Measurement of longitudinal decorrelation of anisotropic flow v_2 and v_3 in 200 GeV Au+Au collisions at STAR

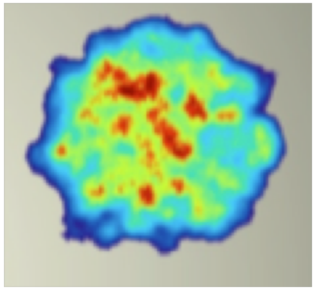
Maowu Nie
(For the STAR Collaboration)
Shandong University

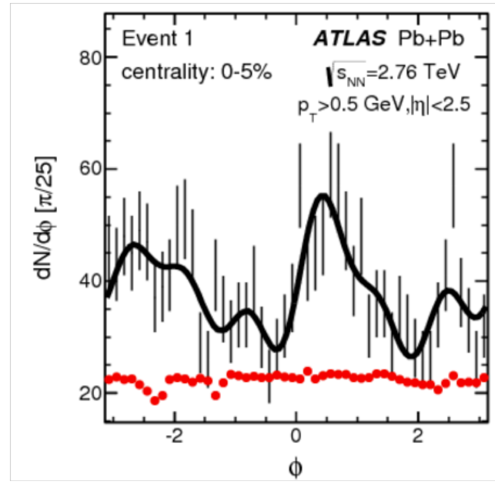
June 4–7, 2019

2019 RHIC & AGS Annual Users' Meeting

Flow observables

A little bang

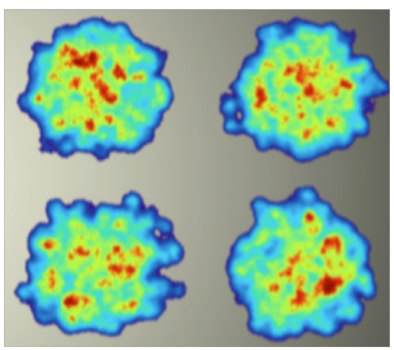




$$\frac{dN}{d\phi} \sim 1 + 2\sum_{n=1} v_n \cos\left(n(\phi - \Phi_n)\right)$$

$$v_n = \langle \cos(n(\phi - \Phi_n)) \rangle, \quad \boldsymbol{v}_n = v_n e^{in\Phi_n}$$

Many little bangs



Flow observables

J.Jia, *arxiv*: 1407.6057

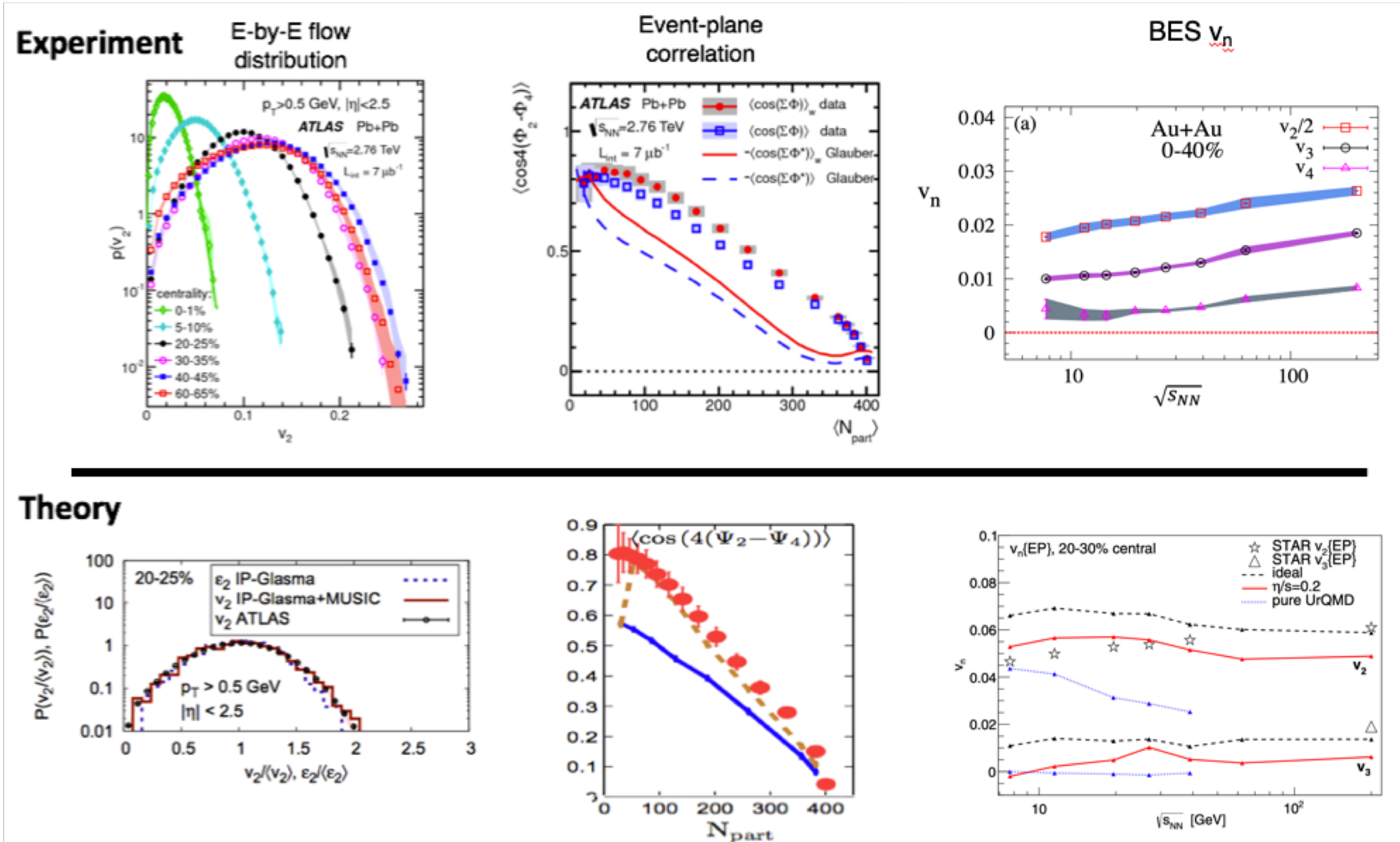
	pdfs	cumulants
	$p(v_n)$	$v_n\{2k\}$, $k = 1,2,...$
Flow-amplitudes	$p(v_n, v_m)$	$\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$, $n \neq m$ ...
	$p(v_n, v_m, v_l)$	$\langle v_n^2 v_m^2 v_l^2\rangle + 2\langle v_n^2\rangle\langle v_m^2\rangle\langle v_l^2\rangle -$ $\langle v_n^2 v_m^2\rangle\langle v_l^2\rangle - \langle v_m^2 v_l^2\rangle\langle v_n^2\rangle - \langle v_l^2 v_n^2\rangle\langle v_m^2\rangle$ $n \neq m \neq l$ ...
	...	Obtained recursively as above
EP-correlation	$p(\Phi_n, \Phi_m, ...)$	$\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k kc_k = 0$
Mixed-correlation	$p(v_l, \Phi_n, \Phi_m, ...)$	$\langle v_l^2 v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle -$ $\langle v_l^2\rangle\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k kc_k = 0$, $n \neq m \neq l...$

Joint p.d.f. of v_n and Φ_n

$$p(v_n, v_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{\text{evts}}} \frac{dN_{\text{evts}}}{dv_n dv_m ... d\Phi_n d\Phi_m ...}$$

Correlations and fluctuations in transverse plane

- Transverse dynamics has been well explored both in experiments and theory



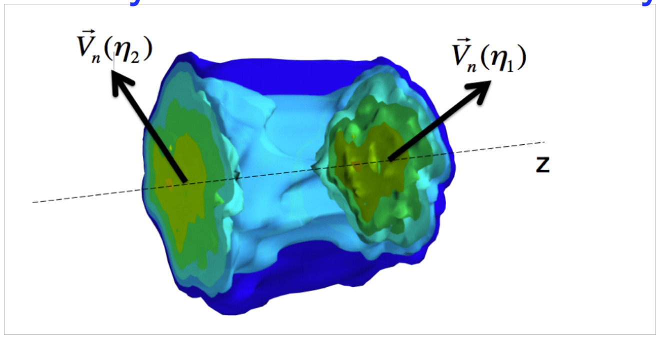
PRL 110.012302

PLB 717, 261 (2012)

PRC.91.064902 (2015)

(3+1)D QGP evolution

- Longitudinal dynamics hasn't been fully explored yet



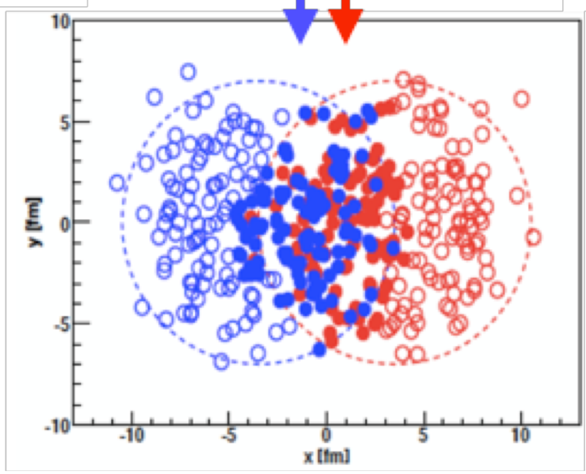
$$\boldsymbol{v}_n(\eta) = v_n(\eta)e^{in\Phi_n(\eta)}$$

