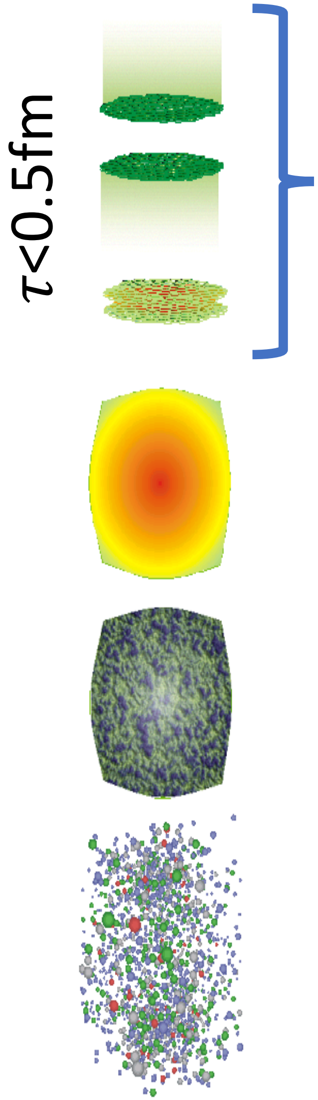
# Selected STAR Highlight

Shengli Huang
for the STAR collaboration

Stony Brook University, Chemistry Department

# Outline




**Physics to address:**

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

$\gamma$+$\gamma$, $\gamma$+nucleus interaction

….

**STAR Measurement:**

Small system: flow, jet

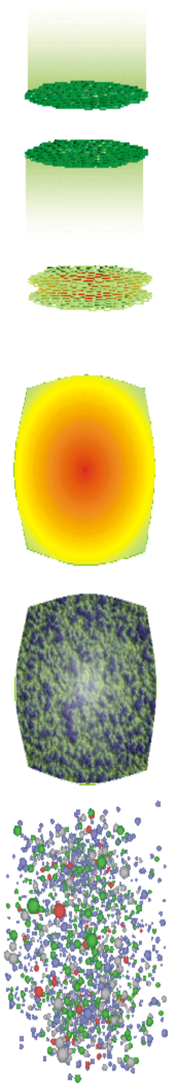
Flow correlation and decorrelation

$D^0$ $v_1$, $\Lambda$ polarization

Low $p_T$ di-lepton, J/$\psi$

# Outline

$\tau$<0.5fm



**Physics to address:**

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

$\gamma+\gamma$, $\gamma$+nucleus interaction

....

**STAR Measurements:**

Small system: flow, jet

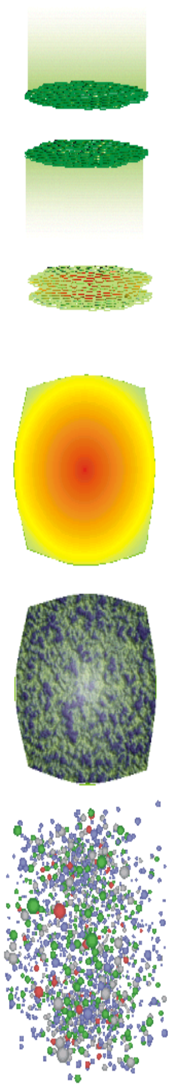
Flow correlation and decorrelation

$D^0$ $v_1$, $\Lambda$ polarization

Low $p_T$ di-lepton, $J/\psi$

# Outline

$\tau$<0.5fm



**Physics to address:**

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

$\gamma+\gamma$, $\gamma$+nucleus interaction

….

**STAR Measurements:**

Small system: flow, jet

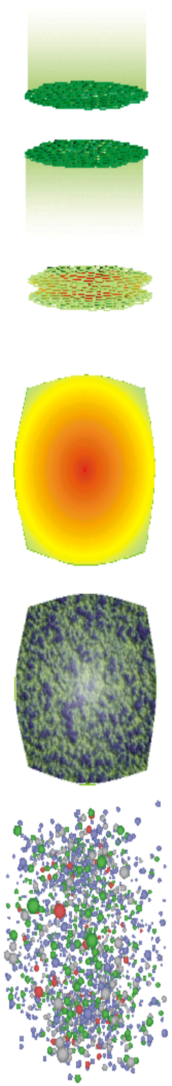
Flow correlation and decorrelation

$D^0$ $v_1$, $\Lambda$ polarization

Low $p_T$ di-lepton, J/$\psi$

# Outline

$\tau$<0.5fm



**Physics to address:**

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

$\gamma$+$\gamma$, $\gamma$+nucleus interaction

….

**STAR Measurements:**

Small system: flow, jet

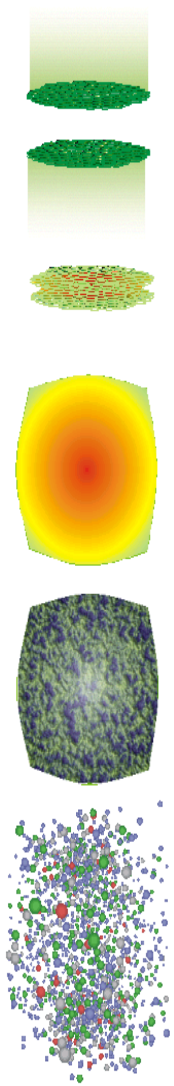
Flow correlation and decorrelation

$D^0$ $v_1$, $\Lambda$ polarization

Low $p_T$ di-lepton, J/$\psi$

# Outline

$\tau$<0.5fm



**Physics to address:**

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

$\gamma$+$\gamma$, $\gamma$+nucleus interaction

….

**STAR Measurements:**

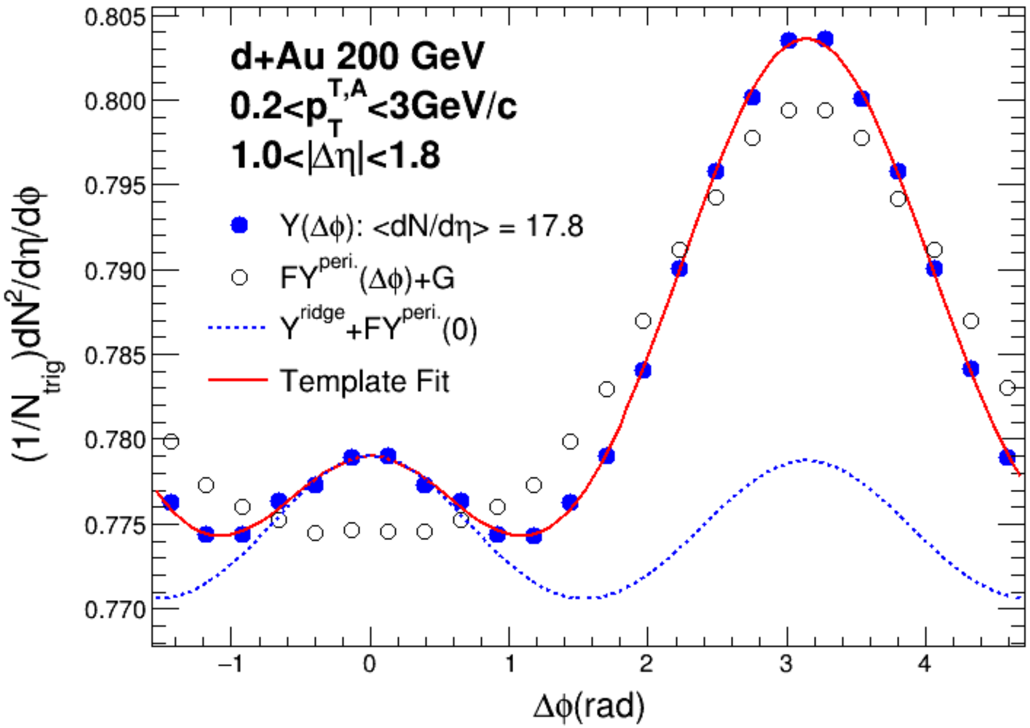
Small system: flow, jet

Flow correlation and decorrelation

$D_0$ $v_1$, $\Lambda$ polarization

Low $p_T$ di-lepton, J/$\psi$

# Flow in Small Systems




Two particle correlation in d+Au@200GeV with $|\eta|$<0.9 and $|\Delta\eta|$>1.0

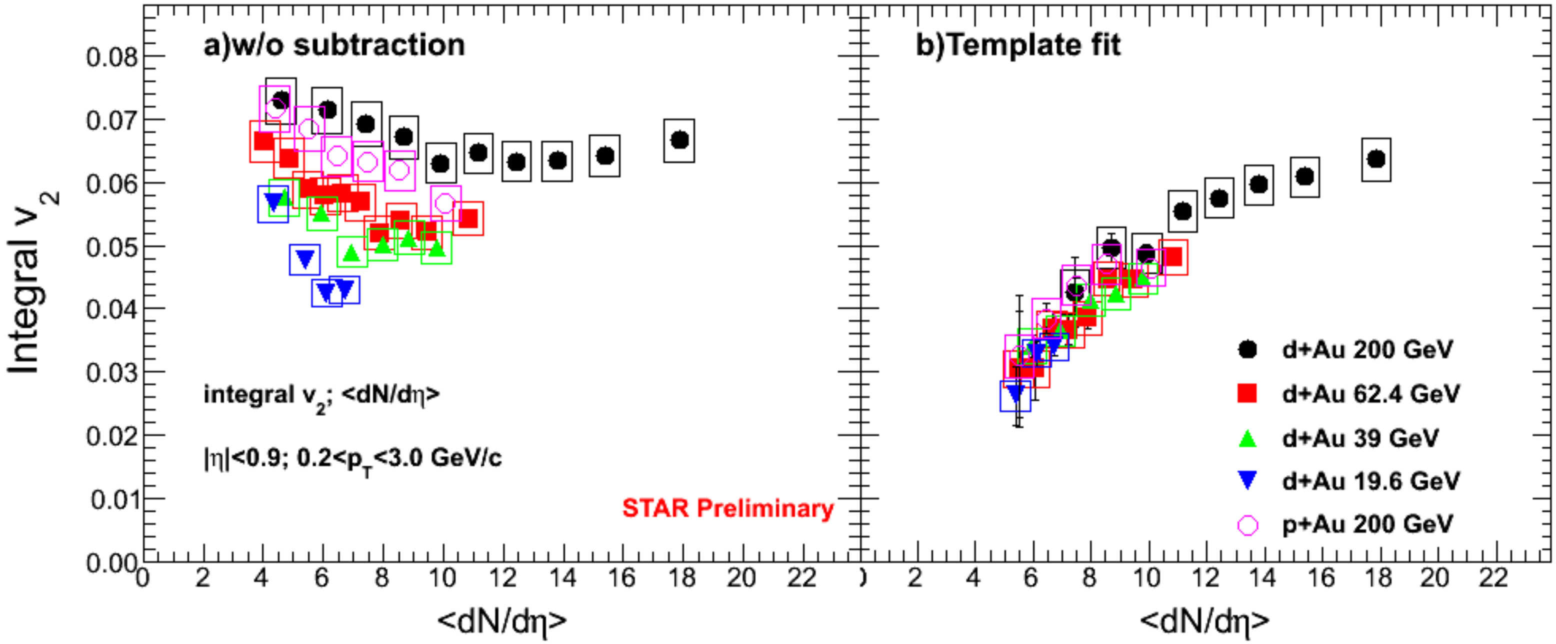
Event activity: BBC (-2>$\eta$>-5)
HM: ridge + jet
LM: jet

Ridge signal (flow) is extracted by template fit

- $Y_{templ.}(\Delta\phi) = \mathrm{F} \times Y_{peri.}(\Delta\phi) + Y_{ridge}(\Delta\phi)$
- where
- $Y_{ridge}(\Delta\phi) = \mathrm{G}\times(1 + 2\times \sum_{n=2}^{4} V_{n,n} \times \cos(n\Delta\phi))$

