# Long-range collectivity in small collision systems with two- and four-particle correlations at STAR

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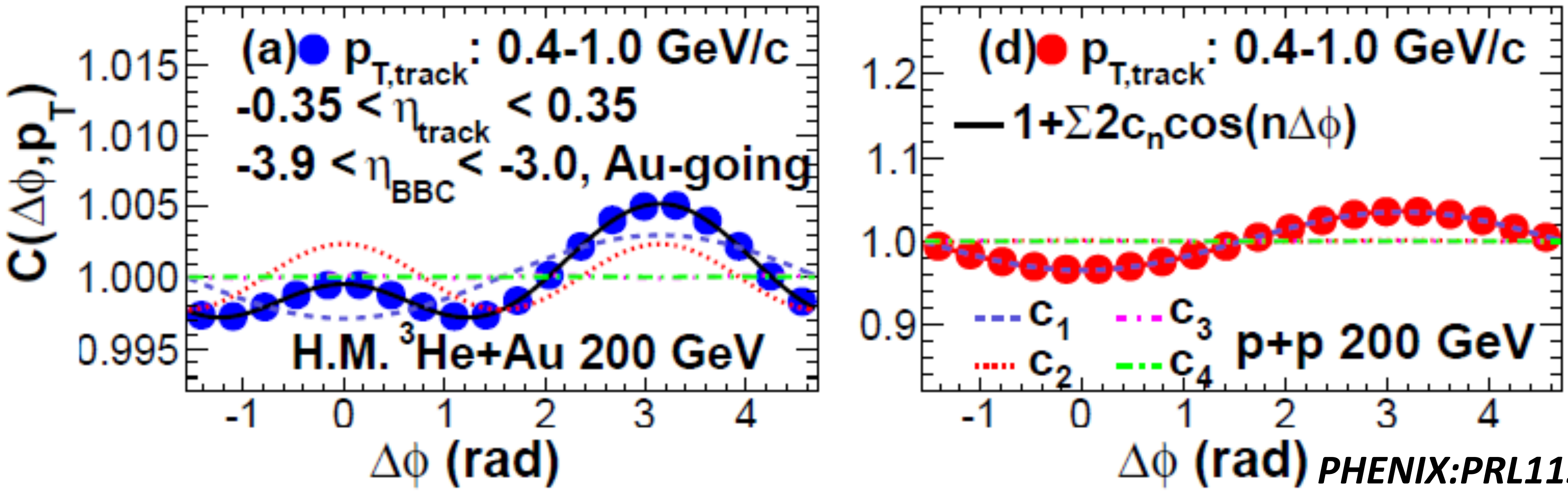
# Outline

- ❑Motivation and Analysis Methods
- ❑Physics Results
- ✓The $v_2$ in different small systems at different collision energies
- ✓The $c_2\{4\}$ in d+Au collisions at different collision energies
- ❑Summary

# What is the Origin of Ridge?




*PHENIX:PRL115(2015)142301*

- ❑ **Ridge (a long-range near-side correlation) is observed in small systems at RHIC:**
  Creation of a small QGP droplet or other mechanisms?

- ❑ **If a small QGP droplet is indeed created:**
  How does the system evolve in a small QGP droplet?
  How about the dependence of multiplicity and collision energy for the flow?

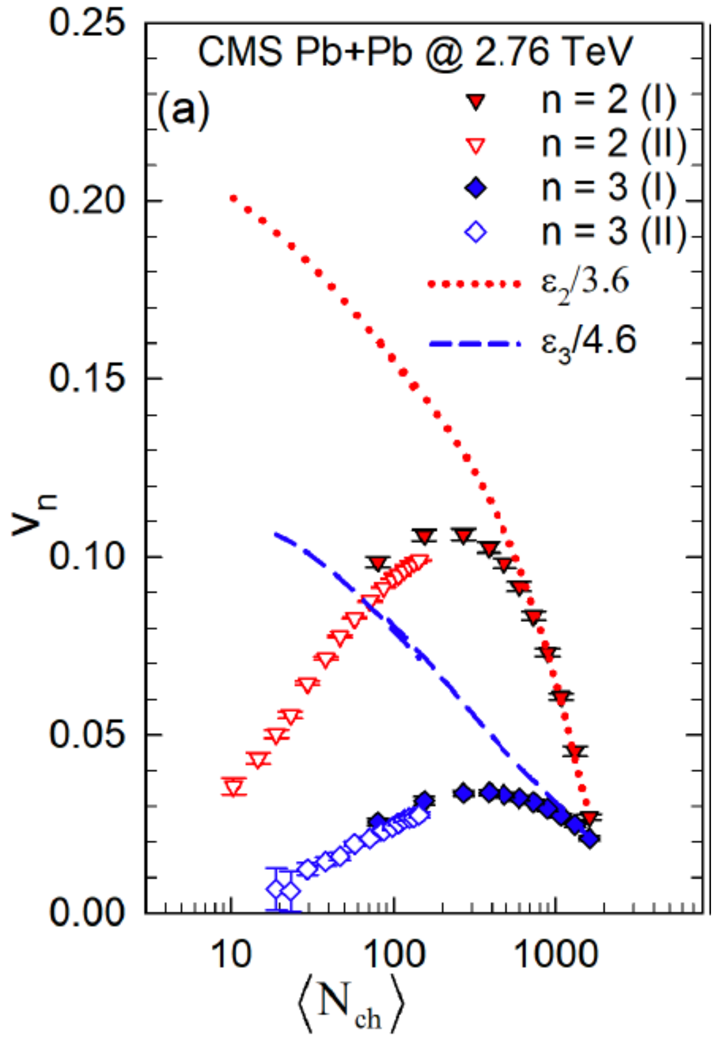
# Initial Geometry and Final State Evolution

**Glauber Model**

| | 0-5% p+Au | 0-5% d+Au | 0-5% He+Au |
|---|---|---|---|
| $\varepsilon_2$ | 0.23 | 0.54 | 0.50 |
| $\varepsilon_3$ | 0.16 | 0.19 | 0.28 |

