



# Azimuthal anisotropy measurements and selection of body-body and tip-tip enhanced samples in U+U collisions at STAR

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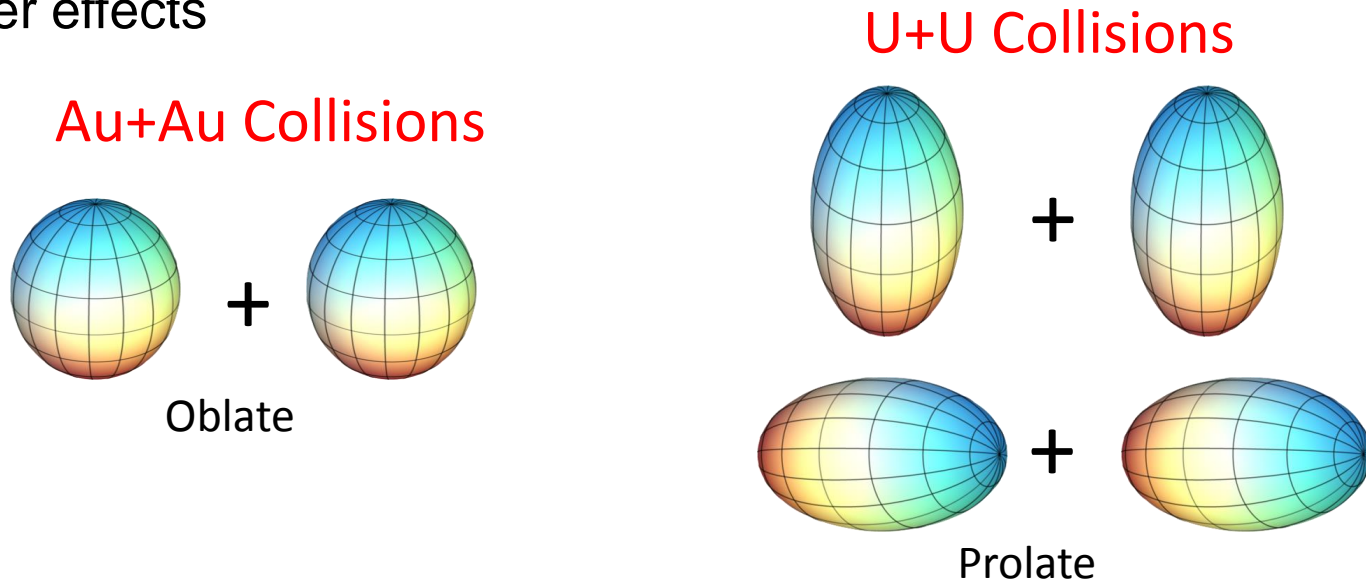
# Outline

- Motivation
- STAR detector and data set
- Azimuthal anisotropy in U+U collisions
- Selection of body-body and tip-tip enhanced samples
- Triangular flow in U+U collisions
- Summary

# Motivation for U+U Collisions

Allows us to manipulate the initial geometry and study:

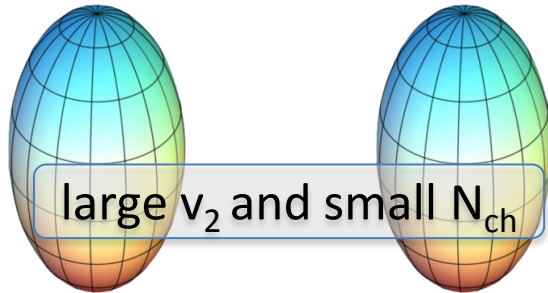
- How multiplicity depends on  $N_{\text{part}}$  and  $N_{\text{coll}}$
- Path-length dependence of jet quenching
- Particle production in heavy-ion collisions
- Other effects



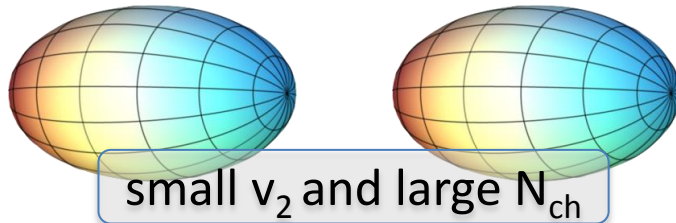
Can we see a difference between **Au+Au** and **U+U** and preferentially select **body-body** or **tip-tip** U+U collisions?

# Selecting Body-body or Tip-tip

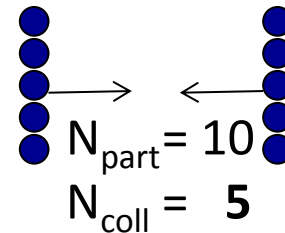
In the two-component model, multiplicity depends on the  $N_{part}$  and  $N_{coll}$  and since  $v_2$  is proportional to initial eccentricity



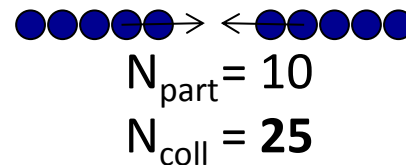
fully overlapping



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



*\*idealizations*

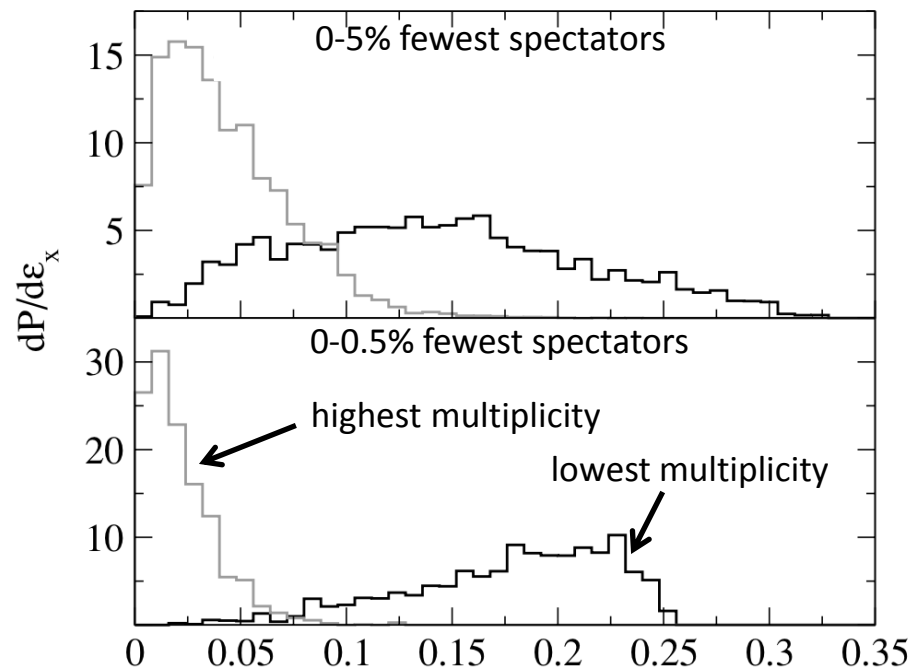


If  $dN/d\eta$  depends on  $N_{coll}$ , large  $dN/d\eta$  should correlate with small  $v_2$ .

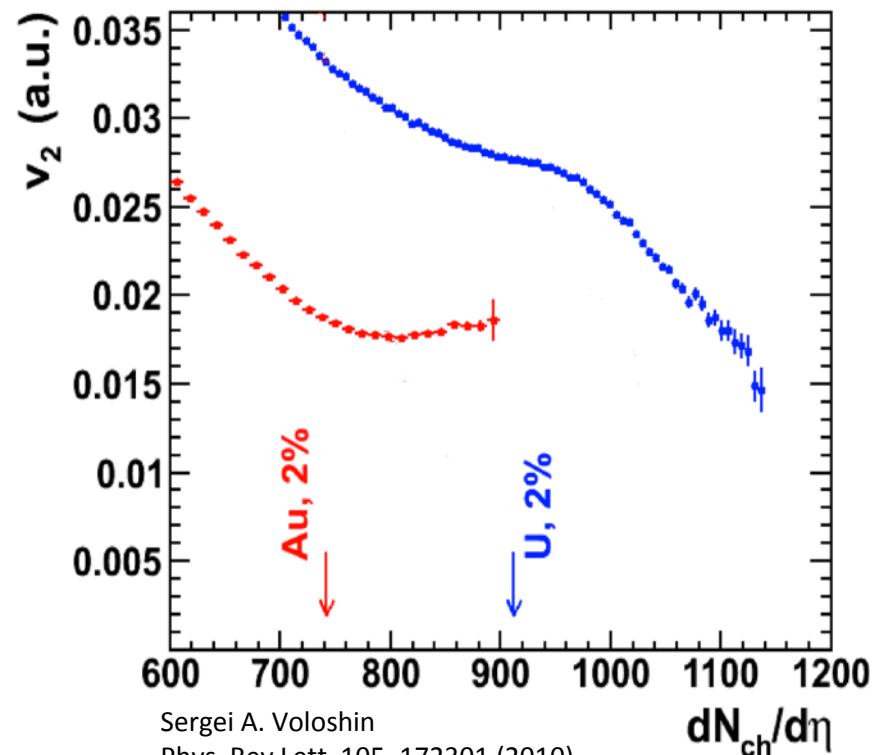
$\Rightarrow$  *Central U+U collisions are ideal for testing particle production*

