Event-by-event flow harmonics

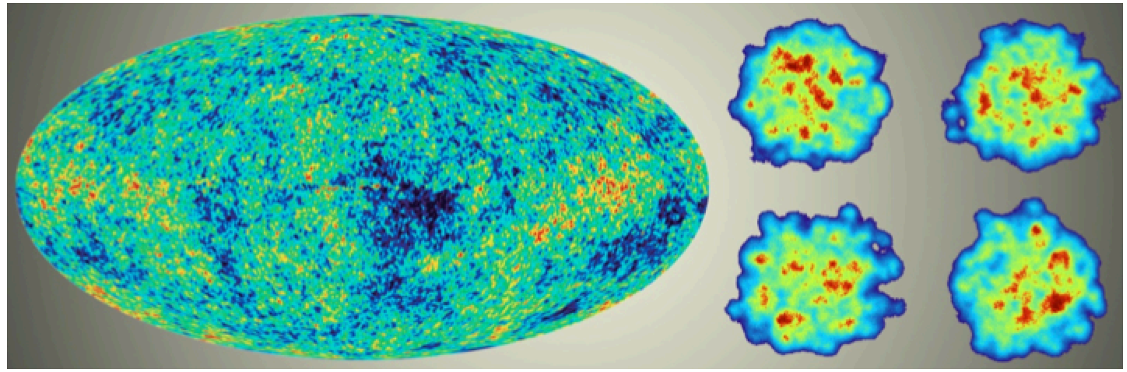
Jiangyong Jia

QCD Chirality Workshop

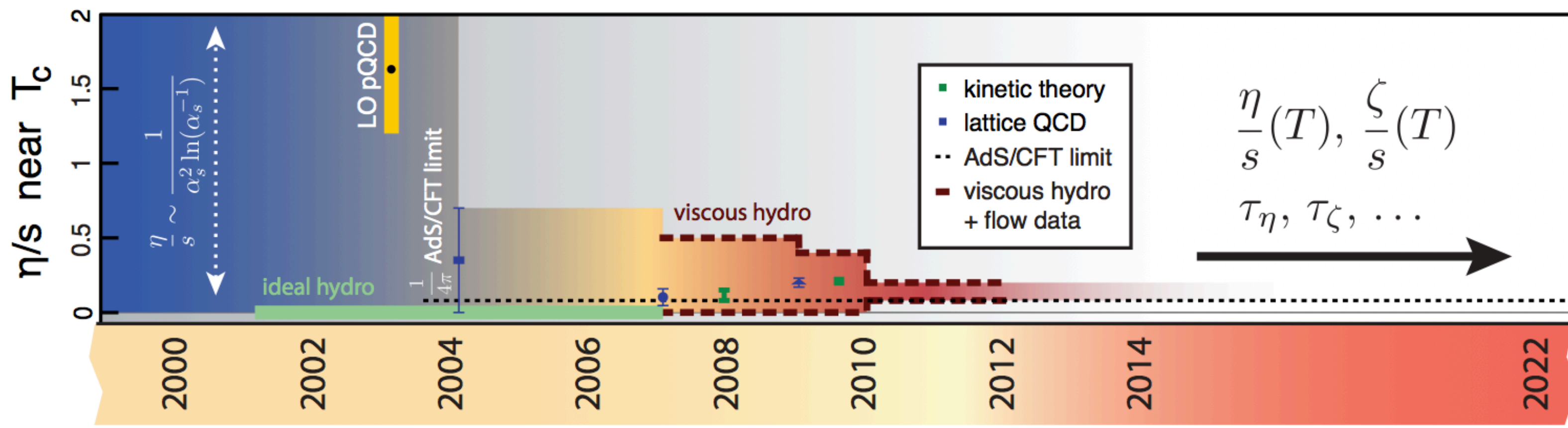
1/21-1/23, 2015, UCLA

Recent accomplishments

Improved the space-time picture of bulk matter evolution



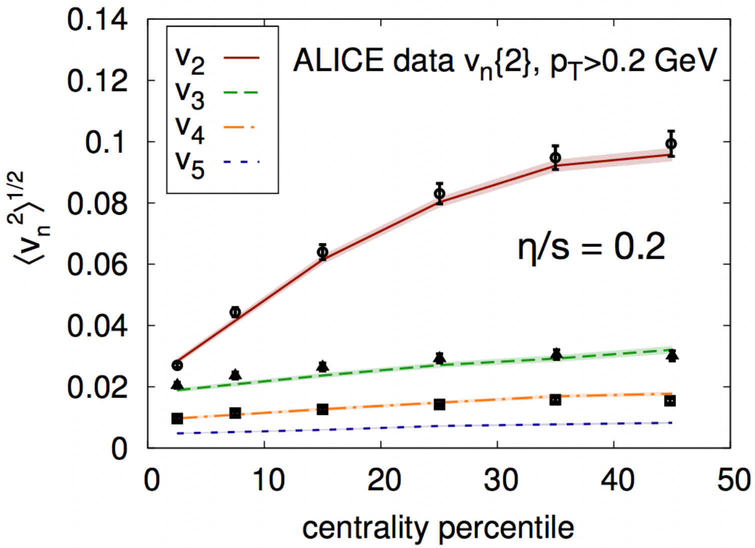
Improved extraction of the medium properties

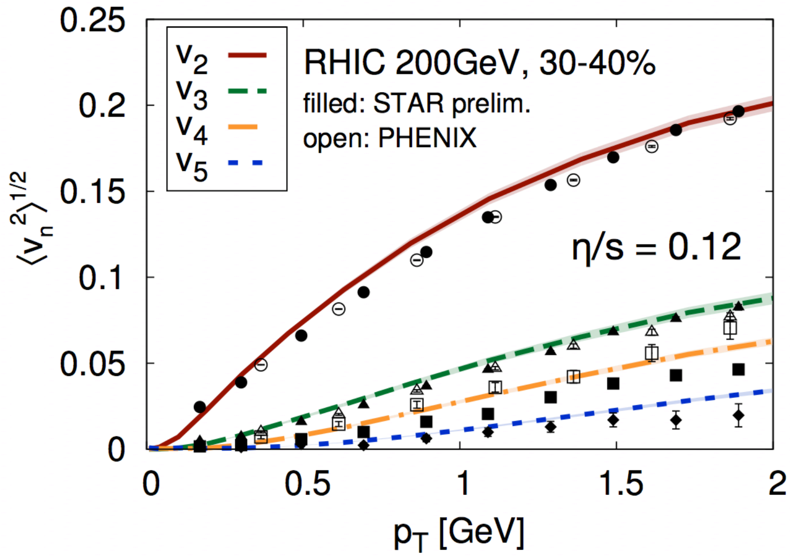


Challenge: simultaneous determination of two unknowns

Future experimental measurements

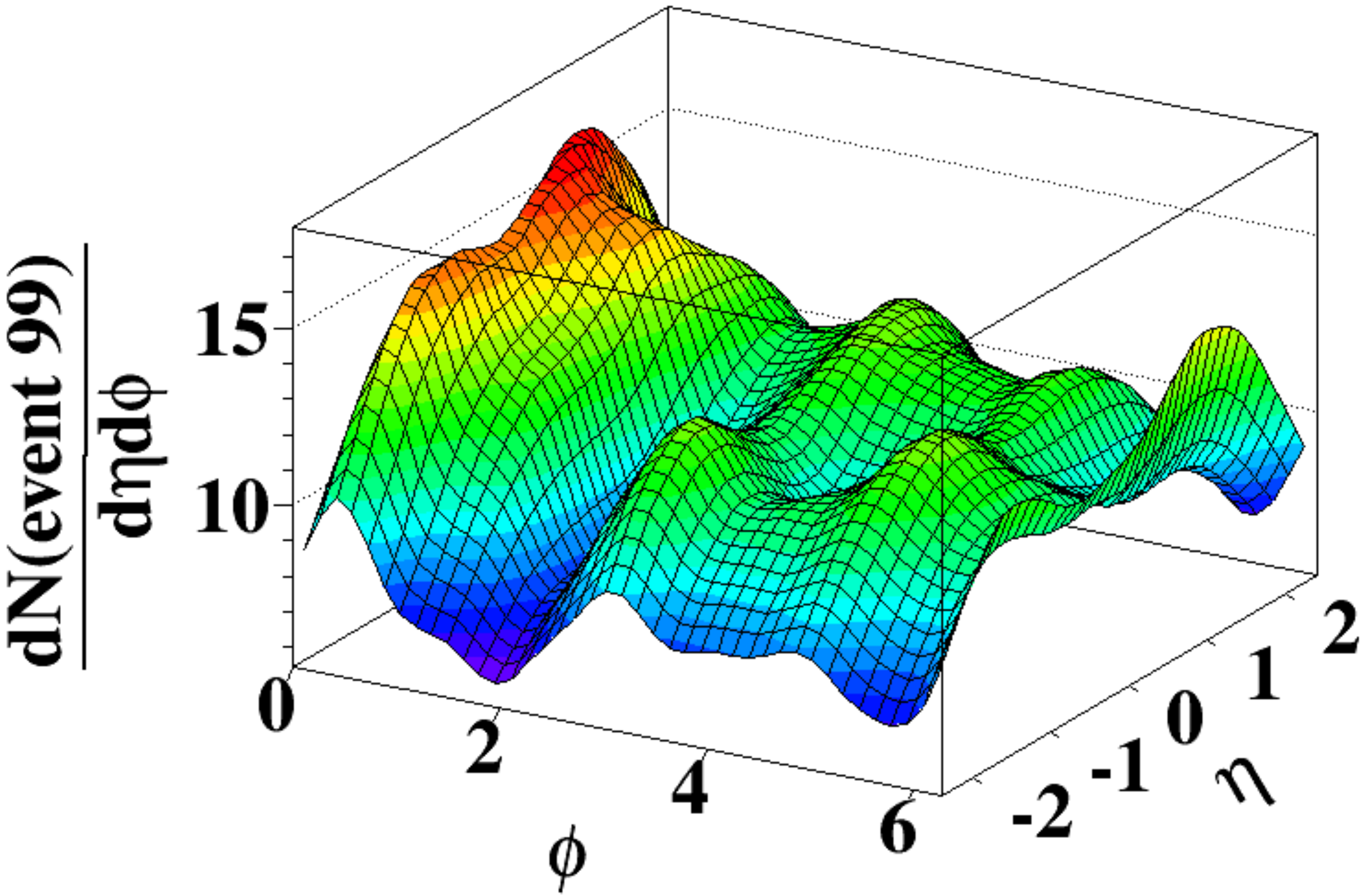
- Experimental error bar no-longer the limiting factors on the η/s





- Measurement aim to provide a picture that is as complete as possible.
  - Event-by-event flow observables→ initial fluctuation & flow correlation
  - Event shape engineering & engen-mode ana.→ geometry & hydro. response
  - Longitudinal fluctuations→ particle production & early time dynamics
  - Medium response→ relaxation mechanism for local perturbation
  - PID v_n → hadronization and hadronic transport
- Supplemented by system size & beam energy scan.