J. L. Nagle *PRL113(2014)112301*

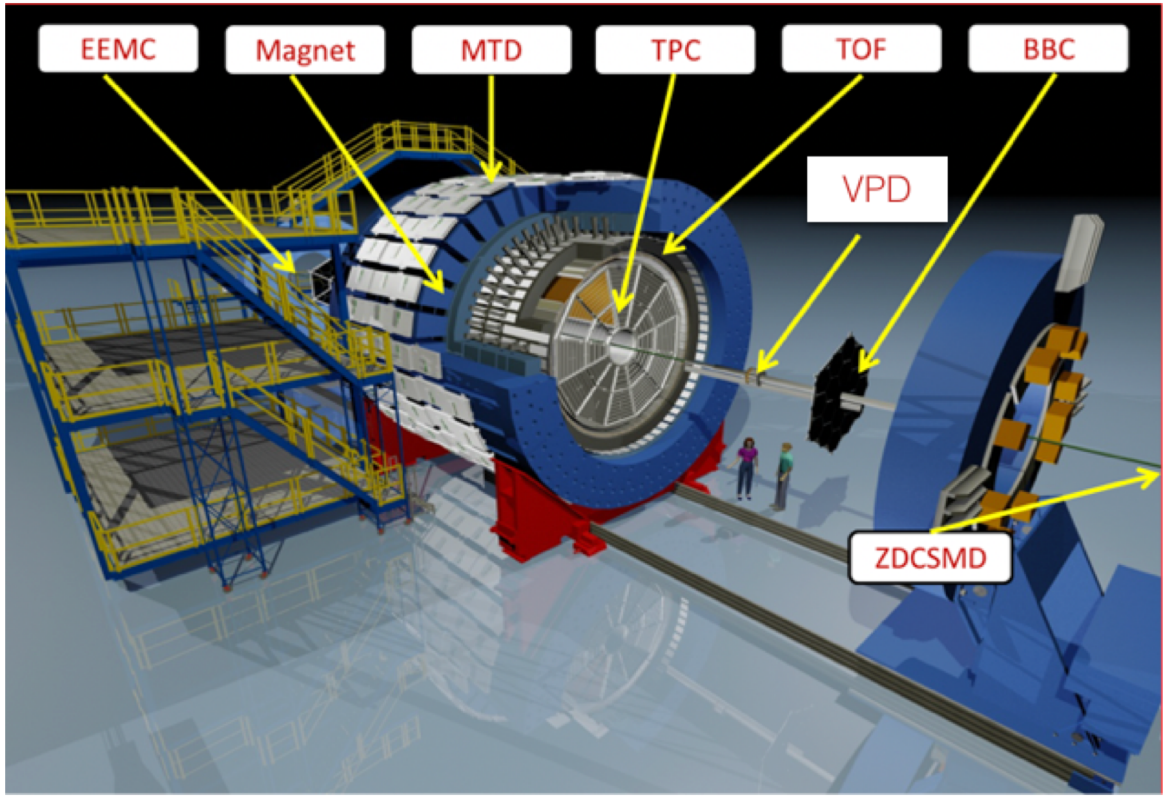
- Different initial geometry in small systems such as p/d/$^3$He+Au
- Large eccentricity ≠ Large flow at low multiplicity: a large shear viscous correction
- The interplay between them can be explored by measuring the flow in different systems for events with same multiplicity

