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The hidden secrets of the event-shape fluctuations

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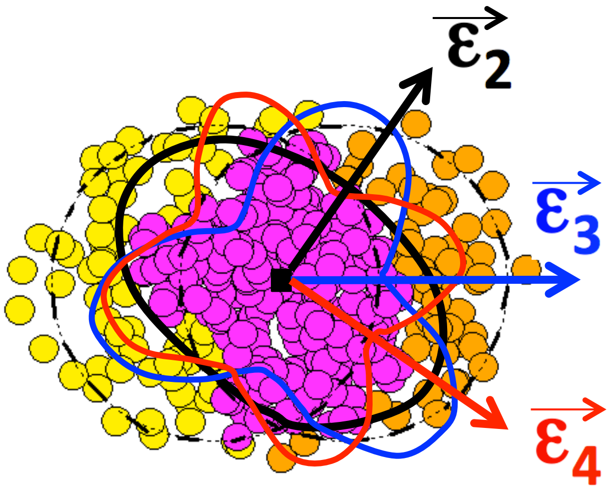
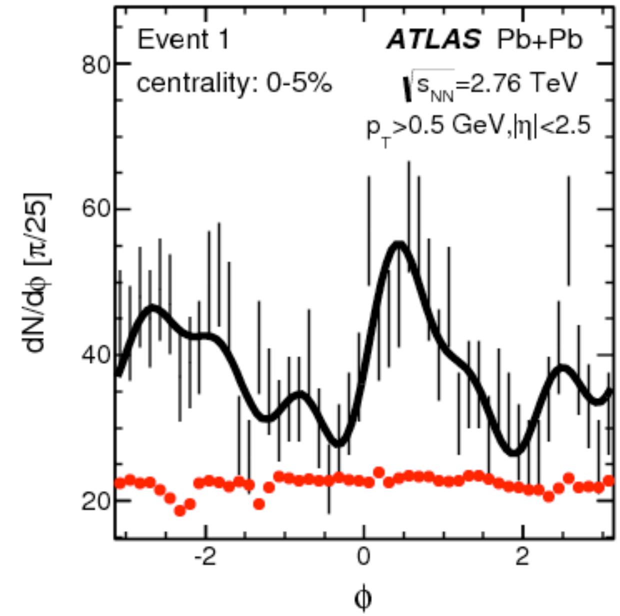
with Peng huo and Soumya Mohapatra

arxiv:1311.7091, 1402.6680, 1403.6077

Geometry and harmonic flow





$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi}\rangle}{\langle r^n\rangle}$$

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

$$\vec{v}_n \equiv v_n e^{in\Phi_n}$$

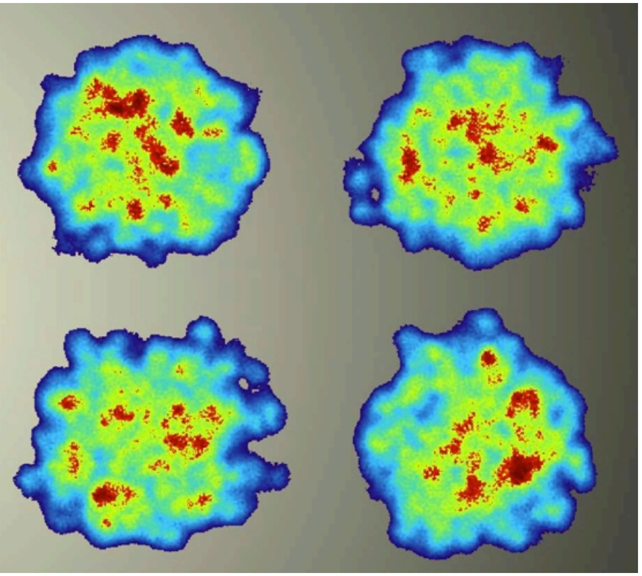
- How $(\varepsilon_n, \Phi_n^*)$ are transferred to (v_n, Φ_n)?
  - What is the nature of final state (non-linear) dynamics?
- The nature of longitudinal flow dynamics?

Event-by-event flow observables

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n \mathrm{v}_\mathrm{n} \cos n\left(\phi - \Phi_n\right)$$

Many little-bang events

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



$$\frac{dN_{\text{evts}}}{d\Phi_1 d\Phi_2 ... d\Phi_l} \propto \sum_{c_n=-\infty}^{\infty} a_{c_1,c_2,...,c_l} \cos(c_1\Phi_1 + c_2\Phi_2 ... + c_l\Phi_l)$$

$$a_{c_1,c_2,...,c_l} = \langle \cos(c_1\Phi_1 + c_2\Phi_2 + ... + c_l\Phi_l)\rangle$$

$$\langle \cos(c_1\Phi_1 + 2c_2\Phi_2 ... + lc_l\Phi_l)\rangle, c_1 + 2c_2 ... + lc_l = 0.$$

JHEP11(2013)183

EbyE v_n distribution: $p(\mathrm{v}_2)$, $p(\mathrm{v}_3)$, $p(\mathrm{v}_4)$

Soumya's talk on Monday

Event-plane correlation: $p(\Phi_n,\Phi_m)$ and $p(\Phi_n,\Phi_m,\Phi_L)$

arXiv:1403.0489

How (ε_n, Φ_n^*) are transferred to (v_n, Φ_n)?

- Flow response is linear for v_2 and v_3: $v_n \propto \varepsilon_n$ and $\Phi_n \approx \Phi_n^*$ i.e.

arXiv:1111.6538 $$v_2 e^{-i2\Phi_2} \propto \epsilon_2 e^{-i2\Phi_2^*}, \quad v_3 e^{-i3\Phi_3} \propto \epsilon_3 e^{-i3\Phi_3^*}$$

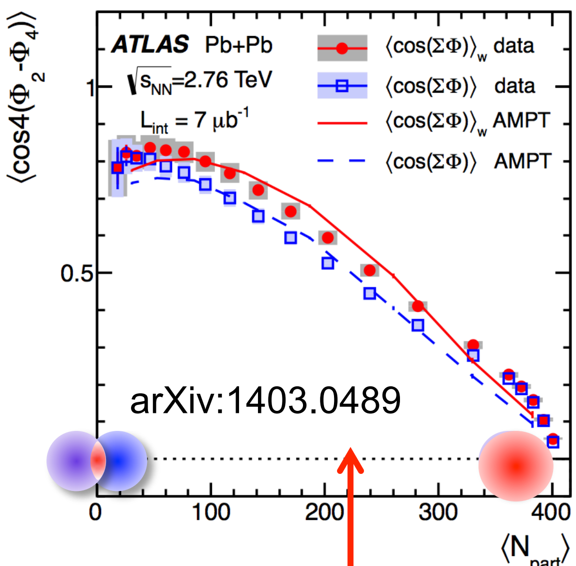
How $(\varepsilon_n, \Phi_n^*)$ are transferred to (v_n, Φ_n)?

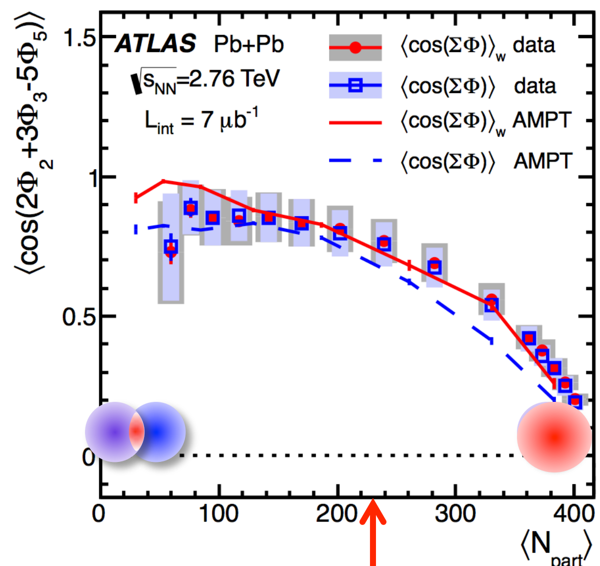
- Flow response is linear for v_2 and v_3: $v_n \propto \varepsilon_n$ and $\Phi_n \approx \Phi_n^*$ i.e.

arXiv:1111.6538 $$v_2 e^{-i2\Phi_2} \propto \epsilon_2 e^{-i2\Phi_2^*}, \quad v_3 e^{-i3\Phi_3} \propto \epsilon_3 e^{-i3\Phi_3^*}$$

- Higher-order flow arises from EP correlations., e.g. :

$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$ $\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$





$$v_4 e^{-i4\Phi_4} \propto \varepsilon_4 e^{-i4\Phi_4^*} + c v_2 v_2 e^{-i4\Phi_2} + \ldots$$

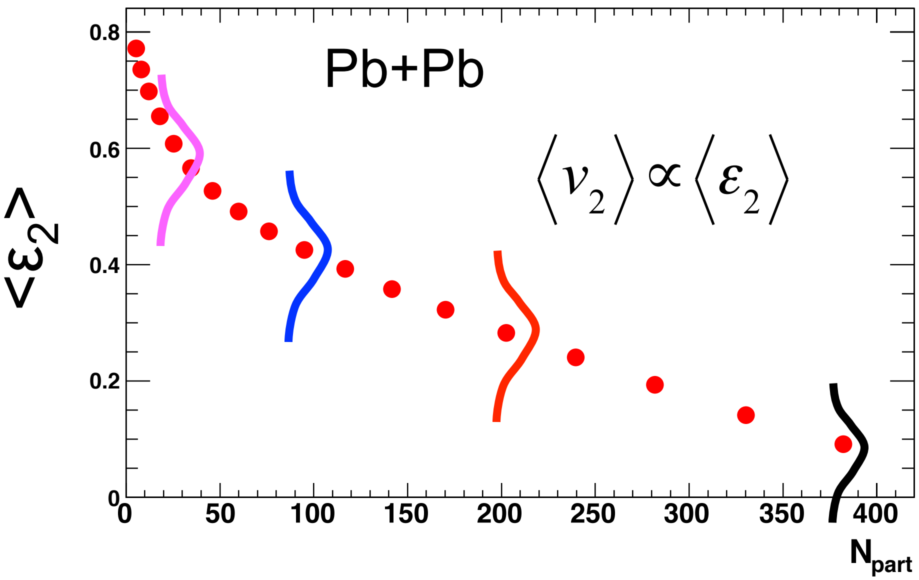
$$v_5 e^{-i5\Phi_5} \propto \varepsilon_5 e^{-i5\Phi_5^*} + c v_2 v_3 e^{-i(2\Phi_2 + 3\Phi_3)} + \ldots$$

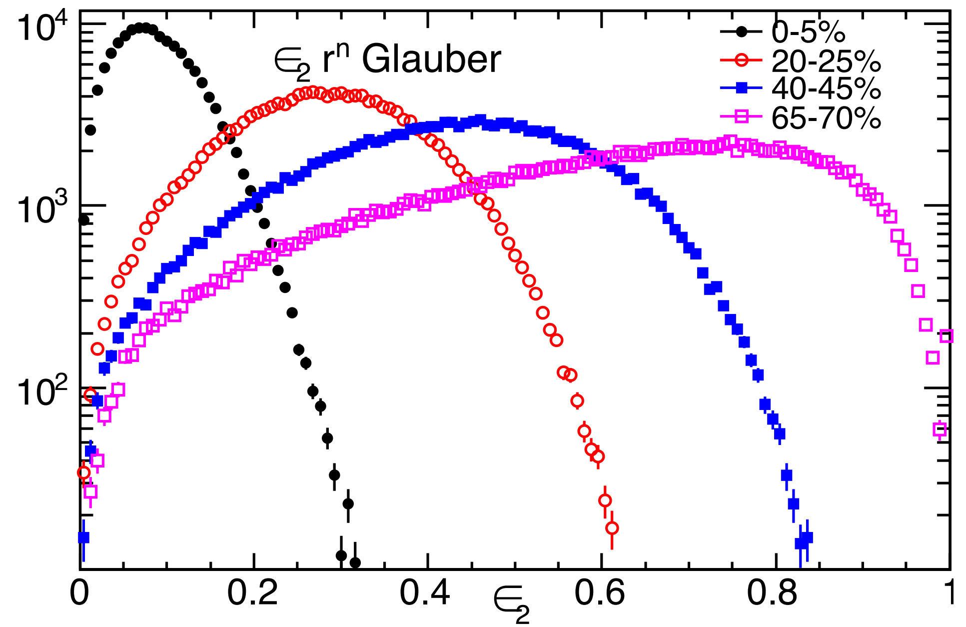
Can we do better?

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

Can we do better?

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

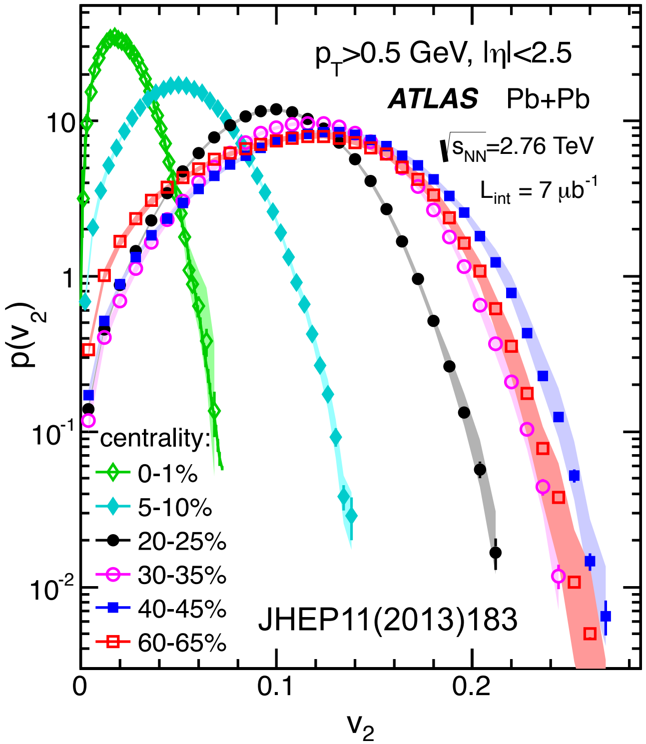


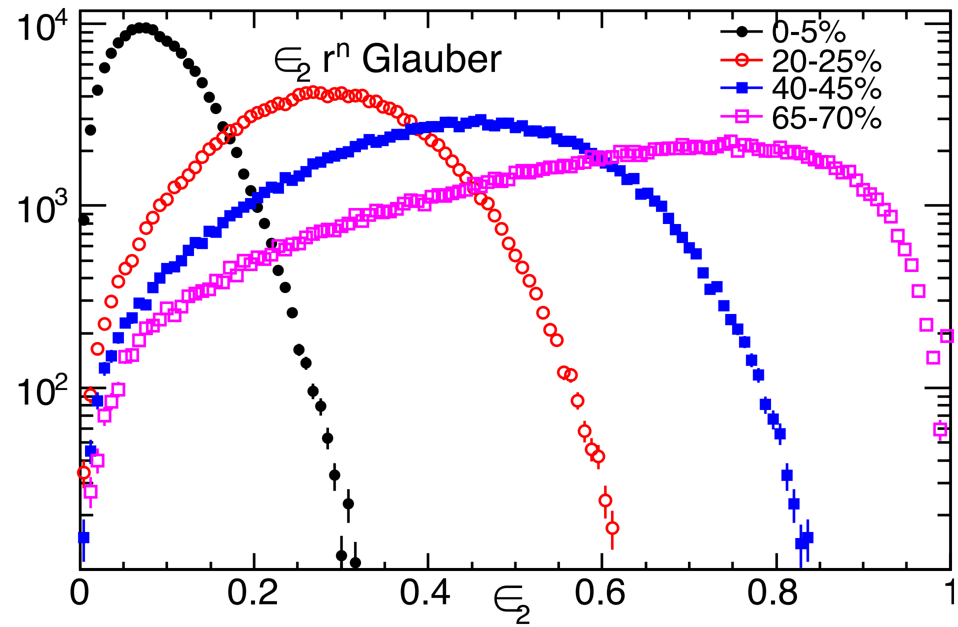


- Variation of event shape at fixed centrality much bigger than Variation of mean across the full centrality range!!
  - All of this information has been averaged out!

Can we do better?

