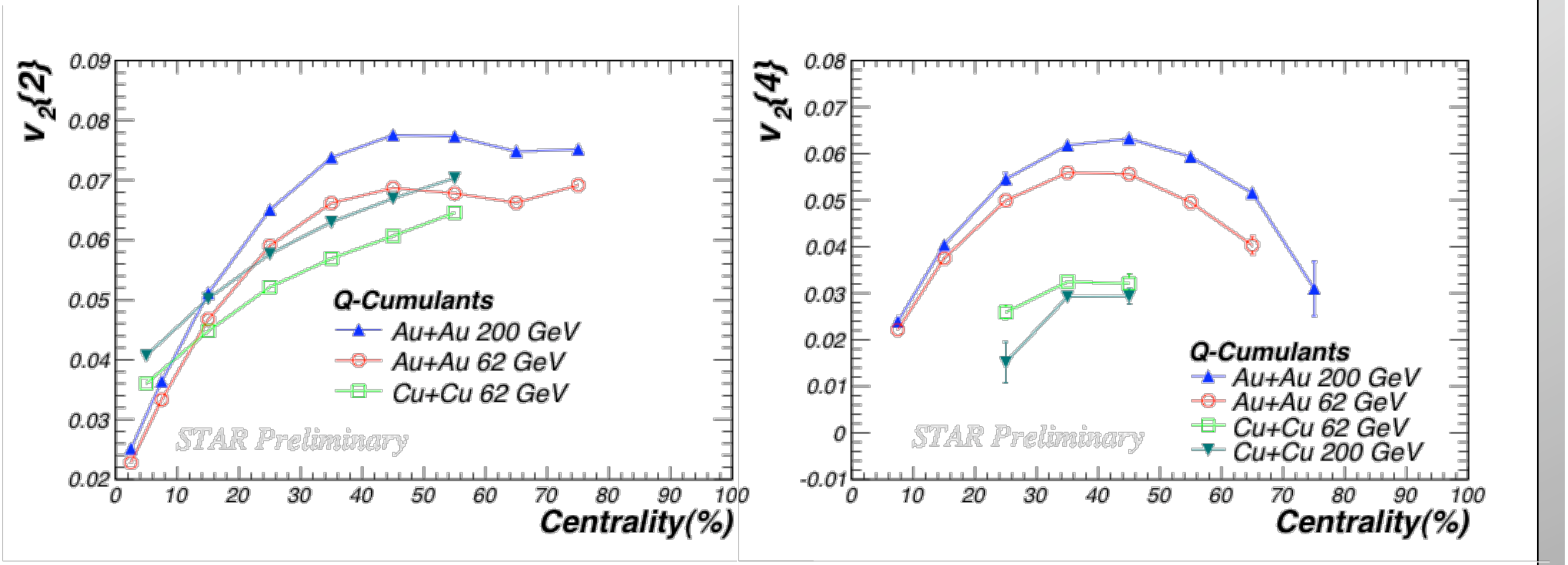
Ollitrault, Poskanzer, Voloshin:
Nucl.Phys.A830:279C-282C,2009

Eccentricity fluctuations should show up in the difference between $v_2\{2\}$ and $v_2\{4\}$: but so should non-flow correlations

Note that non-flow is defined relative to either the reaction- or participant-plane

$$\delta_n = v_n^2\{2\} - \left\langle \cos\left(n(\varphi - \psi)\right)^2 \right\rangle$$

STAR Data at 2 Energies and 2 Systems

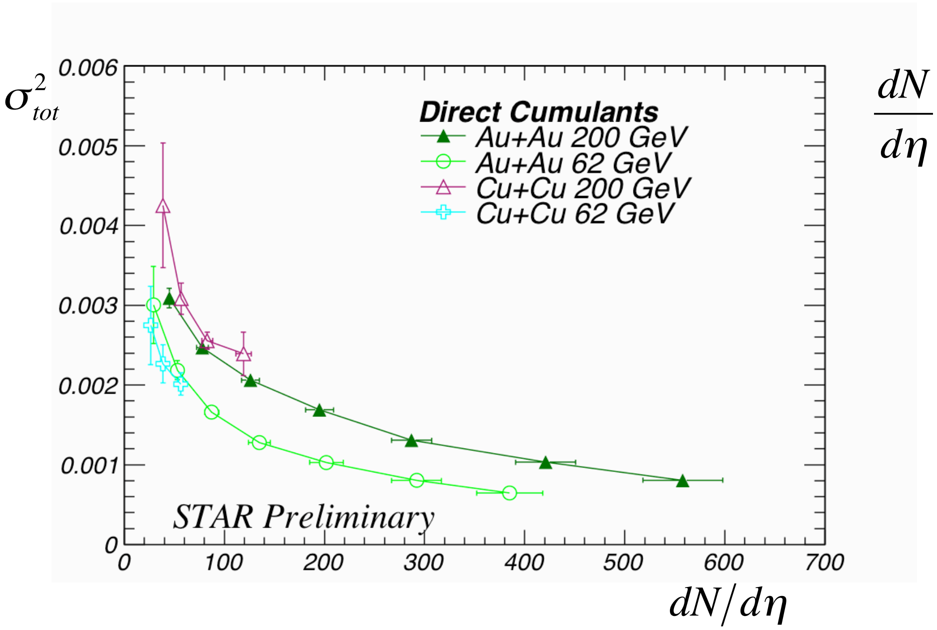


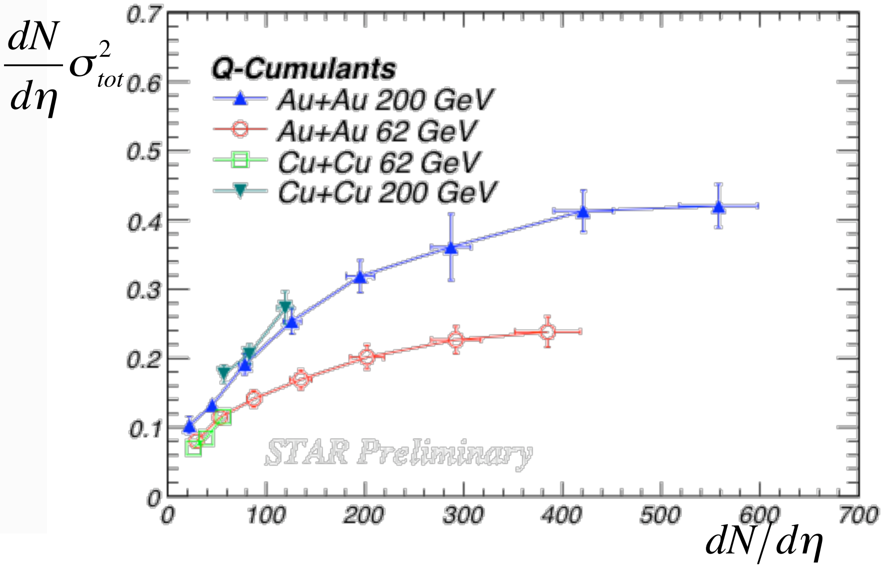
$v_2\{2\}$ and $v_2\{4\}$ have been measured by STAR for Au+Au and Cu+Cu collisions at 62.4 and 200 GeV

Direct Q-cumulant calculation is used Priv. Com.: Voloshin, Bilandzic, Snellings

We will study $\sigma_{tot}^2 = v_2\{2\}^2 - v_2\{4\}^2$

The total width $\sigma_{tot}^2 = v_2\{2\}^2 - v_2\{4\}^2$





Width falls with multiplicity but deviates from the 1/N expected for dilution of correlations with increased combinatorics

Width scales smoothly from Cu+Cu to Au+Au when plotted vs dN/dη

Width scaled by dN/dη increases with centrality (violating a simple linear superposition model for correlations).

Eccentricity Models

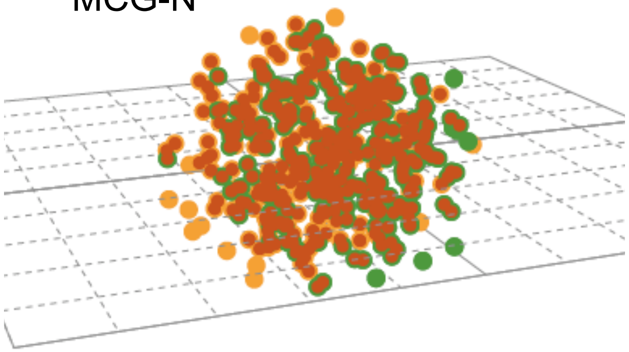
We will compare this width to the widths predicted from three eccentricity models

Model 1: Monte Carlo Glauber with nucleons treated as the participants (MCG-N)

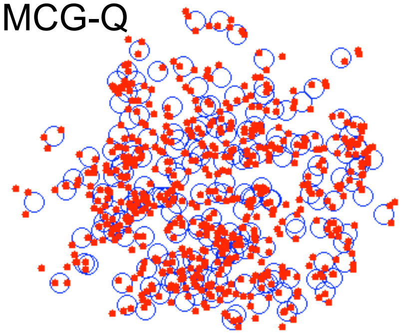
Model 2: Monte Carlo Glauber with constituent quarks treated as the participants (MCG-Q)

