Azimuthal anisotropy in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV with STAR detector at RHIC

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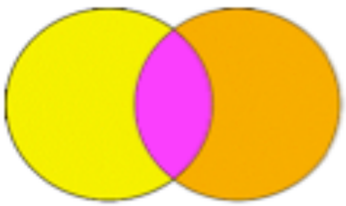
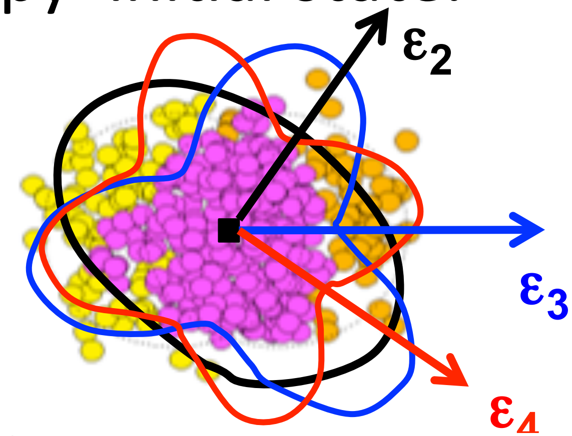
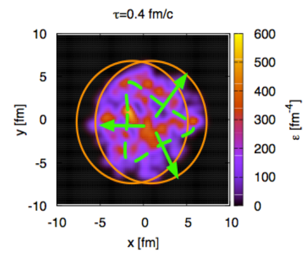
Introduction/Motivation

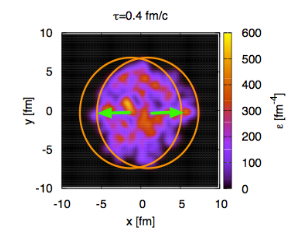
Recent understanding points to the 'lumpy' initial state.





Odd harmonics ≠ 0





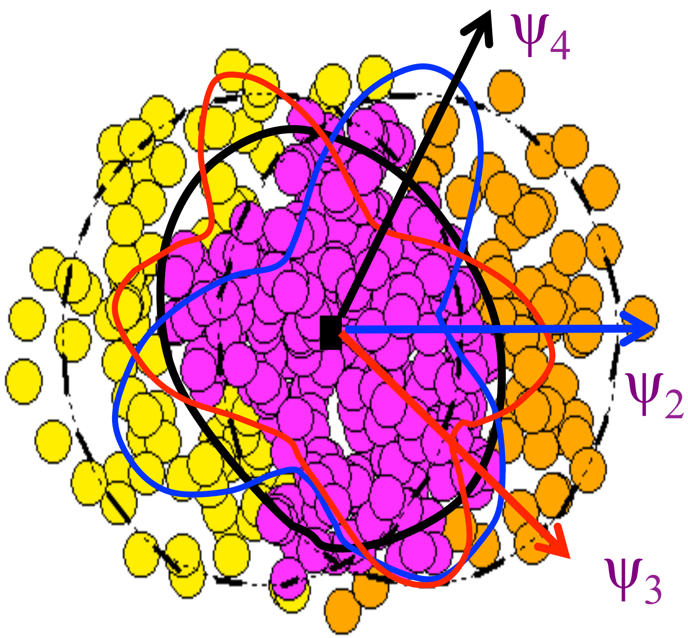
Elliptic flow(v_2)

$v_n(v_1,v_2,v_3,v_4,v_5,.........)$

Fluctuations imply odd terms aren't necessarily zero.

Takahashi et al, PRL 103, 242301 (2009), Hama et al, arXiv:0911.0811, P. Sorensen, et al Phys. Lett B 705, 71 (2011) ,B. Alver et al, PRC 81, 054905 (2010)

Introduction/Motivation



Initial geometry has multi-pole shape due to fluctuations.

B. Alver et al, PRC 81, 054905 (2010)

$$\varepsilon_n^2 = \frac{\left\langle r^n \cos(n\varphi)\right\rangle^2 + \left\langle r^n \sin(n\varphi)\right\rangle^2}{\left\langle r^n \right\rangle^2}$$

$$\tan(n\psi_n) = \frac{\left\langle r^n \sin(n\varphi)\right\rangle}{\left\langle r^n \cos(n\varphi)\right\rangle}$$

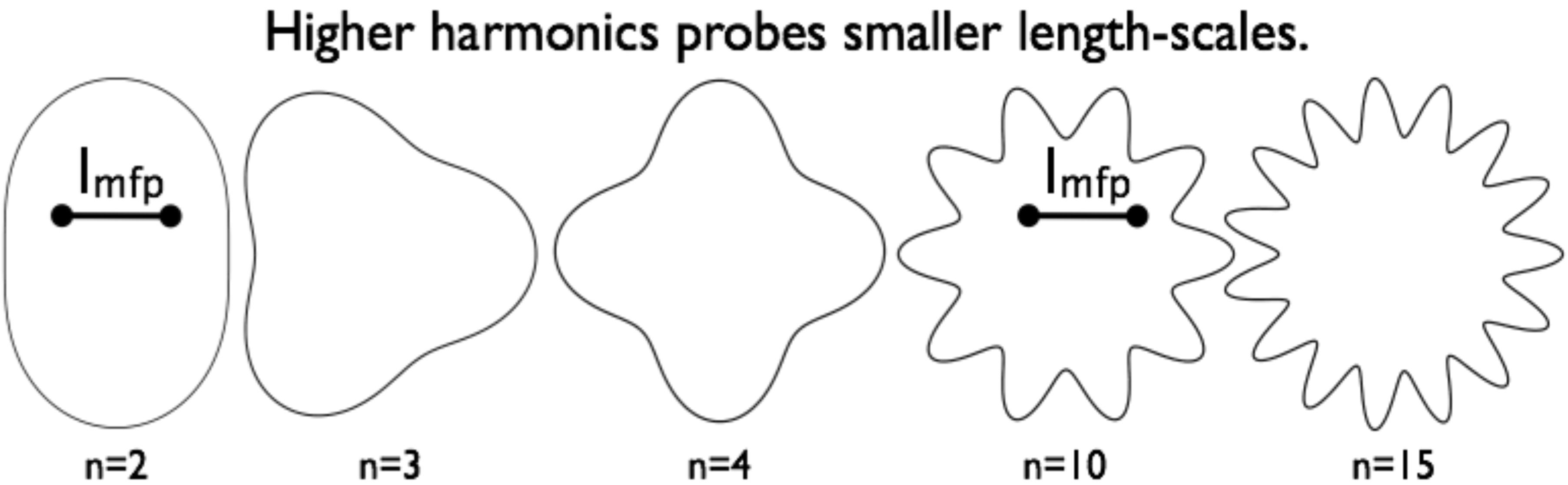
Fourier expansion of azimuthal distribution in momentum space

