Stony Brook University | The State University of New York

Longitudinal dynamics in heavy ion collisions

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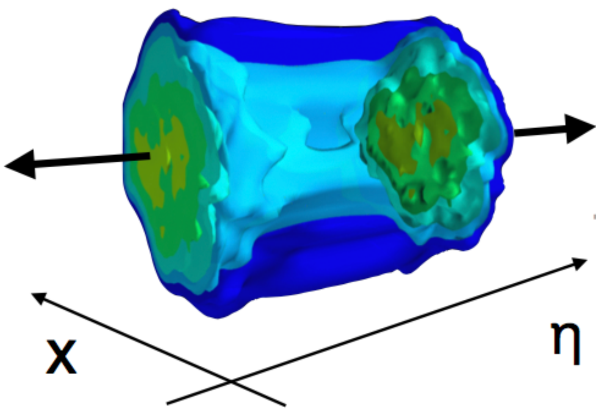
3D initial condition and final state dynamics

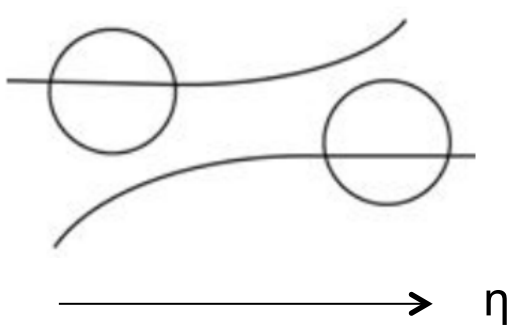
Interesting longitudinal collective dynamics in high energy HIC

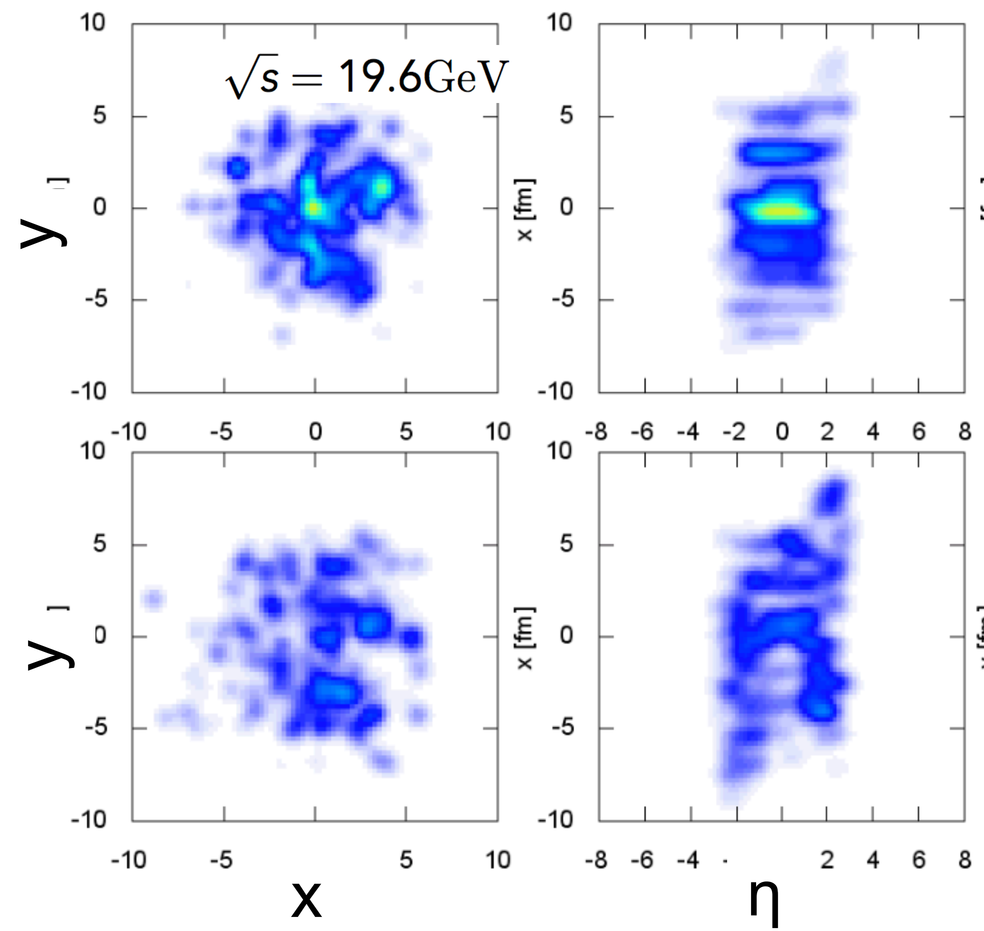
More dramatic at lower √s due to stopping.



energy density

baryon density



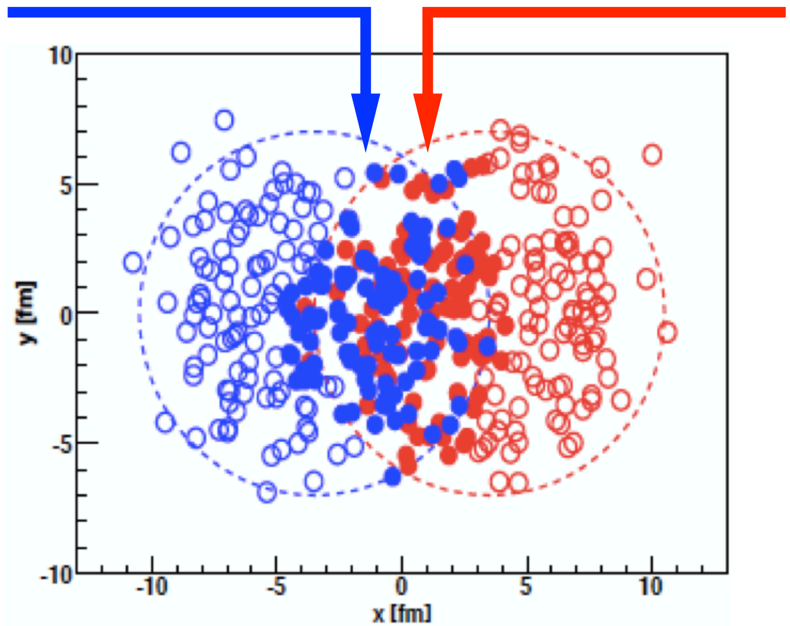


Collectivity is important bg in study of chirality, criticality, vorticity etc.

Three types of longitudinal correlations

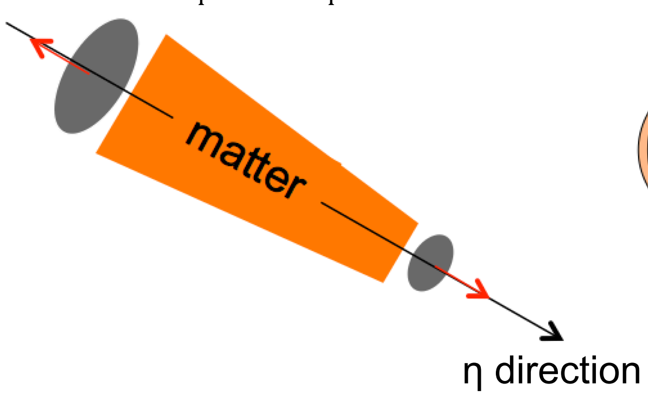
Fluctuation of sources in two nuclei → fluc. of size and transverse-shape

$N^{\mathrm{F}}_{\mathrm{part}}$ $\varepsilon^{\mathrm{F}}_{n} e^{in\Psi^{F}_{n}}$



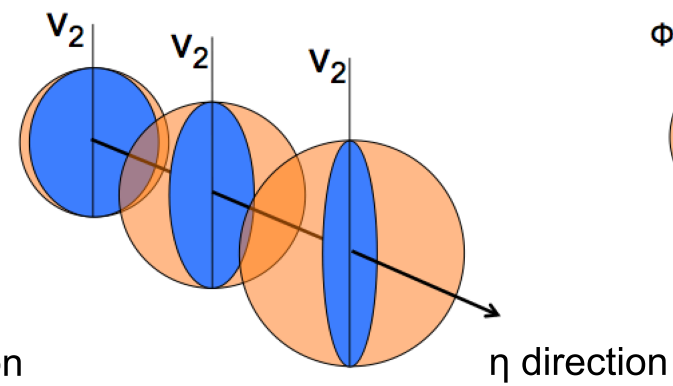
$N^{\mathrm{B}}_{\mathrm{part}}$ $\varepsilon^{\mathrm{B}}_{n} e^{in\Psi^{B}_{n}}$

(a) $N^{\mathrm{F}}_{\mathrm{part}} \neq N^{\mathrm{B}}_{\mathrm{part}}$



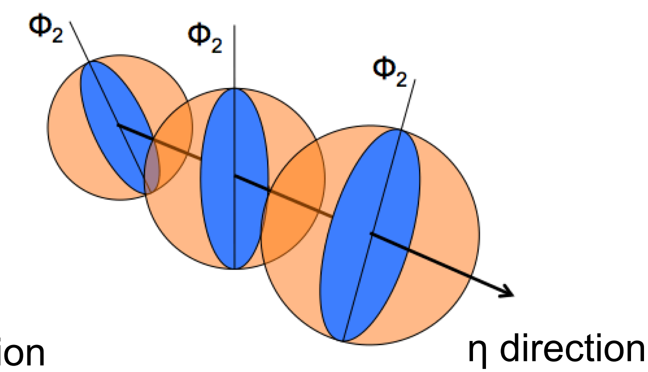
Asymmetry in multiplicity

(b) $\varepsilon^{\mathrm{F}}_{2} \neq \varepsilon^{\mathrm{B}}_{2}$



Asymmetry in flow magnitude

(c) $\Psi^{\mathrm{F}}_{2} \neq \Psi^{\mathrm{B}}_{2}$



Torque/twist of flow plane

Longitudinal dynamics from two-particle corr

$$C(\eta_{1,}\eta_{2,}\Delta\phi)=C_N(\eta_{1,}\eta_2)\left[1+2\sum_n\left\langle\mathbf{v}_n(\eta_1)\mathbf{v}_n^*(\eta_2)\right\rangle\cos n\Delta\phi\right] \quad \boldsymbol{v}_n=v_n e^{in\Phi_n}$$

FB Multiplicity fluctuation

$$C_N(\eta_{1,}\eta_2)=\frac{\left\langle N(\eta_1)N(\eta_2)\right\rangle}{\left\langle N(\eta_1)\right\rangle\left\langle N(\eta_2)\right\rangle}$$

FB flow fluctuation

$$V_{n\Delta}(\eta_{1,}\eta_2)$$

$$\left\langle\mathbf{v}_n(\eta_1)\mathbf{v}_n^*(\eta_2)\right\rangle=\left\langle v_n(\eta_1)v_n(\eta_2)\cos n\left[\Phi_n(\eta_1)-\Phi_n(\eta_2)\right]\right\rangle$$