Forward

$\varepsilon_n^F e^{in\Psi_n^F}$

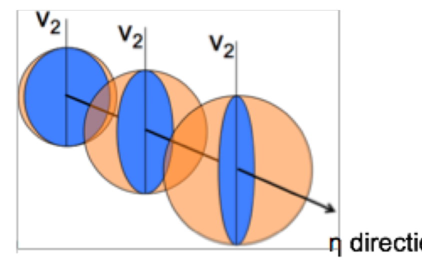
Backward

$\varepsilon_n^B e^{in\Psi_n^B}$



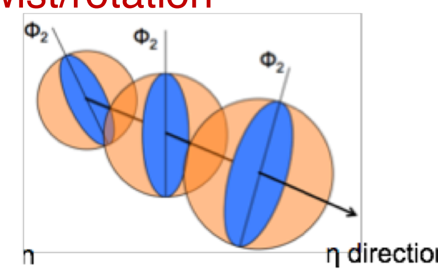
- FB magnitude asymmetry

  $v_n(\eta)$



- Event plane twist/rotation

  $\Phi_n(\eta)$

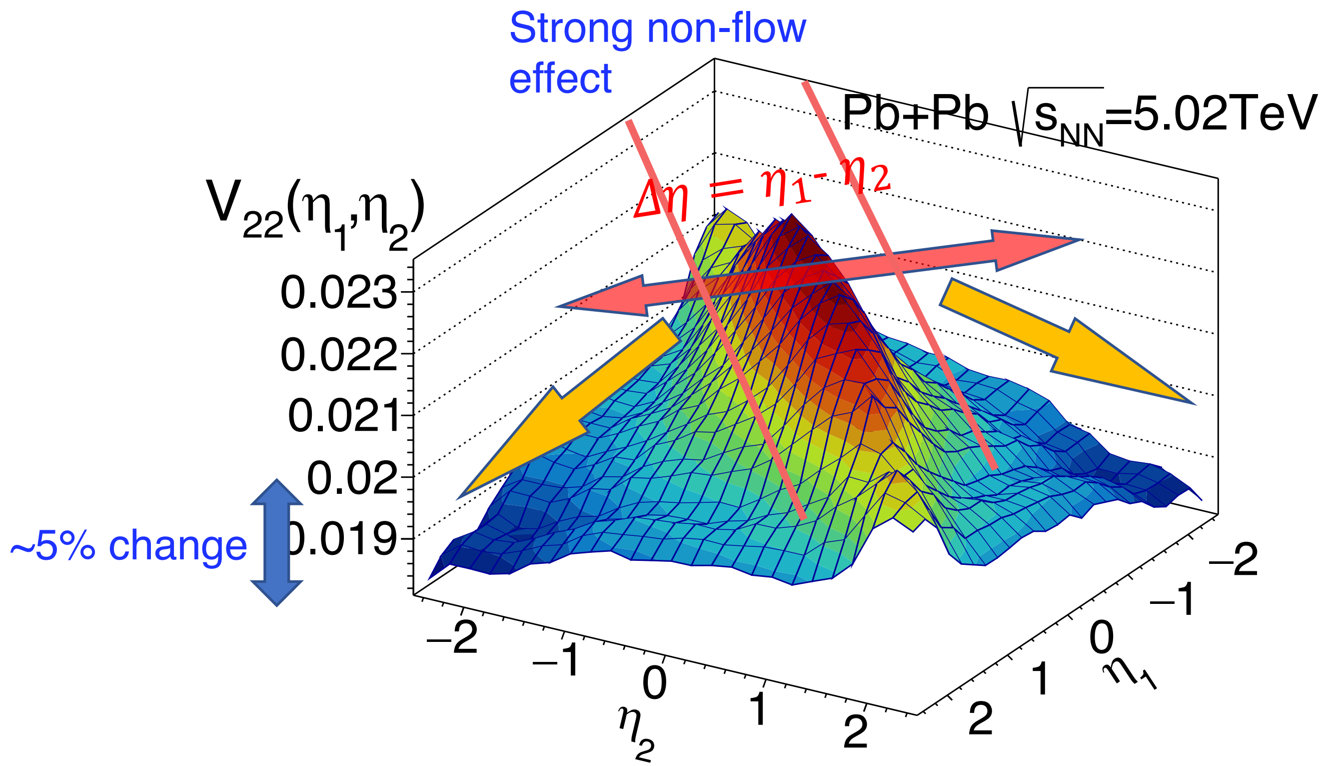


2D map of flow correlation in η

- 2-particle correlator: correlate flow $\mathbf{v}_n$ between η_1 and η_2

$$V_{nn}(\eta_1,\eta_2) = \langle \boldsymbol{v}_n(\eta_2)\,\boldsymbol{v}_n^*(\eta_1)\rangle$$

$$= \langle v_n(\eta_1)\,v_n(\eta_2)\cos n\,(\Psi_n(\eta_1) - \Psi_n(\eta_2))\rangle$$



✓ V_{22} decreases at large $\Delta\eta = |\eta_1 - \eta_2|$

✓ V_{22} has small variation

How to measure flow decorrelation

- 2-particle correlator: correlate flow $\mathbf{v}_n$ between η_1 and η_2

$$V_{nn}(\eta_1,\eta_2) = \langle \boldsymbol{v}_n(\eta_2)\boldsymbol{v}_n^*(\eta_1)\rangle = \langle v_n(\eta_1)v_n(\eta_2)\cos n(\Psi_n(\eta_1)-\Psi_n(\eta_2))\rangle$$

$$\neq \langle \mathbf{v}_n(\eta_1)\rangle\langle \mathbf{v}_n(\eta_2)\rangle$$

flow decorrelation

✓ The intuitive but problematic way:

$$\mathbf{q}_n(\eta) = \frac{\sum_i w_i e^{in\phi_i}}{\sum_i w_i} = v_n(\eta)e^{in\Psi_n(\eta)}$$

$$r_n(\eta) = \frac{\langle \mathbf{q}_n(\eta)\mathbf{q}_n^*(-\eta)\rangle}{\langle \mathbf{q}_n(\eta)\rangle\langle \mathbf{q}_n(-\eta)\rangle}$$

→

$$\langle \mathbf{q}_n\rangle = 0$$

$$r_n(\eta) = \frac{\langle \mathbf{q}_n(\eta)\mathbf{q}_n^*(-\eta)\rangle}{\sqrt{\langle q_n^2(\eta)\rangle\langle q_n^2(-\eta)\rangle}}$$

→

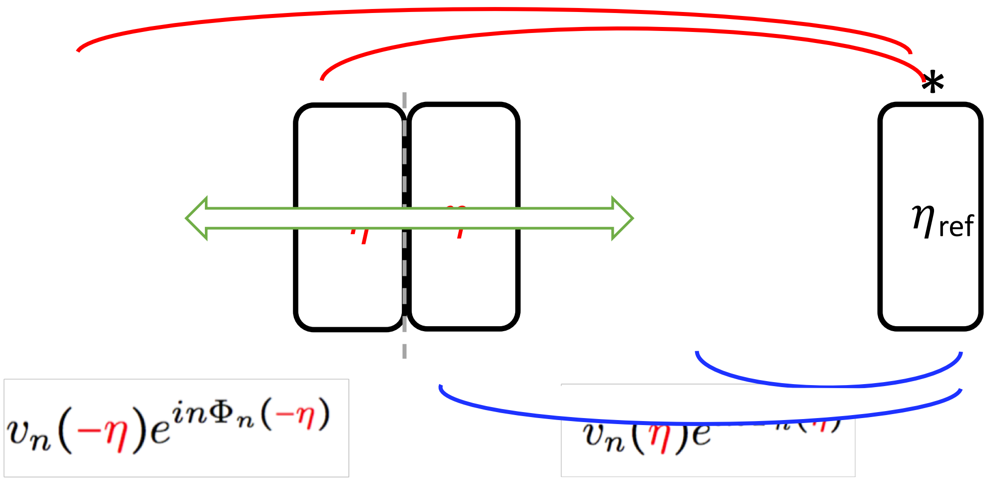
non-flow contributions in the denominator

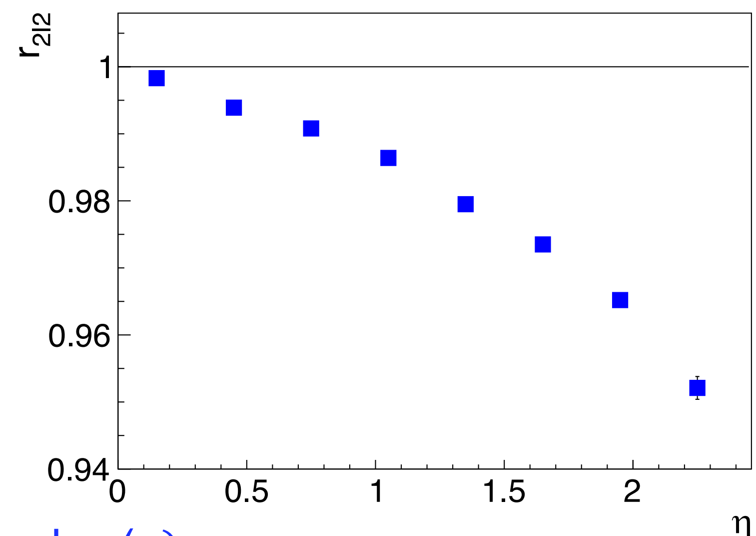
How to measure flow decorrelation

- Factorization ratio r_n is constructed to measure flow decorrelation

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

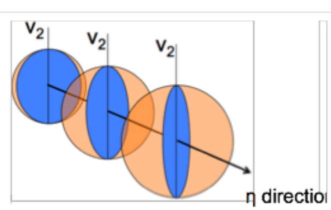
CMS PRC.92.034911



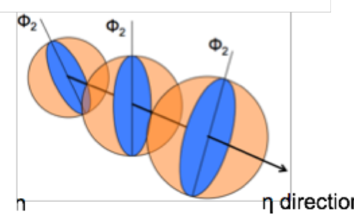


- r_n measures relative variance between $\mathbf{v}_n(-\eta)$ and $\mathbf{v}_n(\eta)$

$$r_n(\eta) = \frac{\langle V_n(-\eta)V_n^*(\eta_{\mathrm{ref}})\rangle}{\langle V_n(\eta)V_n^*(\eta_{\mathrm{ref}})\rangle} = \frac{\langle v_n(-\eta)v_n(\eta_{\mathrm{ref}})\cos n(\Psi_n(-\eta)-\Psi_n(\eta_{\mathrm{ref}}))\rangle}{\langle v_n(\eta)v_n(\eta_{\mathrm{ref}})\cos n(\Psi_n(\eta)-\Psi_n(\eta_{\mathrm{ref}}))\rangle}$$



FB magnitude asymmetry

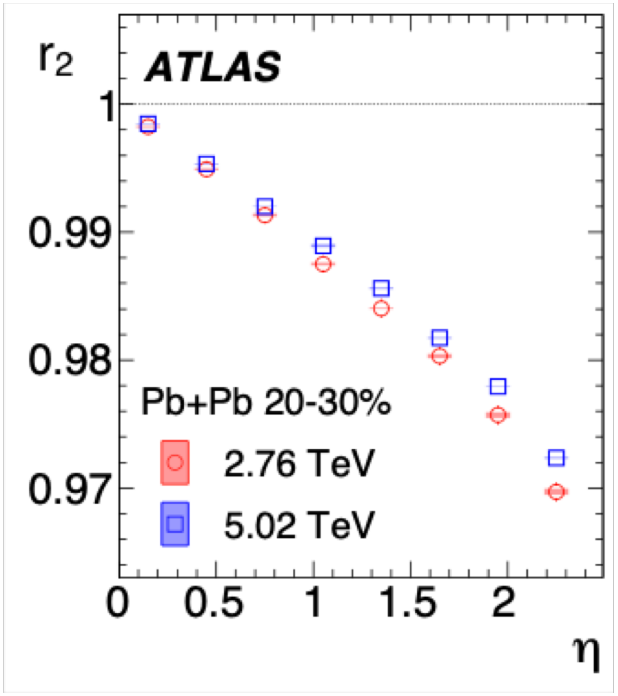


Event Plane (EP) twist

Why are measurements at RHIC important?

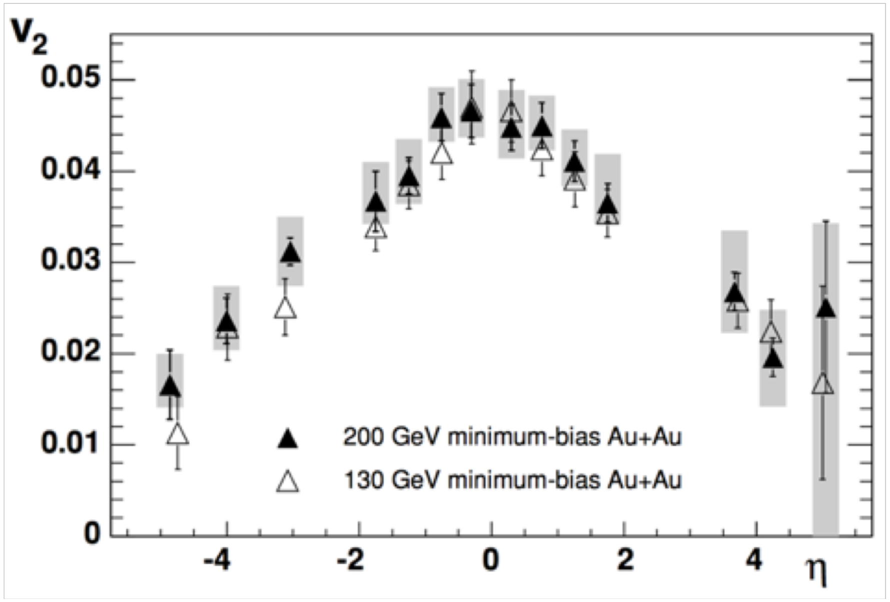
- Energy dependence of r_2 at two LHC energies

ATLAS, EPJC 78, 142(2018)