Model 3: factorized Kharzeev-Levin-Nardi Color Glass Condensate model (fKLN-CGC)

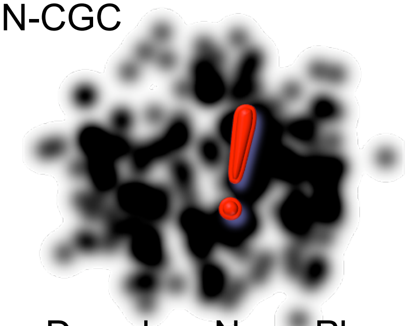
MCG-N



MCG-Q

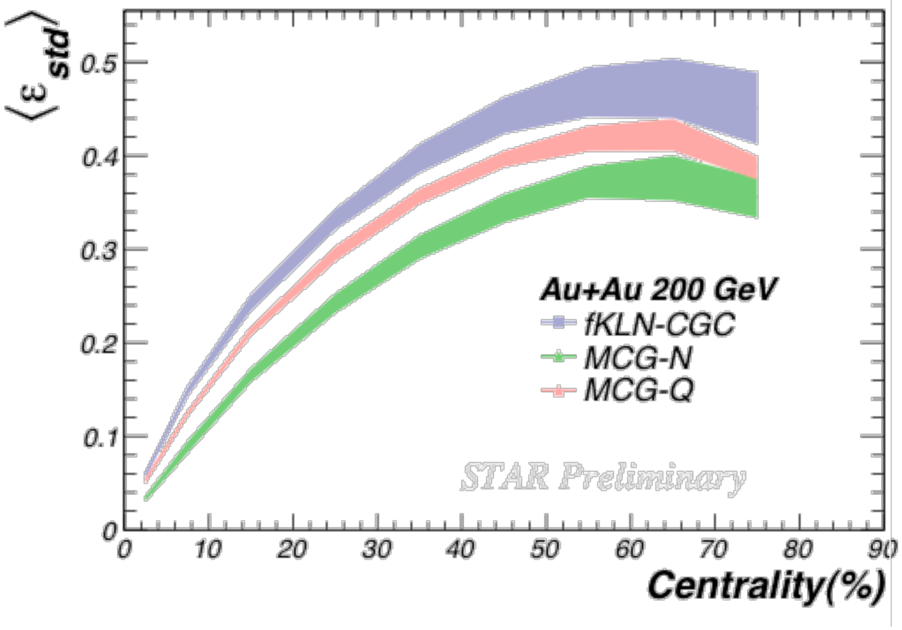


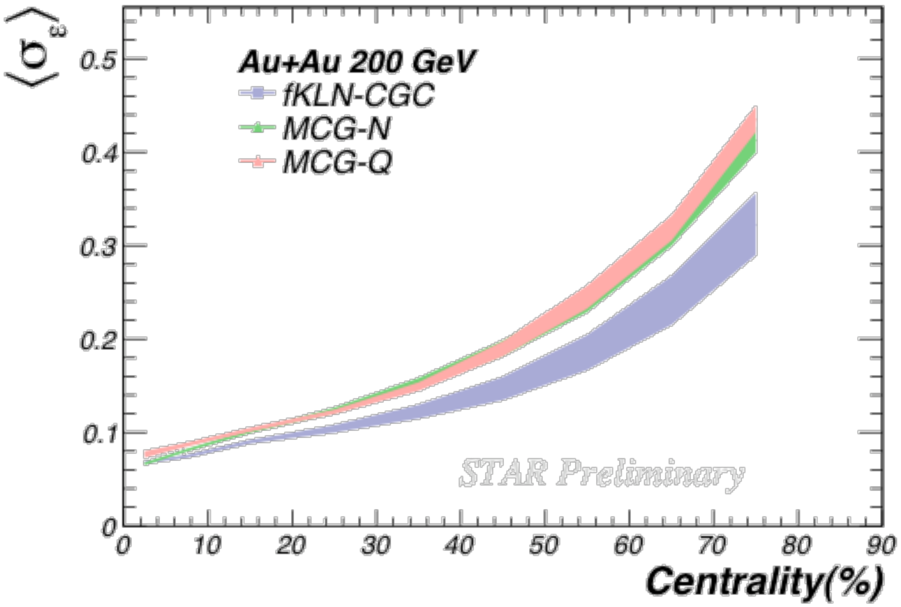
fKLN-CGC



Drescher, Nara: Phys. Rev. C 75: 034905,2007

Model Results Au+Au





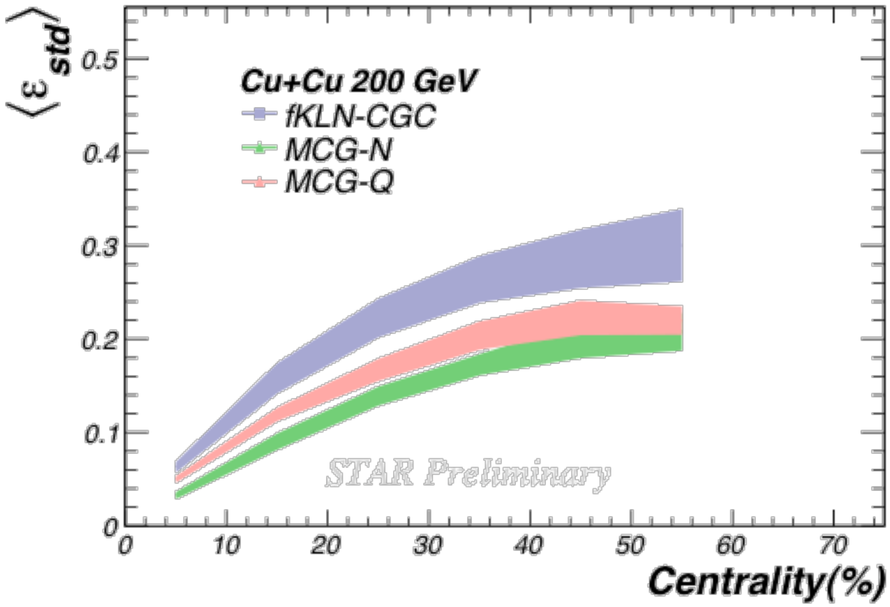
Centrality bins are defined according to the multiplicity from the model: multiplicity modeled using 2-component model (x_{hard}=0.11)

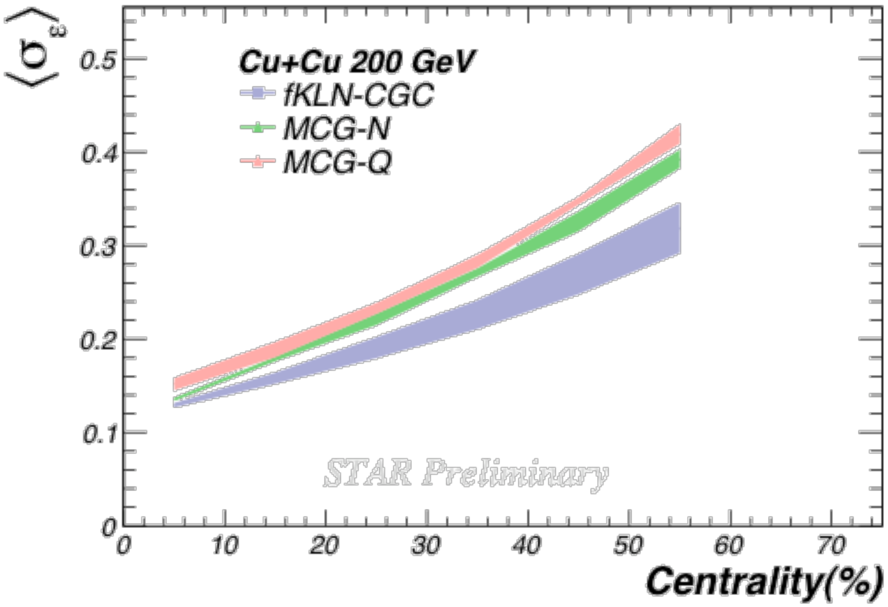
for eccentricity: fKLN-CGC > MCG-Q > MCG-N

for fluctuations in eccentricity: MCG-Q >~ MCG-N > fKLN-CGC

for $\sigma_\varepsilon/\varepsilon$: MCG-N > MCG-Q > fKLN-CGC

Model Results Cu+Cu





The same trends hold for Cu+Cu collisions

for eccentricity: fKLN-CGC > MCG-Q > MCG-N

for fluctuations in eccentricity: MCG-Q > MCG-N > fKLN-CGC

for $\sigma_{\varepsilon}/\varepsilon$: MCG-N > MCG-Q > fKLN-CGC

Comparing Data to Models

$v_2\{2\}$ and $v_2\{4\}$ provide powerful discrimination between models. In the following slides we'll compare data:

$$\sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}} = \frac{\sigma_{v_2}}{v_2}\sqrt{\frac{1+\delta_2/2\sigma_{v_2}^2}{1+\delta_2/2v_2^2}} = \frac{\sigma_{v_2}}{v_2}\bigg|_{\max}$$

to model results for:

$$\frac{\sigma_\varepsilon}{\varepsilon} = \sqrt{\frac{\varepsilon^2\{2\} - \varepsilon^2\{4\}}{2\varepsilon^2\{4\}}}$$