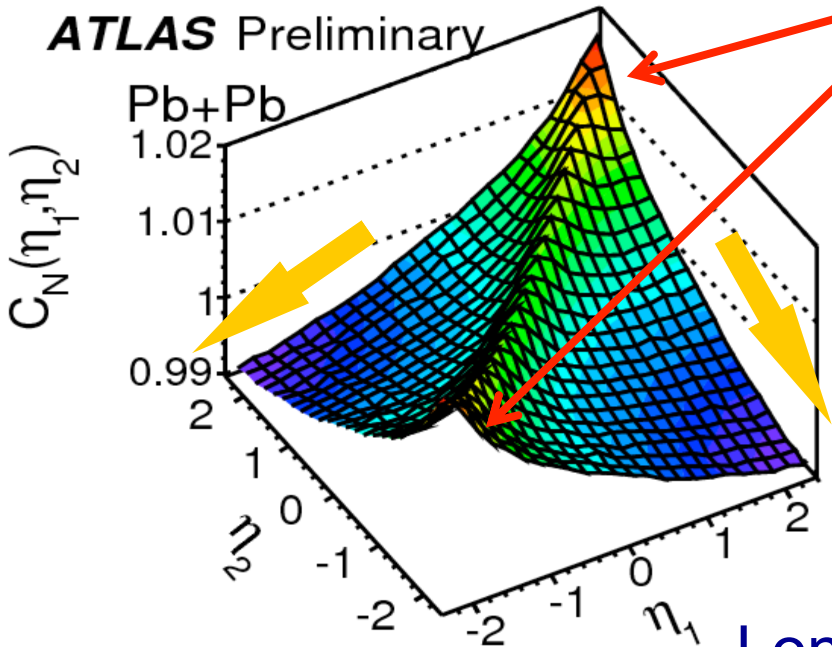
Separating short and long-range correlations

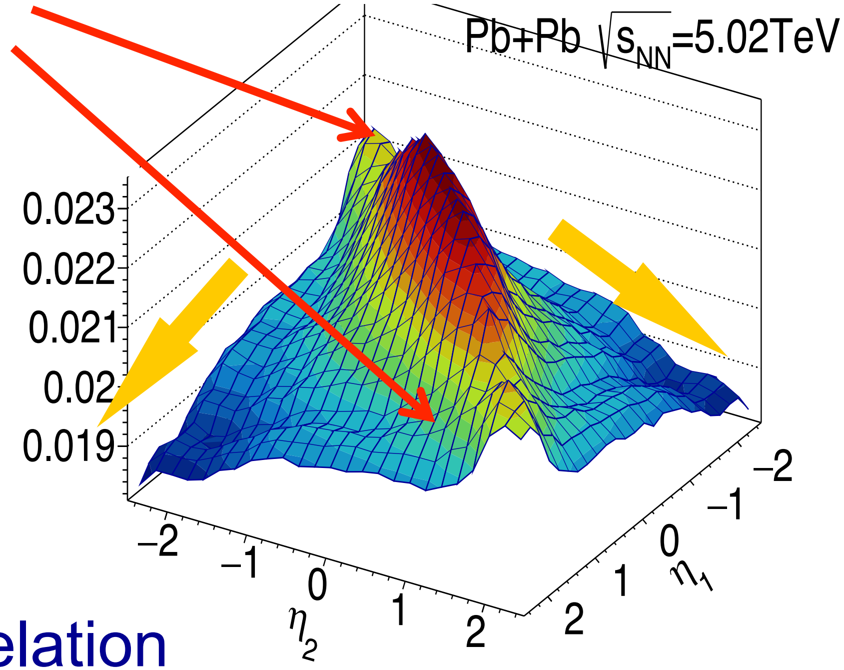
$C_N(\eta_1,\eta_2)$

$V_{2\Delta}(\eta_1,\eta_2)=\left\langle \mathbf{v}_2(\eta_1)\mathbf{v}_2^*(\eta_2)\right\rangle$

Short-range correlation

$\Delta\eta=\eta_1-\eta_2\sim 0$



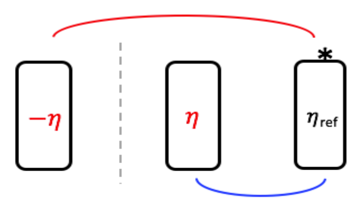


Large $\Delta\eta$

Long range correlation

Require careful separation of LRC from SRC!

$$r_N(\eta)=\frac{C_N(-\eta,\eta_{\text{ref}})}{C_N(\eta,\eta_{\text{ref}})}=\frac{\left\langle N(-\eta)N(\eta_{\text{ref}})\right\rangle}{\left\langle N(\eta)N(\eta_{\text{ref}})\right\rangle}$$



$$r_{n|n}(\eta)=\frac{\langle \boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta_{\text{ref}})\rangle}{\langle \boldsymbol{v}_n(\eta)\boldsymbol{v}_n^*(\eta_{\text{ref}})\rangle}$$

Measure asymmetry or decorrelation between $-\eta$ and η!

Leading-order contribution of LRC

- Assuming multiplicity and v_n in each event varies slowly around η~0

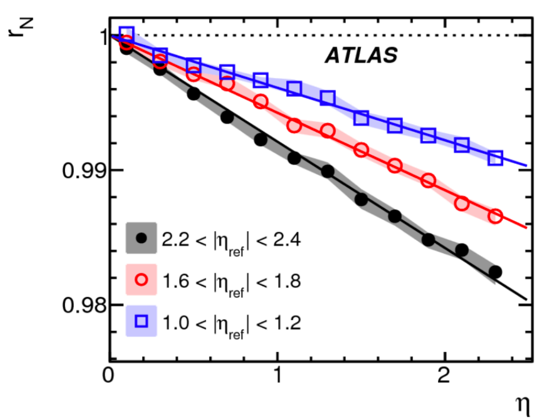
$$N(\eta) \approx \langle N(\eta) \rangle \left[1 + a_1 \eta\right]$$

$$\boldsymbol{v}_n(\eta) \approx \boldsymbol{v}_n(0)(1 + \alpha_n \eta) e^{i\beta_n \eta}$$

- Then

$$r_N(\eta) \approx 1 - 2F\eta$$

$$F \propto a_1^2$$



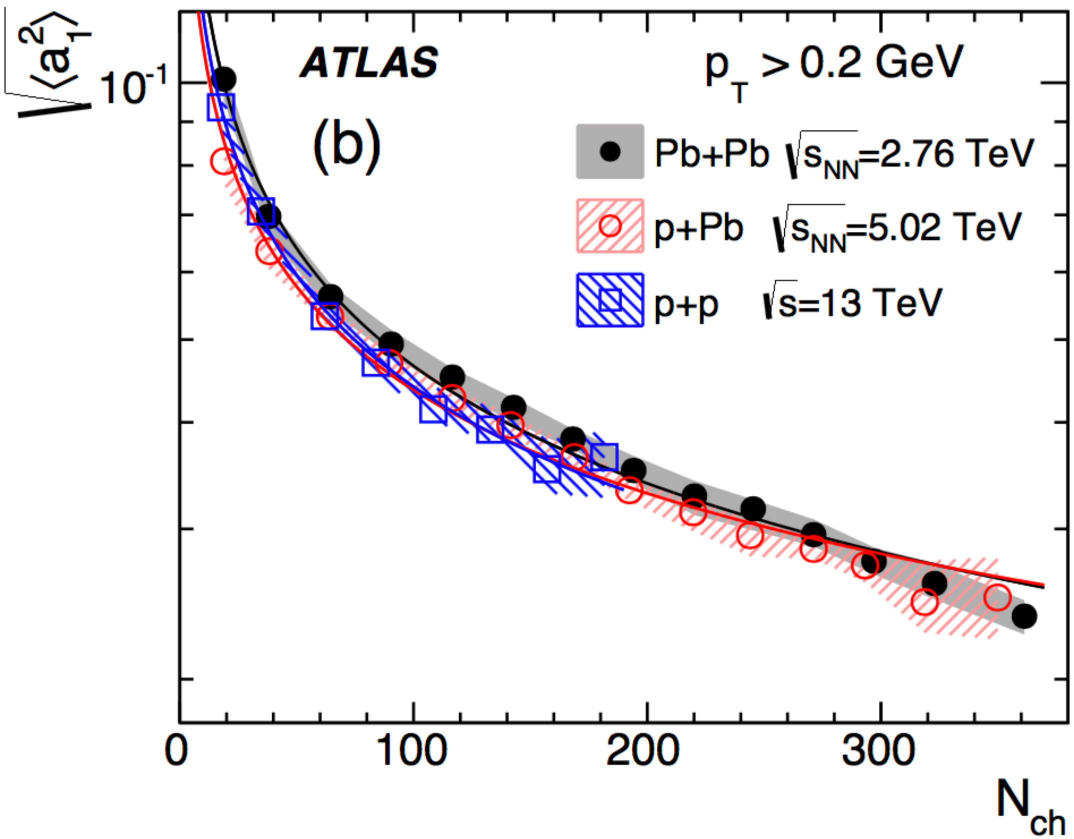
Magnitude asymmetry

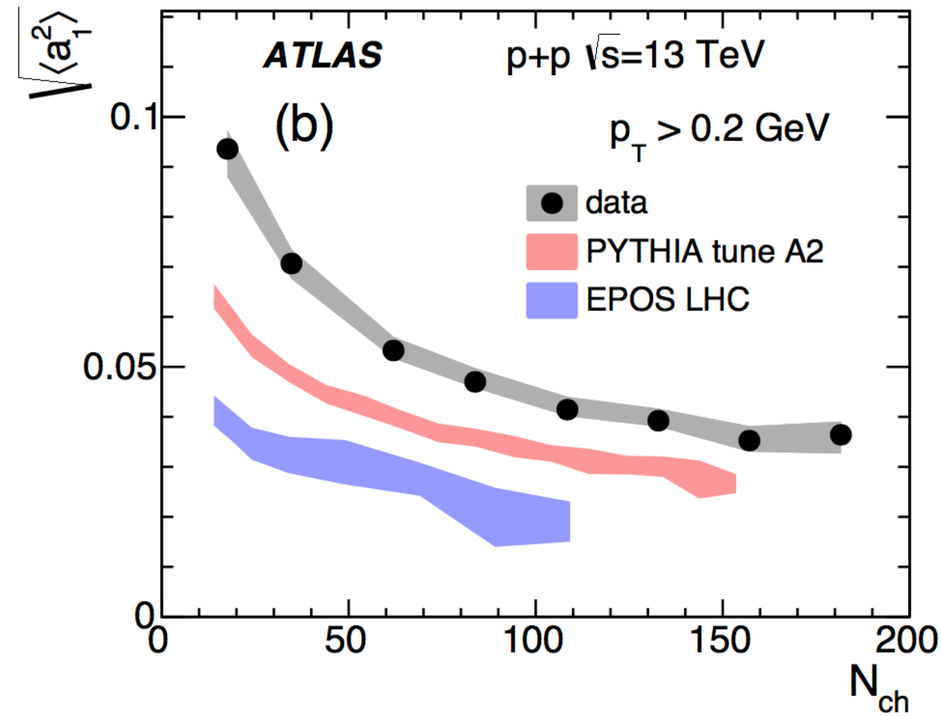
$$r_{n|n}(\eta) \approx 1 - 2F_n^{\mathrm{asy}}\eta - 2F_n^{\mathrm{twi}}\eta$$

