New results from flow, chirality and vorticity at RHIC-STAR

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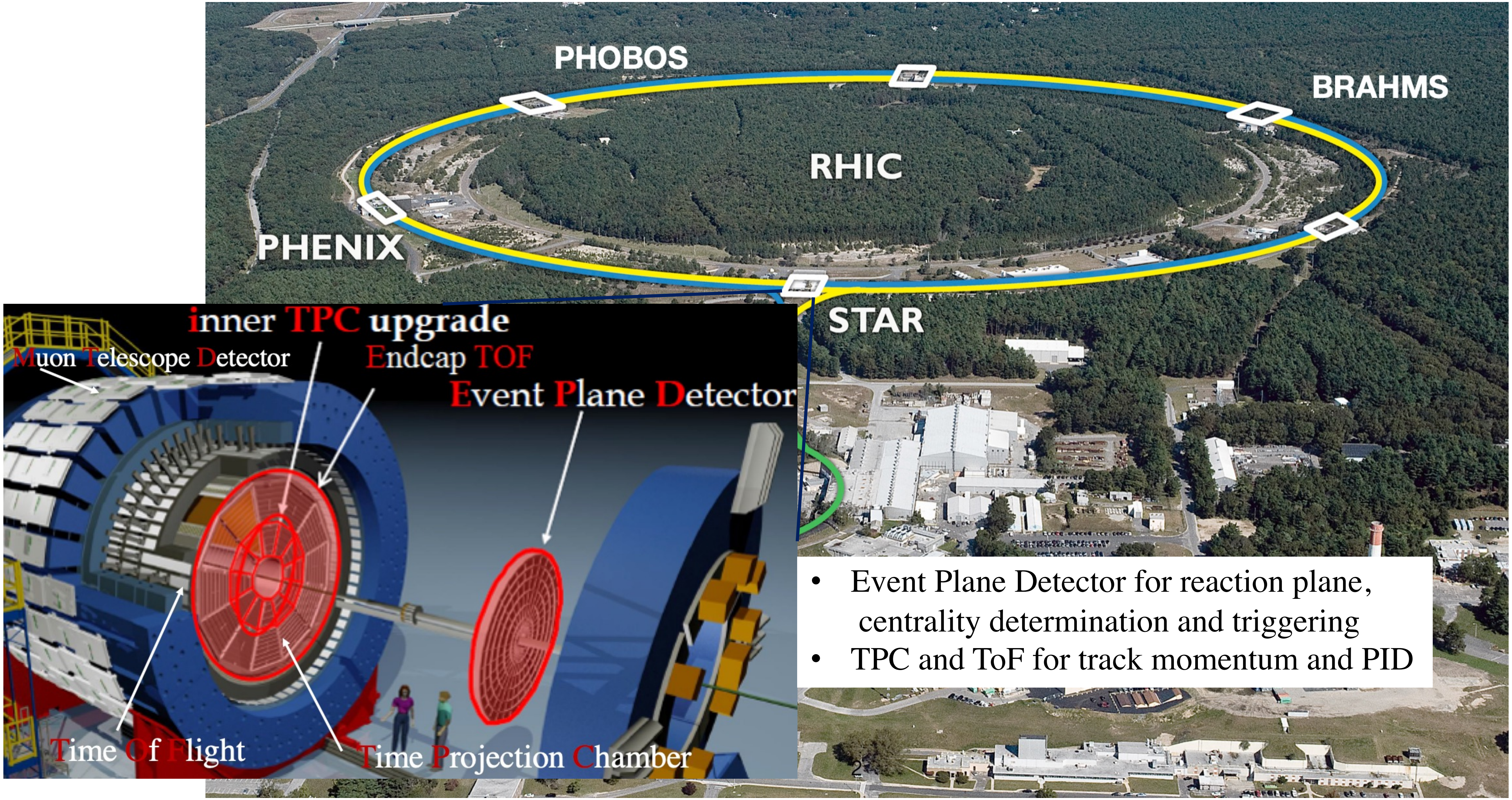
(For the STAR Collaboration)

Supported by the U.S. DEPARTMENT OF ENERGY Office of Science

Stony Brook University

STAR

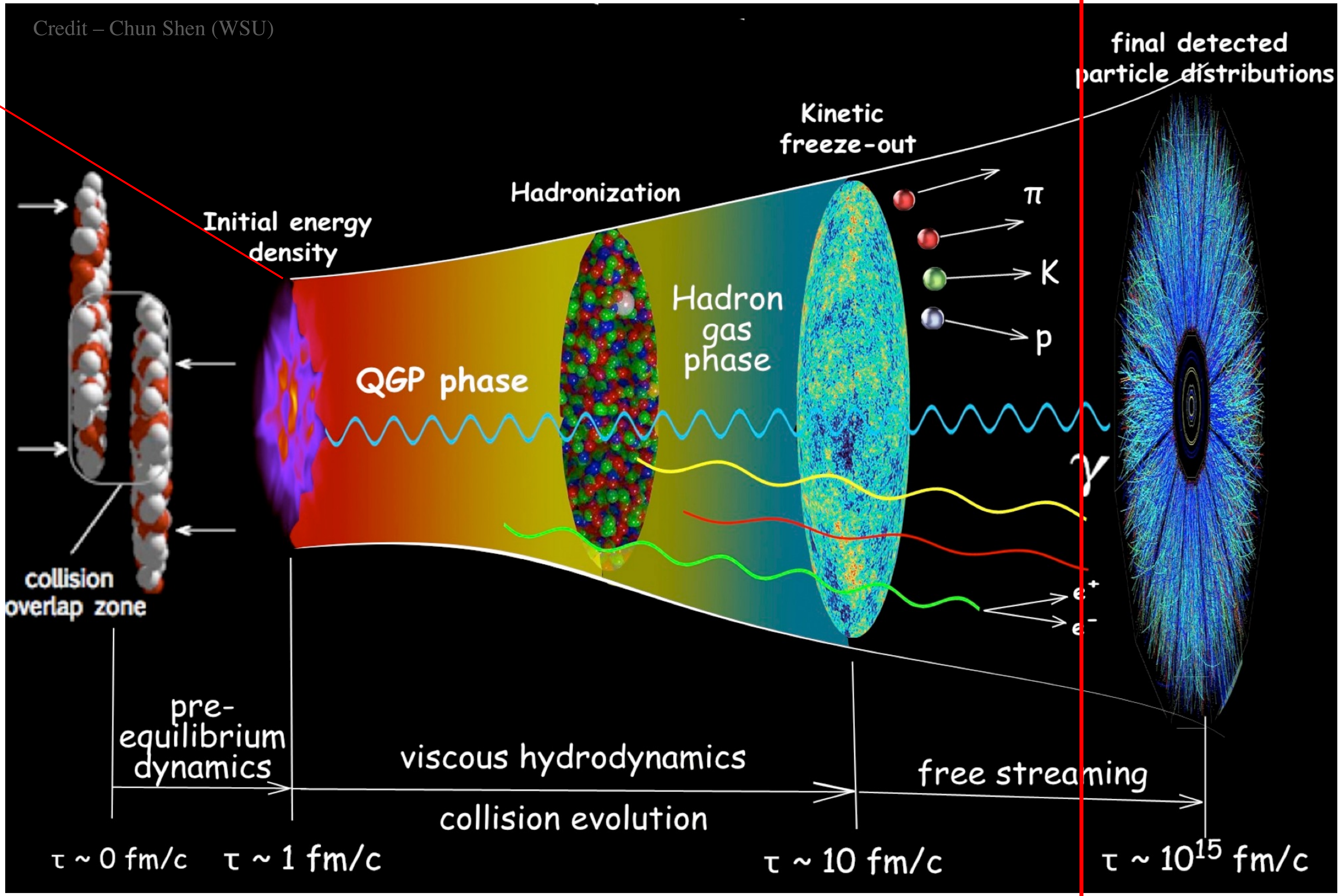
The STAR detector



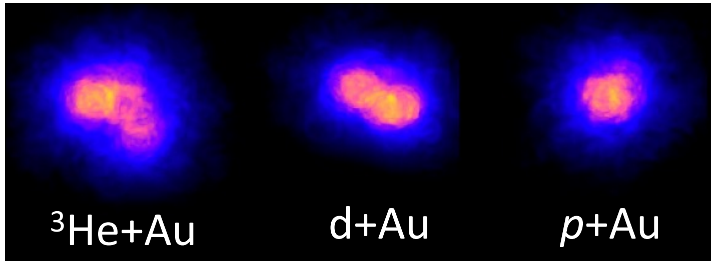
- Event Plane Detector for reaction plane, centrality determination and triggering
- TPC and ToF for track momentum and PID

