Signatures of collectivity in small systems observed by PHENIX

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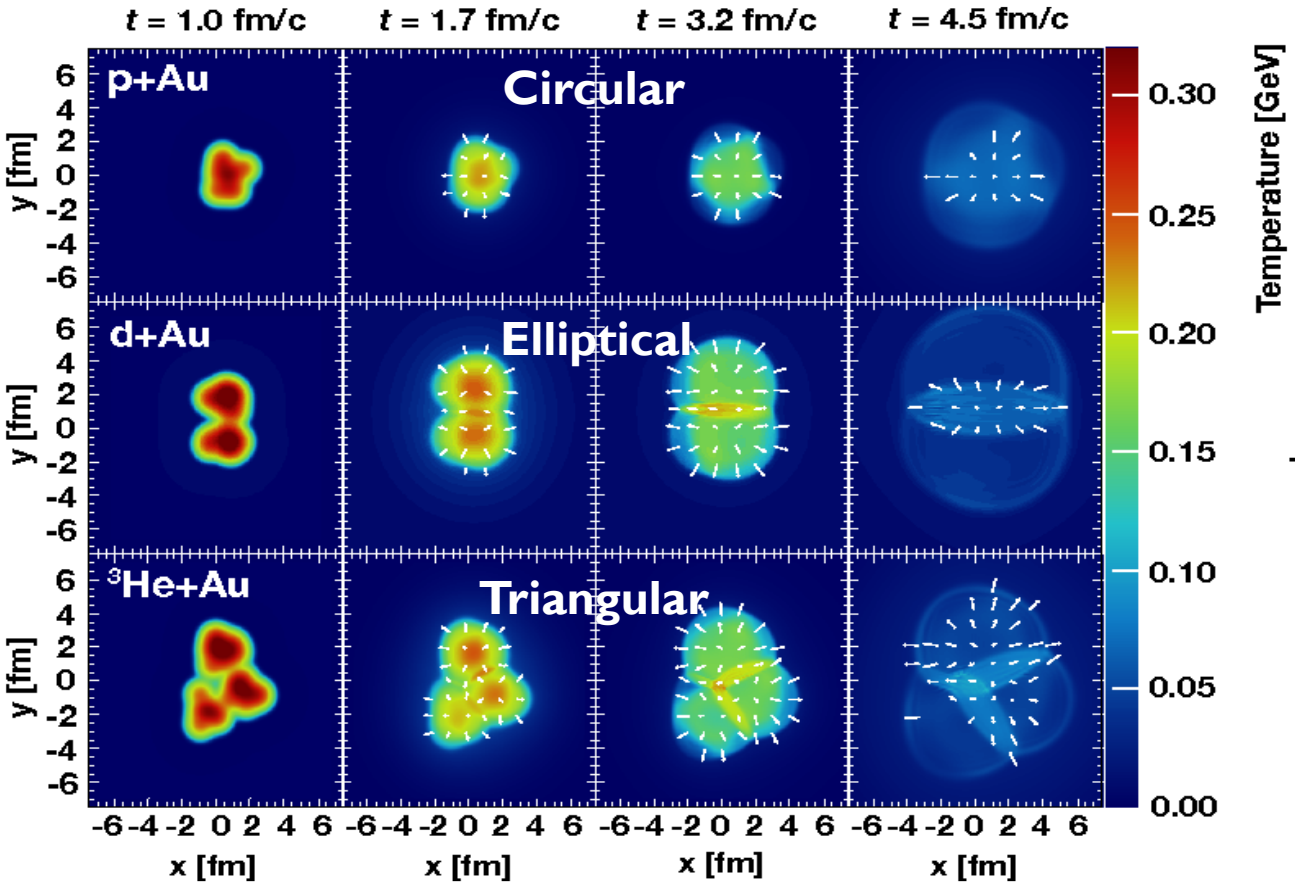
for the PHENIX collaboration

Center for Extreme Nuclear Matters

Nature Phys. **15**, 214 (2019)

Hydrodynamic evolution



Hydrodynamical model calculation of the small collision systems shows collective behavior.

The initial geometry effect propagates to the final stage.

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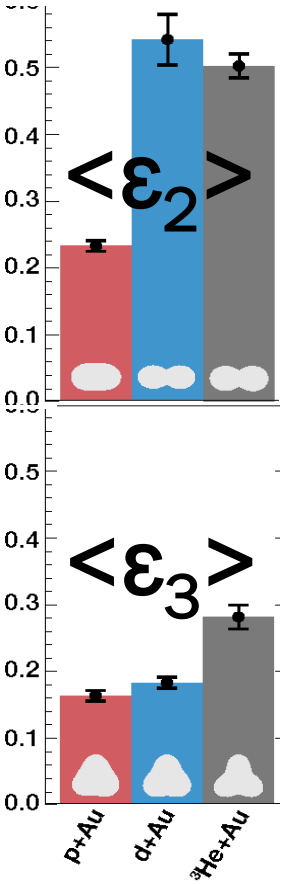
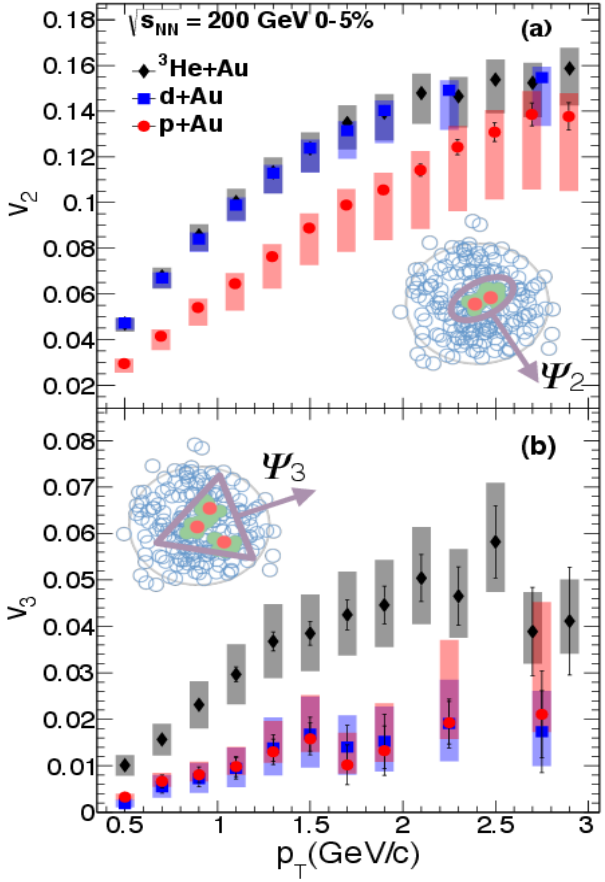
Initial geometry and the v_n





v_2[p+Au] < v_2[d+Au] ≈ v_2[^{3}He+Au]

ε_2[p+Au] < ε_2[d+Au] ≈ ε_2[^{3}He+Au]

v_3[p+Au] ≈ v_3[d+Au] < v_3[^{3}He+Au]

ε_3[p+Au] ≈ ε_3[d+Au] < ε_3[^{3}He+Au]

Initial geometry dependence of v_2 is studied using different collision systems.

The hierarchy of v_2 and v_3 consistent with that of ε_n.