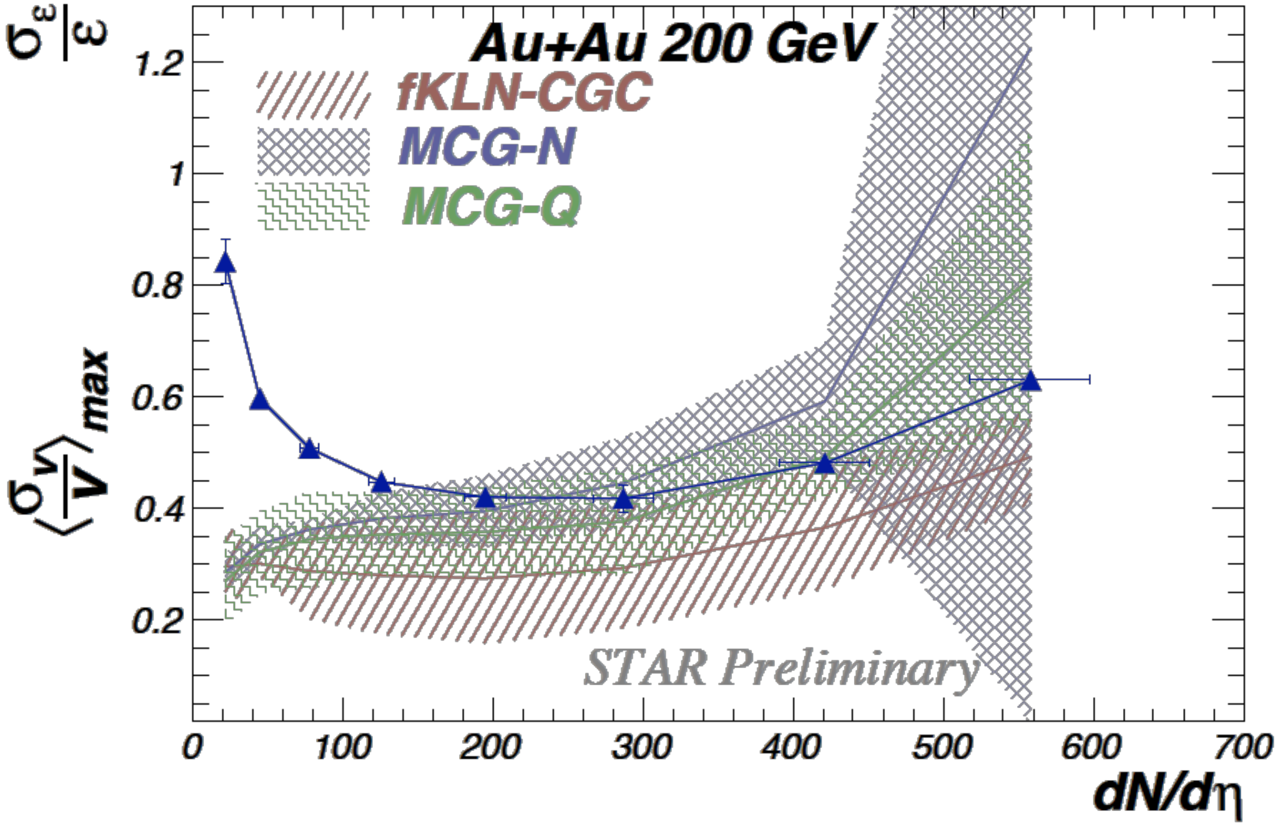
Bhalerao and Ollitrault:
Phys.Lett.B641:260-264,2006

In case that non-flow dominates the width

$$\sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}} = \sqrt{\frac{1}{1+2v_2^2/\delta_2}}$$

Ratio is 1 if non-flow dominates and $v_2=0$ or $\sqrt{(4/\pi-1)}$ if ε fluctuations dominate

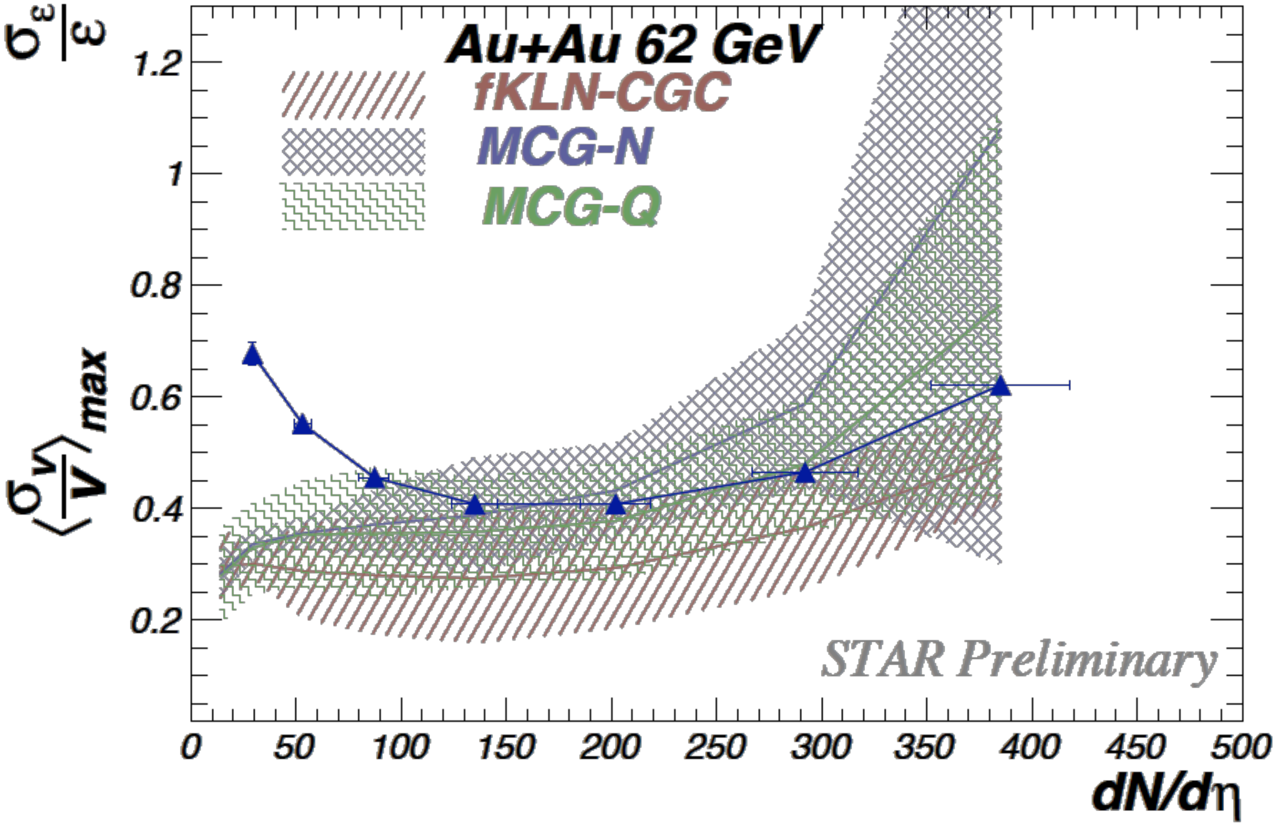
Comparison of models to σ_{tot}



For central 200 GeV Au+Au collisions, the width expected from MCG-N eccentricity fluctuations nearly exceeds the total width of data

MCG-Q and fKLN-CGC remain smaller and consistent with $\delta_2>0$

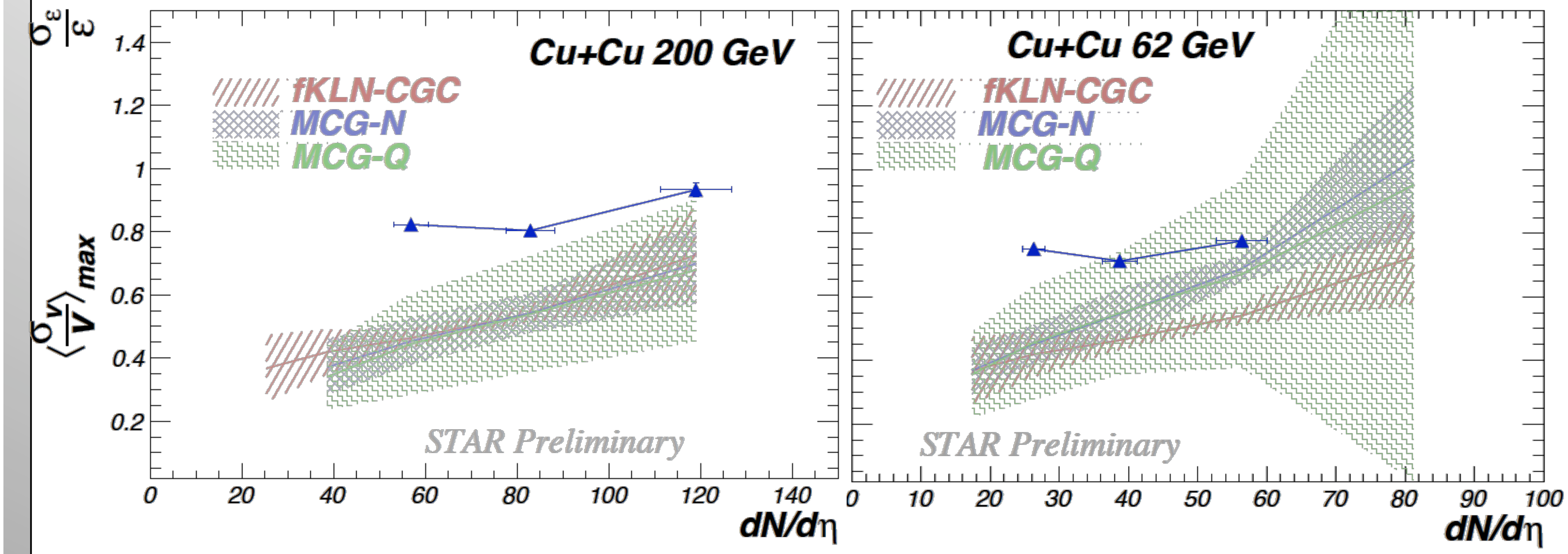
Comparison of models to σ_{tot}



For central 62.4 GeV Au+Au collisions, the width expected from MCG-N and MCG-Q ε fluctuations nearly exceeds the total width of data