Strategy: select events with few spectators (fully overlapping), 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  $dN/d\eta$

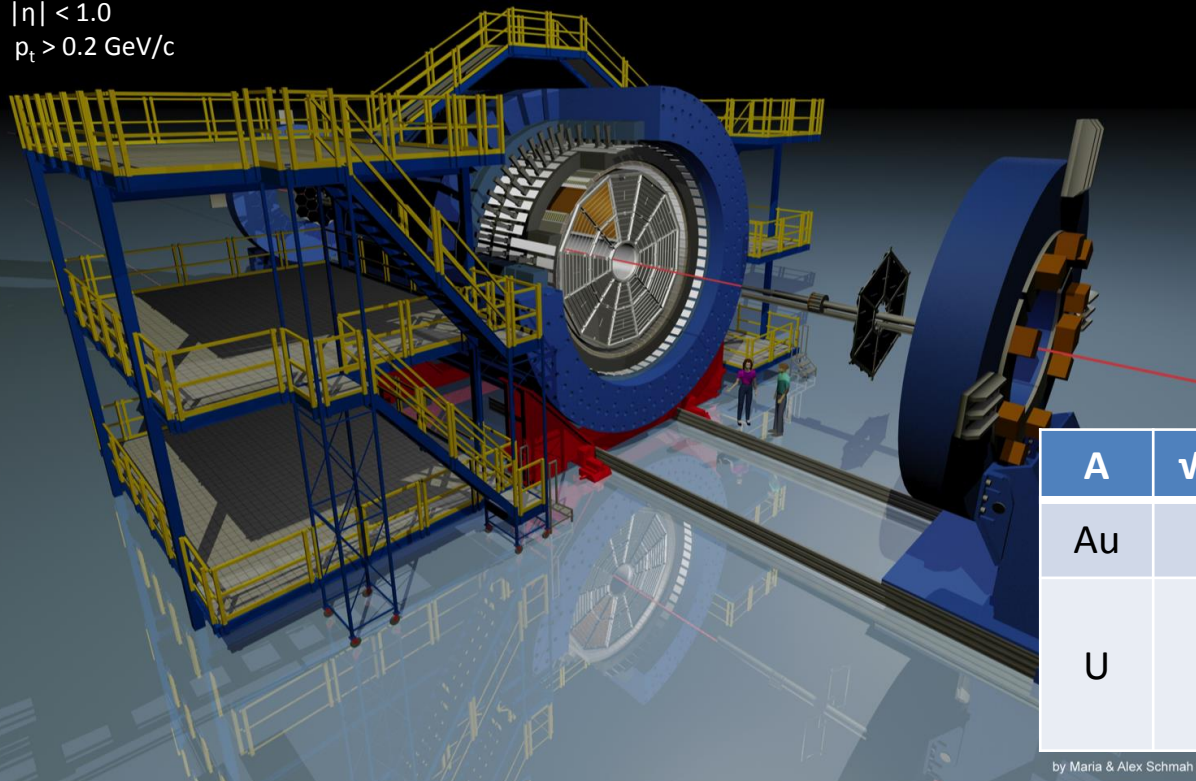
# STAR Detector and Data Set

Full azimuthal coverage

Efficient tracking

$|\eta| < 1.0$

$p_t > 0.2 \text{ GeV}/c$



- 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 ( $\times 10^6$ )
Au	200	2011	700 (mini-bias)
U	193	2012	360 (mini-bias) 13 (central 1% ZDC)

by Maria & Alex Schmah

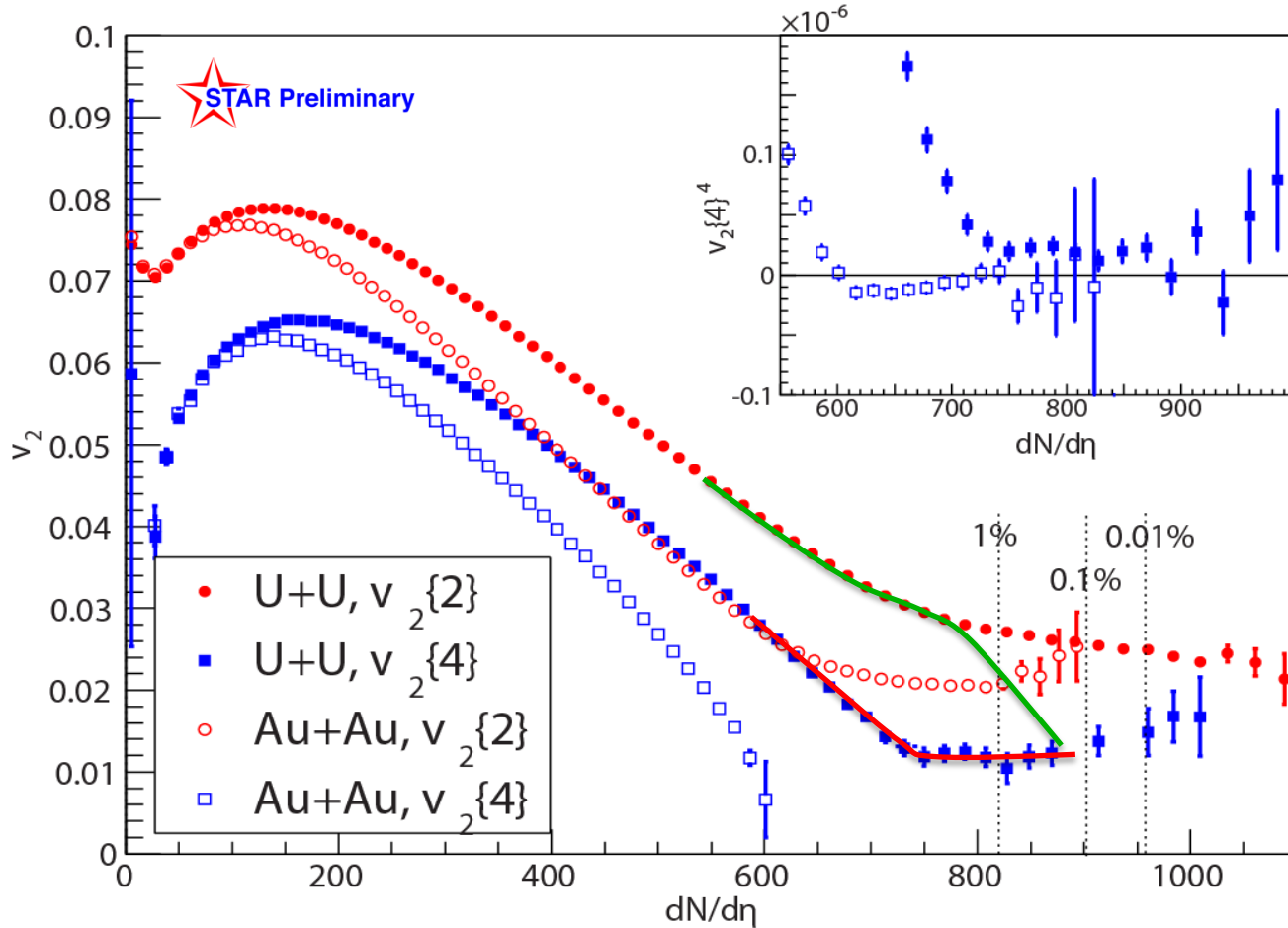
We've measured the efficiency-corrected 2<sup>nd</sup> and 4<sup>th</sup> cumulants using Q-cumulants

Bilandzic, et. al. Phys. Rev. C 83: 044913, 2011

$$v_n^2\{2\} = \left\langle \left\langle e^{in(j_i - j_j)} \right\rangle_{i \neq j} \right\rangle \quad v_n^4\{4\} = - \left\langle \left\langle e^{in(\phi_i + \phi_j - \phi_k - \phi_l)} \right\rangle_{i \neq j \neq k \neq l} \right\rangle + 2V_n^4\{2\}$$

Hui Wang, BNL

# Minimum-bias U+U and Au+Au



No evidence of knee structure for central U+U

- Glauber plus 2-component model suggests knee structure at  $\sim 2\%$  centrality
- Knee washed out by additional multiplicity fluctuations?<sup>1</sup>
- Other interpretations?