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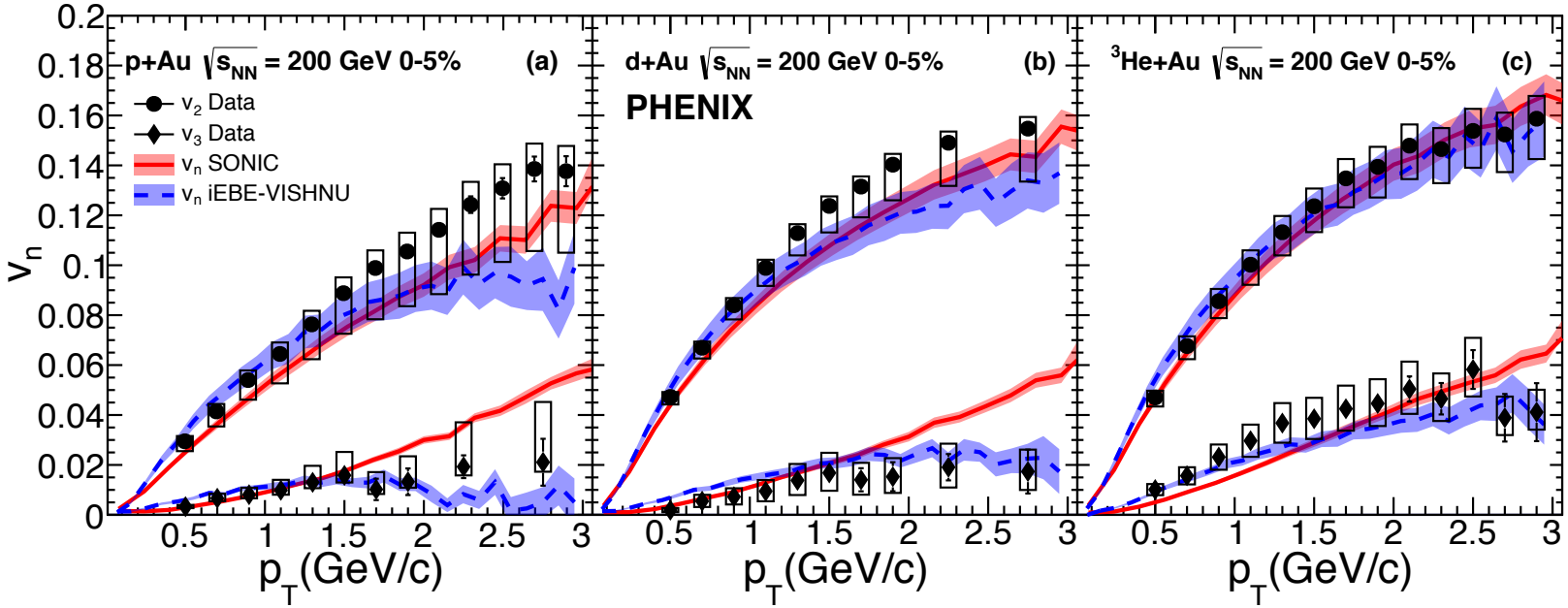
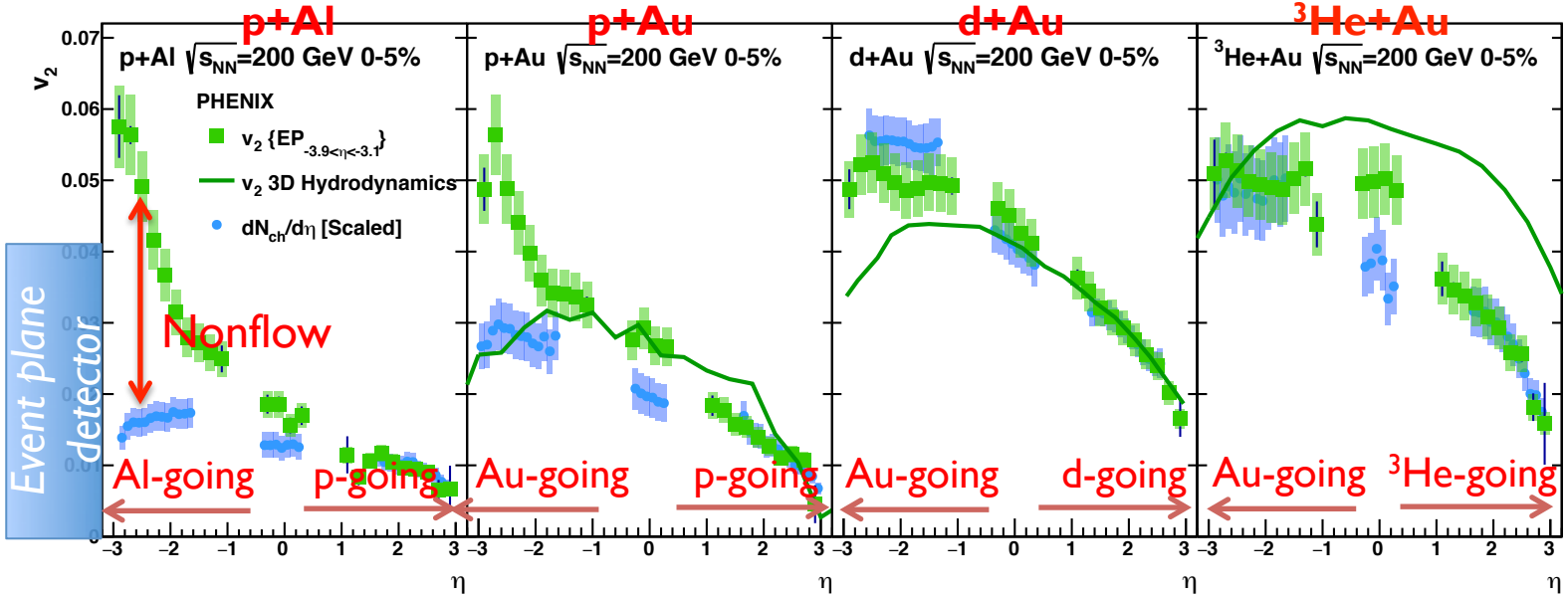
v_n with the theory models



- Hydrodynamic model calculations are showing the best agreement with the v_n measurements in 3 collision systems (p/d/^{3}He+Au)

PRL **121**, 222301 (2018)

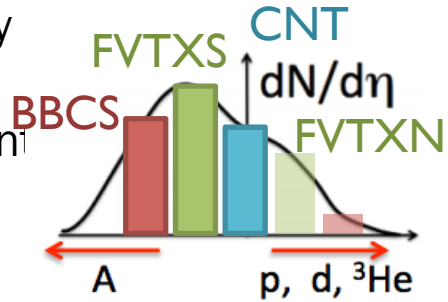
v_2 and the $dN_{ch}/d\eta$ scaling



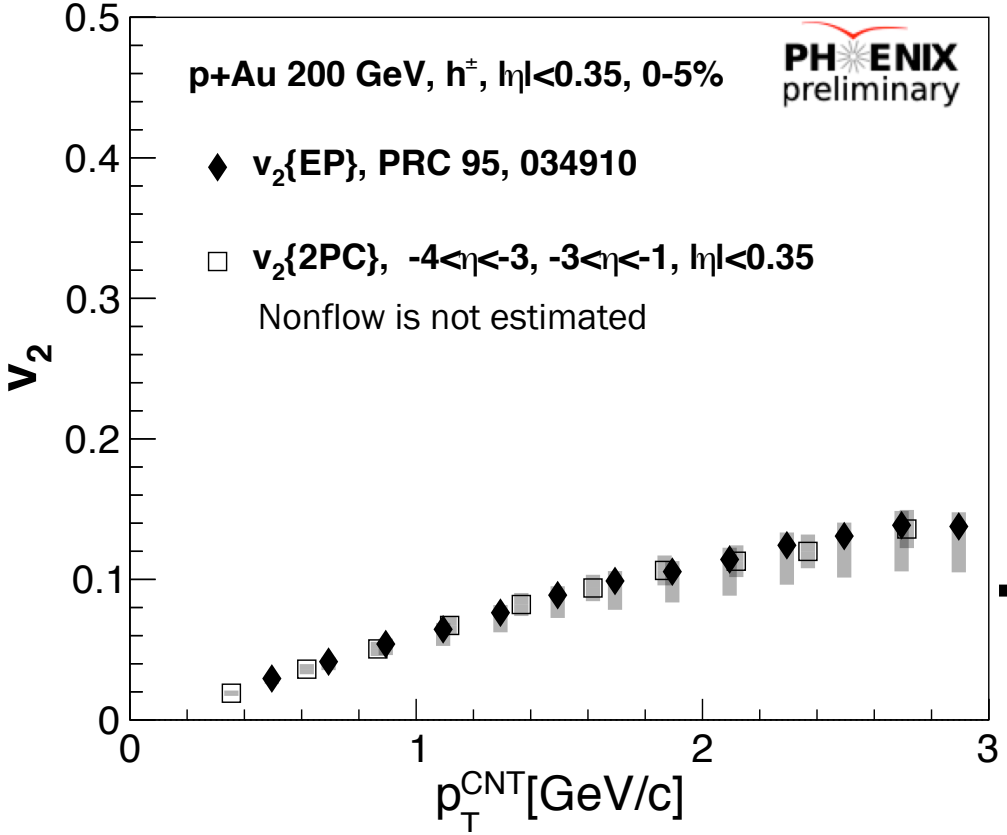
In larger systems (d+Au and ^{3}He+Au) the $dN_{ch}/d\eta$ and v_2 rapidity dependence have the same shape.

In smaller systems (p+Au) deviations are observed near the event plane detector.

Is there some non-flow or other effect?



