Azimuthal Anisotropy in U+U Collisions

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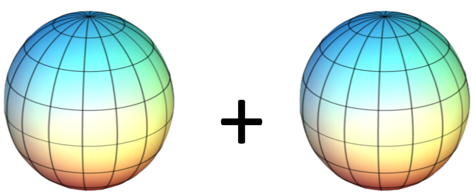
Motivation for U+U Collisions

Allows us to manipulate the initial geometry and study

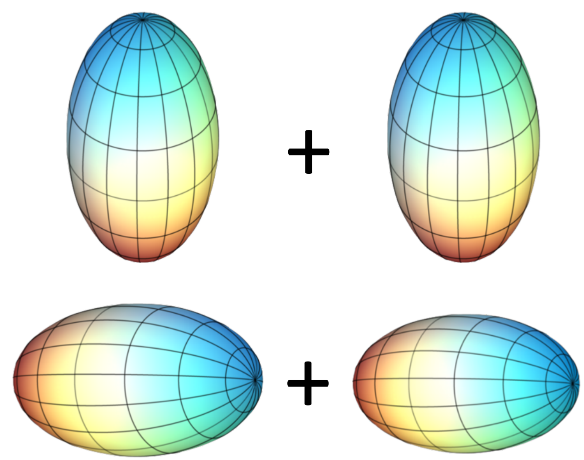
- How multiplicity depends on N_{part} and N_{coll}
- Path-length dependence of jet quenching (and many other effects)

Au+Au Collisions



Slightly Oblate

U+U Collisions

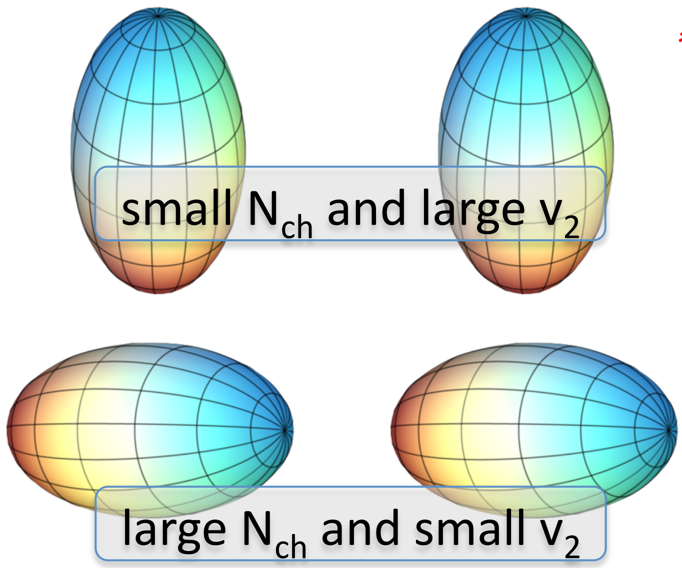


Prolate

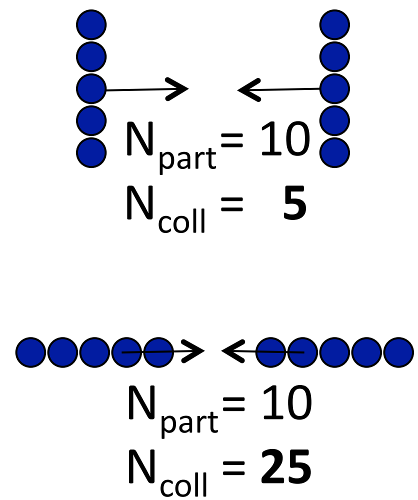
Can we preferentially select body-body or tip-tip collisions?

Selecting Body-Body or Tip-Tip

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



**idealizations*

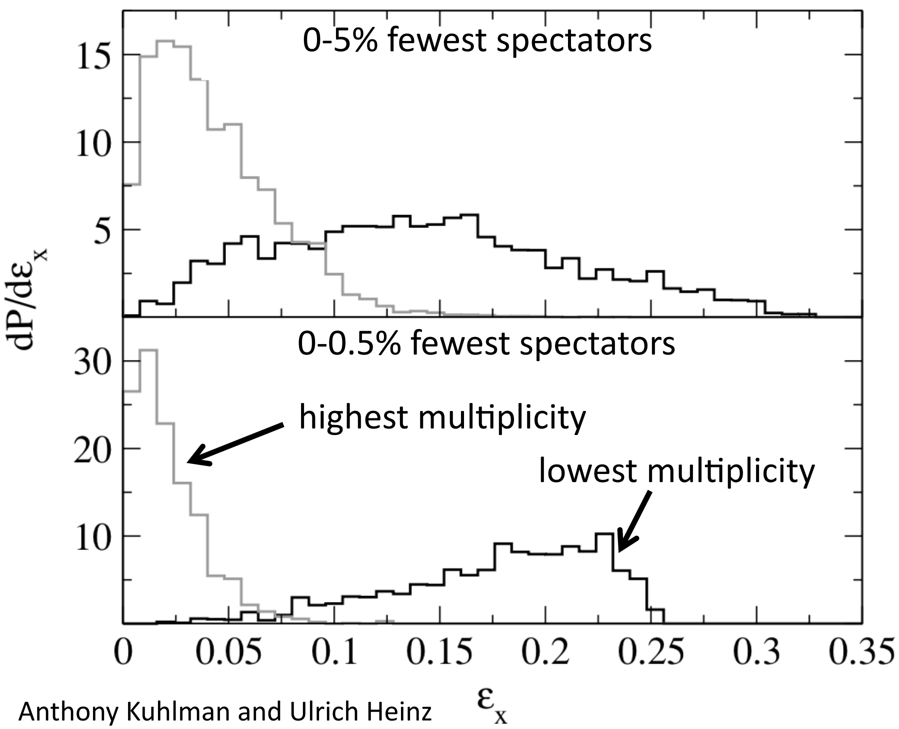


If dN/dη depends on N_{coll} or thickness, dN/dη should correlate with small v_2.
→*Central U+U collisions are ideal for testing particle production*

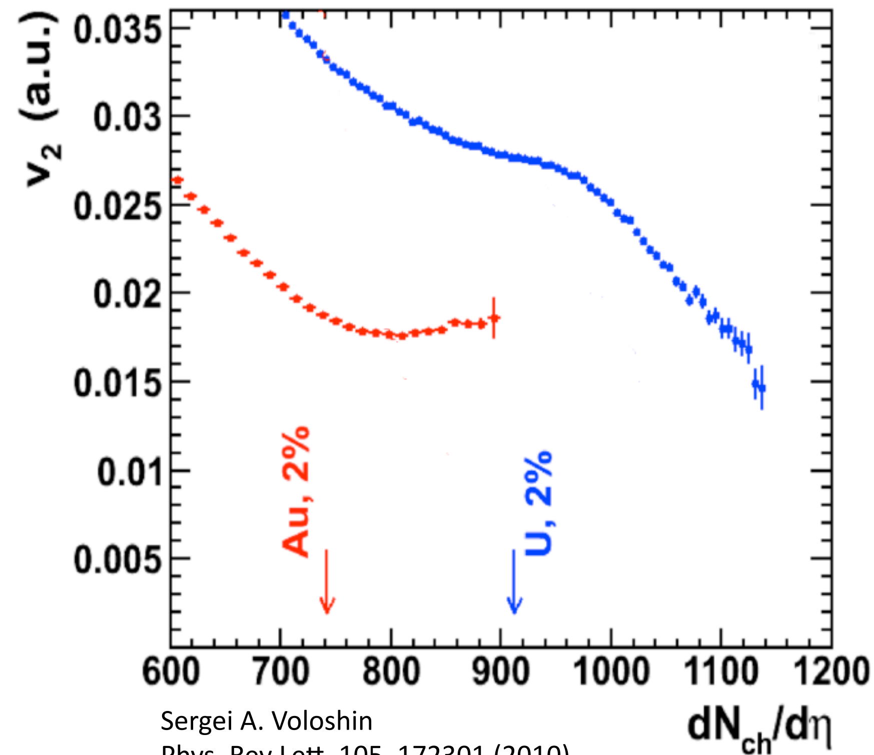
Strategy: select events with few spectators (fully over-lapping), then measure v_2 vs multiplicity: **how strong is the correlation?**