$$\frac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n} \cos n\left(\phi - \psi_n\right)$$

$$v_\mathrm{n} = \left\langle \cos\left[n\left(\phi - \psi_n\right)\right]\right\rangle$$

v_2 (elliptic flow) has been well studied in experiments and model calculations

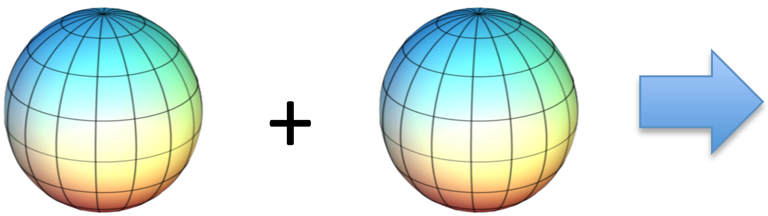
Introduction/Motivation



- Sensitive to initial state fluctuations and hydrodynamic evolution.
- Provide valuable information to study the evolution of the system
- Different harmonics may have different sensitivity to the medium properties(i.e. eta/s)
- Use the full spectrum of harmonics to maximally constrain the models.

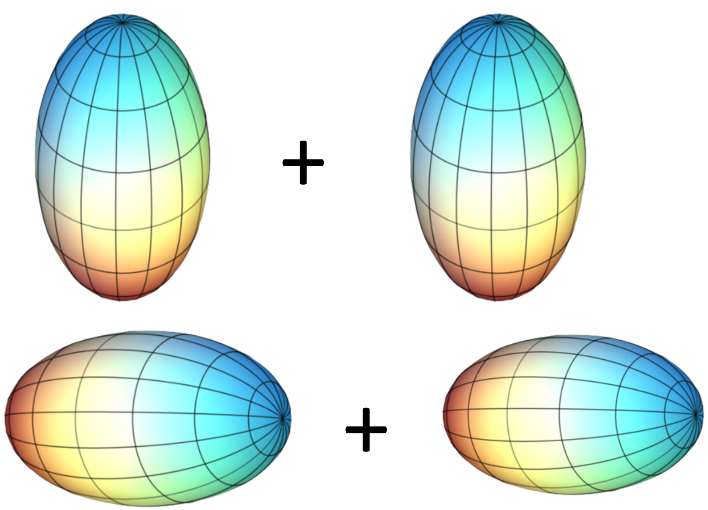
Introduction/Motivation

Au+Au Collisions



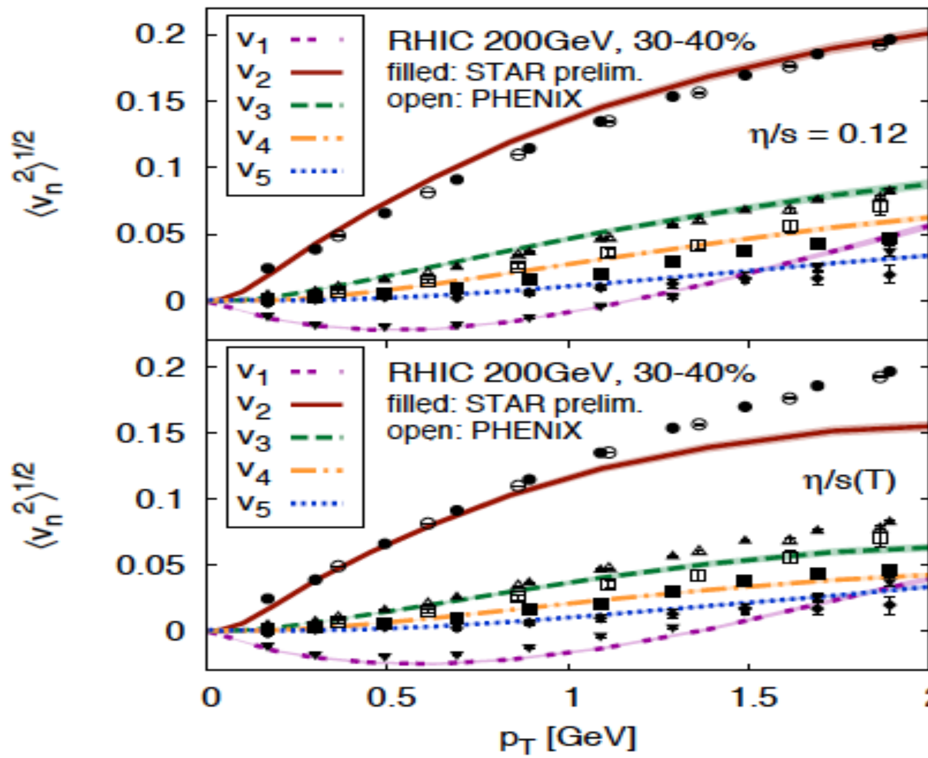
Oblate(in average)

U+U Collisions



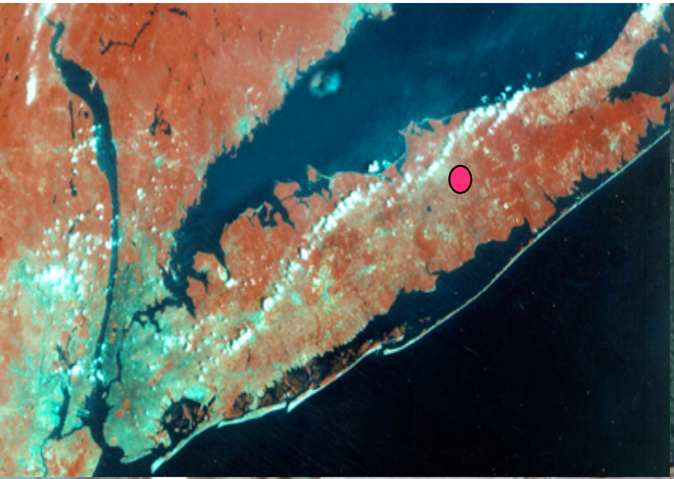
Prolate(in average)