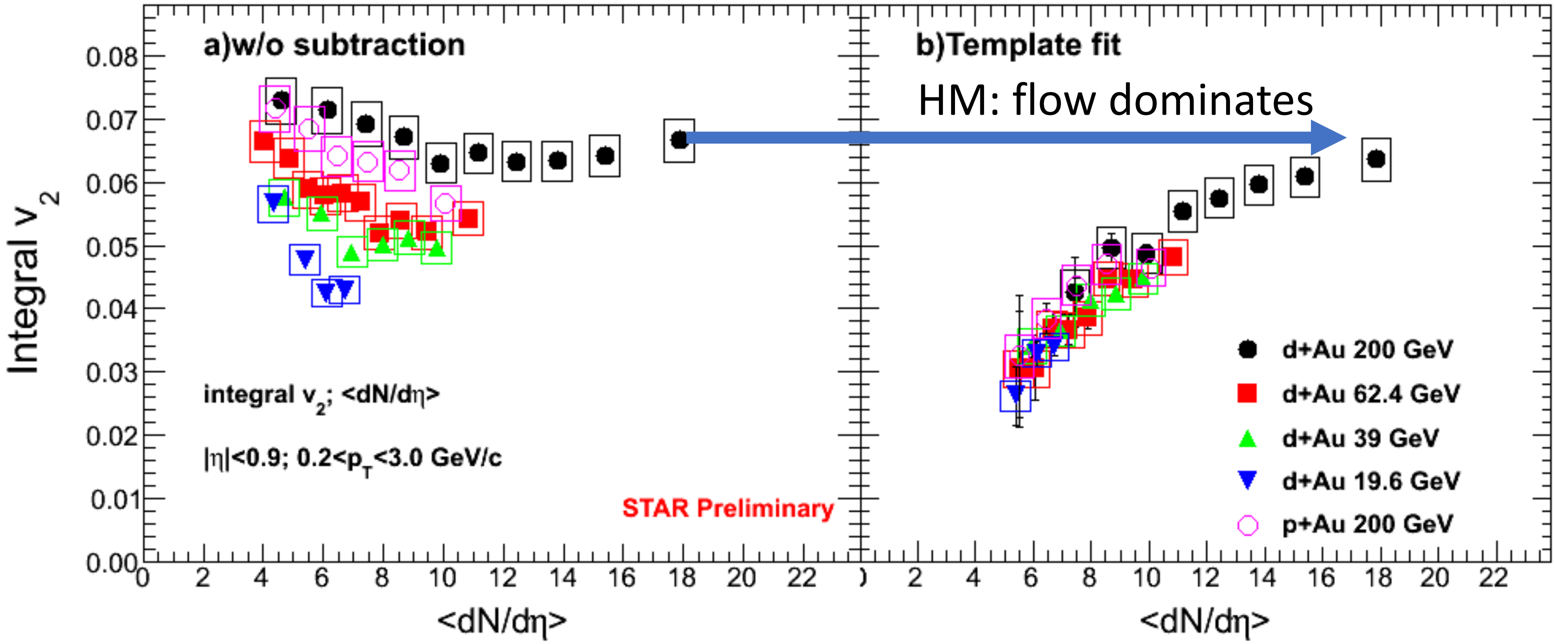
***ATLAS:PRL 116, 172301 (2016)***

# Flow in Small Systems



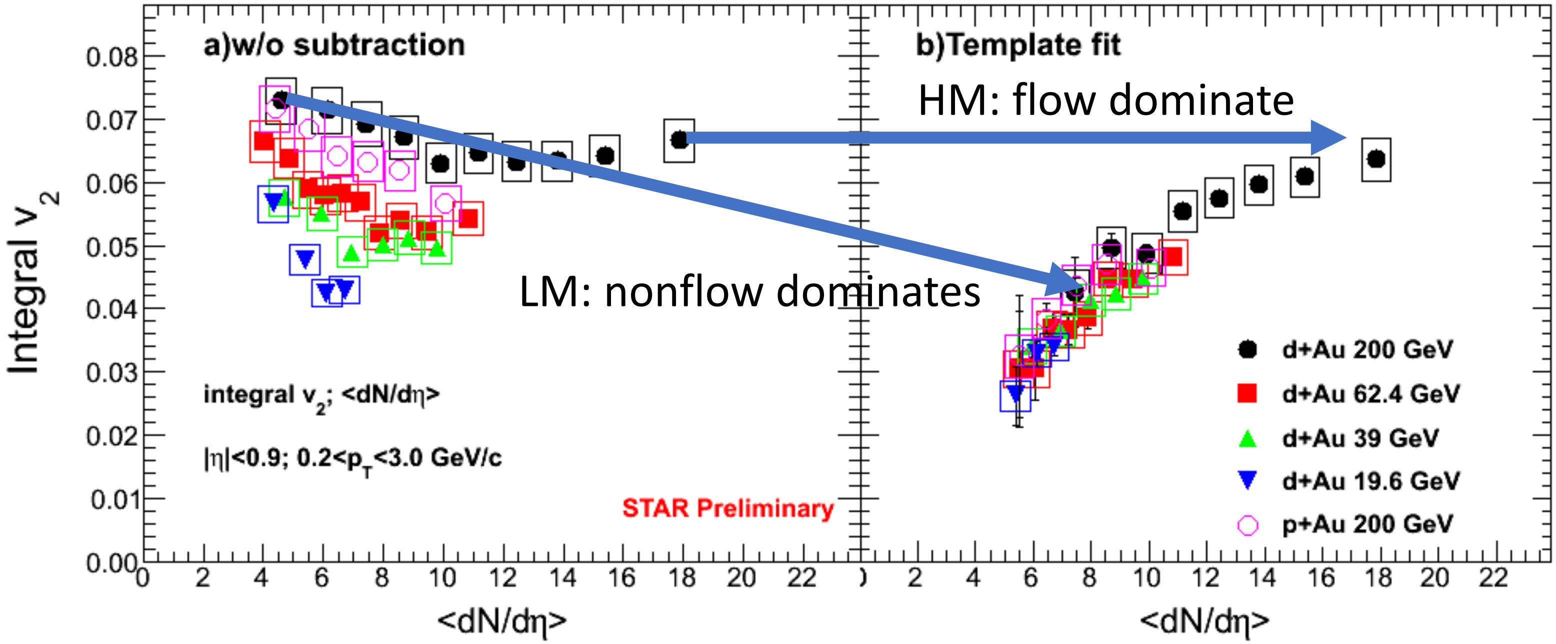

- $v_2$ from template fit shows a universal trend as a function of <dN/d$\eta$>

# Flow in Small Systems



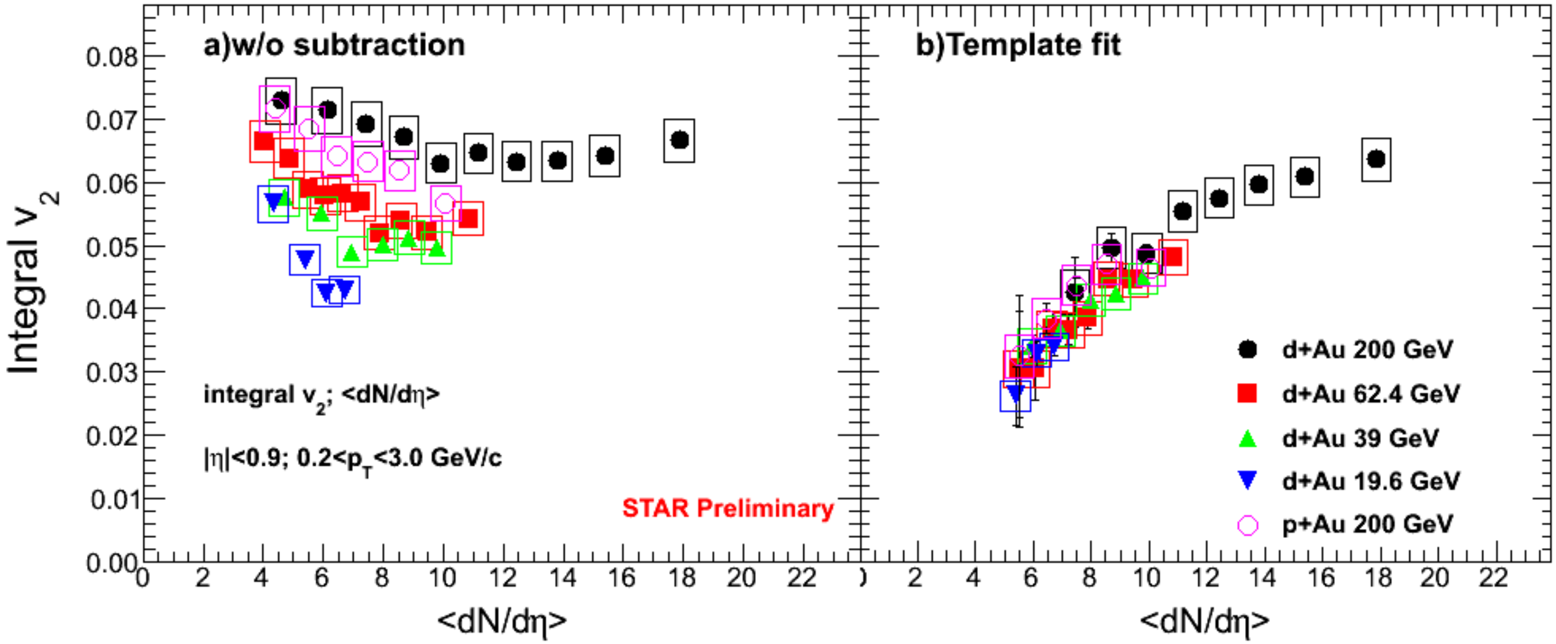

- $v_2$ from template fit shows a universal trend as a function of $\langle dN/d\eta \rangle$

# Flow in Small Systems

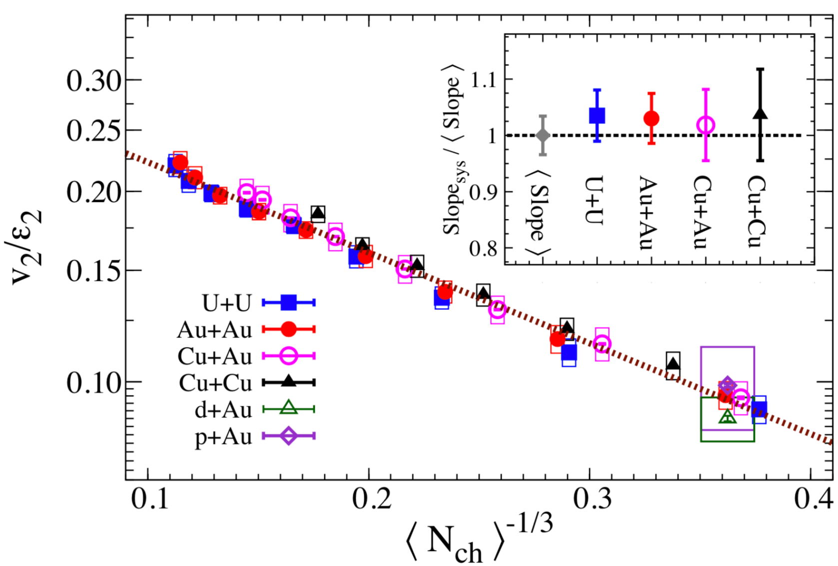



- $v_2$ from template fit shows a universal trend as a function of <dN/d$\eta$>

# Flow in Small Systems

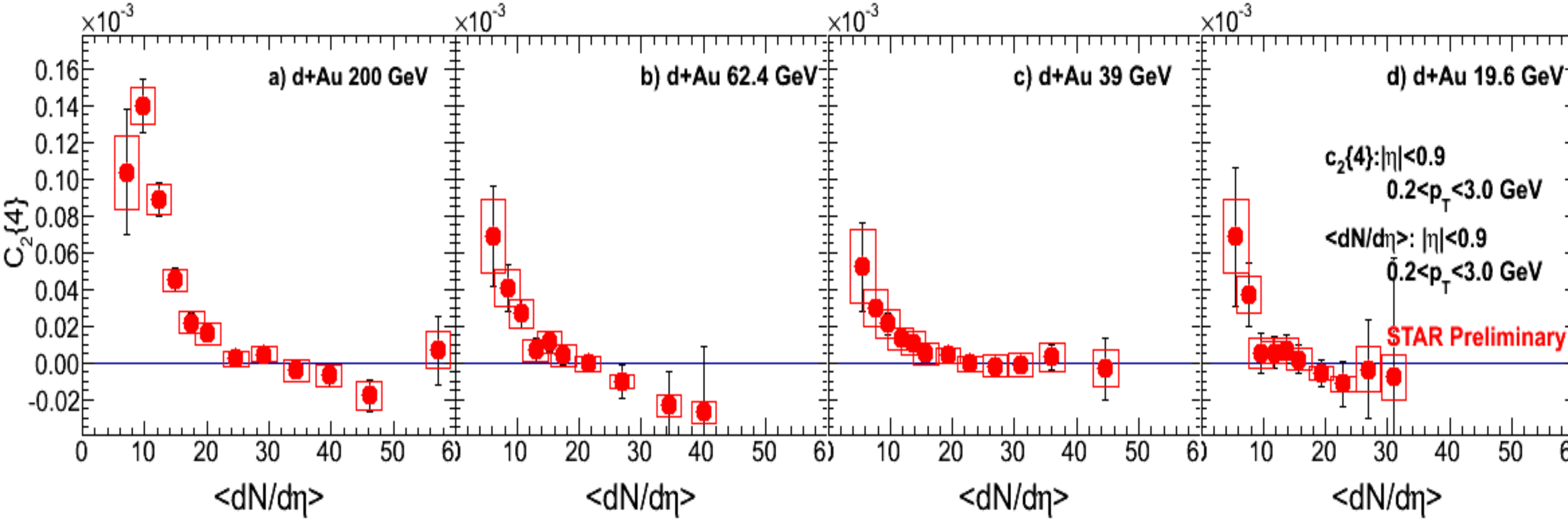



STAR, PRL **122** (2019) 172301




- $v_2$ from template fit shows a universal trend as a function of <dN/d$\eta$>
- A smooth trend from small to large system.
- Driven by hydro flow?

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



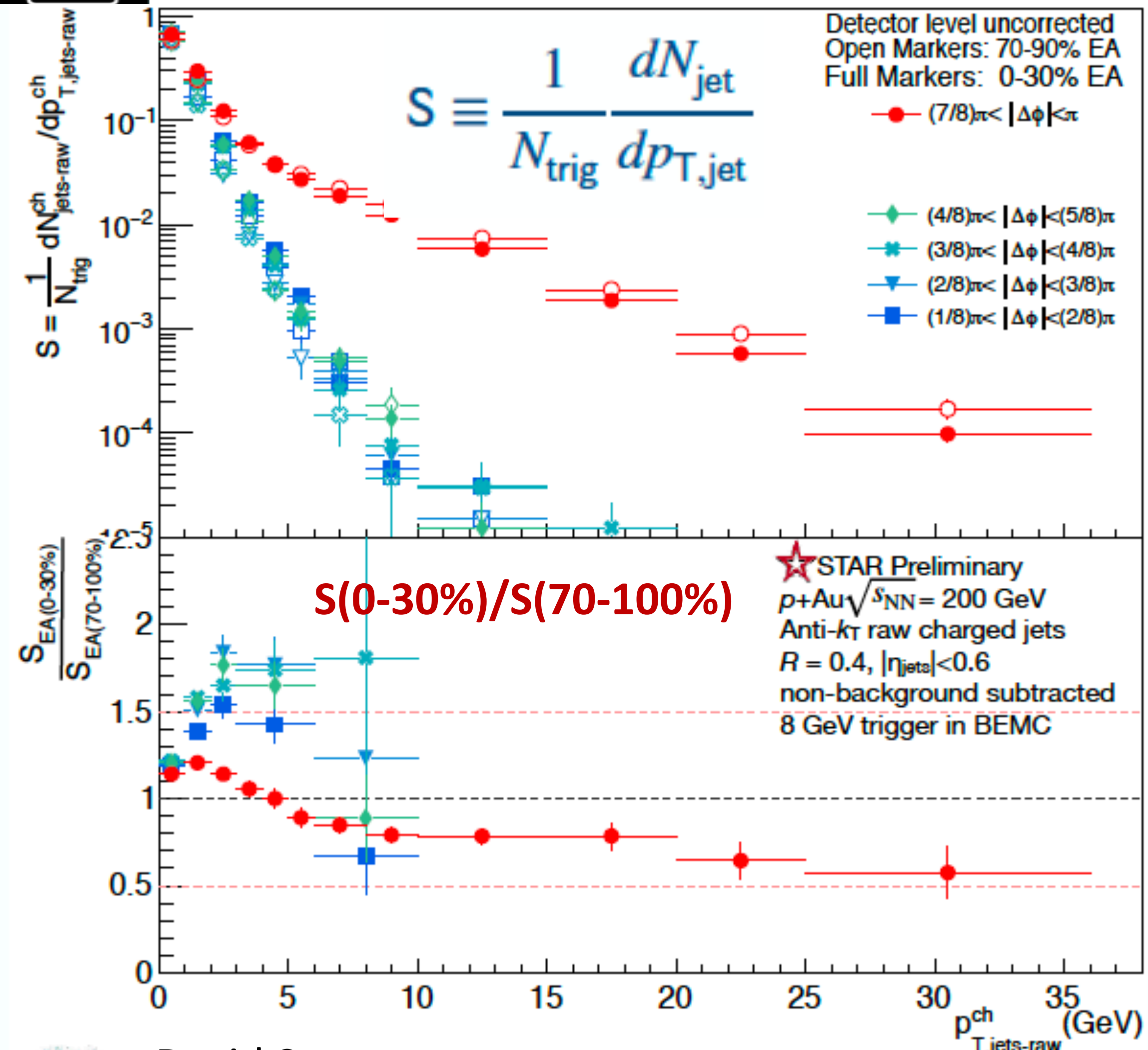

$c_2\{4\} = \ll e^{-i2(\phi_i+\phi_j-\phi_k-\phi_l)} \gg$-2$\ll e^{-i2(\phi_i-\phi_j)} \gg$

$\phi_i$, $\phi_j$, $\phi_k$, $\phi_l$ 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

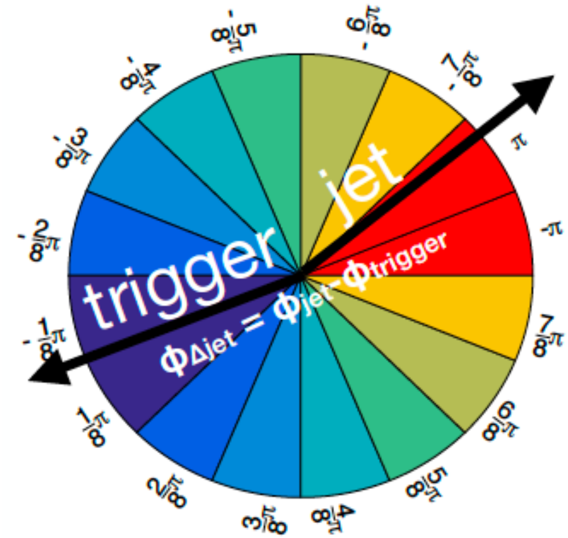
$v_2\{4\} = \sqrt[1/4]{-c_2\{4\}}$

- $c_2\{4\}$ changes sign at high multiplicity ($|\eta|$<0.9) in d+Au collisions at 200 and 62.4 GeV
- Collectivity in small system

# Semi-inclusive Jets in p+Au@200 GeV




p+Au→BEMC$_{hit}$+jet+X

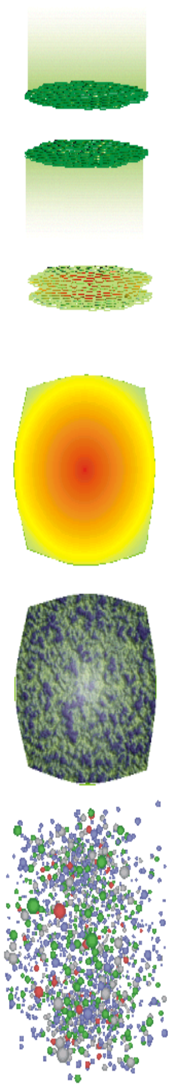



- Event activity by BBC
- Suppression of away side jet above 10 GeV/c
- Due to bias of event selection?
- Is there still room for medium modification?

David Stewart
Wed 5:10 PM ,301

# Outline

τ<0.5fm



**Physics to address:**

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

$\gamma+\gamma$, $\gamma$+nucleus interaction

….

**STAR Measurements:**

Small system: flow, jet

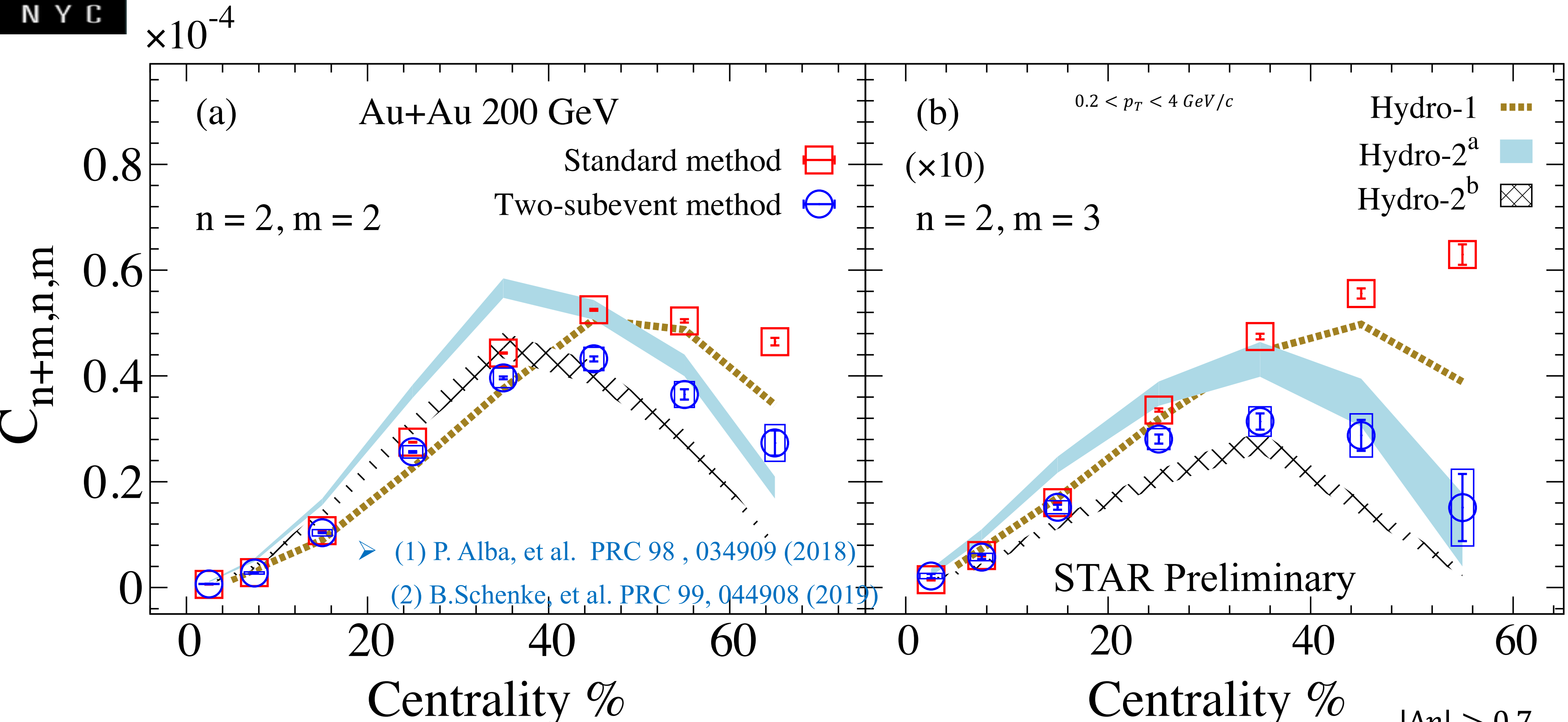
Flow correlation and decorrelation

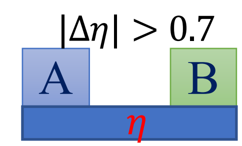
$D^0$ $v_1$, $\Lambda$ polarization

Low $p_T$ di-lepton, $J/\psi$

# Flow correlation

$C_{4,22} = < v_4 v_2^2 cos(4\psi_4 - 4\,\psi_2) >$ $\quad$ $C_{5,23} = < v_5 v_3 v_2 cos(5\psi_5 - 3\psi_3 - 2\psi_2) >$



