BROOKHAVEN NATIONAL LABORATORY

Recent STAR Results from U+U and Au+Au Collisions

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Outline

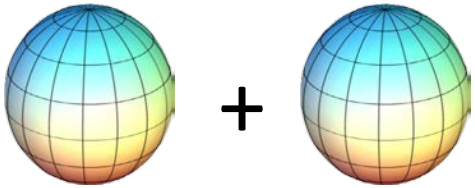
- Motivation
- STAR Detector and Data Set
- Azimuthal anisotropy in U+U collisions
- Open heavy flavor in U+U collisions
- Summary

Motivation for U+U Collisions

Allows us to manipulate the initial geometry and study

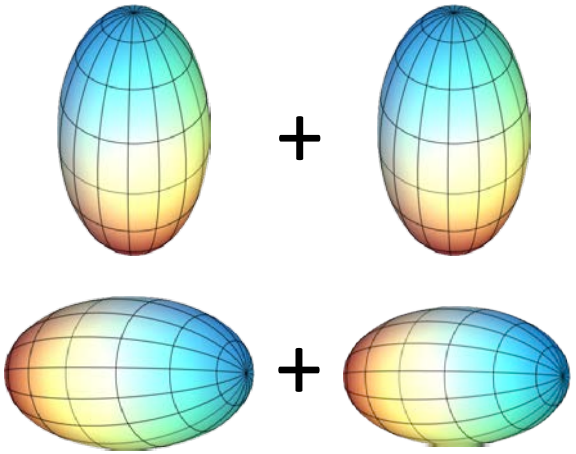
- How multiplicity depends on N_{part} and N_{coll}
- Path-length dependence of jet quenching
- Particle production in heavy ion collisions (and many other effects)

Au+Au Collisions



Oblate

U+U Collisions

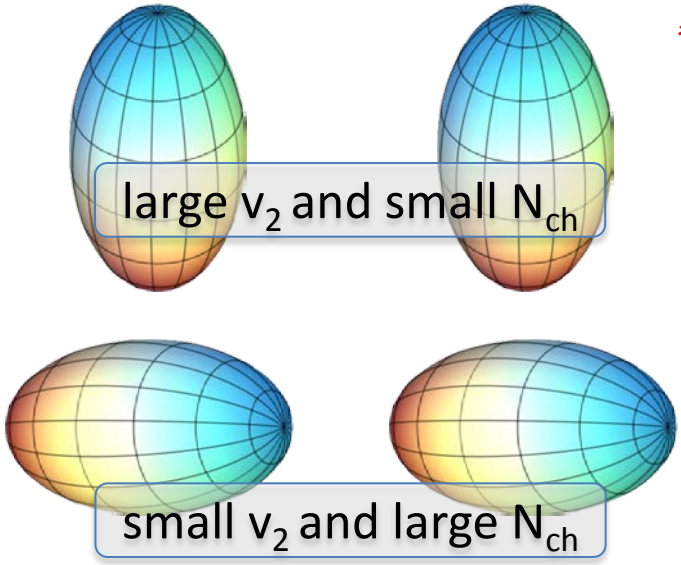


Prolate

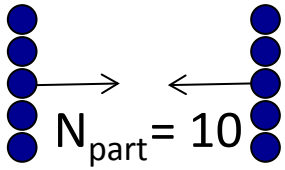
Can we see a difference between Au+Au and U+U and preferentially select body-body or tip-tip U+U collisions?

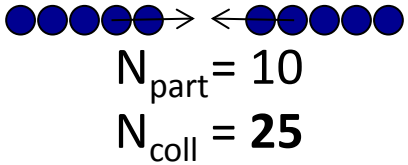
Selecting body-body or tip-tip

Since in most calculations, multiplicity depends on the N_{part} and N_{coll} and since v_2 is propotional to initial eccentricity



**idealizations*



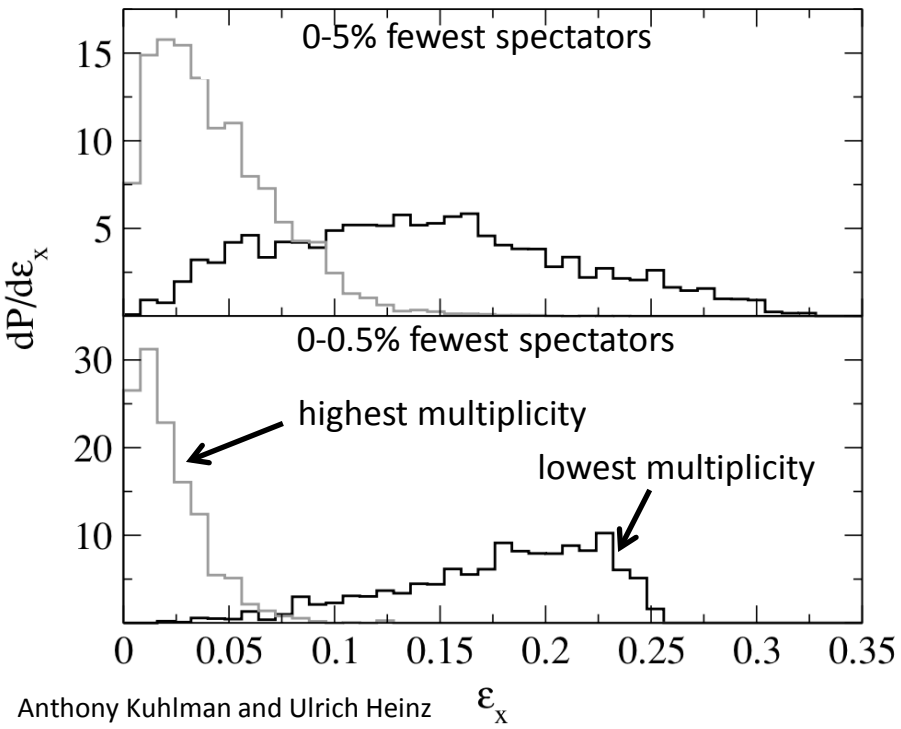


If dN/dη depends on N_{coll}, large dN/dη should correlate with small v_2.

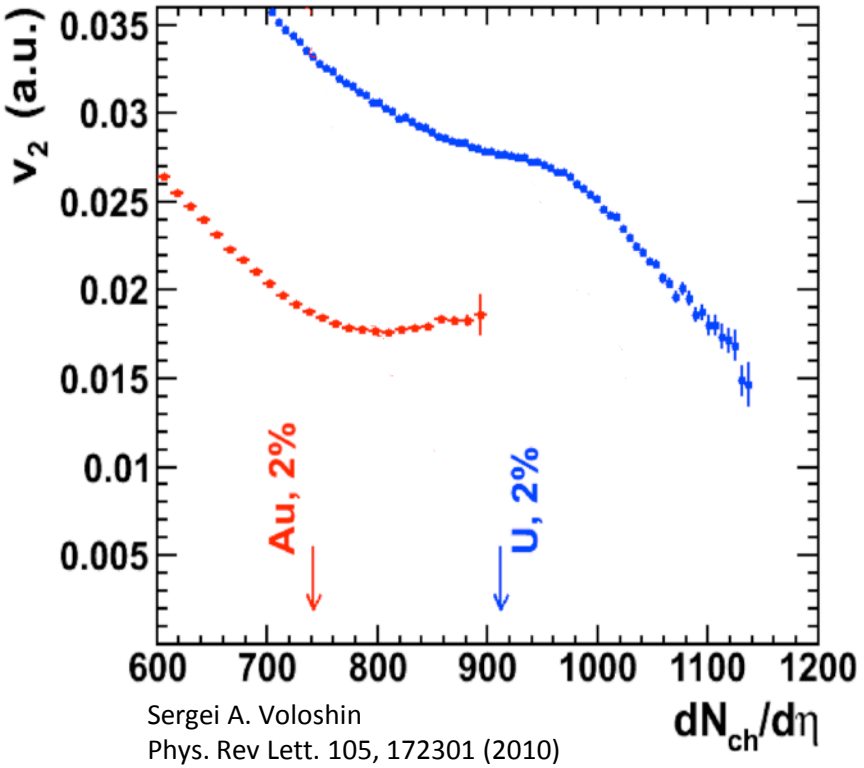
➪*Central U+U collisions are ideal for testing particle production*

Strategy: select events with few spectators (fully over-lapping), then measure v_2 vs multiplicity: **how strong is the correlation?**

Expectations from Models



Anthony Kuhlman and Ulrich Heinz
Phys. Rev. C 72, 037901 (2005)



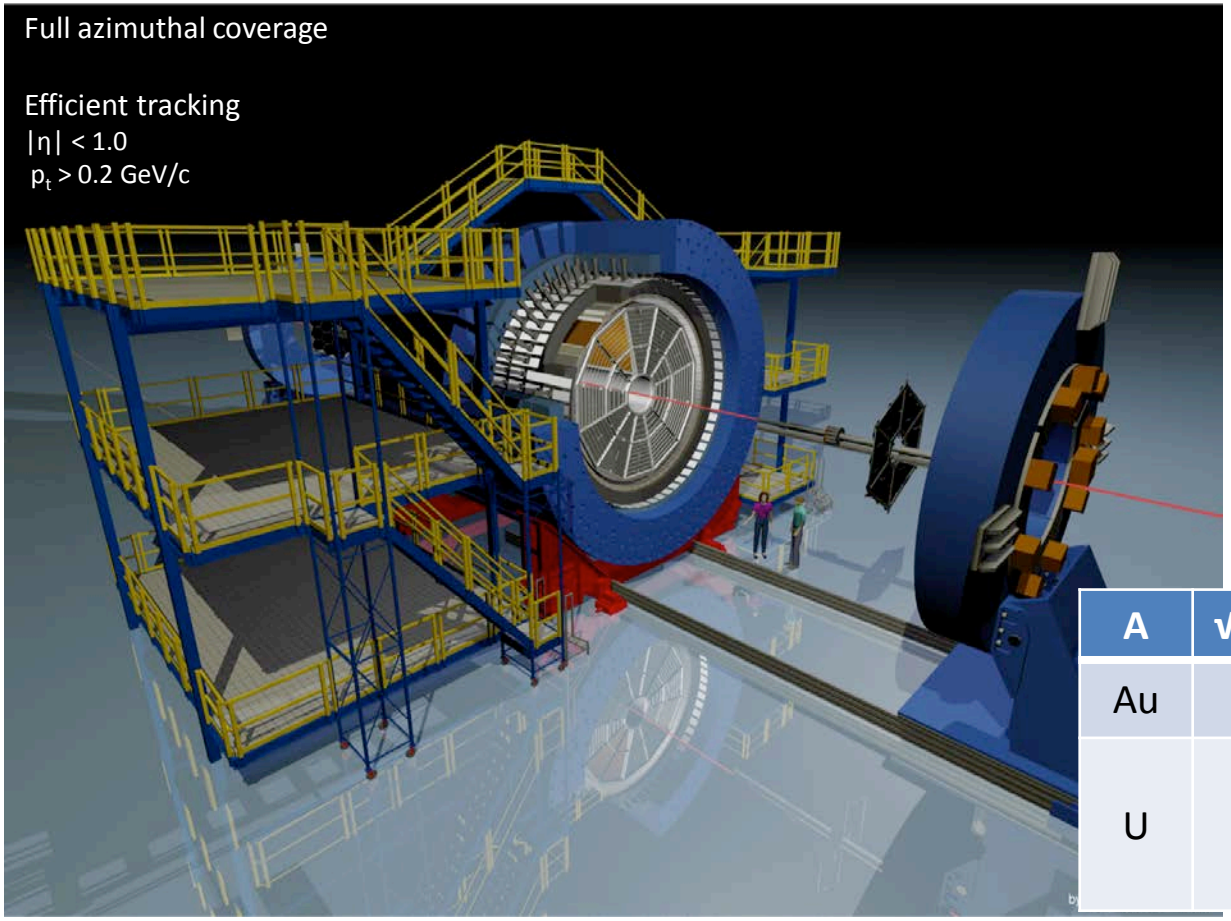
Sergei A. Voloshin
Phys. Rev Lett. 105, 172301 (2010)