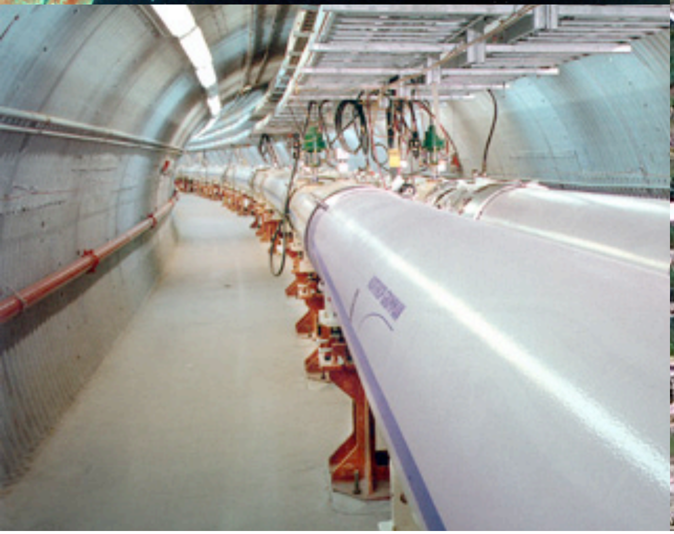
Phys. Rev. Lett. 110, 012302,(2013).

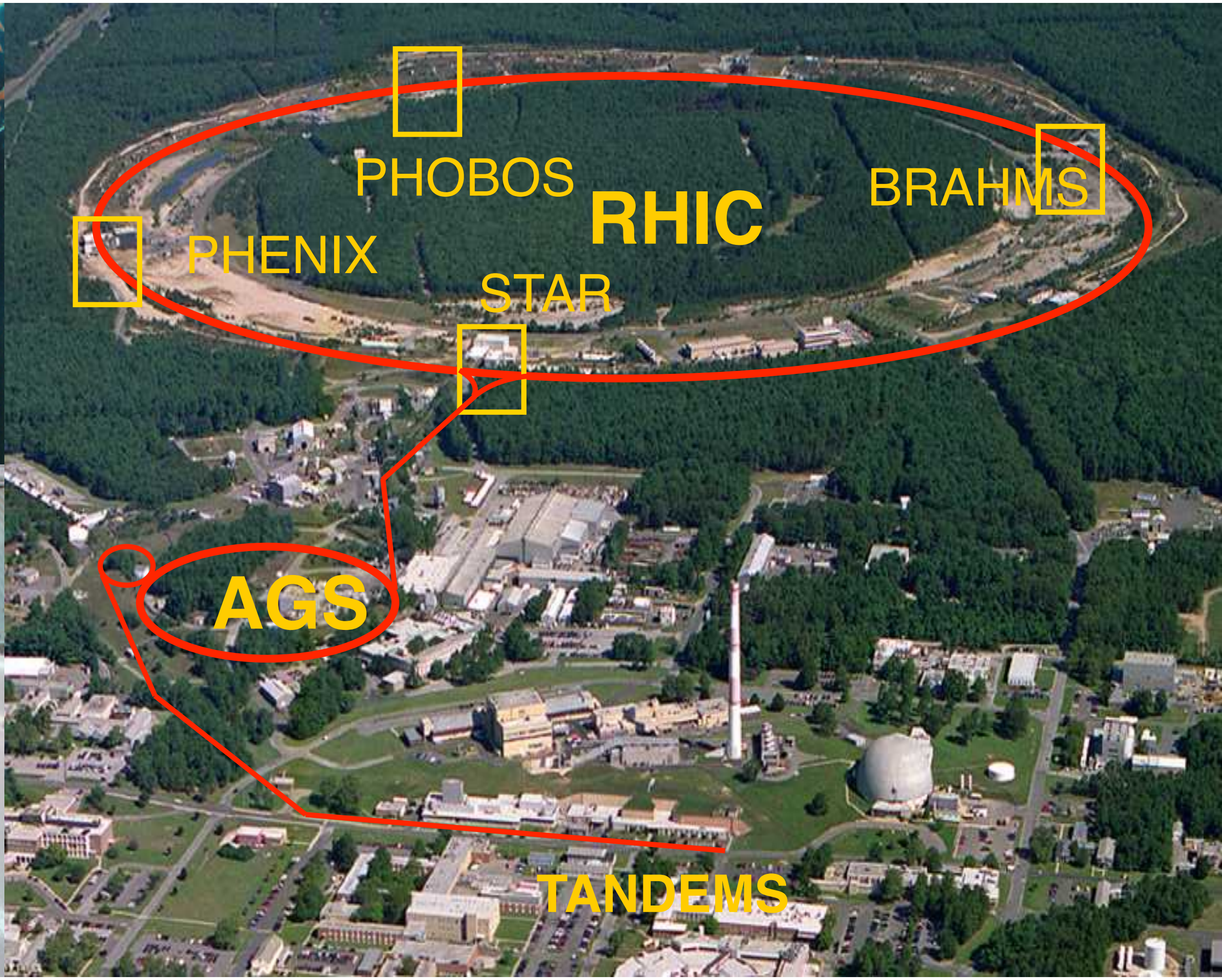


Can we see a difference between Au+Au and U+U ?