EbyE 3+1D hydro with AMPT initial condition

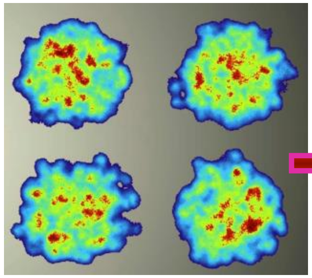


Curtsey of L.Pang and X.N Wang, EbyE 3D hydro+AMPT condition

Event-by-event observables

Many little bangs

1104.4740, 1209.2323,1203.5095 ,1312.3572



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

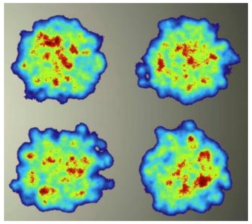
Also access via multi-particle correlations

$$\boxed{\begin{aligned}&\langle \cos(n_1\phi_1 + n_2\phi_2 ... + n_m\phi_m)\rangle = \\ &\qquad \langle v_{n_1} v_{n_2} ... v_{n_m} \cos(n_1\Phi_{n_1} + n_2\Phi_{n_2} ... + n_m\Phi_{n_m})\rangle\end{aligned}} \quad \Sigma n_i = 0$$

Event-by-event observables

Many little bangs

1104.4740, 1209.2323,1203.5095 ,1312.3572



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

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

Event-by-event observables

Many little bangs

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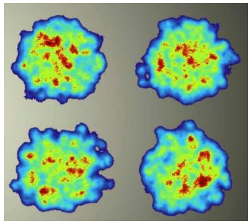
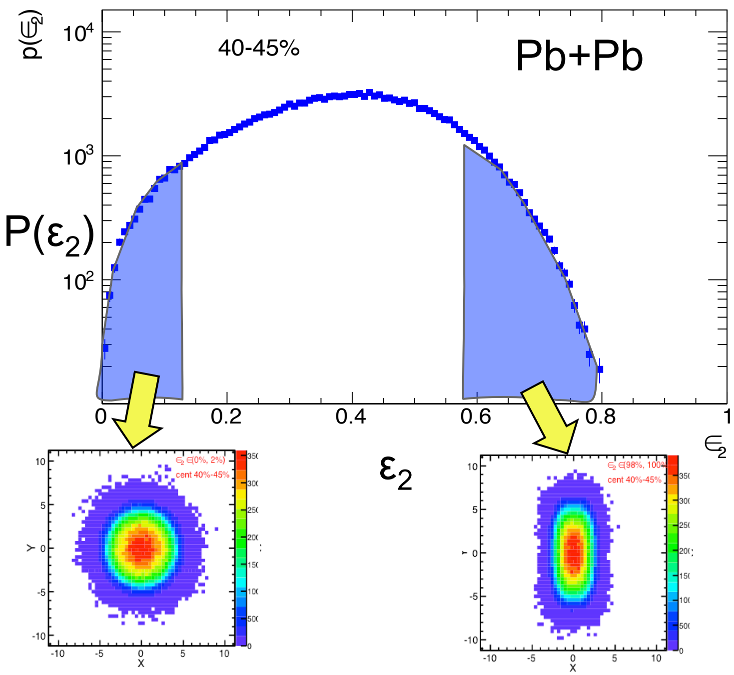


$$p(v_n, v_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{\text{evts}}} \frac{dN_{\text{evts}}}{dv_n dv_m ... d\Phi_n d\Phi_m ...}$$

	pdf's	Moments / cumulants	event-shape method
Flow-amplitudes	$p(v_n)$	$v_n\{2k\},\ k = 1,2,...$	NA
	$p(v_n, v_m)$	$\langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$	yes
	$p(v_n, v_m, v_l)$	$\langle v_n^2 v_m^2 v_l^2 \rangle + 2\langle v_n^2 \rangle \langle v_m^2 \rangle \langle v_l^2 \rangle -$ $\langle v_n^2 v_m^2 \rangle \langle v_l^2 \rangle - \langle v_m^2 v_l^2 \rangle \langle v_n^2 \rangle - \langle v_l^2 v_n^2 \rangle \langle v_m^2 \rangle$	yes
	...	Obtained recursively as above	yes
EP-correlation	$p(\Phi_n, \Phi_m, ...)$	$\langle v_n^{c_n} v_m^{c_m} ... \cos(c_n n \Phi_n + c_m m \Phi_m + ...) \rangle$ $\sum_k k c_k = 0$	yes
Mixed-correlation	$p(v_l, \Phi_n, \Phi_m, ...)$	$\langle v_l^2 v_n^{c_n} v_m^{c_m} ... \cos(c_n n \Phi_n + c_m m \Phi_m + ...) \rangle -$ $\langle v_l^2 \rangle \langle v_n^{c_n} v_m^{c_m} ... \cos(c_n n \Phi_n + c_m m \Phi_m + ...) \rangle$ $\sum_k k c_k = 0$	yes

Event shape selection

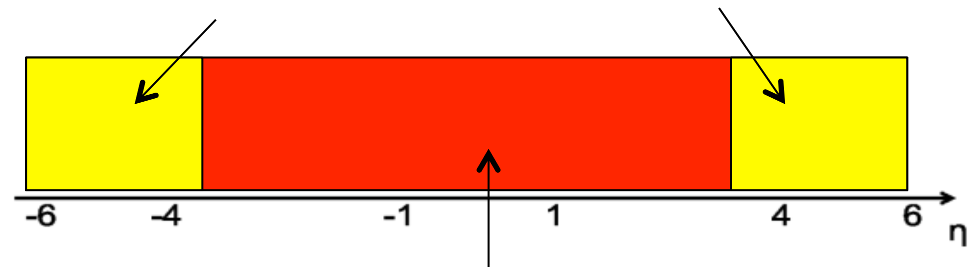
arXiv:1208.4563 arxiv:1311.7091



Fourier expansion of forward E_T distri.:

$$2\pi \frac{dE_T}{d\phi} = \Sigma E_T \left[1 + 2 \sum_n v_n^{\mathrm{obs}} \cos n\left(\phi - \Phi_n^{\mathrm{obs}}\right) \right]$$

Select events with certain v_2^{obs} or v_3^{obs}



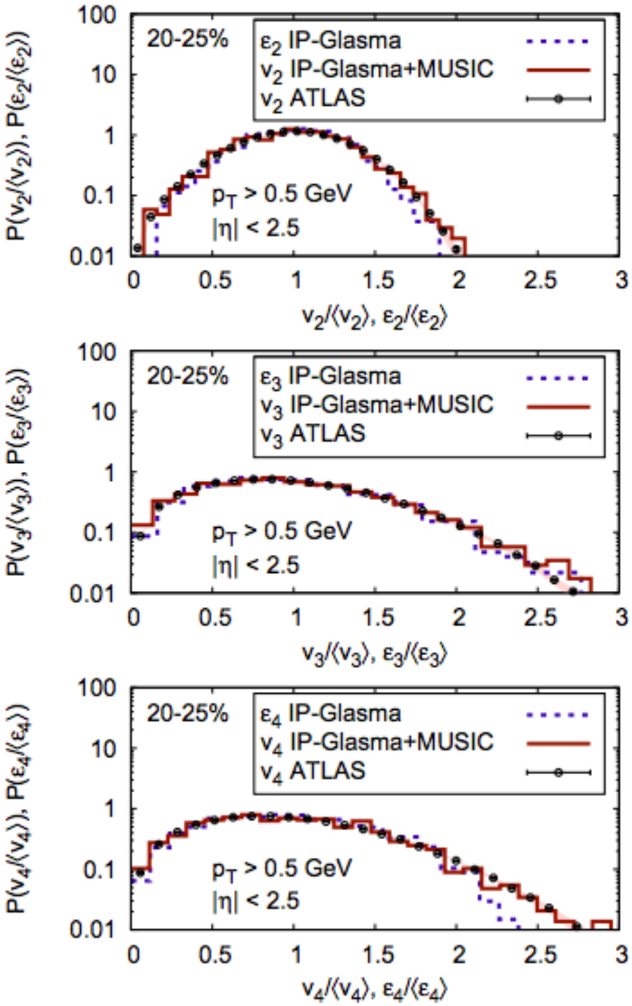
measure $v_n(p_T)$ and $p(v_n, v_m, \ldots, \Phi_n, \Phi_m, \ldots)$

- 0^{th} order event-shape selection: Centrality by ΣE_T (system size)
- 2^{nd} order event-shape selection: ellipticity by v_2^{obs} (system shape)
- 3^{rd} order event-shape selection: triangularity by v_3^{obs} (system shape)

Applications

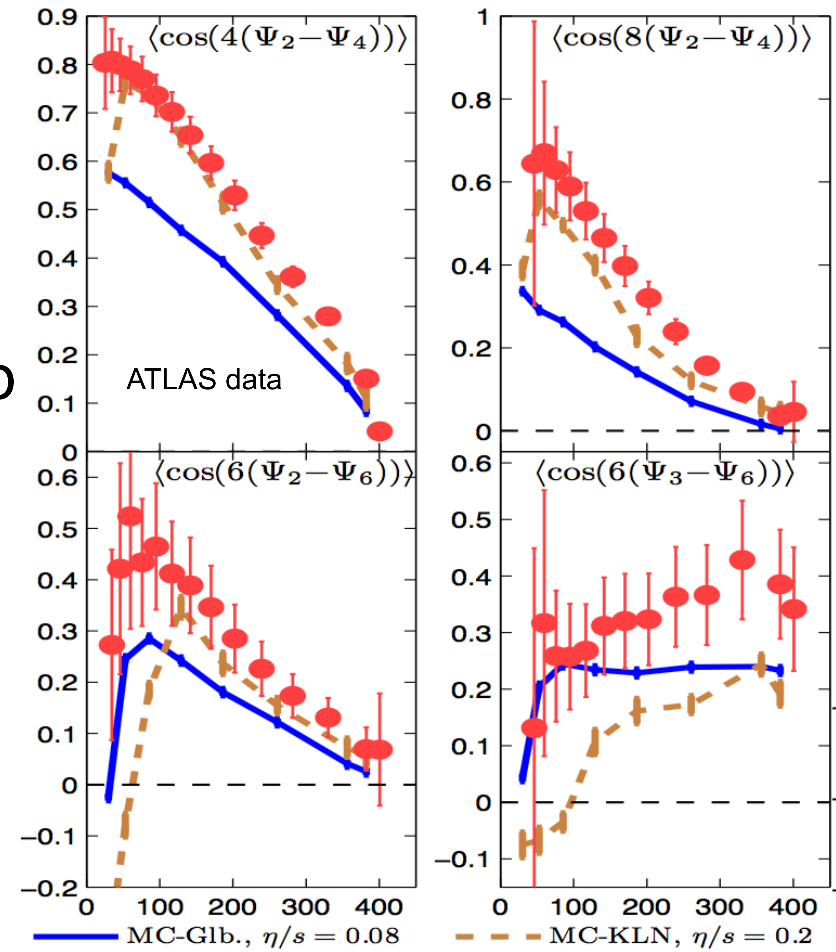
Current measurements of E-by-E distributions

$p(v_2)$, $p(v_3)$, $p(v_4)$



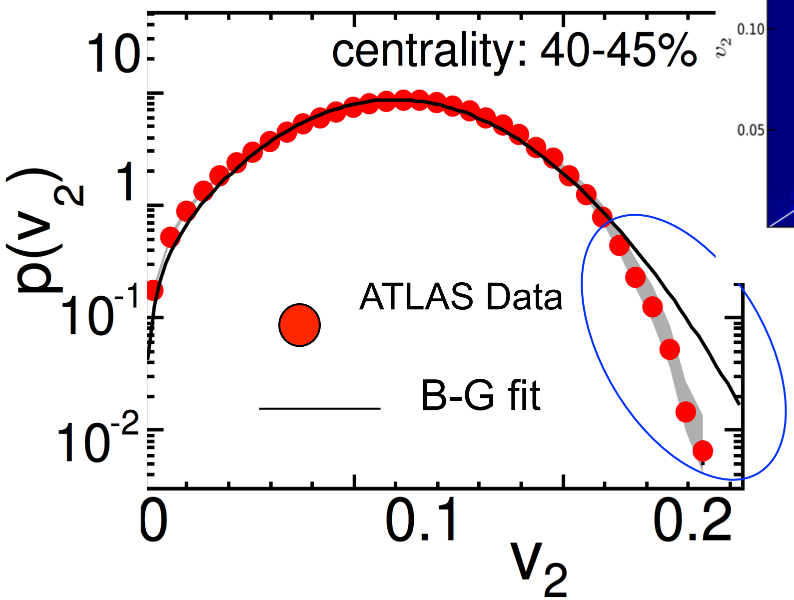
Pb+Pb

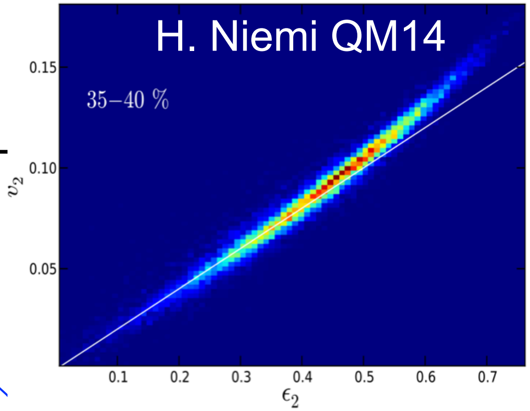
$p(\Phi_n,\Phi_m)$ and $p(\Phi_n,\Phi_m,\Phi_L)$

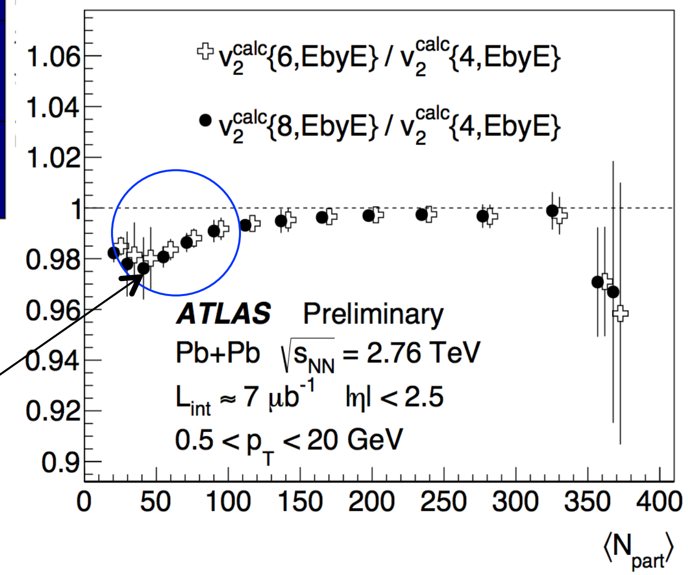


Measured distributions quantitatively described by hydro.