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

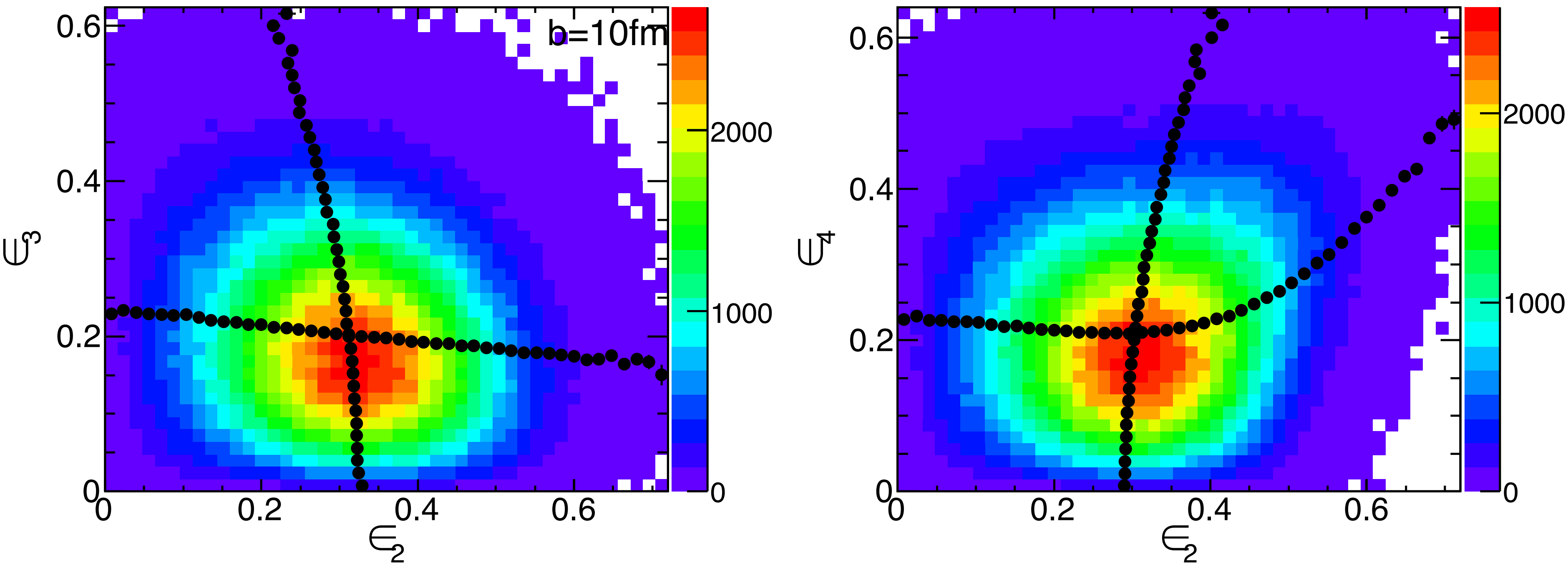




- Variation of event shape at fixed centrality much bigger than Variation of mean across the full centrality range!!
  - All of this information has been averaged out!

Hidden correlations in fixed-centrality

Pb+Pb b=10fm

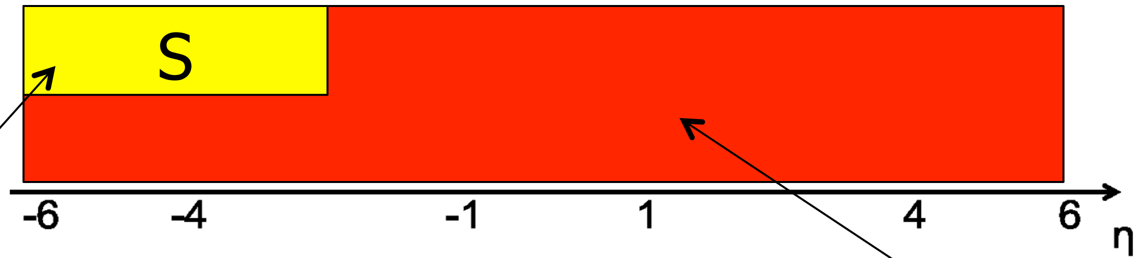


- Correlation already exist in the initial state
  - e.g. anti-correlation between ε_2 and ε_3.
- They are expected to influence the final state.

Event-shape selection technique

Schukraft, Timmins, and Voloshin, arXiv:1208.4563

Huo, Mohapatra, JJ arxiv:1311.7091



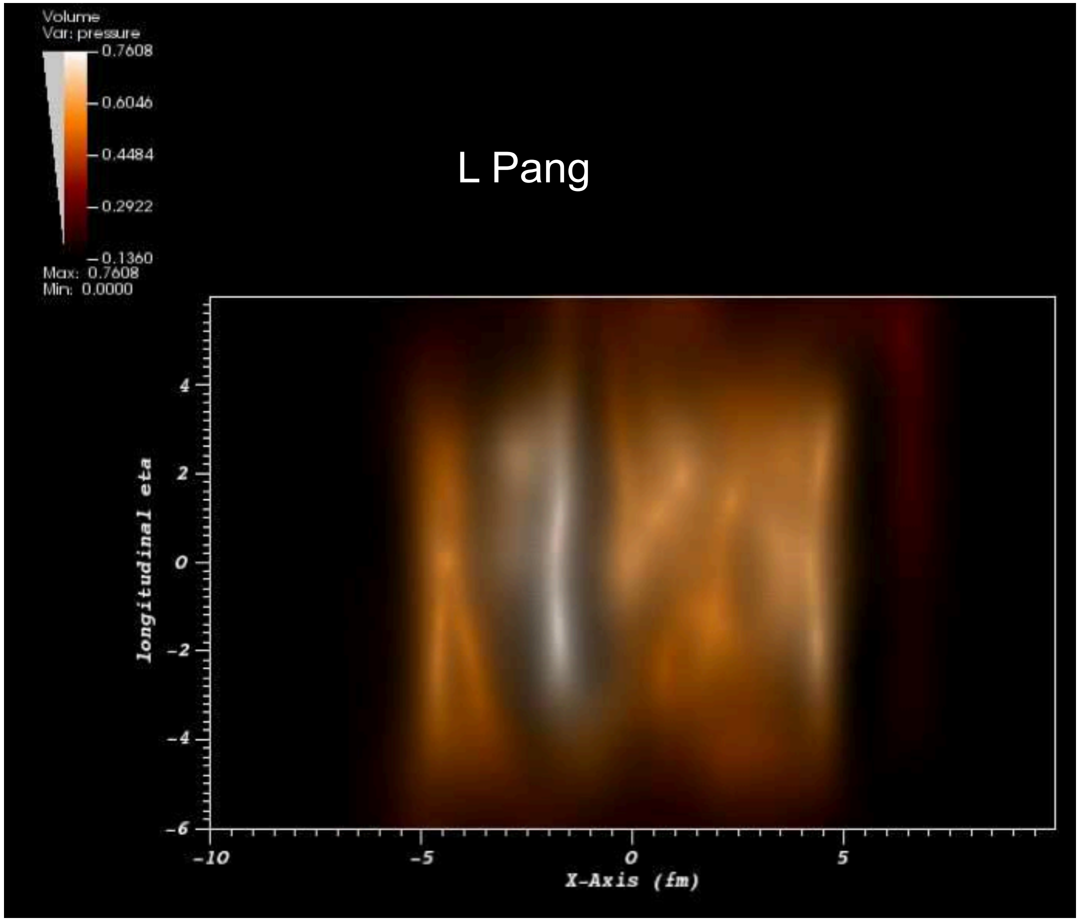
Select events with certain v_2,v_3

$p(v_n)$ or $p(\Phi_n,\Phi_{m,\ldots})$

$$\vec{q}_n = \frac{1}{\Sigma w}(\Sigma w \cos n\phi_n, \Sigma w \sin n\phi_n),\ w = \mathrm{p_T}\ , \qquad q_n = \left|\vec{q}_n\right| \Rightarrow \frac{\sum w \mathrm{v}_n}{\sum w}$$

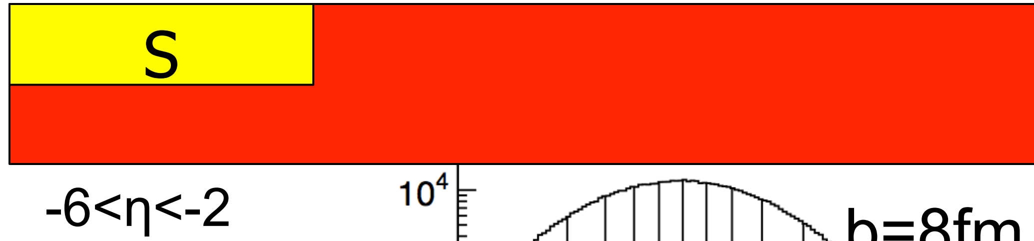
AMPT model

- AMPT model: Glauber+HIJING+transport
  - Has fluctuating geometry and collective flow
  - Longitudinal fluctuations and initial flow

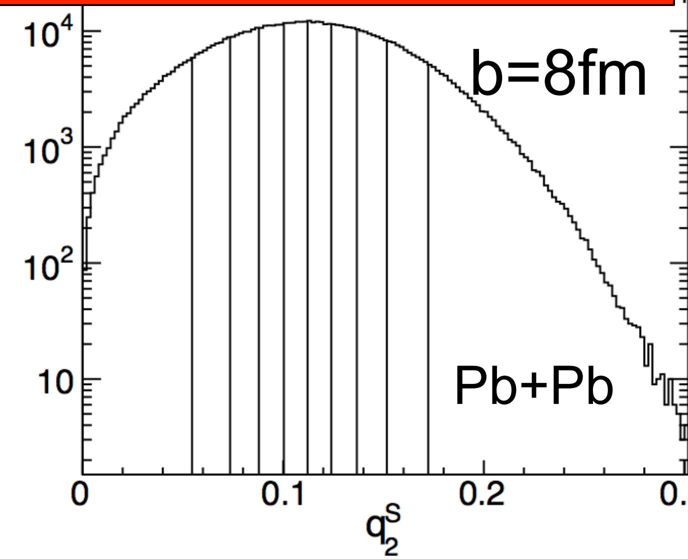


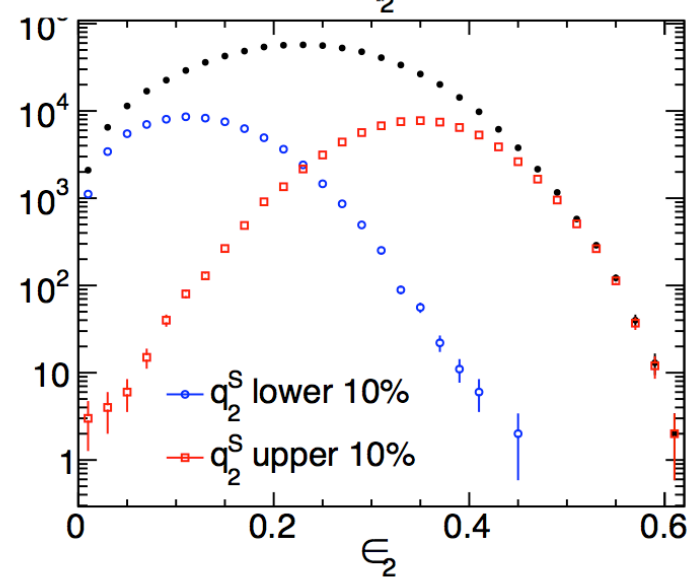
Event shape selection accuracy in AMPT

Events with certain v_2,v_3



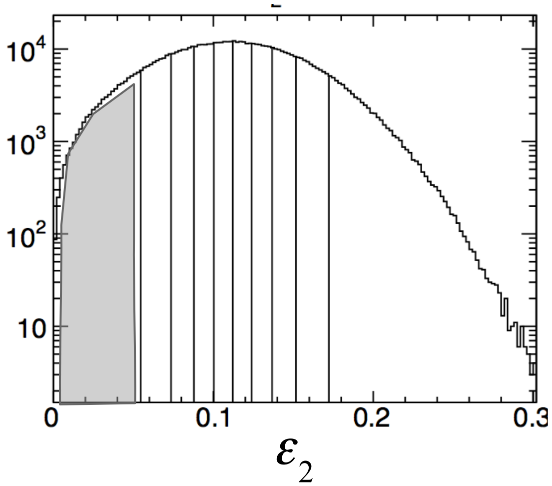
$$\vec{q}_n = \frac{1}{\Sigma w}(\Sigma w \cos n\phi_n, \Sigma w \sin n\phi_n),\ w = p_T$$



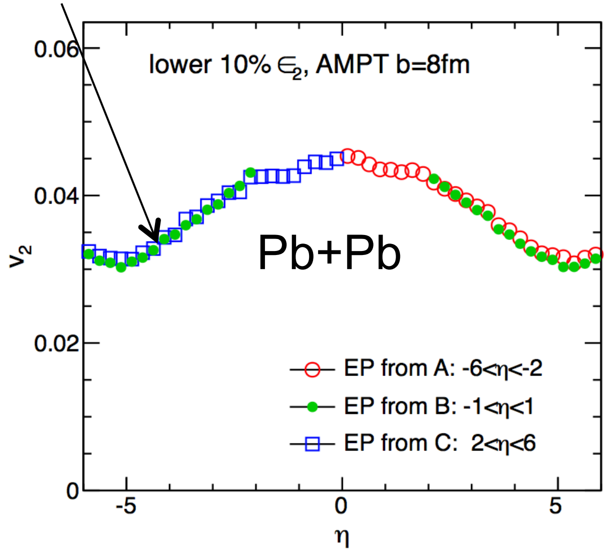


- Fixed impact parameter b=8fm
- Divide events into 10 equal bins
- $\langle\varepsilon_2\rangle$ vary by a factor of 3

$v_2(\eta)$: select on ε_2



Flow suppressed



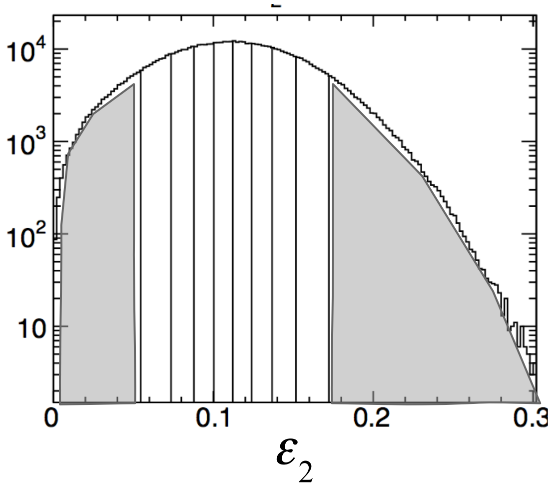
$v_2(\eta)|_{\eta>0}$ when EP in $-6<\eta<-2$

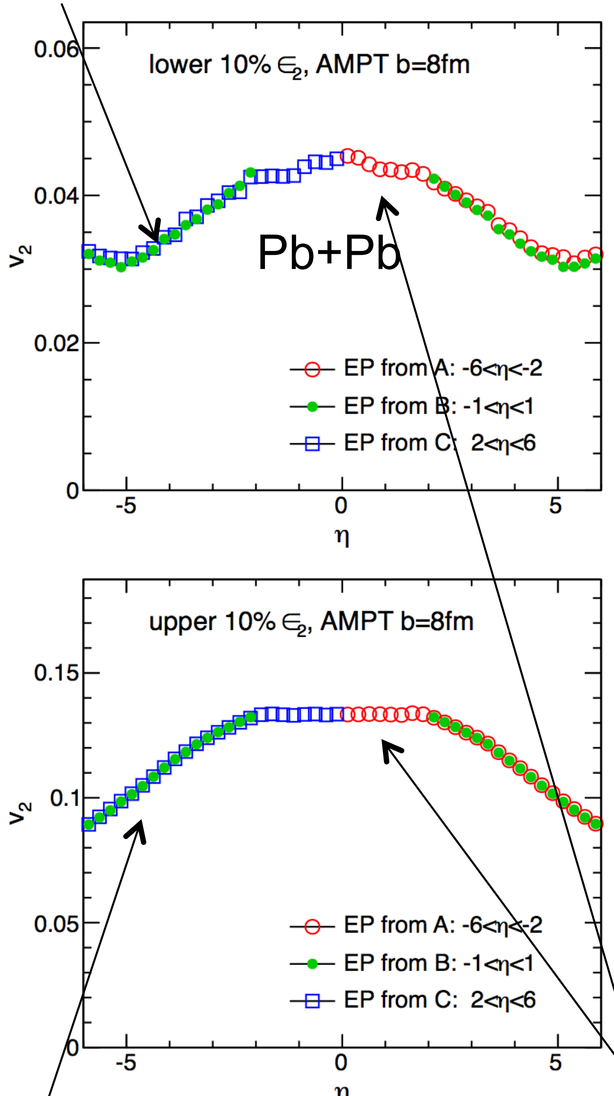
$v_2(\eta)|_{\eta<0}$ when EP in $2<\eta<6$