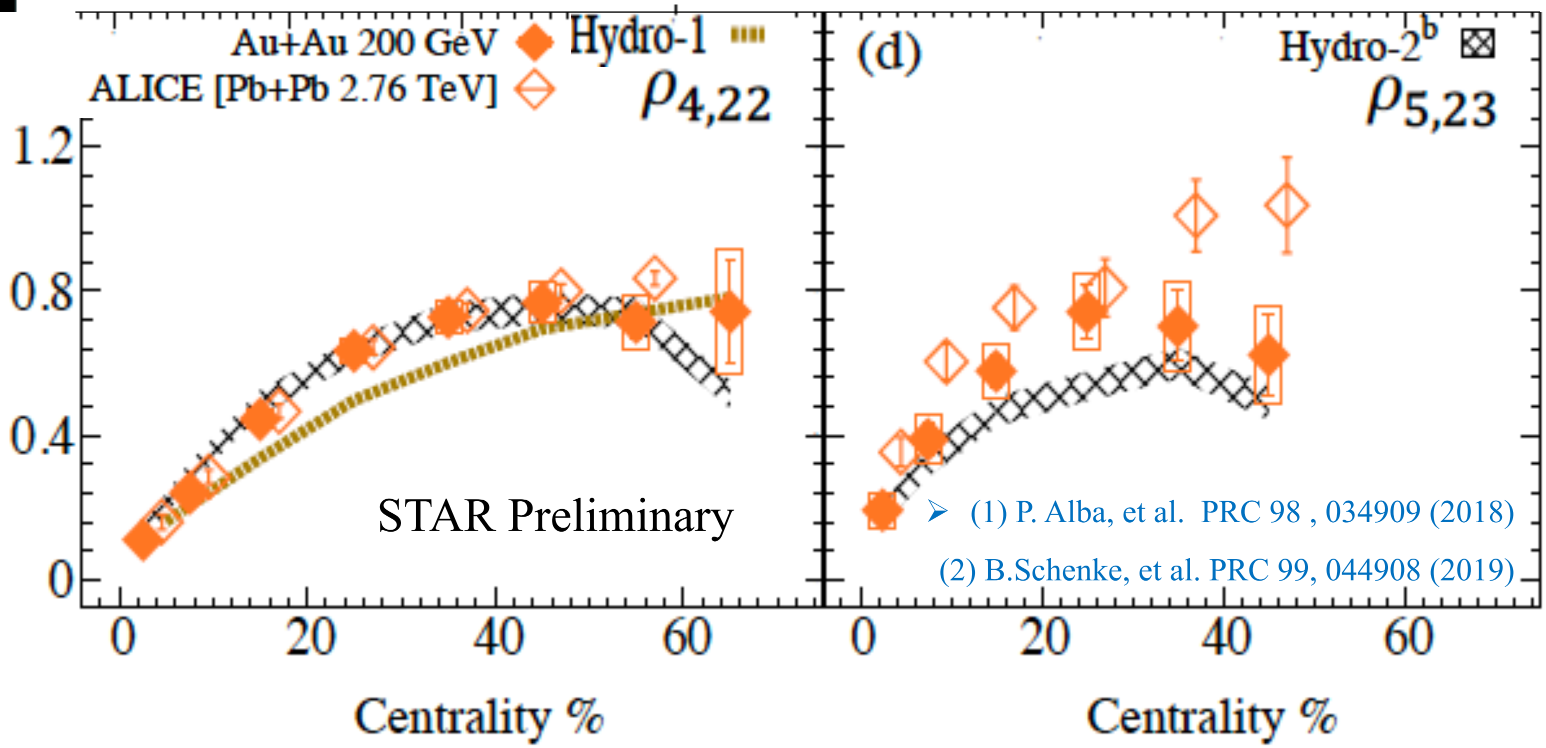




- Two-subevents method to suppress the non-flow
- Sensitive to initial condition, $\eta/s$ etc

Niseem Abdelrahman
Wed 2:40 PM ,301

# Nonlinear mode-mixing

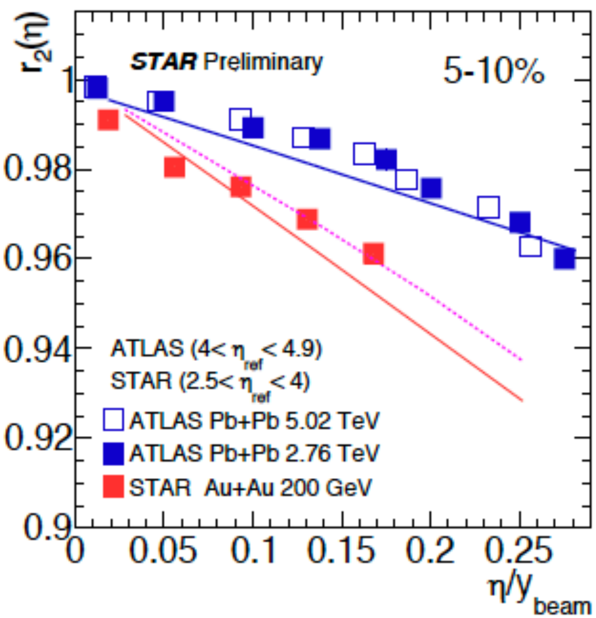
$\rho_{4,22} = \langle cos(4\psi_4 - 4\psi_2) \rangle$ $\rho_{5,23} = \langle cos(5\psi_5 - 3\psi_3 - 2\psi_2) \rangle$



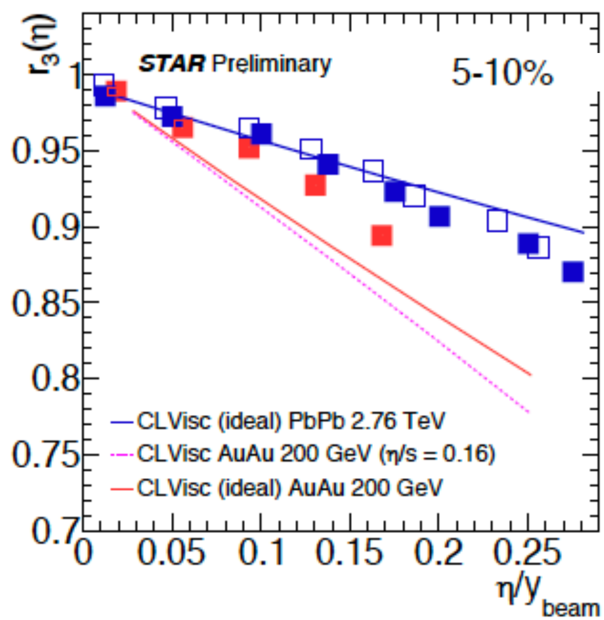

- Carry information about EP angular correlations
- Same as ALICE, nonlinear mode-mixing increase for peripheral
- More constraints on hydro calculation

# Longitudinal flow de-correlation

$r_2$

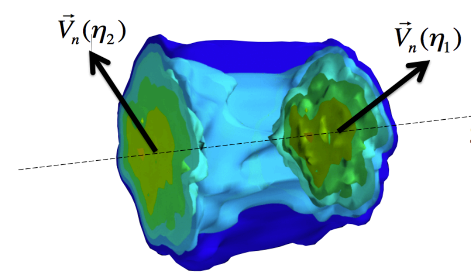



$r_3$




$$r_n(\eta) = \frac{\langle V_n(-\eta)V_n^*(\eta_{\rm ref})\rangle}{\langle V_n(\eta)V_n^*(\eta_{\rm ref})\rangle}$$

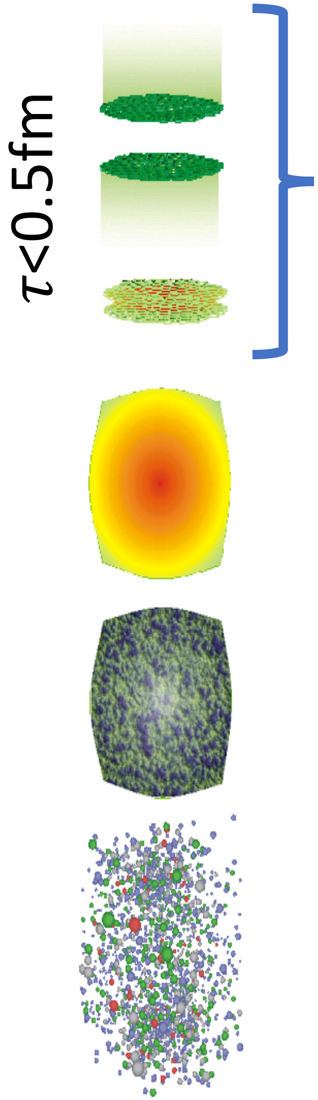
*CMS PRC92, 034911(2015)*




*ATLAS, EPJC 78, 142(2018)*
*EPJA 52(2016) 97*
*PRC 97,064918(2018)*

- Stronger decorrelation at RHIC energy.
- Hydro. cannot describe LHC and RHIC data simultaneously
- Results of 54.4 and 27.6 GeV will come soon!

# Outline




**Physics to address:**

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

$\gamma+\gamma$, $\gamma$+nucleus interaction

….

**STAR Measurements:**

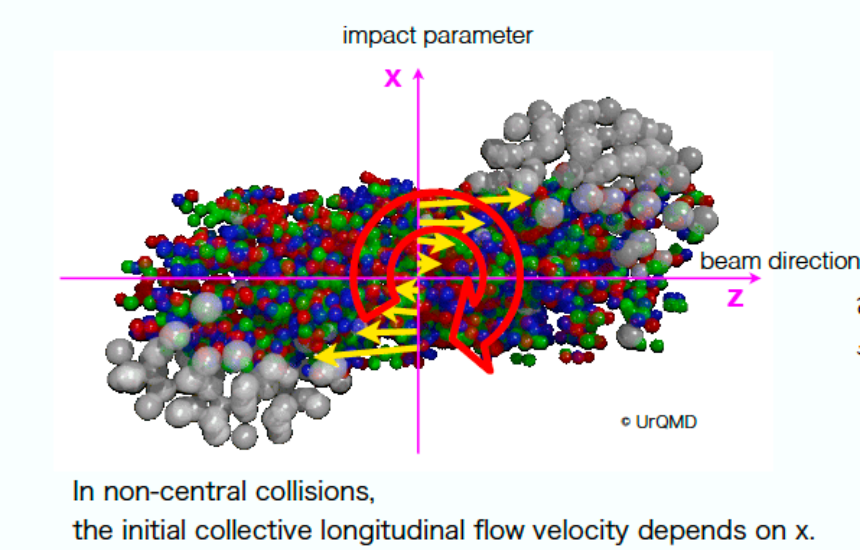
Small system: flow, jet

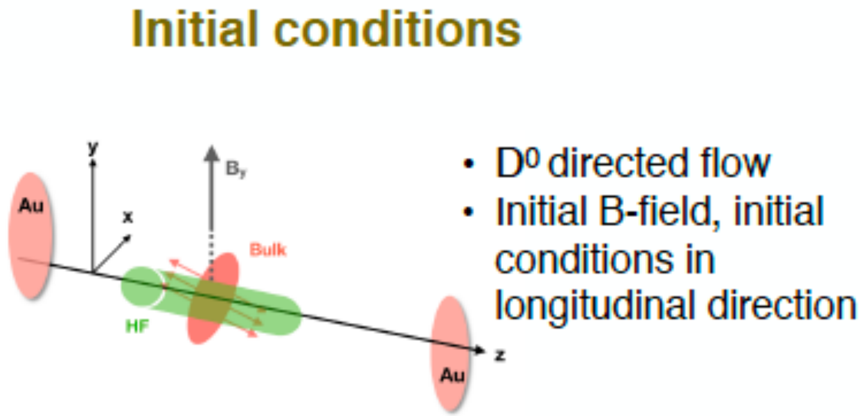
Flow correlation and decorrelation

$D^0$ $v_1$, $\Lambda$ polarization

Low $p_T$ di-lepton, J/$\psi$

# $D^0$ $v_1$: Tilted QGP and EM field Effect

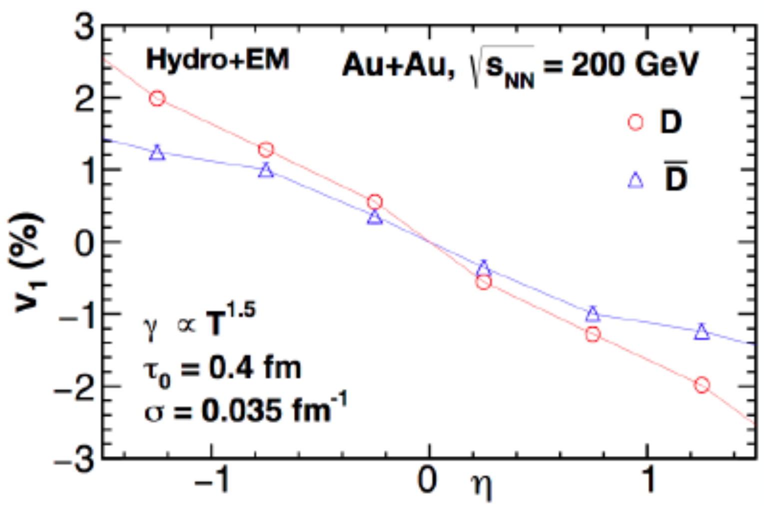



- Charm dragged by tilted QGP, leads to large $v_1$

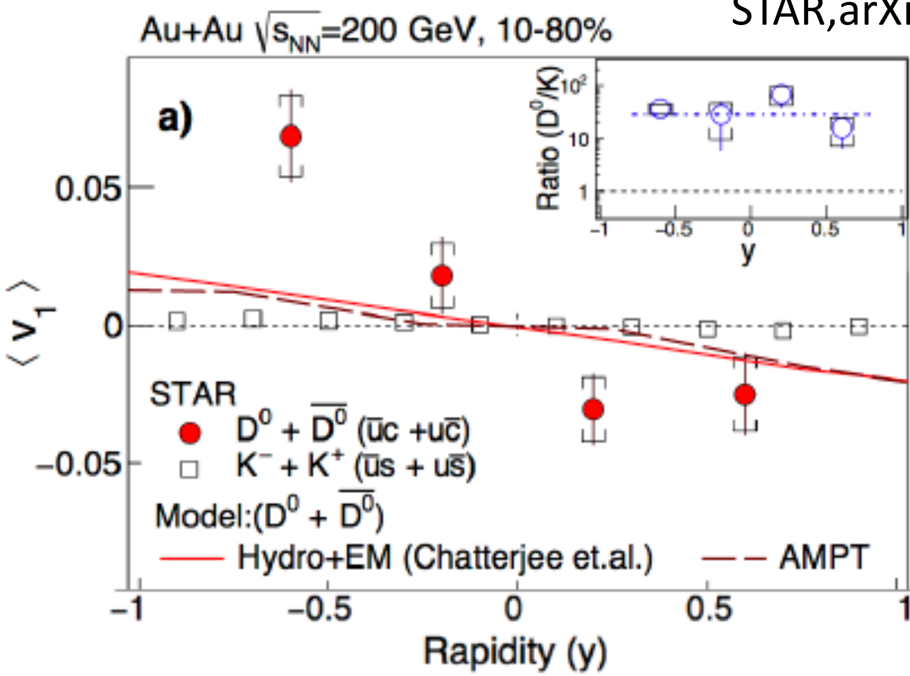
- Due to EM field, further splitting between $D^0$ and $\overline{D^0}$ $v_1$