<sup>1</sup>Maciej Rybczyński, et. al.  
Phys.Rev. C87 (2013) 044908

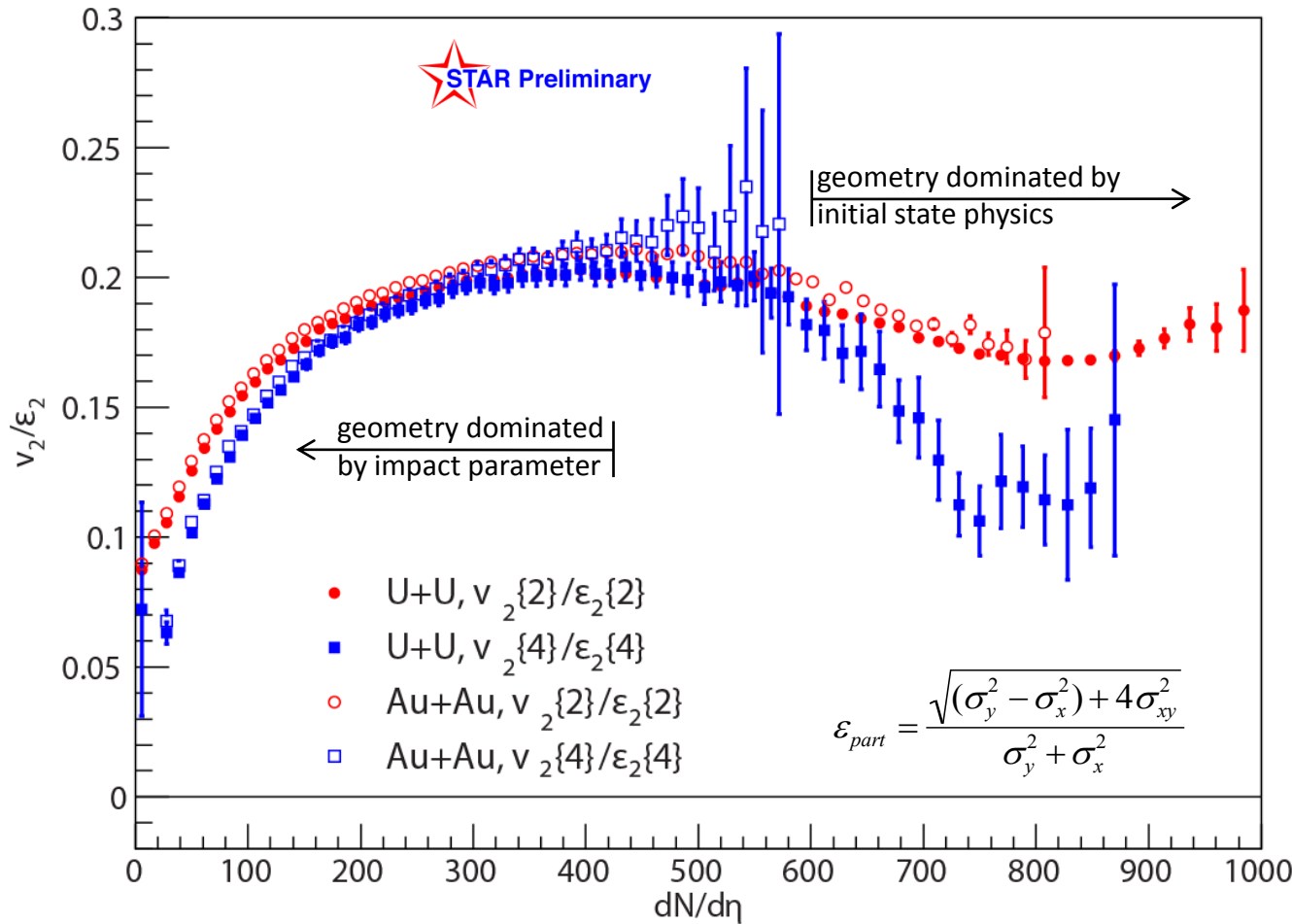
The U+U  $v_2\{4\}$  results are non-zero in central

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

Dashed 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

$$v_2/\epsilon_2$$



$v_2/\epsilon_2$  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,  $v_2/\epsilon_2$  drops in the most central collisions

The drop is sharper for U+U  $v_2\{4\}/\epsilon_2\{4\}$

New glauber parameters under investigation<sup>1</sup>

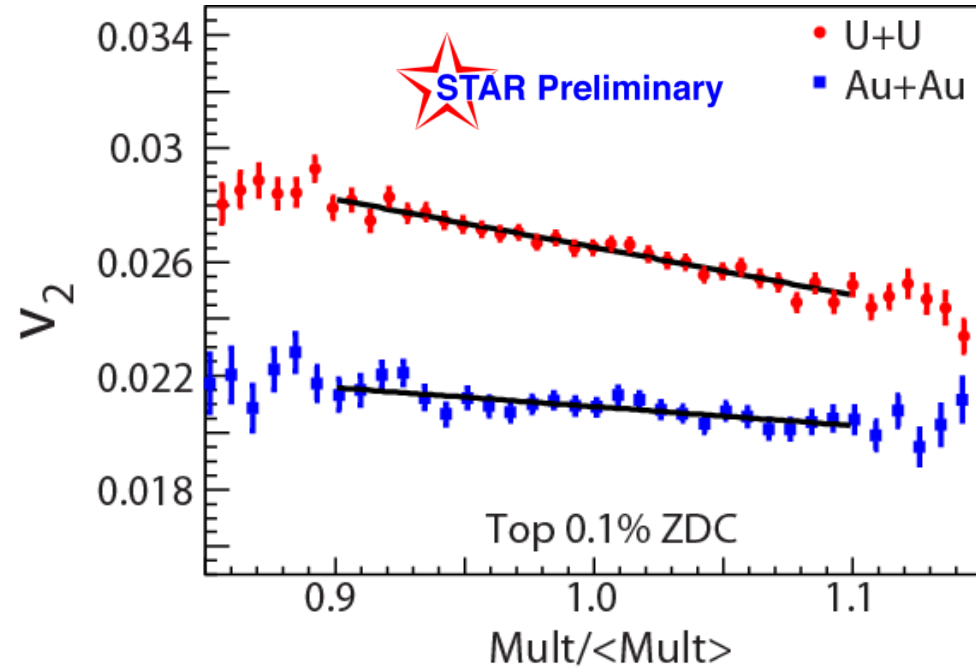
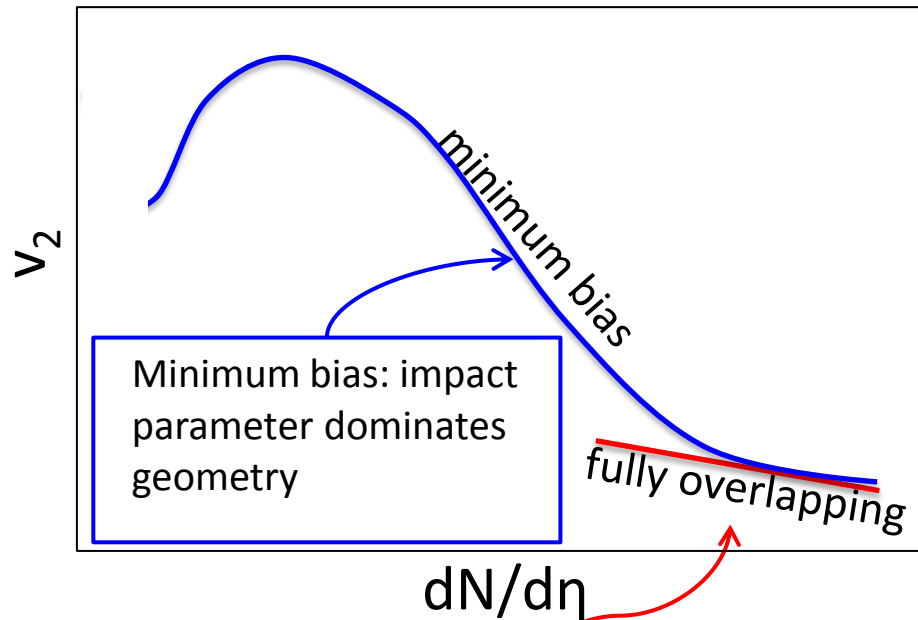
<sup>1</sup>Q.Y. Shou, et. al. arXiv:1409.8375

Results suggest an overestimation of  $\epsilon_2$  in central collisions or deviation from  $v_2 \propto \epsilon_2$  (uncertainties in glauber parameters, non-flow, hydro fluctuations?)