- Rapidity-dependent v2(η) at RHIC energies

PHOBOS, PRC 72, 051901(R) (2005)

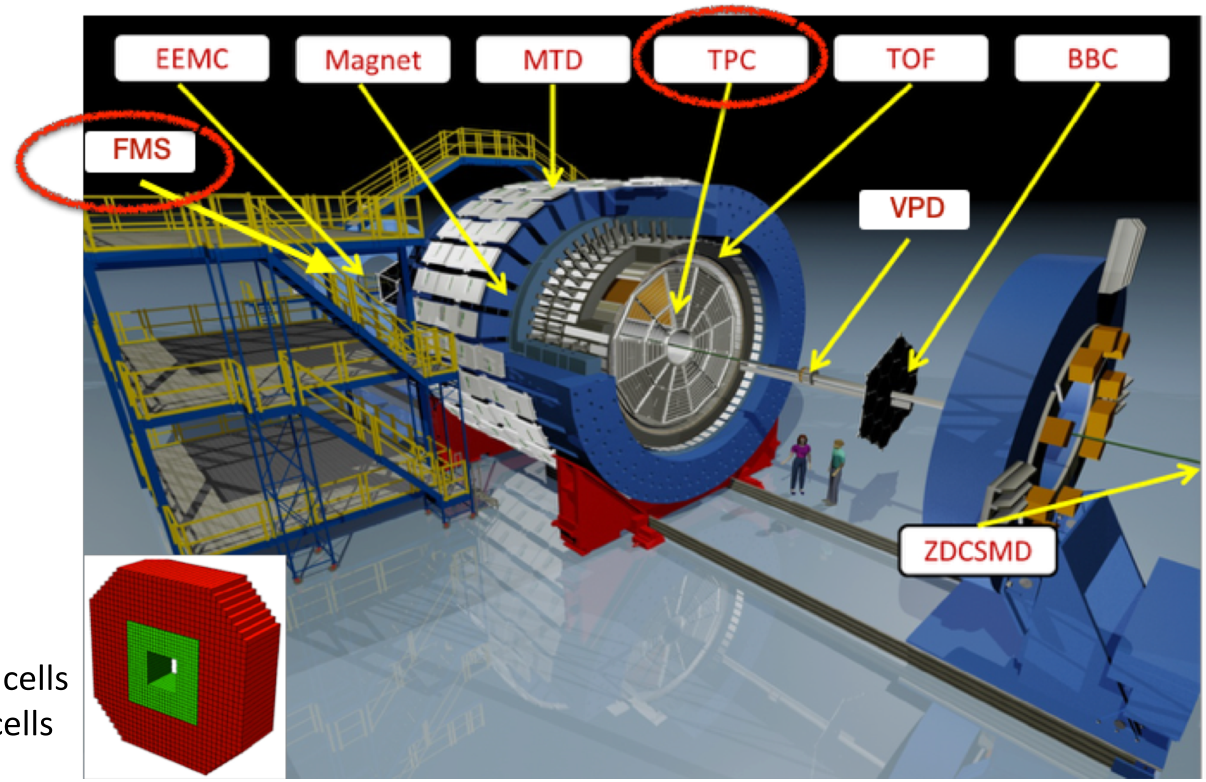


- From 5.02 TeV to 2.76 TeV, slightly stronger decorrelation is observed.
- Dramatic decrease of v_2 with rapidity at RHIC energies -> strong longitudinal dynamics.

Expect an even stronger decorrelation at RHIC energies.

The STAR detectors

- A schematic diagram of the STAR detectors

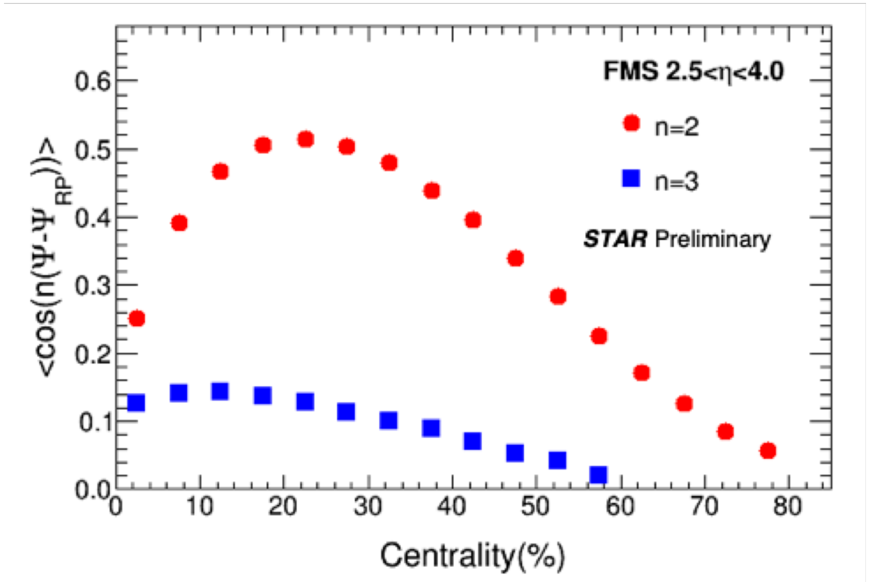


Inner: 476 smaller cells
Outer: 788 larger cells

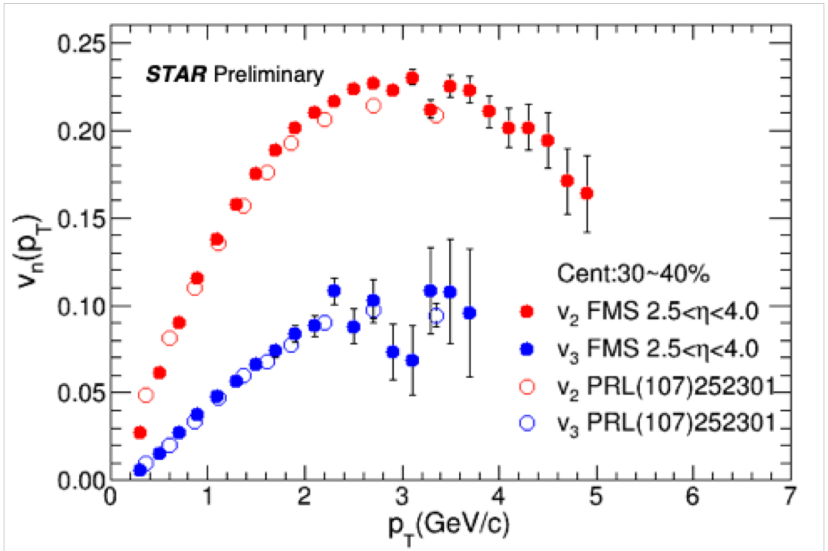
- Forward Meson Spectrometer is an electromagnetic calorimeter.
- TPC acceptance : $-1< \eta <1$; FMS acceptance : $2.5< \eta_{ref} <4$.
- TPC and FMS are used for this analysis, 2016 Au+Au data is used.

FMS as an event plane detector

- FMS event-plane resolution



- Comparison with the published results



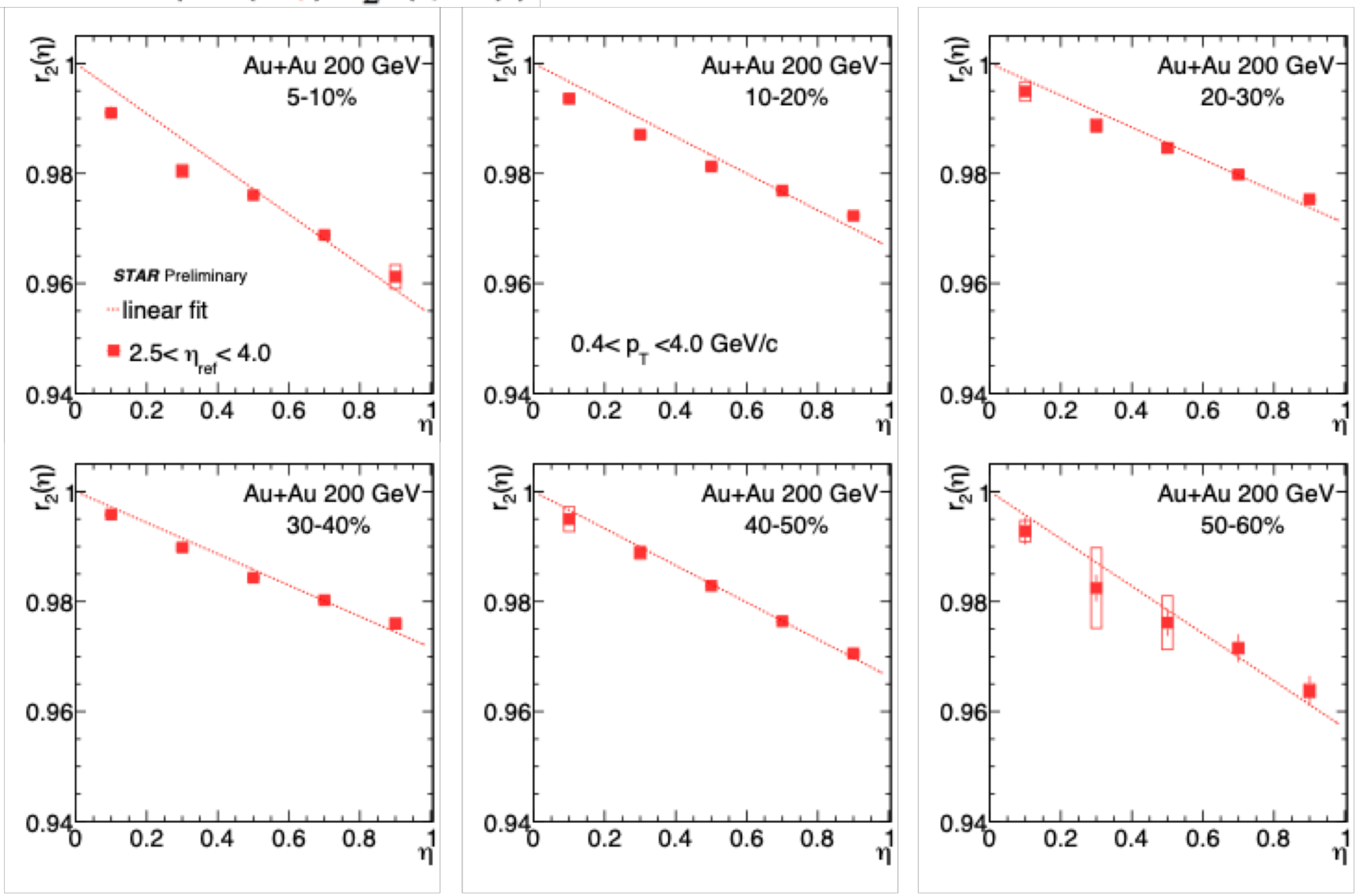
• FMS shows good 2nd- and 3rd-order event plane resolutions.
• Both v_2 and v_3 are consistent with the published results from 200 GeV Au+Au collisions.