Das et. al.,PLB768(260)2016



# $D^0$ directed flow

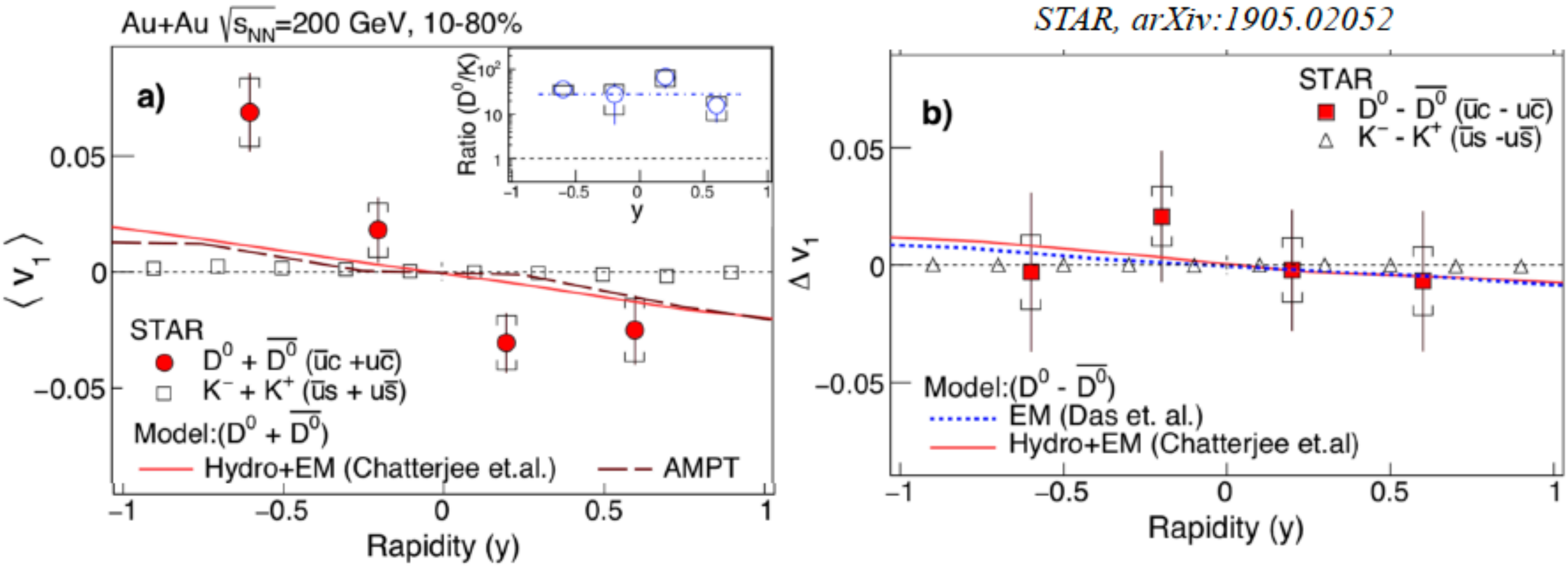
STAR,arXiv:1905.02052




Subhash Singha
Wed 6:10 PM,301

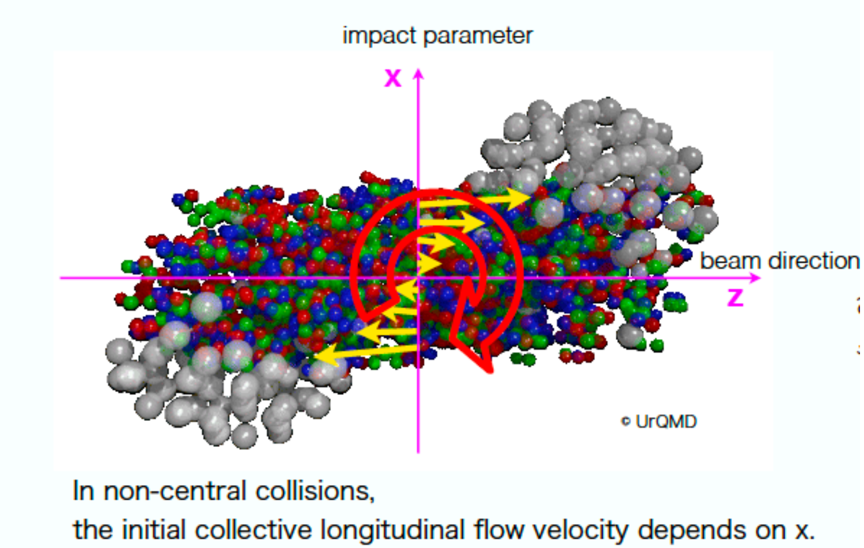
- First observation of $D^0$ $v_1$ , ~10 times larger than kaon's
- Also larger than prediction of hydro

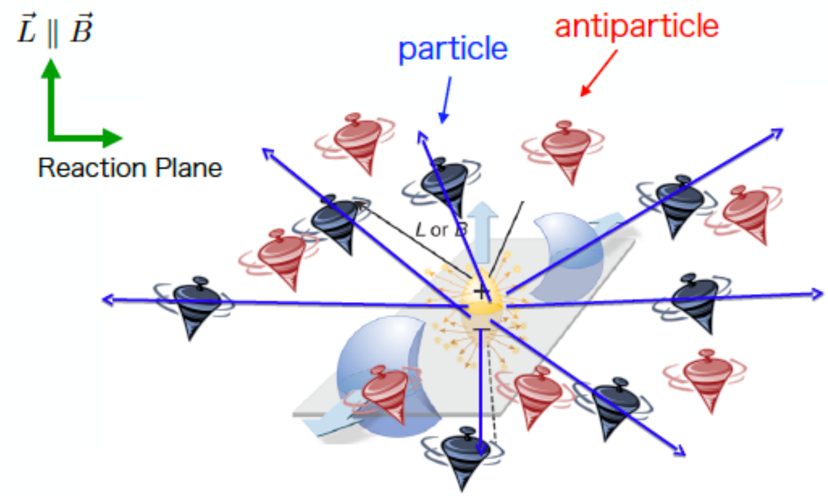
# $D^0$ direct flow



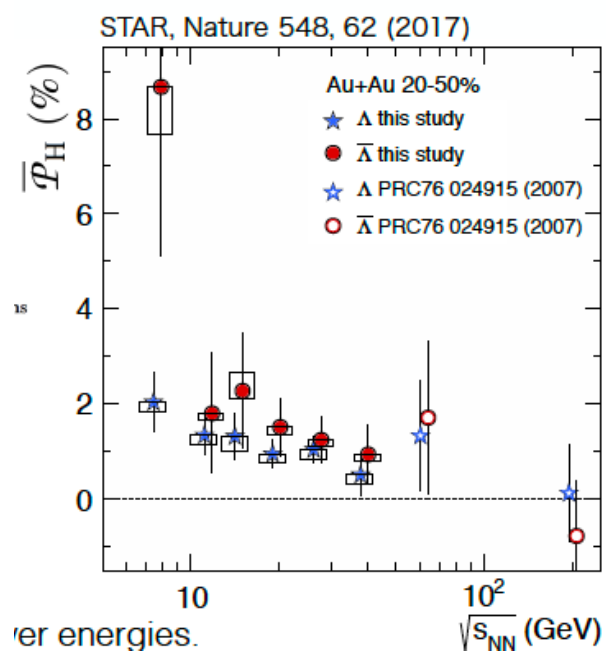

- First observation of $D^0$ $v_1$ , ~10 times larger than kaon's
- Also larger than prediction of hydro and AMPT
- $D^0$ and $\overline{D^0}$ $v_1$ are same within uncertainties. Measurement not yet sensitive to EM field

# $\Lambda$ polarization and Influence of B field

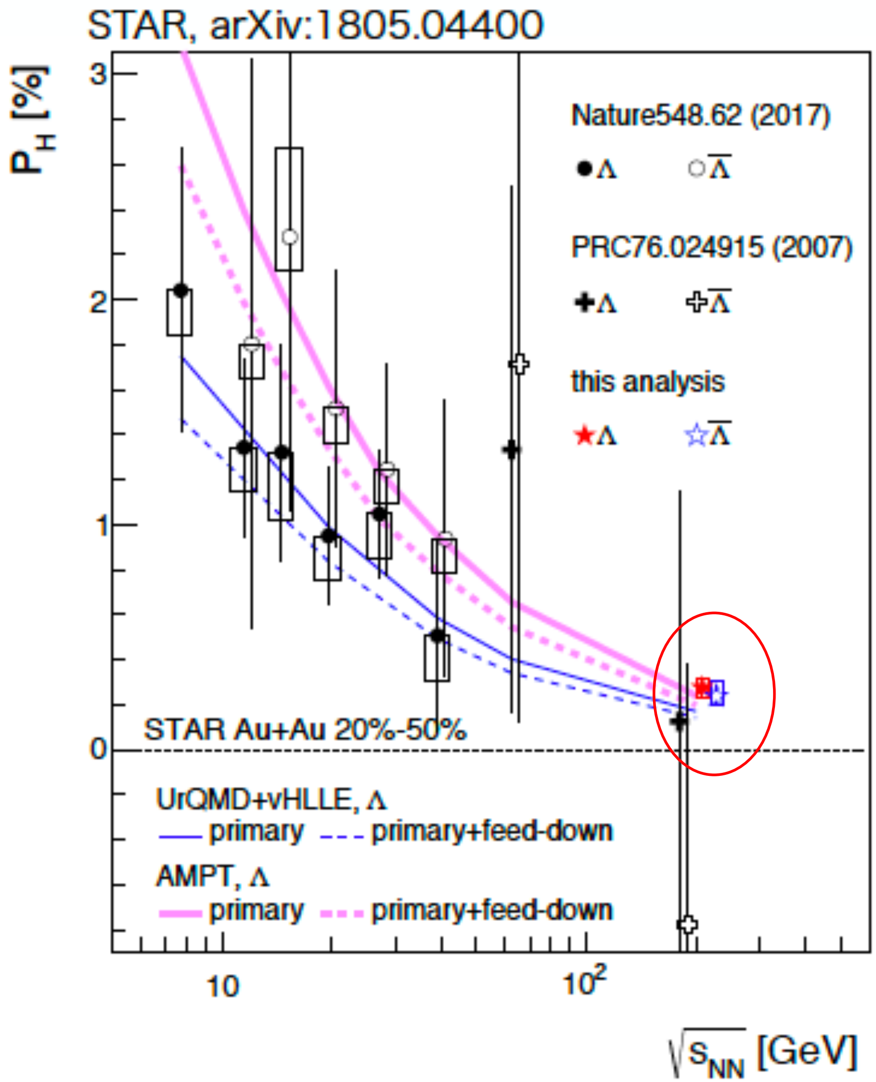



- QGP vorticity can be transferred to $\Lambda$ polarization
- Due to B field, further splitting is expected between $\Lambda$ and $\overline{\Lambda}$



# $\Lambda$ global polarization@200GeV



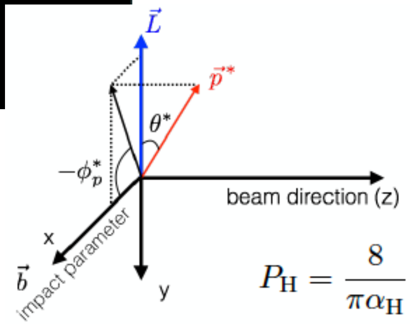

- Global polarization of $\Lambda$ is observed for first time in Au+Au@200 GeV

$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\mathrm{stat}) \pm^{0.039}_{0.049}\ (\mathrm{sys})$$
$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\mathrm{stat}) \pm^{0.061}_{0.045}\ (\mathrm{sys})$$

- Precision not sufficient to see the difference between $\Lambda$ and $\bar{\Lambda}$

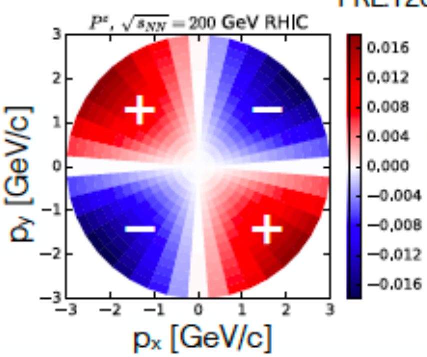
- Analysis of >x10 of 27.6 GeV data is underway!

# $\Lambda$ local polarization@200GeV

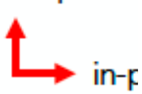


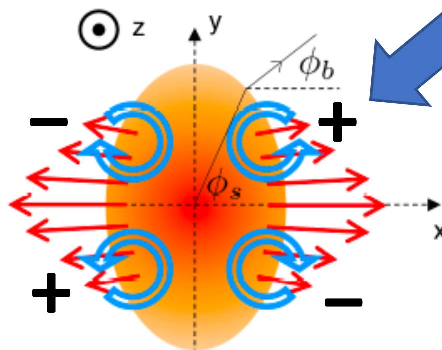

$$P_{\rm H} = \frac{8}{\pi \alpha_{\rm H}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{{\rm Res}(\Psi_1)}$$

Hydro calculation of $P_z$
F. Becattini and I. Karpe
PRL.120.012302 (2018

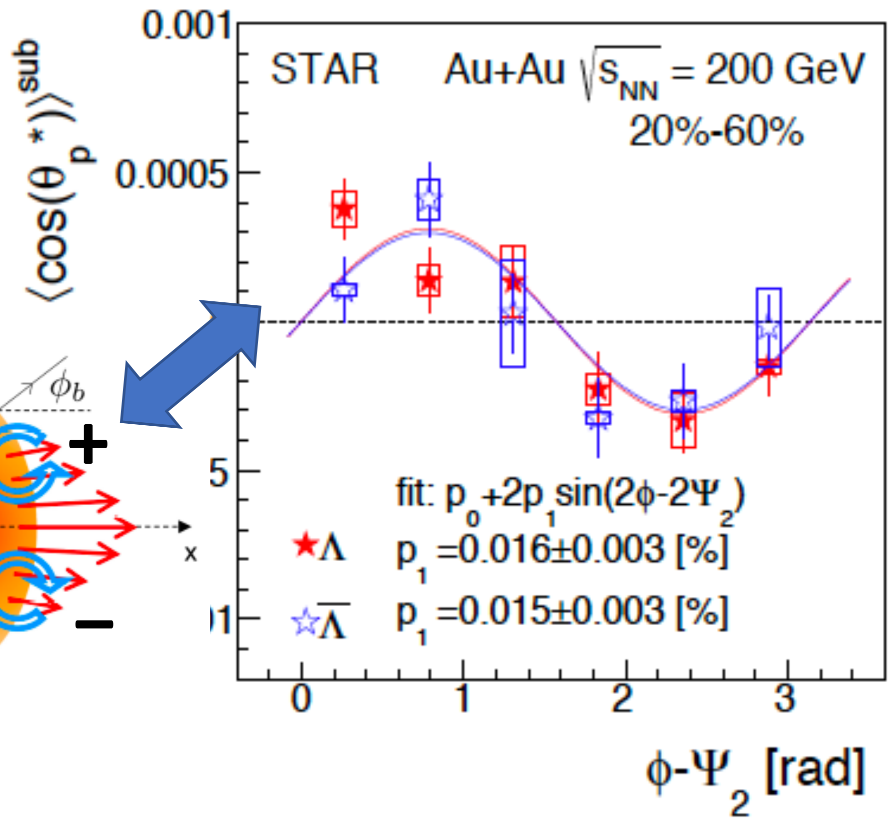



out-of-plane



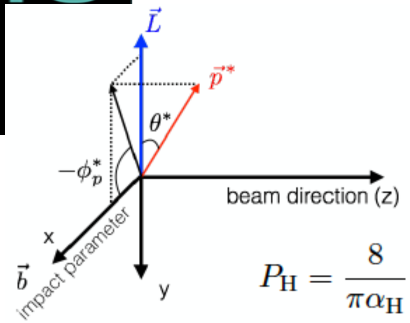

STAR, arXiv:1905.11917




- Local polarization (along beam direction) shows a quadrupole structure, the sign is different from the hydro calculation. It is still not understood

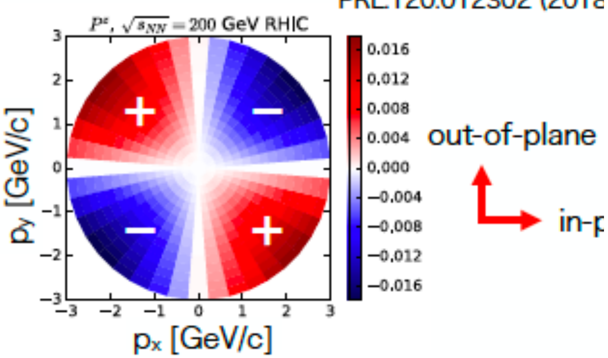
# $\Lambda$ local polarization@200GeV

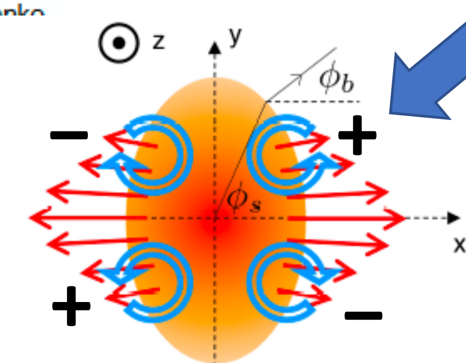
STAR, arXiv:1905.11917

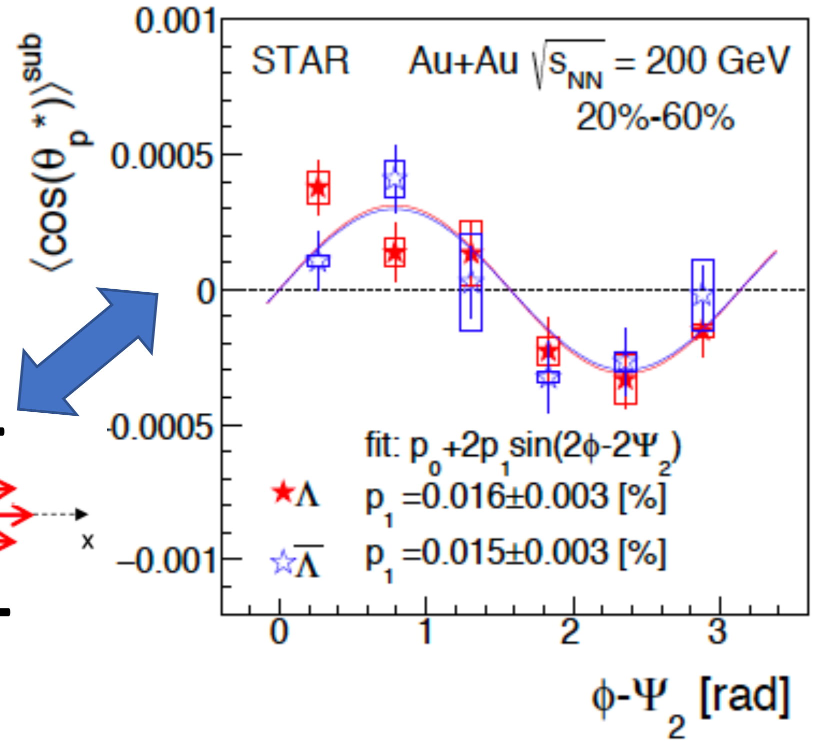



$$P_{\rm H} = \frac{8}{\pi \alpha_{\rm H}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{{\rm Res}(\Psi_1)}$$

Hydro calculation of $P_z$
F. Becattini and I. Karpenko
PRL.120.012302 (2018



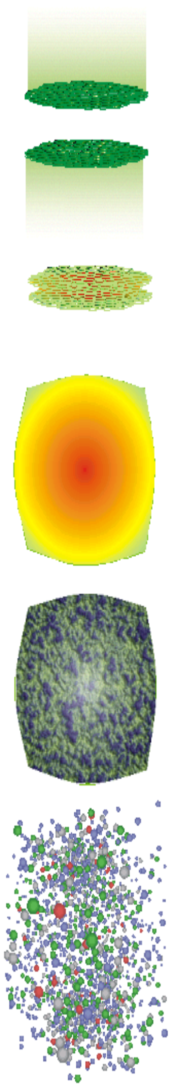






- Local polarization (along beam direction) shows a quadrupole structure,  the sign is different from the hydro calculation. It is still not understood
- The sign may depend on the relation of magnitude between spatial and flow anisotropy from BW model S. Voloshin, arXiv:1710.08934

# Outline

$\tau$<0.5fm



**Physics to address:**

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

$\gamma$+$\gamma$, $\gamma$+nucleus interaction

….