Relativistic heavy-ion collisions

Fluctuates EyE
Classical color-field
Dynamics

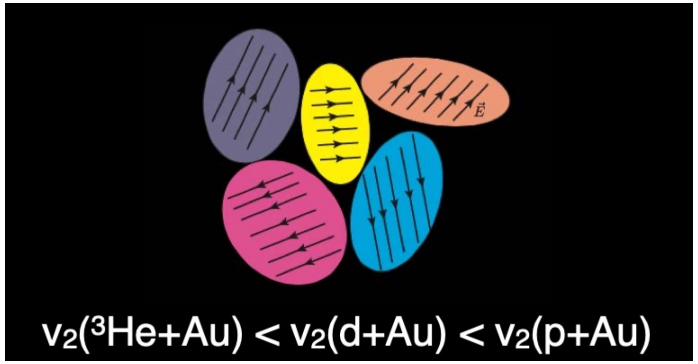


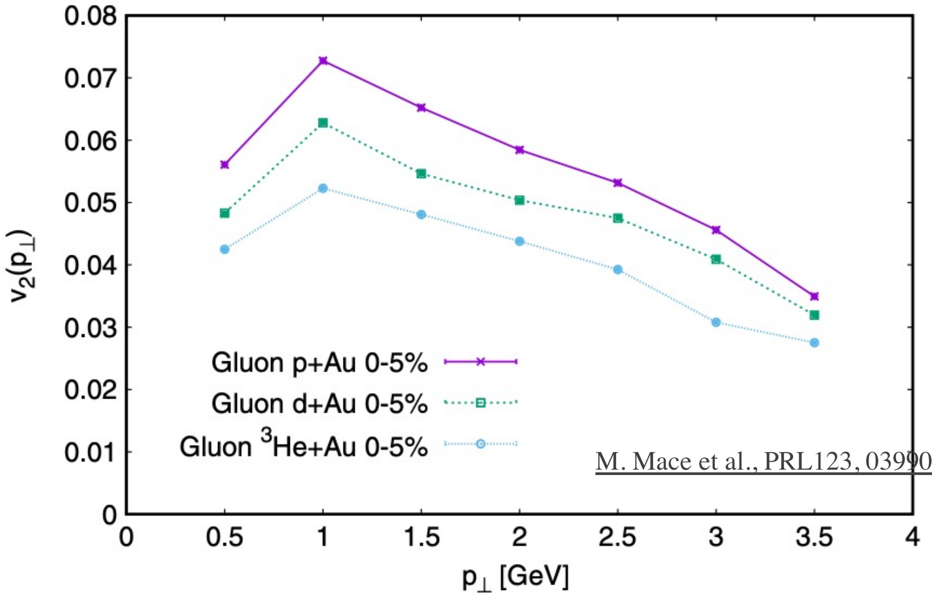
Anisotropic flow in small systems



The initial state vs final state in small systems was under debate for long time:

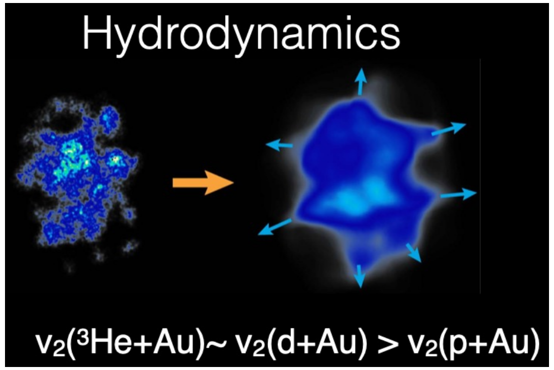
⊳ Initial momentum correlations: Color Glass Condensate

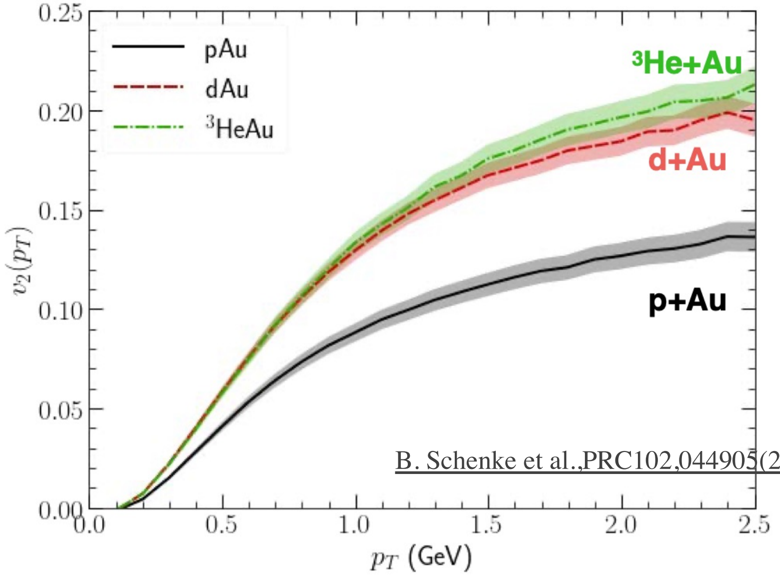




M. Mace et al., PRL123, 039901(E) (2019)

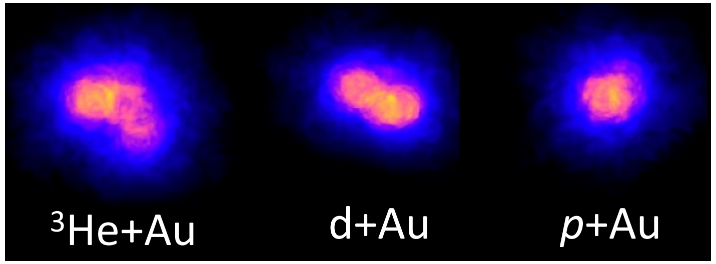
⊳ Final state interactions: hydrodynamics



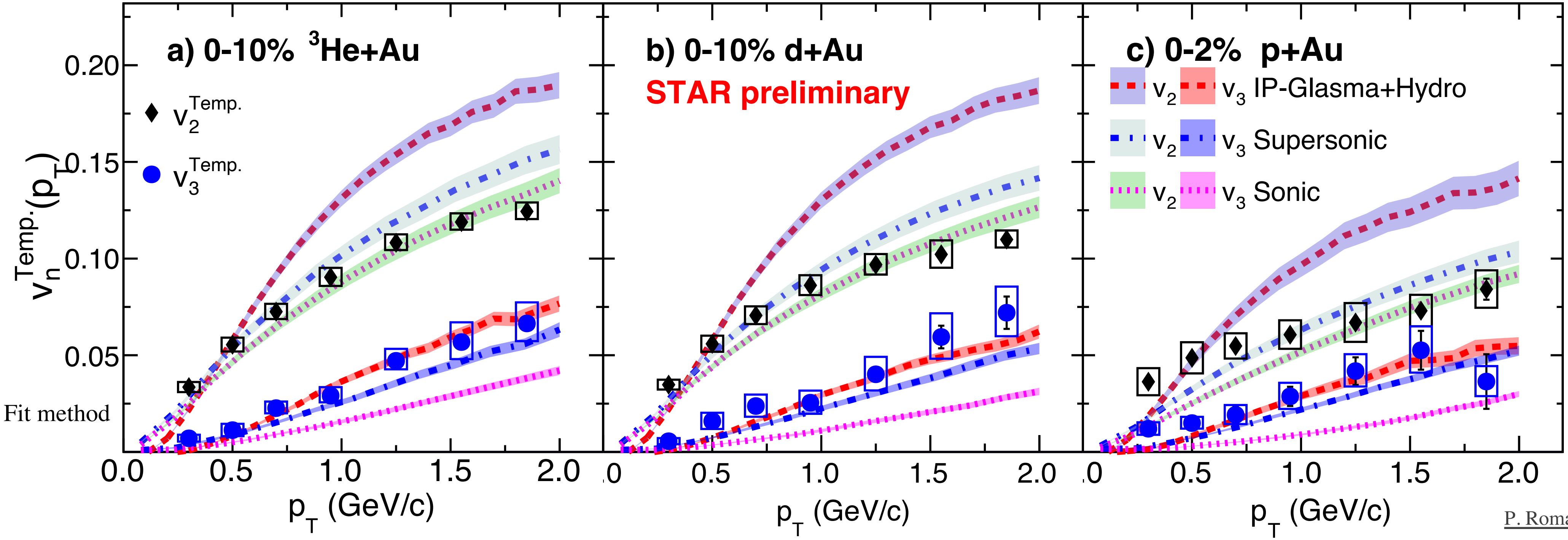


B. Schenke et al.,PRC102,044905(2020)

Anisotropic flow in small systems



Differential v_n measurements for p/d/^{3}He+Au with model comparison



Template Fit method

P. Romatschke, arXi1502.04745v1

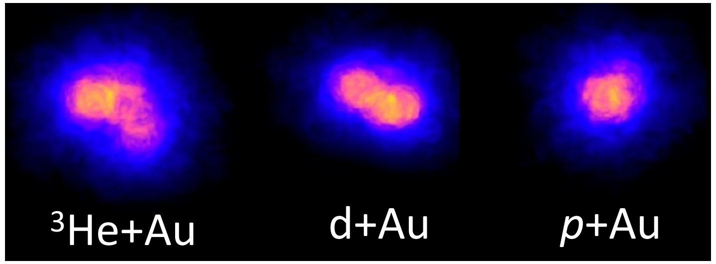
B. Schenke et al., PRC102, 044905 (2020)

- STAR: $v_2(^3\text{He+Au}) \sim v_2(\text{d+Au}) > v_2(\text{p+Au})$; $v_3(^3\text{He+Au}) \sim v_3(\text{d+Au}) \sim v_3(\text{p+Au})$
- **Sonic model** with initial geometry eccentricity from **Nucleon Glauber** under-predicts v_3 in all systems.
- **Supersonic model** can match the v_2 and v_3 better by including the "**pre-flow**".
- **IP-Glasma+Hydro** that includes sub-nucleonic fluctuations + initial momentum correlation over predicts v_2 but reproduces v_3.