v_2 decorrelation for different centralities

- Decorrelation of $\boldsymbol{v}_2(\eta)$

$$r_2(\eta) = \frac{\langle V_2(-\eta) V_2^*(\eta_{\mathrm{ref}})\rangle}{\langle V_2(\eta) V_2^*(\eta_{\mathrm{ref}})\rangle}$$

$$r_2 = 1 - 2F_2\eta$$



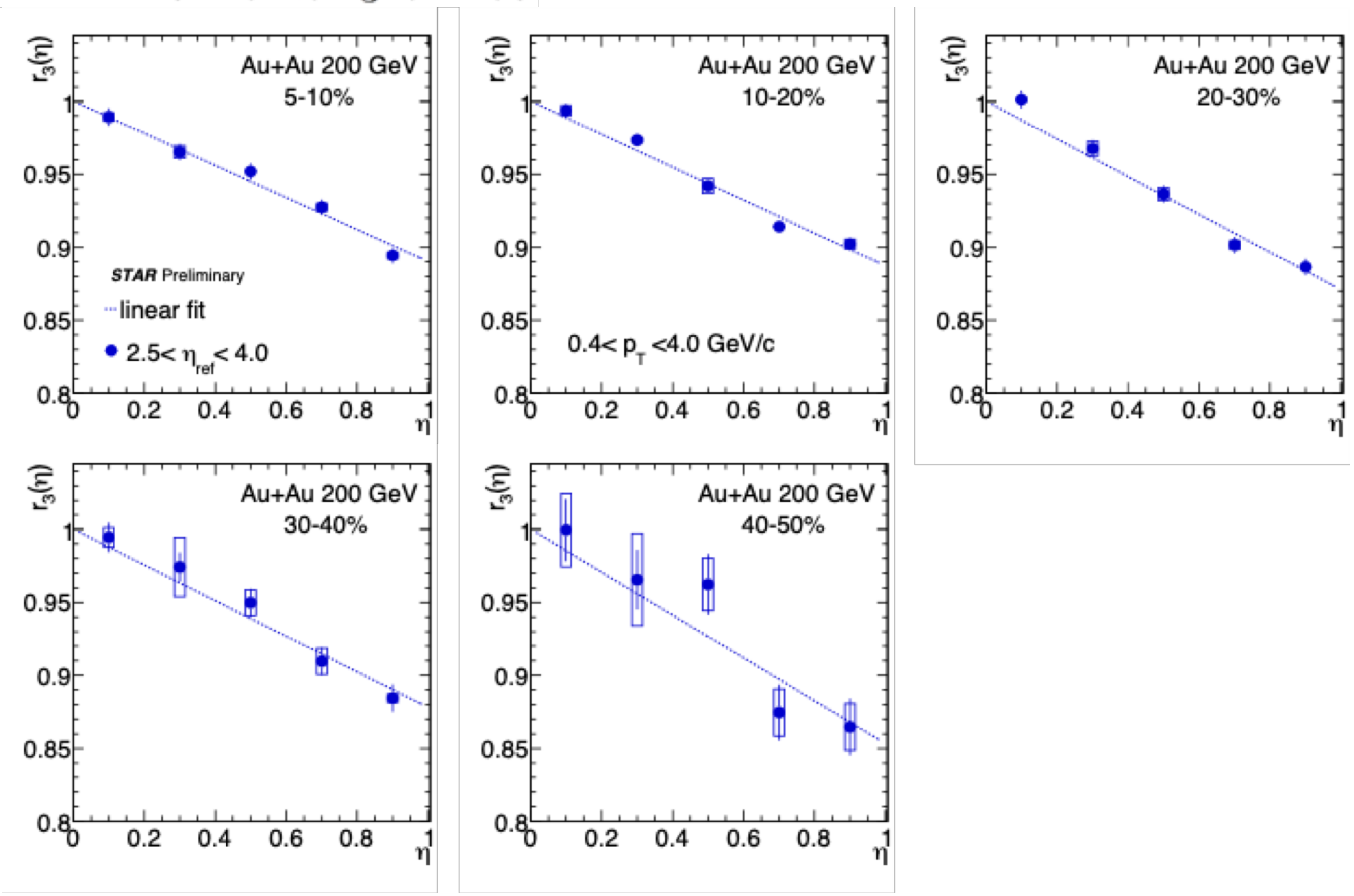
• $r_2(\eta)$ decreases linearly for the shown centralities.

v_3 decorrelation for different centralities

- Decorrelation of $\boldsymbol{v}_3(\eta)$

$$r_3(\eta) = \frac{\langle V_3(-\eta) V_3^*(\eta_{\mathrm{ref}}) \rangle}{\langle V_3(\eta) V_3^*(\eta_{\mathrm{ref}}) \rangle}$$

$$r_3 = 1 - 2F_3\eta$$

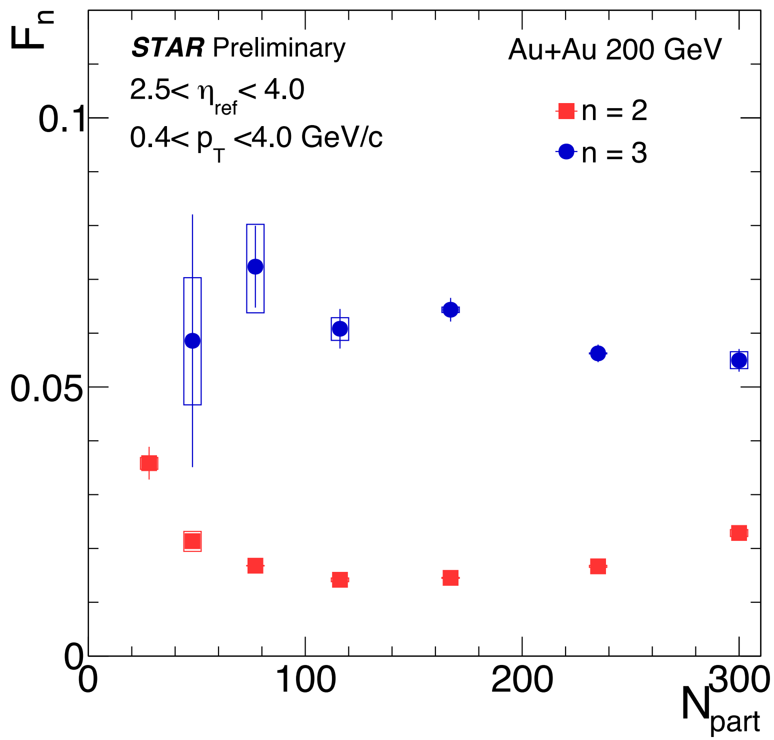


• $r_3(\eta)$ decreases linearly for the shown centralities.

Centrality dependence of linear slope

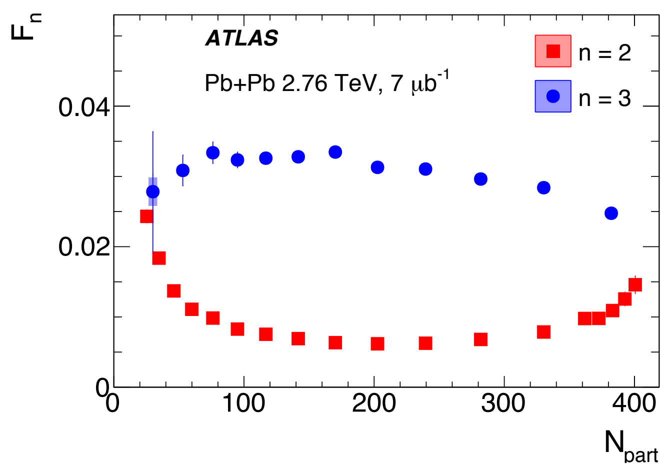
- r_n is parameterized with a linear function

$$r_n = 1 - 2F_n\eta$$



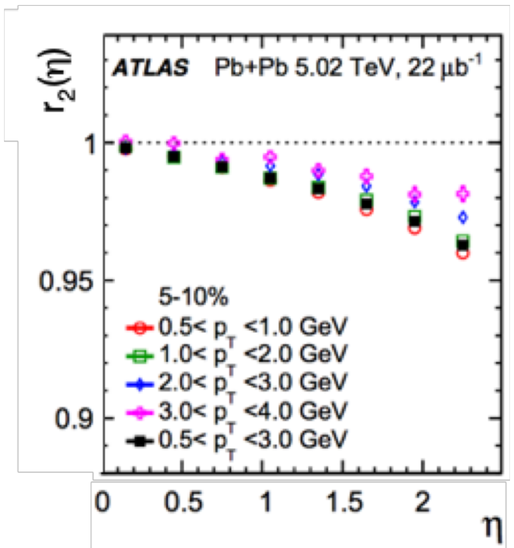
ATLAS Collaboration, Eur. Phys. J. C (2018) 78:142

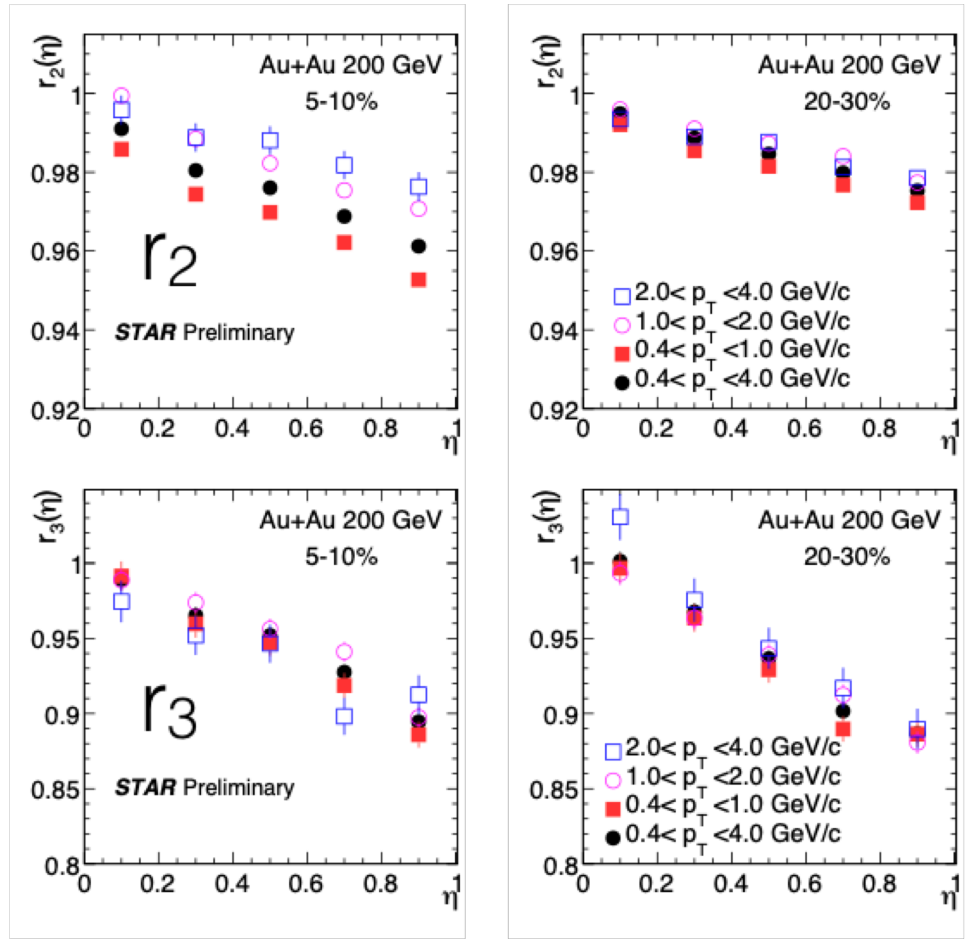
ATLAS results



- For r_2: decorrelation is weakest in mid-central collisions.
- For r_3: weak centrality dependence.
- r_3 slope is factor of ~4 larger than r_2 slope, the trend is similar to LHC results.