**STAR Measurements:**

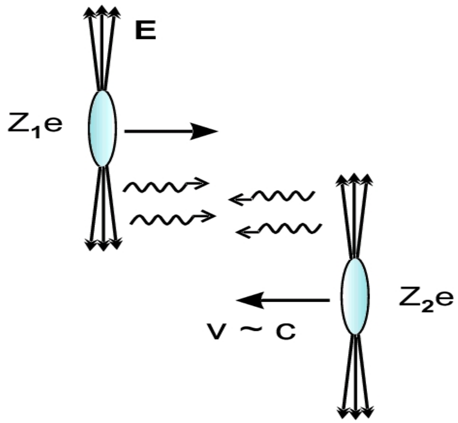
Small system: flow, jet

Flow correlation and decorrelation

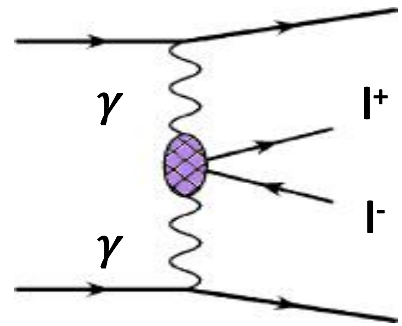
$D^0$ $v_1$, $\Lambda$ polarization

Low $p_T$ di-lepton, J/$\psi$

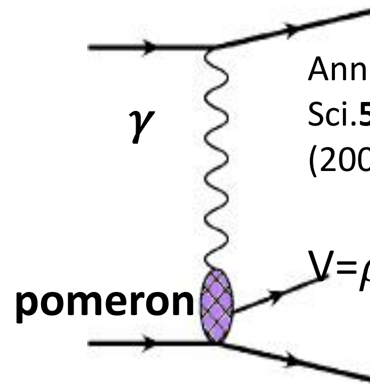
# Coherent $\gamma+\gamma$, $\gamma$+nuclear processes




=




+

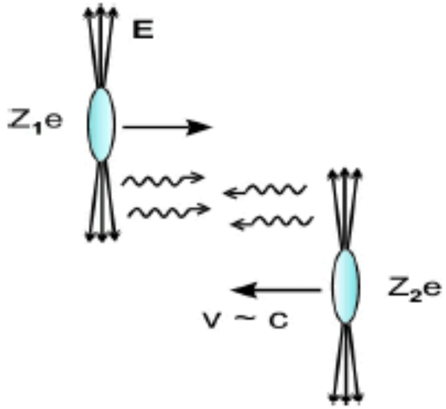


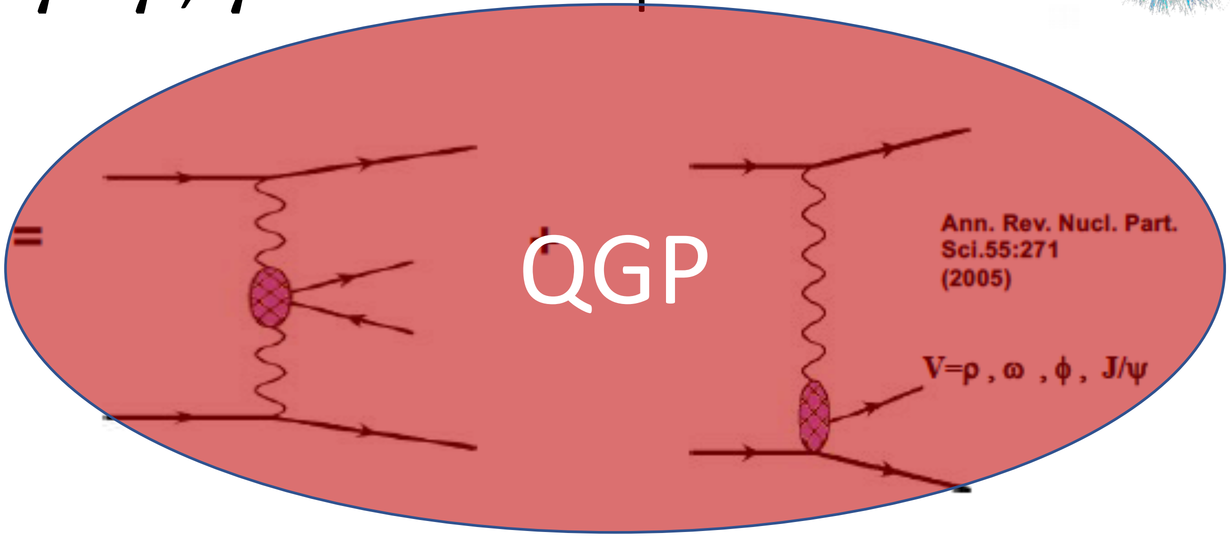

Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

photon-photon interaction ∝ $Z^4$

photonuclear interaction ∝ $Z^2$

# Coherent $\gamma+\gamma$, $\gamma$+nuclear processes



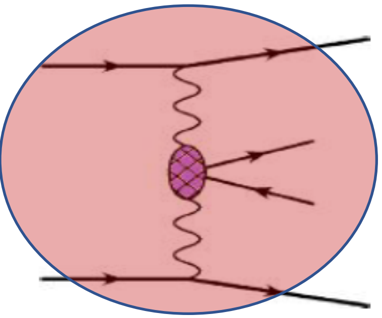




photon-photon interaction ∝ $Z^4$

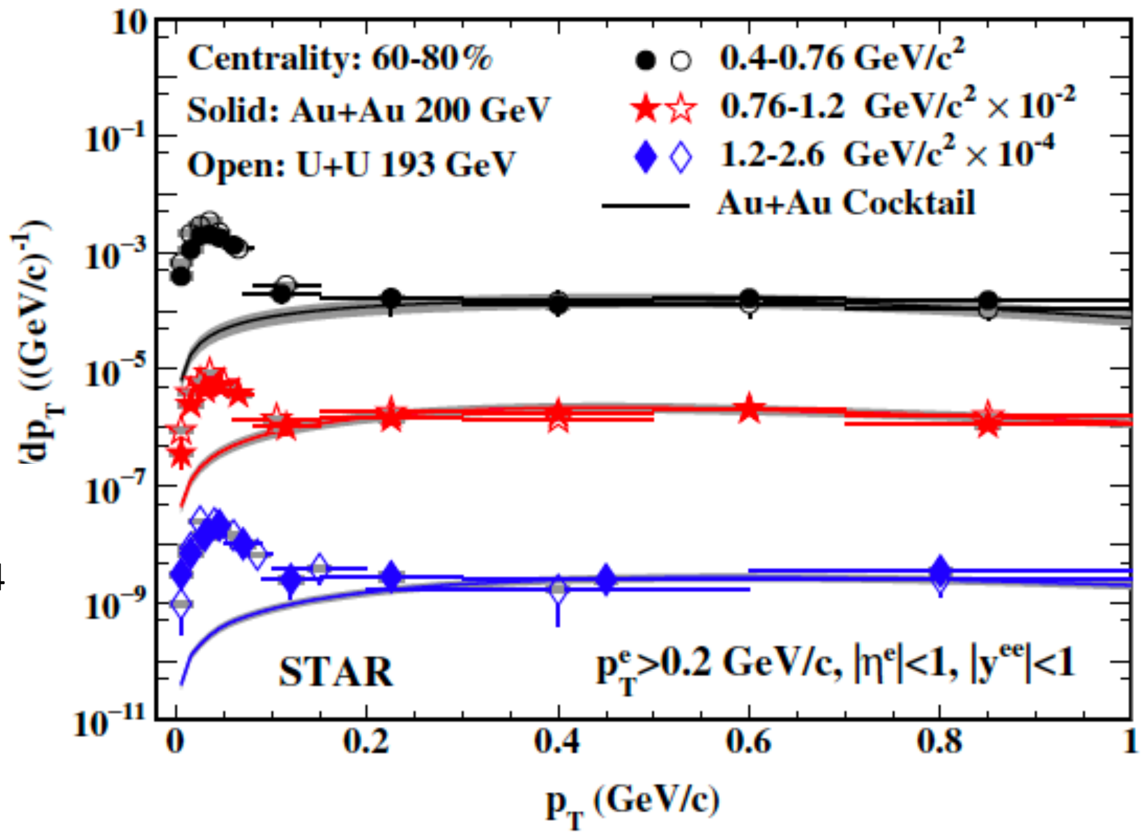
photonuclear interaction ∝ $Z^2$

- How about these processes in hot QGP?
- A new tool to study the QGP properties!

# Di-electron enhancement at low $p_T$



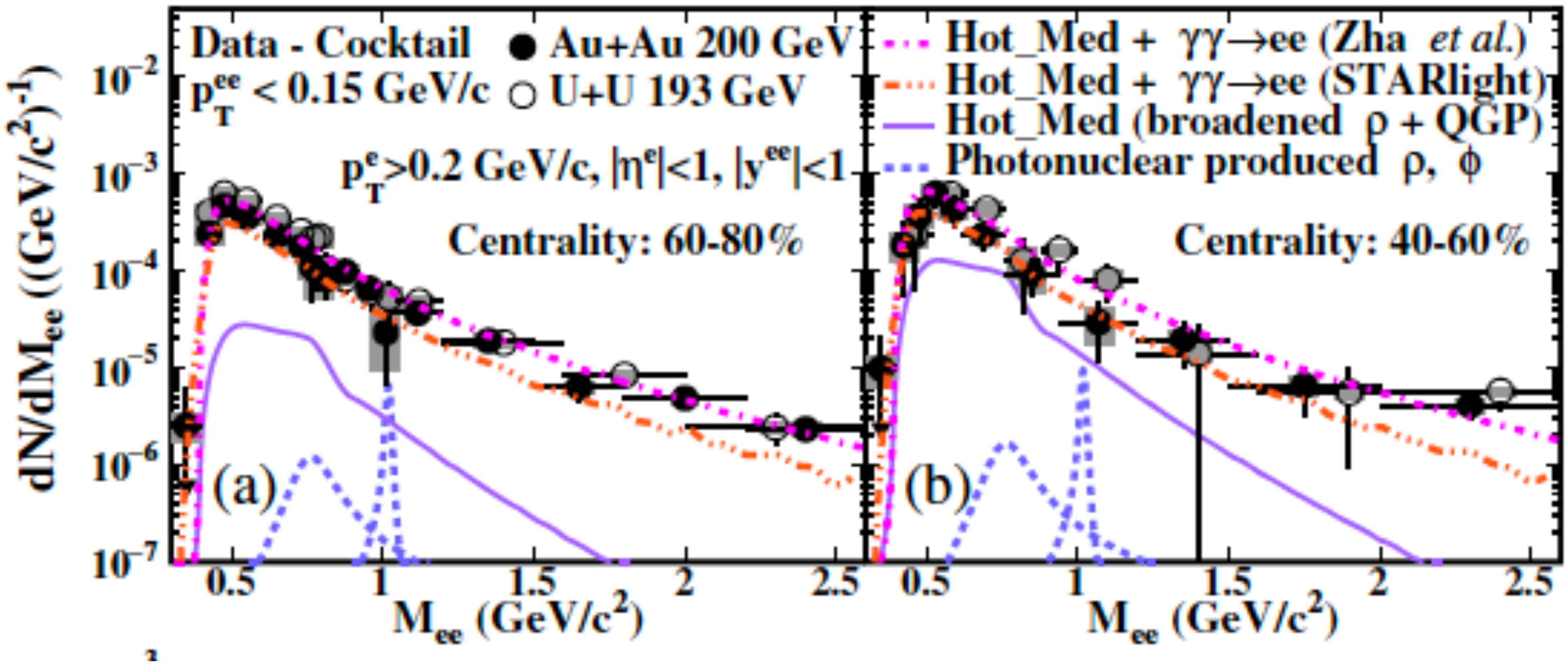
photon-photon interaction ∝ $Z^4$




STAR,PRL121(2018)132301

- Significant di-lepton enhancement at low $p_T$ is observed!

# Di-electron enhancement at low $p_T$



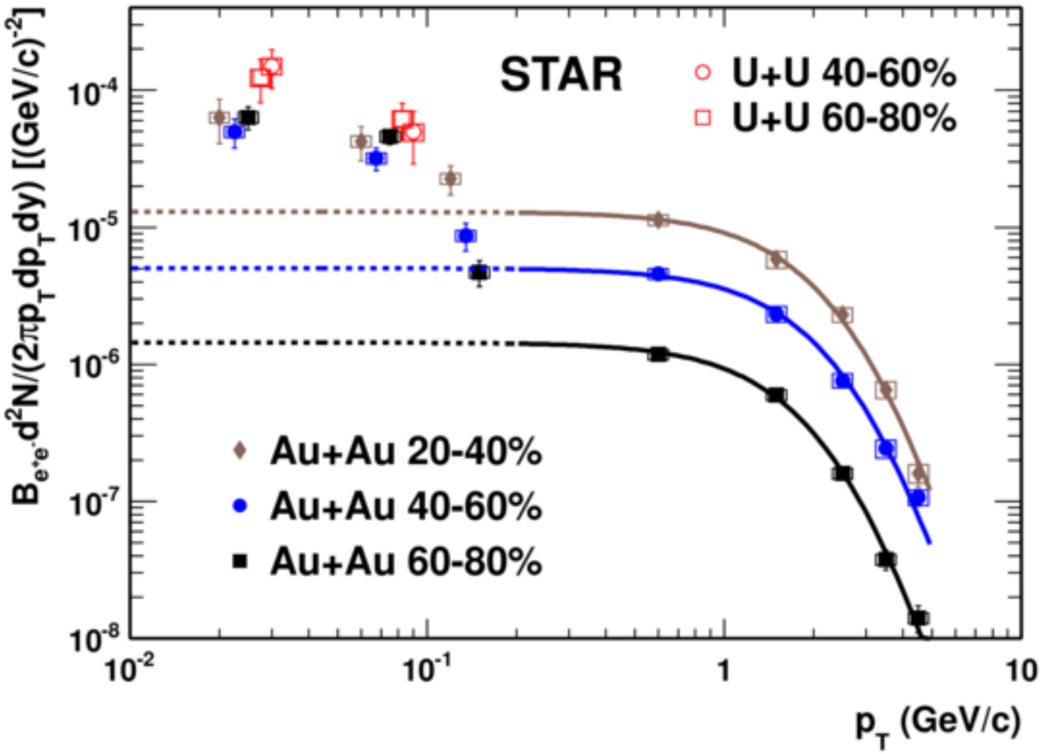

STAR,PRL121(2018)132301

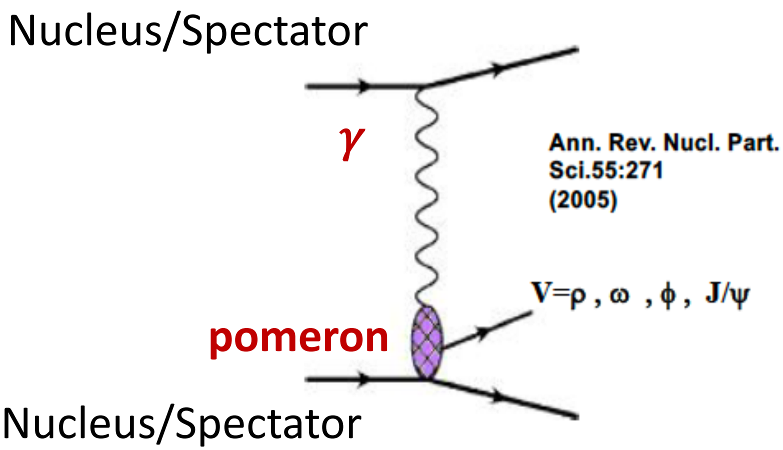
Comparing to model calculations:

- ➢ $\rho$ broadening in QGP can not explain the enhancement!
- ➢ Qualitatively consistent with model including photon-photon interactions