EP Twist

Relation to α_n, β_n more complicated

Long-range multiplicity fluctuations





- LRC strength depends only on total multiplicity in pp, pPb, PbPb
  - controlled by FB asymmetry of sources

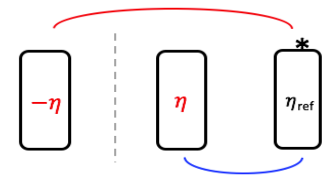
$$A_n = \frac{n_f - n_b}{n_f + n_b}, \quad \langle a_1^2 \rangle \propto \langle A_n^2 \rangle$$

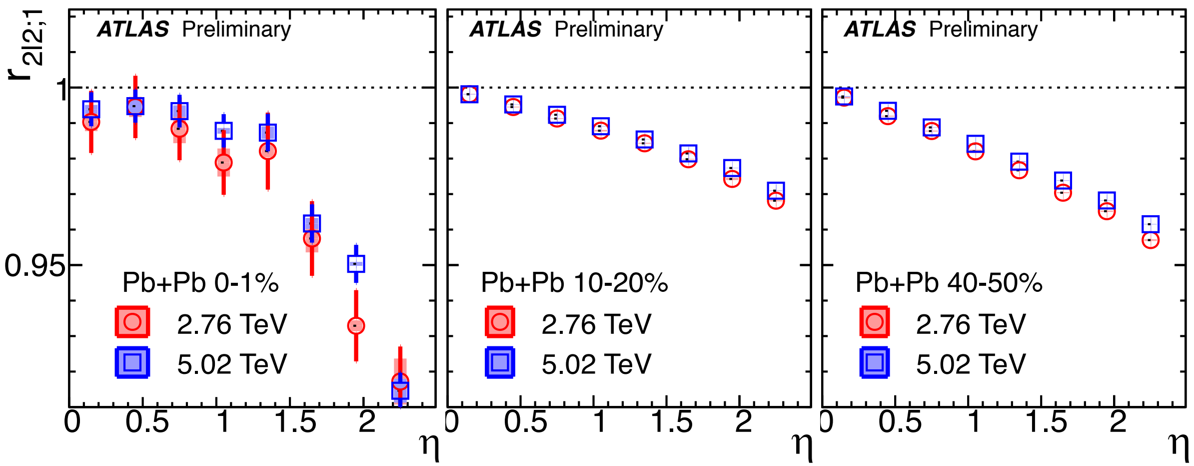
  - Follow expected $1/\sqrt{N_{ch}}$ for independent-source emission
- LRC is underestimated by models
  - EPOS is nearly boost invariant.

Longitudinal decorrelation of v_2 v_3 in PbPb

Decorrelation of v2

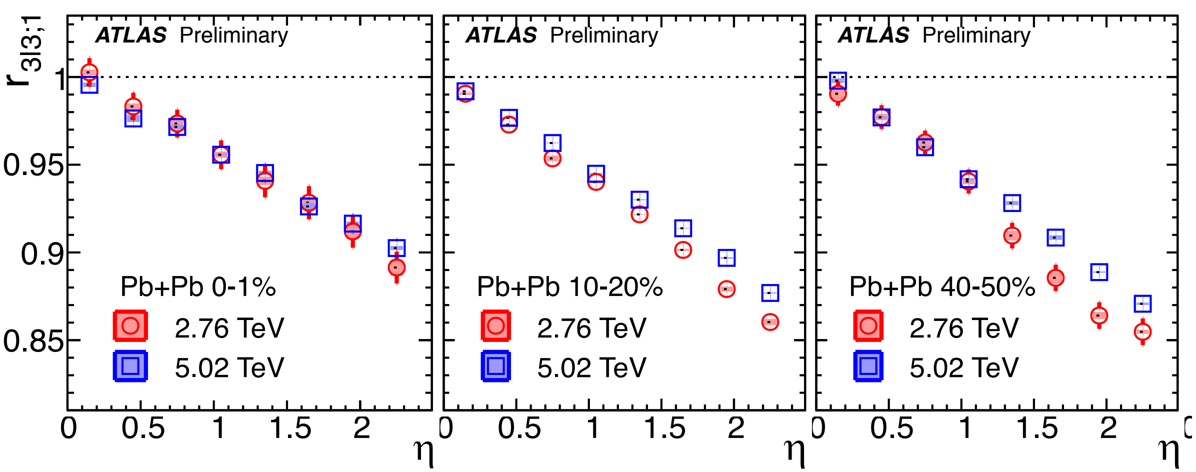
$$r_{n|n}(\eta) = \frac{\langle \boldsymbol{v}_n(-\eta)\boldsymbol{v}_n^*(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_n(\eta)\boldsymbol{v}_n^*(\eta_{\rm ref})\rangle}$$





linear decrease along η
smallest decorrelation in mid-central
stronger decorrelation at lower energy

Decorrelation of v3



linear decrease along η
weak centrality dependence
stronger decorrelation at lower energy

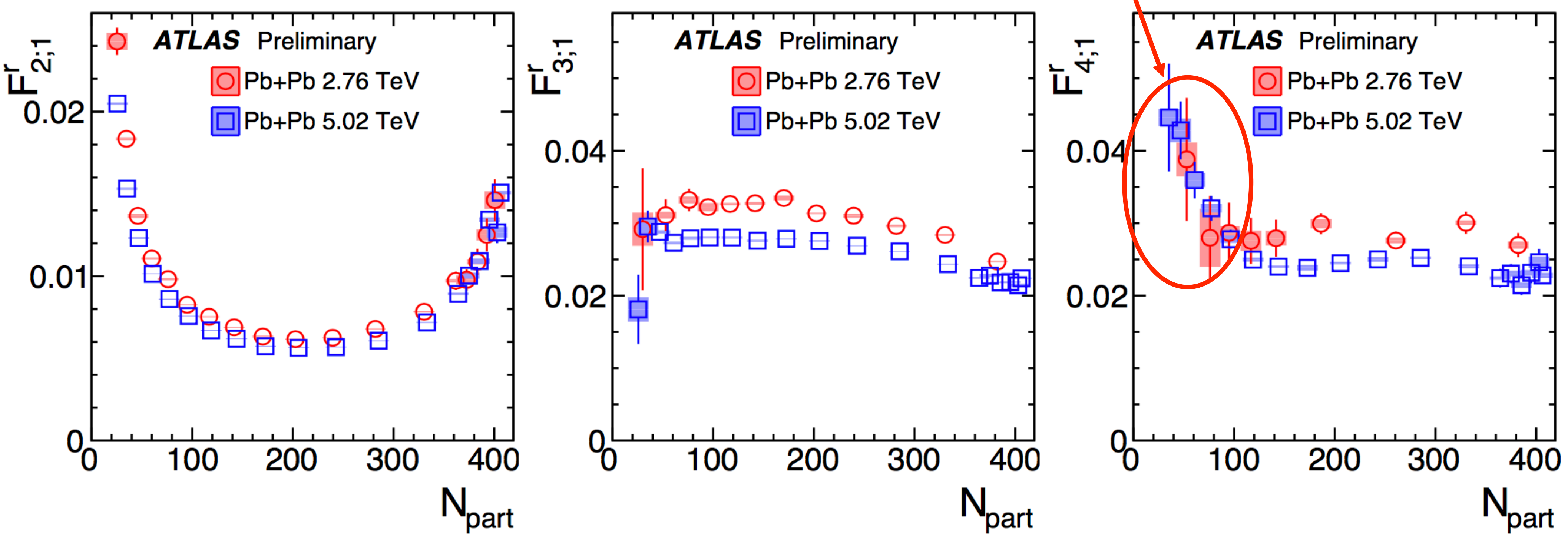
Extract the linear slope

$$r_{n|n;1} = 1 - 2F_{n;1}^{r}\eta$$

Centrality and √s dependence

$$r_{n|n;1} = 1 - 2F^{r}_{n;1}\eta$$

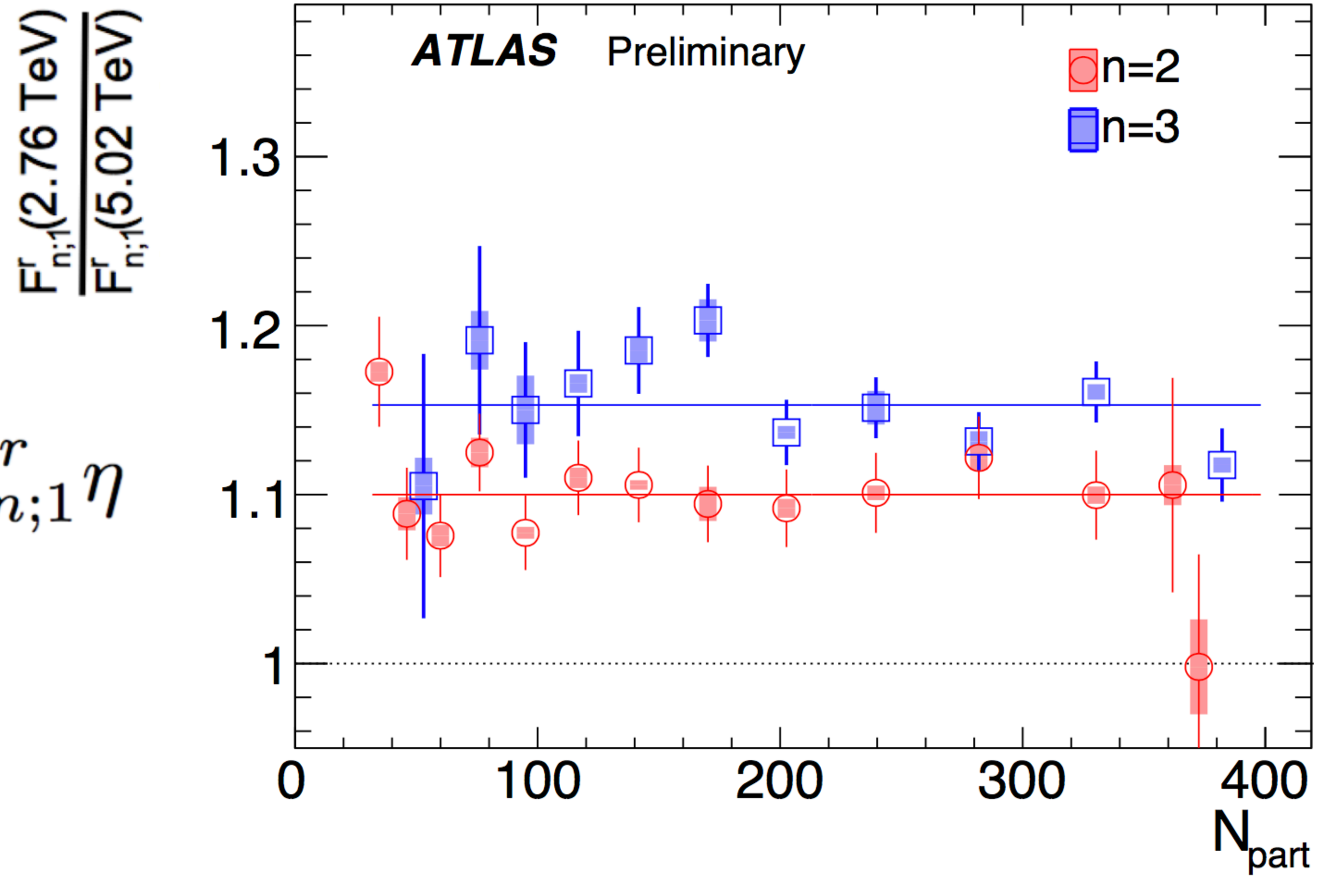
From mode-mixing contribution of v_2^2



- For v_2 : decorrelation is smallest in mid-central collisions.
- For v_3 and v_4 : decorrelation has weak centrality dependence
- Decorrelation is stronger at lower √s.