Simulations show that after selecting most fully overlapping collisions,

- high multiplicity events correlate with small eccentricity (tip-tip)
- lower multiplicity with large eccentricity (body-body)

The correlation of tip-tip collisions with high multiplicity *and* small eccentricity, leads to a kink in v_2 at high dN/dη

STAR Detector and Data Set



- U+U data collected in a 3 week exploratory run
- ZDCs counting spectator neutrons used to select central collisions

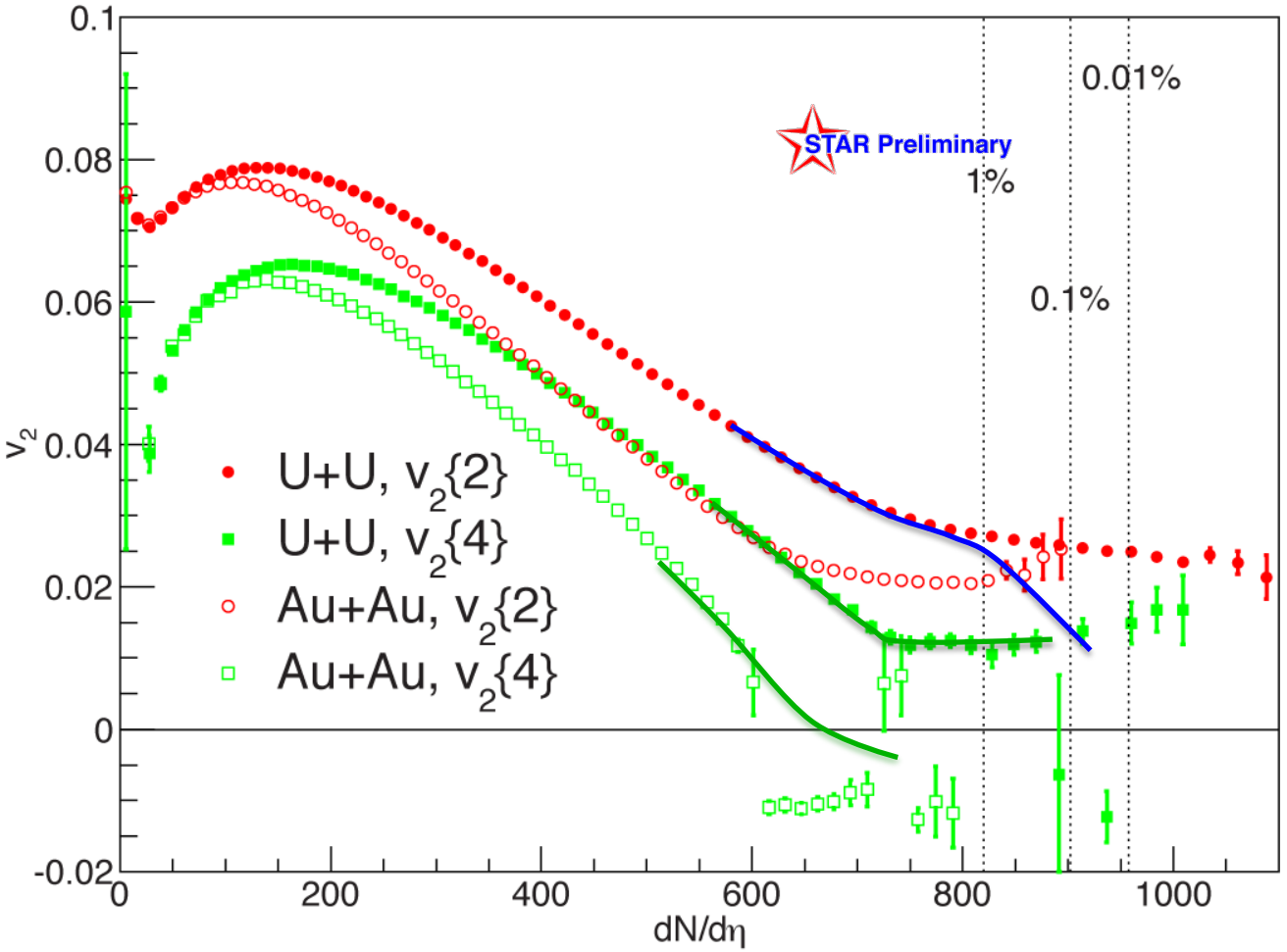
A	$\sqrt{s_{NN}}$ GeV	Year	Events (x10^6)
Au	200	2011	700 (mini-bias)
U	193	2012	360 (mini-bias) 13 (central 1% ZDC)

We've measured the efficiency corrected 2nd and 4th cumulants using Q-cumulants

Bilandzic, et. al. Phys.Rev.C83:044913,2011

$$v_2^2\{2\} = \left\langle \left\langle e^{i2(\varphi_i - \varphi_j)} \right\rangle_{i \neq j} \right\rangle \qquad v_2^4\{4\} = -\left\langle \left\langle e^{i2(\varphi_i + \varphi_j - \varphi_k - \varphi_l)} \right\rangle_{i \neq j \neq k \neq l} \right\rangle + 2v_2^2\{2\}^2$$

Minimum-bias U+U and Au+Au



No evidence of knee structure for central U+U

- Glauber model suggest knee structure at ~2% centrality
- Knee washed out by additional multiplicity fluctuations?[1]
- Other interpretations?

[1]Maciej Rybczyński, et. al. Phys.Rev. C87 (2013) 044908

The U+U $v_2\{4\}$ results are non-zero in central

- Result of intrinsic prolate shape of the Uranium nucleus
- Au $v_2\{4\}^4$ becomes consistent with zero

*Negative $v_2\{4\}^4$ presented as negative $v_2\{4\}$

Dash lines represent top centrality percentages for U+U collisions based on multiplicity, curves are used to guide the eye

$v_2\{4\}$ data: we see the prolate shape of the Uranium nucleus ✓

The lack of a knee indicates a weakness in our multiplicity models

Glauber Model

- Assume deformed Woods-Saxon distribution

$$\rho = \frac{\rho_0}{1+\exp([r-R']/d)} \qquad R' = R[1+\beta_2 Y_2^0(\theta)+\beta_4 Y_4^0(\theta)]$$

- Average number of particles from each nucleon follows 2-component model

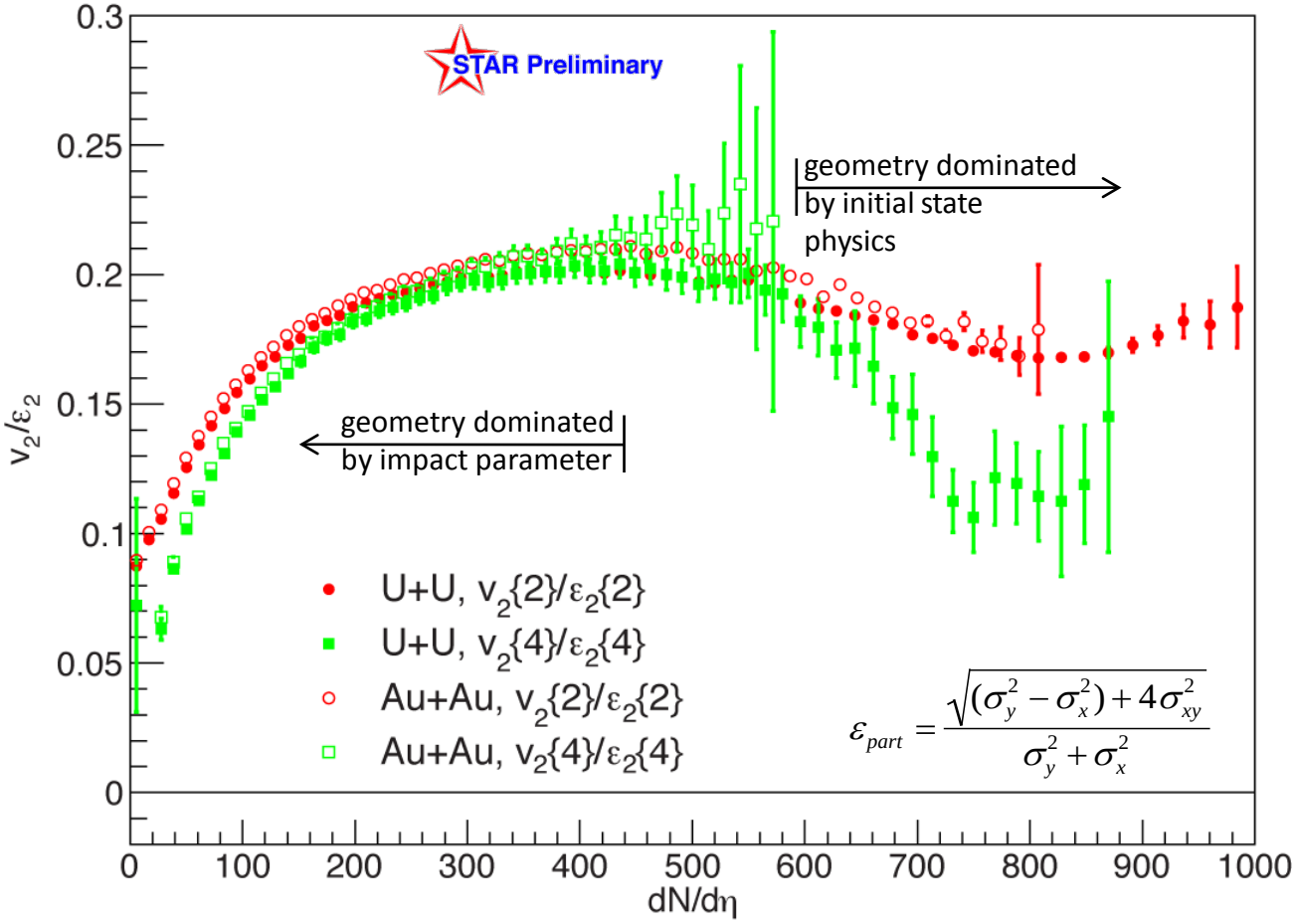
$$n_{AA} \propto n_{pp}[(1-x_{hard})\frac{N_{part}}{2}+x_{hard}N_{coll}]$$