Non-Gaussianity in the $p(v_2)$ distribution







Non-Gaussian behavior

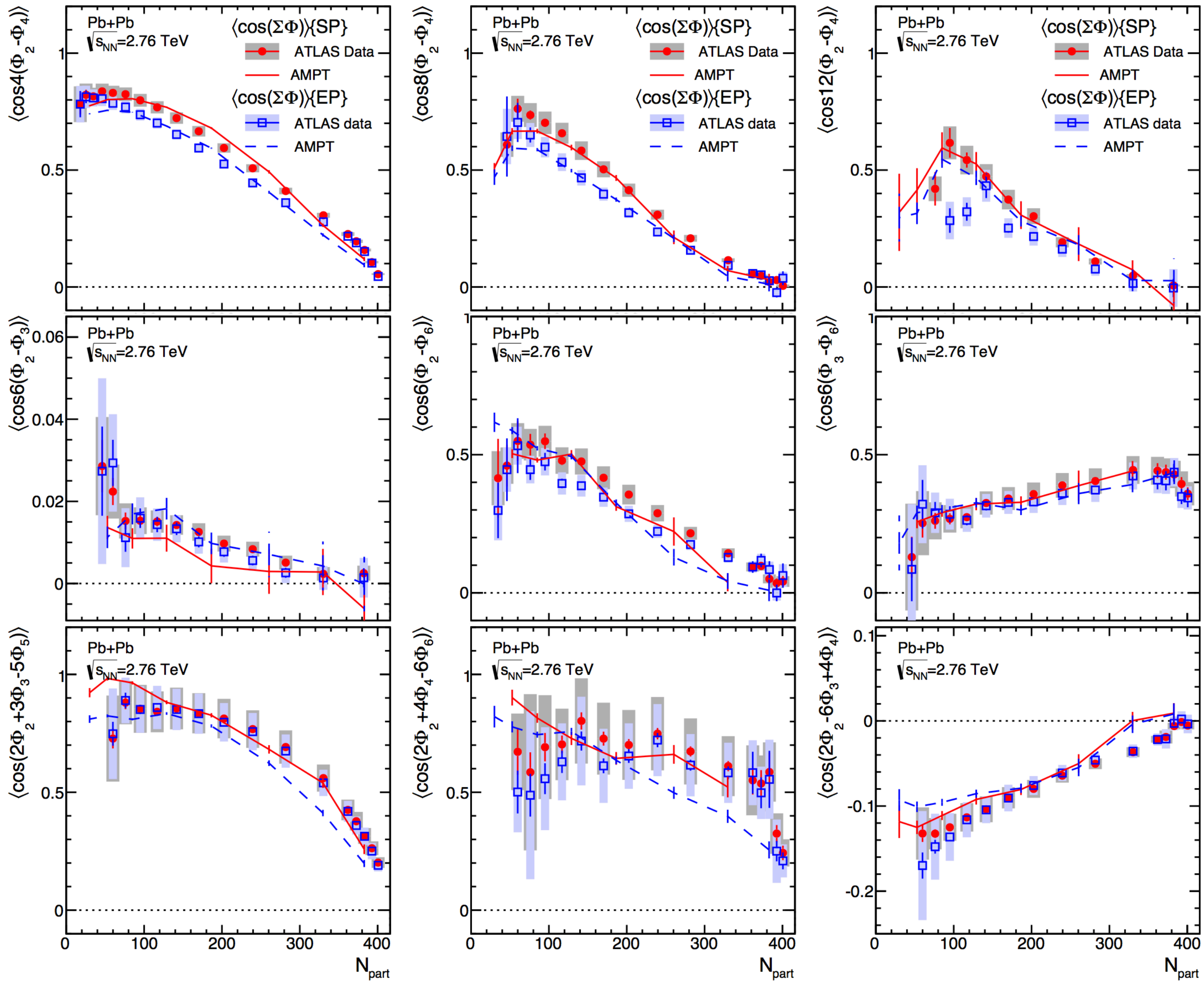
$\langle v_2 \rangle = k \langle \varepsilon_2 \rangle$

- Reflected by a 1-2% change beyond 4th order cumulants
  - Can one reconstruct $p(v_2)$ from $v_2\{2k\}$?

Non-BG in $p(\varepsilon_2)$ or non-linearity of response for large ε_2

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

- EP correlation probes into the mode-mixing (14 correlators from ATLAS)



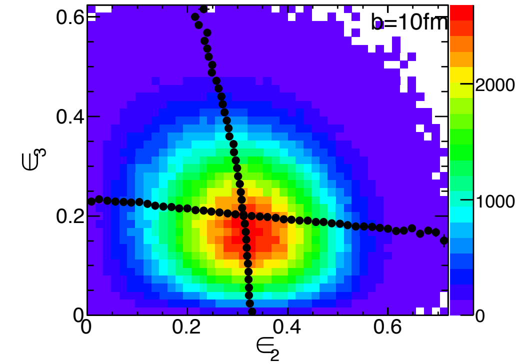
How are (ε_n, Φ_n^*) transferred to (v_n, Φ_n)?

- Flow response is linear for v_2 and v_3:

arXiv:1403.0489 arXiv:1111.6538

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

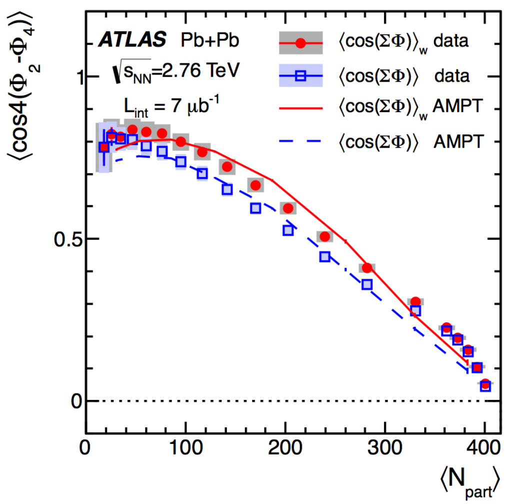
  - But no-trivial correlation between ε_2 and ε_3:

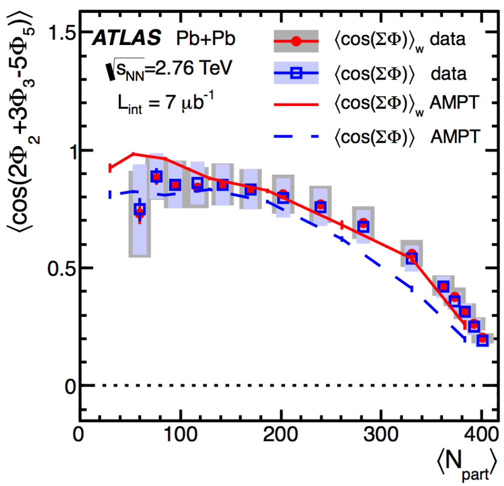


- Higher-order flow arises from EP correlations., e.g. <cos4(Φ_2-Φ_4)>:

$$v_4 e^{i4\Phi_4} \approx c_0 \, \epsilon_4 e^{i4\Phi_4^*} + c_1 \left(v_2 e^{i2\Phi_2}\right)^2$$

$$\boxed{v_4 \approx \sqrt{c_0^2 + (c_1 v_2^2)^2}}$$

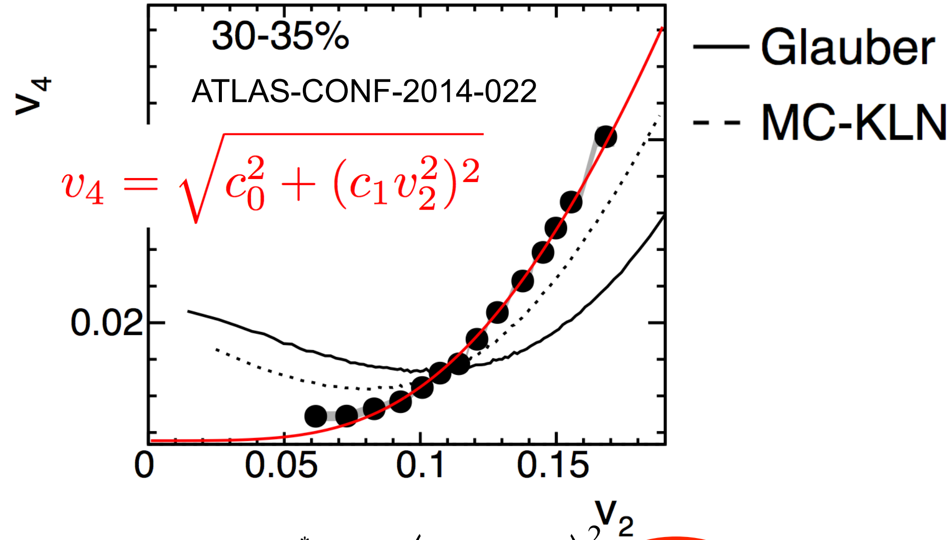




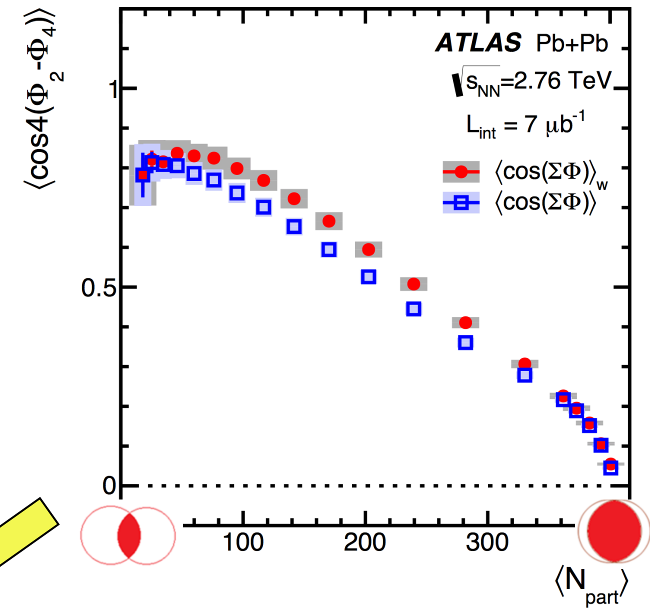
$$v_5 e^{i5\Phi_5} \approx c_0 \, \epsilon_5 e^{i5\Phi_5^*} + c_1 \, v_2 v_3 e^{i(2\Phi_2 + 3\Phi_3)}$$