Only fKLN-CGC remains smaller and consistent with $\delta_2>0$

Comparison of models to σ_{tot}



For Cu+Cu collisions at both energies, data is wider than all three models

Data are limited by difficulty in determining $v_2\{4\}$ at small multiplicities

What About Non-flow?

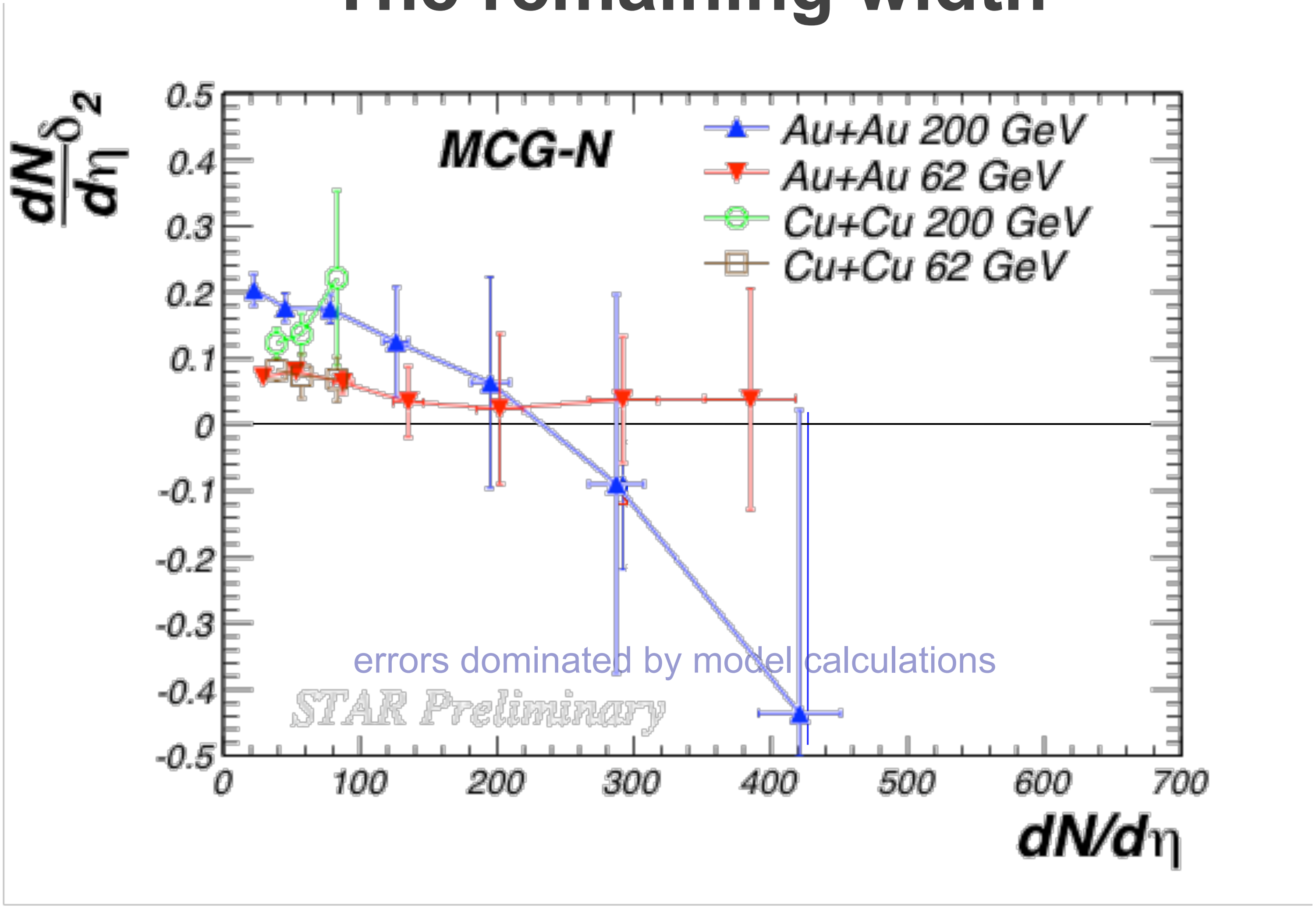
The previous comparisons can be extended by calculating the width that remains after subtracting off the eccentricity fluctuations implied by each model, *e.g.*

$$\delta_2^{MCG-N} = \sigma_{tot}^2 - 2\left(v_2 \frac{\sigma_\varepsilon^{MCG-N}}{\varepsilon^{MCG-N}} \right)^2$$

Let’s see what that looks like for each model.

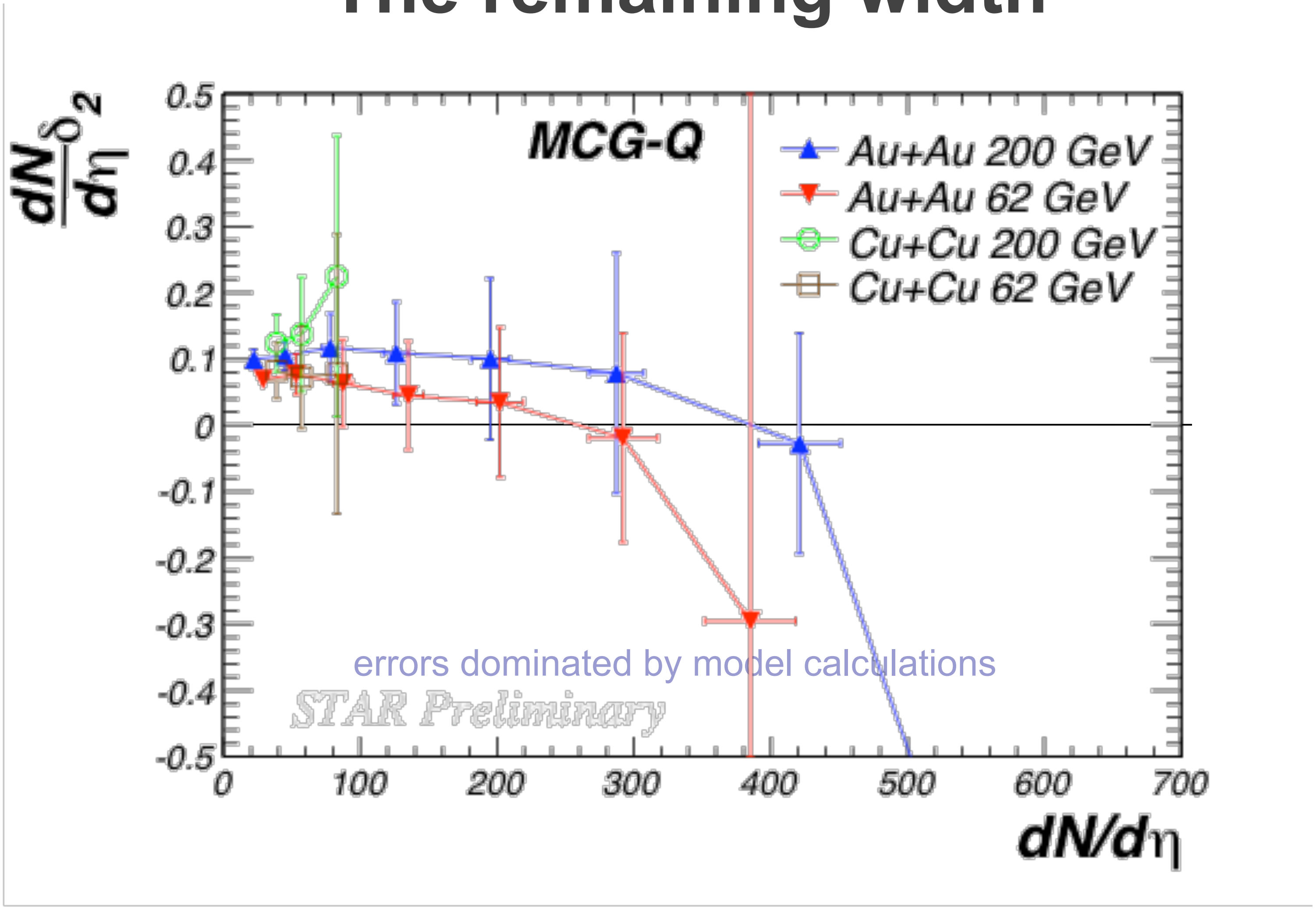
We’ll also scale δ_2 by dN/dη to account for dilution of correlations with increased multiplicity