**Very central collisions provide a stringent test of models**



# Studying Full Overlap Events

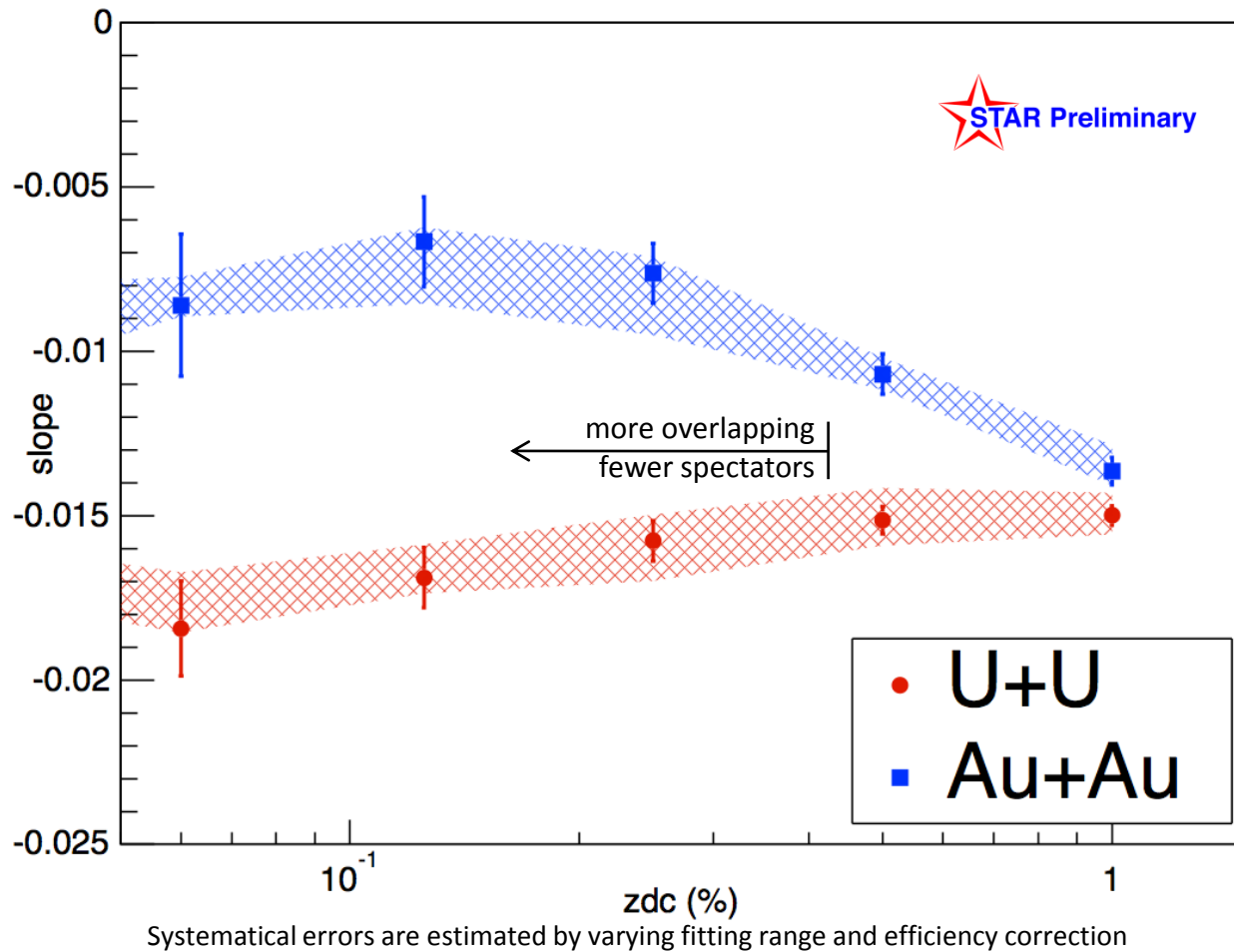


Central ZDC selection  $b \rightarrow 0$

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

- Use slope of  $v_2$  vs  $dN/d\eta$  in U+U to look for correlation between  $dN/d\eta$  and geometry
  - Expect a strong negative slope
- Use Au+Au as the control sample to show we select full overlap
  - Expect a zero or slightly positive slope

# Slope vs. ZDC

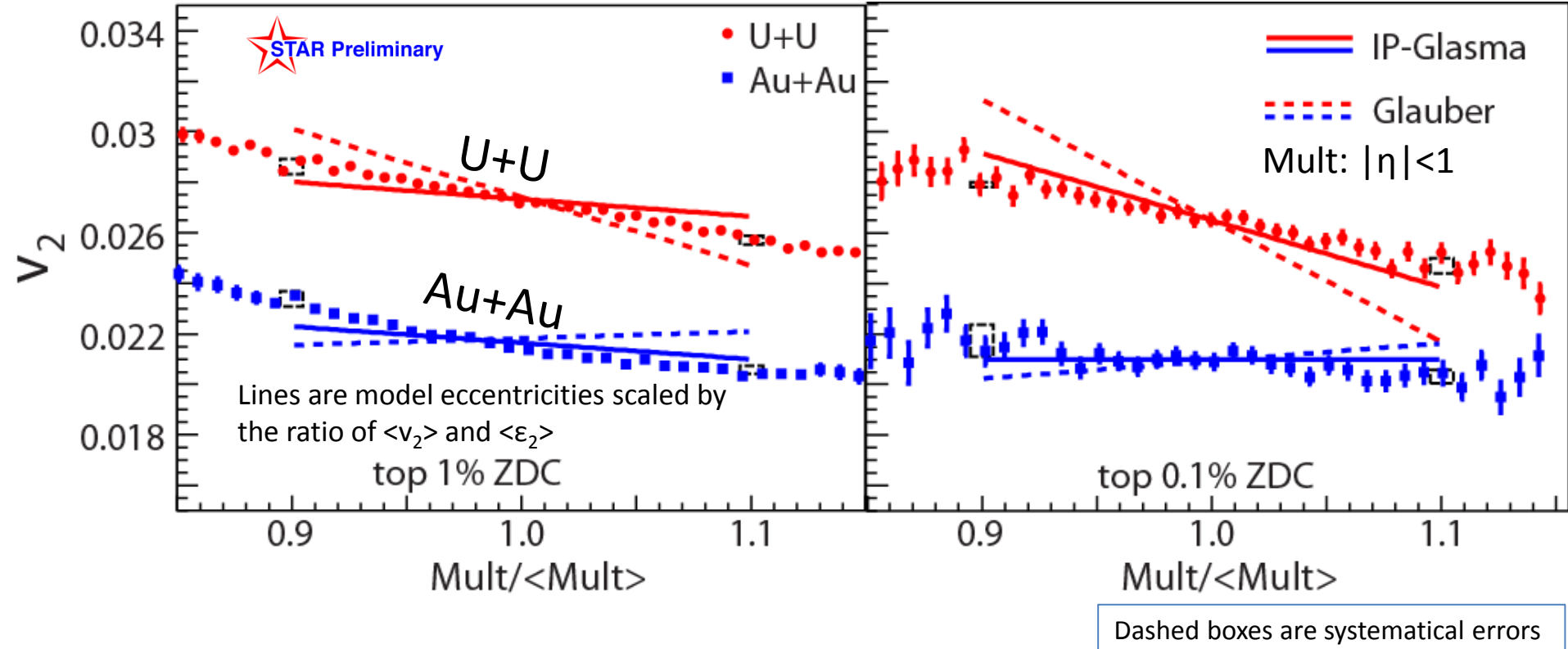


ZDC Centrality	U+U	Au+Au
0.125%	6	4
0.25%	7	5
0.5%	9	6
1.0%	12	8
2.0%	17	12

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  $dN/d\eta$  is larger for tip-tip U+U collisions:  $dN/d\eta$  can be used to select tip-tip vs body-body enhanced samples