Method comparison



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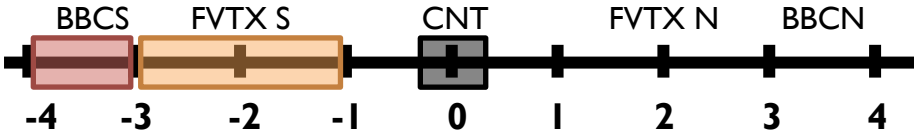
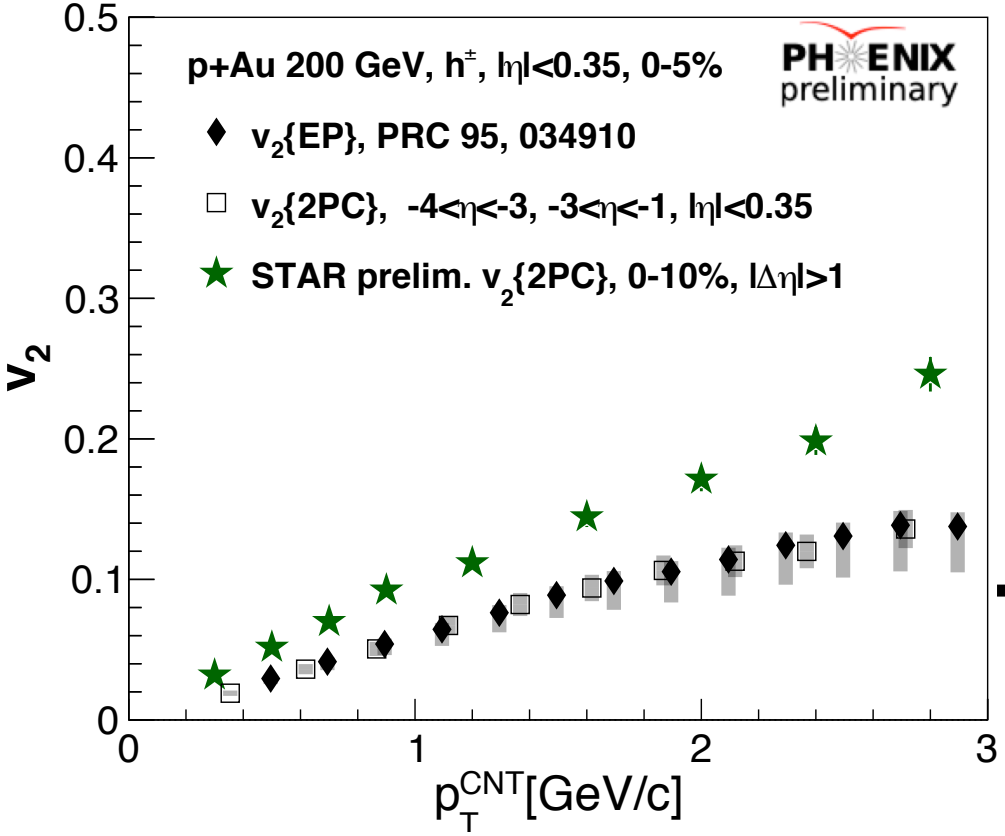
2. two-particle correlation reconstructs the same results (no nonflow estimation in the systematic uncertainties)



PHENIX PRC : BBCS-FVTXS-CNT

Method comparison



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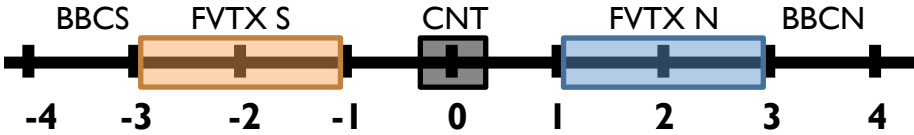
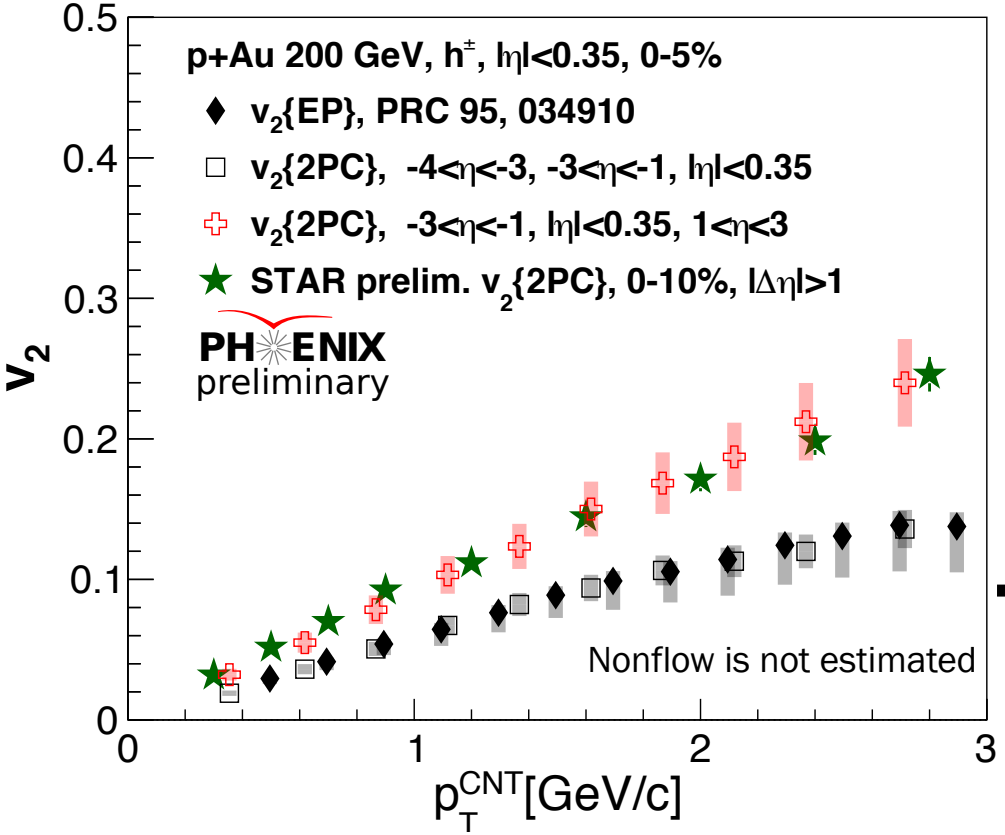
3. STAR two-particle result shows systematically larger v_2 (no nonflow estimation either)



PHENIX PRC : BBCS-FVTXS-CNT

STAR prelim. : $|\Delta\eta|>1$

Method comparison



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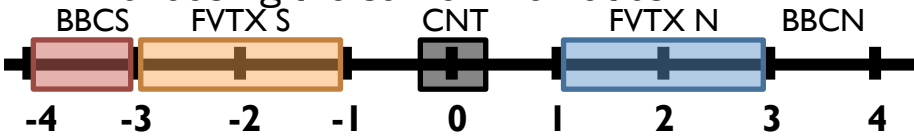


PHENIX PRC : BBCS-FVTXS-CNT

STAR prelim. : $|\Delta\eta|>1$

PRC **83**, 044913 (2011) Ante Bilandzic et al.

Multi-particle correlation

- two-, four-particle angular correlations
- Multi-particle correlation suppress the nonflow

$$v_2\{2\} = \left(v_2^2 + \sigma^2 + \delta^2\right)^{1/2}$$: fluctuation + nonflow effect

$$v_2\{4\} \approx v_2\{6\} \approx \left(v_2^2 - \sigma^2\right)^{1/2}$$: fluctuation

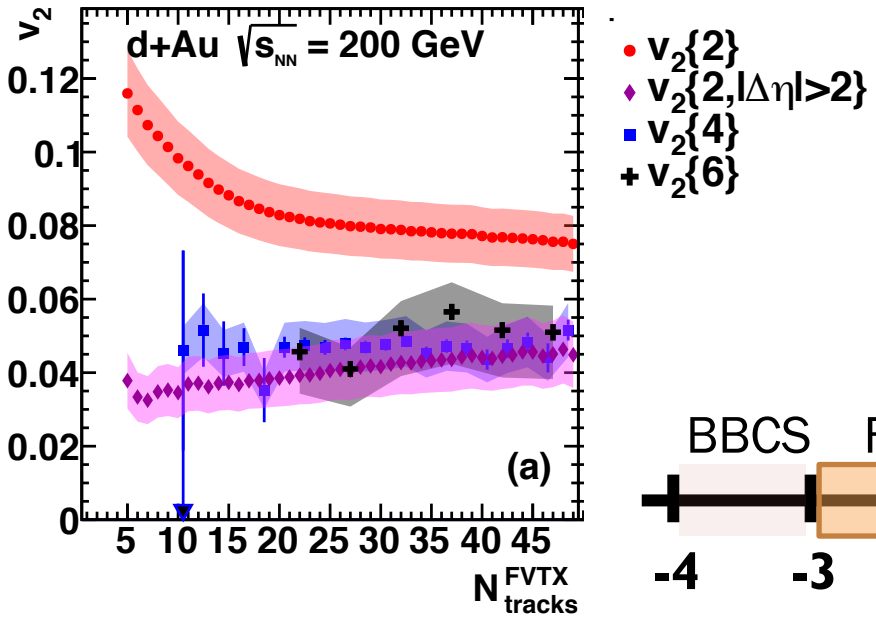
Multi-particle correlation provide information how the event-by-event flow fluctuating

$$v_2\{4\} = \left(-c_2\{4\}\right)^{-1/4}$$

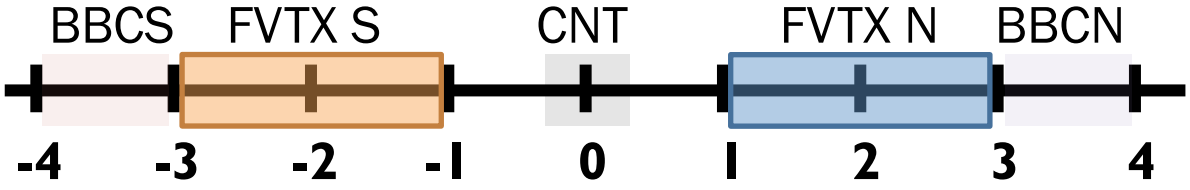
PRL **120**, 062302 (2018)