- Generate N_{ch} by sampling a negative binomial distribution with parameters n_{AA} and k=2

Hiroshi Masui, et. al.
Physics Letters B 679 (2009) 440–444

Species	A	R	d	β_2	β_4	NN cross section
Au+Au	197	6.38	0.535	-0.131	-0.031	42
U+U	238	6.81	0.605	0.28	0.093	41.2

v_2/ε_2



v_2/ε_2 follows the same trend for U+U and Au+Au

- As long as the oblate shape of Au is accounted for

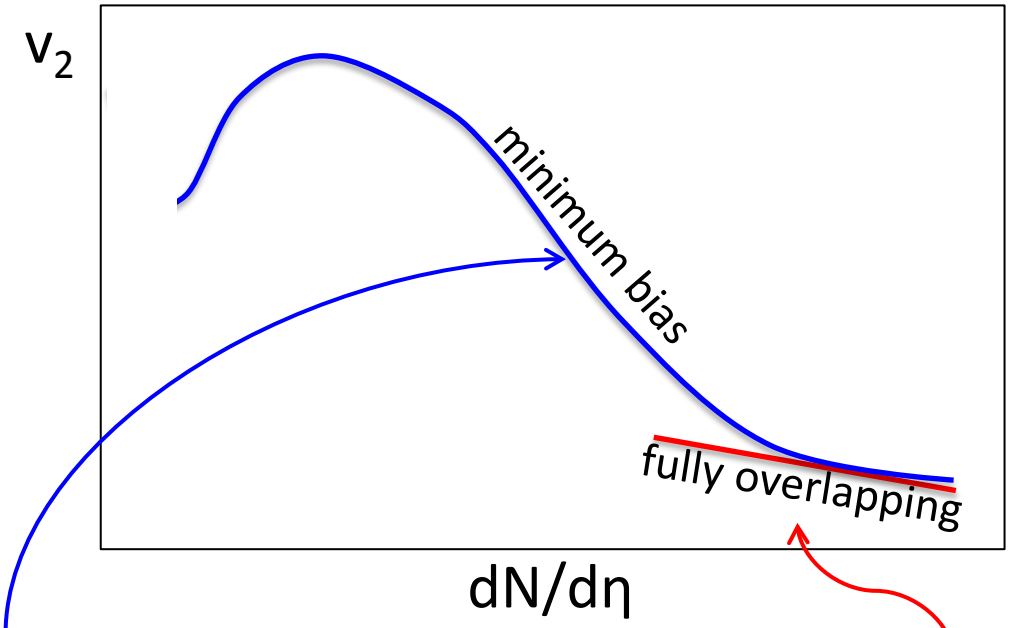
Instead of saturating or slowly rising, v_2/ε_2 drops in most central collisions

The drop is sharper for U+U $v_2\{4\}/\varepsilon_2\{4\}$

Results are consistent with an overestimation of ε_2 in central collisions or deviation from $v_2 \propto \varepsilon_2$ (non-flow, hydro fluctuations?)

Very central collisions provide a stringent test of models

Studying Full Overlap Events



Minimum bias: impact parameter dominates geometry

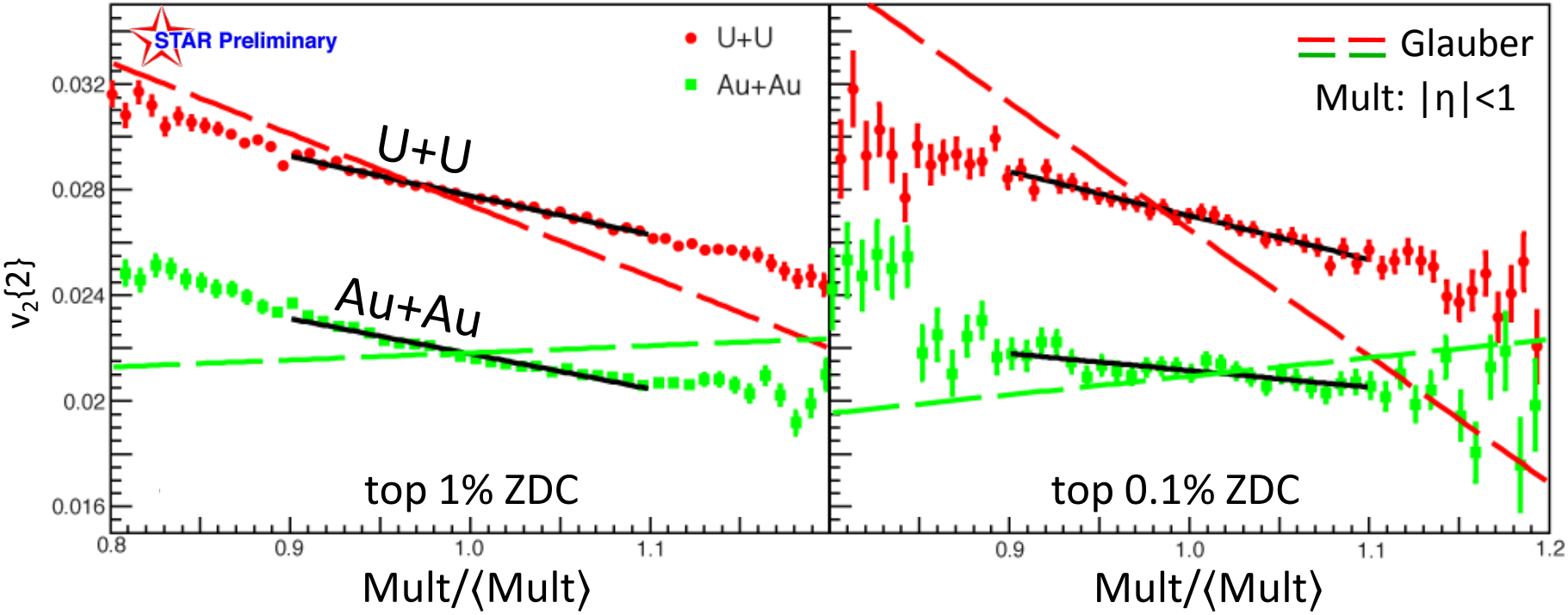
Central ZDC selection b->0

- Au+Au dN/dη is dominated by fluctuations
  - No correlation between v_2 and multiplicity
- U+U dN/dη depends on geometry & fluctuations
  - Larger v_2 associated with small multiplicity

Use slope of v_2 vs dN/dη in U+U to look for correlation between dN/dη and geometry

Use Au+Au as the control sample to show we select full overlap

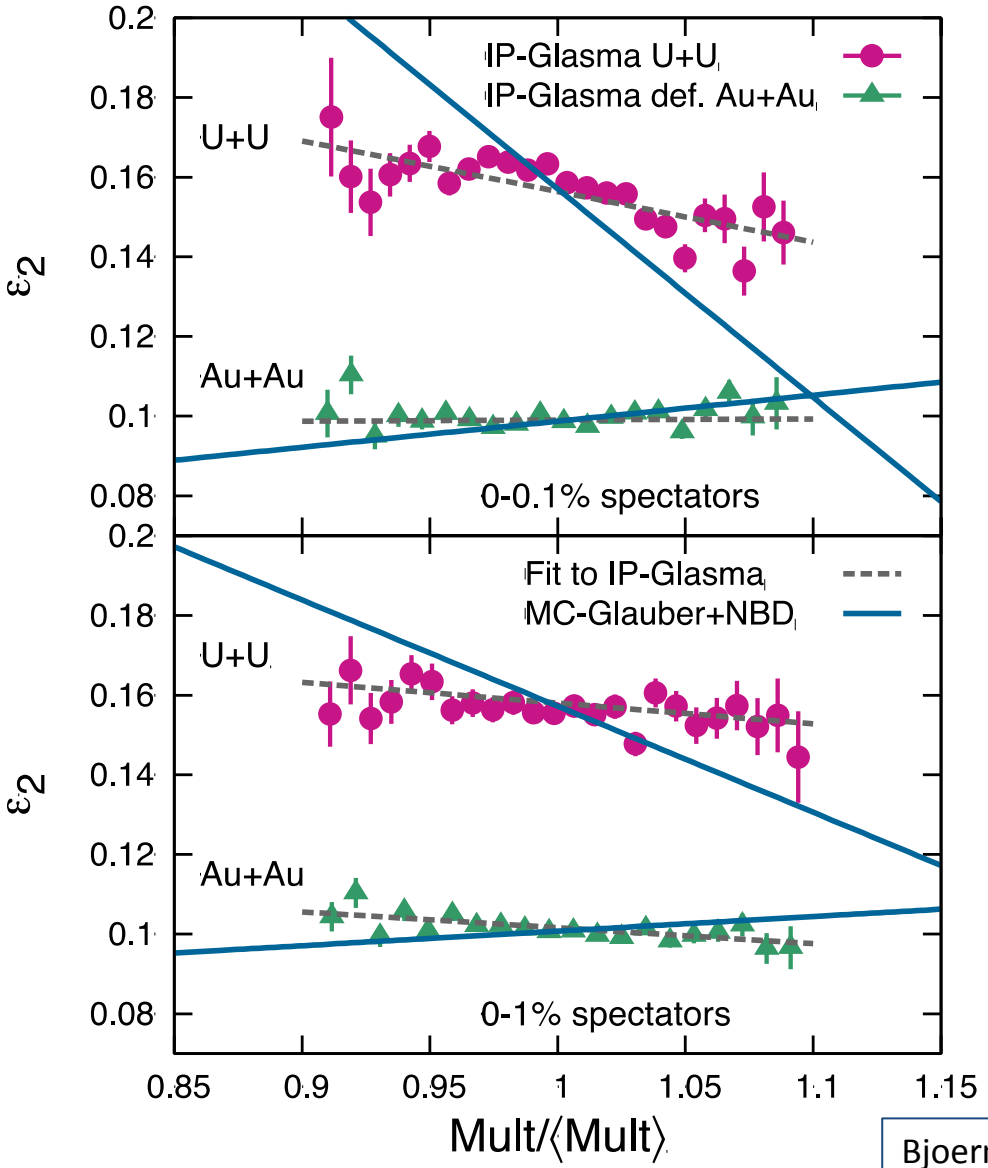
v_2 vs. Multiplicity In Fully Overlapping Events