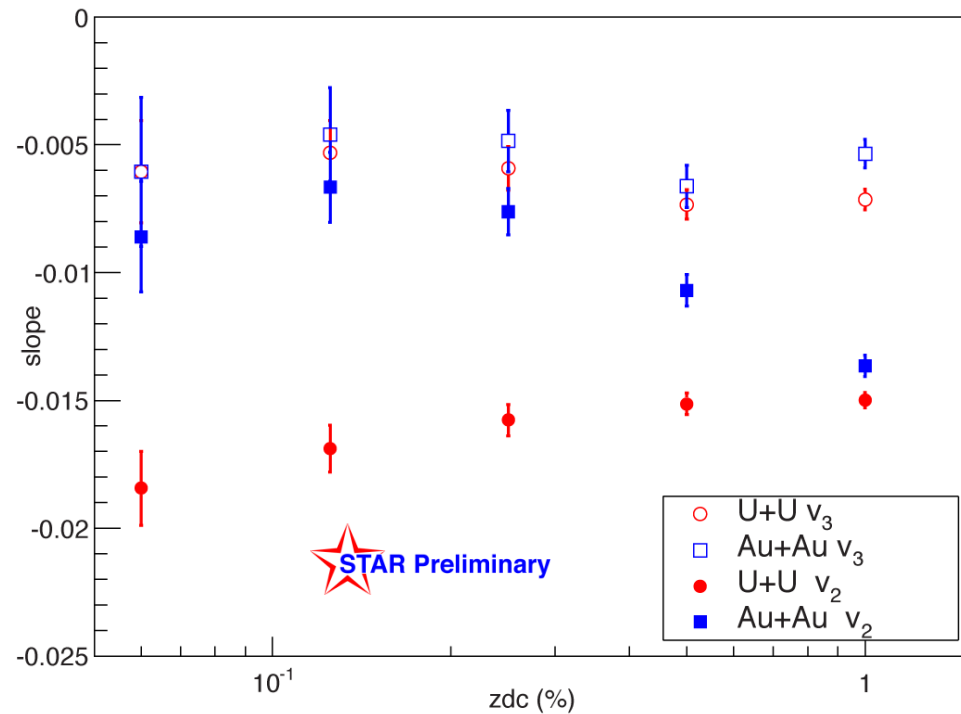
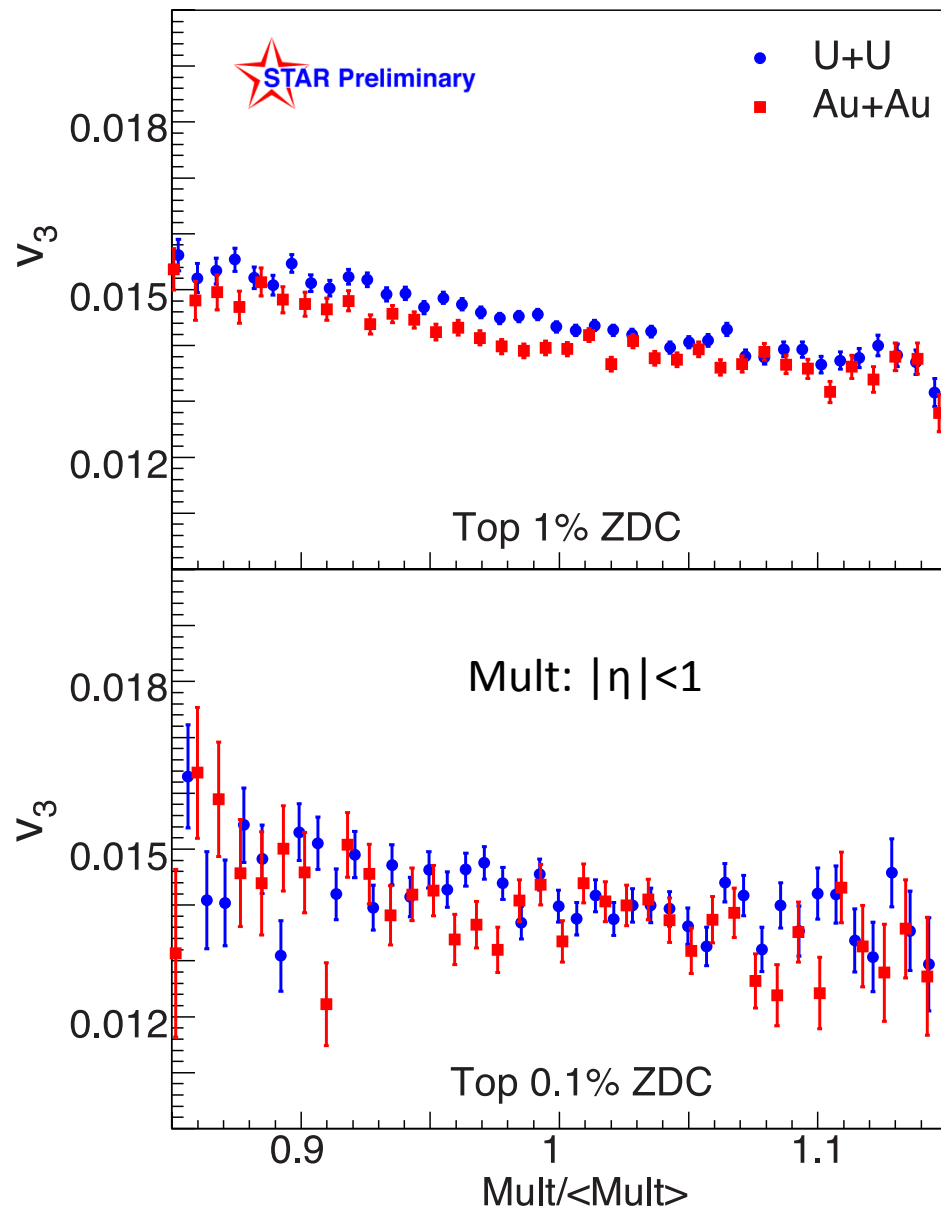
# IP-Glasma vs. Glauber



- Glauber plus 2-component model overpredicts U+U data and predicts positive slopes for Au+Au data
- Within current uncertainties, IP-Glasma model<sup>1</sup> (solid color lines) matches data better, especially for top 0.1% ZDC

<sup>1</sup>Bjoern Schenke, Prithwish Tribedy and Raju Venugopalan  
arXiv:1403.2232

# Triangular Flow



- Test the impact of Uranium's prolate shape on initial state fluctuations
- The slope of  $v_3$  vs. multiplicity is small and negative in both systems
- We observe no differences between U+U and Au+Au  $v_2$  slope

# Summary

- U+U collisions open up a stringent testing ground of initial states and multiplicity production models
- No evidence of kink structure in central  $v_2$  results from current analysis, more fluctuations than NBD? <sup>1</sup>
- $v_2/\epsilon_2$  turns over in central collisions for both Au+Au and U+U!?
  - Overestimation of  $\epsilon_2$  in Glauber model?
- The combination of ZDC and multiplicity can be used to select body-body or tip-tip enhanced samples of central U+U collisions
  - High multiplicity events are biased toward tip-tip enhanced collisions, low multiplicity toward body-body enhanced collisions
  - Data show weaker correlations than model predictions: larger multiplicity fluctuations?
  - IP-Glasma model does a better job of describing data
- We observe no differences between U+U and Au+Au  $v_3$  results

<sup>1</sup>Maciej Rybczyński, et. al.  
Phys.Rev. C87 (2013) 044908

# Back Up

# Glauber Model

- Assume deformed Woods-Saxon distribution

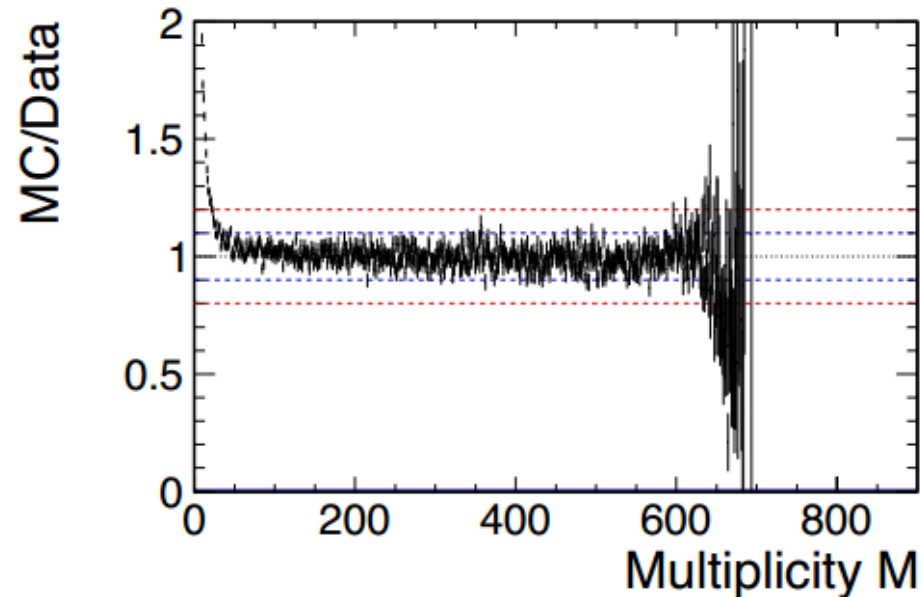
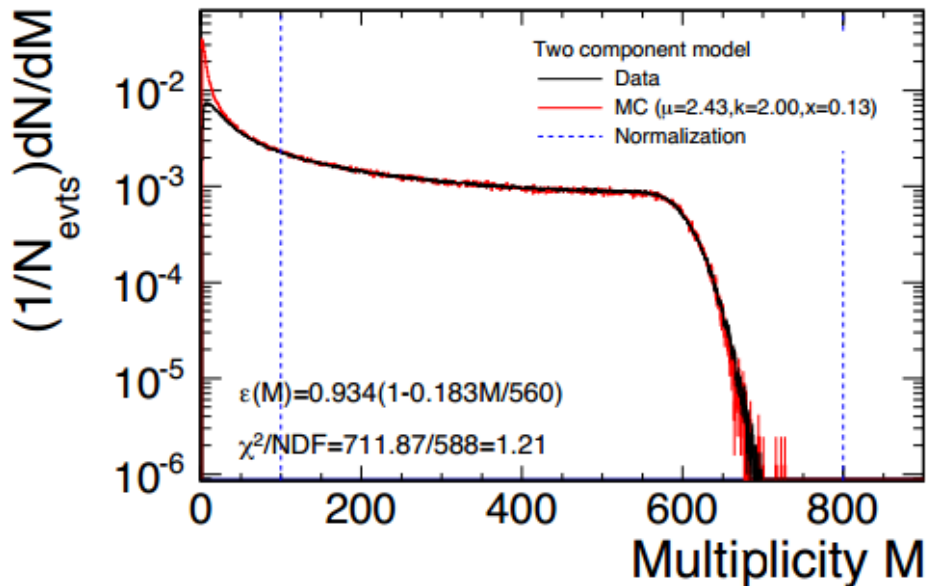
$$\rho = \frac{\rho_0}{1 + \exp([r - R']/d)} \quad R' = R[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$