p_T dependence of r_n



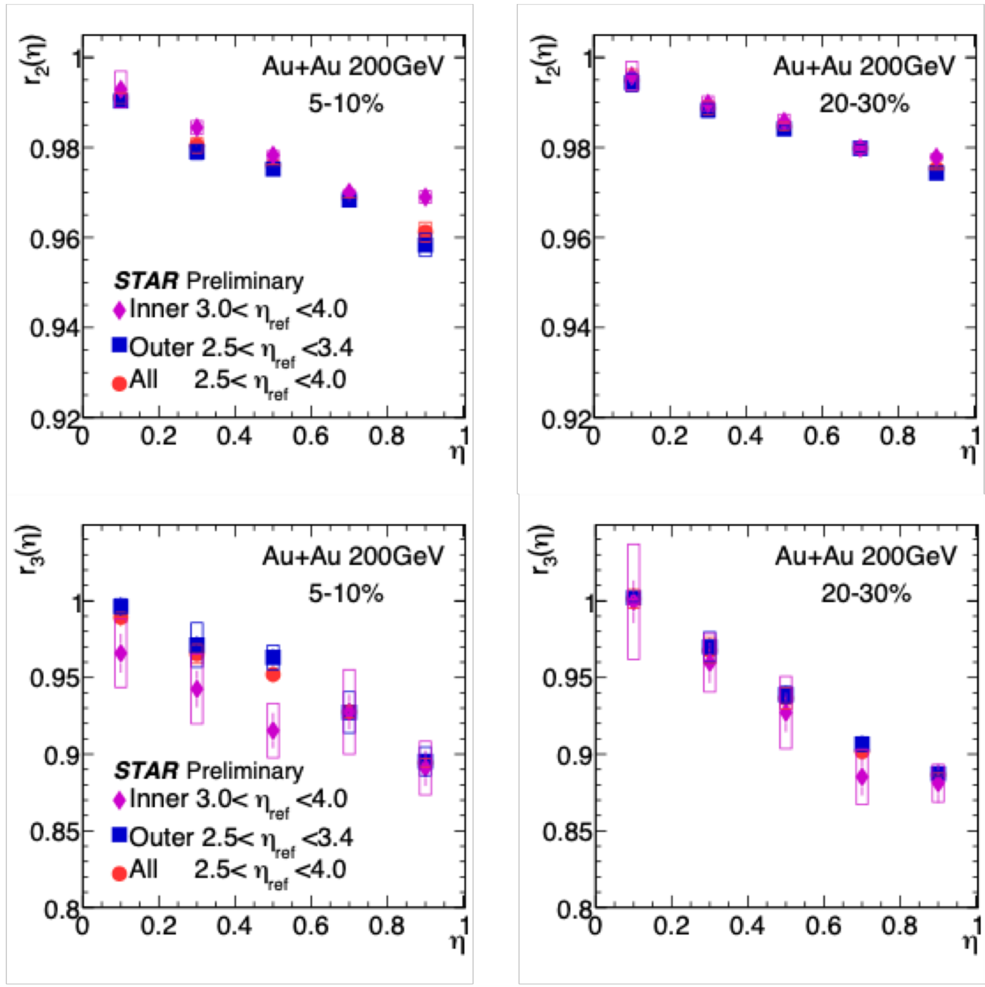


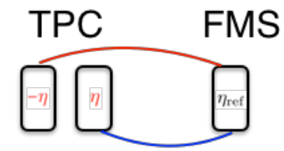
- For r_2: clear p_T dependence for central collisions.
- Similar p_T dependence in central collisions at LHC energy.
- For r_3: weak p_T dependence.

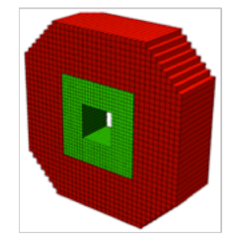
η_{ref} dependence of r_n

r_2

r_3

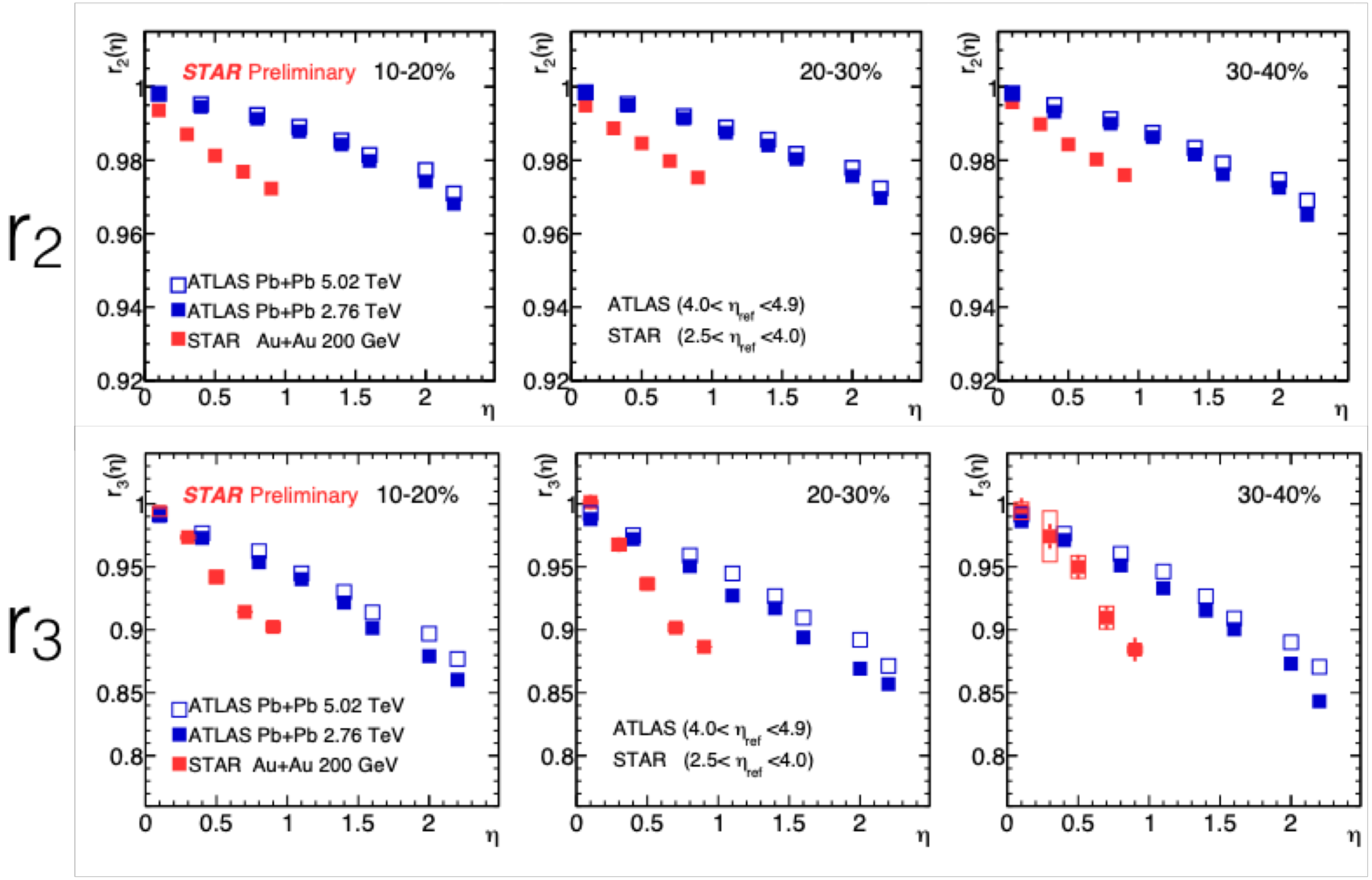






- Short-range correlations are significantly suppressed.
- For longitudinal correlations, both r_2 and r_3, show weak η_{ref} dependence.

Comparison to the LHC results

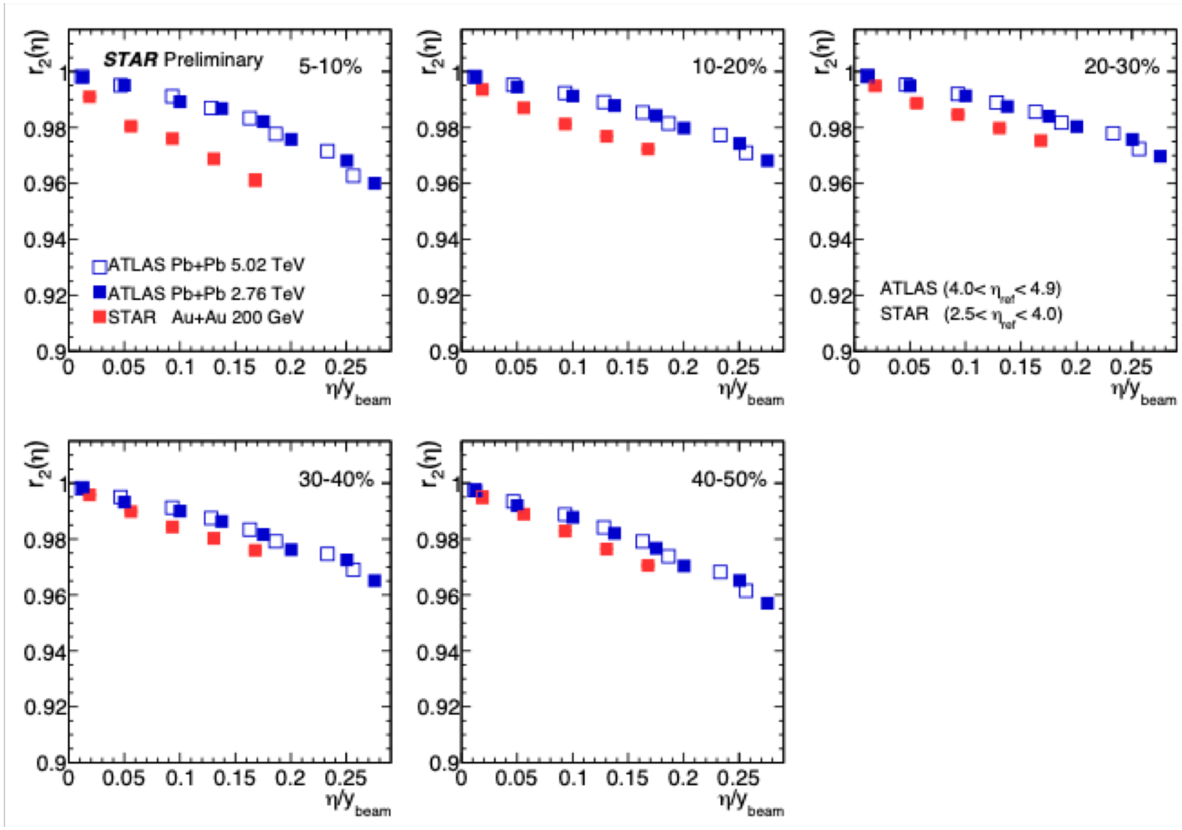


- Significant energy dependence is observed.
- ~2 times stronger decorrelation effect than at the LHC energy 2.76 TeV.

