Measurements of azimuthal anisotropies in $^{16}O+^{16}O$ and γ+Au collisions from STAR

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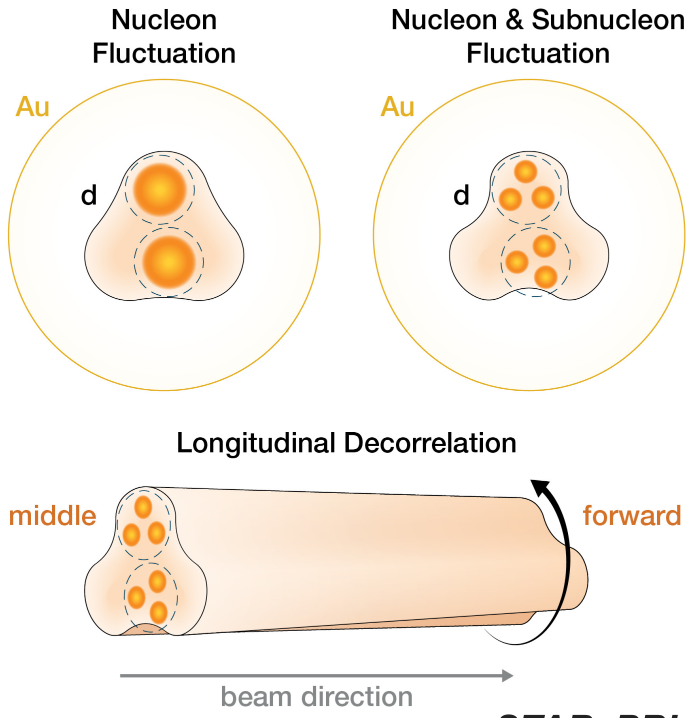
Poster 451 @ Zhengxi Yan

Outline

- Motivation to study collectivity in O+O
- O+O data set and analysis detail
- $v_n(p_T)$ in different centrality in O+O
- $v_2\{2\}$, $v_2\{4\}$ and $v_3\{2\}$ vs centrality in O+O
- Outlook: Anisotropy in γ+Au collision
- Summary

Source of Initial-State Fluctuation in Small System



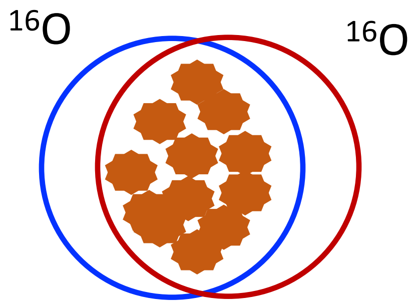
STAR, PRL 130, 242301

Interplay between several possible sources:

1) Fluctuations in nucleon position

2) ***Fluctuations in nucleon position and its quark and gluon constituents***

3) Fluctuations of overlap geometry along the beam direction



Comparing symmetric and asymmetric systems can yield additional insights into sub-nucleon fluctuations.

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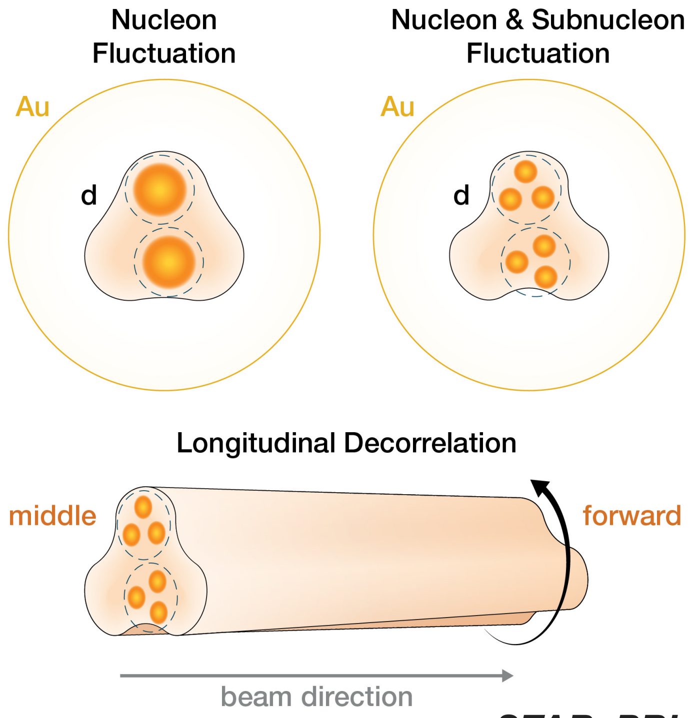

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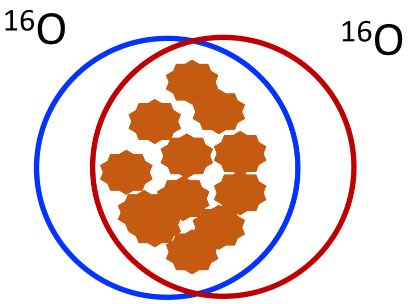
Interplay between several possible sources:

1) Fluctuations in nucleon position

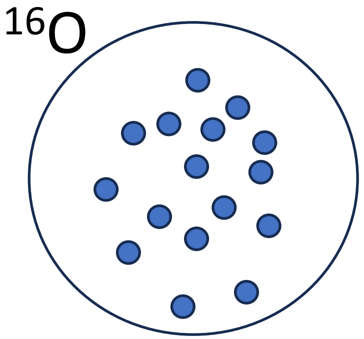
2) ***Fluctuations in nucleon position and its quark and gluon constituents***

3) Fluctuations of overlap geometry along the beam direction

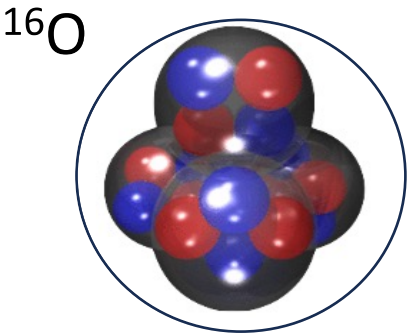
4) **Fluctuations due to many-nucleon correlation(e.g. α-cluster)**



Comparing symmetric and asymmetric systems can yield additional insights into sub-nucleon fluctuations.



Woods-Saxon



α-cluster

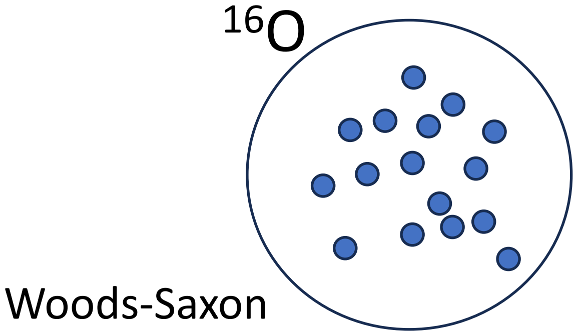
Many-nucleon correlations may also influence the fluctuation in eccentricity as: $\varepsilon_2\{4\}$.

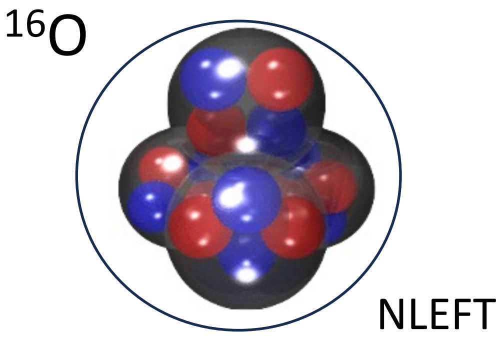
Many-nucleon correlation

***NLEFT:** model with many-nucleon correlation including α cluster*

Lu *et al.*, PLB **797** (2019) 134863

***Woods-Saxon:** without many-body nuclear correlation*





Many-nucleon correlation

***NLEFT:* model with many-nucleon correlation including α cluster**

Lu *et al.*, PLB **797** (2019) 134863

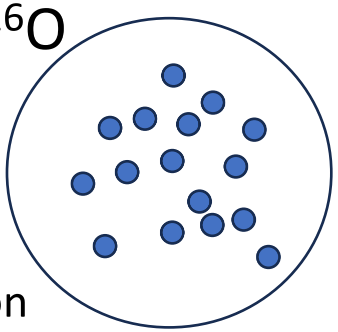
***Woods-Saxon:* without many-body nuclear correlation**

$\varepsilon_2\{4\} / \varepsilon_2\{2\}$ from three models:

1. ***TRENTO: WS ≈ NLEFT***
2. ***Quark Glauber: WS > NLEFT***
3. ***Nulceon Glauber: WS > NLEFT***

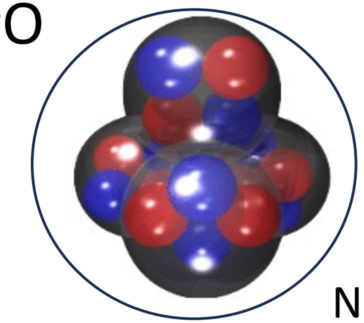
Quark Glauber > Nucleon Glauber for NLEFT