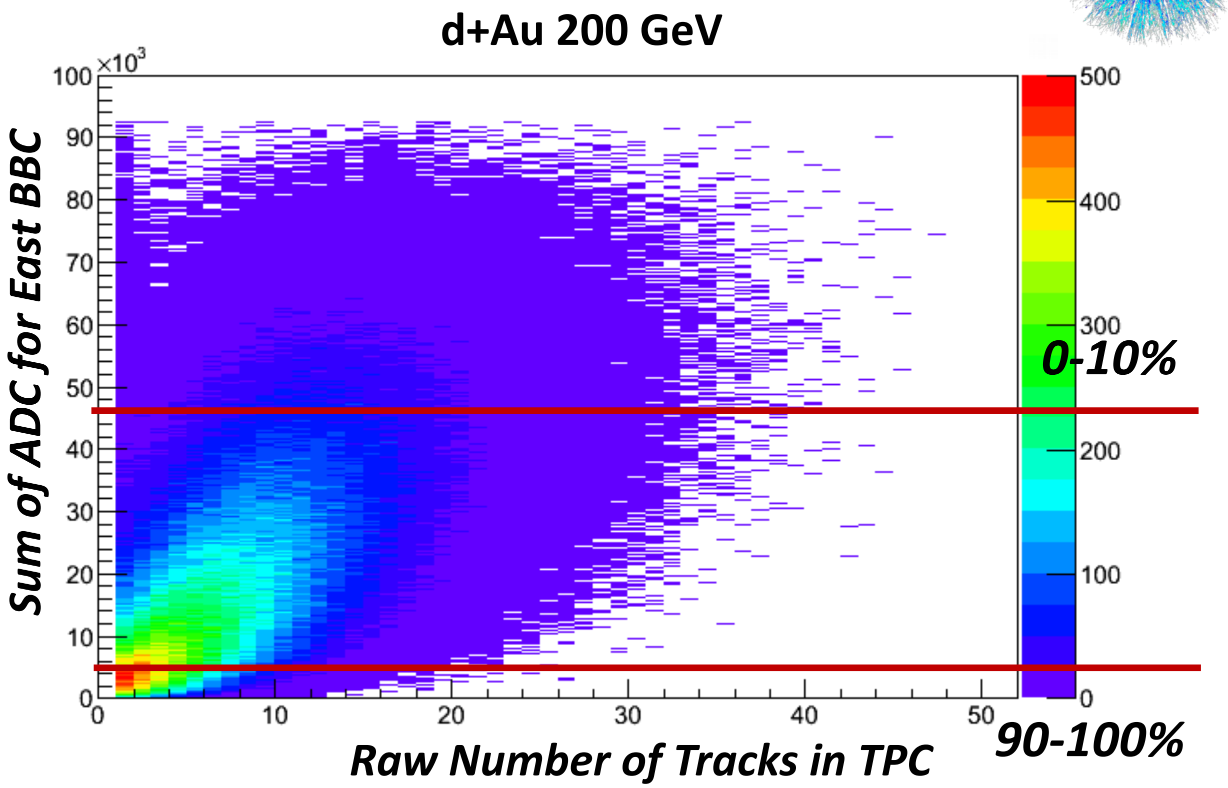



*P. Liu arXiv:1804.04618*

# Event Activity



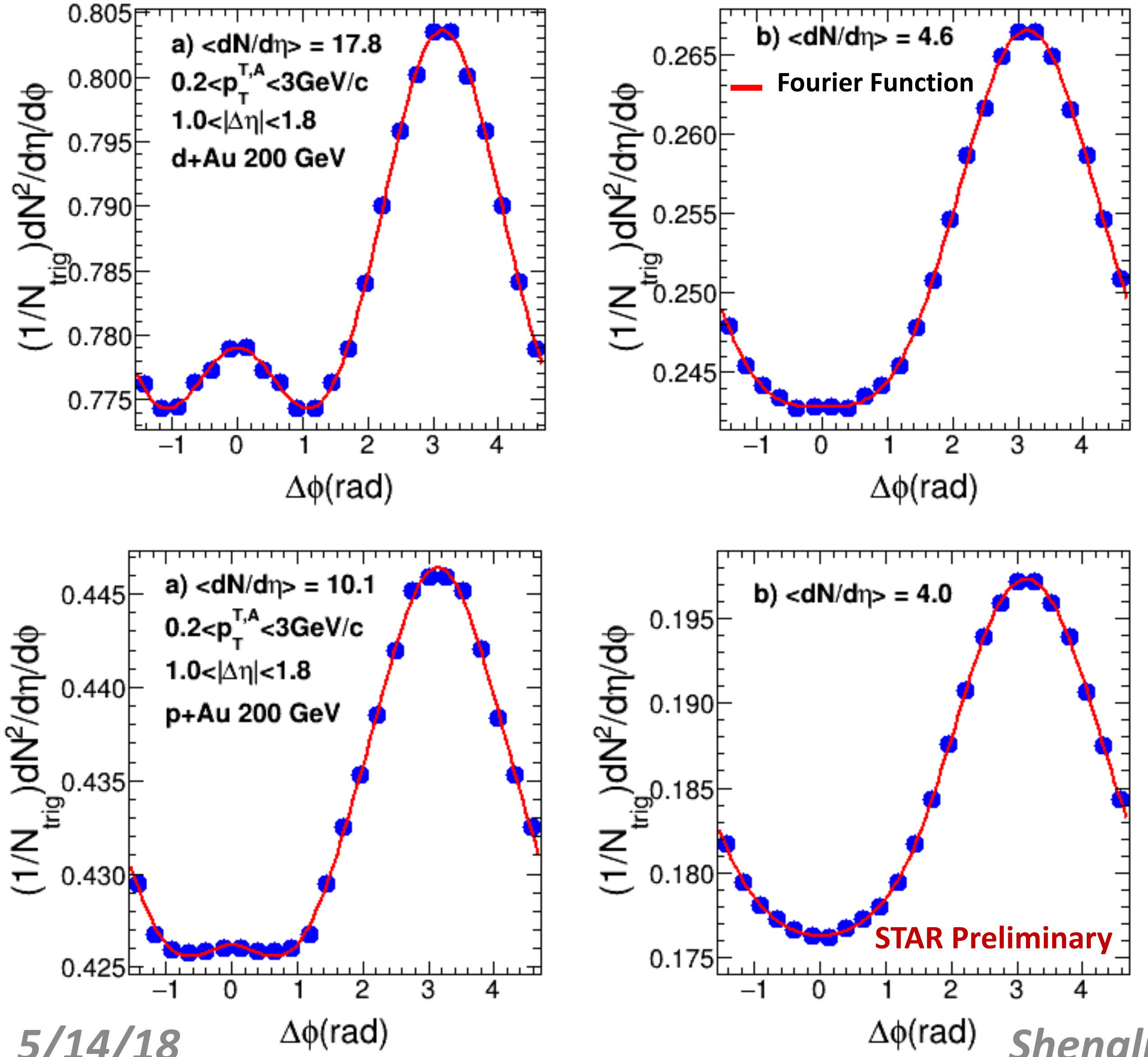



- ❑ Event classes with different activity are selected by using BBC east in the Au-going direction ($-5.0<\eta<-3.3$)
- ❑ Long-range two-particle correlations are measured in TPC($|\eta|<0.9$)
- ❑ Correlation between multiplicity at backward and mid-rapidity
- ❑ 10 event classes with different TPC $\langle dN/d\eta \rangle$ are selected by sum ADC of BBC east in d+Au collisions at 200 GeV

# Long-range Two-particle Correlations

**High Multiplicity (HM)** | **Low Multiplicity (LM)**




**d+Au 200 GeV**

**p+Au 200 GeV**

- ❑ A near-side ridge is observed in the HM d+Au ($<dN/d\eta>$=17.8) and p+Au ($<dN/d\eta>$=10.1) collisions
- ❑ A Fourier function is employed to extract the $V_{n,n}$

$$dN/d\Delta\phi \sim 1 + \sum_{n=1}^{4} 2V_{n,n} \times \cos(n\Delta\phi))$$

Integral $v_n = \text{sqrt}(V_{n,n})$; $v_n(p_T) = V_{n,n}(p_T)/v_n$

# Two Jet Subtraction Methods

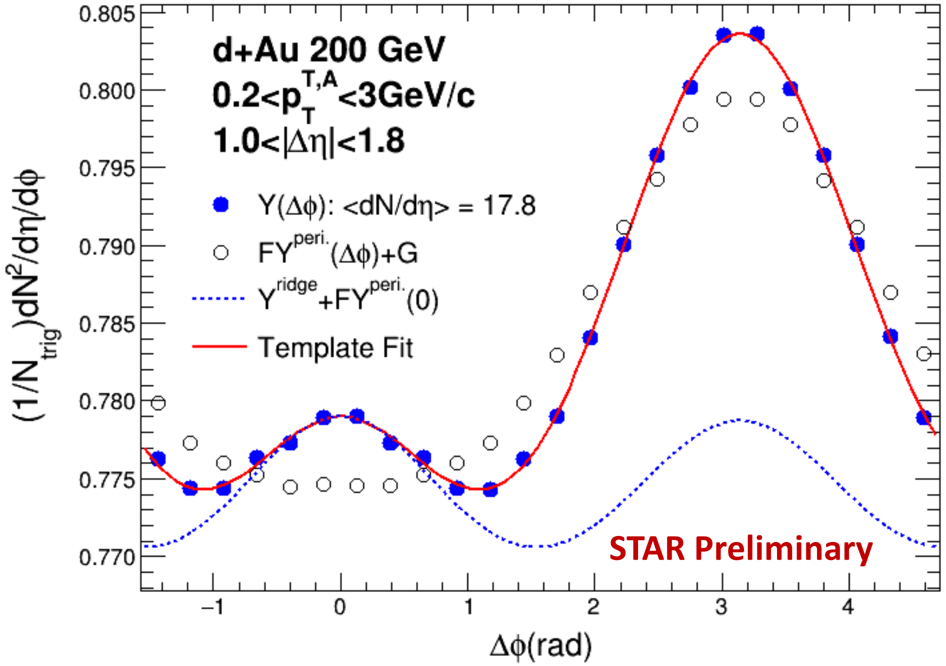
## 1.Low multiplicity subtraction scaled by short-range ($|\Delta\eta|$<0.5) near-side jet yield

$$V_{n,n}^{HM}(subtracted) = V_{n,n}^{HM} - V_{n,n}^{LM} \times \frac{N_{asso.}^{LM}}{N_{asso.}^{HM}} \times \frac{Y_{jet,near-side}^{HM}}{Y_{jet,near-side}^{LM}}$$

*ATLAS:PRC90(2014)044906*
*CMS:PLB765(2017)193*
*STAR: PLB743(2015)333*

✓ ***Assumption: short-range near-side jet modification = long-range away-side jet modification***