Comparison to the LHC and model calculations

- r_2 as a function of scaled rapidity: η/y_{beam}

r_2



$\sqrt{s_{NN}}$	y_{beam}
200GeV	5.36
2.76TeV	7.99
5.02TeV	8.59

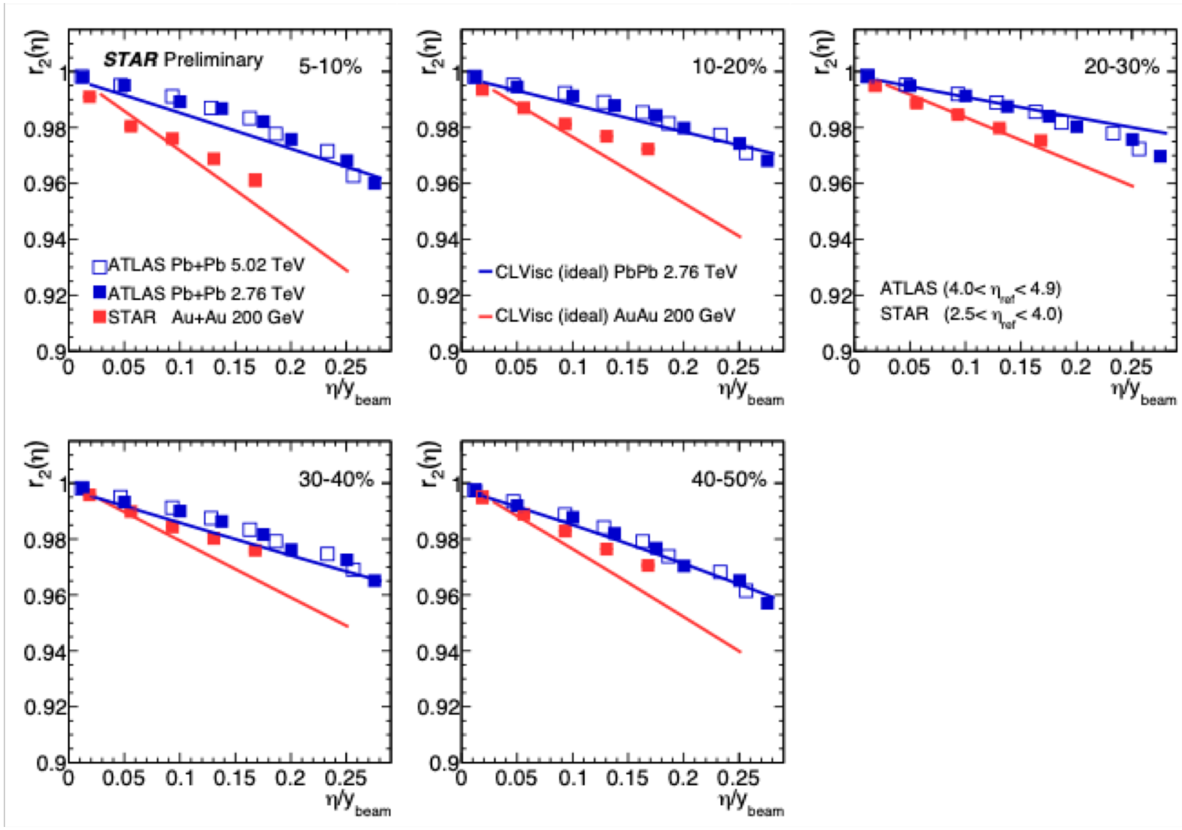
- Energy dependence remains after y_{beam} normalization, and changes with centrality.

  Non-trivial dynamics cannot be explained by simple beam rapidity scaling.

Comparison to the LHC and model calculations

- r_2 as a function of scaled rapidity: η/y_{beam}

r_2



$\sqrt{s_{NN}}$	y_{beam}
200GeV	5.36
2.76TeV	7.99
5.02TeV	8.59

- Energy dependence remains after y_{beam} normalization, and changes with centrality.

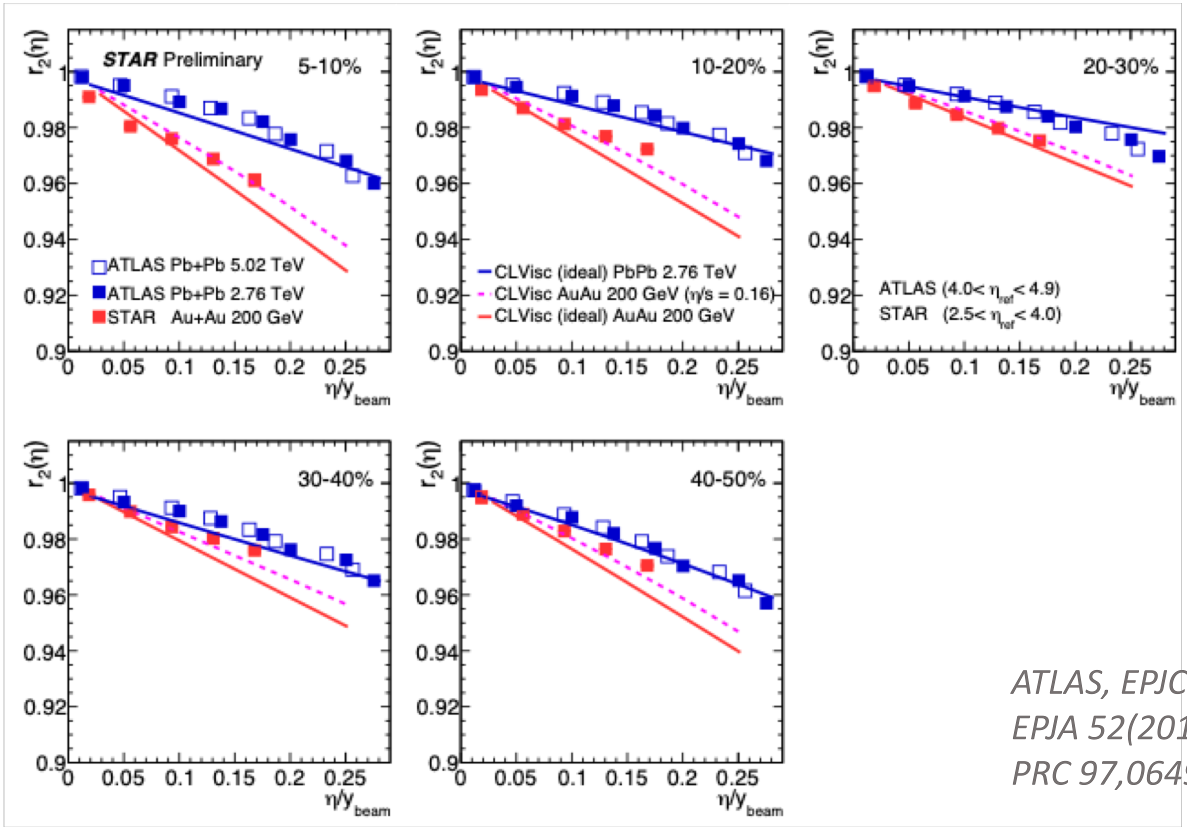
  Non-trivial dynamics cannot be explained by simple beam rapidity scaling.

- Ideal hydro calculation can roughly describe the LHC data, but overestimates the decorrelation effect at RHIC.

Comparison to the LHC and model calculations

- r_2 as a function of scaled rapidity: η/y_{beam}

r_2



$\sqrt{s_{NN}}$	y_{beam}
200GeV	5.36
2.76TeV	7.99
5.02TeV	8.59

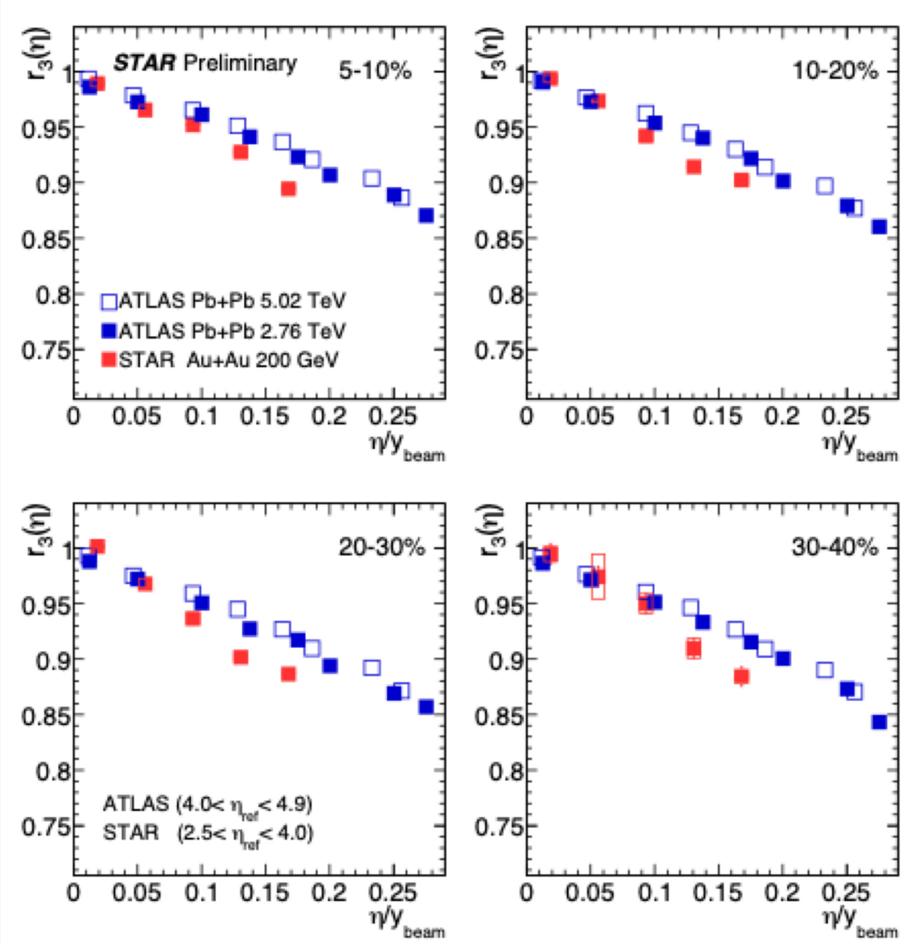
ATLAS, EPJC 78, 142(2018)
EPJA 52(2016) 97
PRC 97,064918(2018)

- Energy dependence remains after y_{beam} normalization, and changes with centrality.
  Non-trivial dynamics cannot be explained by simple beam rapidity scaling.
- Ideal hydro calculation can roughly describe the LHC data, but overestimates the decorrelation effect at RHIC.
- Including a viscosity correction can better describe the RHIC data.

Comparison to the LHC and model calculations

- r_3 as a function of scaled rapidity: η/y_{beam}

r_3



$\sqrt{s_{NN}}$	y_{beam}
200GeV	5.36
2.76TeV	7.99
5.02TeV	8.59

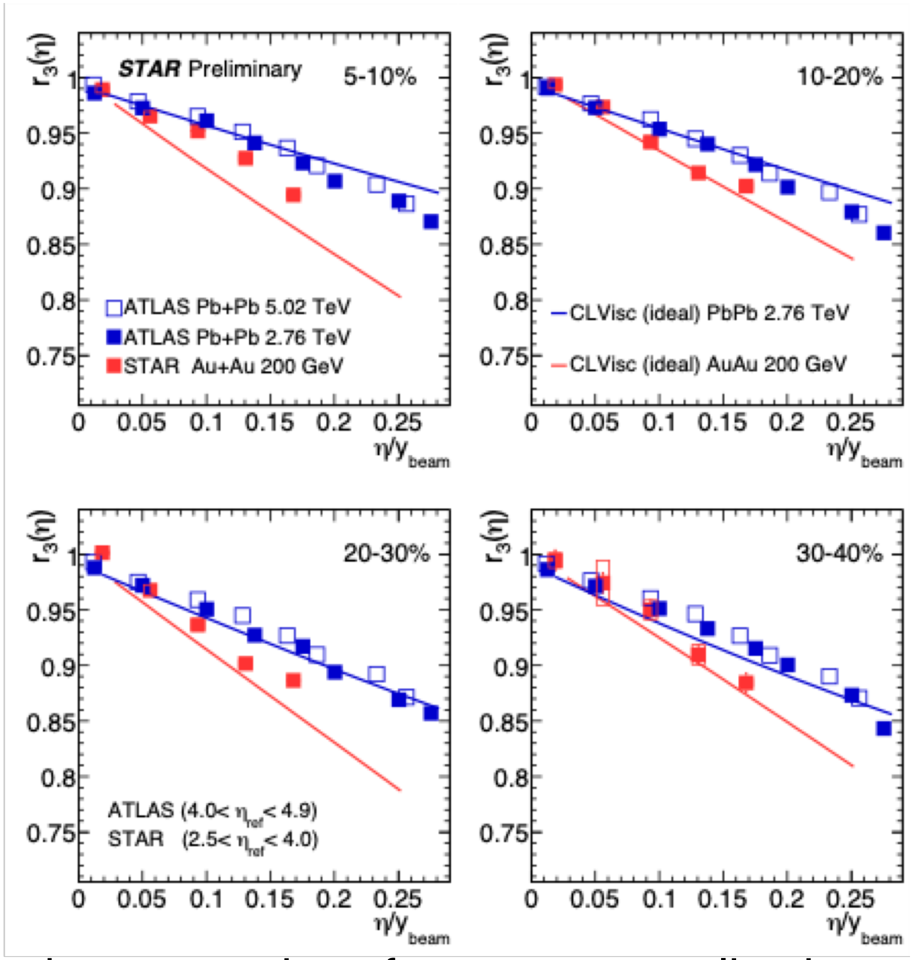
• Energy dependence remains after y_{beam} normalization, weak centrality changes.