Expectations from Models

including all configurations of impact parameters and Euler angles



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



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

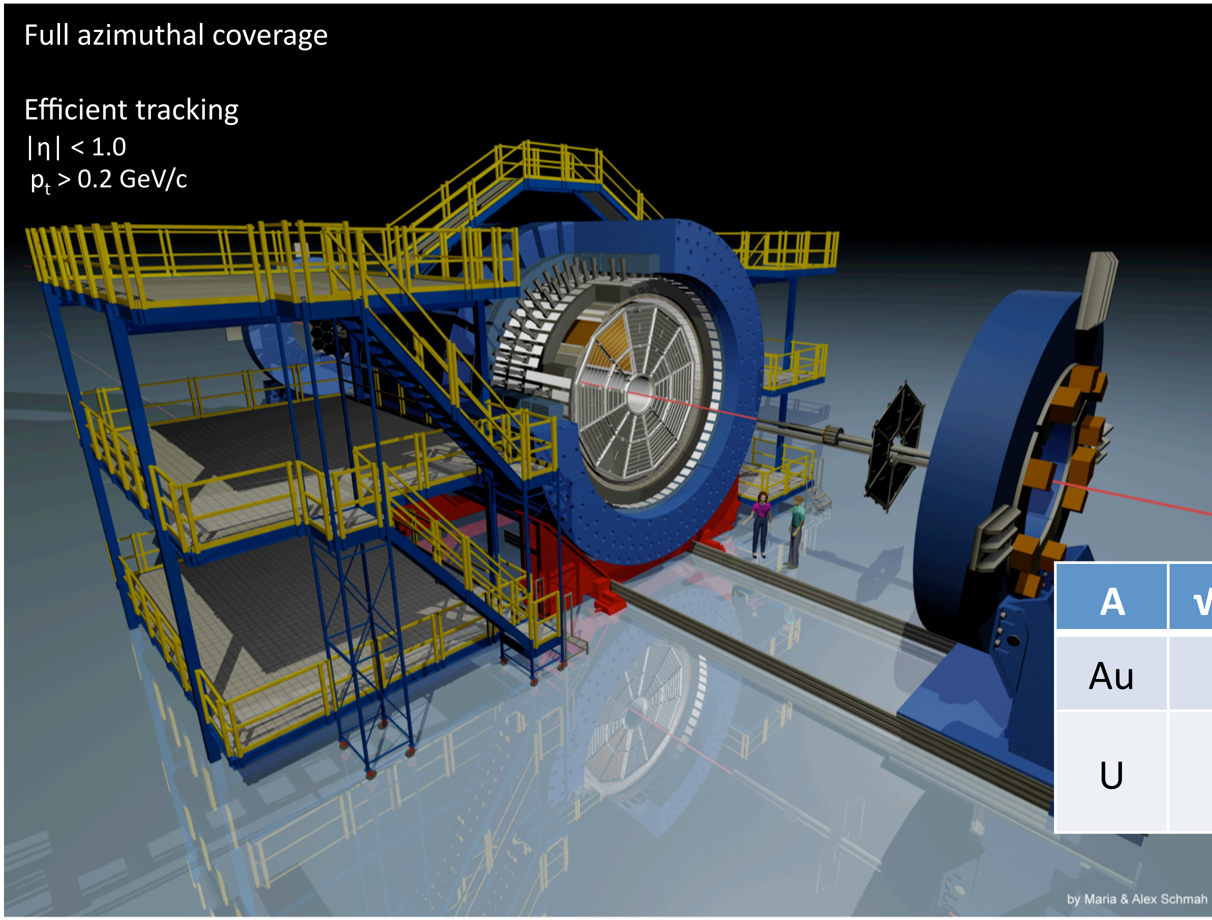
Simulations show that after selecting most fully overlapping collisions,

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

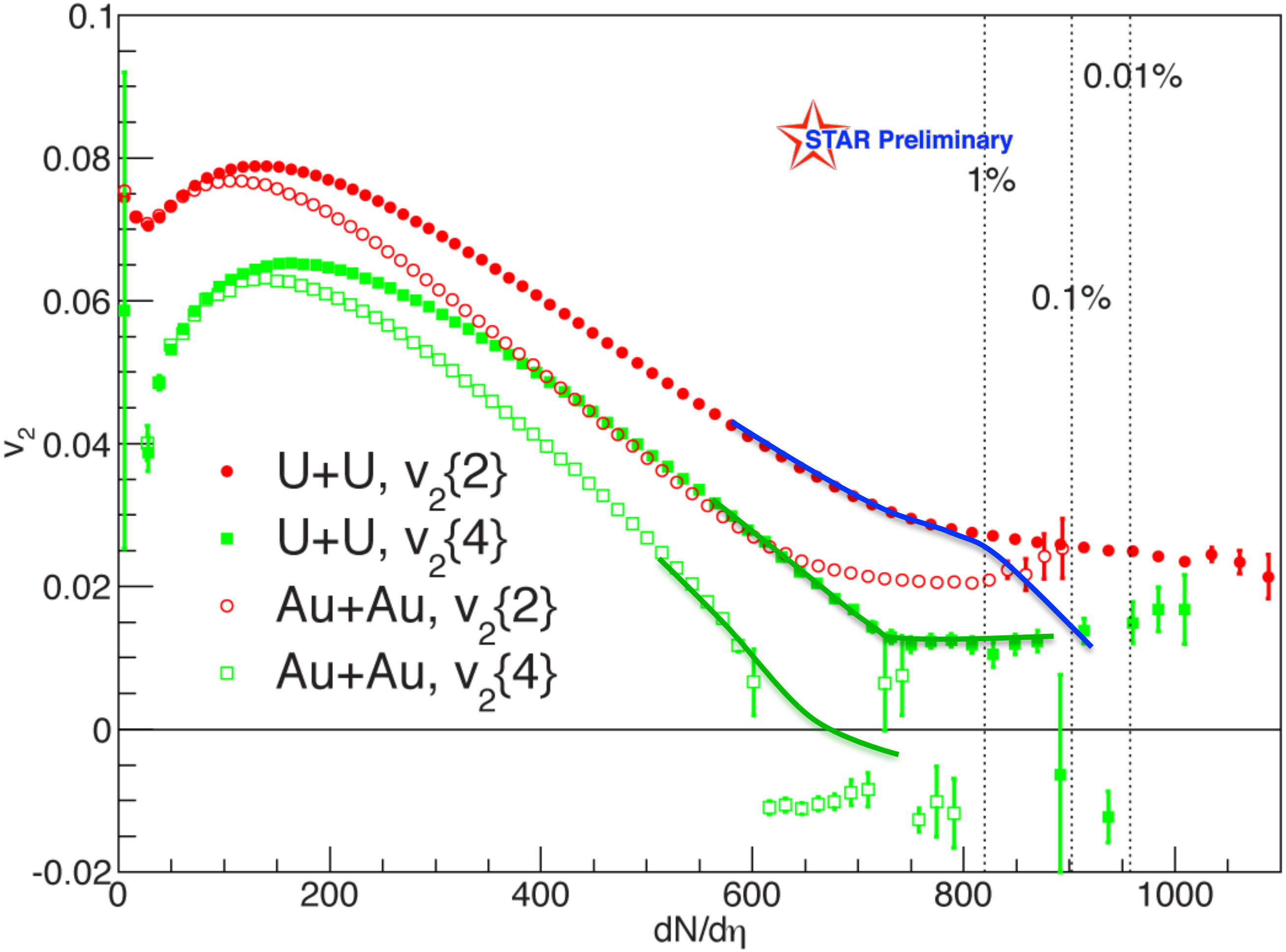
A	$\sqrt{s_{nn}}$ GeV	Year	Events (x10[6])
Au	200	2011	700 (mini-bias)
U	193	2012	360 (mini-bias) 13 (central 1% ZDC)

