Selected STAR Highlight

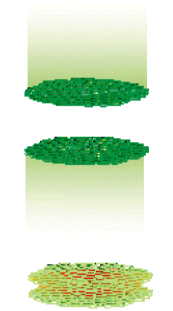
Shengli Huang

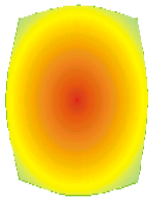
for STAR collaboration

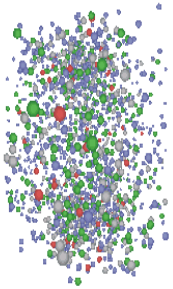
Stony Brook University, Chemistry Department

Outline

τ<0.5fm







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γ+γ, γ+nucleus interaction

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D^0 v_1, Λ polarization

Low p_T di-lepton, J/ψ

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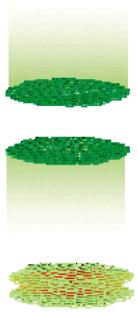

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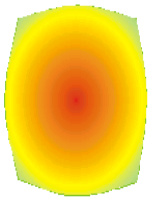

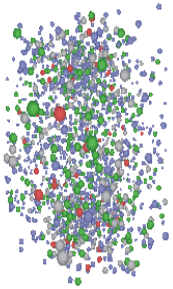

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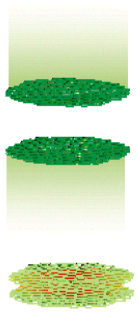

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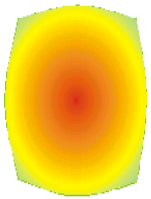

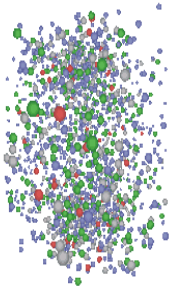

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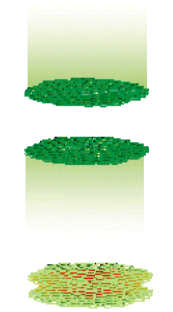

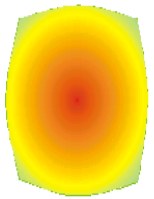

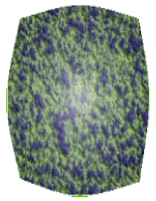

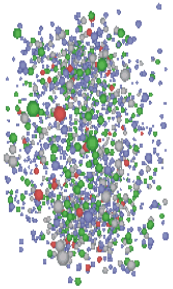

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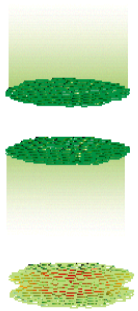

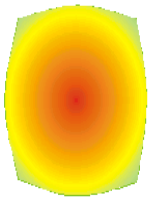

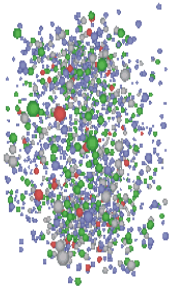

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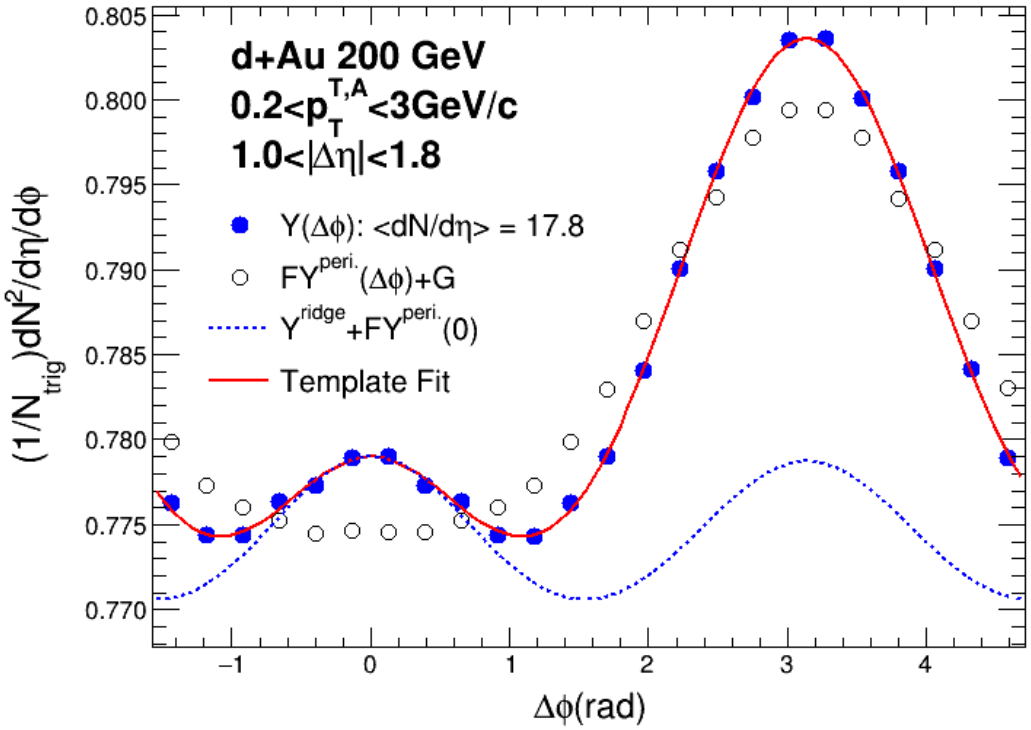

Two particle correlation in d+Au@200GeV with $|\eta|$<0.9 and $|\Delta\eta|$>1.0

Event activity: BBC (-2>η>-5)
HM: ridge + jet
LM: jet

Ridge signal (flow) is extracted by template fit

- $Y_{templ.}(\Delta\phi) = F \times Y_{peri.}(\Delta\phi) + Y_{ridge}(\Delta\phi)$
- 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 (2016)

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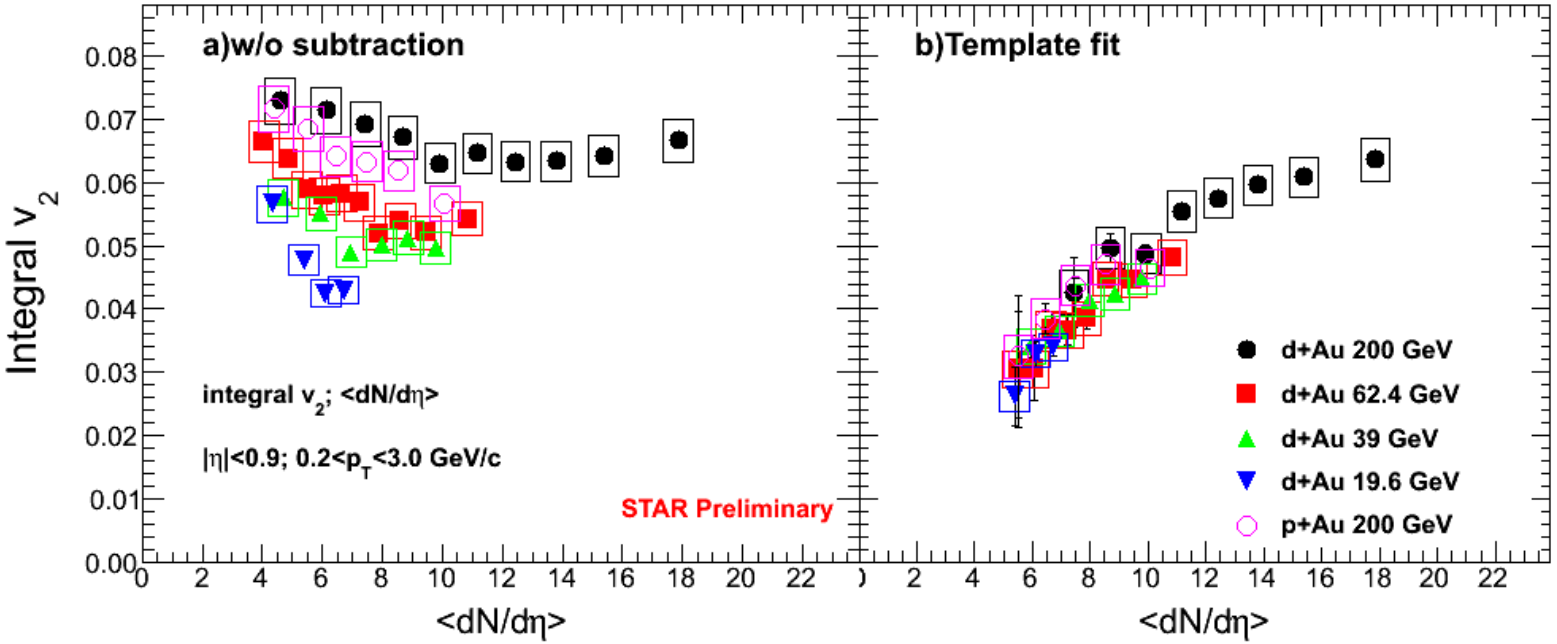

- v_2 from template fit shows a universal trend as a function of <dN/dη>

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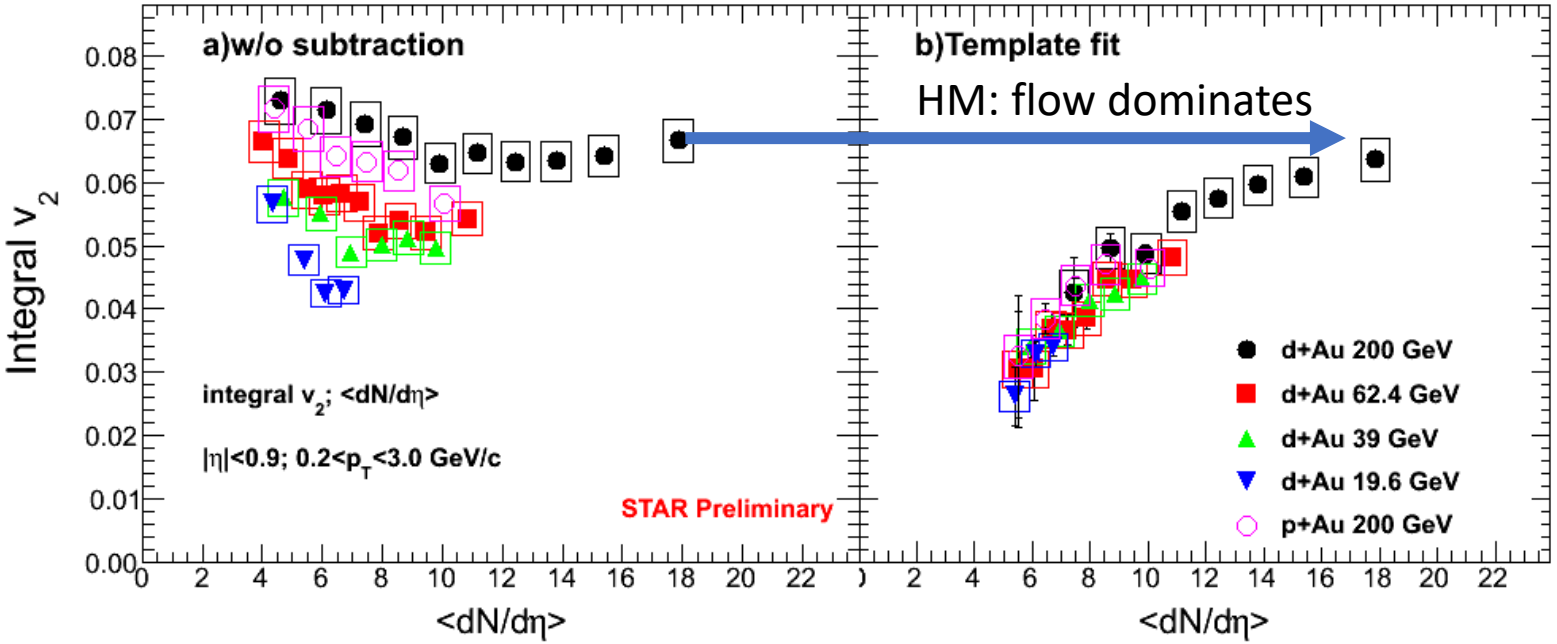

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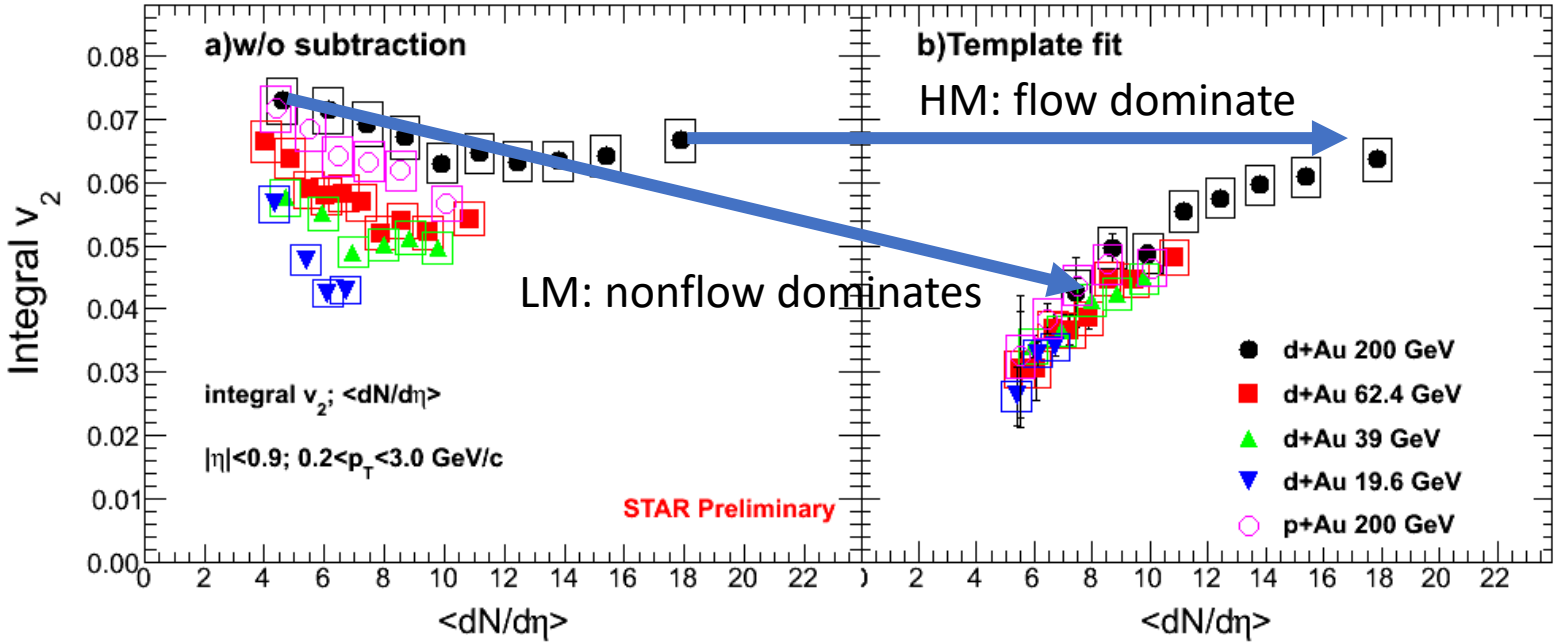