Correlations in d+Au

- two-, four-particle angular correlations

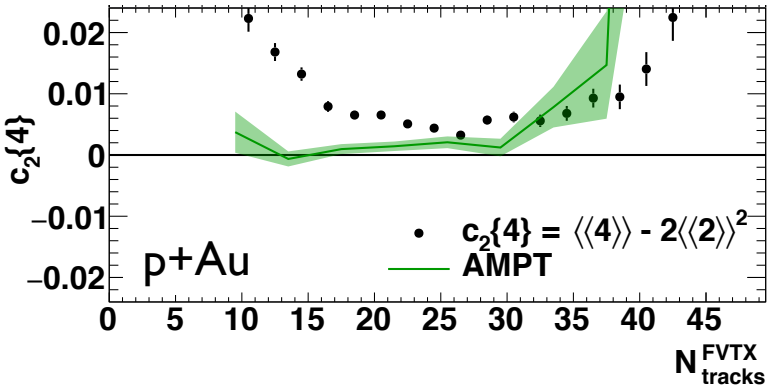


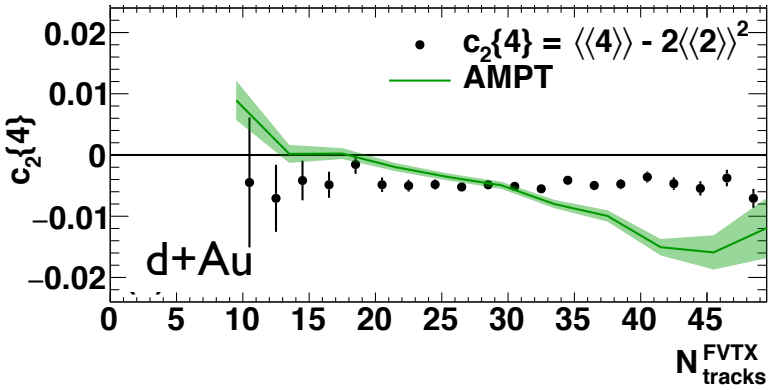
$v_2\{2, |\Delta\eta|>2\}$ and $v_2\{4\}$, $v_2\{6\}$ show the collective behavior in high-multiplicity events.



PRL **120**, 062302 (2018)

Correlations & fluctuations in p/d+Au



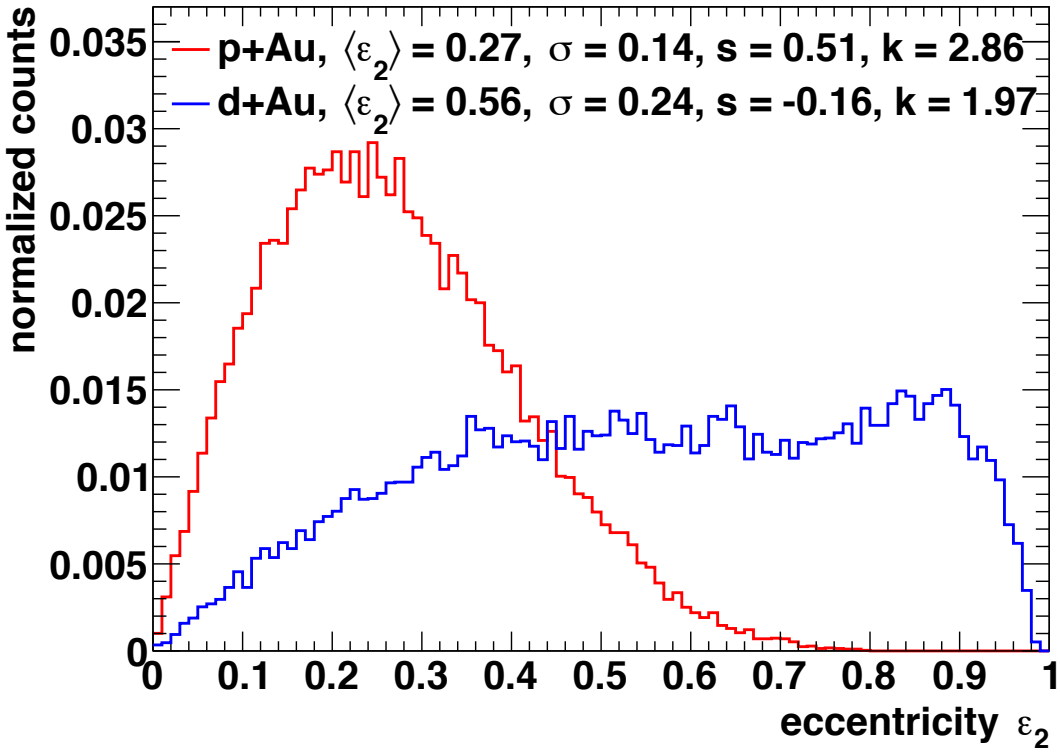


- $v_2\{4\}^2 \approx \langle v_2\rangle^2 - \sigma^2$

  $c_2\{4\}$ in p+Au is dominated by fluctuations
- AMPT (A Multi-phase transport model) describes the sign

PRL **120**, 062302 (2018)

Initial eccentricity distributions



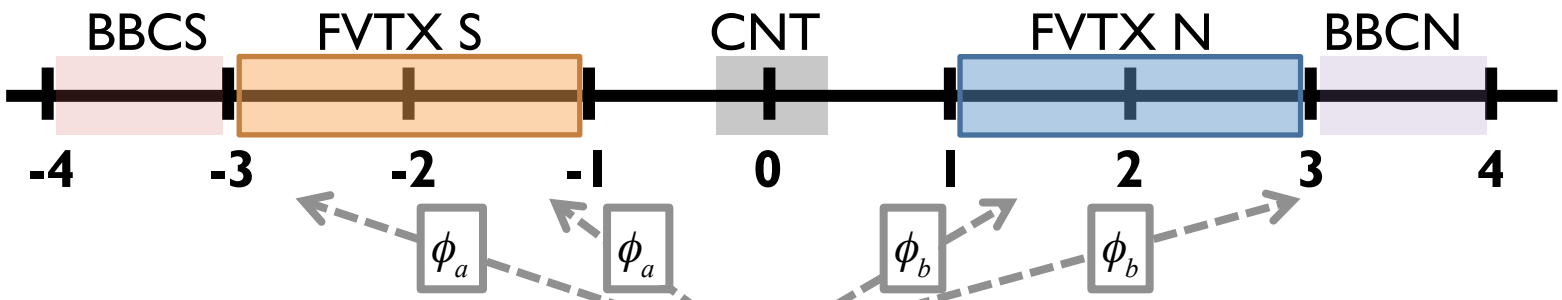
Monte-Carlo Glauber

Initial eccentricity distribution is highly non-Gaussian

Fluctuations are highly non-trivial in small systems.

Sub-event cumulant method

- To investigate further effect of
  - the suppressing the nonflow
  - the role of the fluctuations
- Expected nonflow contaminations: aa|bb < ab|ab < standard method



$$\langle\langle 4 \rangle\rangle = \langle\langle e^{in}(\phi_a + \boxed{\phi_a - \phi_b} - \phi_b) \rangle\rangle$$

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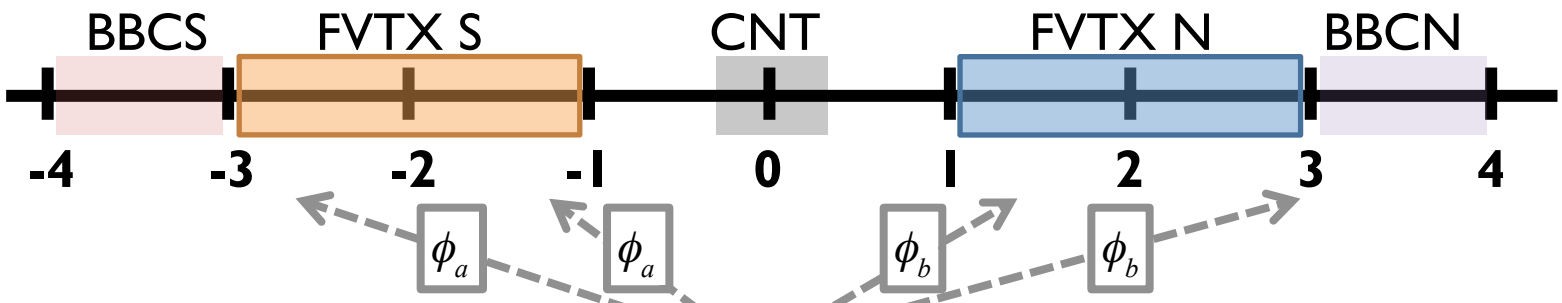
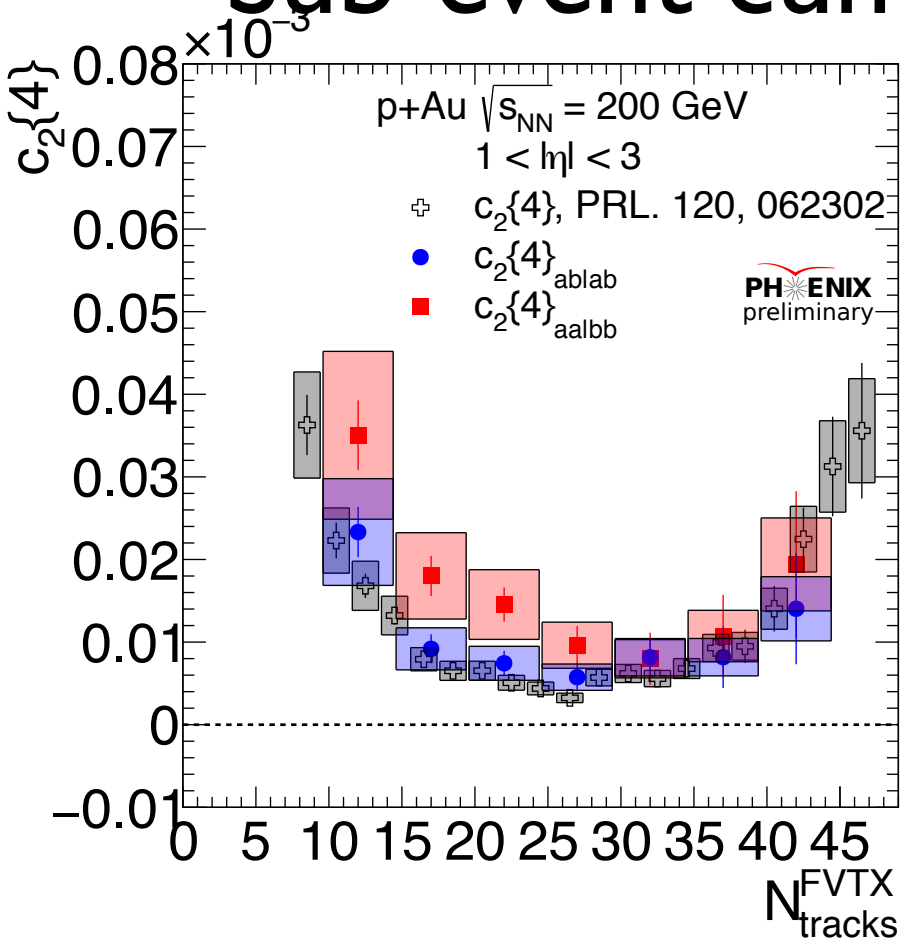