- We expect a strong negative slope for U+U and a zero or slightly positive slope for Au+Au
- Dash lines are Glauber model eccentricities scaled by the ratio of $\langle v_2 \rangle$ and $\langle \varepsilon_2 \rangle$
- U+U slope is weaker than models predicted, but gets stronger for more central events
- Au+Au slope is negative instead of positive, gets closer to zero for more central events

We fit the slope to see how it evolves as the number of spectators decreases and collisions become more and more overlapping

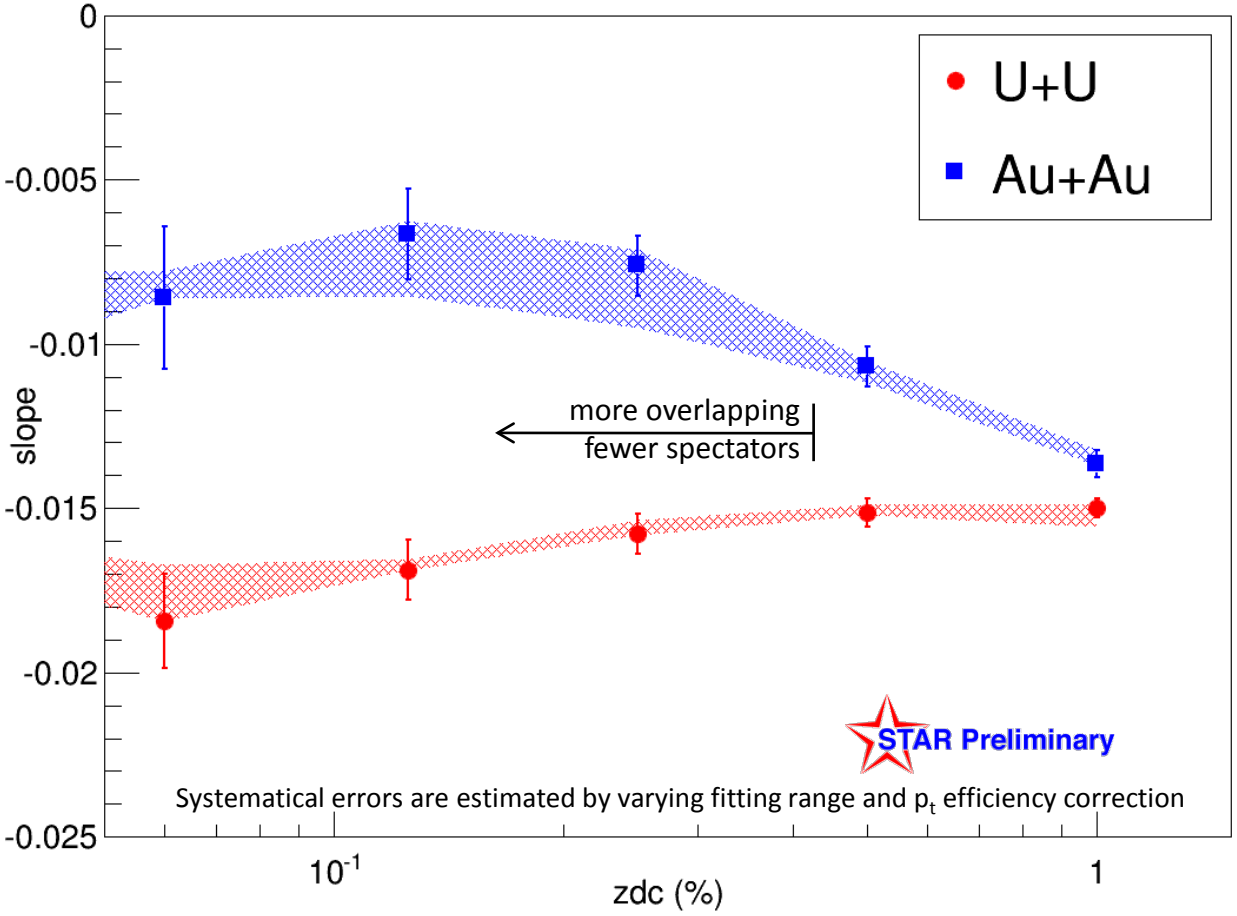
Glauber vs. IP-Glasma



- The IP-Glasma mode is based on the CGC approach
- The Correlation between eccentricity and multiplicity is weaker in the IP-Glasma model compare to two-component MC-Glauber model
- Comparison with data is under investigation, stay tuned!

Bjoern Schenke, Prithwish Tribedy and Raju Venugopalan
arXiv:1403.2232

Slope vs. ZDC

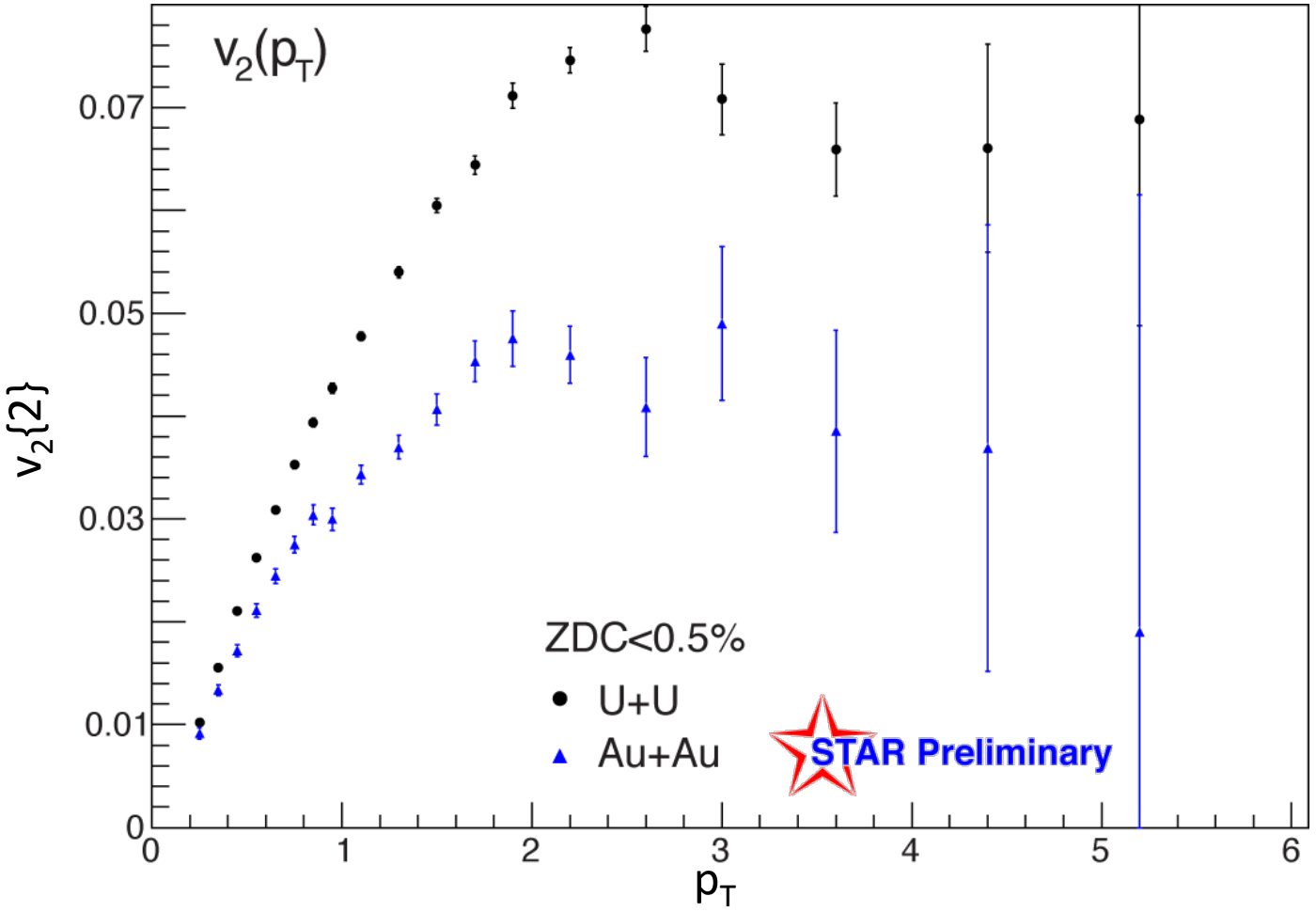


ZDC Centrality	U+U	Au+Au
0.125%	6	4
0.25%	7	5
0.5%	9	6
1.0%	12	8
2.0%	17	12

Number of spectator neutrons in each direction from Glauber model

- For tighter cuts, the U+U slope becomes steeper than the Au+Au control sample
- Demonstrates that dN/dη is larger for tip-tip U+U collisions: dN/dη can be used to select tip-tip vs body-body enhanced samples