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

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

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

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]

[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 $v_2\{4\}$

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

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

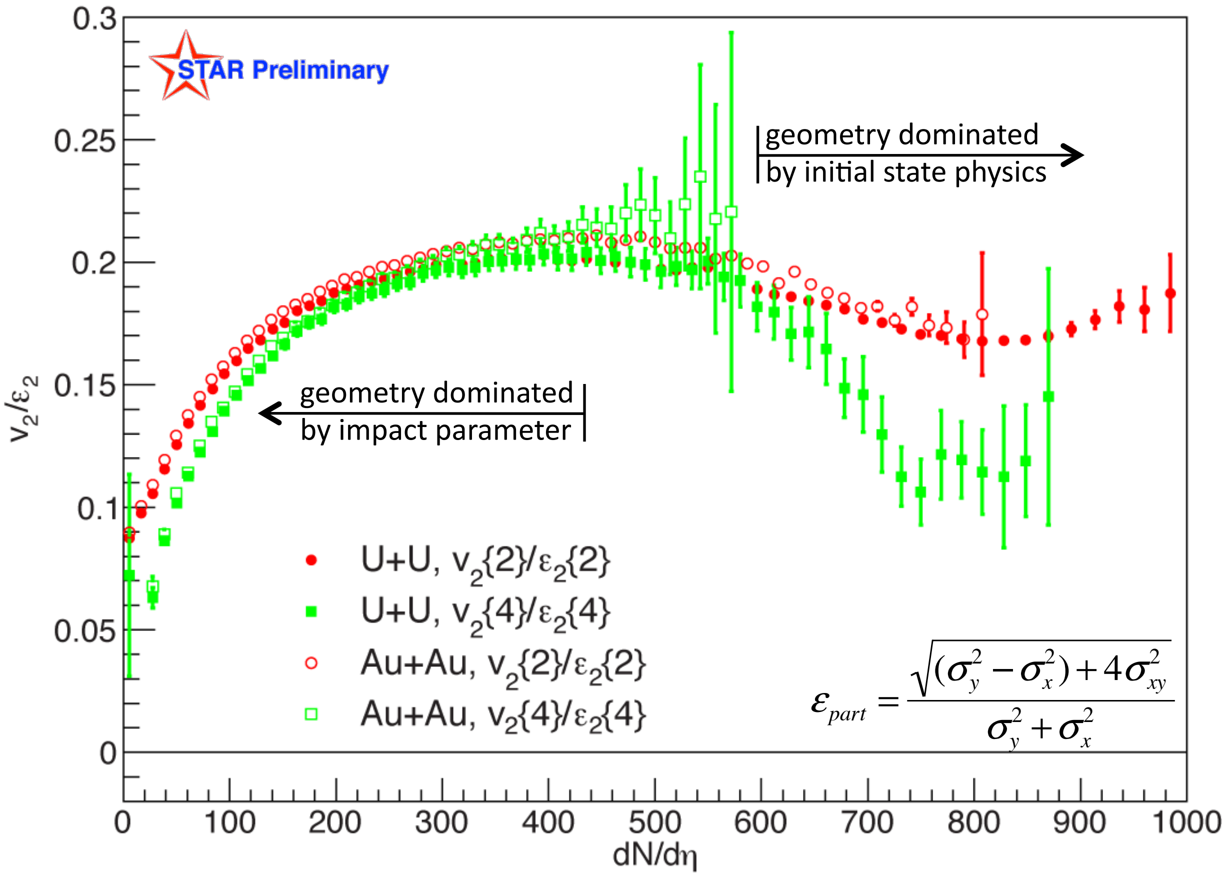
$$n_{AA} \propto n_{pp}[(1 - x_{hard})\frac{N_{part}}{2} + x_{hard} N_{coll}]$$

- 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

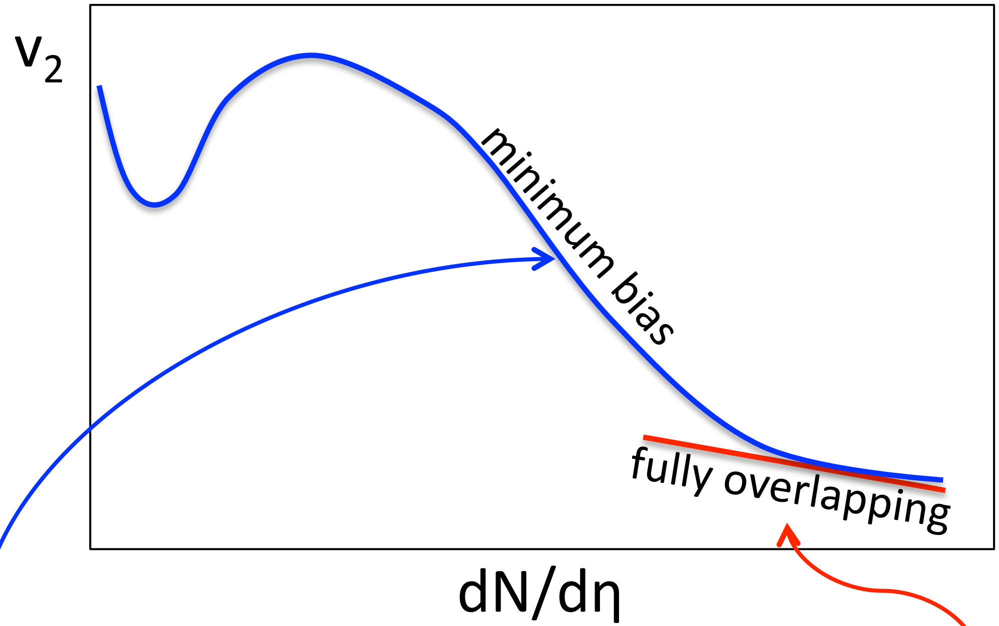
Instead of saturating or slowly rising, v_2/ε_2 drops in most central collisions

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

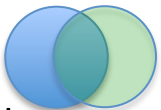
Results are consistent with an overestimation of ε_2 in central collisions or deviation from $v_2 \propto \varepsilon_2$ (non-flow, hydro fluctuations?)