The remaining width



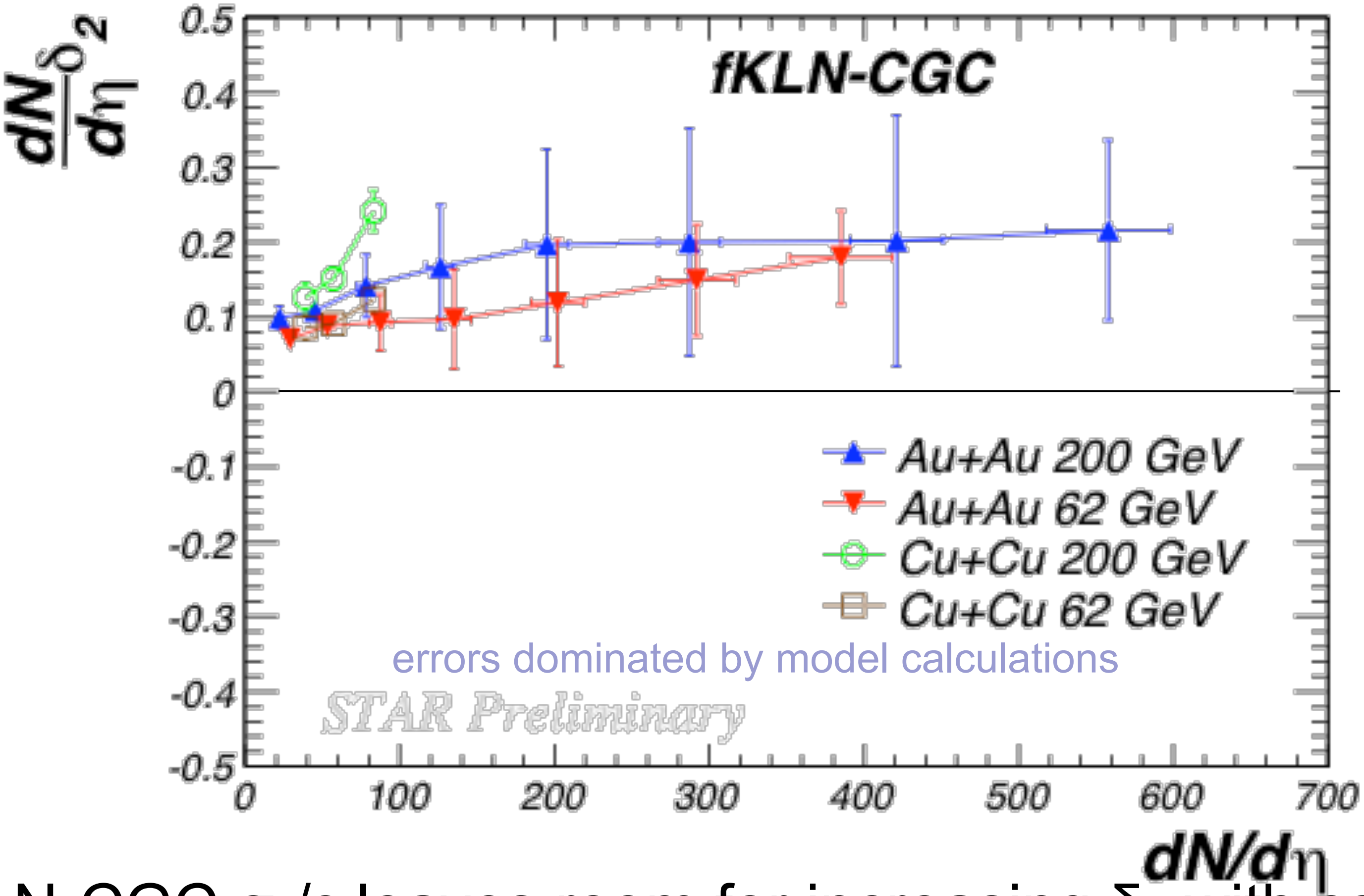
For the MCG-N eccentricity fluctuations to be correct, non-flow would need to be nearly zero or negative in central Au+Au collisions

The remaining width



The MCG-Q eccentricity fluctuations do not require negative non-flow in central 200 GeV Au+Au but still do for 62.4 GeV

The remaining width



fKLN-CGC $\sigma_\varepsilon/\varepsilon$ leaves room for increasing δ_2 with centrality:

σ_ε and ε calculations can be supplemented with predictions for δ_2 to check for consistency

v_2/ε scaling

Now we can address v_2/ε scaling in a consistent way:

v_2 is determined assuming v_2 fluctuations as predicted by the eccentricity fluctuations of each model

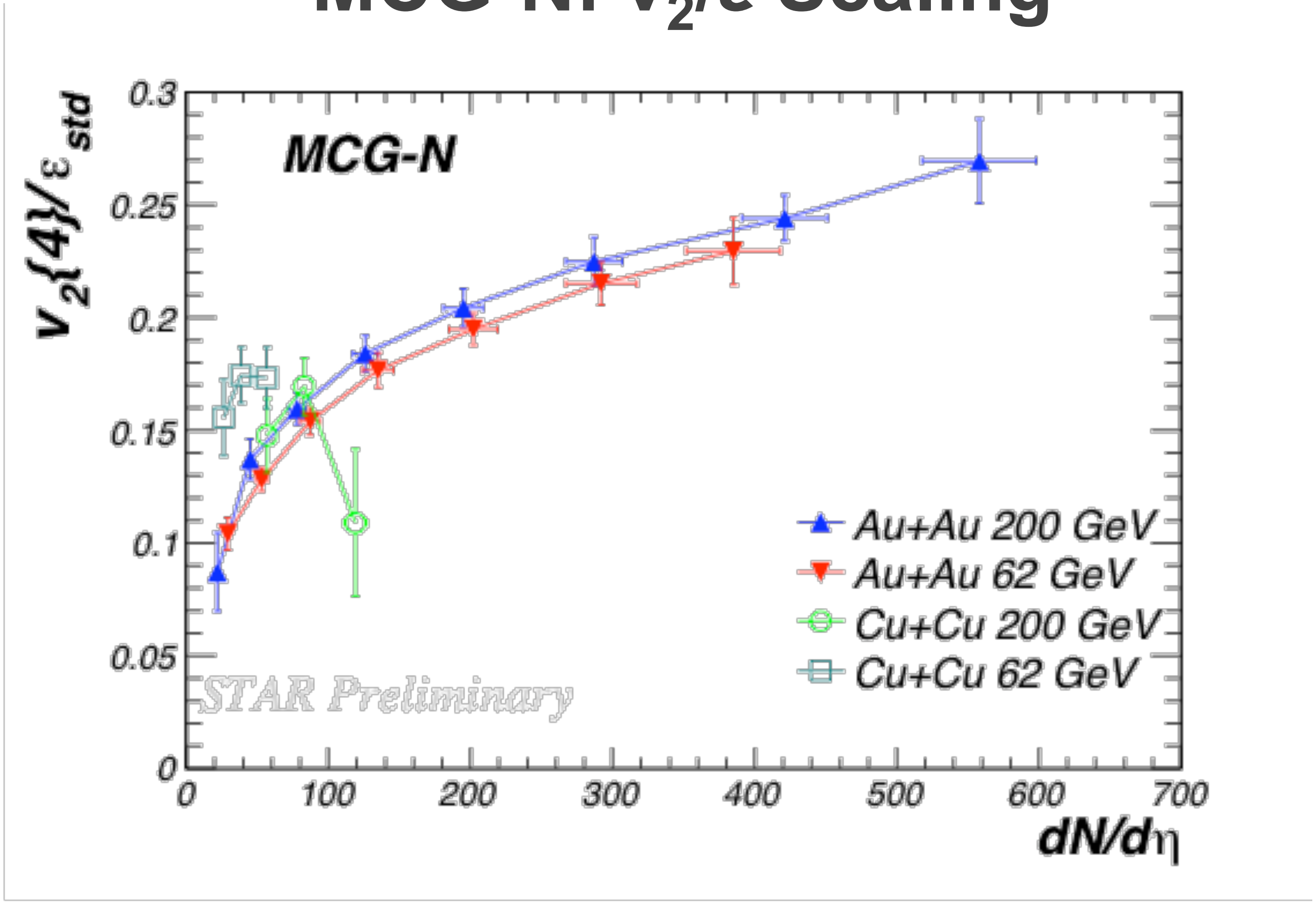
the eccentricity is calculated from the same model

It turns out that in the case that eccentricity fluctuations dominate v_2 fluctuations, this reduces to:

$$\frac{\langle v_2 \rangle}{\langle \varepsilon \rangle} = \frac{v_2\{4\}}{\varepsilon_{std}}$$

where ε_{std} is the eccentricity calculated relative to the reaction plane not the participant plane.