Relativistic Heavy Ion Collider

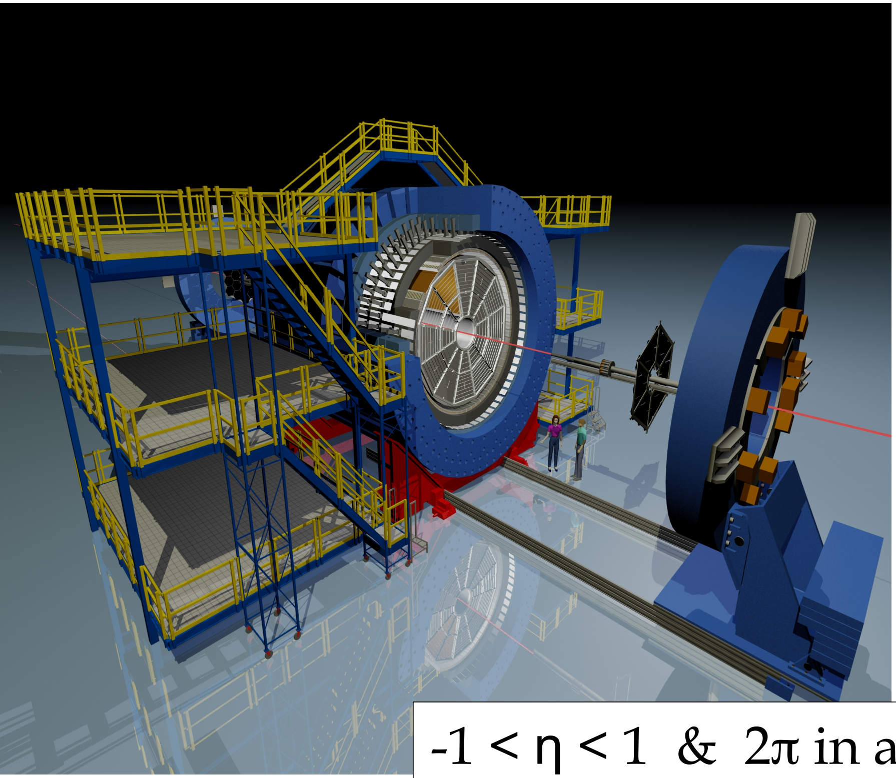


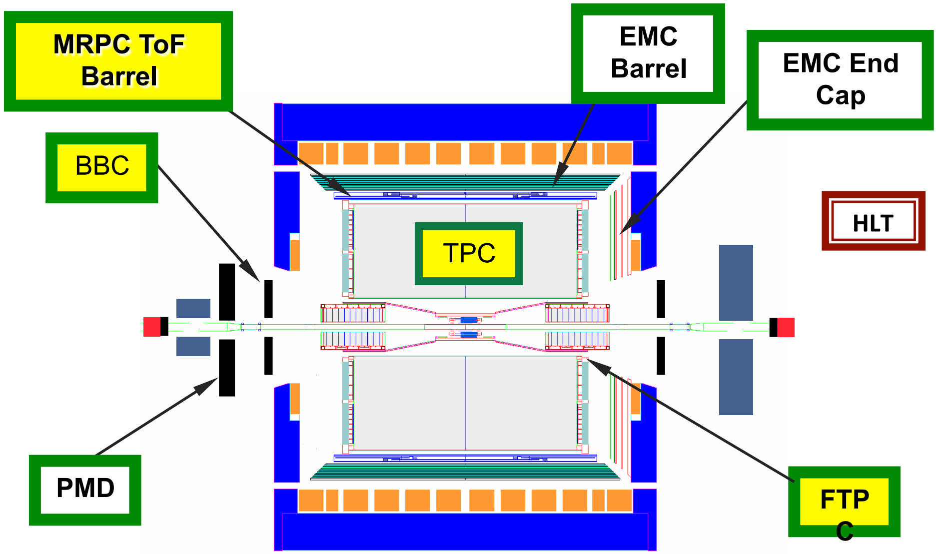




The Relativistic Heavy Ion Collider complex is actually composed of a long chain of particle accelerators and Detectors.

The Solenoid Tracker At RHIC (STAR)





$-1 < \eta < 1$ & 2π in azimuth, Uniform acceptance

STAR is composed of 57 institutions from 12 countries, with a total of 533 collaborators

Analysis Method

Q- Vectors:

-1.0 < η < -0.5	-0.4 < η < 0.4	0.5 < η < 1.0

$$Q_{nx} = \sum w_j \cos n\phi_j$$

$$Q_{ny} = \sum w_j \sin n\phi_j$$

Where,
w_j = p_T for p_T<2.0 GeV/c
= 2 for p_T>2.0 GeV/c
(all harmonics except n=1)

First harmonic(n=1) has rapidity-odd and rapidity even components, for v_1(even),

$$w_j = p_T - \frac{\langle p_T^2 \rangle}{\langle p_T \rangle}$$

Event Plane method

$$\psi_n = \tan^{-1}(\frac{Q_{ny}}{Q_{nx}})$$

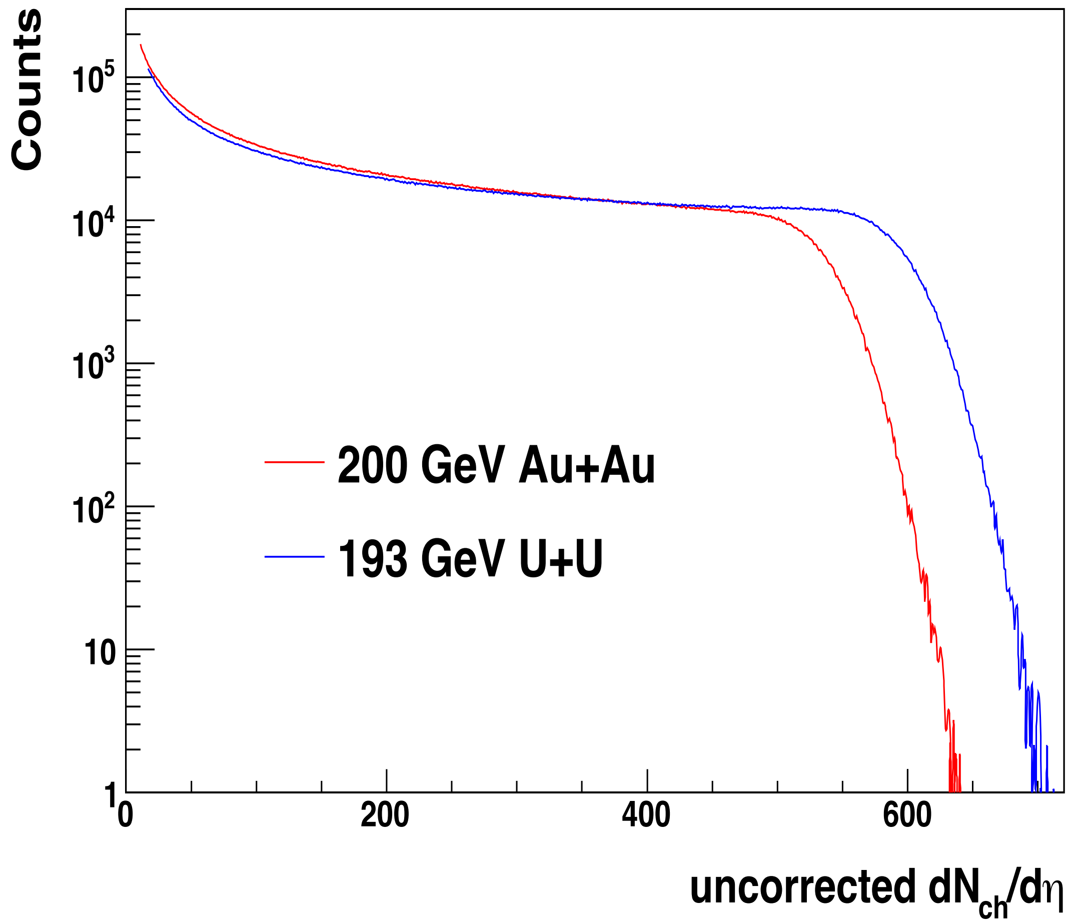
$$v_n = \frac{\langle \cos n(\phi - \psi_n) \rangle}{C\sqrt{\langle \cos n(\psi_n^A - \psi_n^B) \rangle}}$$