^{16}O

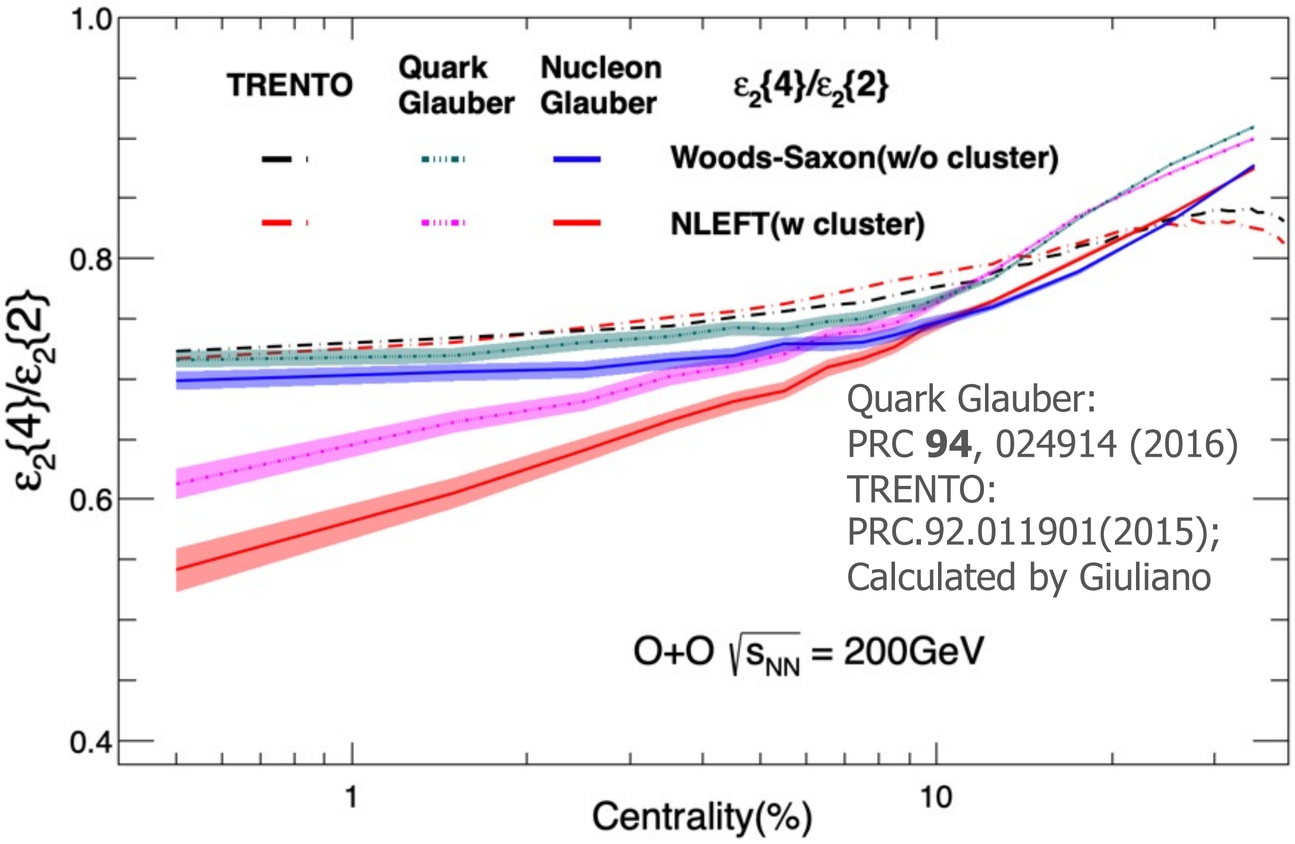


Woods-Saxon

^{16}O



NLEFT



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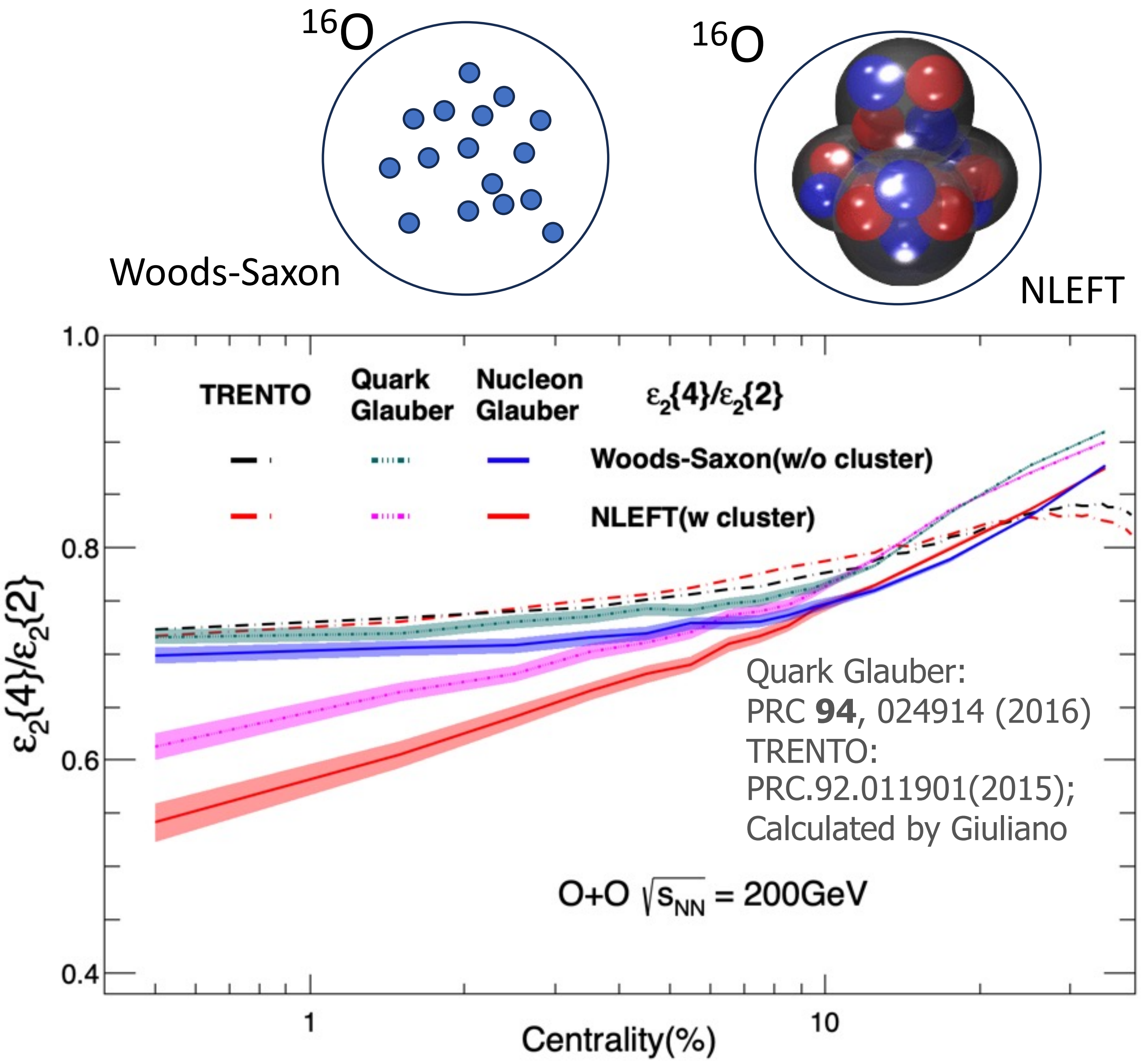
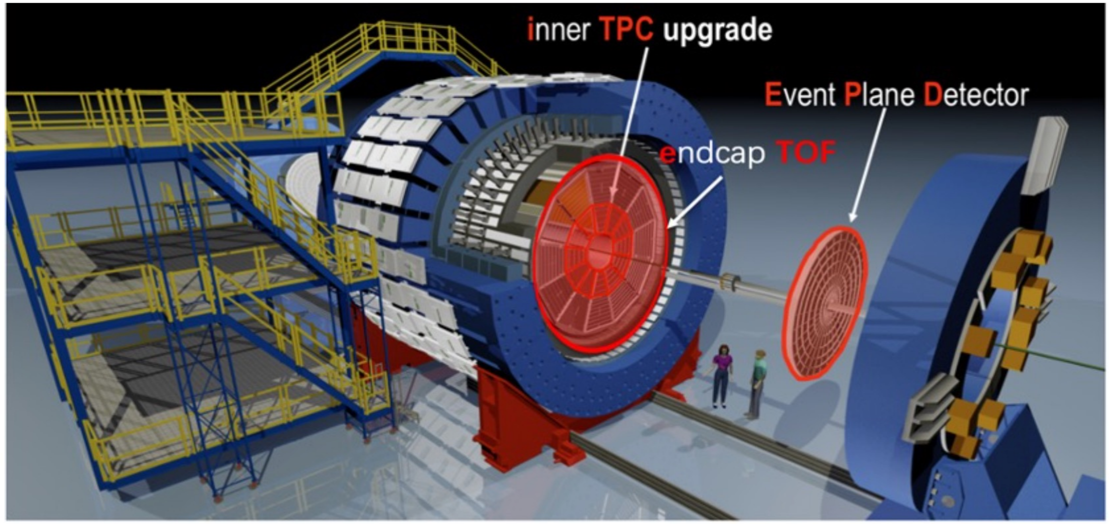
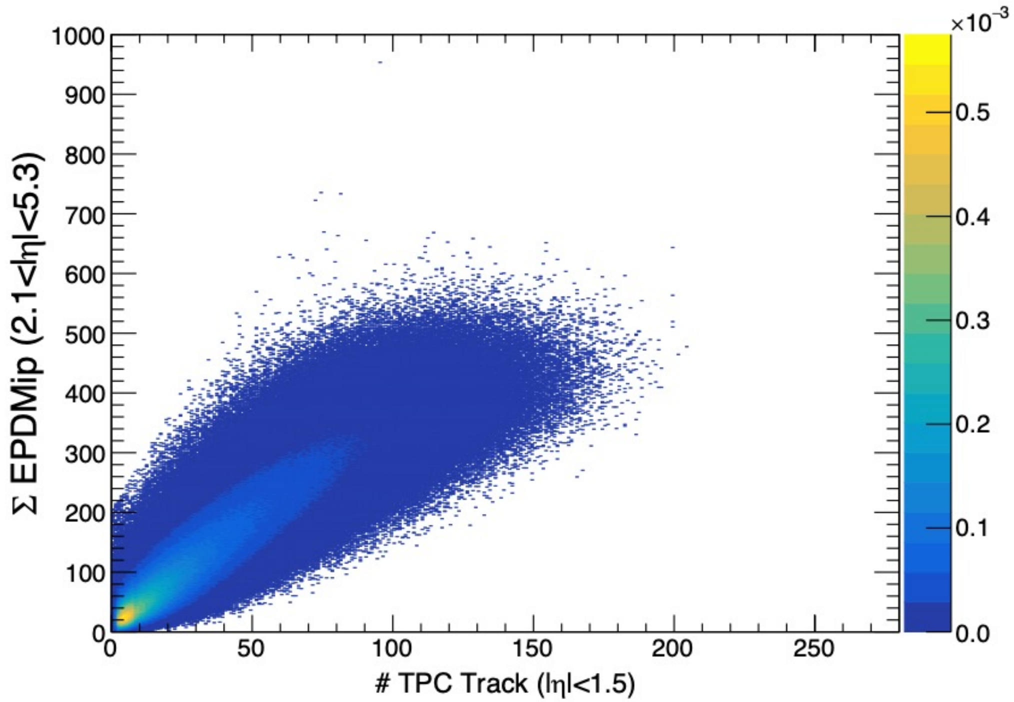
Quark Glauber > Nucleon Glauber for NLEFT

Many-nucleon correlation ***can significantly impact the eccentricity fluctuations. However, these effects tend to be reduced by sub-nucleon fluctuations.***



$^{16}O+^{16}O$ Data Set





- ***STAR has taken 600M MB and 250M high multiplicity O+O events in 2021***
- ✓ Large rapidity coverage due to iTPC $|\eta|<1.5$ and EPD($2.1<|\eta|<5.1$)
- ✓ Trigger on high multiplicity event at both middle and forward rapidity regions

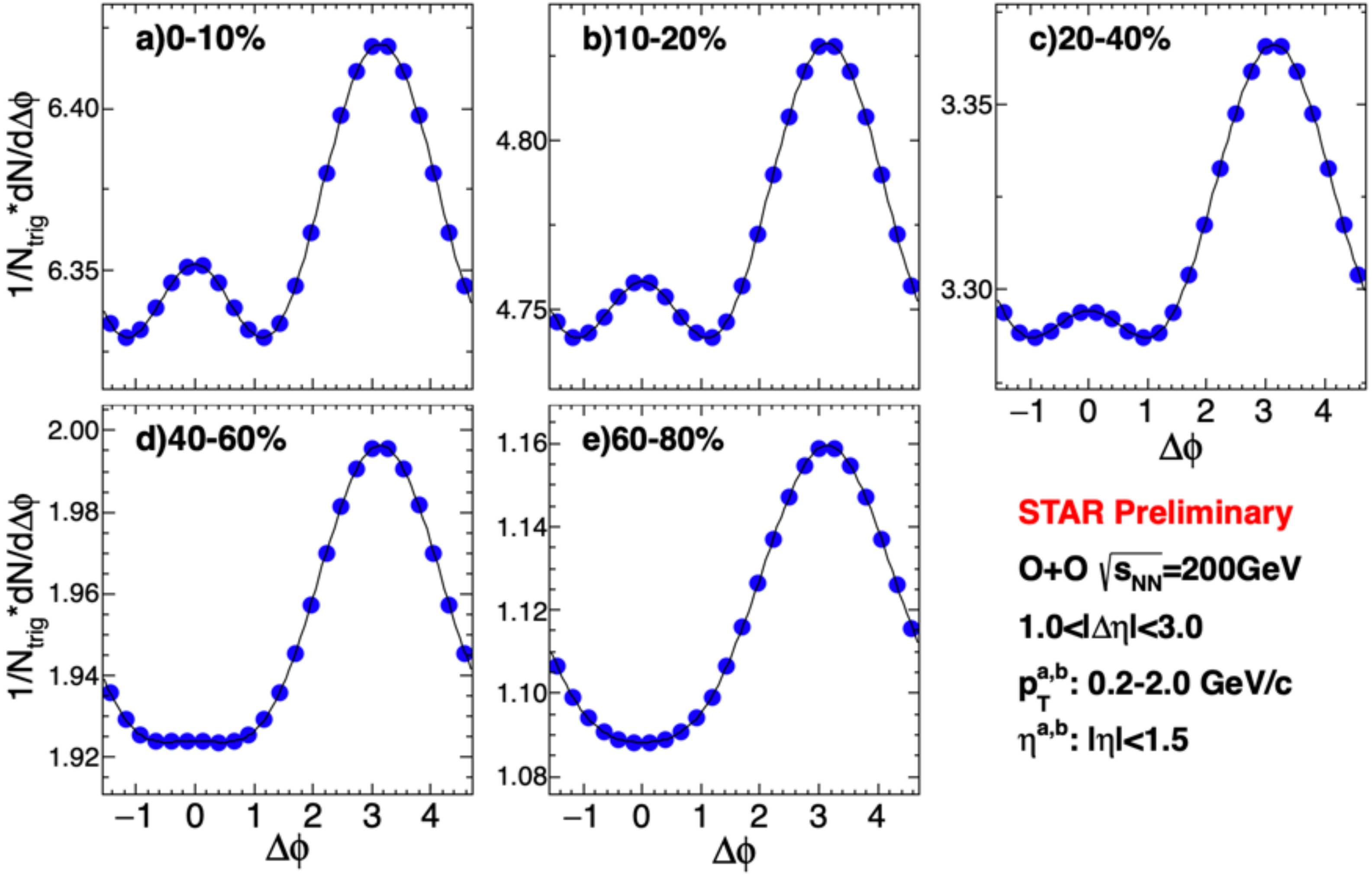
Two types of centrality definitions:
TPC centrality: $|\eta|<1.5$, p_T:[0.2,2] GeV/c
EPD centrality: $2.1<|\eta|<5.1$