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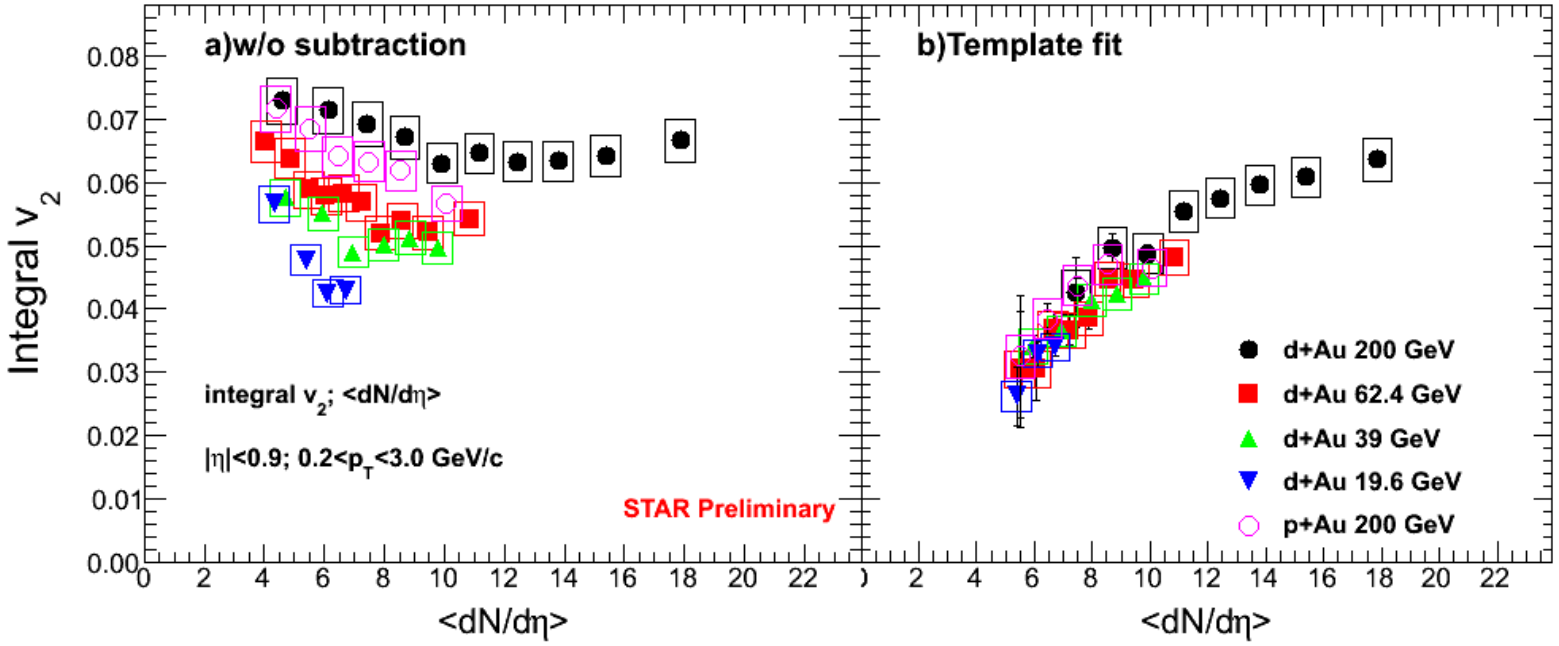
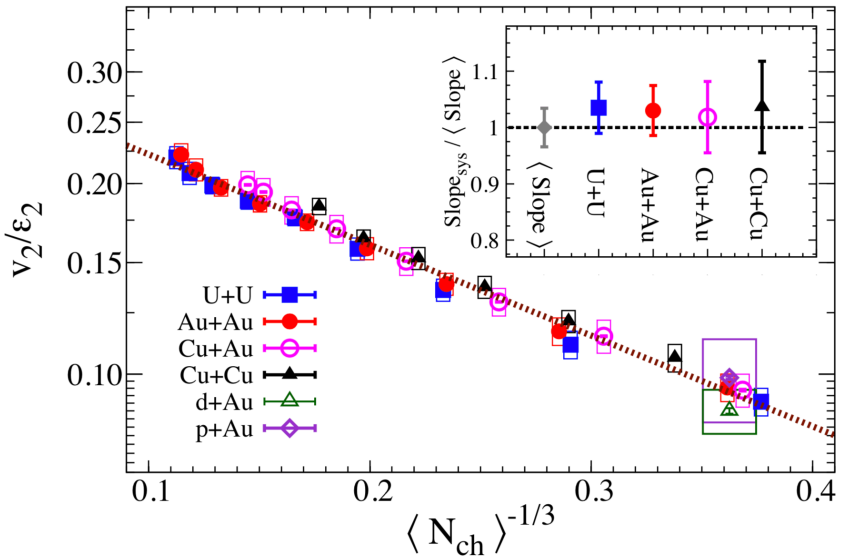
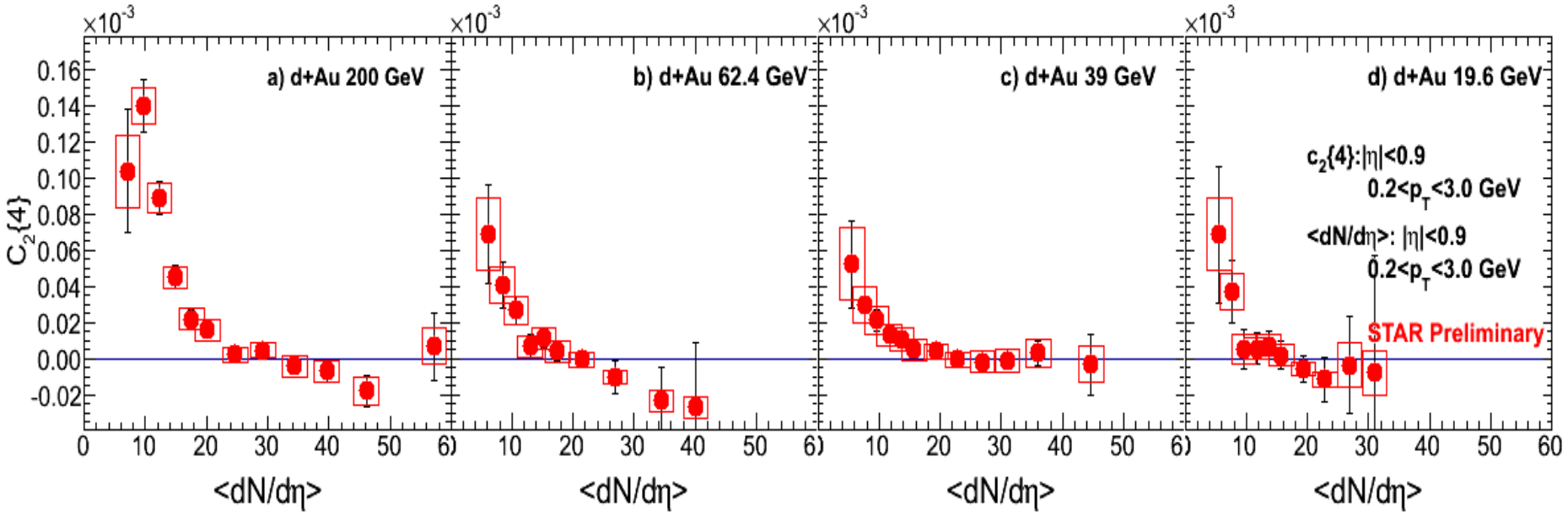


STAR, PRL **122** (2019) 172301



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

$c_2\{4\}$ vs <dN/dη>



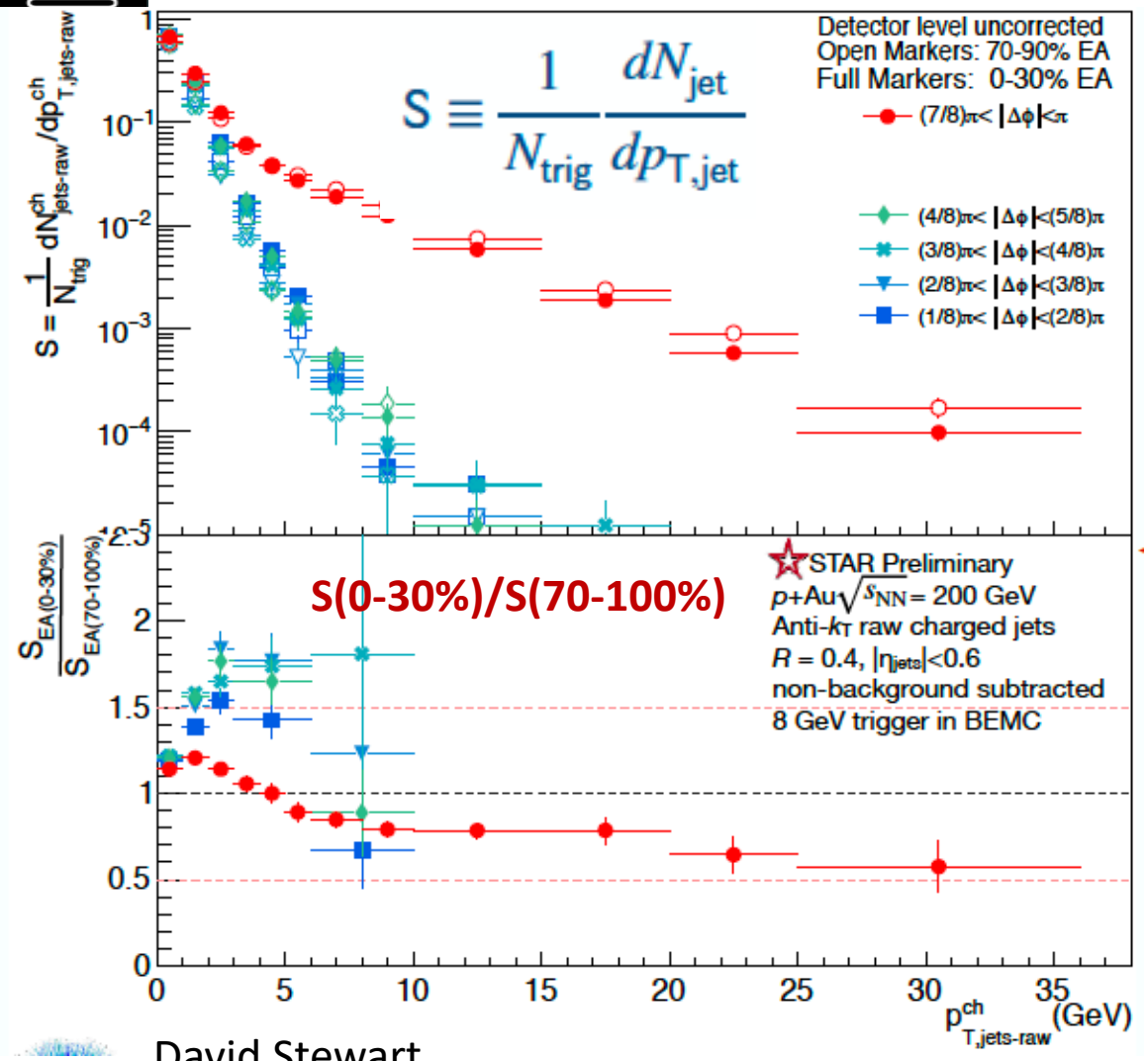
$c_2\{4\} = \ll e^{-i2(\phi_i+\phi_j-\phi_k-\phi_l)} \gg -2 \ll e^{-i2(\phi_i-\phi_j)} \gg$

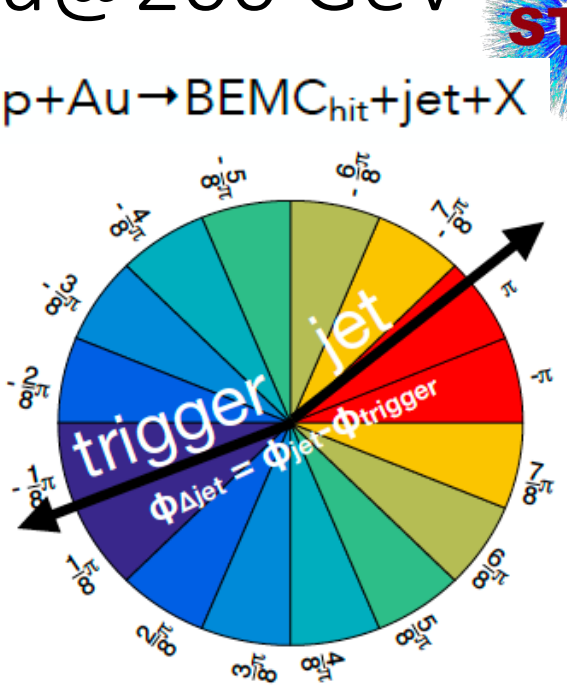
$\phi_i, \phi_j, \phi_k, \phi_l$ are the azimuthal angles of four different particles in an event ; 《》 represents the average over all particles from all events within a given multiplicity range

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

- $c_2\{4\}$ 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

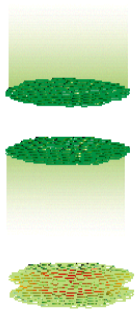
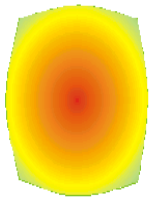
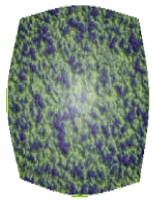
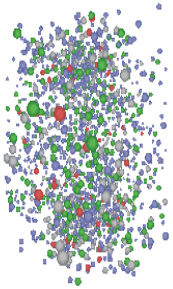




- Event activity by BBC
- Suppression of away side jet above 10 GeV/c
- Due to bias of event selection?
- Is there still room for medium modification?

David Stewart
Wed 5:10 PM ,301

Outline

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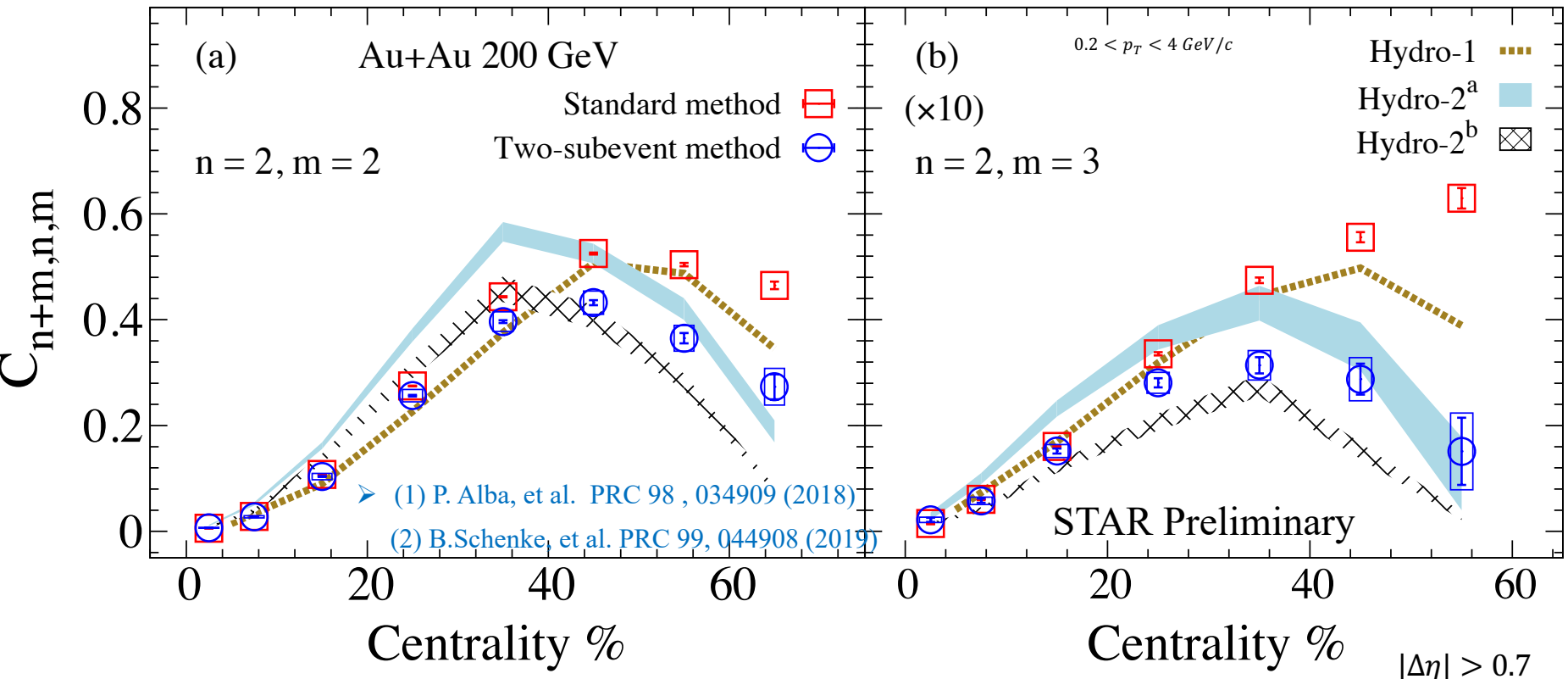
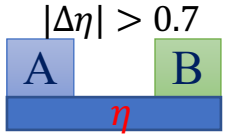
Flow correlation

