Higher Flow Harmonics from the STAR Collaboration at RHIC
Why $v_n$ Matters & What It Means

$N_{\text{pairs}} \propto 1 + 2v_1^2 \cos \Delta \varphi + 2v_2^2 \cos 2\Delta \varphi + 2v_3^2 \cos 3\Delta \varphi + 2v_4^2 \cos 4\Delta \varphi + \ldots$

Fluctuations imply odd terms aren’t necessarily zero and $v_n^2$ vs. $n$ will provide information about the system like lifetime, viscosity, etc.

Kowalski, Lappi and Venugopalan, Phys.Rev.Lett. 100:022303

Why $v_n$ Matters & What It Means

$N_{\text{pairs}} \propto 1 + 2v_1^2 \cos \Delta \phi + 2v_2^2 \cos 2\Delta \phi + 2v_3^2 \cos 3\Delta \phi + 2v_4^2 \cos 4\Delta \phi + \ldots$

Kowalski, Lappi and Venugopalan, Phys.Rev.Lett. 100:022303
K. Werner, I. Karpenko, K. Mikhailov, T. Pierog, arXiv:11043269

Analogous to the Power Spectrum extracted from the Cosmic Microwave Background Radiation

Correlation Landscape at RHIC

The correlation landscape is rich in information on jets, jet modification, transport, early-times, and space-momentum correlations like flow.

The understanding of higher harmonic $v_n^2$ is central to understanding the meaning of the correlations landscape in heavy ion collisions.

We’ll use correlations to extract the power spectrum from heavy-ions and investigate its possible relationship to the early times.

P. S., A. Mocsy, B. Bolliet, Y. Pandit, arXiv:1102.1403
Higher $v_n$ from 2 Particle Correlations

$Q$-Cumulants: 200 GeV Au+Au $|\eta|<1.0$

$n=1$ shows large difference between LS and CI: charge and momentum conserv?

$n=3$ exhibits effects of elliptic overlap geometry

$n=4$ and larger show $1/N$ dependence typical of non-flow correlations

Higher $v_n$ from 4 Particle Correlations

$v_n\{4\}$ consistent with zero for odd terms. Consistent with $v_3^2\{2\}$ being due to non-flow and/or with $v_n \propto \varepsilon_{n,\text{part}}$: $v_n^4\{4\} \propto \varepsilon_{n,\text{std}}$

For 0-2.5% central $v_2\{4\} \approx 0$ indicates elliptic shape is nearly gone. We’ll look at the shape of $v_n^2\{2\}$ vs. n for nearly symmetric collisions.

$v_4$ from mixed harmonics is within errors of $v_4^4\{4\}$:
$v_4 \sim v_2^2 \sim 0.1^2$
$v_4^4 \sim 10^{-8}$


$v_n^2\{2\}$ vs $n$ for 0-2.5% Central

This is the Power Spectrum of Heavy-Ion Collisions

$v_n^4$ is zero for 0-2.5% central: look at $v_2^2\{2\}$ vs $n$ to extract the power spectrum in nearly symmetric collisions

Fit by a Gaussian except for $n=1$. The width can be related to length scales like mean free path, acoustic horizon, $1/(2\pi T)$...

Integrates all $\Delta \eta$ within acceptance: we can look more differentially to assess non-flow

P. Staig and E. Shuryak, arXiv:1008.3139 [nucl-th]
A. Adare [PHENIX], arXiv:1105:3928
Large $\Delta \eta$ $a_n$ necy spectrum

if flow dominates the correlations $a_n \approx v_n^2$

$$R_2 = \frac{\rho_{12}}{\rho_1 \rho_2} - 1$$

(c) 0-5%

→ Fourier Tr. (0.7<$\Delta \eta$<2.0) →

$$C = \frac{\sum_{i=1}^{n_1} \sum_{j=1}^{n_2} p_{T,i} p_{T,j}}{\rho_{1} \rho_{2}} - \frac{\rho_{1} \rho_{2}}{\rho_{1} \rho_{2}}$$

(f) 0-5%

See also: A. Mocsy, P. S., arXiv:1008.3381 [hep-ph]
An Interesting Feature From Models

In models where space-momentum correlations develop, the initial density fluctuations manifest in momentum space.

For $b=0$ fm, at low $p_T$, $v_n$ drops with $n$.

At intermediate $p_T$, $v_3 > v_2$ suggesting a local maximum of the power spectrum at $n=3$: already seen in $v_n^{2/\epsilon^2}_{\text{part,n}}$ from mid-central STAR data.

G. L. Ma and X. N. Wang, PRL106, 162301 (2011)

Correlations at Intermediate $p_T$

$v_3$ should be most evident at intermediate $p_T$ and for central collisions where the overlap geometry is most symmetric.

For 0-1% central, $n=3$ double hump is present on the away-side without $v_2$ subtraction.

We see effects consistent with expectations, we’ll investigate further by looking at various measurements related to $v_n$. 

See Poster: C. de Silva (255, Board 15)
Correlations at Intermediate $p_T$

$v_3$ should be most evident at intermediate $p_T$ and for central collisions where the overlap geometry is most symmetric.