Comparison to the LHC and model calculations

- r_3 as a function of scaled rapidity: η/y_{beam}

r_3

$\sqrt{s_{NN}}$	y_{beam}
200GeV	5.36
2.76TeV	7.99
5.02TeV	8.59

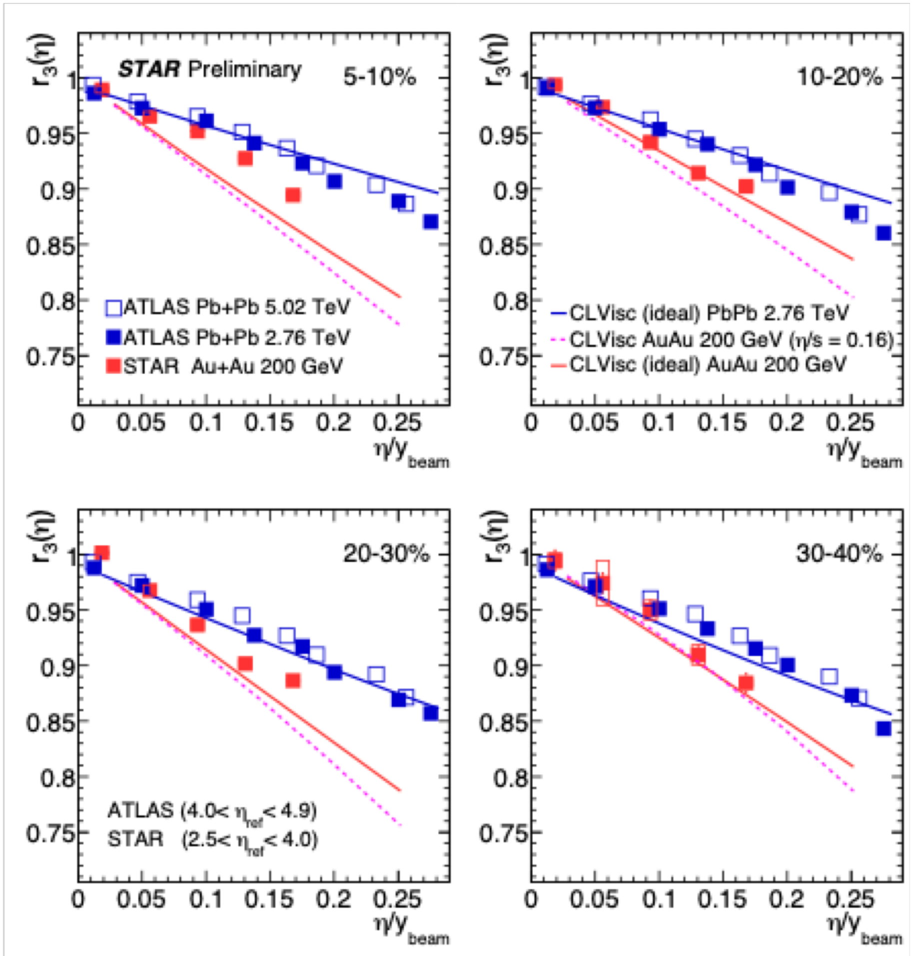


- Energy dependence remains after y_{beam} normalization, weak centrality changes.
- Ideal hydro still slightly overestimates the decorrelation effect at RHIC.

Comparison to the LHC and model calculations

- r_3 as a function of scaled rapidity: η/y_{beam}

r_3



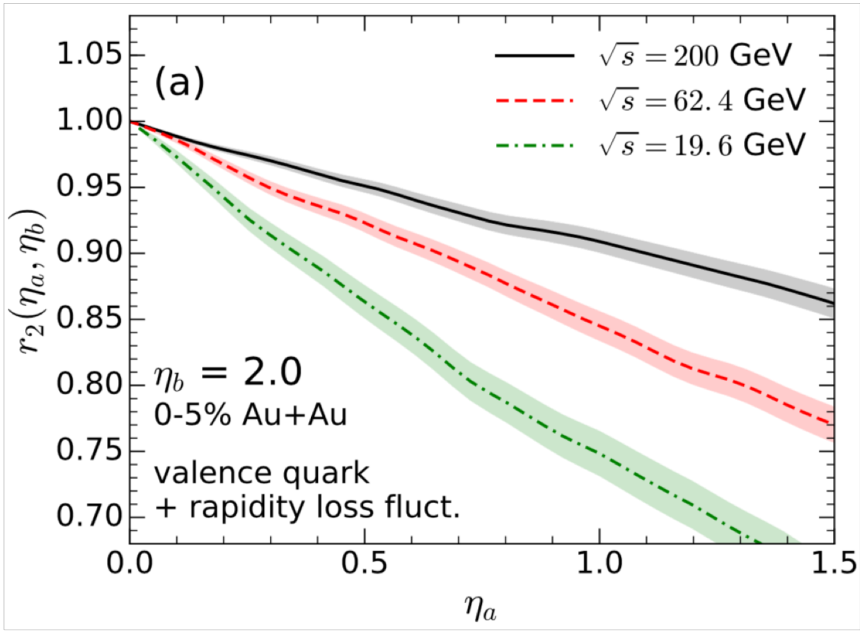
$\sqrt{s_{NN}}$	y_{beam}
200GeV	5.36
2.76TeV	7.99
5.02TeV	8.59

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

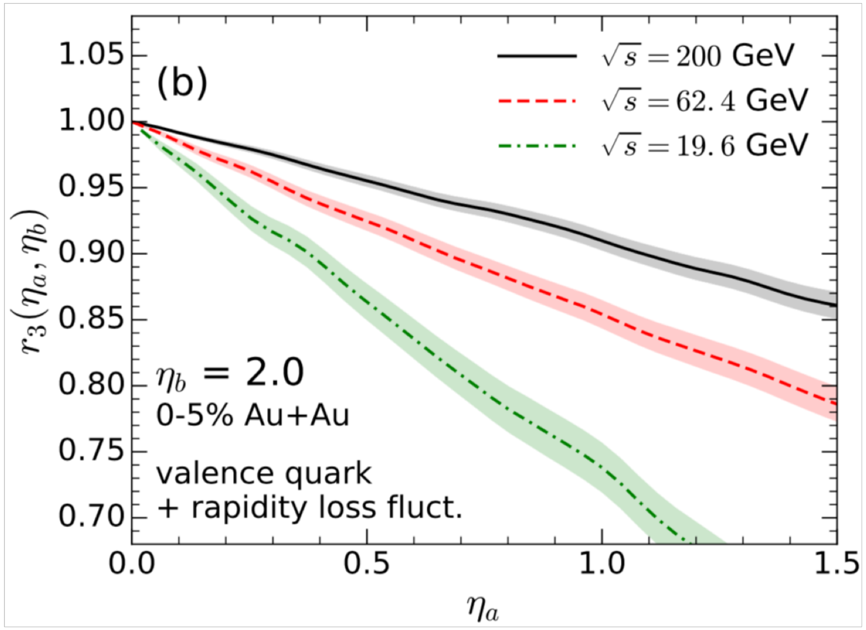
- Energy dependence remains after y_{beam} normalization, weak centrality changes.
- Ideal hydro still slightly overestimates the decorrelation effect at RHIC.
- Viscosity correction estimates an even stronger v_3 decorrelation.

Decorrelation at BES

r_2



r_3



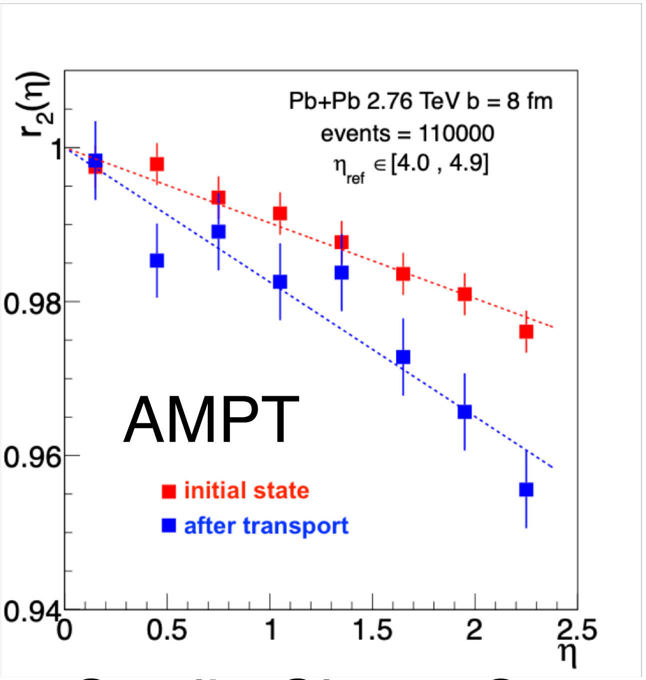
PRC 97,024907(2018)

- Hydrodynamic calculations have further confirmed the stronger decorrelation effect at lower energies.
- 54.4 GeV and 27 GeV Au+Au data will help to better understand the decorrelation effect.(See Xiaoyu's Poster)
- Future BES measurements will provide constraints on the initial and final conditions.

Thoughts and open questions

- Single source vs. multi-source?

  - The AMPT results suggest the decorrelation effect will be further enhanced by the transport dynamics.
  - Further study is still needed.



Credit: Chuan Sun

- Large rapidity gap to remove short-range correlation vs. decorrelation?
- Flow decorrelation in small system?

- How to correct the decorrelation effect in the future flow measurements?

Summary

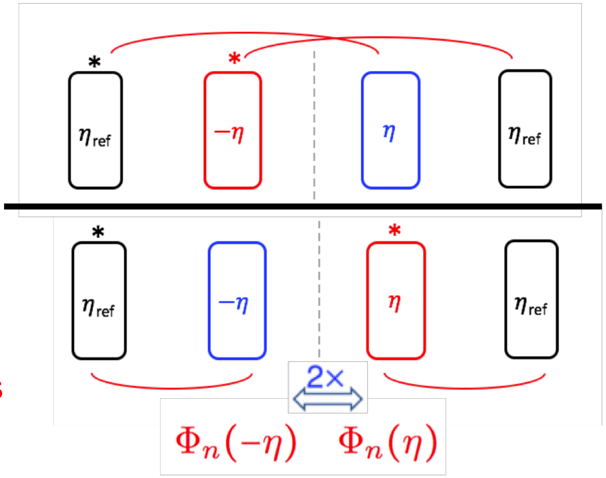
- Longitudinal correlations probe non-boost-invariant initial conditions and rapidity transports in HIC.
  - r_2 shows non-monotonic centrality dependence; r_3 shows weak centrality dependence.
  - Weak p_T dependence of v_n decorrelation suggests this is a global property of the events.
  - v_n decorrelation is η_{ref} independent.
- Decorrelation is ~2 stronger than at LHC energies, cannot be explained by simple beam rapidity scaling.
- Comparison with the (3+1)D hydro calculations:
  - Ideal hydro tuned to LHC data overestimates the decorrelation at RHIC.
  - The viscosity correction leads to a weaker decorrelation for v_2 and stronger decorrelation for v_3.
- The decorrelation measurements at even lower energies are necessary.
- The results provide new constraints on both the initial state geometry and final state dynamics of heavy-ion collisions.