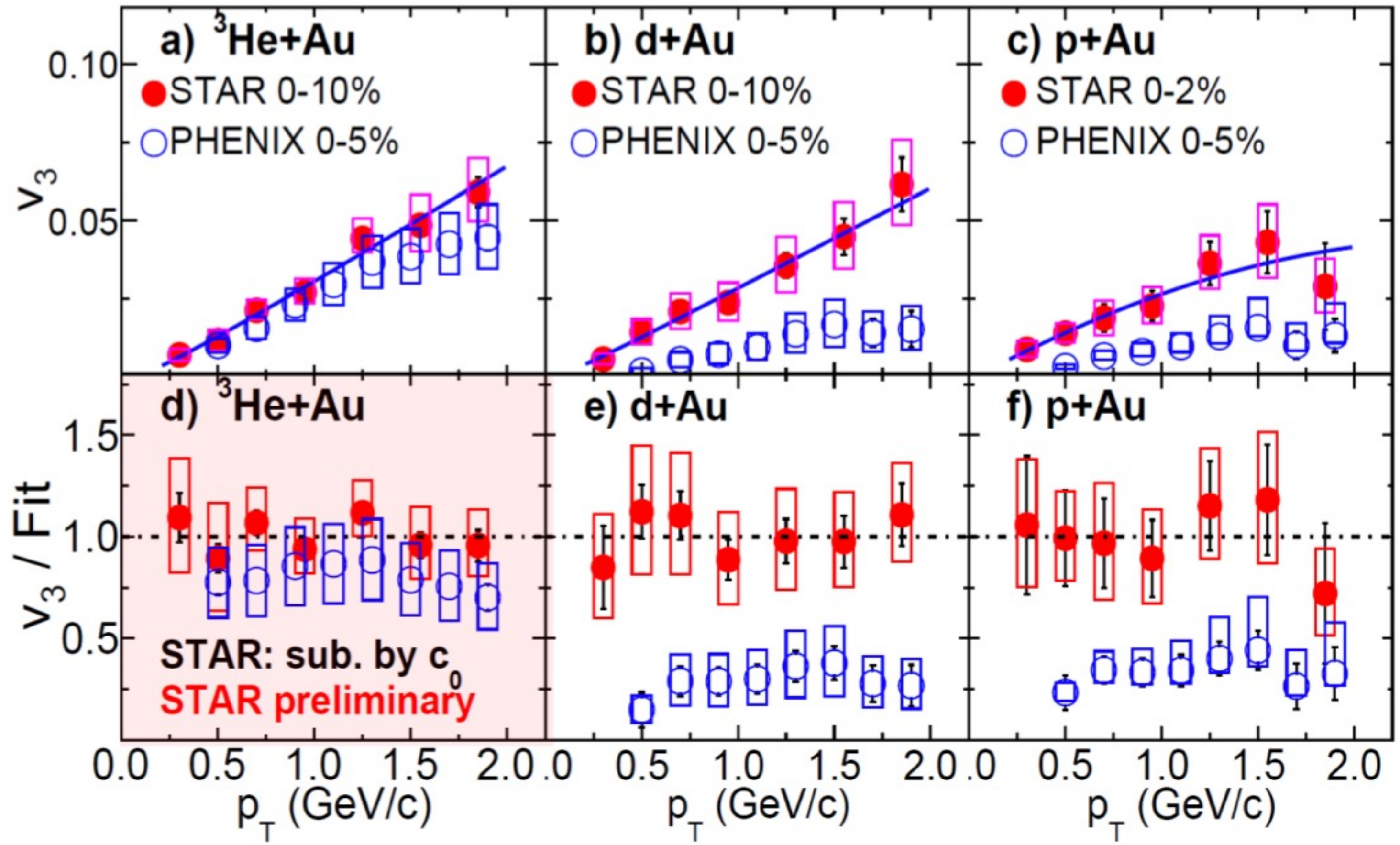
Sub-nucleon fluctuation-driven?

RHIC results decisively established the dominant role of final-state effects. However, the precise role of geometry is not understood.

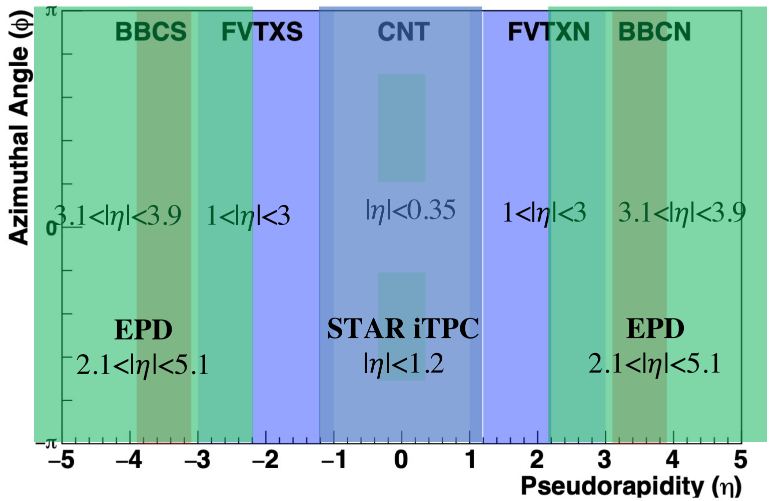
Anisotropic flow in small systems



Comparison with PHENIX results:



- STAR : symmetric acceptance with $|\eta|<0.9$, $|\Delta\eta|>1.5$
- PHENIX: correlate Au-going FVTXS and BBCS with mid-η CNT

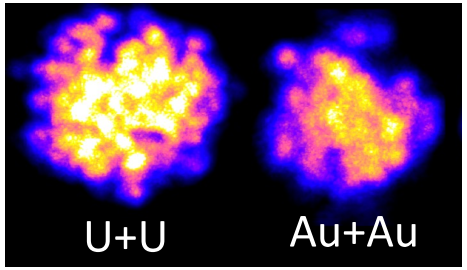


- STAR took **more d+Au data in 2021** with extended iTPC and EPD coverage for further cross-check.

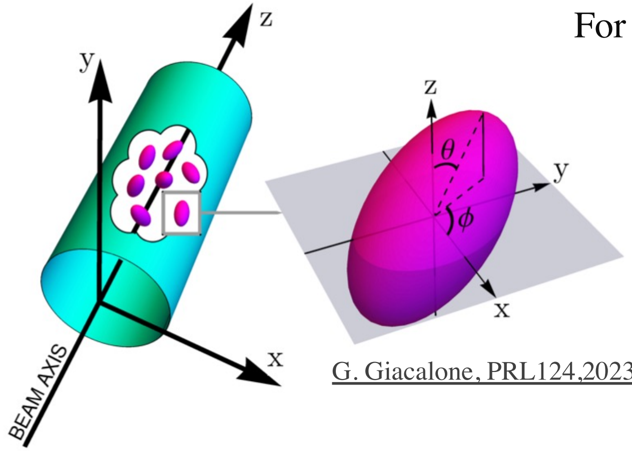
- STAR : $v_3(^3\text{He+Au}) \sim v_3(\text{d+Au}) \sim v_3(\text{p+Au})$
- PHENIX: $v_3(^3\text{He+Au}) > v_3(\text{d+Au}) \sim v_3(\text{p+Au})$ PHENIX, Nature Physics 15, 214(2019) PHENIX, arXiv:2107.06634

- **Disagreement in v_3 between STAR and PHENIX. Nonflow treatment, decorrelation and detector effect?**

Nuclear deformation in large systems



Connecting the initial state to the nuclear geometry:



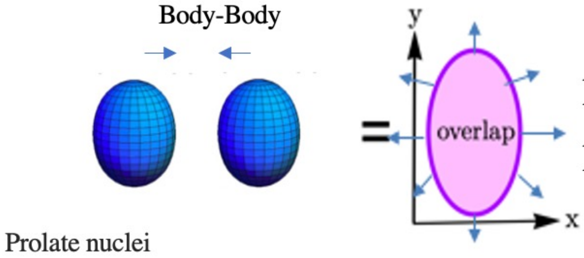
G. Giacalone, PRL124,202301(2020)

For a deformed nucleus, the leading form of nuclear density becomes:

$$\rho(r,\theta) = \frac{\rho_0}{1 + e^{(r-R_0(1+\beta_2 Y_{20}(\theta))/a}} \qquad Y_{20} = \sqrt{\frac{5}{16\pi}}(3\cos^2\theta - 1)$$

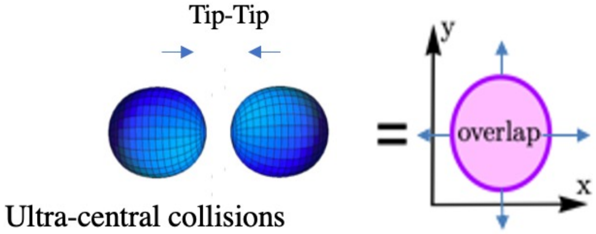
Deformation is dominated by quadrupole component β_2

- $\langle p_T \rangle \sim 1/R$ and $v_2 \propto \boldsymbol{\varepsilon}_2$: $\left\langle \epsilon_n^2 \frac{1}{R} \right\rangle \to \langle v_n^2 p_T \rangle$



