Small scale fluctuations and flow correlations

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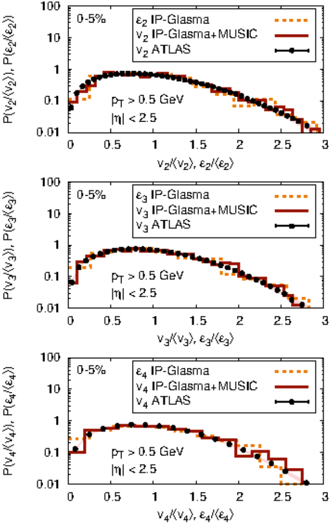
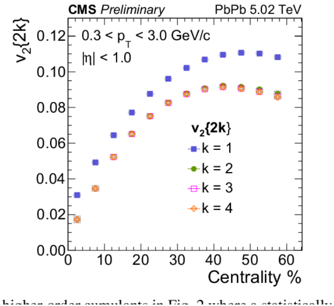
R. Samanta, PB, PRC 109 (2024) 064910

Distribution of flow harmonics



Gale, Jeon, Tribedy, Venugopalan arXiv: 1210.5144

$v_2\{2\} > v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\}$



CMS Nucl. Phys. A937 (2017) 401

$$V_n = \kappa_n \epsilon_n$$
$$\epsilon_n = \int r^n e^{in\phi} \rho(x,y) d^2 r$$

Mapping the flow fluctuations

$$\frac{dN}{d\phi dp d\eta} \propto 1 + 2V_2(p,\eta)e^{-i\ 2\phi} + 2V_3(p,\eta)e^{-i\ 3\phi} + \dots$$

Can we map the flow $V_n(p,\phi)$?

No !

Mapping the flow fluctuations

$$\frac{dN}{d\phi dp d\eta} \propto 1 + 2V_2(p,\eta)e^{-i\ 2\phi} + 2V_3(p,\eta)e^{-i\ 3\phi} + \dots$$

Can we map the flow $V_n(p,\phi)$?

No !

But we could map the covariance

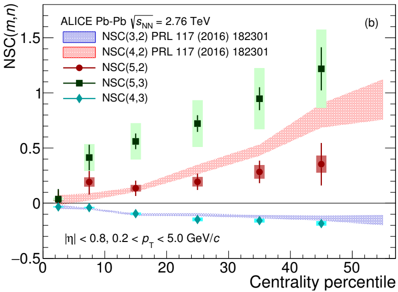
$$\langle V_n(p_1,\eta_1)V_n^\star(p_1,\eta_2)\rangle$$

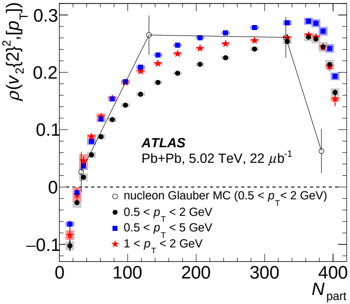
or the correlation

$$\frac{\langle V_n(p_1,\eta_1)V_n^\star(p_2,\eta_2)\rangle}{\sqrt{\langle V_n(p_1,\eta_1)V_n^\star(p_1,\eta_1)\rangle\langle V_n(p_2,\eta_2)V_n^\star(p_2,\eta_2)\rangle}}$$

Fluctuations - covariances . . .

- mixed cumulants/covariances





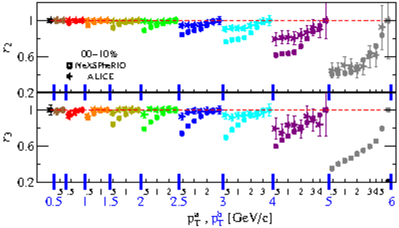
$$\frac{\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle}{\langle v_n^2\rangle\langle v_m^2\rangle}$$

$$\rho(p_t, v_2^2) = \frac{Cov([p_T], v_n^2)}{\sigma([p_T])\sigma(v_n^2)}$$

Flow decorrelation in p_T

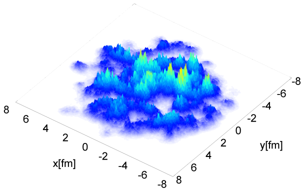
factorization breaking coefficient

$$r_n(p_1,p_2) = \frac{\langle V_n(p_1)V_n^\star(p_2)\rangle}{\sqrt{\langle V_n(p_1)V_n^\star(p_1)\rangle\langle V_n(p_2)V_n^\star(p_2)\rangle}}$$