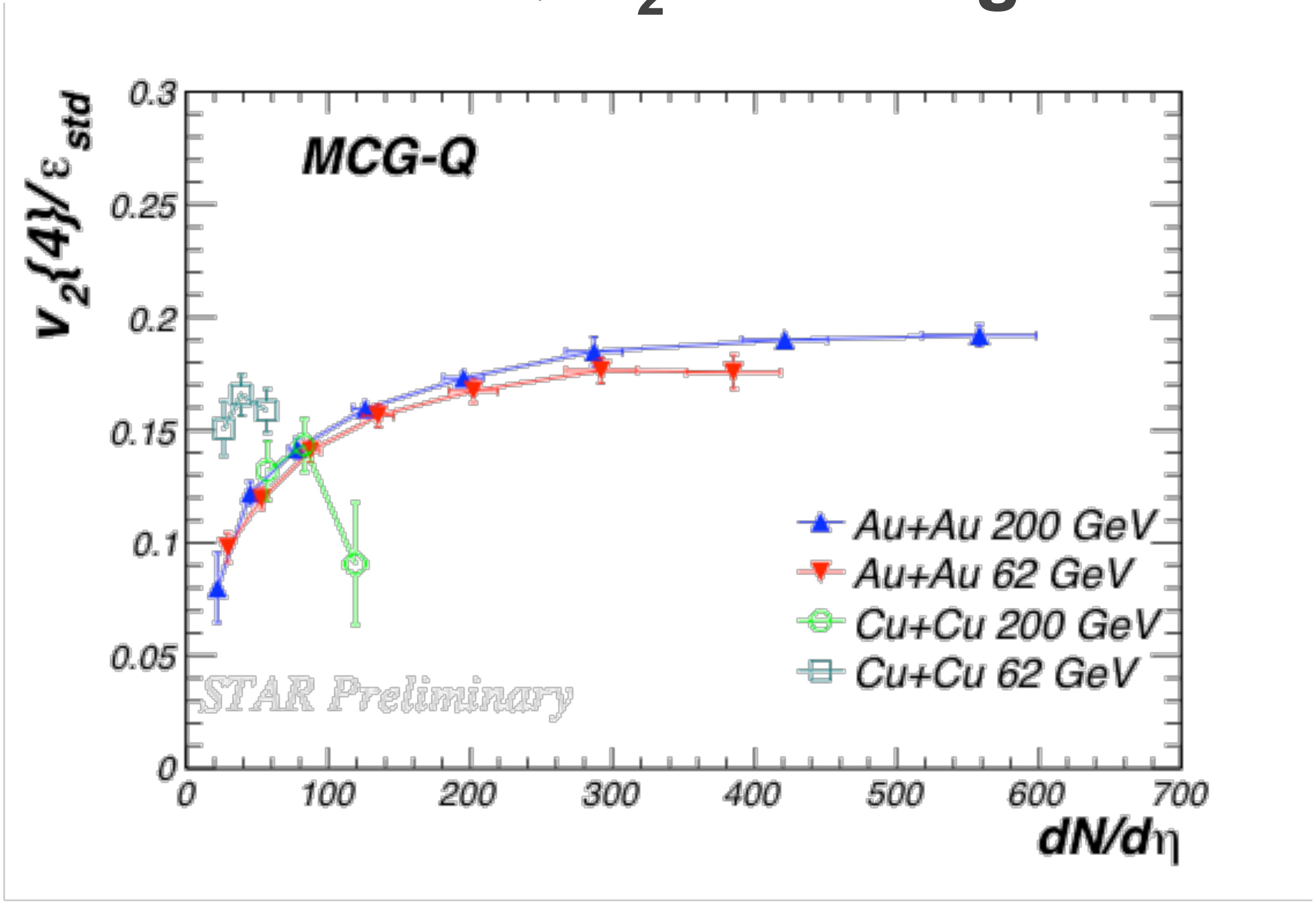
MCG-N: v_2/ε Scaling



For the MCG-N model, v_2/ε rises continuously

No indication of a saturation at a hydro-limit

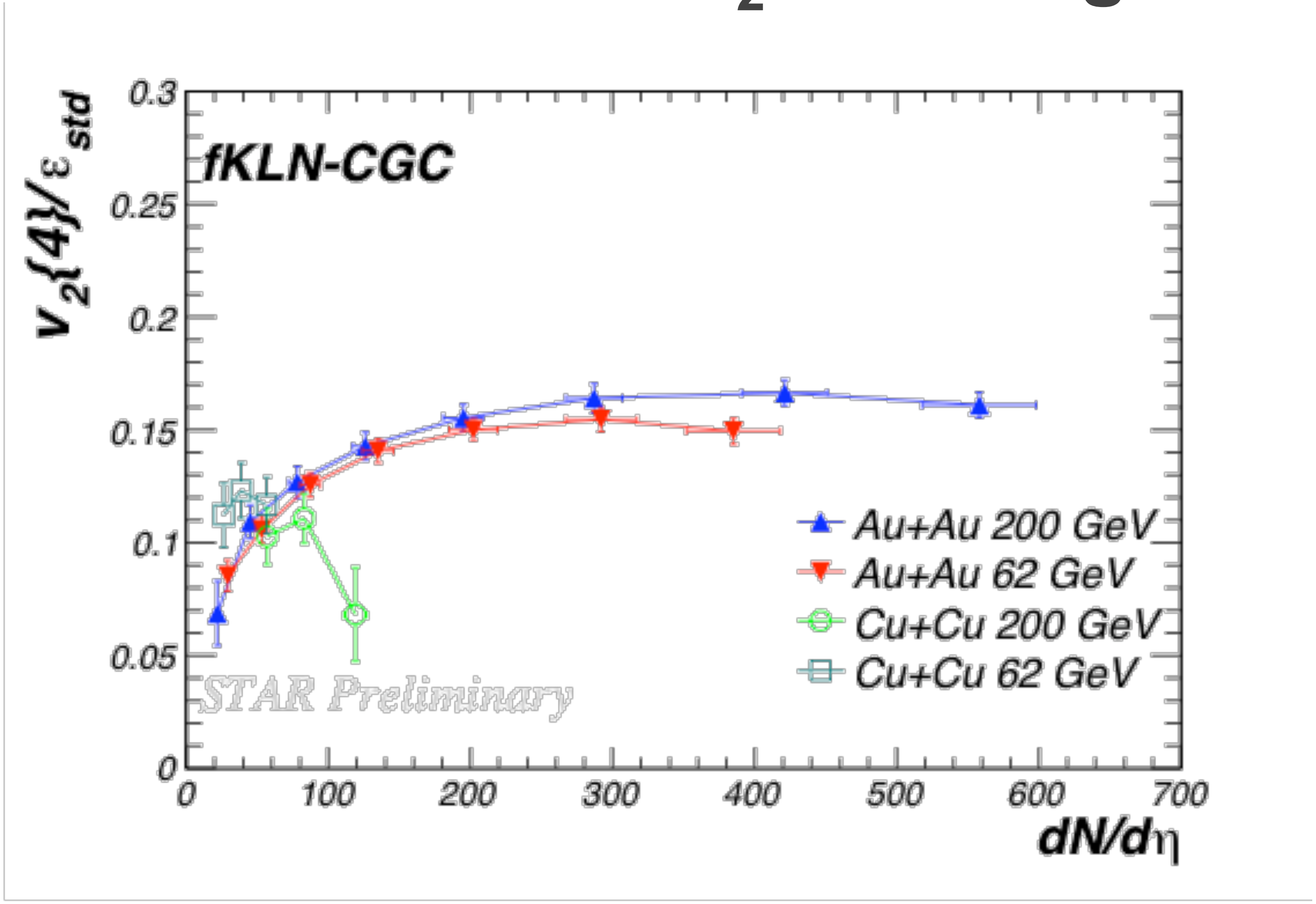
MCG-Q: v_2/ε Scaling



For the MCG-Q model, v_2/ε rises then starts to level-off

Only a small increase in v_2/ε for events with $dN_{ch}/d\eta$ >300

fKLN-CGC: v_2/ε Scaling



For the fKLN-CGC model, v_2/ε rises then saturates

For $dN_{ch}/d\eta > 250$, v_2 scales with ε

Conclusions

The 2- and 4-particle v_2 cumulants have been measured for Au+Au and Cu+Cu collisions at 62.4 and 200 GeV