$$\langle\langle 4 \rangle\rangle = \left\langle\left\langle e^{in}(\phi_a + \boxed{\phi_b - \phi_a} - \phi_b)\right\rangle\right\rangle$$

Sub-event cumulant in p+Au



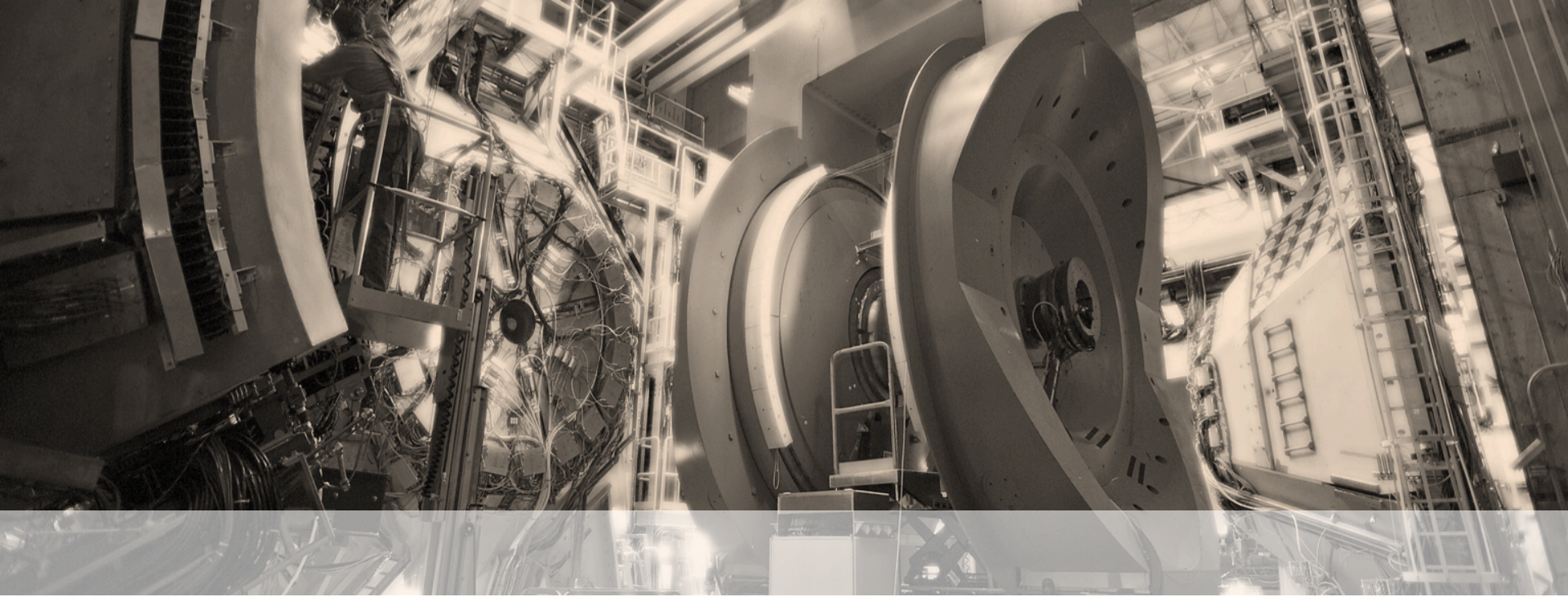
$c_2\{4\}$ remains positive in sub-event selections

The origin could be attributed to the fluctuations

- Poster by Qiao Xu

Summary

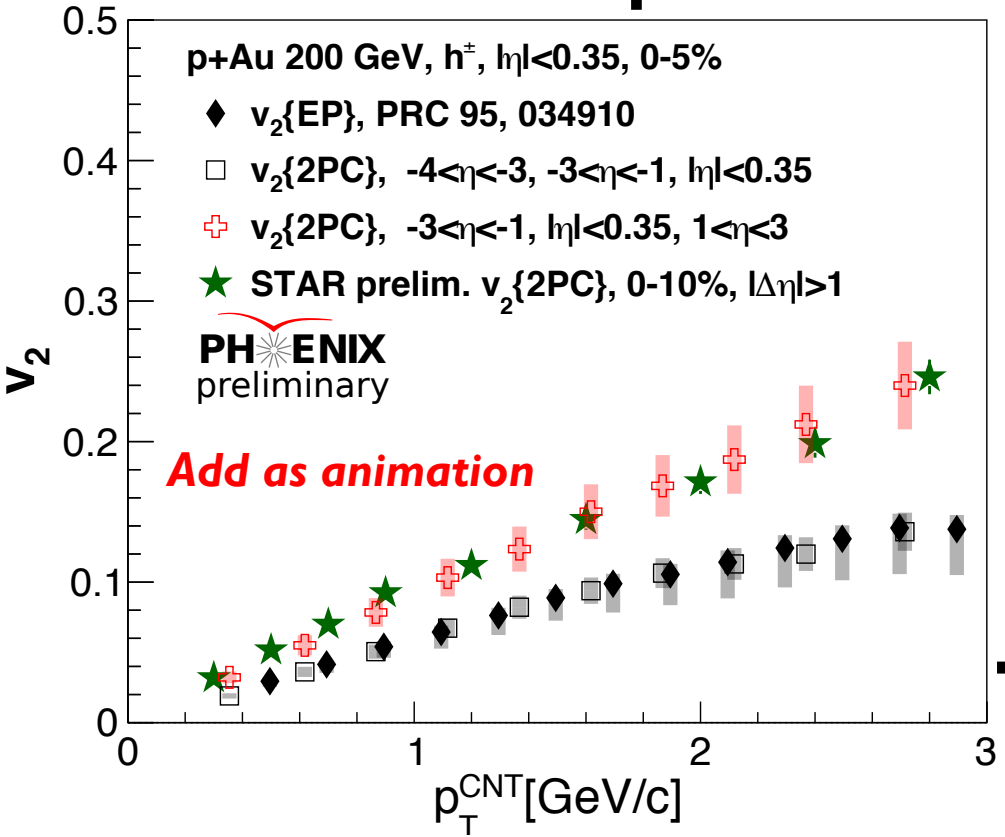
- Collective behavior was observed in small systems by the PHENIX experiment
  - Measured v_n are well described by viscous hydro model
  - Confirmed initial geometry effect in the medium formed in small systems (p/d/^{3}He + Au)
- Systematic studies of non-flow and fluctuation dependencies
  - The v_2{2PC} reconstructed in different kinematics
  - Small variance limit breaks in p+Au and in d+Au collisions
  - Flow fluctuations are significant in c_2{4} in p+Au collisions confirmed by sub-event cumulant analysis