## 2.Template Fit




✓ **A new developed method to subtract away-side jet contribution by ATLAS:**

$Y_{templ.}(\Delta\phi) = F \times Y_{LM}(\Delta\phi) + Y_{ridge}(\Delta\phi)$

where

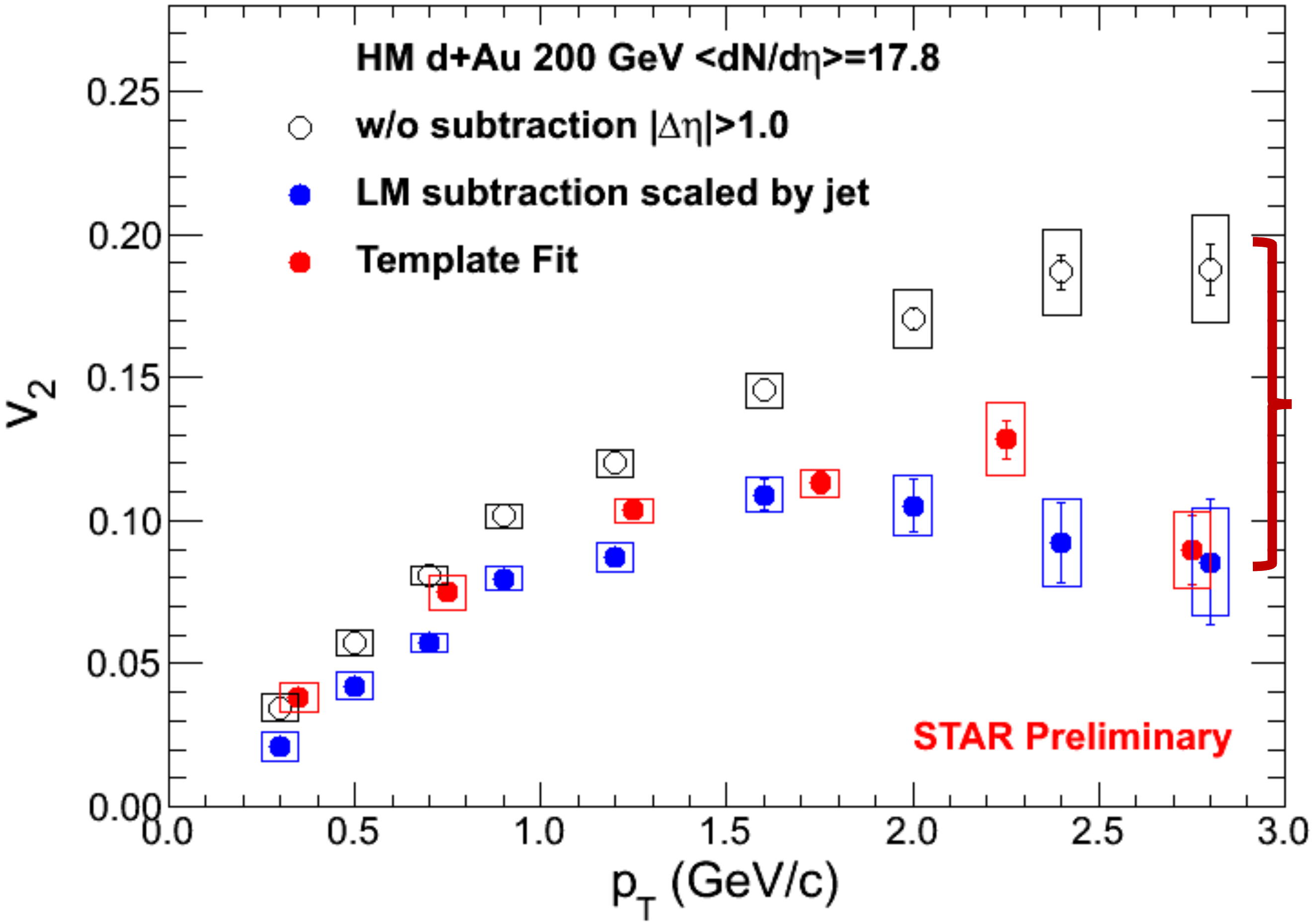
$Y_{ridge}(\Delta\phi) = G\times(1 + 2\times\sum_{n=2}^{4} V_{n,n}\times\cos(n\Delta\phi))$

*ATLAS:PRL(116)172301*

✓ **Assumption: away-side jet shape can be measured in LM events and scaled by fit parameter "F" due to jet modification**

**It will cause a bias if assumptions are not correct**

# $v_2$ in HM d+Au (0-10%) at 200 GeV




- $v_2$ without subtraction is larger than that with subtraction for both methods. ***The subtraction of non-flow is crucial in small system!***