$C_{4,22} = < v_4 v_2^2 cos(4\psi_4 - 4\psi_2) >$

$C_{5,23} = < v_5 v_3 v_2 cos(5\psi_5 - 3\psi_3 - 2\psi_2) >$



- Two-subevents method to suppress the non-flow

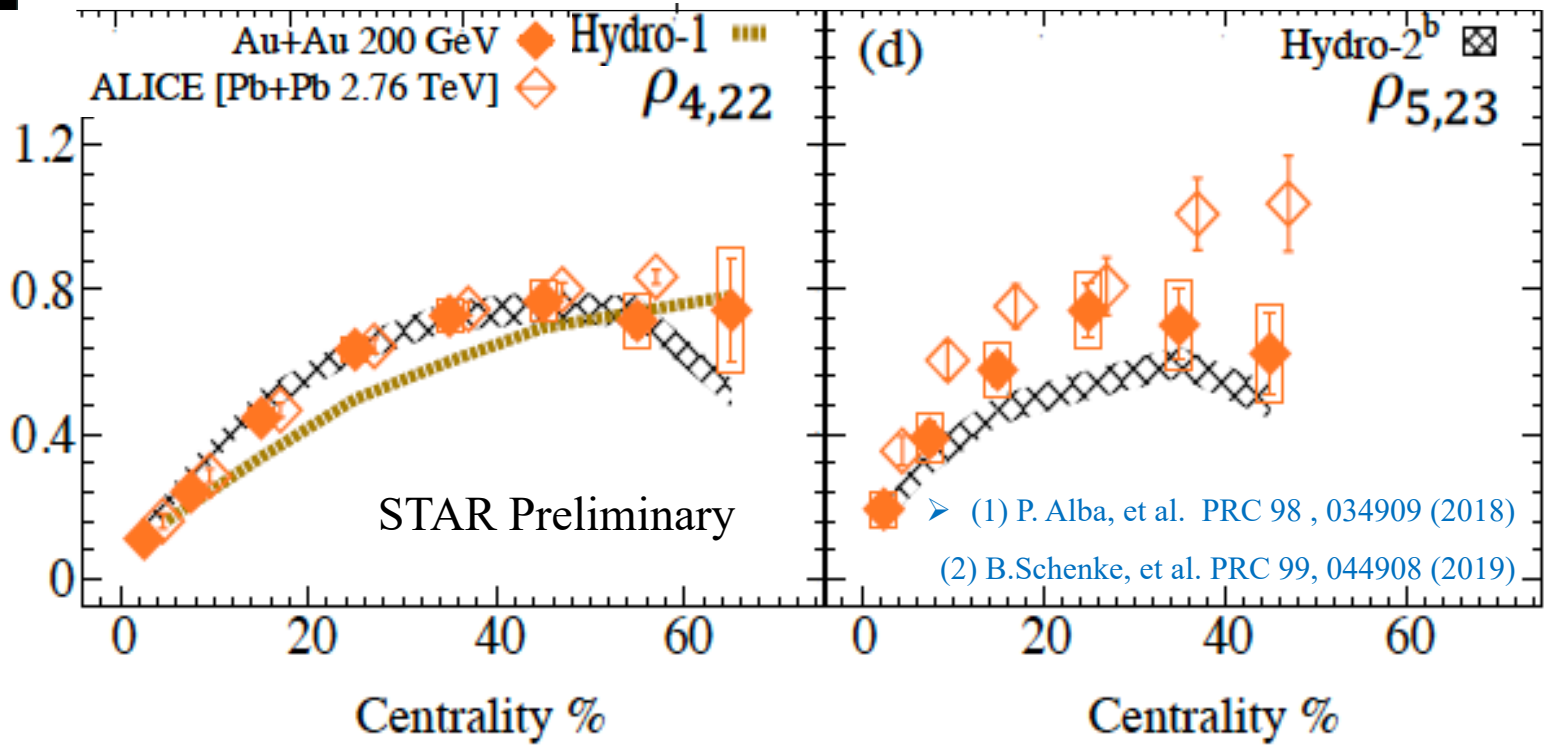


- Sensitive to initial condition, η/s etc

Niseem Abdelrahman
Wed 2:40 PM ,301

Nonlinear mode-mixing

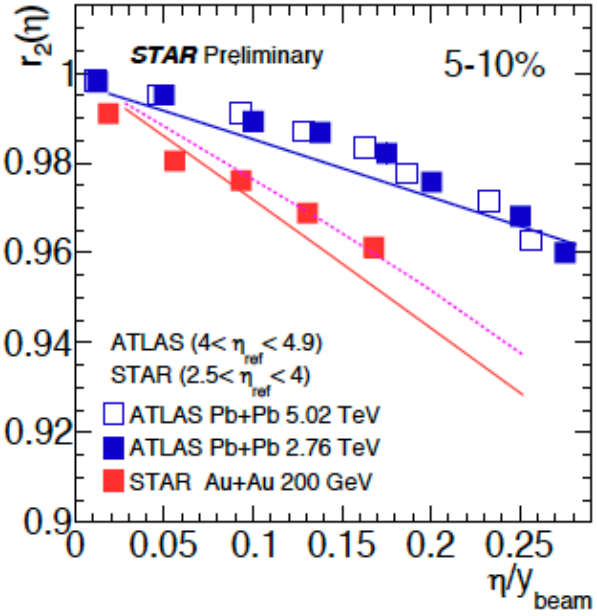
$\rho_{4,22} = < cos(4\psi_4 - 4\psi_2) >$ $\rho_{5,23} = < cos(5\psi_5 - 3\psi_3 - 2\psi_2) >$



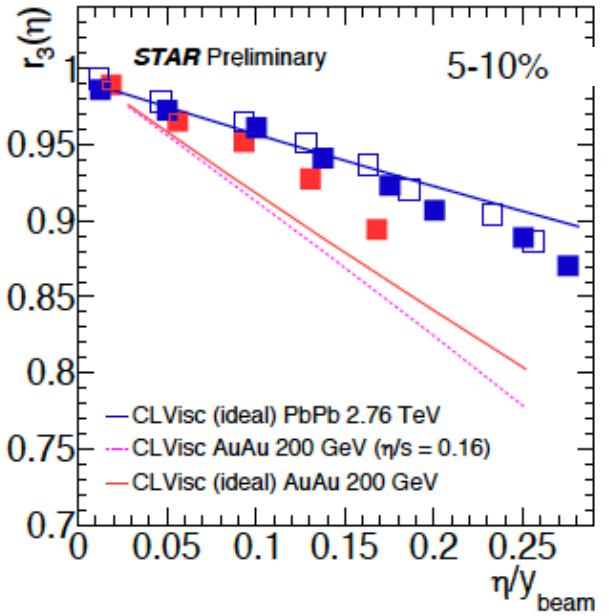
- Carry information about EP angular correlations
- Same as ALICE, nonlinear mode-mixing increase for peripheral
- More constraints on hydro calculation

Longitudinal flow de-correlation

r_2

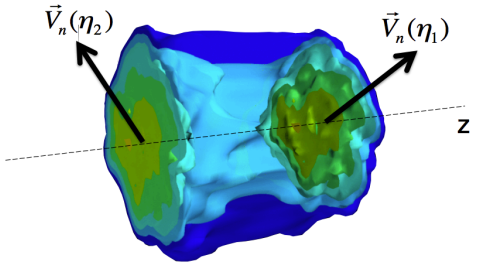


r_3



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

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!

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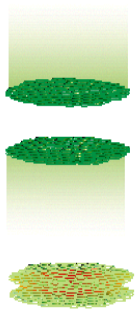

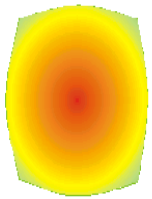

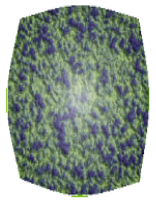

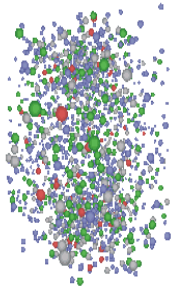

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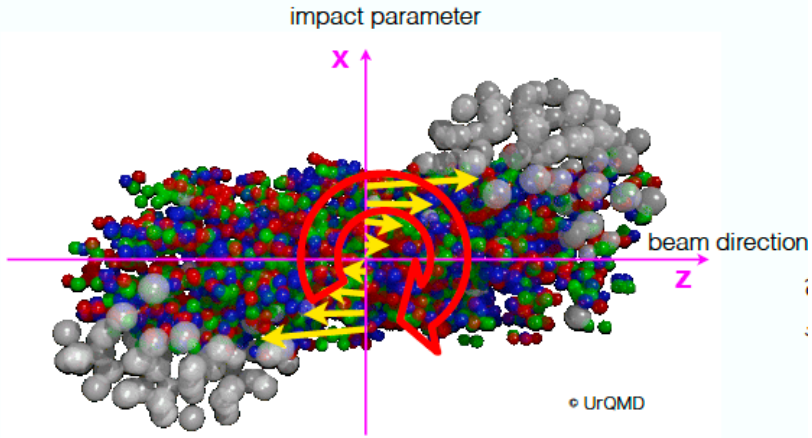
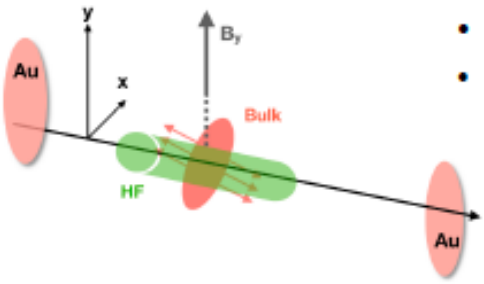
D^0 v_1: Tilted QGP and EM field Effect

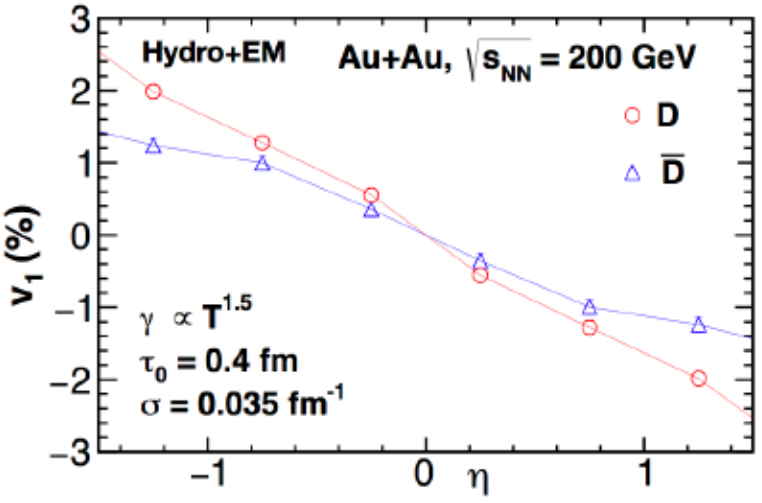


In non-central collisions,
the initial collective longitudinal flow velocity depends on x.



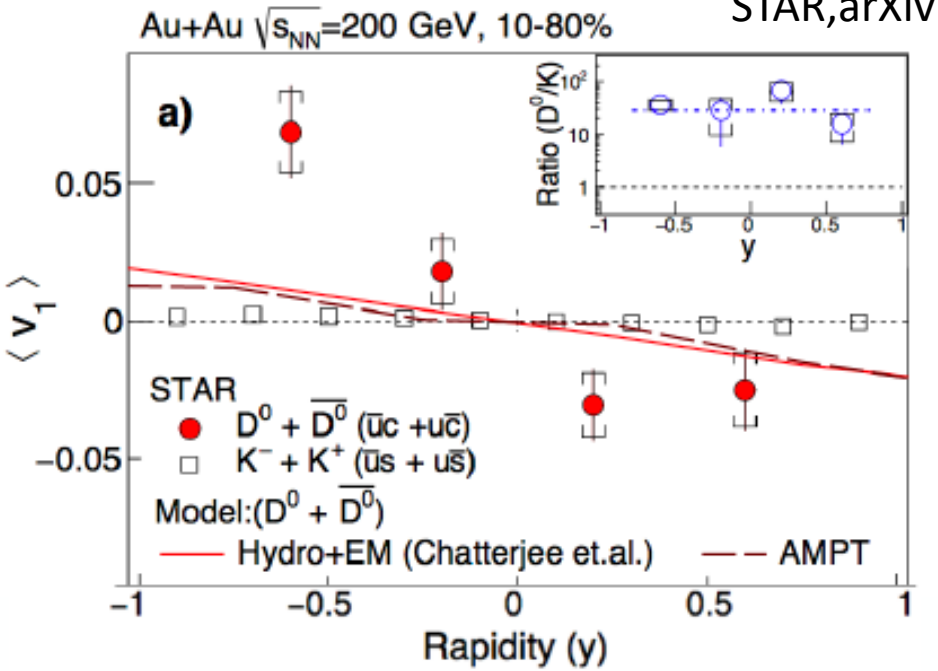
- Charm dragged by tilted QGP, leads to large v_1
- Due to EM field, further splitting between D^0 and $\overline{D^0}$ v_1