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

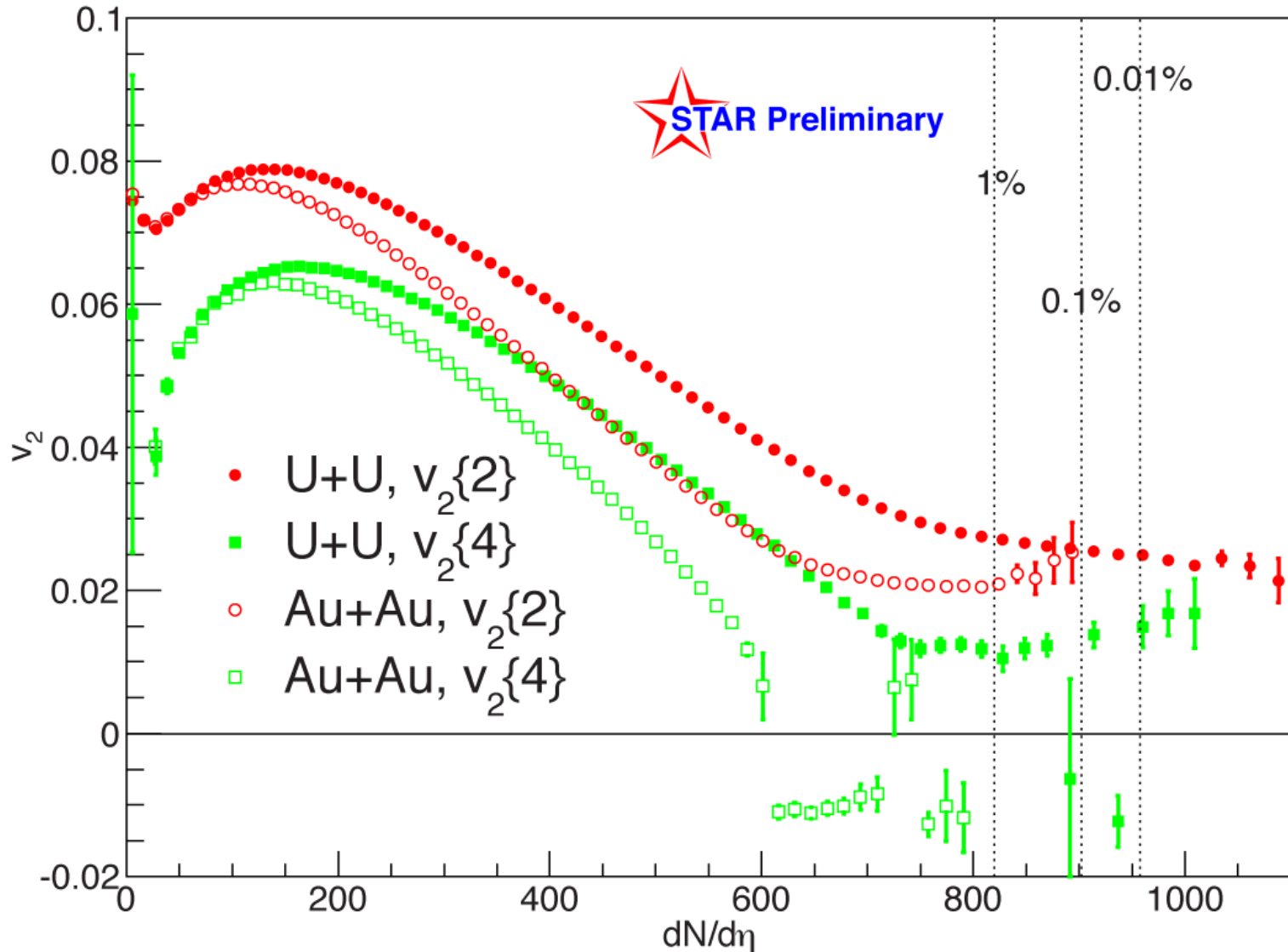
$$n_{AA} \propto n_{pp} \left[ (1 - x_{hard}) \frac{N_{part}}{2} + x_{hard} N_{coll} \right]$$

- 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



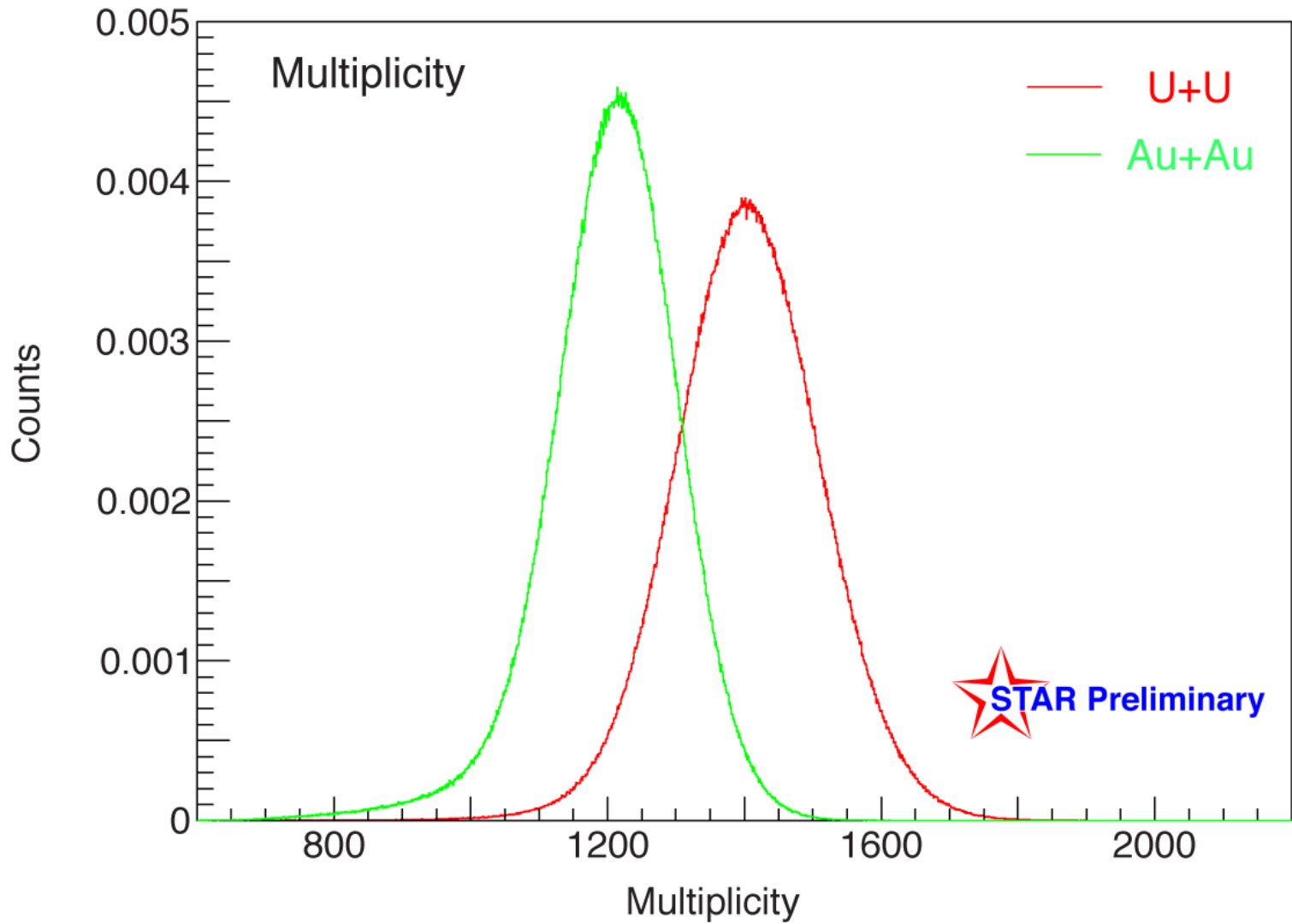
# Minimum-bias U+U and Au+Au



The  $v_2\{4\}$  results are calculated from taking the fourth root of  $v_2\{4\}^4$