$v_2(\eta)|_{|\eta|>2}$ when EP in $|\eta|<1$

$v_2(\eta)$: select on ε_2

Flow suppressed





$v_2(\eta)|_{\eta>0}$ when EP in $-6<\eta<-2$

$v_2(\eta)|_{\eta<0}$ when EP in $2<\eta<6$

$v_2(\eta)|_{|\eta|>2}$ when EP in $|\eta|<1$

Flow enhanced

Symmetric distribution expected

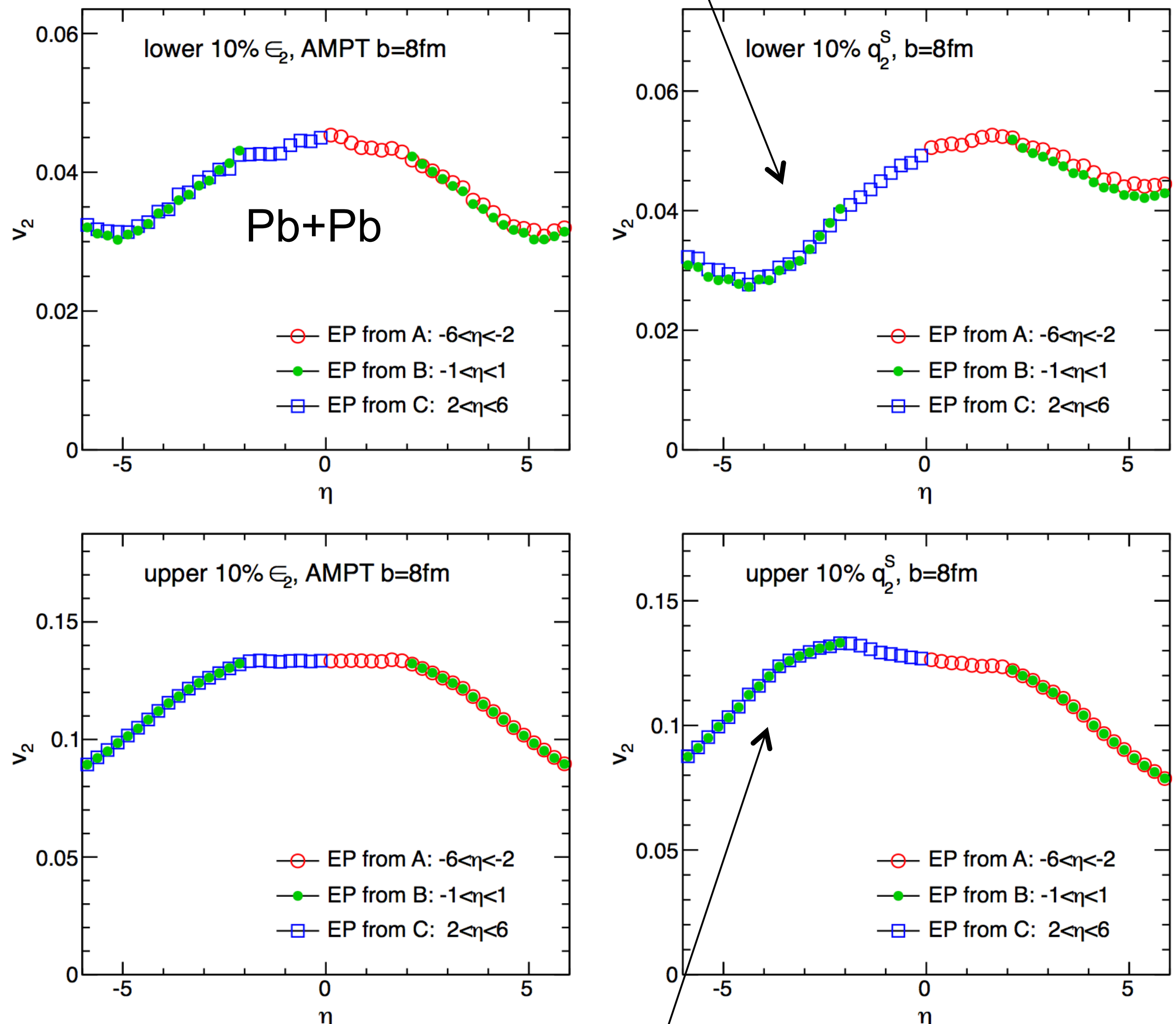
$v_2(\eta)$: compare with selection on q_2

Suppression of flow in the selection window

$v_2(\eta)|_{\eta>0}$ when EP in $-6<\eta<-2$

$v_2(\eta)|_{\eta<0}$ when EP in $2<\eta<6$

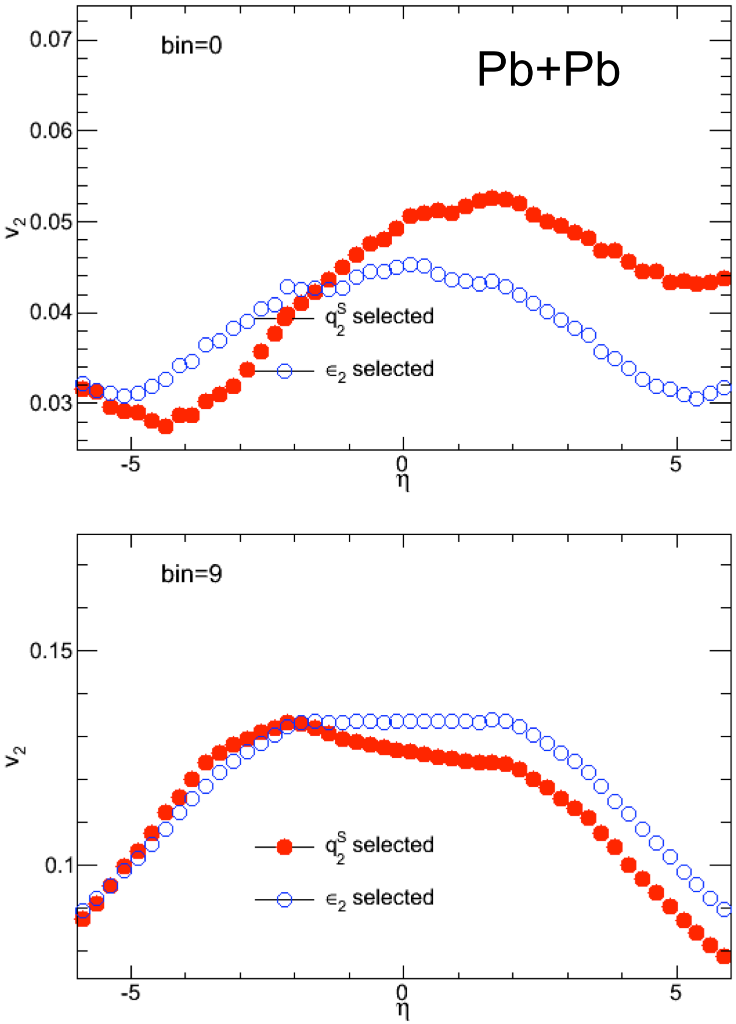
$v_2(\eta)|_{|\eta|>2}$ when EP in $|\eta|<1$

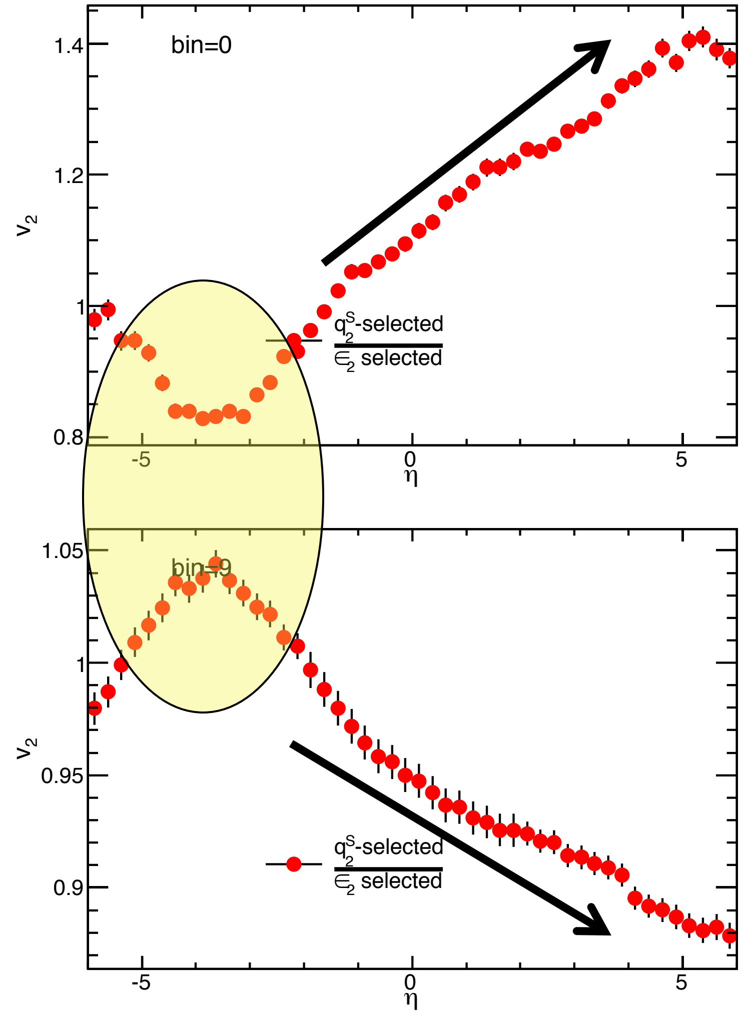


enhancement of flow in the selection window

What is the origin of $v_2(\eta)$ asymmetry?

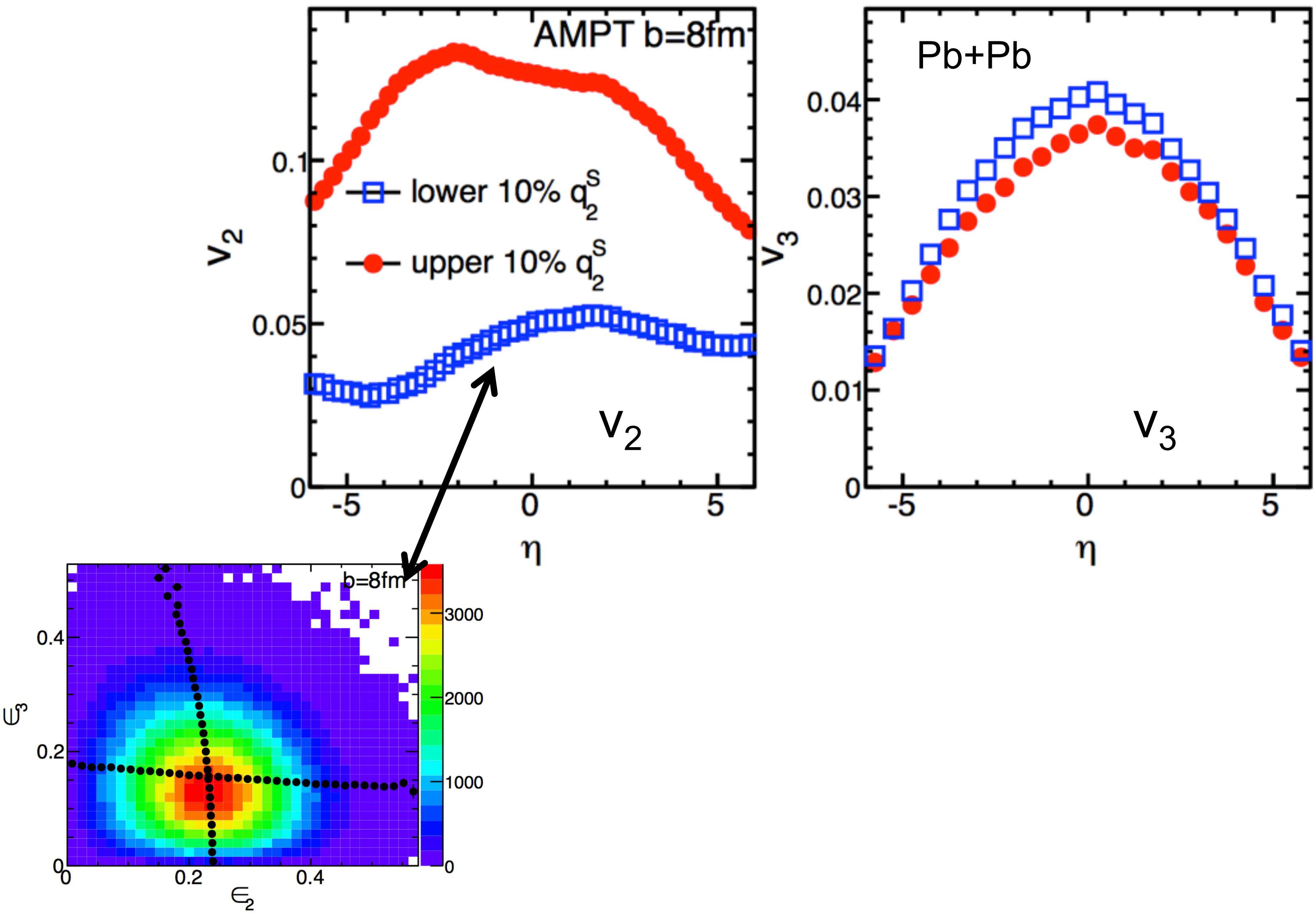
- Suppression/enhancement of flow in the selected window
- Decreasing response to flow selection outside the selection window





Dependence of $v_3(\eta)$ on q_2 in fixed centrality

- v_3 anti-correlated with v_2 → reflection of $p(\varepsilon_2,\varepsilon_3)$

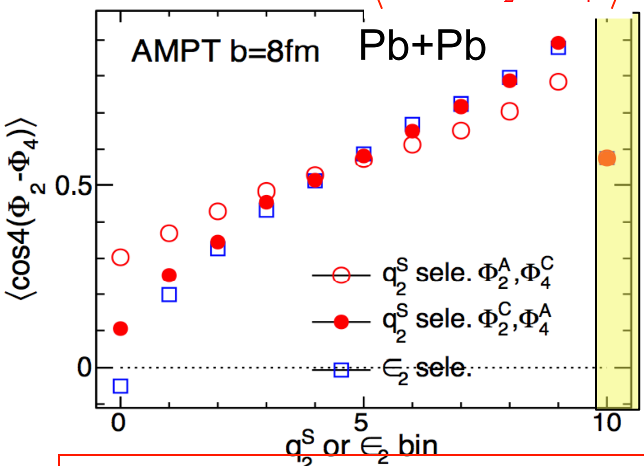


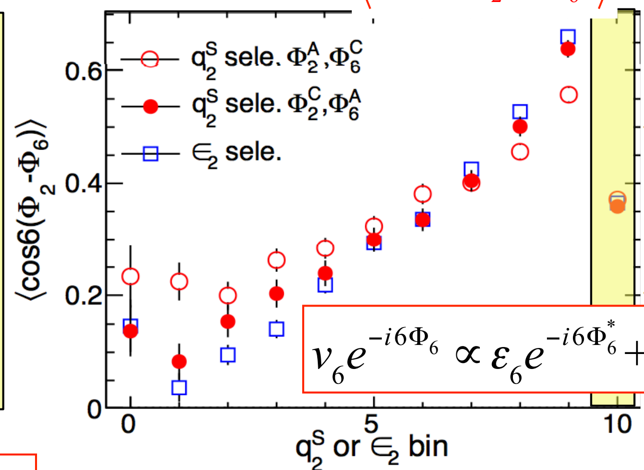
Two-Plane correlation selected on q_2

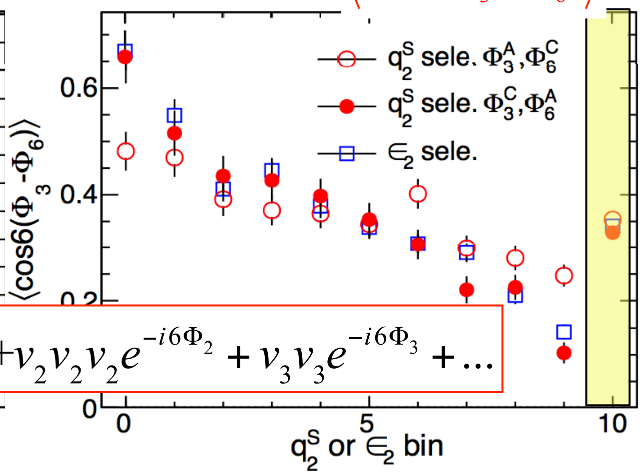
$-6<\eta<-2$ Φ^A_2, Φ^A_4 $2<\eta<6$ Φ^C_2, Φ^C_4

Two types: $4(\Phi_2^A - \Phi_4^C)$ $4(\Phi_2^C - \Phi_4^A)$

$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$ $\langle \cos 6(\Phi_2 - \Phi_6) \rangle$ $\langle \cos 6(\Phi_3 - \Phi_6) \rangle$







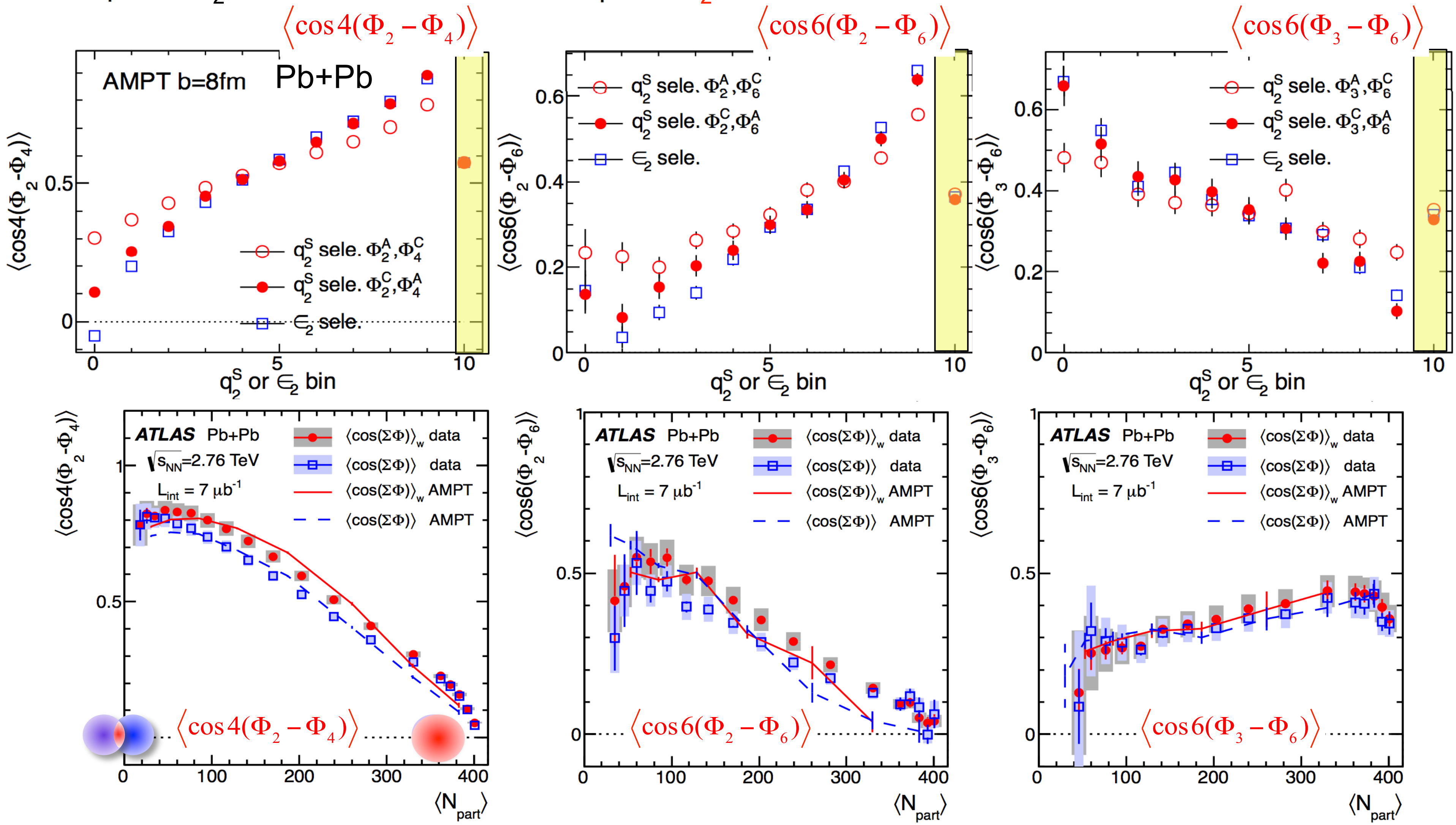
$$v_6 e^{-i6\Phi_6} \propto \varepsilon_6 e^{-i6\Phi_6^*} + v_2 v_2 v_2 e^{-i6\Phi_2} + v_3 v_3 e^{-i6\Phi_3} + \ldots$$

$$v_4 e^{-i4\Phi_4} \propto \varepsilon_4 e^{-i4\Phi_4^*} + c v_2 v_2 e^{-i4\Phi_2} + \ldots$$