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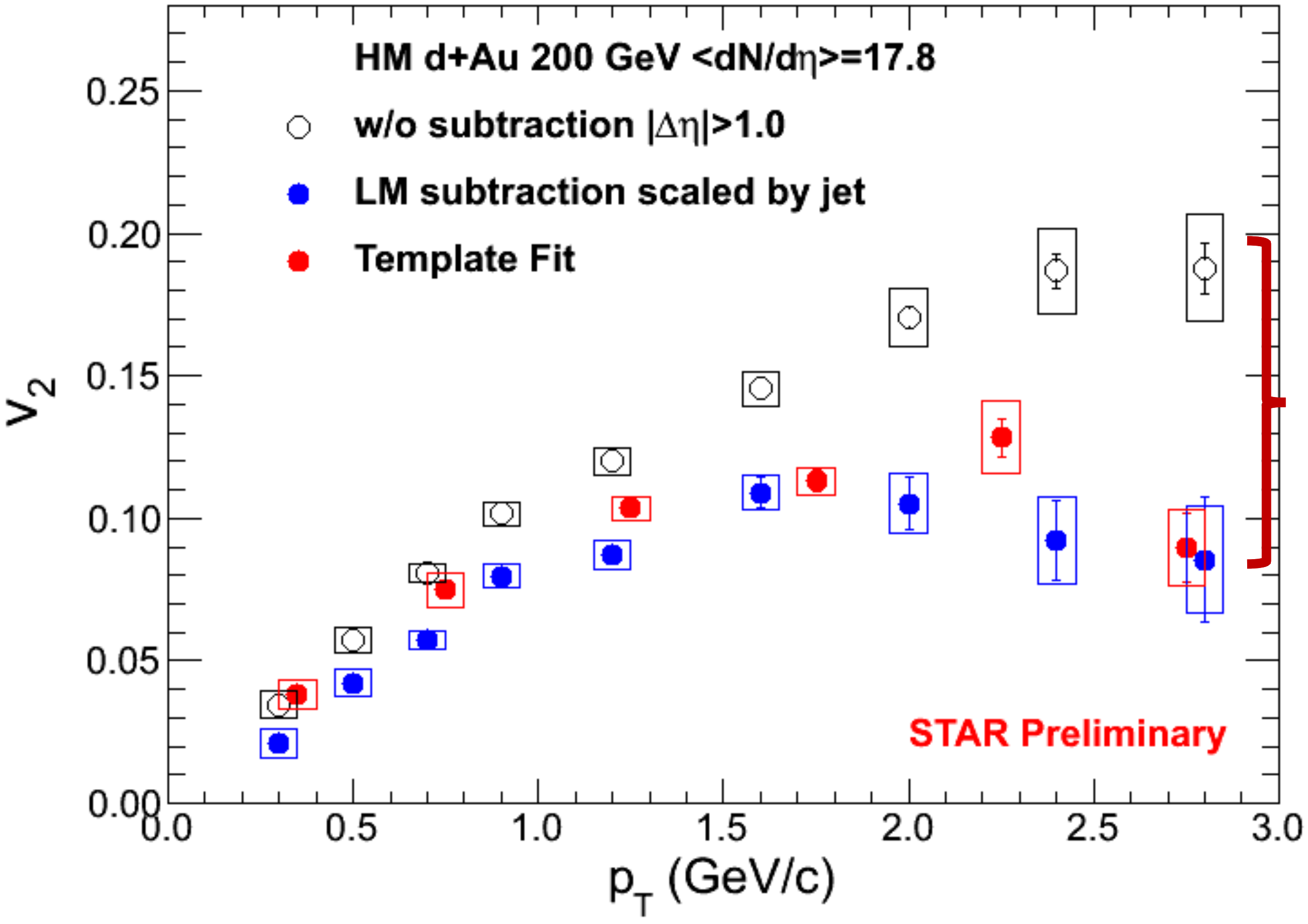
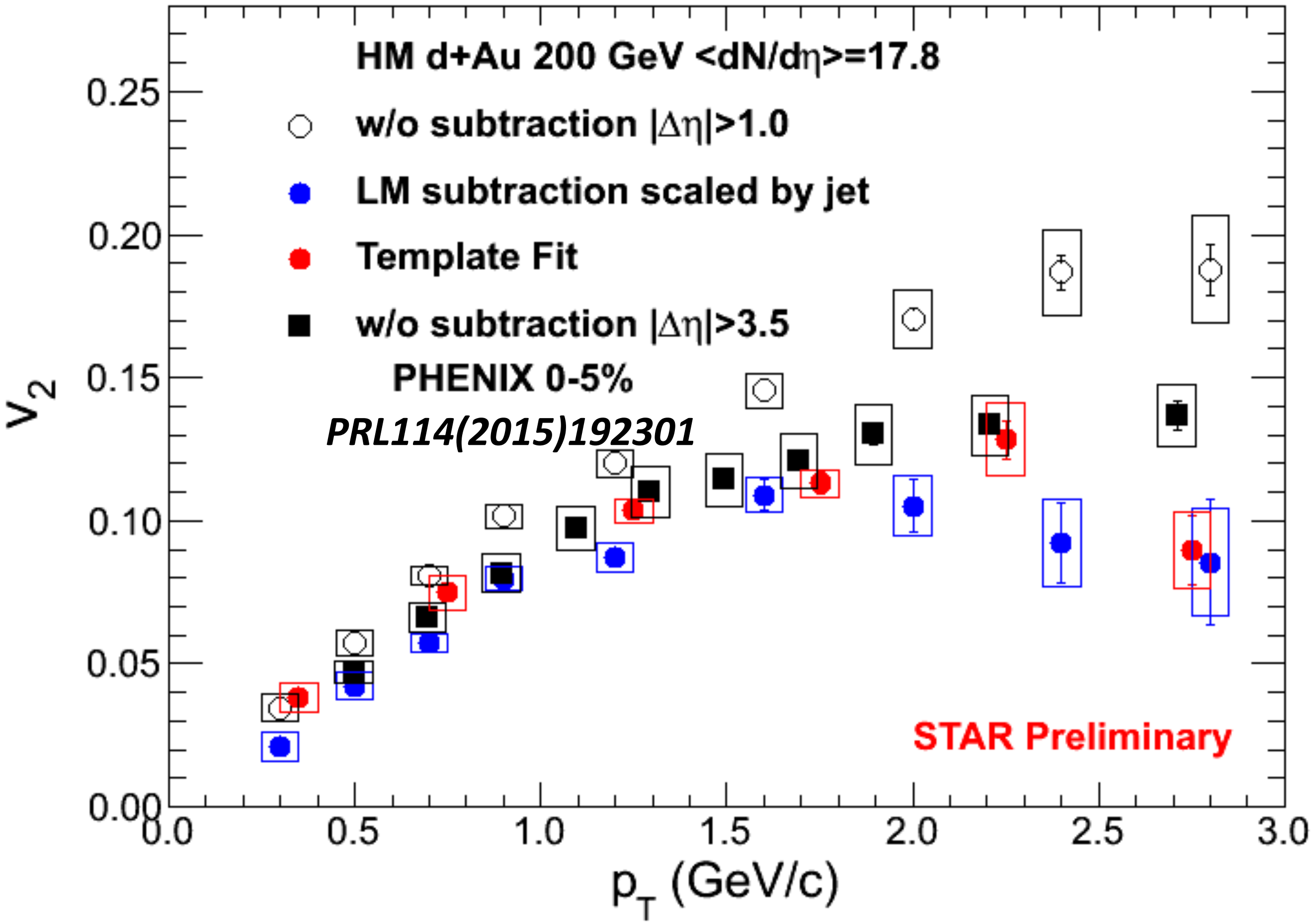