Gardim, Grassi, Luzum, Ollitrault arXiv: 1211.0989

lumpy structure of the initial density



Schenke, Tribedy, Venugopalan arXiv: 1206.6805

$$r_n(p_1,p_2) \le 1$$

correlation coefficient

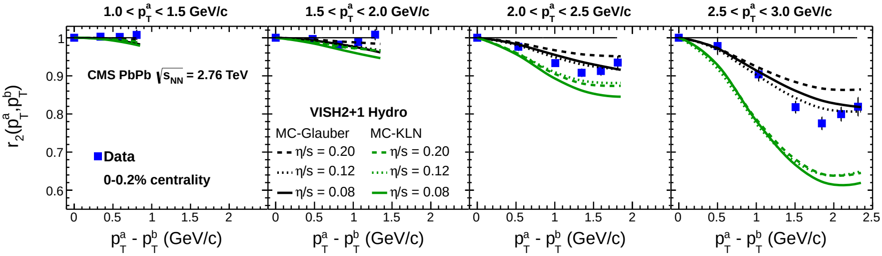
$$r_n(p_1,p_2) = \rho(V_n(p_1), V_n(p_2))$$

other modes in initial density

A. Mazeliauskas, D. Teaney PRC (2015)

$$\epsilon_n \propto \int e^{in\phi} r^n \rho d^2 r \quad , \quad \epsilon_{n,k} \propto \int e^{in\phi} r^k \rho\rho d^2 r$$

Experiment vs theory

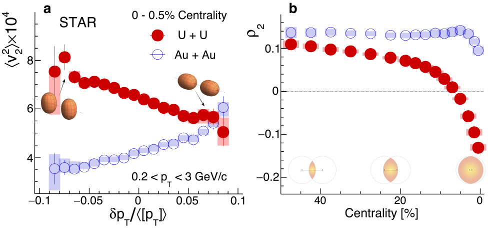


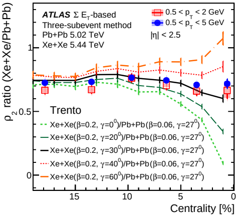
CMS arXiv: 1503.01692

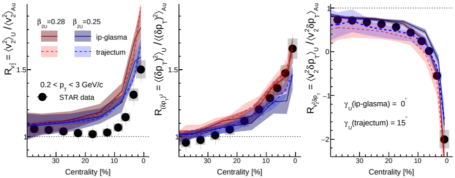
- qualitatively described by models
- can provide constraints on initial fluctuations

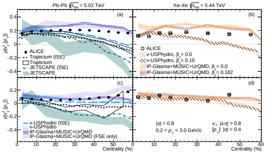
$\rho([p_T], v_n^2)$ correlation coefficient

central collisons, sensitive to nuclear deformation: G. Giacalone PRC 2020

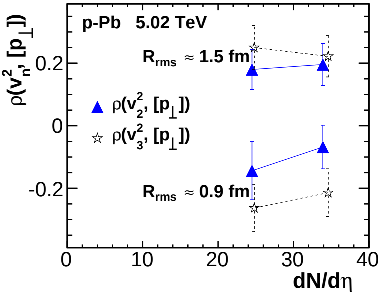








Small scales



ρ sensitive sensitive to small scale flc. in p+Pb

Differential measurements

average flow

- $\langle V_n V_n^\star \rangle$
- higher cumulants $v_n\{4\}$, $v_n\{6\}$
- scaled cumulants
$\langle V_n \ldots V_m^\star \ldots \rangle$
- $\langle \delta p_T v_n^2 \rangle$, $\langle \delta p_T c_n\{4\} \rangle$

$+$ combination $+$ normalizations

differential flow

- $\langle V_n V_n^\star(p) \rangle$ in $v_n(p)$
- $\langle V_n^2 V_n^\star V_n^\star(p)$ in $v_n\{4\}(p)$

- factorization breaking, PCA
$\langle V_n(p_1) V_n^\star(p_2) \rangle$, $\langle V_n^2 V_n^2(p) \rangle$
$+$ combinations $+$ normalizations

IMPORTANCE

$v_n(p)$ model vs data

PID $v_n(p)$ (quark scaling, intermediate and high p_T, viscosity effects, heavy quarks)

factorization breaking $r_n(p_1, p_2)$ (differential map of fluctuations)

there is more in HI than in $v_v = \kappa_n \epsilon_n$

If you measure higher moments, measure covariances

unknown multidim. probability distribution $P([p_T], V_2, V_3, \ldots ?)$

measure as many (mixed) moments (cumulants) as possible

e.g. $\langle \delta p_T^2 \rangle$, $\langle \delta p_T^3 \rangle$, $\langle \delta p_T^4 \rangle$, $\rho([p_T], v_n^2)$, $\rho([p_T], v_2^2, v_3^2)$

differential

If we measure

$\langle \delta p_T^2 \rangle$, $\langle \delta p_T^3 \rangle$, $\langle \delta p_T^4 \rangle$