Two-Plane correlation selected on q_2

Two types: $4(\Phi_2^A - \Phi_4^C)$

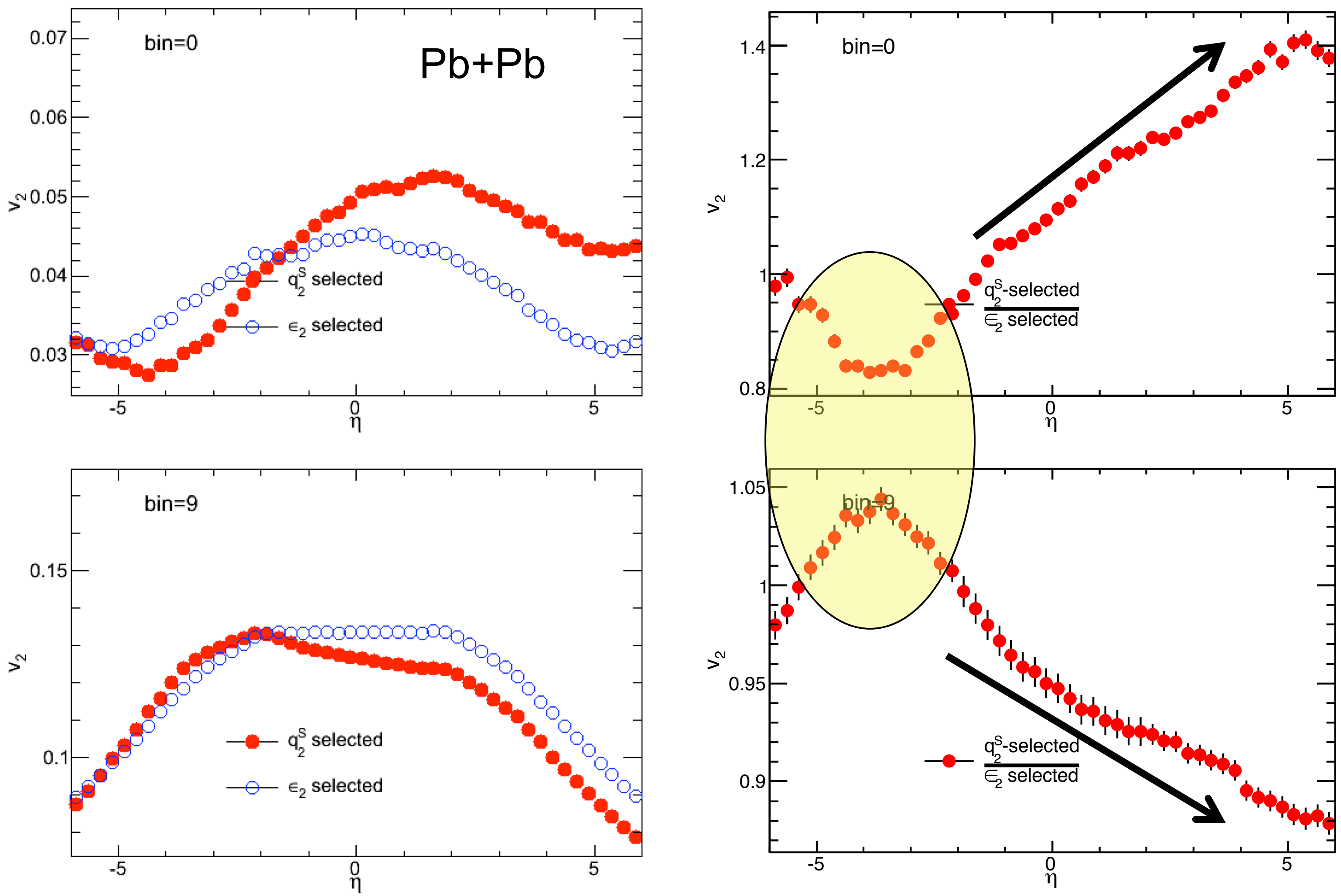
$4(\Phi_2^C - \Phi_4^A)$



The full centrality dependence seen within one centrality bin!

What is the origin of $v_2(\eta)$ asymmetry?

- Suppression/enhancement of flow in the selected window
- Decreasing response to flow selection outside the selection window

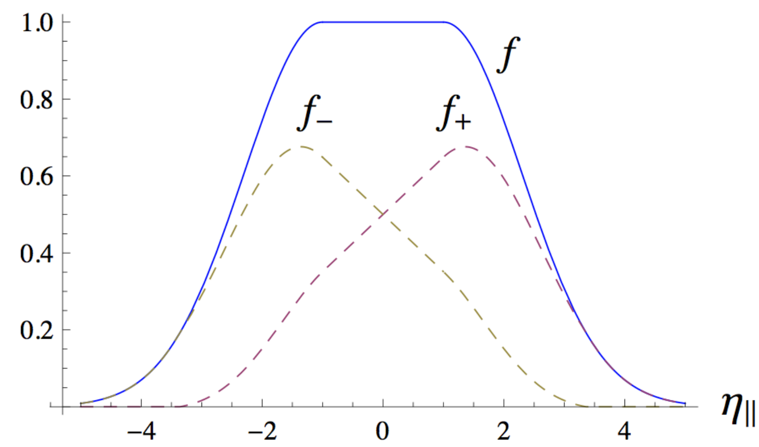


Longitudinal particle production

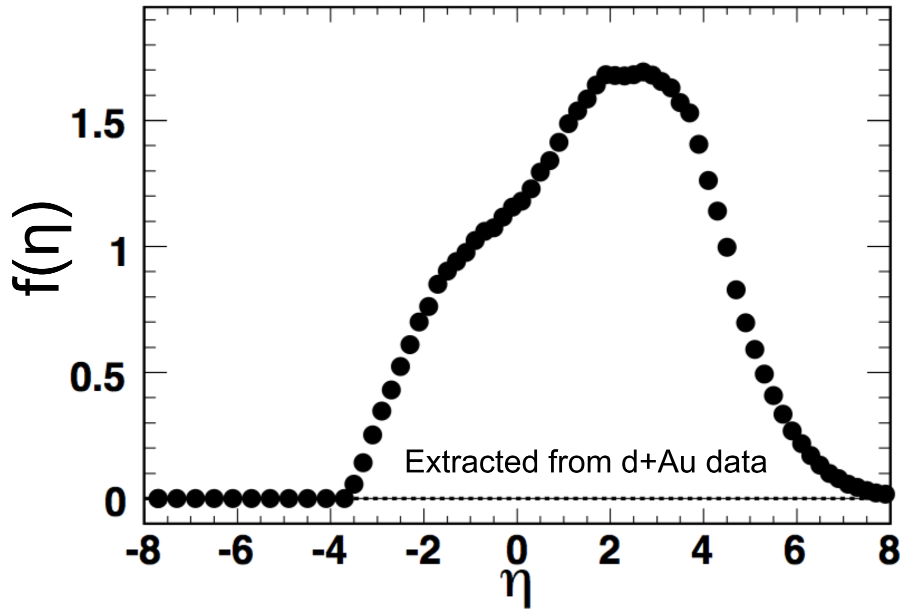
wounded nucleon model Bialas, Bzdak, Zalewski, Wozniak…. STAR/PHOBOS

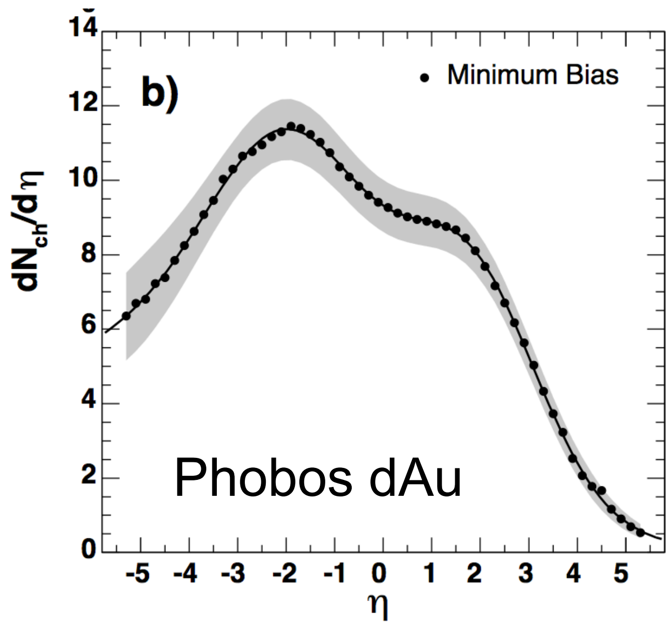
$$dN/d\eta \;\propto\; f^{\mathrm{F}}(\eta)N^{\mathrm{F}}_{\mathrm{part}} + f^{\mathrm{B}}(\eta)N^{\mathrm{B}}_{\mathrm{part}}$$

- Assumes that after the collision of two nuclei, the secondary particles are produced by independent fragmentation of wounded nucleons



Emission function of one wounded nucleon





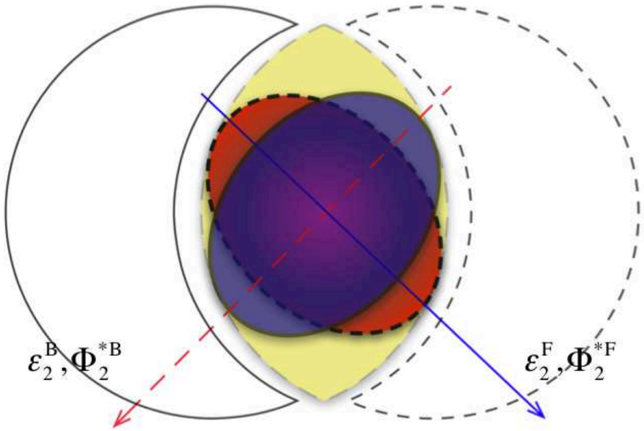
Forward/backward eccentricity fluctuations

- Energy density profile in xy naturally interpolates between two limits

P.Huo, JJ 1403.6077

$$\rho(x,y,\eta) = f^{\mathrm{F}}(\eta)\rho_{\mathrm{F}}(x,y) + f^{\mathrm{B}}(\eta)\rho_{\mathrm{B}}(x,y)$$

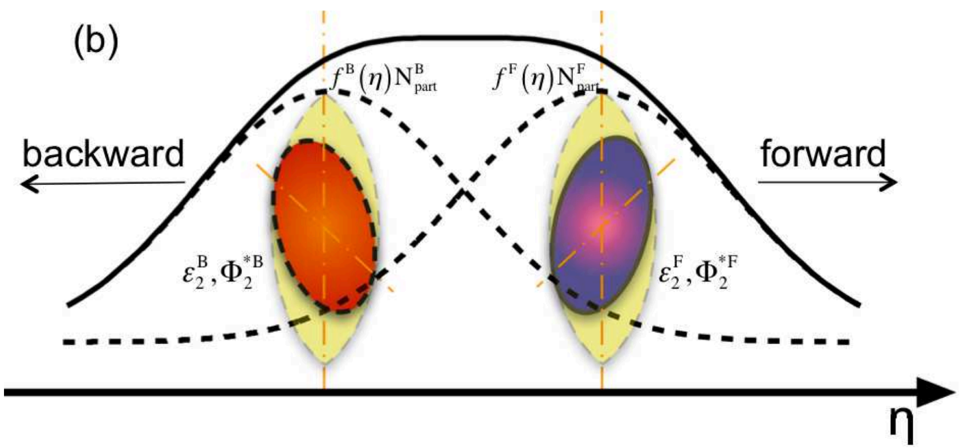
- Fluctuations of participants in the two nuclei are not the same



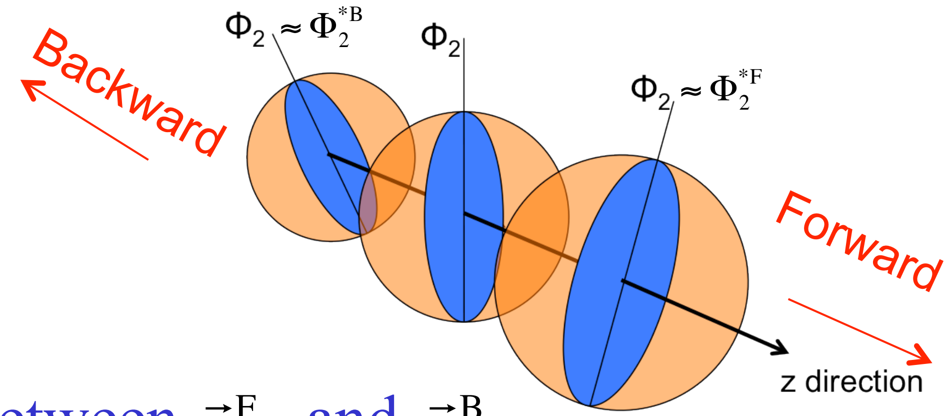
$$\varepsilon_m^{\mathrm{F}},\Phi_m^{*\mathrm{F}} \quad \varepsilon_m^{\mathrm{B}},\Phi_m^{*\mathrm{B}} \quad \varepsilon_m,\Phi_m^{*}$$

$$N_{\mathrm{part}}^{\mathrm{F}},N_{\mathrm{part}}^{\mathrm{B}},N_{\mathrm{part}}$$

- So the forward event shape more correlated with $\varepsilon_m^{\mathrm{F}},\Phi_m^{*\mathrm{F}}$ and vice versa



Consequence……



$$\rho(x,y,\eta) = f^{\rm F}(\eta)\rho_{\rm F}(x,y) + f^{\rm B}(\eta)\rho_{\rm B}(x,y)$$
$$dN/d\eta \propto f^{\rm F}(\eta)N_{\rm part}^{\rm F} + f^{\rm B}(\eta)N_{\rm part}^{\rm B} .$$

- Eccentricity vector interpolates between $\vec{\varepsilon}_n^{\,F}$ and $\vec{\varepsilon}_n^{\,B}$

$$\vec{\epsilon}_n^{\,\rm tot}(\eta) \approx \alpha(\eta)\vec{\epsilon}_n^{\,\rm F} + (1-\alpha(\eta))\vec{\epsilon}_n^{\,\rm B} \equiv \epsilon_n^{\rm tot}(\eta)e^{in\Phi_n^{*\rm tot}(\eta)}$$

$$\alpha(\eta) = \frac{f^{\rm F}(\eta)N_{\rm part}^{\rm F}\langle r^n\rangle^{\rm F}}{f^{\rm F}(\eta)N_{\rm part}^{\rm F}\langle r^n\rangle^{\rm F} + f^{\rm B}(\eta)N_{\rm part}^{\rm B}\langle r^n\rangle^{\rm B}}$$

  - Equal to $\vec{\varepsilon}_n$ only at $\eta=0$

- Assuming hydro-response to be linear then (good for v2 and v3)

$$\vec{v}_n(\eta) \approx c_n(\eta)\left[\alpha(\eta)\vec{\epsilon}_n^{\,\rm F} + (1-\alpha(\eta))\vec{\epsilon}_n^{\,\rm B}\right]$$