THANK YOU

BACKUP

Comparison with STAR



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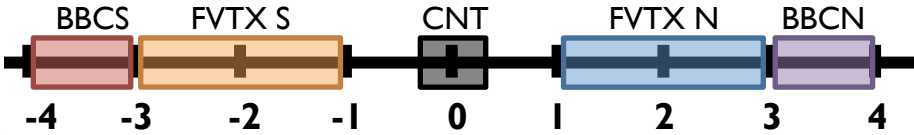
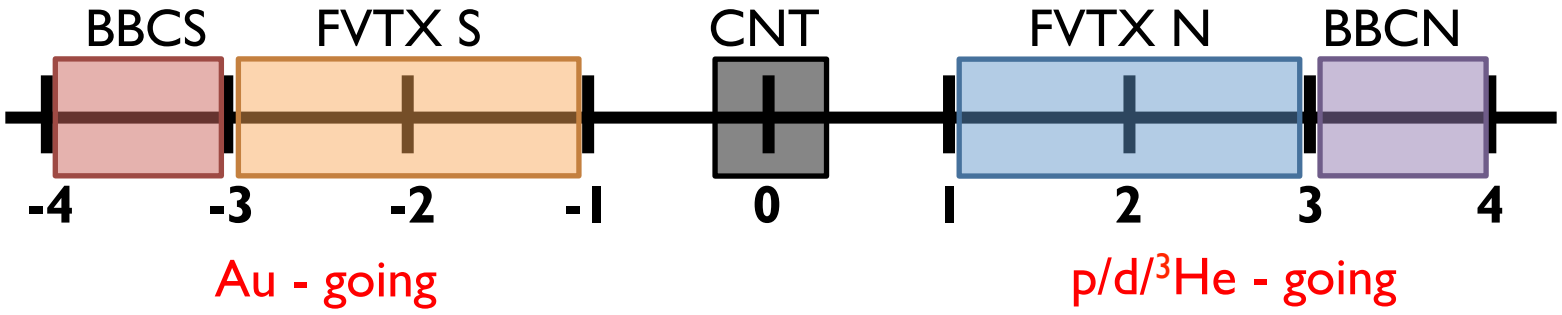


PHENIX : BBCS-FVTXS-CNT
STAR prelim. : FVTXS-CNT-FVTXN

Multi-particle correlation

- two-, four-particle angular correlations



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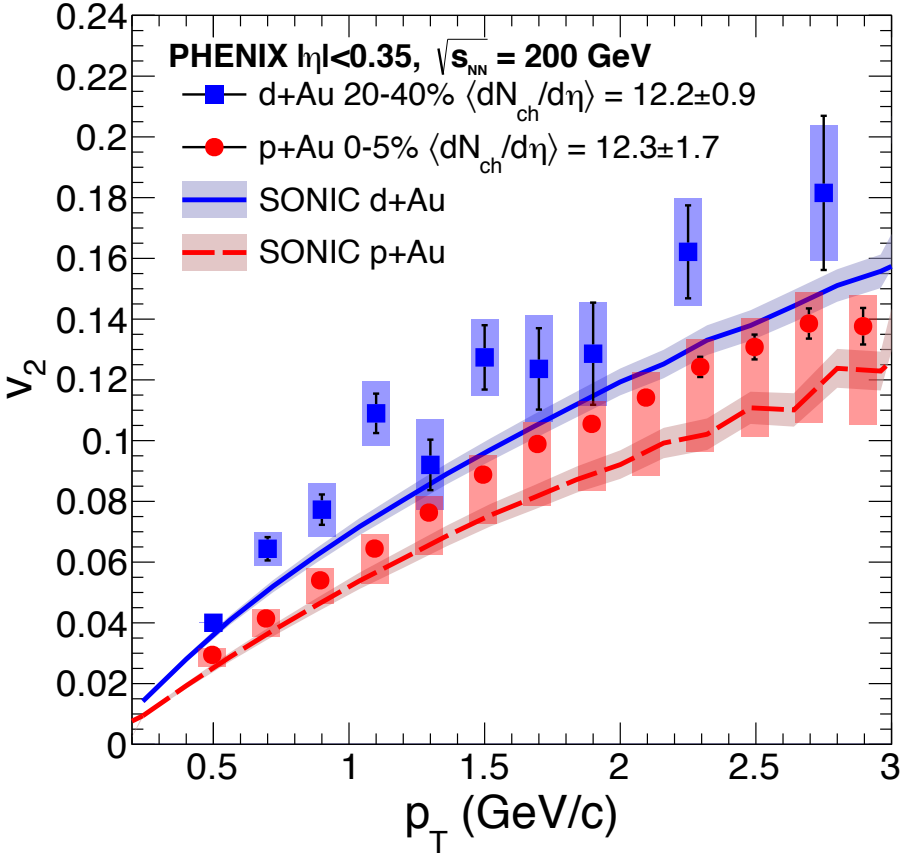
Initial geometry and multiplicity

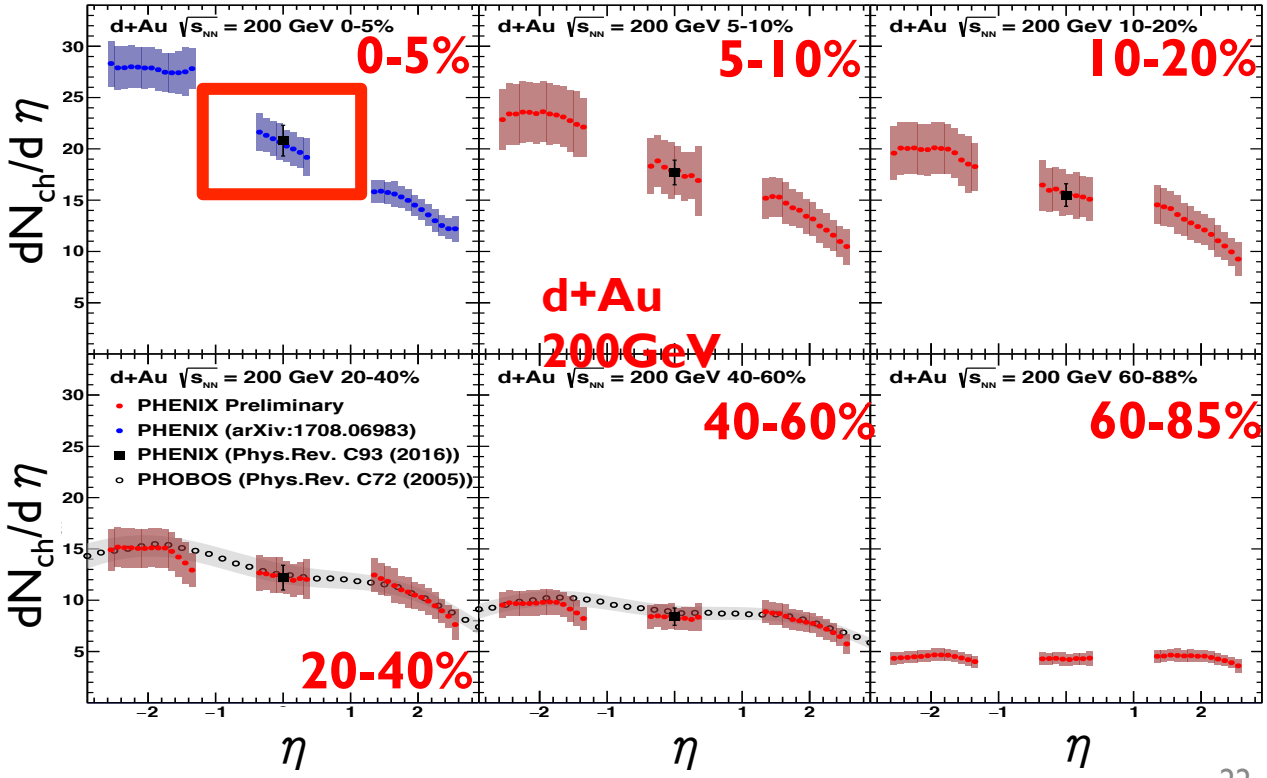


Comparison of dA and pA at same multiplicity

The dA shows larger v2, the initial eccentricity carries into the final result

Expanded pseudo-rapidity

The new PHENIX results are in **good agreement** with the previous PHENIX results (Run 8) at the mid-rapidity.