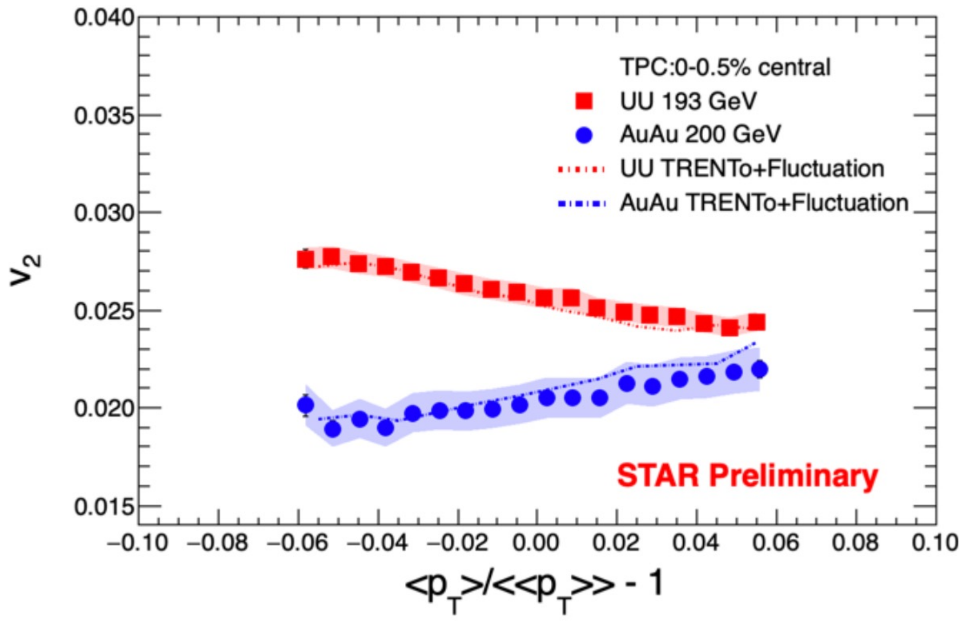
large R, small $\langle p_T \rangle$

large $\boldsymbol{\varepsilon}_2$



small R, large $\langle p_T \rangle$

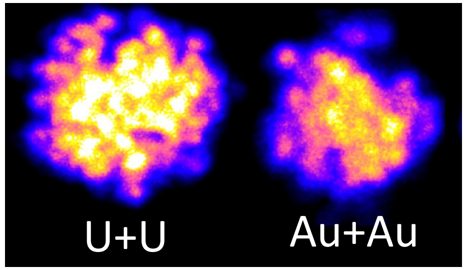
small $\boldsymbol{\varepsilon}_2$



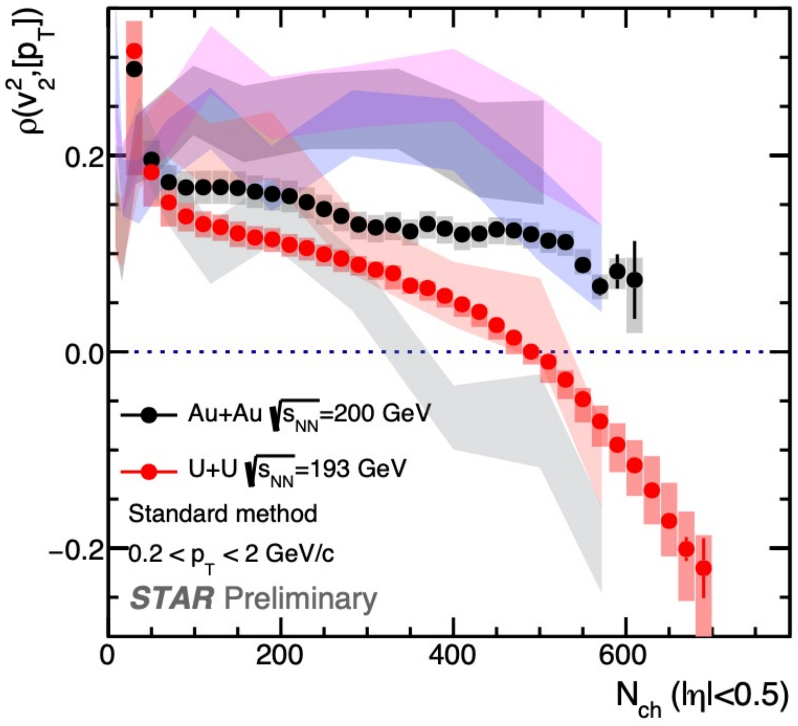
deformation contributes to anticorrelation between v_2 and $\langle p_T \rangle$

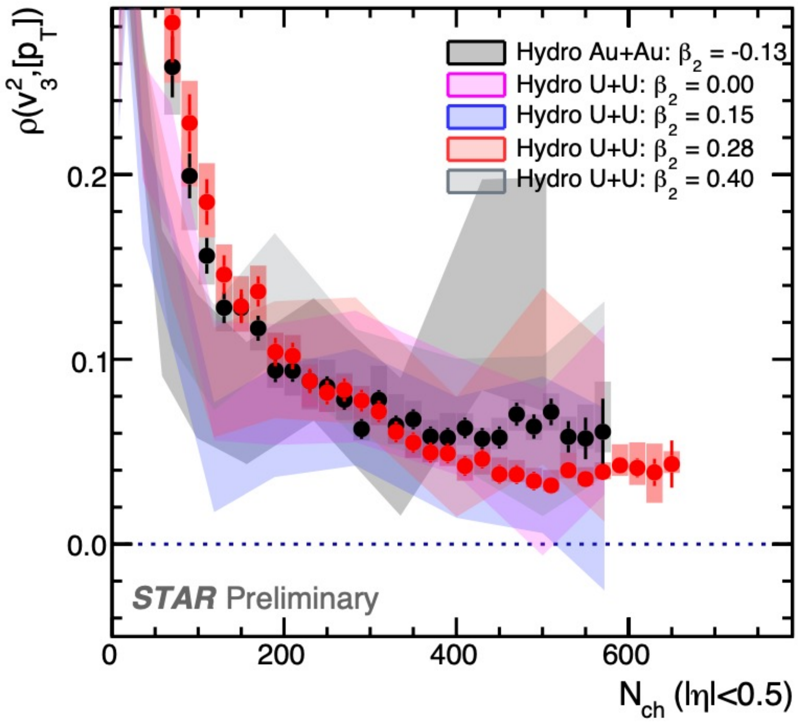
Measuring the v_2 - $\langle p_T \rangle$ correlation could reveal the quadrupole deformation β_2.

Nuclear deformation in large systems



$\rho(v_n^2, [p_T])$ in U+U and Au+Au collisions with model comparisons:





$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}} \langle \delta p_T \delta p_T \rangle}}$$

P. Bozek, PRC93,044908(2016)

G. Giacalone, PRC102,024901(2020)

B. Schenke et al., PRC102,034905(2020)

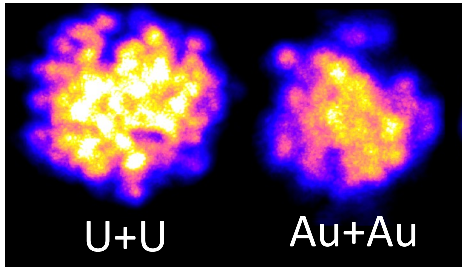
J. Jia et al., arXiv:2105.05713

C. Zhang et al., arXiv:2102.05200

- $\rho(v_2^2, [p_T])$ has clear difference: negative in U+U central, while **positive** in Au+Au.
- $\rho(v_3^2, [p_T])$ is always **positive and similar** in U+U and Au+Au.
- **IP-Glasma+Hydro** could describe the trend of $\rho(v_2^2, [p_T])$ quantifying the β_2 value to be around 0.28.

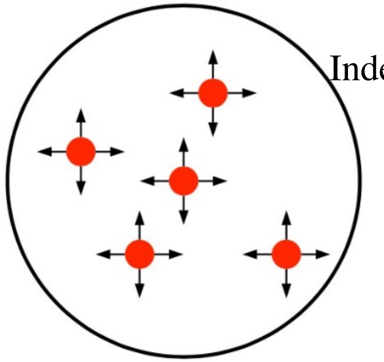
A new experimental test to study nuclear shape in heavy-ion collisions; also intriguing in isobar collisions.