Centrality and √s dependence

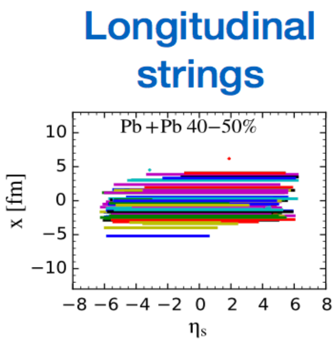
$$r_{n|n;1} = 1 - 2F^{r}_{n;1}\eta$$



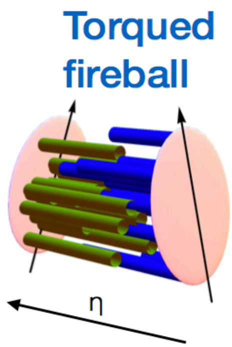
- For v_2 : decorrelation is smallest in mid-central collisions.
- For v_3 and v_4 : decorrelation has weak centrality dependence
- Decorrelation is stronger at lower √s.
  - v2 decorrelation is 10% stronger at 2.76 TeV than at 5.02 TeV
  - v3 decorrelation is 15% stronger at 2.76 TeV than at 5.02 TeV

Model comparison

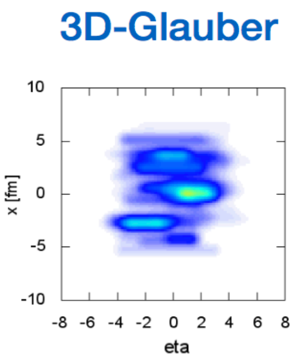
- No model works perfectly in all centrality and systems



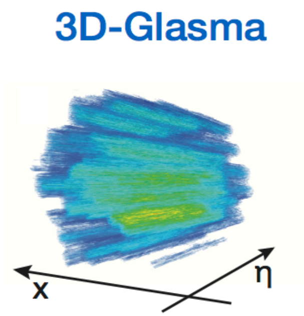
Pang, Petersen, Qin, Roy, Wang 1511.04131



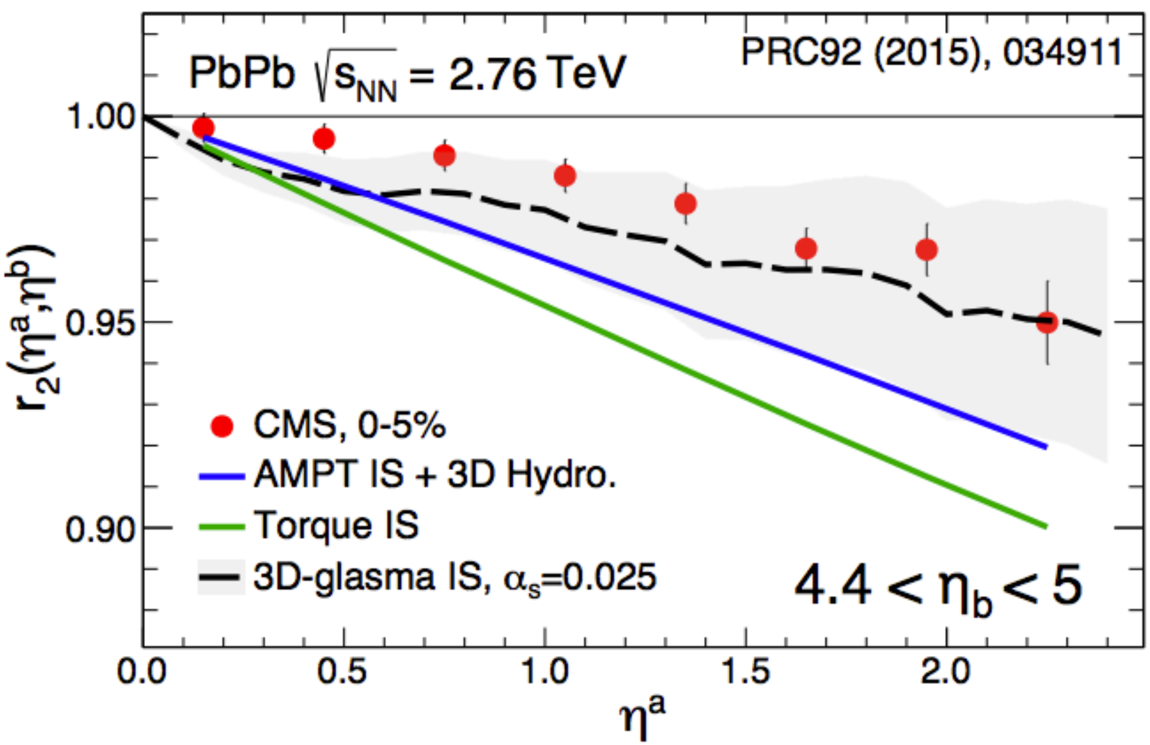
Bozek, Broniowski 1506.02817



Schenke, Monnai 1509.04103



Schenke, Schlichting 1605.07158

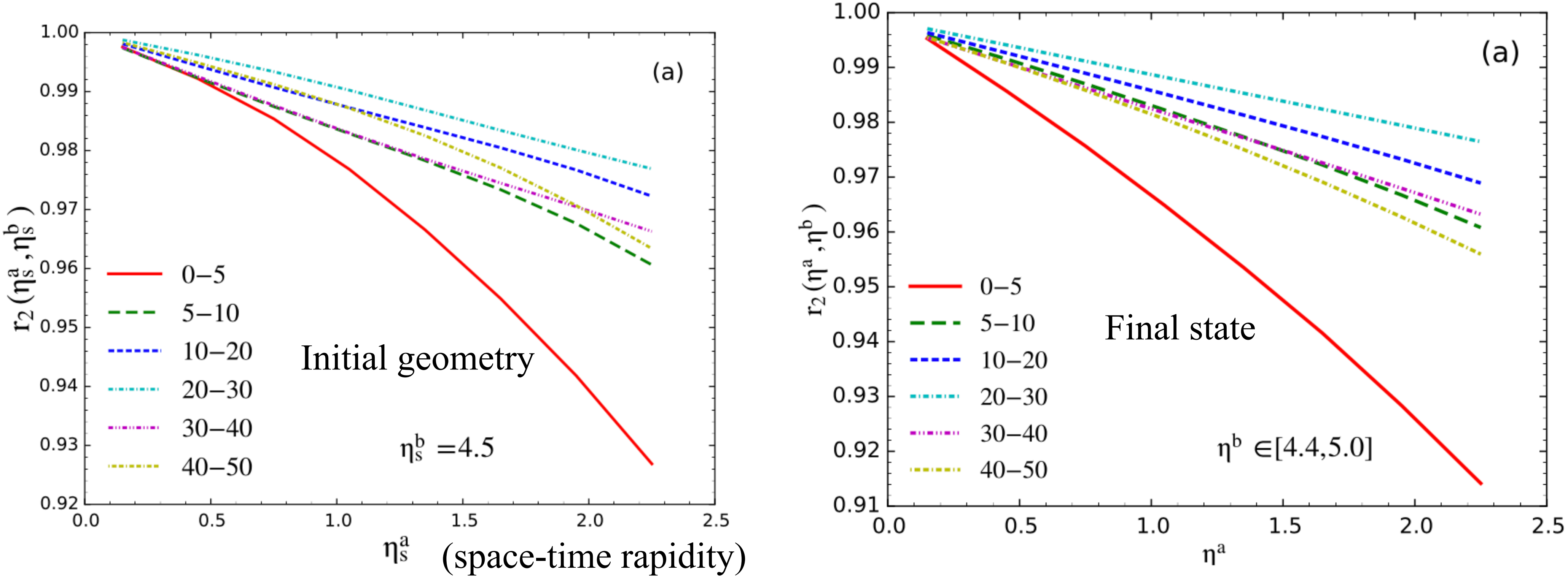


Unique probe of 3D initial condition

Pang. et.al 1511.04131

$$r_n(\eta_s^a, \eta_s^b) = \frac{\langle \vec{\epsilon}_n(-\eta_s^a) \cdot \vec{\epsilon}_n^*(\eta_s^b) \rangle}{\langle \vec{\epsilon}_n(\eta_s^a) \vec{\epsilon}_n^*(\eta_s^b) \rangle}$$

$$r_{n|n}(\eta) = \frac{\langle \boldsymbol{v}_n(-\eta) \boldsymbol{v}_n^*(\eta_{\mathrm{ref}}) \rangle}{\langle \boldsymbol{v}_n(\eta) \boldsymbol{v}_n^*(\eta_{\mathrm{ref}}) \rangle}$$

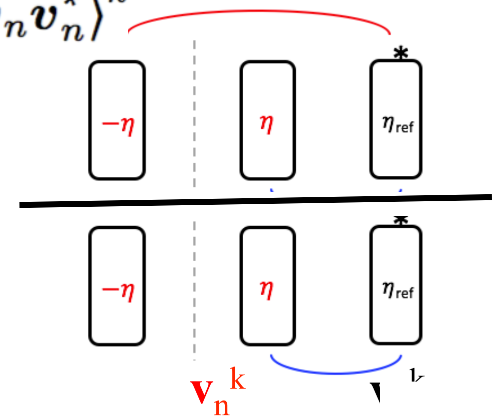


Mostly sensitive to the initial state effects at high √s

What else can we do?