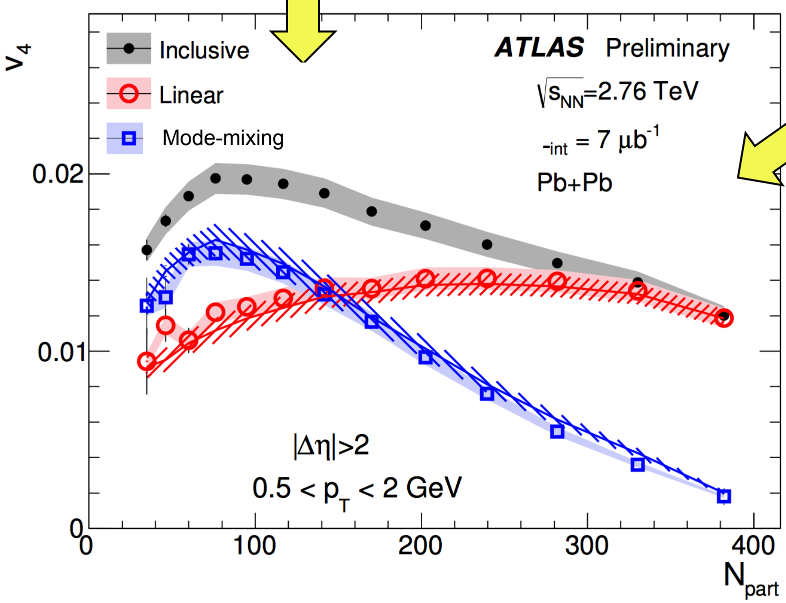
$$\boxed{v_5 \approx \sqrt{c_0^2 + (c_1 v_2 v_3)^2}}$$

v_4-v_2 correlation from event-shape engineering



$$v_4 e^{i4\Phi_4} = c_0 e^{i4\Phi_4^*} + c_1 \left(v_2 e^{i2\Phi_2}\right)^2 + \ldots$$





$$v_4^{NL} = v_4 \langle \cos 4(\Phi_2 - \Phi_4) \rangle$$

$$v_4^{L} = \sqrt{v_4^2 - (v_4^{NL})^2}$$

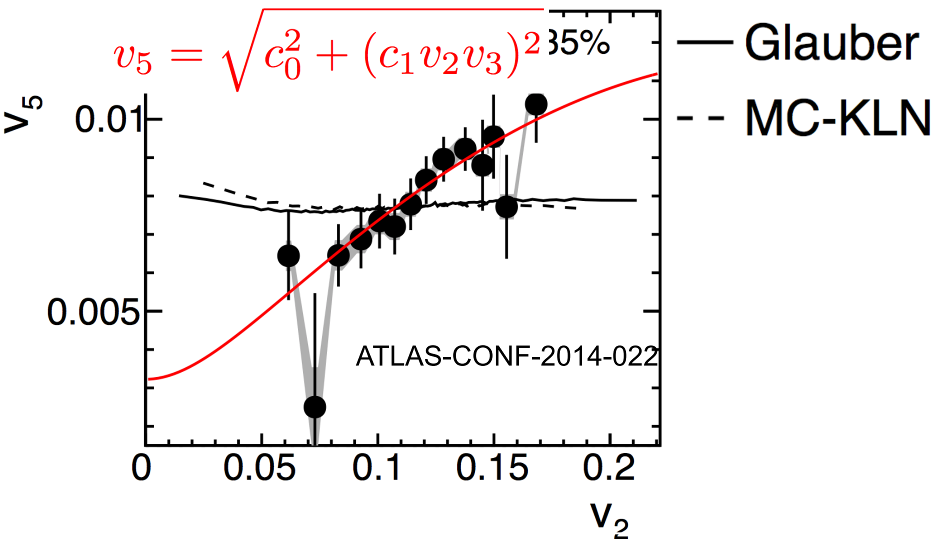
Compare well with expectation from EP correlations.

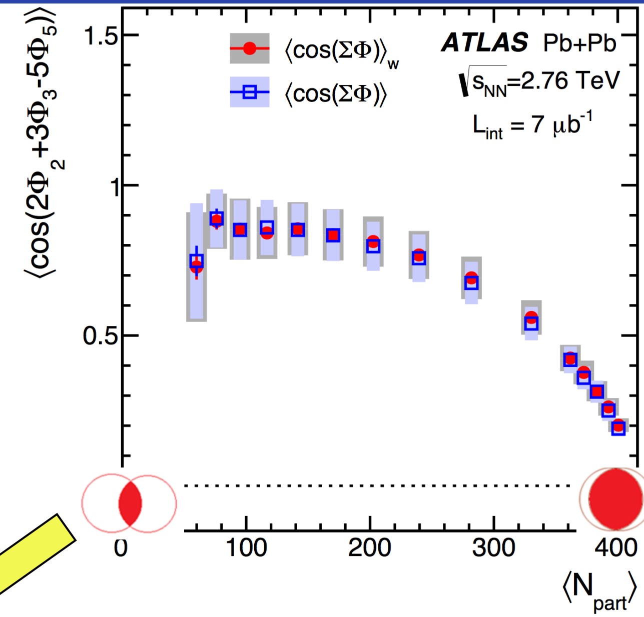
higher-order mode-mixing negligible

Separate geometry and mode-mixing components!!

v_5-v_2 correlation from event-shape engineering

$$v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}$$

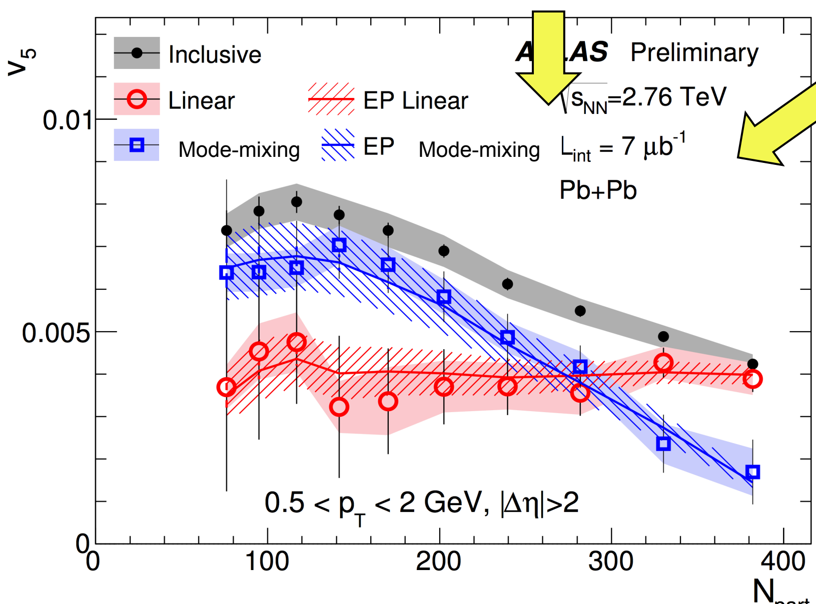




$$v_5 e^{i5\Phi_5} \propto c_0 e^{i5\Phi_5^*} + c_1 v_2 v_3 e^{i(2\Phi_2+3\Phi_3)} + \ldots$$

$$v_5^{\mathrm{NL}} = v_5 \left\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \right\rangle$$

$$v_5^{\mathrm{L}} = \sqrt{v_5^2 - (v_5^{\mathrm{NL}})^2}$$

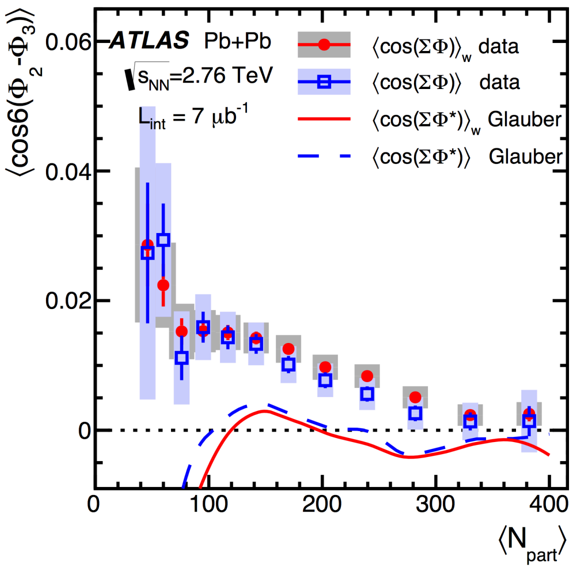


Compare well with expectation from EP correlations.
higher-order mode-mixing negligible

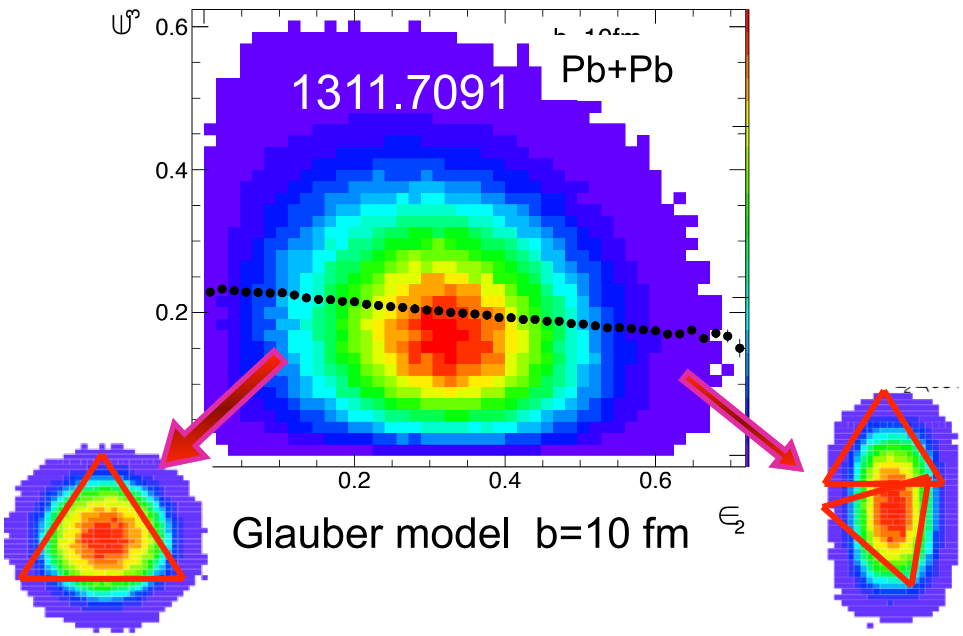
Separate geometry and mode-mixing components!!

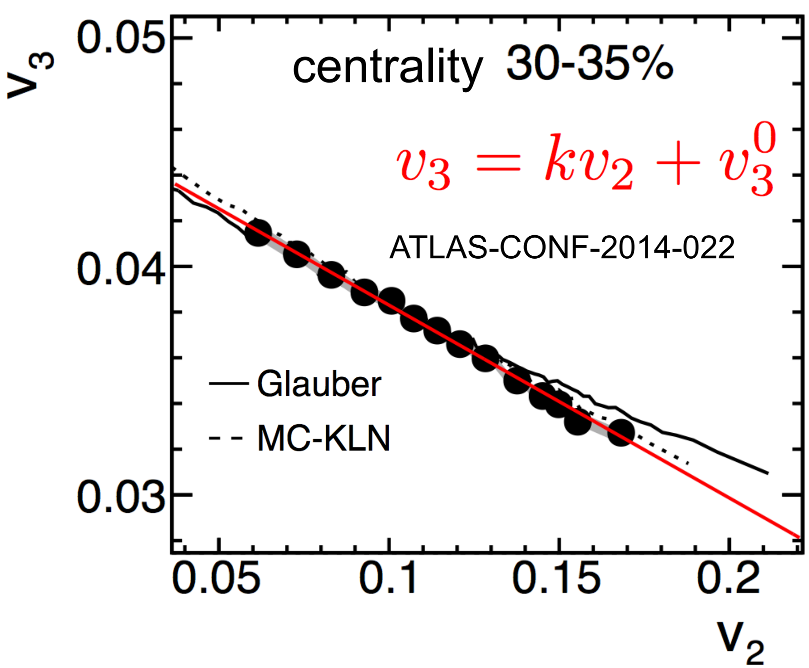
v_3-v_2 correlation from event-shape engineering