Nuclear deformation in large systems



Mean p_T fluctuations in U+U and Au+Au collisions:

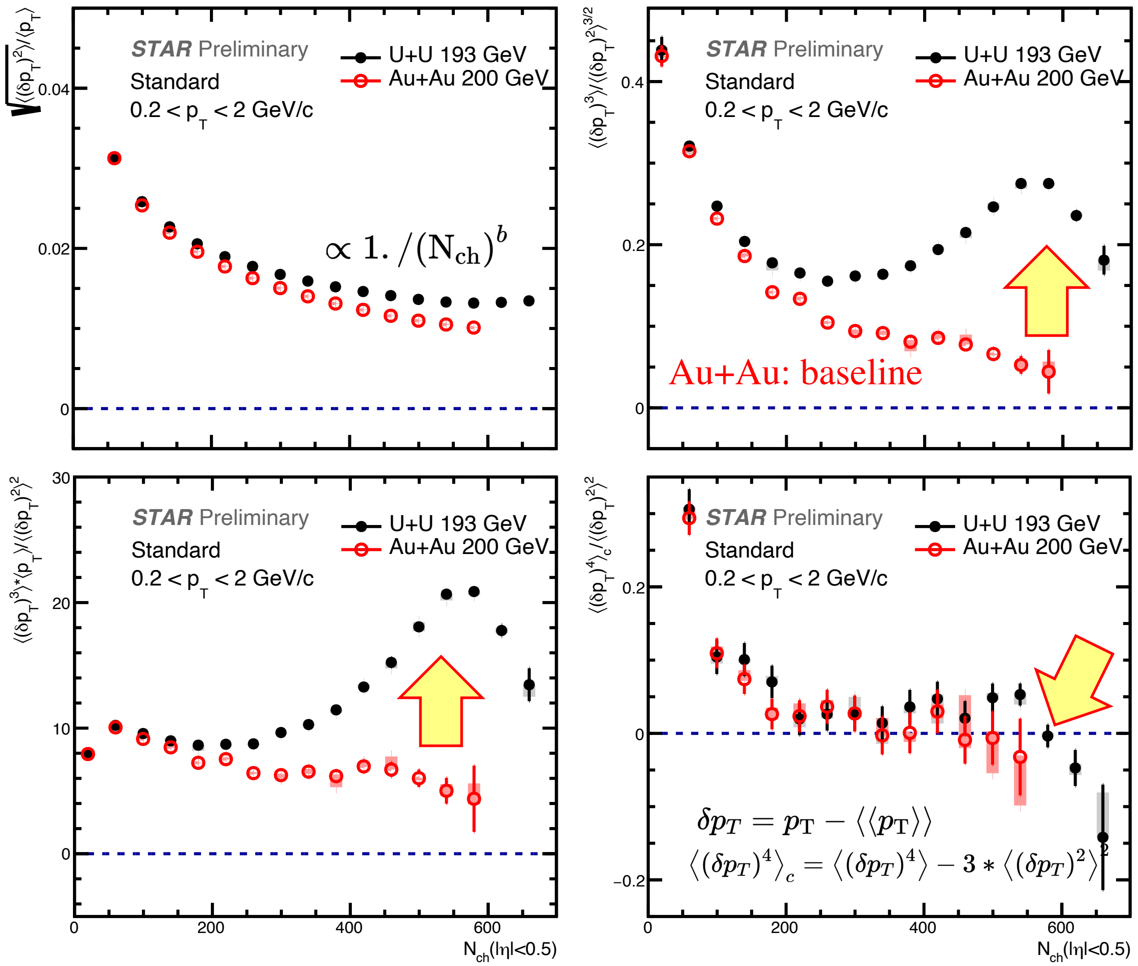
Radial expansion induced by nuclei shape:



$$c_s^2 = \frac{dP}{d\epsilon} = \frac{d\ln T}{d\ln s} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$

$$\frac{d\langle p_t\rangle}{\langle\langle p_t\rangle\rangle} = -3c_s^2\frac{dR}{\langle R\rangle}$$

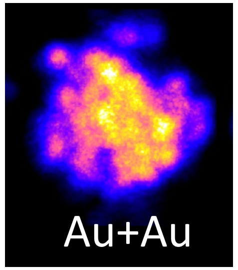
(Hydrodynamic approximations)



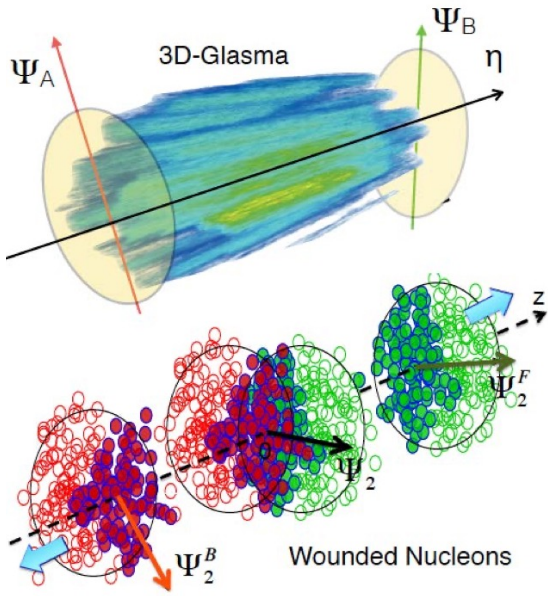
- A power-law function in Au+Au
- Significant enhancement in central U+U
- Clear sign-change in highly deformed U+U collisions

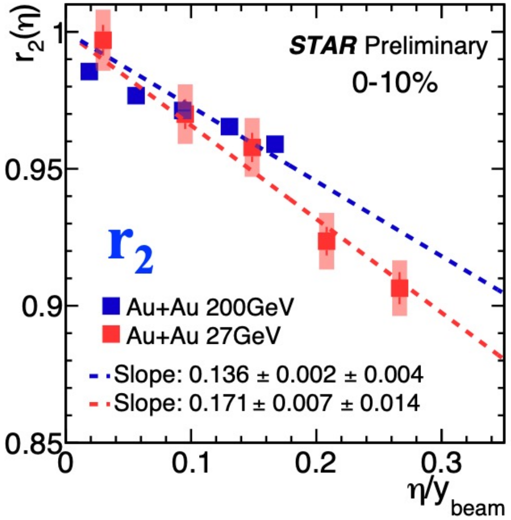
Another probe sensitive to nuclear deformation: mean p_T fluctuations induced by the nuclei shape.

Collectivity in BES energies

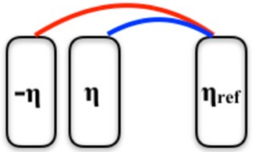


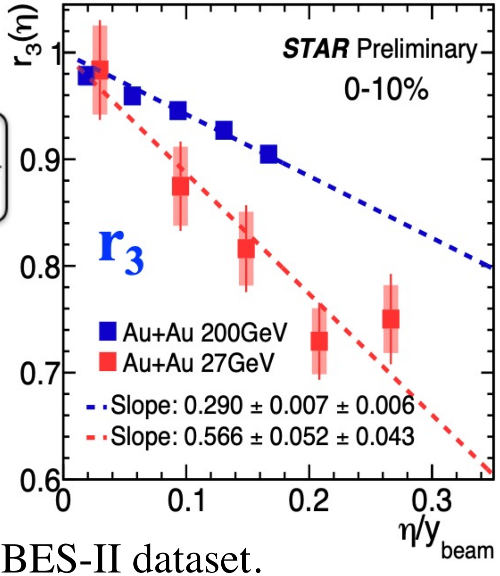
Decorrelation in BES energies: longitudinal dynamics





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



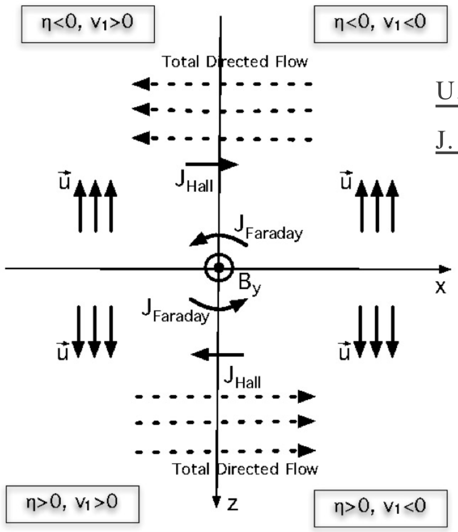


r_2: weak energy dependence

r_3: strong energy dependence

Need further studies using BES-II dataset.

EM-field drives charge splitting in v_1?



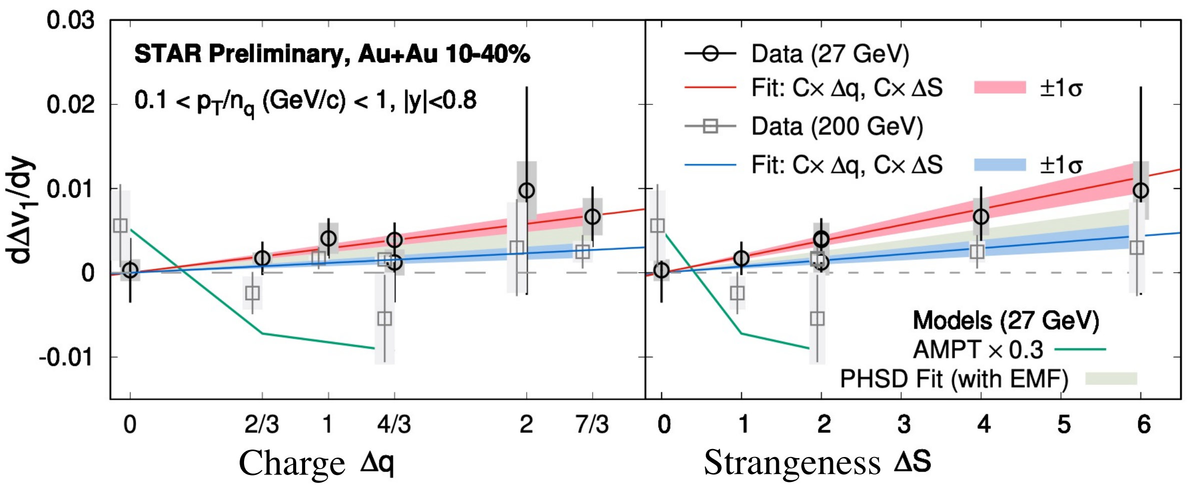
U. Gursoy et al., PRC89, 054905(2014)

J. Brachmann et al., PRC61, 024909(2000)

magnetic field leads to charge currents.

Faraday and Hall effects are competing.