Das et. al.,PLB768(260)2016



D^0 directed flow

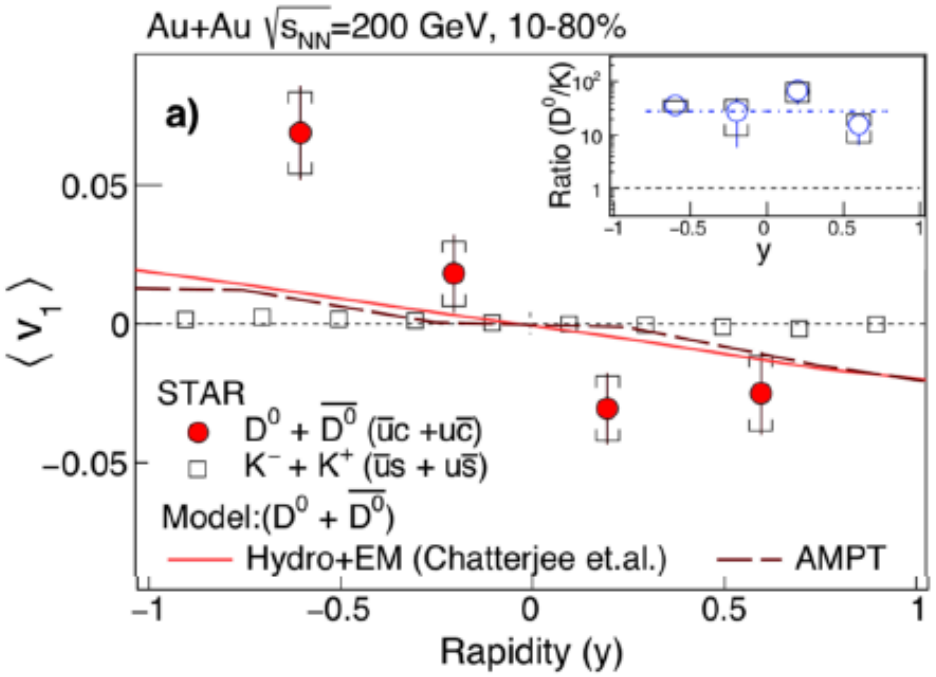
STAR,arXiv:1905.02052

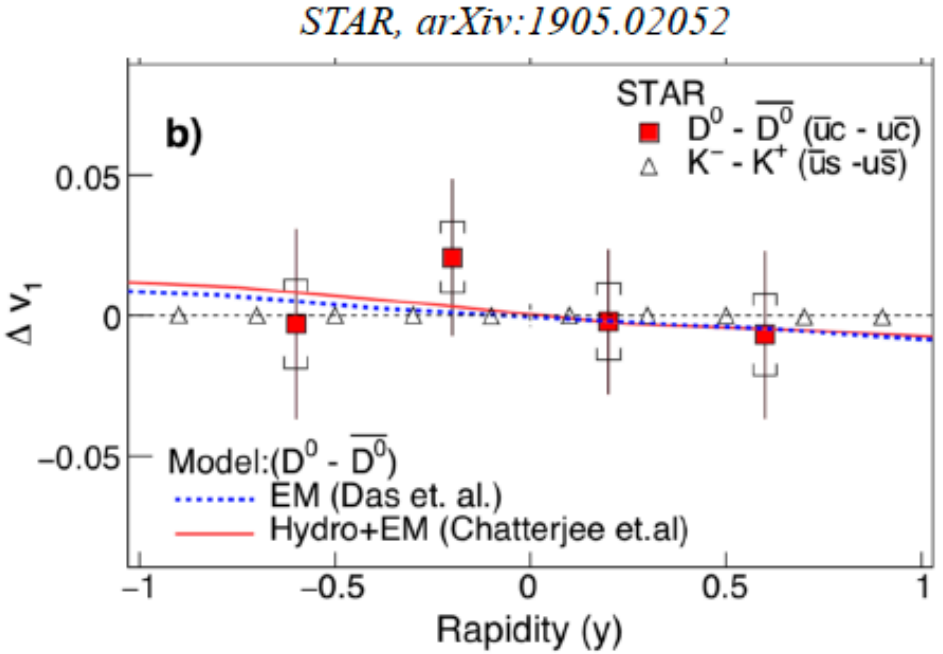


Subhash Singha
Wed 6:10 PM,301

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

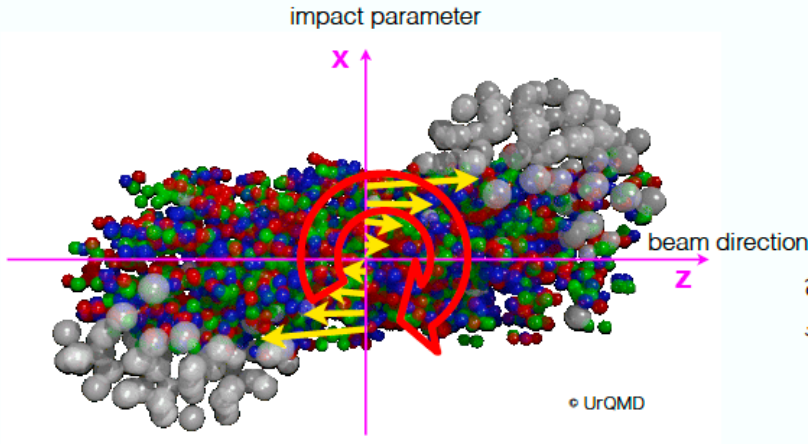
D^0 direct flow





- 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

Λ polarization and Influence of B field



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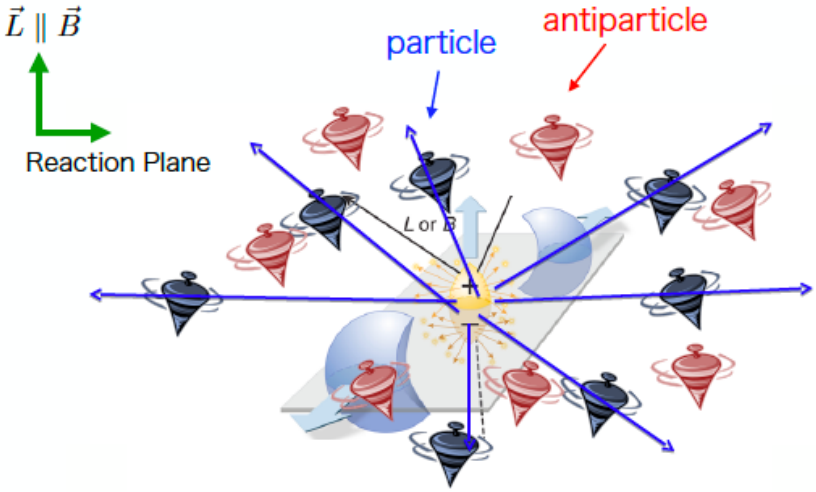
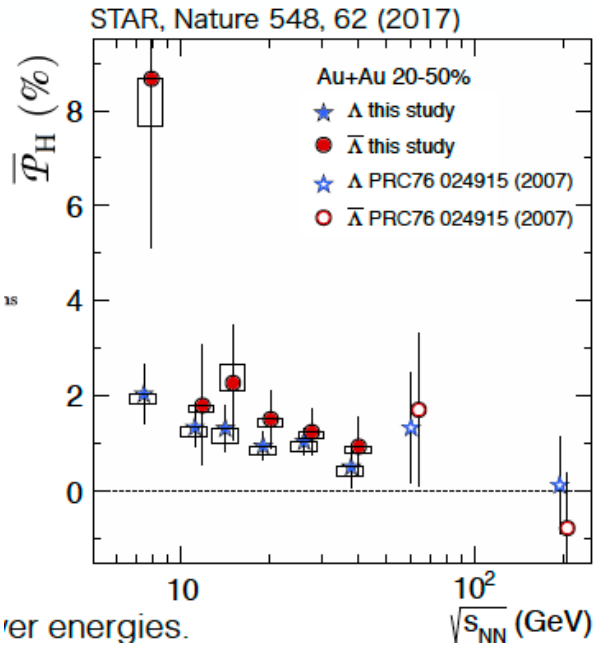
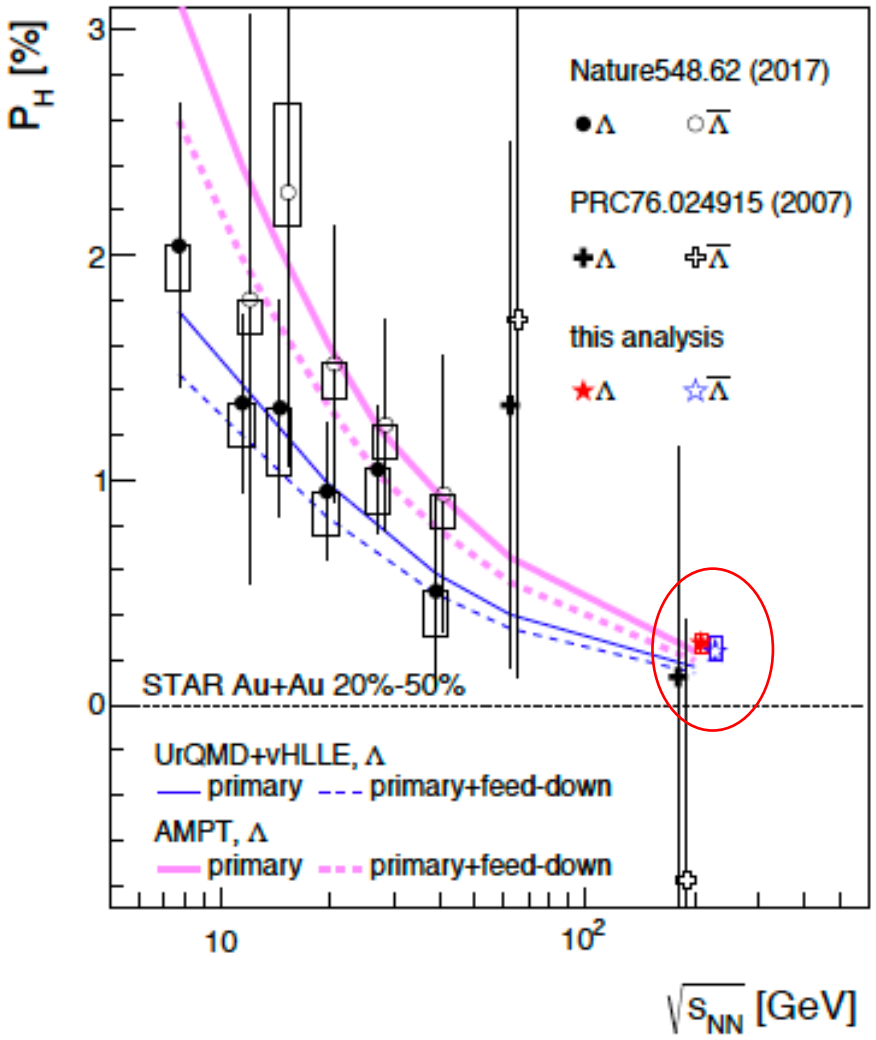


- QGP vorticity can be transferred to Λ polarization
- Due to B field, further splitting is expected between Λ and $\overline{\Lambda}$



Λ global polarization@200GeV

STAR, PRC **98** (2018) 14910



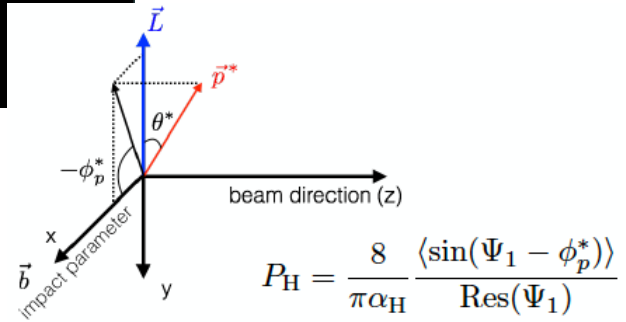
- Global polarization of Λ is observed for first time in Au+Au@200 GeV

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

- Precision not sufficient to see the difference between Λ and $\overline{\Lambda}$
- Analysis of >x10 of 27.6 GeV data is underway!

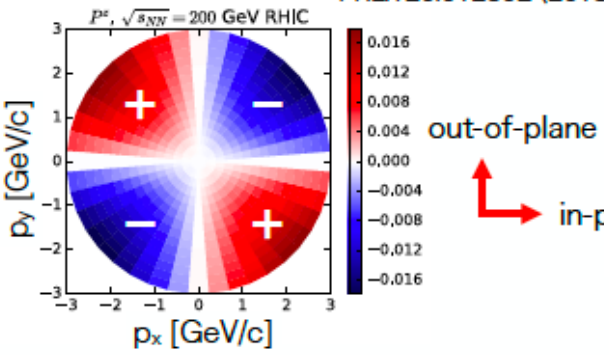
Λ local polarization@200GeV

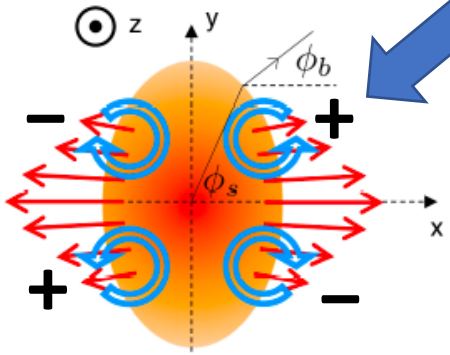
STAR, arXiv:1905.11917

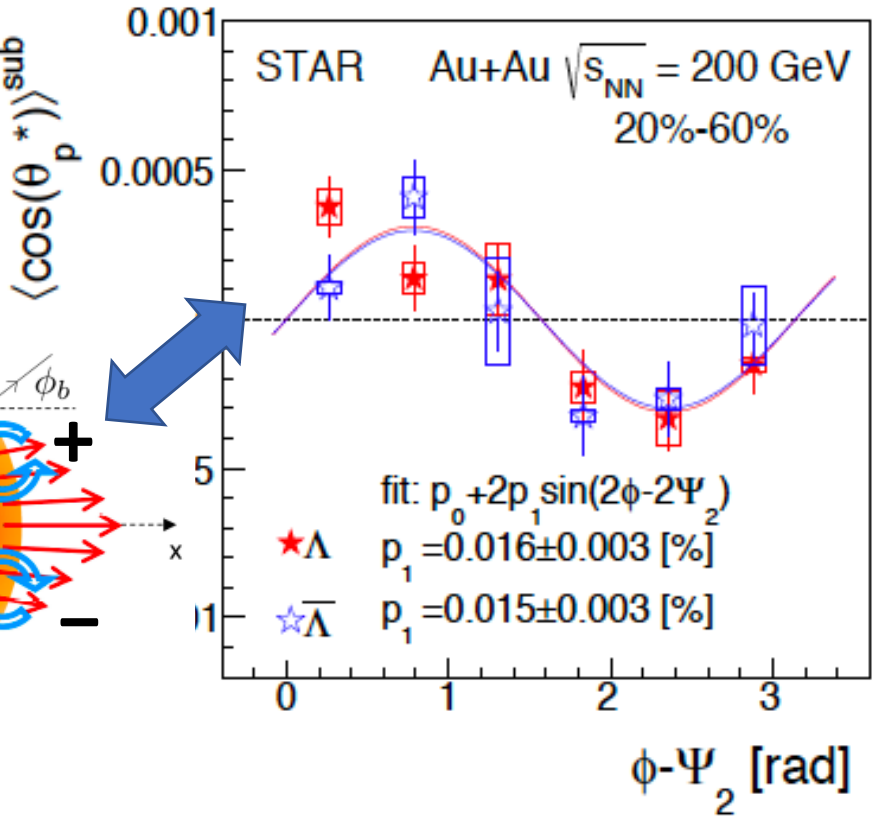


$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

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



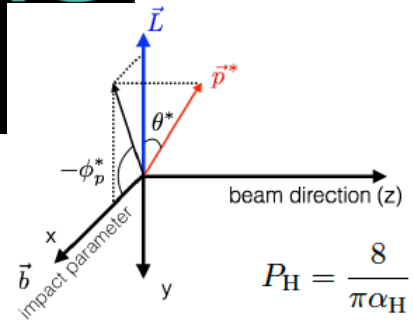




- Local polarization (along beam direction) shows a quadrupole structure, the sign is different from the hydro calculation. It is still not understood

Λ local polarization@200GeV

STAR, arXiv:1905.11917



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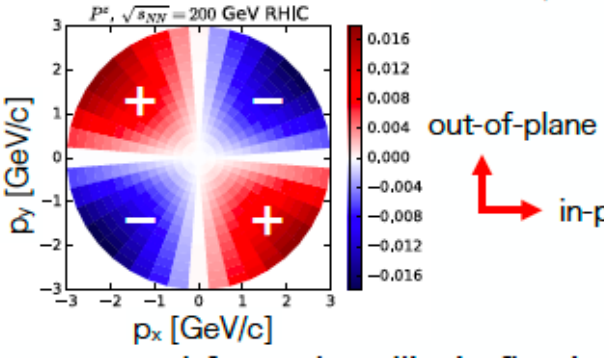
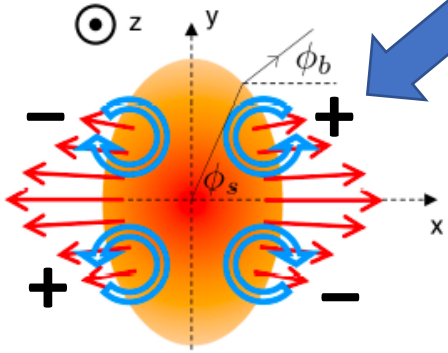
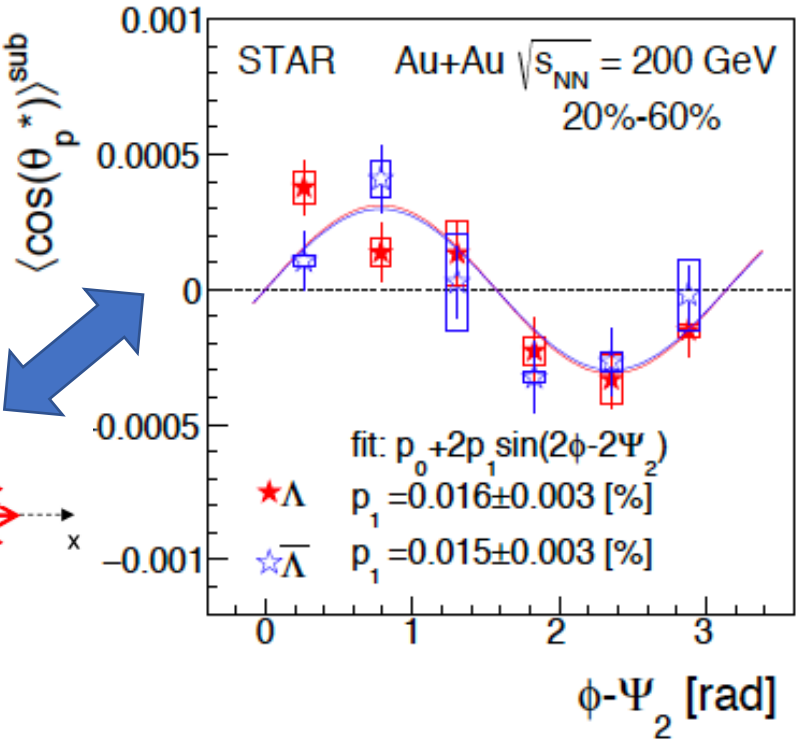
Hydro calculation of P_z
F. Becattini and I. Karpenko
PRL.120.012302 (2018