- Higher-moments $\left\langle v_n^k v_n^{*k} \right\rangle \neq \left\langle v_n v_n^* \right\rangle^k$

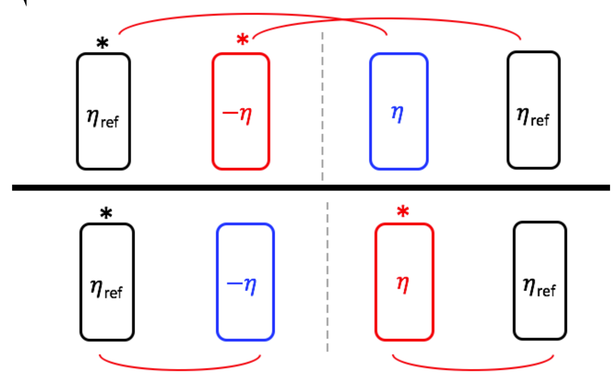
$$r_{n|n;k}(\eta) = \frac{\left\langle v_n^k(-\eta) v_n^{*k}(\eta_{\mathrm{ref}}) \right\rangle}{\left\langle v_n^k(\eta) v_n^{*k}(\eta_{\mathrm{ref}}) \right\rangle} =$$



Sensitive to how decorrelation fluctuates EbyE

- Four-η correlator

$$R_{n|n;2}(\eta) = \frac{\left\langle v_n(-\eta_{\mathrm{ref}}) v_n(-\eta) v_n^*(\eta) v_n^*(\eta_{\mathrm{ref}}) \right\rangle}{\left\langle v_n(-\eta_{\mathrm{ref}}) v_n(\eta) v_n^*(-\eta) v_n^*(\eta_{\mathrm{ref}}) \right\rangle} =$$



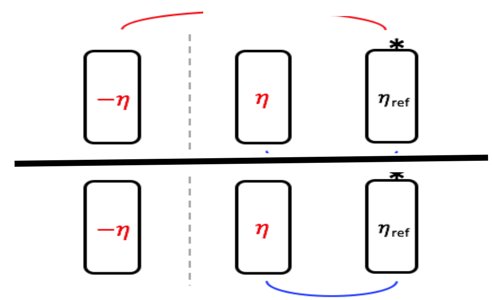
Only sensitive to EP twist effects

- Mixed harmonics

$$r_{2,3|2,3}(\eta) = \frac{\left\langle v_2(-\eta) v_2^*(\eta_{\mathrm{ref}}) v_3(-\eta) v_3^*(\eta_{\mathrm{ref}}) \right\rangle}{\left\langle v_2(\eta) v_2^*(\eta_{\mathrm{ref}}) v_3(\eta) v_3^*(\eta_{\mathrm{ref}}) \right\rangle}$$

$$r_{2,2|4}(\eta) = \frac{\left\langle v_2^2(-\eta) v_4^*(\eta_{\mathrm{ref}}) \right\rangle}{\left\langle v_2^2(\eta) v_4^*(\eta_{\mathrm{ref}}) \right\rangle}$$

$$r_{2,3|5}(\eta) = \frac{\left\langle v_2(-\eta) v_3(-\eta) v_5^*(\eta_{\mathrm{ref}}) \right\rangle}{\left\langle v_2(\eta) v_3(\eta) v_5^*(\eta_{\mathrm{ref}}) \right\rangle}$$



$\mathbf{v}_2\mathbf{v}_3$	$\mathbf{v}_2\mathbf{v}_3$
$\mathbf{v}_2{}^2$	$\mathbf{v}_4$
$\mathbf{v}_2\mathbf{v}_3$	$\mathbf{v}_5$

Sensitive to non-linear/ mode-mixing effects between different harmonics

Also multi-particle correlations: Bzdak, Bozek, Broniowski1509.02967,1509.04124

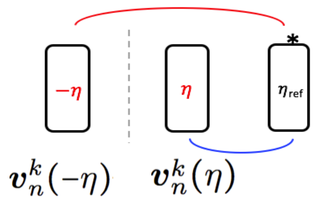
Higher moments decorrelation: $(\mathbf{v}_2)^k$

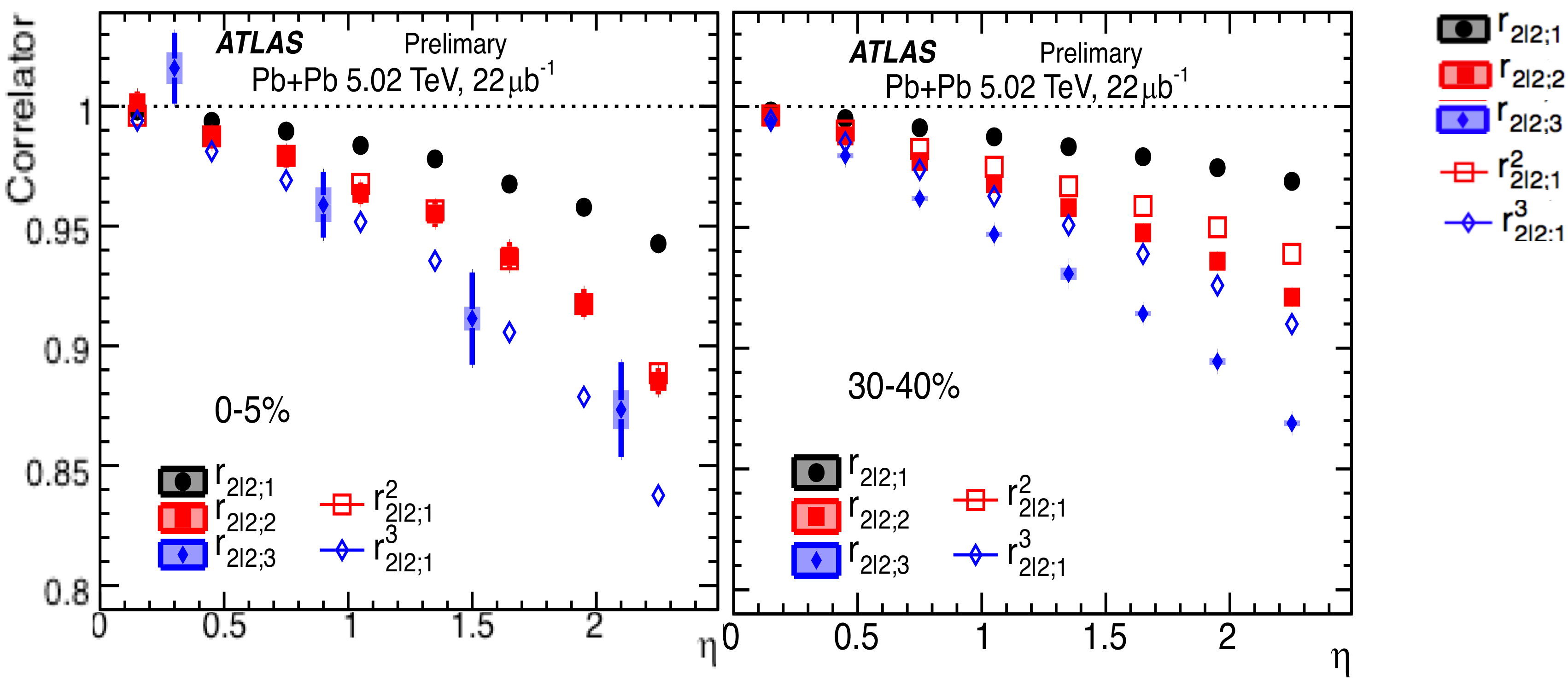
- Higher order moments $\langle A^k \rangle$ provide more constrains on *P(A)*
  - $r_{2|2;k}$ measures decorrerlation of $(\mathbf{v}_2)^k$, stronger decorrelation is expected
  - In general $\langle v_n^k v_n^{*k} \rangle \neq \langle v_n v_n^* \rangle^k$

$$r_{n|n;k} = \frac{\langle v_n(-\eta)^k v_n^*(\eta_{\rm ref})^k \rangle}{\langle v_n(\eta)^k v_n^*(\eta_{\rm ref})^k \rangle} \stackrel{?}{=} \frac{\langle (v_n(-\eta) v_n^*(\eta_{\rm ref})) \rangle^k}{\langle (v_n(\eta) v_n^*(\eta_{\rm ref})) \rangle^k} \equiv r_{n|n;1}^k$$

  - Central: $r_{2|2;k} \approx r^k_{2|2;1}$; Non-central: $r_{2|2;k} > r^k_{2|2;1}$

$$r_{n|n;k} = \frac{\langle v_n(-\eta)^k v_n^*(\eta_{\rm ref})^k \rangle}{\langle v_n(\eta)^k v_n^*(\eta_{\rm ref})^k \rangle}$$





Separating asymmetry and twist contribution

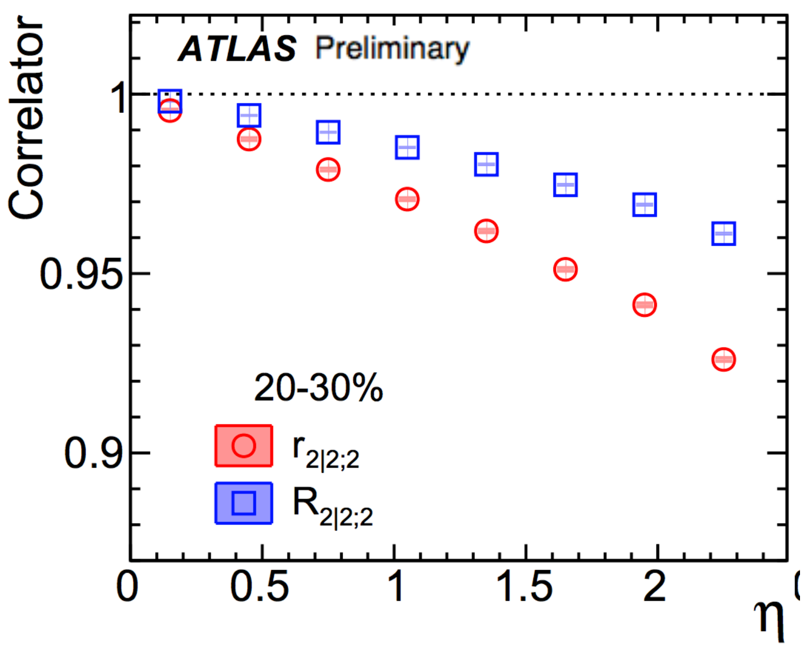
$$r_{n|n;2}(\eta) = \frac{\langle \boldsymbol{v}_n^2(-\eta)\boldsymbol{v}_n^{*2}(\eta_{\rm ref})\rangle}{\langle \boldsymbol{v}_n^2(\eta)\boldsymbol{v}_n^{*2}(\eta_{\rm ref})\rangle}$$