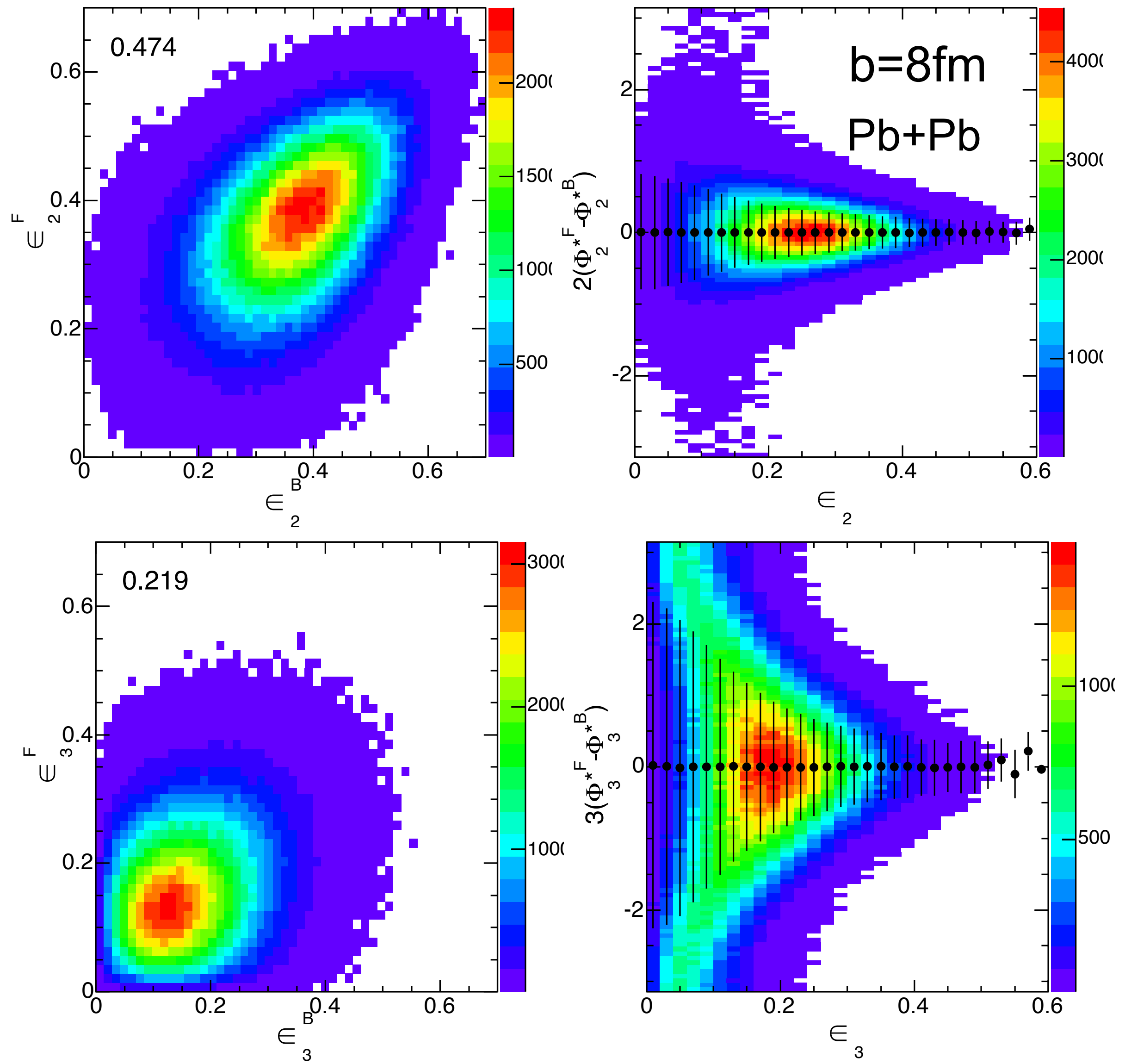
FB eccentricity fluctuations from Glauber

- Significant FB asymmetry:

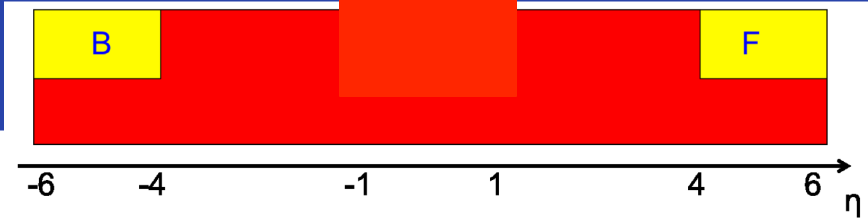
$$\varepsilon_n^{F} \neq \varepsilon_n^{B}$$

- Significant twist:

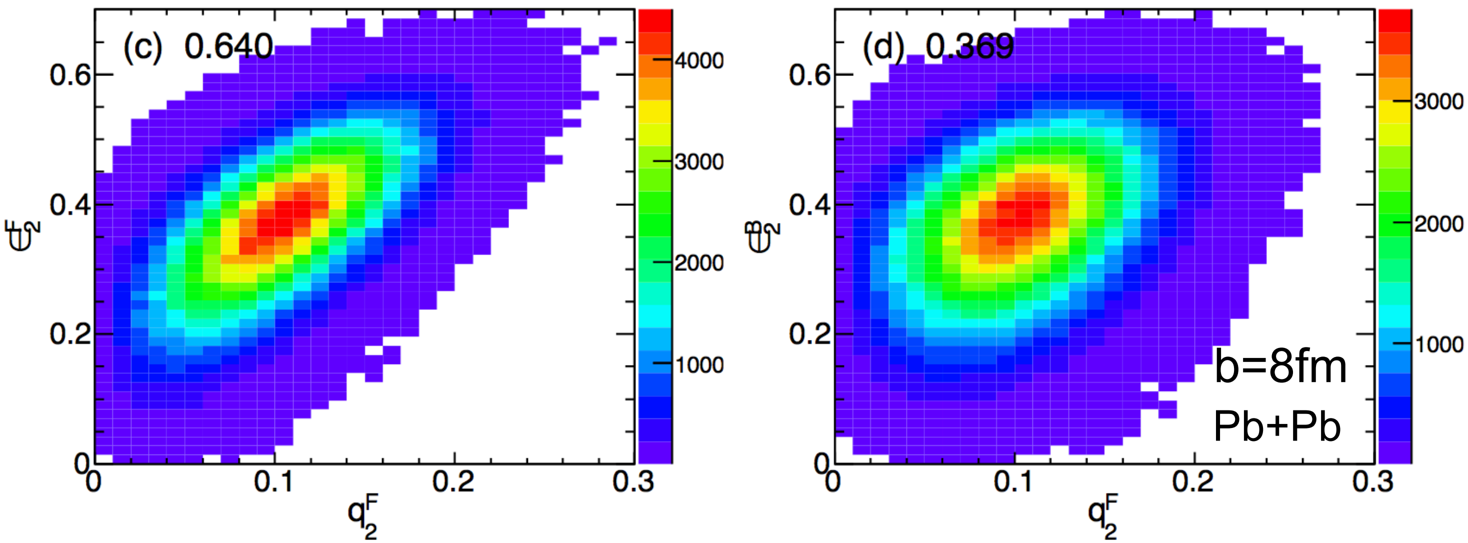
$$\Phi_n^{*F} \neq \Phi_n^{*B}$$



What AMPT tell us?

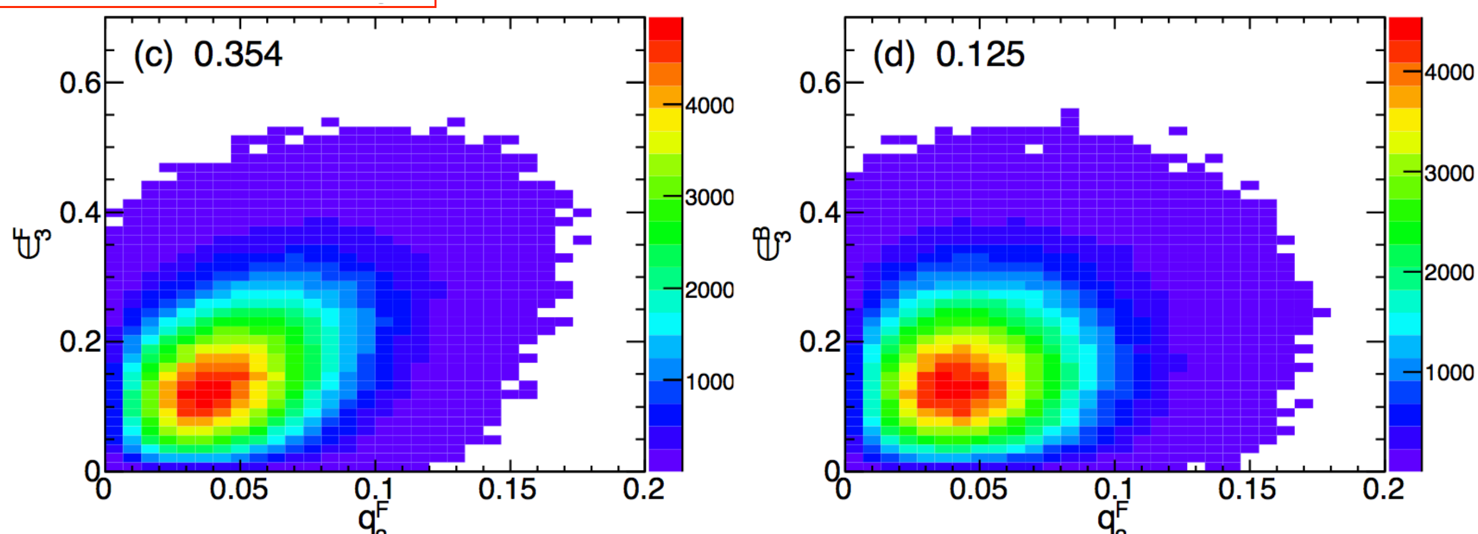


ε_2^F more correlated with q_2^F than q_2^B

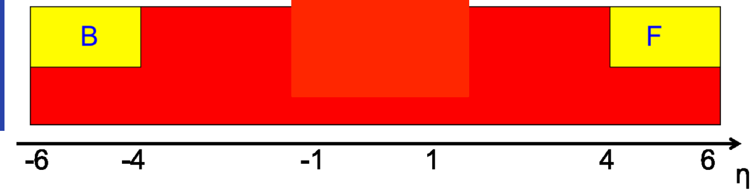


ε_3^F more correlated with q_3^F than q_3^B

FB asymmetry survives



What AMPT tell us?



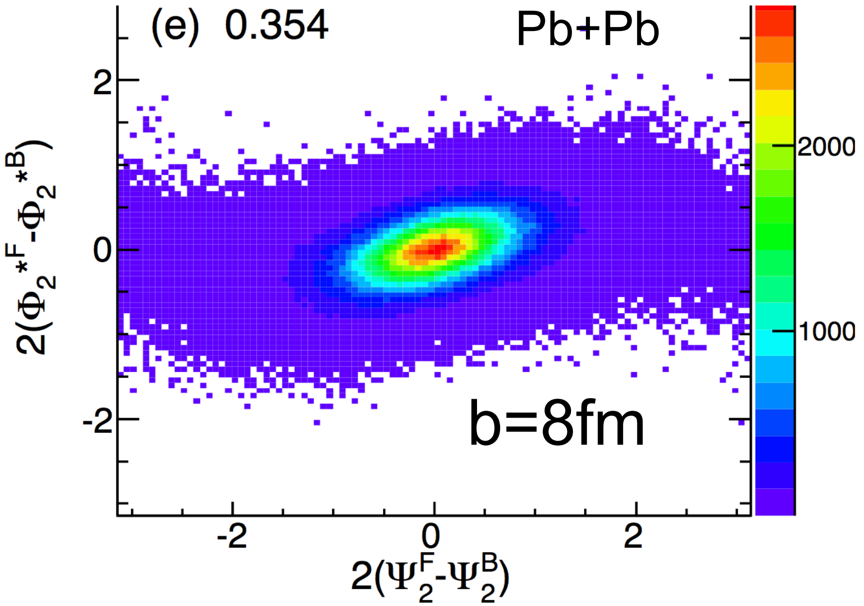
- Twist in initial geometry appears as twist in the final state flow
  - Participant plane angles:

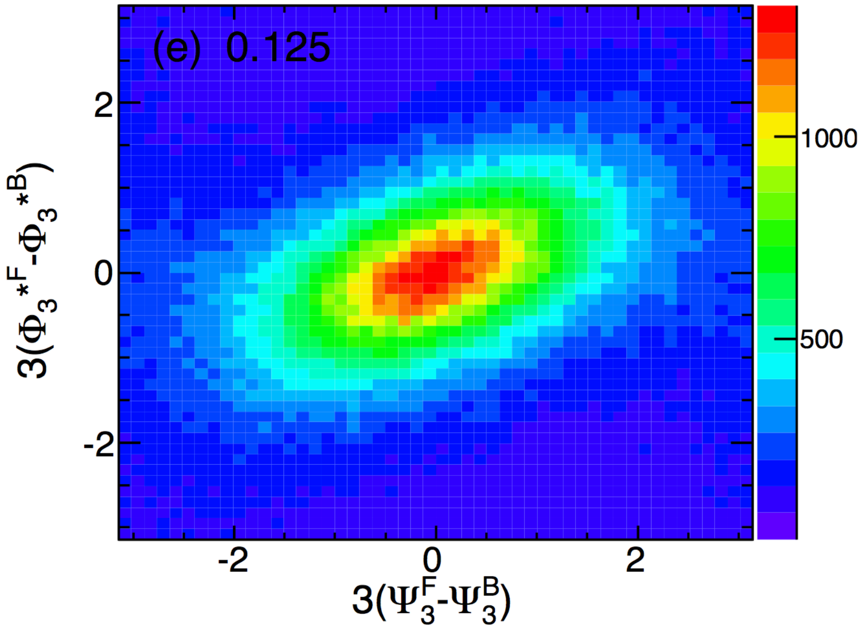
$$\Phi_n^{*F} \quad \Phi_n^{*B}$$

  - Final state event-plane angles

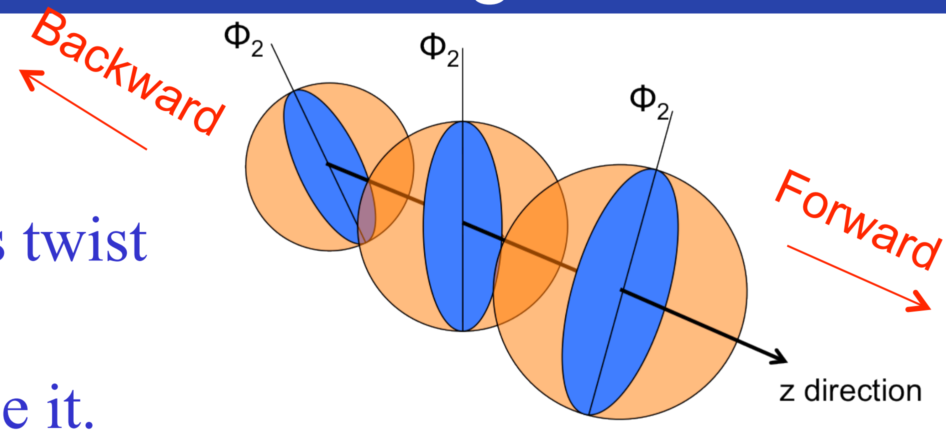
$$\Psi_n^{F} \quad \Psi_n^{B}$$

Initial twist survives





How to measure the twist angle



- Non-vanishing sine term if there is twist
  - Used to extract the twist angle in η.
- Need event selection in order to see it.

$$\Theta_n \in \{\Phi_n^{*F}, \Phi_n^{*B}, \Phi_n^{*}\}$$

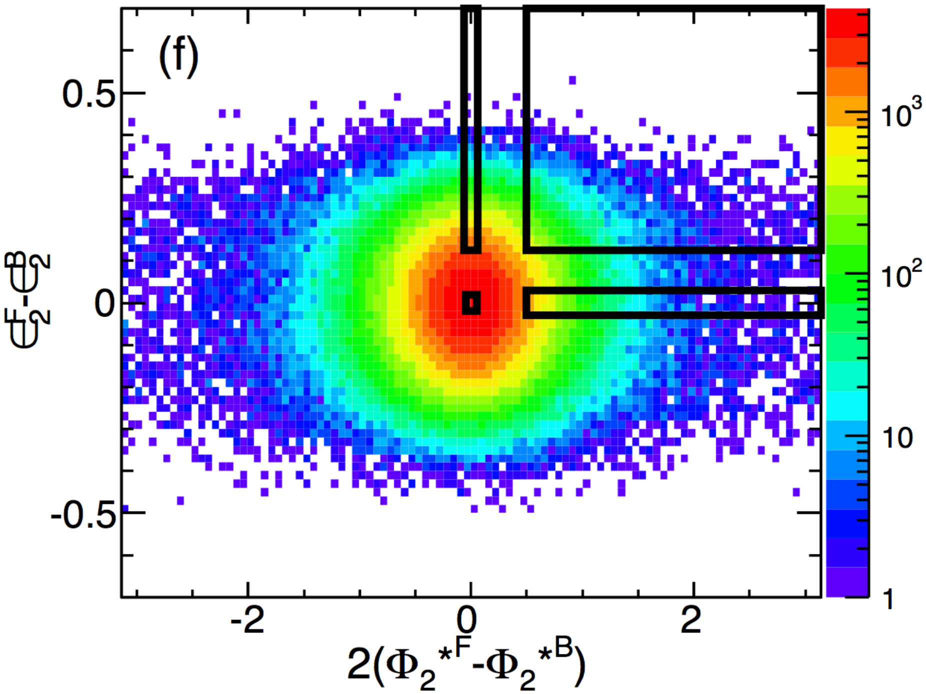
$$v_n^{c}(\eta) = \langle \cos n\left(\phi(\eta) - \Theta_n\right)\rangle$$