Back Up

Decorrelation at BES

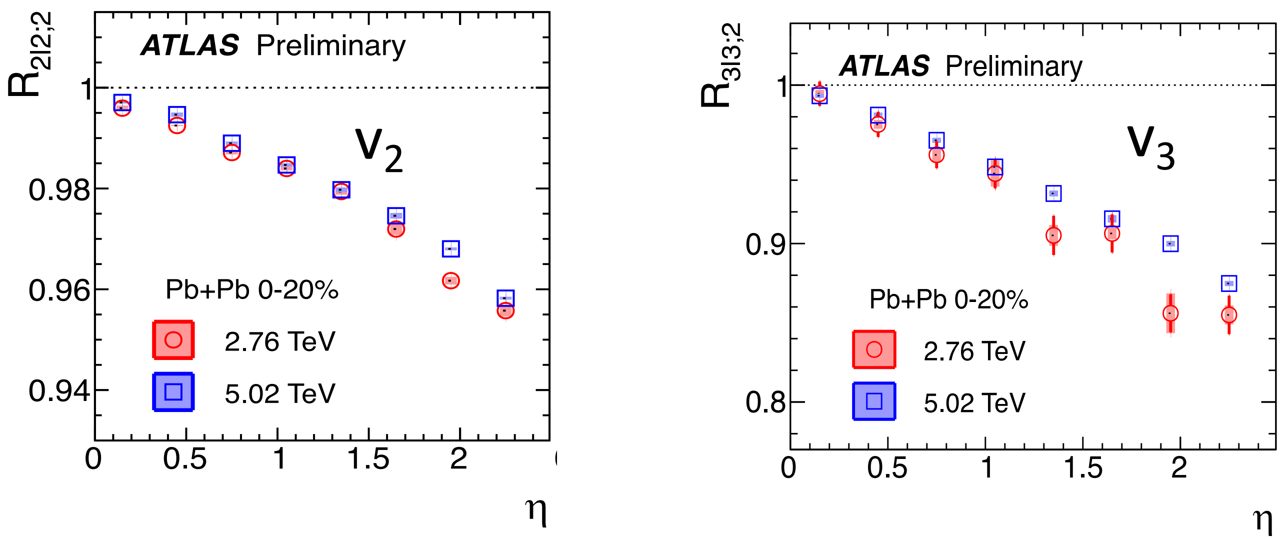
- From r_n to R_n (with the EPD)

$$R_{n|n;2}(\eta) = \frac{\langle \boldsymbol{v}_n^*(-\eta_{\rm ref})\boldsymbol{v}_n^*(-\eta)\boldsymbol{v}_n(\eta)\boldsymbol{v}_n(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_n^*(-\eta_{\rm ref})\boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta)\boldsymbol{v}_n(\eta_{\rm ref})\rangle} =$$



Only sensitive to EP twist effects

$$= \frac{\langle v_n(-\eta_{\rm ref})v_n(-\eta)v_n(\eta_{\rm ref})v_n(\eta)\cos(n[\Phi_n(\eta_{\rm ref})-\Phi_n(-\eta_{\rm ref})+(\Phi_n(\eta)-\Phi_n(-\eta))])\rangle}{\langle v_n(-\eta_{\rm ref})v_n(-\eta)v_n(\eta_{\rm ref})v_n(\eta)\cos(n[\Phi_n(\eta_{\rm ref})-\Phi_n(-\eta_{\rm ref})-(\Phi_n(\eta)-\Phi_n(-\eta))])\rangle}$$

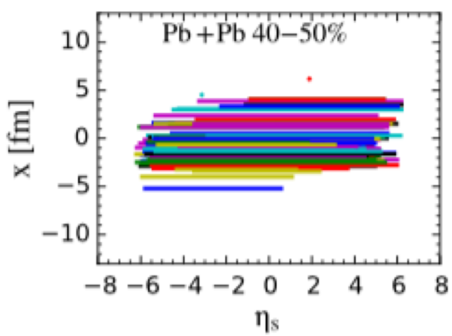


What can we get at RHIC energies(with EPD)?

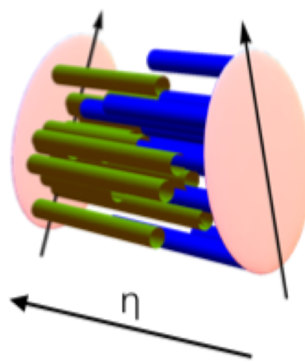
3D initial conditions

- Longitudinal dynamics hasn't been fully explored yet

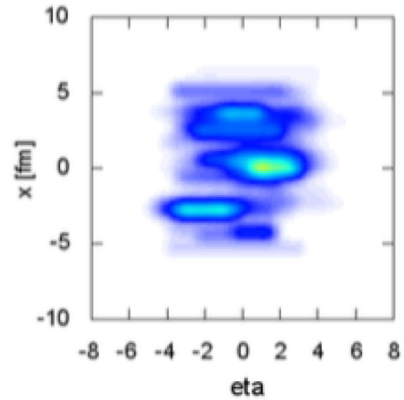
Longitudinal strings
arXiv: 1511.04131



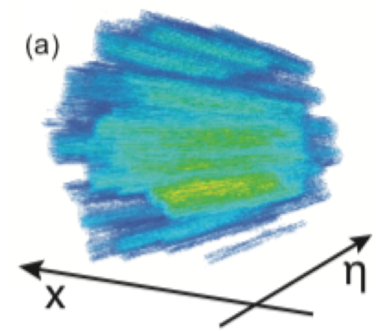
Torqued-fireball
arXiv: 1506.02817



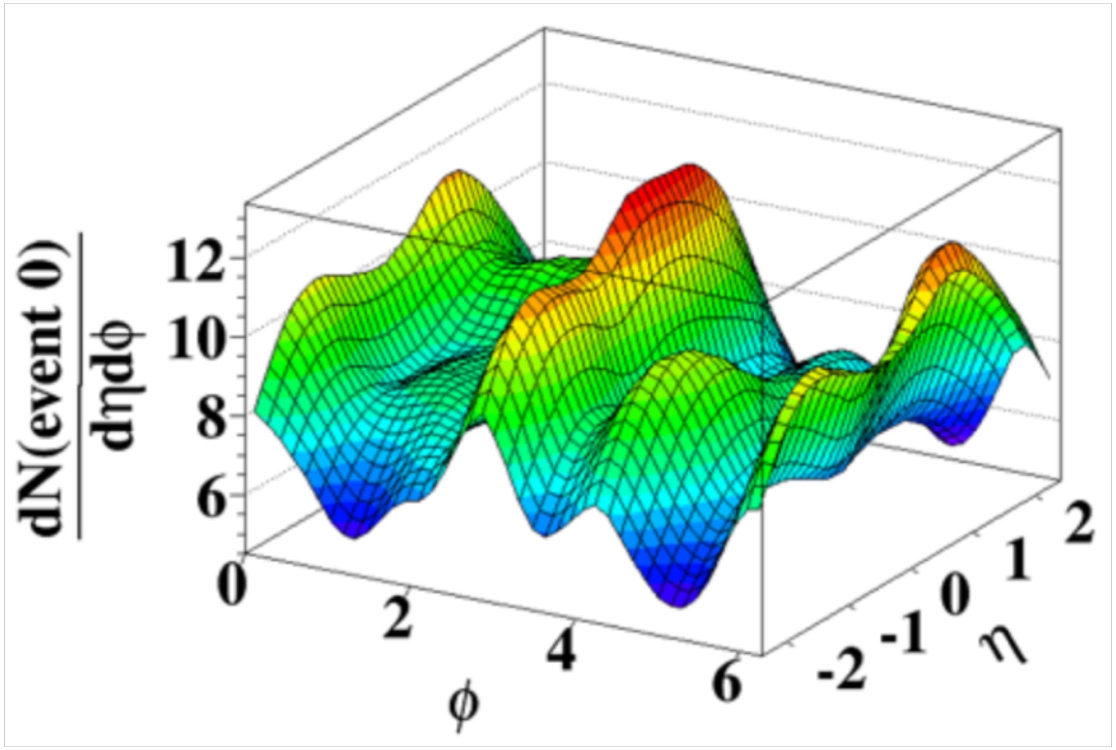
3D-Glauber
arXiv: 1509.04103



3D-Glasma
arXiv: 1605.07158



2D eta-phi map a event in hydro



- The flow measurements are questionable when the anisotropic flow decorrelates along the longitudinal direction.

Why linear decrease

- Assuming v_n in each event slowly varying around $\eta \sim 0$

$$\boldsymbol{v}_n(\eta) \approx \boldsymbol{v}_n(0)\,(1+\alpha_n\eta)\,e^{i\beta_n\eta},\quad \boldsymbol{v}_n^{\mathrm{k}}(0)\boldsymbol{v}_n^{*\mathrm{k}}(\eta_{\mathrm{ref}}) = X_{n;k}(\eta^{\mathrm{ref}}) - iY_{n;k}(\eta^{\mathrm{ref}})$$

Then the two particle correlator $\langle \boldsymbol{q}_n^k(\eta_1)\boldsymbol{q}_n^{*k}(\eta_{\mathrm{ref}})\rangle$ can be expanded

$$\begin{aligned}\langle \boldsymbol{q}_n^k(\eta_1)\boldsymbol{q}_n^{*k}(\eta_{\mathrm{ref}})\rangle &\approx \langle (1+k\eta\alpha_n)\,(X_{n;k}+k\beta_n Y_{n;k})\rangle\\ &\approx \langle X_{n;k} + k\eta\alpha_n X_{n;k} + k\eta\beta_n Y_{n;k}\rangle\\ &\approx \langle X_{n;k}\rangle\left(1+\frac{\langle k\eta\alpha_n X_{n;k}\rangle}{\langle X_{n;k}\rangle}+\frac{\langle k\eta\beta_n Y_{n;k}\rangle}{\langle X_{n;k}\rangle}\right)\end{aligned}$$

With this format then $r_{n£n;k}$ can be approximated by:

$$r_{n|n;k}(\eta) = 1-2F^r_{n,k}\eta,\ F^r_{n,k}\approx F^{\mathrm{asy}}_{n,k}+F^{\mathrm{twi}}_{n,k},\ F^{\mathrm{asy}}_{n,k}=\frac{\langle \alpha_n k X_{n;k}(\eta^{\mathrm{ref}})\rangle}{\langle X_{n;k}(\eta^{\mathrm{ref}})\rangle},\ F^{\mathrm{twi}}_{n,k}=\frac{\langle \beta_n k Y_{n;k}(\eta^{\mathrm{ref}})\rangle}{\langle Y_{n;k}(\eta^{\mathrm{ref}})\rangle}$$

- If twist and asymmetry doesn't depend on k, then expect $F_{n;k}^{r}/k = F_{n;1}^{r}$

$$R_{n|n;2} \approx 1-2F^R_{n;2}\eta = 1-4\eta\frac{\langle \beta_n Y_{n;2}(\eta^{\mathrm{ref}})\rangle}{\langle Y_{n;2}(\eta^{\mathrm{ref}})\rangle},\qquad F^R_{n;2}=F^{\mathrm{twi}}_{n;2}$$

- $R_{n|n;2}$ and $r_{n|n;2}$ together can help separate twist and asymmetry

$$r_{n|n;2} \approx 1-2F^{\mathrm{r}}_{n;2}\eta = 1-2F^{\mathrm{twi}}_{n,2}\eta - 2F^{\mathrm{asy}}_{n,2}\eta$$