$v_2\{2\}$, $v_3\{2\}$: Di-hadron correlation
p_T associated [0.2,2.0 GeV/c]
P_T trigger [0.2,3.0 GeV/c]

$v_2\{4\}$: Cumulant method

$$(v_2\{4\})^4 = -c_2\{4\} = 2 < 2 >^2 - < 4 >$$

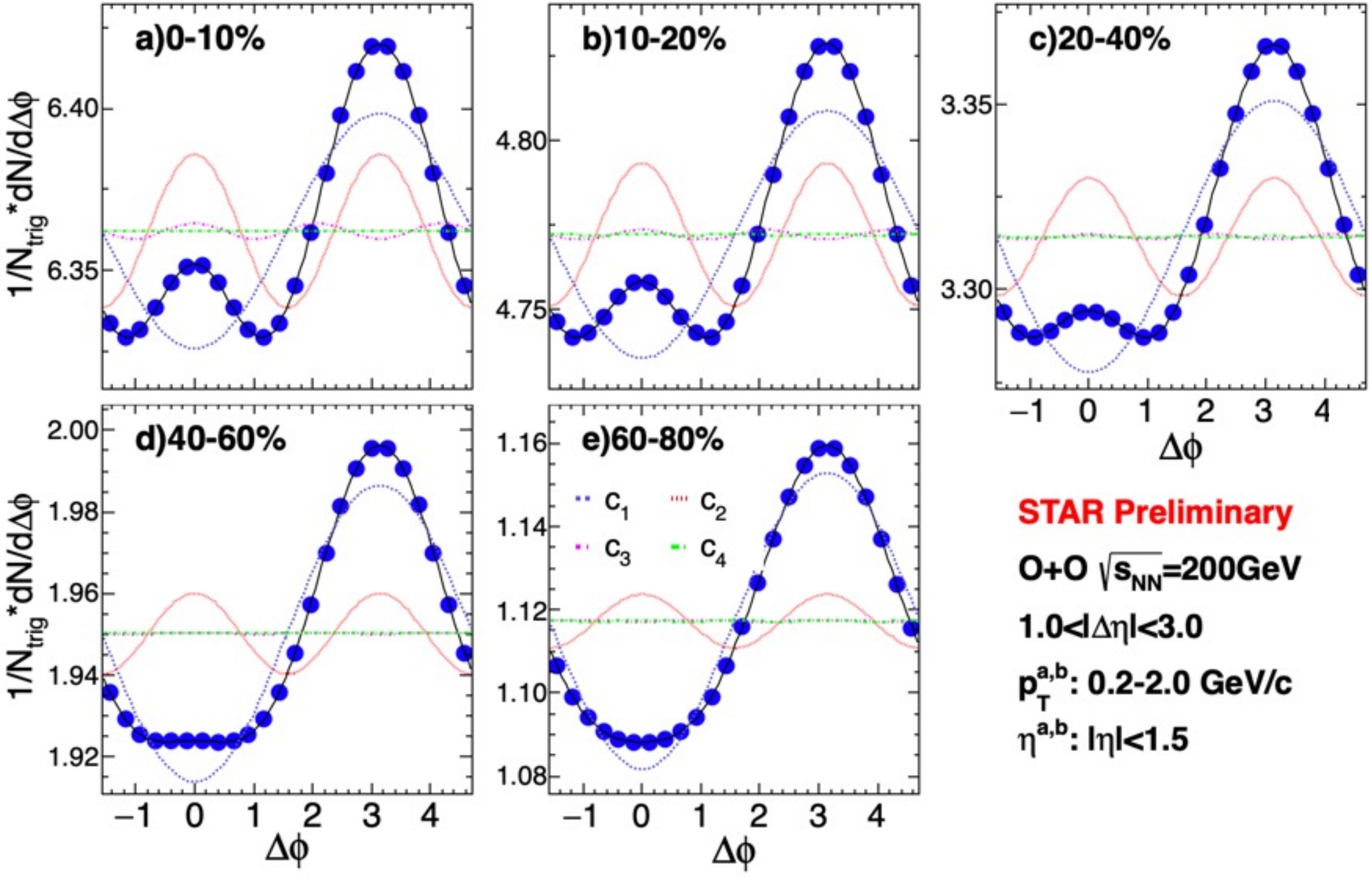
Di-hadron correlation at middle rapidity in $^{16}O+^{16}O$



Ridge is seen in central O+O collisions while not in peripheral collisions

EPD Centrality: 2.1<$|\eta|$<5.1

Di-hadron correlation at middle rapidity in $^{16}O+^{16}O$



Flow is extracted with Fourier fitting and nonflow subtraction with 60-80% centrality:

$$Y(\Delta\phi, p_T^{Trig.}) = c_0(1 + \sum_{n=1}^{4} 2c_n \cos(n\Delta\phi)).$$

$$c_n^{sub} = c_n - c_n^{nonflow} = c_n^{cent.} - c_n^{peri} \times f$$

1. C_0 method: $f = c_0^{peri.}/c_0^{cent.}$
2. Near-side jet-yield method:

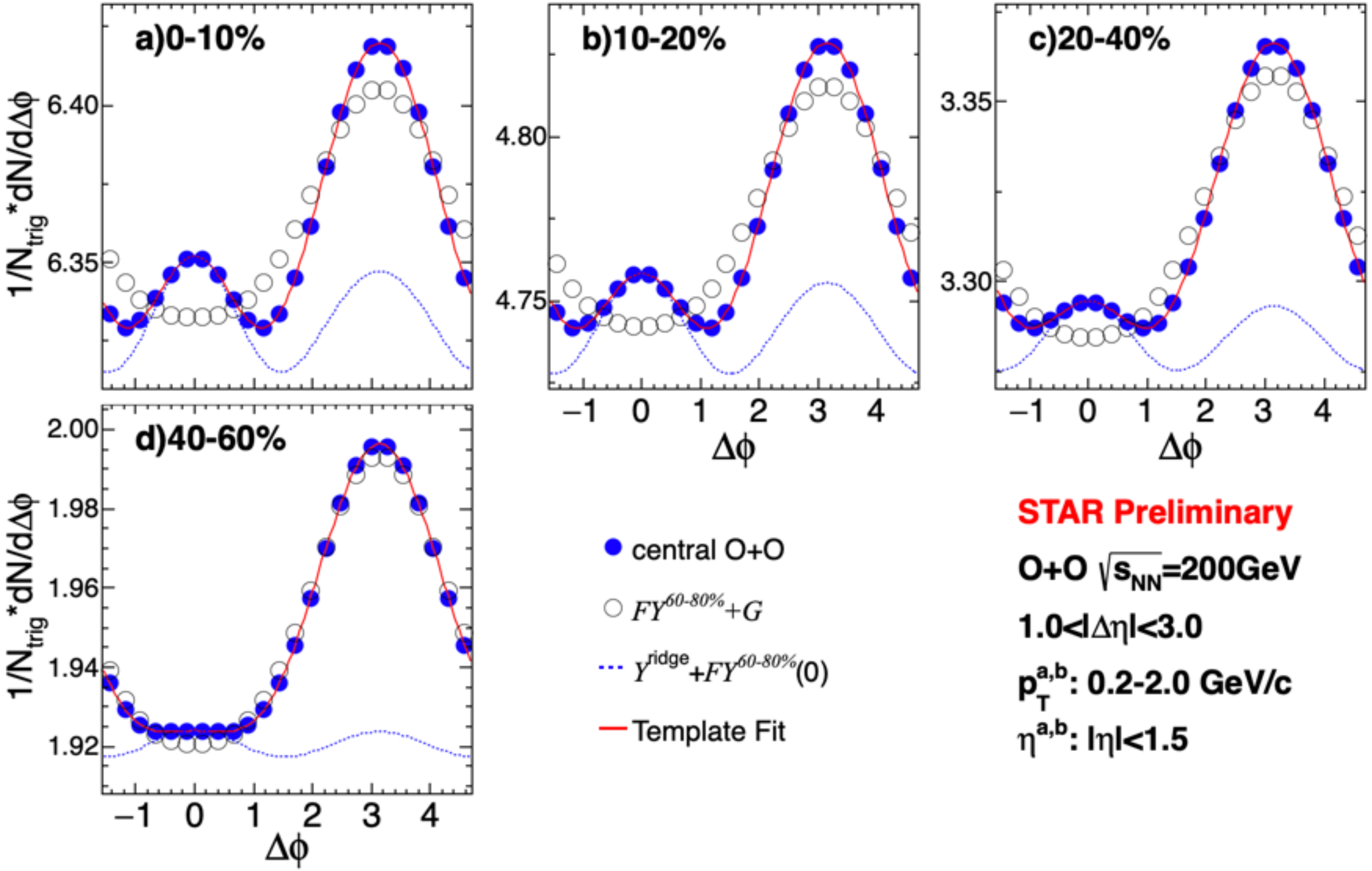
$$f = (Y_{cent.}^N/Y_{peri.}^N) \times (c_0^{peri.}/c_0^{cent.})$$

3. C_1 method $f = c_1^{cent}/c_1^{peri.}$

EPD Centrality: 2.1<|η|<5.1

STAR, PRL 130, 242301(2023)

Di-hadron correlation at middle rapidity in $^{16}O+^{16}O$



EPD Centrality: $2.1<|\eta|<5.1$

STAR, PRL 130, 242301(2023)