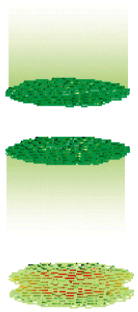




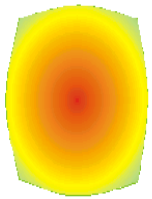


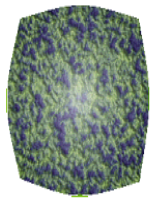
- Local polarization (along beam direction) shows a quadrupole structure, the sign is different from the hydro calculation. It is still not understood
- The sign may depend on the relation of magnitude between spatial and flow anisotropy from BW model S. Voloshin, arXiv:1710.08934

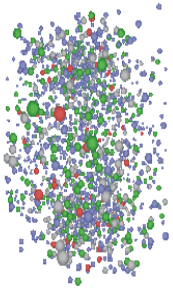
Outline



τ<0.5fm







Physics to address:

Initial Geometry

Pre-equilibrium

Longitudinal structure

Strong EM field

γ+γ, γ+nucleus interaction

…

STAR Measurements:

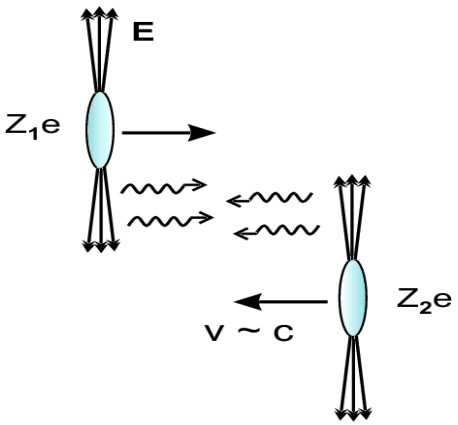
Small system: flow, jet

Flow correlation and decorrelation

D^0 v_1, Λ polarization

Low p_T di-lepton, J/ψ

Coherent γ+γ, γ+nuclear processes



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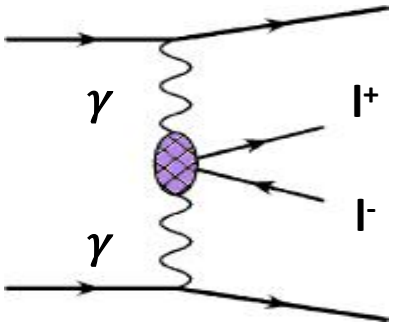

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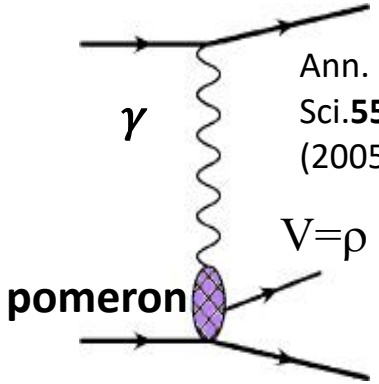


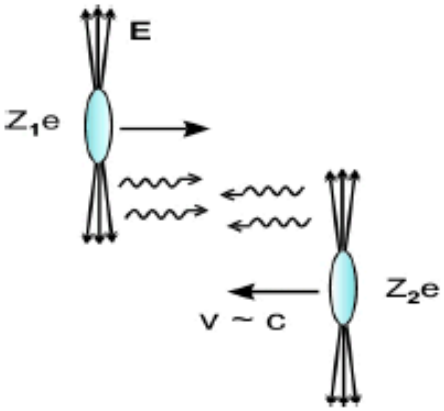
Ann. Rev. Nucl. Part. Sci.**55**:271 (2005)

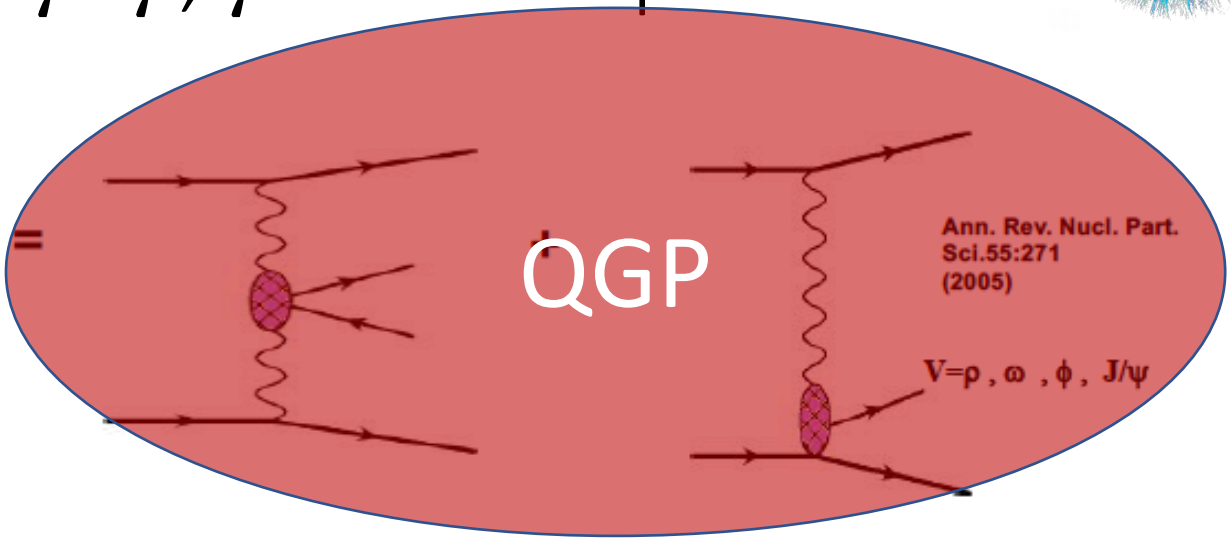
$V=\rho, \omega, \phi, J/\psi$

photon-photon interaction $\propto Z^4$

photonuclear interaction $\propto Z^2$

Coherent γ+γ, γ+nuclear processes



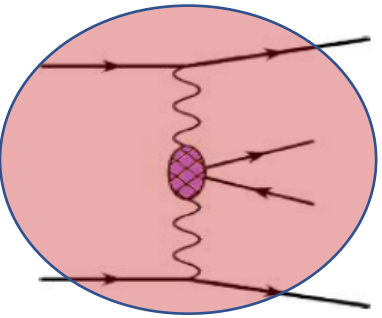


photon-photon interaction $\propto Z^4$

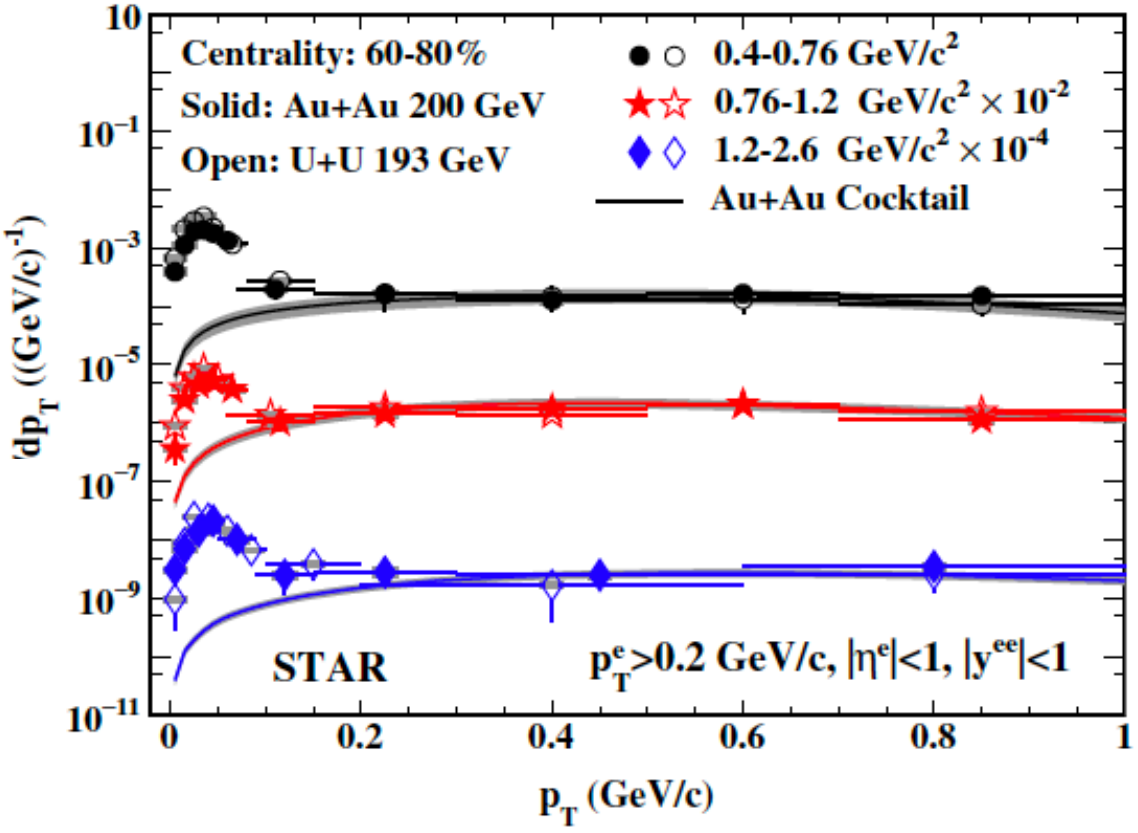
photonuclear interaction $\propto Z^2$

- How about the medium effect from QGP?
- A new tool to study the QGP properties!

Di-electron enhancement at low p_T



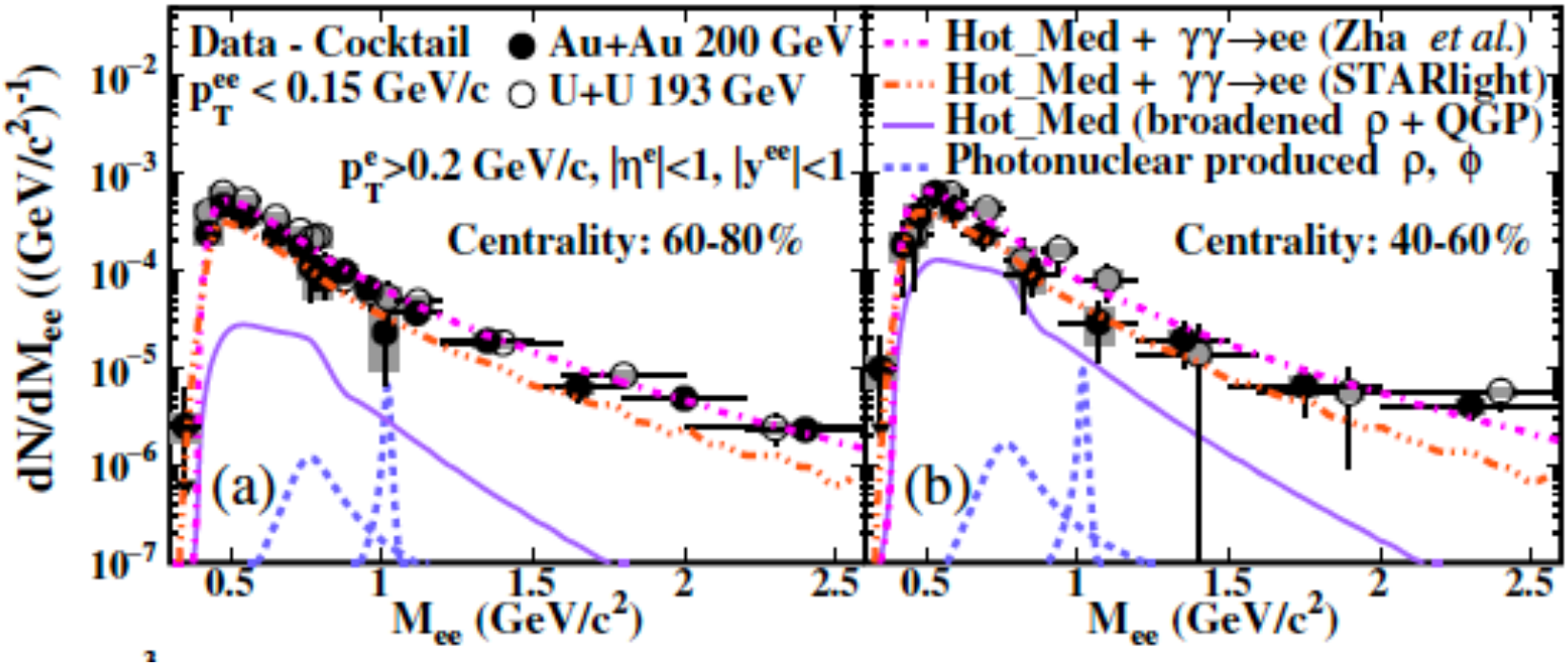
photon-photon interaction $\propto Z^4$



STAR,PRL121(2018)132301

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

Di-electron enhancement at low p_T



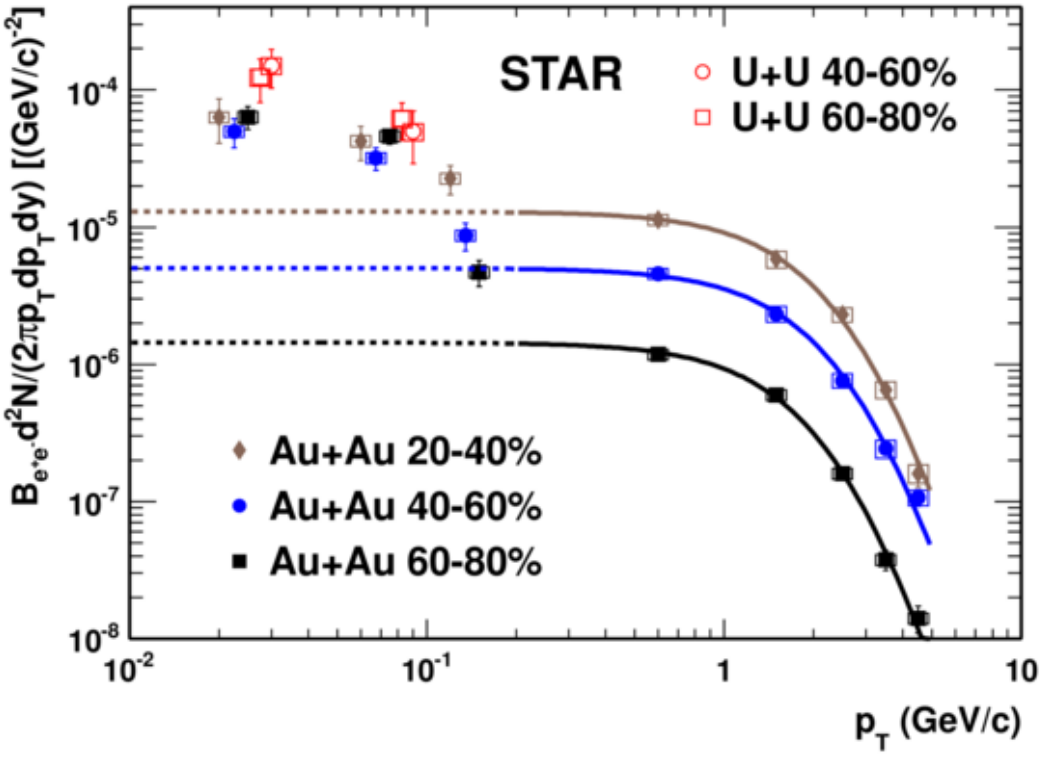
STAR,PRL121(2018)132301

Comparing to model calculations:

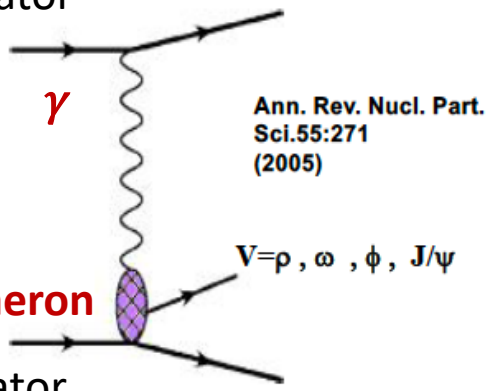
- ρ broadening in QGP can not explain the enhancement!
- Qualitatively consistent with model including photon-photon interactions