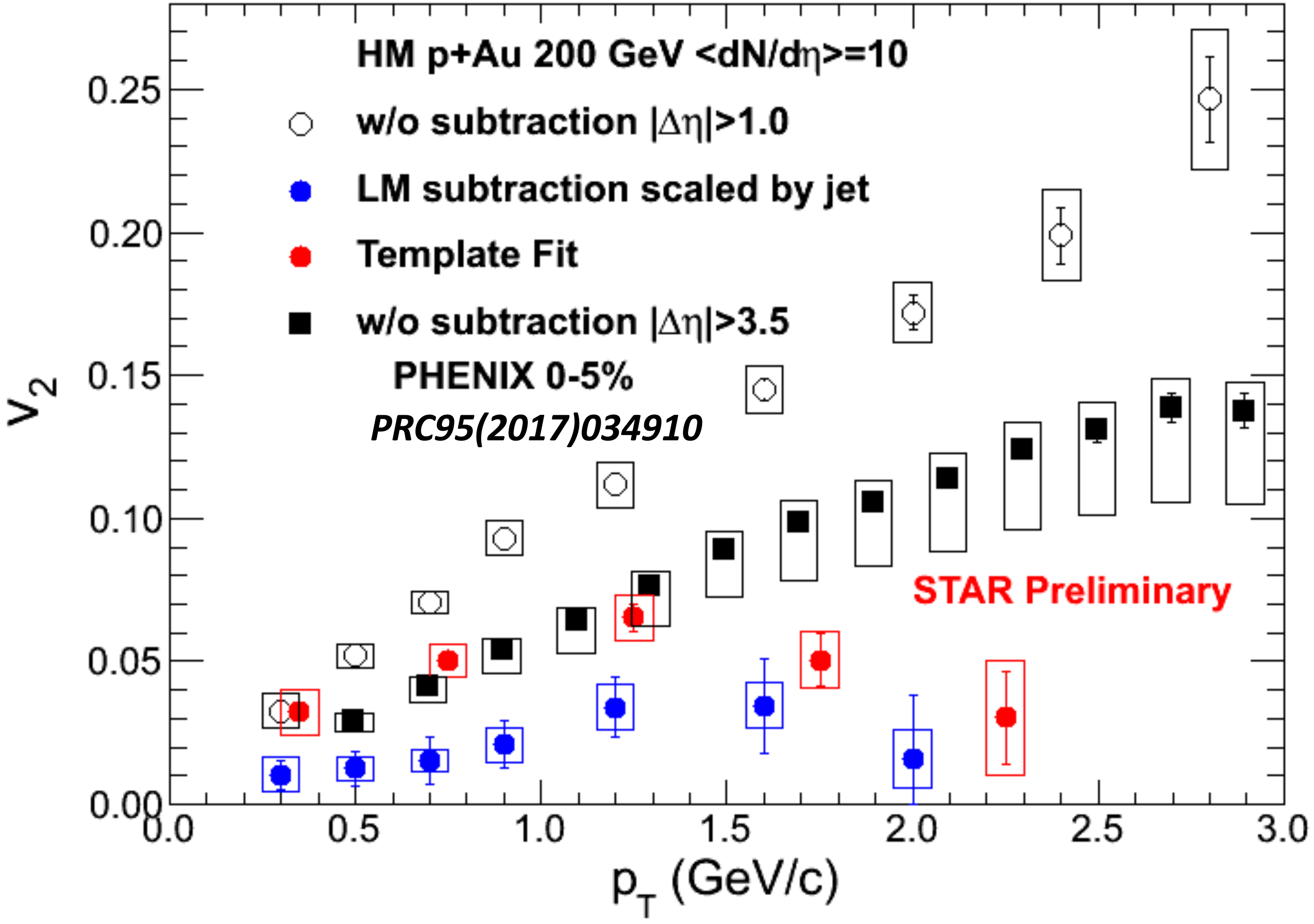

- $v_2$ without subtraction is larger than that with subtraction for both methods. ***The subtraction of non-flow is crucial in small system!***
- At lower $p_T$, the $v_2$ from LM subtraction is around 35% lower than that from template fit, while they are quite similar at intermediate $p_T$

# $v_2$ in HM d+Au (0-10%) at 200 GeV



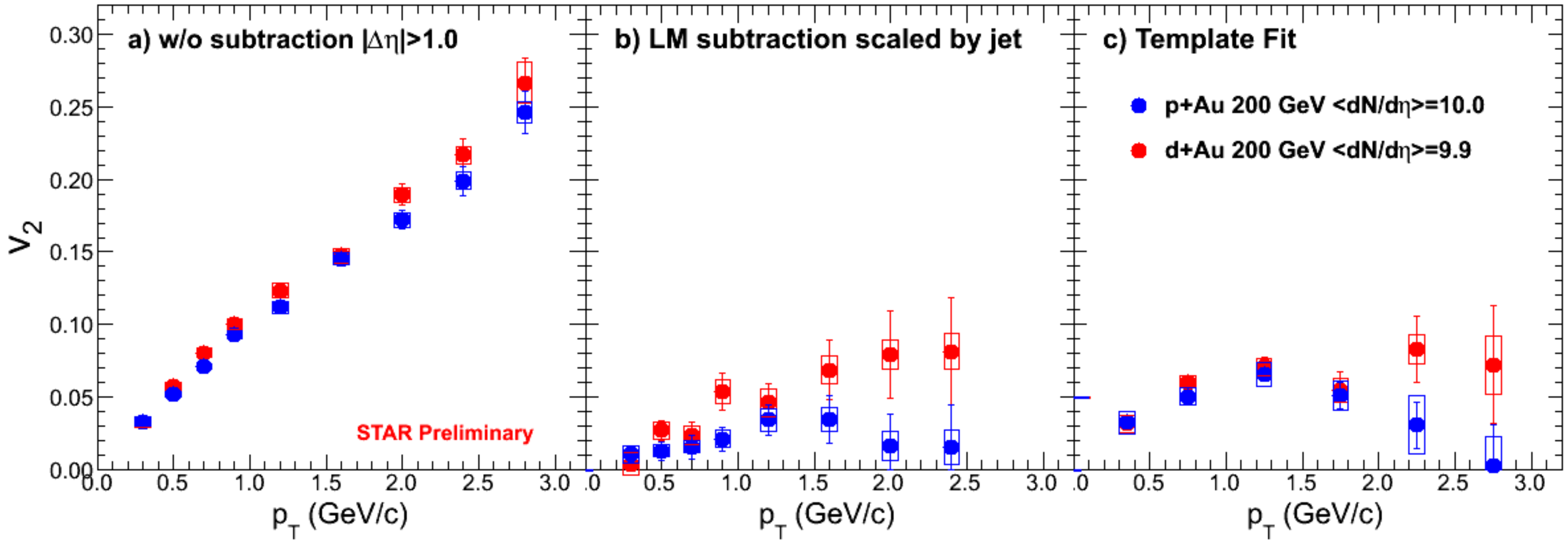

- $v_2$ without subtraction is larger than that with subtraction for both methods. ***The subtraction of non-flow is crucial in small system!***
- At lower $p_T$, the $v_2$ from LM subtraction is around 35% lower than that from template fit. While they are quite similar at intermediate $p_T$
- The subtracted $v_2$ measured by STAR is similar to PHENIX measurement, which has at least 10% non-flow