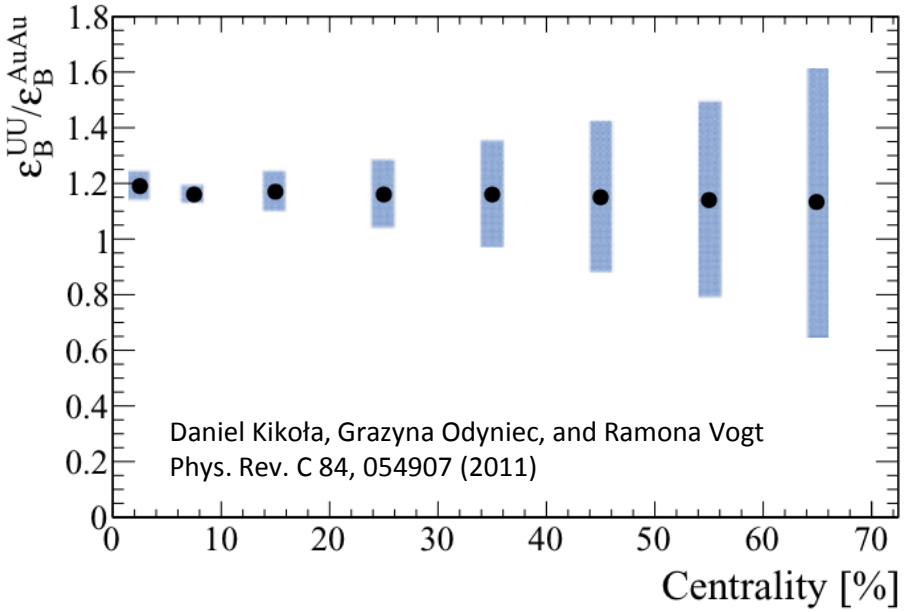
Toward Path Length Dependence of Quenching

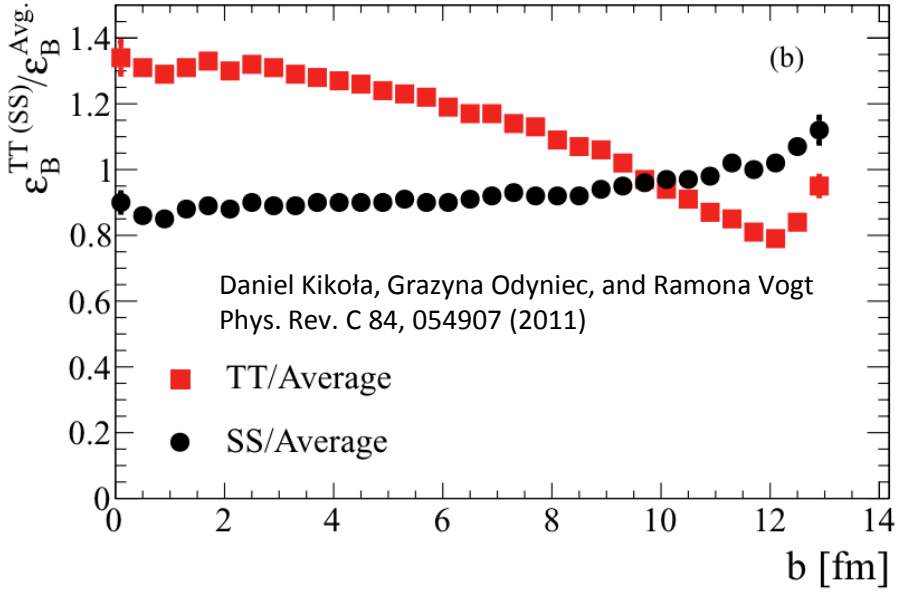


- Larger difference in-plane vs out-of-plane path length in U+U?
  - Need to split U+U results into multiplicity bins (body-body vs. tip-tip)
  - A larger-sized data sample of central U+U events will be needed

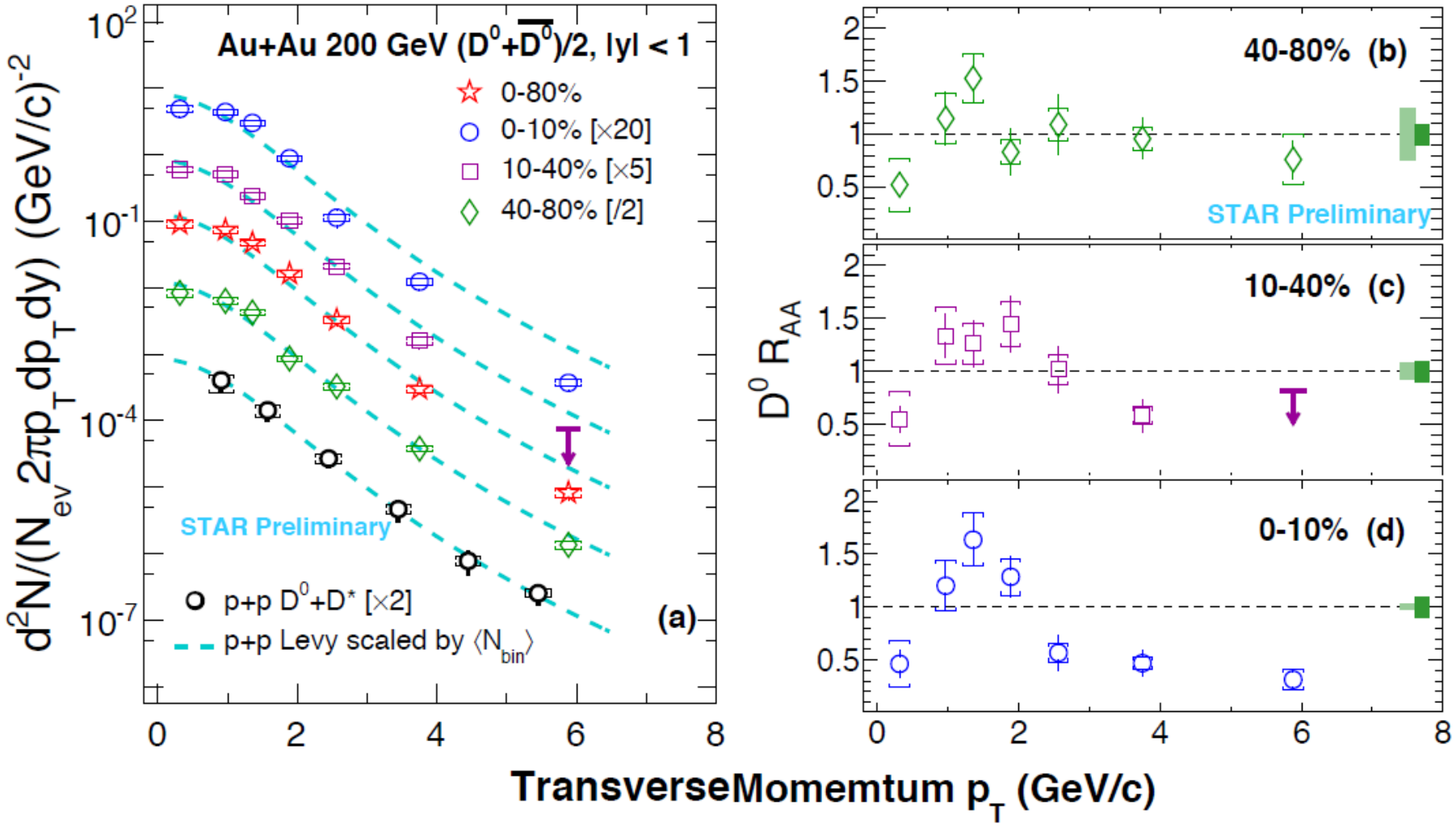
Heavy Flavor in U+U

- HF quarks are produced primarily in initial hard scattering, and are exposed to the evolution of the hot nuclear matter created at RHIC
- Using HF as a probe to study properties of the QGP and their dependence on system size, energy, …
- Bjorken energy densities are 15%–20% larger in U + U collisions relative to Au+Au collisions
  - Tip-Tip configuration provides an increase of up to 30% relative to orientation-averaged collisions