# Low $p_T$ J/$\psi$ enhancement

STAR, arXiv: 1904.11658



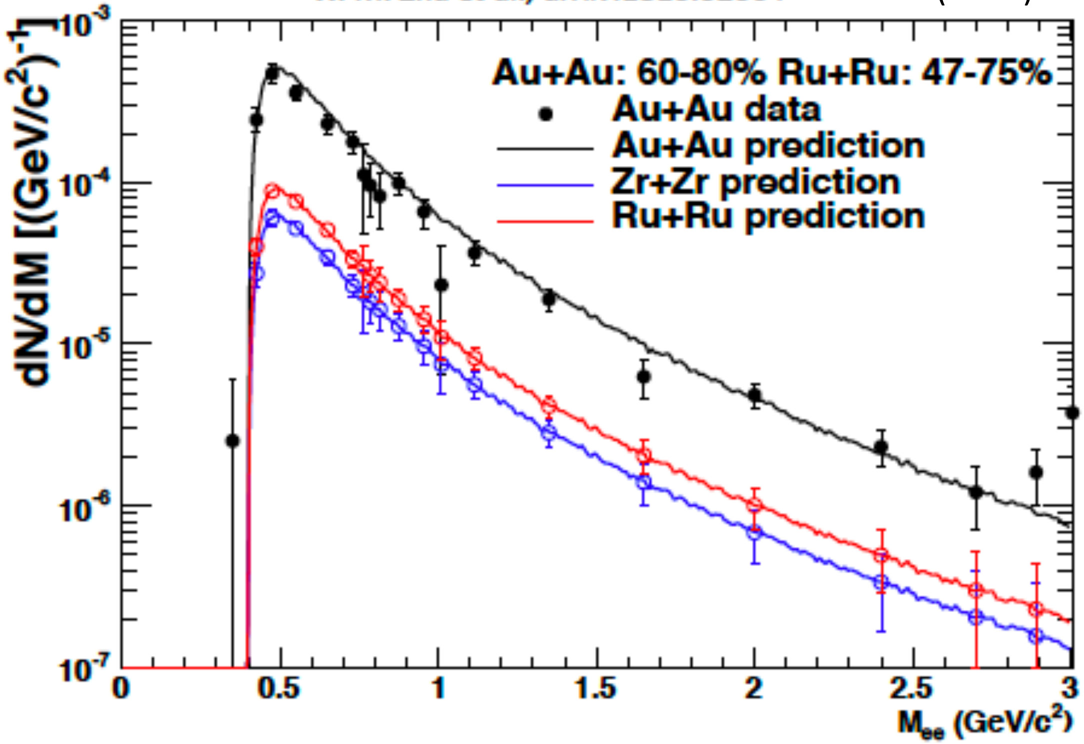



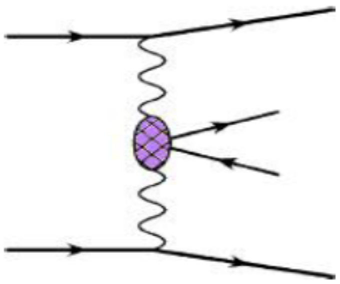

photonuclear interaction $\propto Z^2$

- Significant J/$\psi$ enhancement at low $p_T$ relative to extrapolation

# ${}^{96}_{44}Ru + {}^{96}_{44}Ru \; vs \; {}^{96}_{40}Zr + {}^{96}_{40}Zr$

*W. M. Zha et al., arXiv:1810.02064* PLB789 (2019) 238-242

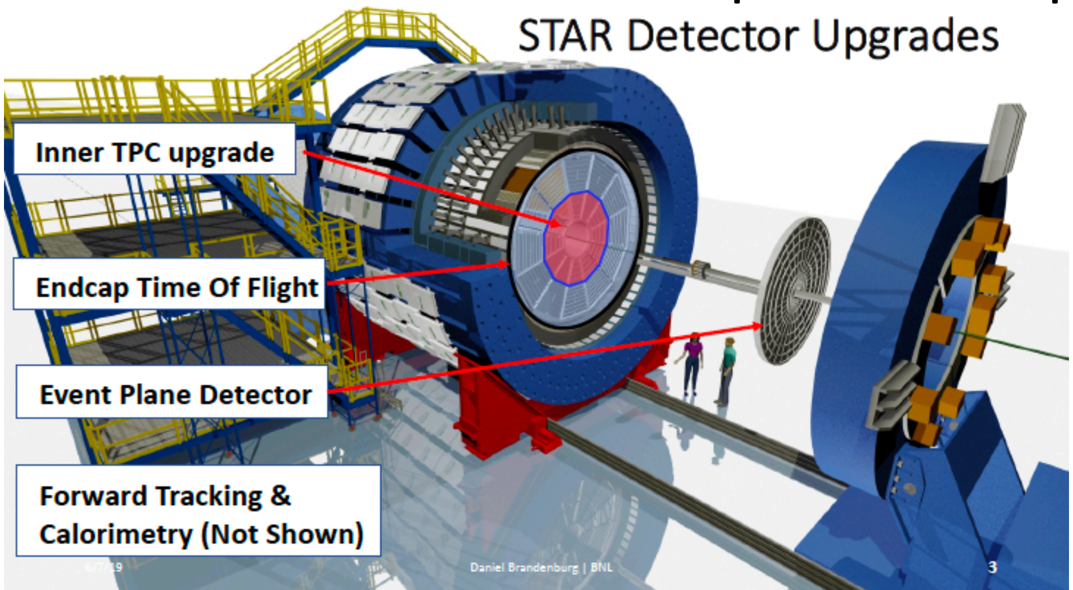


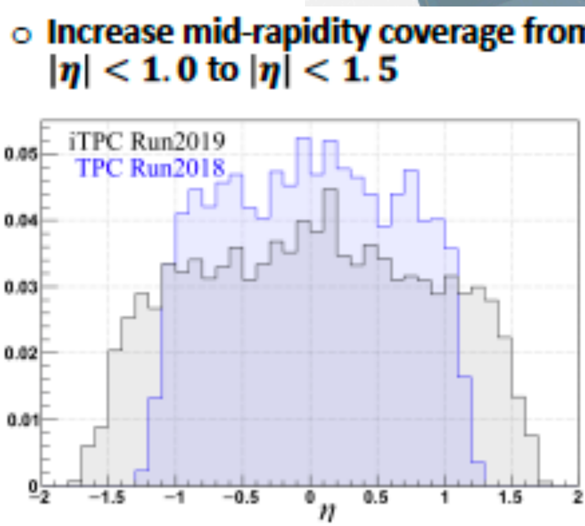
photon-photon interaction $\propto Z^4$

- 60-80% Au+Au vs. 47-75% Ru+Ru:
  Similar hadronic contribution
  Different contribution from photon-photon interactions
- Around 3.7$\sigma$ difference between Ru+Ru and Zr+Zr (estimated from 840M events). STAR recorded 1.6B events for each of them!

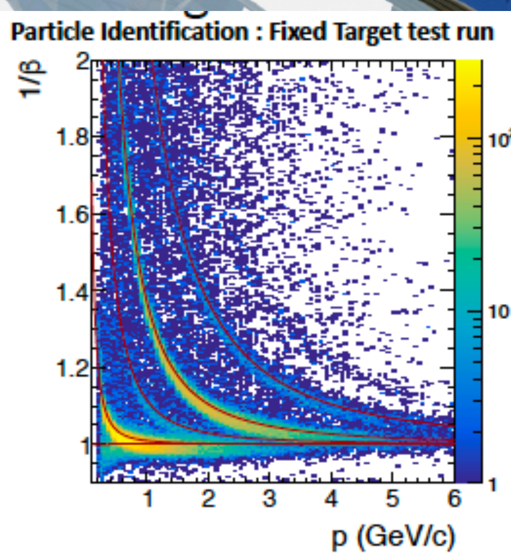
# Outlook: Recent completed upgrades



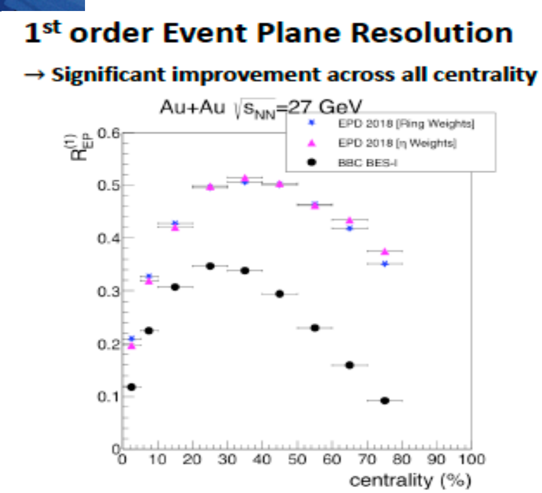

*Daniel Brandenburg*
Wed. 5:10 PM,329




iTPC:Tracking and PID~|$\eta$|<1.5



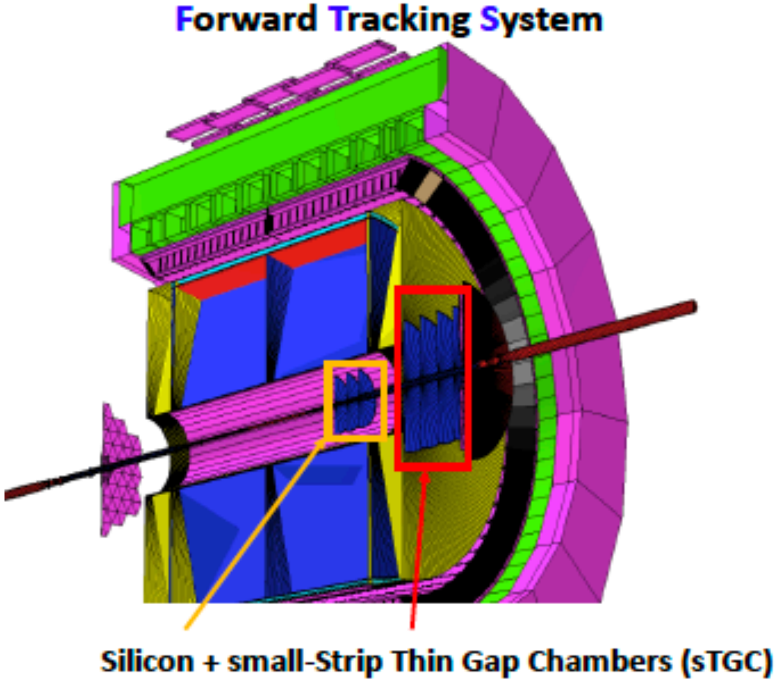

eTOF :PID~-1.6<$\eta$<-1.1

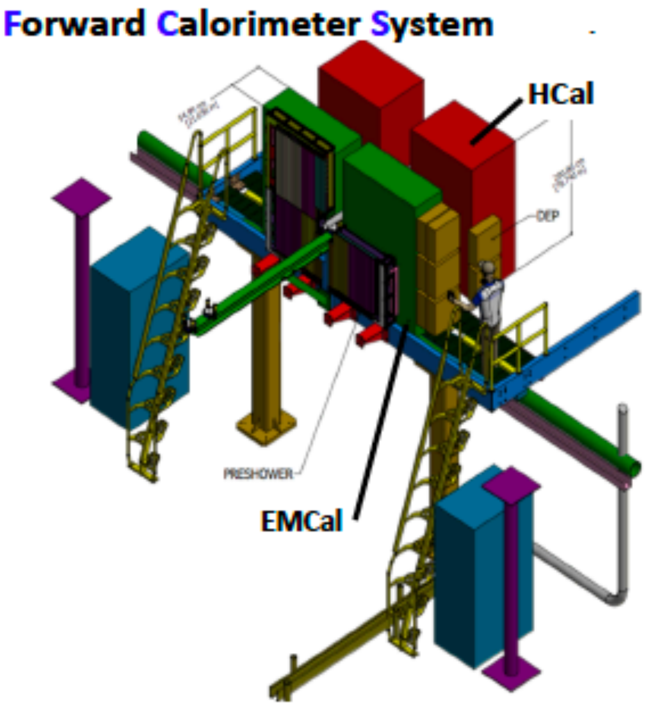



EPD: EP~2.1<|$\eta$|<5.1
and centrality

# Outlook: Forward Upgrade

STAR Forward Detectors: FTS + FCS **(2.5<$\eta$<4.0)**




- Positive BNL internal review last Nov. and will be ready for 2022
- Very valuable for both cold QCD and heavy ion physics

# What STAR can do in small systems in future?

- Enhanced STAR acceptance/kinematics
  - New subsystems: iTPC ($|\eta|<1.5$, PID), EPD ($2.1<|\eta|<5$) and eTOF (2019+)
  - Forward upgrade with $p_T$, $E_T$ and some ID ($K_s$,$\Lambda$,$\pi^0$) at $2.5<\eta<4$ (2021+)

- Enable quantitative improvements over Geometry-scan I
  - Quantitative control of non-flow systematics, behavior of collectivity at low $N_{ch}$.
  - Longitudinal dynamics and their impact on existing results
  - Comprehensive studies of multi-particle correlation (like LHC)
    - Multi-particle cumulants, symmetric and asymmetric cumulants with subevent methods

- As a first step, STAR proposes a one-week O+O run before 2022
  - Take 400 M minbias events and 200 M 0-5% central events

# Why O+O?

- A O+O run at LHC around horizon (likely in 2023)

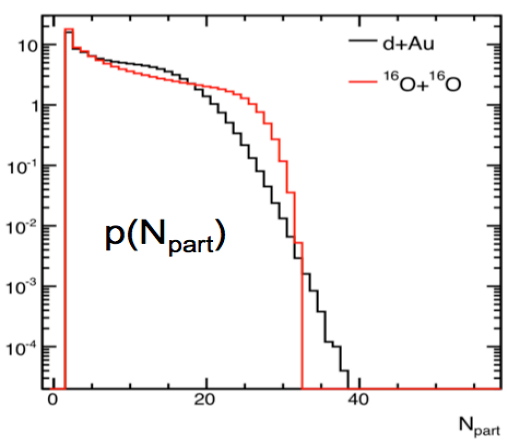
Arxiv.1812.06772

Proposed LHC run schedule

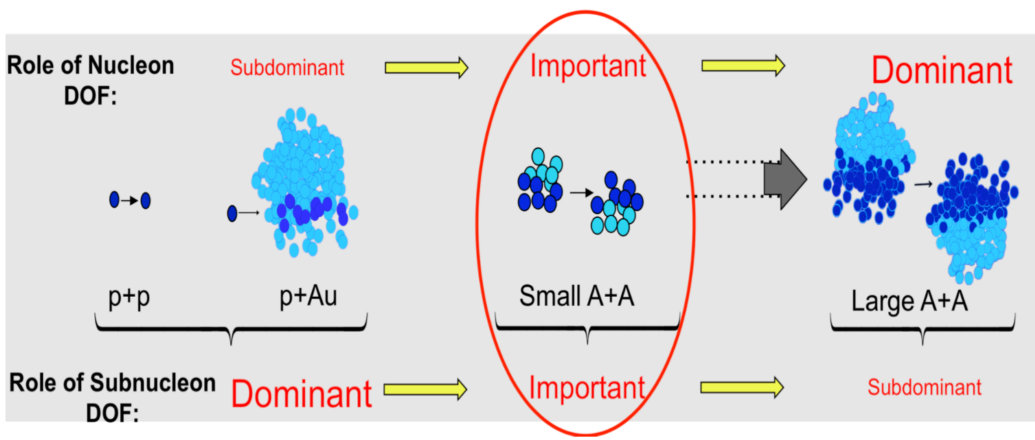
| Year | Systems, $\sqrt{s_{NN}}$ | Time | $L_{int}$ |
|---|---|---|---|
| 2021 | Pb–Pb 5.5 TeV | 3 weeks | 2.3 $nb^{-1}$ |
| | pp 5.5 TeV | 1 week | 3 $pb^{-1}$ (ALICE), 300 $pb^{-1}$ (ATLAS, CMS), 25 $pb^{-1}$ (LHCb) |
| 2022 | Pb–Pb 5.5 TeV | 5 weeks | 3.9 $nb^{-1}$ |
| | O–O, p–O | 1 week | 500 $\mu b^{-1}$ and 200 $\mu b^{-1}$ |
| 2023 | p–Pb 8.8 TeV | 3 weeks | 0.6 $pb^{-1}$ (ATLAS, CMS), 0.3 $pb^{-1}$ (ALICE, LHCb) |
| | pp 8.8 TeV | few days | 1.5 $pb^{-1}$ (ALICE), 100 $pb^{-1}$ (ATLAS, CMS, LHCb) |

## A O+O run at RHIC after BES II is timely

- **First** comparison between RHIC & LHC with ~identical Glauber geometry but different sub-nucleon fluctuation ($Q_s$) for a factor of 10 difference in energy




less centrality bias & better selection of geometry ($N_{part}$, $\varepsilon_n$)




Interplay of nucleon vs subnucleon fluctuations

# Summary

- Collectivity in small system → Small QGP droplet?
- Flow correlations and decorrelation, which supply new constrain on 3D initial condition and medium properties
- $v_1$ of $D^0$ to probe the tilted QGP and large signal is observed. Measured difference between $D^0$ and $\overline{D^0}$ is not precise enough to be sensitive to EM field
- Study vorticity using $\Lambda$ global/local polarization measurement, the local vorticity shows quadrupole structure which can not be explained by hydro calculation
- We measured low $p_T$ di-lepton and $J/\psi$ production from strong EM field, which provide new tool to study the QGP

# Summary

- Collectivity in small system→ Small QGP droplet?
- Flow correlations and decorrelation, which supply new constrain on 3D initial condition and medium properties
- $v_1$ of $D^0$ to probe the tilted QGP and large signal is observed. Measured difference between $D^0$ and $\overline{D^0}$ is not precise enough to be sensitive to EM field
- Study vorticity using $\Lambda$ global/local polarization measurement, the local vorticity shows quadrupole structure which can not be explained by hydro calculation
- We measured low $p_T$ di-lepton and $J/\psi$ production from strong EM field, which provide new tool to study the QGP

- Recently STAR upgrade(iTPC, EPD and eTOF) and future approved STAR forward upgrade significantly extend STAR acceptance and PID ability
- These upgrades will provide new opportunity to study collectivity in small systems
- STAR proposes O+O run before 2022, which will be helpful to study initial geometry, thermalization and jet quench in small system