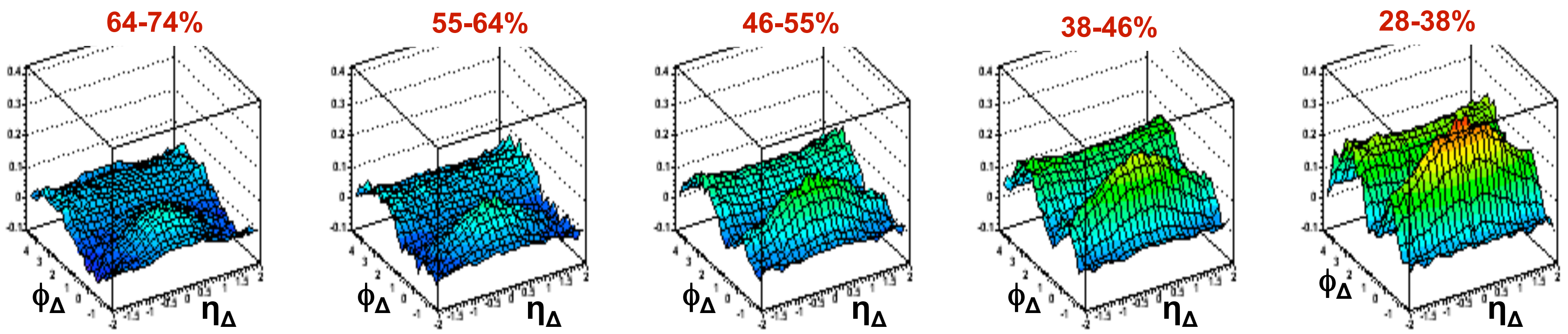
We used the difference $v_2^2\{2\}-v_2^2\{4\}$ to test models of the initial eccentricity (the difference is a measurement not an error)

MCG models predict larger eccentricity fluctuations in central Au+Au collisions leaving little room for non-flow effects while the fKLN-CGC model is well within the range allowed by σ_{tot}

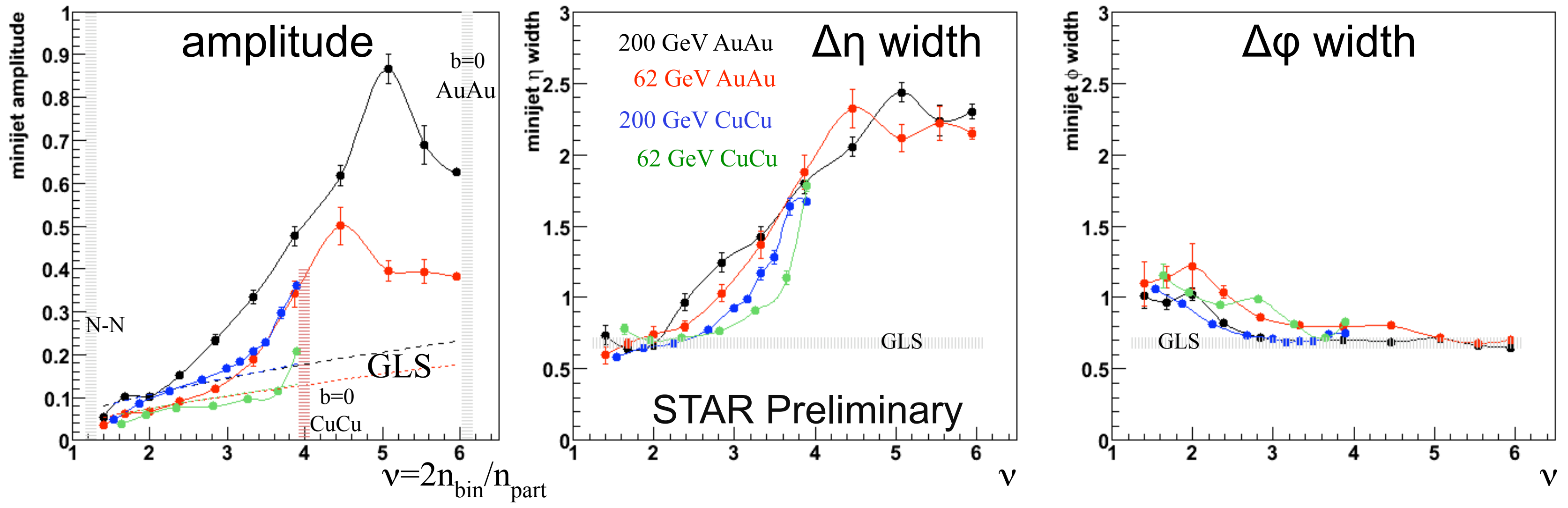
Above $dN/d\eta \sim 200$, v_2 scales with fKLN-CGC eccentricity but not MCG-N eccentricity

For discussion of 2-particle correlations relevant to non-flow see Lanny Ray's talk later this week

2-Particle Correlations



Correlations Between All Pairs: *HBT, and photon conversion pairs subtracted*



Ridge and Cone Phenomenology

Chemical composition of the ridge & cone

- Baryon-to-Meson ratios like the bulk (p/π and K_S/Λ)

Correlation amplitude

- Correlations increase faster than N_{bin} or N_{part}; closer to M(M-1) instead
- Near and Away-side amplitudes have same centrality dependence

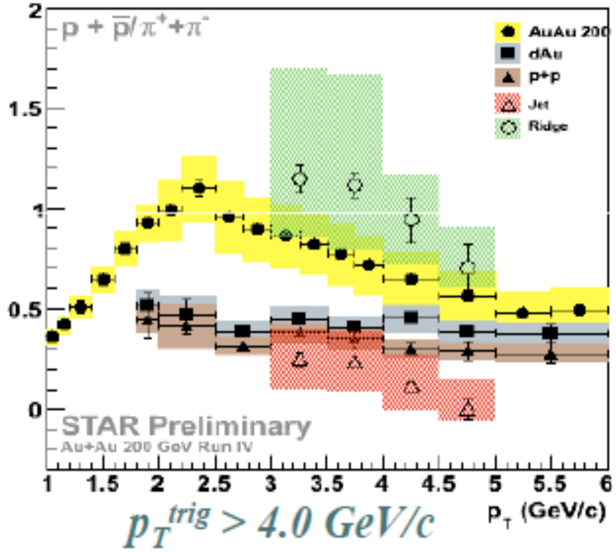
Longitudinal and Azimuthal Width

- both different from fragmentation

p_T spectra of the ridge and cone

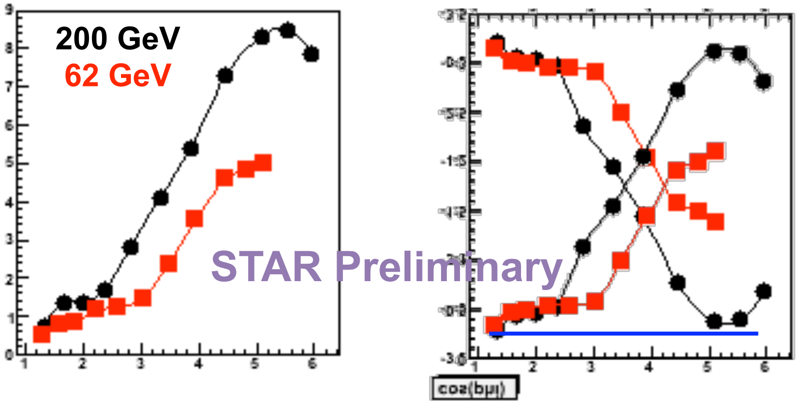
- Both are soft; like the bulk not like jet fragments

Suarez: QM08



near side

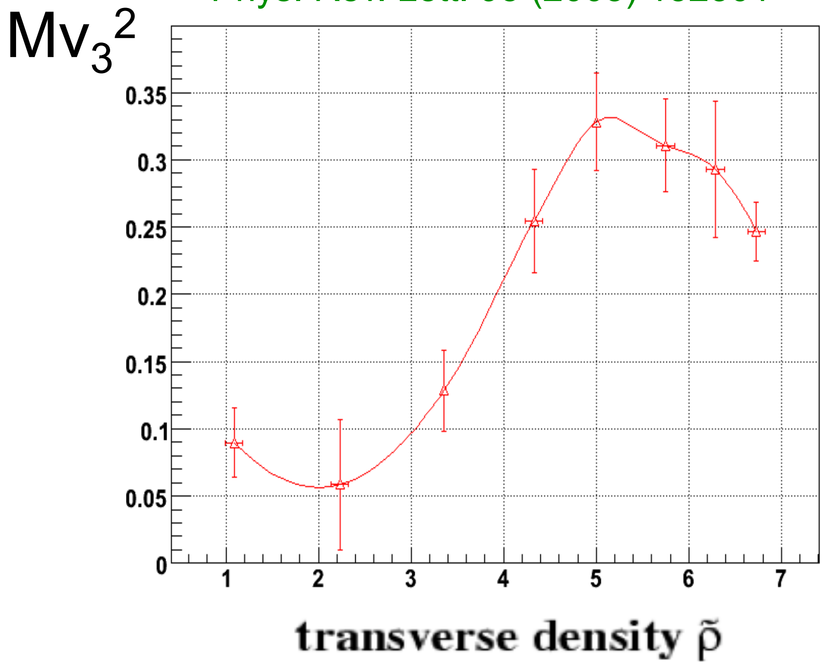
away side



Lanny Ray: CATHIE RIKEN workshop

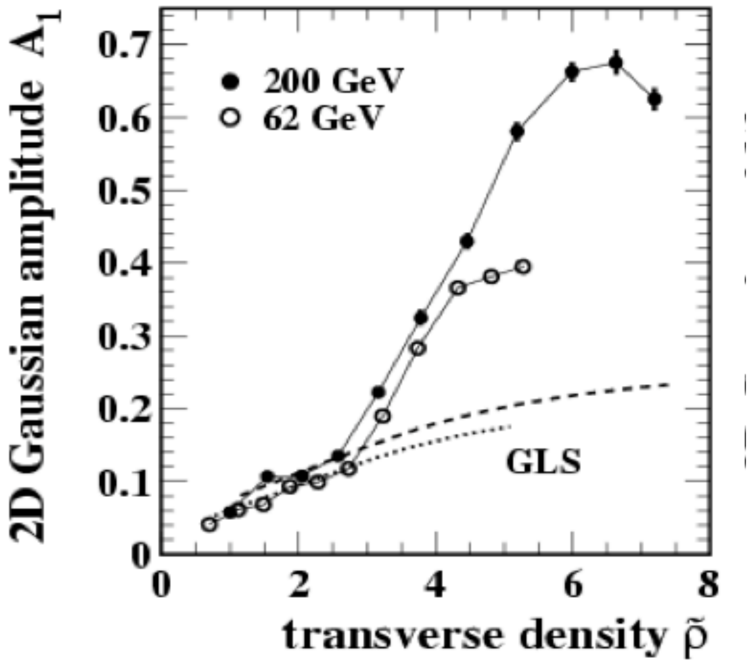
What’s So Odd About the Ridge and Cone?