Open Charm Hadronic Channel
– Au+Au –



Open Charm Hadronic Channel
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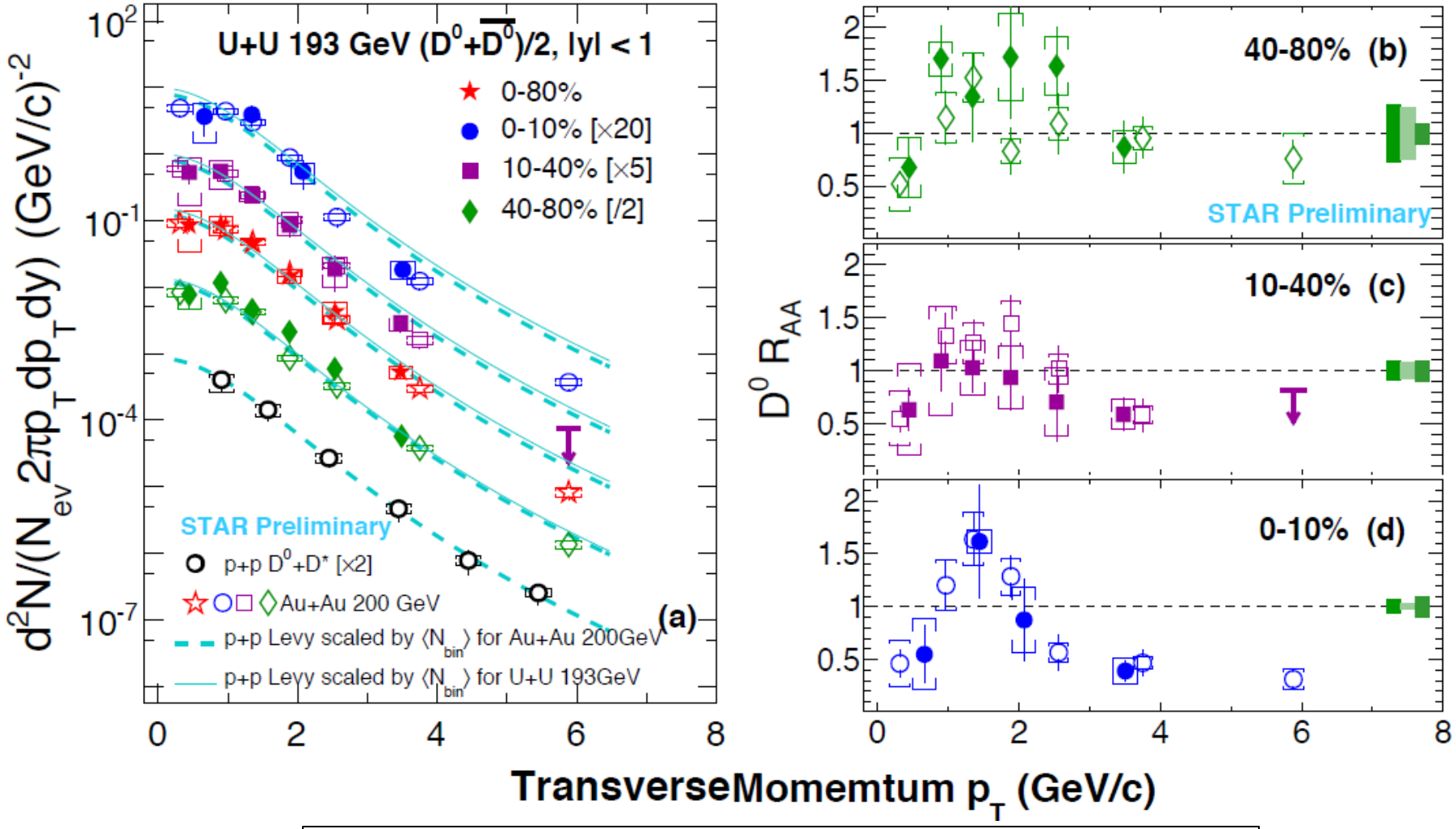
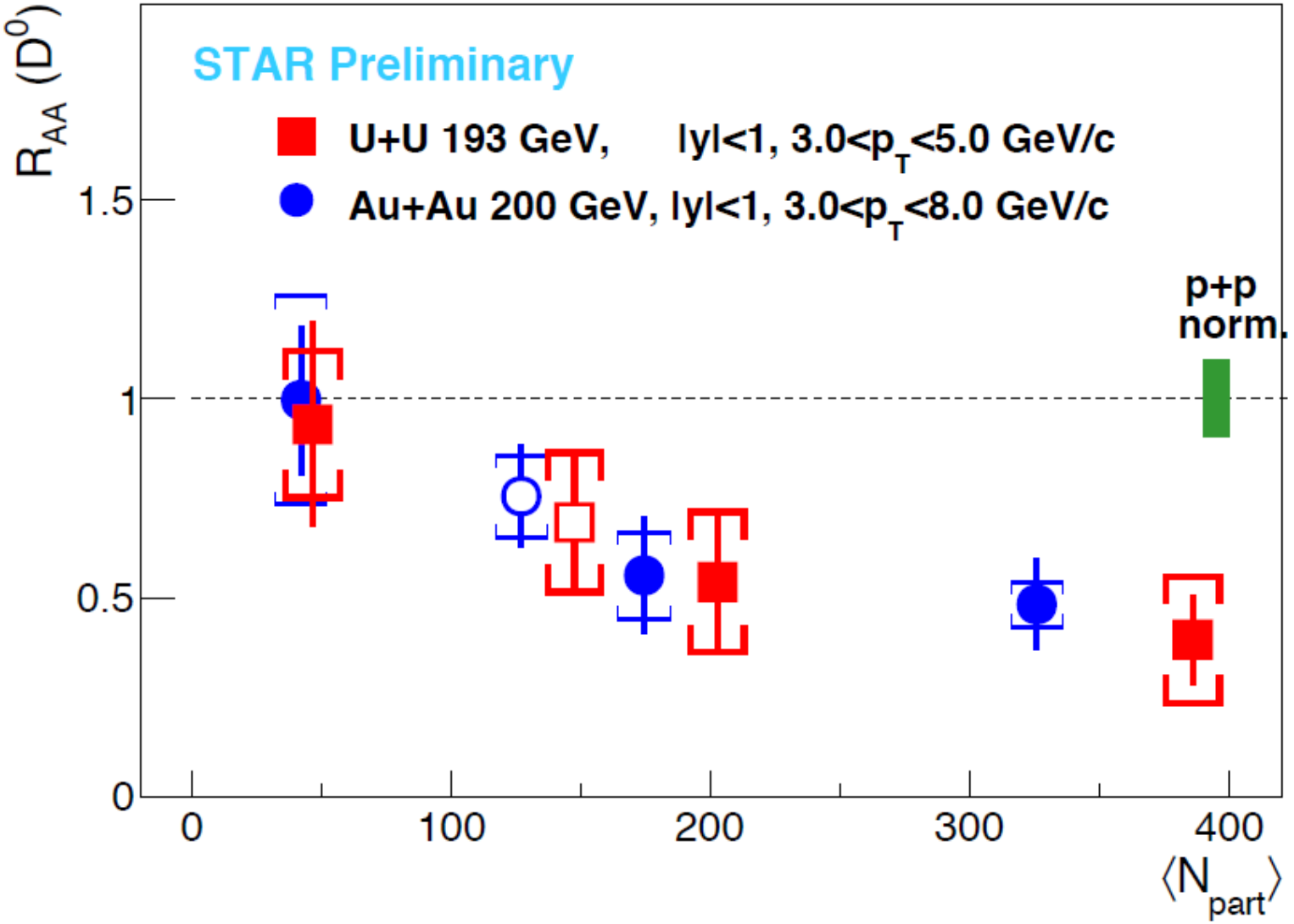


Similar behavior in U+U collisions as Au+Au collisions

Open Charm Hadronic Channel



Similar behavior in U+U and Au+Au collisions observed for D^0 R_{AA}

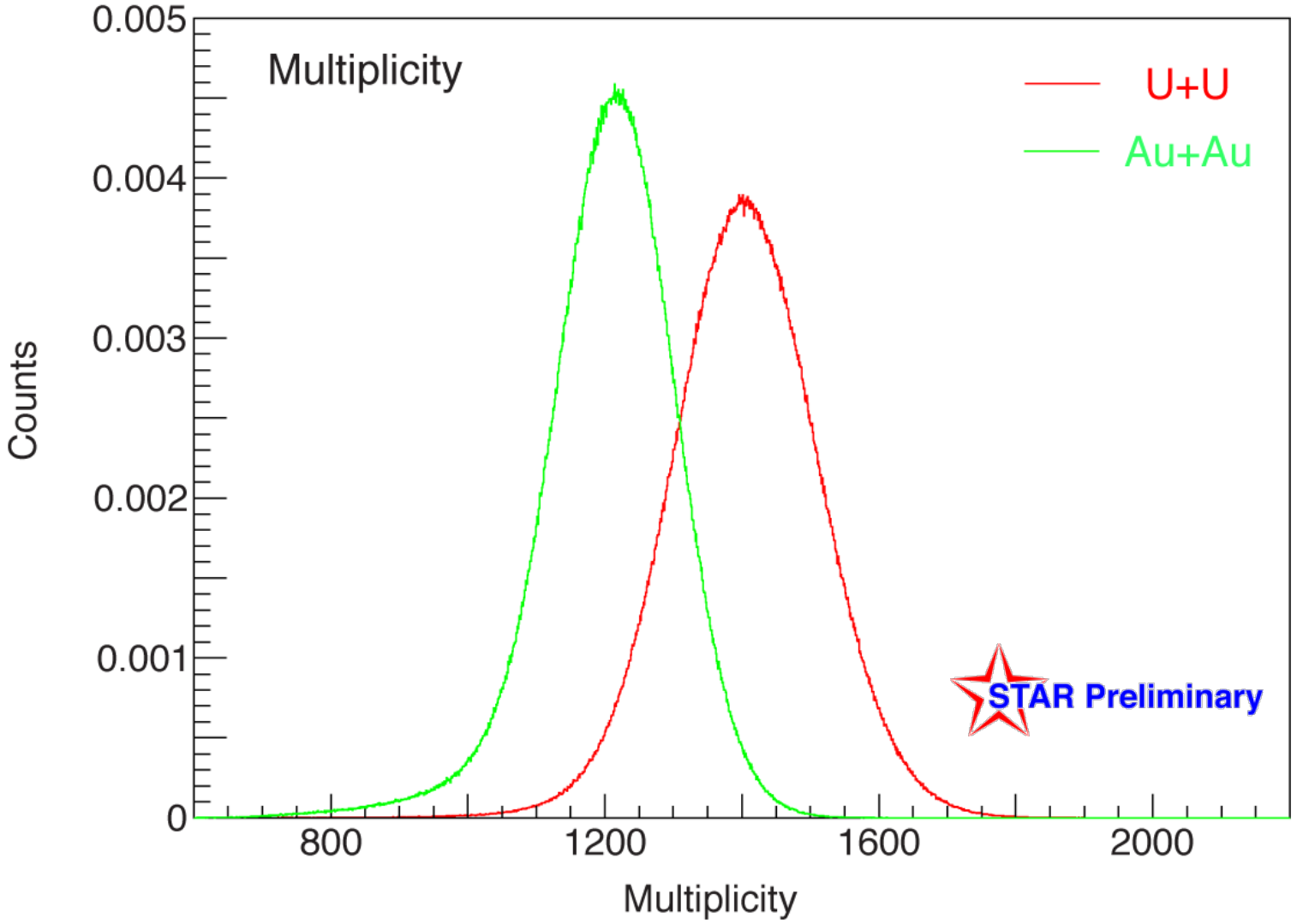
Summary

- No evidence of kink structure in central v_2 results from current analysis, additional fluctuations than NBD? [1]
- v_2/ε_2 turns over in central collisions for both Au+Au and U+U!?
  - Over estimation of ε_2 in glauber model?
- The combination of ZDC and multiplicity can be used in combination to select body-body or tip-tip enhanced samples of central U+U collisions
  - High multiplicity events are biased toward tip-tip collisions, low multiplicity toward body-body
  - Data show weaker correlations than model predictions: larger multiplicity fluctuations?
- U+U collisions provide new opportunities to study path-length dependent jet quenching
  - Need to split U+U results into multiplicity bins (body-body vs. tip-tip)
- Similar behavior in U+U and Au+Au collisions observed for D^0 R_{AA}