Very weak EP correlations

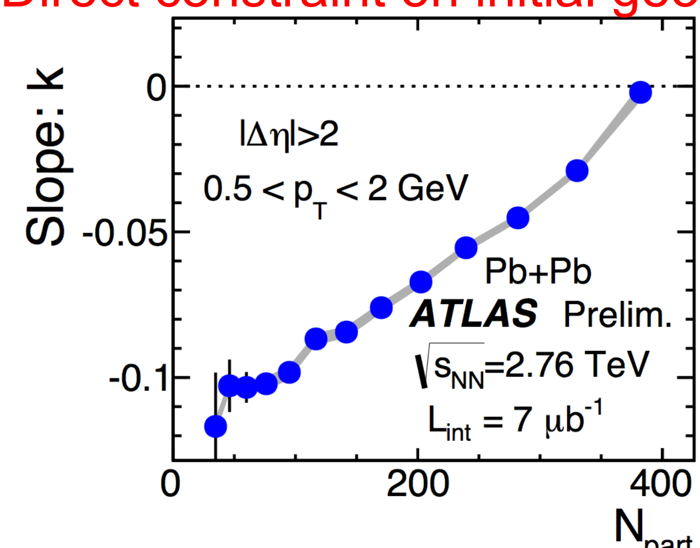


Significant magnitude anti-correlations

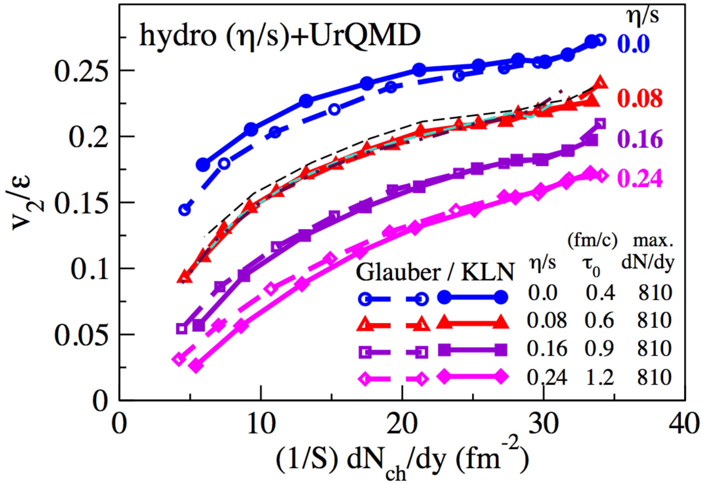




Direct constraint on initial geometry



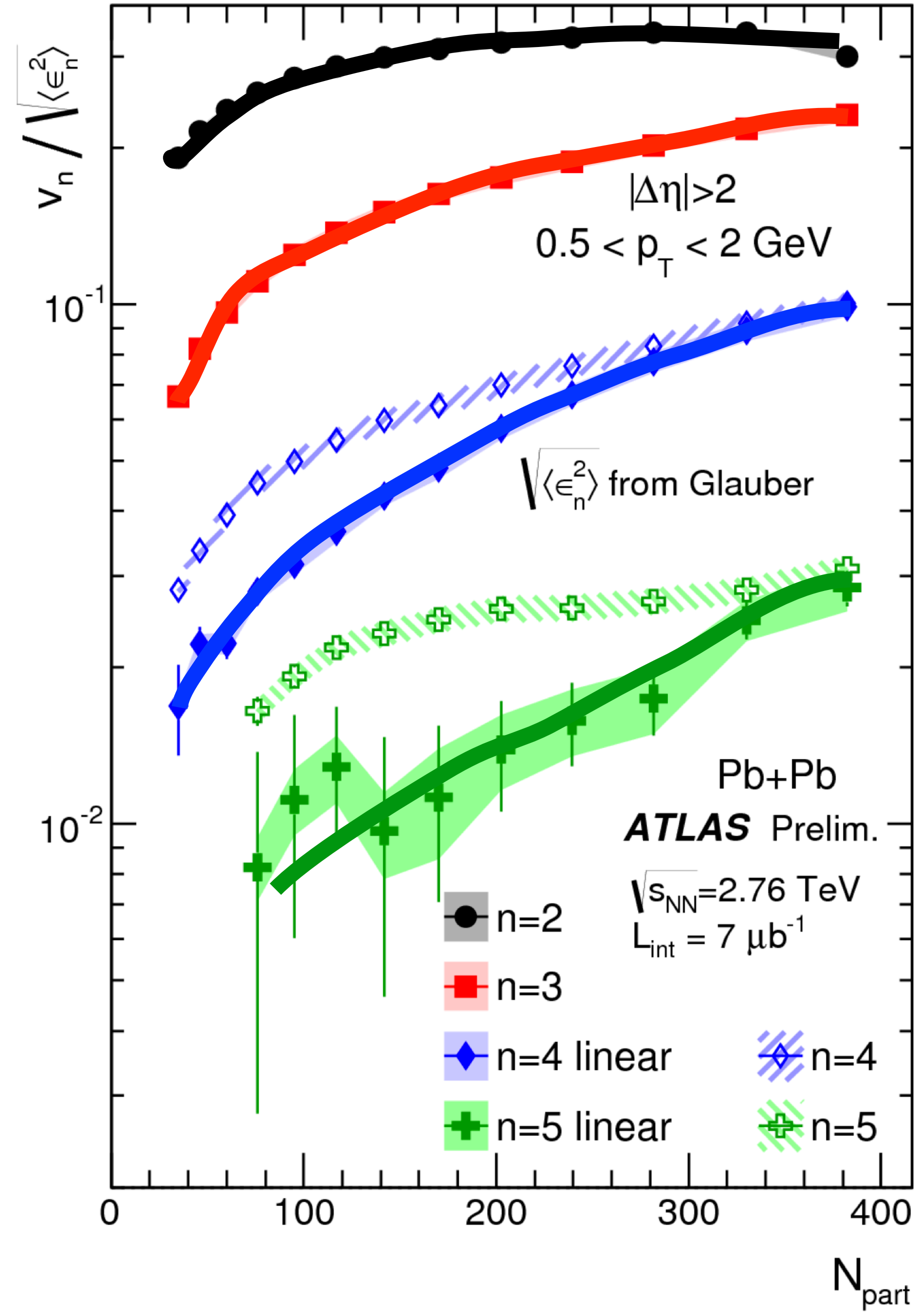
Eccentricity scaling: v_n/ε_n



Teaney and Yan

Viscous correlation: $$-\frac{\Delta w_n}{w_n^{\text{id}}} \sim n^2 \frac{\eta}{s}$$

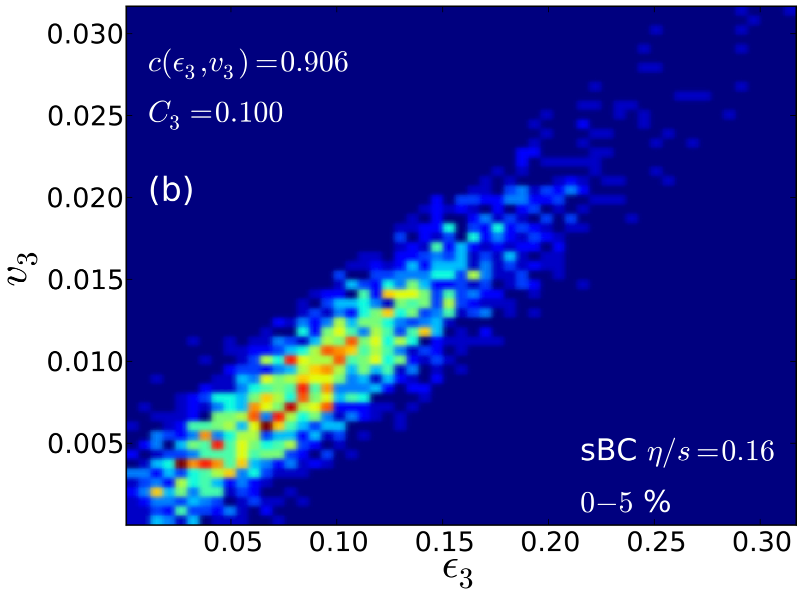
Viscous damping expected to be larger for larger n

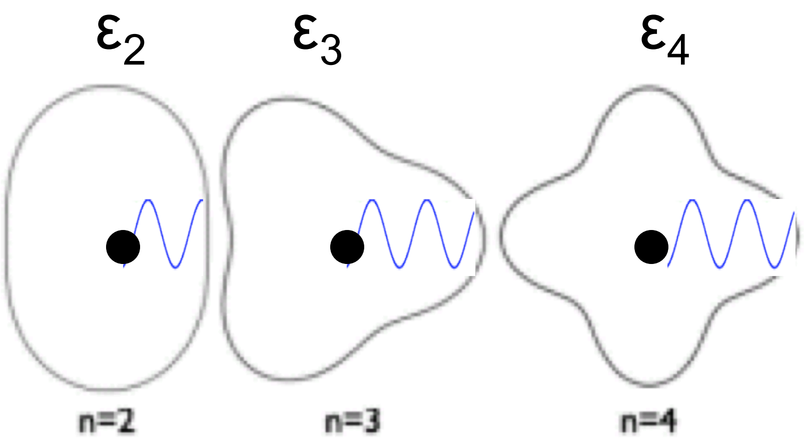


$$p(v_n, v_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{\text{evts}}} \frac{dN_{\text{evts}}}{dv_n dv_m ... d\Phi_n d\Phi_m ...}$$

- Fluctuations can also be differential in p_T, η, PID etc.
  - $v_n(pt,\eta,\ldots)$ & $\Phi_n(pt, \eta, \ldots)$
  - Averaged out in most analyses.

Transverse flow fluctuations





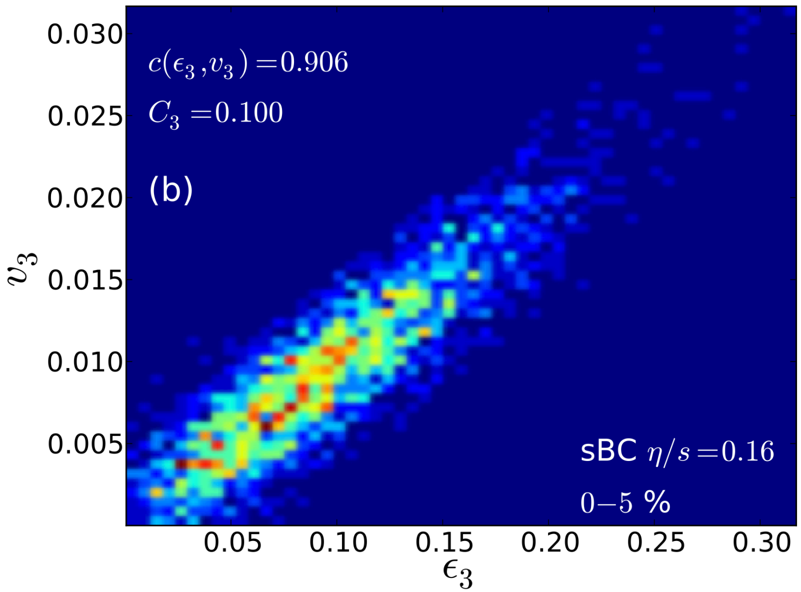
- No-unique mapping between ε_n and v_n, though $\langle v_n \rangle \propto \langle \varepsilon_n \rangle$
  - ε_n defined by different r^m weights → radial degrees of freedom.
- Related to flow angle and amplitude fluctuates in p_T

$$v_n(p_T)e^{in\Phi(p_T)} \qquad V_{n\Delta}(p_T^a, p_T^b) \neq v_n(p_T^a)v_n(p_T^b)$$

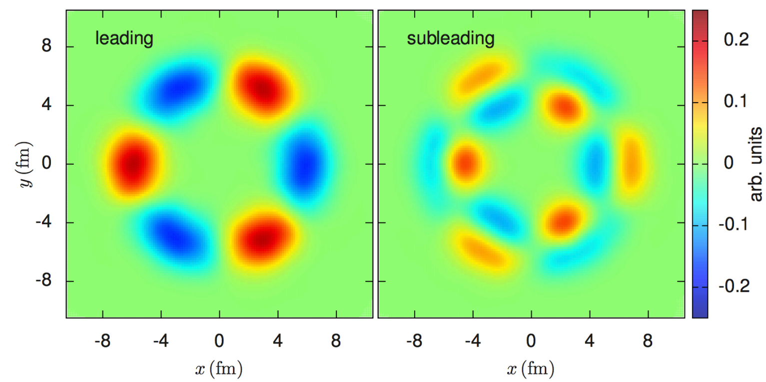
- Decompose the $v_n(p_T)$ into principle modes, each mode factorize

$$V_{n\Delta}(p_T^a, p_T^b) = \sum_{\alpha} < M(p_T^a)M(p_T^b) > v_n^{(\alpha)}(p_T^a)v_n^{(\alpha)}(p_T^b)$$

Transverse flow fluctuations



arXiv:1410.7739,1501.03138



$$v_3 \propto c_1 e^{i3\Phi_3^1} + c_2 e^{i3\Phi_3^2}$$

Magnitude and phase of leading and subleading modes fluctuates independently.

