# Azimuthal Anisotropy: The Higher Harmonics 

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- $\mathrm{v}_{4}$ - a small, but sensitive observable for heavy ion collisions: PRC 68, 031902(R)
- Strong potential to constrain model calculations and carries valuable information on the dynamical evolution of the system
- Magnitude, and even the sign, sensitive to initial conditions of hydro

momentum space

peanut shape


$\sum \bigwedge_{S T A R}$


## $\mathbf{v}_{2}$ determines the reaction plane

- $\mathrm{v}_{1}$ (STAR talk by Aihong Tang), $\mathrm{v}_{4} \mathrm{v}_{6}$ and $v_{8}$ using second harmonic particles
- Possible because $\mathrm{v}_{2}$ is so large at RHIC and event plane resolution is so good in STAR

Correlation of two event planes:
$4^{\text {th }}$ harmonic of one subevent relative to $2^{\text {nd }}$ harmonic of other subevent
$v_{4}$ is positive


## Terminology

- $\mathrm{n}=$ harmonic number
- Common usage
- $\mathbf{v}_{\mathrm{n}}=$ harmonic order n with respect to event plane of same order
- $\mathbf{v}_{\mathrm{n}}\{\mathrm{N}\}=\mathrm{N}$-particle cumulant for $\mathrm{v}_{\mathrm{n}}$
- New addition
- $\mathbf{v}_{\mathrm{n}}\left\{E \mathrm{P}_{2}\right\}=$ harmonic order n with respect to event plane of order 2


## Method

## - Described in methods paper:

- Poskanzer and Voloshin, Phys. Rev. C 58, 1671 (1998)


Signal to fluctuation noise

$$
\mathrm{v}=\frac{\mathrm{v}_{\text {observed }}}{\text { resolution }}
$$

## $v_{4}\left(p_{t}\right)$



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## $\mathrm{v}_{4}\left(\mathrm{p}_{\mathrm{t}}\right)$ Scaling



Definitely greater than 1.

## $\mathrm{v}_{4}$ from $\mathrm{f}_{2}$

$\rho(\phi)=\rho_{0}\left(1+2 f_{2} \cos (2 \phi)+2 f_{4} \cos (4 \phi)+2 f_{6} \cos (6 \phi)+\ldots\right)$
$v_{n}\left(p_{T}\right)=\frac{\int d \phi \cos (n \phi) \mathrm{I}_{n}(k \alpha(\phi)) \mathrm{K}_{1}(k \beta(\phi))}{\int d \phi \mathrm{I}_{0}(k \alpha(\phi)) \mathrm{K}_{1}(k \beta(\phi))}$
Blast Wave

Fit $\mathrm{v}_{2}$


## Blast Wave $\mathbf{v}_{4}$ fit



## Parton Coalescence and Scaling

Assuming coalescence of quarks:

$$
\frac{d N_{n}}{d y p_{T} d p_{T} d \varphi} \sim\left(1+2 v_{2}^{q} \cos (2 \varphi)+2 v_{4}^{q} \cos (4 \varphi)+\ldots\right)^{n} \underset{2 \text { for mesons }}{n}
$$

$$
v_{4} / v_{2}^{2} \approx 1 / 4+1 / 2\left(v_{4}{ }^{q} /\left(\mathrm{v}_{2}^{\mathrm{q}}\right)^{2}\right), \text { but experimentally it is } 1.2
$$

Therefore, $\mathrm{v}_{4}{ }^{9}$ is greater than zero
Assuming scaling for quarks:

$$
\begin{aligned}
& \mathrm{v}_{\mathrm{n}} \mathrm{q}=\left(\mathrm{v}_{2}^{\mathrm{q}}\right)^{(\mathrm{n} / 2)} \\
& v_{4} / v_{2}^{2} \approx 1 / 4+1 / 2=3 / 4, \text { but experimentally it is } 1.2
\end{aligned}
$$

Therefore, $\mathrm{v}_{4}{ }^{\mathrm{q}}$ is even greater than simple parton scaling would indicate

## The Peanut Waist

High $p_{t}$


- No waist:



## $\mathrm{v}_{4}\left(\mathrm{p}_{\mathrm{t}}\right.$, cent $)$



## $\mathbf{v}_{4}$ (centrality)



## $\mathbf{v}_{4}$ (centrality)



## $\mathbf{v}_{4}$ (centrality)




## v triply integrated in MTPC

| $\underline{\mathrm{v}}$ | $\underline{\%}$ |
| :--- | :--- |
| 2 | $5.18+/-0.005$ |
| 4 | $0.44+/-0.009$ |
| Two sigma upper limit |  |
|  | $0.043+/-0.037$ |
| 8 | is $0.1 \%$ |
| 8 | $-0.06+/-0.14$ |

## Conclusions

- $\mathbf{V}_{4}$
- Integrated, a factor of 12 smaller than $\mathbf{v}_{2}$
- $\mathbf{v}_{2}{ }^{2}$ scaling
- Small, but significant
- $\mathbf{V}_{6}$
- Probably another factor of 10 smaller
- Consistent with $\mathbf{v}_{2}{ }^{3}$ scaling
- Blast Wave
- $f_{4}$ finite, $s_{4}$ needed for good fit
- Parton coalescence
- $\mathrm{v}_{4}{ }^{q}$ finite and greater than $\left(\mathrm{v}_{2}{ }^{q}\right)^{2}$
- Hydro
- Predicts a waist, but not observed


## spares

- Hydro
- $\mathbf{V}_{4}$ seems to fit
- $\mathbf{v}_{6}$ is zero instead of negative from hydro


## - $\mathrm{V}_{4}\left\{\mathrm{EP}_{4}\right\}$

.3x high because of either fluctuations or nonflow

## $\mathrm{v}_{4}$ and $\mathrm{v}_{6}$ Hydro

- Points: centrality 20-30\% data for charged particles
- Lines: Kolb hydro at b=7 fm for positive pions



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## Search for higher harmonics

- Long History
- Voloshin at CERES
- Me and Voloshin with NA49 data
- Large, and decreasing slowly with harmonic number
- Probably all non-flow effects
- Except Voloshin and Zhang at AGS
- E877: PRL 73, 2532 (1994)
. Q distribution method


## Non-flow and/or Fluctuations



For $\mathrm{v}_{2}$, about 20\% reduction from $v_{2}\{2\}$ to $v_{2}\{4\}$

For $\mathrm{v}_{4}$, up to a factor 3 difference!



## $v_{4}$ at high $\eta$



- Signal in the FTPCs consistent with 0
- Drop of $v_{4}$ from TPC to FTPC faster than for $\mathbf{v}_{2}$