Low p_T J/ψ enhancement

STAR, arXiv: 1904.11658



Nucleus/Spectator



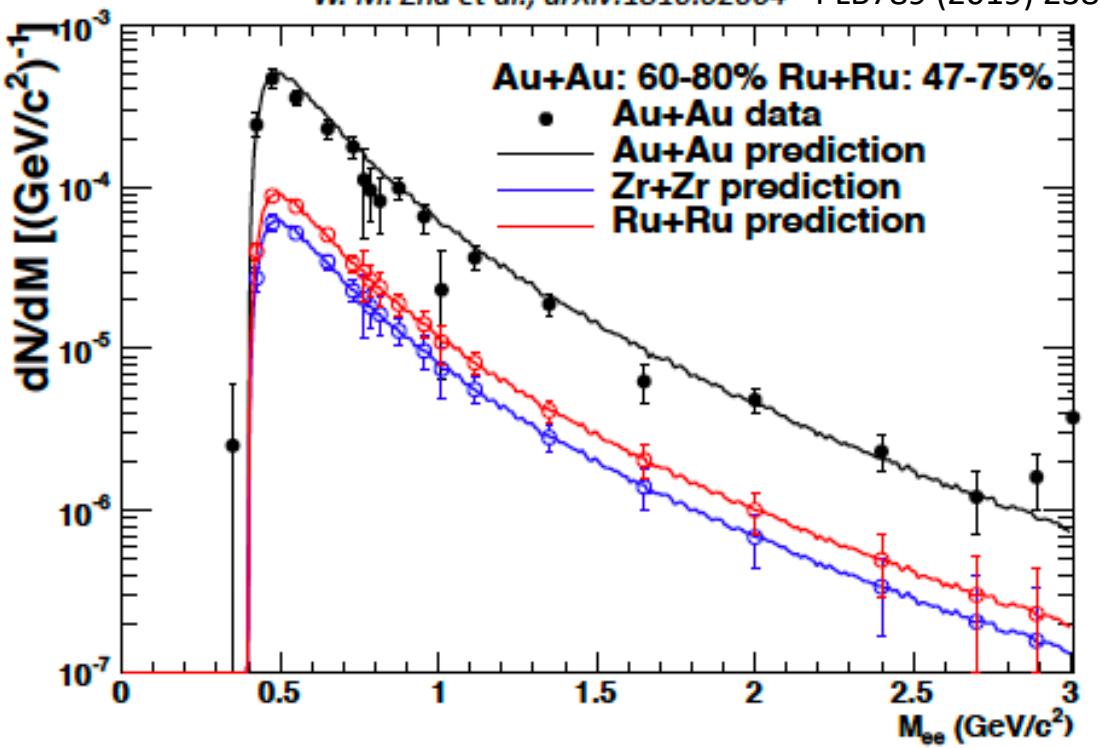
Nucleus/Spectator

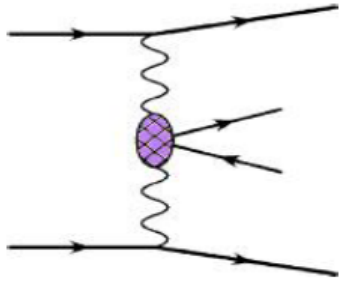
photonuclear interaction $\propto Z^2$

- Significant J/ψ 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

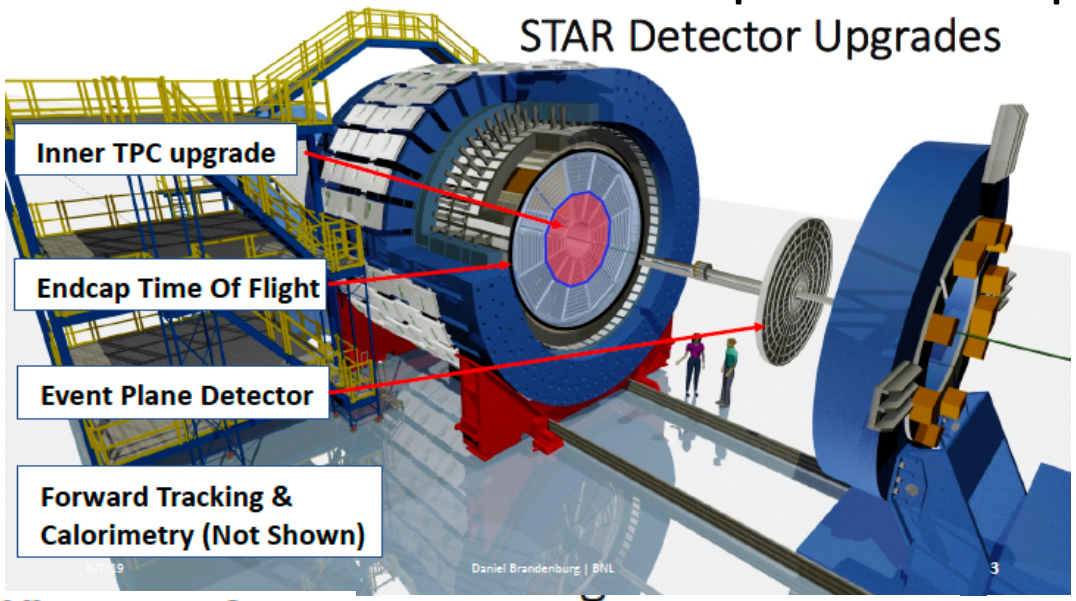




photon-photon interaction $\propto Z^4$

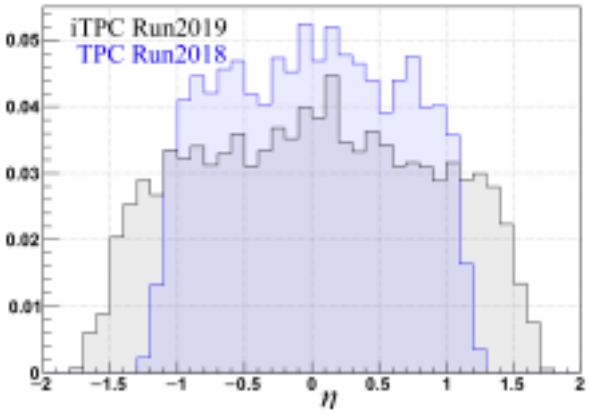
- 60-80% Au+Au vs. 47-75% Ru+Ru:
  Similar hadronic contribution
  Different contribution from photon-photon interactions
- Around 3.7σ difference between Ru+Ru and Zr+Zr (estimated from 840M events). STAR recorded 1.6B events for each of them!

Outlook: Recent completed upgrades



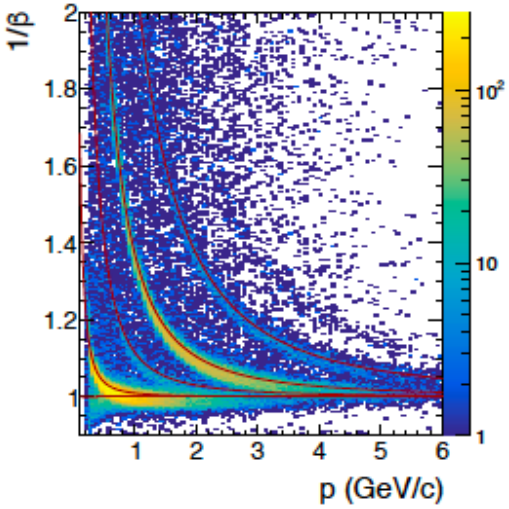
Daniel Brandenburg
Wed. 5:10 PM,329

- **Increase mid-rapidity coverage from $|\eta| < 1.0$ to $|\eta| < 1.5$**



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

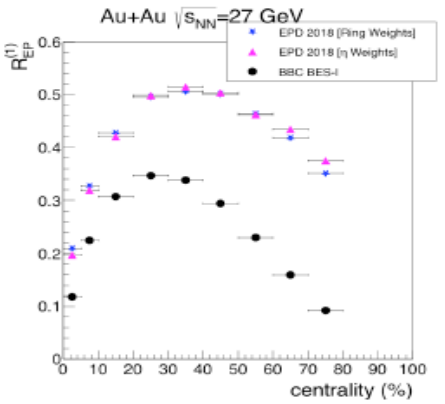
Particle Identification : Fixed Target test run



eTOF :PID~-1.6<η<-1.1

1st order Event Plane Resolution

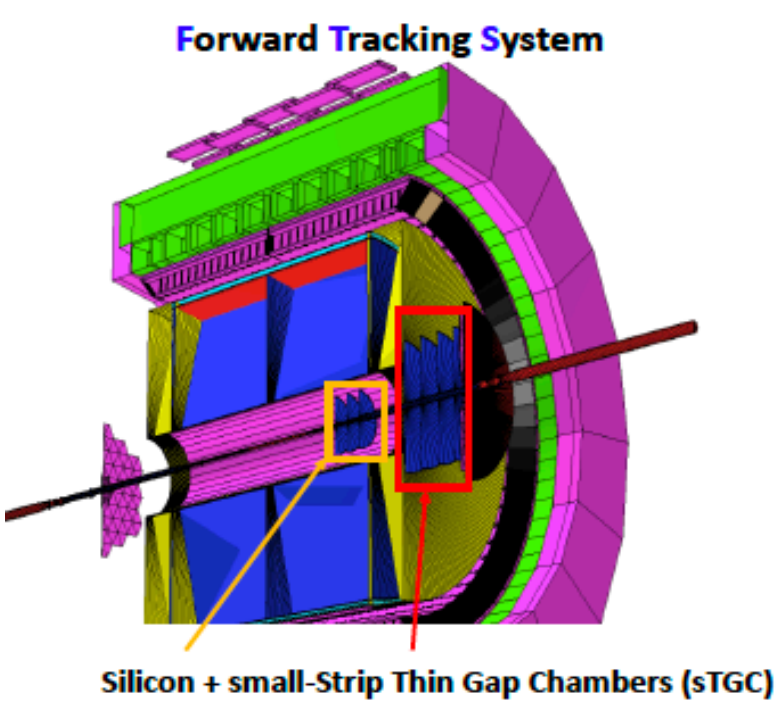
→ Significant improvement across all centrality

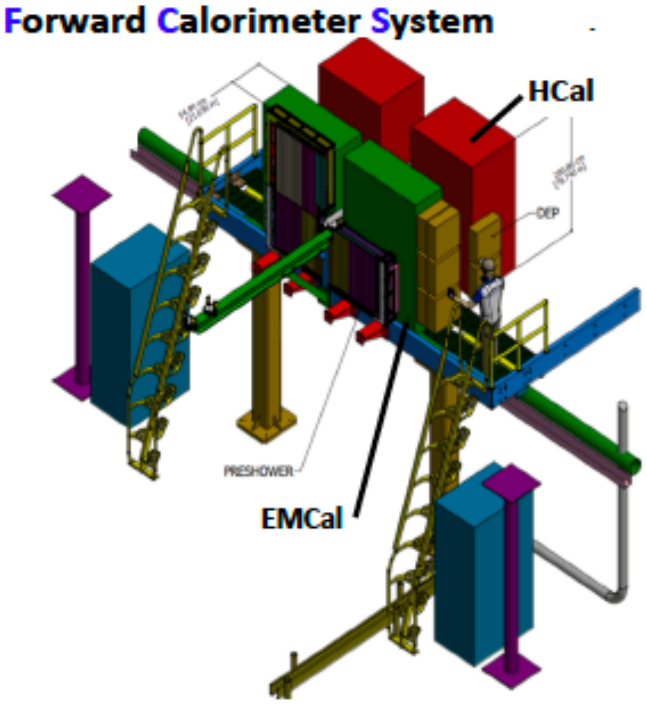


EPD: EP~2.1<$|\eta|$<5.1 and centrality

Outlook: Forward Upgrade

STAR Forward Detectors: FTS + FCS (2.5<η<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,Λ,π^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)

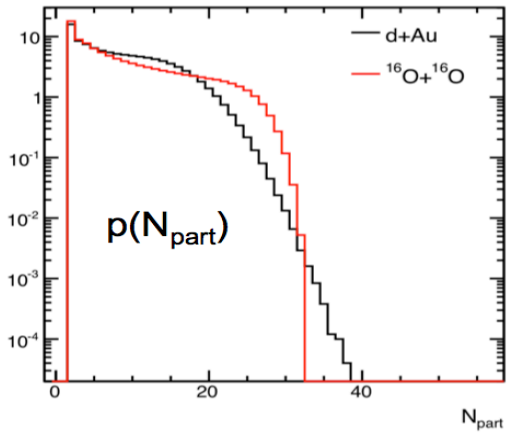
Proposed LHC run schedule

Arxiv.1812.06772

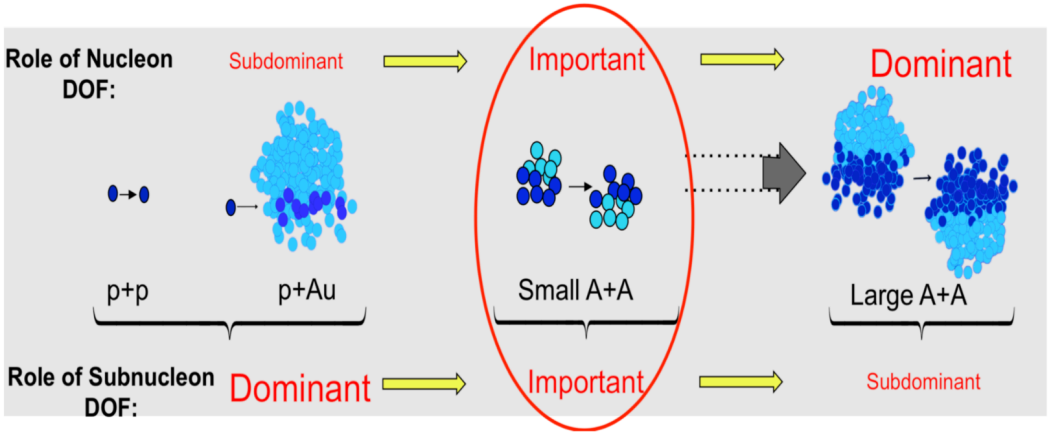
Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3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

arXiv.1904.10415



less centrality bias & better selection of geometry (N_{part}, ε_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 Λ 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/ψ production from strong EM field, which provide new tool to study the QGP

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- We measured low p_T di-lepton and J/ψ 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