$\langle V_n V_n(p)^\star \rangle$, $\langle v_n(p)^2 \rangle$ $\langle V_n^2 V_n(p)^2 \rangle$, $\langle V_n^2 V_n^\star(p)^2 \rangle$

why not

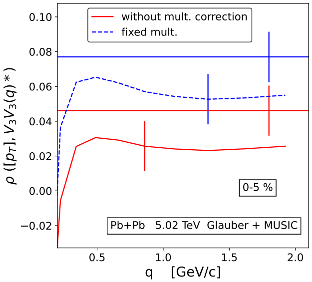
$Cov(\delta p_T, V_n V_n^\star(p))$ or $Cov(\delta p_T, v_n(p)^2)$

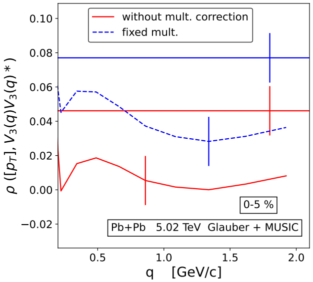
Differential p_T-$v_n(q)$ correlation coefficient

$$\rho\left(V_n V_n(q)^\star, p_T\right) = \frac{Cov\left([p_T], V_n V_n(q)^\star\right)}{\sqrt{Var\left([p_T]\right) Var\left(V_n V_n(q)^\star\right)}}$$

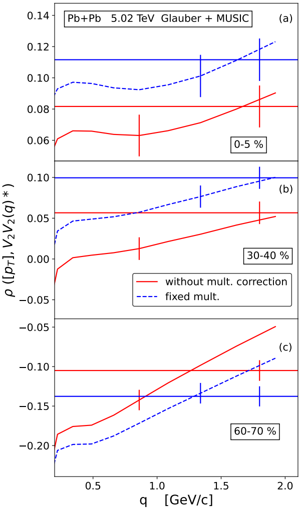
$$\rho\left(V_n(q) V_n(q)^\star, p_T\right) = \frac{Cov\left([p_T], V_n(q) V_n(q)^\star\right)}{\sqrt{Var\left([p_T]\right) Var\left(V_n(q) V_n(q)^\star\right)}}$$