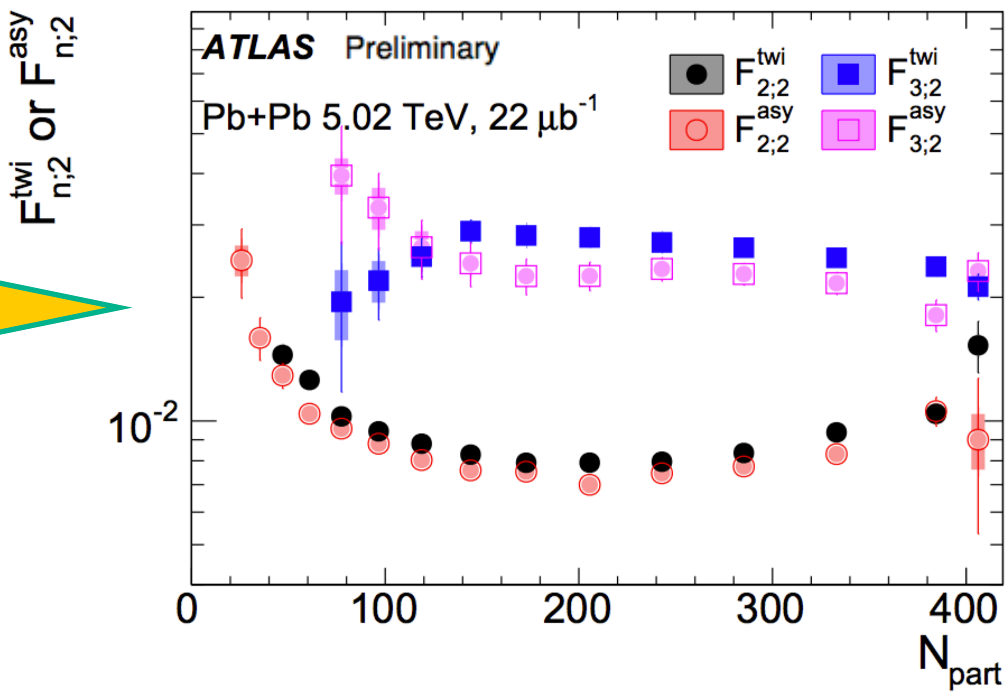
$$r_{n|n;2}(\eta) \approx 1 - 2F_{n;k}^{\rm asy}\eta - 2F_{n;k}^{\rm twi}\eta$$

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

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

$$R_{n|n;2} \approx 1 - 2F_{n;2}^{\rm twi}\eta$$



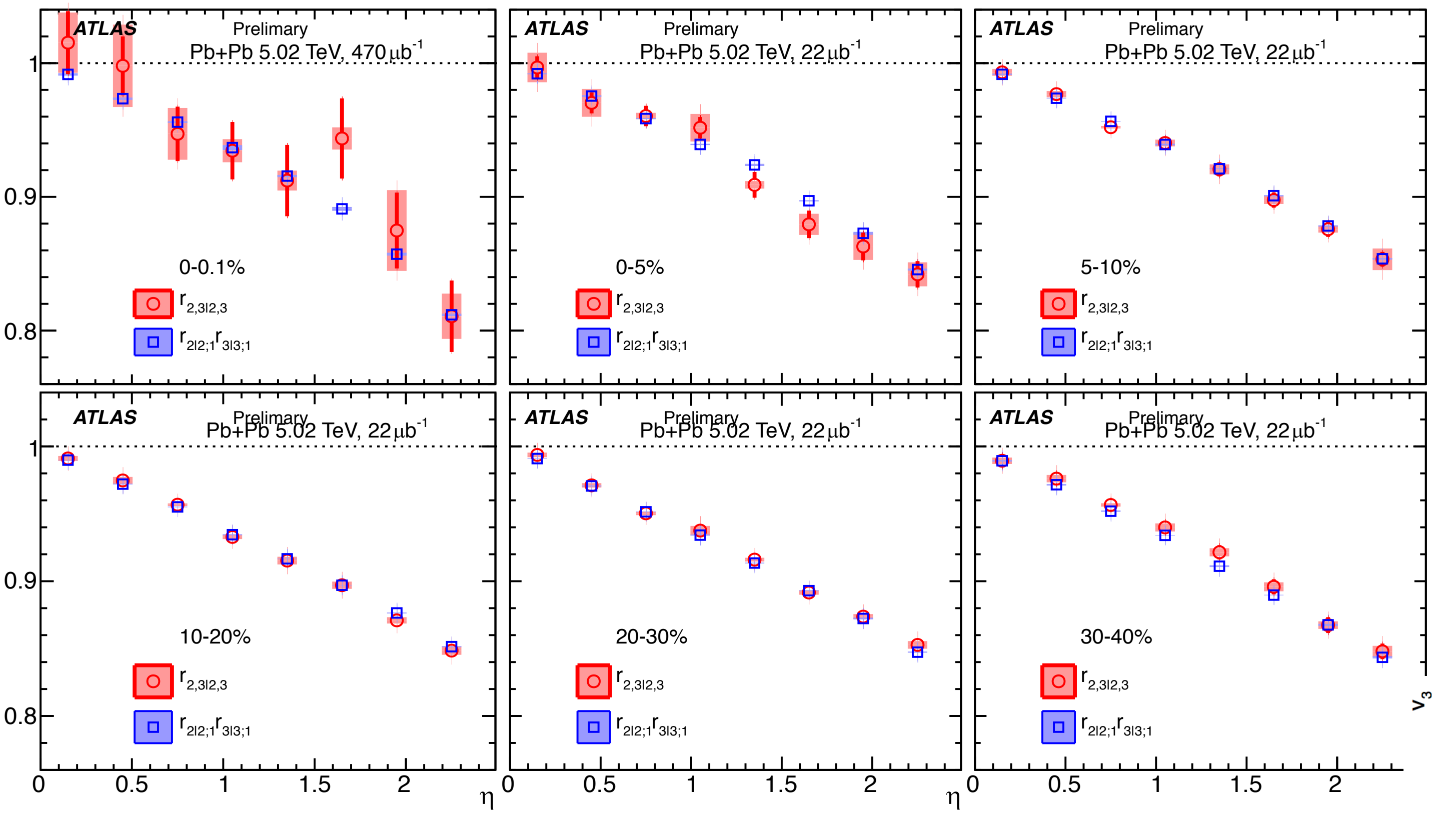


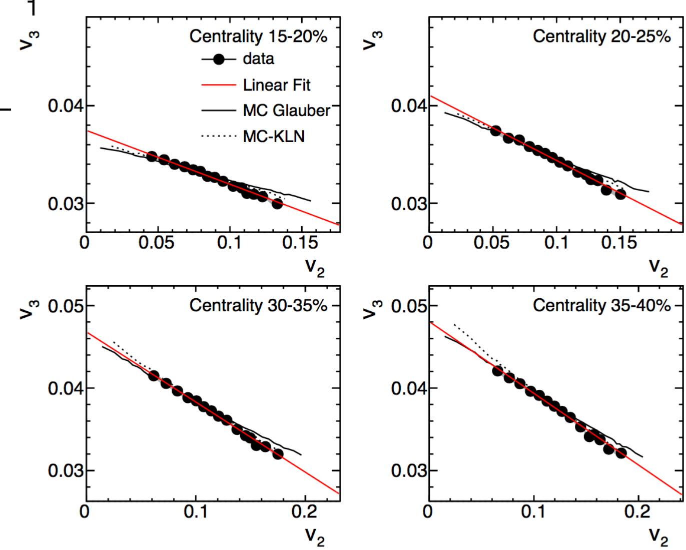
- Twist is slightly larger than asymmetry

Is decor of v2 and decor of v3 correlated?

- $r_{2,3|2,3} = r_{2|2} \times r_{3|3}$ indicates the decorrelation of v_2, v_3 are independent

$$r_{2,3|2,3} = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\text{ref}})\boldsymbol{v}_3(-\eta)\boldsymbol{v}_3^*(\eta_{\text{ref}})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\text{ref}})\boldsymbol{v}_3(\eta)\boldsymbol{v}_3^*(\eta_{\text{ref}})\rangle} = \frac{\langle \boldsymbol{v}_2(-\eta)\boldsymbol{v}_2^*(\eta_{\text{ref}})\rangle \times \langle \boldsymbol{v}_3(-\eta)\boldsymbol{v}_3^*(\eta_{\text{ref}})\rangle}{\langle \boldsymbol{v}_2(\eta)\boldsymbol{v}_2^*(\eta_{\text{ref}})\rangle \times \langle \boldsymbol{v}_3(\eta)\boldsymbol{v}_3^*(\eta_{\text{ref}})\rangle} = r_{2|2;1} \times r_{3|3;1}$$



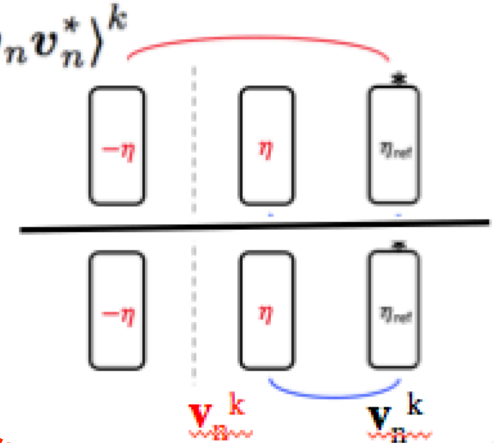


- The previously observed anticorrelation between v_2 and v_3 is a global effect
  - due to anticorrelation between ε_2 and ε_3.

What else can we do?

- **Higher-moments** $\langle v_n^k v_n^{*k}\rangle \neq \langle v_n v_n^*\rangle^k$

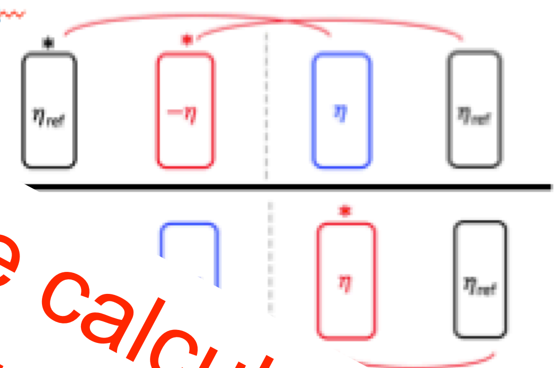
$$r_{n|n;k}(\eta) = \frac{\langle v_n^k(-\eta) v_n^{*k}(\eta_{\rm ref})\rangle}{\langle v_n^k(\eta) \ldots (\eta_{\rm ref})\rangle} =$$



Sensitive to how decorrelation fluctuates EbyE

- **Four-η correla...**

$$R_{n|n;2}(\eta) = \frac{\langle v_n(-\eta_{\rm ref}) v_n \ldots}{\langle v_n(-\eta_{\rm ref}) v_n^*(-\eta) v_n \ldots}$$



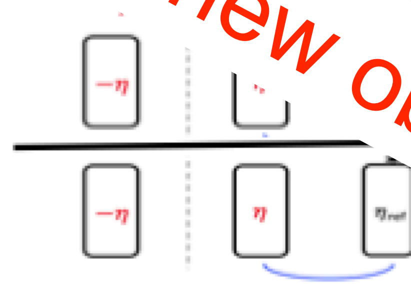
Only sensitive to EP twist e...