4. Template Fit:

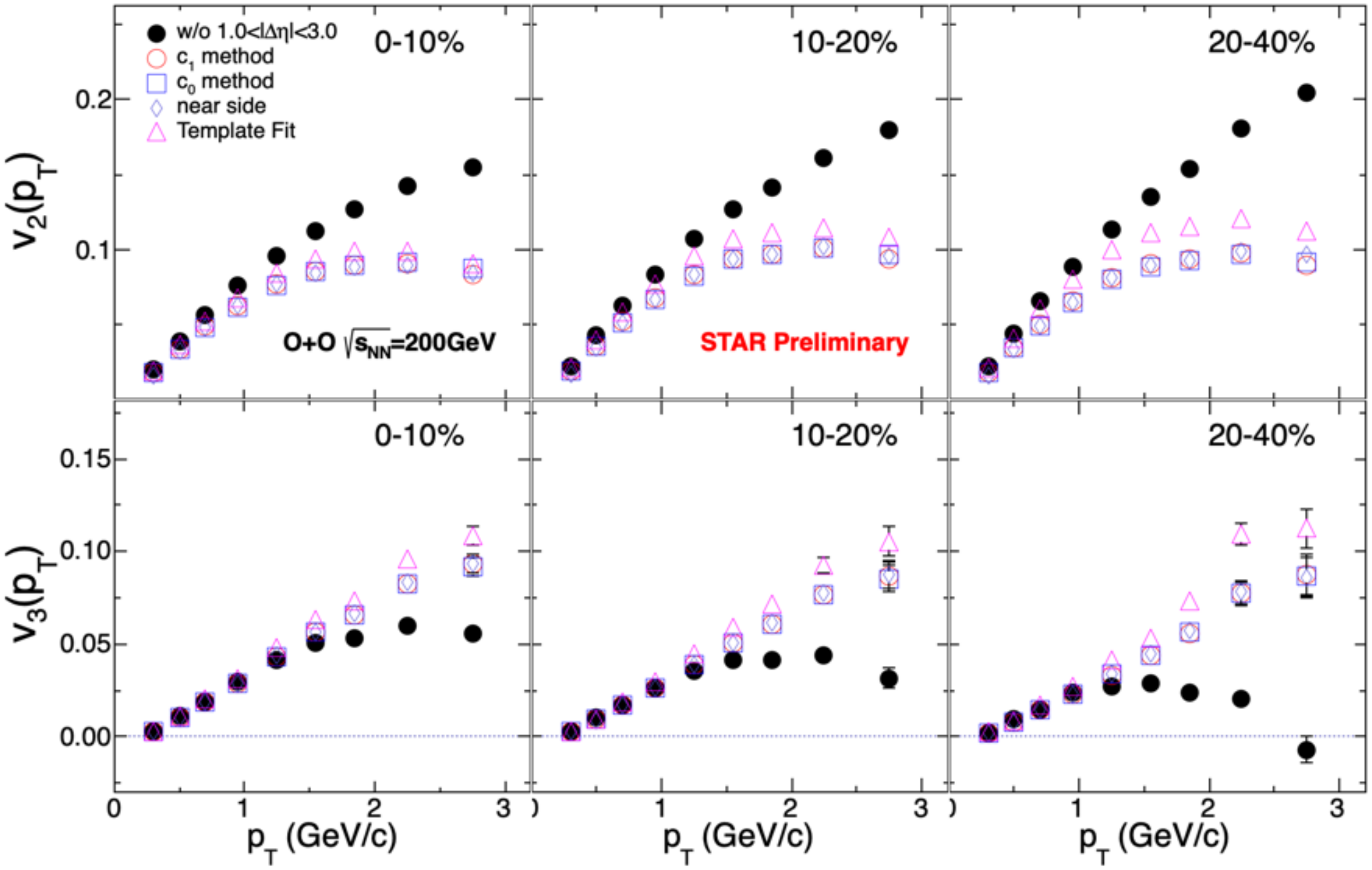
$$Y_{templ.}(\Delta\phi) = Y_{ridge}(\Delta\phi) + \mathrm{F}\, Y_{peri.}(\Delta\phi)$$

$$Y_{ridge}(\Delta\phi) = \mathrm{G}(1 + 2\sum_{n=2}^{4} c_n^{sub}\cos(n\Delta\phi))$$

"F" represents the modification for the long-range away-side jet between **cent. and peri.**

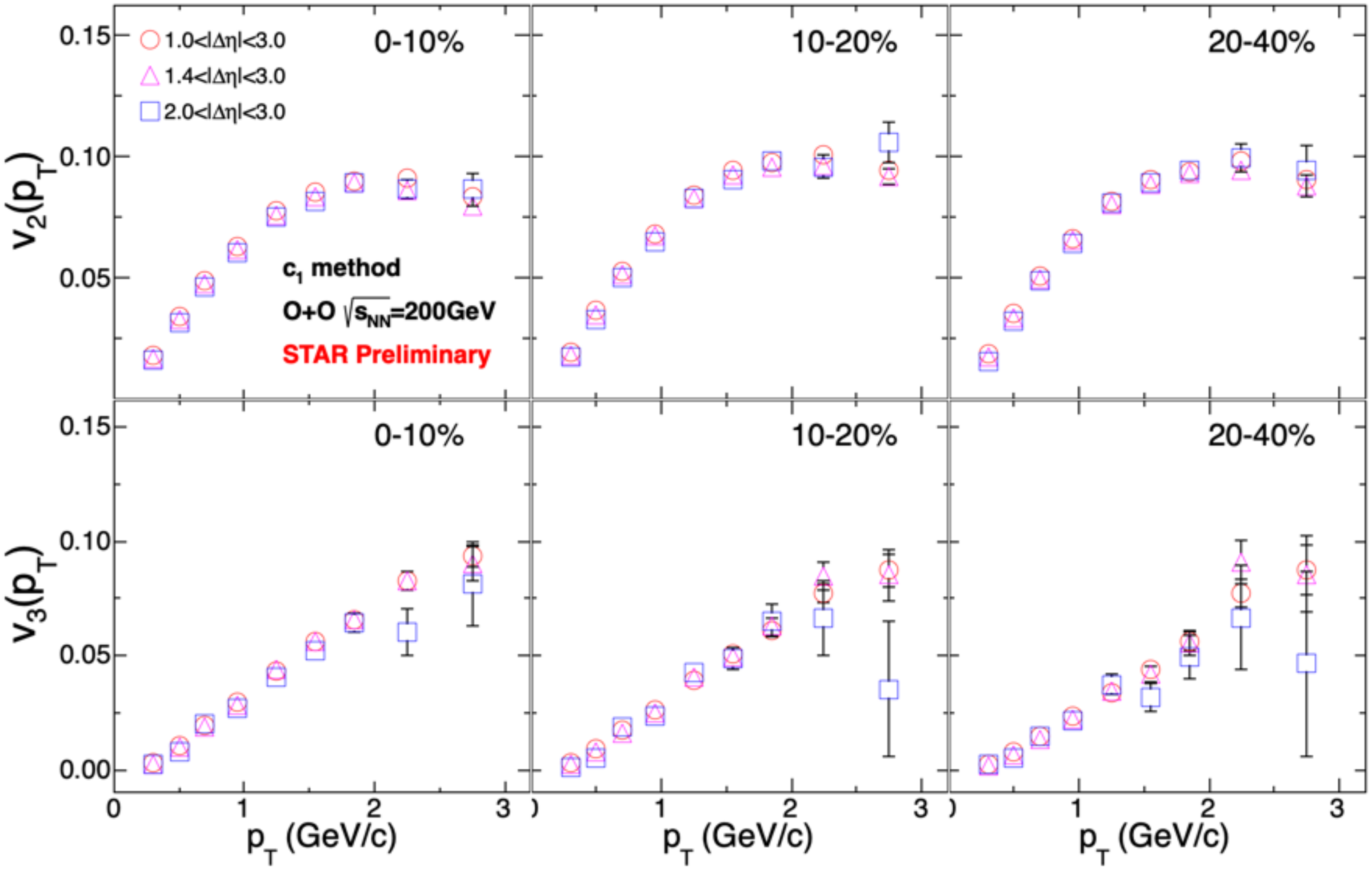
ATLAS, PRL 116, 172301 (2016)

v_n from different subtraction



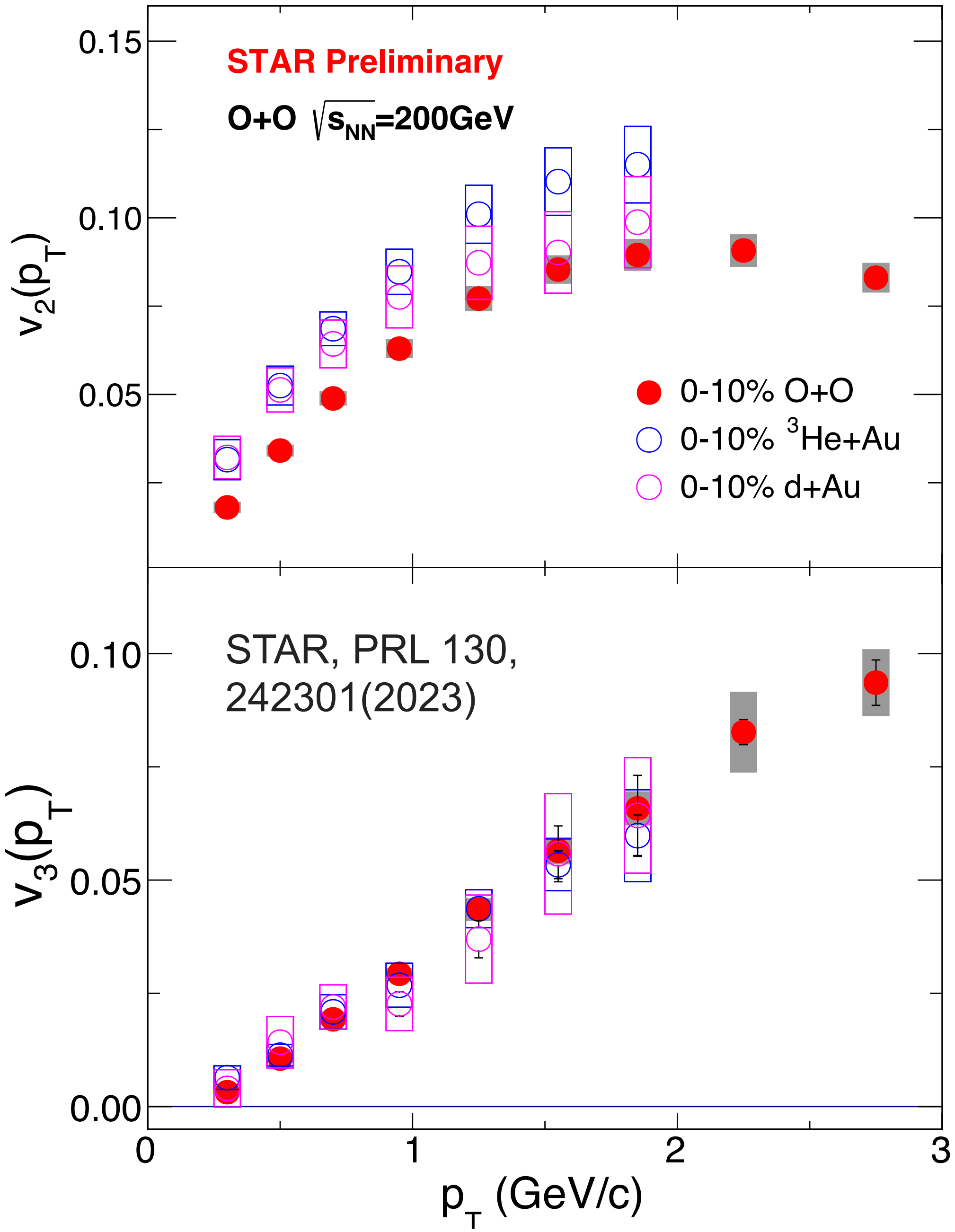
- Non-flow subtraction will always decrease v_2 and increase v_3
- Non-flow subtracted v_2 and v_3 show minimal method dependence

v_2 with different $\Delta\eta$ cut



After nonflow subtraction, v_n are independent of the $|\Delta\eta|$ selection

Compare to asymmetric collisions



Model	point-like quark $\varepsilon_2^c\{2\}(\varepsilon_3^c\{2\})$	fluctuated gluon field $\varepsilon_2^d\{2\}(\varepsilon_3^d\{2\})$
0-10% ^{3}He+Au	0.61(0.47)	0.53(0.38)
0-10% d+Au	0.71(0.45)	0.53(0.36)
0-10% $^{16}O+^{16}O(NLEFT)$	0.44(0.43)	