Very central collisions provide a stringent test of models

Studying Full Overlap Events

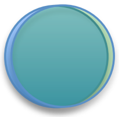


Minimum bias: impact parameter dominates geometry and multiplicity

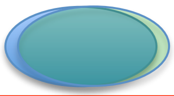


Central ZDC selection b->0

- Au+Au dN/dη is dominated by fluctuations
  - No correlation between v_2 and multiplicity



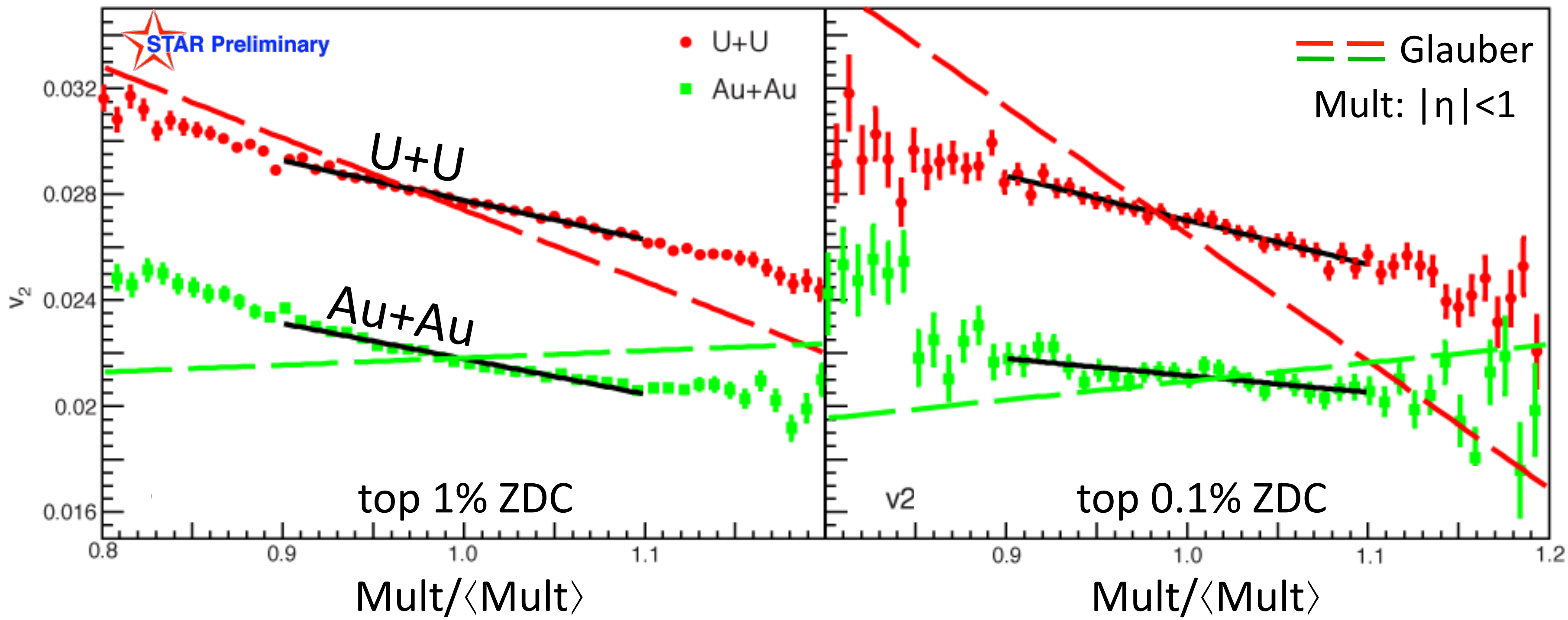
- U+U dN/dη depends on nuclear geometry & fluct.
  - Larger v_2 associated with small multiplicity



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 are selecting full overlap

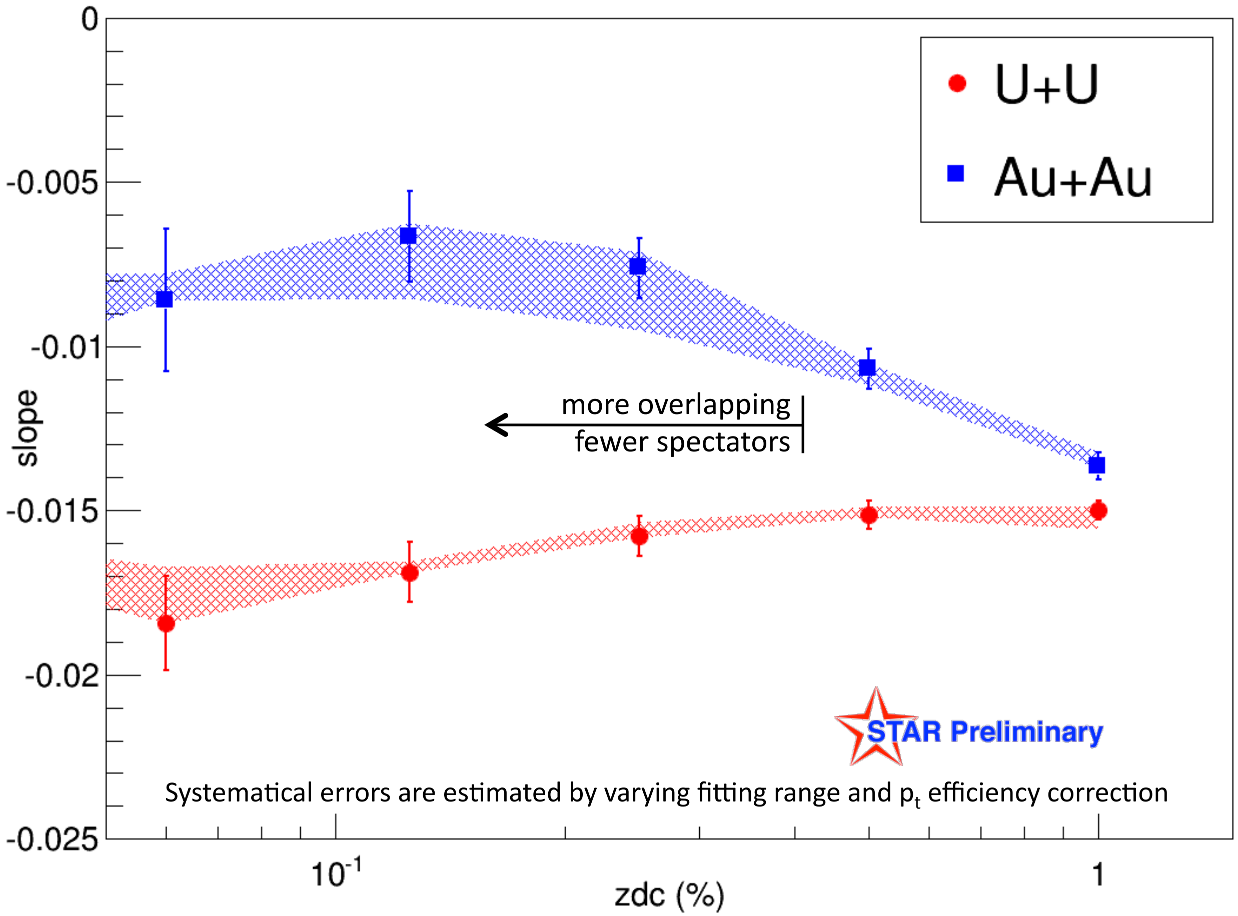
v_2 vs. Multiplicity In Fully Overlapping Events