C is calculated from the known multiplicity dependence of the resolution
Phys. Rev. C 58, 1671 (1998)

Scalar Product method

$$v_n = \frac{\langle Q_n u_n^* \rangle}{2\sqrt{\langle Q_{na} Q_{nb} \rangle}}$$

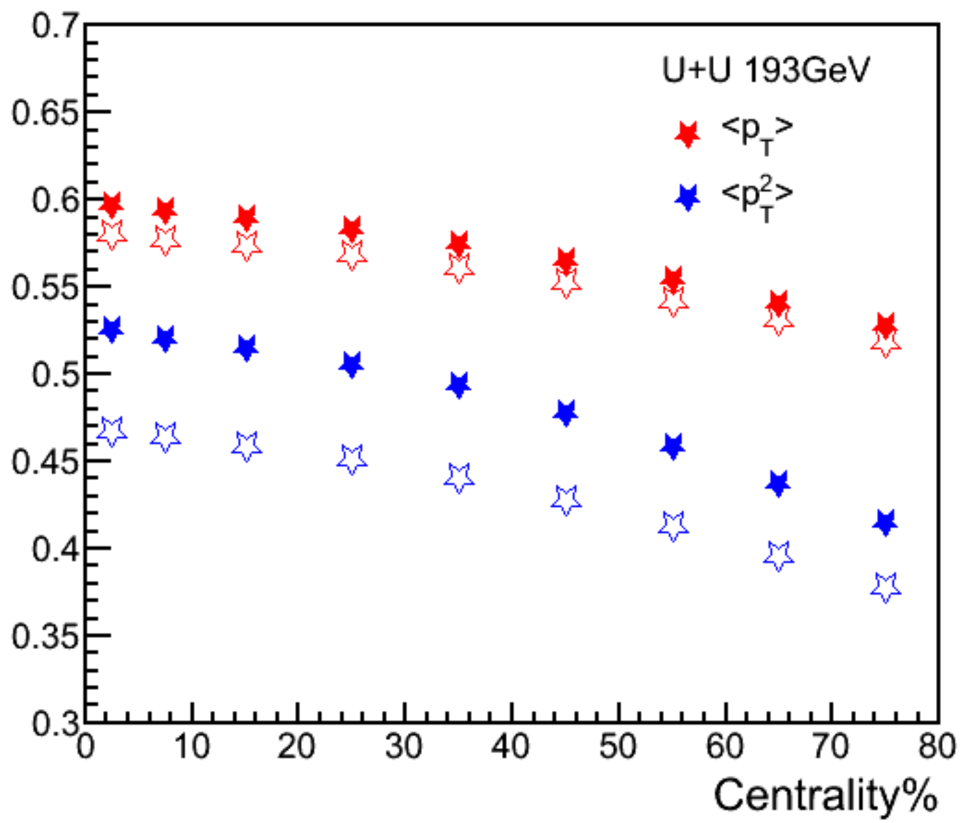
Analysis Method



Cent	RefMult (AuAu 200-IV)	RefMult (UU193)
0-5%	520	523
5-10%	441	464
10-20%	319	345
20-30%	222	247
30-40%	150	168
40-50%	96	107
50-60%	57	63
60-70%	31	33
70-80%	14	16

- RefMult distribution for U+U and Au+Au Collisions.
- Centrality selection is based on RefMult distribution and MC Glauber calculation.

Analysis Method



For v_1(even) component, weight is

$$w_j = p_T - \frac{\langle p_T^2 \rangle}{\langle p_T \rangle}$$

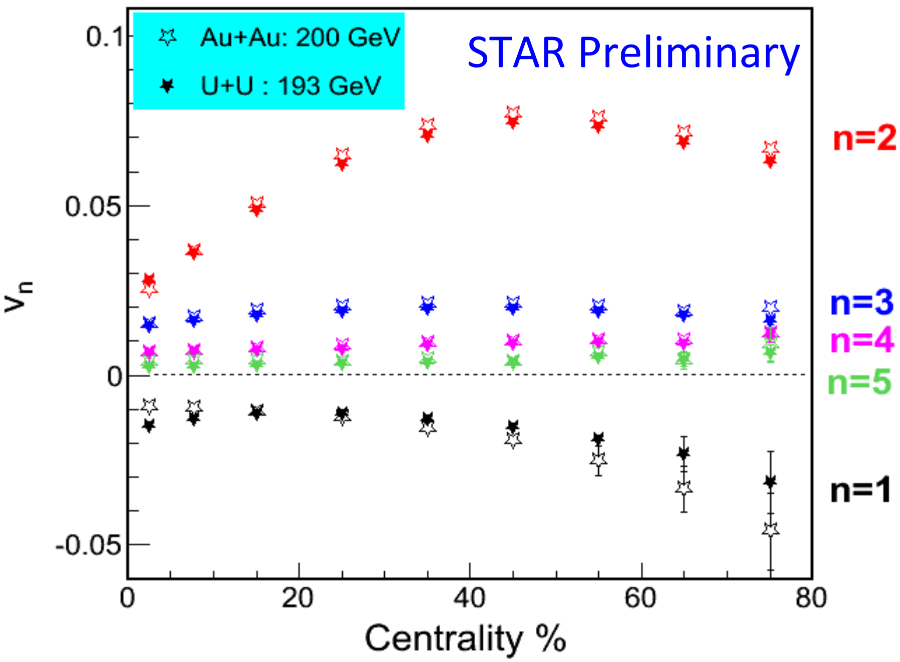
We use full event plane symmetric to η=0;