Y. Pandit and P. Sorensen:
Fourier Transform of data from STAR,
Phys. Rev. Lett. 95 (2005) 152301



low p_T ridge yield

STAR Preliminary



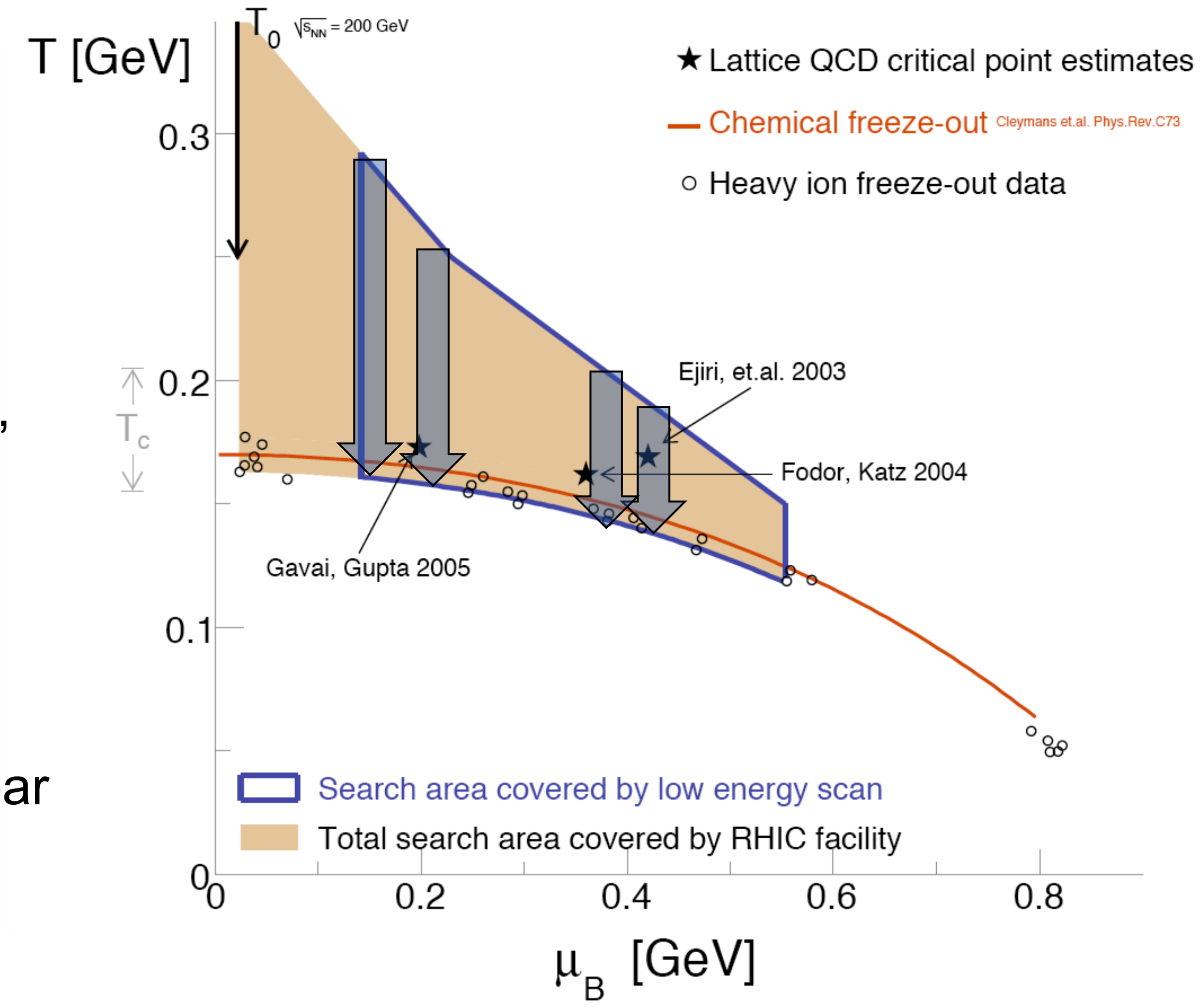
Large possible $\langle v_3^2 \rangle$ component in intermediate p_T data

Centrality dependence is similar to the low p_T ridge

Search for a critical point at RHIC

In 1911, Rutherford discovered the nucleus, making him the first nuclear physicist

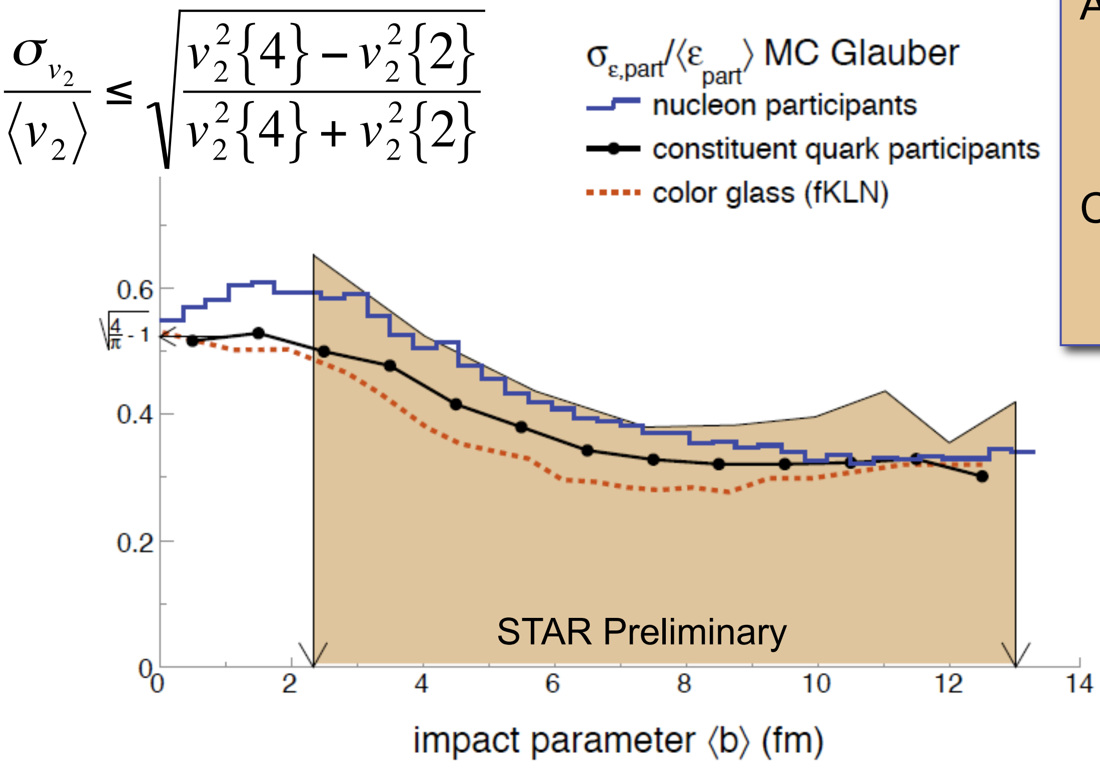
100 years later, RHIC will scan for new landmarks on the nuclear matter phase diagram



The experimental search is underway as we speak

Comparison to Models

Upper limit challenges models: MC Glauber already exhausts entire width with participant fluctuations



$$\frac{\sigma_{v_2}}{\langle v_2 \rangle} \leq \sqrt{\frac{v_2^2\{4\} - v_2^2\{2\}}{v_2^2\{4\} + v_2^2\{2\}}}$$

Additive Quark MC:
treats confined constituent quarks as the participants
decreases eccen. fluctuations

Color Glass MC:
includes effects of saturation
increases the mean eccentricity

comparison to hydro (NexSPheRio): *Hama et.al. arXiv:0711.4544*

eccentricity fluctuations from CGC: *Drescher, Nara. Phys.Rev.C76:041903,2007*

extraction of Knudsen number: *Vogel, Torrieri, Bleicher. nucl-th/0703031*

fluctuating initial conditions: *Broniowski, Bozek, Rybczynski. Phys.Rev.C76:054905,2007*

first disagreement with $\varepsilon_{\mathrm{standard}}$ and use of quark MC: *Miller, Snellings. nucl-ex/0312008*