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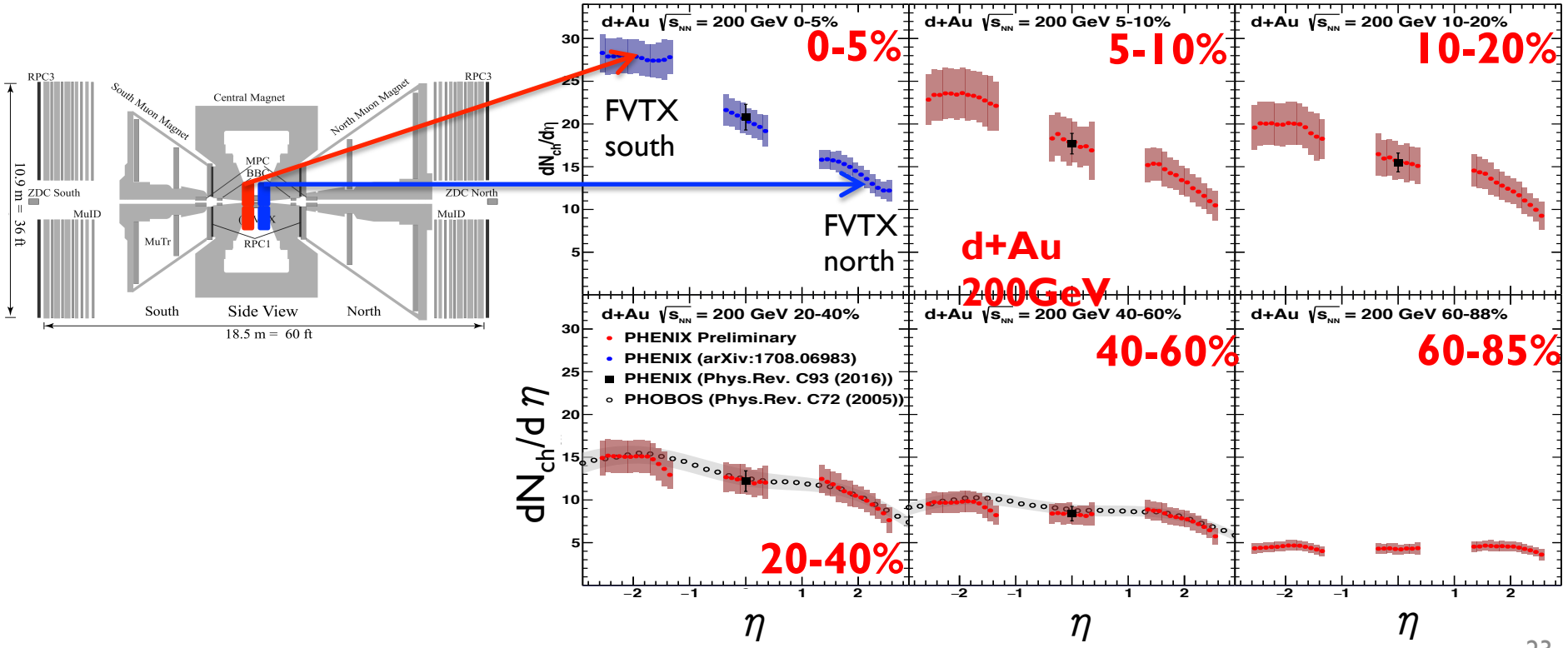
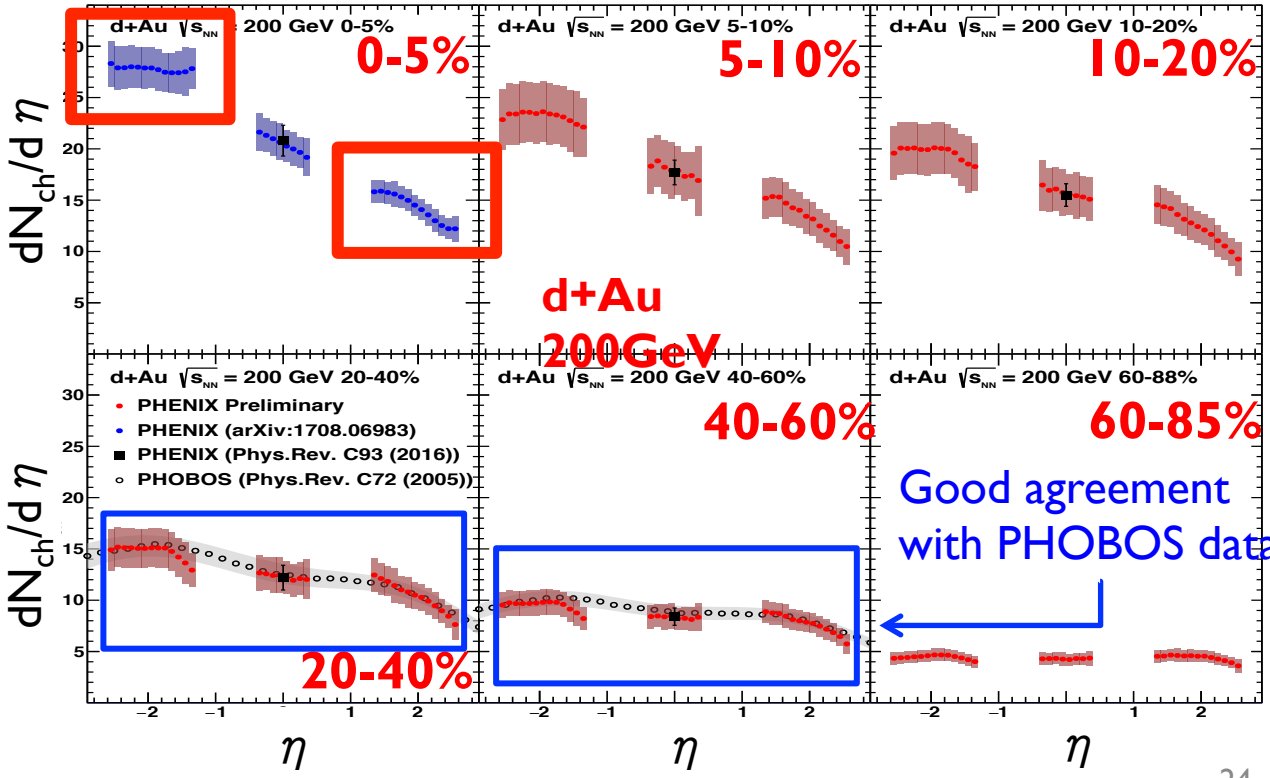


Expanded pseudo-rapidity

The new PHENIX results are in **good agreement** with the previous PHENIX results (Run 8) at the mid-rapidity.

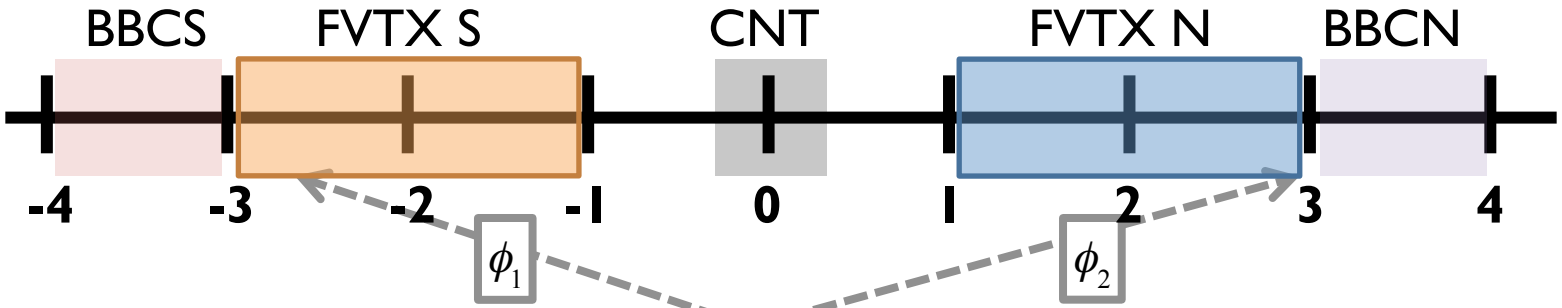
Also the $dN_{ch}/d\eta$ measured at the wider range of rapidity by using the FVTX.



PRC 83, 044913 (2011) Ante Bilandzic et al.

Multi-particle correlation

- two-, four-particle angular correlations



$$\boxed{\langle 2 \rangle = \langle \cos(n(\phi_1 - \phi_2)) \rangle = \langle v_n^2\{2\} \rangle}$$

Average over **particles** in a single event

$$v_2\{2\} = \left(v_2^2 + \sigma^2 + \delta^2\right)^{1/2}$$

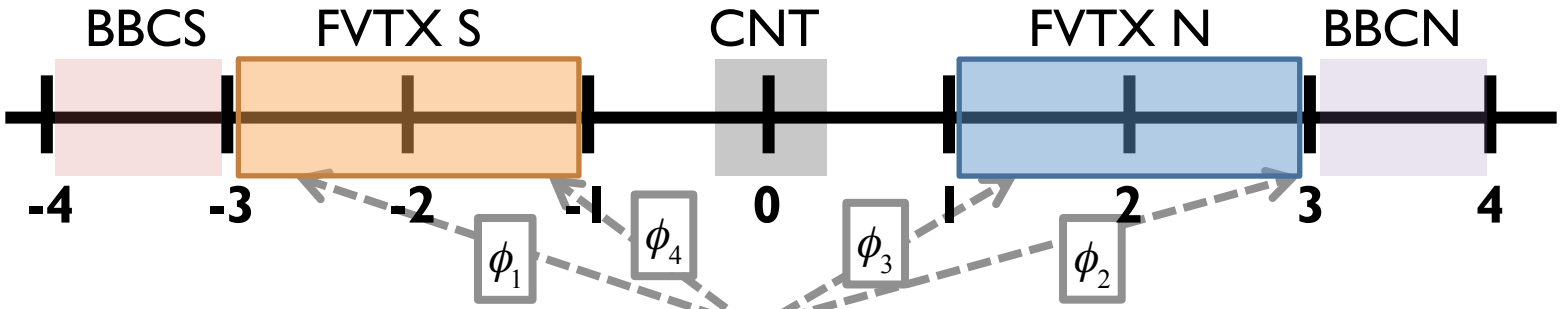
Nonflow

Fluctuations

PRC 83, 044913 (2011) Ante Bilandzic et al.

Multi-particle correlation

- two-, four-particle angular correlations



$$\langle 4 \rangle = \langle \cos(n(\phi_1 + \phi_2 - \phi_3 - \phi_4)) \rangle = \langle v_n^2 \rangle$$

$$v_2\{4\} \approx \left(v_2^2 - \sigma^2 \right)^{1/2}$$

Fluctuations

Negligible nonflow is expected

PRC 83, 044913 (2011) Ante Bilandzic et al.