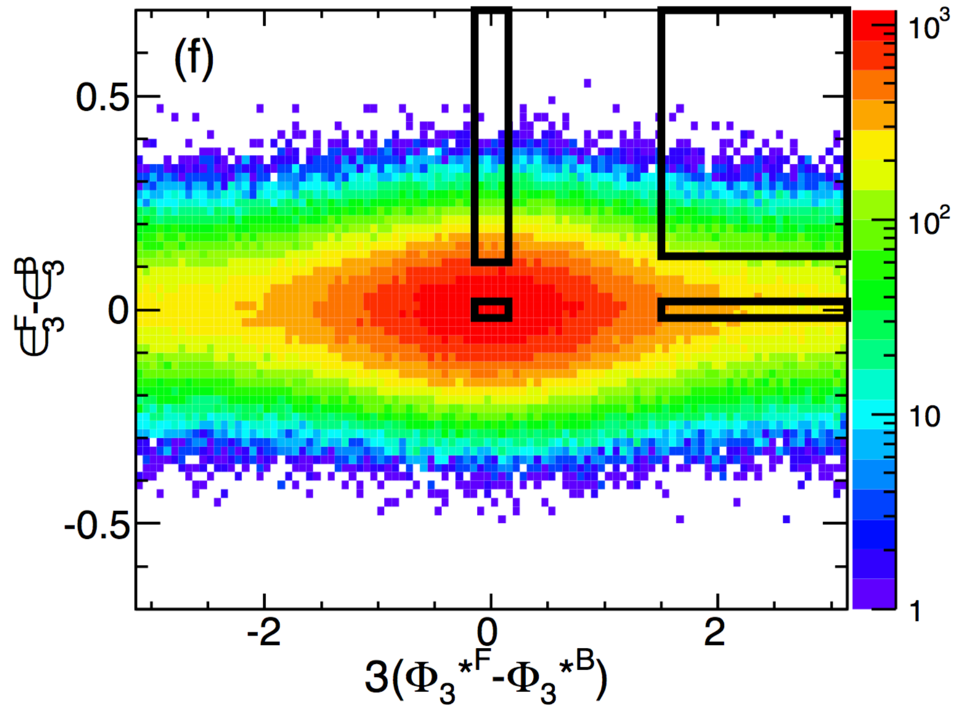
$$v_n^{s}(\eta) = \langle \sin n\left(\phi(\eta) - \Theta_n\right)\rangle$$

$$v_n(\eta) = \sqrt{(v_n^{c}(\eta))^2 + (v_n^{s}(\eta))^2}$$

$$\tan\left[n\Delta\Phi_n^{\mathrm{rot}}(\eta)\right] = \frac{\langle \sin n\left(\phi(\eta) - \Theta_n\right)\rangle}{\langle \cos n\left(\phi(\eta) - \Theta_n\right)\rangle} = \frac{v_n^{s}(\eta)}{v_n^{c}(\eta)}$$

Select initial event-shape





	Cuts	$\langle \epsilon_2^F \rangle$	$\langle \epsilon_2^B \rangle$
type1	$\lvert 2\Delta\Phi_2^{*FB} \rvert < 0.05, \lvert \Delta\epsilon_2^{FB} \rvert < 0.02$	0.4	
type2	$\lvert 2\Delta\Phi_2^{*FB} \rvert < 0.05, \Delta\epsilon_2^{FB} > 0.125$	0.456	0.282
type3	$2\Delta\Phi_2^{*FB} > 0.5, \lvert \Delta\epsilon_2^{FB} \rvert < 0.03$	0.314	
type4	$2\Delta\Phi_2^{*FB} > 0.5, \Delta\epsilon_2^{FB} > 0.125$	0.386	0.197

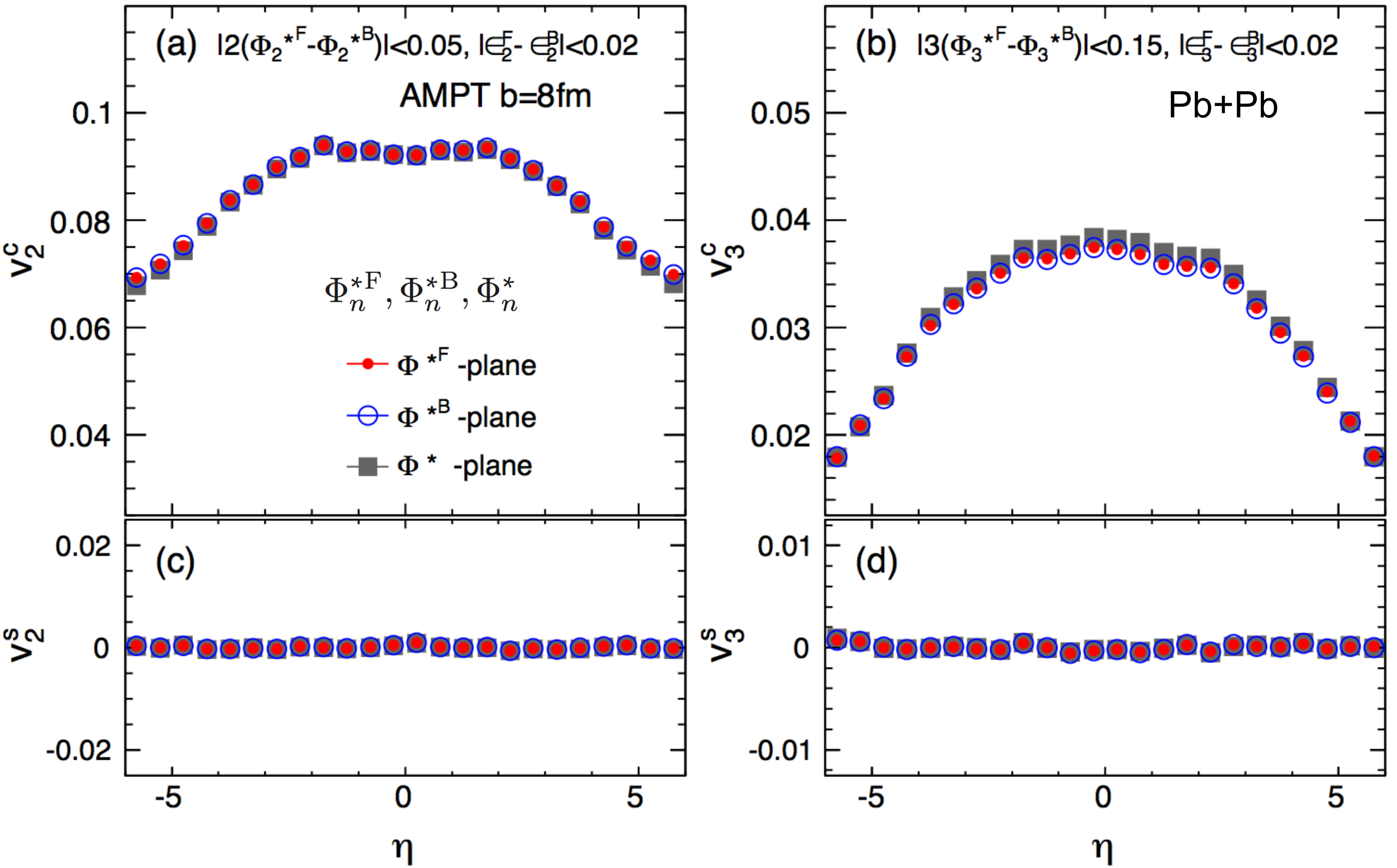
	Cuts	$\langle \epsilon_3^B \rangle$	$\langle \epsilon_3^B \rangle$
type1	$\lvert 3\Delta\Phi_3^{*FB} \rvert < 0.15, \lvert \Delta\epsilon_3^{FB} \rvert < 0.02$	0.182	
type2	$\lvert 3\Delta\Phi_3^{*FB} \rvert < 0.15, \Delta\epsilon_3^{FB} > 0.125$	0.293	0.126
type3	$3\Delta\Phi_3^{*FB} > 1.5, \lvert \Delta\epsilon_3^{FB} \rvert < 0.02$	0.112	
type4	$3\Delta\Phi_3^{*FB} > 1.5, \Delta\epsilon_3^{FB} > 0.125$	0.246	0.0686

Select events with different asymmetry and twist at INITIAL STATE

And then measure relative to the participant planes

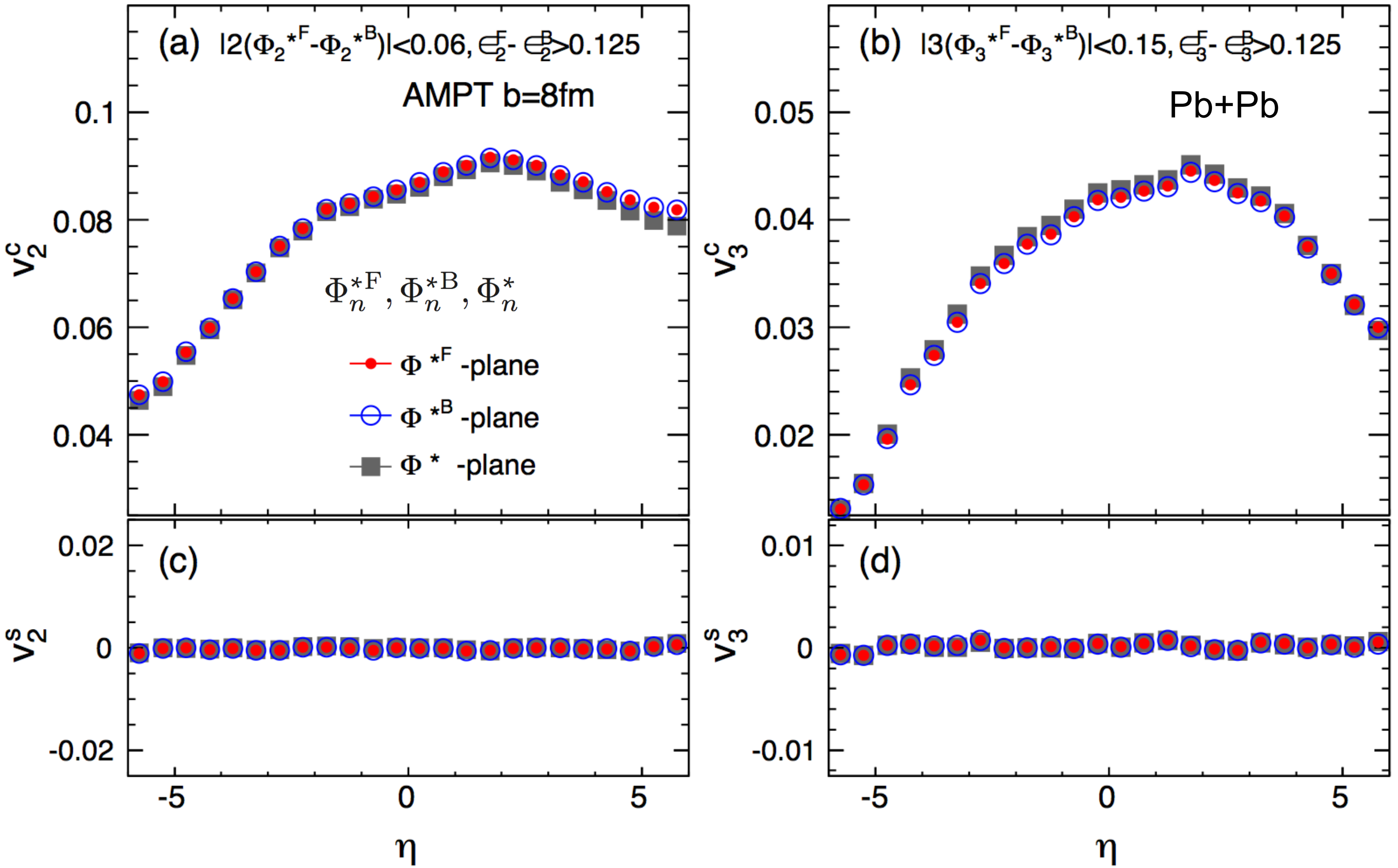
Type-1

$$\Phi_n^{*F} \approx \Phi_n^{*B} \qquad \varepsilon_n^F \approx \varepsilon_n^B$$



Type-2

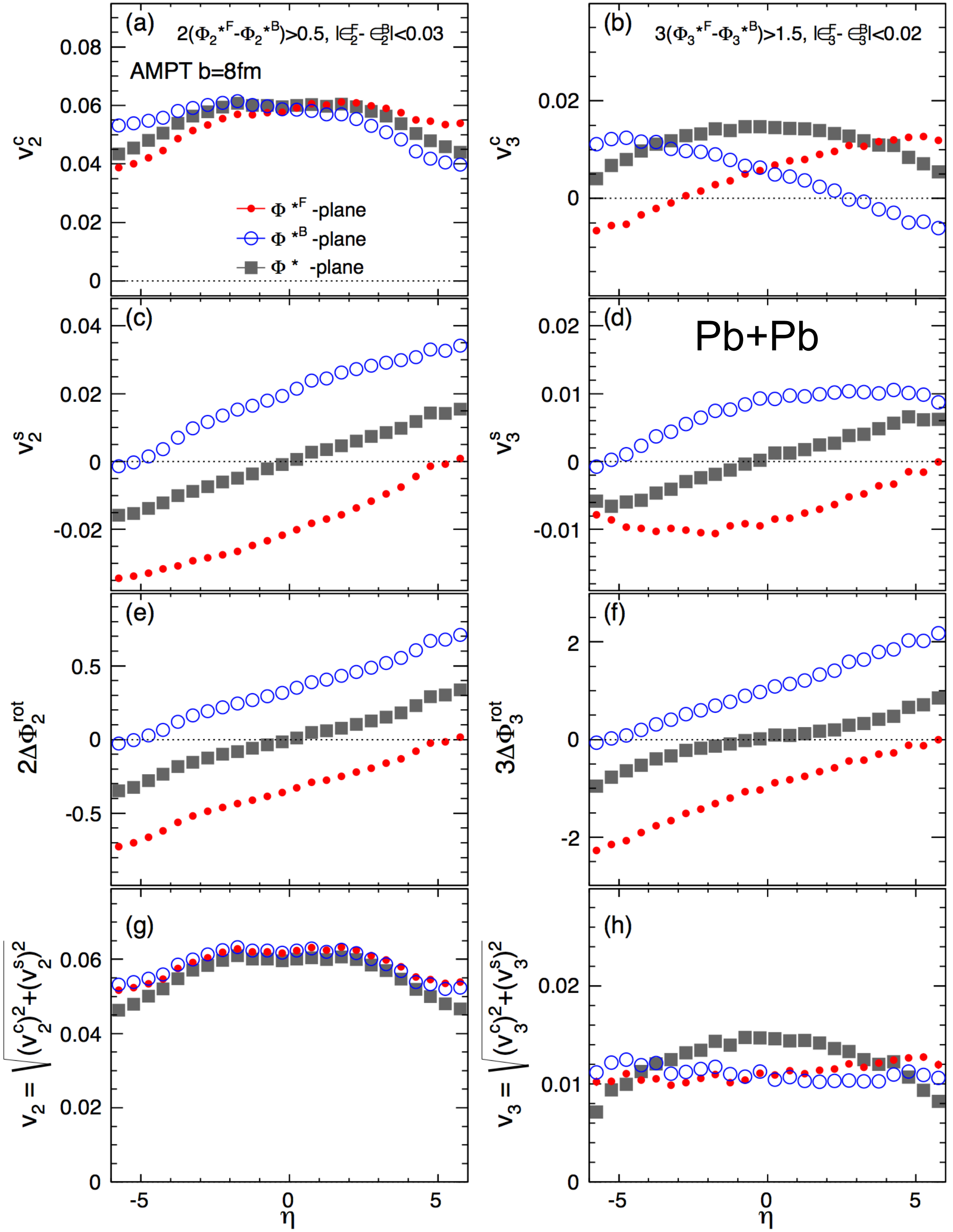
$$\Phi_n^{*F} \approx \Phi_n^{*B} \qquad \varepsilon_n^F > \varepsilon_n^B$$