- 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 $\langle v_2 \rangle / \langle \varepsilon_2 \rangle$
- U+U slope is weaker than models predicted, but gets stronger for tighter cuts
- Au+Au slope is negative instead of positive, gets closer to zero for tighter cuts

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

Slope vs. ZDC

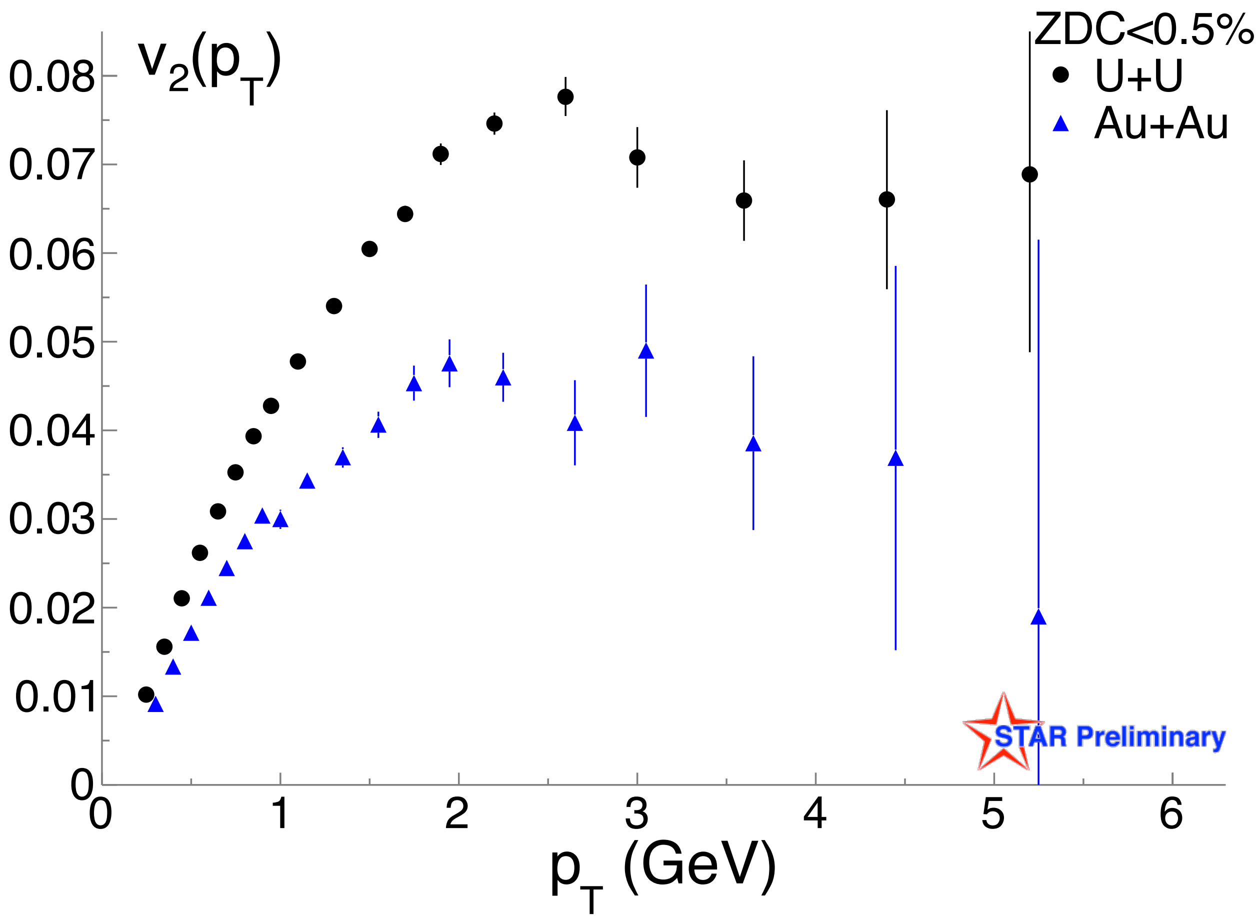


%ZDC	U+U	Au+Au
0.125	6	4
0.25	7	5
0.5	9	6
1.0	12	8
2.0	17	12

Estimated number of spectator neutrons in each direction

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

Toward Path Length Dependence of Quenching



Analysis technique:

$$v_2(p_T) = \frac{\langle \cos 2(\varphi_i(p_T) - \varphi_j) \rangle}{\sqrt{\langle \cos 2(\varphi_i - \varphi_j) \rangle}}$$

HBT and jet-like small Δη correlations subtracted from $\langle \cos 2(\phi_i - \phi_j) \rangle(\Delta\eta)$ for each p_T. See back-up.

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

Summary

- No evidence of kink structure in central v_2 results from current analysis: fluctuations larger than NBD with k=2?

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

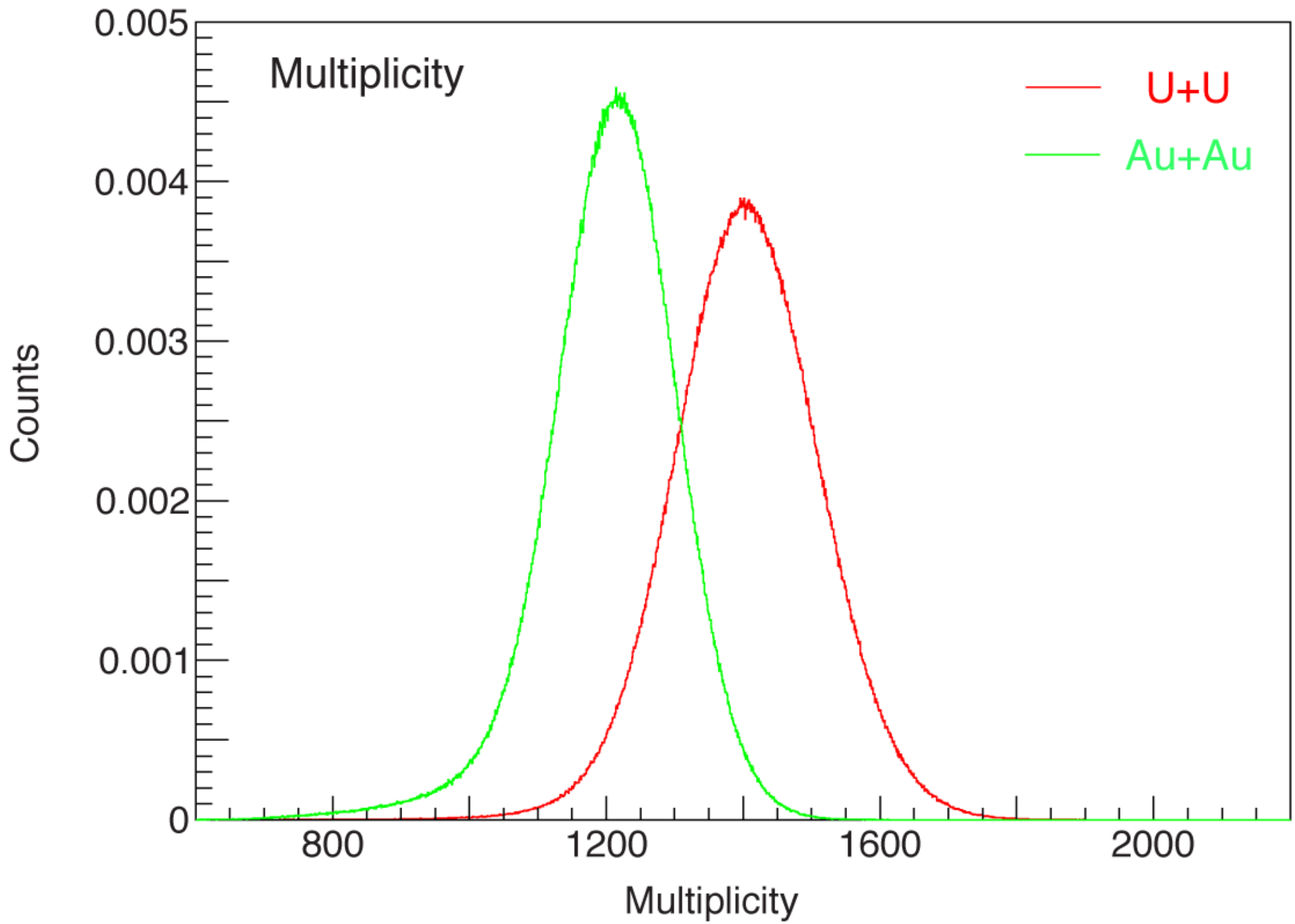
- v_2/ε_2 turns over in central collisions for both Au+Au and U+U!?