[1]Maciej Rybczyński, et. al. Phys.Rev. C87 (2013) 044908

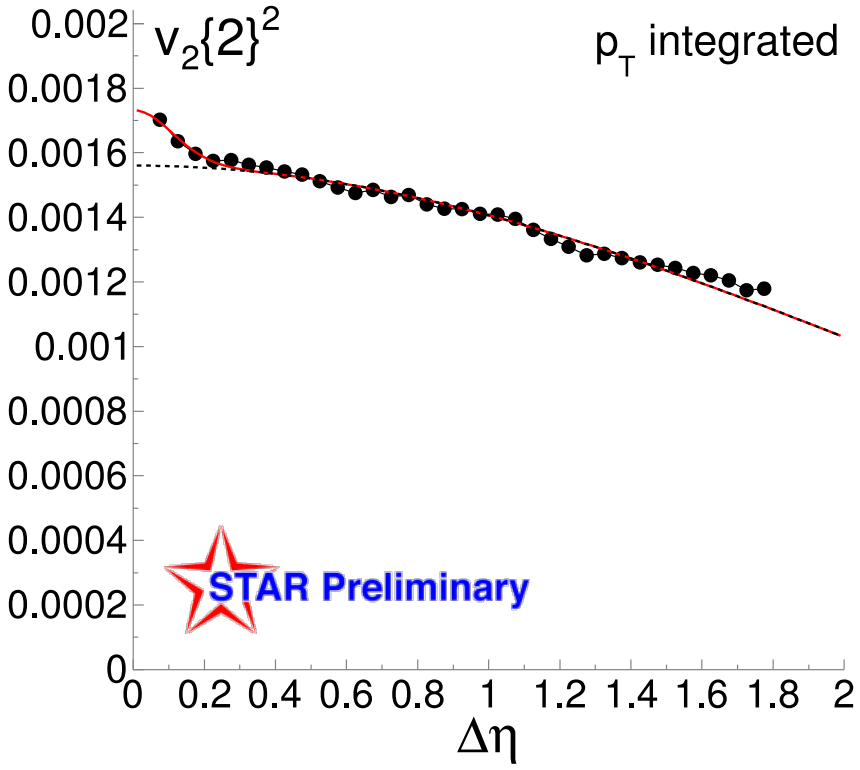
Back Up

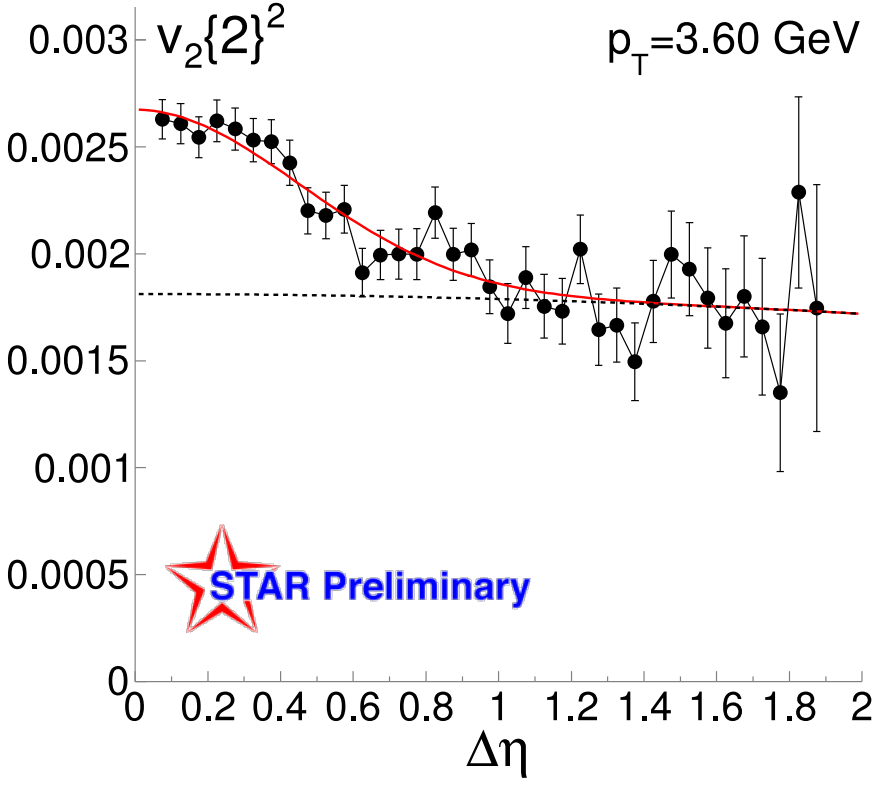
Multiplicity



The corrected multiplicity distribution for 1% central ZDC events

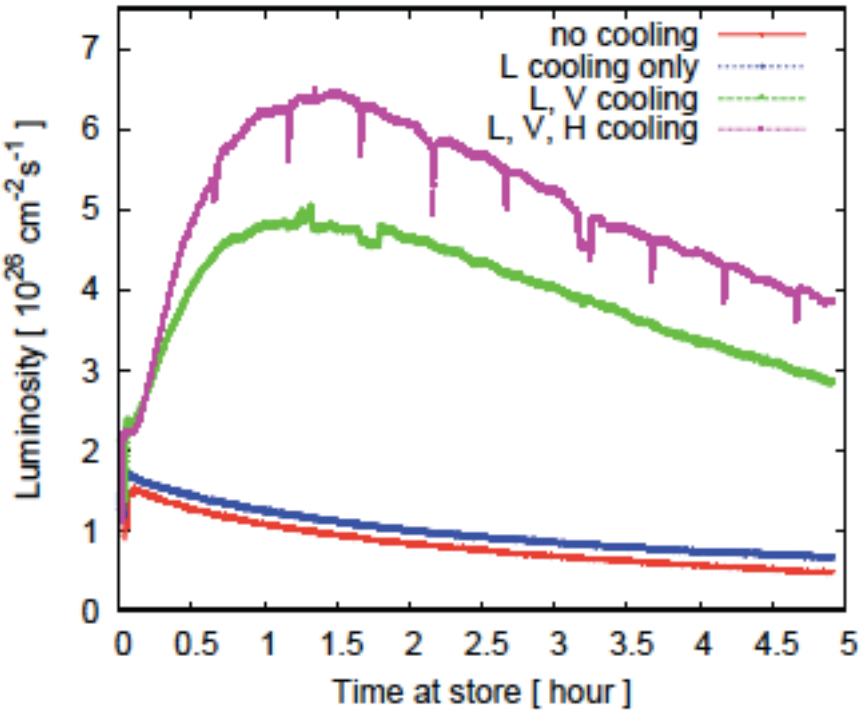
Δη dependence

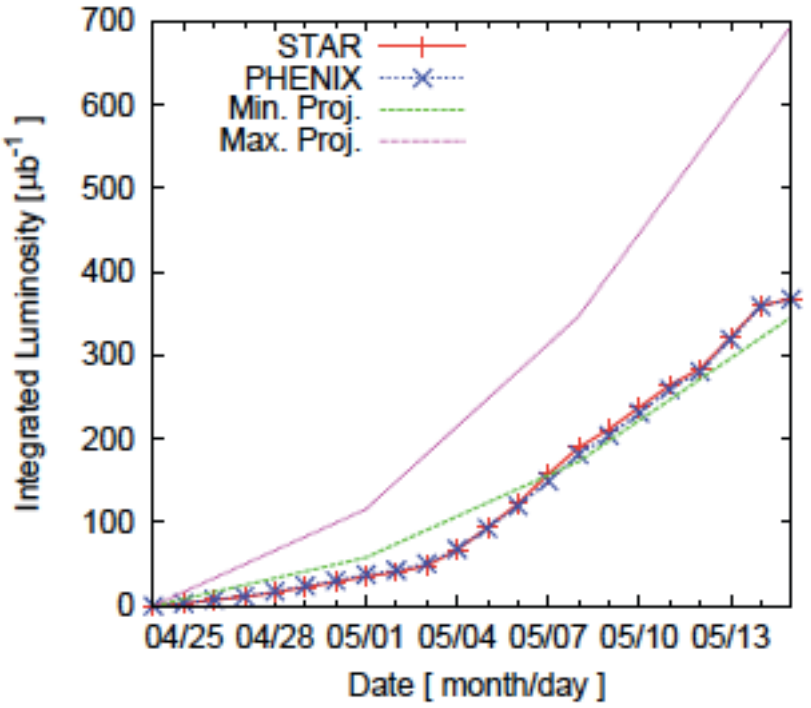




Remove peak at small Δη to reduce non-flow effects

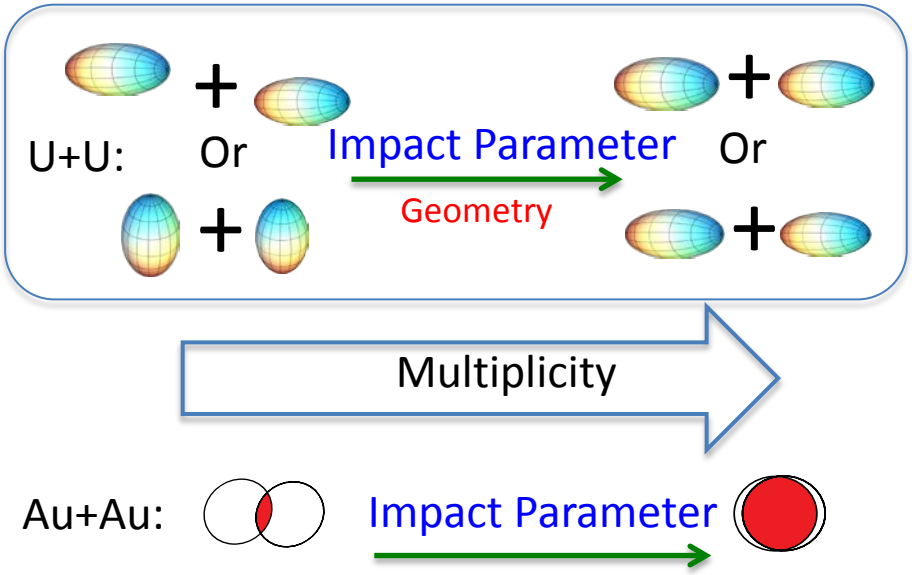
Collection of U+U data sample

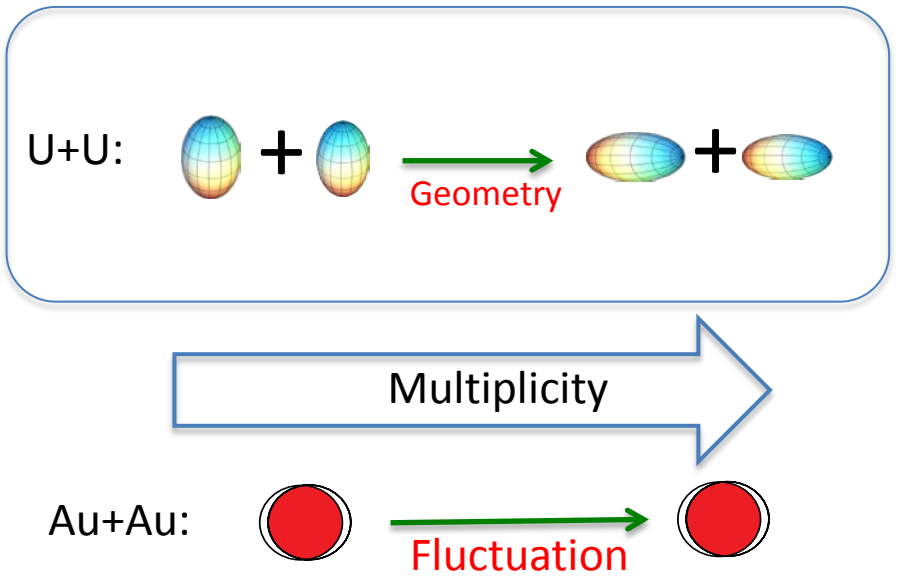




Implementation of cooling led to huge improvement in accessible luminosity
Made acheivement of goals possible

Studying Full Overlap Events

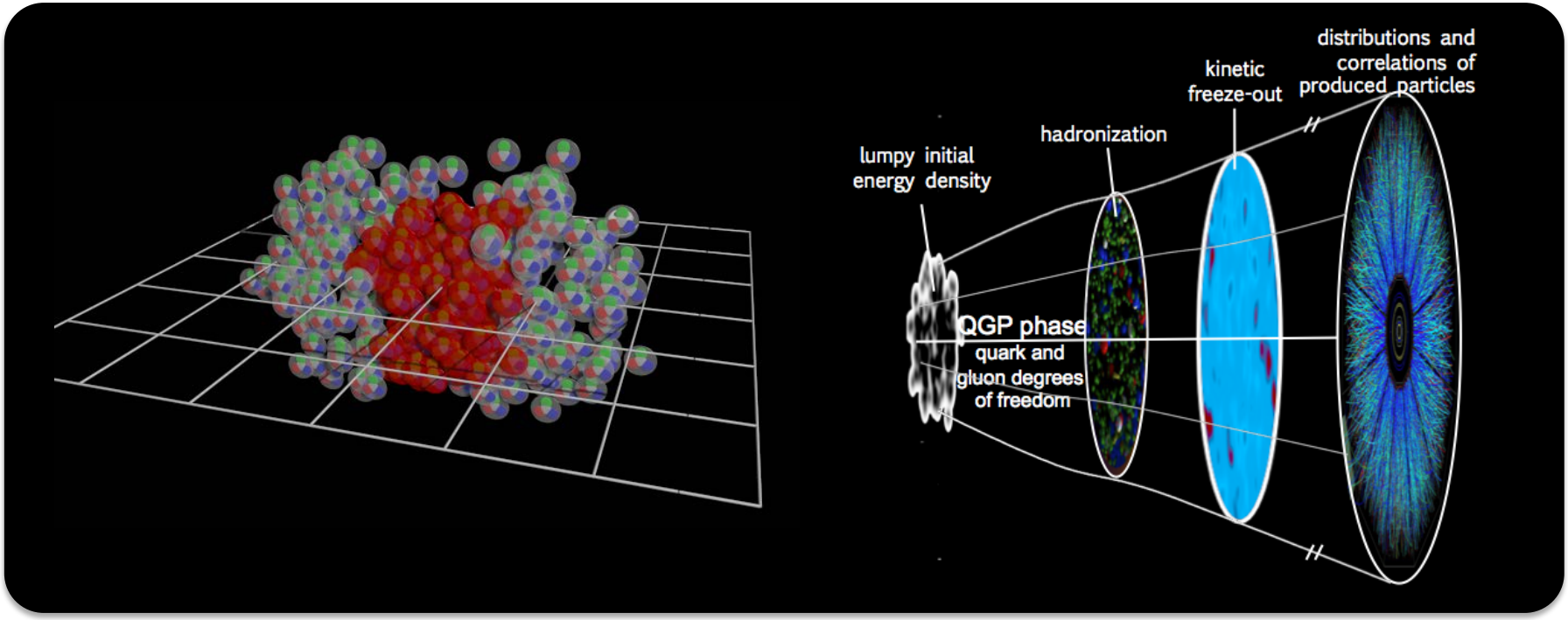




- Without selection on over-lapping region, the impact parameter will dominant geometry
- We will see correlations between v_2 and multiplicity for both Au+Au and UU
  - Larger v_2 associated with small multiplicity

- With the selection on fully over-lapping region, the impact parameter effects are reduced
- The multiplicity difference in Au+Au is dominant by fluctuations