Type-3

$$\Phi_n^{*F} > \Phi_n^{*B} \qquad \varepsilon_n^F \approx \varepsilon_n^B$$

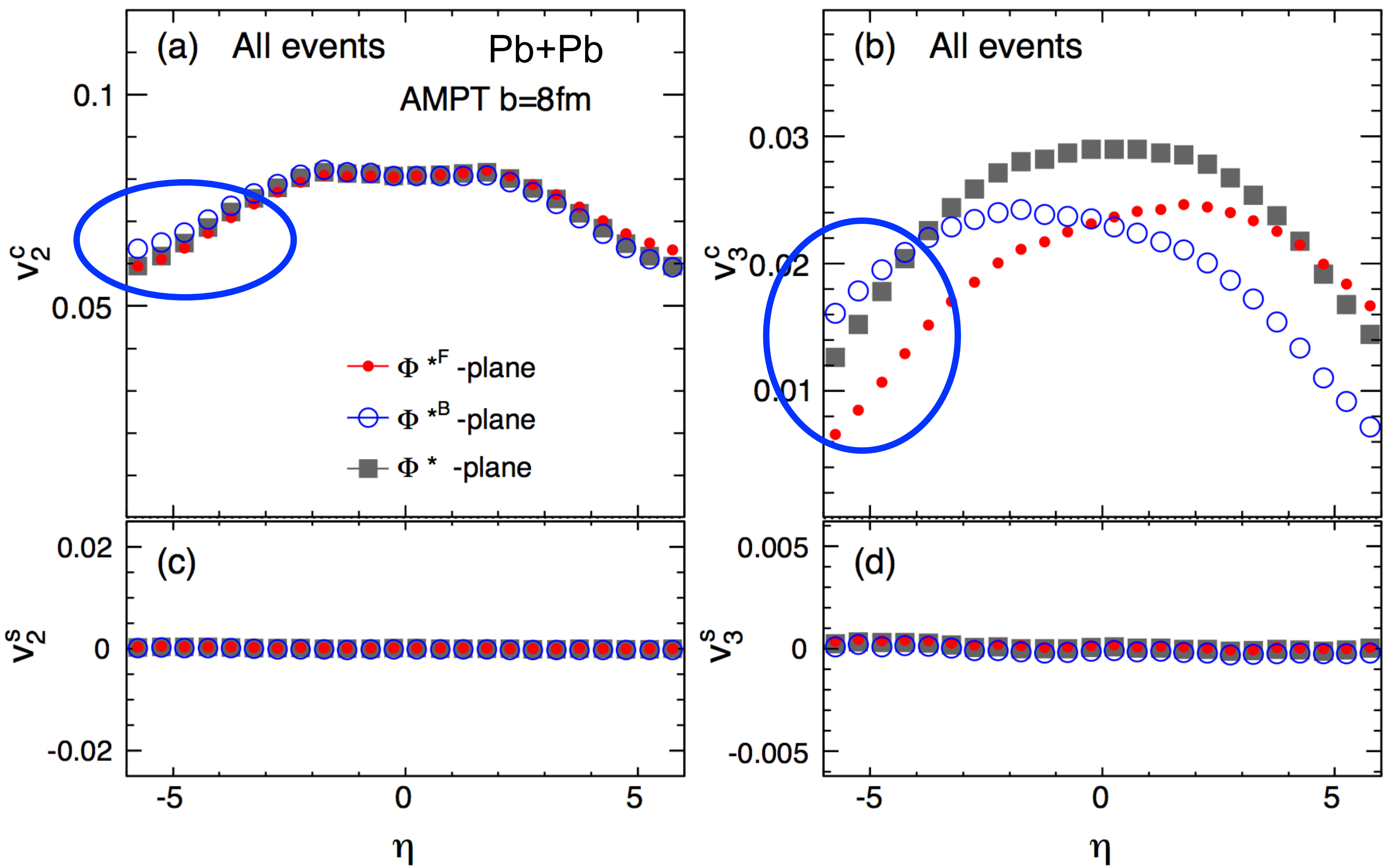
P.Huo, JJ 1402.6680, 1403.6077



- Residual difference indicate other EP-decorrelation sources orthogonal to the event-shape selection

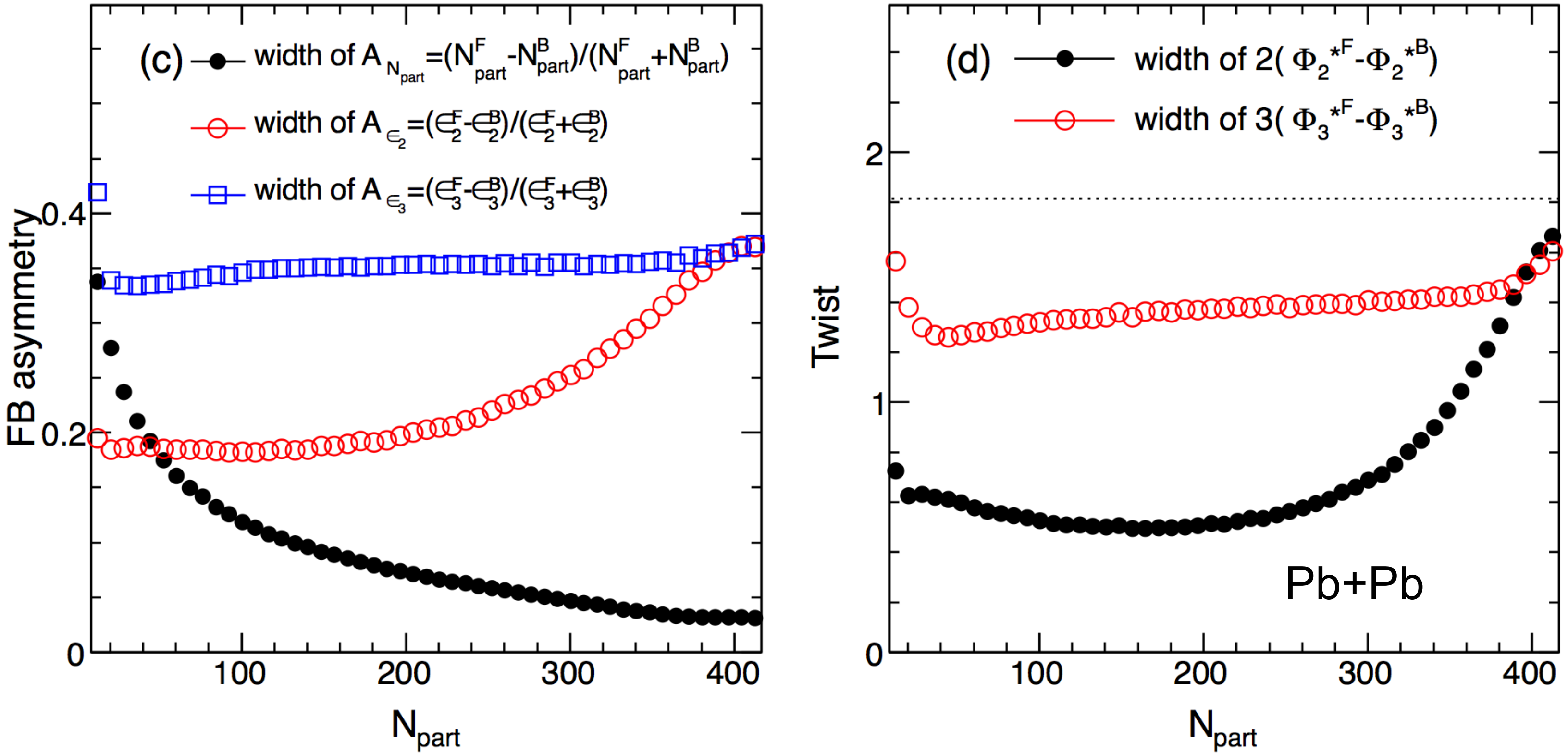
Results for inclusive events

- Results depend on which PP used, clearly suggest the influence of decorrelation effects.



Implications

- System not boost-invariant EbyE not only for dN/dη, but also flow
- Longitudinal decorrelation effects breaks the factorization, despite being initial state effects. $V_{n\Delta}(\eta_1,\eta_2) \neq v_n(\eta_1)v_n(\eta_2)$
- Decorrelation effects much stronger in p+A and Cu+Au system



Summary

- Event-shape fluctuations are much richer than what is currently studied
  - Strong fluctuation/correlation between v_n and Φ_ns within given centrality

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

  - Rich patterns forward/backward EbyE flow fluctuations:

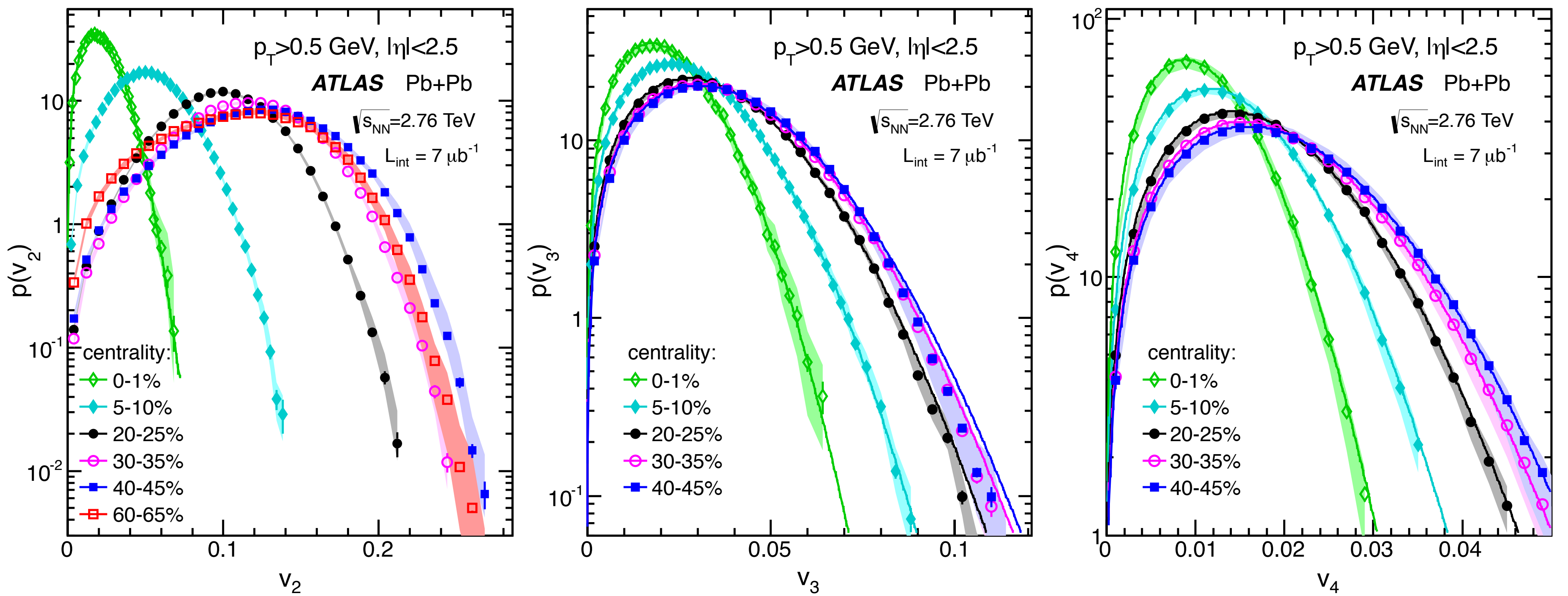
$$\vec{v}_n(\eta) \approx c_n(\eta)\left[\alpha(\eta)\vec{\epsilon}_n^{\rm F} + (1-\alpha(\eta))\vec{\epsilon}_n^{\rm B}\right]$$

Event-shape selection and event twist techniques

- These initial state fluctuations are very large (comparable to the entire centrality dependence) and they are expected to survive collective expansion. We demonstrated this via the AMPT model
- New avenue to study initial state fluctuations, particle production and collective expansion dynamics
- More detailed study via EbyE hydro are needed.

Backup

$p(v_n)$ distributions



Probability distributions for v_2, v_3 and v_4 in many centrality ranges

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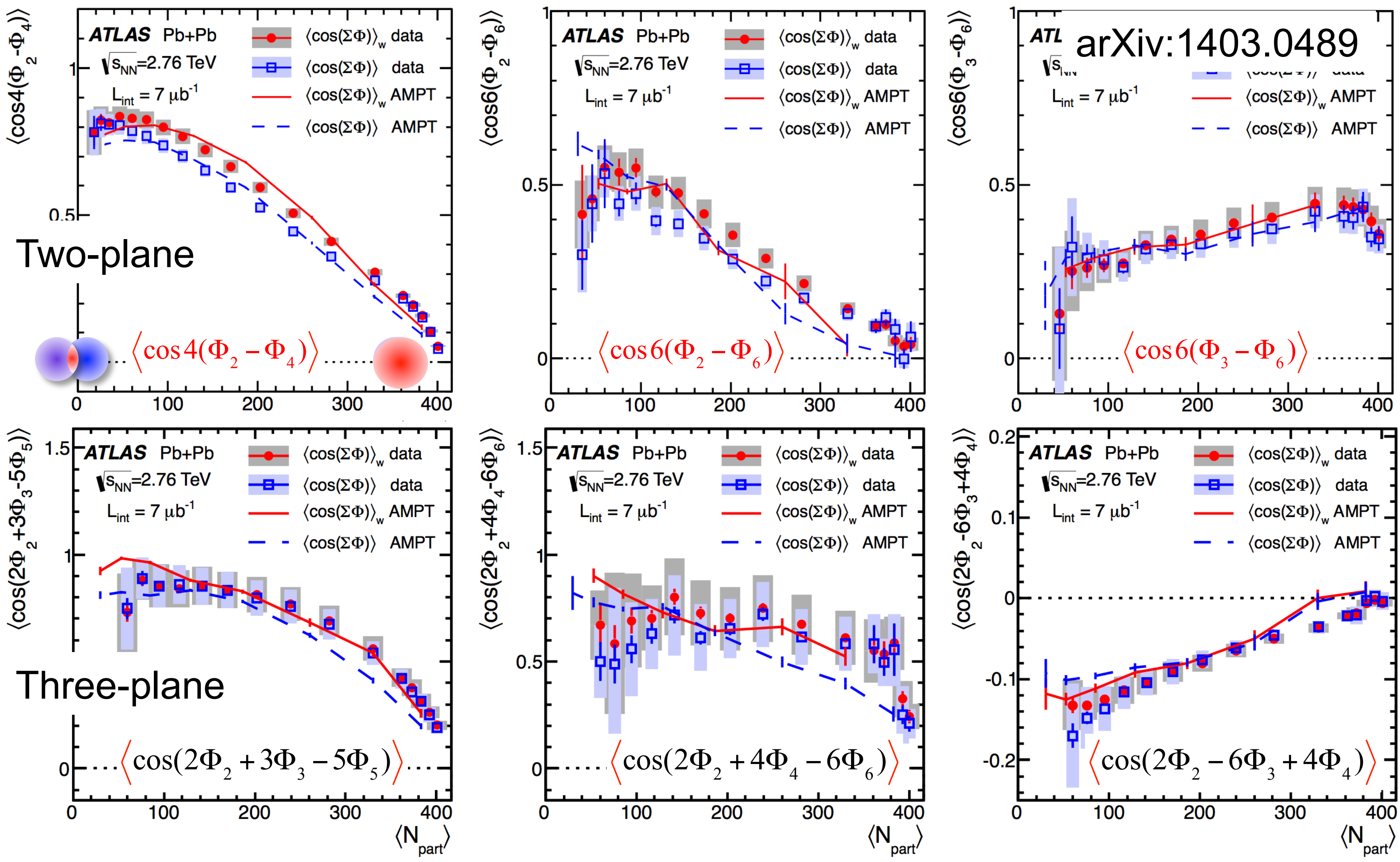
Event-plane correlations

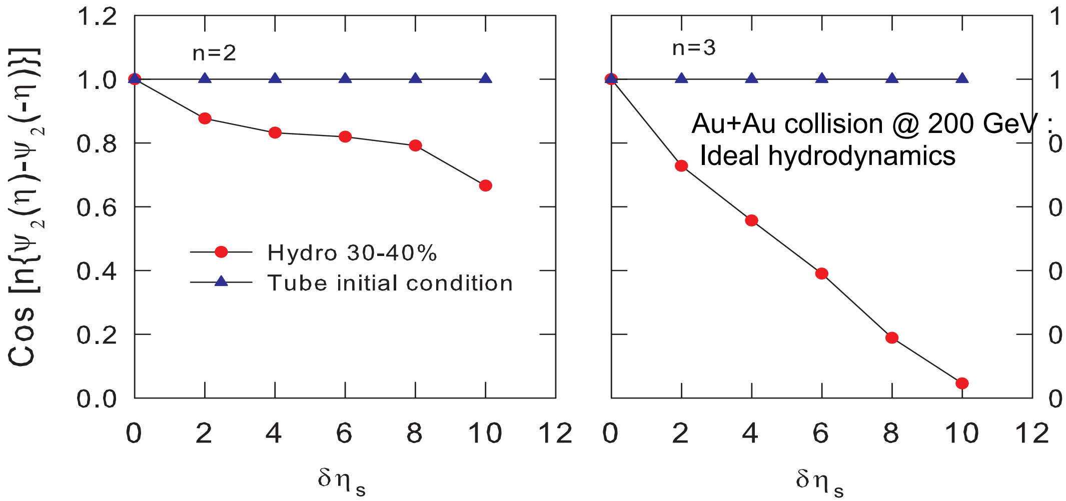
- Event-plane correlators with rich centrality dependence



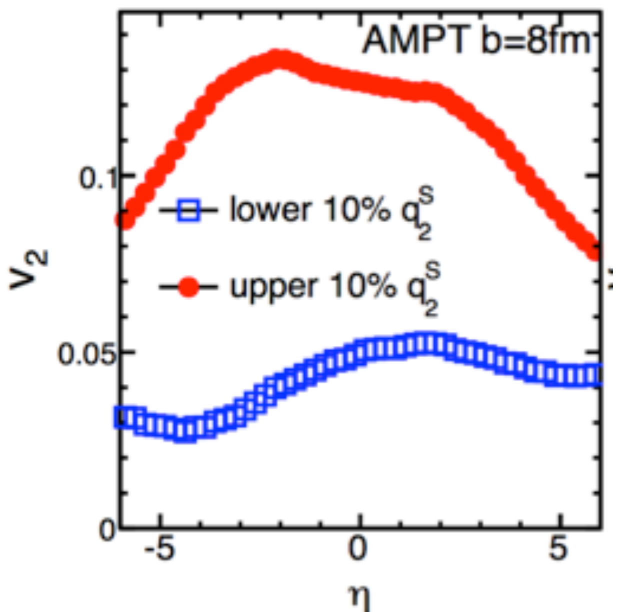
Rapidity fluctuations of flow

- Previous study suggest EP correlation weakens with larger η gap in AMPT

X.N. Wang.