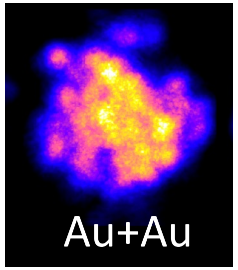
More details see Ashik (STAR), ICNFP2021, Aug 31



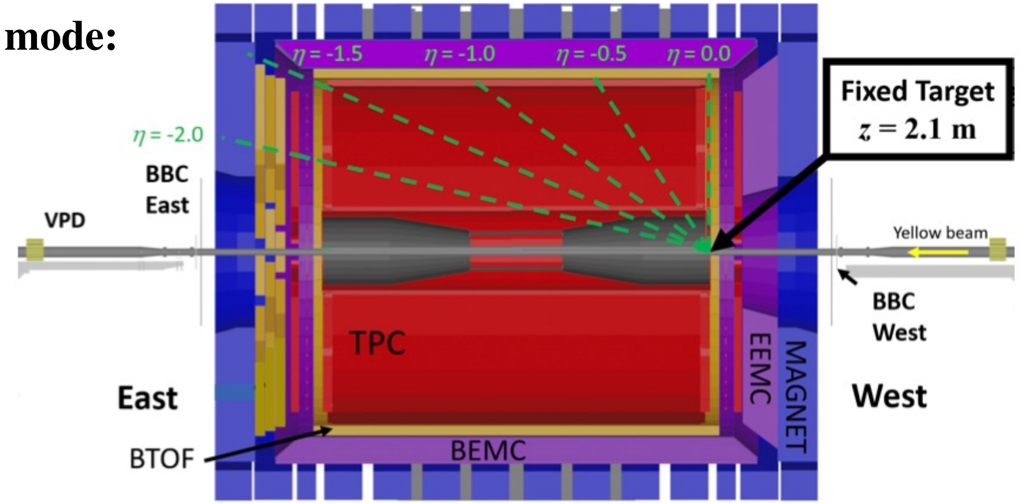
Δv_1 slope ($d\Delta v_1/dy$) seems to increase with increasing Δq and ΔS at 27GeV.

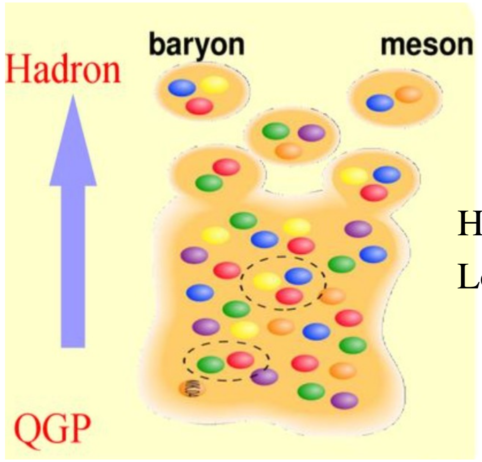
PHSD with EM-field supports this within uncertainties.

Collectivity in fixed-target mode



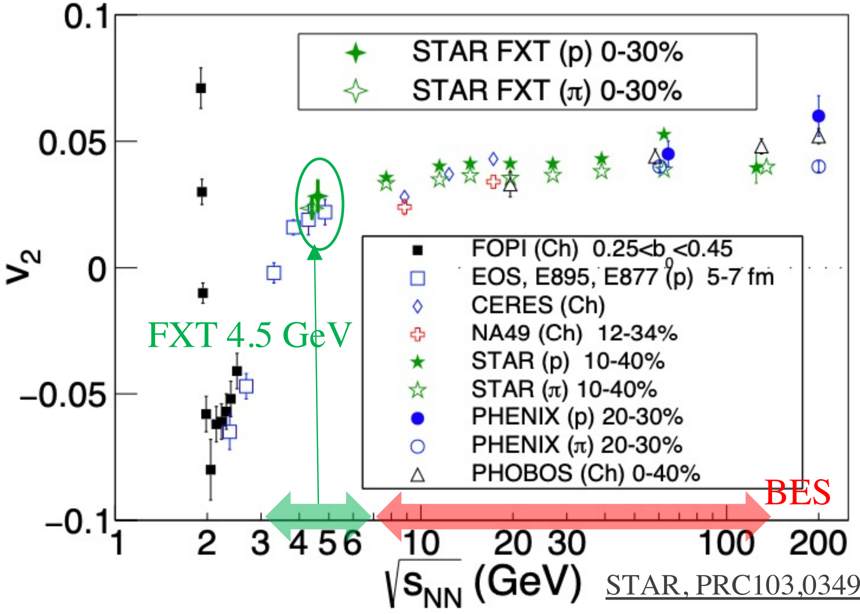
FXT mode:





Higher energy: *quark coalescence behavior* stays

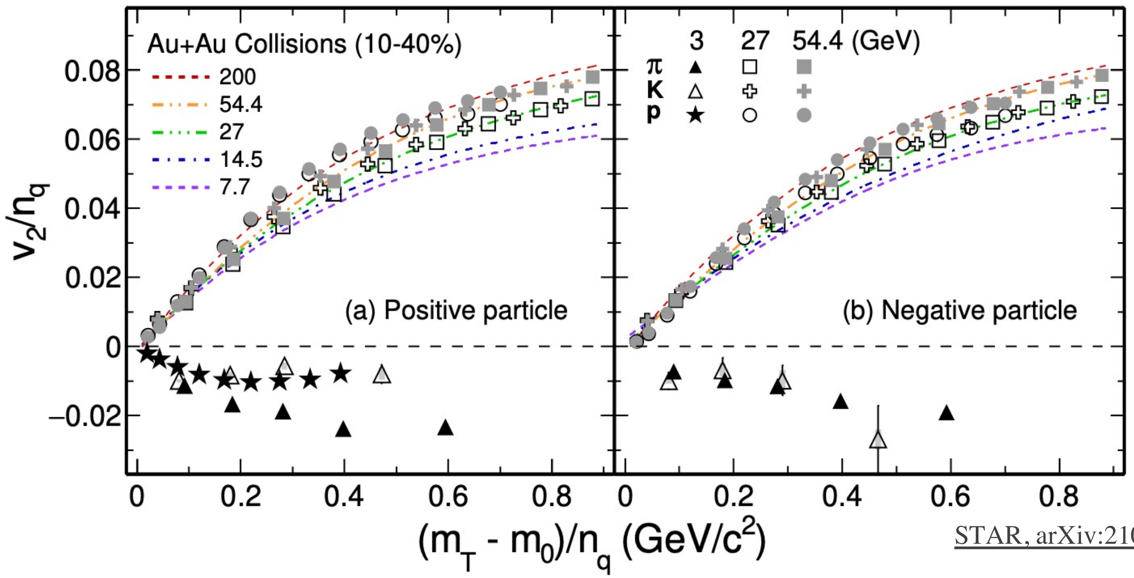
Lower energy: *baryonic scatterings* dominates?



STAR, PRC103,034908(2021)

- from squeeze-out (v_2<0) to in-plane elliptic expansion (v_2>0)

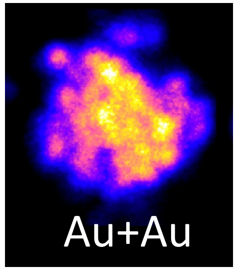
Disappearance of partonic collectivity at 3 GeV



STAR, arXiv:2108.00908v1

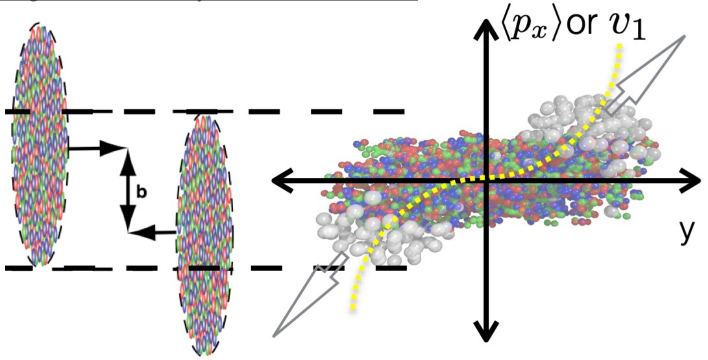
- v_2 of charged hadrons are negative and the NCQ scaling is absent.