Quark Glauber: PRC **94**, 024914(2016)
Gluon field: PRC **94**, 024919(2016)

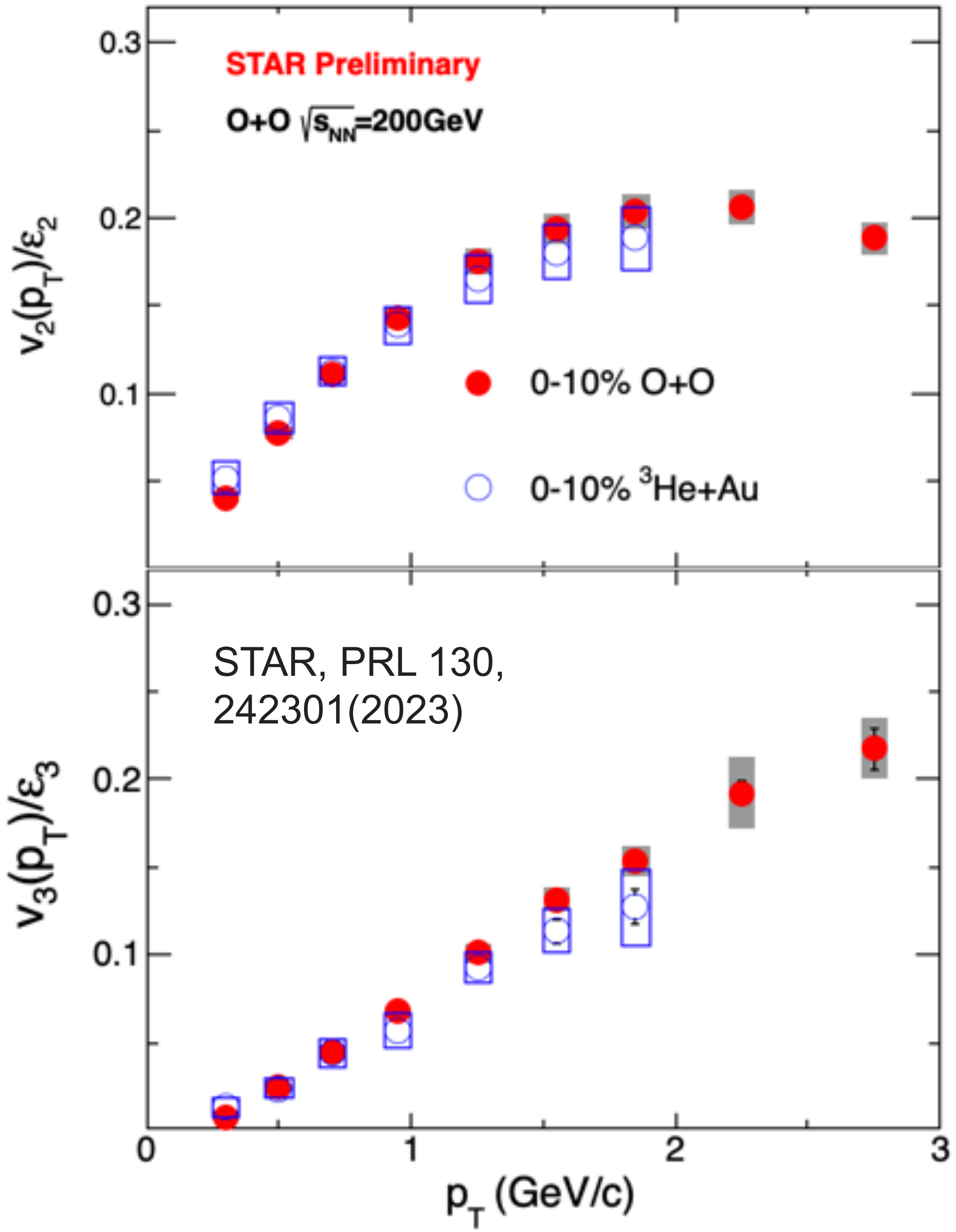
v_2(O+O) < v_2(d+Au) ≈ v_2(^{3}He+Au)
v_3(O+O) ≈ v_3(d+Au) ≈ v_3(^{3}He+Au)

Sub-nucleon fluctuations:

point–like quark
ε_2(O+O) < ε_2(^{3}He+Au) < ε_2(d+Au)
ε_3(O+O) ≈ ε_3(d+Au) ≈ ε_3(^{3}He+Au)

Gluon fluctuation around quark
ε_n(d+Au) ≈ ε_n(^{3}He+Au); n=2,3
It is consistent as v_2(d+Au) ≈ v_2(^{3}He+Au)

Compare to asymmetric collisions



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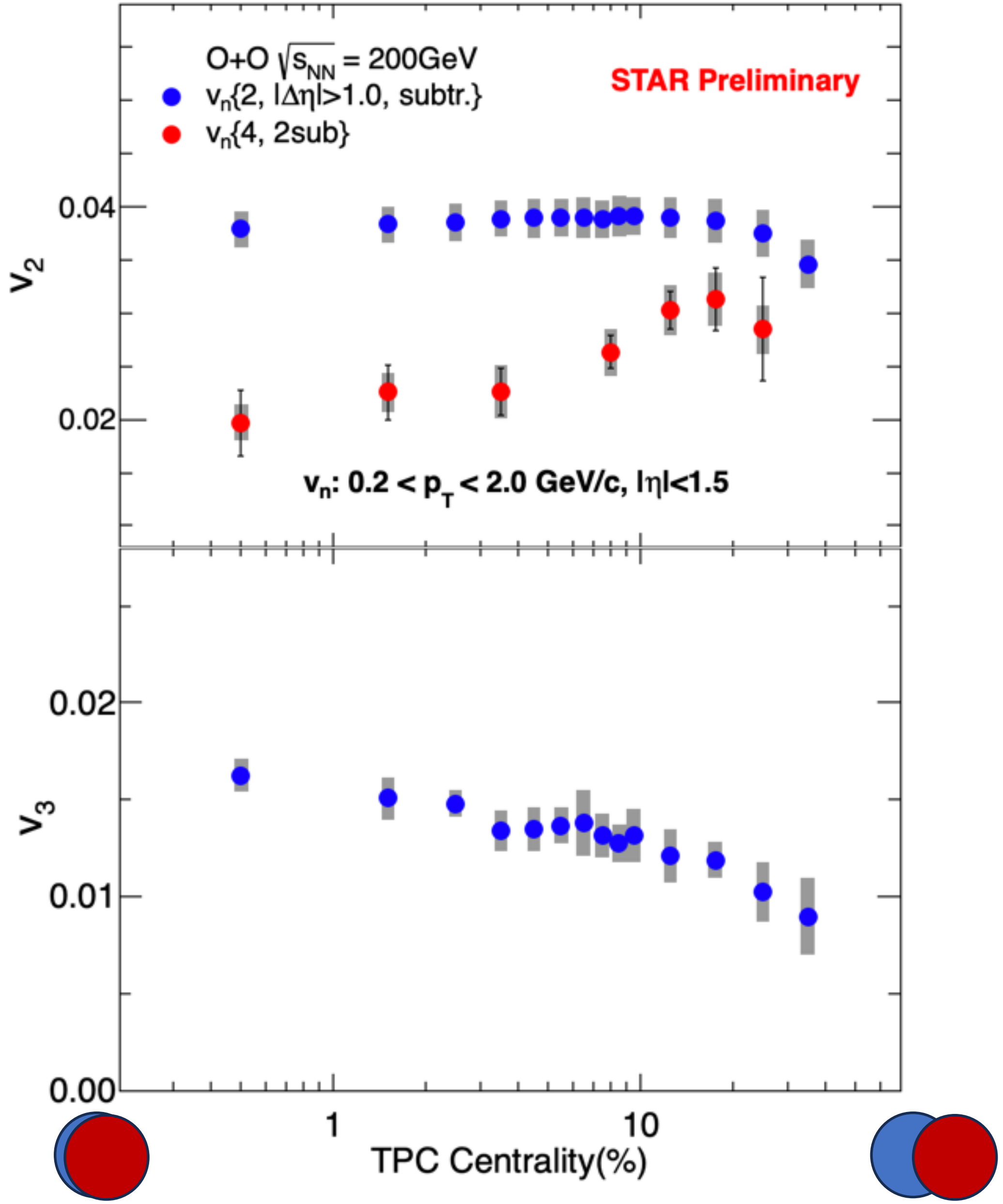
Quark Glauber:
PRC **94**, 024914(2016)
Gluon field:
PRC **94**, 024919(2016)

$v_n/\boldsymbol{\varepsilon}_n$(O+O) ≈ $v_n/\boldsymbol{\varepsilon}_n$(^{3}He+Au) for quark-Glauber

Consistent with expectation of sub-nucleon fluctuation

Four-particle cumulant in O+O



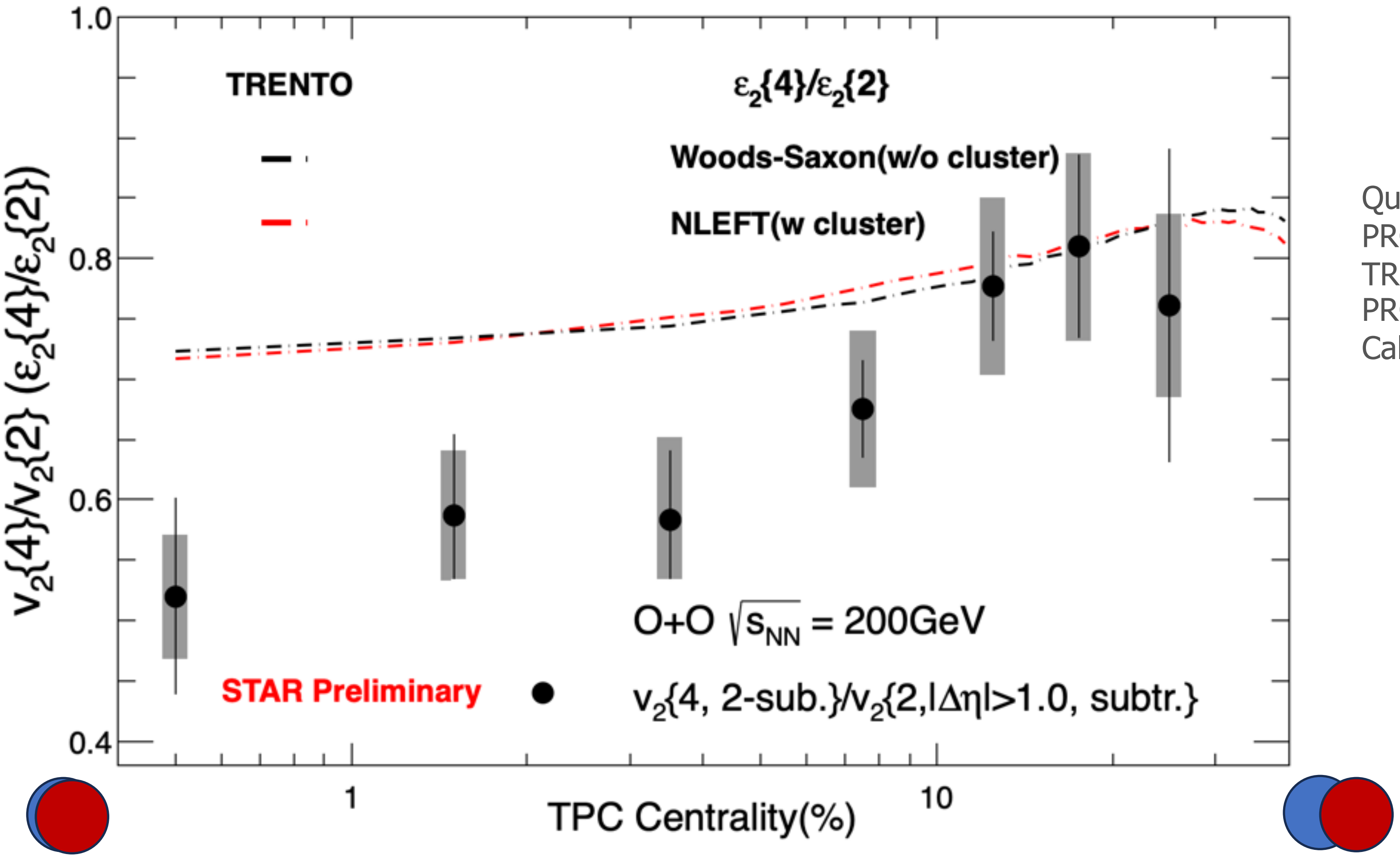
In central collisions:

The $v_2\{2\}$ is nearly flat

The $v_3\{2\}$ increases slightly

However, $v_2\{4\}$ clearly decreases

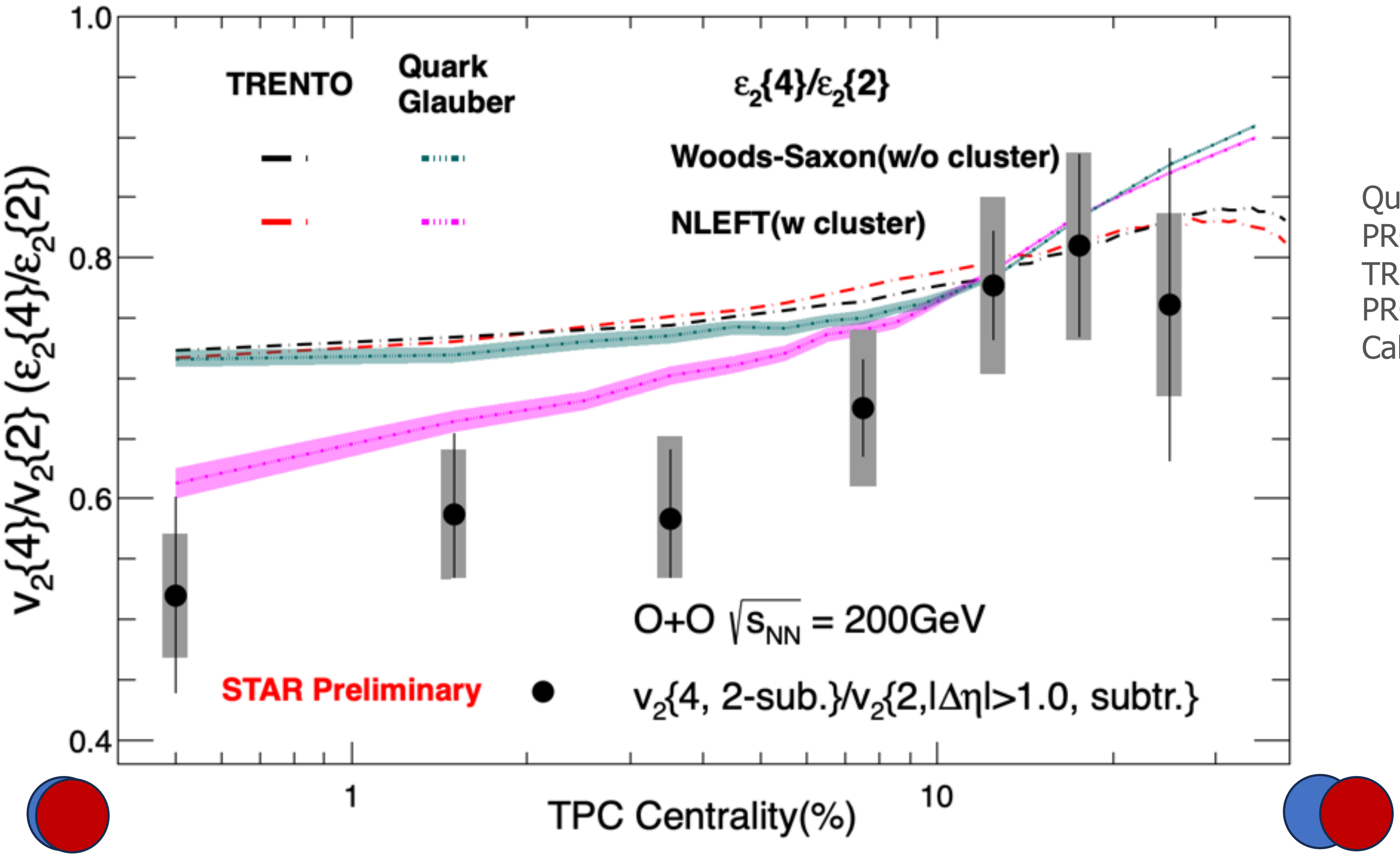
$v_2\{4\}/v_2\{2\}$: Flow fluctuation in central O+O



Quark Glauber:
PRC **94**, 024914 (2016)
TRENTO:
PRC.92.011901(2015)
Calculated by Giuliano

- $\boldsymbol{\varepsilon}_2\{4\}/\boldsymbol{\varepsilon}_2\{2\}$ from TRENTO with NLEFT or Woods-Saxon are similar.
- Larger than $v_2\{4\}/v_2\{2\}$.

$v_2\{4\}/v_2\{2\}$: Flow fluctuation in central O+O



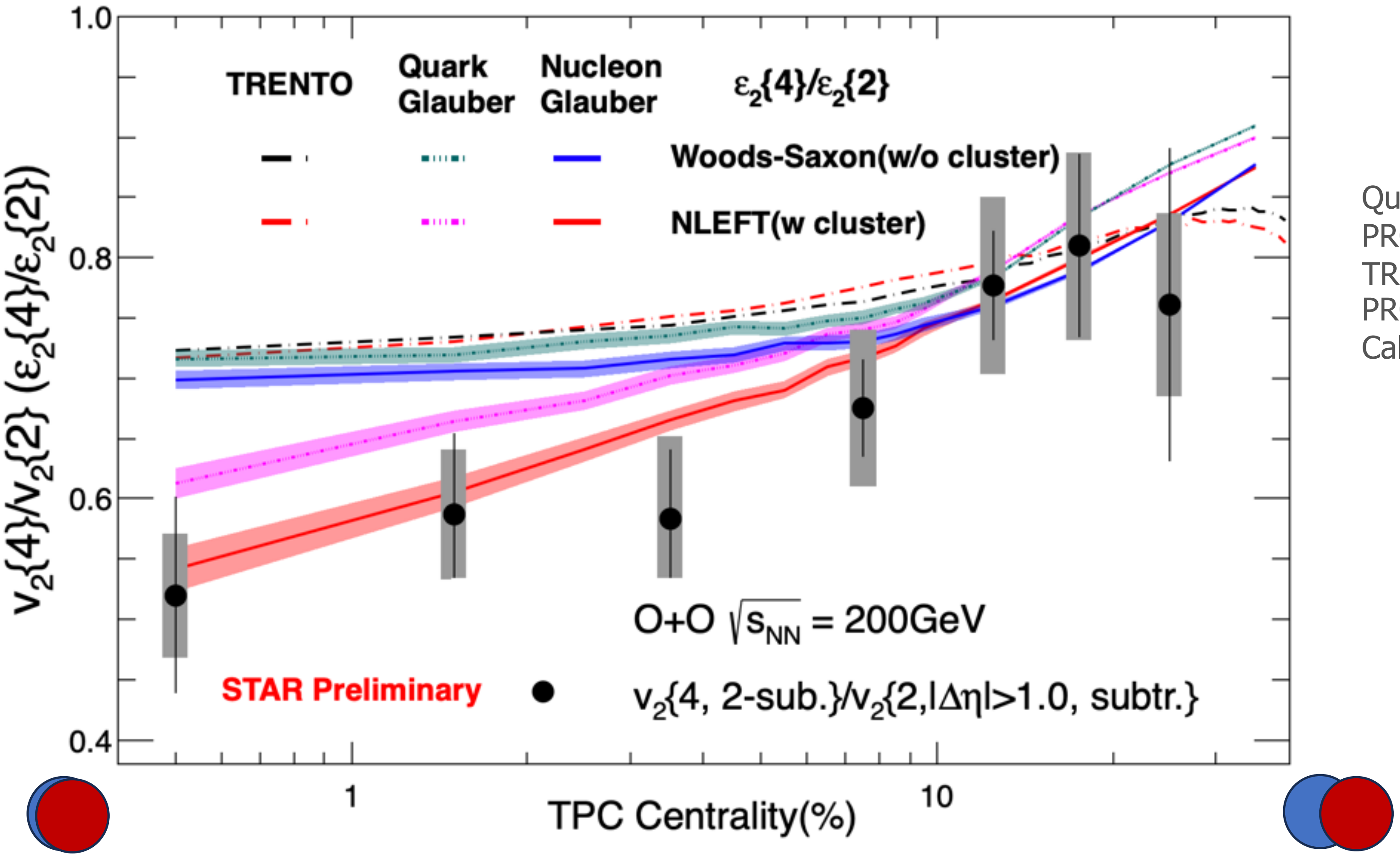
Quark Glauber:
PRC **94**, 024914 (2016)
TRENTO:
PRC.92.011901(2015)
Calculated by Giuliano

$\boldsymbol{\varepsilon}_2\{4\}/\boldsymbol{\varepsilon}_2\{2\}$ from quark Glauber with Woods-Saxon is similar as TRENTO and larger than $v_2\{4\}/v_2\{2\}$

$\boldsymbol{\varepsilon}_2\{4\}/\boldsymbol{\varepsilon}_2\{2\}$ from quark Glauber with NLEFT are much close to $v_2\{4\}/v_2\{2\}$

➔ many-nucleon correlation (e.g. α cluster) enhances the flow fluctuation?

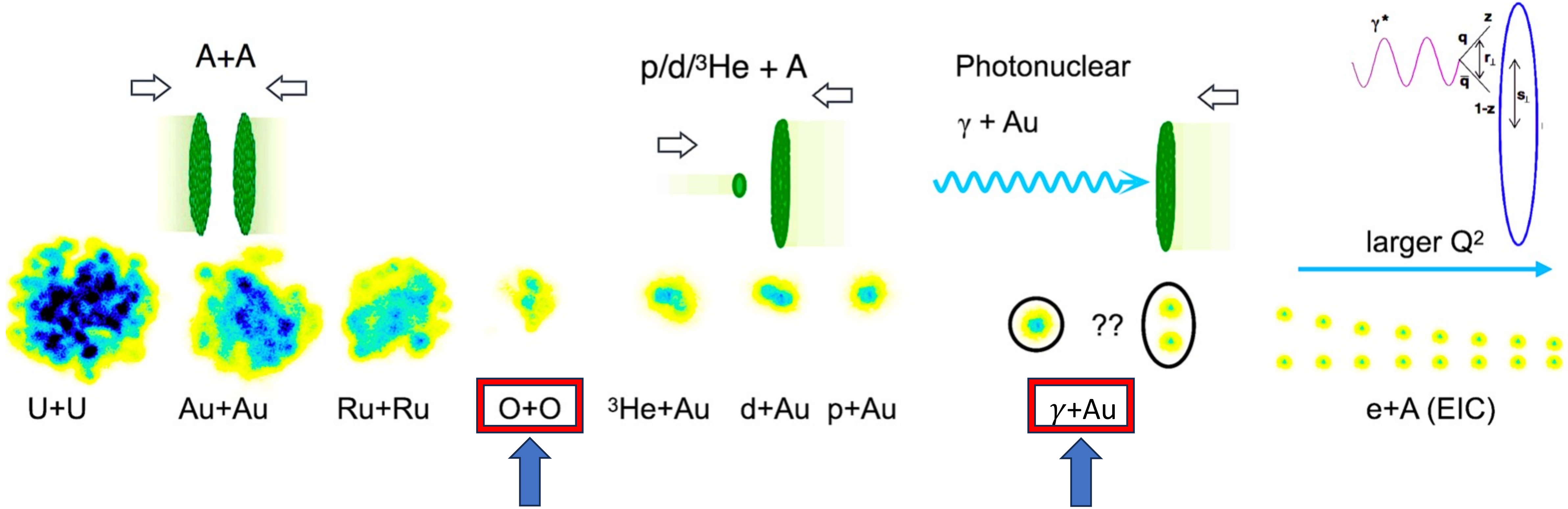
$v_2\{4\}/v_2\{2\}$: Flow fluctuation in central O+O