- No-unique mapping between ε_n and v_n.
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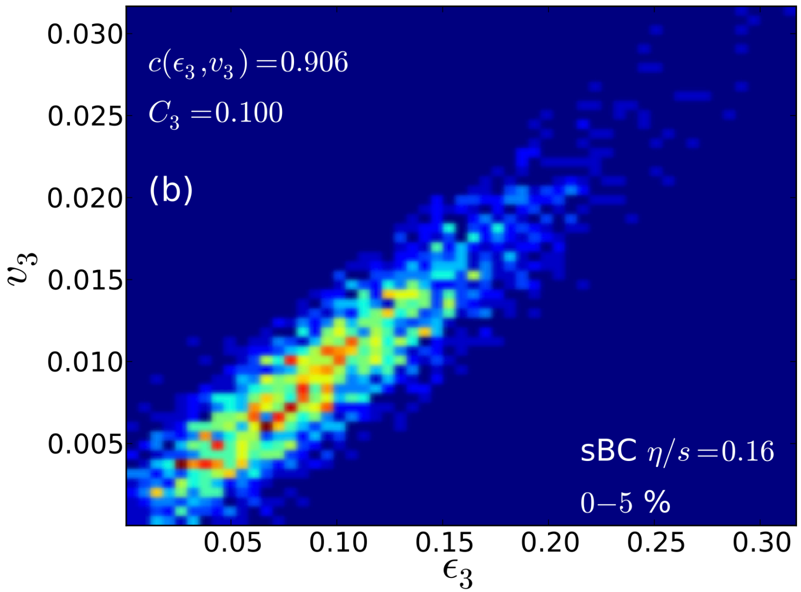
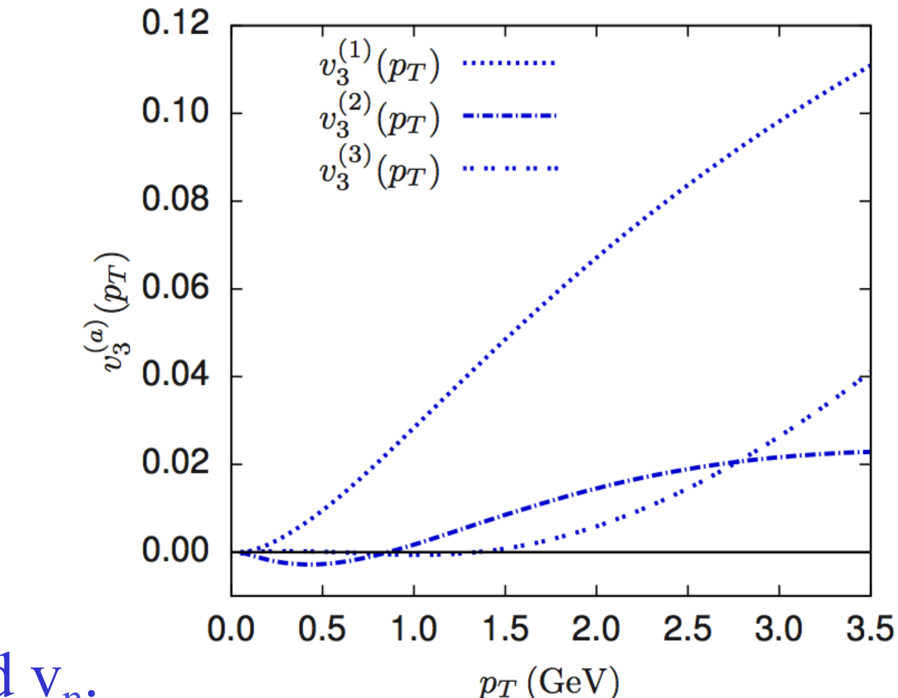
Transverse flow fluctuations

arXiv:1410.7739,1501.03138





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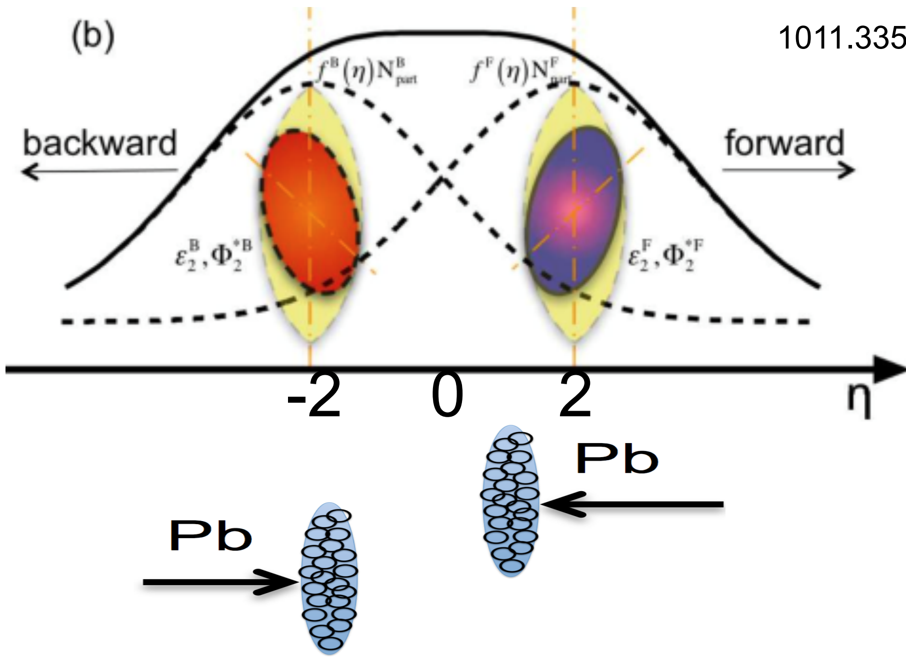
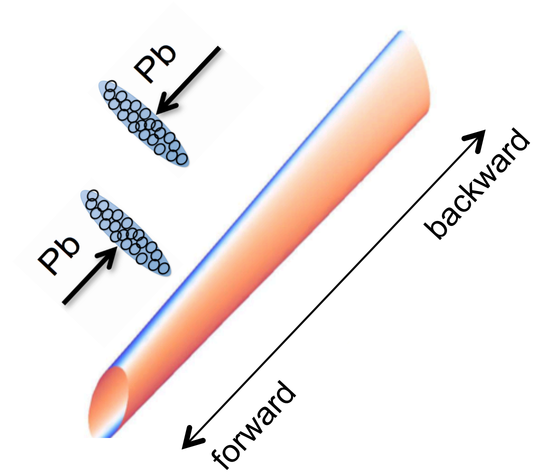
Longitudinal flow fluctuations



1011.3354, 1403.6077



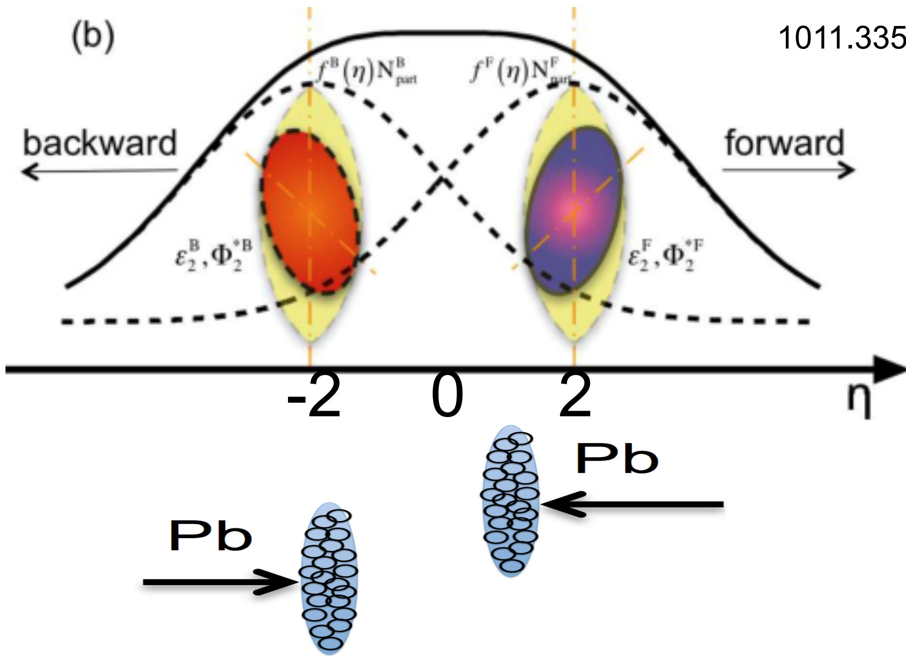
- Shape of participants in two nuclei not the same due to fluctuation

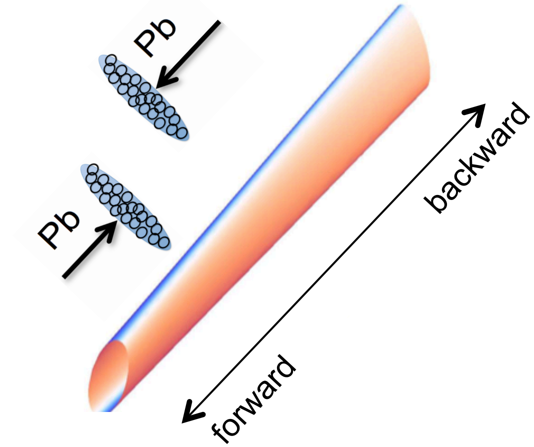
$$\varepsilon_n, \Phi_n^* N_{\text{part}} \qquad \varepsilon_n^{\text{F}}, \Phi_n^{*\text{F}} N_{\text{part}}^{\text{F}} \qquad \varepsilon_n^{\text{B}}, \Phi_n^{*\text{B}} N_{\text{part}}^{\text{B}} \qquad \boxed{\varepsilon_n^{\text{F}}, \Phi_n^{*\text{F}} \neq \varepsilon_n^{\text{B}}, \Phi_n^{*\text{B}}}$$

- Wounded nucleon model: particles are produced by independent fragmentation of wounded nucleons, emission function f(η) not symmetric in η

Longitudinal flow fluctuations

1011.3354, 1403.6077





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

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

Asymmetry:	$\varepsilon_n^F \neq \varepsilon_n^B$
Twist:	$\Phi_n^{*F} \neq \Phi_n^{*B}$

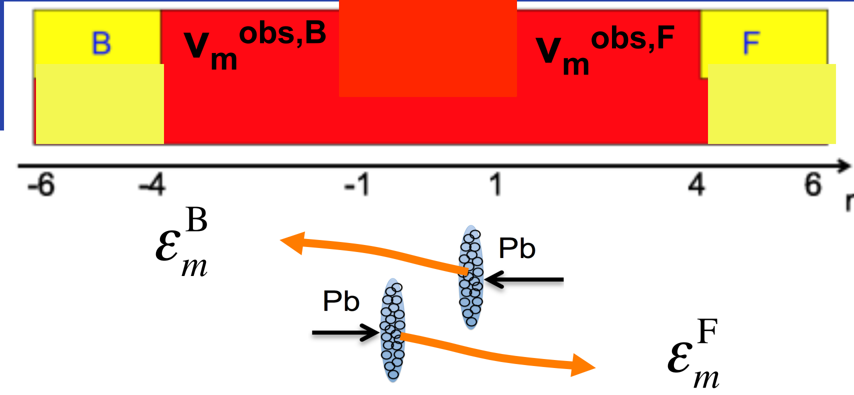
α(η) determined by emission profile f(η)

- Hence $\boxed{\vec{v}_n(\eta) \approx c_n(\eta)\left[\alpha(\eta)\vec{\epsilon}_n^{\,F} + (1-\alpha(\eta))\vec{\epsilon}_n^{\,B}\right]}$ for n=2,3