- ZDC and multiplicity in combinaation provide a way 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
  - More statistics are necessary for detailed studies

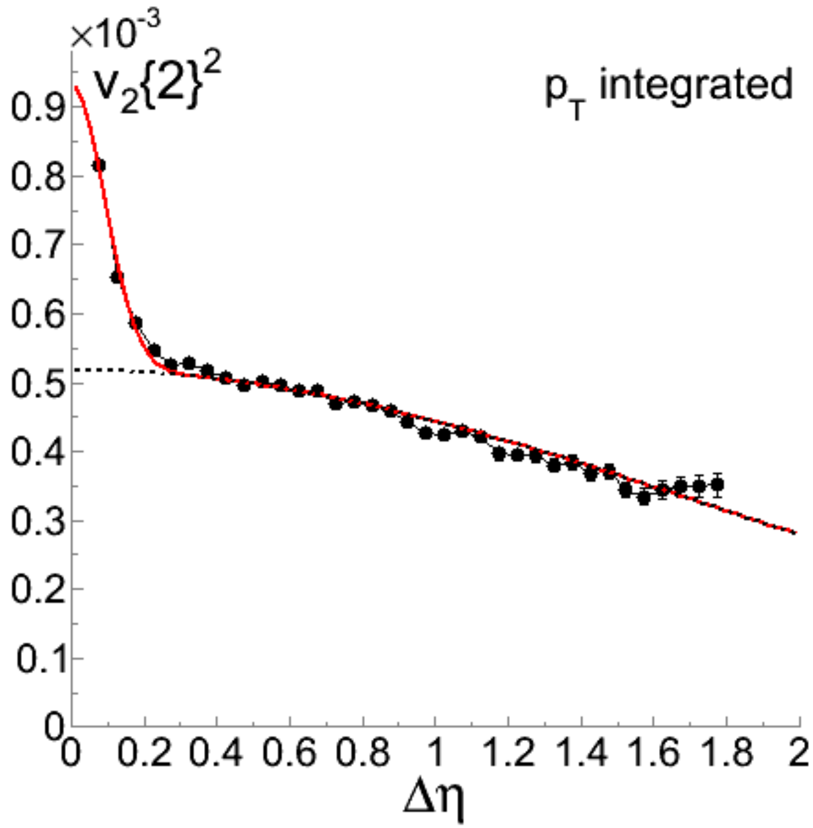
Back Up

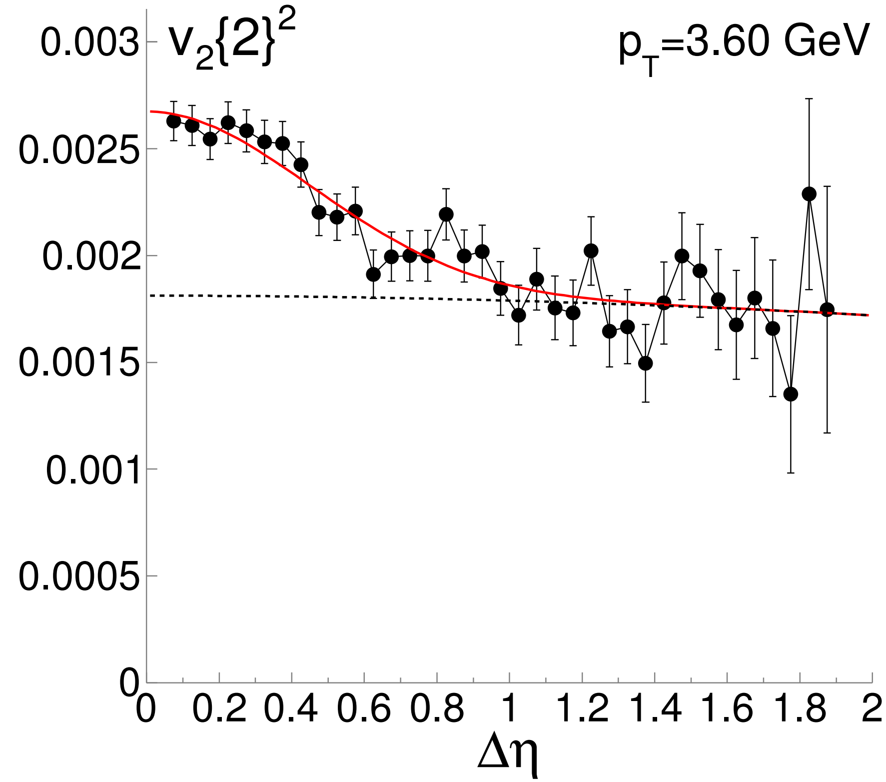
Multiplicity



The corrected multiplicity distribution for 1% central ZDC events

Δη dependence





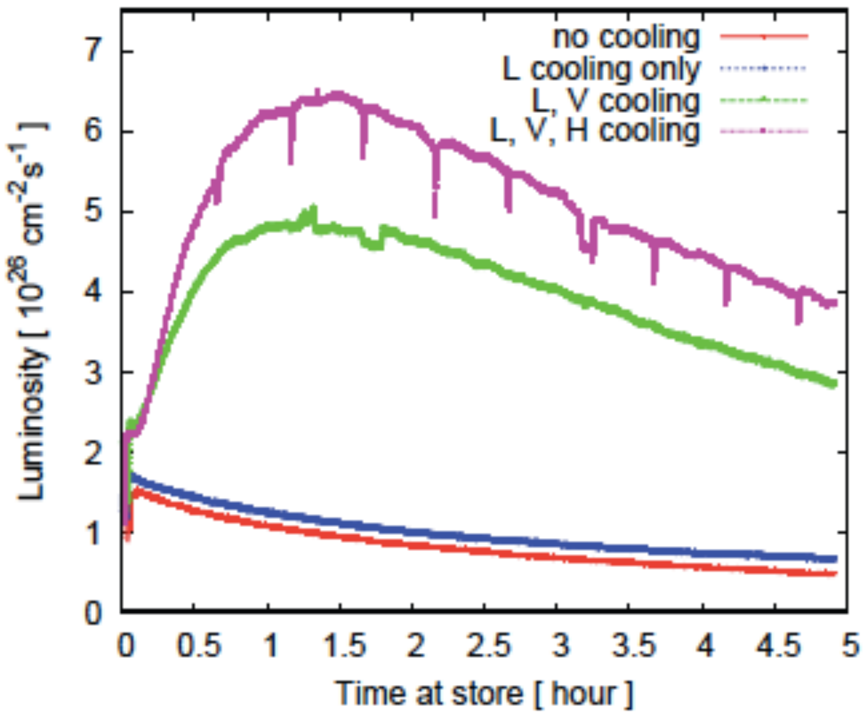
The peak at small Δη is dominated by HBT at low pt and by jets at higher p_T