Quark Glauber:
PRC **94**, 024914 (2016)
TRENTO:
PRC.92.011901(2015)
Calculated by Giuliano

- ✓ Nucleon Glauber with NLEFT describes the $v_2\{4\}/v_2\{2\}$ better than quark Glauber
  Interplay between sub-nucleon fluctuation and many-nucleon correlation?
- ✓ Detailed hydro calculations can elucidate the role of $\boldsymbol{\alpha}$ cluster in light nuclei

Outlook: γ+Au@STAR



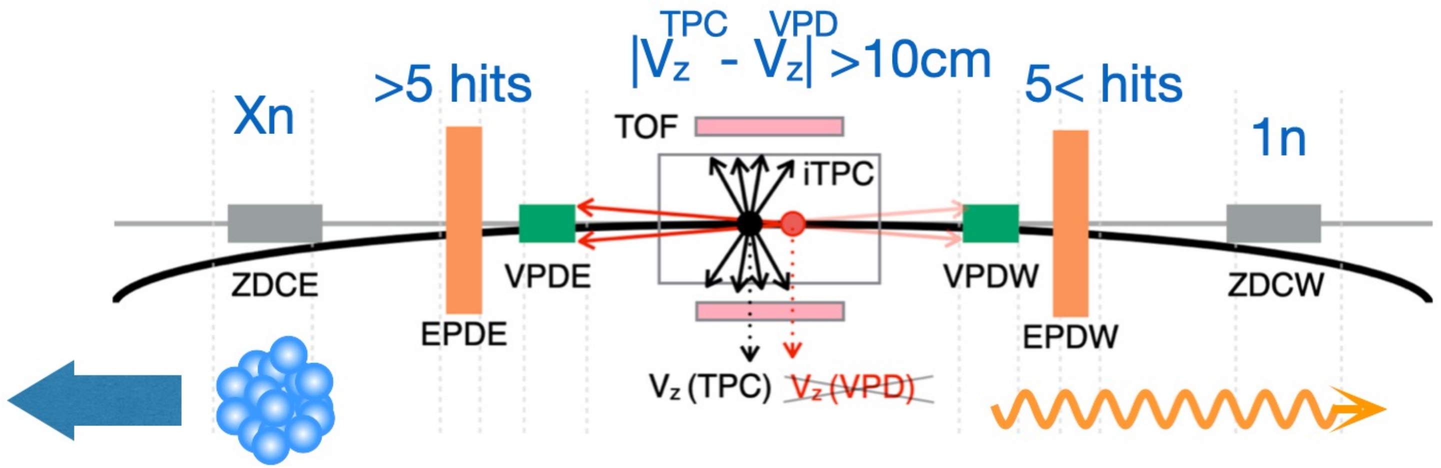
This talk

Symmetric small system (bridge large vs. small systems, α-clustering)

Most asymmetric systems (informative towards EIC science)

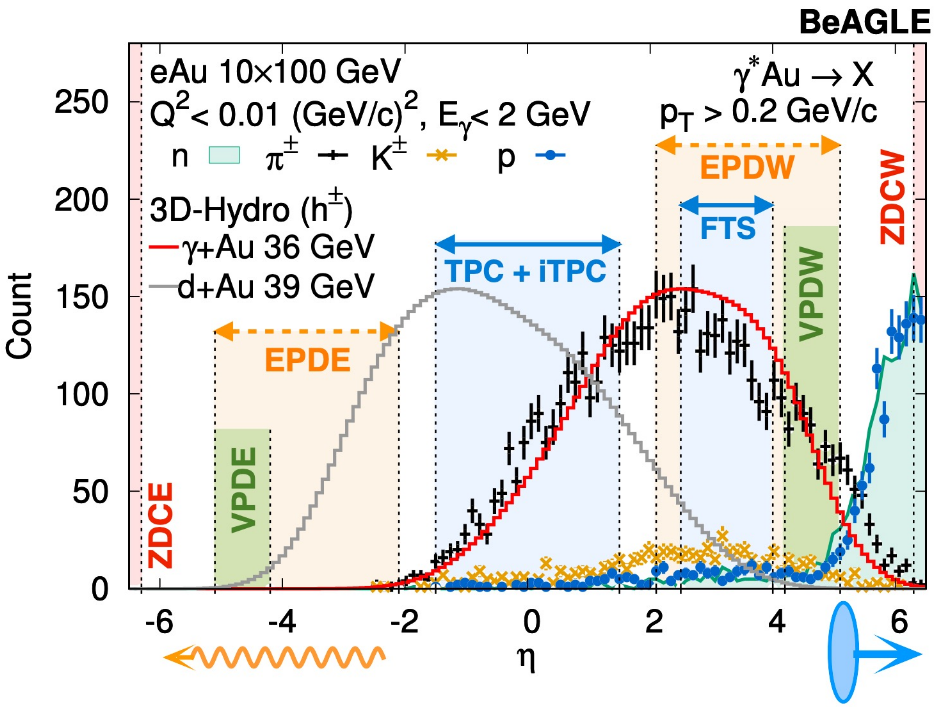
RHIC system scan: unique opportunity to investigate collectivity across various system sizes