This method suppress momentum conservation effects and rapidity odd v_1 component. PRL 106,102301(2011)

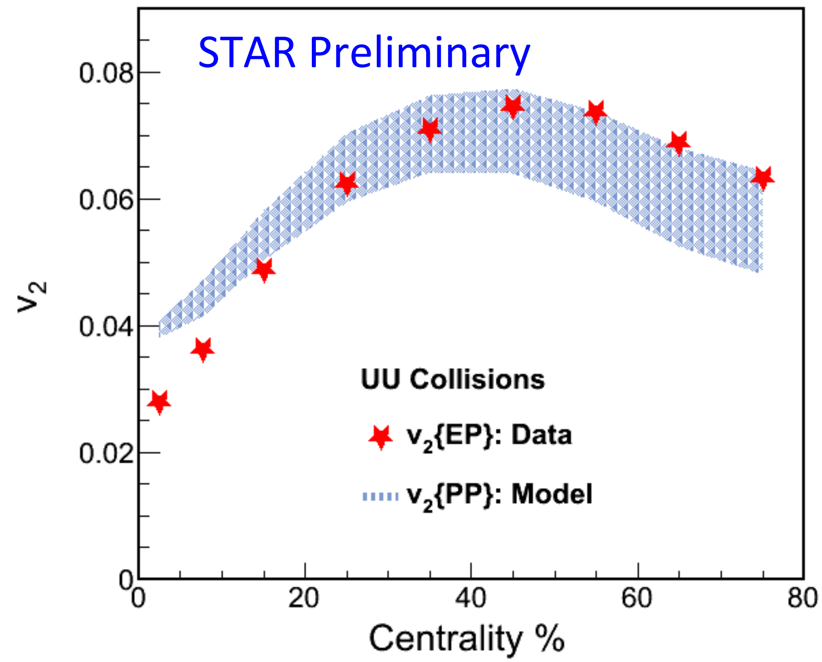
Transverse momentum(p_T) distributions are not corrected for detector acceptance and efficiency

Centrality dependence

Au+Au Results: QM2012, STAR Collaboration

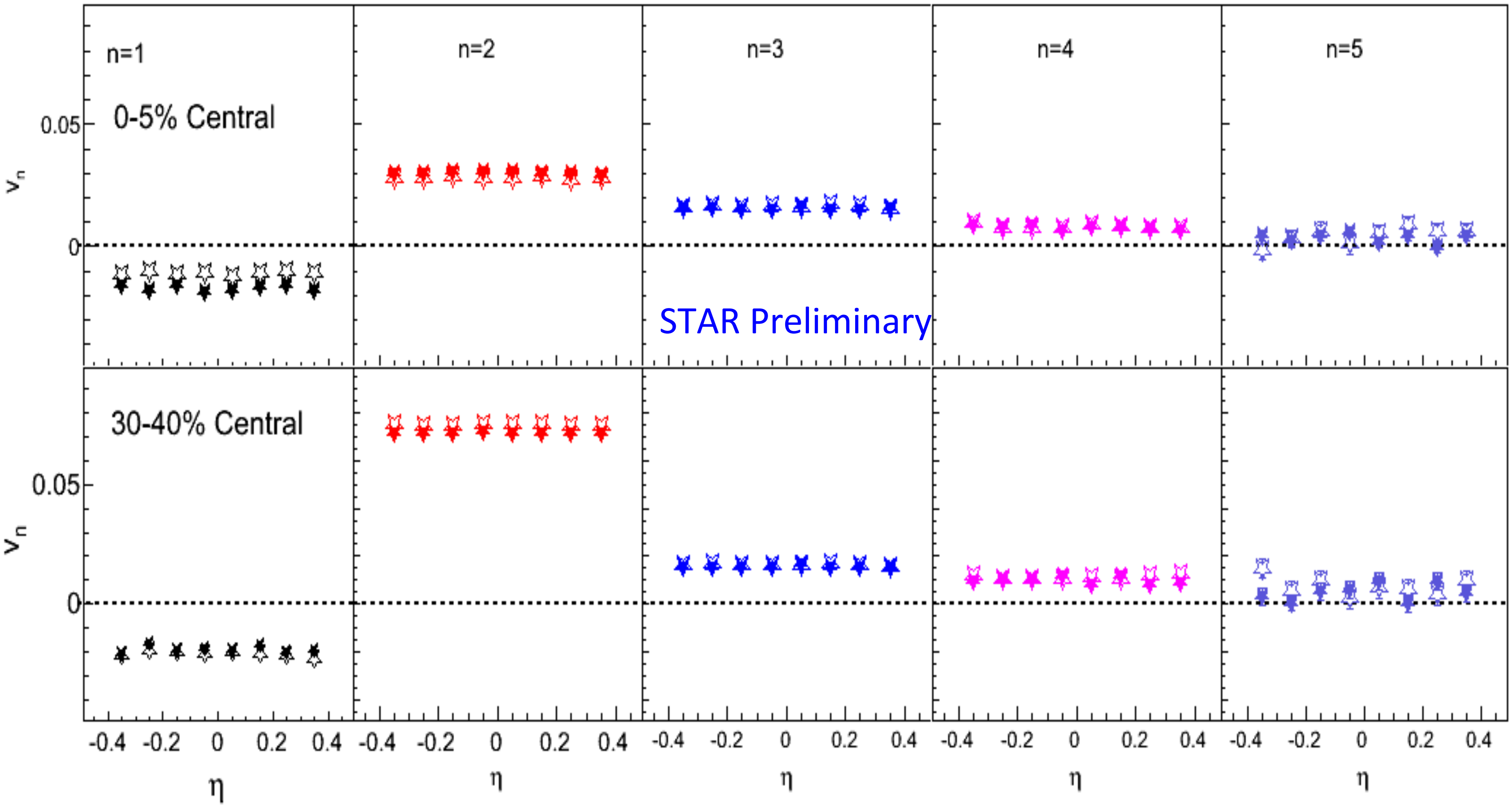


H. Masui et. al, Phys. Lett. B 679, 440(2009)



- v_n integrated in $0.15<p_T< 2$ GeV/c and $|\eta|<0.4$
- η gap of 0.1 units between event plane and particle of interest
- Centrality dependence is week for all other harmonics except n=2.
- v_2 in U+U central collisions is not as large as predicted [Phys. Lett. B 679, 440(2009)]