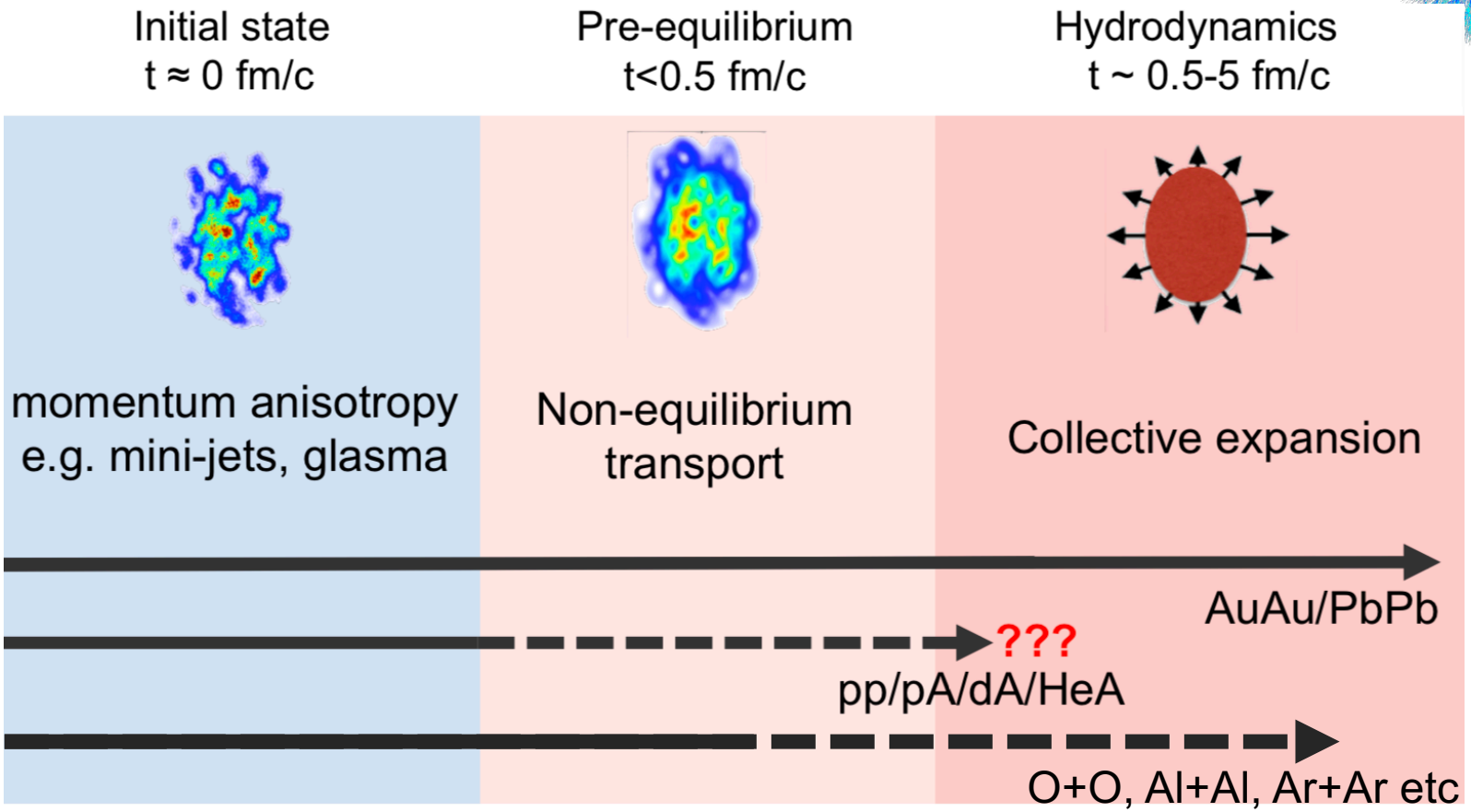
	Hydro−1 [43]	Hydro−$2^{a/b}$ [44]
η/s	0.05	0.12
Initial conditions	TRENTO Initial conditions	IP-Glasma Initial conditions
Contributions	Hydro only	(a) Hydro + Hadronic cascade (b) Hydro only

(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

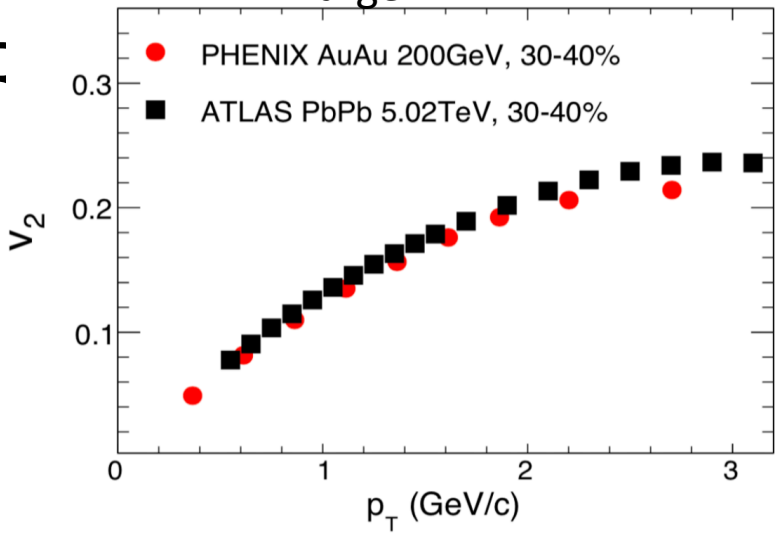


- Extend the lever-arm to disentangle contributions from three stages
  - Where initial-state interaction become sub-dominant?
  - What is the role of pre-equilibrium vs. hydrodynamics?

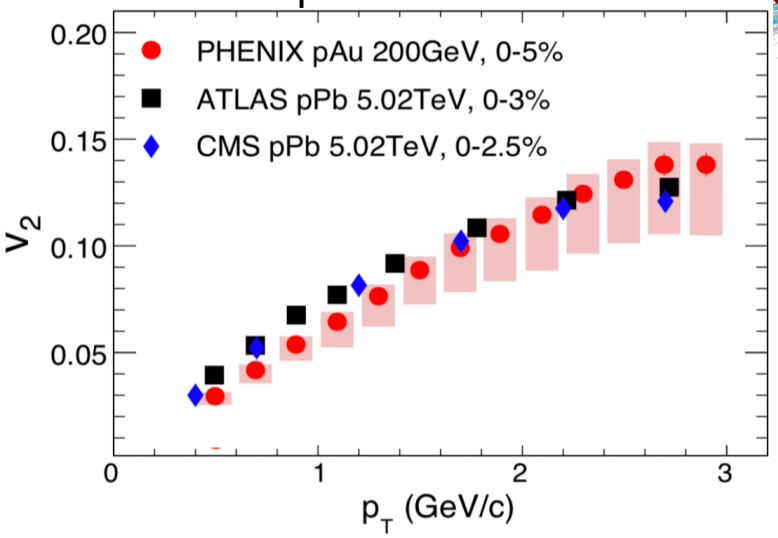
Further system-size scan needed! Only RHIC can do this!

arXiv.1904.10415

Large A+A

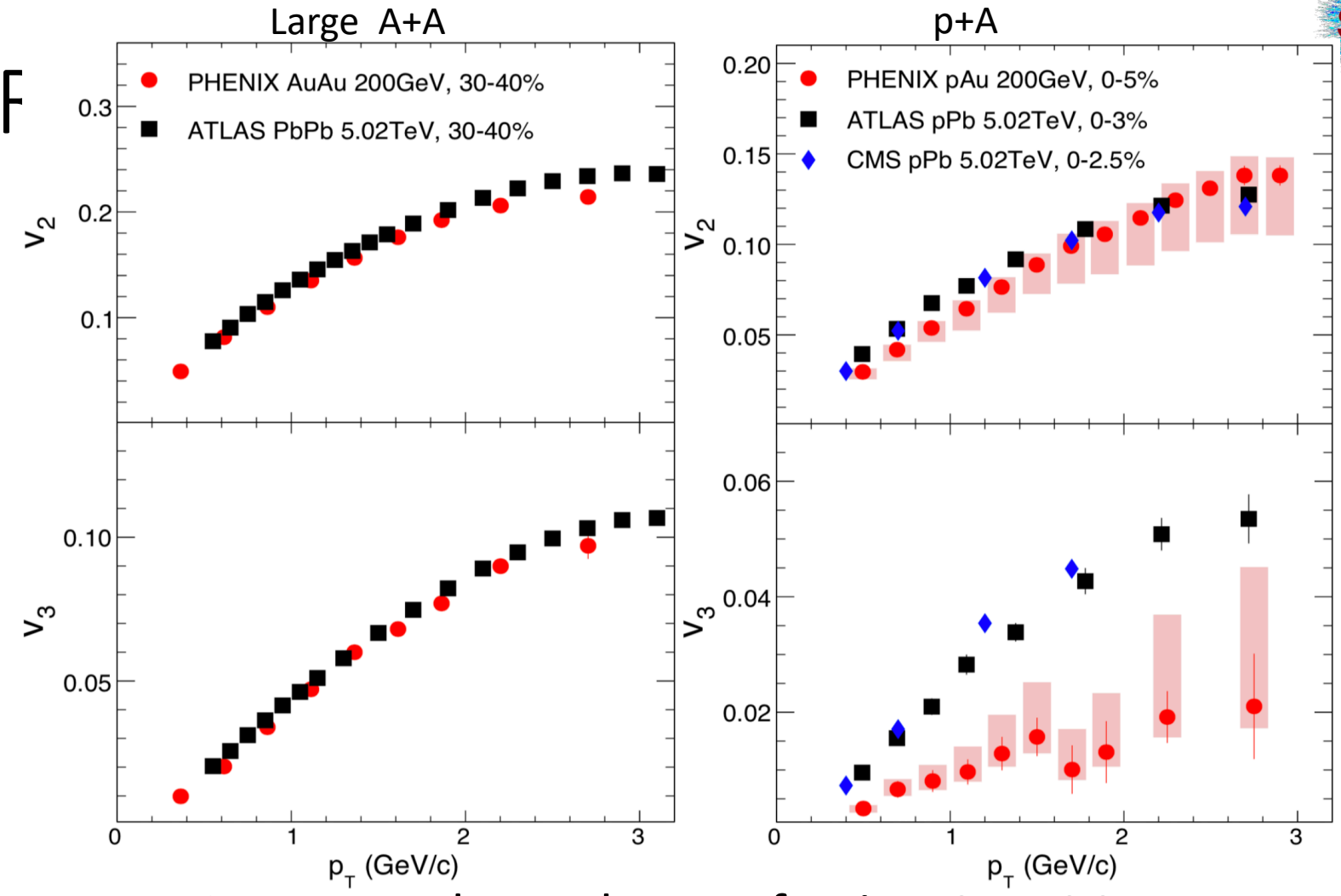


p+A



No energy dependence of v_2 in pA vs AA

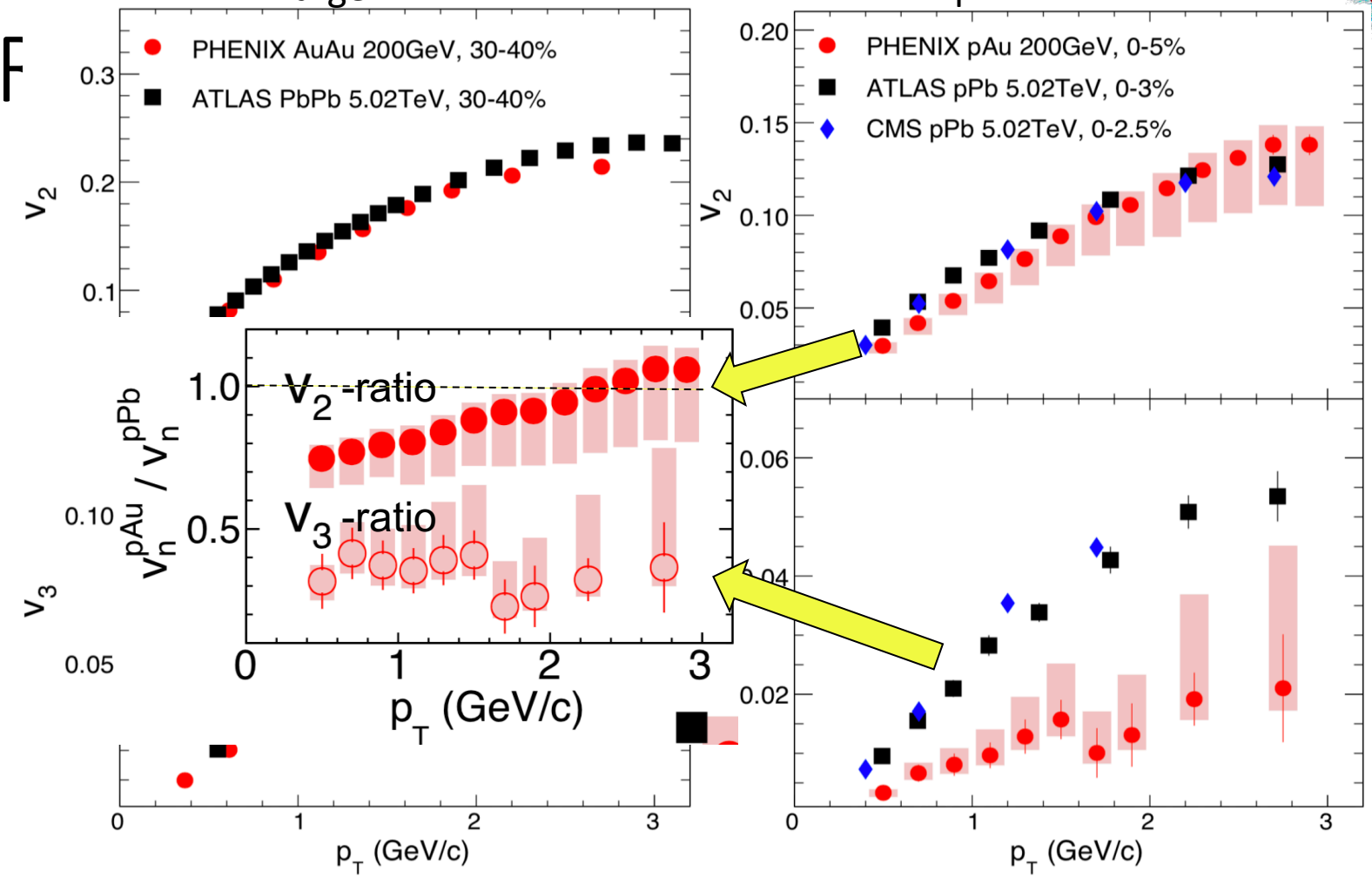
arXiv.1904.10415



No energy dependence of v_2 in pA vs AA

Different energy dependence of v_3 in pA vs AA?

arXiv.1904.10415

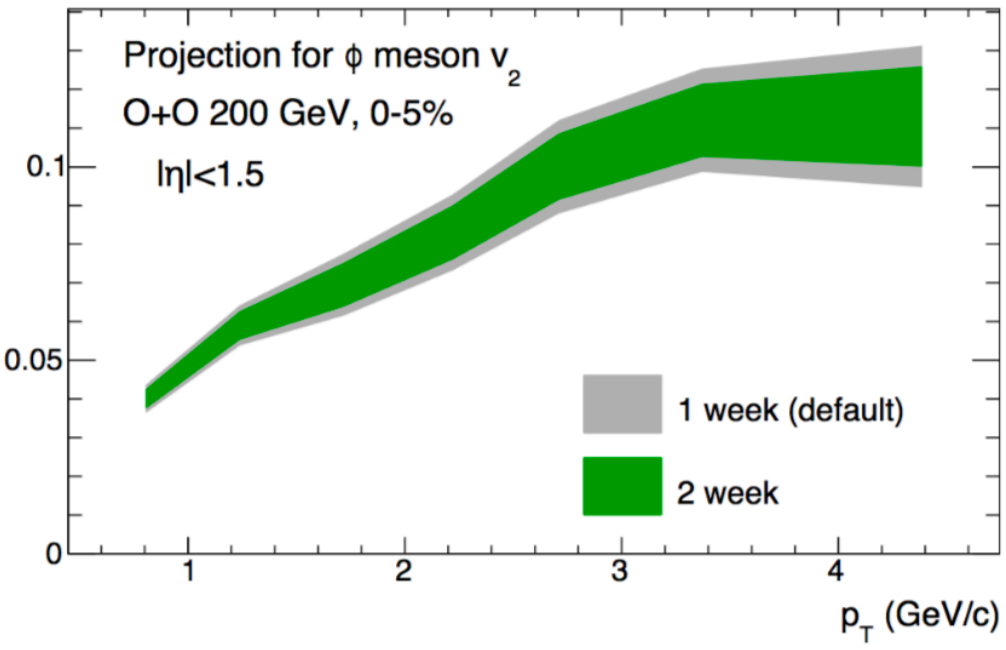


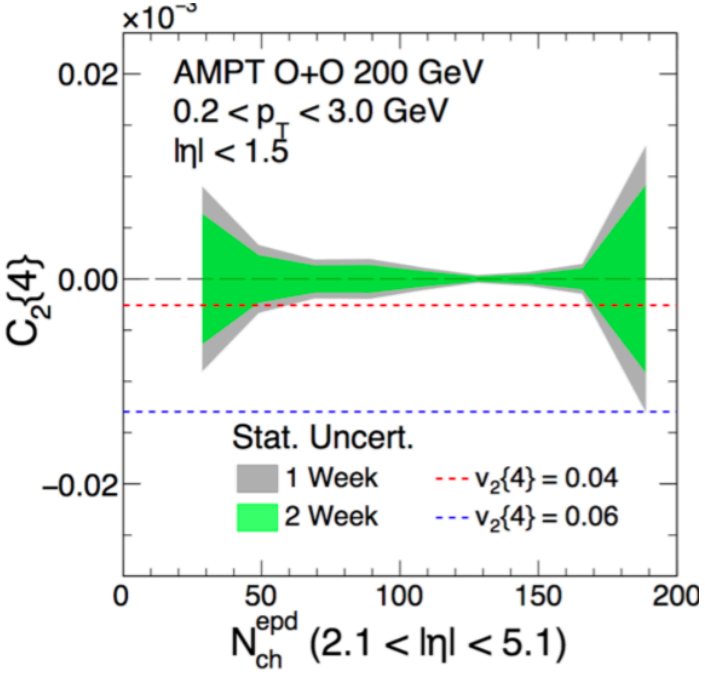
No energy dependence of v_2 in pA vs AA

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...