# $v_2$ in HM p+Au (0-10%) at 200 GeV



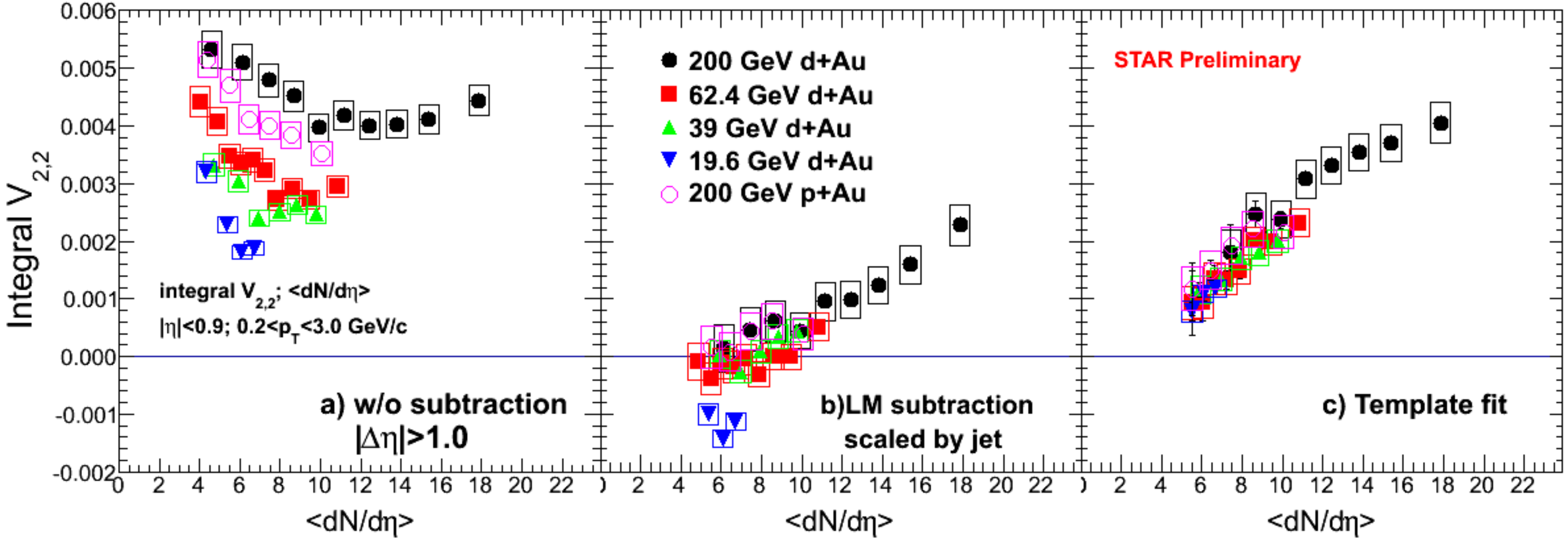

- Compared to d+Au results, $v_2$ in p+Au without subtraction is much larger than that with subtraction for two methods
- In p+Au collision, the $v_2$ from LM subtraction is much lower than that from template fit.
- $v_2$ from template fit method is similar to PHENIX measurement at low $p_T$

# p/d+Au $v_2$ with same <dN/d$\eta$>



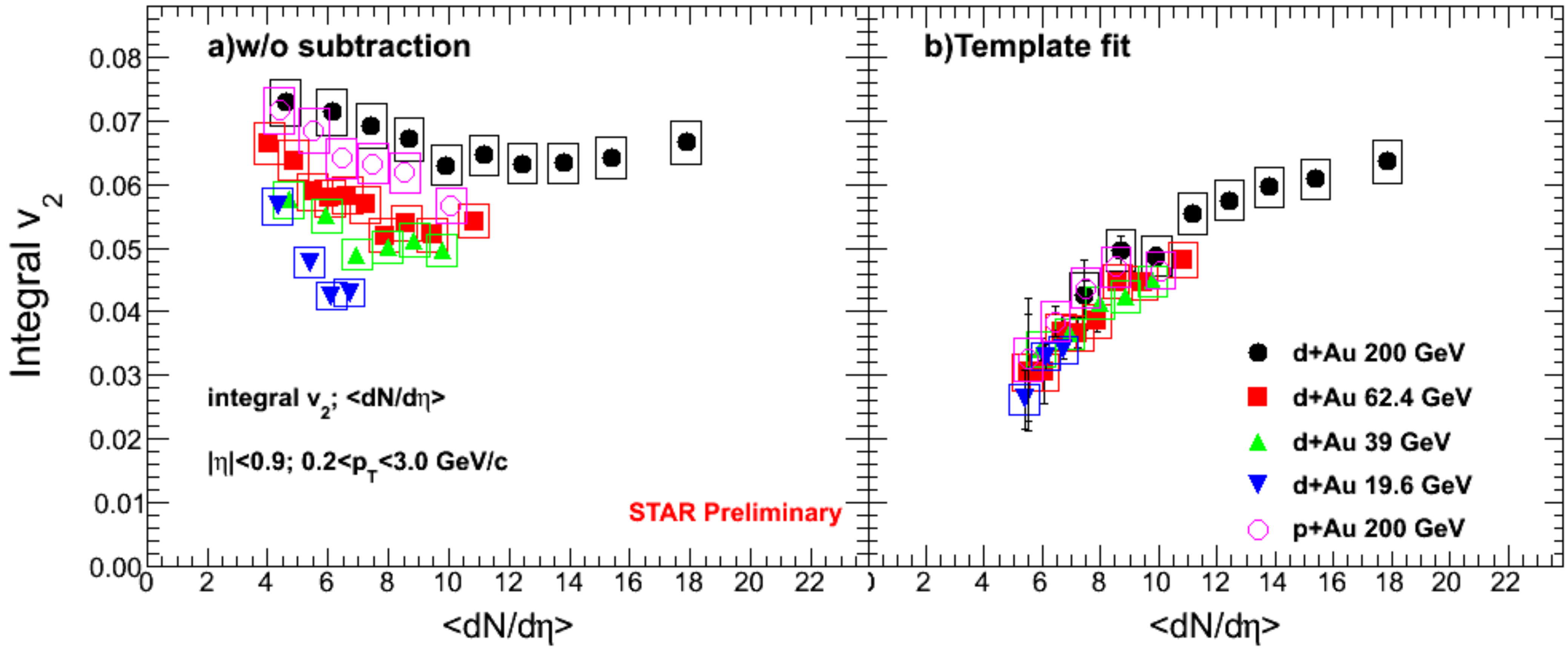

- By LM subtraction method, $v_2$ in d+Au is a little bit larger than that of p+Au collisions
- $v_2$ between p+Au and d+Au collisions from template fit is similar, while the initial eccentricities are different by a factor of two