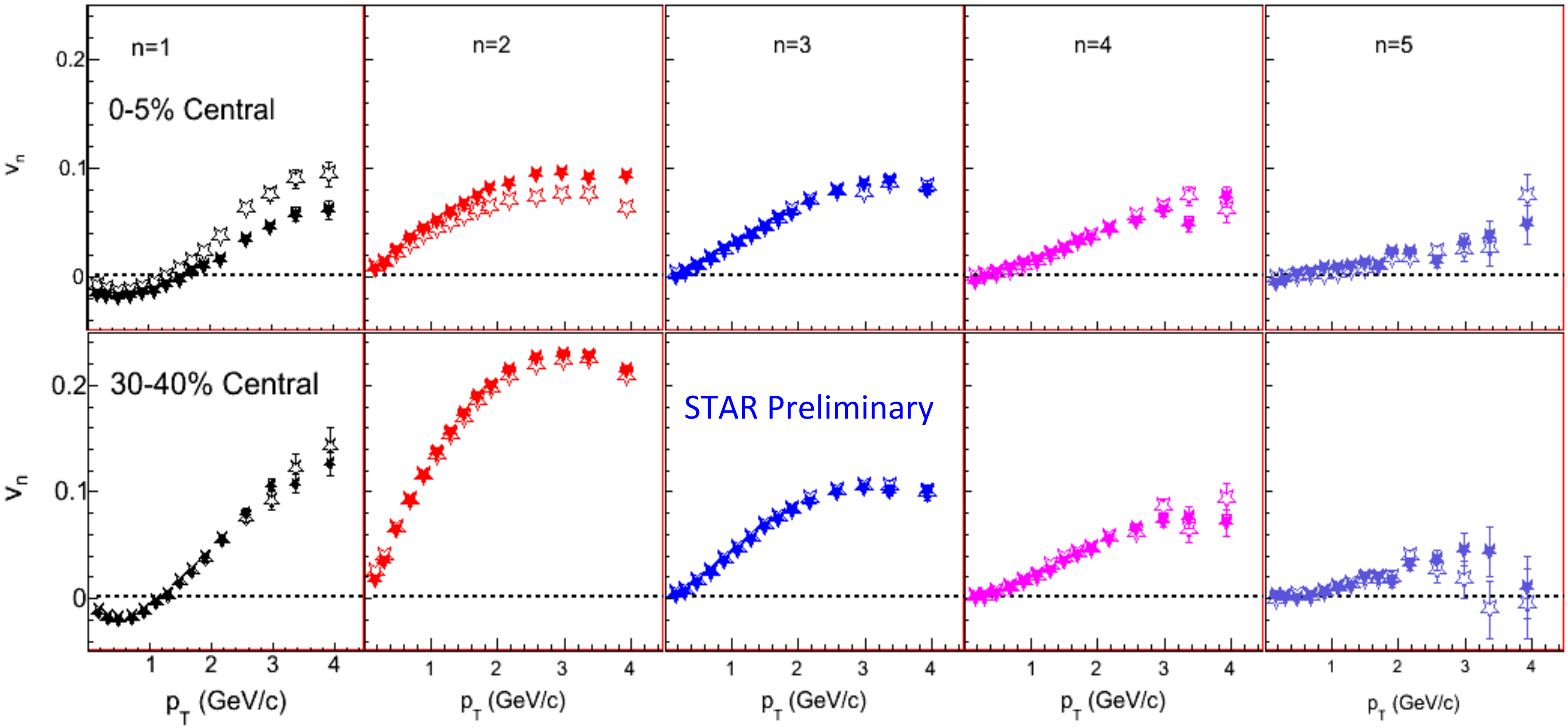
Pseudorapidity(η) dependence



v_n ($0.15<p_T< 2$ GeV/c) as a function of pseudorapidity at mid-rapidity($|\eta|<0.4$) is constant

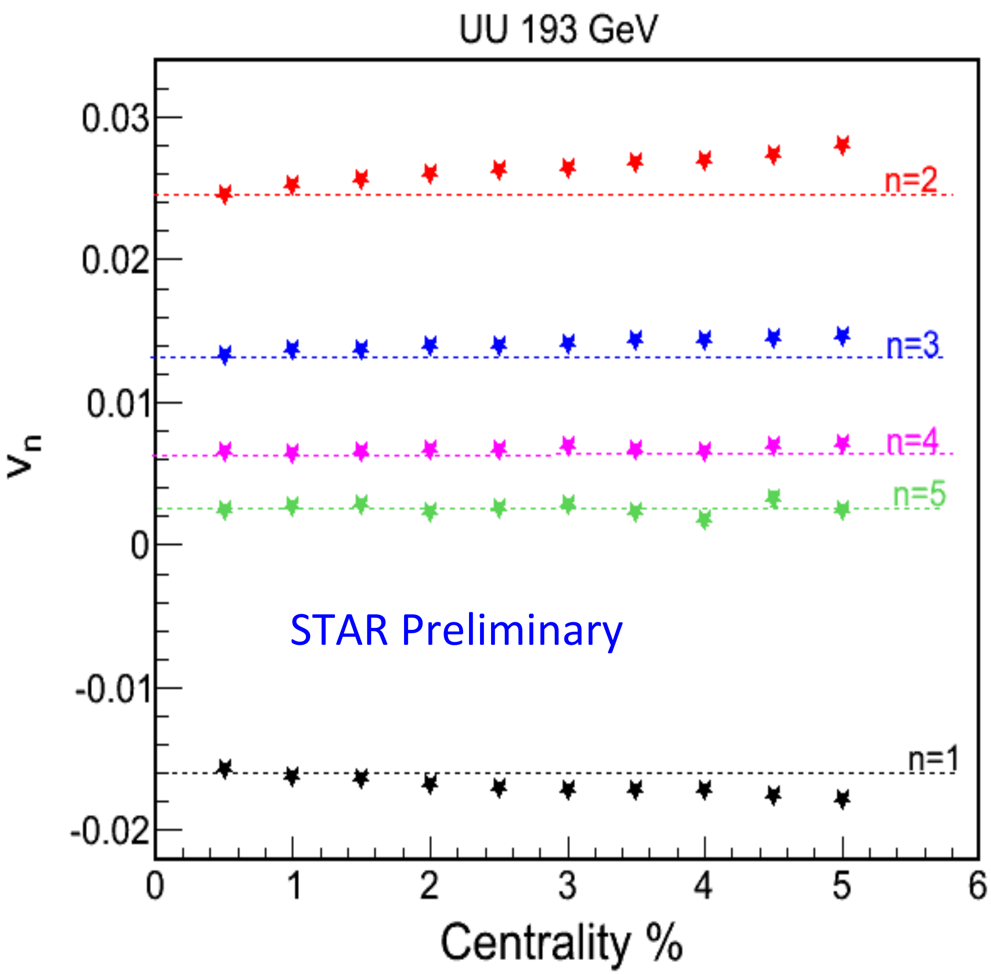
Transverse momentum(p_T) dependence

Au+Au Results: QM2012, STAR Collaboration



- v_1 crosses zero above p_T> 1.2 GeV/c
- v_n for U+U collisions is similar to that of Au+Au Collisions except n=1 and 2 at central collisions