Directed flow in fixed-target mode

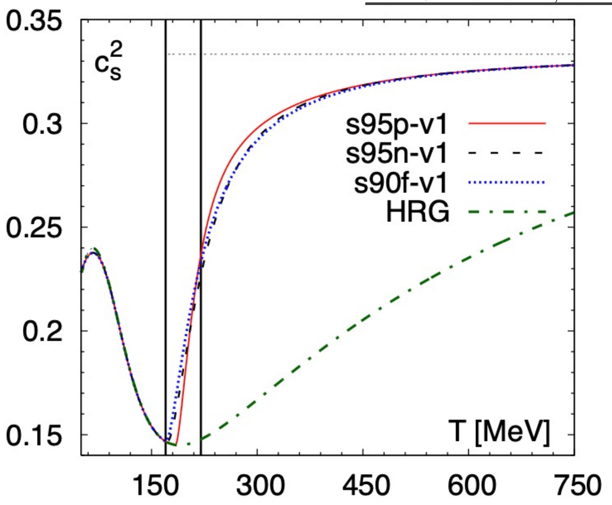


$$v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$$

R. Snellings. New J of Phys13, 055008 (2011)



P.Huovinen et al., NPA837, 26(2010)

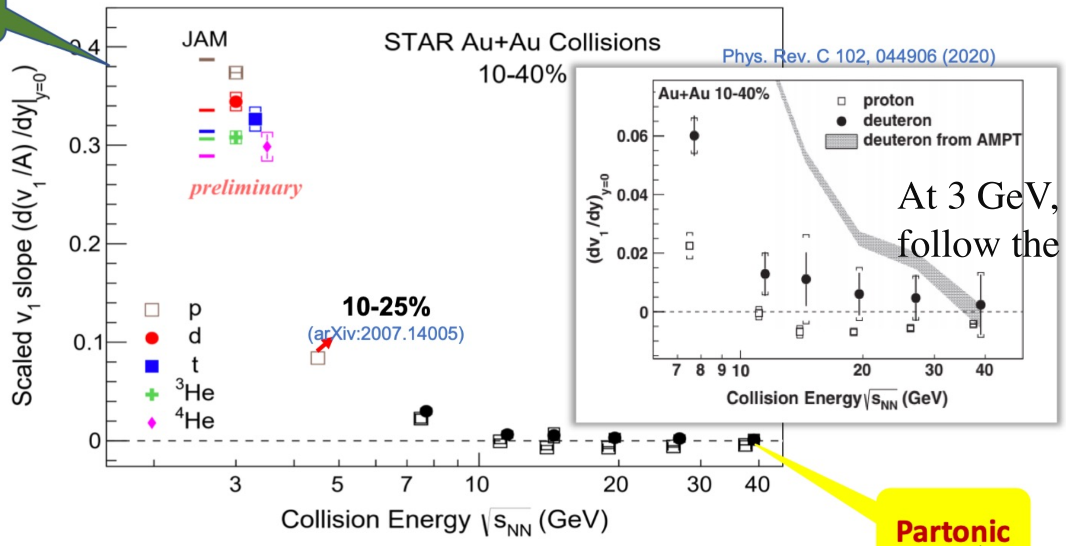


Early time expansion
Sensitive to EoS
First order phase transition

J. Brachmann et al., PRC61, 024909(2000)

Energy dependence of dv_1/dy

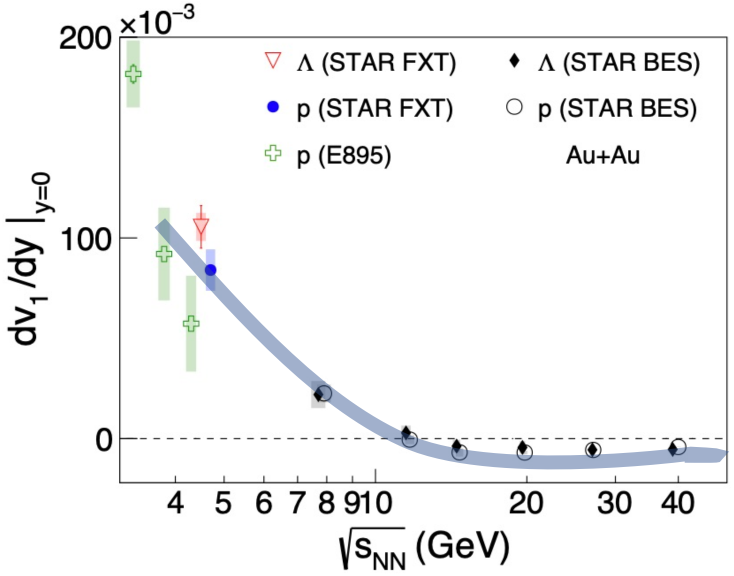
Hadronic



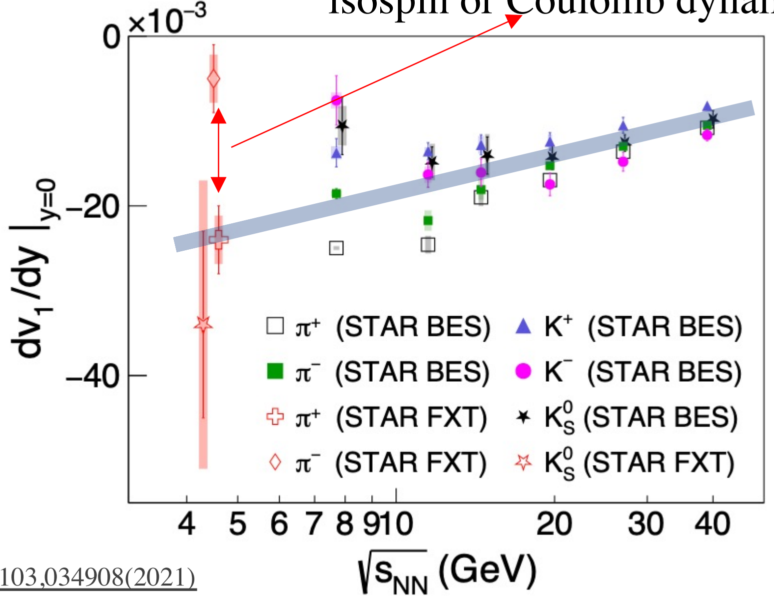
Partonic

At 3 GeV, the light nuclei v_1 slopes follow the atomic-mass-number scaling

Hadronic model JAM reproduces the data

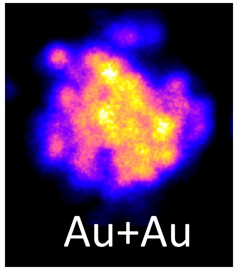


isospin or Coulomb dynamics?

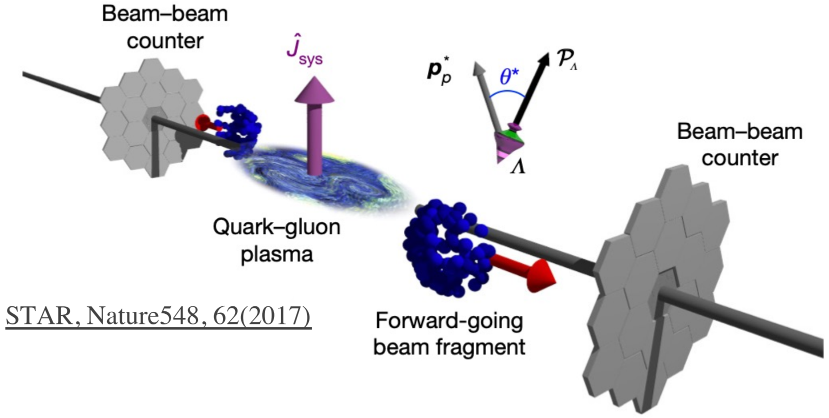


STAR, PRC103,034908(2021)

Global polarization and vorticity in BES and FXT mode



The average vorticity points along the direction of the angular momentum of the $\hat{J}_{sys}$



STAR, Nature548, 62(2017)

Global polarization is measured from the angular distributions of hyperon decay product:

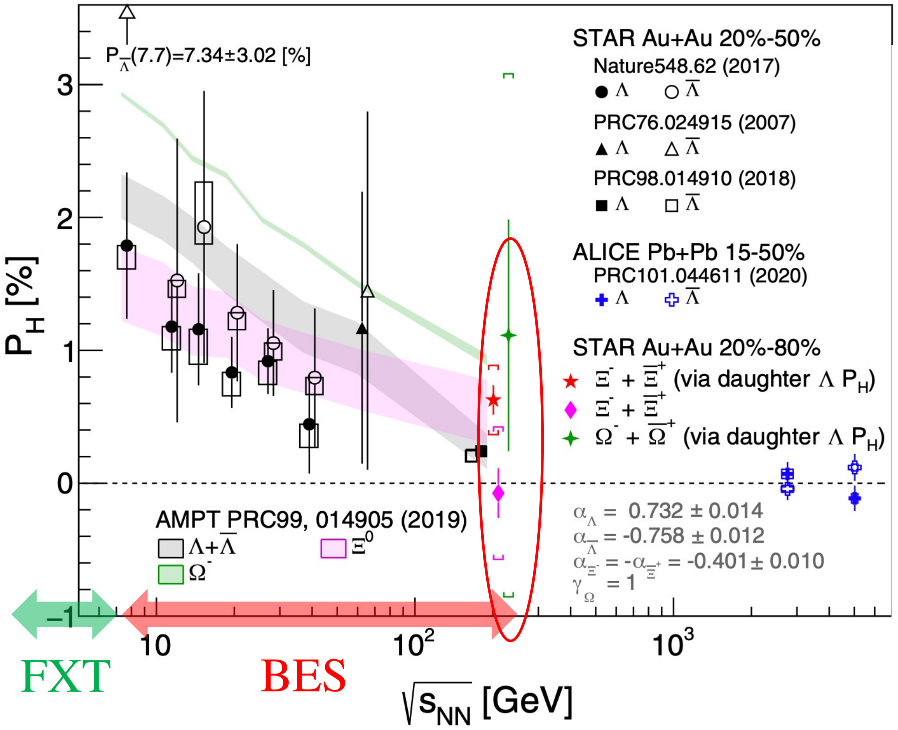
$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle\sin(\Psi_1 - \phi_d^*)\rangle}{\mathrm{Res}(\Psi_1)}$$

Thermal vorticity:

$$\omega = k_B T(P_\Lambda + P_{\bar{\Lambda}})/\hbar \qquad \omega \sim (9 \pm 1) \times 10^{21} s^{-1}$$