# Integral $V_{2,2}$ vs. <dN/d$\eta$>



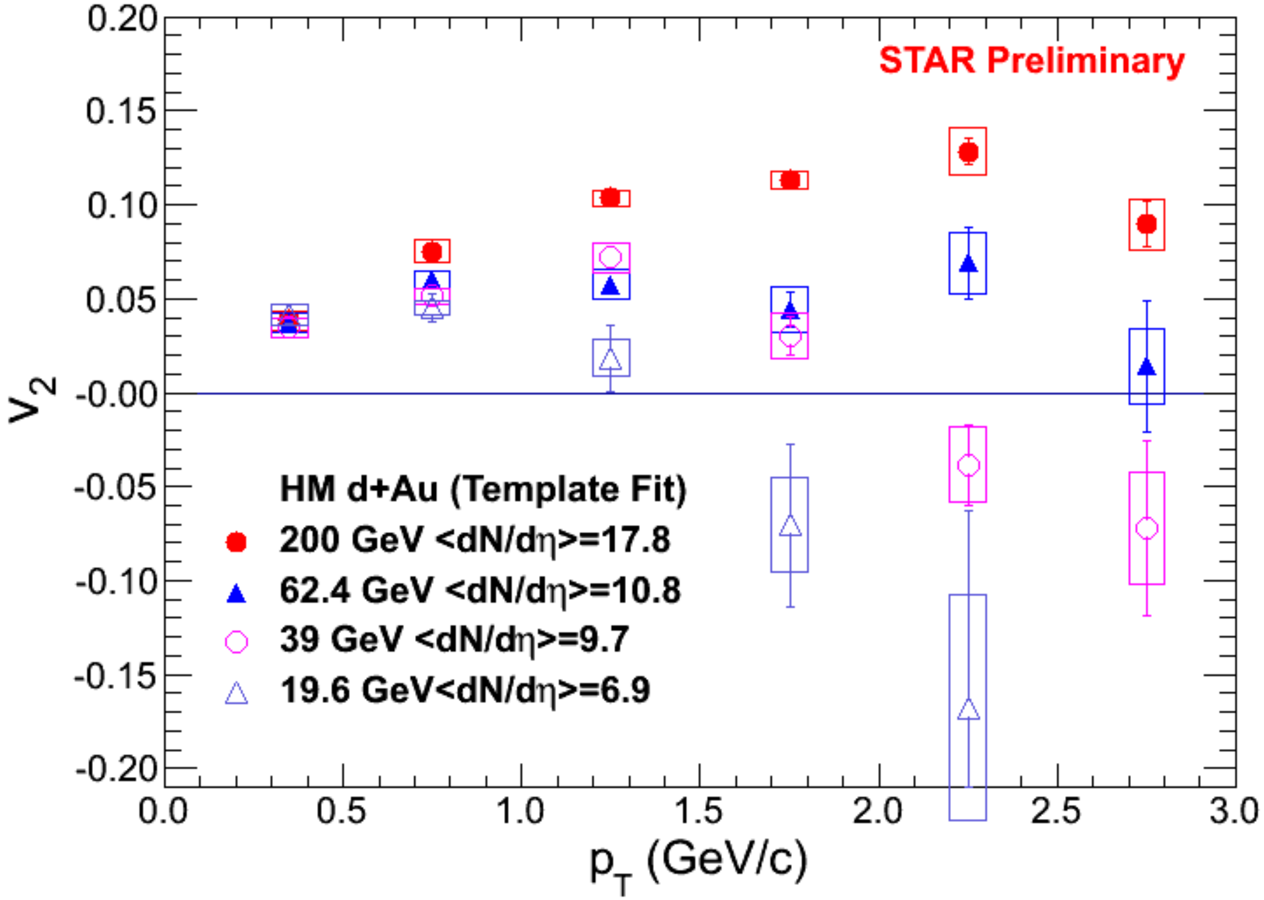

- ❑ There is large difference between two methods
- ❑ LM subtraction leads to a negative $V_{2,2}$ at low energy
  - ✓ Different kinematics between near- and away-side jet-like correlations?
- ❑ $V_{2,2}$ from template fit increases as a function of <dN/d$\eta$>

# Integral $v_2$ from Template Fit




- The unsubtracted integral $v_2$ as a function of <dN/d$\eta$> is different in different systems at different collision energies
- The integral $v_2$ from template fit shows a universal trend as a function of <dN/d$\eta$>

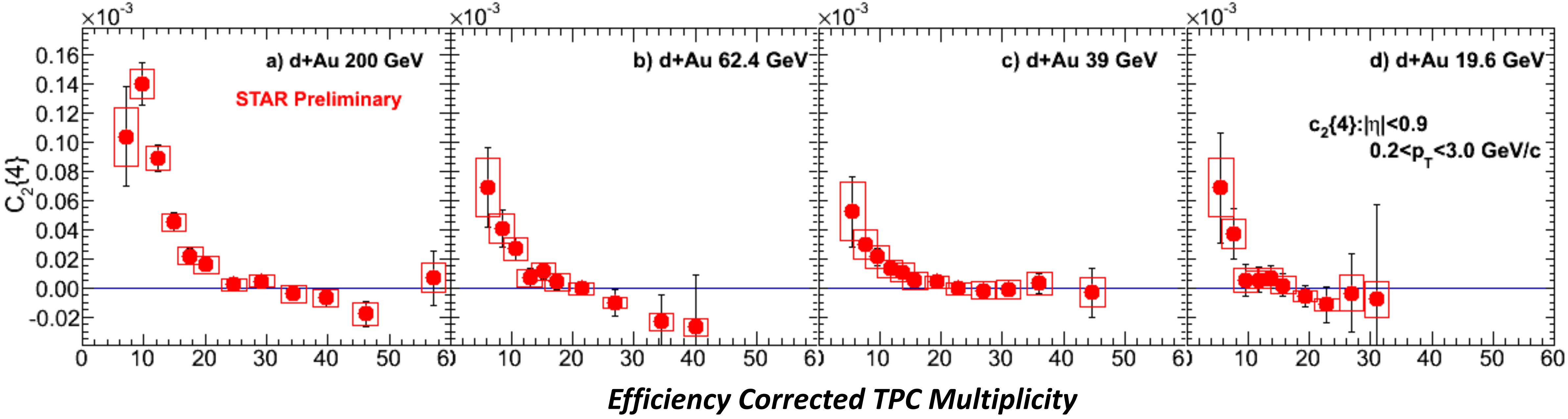
# Differential $v_2$ from Template Fit in d+Au BES




- The differential $v_2$ becomes negative at high $p_T$ in d+Au collisions at low energy
- The correlation from away-side jet is stronger at higher $p_T$. This potentially can lead to large uncertainties in the non-flow subtraction

# $c_2\{4\}$ vs. $<dN/d\eta>$






***Four-Particle Cumulant***

$$c_2\{4\} = \langle\langle e^{-i2(\phi_i+\phi_j-\phi_k-\phi_l)}\rangle\rangle - 2\langle\langle e^{-i2(\phi_i-\phi_j)}\rangle\rangle$$

$\phi_i, \phi_j, \phi_k, \phi_l$ are the azimuthal angles of four different particles in an event ; 《》 represents the average over all particles from all events within a given multiplicity range

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$

***An indication that $c_2\{4\}$ is negative for high multiplicity d+Au collisions at 200 and 62.4 GeV, while the statistical uncertainties are large***

# Summary

- ❑ Large difference between $V_{2,2}$ from two methods has been observed at low energy
  - ✓There are large uncertainties in the non-flow subtraction in small systems
- ❑We see similar $v_2$ between p/d+Au collisions for same multiplicity.
  - ✓$v_2$ is not only driven by initial geometry
- ❑The integral $v_2$ extracted by template fit shows a universal trend as a function of <dN/d$\eta$> for different small systems at different energies
  - ✓Multiplicity plays an important role for the flow in small systems!
- ❑$c_2\{4\}$ is negative at high multiplicity at 62.4 and 200 GeV, but the measurements are limited by statistics.