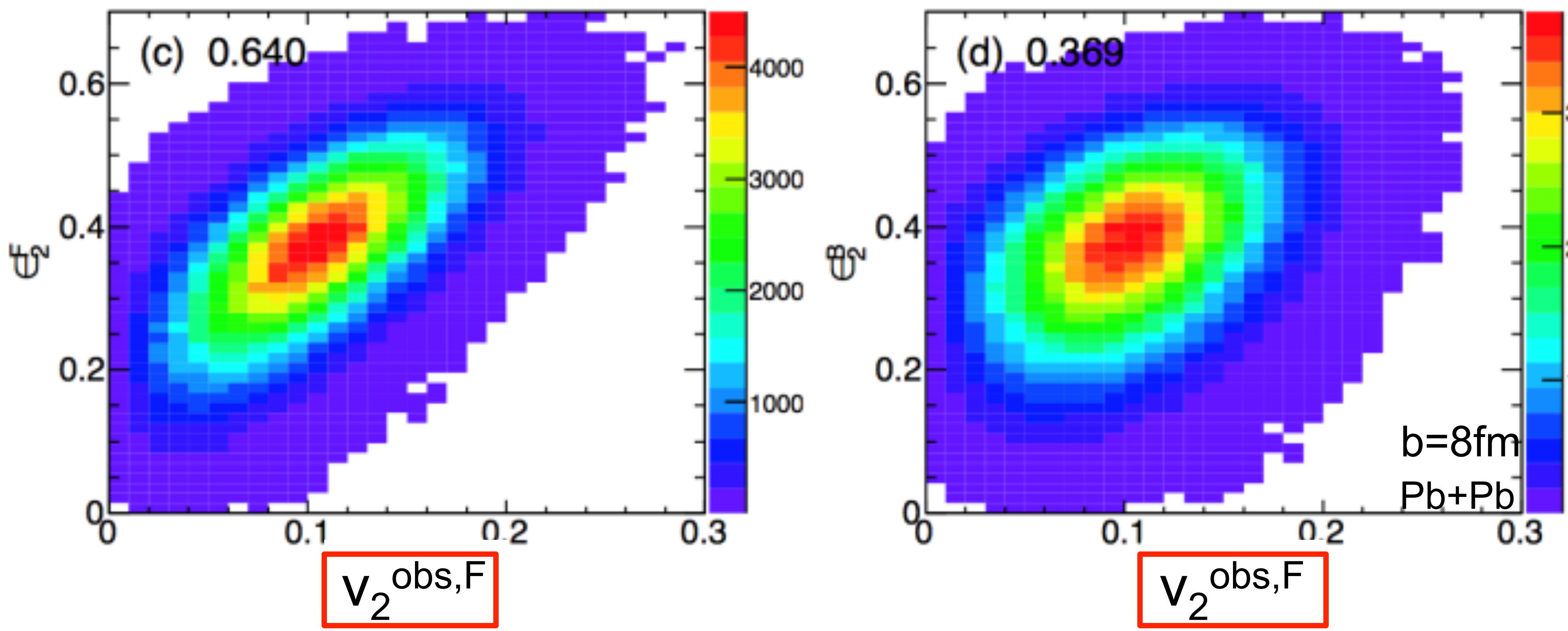
  - Picture verified in AMPT simulations, magnitude estimated 1403.6077

What AMPT tell us?

- F/B asymmetry in initial geometry appears as asymmetry of flow

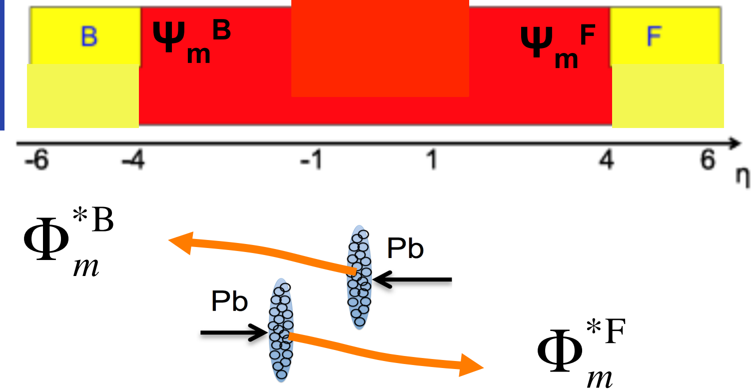


$v_2^{obs,F}$ more correlated with ε_2^F than with ε_2^B



Initial FB asymmetry survives to final state!!

What AMPT tell us?

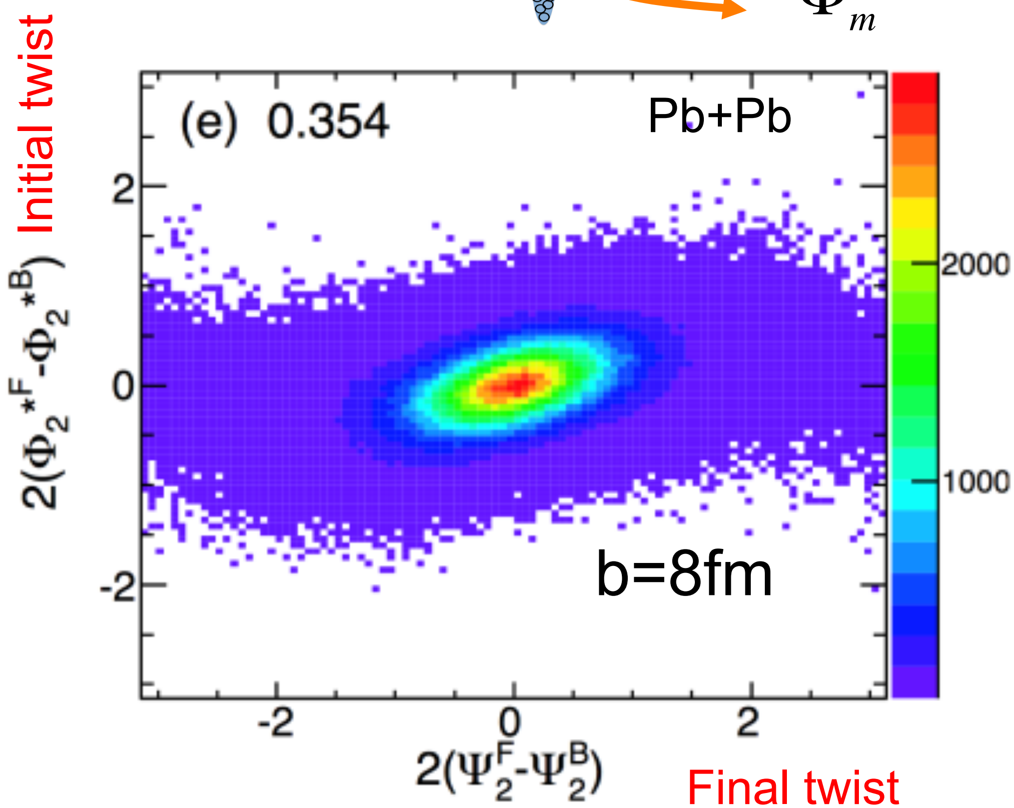


- Twist in initial geometry appears as twist in flow
  - Participant plane angles:

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

  - Final state event-plane angles

$$\Psi_n^F \quad \Psi_n^B$$



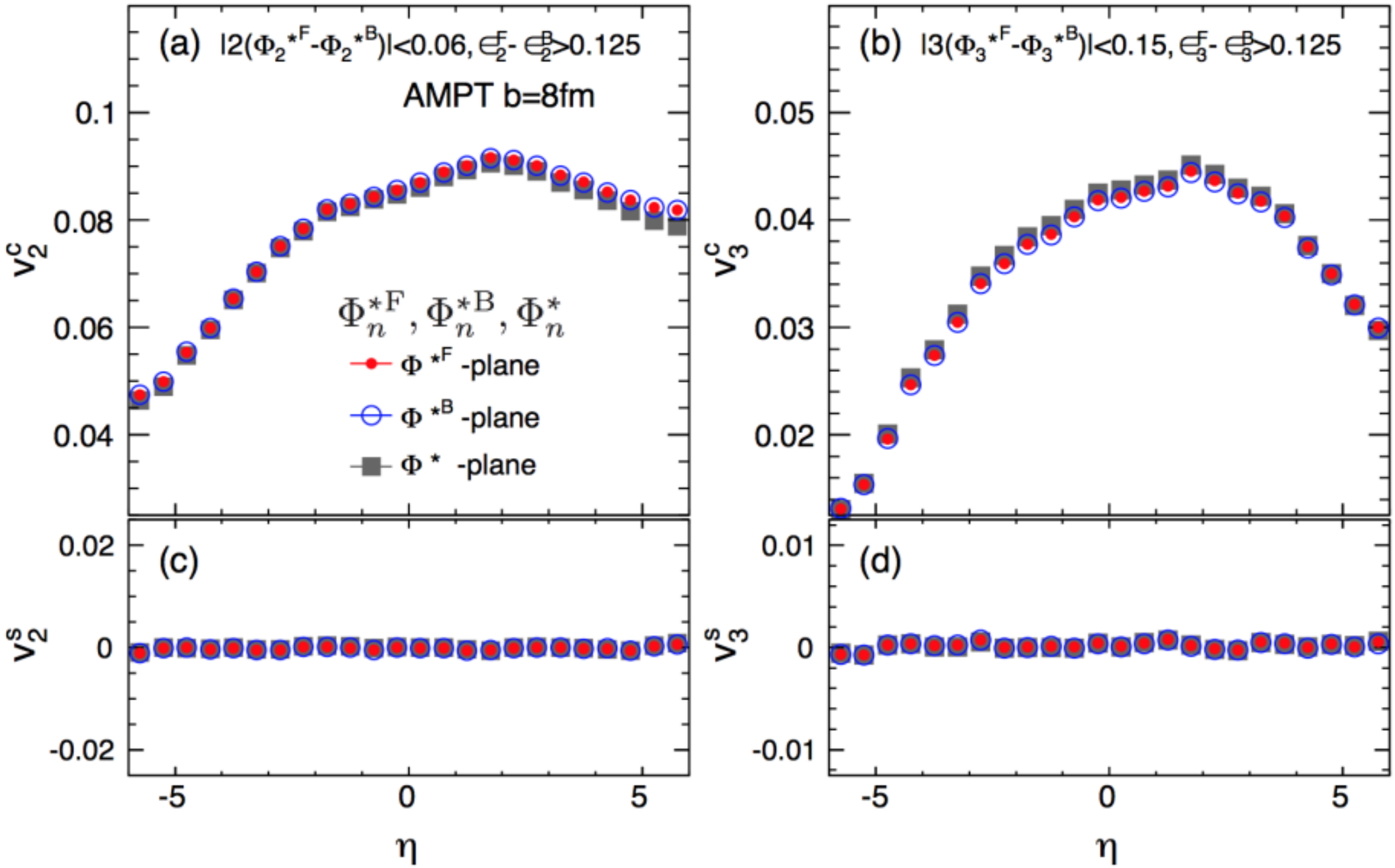
Initial twist survives to final state!!