F. Becattini et al., PRC95, 054902(2017)

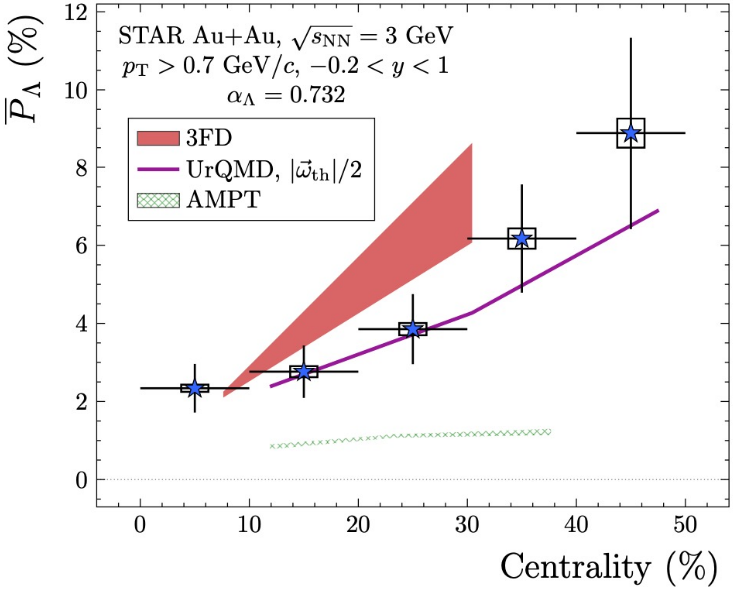
STAR, PRL126, 162301(2021)



Large angular momentum transferred by the two colliding nuclei

Stronger polarization at lower collision energies.

STAR, arXiv:2108.00044



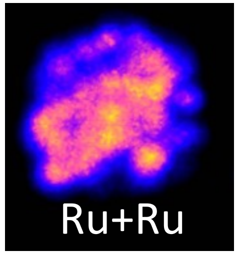
Much larger $\bar{P}_\Lambda$ in FXT 3GeV at 20-50%:

4.91 ± 0.81 (stat.) ± 0.15 (syst.)%

Larger hyperon polarization for more peripheral collisions

Opens up new directions in the study of the hottest, least viscous and most vortical fluid matter.

Search for the Chiral Magnetic Effect



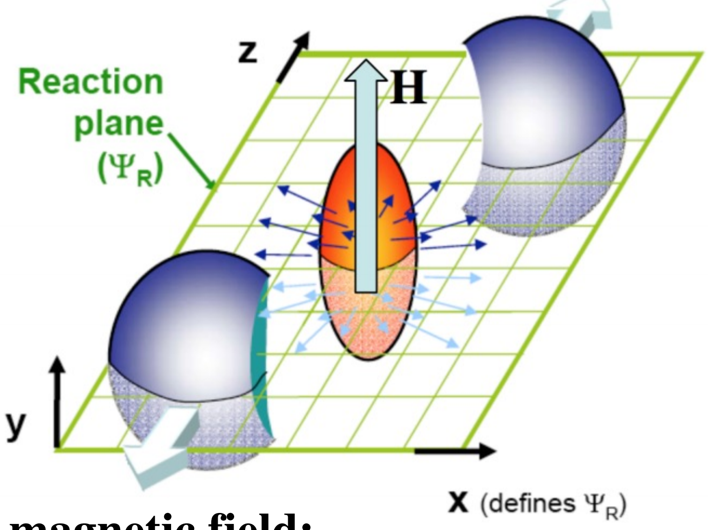
Collisions of two heavy ions create the strongest electromagnetic field in the universe

Strong magnetic field

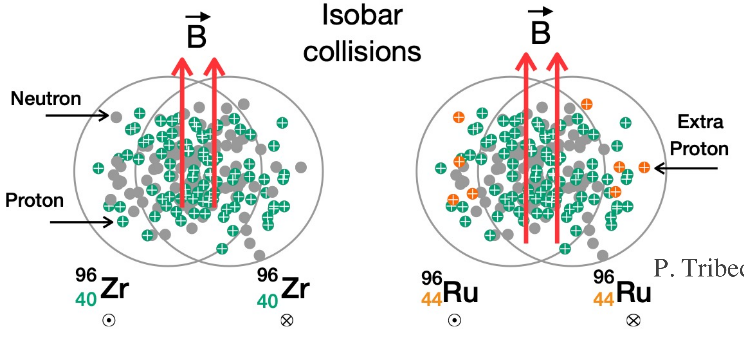
$B \sim 10^{18}$ Gauss

D.E. Kharzeev, arXiv:1312.3348

D.E. Kharzeev et al., NPA803, 227(2008)



Best possible control on background and signal with isobar collisions:



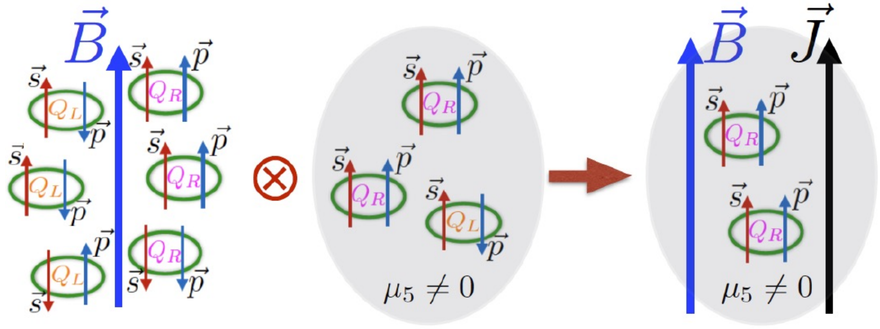
10~18% large B-field square difference, ~4% flow background difference

P. Tribedy (STAR)

STAR BUR Run17-18

STAR, arXiv:1911.00596

Charge separation along the magnetic field:

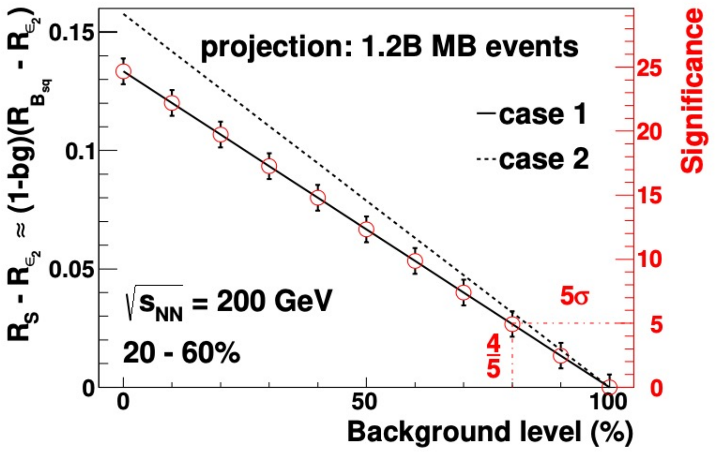


Chiral Magnetic effect: $\mathbf{J} = \frac{Qe}{2\pi^2}\mu_5\mathbf{B}$

D. E. Kharzeev et al., arXiv:15011.04050

An electric current will be induced in chiral domains along the B field in heavy-ion collisions.

The anticipated significance estimation:



~1.2 B events would see 5σ significance signal if background contributed up to ~80%.

Results from isobar collisions are being announced today: zoom 1618659309, 11:00-12:00 PM US/Eastern

RUN21 took all the data we wanted and more

Efficient run and data-taking:

Single-Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)	Priority
3.85	7.7	11-20 weeks	Au+Au	100 M	1
3.85	3 (FXT)	3 days	Au+Au	300 M	2
44.5	9.2 (FXT)	0.5 days	Au+Au	50 M	2
70	11.5 (FXT)	0.5 days	Au+Au	50 M	2
100	13.7 (FXT)	0.5 days	Au+Au	50 M	2
100	200	1 week	O+O	400 M 200 M (central)	3
8.35	17.1	2.5 weeks	Au+Au	250 M	3
3.85	3 (FXT)	3 weeks	Au+Au	2 B	3
100	200	1 week	d+Au	100M MB 100M Central	4

- BES-II concluded with overlapping FXT and Collider energies - various kinematic ranges and baryon chemical potentials for direct comparison!

More impressive and intriguing results in future

Conclusions and Outlooks

Conclusions:

striking results from flow, vorticity and chirality at BES and FXT mode:

- STAR midrapidity small system results support **geometry fluctuations at sub-nucleon scale**.
- **A significant anticorrelation between** v_2 and p_T in central events indicate uranium deformation.
- The new probe **mean p_T fluctuations** indicate sensitivity to nuclear shape.
- **Weak** energy dependence in longitudinal decorrelation measure r_2 but **strong** energy dependence in r_3.
- Electric charge dependent splitting for v_1 of produced quarks observed, could be driven by **electromagnetic field**.
- v_2 of charged hadrons at FXT 3GeV are negative and the NCQ scaling is absent: **partonic collectivity disappears**.
- Light nuclei v_1 slopes follow the atomic-mass-number scaling.
- **Strongest** Λ global polarization seen at FXT.
- **Search for the Chiral Magnetic Effect:** results from isobar blind analysis will appear today.

Outlooks:

- Recent **O+O and d+Au run with extended STAR acceptance** will provide crucial insights on small system collectivity.
- An intriguing possibility to explore **nuclear deformation in isobar collisions** using new observables.
- Precision measurements on global polarization with high statistics **BES-II program and FXT data** coming soon.

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