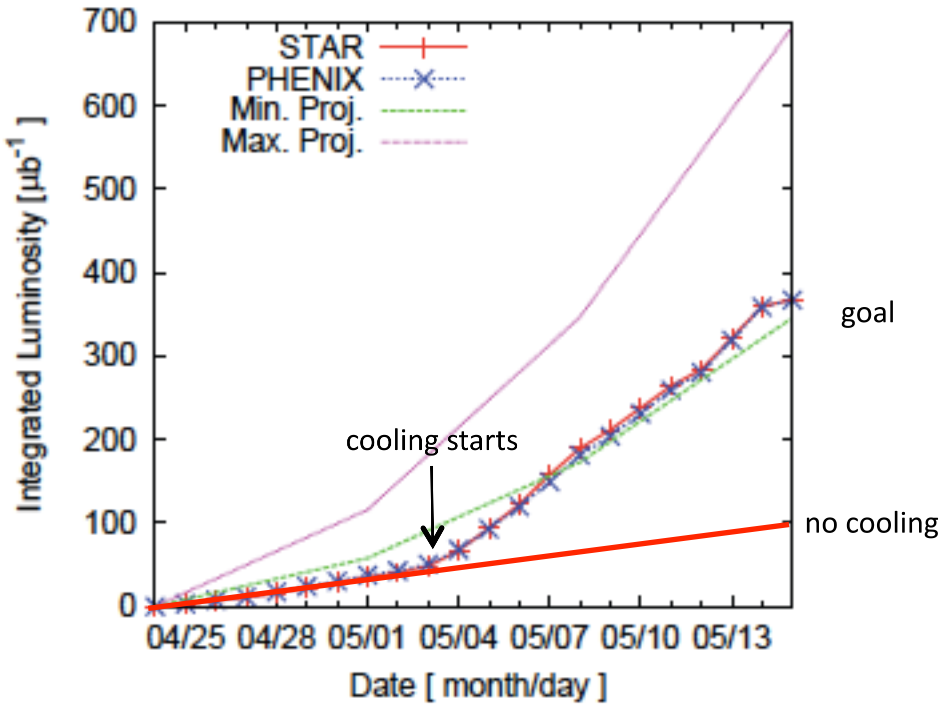
HBT peak only persists to ~0.8 GeV. At ~1.5 GeV, a distinguishable jet-like peak emerges.

We subtract the narrow peaks from our results and integrate the remaining $v_2^2(\Delta\eta)$ weighted by the number of pairs vs Δη in each p_T bin. We then calculate $v_2(p_T)$ using:

$$v_2(p_T) = \frac{\left\langle \cos 2\left(\varphi_i(p_T) - \varphi_j\right)\right\rangle}{\sqrt{\left\langle \cos 2\left(\varphi_i - \varphi_j\right)\right\rangle}}$$

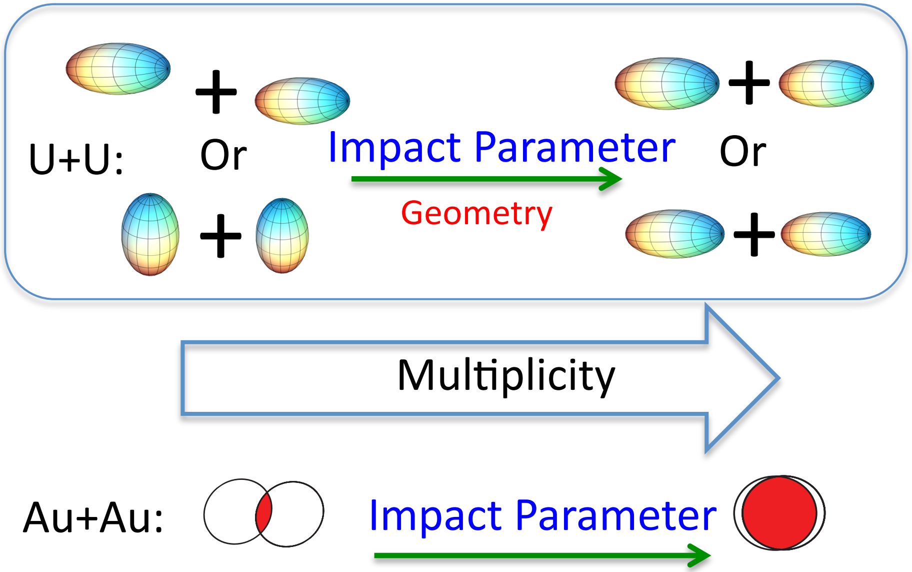
Collection of U+U data sample

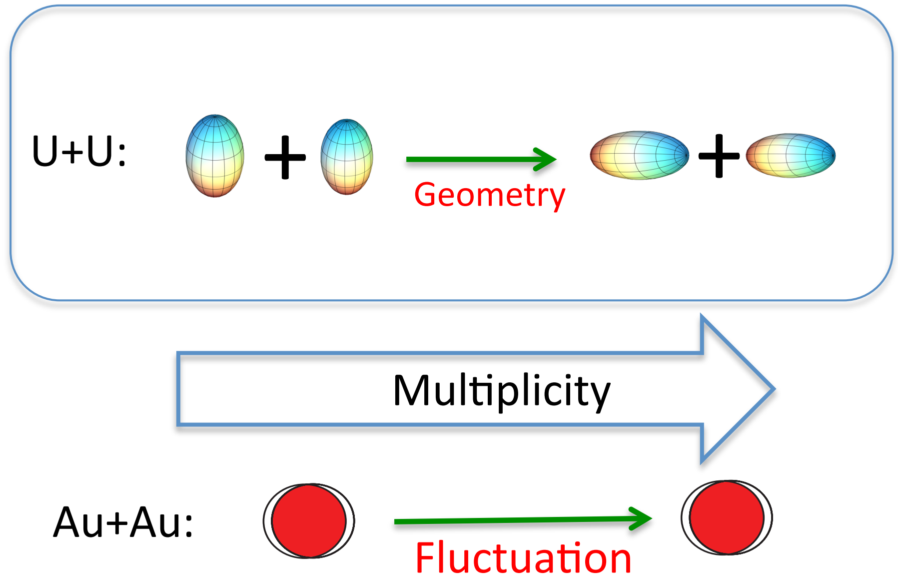




Implementation of cooling led to huge improvement in accessible luminosity
Made achievement of goals possible