Asymmetry

Select events with same PP but different eccentricity:

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

Observe clear F/B flow asymmetry:



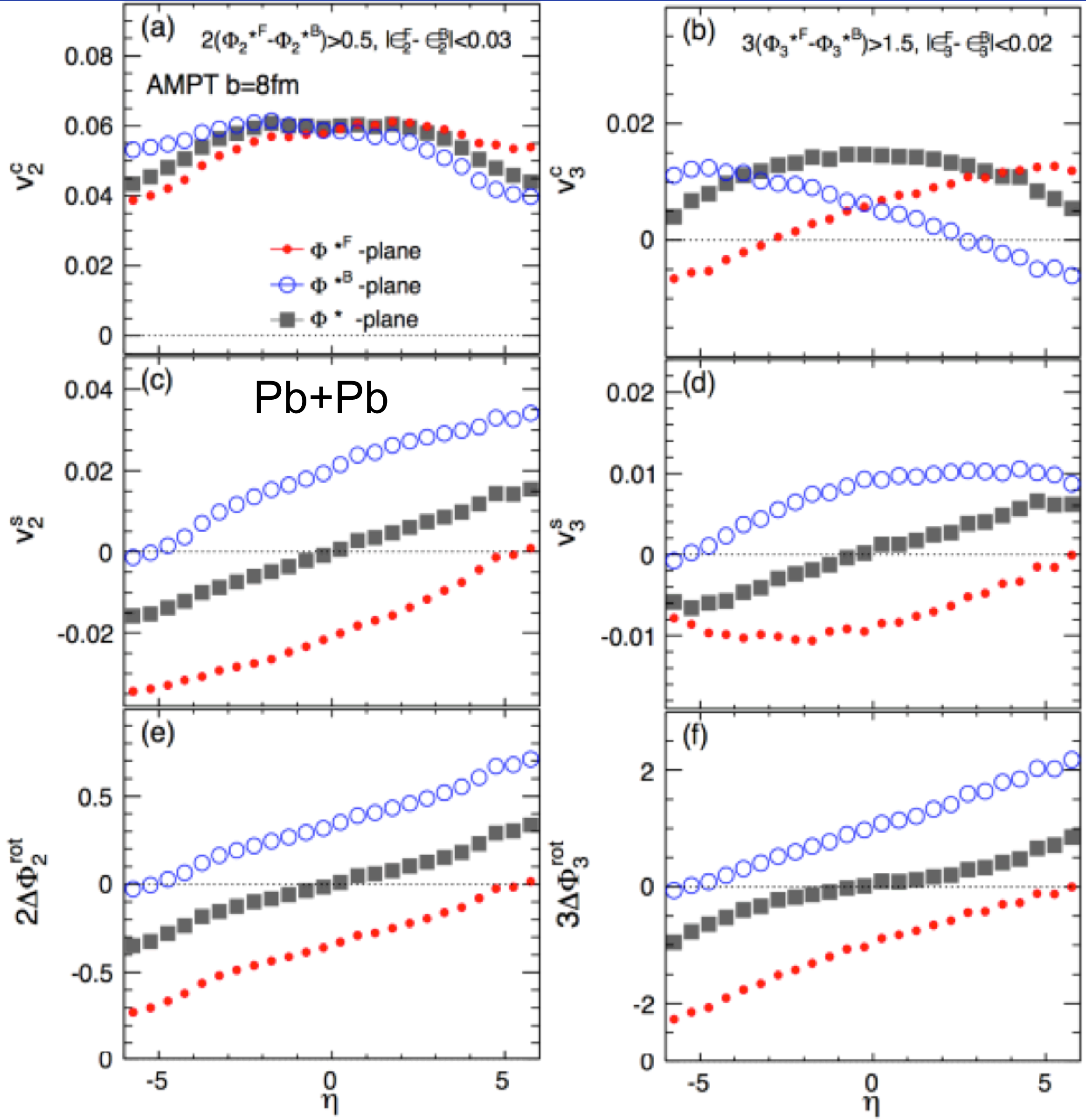
Twist

$$v_n^{\mathrm{c}}(\eta) = \langle \cos n\,(\phi(\eta) - \Theta_n)\rangle$$
$$v_n^{\mathrm{s}}(\eta) = \langle \sin n\,(\phi(\eta) - \Theta_n)\rangle$$

Select events with same eccentricity but different PP:

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

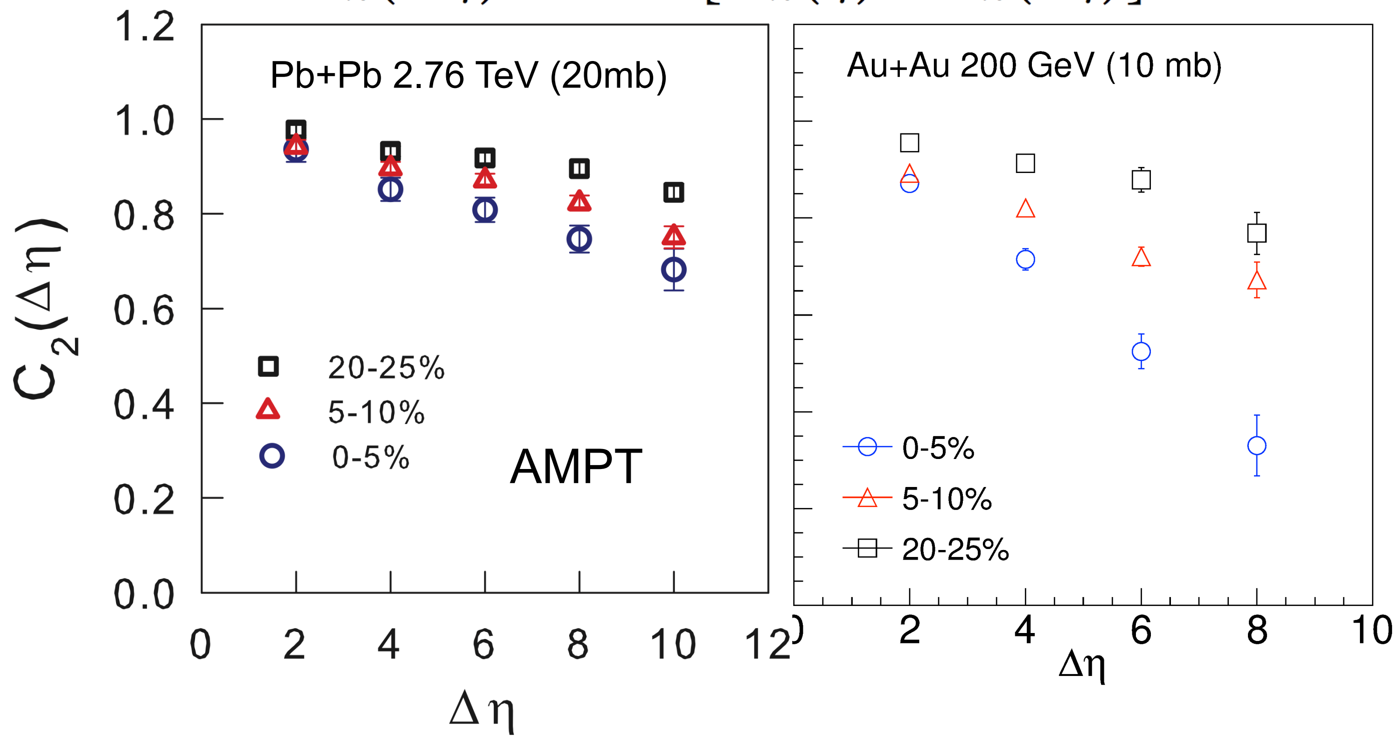
Observe clear F/B twist of EP angle:



Twist

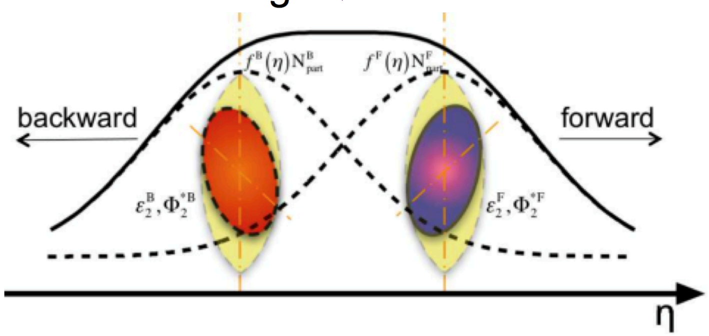
Longgang etc,
arxiv1410.8690

$$C_n(\Delta\eta) \approx \cos n\left[\Psi_n(\eta) - \Psi_n(-\eta)\right]$$

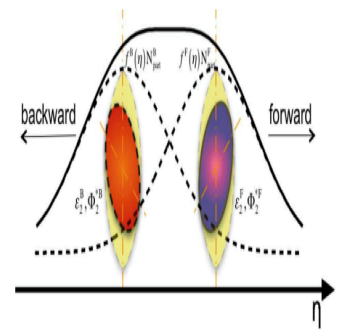


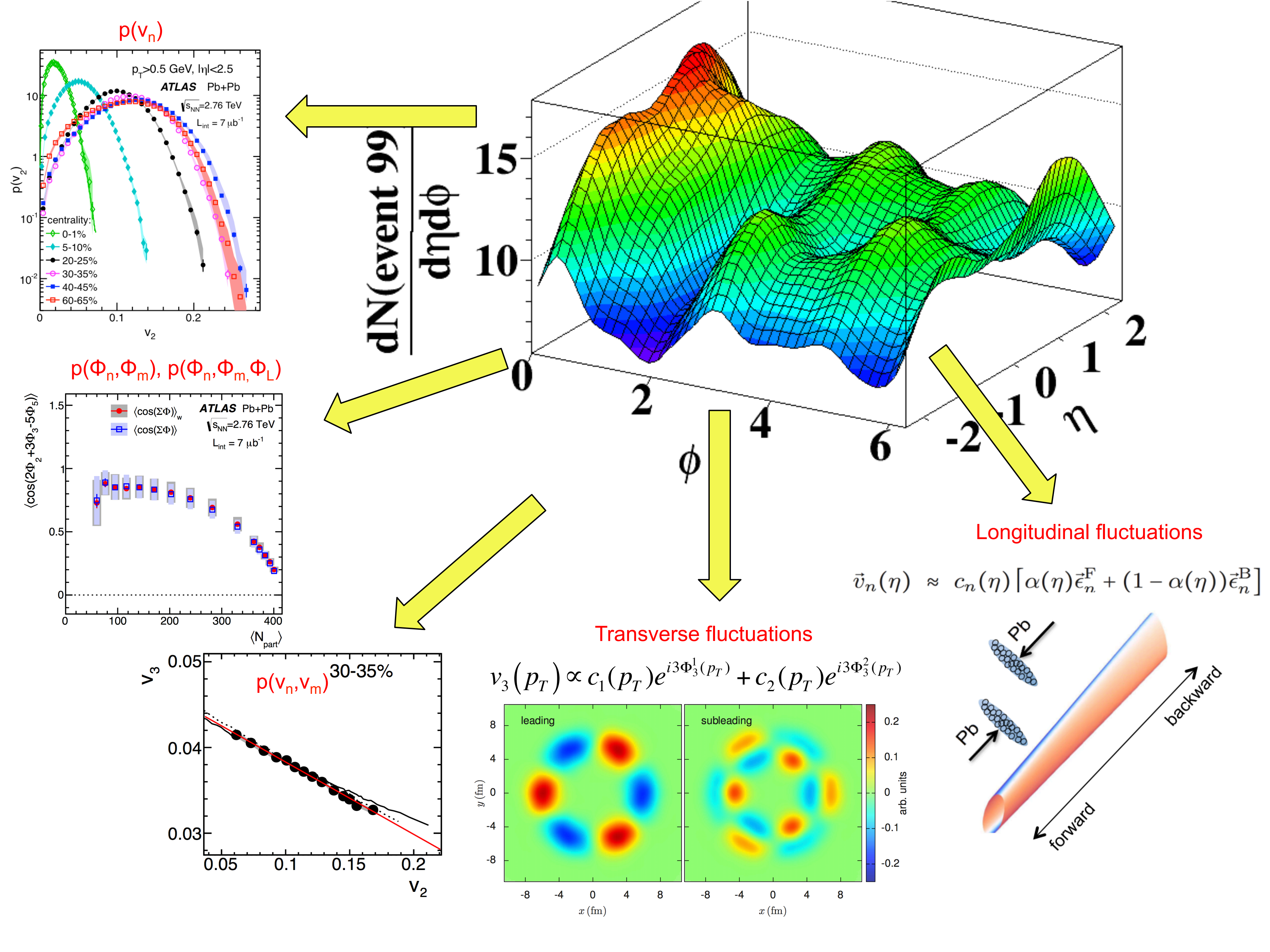
- Strong centrality and √s dependence, need both LHC & RHIC

High √s



Low √s





p(v_n)
p_T>0.5 GeV, |η|<2.5
ATLAS Pb+Pb
√s_NN=2.76 TeV
L_int = 7 μb^-1
p(v_2)
v_2
centrality:
0-1%
5-10%
20-25%
30-35%
40-45%
60-65%
p(Φ_n,Φ_m), p(Φ_n,Φ_m,Φ_L)
⟨cos(2Φ_2+3Φ_3-5Φ_5)⟩
⟨cos(ΣΦ)⟩_w
⟨cos(ΣΦ)⟩
⟨N_part⟩
dN(event 99) / dηdφ
φ
η
p(v_n,v_m)
30-35%
v_3
v_2
Transverse fluctuations
$v_3(p_T) \propto c_1(p_T)e^{i3\Phi_3^1(p_T)} + c_2(p_T)e^{i3\Phi_3^2(p_T)}$
leading
subleading
y (fm)
x (fm)
arb. units
Longitudinal fluctuations
$\vec{v}_n(\eta) \approx c_n(\eta)\left[\alpha(\eta)\vec{\epsilon}_n^{\mathrm{F}} + (1-\alpha(\eta))\vec{\epsilon}_n^{\mathrm{B}}\right]$
Pb
Pb
backward
forward