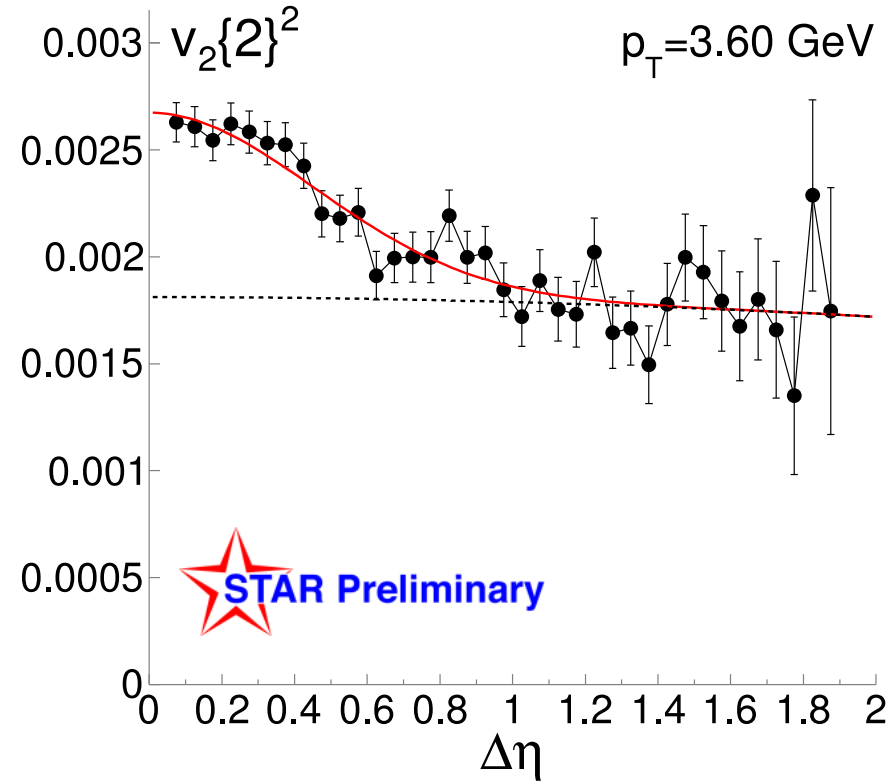
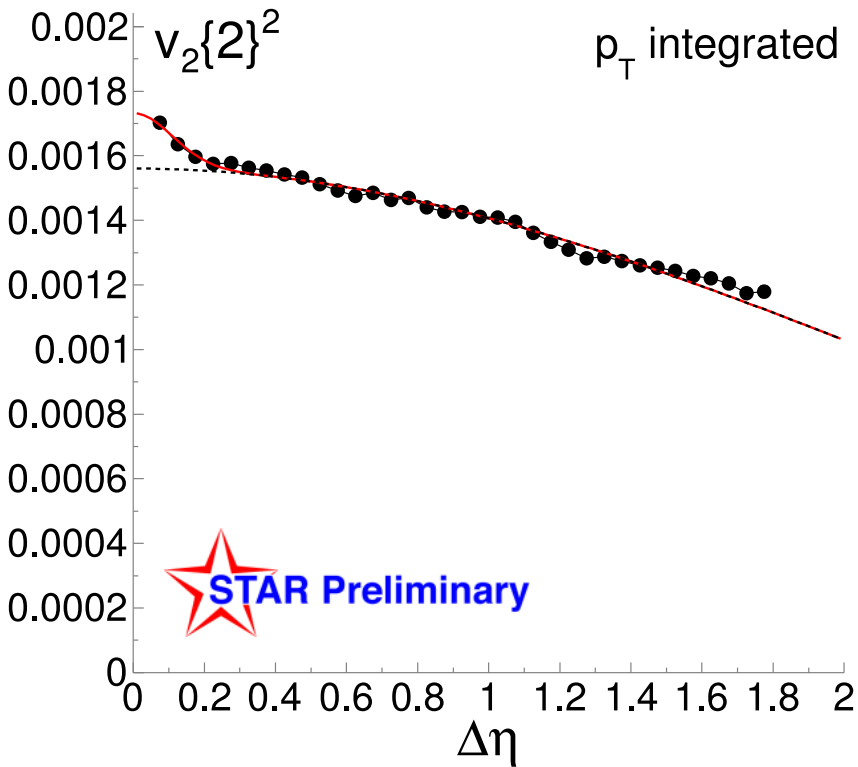


# Multiplicity



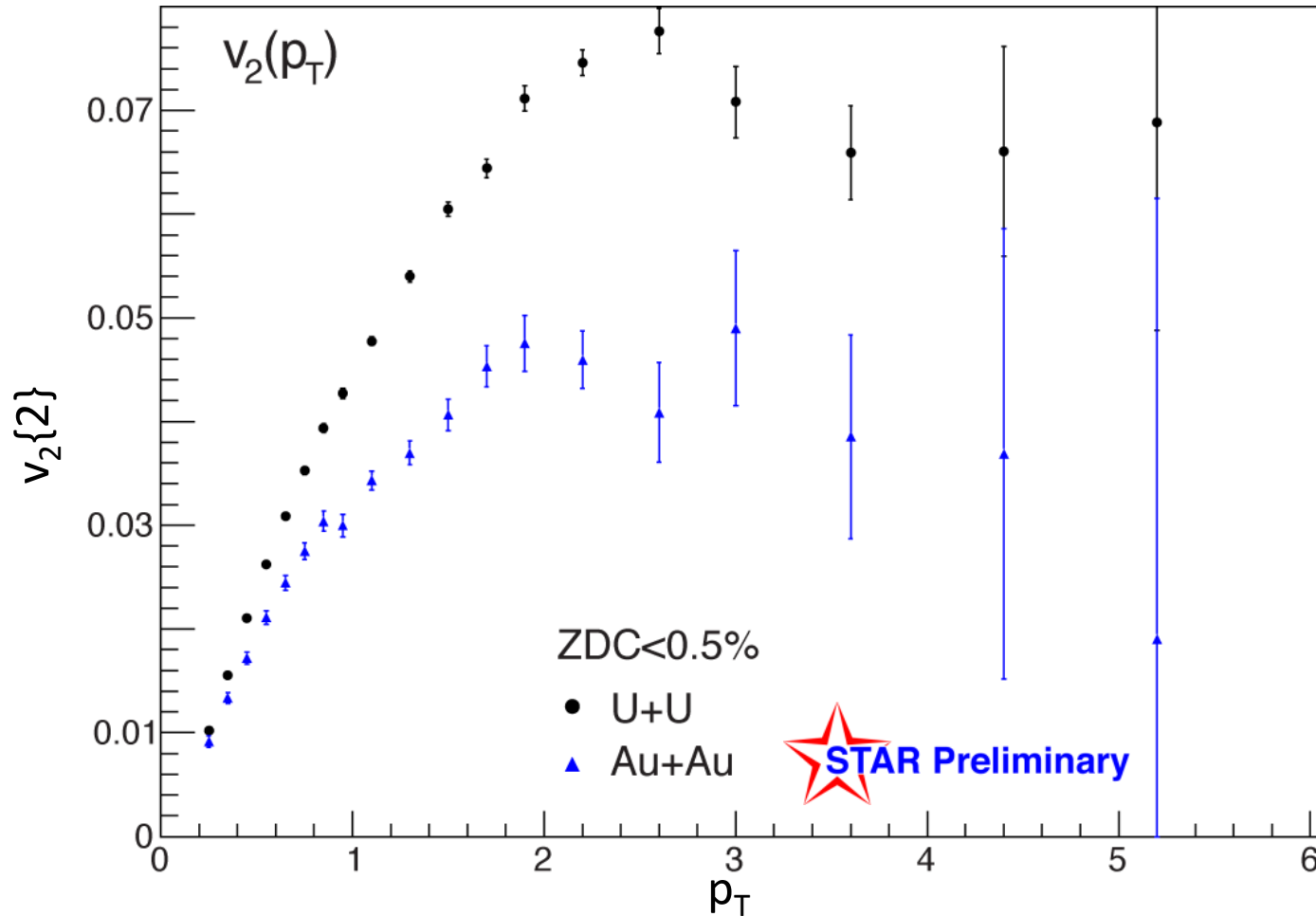
The corrected multiplicity distribution for 1% central ZDC events