- **Mixed harmonics**

$$r_{2,3|2,3}(\eta) = \frac{\langle v_2(-\eta) v_2^*(\eta_{\rm ref}) v_3(-\eta) v_3^*(\eta_{\rm ref})\rangle}{\langle v_2(\eta) v_2^*(\eta_{\rm ref}) v_3(\eta) v_3^*(\eta_{\rm ref})\rangle}$$

$$r_{2,2|4}(\eta) = \frac{\langle v_2^2(-\eta) v_4^*(\eta_{\rm ref})\rangle}{\langle v_2^2(\eta) v_4^*(\eta_{\rm ref})\rangle}$$

$$r_{2,3|5}(\eta) = \frac{\langle v_2(-\eta) v_3(-\eta) v_5^*(\eta_{\rm ref})\rangle}{\langle v_2(\eta) v_3(\eta) v_5^*(\eta_{\rm ref})\rangle}$$



$v_2 v_3$	$v_2 v_3$
v_2^2	v_4
$v_2 v_3$	v_5

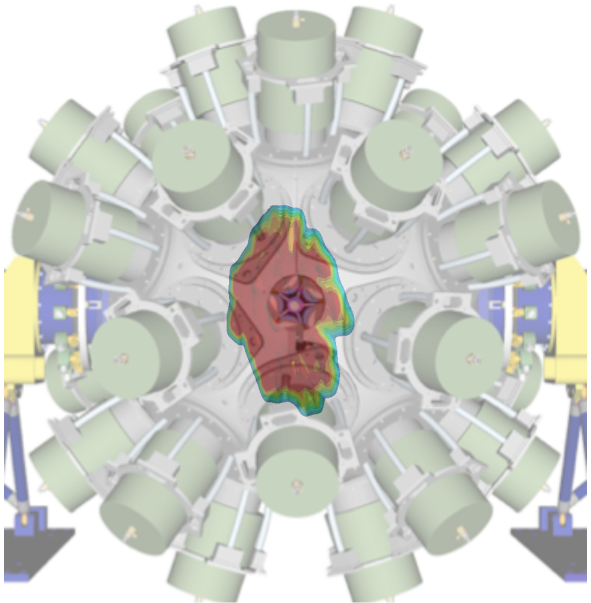
Sen... mode-m... between di... harmonics

Look forward to the calculation for these and many other new observables

Also multi-particle correlations: Bzdak, Bozek, Broniowski1509.02967,1509.04124

Importance of forward coverage

- After 20 years of HI research, we have gained a lot knowledge about the space-time evolution and properties of the QGP matter.
- Further progress requires capture 3+1D event topology with a ~4π detector
  - Fireball evolution has strong EbyE fluctuations, precision medium properties can't be achieved w/o detailed knowledge on these fluctuations.
  - Interesting observables related to chirality, criticality, etc all have large event-by-event fluctuations, as well as unknown transport in rapidity.
  - Often need to disentangle small signal from large background (i.e. flow), both fluctuates event-by-event and along rapidity in each event.
  - Reduce the model dependence.



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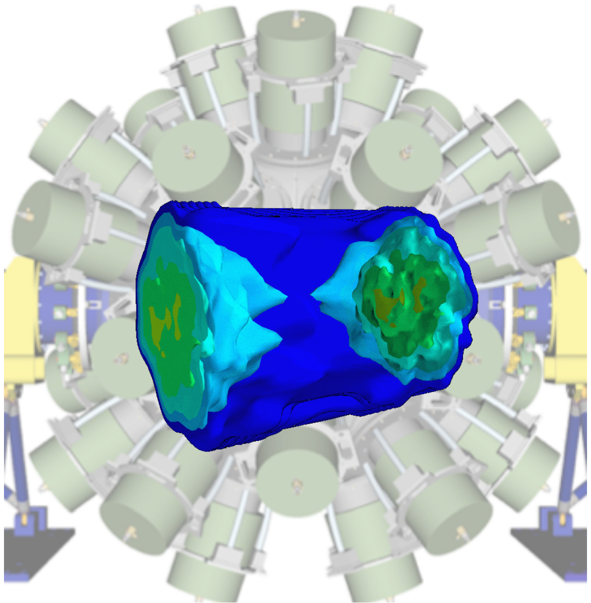
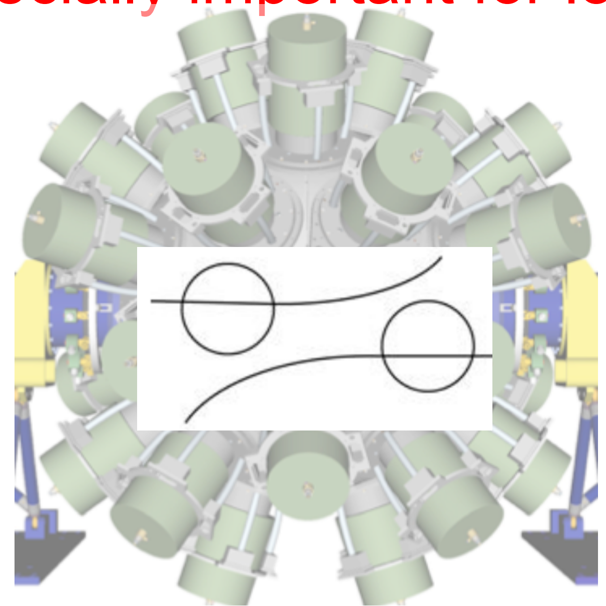
- Further progress requires capture 3+1D event topology with a ~4π detector
  - Fireball evolution has strong EbyE fluctuations, precision medium properties can't be achieved w/o detailed knowledge on these fluctuations.
  - Interesting observables related to chirality, criticality, etc all have large event-by-event fluctuations, as well as unknown transport in rapidity.
  - Often need to disentangle small signal from large background (i.e. flow), both fluctuates event-by-event and along rapidity in each event.
  - Reduce the model dependence.

Especially important for low √s

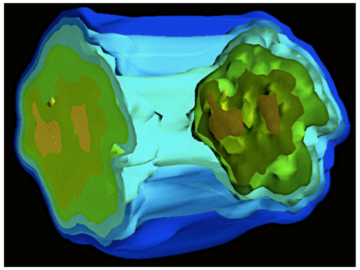


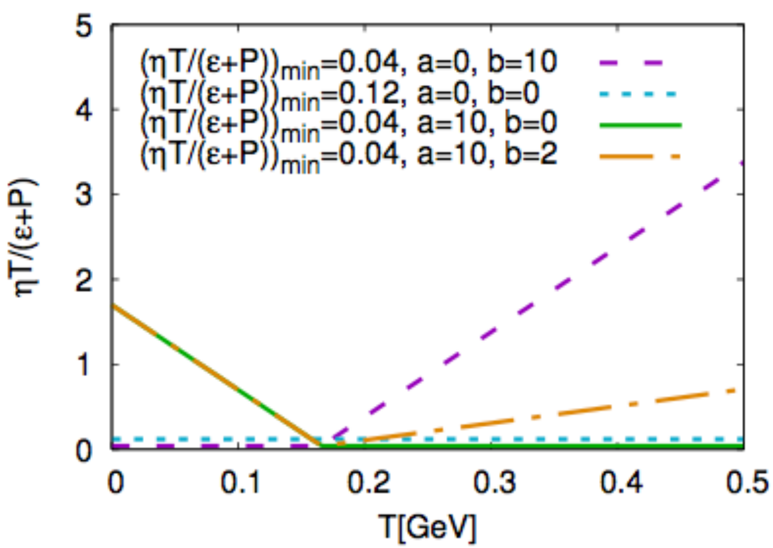


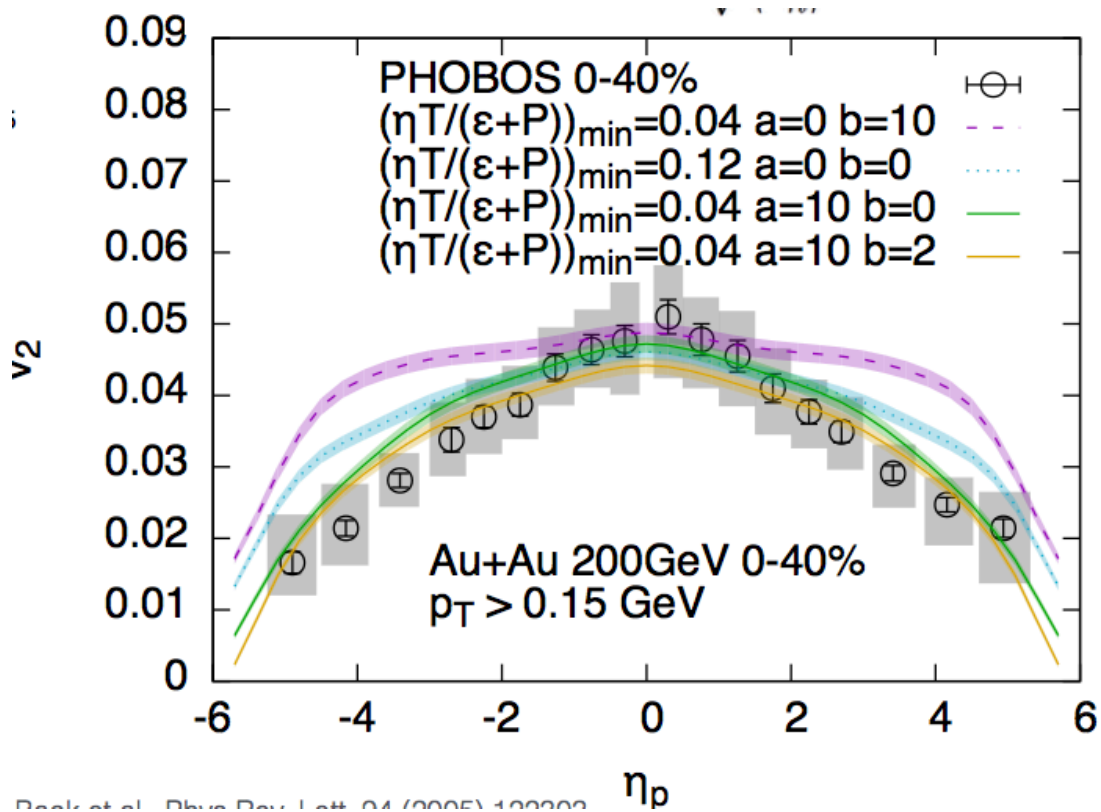
Forward flow measurement at RHIC

forward high-μ at large $\sqrt{s} \neq$ mid-rapidity high-μ at small $\sqrt{s}$

- Differential information on spectra and flow in forward η
  - Map the EbyE fluc & improve full EbyE 3+1D hydrodynamics.
  - Longitudinal pressure, isotropization, hydrodynamic noise….