# Backup

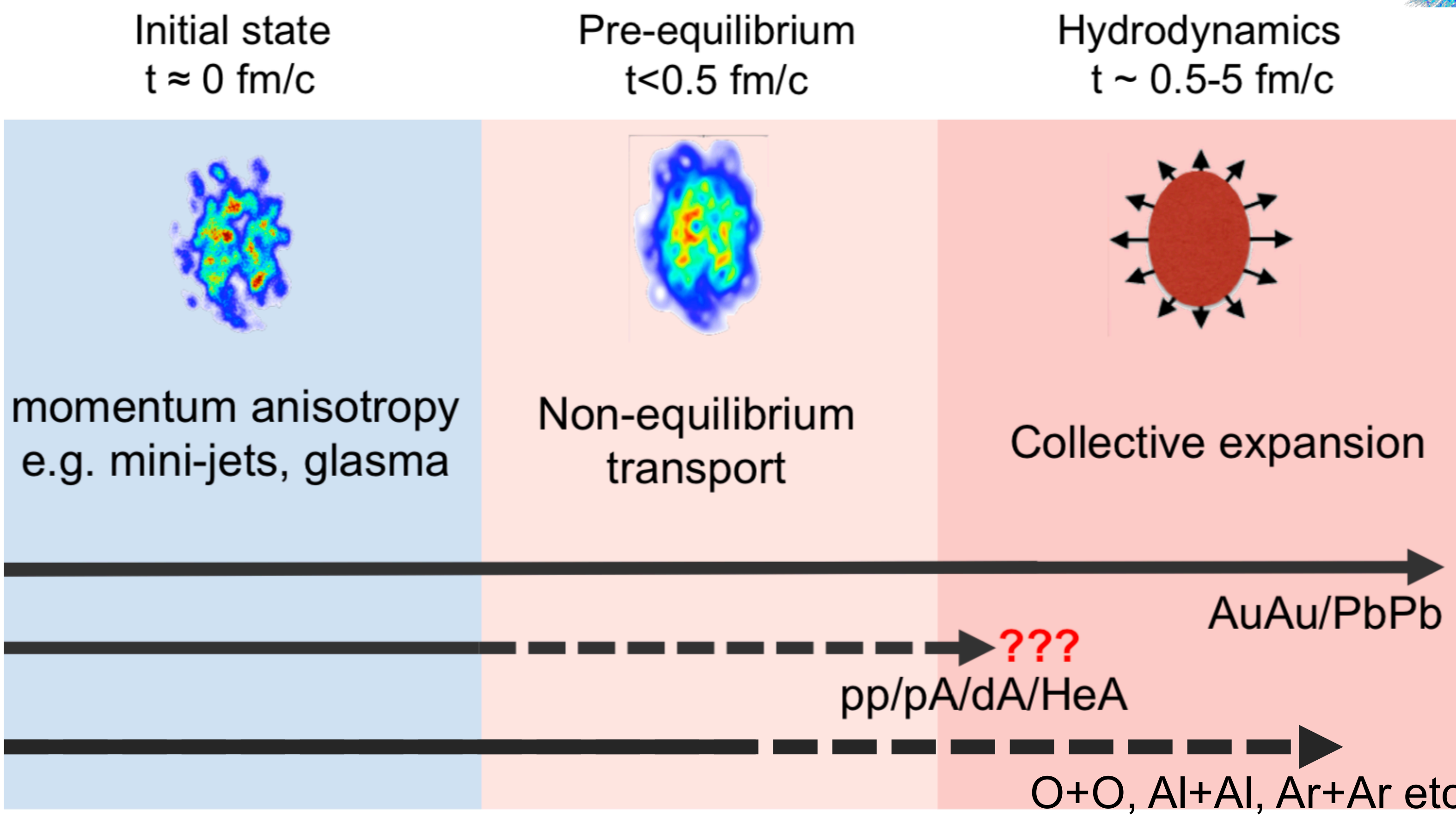
| | Hydro−1 [43] | Hydro−$2^{a/b}$ [44] |
|---|---|---|
| $\eta/s$ | 0.05 | 0.12 |
| Initial conditions | TRENTO Initial conditions | IP-Glasma Initial conditions |
| Contributions | Hydro only | (a) Hydro + Hadronic cascade<br>(b) Hydro only |

(1) P. Alba, et al. PRC 98 , 034909 (2018)

(2) B.Schenke, et al. PRC 99, 044908 (2019)

Hydro. calculations which can describe single particle $v_n\{k\}$ need more work for 3-particle correlations.

# Origin of collectivity in small system

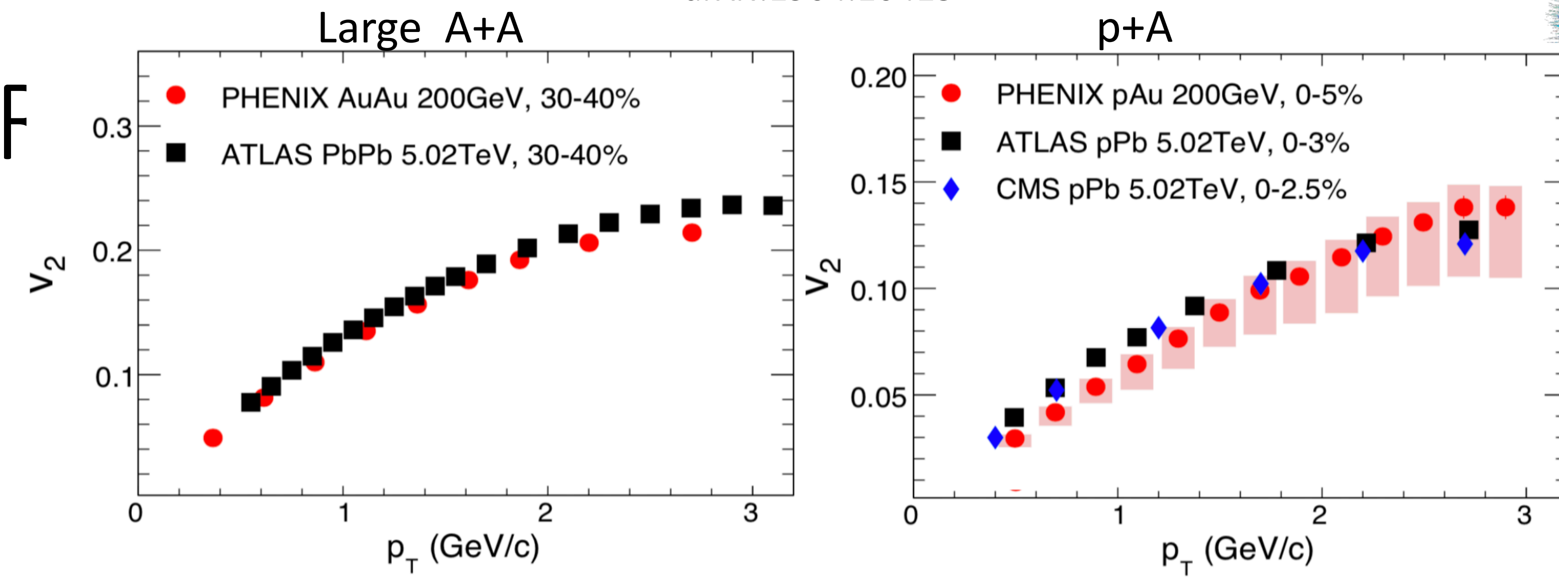



- Extend the lever-arm to disentangle contributions from three stages
  - Where initial-state interaction become sub-dominant?
  - What is the role of pre-equilibrium vs. hydrodynamics?

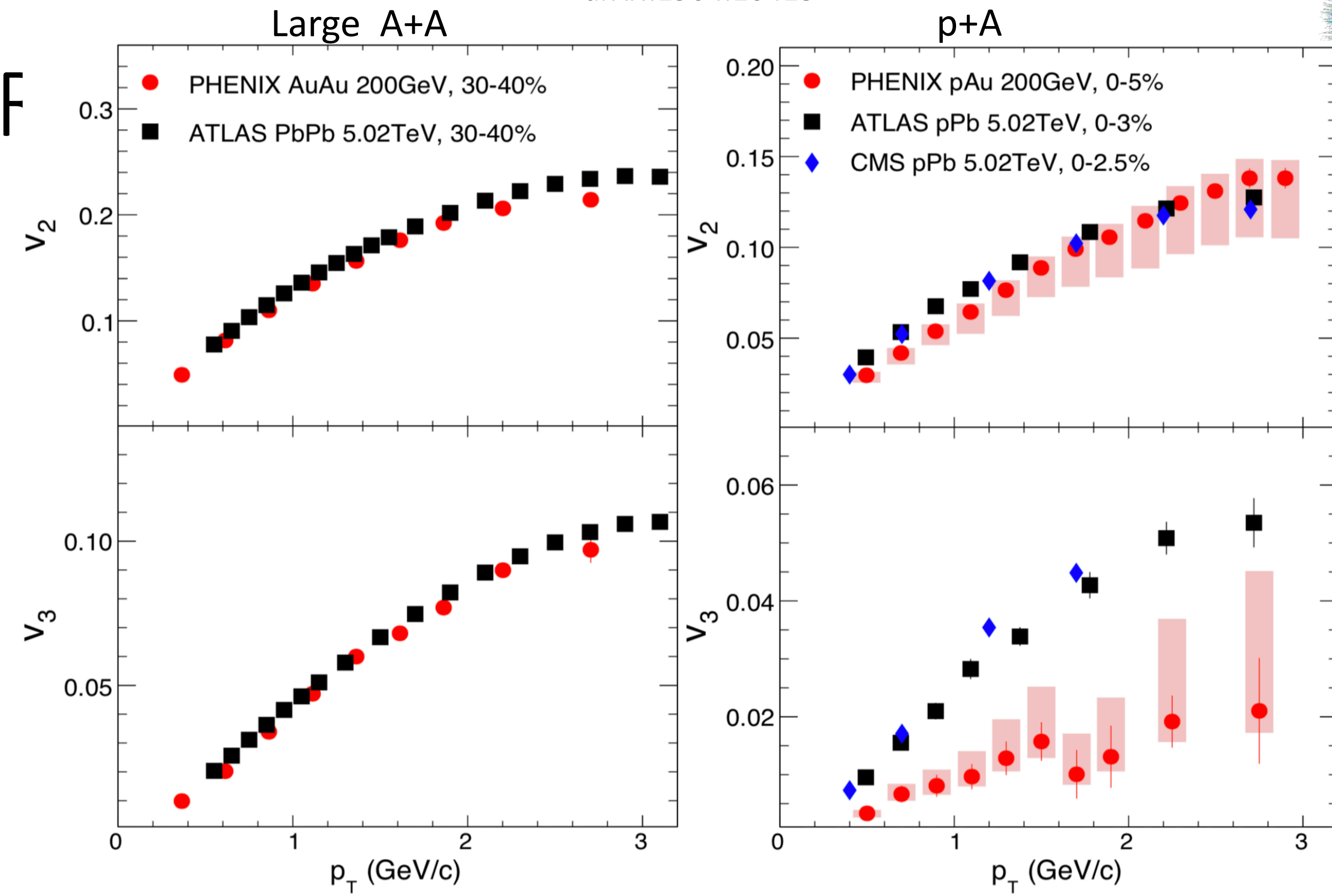
Further system-size scan needed! Only RHIC can do this!

F

arXiv.1904.10415



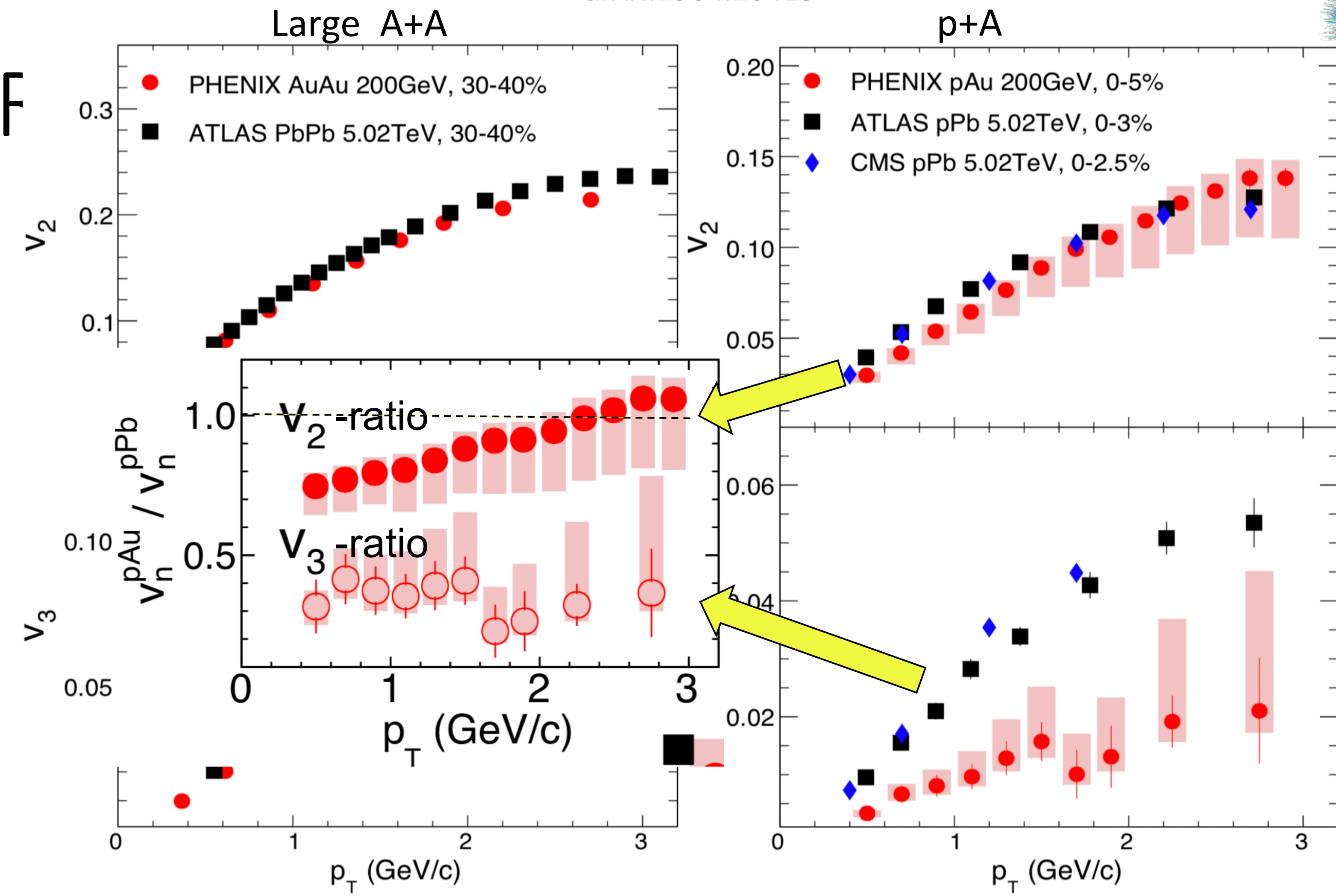

No energy dependence of $v_2$ in pA vs AA arXiv.1904.10415




No energy dependence of $v_2$ in pA vs AA

Different energy dependence of $v_3$ in pA vs AA?

arXiv.1904.10415

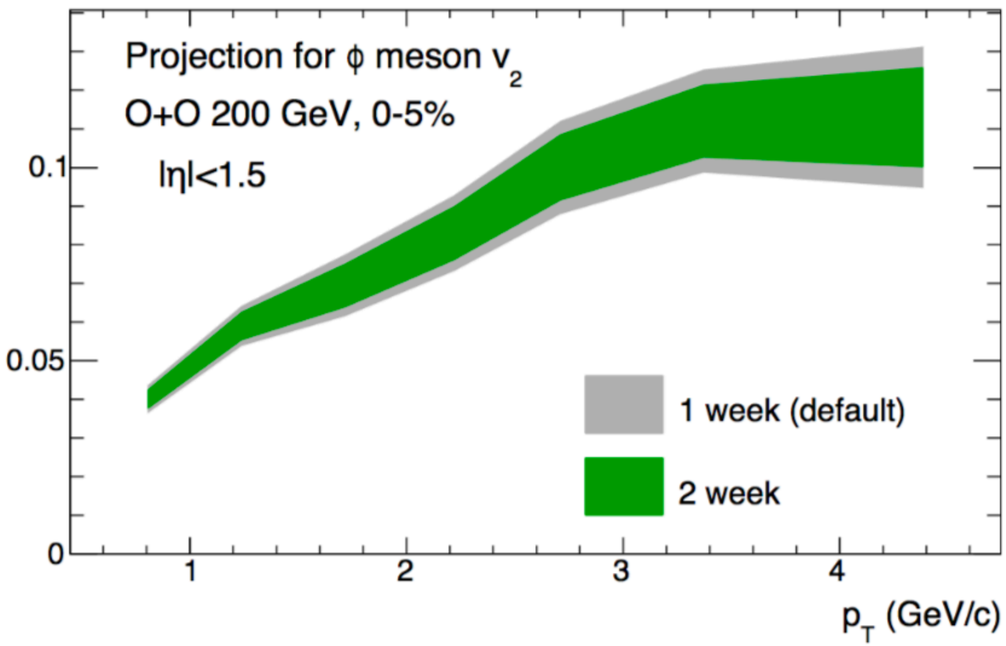


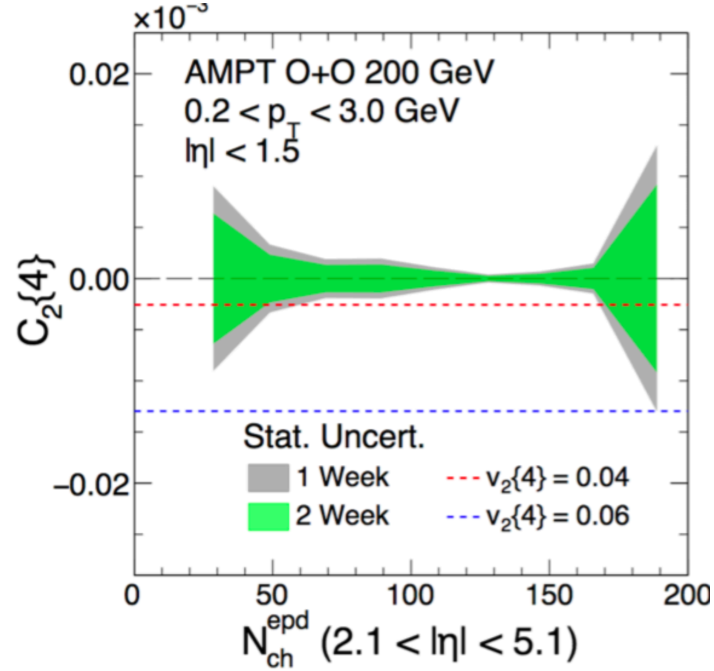

No energy dependence of $v_2$ in pA vs AA

Different energy dependence of $v_3$ in pA vs AA?