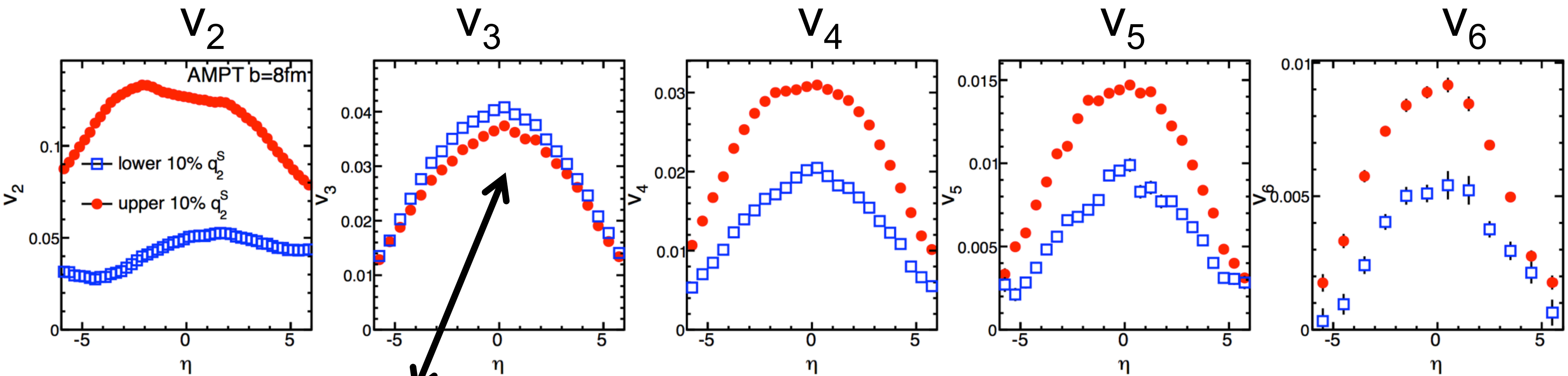


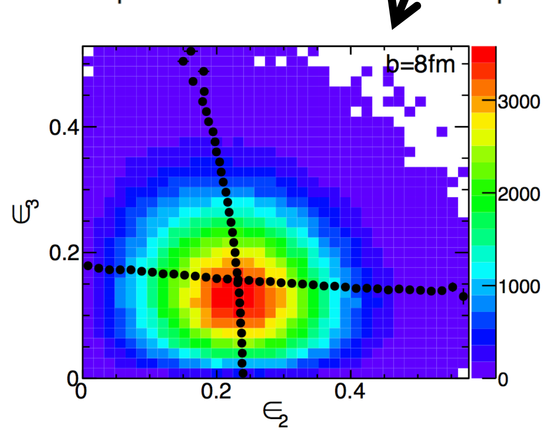
- $v_n(\eta)$ for events selected on ε_n or q_n show direct evidence for decorrelation.



$v_n(\eta)$ shape for all n: select on q_2

- Anti-correlation with v_3 → reflection of $p(\varepsilon_2,\varepsilon_3)$
- v_4, v_5, v_6 correlates with v_2 selection, direct measure of non-linear effects!!

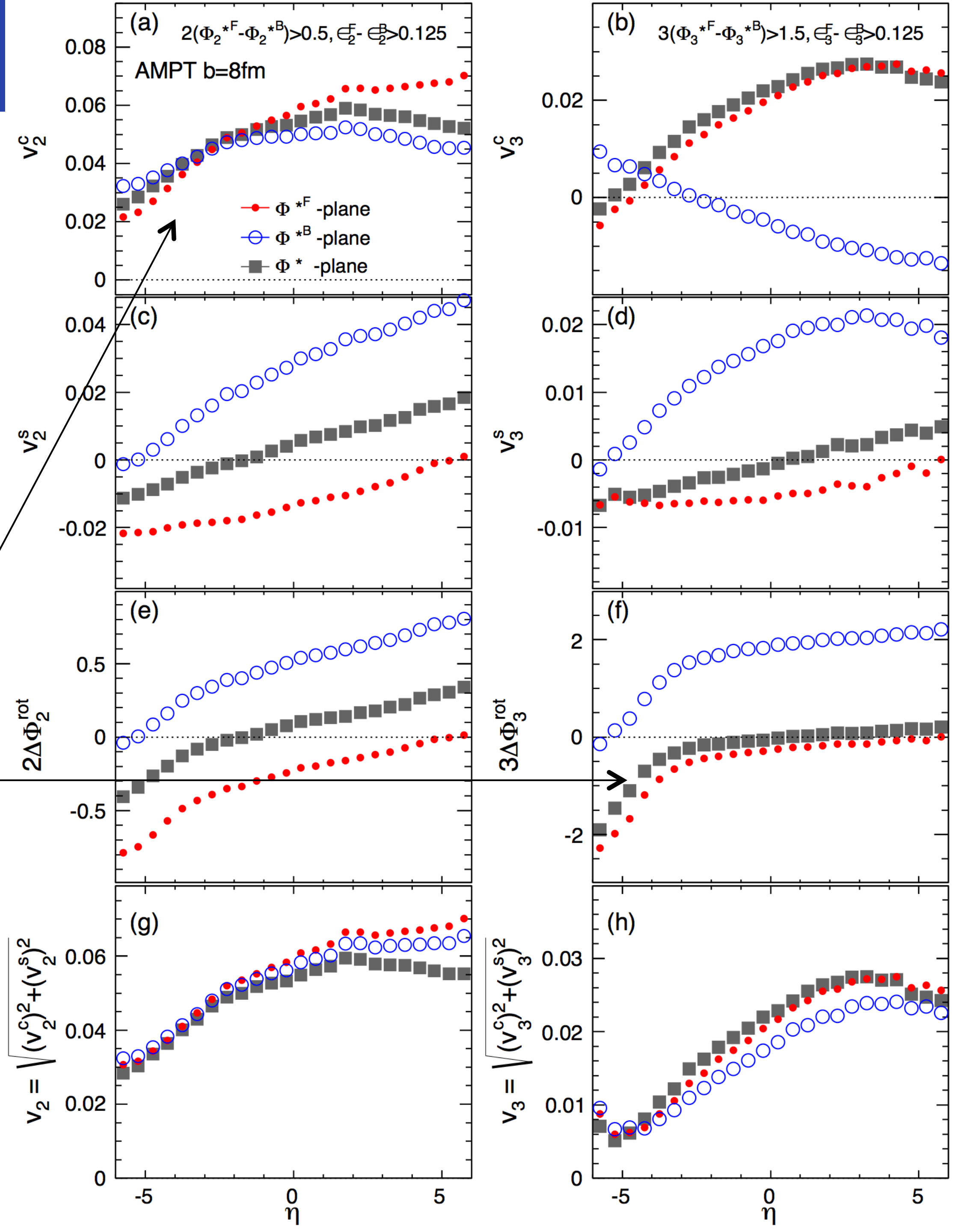




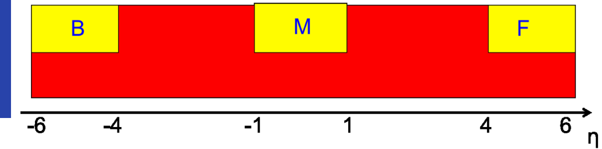
Type-4

$$\Phi_n^{*F} > \Phi_n^{*B} \qquad \varepsilon_n^F > \varepsilon_n^B$$

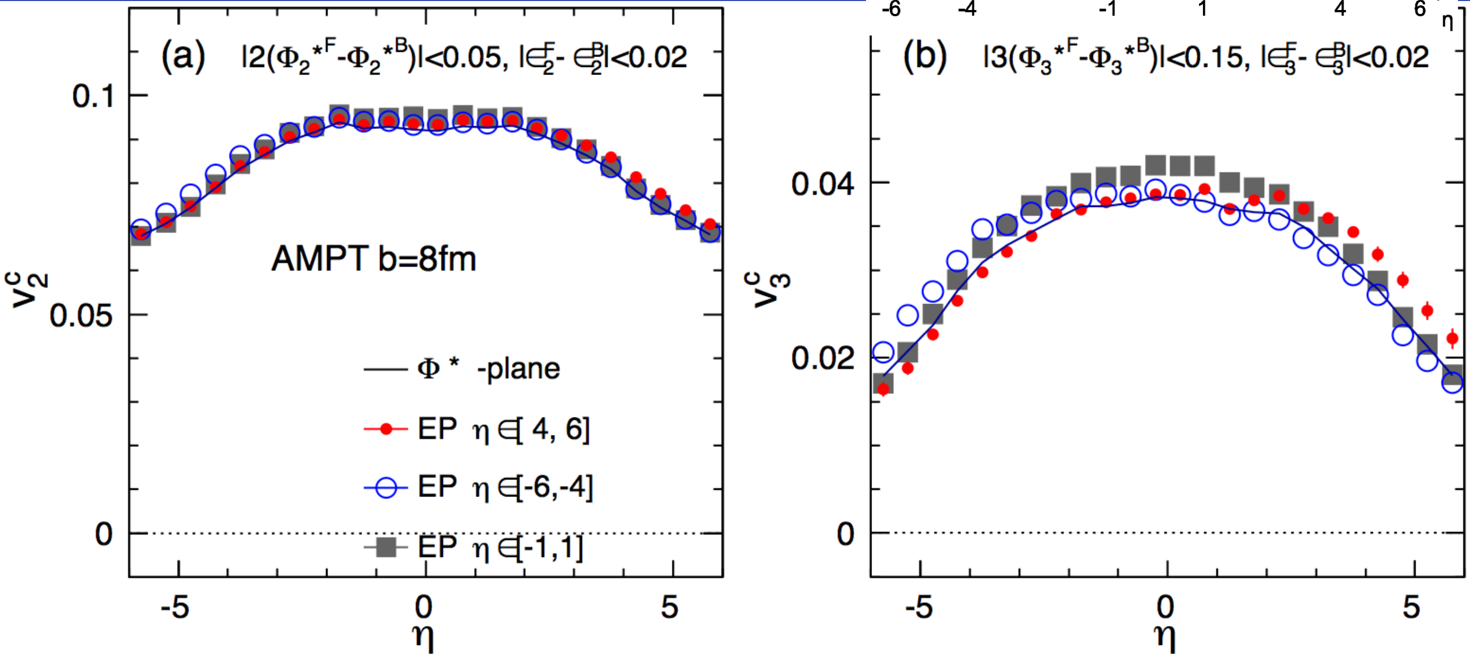
- Similar to Type-3
- But cross point is pushed to backward rapidity.



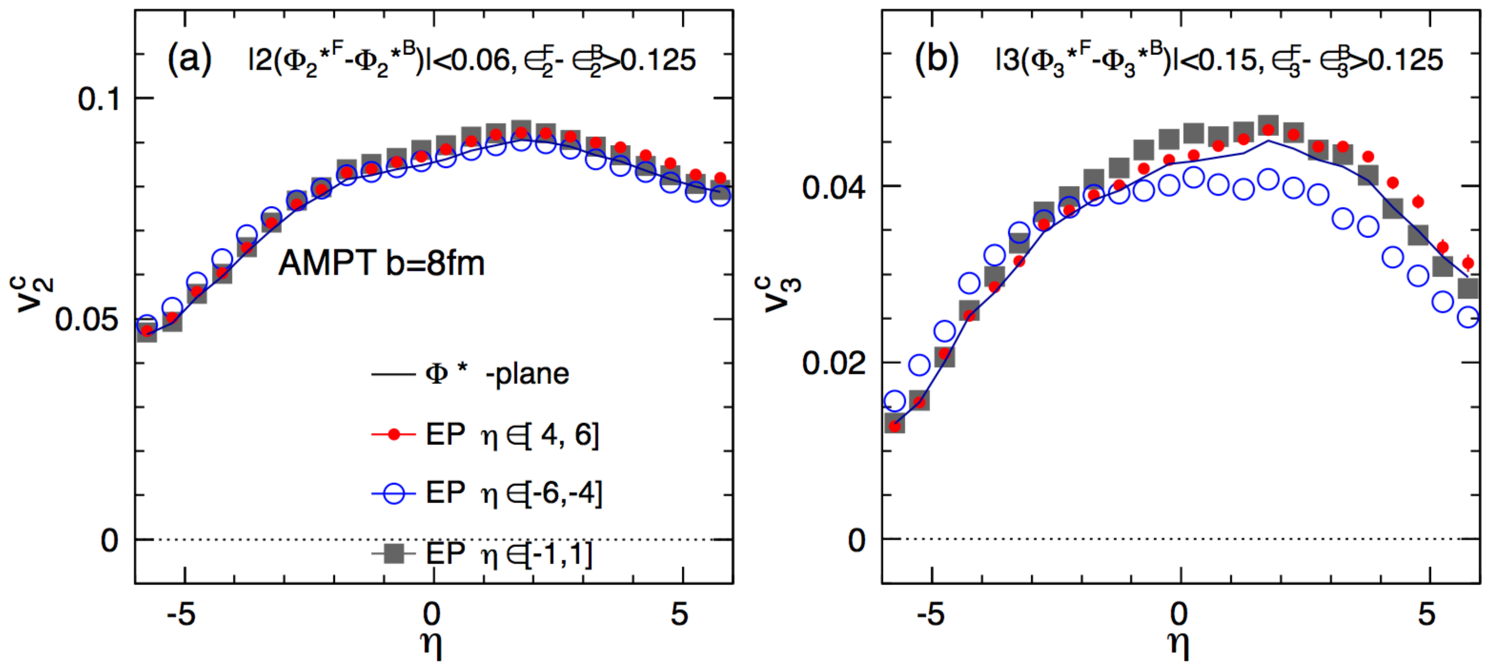
Compare to Event Plane result



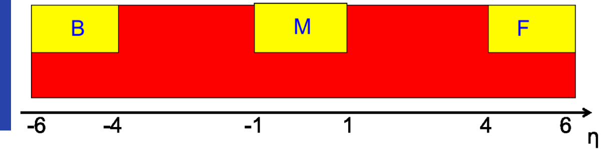
Type-1



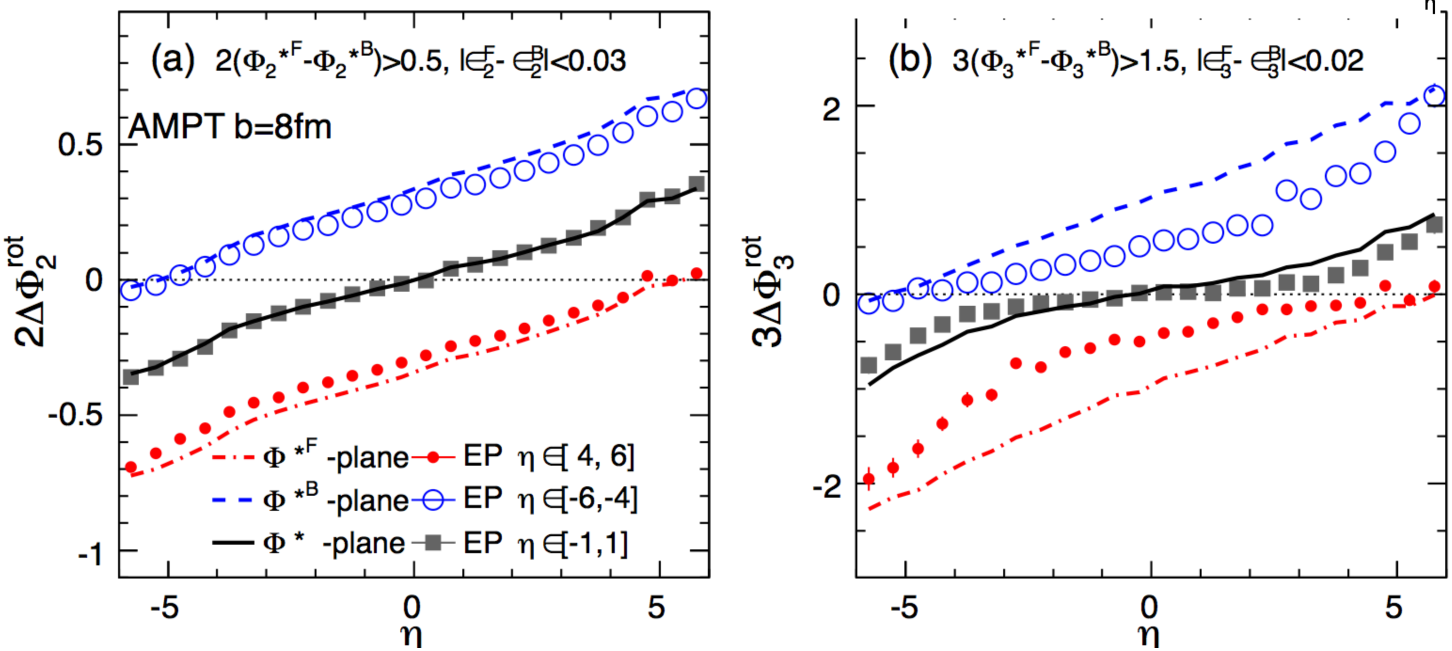
Type-2



Compare to Event Plane result



Type-3



Type-4