  - No correlation between v_2 and multiplicity
- The multiplicity difference in U+U is dominant by geometry
  - Larger v_2 associated with small multiplicity

Measurements of v_2



Early spatial anisotropy leads to anisotropy in the final momentum space

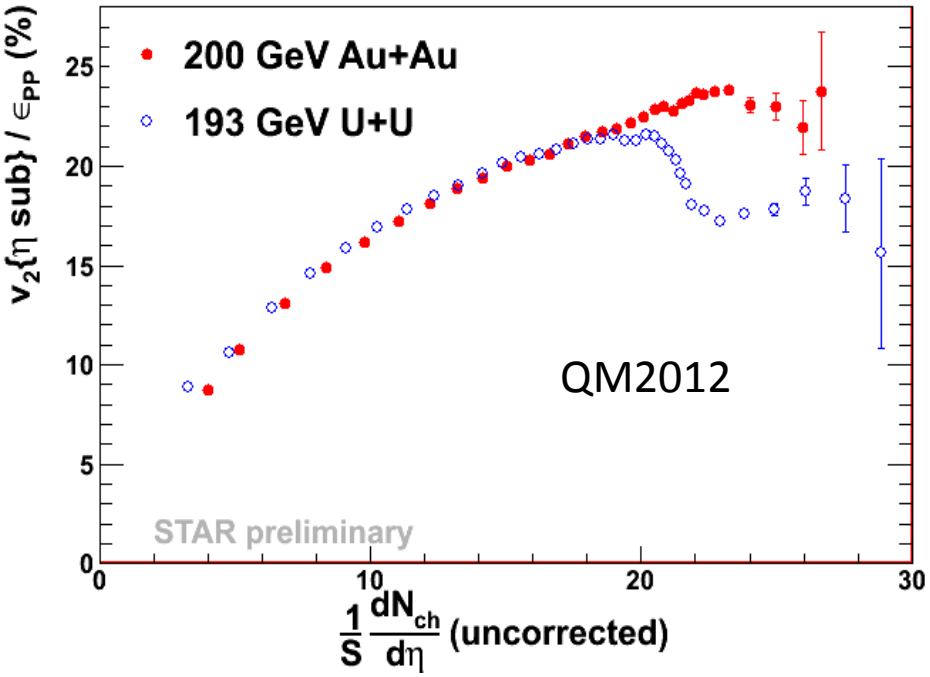
- Cumulants of the $\langle e^{in\phi} \rangle$ distribution characterize the momentum space anisotropy

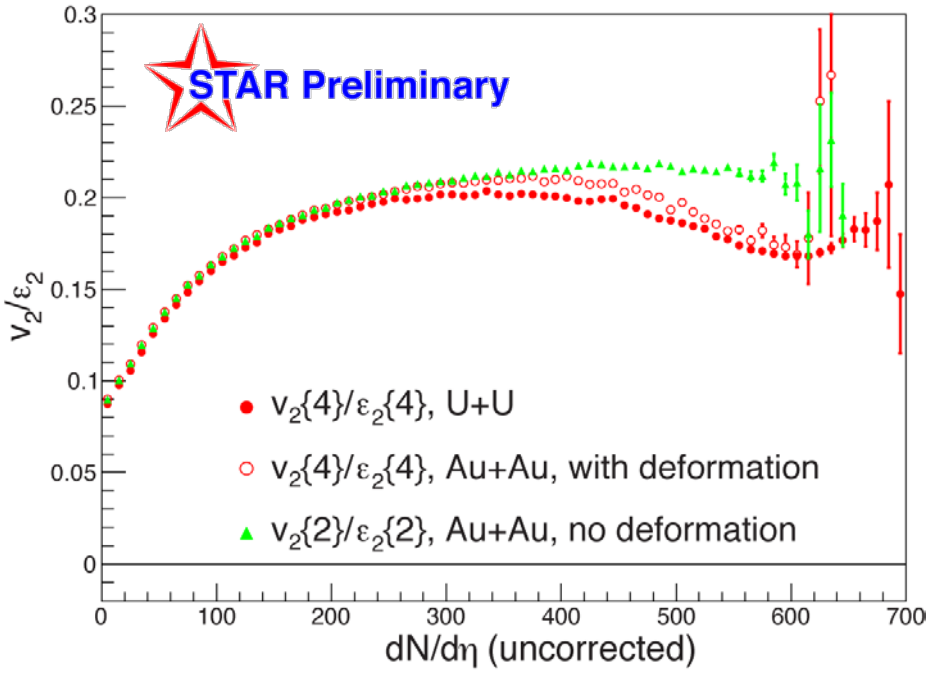
We've measured the 2nd and 4th cumulants using the direct cumulant method

Bilandzic, et. al. Phys.Rev.C83:044913,2011

$$v_2^2\{2\} = \left\langle \left\langle e^{i2(\varphi_i - \varphi_j)} \right\rangle_{i \neq j} \right\rangle \qquad v_2^4\{4\} = -\left\langle \left\langle e^{i2(\varphi_i + \varphi_j - \varphi_k - \varphi_l)} \right\rangle_{i \neq j \neq k \neq l} \right\rangle + 2v_2^2\{2\}^2$$

Effects of deformation in Au





- Previous study assume no deformation for Au nuclei
- With deformation in Au+Au, the split between U+U and Au+Au is reduced