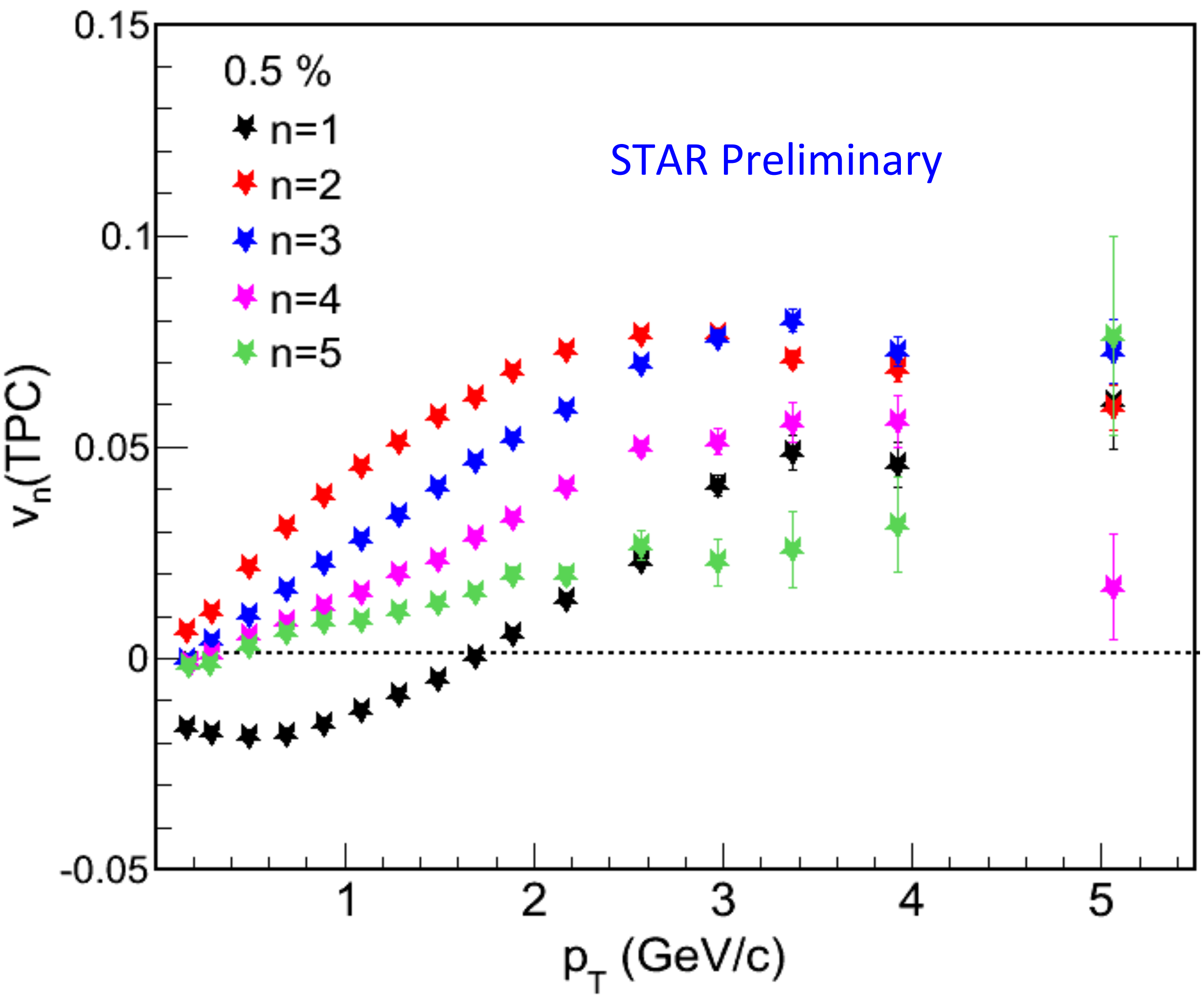
Flow harmonics for ultra central events: v_n as a function of centrality



Cent	RefMult (UU193)
5.0%	523
4.5%	531
4.0 %	538
3.5 %	446
3.0%	554
2.5 %	562
2.0 %	570
1.5 %	580
1.0 %	591
0.5 %	606

p_T ($0.15 < p_T < 2$) integrated v_n: v_2 changes slightly, other harmonics are almost constant.

Flow harmonics for ultra central events: v_n as a function of p_T



- v_2 is still dominant harmonics at low p_T (< 2 GeV/c) at ultra central(0-0.5%) collisions.
- At intermediate p_T (3-5 GeV/c) range, $v_3 \sim v_2$ and $v_1 \sim v_4$ in ultra central collisions

Transverse momentum dependence of 0.5% central collisions.

Summary/Outlook

1. Azimuthal anisotropy measurements provide important clues to understand the properties of hot and dense matter produced at RHIC (and LHC energies)

2. The first measurements of v_1, v_2,v_3, v_4 and v_5 for U+U collisions at 193 GeV are presented as a function of p_T, η and centrality.

   ⇒ v_n is almost constant as a function of pseudorapidity at mid-rapidity.
   ⇒ Centrality dependence is weak for harmonics other than second harmonics.
   ⇒ v_n show strong p_T dependence and v_1 as a function p_T crosses zero above p_T ~ 1.2 GeV/c

   ⇒ For higher harmonics and mid central collisions, v_n{U+U} is similar to v_n{Au+Au}, the difference appears at central collisions for v_1 and v_2.

3. These data may help to constrain initial conditions to the model calculations.