# $\Delta\eta$ dependence



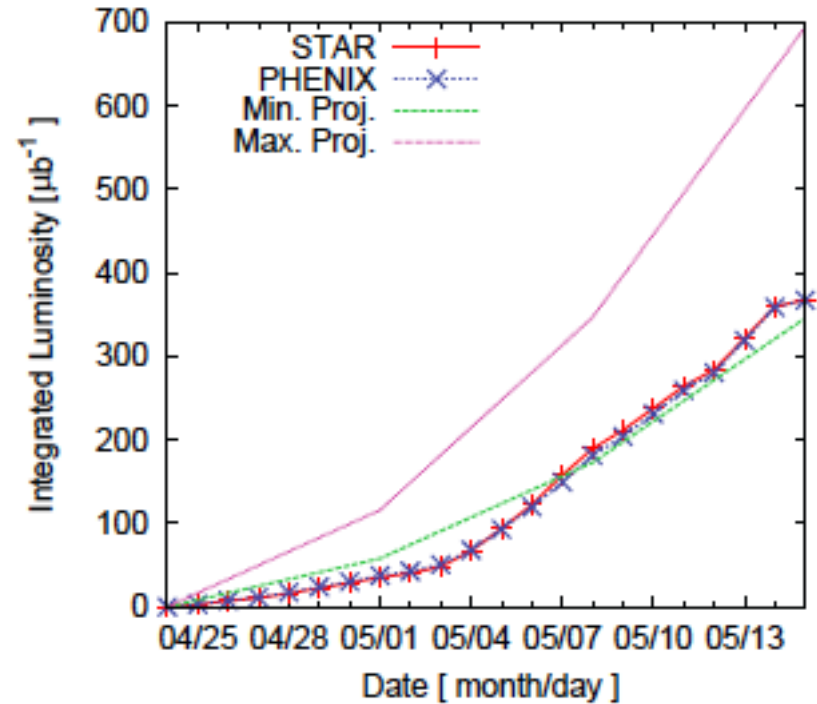
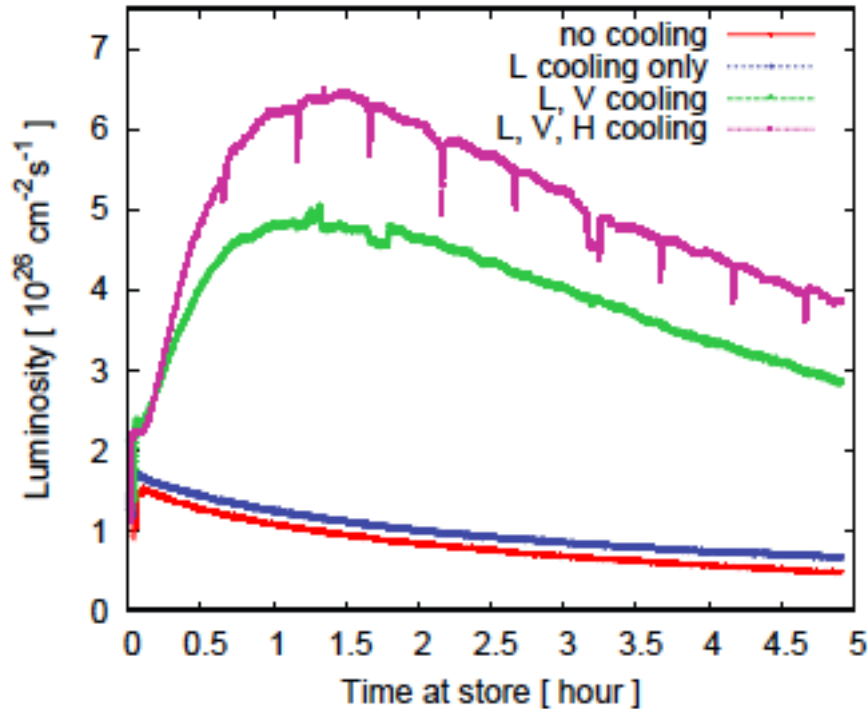
Remove peak at small  $\Delta\eta$  to reduce non-flow effects

# Toward Path Length Dependence of Quenching



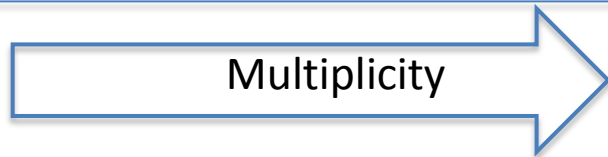
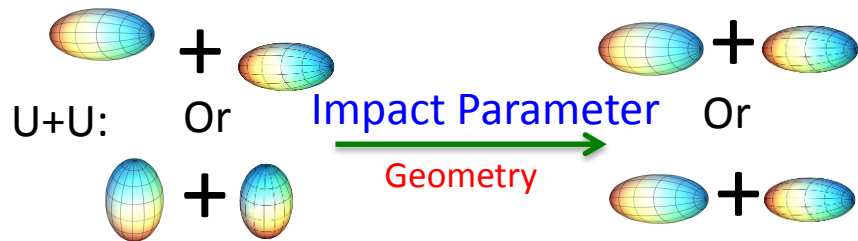
- Larger difference in-plane vs out-of-plane path length in U+U?
  - Need to split U+U results into multiplicity bins (body-body vs. tip-tip)
  - A larger-sized data sample of central U+U events will be needed

# Collection of U+U data sample



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

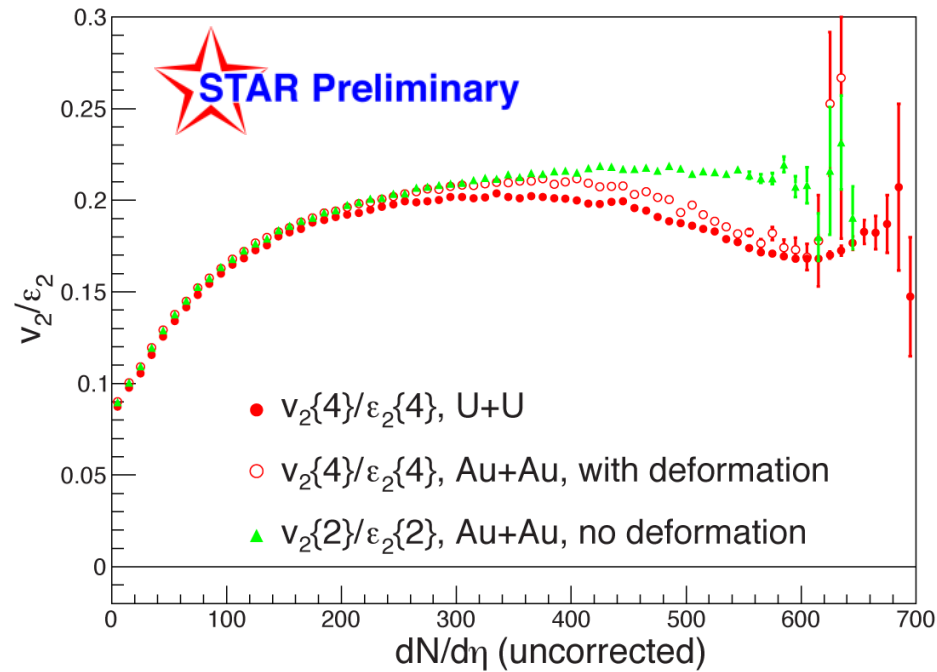
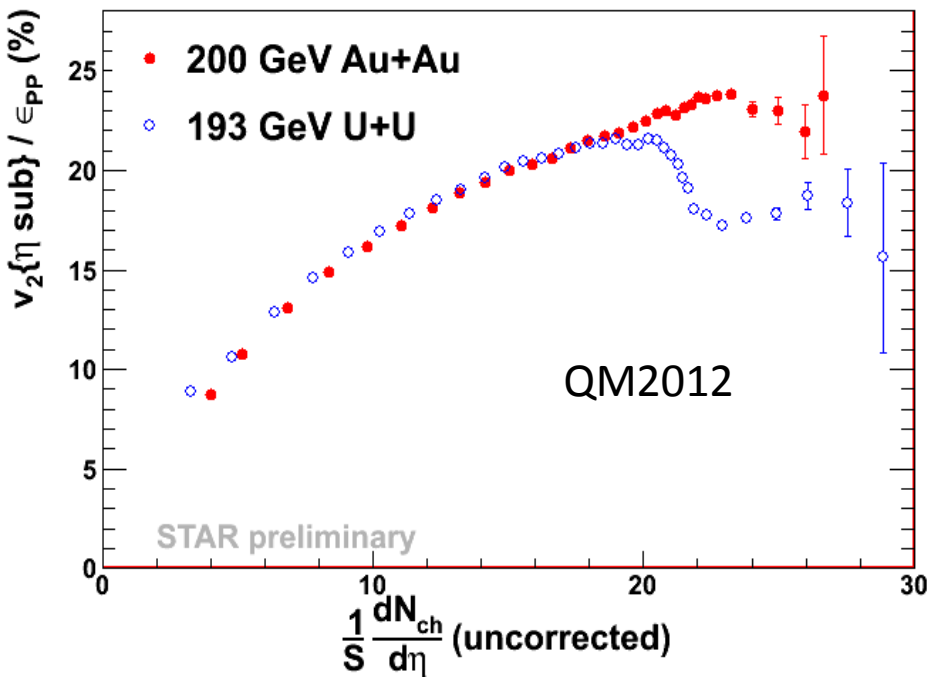
# Studying Full Overlap Events



- Without selection on overlapping region, the impact parameter will dominate 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 overlapping region, the impact parameter effects are reduced
- The multiplicity difference in Au+Au is dominated 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**

# Effects of deformation in Au



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