Multi-particle correlation

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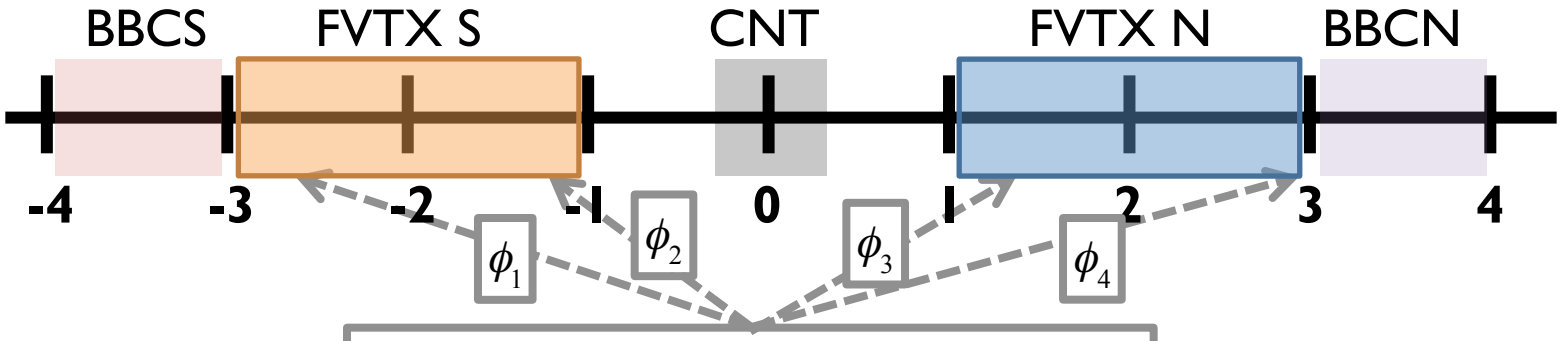

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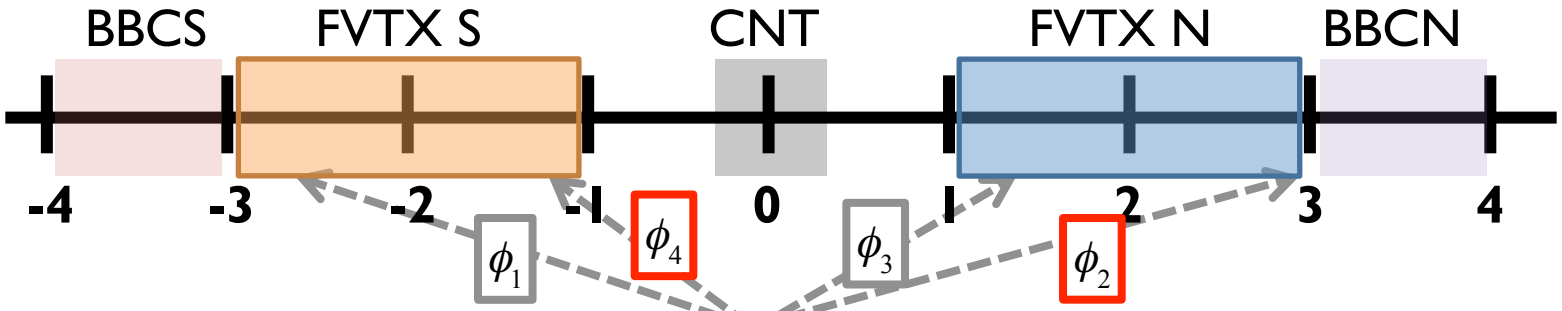
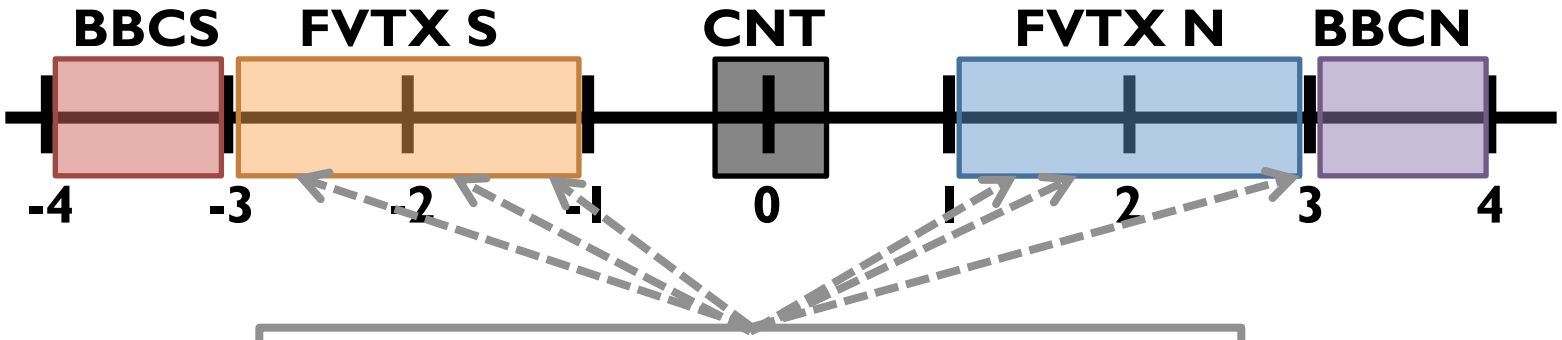


$$\langle 4 \rangle = \langle \cos(n(\phi_1 + \phi_2 - \phi_3 - \phi_4)) \rangle = \langle v_n^2 \rangle$$

This changing derives smaller $|\Delta\eta|$ between the tracks.

Multi-particle correlation

- two-, four-, six-particle angular correlations

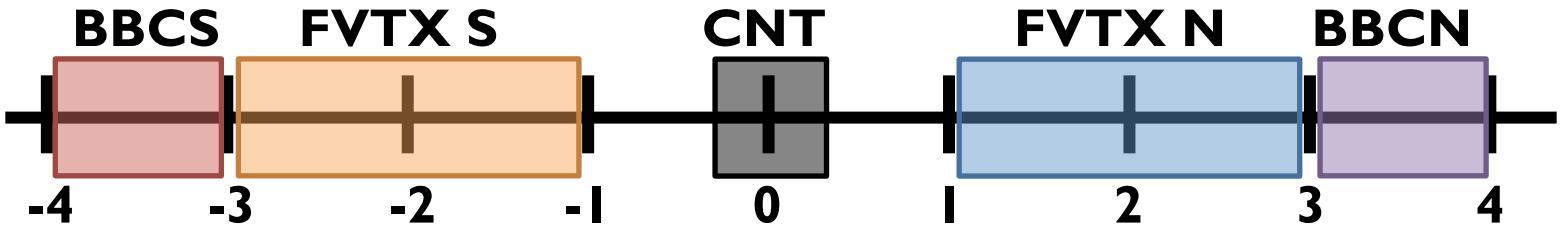


$$\langle 6 \rangle = \langle \cos(n(\phi_1 + \phi_2 + \phi_3 - \phi_4 - \phi_5 - \phi_6)) \rangle = \langle v_n^2 \rangle$$

$$c_n\{6\} = \langle\langle 6 \rangle\rangle - 9\langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle + 12\langle\langle 2 \rangle\rangle^3 = 4[v_n\{6\}]^6$$

Multi-particle correlation

- two-, four-, six-particle angular correlations



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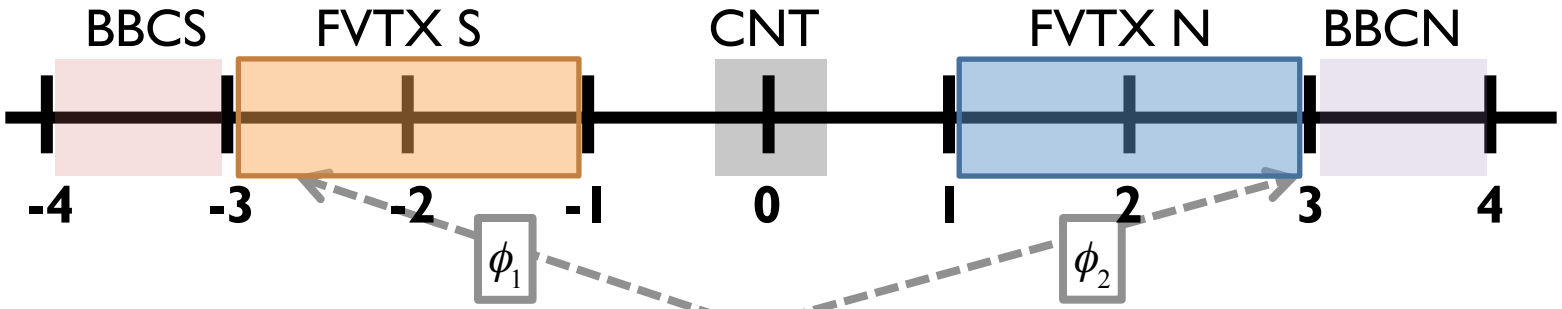
$$v_2\{4\} \approx v_2\{6\} \approx \left(v_2^2 - \sigma^2\right)^{1/2}$$

Multi-particle correlation

- two-, four-particle angular correlations



$$\langle 2 \rangle = \langle \cos(n(\phi_1 - \phi_2)) \rangle = \langle v_n^2\{2\} \rangle$$

Average over **particles** in a single event

$$\langle\langle 2 \rangle\rangle = c_n\{2\} = [v_n\{2\}]^2$$

1. Average over **particles** in a single event
2. Average over **events**