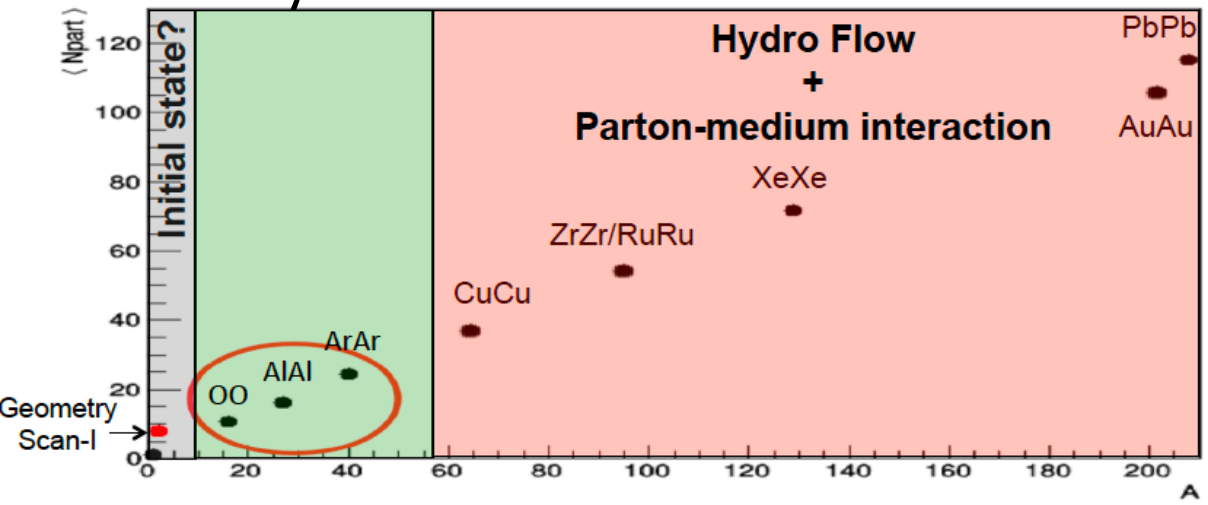
Future Small System Scan

STAR with new detector capability for collectivity in small system:

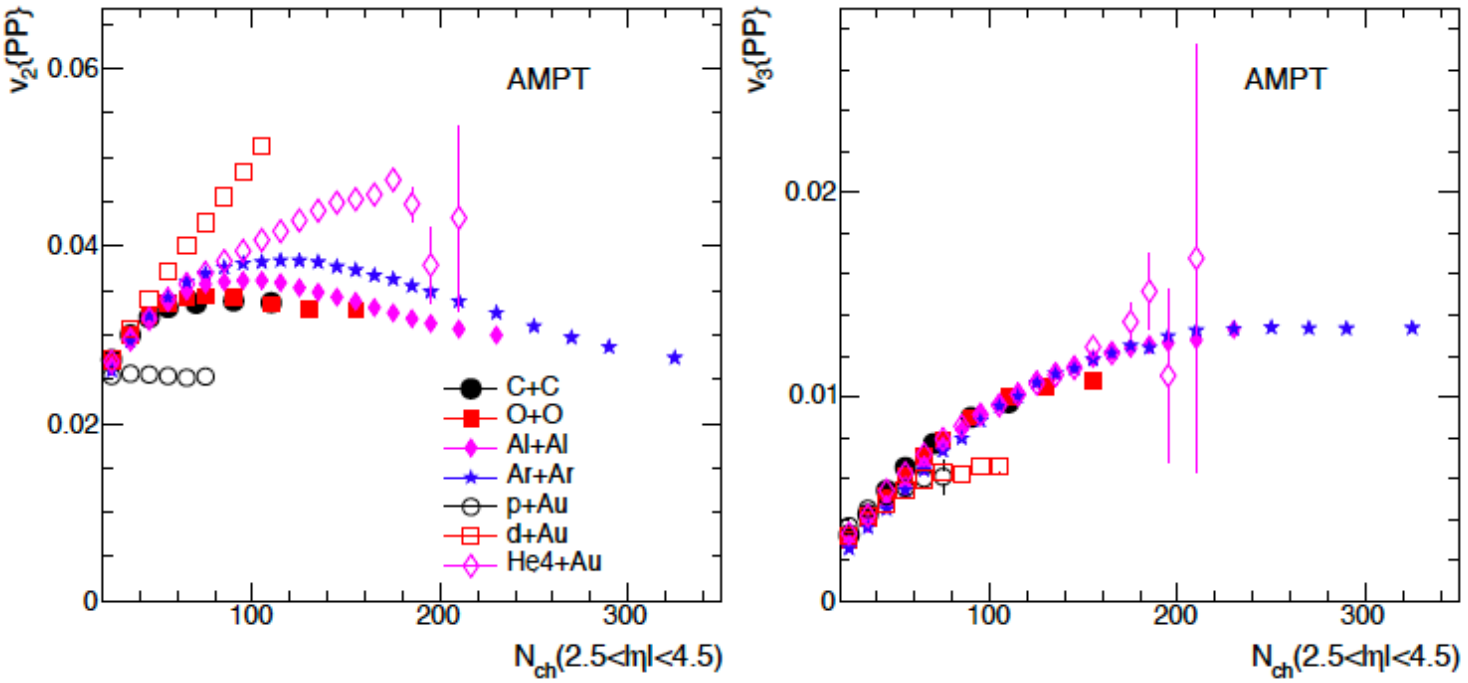
- ✓ Large acceptance to handle the nonflow
- ✓ Study longitudinal decorrelation effect on flow measurement
- ✓ Multi-particle cumulant in different rapidity

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



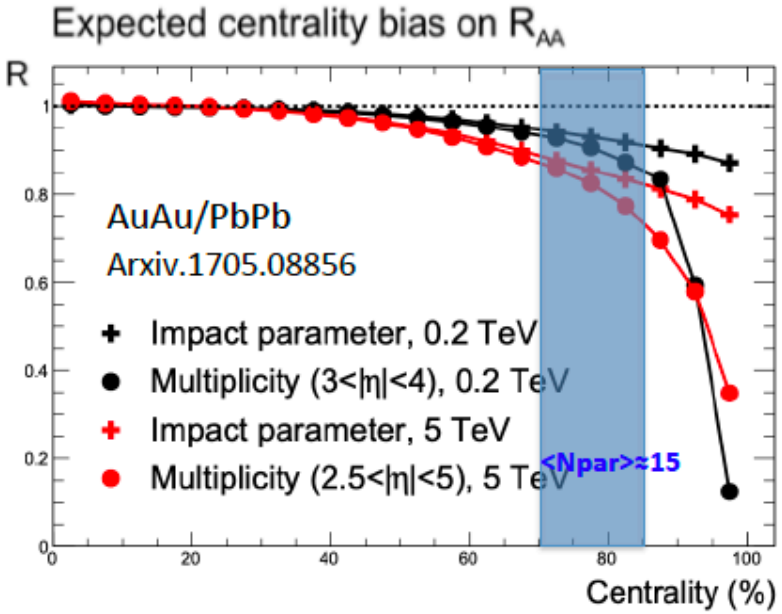
AMPT O+O

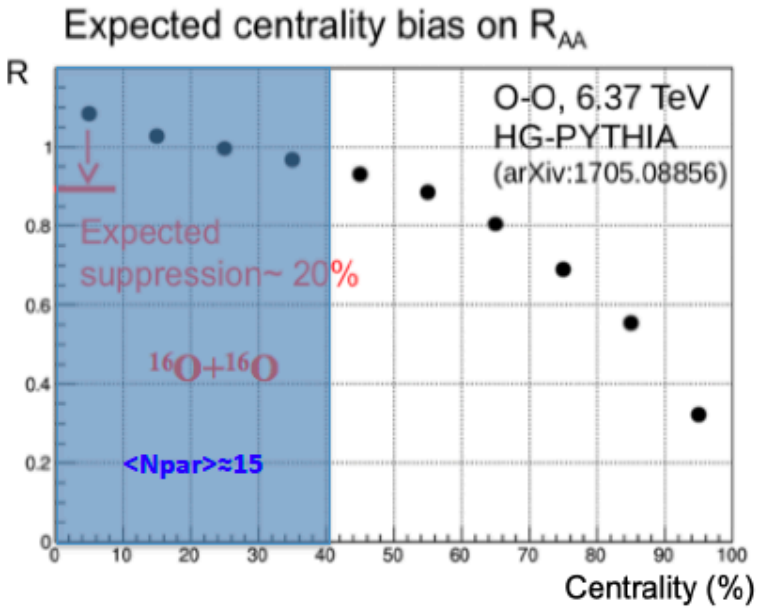


arXive:1904.10415

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

Outlook: O+O run

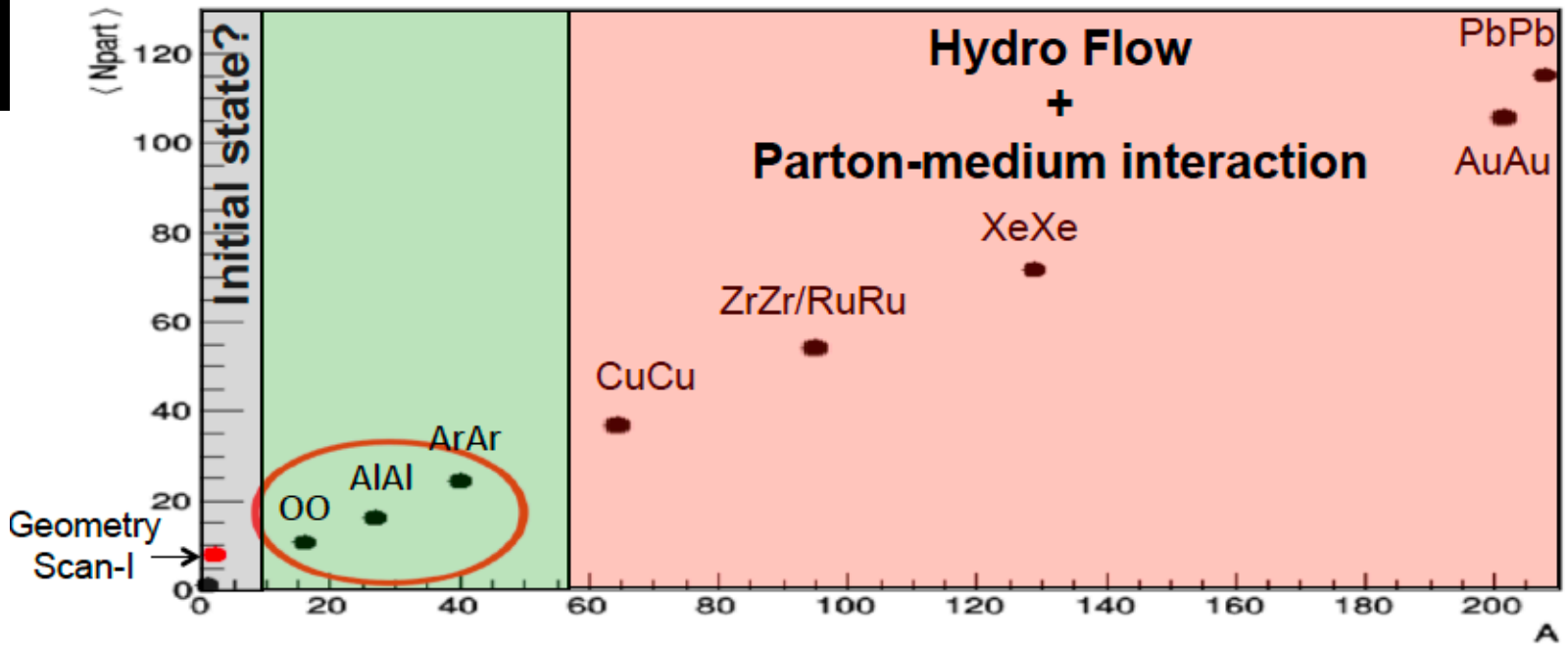




Where initial-state interaction become sub-dominant?
The role of pre-equilibrium vs. hydro?
Turn-on of jet quenching and heavy-flavor "thermalization"?

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!!

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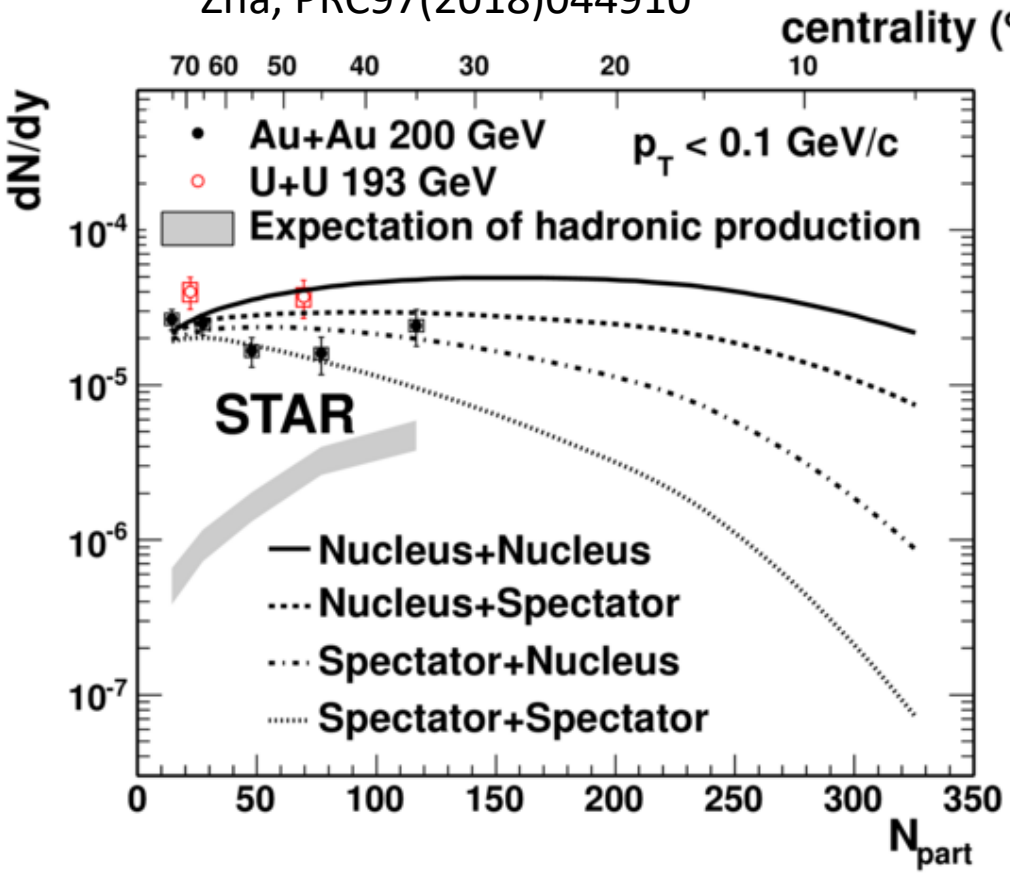
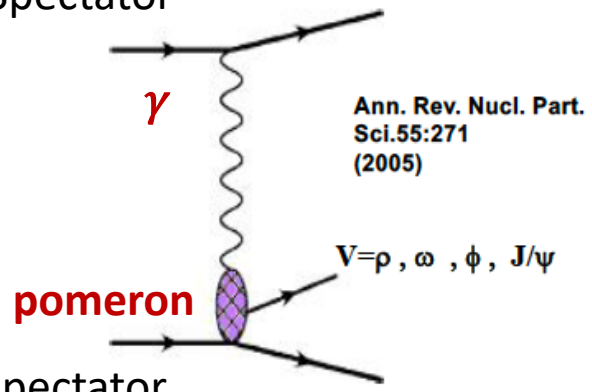
Low p_T J/ψ enhancement

Zha, PRC97(2018)044910



Nucleus/Spectator



Nucleus/Spectator

photonuclear interaction $\propto Z^2$

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