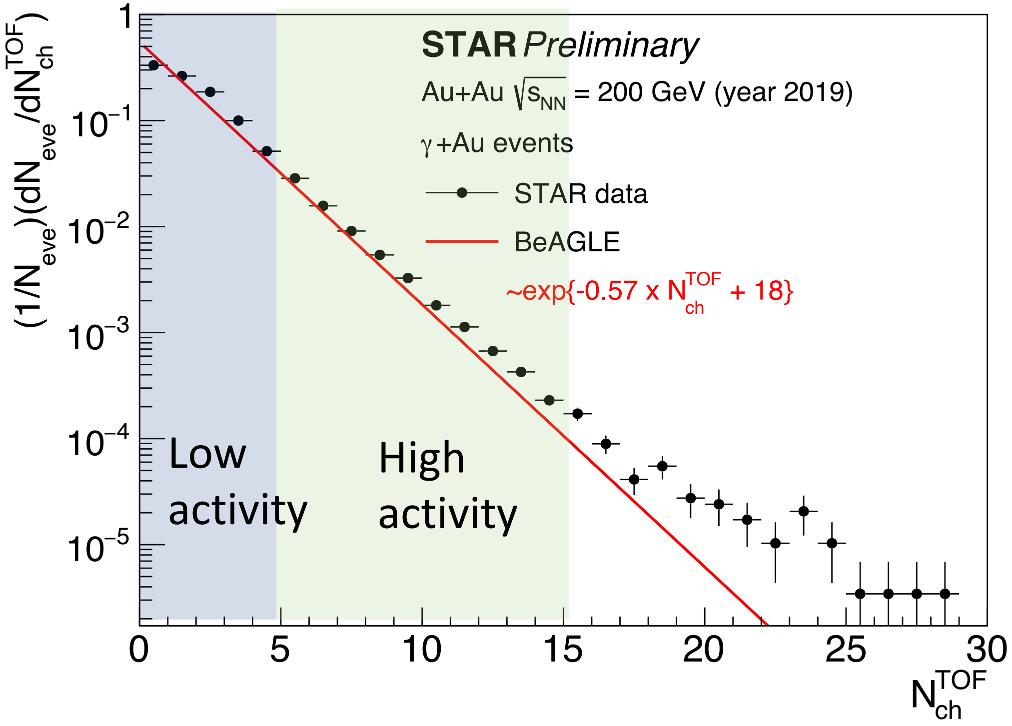
Inclusive photonuclear events at STAR



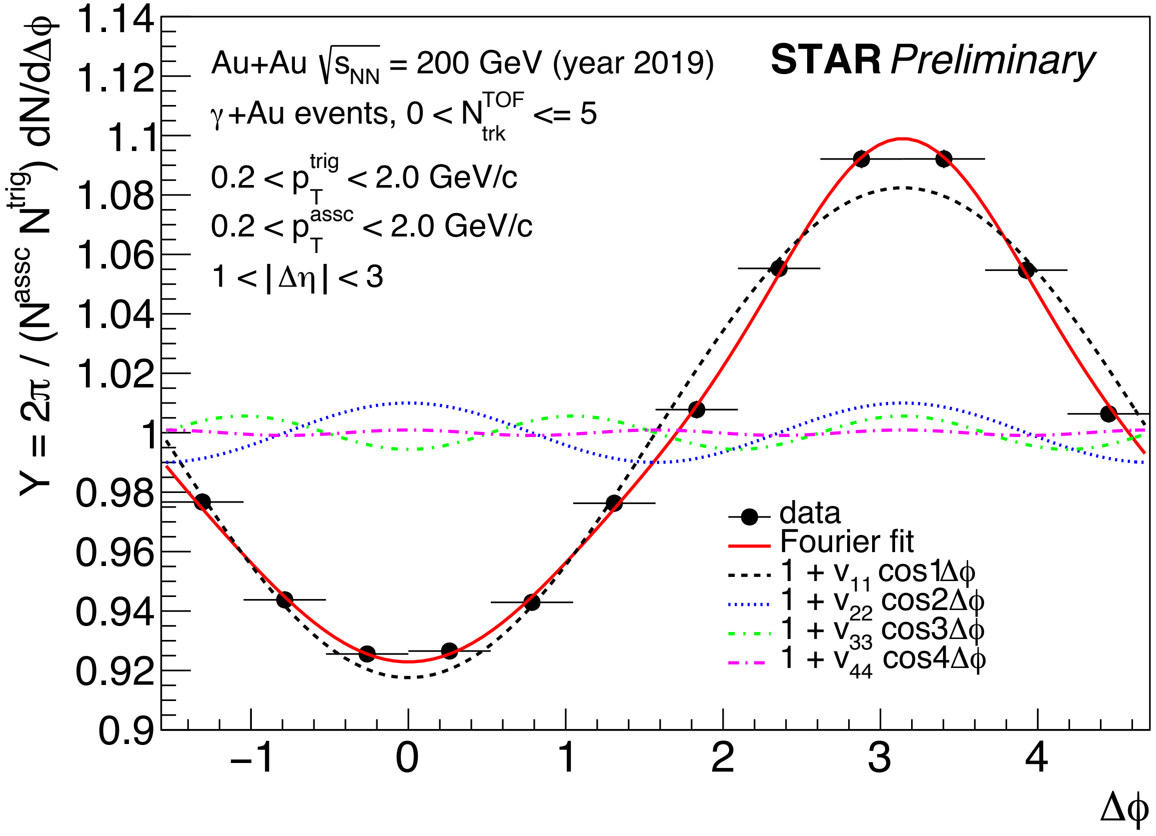
Event selection for γ+Au@STAR

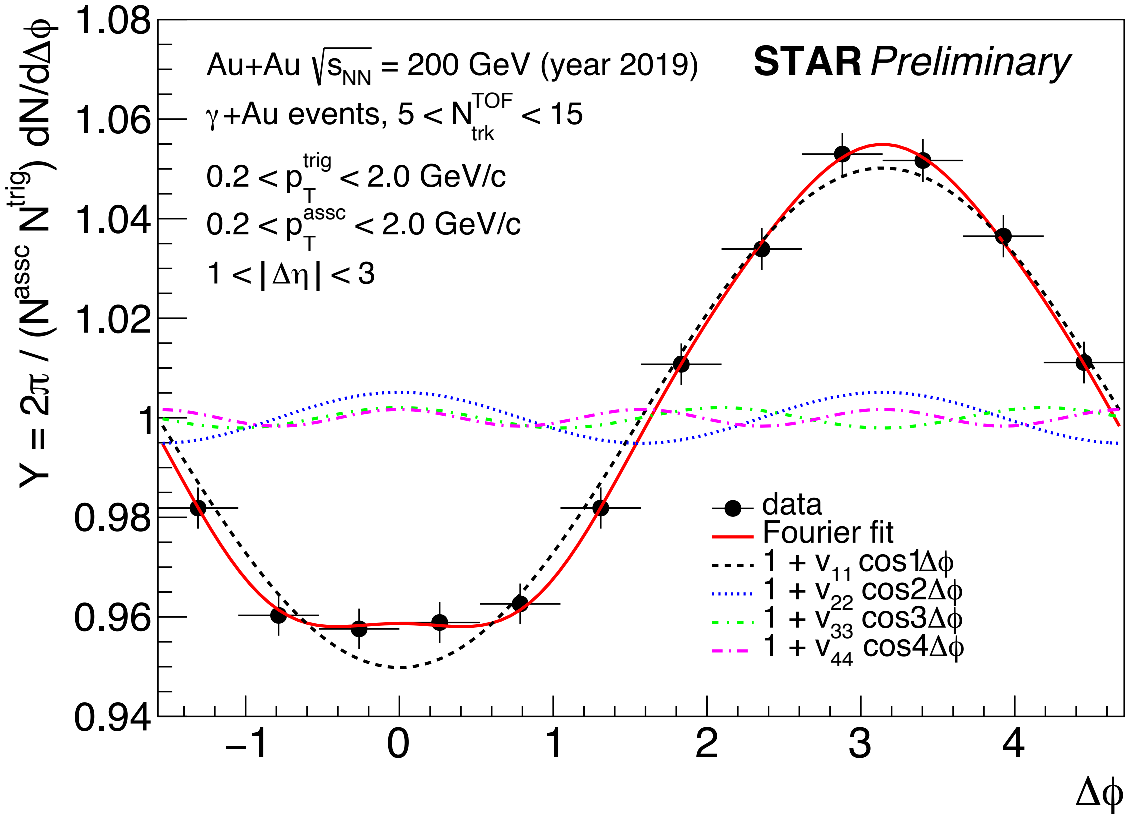
Asymmetic cuts on EPDs & ZDC (1nXn) on Au+Au 200 GeV collisions (year 2019) --> sample of γ+Au (E_{cm}~40 GeV) events





Exploratory study for γ+Au collisions





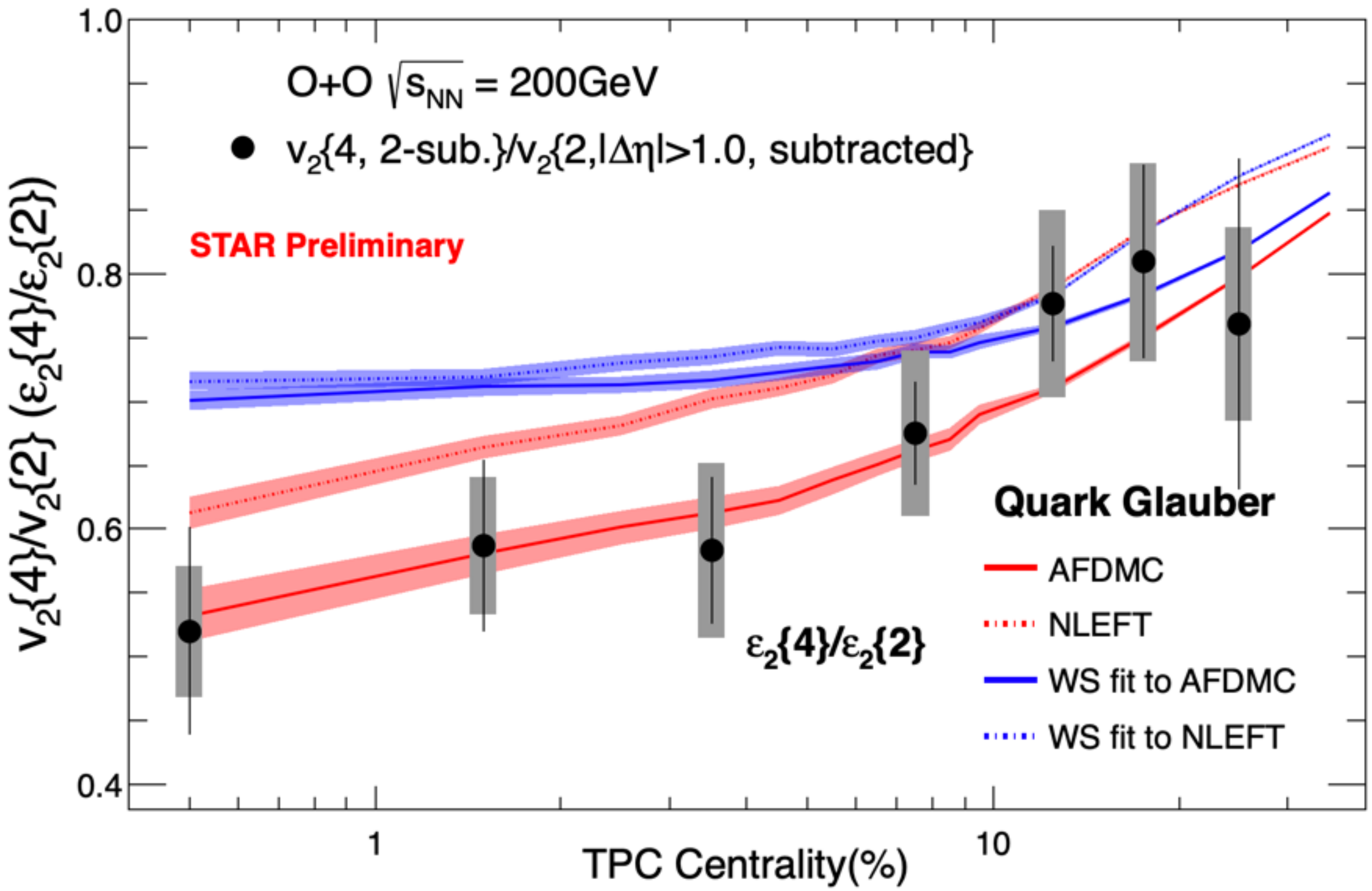
No sign of near side ridge but different near-side di-hadron correlations between low and high activity event class -- nonflow study is under investigation.

Opportunity with Run 2023 data: 6 M (1nXn) and 100 M (0nXn) γ+Au events collected

Summary

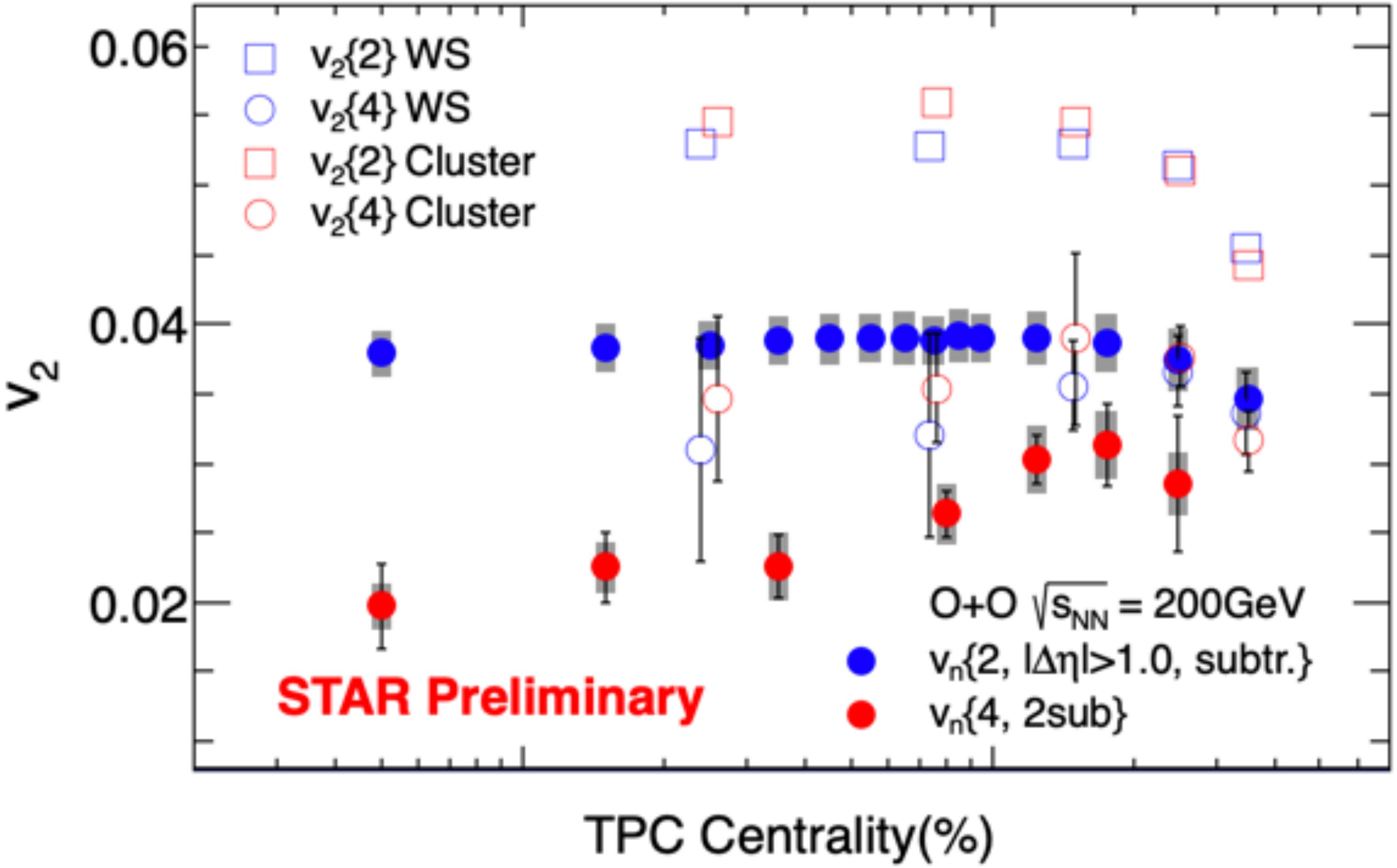
- We measured v_2 and v_3 in O+O collisions via di-hadron correlation and four types of nonflow subtraction methods
- v_n/ε_n are similar between O+O and ^{3}He+Au, within a quark Glauber model
- $v_2\{4\}/v_2\{2\}$ show clear decrease in ultra-central collisions, consistent with $\varepsilon_2\{4\}/\varepsilon_2\{2\}$, indicating enhanced fluctuations due to possible many-nucleon correlations.
- In future, new γ+Au@2023 and d+Au@2021 will provide more information for anisotropy in small system

$v_2\{4\}/v_2\{2\}$



From quark Glauber, the $\boldsymbol{\varepsilon}_2\{4\}/\boldsymbol{\varepsilon}_2\{2\}$ ratio from AFDMC or NLEFT model with many-nucleon correlations can describe the $v_2\{4\}/v_2\{2\}$

Comparing with Hydro



Hydro: TRENTO + iEBE-VISHNU

Nicholas Summerfield et al. PRC **104**, L041901 (2021)