Interesting structure is also seen in raw correlations for non-pion triggers (mostly protons) at $\Delta\eta>0.7$.

We see effects consistent with expectations, we’ll investigate further by looking at various measurements related to $v_n$.

See Talk: K. Kauder
Non-flow or Flow

$v_2$ subtracted di-hadron correlations: $v_2$ estimated using $\Psi_{EP}(2.8<|\eta|<3.8)$

Subtracting $v_2$ measured relative to the event-plane at large $\eta$ leads to residual structure: adding $v_3$ doesn’t account for residual

There could be a $\Delta \eta$-dependence to $\langle \Psi_{EP,1}\Psi_{EP,2}\rangle$ and/or these structures are non-flow

$v_2\{EP\}$ measured with a forward event plane could underestimate the $v_2$ for dihadrons at smaller $\Delta \eta$.

Let’s look at the $\Delta \eta$ dependence of $v_3$ from a Fourier Trans. of 2 particle correlations


Initial state density correlations may drop with Δy: interesting physics σ_{Δy} \sim 1/\alpha_s?

Fit with a wide and a narrow peak. Wide peak amplitude first drops with 1/N but then deviates from trend near N_{part}=50. Above that it follows an N_{part} \varepsilon^2_{3,part} trend

Is the wide Gaussian non-flow as in previous interpretations* and/or Δη dependence of initial density fluctuations?


Petersen, Greiner, Bhattacharya & Bass, arXiv:1105.0340
$v_3^2$ at Large $\Delta \eta$

$\langle \cos 3(\varphi_1 - \varphi_2) \rangle$ for $|\eta_1 - \eta_2| > 0.6$

Centrality variable $L$ estimates the transverse size of the system.

$v_3^2$ for $\Delta \eta > 0.6$ rises then falls with centrality as the overlap shape becomes symmetric. Similar to $v_2$.

Almond shape of the overlap area appears to couple to $n=3$.

See Poster: J. Thomas (576, Board #43)

D. Teaney, L. Yan, arXiv:1010.1876 [nucl-th]
P. S., A. Mocsy, B. Bolliet, Y. Pandit, arXiv:1102.1403

See Poster: Li Yi 520, board #33
$v_3$ and $(v_3/v_2)^2$ vs centrality and $p_T$

$v_3\{2\}$ using separate $\eta$ ranges: $\eta_1<-0.5$ and $\eta_2>0.5$

For central collisions at intermediate $p_T$, $v_3\{2\} \geq v_2\{2\}$: what non-flow source would give such a behavior?

Weak $v_3\{2\}$ centrality dependence & $v_3 \geq v_2$ in central were predicted by models based on initial state density inhomogeneity $\rightarrow$ leading explanation
Analysis based on Q-Cumulants for all charges and \(-1<\eta<1\)

\(v_{3}^{2}/\varepsilon_{3,\text{part}}^{2}\) follows a simple trend with \(N_{\text{part}}\): consistent with fits to \(v_{3}^{2}\{2\}\) vs \(\Delta\eta\)

Slope of \(v_{3}^{2}/\varepsilon_{3,\text{part}}^{2}\) is increasing with beam energy: what about the difference between \(v_{2}^{2}\{2\}-v_{2}^{2}\{4\}\)
$v_2^2\{2\} - v_2^2\{4\} \approx \delta + 2\sigma_v^2$ also shows an intriguing energy dependence: rise of jets or increase in conversion of initial anisotropy into momentum space?

Possible sensitivity to EOS needs to be further investigated

Data at 5, 19.6 (taken) and 27 GeV are needed
Conclusions

We presented the 2 & 4 particle cumulants for $v_n$ up to $n=6$: results are consistent with $v_n \propto \varepsilon_{\text{part},n}$ and/or non-flow

Indications of higher harmonic flow seen in RAW dihadron correlations (consistent with initial density fluctuation models)

We examined the $\Delta \eta$ dependence of $v_3^2\{2\}$ and decomposed it into a narrow and wide Gaussian: the centrality evolution of the amplitude of the wide Gaussian follows $N_{\text{part}}\varepsilon^2_{\text{part},n}$

In central collisions, $v_3\{2\}$ at intermediate $p_T$ becomes larger than $v_2\{2\}$ also consistent with models of fluctuating initial conditions

Data appear to favor $v_n^2 \propto \varepsilon^2_{\text{part},n}$ and non-negligible higher harmonics; where $v_n^2$ drops with $n$ as a Gaussian. Other non-flow interpretations are also being pursued
An Interesting Feature From Models

In a system where space-momentum correlations develop, the initial density fluctuations appear to manifest in momentum space.

For $b=0$ fm, at low $p_T$, $v_n$ drops with $n$.

At intermediate $p_T$, $v_3 > v_2$ suggesting a local maximum of the power spectrum at $n=3$: already seen in $v_n^2/\varepsilon_{\text{part},n}^2$ taken with STAR data.

G. L. Ma and X. N. Wang, PRL106, 162301 (2011)