O+O comparison probe the behavior in between

# Physics potential




Decent measurement of PID flow
Decent measurement of multi-particle correlation More to come...

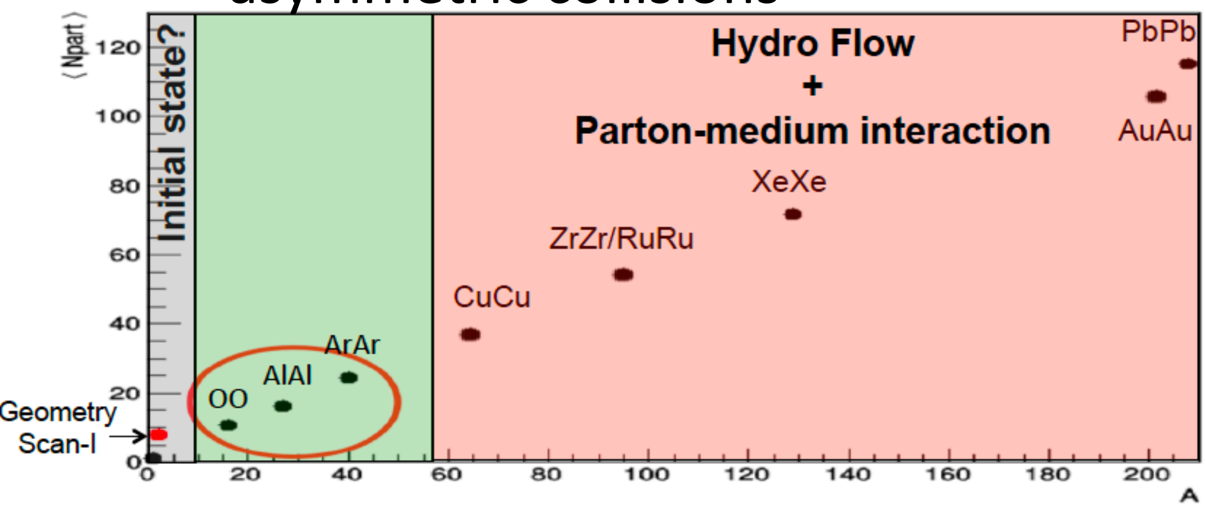
# Future Small System Scan

STAR with new detector capability for collectivity in small system:

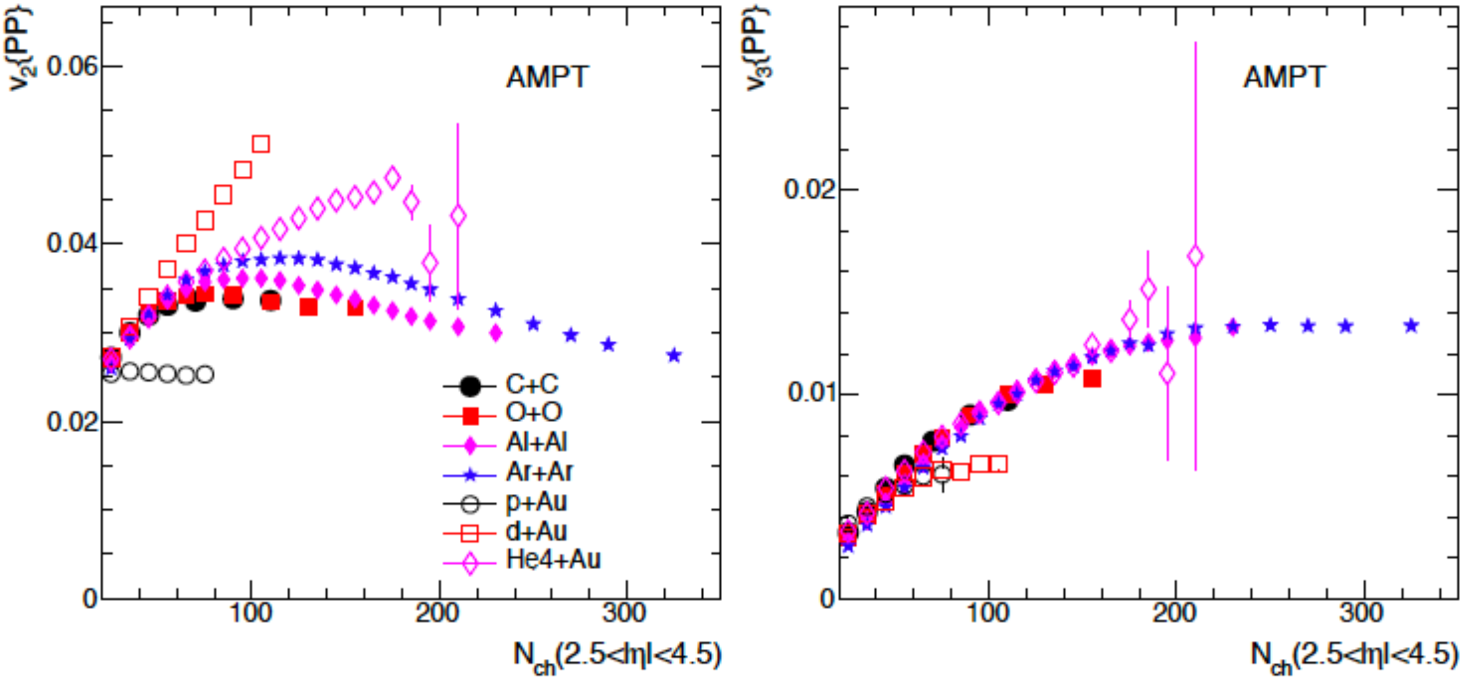
- ✓ Large acceptance to handle the nonflow
- ✓ Study longitudinal decorrelation effect on flow measurement
- ✓ Multi-particle cumulant in different rapidity

Opportunity for further small system scan at RHIC :

- ✓ Extend the level-arm with small AA collisions
- ✓ Initial geometry is different between symmetric and asymmetric collisions



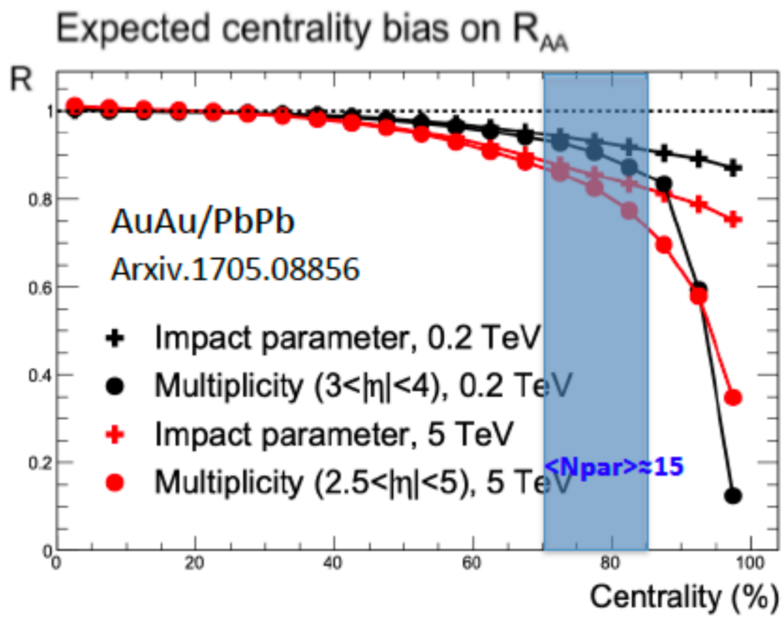
# AMPT O+O

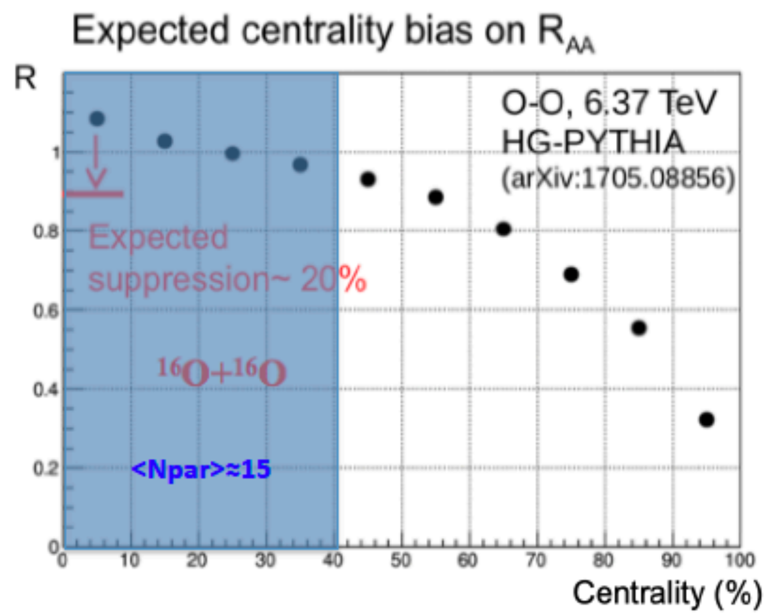



arXive:1904.10415

Where initial-state interaction become sub-dominant?
The role of pre-equilibrium vs. hydro?

# Outlook: O+O run



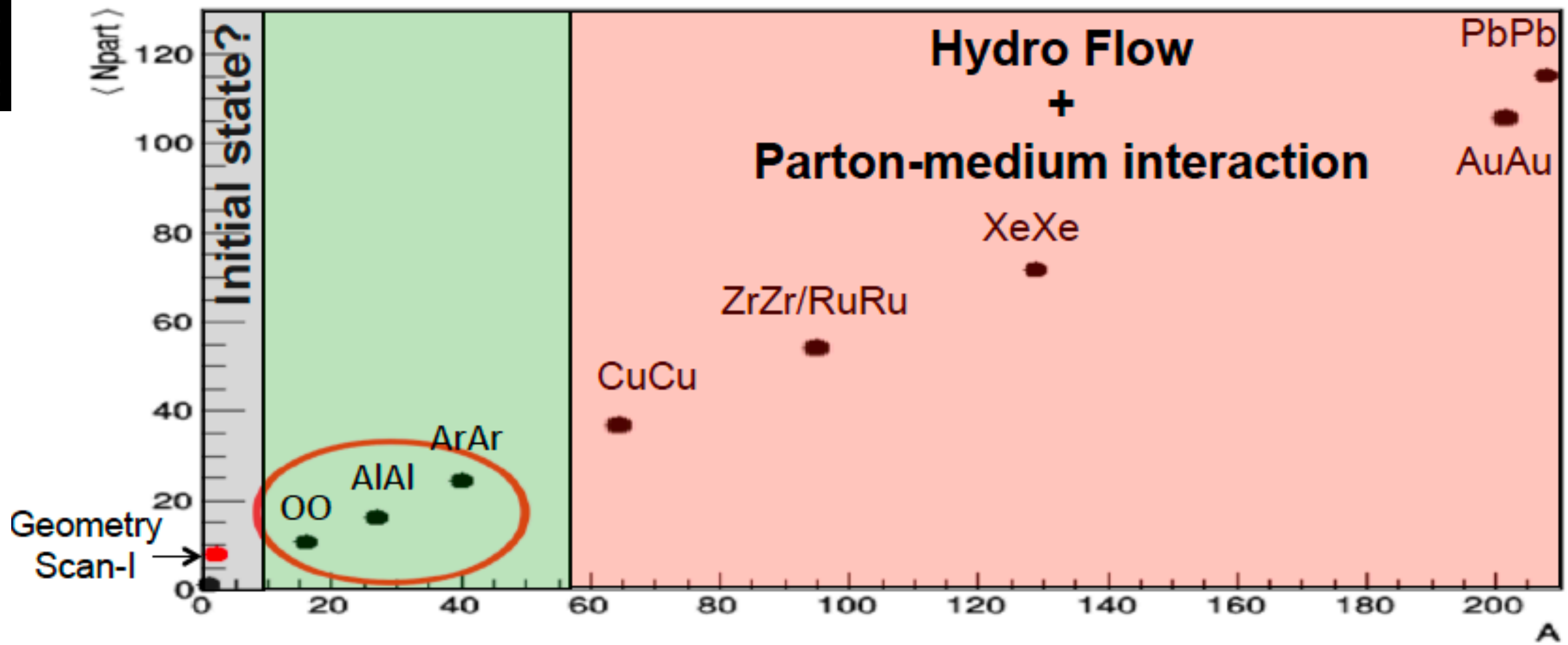




Where initial-state interaction become sub-dominant?
The role of pre-equilibrium vs. hydro?
Turn-on of jet quenching and heavy-flavor "thermalization"?



arXive:1904.10415

# Outlook: O+O run



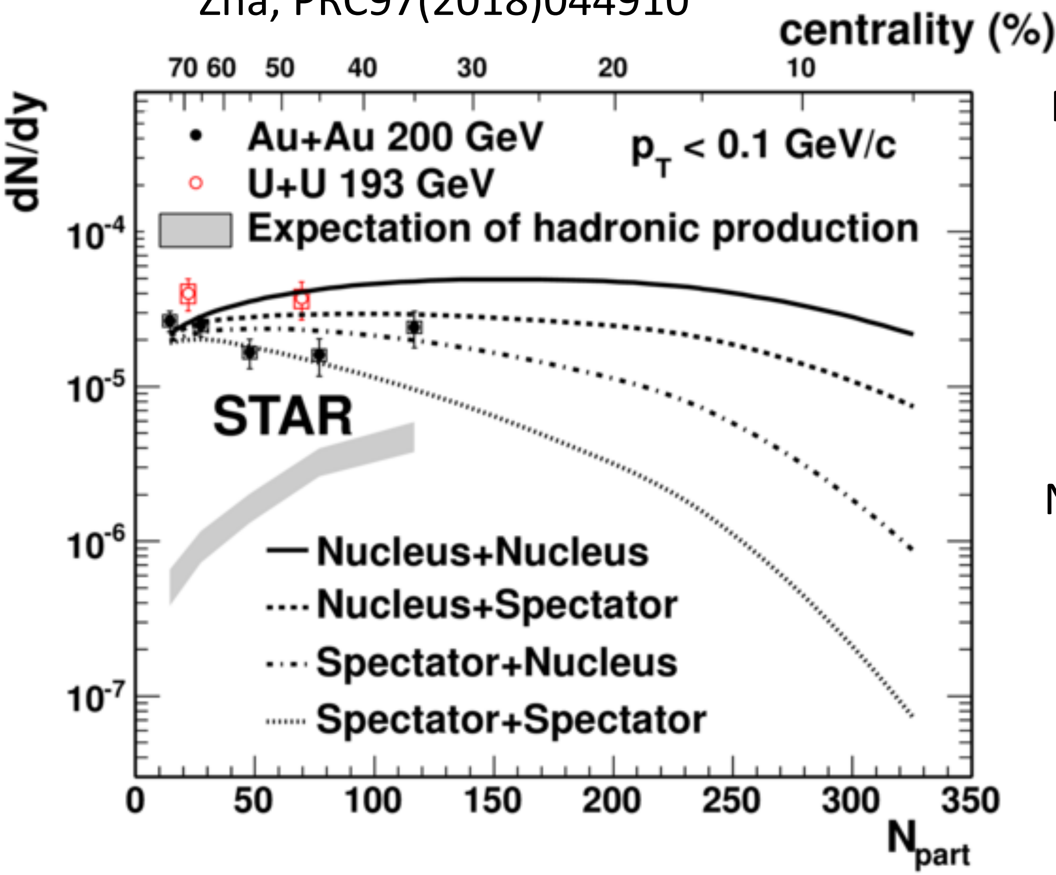

Where initial-state interaction become sub-dominant?
The role of pre-equilibrium vs. hydro?
Turn-on of jet quenching and heavy-flavor "thermalization"?
**System size scan needed!! Only RHIC can do!!**

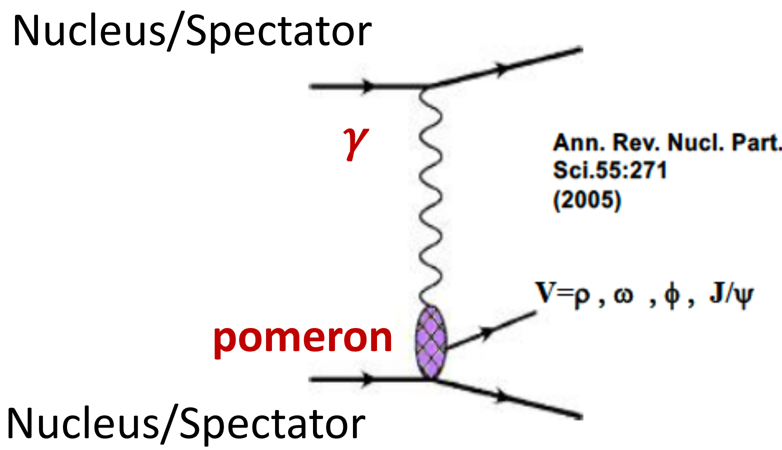


arXive:1904.10415

# Low $p_T$ J/$\psi$ enhancement

Zha, PRC97(2018)044910




photonuclear interaction $\propto Z^2$

- Much larger than expectation from hadronic production
- Qualitatively described by photonuclear interaction