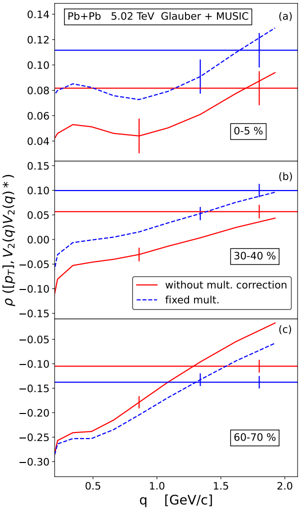
Note: other normalizations possible



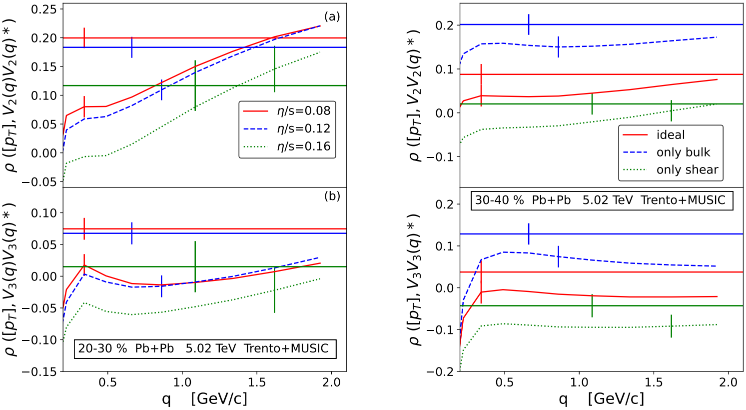


Differential p_T-$v_n(q)$ correlation coefficient





Viscosity dependence

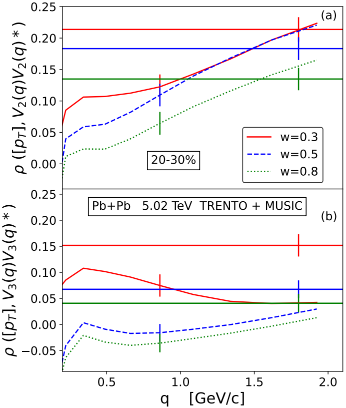


shear viscosity - shift, same shape

bulk viscosity - shift same shape

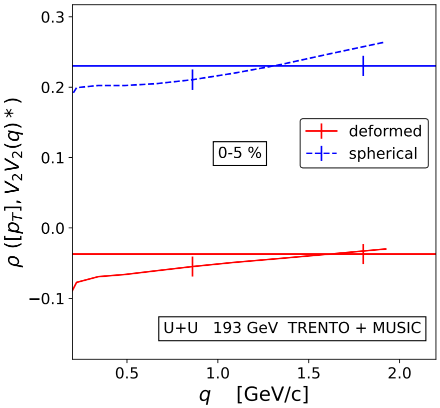
Change in $\rho\left([p_T], V_n V_n^\star\right)$ same q-dependence of $\rho\left([p_T], V_n V_n(q)^\star\right)$

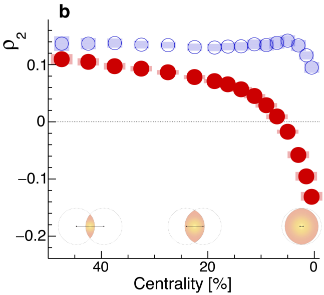
granularity in the initial state



$\rho\left([p_T], V_n(q) V_n(q)^{\star}\right)$ sensitive to granularity in the initial state

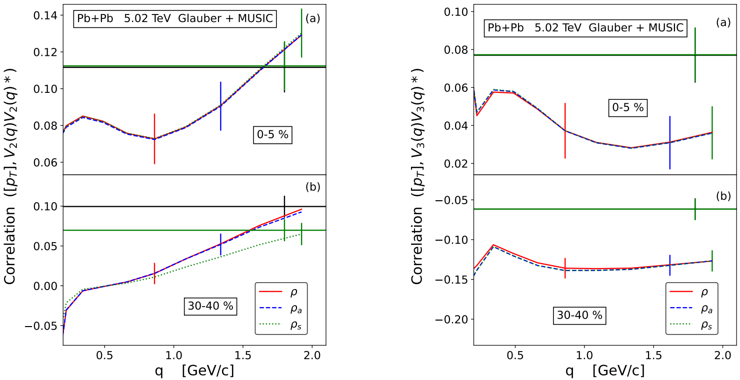
Deformation





deformation - similar to usual correlation $\rho(v_2^2, p_T)$

simplified expressions - experimentally accessible

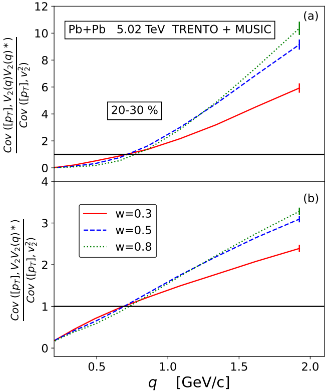


$$\rho_a\left([p_T], V_n(q)V_n(q)^\star\right) = \frac{Cov\left([p_T], V_n(q)V_n(q)^\star\right)\langle v_n^2\rangle}{\sqrt{Var\left([p_T]\right)\, Var\left(v_n^2\right)}\langle V_n(q)V_n(q)^\star\rangle}$$

$Var(v_n^2)$ instead of $Var\left(V_n(q)^2\right)$

Covariance

$$\frac{Cov\left([p_T], V_n(q) V_n(q)^\star\right)}{Cov\left([p_T], v_n^2\right)}$$



accessible experimentally

- q dependence sensitive to granularity

Results

- differential v_n-p_T correlators
- correlation coeffficient $\rho_s = \frac{Cov([p_T], V_n(q)V_n(q)^\star)\langle v_n^2\rangle}{\sqrt{Var([p_T])Var(v_n^2)\langle V_n(q)V_n(q)^\star\rangle}}$
- scaled covariance $\frac{Cov\left([p_T], v_n(q)^2\right)}{Cov([p_T], v_n^2)}$
- q-dependence sensitive to small scale flc. , ...

Outlooks

- subnucleonic d.o.f., small systems, clustering
- PID $\rho_s\left([p_T], V_n(q)V_n(q)^\star\right)$ and $\rho_s\left([p_T], V_n V_n(q)^\star\right)$
- mapping of p_T-V_n fluctuations
  $\langle V_n(q_1)V_n^\star(q_2)\rangle$, $\langle \delta p_T V_n(q_1)V_n^\star(q_2)\rangle$, $\langle (\delta p_T)^2 V_n(q_1)V_n^\star(q_2)\rangle$, ...
  different radial modes