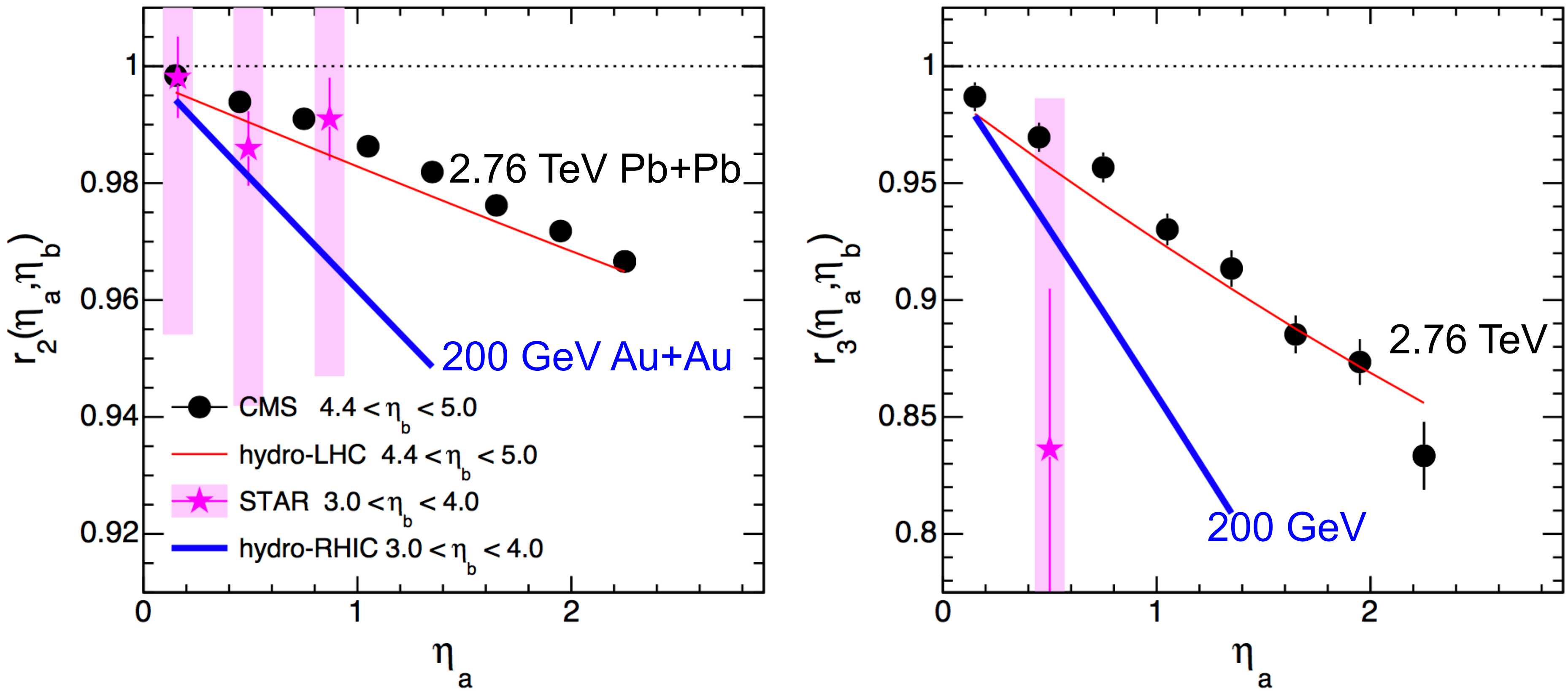




Denicol, Monnai, Schenke 1512.01538

Much stronger decorrelation effect expected at RHIC

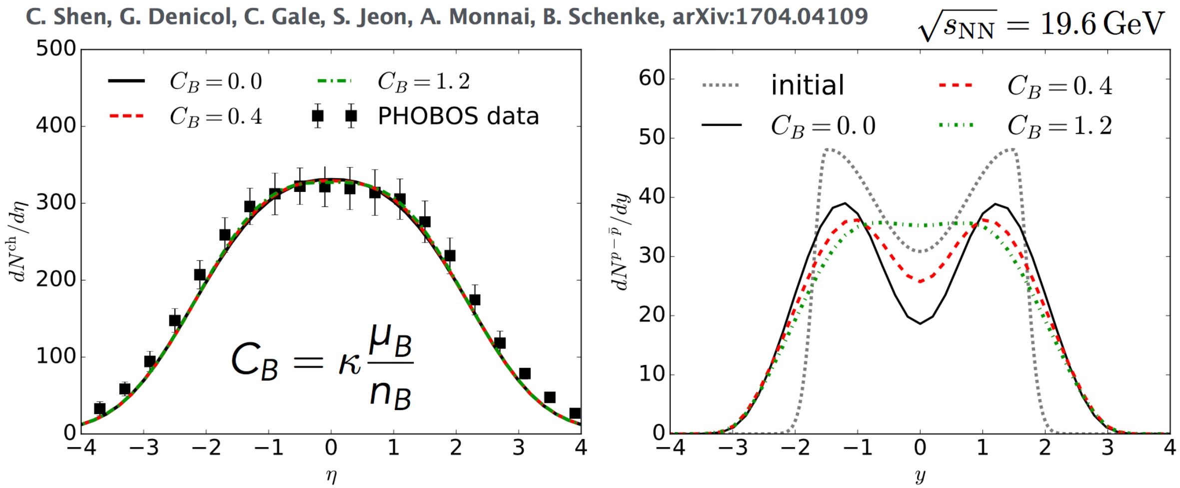
1511.04131



- Event-averaged decorr. as large as 20% in STAR TPC acceptance
- Much larger at BES energies
  - Initial condition and final state dynamics vary strongly event-by-event, and as a function of η.

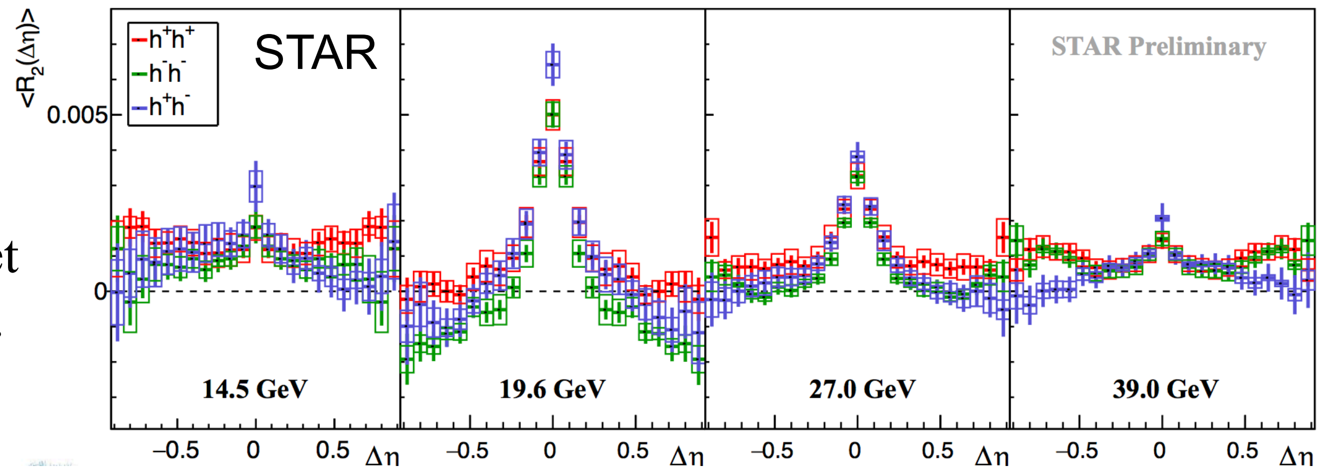
FB multiplicity correlation of net-baryon at RHIC

- Sensitive to baryon number transport.



- Strong and non-trivial √s dependence observed by STAR.

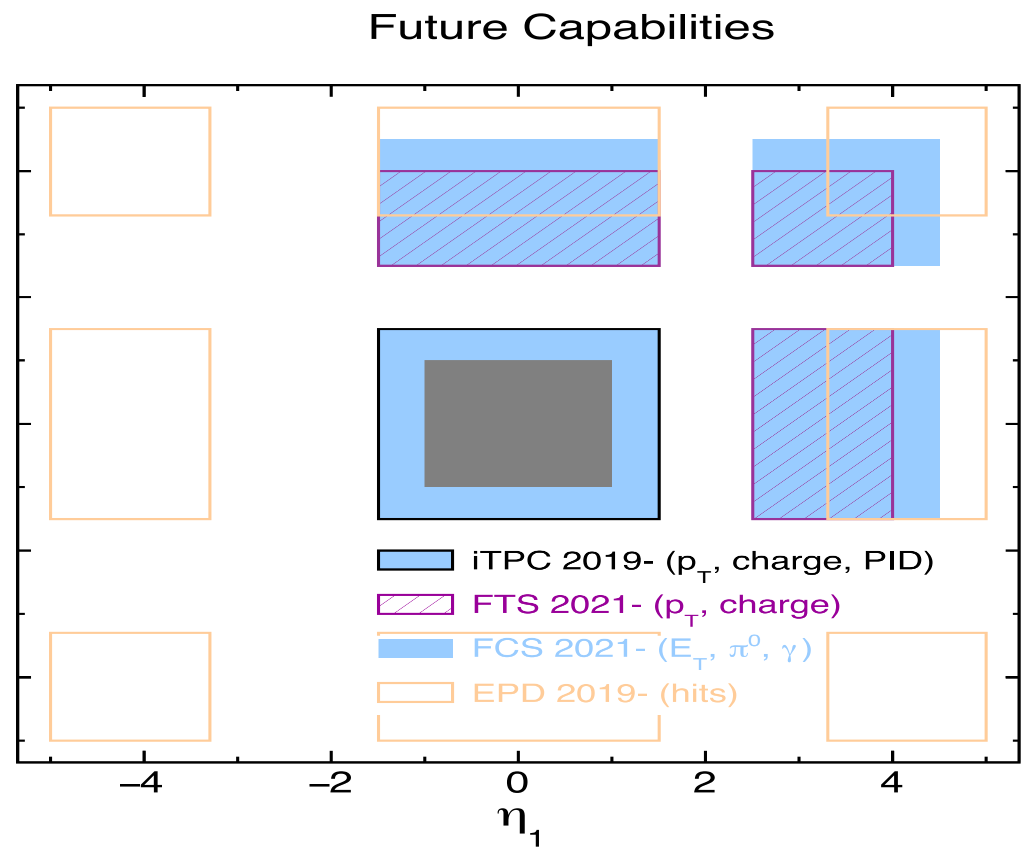
Can be done for all conserved quantities: net charge, strangeness etc.



Very important in the context of BES-II at RHIC

STAR forward upgrade

- Current upgrade planned:
  - BESII: iTPC+EPD+eTOF
  - Beyond BESII: FCS+FTS



- Physics enabled by these upgrades
  - Rapidity de-correlation to quantify QGP hydrodynamics
  - Longitudinal conserved charge fluctuations
  - Rapidity dependence of Global Hyperon Polarization
  - Jet-medium interactions with large rapidity range
  - Nucleon and nuclear parton structure from forward measurements

Summary

- Longitudinal correlations probe non-boost-invariant initial conditions & rapidity transports in HI collisions
  - Longitudinal multiplicity correlations
    - LRC depends only on Nch, constrains the particle production sources.
  - Longitudinal flow correlations
    - Consistent with rapidity-dependent mixing of initial condition controlled by projectile and target sources.
    - New observables imply rich EbyE fluctuations, model calculation are required.
  - Both stronger at lower $\sqrt{s}$, longitudinal dynamics important for BESII.

- Large η coverage in each event is important to disentangle signal from background, and reduce model dependence.
  - Forward upgrade is important next step