Studying Full Overlap Events

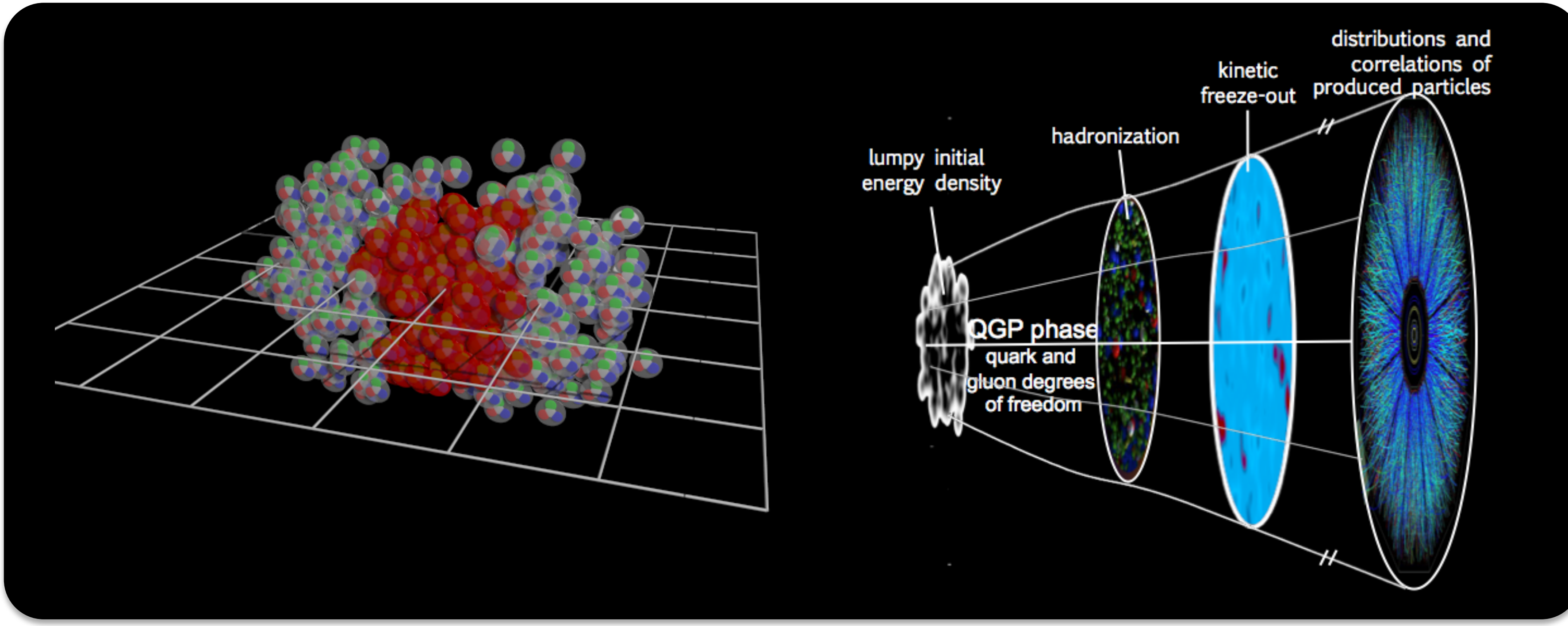




- Without selection on over-lapping region, the impact parameter will dominant geometry
- We will see correlations between v_2 and multiplicity for both Au+Au and UU
  - Larger v_2 associated with small multiplicity

- 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

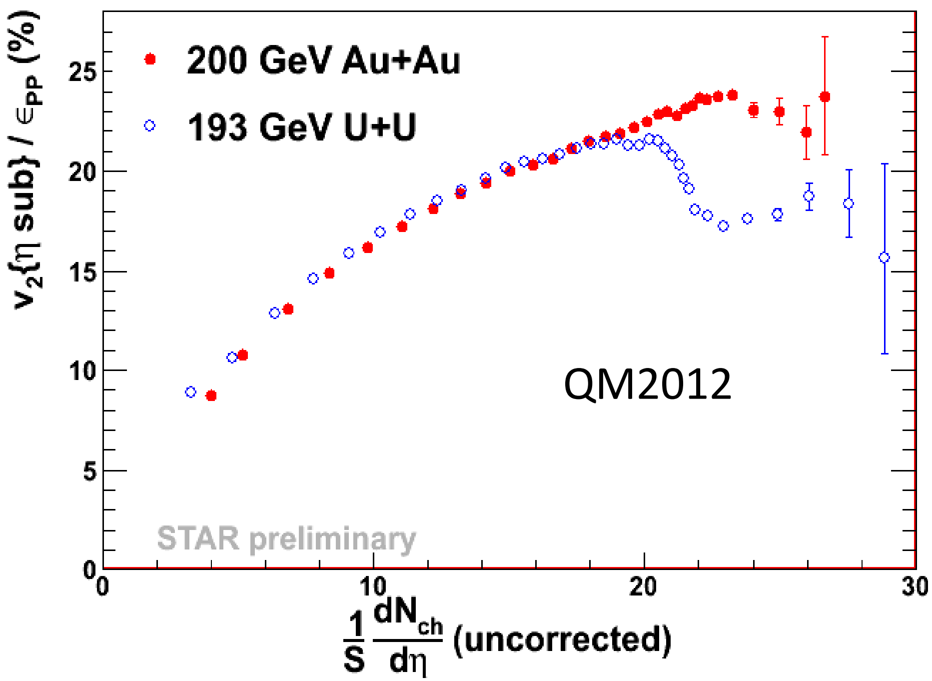
- Cumulants of the $\langle e^{in\phi} \rangle$ distribution characterize the momentum space anisotropy

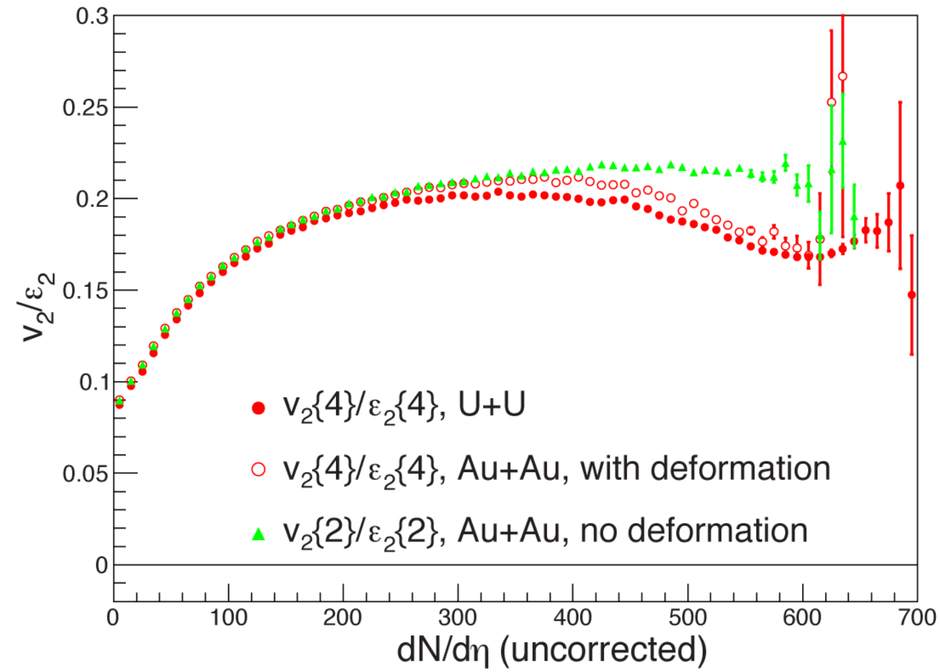
We've measured the 2nd and 4th cumulants using the direct cumulant method

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

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

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